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Tutorial

Beam-cavity Interaction and Operational Aspects of SRF Systems with Beam

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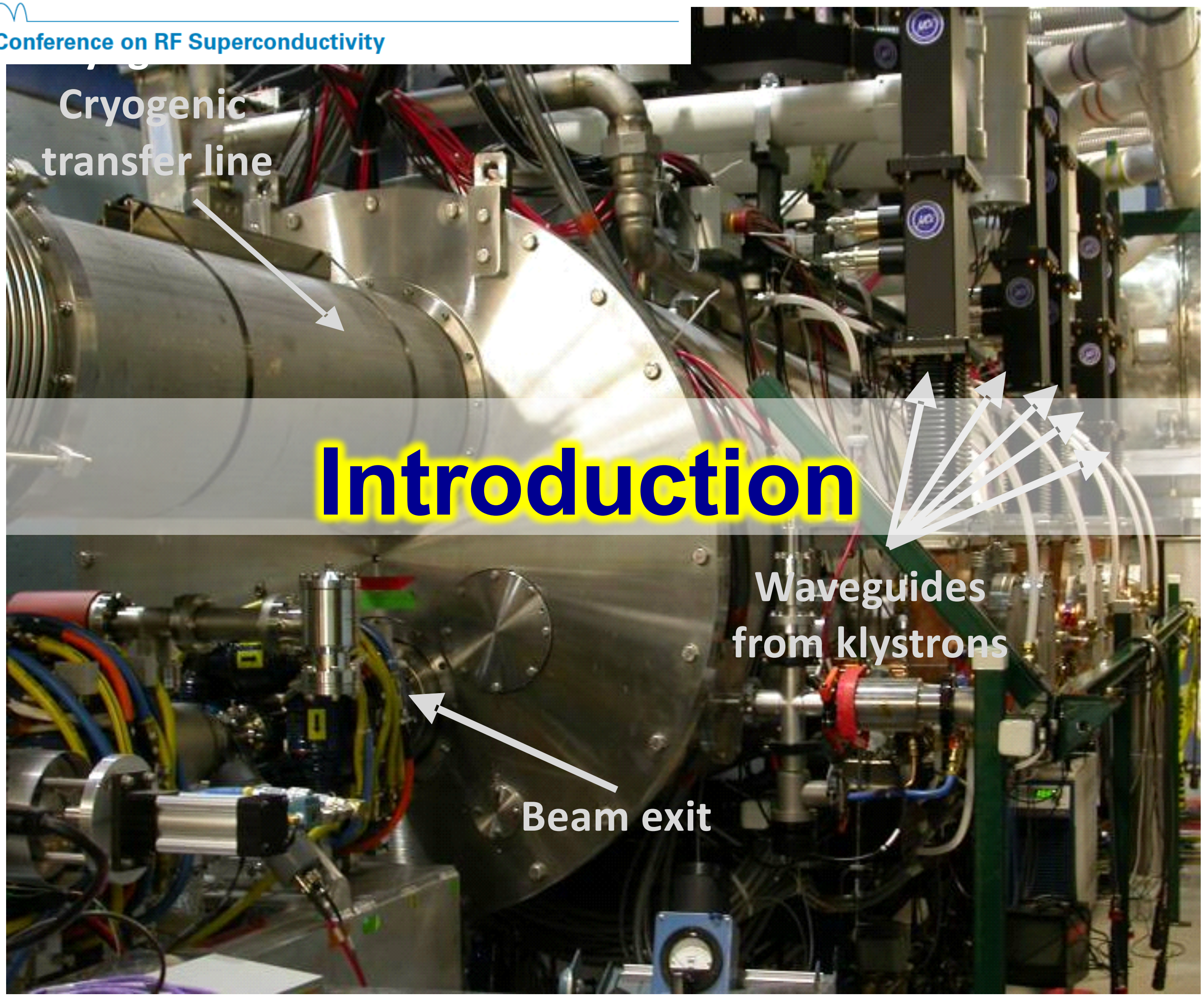
Outline

- **Introduction**
- **Beam-cavity interaction**
  - Fundamental theorem of beam loading
  - Time domain considerations: wakefields, loss factor
  - Frequency domain: higher order mode excitation
  - Beam instabilities
- **Fundamental mode considerations**
  - Circuit model and phasor diagram
  - RF power requirements
- **Some other operational aspects: real-life examples**
  - RF system, interlocks, quench detection, beam-based calibration
  - Vacuum, multipacting & field emission
  - Cryogenics

Introduction

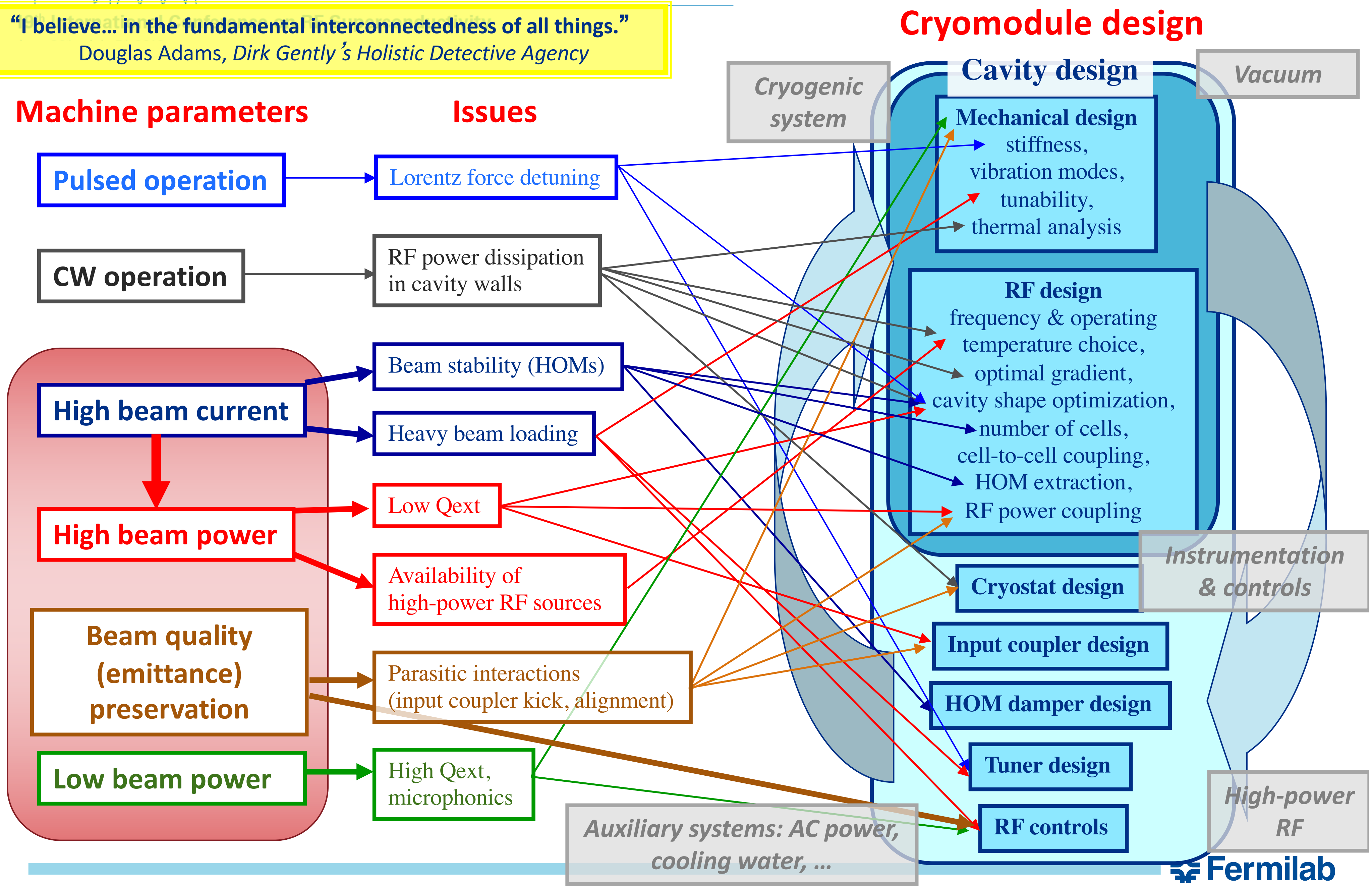


General remarks

- While operational aspects depend on the accelerator type and on the function the SRF system is serving, there are more commonalities than differences. In this tutorial we will try to highlight both.
- Machine and beam parameters define requirements to the SRF system and its auxiliary systems.
- The operational aspects related to beam must be taken into account early during the SRF system design process to avoid unpleasant surprises during operation. Various aspects of the beam-cavity interaction dictate design choices.
- Those aspects include both an impact of the beam on the cavity, which creates problems for sub-systems to deal with, and an impact of the cavity on the beam.
- Depending on the function an SRF system performs, the same aspect of the beam-cavity interaction may be desirable or not.
- The ultimate goal of any SRF system is to reliably provide a stable, high-quality beam with parameters meeting or exceeding the accelerator design specifications for use in experiments.
- As the SRF system developers, we should focus on this goal and utilize the systems approach.

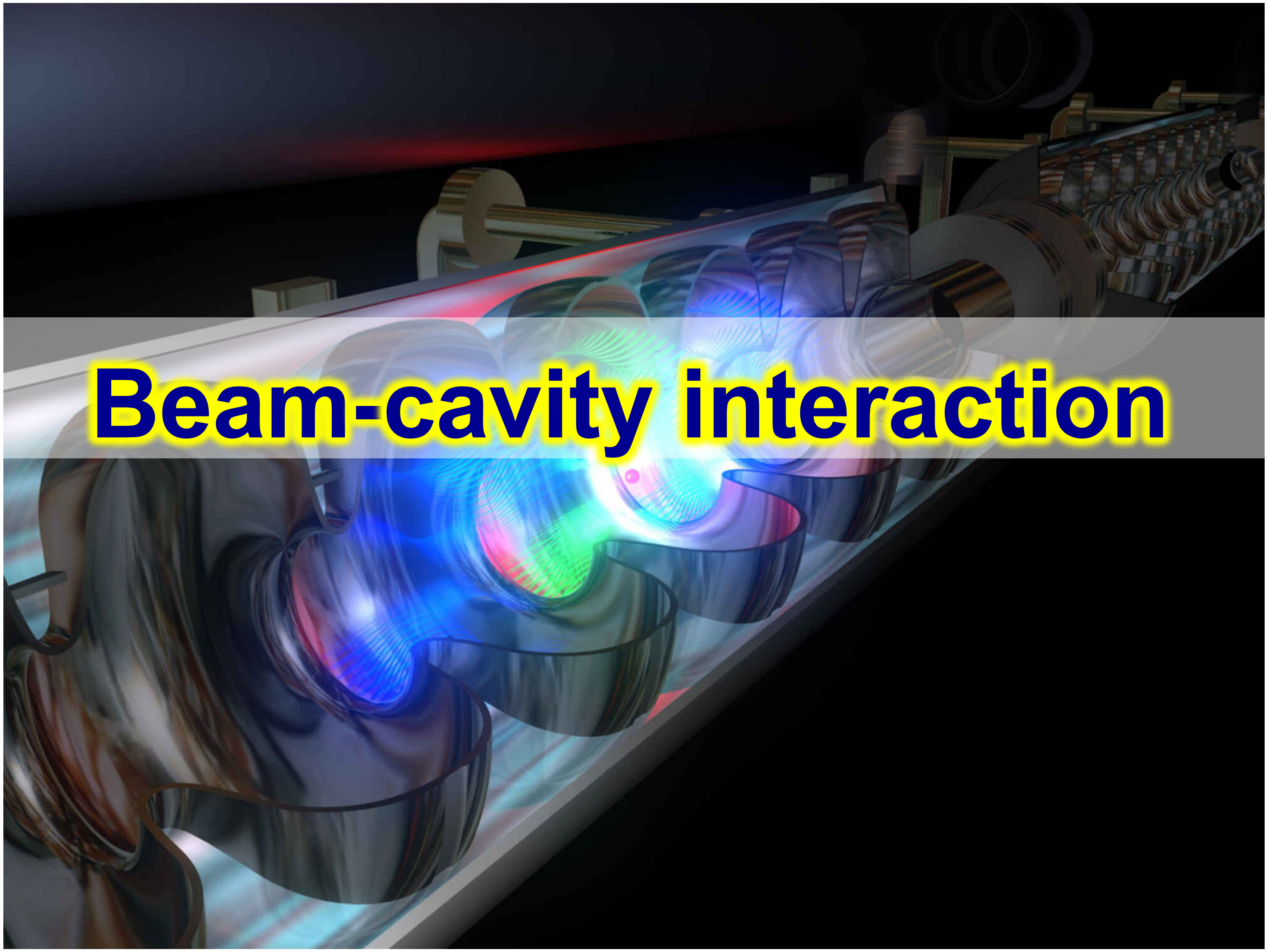
SRF system design interdependences

"I believe... in the fundamental interconnectedness of all things."
Douglas Adams, *Dirk Gently's Holistic Detective Agency*



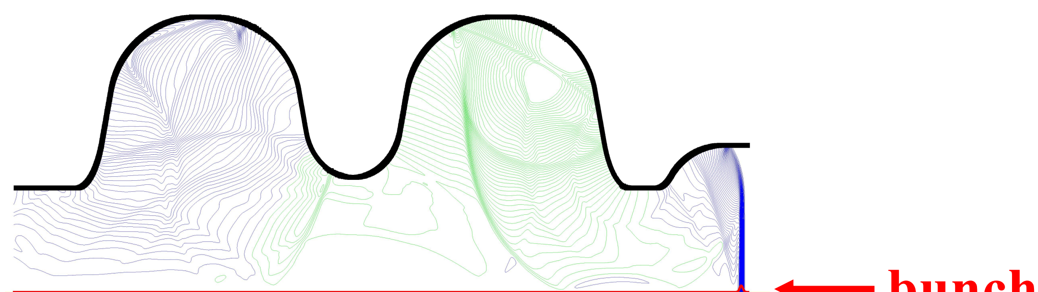
Some beam-related issues

- **High beam current** → beam instability due to interaction with cavity higher-order modes (HOMs) → cavity and HOM absorber design for strong damping; high HOM power handling and heating issues
- **High beam current** → heavy beam loading → tuner design to compensate reactive component; RF controls to fight field perturbations due to transient effects; high RF power amplifiers, input couplers
- **Beam quality (emittance) preservation** → minimize parasitic interactions (coupler kick, HOMs) → input coupler and cavity design; frequency choice; cavity alignment; short range wake fields; RF focusing; high amplitude and phase stability (RF controls)
- **High beam power** → low Q_{ext}, availability of high-power RF sources → input coupler design, frequency choice
- **Low beam power** → high Q_{ext}, microphonic noise → mechanical design (cavity, cryomodule, cryogenic distribution), feedback


Beam-cavity interaction

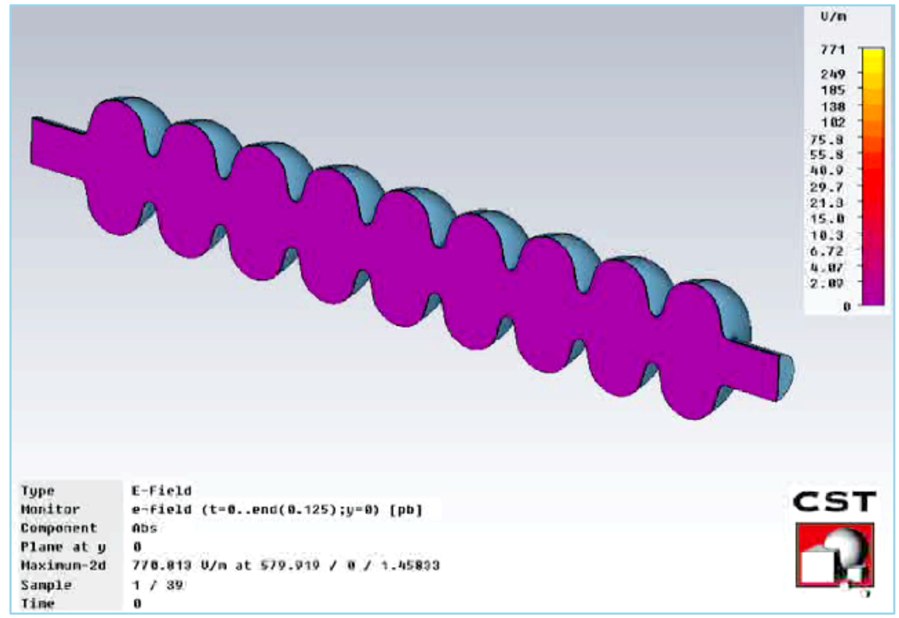
Basic considerations

- As a bunch of charged particles traverses a cavity, it deposits electromagnetic energy, which is described in terms of wakefields.
- The wakefields, in turn, can be presented (via a Fourier transformation) as a sum of cavity eigenmodes (fundamental and HOMs).
- Thus, we can represent the electromagnetic filed excited by the bunch either in time domain (wakefields) or in frequency domain (HOMs).
- If a charge passes through the cavity exactly on axis, it excites only monopole modes. For a point charge this excitation depends only on the amount of charge and the cavity shape.
- Subsequent bunches may be affected by these fields and at high beam currents one must consider beam instabilities and additional heating of accelerator components.

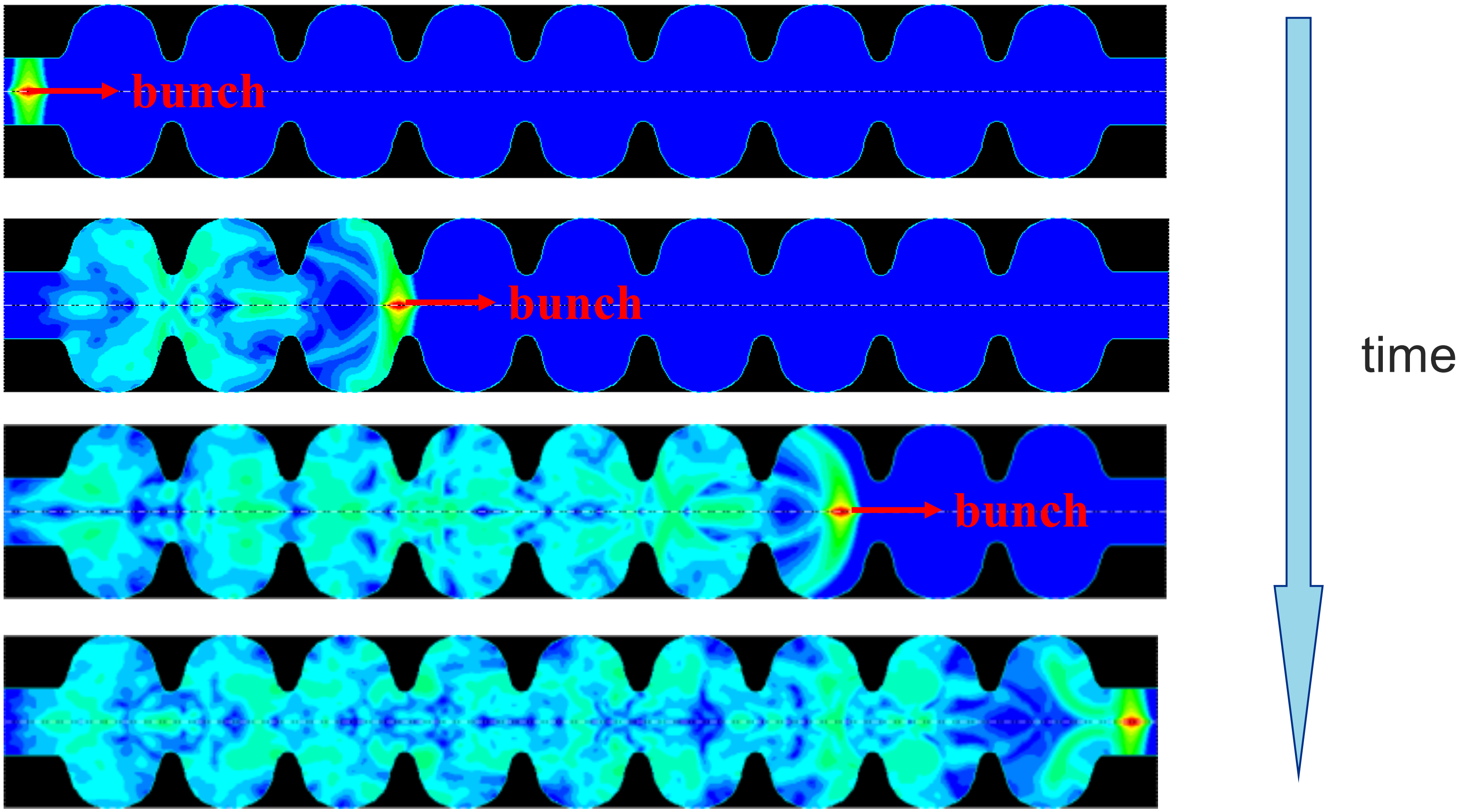


Short- and long-range wakefields

- Short range wake-field → Fields along the bunch and just behind it:
  - Cause bunch energy loss and energy spread along the bunch
  - Single bunch break up instability
  - Cooper pair breaking in the case of extremely short bunches
- Long range wakes (HOMs):
  - Monopole modes: Longitudinal coupled bunch instabilities; RF heating; Longitudinal emittance dilution …
  - Dipole modes: Transverse transverse coupled bunch instabilities; Emittance dilution; beam break-up instabilities …



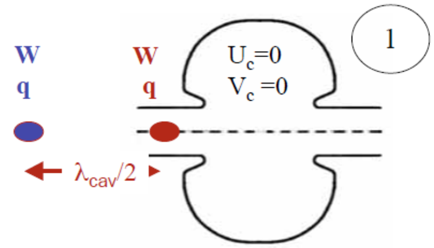
Electromagnetic field excited by bunch



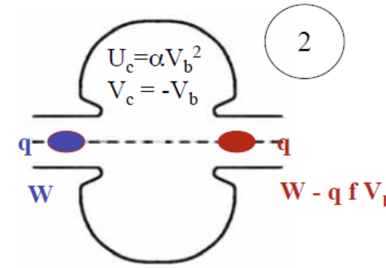
The bunched beam excites electromagnetic field inside an originally empty cavity.

Fundamental theorem of beam loading

- This theorem relates the energy loss by a charge passing through a structure to the electromagnetic properties of modes of that structure.
- A point charge crosses a cavity initially empty of energy.
- After the charge leaves the cavity, a beam-induced voltage $V_{b,n}$ remains in each mode.
- By energy conservation the particle must have lost energy equal to the work done by the induced voltage on the charge.
- What fraction (f) of $V_{b,n}$ does the charge itself see?



Half an rf period later, the voltage has changed in phase by π



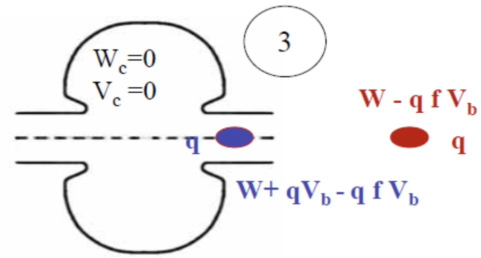
For simplicity:

Assume that the change in energy of the particles does not appreciably change their velocity

Notice:

$\alpha V_b^2 = q\, f\, V_b \implies V_b = q\, f / \alpha$

V_b is proportional to q



Note that **the second charge** has gained energy

$$\Delta W = 1/2\ qV_b$$

from longitudinal wake field of **the first charge**

To summarize:

1. The induced voltage of a beam must have a phase exactly opposite the motion of charge.
2. The particle sees exactly ½ of its own induced voltage

By energy conservation:

$$W + qV_b - q\, fV_b + W - q\, fV_b = W + W$$

$$\implies f = 1/2$$

P. B. Wilson, “High energy electron linacs: Application to storage ring RF systems and linear colliders,” *AIP Conf. Proc.* **87**, 452 (1981). Also, SLAC-PUB-2884 (Rev.), November 1991.

Loss factor

- The energy left behind in the cavity by a charge *q* is

$$W = \alpha V_b^2 = \frac{q^2}{4\alpha} \equiv kq^2$$

- The quantity *k* is called the *loss factor*:

$$k = \frac{V_b^2}{4W}; \ \ V_b = 2V_e = 2kq$$

(here V_e is the effective voltage seen by the charge)

- Thus, the loss factor relates the beam-induced voltage to the charge and to the energy loss by a charge passing through a cavity initially empty of energy.
- Each resonant mode of the cavity has its own value of the loss factor. Recollect that

$$W_{\mathrm{mode}} = \frac{V_{b\,\mathrm{mode}}^2}{\omega_{\mathrm{mode}}(R/Q)_{\mathrm{mode}}}$$

- and thus

$$\boxed{k_{\mathrm{mode}} = \frac{1}{4}\omega_{\mathrm{mode}}\left(\frac{R}{Q}\right)_{\mathrm{mode}}}$$

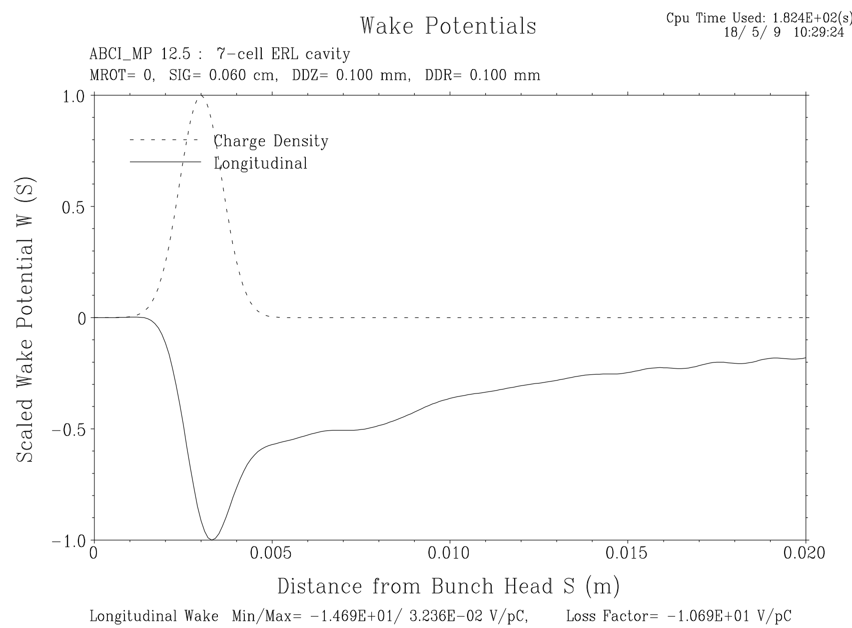
(R/Q is in accelerator definition)

Beam-cavity interaction: time domain

The details of the wakefields themselves are usually of a lesser interest that the integrated effect of a driving charge on a traveling behind it test particle as both particles pass through a structure (the cavity, for example).

The integrated field seen by a test particle traveling on the same path at a constant distance *s* behind a point charge *q* is the longitudinal wake (Green) function *w(s).* Then the *wake potential* is a convolution of the linear bunch charge density distribution *λ(s)* and the wake function:

$$W(s) = \int_{-\infty}^{s} w(s-s')\lambda(s')ds'$$



Once the longitudinal wake potential is known, the total energy loss is given by

$$\Delta U = \int_{-\infty}^{\infty} W(s)\lambda(s)ds$$

and we can calculate the loss factor

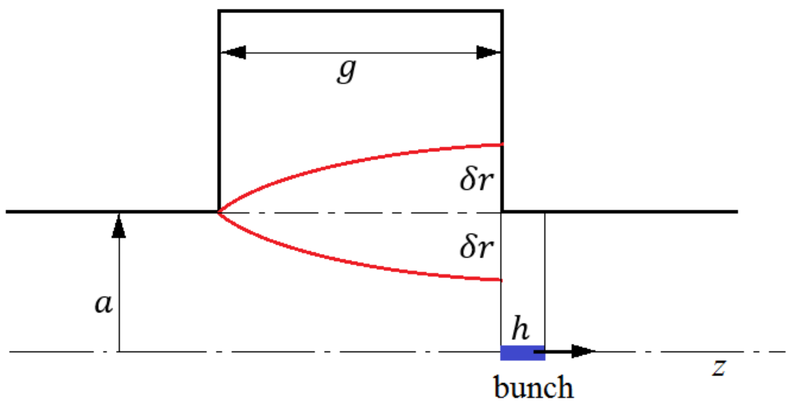
$$k = \frac{\Delta U}{q^2}$$

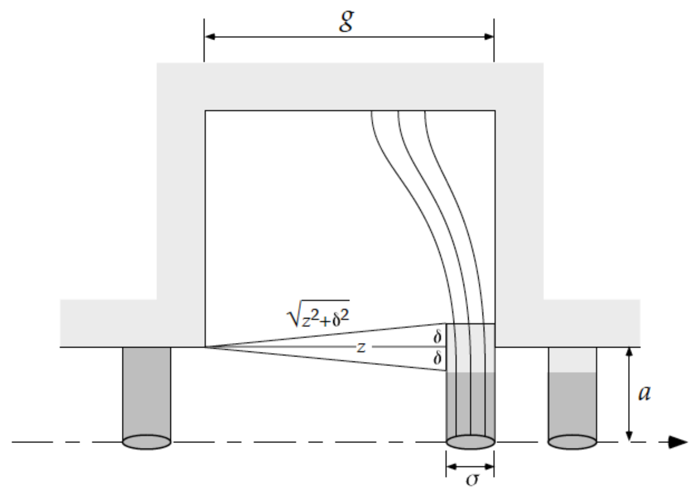
The more energy the bunch looses, the more is the likelihood of adverse effects on the subsequent bunches.

The shape of the wake potential *W(s)* tells us how much energy spread is introduced along the bunch and its distribution.

Loss factor of a pill-box cavity

- Only for a few simple geometries formulas for the loss factor can be derived analytically. One of such geometries is a pill-box cavity.
- For a gaussian beam with the rms length σ interacting with the pill-box cavity having the accelerating gap *g*, and the beam pipe radius *a* we can apply a diffraction model and get





$$k(\sigma) = \frac{\Gamma(1/4)}{4\pi^{5/2}\varepsilon_0 a}\sqrt{\frac{g}{\sigma}},$$

where Γ is gamma-function, $\Gamma(1/4) \approx 3.63$

- For cases where analytic solution cannot be found, we use computer codes such as ABCI, NOVO, CST Particle Studio, …

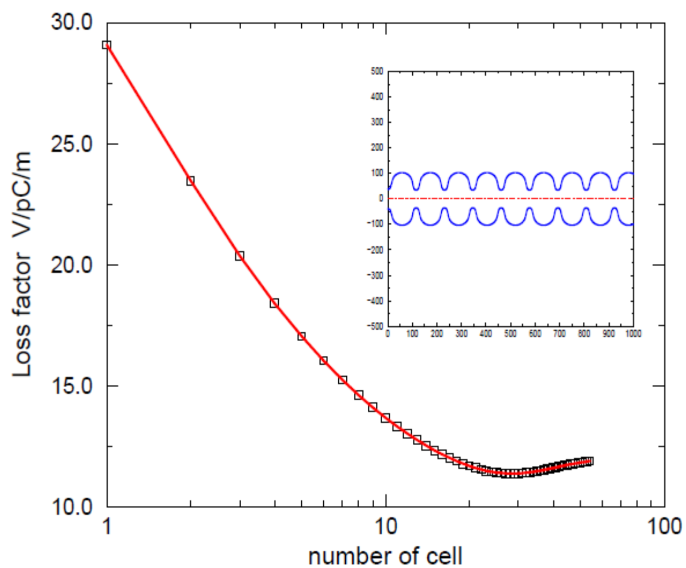
K. L. F. Bane and M. Sands, "Wakefields of very short bunches in an accelerating cavity," SLAC-PUB-4441, November 1987

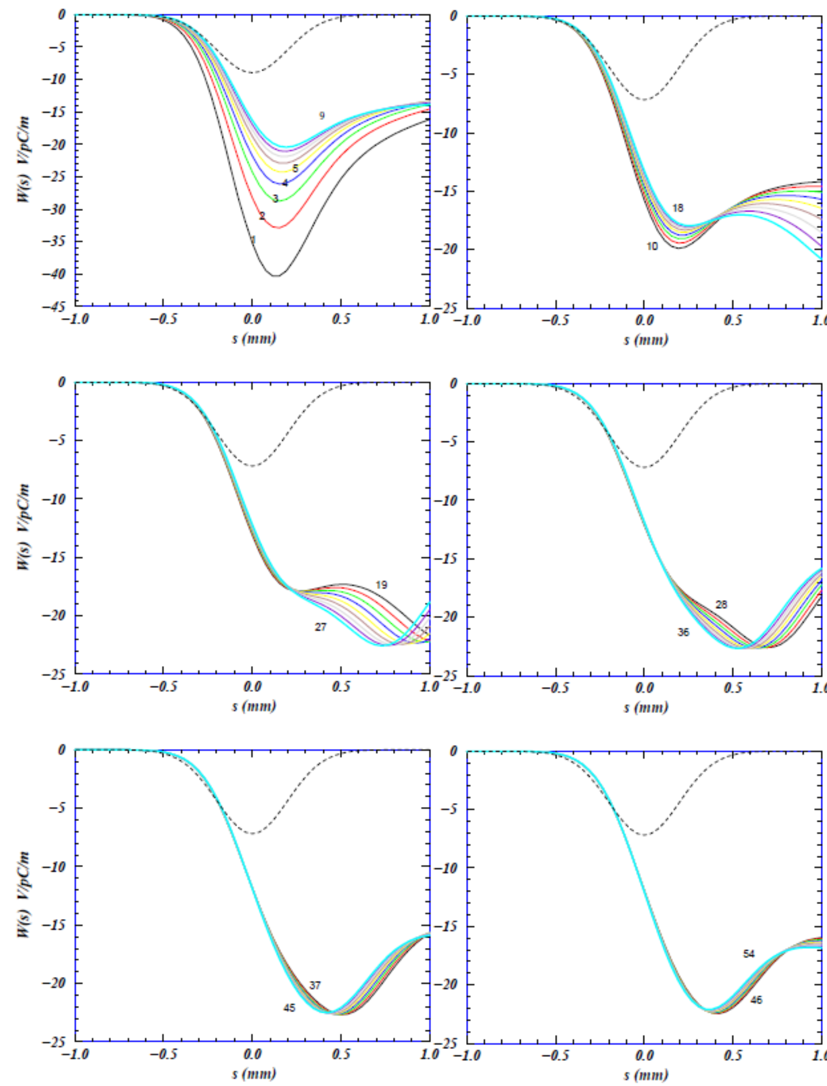
R. B. Palmer, "A qualitative study of wake fields for very short bunches," *Particle Accelerators*, **25**, 97-106 (1990)

Transient wake: chain of TESLA cells

- The modern numerical methods allow simulations of the transient process of the wake field formation in multi-cell cavities and cryo-modules containing very large number of cavities.
- Calculations were performed for a chain of TESLA cells. The loss factor and wake amplitude decrease with the cell number. The shape of the wake does not change significantly after the bunch exceeds the catch-up distance, which is ~3 m (27 TESLA cells) for this case (σ = 0.2 mm, a = 35 mm)

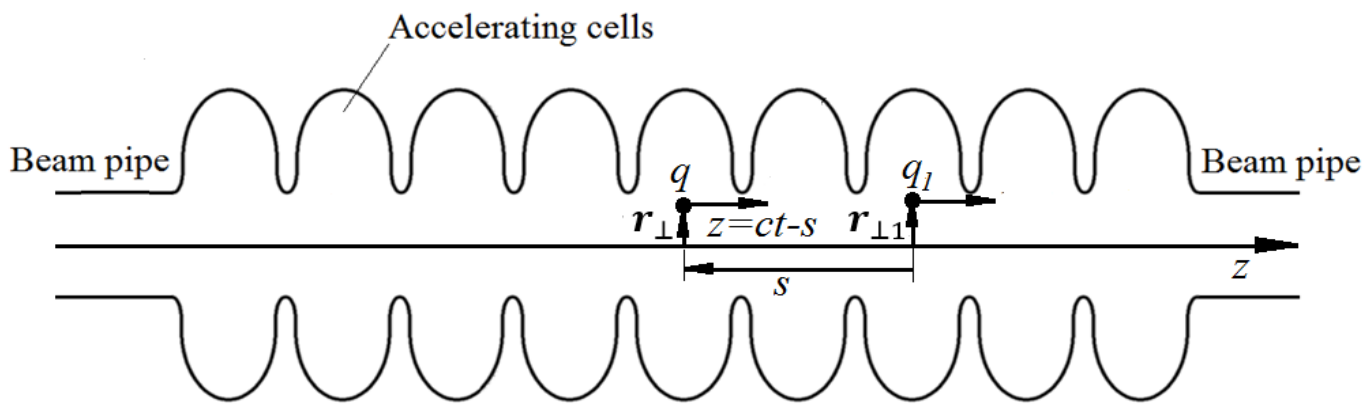
$$L = \frac{a^2}{2\sigma_z}$$





A. Novokhatski, M. Timm and T. Weiland, “Transition dynamics of the wakefields of ultra short bunches,” TESLA Preprint, TESLA 2000-03, (2000)

Transverse wake potential



A multi-cell cavity is excited by a point source charge q_1 moving along the axis z and having transverse coordinate $r_{\perp 1}$. The test charge q also moves along the axis at the distance s behind the source charge. The test charge has the transverse coordinate $r_\perp$.

Similar to the longitudinal case, one can define the transverse wake potential $W_\perp(r_\perp, r_{\perp 1}, s)$, which describes transverse momentum kick delivered to the test particle:

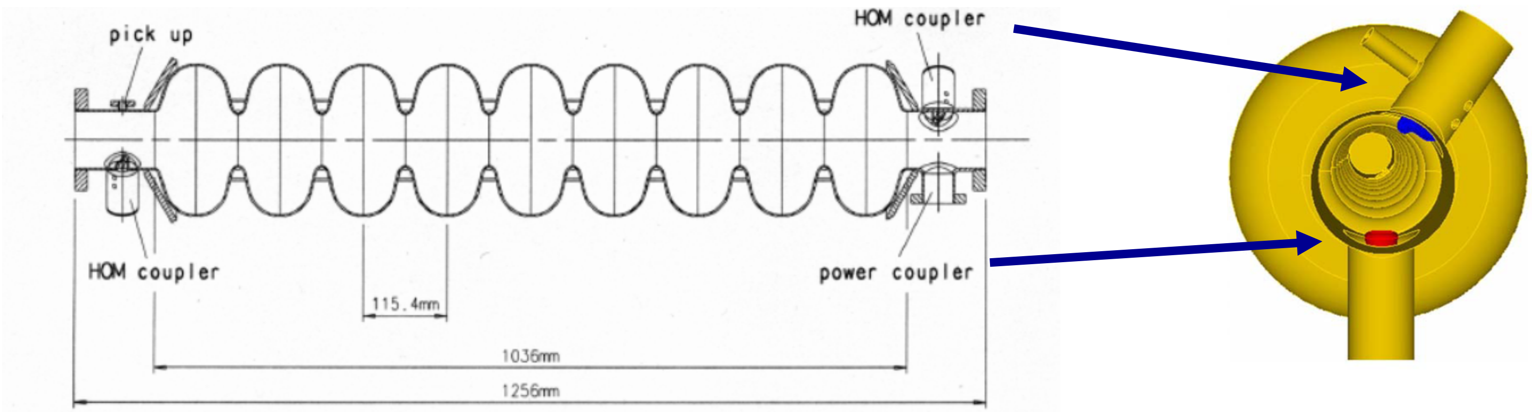
$$\Delta \boldsymbol{p}_\perp c = \int_{-\infty}^{\infty} \boldsymbol{W}_\perp(\boldsymbol{r}, s)\rho(s)ds = \boldsymbol{r} q^2 k_\perp$$

here $k_\perp$ is the kick factor.

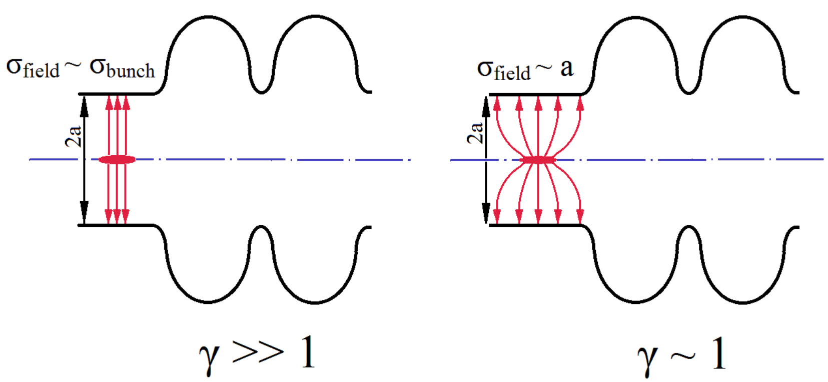
Other issues to consider

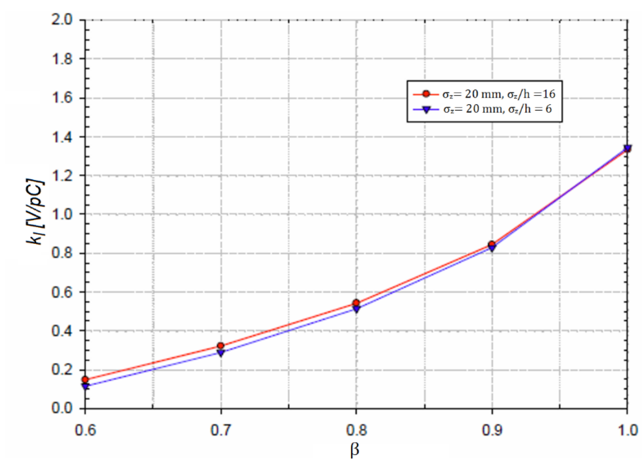
Here are some other issues I would like to mention:

- Asymmetries in the accelerating cavities of the linac generate fields that kick the beam transversely and may degrade the beam emittance and thus the accelerator performance.



- For a non-relativistic case, the “field size” at the aperture is about the aperture radius *a*. So, the loss factor increases with the bunch velocity β.





Loss factor of cavity modes

- In the frequency domain, the loss factor can be represented as a sum of individual loss factors of cavity modes

$$k = \sum_n k_n = \sum_n \frac{\omega_n}{4}\left(\frac{R}{Q}\right)_n$$

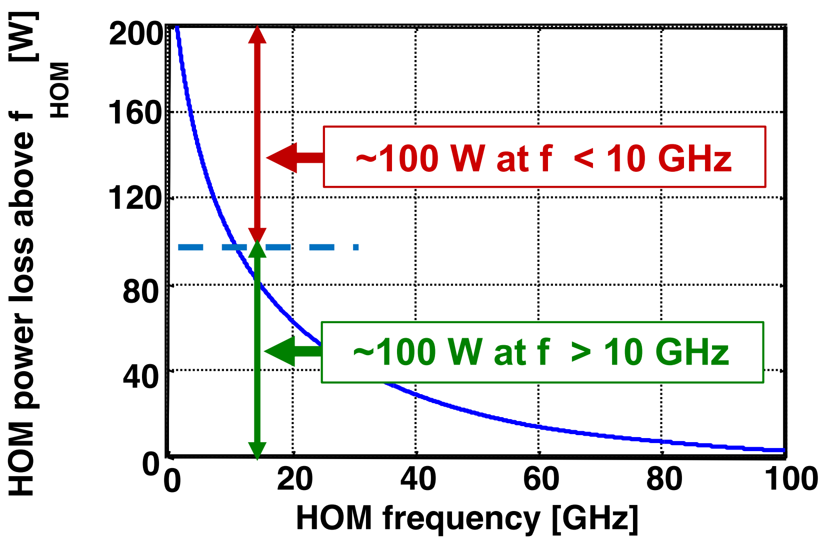
- The loss factor can be used to calculate beam losses due to HOMs over the whole bunch spectrum. This approximation works usually quite well.

$$P_{HOM} = k_{HOM} \cdot q \cdot \boxed{I_{av}}$$

(here q is the bunch charge, I_{av} is the average beam current)

<u>*Example*</u>:

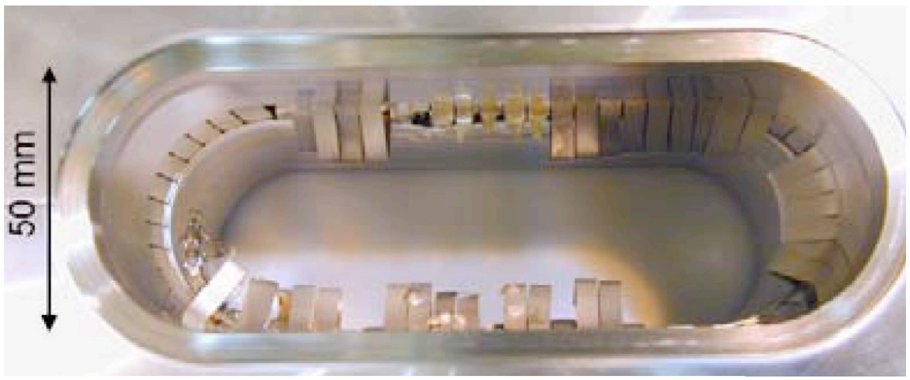
- 100 mA ERL beam
- 0.6 mm (rms) long 77 pC bunches
- 7-cell cavities with loss factor of 13 V/pC

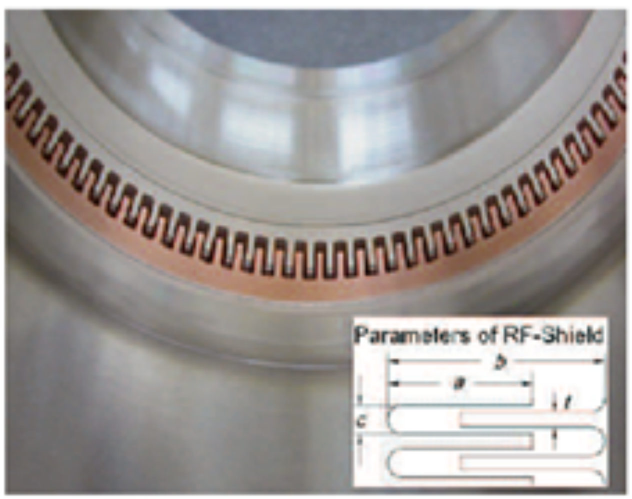


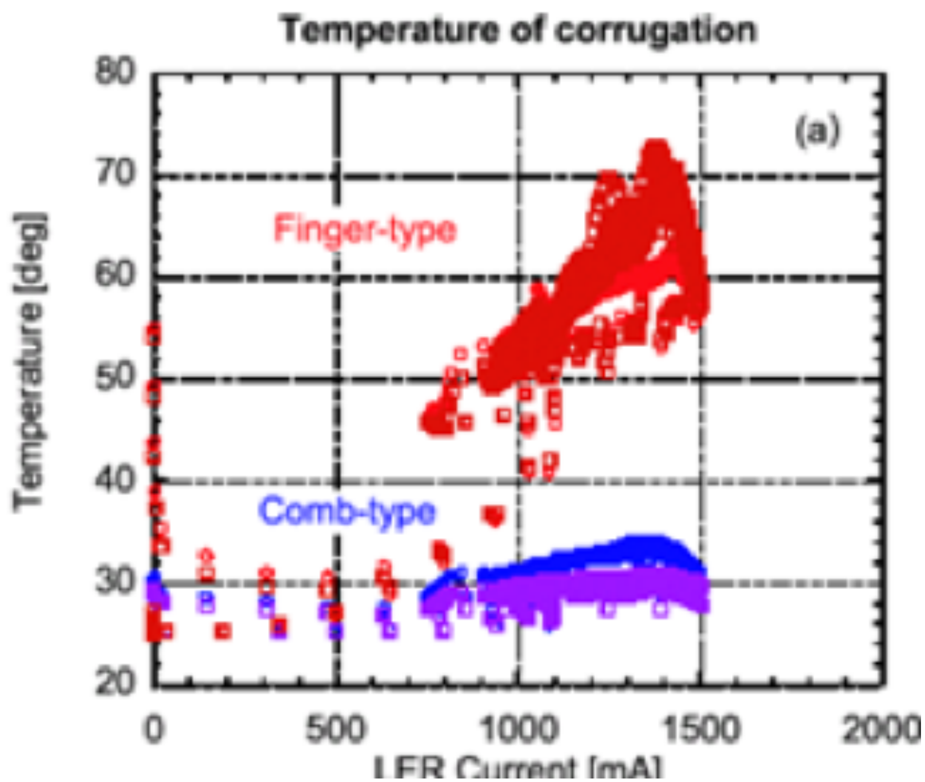
- ~50% of HOM power is above 10 GHz!
- Short bunches can excite very high frequency modes

HOM power heating

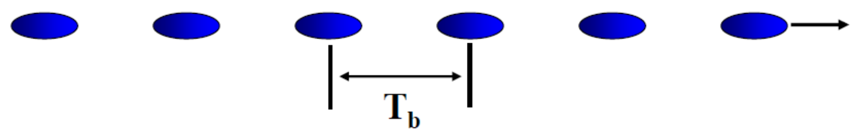
- Shielded bellows at KEK-B: A comb-type RF shield was developed to replace RF fingers damaged by HOM power heating



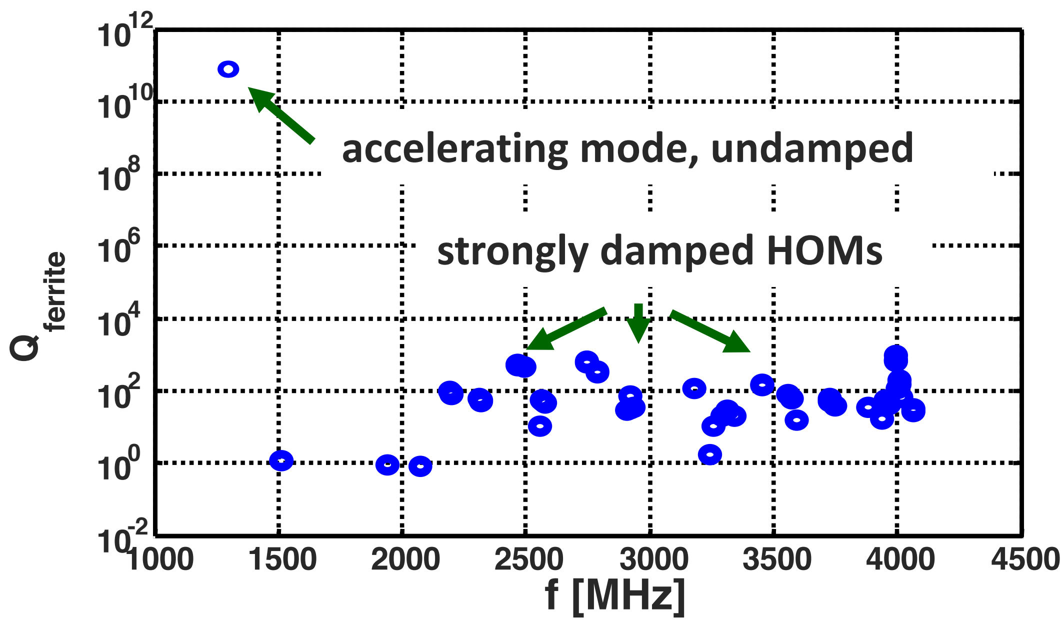




Beam-cavity interaction: frequency domain



- If the wakefields (HOMs) do not decay sufficiently between the bunches, then fields from subsequent bunches can interfere constructively (resonant effect, if $f_{HOM} \approx N/T_b$) and cause excessive HOM power loss and various instabilities.
- That is why practically all SRF cavities have special devices to damp HOMs (absorb their energy). For analysis of many instabilities, it is more convenient to use frequency domain rather than time domain approach.



$$P_{HOM}^{res} = (R/Q)_{HOM} Q_{L,HOM} I_{beam}^2$$

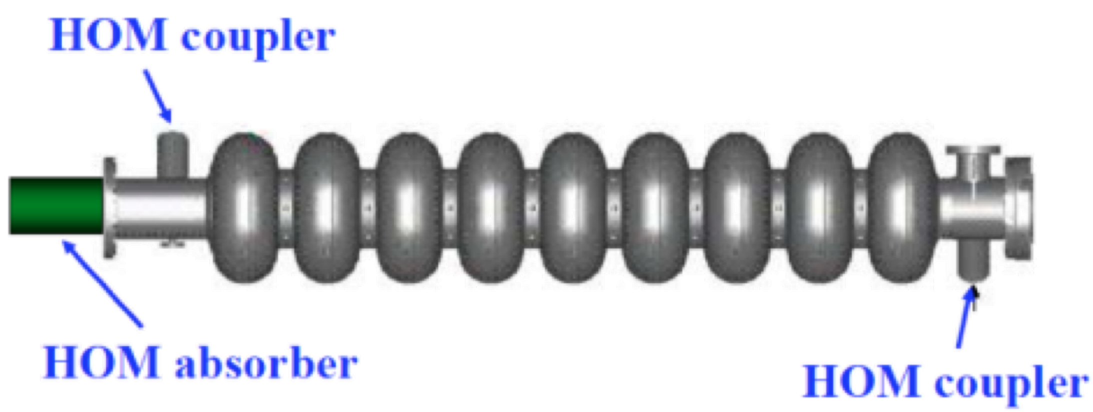
Beam quality deterioration and instabilities

Beam-excited wakes/HOMs can cause detrimental effects such as:

- Multi-bunch instabilities (longitudinal and transverse) in storage rings
- Multi-pass beam break-up (BBU) instabilities (transverse and longitudinal) in re-circulating linacs
- Single-pass BBU in linacs
- Increased beam energy spread and/or beam emittance dilution

Most of these effects are associated with HOMs. This is why most SRF cavities have special devices to damp HOMs (absorb their energy and reduce parasitic impedance).

In the following we will consider two examples of beam instabilities.



Example 1: Multi-bunch instability in storage rings

- Consider a single-bunch beam interacting with a narrow-band resonance.
- The revolution time of the bunch depends on the average energy of particles within a bunch and the Fourier spectrum of the bunch current being made up of harmonics of the revolution frequency is therefore energy dependent.
- On the other hand, by virtue of the frequency dependence of the cavity impedance, the energy loss of a bunch in the cavity depends on the revolution frequency.
- We have therefore an energy dependent loss mechanism which can lead to damping or growth of *coherent longitudinal oscillations*. This effect is generally referred to as ***Robinson instability***.
- In case of M bunches one can generalize this to get M coupled-bunch modes with the phase shift between adjacent bunches for the mode number n

$$\Delta\varphi_n = \frac{2\pi}{M} n, \quad n = 0, 1 \ldots M-1$$

Growth rate of the multi-bunch instability

The exact location of the HOM resonant frequency ω_r relative to the nearest harmonic of revolution frequency $p\omega_0$ is of critical importance for the stability of the beam as one can see from the equation for the growth rate and the figure in the next slide:

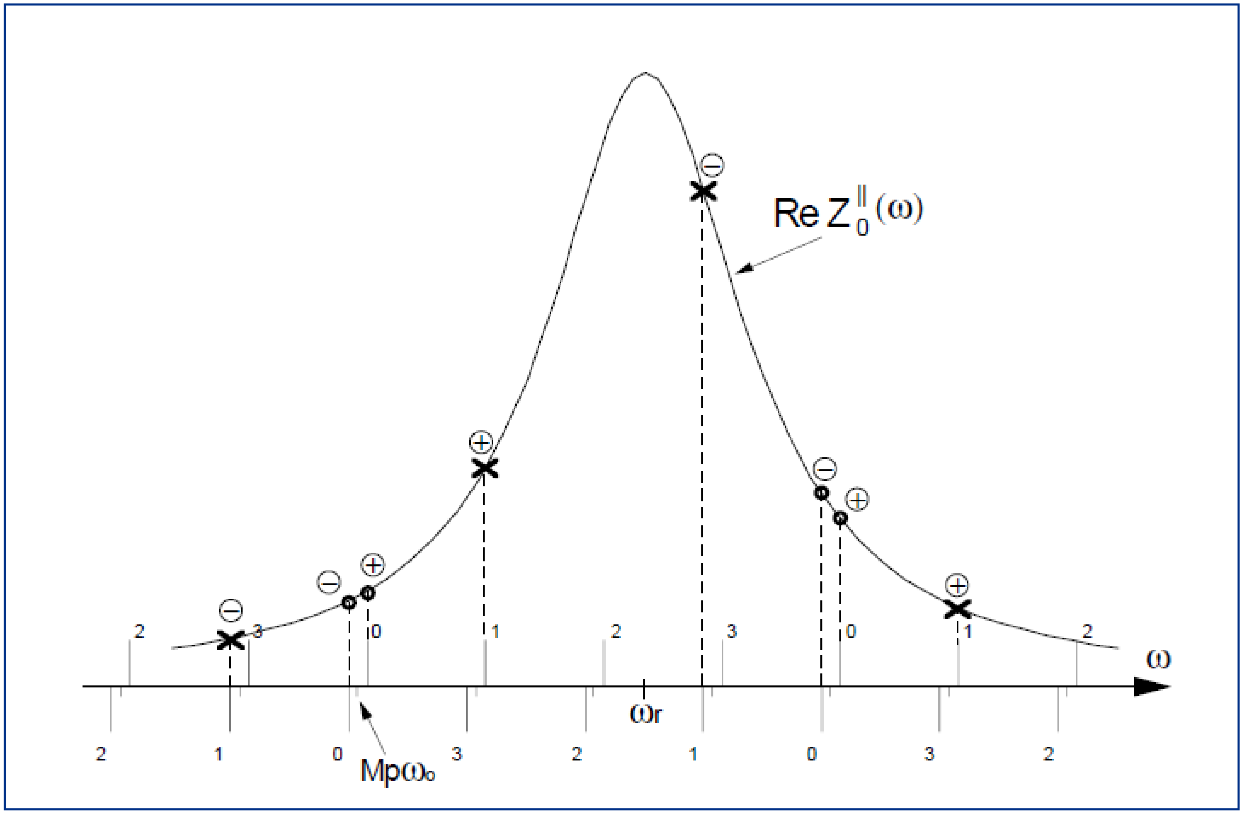
$$\begin{aligned}
\tau_n^{-1} &= \omega_s \frac{I_0}{2hV_c \cos(\phi_s)\omega_0} \sum_{p=-\infty}^{\infty} (pM\omega_0 + n\omega_0 + \omega_s) ReZ_0^{||}(pM\omega_0 + n\omega_0 + \omega_s) \\
&= \omega_s \frac{I_0}{2hV_c \cos(\phi_s)\omega_0} \times \\
&\quad \times \sum_{p=0}^{\infty} \left[(pM\omega_0 + n\omega_0 + \omega_s) ReZ_0^{||}(pM\omega_0 + n\omega_0 + \omega_s) - (pM\omega_0 - n\omega_0 - \omega_s) ReZ_0^{||}(pM\omega_0 - n\omega_0 - \omega_s) \right] \\
&\approx \boxed{\omega_s \frac{I_0}{2hV_c \cos(\phi_s)} \sum_{p=0}^{\infty} \left[(pM + n) ReZ_0^{||}(pM\omega_0 + n\omega_0 + \omega_s) - (pM - n) ReZ_0^{||}(pM\omega_0 - n\omega_0 - \omega_s) \right]}
\end{aligned}$$

here ω_s is the synchrotron oscillation frequency,

$$\omega_s = \omega_0 \sqrt{\frac{\eta \cdot h \cdot V_c \cos\varphi_s}{2\pi \cdot E_0}}$$

h is the RF harmonic number, η is the slippage factor, I_0 is the total beam current, V_c is the total cavity voltage (sum over all cavities), φ_s is the synchronous phase, Z_0 is the cavity impedance (sum over all cavities), E_0 is the beam energy.

HOM impedance and beam spectrum



Real part of an HOM impedance and spectrum of the 4-bunch beam sidebands for $n = 0$ and 1.

Threshold current

Assuming the worst case, when the HOM resonant frequency coincides with the "bad" sideband, so that the growth rate is dominated by just one term in the equation, one can derive the following formula for the instability threshold current (τ_d is the "natural" damping time of oscillations, N_{cav} is the number of identical cavities)

High E_{acc} reduces the number of cells

$$I_{th} = \frac{1}{\tau_d} \frac{2V_c \cos(\varphi_s) \cdot \omega_{rf}}{\omega_s \cdot \omega_r \cdot (R/Q)_{HOM} \cdot Q_{L,HOM} \cdot N_{cav}} \propto \frac{E_{acc}}{(R/Q)_{HOM} \cdot Q_{L,HOM} \cdot \omega \cdot \omega^{1/2}}$$

Choose a geometry that has low *R/Q* for HOMs

Design couplers that extract HOMs efficiently, use single-cell cavities

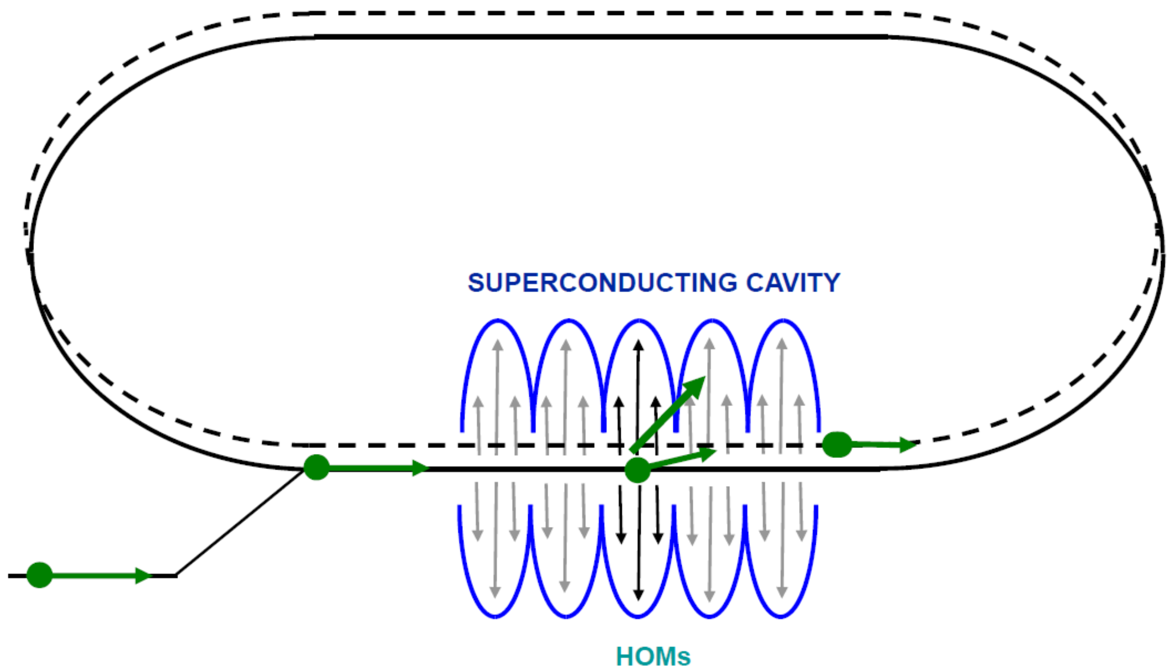
Low frequency reduces synchrotron frequency

Low frequency reduces number of cells

As we see from this formula, the beam instability threshold current is inversely proportional to the impedance of HOMs and frequency.

Example 2: BBU in re-circulating linacs

- If a particle enters a cavity on axis when a dipole HOM has been excited, then the particle will leave with a deflection in the horizontal or vertical direction.
- The optics of the recirculation line will cause the transverse momentum imparted to the particle by the HOM to result in the particle entering the cavity with a transverse displacement when it returns back.
- The transverse offset can cause the particle to further excite the HOM and this process can continue until the particle collides with the cavity wall.



BBU threshold current

- The threshold current at which a multi-pass BBU occurs is predicted by the approximate expression

$$I_{th}^{l} = \frac{-2pc}{e\cdot(R/Q)_m Q_{L,m} k_m M_{ij} \sin(\omega_m t_r + l\pi/2) e^{\omega_m t_r/2Q_m}} \propto \frac{-2pc}{e(R/Q)_m Q_{L,m} k_m M_{12}}$$

for transverse BBU

where
for $i,j = 1,2$ or $3,4$ and if the mode m is the transverse HOM, this formula is for the transverse BBU
for $i,j = 5,6$ and if the mode m is the monopole HOM, this formula is for the longitudinal BBU;
if the mode m is fundamental mode, it is for the beam-loading instability;
$l = 1$ for longitudinal HOMs and 0 otherwise;

p is the momentum of the particle, c is the speed of light, e is the charge of the electron, R/Q is the shunt impedance of the mode m, Q is the quality factor of the mode, $k = \omega/c$ is the wave number of the mode, and M_{12} is the transfer matrix element relating the transverse momentum at the cavity exit to the transverse displacement of the particle at the entrance of the same cavity during the next pass. The HOM of concern is the one which corresponds to the lowest threshold current.

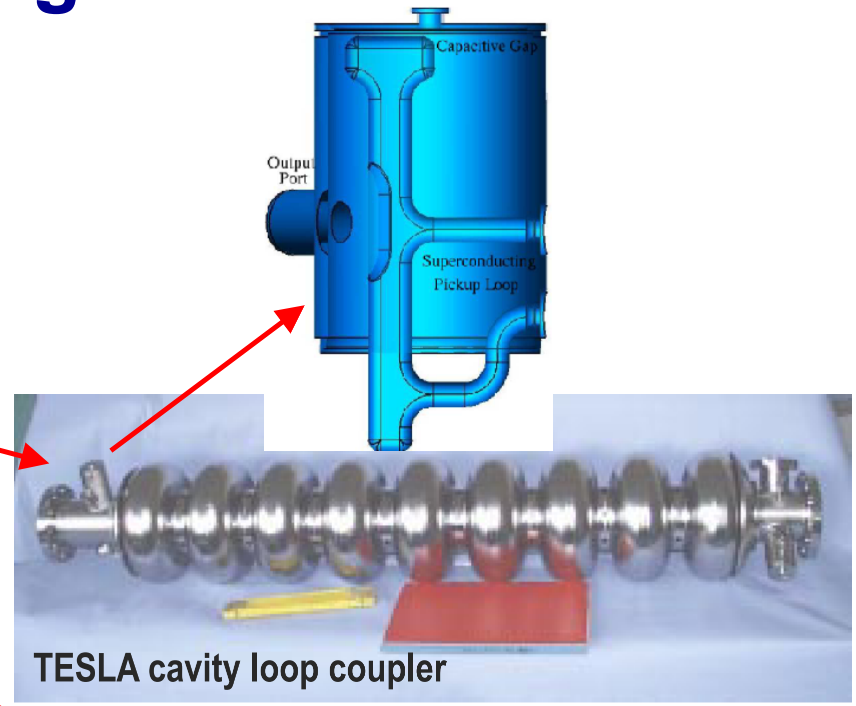
- One can see that similarly to the storage sing case, the threshold current is inversely proportional to the impedance of HOMs and frequency.
- **The HOM impedance must be controlled to achieve high beam currents!**

HOM extracting/damping solutions

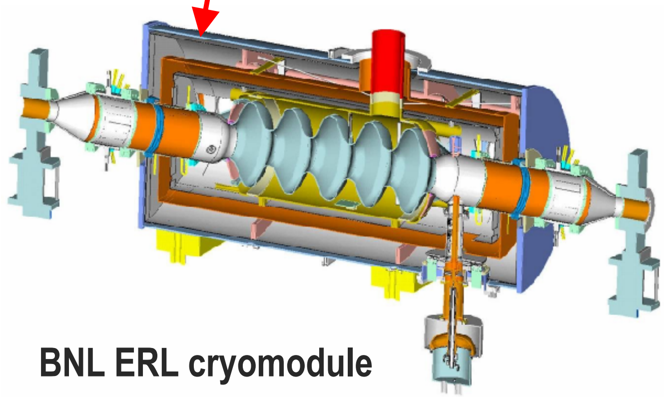
Several approaches are used:

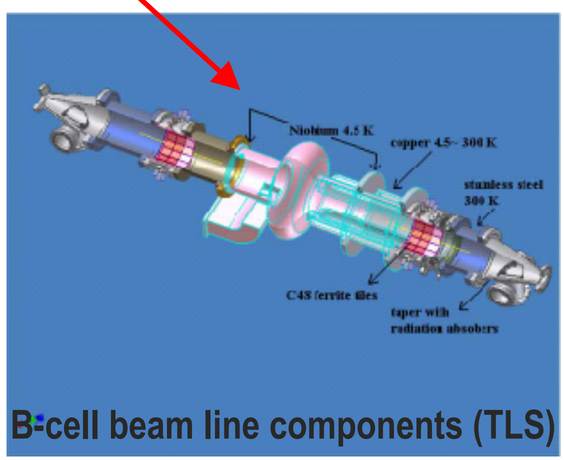
- Loop couplers (several per cavity for different modes/orientations)
- Waveguide dampers
- Beam pipe absorbers (ferrite or ceramic)

see details in E. Kako's tutorial

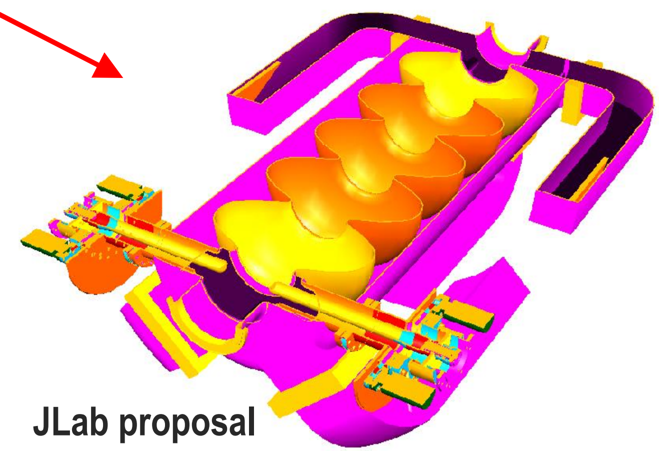


TESLA cavity loop coupler

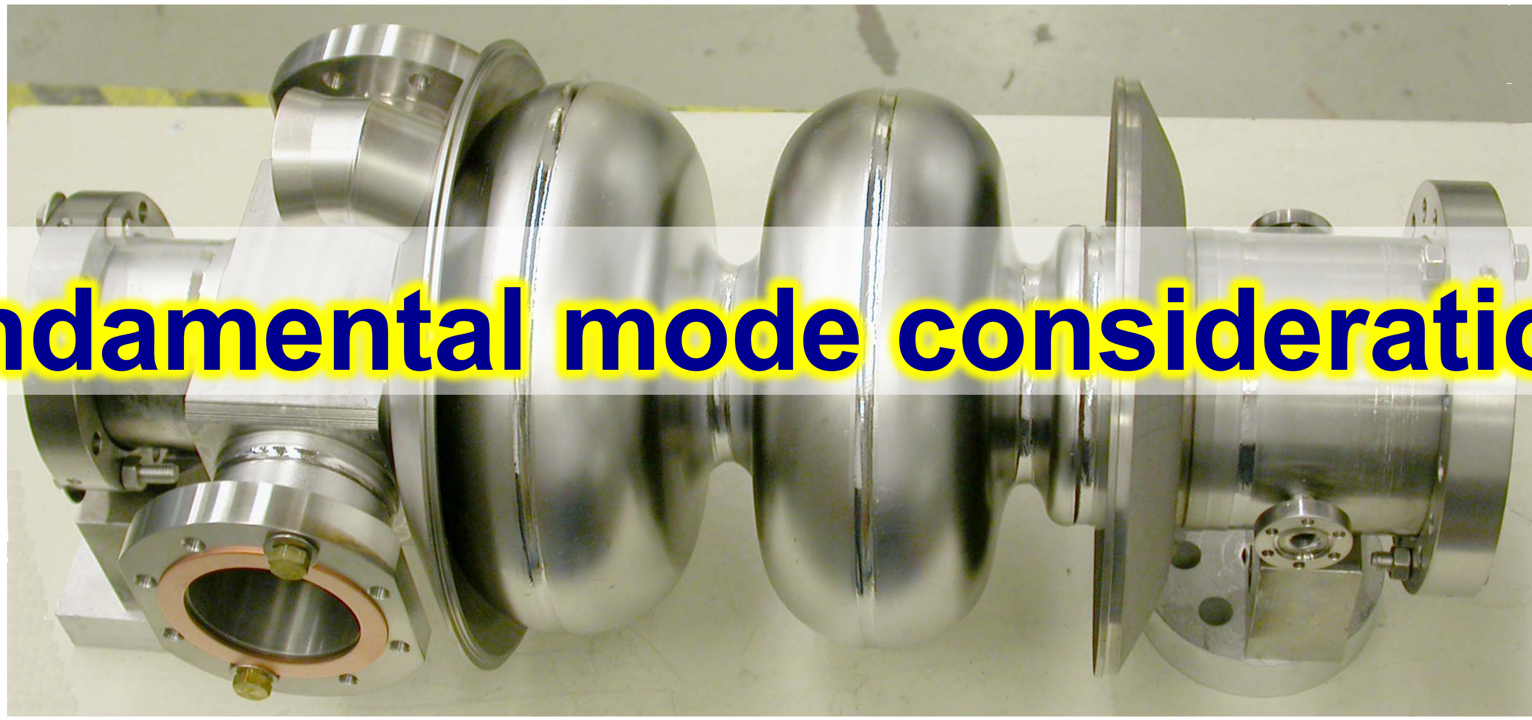

BNL ERL cryomodule



B-cell beam line components (TLS)

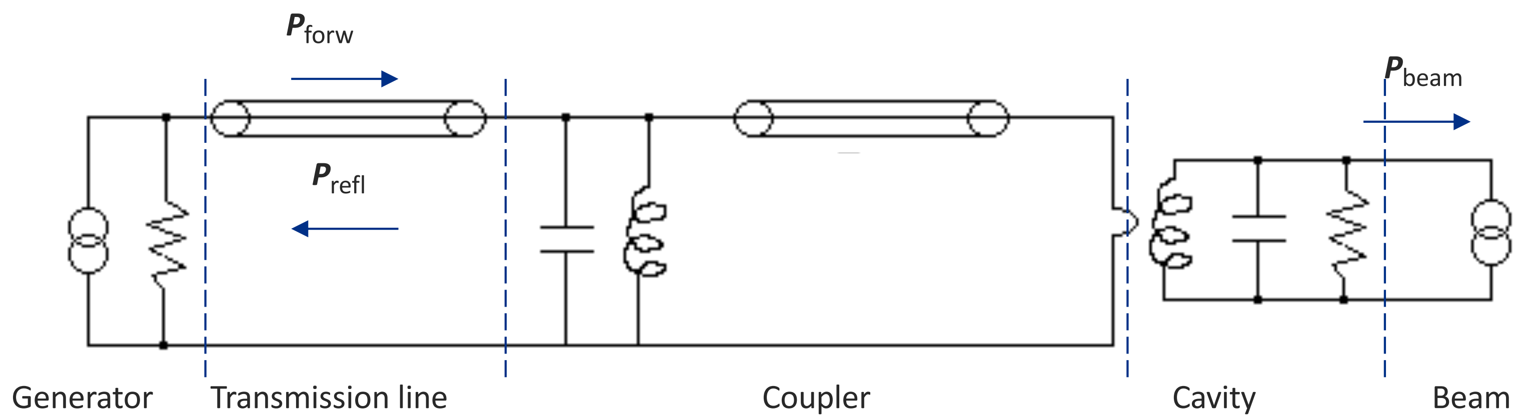

JLab proposal

Fundamental mode considerations

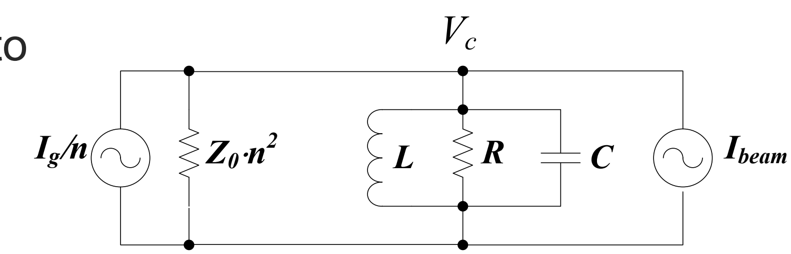


Circuit model for the fundamental mode

- At the fundamental mode frequency there are high fields induced by an RF power source therefore interaction with the fundamental mode is considered separately from HOMs.
- When considering beam interaction with the fundamental mode, it is convenient to use an equivalent circuit model:



which can be simplified to



- This model is used to simulate: the cavity filling with electromagnetic power; RF controls; beam loading, …

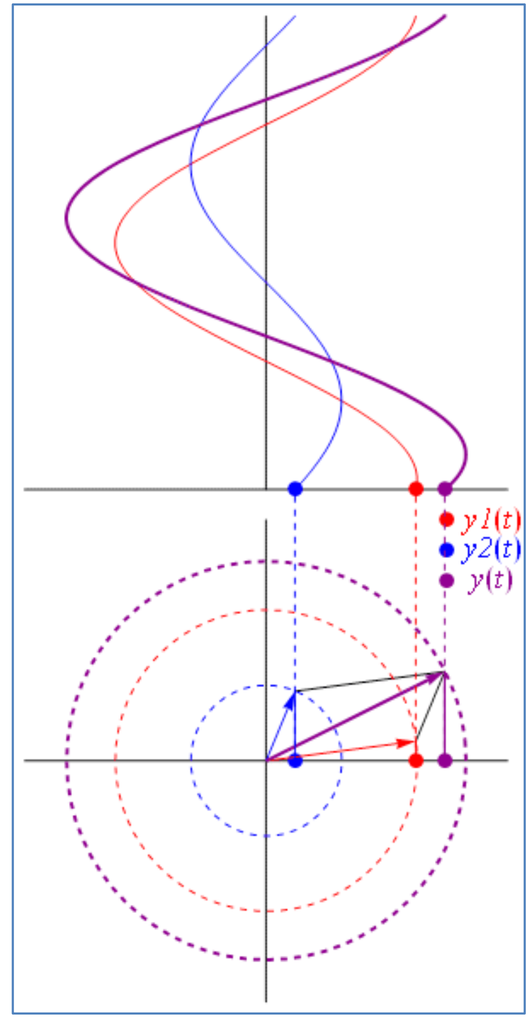
Phasor diagrams

- To obtain the total cavity voltage we need to add the generator-induced voltage and beam-induced voltage (this follows from the principle of linear superposition consequence of the linearity of Maxwell equations.)
- For the case of sinusoidal voltages (and currents), one must add them taking into account the relative phases. It is convenient to describe the voltages as vectors in the complex plane as

$$\mathbf{V} = Ve^{i(\omega t+\varphi)} = Ve^{i\varphi} \cdot e^{i\omega t}$$

- This vector rotates counterclockwise in the complex plane and is called phase vector or ***phasor***.
- The sinusoidal voltage is then the real part of this complex function or a projection of the rotating vector onto the real axis of the complex plane.
- It is convenient to choose a frame that is rotating with the frequency ω, so that the phasors remain fixed in time. In this case we can use just the complex constant (shorthand notation):

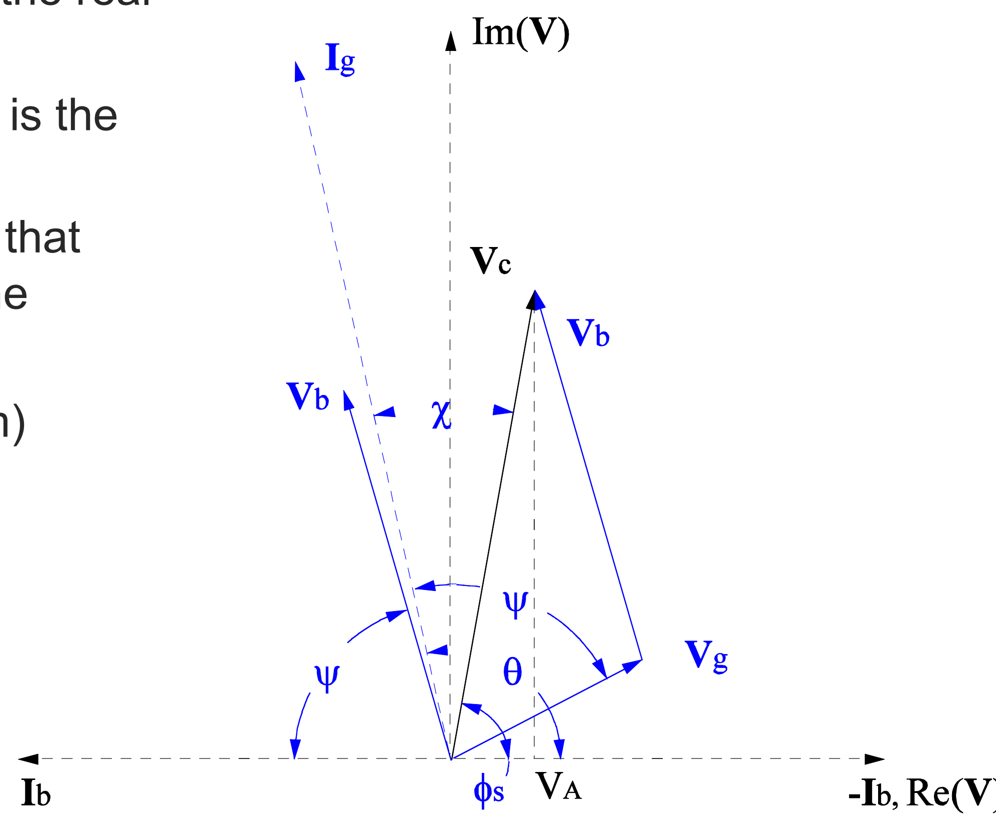
$$\mathbf{V} = Ve^{i\varphi}$$



Phasor diagram of a beam-loaded cavity

- We can align the beam current phasor with the real axis.
- Then the total voltage seen by the beam V_c is the vector sum of two other voltages.
- Finally, the component of the cavity voltage that contributes to acceleration of the beam is the projection of the voltage onto the real axis.
- Here φ_s (or φ_0) is the synchronous (or beam) phase.
- And ψ is the cavity tuning angle:

$$\tan\psi = 2Q_L \frac{\Delta\omega}{\omega}$$



Beam loading of the fundamental mode

- From the equivalent circuit diagram one can derive for the forward power

$$P_{\mathrm{forw}} = \frac{{V_{\mathrm{c}}}^2}{4\,R/Q \cdot Q_{\mathrm{ext}}} \cdot \frac{(\beta+1)^2}{\beta^2} \cdot \left\{ \left[1 + \frac{I_{\mathrm{b}}\, R/Q \cdot Q_{\mathrm{L}}}{V_{\mathrm{c}}} \cos\varphi_0 \right]^2 + \left[\tan\psi + \frac{I_{\mathrm{b}}\, R/Q \cdot Q_{\mathrm{L}}}{V_{\mathrm{c}}} \sin\varphi_0 \right]^2 \right\}$$

active beam loading term **reactive beam loading term**

(here β is the coupling coefficient: $\beta = \frac{Q_0}{Q_{\mathrm{ext}}}$, I_{b} is the average beam current, *R/Q* is in accelerator definition)

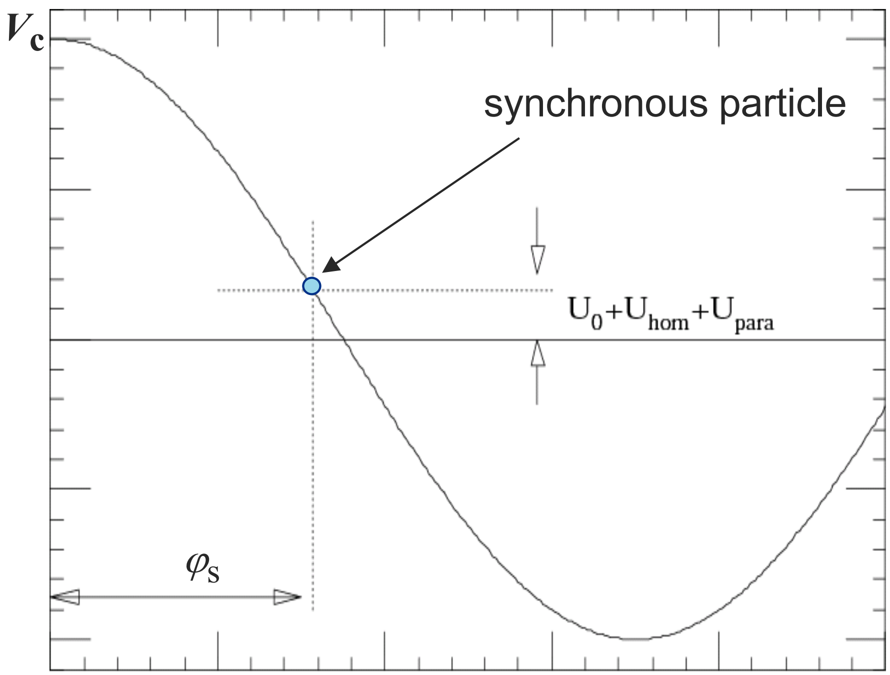
- The two terms correspond to active and reactive parts of the beam loading

P. B. Wilson, "High Energy Electron Linacs: Application to Storage Ring RF Systems and Linear Colliders," SLAC-PUB-2884 (1982)

Example 1: Storage ring RF

Functions of the storage ring RF system

- Provide energy gain → deliver RF power to a high-current beam(s);
- Provide high voltage for high synchrotron tune and short bunch length (colliders);
- Provide over-voltage for good quantum lifetime;
- Provide voltage for good energy acceptance;
- Suppress parasitic interaction of a beam with HOMs by providing strong HOM damping. HOM power may be high.



$$P_{beam} = I_{beam} \cdot \left(U_0 + U_{hom} + U_{para} \right)$$

$$f_s = f_{rev} \sqrt{\frac{\alpha \cdot h \cdot V_c \sin \varphi_s}{2\pi\, E/e}}$$

$$\sigma_z = \frac{c \cdot \alpha}{\omega_s} \cdot \frac{\sigma_E}{E}$$

Storage ring RF power optimum

$$P_{\text{forw}} = \frac{V_c^{\ 2}}{4\,R/Q \cdot Q_{\text{ext}}} \cdot \frac{(\beta+1)^2}{\beta^2} \cdot \left\{ \underbrace{\left[1 + \frac{I_b\,R/Q \cdot Q_L}{V_c}\cos\varphi_0\right]^2}_{4} + \underbrace{\left[\tan\psi + \frac{I_b\,R/Q \cdot Q_L}{V_c}\sin\varphi_0\right]^2}_{0} \right\}$$

- In storage rings, where the beam is passing cavity off-crest, the minimum RF power is achieved when two requirements are met.
  1. The reactive beam loading is compensated by an appropriate cavity detuning (the second term vanishes):

$$\frac{\Delta\omega}{\omega} = -\frac{I_b \cdot R/Q}{V_c}\sin\varphi_0$$

  2. Then the coupling β is chosen to achieve the matching condition (zero reflected power) at the nominal beam current:

$$\frac{\beta - 1}{\beta} = \frac{I_{b\_\text{nom}}\,R/Q\;Q_{\text{ext}}}{V_c}\cos\varphi_0$$

- And the corresponding forward power is

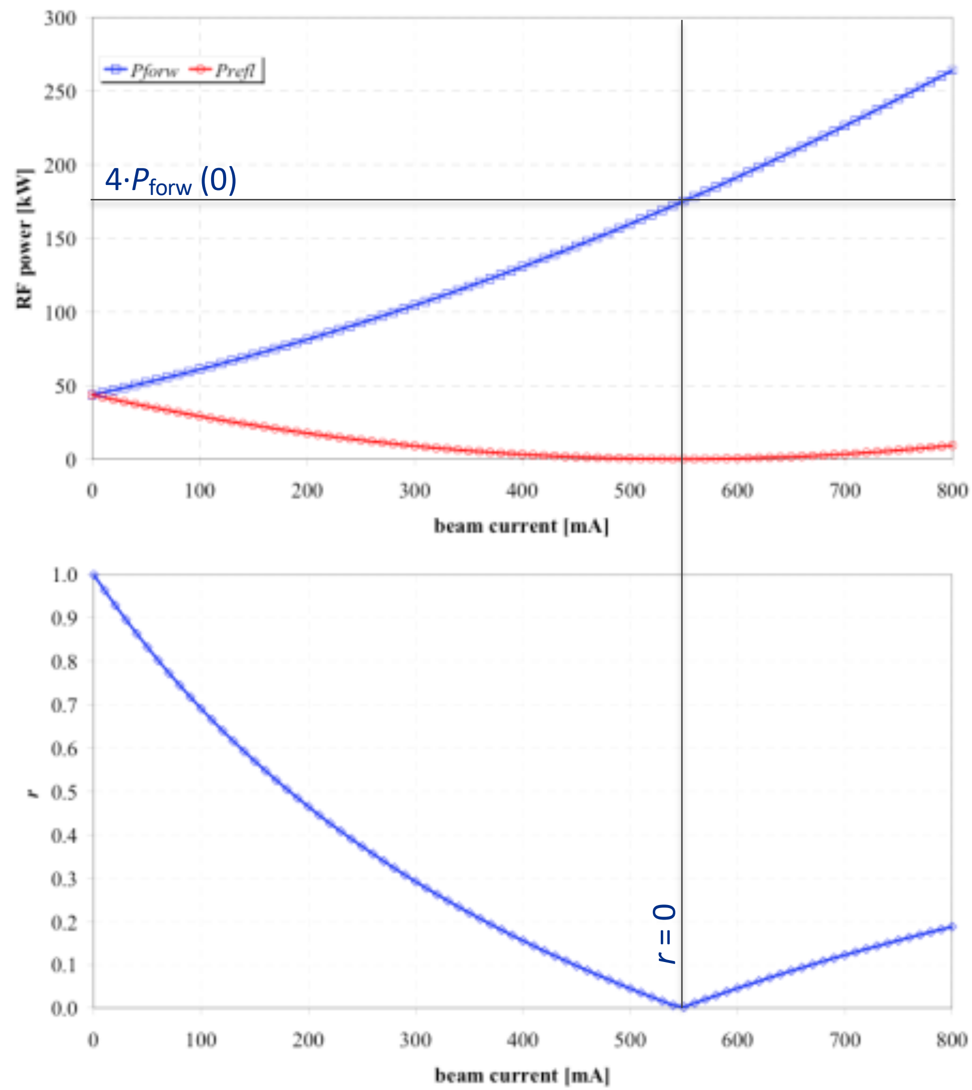
$$P_{\text{forw}} = \frac{V_c^2}{R/Q\;Q_{\text{ext}}} = P_{\text{beam}} = I_{\text{b\_nom}} V_c \cos\varphi_0$$

RF power *vs.* beam current at fixed coupling

- For fixed coupling, chose the coupling to match beam at the nominal current
  - Standing wave pattern in the input coupler and transmission line goes from full reflection (without beam) through matched condition at the nominal beam current to partial reflection.
- Initially over-coupled input coupler becomes under-coupled at beam currents above nominal

*Here **r** is the reflection coefficient.*

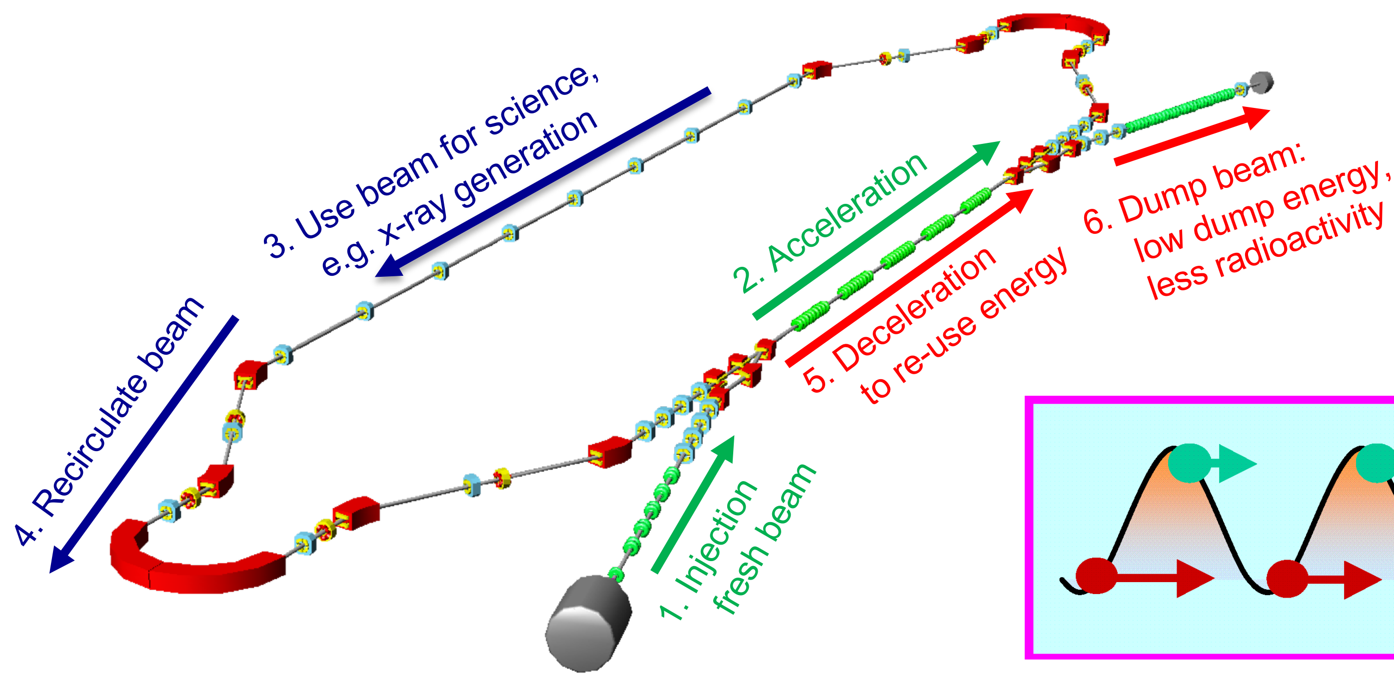
$$Q_{\mathrm{ext}} = \frac{V_c}{I_{\mathrm{b\_nom}}\, R/Q \cos\varphi_0}$$

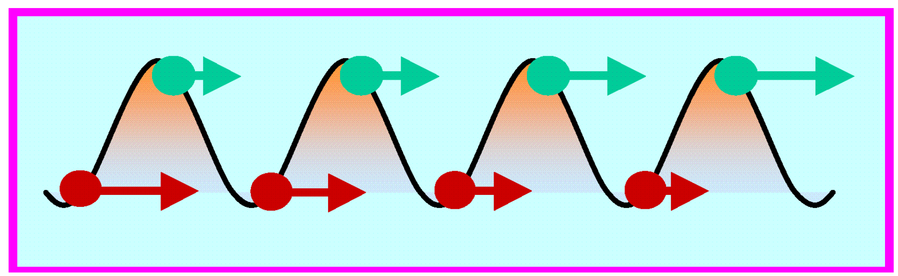


Example 2: Energy Recovery Linac RF

Functions of the ERL RF system

- Provide energy gain → Due to energy recovery, the required RF power is nearly independent of the beam current. The beam loading is zero in an ideal case.
- Small deviations can induce strong effects → hence very tight requirements to RF amplitude and phase stability at high loaded *Q*.
- Suppress parasitic interaction of a beam with HOMs by providing good HOM damping. HOM power may be high.





ERL RF power

$$P_{\text{forw}} = \frac{V_{\text{c}}^{\;2}}{4\,R/Q\cdot Q_{\text{ext}}}\cdot\frac{(\beta+1)^2}{\beta^2}\cdot\left\{\left[1+\overset{0}{\cancel{\frac{I_{\text{b}}\,R/Q\cdot Q_{\text{L}}}{V_{\text{c}}}}}\cos\varphi_0\right]^2+\left[\tan\psi+\overset{0}{\cancel{\frac{I_{\text{b}}\,R/Q\cdot Q_{\text{L}}}{V_{\text{c}}}}}\sin\varphi_0\right]^2\right\}$$

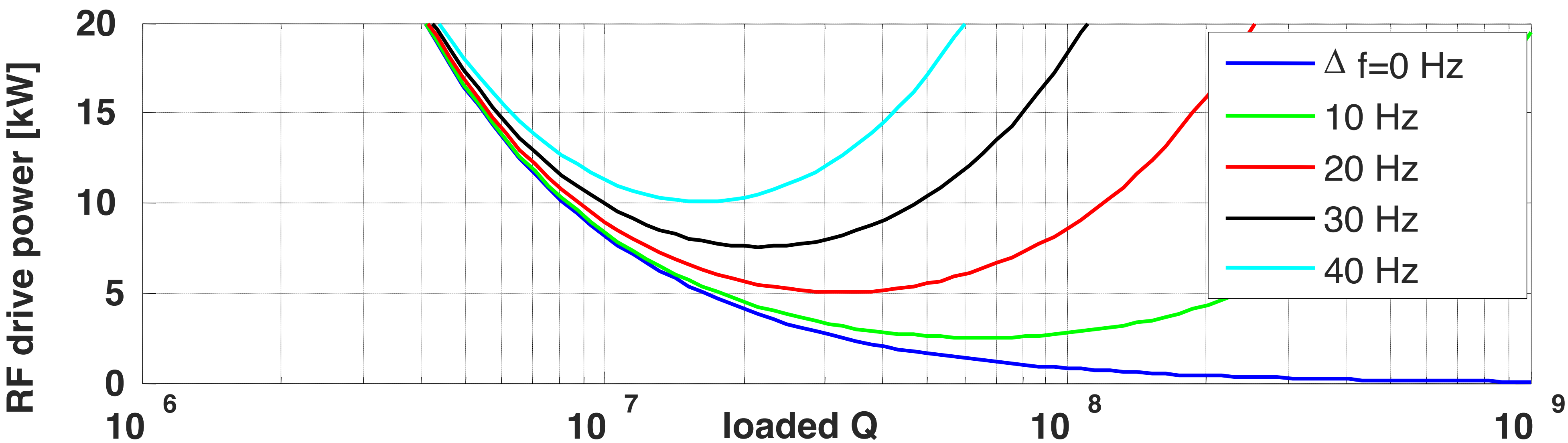
- In ERLs, with two beams passing the cavity 180º apart, the beam loading is zero for perfect energy recovery and the cavity is tuned to resonance.
  1. Both beam loading terms vanish
  2. Then RF power is determined by residual beam current phase and amplitude errors and by the cavity resonant frequency fluctuations due to environmental noise (microphonics)

- Assuming that amplitude and phase errors are negligibly small, the peak forward power is determined only by frequency fluctuations

$$P_{\text{forw}} = \frac{V_c^2}{4R/Q\;Q_{\text{ext}}}\frac{(\beta+1)^2}{\beta^2}\left\{1+\left(2Q_L\frac{\delta\omega}{\omega}\right)^2\right\}$$

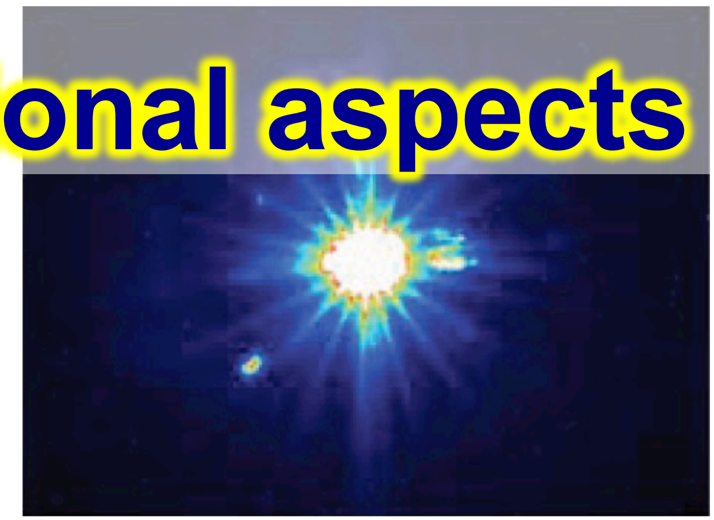
Optimal RF coupling for ERL main linac

ERL: No effective beam loading in the main linac
(accelerated and decelerated beam compensate each other)



$$Q_{\mathrm{L\_opt}} = \frac{1}{2}\frac{\delta\omega}{\omega}, \quad \text{for } \beta \gg 1$$

Other operational aspects



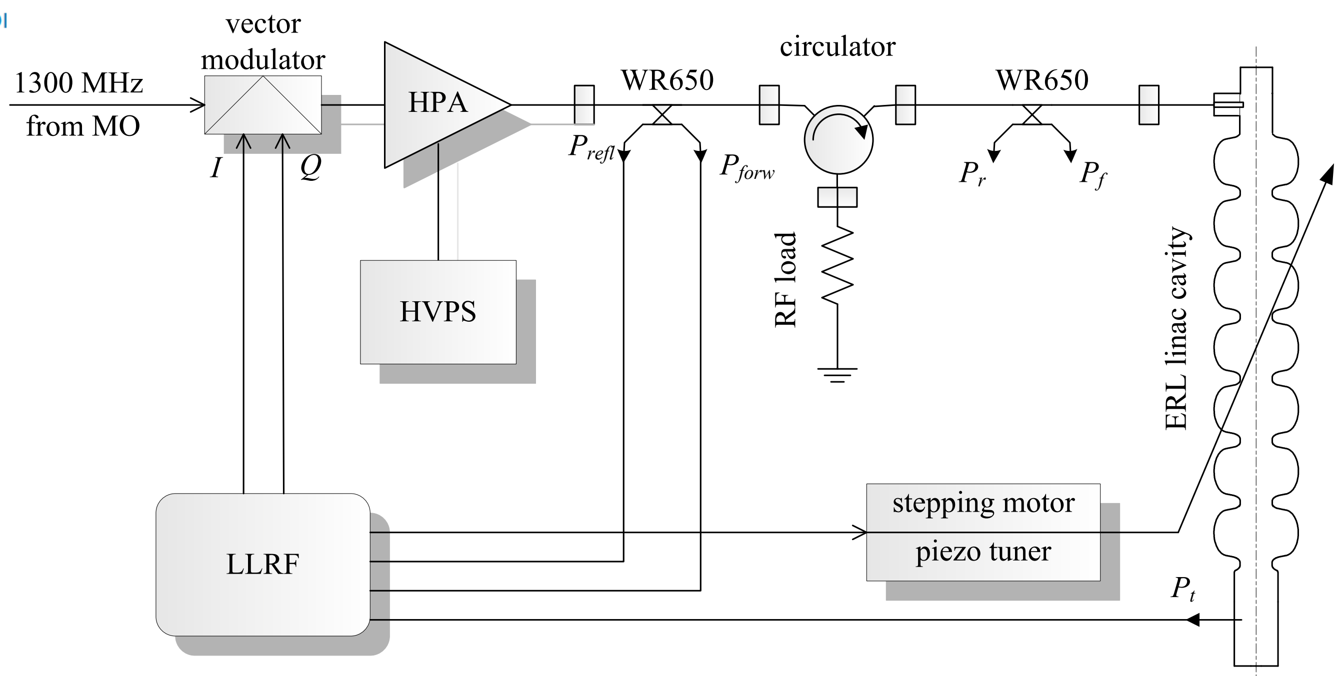
After installation in an accelerator…

- After the cryomodule is assembled, they are installed in an accelerator where connected to cryogenic, RF, instrumentation and control, other auxiliary systems.

- *Conditioning*
  - The cavities and input couplers are subjected to *in situ* conditioning and/or acceptance testing
  - Quite often a need arises for re-conditioning or conditioning to new operating requirements
  - SRF cavity performance can change with time:
    - Dust particle can propagate through beam pipes triggering field emission or causing quenches
    - Special events (e.g. vacuum leaks, accumulation of adsorbed gases on cold surfaces) can degrade cavity or coupler performance
  - It is not always possible to recover initial performance

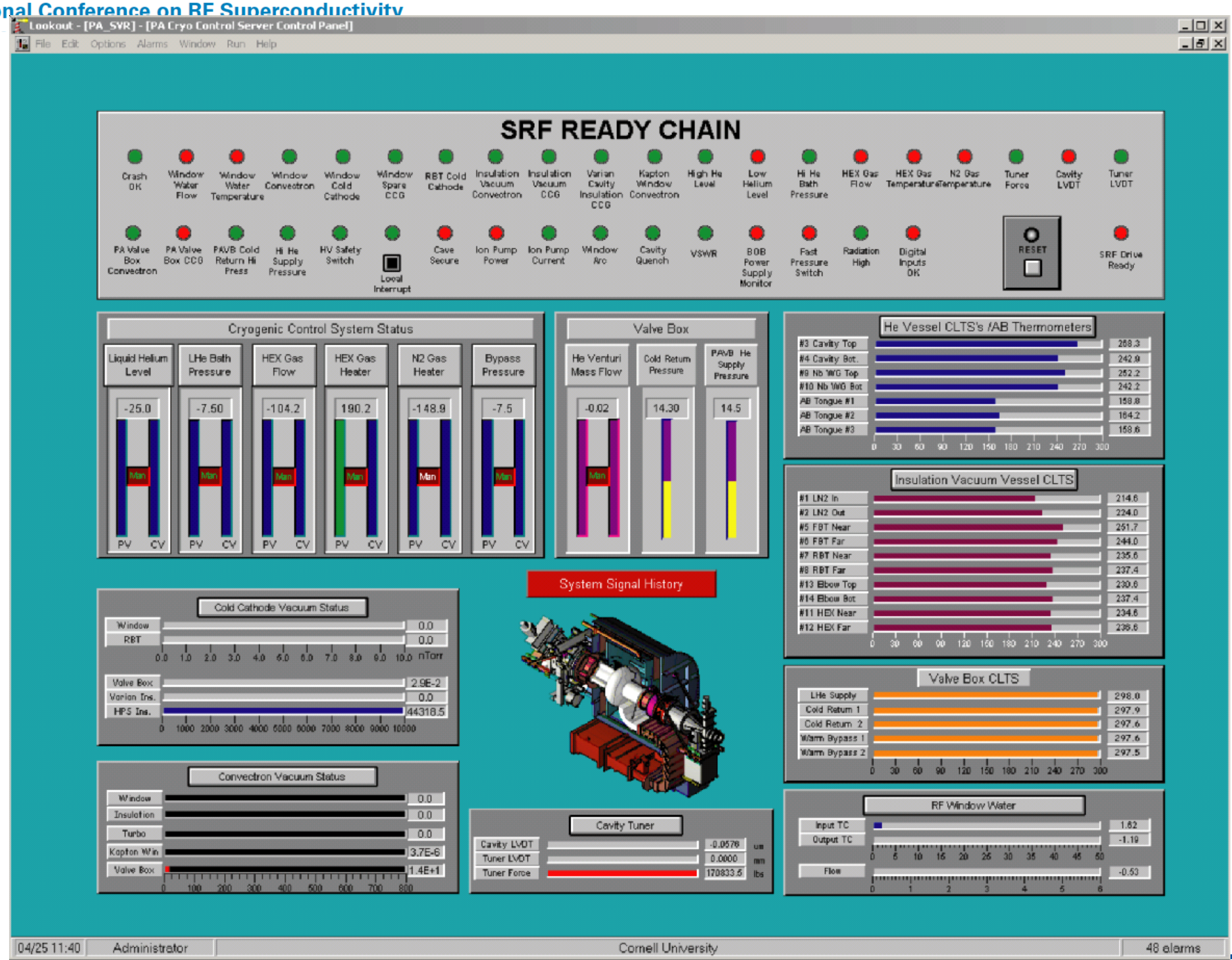
- *Trips*
  - Operating close to the maximum accelerating gradient or RF power level leads to increased frequency of RF trips, which in turn cause beam loss.
  - Tolerance to the frequency of RF trips depends on the type of accelerator and experiment. HEP and NP experiments rely on integrating statistics and more tolerant to brief interruptions than user facilities, such as X-ray light sources, where uninterrupted beam availability close to 100% is expected.

RF system and interlocks



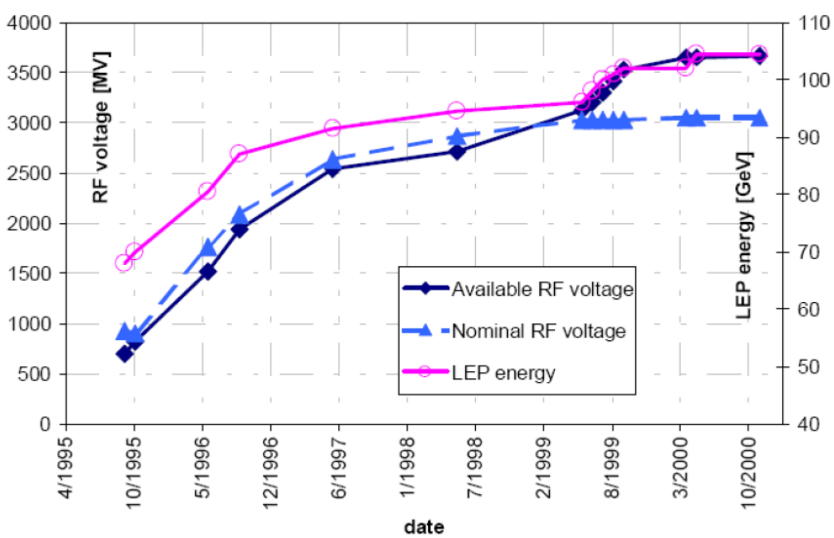
- To run an RF system, one needs LLRF controls to maintain the cavity field amplitude and phase stable (see ***J. Branlard's tutorial***). Beam-base measurements are used to calibrate RF amplitude and phase.
- A machine protection system (MPS) shall be provided to turn off RF and/or beam in a case of non-standard conditions to protect personnel and equipment.
- Fast interlocks can be part of the LLRF, but there should be redundancy with MPS.
- In particular, a multilayer quench protection is important for SRF: LLRF to look for large deviation of the field amplitude from the set point; fast He bath pressure switch; temperature sensors.
- Vacuum and arc detector interlocks are critical for power couplers.

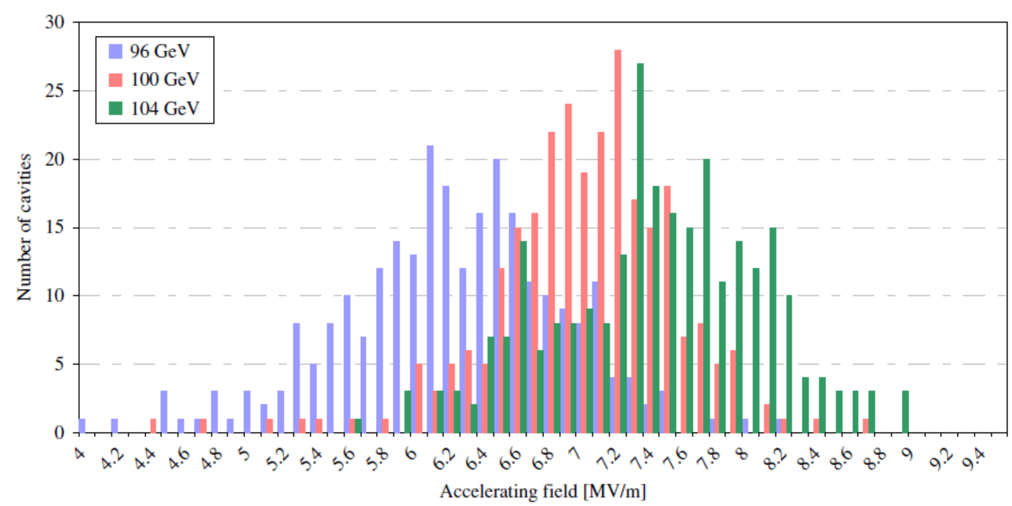
Cryomodule controls & interlocks



Maximizing the energy reach of LEP2

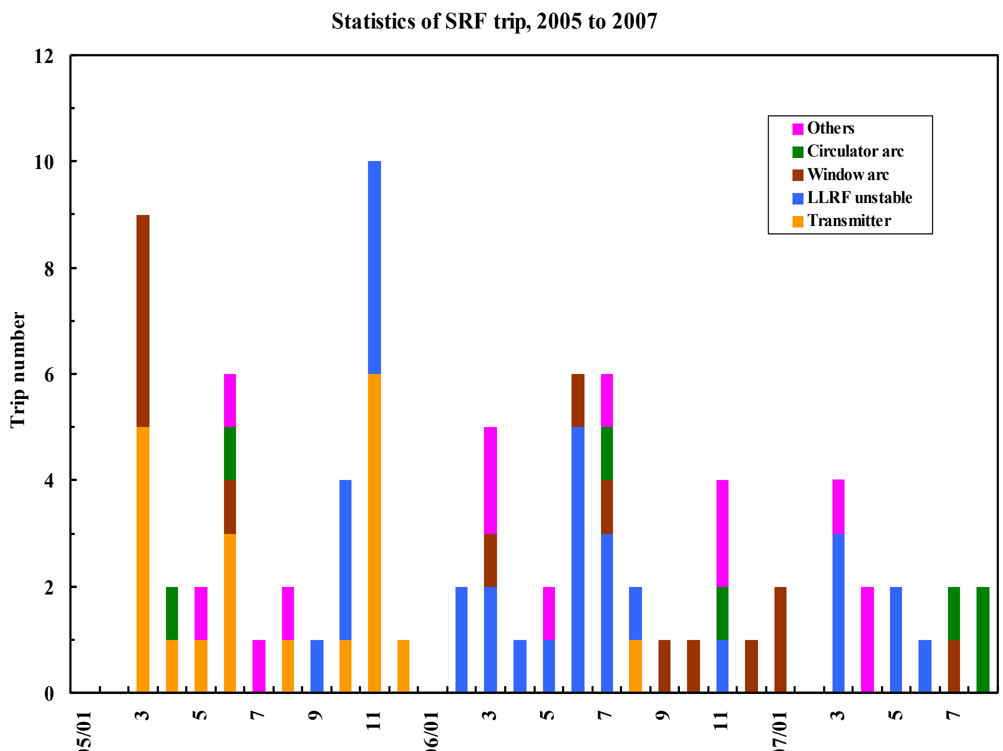
- CERN installed the largest SRF system in 90s to double the energy of its electron-positron collider LEPP. LEPP-II has ultimately reached 104.5 GeV.
- The experience there was dominated by the quest to deliver the highest possible energy beams with the available RF.
- The accelerating gradient increase came from optimizing the RF power distribution and high power RF processing to suppress field emission. For stable operation with beam the total gradient was set about 5% below the maximum achieved during conditioning.
- However, to operate at the maximum beam energy, the experiments had to tolerate very high frequency of RF trips. The trip rate was about **2 per hour** at 98 GeV rising to about **4 per hour** at 100 GeV. Above 5 mA the trip rate rose even higher. Most trips occurred mainly due to field emission so that *in-situ* processing played a crucial role.



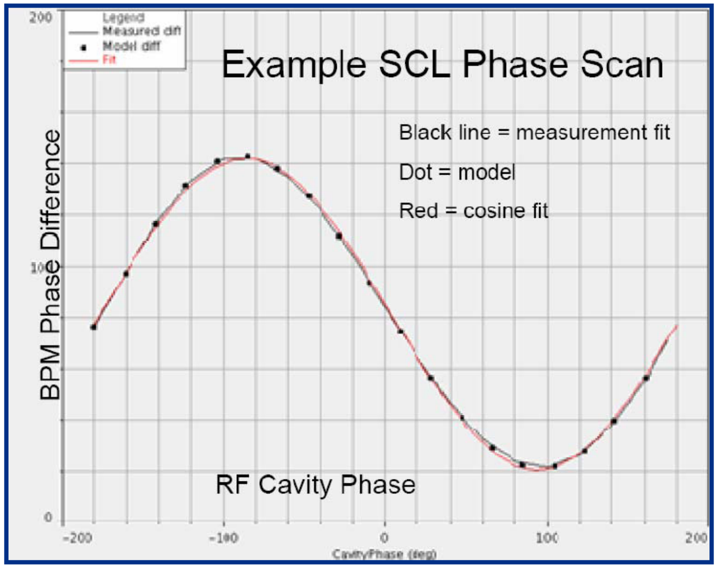


RF trips in light sources

- Light sources are the user facilities. The specifics of the experiments there requires long exposure of samples to an uninterrupted X-ray beam, hence a very low RF trip rate is absolutely necessary.
- A typical example: Taiwan Light Source (TLS), where over time the trip rate was reduced to **~0.5 per week**.
- It is interesting to note, that SRF cavity almost never the cause of trips in this case as it operates well below its gradient limit.



SNS beam phase scan calibration



- Beam-based measurements are done to set each cavity RF phase correctly. The beam's $\beta = v/c < 1$
- The cavity "s" phase is scanned 360º and the change in Time Of Flight (TOF) between two down-stream detectors is measured.
- Measurements are compared with simulations. This gives beam energy, cavity voltage and beam phase offset calibration.
- Each cavity is scanned sequentially. After initial calibration (takes 4 to 8 hours for 75 SCL cavities) one can use a model prediction to adjust for any changes.

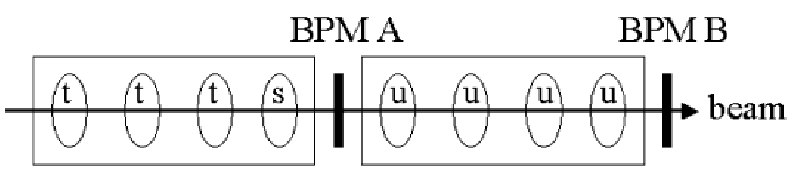
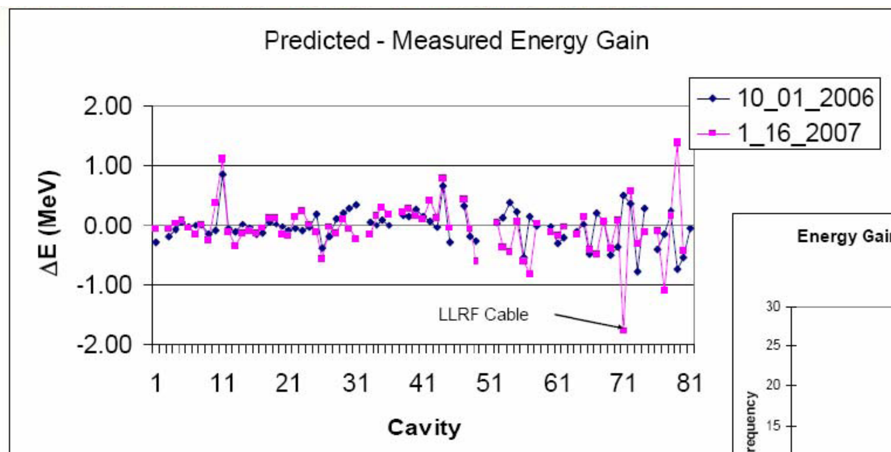
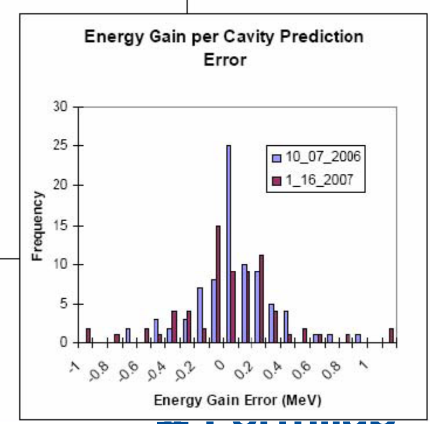


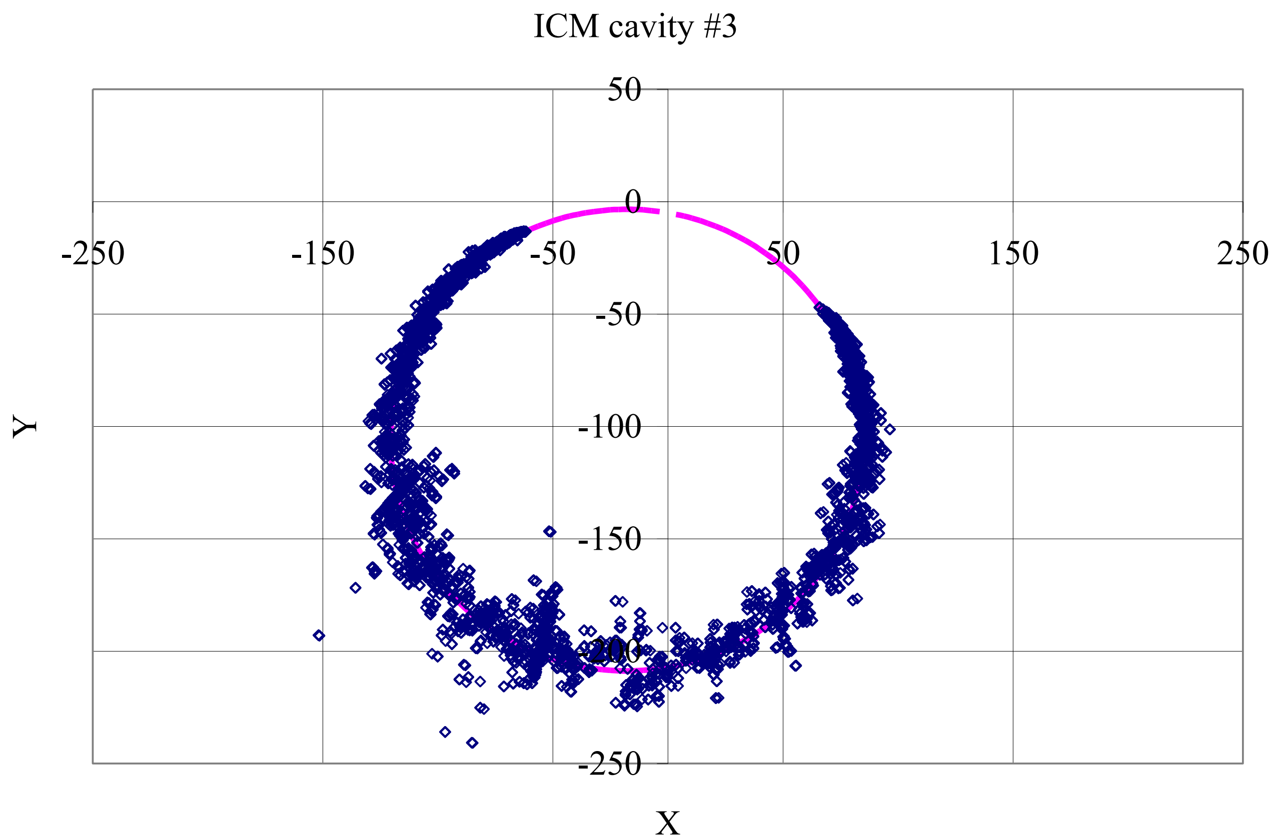
Fig. 1. Schematic drawing of the phase scan. The "*u*" cavities between BPM *A* and BPM *B* are unpowered, and those with "*t*" are already tuned. The "*s*" cavity just upstream of BPM *A* is being scanned.





- **Energy gain per cavity is predictable to a few 100 keV and distributed about 0.**
- **Final energy is predictable to within a few MeV**

Cornell ERL injector beam phase scan

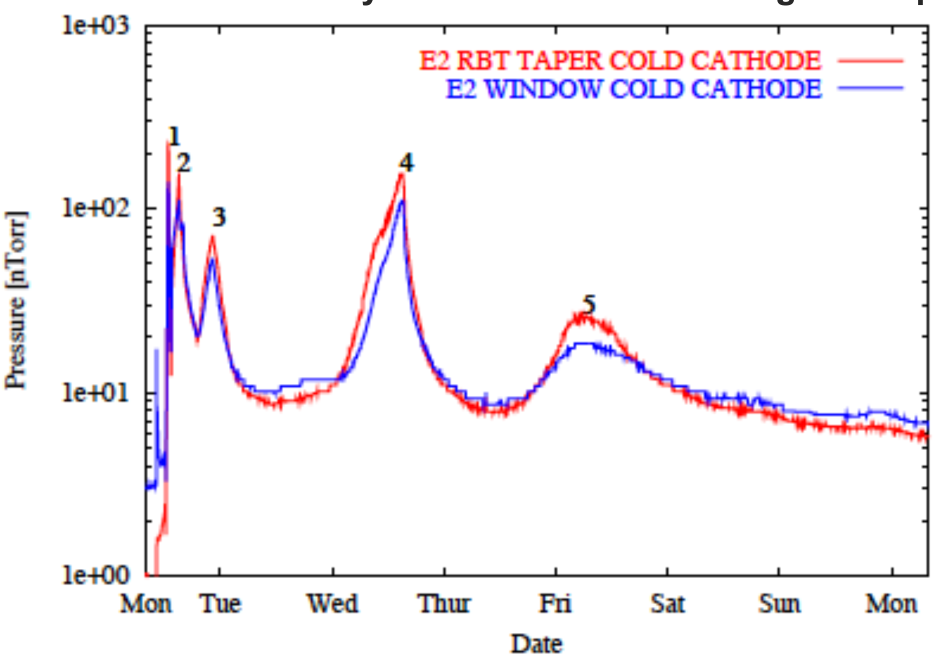


- In this case the frequency of an un-powered cavity is scanned.
- The data are fitted with a resonance formula to obtain the amplitude and phase calibrations.

Vacuum and SRF cavity performance

- Condensed/adsorbed gases can enhance field emission in SRF cavities and deteriorate the power coupler performance.
- The cold cavities act as huge cryopumps, so maintaining UHV conditions in warm components connected to the cavities is very important.
- Experience at CESR indicates that the cavity performance deterioration starts after adsorption of ~10 monolayers (H_2 equivalent). The performance recovers after warmup to room temperature and subsequent cooldown.

CESR SRF cavity vacuum evolution during warmup



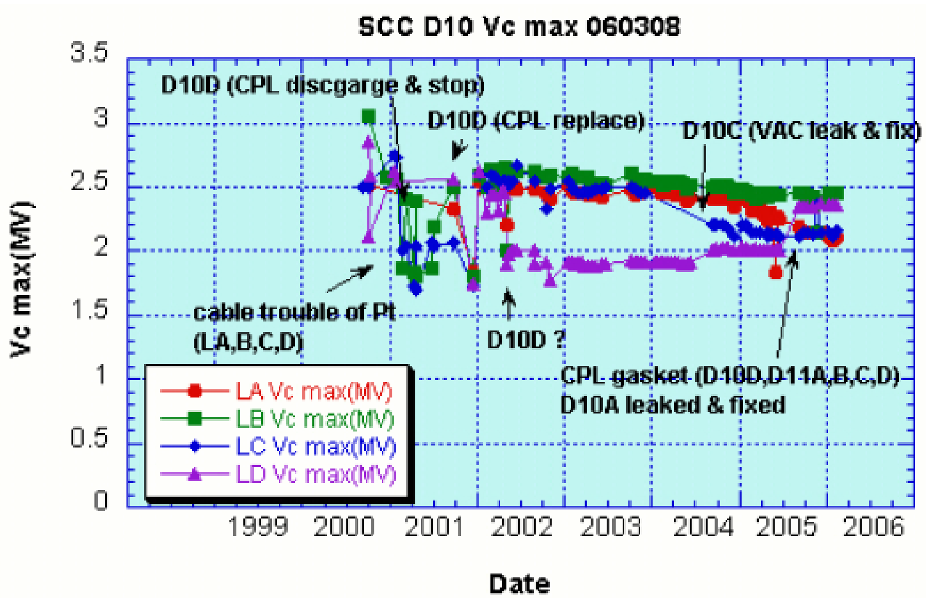
Prevailing gas species

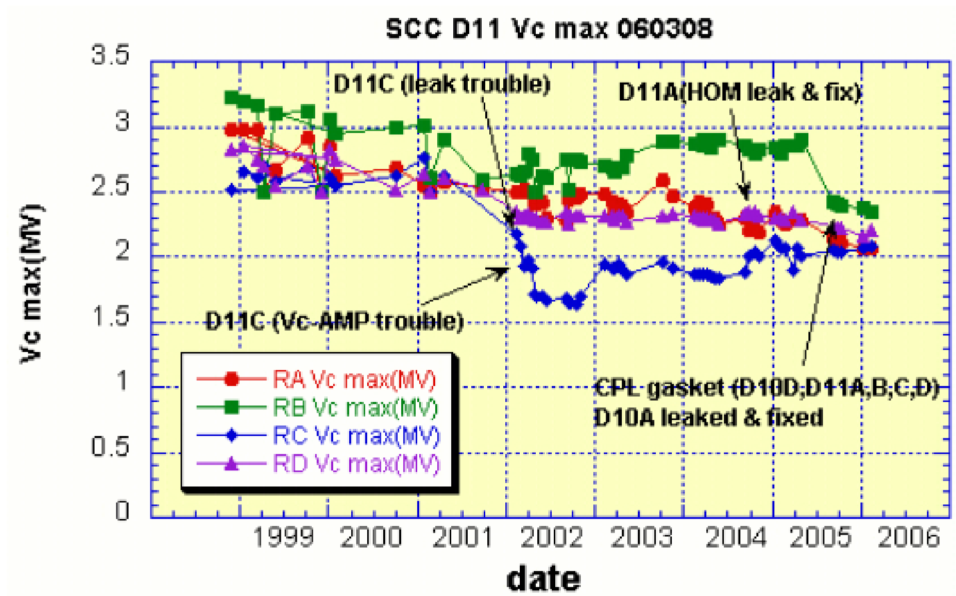
Peak #	*Gas species*	*Cavity [°K]*	*HEX [°K]*	*Elbow [°K]*
1	H_2, He	9	22	85
2	CO/N_2,H_2,O_2,Ne	27	35	92
3	CO_2,CO/N_2	83	92	130
4	H_2,H_2O,CO/N_2	163	165	190
5	H_2,H_2O	230	220	240

R. L. Geng, "Condensation/adsorption and evacuation of residual gases in the SRF system for the CESR luminosity upgrade," PAC’1999

KEKB experience: operating voltage

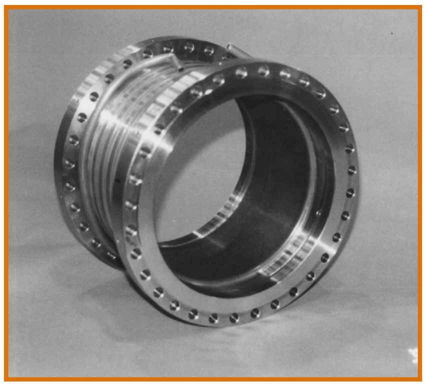
- All cavities could operated at > 2 MV for many years of operation
- Voltage of D11C degraded after vacuum leak
- Voltage of D11B degraded after changing the coupling of the input coupler
- Overall, very positive experience





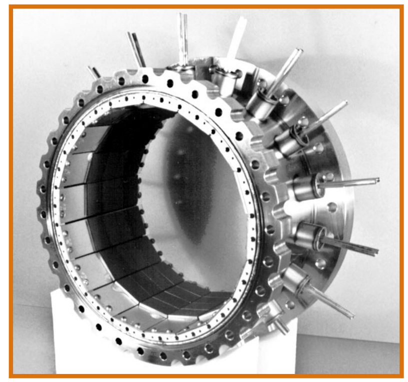
Experience with ferrite beam pipe absorbers (CESR and KEKB)

- Originally developed at Cornell and KEK for very high average power absorption
- Operate at room temperature outside the cryomodule
- Nowadays widely used in high-current storage rings



KEKB HOM absorbers

- Ferrite is bonded to copper plated steel housing using HIP process
- Designed to for 5 kW absorption, reached 16 kW in operation

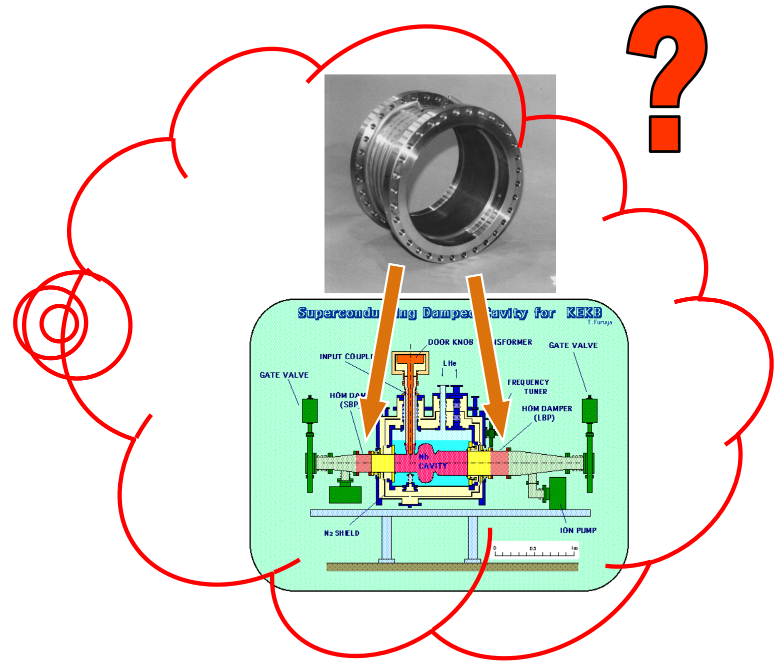


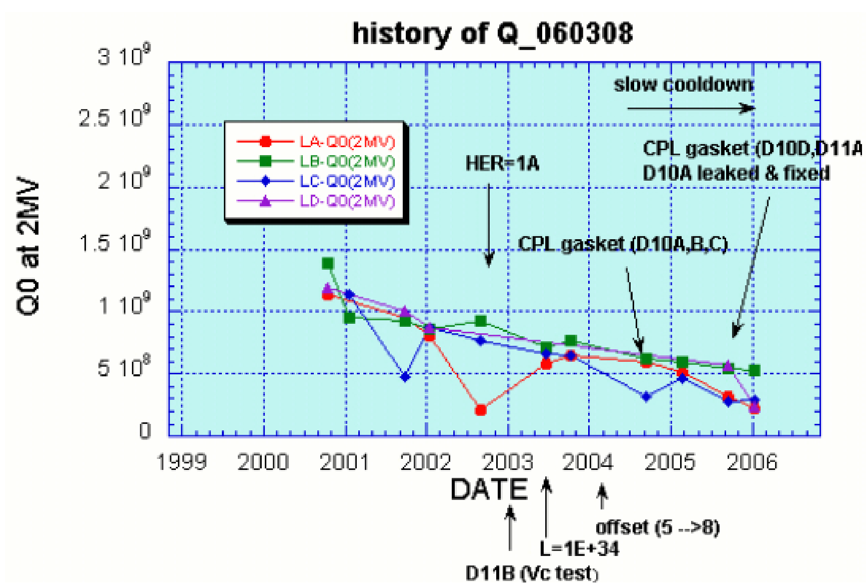
CESR HOM absorber

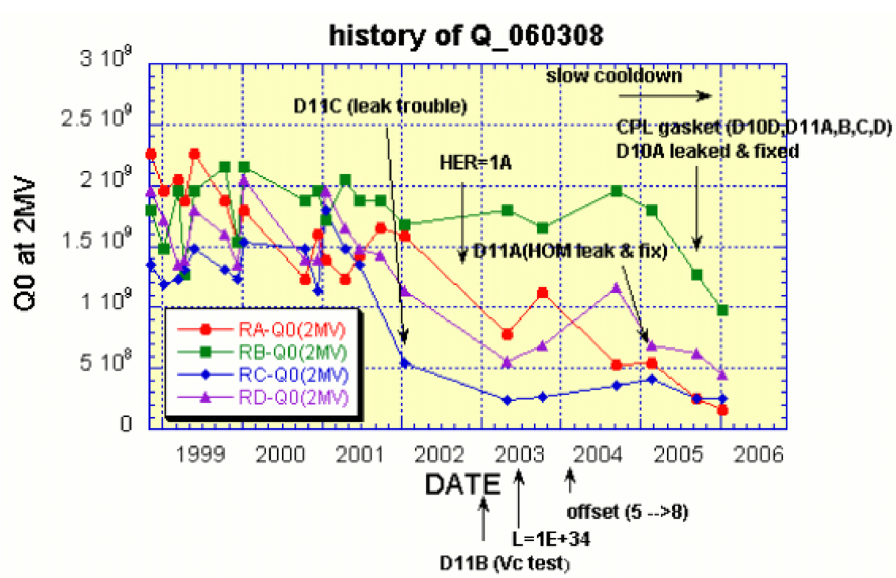
- Ferrite tiles are soldered to water-cooled Elkonite plates, which in turn are mounted inside a stainless steel shell
- Absorbed up to 5.7 kW in operation

KEKB experience: Q degradation

- Unloaded Q at 2 MV (8 MV/m) has gradually degraded to $3..5\times10^8$.
- Out-gassing and/or ferrite dust from the HOM dampers?
- Exact cause is unknown.
- The Q at the operating voltage (1.4 MV) still higher than 1×10^9







Cryogenics and thermoacoustic oscillations

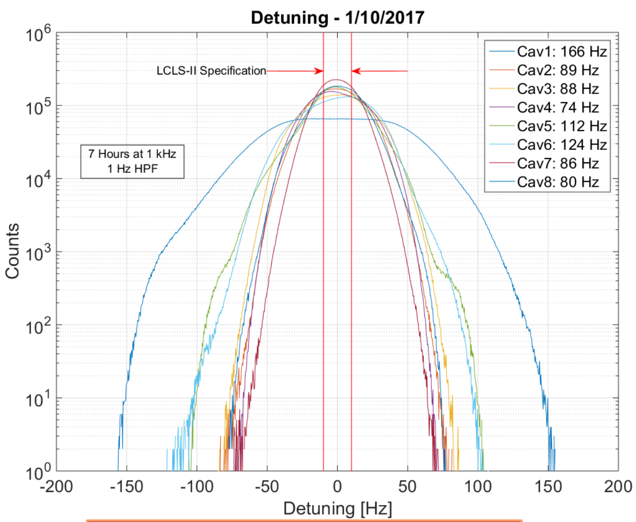
- LCLS-II is a low-beam-current SRF linac → cavities have very narrow bandwidth, ~10 Hz.
- During acceptance testing of the prototype LCLS-II cryomodule, unexpectedly high level of microphonics was encountered preventing stable operation of the cavities in a GDR mode.
- The problem was traced to thermoacoustic oscillations in the supply JT valves.
- Thermoacoustic oscillations generally occur in long gas-filled tubes with a large temperature gradient.
- Acoustic modes couple to mass transport up and down column especially well when gas density is strongly tied to temperature. E.g. Warm gas from the top of a valve column moving to the cold bottom contracts, reducing pressure at warm region, driving the now cold gas back.
- These oscillations are generally important for the tremendous heat leaks they can represent, not microphonics.

- Low pressure operation consistently eliminated icing on the supply valves (JT, bypass)
- **Indicates *suppression* of thermo-acoustic oscillations**

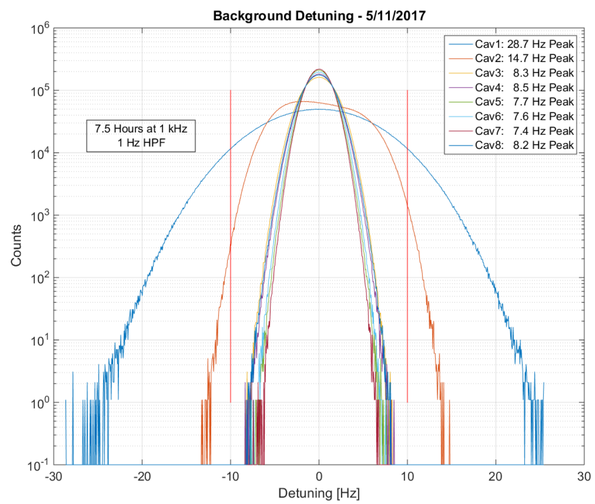
J. Holzbauer, "1.3 GHz Microphonics measurement and mitigations," MRCW18

Thermoacoustic oscillations and microphonics

- Wipers were added to close space in valve stem, acting as a damping term for the thermoacoustic oscillations.
- Significant improvements in stability of the system, leading to a far more predictable detuning environment.
- After further improvements in other areas, all cryomodules perform within spec (10 Hz) now.



pCM as cooled down

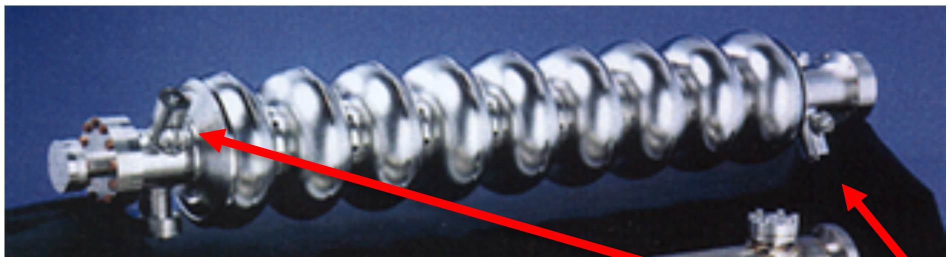


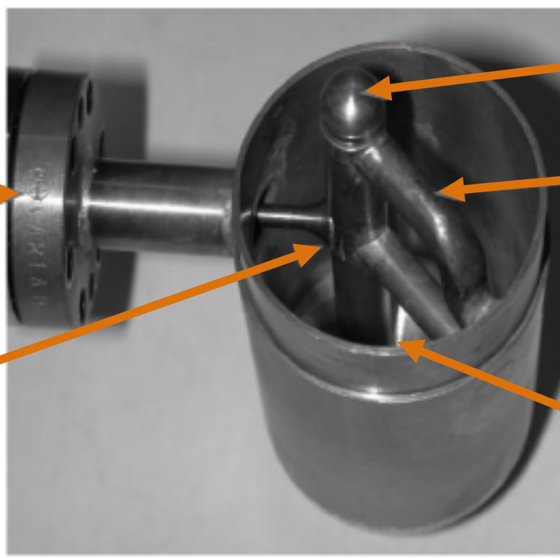
F1.3-02 after improvements

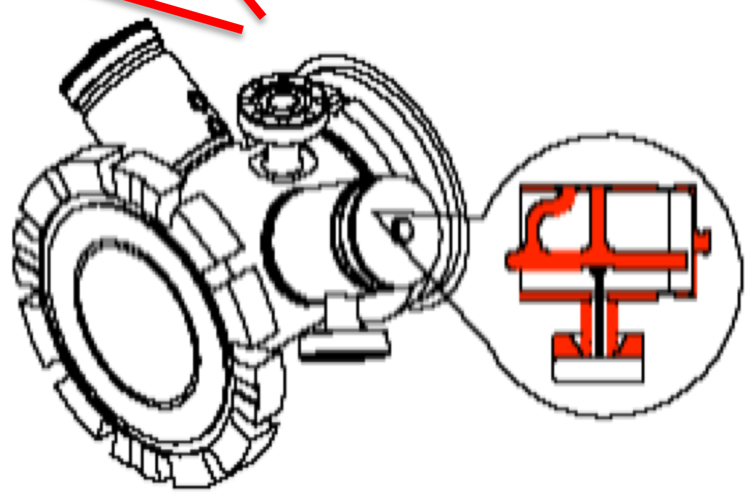
Optimized wiper placement going forward

Using an existing HOM coupler design …

- Consider an antenna HOM coupler *successfully used in TESLA cavities around the world*.
- A simplified version of an HOM coupler developed originally for HERA.
- Located outside helium vessel, requires no extra beampipe length, but a rejection filter is needed for fundamental mode.
- Relatively easy to clean.
- HOM power is absorbed at room temperature.



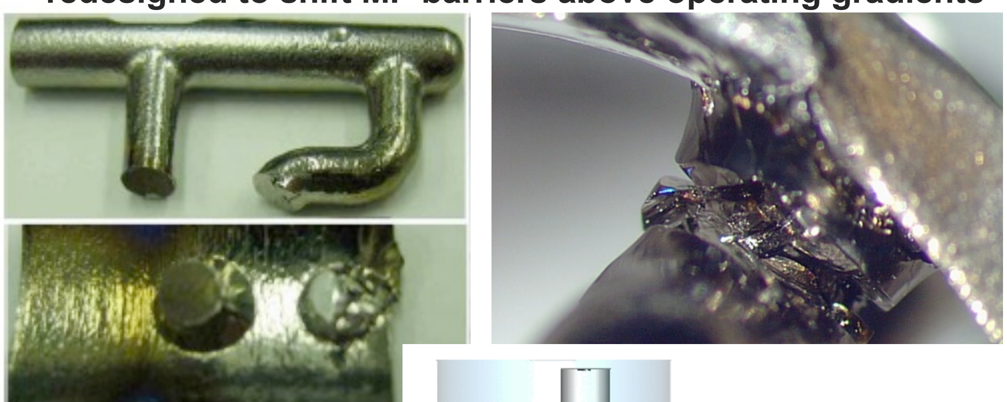




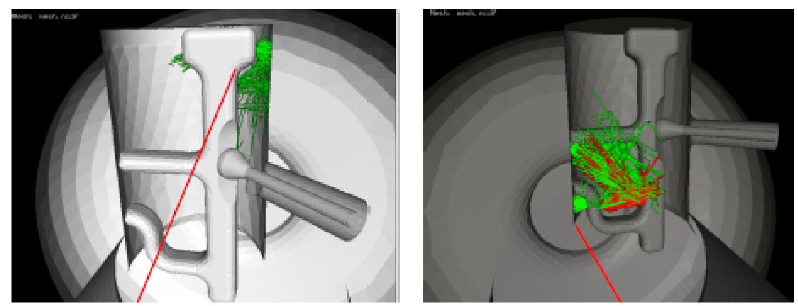
… scaling challenges

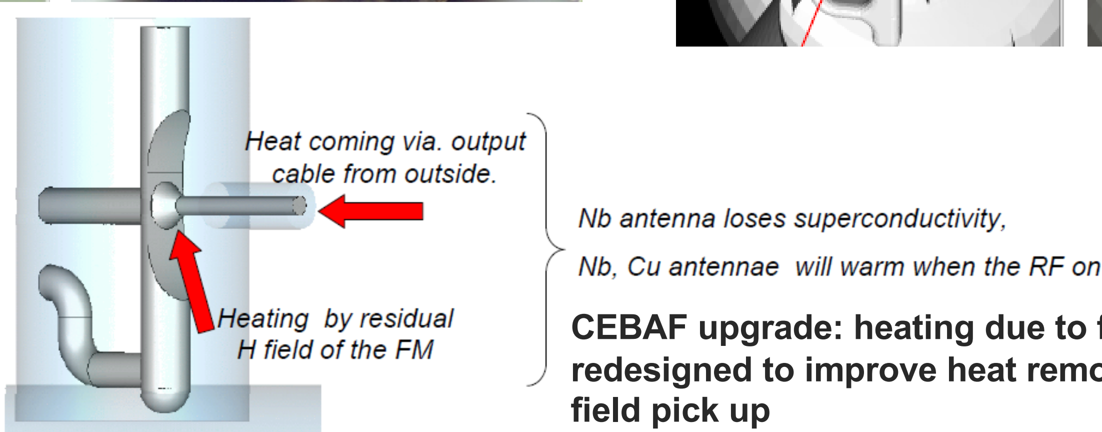
- Scaling of this design to other applications (different frequency, CW vs. pulsed operation) presented serious challenges:
  - Risk of multipacting (e.g. initial 3.9 GHz FNAL/FLASH cavities, SNS cavities at 805 MHz)
  - Potential thermal issues in CW applications (12 GeV CEBAF upgrade, 1.5 GHz)
- Required re-design (3.9 GHz and CEBAF upgrade) or removal of HOM couplers (SNS).

3.9 GHz HOM coupler failure due to overheating caused by MP: redesigned to shift MP barriers above operating gradients



Multipacting in HOM2 at SNS





CEBAF upgrade: heating due to fundamental mode: redesigned to improve heat removal and reduce residual field pick up

Takeaway points

- Taking into consideration beam-cavity interaction and operational conditions from the very beginning of the SRF system design process can bring huge benefits during the machine commissioning and operation.
- Using an existing design as a base for developing a new system is OK and can shorten the new system development time, but the system designers should be aware that even seemingly small changes could bring big consequences.
- As accelerator application demands continue to increase (higher energy, higher luminosity, brighter beams, more efficient accelerators, …) there will be no shortage of new challenges to tackle in the future.