The European Spallation Source

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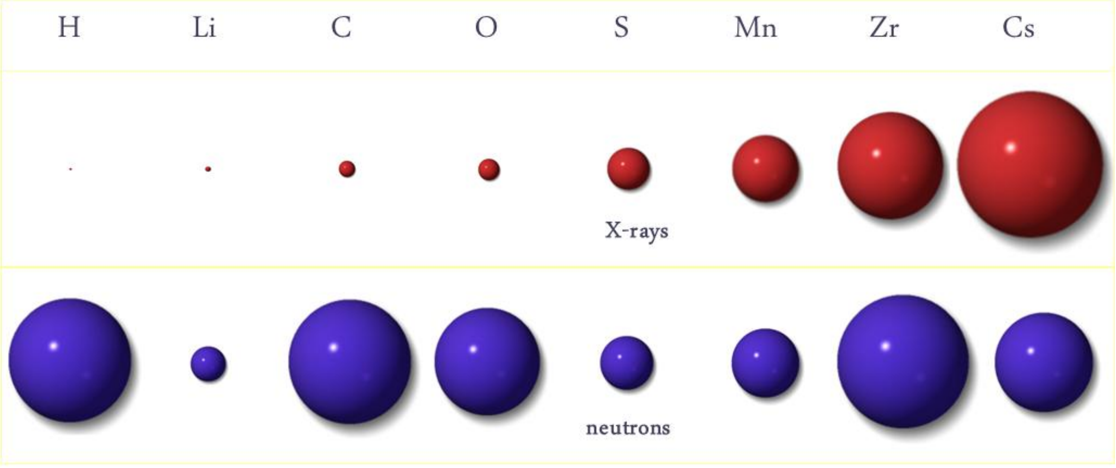
Overview

- 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.



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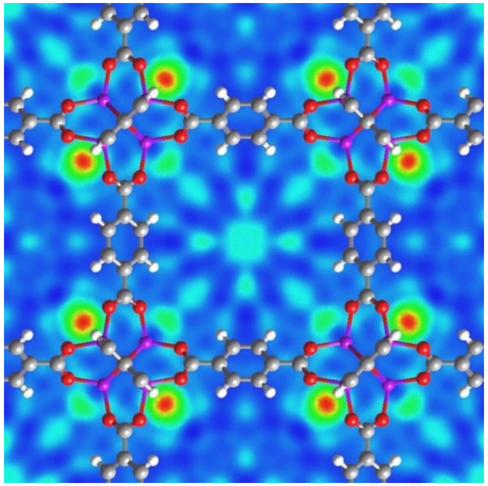
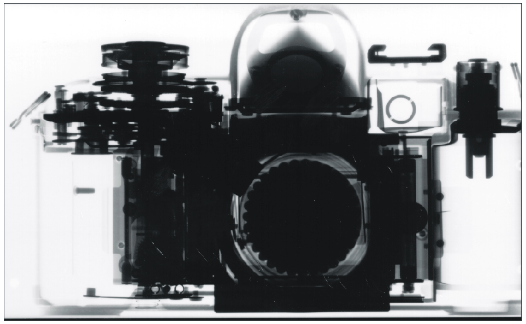
Neutron Scattering

- 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

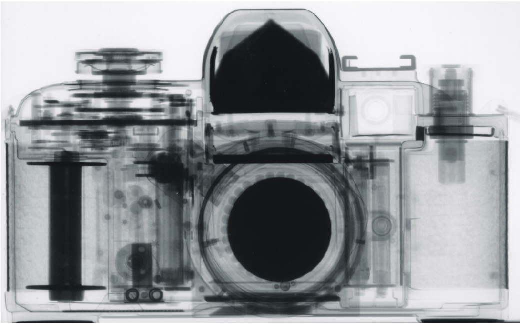


Neutron scattering of hydrogen in a metal organic framework

Neutron radiograph of a flower corsage



X-Ray Image



Neutron radiograph

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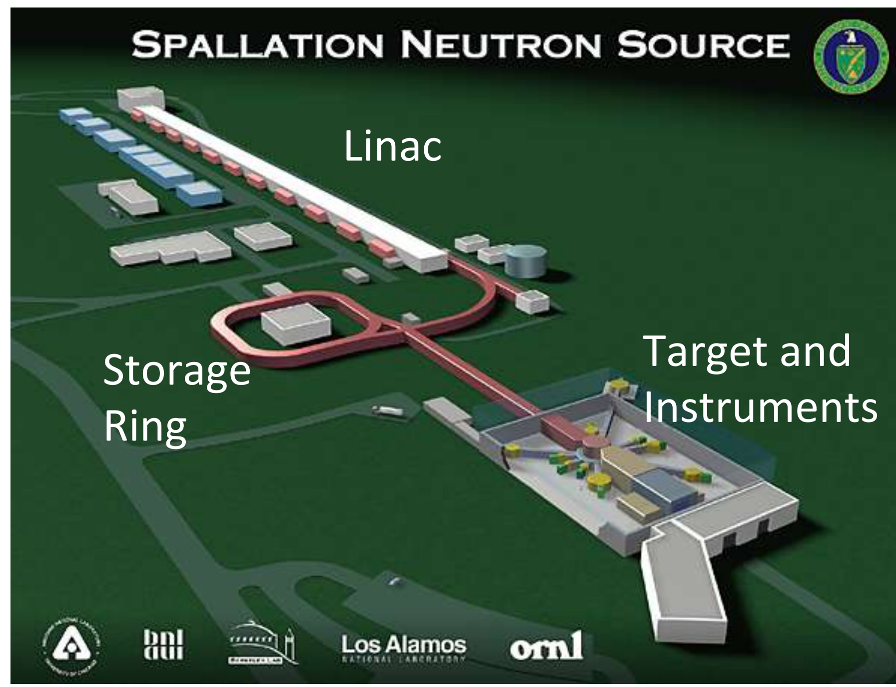
Neutron Spallation Sources

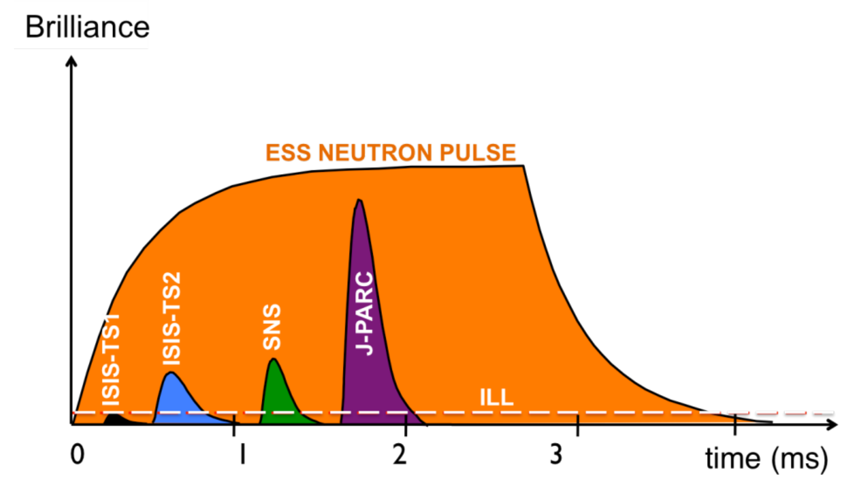
- Traditional neutron sources are reactor based
  - Neutron flux is limited by reactor cooling
  - Neutron energy spectrum is measured by time of flight using neutron choppers
  - Chopping throws away neutrons and limits neutron brightness
- Spallation sources consist of a:
  - pulsed accelerator that 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 atypical spallation sources consist of a:
  - Linac to accelerator the protons
  - A storage ring to compress the linac beam pulse



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



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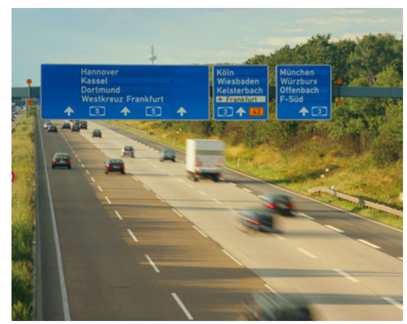
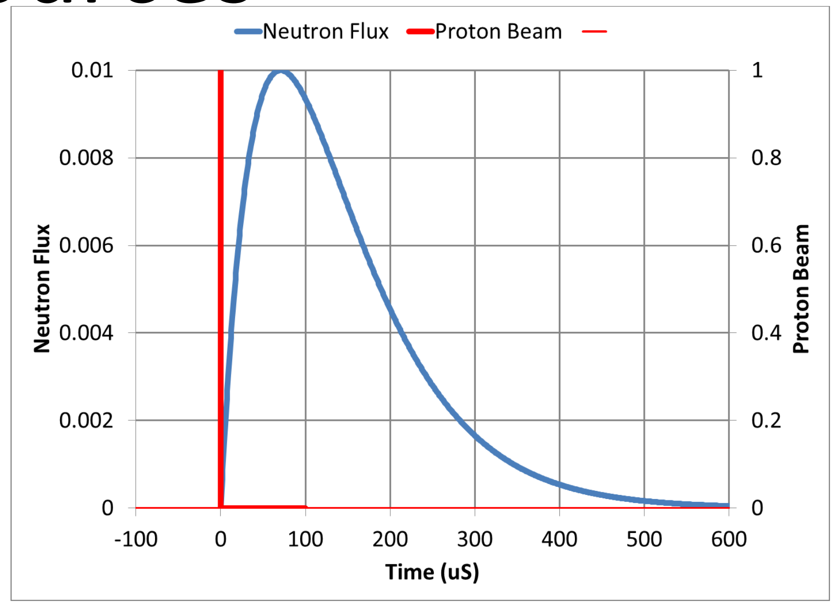
What is 5 MegaWatts?

- 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

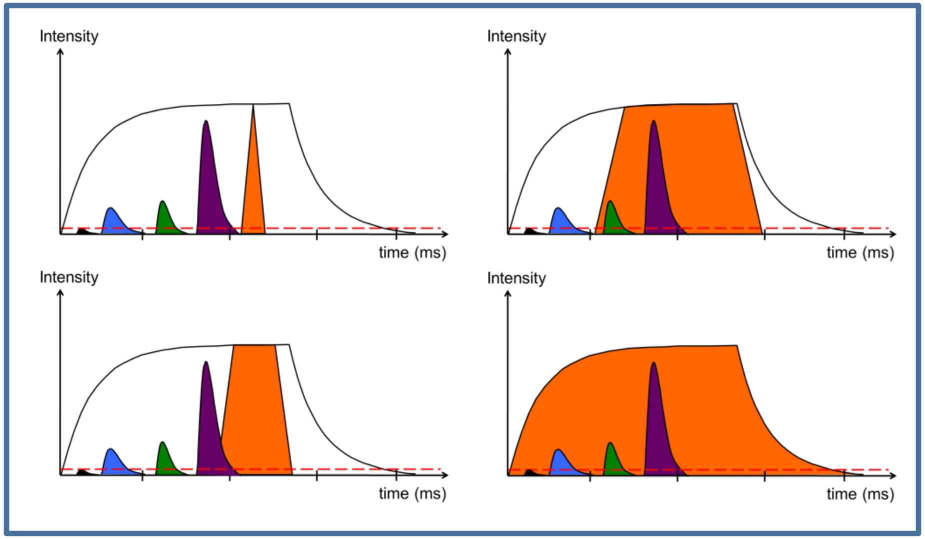
- The neutrons are cooled by a moderator downstream of the target
- The time constant of the moderation process is about 100 μs
- Proton beam pulses shorter than 100 us serve only to stress the metal target and limit the beam power
  - Typical short pulse spallation sources have storage ring circumferences ~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

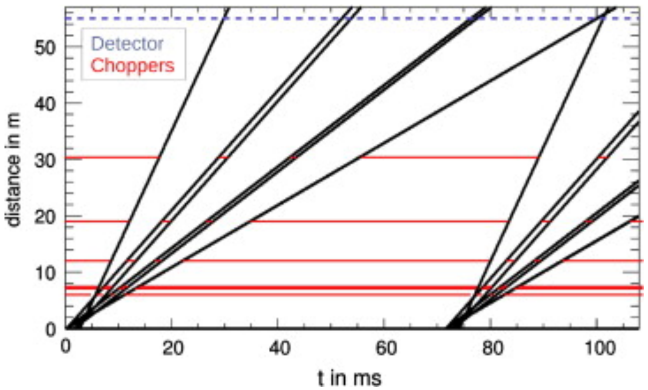


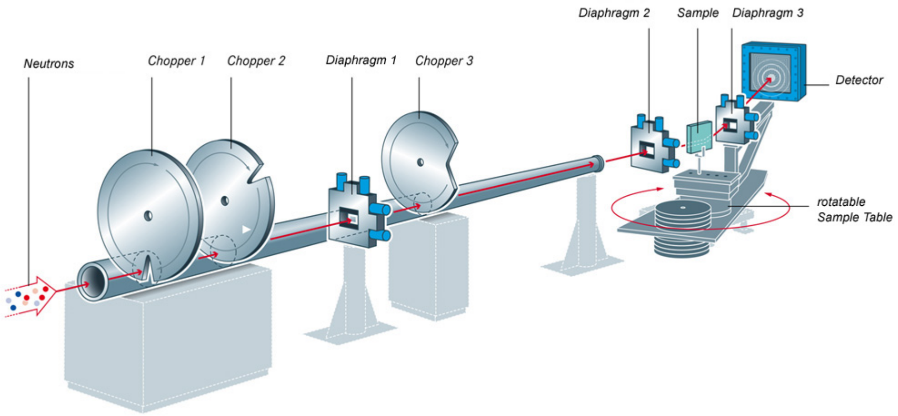
- The target stress from the short beam pulse places a limit on:
  - proton beam power
  - and ultimately neutron flux and brightness
  - The proton beam power of SNS (Oak Ridge Tennessee, USA) is limited to 1MW (17 MW peak)

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

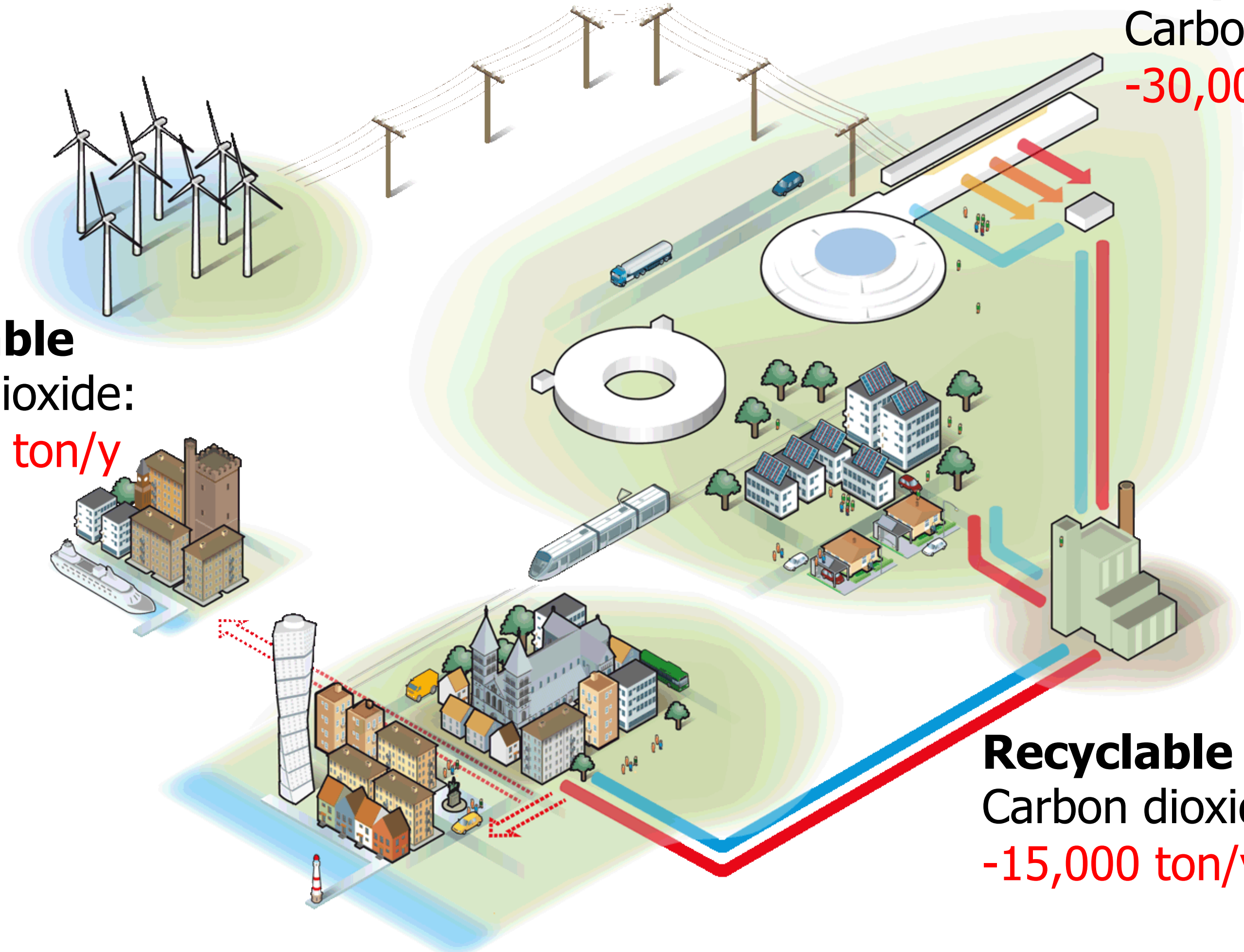






What is Different About ESS?

Sustainable Energy Concept



Responsible
Carbon dioxide:
-30,000 ton/y

Renewable
Carbon dioxide:
-120,000 ton/y

Recyclable
Carbon dioxide:
-15,000 ton/y

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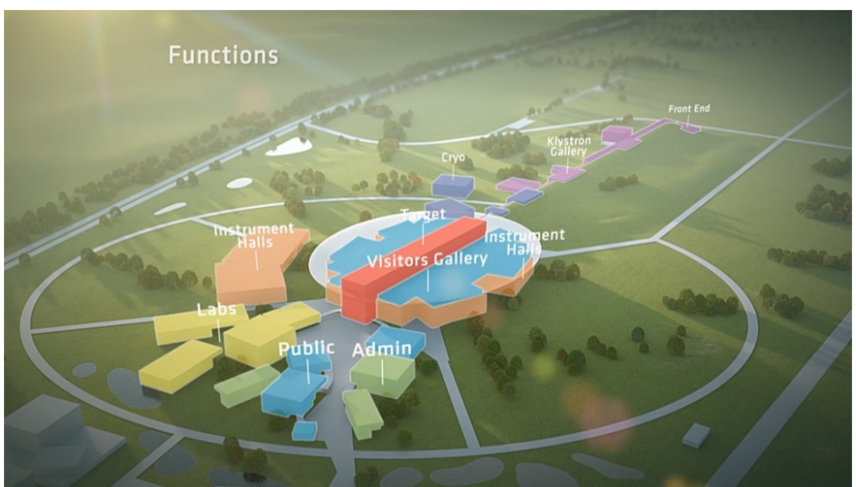
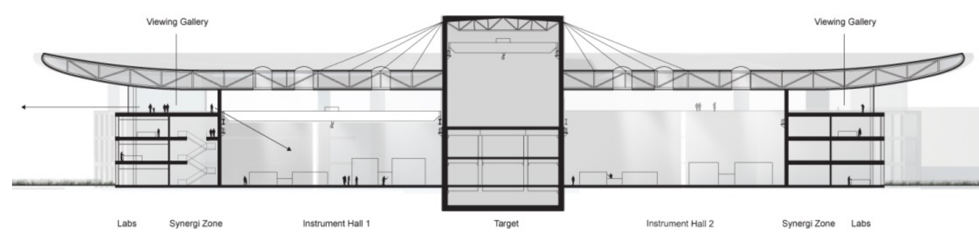
What Will ESS Look Like?





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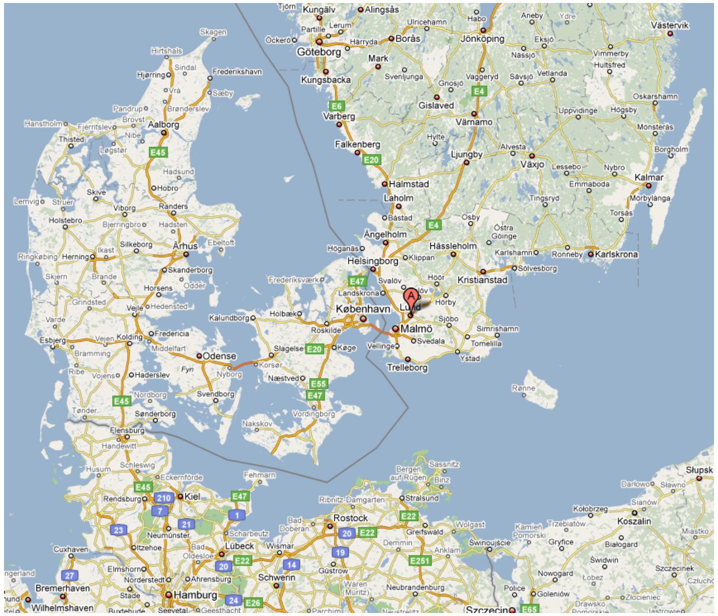
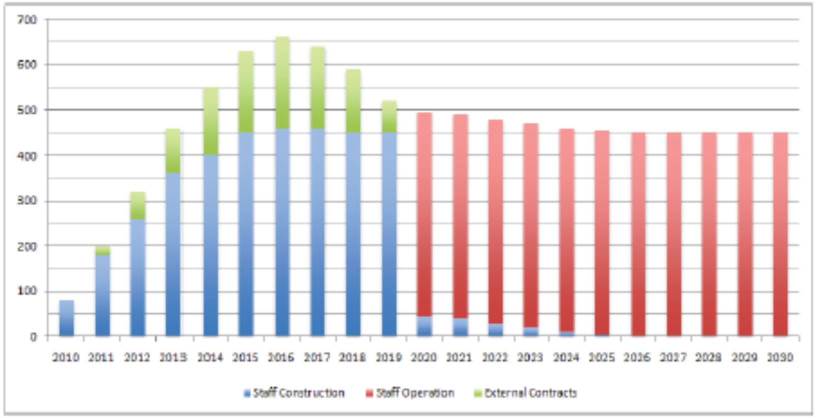
Where Will ESS Be Built?

- 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



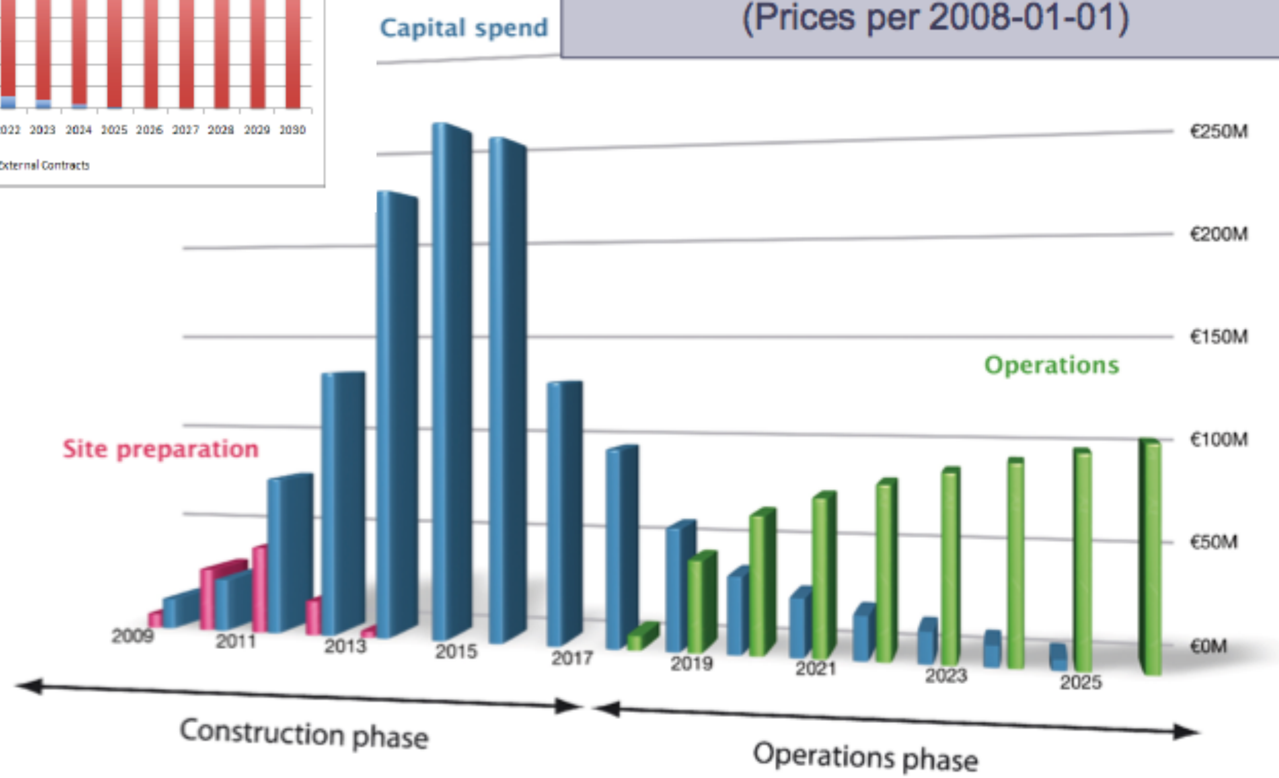
How Much Will ESS Cost?

Personnel



Investment

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



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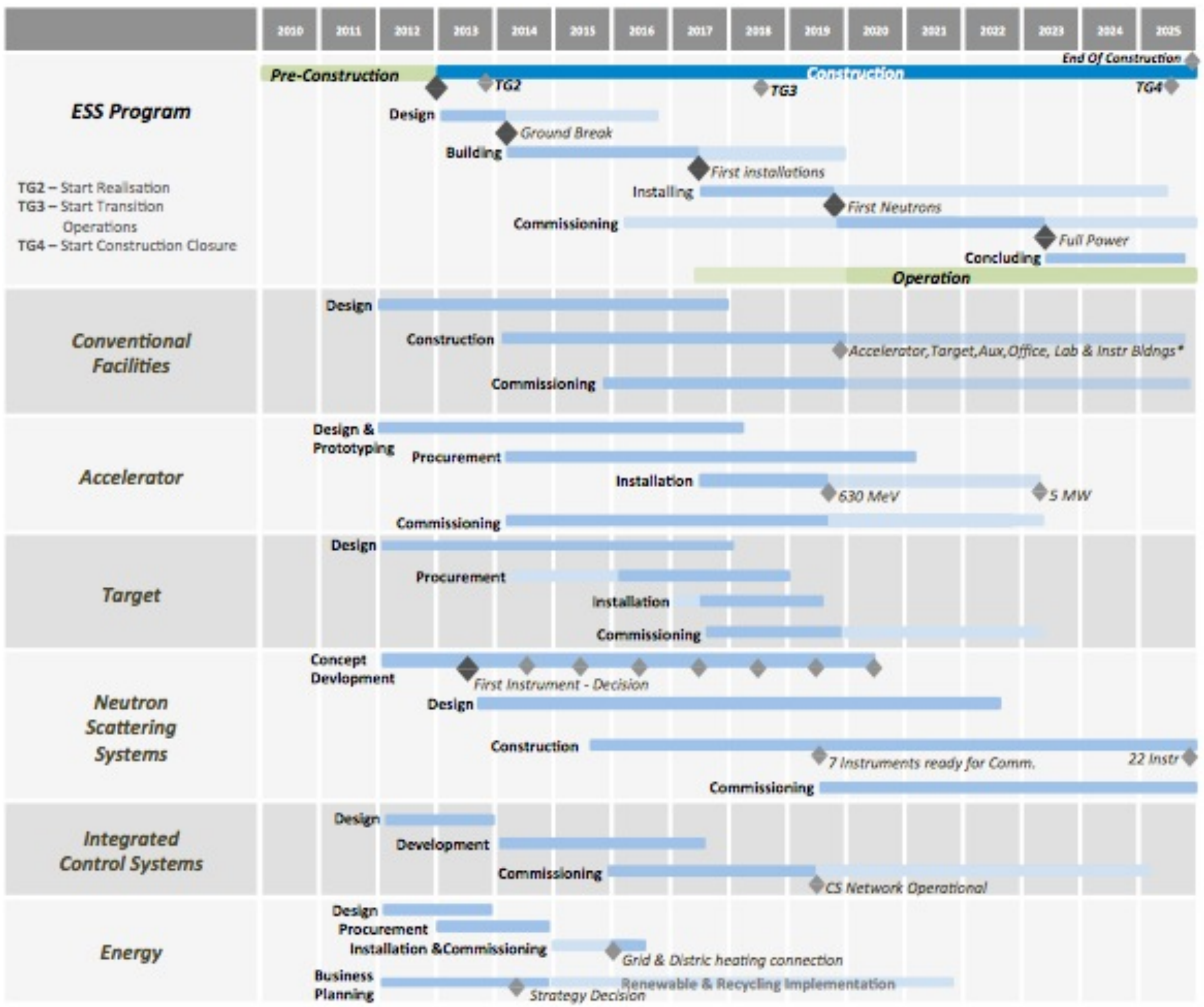
How Will ESS be Funded?

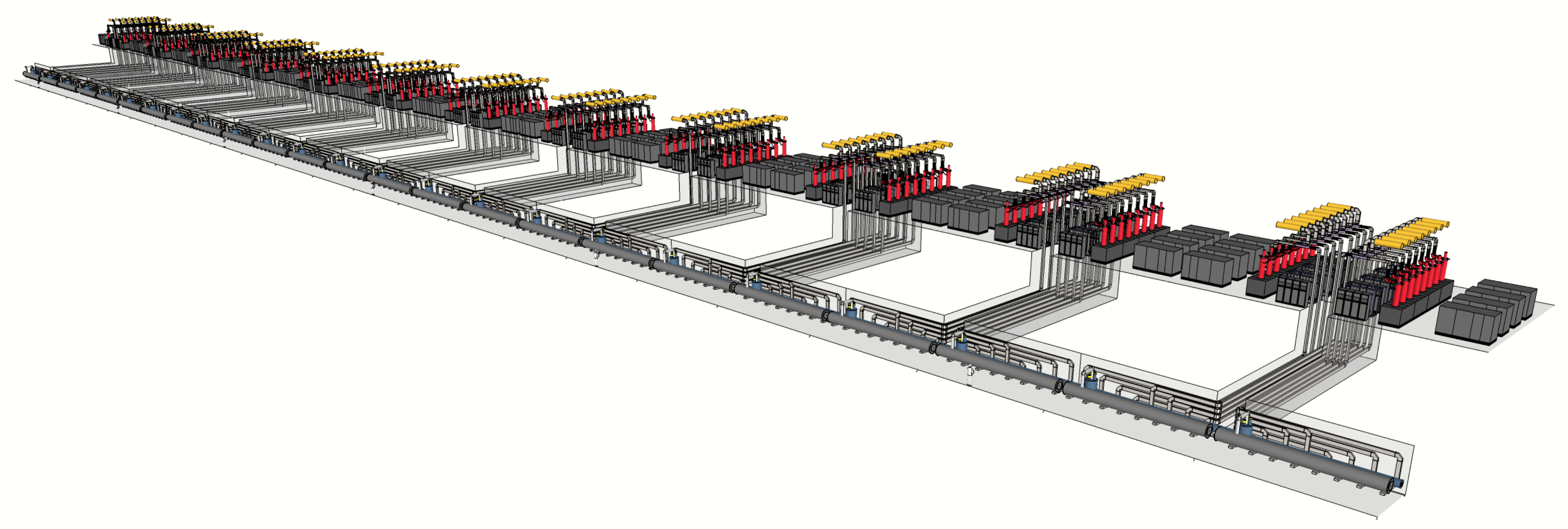
Sweden, Denmark and Norway covers 50% of cost

The remaining ESS members states covers the rest!

with in-kind and cash contributions.

How Long Will ESS Take to Build?





ESS LINAC

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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

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Redesign Phase

- ESS Accelerator is currently in a redesign phase to
  - 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
- Design contingency
  - Instead of cost contingency
  - Keeping the length between Ion source and Target at the maximum possible distance
  - Add cryo-modules as contingency

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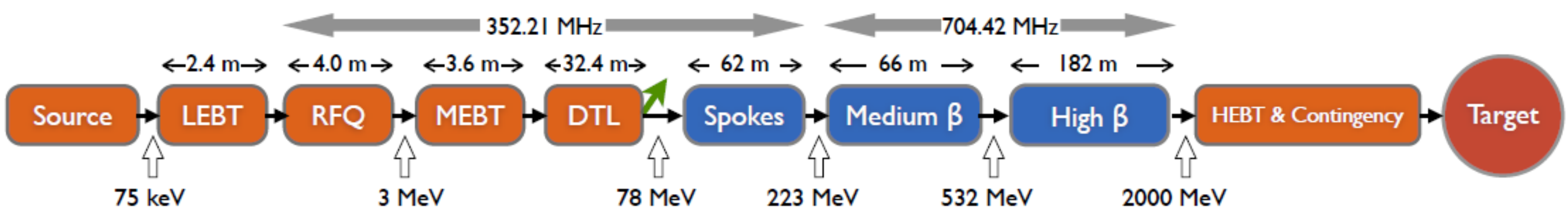
Linac Design Choices

- 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



Accelerator Collaboration

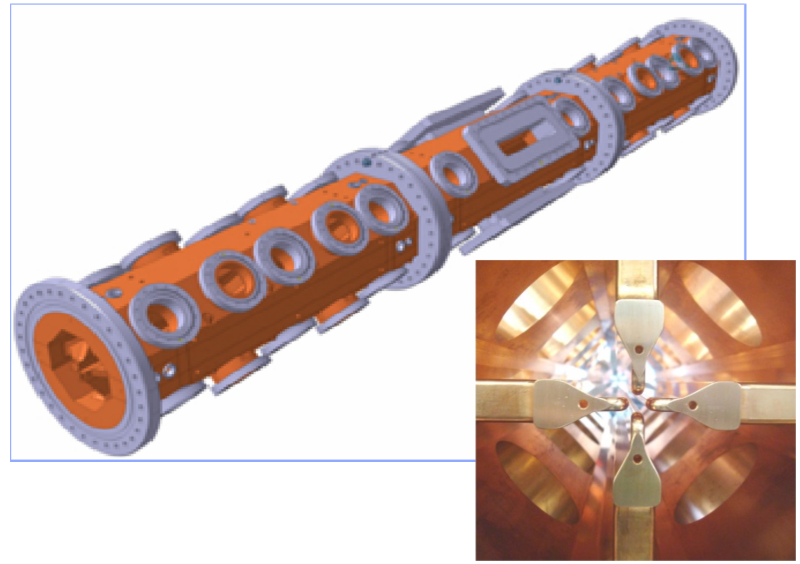
- Ion source : Istituto Nazionale di Fisica Nucleare (INFN) – Catania, Italy
- Radio Frequency Quadrupole (RFQ): Commissariat à l'énergie atomique (CEA) – Saclay, France
- Medium Energy Beam Transport (MEBT): ESS-Bilbao, Spain
- Drift tube Linac (DTL): Istituto Nazionale di Fisica Nucleare (INFN) – Legnaro, 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

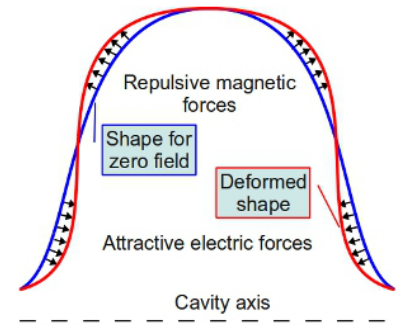


Superconducting RF

- 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

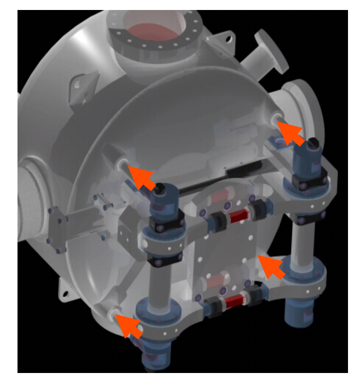
Lorentz De-tuning

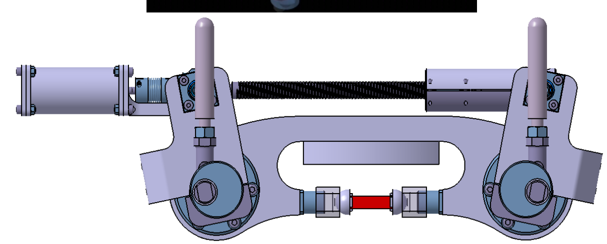
- Because of the enormous gradients in superconducting cavities,
  - the radiation pressure deforms the cavities
- We expect over 400 Hz of detuning in the ESS cavities.
  - Unloaded cavity bandwidth = 0.07 Hz
  - Loaded cavity bandwidth = 1 kHz
- The mechanical time constant of the cavities is about 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



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

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





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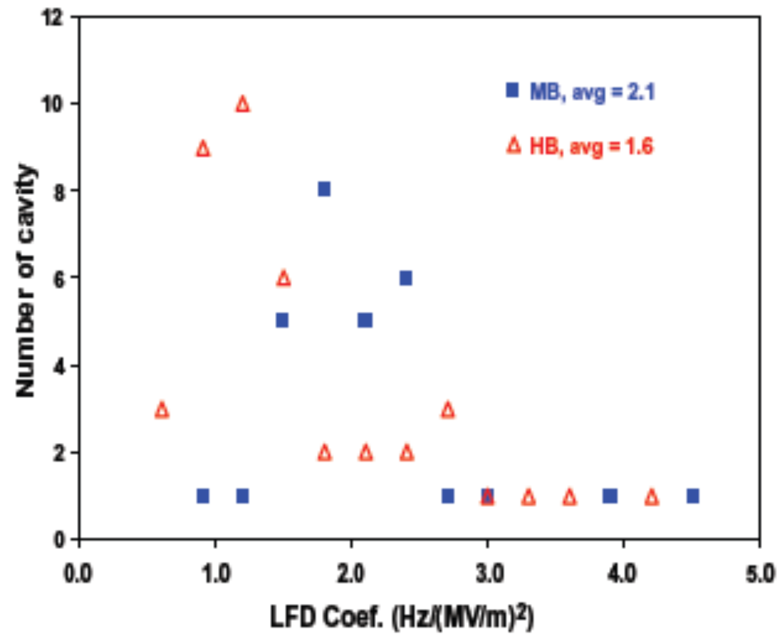
Cavity Power Configuration

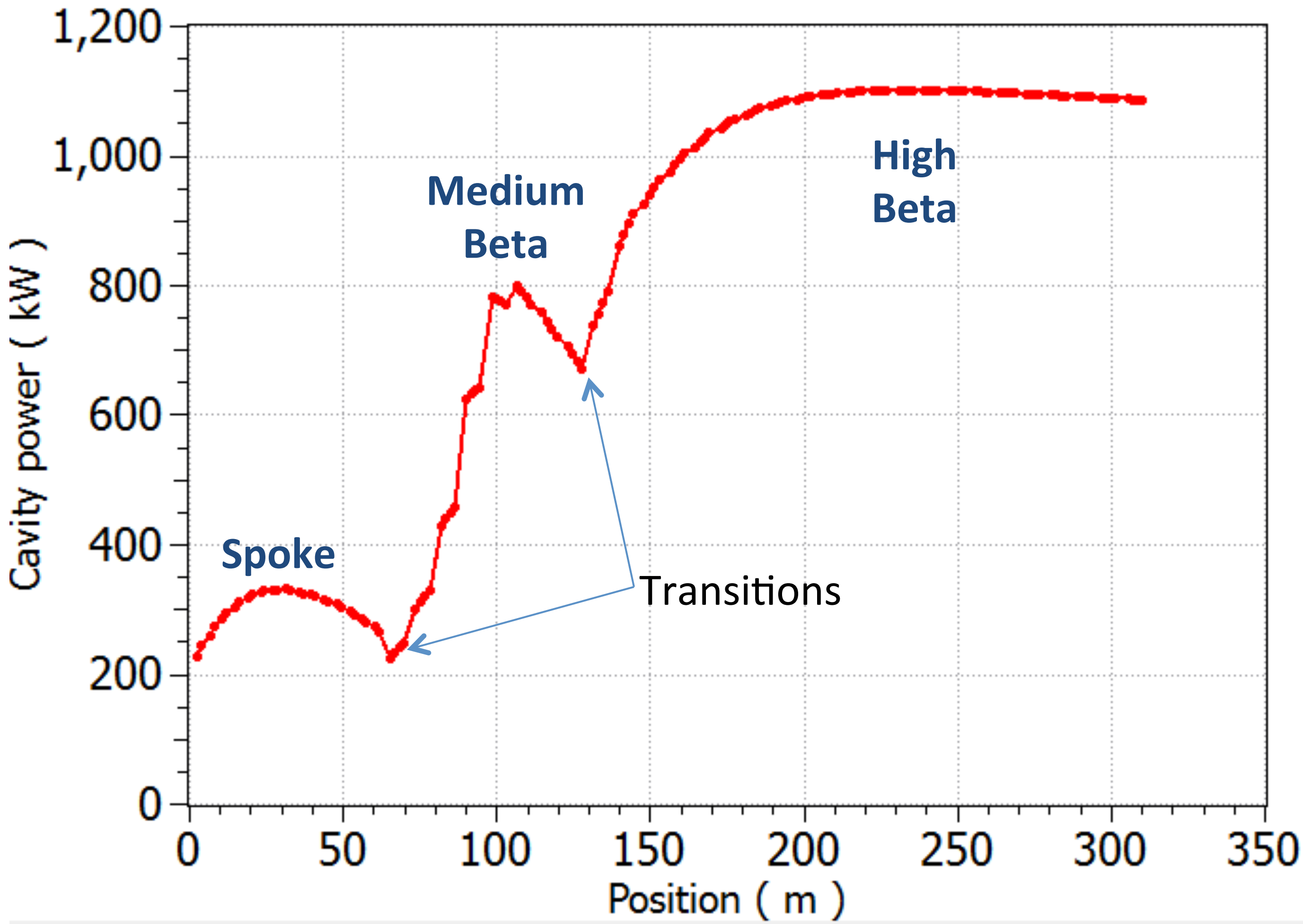
- Because of fabrication techniques,
  - superconducting cavity strings are usually much shorter (< 1 m) than copper cavity strings (> 5m).
  - The Lorentz de-tuning coefficient varies from cavity to cavity
- Therefore, each superconducting cavity has its own RF power source



Transit Time Factor

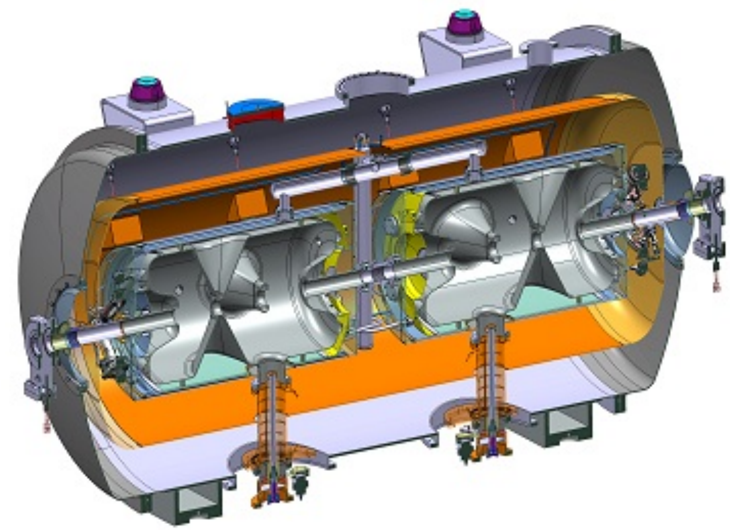
- For proton linacs using copper RF cavities
  - the cavity cell structure is tuned to match the changing proton velocity as it accelerates.
  - The power profile is usually flat
- Because of high fabrication costs and difficulty,
  - The cell structure of superconducting cavities is tuned for only one beam velocity.
  - Multiple families of cell velocities are chosen. ESS cell velocities:
    - Spoke: $\beta_g = 0.5$
    - Medium beta: $\beta_g = 0.67$
    - 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**

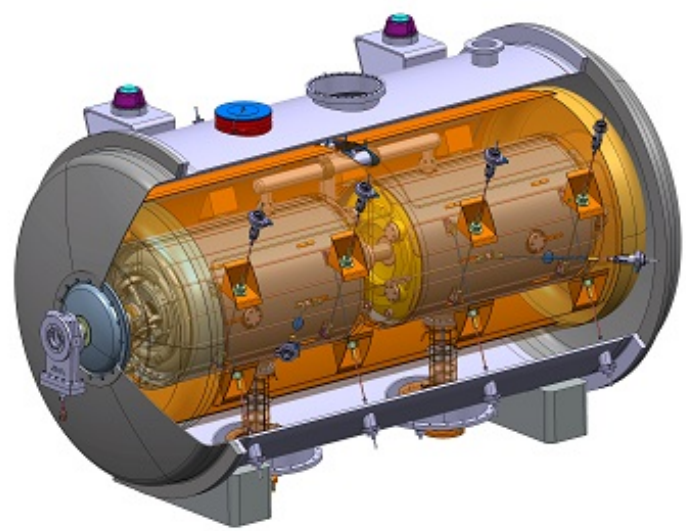
ESS Linac Cavity Power Profile



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





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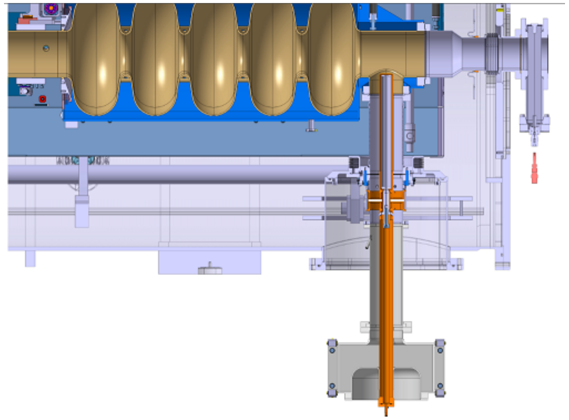
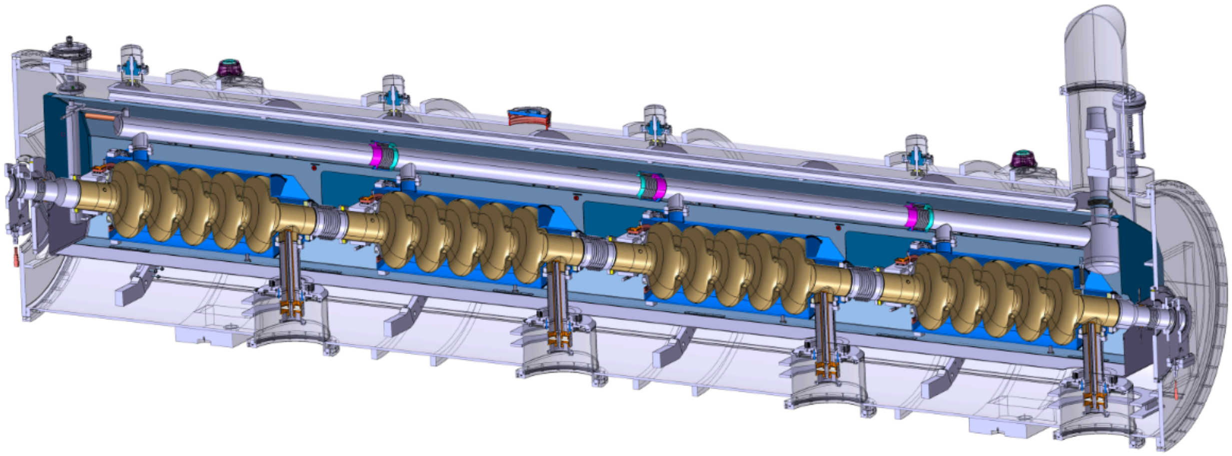
Elliptical Cavities

- 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 β_g = = 0. 86
  - 5 cell cavities
  - Cavity length = 0.92 m
  - 88 cavities packaged in 22 cryomodules
  - Maximum peak RF power = 1100kW





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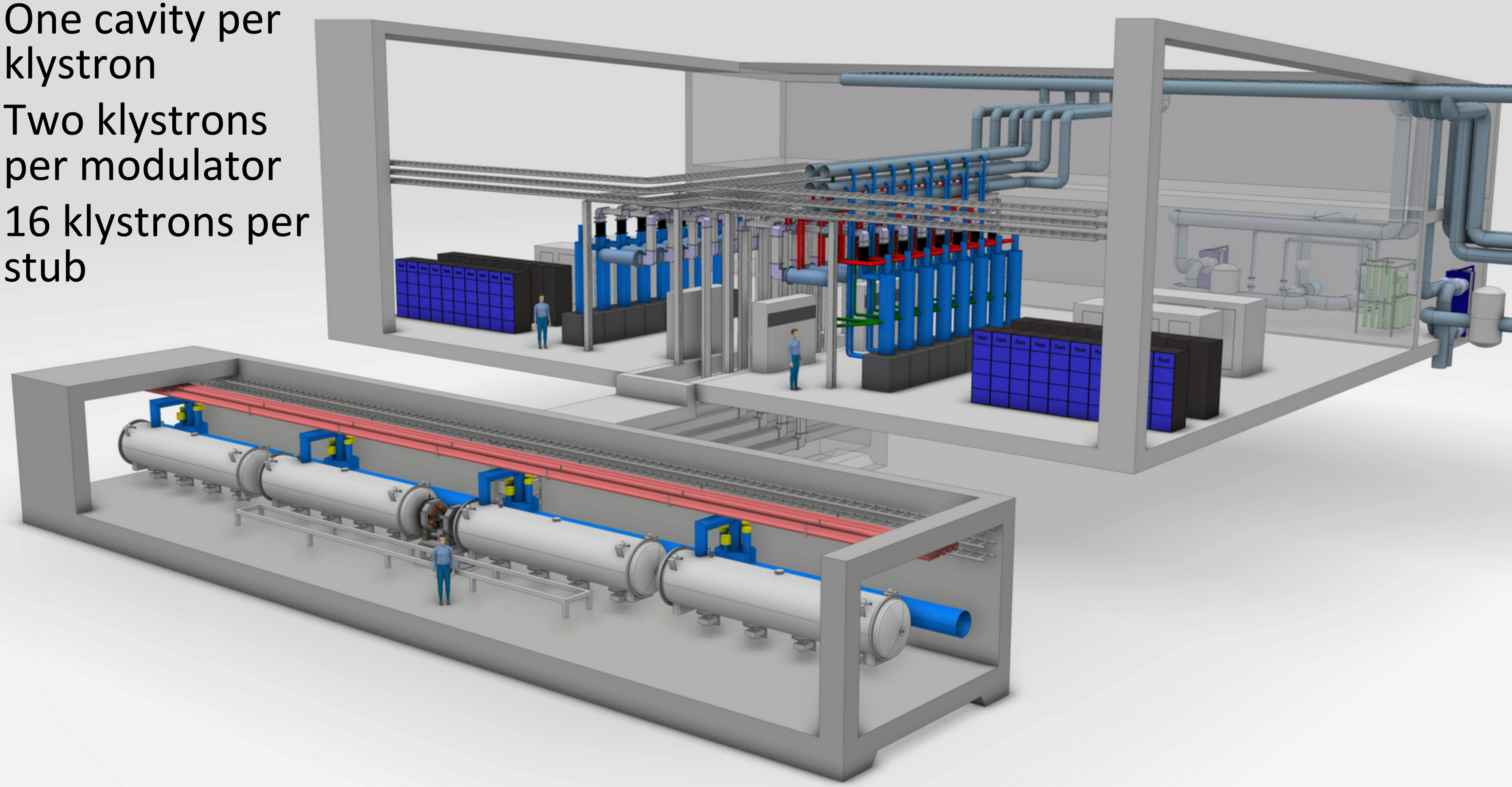
Elliptical RF System Layout

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



Cost Drivers

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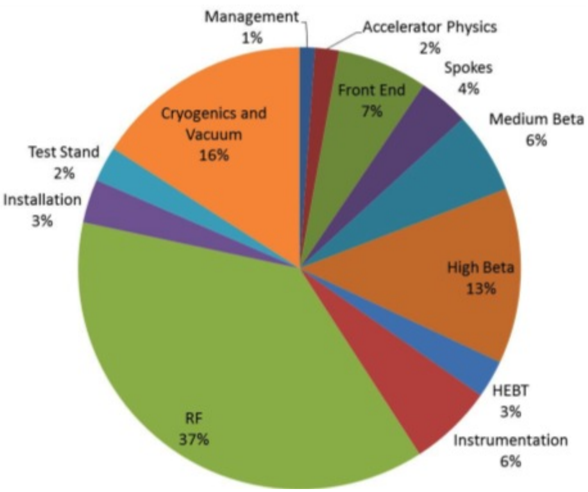
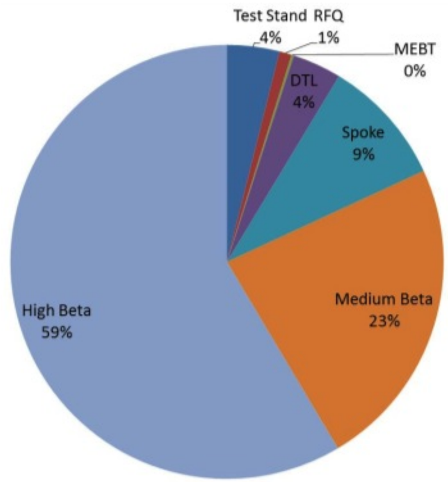
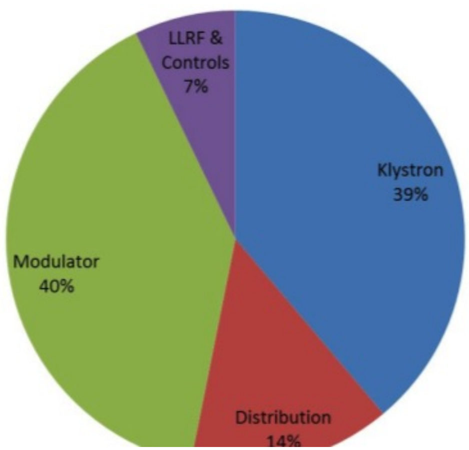


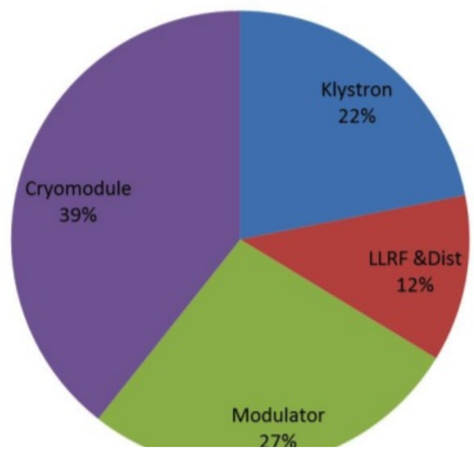
ESS Cost Distribution as of October 2012



RF System Cost Distribution



Cost breakdown for 704 MHz Elliptical RF systems



Cost breakdown for high beta cryomodule system.

- Elliptical cryomodules occupy 19% of the cost
  - There are 45 elliptical cryomodules
- The cryogenic plant absorbs 14% of the total cost.
- RF systems comprise 37% of the cost.
  - The RF costs are distributed over five major systems
  - The elliptical section comprises 82% of the RF system cost.
- For the elliptical section,
  - the klystrons and modulators comprise 80% of the RF system cost.
  - 62% of the total cost of the linac.
  - 92% of the acceleration energy

Courtesy of S. Gysin

Deliverables For the Redesign

- Lattice Design with Error Studies
- Level 1-4 requirements
- Cost Targets at Level 4
  - (Level 4 = Disciplines -> RFS, CRYO, PBI, etc.)
- Our goal is to deliver this by 1-October-2013

Timetable

- Level 1 and Level 2 requirements
  - Finalized by 15-August
- Level 3-4 requirements.
  - 15-August though 15-September
- 2nd iteration Cost Targets to Level 4.
  - 15-September through 1-October
- Work package re-Cost Estimate.
  - 1-October through 15-October
- Primavera Entry.
  - 15-October through 1-November
- Primavera Review.
  - 1-November through 10-November