Superconducting radiofrequency cavities – An introduction

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USPAS – Cryogenic Engineering

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Goals of this lecture

- SRF is a humongous topic! – offered as a separate 3-credit USPAS course
- Here, we will look at basics of SRF cavities including the topics of:
  - Working principle
  - Figures of merit
  - Cavity types
  - Processing techniques for performance enhancement
- Look at some new frontiers in SRF

Introduction

Superconducting radiofrequency (SRF) cavities

- A technology for production of energetic particle beams,
- Invented half-a-century ago, matured *via* solid R&D
- One of the two largest applications of low temperature superconductivity

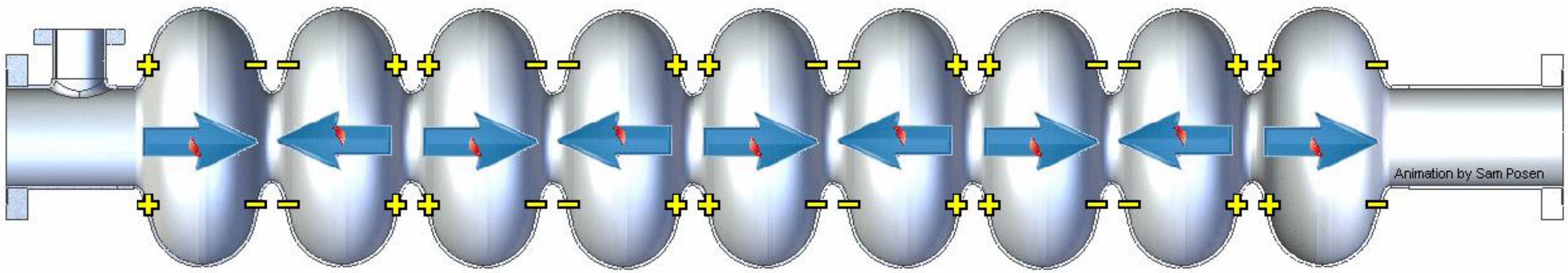
Today, SRF cavities is a core technology used in the construction of large linear particle accelerators for discovery science

- Electron-positron collider
- X-ray/light sources
- Neutron, neutrino production
- Acceleration of rare isotopes, heavy ions

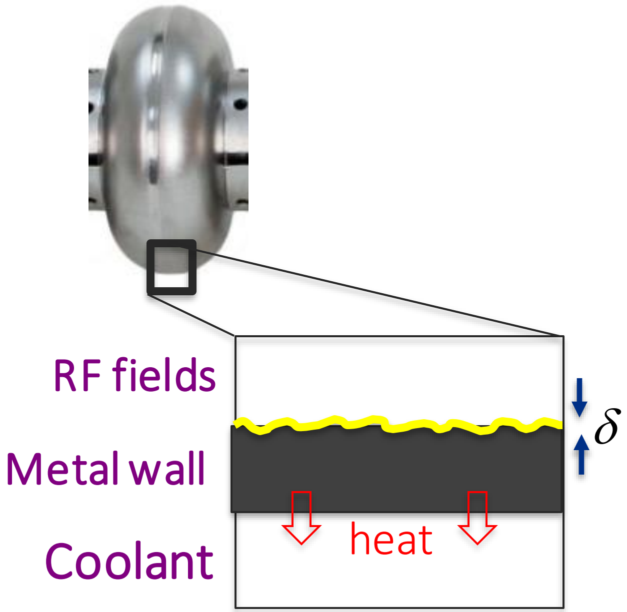
ess LCLS-II PIP-II

European XFEL ilc FRIB

RF cavity working principle



- Metallic cells maintain a standing-wave RF field
- Particle bunches in phase with the RF field gain energy



- RF fields penetrate a ***penetration depth***, ***δ*** the metallic cell walls and dissipate heat in the ***surface resistance, R_s***
- A coolant on the outside extracts the heat and prevents the cavity from heating above its operating temperature

RF surface resistance

Why is RF surface resistance a key parameter?

- Dissipated power in the cavity is proportional to its surface resistance
- The cost of cooling the cavity (coolant fluid, temperature, fluid pumping power, etc.) scales with dissipated power
- With hundreds of cavities in a particle accelerator, the cavity cooling cost forms a significant fraction of accelerator operating cost

Keeping low RF surface resistance is therefore necessary to reduce the accelerator operating cost.

Normal vs. superconducting cavities

How does the surface resistance compare?

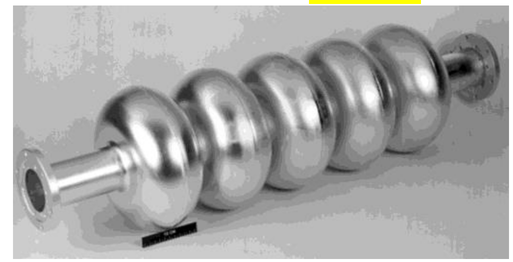
Water cooled copper cavities near room temperature

$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0 \omega}{2\sigma}}$$

ω = angular frequency
σ = electrical conductivity

With σ ~ 5.8 x 10^7 S/m at 1.5 GHz and 300 K, we get **R_s = 10 mΩ**

Liquid helium cooled niobium cavity ≤ ~5 K



$$R_s = R_{BCS}(T) + R_{res}$$

$$\approx A\frac{\omega^2}{T}\exp\left(\frac{-1.85T_c}{T}\right) + R_{res}$$

At 1.5 GHz and 2 K, and neglecting the residual R_{res}, we get **R_s = 20 nΩ**

Normal vs. superconducting cavities

Ratio of surface resistance at 1.5 GHz:

$$\frac{R_s(niobium, 2K)}{R_s(copper, 300K)} = \frac{20\,n\Omega}{10\,m\Omega} \sim 10^{-6}$$

Penalty for 2 K cryogenics:

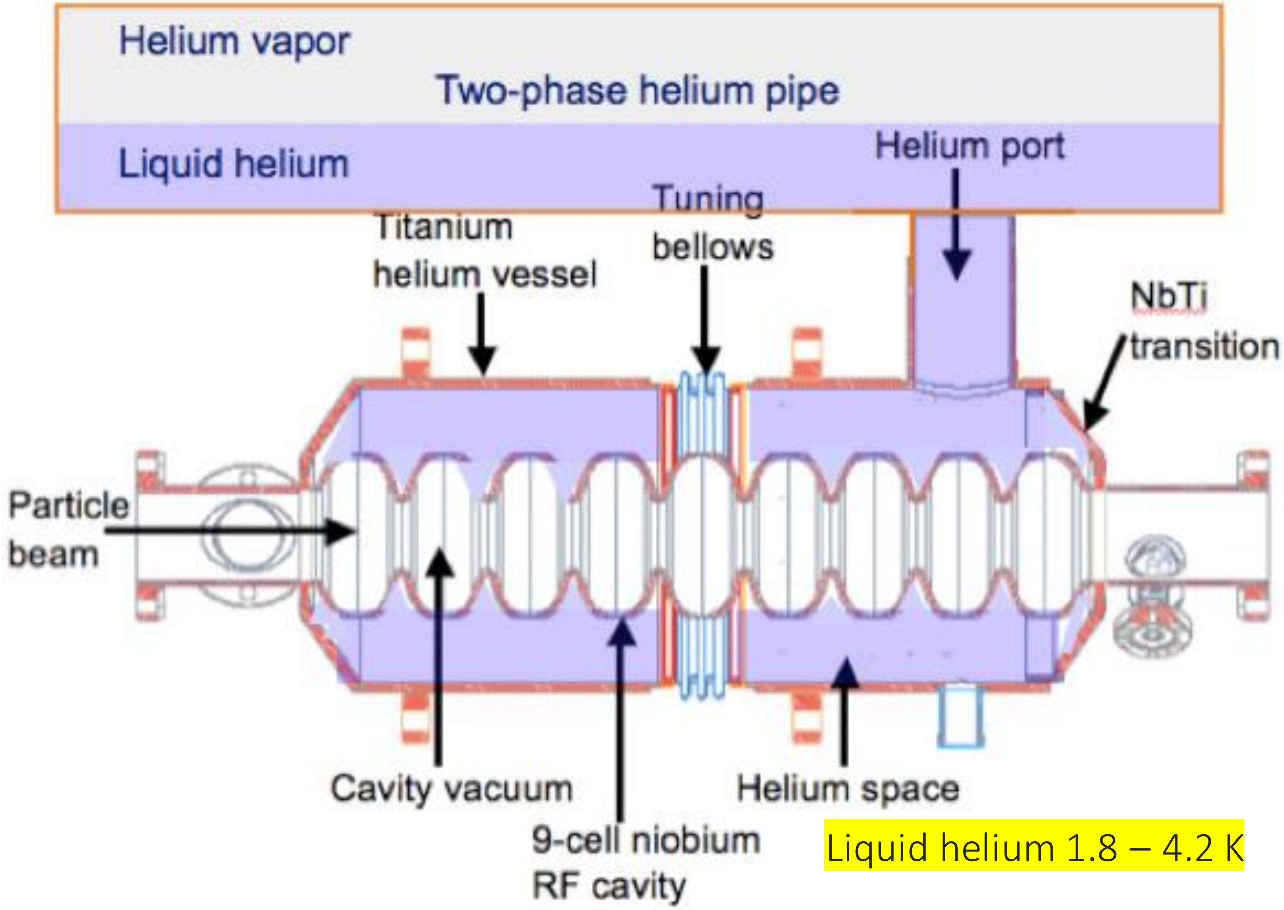
$$\eta_{Carnot} = 0.67\% \qquad \eta_{plant} \approx 20\%$$

Even after accounting the premium for 2 K cryogenics, SRF drives down the cooling driven operating cost by a factor ~1000 !!!

The significantly lower surface resistance in SRF also offers other benefits:

- Cavities can be operating with 100% RF duty cycle that facilitate production of high average power particle beams
- Cavities can be made with larger aperture (by relaxing shunt impedance) that reduce loss of high-power beams during transport through the cavity

Helium cooling of SRF cavities



Liquid helium 1.8 – 4.2 K

https://lss.fnal.gov/archive/test-tm/2000/fermilab-tm-2620-td.pdf

Optimal operating temperature with helium?

$$R_s = A\left(\frac{1}{T}\right)f^2 e^{(-\Delta(T)/kT)} + R_0$$

- The surface resistance goes up with frequency and down with temperature: lower temperature equals less resistance, particularly at higher frequencies
- What is the optimal temperature?
  – Above about 500 – 700 MHz you win by operating below 4.2 K (typically 1.8 – 2 K)
  – At lower frequencies (eg. 80 MHz) you are better at 4.2 K thermodynamically but there may be other considerations (FRIB)
  – Between these limits it's a fairly broad minimum. Most systems operate ~ 2 K – He II

Content courtesy: J. G. Weisend II (ESS)

SRF accelerators under operation/construction

Name	Accelerator Type	Lab	T (K)	Refrigeration Capacity	Status
CEBAF	Electron Linac	JLab	2.1	4.2 kW @ 2.1 K	Operating
12 GeV Upgrade	Electron Linac	Jlab	2.1	4.2 kW @ 2.1 K	Operating
ESS	Proton Linac	ESS	2.0	3 kW @ 2 K	Under Construction
PIP-II	Proton Linac	Fermilab	2.0	2.4 kW @ 2 K	Under design
E Linac	Electron Linac	TRIUMF	2.0	288 L/Hr	Operating
S-DALINAC	Electron Linac	TU Darmstadt	2.0	120 W @ 2.0 K	Operating
XFEL	Electron Linac	DESY	2.0 5 -8 40-80	2.5 kW @ 2 K 4 kW@ 5 -8 K 26 kW @ 40-80 K	Under construction
ATLAS	Heavy Ion Linac	ANL	4.7	1.2 kW @4.7	Operating
LCLS II	Accelerator	SLAC	2.0 K	8 kW @ 2 K 2.6 kW @ 4.5 -6 K	Under construction
ISAC - II	Heavy Ion Linac	TRIUMF	4		Operating
FRIB	Heavy Ion Linac	MSU	2.1 4.5	3.6 k W @ 2.1 K 4.5 kW @ 4.5 K	Under Construction

Content courtesy: J. G. Weisend II (ESS)

SRF cavity – figures of merit

Accelerating gradient, E_{acc}

- defined as the ratio of the accelerating voltage, V_c, divided by the cavity length, L. V_c is obtained by integrating the electric field at the particle's position as it traverses the cavity:

$$E_{acc} = \frac{V_c}{L} = \frac{1}{L}\left|\int_0^L E_z(r=0,z)e^{i\omega_0 z/c}dz\right|$$

ω_0 = RF frequency
c = speed of light in vacuum
z = beam travel direction

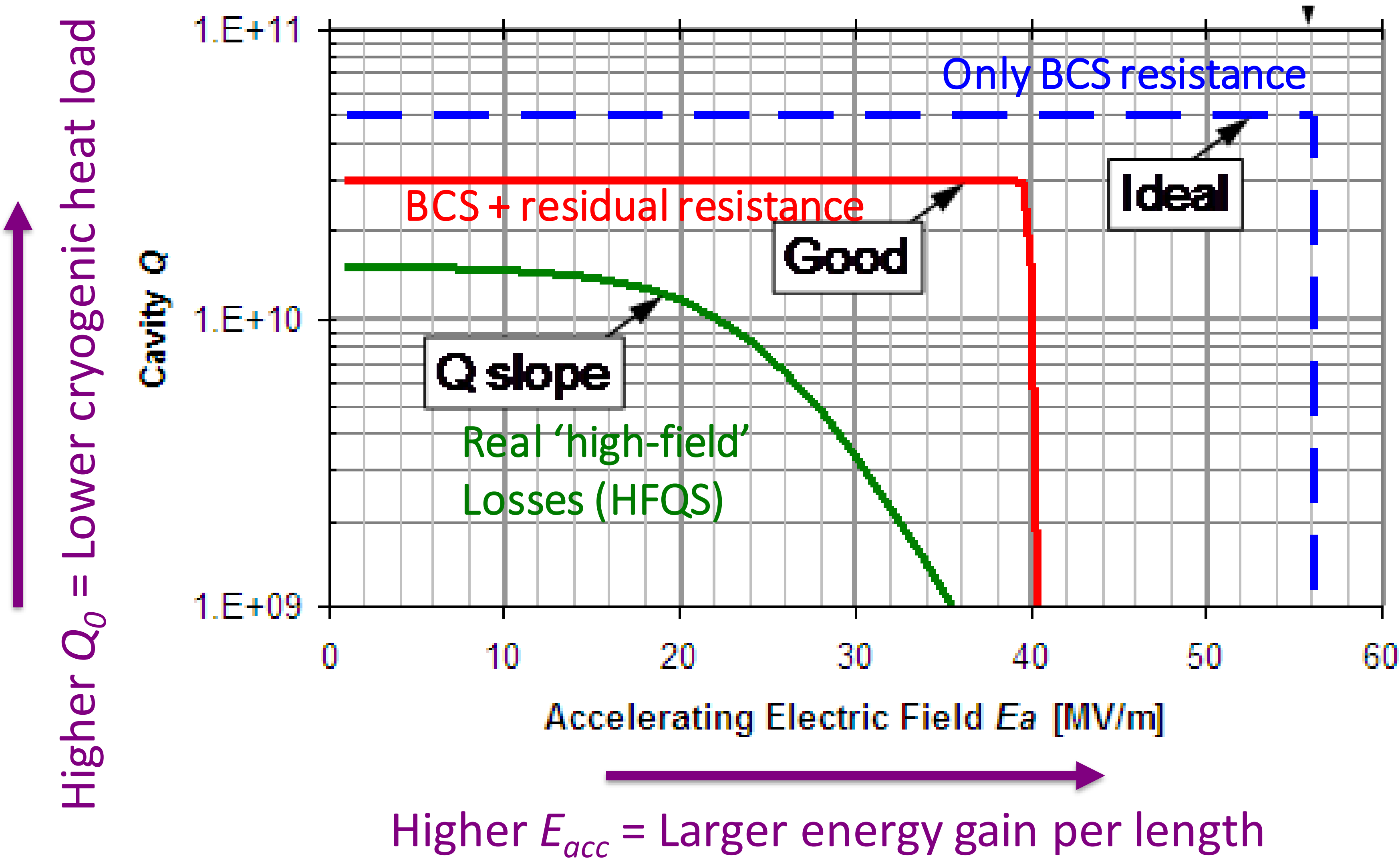
Intrinsic quality factor, Q_0

- defined as the ratio of the energy stored, U_{stored} divided by the energy dissipated in in one RF period, P_{diss}

$$Q_0 = \frac{\omega_0 U_{stored}}{P_{diss}} = \frac{\omega_0 \mu_0 \int_V |H|^2 dv}{\int_S R_s |H|^2 ds} = \frac{G}{R_s}$$

G = shape factor (a constant)
R_s = surface resistance
H = magnetic field (A/m)

SRF cavity – figures of merit



SRF cavity – figures of merit

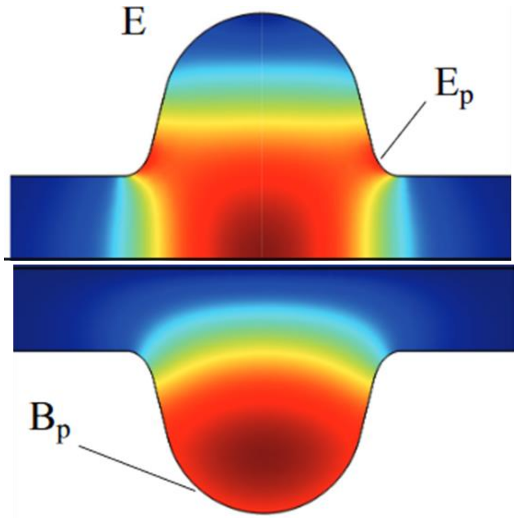
Peak field ratios (geometry dependent only, smaller are better)

$$\frac{B_{peak}}{E_{acc}}$$

Determines max. E_{acc} that can be generated before reaching quench magnetic field at the cavity surface

$$\frac{E_{peak}}{E_{acc}}$$

Determines max. E_{acc} that can be generated before E_{peak} induced field emission sets in



Shunt impedance, R_{sh} (geometry dependent only, larger is better)

$$R_{sh} = \frac{V_c^2}{P_{diss}} = \frac{(E_{acc}L)^2}{P_{diss}}$$

A measure of voltage that can be generated for a given dissipated power (analogous to Ohm's law)

Dissipated power

$$P_{diss} = \frac{(E_{acc}L)^2}{(R_{sh}/Q)*Q_0} DF = \frac{(E_{acc}L)^2 (R_{res} + R_{BCS})}{(R_{sh}/Q)*G} DF$$

$E_{acc}L$ = Voltage gain – dictated by end-application

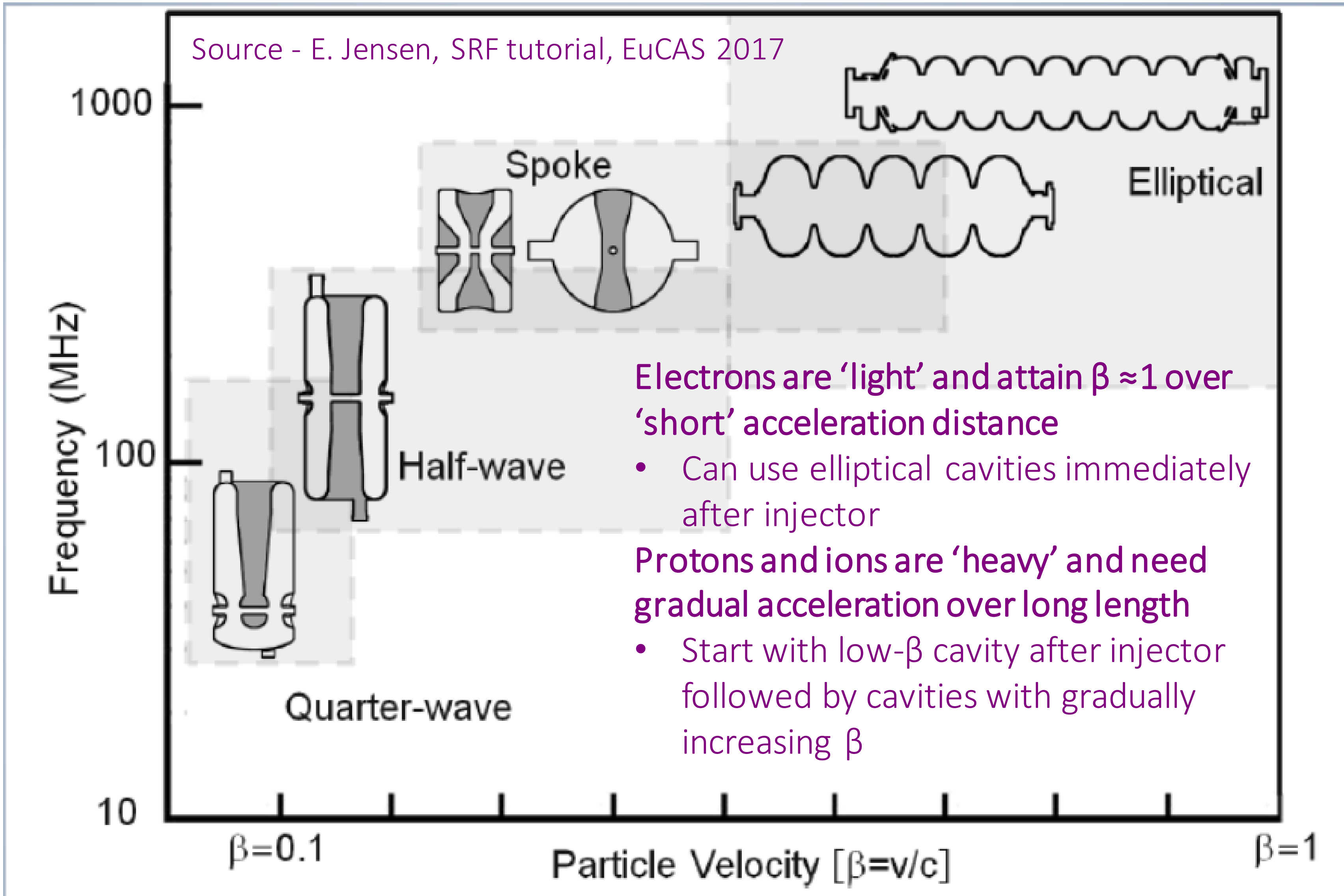
DF = RF duty factor – fraction of unit time when the RF power supply is ON; usually dictated by end-application

P_{diss} = Cryogenic load – need to minimize this to lower the cost of refrigeration

$R_{sh}/Q*G$ = Geometry factor – should be made as high as practical; this is optimized using FEA codes during cavity design stage

$R_s = R_{res} + R_{BCS}(T)$ = RF surface resistance – must be kept small; several recipes for surface treatment have been developed to reduce R_{res}

SRF cavity types



Electrons are 'light' and attain β ≈1 over 'short' acceleration distance

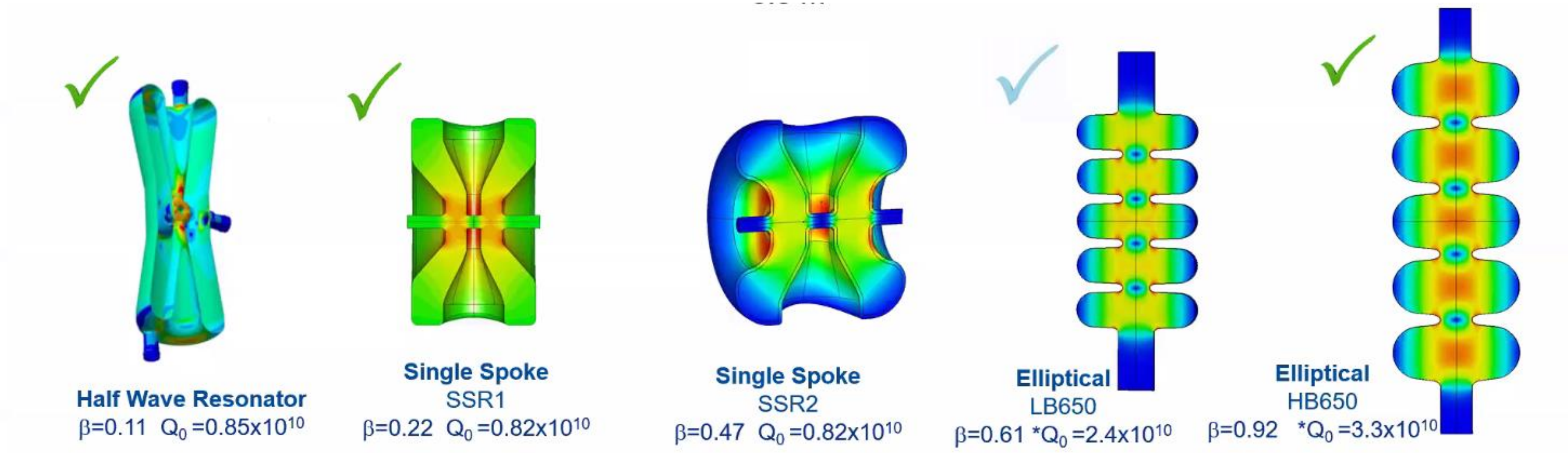
- Can use elliptical cavities immediately after injector

Protons and ions are 'heavy' and need gradual acceleration over long length

- Start with low-β cavity after injector followed by cavities with gradually increasing β

SRF cavities for Fermilab PIP-II

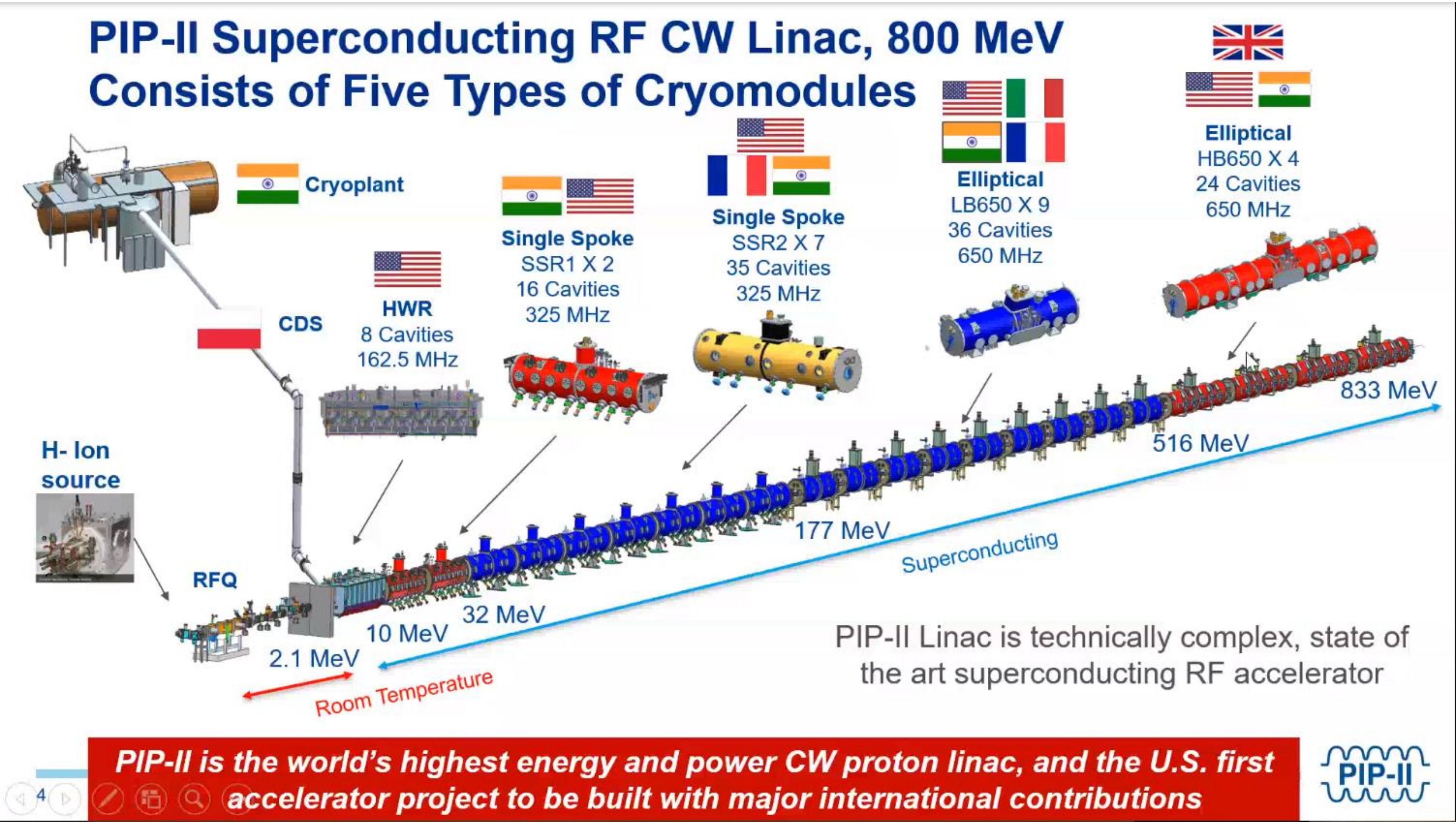
PIP-II is a proton accelerator being built at Fermilab
that will provide 800 MeV proton beam for neutrino experiments



162.5 MHz, v/c = 0.11	325 MHz v/c = 0.22	325 MHz, v/c = 0.47	650 MHz, v/c = 0.61	650 MHz, v/c = 0.92

Increasing proton energy

PIP II linac layout



Content courtesy: PIP II integration team

SRF cavity material

- Niobium has been the material of choice for SRF cavities for the last ~50 years
- Some of the best superconducting properties of all elements including highest critical temperature T_c ~ 9.2 K and high H_{c1} ~190 mT
- Easy metallurgy – purify, make sheets, form, weld, heat treat. No need to achieve precise stoichiometry as niobium is not a compound or alloy
- Good structural and thermal properties in bulk form, doesn't react with water
- SRF grade niobium is RRR > 300 that provides good bulk thermal conductivity for heat conduction from RF surface to helium coolant
- Some accelerators (eg. LEP at CERN) used bulk copper cavities sputtered with a few microns of niobium on the inner RF surface

Surface processing techniques

- Niobium cavities are produced from bulk sheets deep drawn into the desired shape (eg. elliptical half-cells) and then e-beam welded together
- The cavities undergo several heat/surface treatments before assembly in an accelerator. The goals are to:
  - Repair the RF surface as well as reduce bulk stresses arising from the fabrication processes
  - Enhance the surface RF properties for maximizing Q0
- **Common steps (both done to all cavities):**
  1. **Bulk electropolishing** – 100-200 um of 'damaged' RF surface is removed
  2. **800 ^{0}C bake in vacuum for ~3 hours (aka high T bake)** – reduce residual stress, improve microstructure, remove absorbed hydrogen during fabrication process

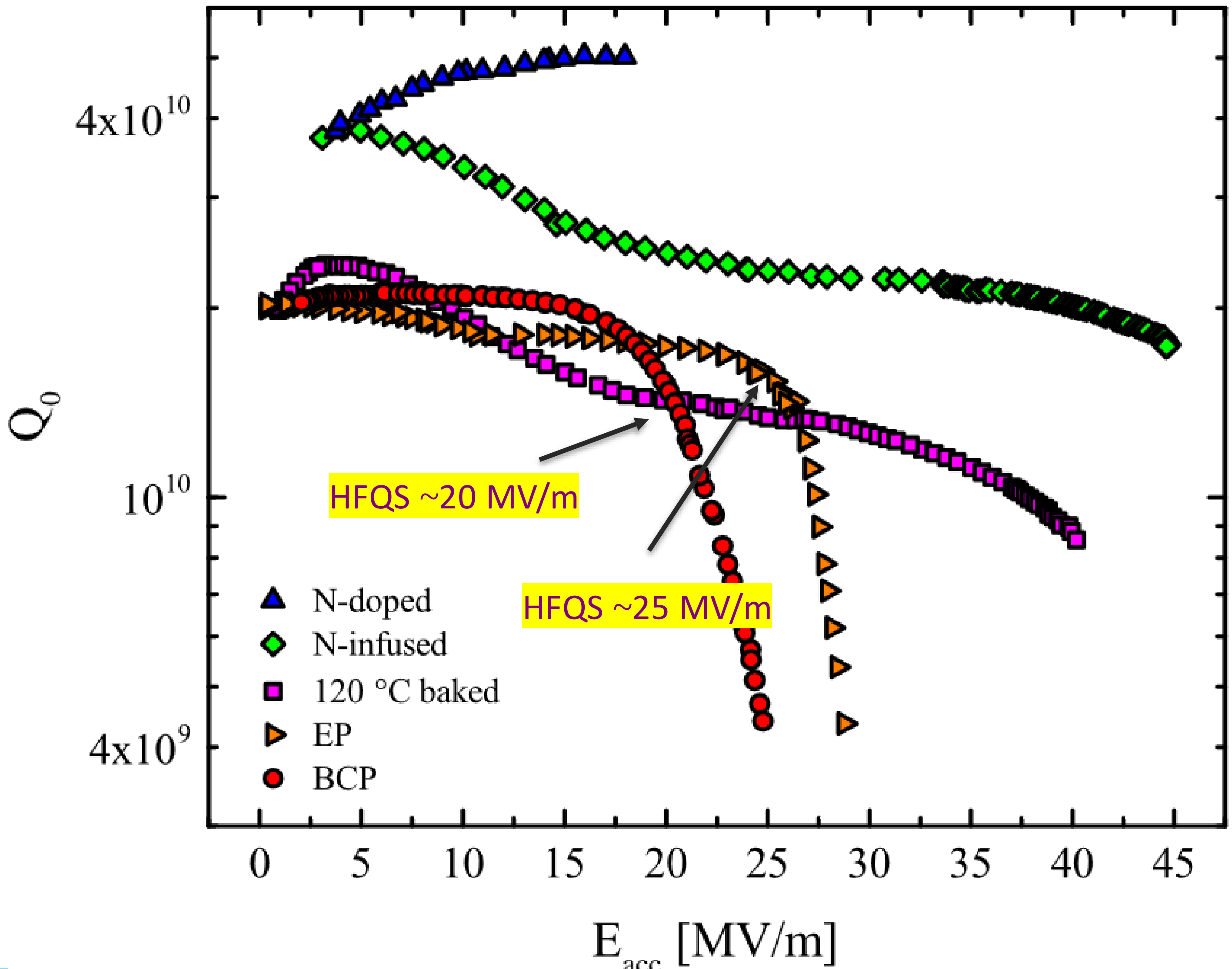
Surface processing techniques

- **Special treatments** – these are selected according to the desired performance (Q_0 and E_{acc}):
  1. **Buffer Chemical Polishing (BCP):**
     - 10-20 um of RF surface is etched using 1:1:2 solution of hydrofluoric, nitric and phosphoric acids
     - Cavities shows good performance up to ~20 MV/m followed from Q-slope
  2. **Electropolishing:**
     - 10-20 um of RF surface is etched using hydrofluoric and sulfuric acids usually with ratio 1:10
     - Cavities shows good performance up to ~25 MV/m followed from Q-slope
  3. **Low T bake:**
     - Vacuum baking at 120 ^{0}C for ~48 hours
     - Cavities do not see the Q-slope and gradient up to ~40 MV/m can be attained

Surface processing techniques

- **Special treatments** – these are selected according to the desired performance (Q_0 and E_{acc}):
  4. **Nitrogen doping:**
     - After high T bake, nitrogen is let in the furnace at a constant pressure of 25 mTorr;
     - cavity is let to anneal for several minutes and then heating is stopped
     - The cavity is cooled and then 5-10μm of material is removed by electropolishing
     - Eacc can be pushed beyond 50 MV/m
  5. **Nitrogen infusion:**
     - After high T bake, the furnace temperature is lowed to 120-160 ^{0}C
     - Nitrogen is let in at 25 mTorr
     - Temperature is held steady for ~48 hours
     - No chemical treatment done after cooling the cavity to room temperature
     - The technique produces very high Q_0 and highest E_{acc}

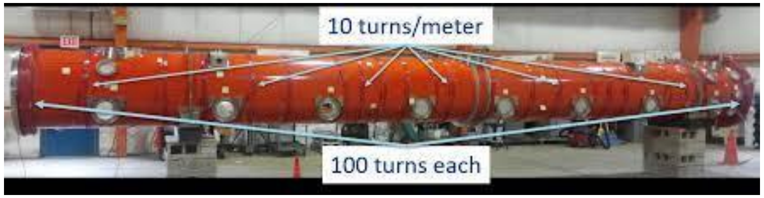
Effect of surface treatments on performance



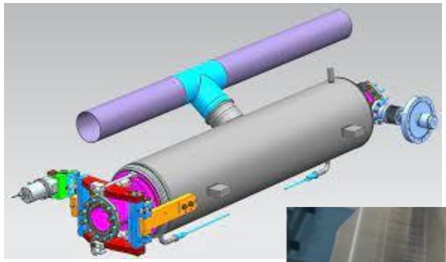
Practically important aspects of SRF cavities

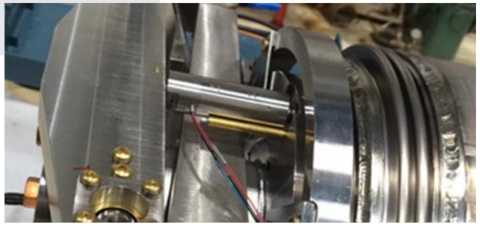
- Local magnetic fields (including the Earth's) degrade cavity performance (Q_0)
  - Result is that cavities are designed with passive and sometimes active magnetic shields. Use of magnetic materials near cavities must be carefully examined
- Cavities are resonant structures that require tuning frequently at cryogenic temperatures
- Vibrations (microphonics) can detune cavities depending on cavity stiffness and design
  - This may put strict limits on vibrations near cavities
  - Use of He II (see lecture on superfluid helium) prevents bulk boiling in the helium bath that may affect the cavity tune

Magnetic shields provide passive shielding



Current coils around cryomodule actively negate the magnetic field inside





Tuner for LCLS II cavities

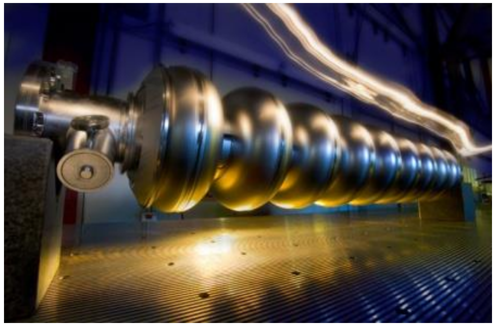
Content courtesy: J. G. Weisend II (ESS)

SRF cavities – cost perspective

Processed One-Cell

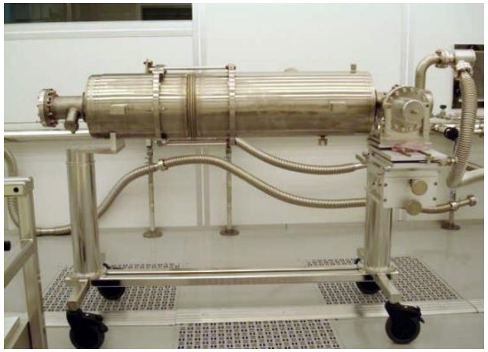
$40k Cadillac CTS

New Nine-Cell



$85k BMW M5

Dressed Nine-Cell



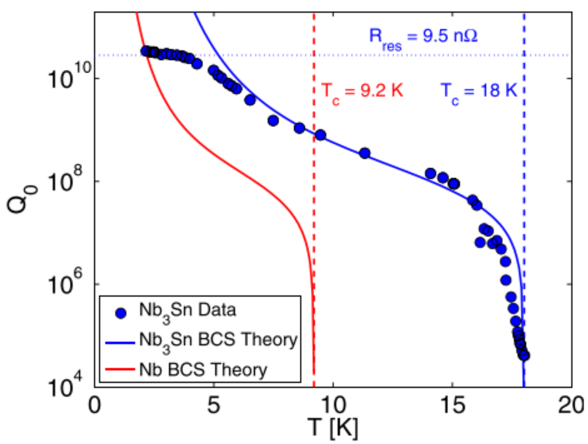
$250k Aston Martin DBS

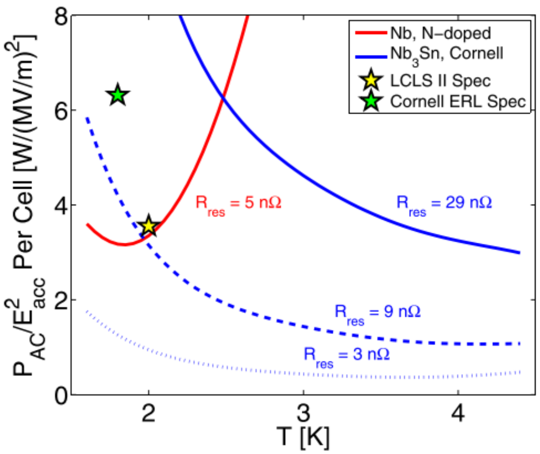
Content courtesy: A. Rowe (Fermilab)

New frontiers in SRF

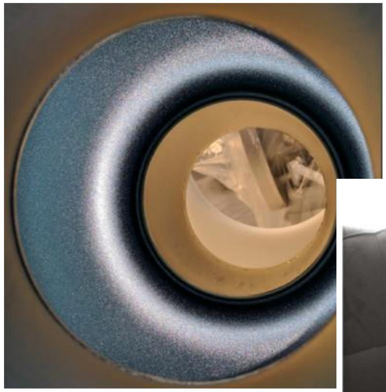
Nb_3Sn as an alternative to traditional niobium

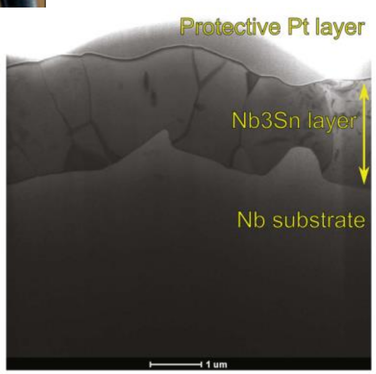
- Superconductor with $T_c \approx 18$ K, almost twice that of niobium's 9.2 K
- Has significantly lower R_{BCS} than niobium at liquid helium temperatures < 4.2 K
- If R_{res} is kept small (by ensuring proper stoichiometry, surface treatments, and magnetic shielding), Nb_3Sn cavities exhibit very high Q_0 even at ~4 K
  - An accelerator can be operated with 4.2 K LHe systems, which are much cost effective compared to 2 K helium systems needed for niobium cavities
- **Active research areas** – growing thin layer of Nb_3Sn on inner walls of niobium cavities; cooling and mag-shielding techniques to minimize trapped flux





DOI: 10.1088/1361-6668/30/3/033004

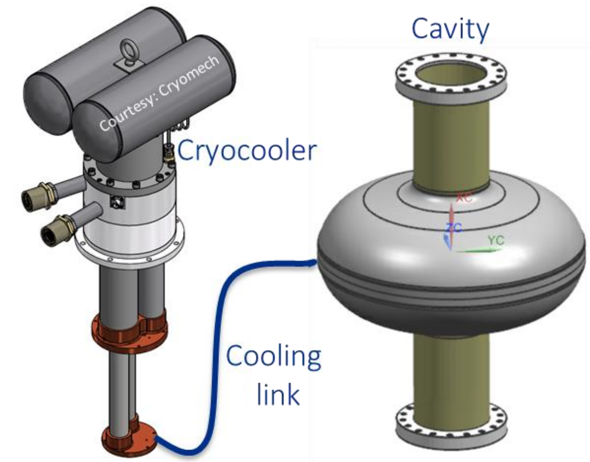




New frontiers in SRF

Cryogen-free, cryocooler conduction cooled SRF cavities

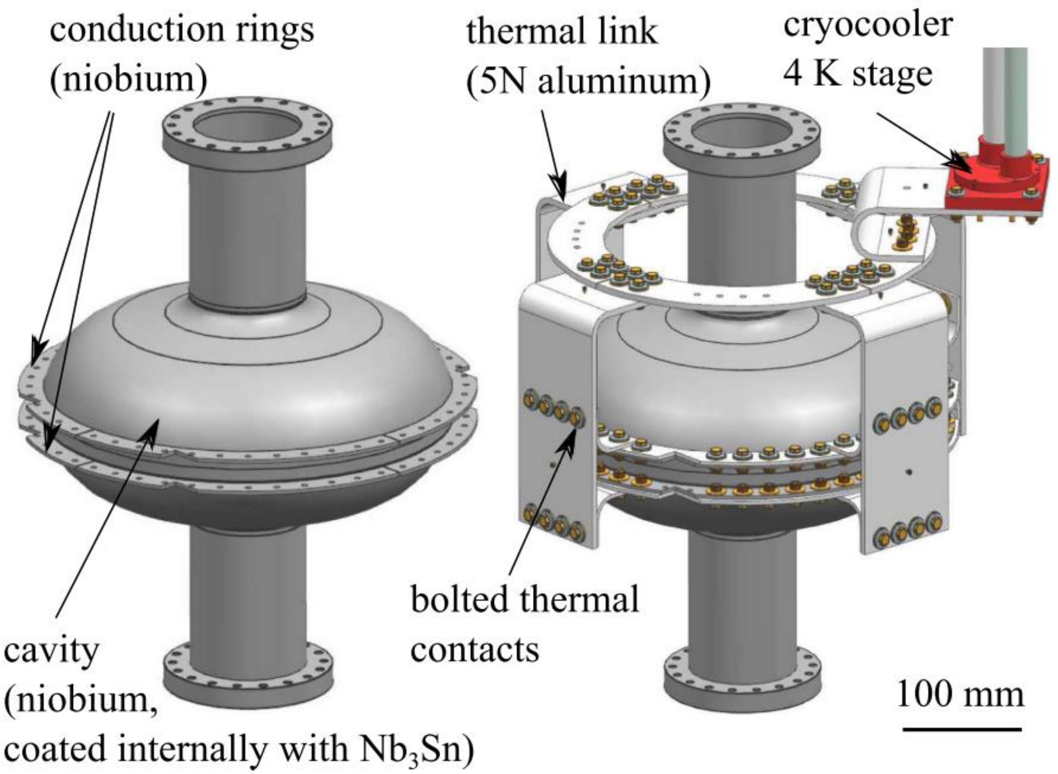
- Use closed-cycle 4 K cryocoolers and conduction links to extract P_{diss} from Nb3Sn SRF cavities
  - Liquid helium around the SRF cavity not needed
    -> no cryoplant, no distribution or recovery system
    -> no complex pressure vessel design of the cryomodule
- Cryocoolers are plug-n-play machines that turn on/off with the push of a button
  - Unlike helium cryo-plants that are operationally complex
- Potential use of conduction cooled **SRF** in e-beam irradiation machines for **industrial applications**:
  - Industrial and municipal waste-water treatment
  - Medical device sterilization, medical waste treatment
- Active research areas
  - Design of cavities and thermal links for SRF conduction cooling
  - Design of low heat leak, magnetically shielded, compact cryomodules



wastewater under treatment

New frontiers in SRF

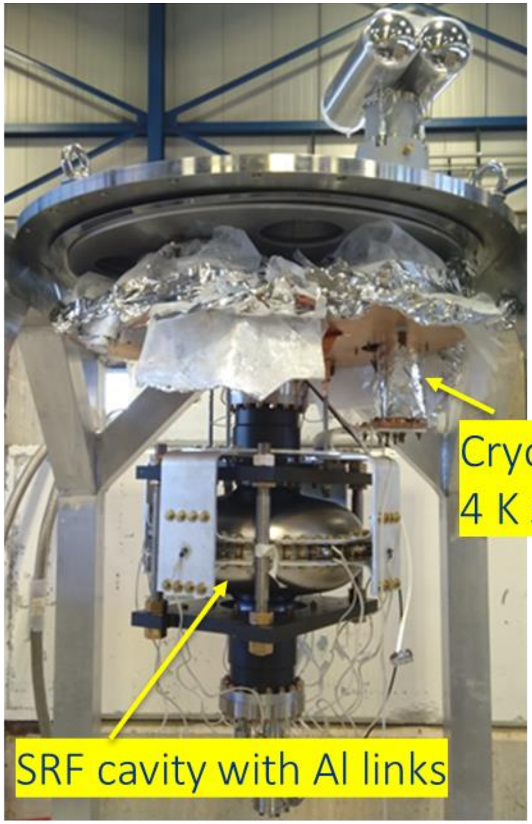
Fermilab efforts for conduction cooled SRF cavity development



New frontiers in SRF

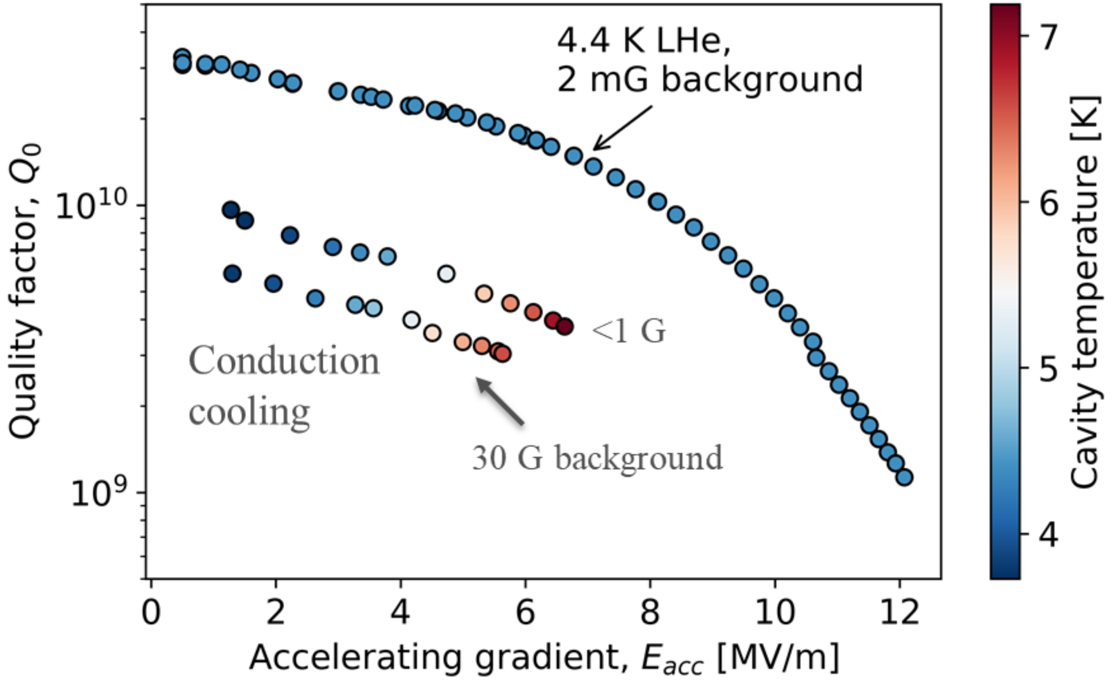
Fermilab efforts for conduction cooled SRF cavity development

Conduction cooled SRF test setup at Fermilab



World's first demonstration of practical E_{acc} on a conduction cooled SRF cavity

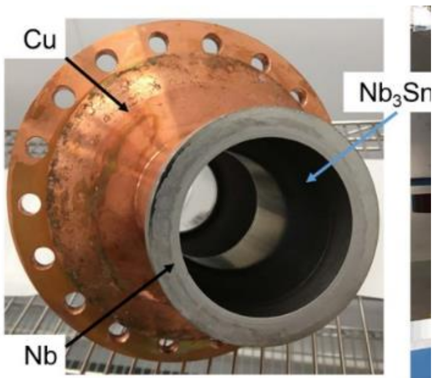
R.C. Dhuley *et al.*, https://doi.org/10.1088/1361-6668/ab82f0



New frontiers in SRF

Other ongoing efforts for conduction cooled SRF cavity development

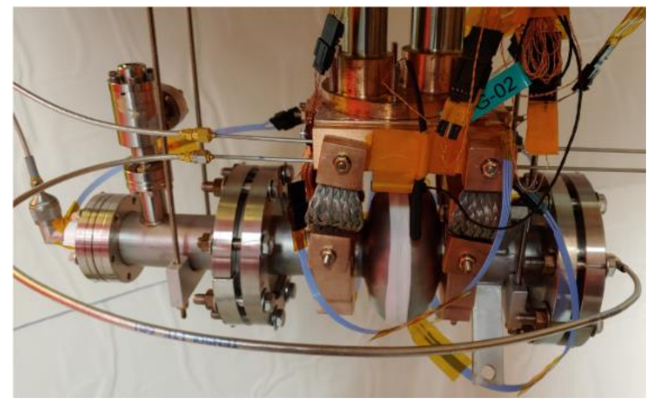
Jefferson Lab



https://doi.org/10.1088/1757-899X/755/1/012136

- 1.5 GHz
- Cold sprayed + electrodeposited copper

Cornell University

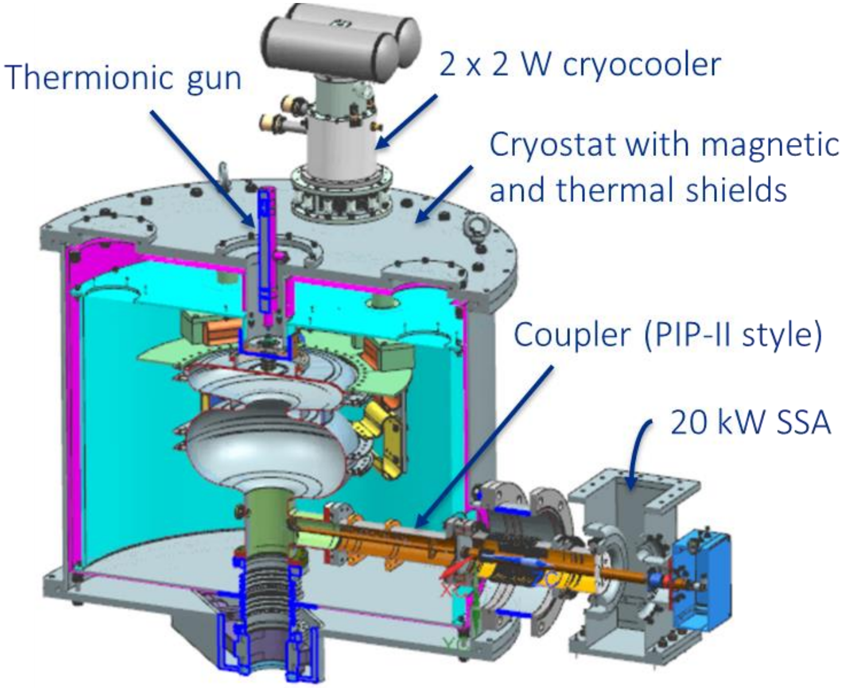


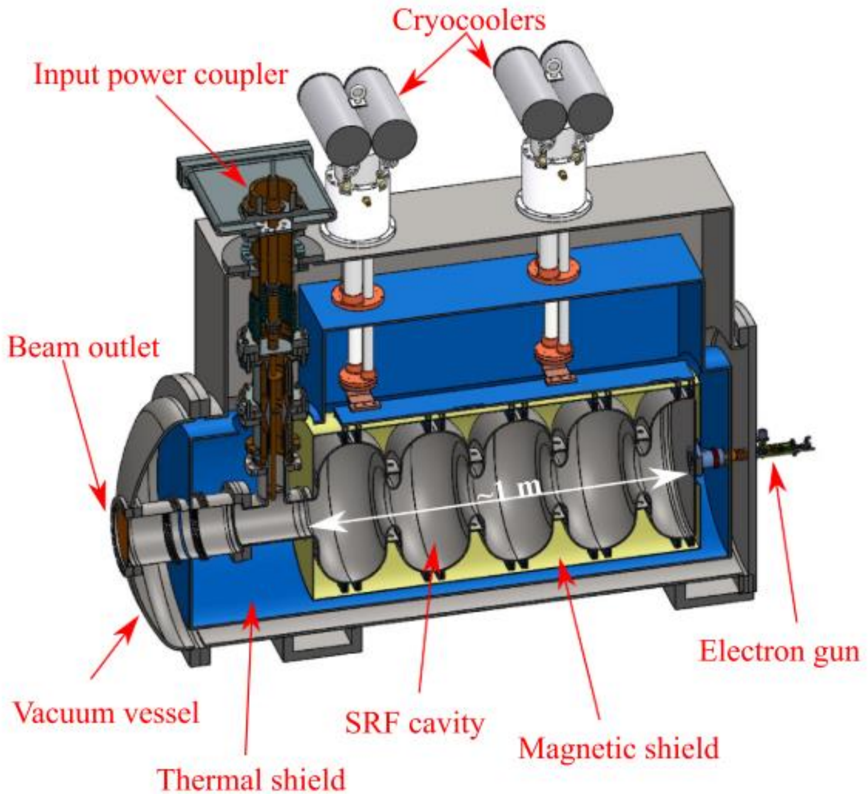
https://arxiv.org/abs/2002.11755

- 2.6 GHz
- Copper clamps

New frontiers in SRF

Compact e-beam accelerator development at Fermilab using conduction cooled SRF cavities





Further reading

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2. Hasan Padamsee, "RF Superconductivity: Science, Technology, and Applications," Wiley-VCH; 1st edition (April 20, 2009)
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4. A Grassellino *et al* 2017 *Supercond. Sci. Technol.* 30 094004
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