Basic Linac Concepts

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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 (our closest competitor).
  - 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

5 MW of Beam Power

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

Difference Between ESS and the LHC

EUROPEAN SPALLATION SOURCE

- The LHC (Large Hadron Collider) in Switzerland is the most energetic accelerator in the world
- Is analogous to a power washer
  - Little volume
  - Comes out at high speeds

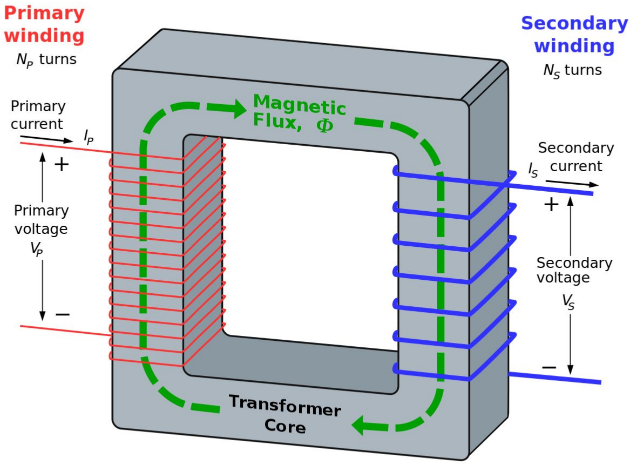
- ESS will be the most powerful accelerator in the world
- It is analogous to an open fire hydrant
  - Large volume
  - Comes out at low speeds

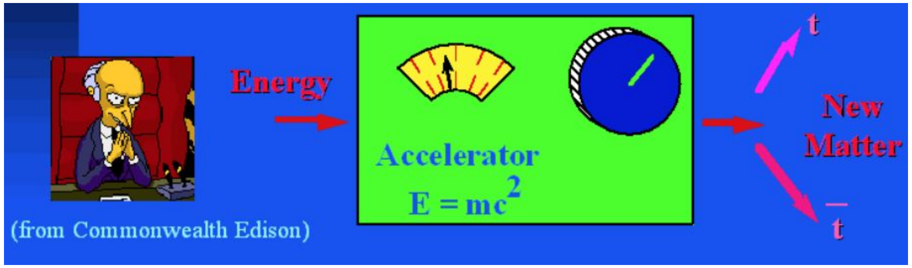
Accelerator 101

www.europeanspallationsource.se

Energy Transformer

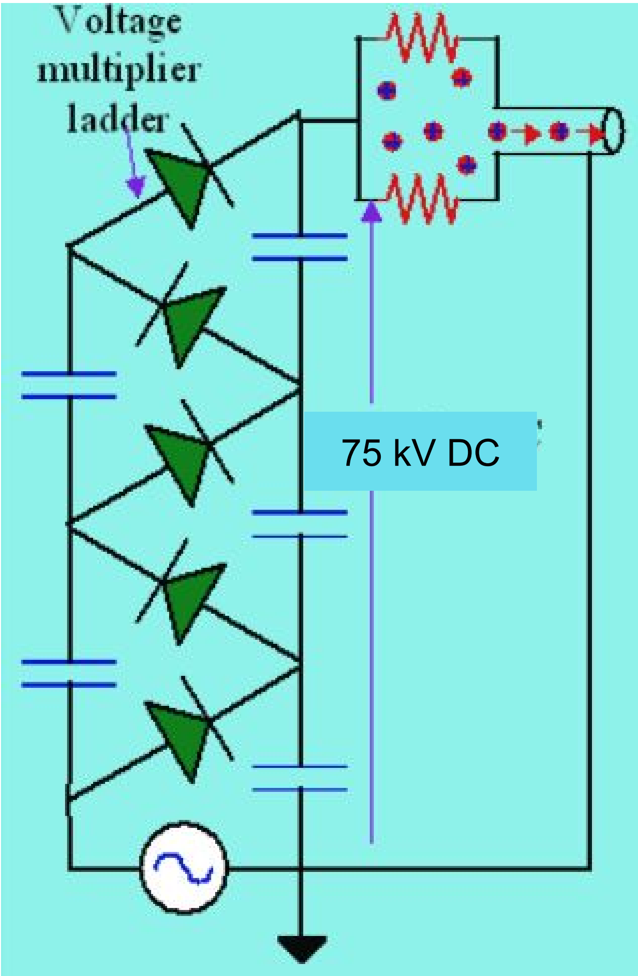
- The ESS Linac can be thought of as an energy transformer
- Conventional electric energy comes in from power lines
  - 400V x 35 x 1600 A
- Energy comes out of the Linac
  - 2,000,000,000 V x 0.0025 A
  - A rate of 5 MW
- Effective voltage step up ratio of 5,000,000
- Efficiency ~ 20%





First Stage of Acceleration

- The Ion Source is the first stage of acceleration
  - Can be thought of as a simple DC voltage
  - ESS will use a 75 kV source
- The effective final "voltage" of the Linac is 2,000,000,000 V.
  - Air can stand off about 3MV/meter
  - For a DC accelerator, would need over 600 meters keep clear distance in all 3 directions of keep clear space to stand off 2 GV DC
- Must use a different technique than DC to accelerate.



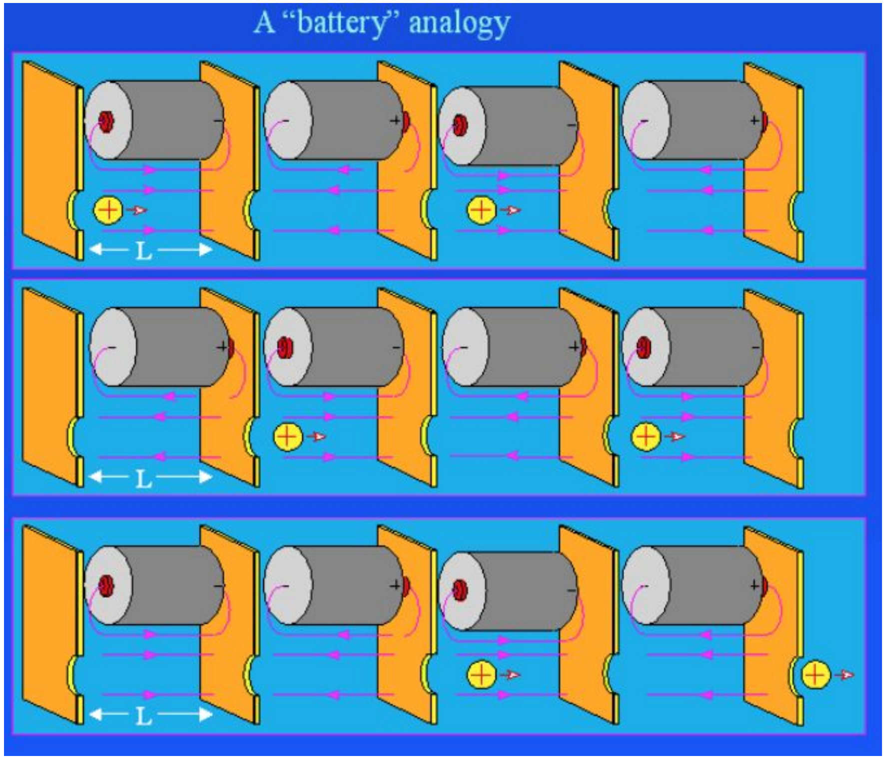
RF Acceleration - Battery Analogy

- Consider batteries placed end to end with opposite polarity
    - Average voltage is zero
- Flip batteries as particle goes through
    - Particle sees the effective voltage of N batteries
- We don't really use batteries...

$$t = 0\,\text{sec.}$$

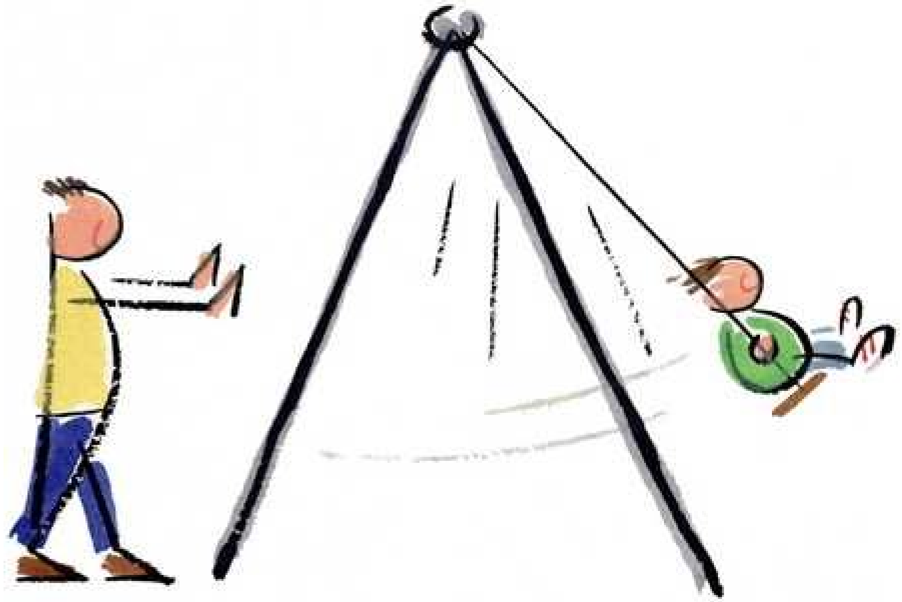
$$t = \frac{L}{v}\,\text{sec.}$$

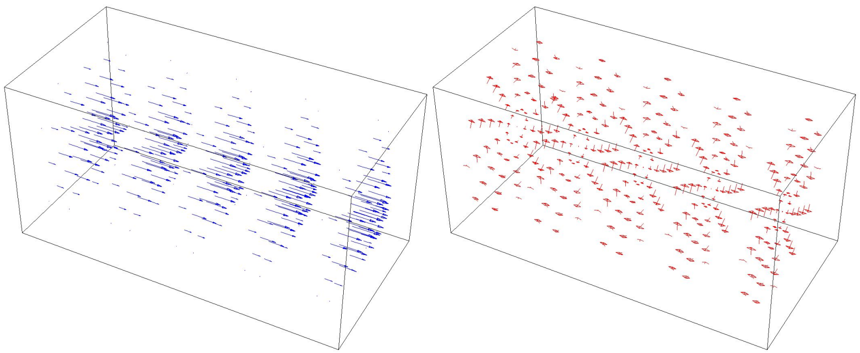
$$t = \frac{2L}{v}\,\text{sec.}$$



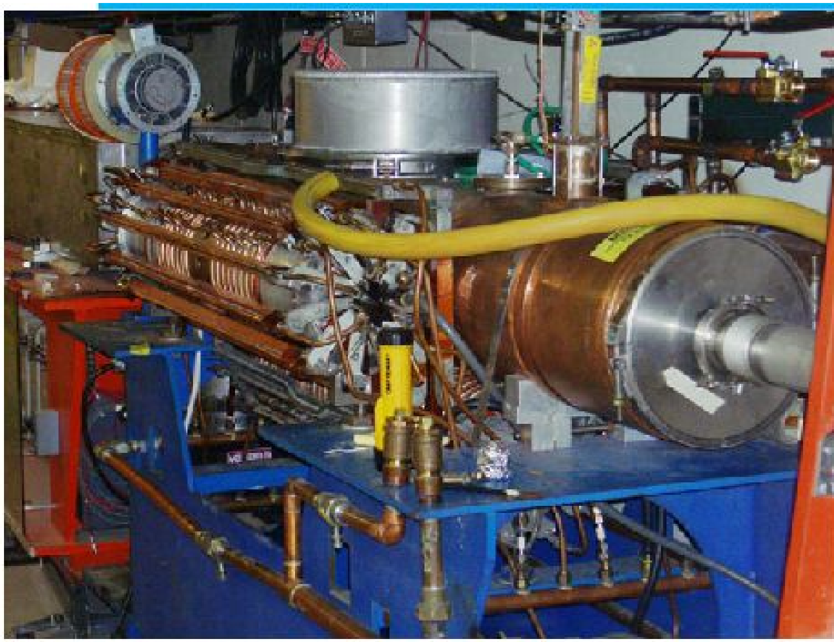
Radio Frequency (RF) Cavities

- A hollow copper box (cavity) can store electromagnetic waves
  - Electromagnetic waves bounce off the copper walls
  - Similar to light reflecting off a mirror
  - If the frequency is right, the reflected waves can build up in resonance
    - Similar to pushing somebody on a swing - you have to push at the right frequency

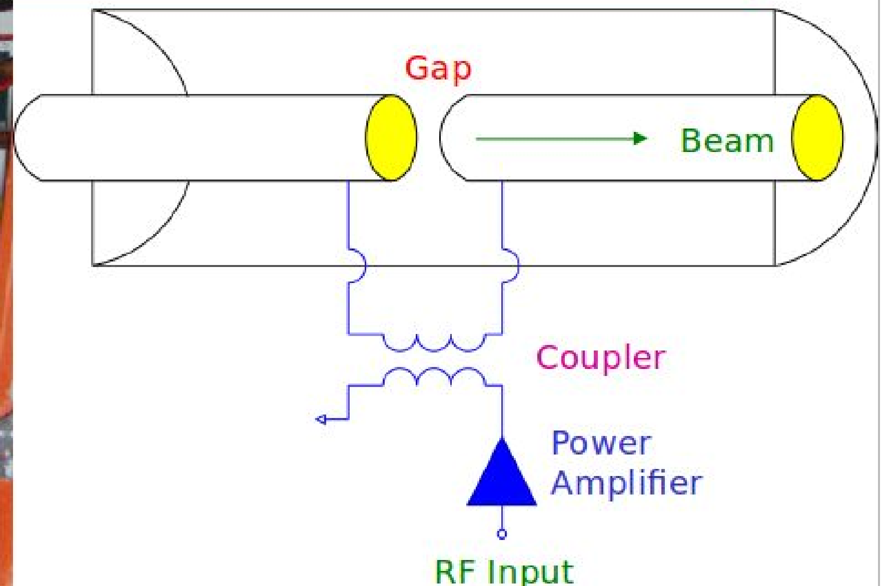




RF Cavities



New FNAL Booster Cavity

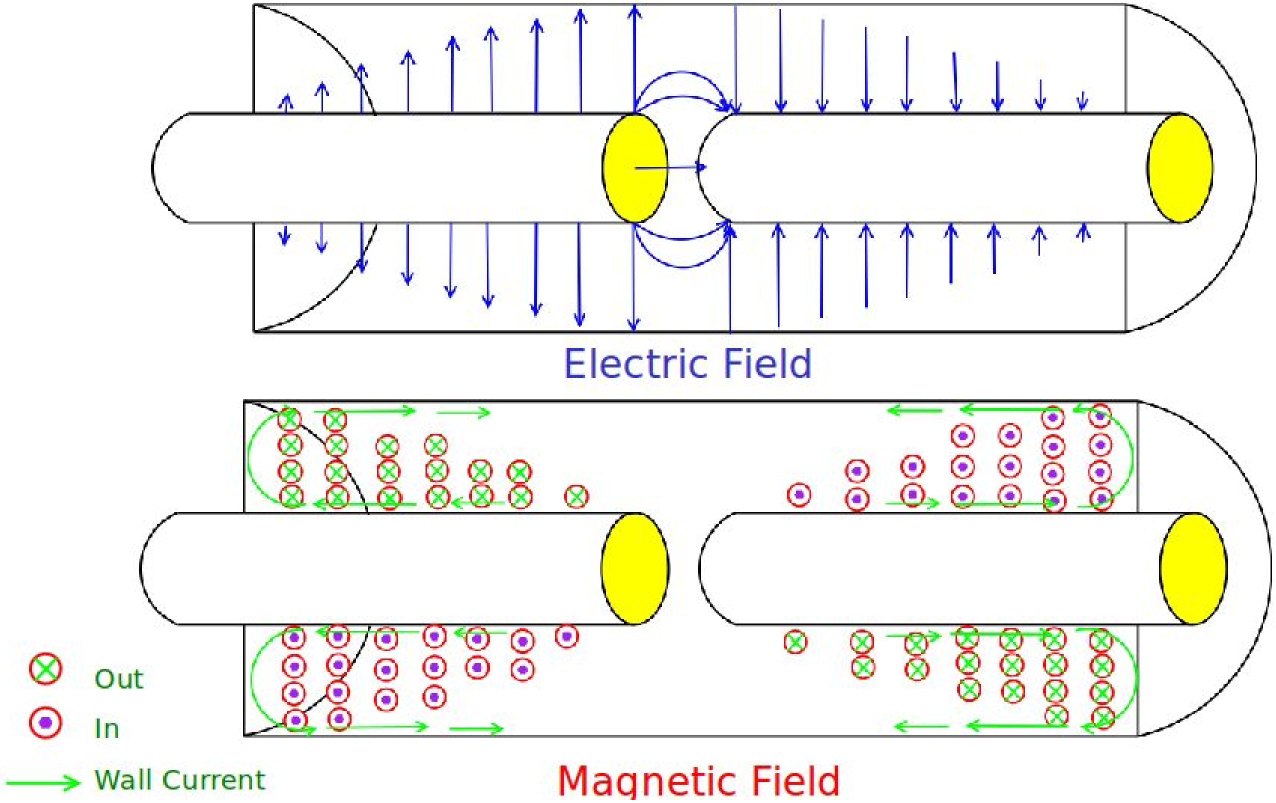


Transmission Line Cavity

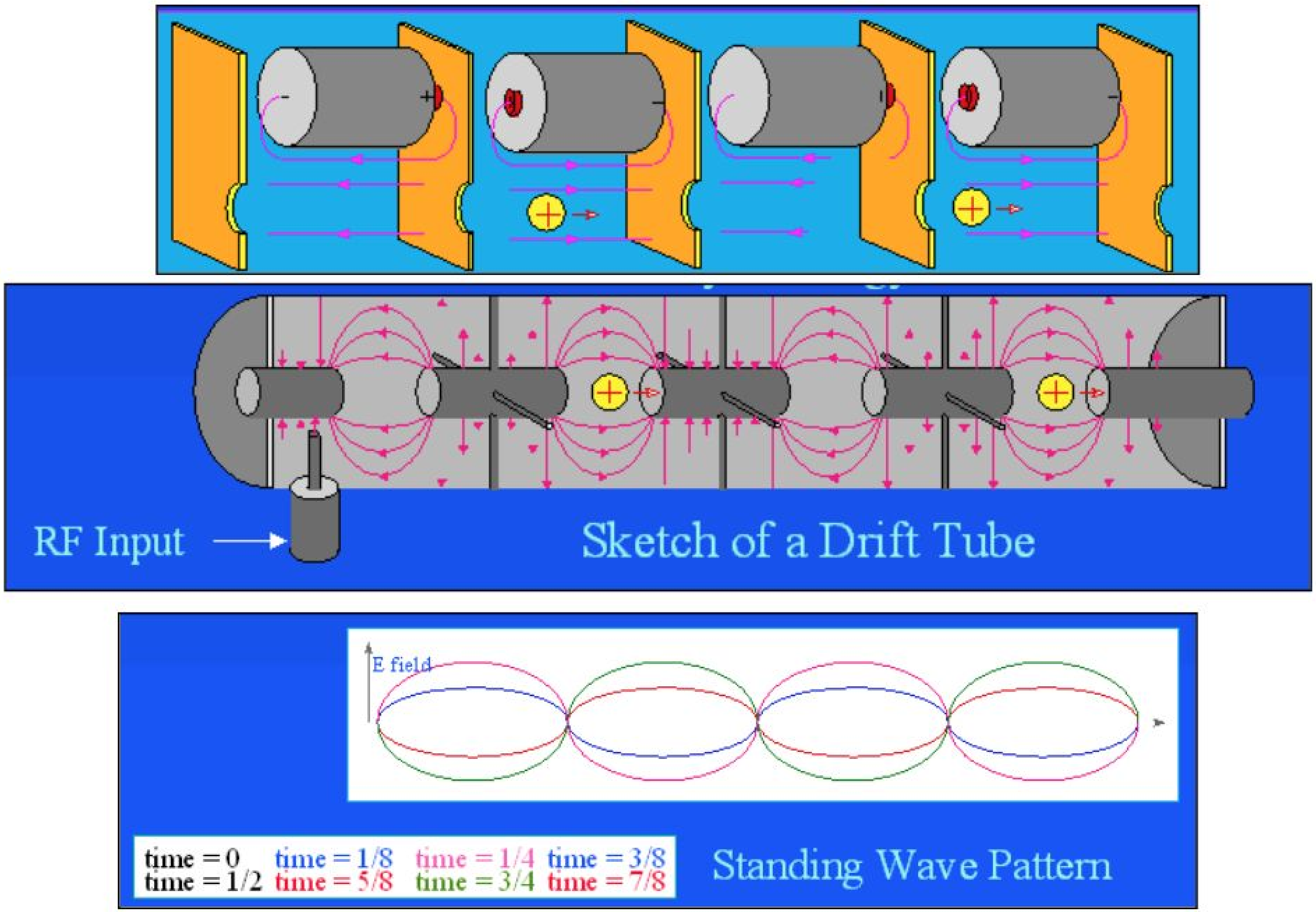
Multi-cell superconducting RF cavity

Rf Cavity Modes

For the fundamental mode at one instant in time:

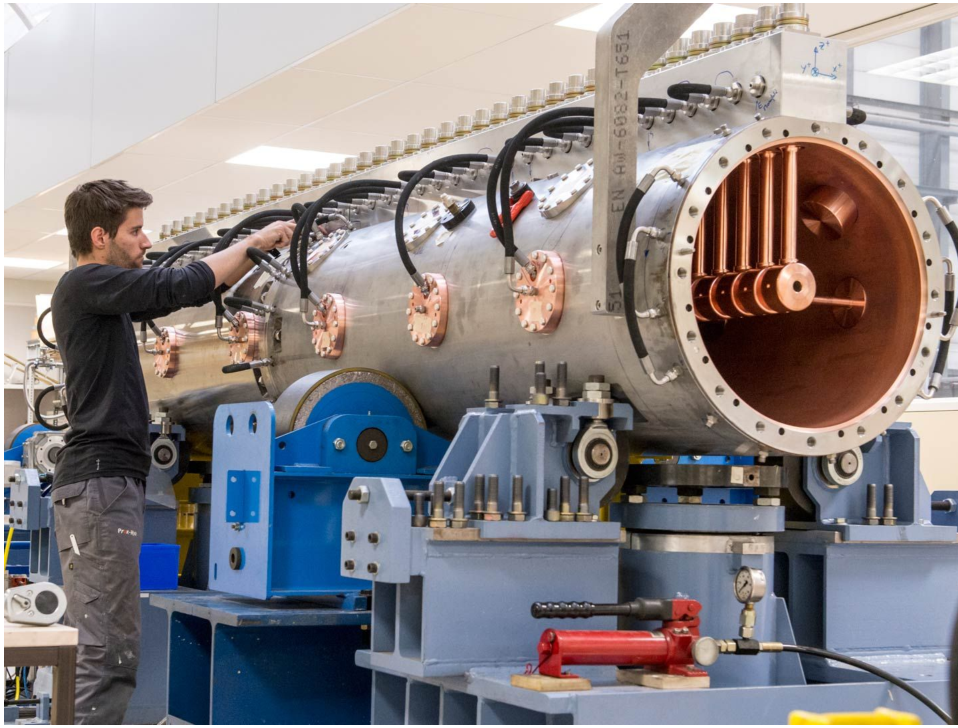


Drift Tube Linac



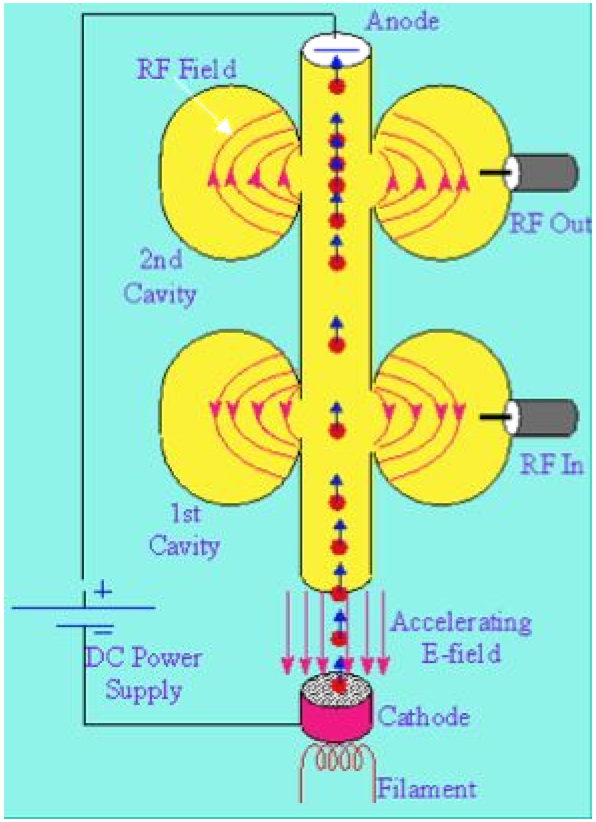
Drift Tube Linac

EUROPEAN SPALLATION SOURCE

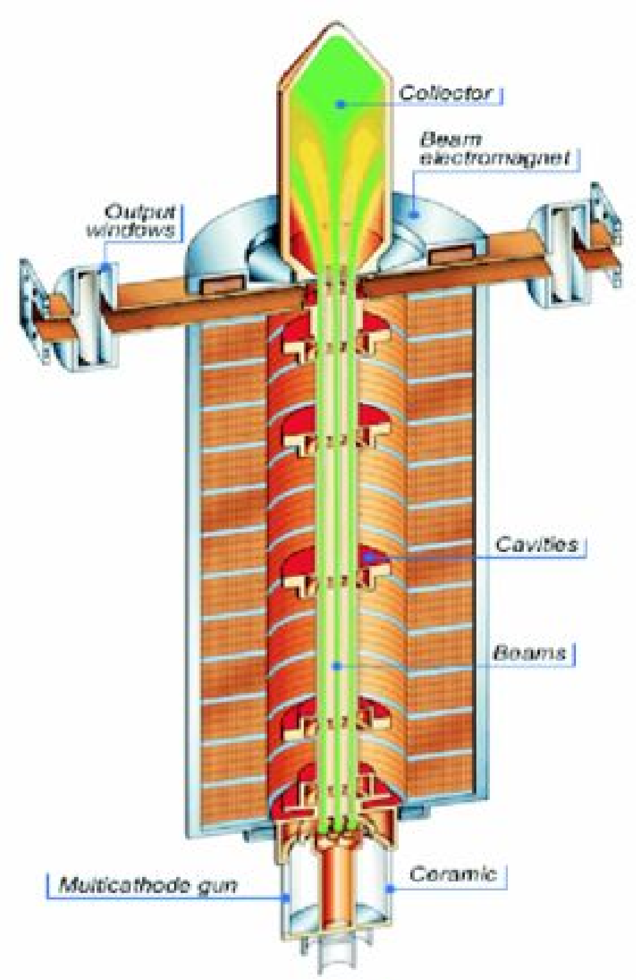


RF Power - Klystrons

- Electromagnetic energy must supplied to the RF accelerating cavities to compensate for:
  - Power lost in the walls of the cavity
  - Power supplied to the beam
- A standard device for supplying RF power to cavities is called a Klystron (invented in 1937)
  - The filament boils electrons off the cathode
  - The velocity (or energy) of the electrons is modulated by the input RF in the first cavity
  - The electrons drift to the cathode
  - Because of the velocity modulation, some electrons are slowed down, some are sped up.
  - If the output cavity is placed at the right place, the electrons will bunch up at the output cavity which will create a high intensity RF field in the output cavity
  - Klystrons need a minimum of two cavities but can have more for larger gain.
  - A Klystron size is determined by the size of the bunching cavities.
  - Klystrons are used at high frequencies (>300 MHz))



Klystrons


Collector
Beam electromagnet
Output windows
Cavities
Beams
Multicathode gun
Ceramic

Powering a Klystron

- A klystron requires a DC (or pulsed DC power source to accelerate the electrons in the tube
- A modulator converts AC power to pulsed DC power for a klystron
  - AC is converted into DC with an input rectifier
  - DC Charges a capacitor bank
  - When beam comes, the main switch opens the capacitor reservoir is emptied into a pulse transformer that is connected to the klystron
- ESS Modulator
  - Number of Modulators = 35
  - Klystrons per modulator = 4
  - Modulator input power = 650 kW
  - Modulator output voltage = 120kV
  - Klystron Pulsed current = 25 A

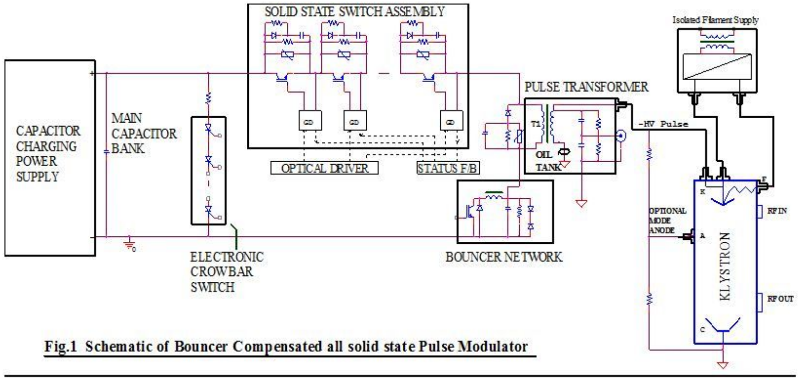
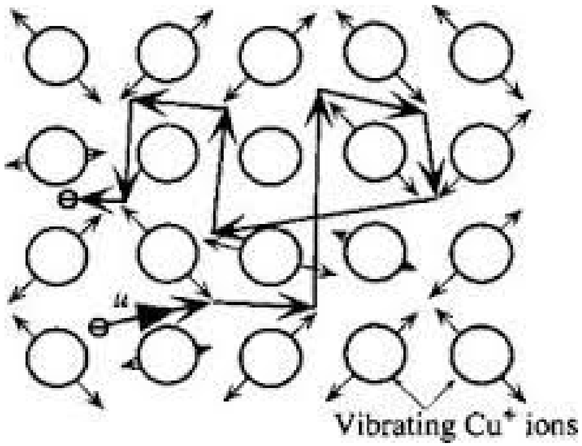


Fig.1 Schematic of Bouncer Compensated all solid state Pulse Modulator

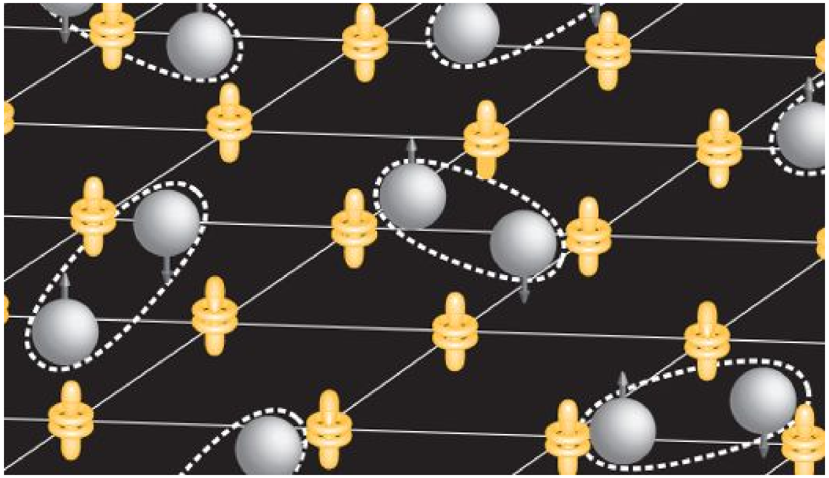
Superconducting RF

- Copper is not a perfect conductor
  - A wire heats up when current is passed through a wire
  - Caused by electrons scattering off the metal ions.
  - The warmer the temperature, the more the ions jiggle, the higher the probability that the electrons will bump into the ions
  - As copper is cooled down the ions jiggle less and the wire resistance goes down
  - Because of the resistance in the walls, the electromagnetic energy is lost in the walls and the cavity empties its energy



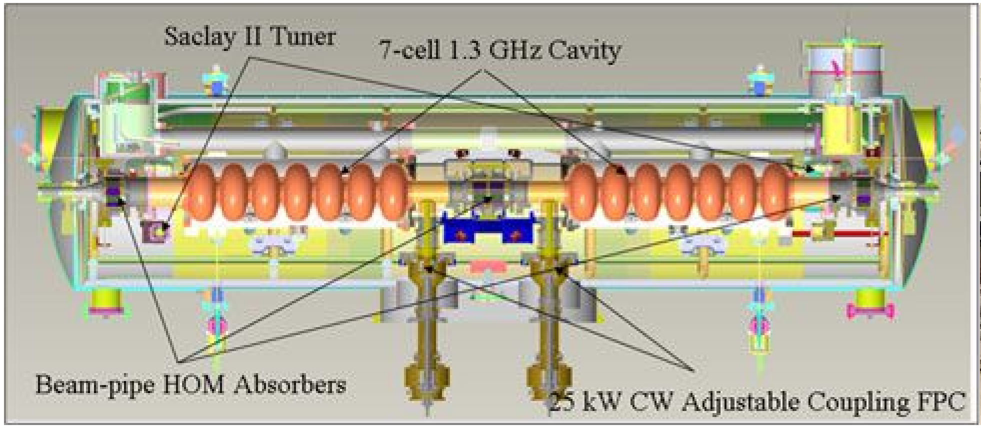
Superconducting RF

- Certains metals (Niobium, Lead, …) go a step further
  - As the metal is cooled down, electrons begin to pair up
  - As one of the electrons in the pair goes near a metal ion
    - It attracts the metal ion to it
    - Opening up a gap for the other electron to slip through and not bump the ions
  - The resistance of the metal goes to zero
  - Energy will stay in the cavity and less power is required
  - This pairing up only happens at very cold temperatures (-269C)



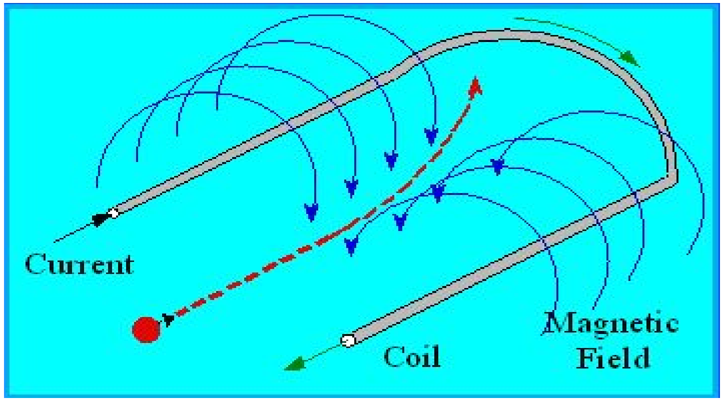
Superconducting RF: Cryomodules

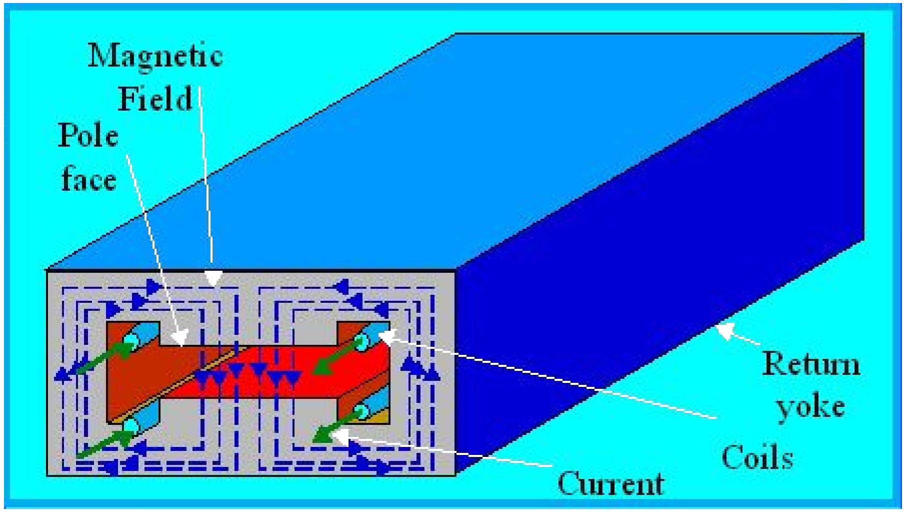
- The only problem with superconducting RF is that the cavities must be cooled to below -269C.
- Cavities are cooled to this temperature with liquid helium
- The cooling vessel that contains the cavities and liquid helium is called a cryomodule.



Other Technologies: Bending Magnets

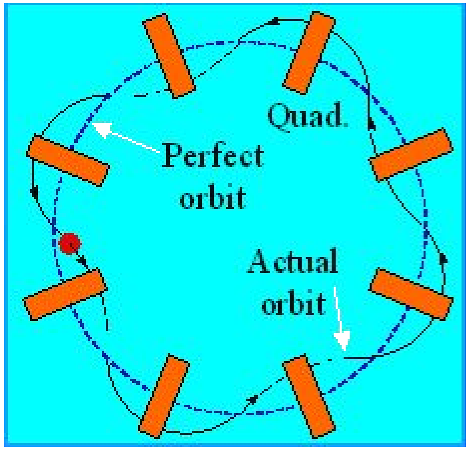
- Bending magnets are used to control a charged particle’s path.
  - Perpendicular to the particle’s direction
  - Perpendicular to the field’s direction
- Bending magnets are made of dipoles.
  - The magnet body confines and concentrates the magnetic field
  - The pole faces shape the magnetic field

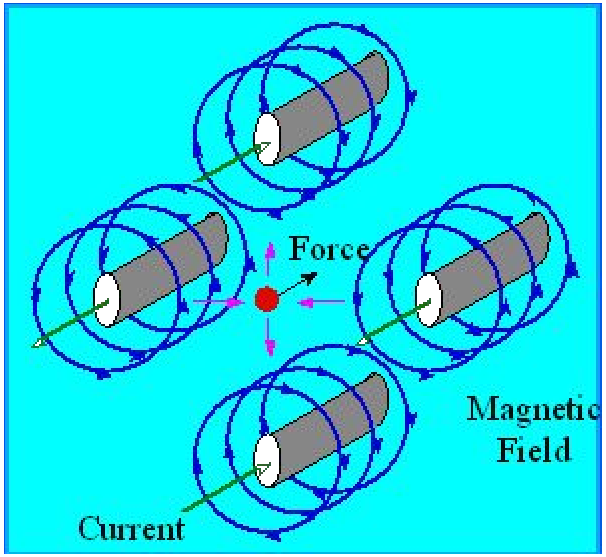


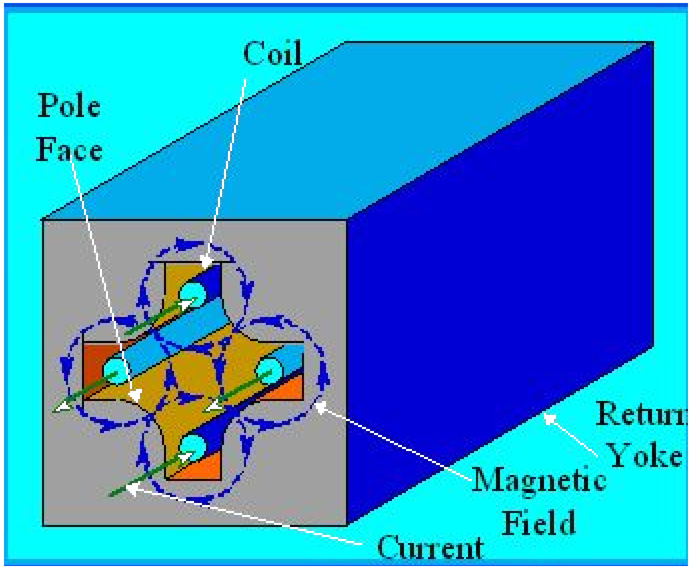


Focussing Magnets

- Not all the particles are on the perfect path.
- Quadrupoles are needed for focussing particles
  - If the particle is on the correct path: don't do anything
  - If the particle is on the inside path: bend to the outside
  - If the particle is on the inside path: bend to the inside

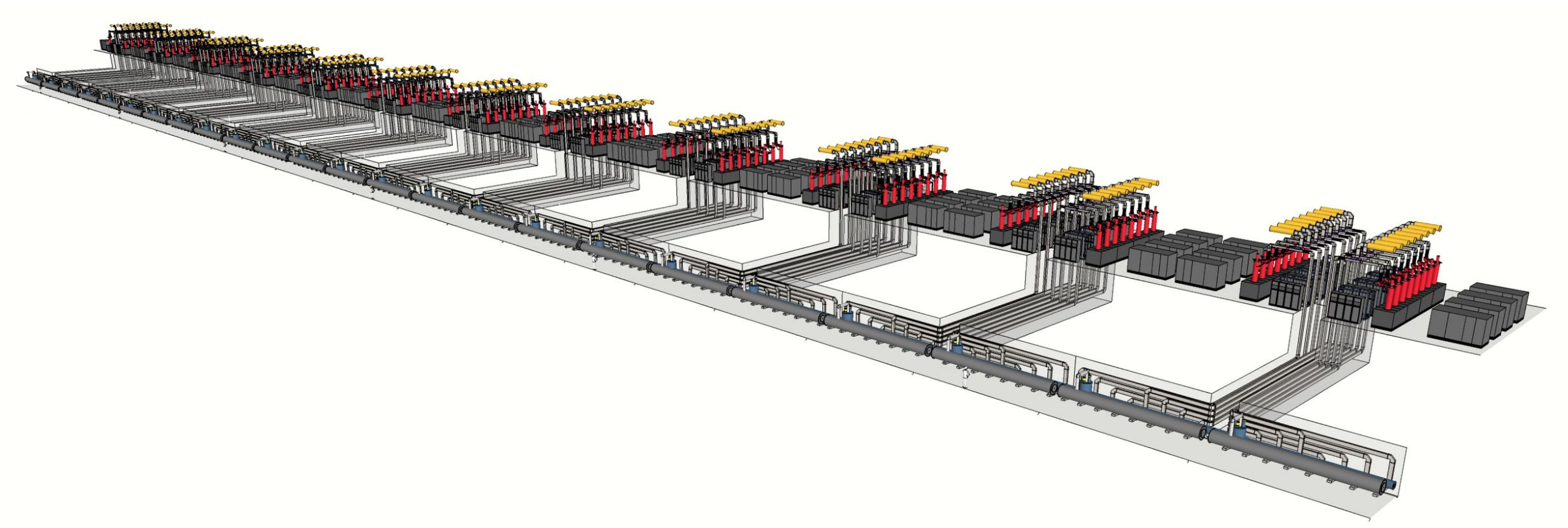






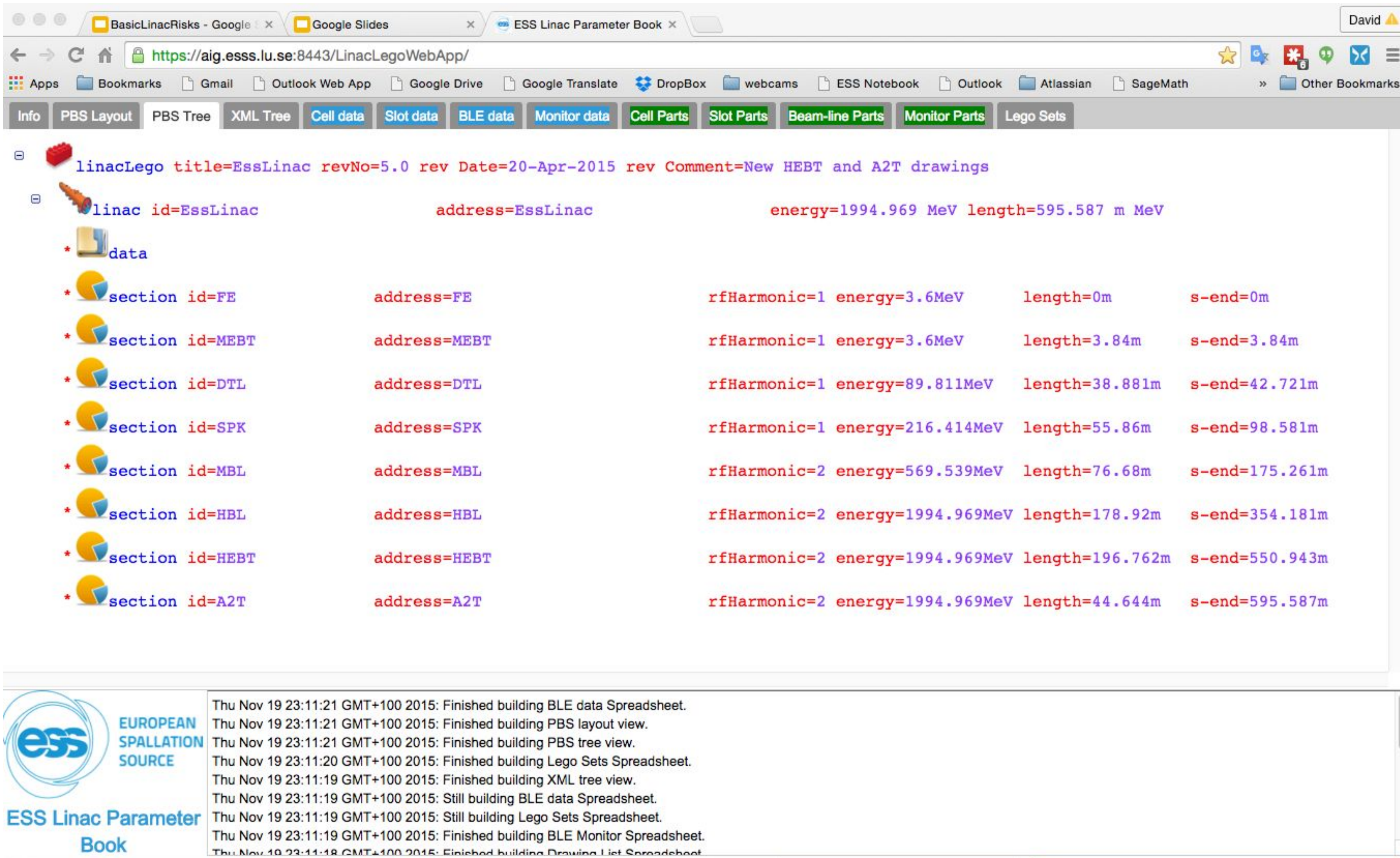
Magnet lattice

- Eventually particles that are on the inside and bent to the outside with a quadrupole will reach to the outside and overshoot (and vice-versa)
- You need more than one quadrupole to focus the beam as travels the linac.
- The arrangement of quadrupoles is called a lattice in which the strengths of the quadruples is carefully chosen.



ESS LINAC

Linac Configuration (LinacLego)



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".

Conventional Facility Costs

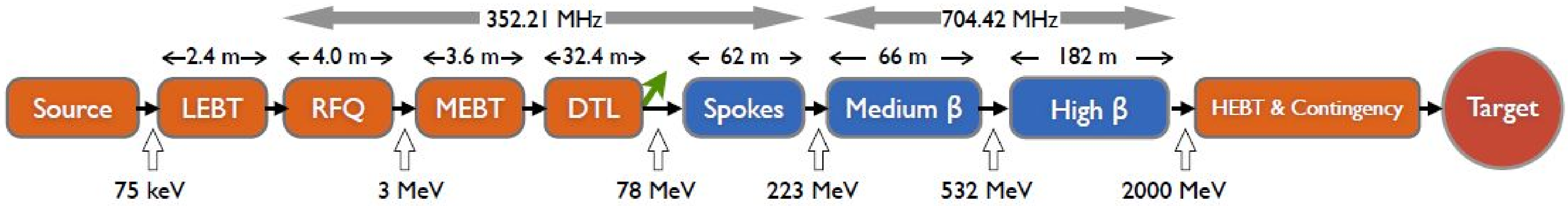
- The approximate costs for conventional facilities are:
  - Tunnel: 22,900 €/m (3270 k€ / m^2) including berm, auxiliary costs
  - Gallery: 46,200 €/m (2800 k€ / m^2)
- The cost of accelerator equipment is:
  - 6.5 M€ / cryomodule which includes the RF power
  - Average cost of superconducting RF accelerator equipment is:
    - 790,000 €/m
    - 35x more expensive than tunnel cost
    - 11.4x more expensive than total CF cost
  - Average beam power cost for the accelerator equipment in a cryomodule cell is 18kW / M€.
- The cost of the 127 meter contingency space without stubs and gallery is 2.9 M€
  - Equivalent to the cost of accelerator equipment needed to supply 0.052 MW of average beam power (1% of 5 MW)

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

EUROPEAN SPALLATION SOURCE

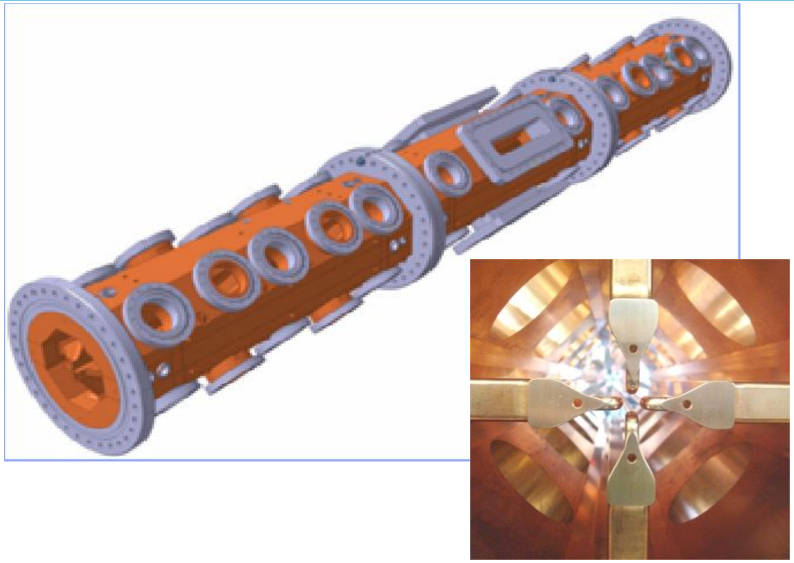
- Ion source : Istituto Nazionale di Fisica Nucleare (INFN) – Catania, Italy
- Radio Frequency Quadrupole (RFQ): Commissariat à l'énergie atomique (CEA) – Saclay, France
- Medium Energy Beam Transport (MEBT): ESS-Bilbao, Spain
- Drift tube Linac (DTL): Istituto Nazionale di Fisica Nucleare (INFN) – Legnaro,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

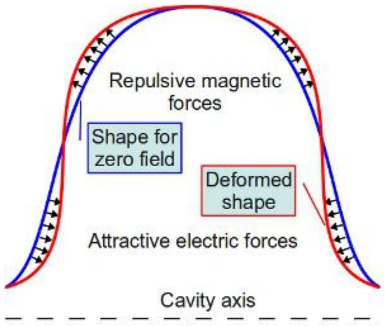


Superconducting RF

- 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

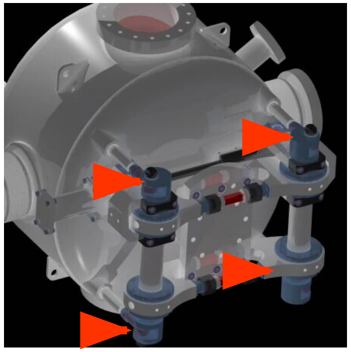
Lorentz De-tuning

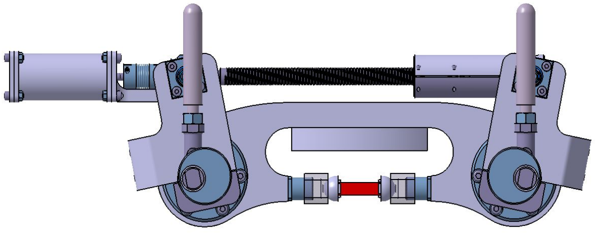
- Because of the enormous gradients in superconducting cavities,
  - the radiation pressure deforms the cavities
- We expect over 400 Hz of detuning in the ESS cavities.
  - Unloaded cavity bandwidth = 0.07 Hz
  - Loaded cavity bandwidth = 1 kHz
- The mechanical time constant of the cavities is about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



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

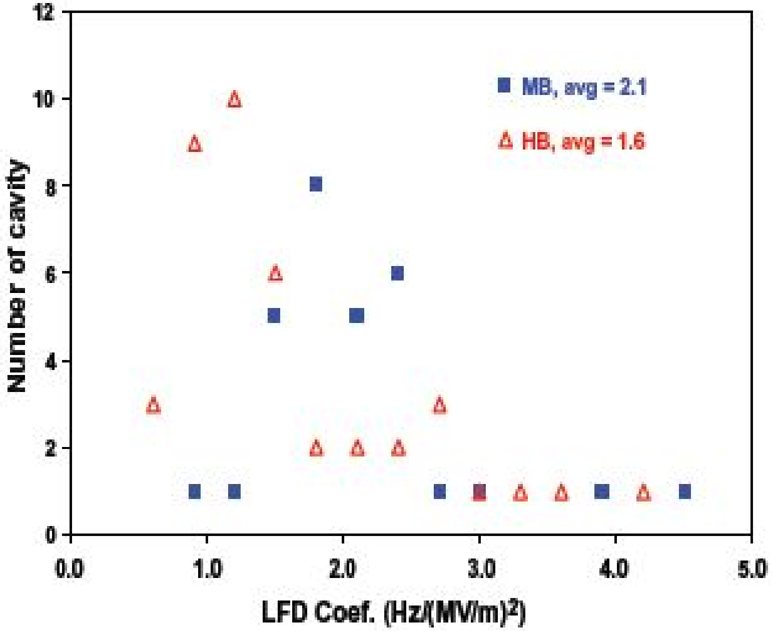
$$\Delta f_0=(f_0)_2-(f_0)_1=-K E_{acc}^2$$





Cavity Power Configuration

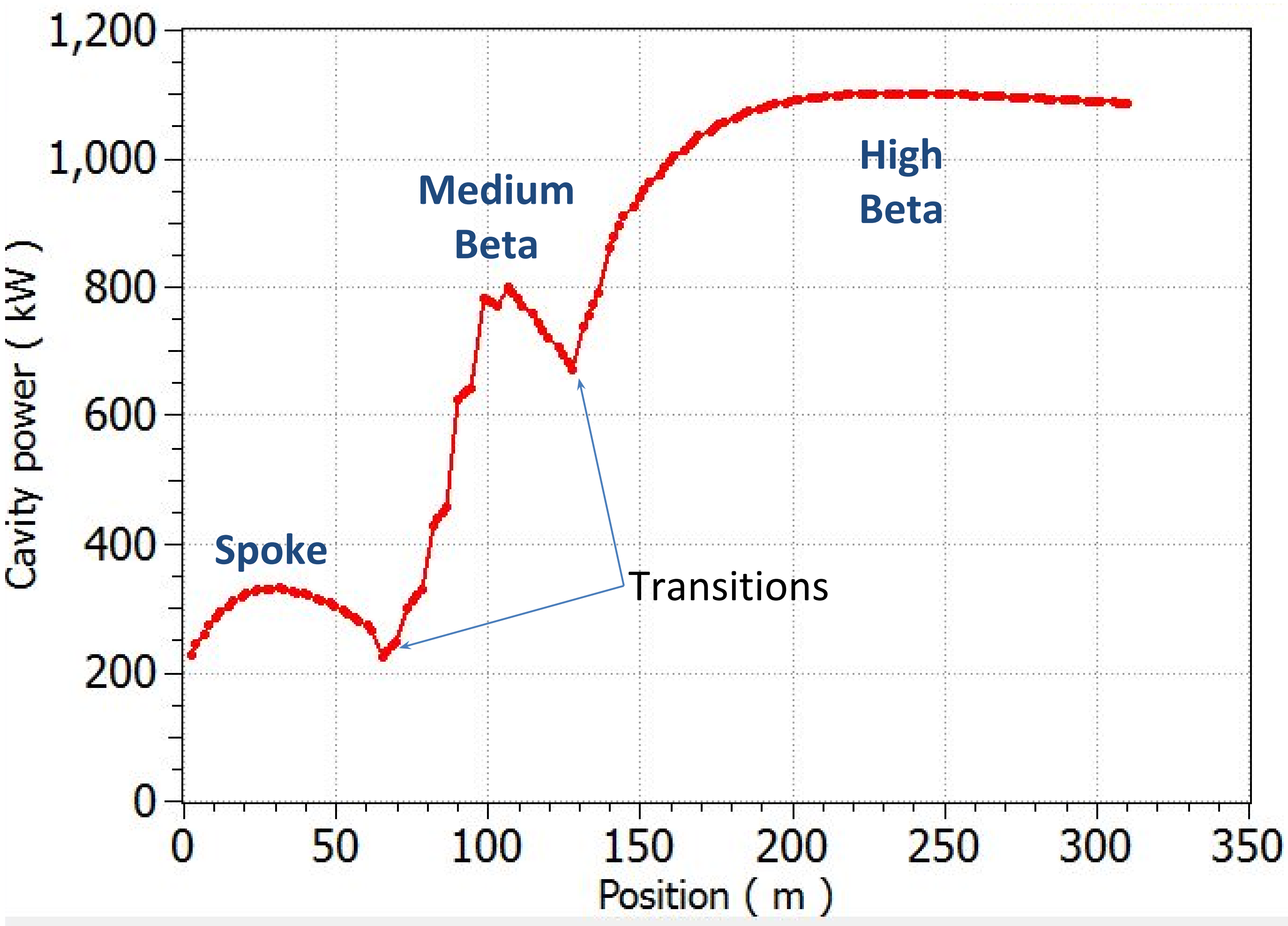
- Because of fabrication techniques,
  - superconducting cavity strings are usually much shorter (< 1 m) than copper cavity strings (> 5m).
  - The Lorentz de-tuning coefficient varies from cavity to cavity
- Therefore, each superconducting cavity has its own RF power source



Transit Time Factor

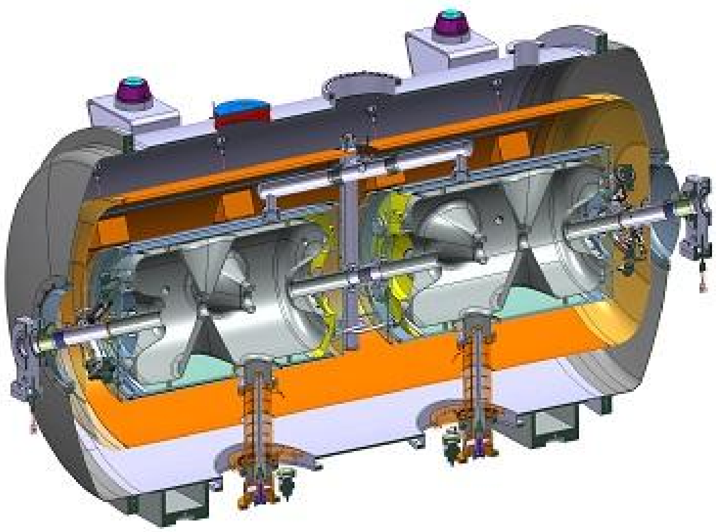
- For proton linacs using copper RF cavities
  - the cavity cell structure is tuned to match the changing proton velocity as it accelerates.
  - The power profile is usually flat
- Because of high fabrication costs and difficulty,
  - The cell structure of superconducting cavities is tuned for only one beam velocity.
  - Multiple families of cell velocities are chosen. ESS cell velocities:
    - Spoke: $\beta_g = 0.5$
    - Medium beta: $\beta_g = 0.67$
    - High beta: $\beta_g = = 0.86$
  - 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

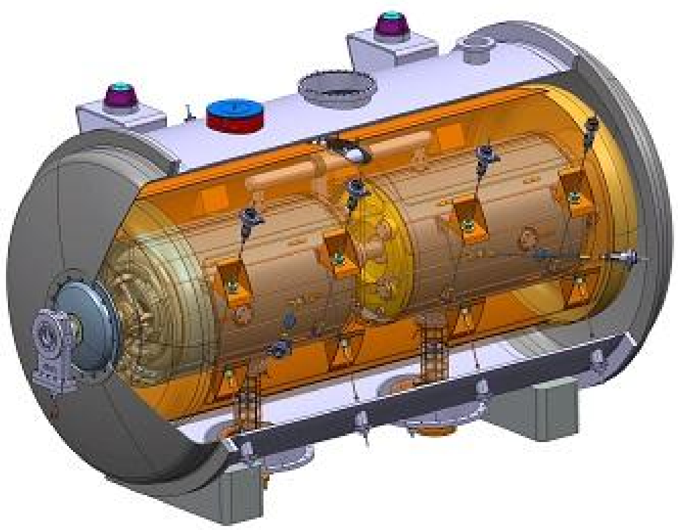
ESS Linac Cavity Power Profile



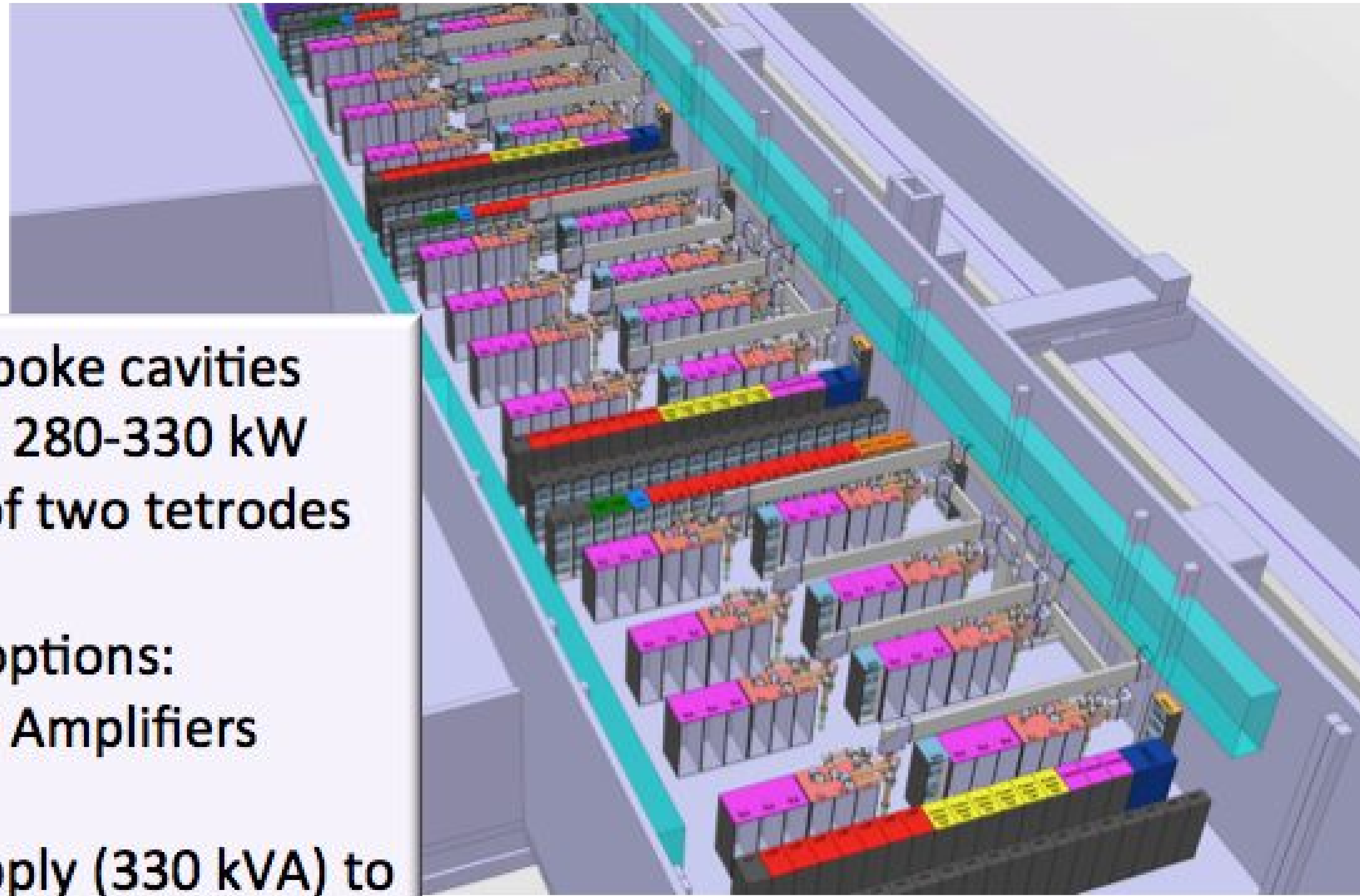
Spoke Cavities

- 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

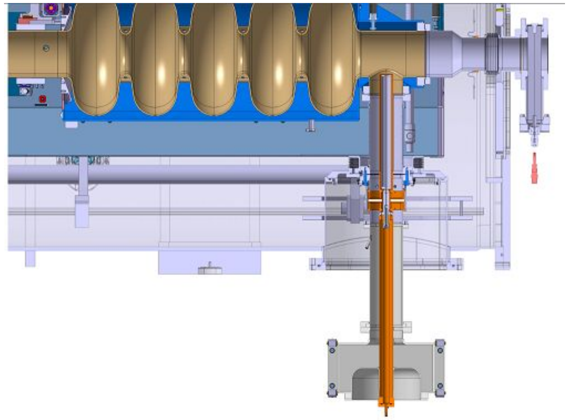
Other options:
Solid State Amplifiers

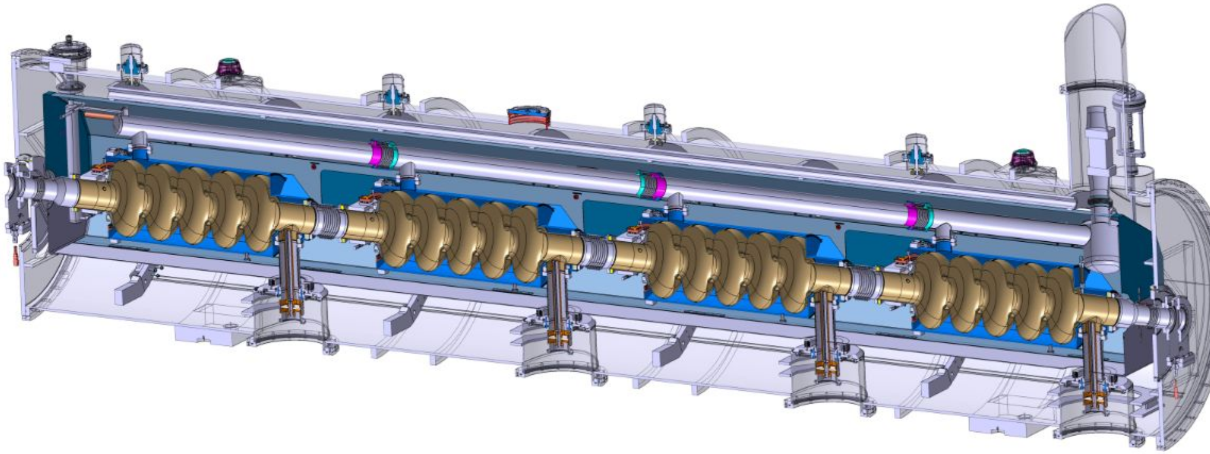
Large power supply (330 kVA) to supply 8 stations (16 tetrodes)

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)

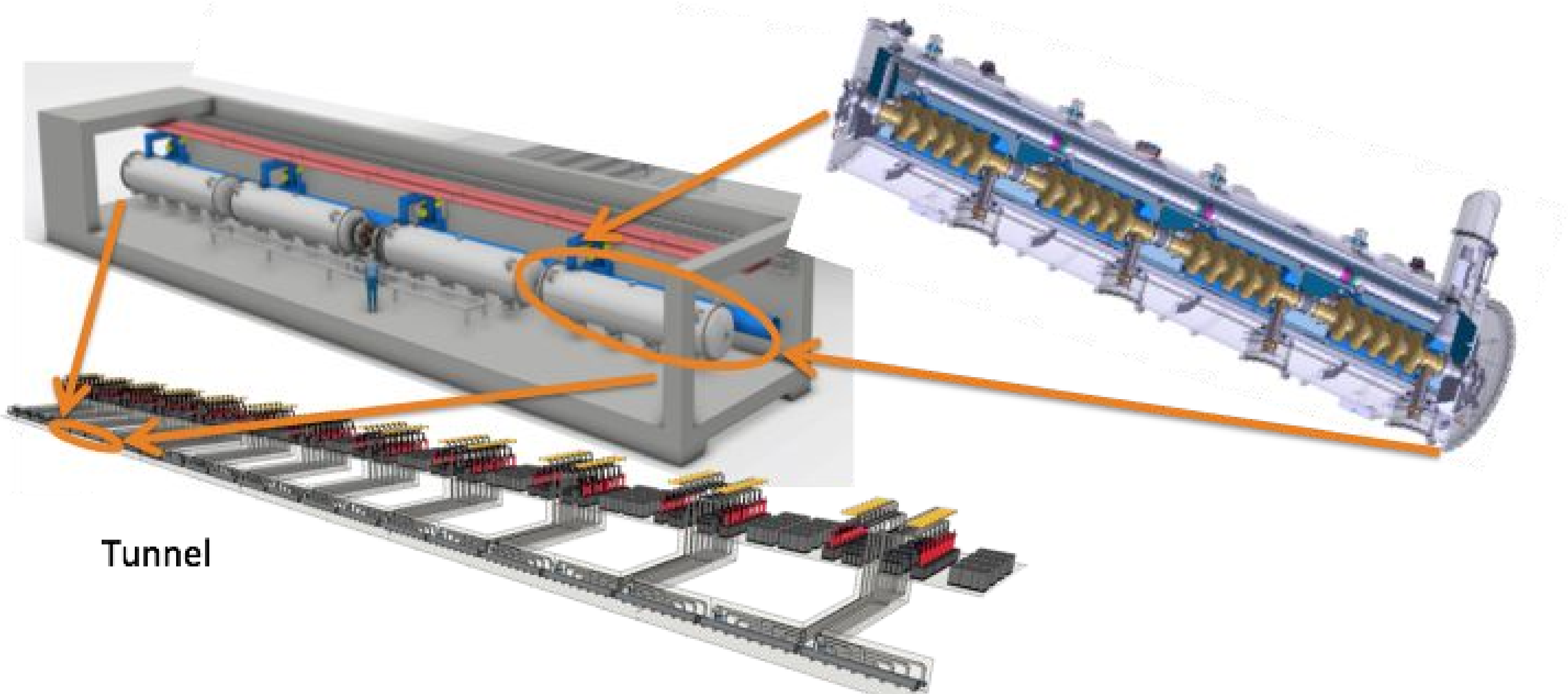
- Medium Beta β_g = 0.67
  - 6 cell cavities
  - Cavity length = 0.86 m
  - 32 cavities packaged in 8 cryomodules
  - Maximum peak RF power = 800kW
- High Beta β_g = = 0. 86
  - 5 cell cavities
  - Cavity length = 0.92 m
  - 88 cavities packaged in 22 cryomodules
  - Maximum peak RF power = 1100kW





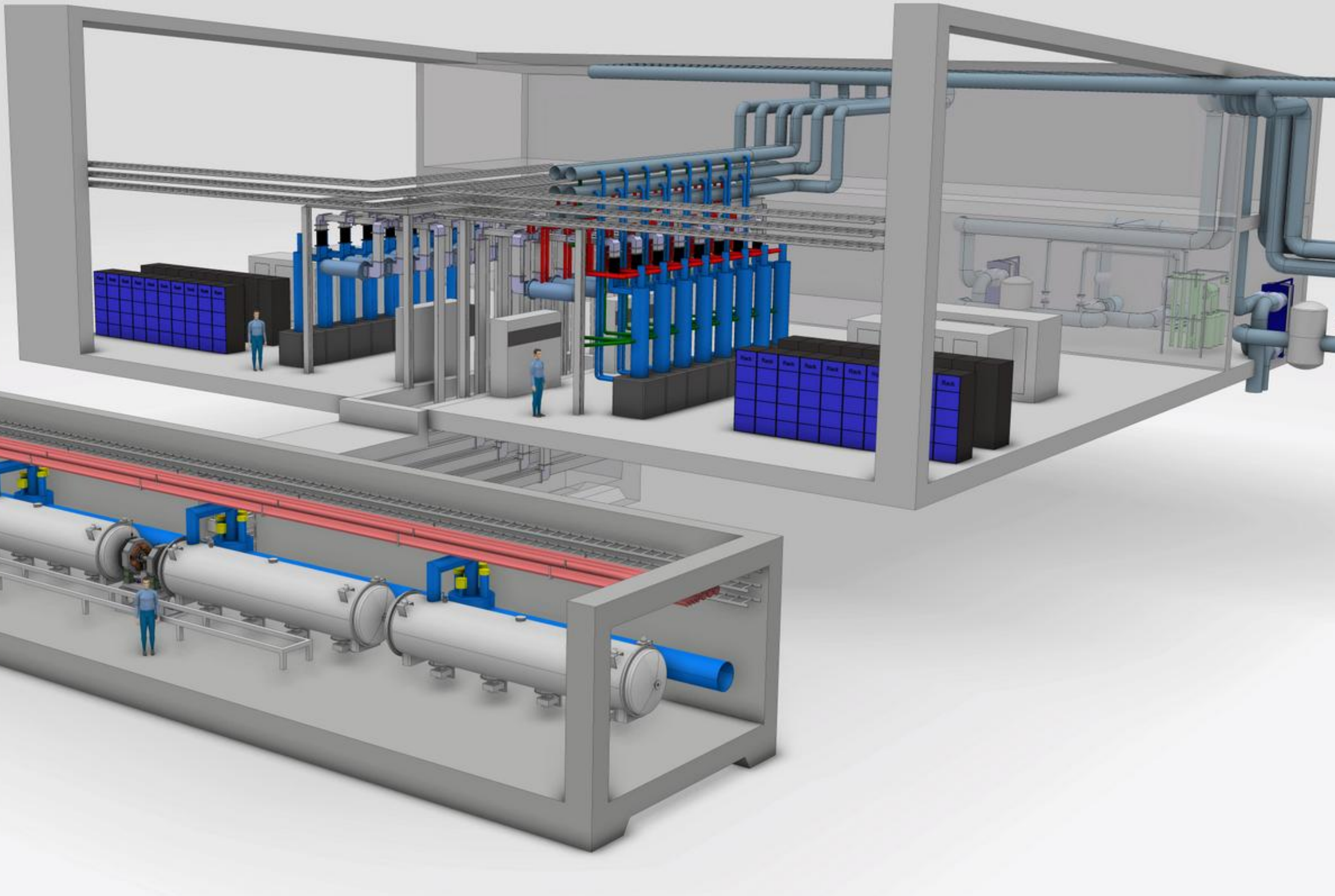
Elliptical (704 MHz) Layout

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

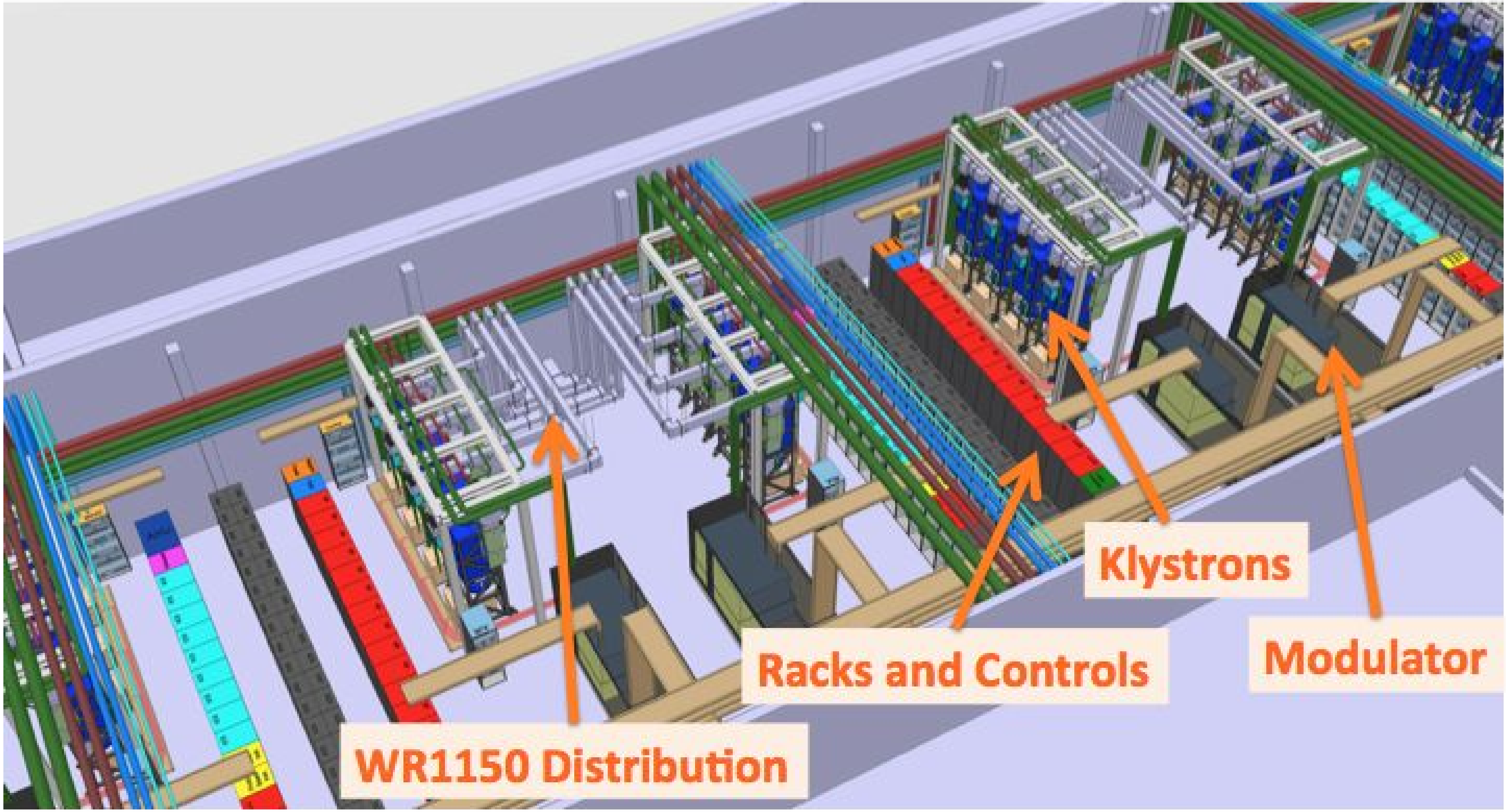


Elliptical RF System Layout

- 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