RF Deflecting Resonators: Beam Manipulation to Push Performance

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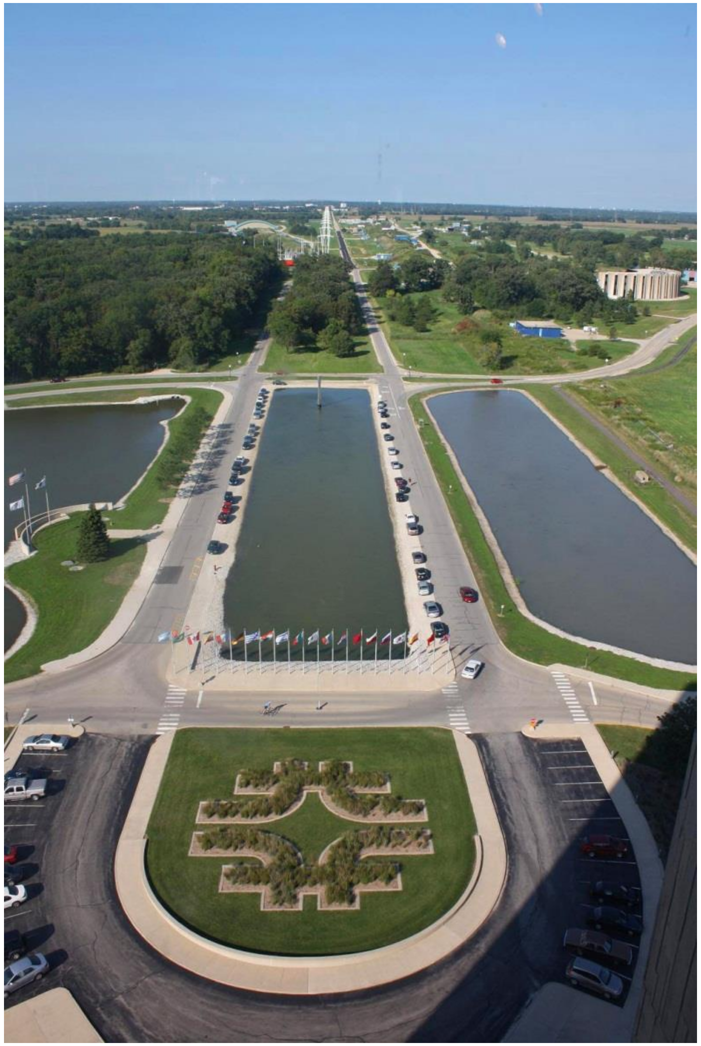
University of DØ Seminar Series - April 17th, 2014

Overview

- Radio Frequency Design
  - Resonator Theory
  - Deflecting Cavities
- Beam Manipulation
  - Past Experience
    - KEK
    - CEBAF
  - Future Plans
    - SPX
    - LHC Upgrade
    - Mu2e (PIP-II Complex)



Design and Optimization

RADIO FREQUENCY RESONATORS

A Primer – Radio Frequency Resonators

- Useful to remember:
  - $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$
  - Magnetic Fields do no work
  - Stationary charges create Electric Fields
  - Moving charges create Magnetic Fields
  - Charges flow on metallic surfaces

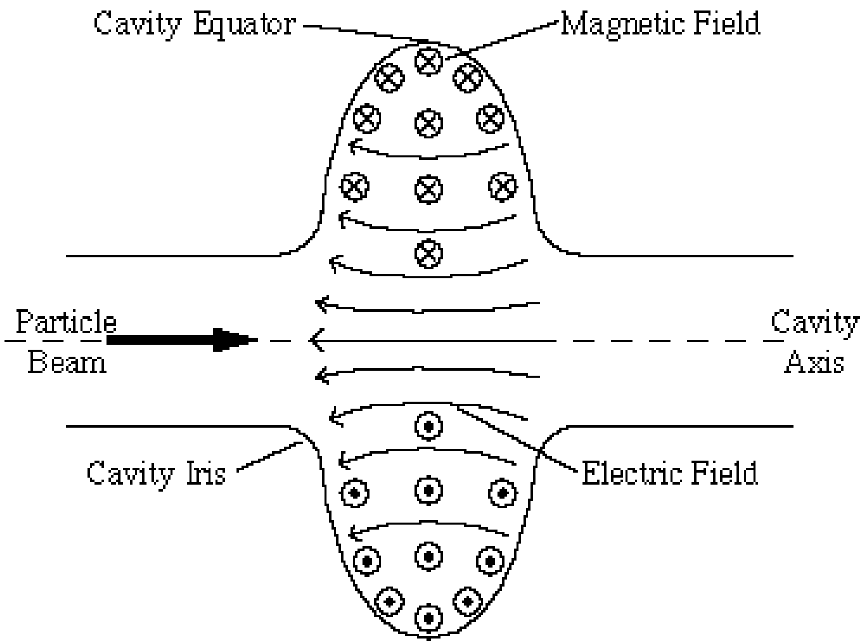
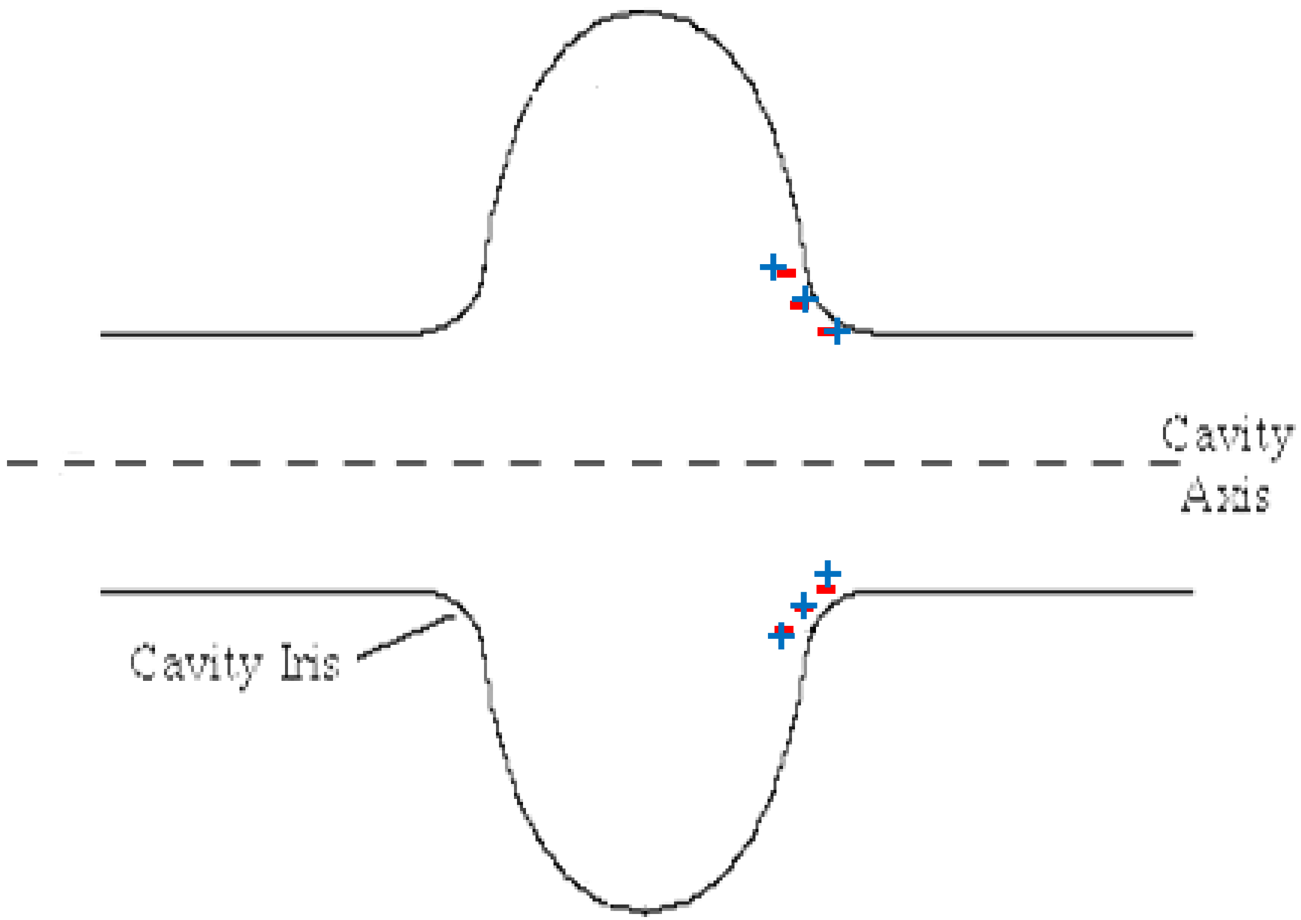


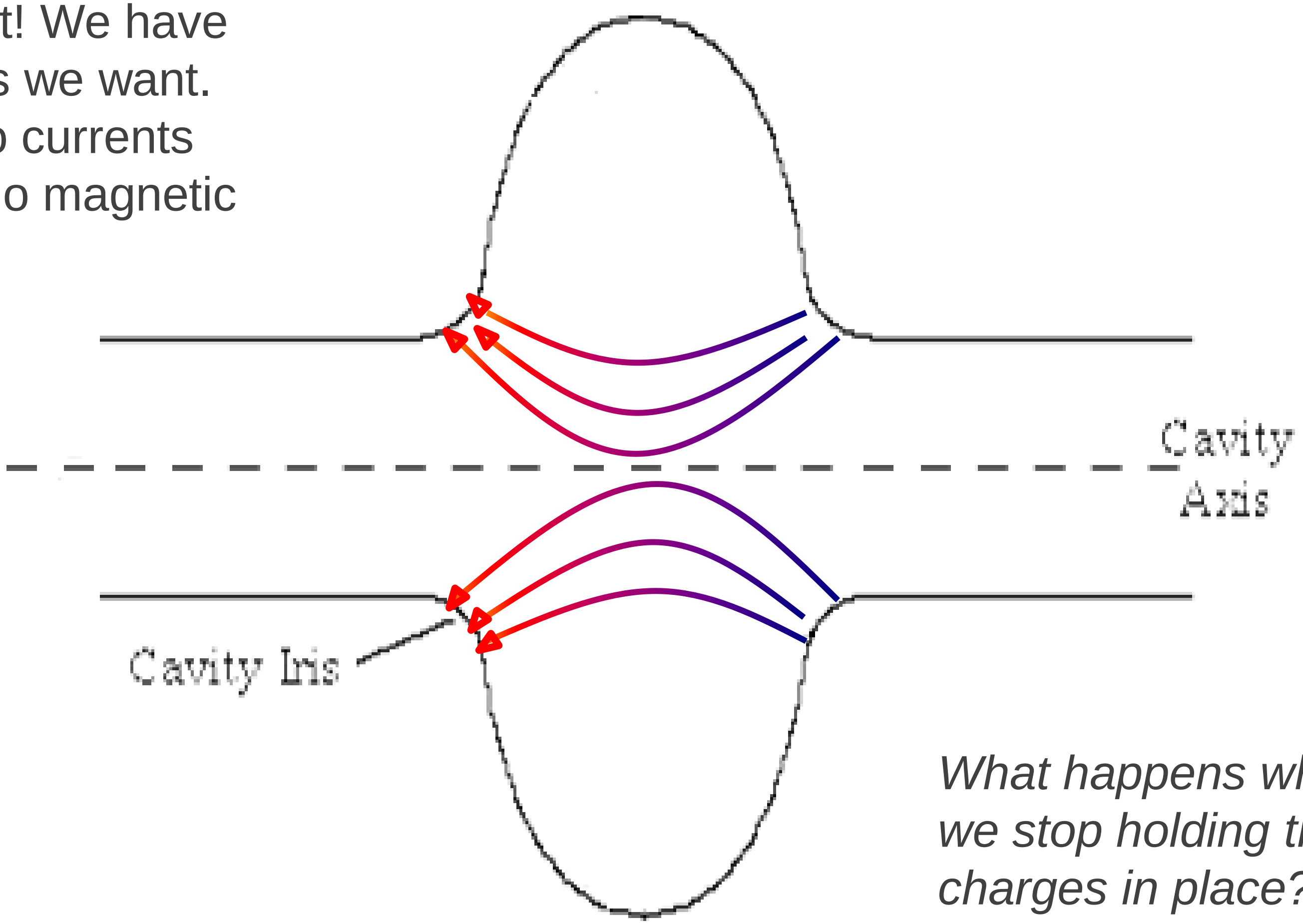
Diagram courtesy of LEPP

Monopole Mode Resonance – Test Charges



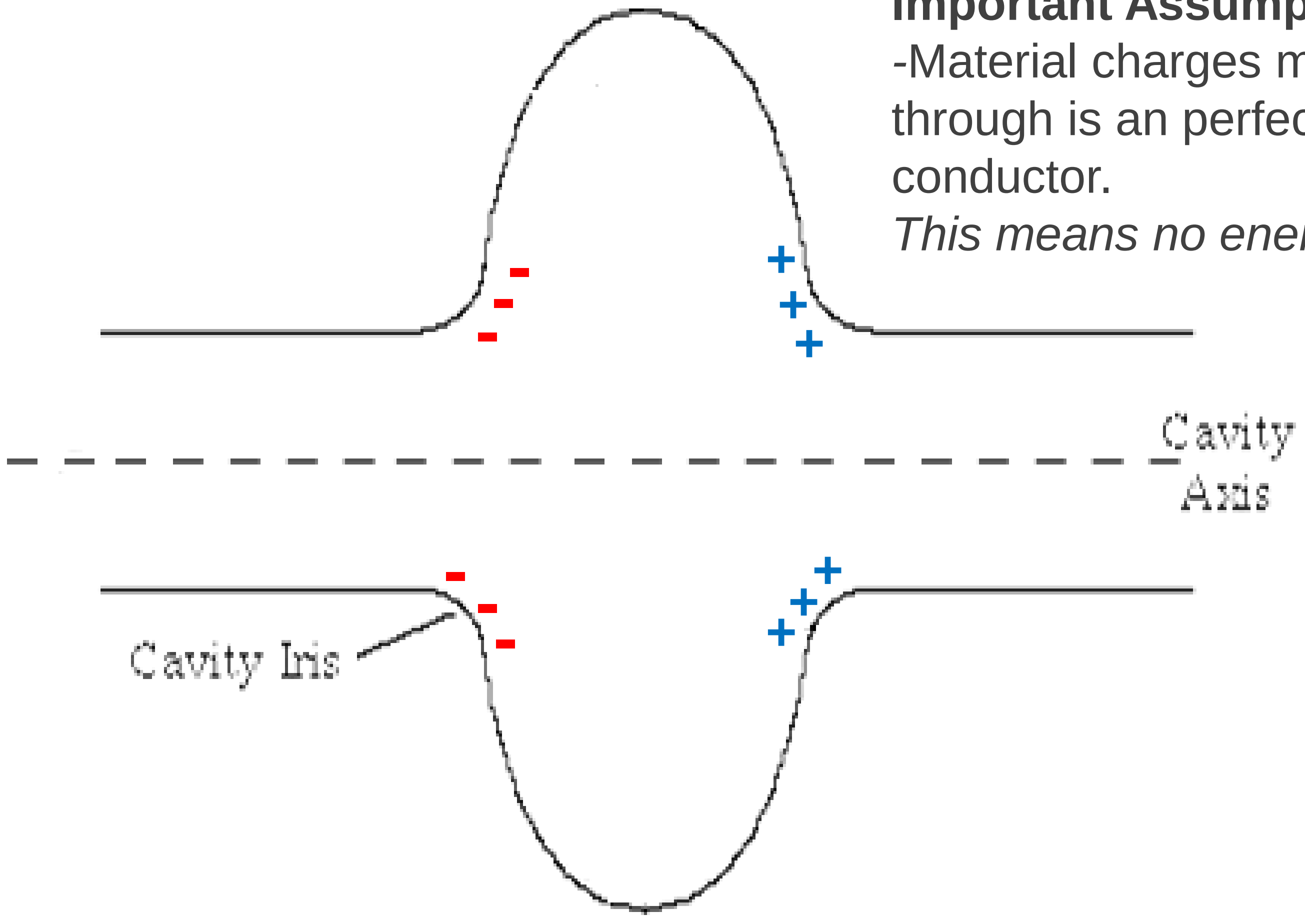
Resulting Electric Fields

Excellent! We have the fields we want. Note: No currents means no magnetic fields



What happens when we stop holding the charges in place?

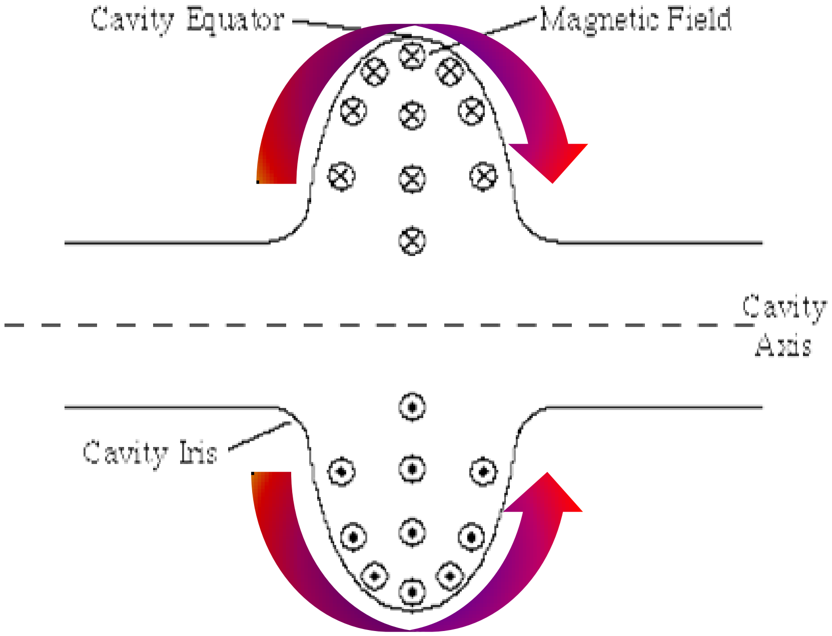
Releasing the Spring



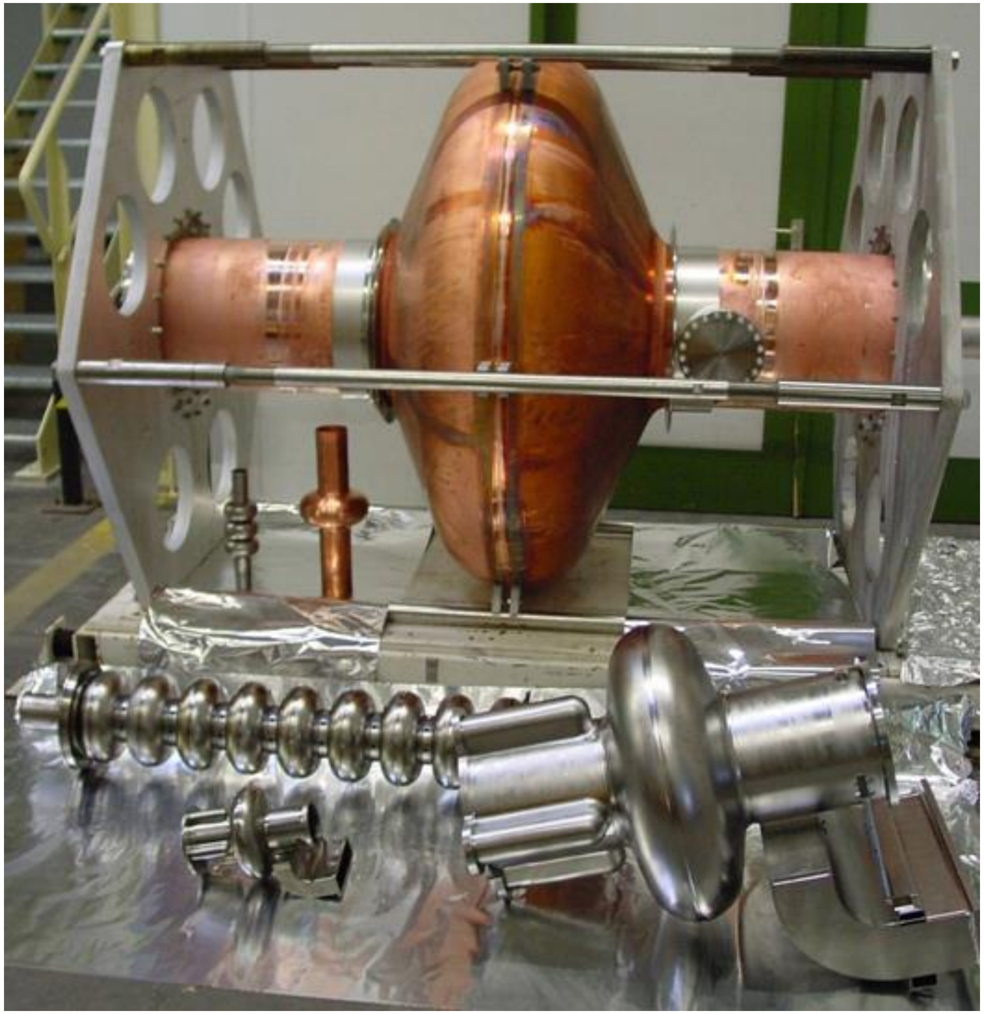
Important Assumption:
-Material charges move through is an perfect conductor.
This means no energy is lost.

Resonant Behavior

- $\vec{E}(\vec{r},t) = \vec{E}(\vec{r},0)\cos(\omega t)$
- Where $\omega = \frac{2\pi}{T}$
- Period is mostly determined by distance between electric field regions
- Remember Maxwell:
- $\nabla \times \vec{B} = \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$ (in vacuum)

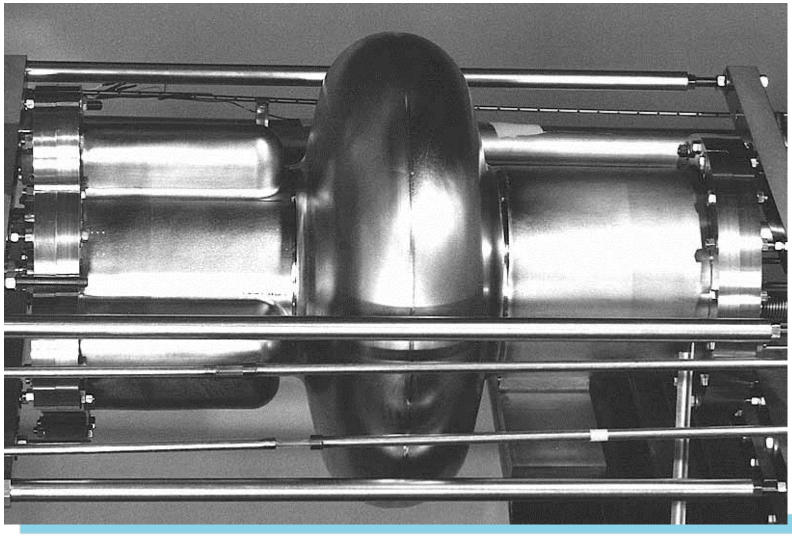


Examples of Monopole-Mode (Accelerating) Cavities



Cavity Design for Different Accelerator Applications

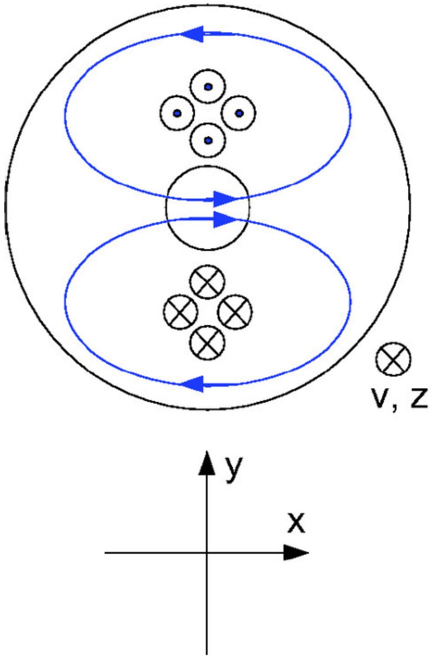
- Synchrotrons (Ring Machines)
  - The beam sees the cavity MANY times, low gradient is typical
  - Field must be very clean and stable
  - Very heavy higher order mode damping
  - Very large aperture
  - Acceleration and bunching
- Linacs (Linear Accelerators)
  - Single (or low #) pass machine
  - High Gradient is KEY (reduces # of cavities needed, therefore $$$)
  - Reliability and ease of fabrication is very important (many cavities)
  - Efficiency of operation also important

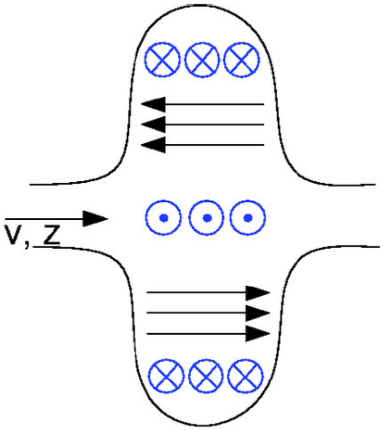


Dipole-Mode Cavity

- Dipole-Mode: Two high electric field regions
- A repetition of the process we used for the monopole mode shows:
  - Shape of Magnetic field
  - T will be smaller (higher frequency)
- **Strong, Transverse Magnetic Field on Axis**
  - Degenerate Modes must be split

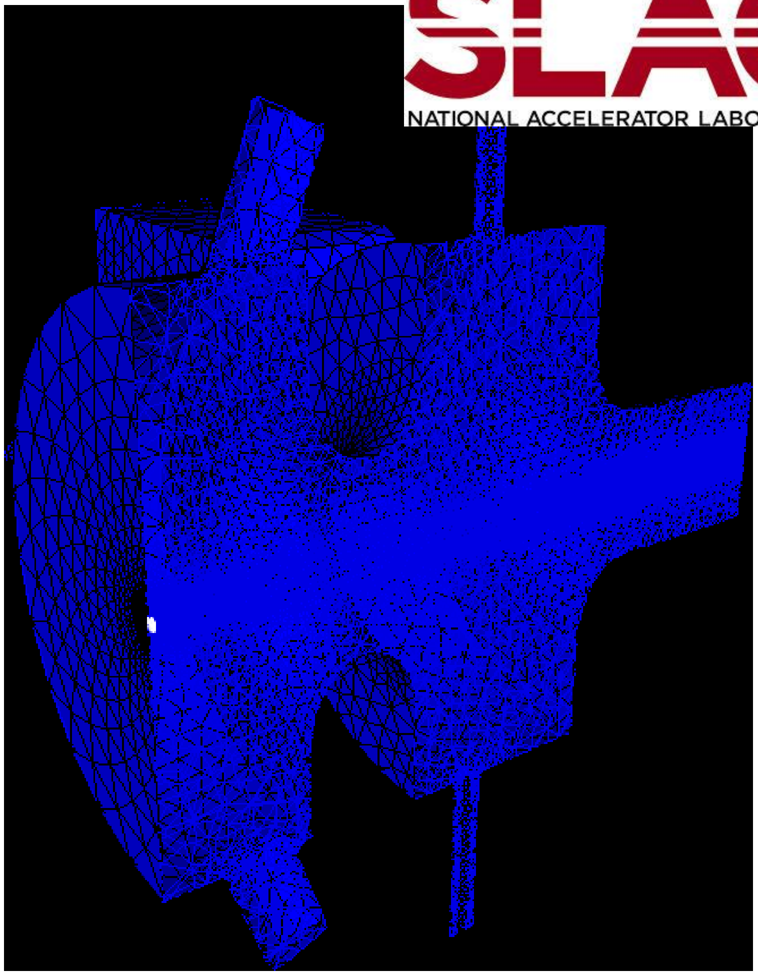
- Deflecting Mode





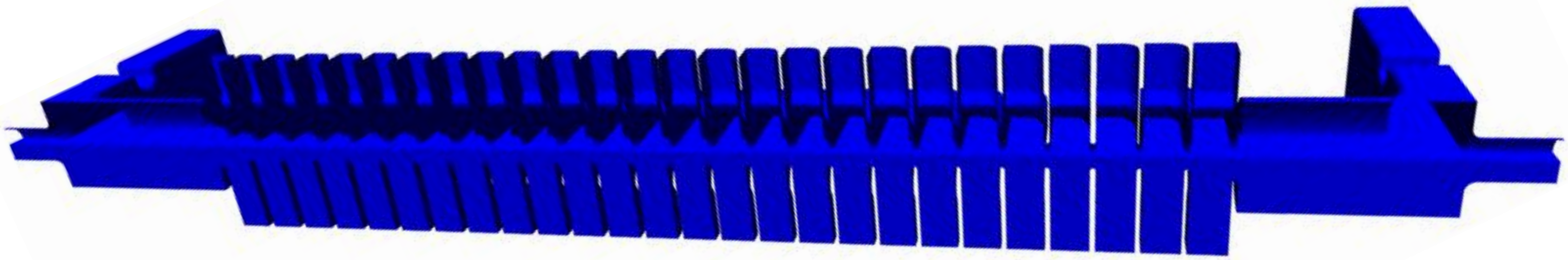
Cavity Requirement: Wakefield Damping

- Change in beam impedance (read: cross-section) generates EM wakefields
- Depending on geometry, power generated can be from Watts to kiloWatts
  - If symmetry of beam matches symmetry of mode, more power is deposited
- Power must be damped/removed before it disrupts beam



Temporal evolution of electron bunch and scattered self-fields

Cavity Requirement: Wakefield Damping



KEK-B and CEBAF

HISTORICAL USAGE

Bunch "Crabbing"

- Colliding bunches at an interaction point must have some crossing angle
- This angle geometrically decreases instantaneous luminosity
- Most of this lost luminosity can be recovered by using deflecting (crabbing) cavities to rotate the bunches
- Rotation is removed after IP

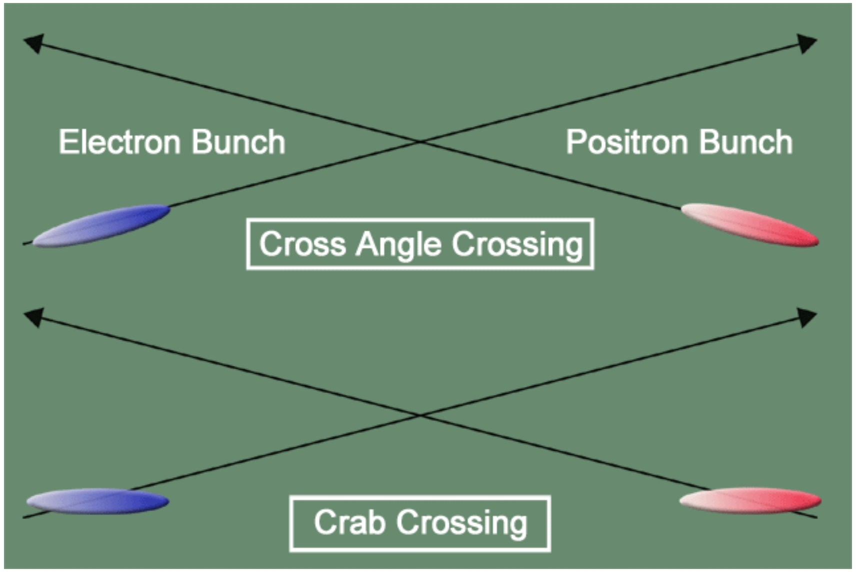
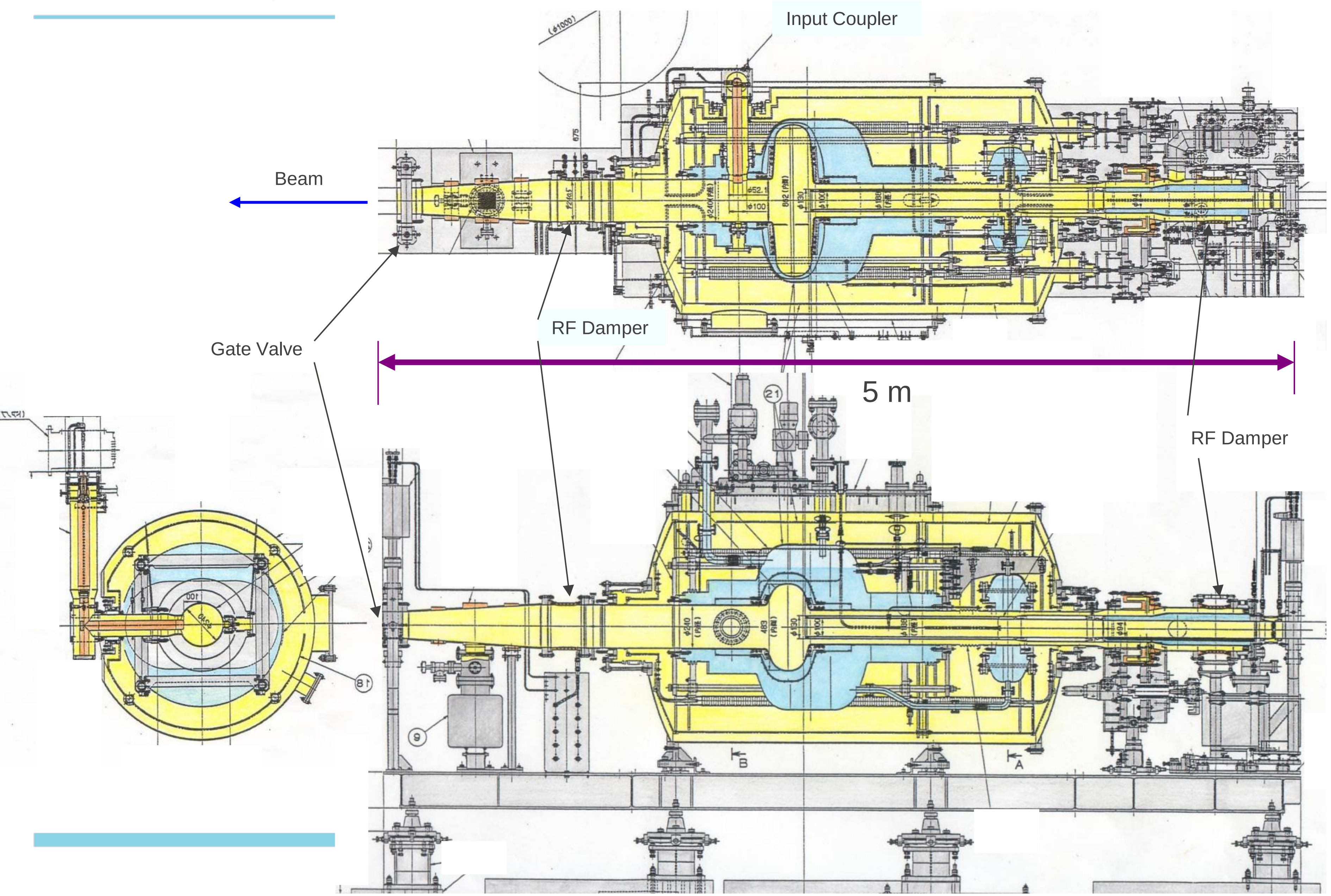


Image Source: ILC Newsline

Cryostat for KEKB Crab Cavity

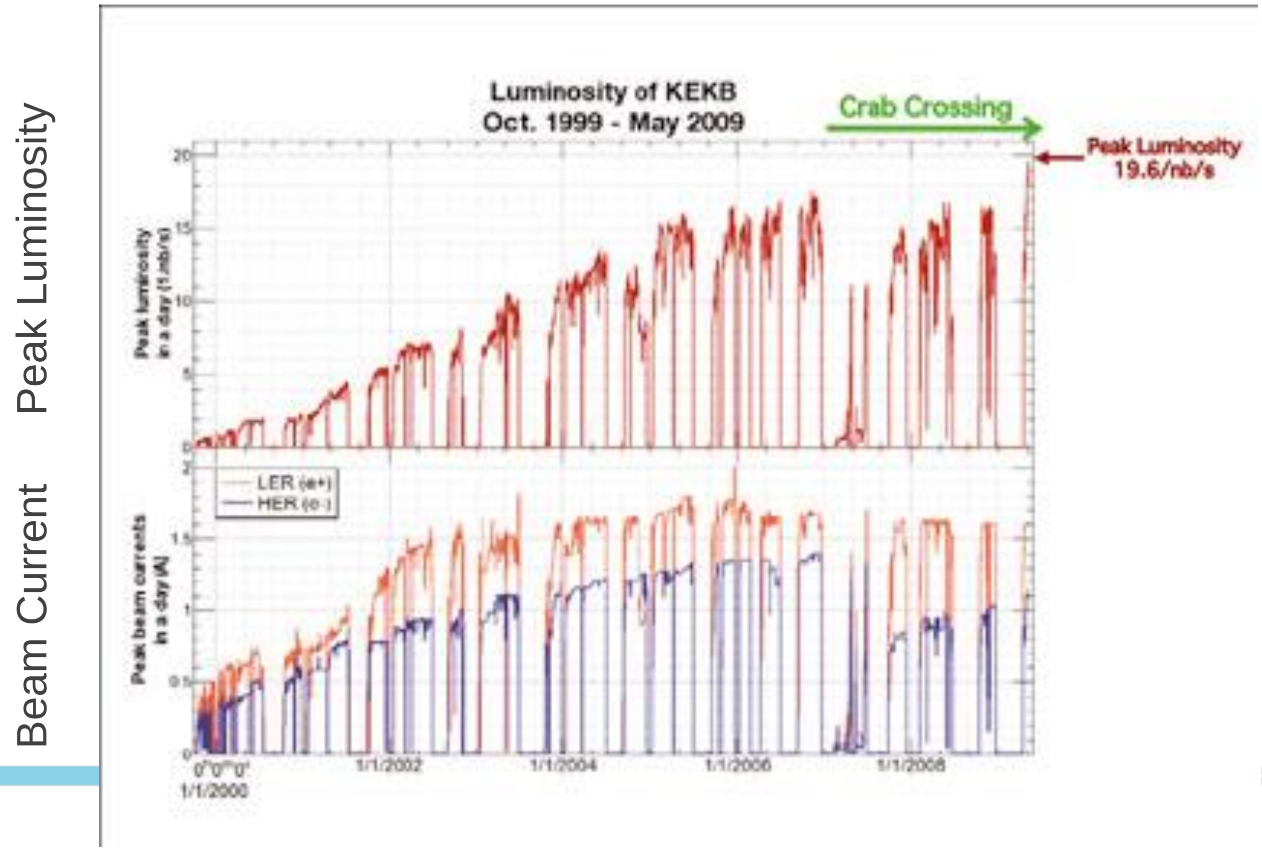
From Kenji Hosoyama at KEK



Operation of KEKB Crab cavity

From Kenji Hosoyama at KEK

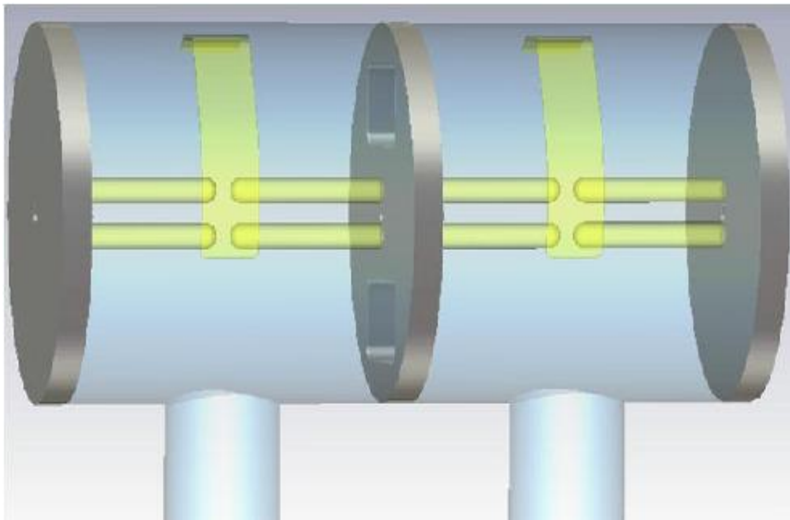
- The crab cavities operate
  about 3 years without serious problems.
- Peak Luminosity L_{peak} =19.6 x 10^{33} /cm^2/s
  attained under crab on operation.

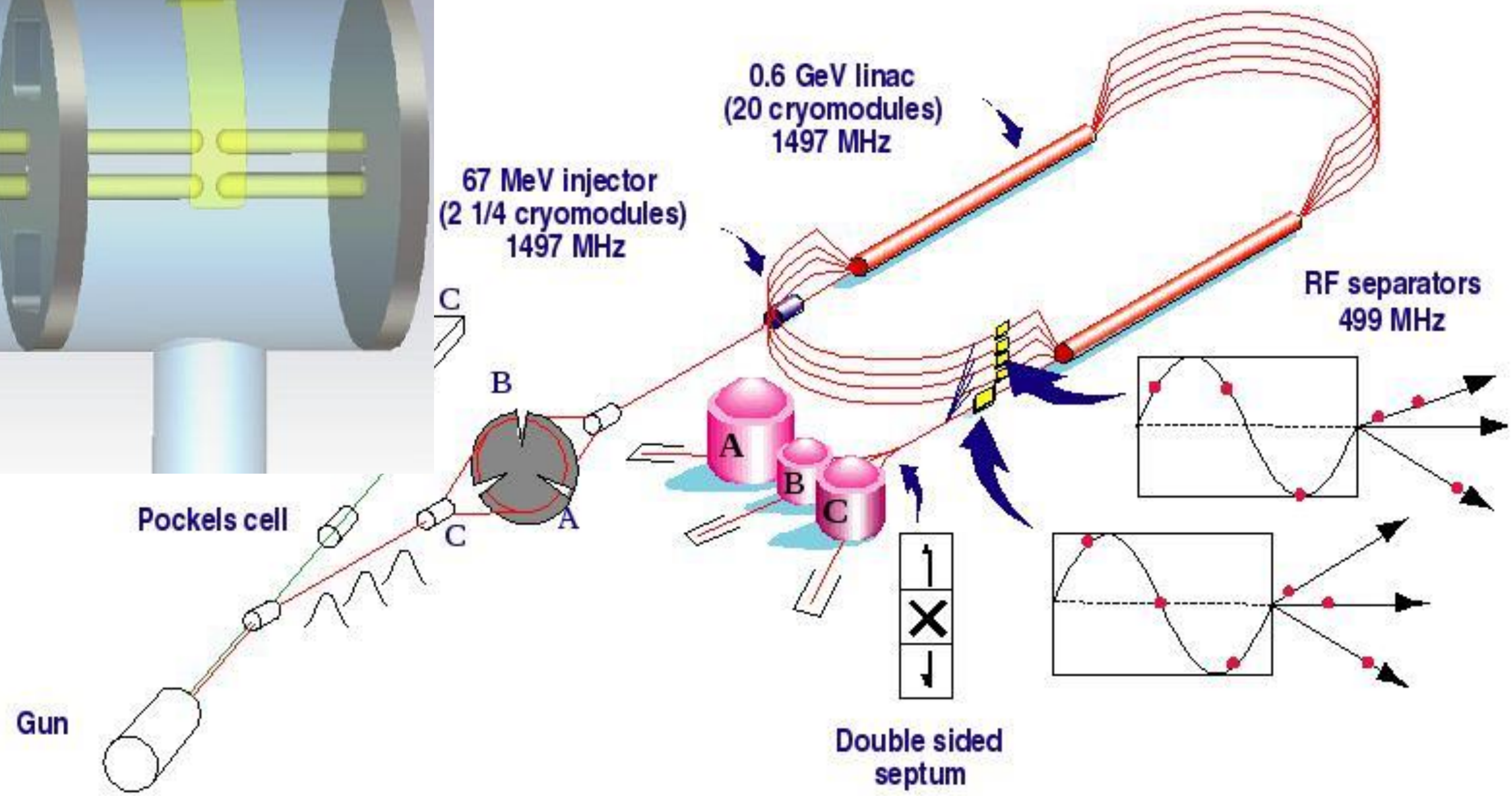


Jefferson Laboratory – RF Switchyard

Lessons learned from CEBAF commission ---- A. Hutton
CEBAF switchyard ---- C. Hovater

CEBAF

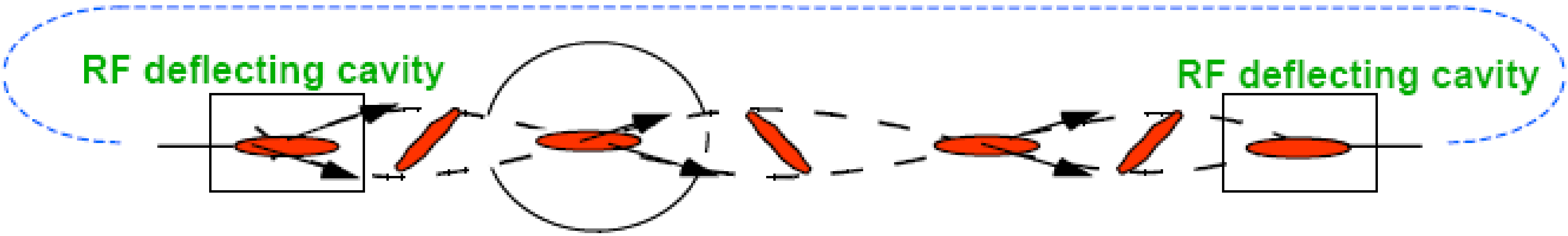


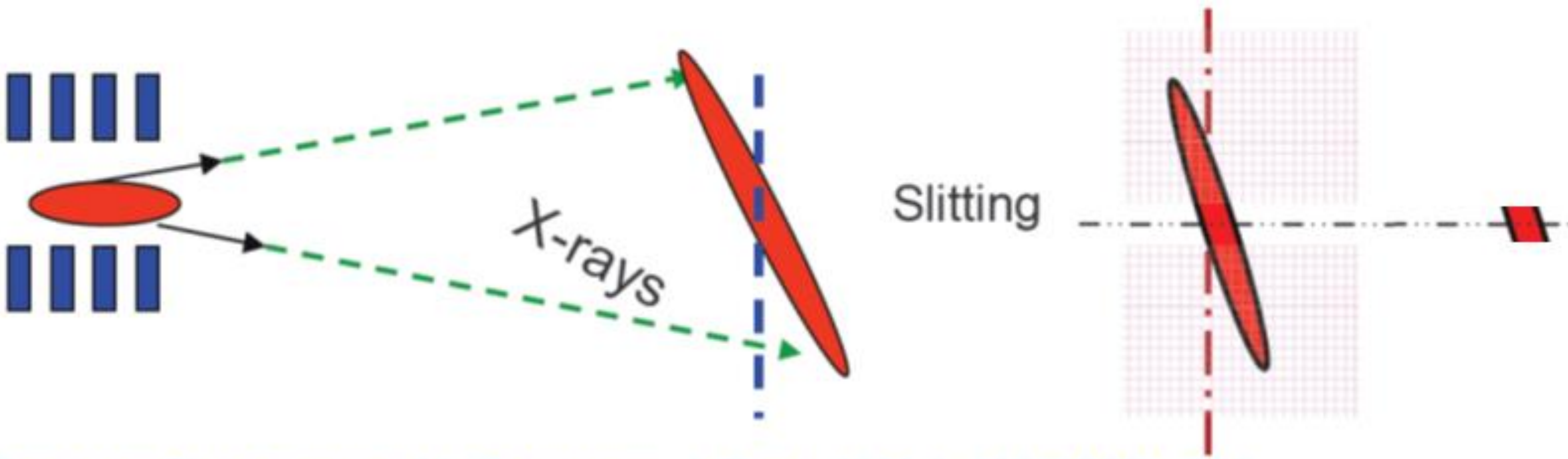


SPX, HL-LHC, FNAL

FUTURE USAGE

SPX Short-Pulse X-Ray Scheme





A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425(1999), 385

Images Courtesy of A. Nassiri

SPX Cavity Design

- Notable RF Features:
  - Forward Power Coupler
  - Wakefield damping
    - Higher-order modes like quadrupole and above
    - Lower-order mode is the monopole
    - Because the monopole mode is symmetrically similar to the beam, it must be damped very heavily
  - Field Probe

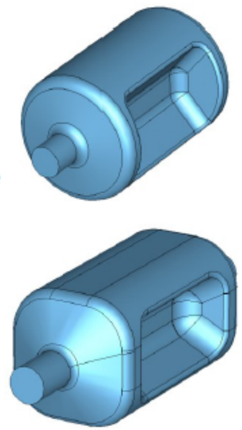
Superconducting Cavity

- Superconducting RF
  - Operates at 2 Kelvin (super-fluid helium)
  - Cut from large-grain, high-purity niobium ingot
  - All welds are done by electron beam in vacuum to maintain material purity
  - Heavily etched for optimal RF surface (field enhancement)
  - Requires rigorous/time-consuming cleaning and assembly in a class 10 clean-room

LHC Upgrade – Advanced Crabbing Cavities

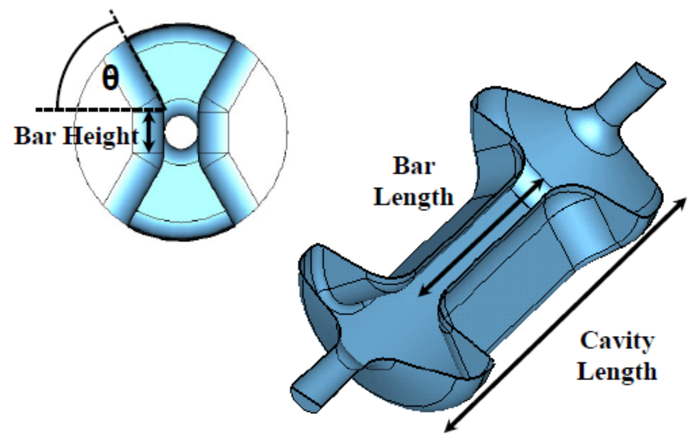
RF-Dipole Design

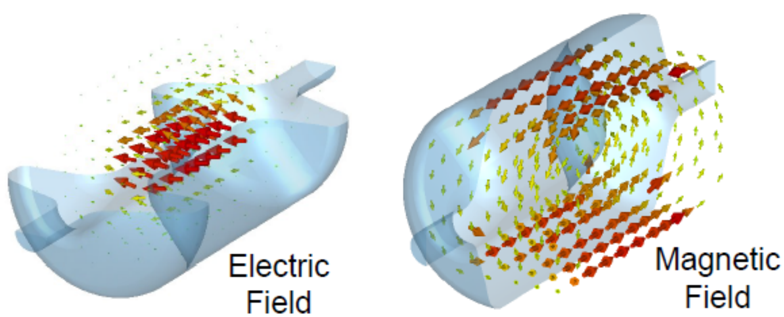
- Small size
- Square shape for additional compactness
- Lower and balanced peak surface fields
- High shunt impedance
- Wider separation in HOM spectrum and no LOMs
- Multipacting processes easily
- Cavity processing – Curved end plates for cleaning the cavity



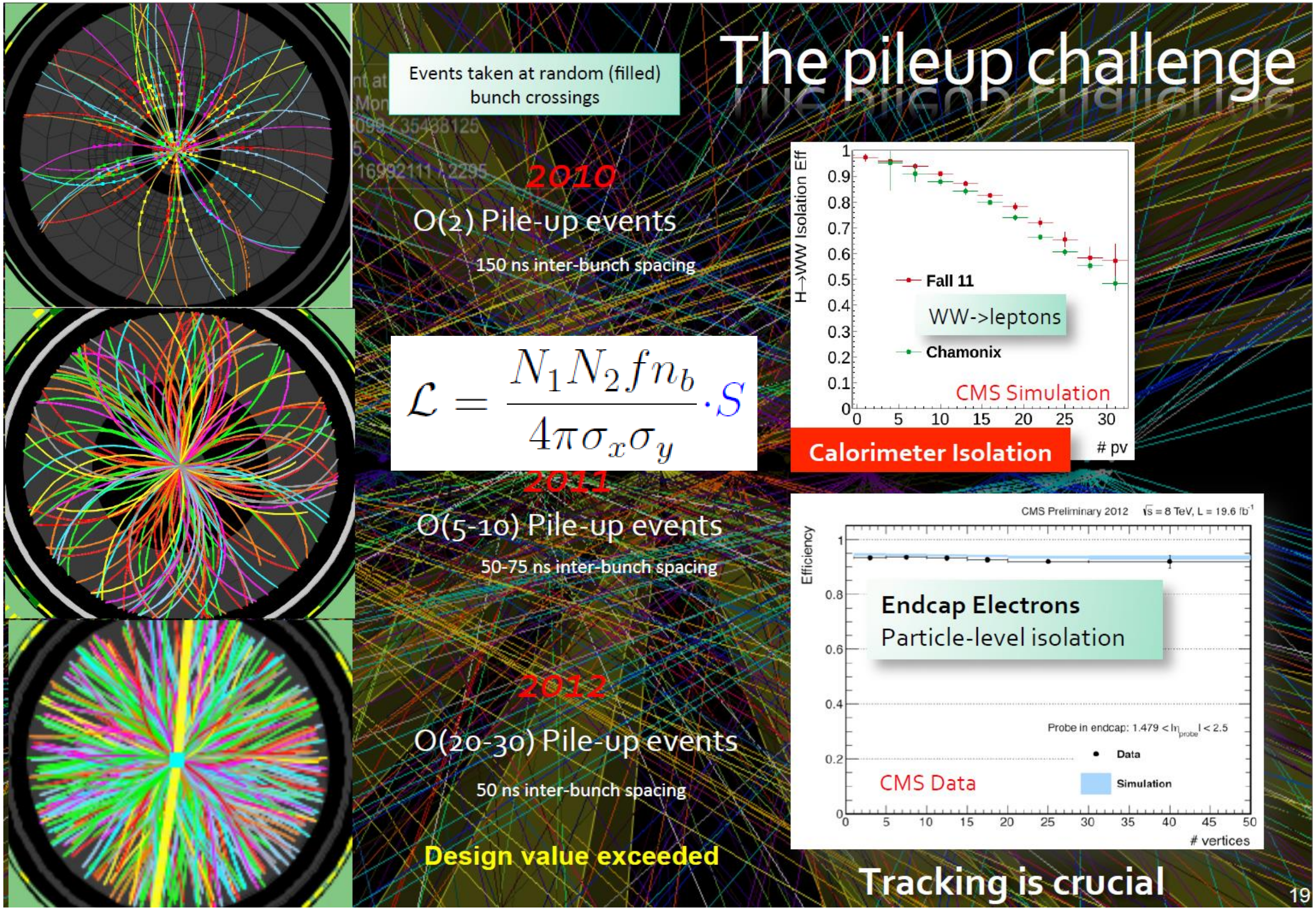
Properties depend on a few parameters

- Frequency determined by diameter of the cavity design
- Bar Length ~$\lambda/2$
- Bar height and aperture determine E_P and B_P
- Angle determines B_P/E_P



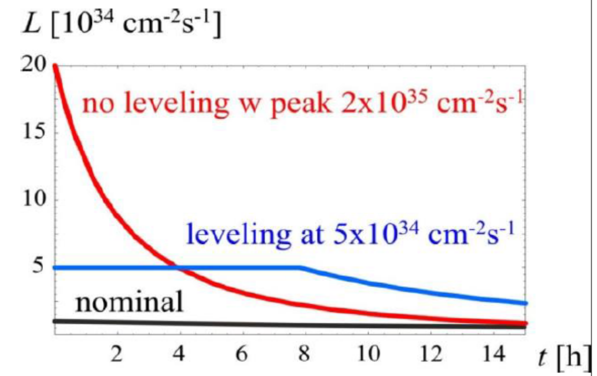


P5 Workshop (12/15/’013)
Heinemann Presentation on High Lumi - LHC

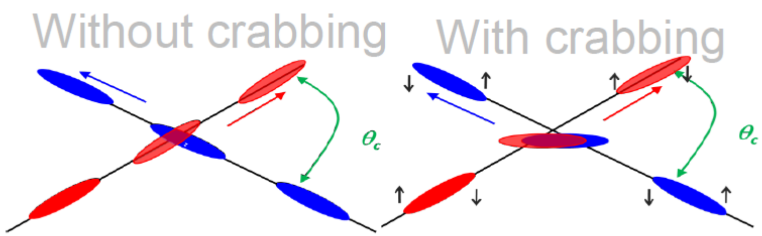


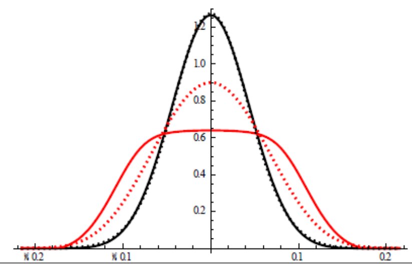
HL-LHC Collision Region

- Luminosity leveling reduces pileup in experiments
  - $5x10^{34}$ $cm^{-2}s^{-1}$ corresponds to ~140 pileup interactions
  - Exact amount of pileup tolerable by experiments still under discussion
    - Can experiments tolerate 200? Or more?

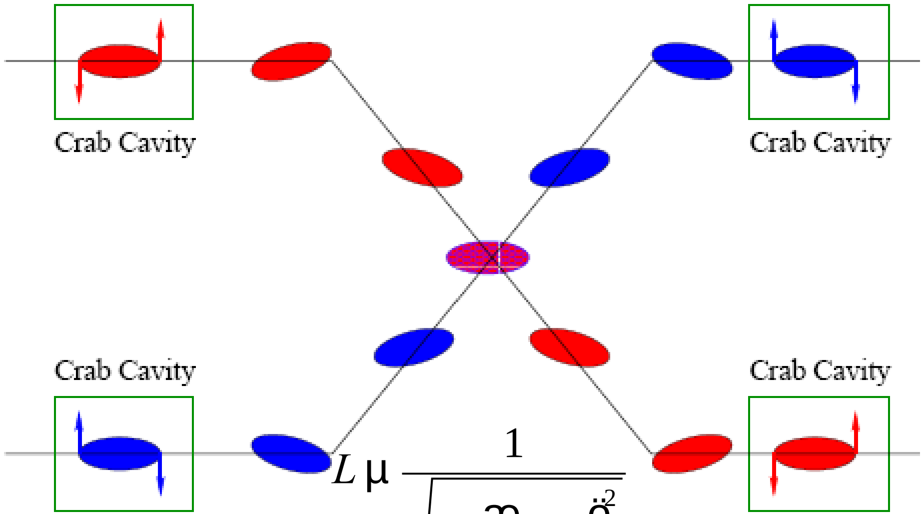


- Introduce crab cavities rotate beams to increase fraction of collisions per bunch
- Shape of luminous region still under discussion
  - Try to minimize peak vertex density



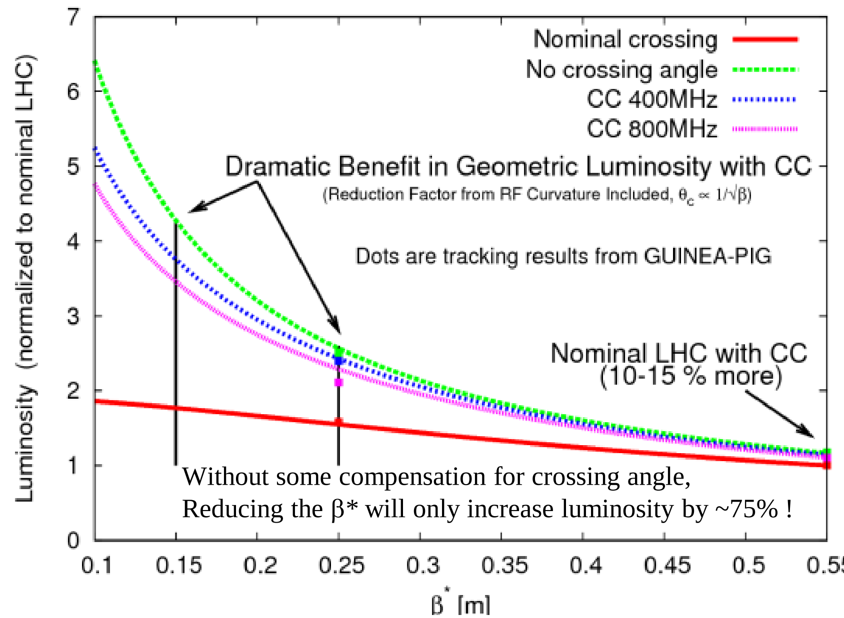


Crab Cavities

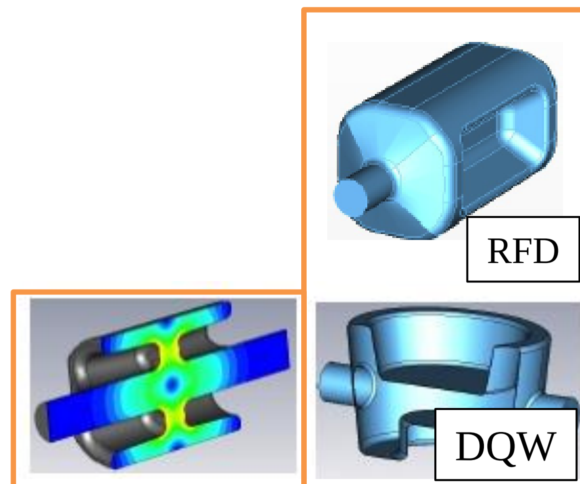


$$L \propto \frac{1}{\sqrt{1+\left(\frac{\theta_c \sigma_z}{2\sigma_x}\right)^2}}$$

"Piwinski Angle"



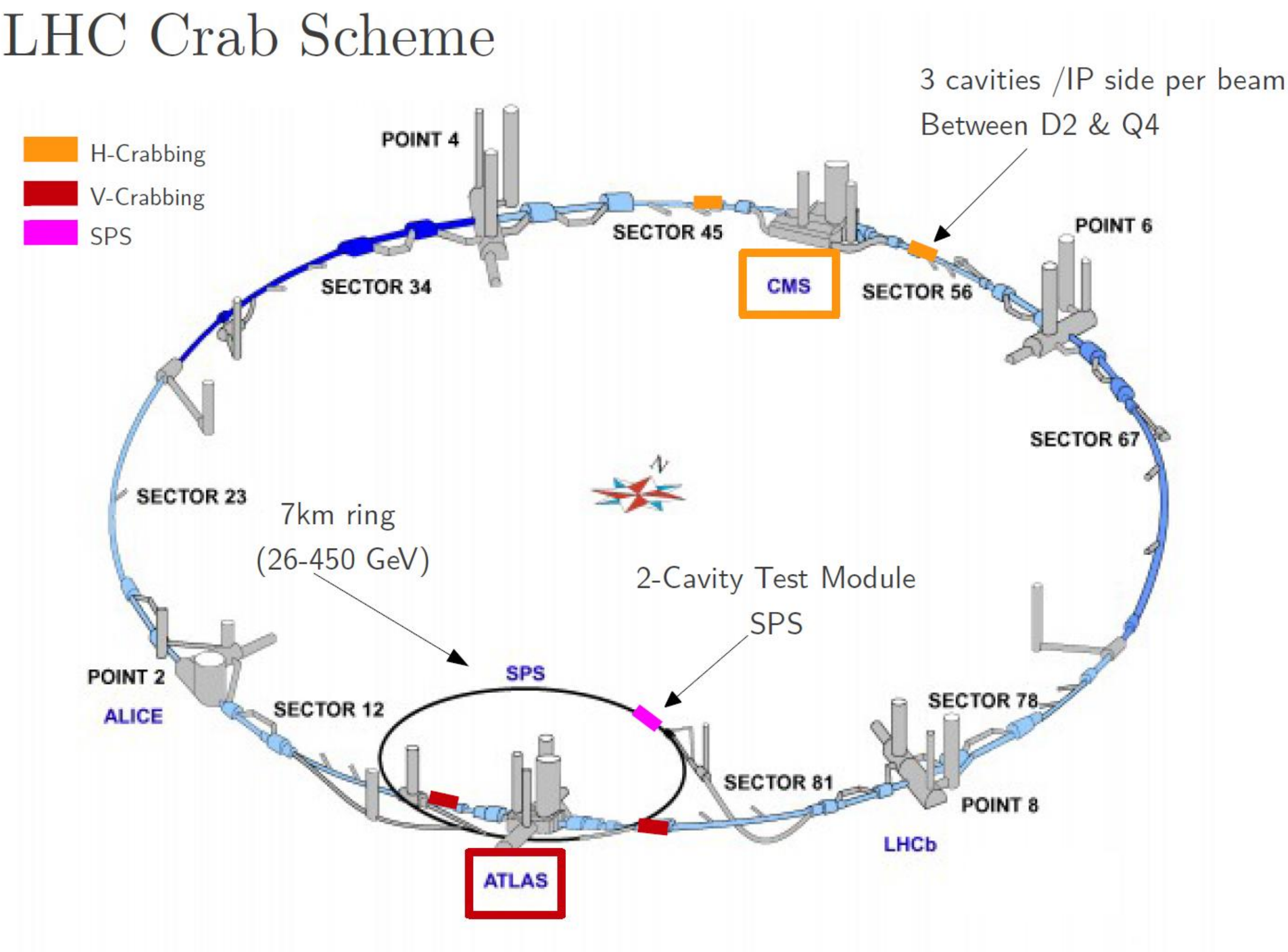
- Technical Challenges
  - Crab cavities have only *barely* been shown to work.
    - Never in hadron machines
  - LHC bunch length requires low frequency (400 MHz)
  - 19.4 cm beam separation needs "compact" (exotic) design
- Additional benefit
  - Crab cavities are an easy way to level luminosity!



UK LARP

Q:a1 Q:a2

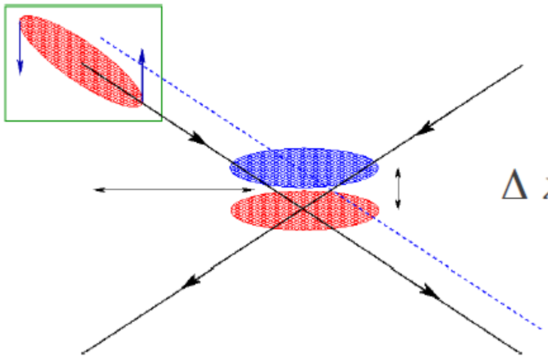
SRF 2013 (9/27/'013)
R. Calaga Presentation on LHC CC Collaboration



Precise control of voltage & phase

Main RF phase jitter

$\Delta\phi = 0.005^0$ @400 MHz



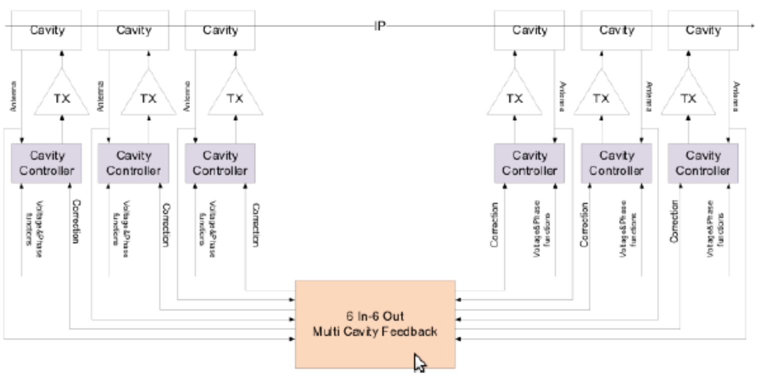
$$\Delta x_{IP} = \frac{\theta_c}{k_{RF}} \delta\varphi$$

For Crabs (θc=570µrad):

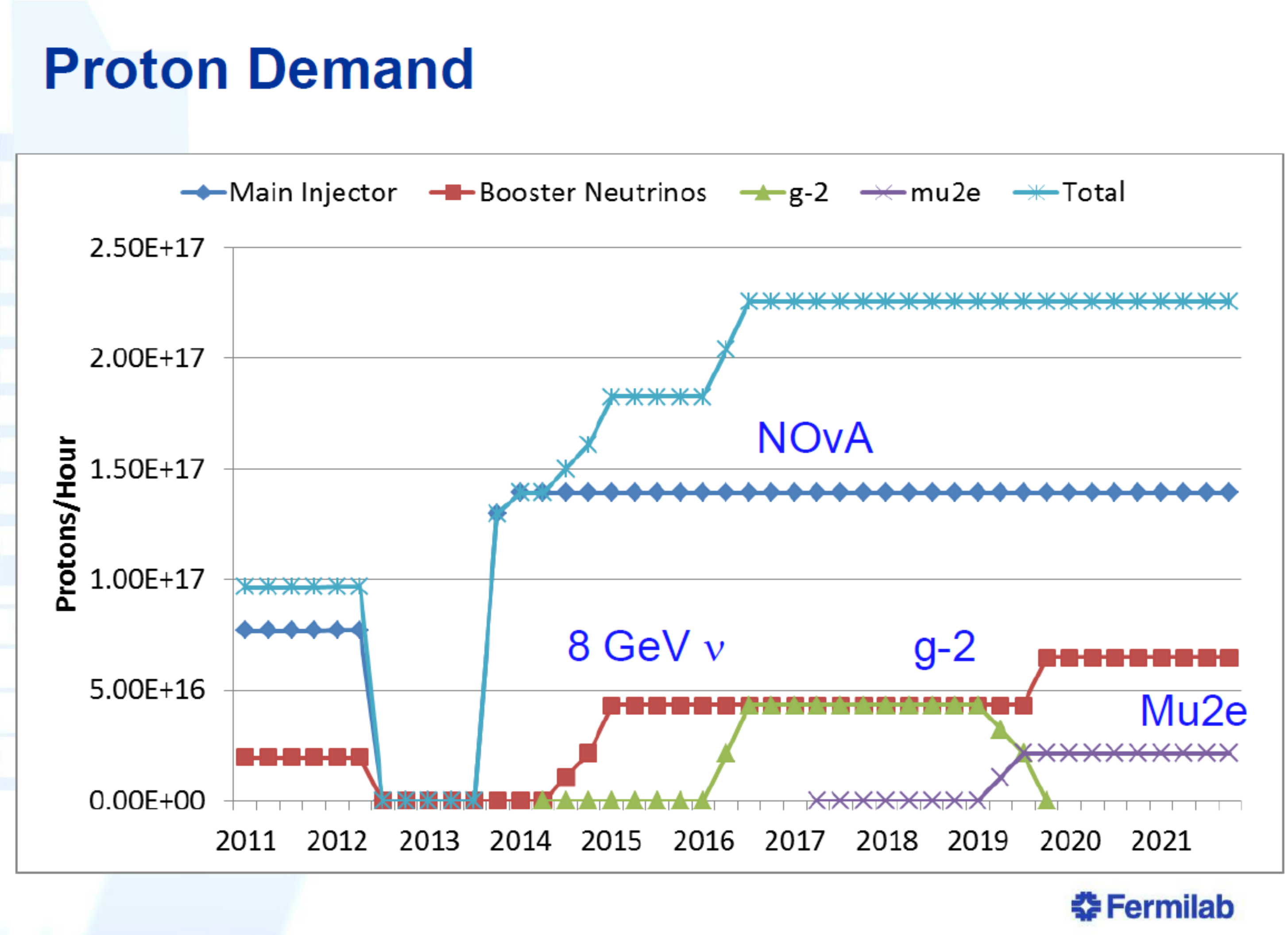
Δx_{IP} = 0.3µm (5% of σ_x^*)

Independent control of ampl/phase

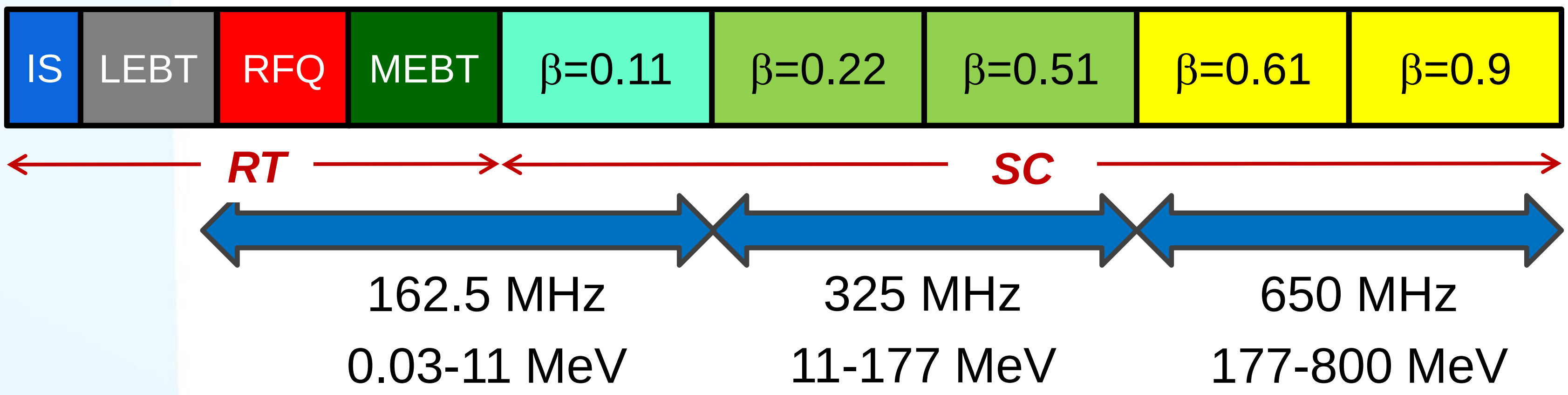
Strong feedback across IP



Current Fermilab Usage Plan

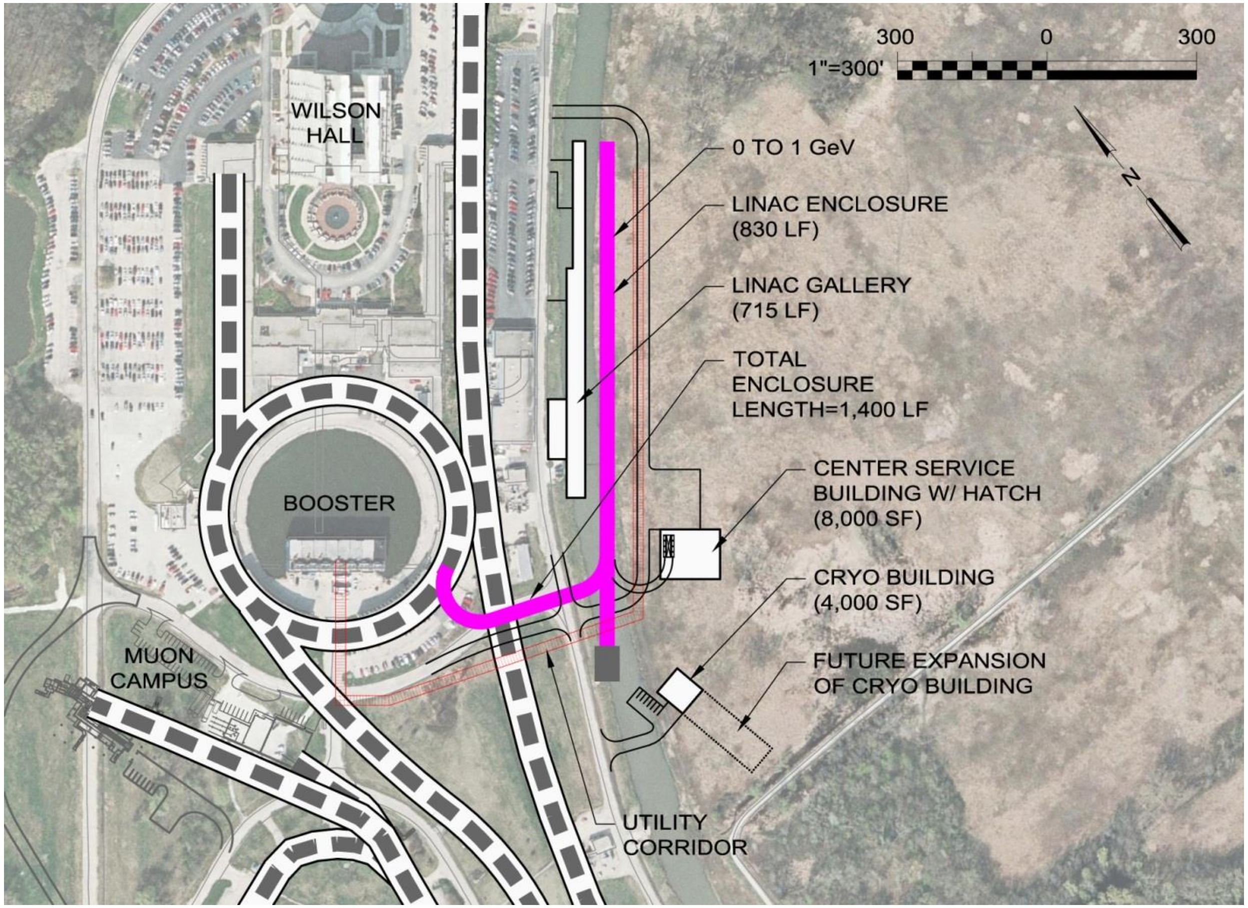


Proton Improvement Plan-II
Linac Technology Map



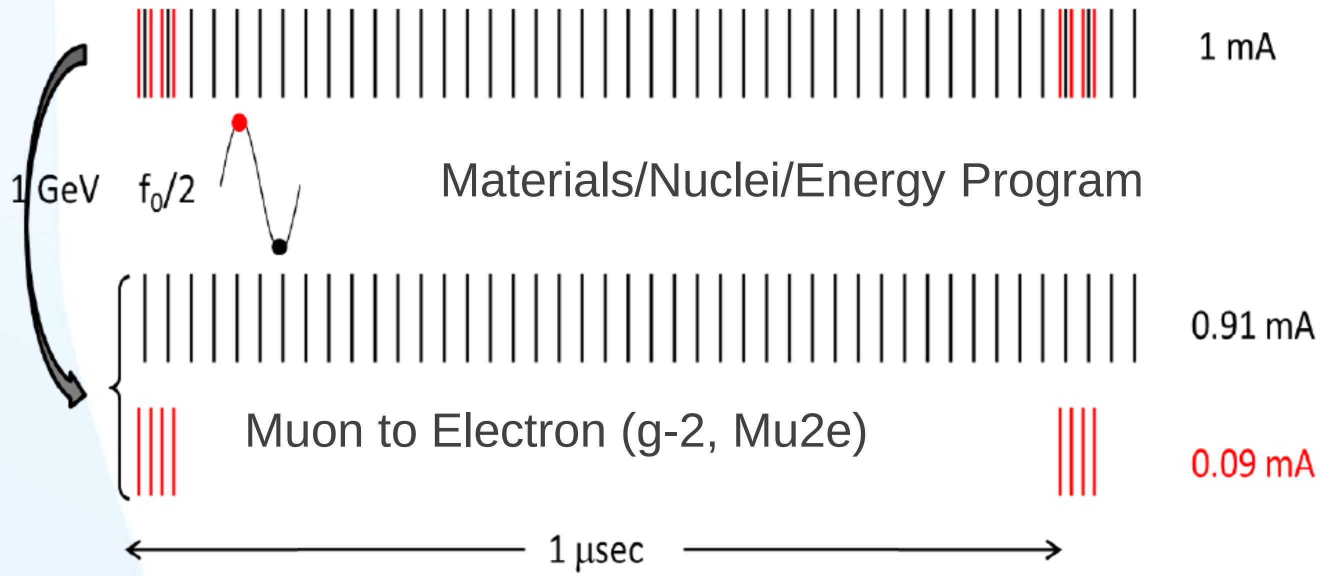
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-11	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	11-38	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.51)	325	38-177	35/21/7	SSR, solenoid
LB 650 (β_G=0.61)	650	177-480	30/20/5	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	480-800	24/10/4	5-cell elliptical, doublet

Proton Improvement Plan-II
Site Layout (provisional)

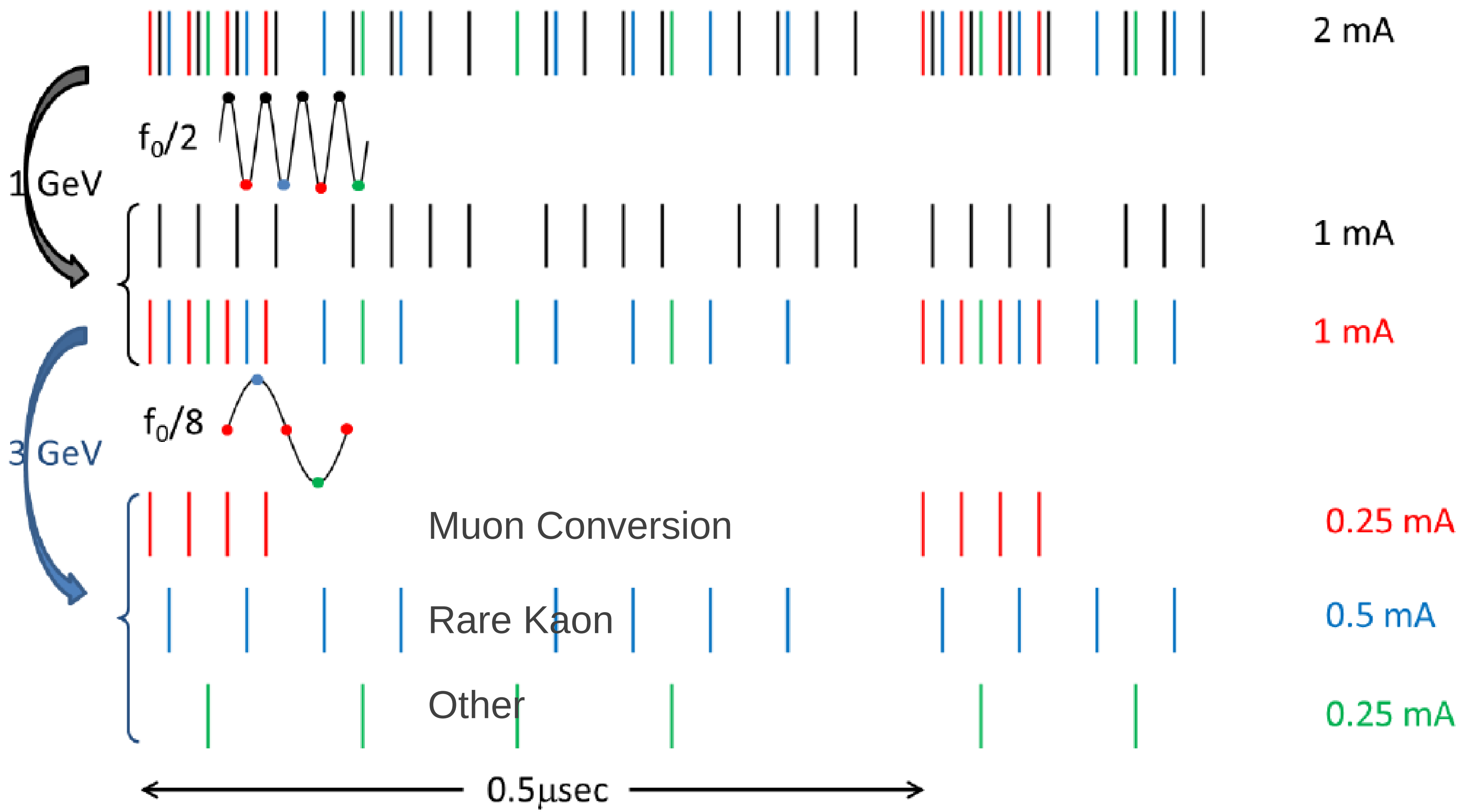


Fermilab Upgrade Applications PIP-II to Project X (2024?)

Flexible Beam Formats

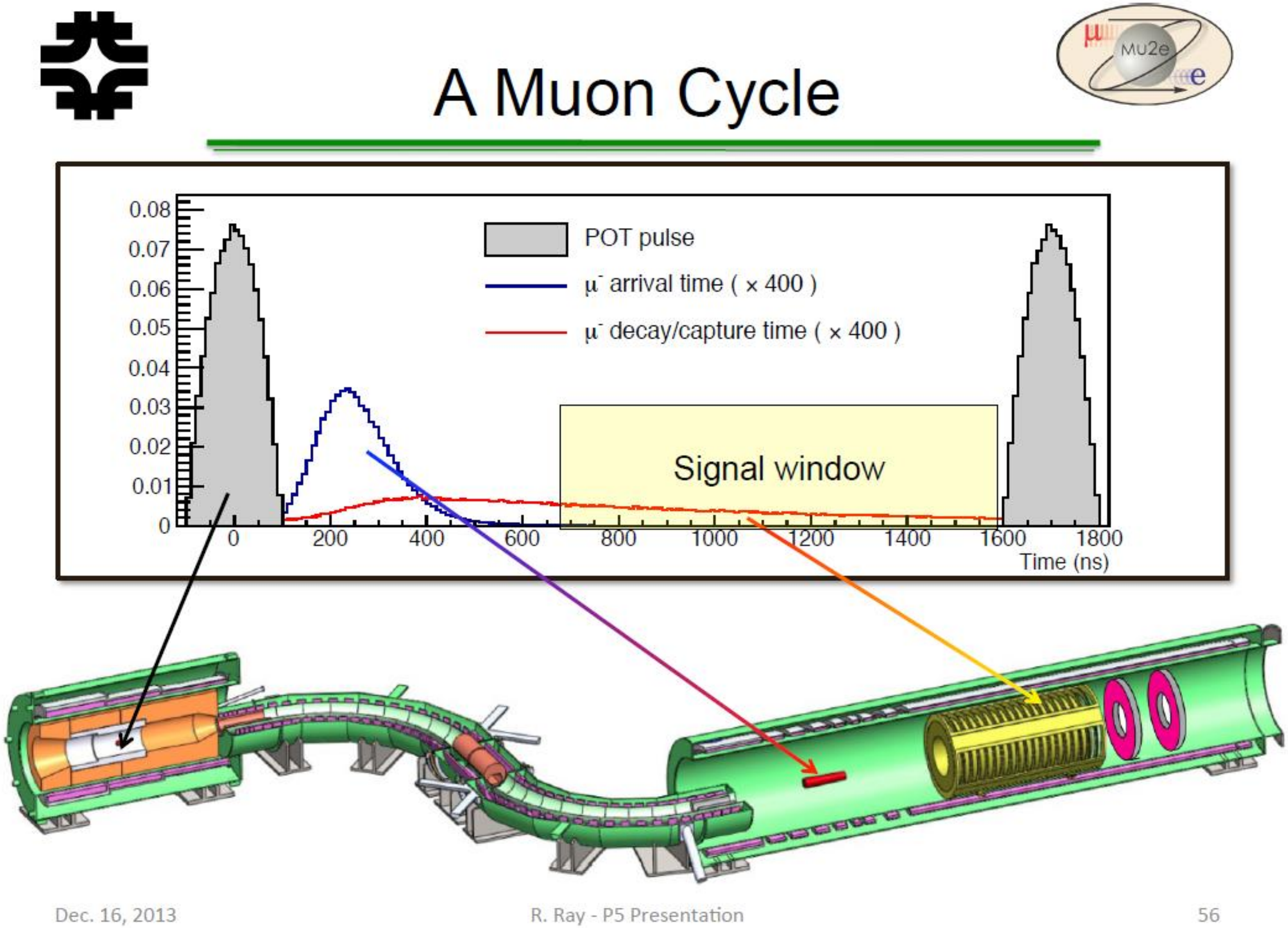


Project X Stage Two



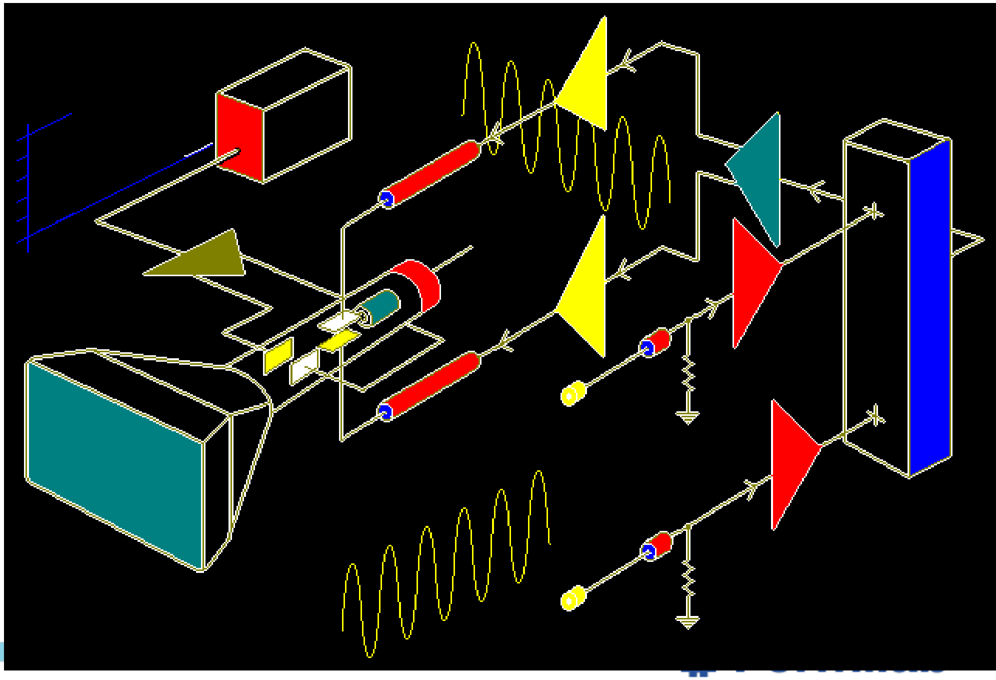
*Project X Accelerator Reference Design Document

Specialized Beam Delivery (Extinction Magnet)



Conclusions

- Why do you care?
  - Beam Manipulation
    - Higher luminosity
      - KEK
      - HL-LHC
      - ILC (eventually)
    - SPX
    - Mu2e low background
  - Beam Delivery
    - CEBAF recirculation
    - PIP-II/Project X delivery to different experiments
- Deflecting Systems not mentioned:
  - CRT TVs
  - Oscilloscopes
  - Making Saran Wrap (!)

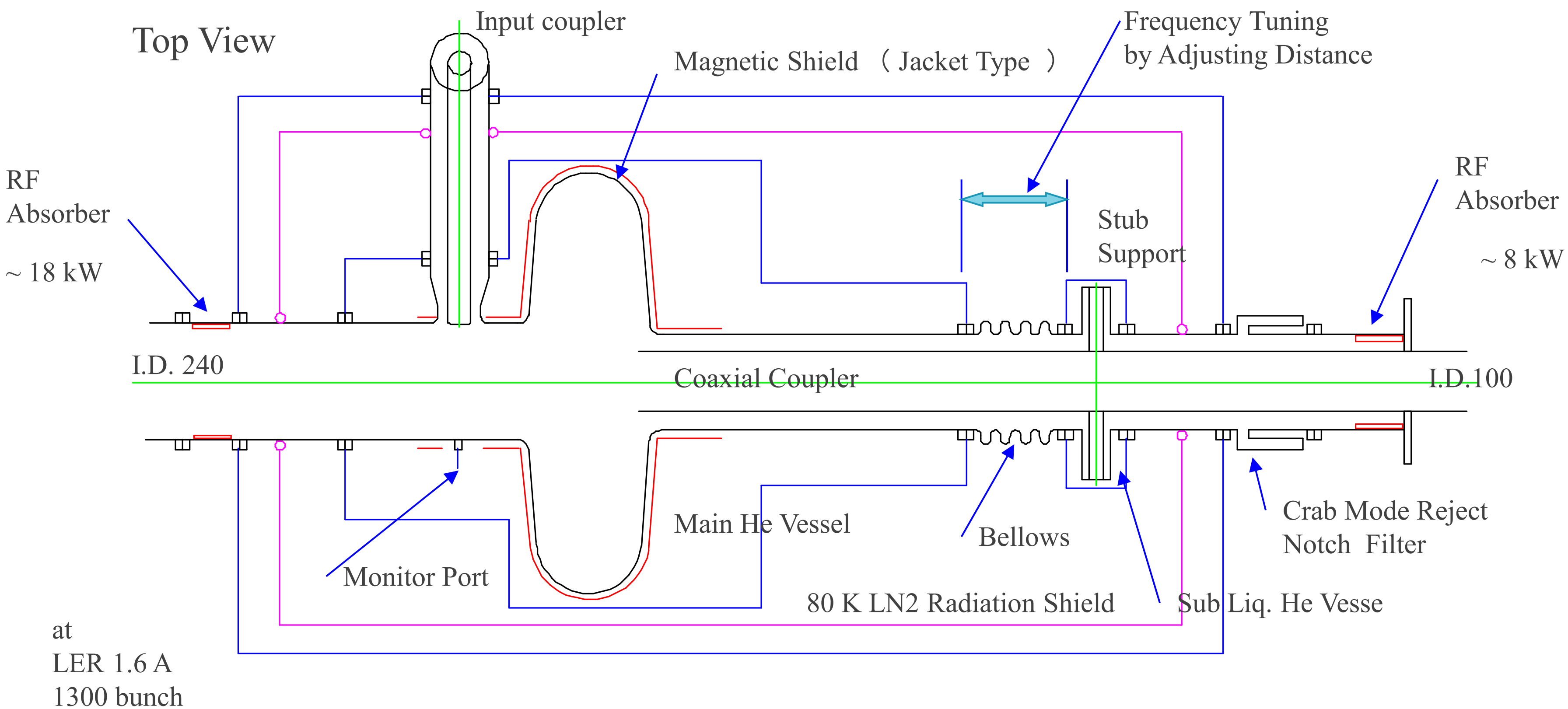


Thanks for your attention!

QUESTIONS?

Conceptual Design of Cryostat for KEKB Crab Cavity

From Kenji Hosoyama at KEK



Jacket-type Helium Vessel

Coaxial Coupler *Frequency Tuning*

Stub-Support -- Mechanical Support & Cooling of Coaxial Coupler

Jacket-type Helium Vessel

SRF 2013 (9/27/'013)
R. Calaga Presentation on LHC CC Collaboration

SPS Test Module

Courtesy: EN-MME

Proof of principle demonstration with protons

Important beam tests

- Technology validation, performance, stability
- Effects on the beam, cavity failures, radiation