# SRF Cavities II

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# Outline of SRF Cavity Lectures

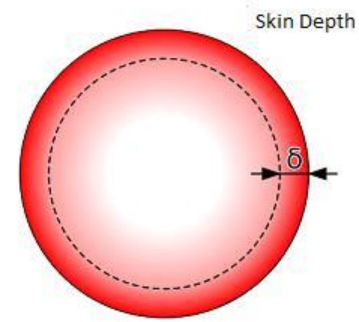
- SRF-I – July 13, 2023
  - Introduction to EM fields in resonators
  - Pill-box cavities, elliptical cavities, TEM mode cavities
  - Linac architecture and choice of cavity and frequency
  - Other cavity types
  - Cavity circuit representation
- SRF-II – July 14, 2023
  - Superconducting RF resistance
  - Fundamental parameters of RF resonators (Q-value, geometry factor, shunt impedance, stored energy, transit time factor)
  - Achieving peak performance (extrinsic issues and mitigations)
  - State of the art
- ✓ Slides I will cover

# Surface resistance of rf resonators

# Room temperature rf surface resistance



- RF currents flow at the surface within a characteristic length $\delta$ called the skin depth with rf surface resistance given by




$$R_s = \sqrt{\frac{\pi f \mu_0}{\sigma}} = \frac{1}{\sigma\delta} \qquad \delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}}$$

$\mu_0 = 4\pi \times 10^{-7}$ H/m

| **Material** | **σ (S/m)** | **ρ (Ω-m)** |
|---|---|---|
| Copper | $58 \times 10^{6}$ | $17 \times 10^{-9}$ |
| Aluminum | $35 \times 10^{6}$ | $28 \times 10^{-9}$ |
| Niobium | $6.7 \times 10^{6}$ | $150 \times 10^{-9}$ |

where f is the rf frequency, $\sigma$ is the conductivity and $\rho$ is the resistivity ($\rho=1/\sigma$)

S -> Siemens or mho or $\Omega^{-1}$

Example: For copper conductor and using TRIUMF rf frequencies

| Cavity | *f* | *σ(Cu-300K)* | *δ* | $R_s$ |
|---|---|---|---|---|
| | (GHz) | $(\mu\Omega\text{-m})^{-1}$ | (μm) | (mΩ) |
| Cyclotron | 0.023 | 58 | 13.8 | 1.2 |
| ISAC-II DTL | 0.106 | 58 | 6.4 | 2.7 |
| E-Linac Buncher | 1.3 | 58 | 1.8 | 9.4 |

Example

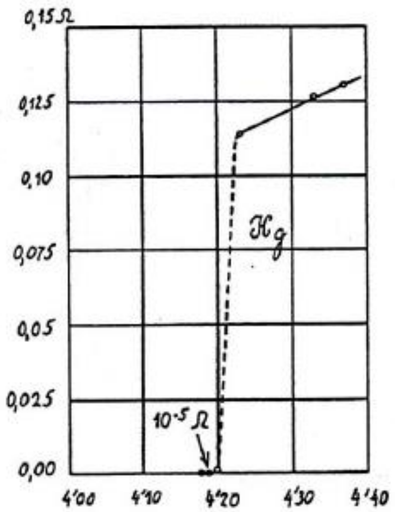
$\sigma$= 2 S/m = 2 mho/m

$\rho$ = 0.5 **Ω** -m

# Superconductivity



## Resistivity of Mercury Drops to Zero




Kamerlingh Onnes and van der Waals in Leiden with the helium 'liquefactor' (1908)

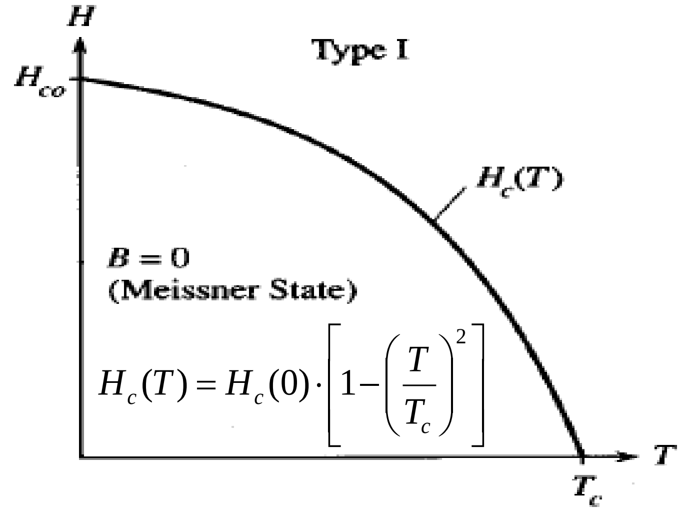
$$\frac{\rho_s}{\rho_n} < 10^{-12}$$

Table 1: The critical temperature of some common materials at vanishing magnetic field.

| material | Ti | Al | Hg | Sn | Pb | Nb | NbTi | $Nb_3Sn$ |
|---|---|---|---|---|---|---|---|---|
| $T_c$ [K] | 0.4 | 1.14 | 4.15 | 3.72 | 7.9 | 9.2 | 9.2 | 18 |

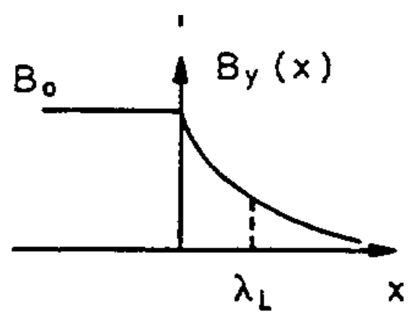
# Superconductors

- Below a certain temperature ($T_c$) and magnetic field ($H_c(T)$) some materials enter the superconducting (Meissner) state and DC electrical resistance is 0
- In the Meissner state surface currents are set up to repel the penetration of magnetic field
- The surface currents and magnetic field decay rapidly through a narrow shell characterized by the London penetration depth

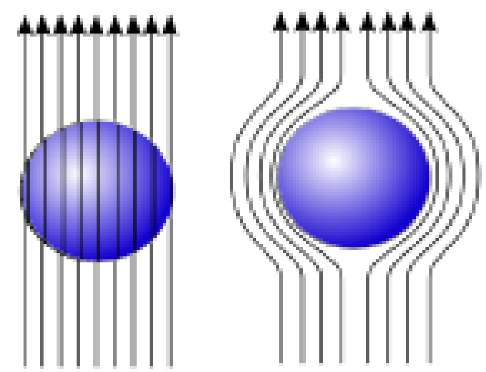



$$\lambda_L(T) = \sqrt{\frac{m_e}{\mu_0 n_s(T) e^2}}$$

$n_s$ - density of SC electrons




$$B_y = B_0 e^{-x/\lambda_L}.$$



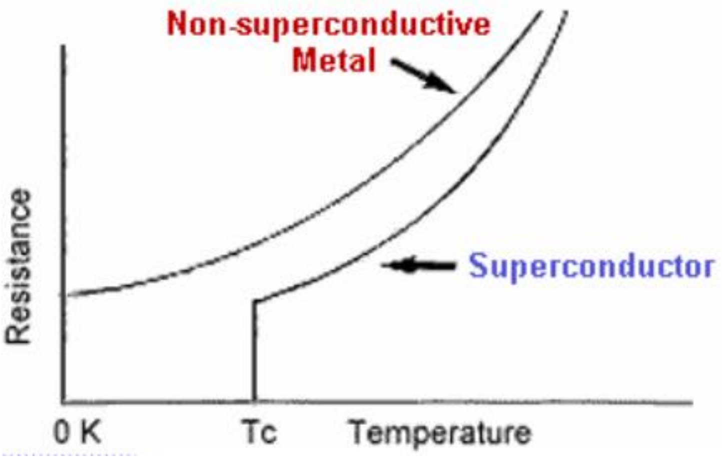
$T>T_c$
$H>H_c(T)$

$T<T_c$
$H<H_c(T)$

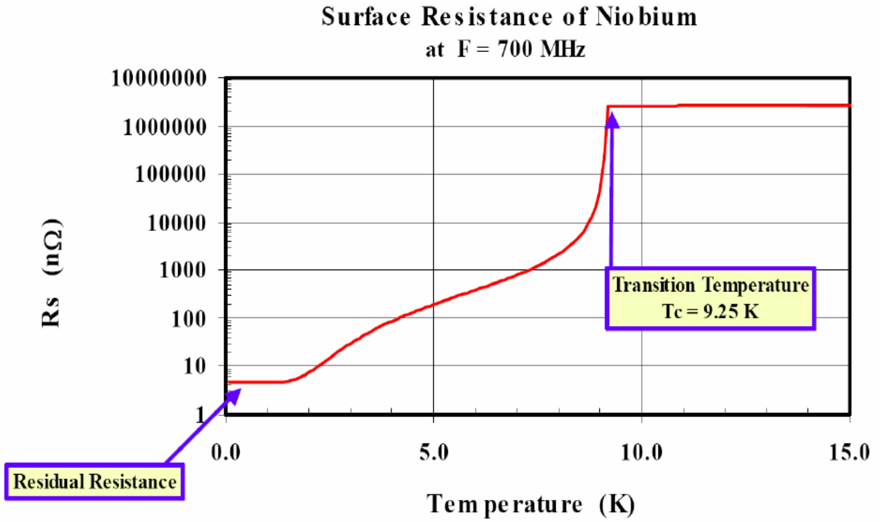
For Niobium $\lambda_L(0)$ = 39 nm

# RF Superconductivity

- In the Superconducting state DC resistance is zero




- RF resistance is small but finite
  - SC Nb has a rf surface resistance >five orders of magnitude lower than room temperature Niobium



# SRF Surface Resistance ✓

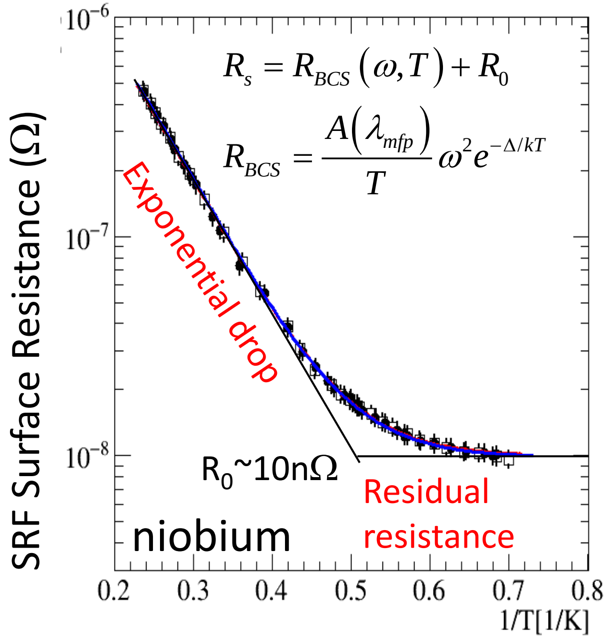
The SRF surface resistance is a combination of a temperature dependent component, $R_{BCS}$, and a residual resistance, $R_0$, due to impurities, trapped magnetic flux, defects, smearing of Density of states, …

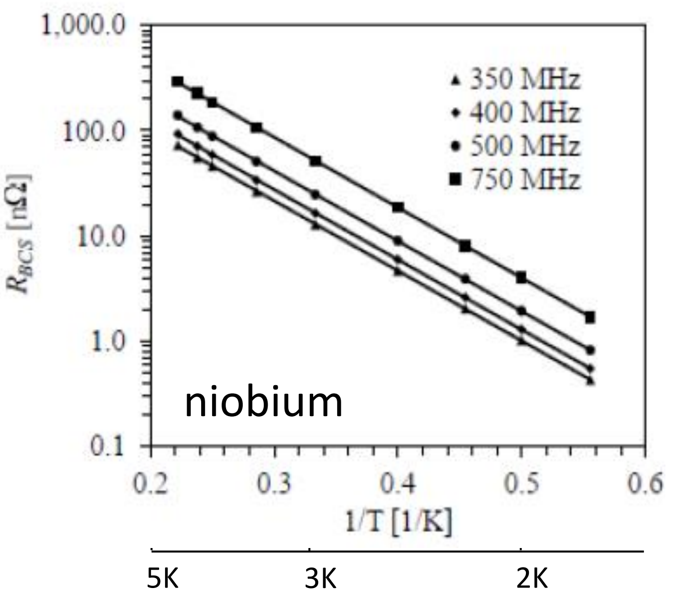
$$R_s = R_{BCS} + R_0$$

For Niobium for $T < T_c/2$, $T_c$=9.2K

$$R_{BCS}(\Omega) \approx 2\times10^{-4}\,\frac{1}{T}\left(\frac{f\,(GHz)}{1.5}\right)^2 \exp\left(-\frac{17.67}{T}\right)$$

| TRIUMF Cavity | 106MHz | 141MHz | 1.3GHz |
|---|---|---|---|
| $R_{BCS}$@4.2K | 3.5 nΩ | 6.3 nΩ | 530 nΩ |
| $R_{BCS}$@2K | 0.07 nΩ | 0.13 nΩ | 10.9 nΩ |
| $R_{BCS}$@1.8K | 0.03 nΩ | 0.05 nΩ | 4.6 nΩ |



# RF surface resistance in NC and SC

Normal Conductors

- Skin depth is proportional to $\omega^{-1/2}$ (Cu 300K 1GHz $\delta$=2μm)
- Surface resistance is proportional to $\omega^{1/2}$
- For Cu at 300K and 1GHz, Rs~10 m$\Omega$
- Surface resistance somewhat independent of temperature

Superconductors

- Penetration depth is independent of $\omega$ (Nb~39nm at 2K)
- Surface resistance is proportional to $\omega^2$
- For Nb at 2K and 1GHz, Rs~10n$\Omega$
- Surface resistance strongly dependent on temperature

# Fundamental Parameters of RF Resonators

# Figures of Merit for RF Structures

Ideally cavities should have:

- Large accelerating field for small drive current
- Low losses to reduce the power consumption
- Shapes that reduce peak fields and enhance volume
- Efficient energy transfer to beam
- These are quantified by the figures of merit:
  - shunt impedance, surface resistance, geometry factor, surface fields, transit time factor and quality factor

# Cavity power loss

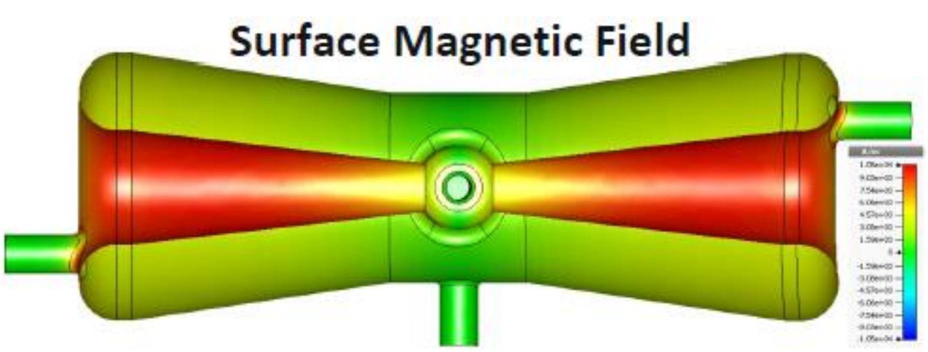
Resonators with fields at the surface have currents that flow within a thin surface layer ($\delta$ or $\lambda_L$) of the walls

The currents dissipate energy in the walls due to surface resistance (Ohmic heating) – the heat is typically removed by water cooling in warm cavities or by liquid helium in superconducting cavities. (Here S denotes surface)

$$\frac{dP_c}{ds} = \frac{1}{2} R_s |H|^2 \quad \text{so that} \quad P_c = \frac{1}{2} \int_s R_s |H|^2 ds$$

$$\text{or} \;\; P_c \approx \frac{1}{2} R_s \int_s |H|^2 ds \quad \text{for} \sim \text{constant} \;\; R_s$$

Note – the power loss is not uniform – dependent on the distribution of the surface H field



# Stored Energy

- The energy density in an electromagnetic field is given by

$$u = \frac{1}{2}\left(\varepsilon \cdot E^2 + \mu \cdot H^2\right)$$

- Due to the sinusoidal time dependence and the 90 degree phase shift the energy oscillates between the electric and the magnetic field with the total stored energy given by (here V denotes volume – not Voltage)

$$U = \frac{1}{2}\mu_0 \int_V |H|^2 dV = \frac{1}{2}\varepsilon_0 \int_V |E|^2 dV$$

# Quality Factor

✓

The Quality factor is defined as:

$$Q_0 \equiv \frac{\text{Energy stored in a cavity}}{\text{Energy dissipated in walls per radian}} = \frac{U}{\Delta u} = \frac{U}{P_c \frac{T}{2\pi}} = \frac{\omega_0 U}{P_c}$$

where $U$ is the stored energy, $P_c$ is the power loss in the cavity walls and $T$ is the rf period (here V denotes volume and S denotes surface)

$$Q_0 = \frac{\omega_0 \mu_0 \int_V |H|^2 dV}{\int_S R_s \cdot |H|^2 ds} \approx \frac{\omega_0 \mu_0 \int_V |H|^2 dV}{R_s \int_S |H|^2 ds} \quad \text{for} \sim \text{constant } R_s$$

# Geometry Factor

The two integrals in the equation on the previous slide are determined only by cavity geometry so we can define a characteristic constant *G*

$$\text{i.e.} \quad Q_0 = \frac{\omega_0 \mu_0 \int_V |H|^2 \, dV}{R_s \int_S |H|^2 \, dS} \quad \text{so} \quad Q_0 = \frac{G}{R_s} \quad \text{for constant } R_s$$

$$\text{where} \quad G = \frac{\omega_0 \mu_0 \int_V |H|^2 \, dV}{\int_S |H|^2 \, dS} \quad \text{is called the Geometry Factor}$$

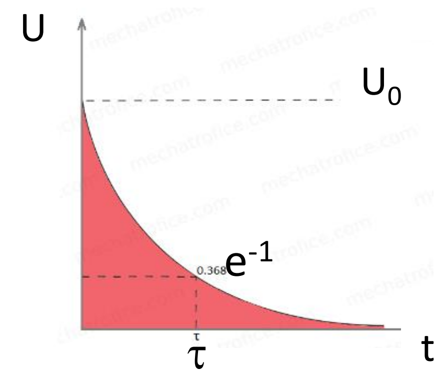
The geometry factor depends only on the cavity shape and the electromagnetic mode but not its size. Hence it is very useful for comparing different cavity shapes. Higher G means higher Q for the same surface resistance - this favours more spherical shapes.

# RF Decay constants

If the rf power feeding the cavity is turned off the stored energy *U* and cavity voltage *V* will drain from the cavity due to the power losses in the conducting walls

$$\frac{dU}{dt} = P_c = -\frac{\omega_0 U}{Q_0} \quad \text{also} \quad U \propto E^2 \propto V^2 \quad \text{so} \quad 2\frac{dV}{dt} = -\frac{\omega_0 V^2}{Q_0}$$

This has the solution




$$U = U_0 e^{-\left(\frac{\omega_0 t}{Q_0}\right)} \qquad V = V_0 e^{-\left(\frac{\omega_0 t}{2Q_0}\right)}$$

The energy will drop exponentially with time constant

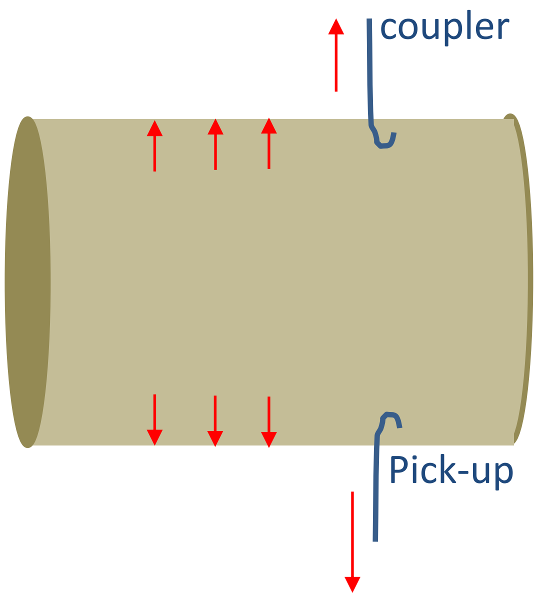
$$\tau_U = \frac{Q_0}{\omega_0} \quad \text{where} \quad U = U_0 e^{-t/\tau_U} \quad \text{also} \quad \tau_V = \frac{2Q_0}{\omega_0}$$

Measuring $\tau$ is a practical way to measure the quality factor of a resonant system

# External Quality Factor

- In a circuit when the rf is turned off the stored energy in the cavity will drop due to both dissipation in the cavity walls and any power coupled back into the coupler or pick-up probe

$$\frac{dU}{dt} = P_c + P_{ext1} + P_{ext2}$$




- We define an external quality factor, $Q_{ext}$, to account for the external drain on the cavity power

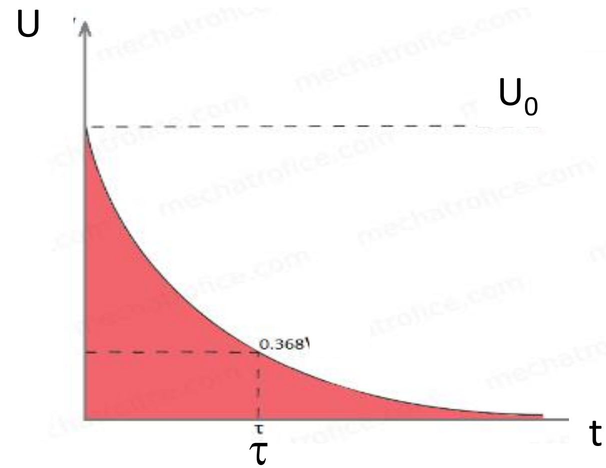
$$\frac{dU}{dt} = P_{total} = -\omega_0 U \left( \frac{1}{Q_0} + \frac{1}{Q_{ext1}} + \frac{1}{Q_{ext2}} \right)$$

# Loaded Q and Coupling constant

- the total power loss can be associated with a loaded quality factor for the system,

We define a `loaded' Q $\quad Q_L \equiv \dfrac{\omega U}{P_{total}}$ with

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}} \qquad \text{and} \qquad \tau = \frac{Q_L}{\omega_0}$$




- the coupling can be characterized by a coupling factor β relating $Q_0$ to $Q_{ext}$

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{\beta}{Q_0} \text{ so } \quad Q_{ext} = \frac{Q_0}{\beta} \quad \text{and} \quad Q_L = \frac{Q_0}{1+\beta}$$

- the bandwidth of the loaded system is calculated using the loaded $Q_L$

$$\Delta\omega_L = \frac{\omega_0}{Q_L} = \frac{\omega_0}{Q_0}(1+\beta), \; Q_L = \frac{\omega_0}{\Delta\omega_L} \qquad\qquad \tau = \frac{1}{\Delta\omega_L}$$

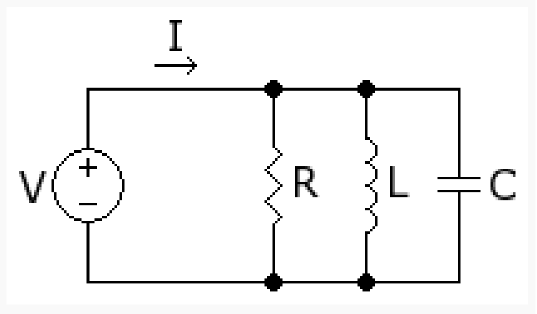
# Shunt Impedance

Effective shunt impedance (accelerator Ohm's Law) – rf efficiency

$$R_a = \frac{V_{eff}^{\ 2}}{P_{cav}} \quad \text{or} \quad \frac{R_a}{Q_0} = \frac{V_{eff}^{\ 2}}{\omega_0 U} \quad \text{or} \quad P_{cav} = \frac{V_{eff}^{\ 2}}{\frac{R_a}{Q_0} \cdot Q_0}$$

$R_a/Q$ is a common figure of merit of a design since it is independent of surface resistance; it is commonly used to describe the efficiency of accelerating charge particles. Since it includes $V_{eff}$ the transit time factor is included.

Beware - shunt impedance has a few definitions. A popular one is the one we saw in rf circuit theory

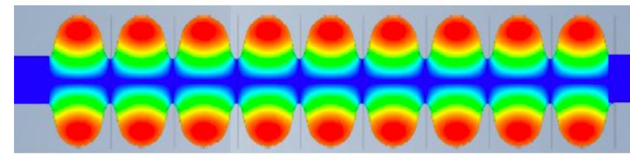



$$R_{sh}\big|_{rf} = \frac{V_0^2}{2P_{cav}} \quad \text{also} \quad \frac{R_{sh}}{Q} = \sqrt{\frac{L}{C}}$$

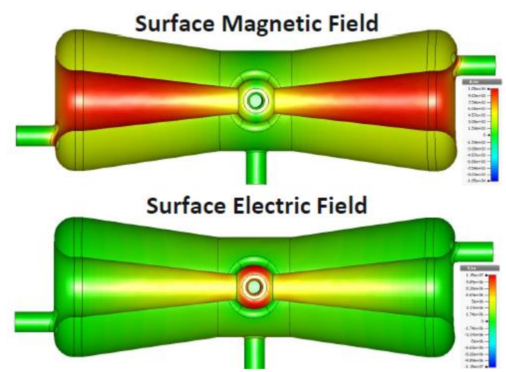
# Peak Field Limitations

- While the field gradient, $E_a$, is a useful performance metric, actual performance is limited by peak surface field $E_p$ and peak magnetic field $B_p$
- Cavities are designed to reduce $E_p/E_a$ and $B_p/E_a$
- High surface magnetic fields have high power density (heating) and is fundamentally limited due to SRF state ($B_p$<~180mT for Nb).
- Typical design values for Bp
    - For CW applications is Bp = 70mT.
    - For pulsed operation is Bp=135mT
- High electric surface fields can cause field emission
- Typical design values for Ep
    - for CW application is Ep = 35MV/m
    - for pulsed application is Ep = 60MV/m

Elliptical cavity Ep/Ea~2 and Bp/Ea~4.3mT/MV/m



Coaxial cavity depends on beta and customization: Ep/Ea=4-5 and Bp/Ea=6-10mT/MV/m



# Design considerations

The cavity shape is chosen to minimize the power for a given accelerating voltage – this means maximizing the two figures of merit the shunt impedance, $R_a/Q$, and the Geometry factor, $G$

$$Q_0 = \frac{G}{R_s} \qquad P_{cav} = \frac{V_{eff}^{\;2}}{R_a} = \frac{E_a^{\;2} L^2}{\frac{R_a}{Q_0} \cdot Q_0} \qquad P_{cav} = \frac{E_a^{\;2} L^2}{\frac{R_a}{Q_0} \cdot G} R_s$$

Conclusion: we want to minimize $R_s$ and maximize $R_a/Q$ and $G$ for minimum power

Note: $R_s$ and $R_a$ are two very different parameters – **don't be confused**

- typical values for normal conducting cavities are $R_s$=5m$\Omega$ and $R_a$=2M$\Omega$
- typical values for superconducting cavities are $R_s$=50n$\Omega$ and $R_a$=2x10$^{11}\Omega$

# Acceleration and transit time factor in RF Resonators

# RF Acceleration

- Consider a time varying $E_z$ field on axis in a pill-box cavity (or in a gap between two drift tubes)
- The ion travels with velocity $\beta c$ on axis and experiences a field that is the product of the spatial variation and the time modulation

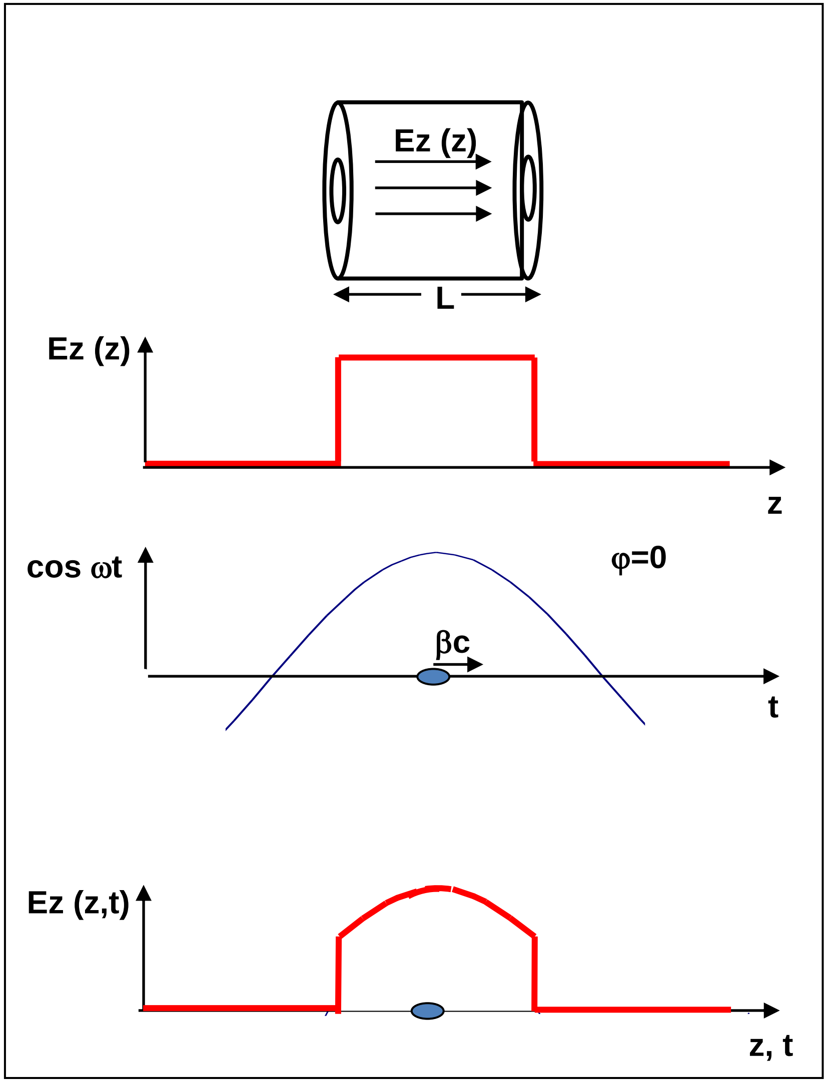
$$E_z(z,t) = E_z\left(r=0,z\right)\cdot\cos(\omega t+\varphi)$$

  – Where φ is a constant (the rf phase) that defines the time of arrival of the particle with respect to the rf time modulation.

  – A phase of φ=0 corresponds to the maximum acceleration that can be given to the particle (\`on crest' acceleration)

- One can calculate the accelerating voltage imparted to the ion by

$$V(\phi) = \int_{-\infty}^{\infty} E_z\left(r=0,z\right)\cos(\omega t(z)+\varphi)dz$$



# Accelerating voltage

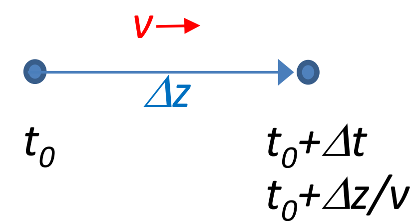
$$V(\varphi)=\int_{-\infty}^{\infty}E_z\left(r=0,z\right)\cos(\omega t(z)+\varphi)dz$$

- Note also that time and position are linked through the velocity

$$t=\frac{z}{v}=\frac{z}{\beta c}\quad \text{and noting}\quad c=f\lambda \quad\text{and}\quad \omega=2\pi f$$

$$V(\varphi)=\int_{-\infty}^{\infty}E_z\left(r=0,z\right)\cos\left(\frac{2\pi z}{\beta\lambda}+\varphi\right)dz$$

$$V(\varphi)=\int_{-\infty}^{\infty}E_z\left(r=0,z\right)\left(\cos\left(\frac{2\pi z}{\beta\lambda}\right)\cos\varphi-\sin\left(\frac{2\pi z}{\beta\lambda}\right)\sin\varphi\right)dz$$




- Since $E_z$ is typically an even function this simplifies to

$$V(\varphi)=\int_{-\infty}^{\infty}E_z\left(r=0,z\right)\left(\cos\left(\frac{2\pi z}{\beta\lambda}\right)\right)dz\cdot\cos\varphi=V_{eff}\cdot\cos\varphi$$

$$\text{where}\quad V_{eff}=\int_{-\infty}^{\infty}E_z\left(r=0,z\right)\left(\cos\left(\frac{2\pi z}{\beta\lambda}\right)\right)dz$$

- $V_{eff}$ is called the accelerating voltage or effective voltage

# Transit Time Factor

It is convenient to define an axial RF voltage corresponding to the `frozen' spatial field component (evaluated at cos φ = 1)

$$V_0 \equiv \left| \int_{-\infty}^{\infty} E_z(r=0,z)\cdot dz \right|$$

Due to the time varying nature of the field as the ion passes through the cavity the particle receives less than the full `frozen' accelerating voltage so

$$V_{eff} = V_0 \cdot T \quad \text{with} \quad T < 1$$

$T$ is called the transit time factor given by

$$T \equiv \frac{\int_{-\infty}^{\infty} E_z(r=0,z)\cdot \cos\frac{2\pi z}{\beta\lambda} dz}{\left| \int_{-\infty}^{\infty} E_z(r=0,z)\cdot dz \right|}$$

**Achievable voltage**

**`frozen' spatial voltage**

A convenient voltage gain formula is

$$V(\varphi) = V_0 \cdot T \cdot \cos\varphi$$

A useful figure of merit called the acceleration gradient is given by

$$E_a = \frac{V_{eff}}{L} = \frac{V_0 T}{L}$$

With units of MV/m

# Example: Pillbox TM010 Mode

- Here the electric field on axis is given by

$$E_z(r=0,z) = E_0\Big|_{-L/2}^{L/2} \quad \text{else} \quad E_z(0,z)=0$$

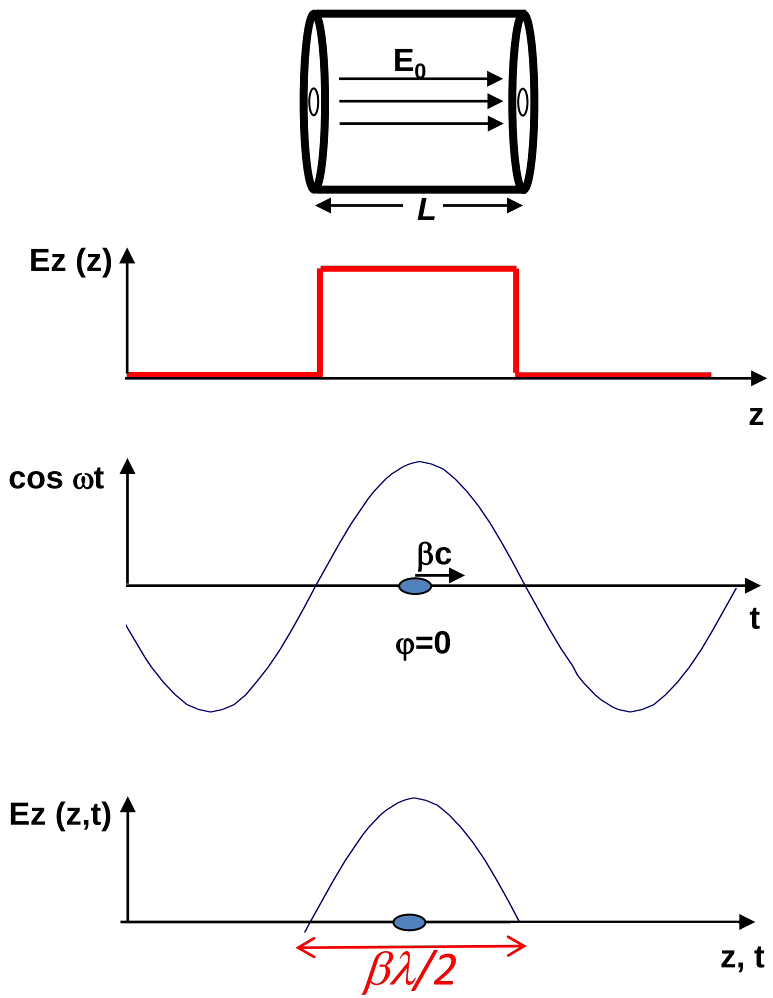
Therefore $\qquad V_0 = E_0 \cdot L$

$$V_{eff} = \int_{-L/2}^{L/2} E_0 \cos\left(\frac{2\pi z}{\beta\lambda}\right) dz = E_0 \frac{\beta\lambda}{\pi} \sin\left(\frac{\pi L}{\beta\lambda}\right)$$

This can be rewritten

$$T = \frac{V_{eff}}{V_0} = \frac{\beta\lambda}{\pi L} \sin\left(\frac{\pi L}{\beta\lambda}\right)$$

Example: Pillbox TM010 Mode



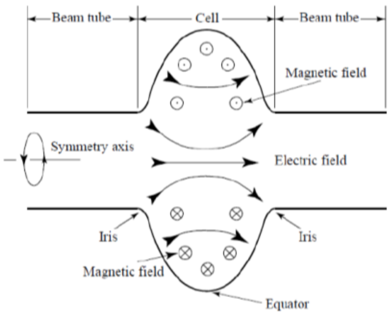

- If we choose $L = \beta\lambda/2$ then

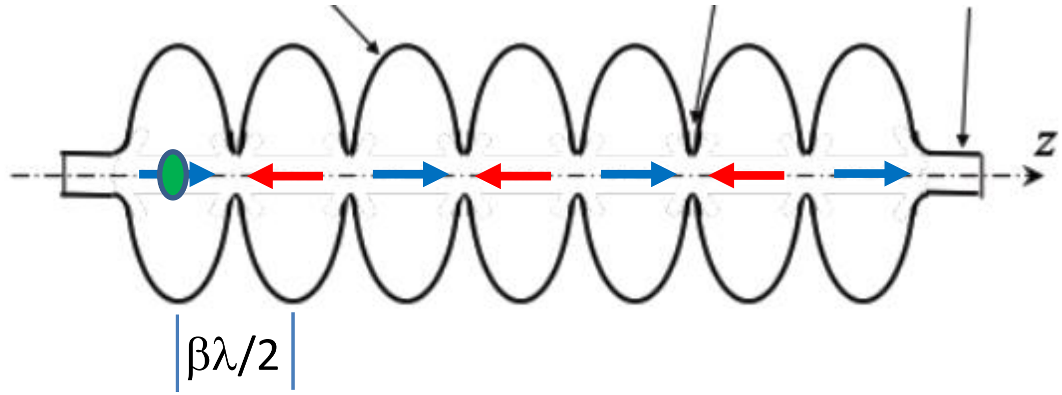
$$V_{eff} = \frac{2}{\pi} E_0 L \quad \text{and} \quad T = \frac{2}{\pi} = 0.64$$

$$\text{and} \quad E_a = \frac{V_{eff}}{L} = \frac{2}{\pi} E_0$$

# Elliptical cavities

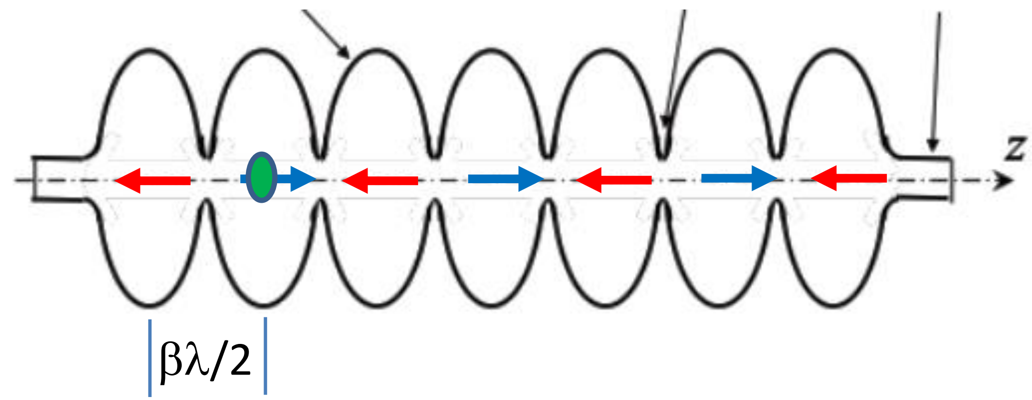
- Recall: popular cavity style for electron acceleration is the elliptical cavity that uses the TM010 mode and is formed into multiple cells



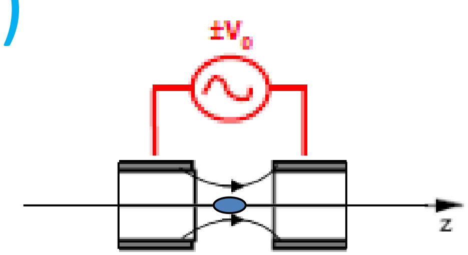




- The cavity typically operates in `pi' mode (180 degrees from cell to cell and each cell center separated by $\beta\lambda/2$
- For relativistic electrons $\beta$=1 and all cells are $\lambda/2$ apart
- The effective voltage is given by

$$V_{eff} = E_a L = E_a N\lambda/2$$



# Single Gap Transit time factor (TTF)

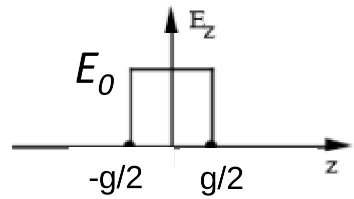


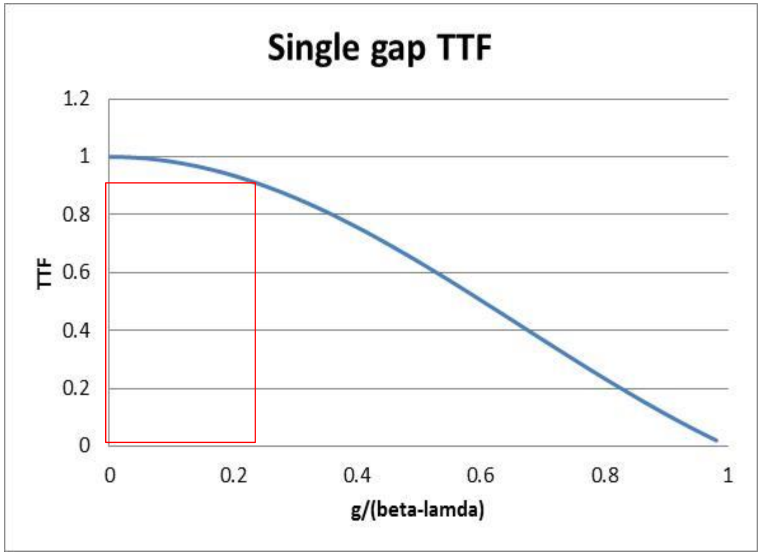

- Assume an accelerating gap with an accelerating field approximated with a square profile

$$E_z(z) = E_0\Big|_{-g/2}^{g/2} \quad \text{else} \quad E_z(z) = 0$$

$$\text{so} \quad V_0 = E_0 \cdot g$$

$$T = \frac{V_{eff}}{V_0} = \frac{\beta\lambda}{\pi g}\sin\left(\frac{\pi g}{\beta\lambda}\right) \quad \text{and} \quad V_{eff} = V_0 T$$




- Here note that as g->0 the TTF -> 1 but small gaps cannot support high fields
- The gap geometry is optimized using a number of considerations
  - typically the gap is ~half a cell where a cell is $\beta\lambda/2$
  - So g=$\beta\lambda/4$
  - and $T = \frac{V_{eff}}{V_0} = \frac{4}{\pi}\sin\left(\frac{\pi}{4}\right) = 0.9$

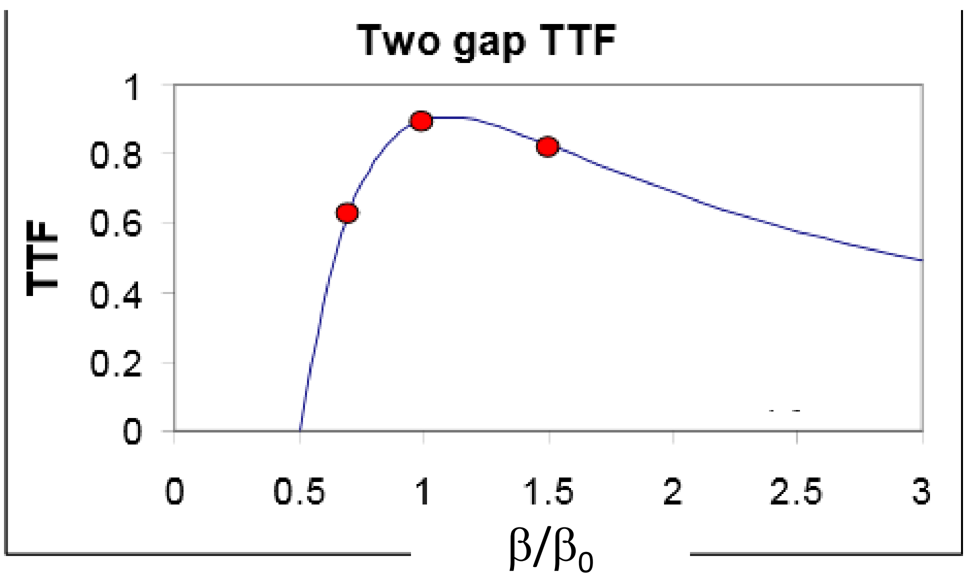
**Energy gain**

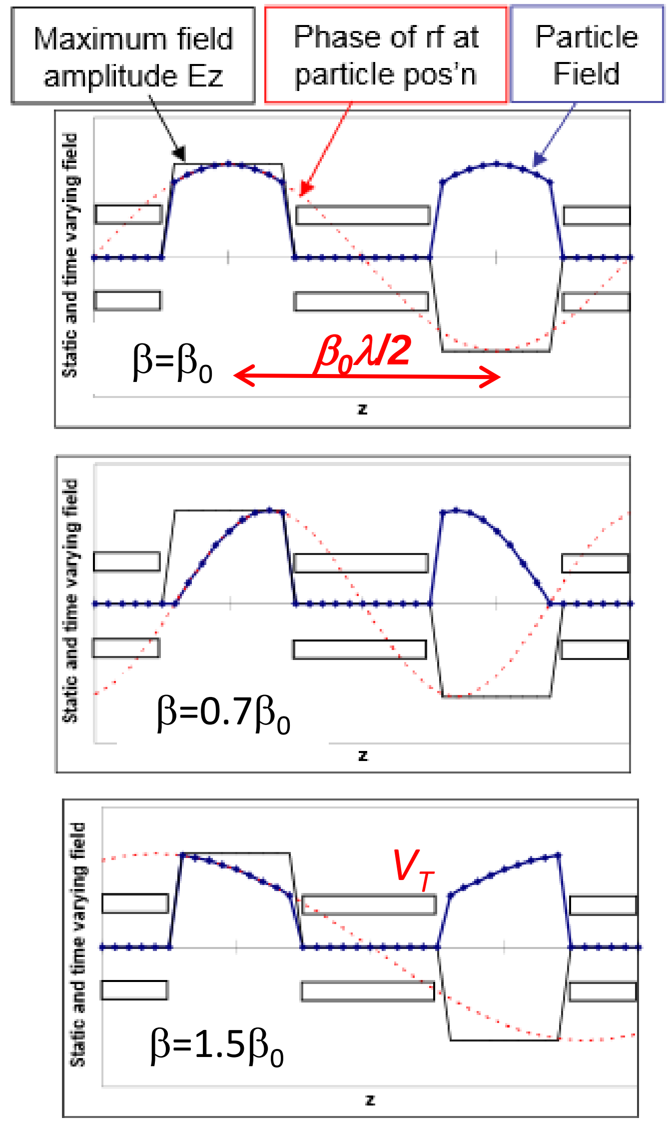
$$\Delta W = qV_{eff} \cdot \cos\varphi$$
$$\Delta W = qV_0 T \cdot \cos\varphi$$

# Two Gap TTF (QWR, HWR, SSR)

- For a two gap structure the optimum acceleration occurs when the rf gains 180 degree ($\pi$) from gap to gap at design velocity, $\beta_0$
- Slower or faster particles will get less kick due to reduced synchronization with the rf phase
- Assuming a square field distribution of field in the gap the combined two-gap transit time factor is given by

$$T_{2-gap}(\beta,g)=\frac{\int_{cav} E(0,z)\sin(2\pi z/\beta\lambda)\,dz}{\int_{cav}\left|E(0,z)\right|dz}=\frac{\sin(\pi g/\beta\lambda)}{\pi g/\beta\lambda}\sin\frac{\pi\beta_0}{2\beta}$$




$V_T$ = inner conductor tube voltage

# Energy Gain in a Two-gap structure

For $\beta = \beta_0$ ion is synchronized with the rf

- Maximum energy gain in a first gap

  $\Delta W_1 = qE_0 g\, T \cos\varphi = qV_T\, T \cos\varphi$

- Maximum energy gain in a second gap

  $\Delta W_2 = qE_0 g\, T \cos\varphi = qV_T\, T \cos\varphi$

Total gain $\Delta W = \Delta W_1 + \Delta W_2 = 2\, qV_T\, T \cos\varphi = qV_{eff} \cos\varphi$

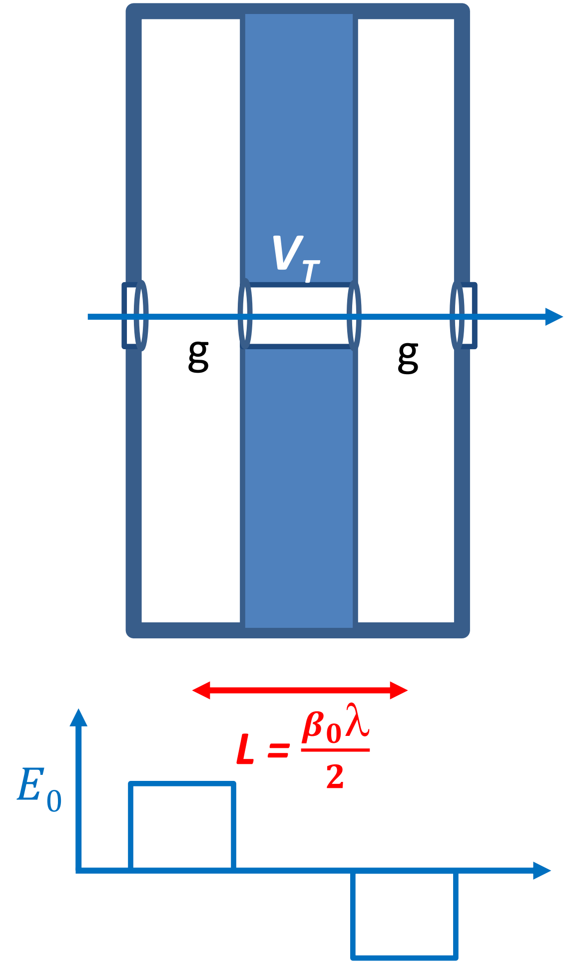
where T is the single gap TTF, $T(\beta_0) = \frac{\beta_0 \lambda}{\pi g} \sin\left(\frac{\pi g}{\beta_0 \lambda}\right)$

For other ion velocities, $\beta$, the efficiency is reduced

- Total gain $\Delta W = qV_{eff} \frac{T(\beta)}{T(\beta_0)} \cos\varphi$

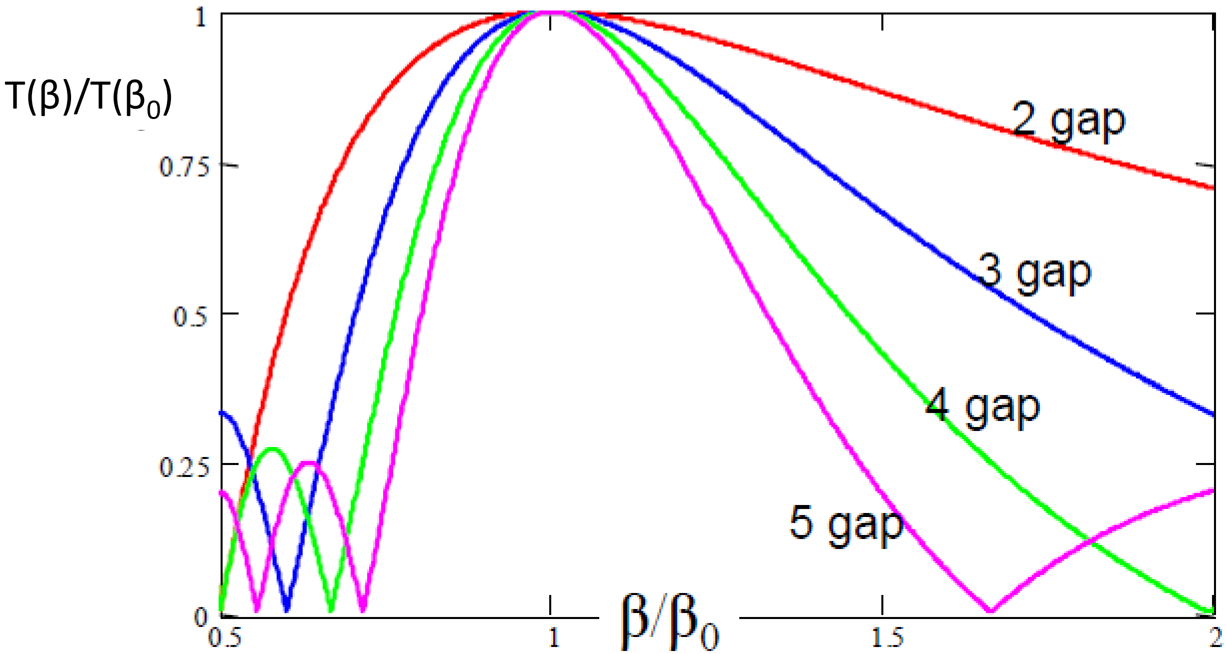
where $T(\beta) = \frac{sin\left(\frac{\pi g}{\beta\lambda}\right)}{\left(\frac{\pi g}{\beta\lambda}\right)} sin\left(\frac{\pi \beta_0}{2\beta}\right)$ and $V_{eff} = 2\, V_T\, T\,(\beta_0)$

The effective voltage is $V_{eff} = V_0 T$ where $V_0$ is the sum of the voltages that could be gained in each gap assuming no TTF and $T$ is the single gap transit time factor




**$V_T$** = the voltage on the drift tube

# Multiple gaps (Normalized Transit time)




*Normalized transit time factor curves vs. normalized velocity, for cavities with different number of gap*

$$T_{2-gap}(\beta) = \frac{\sin\left(\frac{\pi g}{\beta\lambda}\right)}{\frac{\pi g}{\beta\lambda}} \sin\frac{\pi\beta_0}{2\beta}$$

$$T\Big|_{3-gap}(\beta) = \frac{\beta\lambda}{\pi g} \sin\frac{\pi g}{\beta\lambda}\left[\sin^2\frac{\pi}{2}\frac{\beta_0}{\beta}\right]$$

$$\Delta W = qV_0 T\cos\varphi$$

$$V_{eff} = V_0 T(\beta_0)$$

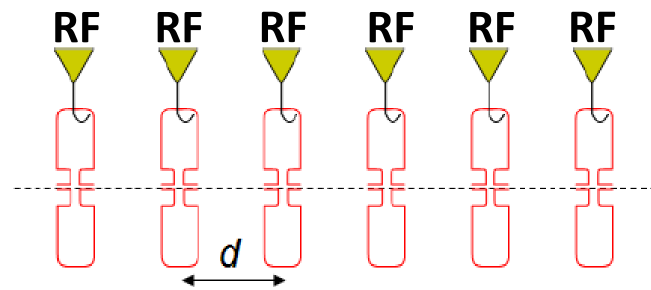
$$\Delta W = qV_{eff}\frac{T(\beta)}{T(\beta_0)}\cos\varphi$$

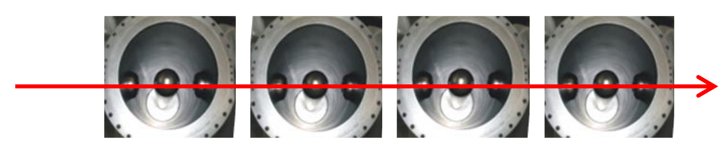
- $V_0 = \sum_n V_n$ where $V_n$ is the maximum voltage a synchronized particle can achieve independent of transit time factor
- Multiple gaps (n) will increase the total voltage gain since $V_{eff}=E_a*L$ and $L=n*\beta\lambda/2$
- But the velocity acceptance of the transit time factor is reduced as n increases

# Hadron linacs – multiple short cavities

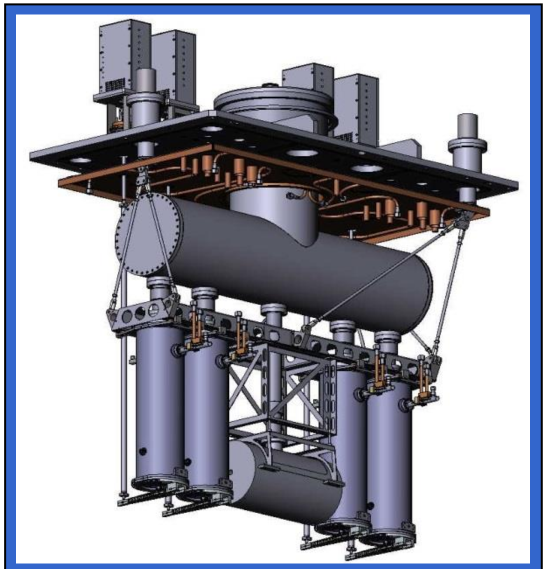
Short (few gap) independently driven cavities can also be used with broad velocity acceptance

- Very flexible – each cavity has a unique rf system with adjustable phase and voltage
- Allows variable velocity profile – acceleration can be optimized for each ion (ie each A/Q)
- Lighter ions can be accelerated to higher velocities than heavier ions
- High number of rf systems - increases costs
- Favours superconducting linacs where cavity rf losses are very small (ie ISAC-II heavy ion linac)

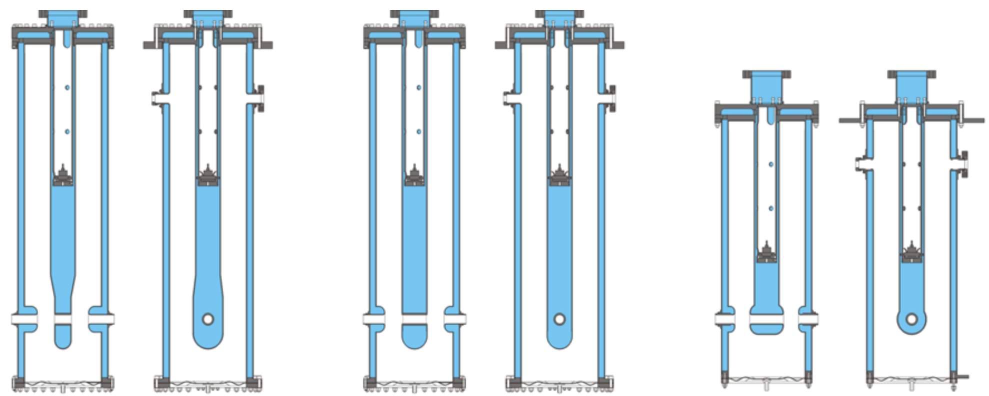


# Example ISAC-II (TRIUMF)



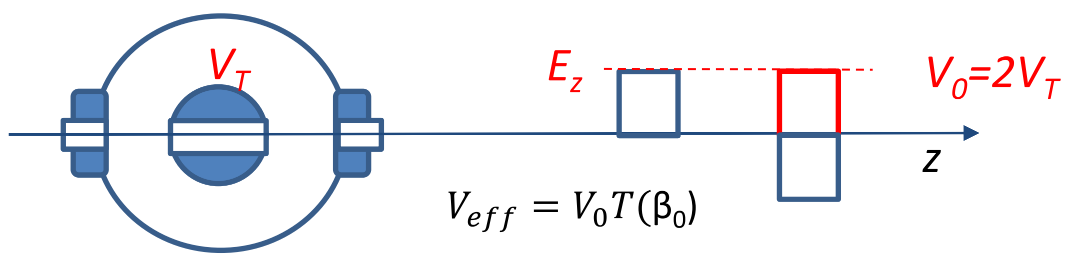
- Consists of 40 QWRs with three different cavity types of $\beta_0$=5.7%, 7.1% and 11% with N= 8, 12 and 20
- All cavities have same outer and inner conductor diameter to reduce fabrication cost



106.1 MHz
$\beta_0$=5.7%

106.1 MHz
$\beta_0$ =7.1%

141.4 MHz
$\beta_0$ =11%



# Example – ISAC-II (TRIUMF)

- Cavities take time and $$ to engineer – a project will choose only a few variants to cover the full velocity range required – two gap cavities give a broad velocity acceptance that can produce a reasonable efficiency over different ions

- The energy gain from one cavity is

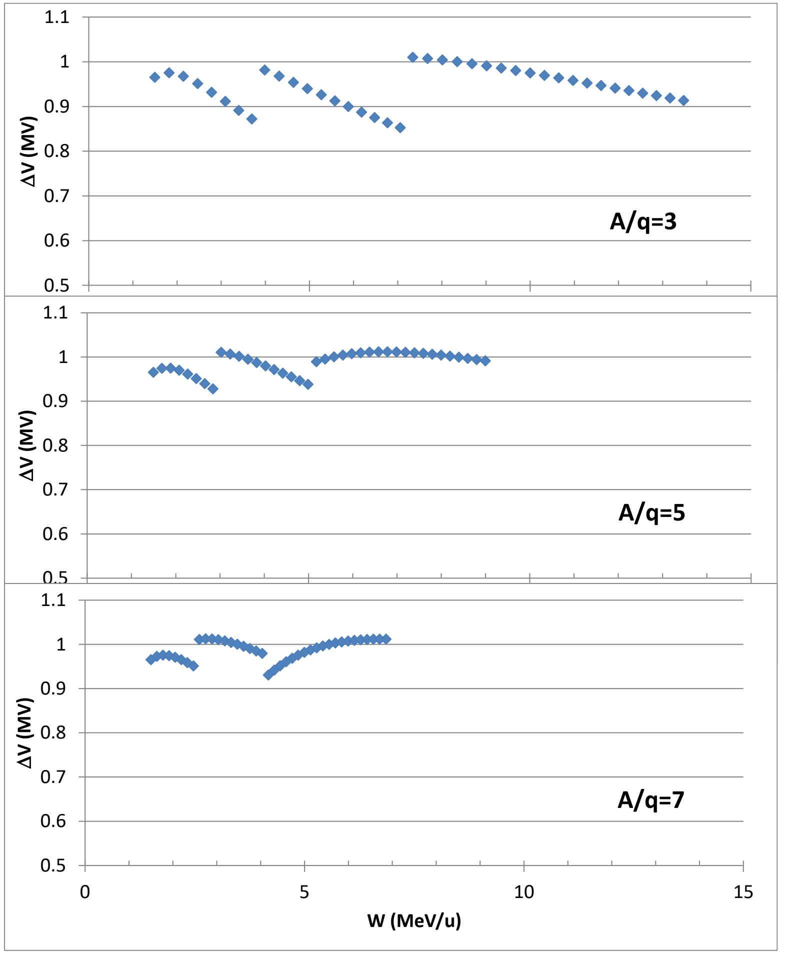
$$\Delta W_n(\beta)/A = Q/A \cdot V_{eff}\Big|_n \cdot \frac{T(\beta)}{T_0(\beta_0)} \cdot \cos\phi_n \qquad V_{eff} = V_0 T(\beta_0)$$

where for two gap TTF

$$\frac{T(\beta)}{T(\beta_0)} = \frac{\beta}{\beta_0}\frac{\sin(\pi g/\beta\lambda)}{\sin(\pi g/\beta_0\lambda)}\sin\frac{\pi\beta_0}{2\beta}$$

- The final energy is given by

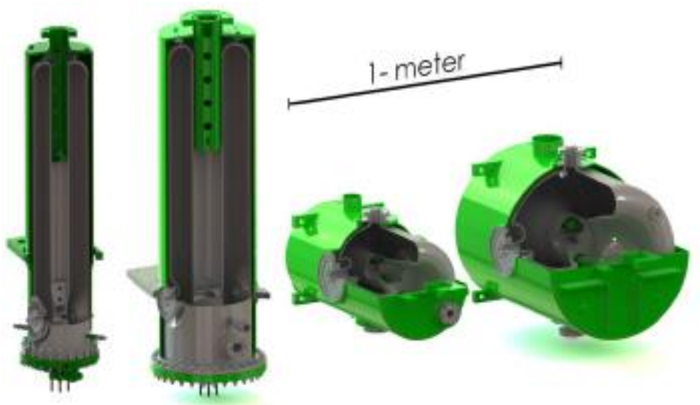
$$W/A\Big|_{final} = W/A\Big|_{initial} + \sum_n \Delta W_n(\beta)/A$$

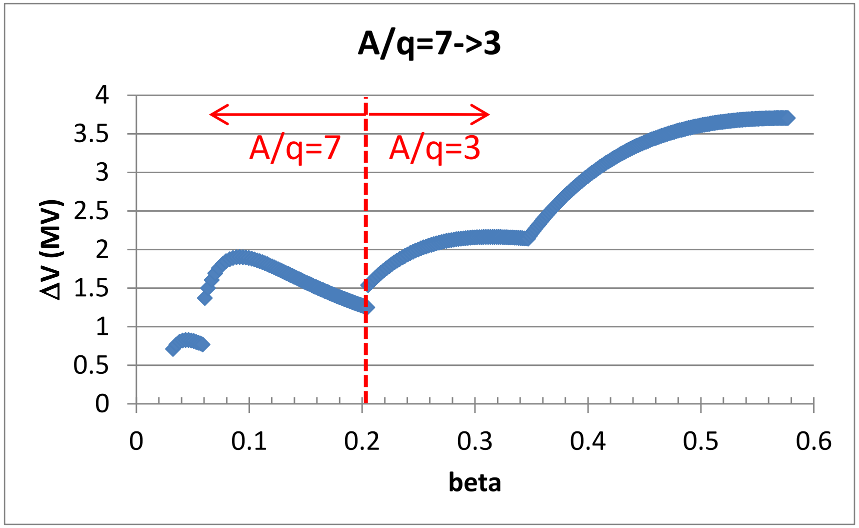


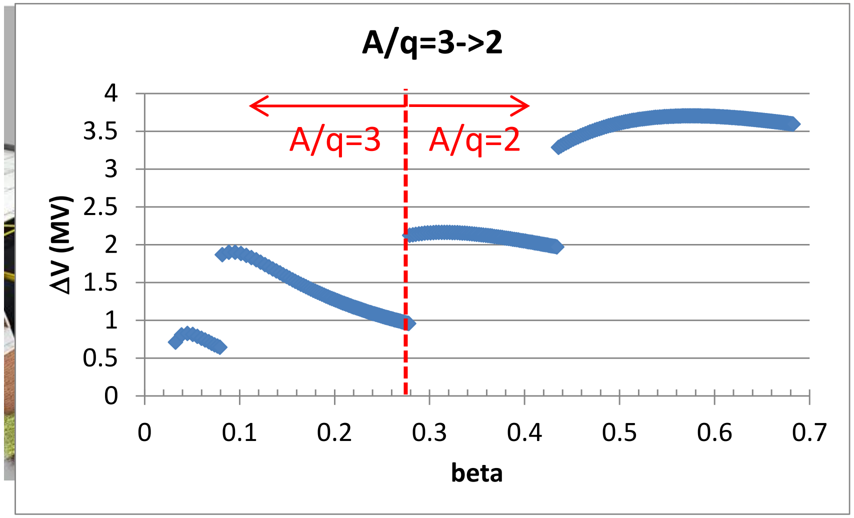

ISAC-II – three cavity types with $\beta_0$=0.057, 0.071 and 0.11 of n = 8, 12 and 20 respectively

# FRIB – MSU (Lansing Michigan)

| Resonator | QWR1 | QWR2 | HWR1 | HWR2 |
|---|---|---|---|---|
| $\beta_0$ | 0.041 | 0.085 | 0.29 | 0.53 |
| $f$ (MHz) | 80.5 | 80.5 | 322 | 322 |
| $V_a$ (MV) | 0.81 | 1.8 | 2.1 | 3.7 |
| $E_p$ (MV/m) | 31 | 33 | 33 | 26 |
| $B_p$ (mT) | 55 | 70 | 60 | 63 |
| $Q_0$ ($10^9$) | 1.2 | 1.8 | 5.5 | 7.6 |
| R/Q (Ω) | 402 | 452 | 224 | 230 |
| G (Ω) | 15 | 22 | 78 | 107 |
| Aperture (mm) | 34 | 34 | 40 | 40 |
| $L_{eff} \equiv \beta\lambda$ (mm) | 160 | 320 | 270 | 503 |
| Number of cavities | 12 | 94 | 76 | 148 |



# Normal vs Superconducting?

✓

- An example below for an ISAC-II quarter wave cavity and ARIEL nine-cell 1.3GHz cavity comparing rf power required assuming superconducting niobium or room temperature copper

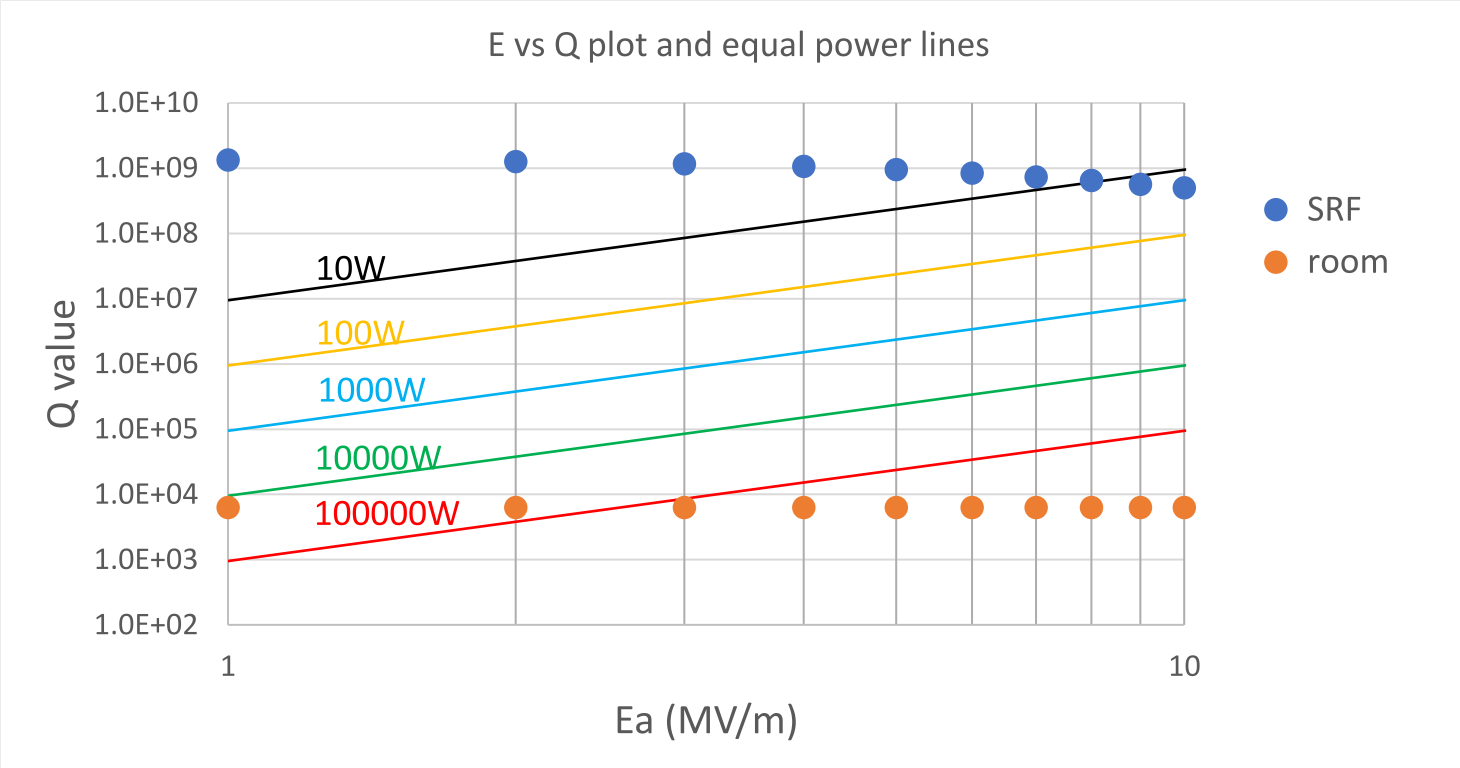
$$Q_0 = \frac{G}{R_s}$$

$$P_{cav} = \frac{V_{eff}^{\ 2}}{\frac{R_a}{Q_0} \cdot Q_0}$$

| Parameter | Nb@4K | Cu@300K | Nb@2K | Cu@300K |
|---|---|---|---|---|
| Frequency (MHz) | 106 | 106 | 1300 | 1300 |
| G (Ohms) | 19 | 19 | 280 | 280 |
| $R_{sh}/Q$ (Ohms) | 540 | 540 | 1000 | 1000 |
| $V_a$ (MV) | 1.1 | 1.1 | 10 | 10 |
| $R_s$ (Ohm) | $20\times10^{-9}$ | $3\times10^{-3}$ | $20\times10^{-9}$ | $10\times10^{-3}$ |
| $Q_o$ | $1\times10^{9}$ | 6600 | $1.4\times10^{10}$ | 28000 |
| $P_{cav}$ (W) | 4 | $3\times10^{5}$ | 10 | $3.5\times10^{6}$ |
| $P_{wall}$ (kW) | 4 | 600 | 30 | 7000 |

- Conclusion: Superconducting cavities are ~100 times more efficient in AC wall power for non-beam-loaded regime

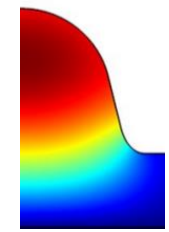
# Room Temperature vs SRF



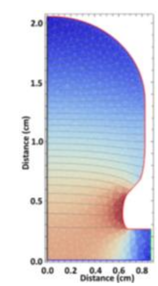

Operating room temperature rf resonators at high gradient would require adopting pulsed operation. In the plot above for 3MV/m and 1% duty factor would require an average power of 1kW instead of 100kW.

# NC vs SC

- Superconducting RF
  - a more complex technology requiring cryogenic and clean room infrastructure - requires an investment in know how and process
  - more efficient electrically especially for modest beam loading and high duty factor applications – reduced rf cost
  - SRF allows larger apertures and lower frequencies therefore higher acceptance
  - SRF allows short two gap structures for flexible hadron acceleration



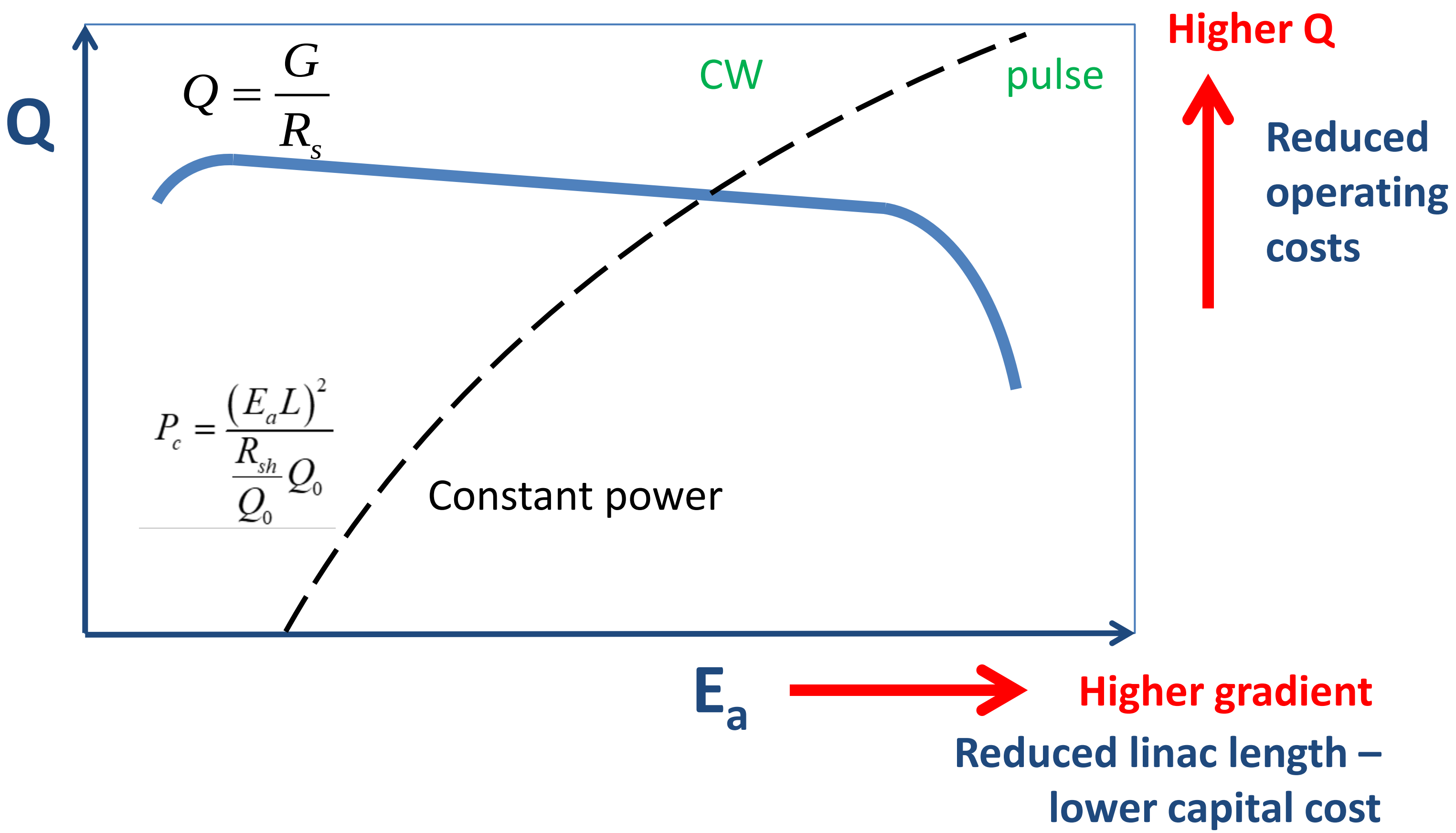
- Normal conducting
  - less technical demanding
  - Requires rf cavities with high rf efficiency – small apertures – long multi-gap structures – higher frequencies and smaller acceptances
  - Consider for short linacs with high beam power and low duty factor where rf average power is reduced



# Optimizing performance

# Performance Optimization

Global SRF studies concentrate on developing customized processes to increase both quality factor and maximum gradient to limit capital and operating costs.

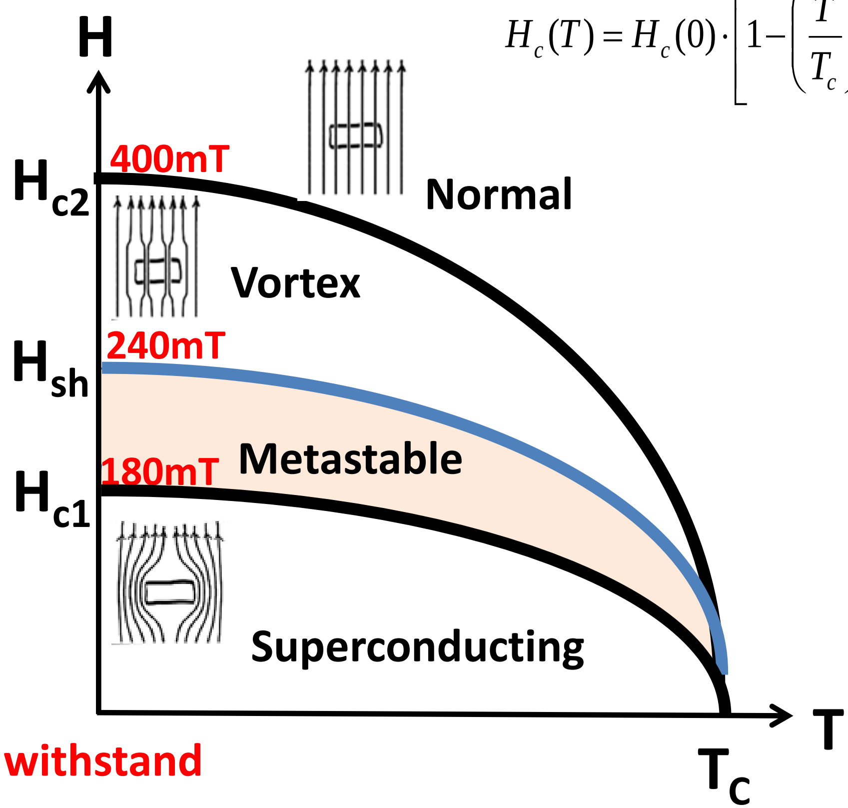


# Superconducting (H,T) Space for Niobium

**Niobium is a Type II superconductor**

- SC state: 0 → $H_{c1}$
- Vortex state: $H_{c1}$ → $H_{c2}$
- Meta-stable state: $H_{c1}$ → $H_{SH}$
  - surface energy barrier can inhibit vortex nucleation
- Flux vortices cause rf heating

$$H_c(T) = H_c(0) \cdot \left[1 - \left(\frac{T}{T_c}\right)^2\right]$$




**For high gradient we need a material that can withstand vortex penetration up to a high magnetic field.**

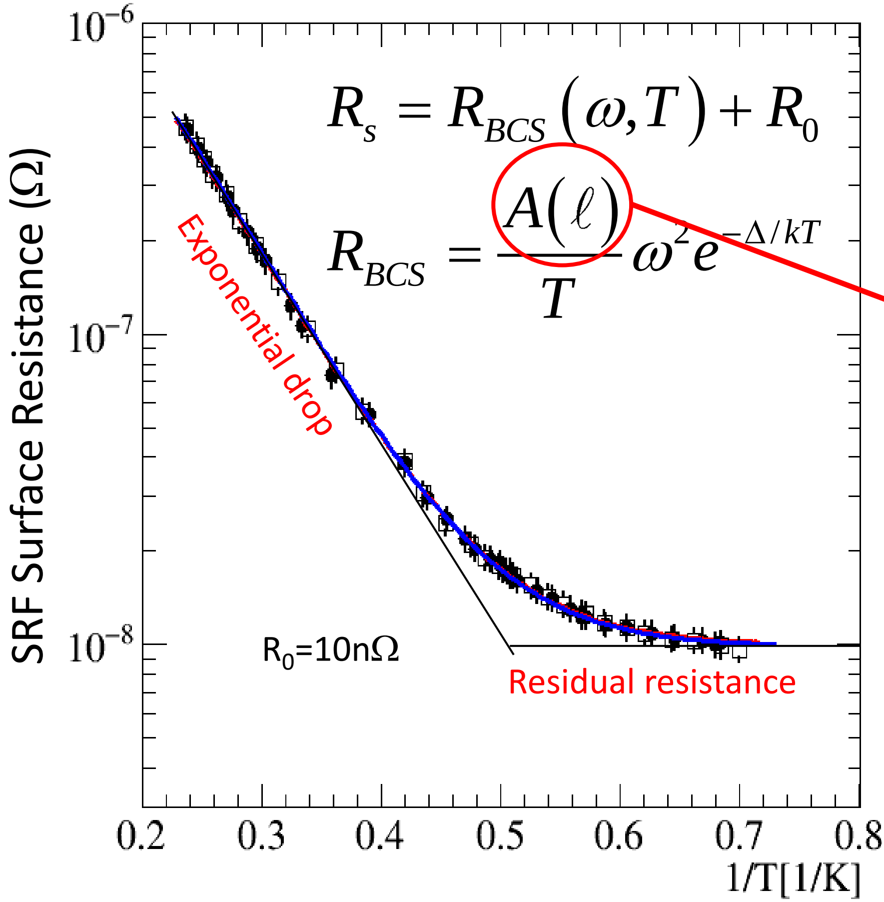
# Cavity performance

- Recall $Q_0 = G/R_s$ and $R_s = R_{BCS} + R_0$
- Intrinsic losses
  - $R_{BCS}$ can be modified by manipulation of the surface mean free path and the choice of operating temperature and rf frequency
  - Smearing of density of states (see Tobi lecture #2) – adds to Ro
- Extrinsic losses
  - The residual resistance $R_0$ is impacted by cavity surface preparation and environmental effects
  - Possible degradation from Insufficient cleaning – chemical residues – bad welds – inclusions – trapped flux – Q-disease
  - Rf performance can also be degraded by field emission and multipacting

# Intrinsic SRF surface resistance

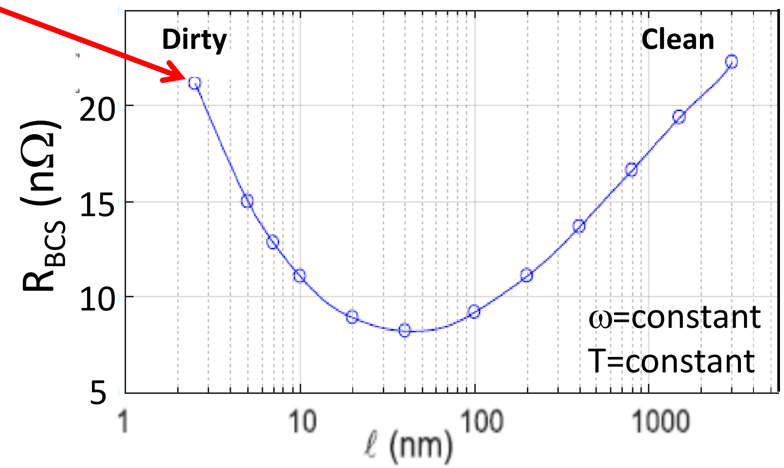
$$R_s = R_{BCS}(\omega, T) + R_0$$

$$R_{BCS} = \frac{A(\ell)}{T}\omega^2 e^{-\Delta/kT}$$




$$Q = \frac{G}{R_s}$$

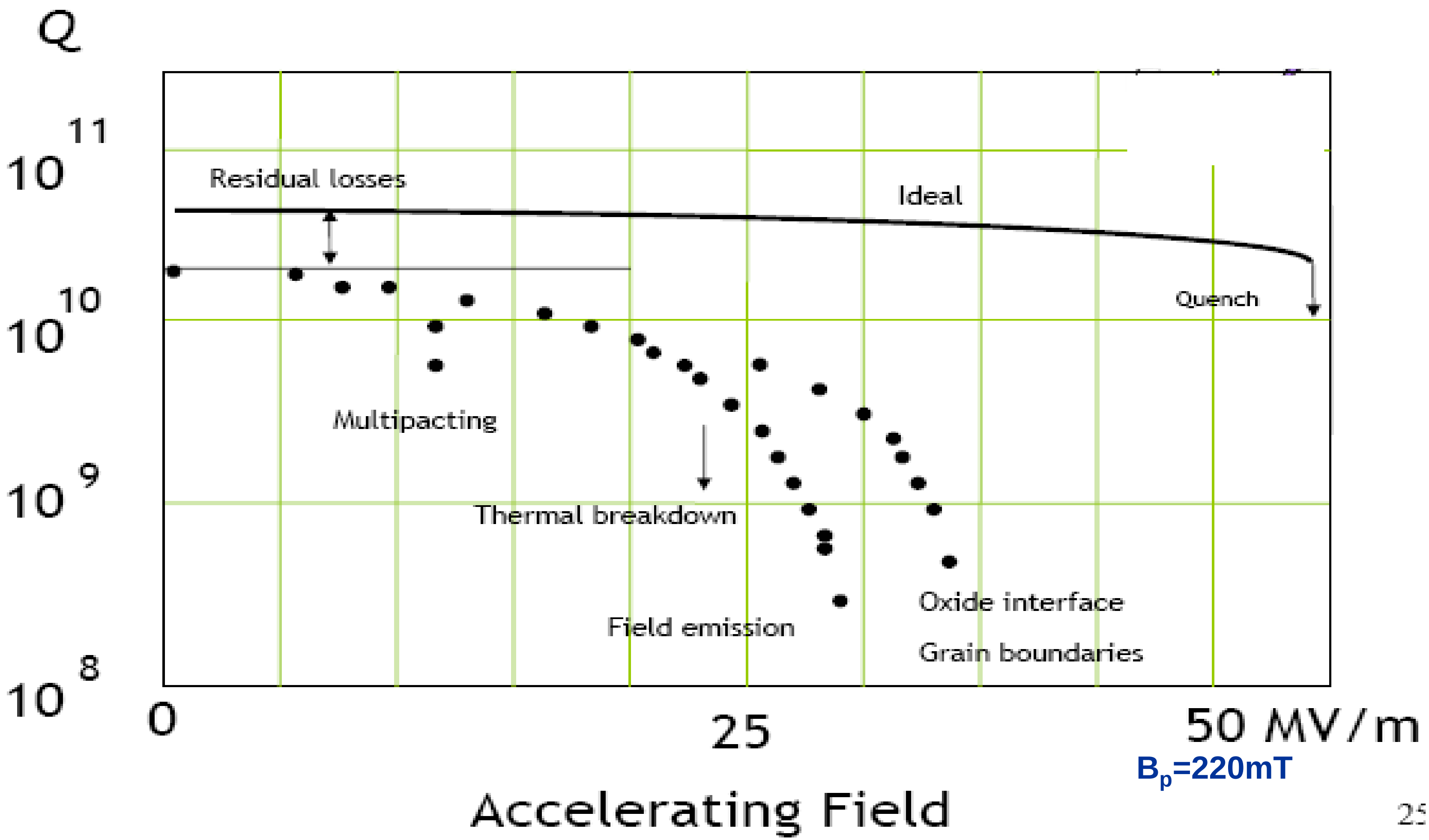
constant




RBCS is dependent on $\ell$, the electron mean free path

# Reality – Extrinsic losses

- The superconducting resistance is so low that it is very easy to make it worse
- In fact it needs great care to make SRF perform well



# A Standard Recipe

## Processing/Testing steps (ANL, FNAL)

| | |
|---|---|
| 1 | Bare Cavity Inspection – Visual, Dimensional, Vacuum, RF |
| 2 | US cleaning and rinse |
| 3 | BCP 120-150 µm (flip half-way) |
| 4 | High-Pressure Rinse |
| 5 | Hydrogen Degassing 600 °C, 10 h |
| 6 | RF Tuning |
| 7 | BCP 20-30 µm |
| 8 | HPR (horiz + vert) |
| 9 | Clean Room Assembly |
| 10 | Low Tem Bake 120 °C, 48 h |
| 11 | Vertical Test @ 2K |
| 12 | Helium Vessel Welding |
| 13 | US cleaning |
| 14 | BCP 20-30 µm |
| 15 | HPR |
| 16 | Clean Room Assembly |
| 17 | Low Temp Bake 120 °C, 48 h |
| 18 | Horizontal Test @ 2K |
| 19 | Ready for String Assembly |







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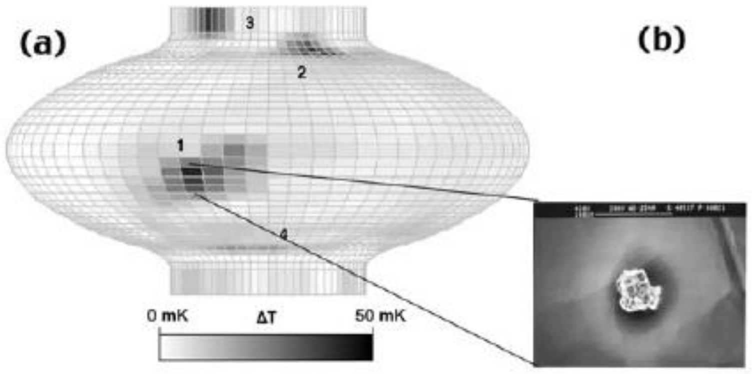
# Thermal Breakdown

- A normal conducting defect (ie Cu flake) embedded in the niobium can heat up in the magnetic field through resistive heating and drive the local niobium above Tc
- This precipitates a large change in the surface resistance and the absorption of the cavity stored energy (a few Joules) and a quench results noted as a collapse of the cavity voltage
- High RRR material is chosen to improve the thermal conductivity of the Nb – in some projects people use a Nb rf layer on copper underlayer to improve thermal conductivity



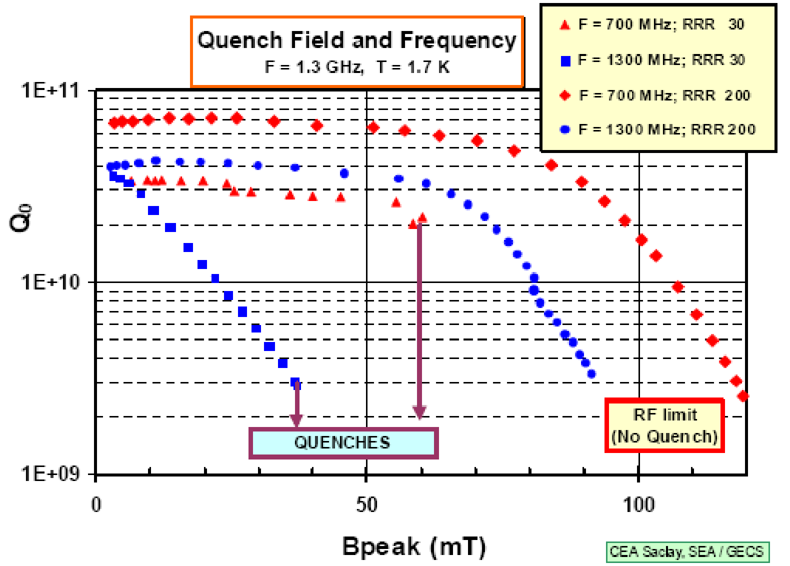



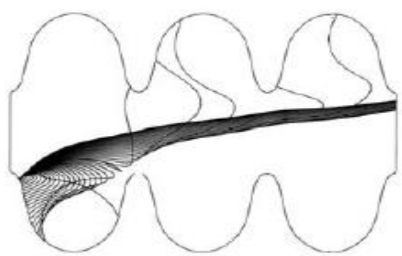

Fig. 6 The quench limit strongly depend on the niobium RRR value.

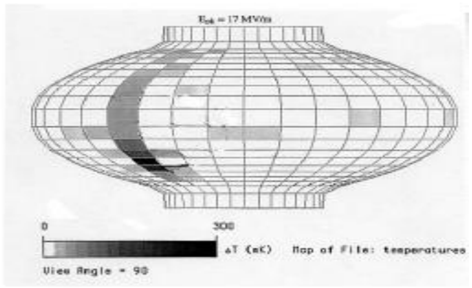
# Surface purity and finish

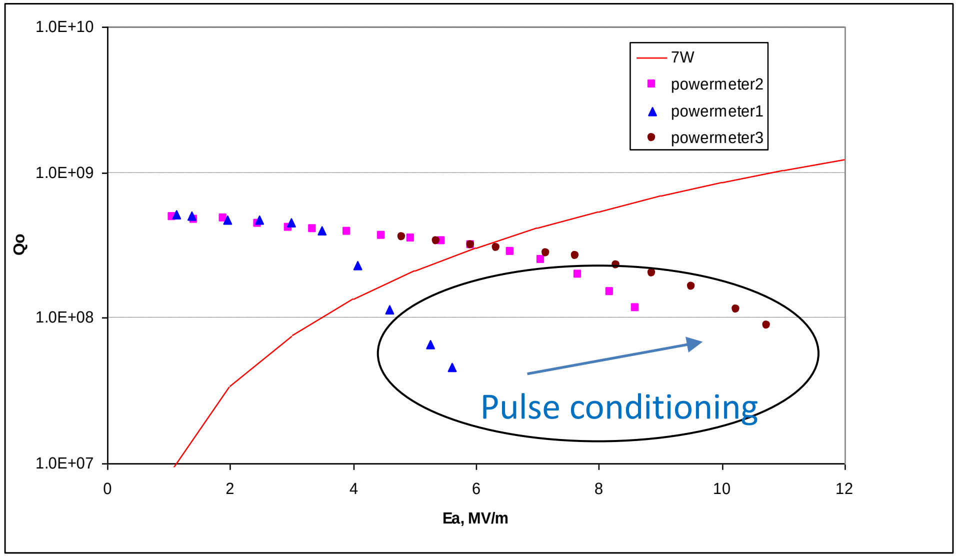
- Chemical treatments are used to remove the damaged layer after fabrication (150 microns) or to remove surface contaminants after heat treatments (5-10microns) - supercleaning
- Two common finishing techniques
  - Buffered chemical polish with 1:1:2 (HF(48%), $HNO_3$(65%), $H_3PO_4$(85%)) acid mixture
    - Cavity filled during polish and acid recirculated to maintain the temperature
    - Most TEM mode cavities use this due to complicated internal geometry
    - Satisfactory for medium field regime
  - Electropolishing with 85:10 $H_2SO_4$ and HF(40%)
    - More complicated than BCP but smoother finish
    - Cavity half-filled and rotated horizontally during polish
    - Typical for elliptical cavities
    - More labs are starting to develop this for TEM mode cavities (ANL, FRIB, TRIUMF, …)

# Field Emission

- Field Emission occurs when surface electrons are released and accelerated due to a high local electric field
- At the on-set of field emission the $Q_0$ of a cavity begins to drop as more power goes into the emitted electrons
- Accompanied by bremstrahlung x-ray radiation from the accelerated electrons
- Particulate on the cavity surface amplifies the local field
- Rf pulsed conditioning can be used to condition the emitters and help push the field to higher levels

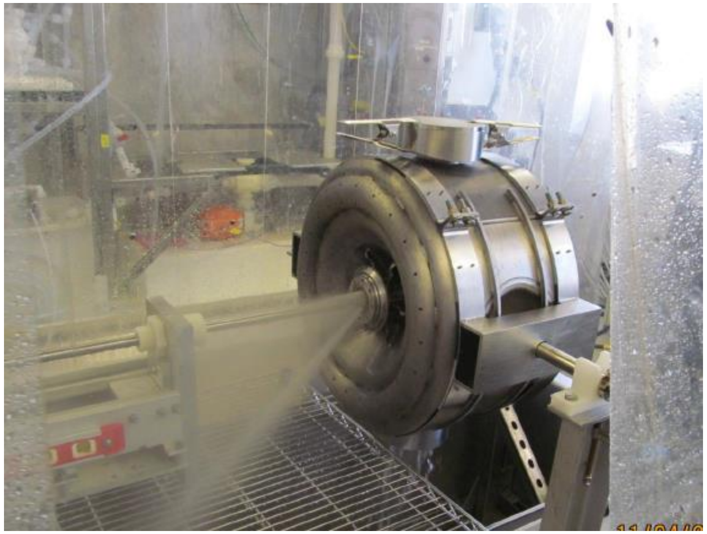


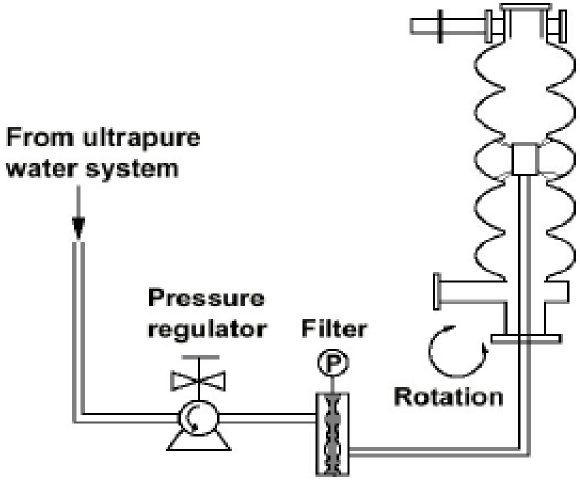




# High Pressure Water Rinse and clean assembly ✓

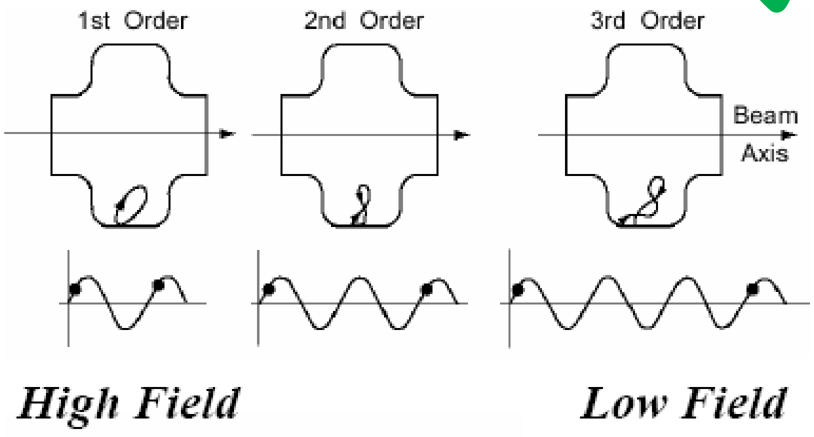
- Controlling field emission is fundamental to good SRF performance – HPWR and clean room assembly is a  key to success
- Elliptical cavities are rinsed vertically
- In low beta cavities the geometry can be more complicated than the elliptical cavities
- Need to plan during the design stage – require sufficient ports at the right position to guarantee full coverage – also the nozzle design is important

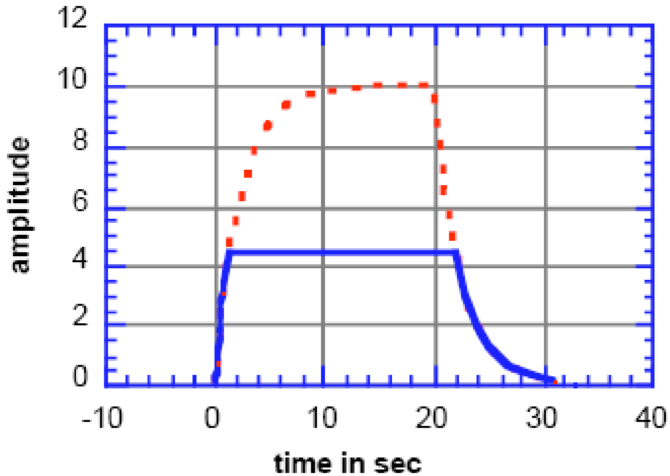




# Multipacting

- Multipacting is due to an exponential increase in secondary emission electrons due to resonance conditions with the rf field
- The order of the multipactor is defined as the number of rf periods taken for the electron to transit from its creation to its impact point – in the case of two-point multipacting the electron takes 2n-1 half periods to reach the other wall where n is the order
- Impacted by the geometry of the cavity and the secondary electron yield (SEY) of the cavity surface



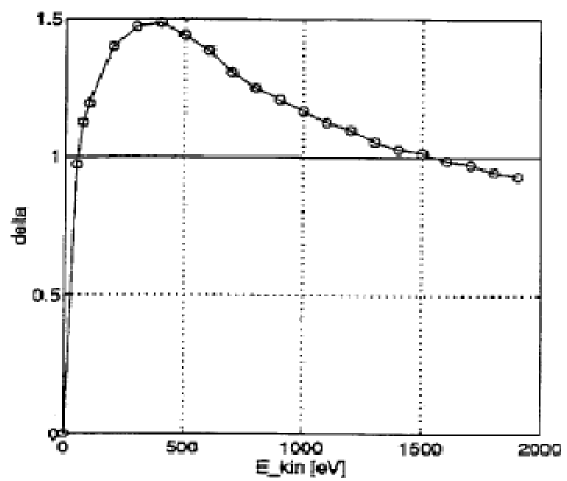
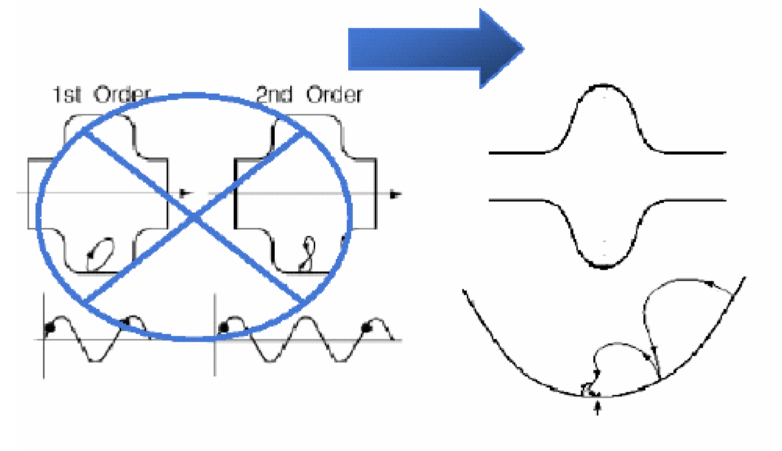
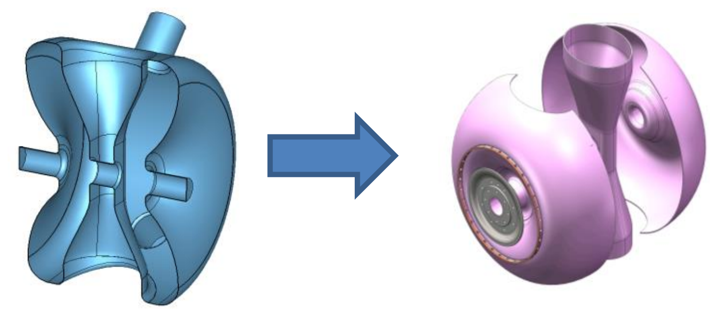



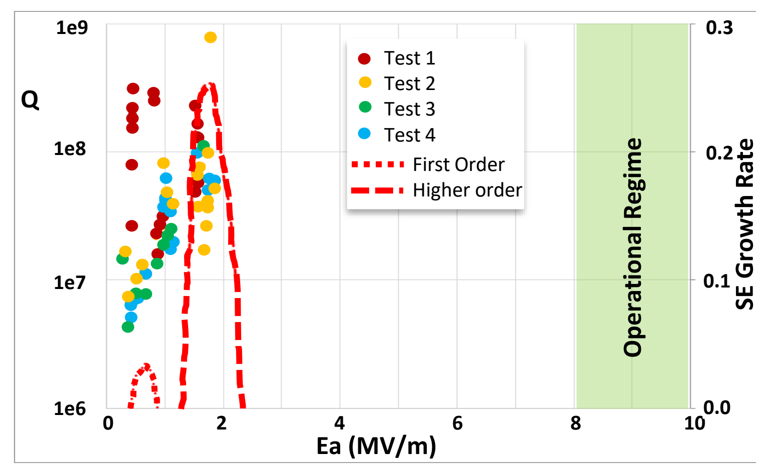

Fig. 10 Production rate (delta) of secondary electrons after impacting a metal surface by one primary electron (= secondary yield) as function of the impact energy

# Multipacting Mitigation

- Care in cavity design
  - Simulation tools are available
  - Solved in TM cavities by changing the cavity shape to elliptical surfaces to remove constant B and high $E_{surface}$ conditions - electrons drift toward equator and stop due to zero $E_{surface}=0$
  - Similar solution demonstrated at TRIUMF with `balloon' shape SSR
- In situ bake to outgass the cavity – lowers SEY
- Pulsed and modulated rf conditioning – promotes outgassing at the surface to lower SEY





# Flux trapping

- Despite the Meissner effect non-ideal materials can trap residual magnetic flux during cooldown and increase surface resistance

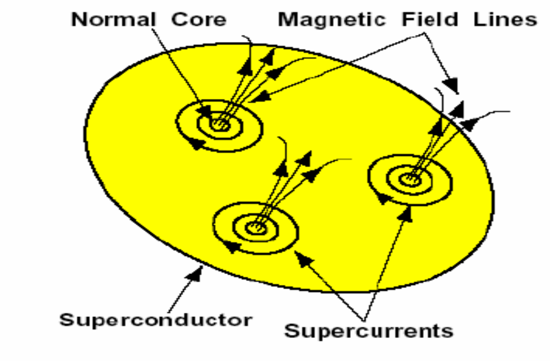
$$R_{mag}(\mathrm{n\Omega}) \approx 0.3 H_{ext}(\mathrm{mOe})\sqrt{\mathrm{f(GHz)}}.$$

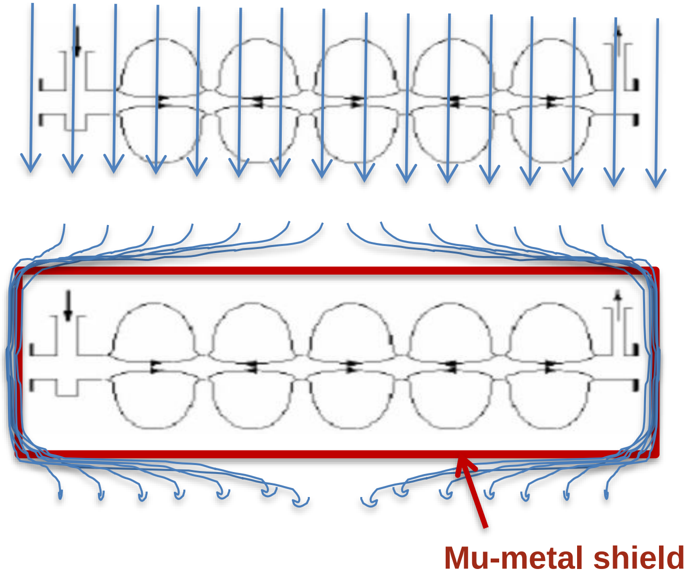
- we can explicitly write the magnetic contribution to the surface resistance as

$$R_s = R_{BCS} + R_{mag} + R_0$$

- The earth's field is ~500mG so we need to add mu-metal around the cavity to suppress the field and reduce $R_{mag}$ to tolerable levels

| Frequency | $R_{BCS}$ (n$\Omega$) | $B_{ext}$ for 5n$\Omega$ | Suppression |
|---|---|---|---|
| 106MHz | 3.5@4.2K | 30mG | ~15 |
| 1.3GHz | 10.9@2K | 10mG | ~50 |





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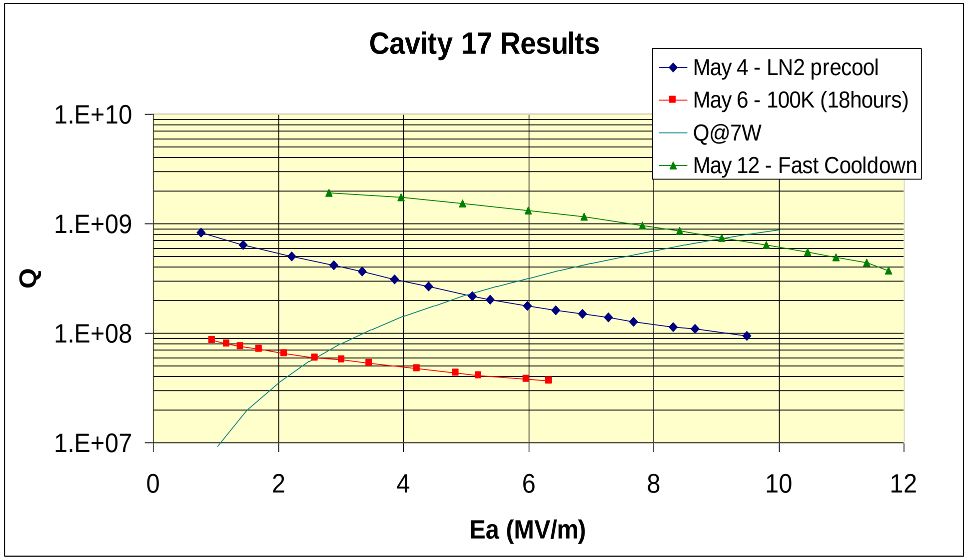
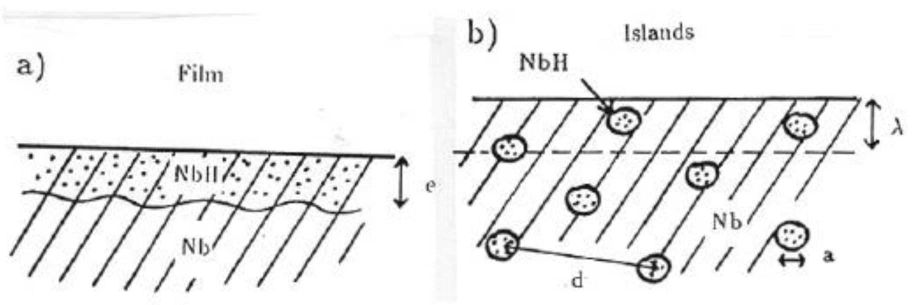
# Q-disease

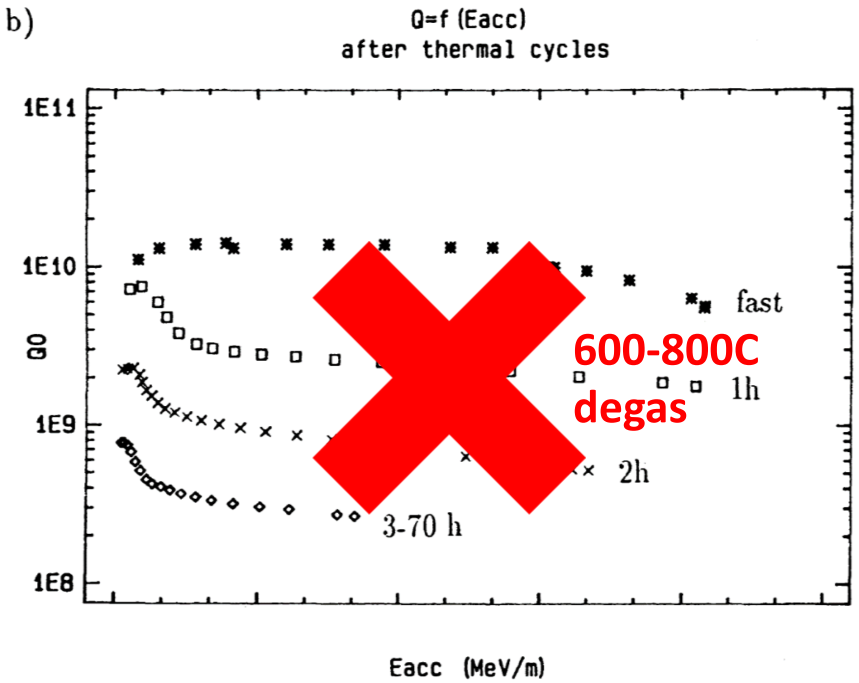
- Hydrogen is absorbed into the bulk niobium during manufacture or chemistry
- At temperatures between 80 and 150K the dissolved hydrogen can diffuse to the surface and precipitates as a hydride at <10ppm
    - hydride has a high rf loss ($T_c$=2.8K and $H_c$=60 Oe)
- Effect can be minimized by fast cooldown or eliminated by furnace degassing to reduce Hydrogen concentration



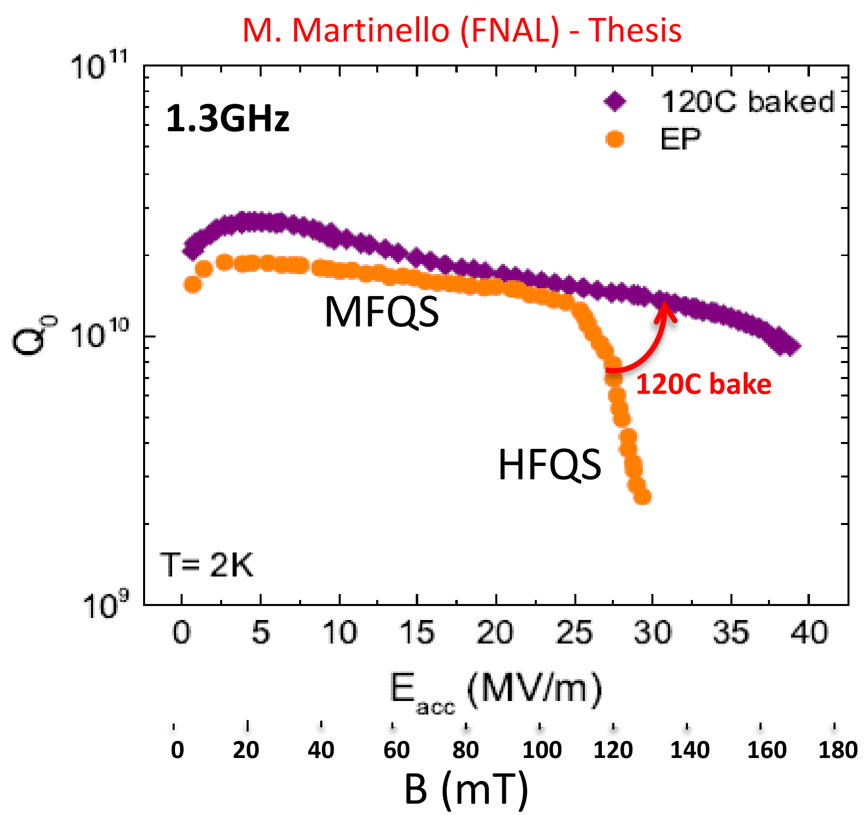
# Mitigating Q-disease - Degassing– 600-800C

- A 600 - 800C degas to reduce hydrogen concentration in Niobium and avoid Q-disease
- all cavity types benefit from this degassing
  - elliptical 800C - 3 hours
  - coaxial cavities 600C - 10 hours



# 120 C Bake

- Bake in vacuum at 120C for 48 hours mitigates high field Q-slope (HFQS) in 1.3GHz cavities
- Bake manipulates the surface oxide layer
    - Reduces the  mean free path (dirtier) in the first 20-50nm to reduce the $R_{BCS}$
    - reduces lossy nano-hydrides
- Any cavity operating with $R_{BCS}>R_0$ can typically benefit from a 120C bake including low frequency cavities operating at 4K



# Where are we?

- XFEL and FRIB are successfully completed - LCLS-II is in commisisoning
  - XFEL with 815 cavities is the largest SRF linac every built – **high gradient frontier**
  - FRIB with 340 TEM mode cavities is the **largest hadron SRF linac** every built
  - LCLS-II is the linac with the highest installed Q of 2.8e10 – **high Q frontier**
- Projects drive SRF development and SRF developments enable projects

| Timeline | Elliptical | Non-elliptical |
|---|---|---|
| Recent past | XFEL | FRIB |
| Present | LCLS-II | ESS, RISP |
| Future | EIC, ILC | PIP-II, ADS |

# Where are we? XFEL

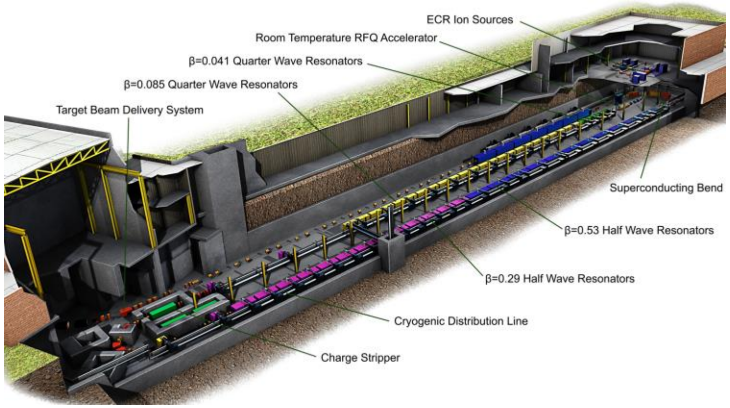
- Remarkable and sustained on-line performance comparable with vertical tests
- XFEL is like a 1/20 prototype for the ILC – 815 cavities vs 16000 for ILC

| | $N_{cavs}$ | Average | RMS |
|---|---|---|---|
| VT | 815 | 28.3 MV/m | 3.5 |
| CM | 815 | 27.5 MV/m | 4.8 |

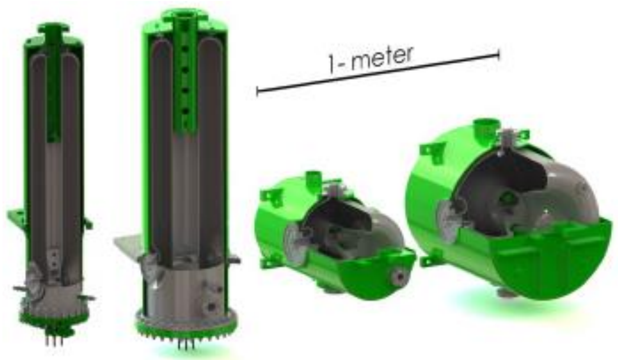
XFEL cavity useful gradient in vertical test and in cryomodule (goal 23.6MV/m)

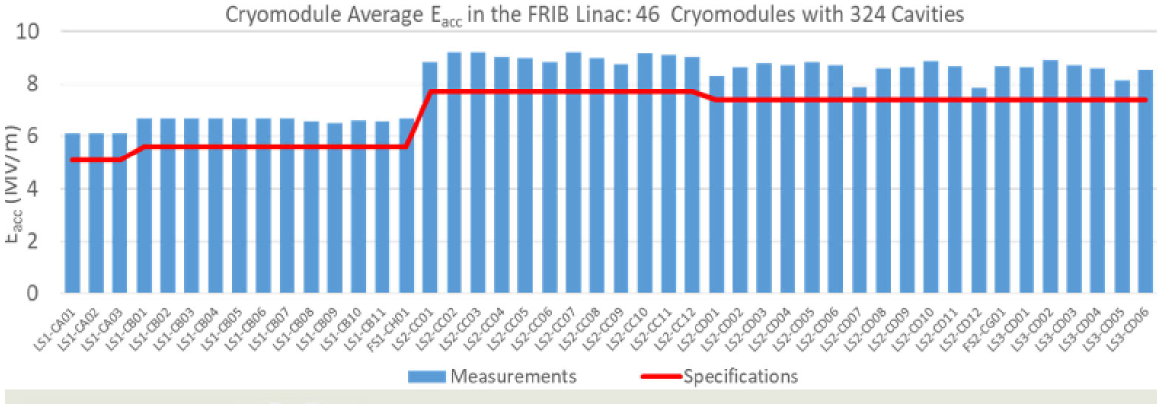
# Where are we? FRIB

- 324 SRF cavities in 46 cryomodules with four cavity types ranging from beta=0.041 to beta=0.53







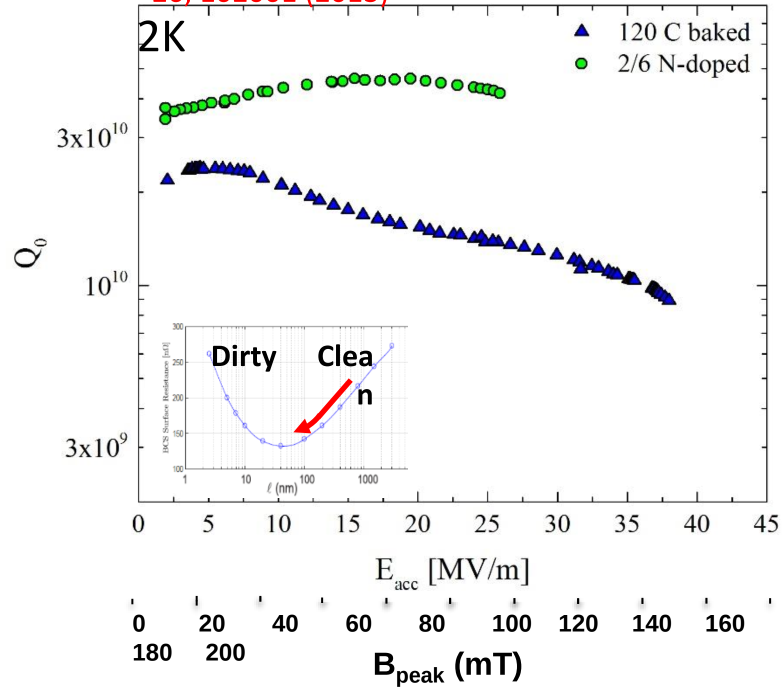



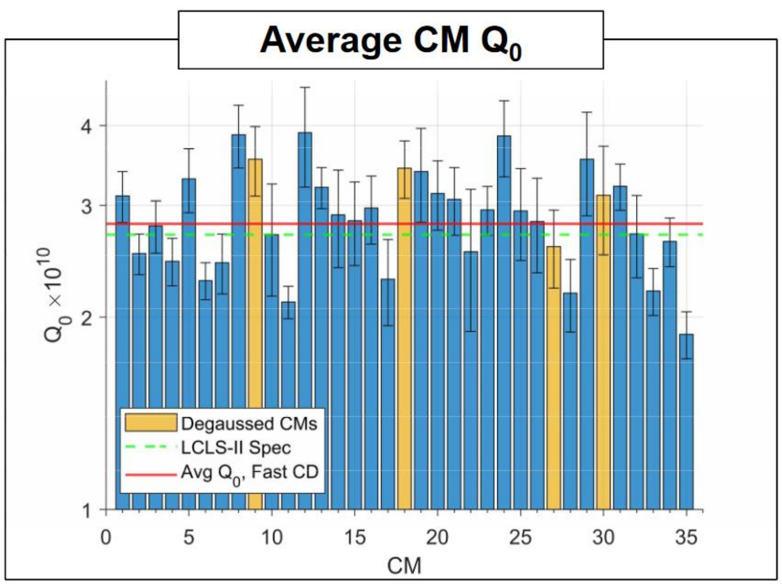
# Nitrogen Doping – LCLS-II (SLAC)

✓

- N2 is introduced at 25 mTorr after 800C degassing for a few minutes
- N2 doping increases Q substantially by reducing electron mean free path, reducing BCS resistance with signature anti-Q-slope – less hydride precipitations
- Requires 5-10 micron EP to clean the surface

A.Grassellino, et al, Supercond. Sci. Technol. 26, 102001 (2013)



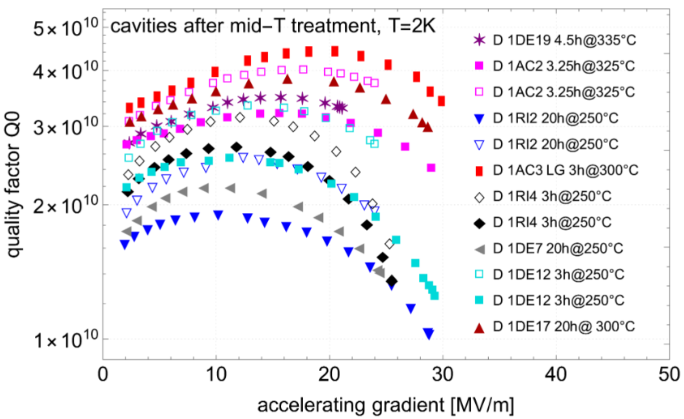




LCLS-II installed performance

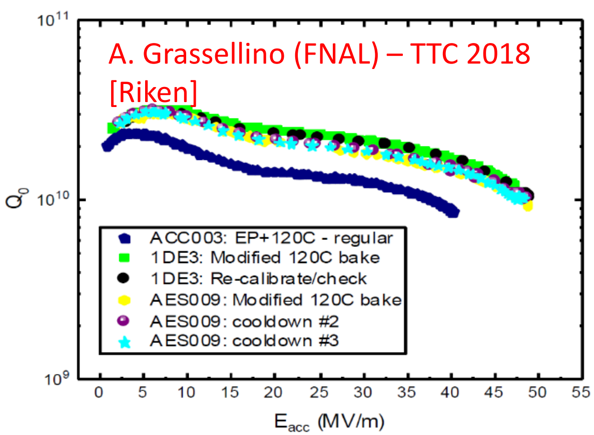
- Installed average Qo=2.8e10
- No measurable change in field emission onsets

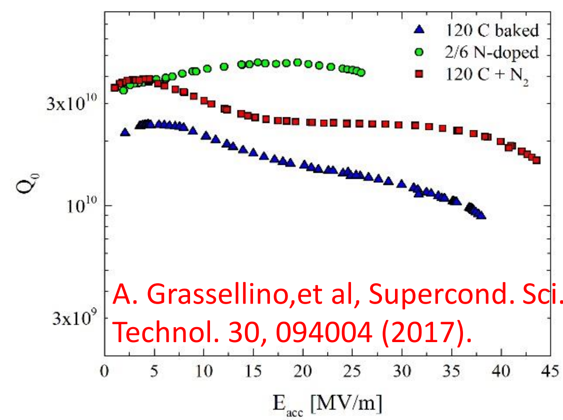
# State of the art - New heat treatments

- We know that variations in the surface layer produce significant variations in performance
- Mid-T (O-doping) – heating cavity to 300-400C for a few hours – diffuses the natural oxide layer into the bulk – no chemistry required – **high Q**
- Two-step baking – 70C for a few hours followed by 48 hours of 120C – **high gradient**
- Nitrogen infusion 120C bake with small quantity of N2 – **high gradient**
- N-doping – adding small amounts of N2 at 800C for a few minutes – requires post treatment EP – **high Q**




C. Bate et al (DESY) – SRF2023 – Grand Rapids



# Summary

## RF surface resistance:

- Room temperature rf currents flow within the skin depth (few µm in Cu) while SRF currents flow within the LPD (ten's of nm in cold Nb)
- SRF surface resistance is ~$10^5$ lower than room temperature – SRF power ~100 times more efficient than room temperature

## Ideally cavities should have:

- Large accelerating field for small drive current
- Low power losses to reduce the power consumption
- Shapes that reduce peak fields and enhance volume
- Efficient energy transfer to beam
- These are quantified by the figures of merit:
  - shunt impedance, geometry factor, surface resistance, peak surface fields, transit time factor and quality factor

Current cavity performance has been pushed by projects like XFEL (high gradient), LCLS-II (high Q) and FRIB (TEM mode cavities)