COMSOL CONFERENCE 2016 BOSTON

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Multiphysics Analysis of RF Cavities for Particle Accelerators: Perspective and Overview

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Comsol 2016

6th Oct 2016

Particle Accelerators: Why?

High Energy Physics
- Standard Model
- Matter and Anti Matter
- Symmetry Violation

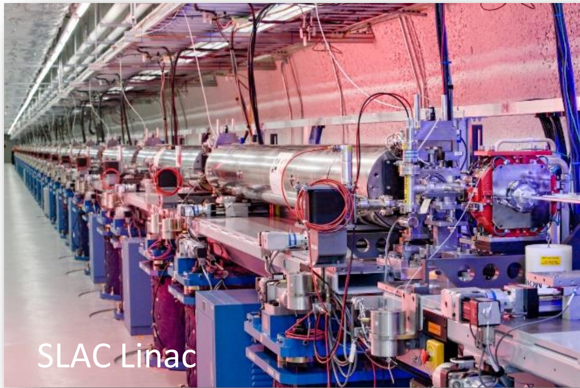
Medical Applications
- Medical Isotopes
- Cancer Therapy
- Analyze and define how the ribosome translates DNA information into life (DNA research)

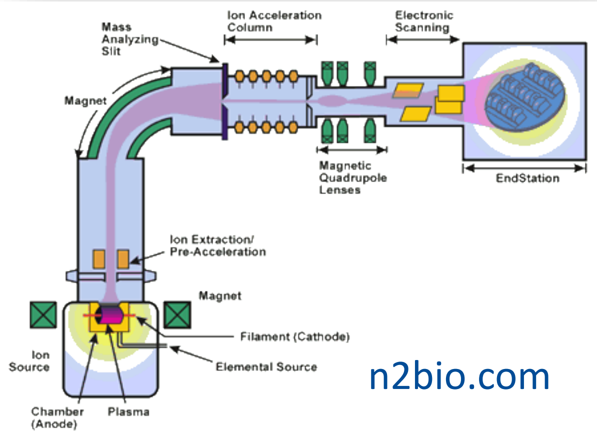
Industrial Applications
- Implant ions in silicon chips (Semiconductor industry)
- Analyze protein structures, leading to the development of new drugs to treat major diseases such as cancer, diabetes, malaria and AIDS

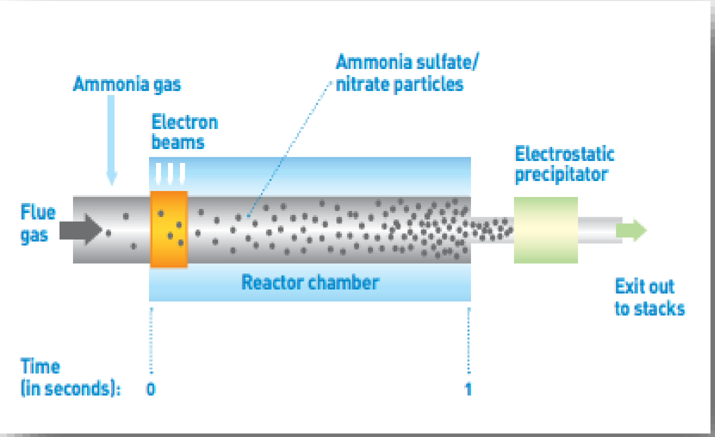
Nuclear Applications
- Nuclear Waste Transmutation
- Nuclear Energy Production with Alternative Fuel
- Radio Isotopes

Environmental Applications
- Clean up dirty water, sewage sludge and polluted gases from smokestacks.

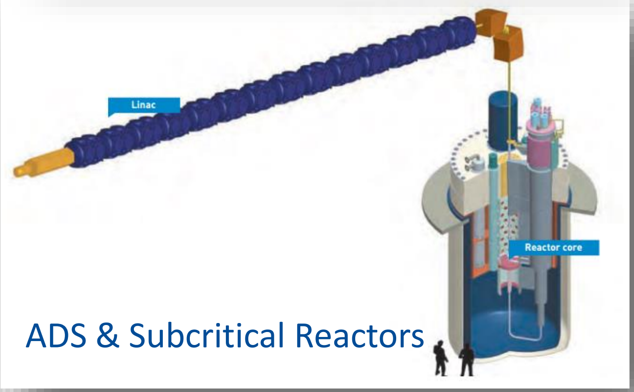
Particle Accelerator: Why?







A Rhodotron, a commercial electron-beam accelerator for industrial applications including sterilization of medical devices
Image courtesy of IBA

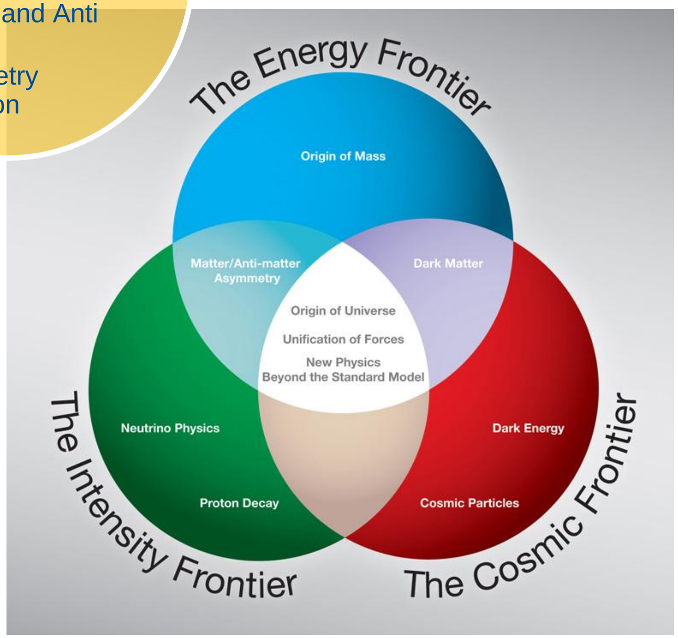


Accelerators for Americas Future, http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Report.pdf

Fermi National Accelerator Laboratory

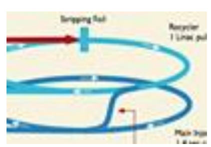
Fermilab is a main player in the High Energy Physics Research

High Energy Physics
- Standard Model
- Matter and Anti Matter
- Symmetry Violation




LBNF

Mu2e


PIP-II


NOVA


µBooNE


MICE


DE Survey


LSS Telescope

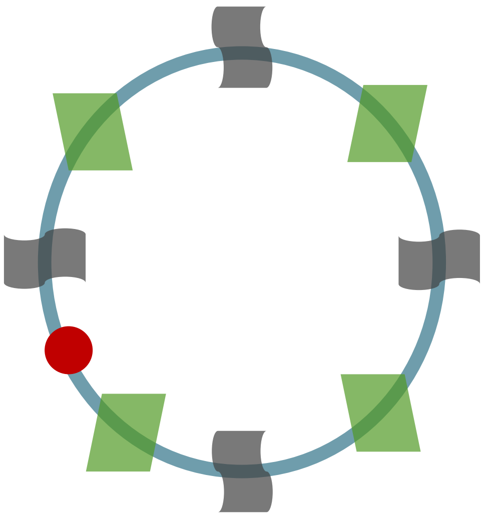
http://www.fnal.gov/pub/science/experiments/works-in-progress/

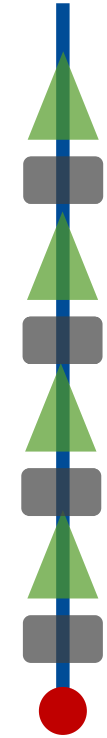
Classification of Particle Accelerators

$$F = q(E + v \times B)$$

Electric field for acceleration

Magnetic field for bending/focusing





Cyclic

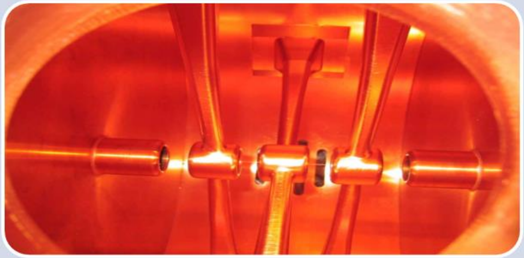
- Tunable RF Cavities
- Bending and Focusing Magnets

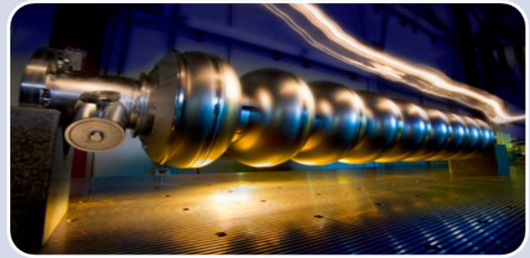
Linac

- Fixed Frequency RF Cavities
- Focusing Magnets

Cyclotron	Syncho-cyclotron	Synchrotron
Fixed f	Variable f	Variable f
Fixed B	Fixed B	Variable B
Variable R	Variable R	Fixed R

RF Cavities for Particle Accelerators





Normal-conducting Cavities

- Copper
- Q~1e4
- Rs~mΩ
- Room Temperature
- Power loss~10kWatts
- Gap Voltage~10kV
- Limited by electromagnetic heating

Super-conducting Cavities

- Niobium
- Q~1e10
- Rs~nΩ
- ~2K
- Power loss~Watts
- Gap voltage~MV
- Limited by either field emission (surface cleanliness) or quench due to surface magnetic field (cavity loses its superconductivity)

Needed Multiphysics

Eigenfrequencies Electromagnetic Heating, Frequency Shifts

Eigenfrequencies Mechanical Vibrations, Frequency Shifts, Thermal Quench

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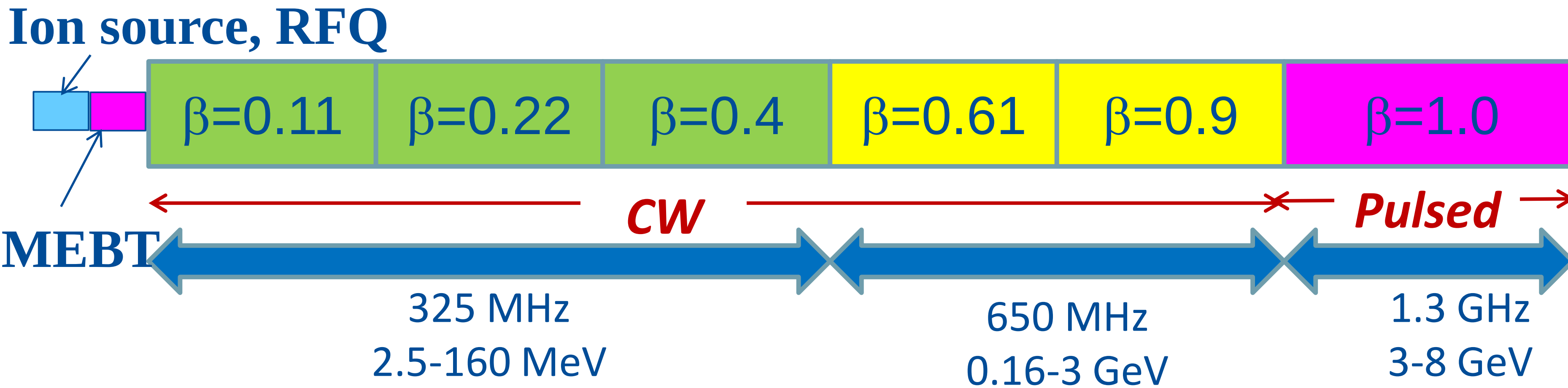
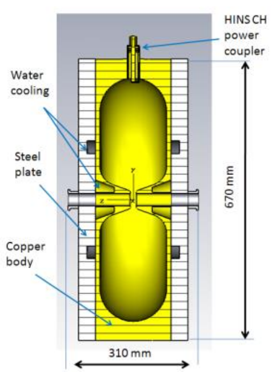
Typical SRF Linac

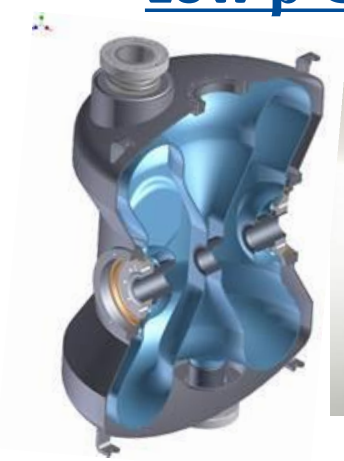


Low β Cavities

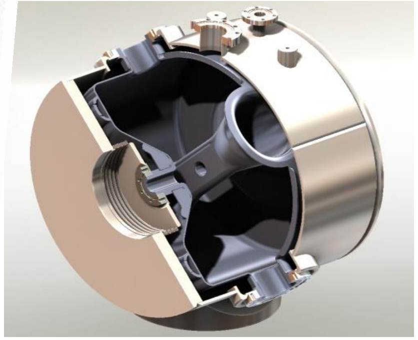
Highβ Cavities



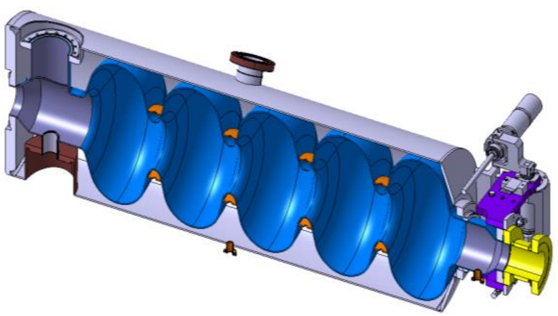
ReBuncher Cavity



HWR

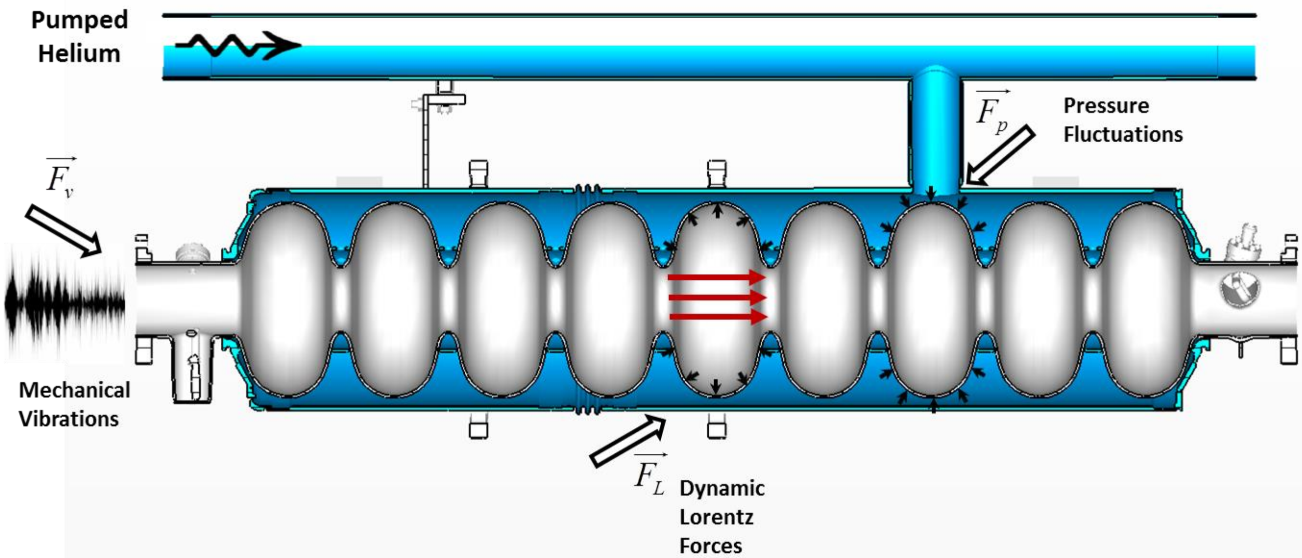


SSR



Elliptical Cavity

Sources of Frequency Detuning in SRF Cavities



Mechanical Vibrations

- Mechanical vibration that is already exist in the cavity system due to pumps and motors travel through the pipes and reach the cavity.
- Random effect

Pressure Fluctuations

- Helium pressure in the cryogenic system inherently fluctuates causing continuous pressure fluctuations on the cavity walls which induces detuning to the resonant frequency

Lorentz Force Detuning

- Electromagnetic fields inside the cavity exerts forces on the cavity wall that is proportional to the electric and magnetic energy

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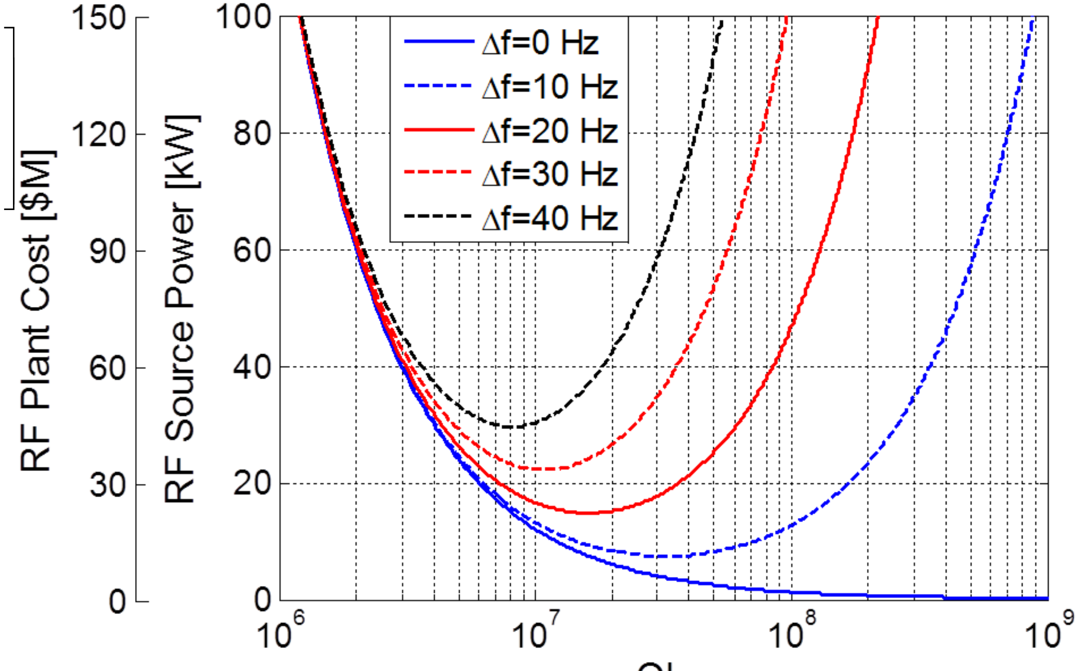
Significance of Minimizing Frequency Detuning

$$P_g = \frac{V_{cav}^2}{4\frac{r}{Q}Q_L}\left[\left(1+\frac{\frac{r}{Q}Q_L I_b}{V_{cav}}\cos(\Phi_b)\right)^2 + \left(\frac{\Delta f}{f_{1/2}}+\frac{\frac{r}{Q}Q_L I_b}{V_{cav}}\sin(\Phi_b)\right)^2\right]$$

$$I_b = 0,\ P_g = \frac{V_{cav}^2}{4\frac{r}{Q}Q_L}\left[1+\left(\frac{\Delta f}{f_{1/2}}\right)^2\right]$$

$$f_{1/2} = \frac{f_0}{2Q_L},\quad P_g = \frac{V_{cav}^2}{4\frac{r}{Q}Q_L}\left[1+\left(\frac{\Delta f}{f_0/2Q_L}\right)^2\right]$$

$$Q_{opt} = \frac{f_0}{2\Delta f},\quad P_{g,\min} = \frac{V_{cav}^2}{2r/Q}\frac{\Delta f}{f_0}$$



RF source power calculated for Fermilab's 650 MHz β=0.9 SRF cavity; Vcav=17.5 MV r/Q=638

Amount of RF source power needed to drive the cavity is highly dependent on the expected detuning frequency shift (Δf) specially for low beam current medium energy particle accelerators where the loaded quality factor is in the order of 10^7-10^8 .

Multi-Physics of Super-Conducting Cavities: Microphonics Cont.

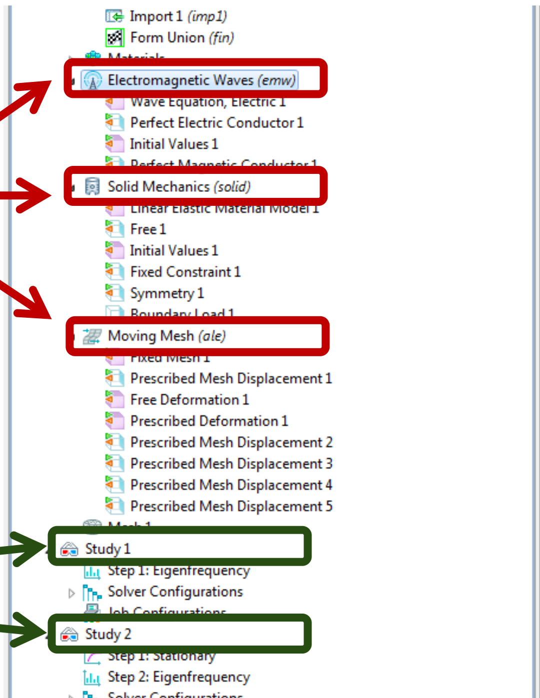
Electromagnetic Waves
- Solving only for the RF domain
- Applying the prober boundary conditions

Solid Mechanics
- Solving only for the Cavity Vessel
- Applying the proper fixed constraints, symmetries, displacements, and boundary load

Moving Mesh
- Solving for all domains
- Applying the proper prescribed and free mesh deformation/displacement

Three Multiphysic Modules

Two Simulation Studies



$Study_1$
- Eigen-frequency (to find f_0)

$Study_2$
- Stationary (solving only for solid mechanics and moving mesh)
- Eigen-frequency (to find f_p)

EM
- Eigen frequency simulation to find the resonant frequency (f_0)

Solid Mechanics
- Find the deformation under given pressure load (P_L)

Moving Mesh
- Update the mesh after deformation

EM
- Eigen frequency simulation to find the resonant frequency after deformation (f_p)

$$\frac{df}{dp} = \frac{f_p - f_0}{P_L}$$

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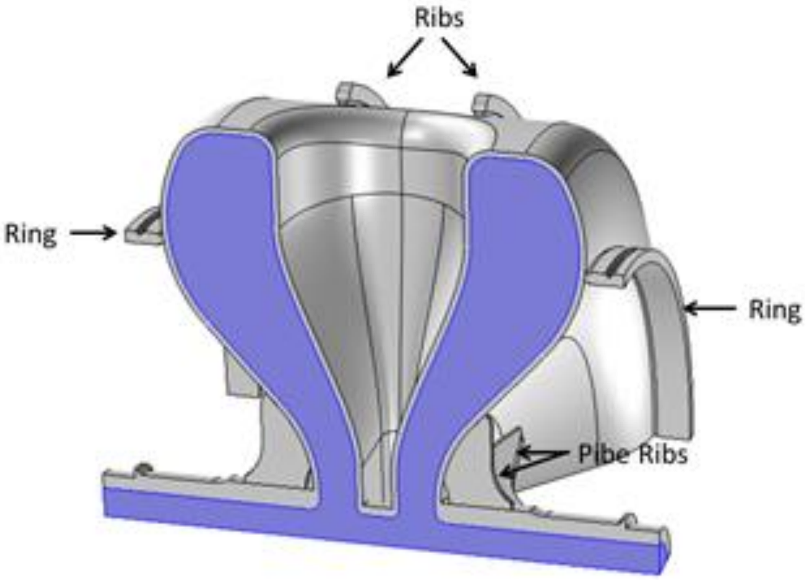
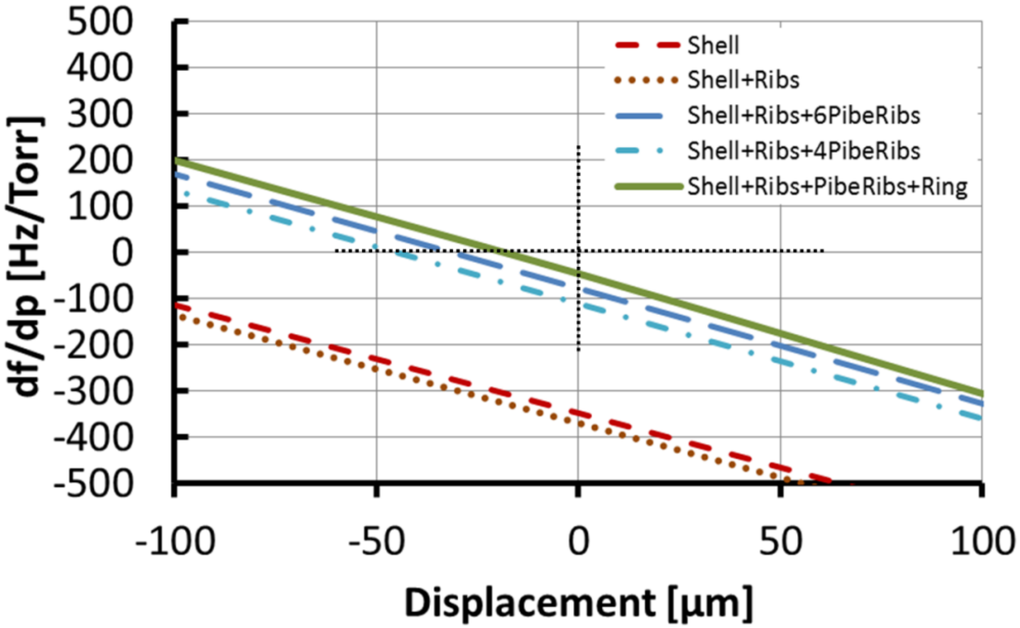
Multi-Physics of Super-Conducting Cavities: Microphonics Cont.

Stiffening the Cavity





- » Pipe Ribs are very important to reduce df/dp
- » Ring between the shell and the Helium vessel would simplify the vessel design

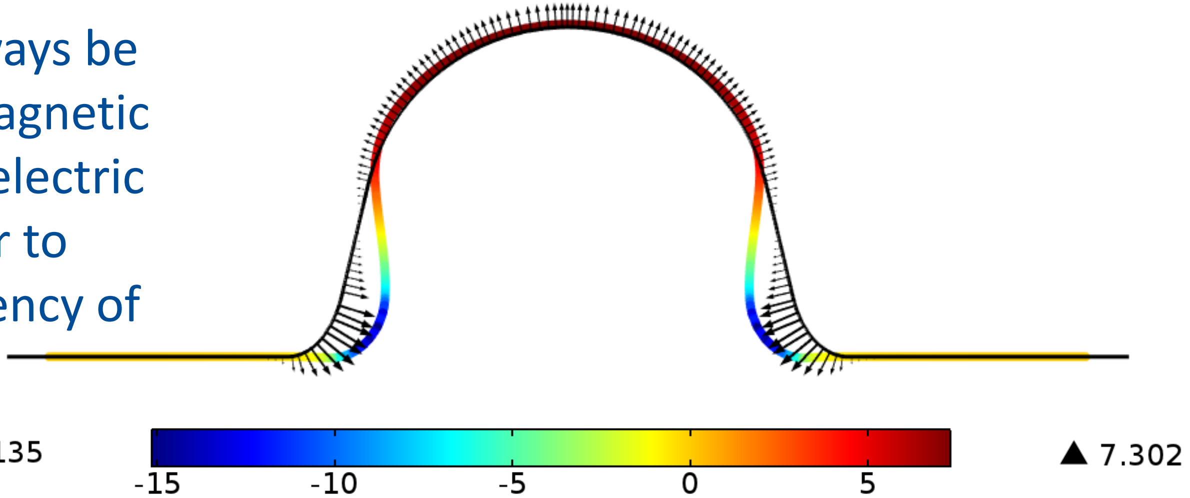
Detuning Simulation: LFD

Electromagnetic fields inside the cavity exerts radiation pressure on the cavity inside walls that is defined as

$$P_{rad} = \frac{1}{4}\left(\mu\left|H\right|^{2} - \varepsilon\left|E\right|^{2}\right)$$

Radiation pressure exerted by the magnetic field is positive pushing pressure, while it is negative puling for the electric field

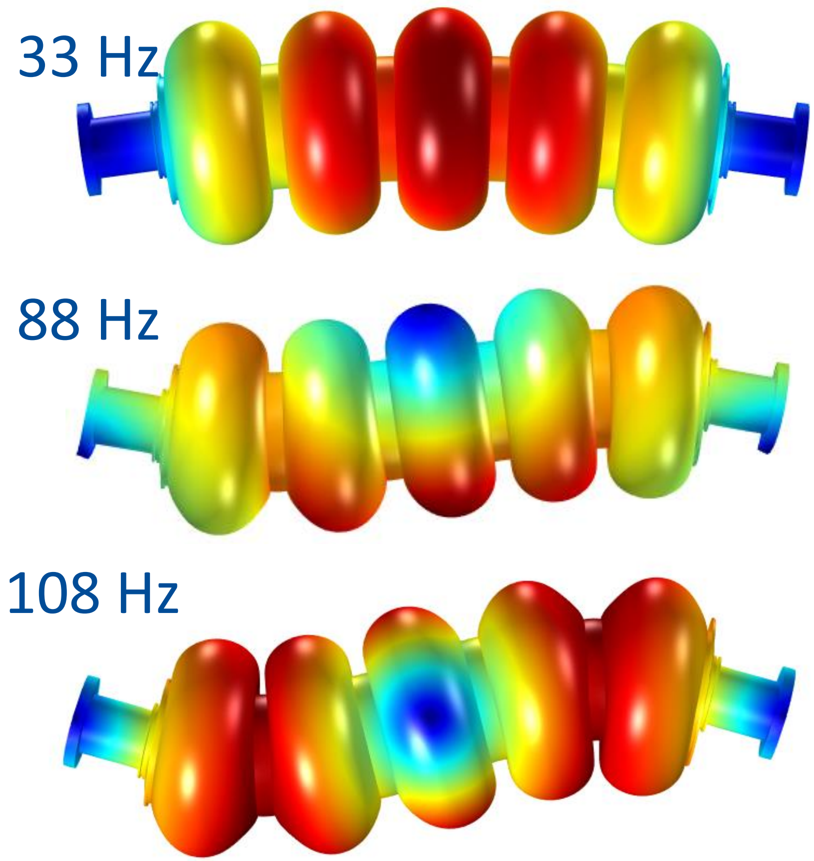
Overall frequency shift will always be negative since the repulsive magnetic field forces and the attractive electric field forces both work together to decrease the resonance frequency of the deformed cavity



Lorentz forces exerted on the 650 MHz β=0.9 single cell cavity ahead with the radiation pressure values in mbar at the 3.5 MV cavity voltage. Deformation is exaggerated by 20000 times

Detuning Simulation: Mechanical Vibration

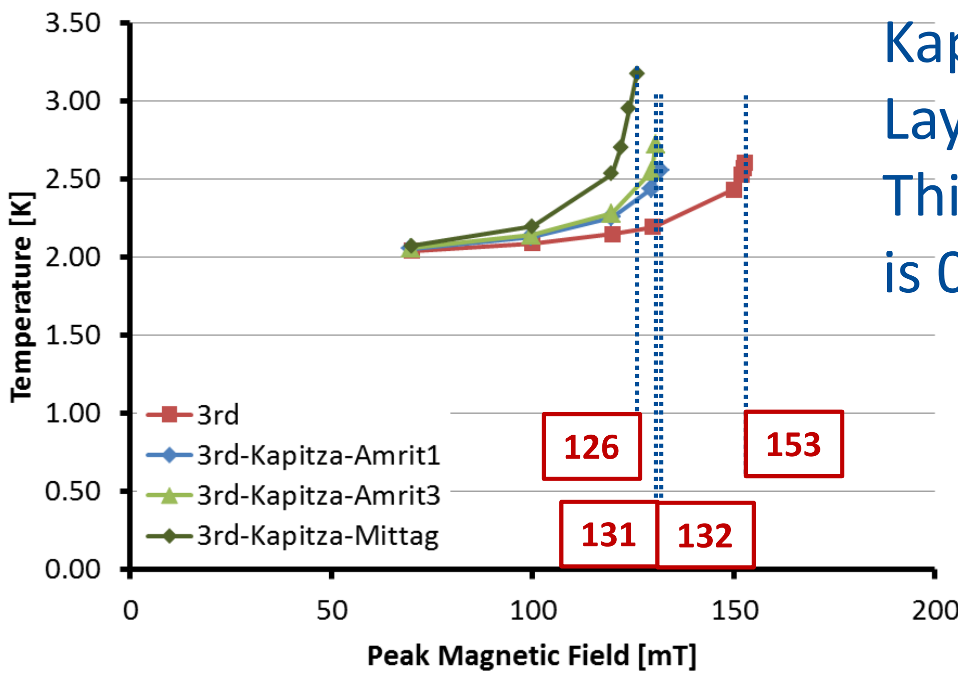
- Modal eigen-frequencies of each cavity structure can be numerically calculated using a solid mechanics solver
- Any modification on the cavity structure would necessarily change the modal frequencies.
- The frequency shift in the electromagnetic resonance frequency due to the excitation of a certain modal eigen-frequency could be computed knowing the energy of that eigen-frequency.
- Moreover, we believe that the modal frequency will be affected by the liquid Helium filling the cavity during operation



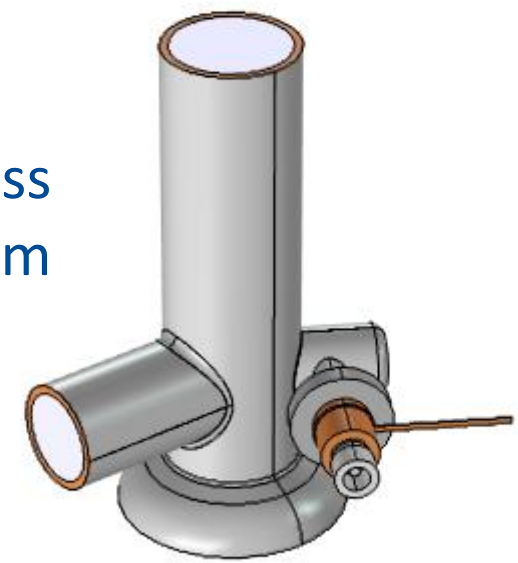
Modal frequencies of the 650 MHz β=0.9 cavity

Quench Analysis of Superconducting Cavity

- Given the several models of Kapitza Resistance, we tried to use our experience with the third harmonic cavity to check which one is closer to measurements
- Mittag model looks the closest with quench field 126mT vs 120mT observed in measurements, thus it will be adopted



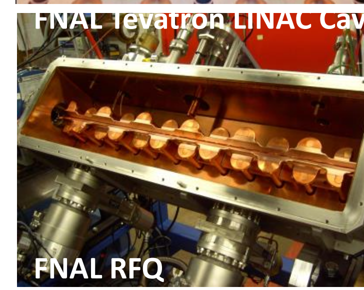
Kapitza Layer Thickness is 0.5 mm



Multiphysics of Normal Conducting Cavities

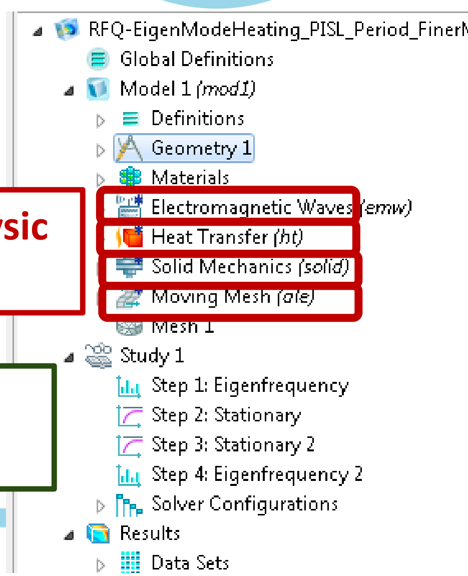
- Copper cavities are being used in many particle accelerators
- RF heating needs to be carefully modeled in such cavities
- Thermal stresses and frequency shifts are main concerns

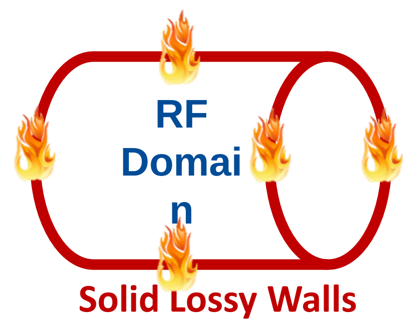
EM Fields → RF Heating → Thermal Stresses → Frequency Shift



Four Multiphysic Modules

Simulation Studies





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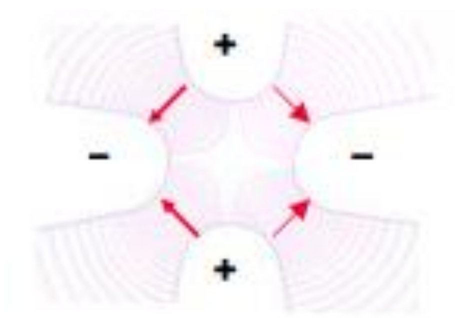
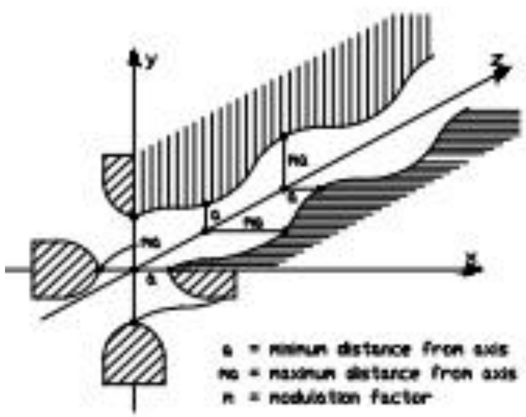
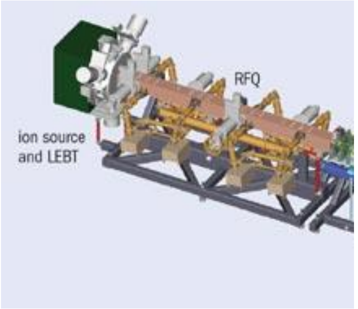
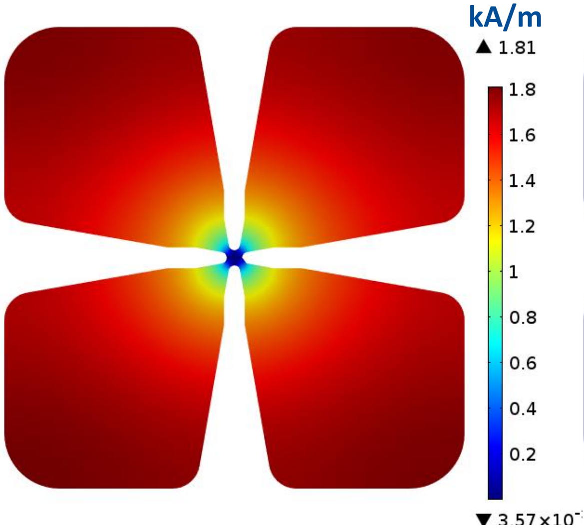
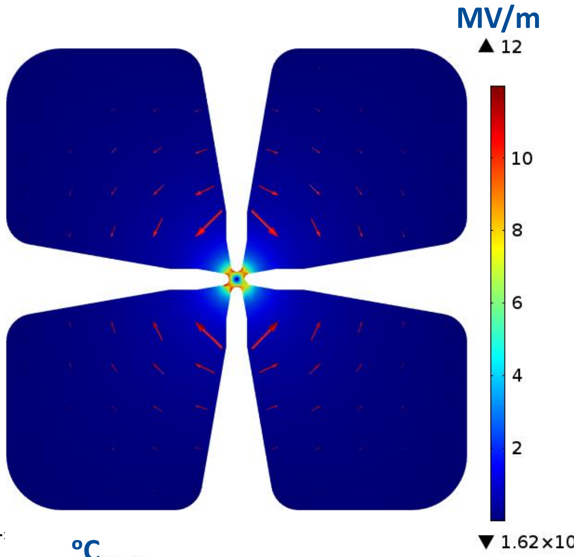
Multi-Physics Analysis of Radio Frequency Quadrupole

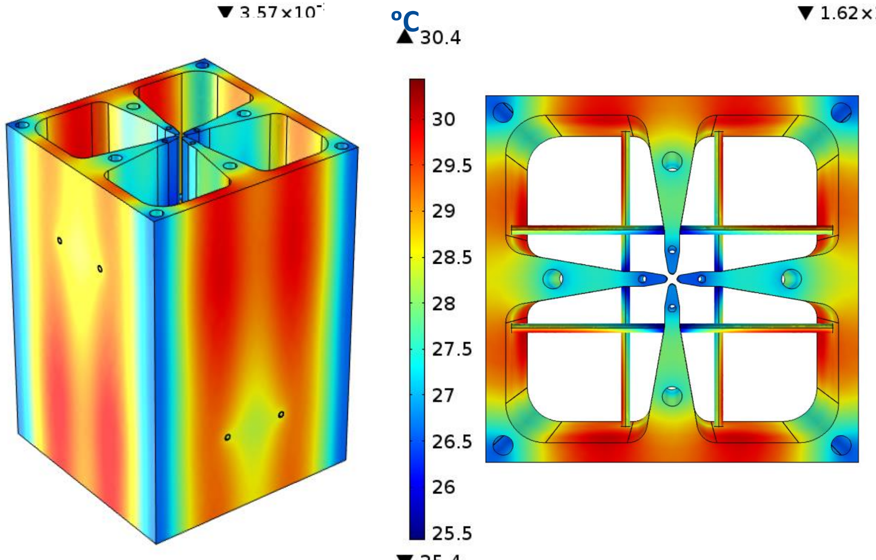












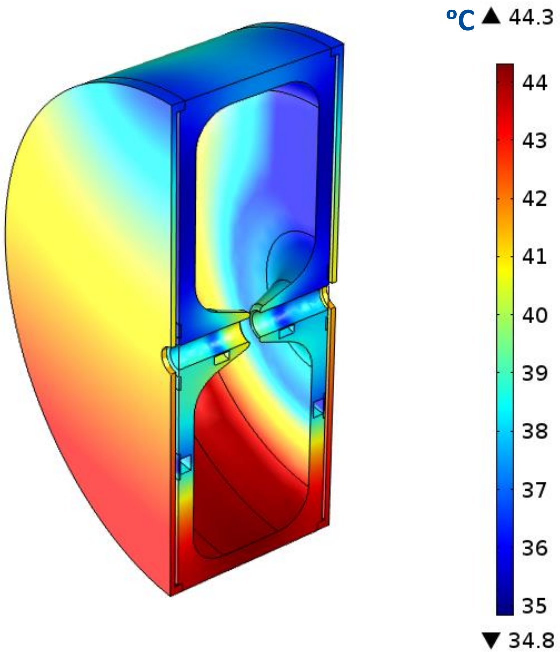
Frequency Shift=-4.4 kHz

The RFQ is a linear accelerator which focuses, bunches and accelerates a continuous beam of low velocity charged particles ~ 0.03 C

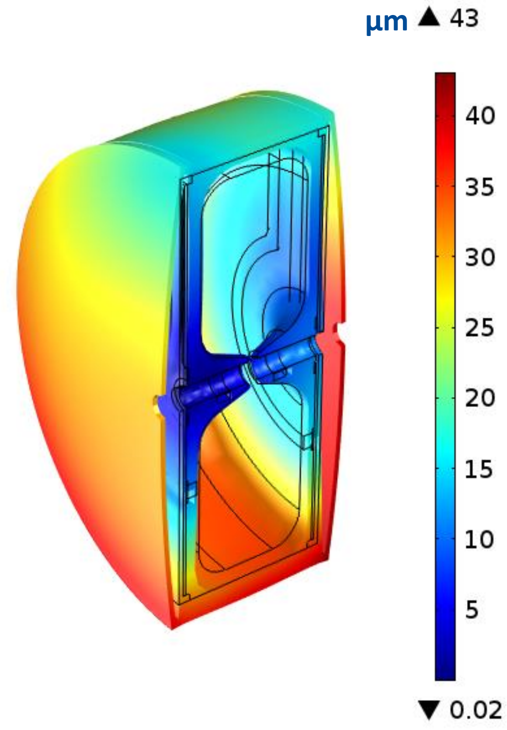
Multiphysics of a Buncher Normal Conducting Cavity

- Input Port Power is 3725 Watt, adjusted to induce 127 KV (75 KV Effective)
- Fixed Beam Pipe in transverse plane

Temperature Profile



Thermal Displacement



Amount of frequency shift due to the thermal stresses is -28.7 KHz

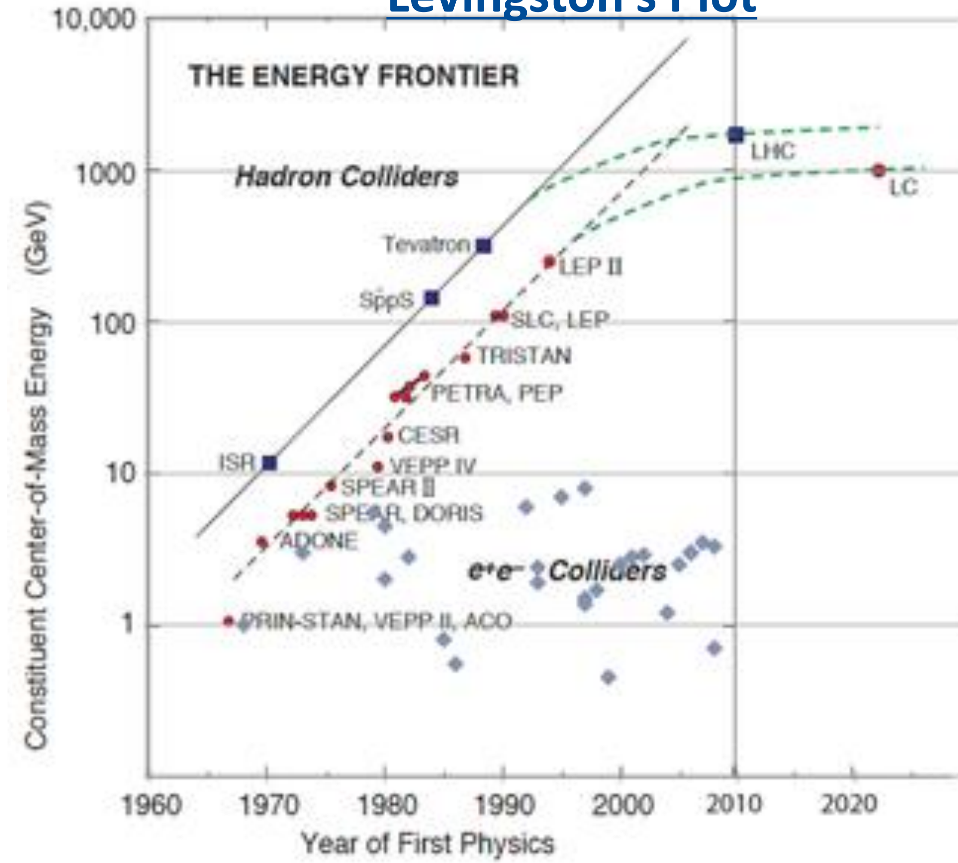
Future of Particle Accelerators

» Today more than 30,000 accelerators are in operation around the world—in industry, in hospitals, and at research institutions

» Many large scale projects are on going or coming soon!

Project	SRF Cavities	Cryo Modules	Est. Market (in millions)
Continuous Electron Beam Accelerator Facility (CEBAF) Upgrade, Thomas Jefferson Lab National Accelerator Facility, Newport News, VA	86	10	17
Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI	336	45	100
Proposed Project X, Fermilab, Batavia, IL	445	58	87
Proposed Cornell Energy Recovery LINAC, Cornell University, Ithaca, NY	304	58	57
Proposed SNS Upgrade, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN	36	9	18
TOTAL	1207	160	279

Levingston's Plot



Livingston: the energy records achieved by new machines by a factor of 10 every six years

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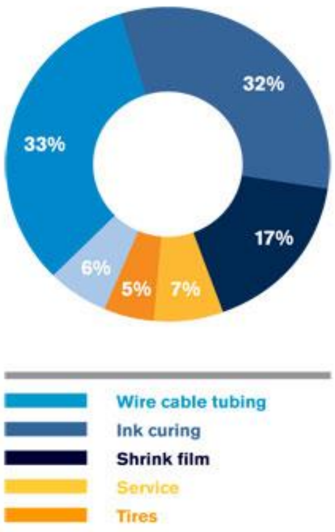
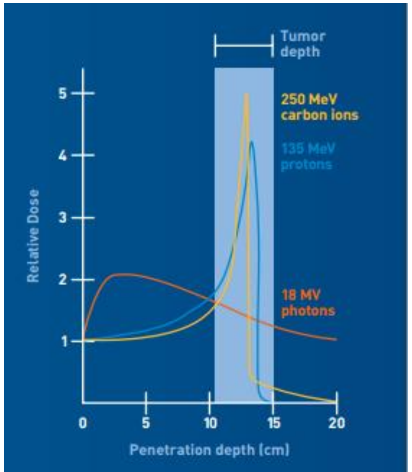
Future of Particle Accelerators Cont.

Markets for industrial electron beams total $50 billion per year.
Image source: IAEA Working Material on Industrial Electron Beam Processing





Energy deposition (dose) of photon, proton and carbon as a function of penetration depth in tissue. The Bragg peak for the ions and protons indicates that the highest energy deposition occurs at the particles' stopping point. Because of the Bragg peak, tissues surrounding a tumor receive a reduced dose. *Image source: Private from George Laramore*

	Low energy	Medium energy	High energy
Energy range	70 keV–300 keV	300 keV–5 MeV	5 MeV–10 MeV
Features	Wide unscanned beams less ≤3 m	Scanned beams ≤3 m	Linacs or SRF
Current applications	• Curing of inks • Crosslinking of polymers • Surface sterilization • Remediation of liquids and gases	• Crosslinking of wire and cable insulation • Crosslink heat-shrinkable plastic tubing • Manufacture of closed-cell foam • Crosslink plastic • Crosslink rubber • Medical sterilization	• Bulk sterilization of medical devices • Crosslinking thicker plastics

Concept for a compact proton therapy system for treating cancer patients, based on a dielectric wall accelerator *Image courtesy of S. Hawkins, Lawrence Livermore National Laboratory*

Accelerators for Americas Future, http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Report.pdf

Summary

» A particle accelerator is a device that uses electromagnetic fields to propel charged particles to high speeds

» It consists of a series of cryomodules. Each cryomodule houses several RF cavities and magnets

» Normal conducting and superconducting cavities are used in particle accelerators

» SRF cavities needs a series of complicated multiphysics analyses to properly address the design issues (microhonics and Lorentz force detuning)

» Normal conducting cavities needs also a series of complicated multiphysics analyses (electromagnetic heating is the main concern)

Thanks for your Attention