Superconducting RF Cavities

Rama Calaga, CERN, 2016

Superconductivity & SC-RF Basics

Practical Aspects I & II

†Note: For a detailed treatment, see references (slide 2)

Some References

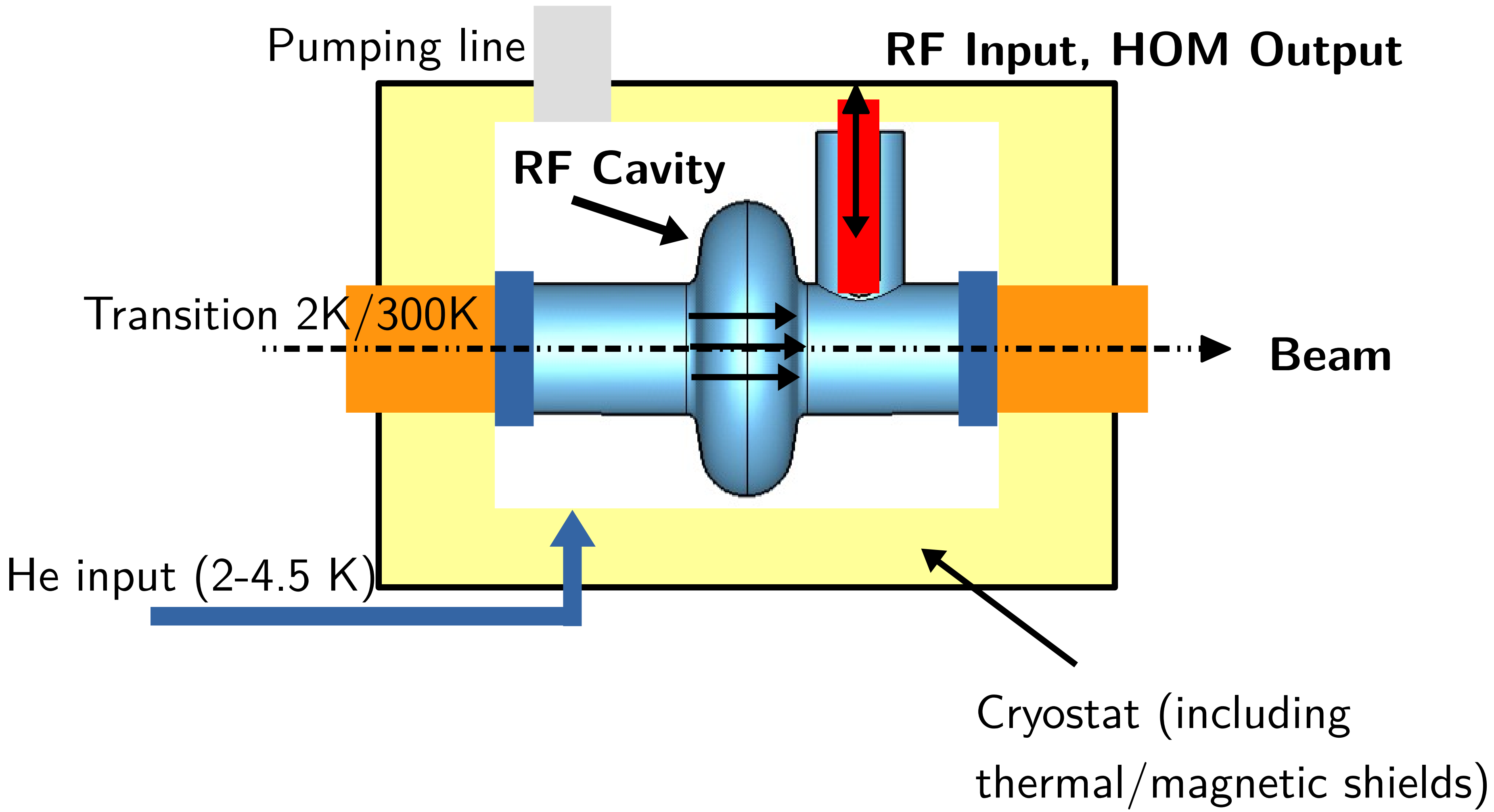
1. RF Superconductivity: Science, Technology, and Applications

   H. Padamsee et al., Wiley-VCH (2009).

2. SRF Conferences & Tutorials (link for SRF2015)

3. CAS (1992), USPAS (2013, 2015), JUAS (2015) ...

Outline


Pumping line
RF Input, HOM Output
RF Cavity
Transition 2K/300K
Beam
He input (2-4.5 K)
Cryostat (including
thermal/magnetic shields)

SC-RF, European XFEL

2.5-20 GeV electron linac, 800 SC-RF Cavities (2.1 km)

Will be one of the largest SC-RF Linear Accelerator in the world

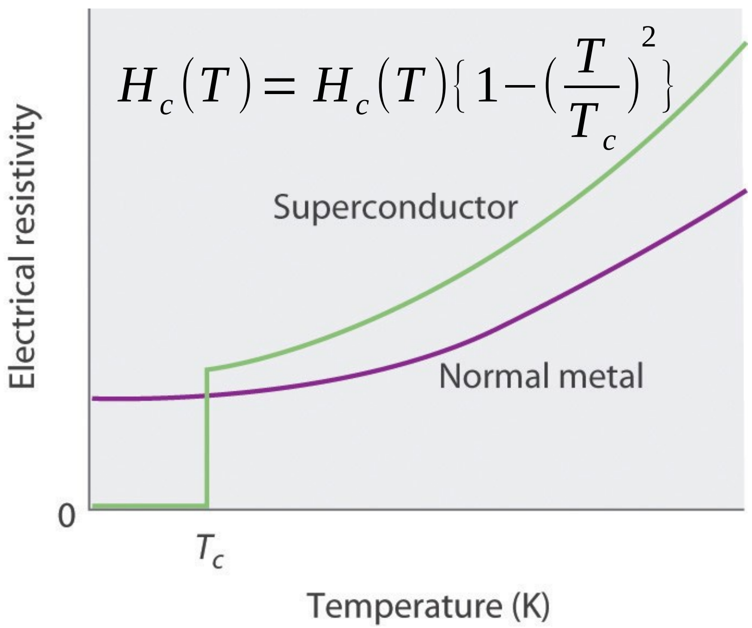
SC-RF is the basis of practically all high energy accelerators

& w/o which ERLs probably cannot be realized

Superconductivity & RF
(Qualitative Look)

Superconductivity

A thermodynamic phase transition below T=Tc, a macroscopic quantum phenomena

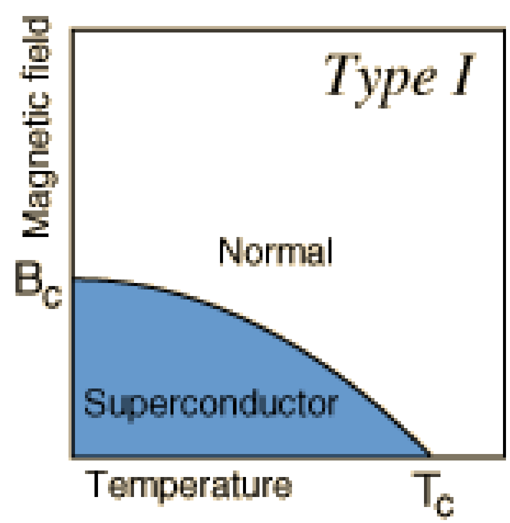


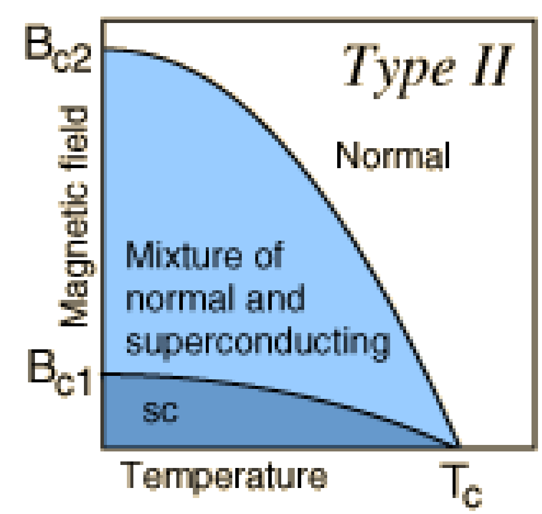
Can be qualitatively understood using two-fluid model (*Jn*, *Js*), where below Tc electrons pair-up into cooper pairs (condensation)

Type I – Complete flux expulsion

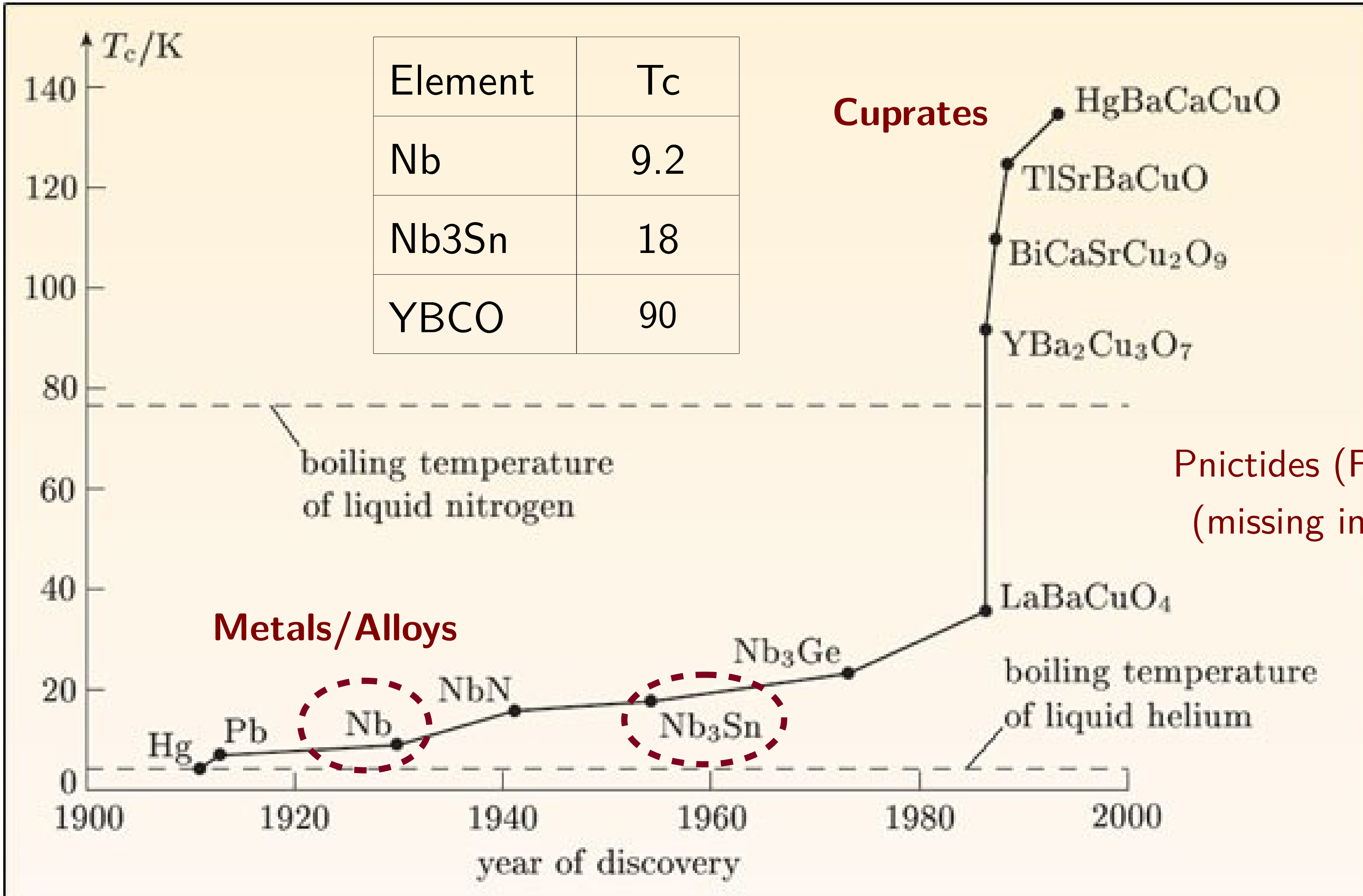
Type II – Mixed states with flux penetration in quantized vortices

$$\phi_0 = \frac{\hbar}{2e}$$





SC-Elements, Evolution



Element	Tc
Nb	9.2
Nb3Sn	18
YBCO	90

Pnictides (Fe-based) (missing in graph)

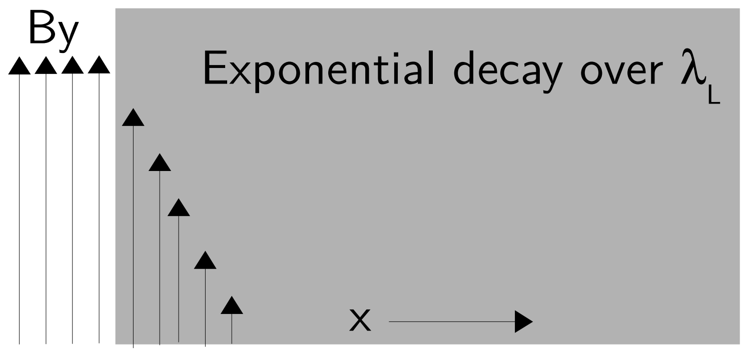
For Nb (type II): B_{c1} ~180 mT, B_{c2} ~400 mT

Characteristic Length Scales

London penetration depth – length scale over which the B-field decays in SC

Coherence length – distance over the which cooper pairs are correlated

$$B_y(x) = B_0 e^{-\frac{x}{\lambda_L}}$$



$$\lambda_L = \sqrt{\frac{m_e}{\mu_0 n_s e^2}} \qquad \xi_c = \frac{\hbar v_F}{\Delta}$$

Element	$\lambda(0)$
Pb	390
Nb	470
Sn	510
YBCO	1700

Critical Field: $$B_c = \frac{\phi_0}{2\sqrt{2}\pi\lambda_L \xi}$$

Surface Resistance

Av. power dissipated on the surface: $P_d = \frac{1}{2} R_s H_0^2$

<u>Normal-Conductor</u>

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

For Copper:

$\sigma = 5.85 \times 10^7$ S/m (300 K)

$\mu_0 = 4\pi \times 10^{-7}$ N/A^2

$\omega = 2\pi \times 1$ GHz

$\delta =$ <u>2 μm</u>

Rs = 8.2 mΩ

(Don't forget anamolous skin effect)

<u>Super-Conductor</u>

$$R_s = \frac{1}{(\sigma_n - i\sigma_s)\lambda_L} = \frac{1}{2}\sigma_n \omega^2 \mu_0^2 \lambda_L^3$$

For Niobium:

$\mu_0 = 4\pi \times 10^{-7}$ N/A^2

$\omega = 2\pi \times 1$ GHz

$\xi = 39$ nm

λ_L (T=0K) = <u>36 nm</u>

Rs ~ nΩ

Surface Resistance from BCS

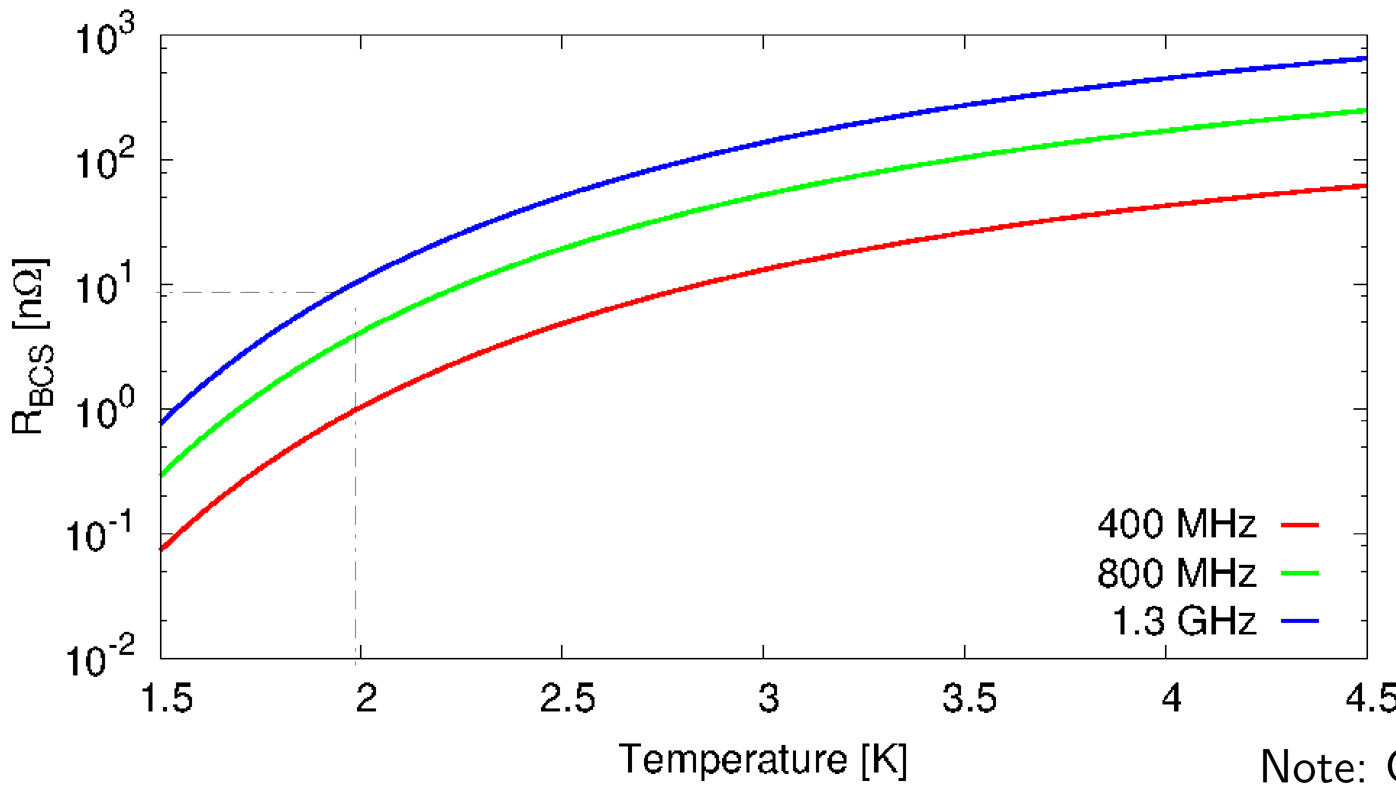
$$\left(\lambda_L^4, \xi, l, \rho^{0.5}\right)$$

Mattis-Bardeen approx (BCS theory):

$$R_{BCS} = A\frac{\omega^2}{T}e^{-\frac{\Delta}{k_B T}}$$

energy gap

For Niobium: $$R_{BCS} \approx 2.4\,x\,10^{-4}\left(\frac{f\,[MHz]}{1500}\right)^2 \frac{1}{T}e^{\frac{-17.67}{T}}$$

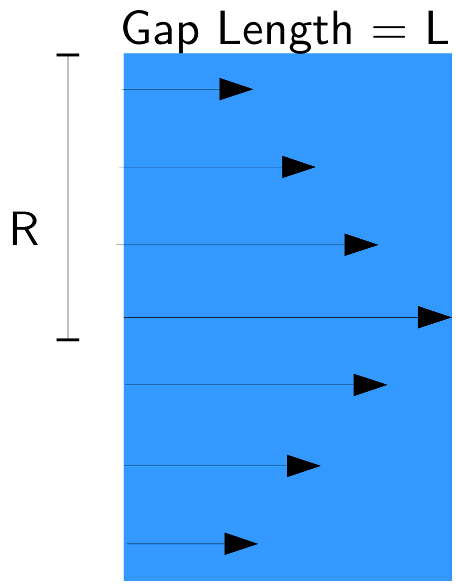


$$R_s = R_{BCS} + R_{res}$$

There is also temperature independent residual resistance which is lower limit

Note: Cryogenic to wall plug power

Cylindrical Cavity



Standing waves of TM & TE

$$\omega_{mnp} = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \sqrt{\left(\frac{p_{mn}}{r}\right)^2 + \left(\frac{p\pi}{l}\right)^2} \quad - \quad (\mathrm{TM})$$

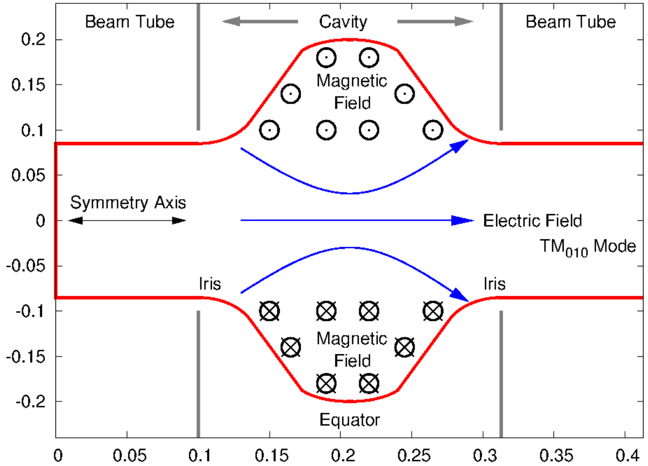
$$\omega_{mnp} = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \sqrt{\left(\frac{p'_{mn}}{r}\right)^2 + \left(\frac{p\pi}{l}\right)^2} \quad - \quad (\mathrm{TE})$$

$$E_z = E_0 J_0(\omega_0 r/c) \cos(\omega_0 t)$$

$$H_\phi = -\frac{1}{\mu_0 c} E_0 J_0(\omega_0 r/c) \sin(\omega_0 t)$$

$$\omega = \frac{2.405\ c}{R}$$

Standard SC-RF Cavity

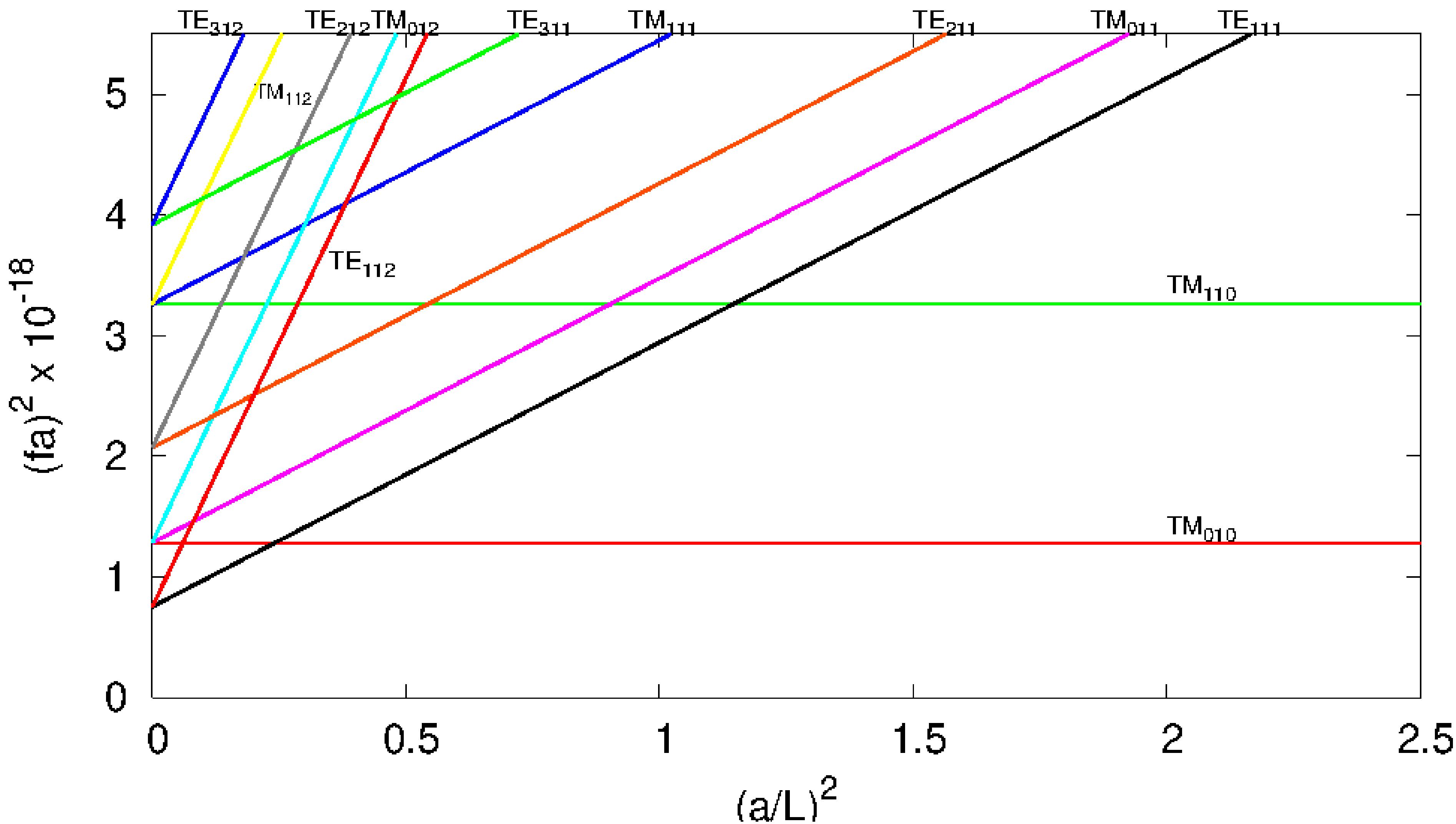


1^{st} mode (m=0, n=1,p=0) suited for acceleration with field lines uniform over z

The frequency is only dependent on radius and

Mode Spectrum Vs Geometry

Cylindrical Cavity



Figures of Merit I

Voltage:

$$V_{acc} = \left| \int\limits_{z=0}^{z=l} E_z e^{i\omega_0 z/c} dz \right|$$

Transit Time:

(βcT=distance covered in a RF period)

$$T = \frac{\int\limits_0^l E_0 e^{i\omega z/c}\ dz}{\int\limits_0^l E_0\ dz}$$

Stored Energy:

$$U = \frac{1}{2}\epsilon_0 \int\limits_V |\vec{E}|^2\ dv = \frac{1}{2}\mu_0 \int\limits_V |\vec{H}|^2\ dv$$

Figures of Merit II

Quality Factor:

$$Q_0 = \frac{\omega_0 U(t)}{P_d(t)} \qquad U(t) = U_0 \; e^{-t/\tau}$$

Shunt Impedance:

$$R_{shunt} = \frac{V^2}{P_d} \qquad \frac{R_a}{Q_0} = \frac{V^2}{\omega U}$$

Geometric Factor:

$$G = R_s Q_0 = \frac{\omega_0 \mu_0 \int_V |\vec{H}^2 dv}{\int_S |\vec{H}|^2 ds}$$

Power dissipated:

$$P_{walls} = \frac{V_c^2}{R/Q\,.\,G} R_s$$

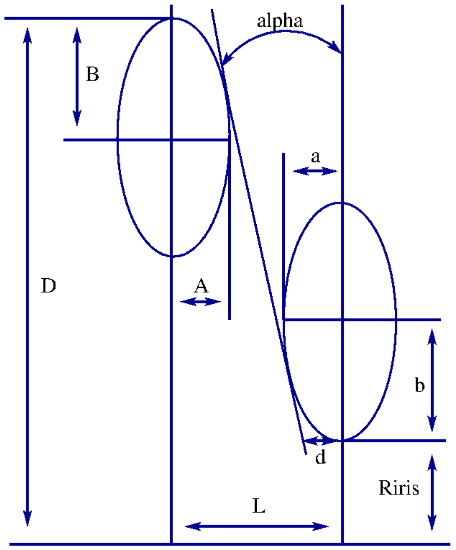
Material

Geometry

Cavity Design, TM-Class

½-cell parametrization

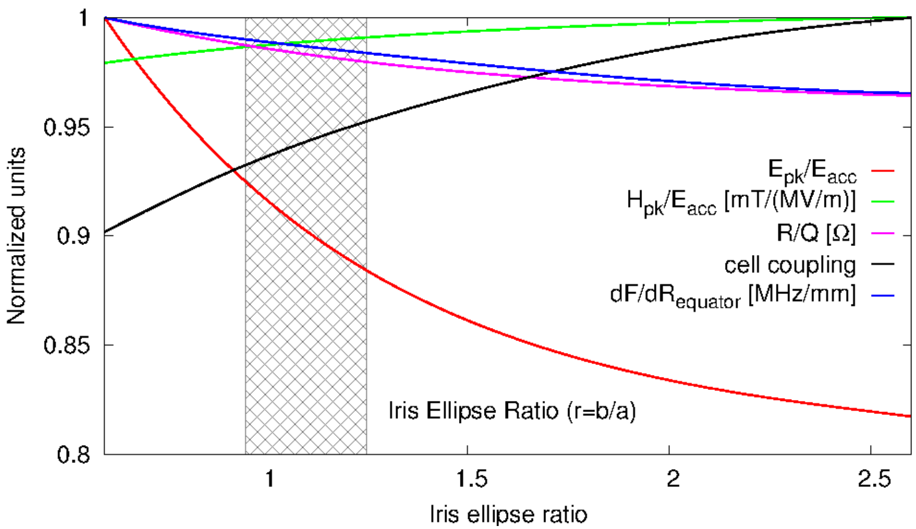
(P. Pierini et al.)

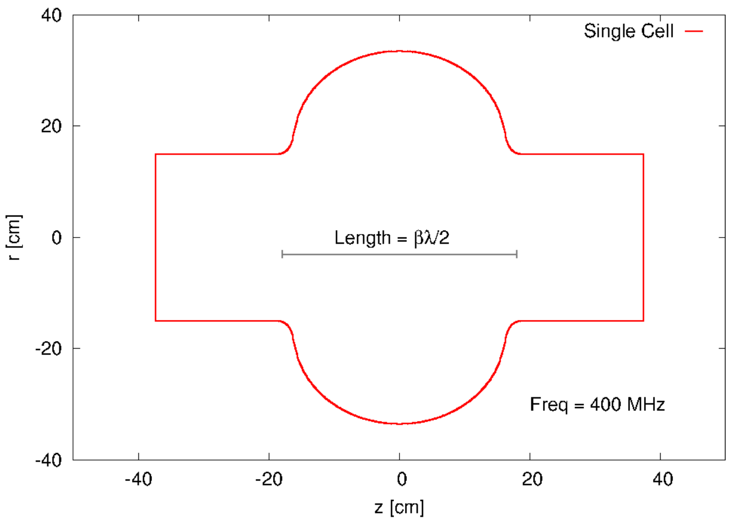


Standard Criteria:

- Minimize peak surface fields (E, B)
- Optimum R/Q based upon application
- Optimum mechanical stiffness (tuning vs. de-tuning)
- Strong cell-to-cell coupling (multi-cell)

Example scan vs iris ratio



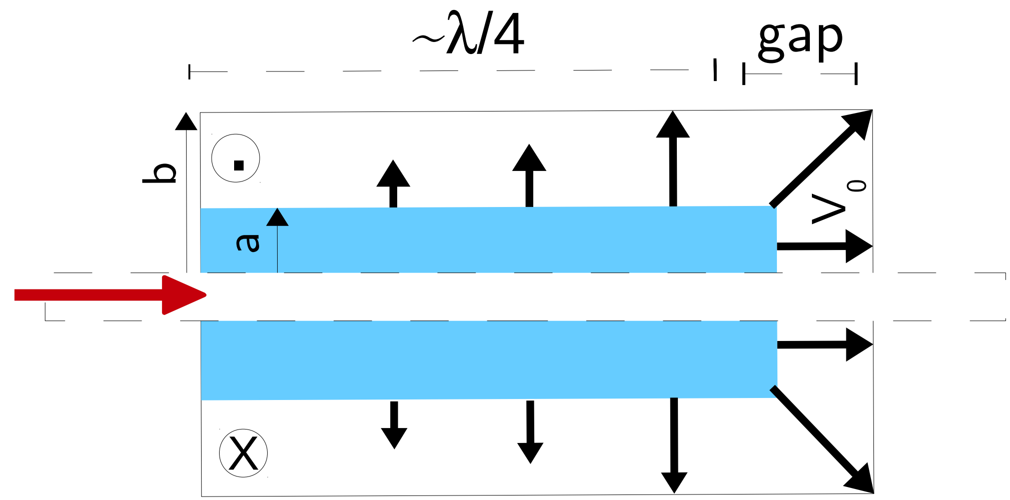


Note: No single optimum shape for everything

TEM Class Resonators

Another important class are using uniform transmission lines

$\lambda/4$ being one of the simplest form



$$V_z = V_0 \sin(k z)$$

$$I_z = I_0 \cos(k z)$$

Line Impedance: $$Z_0 = \frac{\eta}{2\pi} \ln \frac{b}{a} \longrightarrow \frac{R}{Q} = 4 \frac{Z_0}{\pi}$$

Geometric Factor: $$G = \frac{2\pi\eta}{\lambda} \frac{\ln b/a}{a^{-1} + b^{-1}}$$

Widely used in low velocity (protons, ions) applications for compactness

Cavity Design, Numerical

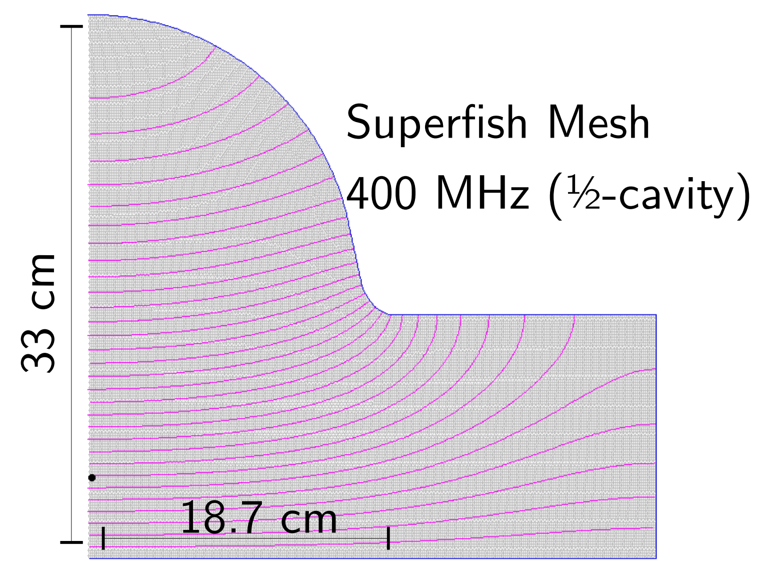
Almost all practical applications requires a deviation from idealized cavity. Therefore, spatial discretization of the structure and solve Maxwell's equation numerically.

Frequency Domain (eigenvalue problem)
Time Domain (transient response)

Different methods: Finite (difference, integration, element)

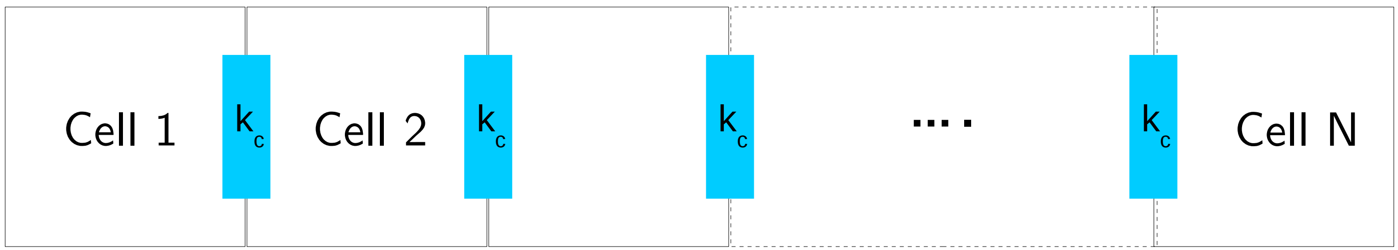
Generally used (but not comprehensive):

- 2D: Superfish, SLANS, ABCI
- 3D: CST, HFSS, ACE3P, GdfidL

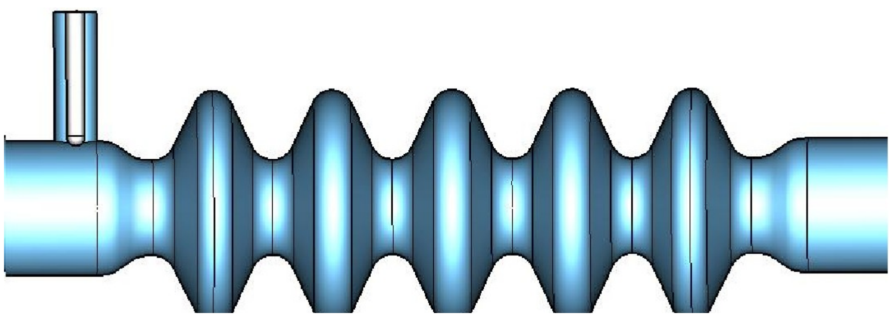


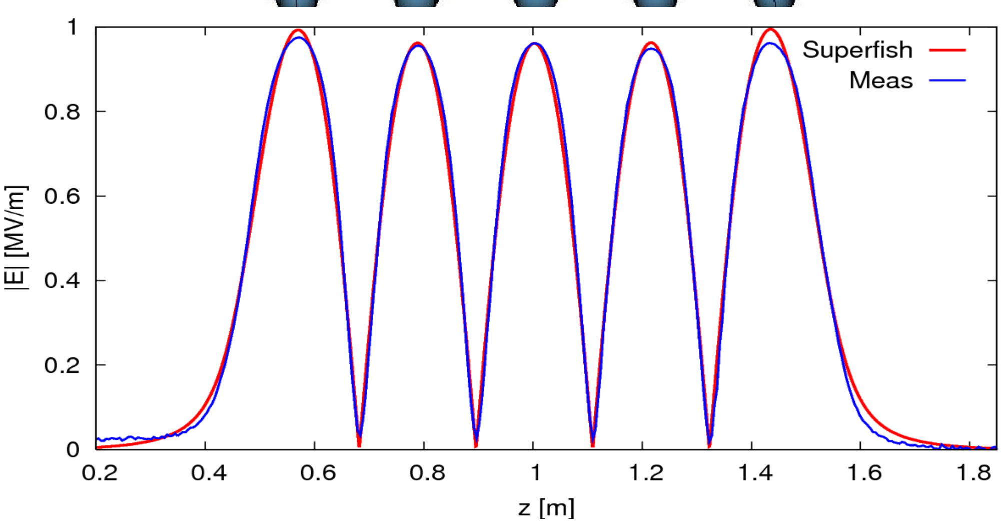
Multi-Cells (mainly for Linacs)

To improve the “real-estate” gradient & ancillary equipment (couplers, flanges, warm-cold transitions, etc...) it is often efficient to go to N-coupled cells

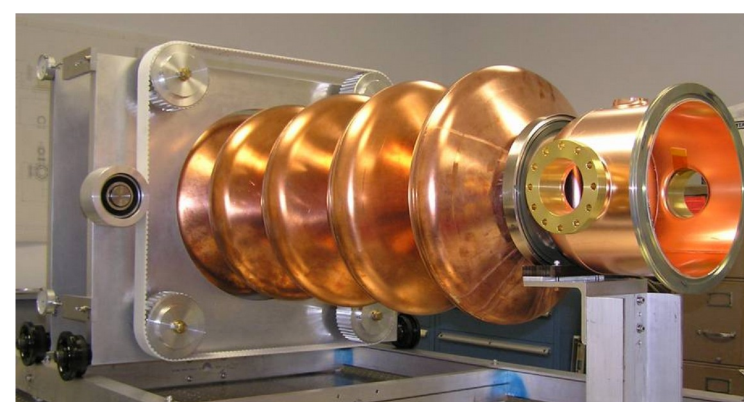


$$\left(\frac{\omega_n}{\omega_0}\right)^2 = 1 + 2k_c\left[1 - \cos\left(\frac{n\pi}{N}\right)\right]$$

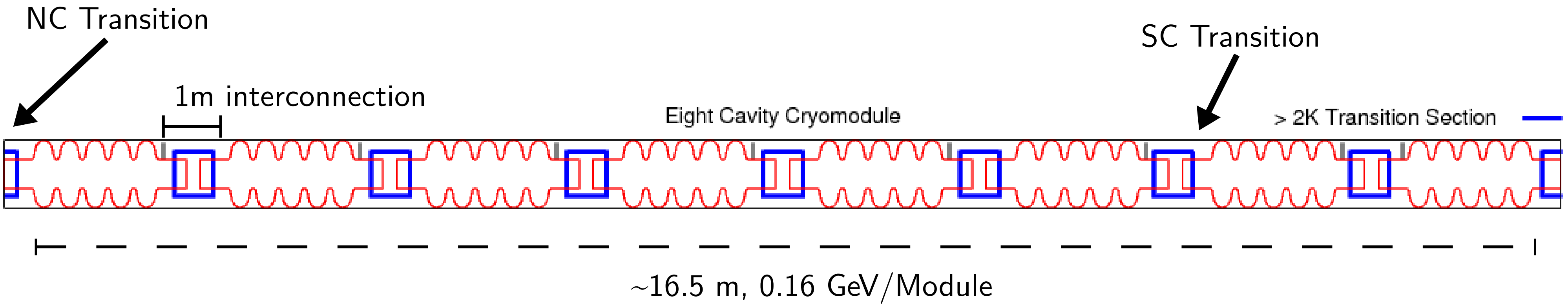




$$a = \frac{N^2}{k_c}$$



Towards a Compact Footprint



Example 5-cell cavity at 700 MHz:

In the above, 8-cavity cryomodule: 0.16 GeV, 16.5 m

For 20 GeV, LINAC-FEL $\rightarrow$ 2 km

Homework :

Calculate the real estate length assuming only single cells/cavity

Practical Aspects I

(Measurements, Freq. Detuning, HOMs)

Field Measurements

Standard practice to use Cu-models for fabrication trials & RF measurements

Slaters thoerem: $\Delta\omega/\omega$ μ $\Delta U/U$ (for small perturbations)

Bead inside a cavity:

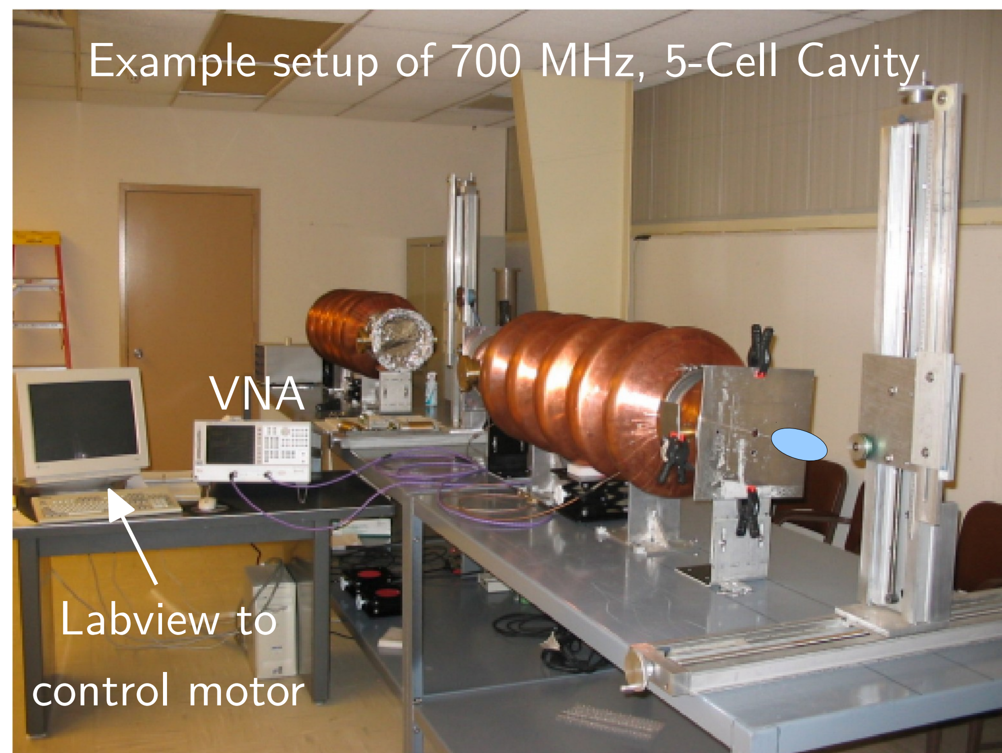
$$\frac{\delta\omega}{\omega_0} = \begin{cases} -\frac{\pi r^3}{U}\left(\epsilon_0 \frac{\epsilon_r+2}{\epsilon_r-1} E_0^2\right) & : \quad dielectric \\ -\frac{\pi r^3}{U}\left(\epsilon_0 E_0^2 - \frac{\mu_0}{2} H^2\right) & : \quad metal \end{cases}$$

Vector Network Analyzer $\rightarrow$ S-parameters

$$S_{21} = \frac{2\sqrt{\beta_1\beta_2}}{(1+\beta_1+\beta_2) + iQ_0\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)}$$

β_1, β_2 are coupling factors for antenna's, assuming they are small:

$$\frac{\delta\omega}{\omega_0} \approx -\frac{1}{2Q_L} tan(\phi)$$



Detuning from Lorentz Force

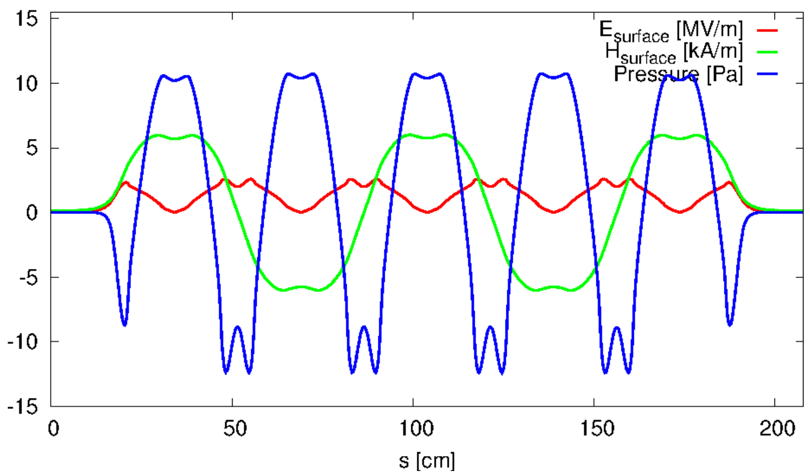
SC-Cavities are operated typically with narrow bandwidth
It implies careful control/tracking of frequency

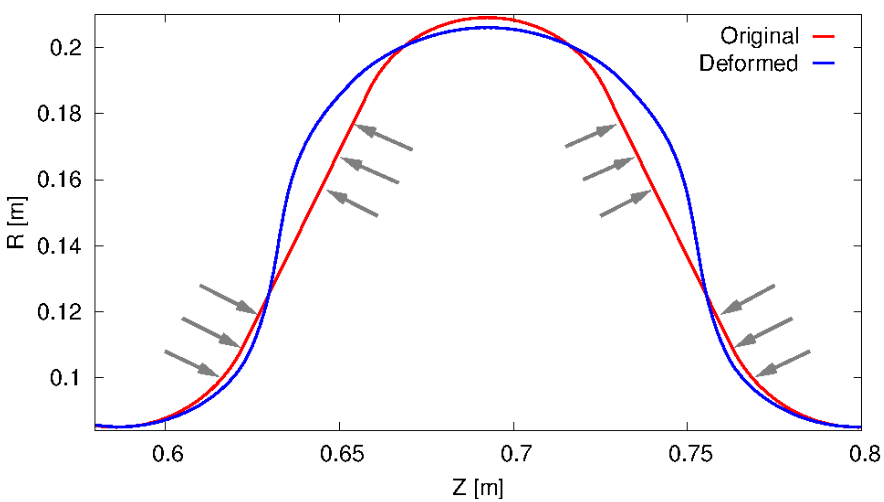
Radiation pressure from the very high electro-magnetic fields will distort the cavity shape and therefore the frequency

inductive

$$\delta f \propto \frac{f_0}{4U} \int_{\delta V} (\epsilon_0 \vec{E}^2 - \mu_0 \vec{H}^2) dV$$

capacitive



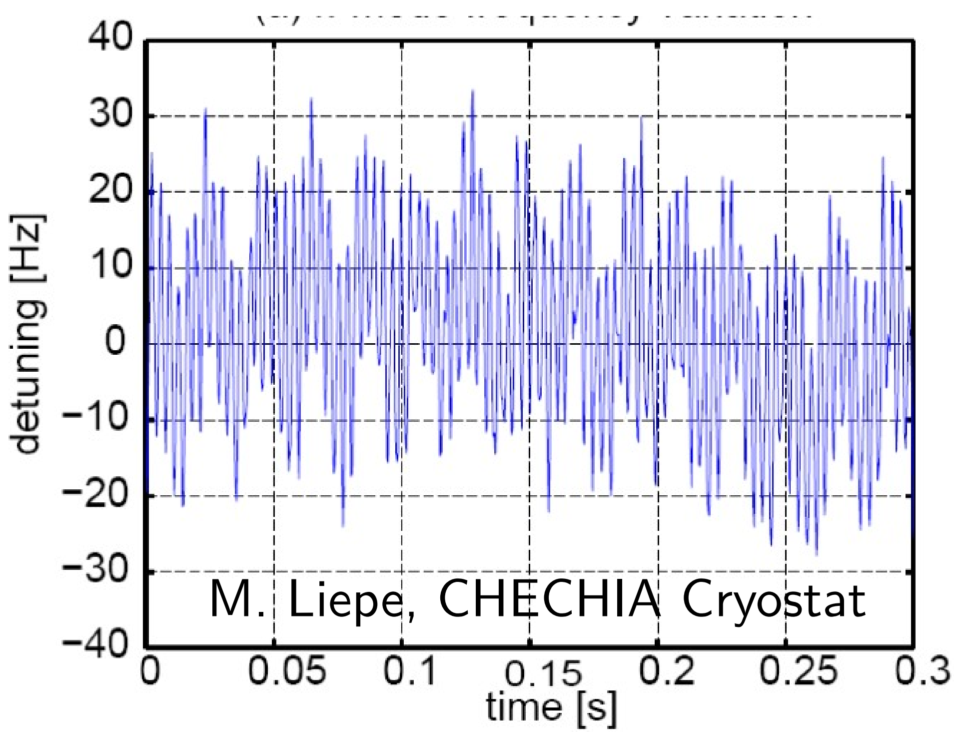


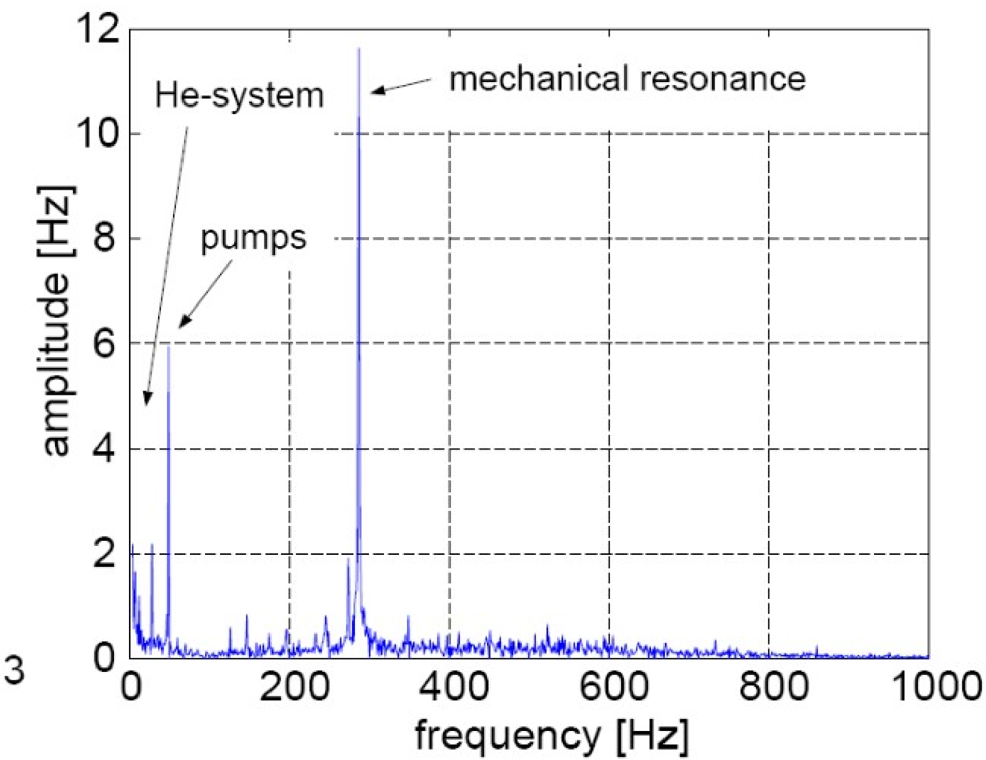
Detuning From External Forces

External noise can be transferred to cavity via the cryostat (Microphonics)

Mitigation

- Tuning system: Mechnical - slow and/or electro-mechanical - moderate
- RF feedback - fast, BW limited ($\Delta\omega$)





RF Power

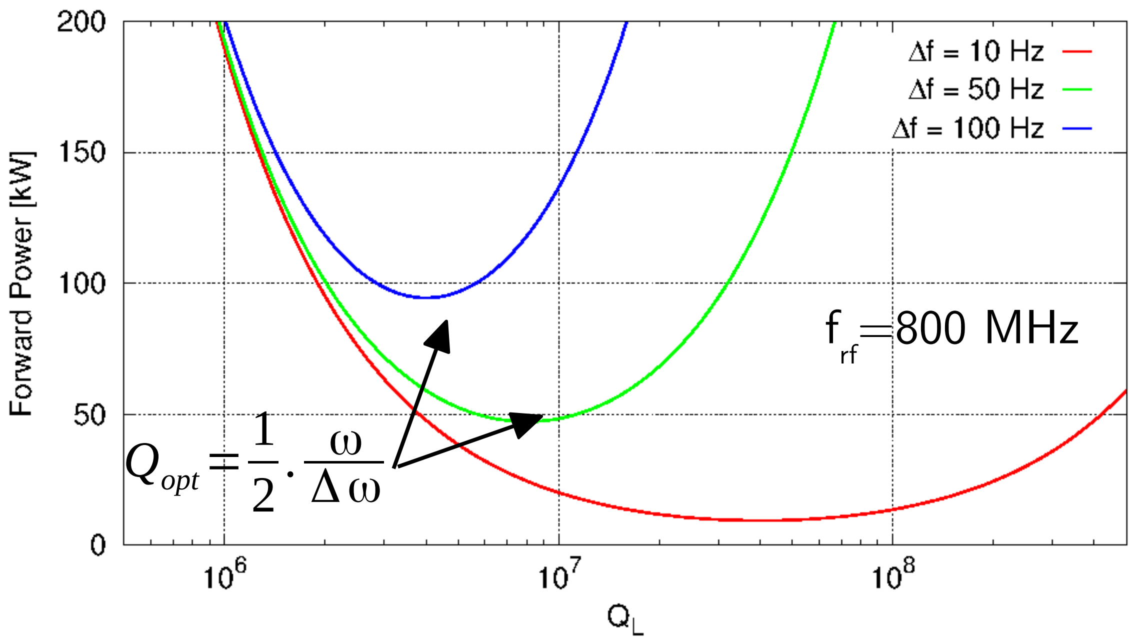
$$P_f = \frac{R_s}{4\beta}\left[\frac{(1+\beta)^2 V^2}{R_s^2} + \left(\frac{V}{X} - I_b\right)^2\right]$$

$$Z(\omega) = \frac{R/Q \, . \, Q_L}{1 + i\tan\psi} \qquad Q_L = \frac{Q_0}{(1+\beta)} \qquad X = \frac{R}{Q}\frac{\omega}{\Delta\omega} \qquad \tan(\psi) = 2 Q_L \frac{\Delta\omega}{\omega}$$

Assuming no beam-loading (ERL), one can show

$$P_f = \frac{V^2}{R/Q} \cdot \frac{\Delta\omega}{\omega}$$

To maintain a constant gap voltage, the input power scales linearly with detuning



$$Q_{opt} = \frac{1}{2} \cdot \frac{\omega}{\Delta\omega}$$

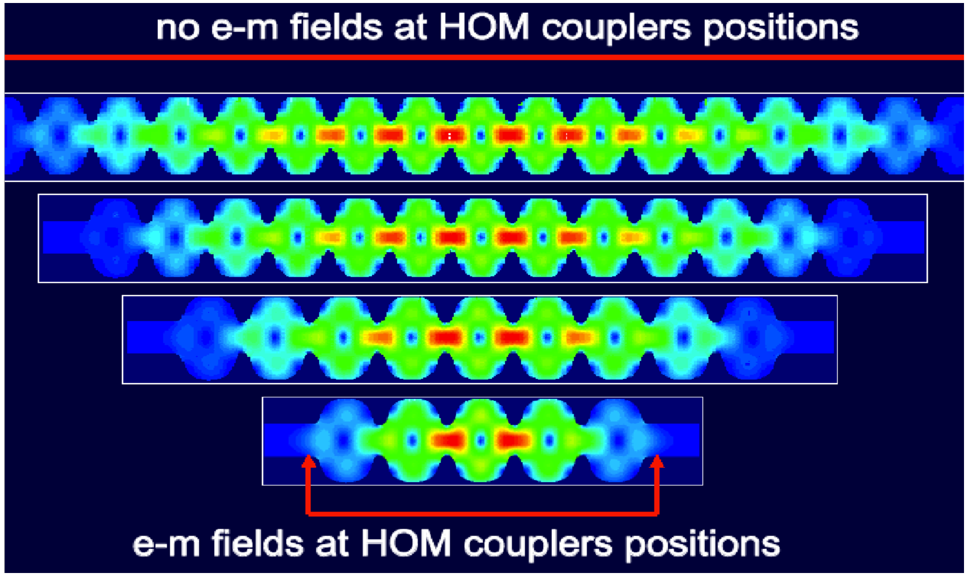
Higher Order Modes

Beyond the fundamental (accelerating) mode, there exists infinite eigenmodes

$$\omega_{mnp} = \frac{1}{\sqrt{\mu_0\epsilon_0}}\sqrt{\left(\frac{p_{mn}}{r}\right)^2+\left(\frac{p\pi}{l}\right)^2} - \text{(TM)}$$

$$\omega_{mnp} = \frac{1}{\sqrt{\mu_0\epsilon_0}}\sqrt{\left(\frac{p'_{mn}}{r}\right)^2+\left(\frac{p\pi}{l}\right)^2} - \text{(TE)}$$

They can be excited by the beam which typically has a wide frequency range ($1/\sigma_z$) depending on the synchronism condition



Graphic: J. Sekutowicz

Multi-Cells have N-times the number of HOMs (passbands)

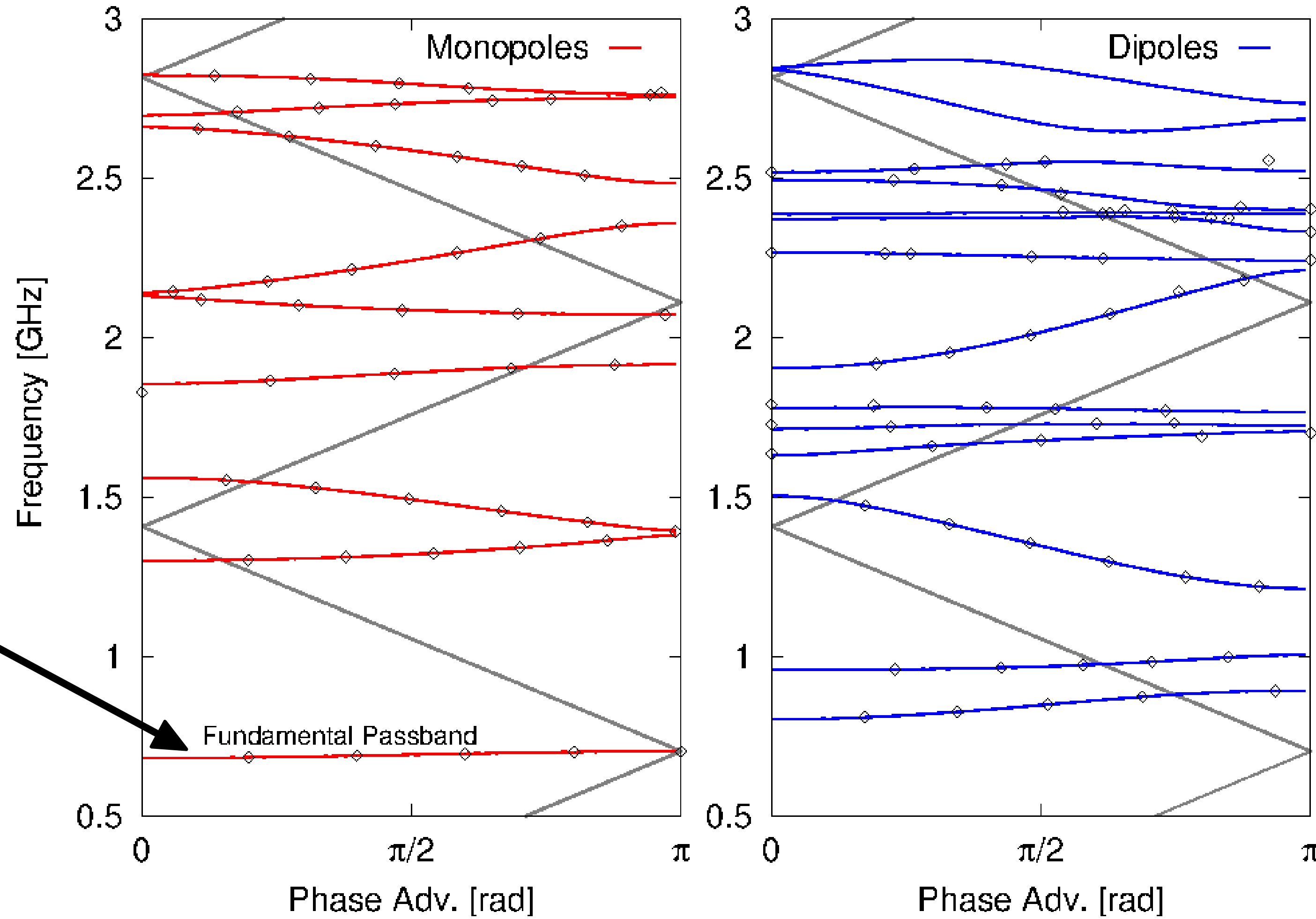
Strong damping of the HOMs is often key to aspect to reach high currents and beam quality

Dispersion Curves

Approximation of an infinitely periodic structure

Modes with phase velocity $= \beta c$ are strongly excited (also high R/Q)

$$v_g = \frac{d\omega}{dk}$$



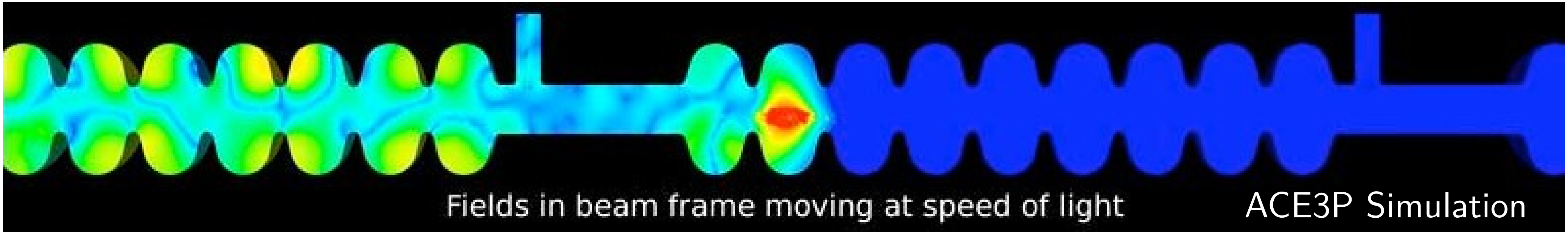
Light cone

$$f_\phi = \frac{\phi c}{2\pi L}$$

Loss Factor

Bunch traversing the structure losses energy and leaves behind a wakefield into parasitic modes, which can be characterized by loss factor (k)

- For pulsed linacs (FELs), resulting energy spread & emittance growth
- High current CW (storage rings, ERLs) limited by power



Energy loss: $\Delta U = k_n q^2$ $\qquad$ $k_n = \frac{\omega}{2} \cdot \frac{R}{Q}$ (loss factor/mode assuming TM-like)

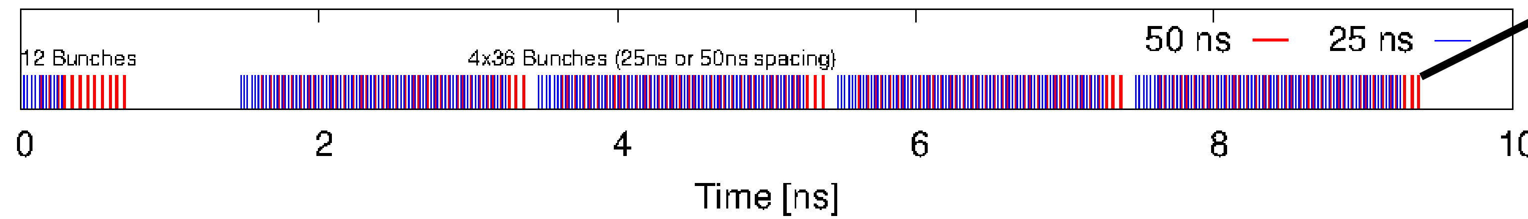
$$k_{||}(n) = \frac{1}{2\pi} \int_{-\infty}^{\infty} Re Z_{||}(\omega) d\omega.$$

Analogous transverse loss factor

$k_t \rightarrow$ emittance growth

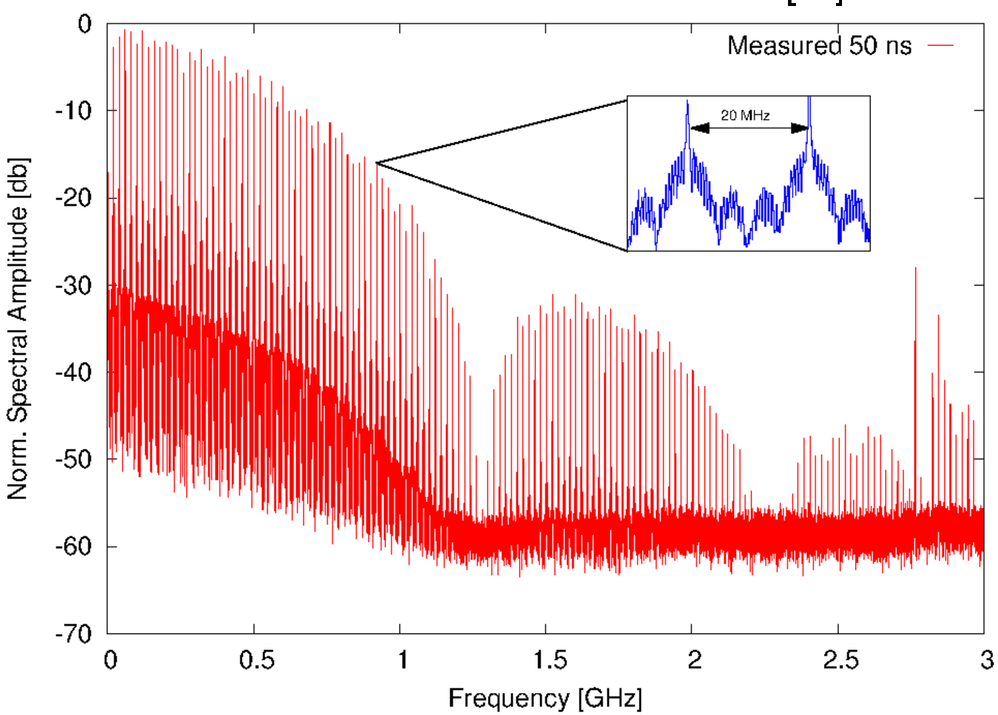
HOM Losses

LHC Filling scheme



$T_b = 50$ ns

(bunch spacing)



Non-Resonant Case:

$$P_{HOM} = \left(\Sigma k_n - k_0\right).q.I_b$$

Fundamental

Resonant Case:

$$P_{HOM} = I_b^2.\frac{R}{Q}.Q_L.F_n^2$$

Damping <u>essential</u>

for SC-Cavities

<u>Homework</u>:

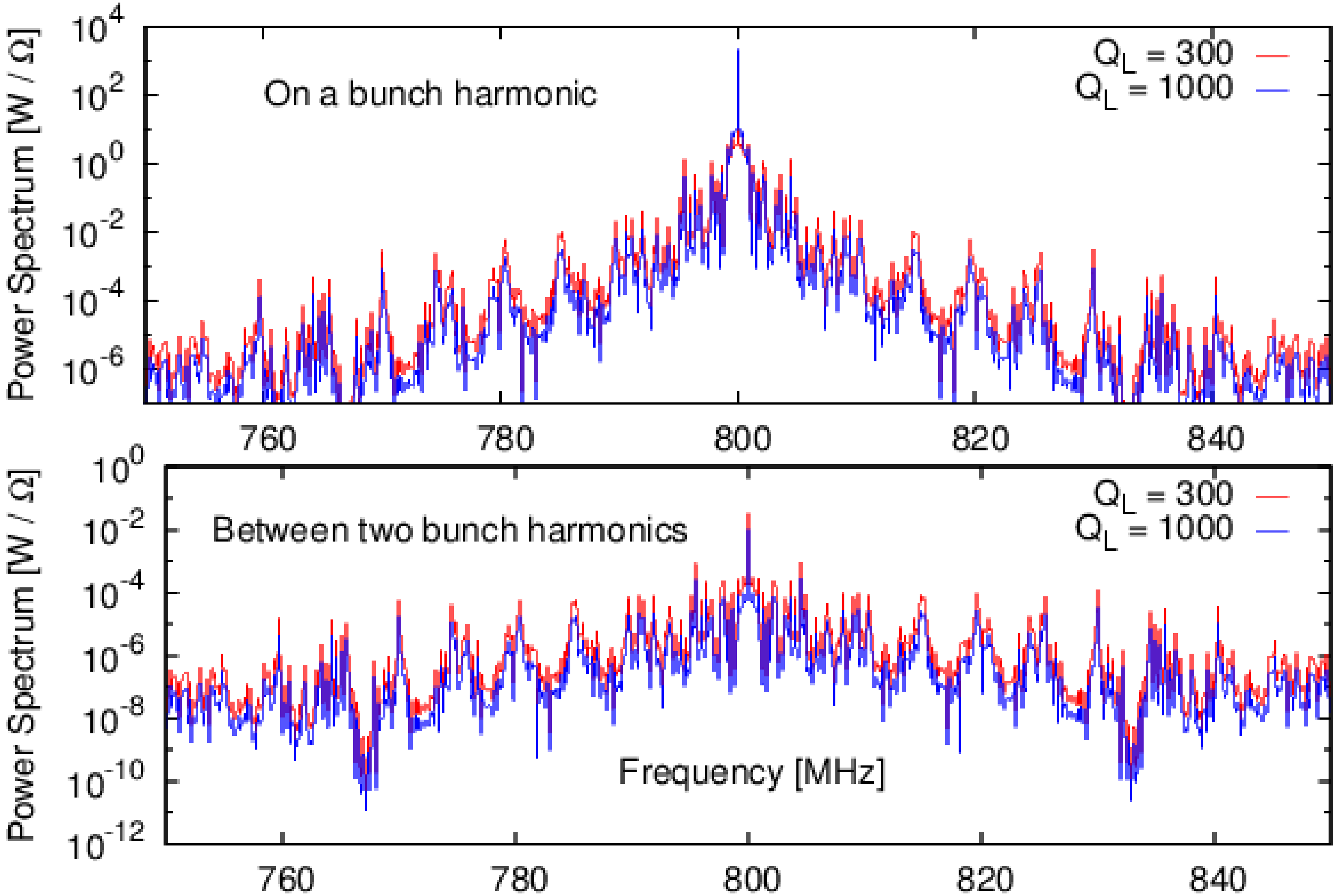
Calculate energy spread, HOM power/cavity for 6-pass ERL

q=1nC, frev = 1 MHz, k = 1 V/pC

HOM Power Contd.

In reality one integrated numerically the HOM impedance over the bunch spectrum/filling scheme

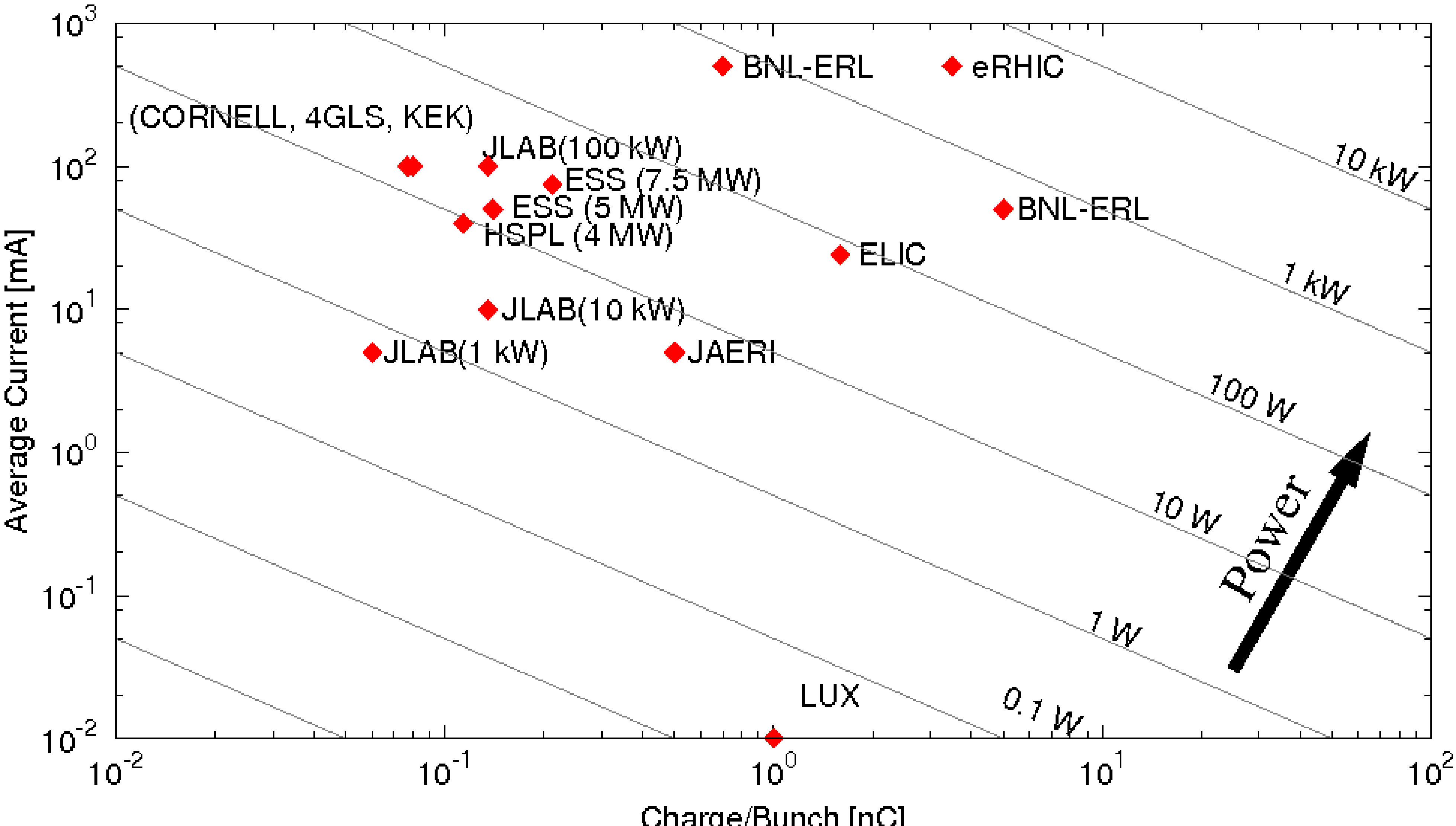
LHC example with an 800 MHz HOM (1 Ω)



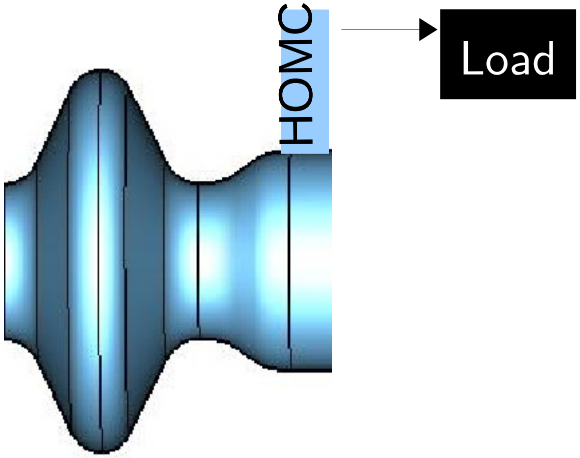
HOM Power, ERLs

$$P_{avg} = k_L Q_b I_a$$

Power to be extracted but <u>NOT</u> into 2K



HOM Damping & Extraction



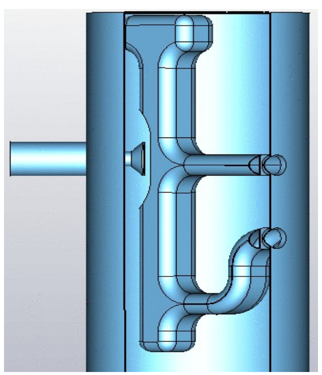
Notch Filters $\rightarrow$ Narrow-band & targeted damping

Waveguides $\rightarrow$ Higher frequencies more suitable

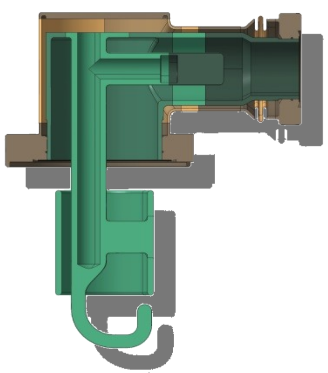
Ferrites $\rightarrow$ Broadband room temp

SC $\longrightarrow$ NC

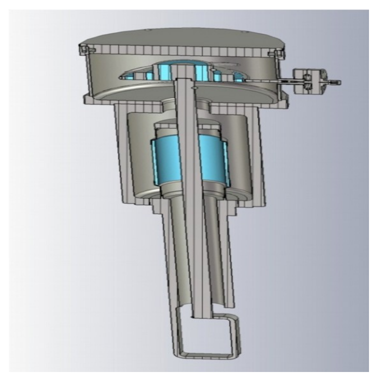
Notch filters



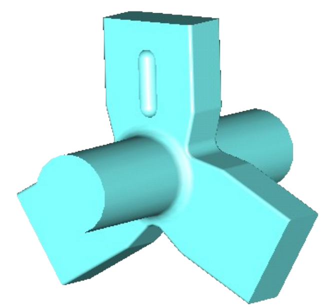
Double-Notch



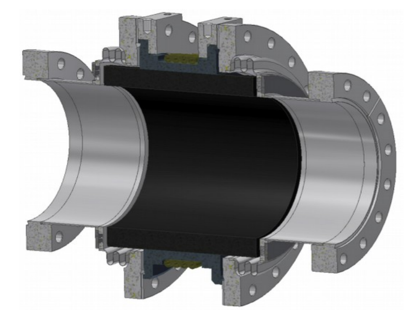
Band-Pass



Waveguides



Ferrites

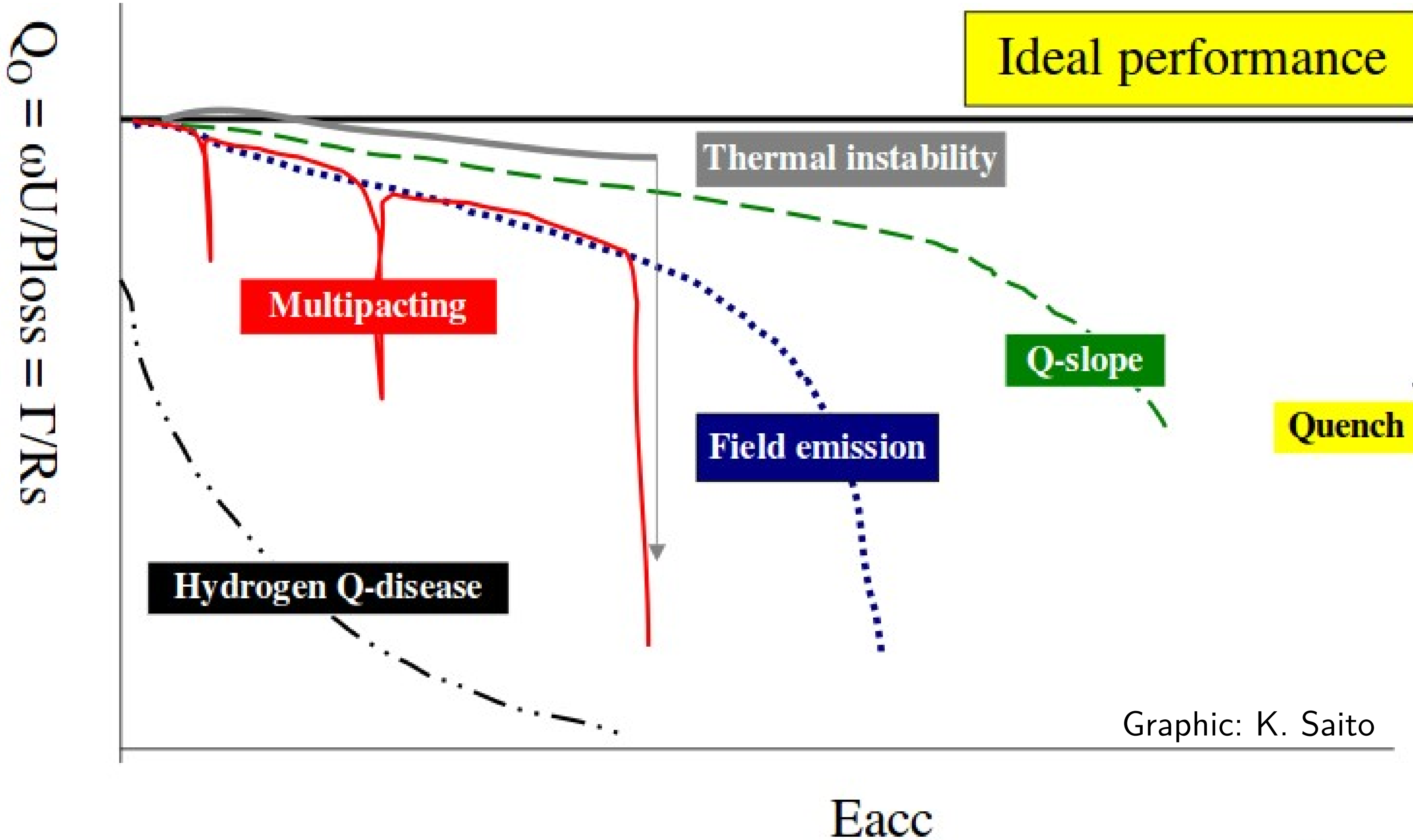


Main objective is have high impedance for the fundamental mode while high transmission for HOMs

Practical Aspects II

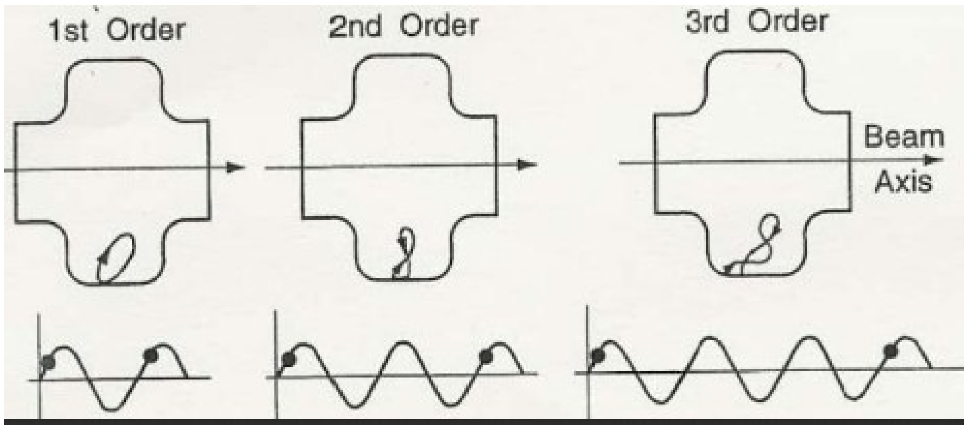
(Surface Treament & Cold Measurements)

SC Cavity Performance Limitations



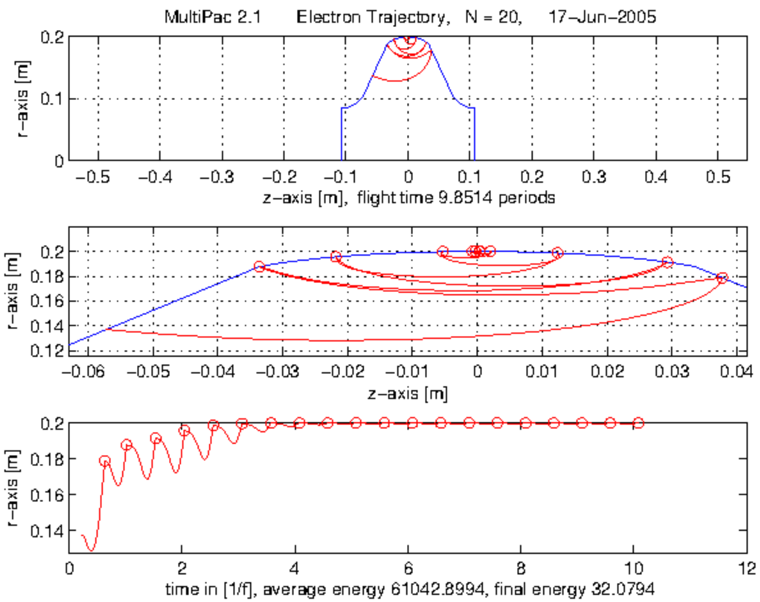
Multipacting

Resonant electron multiplication of electrons from the cavity surface impacting back in integer RF cycles with a surface emission coefficient (SEY) > 1



Consequence

An electron avalanche of electrons absorbing all RF power, leading a thermal breakdown



Mitigation

It is field, phase and SEY dependent.

RF conditioning and/or geometrical shaping to suppress the resonant behavior (ex: elliptical shape)

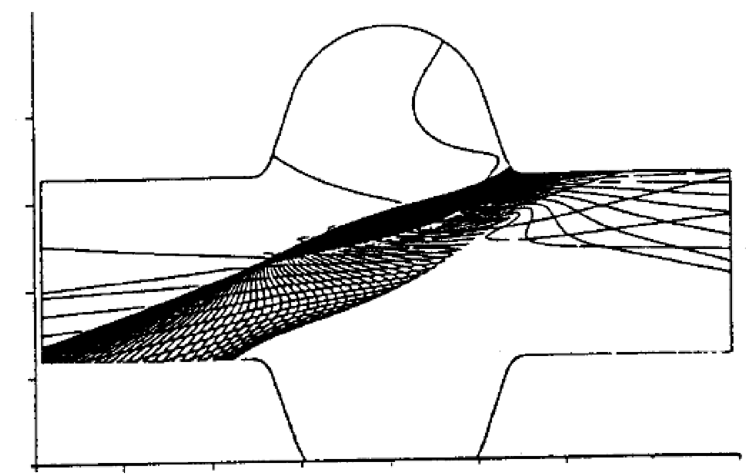
Field Emission

An electron emitting site on the cavity surface (due to impurities, surface defects etc..) with a sufficient local field enhancement (10^2 – 10^3).

They get accelerated/bent by the strong RF field and impact elsewhere on the surface with the typical signature of strong x-rays leading to vacuum and/or thermal breakdown ("hot zones")

Explained by modified F-N theory
(β-enhancement factor)

$$j = \frac{A \, . \, \beta^{2.} E^2}{\Phi} e^{-B \frac{\Phi^{3/2}}{\beta E}}$$



Mitigation by surface smoothness, cleanliness (HPR + Cleanroom) and RF conditioning

Surface Treatment(s)

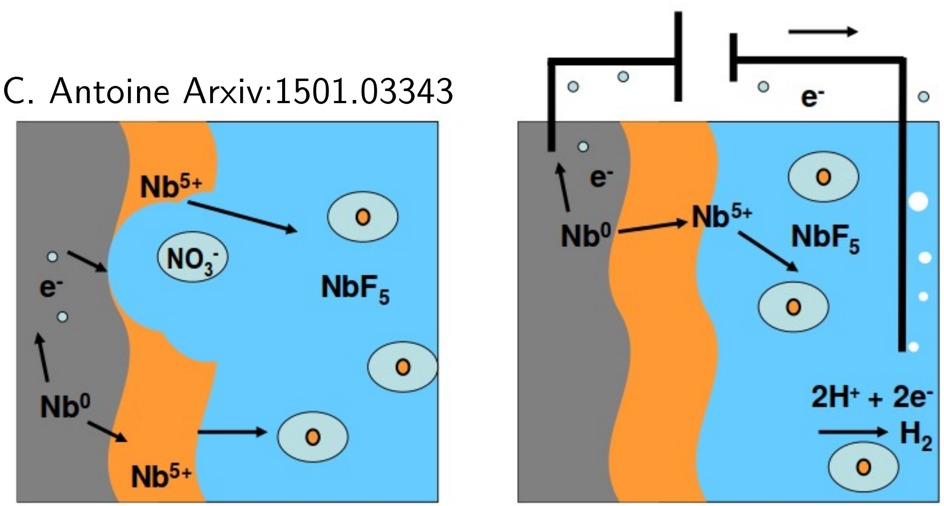
Cavity surfaces are typically formed by mechanical means which leave a damaged cortical layer (impurities, inclusions, hydroxides, oxides...)

Standard practice (after degreasing) is to remove 100-200 µm by <u>oxidation</u> & <u>reduction</u>:

- Buffer Chemical Polishing (HNO_3, HF, H_3PO_4)
- Electro-Polishing (HF, H_2SO_4) – roughness ~micron level
- Mechanical Barrel Polishing

G. Ciovati, USPAS Lecture, 2015

C. Antoine Arxiv:1501.03343

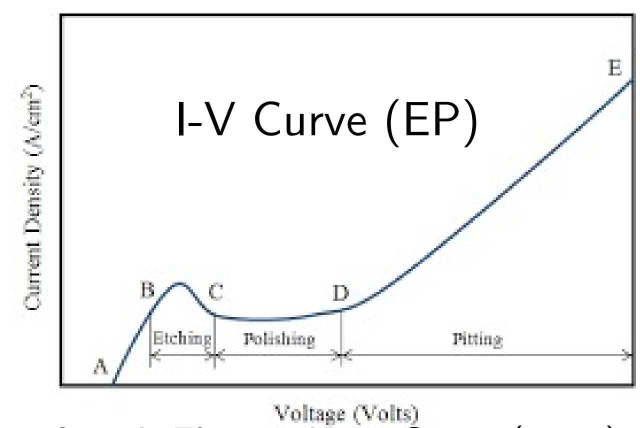


$6\,Nb + 10\,HNO_3 \rightarrow 3\,Nb_2O_5 + 10\,NO\uparrow + 5\,H_2O$

$Nb_2O_5 + 10\,HF \Leftrightarrow 2\,NbF_5 + 5\,H_2O$

$Nb \rightarrow Nb^{5+} + 5\,e- \rightarrow Nb_2O_5$

$Nb_2O_5 + 10\,HF \Leftrightarrow 2\,NbF_5 + 5\,H_2O$



Int. J. Electrochem. Sci.,7 (2012)

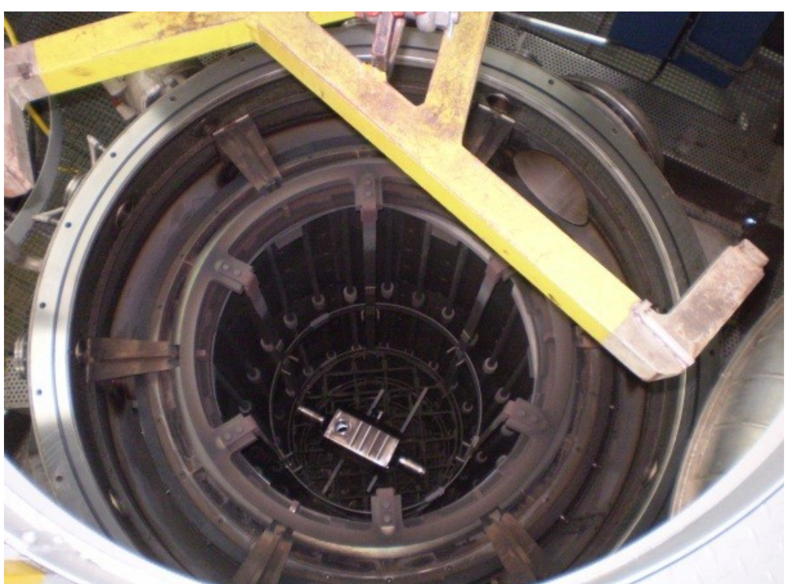
Heat Treatment

Substantial Hydrogen concentration is shown to yield Q-disease due to Hydrogen dissolution into the Niobium bulk during chemistry

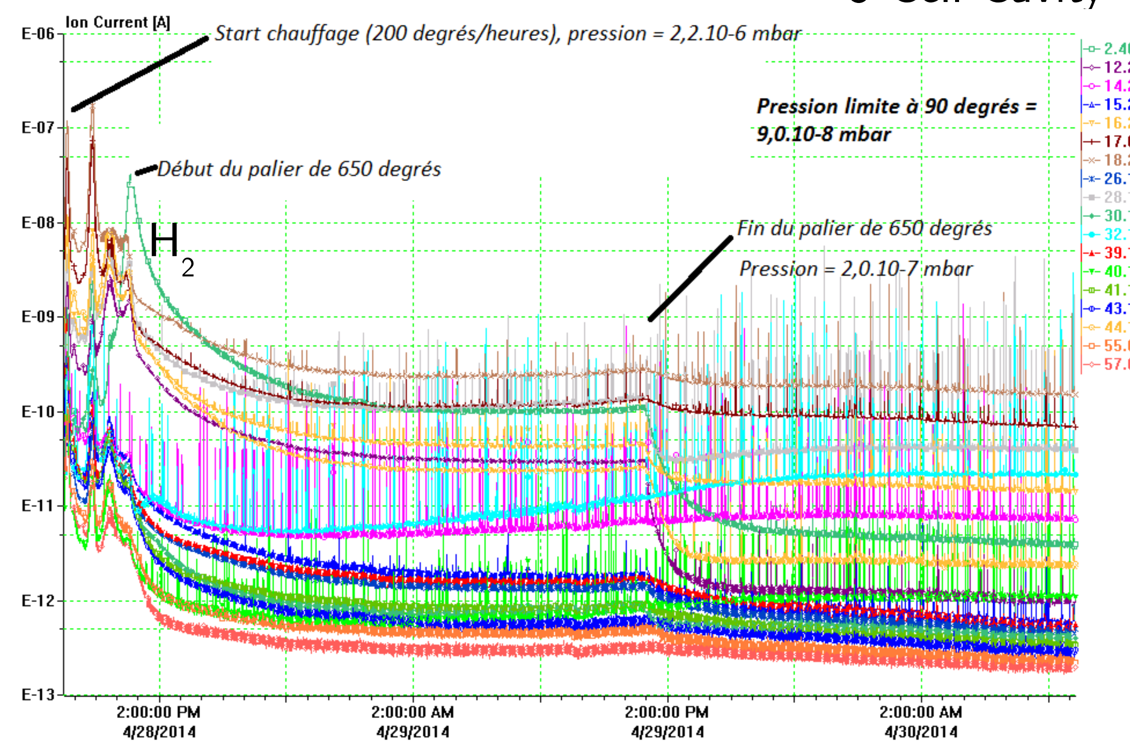
Heat treatment (UHV) at 600-800 ^{0}C (10-24 hrs) – Removal of the H2

Niobium is a strong getter above 250 ^{0}C $\rightarrow$ Requires a light chemistry after + (high pressure) water rinsing

CERN UHV Furnace



5-Cell Cavity

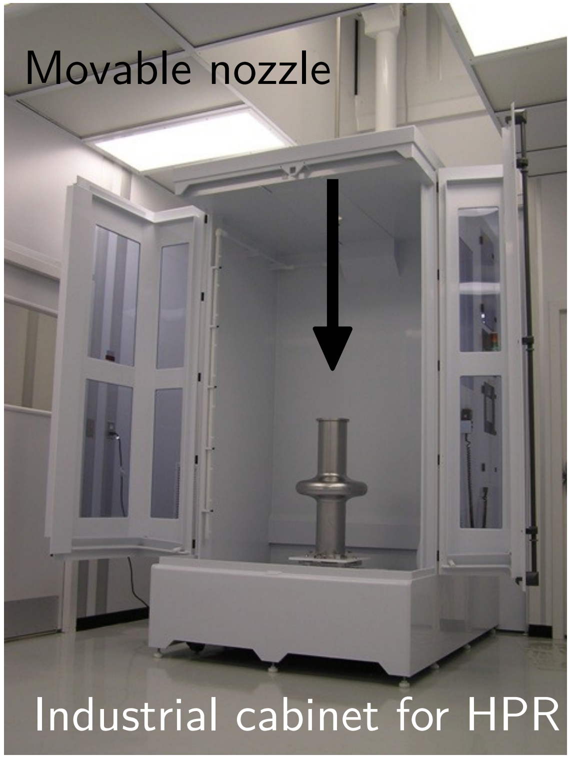


HPR & Clean Room

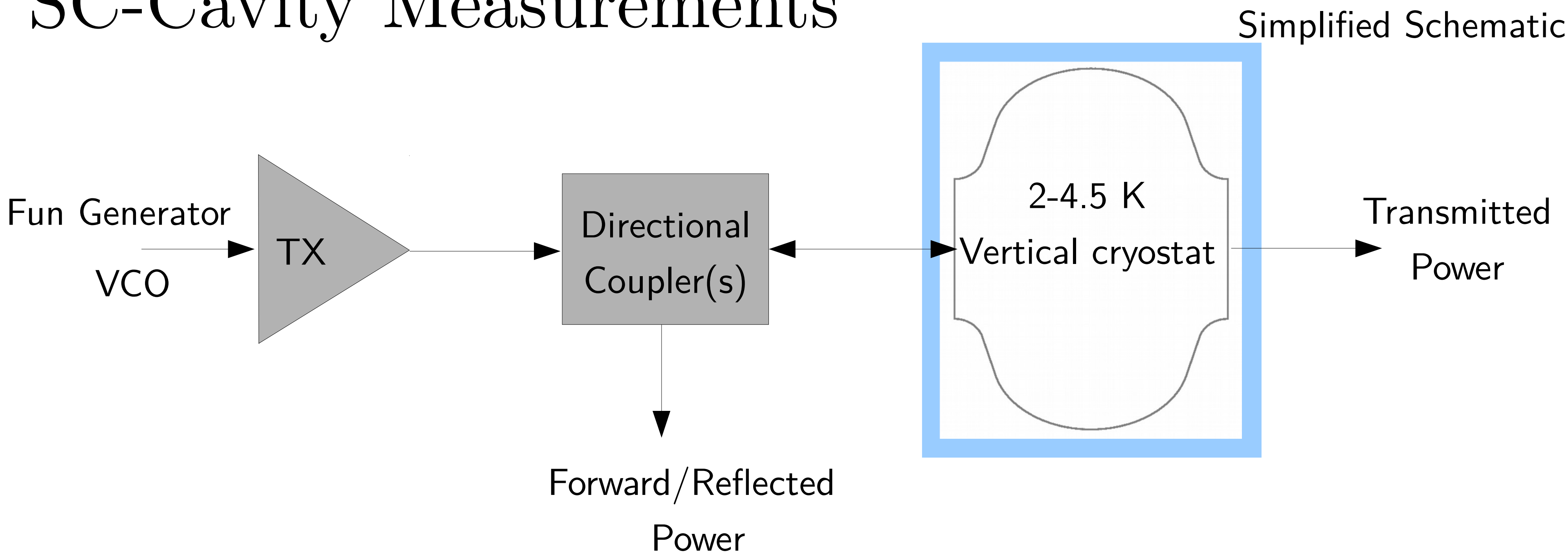
High Pressure Rinsing (ρ=18 MΩcm) and clean room assembly (ISO4) have shown great success in suppressing field emission & improve cavity performance.

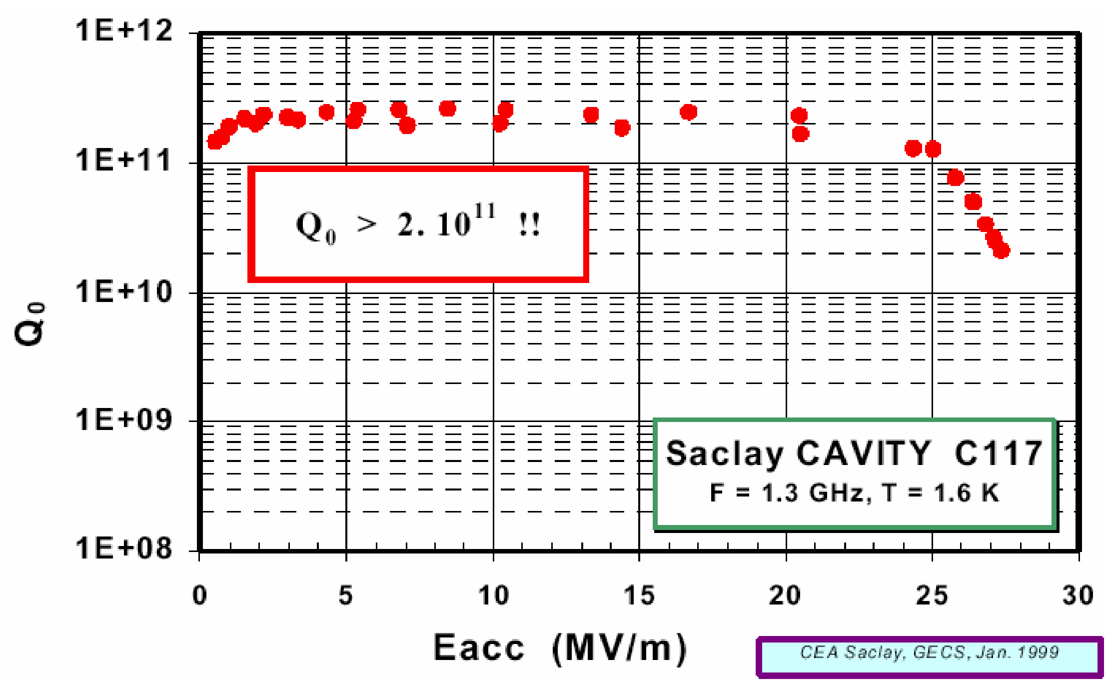
Additional low temp baking (120 ^{0}C) shown to improve high field Q-drop

Clean Room Assembly (ISO4)



SC-Cavity Measurements



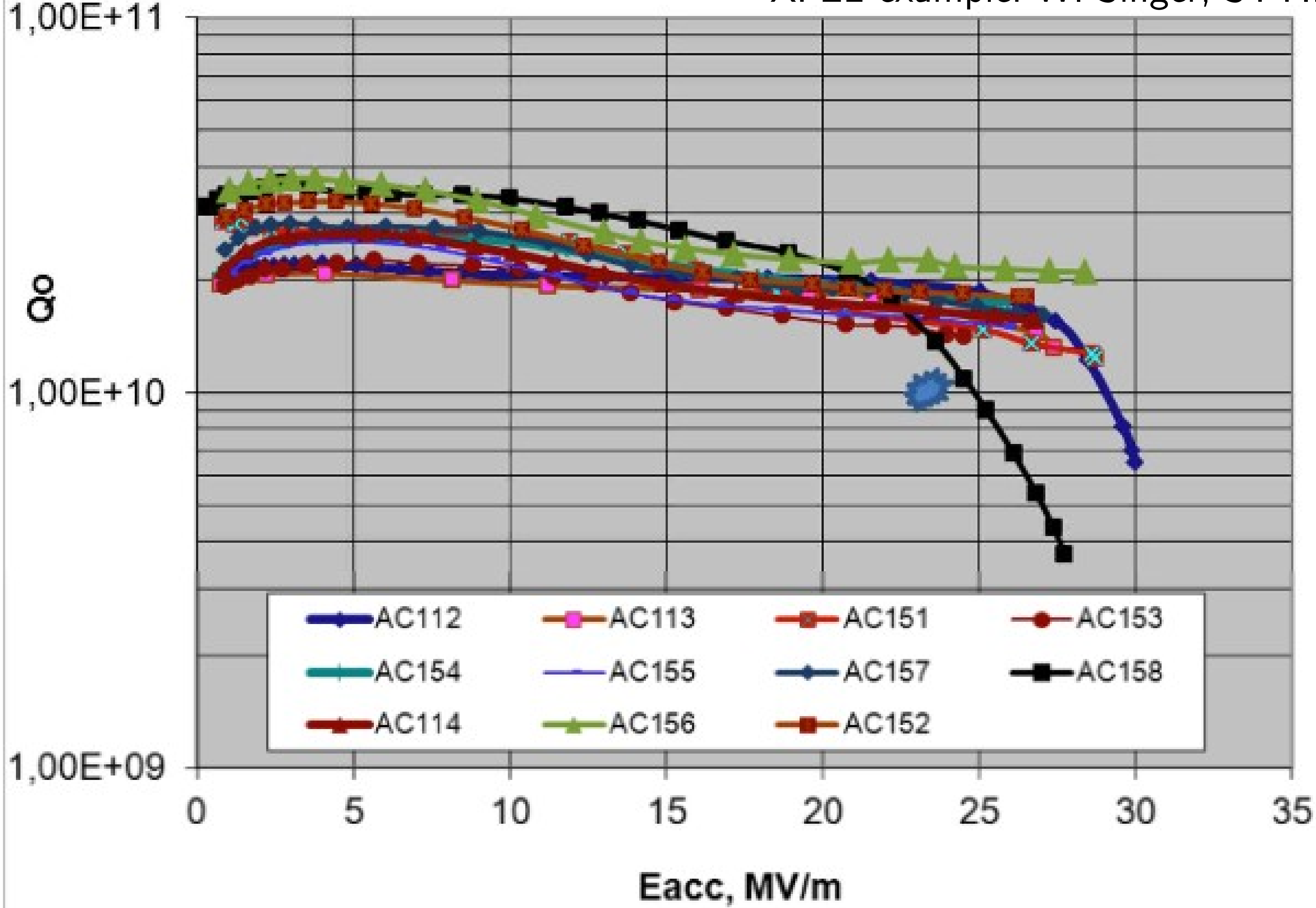


Estimate Q0 vs field from power & field decay measurements

Example single cell (Rs ~ 0.5 nΩ)
Requires very precise setup/calibration

High Q, High Gradient

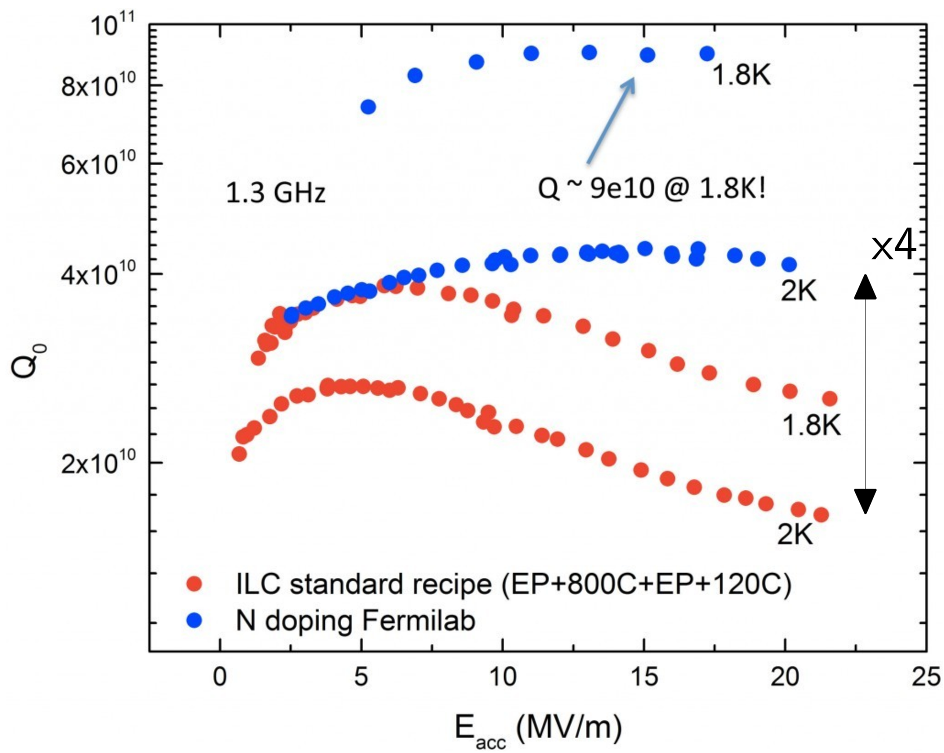
XFEL example: W. Singer, STTIN2010

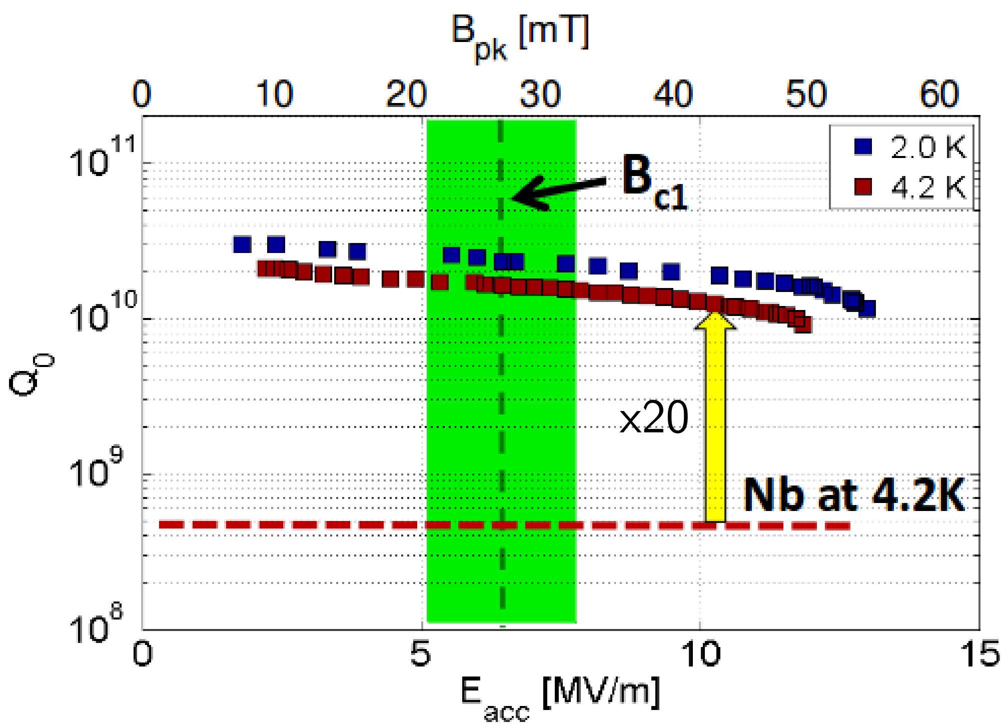


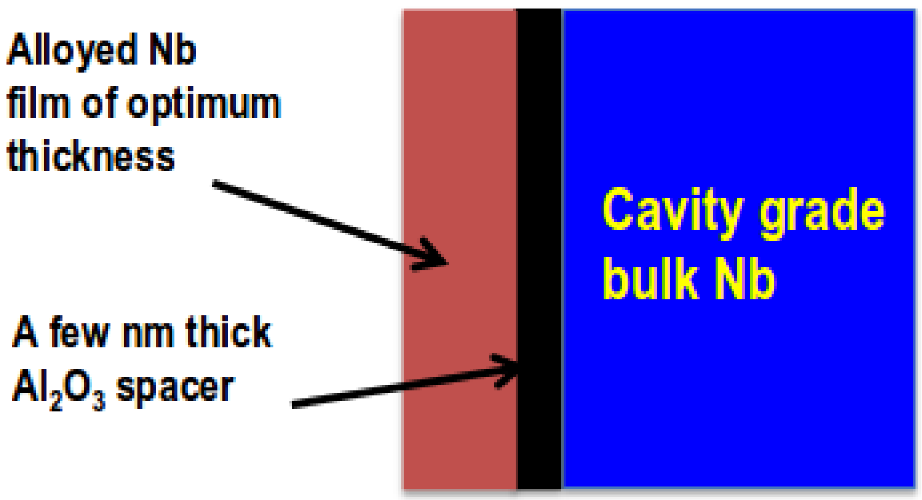
New Paths

Looking beyond state-of-the-art Niobium
Nitrogen doping, Nb3Sn, Multi-layer..

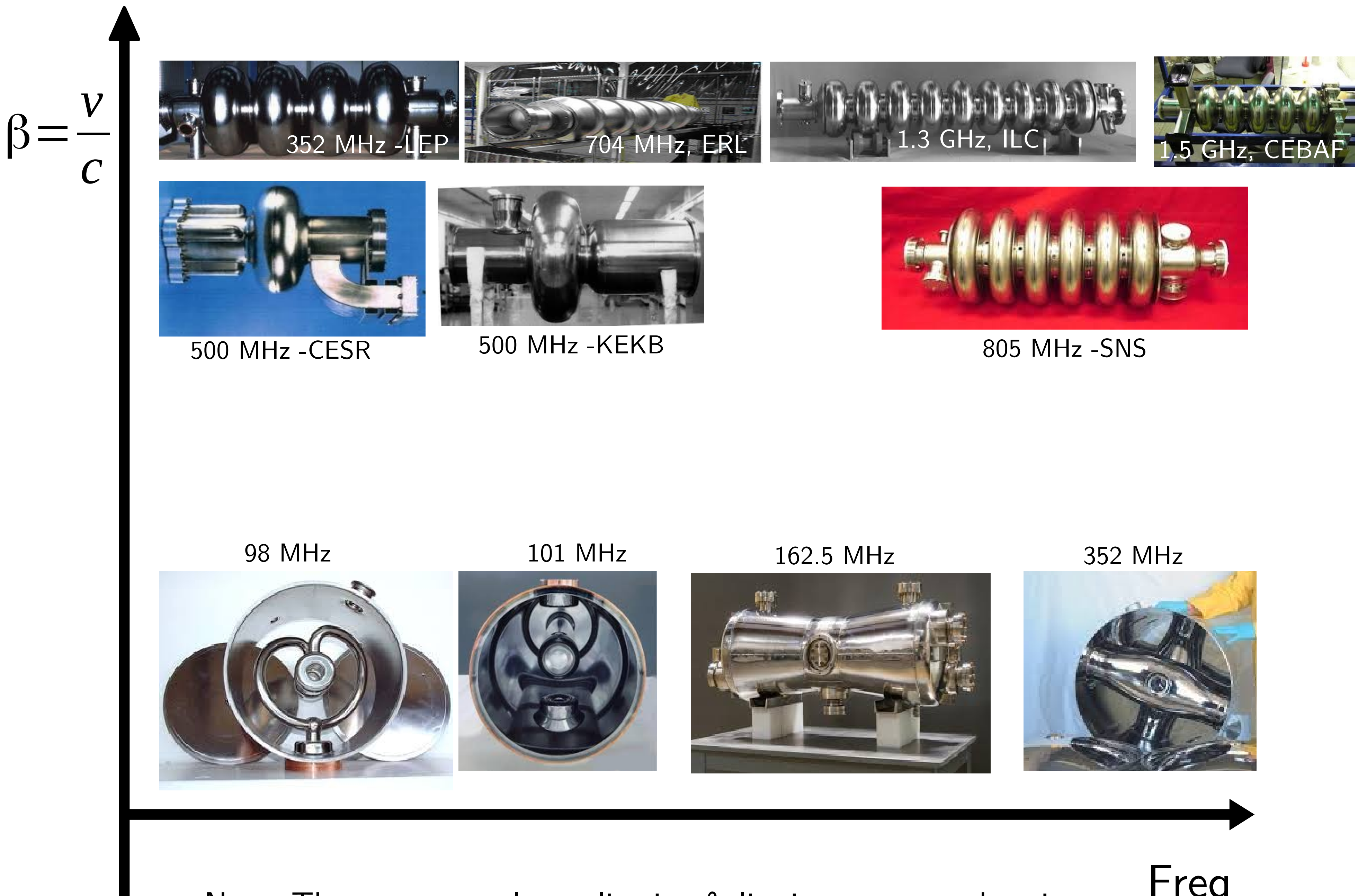
Controlled cool-down for better flux explusion and good magnetic screening







Finally, Some SC-Cavities in Real Life



Note: The axes are only qualitative & list is not comprehensive