CW SRF Proton Linacs

Proton Driver Efficiency Workshop at PSI

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1-March-2016

Major Issues for SCRF CW Linacs

- Normal to SCRF crossover point
- Cryogenic Load
- Cavity bandwidth
- Power amplifier choice
- Civil Engineering choices
- Schedule

SCRF Linac Design Choices

$$\langle P \rangle = P_{pk} D = P_{pk} f_r \tau_p$$

$$P_{pk} = I_b \left(E_{pk} \sum_{n=1}^{N} \left(M_{cell} \frac{E_{acc} T}{E_{pk}} \frac{\beta_g \lambda}{2} \right)_n + \frac{\mathcal{E}_{FE}}{q} \right)$$

- Major Parameters
  - duty factor, D
  - peak surface field, Epk
  - peak beam current, I_b
  - average value of $E_{acc}T$ sum by adjusting the power profile
  - ratio of $E_{acc}T/E_{pk}$ by appropriate choice of β_g
  - energy of the front end linac, E_{FE}

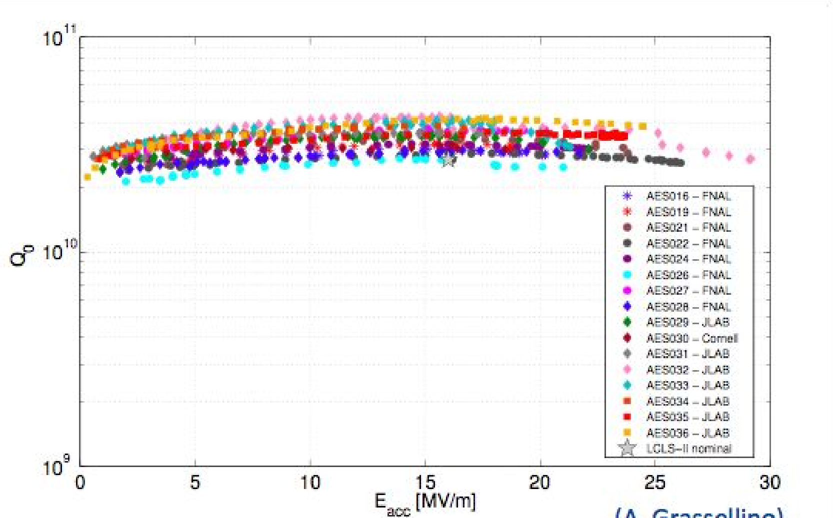
Cryogenic Costs: the Quest for High Q_o

- N-doping evolved from discovery to proven technology;
- It is a basic technology for LCLS II, operating at 1.3 GHz;
- It Is necessary to finalize the technology proof at proton driver frequencies (~700 MHz).

$$P_{d_n} = \frac{\left(E_{pk}\frac{E_{acc}T}{E_{pk}}M_{cell}\frac{\beta_g\lambda}{2}\right)^2}{\frac{R}{Q}_{acc}Q_0} f_r\tau_p$$

$$P_{d_n} = \frac{E_{pk}\frac{E_{acc}T}{E_{pk}}M_{cell}\frac{\beta_g\lambda}{2}}{I_b\cos(\phi_s)\frac{R}{Q}_{acc}Q_0}\left(P_{bpk}D\right)_n$$

$$P_d \propto \frac{E_{pk}}{I_bQ_o}\langle P_b\rangle$$



(A. Grassellino)

LCLS2 protoype cryomodules nine cell vertical test resultsdoping recipe 2/6 (FNAL developed)

Jlab and FNAL prototype cryomodules cavities achieved world record values:Avg Q (16 MV/m, 2K)= 3.5e10,

Cavity Bandwidth

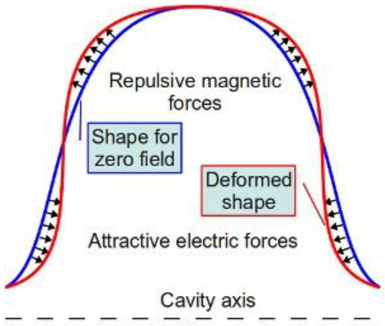
- For a given beam power, high duty factor gives less beam current
- Light beam loading implies light coupling of the RF source to the cavity
  - impedance matching
- Light coupling results in extremely narrow cavity bandwidths
  - Fractional bandwidths ~ 0.05x10^{6} (~tens of Hz out of a center frequency of 700 MHz)

$$I_b = \frac{\langle P_b \rangle}{D \frac{\mathcal{E}_L}{q}}$$

$$Q_L = \frac{V_c}{I_b \cos(\phi) \frac{R}{Q_{acc}}}$$

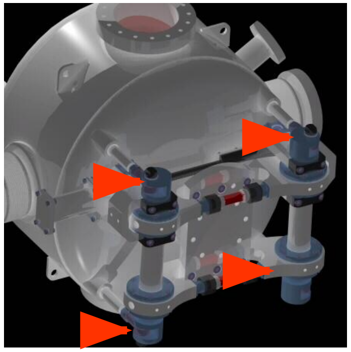
Lorentz De-tuning and Microphonics

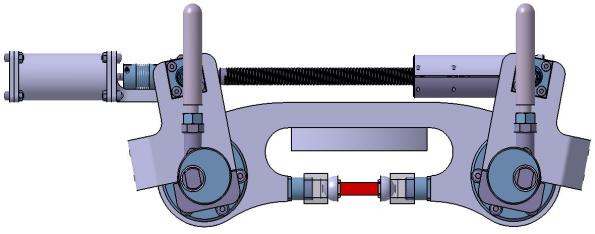
- Because of the enormous gradients in superconducting cavities, the radiation pressure deforms the cavities.
  - Small changes in amplitude in the cavity can cause the cavity to quickly go out of tune
- Because of the narrow bandwidth cavities are very sensitive to mechanical noise - microphonics (pumps, fans, etc.)
- Microphonics require advance controls on piezo tuners
- Or extra RF Power!



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

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





General Concerns on SCRF for Proton Drivers

Increasing The Duty Factor

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- Superconducting RF is the latest fashion in accelerator technology
  - SNS, ESS, LCLSII,PIPII
- In the limit, the best conditions for an SCRF Linac is in CW
  - It costs money (energy) to keep the Linac cold
  - Keep it running!

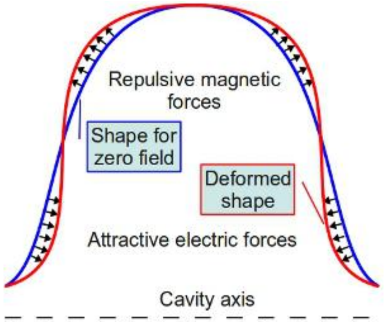
- A good rule of thumb ???
  - Duty factor > 10%
  - Dynamic / static load > 5

Needs for High Duty Factor Accelerators

- High Energy Physics and Intensity Frontier Physics
  - Looking for rare processes so beam brightness is of ultimate importance
  - Filling colliders, Neutrino physics, etc required pulsed structures
- Neutron Sources
  - Again beam brightness is extremely important
  - Latest generation neutron spallation sources are pulsed at a very low duty factor (<10%)
- Accelerator Driven Systems?

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**



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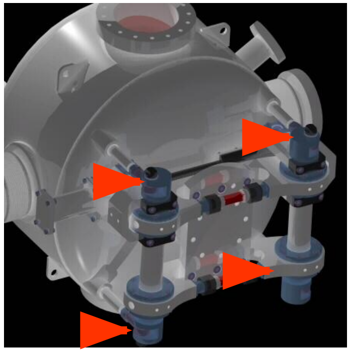
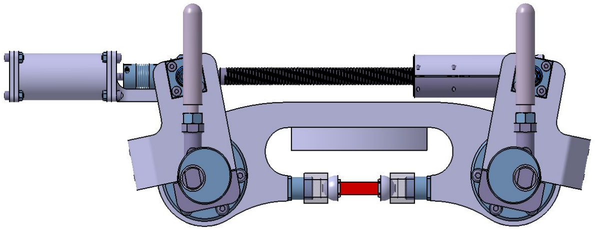
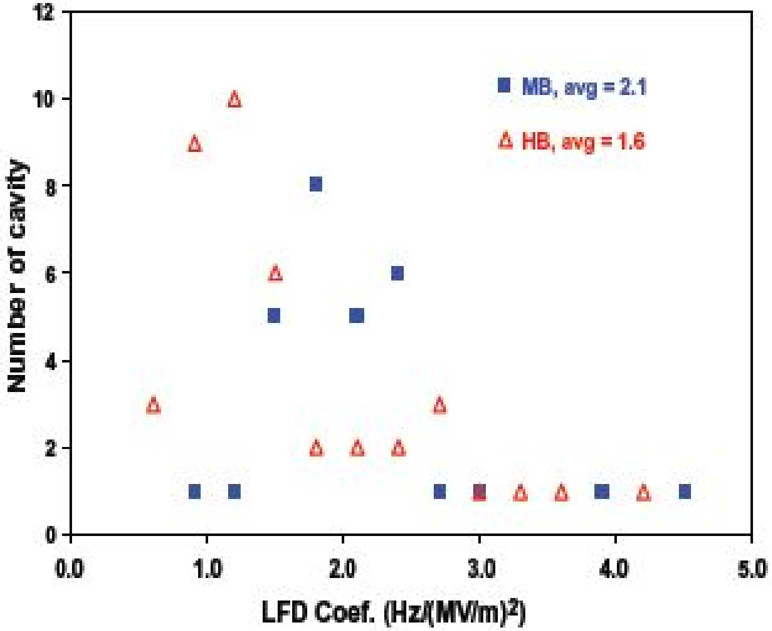




Cavity Power Configuration

- 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 usually has its own RF power source



RF Cost Models

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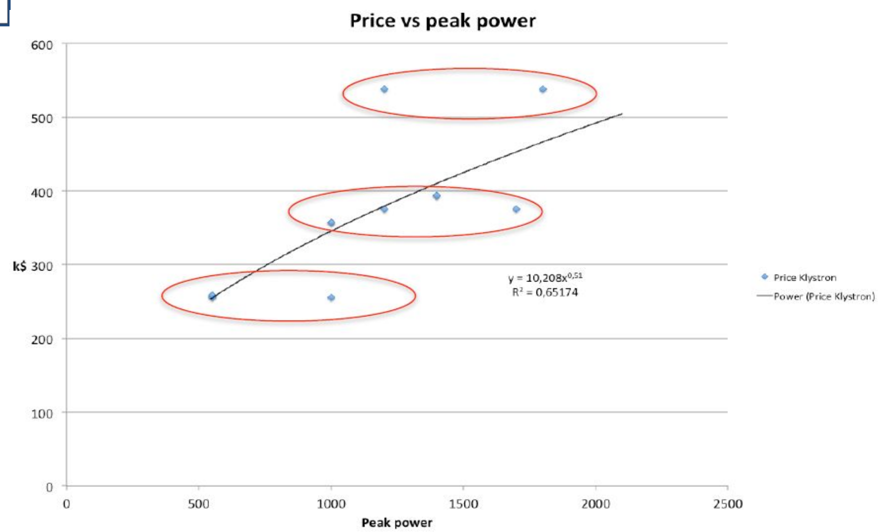
Modulator Cost Model

$$C(P) = C_{P_o}\left(R_{cc}\frac{P}{P_o} + R_{cb}\frac{P}{P_o} + R_{ss}\left(\frac{P}{P_o}\right)^{\frac{1}{3}} + R_{xt}\left(\frac{P}{P_o}\right)^{\frac{2}{3}} + R_{cab} + R_{at}\right)$$

Modulator Part	Symbol	Cost (%)	Power Factor
Capacitor Charger	R_{cc}	30	1
Capacitor Banks	R_{cb}	5	1
Solid State Switch	R_{ss}	15	0.33
Transformers	R_{xt}	15	0.67
Cabinets & Controls	R_{cab}	10	0
Assembly & testing	R_{at}	25	0

Klystron Cost Model

$$C(P) = C_{P_o}\left(0.87 + 0.13\frac{P}{P_o}\right)$$



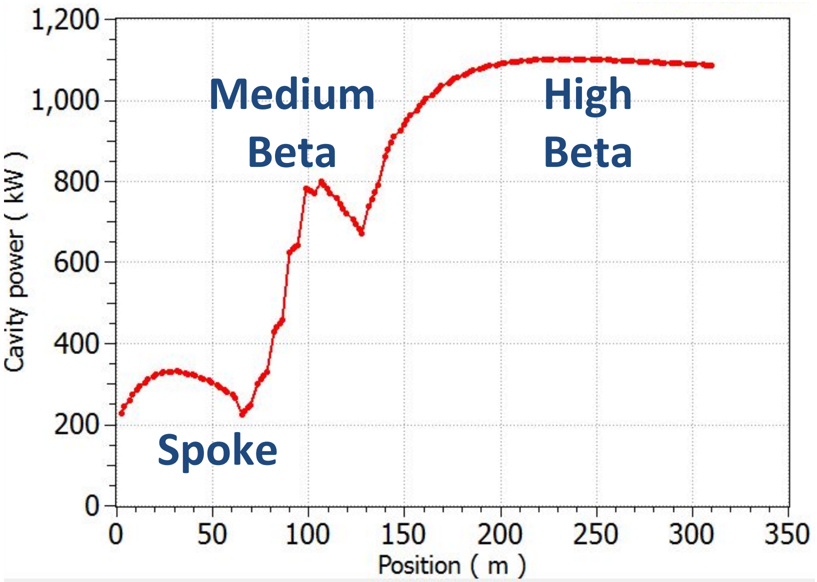
- **Zero (or low power) costs money (and efficiency)**
  - cost of cabinets, controls, profit, etc.
- Rough rule of thumb
  - RF costs scale approximately as the square root of power

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**

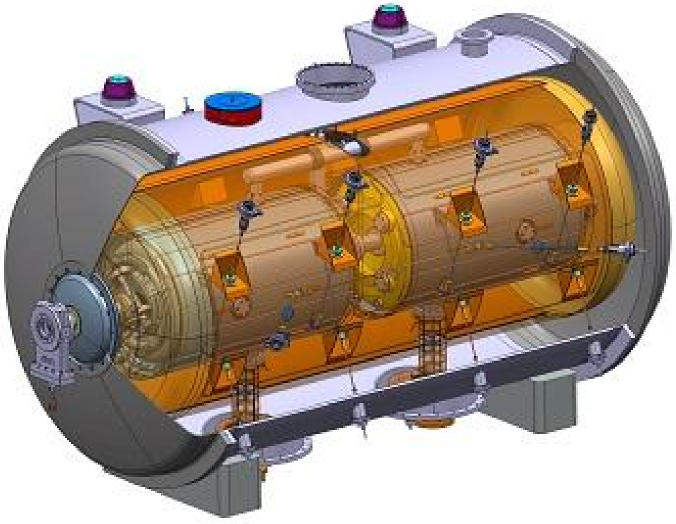
ESS Linac Cavity Power Profile

- A non-flat power profile raises challenges for the efficiency of the power amplifier
- Most RF amplifier technologies are most efficient when operated near their saturation point
- In a SCRF Proton Linac, many of the amplifiers are not operated near the saturation point.



Power Sources for Low Frequency - Low Power 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 - too high frequency
  - Klystron - overkill
  - IOT - not enough power
  - Solid State - not enough power
- A no-man's land in RF



ESS Conventional Facility Costs

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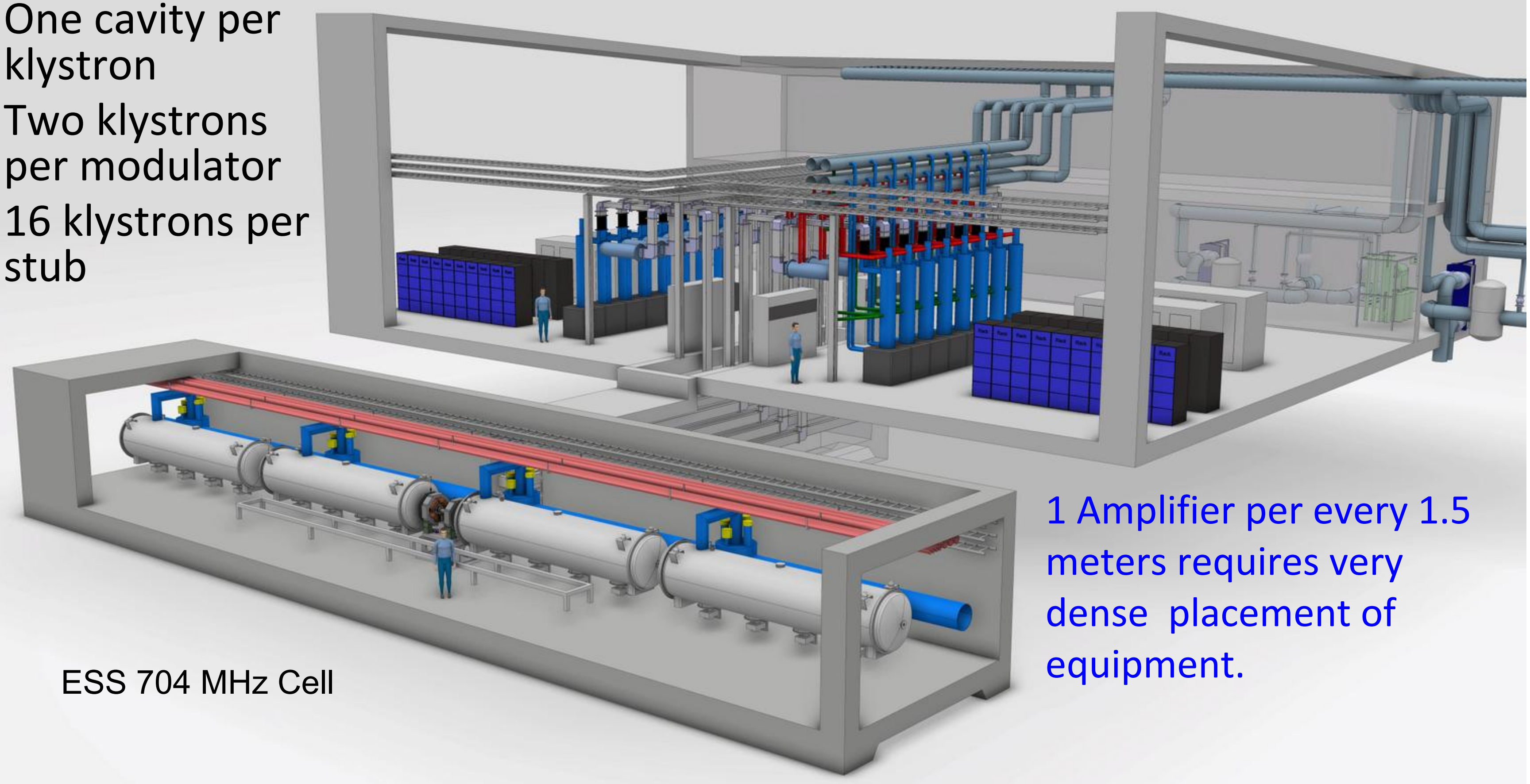
- The approximate costs for conventional facilities are:
  - Tunnel: 22,900 €/m (3270 k€ / m^2) including berm, auxiliary costs
  - Gallery: 46,200 €/m (2800 k€ / m^2)
- The cost of accelerator equipment is:
  - 6.5 M€ / cryomodule which includes the RF power
  - Average cost of superconducting RF accelerator 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€.
- **Since CF costs are so much less than SCRF, the argument that SCRF saves in CF costs is hard to justify**

Density of Equipment in the Gallery

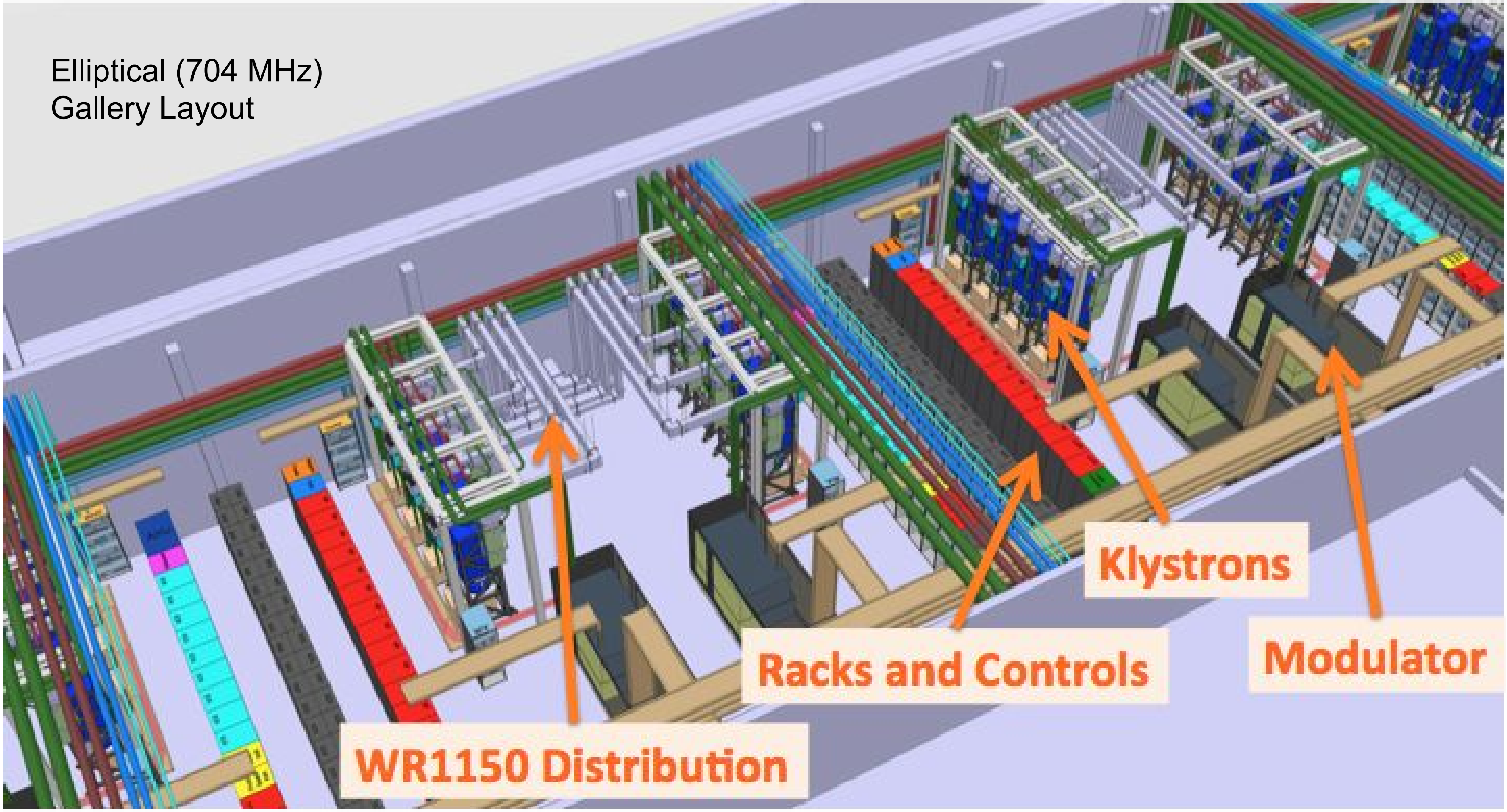
- One cavity per klystron
- Two klystrons per modulator
- 16 klystrons per stub



ESS 704 MHz Cell

1 Amplifier per every 1.5 meters requires very dense placement of equipment.

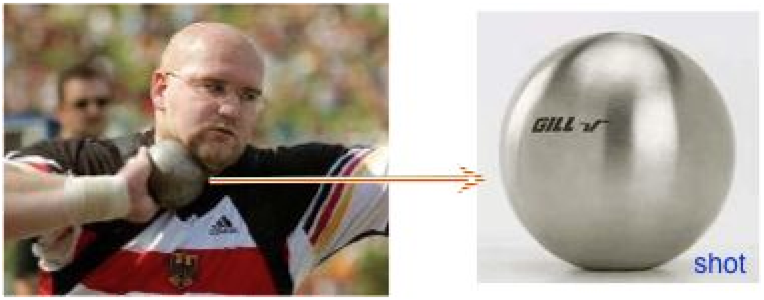
Density of Equipment in the Gallery



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

Beam Power and Machine Protection

- For ESS 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!!!



Proton impacts on Niobium

Preliminary Results by Stephen Molloy-ESS

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- De Broglie wavelength of 50 MeV protons is ~4 fm
  - Similar to the nuclear radius of Nb
- Therefore impacts do not just disrupt the crystal lattice,
  - but also change the elemental composition
  - Fracture or spallation of Nb nuclei leading to new species
  - Zirconium, Yttrium, Strontium, etc.
- What is the scale of this effect?
- How does this affect the behaviour of the SC cavity?
- What are the implications for SC acceleration of proton beams?

Geant4 simulations

Preliminary Results by Stephen Molloy-ESS

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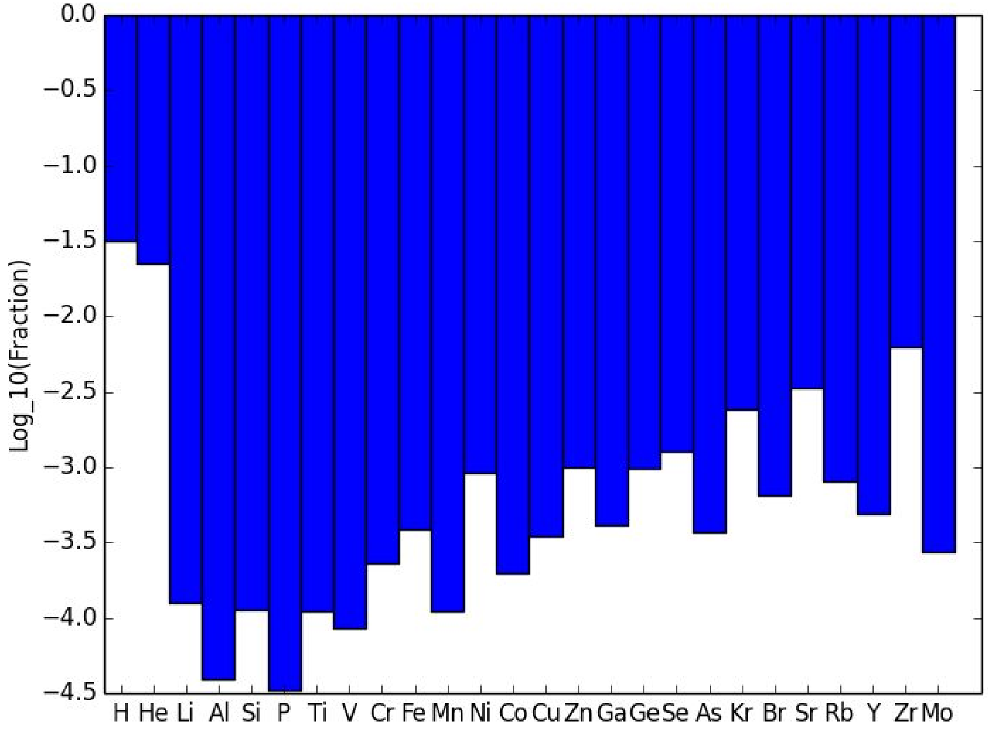
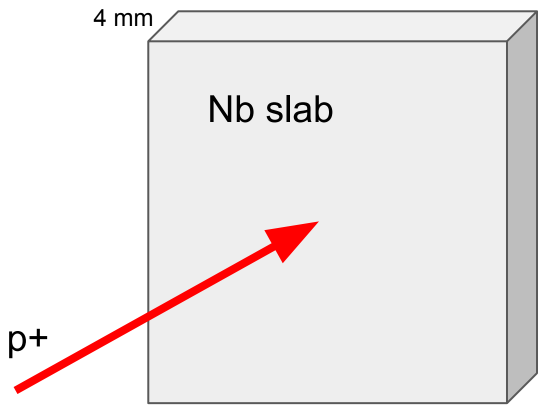
- 10^9 individual impacts at each of 36 proton energies
- Zero-momentum products extracted from output data
- Short-lived isotopes transitioned through their decay chain



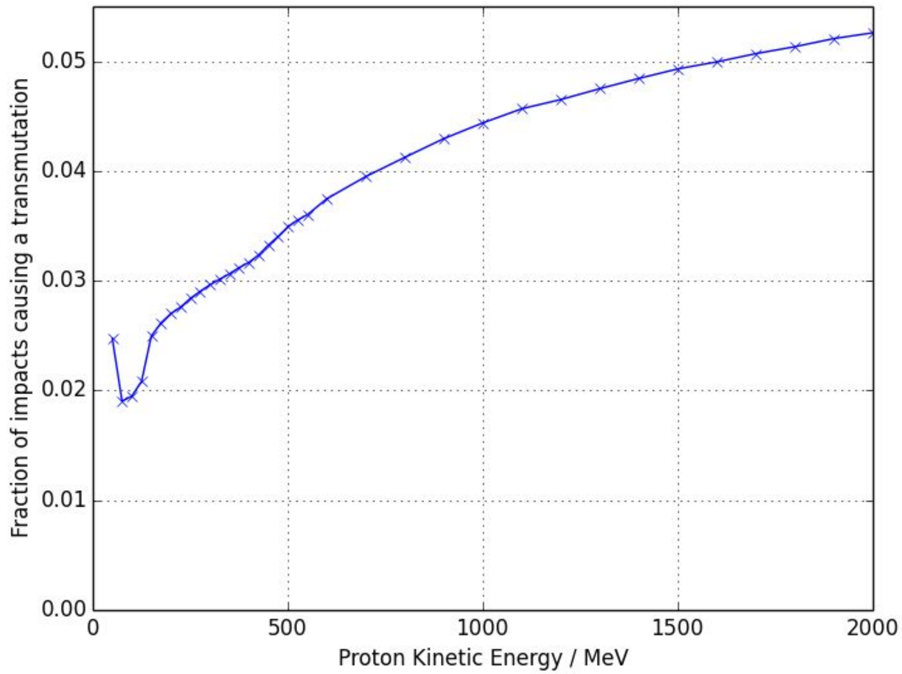


This analysis only looks at nuclear transmutation, not lattice damage.

Probability of Damage

Preliminary Results by Stephen Molloy-ESS

- Scenario 1
  - Impact by full-power ESS beam
  - ~1014 transmutation events
  - 1 mm x 1 mm impact area
  - **~1 part in 10^7 converted in the impact volume**
- Scenario 2
  - 10 yrs of 10-6 halo
  - Deposited on 5 cm length of cylinder
  - Radius = 9 cm
  - **~1 part in 10^8 converted in the impact volume**



Probability of Damage

Preliminary Results by Stephen Molloy-ESS

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- These are small fractions, but not negligibly small
    - Considerable effort goes into achieving a very particular chemical composition of the material
- Scenario #1 can be alleviated by 2 or 3 orders of magnitude with a properly configured MPS - But:
    - #2 may be unavoidable (p+ beams are typically kept large to alleviate space-charge effects)
    - #1 is still comparable to #2 if several of the MPS-mitigated events occur during the ten-year period
- So, a choice to accelerate p+ in SC cavities significantly increase the criticality of:
    - MPS reaction times
    - Understanding of halo formation & propagation

Cumulative Energy Demand

- Operational power savings is not the only figure of merit for an efficiency
- The construction of SCRF is energy and time intensive
- The Cumulative Energy Demand (CED) is the ratio
  - of the energy required to produce SCRF including life cycle costs
  - to the beam power the linac
- What are the CED's for current facilities?
- What should the range be?

Human Factors

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- Time Scale
  - Long time scale gives little time for prototyping rounds
    - Less innovation
  - Interest and retention of staff
- Lots of effort on cryogenics and Material science
  - Not so much innovative RF design

Guidelines for Chooseing SCRF for Proton Drivers

- Duty factor (>10% ?)
- Dynamic to Static load (> 5 ?)
- Emin (> 400 MeV ?)
- Emax (< 2 GeV ?)
- Average Beam Power (> 1 MW)
- $T_{flattop}$ / T_{fill} (> 5)
- CED (< 2 years ?)
- …..