EUROPEAN
SPALLATION
SOURCE

Introduction to the European Spallation Source Linac

Dave McGinnis

Accelerator Division

8-December-2015

www.europeanspallationsource.se

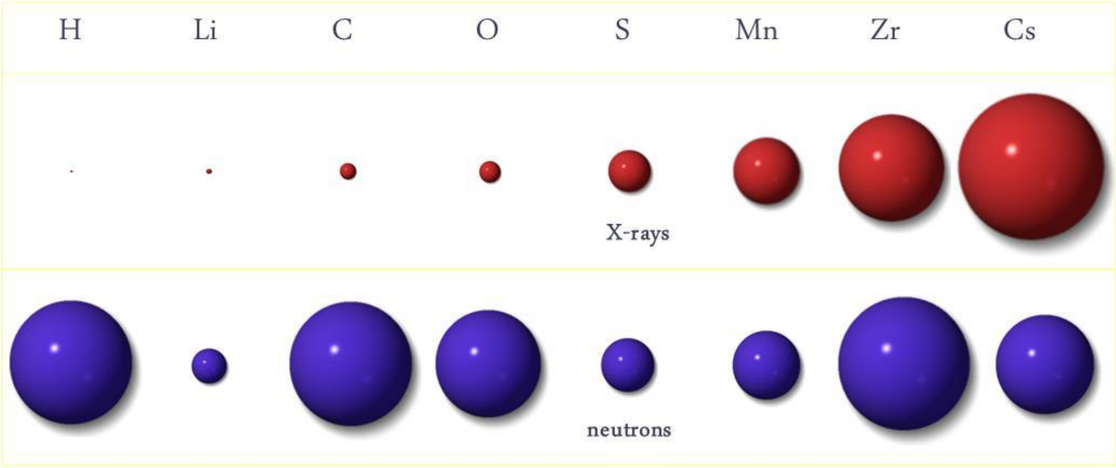
Overview

- The European Spallation Source (ESS) will house the most powerful proton linac ever built.
  - The average beam power will be 5 MW which is five times greater than SNS.
  - The peak beam power will be 125 MW which is over seven times greater than SNS

- The linac will require over 150 individual high power RF sources
  - Based on high power electron tubes
  - with 80% of the RF power sources
    - requiring over 1.1 MW of peak RF power at a 4 % duty factor
  - We expect to spend over 200 M€ on the RF system alone

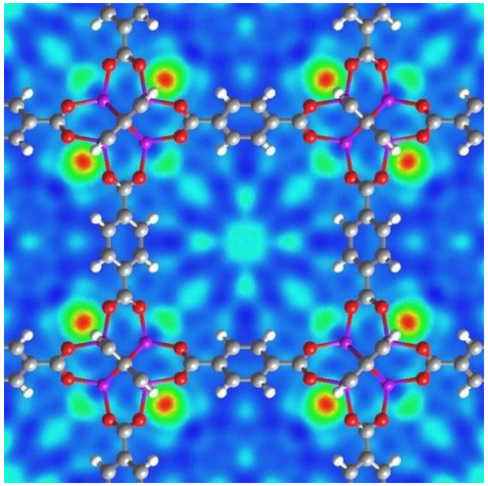
What is ESS?

- ESS is a neutron spallation source for neutron scattering measurements.
- Neutron scattering offers a complementary view of matter
  - in comparison to other probes such as x-rays from synchrotron light sources.
  - The scattering cross section of many elements can be much larger for neutrons than for photons.



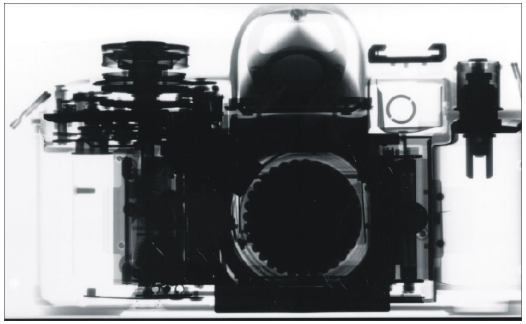
Neutron Scattering

- Neutron scattering can reveal the molecular and magnetic structure and behavior of materials, such as:
  - Structural biology and biotechnology, magnetism and superconductivity, chemical and engineering materials, nanotechnology, complex fluids, and others

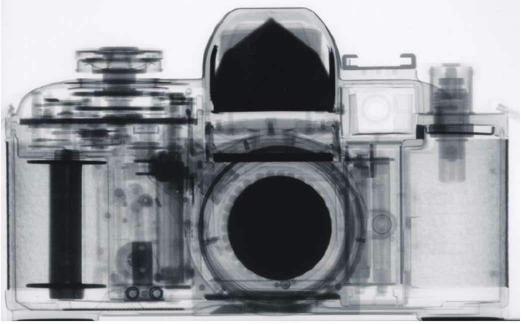


Neutron scattering of hydrogen in a metal organic framework

Neutron radiograph of a flower corsage



X-Ray Image

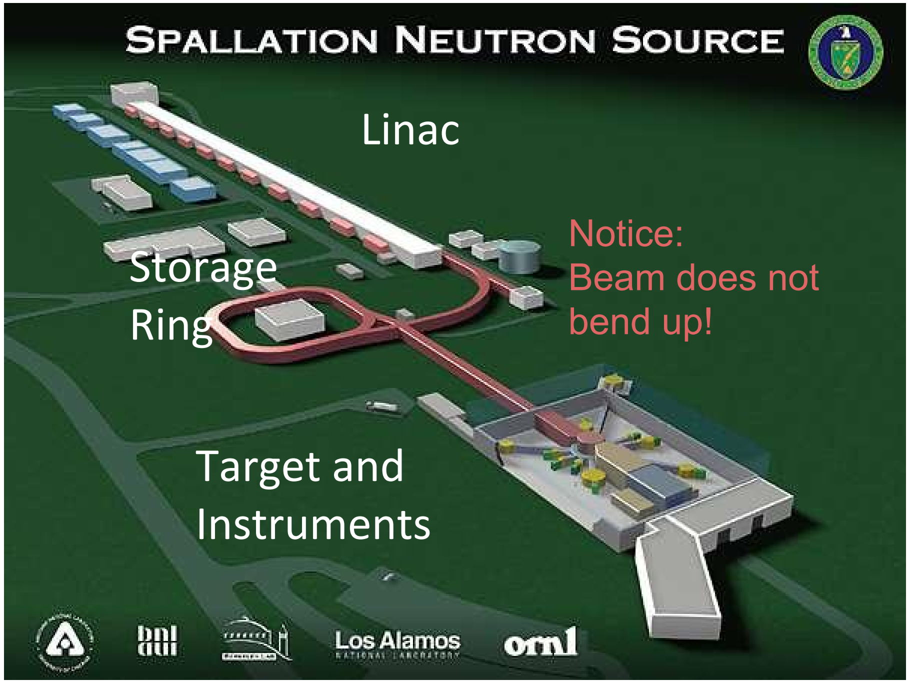


Neutron radiograph

Neutron Spallation Sources

- Traditional neutron sources are reactor based
    - Neutron flux is limited by reactor cooling
    - Neutron energy spectrum is measured by time of flight using neutron choppers
    - Chopping throws away neutrons and limits neutron brightness
- Spallation sources consist of a:
    - pulsed accelerator that shoots protons into:
    - a metal target to produce the neutrons
- The pulsed nature of the accelerator makes the neutron brightness
    - much higher for a spallation source
    - for the same average neutron flux as a reactor

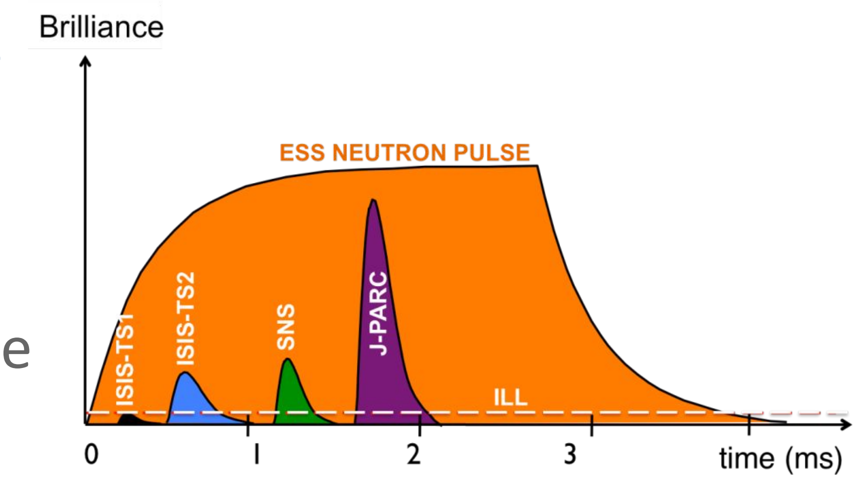
- The accelerator complex of a typical spallation sources consist of a:
    - Linac to accelerator the protons
    - A storage ring to compress the linac beam pulse



Notice:
Beam does not bend up!

What is Different About ESS?

- The average proton beam power will be 5 MW
  - Average neutron flux is proportional to average beam power
  - 5 MW is five times greater than SNS beam power
- The total proton energy per pulse will be 360 kJ
  - Beam brightness (neutrons per pulse) is proportional to total proton energy per pulse
  - 360 kJ is over 20 times greater than SNS total proton energy per pulse

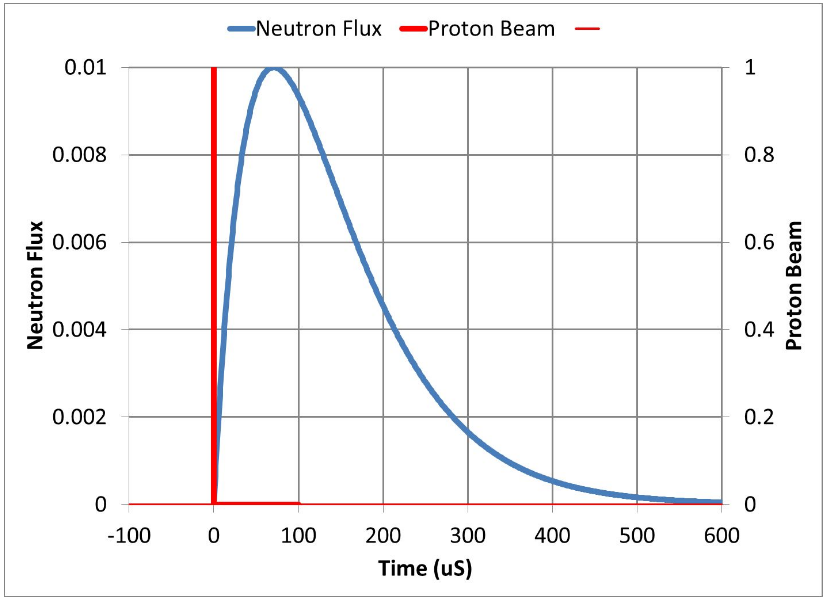


What is 5 MegaWatts?

- At 5 MegaWatts,
  - one beam pulse
    - has the same energy as a 16 lb (7.2kg) shot traveling at
      - 1100 km/hour
      - Mach 0.93
    - Has the same energy as a 1000 kg car traveling at 96 km/hour
    - Happens 14 x per second
  - You boil 1000 kg of ice in 83 seconds
    - A ton of tea!!!

Short Pulse Neutron Spallation Sources

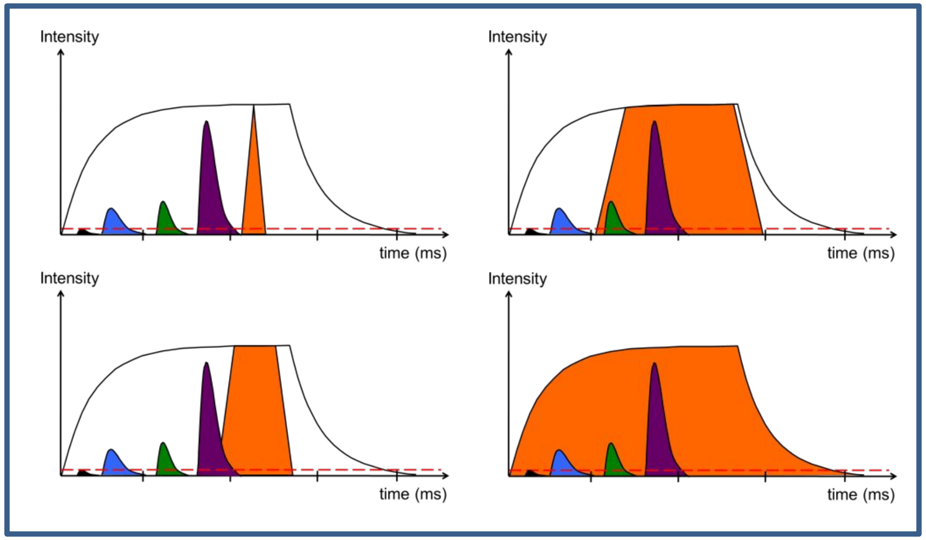
- The neutrons are cooled by a moderator downstream of the target
- The time constant of the moderation process is about 100 µs
- Proton beam pulses shorter than 100 us serve only to stress the metal target and limit the beam power
    - Typical short pulse spallation sources have storage ring circumferences ~300 meters which produce 1 µs beam pulses
    - To build a storage ring with a 100 µs pulse would require a ring 30 km in circumference

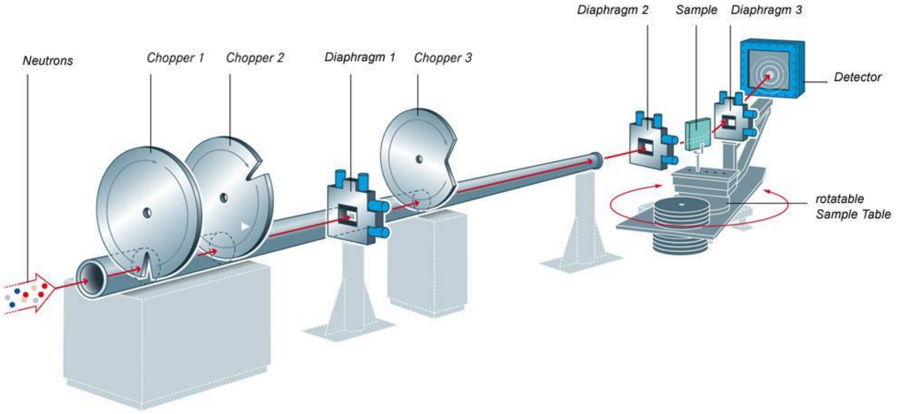


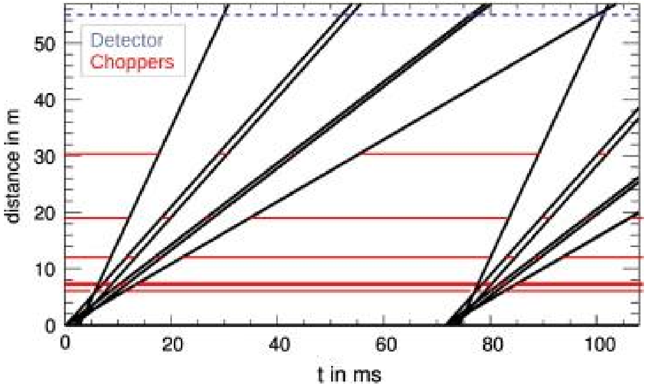
- The target stress from the short beam pulse places a limit on:
    - proton beam power
    - and ultimately neutron flux and brightness
    - The proton beam power of SNS (Oak Ridge Tennessee, USA) is limited to 1MW (17 MW peak)

Long Pulse Concept

- 360 kJ packed into a short pulse of 1 μs (360 GW peak) would destroy a target
- ESS will not use a compressor ring
  - The linac will send the beam directly to the target over a period of 3 ms at a rate of 14 Hz.
  - Peak beam power on the target is less than 125 MW
- The tradeoff is that ESS will
  - Have longer neutron guides between experiments and the target
  - Require a neutron choppers for precision energy measurements

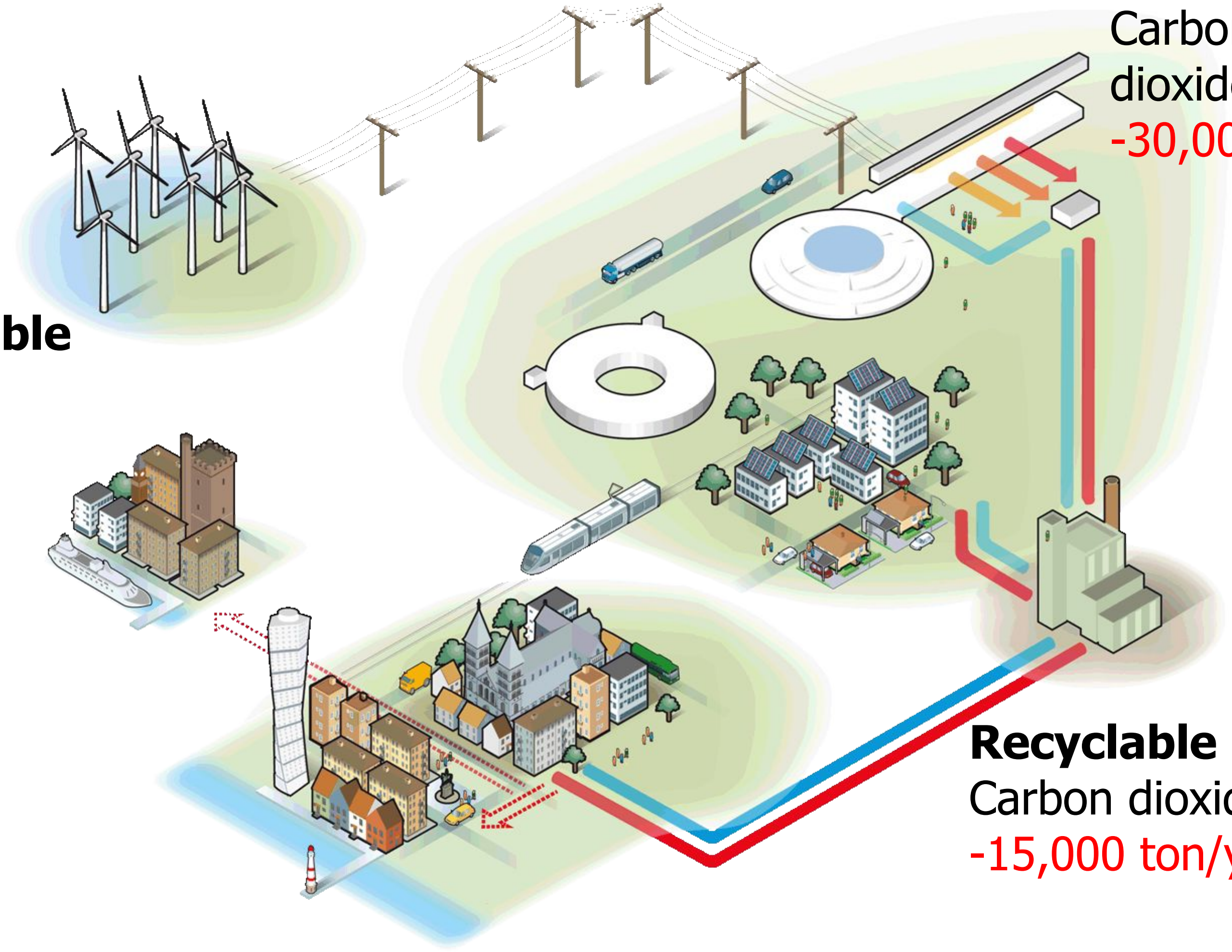






What is Different About ESS?

Sustainable Energy Concept



Responsible
Carbon dioxide:
-30,000 ton/y

Renewable
Carbon dioxide:
-120,000 ton/y

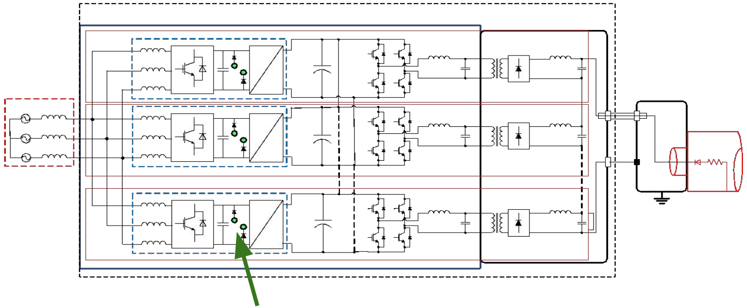
Recyclable
Carbon dioxide:
-15,000 ton/y

ESS Solar Potential

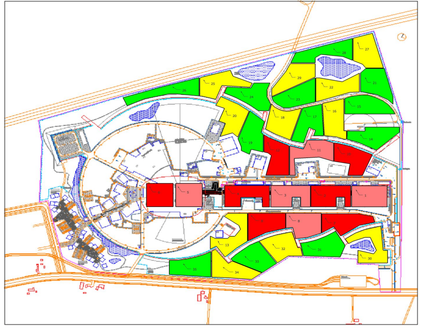
(Warning! Not approved! Preliminary! Read at your own Risk!)

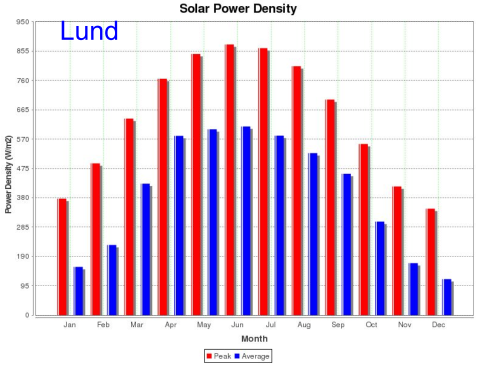
- The solar energy potential of ESS site is comparable to many of the large scale solar fields found in Europe.
  - Over half of the ESS site has the potential to be used as a solar field.
- Using active front end technology, a 26 hectare (⅓ of the ESS site) photovoltaic facility can be directly connected into the heart the ESS linear accelerator power convertors to
  - produce a peak electrical power of 23 MW at a yearly average power generation of 30 GW-hr. (***This is enough energy to more than offset the amount of energy supplied to the ESS proton beam)***
- Collection of thermal energy from photovoltaic array
  - Could potentially yield 20.7 MW-years (180 GWh) at 80C (***over 5x the amount of heat planned to be recycled from the ESS linac)***
  - Could potentially provide a daily average of 8.8 MW-day (211 MWh)for the months from October through March.

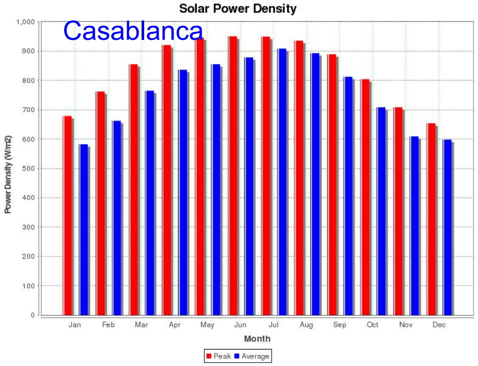
ESS Modulator



Solar Array Connection

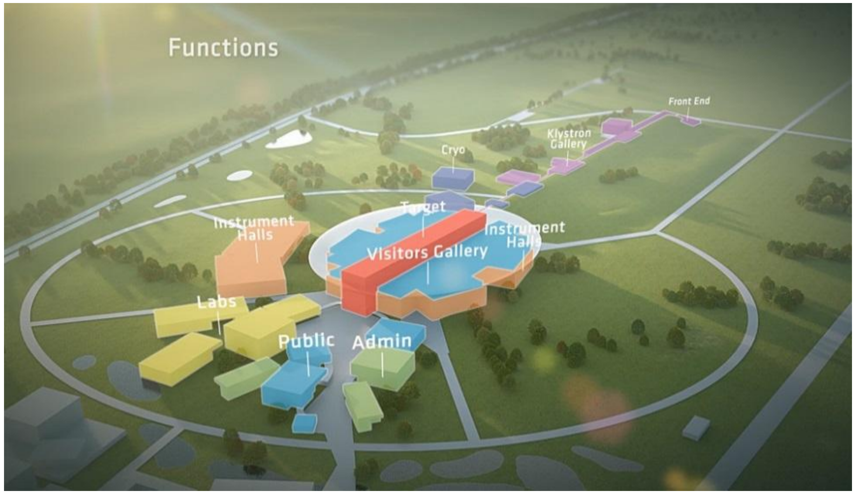


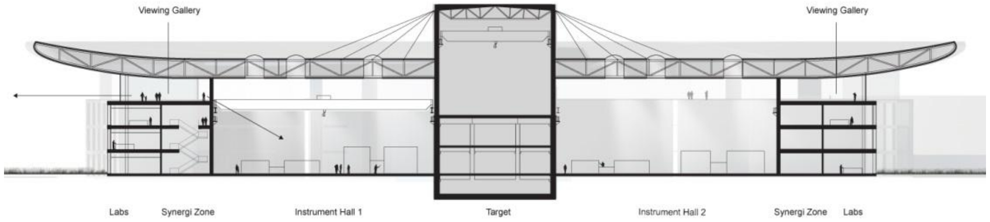




EUROPEAN
SPALLATION
SOURCE

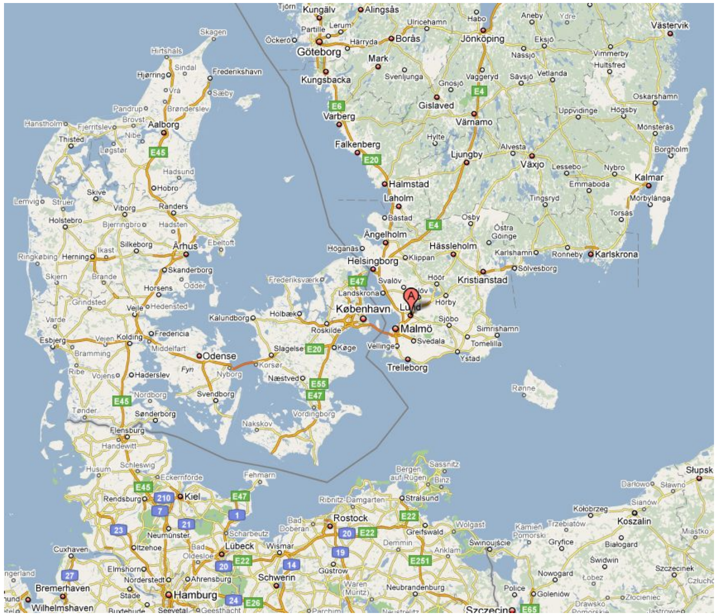
What Will ESS Look Like?



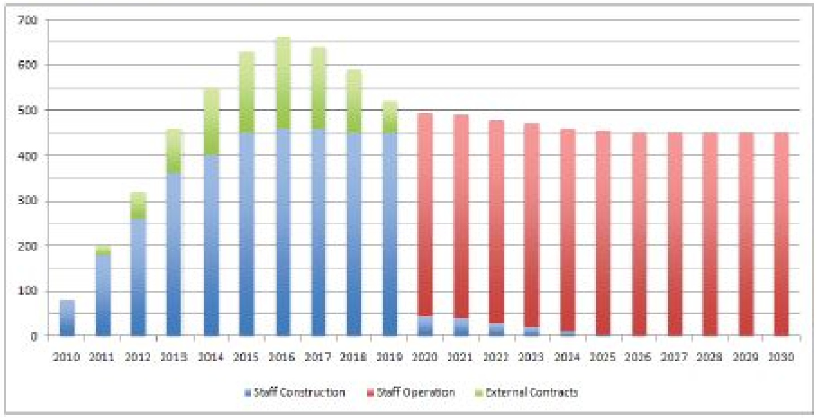


Where Will ESS Be Built?

- ESS is located in southern Sweden adjacent to MAX-IV (A 4th generation light source)
- To provide a world-class material research center for Europe



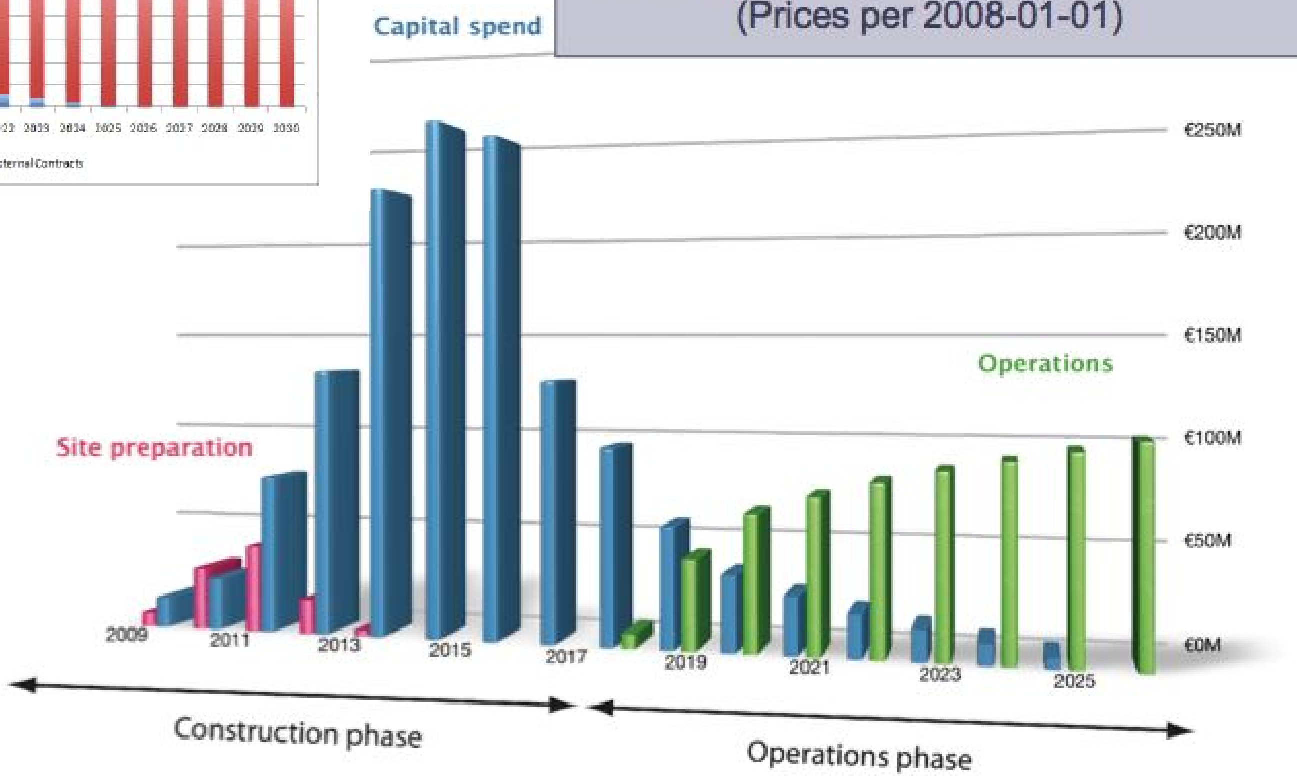
How Much Will ESS Cost?



Personnel

Investment

Investment: 1478 M€ / ~10y
Operations: 89 M€ / y
Decommissioning. : 346 M€
(Prices per 2008-01-01)



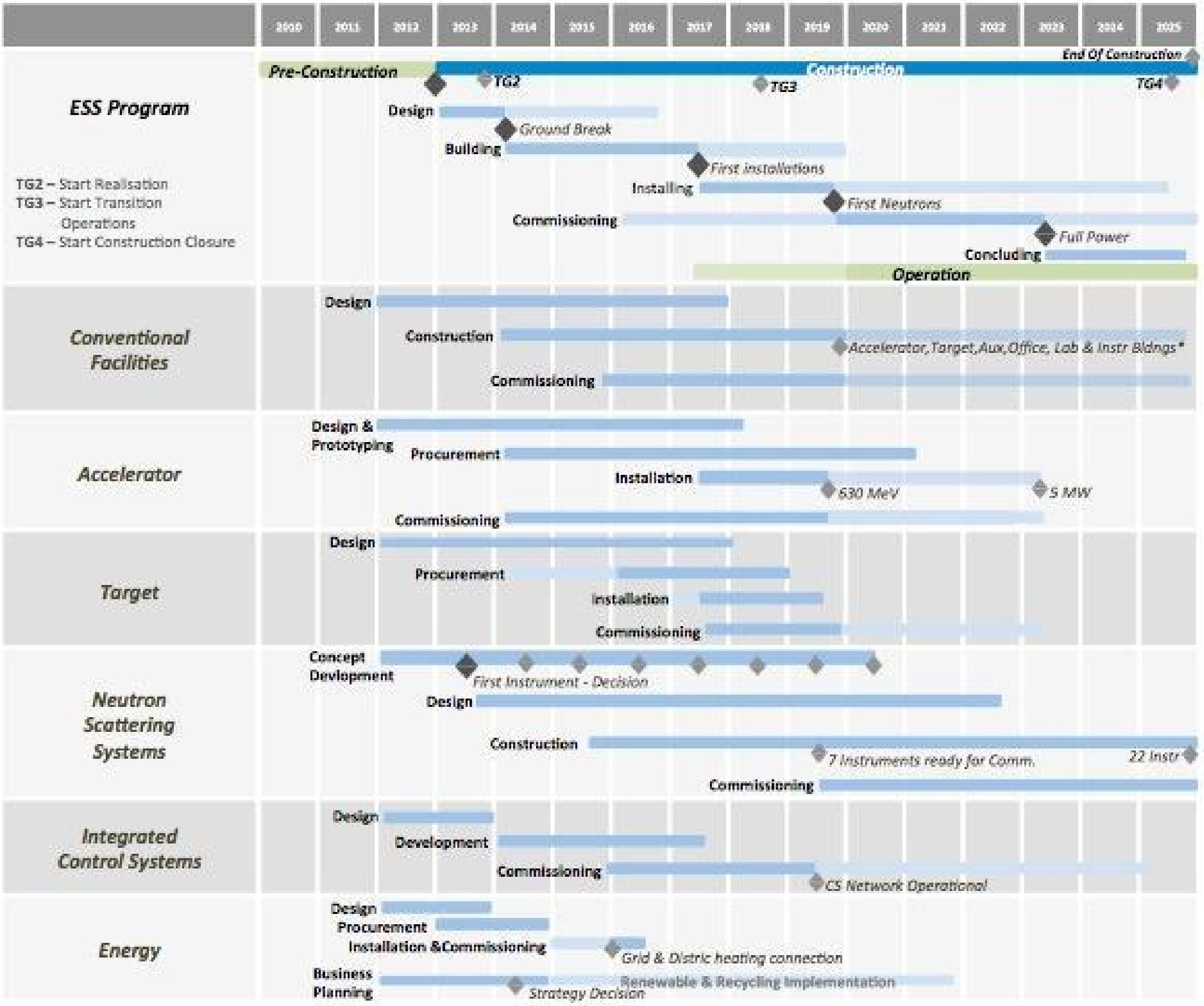
How Will ESS be Funded?

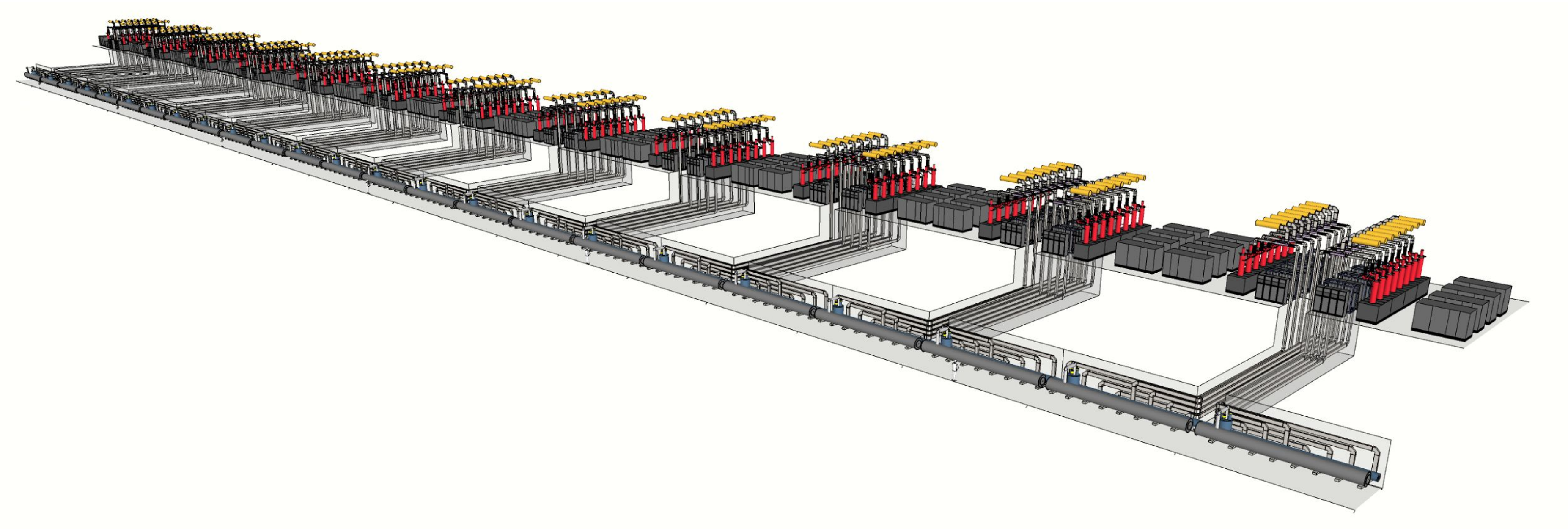
Sweden, Denmark and Norway covers 50% of cost

The remaining ESS members states covers the rest!

with in-kind and cash contributions.

How Long Will ESS Take to Build?





ESS LINAC

Top Level Requirements

- 5 MW of average beam power
- Pulse repetition rate of 14 Hz
  - driven by neutron chopper constraints
- Pulse length of 3 ms
  - Driven by instrument location
  - And beam brightness
- Gives:
  - Peak beam power of 125 MW
  - 4% duty factor

Redesign Phase

- ESS Redesigned the Accelerator in 2013
  - reduce cost without reducing scope.
  - By adding more technical risk
- Major redesign changes
  - Energy Reduction: 2.5 GeV -> 2.0 GeV
    - Gradient increase by 10%
    - 33% fewer 704 MHz cryomodules and RF systems
  - Beam Current Increase: 50 mA -> 62.5 mA

New Baseline

- New Baseline Headline Parameters
  - 5 MW Linac
    - 2.0 GeV Energy (30 elliptical cryomodules)
    - 62.5 mA beam current
    - 4% duty factor (2.86 mS pulse length, 14 Hz)
  - First beam by 2019 (1.0 MW at 570 MeV)
- The new baseline was achieved by:
  - Increasing beam current by 25%
  - Increasing Peak Surface Field by 12%
  - Setting High Beta β_g to 0.86
  - Adopting maximum voltage profile
  - Adopting a uniform lattice cell length in the elliptical section to permit
    - design flexibility
    - schedule flexibility.

Design Risk

- Reduced the number of elliptical cryomodules from 45 to 30
  - Each cryomodule + RF to power the cryomodule costs ~6.5 M€
  - Elimination of 15 cryomodules yields 78 M€ savings (6.5 M€ x 15 x 80% (power factor))
- By accepting large technical risk
  - Power Couplers:
    - Maximum coupler power is 1200 kW
    - Went from 850 kW/coupler to 1100 kW/coupler
    - **Reduced our design margin by 70%**
  - Cavity Peak Surface Field
    - Maximum surface field is 50 MV/meter
    - Went from 40 MV/meter to 45 MV/meter
    - **Reduced our design margin by 50%**

Design Contingency

- ESS uses the Long Pulse concept
  - No compressor ring is required
  - Peak beam current can be supplied at almost any energy
- If we fail to meet our goals on:
  - Beam current
  - Cavity gradient
  - Power coupler power
- The accelerator complex will still function but at a reduced beam power
- We can buy back the beam power in the future by adding high beta cryomodules to the end of the linac
  - As long as the additional space is reserved.
- We proposed to mitigate these risks by reserving the tunnel space for 15 cryomodules (127.5 meters) as “design contingency”.

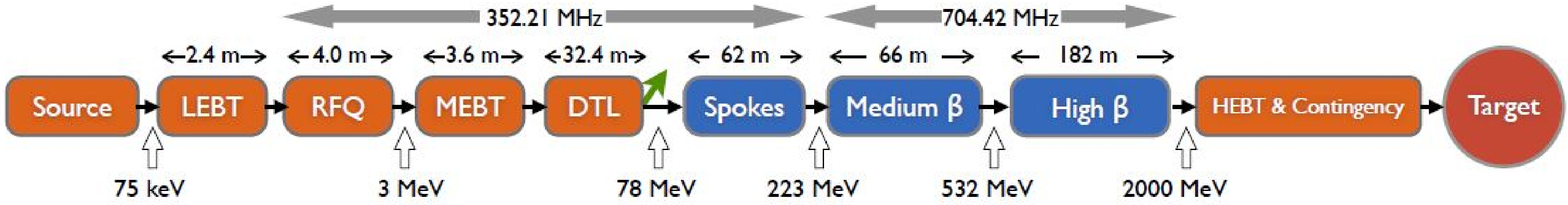
Linac Design Choices

EUROPEAN
SPALLATION
SOURCE

- The energy of the linac is a tradeoff of
  - Linac length
  - Beam current:
    - Space charge forces
    - Halo losses
- Copper Linac
  - Low construction costs but high operational costs
  - Small bore radius < 3 cm
  - Long linac > 750 meters for 2 GeV
- Superconducting Linac
  - High construction costs but low operational costs
  - Large bore radius > 7 cm
  - Short Linac < 360 meters for 2 GeV

Linac Design Choices

- User facilities demand high availability (>95%)
- ESS will limit the peak beam current below 65 mA
- Linac Energy > 2 GeV to accomplish 125 MW peak power.
- The linac will be mostly (>97%) superconducting
- Front end frequency is 352 MHz (CERN Standard)
- High energy section is at 704 MHz



352.21 MHz
704.42 MHz

←2.4 m→ ←4.0 m→ ←3.6 m→ ←32.4 m→ ← 62 m → ← 66 m → ← 182 m →

Source → LEBT → RFQ → MEBT → DTL → Spokes → Medium β → High β → HEBT & Contingency → Target

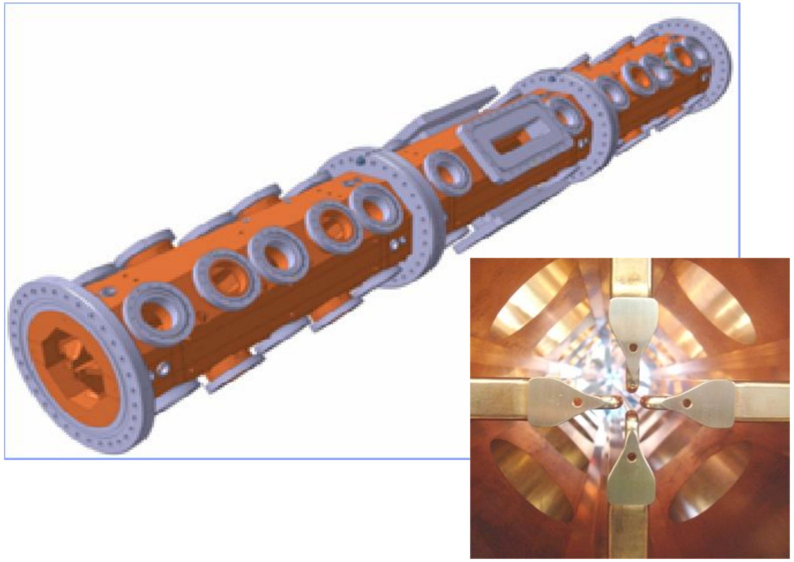
75 keV
3 MeV
78 MeV
223 MeV
532 MeV
2000 MeV

Accelerator Collaboration

- Ion source : Istituto Nazionale di Fisica Nucleare (INFN) – Catania, Italy
- Radio Frequency Quadrupole (RFQ): Commissariat à l'énergie atomique (CEA) – Saclay, France
- Medium Energy Beam Transport (MEBT): ESS-Bilbao, Spain
- Drift tube Linac (DTL): Istituto Nazionale di Fisica Nucleare (INFN) – Legnaro, Italy
- Spoke cavities: Institut de Physique Nucléaire (CNRS) – Orsay, France
- Elliptical cavities: Commissariat à l'énergie atomique (CEA) – Saclay, France
- High Energy Beam Transport: Aarhus University, Denmark
- Spoke RF sources: Uppsala University, Sweden
- RF regulation: Lund University, Sweden

Front End Section

- The RFQ and DTL will be similar to the CERN Linac 4 design.
- The RFQ
  - will be 4.5 meters long
  - and reach an energy of 3.6 MeV
- The DTL
  - Will consist of five tanks
  - Each tank ~7.5 meters in length
  - Final energy will be 88 MeV
- Six klystrons
  - at 352 MHz
  - with a maximum saturated power of 2.8 MW
  - and a duty factor of 4% are required for the Front End

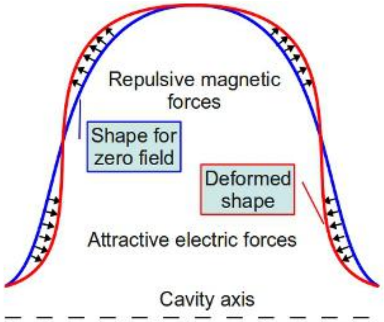


Superconducting RF

- Over 97% of the ESS linac will be superconducting cavities.
- Compared to copper cavities, superconducting cavities can offer:
  - over three times the gradient
  - over 10 times the aperture
  - with virtually no power dissipated in the cavities

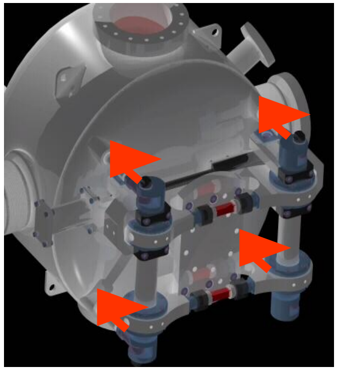
Lorentz De-tuning

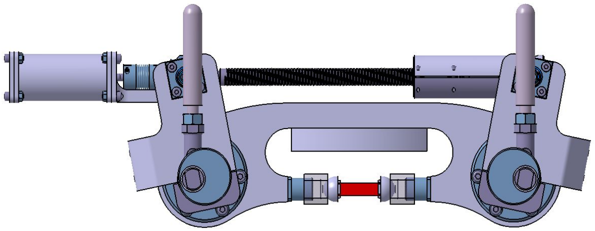
- Because of the enormous gradients in superconducting cavities,
  - the radiation pressure deforms the cavities
- We expect over 400 Hz of detuning in the ESS cavities.
  - Unloaded cavity bandwidth = 0.07 Hz
  - Loaded cavity bandwidth = 1 kHz
- The mechanical time constant of the cavities is about 1 ms compared to the pulse length of 3 ms
  - Static pre-detuning as done in SNS will not be sufficient
  - Dynamic de-tuning compensation using piezo-electric tuners is a must!
  - Or else pay for the extra RF power required



$$P_s=\frac{1}{4}(\mu|\vec{H}|^2-\varepsilon_0|\vec{E}|^2)$$

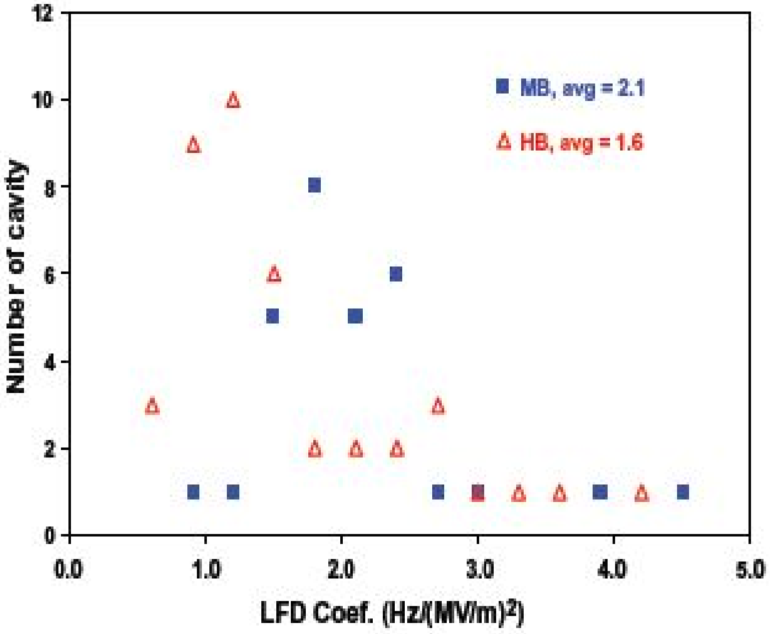
$$\Delta f_0=(f_0)_2-(f_0)_1=-K E_{acc}^2$$





Cavity Power Configuration

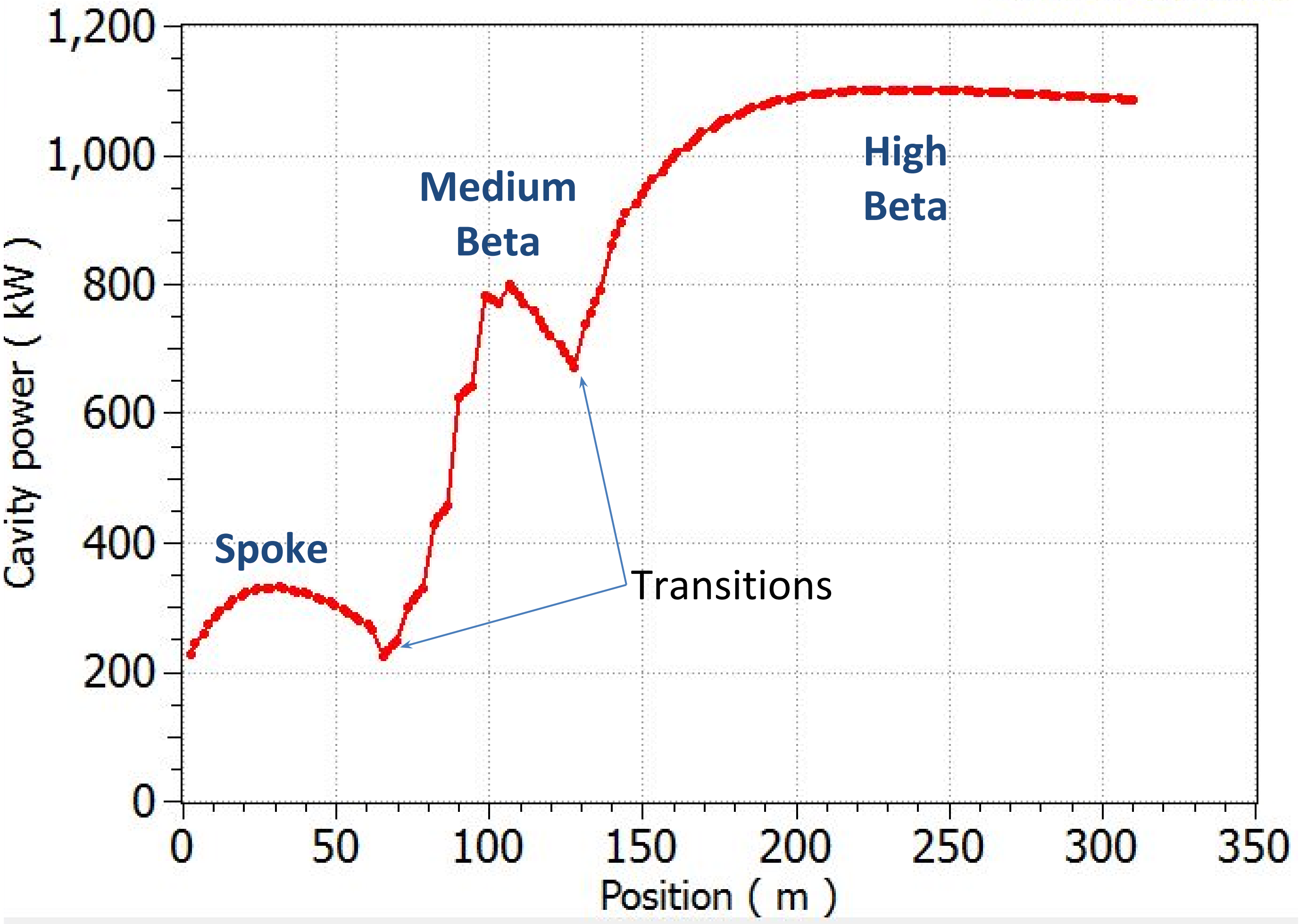
- Because of fabrication techniques,
  - superconducting cavity strings are usually much shorter (< 1 m) than copper cavity strings (> 5m).
  - The Lorentz de-tuning coefficient varies from cavity to cavity
- Therefore, each superconducting cavity has its own RF power source



Transit Time Factor

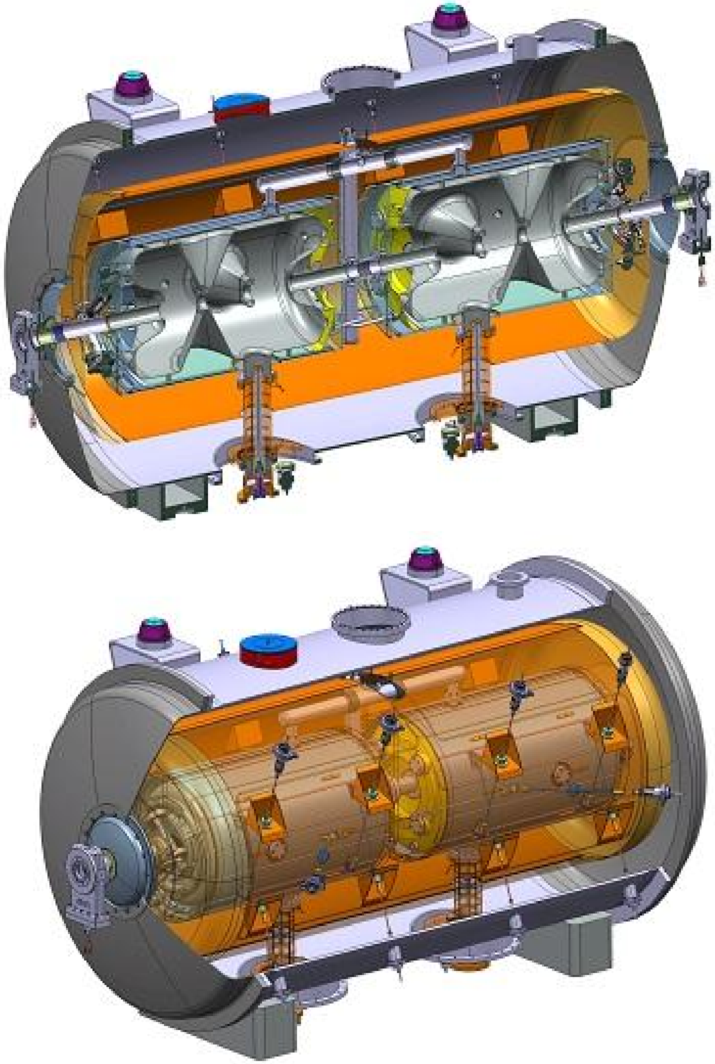
- For proton linacs using copper RF cavities
  - the cavity cell structure is tuned to match the changing proton velocity as it accelerates.
  - The power profile is usually flat
- Because of high fabrication costs and difficulty,
  - The cell structure of superconducting cavities is tuned for only one beam velocity.
  - Multiple families of cell velocities are chosen. ESS cell velocities:
    - Spoke: β_g = 0.5
    - Medium beta: β_g = 0.67
    - High beta: β_g = = 0. 86
  - There is a limit on the surface field in a SCRF cavity (ESS 45 MV/m)
    - Since, the particle velocity does not match the geometrical velocity for the entire acceleration range,
    - The power profile is not flat

ESS Linac Cavity Power Profile

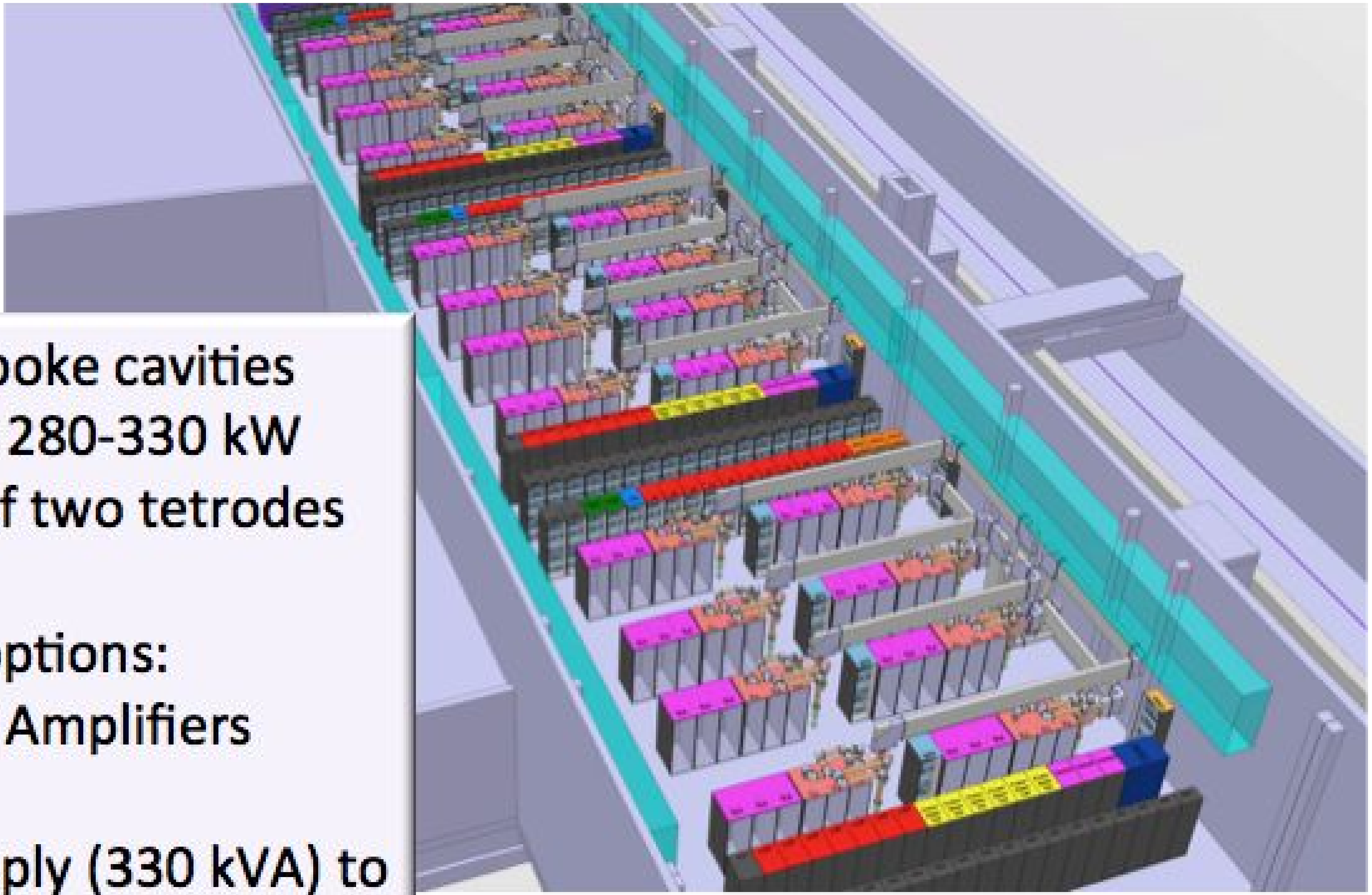


Spoke Cavities

- ESS will transition to superconducting cavities at 88 MeV
- ESS will be the first accelerator to use 352 MHz double spoke cavity resonators
- Twenty-eight cavities with an accelerating gradient of 8 MV/m are required.
- Each cavity will operate at a nominal peak power of 320 kW
- What type of power source to choose?
  - Tetrode
  - Klystron
  - IOT
  - Solid State



Spoke linac (352 MHz) Layout



26 Double Spoke cavities
Power range 280-330 kW
Combination of two tetrodes

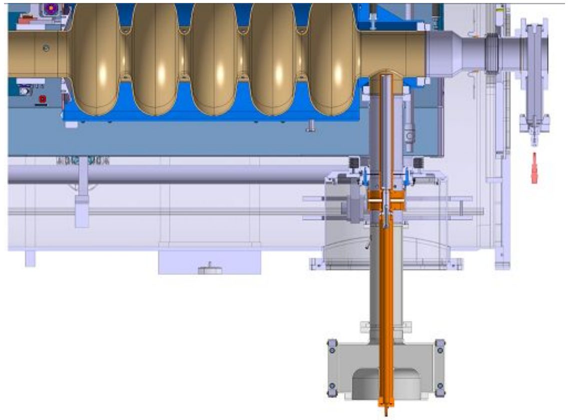
Other options:
Solid State Amplifiers

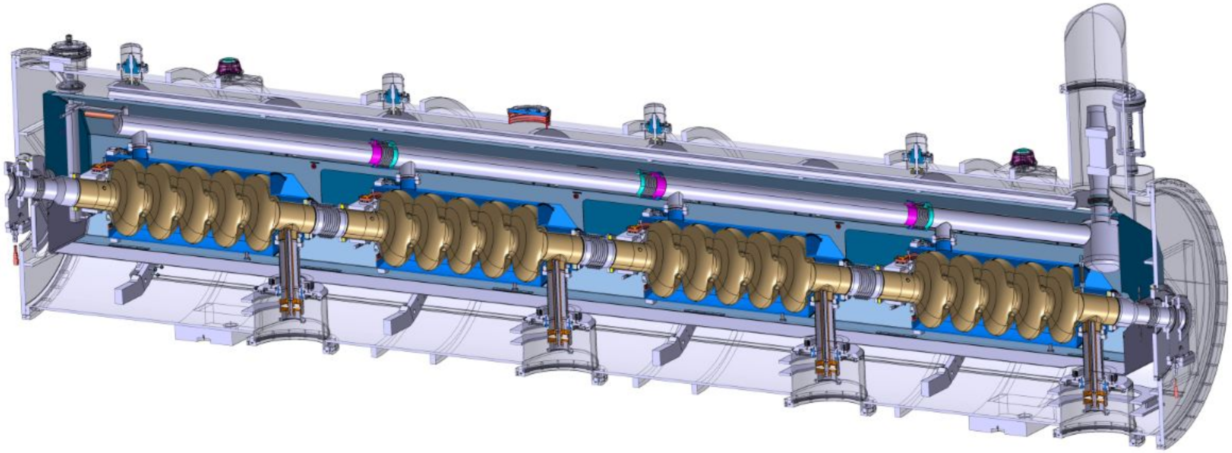
Large power supply (330 kVA) to supply 8 stations (16 tetrodes)

Elliptical Cavities

- Universal Cryomodule
  - Cryomodules are expensive and difficult to fabricate
  - Pick cavity β_g and number of cells
    - Optimize power transfer
    - Optimize length
  - Power in couplers is limited to 1200 MW (peak)

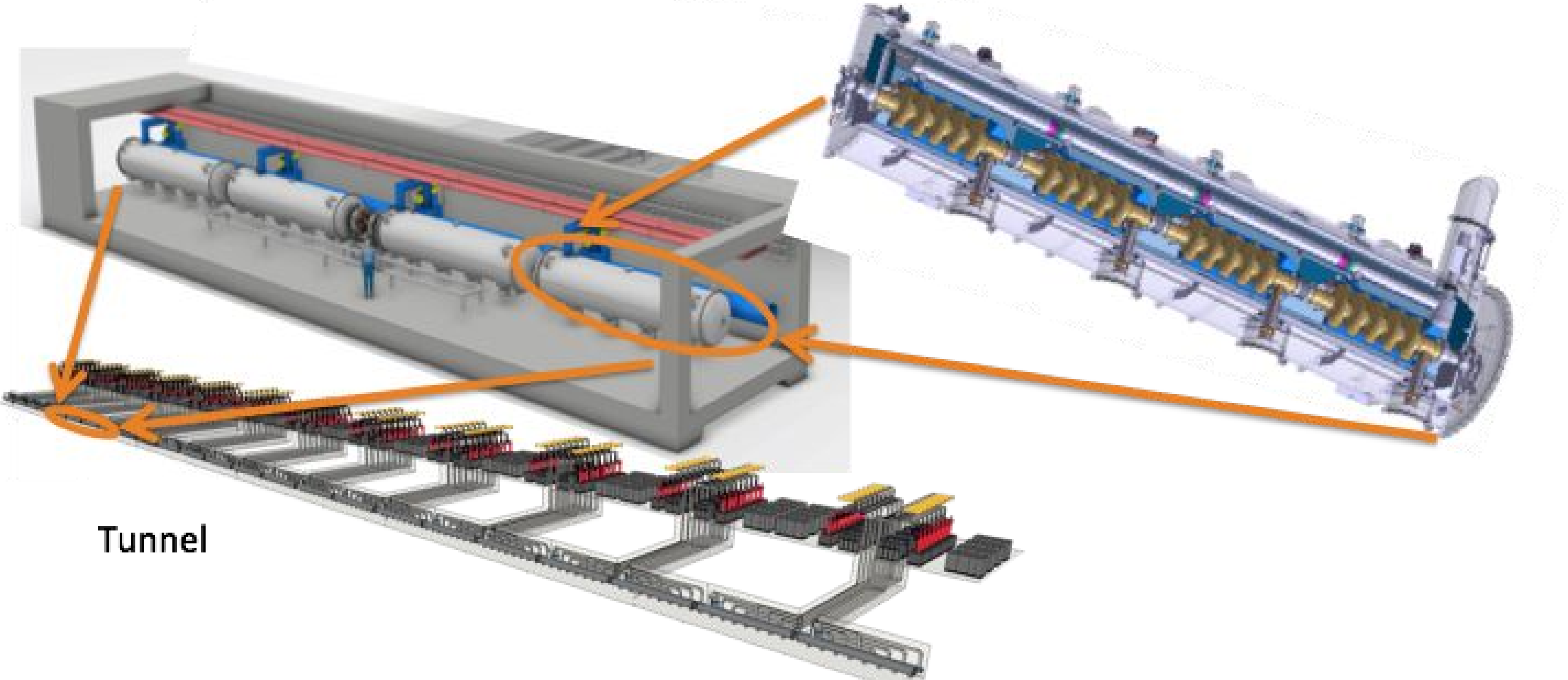
- Medium Beta $\beta_g = 0.67$
  - 6 cell cavities
  - Cavity length = 0.86 m
  - 32 cavities packaged in 8 cryomodules
  - Maximum peak RF power = 800kW
- High Beta $\beta_g = = 0. 86$
  - 5 cell cavities
  - Cavity length = 0.92 m
  - 88 cavities packaged in 22 cryomodules
  - Maximum peak RF power = 1100kW





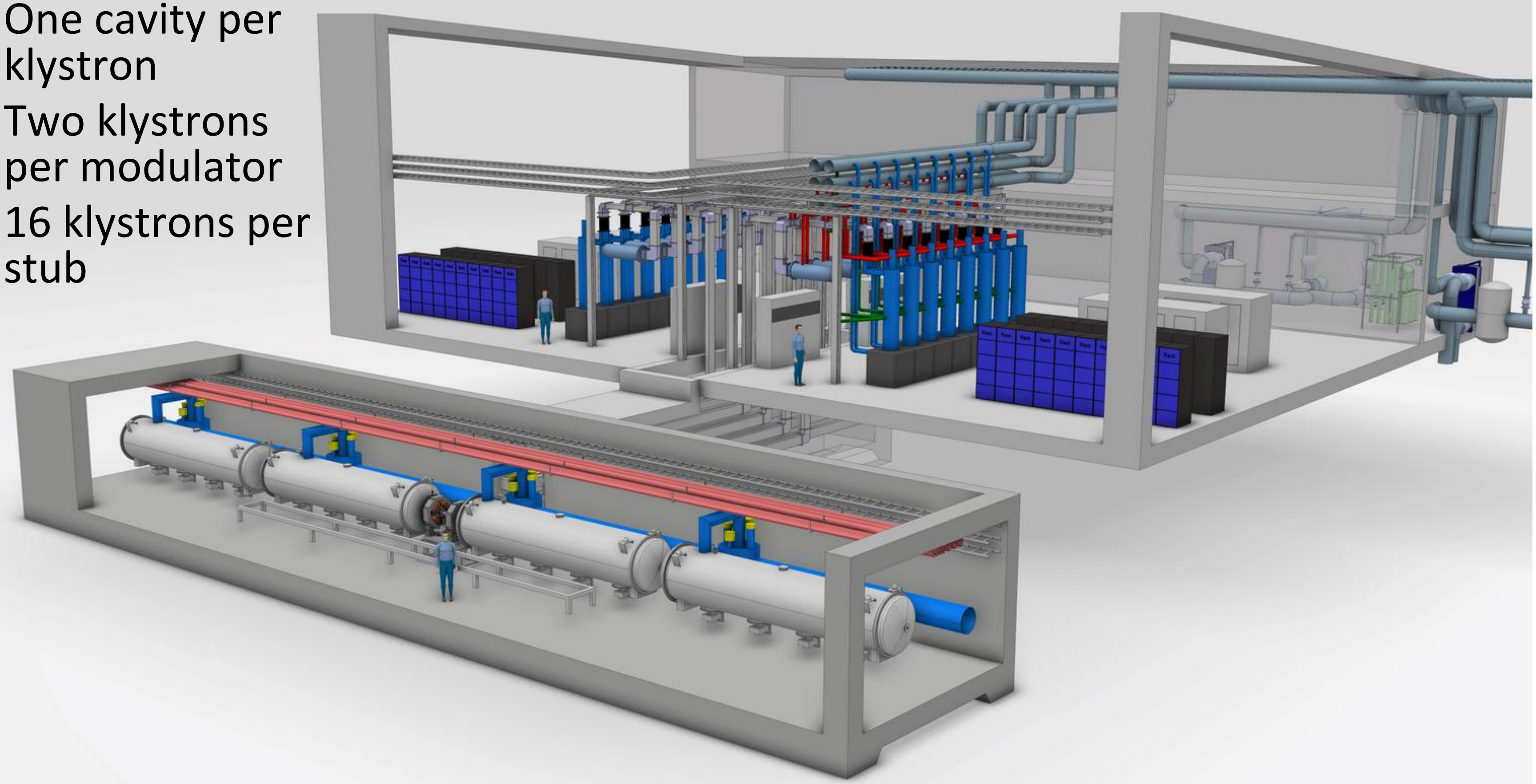
Elliptical (704 MHz) Layout

- One cavity per klystron
- 4 klystrons per modulator
- 16 klystrons per tunnel penetration

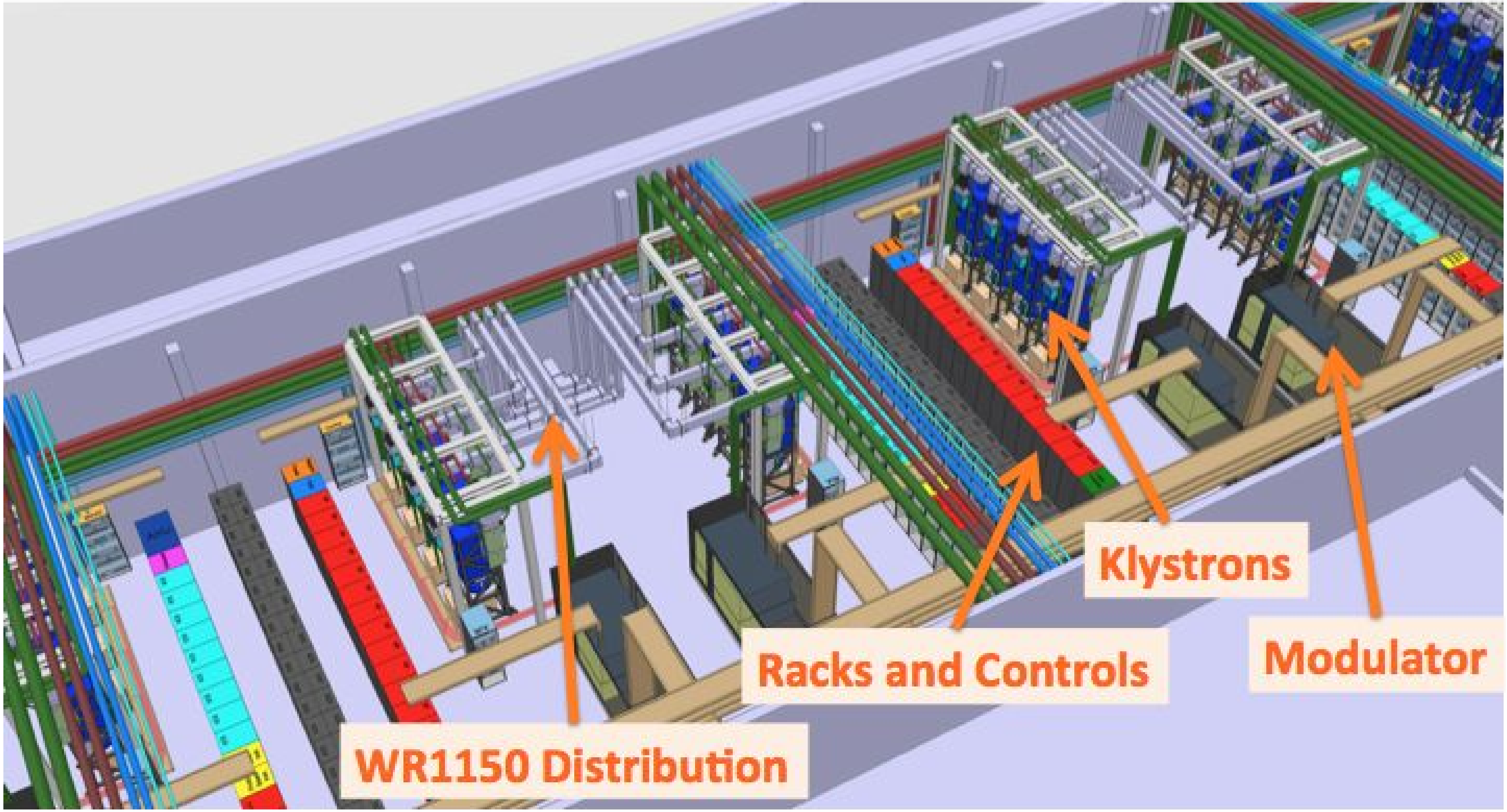


Elliptical RF System Layout

- One cavity per klystron
- Two klystrons per modulator
- 16 klystrons per stub



Elliptical (704 MHz) Gallery Layout



4.5 Cells of 8 klystrons for Medium Beta
10,5 Cells of 8 klystrons (IOTs) for High Beta

AD Engineering Resource Group Views on Machine Protection

Machine Protection Philosophy

- The Accelerator MPS must protect against
  - Damage to the Accelerator
  - Damage to other ESS Systems (Target, CF, ..)
- To protect against other systems, AD will receive requirements from the Machine Protection Committee (MPC)
  - Speed of protection
  - Protection interfaces
  - Best practices
- AD has a membership in the MPC and AD will participate in risk analysis that will aid in the formulation of machine protection requirements
- AD will have a two-tier system for active machine protection
  - Beam Permit System (BPS) also known as Software Interlock System (SIS)
  - Beam Abort System (BAS) also known as Beam Interlock System (BIS)

Beam Permit System

- The purpose the BPS is to prevent beam from being injected into the accelerator if the accelerator is not ready.
  - Decision to inject made prior to the beam pulse
  - Relatively slow system (> 10ms)
  - Should catch 96 % of the failures
- The sensors to the BPS will be the local protection systems (LPS)
  - Mostly every energy source (or power convertor) in the Accelerator will have a local protection system (LPS).
  - The purpose of the LPS is to protect the power source and the load attached to the power source
  - The LPS will be specified (and it most cases designed and built) by AD
    - Using a platform approved by ICS (i.e. approved PLC's or crates that interface to EPICs)
  - The LPS will report status to the high level control system (EPICs)
- The controller of the BPS will be high level control system (EPICS)
- The controller of the BPS will be configurable
  - masks
  - states

Beam Abort System

- The purpose of the Beam Abort System is stop injecting beam into the accelerator if an accident is happening or about to happen
  - Decision to abort made during beam pulse
  - Relatively fast system (< 0.020 milliseconds)
  - Should be used relatively rarely
- Speed of system set by MPC
- Beam inhibit devices approved by the MPC
- System reconfiguration
  - should be minimal
  - approved by the MPC

Beam Abort System Configuration

- Two beam inhibit devices (RFQ drive and Ion source voltage?)
- Detectors
  - Tunnel (BLMs, BCMs, etc..)
  - Gallery (selected LCS's)
  - Other ESS systems (Target)
- Signal Conditioners
  - The detectors are conditioned by signal conditioners to a prescribed transfer function
- A single serial link along the gallery connected that drives the beam inhibit signal to the beam inhibit devices
- Link interrupts
  - Placed along the gallery
  - Fed by signal conditioners
- The signal conditioners, link interrupts, serial link, should all be constructed by ICS
- The choice of detectors shall be proposed by AD and approved by MPC

Safety Risks

www.europeanspallationsource.se

Safety Risks - Equipment Gallery

- The safety risks in the ESS Linac are segregated between the Equipment Gallery and Tunnel
- The Equipment Gallery will be design to follow industrial safety procedures.
  - People entering the gallery will have some knowledge of the safety risks present in the gallery (i.e. a controlled worker)
  - There will be no ionizing radiation present
    - Tunnel Shielding
    - Equipment shielding (Klystron X ray Shielding)
  - All equipment will follow industrial standards for
    - Mechanical safety
    - Electrical safety
    - non-ionizing radiation safety
    - human factors
      - Noise
      - Temperature
      - etc.
  - To make sure the equipment gallery complies with these risks
    - is hard to do !!!
    - will require a will established and often practiced review procedure **(being developed at the Integration Test Stand by E. Tanke)**

Safety Risks - Tunnel

- Hazards Present in the Tunnel
  - Ionizing radiation
    - Prompt
      - Beam Induced
      - Equipment induced (i.e. X rays in cavities)
    - Residual
    - Contamination
  - Electrical Hazards
    - Non Ionizing radiation
    - Electrocution
  - Mechanical Hazards
    - Confined spaces, heavy loads, pinch risks, etc
  - Cryogenic Hazards
    - Oxygen Deficiency
    - Direct exposure (burns, etc due to ruptures)

- Hazard mitigation
  - It is not cost effective to control tunnel hazards via industrial standards
  - The tunnel itself will be interlocked with a Personal Safety System (PSS)
    - that minimizes hazards
      - Electrocution
      - Prompt Radiation
    - but does not guarantee hazards are eliminated
      - Cryogenics
      - Mechanical
      - Radioactive contamination
  - Training will be a key component in addition to a PSS

Beam Loss

EUROPEAN
SPALLATION
SOURCE

- We have designed the berm thickness to handle a loss rate of 1 W/meter
  - The Linac is ~500 meters long so we can afford to lose on average 500W of beam power
  - The total beam power is 5 MW
  - Average acceleration efficiency must be better than 99.99% !!!!
- The dynamic loss (electrical energy lost in the walls) in the superconducting cavities is less than 4 W
  - 20 MV; R/Q=400 Ohms; Q=1e10; Duty=4%
  - The cavities are about 1 meter long so a beam loss of 1 W/ meter would be 25% of the dynamic load!!
  - Therefore beam loss in cavities must be << 1 W meter

Maximum Credible Incident

- In the USA, DOE Accelerator Facilities have to build their passive radiation shielding on a Maximum Credible Incident (MCI)
- MCI is the total energy deposition of an incident
- The MCI is defined by
  - The radiation authority (DOE)
  - Not the operating institution !!!
- For Example, From 1992-2003, DOE Labs operated under the “Dugan Criterion” for the MCI
  - Full beam power lost a single point at any point in the accelerator
  - For 1 hour
  - This lead to the Fermilab Main Injector to have 8 meters of shielding for a 200 kW accelerator.
- ESS does not have an MCI defined.
  - Risk: More shielding could be required by SSM at a later date

Views

- Please note that
  - these are opinions of the author
  - and do not necessarily reflect the unanimous consent of the ACCSYS Management Team
- Major unmitigated radiation issues
  - We bend a 5 MW beam **up** at the Dogleg
  - We do not have an MCI defined and accepted by SSM
- Major unmitigated conventional safety issues
  - Cryogenic burns to due ruptures in the tunnel
  - Hot water burns due to elevated temperatures and pressures in Klystron collector cooling circuits
- Over-blown safety issues
  - Fire safety
    - Sprinklers in tunnel and gallery pose more hazards than they solve