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
    \[ I_p = \frac{2\pi |\Omega| \left( \frac{E}{e} \right) (\beta \sigma_p)^2}{\left| \frac{Z}{n_{\text{eff}}} \right|} \]
  - Transverse mode coupling
    \[ I_b = \frac{4 \left( \frac{E}{e} \right) v_s}{\text{Im}(Z_{\perp}) \beta_{\perp} R} \frac{4\sqrt{\pi} \sigma_z}{3} \]
- Related to “effective” impedance experienced by a single bunch
  - Short-range wakefield
    » All vacuum chamber components

- Narrowband
  - Coupled-bunch instabilities
    \[ \Delta \omega_{\text{transverse}} = -j \frac{f_0 \beta_{x,y} Z_{\text{eff}}}{2E_e} \]
    \[ \Delta \omega_{\text{longitudinal}} = j \frac{f_0 \alpha_p \frac{f_0}{f_s} Z_{\text{long.}}}{2E_e} \]
- 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
    \[ p = k T_\alpha I_b^2 \]
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
- Capacitive wake
- Resistive wake
Narrowband impedance calculation

- Multi-bunch effects
- Important to include detail of structures
- Frequency domain analysis
  - Calculate resonant-mode parameters
    - $F_{\text{resonant}}, Q, R/Q, T, \ldots$
- Time domain analysis
  - Calculate long-range wakefield
  - Wake is calculated for lossless materials
    - OK for heavily externally loaded structures

\[
P(\omega) = \bullet I_b^2(\omega) R(\omega)
\]

\[
W_{\text{longitudinal}}(s) = - \sum_{p=1}^{\infty} \frac{\omega_p}{2} \left( R \right)_p e^{i\omega_p s} e^{-2Q_p s}
\]
Computer modeling

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

**Frequency domain**
- $F_{\text{resonant}}$
- $Q$
- $R/Q$
- 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 $\frac{a_\phi \sigma_z}{\Delta z \Delta z} > 100$

• 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

- Transverse
- Increasing radius helps but usually not an option
- Use high-conductivity materials where possible
  - \( \rho = 17.7 \text{ n}! -\text{m Cu}, 33 \text{ n}! -\text{m Al}, 900 \text{ n}! -\text{m st. st.} \)
  - Transverse coupled-bunch motion dominated by resistive wall at low frequency
    - Lowest mode determined by tune
      \[ \omega = 2 \pi f_{\text{orbit}} (1 - \Delta Q) \]
    - Feedback systems may be required

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

\[
f(u) = |u|^{1/2} e^{-u^{2/4}} (1_{1/4} \pm 1_{1/4}) u^{1/4}
\]

\[
Z_{\text{transverse}} \approx A \left( 1+j \right) \frac{c L}{\pi} b^3 \frac{1}{\mu_0} \frac{\rho}{2} \frac{1}{\sqrt{\omega}}
\]

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

Graph showing LER resistive wall impedance and transverse feedback system power requirements (\( \Delta \nu = 0.9 \))
Resistive wall

- **Longitudinal**
  - Short-range wake is strong for very small vacuum chambers and short bunches
  
  \[ W_z(s) = \frac{C}{4b \sigma_z^{3/2}} \sqrt{\frac{c}{2 \pi \sigma_{d.c.}}} f(s/\sigma_z) \]

  \[ f(u) = |u|^{3/2} e^{-u^{3/4}} \left( I_{1/4} - I_{3/4} \right) + I_{1/4} - I_{3/4} \]

- **Resistive heating**

  \[ P = \frac{L}{8 \pi^2 \tau} I_0^2 \Gamma \left( \frac{3}{4} \right) \sqrt{\frac{\mu_0}{2 \sigma_{d.c.}}} \frac{T_b}{\left( \frac{3}{\sigma_z^{1/2}} \right)} \]

  - 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

Cavity with 30° spherical mid section (714m)
30° nosecone, 3 dumbell wgs @30°, offset pep-type coupler
(714 MHz, 100m wake, 3 cm sigma)

nlc_714m_opc30_zb
HOM damping

- Transverse

Cavity with spherical mid section (714m)
3 dumbell waveguides at 30°,
dipole modes, offset pep-type coupler
(714 MHz, 100m wake, 3 cm sigma, x=3cm)

Offset pep type coupler
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

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**Slide 25**

John Corlett, Instabilities Workshop, ESRF, March 2000
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