Impedance modeling: simulations, minimization

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Outline

- Broadband impedance
- Narrowband impedance
- Computer modelling
- Examples
  - Bellows
  - Tapers
  - BPM's
  - Resistive wall
  - Cavities
  - Kickers

Impedance related effects

- Broadband
  - Microwave instability

$$I_p = \frac{2\pi|\eta|\left(\frac{E}{e}\right)(\beta\sigma_p)^2}{\left|\frac{Z_{\parallel}}{n}\right|_{eff}}$$

  - Transverse mode coupling

$$I_b = \frac{4\left(\frac{E}{e}\right)\nu_s}{\left\langle \mathrm{Im}(Z_{\perp})\,\beta_{\perp}\right\rangle R}\,\frac{4\sqrt{\pi}}{3}\,\sigma_l$$

    - Related to “effective” impedance experienced by a single bunch
      - Short-range wakefield
        - » All vacuum chamber components

- Narrowband
  - Coupled-bunch instabilities

$$\Delta\omega_{transverse} = -j\,\frac{I f_0}{2\frac{E}{e}}\,\beta_{x,y}\,Z^{trans.}_{eff}$$

$$\Delta\omega_{longitudinal} = j\,\frac{I f_{rf}}{2\frac{E}{e}}\,\alpha_p\,\frac{f_0}{f_s}\,Z^{long.}_{eff}$$

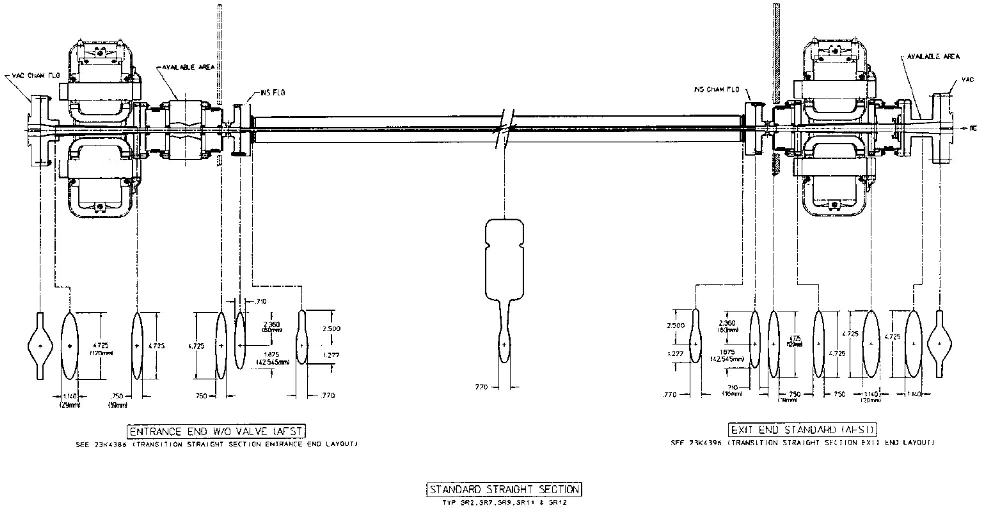
    - Related to narrow-band resonant impedance
      - Long-range wakefield
        - » RF cavities
        - » Resistive wall

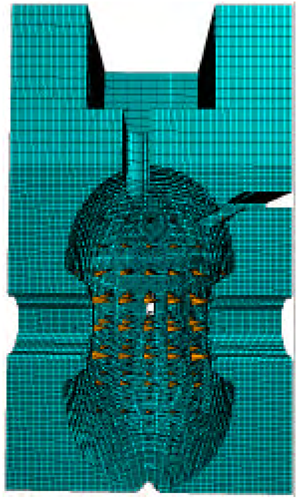
- Heating
  - Power deposited in a resistive impedance may cause heating and damage

“Impedance police”

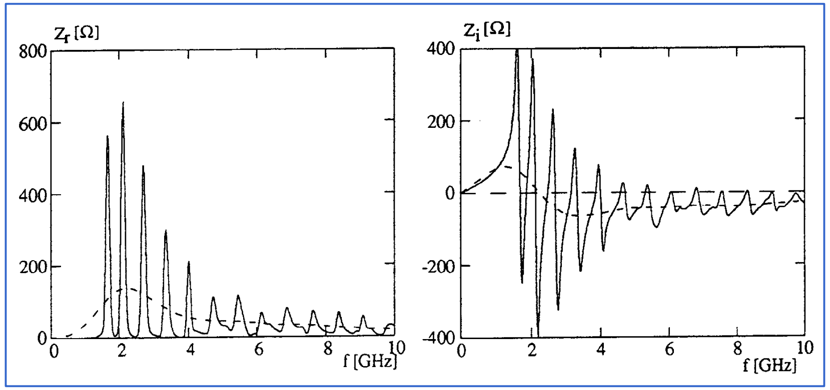
- Minimize beam impedance at the design stage
  - Maintain instability thresholds above operating parameters
  - Avoid heating of uncooled components
    - Close interaction between physicists, engineers, and designers

- tapers
- flanges
- synchr. radiation masks
- BPM’s
- kickers
- resistive wall
- septum magnets
- beam scrapers
- pumping slots
- RF cavities
- etc ….





Broadband impedance calculation



- Single-bunch effects
- Time-domain analysis
- Calculate wakefield over length of bunch
- Not necessary to model all detail of structures
  - Require that fields that can catch up with the beam be properly included
    - Dominated by end effects in many devices
      - » striplines, synchrotron radiation slots, …
- Loss factor
  - Energy loss to the bunch self-induced field

$$k = \frac{\int_{-\infty}^{\infty} W_z(\tau)\, i_b(\tau)\, d\tau}{q}$$

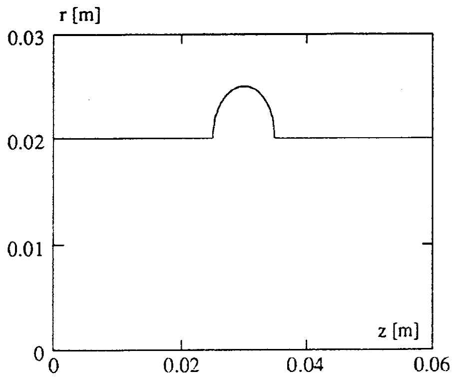
$$P = k\ T_o\ I_b^2$$

Broadband impedance calculation

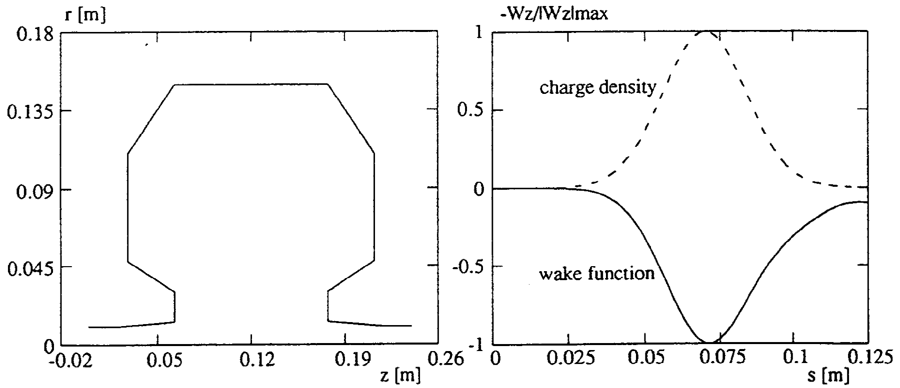
- Require “delta-function” or “Green’s function” wake for inclusion in self-consistent singlebunch phenomena modeling
    - Particle tracking
    - Numerical solution of Fokker-Planck equation
    - Modal analysis from Vlasov equation
        - Improvement over broadband impedance models
        - Require wake from very short bunch to generate an effective Green function
            - Dense mesh
            - Long run time

Broadband impedance calculation

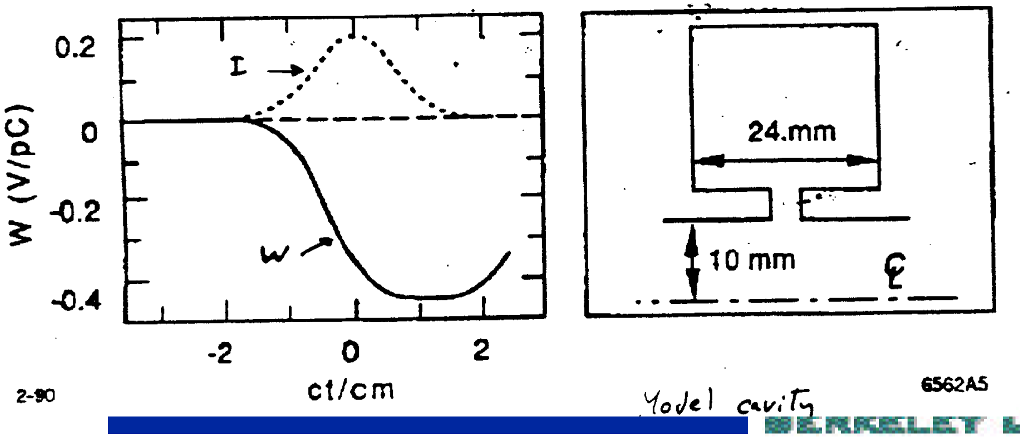
- Inductive wake



- Resistive wake

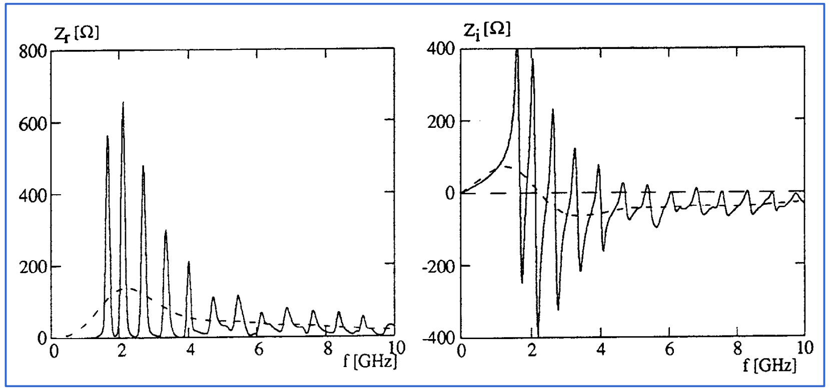


- Capacitive wake



Narrowband impedance calculation

- Multi-bunch effects
- Important to include detail of structures
- Frequency domain analysis
  - Calculate resonant-mode parameters
    - $F_{resonant}$, Q, R/Q, T, …



$$P(\omega) = \underset{\text{beam spectrum}}{\sum} I_b^2(\omega)\, R(\omega)$$

- Time domain analysis
  - Calculate long-range wakefield
  - Wake is calculated for lossless materials
    - OK for heavily externally loaded structures

$$W_{longitudinal}(s) = -\sum_{p=1}^{\infty} \frac{\omega_p}{2}\left(\frac{R}{Q}\right)_p e^{j\frac{\omega_p}{c}s}\, \boxed{e^{-\frac{\omega_p}{2Q_p}s}}$$

Computer modeling

- Time domain
  - Wakefields
    - “moving mesh” for short-range wakes
  - Loss factor
  - F.T. to frequency domain
    - resonant impedance information

- Frequency domain
  - $F_{resonant}$
  - Q
  - R/Q
  - Transit time T
  - …

- Boundary conditions
  - E, H boundary conditions
    - Symmetry planes
  - Periodic boundary conditions
    - Periodic structures (cavities)
  - Waveguide boundary conditions
    - Damping waveguides
  - Resistively matched boundaries
    - Broad-band match

Computer modeling

- Finite-difference codes
  - MAFIA, GDFIDL, URMEL, ABCI, etc
  - Rectangular meshing
    - May be crude geometric model
    - Large memory demands
      - Matrix includes points outside “active” volume
    - Many mesh points for improved accuracy

- Boundary-element codes, etc
  - Not commonly used in this application

- Finite-element codes
  - HFSS, ANSYS, SOPRANO, PRIAM, etc
  - Efficient meshing with polygons
    - Good geometric fit
    - Mesh only the active volume
  - Analysis less robust
    - “ghost modes”
      - Non-physical solutions
    - Maxwells equations may be solved explicitly on rectangular mesh

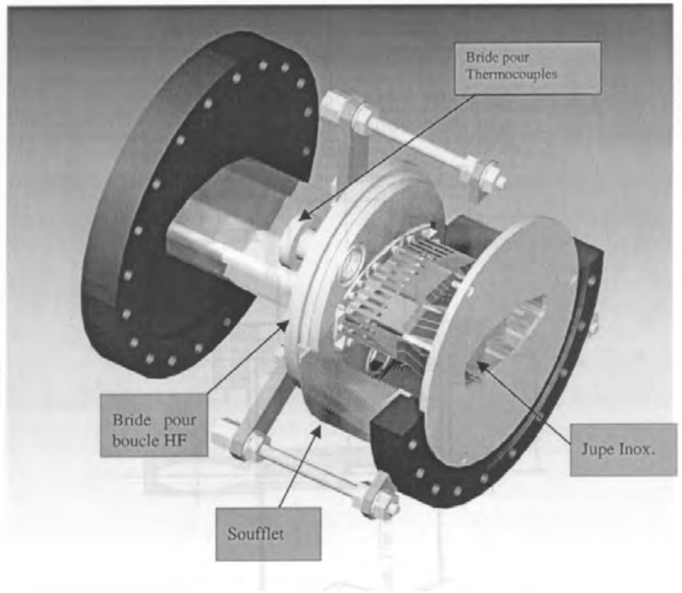
2-D / 3-D

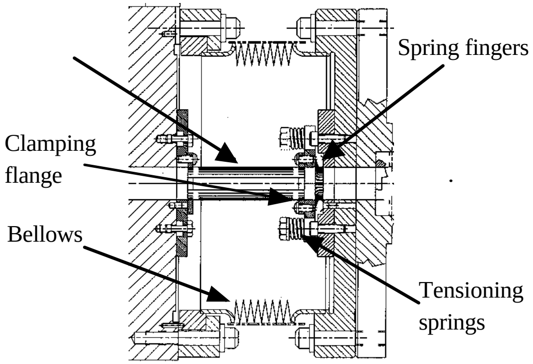
- 2-D
- Simple cylindrically symmetric geometries
- Define azimuthal variation for each computation run
  - m=0 (monopole)
  - m=1 (dipole) … etc
    - Efficient use of memory and CPU time

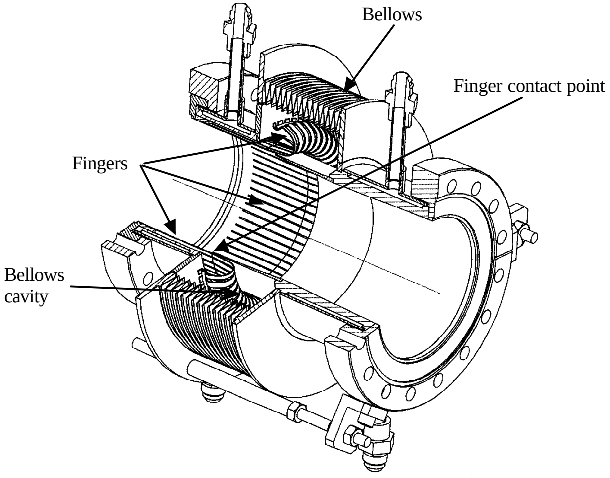
- 3-D
- Allows complex geometries without longitudinal or azimuthal symmetry to be modeled
  - Gobbles up memory and CPU cycles

Bellows

- Shield bellows with “smooth” conductors
  - Carry image currents
  - Prevent coupling to volume enclosed by bellows
    - Must have some compliance to allow bellows movement

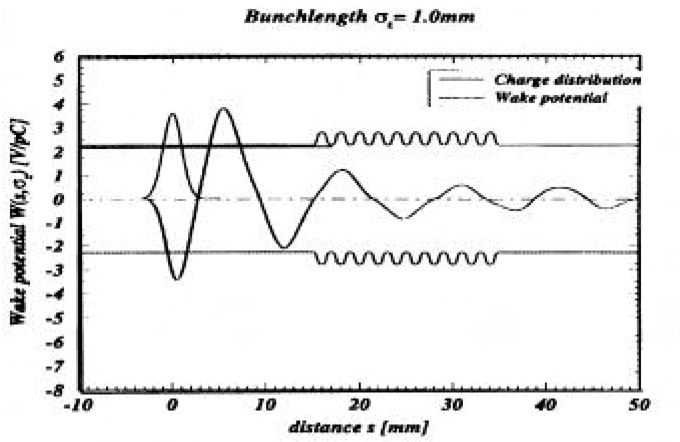




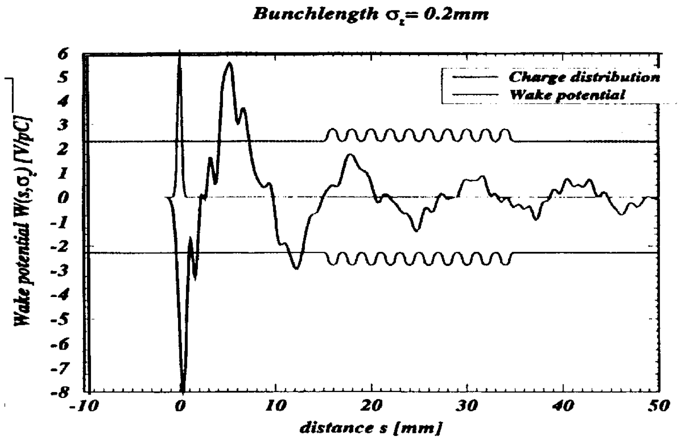


Bellows

- Unshielded bellows have strong resonances
  - May drive instabilities
  - May be damaged by beam-induced heating



- Shielded bellows difficult to model
  - Intricate details of fingerstock
  - Small changes in cross-section at moving joints
    - Generally approximate model as solid with small step changes in cross-section at sliding joints

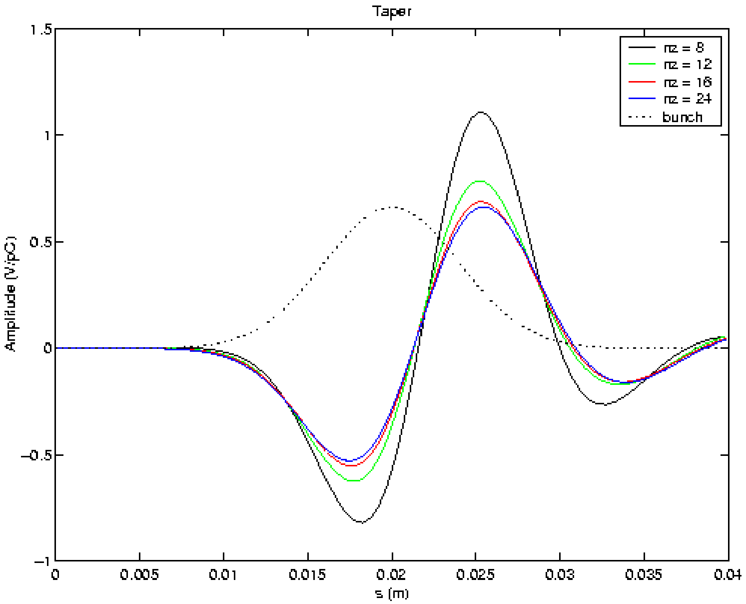


Tapers

- Strongly inductive at low frequencies
- Minimize angle / maximize length
  - Smooth linear tapers as good as more complex shapes
- Generally model as pairs
  - Energy loss from outward taper, gain from inward taper
- Beware of cross-talk with adjacent components
  - May need to model longer sections of vacuum chamber
- Good agreement with theory for 2-D structures
  - Wakefield sensitive to mesh size
    - Ensure convergence
- Poor correlation extrapolating from 2-D to 3-D

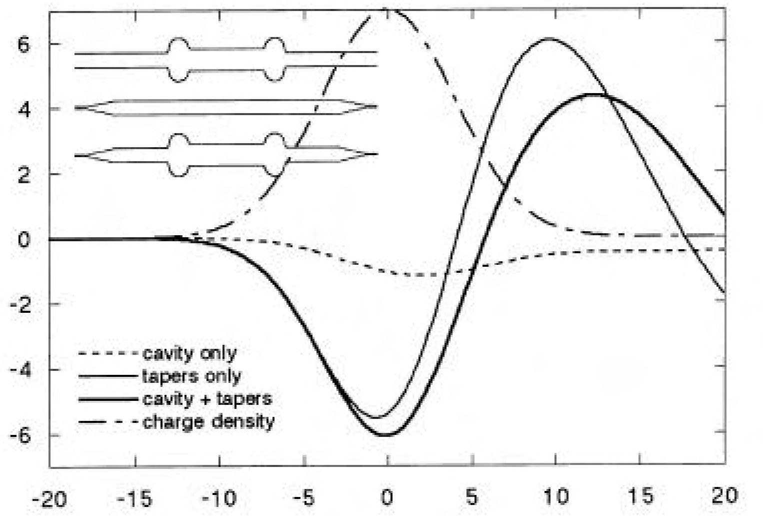
Tapers

- Sensitivity to mesh size
  - 10:1 taper



  - Ensure convergence as mesh size reduced $\frac{a\phi}{\Delta z}\frac{\sigma_s}{\Delta z} > 100$

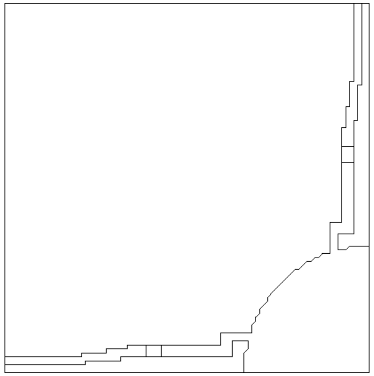
- Cavity / tapers wakes

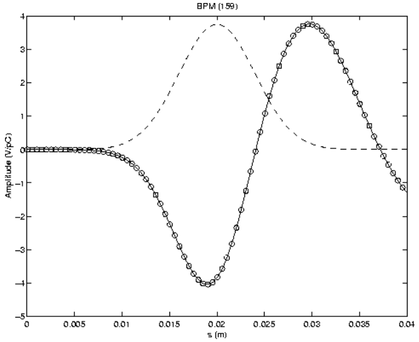


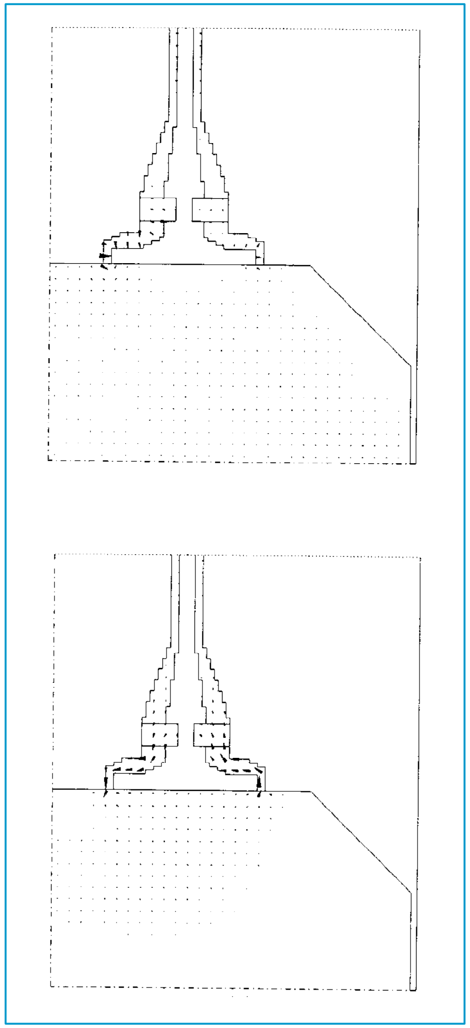
  - Tapers dominate wake in this case

BPM's

- High-frequency circumferential modes dominate impedance
  - Narrowband effects as well as low frequency inductance and resistance
    - Increase resonant frequency by making smaller buttons
    - De-Q resonance by introducing asymmetry
      - D-shaped button or perturbation to couple mode into coaxial line

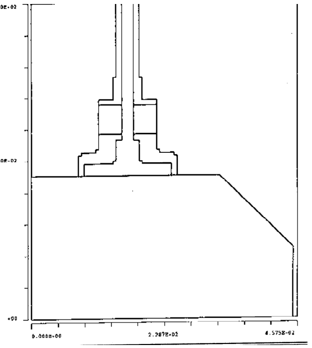


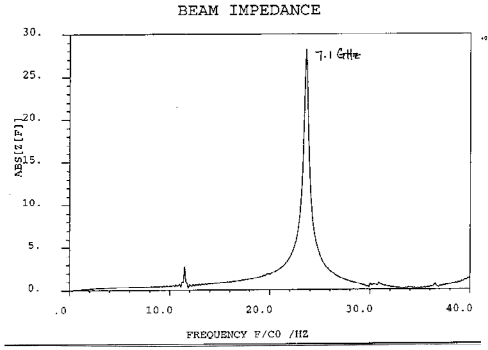


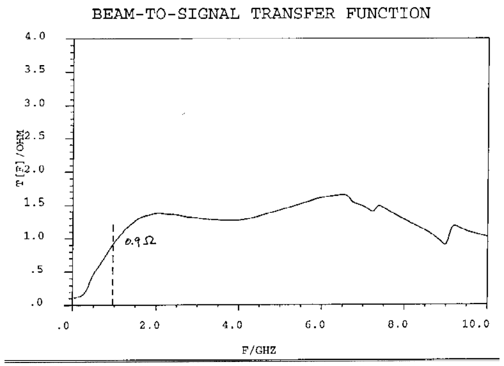


BPM’s

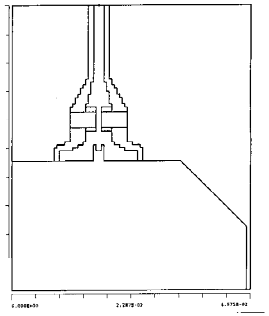
- K-type

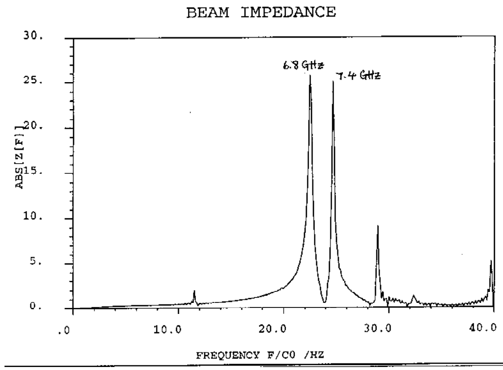


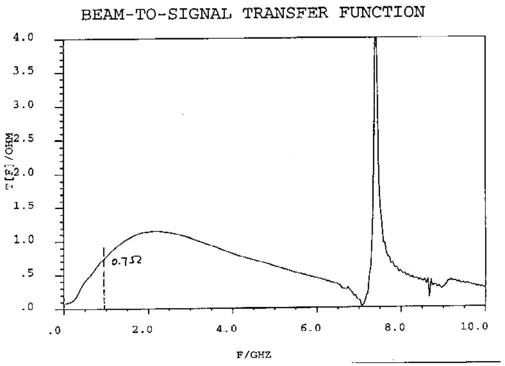




- M-type







Resistive wall

$$W_1(s) = \frac{C}{b^3\sigma_z^{1/2}}\frac{c}{2\pi}\sqrt{\frac{Z_o}{2\sigma_{d.c.}}}\,f(s/\sigma_z)$$

$$f(u) = |u|^{1/2}\ e^{-u^2/4}\ \left(I_{-1/4} \pm I_{1/4}\right)\Big|_{u^2/4}$$

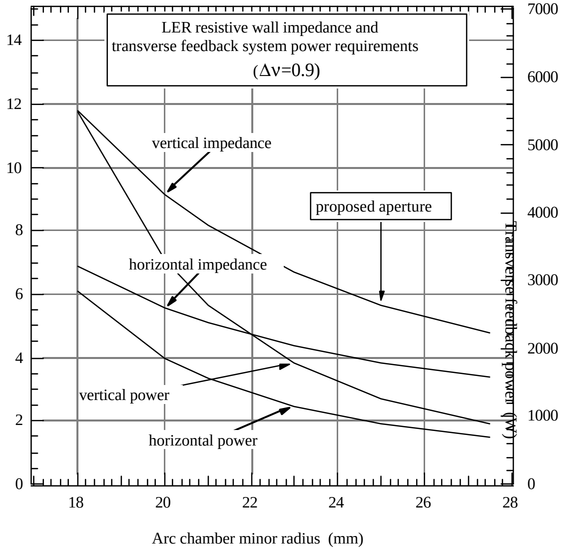
- Transverse
- Increasing radius helps but usually not an option
- Use high-conductivity materials where possible
  - ρ = 17.7 n! -m Cu, 33 n! -m Al, 900 n! -m st. st.
  - Transverse coupled-bunch motion dominated by resistive wall at low frequency
    - Lowest mode determined by tune

$$\omega = 2\,\pi f_{orbit}\left(1 - \Delta Q\right)$$

    - Feedback systems may be required

$$Z^{\text{resistive wall}}_{\text{transverse}} = A\ (1+j)\,\frac{c\,L}{\pi\, b^3}\sqrt{\frac{\mu_0\,\rho}{2}}\ \frac{1}{\sqrt{\omega}}$$

$$A_{\text{vertical}} = \pi^2/12$$
$$A_{\text{horizontal}} = \pi^2/24$$
$$A_{\text{circular}} = 1$$

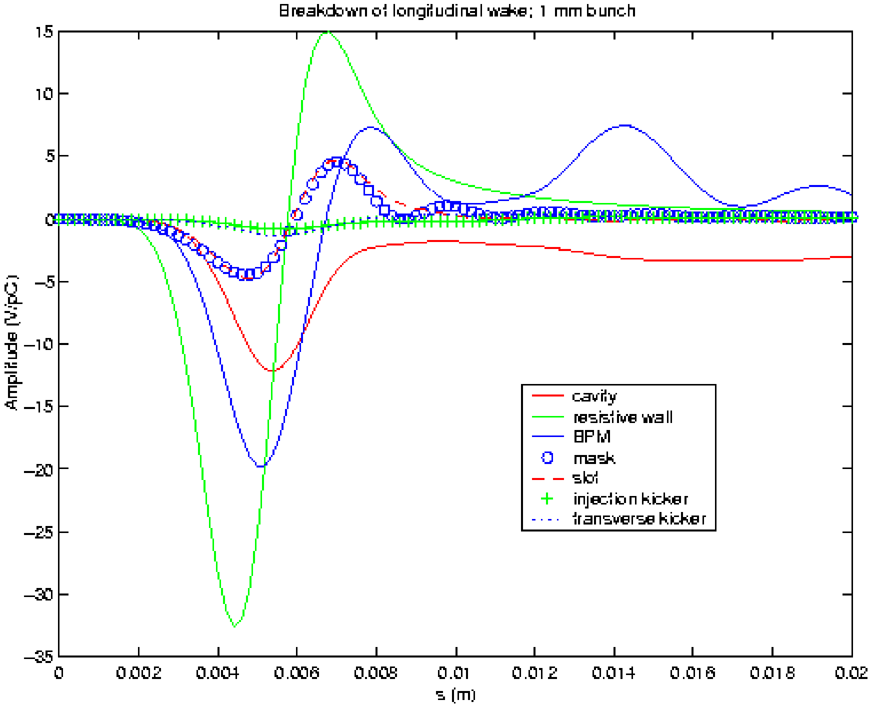


Resistive wall

- Longitudinal
  - Short-range wake is strong for very small vacuum chambers and short bunches

$$W_z(s) = \frac{C}{4b\,\sigma_z^{3/2}} \sqrt{\frac{c}{2\pi\sigma_{d.c.}}}\, f(s/\sigma_z)$$

$$f(u) = |u|^{3/2}\; e^{-u^2/4} \left(I_{1/4} \;-\; I_{-3/4} \;-+\; I_{-1/4} \;+-\; I_{3/4} \right)\Big|_{u^2/4}$$



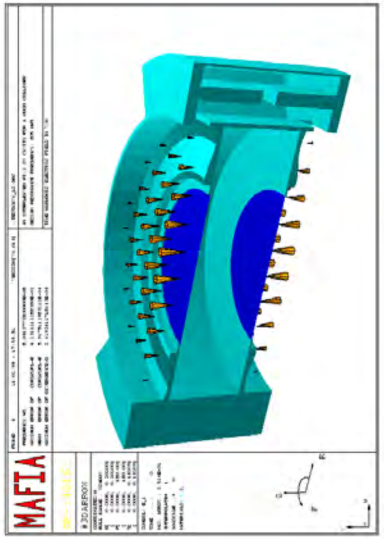
- Resistive heating

$$P = \frac{L}{8\pi^2 r}\, I_o^2\, \Gamma\!\left(\frac{3}{4}\right) \sqrt{\frac{\mu_o}{2\sigma_{dc}}}\; \frac{T_b}{\sigma_t^{\left(\frac{3}{2}\right)}}$$

  - May demand cooling of vacuum chambers

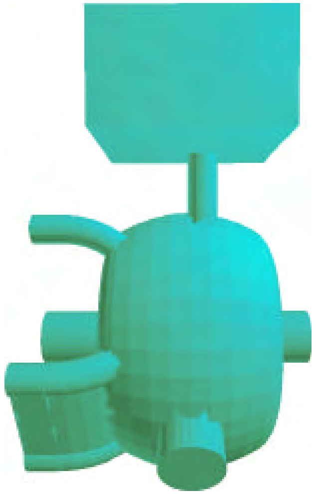
RF cavities - frequency domain

- Details of mode parameters
  - Must calculate many modes
    - Not all of interest
  - Damped cavities require careful analysis
    - Kroll-Yu method
      - Several runs with different waveguide lengths



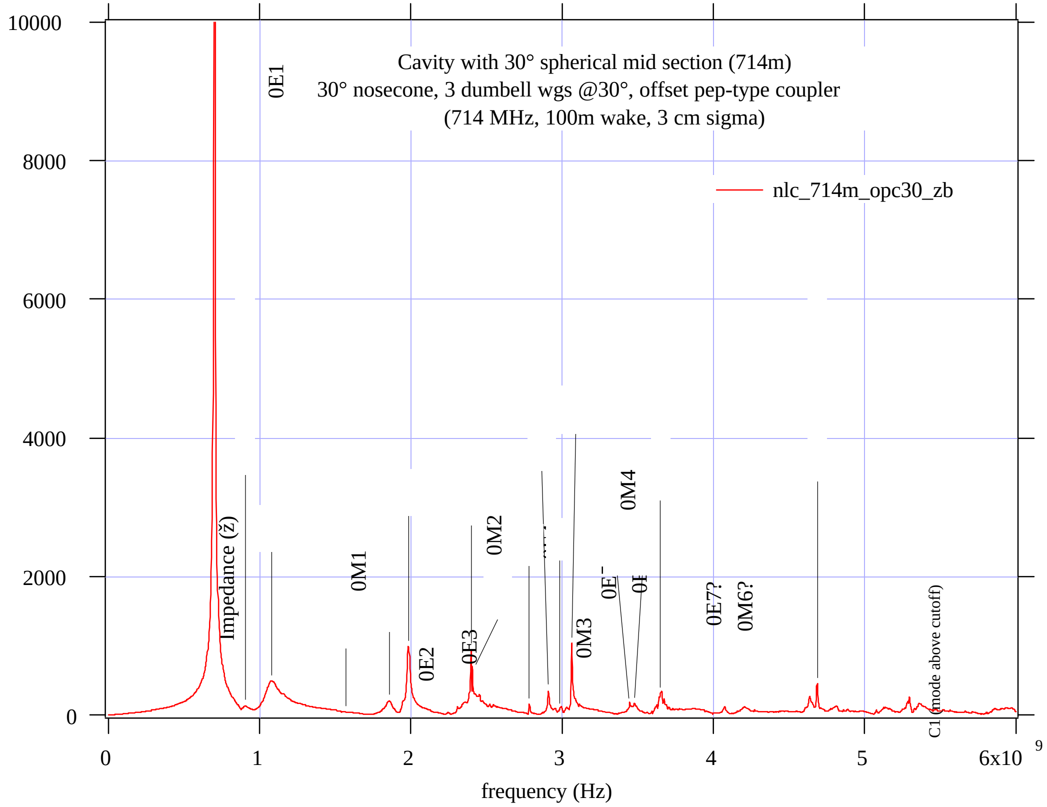
RF cavities - time domain

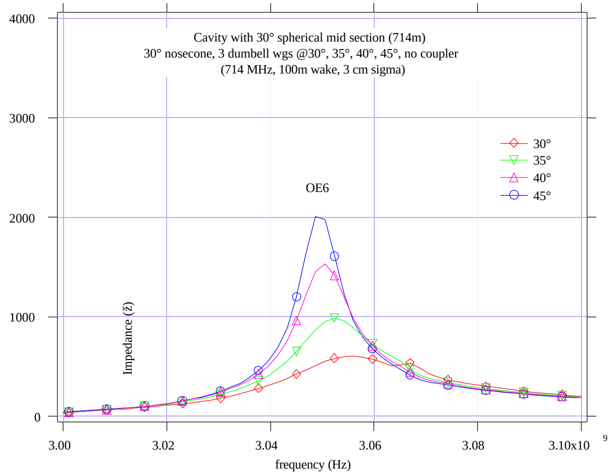
- Allows matched waveguide boundaries
  - Good for damped cavities
  - Many modes sampled in one run
    - Long wake required to resolve modes
  - Less accurate mode parameters
    - Calculated wake is for lossless materials
      - OK if heavily damped (externally loaded)



HOM damping

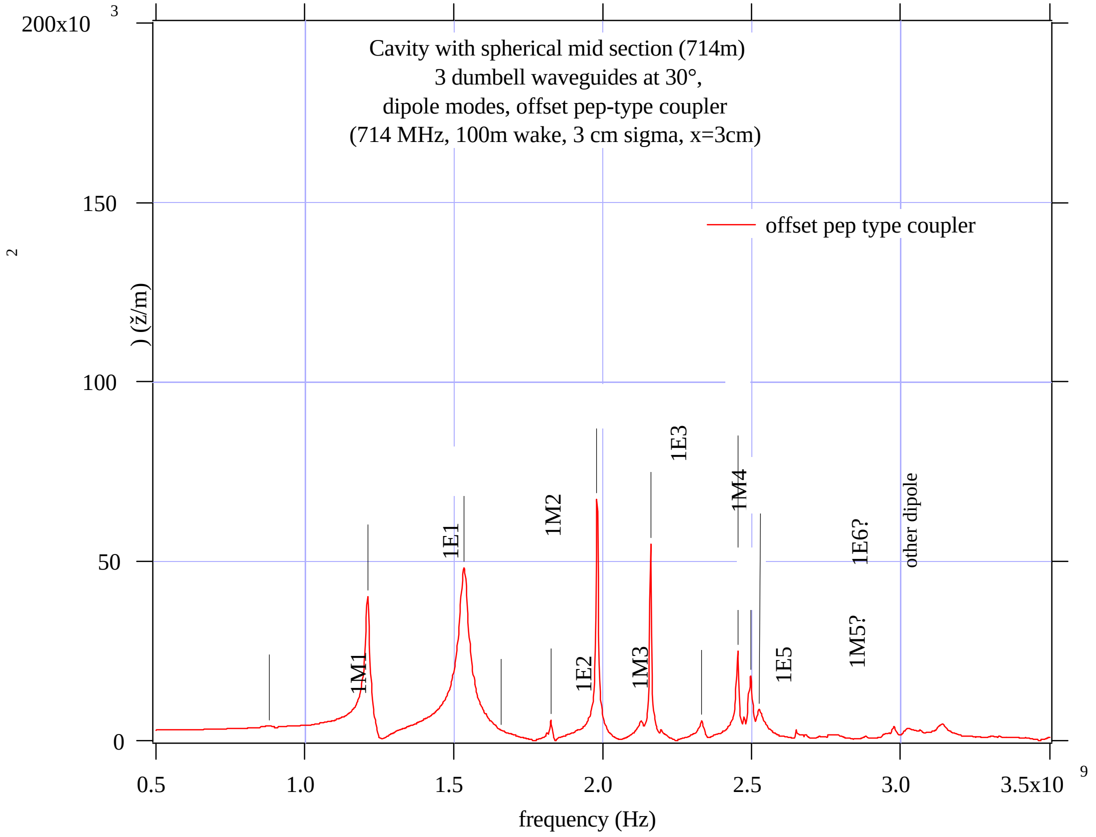
- Longitudinal





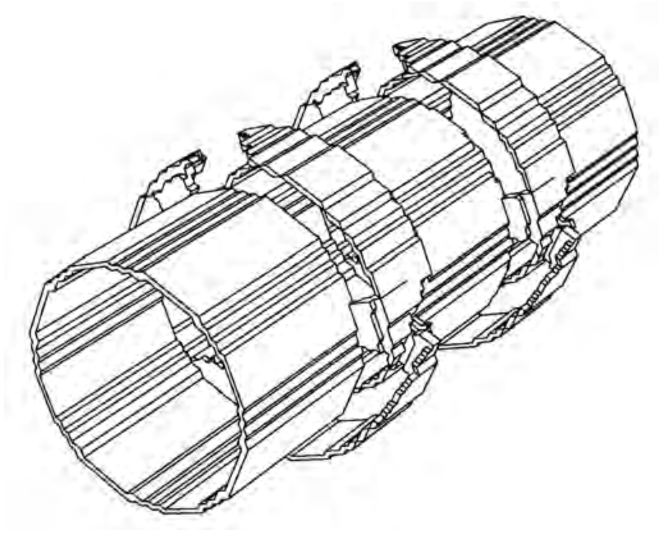
HOM damping

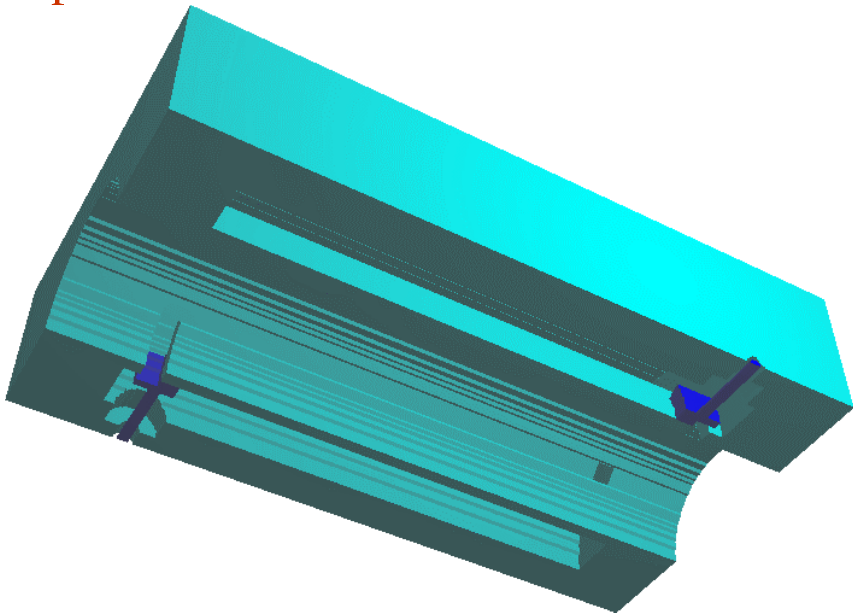
- Transverse



Kicker structures

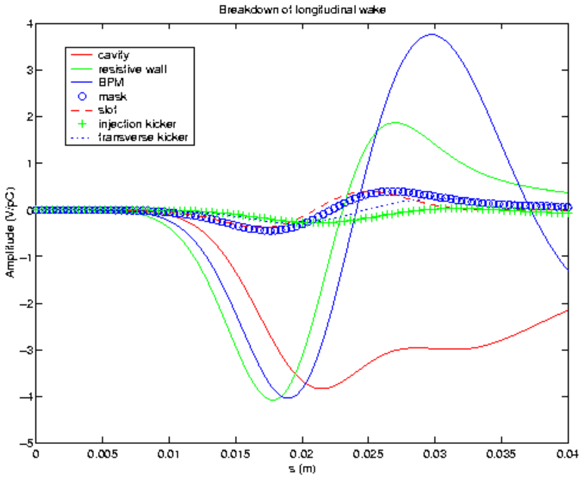
- End effects often adequate for broadband impedance
- Resonant effects
  - Careful model including more structure details
  - Beware of details!
- Parasitic resonances may be damped with antennae

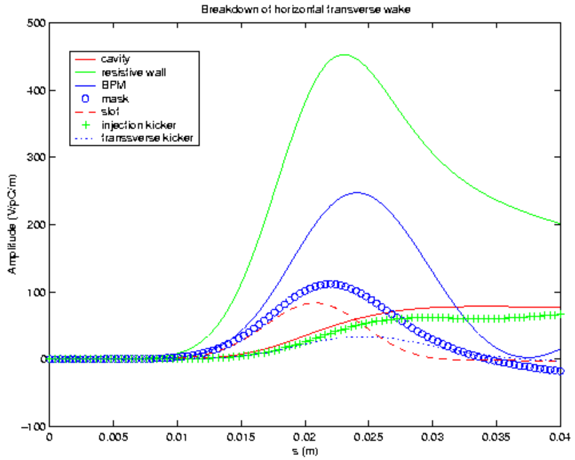


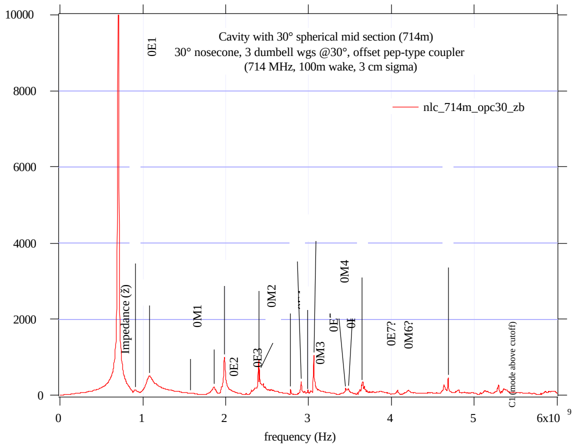


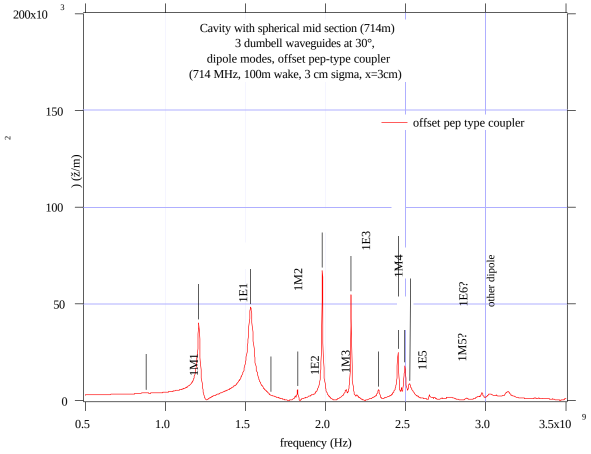
Total wake

- For NLC main damping rings









Conclusions

- Computational tools for impedance calculation are highly developed
- Several techniques available for many calculations
- Computing power now sufficient to allow complex geometries
  - 1,000,000 mesh points
  - 100’s meters wake
    - " 24 hrs CPU time
- Wakefield calculations for single-bunch effects
  - Use Green function wake in simulation codes
- Simple to use F.T. to optimize HOM damping in cavities
- Frequency domain for devices with few resonances