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(S)RF Cavities: Putting the Accelerator in Particle Accelerators

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Summer Lecture Series

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About Myself

- Jeremiah Holzbauer
  - B.S. Applied Math, Nuclear Engineering, Physics
  - Ph.D. Accelerator Physics (SRF Cavity design for FRIB)
  - Postdoc at ANL-APS (SRF Deflecting Cavity for SPX)
  - Broad experience with SRF systems at FNAL since 2014
    - Cavity design, integrated testing, delicate equipmen transport
    - Primary author and Panel Chair of FESHM 10210
    - Lead for PIP-II HB650 Cryomodule Testing
    - PIP-II Accelerator Systems Level 2 Manager

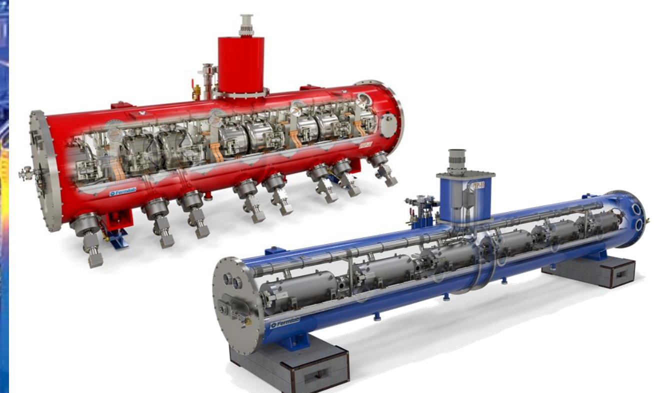
Lecture Questions

- What is a Radio Frequency (RF) Cavity?
- Why are there so many different RF Cavities?
- What is Superconductivity and why have SRF Cavities?
- What are the Big Problems in achieving (S)RF?
- How does this all apply to Fermilab?

Thanks to Sam Posen and Sergey Belomestnykh for slide content

Introduction to RF Cavities

- RF Cavities are the ‘Accelerator’ in Particle Accelerator
  – Goal: Concentrate electromagnetic energy & give it to the beam as it passes through the cavity, accelerating it
- Three Major Design Criteria:
  1. Want the cavity to store as much energy as practical
  2. Cavities are carefully designed to transfer as much energy to the beam as possible
  3. Want this cavity to store this energy as efficiently as possible



Why Electromagnetic Acceleration?

- Strong
- Weak
- Electromagnetic
- Gravity

$$\frac{d\vec{p}}{dt} = \vec{F}$$

- Radioactive decay
  - Limited Natural Sources (some artificial sources, not much better)
  - Limited Intensity
  - Very specific energies
  - Limited set of available beams
- Extremely weak
  - Using the Sun's gravity well, you could get a proton up to ~22 MeV
  - No comments on the practicality
- Electric Fields!
  - Magnetic fields can't do work

$$\Delta E = F \cdot \Delta x = \left(q\vec{v} \times \vec{B}\right) \cdot \vec{v}\Delta t = 0$$

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The Math Slide

- Maxwell's Equations are very general, govern all classical electromagnetic interactions

- $\vec{\nabla} \cdot \vec{D} = \rho$
- $\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$
- $\vec{\nabla} \cdot \vec{B} = 0$
- $\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$

Where $\vec{\mathrm{D}} = \epsilon_0 \vec{E}$ and $\vec{\mathrm{B}} = \mu_0 \vec{H}$

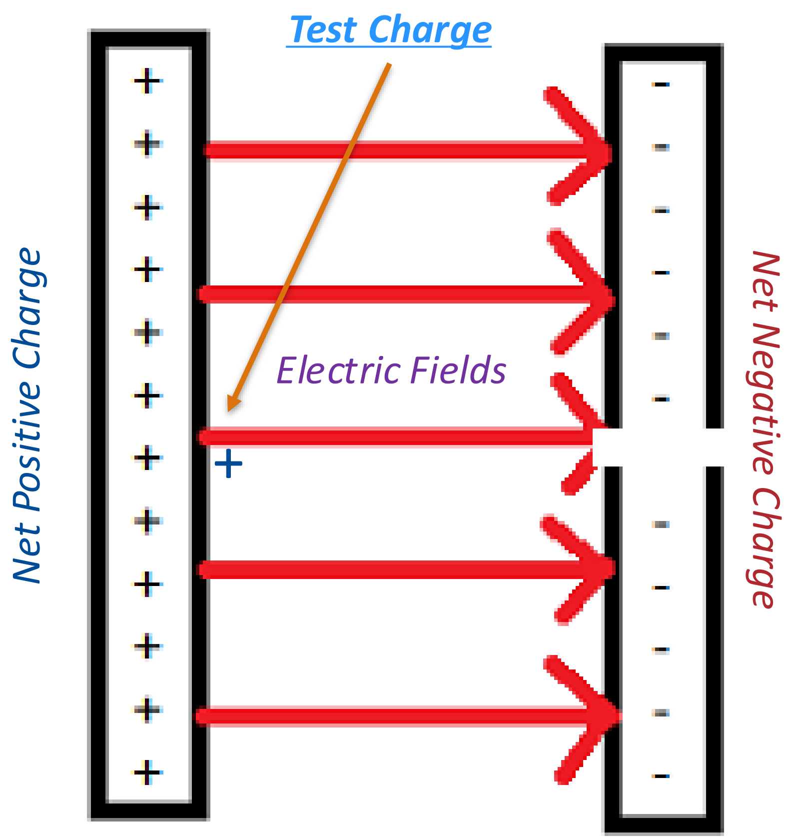
- Lorentz Force
- Stored Energy density in EM fields
- Poynting Vector is useful conceptual tool (direction of energy flow in EM fields)

- $\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$
- $u = \frac{1}{2}\left(\epsilon_0 \vec{E}^2 + \frac{1}{\mu_0} \vec{B}^2\right)$ in vacuum
- $\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$ in vacuum

Simplest Accelerator

- Charged particles are accelerated by EM fields
- EM fields are also generated by charges
  - Static charges: Electric Field (red arrows) run from positive to negative charges
- Two (equivalent) interpretations:
  - Positive charge is pushed along electric fields
  - Like charges repel, opposites attract
- Also can calculate potential difference between two sides
  - $\Delta PE = q\Delta V$
  - Energy gain will generally be in electron-volts [eV]

Stolen from study.com



$$\Delta V_{AB} = -\int_A^B \vec{E} \cdot d\vec{l}$$

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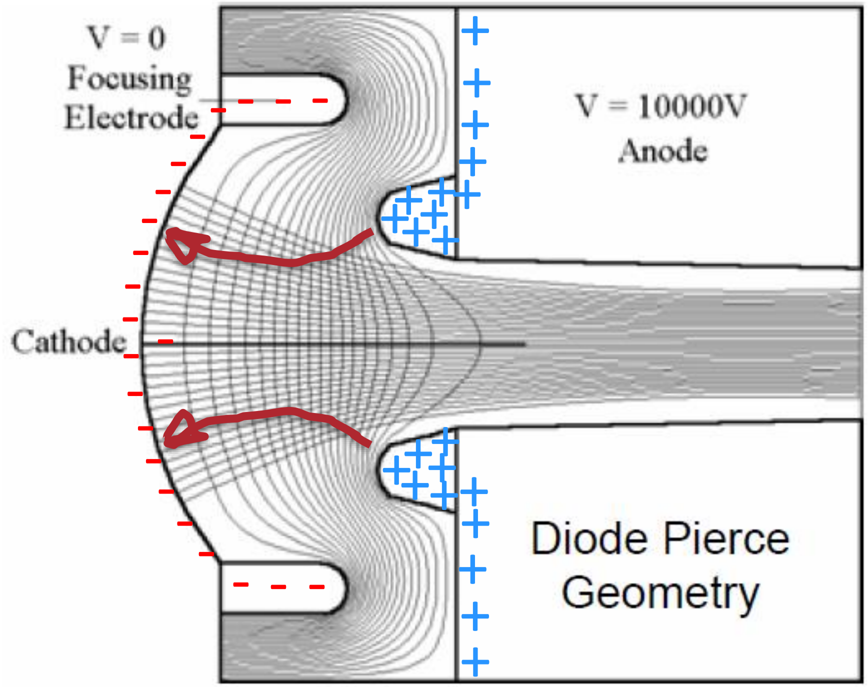
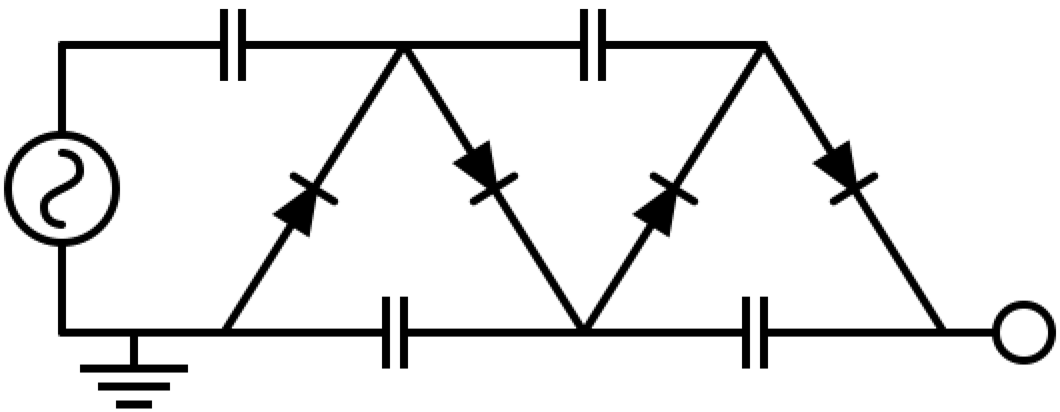
Slightly Less Simple Accelerator

- We shape the surfaces to concentrate fields where we want it
  - More charges concentrated means stronger accelerating electric field
- Changed things up, now accelerating a negative charge
  - Runs against electric field
  - Attracted/repelled by positive/negative charge
- Because we know the potential difference (10kV), and we're accelerating an electron (q = -e)
  - Energy gain is 10keV

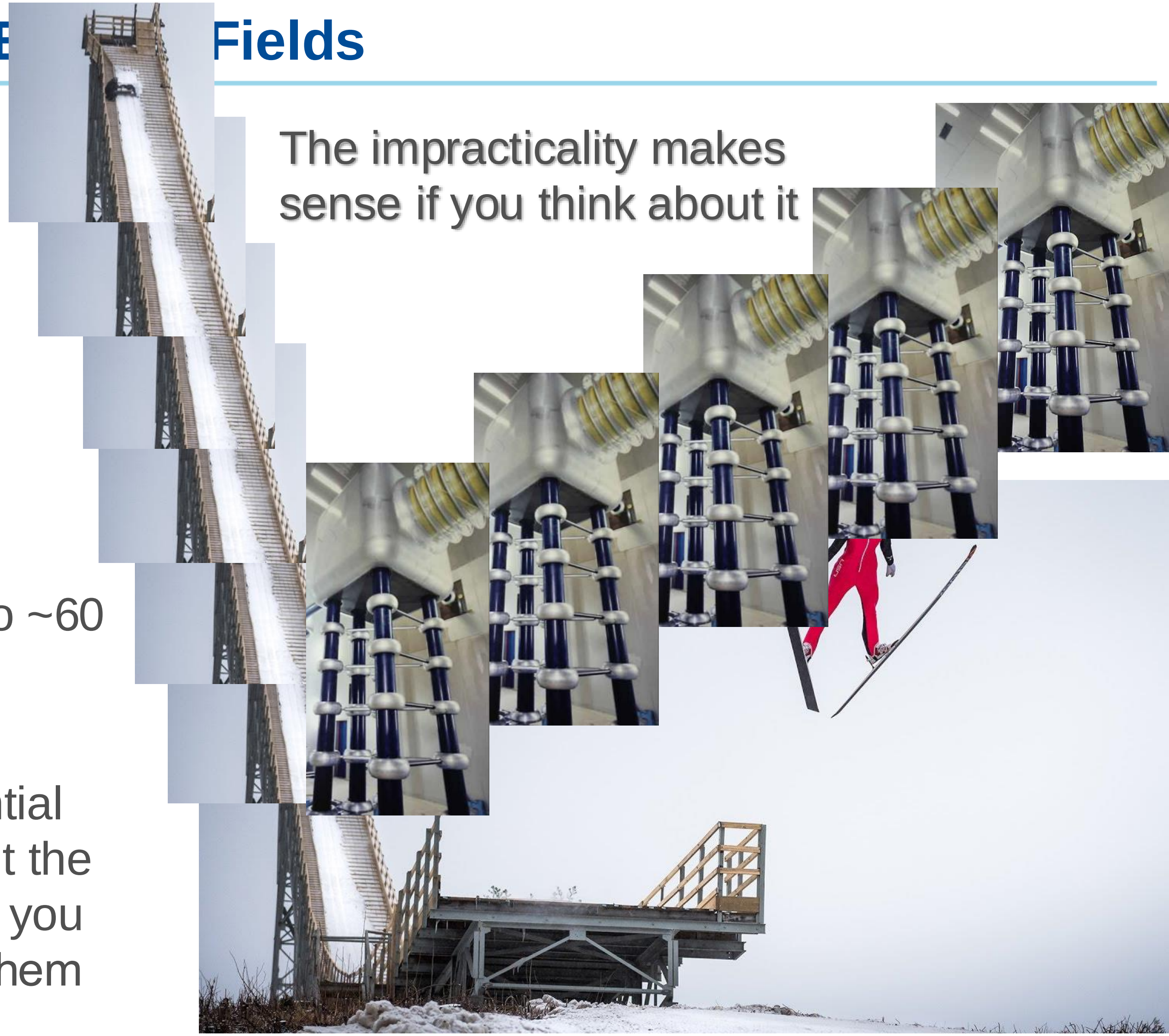


Static Electric Fields

- Electrostatic Accelerators
  - Limited energy gain (60 MeV/q)
  - Can accelerate DC beams (used often for particle sources)
- Tandem Accelerators
  - By changing the particle charge from negative to positive, twice the energy can be achieved (limited current)



Limits of Static E… Fields



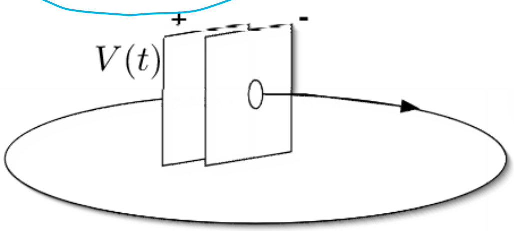
The impracticality makes sense if you think about it

Why are we limited to ~60 MeV?

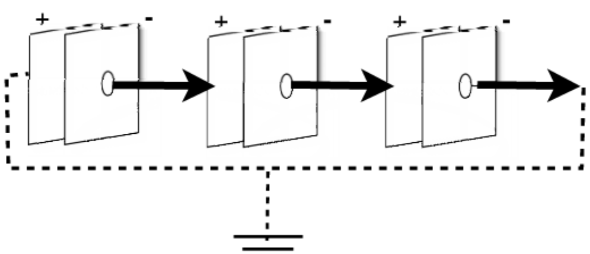
Making a large potential difference is hard, but the real challenge is that you can't stack many of them together

Time Varying Fields Push Us Farther

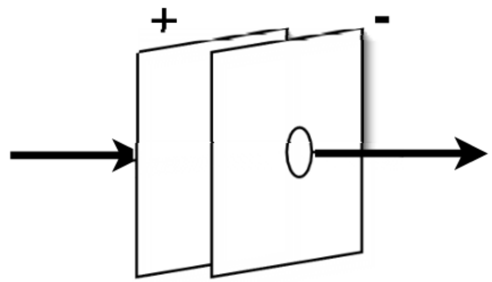
Circular Accelerator



Linear Accelerator



$$\text{energy gain} = q \cdot V$$



DC systems limited to a few MV

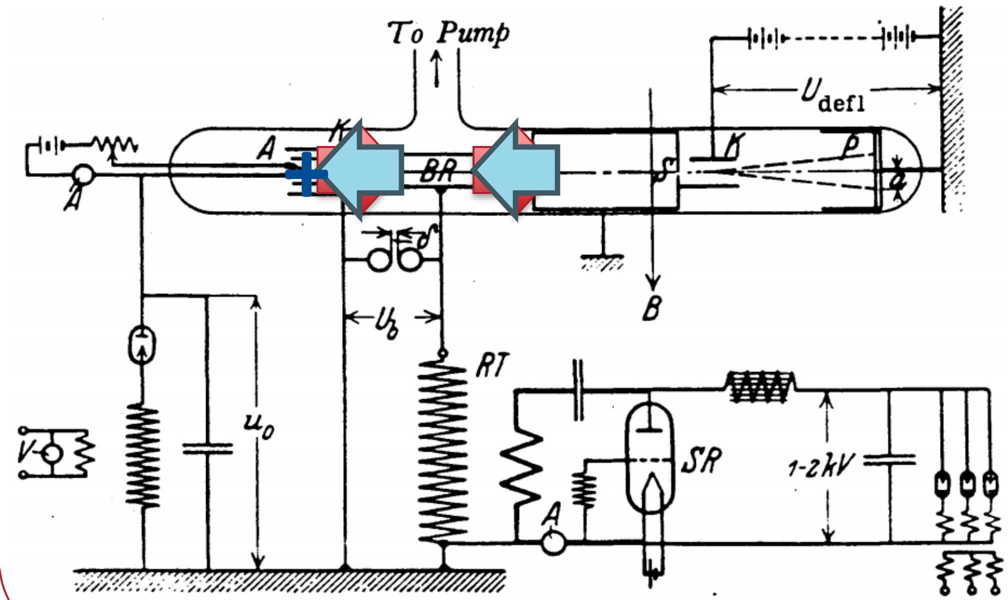
$$\oint (q\vec{E}) \cdot d\vec{s} = work = \Delta(energy)$$

To gain energy, a time-varying field is required:

$$\oint \vec{E} \cdot d\vec{s} = -\frac{\partial}{\partial t} \oint \vec{B} \cdot d\vec{A}$$

Wideroe Drift Tube Linac

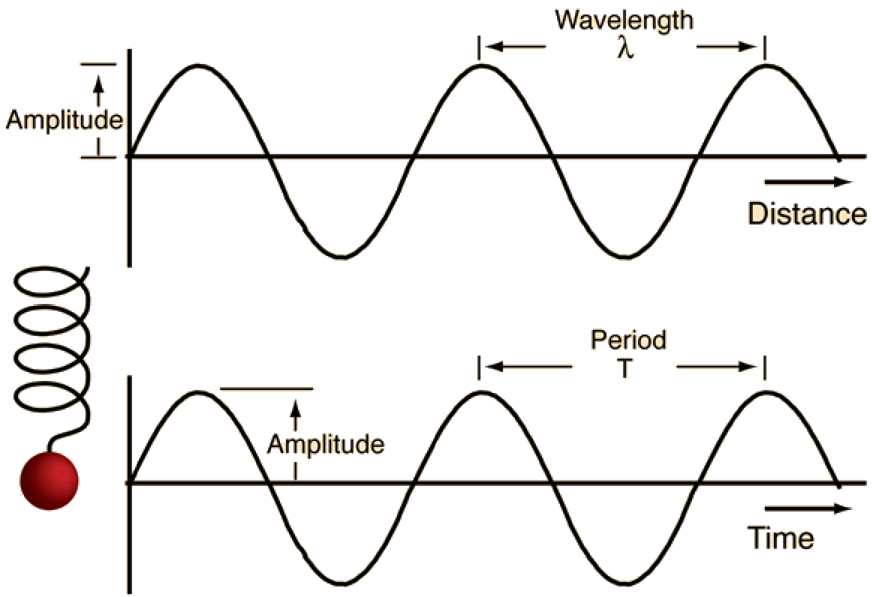
- First RF accelerator conceived and demonstrated by Wideroe in 1927 in Aachen, Germany
- RF voltage of 25 kV from 1 MHz oscillator was applied to single electrode between two ground planes
- Accelerated potassium ions to 50 keV, two gaps for twice the voltage
- Sloan and Lawrence built one of these style linacs with 30 electrodes, applying 42 kV to get mercury ions up to 1.36 MeV



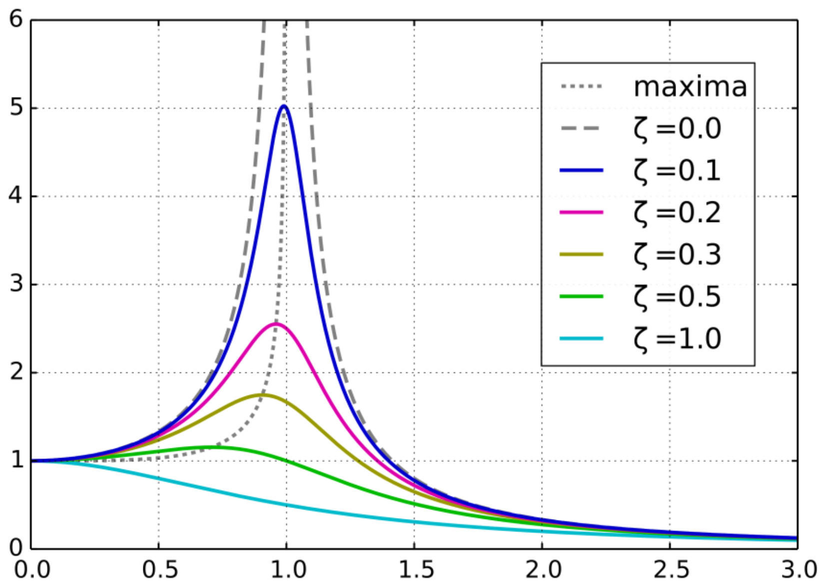
Wideroe's Device (from his thesis)

Concentrating Energy via Resonance

http://hyperphysics.phy-astr.gsu.edu/hbase/Waves/funhar.html



https://en.wikipedia.org/wiki/Resonance



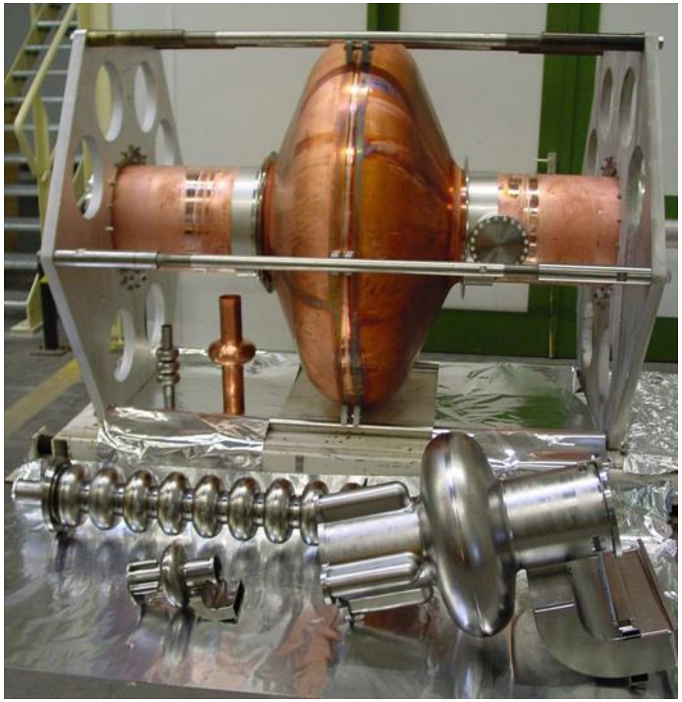
- Almost all systems respond differently when driven at different frequencies.

Examples: mass on spring, instruments, buildings and bridges

- Systems have resonances, frequencies of high response to a small driving force
- ζ represents fractional losses per cycle (0 is optimal, 1 is total loss)

Scaling for Frequency

- Presented without proof:
  - Length of a cavity:
    - $\frac{\beta\lambda}{2} \approx L$
  - Transverse size of cavity:
    - $f = \frac{2.405c}{2\pi R}$
- Other details:
  - $\lambda f = c$
  - $c \approx$ 3e8 [m/s] (Speed of light)
  - Want $L \approx R \approx 0.1$-0.2 [m]
  - $\beta =$ particle's speed as fraction of c, (0<β<1)
- Notice, this is over constrained

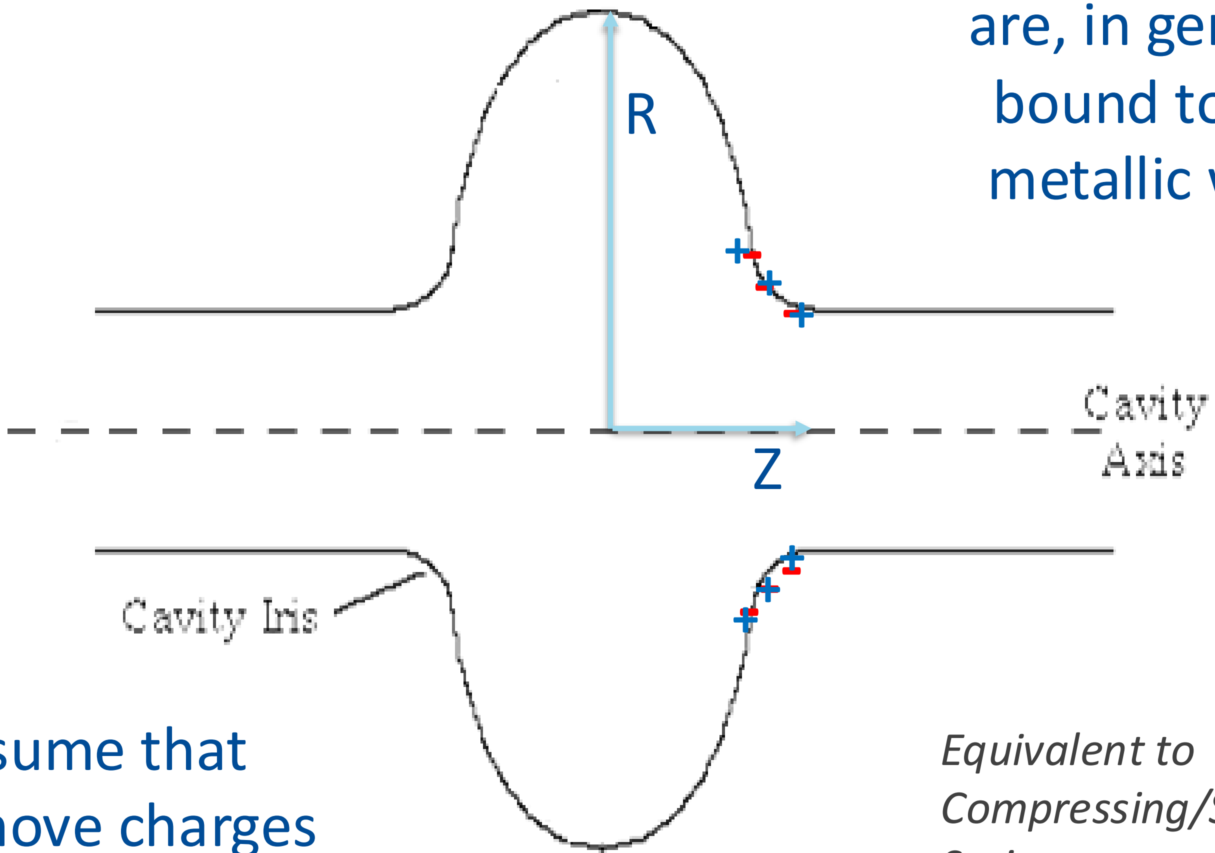


For $\beta = 0.5 \sim 1.0$ gives

$f \approx 500$ [MHz] ~ 1 [GHz]

Simple EM Resonator – Charges and Currents Model

Note: Charges are, in general, bound to the metallic walls

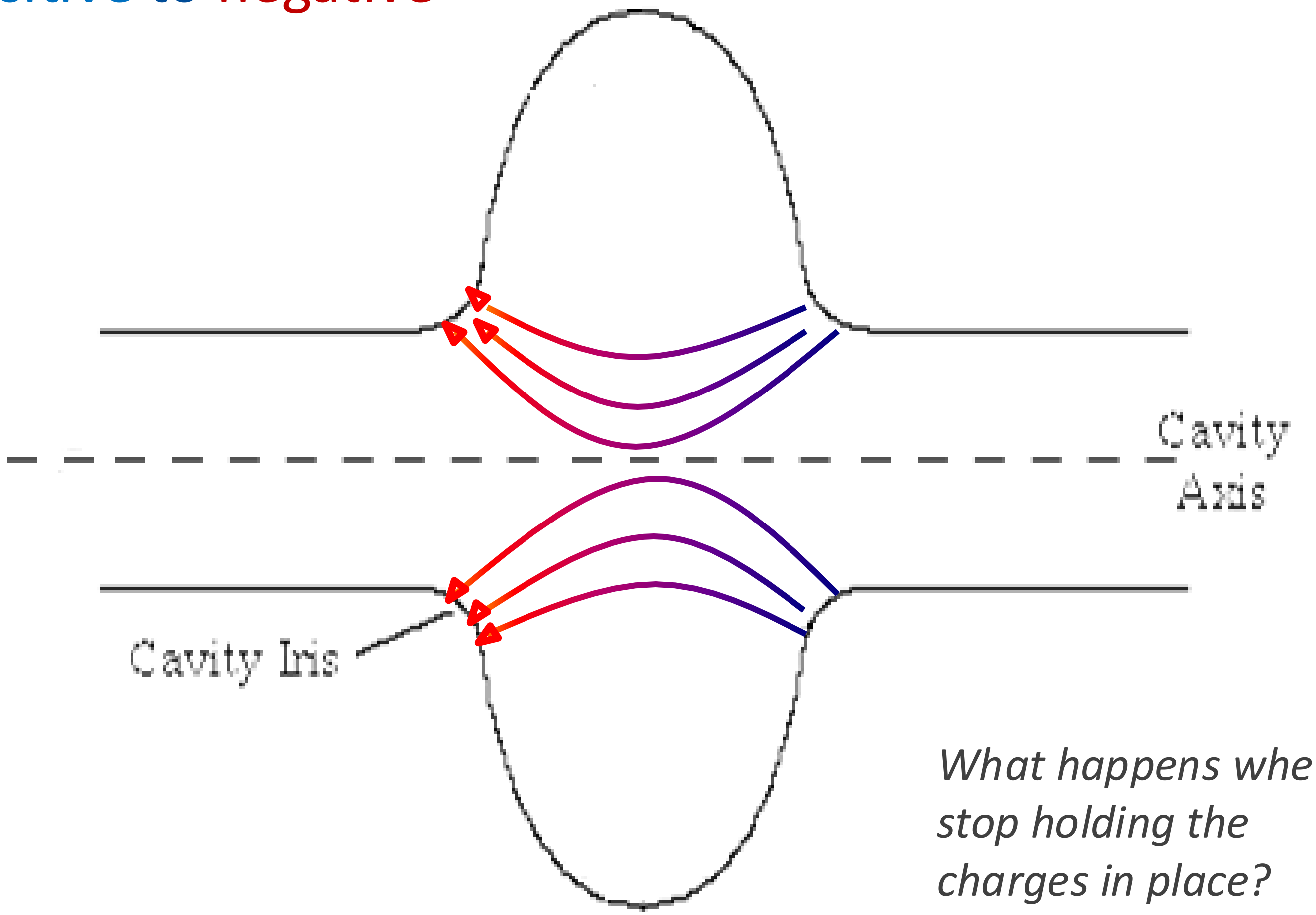


Let us assume that we can move charges and pin them in place

Equivalent to Compressing/Stretching Spring

Resulting Electric Fields

Static charges: Electric Field run from positive to negative charges



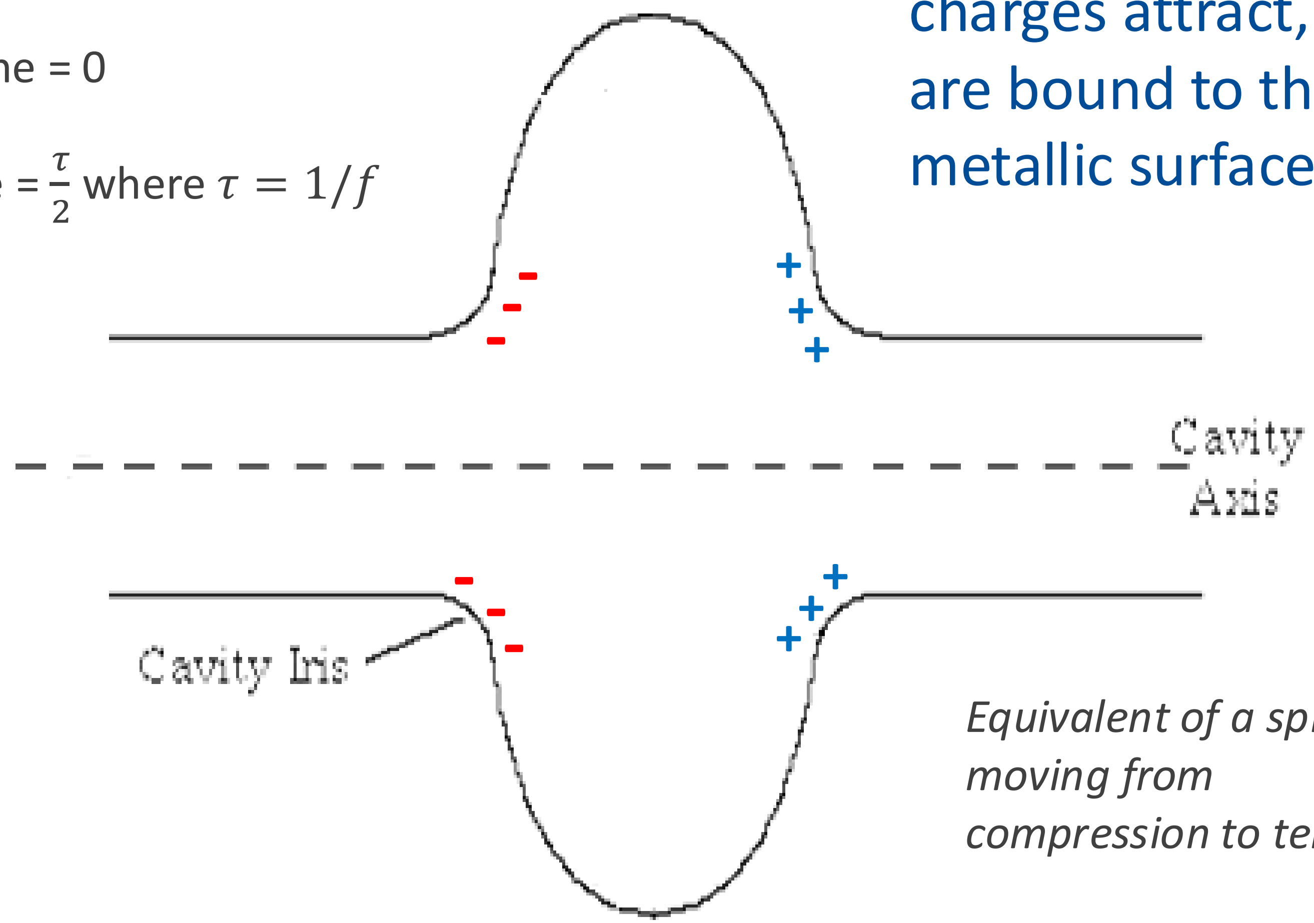
What happens when we stop holding the charges in place?

Releasing the Spring

Time = 0

Time = $\frac{\tau}{2}$ where $\tau = 1/f$

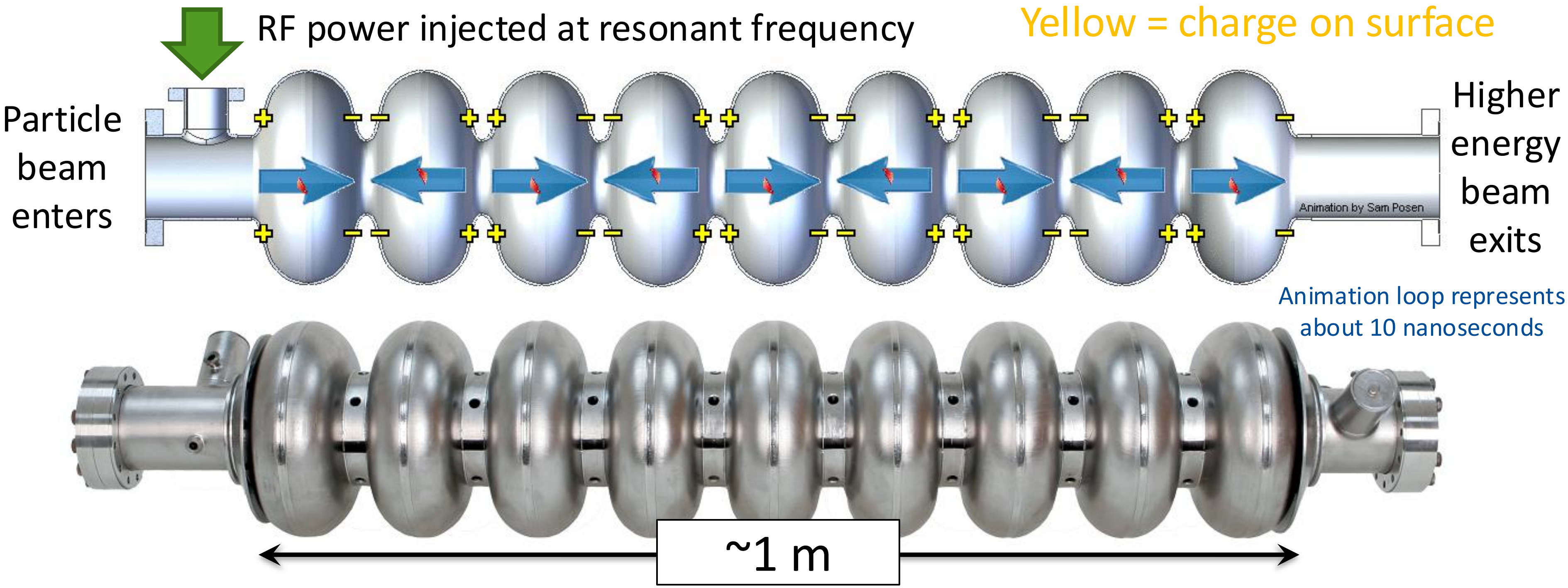
Remember: opposite charges attract, but are bound to the metallic surface



Equivalent of a spring moving from compression to tension

Radiofrequency Cavity

Blue = electric field
Red = magnetic field
Yellow = charge on surface

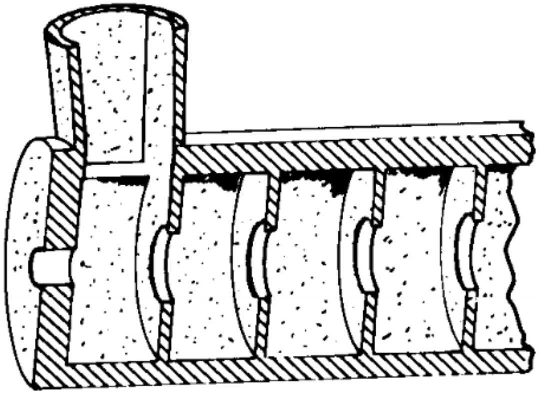


- Cavities are carefully designed for specific particle, particle speed, and timing
- Required magnetic fields are off-axis, so they don't disrupt the beam
- <u>Note: If the speed of the particle is different, the efficiency of the acceleration is going to be very much harmed! Design Particle stays synchronized the whole time and gets full acceleration.</u>

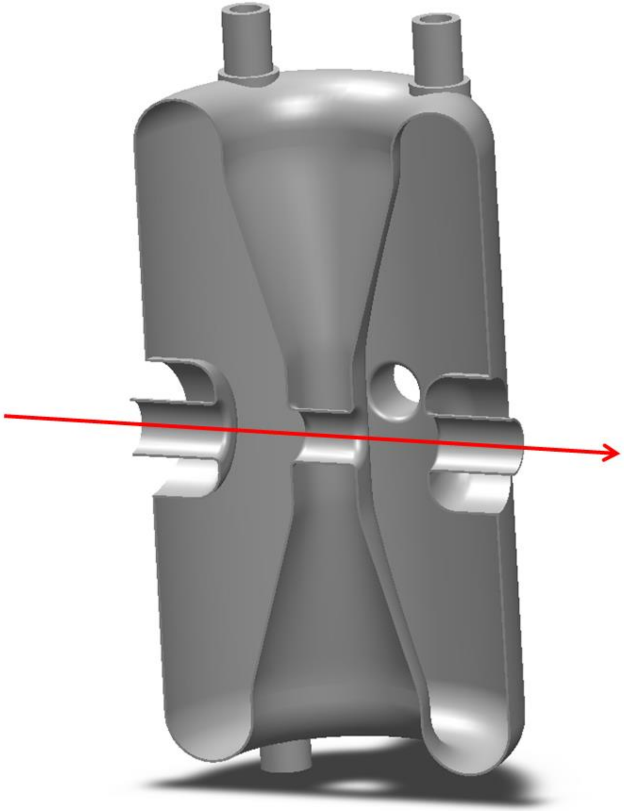
Helmholtz Equations (The Other Math Slide)

- If you ram Maxwell's equations together in a vacuum (no charges or currents), you get:
- $\left(c^2\nabla^2 - \frac{\partial^2}{\partial t^2}\right)\vec{E}(\vec{r},t) = 0$
- Skipping the math, you get:
  - A simple harmonic form for the time: $e^{i\omega t}$, where $\omega = 2\pi f = kc$
  - A simply geometric differential equation to solve, the Helmholtz Equation: $\left(\boldsymbol{\nabla^2 + k^2}\right)\vec{\boldsymbol{E}}_{\boldsymbol{s}} = \boldsymbol{0}$
  - Note that the magnetic field is also specified: $\vec{B} = \frac{i}{\omega}\vec{k} \times \vec{E}$
- This is constrained by the boundary conditions (metallic walls, dielectric materials, whatever is appropriate), and the solutions gives k, and thus the f.
  - Note: All geometries end up having an infinite number of resonances with different frequencies

What’s Defines a “Good” Cavity?



- What do we need?
  - Correct Frequency (and a way to control it)
  - Accelerating fields that are easy to access
  - “Clean” accelerating field distribution
  - Reasonable mechanical properties
  - Efficiency energy storage



- Coaxial Waveguide Modes!
- Cylindrical Waveguide Modes!
  - Everything else is just topological adjustments of these

How Are These Cavities Judged?

$$\Delta W = q \times V_0 \times TTF(\beta) \times \cos(\phi)$$

Charge

Maximum Accelerating Voltage

Transit Time Factor

Longitudinal Focusing Term

Electrostatic Part

What if the particle speed isn't right?

What if the particle arrives at the wrong time?

How Are These Cavities Judged?

$$\Delta W = q \times V_0 \times TTF(\beta) \times \cos(\phi)$$

Charge

Maximum Accelerating Voltage

Transit Time Factor

Longitudinal Focusing Term

- R/Q
  - Measure efficiency of transferring energy to the beam

$$R/Q = \frac{V_{acc}^2}{\omega U}$$

- Geometry Factor
  - Measure of efficiency of energy storage in the cavity

$$G = \frac{\omega U}{P_d / R_s}$$

PIP-II Cavity Choices (Protons are a challenge)

- Cavities only work in a certain range of particle speeds
- Optimization of cavity styles, number, etc. is a very complex process
- Ultimately it comes down to complexity and cost
- Largest cost savings comes from reducing number of cavity types
- Electron machines don't worry about this
  - **The particle speed is always 'right'**

Table 3.6: Accelerating cavities in the PIP-II Linac and their operating ranges in the Linac. ($\beta_g = \beta_G$ for the HWR, SSR1 and SSR2 cavities, β_g for the elliptic cavities is defined as the ratio of regular cell length to half-wavelength. Fitting to Eq. 3.3 for the elliptic cavities yields: $\beta_G = 0.64$ for LB650 and $\beta_G = 0.947$ for HB650.)

Cavity name	β_g	β_{opt}	Freq. (MHz)	Cavity type	Energy gain at β_{opt} per cavity (MeV)	Energy range (MeV)
HWR	-	0.112	162.5	Half wave resonator	2	2.1 - 10.3
SSR1	-	0.222	325	Single-spoke resonator	2.05	10.3 - 35
SSR2	-	0.475	325	Single-spoke resonator	5	35 - 185
LB650	0.61	0.65	650	Elliptic 5-cell cavity	11.9	185 - 500
HB650	0.92	0.971	650	Elliptic 5-cell cavity	19.9	500 - 800

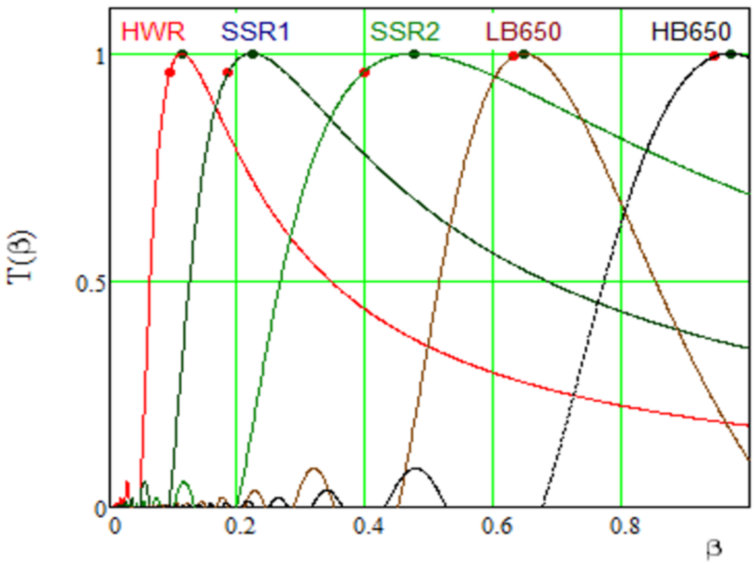


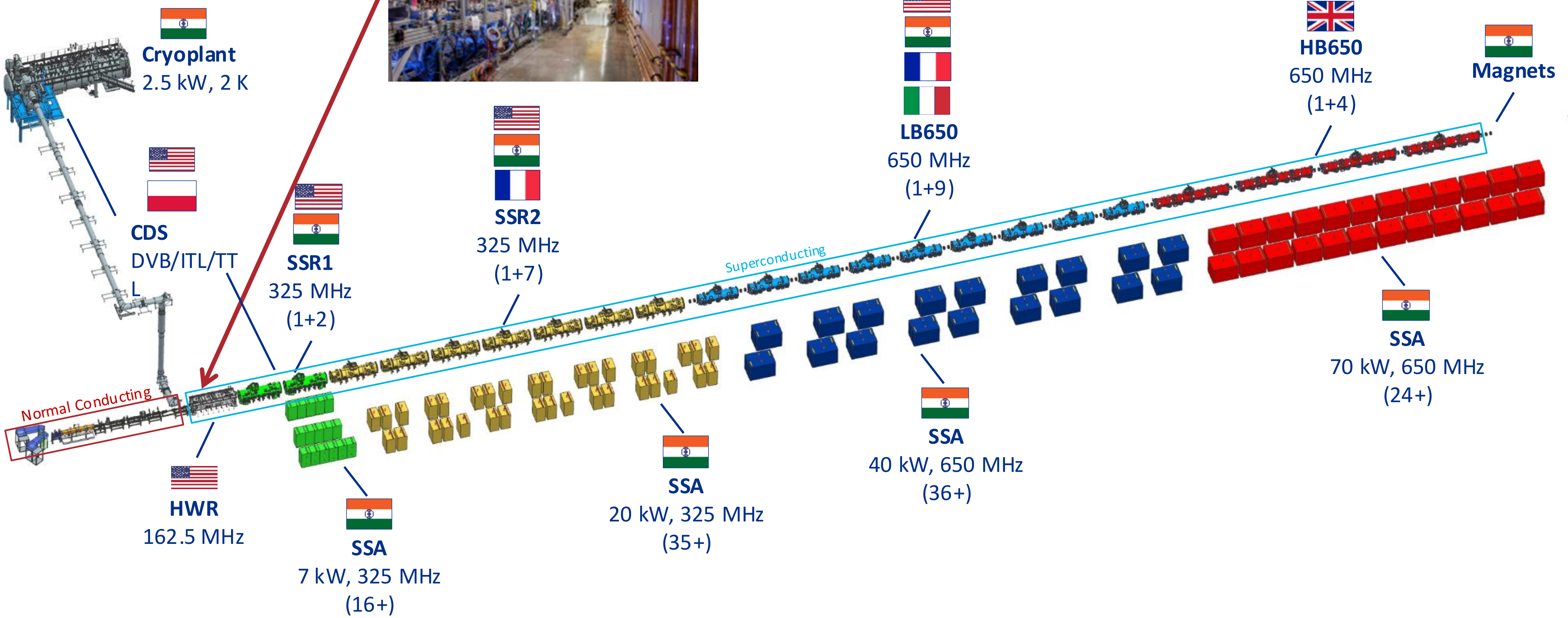
Figure 3.18: Variation in the transit time factor with beam velocity for the PIP-II cavities. Red dots mark the position of β_G, and blue dots the position of β_{opt}.

PIP-II Machine Design

PIP-II will provide a highly capable, reliable, upgradeable and expandable scientific infrastructure with significant savings to DOE

PIP-II Linac Design

PIP2IT successfully demonstrated 17 MeV beam with parameters required for LBNF/DUNE operations



Lecture Questions

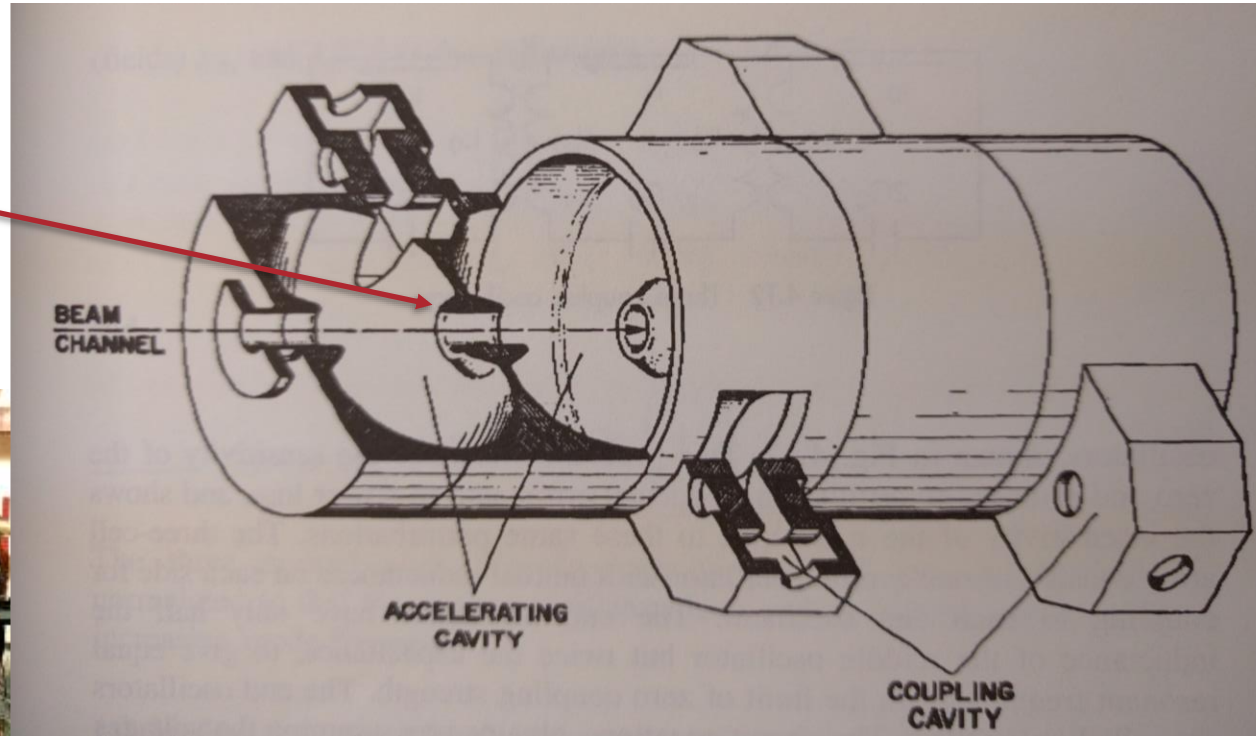
- What is a Radio Frequency (RF) Cavity?
  - Electromagnetic Resonator, concentrating EM energy to efficiently accelerate particles
  - Required to get particles to ‘modern’ energies (>60 MeV or so)
- Why are there so many different RF Cavities?
  - Synchronization of particles coming through cavity at high speed with fields changing at RF speeds is tight constraint
  - Many different particles and speeds, each machine is different
  - Frequencies must all be harmonic (multiples of something)
    - Often driven by some other frequency (a storage ring or other historical constraint)
    - If frequencies change, cavity design changes completely.

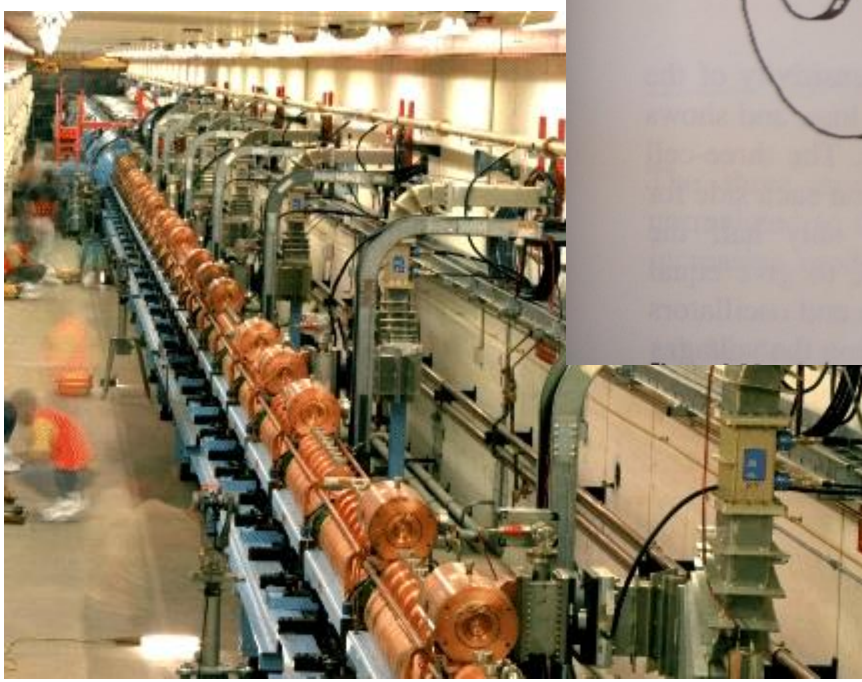
RF Cavity Design Implications – Maximum Energy

- Maximum Energy Storage: Concentrate as much energy as possible
  - Design cavities and processing techniques to avoid limitations
    - Shape cavities to avoid sharp edges
    - Polish and etch surface to give best surface properties and shape
    - Semi-conductor level cleaning and handling to minimize contaminants on the surface (oil, dust, etc.)

Side-Coupled Copper Linacs in Practice

Copper cavities push surface fields quite hard to maximize accelerator for the limited stored energy

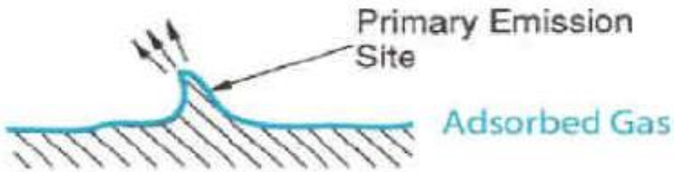


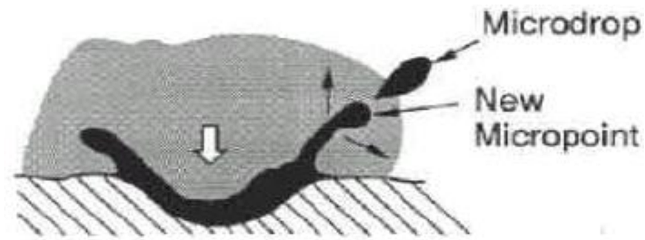


-Solid Copper structures, water cooled

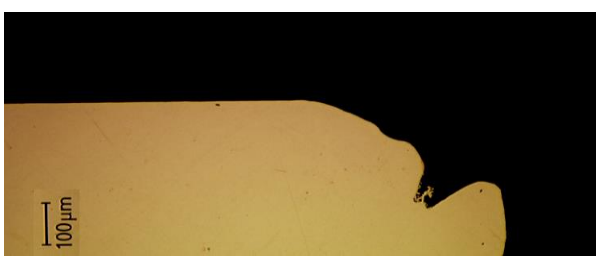
-Pulsed at low duty factor to prevent melting surface

Conditioning limits

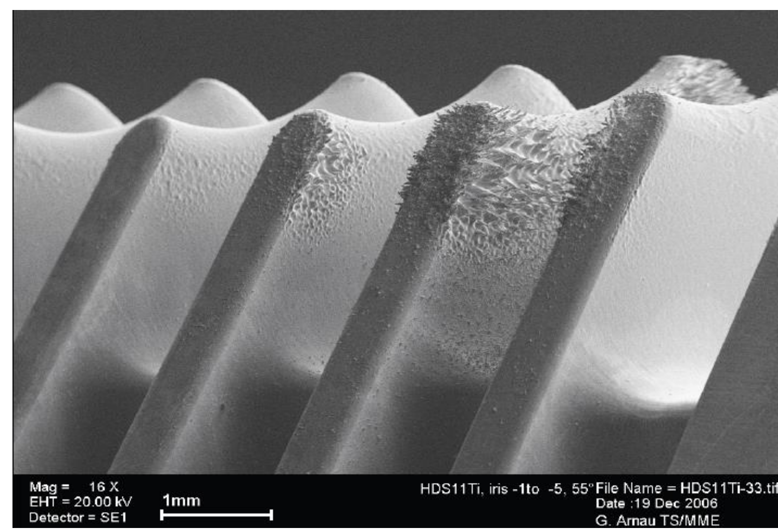




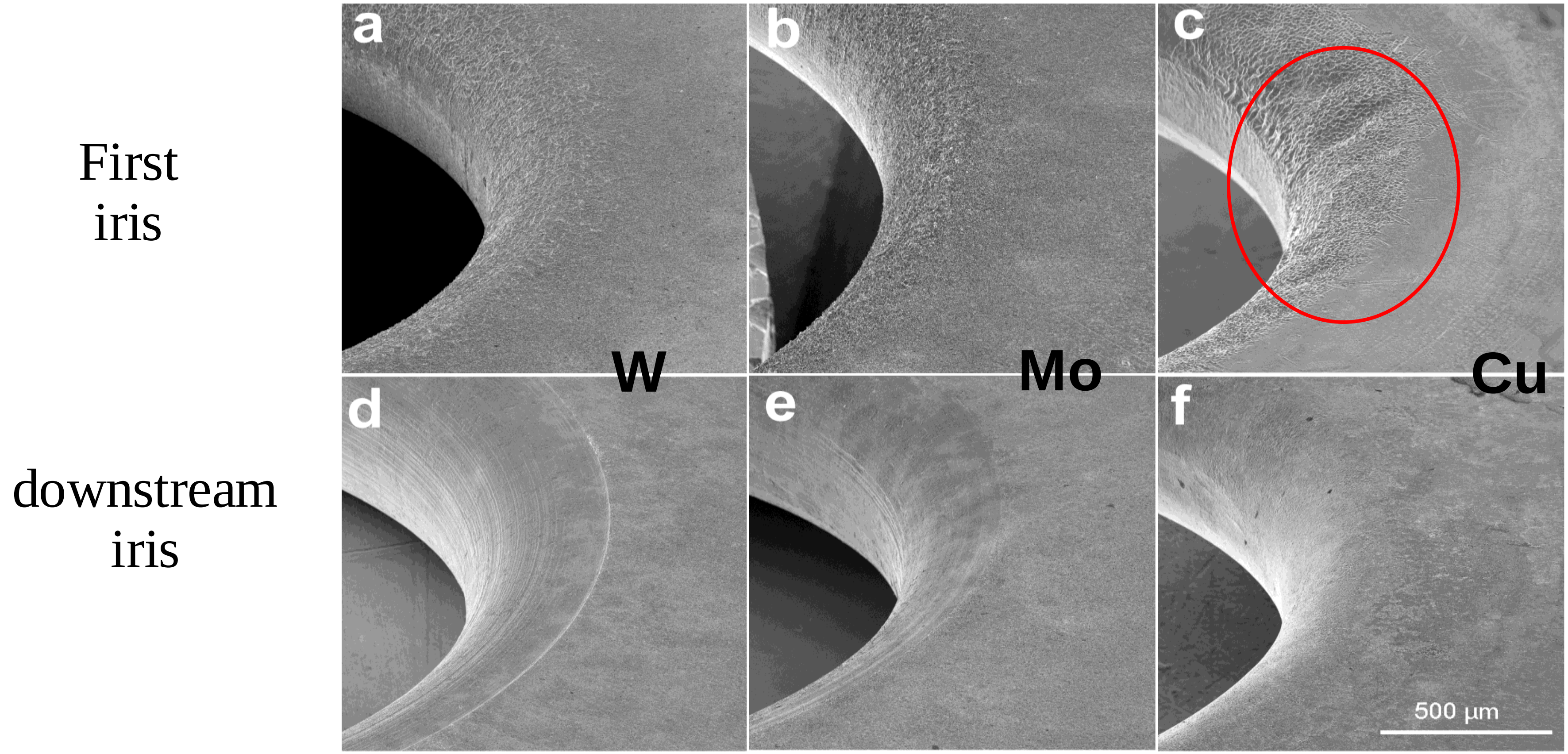
- More energy: electrons generate plasma and melt surface
- Molten surface splatters and generates new field emission points!
  $\Rightarrow$ limits the achievable field
- Excessive fields can also damage the structures
- Design structures with low E_{surf}/E_{acc}
- Study new materials (Mo, W)



Damaged CLIC structure iris



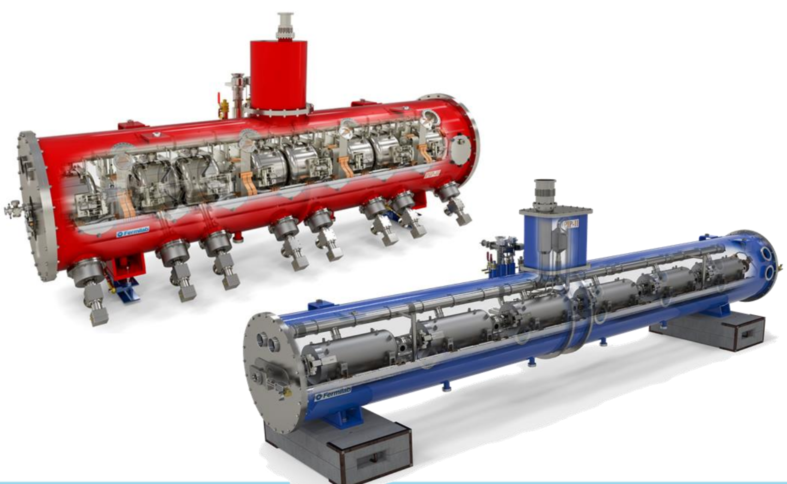
Iris material tests in CTF2



Damage on iris after runs of the 30-cell clamped structures tested in CTFII.
First (a, b and c) and generic irises (d, e and f) of W ,Mo and Cu structures respectively.

RF Cavity Design Implications – Efficient Storage

- Efficient Energy Storage: Superconducting Materials
  - Can use low resistance materials (copper), but PIP-II/LCLS-II requires higher efficiency, otherwise we would melt the cavities
  - Use of superconducting material for cavity (Niobium) has two major implications:
    - Gain factor of ~1000 in efficiency vs Copper cavity (mΩ vs nΩ, but cooling efficiency is lower by ~1000)
    - Must operate cavities at very low temperatures



Superconducting RF (SRF) Cavity Summary

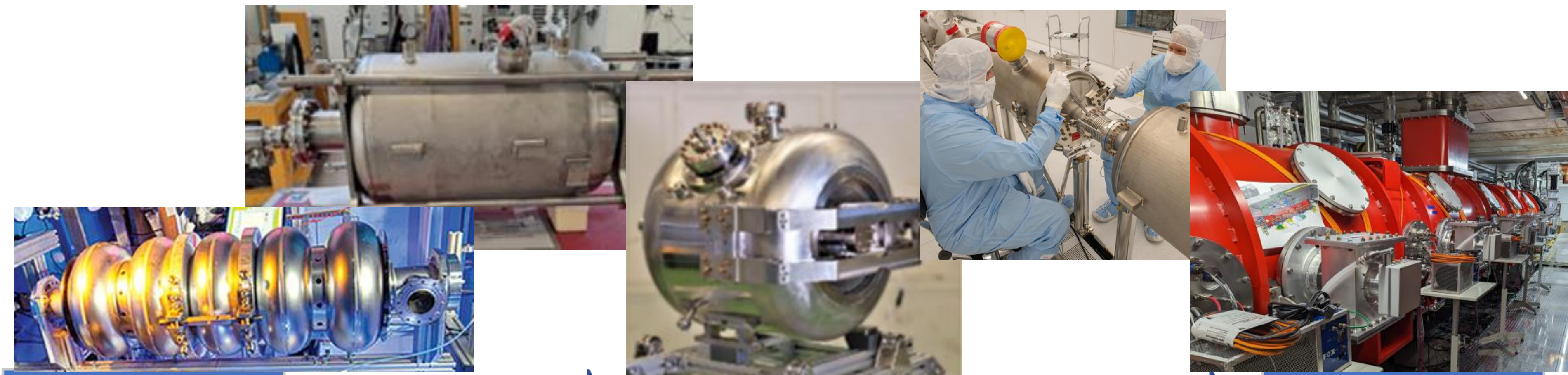
- SRF Cavities:
  - Are designed to accelerate charged particles as rapidly as practical
  - Concentrate large amounts of EM energy in a small space
  - Require very careful processing to ensure best surface quality and highest standard of cleanliness
- SRF Cavities are prone to generate unintended radiation: ***Field Emission***
  - Electrons can be generated by high electric fields enhanced by surface contamination, dust or sharp features
  - These are rapidly accelerated, and generate gamma or neutron radiation when they strike the cavity walls
- Field Emission is combatted by iterative testing: ***Test Stands***
  - Each step of production can introduce contamination, so specialized test stands are setup to iteratively demonstrate designs
  - Test stands provide all required infrastructure for each stage of production
    - RF Power, Vacuum, Cryogenics, Instrumentation, Radiation Monitoring/Shielding, etc.

SRF Limitations: Radiation from Cleanliness

- All SRF Test Stands operate without Beam Source
- Self-Generated Radiation concerns are similar between test stands and fall into two different categories:
- *Field Emission*: electrons generated from imperfect cleaning are accelerated *chaotically and parasitically* in the cavity, striking cavity walls and generating radiation
- *Dark Current*: If an electron's trajectory aligns with the beam axis, it can be accelerated to higher energy
  - Electrons can gain large fraction of design energy
  - Possible to accelerate via multiple cavities, depends on cavity design
    - Multi-cavity acceleration only possible at PIP2IT and CMTS-1
- All self-generated radiation drops cavity efficiency

SRF Cavity Production at FNAL Test Stands

- *Bare Cavity (VTS)*: Demonstrate basic cavity design (R&D) is sound and verify production cavity performance
- *Dressed Cavity (STC)*: Test cavity package with critical sub-systems in realistic environment, verify designs and assembly techniques
- *Integrated Cryomodule (PIP2IT/CMTS-1)*: Fully integrated accelerator component validation, several cavities and sub-systems in machine ready configuration

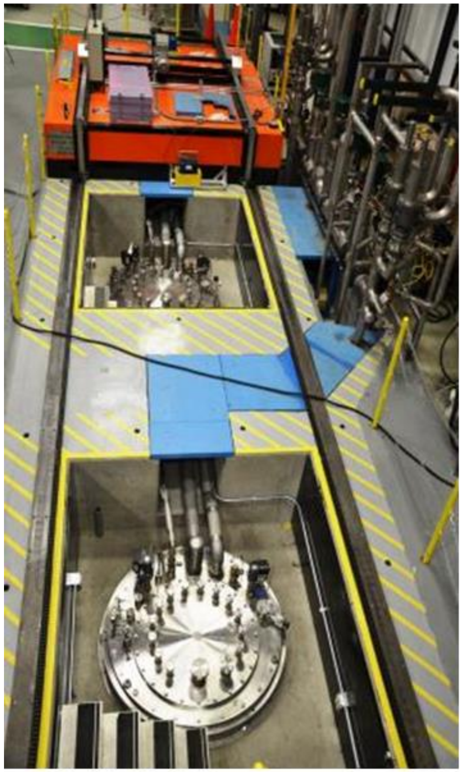


Bare Cavity (VTS) → Install helium vessel, tuner, coupler, etc. → Dressed Cavity (STC) → Cavity string assembly and Cryomodule integration → Integrated Cryomodule (PIP2IT/CMTS-1)

SRF Cavity Workflow at FNAL

Vertical Test Stands (VTS-1, 2, 3) – IB1

- Test Stand designed for short testing cycles
  - R&D and production testing
  - Main users: SRF R&D, SQMS, projects such as PIP-II and LCLS-II HE.
- Deep test pits with Dewars for submerging cavities in liquid helium
  - Cryogenic RF measurements of bare and dressed cavities of various frequencies (325 MHz - 1300 MHz) at temperatures down to 1.4 K
  - Full diagnostics instrumentation: Magnetic field measurement, quench detection, T-map
- Up to 300 tests per year during peak of the LCLS-II production



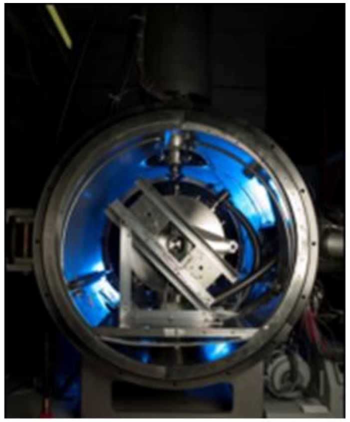
VTS1, VTS2 and VTS3 pits

VTS1 insert with 1.3 GHz 9-cell

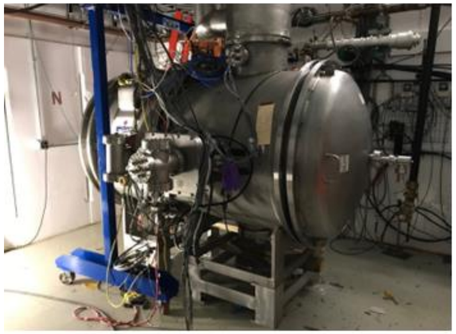
Spoke Test Cryostat

- Originally designed for testing jacketed SSR1 and SSR2 cavities for PIP-II
  - 36 cold cycles between 2013 and 2018 (record throughput: 4 complete qualification cold tests during 3 weeks in March 2018)
  - Characterized and qualified 10 SSR1 prototype cavities and selected 8 best for the SSR1 prototype cryomodule
- Upgraded in 2019 for testing of HB/LB650 and SSR2 cavities
  - 3 tests of 650 MHz cavities in 2020-2022 (2 HB650 and 1 LB650)

Original Spoke Test Cryostat (STC)



STC with SSR1 cavity installed

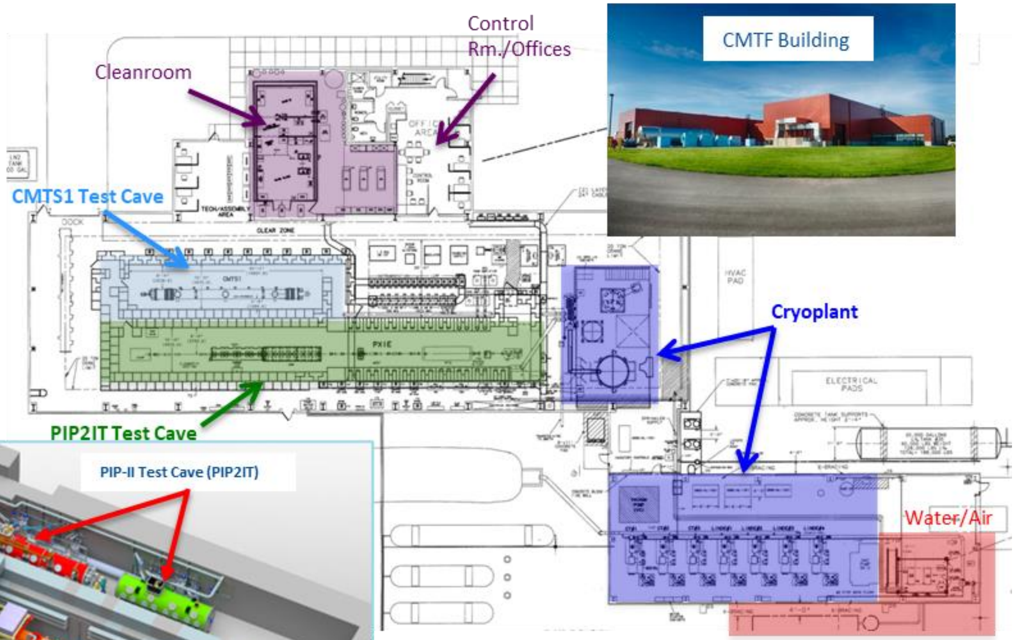


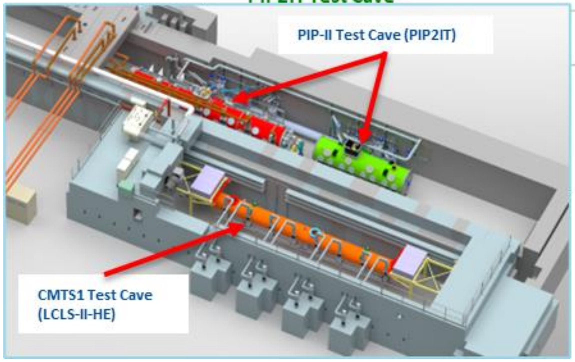
Upgraded STC

HB650 B9A-AES-010

Cryomodule Test Facility (CMTF)

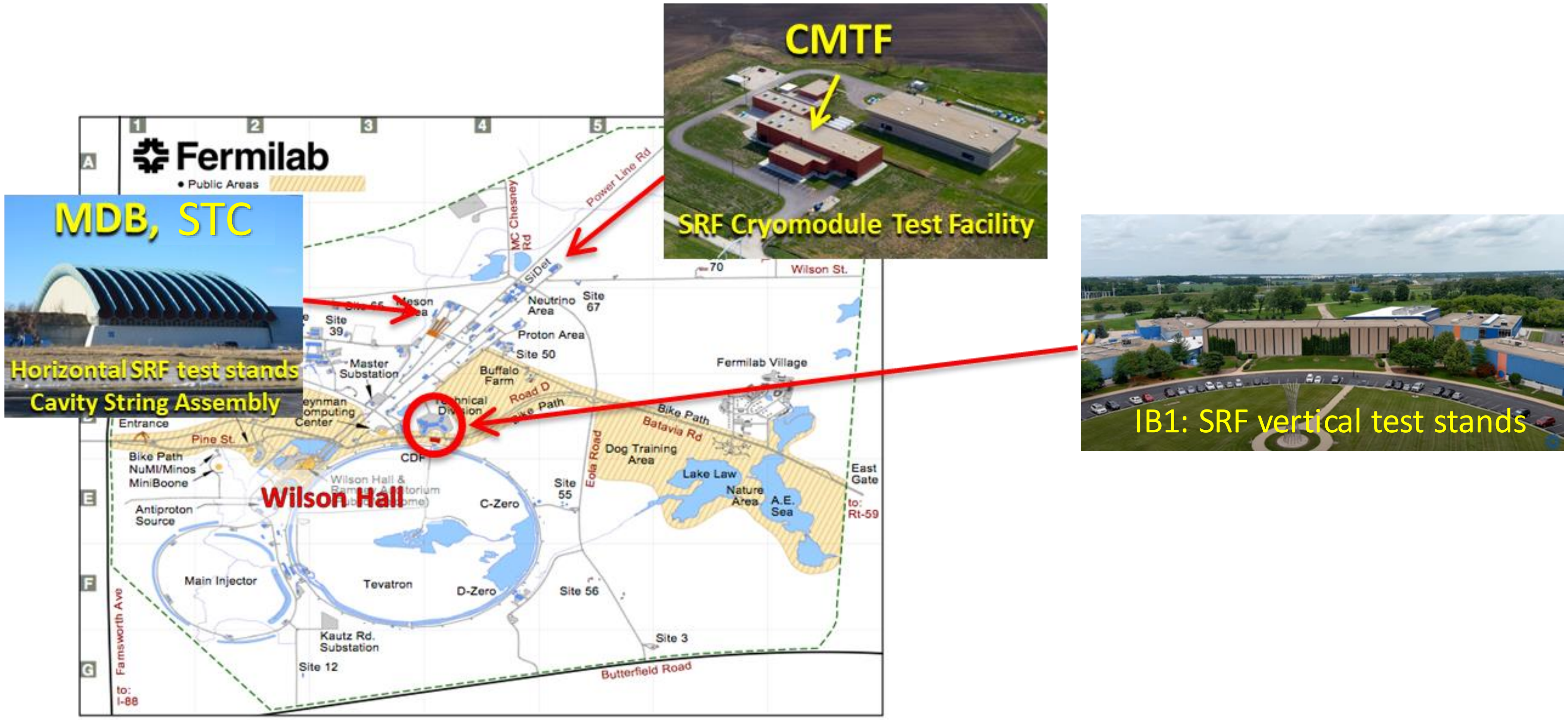
- Dedicated facility for testing SRF cryomodules
- Contains **two test caves and a large cryogenic plant**
  - Cryomodule Test Stand (CMTS1)
  - PIP-II Test Cave (PIP2IT)
  - Superfluid cryoplant (500 W at 2 K)
- **2 independent test stands** capable of operating simultaneously
  - Can be reconfigured to test 6 different types of cryomodules





Fermilab

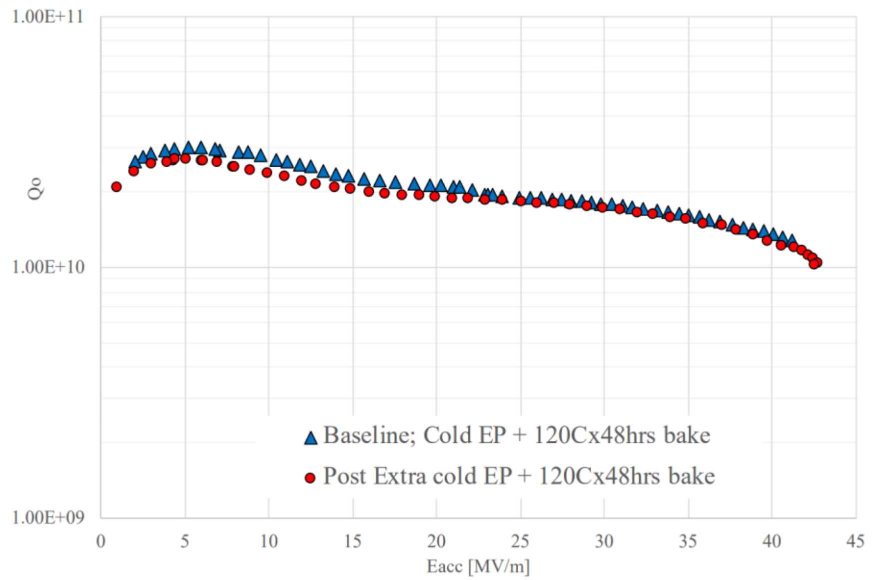
Map of SRF Test Facilities



- Cleanroom facilities mostly at MP9 and ICB, well established at the lab for SRF
- Test Stands are “owned” by either Applied Physics and Superconducting Technology Directorate (APSTD) or Accelerator Directorate (AD).
- Projects, Centers, and R&D efforts all use the facilities and support their operational costs.

SRF Limitations: Efficiency of Material

- FNAL has been a center of innovation in SRF materials for a long time
- Developed and extensively researched Nitrogen doping technique which has improved SRF material efficiencies by almost 10x
- Identified vulnerabilities to ambient magnetic fields and have developed techniques to maximize efficiency in operations



The physics of superconducting material is quite a bit more complex than standard materials, and even small changes can majorly impact performance

Lecture Questions

- What is Superconductivity and why have SRF Cavities?
  - RF Cavities made with superconducting materials have far smaller losses than an equivalent copper cavity, which opens up many attractive options
    - PIP-II leverages these options not only for today, but for the next 40 years of the lab’s scientific program
- What are the Big Problems in achieving (S)RF?
  - Concentrating all this energy requires extremely clean cavities, everything the cavity does and touches has to be low-particulate cleaned
  - Preserving the best, state of the art superconducting properties (read: efficiency) is tough in practice, and puts many constraints on the overall system design

How does this all apply to Fermilab?

- Fermilab is now a world-leading center for SRF technology
  - Delivered LCLS-II, delivering LCLS-II HE
  - Professional workforce including:
    - Electrical, mechanical, cryogenic, and cleanroom technicians
    - Engineers of many varieties specialized in SRF
  - Infrastructure for rapid R&D up through major Project production
  - Project Engineering, Quality Control, and Safety Culture ready for these large, challenging projects
- In addition to Accelerators, SRF technology is leveraged for Quantum Technology research at SQMS
- The PIP-II linac is an excellent demonstration of what an SRF accelerator can be, but it is also built as a platform for the next 40 years
  - What does the next generation of accelerator upgrade really look like? We don’t know, but PIP-II gives us a lot of options.


Questions?
FOX