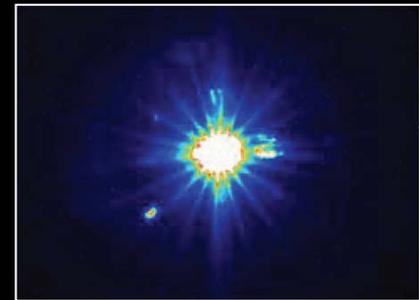




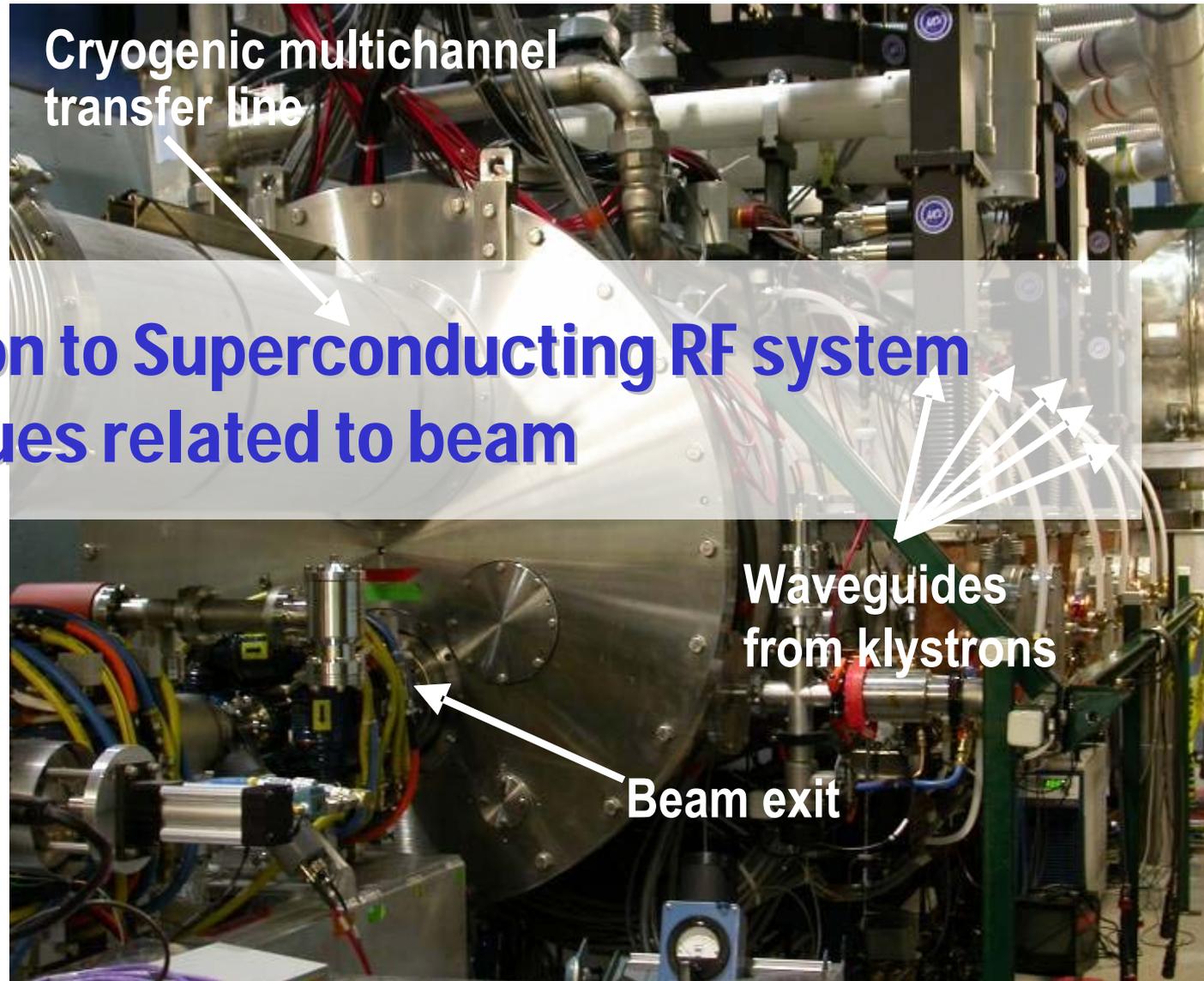
# Tutorial on Operational Aspects of Superconducting RF Cavities with Beam

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- ❑ Introduction to Superconducting RF system design issues related to beam
- ❑ Accelerator types and functions performed by SRF cavities
- ❑ Fundamental mode
  - Beam loading
  - Beam-based field calibration
  - After installation in an accelerator...
- ❑ Higher-Order Modes (HOMs) and beam instabilities
  - Beam instabilities
  - Examples of experience with beam
- ❑ Summary



## Introduction to Superconducting RF system design issues related to beam



- ❑ 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.
- ❑ The operational aspects related to beam (machine and beam parameters) 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.
- ❑ As 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, the systems approach helps to keep the SRF system developers focused on this goal.
- ❑ Some operational issues have already been covered in the previous tutorials (microphonics by C. Hovater, input and HOM couplers by S. Noguchi, ...) so we will only briefly mention those here.



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

## Cryomodule design

### Machine parameters

### Effects/cavity parameters

*Cryogenic system*

### Cavity design

*Vacuum*

**Mechanical design:**  
stiffness,  
vibration modes,  
tunability,  
thermal analysis

**RF design:**  
frequency & operating  
temperature choice,  
optimal gradient,  
cavity shape optimization,  
number of cells,  
cell-to-cell coupling,  
HOM extraction,  
RF power coupling

*Instrumentation & controls*

**Cryostat design**

**Input coupler design**

**HOM damper design**

**Tuner design**

**RF controls**

*High-power RF*

*Auxiliary systems: AC power, cooling water, ...*

Pulsed operation

CW operation

High beam current

High beam power

Beam quality (emittance) preservation

Low beam power

Lorentz force detuning

RF power dissipation in cavity walls

Beam stability (HOMs)

Heavy beam loading

Low Qext

Availability of high-power RF sources

Parasitic interactions (input coupler kick, alignment)

High Qext, microphonics



- ❑ **High beam current** → beam instability due to interaction with cavity higher-order modes → 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; 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
- ❑ **Beam quality (emittance) preservation** → 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, feedbacks

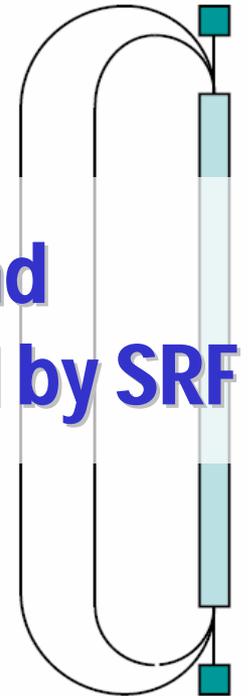


# Accelerator types and functions performed by SRF cavities

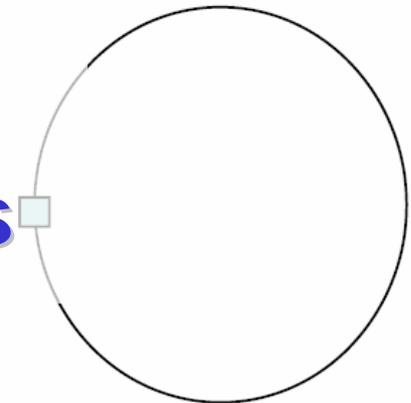
- RF Installation
- Beam injector and dump
- Beamline



Linac



Recirculating  
Linac



Ring



## ❑ Fundamental RF for beam acceleration

- Provide energy gain
- Secondary functions: bunching, quantum lifetime, energy acceptance

## ❑ (3<sup>rd</sup>) Harmonic RF for altering linearity of fundamental RF waveform

- Reduce beam energy spread by flattening effective RF wave at crest
- Shorten bunch length by increasing RF wave slope
- Lengthen bunches by flattening RF wave at synchronous phase and thus making wider potential well (often beam-induced voltage on passive cavities is used)

## ❑ Dipole mode RF for beam deflection

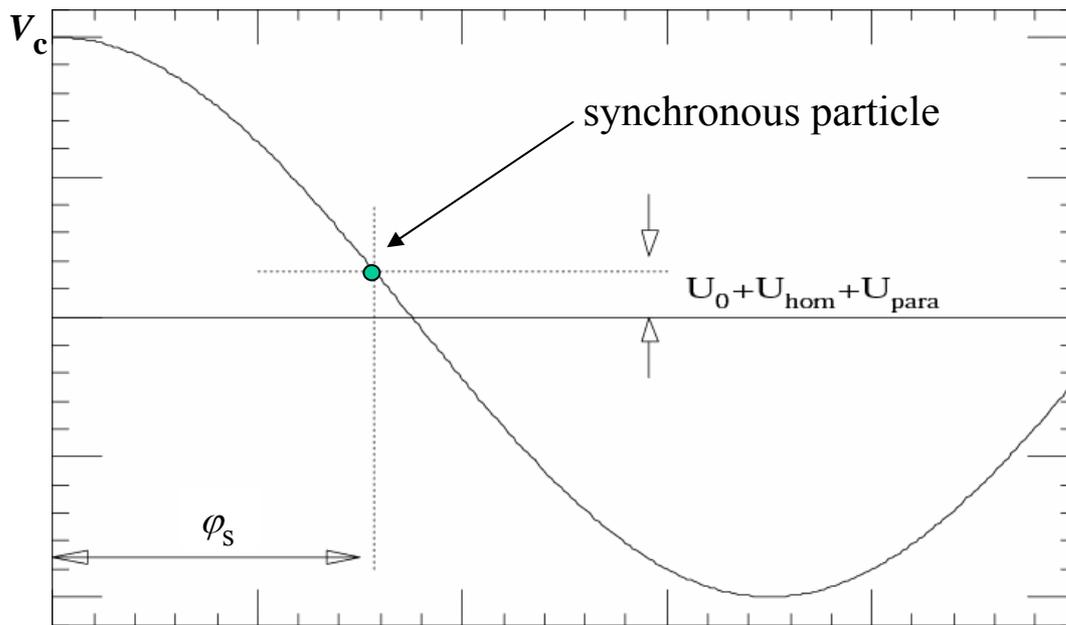
- Crab cavities rotate bunches for head-on collisions

## ❑ SRF guns

- Fast acceleration and RF focusing of the beam (possibly using magnetic field from a HOM)



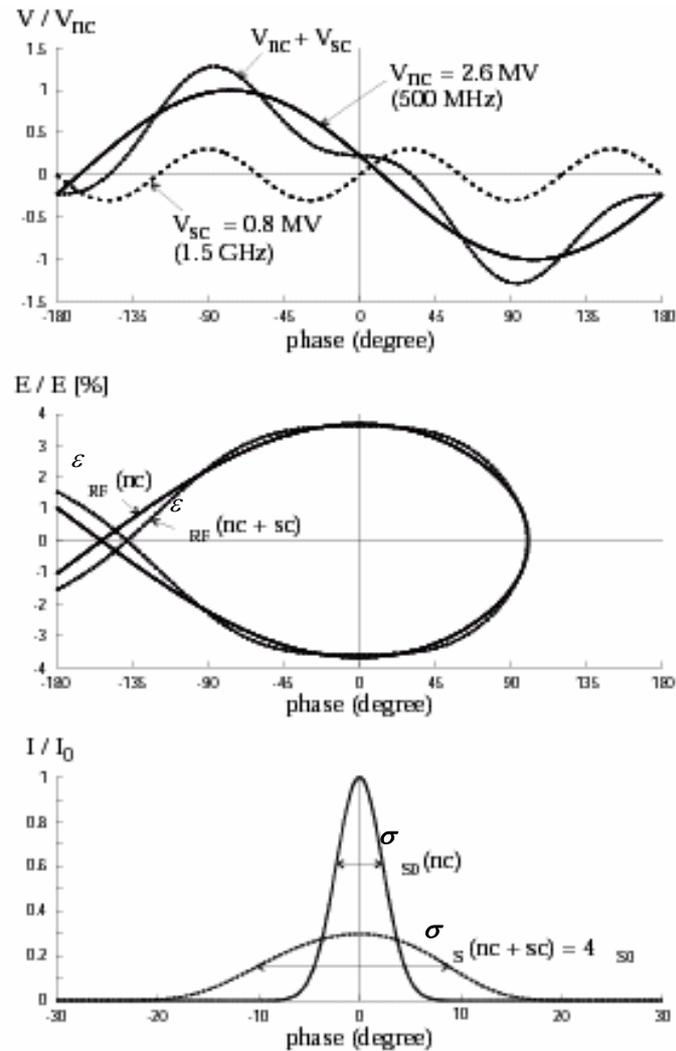
- Provide energy gain → deliver RF power to a high-current beam(s).
- Provide high voltage for high synchrotron tune and short bunch length (colliders).
- Provide enough voltage for good quantum lifetime.
- Provide voltage for good energy acceptance.
- Suppress parasitic interaction of a beam with higher-order modes (HOMs) by providing good HOM damping (concept of so-called HOM-damped, HOM-free or single-mode cavity).



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

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

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



- Bunch shortening to enhance luminosity (colliders).
- Bunch lengthening to improve the Touschek beam lifetime (light sources).
- Improved beam stability due to Landau damping.
- Typically 3<sup>rd</sup> harmonic beam-driven (passive) cavities are used.

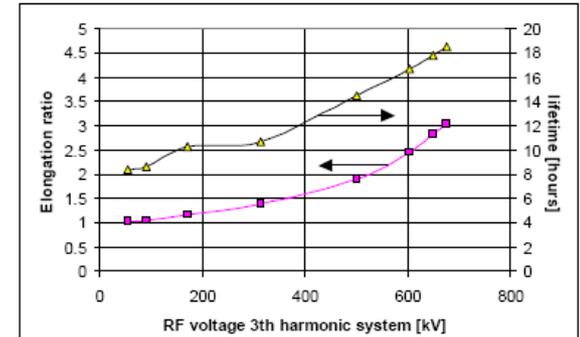


Figure 4: Average elongation ratio and lifetime versus 3HC voltage (180 mA – 2.08 MV operation).

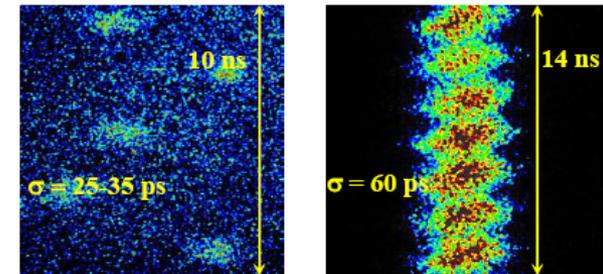
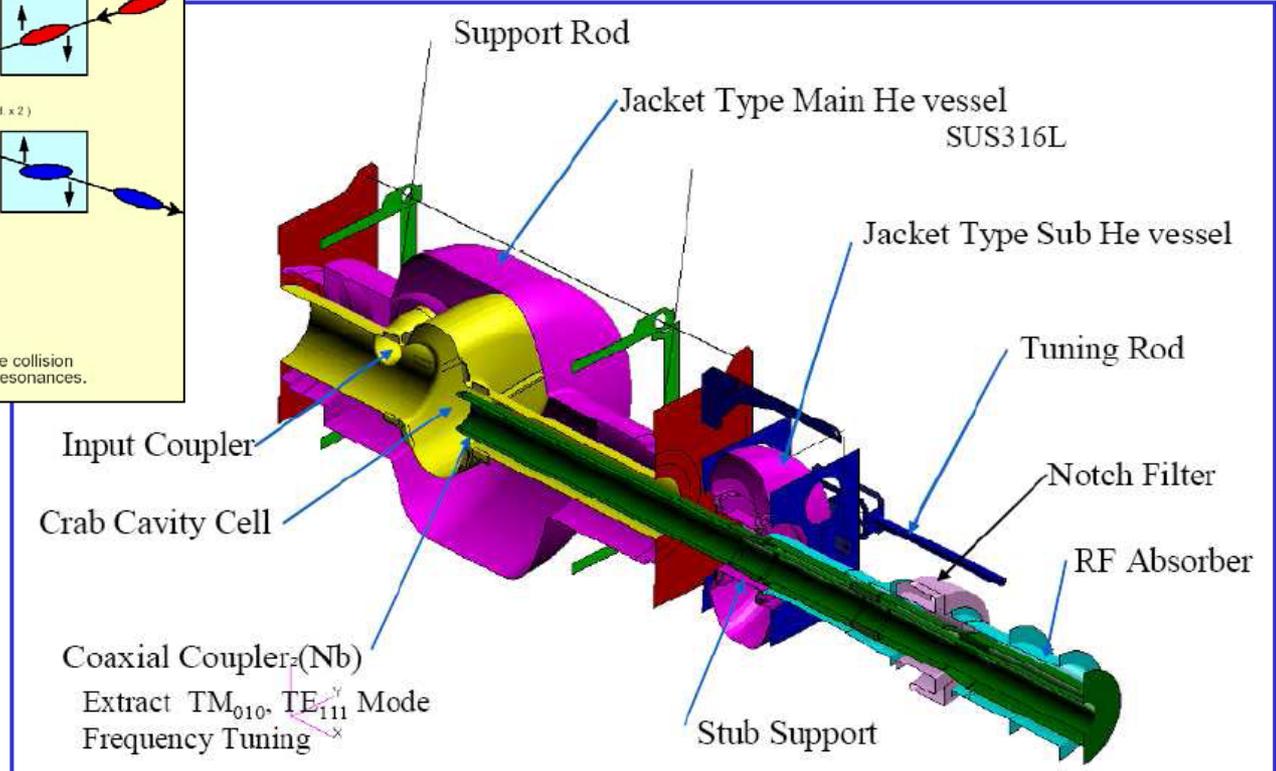
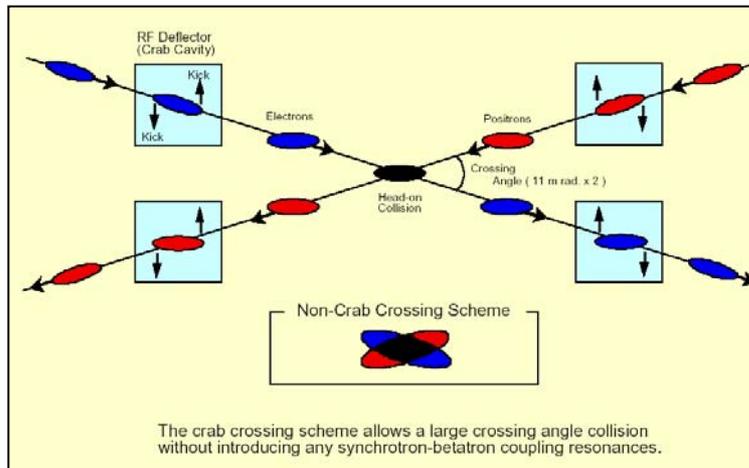


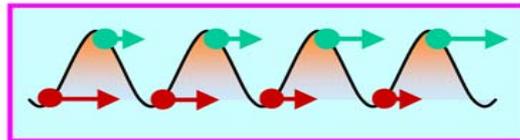
Figure 5: 250 mA, 2.0 GeV, streak camera images. On the left S3HC detuned, longitudinal oscillations present; on the right S3HC tuned, stable beam. Theoretical  $\sigma$  without S3HC is 18 ps.



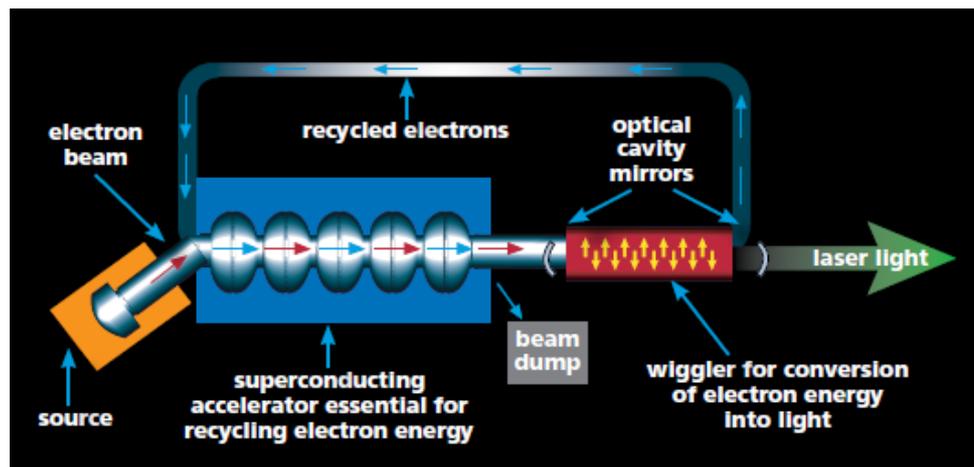
# Crab cavities

- These cavities are used in colliders (KEKB) to reduce synchro-betatron oscillations coupling in a scheme with collisions at large crossing angles.
- A crab cavity provides a transverse kick to bunches so that they collide head-on.
- Its operating mode is  $TM_{110}$  deflecting mode.

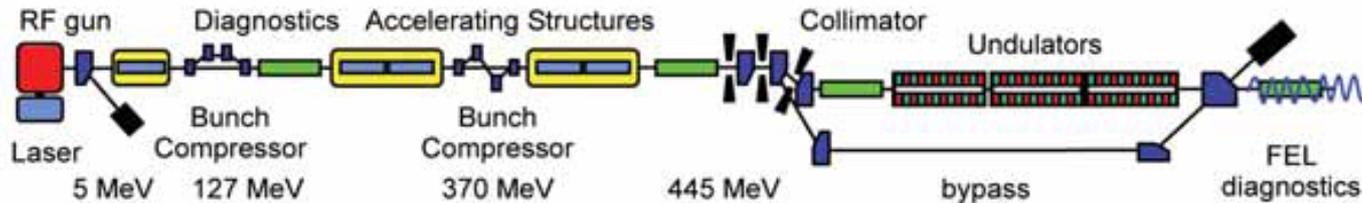




- Due to energy recovery, the required RF power is nearly independent of the beam current. Beam loading is zero in an ideal case.
- However, small deviations can induce strong effects → hence very tight requirements to RF amplitude and phase stability at high loaded  $Q$ .
- Multipass Beam Breakup (BBU) due to interaction with dipole HOMs is the major limitation of the beam current in ERLs. Strong damping of HOMs in multi-cell cavities is required.
- HOM power dissipation may be high.

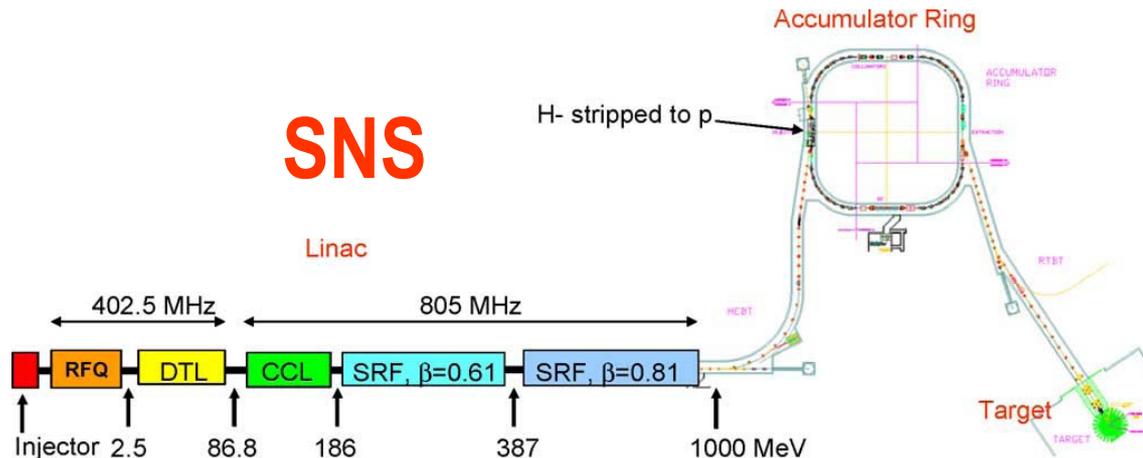


## FLASH



- SRF straight linacs operate in pulsed mode if high energies are needed, CW mode for lower energies.
- Higher gradients ( $\geq 25$  MV/m) are typically used in pulsed mode than in CW mode.
- HOM damping requirements are relaxed compared to ERLs.

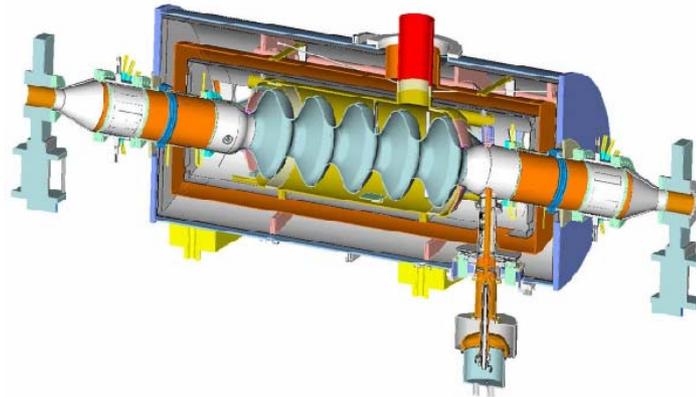
## SNS





# Typical requirements

	Examples	Accelerating gradient	RF power	HOM damping
<b>Pulsed linacs</b>	FLASH, XFEL, SNS	Moderate to high	High peak (> 250 kW), low average (~ 5 kW)	Moderate ( $Q = 10^4 \dots 10^6$ )
<b>Low-current CW linacs</b>	JLab FEL, ELBE	Moderate to low (8...20 MV/m)	Low (5...15 kW)	Relaxed
<b>High-current ERLs</b>	Cornell ERL, Electron cooler for RHIC	Moderate (15...20 MV/m)	Low (few kW)	Strong ( $Q = 10^2 \dots 10^4$ )
<b>High-current ERL injectors</b>	Cornell ERL injector, JLab FEL 100 mA injector	Moderate to low (5...15 MV/m)	High (50...500 kW)	Strong ( $Q = 10^2 \dots 10^4$ )
<b>High-current storage rings</b>	CESR, KEKB, LHC, CLS, TLS, BEPC-II, SOLEIL, DIAMOND, SRRF	Low (5...10 MV/m)	High (up to 400 kW)	Strong ( $Q \sim 10^2$ )



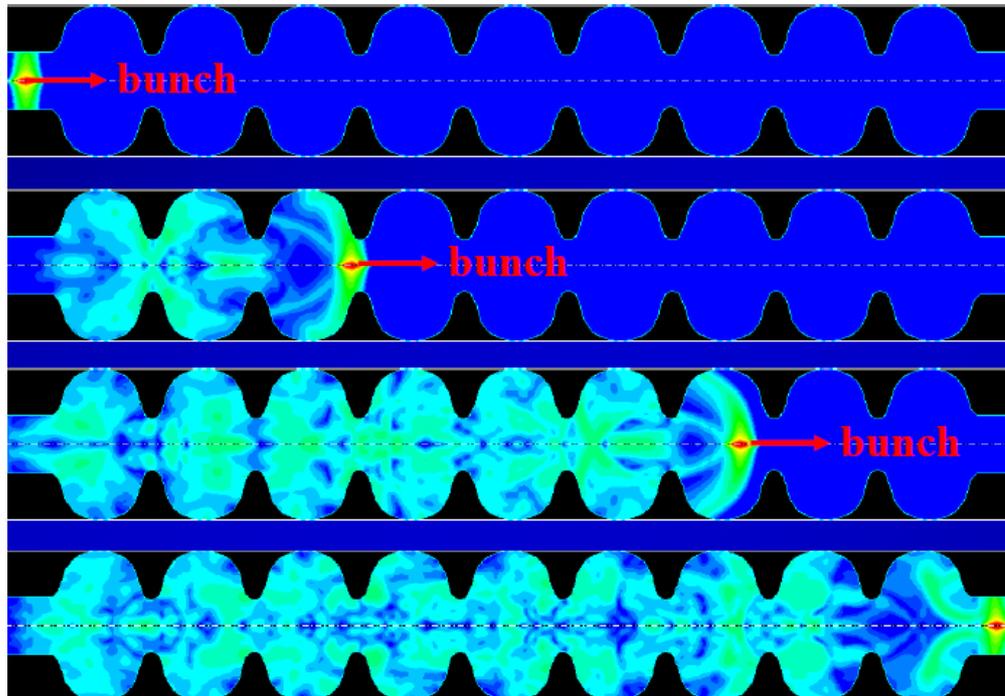


## Fundamental mode



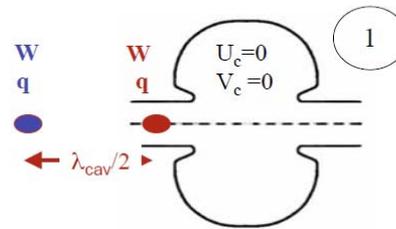


- As bunch traverses a cavity, it deposits electromagnetic energy, which is described in terms of wakefields.
- The wakefields, in turn, can be presented as a sum of cavity eigenmodes (fundamental and HOMs).
- If a charge passes a cavity exactly on axis, it excites only monopole modes. For a point charge 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.



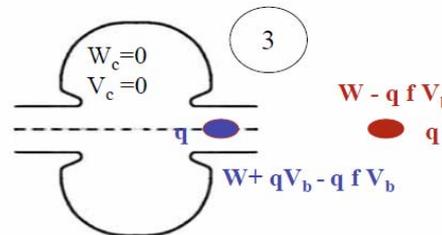
# Fundamental theorem of beam loading

- 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?



For simplicity:

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

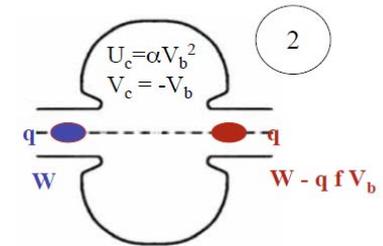


By energy conservation:

$$W + qV_b - qfV_b + W - qfV_b = W + W$$

$$\implies f = 1/2$$

Half an rf period later, the voltage has changed in phase by  $\pi$



Notice:

$$\alpha V_b^2 = qfV_b \implies V_b = qf / \alpha$$

$V_b$  is proportional to  $q$

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

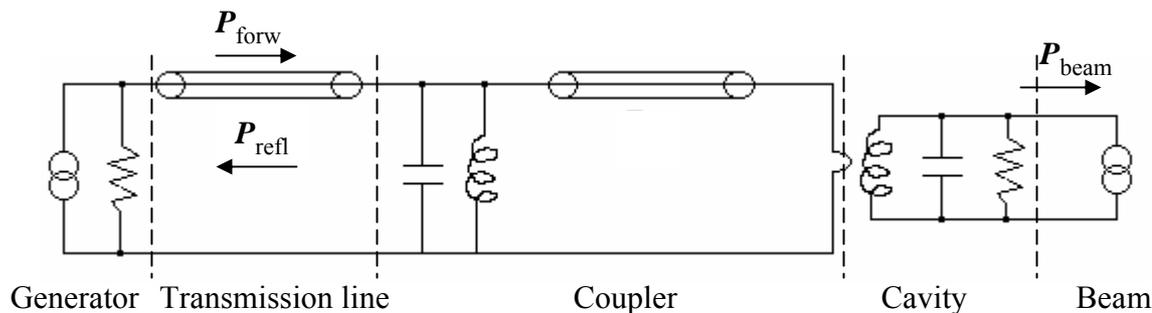
$$\Delta W = 1/2 qV_b$$

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

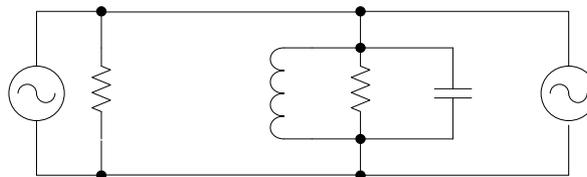


# Circuit model of the fundamental mode with beam

- 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



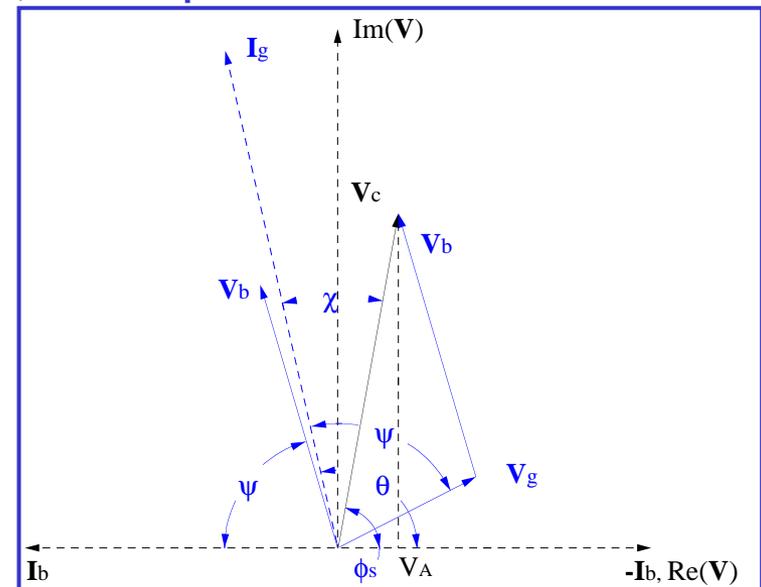


# Phasor diagrams

- 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 sinusoidally varying 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

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

- This vector rotates counterclockwise in the complex plane and is called *phasor*.
- If now one chooses a frame that is rotating with a frequency  $\omega$ , then the phasors remain fixed in time.
- The component of any voltage that contributes to acceleration of the bunch is the projection of the voltage onto the real axis.





- From the equivalent circuit diagram, and introducing cavity tuning angle  $\psi$

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

and beam phase relative to RF wave crest  $\varphi_0$ , one can derive for the forward power

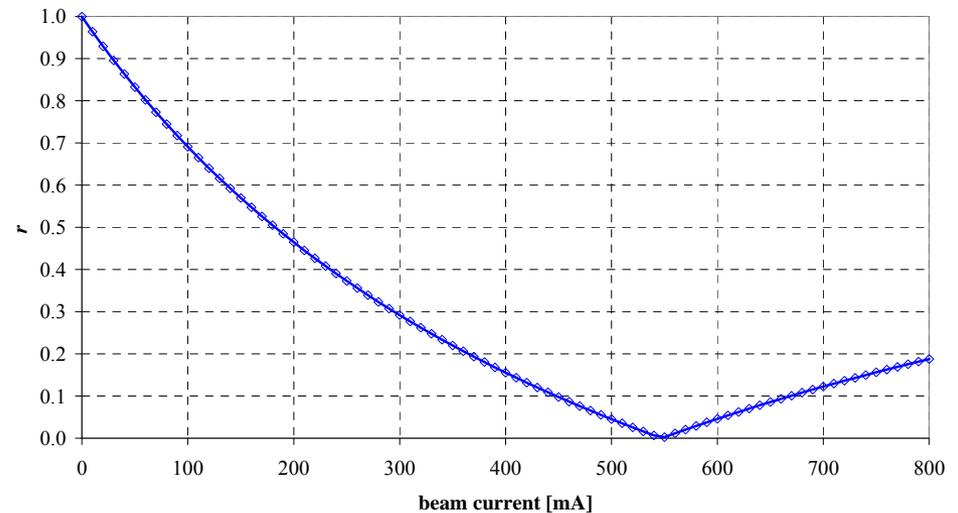
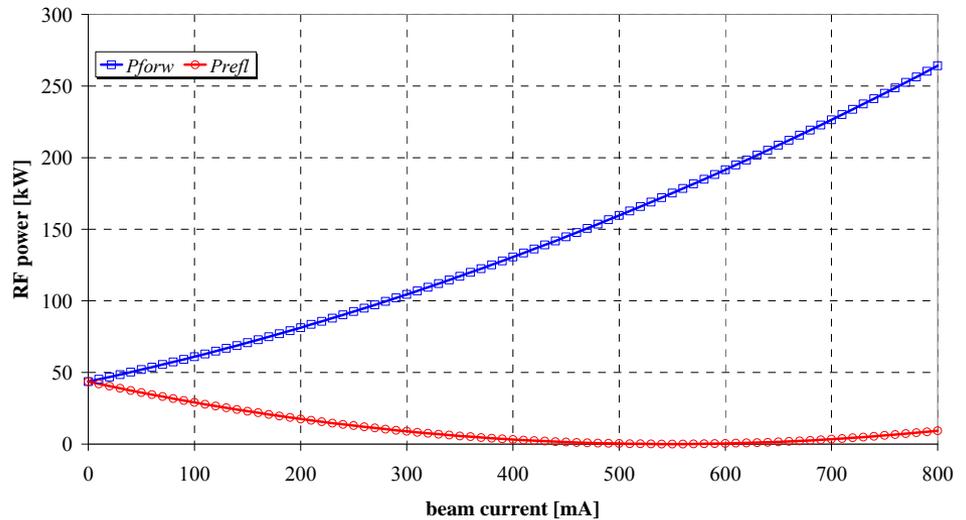
$$P_{\text{forw}} = \frac{V_c^2}{4R/Q \cdot Q_{\text{ext}}} \cdot \frac{(\beta+1)^2}{\beta^2} \cdot \left\{ \left[ 1 + \frac{I_b R/Q \cdot Q_L}{V_c} \cos \varphi_0 \right]^2 + \left[ \tan \psi + \frac{I_b R/Q \cdot Q_L}{V_c} \sin \varphi_0 \right]^2 \right\}$$

- The two terms correspond to active and reactive parts of the beam loading.
- In storage rings, where the beam is passing cavity off crest, the reactive beam loading is compensated by appropriate cavity detuning. The coupling  $\beta$  is chosen to achieve matching conditions at a maximum beam current.
- In ERLs, with two beams passing the cavity  $180^\circ$  apart, the beam loading is zero for perfect energy recovery and the cavity is tuned to resonance. 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).



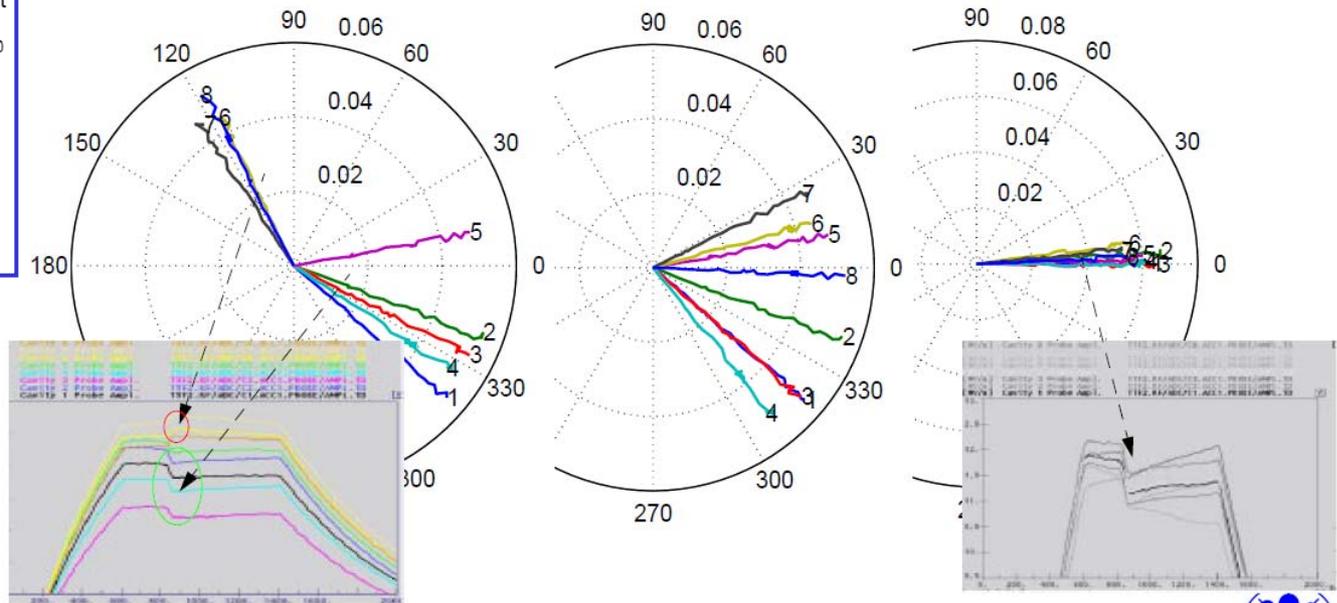
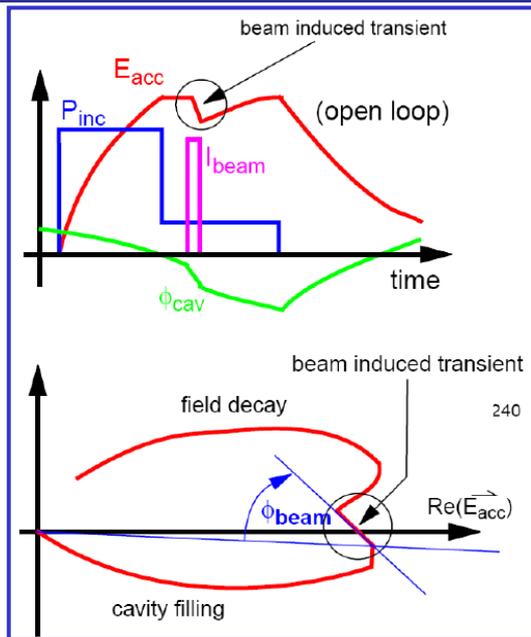
# RF power vs. beam current

- For a fixed coupling, chosen to match beam at nominal current, standing wave pattern in the input coupler and transmission line goes from full reflection (without beam) through matched condition at nominal beam current to partial reflection.
- Initially over-coupled input coupler becomes under-coupled:  $\beta$  depends on the beam current.



## Beam Based Calibration at FLASH

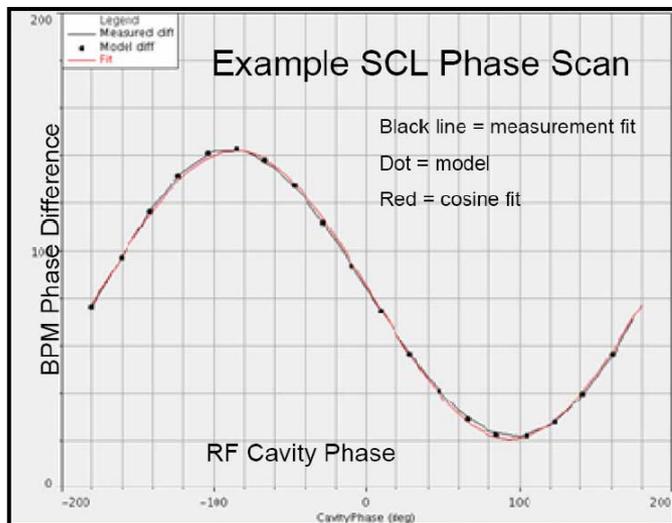
- Good beam required to get sufficient signal (8nC, 30μs, 15MV/m)
- Preliminary calibration (to 10%)
- Gradient calibration (to 3-5%)



for  $\Delta t \ll \tau_{cav}$ :

$$\Delta V_{ind} = I \cdot \Delta t \cdot \left(\frac{r}{Q}\right) \cdot \pi \cdot f$$

Ayvazyan / Simrock, Workshop on Low Level RF, CERN, Oct. 10-13, 2005



- 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 360 degrees 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.

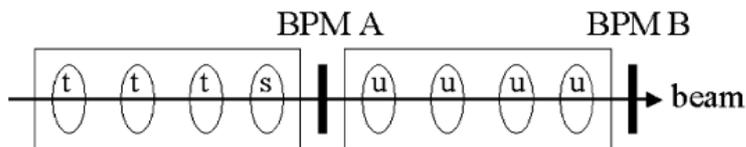
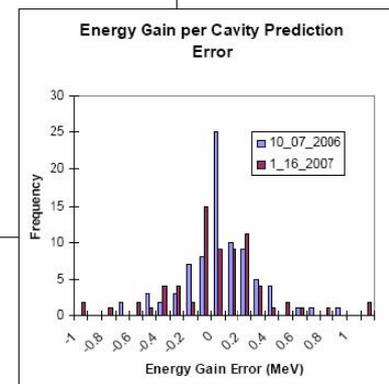
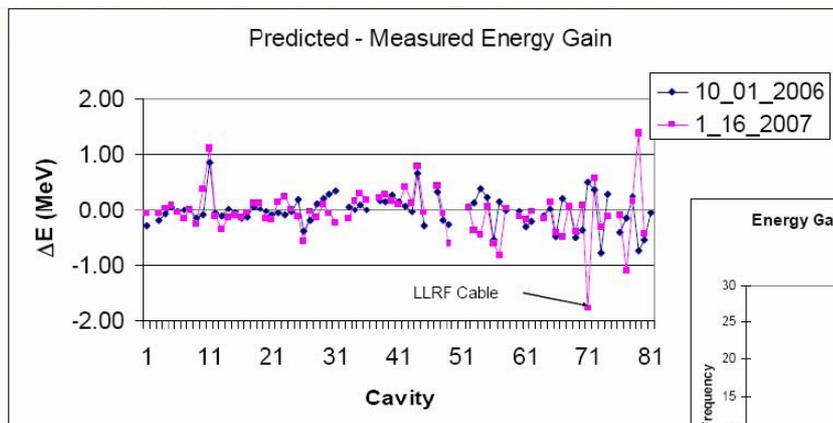
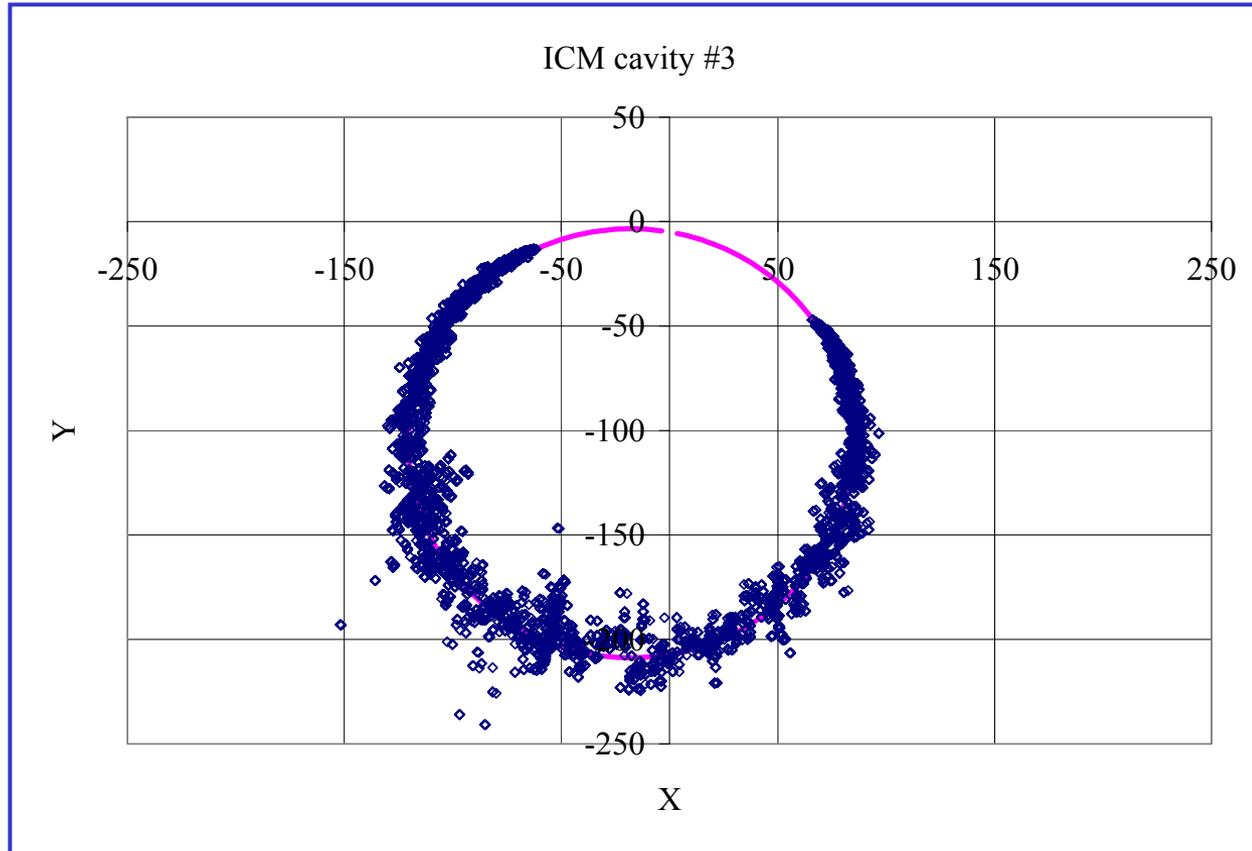


Fig. 1. Schematic drawing of the phase scan. The "u" cavities between BPM A and BPM B are unpowered, and those with "t" are already tuned. The "s" cavity just upstream of BPM A is being scanned.



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



- 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.

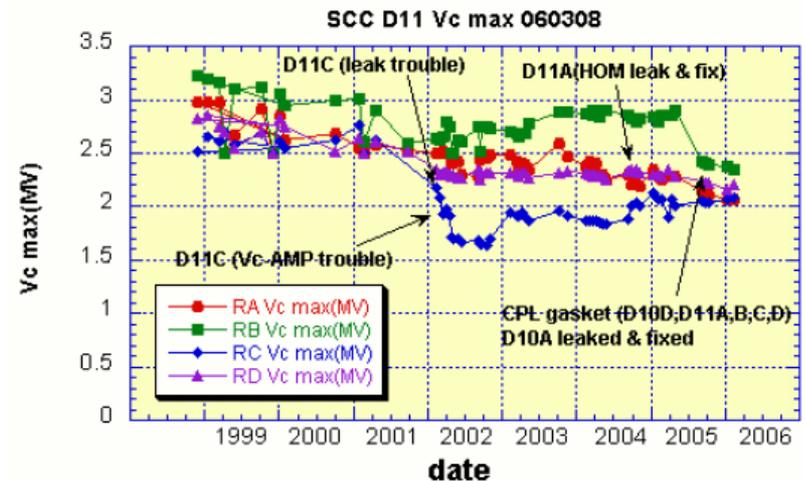
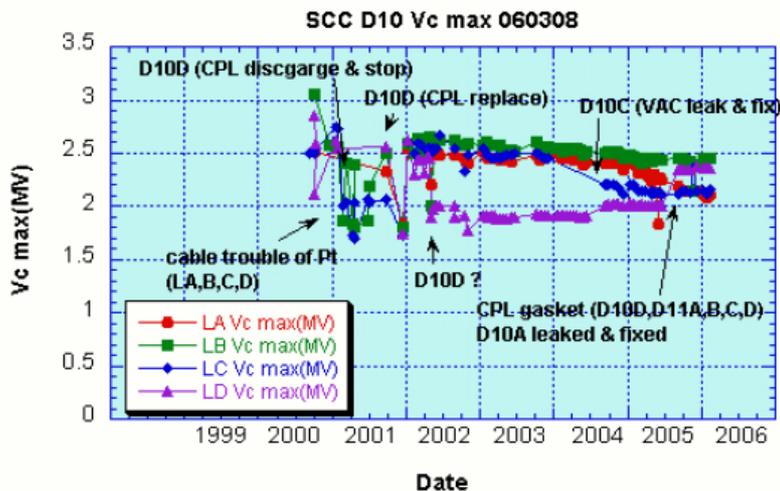


- After the cryomodule is assembled, its cavities and input couplers are usually subjected to the *in situ* conditioning and/or acceptance testing.
- However, quite often the need arises for re-conditioning or conditioning to new operating requirements.
- Not always it is possible to recover cavity/coupler performance.
- Operating close to the maximum accelerating gradient or RF power level leads to increased frequency of RF trips, which in turn cause beam loss.
- RF trip frequency tolerance depends on the type of accelerator and experiment. HEP and NP experiments rely on integrating statistics and more tolerant to interruptions than user facilities, such as X-ray light sources.
- Next, we consider examples of operational experience with SRF cavities and couplers at different facilities.



# Example 1: maximum accelerating voltage of KEKB cavities, long term

- **Example 1: maximum voltage of KEKB cavities, long term experience.**
  - All cavities could operate at  $> 2$  MV after 7 years of operation.
  - Voltage of D11C degraded after the vacuum trouble.
  - Voltage of D11B degraded after changing the coupling of the input coupler.
  - Overall, very positive experience.

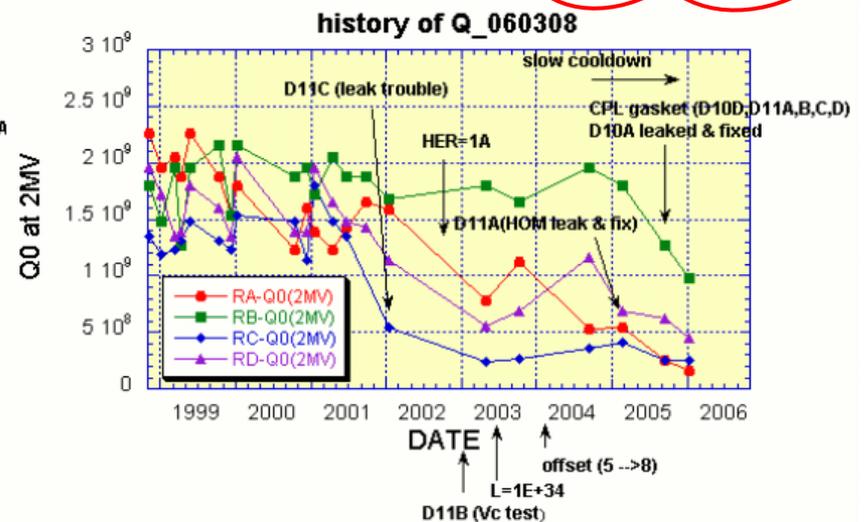
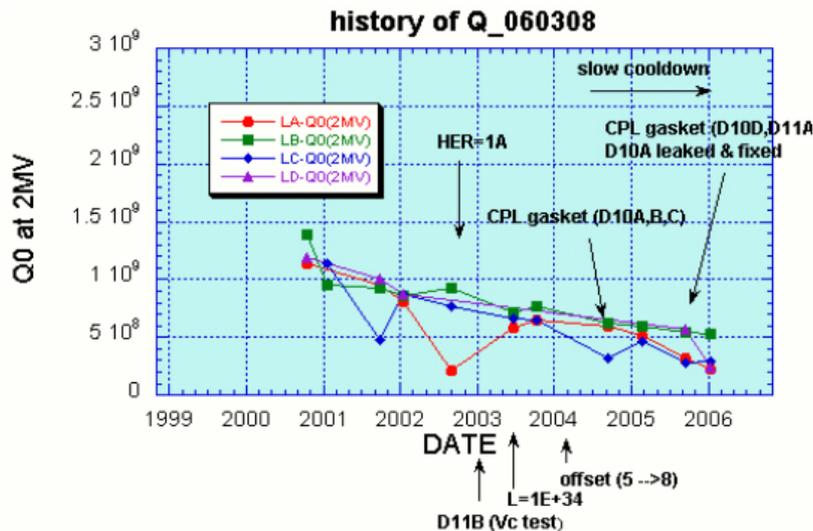
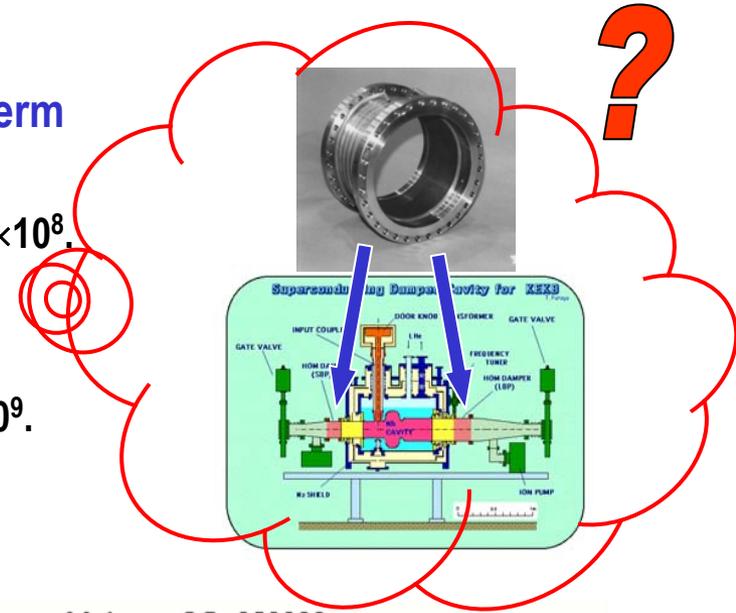


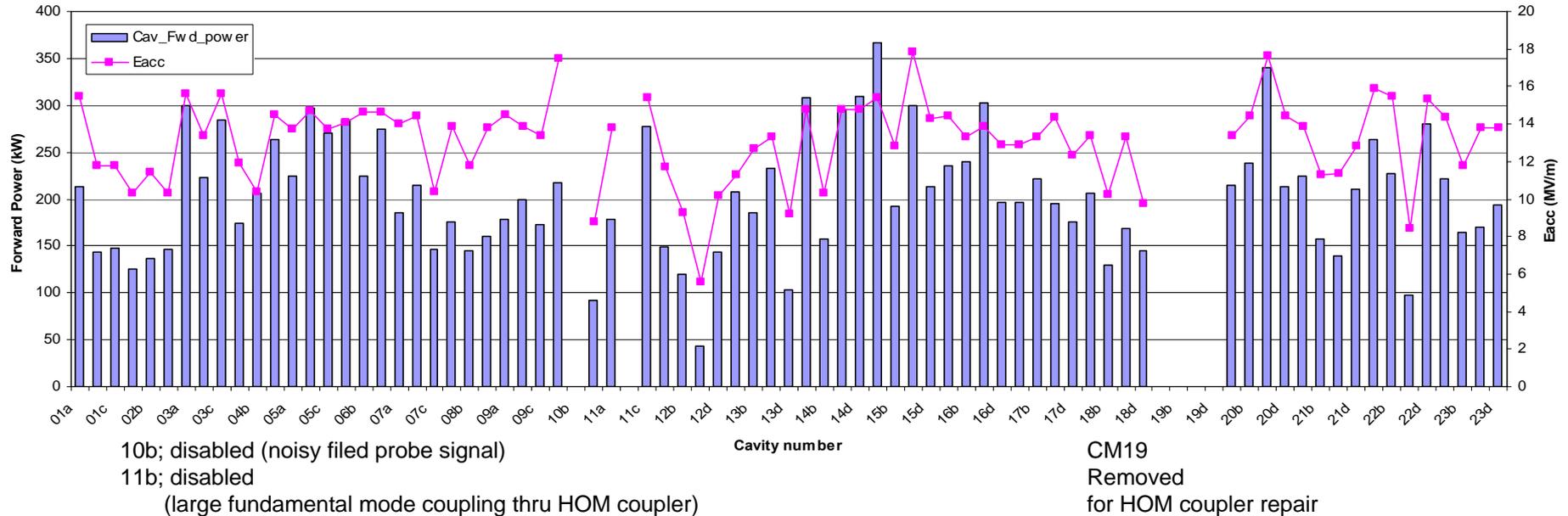


# Example 2: $Q$ degradation at KEKB over long time

## Example 2: intrinsic $Q$ degradation of KEKB cavities, long term experience.

- Unloaded  $Q$  at 2 MV (8 MV/m) has gradually degraded to  $3.5 \times 10^8$ .
- Out-gassing and/or ferrite dust from the HOM dampers?
- Exact cause is still unknown.
- The  $Q$  at the operating voltage (1.4 MV) still higher than  $1 \times 10^9$ .





## ❑ Cavity-coupler interaction

- Electron current at the full traveling wave
- Radiation spikes at the same time
- Can cause multipacting

## ❑ Cold cathode gauge (interlock to protect coupler window)

- Sleeping and wake-up with erratic signals
- Made turn-on difficult before new procedure were implemented
- Moving towards interlocking on electron probe signals

## ❑ Coupler outer conductor cooling circuit

- Difficult adjustment of helium flow under changing average power
- Cross-interactions between cavities in a cryomodule

## ❑ Multipacting (MP) in FPCs

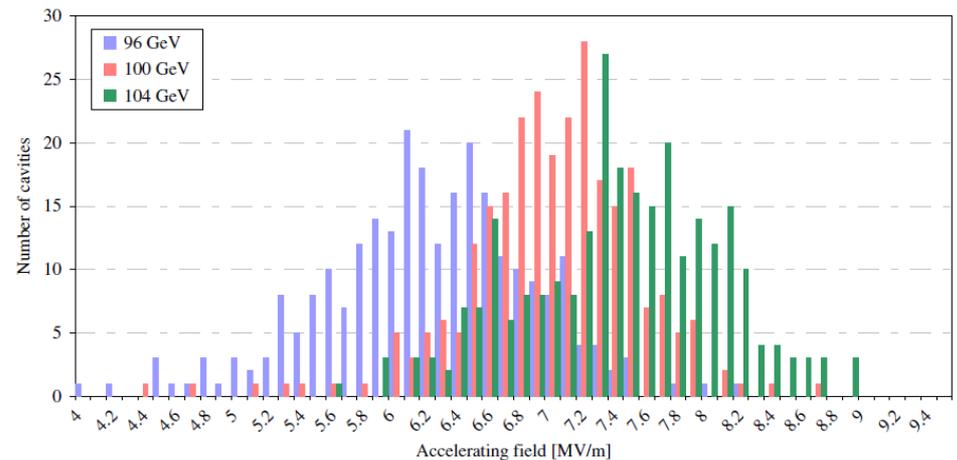
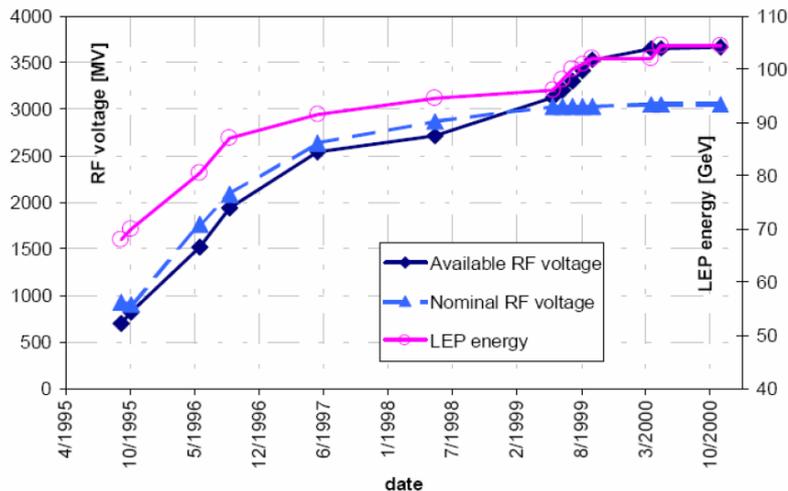
- As the beam power is increased, the multipacting purely in the FPC in several cavities is observed
- DC biasing will help to suppress MPs

## ❑ Otherwise the FPCs are working fine and very robust.



# Example 4: maximizing the energy reach of LEPP-II

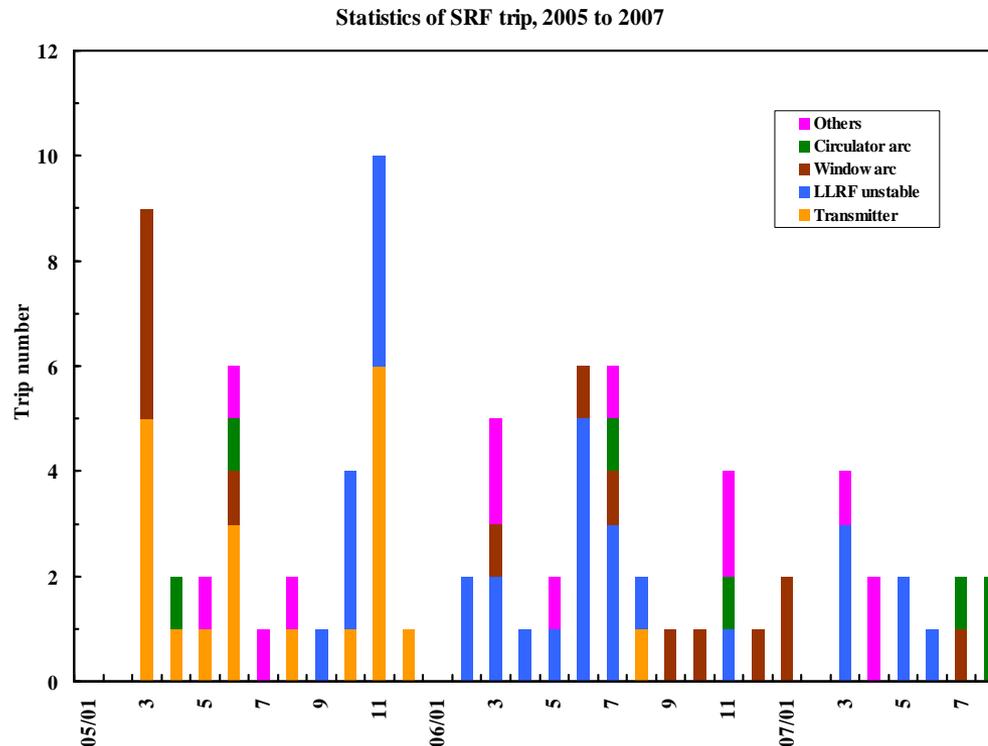
- CERN installed the largest SRF system in 90s to double the energy of its electron-positron collider LEPP. LEPP-II has ultimately reached 104.5 GeV.
- The experience there was dominated by the quest to deliver the highest possible energy beams with the available RF.
- The accelerating gradient increase 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% lower than 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.





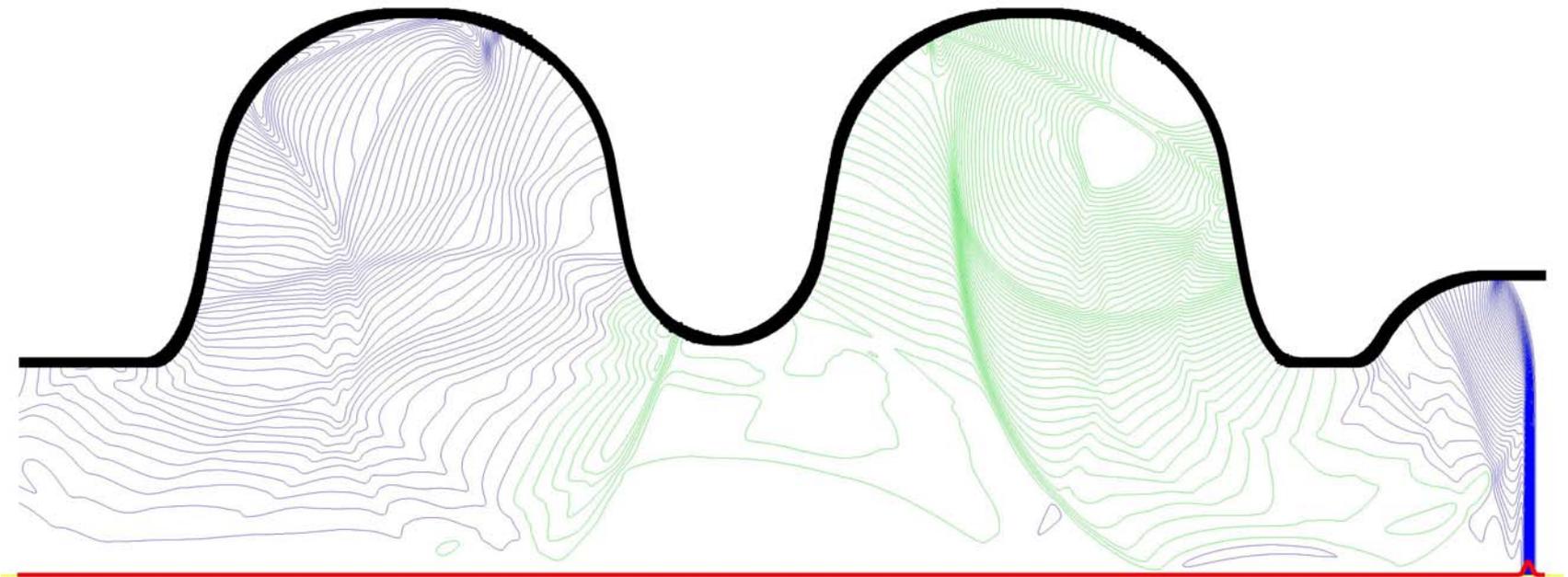
# Example 5: RF trips in light sources

- Light sources are user facilities. The specifics of the experiments there requires long exposure of samples to an uninterrupted X-ray beam. Hence: very low RF trip rate is required
- 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.





# Higher Order Modes & beam instabilities



The details of the wakefields themselves are usually of a lesser interest than 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  $\lambda(s)$  and the wake function:

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

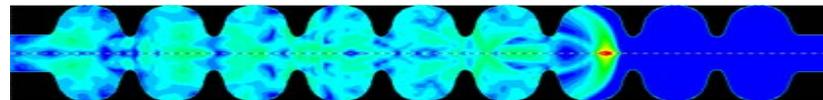
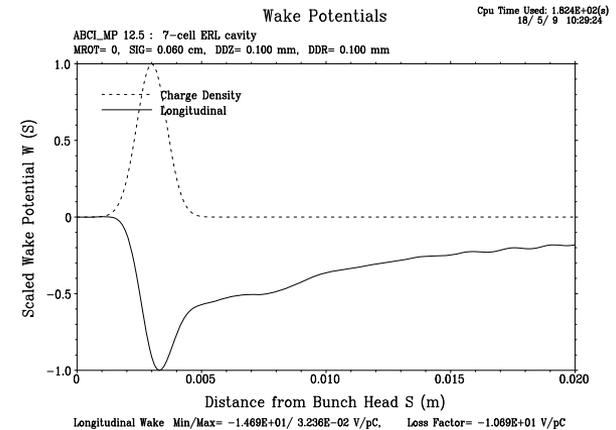
Once the longitudinal wake potential is known, the total energy loss is given by

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

Now we can define a figure of merit, the loss factor, which tells us how much electromagnetic energy a bunch leaves behind in a structure:

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

The more energy it loses, the more is the likelihood of adverse effects on the subsequent bunches.





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

$$k = \sum_n k_n = \sum_n \frac{\omega_n}{2} \left( \frac{R}{Q} \right)_n$$

here  $R/Q$  is in circuit definition.

The loss factor can be used to calculate beam losses due to HOMs over the whole bunch spectrum.

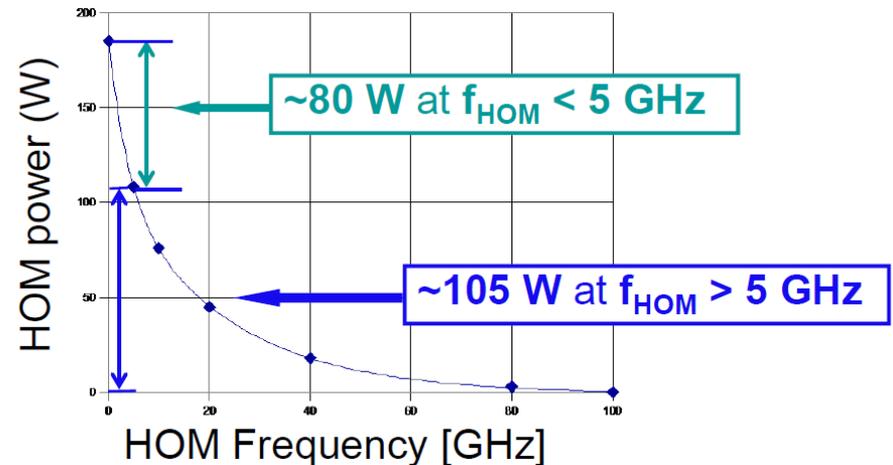
This approximation works usually quite well.

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

here  $q$  is the bunch charge,  $I_{av}$  is the average beam current.

Example:

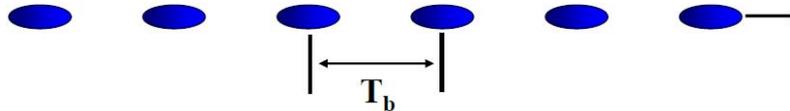
- 100 mA ERL beam
- 0.7 mm (rms) long 77 pC bunches
- 9-cell cavities with loss factor of 12 V/pC



The HOM power loss is 185 W over a frequency range up to 100 GHz.



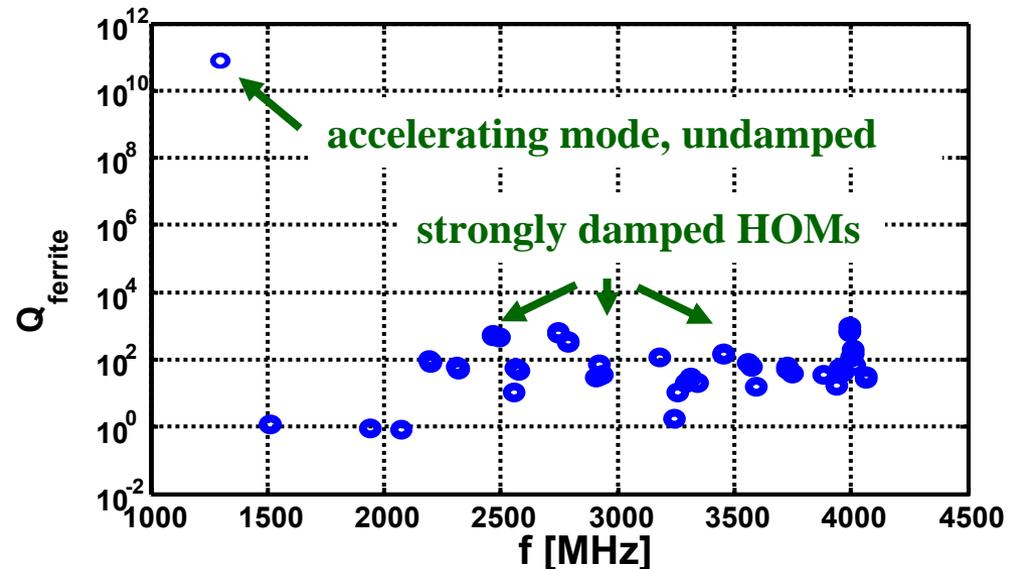
# Beam-cavity interaction: frequency domain



- 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.

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

- That is why practically all SRF cavities have special devices to damp HOMs (absorb their energy). For analysis of instabilities, it is more convenient to use frequency domain rather than time domain approach.





**Detrimental effects caused by the beam interaction with cavity HOMs include:**

- **multi-bunch instabilities (longitudinal and transverse) in storage rings**
- **multipass beam break-up (BBU) instabilities (transverse and longitudinal) in re-circulating linacs**
- **single-pass BBU in linacs**
- **resonant excitation of longitudinal HOMs**
- **increased beam energy spread**
- **additional cryogenic losses**

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



Let us consider a single-bunch beam interacting with a narrow-band resonance. The revolution time of a particle 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  $n$

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

The exact location of the HOM resonant frequency  $\omega_r$  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 on the next slide

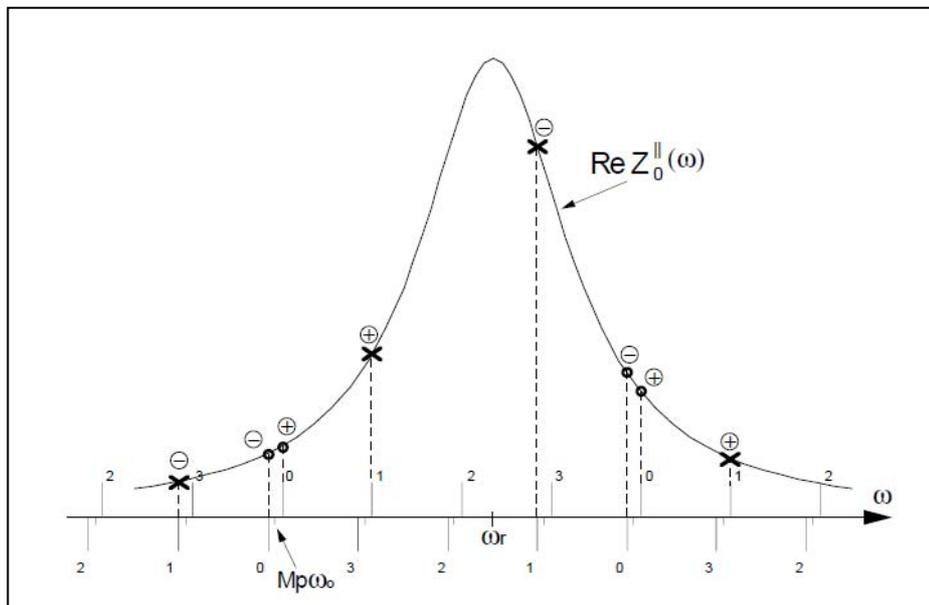
$$\begin{aligned} \tau_n^{-1} &= \omega_s \frac{I_0}{2hV_c \cos(\phi_s)\omega_0} \sum_{p=-\infty}^{\infty} (pM\omega_0 + n\omega_0 + \omega_s) \operatorname{Re}Z_0^{\parallel}(pM\omega_0 + n\omega_0 + \omega_s) \\ &= \omega_s \frac{I_0}{2hV_c \cos(\phi_s)\omega_0} \times \\ &\quad \times \sum_{p=0}^{\infty} \left[ (pM\omega_0 + n\omega_0 + \omega_s) \operatorname{Re}Z_0^{\parallel}(pM\omega_0 + n\omega_0 + \omega_s) - (pM\omega_0 - n\omega_0 - \omega_s) \operatorname{Re}Z_0^{\parallel}(pM\omega_0 - n\omega_0 - \omega_s) \right] \\ &\approx \omega_s \frac{I_0}{2hV_c \cos(\phi_s)} \sum_{p=0}^{\infty} \left[ (pM + n) \operatorname{Re}Z_0^{\parallel}(pM\omega_0 + n\omega_0 + \omega_s) - (pM - n) \operatorname{Re}Z_0^{\parallel}(pM\omega_0 - n\omega_0 - \omega_s) \right] \end{aligned}$$



here  $\omega_s$  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,  $\eta$  is the slippage factor,  $I_0$  is the total beam current,  $V_c$  is the total cavity voltage (sum over all cavities),  $\varphi_s$  is the synchronous phase,  $Z_0$  is the cavity impedance (sum over all cavities),  $E_0$  is the beam energy.





# Multi-bunch instability in a storage ring

## (3)

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

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

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

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

Low frequency reduces number of cells

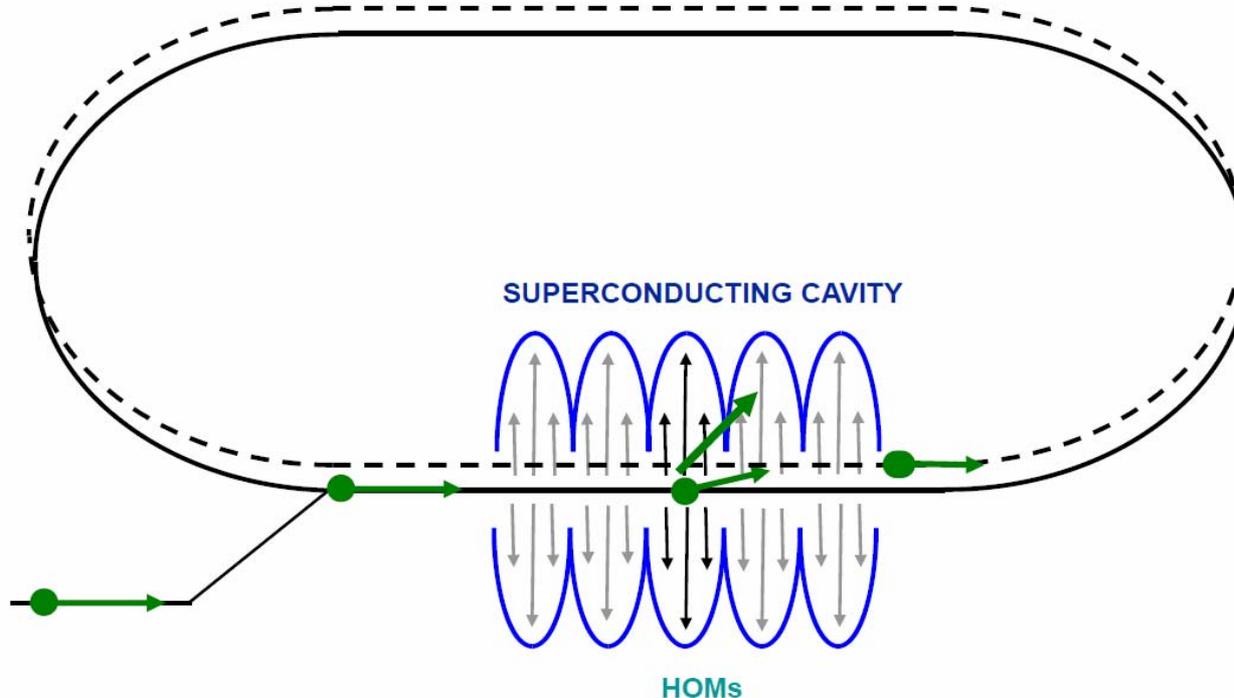
High  $E_{acc}$  reduces number of cells

Low frequency reduces synchrotron frequency

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



If a particle enters a cavity on the 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.





The threshold current at which a multipass 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;

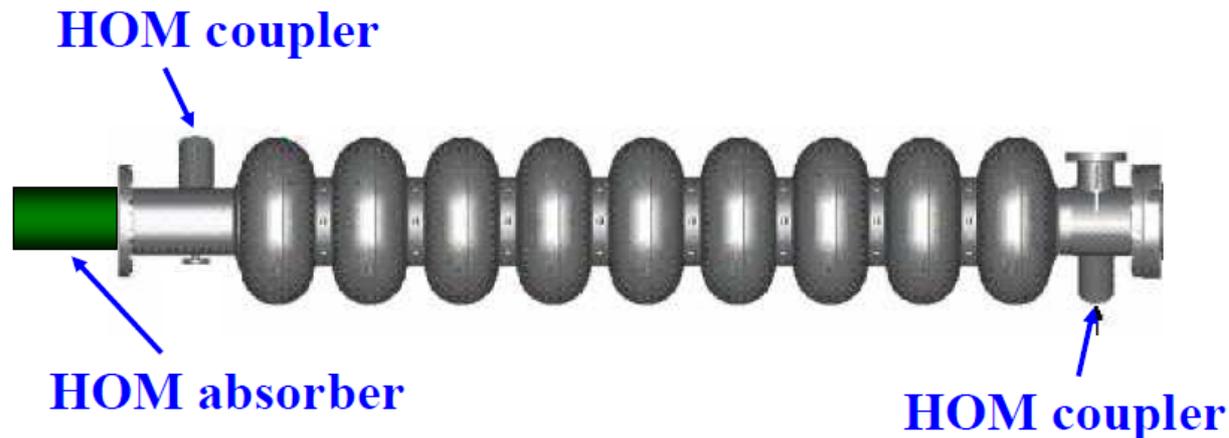
$p$  is the momentum of the particle,  $c$  is the speed of light,  $e$  is the charge of the electron,  $R/Q$  is the shunt impedance of the mode  $m$ ,  $Q$  is the quality factor of the mode,  $k = \omega/c$  is the wave number of the mode, and  $M_{12}$  is the transfer matrix element relating the 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 ring 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!**



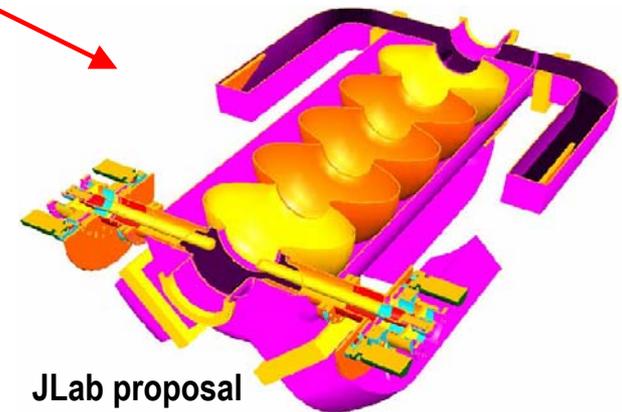
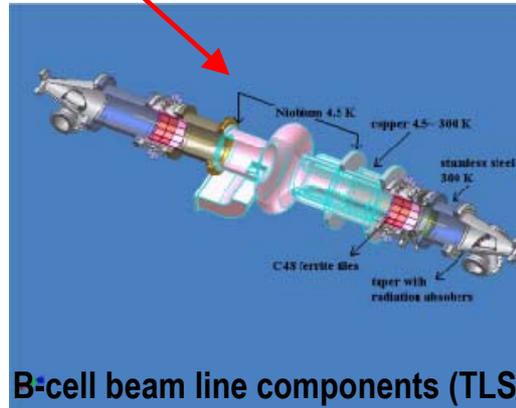
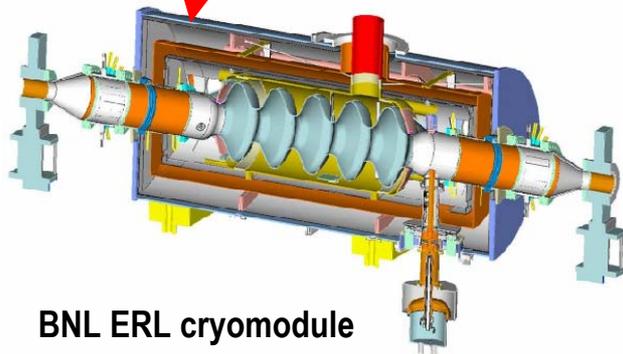
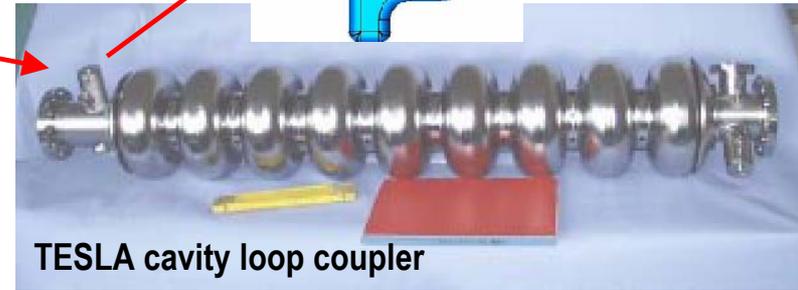
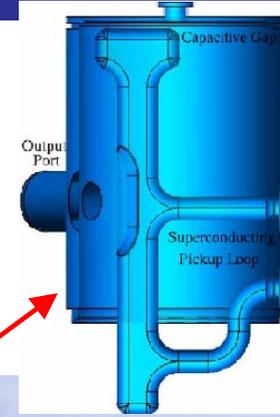
- Extremely low RF losses that make SC cavities so attractive in the first place are a handicap when we consider higher-order modes (HOMs).
- The parasitic interaction of a beam with HOMs can cause additional cryogenic loss, excite multi-bunch instabilities (longitudinal and transverse in storage rings, BBU in linacs and ERLs), lead to emittance growth and bunch-to-bunch energy spread.
- Depending on accelerator type, different levels of damping HOM's quality factors is required: from  $10^2 \dots 10^3$  for storage rings to  $10^4 \dots 10^5$  for some linacs.
- To keep the impedance of HOMs under control, special HOM dampers are usually attached to the beam tubes of SC cavities.





Several approaches are used:

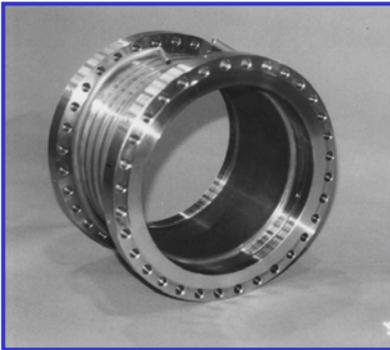
- Loop couplers (several per cavity for different modes/orientations)
- Waveguide dampers
- Beam pipe absorbers (ferrite or ceramic)





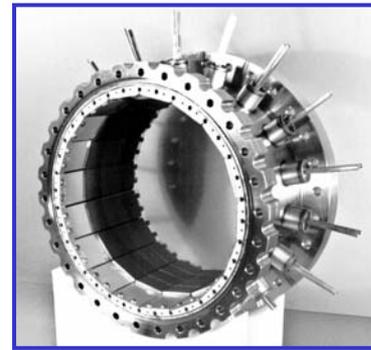
# Example 1: Experience with ferrite beam pipe absorbers (CESR and KEKB)

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



## 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



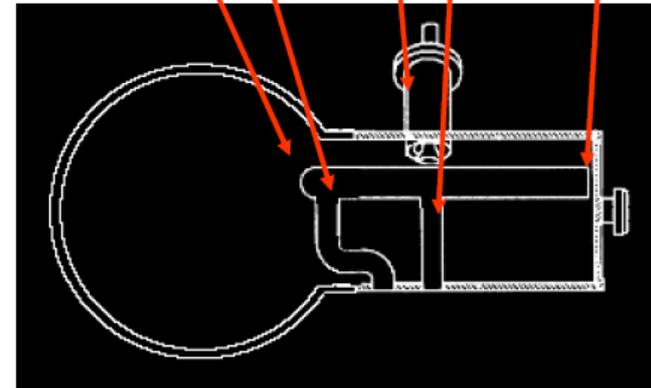
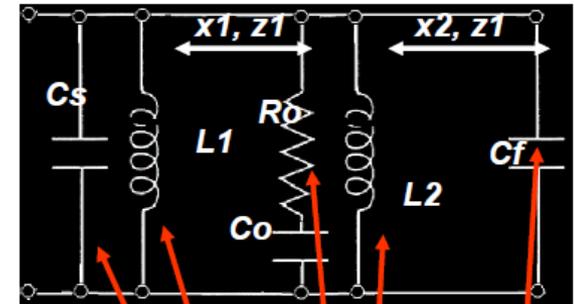
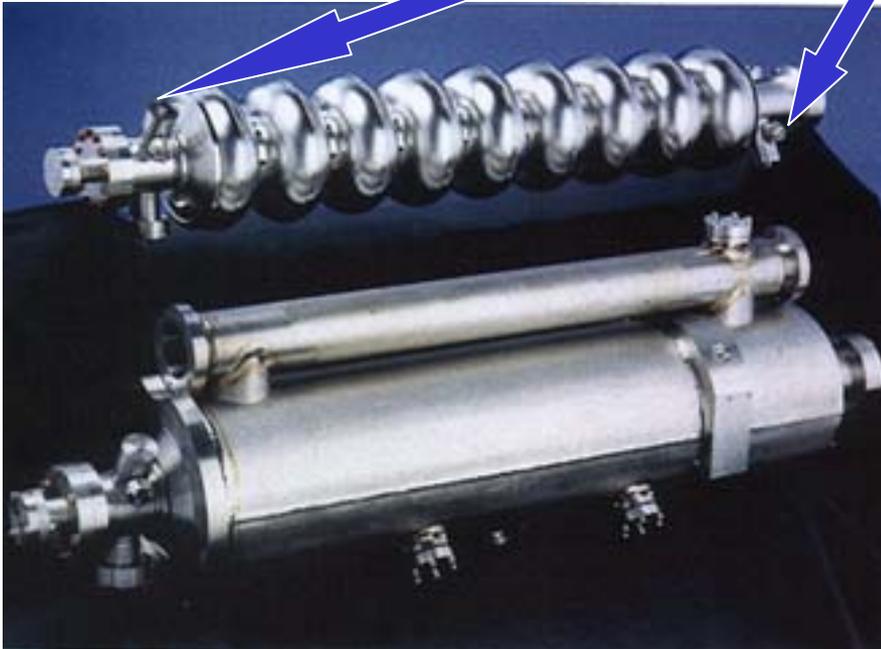
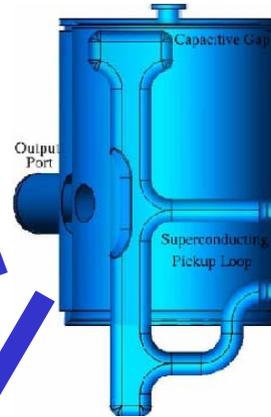
## CESR HOM absorber

- 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



# Example 2: TESLA HOM couplers

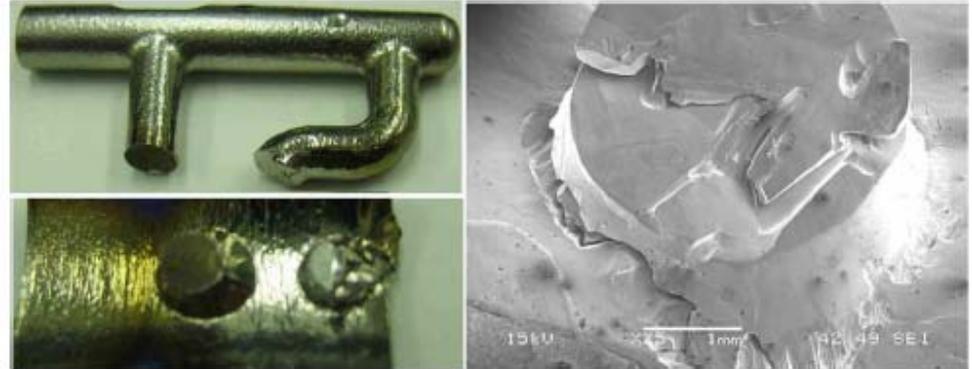
- ❑ Simplified version of HERA HOM couplers: less damping required
- ❑ Locating outside helium vessel is possible because of negligibly small heating (1% duty factor)
- ❑ Successfully used on all TESLA-type cavities in pulsed mode



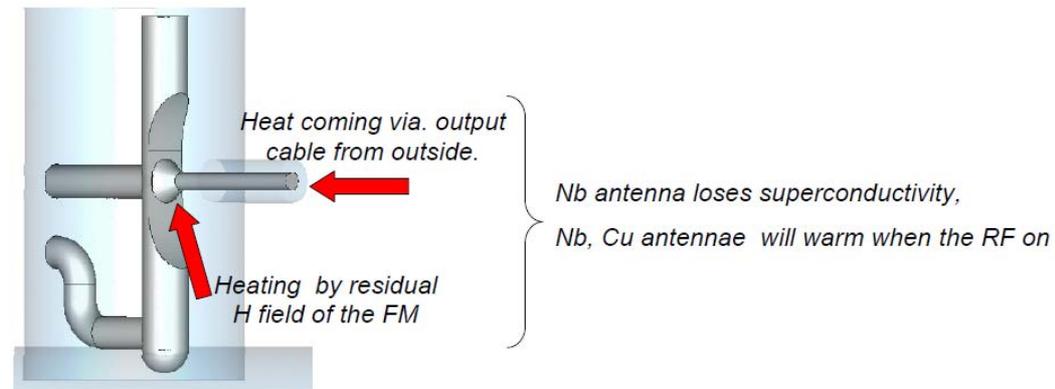


# “Bumps in the road”

- ❑ **Fermilab: multipacting damage to HOM couplers on 3.9 GHz cavities (MP → overheating → fracture) → redesigned to shift MP levels above operating gradients**

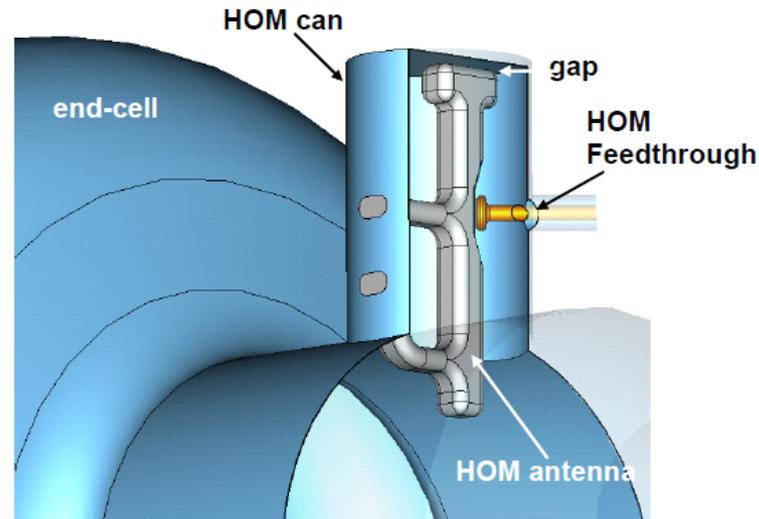


- ❑ **CW operation (12 GeV CEBAF upgrade): heating of the output antenna by the residual magnetic field of the fundamental mode → redesigned to improve heat removal and reduce residual field pick up**



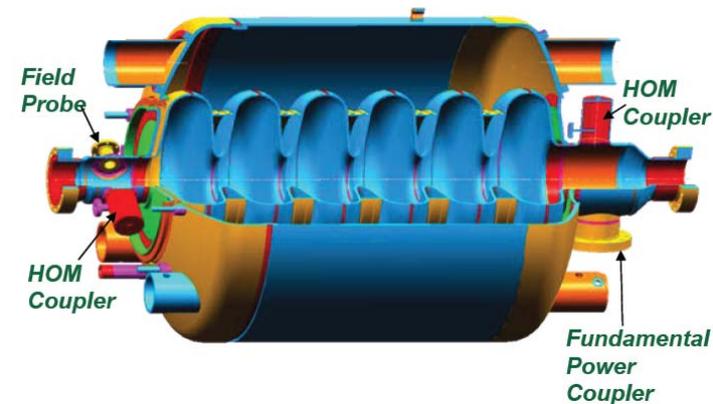
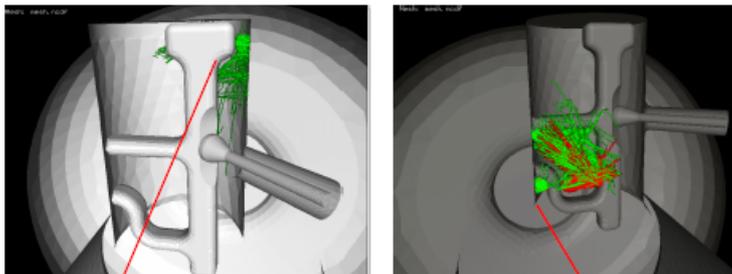


- ❑ Two cryomodules are removed from the linac
- ❑ One showed large coupling of the fundamental RF power to HOM port. Removed feedthroughs, blank-off, and detuned HOM notch frequency. This cryomodule has been back in service with good performance.
- ❑ Second cryomodule: found 3 places having leaks at HOM feedthroughs. Removed feedthroughs, blank-off, and detuned. Will be back in service soon.

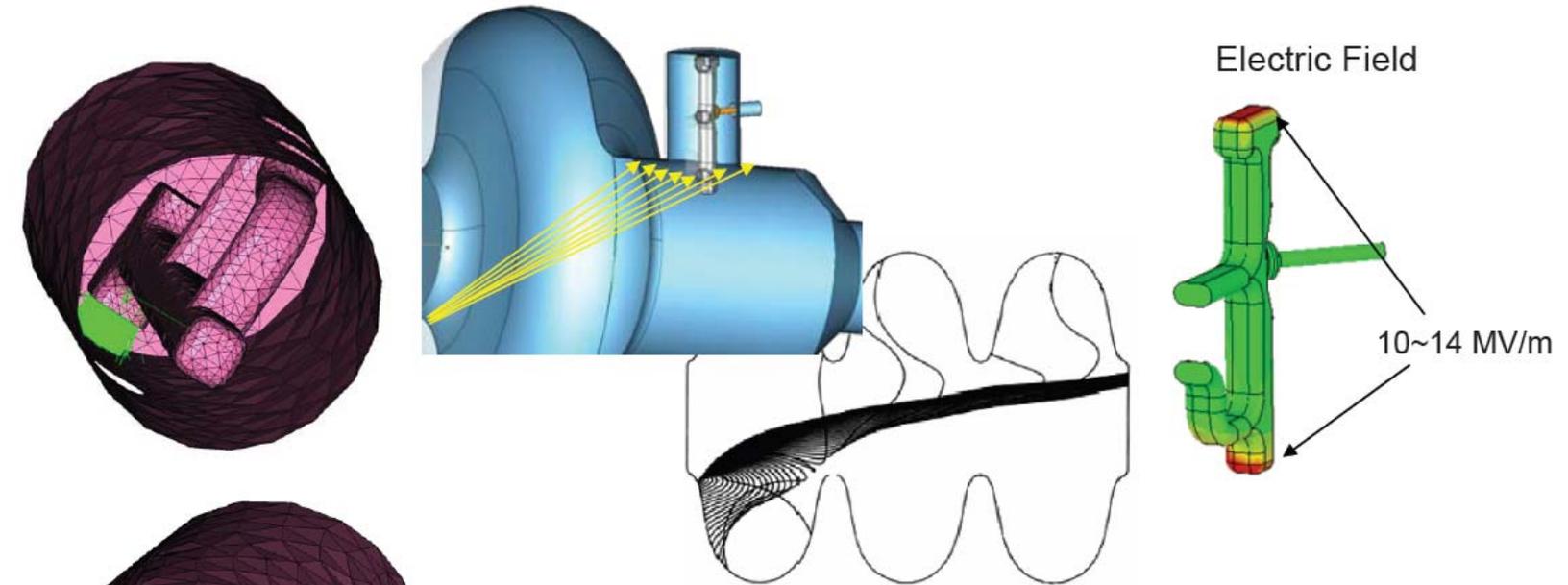


- HOM couplers added as extra safety against longitudinal instabilities
- Some HOM feed-throughs have been damaged or show abnormal transmission curves
- Exact cause of anomalies not completely known, but conservatively turned off of run at limited gradients

## Multipacting in HOM2



## Electron activities → damage HOM coupler



- Any electron activity
- Destroy standing wave pattern  
(or notching characteristics)
- Large fundamental power coupling
- Feedthrough/transmission line damage
- Irreversible



# Summary

- ❑ The operational aspects related to beam must be taken into account early during the SRF system design process to avoid unpleasant surprises during operation.
- ❑ The beam and machine parameters dictate and limit design choices.
- ❑ The beam-cavity interaction goes both ways: The beam loading creates difficulties for LLRF, input power couplers, HOM dampers...; HOMs of an accelerating structure can cause beam instabilities, dilute emittance, ...
- ❑ Depending on the function an SRF system performs, the same aspect of the beam-cavity interaction may be desirable or not: beam loading is parasitic for the fundamental mode operation, but is used to drive passive third harmonic cavities.
- ❑ 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 beam losses than user facilities, such as X-ray light sources. Operational safety margins for the accelerating gradient and input coupler power should be chosen accordingly.
- ❑ Quite often the need arises for re-conditioning cavities and couplers or conditioning them to new operating requirements. One needs to plan ahead for this.
- ❑ There are more operational aspects than can be covered in a short tutorial. Some of those (microphonics, Lorentz force detuning, transverse kicks created by input couplers, RF phase transient due to beam gaps, ...) were barely mentioned here.
- ❑ Careful consideration of the operational aspects and choosing appropriate measures to counteract parasitic effects at the design stage should allow one to build a superconducting RF that would be trouble-free during operation with beam.