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Test Infrastructure and Accelerator Research Area

Status Report

General Report on key accelerator research areas and key R&D issues

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Test infrastructure and Accelerator Research Area

General Report on Key Issues

Deliverable 4.1

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D4.1 - KIR
General Report on Key Issues

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1 Introduction

The overall purpose of the TIARA Consortium is to create a single European distributed accelerator R&D infrastructure, allowing the relevant communities to develop a strong and sustainable accelerator programme.

In this context the general objective of WP4 "Joint R&D Programming" of TIARA is the promotion and support of a coherent and comprehensive Joint R&D programme in the field of accelerator science. This process will identify the activities in accelerator science to be carried out by a broad community within the distributed TIARA infrastructure (as assessed by WP3 "R&D Infrastructures").

The first task of the WP4 (WP4.1 "*Identification of Key Accelerator Research Areas and Key Technical Issues for a coherent joint R&D programme*") is therefore devoted to identify the critical areas and specific technical issues in the field of accelerator science to promote and support, at later stages, the development of a joint R&D programme which will be carried out with the European distributed accelerator R&D infrastructure, as proposed by TIARA. For many accelerators in construction or being planned, as well as for novel accelerator concepts, there is currently significant overlap in several technical requirements and in the designs of many needed components. Therefore the coordination of key R&D activities will lead to higher efficiencies and substantial savings in resources and production times. In addition this coordination will enable shorter commissioning times and more robust operation of the future facilities.

The WP4 work plan implies that the R&D Programme which will be presented at the end of the TIARA-PP activities is by its nature “infrastructure oriented”, that is, it deals with R&D topics that will strongly benefit from the access to existent or new infrastructures of the distributed TIARA network and their future consolidation, which is the scope of the WP3 ongoing survey and future activities.

2 Identification of critical research areas and technical issues and future WP4 work plans

Objective of this deliverable is the identification of the critical Key Accelerator Research Areas (KARA) and Key Technical Issues (KTI) for R&D – and their synergies – in close interaction with the other TIARA coordination and technical work packages.

In order to fulfill this task, an analysis of both the needs for the accelerators currently being developed and those that are being planned has been carried by the work package participants. In particular, future or foreseeable new large accelerator based facilities (e.g. LHC upgrades, ESS, IFMIF, ILC/CLIC, Neutrino and flavor factories, EURISOL, 4th generation light sources…) have been taken into consideration (as Subtask 4.1.1) for the identification of the R&D issues for particle accelerators ("project-oriented" R&D topics). The new challenging initiative of the SuperB factory in Italy, with plans of a wide European involvement of researchers and infrastructures, has also been considered and may lead to the identification of additional R&D key issues during its development. Furthermore emerging ideas and technologies have been analyzed (as Subtask 4.1.2) in terms of the R&D needs, so as to identify relevant issues and common component developments ("project-independent" topics).

A second task of WP4, (WP4.2 "*Procedures for initiating and methodology for costing and implementing collaborative R&D projects in a sustainable way*") – starting after the identification of the KARA and KTI – will be dedicated to the development of a common methodology and procedure for initiation, costing and implementing collaborative R&D projects. This task will be dedicated to the methodology and the procedure for evaluation of scientific and technical R&D activities, and to the assessment of their costs. The clear intention of this activity is to provide a common ground for the emergence and the development of international collaborative R&D activities that propose the exploitation of the analytical and instrumental capabilities offered by the distributed TIARA infrastructure. For the investigation of the proper communication tools needed for effective knowledge exchange between the partners, a link with WP5 ("Education and Training in Accelerator Science") activities will be established, whereas the Governance work package (WP2) will provide assistance for legal matters.

The outcome of the two tasks 4.1 and 4.2 will introduce the activity planned for WP4.3 "*Definition of the coherent collaborative accelerator R&D Program*" which will lead to the proposal of a coherent collaborative R&D programme to be carried on in the TIARA framework. In cooperation with WP3, the infrastructures needed for the validation of new proposed technologies and for the test of important prototypes will be assessed.

3 The list of KARA/KTI

The list presented in this deliverable has been based on a survey initiated in summer 2010 amongst the 37 EuCARD partners, on request of ESGARD [1, 2], for the preparation of a new proposal on accelerator R&D under the FP7 EC Call in 2011. It has been further extended in direct consultation between the institutional representative members in WP4, in many cases supported by consultation with further experts from their home institutions, acknowledged at the end of this document.

In order to provide structure to an otherwise seemingly scattered list of research topics, these have been aggregated in three very general domains:

- **Accelerator Components**,
  to collect research areas that are specific to a particular kind of fundamental component class of an accelerator facility (e.g. particle sources, RF structures or devices, magnets, diagnostics...).
- **Accelerator Technologies**,
  to collect research areas specific to a particular kind of accelerator technological system or subsystem needed for the operation of an accelerator facility (e.g. vacuum, RF, electronics...).
- **Accelerator Concepts**,
  to collect research areas specific to either novel concepts not currently exploited in accelerator facilities, or to general design concepts or issues that could be further exploited in the TIARA distributed network of infrastructures.

Within these domains, a limited number (~20) of broad Key Accelerator Research Areas have been identified in order to further aggregate a number of critical Key Technical Issues for each KARA under an organized structure. A larger number (>120) of Key Technical issues have been thus identified in this hierarchical structure (domain/KARA/KTI).

Scope of this deliverable is to summarize each of the identified Key Accelerator Research Area with a description of the relevant Key Technical Issues that have been identified as needing further R&D activities. A spreadsheet containing all these issues has been developed and will be used to later match each KTI to the relevant infrastructure list identified by WP3.
In the following each main domain will be presented, listing the underlying KARA and providing a concise textual description highlighting the main KTI identified by the WP.

3.1 Accelerator Components

This domain collects KARA related to the main functional components of accelerator facilities:

- Sources and Injectors
- RF structures
- RF systems
- SC magnets
- Conventional NC magnet systems (magnets, undulator/wigglers and pulsed devices)
- Diagnostics and instrumentation
- Targetry
- Radiation issues

For each of these very broad areas several more specific KTI have been identified and will be discussed in the following subsections.

3.1.1 Sources and Injectors

The particle injector is at the start of any accelerator facility and is one of the crucial key elements for providing the necessary beam characteristics (in terms of quality and intensity) to the application. Key technical issues have been identified for various types and technologies of source/injector systems:

- The achievement of **high brightness electron photoinjectors**
- The achievement of **high intensity ion and proton injectors**
- **High polarisation** electron and positron sources
- Generation of **hollow beams**
- **RFQ** design and development
- Beam **Funneling**

Improvements with respect to the present state of the art in the beam characteristics from these injector systems, in terms of quality, stability and reliability, will be beneficial for all future projects: for the planned LHC luminosity and intensity upgrades, for short wavelength compact FELs and ERLs, for high intensity hadron facilities (EURISOL, IFMIF, ESS, Neutrino factories, …) and for linear colliders.

3.1.1.1 High Brightness Electron Photoinjectors

The necessity to produce *ultra-low emittance* electron beams to drive short wavelength Free Electrons Lasers (FEL) and *high-intensity* electron beams to drive light sources based on the Energy Recovery Linac concept is an R&D challenge for the development of **high brightness electron photoinjectors**. Each of these two requirements presents challenges of its own for the source design and optimisation, particularly concerning the drive laser technology and photocathode material issues. At the high intensity end, Continuous Wave (CW) operation of photoinjectors represents a significant issue for several aspects, such as cathode lifetime, especially when the application combines this request with a gun technology capable of delivering low emittance beams. In order to address this combined challenge of low emittances and high intensities (~100 mA), a priority is the development of a super conducting CW photoinjector system. A crucial issue for high brightness electron injector systems in 4th generation light sources is the full control of the bunch compression stages, which is often limited by non-uniform beam shapes and coherent radiation effects driven by beam noise and intensity modulation, affecting ultimately output power levels and the length of the FEL device. Higher harmonic RF-linearizing systems, alternative compression schemes, laser heaters systems have been proposed and tested successfully to mitigate these phenomena; R&D aimed to their design consolidation and to the full integration in the injector systems will be beneficial to all future 4th generation light sources, improving the photon energy reach or making them compact and cheap. The combination of low emittance and ultra-short bunch length (fs to attosecond range) with high repetition rates is also one of the requirements in future light sources, e.g. for single shot crystallography of single molecules at high resolution.

3.1.1.2 Heavy Ion and Proton Injectors

For **heavy ion injectors** the technological critical issues are connected with the production of high intensity beams required by present and future heavy ion accelerator complexes. Basic studies for beam extraction and transportation from the plasma have been in the past – and still are – of outmost importance for improving the performances of ECR Ion Sources (ECRIS). Extraction matching of ECRIS beams via hexapole fields is one of the methods currently under study. In order to extract higher intensities from ECRIS, the development of higher frequency sources is an ongoing effort in the community. Other source types, e.g. MEVVA, CHORDIS or MUCIS, may provide higher heavy ion pulse intensities at low charge states and a lower duty cycle. The efficient acceleration of heavy ions at low energies in injection systems after the source is another issue which could be solved by demonstrating its feasibility with properly designed prototypes of Radio Frequency (RF) cavities of the CH-type. Space charge neutralized beam transport is a specific necessity for LEBT systems operated with high intensity beams in the heavy ion injection systems. This KTI is particularly important for the FAIR and IFMIF projects.

For **proton injectors**, the development of new ECR proton sources with better RF coupling and plasma diagnostics would be of significant benefit for the efficient productions of high intensity sources, required for many applications, e.g. ESS, EURISOL or MYRRHA/ADS. The understanding, modeling and optimization of these intense beams at low energies require also the improvement of current high space charge bunch transport simulation methods, since the challenge for high power proton injectors is often the beam transport and matching to the subsequent acceleration stages (e.g. the RFQ), without spoiling the beam performances obtained at the source.

3.1.1.3 High Polarization Electron and Positron Sources

Highly polarised electron and positron sources are an intrinsic requirement for any linear collider scheme, independently of the main linac technology (e.g. both for normal-conducting CLIC and the superconducting ILC proposals). There are still many technological challenges to be solved in order to cross the gap from today’s concepts to the actual devices that will be required in operation in the colliders of tomorrow. Polarized positron production schemes based on the conversion of polarized photons – produced in helical undulator by high energy (250 GeV) electron beams – or based on Compton sources require intensive R&D in most key components (e.g. lasers, rings, capture RF structures, conversion targets) for their technical demonstration. High degree polarized electron beams are also necessary to achieve the physics goals of the SuperB project in Italy, and this is obtained with a polarized electron injector and the control of its depolarization in the accelerator complex.

3.1.1.4 Hollow Beams

Given the present challenges in the collimation systems for high intensity proton beams and the successful experiment at the Tevatron, there has been renewed interest in the production of **hollow beams** for high intensity proton beam. The use of hollow beams would allow to extend conventional collimation systems beyond the present foreseen limits imposed by tolerable losses. While the concept has been proven at Tevatron, R&D is needed to provide the necessary alignment and control of the hollow beam profile and intensity.

3.1.1.5 RFQ Development

Radio Frequency Quadrupoles (**RFQs**) remain a major component system in many low energy accelerator chains for protons and ions (e.g. ESS, IFMIF, ADS systems, Radioactive beam facilities…). The development of specialized devices tailored for specific applications still present significant challenges for the realization (e.g. preservation of tight mechanical tolerance budget during brazing of long sections) and operation (e.g. handling of substantial heat loads in CW structures) of these devices as the design intensities continue to increase.

3.1.1.6 Beam Funneling for High Intensities

The combination of pre-accelerated beams from two independent sources by means of RF **funneling** stages as a mean to double the beam current for extremely high current applications (e.g. ADS systems for "industrial" waste transmutation with beam power levels in the range 10-100 MWs) need further study and demonstration. Double pre-accelerator stages with fast switching capabilities are currently envisaged in experimental ADS schemes (e.g. MYRRHA) as a way to meet the stringent demands on reliability and beam availability.

3.1.2 RF structures

A constant issue for RF structures, both for the normal conducting, room-temperature and for the superconducting, He-cooled, resonators is the possibility of increasing the accelerating gradients in a reliable way. Higher gradients are needed to reduce the footprint of next generation linear colliders (CLIC being the resistive option and ILC the superconducting one). Limits exist today for both technologies, which are set either by material issues or by fabrication and treatment procedures of the structures. Key issues in the RF structures area are:

- **High gradient** acceleration at low breakdown rates for normal conducting structures
- Development of **C-Band and X-Band** accelerating structures
- Stabilization of the **Bulk Nb technology** for maximal **yield** at the highest gradients
- Improvements of the **low beta cavity fabrication** technology
- **Power Couplers** for SRF Cavities at High Average Power
- **Overcoming the Performance** Limits of the Bulk Nb SRF Technology
- **Crab Cavity** Developments
- RF Structures for **6D Muon Beam Cooling**

3.1.2.1 High Gradient Acceleration at Low RF Breakdown Rates

At the forefront of the gradient requests is CLIC, with a design **accelerating gradient of 100 MV/m at low RF breakdown rates**. Fundamental studies are still needed to understand the characteristics of RF breakdown, in order to open the possibility of preventing, mitigating or controlling its occurrence. The CLIC structures present many challenges for their fabrication, processing and operation, especially in view of their industrialization towards mass production. Several alternative designs and fabrication procedures have been studied and prototypes will be built and qualified at the CERN CTF3 by the CLIC Collaboration in order to demonstrate the full achievement of CLIC goals. The state of RF surfaces play a role in understanding field emission mechanisms, and this KTI overlaps with the KTI on stabilization of the Nb technology, sharing common R&D actions on cleaning and characterizing RF surfaces, as already explored by the Linear Collider community.

3.1.2.2 Development and Engineering of C-Band and X-Band Structures

RF structures in C-Band and X-Band are also being considered in most FEL facilities driven by normal conducting linacs in Europe (e.g. PSI, SPARC at INFN, Elettra) either in order to profit from higher gradients than the standard S-Band systems or as RF linearizer systems in the injector stage. A wide synergy exists in the scope of these programmes, and common R&D measures would be beneficial to a wide and diversified community, as also demonstrated by the TIARA-PP WP8 HGA exploiting the C-Band technology as a mature option for both the FEL projects (SPARC, SwissFEL) and the high luminosity electron-positron collider communities (SuperB). The performances of these devices have been confirmed in prototypical activities and at the Japanese SACLA XFEL facility, but an intensive R&D program is still needed, especially in Europe, in order to address the detailed engineering and industrial fabrication procedures of the structures needed for their cost reduction to a level comparable to that reached by standard S-Band systems.

3.1.2.3 Consolidation of Nb Technology for Maximum Yield at Highest Gradients

For the **superconducting RF structures** - field in which Europe, driven by the TESLA Technical Collaboration in the 90s [3], is at the state-of-the-art both in the research and industrial sectors - the bulk Nb technology for electron resonators is approaching its fundamental limits, set by the breakdown magnetic field. For this technology it is however still needed to reach the extremely good results that have been demonstrated in laboratory results (up to 45 MV/m in multicell structures) in a **stable cavity production with high yields at the highest gradients**. In order to reach these goals, it is important to develop more reliable cleaning procedures for the RF surfaces, consolidating the very successful technique of high pressure rinsing to achieve better performances, or introducing variants (as dry ice cleaning). The close interaction between the research institutions and the industrial cavity producers, already achieved by the European XFEL Project, should be maintained and strengthened for the maturity of this technology, in order to meet in a cost effective way the needs of future European projects as ESS, EURISOL and ILC.

3.1.2.4 Improvements of the “Low Beta” Cavity Technology

New application areas are increasingly proposing the use of superconducting resonators in proton/ion acceleration for spallation sources or radioactive ion beams (e.g. SPIRAL2, ESS, EURISOL, MYRRHA,…). The current status of bulk Nb “**low beta**” superconducting resonators is not yet fully matched to the performances reached by the same technology for electron cavities and a margin exists for bridging the communities to use consistent fabrication and treatment procedures and to close the gap in performances and reproducibility.

3.1.2.5 Couplers for SRF Cavities at High Average Power

High beam power applications (e.g. ESS) need the development and engineering of **power couplers at high average power and duty cycles**. **CW operation**, as foreseen in High Q, CW acceleration for ERLs, will require to solve the combined problem of managing the thermal loads and achieving stabilization of extremely narrow bandwidth resonators at level not yet attained in operation. A further issue for CW operation at high current and short bunches in SRF machines is the minimization of higher order modes (HOM) excitation and to provide their extraction and dissipation in higher temperatures cooling circuits.

3.1.2.6 Overcoming the Performance Limits of Bulk Nb

Besides the issues outlined above, **further increases in accelerating gradients from superconducting cavities** could only be obtained abandoning the bulk Nb technology in favor of alternative fabrication procedures, the most promising coming from the thin film technology: either with high critical temperature (HTc) material deposition (such as MgB_2) or with multilayers shielding the bulk Nb and increasing the breakdown field. These techniques are nowadays mostly explored on samples or in high frequency, small size single cell cavities, and a wide collaborative support to the needed material science R&D activities would be beneficial for their successful transfer to the fabrication of prototype resonators.

3.1.2.7 Crab Cavity Developments

As part of the High-Luminosity LHC programme (HL-LHC), a global collaboration effort is underway researching appropriate SRF solutions (at the frequency of 400 or 800 MHz) for providing **local crab cavity crossing** around the LHC detectors. The stringent transverse space availability between the two LHC beam-lines, close to the detector regions, makes provision for these systems extremely challenging, requiring novel and innovative compact structure solutions, which can facilitate the rotational fields required whilst also providing effective wakefield management. For the CLIC linear collider, crab cavities are also required in order to maximize operational luminosity. The challenging requirement for these normal conducting structures at 12 GHz is the ability to sustain the high deflecting gradients, combined with the capability to damp all dangerous HOMs to extremely low magnitudes. Precise synchronization of both the LHC and CLIC crab systems requires demanding LLRF control architectures in order to maintain peak luminosity performance for these facilities.

3.1.2.8 RF Structures for 6D Muon Beam Cooling

Both normal and superconducting cavities are foreseen for the **acceleration and phase space manipulation of muon beams for Neutrino Factory and Muon Colliders**. High gradient performance for low frequency SRF systems is a principal requirement for the proposed neutrino factories. As the muons are produced by the decay of pions created in a target, the 6D phase space occupied by the beam is enormous and low frequency (200 MHz), large aperture cavities are required. Rapid acceleration is essential (as the muons decay after 2.2 μs) for a high muon yield, requiring large field gradients at relatively low frequencies. The **sputtered Nb technology** has been adopted to achieve such requirements, yet the physical size of these structures makes the sputtering process extremely difficult to precisely control, resulting in the current achievement of poor gradient performances with respect to the capabilities shown by this technology. For such SRF cavities, the "Q slope" (i.e. the decreas e of the quality factor at high fields) for Nb sputtered structures prevents the required gradients from being achieved and so a more effective fabrication technology must be identified. Alternative approaches to conventional bias and magnetron sputtering are being pursued, such as explosion bonding and atomic layer deposition techniques, which can hopefully breakthrough this technological barrier. For **normal conducting cavities** for phase rotation, bunching and cooling of the muon beam, the cavity performance is reduced in the presence of strong magnetic fields required for focusing. It is believed that surface quality has a major influence on the achievable gradients of normal conducting RF cavities in the presence of strong magnetic fields (>1 T). Surface roughness created in the manufacturing process, together with material impurities are most likely to blame for this effect and surface treatment and new cavity manufacturing techniques are required to mitigate the problem.

3.1.2.9 Variable Frequency Resonators for Synchrotrons or FFAG

The use of metallic alloy materials for providing the necessary fast reacting inductance for **variable low-frequency resonators** in applications for fast proton synchrotrons or Fixed-Field Alternating Gradient accelerators (FFAGs) requires the identification of novel materials which can vary the circuit resonant frequency at high repetition rates and field intensities. New Finemet meta-materials offer the prospect of being able to achieve higher performances than conventional ferrite solutions, with an appropriate demonstration yet to be realised. Low frequency cavities (in the MHz range), typically using ferrite rings to provide the inductive load, are required for booster or hadron synchrotrons. **Magnetic alloy (MA) loaded RF structures** may provide higher voltages per unit length and allow the development of low-Q broadband cavities. Such devices can be used as CW acceleration systems, bunch compression systems or broadband feedback systems. The development of low duty cycle, fast bunch rotation systems enables efficient compression of single bunches for production targets, as the one required by the FAIR experimental program. High field gradients can be realized easily using magnetic alloy cavities, since their saturation field strength is about ten times higher than that of the NiZn-ferrites.

3.1.3 RF systems

RF systems represent a substantial portion of the investment and operational costs of large accelerator facilities and a key ingredient for reaching their specifications, especially concerning beam parameters and stability. Key issues in this area are:

- Development of **RF systems for high brilliance damping rings**
- Development of **X-Band and C-Band** systems
- Precision **LLRF controls**

3.1.3.1 RF Systems for High Brilliance Damping Rings

The **RF systems in high brilliance damping rings** have to provide a large accelerating voltage/turn, whilst sustaining low broadband impedance and effective wakefield management of HOM contributions from the accelerating cavities. The size, efficiency and overall cost of the high power RF systems necessitates a requirement for their optimization, both in terms of efficient amplifier system development (i.e. Magnetrons, IOTs, klystrons, diacrodes and solid state amplifiers) and also efficient RF power transmission (i.e. circulators/isolators and RF splitters).

3.1.3.2 RF Systems at X-Band and C-Band

The development of high repetition rate **X-band and C-band** systems is highly desirable to produce compact accelerator solutions for FELs and for applications requiring small-footprint installations, such as cargo scanning or compact hard X-ray Compton sources.

3.1.3.3 Precision LLRF Controls

Precision RF control of accelerator systems for advanced ERL and FEL facilities are targeting stability tolerances of $<0.01^{o}$ in phase and better than 2×10^{-5} in amplitude for both pulsed and CW implementation. The inherent flexibility of digital LLRF control systems has enabled such requirements to be achieved, yet only in single amplifier per cavity applications. When multiple cavities are fed from a single amplifier, error contributions from vector sum manipulation of the applied accelerating fields will limit the achievable performance. Development of appropriate control architectures which can effectively manage all potential noise sources, to maximize system performance is seen as the primary challenge for stable delivery of next generation FEL facilities.

3.1.4 SC magnets

The present LHC constitutes the summit of 30 years of development in the domain of the mature NbTi superconducting technology in the SC magnet Key Area, as shown by the graph in Figure 1. Despite the fact that peak field of superconducting magnets in superfluid helium (below 2 K temperature) can approach 10 T, for a large series of magnets (some 1,700 large magnets have been installed in LHC), a margin of 20% from the maximum theoretical field must be provided. This in practice reduces the useful operating field of a Nb-Ti magnet system to 8-8.5 T.

Key issues for developments in the SC magnets area are:

- **Materials and technologies** to increase magnet fields to the **20 T range and beyond**
- **Fast cycling** superconducting magnets for synchrotrons
- **Engineering** challenges for **high field magnets**
- **Cryogen-free** magnet systems
- High-Field **short period undulators**
- Small magnets with **rare earth pole tips**

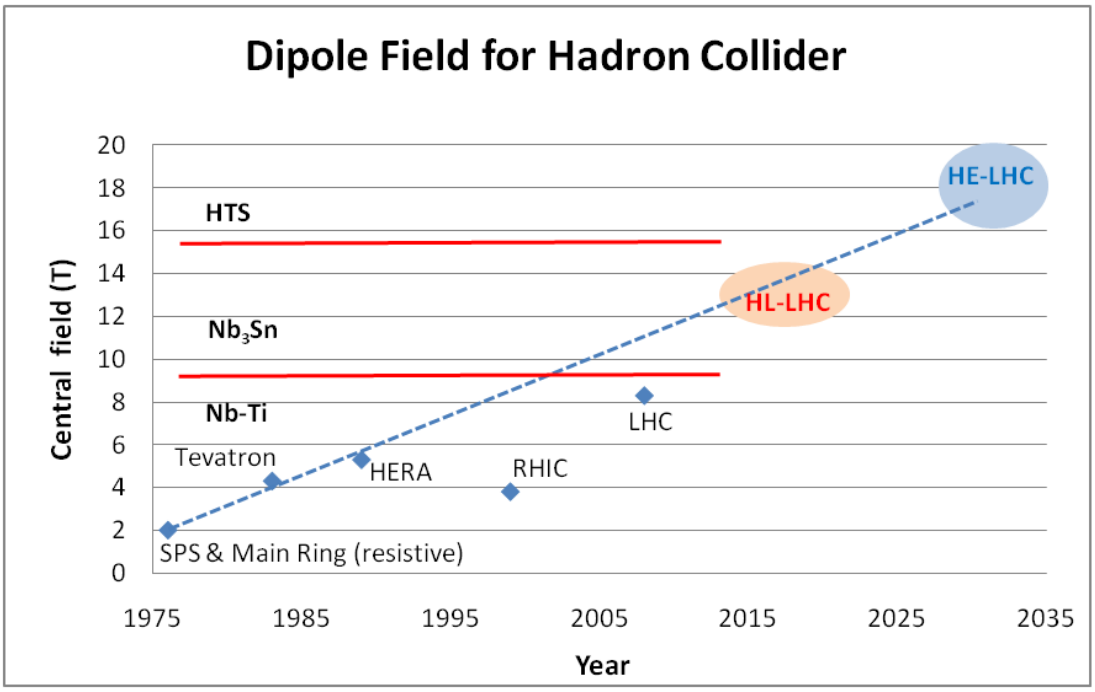

Figure 1: Progress of magnetic field in the main magnets of large accelerators.

3.1.4.1 Material and Technologies for the 20 T range and beyond

Higher energy or more compact future accelerators will need to overcome the 10 T barrier, in order to reach the **20 T range**. The technology under development is based on the Nb_3Sn superconductors, whose higher critical surface should allow reaching about 15 T (at a margin of 20% with respect to the maximum field of 18 T). This technology is already in use for NMR spectroscopy solenoids and has been selected for the ITER Project. Accelerator magnets will however need significantly larger current densities with respect to tokamaks for fusion or NMR solenoids, as shown in Table 1. In addition, the precision in coil dimension and positioning, as well as control of magnetization (persistent currents generate field errors at low fields) must be simultaneously controlled, with an order or magnitude better accuracy than in tokamaks and NMR magnets. To then reach the 20 T range, as needed by future colliders, a combination of Nb_3Sn and high temperature superconductors (HTS) becomes necessary, as shown in Figure 1. Preparatory studies of a 15 T dipole relying on Nb3Sn conductors have been performed in the FP6-CARE-NED (Next European Dipole) program, where a large aperture (up to 88 mm) solution was developed. Furthermore, studies of HTS solenoids and coil inserts are underway in the context of the HFM work package of the FP7-EuCARD Project.

Second Generation (2G) HTS cables, such as the YBCO cables developed by several industries worldwide, have shown the capabilities of sustaining high critical currents in high magnetic fields, opening the possibility to develop magnets with fields in the 30 T range, reducing the operation cost of high field magnets. These 2G HTS superconductors share the same long list of engineering challenges described in the relevant KTI in the following, and need focused R&D in support of specific issues concerning the low quench speed, reduced thermal stability and coil fabrication procedures.

Table 1 Table of superconductor characteristics of various systems using SC magnets.

Magnetic System (only DC)	**Current density [A/mm^2]**	**Operating Current [kA]**	**Typical field range [T]**	**Stored energy in the system [MJ]**
Resistive – air cooled	1-5	1-2	1	0.01
Resistive – water cooled	10-15	1-10	2	0.05
SC large coils for detectors	20-40	2-20	2-6	5-2,500
SC MRI magnets	20-50	1	1-10	1-40
SC Tokamaks for fusion (ITER)	25-50	5-70	8-13	5-40,000
SC laboratory solenoids	100-200	0.1-2	5-20	1-20
SC accelerators (today)	200-400	1-12	4-10	1-10,000
High Energy LHC (2030)	400	15-20	16-20	100,000

3.1.4.2 Fast Cycling Superconducting Magnets

The push for the high field colliders is also triggering the revision of the characteristics of the injector chains, that can be made much more compact and energy-saving if made with **superconducting fast cycling magnets** (today CERN SPS requires about 70 MW of power: a SC machine would require about 20 MW or less). This development is also necessary for future high repetition rate synchrotron for intense proton and ion beams (e.g. in FAIR). Critical aspects needing R&D are the development of low loss superconducting cables and the proper handling and minimization of the eddy current and hysteresis losses in the magnet structure in the AC regime.

3.1.4.3 Engineering Challenges for High Field Magnets

While the scientific foundations of superconductivity and the basic material understanding are sufficient for the electromagnetic design of very high field magnets, their integrated design is an extreme engineering challenge. The main issues for high field magnet engineering are:

- The design and fabrication of compact (85-90% compactness) **High Temperature Superconductor (HTS) cable** capable of carrying 10 kA under high stresses;
- The restraining of the **enormous electromagnetic forces** by means of compact structures;
- Dealing with the **huge stored energies**: 5 MJ/m, more than 100 GJ in total;
- Use of different superconductor in the same coil (called “**grading**”) with separate powering of each superconductor to minimize the volume and the cost of the magnet;
- Development of **radiation resistance** components both for magnet coils (namely insulators but also superconductors) and for structural material. Indeed the beam intensity and accelerator luminosity will likely increase with beam energy. Radiation hard components are a common issue of all future accelerators.
- **Improved He cooling capabilities** inside the magnets to remove heat in thick coils: the larger beam energy and luminosity will generate radiation and then increase the heat released in magnets and other associated devices, like cold collimators. Improving the efficiency in the heat transport along the cryogenic line may become also a challenging issue, especially if an optimization at 4.4 K, much more energetically favorable, is devised.

- Development of **superconducting fast cycling magnets** for a new generation synchrotron, with peak field of 5-6 T, and ramp rate of the order of 1 to 4 T/s. The challenge is to develop them with low cost HTS, like MgB_2 (and to compare it with the performance foreseen for FAIR-SIS300 project). Suitable HTS will allow to remove heat at higher temperature with considerable energy saving.

Overcoming these extreme challenges, all new with respect to the present technology will require sustained collaborative efforts for typically a decade.

3.1.4.4 Cryogen-Free Magnet Systems

This applied research area is one of the key issues for the future of accelerators at the energy frontier, and is likely to impact lower energy accelerators by opening the way to more compact and perhaps simpler **accelerator based on cryogen-free magnet systems**, which would be an important asset for medical, industrial and increasingly interesting security applications. It will all also impact on other areas, like NMR and MRI, as happened in the past (as an example, MRI was developed following the success of the Tevatron accelerator in producing the first high quality superconducting cables).

3.1.4.5 High-Field Short Period Undulators

Another special area of development beyond the state of the art that is required by next generation acceleration is **high field very short period SC undulator/wiggler magnets**. Given the push for more brilliant electron beam, the use of powerful wiggler is foreseen for high energy linear colliders. Especially the CLIC would profit from a development of wigglers capable of more than 12 T with very short period, which can make the damping rings extremely compact and efficient, a pre-requisite for such an accelerator.

3.1.4.6 Small Magnets with Rare Earth Pole Tips

Certain rare-earth elements have a high magnetization ferromagnetic phase below the Curie temperature and can be used to manufacture magnet pole tips, allowing reaching field enhancements of several Tesla (e.g. Holmium saturates at 4 T below 20 K, Dysprosium at 3.5 T below 85 K and Gadolinium at 3.2 T below 80 K). This could allow the fabrication of **high field small magnets with rare earth pole tips** required for example, by a muon collider where the high luminosity would be guaranteed by high gradient quadrupole magnets in the final focus region very close to the interaction point.

3.1.5 Conventional NC magnet systems

The technology of normal conducting electro-magnets is well established, however the key issues for this device class comes primarily from the light sources community (synchrotrons and FELs) and for the development of compact accelerators. Key issues are:

- Development of **compact magnets**
- **Radiation resistant magnets**
- Development of **insertion devices** for X-ray production and damping rings

3.1.5.1 Compact Magnets

For the development of **high field compact dipoles**, super-ferritic material can be used in order to increase the iron saturation level. **Hybrid systems** using permanent magnet and additional tuning coils could also be of interest for small accelerators with limited realization and operating costs.

3.1.5.2 Radiation Resistant Magnets

Radiation hardness is another R&D issue for permanent or hybrid magnet systems, especially important in hard beam environments of high intensity machines. MgO insulated cables may also be investigated in order to provide higher radiation hardness.
In particular the **synchrotron radiation damage** of the magnetic materials in light sources induces demagnetization of the permanent magnets, limiting their lifetime.

3.1.5.3 Insertion Devices for X-Ray Production and Damping Rings

The R&D on **permanent magnet undulators** is a key issue in the coherent synchrotron radiation production via Free Electron Lasers (FEL) and storage rings. The emitted wavelength is inversely proportional to the square of the electron beam energy, to the undulator period and to the undulator magnetic field and gap. Permanent magnet materials with high magnetic fields should be investigated.

The limit in **shortening the undulator period** is due to the transverse non linearity introduced by the poles rectangular shape, commonly used in the undulator: special studies and simulations with 3D codes are needed to shape the magnet poles and mitigate these effects. Reducing the vertical gap is foreseen to increase the magnetic field for **in-vacuum undulators**: the magnetic materials must have a low desorption rate and low beam coupling impedance in order to preserve beam quality.

The **wiggler electro-magnets** are mainly installed as insertion device in the electron circular accelerators to produce high flux of synchrotron radiation and in electron-positron colliders to increase the damping of the transverse oscillation due to injection or to cope with instabilities. The key issue in this case is the careful pole design to decrease the multipolar components.

3.1.5.4 Pulsed Magnets and Kickers

Fast **pulsed magnets and kickers** are used for injection and extraction in accelerator complexes and they are generally installed inside the vacuum pipe. The R&D on kickers is mainly devoted to realize the best device shape in order to achieve simultaneously: characteristic impedances well matched with the pulsers; high transfer impedances to the beam, to optimize the efficiency; low coupling impedances in the bunch spectrum range, to avoid multi-bunch instabilities.

Strong effort is devoted to the R&D of pulser-kicker systems able to **kick single bunches in a bunch train**: high repetition rate is needed to inject and extract individually the bunch in damping rings or to distribute individual bunches of a train to user beamlines. These same R&D issues are related to the ferrite type fast magnets used in the high energy accelerators.

FFAGs present a challenge for the pulse magnet systems due to a combination of their compact nature and relatively large apertures. Consideration of a proton facility based on a non-scaling FFAG indicates that although designs have been identified for both the kicker and septum magnet systems, prototyping is needed for the feasibility of these demanding designs.

3.1.5.5 Transparent Injection in Top-Up Schemes

A challenge for the light source facilities is the development of an injection scheme which is transparent for the stored beam (Top-Up). Systems which can inject beam, maintaining virtually constant circulating beam currents with minimal disruption, will allow avoiding or reducing the dead time caused by gating and ease the handling of photon-demanding experiments. The tight tolerances and stabilities required to the systems aimed at the "**transparent injection**" present many challenges, especially kickers, septum and pulsers.

3.1.5.6 Fast Quadrupole Magnets

Fast pulsed quadrupole magnets are of interest for the optimization of the energy efficiency of beam transport lines, since they may provide gradients similar to those of superconducting magnets and consume much less electrical energy since the magnetic field is only produced for a time scale comparable to the beam pulse duration.

3.1.6 Diagnostics and instrumentation

Beam diagnostics and instrumentation is an area under constant improvement and evolution, driven by the ever-increasing application demands in resolution, bandwidth dynamic range, time stability. Key issues in this area, needed by almost all future facilities, are:

- Beam **Position Monitor** developments
- Beam **size and emittance monitor** devices development
- **fs-timin**g control
- **Radiation-hard** diagnostic devices

3.1.6.1 Beam Position Monitor Development

The diagnostic workhorse in most accelerator facilities is the **Beam Position Monitor** (BPM) system and its optimization in operating accelerators, as well its performance extrapolation to serve future accelerators - such as ultra-low emittance light sources or high energy colliders – are of great importance. One clear direction of current BPM developments is its resolution increase, which leads to improvements in the performance of light sources, damping rings, and linear colliders. This development will benefit orbit correction, beam based alignment and feedback systems, enabling the control of the single and multi-bunch motion to a larger extent. The reduction of the system latency and the simultaneous increase in bandwidth and dynamic range of the position monitor systems could be obtained moving towards a digital signal processing architecture, which can exploit the developments of commercial communication systems such as software-based radio. This development will also aid the adaptation to widely different time structures of the beams in rings or normal- and super-conducting linacs. Integrating 'unwanted' parasitical signals, such as those generated in higher-order mode couplers or generated as wake fields, is another attractive extension of the BPM system, which can lead to a brand new class of devices.

3.1.6.2 Beam Size and Emittance Monitor Devices Development

The second workhorse is represented by the **diagnostic devices for beam sizes and emittances**, both in transverse and longitudinal planes. In damping rings or light sources the current development trend is towards measuring and controlling the extremely small transverse beam sizes and emittances with optical methods, by means of using either the emitted synchrotron radiation - in rings - or optical transition radiation monitors - in single pass machines. Often these systems have limitations due to the superimposed coherent radiation, which needs to be investigated further. Laserwire devices are also developed to provide profile data at high resolution. Diagnostics of longitudinal beam sizes in the sub-ps regime utilize methods borrowed from laser physics, such as electro-optical methods or other methods to manipulate the electron beam with laser pulses, and diagnosing its effect. For the determination of the transverse and longitudinal beam sizes and the assessment of the beam halo in future high-intensity proton or ion accelerators **non-invasive/non-intercepting techniques** are required, in order to guarantee stable operation with low beam losses to avoid radioactive activation of accelerator components. Having a reliable beam size measurement system facilitates the full reconstruction of phase space by tomographic methods, both transversely and longitudinally. Secondary ion beams that will be produced at future radioactive beam facilities will also need **extremely sensitive beam diagnostics for low beam currents**.

3.1.6.3 fs-Timing Control

A third field that will become more and more important, especially in FEL facilities is the **control of timing to the fs-level** which is especially important for pump-probe experiments, but also for linear colliders that utilize sub-ps bunches as well. Even for timing, borrowing laser techniques for ultra-short pulse analysis, is highly attractive. Finally, we suspect that in radiation facilities the integration of signals from user-experiments into the accelerator diagnostic system will become a future important subject. The ultrafast diagnostics for position, size and spectrum of the photons delivered to the users is of special interest.

3.1.6.4 Radiation-Hard Diagnostic Devices

With the continuous integration of digital processing capabilities into all diagnostic systems, the design and development of **radiation-hard electronic** components needed for operation in the tunnel environment is another key technical issue to address.

3.1.7 Targetry

The high hadron beam power foreseen by several projects (e.g. for LHC upgrades, ESS, ADS, FAIR, EURISOL) generate tough requirements for targetry devices, which need to sustain the high beam power impinging from the accelerator. Main key issues in this area are:

- Challenges for **high power targets for secondary particle production**
- **Radiation damage phenomena** in target materials
- Monte Carlo **particle transport codes** validation
- **Bent crystal channeling** for beam collimation

3.1.7.1 Challenges for High Power Targets for Secondary Particle Production

Targets at high power accelerators (i.e. power in excess of 100 kW) are generally needed for the **production of secondary particles** which are either used as probes to investigate physical properties of other objects or are to be investigated themselves, e.g. neutrinos. There is a broad range of different possible targets for the production of secondary particles; for instance neutrons are generated in thick, high Z, production targets in the case of spallation neutron sources. Rare isotopes, in case of ISOL (Isotope Separation On-Line) facilities, are produced in thick targets, extracted and post-accelerated while in the case of IFF (In Flight Fragmentation) facilities thin targets are employed. For the production of neutrinos pions, kaons and other mesons are produced by high energy hadrons hitting (currently) long, thin, low-Z material targets. The emerging mesons are focussed in magnetic horns and decay in long tunnels into muons and neutrinos. In ADS (Accelerator Driven System) a production (spallation) target is used to generate the large neutron flux, in the middle of a subcritical nuclear reactor core, to sustain the fission. This mechanism allows the transmutation of a large portion of the spent nuclear fuel into more stable elements, so that radiotoxicity and storage time of the remaining waste is significantly reduced.

The tendency to increase the beam power of new facilities (above 1 MW) in order to produce larger fluxes of secondary particles sets high demands for the development and engineering of particle production targets. As mentioned in the recent NuPECC Long Range report [4], it is necessary to *"secure and further develop the Nuclear Physics skills base in view of current and future needs, in particular regarding: [....] Development of novel sources, (micro) beams,* *(higher power) targets and radiation detection instrumentation that will also be used in other fields of science and engineering, and in the life sciences."*

Major areas of interest with respect to high power targetry are the changes of material properties due to irradiation - from now on called radiation damage phenomena – such as hydrogen and helium production, hardening, embrittlement, fatigue, shock-wave production, cavitation, erosion and more, as well as the high power densities (W/cm^3), especially at pulsed operation, which entail the development of innovative cooling schemes. Last but not least the predictive power of Monte Carlo particle transport codes, their constant development and benchmarking is of fundamental importance, because predictions of basic quantities (power deposition, damage rates, particle production yields etc.) from these simulation packages are used as inputs in subsequent investigations on structural mechanics, thermo-hydraulic, thermo-mechanical behavior of target components by suitable engineering codes.

3.1.7.2 Radiation Damage Phenomena in Target Materials

At existing accelerator facilities **radiation damage phenomena**, which often are not completely described in literature or cannot be assessed during the design phase of targets, beam dumps or other accelerator components are studied by extensive Post Irradiation Examination (PIE). Of course investigations on certain radiation damage effects are extensively performed during the design phase based on existing data; a good example is the strong collaboration of the SNS in Oak Ridge Tennessee and the Japanese SNS at Tokai (JSNS) on cavitation erosion (pitting). Nevertheless only the extensive PIE of operated targets (beam dumps etc.) will reveal a real picture of all radiation damage phenomena. To overcome the lack of radiation damage data, a program devoted to material behavior under irradiation is carried out since 1999 at the Swiss SINQ Target Irradiation Program (STIP). In this program, a number of the normally lead filled rods are replaced by rods containing miniaturized irradiation samples of various materials (mainly steels). As a by-product of neutron production for the users of SINQ, experience is gained by STIP. However, the number of samples is limited because of the influence of the samples on the neutron production by the target. A new facility at CERN called HiRadMat, will start operation soon, in which irradiation tests of target materials for the planned Neutrino Factory will be carried out.

Although **Post Irradiation Examination** (PIE) is locally done at the different accelerator laboratories, a dedicated facility with the mission to study irradiation damage phenomena would certainly improve the situation of the scarcity of existing data bases. New and planned facilities, such as MYRRHA, ESS, EURISOL, the Neutrino Factory and others certainly will benefit from such a facility; variable energies as well as a flexible target complex (allowing for different target types, temperature control ...) would help to study irradiation damage phenomena systematically for the first time. In the US, a facility with the purpose to test materials for generation-4 reactors has been proposed at LANL - MTS. It is a spallation driven source which is planned to irradiate fuel samples for GEN4 reactors. A similar approach coping not only GEN4 fuel elements but also spallation target materials samples would allow to systematically study radiation damage phenomena under well controlled conditions for the first time.

3.1.7.3 Monte Carlo Particle Transport Codes Validation

In spallation neutron sources, the interplay of the target-, reflector-, moderator and neutron guide-system influences neutron spectra, intensities, neutron time structures of neutrons delivered to instruments. Therefore, all systems ideally have to be studied and optimized at the same time. However, the only way to check the validity of such simulations is to measure these observables when the facility is finally built. For these reasons, it would be preferable to **test/validate the Monte Carlo particle transport codes** used for the predictions on a "test setup" in advance. Additionally data used in the simulations, i.e. scattering kernels of new moderator materials for the production of (long-wavelength) neutrons, could be approved in experiments. A low power "test bed facility" with large flexibility on moderator, reflector and guide setup would be a powerful tool which could boost developments of new moderator, reflector or even guide systems. Such a platform can be used by high power sources to improve their performance faster, by first checking new ideas experimentally on a low power source and validating simulation tools at the same time. An example for such a facility is LENS (Low Energy Neutron Source) operated at Indiana University in the US. LENS offers a platform to easily test new moderator concepts - as for instance the idea of directional moderators - to measure data necessary for the development of new scattering kernels. At the same time, new ideas for neutron scattering instruments can be tested. As the example of LENS shows such a low power facility can as well be used for the education of physicists in fields of accelerator physics, target, moderator, reflector and neutron-guide development as well as neutron scattering.

3.1.7.4 Bent Crystal Channeling for Beam Collimation

Beam **collimation** in high power machines is another critical issue which shares many topics and issues with targetry. **Bent crystal channeling** has been used for many years as a means of deflecting, extracting and collimating charged particle beams in high-energy accelerators.

In 1993, the experiment RD 22 at CERN demonstrated the possibility of extracting primary protons in the peripheral of the circulating beam. The goal was to extrapolate such a technology to LHC in order to have extracted beam for B-physics experiments to be made parasitically during the high luminosity runs. In 1994, the principle of bent crystal channeling was applied to produce simultaneous, nearly-collinear beams of long- and short-lived neutral kaons to the CP-violation experiment NA48. In the 1990s at IHEP, several lines of extracted protons were setup in the U70 synchrotron using bent crystals to enhance the flux of particles for simultaneous fixed target experiments. In 2008, the UA9 Collaboration demonstrated the existence of a reflection mechanism in the interaction of high energy protons and ions with bent crystals. This made available a coherent mechanism of particle deflection having an efficiency exceeding 95 %. In 2009, the UA9 Collaboration demonstrated that bent crystals can be used to enhance the efficiency of collimation in hadron colliders, while reducing the off-momentum self-produced secondary halo.

Open issues exist and should be addressed with R&D programs for an optimal use of bent crystals in particle accelerators. First, crystals must be produced with very tight quality criteria, such as a very small residual angle between the crystal surface and the crystal planes, with reduced defects of the crystal planes, especially close to the crystal faces. They must be bent with very regular curvature shapes and with a very small residual torsion. Goniometers with ten times the accuracy obtained with the present technology must be made available in order to align the crystals to the incoming beam trajectory, with accuracy smaller than the critical angle for channeling. Simulation studies are furthermore required to optimize the integration of crystals in high intensity high energy large colliders, to maximize performances.

3.1.8 Radiation issues

Radiation protection issues include an evaluation of the potential hazards in the various stages of the accelerator facilities lifetime (commissioning, operation, maintenance and decommissioning) and should describe the relevant measurements required for its implementation. The radiation protection approach starts already during the early stages of a facility, consequently many aspects of this evaluation should be included in the design phase. The main key issues in this area are:

- determination of the **prompt radiation levels** through reliable simulation tools
- handling of **component activation** by multistage collimation schemes
- development of **compact shielding** for medical applications

3.1.8.1 Determination of the Prompt Radiation Levels through Reliable Simulation Tools

Estimation of **prompt irradiation** and radioactivity to the desired accuracy level is a difficult task for some type of accelerators, and in some cases, is mandatory to develop new tools for acceptable radioprotection analysis. Advances in computer codes and methods for evaluating accelerator radiation protection are needed in several areas, discussed in the following.

Depending on the type of primary accelerated particle beam, its maximum energy and intensity, **computer simulation tools** are not always able to satisfactory predict the secondary radiation field generated by the interaction of the primary beam with the materials of the accelerator system and to determine prompt doses. These tools consequently fail in these cases to assist in the radiological zoning and shielding design. This is, for example, the case of low energy deuteron accelerators, where current Monte Carlo codes are not able to handle deuteron nuclear data libraries, failing to describe the angular and energy distribution of the secondary radiation sources. The same happens for other light ions, and even for proton libraries, that are often limited to a number of nuclides too short for the applications. The limitations of present tools appear in regions of **low secondary production yields**, where it is difficult to reach an acceptable statistics, or in regions not adequately covered by the **nuclear data libraries and models**.

New computational tools and **reliable, benchmarked, nuclear data** would be necessary to allow more reliable calculations of prompt doses, to optimize accelerator shielding thickness and investigate new shielding materials alternatives to the traditional ones. The development of activation codes with better activation/production cross sections will allow to reduce component activation, allowing the implementation of maintenance operations and decommissioning of the installation with lower exposure doses.

3.1.8.2 Component Activation Handling by Multistage Collimation Schemes

Accelerator components, and particularly protection devices as **collimators** in proton and heavy ion accelerators, have to be operated in high dose environments. The radiation hazard occurs either by the primary proton beam or by the secondary radiation after initial beam loss, as described above. Collimators provide the possibility to concentrate **activation** on well-defined places and devices. Detailed simulation studies have to be carried out to study the damage caused to solid targets by the full impact of the beam. Tungsten, copper, graphite and metal-diamond composites are being studied as possible collimator materials. Experimental and theoretical studies on radiation damage on materials used for the LHC upgrade and the FAIR accelerators are performed at the present experimental facilities at GSI. In particular, **halo collimation systems** are designed to produce a peaked and well known loss distribution, and consequently activation of the accelerator complex. Multiple stage collimators are developed for high intensity proton beams and also for heavy ion beams – especially in the case of high intensity low charge states – these systems play an important role to restrict machine activation to well defined locations.

3.1.8.3 Compact Shielding for Medical Applications

Regarding the aspects of radiation protection for specific types of accelerators, it is worthwhile referring to medical accelerators. The main design priorities in the design of a medical accelerator, like a cyclotron, are to minimize the weight and power consumption of the machine. However, any low weight advantage would be lost if, to install the machine in a practical site, such as an hospital, a large amount of shielding is required to reduce either the radiation background or the stray magnetic fields. Thus, low background levels of radiation and magnetic fields are key design criteria. New multi-component composite materials and techniques for **improved shielding of neutron and gamma radiation** should be investigated. Such materials are enriched with atoms that provide a substantial cumulative absorptive capacity to absorb or shield neutron and gamma radiation of variable fluxes and energies. Development of new shielding materials as an alternative to conventional concrete and lead-shielding technology products is an important activity as a response to the societal needs of accelerator applications in the medical sector.

3.2 Accelerator Technologies

This domain collects KARA related to the main technological systems and subsystems which are of outmost importance in the operation of large accelerator facilities:

- Electronics and Software
- UHV
- RF sources
- Cryogenics
- Alignment and Stabilization

For each of these very broad areas several more specific KTI have been identified and will be discussed in the following subsections.

3.2.1 Electronics and Software

Physics laboratories and collaborations – particularly Rutherford and CERN in Europe and the National Bureau of Standards in the US – have been leading since the early 1960s the development of modular instrument standards in experimental and nuclear physics. The early developments led to the definition of the NIM standard in the 60s for mechanical and electrical specification of the modules, then the CAMAC standard in the 70s introducing inter-module communication, later replaced by the FASTBUS standard in the 80s. Each development introduced faster and wider data buses compatible with faster computers, bandwidth increases, and modern control structures. For decades, the control systems for accelerator facilities have been based on these lab-based standards. New industrial standards, driven by the rapid growth of the telecommunication sector, open the path for a new generation of modular instruments. Key issues in this area are mainly:

- Adoption of the **xTCA standard** in control systems
- **LLRF performances and costs**

3.2.1.1 xTCA Standard

In recent years, the appearance of a new standard, the **ATCA**, Advanced Telecommunications Computer Architecture, and its sibling **MicroTCA**, and new off-the shelf devices, the FPGA, Field Programmable Logic Array including high speed communication channels, have changed the background scenario. These architectures have been designed for the development of high availability systems, through the combination of redundancy measures, hot-swappability and management capabilities. The technological development was driven by a wide collaboration within the telecommunication and computer industry – strongly focused on the availability goals – which implemented standardization to achieve larger profit margins with faster development cycles and providing interoperable products.

3.2.1.2 LLRF System Cost and Performances

The control system community has recognized the strong opportunity of this emerging xTCA standard and requested of extensions of IO and timing features for physics applications. This activity has led to the creation of mixed laboratory-industry working groups for the development of the specifications for the physics extensions, concerning hardware and software platforms. Several laboratories, following the choice by DESY in 2008 to explore xTCA standards for the development of XFEL LLRF and control systems, are therefore moving their control systems to benefit from the capabilities, performances and availability offered by the xTCA, with the additional benefit of the wide integration of inexpensive Consumer-Off-The-Shelf (COTS) components readily available from industrial vendor. However, several critical modules are not available as COTS components, e.g. Timing modules suitable for accelerator applications, which are currently developed in a laboratory environment. A sustained R&D effort is still necessary to allow the main laboratories to support the adoption of this new standard and to develop the necessary adaptations required by the physics applications jointly with the industrial members. This will allow the opportunity of mitigating the increasing costs for the accelerator facilities and decreasing budgets with the benefits of standardization.

3.2.2 UHV

Ultra-high vacuum is an important pre-requisite for high-quality particle beam transport. Long-standing experience with huge vacuum has been accumulated within the particle accelerator community. While each accelerator has its own particular R&D issues, there are several issues which are relevant for several projects. Key items are:

- Control of **radiation-induced outgassing** and **secondary particle generation**
- Achievement of **low outgassing rates** to limit pumping times
- Handling of the effects of **chamber conductivity** and eddy currents
- Achievement of **large pumping power**

3.2.2.1 Control of Radiation-Induced Outgassing and Secondary Particle Generation

The impact of radiation or scattered particles onto the vacuum chamber walls inevitably leads to both **outgassing and to the generation of secondary particles**, most notably electrons. A detrimental effect of such a process to the particle beam can be observed for example as an electron cloud in storage rings. As mitigation, the vacuum chamber surface could be modified to have a **lower secondary yield**. Coatings on the chambers are one option to achieve this.

The operation of high intensity heavy ion beams (of about 10^{11} ions per cycle) at intermediate charge states is limited by the significant cross section for electron loss or electron capture (depending on the beam energy). Thus it directly depends on the residual gas pressure and composition. With a higher cross section, more ions hit the walls of the beam pipe, setting weakly bound molecules free in a process called ion **induced gas desorption**, that contributes to an increase in the gas pressure, and eventually causing the development of a major vacuum instability and major beam losses. In order to ensure a reliable operation, special **ion-catcher** systems are under development. These systems provide special low desorption yield surfaces, so that the amount of ionization loss due to charge exchange in collision with the residual gas molecules is stabilized during operation. Low desorption catcher systems in warm and cryogenic variants have been proposed and are under development for FAIR.

3.2.2.2 Achievement of Low Outgassing Rates to Limit Pumping Times

Another important issue in the area of ultra-high vacuum technology is to achieve **low outgassing** rates in chambers with small apertures, i.e. limited conductance. This is relevant for example for undulator chambers where the magnetic poles should be placed as close to the particle beam as possible. For the commissioning of large accelerator vacuum systems, the outgassing due to synchrotron radiation can be time limiting. Therefore, materials with low outgassing under these conditions have to be developed. Again, surface coatings can play a crucial role.

3.2.2.3 Effects of Wall Chamber Conductivity and Eddy Currents

Apart of the interaction of the particle bunches with particles e.g. in the residual gas, the bunch electrical field interacts with the vacuum chamber material. Detrimental effects on high-quality particle bunches can be caused e.g. by **low conductivity** and surface roughness.

Eddy currents in vacuum chambers play an important role for fast ramped synchrotrons and may degrade the magnet field quality or induce heat loads in cryogenic systems. Thin vacuum chambers (e.g. 0.3 mm), reinforced by ribs, or ceramic vacuum chambers with embedded RF shields are proposed to mitigate these effects.

3.2.2.4 Achievement of Large Pumping Power

The handling of the gas densities needed for the new acceleration (plasma-based) techniques or the high-power lasers used for particle beam diagnostics have a different set of R&D issues. Operation typically requires the use of **mechanical pump units** (e.g. turbomolecular pumps). For accelerator applications, thus a reliable integration of these pumps into the overall vacuum system must be ensured.

Large average and local pumping powers are required for several applications, especially in conditions of severe synchrotron radiation outgassing or beam induced gas desorption, and can be provided by NEG coated or cryogenic vacuum chambers.

3.2.3 RF sources

RF sources have always been a key issue for accelerators and will remain so in the future, even more acutely, as power has to be delivered to the beam in the most efficient and reliable way. Key issues for this area are:

- Development of reliable RF sources based on **solid state technology**
- **Energy efficiency** improvements

3.2.3.1 Development of Reliable RF Sources Based on Solid State Technology

The reliability improvement of an accelerator complex is often achieved through the reliability improvement of its RF sources. Tremendous progress has been made in this field, in particular with the **solid state technology** but a steady pace should be maintained through R&D activities.

The range of RF source parameters is very wide: frequencies span from as low as 10 MHz up to more than 10 GHz, power levels range from kW to MW, with a range of pulse duty cycles and DC operation. Each accelerator type and application requires efficient sources within this wide range of parameters: cyclotrons need DC sources in the 10-100 MHz range, sometimes at MW power levels; superconducting devices ask DC and pulsed sources in the 100 MHz to few GHz range; while R&D programs such as CLIC require 12 GHz sources, the search for efficient heavy ion ECR sources pushes the frequency requirements for DC sources up to 60 GHz. The scarce availability of C-Band RF sources is currently limiting the potential benefit of this frequency choice proven by the results obtained from the structures, due to the high costs associated to these devices.

DC power levels in the MW range are common, and pulsed power in the 10’s of MW range is reached at an average power of tens or hundreds of kW. Recently, the solid state RF technology has made a spectacular breakthrough for synchrotron radiation facilities, improving tremendously their reliability, compared with the klystron technology that has been used in the past. The effort will continue, exploring higher frequencies for these devices.

3.2.3.2 Energy Efficiency Improvements

Development and success of new facilities at high beam power such - as ESS or the Linear Collider schemes - will require a large effort in **improving the energy efficiency** of the power sources: reducing the overall power consumption of large scale accelerator complexes has become a necessity to reduce operational costs. This is one of the most important issues of new accelerators and strong R&D is this field is strongly needed. However, in Europe these sources have been mostly developed by industry and a strong partnership between research/academic institutions with industrial firms should be fostered.

3.2.4 Cryogenics

An increasing number of medium to large accelerator facilities, in operation or to be commissioned in the near future, are based on the superconducting technology, either for high-field magnets or for RF acceleration. Superconducting accelerators are found in all domains, from high energy physics – with LHC the state-of-the-art infrastructure for the SC magnet technology and ILC committed to pushing the SRF Niobium technology close to its fundamental limits – to nuclear physics – with SPIRAL2, ALPI, REX-Isolde and FAIR in Europe – to user facilities – like the European XFEL, and the European Spallation Source, ESS – and finally to application based accelerator infrastructures – e.g. IFMIF. Key issues in the cryogenics area are:

- **Cryoplant efficiency** improvement
- Improvements in **cryogenic distribution and cryostat insulation**

3.2.4.1 Cryoplant Efficiency Improvements

All superconducting facilities need to cope with the fact that cooling at liquid helium temperatures requires large amounts of primary power. The Coefficient of Performance (COP, measured with the ratio of W spent at the plug per each W dissipated at the cold temperature) of large cryogenic systems has been steadily improving over the years as larger and larger installations come to existence (see Table 2). Nonetheless, all future projects will directly benefit from further increased efficiency both by reducing the capital cost sizes for the plants and decreasing their operation costs. **Improvements in cryoplant efficiencies** can be obtained by careful process engineering of the plant cycle, by additional introduction of energy recovery practices, and by improved design of subcomponents (e.g. the centrifugal compressors). Also, advanced control and regulation strategies (e.g. for cold turbo compressors) could increase efficiency.

Table 2. Evolution of large helium refrigerators Coefficient Of Performance.

	RHIC	CEBAF	HERA	LEP	LHC
4.5 K equivalent capacity [kW]	25	13	8	6/12	18
Power required [W/W]	450	350	285	230	230
Carnot Efficiency	16%	20%	25%	30%	30%

3.2.4.2 Improvements in Cryogenic Distribution and Cryostat Insulation

Medium to large scale superconducting facilities (i.e. projects ranging in sizes from the ESS to ILC) would also benefit from new methods to **improve the helium distribution** and the **cryostat insulation** from heat leaks from the environment to the cold regions. Moreover, the cryomodules for SRF linacs, especially under conditions of large RF dynamic loads as in ERLs or in large footprint machines, are an integral and important part of the cryogenic support system, which should then be optimized for overall efficiency across all its components. Thus, in order to further increase the linac energy efficiency, the linac cryomodule should not be designed as an independent object, but its design should follow an optimization tradeoff together with the overall cryogenic system design.

3.2.5 Alignment and Stabilization

Beam sizes of particle accelerators evolve towards the nanometer scale all along the accelerator, often with the target of a minimal emittance at the collision or extraction points. This results in high requirements for the (quasi-static) alignment and (dynamic) stabilization of machine elements, are especially demanding for the case of the CLIC linear collider. Key issues in this area are:

- Further developments of **laser and wire positioning systems**
- **Nanometer** level **stabilization**

3.2.5.1 Developments of Laser and Wire Positioning Systems

Alignment accuracy is steadily improved since years; presently, the target is the ten micrometers level on hundreds of meters; more recent developments are based on **lasers and wire positioning systems** and the applicability of new strategies are being demonstrated for kilometers long machines.

3.2.5.2 Nanometer Level Stabilization

Stabilization issues came into play only recently to tackle the **handling of nanometer level**. At that scale, beams are disturbed by many sources of noise such as ground motion, pumping and cooling devices, acoustic noise... This environment generates vibrations with large amplitudes, responsible for blowing up the beams, and needs countermeasures based on active system. The R&D on active control strategies involves high precision sensors, usually inertial and soon interferometric, actuators (piezo-electric) associated with highly performing electronics for signal processing.

Compatibility between the alignment system, the stabilization devices and the beam-based feedback should be tested in a real environment of large scale demonstrators.

Even if stabilization strategies for accelerators are somewhat specific, similarities exist with the need of isolation of other high precision machines from external disturbances (e.g. telescopes, interferometers, lithography machines or atomic force microscopes). Collaborations with industries in these sectors are foreseen and should be settled in the near future.

3.3 Accelerator Concepts

This domain contains KARA related to design issues for future facilities (e.g. final focus systems, beam dynamics, crab crossing...) or for promising technologies not yet implemented in accelerator facilities, or new application fields.

- Accelerator Design
- Beam Dynamics
- FEL processes
- Beam cooling
- New techniques for high gradient acceleration
- Medical and Industrial Accelerators

For each of these very broad areas several more specific KTI have been identified and will be discussed in the following subsections.

3.3.1 Accelerator Design

Accelerator design is the art of integrating accelerator concepts and technologies into design studies that fulfill performance requirements within a set of boundary conditions. It is a practice that relies on past experience and builds on promising results from accelerator R&D activities, which may finally lead to the need of further R&D studies to explore new concepts for the accelerators of tomorrow. Accelerator design is a key area that guides and motivates most other aspects of accelerator sciences. New, or more stringent, boundary conditions and performance goals to fulfill in accelerator design are added continuously for research facilities, and even more for application facilities. Key issues in this broad area are:

- Design for **Reliability and Availability**
- **Beam Losses and machine protection** at high beam power
- **Compactness and simplicity**
- **Energy efficiency and storage**

3.3.1.1 Design for Reliability and Availability

High reliability and availability is a common concern, evidently more pronounced for application accelerators, but more and more important for research accelerators: the technological choices, such as the use of normal or super conducting magnets or cavities, can change the access to the machine components and repair times by orders of magnitude. With the growing sizes of research accelerators for basic physics, the high demands on beam availability required by all user facilities (as light sources or neutron sources) and the tight beam reliability goals of particular applications (as the ADS case for nuclear waste transmutation), the accelerator design of future European facilities will require the inclusion of formal reliability / availability assessment methodologies from the early conception stages.

3.3.1.2 Beam Losses and Machine Protection at High Beam Power

With either larger energies, as required by the LHC upgrades, or higher beam currents, as for the case of ESS, EURISOL or ADS, **machine protection against beam losses and activation considerations** are playing an increasing role since the early stage of the accelerator design, and often represent a driver for the design process or for the selection of competing technologies.

As an example, the acceleration of low charge state heavy **ion beams** – suffering from charge exchange mechanisms due to their high cross sections – requires further developments of new design concepts, as the charge separator lattice.

3.3.1.3 Compactness and Simplicity

For application accelerators, **smaller volumes, lower weights and costs are key issues**, together with **simplicity, robustness and safety**. By confronting the design of very different accelerators in different fields and promoting the involvement of industrial partners, common strategies are liable to emerge and the transfer of the research/academia know-how to the industrial context could represent a significant path towards the achievement of these objectives.

3.3.1.4 Energy Efficiency and Storage

The concepts and the technologies used in the accelerator design must aim at highest energy efficiency, in addition to the pure accelerator performance requirements. Particle accelerator facilities of medium or large size require significant amounts of electrical power, in the range of a few Megawatts up to hundreds of Megawatts. In view of cost effectiveness and minimization of the environmental impact, efforts must be undertaken to **improve the efficiency of accelerators** and to lower their overall power consumption.

In every accelerator the electrical power grid is used to accelerate a particle beam, which finally carries a certain amount of power. The overall efficiency of this conversion process is given by the product of the efficiencies of each individual component in the chain, such as AC/DC converters, RF sources and the accelerating structures. The improvement of established RF sources such as klystrons, the investigation of alternative sources with high efficiency and the design of accelerator structures with high RF-to-beam conversion efficiency should be in the focus for **energy efficient accelerator development**. All electrical power taken from the grid by an accelerator facility is finally converted into heat. This heat is removed by cooling circuits from beam targets, dumps, RF loads, RF sources and structures, magnet coils, warm helium gases, and so forth. It is desirable to recover a part of this spent power from the cooling circuits and to use it for other purposes. The efficiency of heat recovery increases with higher temperature levels in the circuits. Thus, for efficient heat recovery a technological development goal is to optimize accelerator components for operation at higher temperatures.

Depending on the nature of an accelerator facility the power consumption can also vary dynamically on timescales ranging from sub-seconds up to hours. For such facilities short term **energy storage systems** are necessary to level the load on the public grid. Storage systems can also bridge short grid interruptions resulting in long recovery times and thereby improve the operational efficiency and facility availability. The development of efficient, cost effective and reliable storage systems, for example based on superconducting coils, is therefore another goal of development for the future.

For the case of the light sources, an **Energy Recovery Linac** would allow a cost-effective delivery of high average beam currents, but at present the design of these machines presents many challenges in several technological (for the SRF gun injector, its photocathode material and the associated laser drive; for the development of undulators and high power beam diagnostics) and fundamental accelerator design aspects (emittance preservation issues, beam halo and ion effects, beam stability and required computational capabilities).

3.3.2 Beam Dynamics

The development of particle accelerators at the frontier of physics and societal applications requires **pushing beam physics and beam dynamics to a new realm of modeling tools, simulation capabilities and prediction accuracies**. The beam physics-demanding critical key issues in this area for future accelerators include:

- the achievement of **high luminosity** for circular and linear colliders, being upgrades or new facilities
- the achievement of **higher energy for hadron colliders,** entering a regime where synchrotron excitation and damping become significant
- the achievement of **high beam stability** and long lifetime in circular accelerators
- the generation, storage and transport of small emittance
- the generation and low-loss acceleration of high intensity ion beams for linear accelerators
- the achievement of unprecedented **high reliability operation**, especially for energy application of proton linear accelerators
- successful validation of **laser–beam interaction** schemes for plasma acceleration, positron production and X-ray generation
- development of innovative **fast acceleration systems** for unstable particles

Several of the above mentioned items in the previous list, like beam stability, small emittance and high reliability, are shared with the "accelerator design" critical key area outlined in the previous paragraph, because in order to address them properly both system design provisions and modeling tools should progress beyond the current state of the art.

Progress in these fields originates either from **new optics concepts** (like low beta and nanobeam schemes), **new beam manipulation concepts** (higher harmonic generation, space charge compensation), and **new beam correction algorithms**, or from higher calculation predictability resulting from innovative computing methods (frequency maps, start-to-end simulations, multiple error generation) and computer power (distributed and parallel computing architectures). Avoiding γ_T transition is an issue for future proton synchrotrons, providing negative or imaginary transition energies.

All these topics constitute Key Technical Issues in the Beam Dynamics Key Accelerator Research Area, where all aspects and approaches must be carefully balanced and supported. The variety of methods and of minds is essential to ensure a lively progress in this most abstract and theoretical branch of accelerator physics.

3.3.3 FEL processes

Several 4th Generation FEL Light Sources have come into operation worldwide in recent years as user facilities, with the European XFEL as the near-future EU facility opening the access to ultrashort brilliant X-Ray photon beams. Future long term exploitation of FEL facilities will benefit from R&D focussed to the following key critical issues:

- Development of **New Seeding Techniques** for FELs
- **Circularly Polarized** X-Ray FELs
- **Attosecond Pulse Generation**

3.3.3.1 Development of New Seeding Techniques for FELs

Typically, SASE FEL output is poorly longitudinally coherent due to the start-up from shot noise. **Self-seeding schemes** aim to provide single-mode hard and soft X-ray pulses. In its simplest configuration, the scheme foresees a two-undulator setup: the first undulator allows the creation of the seed signal which passes first into a single-crystal (or gas) monochromator and then is amplified in the second device (radiator), after the electron beam microbunching is washed out by a weak chicane. The scheme can be further extended in a multi-undulator setup, combined with tapering of the radiator to achieve high power and high brightness pulses.

For other lower energy FELs working in regimes where **external seeding** is a practical option, R&D should be focussed in the development of appropriate seeding systems, the exploitation of techniques for the generation of coherent higher harmonics of the seed signal, the development of techniques for generation and control of bright electron bunches, including the manipulation of externally injected radiation fields and the mitigation against detrimental short bunch effects (e.g. microbunching and CSR).

3.3.3.2 Circularly Polarized X-Ray FELs

The possibility of producing **X-ray radiation with high degree of circular polarization** is another important asset at XFEL facilities especially in the soft X-ray region. However, the baseline of many existing or proposed facilities foresees only planar undulators. Adding an APPLE II - type undulator at the end of the planar undulator, in order to exploit the micro bunching from the baseline FEL leads to the problem of background suppression. Background radiation could be suppressed by spatial filtering, with slits behind the helical radiator, where the linearly-polarized radiation spot size is much larger than the helically polarized.

3.3.3.3 Attosecond Pulse Generation

The scope of large X-ray facilities, as the European XFEL currently under implementation, can be extended to the generation of **attosecond x-ray pulses** with peak powers in the hundreds MW range and high contrast for pump and probe experiments in the ultrafast region. Generation of few-cycle pulses in the x-ray regime can be realized by the strong nonlinear manipulation of the longitudinal space charge, as proposed for the so-called Longitudinal Space Charge Amplifier (LSCA) - in which a sequence of focussing and chicane channels is followed by a few undulator periods radiator.

3.3.4 Beam cooling

Methods for beam cooling are of great importance in heavy ion storage rings and muon storage rings. Key issues in this area are:

- **Electron and Stochastic Cooling** for Heavy Ion Beams
- **Ionization Cooling** for muon beams

3.3.4.1 Electron and Stochastic Cooling for Heavy Ion Beams

In ion storage rings beam cooling is needed to counteract the emittance blow up in experiments with internal targets and to enable the accumulation of secondary radioactive beams. A development of the concept of **electron cooling at high energies** (several MeV) is particularly relevant and needed for the operation with hydrogen-pellet targets.

Another key issue is the optimization of the **stochastic cooling method at higher bandwidths**. For this development, adequate amplifier systems and high frequency structures have to be designed and more realistic simulations are needed to support the design work of the installations. Beam tests with the technical components under development need to be conducted in order to validate the method.

3.3.4.2 Ionization Cooling

Muon storage rings have been proposed for use as sources of intense high-energy neutrino beams at the Neutrino Factory and as the basis for multi-TeV lepton-antilepton collisions at the Muon Collider. The performance optimization of such facilities requires the phase-space compression (cooling) of the muon beam prior to acceleration and storage. The short muon-lifetime makes it impossible to employ traditional techniques to cool the beam while maintaining the muon-beam intensity. **Ionization cooling**, a process in which the muon beam is passed through a series of liquid-hydrogen absorbers followed by accelerating RF-cavities, is the technique proposed to cool the muon beam. A globally unique Ionisation Cooling Test Facility (ICTF) is under construction at the Rutherford Appleton Laboratory to provide the infrastructure required to allow the first steps in an ionization-cooling R&D programme to be carried out: the Muon Ionisation Cooling Experiment (MICE). The goal of the international MICE collaboration is to construct a single lattice cell of the Neutrino Factory cooling channel and to measure its performance in a variety of beam conditions and lattice configurations.

A future Muon Collider would require an even more aggressive ionization cooling system that would reduce the size of the beam in all six phase-space dimensions and various schemes have been proposed to achieve this, but a strong R&D and demonstration effort will be required.

3.3.5 New techniques for high gradient acceleration

The most promising concept for high-gradient accelerator currently assessed at exploratory R&D infrastructures and proposed for future generation accelerator facilities is the Plasma Based Acceleration Technique, which can be used to accelerate electrons, protons and light ions. Under this Key Accelerator Research Area, the following Key critical Technical Issues have been identified [5]:

- the **self-injection Laser Wake-Field Acceleration** schemes (LWFA),
- the **external injection** of pre-generated electron bunches into non-linear **Laser induced plasma waves Below Wave-Breaking** (LBWB),
- the **external injection** of pre-generated electron bunches into **plasma waves driven by dense particle beams** (**Particle Wake-Field Acceleration, PWFA**),
- the development for a scheme of a **5th Generation Light Source** based on one of the above mentioned plasma acceleration schemes,
- **Proton and light ion generation** with laser driven plasmas.

The LWFA and LBWB techniques rely on intense laser pulses, while PWFA needs relativistic multi-GeV electron beams of high phase-space density.

3.3.5.1 Self-Injection Laser Wake-Field Acceleration

The advantage of the **LWFA** method is to require only the laser pulse, which is shot at high intensity (typically greater than 10^{19} W/cm^2) into a high density gas-jet (higher than 10^{18} n_e/cm^3) to drive a plasma wave well into the so called "bubble-regime", where full cavitation of the plasma electrons is formed just behind the laser pulse. Some of the plasma electrons are injected and accelerated into the plasma bubble, experiencing very high accelerating fields (> 100 GV/m). The drawback of this method is the high instability and low repeatability of the electron beam characteristics, as well as severe chromatic effects in the electron beam, which is produced with relativistic transverse momentum and over-focused by strong plasma fields into the bubble. These phenomena lead to a beam emittance dilution in the beam transport downward the plasma target. Beams of GeV top energies, although with relevant energy spreads, have been generated since many years at several laboratories world-wide (e.g. LBNL in USA, LOA in France, RAL and Strathclyde Univ. in the UK). Recently, at Strathclyde Univ. (UK), a lower energy beam (250 MeV) has been generated with good qualities (energy spread about 1% with stable beam propagation, normalized rms beam emittances of approximately 1 mm mrad).

3.3.5.2 External Injection in Laser Plasma Waves Below Wave Breaking

The main complication of the **LBWB** method is the production and injection of ultra-short (~ fsec) electron bunches into a plasma wave excited by the laser pulse. Electron and Laser pulse synchronization is a key issue: the time jitter is the challenge. But the high beam quality of the injected beam, if preserved along the plasma acceleration, would be the real breakthrough of the Laser acceleration technology (and is the goal of the PLASMONX test infrastructure at INFN-LNF). Solutions for addressing the jitter problem via a two stage generation/acceleration layout driven by a single laser pulse are under study and experimental exploration, aiming at using an Optical Master Oscillator as the reference clock and an optical fiber distribution for the timing signal.

3.3.5.3 External Injection in Particle Wake-Field Acceleration

The last plasma acceleration method, **PWFA**, has been proven so far by observing differential energy gain in one single 25 GeV electron bunch driving the plasma: the bunch head lost energy while the bunch tail experienced plasma acceleration. The real challenge of this method is the capability to produce long (20-50 cm) uniform plasma channel and inject couples of bunches: the leading one - dense and high charge - drives the plasma waves and the trailing one - low charge - gains energy from the plasma. While the FACETT Project at SLAC will pursue this impulsive single-driver scheme, resonant schemes are under investigation, using a train of properly spaced and modulated bunches to drive the plasma wave in a resonant fashion: these so called COMB beams are challenging to produce - various schemes are being tested at BNL and INFN-LNF, but offer the advantage of requiring lower phase-space densities for the driving beam than those of the impulsive scheme tested at SLAC.

3.3.5.4 5th Generation Light Sources: Compact Hard X-Ray Sources

An interesting application of these advanced schemes for high gradient acceleration is the attempt to build a **compact hard-X ray source** based on a FEL driven by these electron beams, produced either by LWFA or LBWB: this concept may be viewed as an example of **5th generation light source**, i.e. a X-FEL based on a compact (from table-top to a few tens of meter long) machine, to be compared with present km-footprint 4th generation sources like LCLS or European XFEL. The challenge for this task is clearly the demonstration of the electron beam generation at the high brightness required by FELs.

3.3.5.5 Proton and light Ion Generation with Laser Driven Plasmas

Laser driven plasmas have been used in the last few years also to **generate protons and light ions** up to several tens of MeV/n. Instead of firing the laser in a transparent medium (like the gas jets used in the LWFA scheme) to create a plasma wave, in this case the medium is a solid metallic target, which explodes at relativistic velocities under the effect of the radiation pressure carried by the high intensity laser pulse (> 10^{21} W/cm^2). Many laboratories world-wide already demonstrated the concept, with the production of protons in the 10-60 MeV range: the challenge for this activity is to produce quasi-monochromatic beam of protons (with energy spread < 5%). Presently, the state of the art is the production of beams with large energy spread, i.e. almost a continuous energy distribution from 1 MeV to the maximum energy spectrum edge (with a quasi-maxwellian spectral density distribution). The long-term aim is achieving compact systems able to deliver stable beams of protons up to 200 MeV, which for example are of interest for proton-therapy.

3.3.6 Medical and Industrial Accelerators

Since 1989, when the world's first hospital-based proton therapy center opened at the Clatterbridge Hospital in the UK and, in 1990, in Loma Linda, California, interest in dedicated **proton and carbon ion therapy facilities** has been growing steadily. Today, many proton therapy centers are in operation and the number of centers offering carbon ion therapy at hospital based centers is increasing. Carbon ion centers already exist or are under construction in Japan, Germany, Italy, Austria and China. All of these centers are based on synchrotrons but there are studies on carbon ion cyclotrons (Archade in Caen) and other types of accelerator solutions have been proposed like FFAG, rapid cycling synchrotrons and cyclotrons + linac booster. Concerning other applications, accelerators have a potential strong impact on the **Energy, Industry, Environment and Security sectors**.

The Key Issues in the Medical and Industrial Accelerator area are:

- improvement of **dose delivery techniques for hadron therapy**,
- improvement of **image guided radiation therapy techniques** and target recognition,
- reduction of **costs, size and complexity** of the equipment,
- systems for **Boron Neutron Capture Therapy**,
- production of **PET Isotopes and Tracers**,
- **Accelerator Driven Systems**, for nuclear waste transmutation,
- **Accelerators for Fusion**,
- **Industrial Application** in the sectors,
- **Environmental applications**,
- systems for Detection of **Illegal Nuclear Material**.

3.3.6.1 Improvement in Dose Delivery for Hadron Therapy

The field of hadron therapy is rather active and R&D is needed in many subjects. On the medical side, protocols are being defined and research on hypo-fractionation is being carried on; on the radiobiological side, RBE studies and models are being pursued to **improve treatment planning**; on the technical side, there are studies both on the **machine design** (including gantries) and on the **beam delivery**. In particular, the treatment of tumors in moving organs is an important development to increase the number of possible targets. In this respect, also medical diagnostic needs development of 4D medical imaging devices.

Most facilities are employing dose delivery methods developed in the period 1960-1990. A second generation of dose application techniques, based on **pencil beam scanning**, is slowly being introduced into the commercially available proton therapy systems. However, new developments in accelerator physics are needed to accommodate and fully exploit these new techniques. Especially the problem of organ/tumor motion during treatment needs to be tackled; otherwise the optimal characteristics of the dose distribution obtainable with pencil beam scanning cannot be achieved. Key solutions are aimed at gating techniques, very fast dose application and tumor tracking.

To enable an **optimal application of the scanning technique,** a CW beam with a well-controlled intensity or a pulsed beam with pulse rate of at least 1 kHz and accurate control of the dose per pulse are needed, as well as the possibility to have fast energy changes. This is achieved with cyclotrons and could be achieved with FFAGs, but in order to benefit from specific advantages of these and other accelerator types, more R&D is needed. On a mid term time scale particle therapy would benefit from accelerator developments aimed at achieving higher flexibility (to allow future upgrades of technology in a typical 30 years equipment life time, e.g. to allow fast energy variation), higher speed in dose delivery (to deal with motion problems), the possibility of higher beam energy (to allow proton radiography to determine stopping powers more accurately as well as to obtain sharper beams for stereotactic treatment of small lesions) and higher beam intensity (to allow beam splitting for optimal usage of the treatment rooms).

Apart from the use of superconducting magnets to enable the acceleration of carbon ions in a cyclotron, also the use of superconducting magnets in gantry systems is becoming increasingly interesting and these technological challenges (large rotating SC-structures and fast field changes) need intensive further investigation. The potential reduction in size and weight of particle therapy **gantries** is of utmost importance to reduce costs and to enable more use of gantries in ion therapy.

3.3.6.2 Image Guided Radiation Therapy

Non-invasive **tumor tracking and imaging techniques** are becoming of utmost importance to provide the dose distribution, in combination of beam scanning system. Upcoming new technologies like the acquisition and evaluation of MRI images during the irradiation need to be developed for particle therapy, and integrated in the dose delivery systems.

3.3.6.3 Cost and Complexity Reduction of Medical Accelerators

In the accelerator field, new developments such as **small superconducting cyclotrons** and, on a longer term, **Dielectric Wall Accelerator** (DWA), **laser driven** systems and **plasma wave** accelerators aim for smaller, single room treatment units. A lot of work is still needed to ensure that such new concepts indeed may lead to systems providing cheaper treatments, without compromising the quality of the dose delivery and the system reliability.

3.3.6.4 Boron Neutron Capture Therapy

Another new form of cancer therapy showing promise and requiring accelerator development is **Boron Neutron Capture Therapy** (BNCT). In this, a boron-10 carrying compound, which is preferentially absorbed by very active tumors, is injected into the patient. Boron-10 has a very large cross-section for thermal neutron absorption and upon interaction with a neutron, kills the cell it has been absorbed into. In this way, a much larger dose can be delivered to the cancerous cells than to the surrounding healthy cells. BNCT is then very good for treating aggressive tumors which infiltrate the healthy tissue, making it complementary to other forms of cancer therapy which usually have a poor outcome in these situations. However, BNCT requires a large flux of neutrons and the only current sources are test nuclear reactors. This flux could be achieved using an accelerator to produce around 5-10 mA of 3 MeV protons and producing the neutrons in a solid lithium target. Although accelerators meeting these requirements exist, there would be significant benefits in reducing their size. Further, a working solid target has so-far not been created, despite many attempts.

3.3.6.5 Production of PET Isotopes and Tracers

Accelerators are used to create **PET isotopes**, usually with commercially produced machines, typically cyclotrons. Furthermore, the most commonly used medical radioactive tracer is **99mTc**, produced by the decay of 99Mo, which comes almost exclusively from 5 aging nuclear reactors. Due to recent problems with the cooling systems of two of these, there is significant concern about the availability of 99Mo in the future. Accelerators could help in a number of ways: via spallation, via low energy protons (as for BNCT, but with larger currents) and via photo-fission. However, it is important that these methods do not significantly increase the cost of production and R&D is required for each method to meet the demand for 99Mo at the correct price.

3.3.6.6 Accelerator Driven Systems for Nuclear Waste Transmutation

High power proton accelerators have a possible important application which could help to the solution of the nuclear waste disposal and to meet the world’s future energy needs. The so-called **Accelerator Driven Systems** (ADS) use these high power beams to create large fluxes of neutrons by means of spallation targets within nuclear reactors safely operating below criticality. The large spectrum of the neutron flux allows an efficient transmutation of existing radioactive waste into stable elements, reducing the inventory and storage time of the processed waste. ADS will allow deployment of smaller footprint geological repositories needing to guarantee the waste integrity without contamination of the biosphere for a few hundred years, rather than the several hundred thousands required by the current storage schemes. The neutron production capabilities of the ADS concept, combined with a new generation of uranium-free fuel, based on thorium, could also open a new proliferation resistant fuel cycle producing much less waste to be sent to geological storage. Due to the potential, there is significant interest in ADS worldwide and in particular in Europe, with several dedicated programs which started in the FP5 (PDS-XADS, EUROTRANS in FP6 and MAX in FP7 in support of the MYRRAH proposal). The accelerator challenges are many, in particular meeting the goal of delivering several MW of beam power with no interruptions greater than approximately a second for several months continuously. The beam also has to be transported into a working subcritical reactor and delivered to a relatively small liquid metal target capable of operating in that severe radiation environment.

3.3.6.7 Accelerators for Fusion

The other application is in the area of **fusion**, where very high current ion accelerators are being investigated for a number of purposes. The first is the IFMIF project, which will produce a huge flux of neutrons to study the effect of those produced in fusion reactions on the structure of the containment vessel. Ion accelerators to accelerate tens of Ampere intensity beams to 1 MeV are also being studied as a way of **heating the plasma** in a magnetic confinement reactor. The last purpose is to create fusion directly using accelerators via **heavy ion inertial fusion**, in which the ion beams are used to compress and ignite the fuel directly. The requirements for this application are extraordinary: GeV beams with intensities of thousands of Amperes. Significant R&D is required in each of the cases listed above.

3.3.6.8 Industrial and Societal Applications

Electron and ion accelerators are used for a number of **industrial applications**. Electron beams up to 10 MeV are used for **modifying the structure** of plastics, polymers and rubbers to improve their properties and are also used to sterilize medical instruments. In all cases, the accelerators used are commercially produced. Ion beams are used predominantly for **ion implantation**. This employs mainly beams of boron, phosphorus and arsenic, which are implanted in silicon and germanium. The beams are typically 500 MeV, though higher energies are sometimes used. The main future challenge in this area is producing the higher beam currents required for implantation into smaller structures. The main problem with this will be overcoming collective effects, in particular space charge, and this will require R&D. MeV ion beams are also used for non-destructive elemental analysis, for example, in **carbon dating** or the **analysis of Cultural Heritage** masterpieces with Particle Induced X-Ray/Gamma-Ray Emission (PIXE/PIGE). These techniques allow to solve questions about origin and authenticity of works of art, to deepen the knowledge of materials and production technologies used in their realization. The elemental analysis can also lead to a better understanding of the technological skills of the artist and allows to investigate the objects before a restoration, devising suitable conservative actions.

3.3.6.9 Environmental Application

Electron beams are also under study for two **environmental applications**. The first is reducing pollution and acid rain by **catalyzing reactions** of nitrogen and sulphur oxides in the gases emitted from the chimney stacks of conventional power stations and factories. This is currently being investigated in Poland and requires beams of 0.8 MeV with a power of 1 MW per 100 MW of plant power. The accelerators must have industrial reliability and work in a very unclean environment. The second application, studied in the US for example, is for **water treatment**, in particular disinfecting and decontaminating both waste and drinking water. In addition, a full-scale facility in Korea uses electron beams to break down residual dyes from a fabric plant before discharge into a river. The requirements are for beams up to 5 MeV and a beam power of 0.4 MW for a small plant size and 20 MW for a large one.

3.3.6.10 Accelerators for Detection of Nuclear Material

There is much concern in a number of countries about the import and use of nuclear material for **terrorist activities**. As a result, various methods are being studied for identifying so-called **shielded nuclear material in cargo containers**. Detection is a challenge, as these containers are large, have diverse cargoes, must be scanned quickly, in less than one minute, and a variety of material must be detected, with a low rate of failures and false positives. A number of accelerator produced beams are under consideration for this. They include THz radiation produced from free electron lasers, neutrons up to 10 MeV, protons up to tens of GeV and even muon beams. In each case, significant R&D is required to produce a device which can be used reliably and safely in a port by non-experts, which does not take up too much space and which meets the scanning requirements.

4 KARA relevance for future projects and facilities

Domain	**Projects** **KARA**	ESFRI Project List					Flavour Factories (SuperB)	Neutrino Factories Muon Colliiders	High Intensity Hadron Facilities (Eurisol, ADS/MYRRHA, IFMIF)	3^{rd} Generation radiation sources	4^{th} Generation radiation sources, FEL, ERL	5^{th} Generation radiation sources
		XFEL	FAIR	ESS	LHC Upgrades (HL-HE)	Linear Colliders (ILC, CLIC)						
Accelerator Components	Sources and Injectors	x	x	x	x	x	x	x	x	x	x	
	RF Structures	x	x	x	x	x	x	x	x		x	
	RF Systems	x		x		x	x		x		x	
	SC Magnets		x		x	x	x	x				
	Conventional NC Magnet Systems		x			x				x	x	x
	Diagnostic and Instrumentation	x	x	x	x	x	x	x	x	x	x	x
	Targetry		x	x	x	x		x	x			
	Radiation Issues		x	x	x	x		x	x			
Accelerator Technologies	Electronics and Software	x	x	x	x	x	x	x	x	x	x	x
	UHV	x	x	x	x	x	x	x	x	x	x	x
	RF Sources	x	x	x	x	x	x	x	x	x	x	x
	Cryogenics	x	x	x	x	x		x	x			
	Alignment and Stabilization	x	x	x	x	x	x	x	x	x	x	x
Accelerator Concepts	Accelerator Design	x	x	x		x	x	x	x			x
	Beam Dynamics	x	x	x	x		x	x	x			x
	FEL Processes	x									x	x
	Beam Cooling		x					x				
	New Techniques for High Gradient Acceleration					x						x
	Medical and Industrial Accelerators	N/A										

5 Future updates

The present TIARA-PP goal of identifying the key technical issues in the accelerator R&D cannot be intended as a frozen snapshot of our present understanding of the technological challenges to address in present and future machines.

Technology evolves, new concepts are proposed, further critical key items may appear, new breakthroughs will eventually lead to a change of scope in some Key ARA, or new problems will show up, requiring diversion of resources from other, less priority, areas. All these possibilities could easily show up in the near or long term future, and need to be accounted in the interpretation of this work.

6 Acknowledgments

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7 References

[1] ESGARD is the European Steering Group on Accelerator R&D, formed in 2002 by the directors of CCLRC, CERN, DAPNIA/CEA, DESY, INFN/LNF, Orsay/IN2P3, and PSI in consultation with ECFA. Home page available at http://www.esgard.org.

[2] See EuCard web pages https://eucard.web.cern.ch/EuCARD/index.html.

[3] The TESLA Technical Collaboration (http://tesla.desy.de) is an International Collaboration on the superconducting technology that supports and encourages free and open exchange of scientific and technical knowledge, expertise, engineering designs, and equipment across project based on this technology. The TTC holds yearly meetings to review the R&D status and the technological issues for large SRF projects.

[4] Perspectives of Nuclear Physics in Europe - NuPECC Long range plan 2010, available at http://www.nupecc.org/index.php?display=lrp2010/main

[5] For a comprehensive up-to-date status on European and worldwide activities on advanced accelerator schemes, refer to the EuroNNAc (European Network for Novel Accelerator) May 2011 meeting at CERN, available at http://indico.cern.ch/conferenceDisplay.py?confId=115336.

[6] ARD – Accelerator Research and Development, Accelerators – Motors for Discovery and Innovation, Helmholtz Association

A. The list of KARA/KTI

Accelerator Components

Key Accelerator Research Area	Key Technical Issue
Sources and Injectors	High Brightness Photo Injectors
	High Intensity Heavy Ion Injectors
	High Intensity Proton Injectors
	High-polarization electron/positron sources
	Hollow beams for proton beam collimation
	RFQ development
	Beam funneling
RF structures	High Gradient Acceleration at Low RF Breakdown Rates
	Development and engineering of C-Band and X-Band Structures
	Consolidation of the Nb Technology for Maximum Yield at Highest Gradients
	Improvements of the “Low Beta” Cavity Technology
	Coupler for SRF Cavities at High Average Power
	Overcoming the Performance Limits of Bulk Niobium
	Crab cavity Developments
	RF Structures for 6D Muon Beam Cooling
	Variable Frequency Resonators for Synchrotrons or FFAG
RF systems	Optimization of RF Systems for high brilliance damping rings
	X-Band and C-Band RF Systems
	Precision LLRF control
SC magnets	Material and Technologies for the 20 T Range and Beyond
	Fast Cycling SC Magnets
	Engineering Challenges for High Field Magnets
	Cryogen-free magnet systems
	High-Field short period undulators
	High Field Small Magnets using rare-earth pole tips
Conventional NC magnet systems	Compact Magnets
	Radiation Resistant Magnets
	Insertion Devices for X-Ray Production and Damping Rings
	Pulsed Magnets and Kickers
	Insertion devices for damping and X-Ray production
	Transparent Injection in Top-Up Schemes
	Fast pulsed quadrupole magnets for beam lines

Diagnostics and instrumentation	Beam Position Monitor Development
	Beam Size and Emittance Monitor Devices Development
	Synchronization, fs or sub-fs
	Radiation hard electronics components and design
Targetry	Challenges for High Power Targets for Secondary Particle Production
	Radiation Damage Phenomena in Target Materials
	Monte Carlo Particle Transport Codes Validation
	Collimation Systems
	Bent Crystal channelling
Radiation issues	Determination of Prompt Radiation Levels
	Component Activation Handling
	Compact Shielding

Accelerator Technologies

Key Accelerator Research Area	Key Technical Issue
Electronics and Software	xTCA Standards
	LLRF cost, performance
UHV	Radiation-Induced Outgassing and Secondary Particle Generation
	Low Outgassing Rates to Limit Pumping Times
	Wall Chamber Conductivity and Eddy Currents
RF sources	Energy efficiency
	Solid State Technology RF Sources
Cryogenics	Cryoplant Efficiency Improvements
	Cryogenic Distribution and Cryostat Insulation
Alignment and Stabilization	Laser and Wire Positioning Systems
	Nanometer Level Stabilization

Accelerator Concepts

Key Accelerator Research Area	**Key Technical Issue**
Accelerator Design	Design for Reliability and Availability
	Beam Losses and Machine Protection at High Beam Power
	Compactness and Simplicity
	Energy Efficiency and Storage
Beam Dynamics	Enhanced Beam Modeling Tools
	High Luminosity and High Energy Hadron and Lepton Colliders
	Beam Stability and Lifetimes in Circular Accelerators
	Small Emittance Beam Generation and Transport
	Transport of electrons in plasma accelerating structures
	Low Losses in High Intensity Linacs
	High Reliability Operation
	Laser-Beam Interaction for Acceleration and X-Ray Production
	Fast Acceleration for Unstable Particles
FEL processes	Develop New Seeding Techniques for FELs
	Circularly Polarized X-Ray FELs
	Attosecond Pulse Generation
Beam cooling	Electron and Stochastic Cooling for Heavy Ion Beams
	Ionization Cooling
New techniques for high gradient acceleration (laser-plasma etc.)	Self Injection Laser Wake-Field Acceleration
	External Injection in Laser Plasma Waves Below Wave Breaking
	External Injection in Particle Wake-Field Acceleration
	Proton and light Ion Generation with Laser Driven Plasmas

Medical and Industrial Accelerators	Improvement in Dose Delivery for Hadron Therapy
	Image Guided Radiation Therapy
	Cost and Complexity Reduction of Medical Accelerators
	Boron Neutron Capture Therapy
	Production of PET Isotopes and Tracers
	Acceleration Driven Systems for Nuclear Waste Transmutation
	Accelerators for Fusion
	Industrial and Societal Applications
	Environmental Applications
	Accelerators for Detection of Illegal Nuclear Material