EUROPEAN
SPALLATION
SOURCE

HIGH POWER ACCELERATORS

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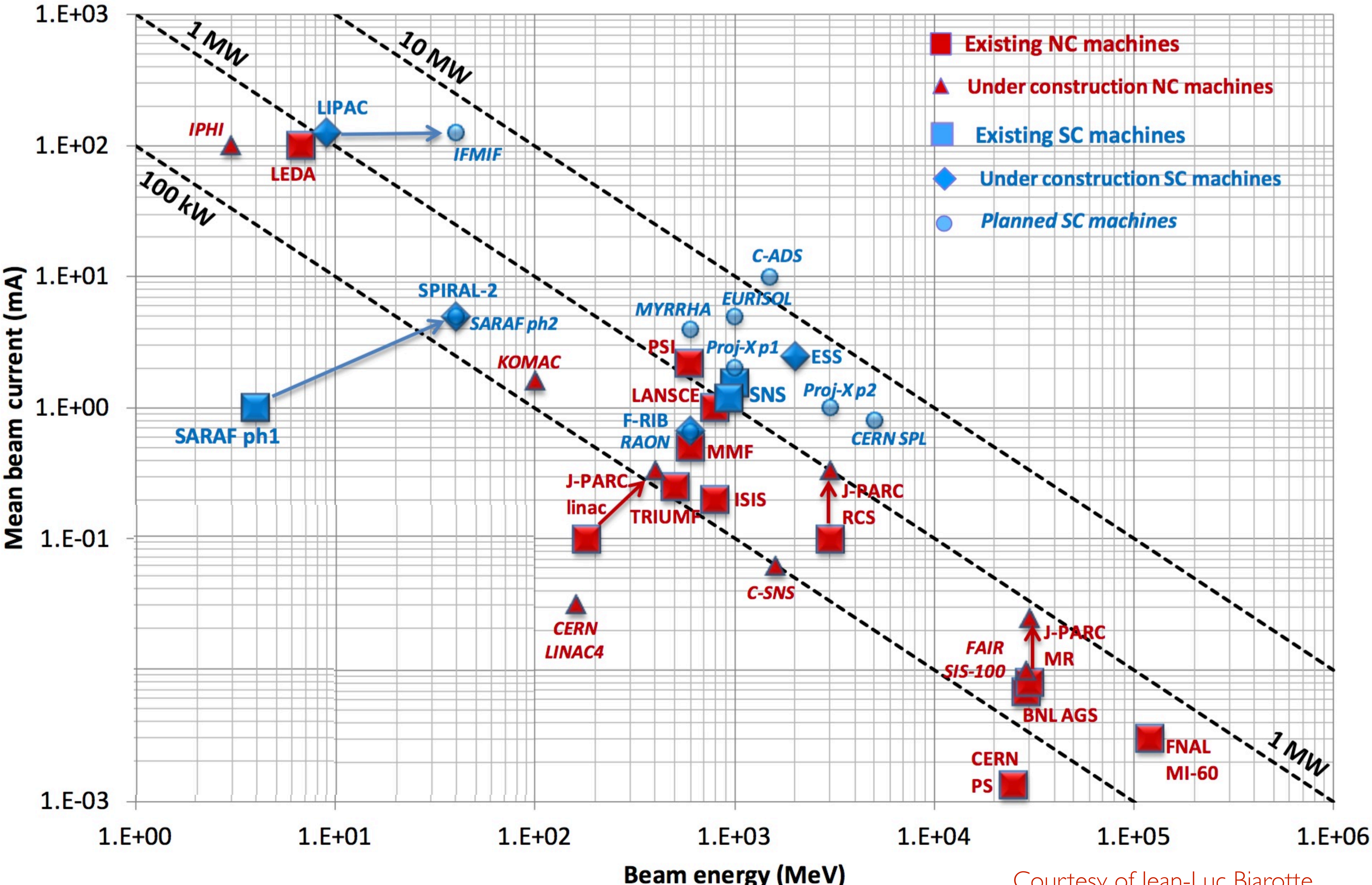
OUTLINE

- We will look at three applications of high power accelerators, with examples of each, and then use ESS as an example of a high power linac and investigate it in more details.
  - Radioactive Ion Beams
    - SPIRAL2
  - Accelerator Driven Subcritical Reactors
    - C-ADS
    - MYRRHA
  - Spallation Neutron Sources
    - PSI
    - J-PARC
    - SNS
    - ESS

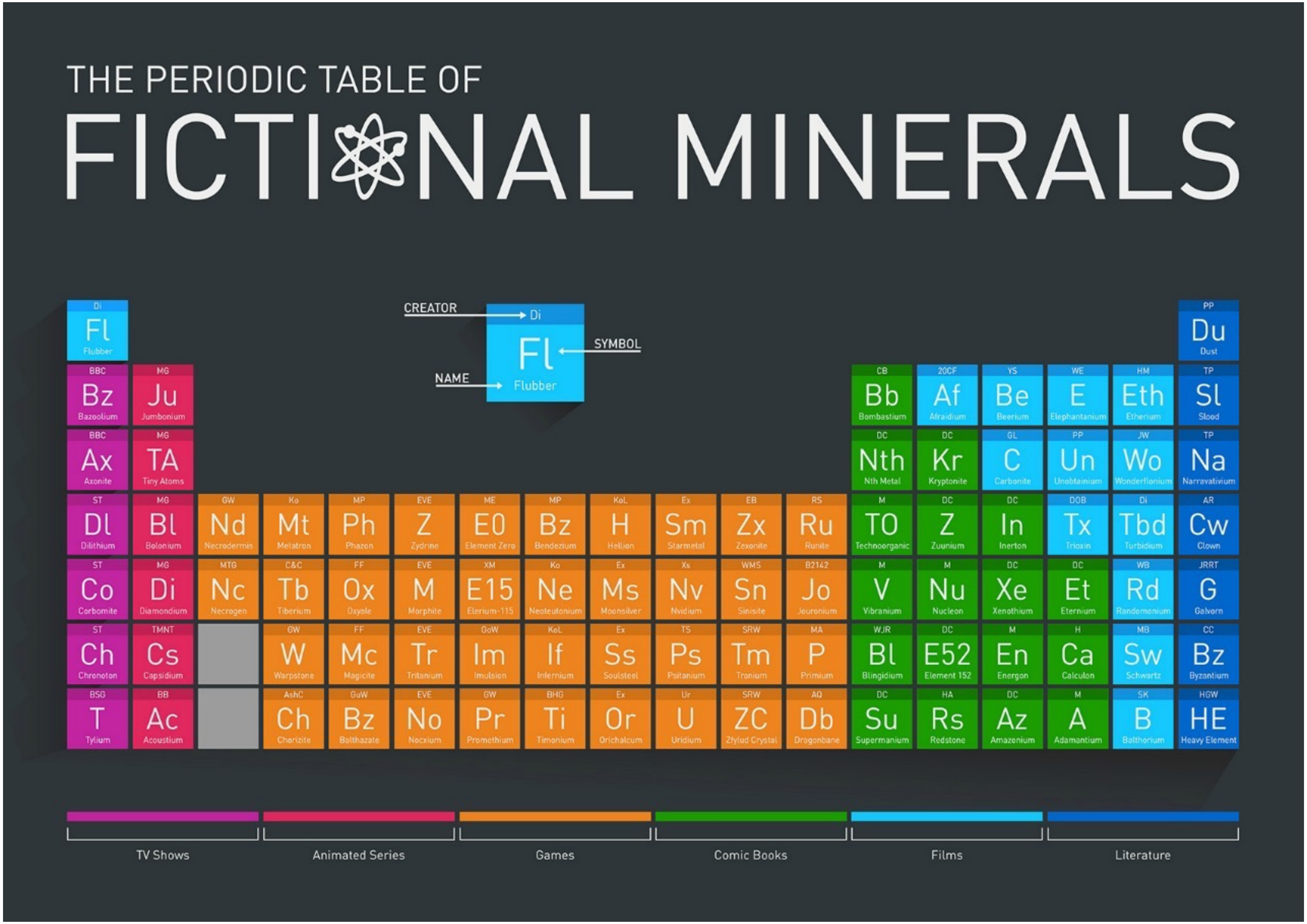
High power beams



Courtesy of Jean-Luc Biarotte

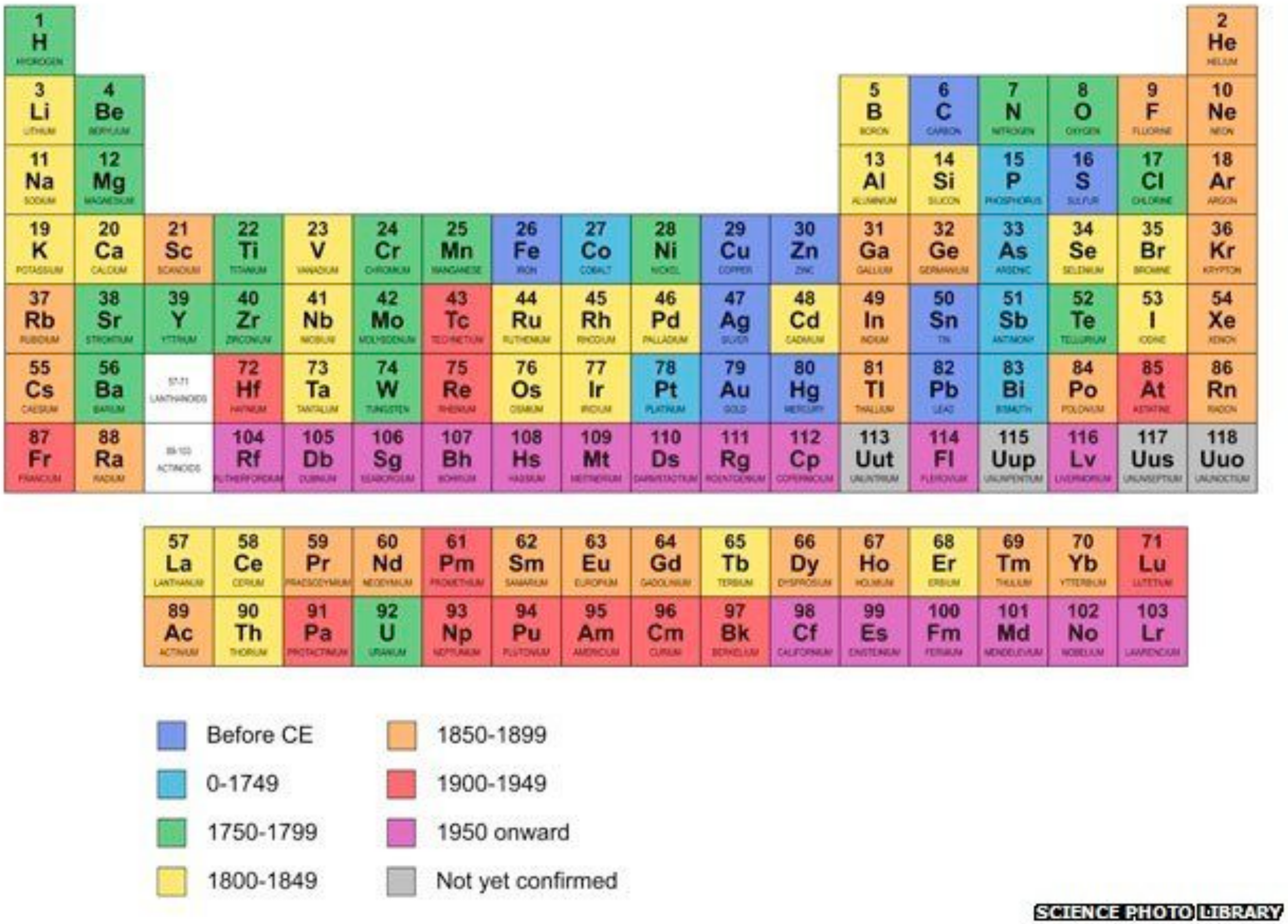
Periodic Tables of Elements

The fictional one!



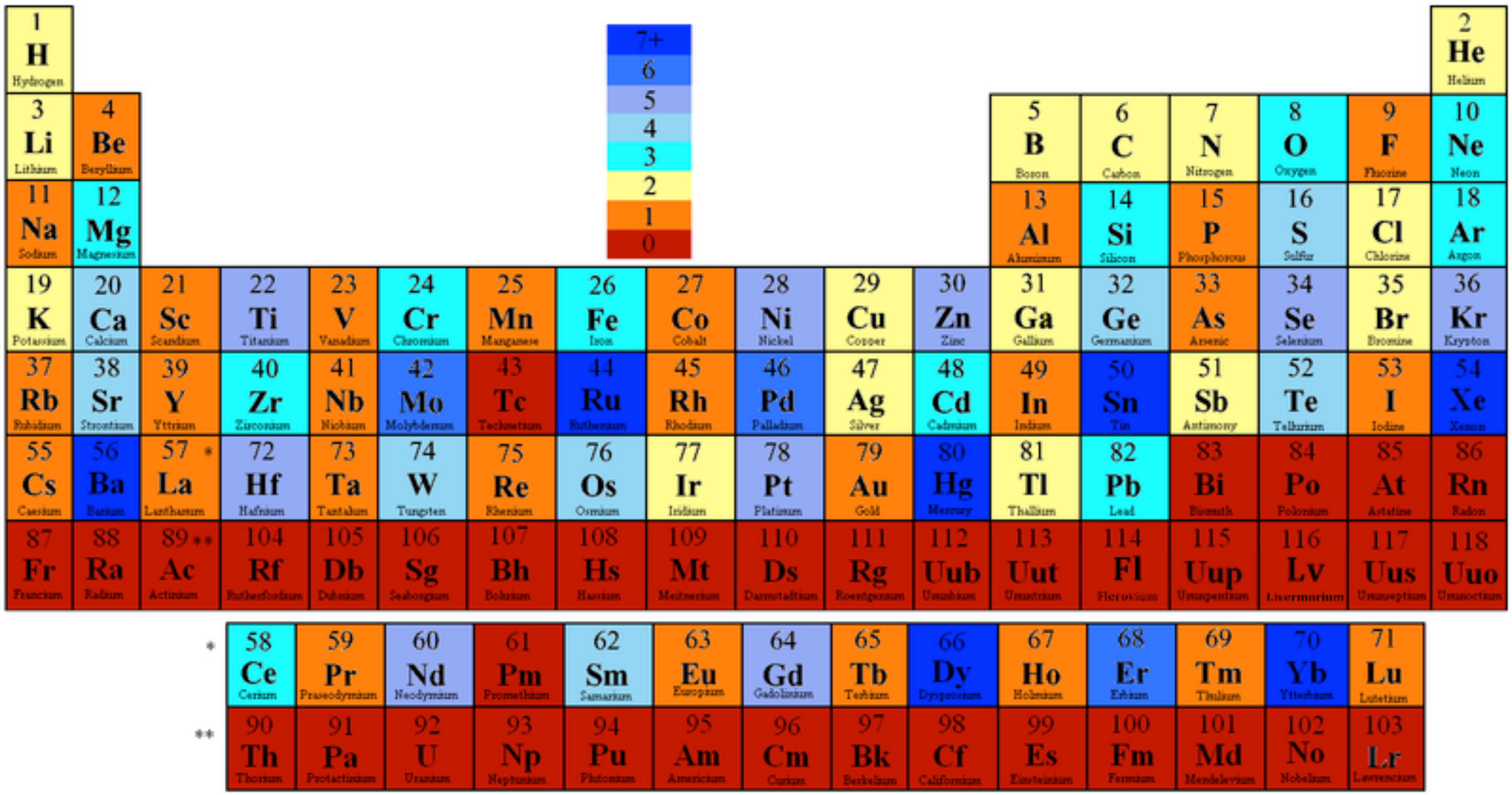
Periodic Tables of Elements

Date of discovery



PERIODIC TABLES OF ELEMENTS

NUMBER OF STABLE ISOTOPES PER ELEMENT



Studying the Nature

- One has claimed that all the interesting nuclear physics with stable beams is already done and now one has to use radioactive beams!
  - Even though that is partly through, to understand how the elements were formed in the early universe we need to investigate beyond the existing isotopes of the elements we find in the nature.

- All the elements we know, and their isotopes, make what we call the valley of stability.

- The isotopes further away from this valley are interesting to be studied, but hard to be produced.

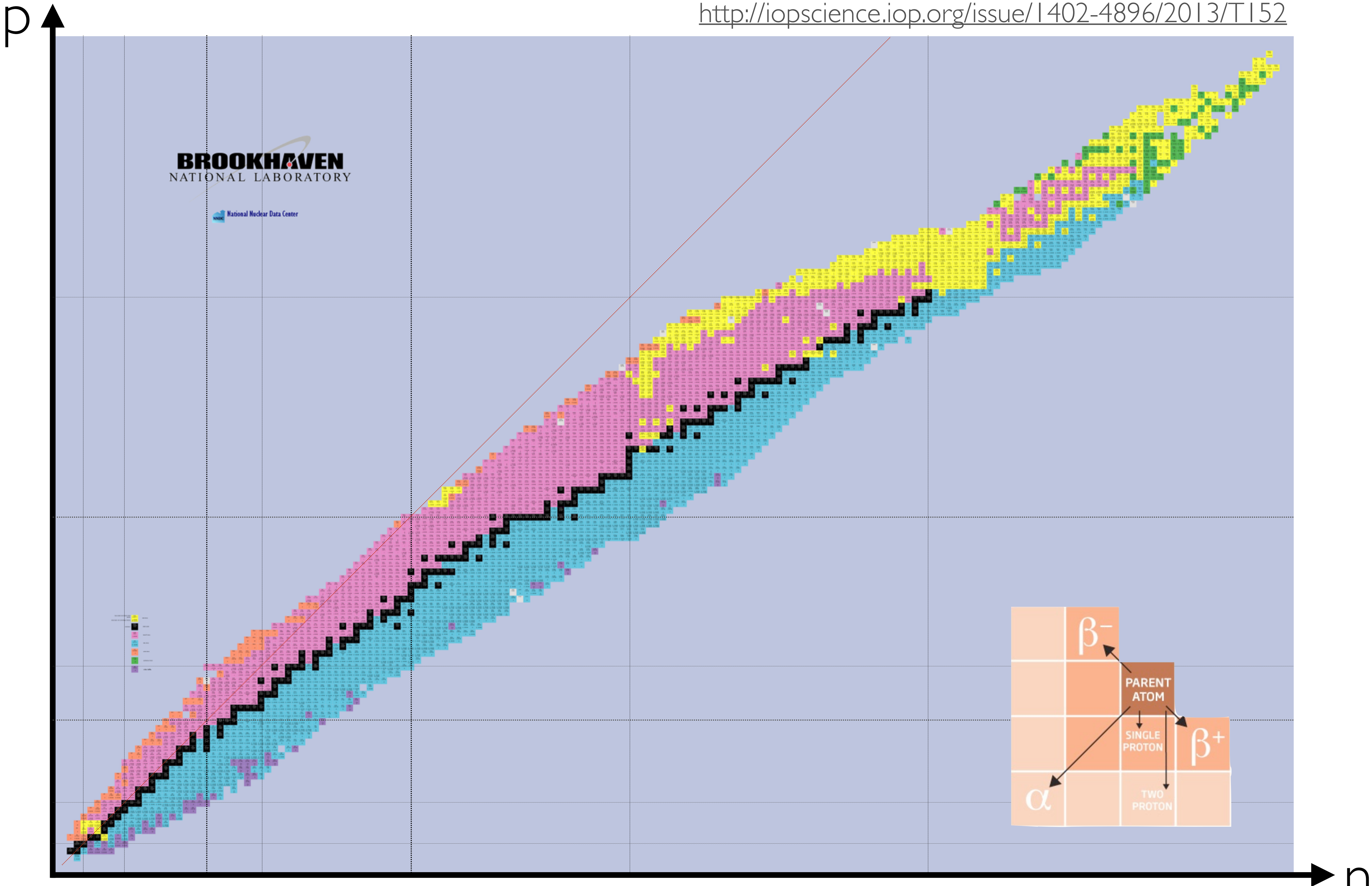
- The further from the stable ratio of proton to neutrons they are, the harder is their production, due to their very short life times, low production cross-sections, and the wanted isotopes making a very small fraction of the total secondary particles produced (which would include stable species or other unwanted radioactive isotopes).

- Their production paves the way forward for understanding the fundamentals of nuclear physics, stelar nucleosynthesis, and applications in nuclear science.

PERIODIC TABLES OF ELEMENTS

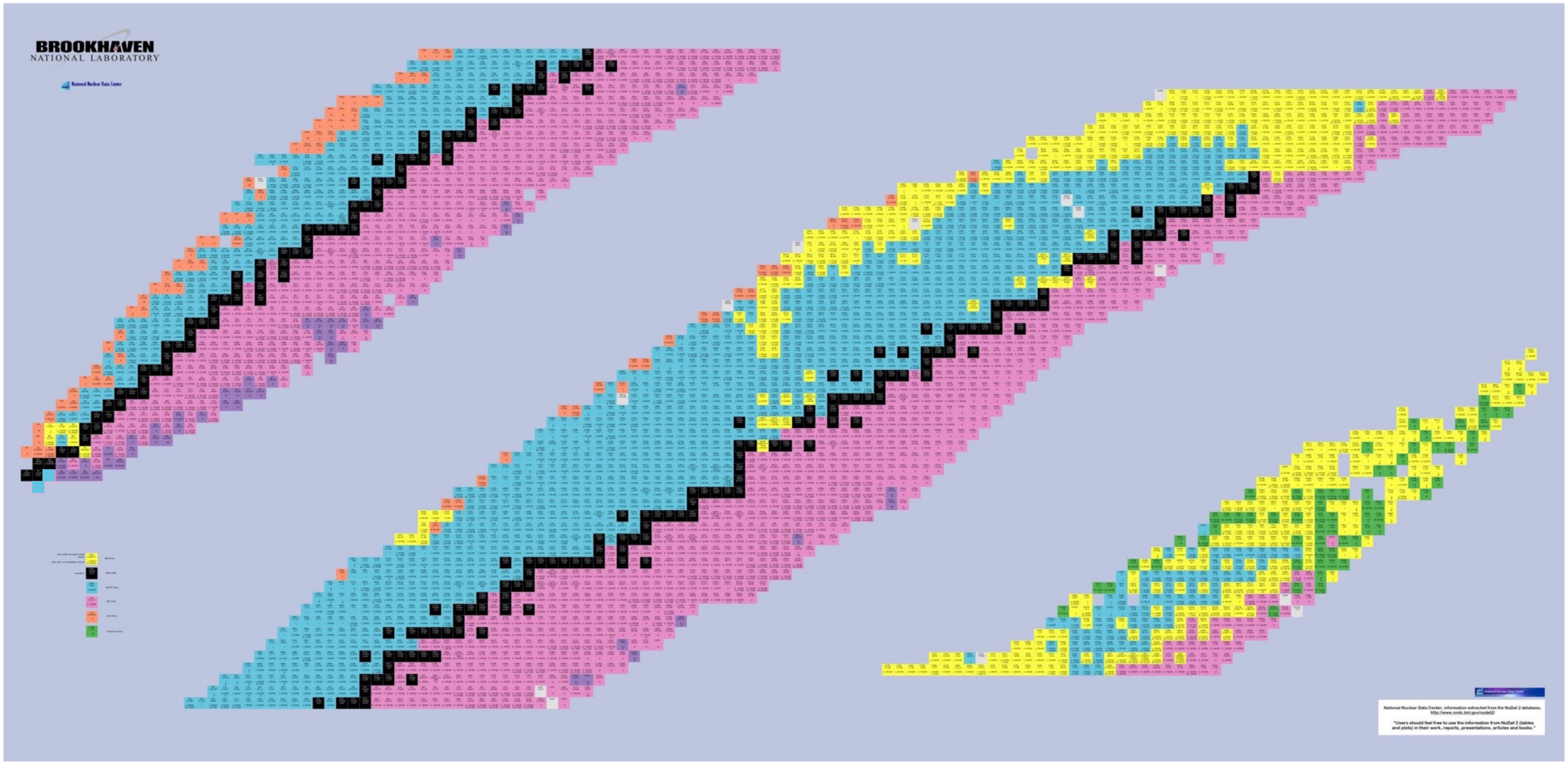
GRAPH OF ISOTOPE STABILITY

http://iopscience.iop.org/issue/1402-4896/2013/T152



Periodic Tables of Elements

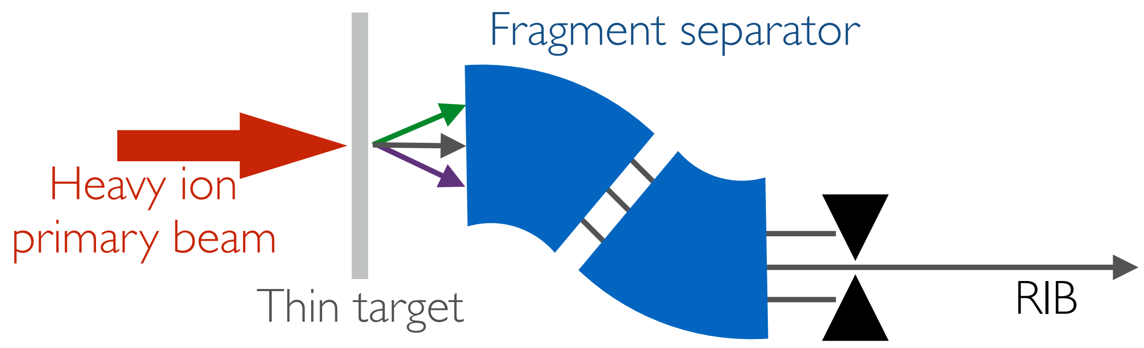
Graph of isotope stability



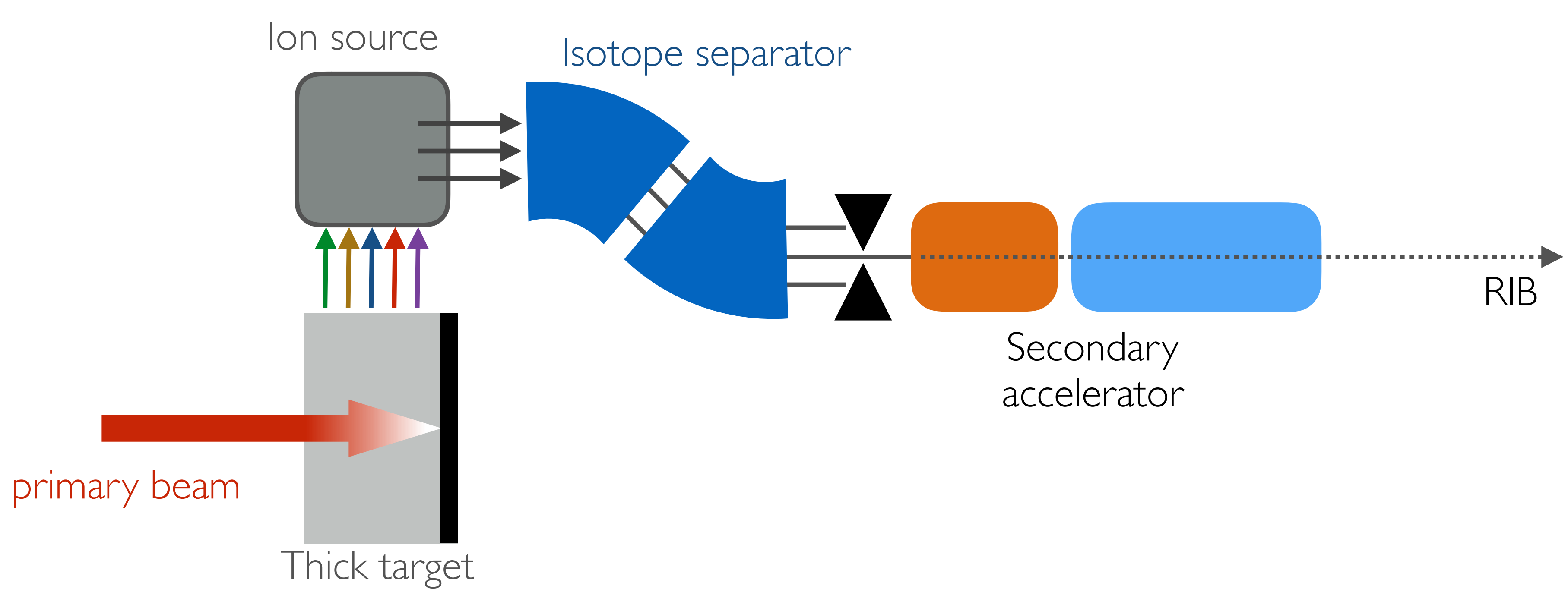
None	Beta decay	Proton emission	e+ emission e- capture	Neutron emission	Alpha decay	Spontaneous fission

IN-FLIGHT VS. ISOL

- There are two methods for producing the RIBs (Radioactive Ion Beams)
  - In-flight



  - ISOL, Isotope Separation On-Line



Further reading: https://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/frxcb201.pdf

In-flight vs. ISOL

- ISOL
  - Good beam quality (dE/E small)
  - Pure beam (better selectivity with chemistry)
  - Higher production rate for the "extractable" species
  - Low energy, light ions => smaller facility
  - Life time has to be ≥ 10ms
  - Beam energy varies within the thick target (and so does the efficiency of the production)
  - Safety issues with the inserted hot cells
- In-flight
  - Access to very short lived fragments (≥ 600ns)
  - Direct relation between cross sections and observed production rates
  - Provides beams with energy near that of the primary beam
  - Significant dE/E
  - Simplest production target but sophisticated fragment separation
  - High energy, heavy particles lead to big facility

- Reaction mechanism are mostly different and result in different fission fragments.

Slide courtesy of Robin Ferdinand GANIL

Spallation, Fission and Fragmentation

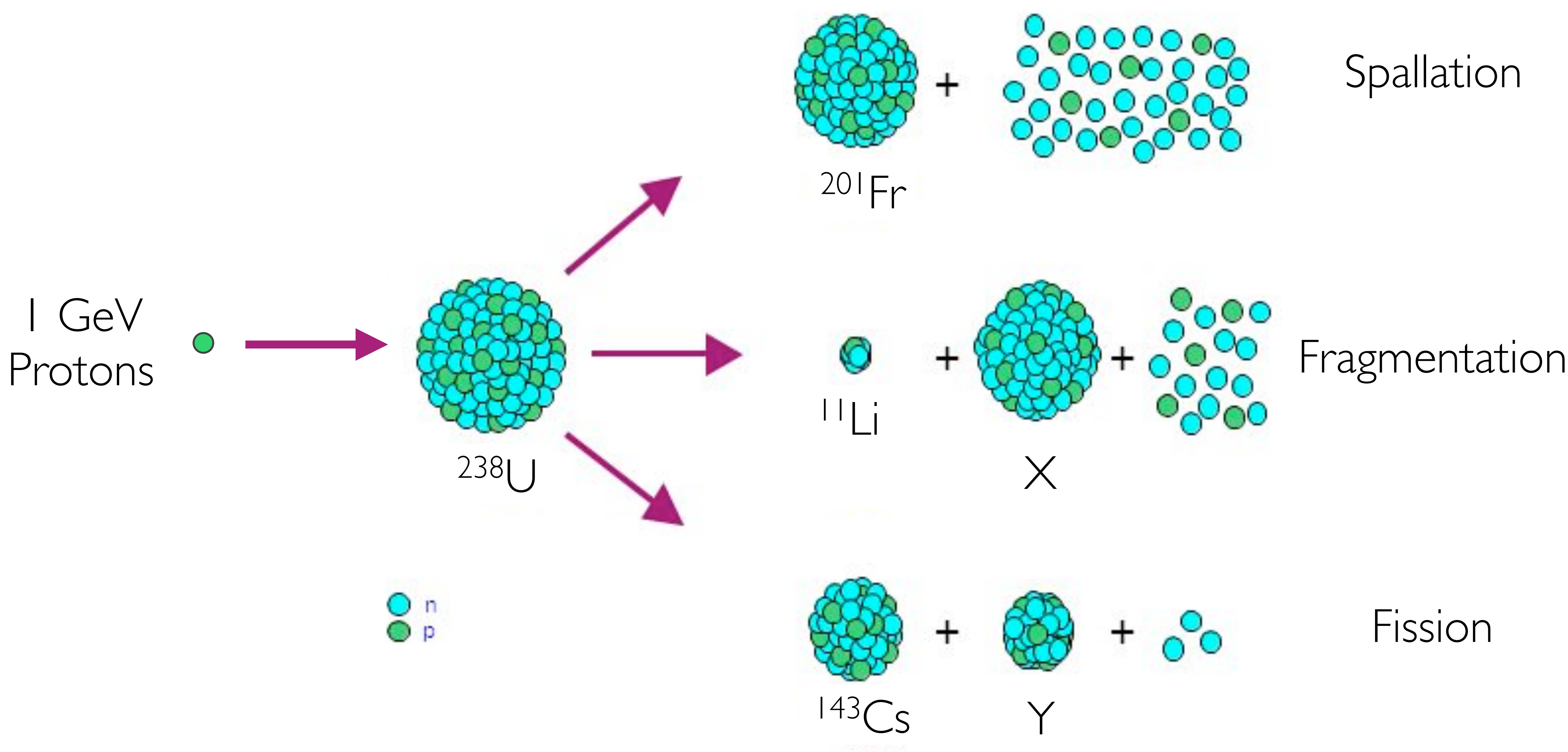
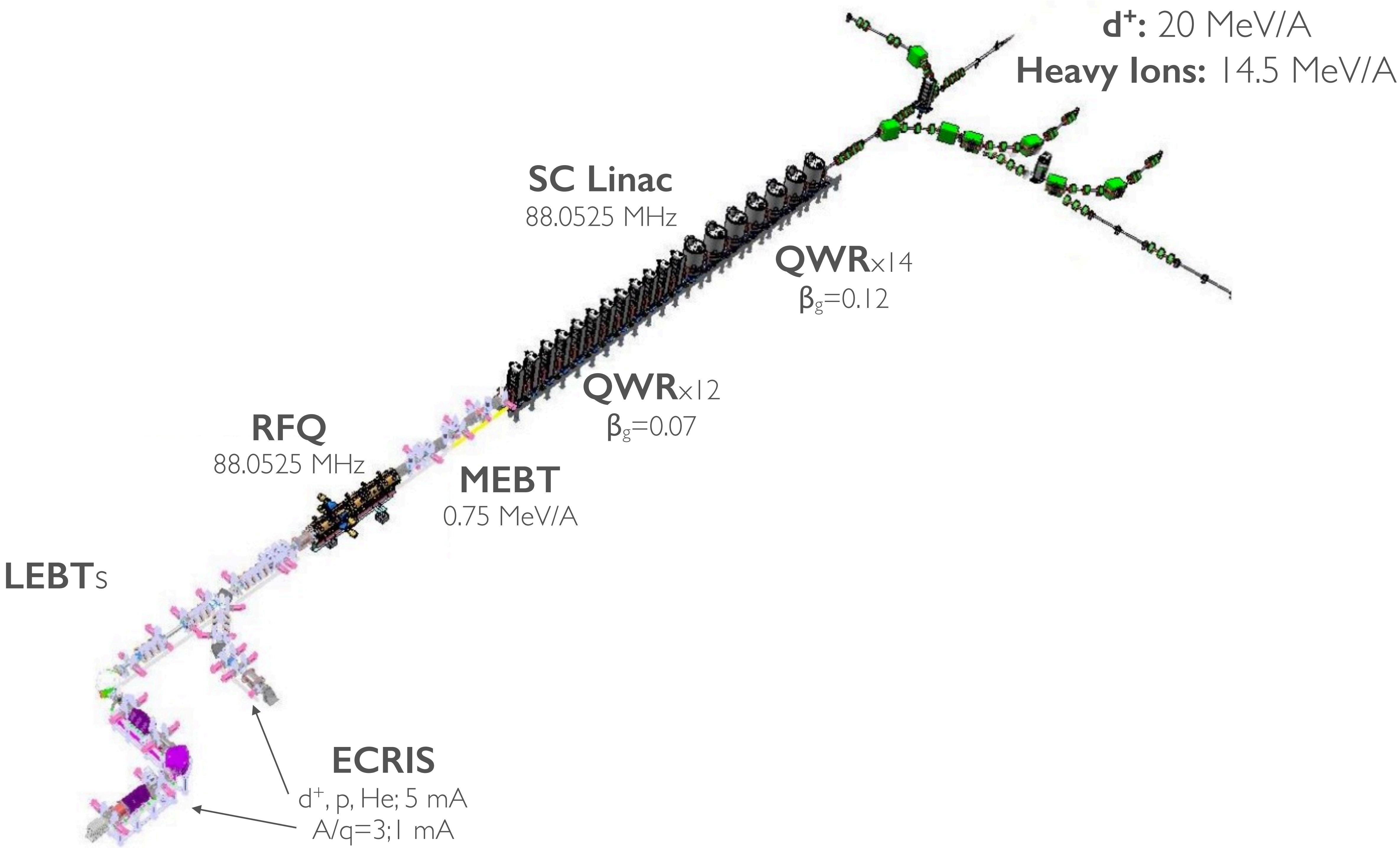


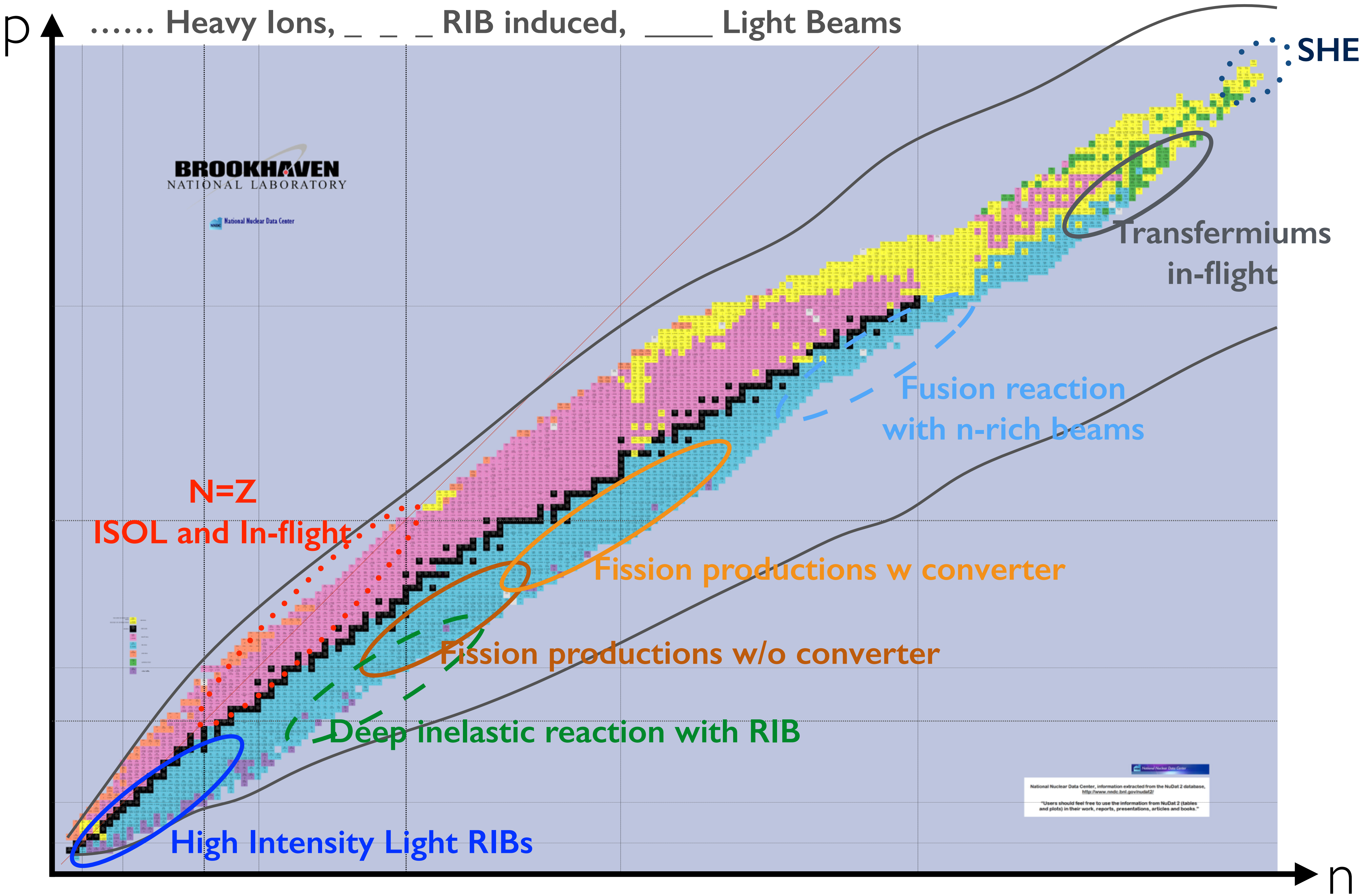
Illustration courtesy of K. Riisager, ISOLDE

SPIRAL2

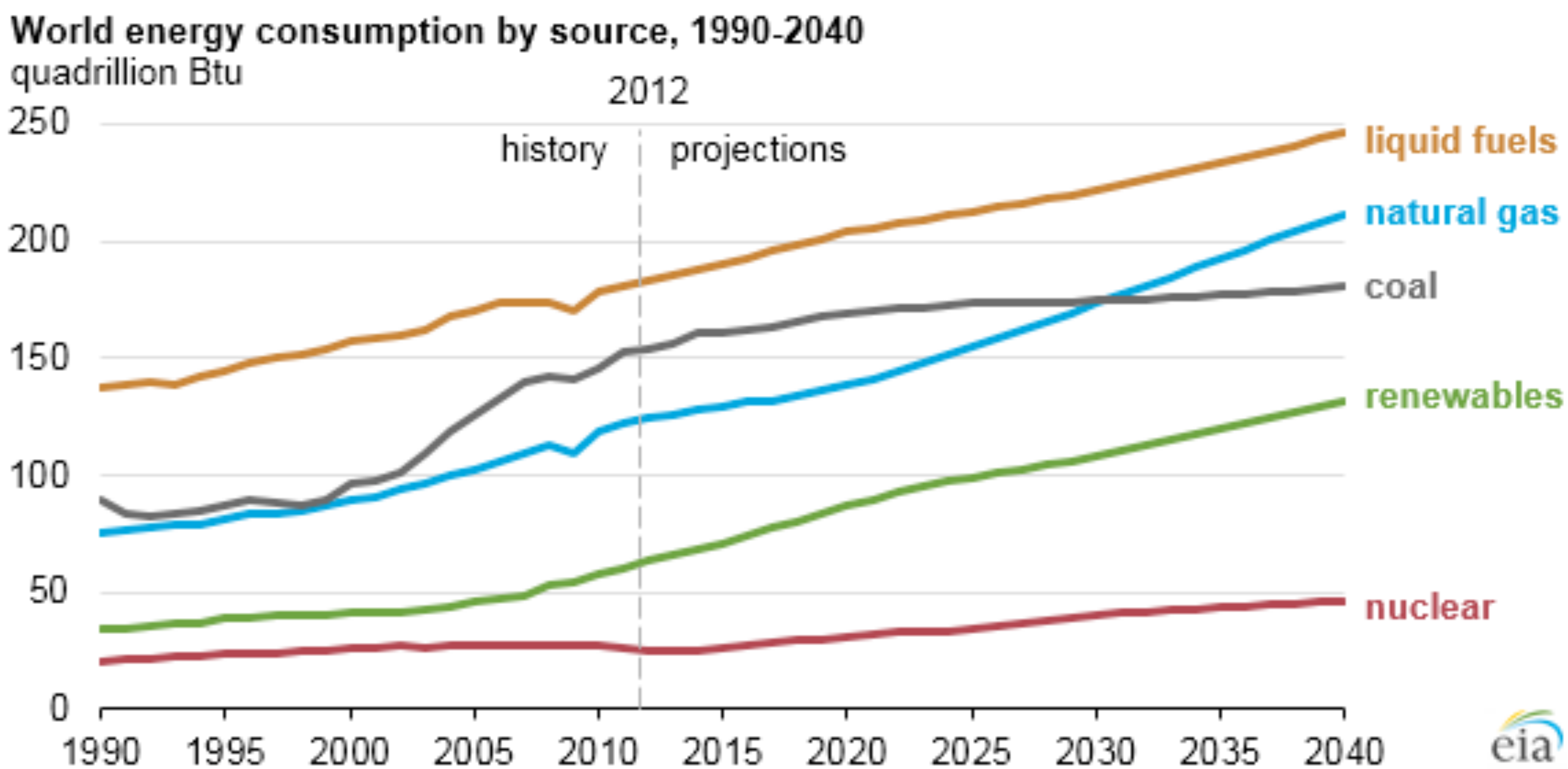


d⁺: 20 MeV/A
Heavy Ions: 14.5 MeV/A
SC Linac
88.0525 MHz
QWRx14
β_g=0.12
QWRx12
β_g=0.07
RFQ
88.0525 MHz
MEBT
0.75 MeV/A
LEBTs
ECRIS
d⁺, p, He; 5 mA
A/q=3; 1 mA

SPIRAL2, WHICH REGIONS BECOME ACCESSIBLE



THE ENERGY PROBLEM

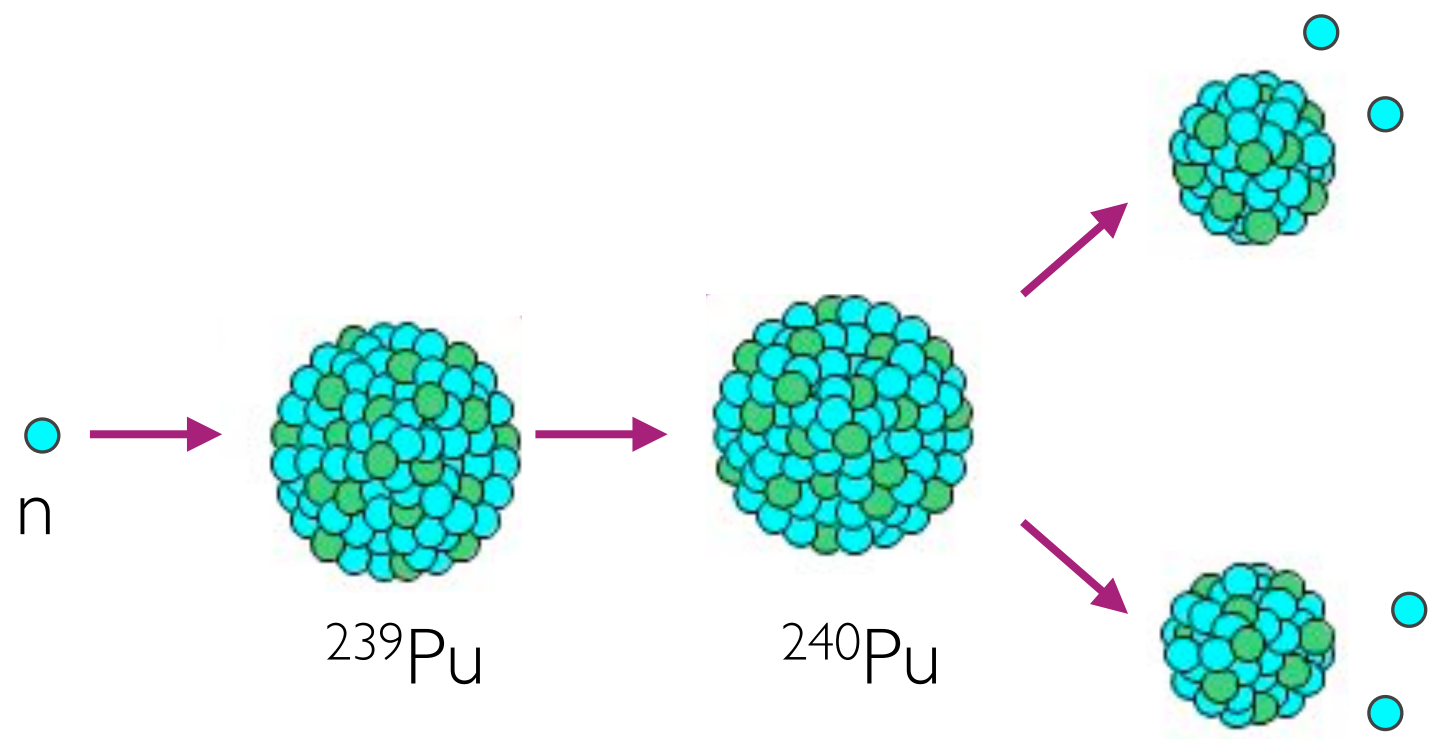


Source: US Energy Information Administration

- We are consuming more and more energy, based on EIA, ~50% increase by 2040!
  - What do we do with the climate change?
  - What do we do with the nuclear waste?

Transmutation

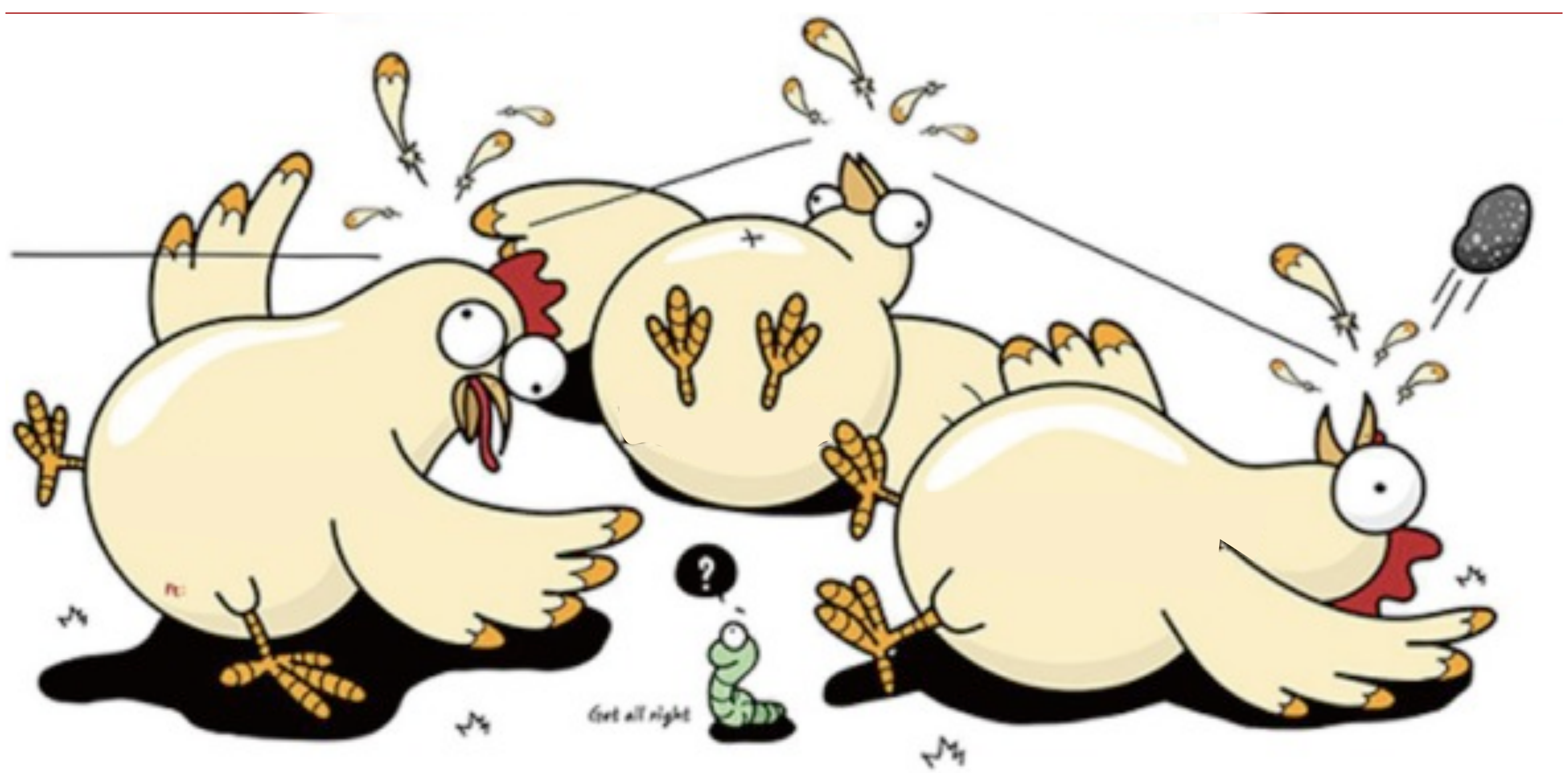
- One of the problems of the nuclear energy is the production of daughter nuclei with medium life time 100-1000 years.
  - Can we convert those nuclei to something different, the same way we use accelerators to create RIBs?



- E.g. Bombarding a highly radioactive ^{239}Pu with neutrons would initiate a fission, where the products have a much lower half-life (or very very long)!

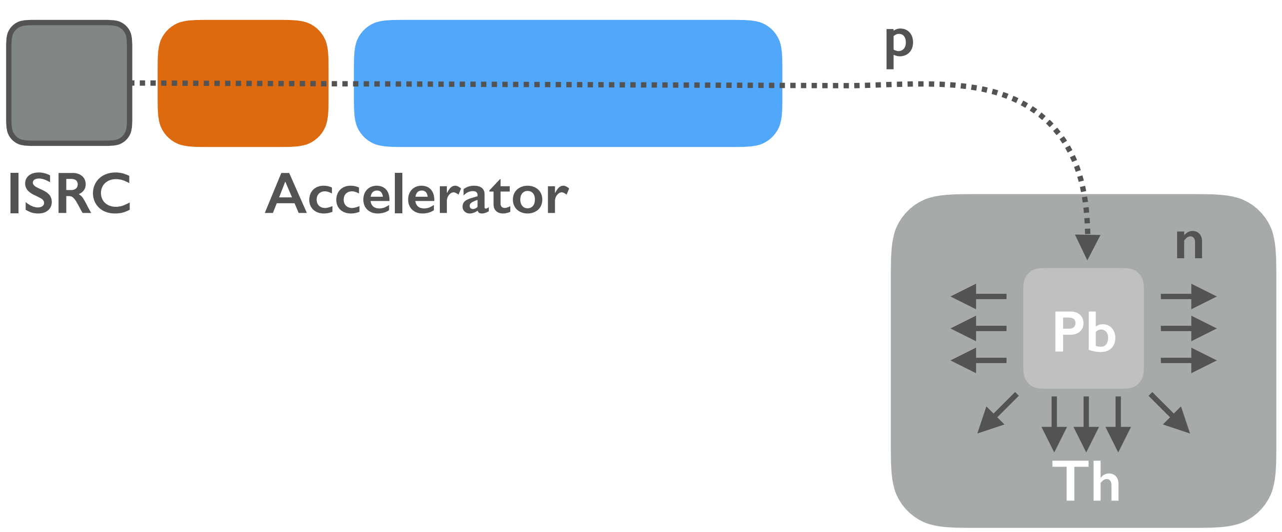
Nuclear Energy

- Today's nuclear reactors are operating close to the critical limit and the moderation is done using the control rods and use uranium as the fuel, leaving plutonium as a residue.
  - Control rods need to be operated actively
  - Uranium resources are limited
  - Plutonium could be used for nuclear weapons
- What if we could kill three birds with one stone?



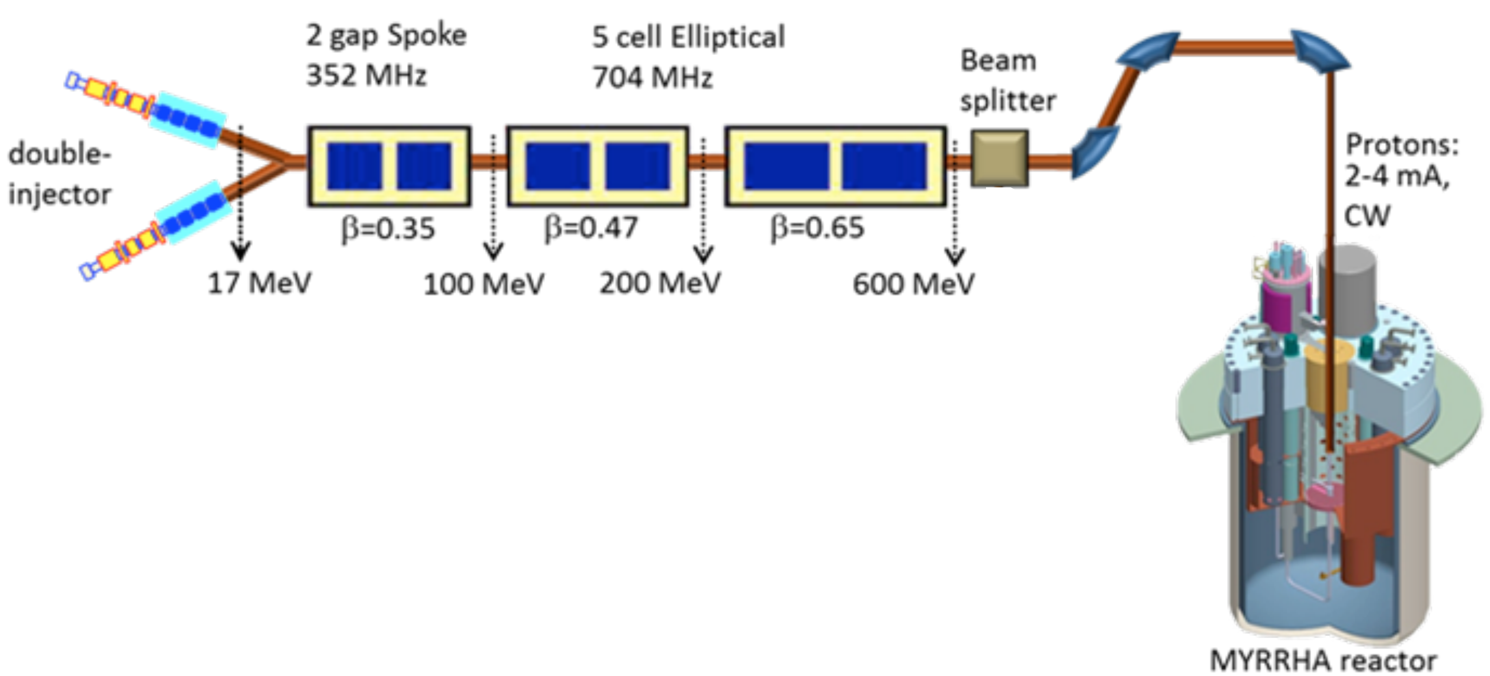
ADS

- In an Accelerator Driven System, ADS, also called, Accelerator Driven Subcritical Reactor, ADSR, the nuclear reactor functions by coupling a high power accelerator, to a subcritical nuclear reactor.
  - Control is achieved by adjusting the accelerator power
  - Thorium is used as fuel which is more abundant
  - Plutonium residue of conventional reactors could be used as fuel
  - The net energy output is reduced as some energy is consumed by accelerator, the further from criticality, the higher the consumed energy



MYRRHA

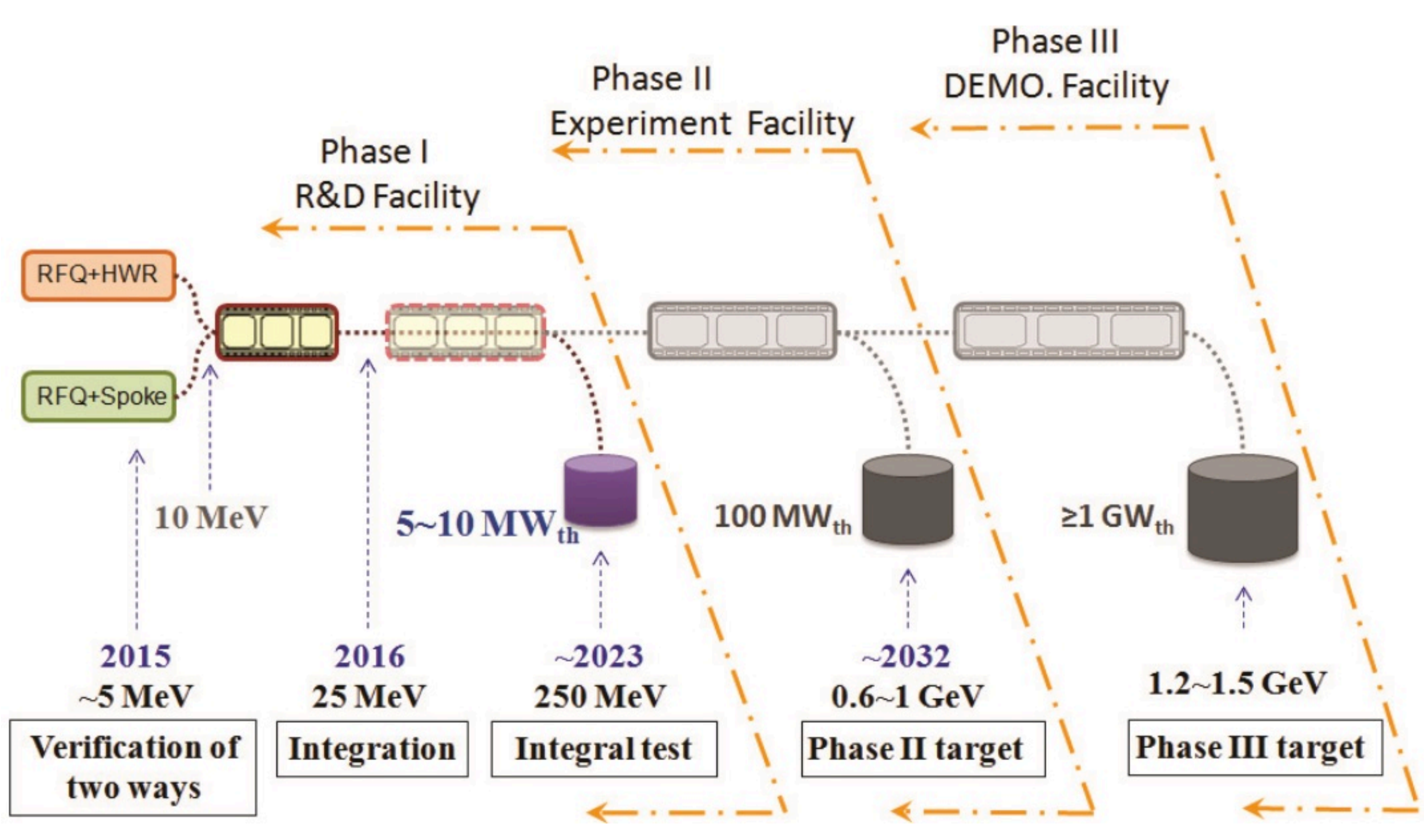
- As an energy source and also to avoid thermal cycles in the core of the reactor and the target the reliability of the accelerator is one of the challenges of the ADSs.
  - MYRRHA uses few concepts to increase the reliability
    - Doubling the single points of failure, e.g., ISRC, front end, …
    - Powering the accelerating structures below their operations limit such that each pair can compensate for a third lost cavity, in power and energy gain



C-ADS

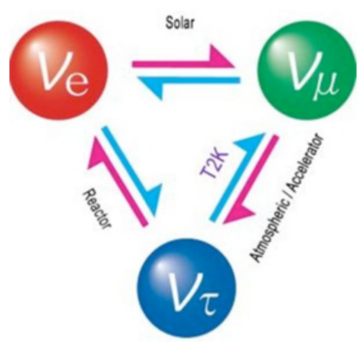
- Similar approach to MYRRHA, but two different injector designs to test the reliability and performance of two different systems (designed by two independent teams).
  - Inj. I, *IHEP*: RFQ (35 keV-3.2 MeV @325 MHz) + Spoke (10 MeV)
  - Inj. II, *IMP*: RFQ (35 keV-2.1 MeV @162.5 MHz) + HWR (10 MeV)

- Project is divided in few phases, the first phase is ready now and the beam is commissioned to 10 MeV.

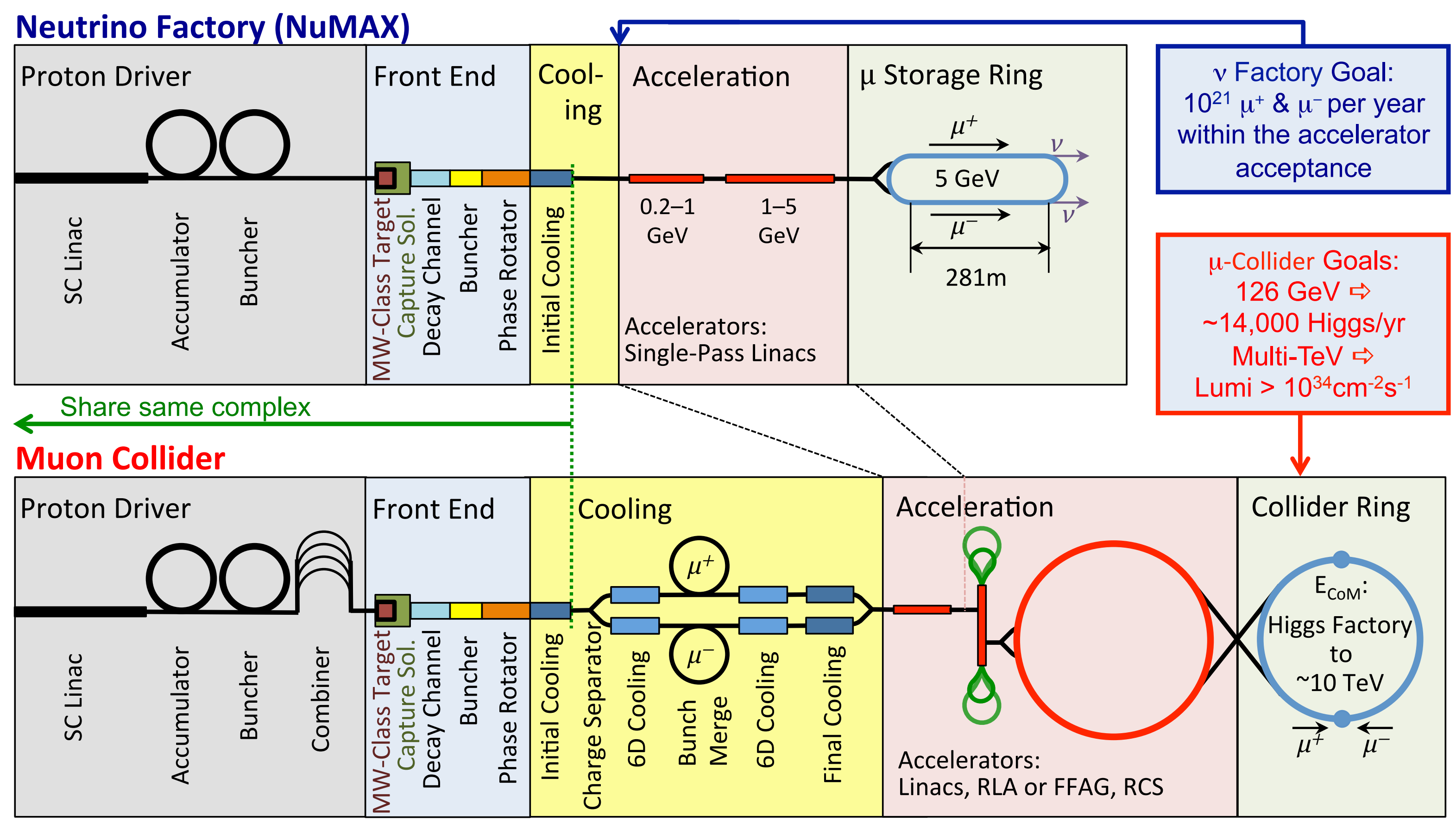


NEUTRINO SUPERBEAMS AND FACTORIES

- The physics of neutrinos, how they change flavour, do they have mass, are they a superposition of few states and several other questions could be answered by using high intensity beams of neutrinos.
  - Could be produced at Neutrino factories
  - From reactors
  - Solar and extra-terrestrial neutrinos
  - Geoneutrinos



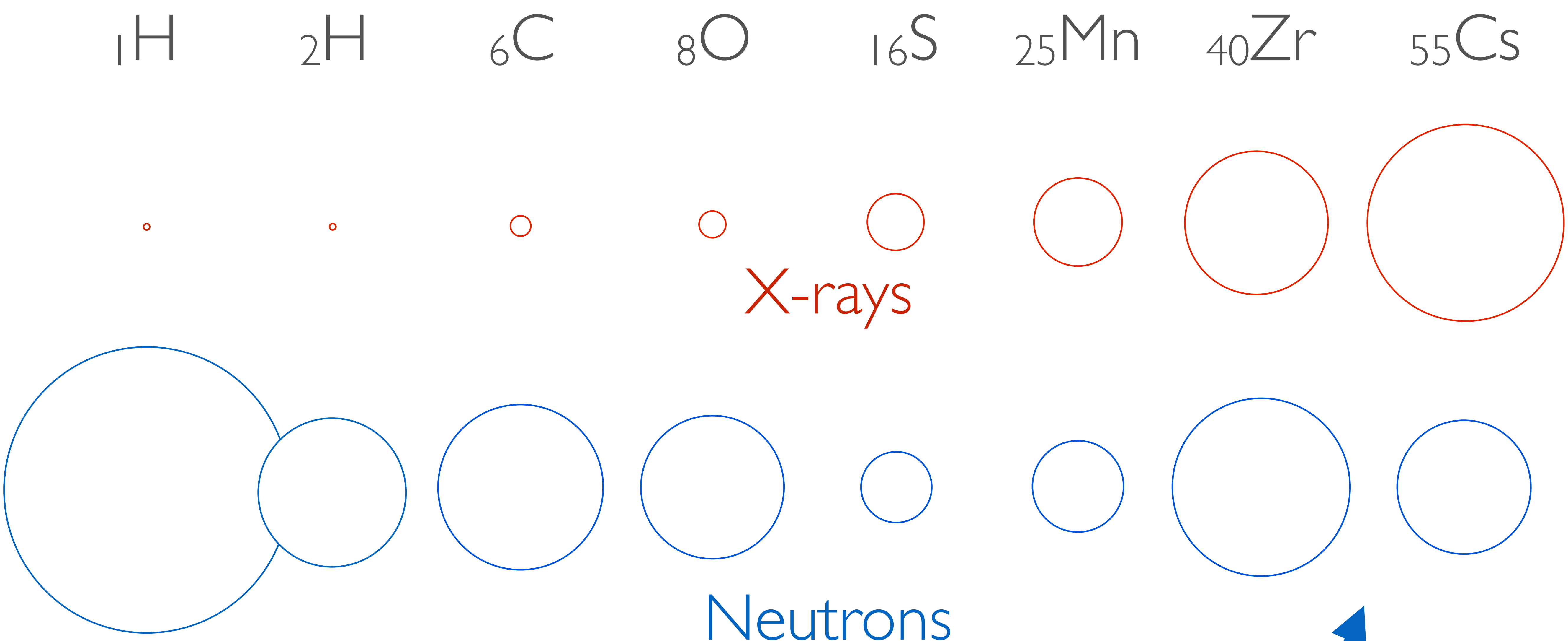
- NFs could also pave the way for the future muon colliders!

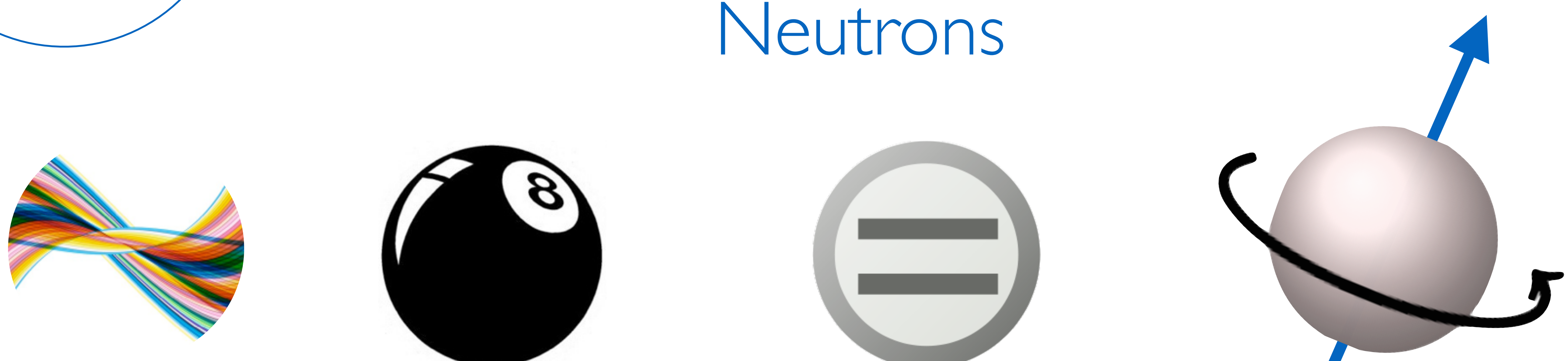


SPALLATION SOURCES

- Reminder of what Mats told you about why we need spallation sources!

Photons vs. Neutrons

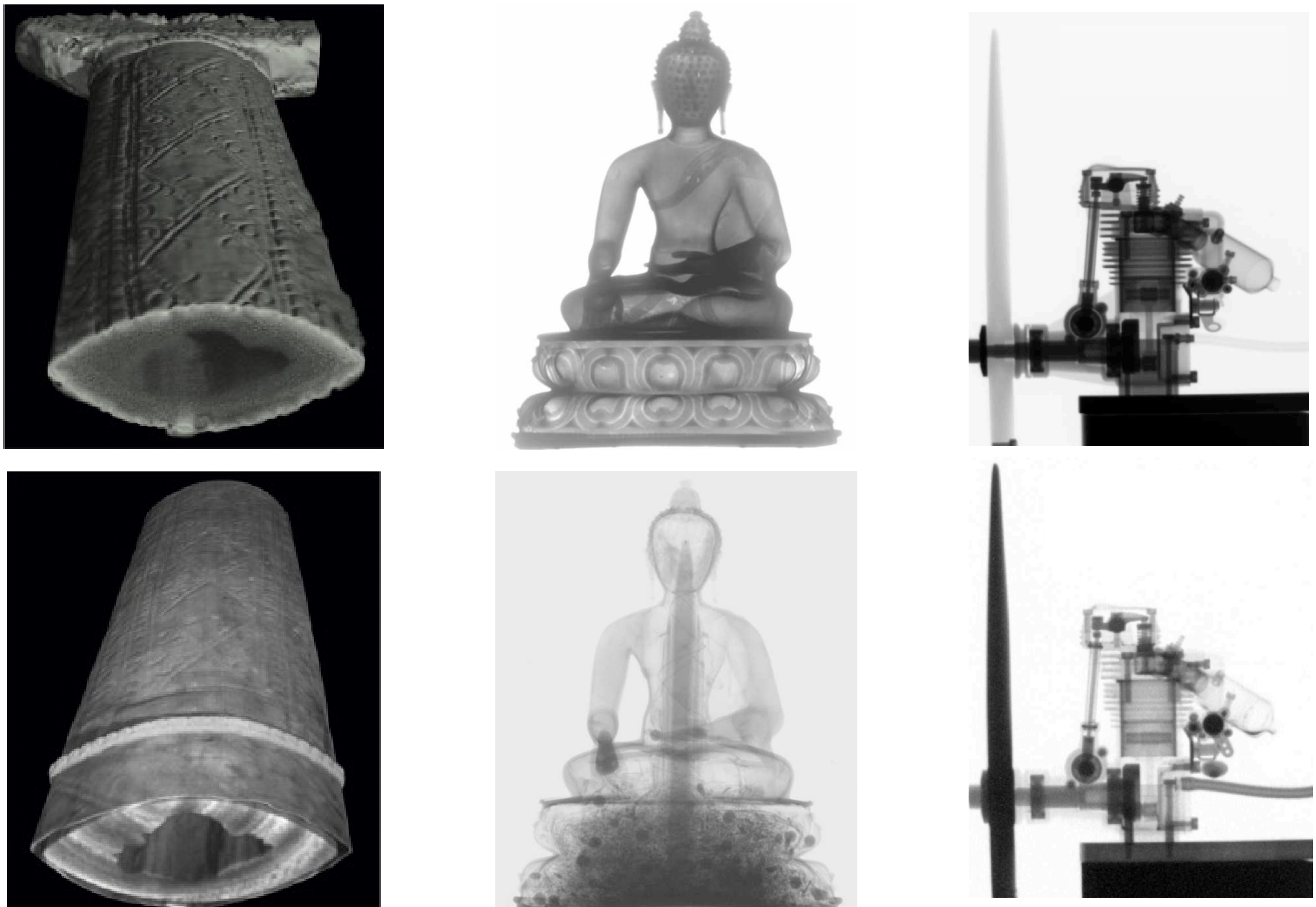




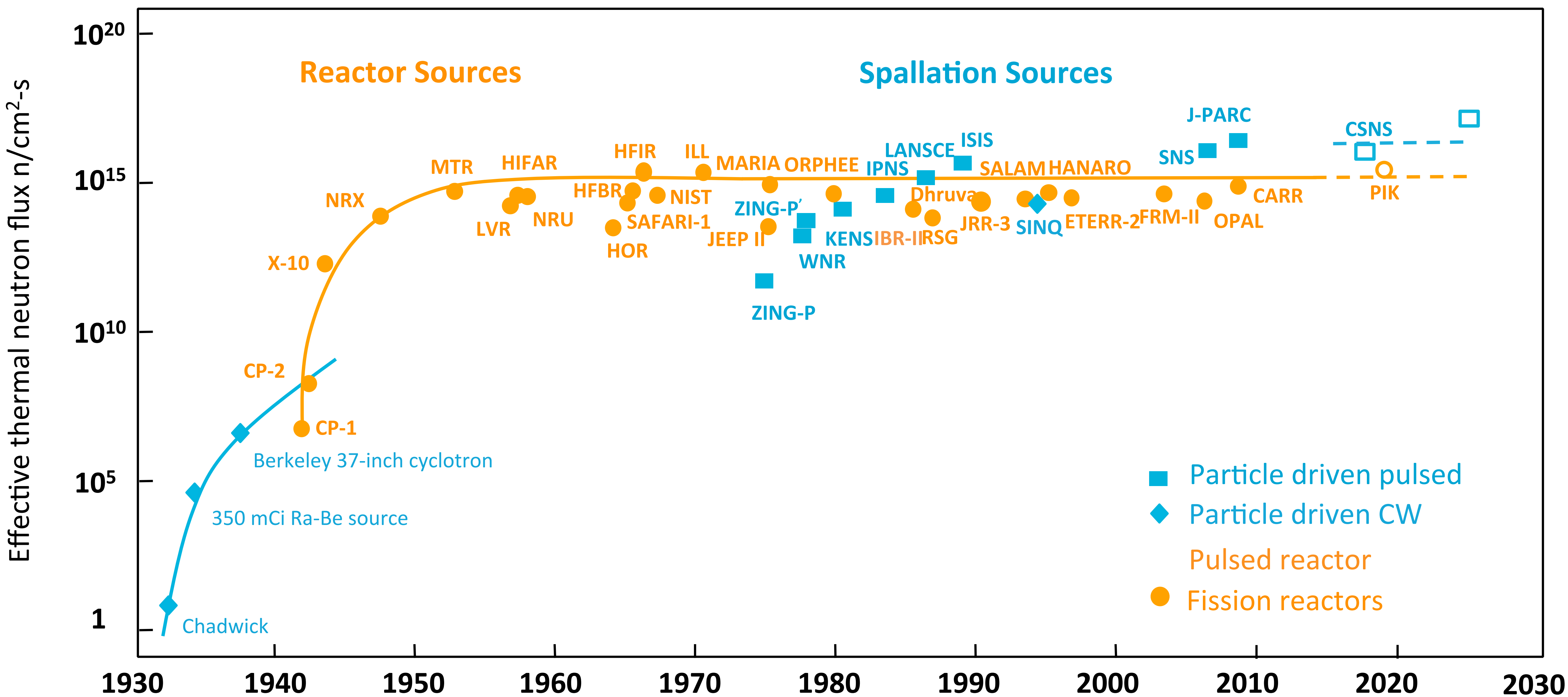
NEUTRON IMAGING

X-rays

Neutrons



History

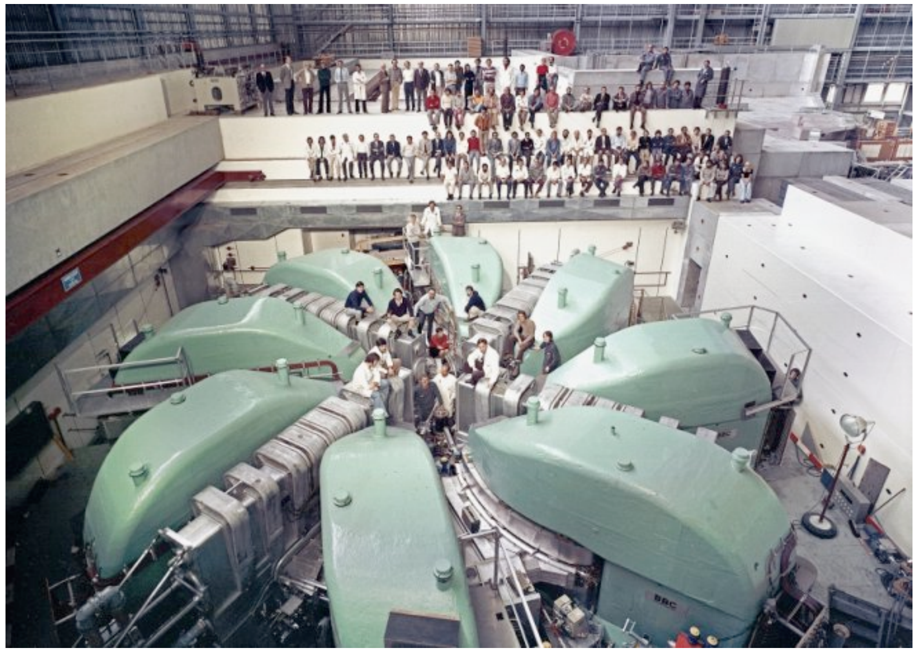


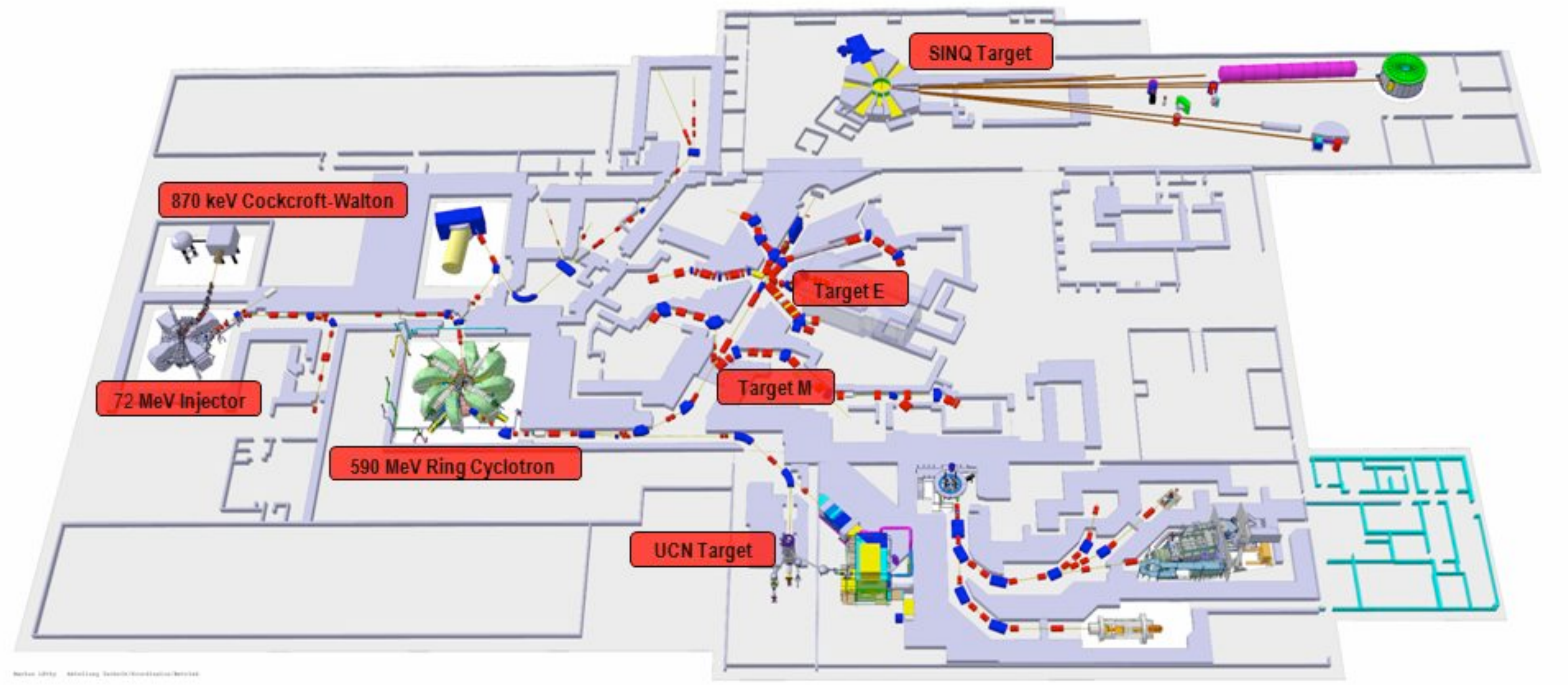
(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

Courtesy: Roland Garoby

PSI

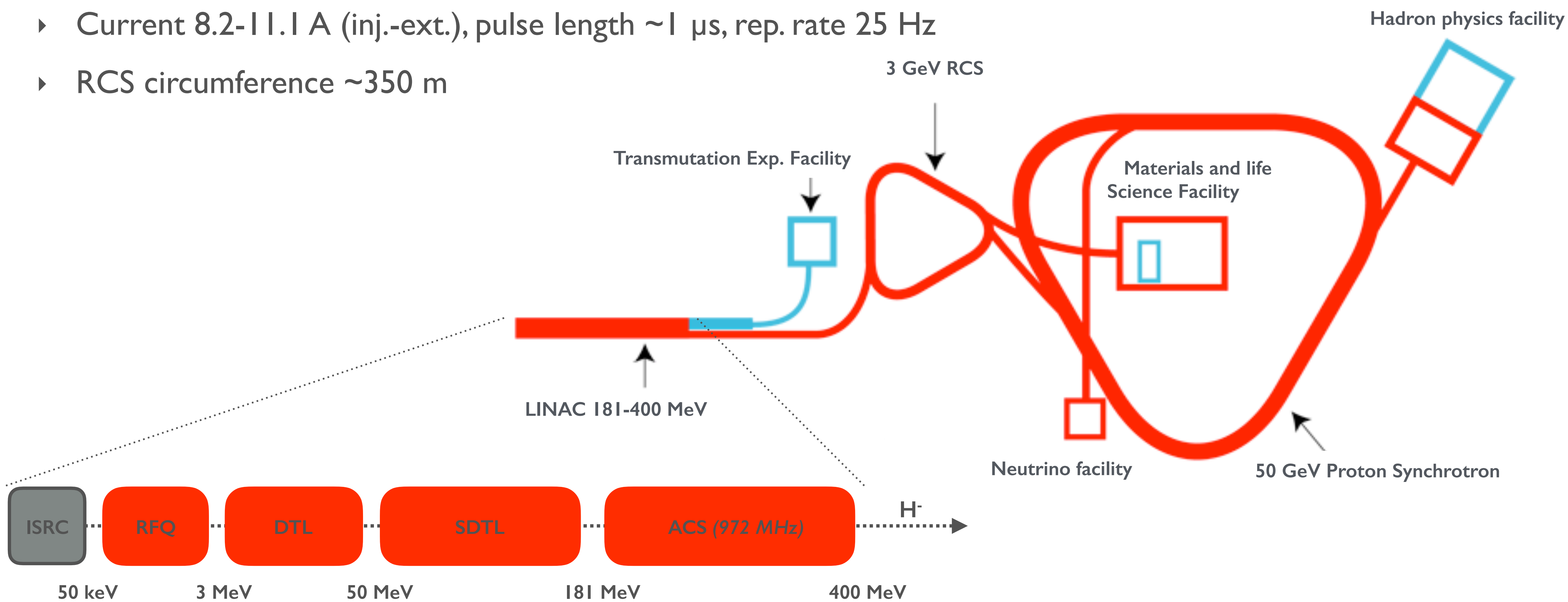
- Neutron targets:
  - UCN: 590 MeV, 2.2 mA (1.3 MW) @ 1% Dutycycle
  - SINQ: 575 MeV, 1.5 mA (0.86 MW) CW
- Meson production (M and E):
  - 590 MeV, 2.2 MeV (1.3 MW) CW





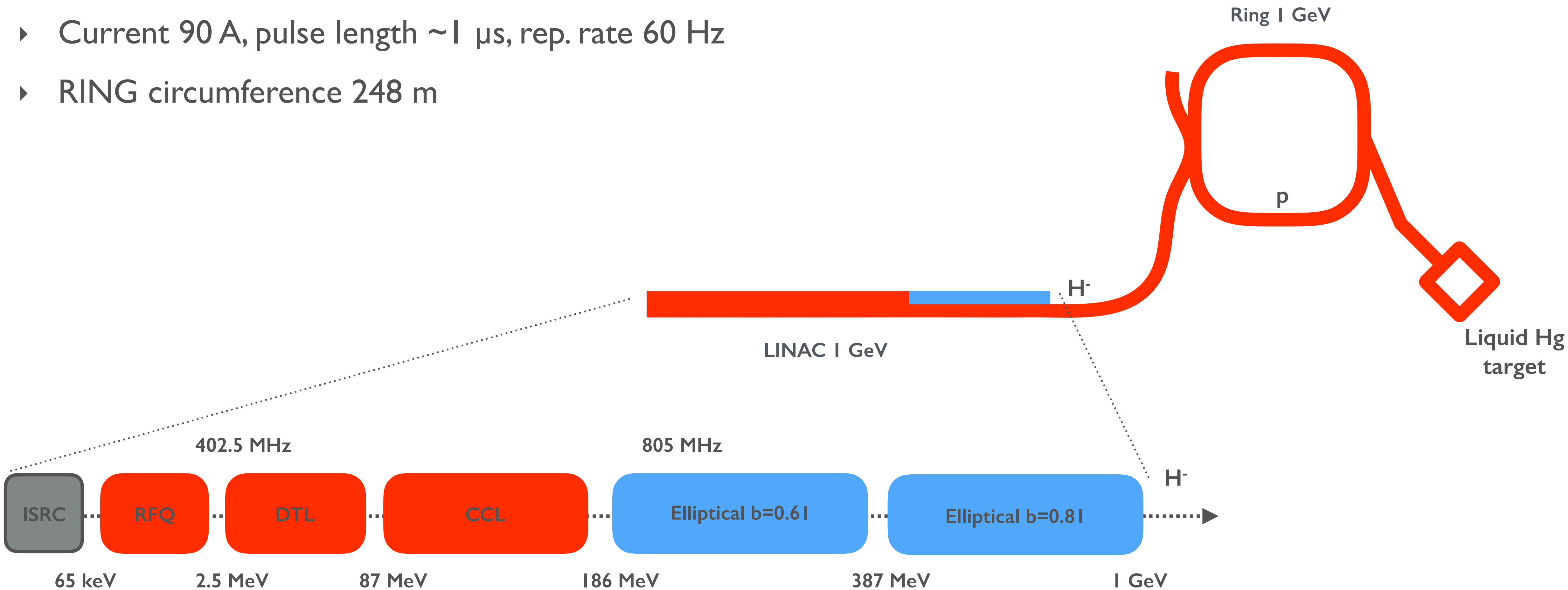
J-PARC

- The beam for spallation purposes to the materials and life science facility is accelerated in the linac to 181 MeV, to be upgraded to 400 MeV, and then further accelerated to 3 GeV in a Rapid Cycling Synchrotron.
  - LINAC
    - Current 50 mA, pulse length 0.5 ms, rep. rate 50 Hz, 324 MHz
    - Length of the linac ~250 m
  - RCS:
    - Current 8.2-11.1 A (inj.-ext.), pulse length ~1 μs, rep. rate 25 Hz
    - RCS circumference ~350 m



SNS

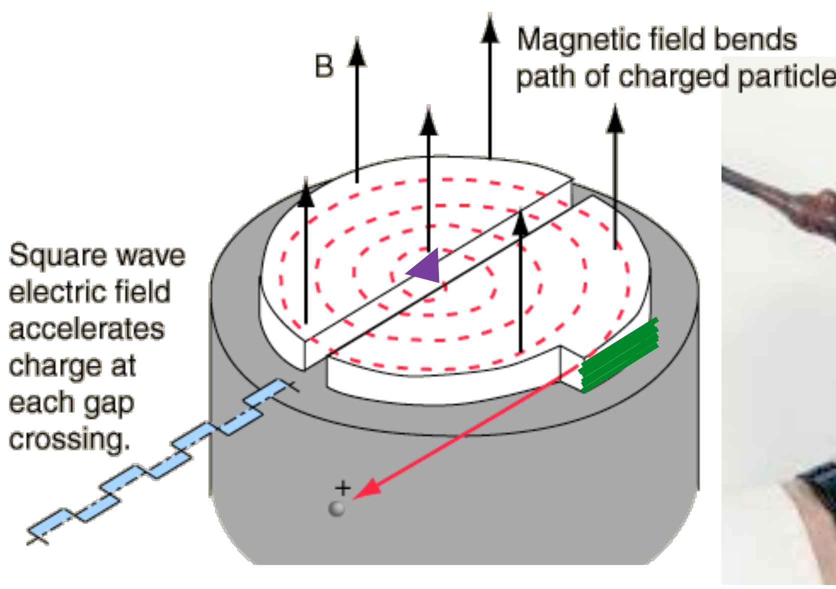
- The linac increases the beam energy to 1 GeV and a compressor ring compresses the 1ms pulse of the linac to 700 ns before sending it to the liquid mercury target
  - LINAC
    - Current 38 mA, pulse length 1 ms, rep. rate 50 Hz, 402.5 and 805 MHz
    - Length of the linac 331 m + HEBT 170 M
  - Ring:
    - Current 90 A, pulse length ~1 μs, rep. rate 60 Hz
    - RING circumference 248 m



CYCLOTRON

- The first cyclotron (Ernest Lawrence and Stanley Livingston) was only 11 cm in diameter and could accelerate the protons to 80 keV

- A cyclotron is composed of:
  - two circular magnet poles (grey)
  - two D shaped dees (white)
  - an ion source (violet)
  - an extraction electrode (green)



$$F_c = \frac{mv^2}{r}$$
$$F_b = qvB$$
$$\Longrightarrow \quad \frac{mv^2}{r} = qvB$$

The frequency is constant for constant mass

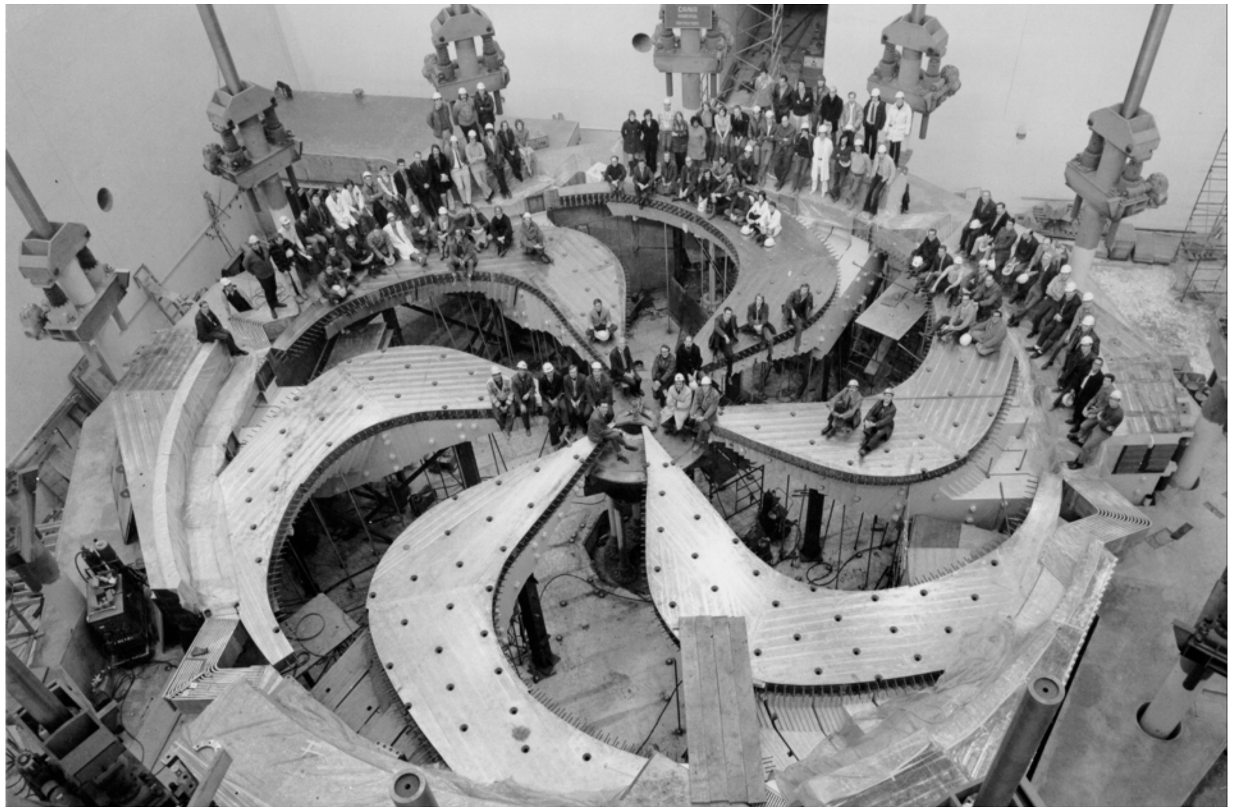
$$\omega = v/r = \frac{qB}{m}$$

and the final energy is

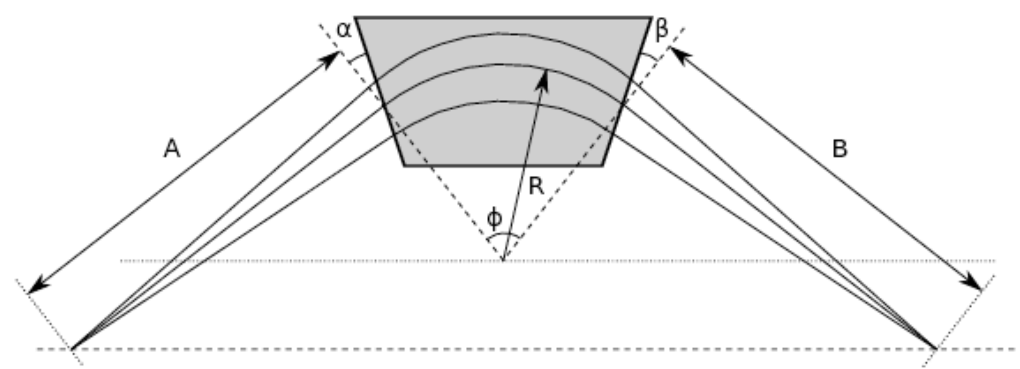
$$E = \frac{1}{2}mv^2 = \frac{(qBr_{max})^2}{2m}$$

SYNCHROCYCLOTRON

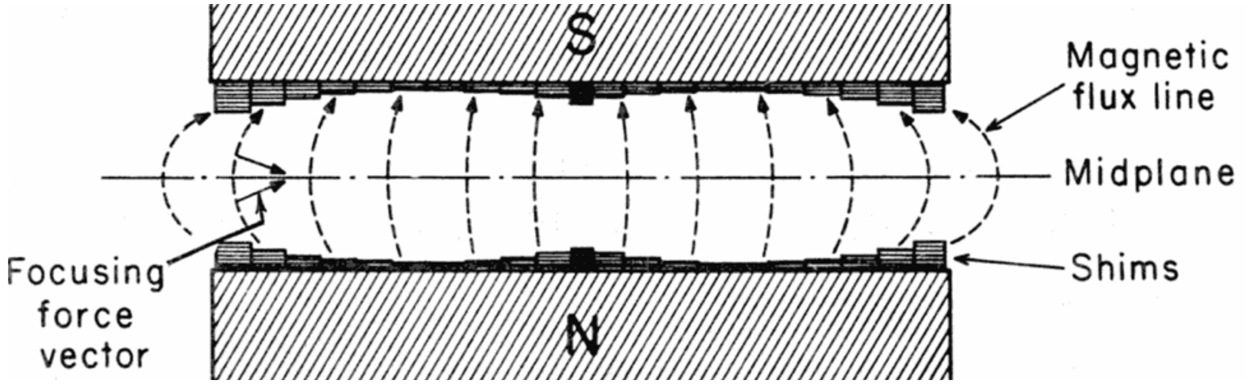
- For relativistic particles the cyclotron losses the synchronous condition and can not accelerate them any further,
  - $m_{rel} = m_0\gamma$, so, if the rf frequency is varied by the same ratio, the synchronous acceleration could be preserved



- Another principle used in high energy cyclotrons is the edge focusing, providing horizontal focusing of the beam

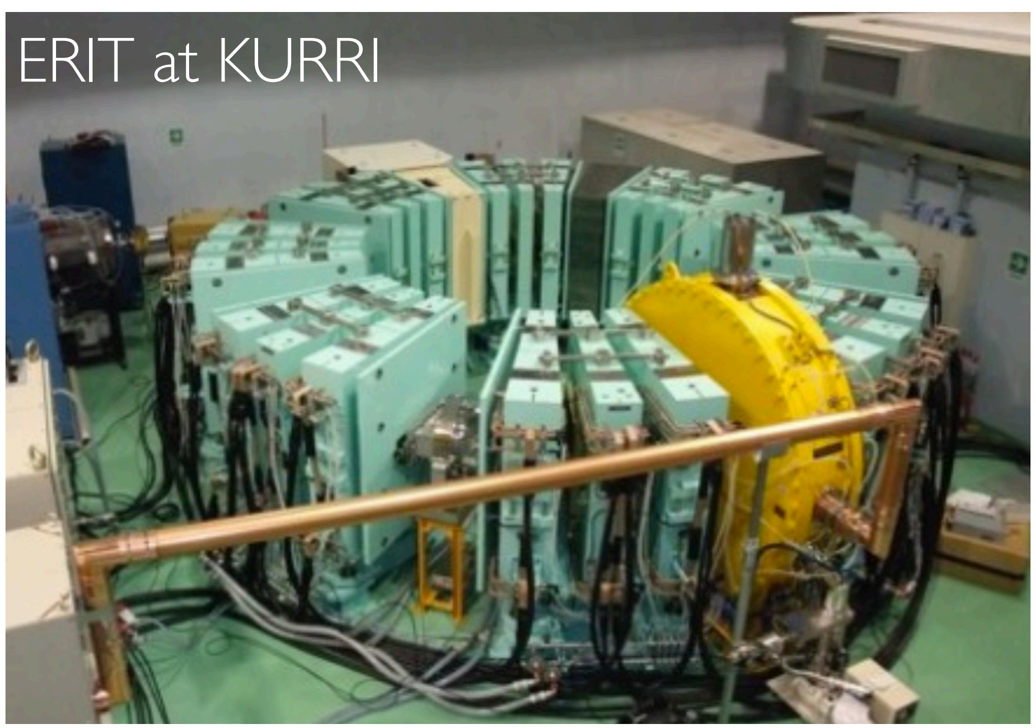


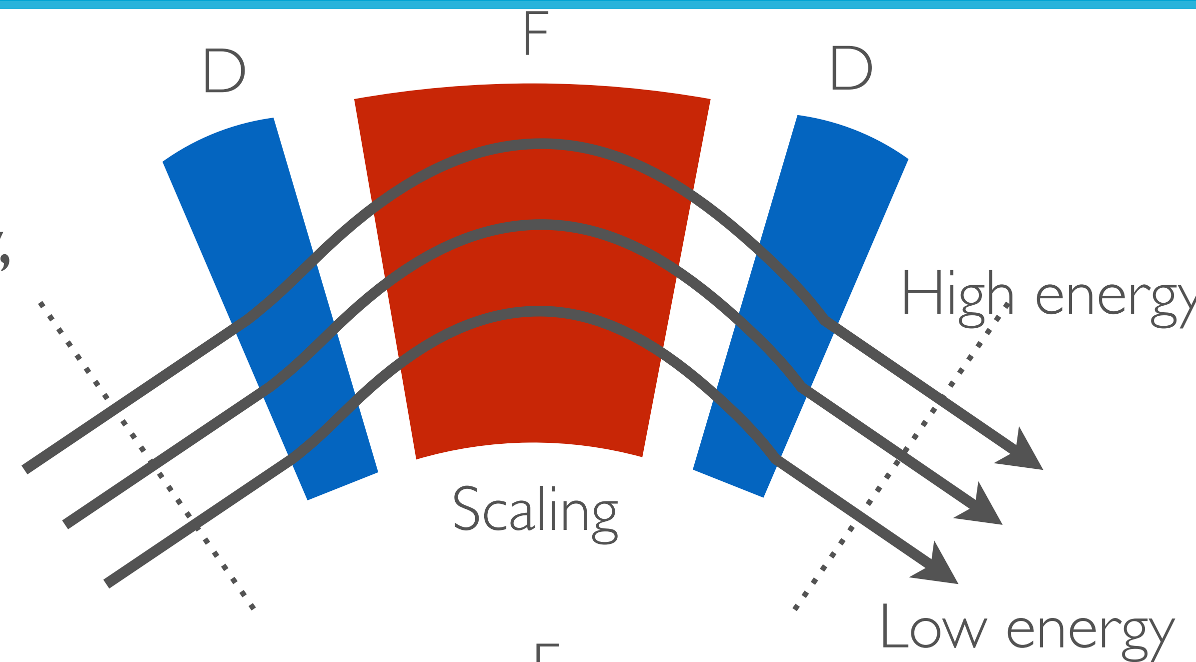
- Horizontal focusing is achieved by the field gradient

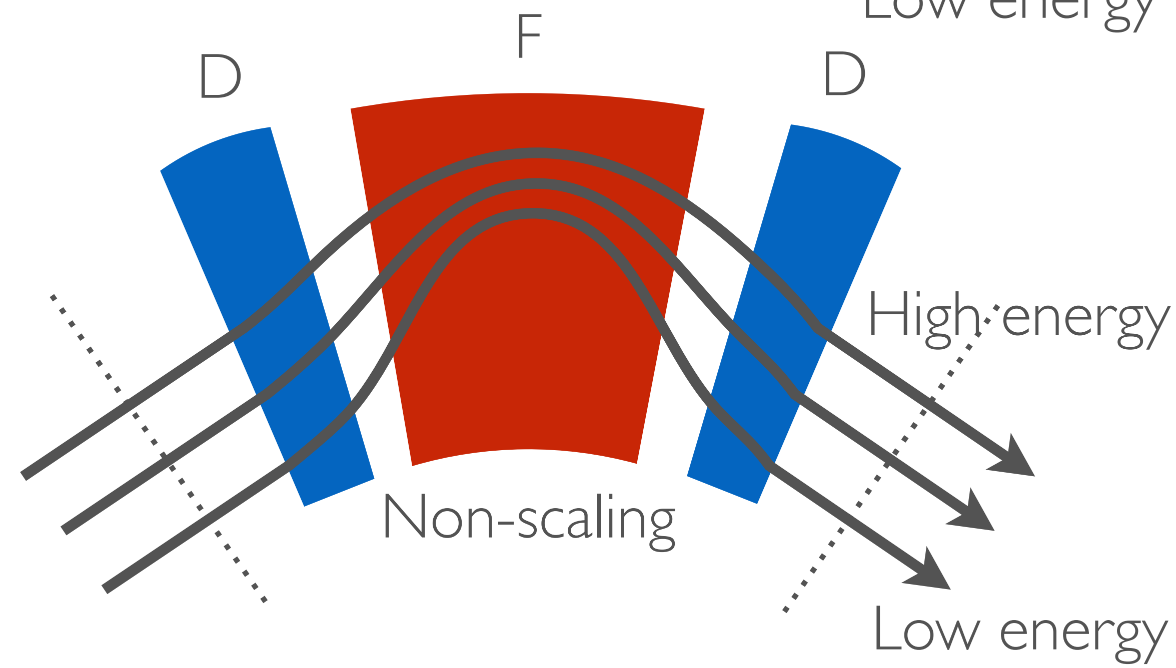


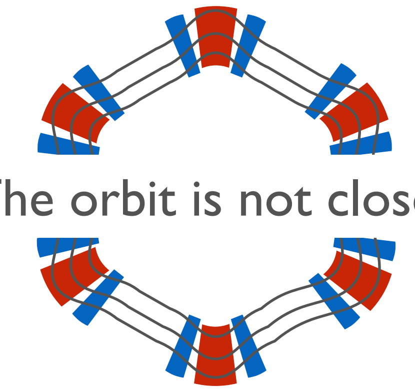
FFAG

- Another incarnation of cyclotrons is the Fixed Field Alternating Gradient accelerator, invented independently by Ohkawa, Symon and Kolomensy, in Japan, USA and USSR (1953, 54, 56).
- The advantage of FFAGs to cyclotrons is the existence of strong focusing, higher achievable energies and higher available currents.
- They could be scaling (everything scales with energy the same way) or non-scaling (the orbits grow, and their shapes change too).









Maxwell Equations

- Differential form of Maxwell equations (SI):

Gauss's law

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

No magnetic monopoles

$$\nabla \cdot \mathbf{B} = 0$$

Faraday's law (of induction)

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Ampere's circuital law*

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

Lorentz Force

The electric field will increase the kinetic energy of the charged particles,

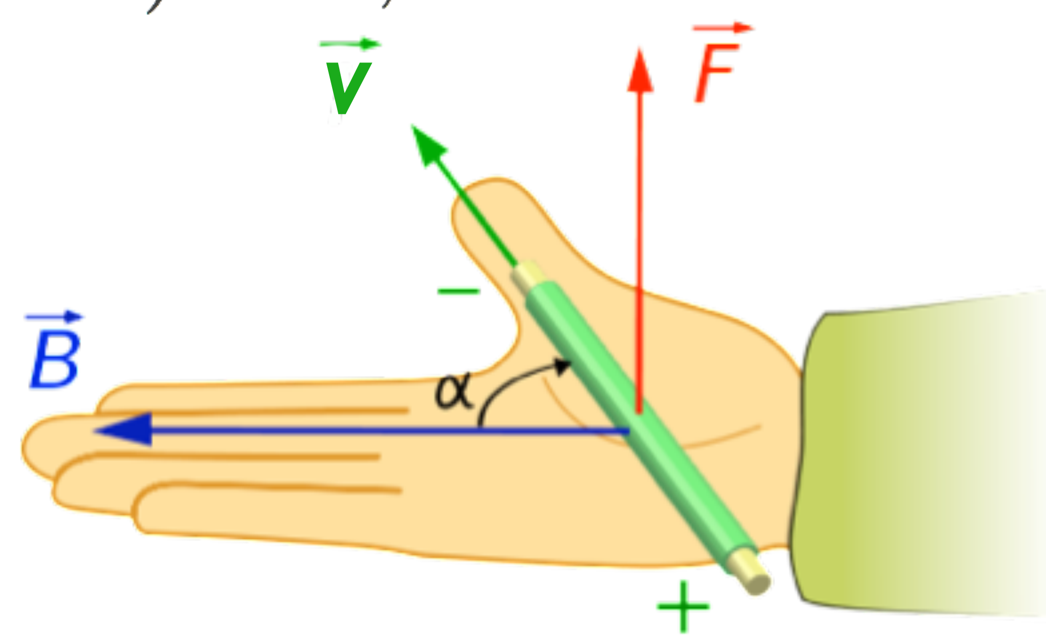
$$\frac{d\mathbf{p}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\Delta W = d\mathbf{x} \cdot q\mathbf{E}.$$

The magnetic field cannot affect the energy,

$$d\mathbf{x} \cdot (\mathbf{v} \times \mathbf{B}) = dt \; (\mathbf{v} \cdot \mathbf{v} \times \mathbf{B}) = 0,$$

but, it can change the moving particles trajectory.



Can you show the ratio of electric (10 MV/m) to magnetic (1 T) force for a particle travelling at c?

GAUSS'S LAW

- Using Gauss's law one can calculate the electric field of *any* charge distribution,

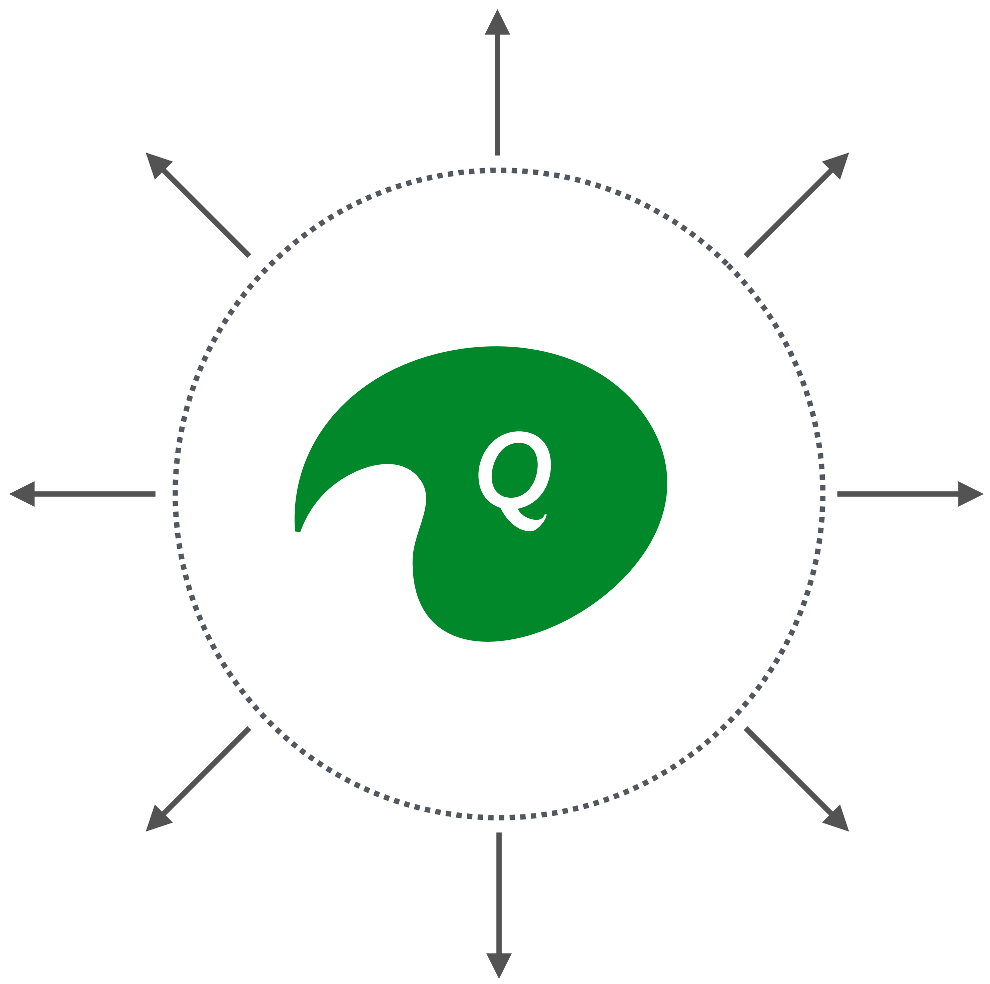
or $$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{1}{\epsilon_0} \int \rho dv = \frac{Q}{\epsilon_0}$$

in 2D:

$$\mathbf{E} = \frac{Q}{2\pi\epsilon_0 r}\hat{\mathbf{r}}$$

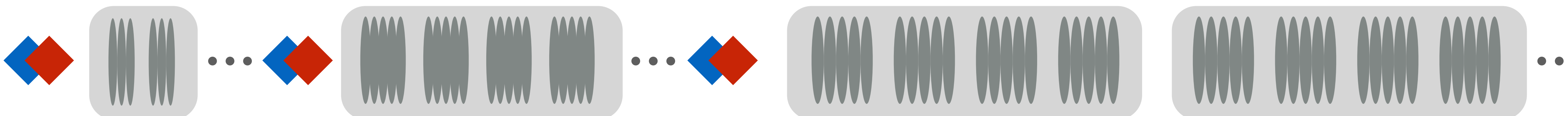
in 3D:

$$\mathbf{E} = \frac{Q}{4\pi\epsilon_0 r^2}\hat{\mathbf{r}}$$

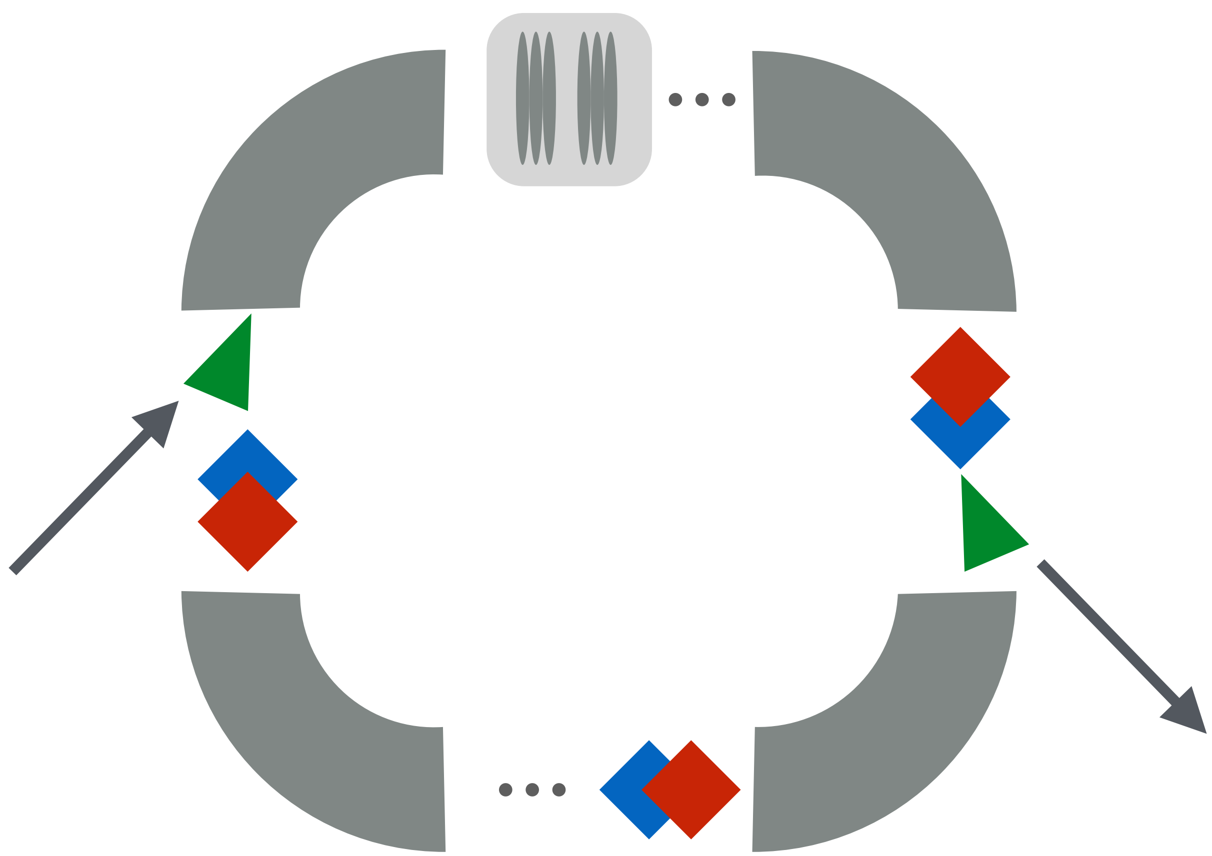


Synchrotron vs. LinaC I

- Linear accelerators:

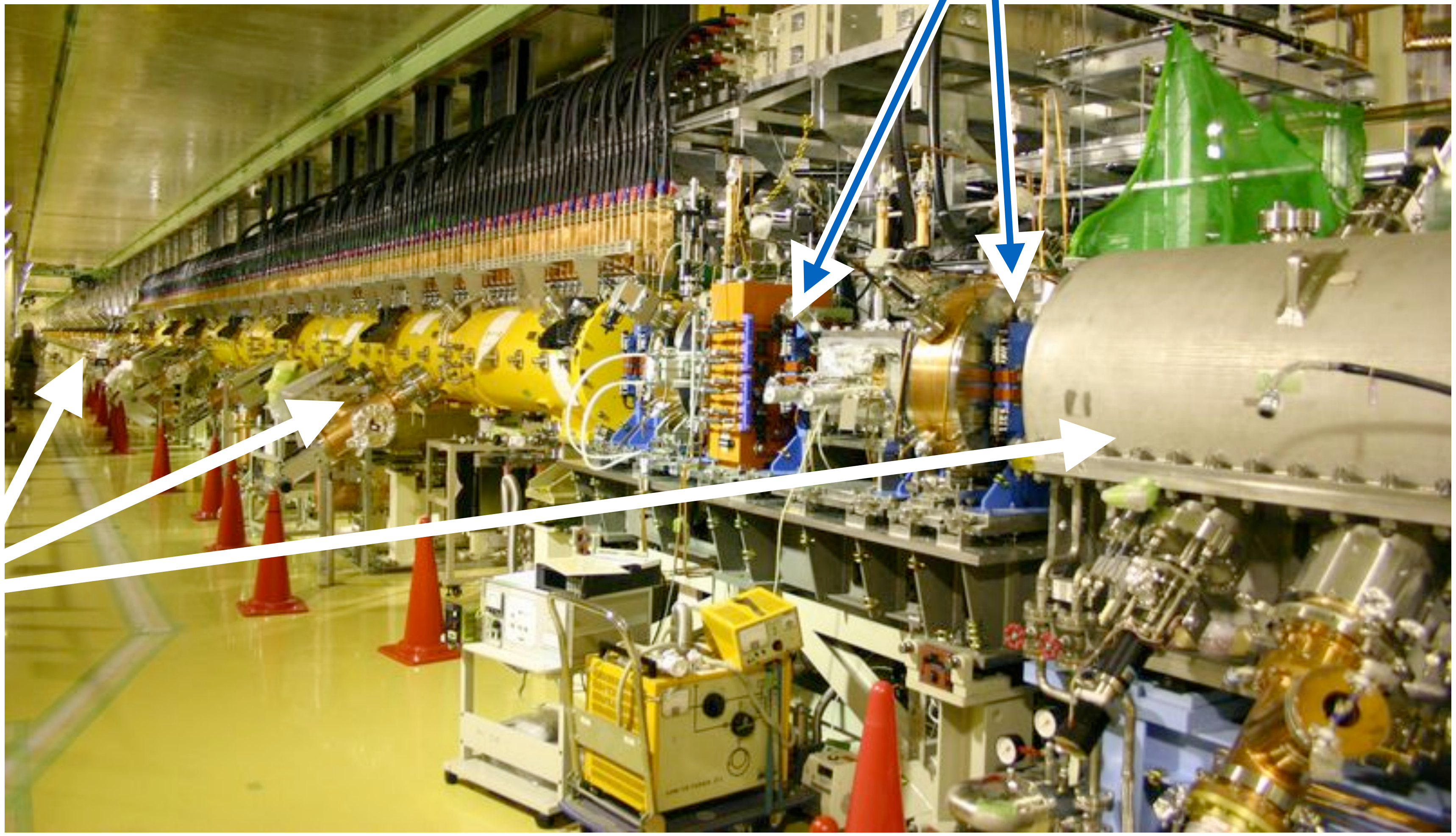


- Circular accelerators:



Synchrotron vs. LinaC II

- Linear accelerators:

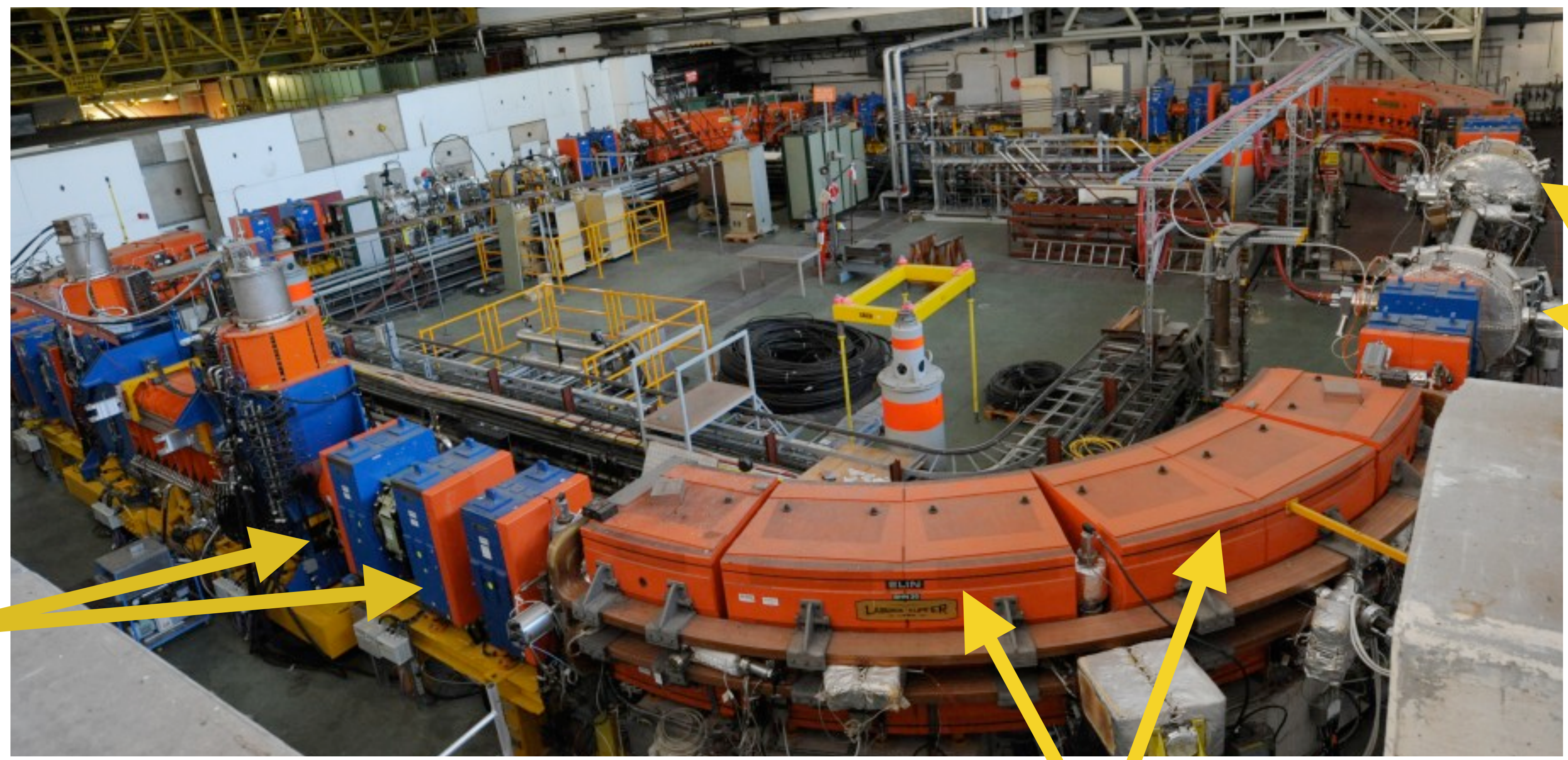


Focusing elements

Accelerating elements

SYNCHROTRON VS. LINAC III

- *Not-so*-Circular accelerators:



Accelerating elements

Focusing elements

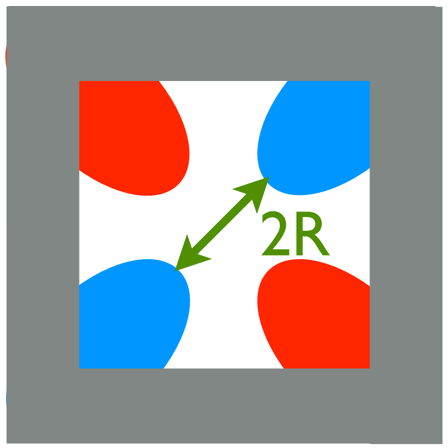
Bending elements

Synchrotron vs. LinaC IV

- Linear accelerators:
  - Are mainly filled with cavities (and focusing elements)
  - Do not have an ultimate energy
  - Are single pass (errors do not accumulate)
  - Can provide any pulse length (train of bunches)

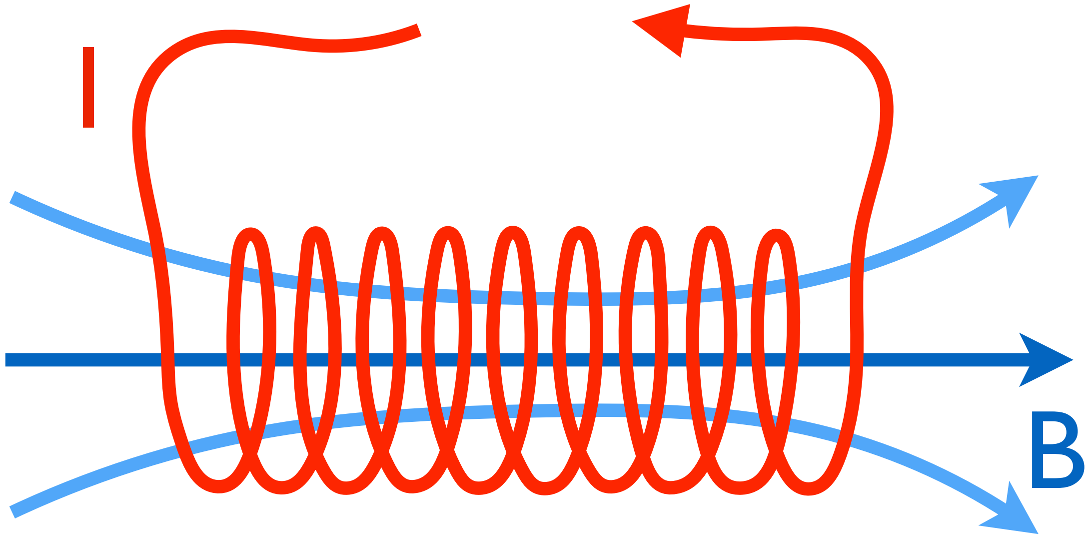
- Circular accelerators (synchrotrons):
  - Are mainly filled with dipoles (and focusing elements)
  - Are limited in their ultimate energy *(do you know why?)*
  - Beam is accelerated for several thousands to millions of turns (errors accumulate)
  - Pulse length is limited to the circumference of the ring

Magnetic Quadrupole



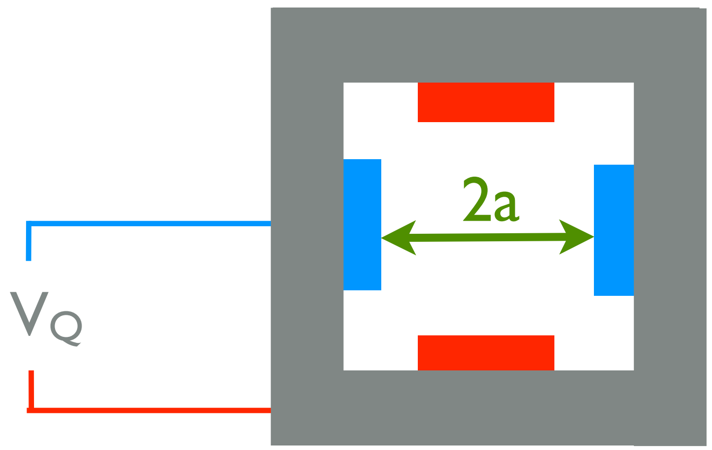
$$f_{MQ} = \frac{p}{q}\frac{R^2}{2\mu_0 nI}\frac{1}{L_Q}$$

Solenoid



$$f_{sol} = \frac{4p^2}{q^2B^2}\frac{1}{L_{sol}}$$

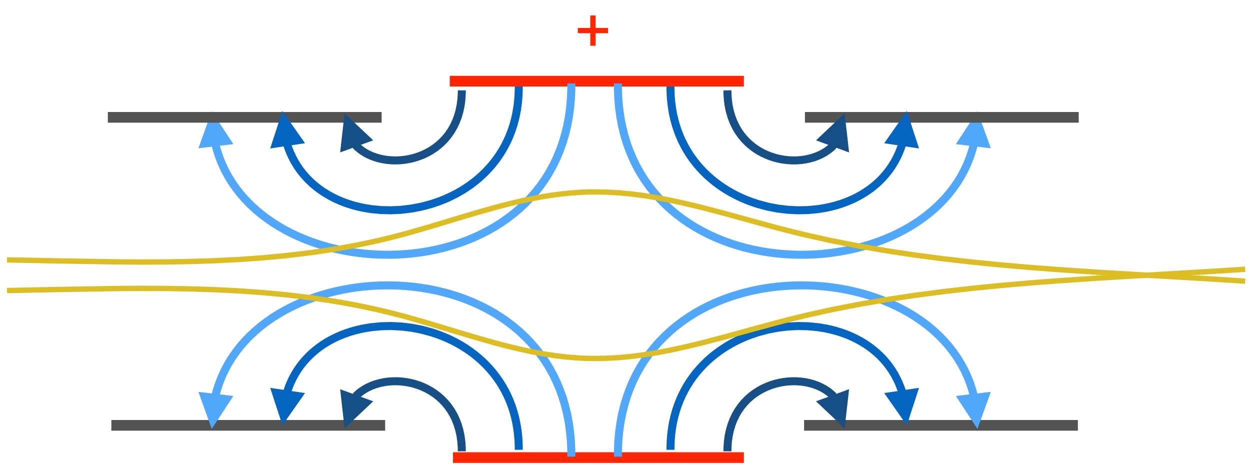
Electric Quadrupole



$$f_{EQ} = \frac{pc}{q}\frac{a^2}{2V_Q}\frac{1}{L_Q}$$

It works best at low energies

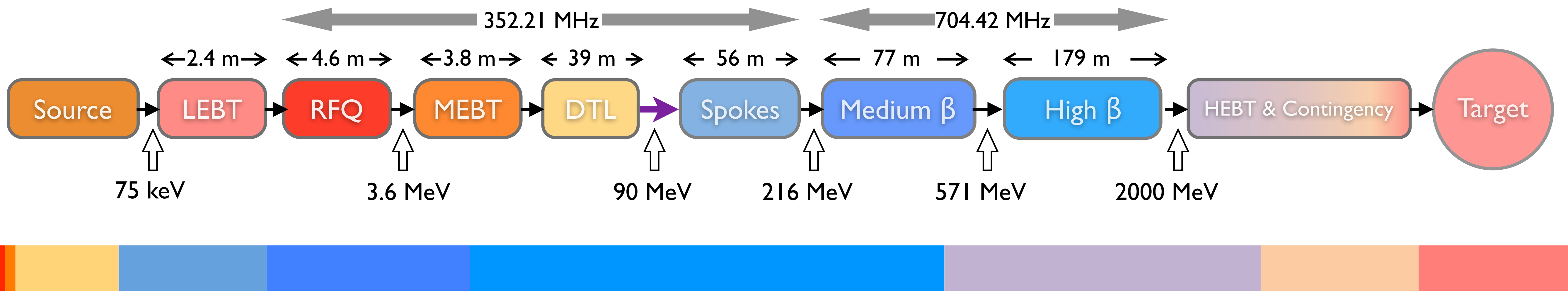
Einzel lens



$$f_{Einzel} = \frac{pc}{q}\frac{1}{E_r}\frac{1}{L_{Einzel}}$$

It focuses irrespective of charge

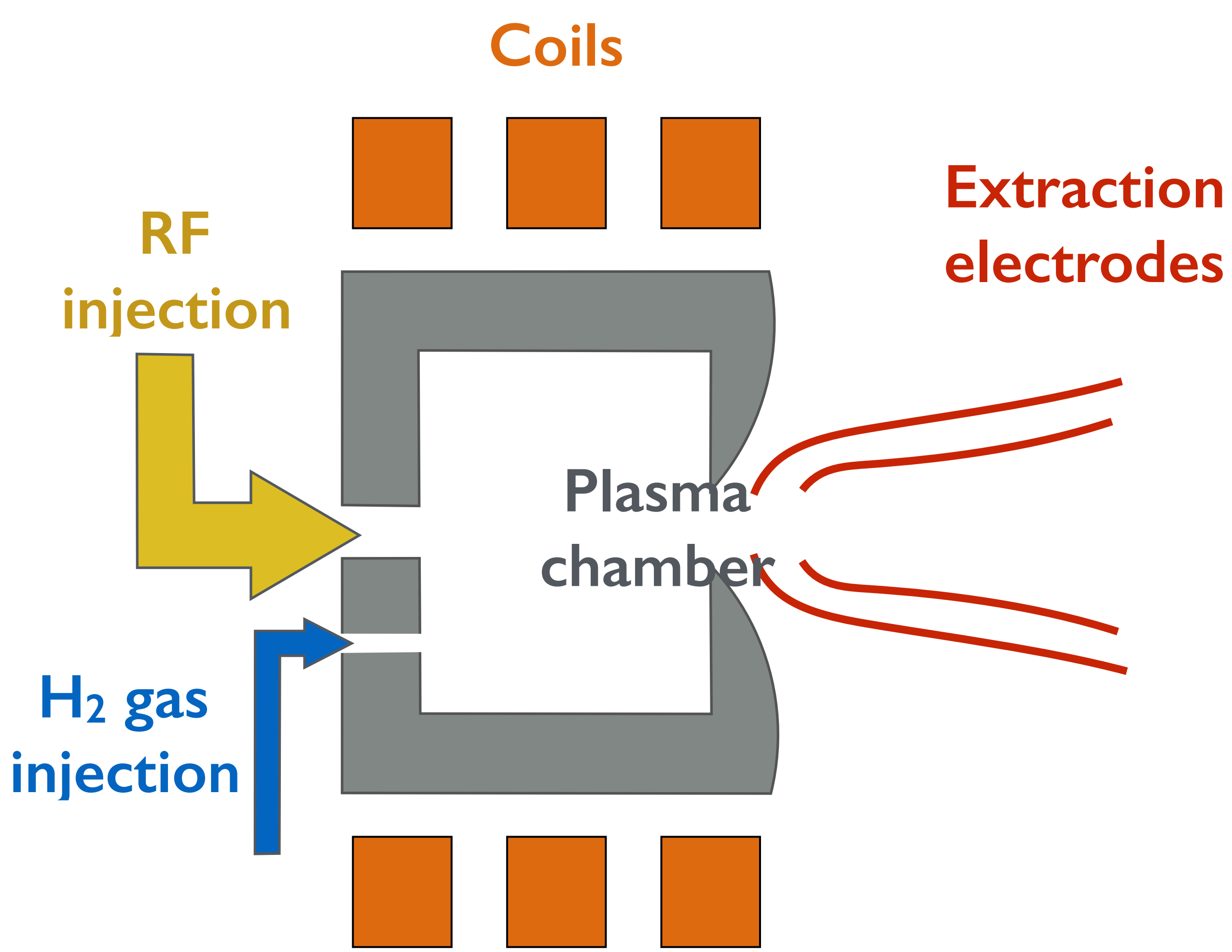
ESS Linac at a glance



- Proton source (also called Ion source) produces a continues beam of protons at 14 Hz
- Low Energy Beam Transport, LEBT, adjusts and matches the beam out of source to the next structure
- Radio Frequency Quadrupole, RFQ, Focuses, Accelerates and bunches the beam
- Medium Energy Beam Transport, MEBT, adjusts and matches the beam out of RFQ to DTL
- Drift Tube Linac, DTL, is the longest normal conducting part of ESS linac
- Spoke section is the first superconducting part of ESS linac
- Medium and High beta elliptical cavities increase the beam energy to 2 GeV
- High Energy Beam Transport, HEBT, adjusts and matches the beam to the target requirements

ION SOURCE

- An Electron Cyclotron Resonance, ECR, ion source uses the resonance between the magnetic and electric field to create ionized beams of particles.



$$F = qvB$$

$$F = \frac{mv^2}{r}$$

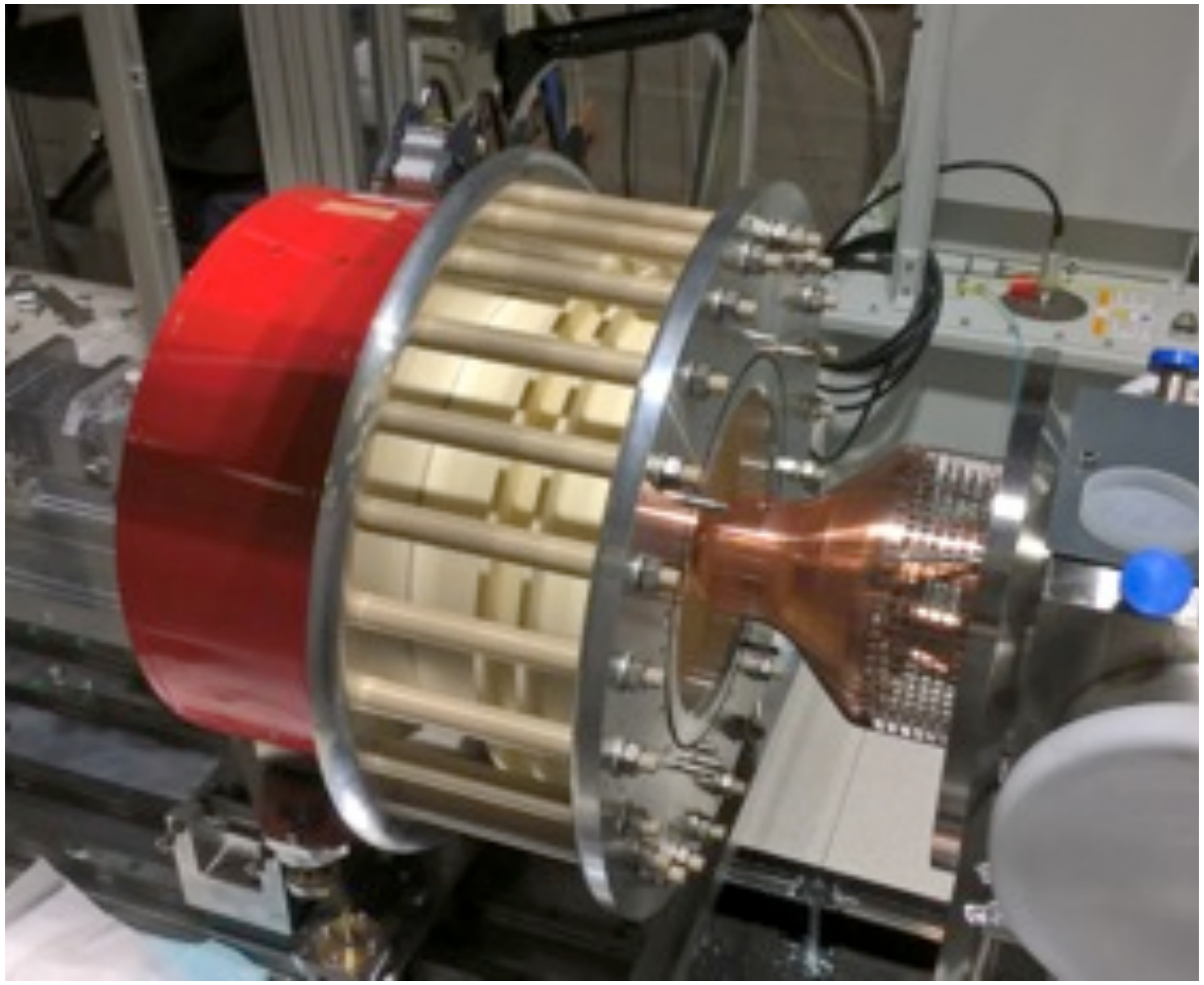
$$\frac{mv^2}{r} = qvB$$

$$\frac{mv}{r} = qB$$

$$\omega = \frac{qB}{m}$$

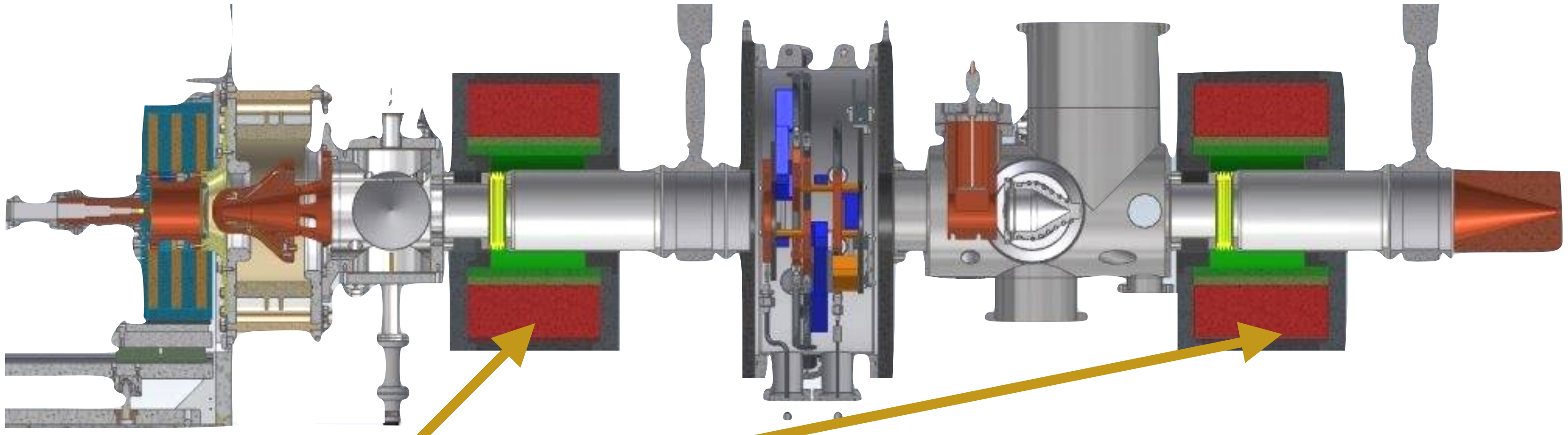
ESS ION SOURCE

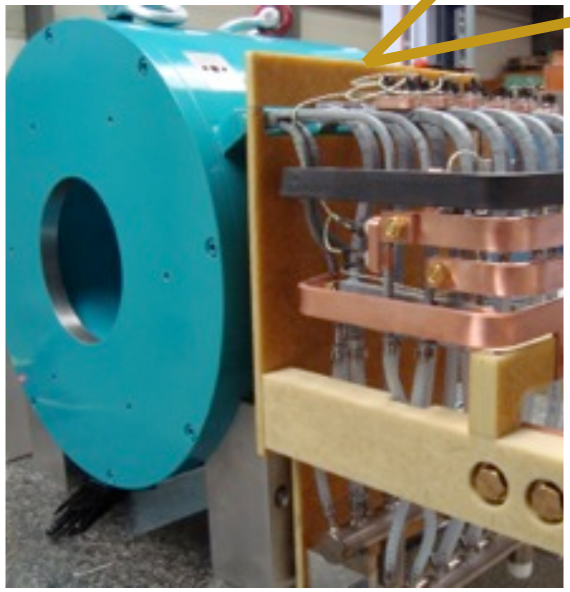
- A Microwave Discharge Ion Source generates a proton beam pulse of up to 3 ms with an energy of 75 keV and an intensity exceeding 80 mA at the source exit.



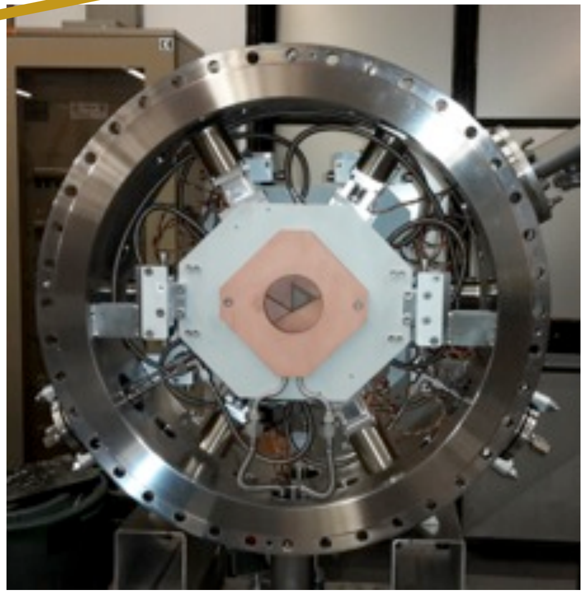
Low Energy Beam Transport

- The diverging beam out of ion source should be transported, measured and adjusted to the next structure.
- Two magnetic solenoids provide the required transverse focusing.

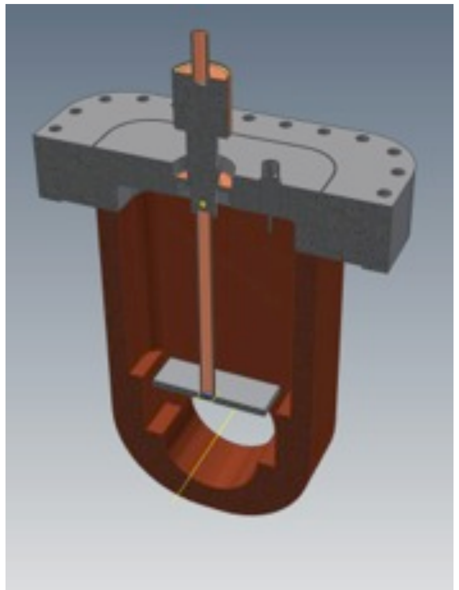




Solenoid

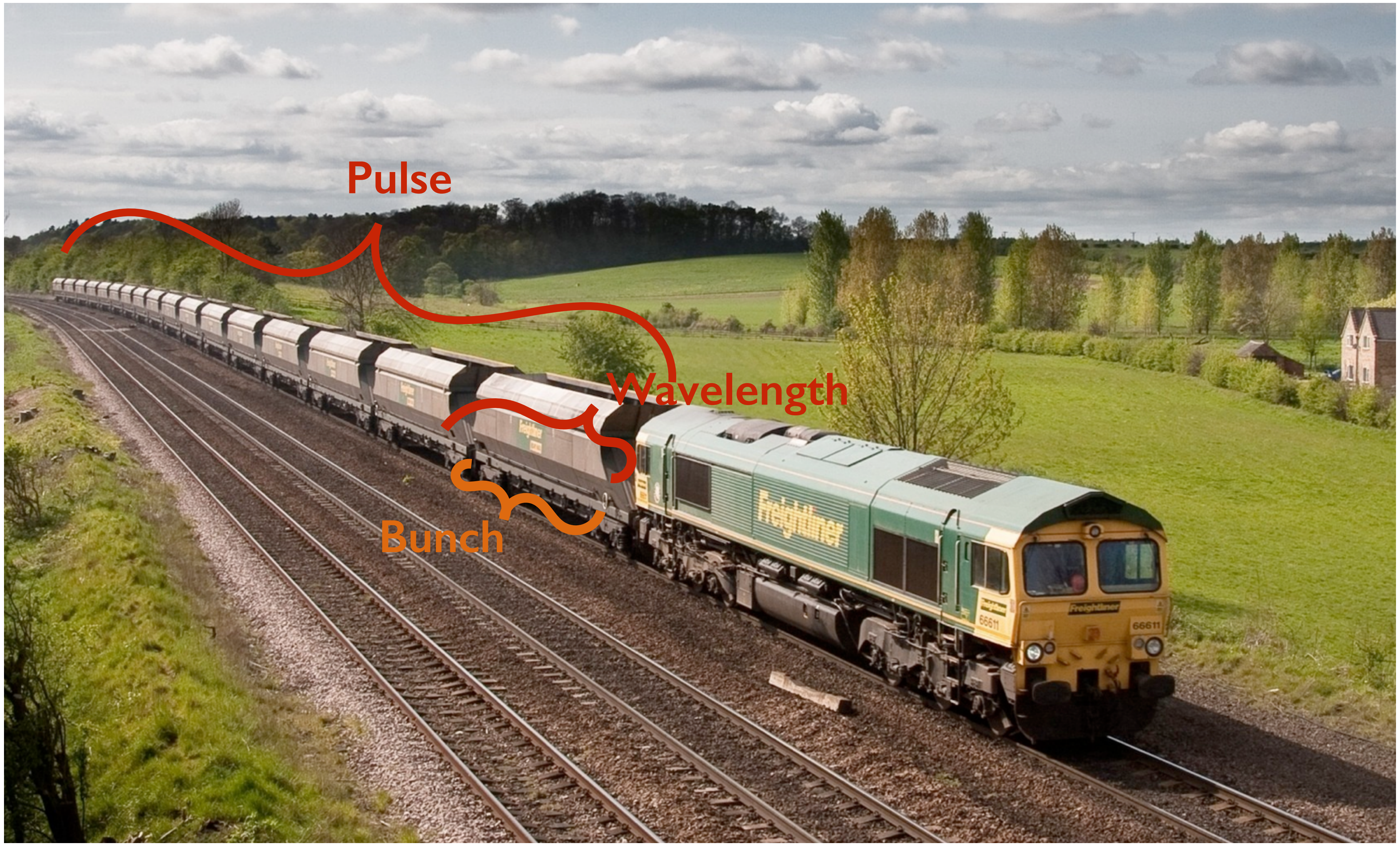


Iris



Chopper

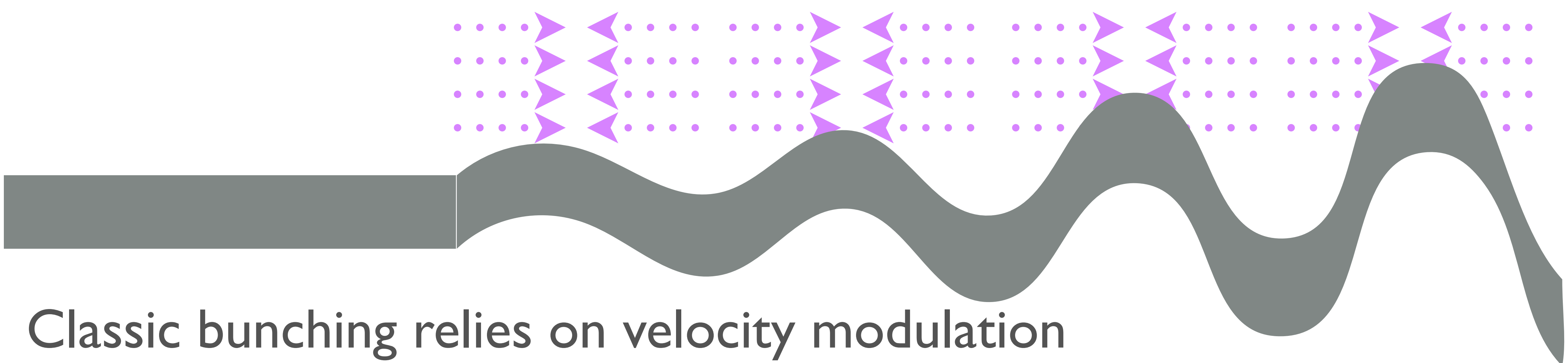
Pulse vs. Bunch



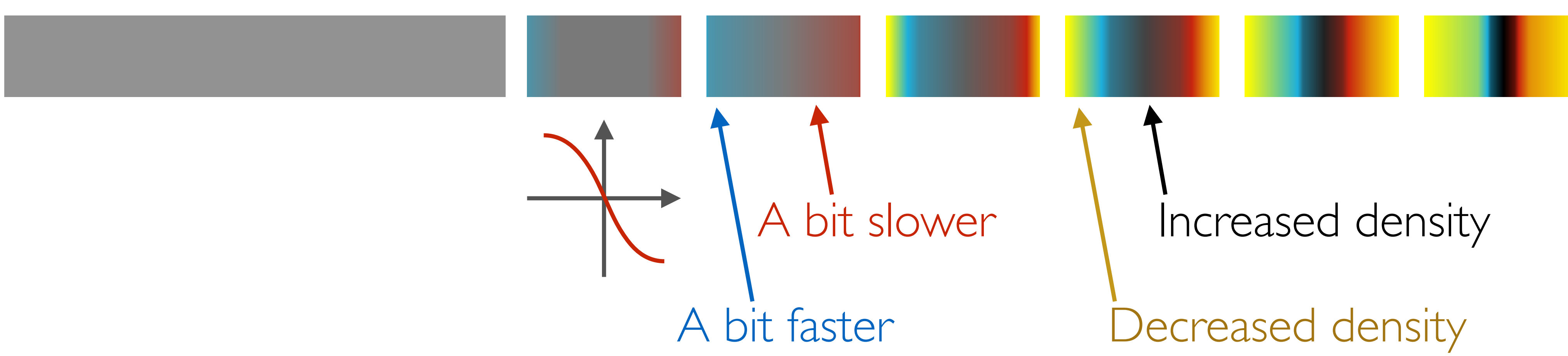
- ESS case:
  - 14 pulses per second, each 2.86 ms long (at 0.95 c this is ~815 km)
  - ~1E6 Bunches per pulse

RF Acceleration of DC beam

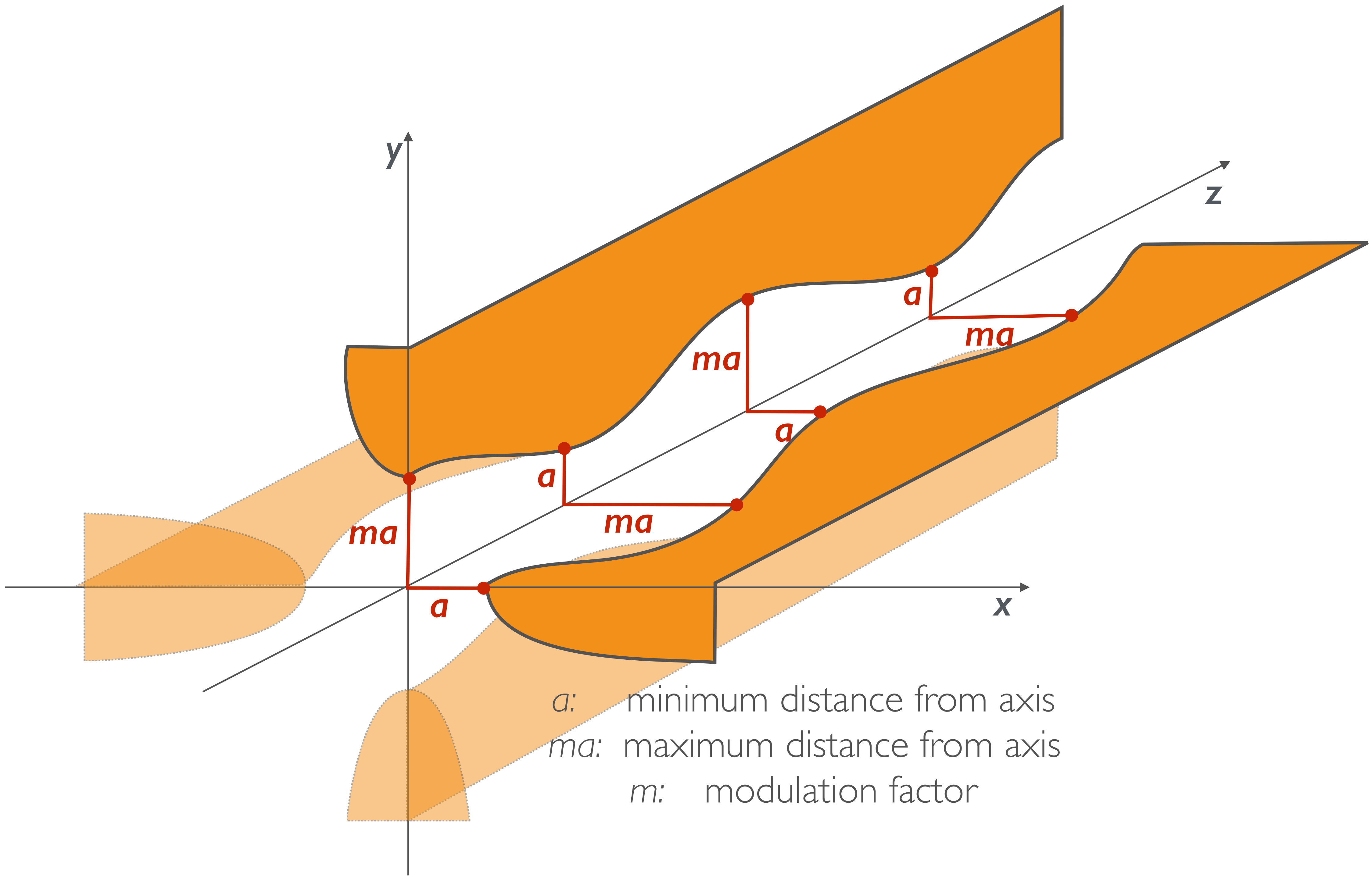
- The full pulse length of a DC beam could not be efficiently accelerated using an RF field as part of beam (half of it) losses energy in the decelerating field and a significant part does not get enough acceleration
-



- Classic bunching relies on velocity modulation

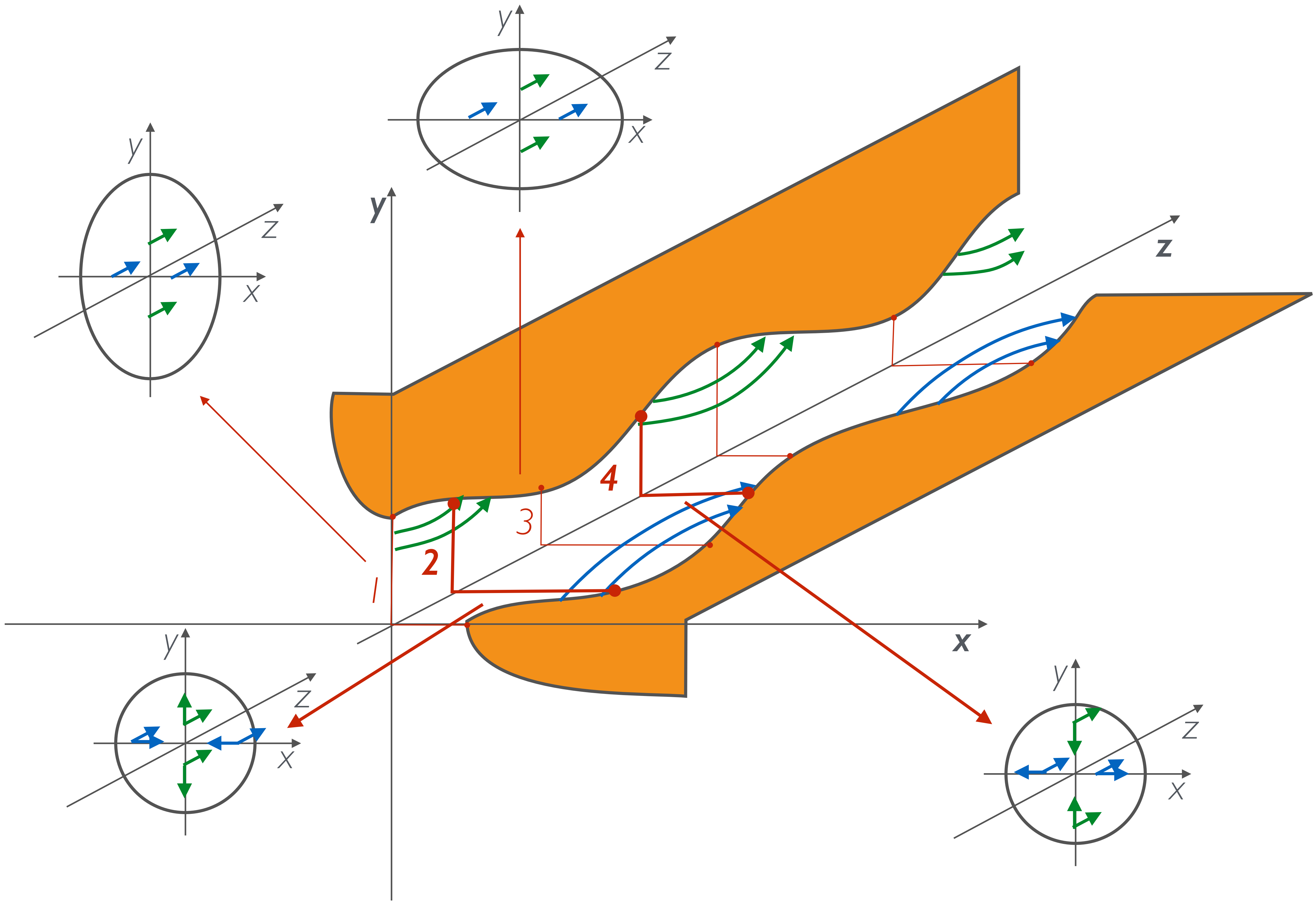


RADIO FREQ. QUAD. (RFQ) I



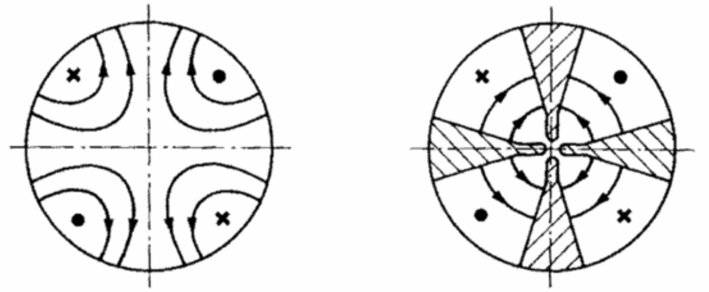
a: minimum distance from axis
ma: maximum distance from axis
m: modulation factor

Radio Freq. Quad. (RFQ) II



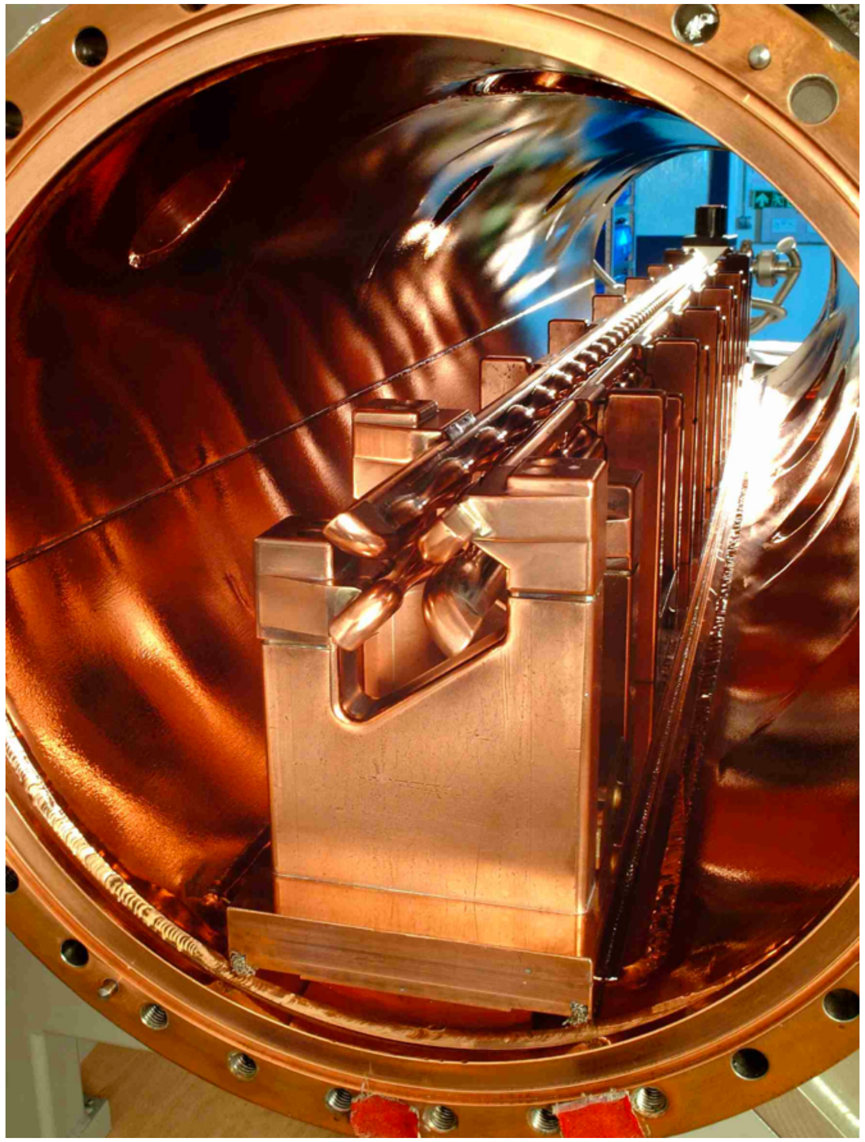
RADIO FREQ. QUAD. (RFQ) III

- Modern hadron accelerators use RFQs as their first accelerating and bunching structure.
  - RFQs can have bunching efficiency of >90%, while the classic methods are limited to ~50-60%.
  - RFQs can provide beams of high quality and high current
- There are two main types of RFQs, four-rods and four-vanes
- Both acceleration and bunching is achieved by RF field
- RFQs work in the TE_{21} mode (in TE mode, the electric field is perpendicular to beam direction of propagation.
- Longitudinal modulation of the electrodes vanes or rods) creates a field in the direction of propagation.

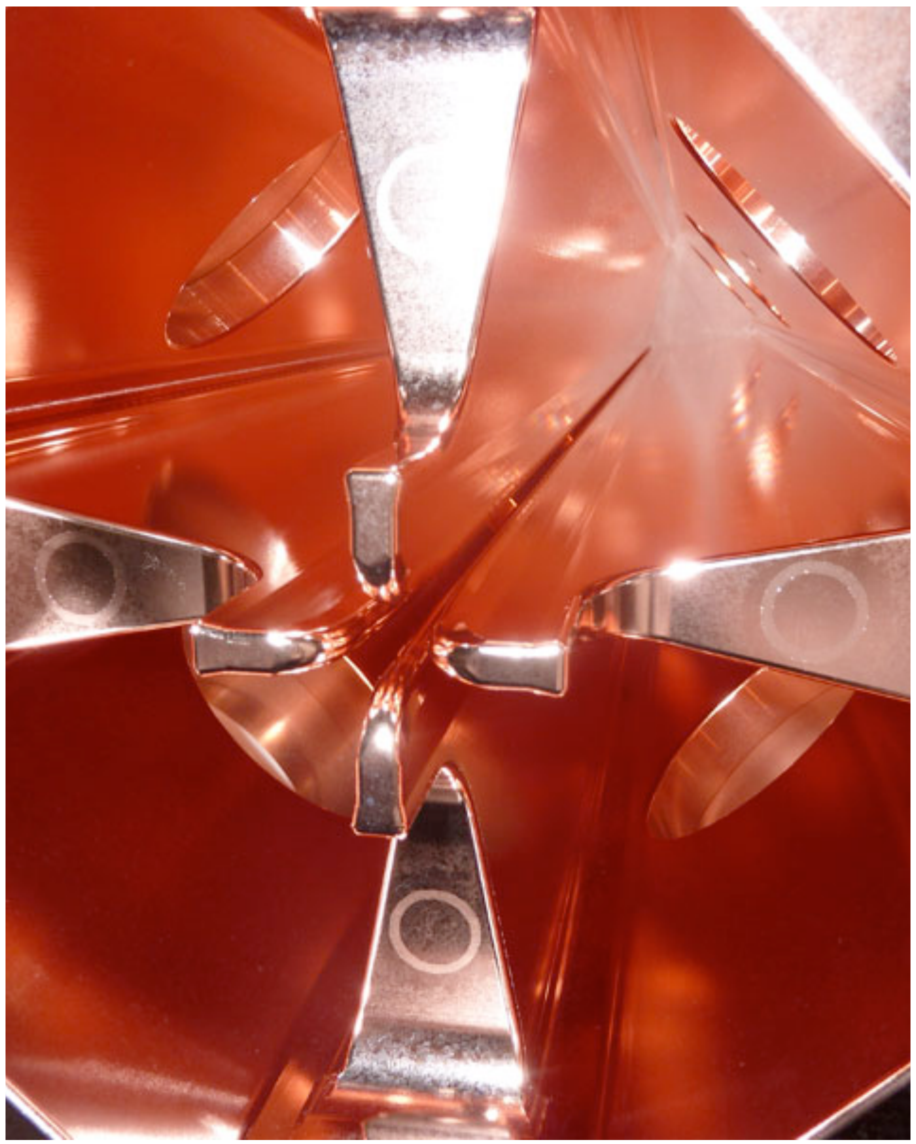


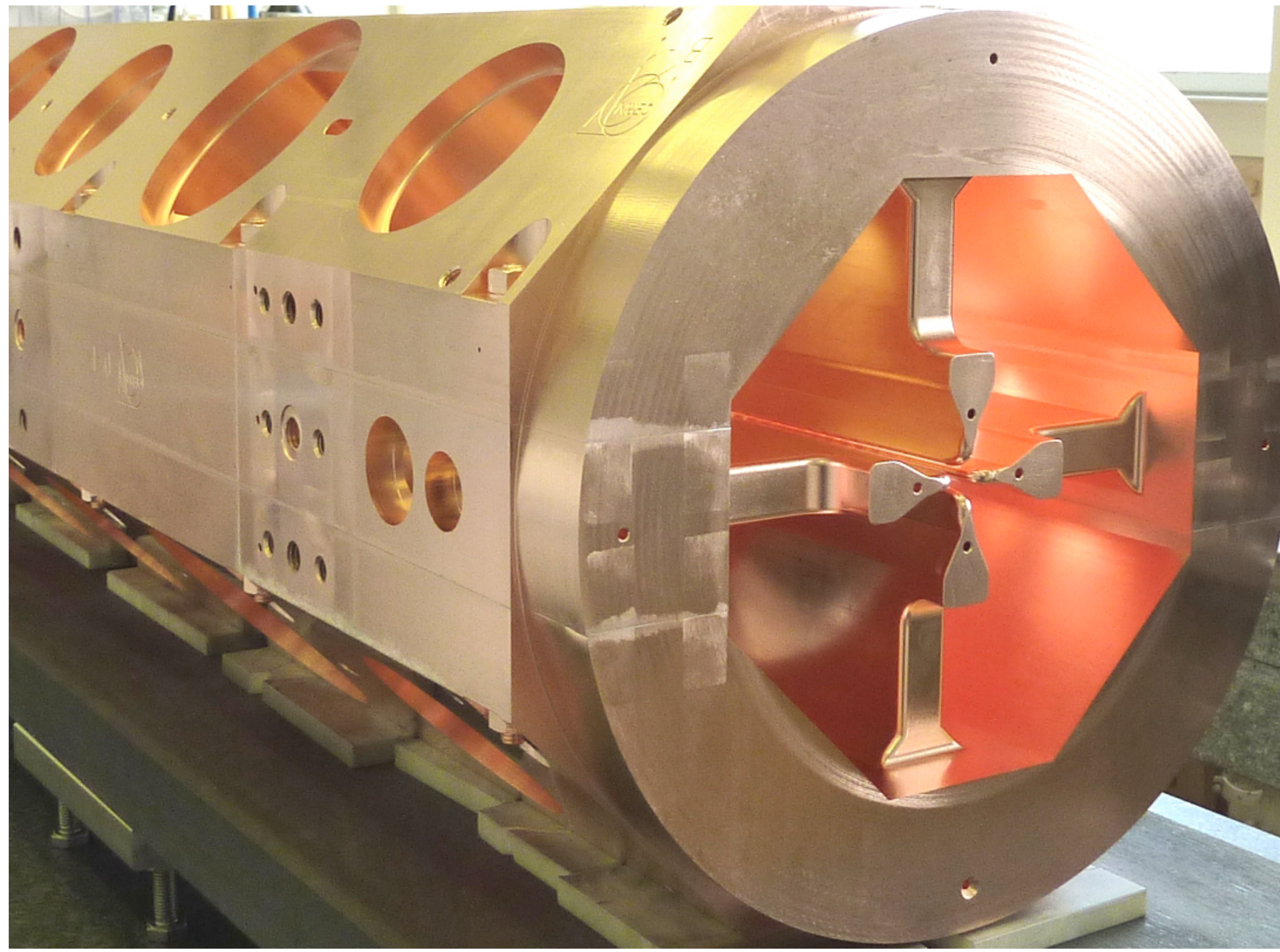
empty cavity   Cavity with vanes

FOUR-ROD RFQ



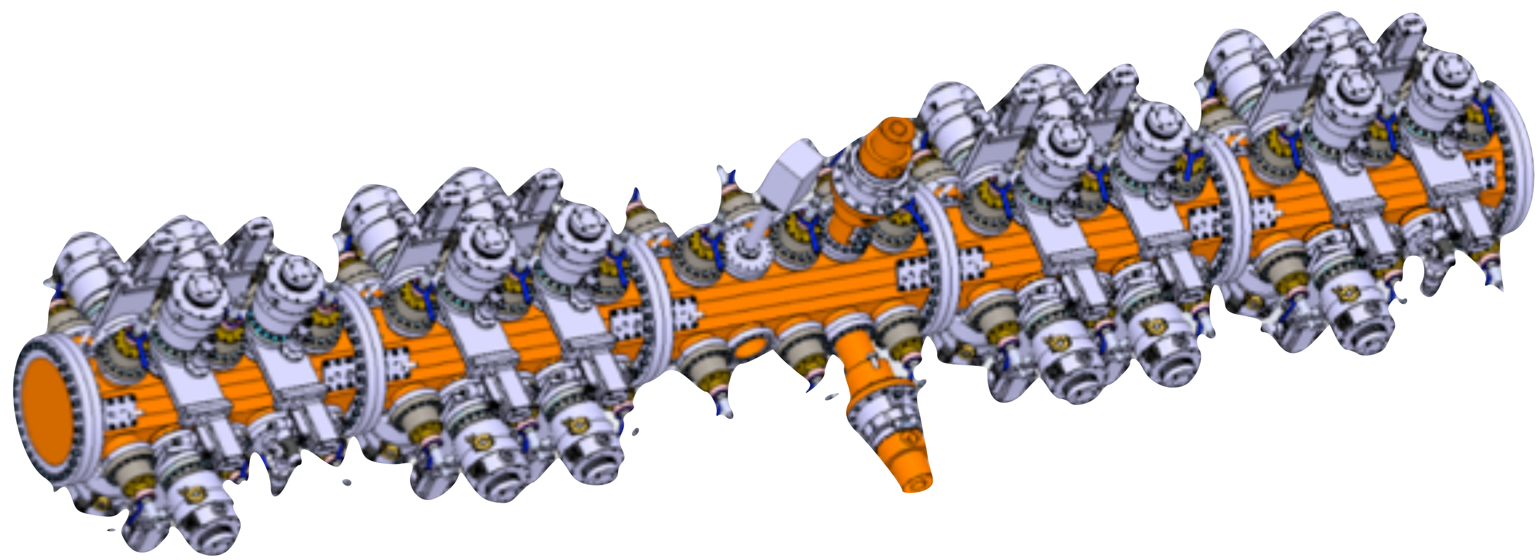
FOUR-VANE RFQ

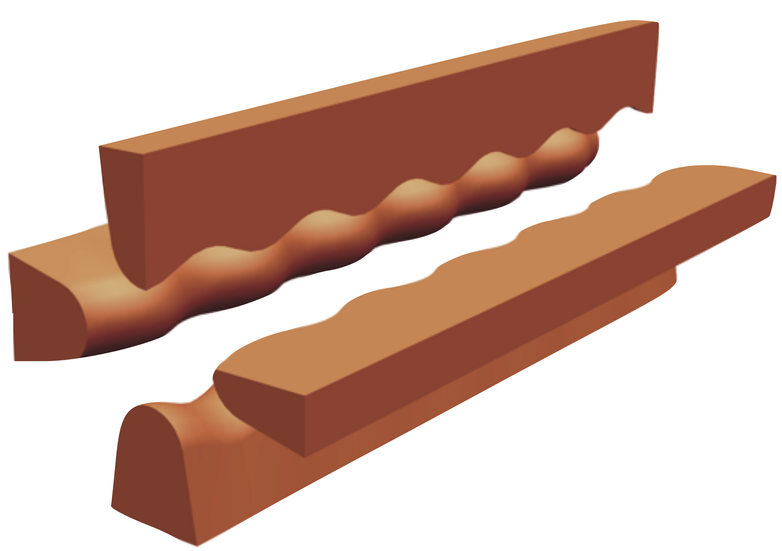




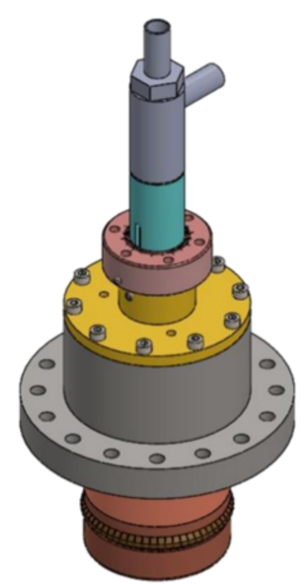
ESS RFQ

- Accelerates the beam from 75 keV to 3.62 MeV.
- It has 60 tuners and 2 RF couplers.

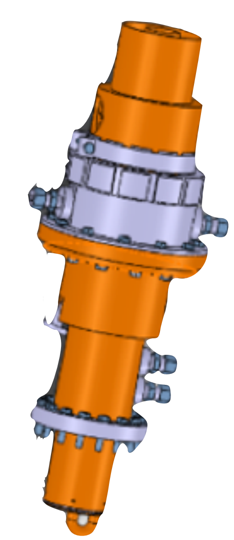




4 vane RFQ



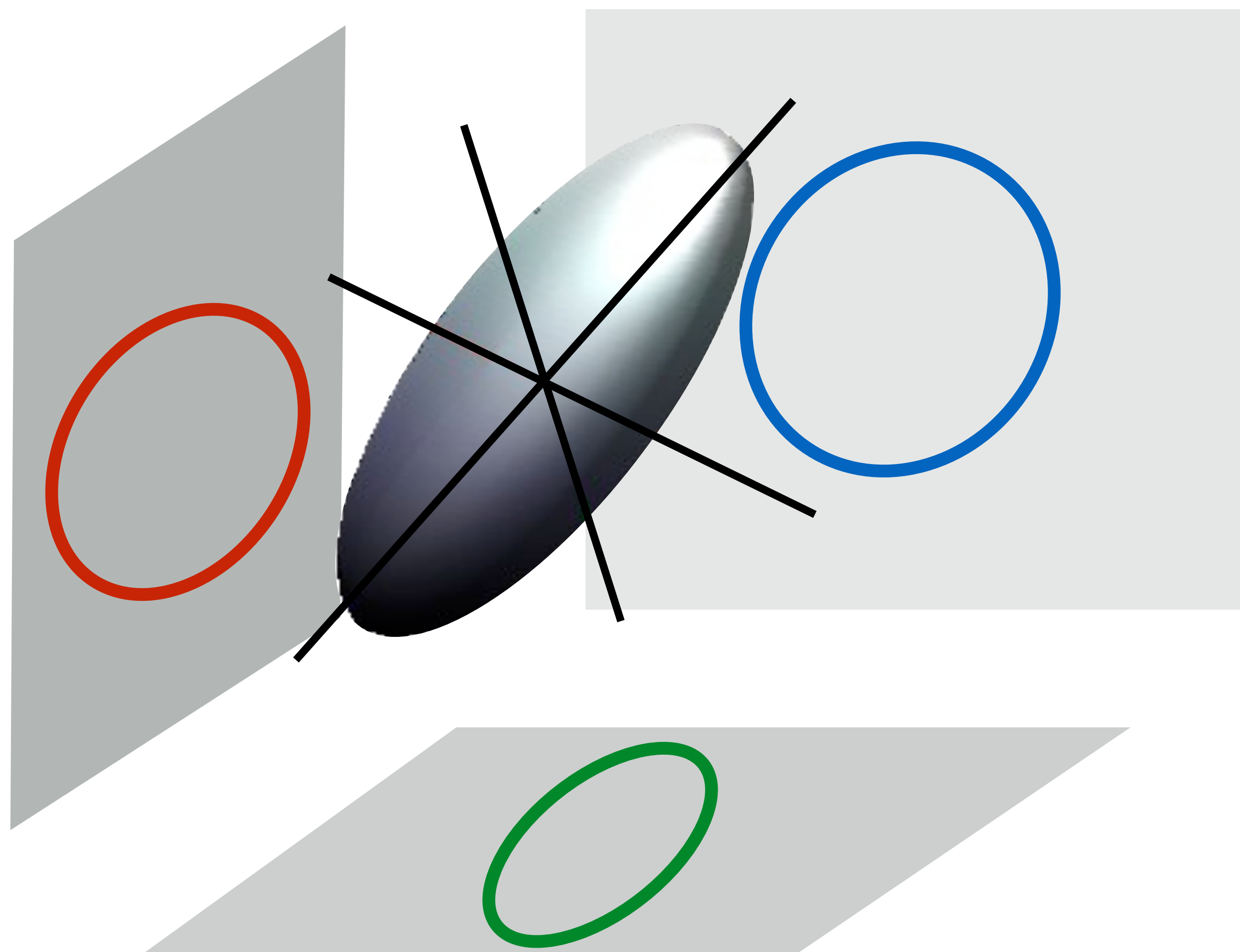
Tuners



RF coupler

A Bunch of particles

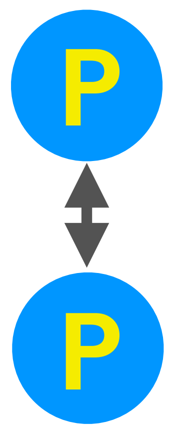
- Beam at the exit of the RFQ is an ellipsoid in the 6D phase-space (3D space shown here).



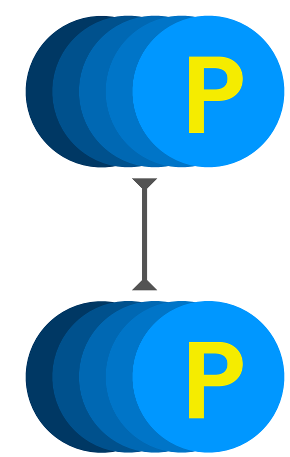
- ESS case:
  - There are ~1E9 protons per bunch, how about their repulsion?

SPACE CHARGE I

2D point charges



- $F_E = q^2/2\pi\epsilon_0.r$



- $F_B = -\mu_0 I^2/2\pi r = -(1/c^2\epsilon_0)(q\mathbf{v})^2/2\pi r = -\mathbf{v}^2/c^2.\ F_E$

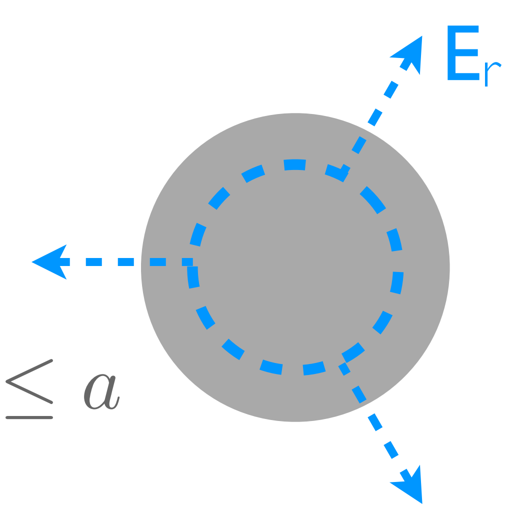
- $F_{tot} = (1-\mathbf{v}^2/c^2).\ F_E$

SPACE CHARGE III

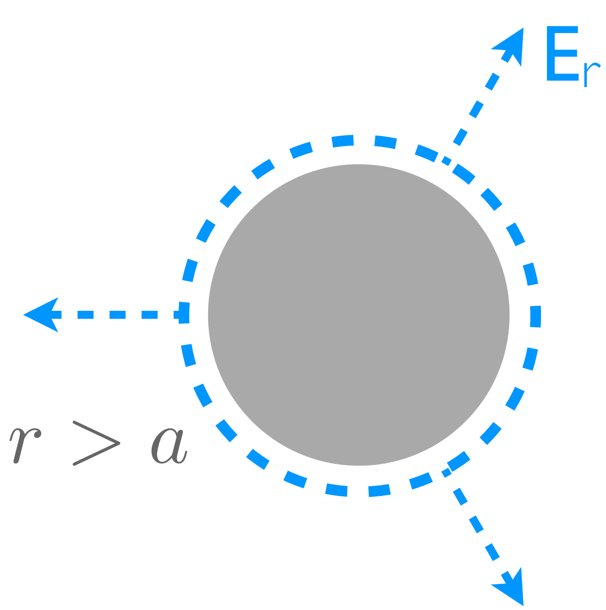
- Unless the beam has a very special distribution, the space charge forces are non-linear.
- A non-linear force will increase the beam emittance.
- It also has a defocusing effect which could be approximated be a series of defocusing lenses.
- In rings the space charge will also affect the tune of the ring
- As the forces are much stronger in lower energies the beam should be confined in all the three planes, horizontal, vertical and longitudinal.

$$2\pi r \mathbf{E} = \frac{Q}{\epsilon_0}$$

$$\mathbf{E} = \frac{Nqr}{2\pi\epsilon_0 a^2} \quad r \leq a$$



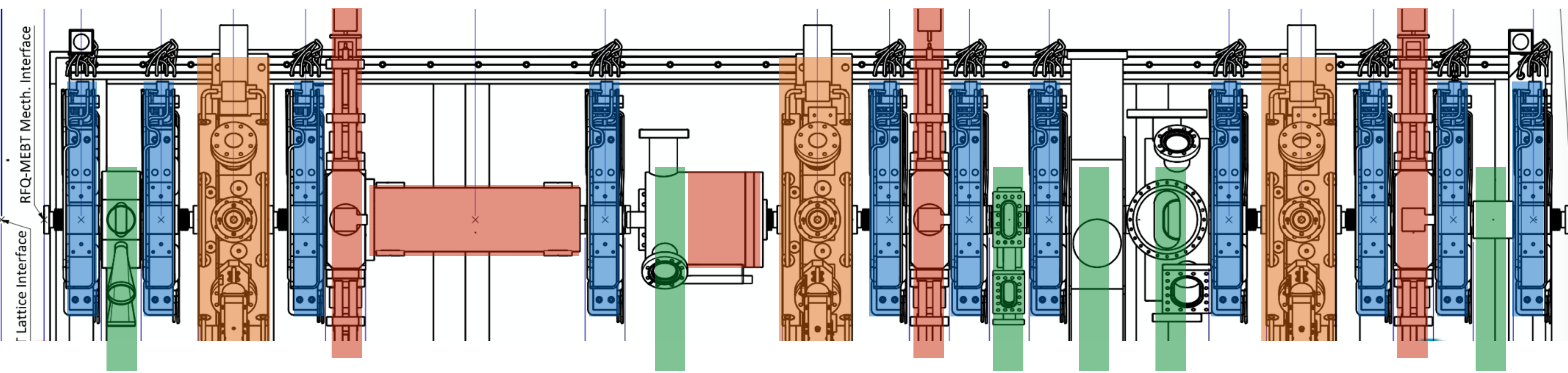
$$\mathbf{E} = \frac{Nq}{2\pi\epsilon_0 r} \quad r > a$$



MEBT

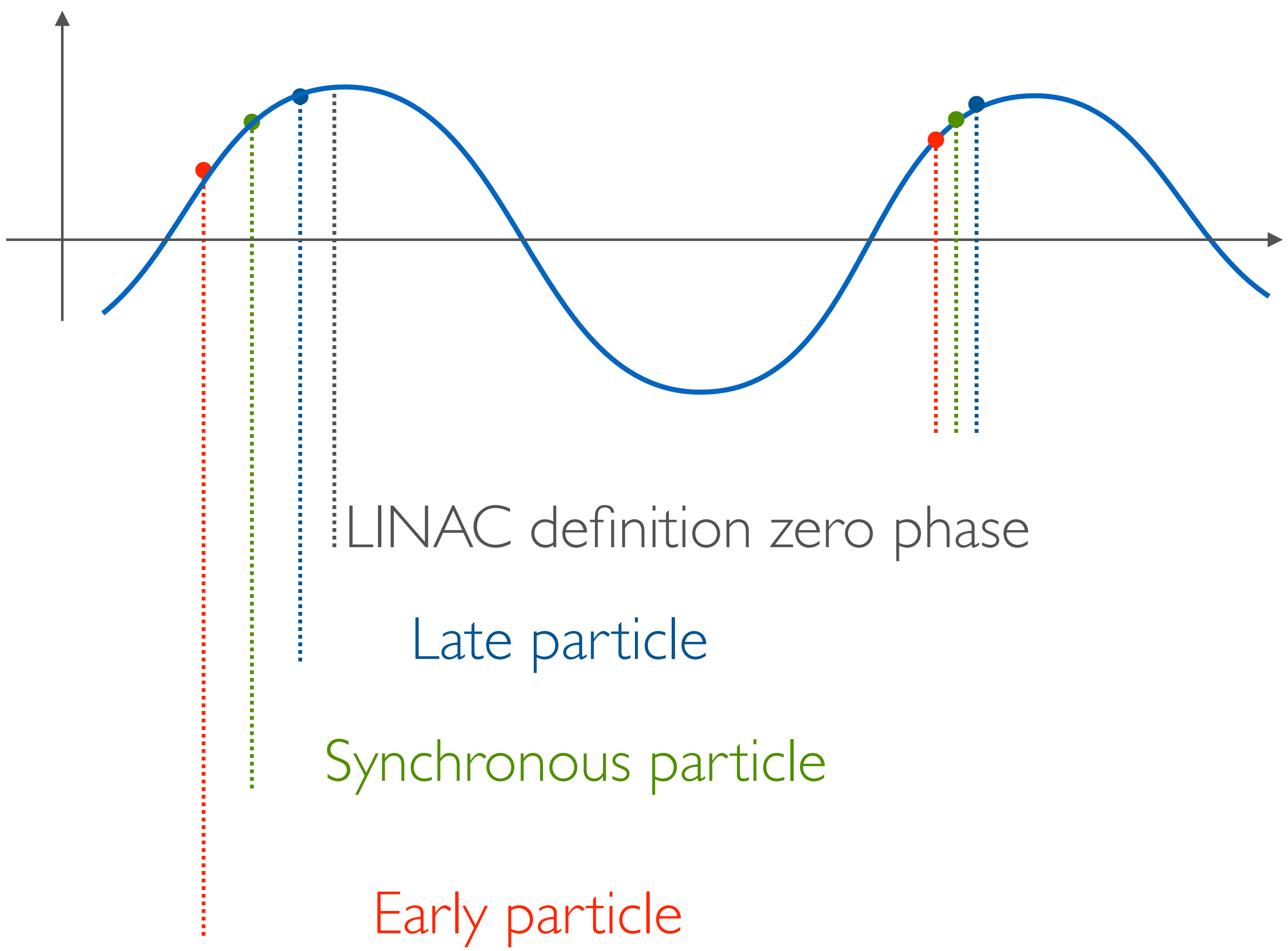
- Match RFQ output beam to the DTL (Three planes)
- Characterise the beam (Three planes)
- Clean the head of pulse using a fast chopper
- Clean the transverse halo using scrapers

QUADs/Correctors, Cavities, Measurement Devices, Cleaning Devices



SYNCHRONOUS PHASE

- The highest acceleration is on the voltage peak.
- To keep the beam bunched, acceleration must be done at a lower phase

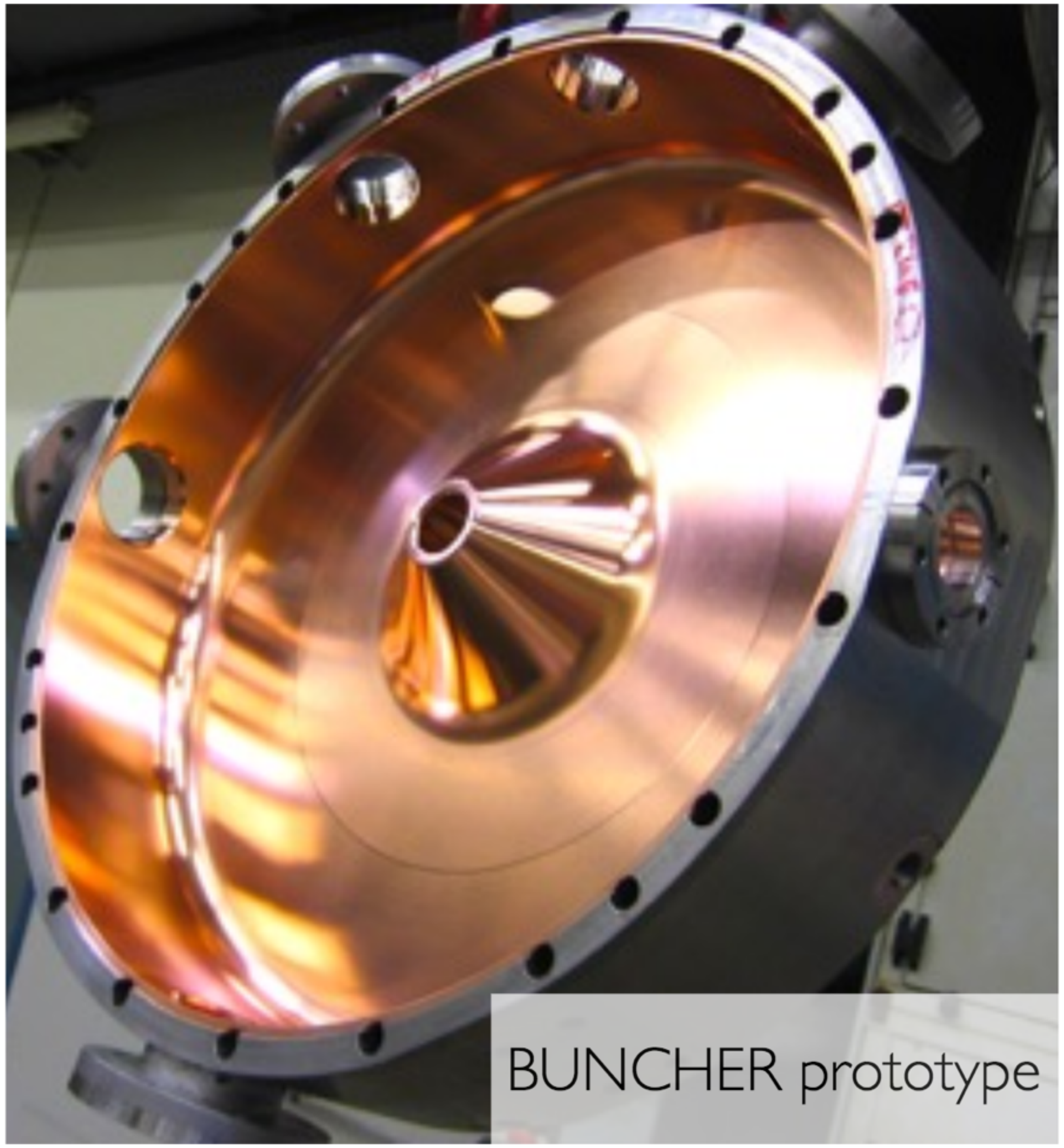


MEBT Buncher

- A buncher cavity is used to focus the beam in the longitudinal direction (direction of propagation).

- ESS MEBT has three buncher cavities
  - E0TL ~150 kV
  - Power coupler limit ~22.5 kW

- These bunchers do not increase the beam energy.



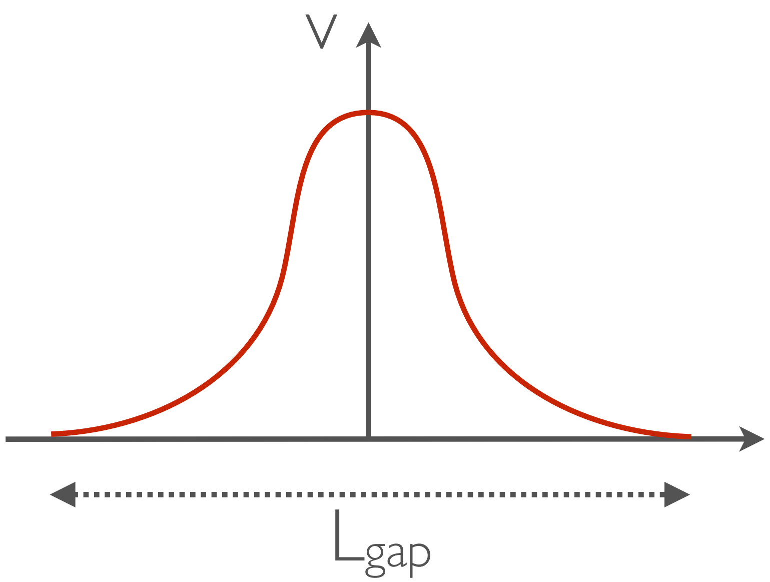
MEBT Diagnostics

- ESS linac is equipped with beam instruments to measure the beam properties:
  - Beam Current Monitors (BCM or BCT) for measuring the beam current
  - Beam Position Monitors (BPM) to measure the beam's position and time
  - Emittance Measurement Unit (EMU) which measures the beam emittance and its orientation
  - Beam Profile Monitors, these measure only the beam profile in transverse
  - Beam Shape Monitors (BSM) to measure the longitudinal span of the beam

DRIFT-KICK-DRIFT

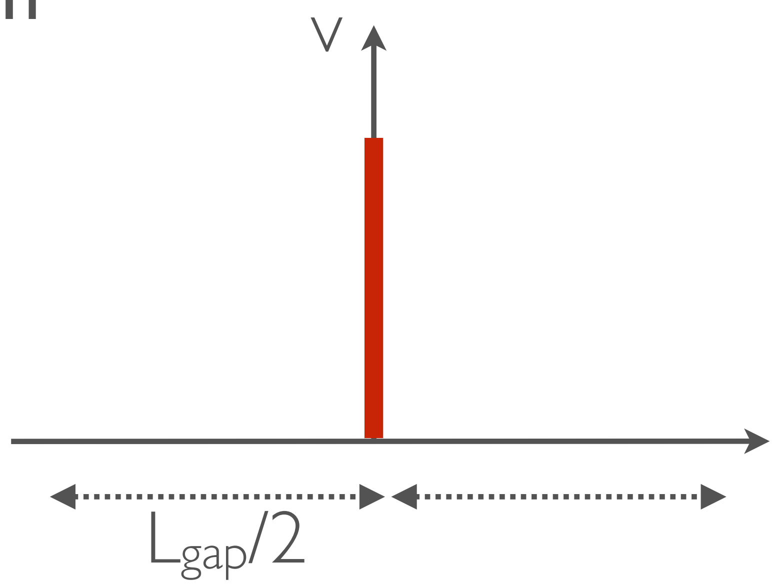
- The RF acceleration in a gap with finite length could be approximated by a drift (with half the gap length), a sudden increase in energy, and a second drift.

- $$E_z(r,z) = \sum_{0}^{\infty} A_m J_0(a_m r)\cos(2\pi m z/L_{gap})$$
  $$E_z(r,z,t) = E_z(r,z)\cdot\cos(\omega t+\phi)$$

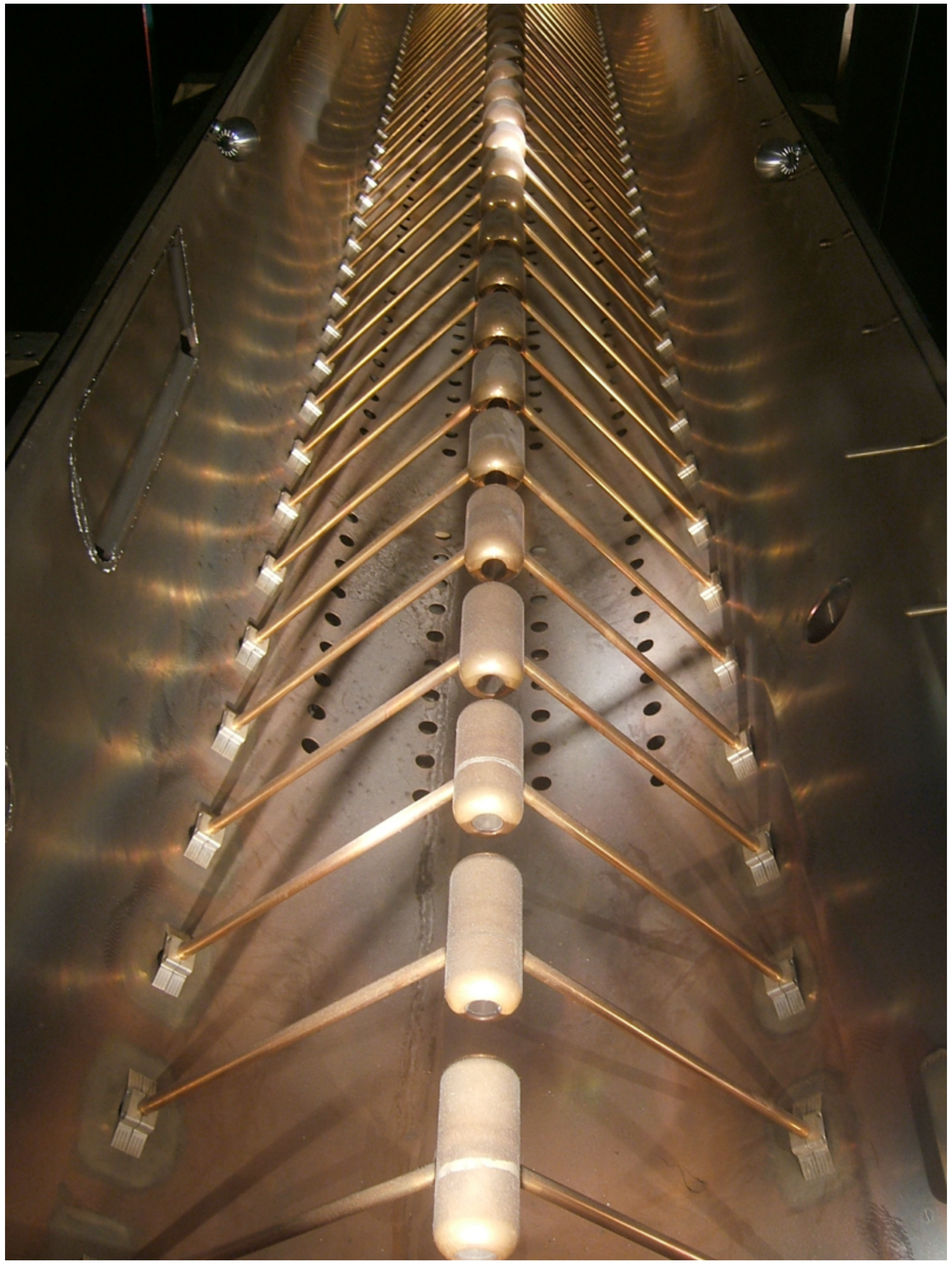


- However, while a particle with finite velocity traverses the cavity, the field changes and the effective voltage seen by the beam is reduced by a factor called Transit Time Factor.

$$\Delta W = qE_zTL_{gap}cos(\phi)$$

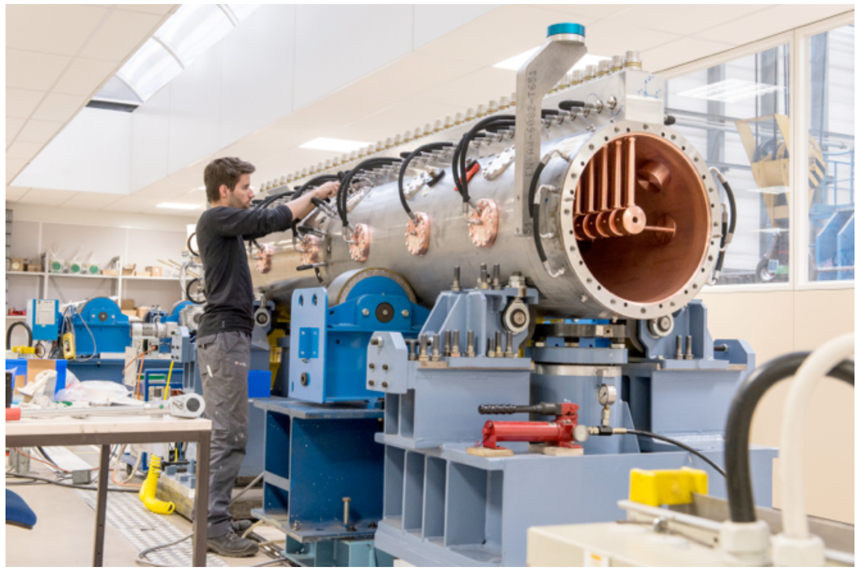


DRIFT TUBE LINAC II



Linac1, 202.56 MHz

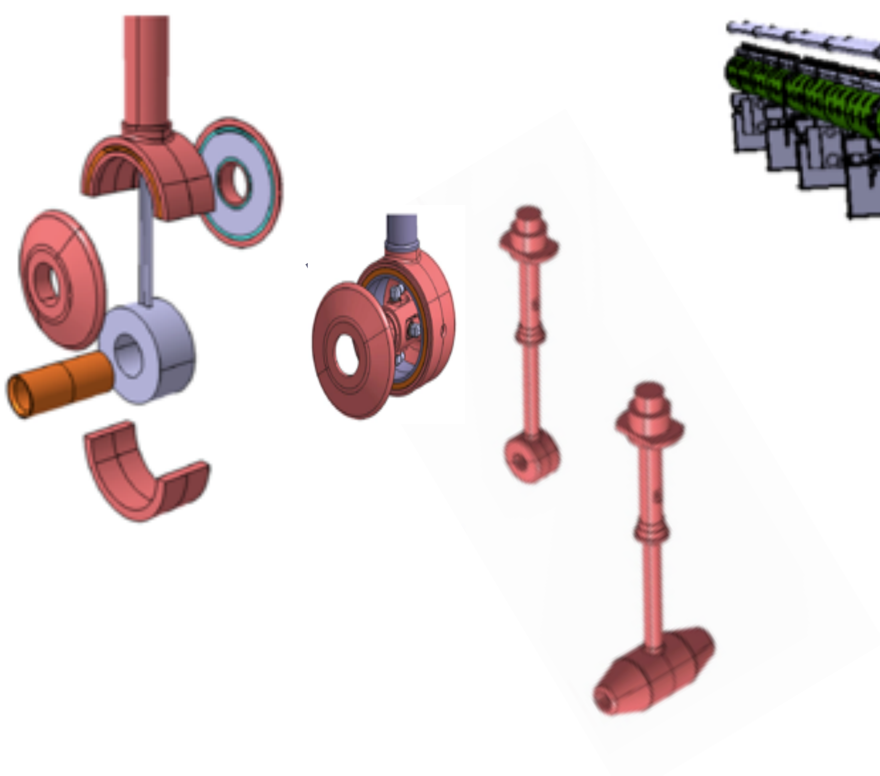
SuperHilac, 70.285 MHz

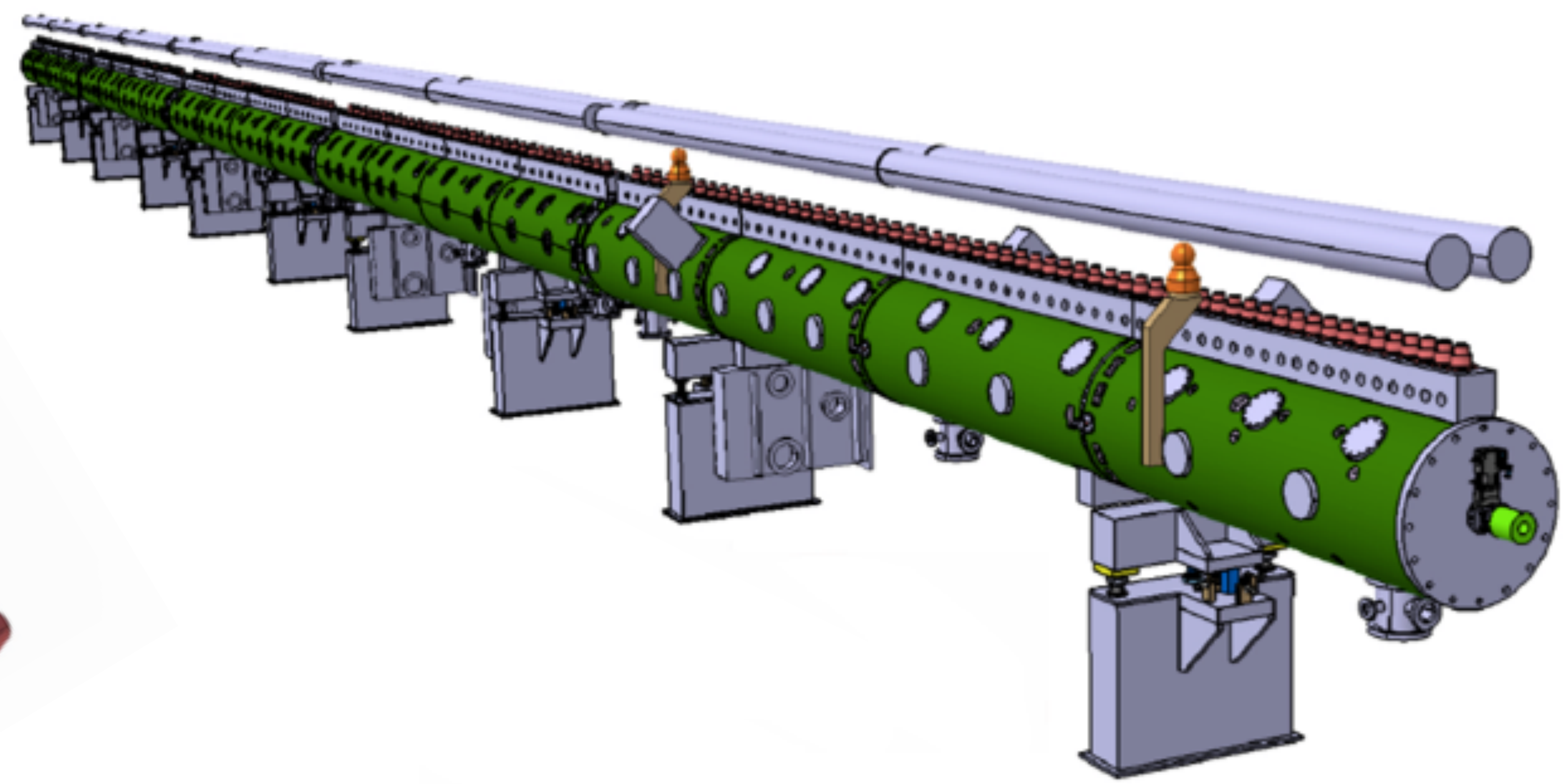


Linac4, 352.21 MHz

ESS DTL

- DTL accelerates the beam from 3.62 to ~90 MeV





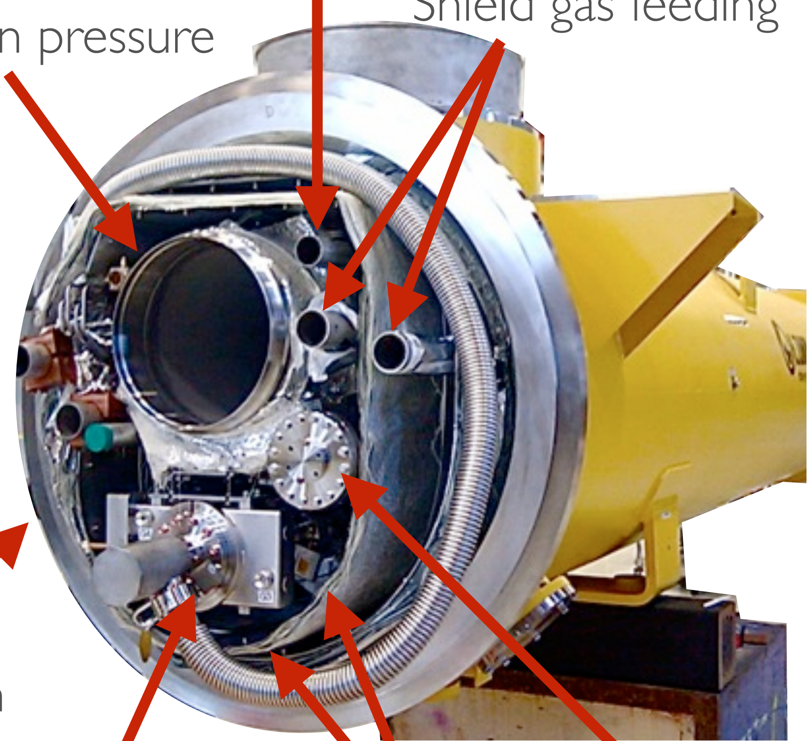
Transition to SC cavities

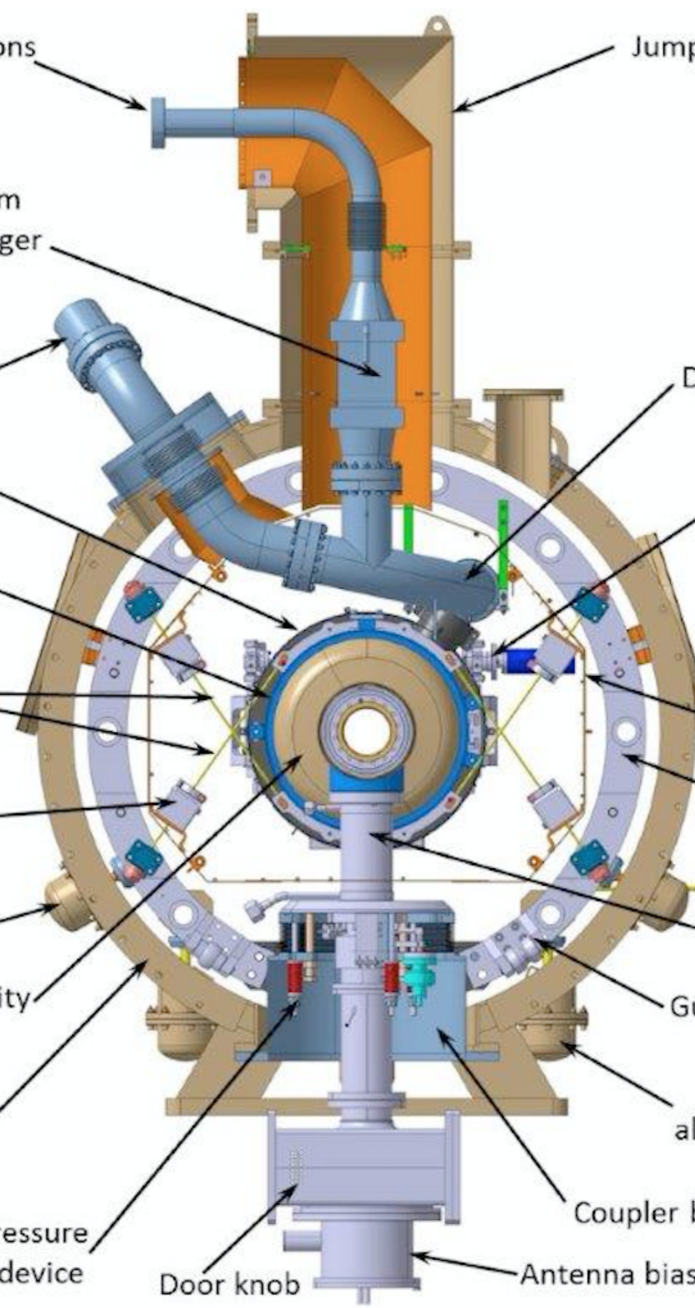
- In normal conducting cavities, a significant part of the RF power is wasted in the copper structure in the form of ohmic loss.
  - For the ESS linac, after several rounds of optimizations, the ratio of wasted power to beam power is 1 to 1, i.e., half the provided power is wasted!
- Superconducting cavities do not have this problem, they have other problems!
- RF efficiency of SC cavities is ~100% (compare to 50% in the ESS DTL).
- But, they operate at cryogenic temperatures (few Kelvin), and cooling them down to that temperature requires significant energy.
- Depending on the duty factor, energy, … one chooses the optimized transition energy.

SUPERCONDUCTIVITY

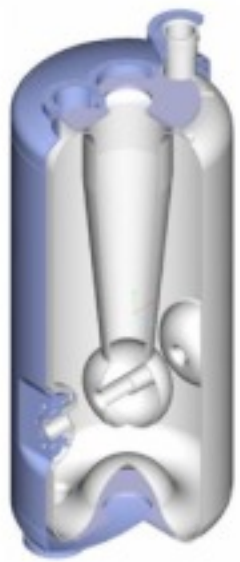
CRYOMODULE

- ILC cryomodule (left) with integrated He distribution line and ESS cryomodule (right) with separated He distribution line.



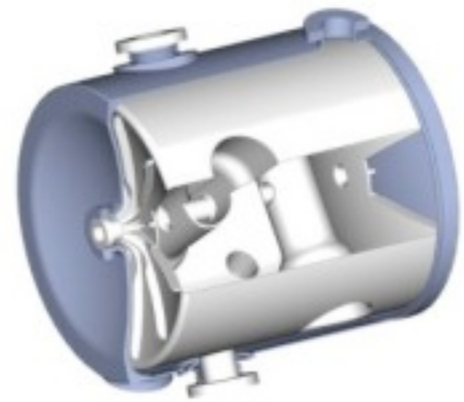


SC CAVITY TYPES

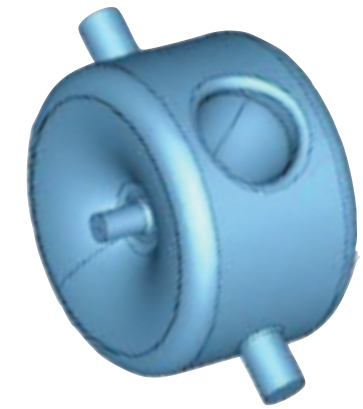


QWR, 115 MHz, β_{opt}=0.15
Quarter wave resonator

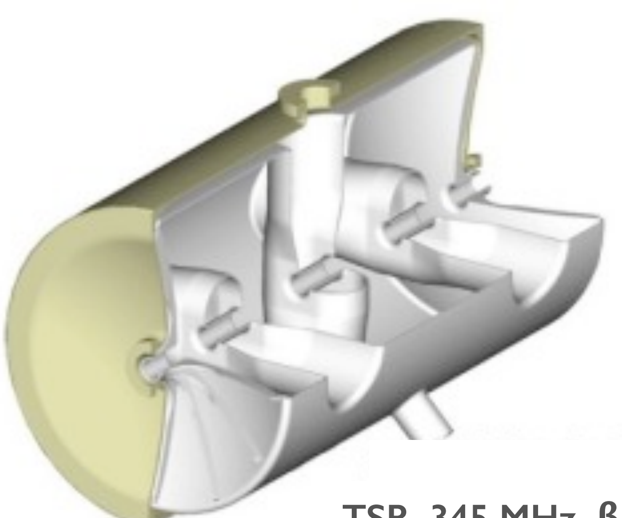
HWR, 172.5 MHz, β_{opt}=0.25
Half wave resonator



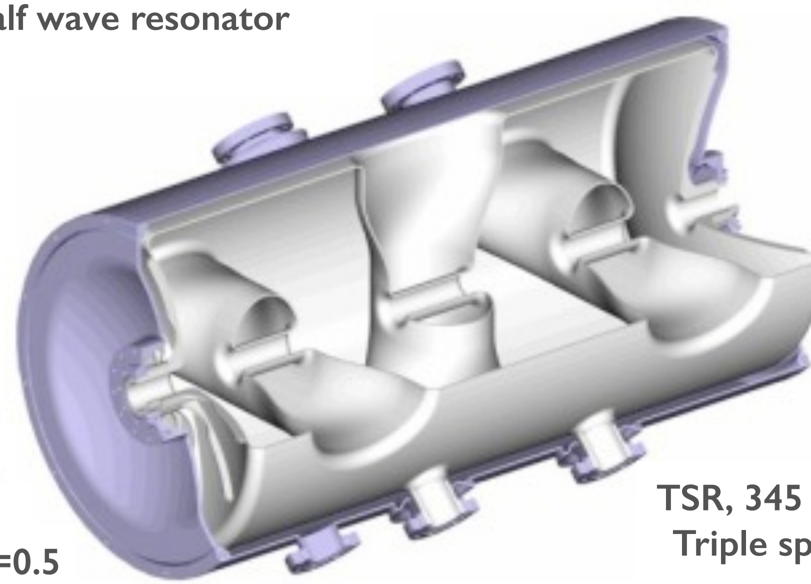
DSR, 172.5 MHz, β_{opt}=0.25
Double spoke resonator



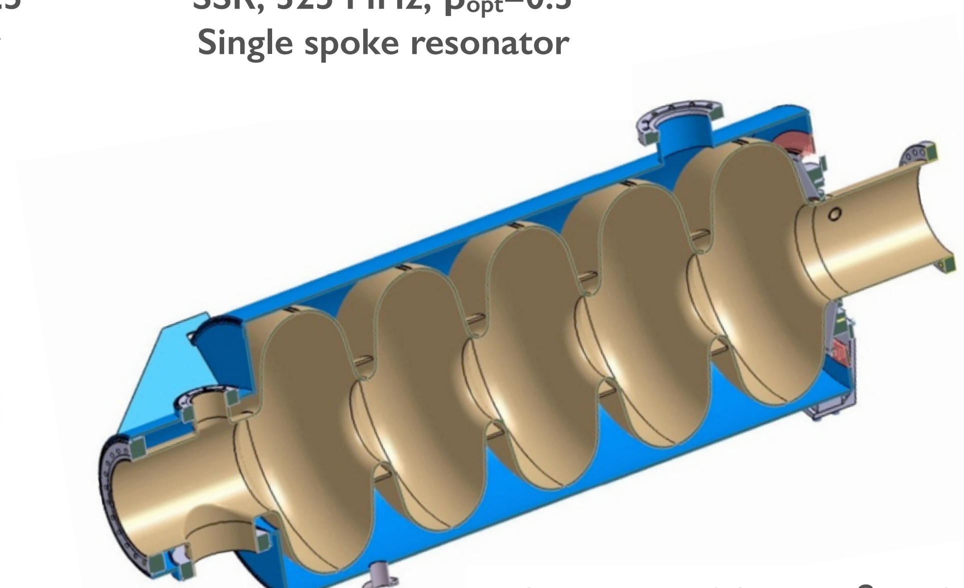
SSR, 325 MHz, β_{opt}=0.3
Single spoke resonator



TSR, 345 MHz, β_{opt}=0.5
Triple spoke resonator



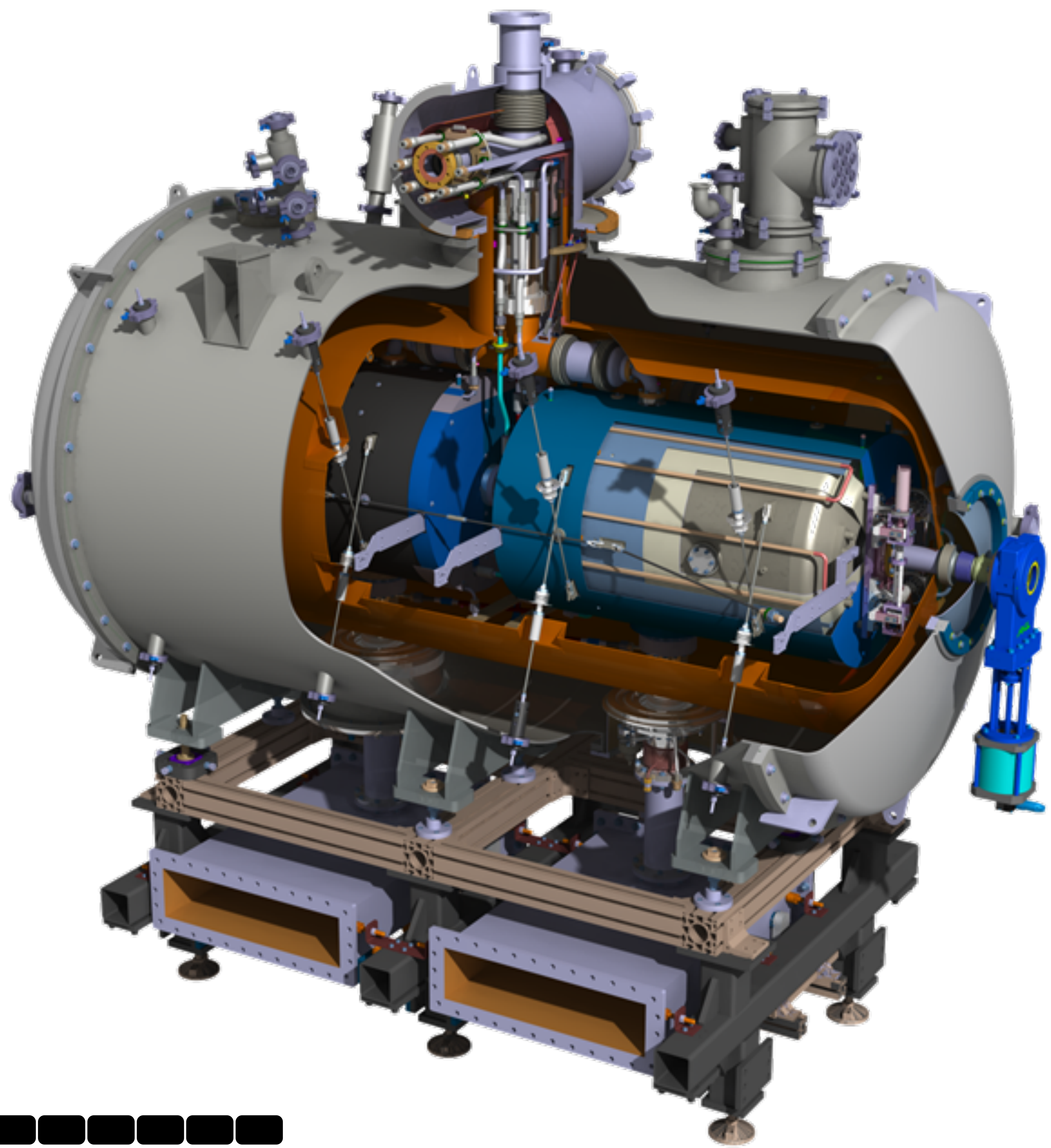
TSR, 345 MHz, β_{opt}=0.62
Triple spoke resonator

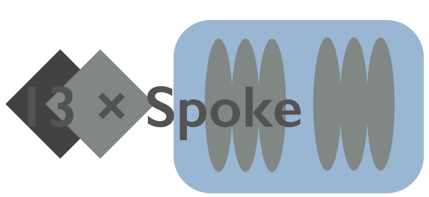


5 Cell Ellip., 704 MHz, β_{opt}=0.86
5 cell elliptical cavity

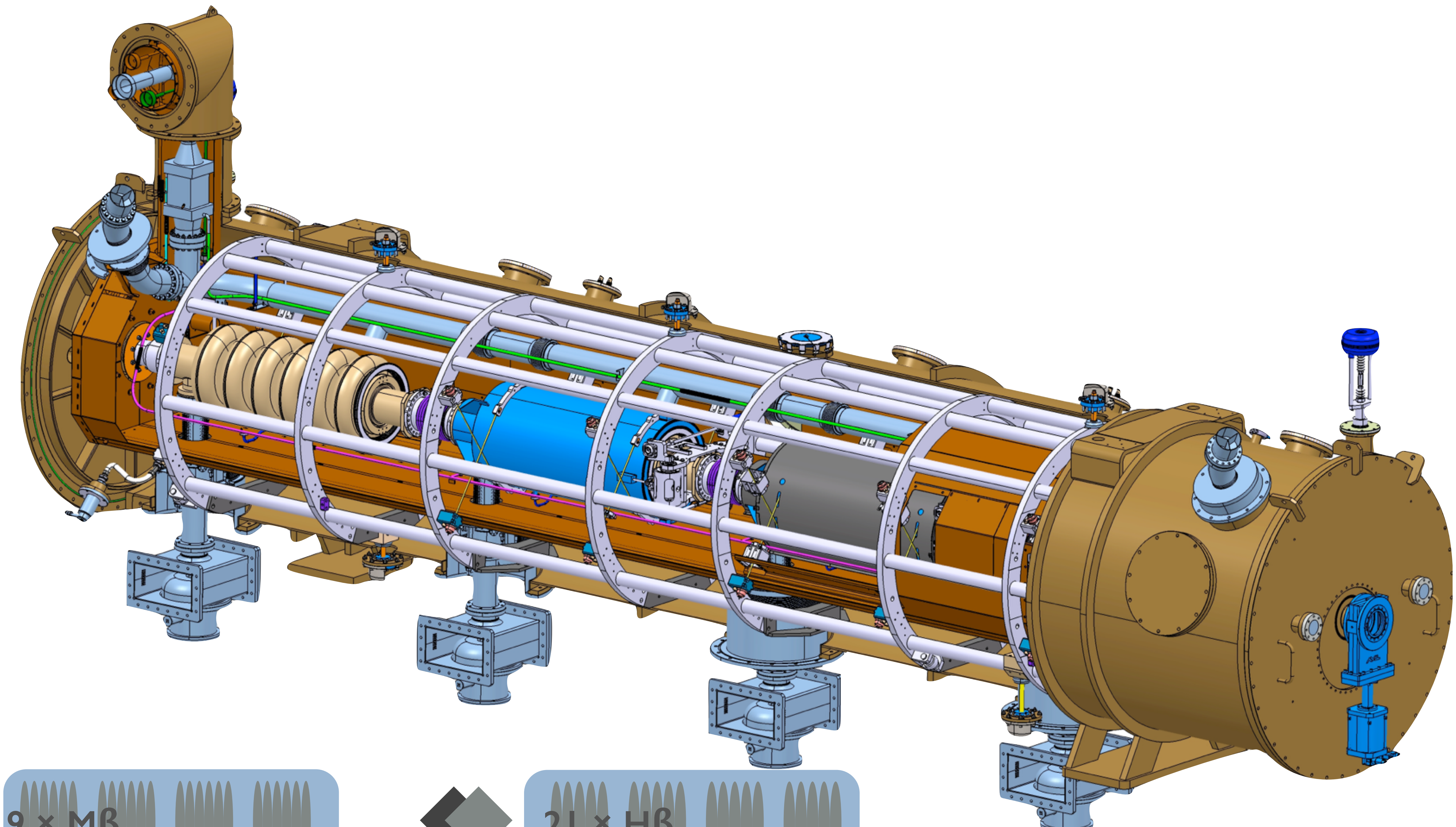
Courtesy: **Argonne National Lab., CEA, RAON**

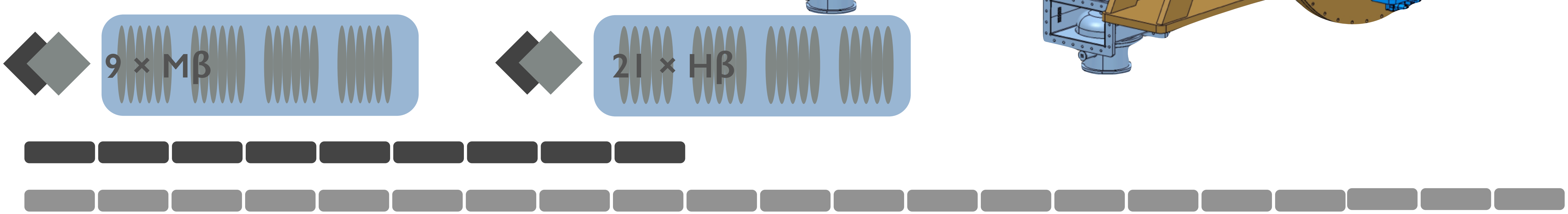
ESS Spoke Cryomodule





ESS Elliptical Cryomodule

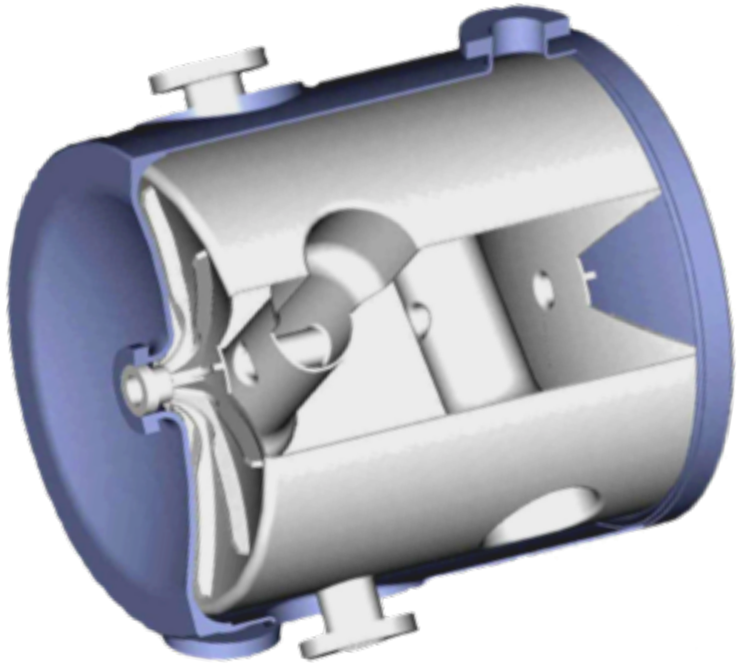


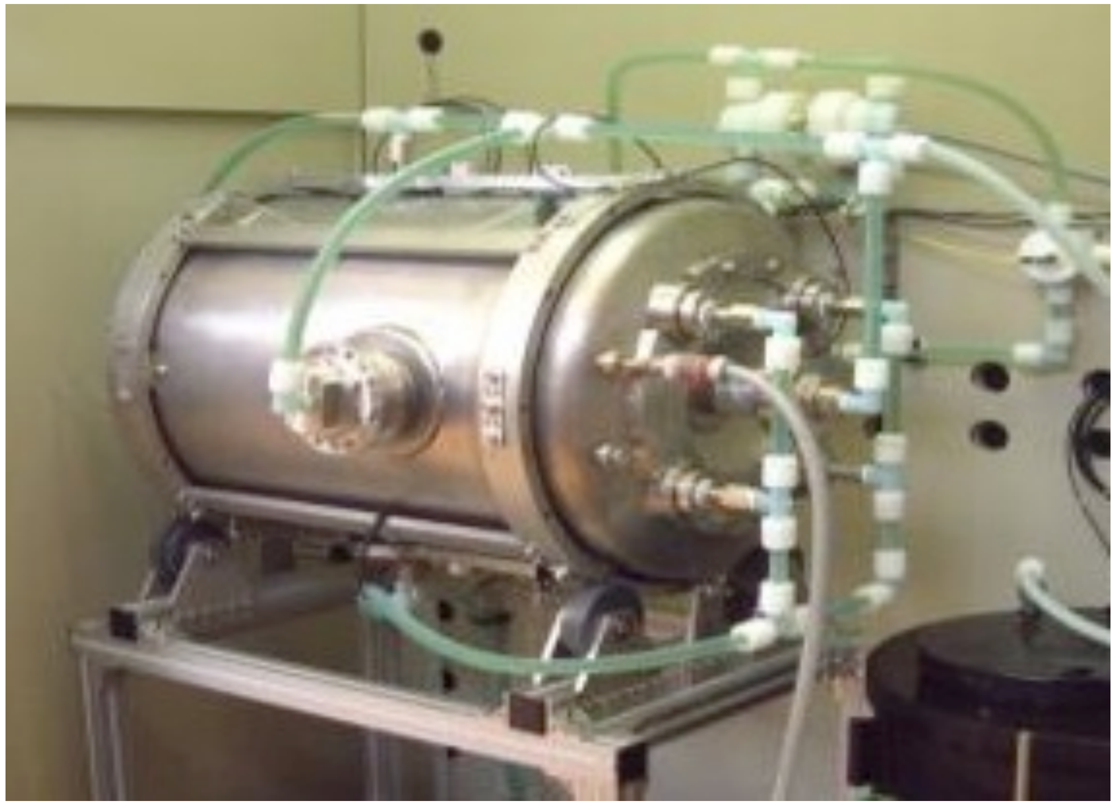


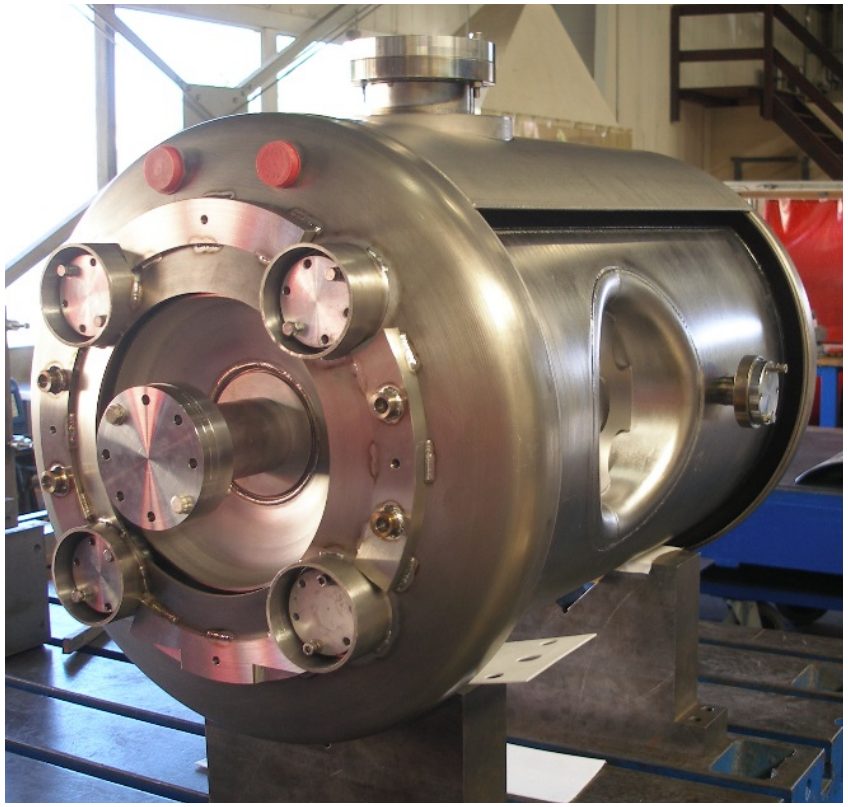
ESS Spoke Cavity

- Quadrupole Doublet Focusing
- Starts with a differential pumping section (LEDP)
- Accelerates the beam from 90 to 216 MeV

  Double spoke, β_{opt} = 0.5, E_{acc} = 9 MV/m

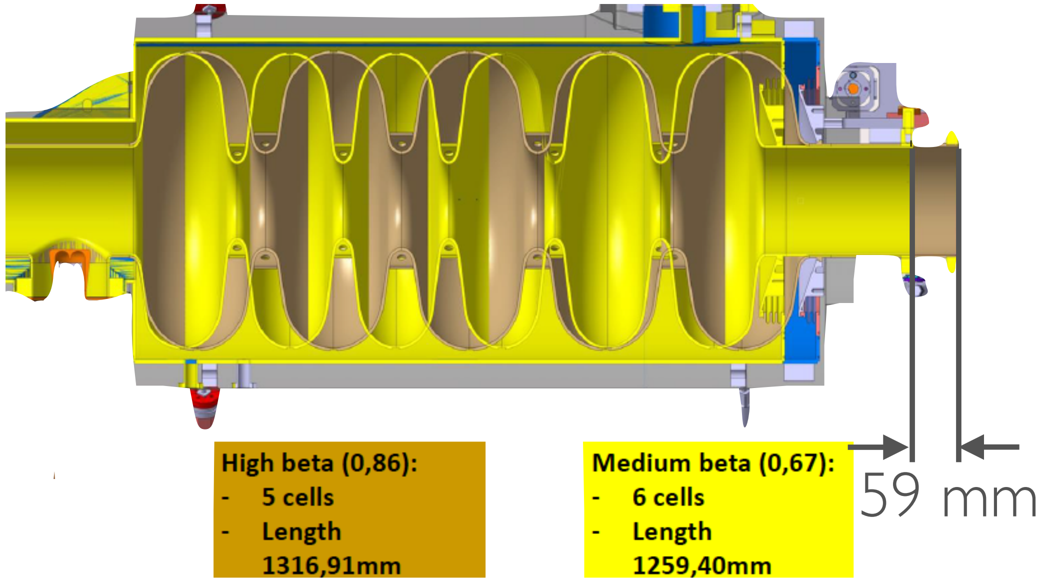






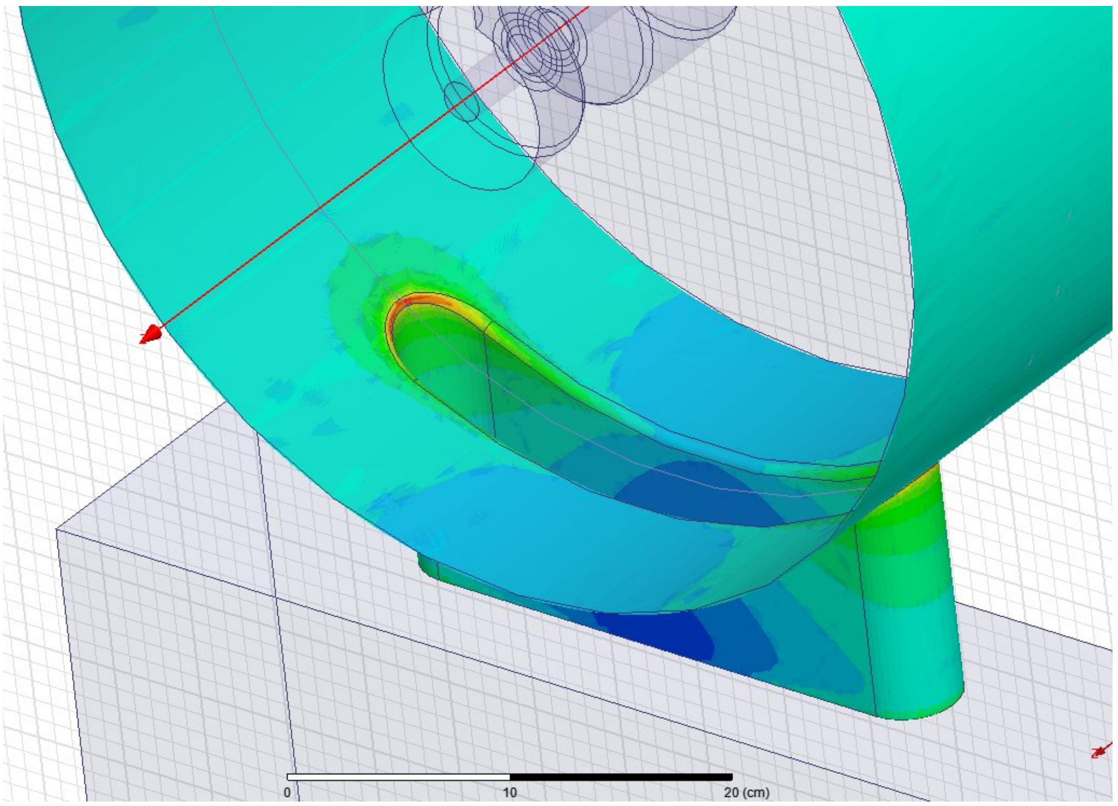
ESS Elliptical Cavity

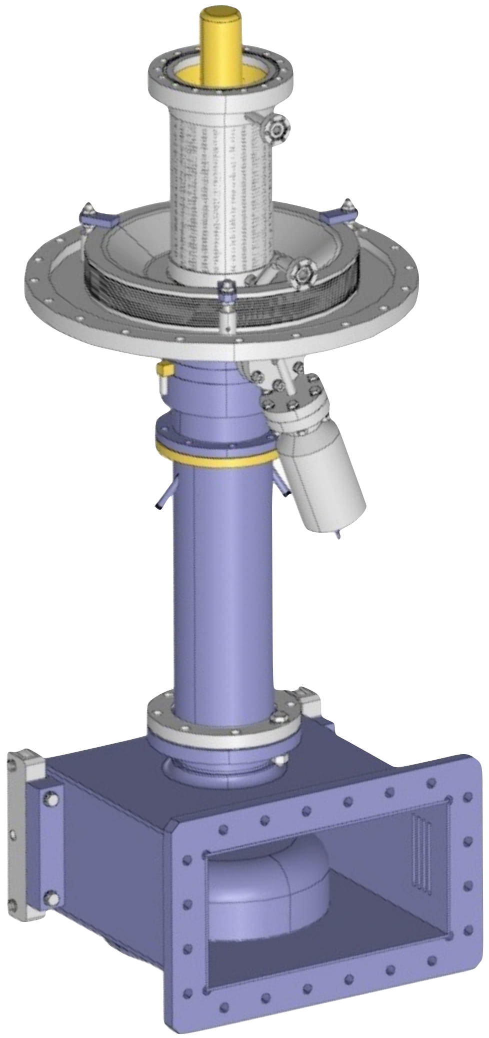
- Quadrupole Doublet Focusing
- Accelerates the beam from 216 MeV to 571 MeV to 2 GeV in Two families:
  - 6-cell, $\beta g = 0.67$, $E_{acc} = 16.7$ MV/m
  - 5-cell, $\beta g = 0.86$, $E_{acc} = 19.9$ MV/m



Coupler

- The RF power generated by the RF sources is fed to the cavity through couplers.
- Coupler should stand very high voltages, preserve the vacuum and convert the waves from waveguide geometry to cavity geometry.





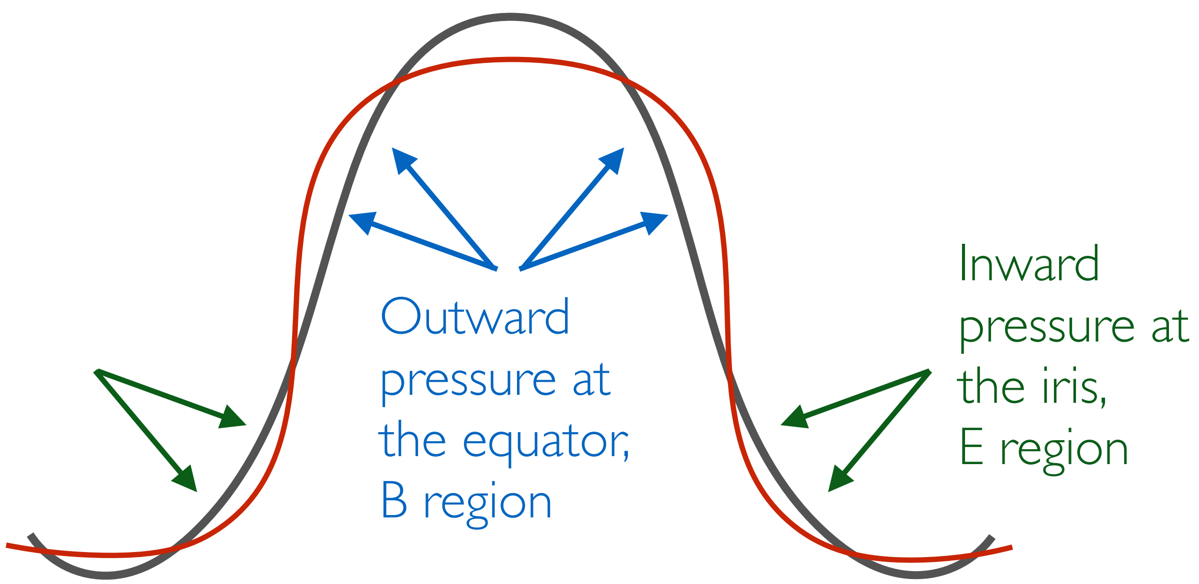
Radiation Pressure

The electromagnetic field in the cavity causes a radiation pressure on the cavity surface:

$P = (\mu_0 H^2 - \varepsilon_0 E^2)/4$

This deforms the cavity shape which causes a frequency shift in the cavity:

$\Delta f = KL \times E^2_{acc}$



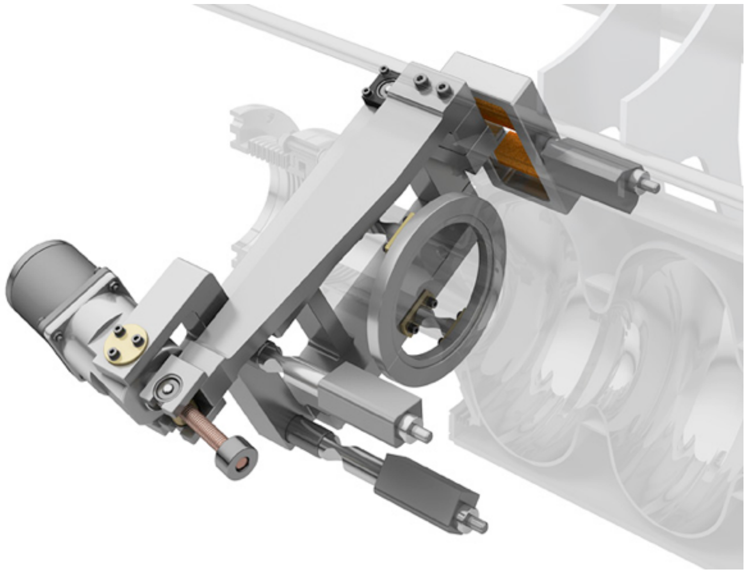
Temperature changes in normal conducting cavities can also alter cavity volume.

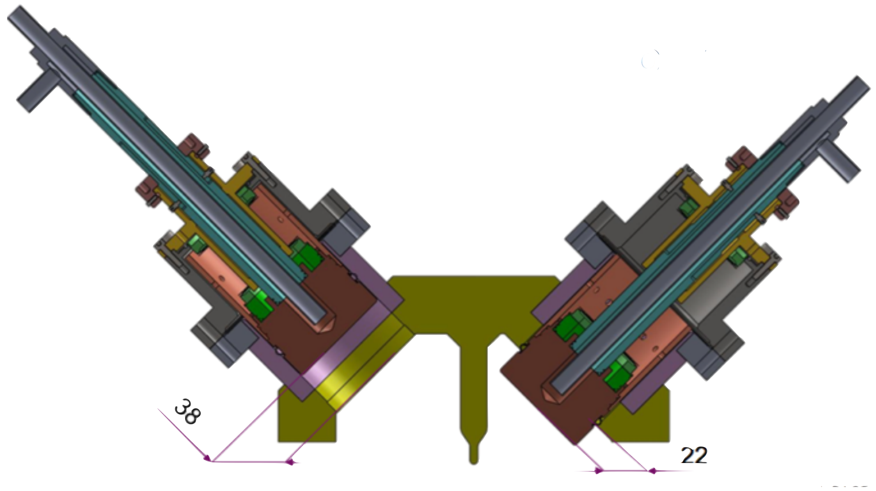
TUNERS

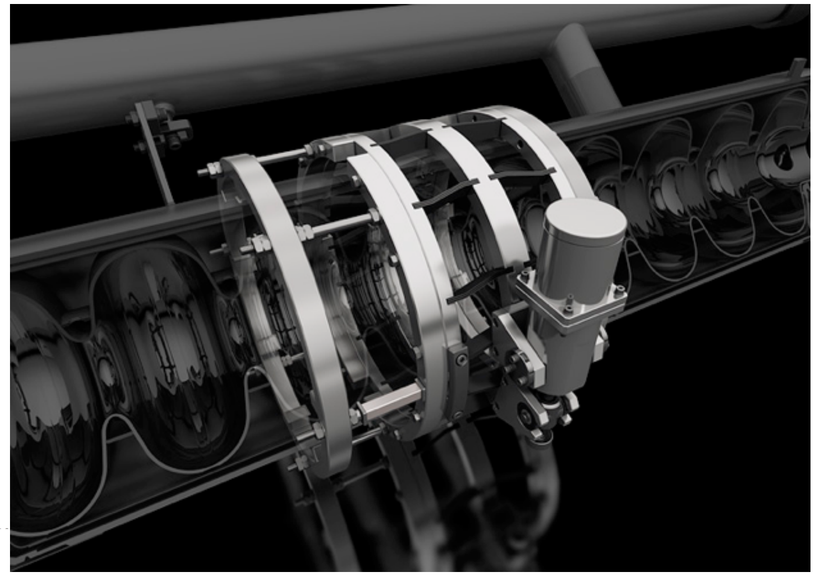
Any deformation of the cavity (either due to radiation pressure, or thermal expansion) will alter the resonant frequency of the cavity.

Tuners are used to adjust the frequency of the cavity to the desired resonant frequency.

The principle is to change the volume of the cavity where the electric or magnetic fields are non-zero (Slater perturbation theory).

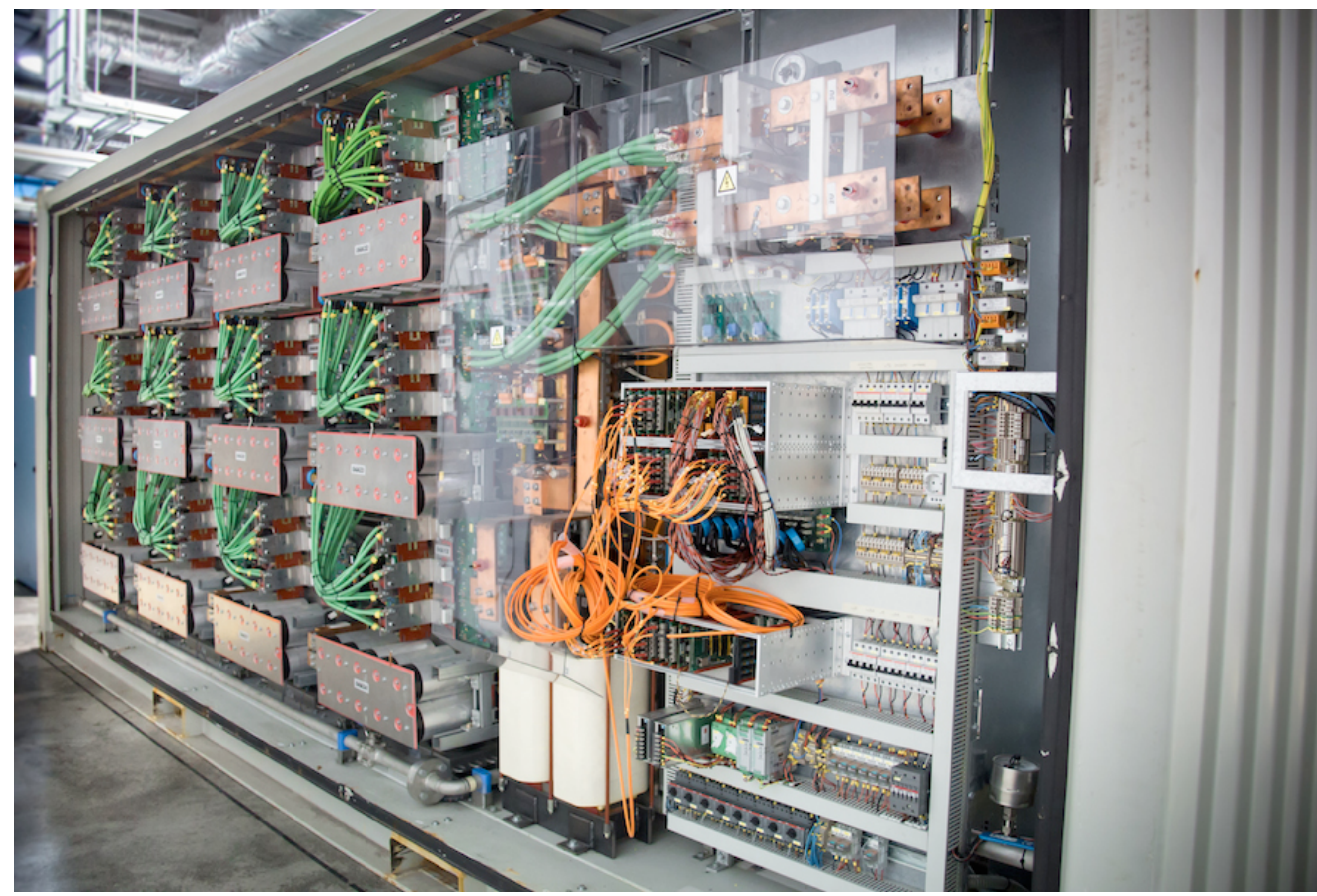




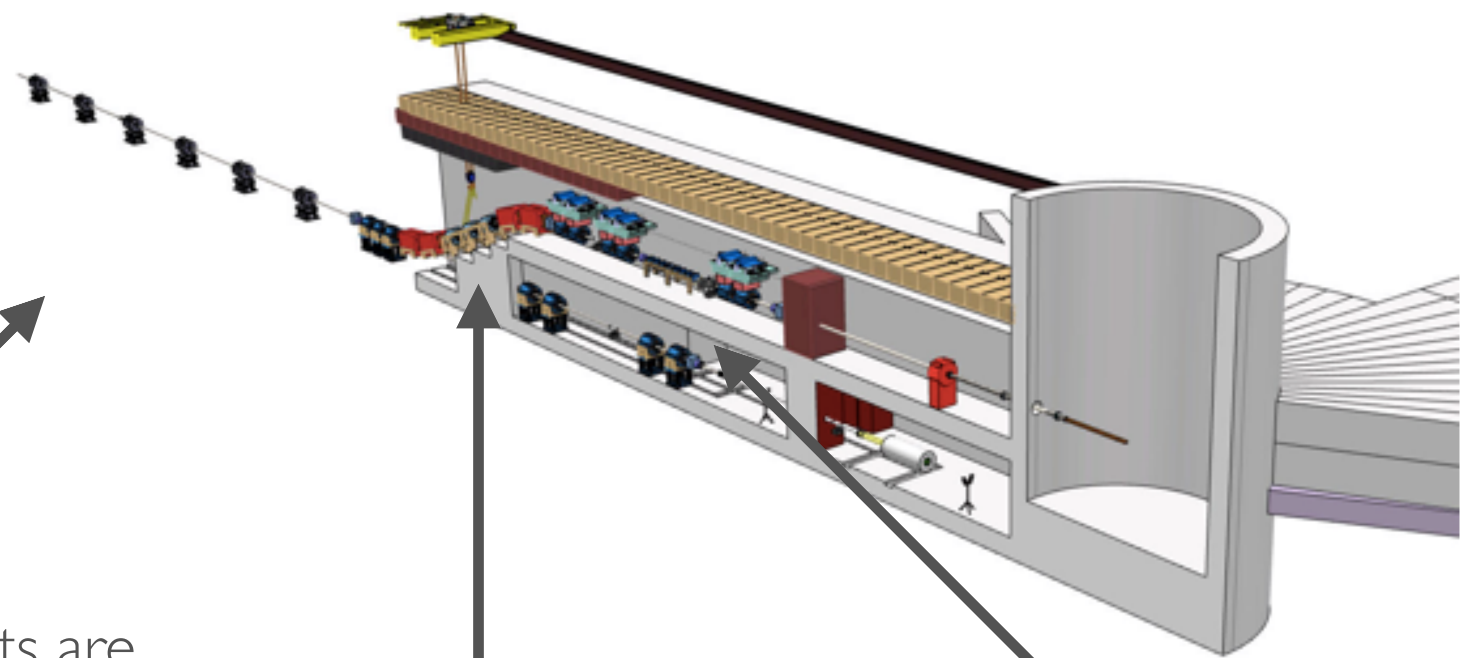


Major RF Pieces

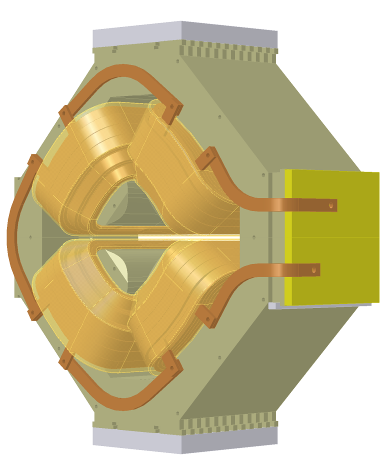
Radio Frequency



HEBT



HEBT, Magnet doublets are designed and built in Elettra. 12 periods, identical length to HB cryomodules



A2T (DogLeg), Magnets are designed and built in Elettra. 6 periods, achromat.

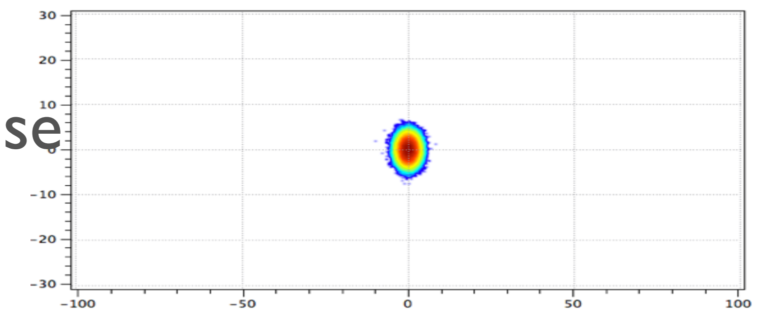
A2T Quadrupoles doublets are designed and built in Elettra, and Raster magnets are designed and built in Aarhus University

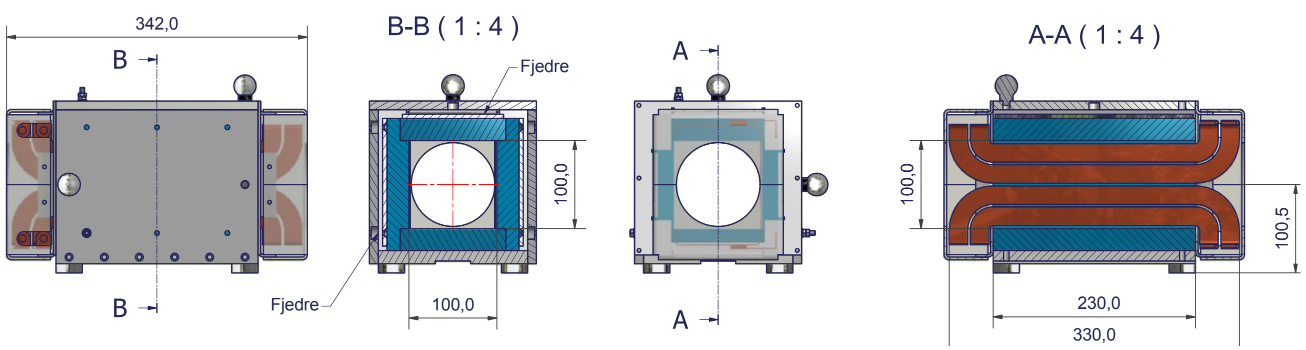
12 × Contingency

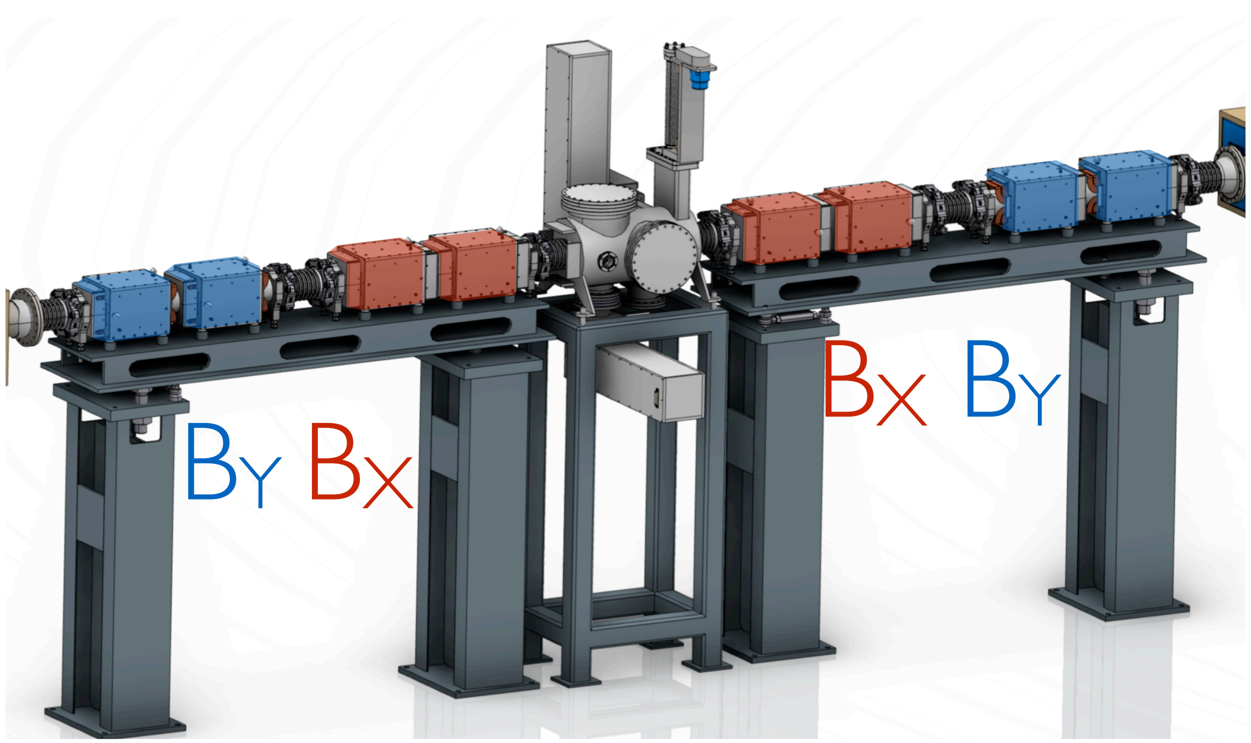
AARHUS UNIVERSITY

THE RASTER SYSTEM

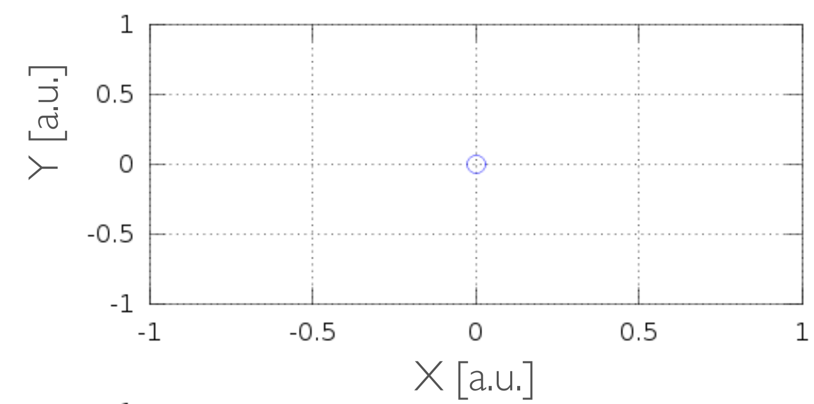
- Raster system sweeping beam in 2D pattern
- 8 colinear magnets, 8 dedicated, identical supplies
- Crosshatch pattern (fx/fy, ϕxy, ax, ay) within 2.86 ms pulse

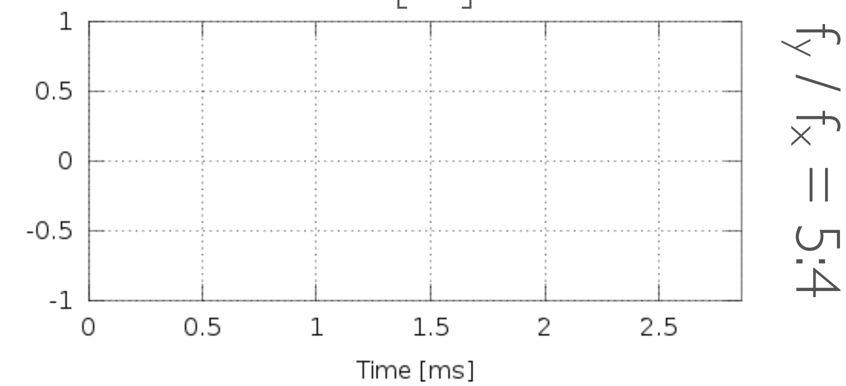


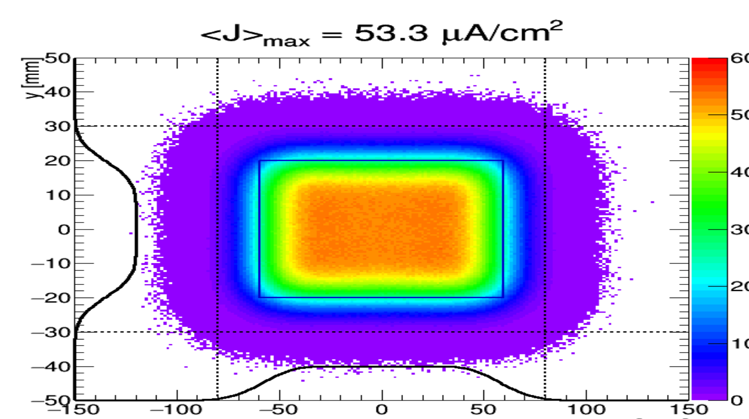




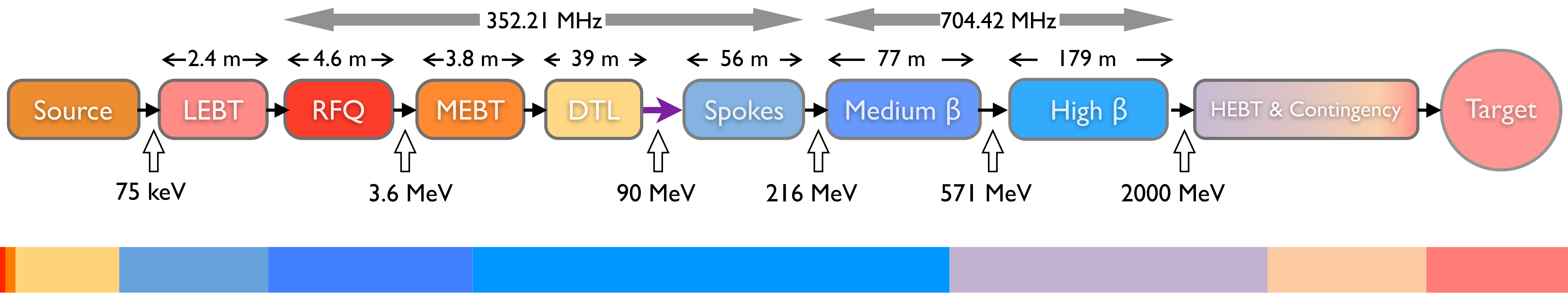
Courtesy: **Heine Dølrath Thomsen**







ESS Linac, again



	Length (m)	W_in (MeV)	F (MHz)	β Geometric	No. Sections	T (K)
LEBT	2.38	0.075	--	--	1	~300
RFQ	4.6	0.075	352.21	--	1	~300
MEBT	3.81	3.62	352.21	--	1	~300
DTL	38.9	3.62	352.21	--	5	~300
LEDP + Spoke	55.9	89.8	352.21	0.50 (Optimum)	13	~2
Medium Beta	76.7	216.3	704.42	0.67	9	~2
High Beta	178.9	571.5	704.42	0.86	21	~2
Contingency	119.3	2000	704.42	(0.86)	14	~300 / ~2

Linac Design

- **RF design :**
  1) Control the field pattern inside the cavity,
  2) Minimize the ohmic losses on the cavity walls.
  3) Optimize (minimize) the total energy consumption.

- **Beam dynamics design :**
  1) Choose the right phase, and keep it right during acceleration,
  2) Choose the right focusing scheme and strength.
  3) Optimize the design for best beam quality and minimised losses.

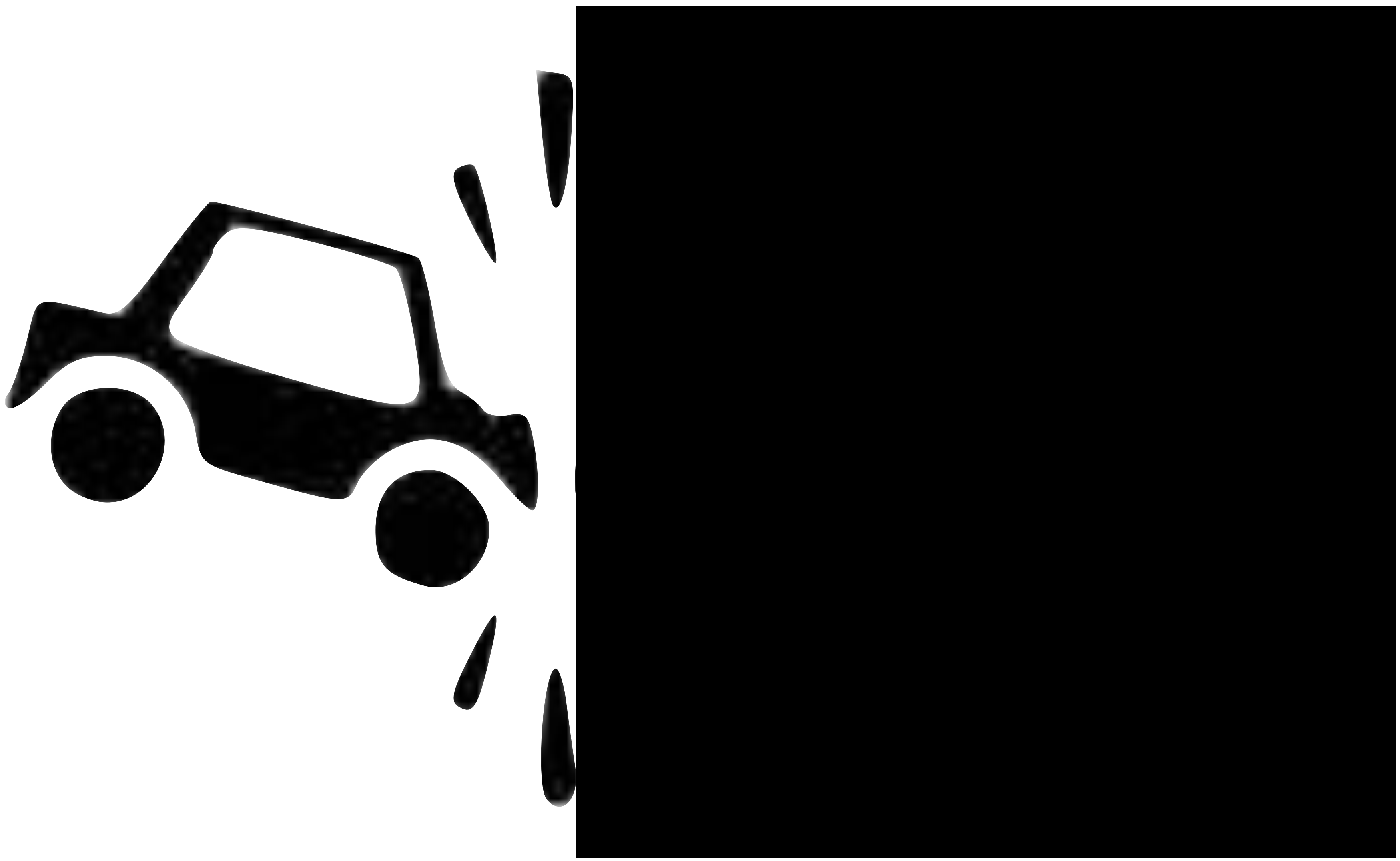
Further reading

- CAS lectures
- RF Linear Accelerators, T. P. Wangler
- Charged Particle Beams, M. Reiser
- Classical Electrodynamics, J. D. Jackson
- Linear Accelerators, P. M. Lapostolle
- Engines of Discovery, Sessler and Wilson
- The Physics of Particle Accelerators, Klaus Wille

ACKNOWLEDGMENTS

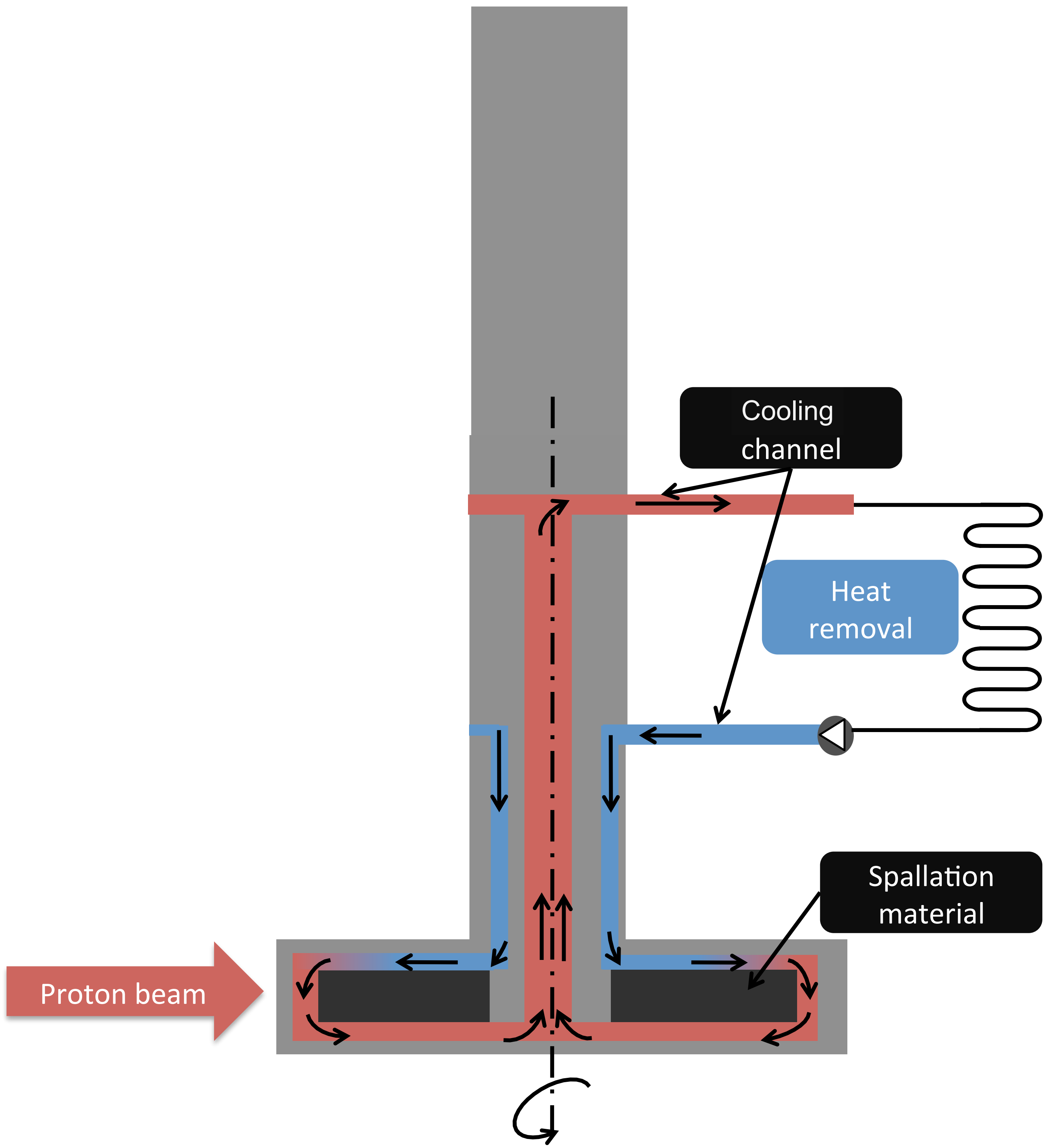
- I have used several images, drawings and illustrations which have been provided by our partner labs or other international labs.

Target



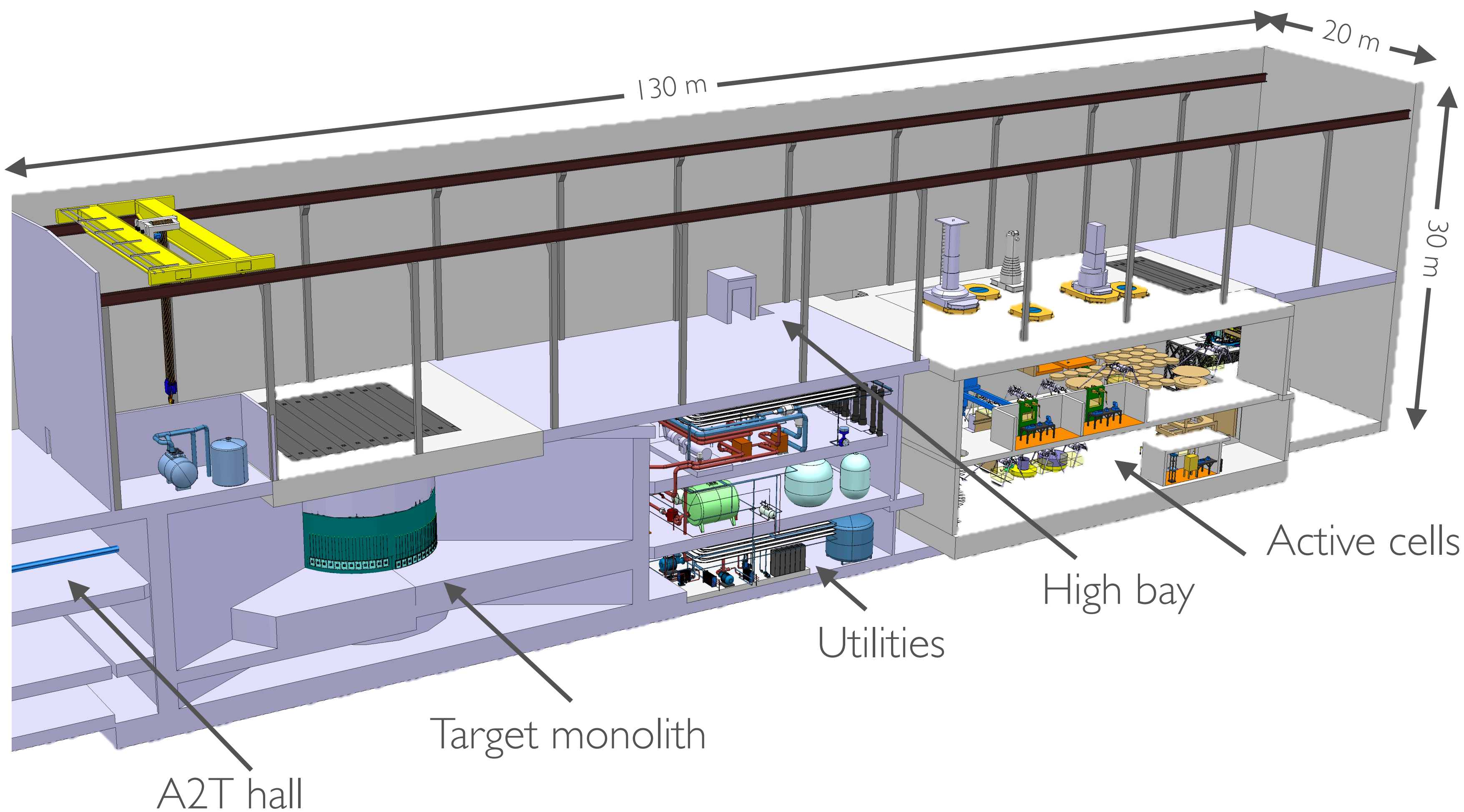
PROTON BEAM WINDOW

Target Wheel



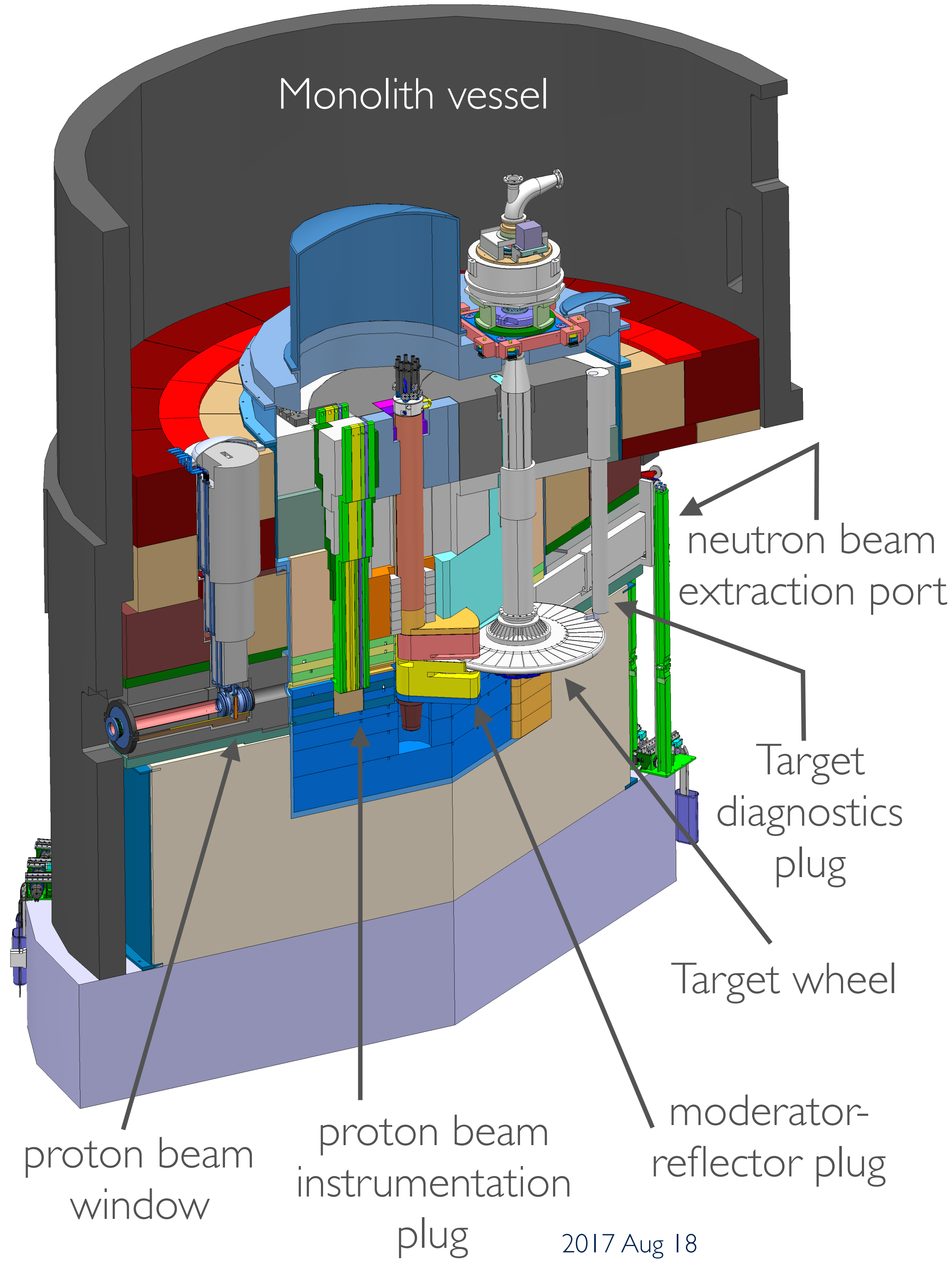
Target Station High Level Functions

- Generate neutrons via the spallation process using protons produced by the accelerator
- Slow the neutrons to speeds useful for neutron scattering
- Direct neutrons to neutron scattering instruments
- Safe and reliable operation with high availability



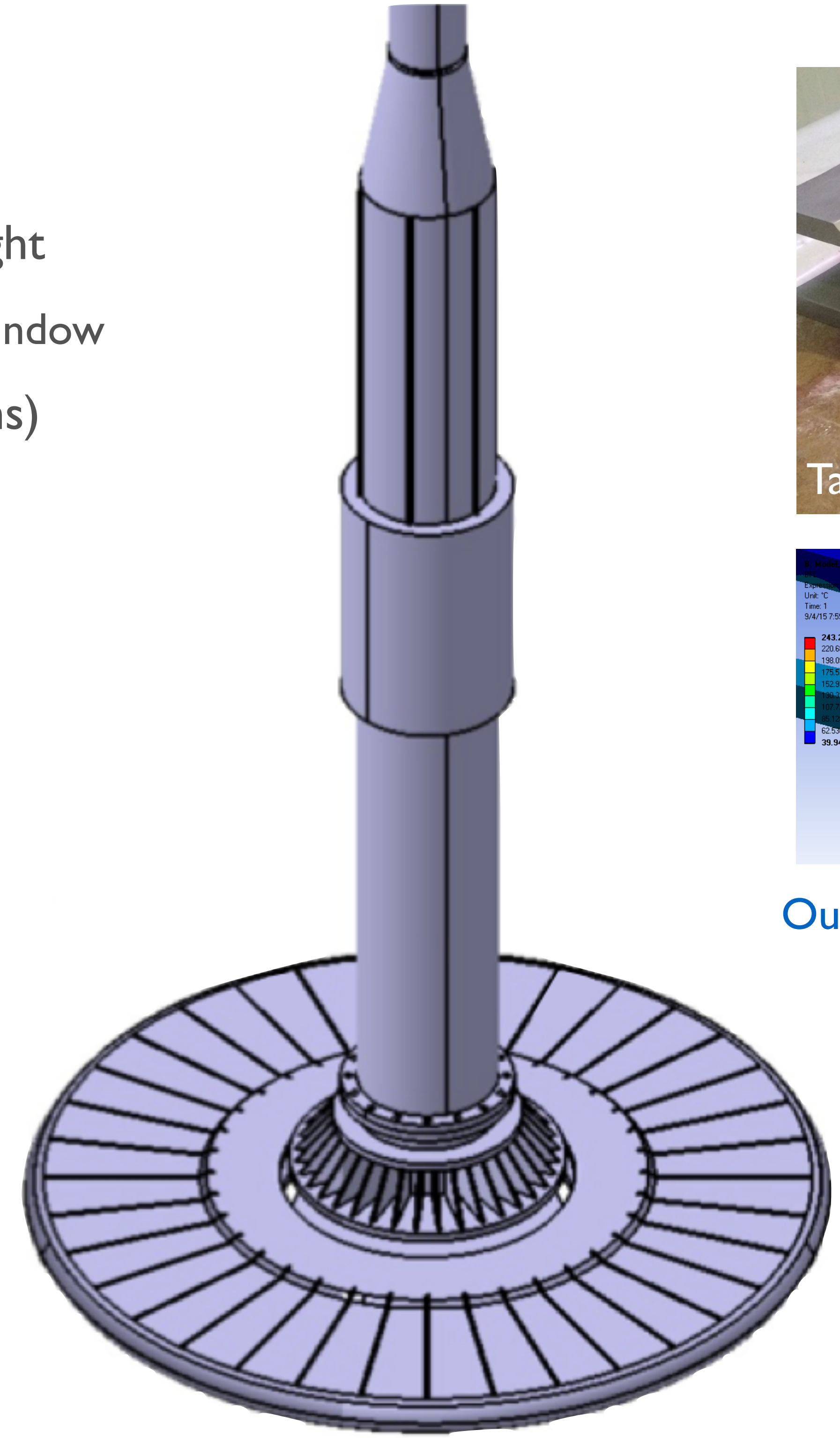
Target, Monolith, Moderators

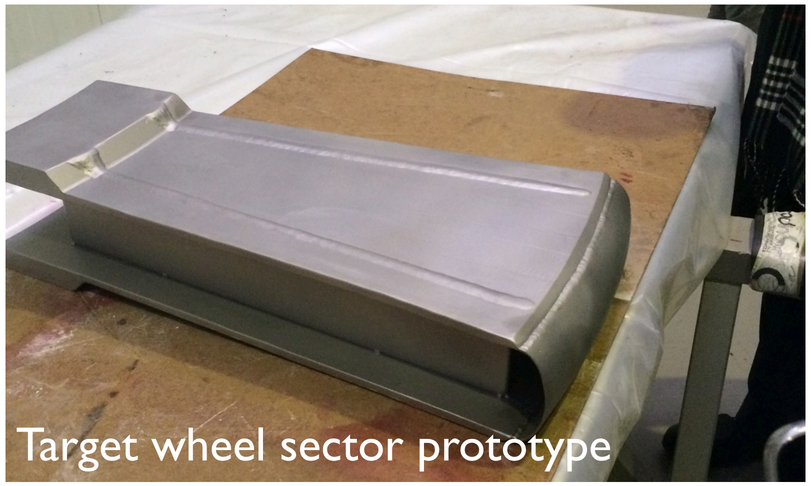
- Monolith:
  - Vessel (6 m diameter x 8 m height) (ESS-Bilbao, SP)
  - Steel shielding (6000 tons)
  - Instrumentation plugs (ESS-Bilbao, SP)
  - Proton beam window (ESS-Bilbao, SP)
  - Neutron shutters (ESS-Bilbao, SP)
  - Neutron beam extraction system
- Rotating Tungsten target (ESS-Bilbao, SP)
  - 2.5 m diameter x 10 cm height
  - 7500 Tungsten bricks (3.5 tons)
  - 0.39 rev./s
- Target He gas-cooling (UJF, CZ)
  - 3 MW capacity
  - 3 kg/s flow rate
  - Δt = 200 °C
- High brightness moderators (FZJ, DE)
  - 2 liquid H2 moderators
  - Water premoderators and moderators
  - He cryoplant (35 kW – 16 K)

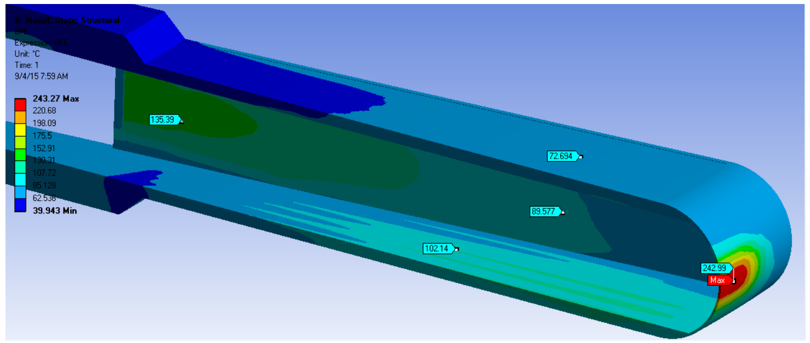


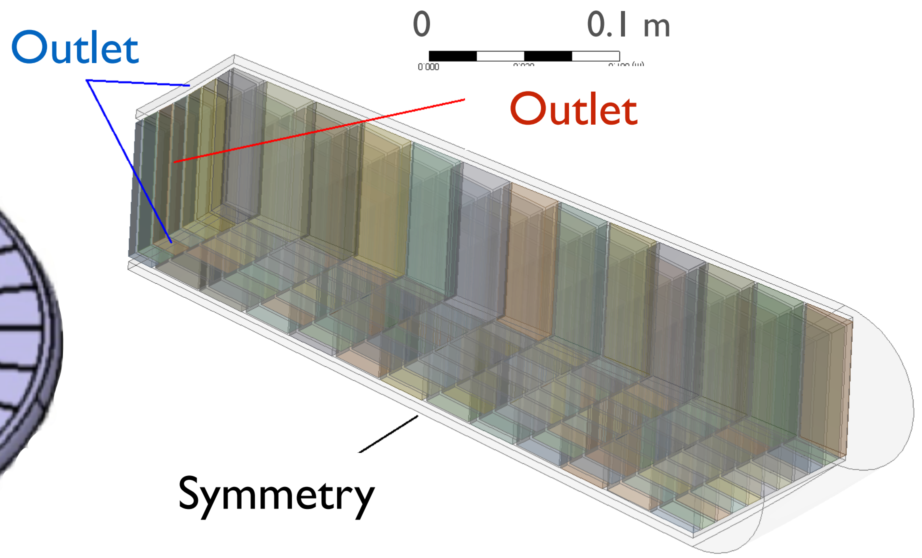
TARGET WHEEL

- Rotating target wheel
  - 2.5 m diameter x 0.08 m height
    - ~2.6x0.1 m^2 including the window
  - 7500 Tungsten bricks (3.5 tons)
  - 0.39 rev./s
  - 36 sectors





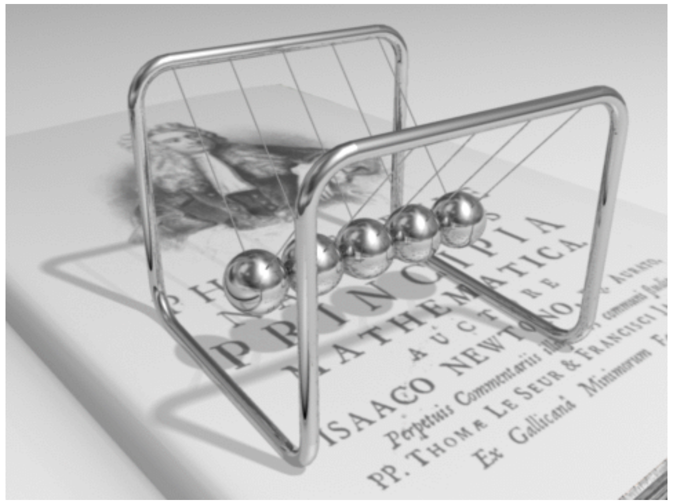
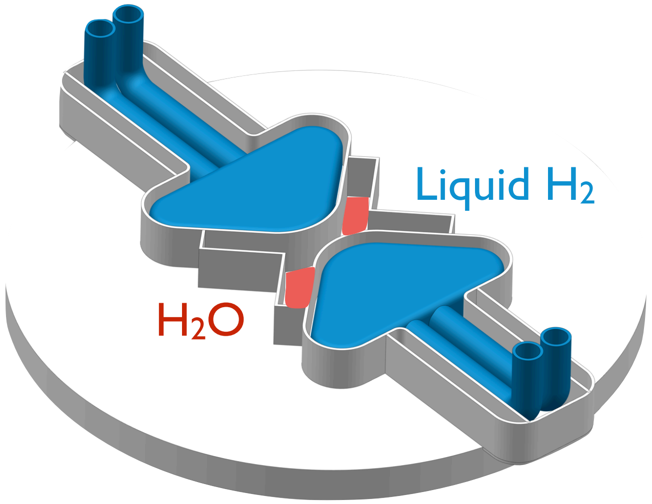


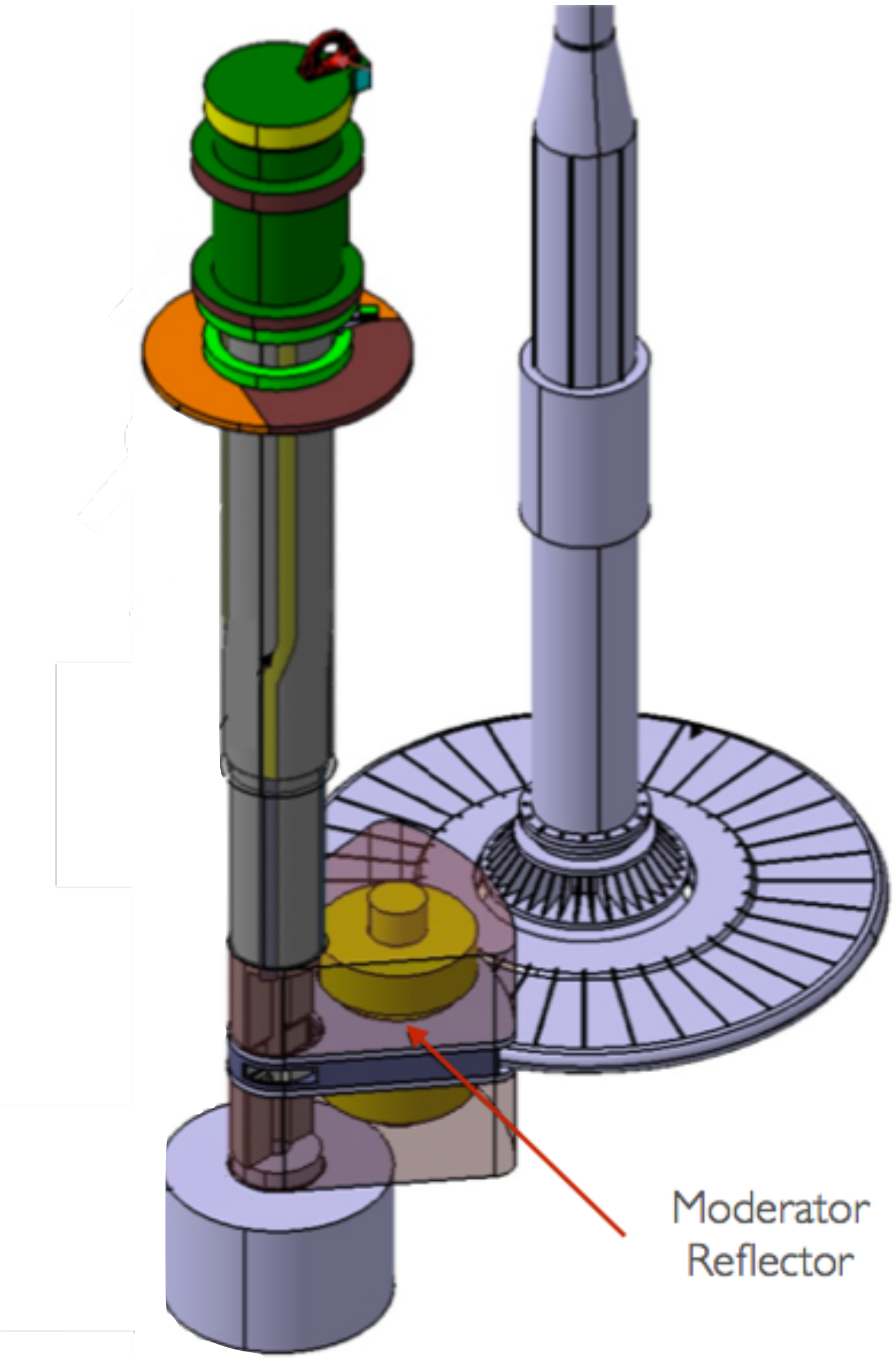


Courtesy: Eric Pitcher

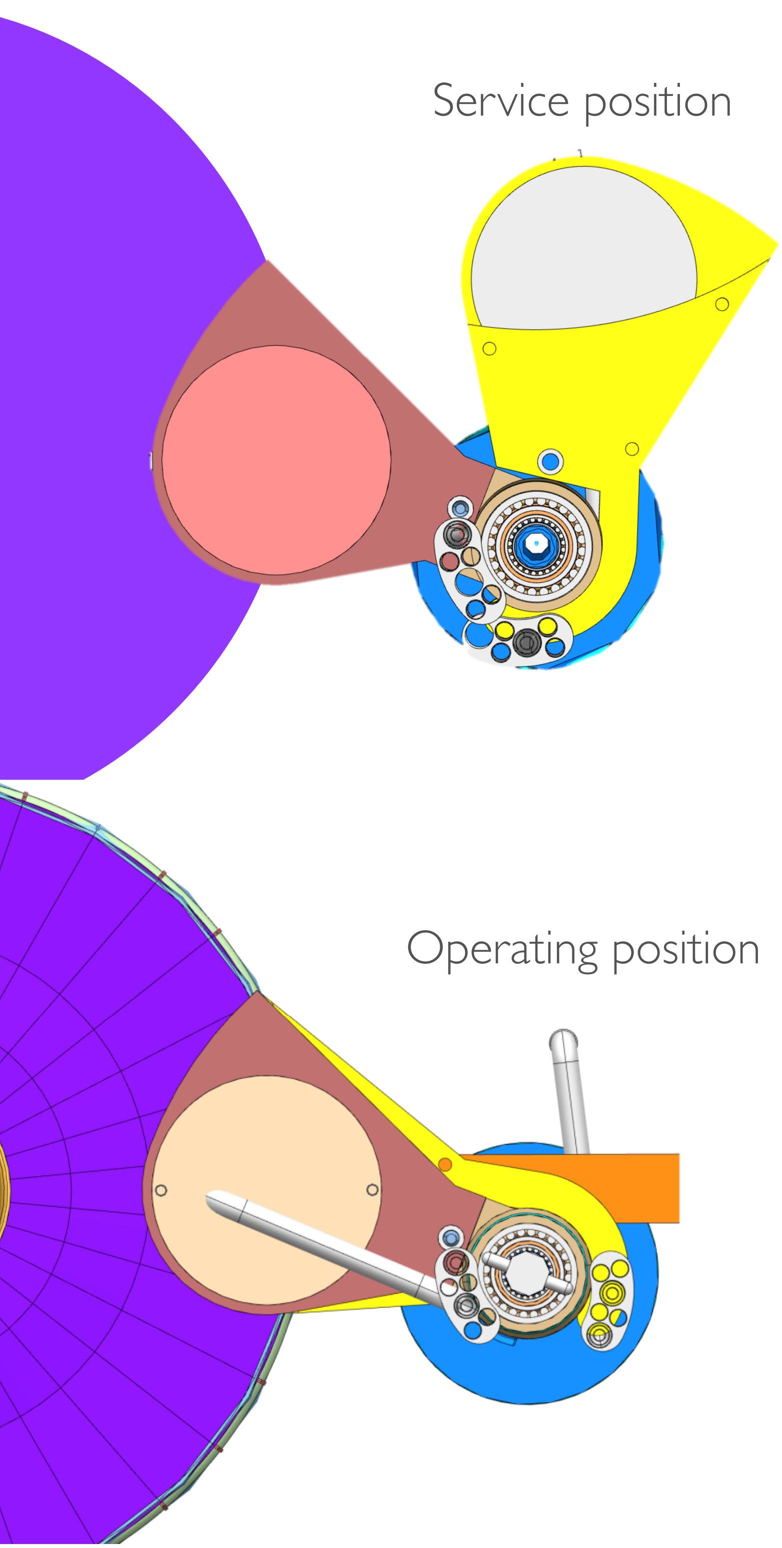
Moderator

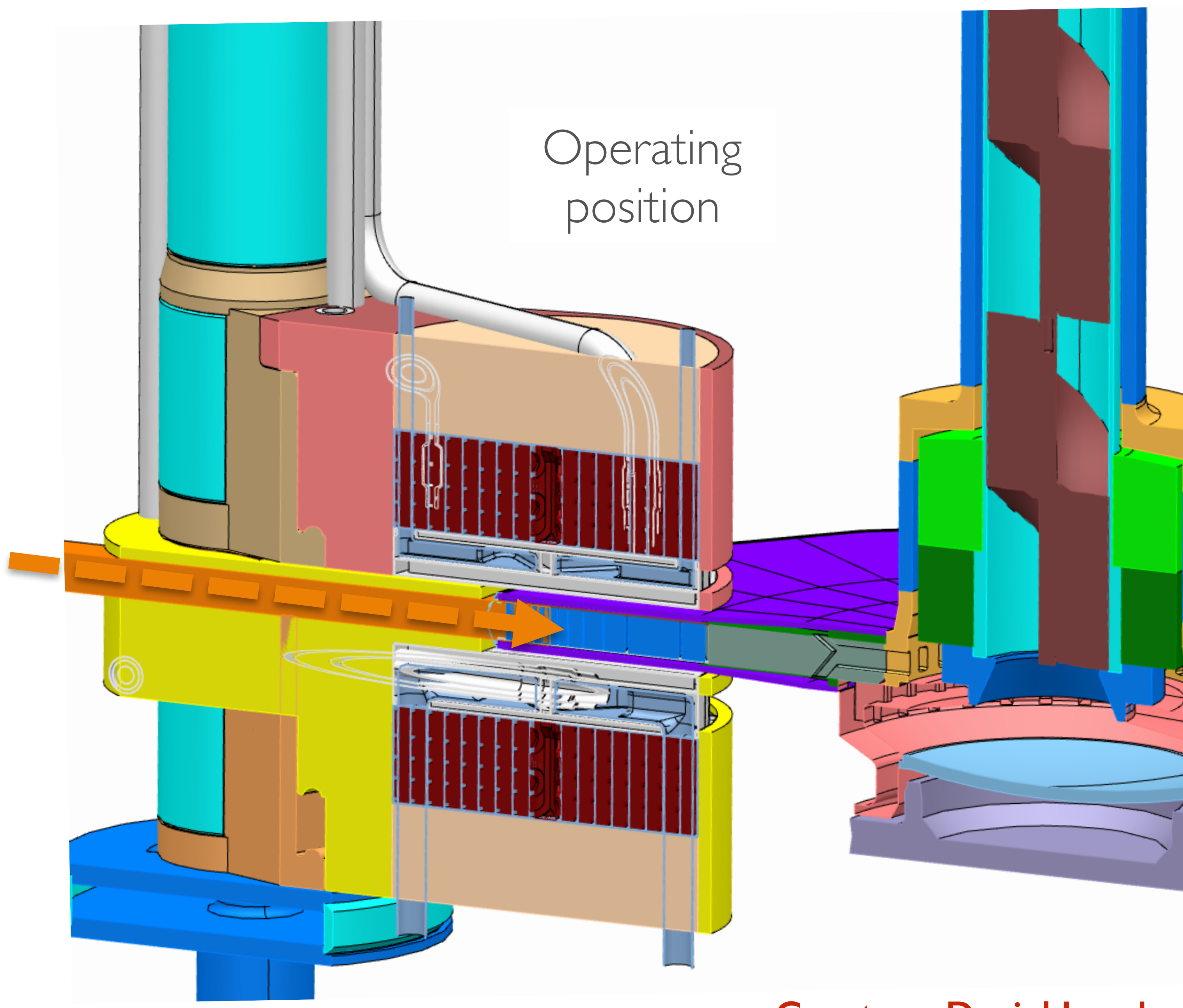
- ESS butterfly moderator
  - 3 cm tall butterfly on top
    - Cold neutron brightness same as pancake, thermal brightness x 1.6
  - 6 cm tall butterfly on bottom
    - Flexibility, viewable at all locations (2 x 120°)



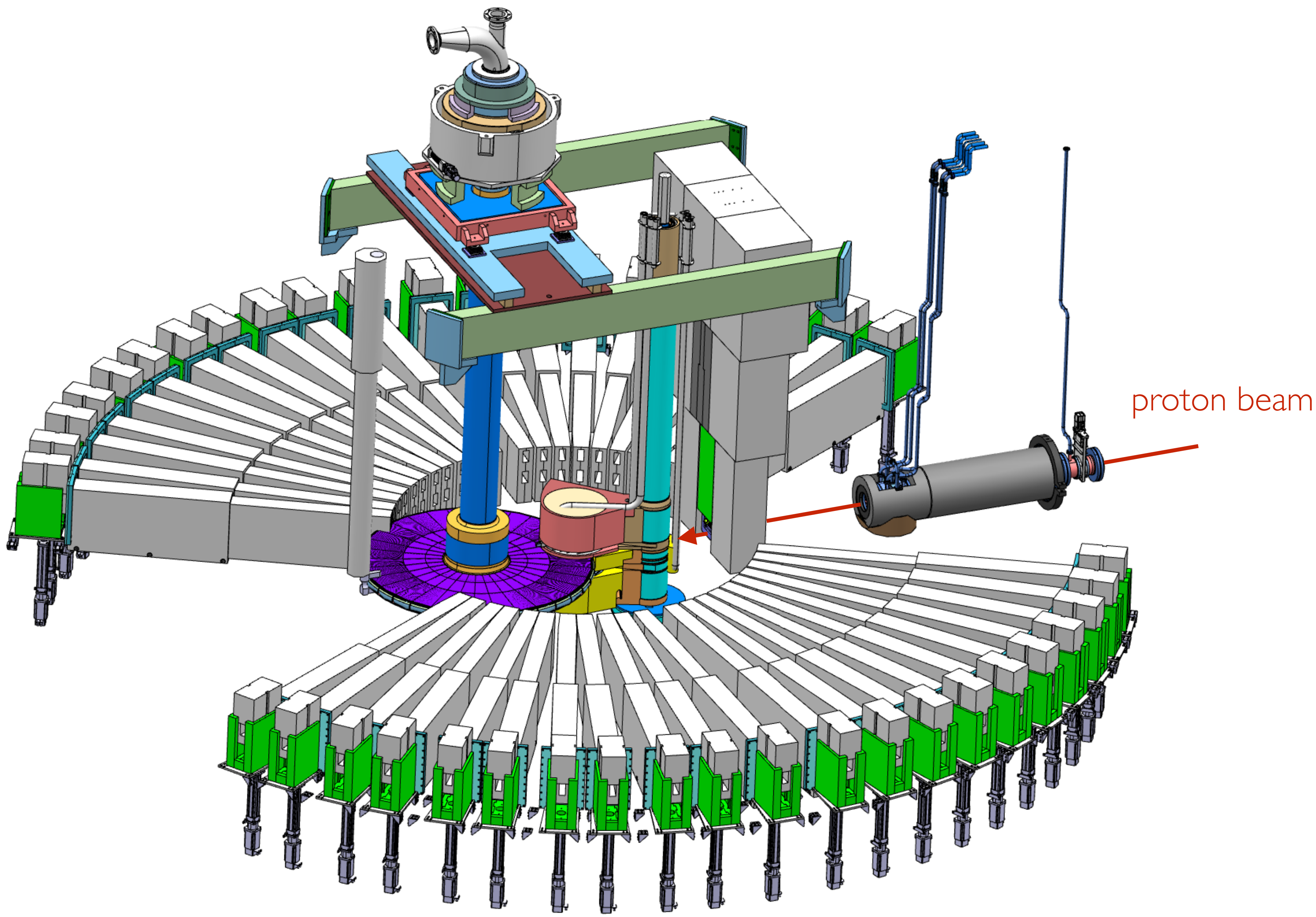
Twister Moderator Reflector





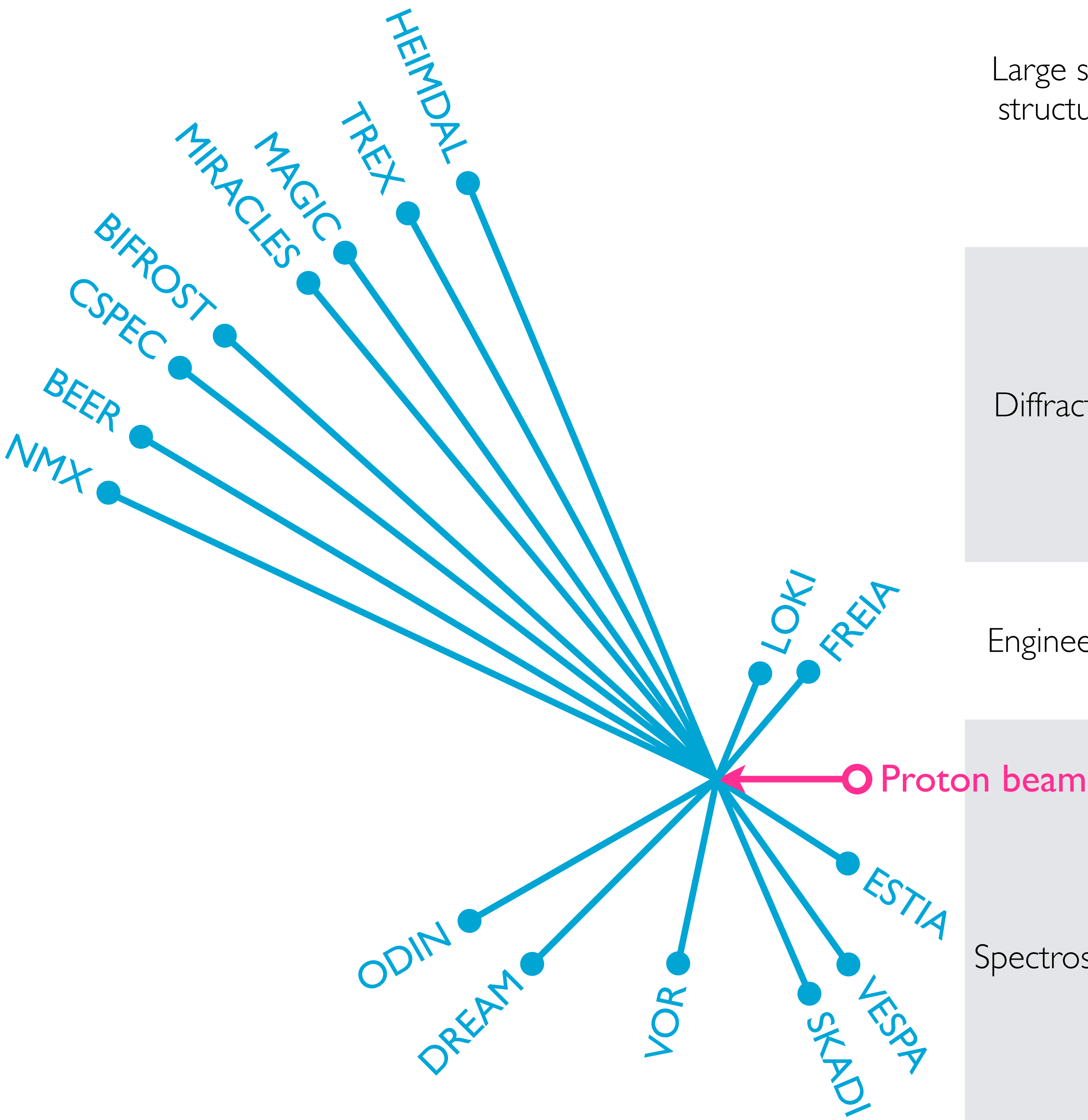
Courtesy: Daniel Lyngh

Neutron Ports



Courtesy: Daniel Lyngh

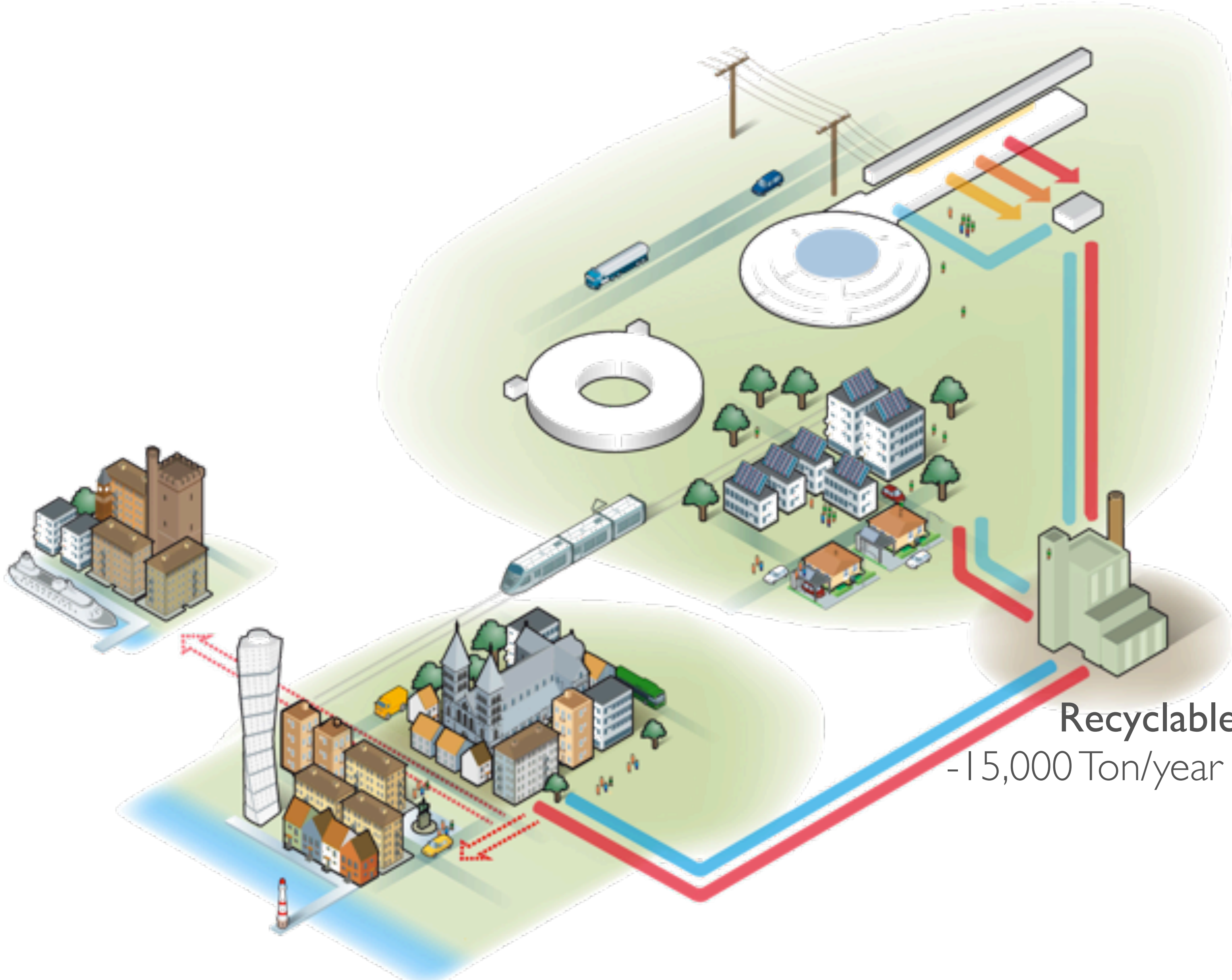
ESS Suite of Instruments



Large scale structures	LOKI Broadband SANS	UK (ISIS)
	SKADI general purpose SANS	DE (FZJ 50%) + FR (LLB 50%)
	ESTIA focusing reflectometer	CH (PSI)
	FREIA liquids reflectometer	UK (ISIS)
Diffraction	NMX macromolecular crystallography	ESS (<30%) + HU (Wigner and Centre for Energy Research) + FR (LLB) + NO (Bergen Uni)
	DREAM powder diffractometer (bispectral)	DE (FZJ 75%) + FR (LLB 25%)
	HEIMDAL hybrid diffractometer	DK (AU 30%) + CH (PSI) + NO (IFE)
	MAGIC magnetism single-crystal diffractometer	FR (LLB 65%) + DE (FZJ 20%) + CH (PSI (15%)
Engineering	BEER engineering diffractometer	DE (HZG 50%) + CZ (NPI 50%)
	ODIN multi-purpose imaging	ESS >> DE (TUM 50%) + CH (PSI 50%)
Spectroscopy	CSPEC cold chopper spectrometer	DE (TUM 50%) + FR (LLB 50%)
	BIFROST extreme-environments spectrometer	DK (DTU/KU 30%) + CH (PSI) + HU (Wigner) + NO (IFE) + FR (LLB)
	T-REX bispectral chopper spectrometer	DE (FZJ 75%) + IT (CNR 25%)
	VESPA vibrational spectroscopy	IT (CNR) + US (ISIS)
	MIRACLES backscattering spectrometer	ES (Bilbao) + FR (LLB) + HU (Wigner) + ESS
	16th, VOR or Spin-Echo, TBD 2018	HU (Wigner [VOR]) or DE (FZJ and TUM [Spin-Echo])

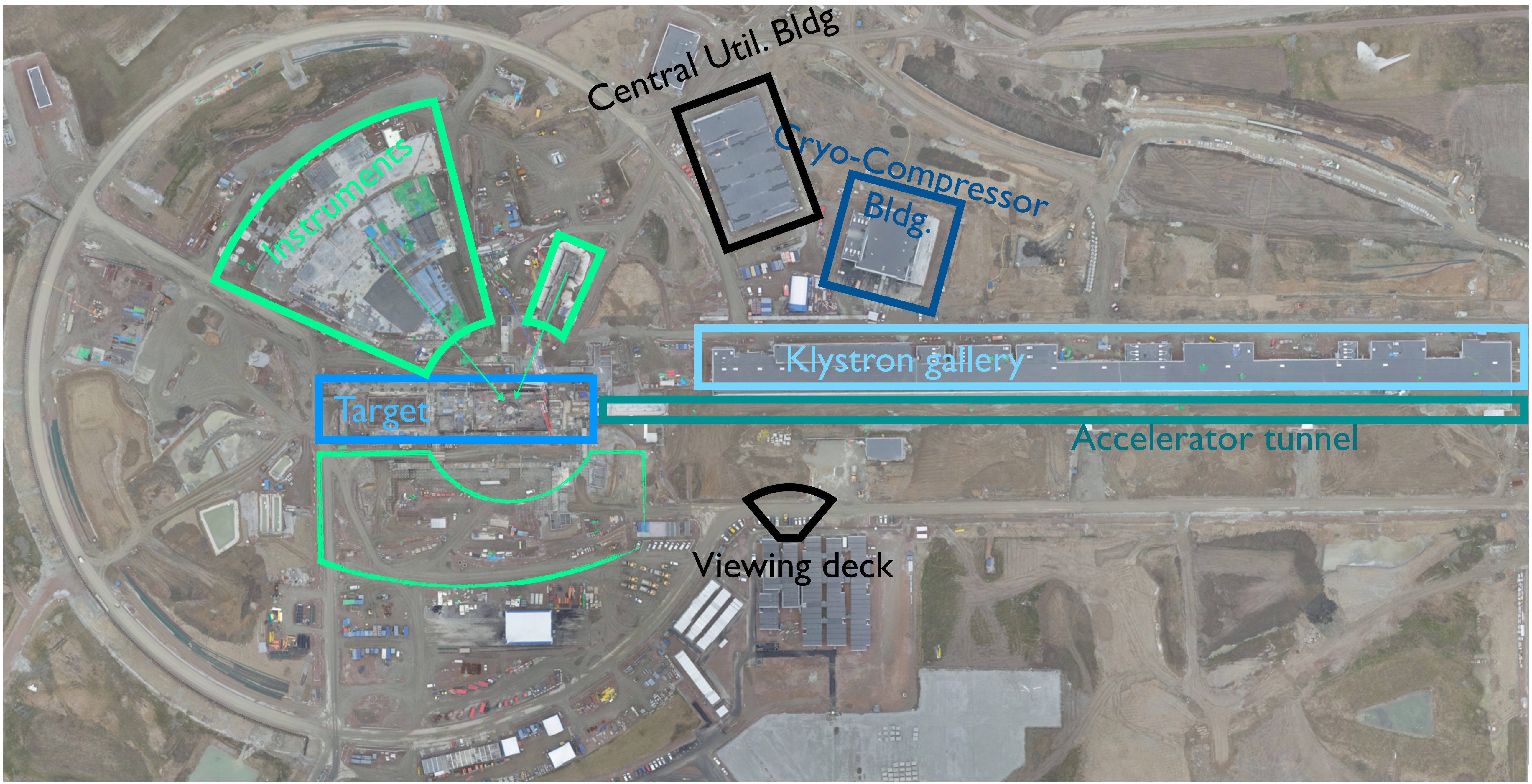
Engine

SUSTAINABLE RESEARCH LAB



The volume of the CO2 saved is more than one Turning Torso annually!

Aerial view


Central Util. Bldg
Cryo-Compressor Bldg.
Instruments
Klystron gallery
Target
Accelerator tunnel
Viewing deck

EUROPEAN
SPALLATION
SOURCE

THANK YOU FOR YOUR ATTENTION

Hope you enjoy your ESS tour