WAKEFIELDS, IMPEDANCES, INSTABILITIES AND HIGHER-ORDER MODES

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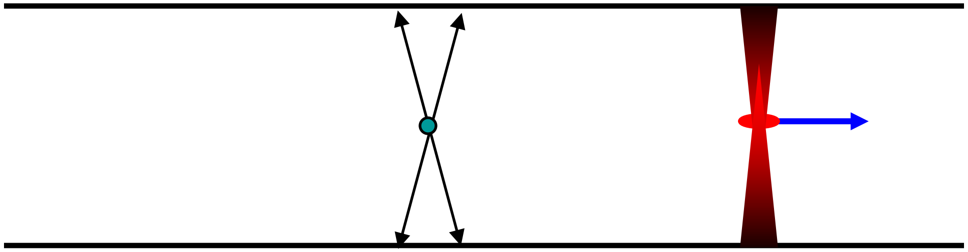
Outline

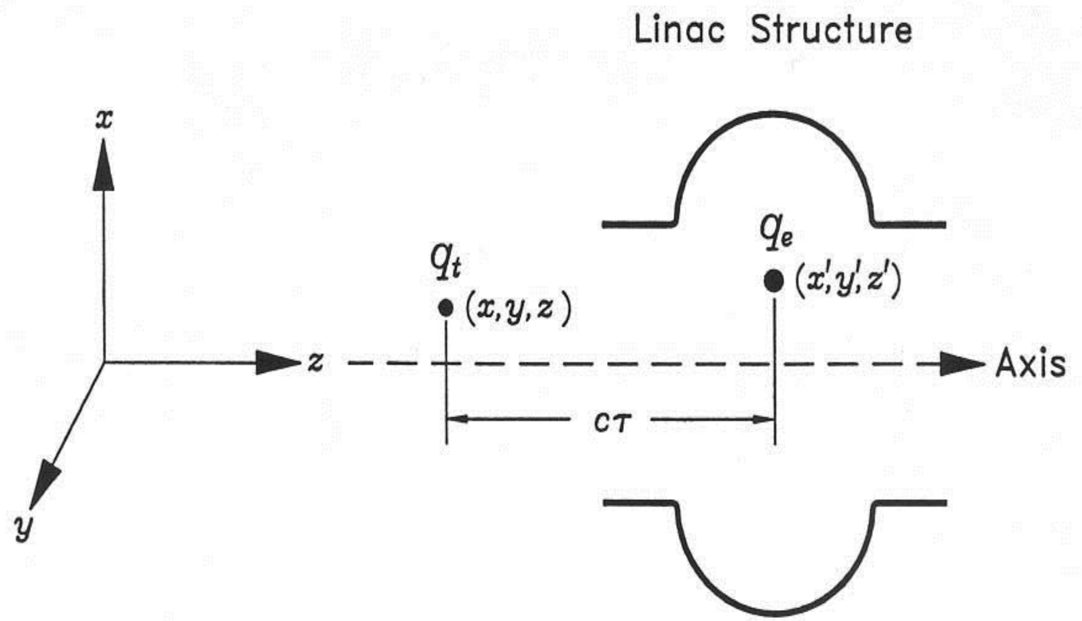
- Linear systems
- Longitudinal wakefield and impedance
- Transverse wakefield and impedance
- Regenerative beam breakup
- Single-pass cumulative beam breakup
- Multi-pass cumulative beam breakup

Relativistic Particle In a Lossless Smooth Pipe



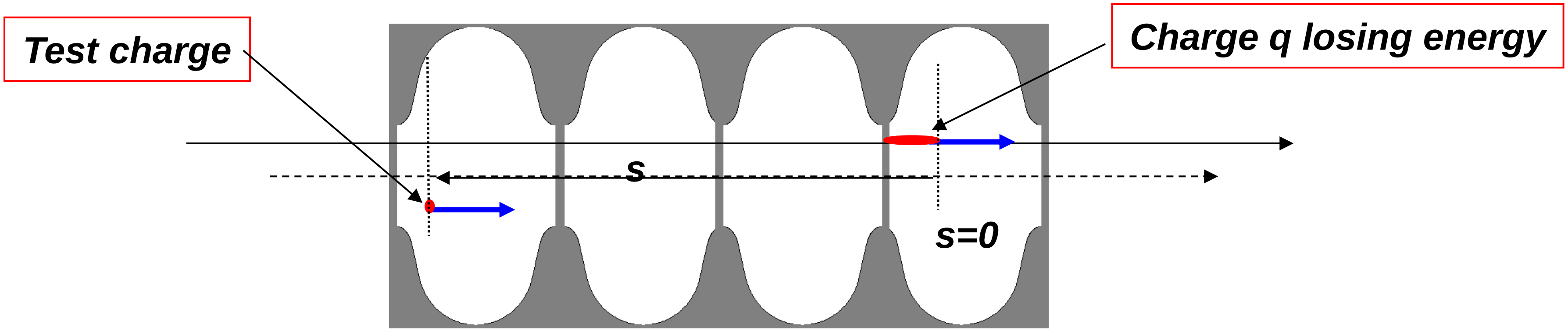
- All the fields are concentrated in a disk moving along with the particle
  - No wakefields
  - No instability
- In order to get wakefields:
  - Non relativistic particles (outside this subject)
  - Lossy walls (resistive wall instability)
  - Non-uniform outer conductors (cavities, bellows,…)

Wake Function Definition



A unit charge will generate electromagnetic fields that will be experienced by a trailing (test) charge

Wake Potential

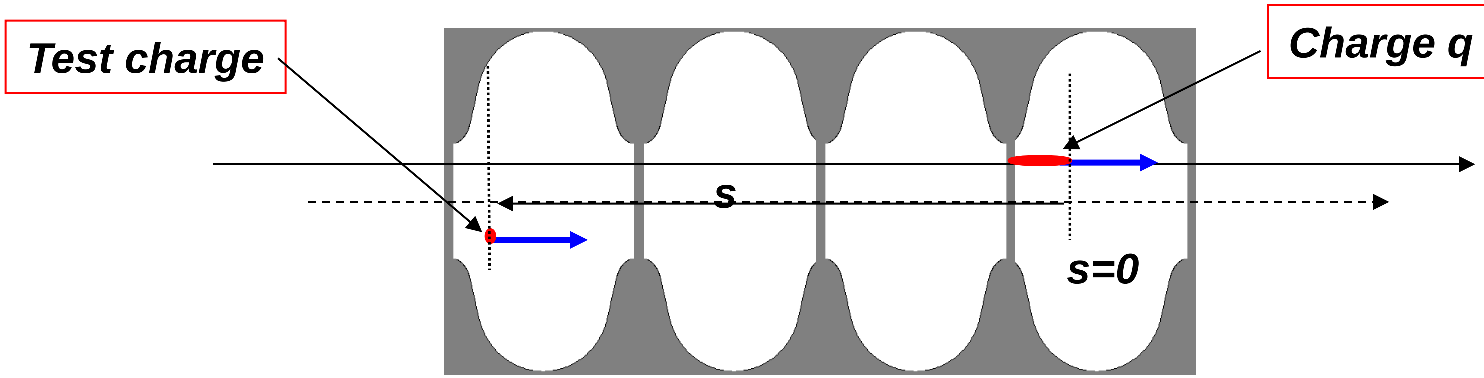


The wake potential is the potential experienced by the test particle trailing the unit charge

Beam-Cavity Interaction

Definition:

the wake potential W is the potential seen by a test particle following the unit charge losing the E-H energy to the cavity.



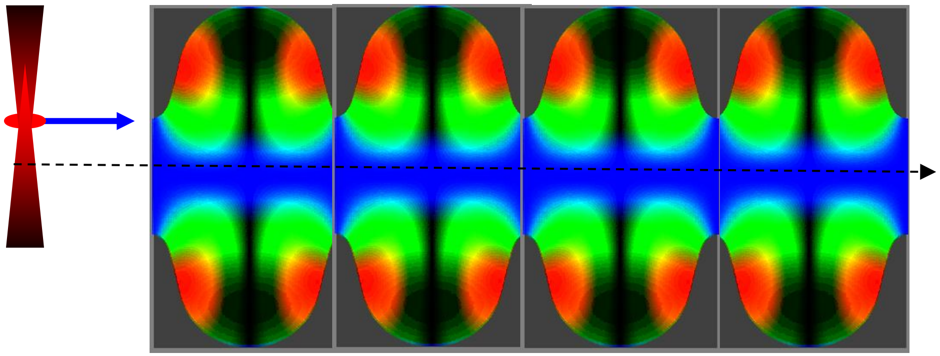
The wake depends on:

W (position of charge q, position of the test charge, charge distribution q(z), shape of cavity, s)

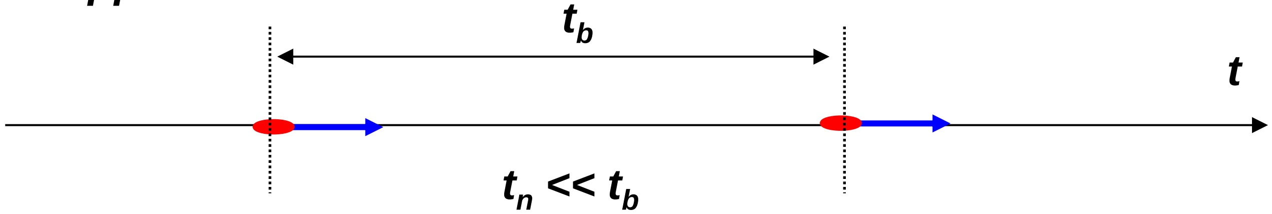
Beam-Cavity Interaction

Single passage:

The energy lost by the bunch to a mode n totally dissipates or/and radiates out of the cavity before the next bunch enters the cavity (there is no build up effect).



When does it happen?



where: $t_n = \omega_n \cdot Ql_n$ ***is the decay time of mode n***

Decay of the energy stored in mode n:

$$W(t)_n = W(0)_n e^{\left(-\frac{\omega_n \cdot t}{t_n}\right)}$$

Loss Factors

The amount of energy lost by charge q to the cavity is:

$\Delta U_q = k_{\|} \cdot q^2$ ***for monopole modes (max. on axis)***

$\Delta U_q = k_{\perp} \cdot q^2$ ***for non monopole modes (off axis)***

where $k_{\|}$ ***and*** $k_{\perp}(r)$ ***are loss factors for the monopole and transverse modes respectively.***

The induced E-H field (wake) is a superposition of <u>cavity eigenmodes</u> (monopoles and others) having the $E_n(r,\varphi,z)$ ***field <u>along the trajectory</u>.***

For individual mode n and point-like charge:

$$k_{\|,n}^{\mathbf{p}} = \frac{\omega_n \cdot (R/Q)_n}{4}$$

Note please the linac convention of (R/Q) definition.

Similar for other loss factors…….

Beam-Cavity Interaction

Two kind of phenomena can limit performance of a machine due to the beam induced HOM power:

- ***Beam Instabilities and/or dilution of emittance***
- ***Additional cryogenic power and/or overheating of HOM couplers output lines***

<u>Beam instabilities and/or dilution of emittance</u>

ansverse modes (dipoles) causing emittance growth+ monopoles causing energy spread

This is mainly problem

in linacs: TESLA or ILC, CEBAF, European XFEL, linacs driving FELs.

<u>Additional cryogenic power and/or overheating of HOM couplers output lines</u>

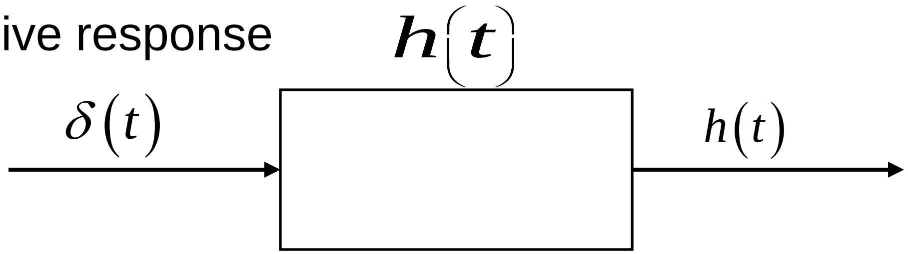
onopoles having high impedance on axis are excited by the beam and store energy which must coupled out of cavities, since it causes additional cryogenic load, and induces energy spread.

This is mainly problem

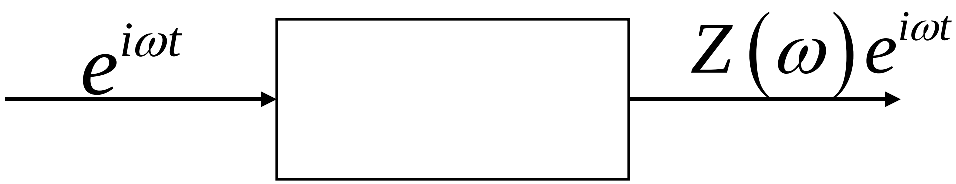
in high beam current machines: B-Factories, Synchrotrons, Electron cooling.

Linear Systems

- Impulsive response



- Transfer function



- $h(t)$ and $Z(\omega)$ are related to each other through a Fourier Transform

$$Z(\omega) = \int_{-\infty}^{+\infty} e^{i\omega t}\, h(t)\, dt$$

Linear Systems (cont.)

- Causality

  $h(t) = 0$ for $t < 0$

  $Z(\omega)$ analytic and bounded for $\mathrm{Im}(\omega) > 0$

  (no pole in the upper half-plane)

- For Resonant systems

  $h(t)$ is called a wake function

  $Z(\omega)$ is called an impedance

Example: Single-Mode Cavity

$$\ddot{v} + \frac{\omega_r}{Q}\dot{v} + \omega_r^2 v = \omega_r \frac{R}{Q}\dot{i}_b \qquad \omega_c = \omega_r\sqrt{1-\frac{1}{4Q^2}} \qquad \alpha = \frac{\omega_r}{2Q} \qquad \kappa = \frac{\omega_r R}{2Q}$$

$$i(t) = \delta(t) \qquad v(t) = \begin{cases} \dfrac{\omega_r R}{Q} e^{-\alpha t}\left[\cos\omega_c t - \dfrac{\sin\omega_c t}{\sqrt{4Q^2-1}}\right] & t > 0 \\ \dfrac{\omega_r R}{2Q} & t = 0 \\ 0 & t < 0 \end{cases}$$

$$i = i_0 e^{i\omega t} \qquad Z(\omega) = \frac{R}{1 + iQ\left[\dfrac{\omega}{\omega_r} - \dfrac{\omega_r}{\omega}\right]}$$

Longitudinal Wake Function, Impedance

Energy loss ΔW of a test particle with charge e, that follows at a distance s, a point like bunch having total charge q = eN

$$\Delta W = eq\, w_{||}(s)$$

$$w_{||}(s,r) = -\frac{c}{q}\int_{-\infty}^{+\infty} dt\, E(z,r,t)\Big|_{z=ct-s}$$

$w_{||}$ is of dimension $\frac{\mathrm{V}}{\mathrm{C}}$ in MKS, cm^{-1} in CGS

Since $s = ct$, $w_{||}(s,r)$ can be expressed as a function of time

$$Z_{||}(\omega,r) = \frac{1}{c}\int_{-\infty}^{+\infty} ds\; w_{||}(s,r)\, e^{\frac{i\omega s}{c}} = \int_{-\infty}^{+\infty} dt\, w_{||}(t,r)\, e^{i\omega t}$$

$Z_{||}$ is of dimension Ω in MKS, s/cm in CGS

Longitudinal Wake Function, Impedance

- For narrow-band structures with cylindrical symmetry: sum over monopole modes

$$w_{\parallel}(t) = \begin{cases} \frac{1}{2}\sum_n \left(\frac{R}{Q}\right)_n \omega_n \, e^{-\frac{\omega t}{2Q_n}} \cos(\omega_n t) & t > 0 \\ \frac{1}{4}\sum_n \left(\frac{R}{Q}\right)_n \omega_n & t = 0 \\ 0 & t < 0 \end{cases}$$

$$Z_{\parallel}(\omega) = \frac{i}{4}\sum_n \left(\frac{R}{Q}\right)_n \omega_n \left[\frac{1}{\omega - \omega_n + \frac{i\omega_n}{2Q_n}} + \frac{1}{\omega + \omega_n + \frac{i\omega_n}{2Q_n}} \right]$$

Example: SLAC Structure

R. Ruth, SLAC-PUB-4948, April 1989

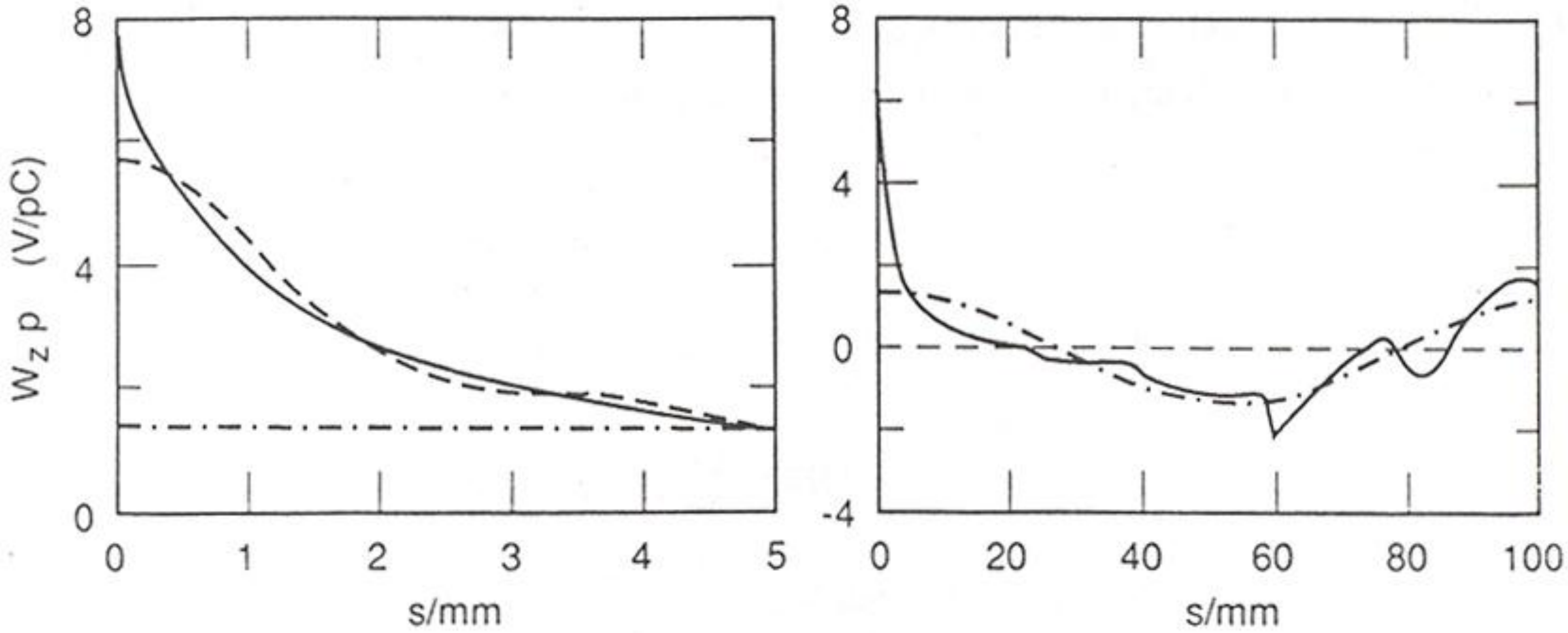
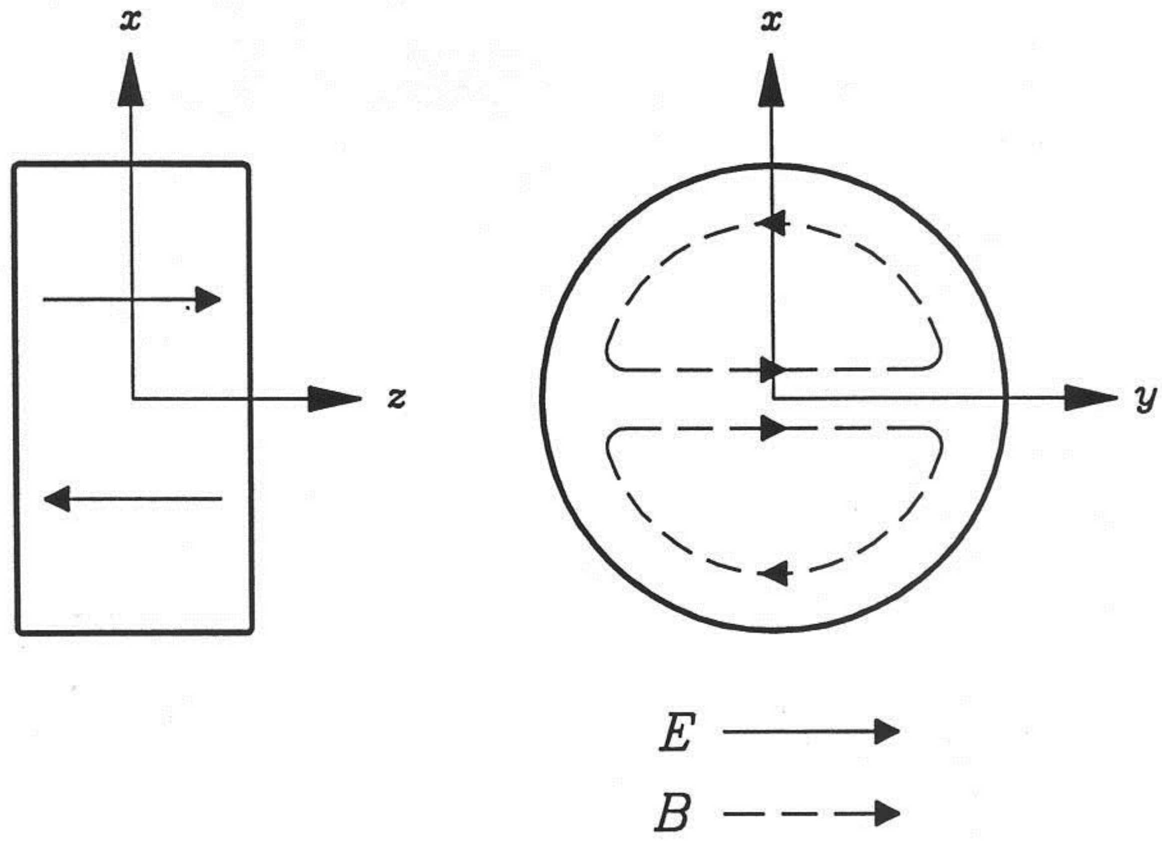


Fig. 10 Longitudinal wake per cell for an average SLAC cell. The solid curve includes an analytical extension for the high frequency behavior.

EM Field of “Deflecting” Mode



Transverse Wake Function, Impedance

- The transverse point wake function is defined as the integrated transverse kick experienced by a test particle caused by the transverse component of the radiated field of a point-like bunch divided by the bunch offset (r_0)

$$w_\perp(t,r) = -\frac{1}{q r_0}\int_{-\infty}^{+\infty} dz \left[E + \frac{v}{c}\times \mathrm{H}\right]_\perp (z,r,t)\Big|_{t=\frac{z+s}{c}}$$

$w_\perp$ is of dimension $\frac{\mathrm{V}}{\mathrm{C\ m}}$ in MKS, cm^{-2} in CGS

$$Z_\perp(\omega,r) = -\frac{i}{c}\int_{-\infty}^{+\infty} ds\; w_\perp(s,r)\, e^{\frac{i\omega s}{c}} = -i\int_{-\infty}^{+\infty} dt\; w_\perp(t)\, e^{i\omega t}$$

$Z_\perp$ is of dimension Ω/m in MKS, s/cm^2 in CGS

Transverse Wake Function, Impedance

- For narrow-band structures with cylindrical symmetry: sum over dipole modes

$$w_\perp(t) = \begin{cases} \dfrac{1}{2c}\sum_n \left(\dfrac{R}{Q}\right)_n \omega_n^2 \, e^{\frac{-\omega_n t}{2Q_n}} \sin(\omega_n t) & t \geq 0 \\ 0 & t < 0 \end{cases}$$

$$Z_\perp(\omega) = \frac{i}{4c}\sum_n \left(\frac{R}{Q}\right)_n \omega_n^2 \left[\frac{1}{\omega - \omega_n + \frac{i\omega_n}{2Q_n}} - \frac{1}{\omega + \omega_n + \frac{i\omega_n}{2Q_n}} \right]$$

Example: SLAC Structure

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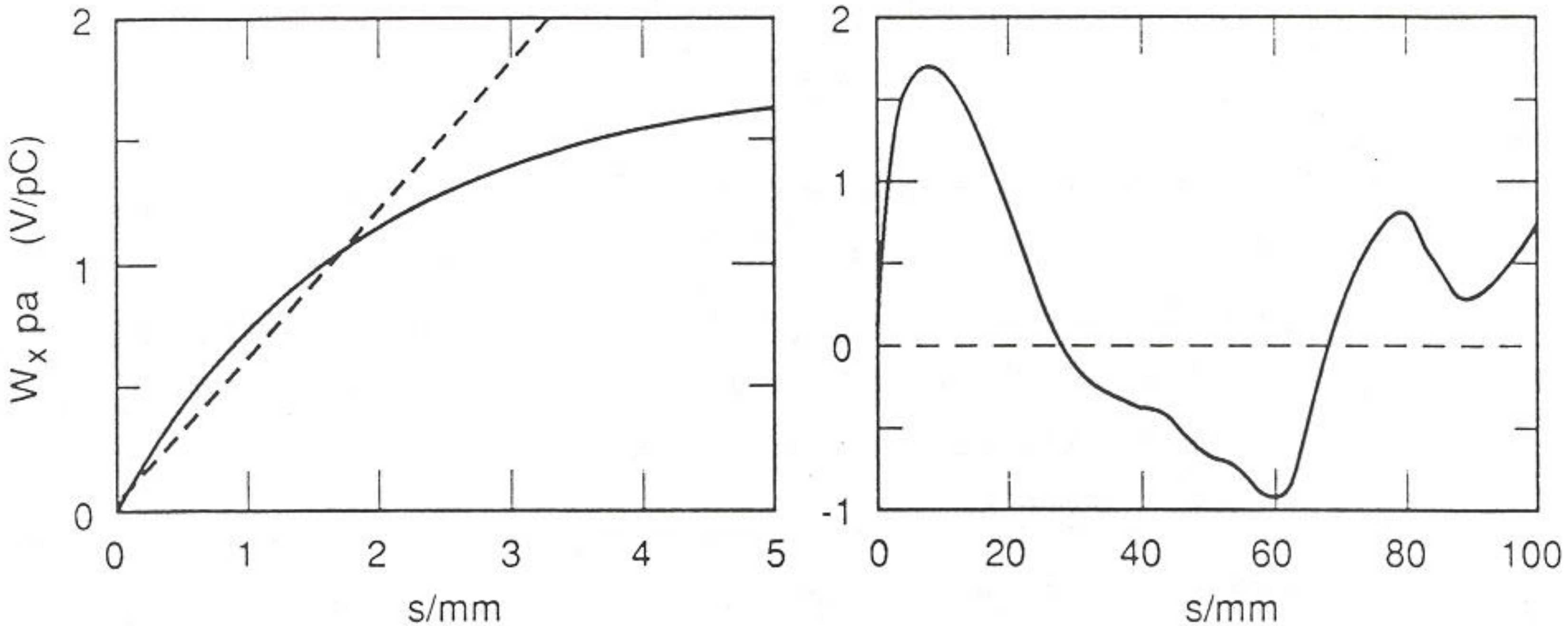


Fig. 9. Transverse wakefield per cell for the SLAC structure for a particle at the iris radius. The dashed line is a linear approximation to the wake seen by a 1 mm bunch.

Resistive Wall Wake Functions and Impedances

$$\frac{\partial w_{||}(t)}{\partial z} = \frac{1}{4a}\left[\frac{Z_o}{\pi c\sigma}\right]^{\frac{1}{2}}\left[\frac{1}{t}\right]^{\frac{3}{2}} \quad \text{for } t > 0 \qquad \frac{\partial Z_{||}(\omega)}{\partial z} = \frac{(1-i)}{2\pi a}\left[\frac{Z_0}{2c\sigma}\right]^{\frac{1}{2}}\omega^{\frac{1}{2}}$$

$$\frac{\partial w_{\perp}(t)}{\partial z} = \frac{1}{\pi a^3}\left[\frac{cZ_0}{\pi\sigma}\right]^{\frac{1}{2}}\left[\frac{1}{t}\right]^{\frac{1}{2}} \quad \text{for } t > 0 \qquad \frac{\partial Z_{\perp}(\omega)}{\partial z} = \frac{(1-i)}{2\pi a^3}\left[\frac{Z_0 c}{2\sigma}\right]^{\frac{1}{2}}\left[\frac{1}{\omega}\right]^{\frac{1}{2}}$$

a: Beam pipe radius

σ: Wall conductivity

Z_0: Impedance of vacuum (377 Ω)

Relationship Between Longitudinal and Transverse Wake Functions

Panofsky – Wenzel Theorem:

$$\frac{\partial}{\partial t} w_{\perp}\left(\mathbf{r},t\right) = \frac{c}{r_0} \nabla_{\perp} w_{\parallel}\left(\mathbf{r},t\right)$$

$$Z_{\perp}\left(\mathbf{r},\omega\right) = \frac{c}{\omega r_0} \nabla_{\perp} Z_{\parallel}\left(\mathbf{r},\omega\right)$$

Scaling Laws

$$w_{\|}(t) = \frac{1}{2}\sum_n \left(\frac{R}{Q}\right)_n \omega_n \, e^{-\frac{\omega t}{2Q_n}} \cos(\omega_n t) \qquad t > 0$$

$$w_{\perp}(t) = \frac{1}{2c}\sum_n \left(\frac{R}{Q}\right)_n \omega_n^2 \, e^{\frac{-\omega_n t}{2Q_n}} \sin(\omega_n t) \qquad t \geq 0$$

$\left(\frac{R}{Q}\right)$ is a geometrical property of a mode, independent of size or material;

it is a function only of shape

$\frac{w_{\|}(s)}{L}$ scales as ω^2 $\qquad$ $\frac{w_{\perp}(t)}{L}$ scales as ω^3

Regenerative Beam Breakup

- Time instability
- A particle can be deflected inside a cavity to regions of higher field and increased coupling.
- If the increase in transverse field due to one bunch is not compensated sufficiently by the decay when the next bunch arrives, an instability occurs.
- Threshold current

$$I_{th} \simeq \frac{\pi^3}{2} \frac{p}{e} \frac{\omega}{Z_\perp L}$$

$p:$ particle momentum

$L:$ cavity length

- Since $Z_\perp \propto L$ $\quad I_{th} \propto L^{-2}$

Single – Pass Cumulative Beam Breakup

- Instability in space, not in time.
- Initial offsets are amplified.
- Transient cumulative BBU can be much larger than steady state.
- Unless exactly on resonance, steady state behavior relatively insensitive to Q. Most effective cure is to increase focusing.

Equation of Transverse Motion

$$\left[\frac{1}{\beta\gamma}\frac{\partial}{\partial\sigma}\left(\beta\gamma\frac{\partial}{\partial\sigma}\right)+\kappa^2\right]x(\sigma,\zeta)=\varepsilon\int_{-\infty}^{\zeta}d\zeta_1\; w(\zeta-\zeta_1)\;F(\zeta_1)\;x(\sigma,\zeta_1)$$

Approximations:

- Cavities have negligible length
- Cavities are electromagnetically decoupled
- Cavities and focusing elements are sole source of deflecting fields
- Discrete deflecting fields are smoothed along the linac
- Beam is longitudinally rigid

$\sigma = s/\mathcal{L}$, $\mathcal{L}$: linac length, $\zeta = \omega\left(t-\int\frac{ds}{\beta c}\right)$, ω : angular frequency of deflecting field

$\varepsilon(\sigma)=\left[\frac{\bar{I}Ze}{2\beta\gamma mc}\right]\left[\frac{\Gamma_\perp}{\omega}\right]\left[\frac{\mathcal{L}^2}{L}\right]$ coupling strength to dipole mode

$F(\zeta)=I(\zeta)/\bar{I}$: current form factor, $w(\zeta)$: wake function $= U(\zeta)\; e^{-\frac{\zeta}{2Q}}$ sin ζ for single mode

$$\Gamma_\perp=\frac{2}{\varepsilon_0\omega}\frac{\left|\int_0^L e^{-\frac{i\omega z}{\beta c}}\frac{\partial E_z(0,0,z)}{\partial x}\right|^2}{\int_V \boldsymbol{E}^2(\boldsymbol{x})\,d\boldsymbol{x}}$$: transverse shunt impedance

Equation of Transverse Motion (Cont.)

Example: Steady-state, coasting, delta function periodic beam

$$\text{Steady State:}\quad x(\sigma=0,\zeta)=x_0 \quad , \qquad \frac{\partial x(\sigma=0,\zeta)}{\partial z}=0$$

$$\left(\frac{\partial^2}{\partial\sigma^2}+\kappa^2\right)x(\sigma,\zeta)=\varepsilon\int_{-\infty}^{\zeta}d\zeta_1\,w(\zeta-\zeta_1)\,F(\zeta_1)\,x(\sigma,\zeta_1)$$

$$F(\zeta)=\sum_{k=-\infty}^{+\infty}F_k\;e^{ik\frac{2\pi}{\omega\tau}\zeta}, \qquad \delta-\text{function beam}\quad F_k=1$$

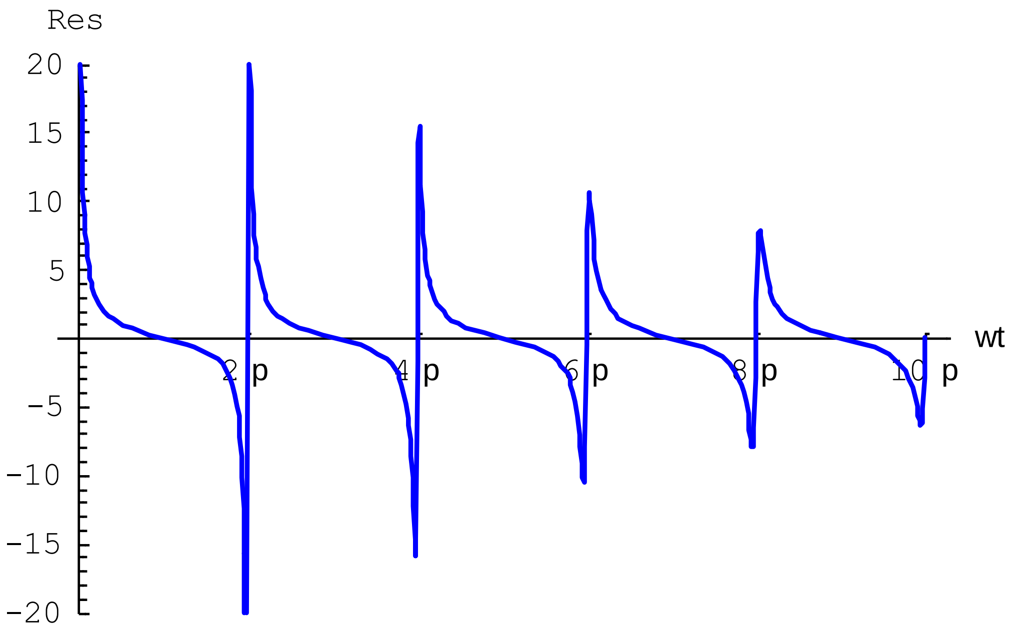
$$\tilde{W}(Z)=\sum_{k=-\infty}^{+\infty}\tilde{w}\left(Z-k\frac{2\pi}{\omega\tau}\right)\quad ,\quad \tilde{w}(Z)=\int_{-\infty}^{+\infty}w(t)\,e^{-iZt}\,dt$$

$$\Lambda^2(Z)=\kappa^2-\varepsilon\,\tilde{W}(Z)$$

$$x(\sigma,\zeta=\mathrm{M}\omega\tau)=x_0\cos\left[\Lambda(0)\sigma\right]$$

$$\text{For single deflecting mode}:\;\Lambda^2(0)=\kappa^2-\varepsilon\frac{\omega\tau}{2}\frac{\sin\omega\tau}{\cosh\frac{\omega\tau}{2Q}-\cos\omega\tau}$$

Resonance Function



Resonance function for Q=100.

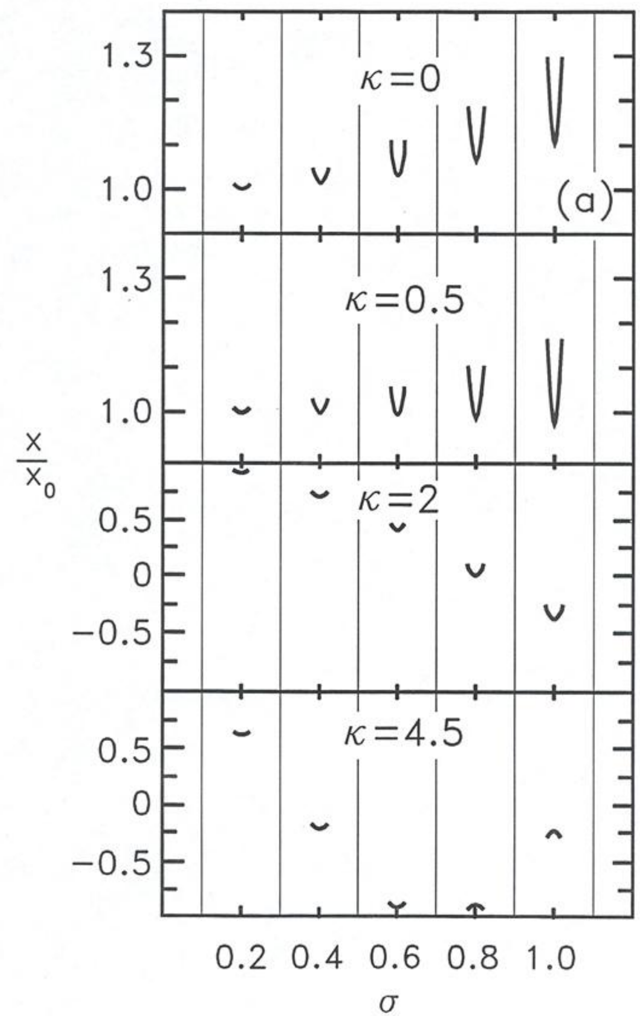
Example: Elimination of BBU Instability by Increasing Focusing

$$Q = 1000$$

$$\varepsilon = 0.2$$

$$\omega\tau = 10$$

$$M = \infty$$



Example: Transient BBU

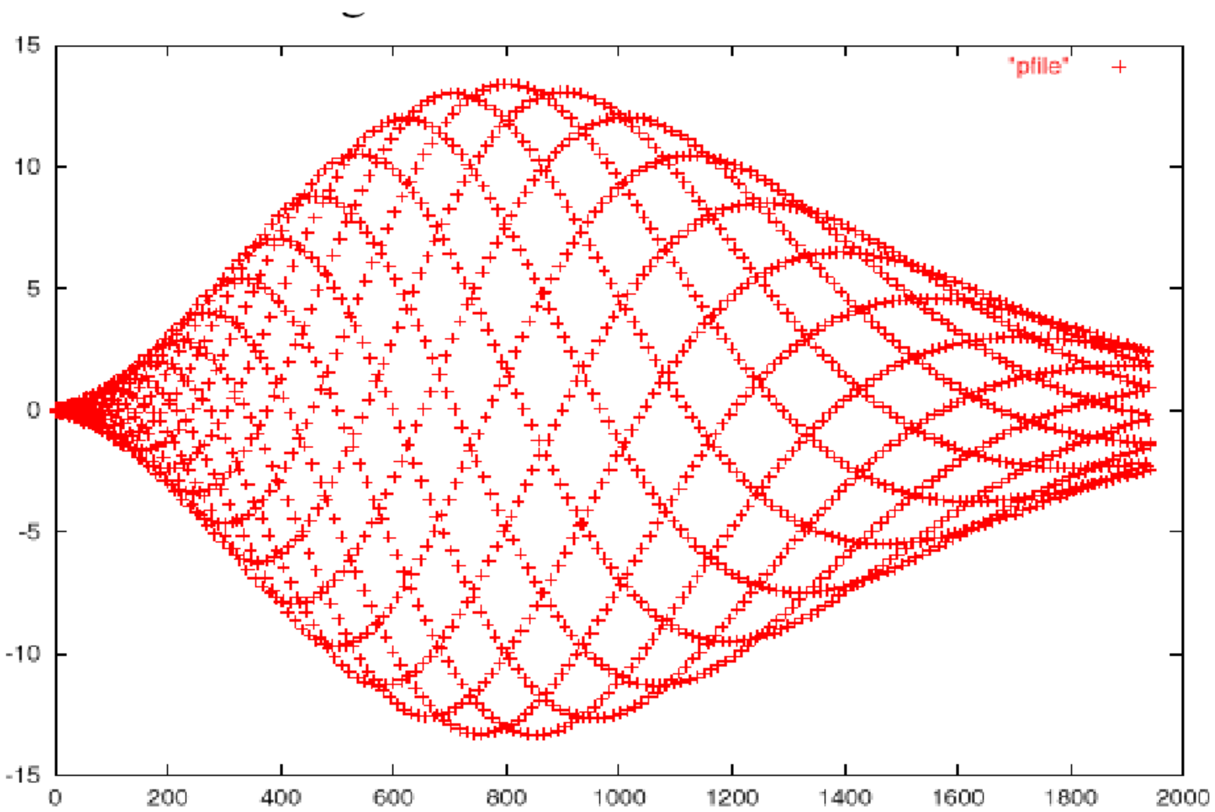


Figure 1: Plot of transverse beam centroid displacement at the end of the linac.

Distribution of Dipole Mode Frequency

- Assume the dipole mode frequencies are not identical along the linac but follow a probability density $\tilde{f}(\omega)$ around ω_0

Define $\tilde{g}(Z) = \tilde{f}[Z + \omega_0]$

$$g(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} e^{iZt}\, \tilde{g}(Z)\, dZ$$

Define a new "modified" wake function

$$\hat{w}(t) = 2\pi g(t)\; w(t)$$

- A distribution of dipole mode frequencies can be modeled by using this “modified” wakefunction

Distribution of Dipole Mode Frequency

<u>Example</u>: Lorentzian Probability Density

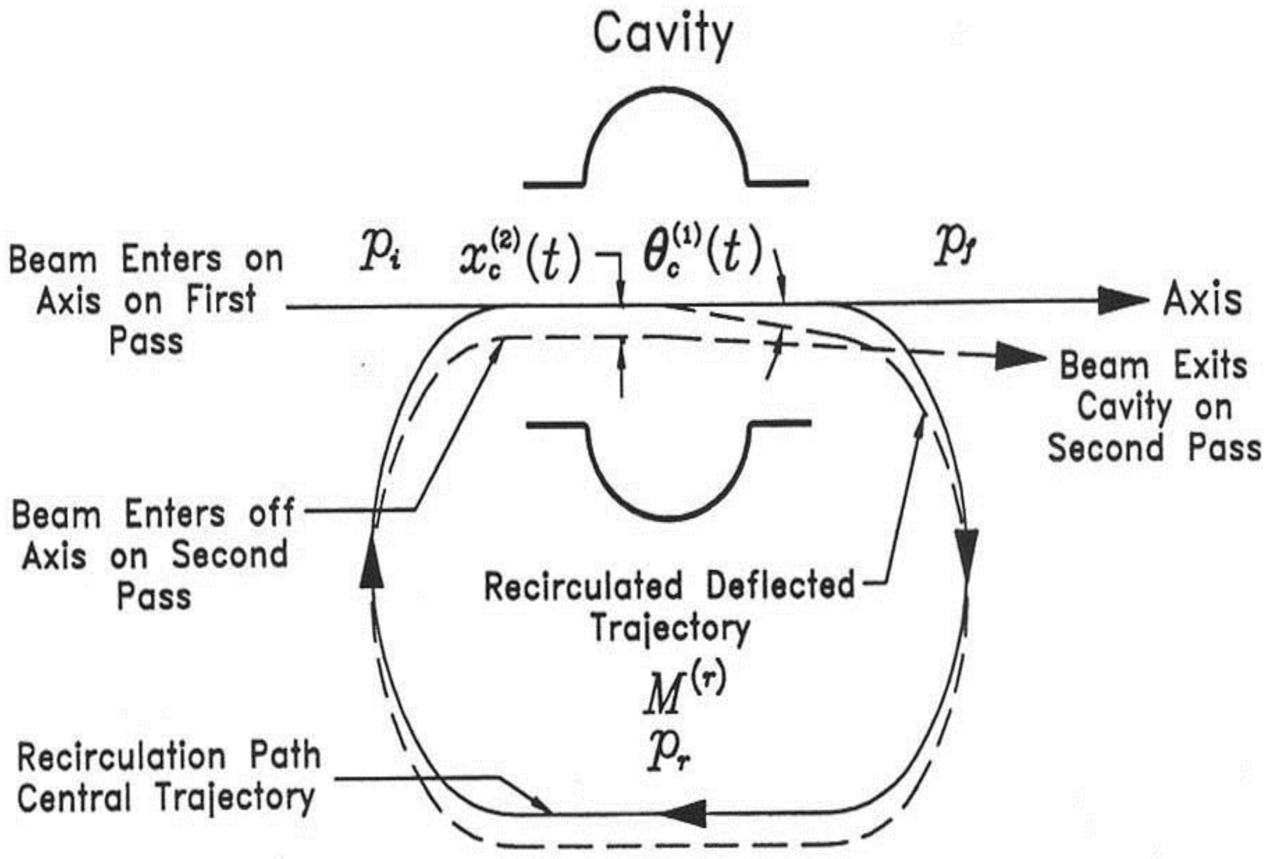
$$\tilde{f}(\omega) = \frac{1}{\pi} \frac{\Delta\omega}{\left(\omega - \omega_0\right)^2 + \Delta\omega^2} \qquad \tilde{g}\left(Z\right) = \frac{1}{\pi} \frac{\Delta\omega}{Z^2 + \Delta\omega^2}$$

$$2\pi\, g\left(t\right) = e^{-\Delta\omega|t|}$$

$$\hat{w}(t) = U(t)\, e^{-\omega_0 t\left(\frac{1}{2Q} + \frac{\Delta\omega}{\omega_0}\right)} \sin\left(\omega_0 t\right)$$

$$\frac{1}{Q_{\mathrm{eff}}} = \frac{1}{Q} + \frac{2\Delta\omega}{\omega_0}$$

Transverse Multipass BBU Instability



Longitudinal Multipass Instability

- Longitudinal HOMs Suppose HOM excited
  - Get an energy error
  - M_{56} converts to a phase error
  - Phase modulation plus bunch beam spectrum can generate sideband at HOM frequency
  - Depending on the sideband phase, HOM may be further excited

Multipass BBU Instability

- Multi-pass BBU is an instability in time
- There is a threshold current above which the instability occurs
- It is a form of regenerative instability (closed loop system where a bunch experiences its own wakefield)
- Very sensitive to Q. ost effective cure is to decrease Q of dipole modes

Instability Threshold

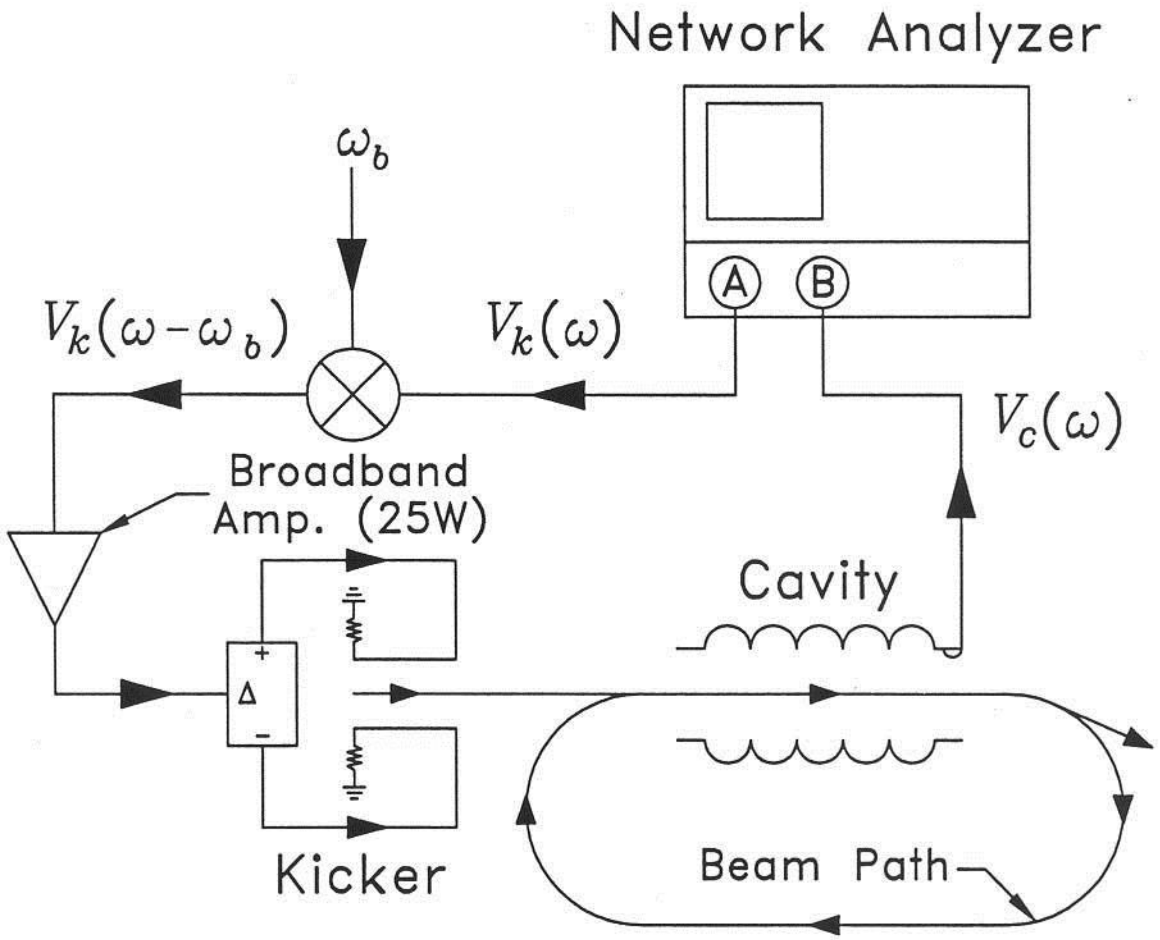
- There is a well-defined threshold current that occurs when the power fed into the mode equals the mode power dissipation

- An analytic expression that applies to all instabilities:

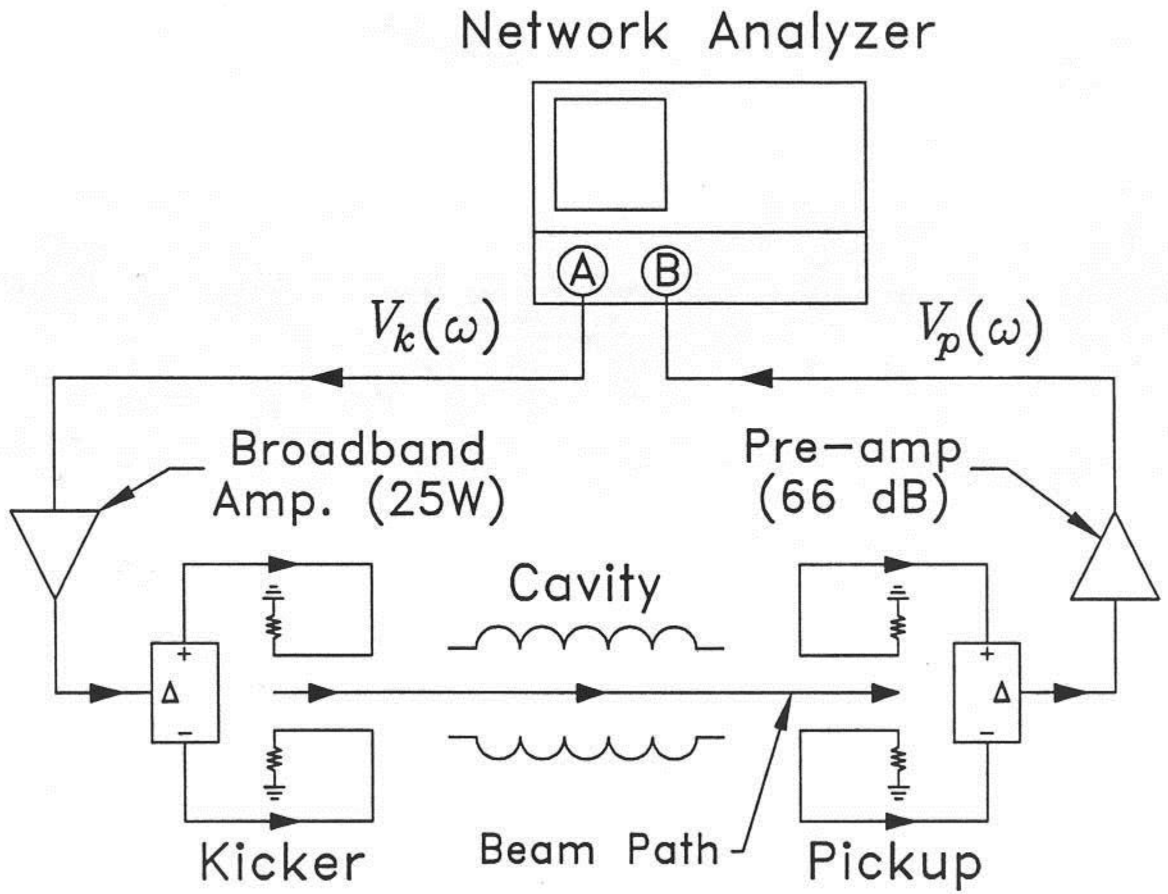
$$I_{th}^{(1)} = \frac{-2 p_r c}{e(R/Q)_m Q_m k_m M_{ij} \sin(\omega_m t_r + l\pi/2) e^{\omega_m t_r / 2Q_m}}$$

- For *i,j* = 1,2 or 3,4 and *m* $\rightarrow \perp$ HOM $\Rightarrow$ Transverse BBU
- For *i,j* = 5,6 and *m* $\rightarrow$ || HOM $\Rightarrow$ Longitudinal BBU
- For *i,j* = 5,6 and *m* $\rightarrow$ Fundamental mode $\Rightarrow$ Beam-Loading Instabilities
- *l=1* for longitudinal HOMs and l=0 otherwise

HOM Coupling Measurement



Beam Transfer Function

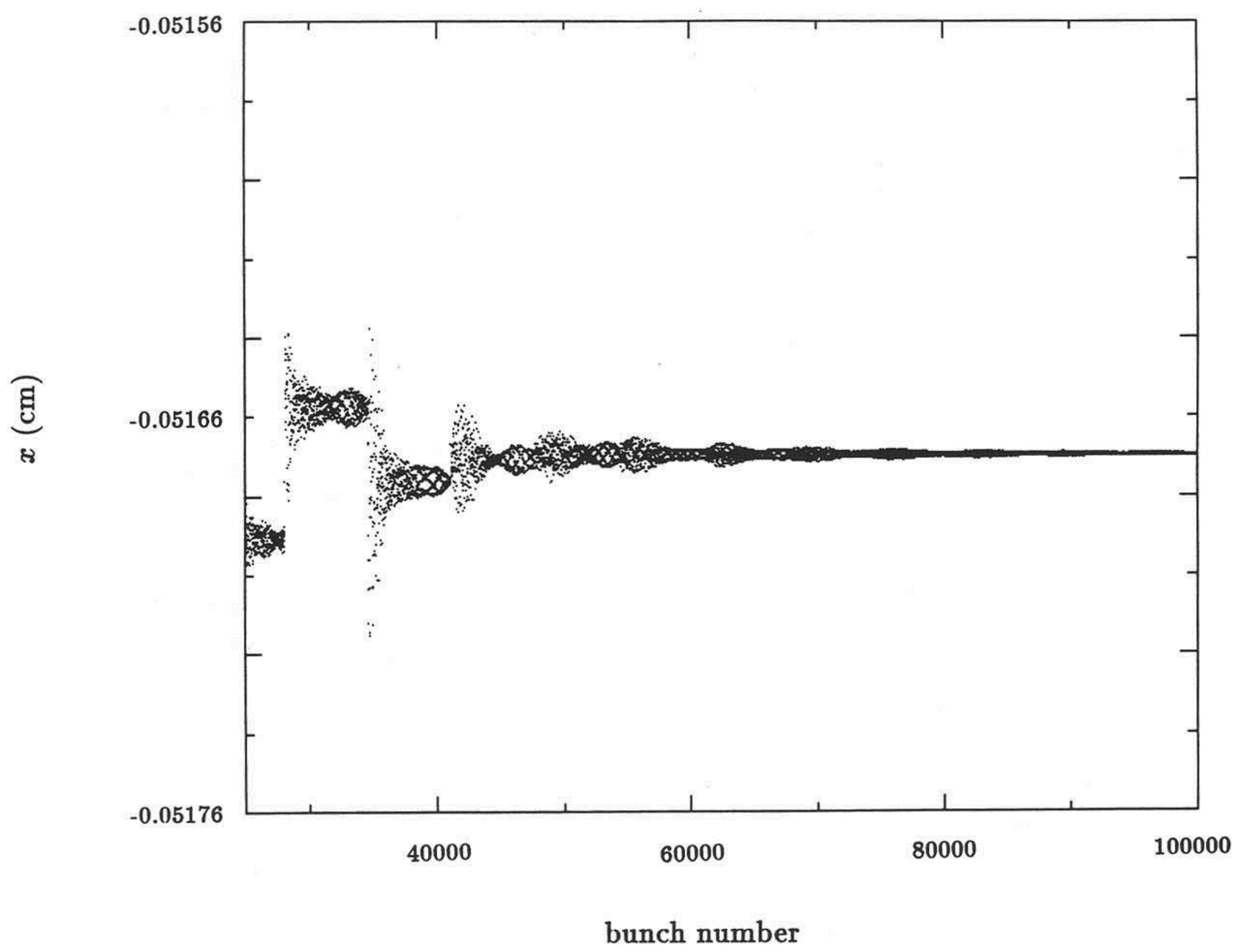


TDBBU Simulation

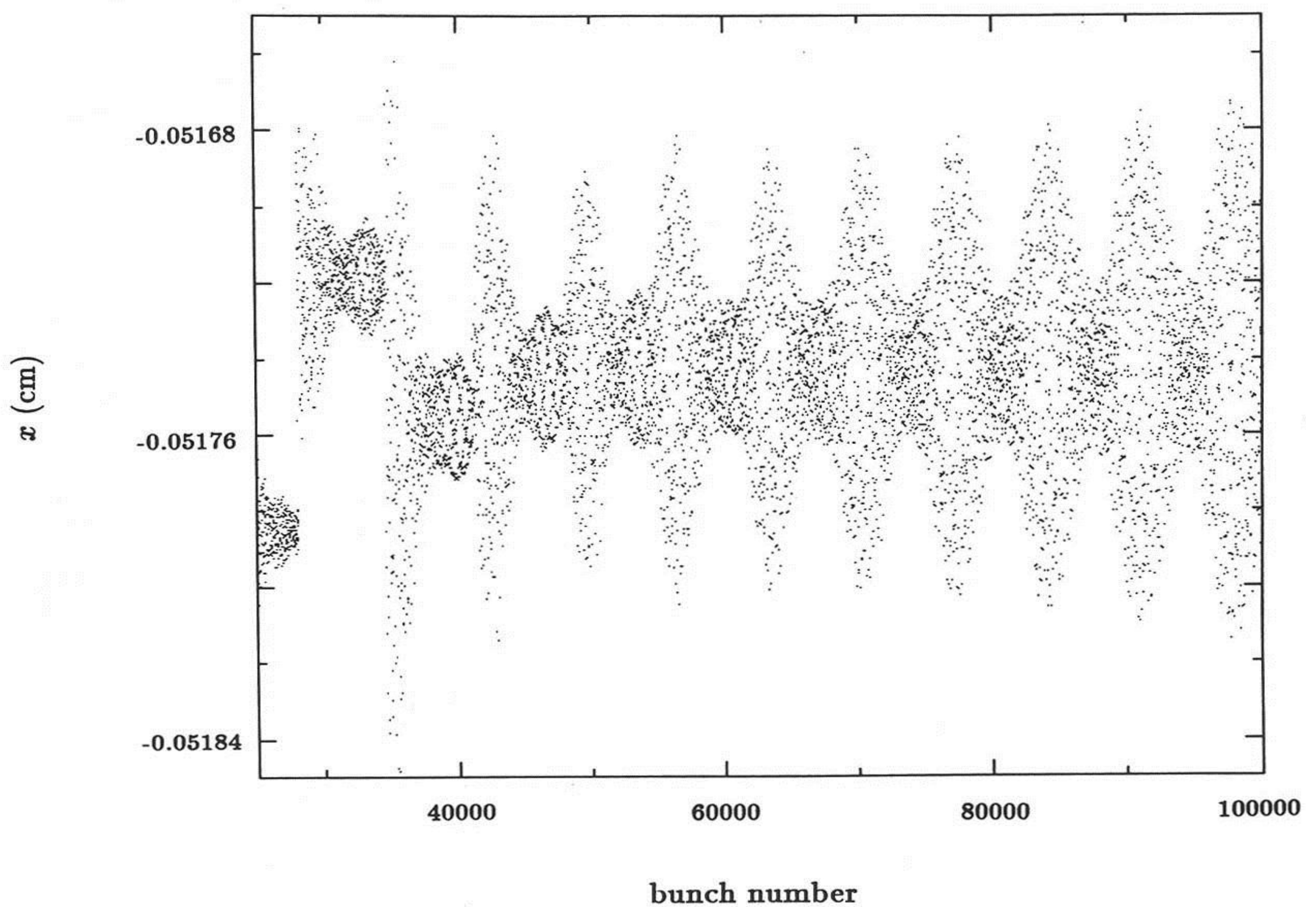
- Short bunch simulation of Multibunch BBU assuming multiple cavity deflecting modes
- Multipass accelerators may be simulated
- Accelerators with several linac segments may be simulated
- Accelerators with accelerating passes and decelerating passes may be simulated
- Simulations include effects of differing path lengths from differing linac segments
- The current in successive bunches may be varied in a programmed manner

One iteration of code corresponds to one fundamental RF period

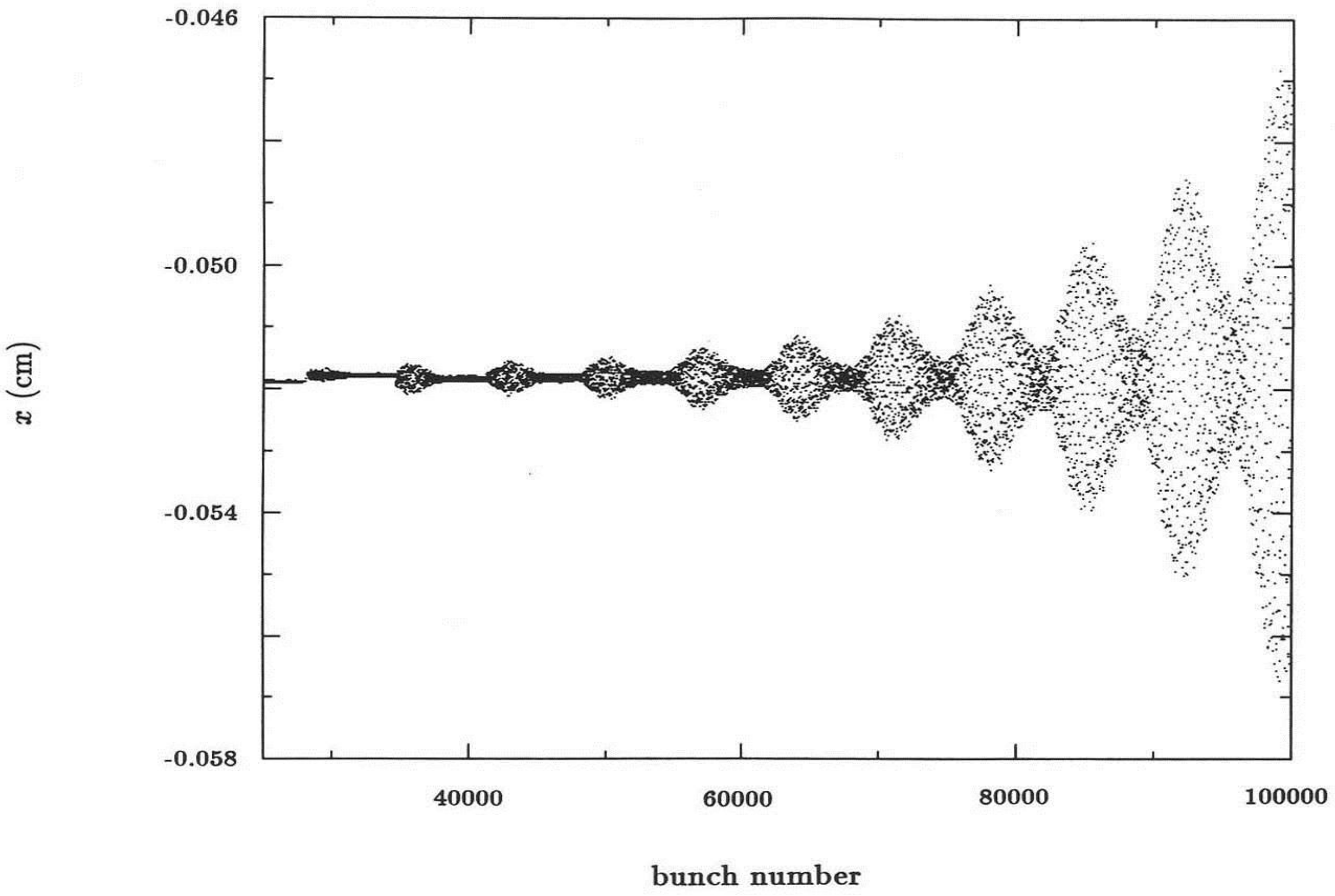
10 mA, Below Threshold



20 mA, Just Beyond Threshold



30 mA, Above Threshold



HOM Power Dissipation

- High average current, short bunch length beams in srf cavities excite HOMs. Power in HOMs, primarily longitudinal:

$$P_{HOM} = 2\, k_{||}\, Q^2\, f_{bunch}$$

- For I_{ave}= 100 mA, Q = 77 pC $\Rightarrow$ P_{HOM}~ 160 W per cavity for $k_{||}$=10.4 V/pC at σ_z~ 0.6 mm
- In the JLab IRFEL: I_{ave}= 5 mA, P_{HOM}~ 6 W
- Fraction of HOM power dissipated on cavity walls depends on the bunch length
- It can potentially limit I_{ave} and I_{peak} due to finite cryogenic capacity

HOM Power Dissipation

- The fraction of HOM power dissipated on cavity walls increases with HOM frequency, due to $R_s \sim \omega^2$ degradation from BCS theory
- Several models have been developed to address the high frequency behavior of HOM losses
- Models predict:
  - Frequency distribution of HOM power
  - Fraction of power dissipated on the cavity superconducting walls is
    - a strong function of bunch length
    - much less than the fundamental mode load
  - High frequency fields propagate along the structure

Frequency Distribution of HOM Losses

- ~20% of HOM losses (30 W) occur at frequencies $<$ 3.5 GHz

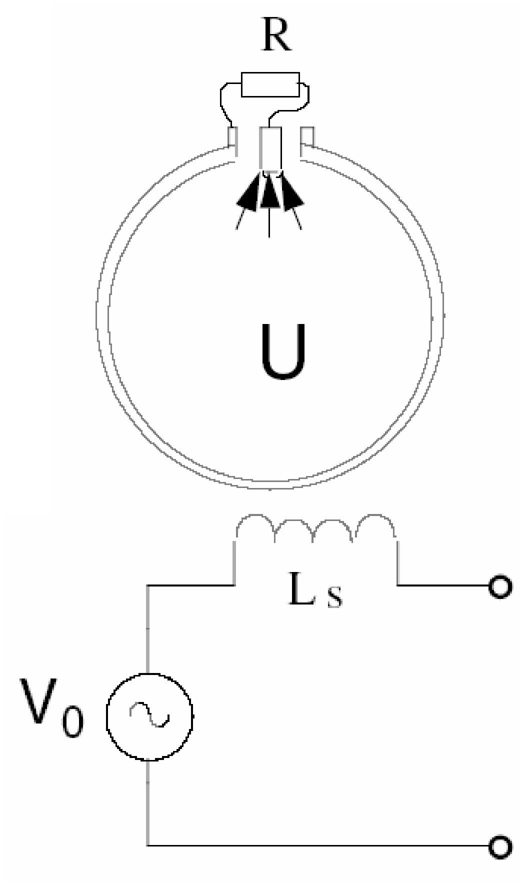
  $\Rightarrow$ This power is typically extracted by input couplers and HOM couplers and is absorbed in room temperature loads

- The remaining losses, at frequencies $\geq$ 3.5 GHz, will propagate along the structure and be reflected at normal and superconducting surfaces

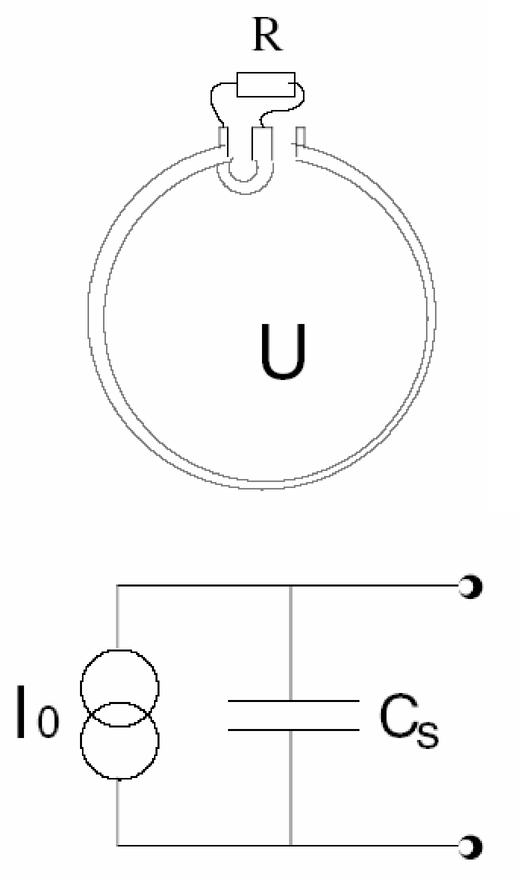
  $\Rightarrow$ on-line absorbers are required

- Effect of losses in frequency range beyond the threshold for Cooper pair breakup (750 GHz) in superconducting Nb has been investigated: the resulting Q_0 drop is negligible

Coaxial Coupler Types



Coupling to the electric field



Coupling to the magnetic field

LEP II HOM Coupler

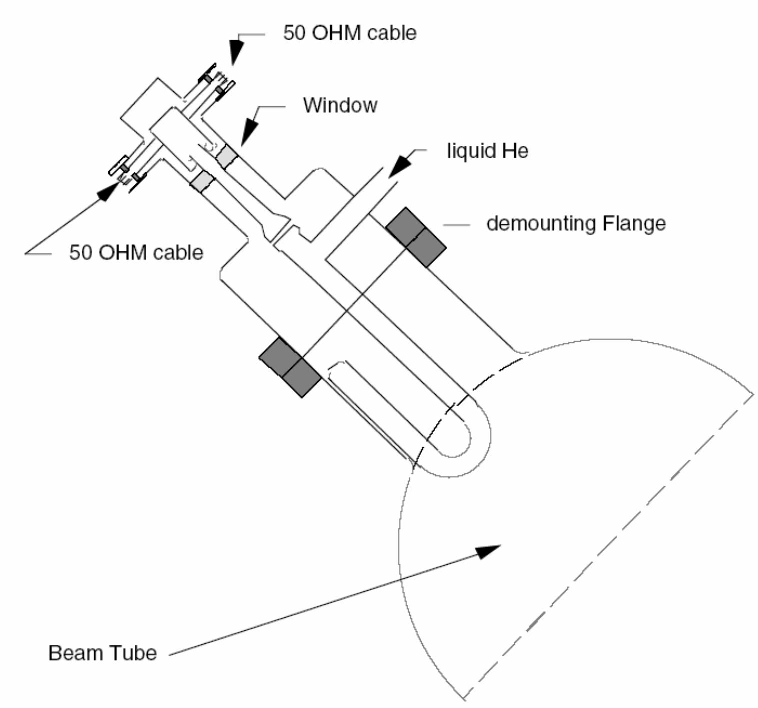
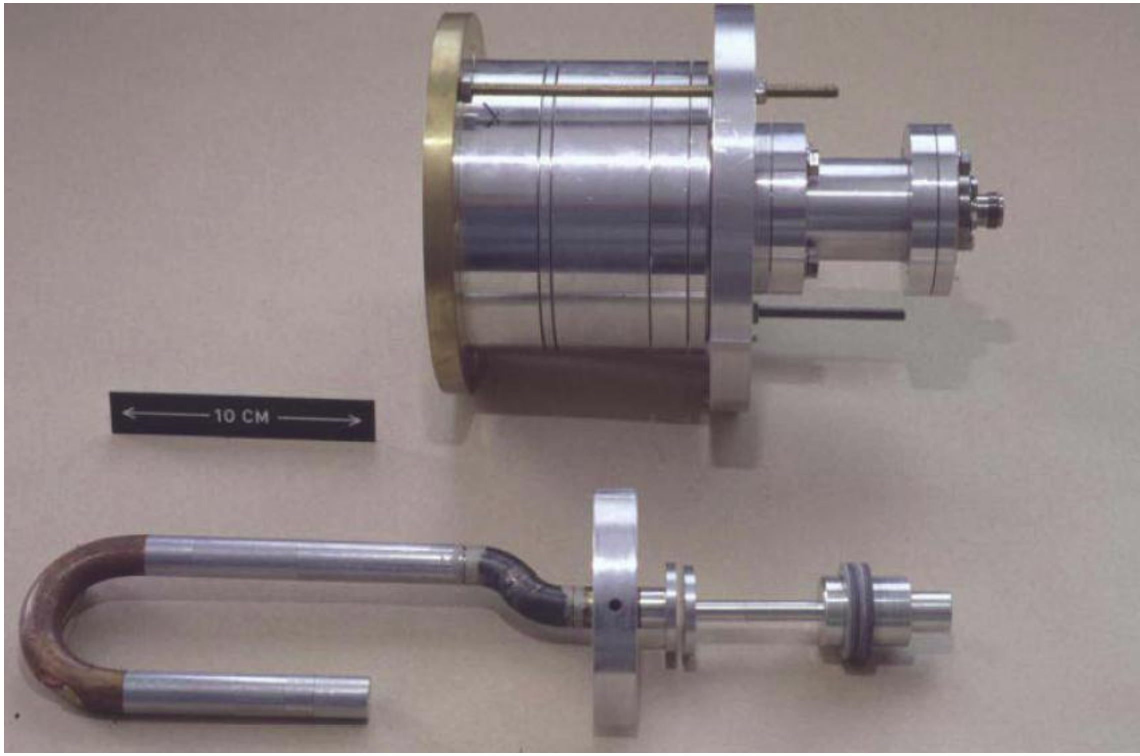


Fig. 1 Geometry of the HOM coupler used in LEP

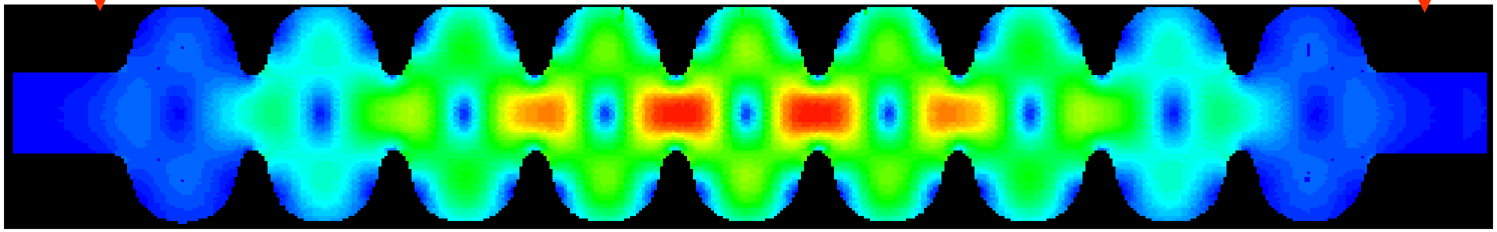


LHC HOM Couplers

Mode Trapping

HOM couplers limit RF-performance of sc cavities when they are placed on cells

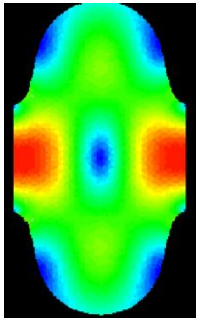
no E-H fields at HOM couplers positions,
which are always placed at end beam tubes



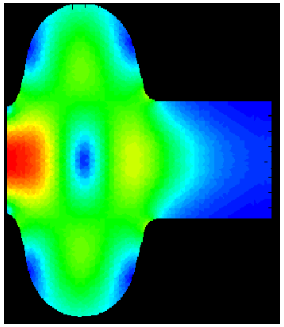
The HOM trapping mechanism is similar to the FM field profile unflatness mechanism:

- *weak coupling HOM cell-to-cell, $k_{cc,HOM}$*
- *difference in HOM frequency of end-cell and inner-cell*

f = 2385 MHz



That is why they hardly resonate together



f = 2415 MHz

Trapping of Modes within Cavities

To untrapp HOMs we can:

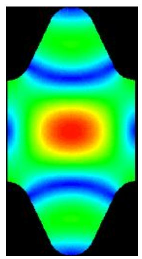
1) open both irises of inner cells and end-cells (bigger $k_{cc,HOM}$) and keep shape of end cells similar

Example:

RHIC 5-cell cavity for the electron cc

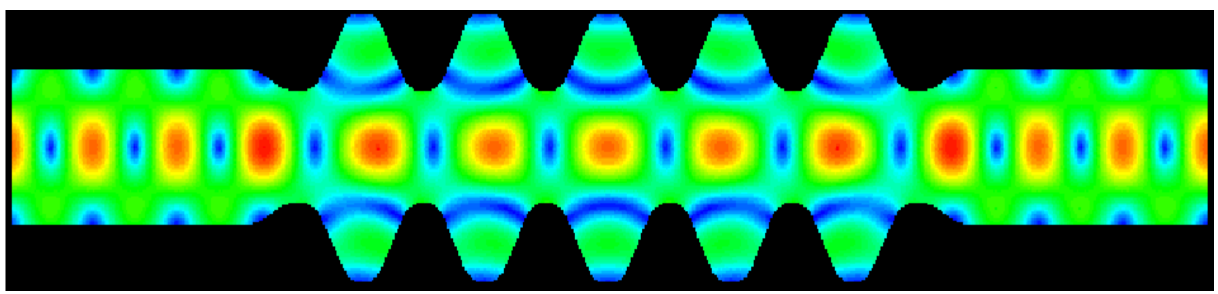
Monopole mode $k_{cc\,,HOM}$ = 6.7 %

f_{HOM} = 1394 MHz



f_{HOM} = 1

f_{HOM} = 1403 MHz



The method causes (R/Q) reduction of fundamental mode, which in this application is less relevant.

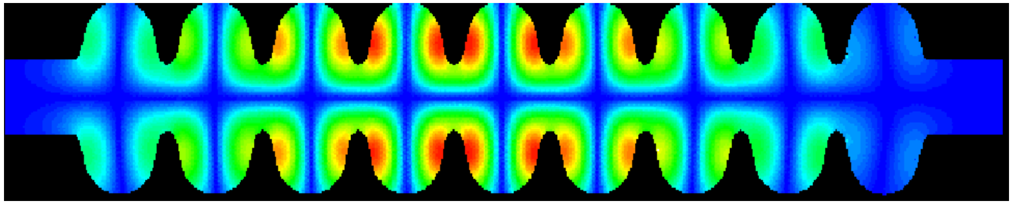
Trapping of Modes within Cavities

2) tailor end-cells to equalize HOM frequencies of inner- and end-cells

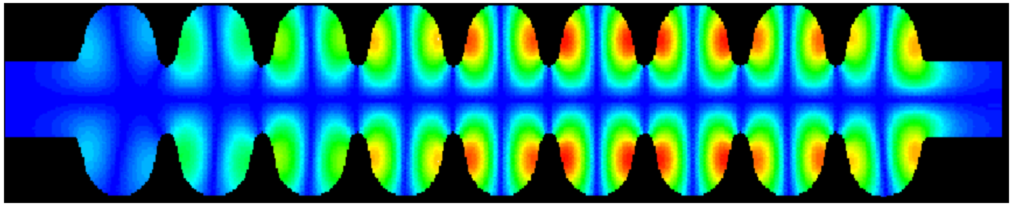
Example:

TESLA 9-cell cavity, which has two different end-cells (asymmetric cavity)

The lowest mode in the passband f_{HOM} = 2382 MHz



The highest mode in the passband f_{HOM} = 2458 MHz



The method works for very few modes but keeps the (R/Q) value high of the fundamental mode.

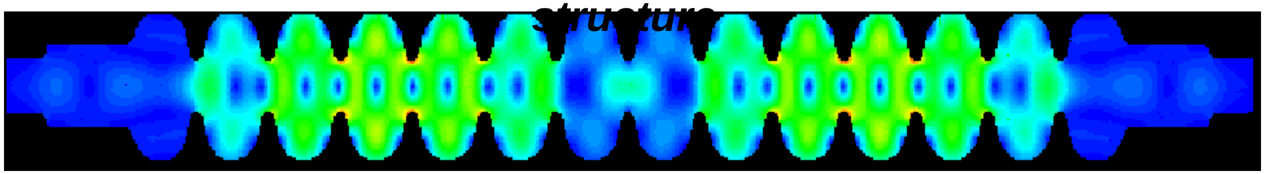
Trapping of Modes within Cavities *HOM*

3) one can also split a long structure in weakly coupled subsections to have space for HOM couplers in mid of a structure.

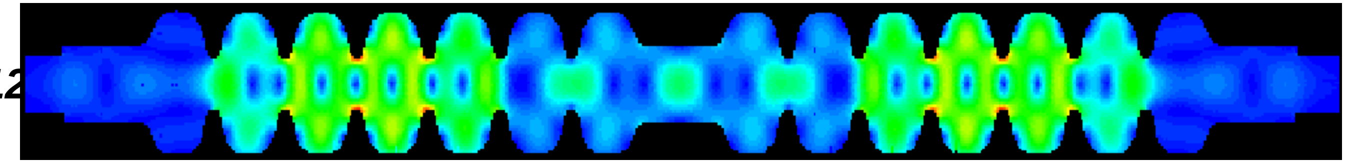
Example: 2x7-cell instead of 14-cell structure (DESY)

High (R/Q) monopole mode trapped in the 14-cell structure

2453 MHz, (R/Q) = 230 Ω



2451 MHz, (R/Q) = 212

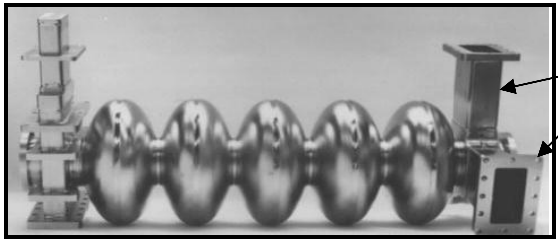


E-H fields at HOM couplers positions, no trapping

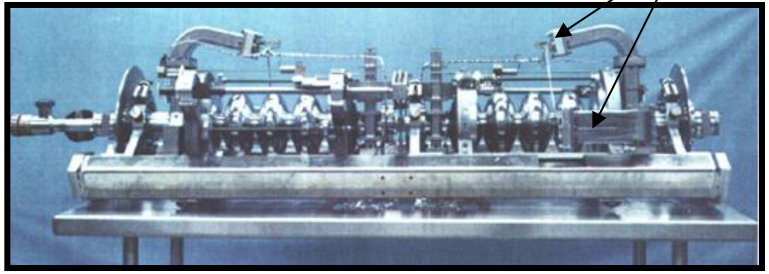
HOM couplers and Beam Line Absorbers

Waveguide HOM couplers

CEBAF/Cornell 1.5 GHz



HOM ports

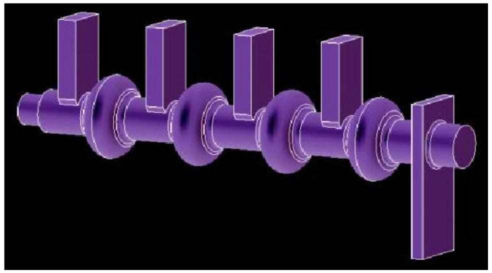


HOM loads

Design (1982) works at present in CEBAF both linacs with

I_{beam} ~ 80μAx4 @ Eacc 7 MV/m

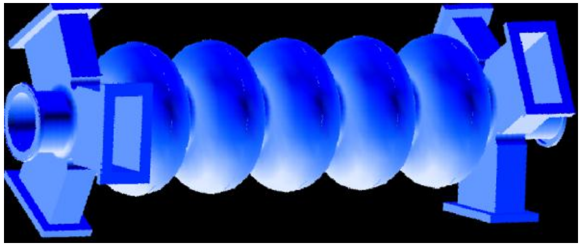
HOM power is very low. It can be dissipated inside cryomodule.



Design proposed by G. Wu (JLab)

1500 MHz for 100 mA class ERLs

LINAC2004



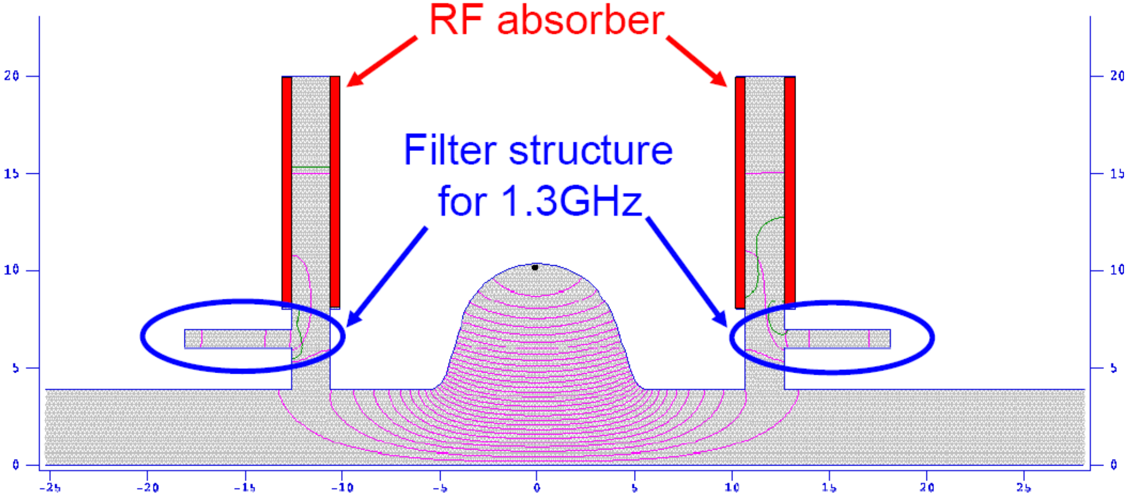
Design proposed by R. Rimmer (JLab)

750 MHz for 1A class ERLs

PAC2005

HOM couplers and Beam Line Absorbers

Waveguide HOM couplers, cont.

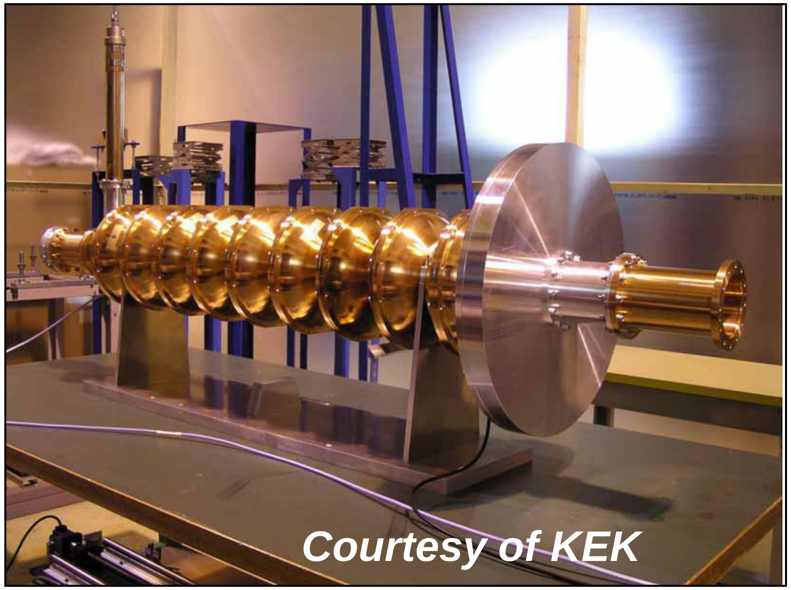


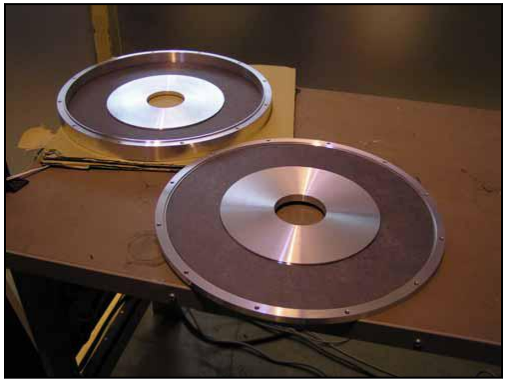
Design proposed by

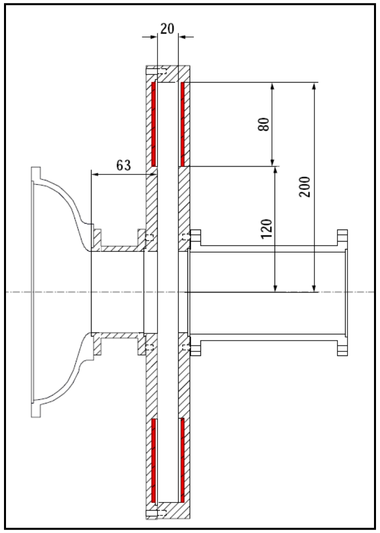
T. Shintake and continued by K. Umemori (KEK)

1.3 GHz TESLA cavity, very good damping.

Proceedings ERL2005







14. HOM couplers and Beam Line Absorbers HOM

Coaxial line HOM couplers

HERA 0.5 GHz

3 couplers
P_{HOM} ~ 100W

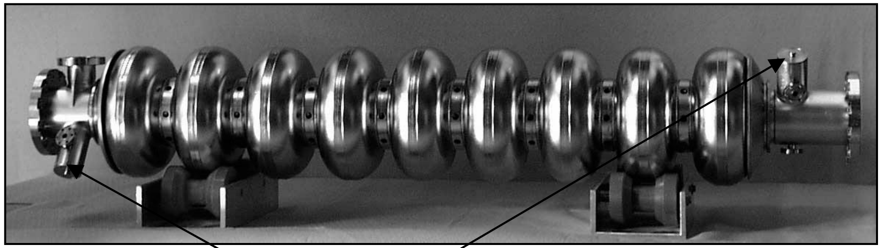
Design (1985/86), 48 work still in HERA e-ring cw operation I_{beam} ~ 40 mA @ Eacc 2 MV/m

TM011 monopole modes with highest (R/Q) damped in 4-cell cavity to Qext < 900 !!

Couplers are assembled in the LHe vessel

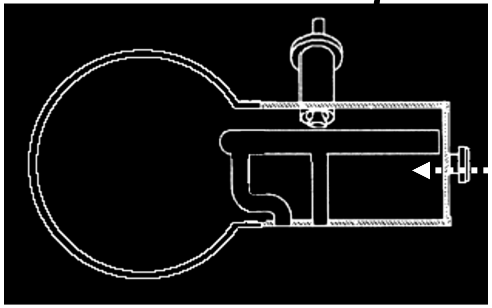
TESLA HOM coupler is a simplified version of HERA HOM couplers for pulse operation with DF of a few percent !!!!!

TESLA 1.3 GHz



2 HOM couplers
<P_{HOM}> ~ few watts

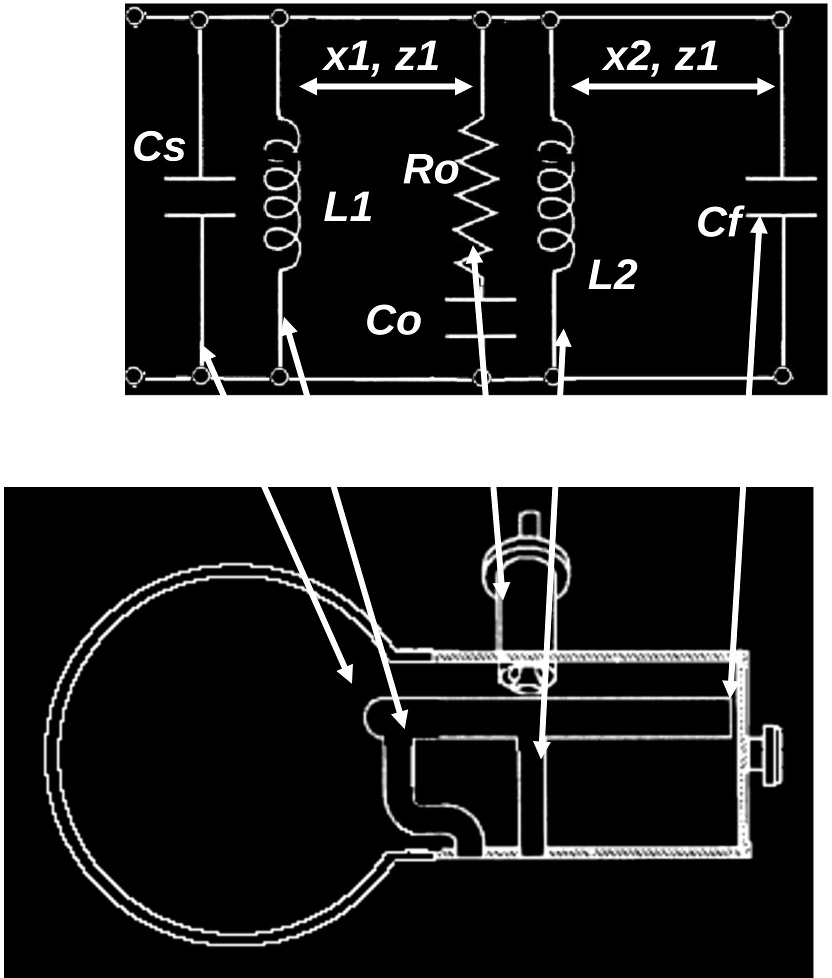
output

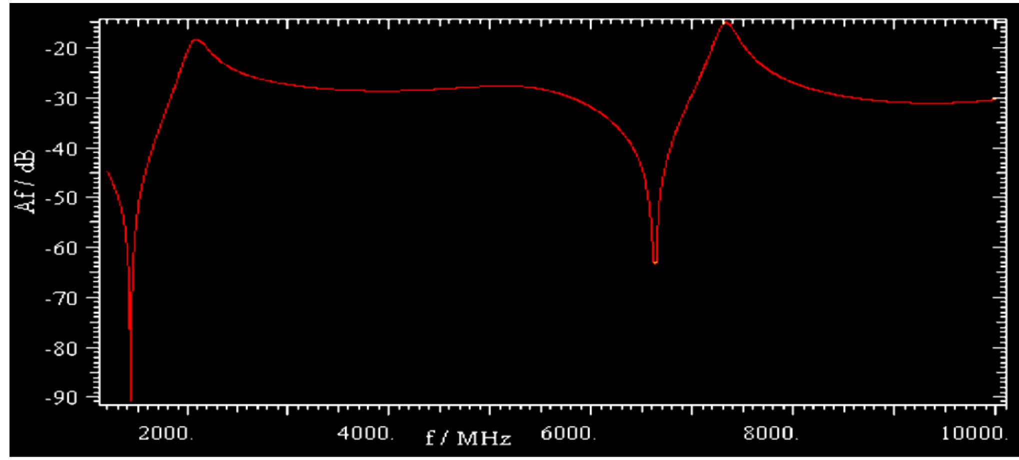


FM rejection filter

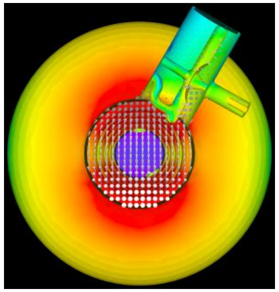
Couplers are assembled outside the LHe vessel !!

The TESLA –like HOM couplers are nowadays designed in frequency range: 0.8-3.9 GHz

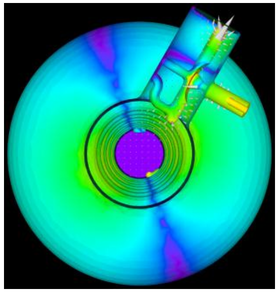




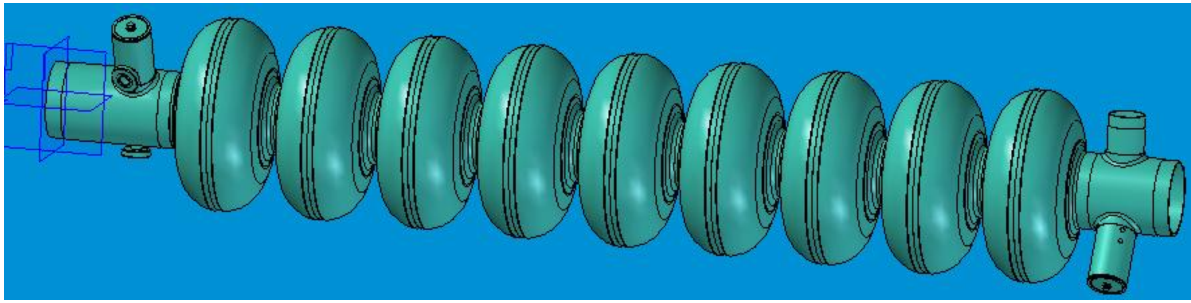
There is big progress in modeling (2D and 3D). Example: Modeling of HOM damping in TTF 9-cell structures by ACD-SLAC (Nov, 2004) . Very good agreement with the measured data !!!

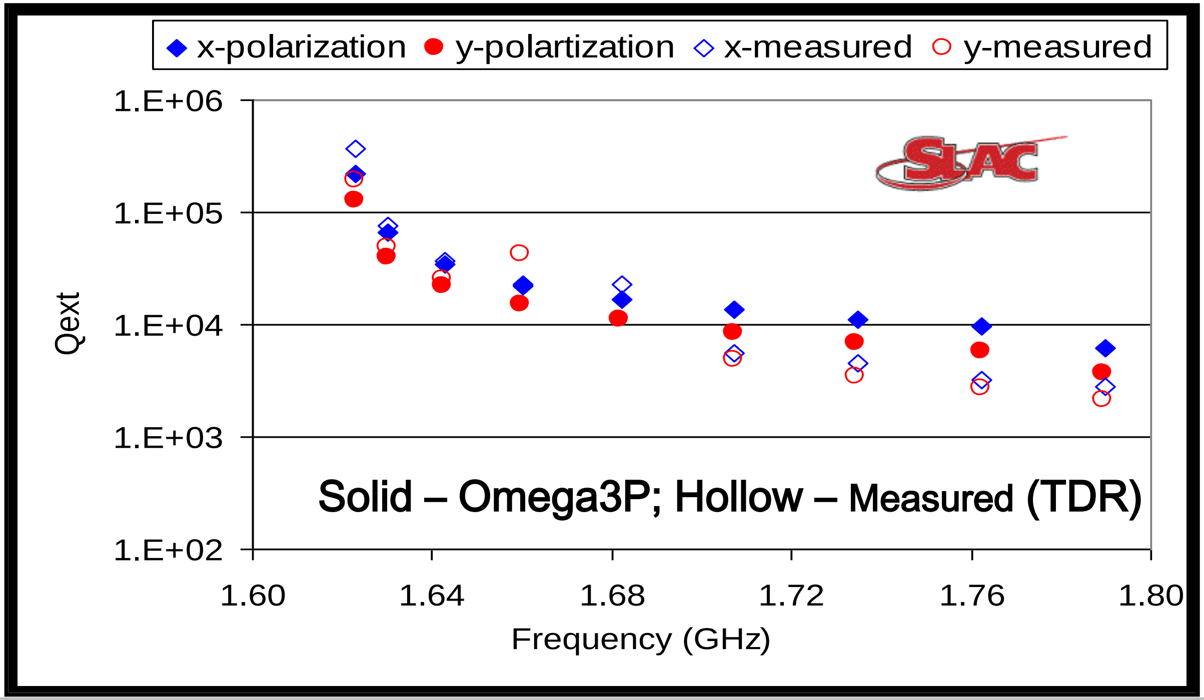


B



E

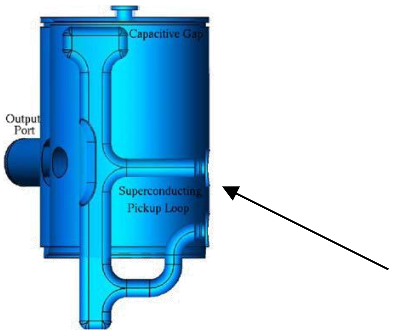


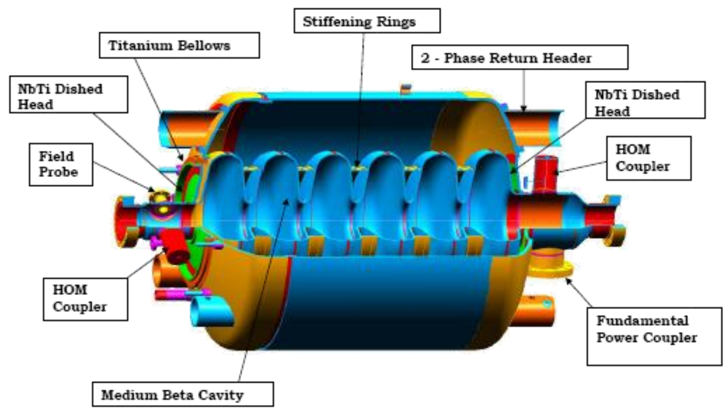


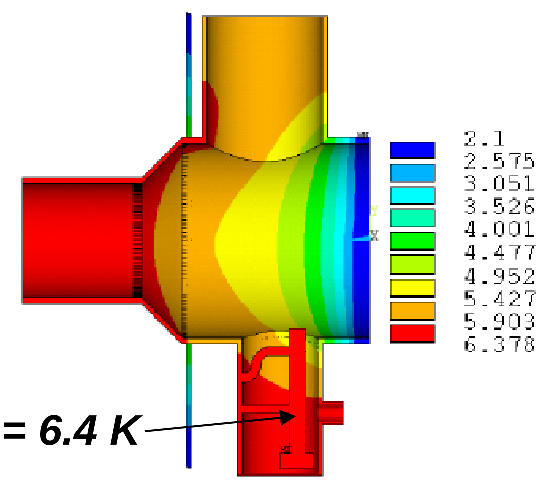
HOM couplers and Beam Line Absorbers

Increasing Duty Factor, one needs to improve cooling of HOM couplers.

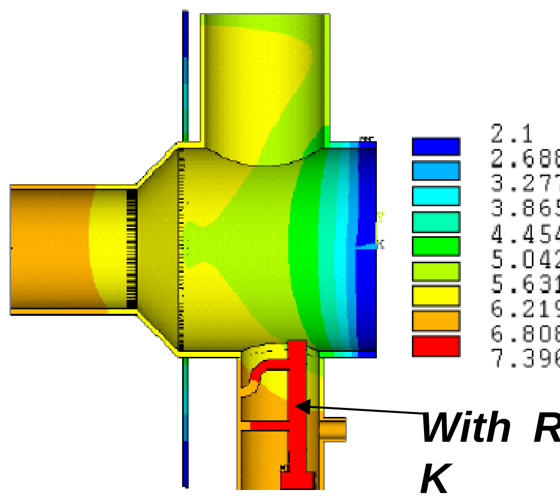
SNS cavities: Linac DF = 6%







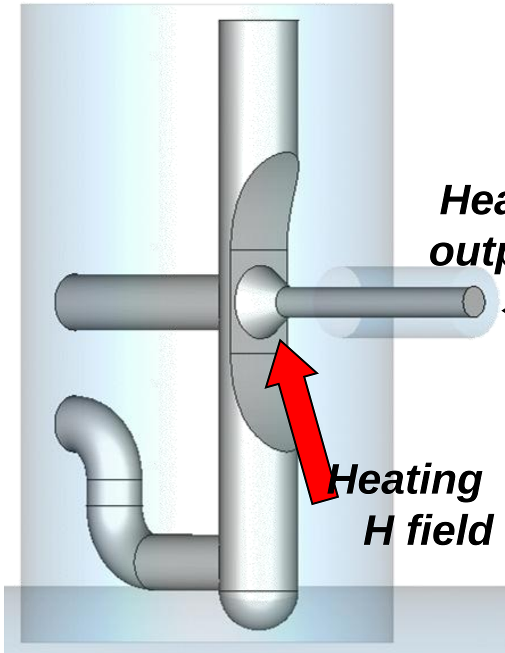
No RF Tmax = 6.4 K



With RF Tmax = 7.4 K

(Courtesy of Oak Ridge Group: I. Campisi, Sang-Ho Kim)

The main problem is heating of the output line.



Heat coming via. output cable from outside.

Heating by residual H field of the FM

Nb antenna loses superconductivity,

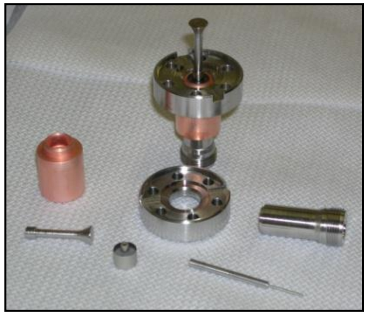
Nb, Cu antennae will warm when the RF on

Three solutions to that problem are currently under investigation:

HOM couplers and Beam Line Absorbers

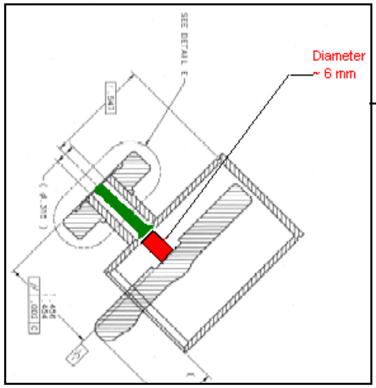
1. High heat conductivity feedthrough, ensuring thermal stabilization of Nb antenna below the critical temperature (9.2 K) at 20 MV/m for the cw operation.

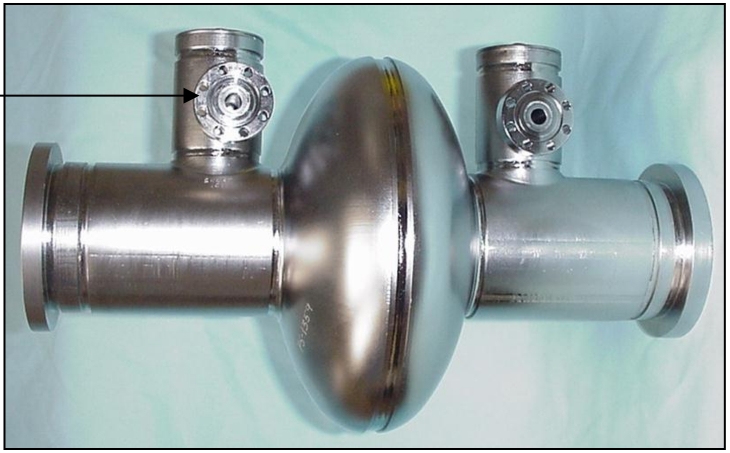
JLab R&D for the 12-GeV CEBAF upgrade.



$Al_2 0_3$ replaced with sapphire

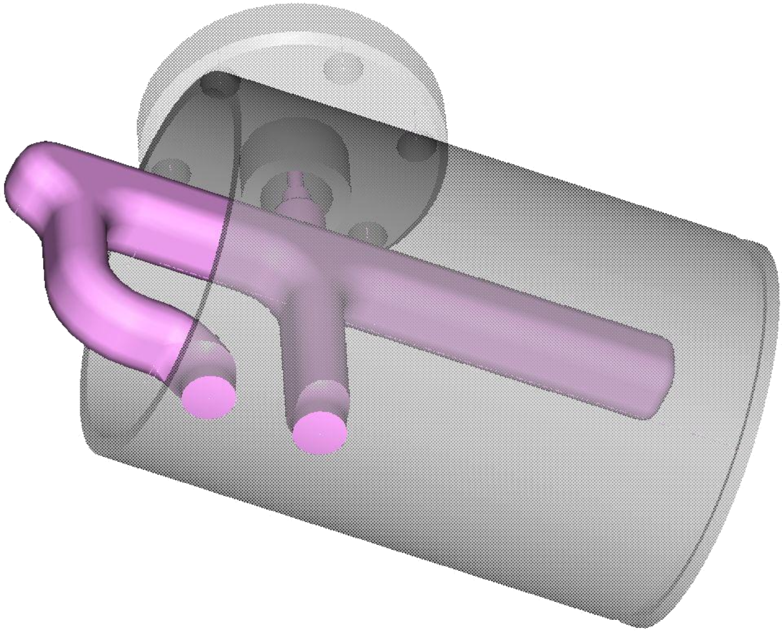
2. New HOM coupler design with hidden output antenna (JLab).

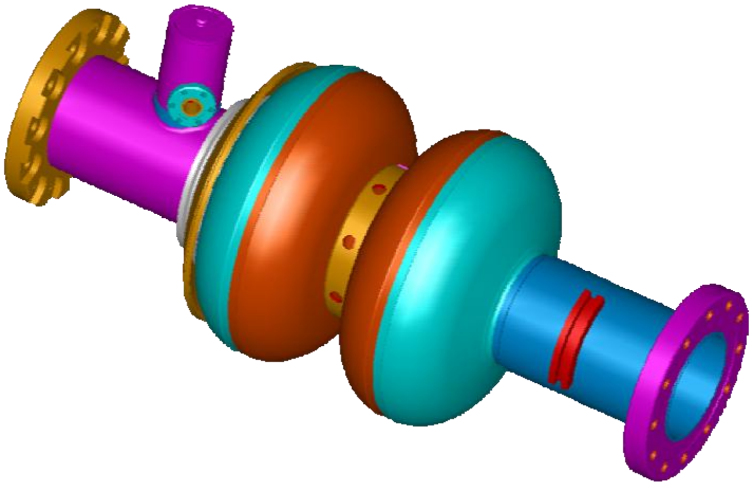




New HOM coupler. ***Old HOM coupler.***

3. New HOM coupler design without output capacitor (DESY).





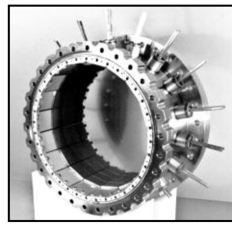
The problem mentioned here looks very unimportant but following projects need a solution to it:

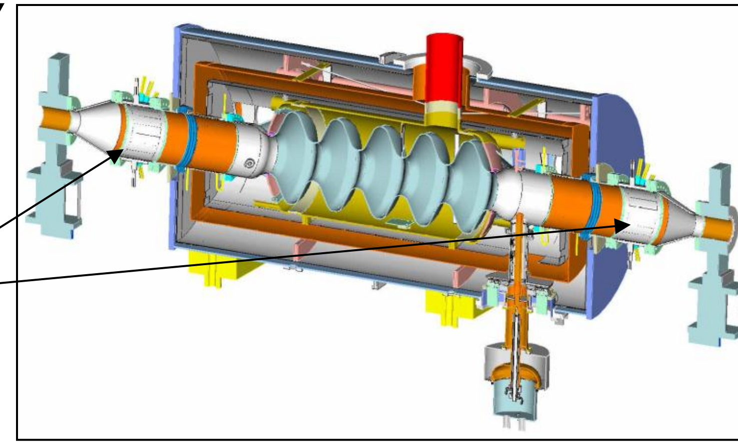
12-GeV CEBAF upgrade, 4 GLS Daresbury, Elbe Rossendorf, BESSY Berlin, CW upgrade of European XFEL, ERL Cornell…

HOM couplers and Beam Line Absorbers

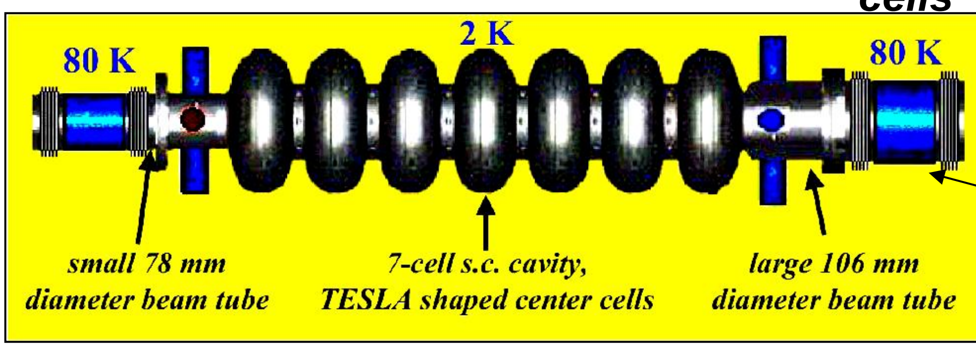
Beam Line Absorbers ; multi-cell cavities

BNL e-cooling for RHIC (four 704 MHz cavities 54 MeV





ERL-Cornell, 310 TESLA 1.3 GHz cavities with modified end cells



TESLA 6 HOM couplers/cavity + 2 Beam Line Absorbers