PHYS 854
Old Dominion University

Chapter 14.5+: Beam Breakup

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https://casa.jlab.org/publications/ODU_F2019.shtml

Happy Birthday to Peter Drucker, Jodie Foster, Adam Driver, and Jean-Antoine Nollet!
Happy National Carbonated Beverage with Caffeine Day, World Toilet Day, and "Have A Bad Day" Day!

Overview

- Chapter 14.5+: Beam Breakup
  - Introduction: Impedances and instabilities
  - Review: RF higher order modes
  - Linear accelerator beam breakup
    - Amelioration: BNS damping
  - Regenerative (or ERL) beam breakup

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PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **6**, 084402 (2003)

Cumulative beam breakup in linear accelerators with arbitrary beam current profile

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(Received 17 June 2003; published 27 August 2003)

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Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 495, Issue 2, 11 December 2002, Pages 85-94

Cumulative beam break-up study of the spallation neutron source superconducting linac ☆

D Jeon [a], L Merminga [b], G Krafft [b], B Yunn [b], R Sundelin [b], J Delayen [b], S Kim [a], M Doleans [a]

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STUDIES OF ENERGY RECOVERY LINACS AT JEFFERSON LABORATORY

1 GeV Demonstration of Energy Recovery at CEBAF and Studies of the Multibunch, Multipass Beam Breakup Instability in the 10 kW FEL Upgrade Driver

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Multipass Beam Breakup Study at Jefferson Lab for the 12 GeV CEBAF Upgrade

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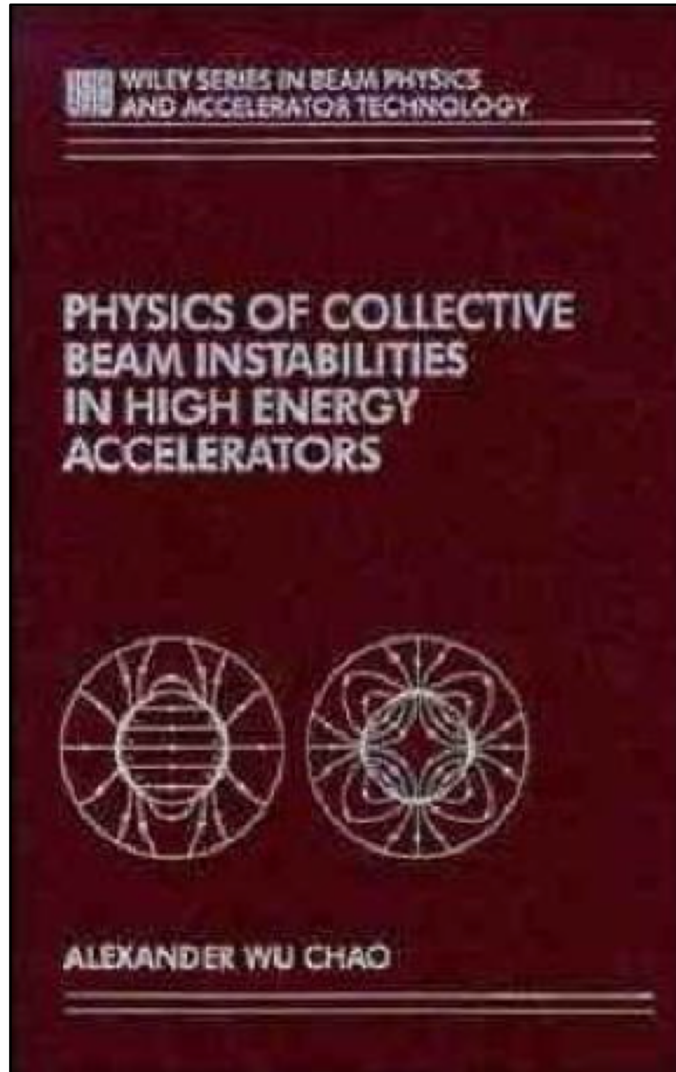
https://casa.jlab.org/publications/CASA_PhDs.shtml

Introduction: Impedances and Instabilities

- Until now we have mostly only considered beam dynamics as affected by externally-generated EM fields
  - Single-particle dynamics
  - Beam fields dominated by external fields
- But *by definition* the beam has its own EM fields
  - Beam acts like a (time-dependent) current
  - These fields interact with their environment
    - In particular, they interact with resonators in the environment
    - These resonators look very much like impedances in circuits
  - Fields created by the beam can act back upon the beam
  - These fields created in the beam's wake are called "wakefields"
- These interactions create *feedback loops*
  - Like any feedback, this can create unstable feedback loops

Entire Textbooks on Impedances/Instabilities

- My canonical book on this subject is Alex Chao's textbook
- Free on the web at
  - https://www.slac.stanford.edu/~achao/wileybook.html



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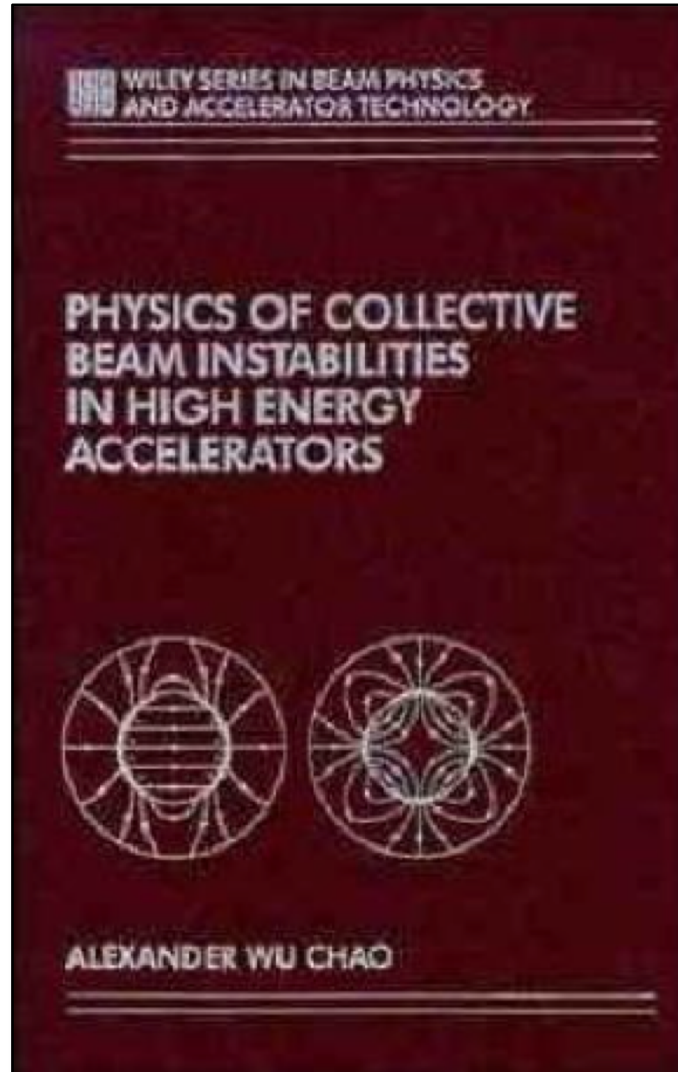
Beam breakup

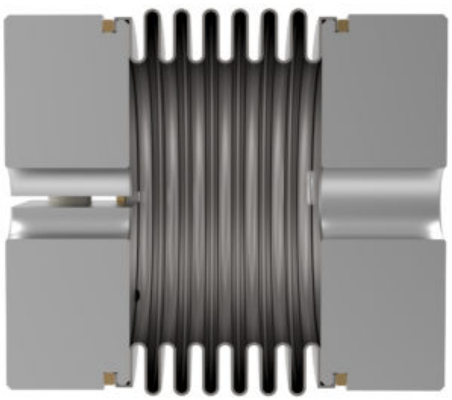


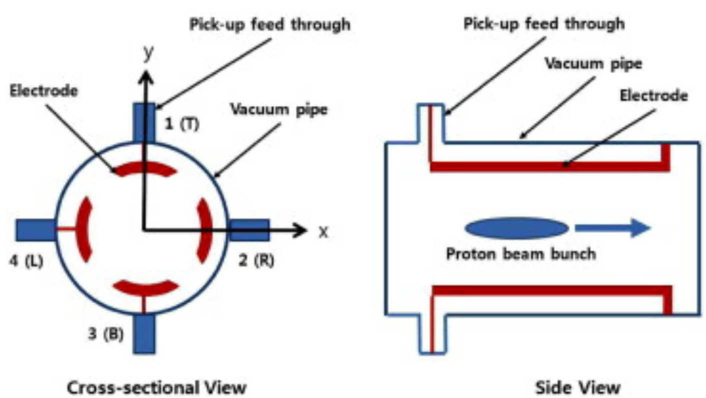
Impedances

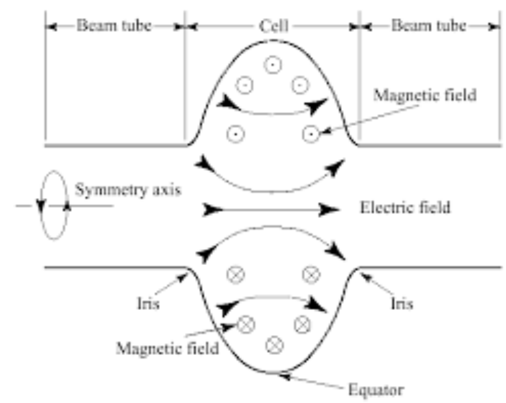
- Any structure that interacts with the beam fields can be treated as an impedance
  - Fortunately many of them are bad (low Q) resonators
    - Wakefields do not persist a long time compared to time between bunches, or even bunch length
    - Damp quickly in residual resistance of conductors
- Examples of impedances that can contain wakefields
  - Beam pipe
  - Bellows

Diagnostics

RF cavities







high Q by design!

Beam Pipe Wakefield

Wakefield only trails behind beam by o(1mm) or a few oscillations.

A pretty low-Q resonator (order of 1!) vs RF cavities (order of 10^6 to 10^{11}!)

Because this is an on-axis charge, this is by definition a *dipole mode* wakefield.

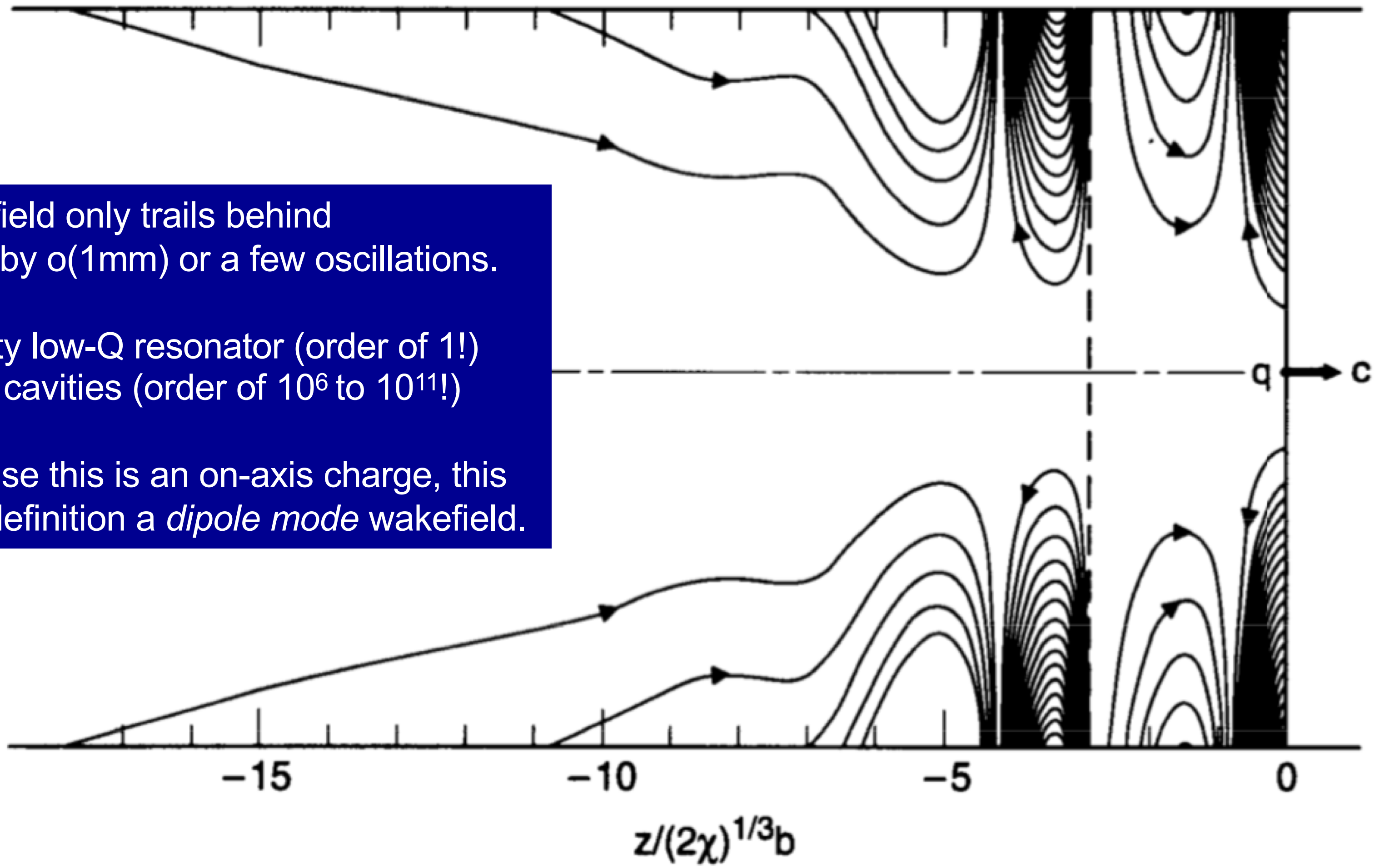


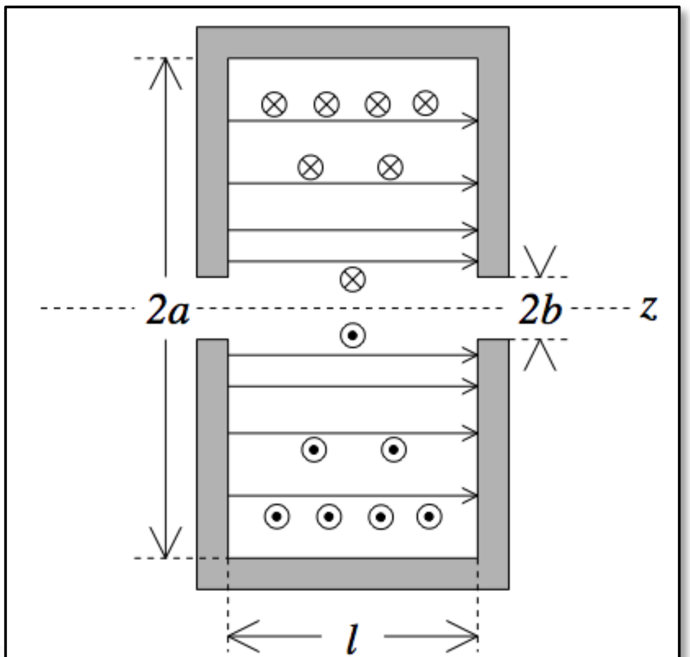
Figure 2.3. Wake electric field lines in a resistive wall pipe generated by a point charge q. The field pattern shows oscillatory behavior in the region $|z| \lesssim 5(2\chi)^{1/3}b$ (or $|z| \lesssim 0.35$ mm for an aluminum pipe with $b = 5$ cm). The field line density to the left of the dashed line has been magnified by a factor of 40. (Courtesy Karl Bane, 1991.)

From Chao textbook: https://www.slac.stanford.edu/~achao/wileybook.html

Review: RF Cavity Modes

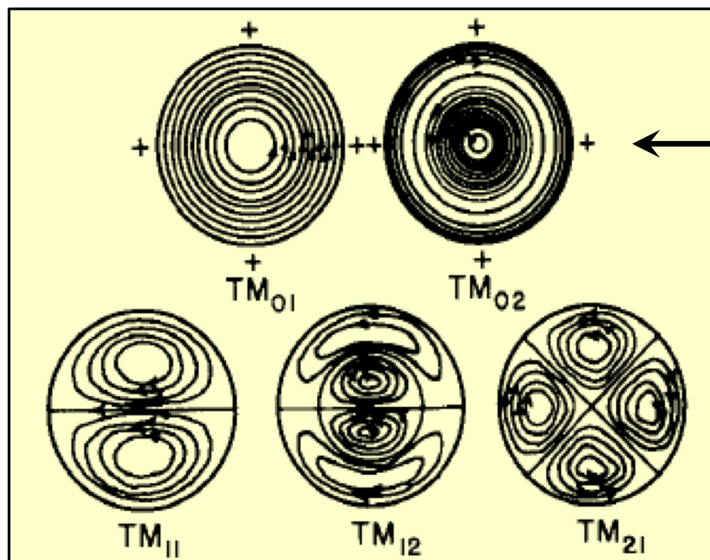
- Currents couple to RF cavity modes through electric field
  - We therefore restrict our discussion to TM_{njl} modes
    - These are the RF modes that have longitudinal electric field

$$E_z(r,\theta,z) \sim J_n(k_c r)(C_1 \cos n\theta + C_2 \sin n\theta) \cos\left(\frac{m\pi z}{l}\right)$$



$$H_z = 0 \text{ everywhere}$$

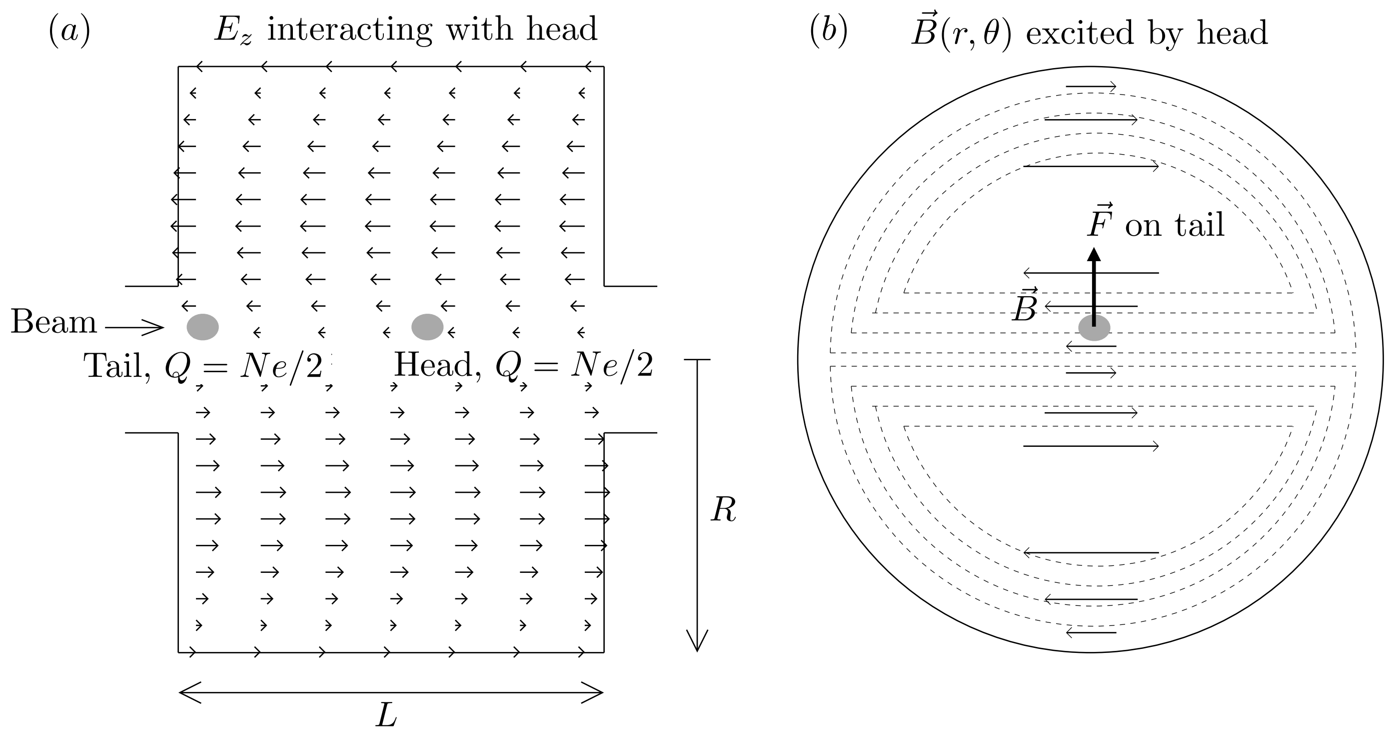
$$J_n(k_c a) = 0 \qquad X_{nj} \text{ is the j}^{\text{th}} \text{ root of } J_n$$

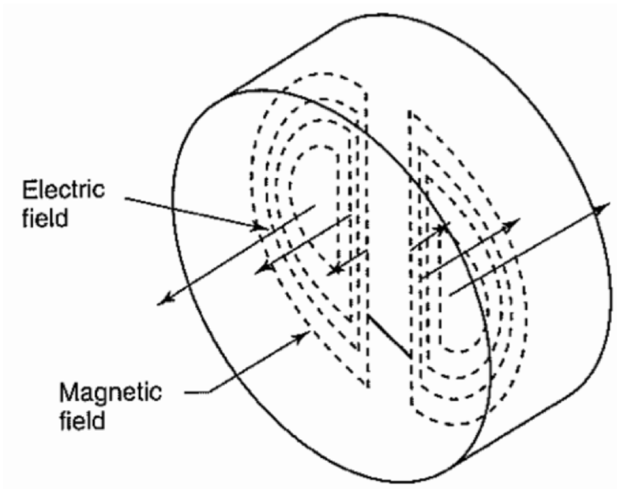


TM_{0j} are only modes with E field on axis. Radial magnetic forces.

Lecture 19

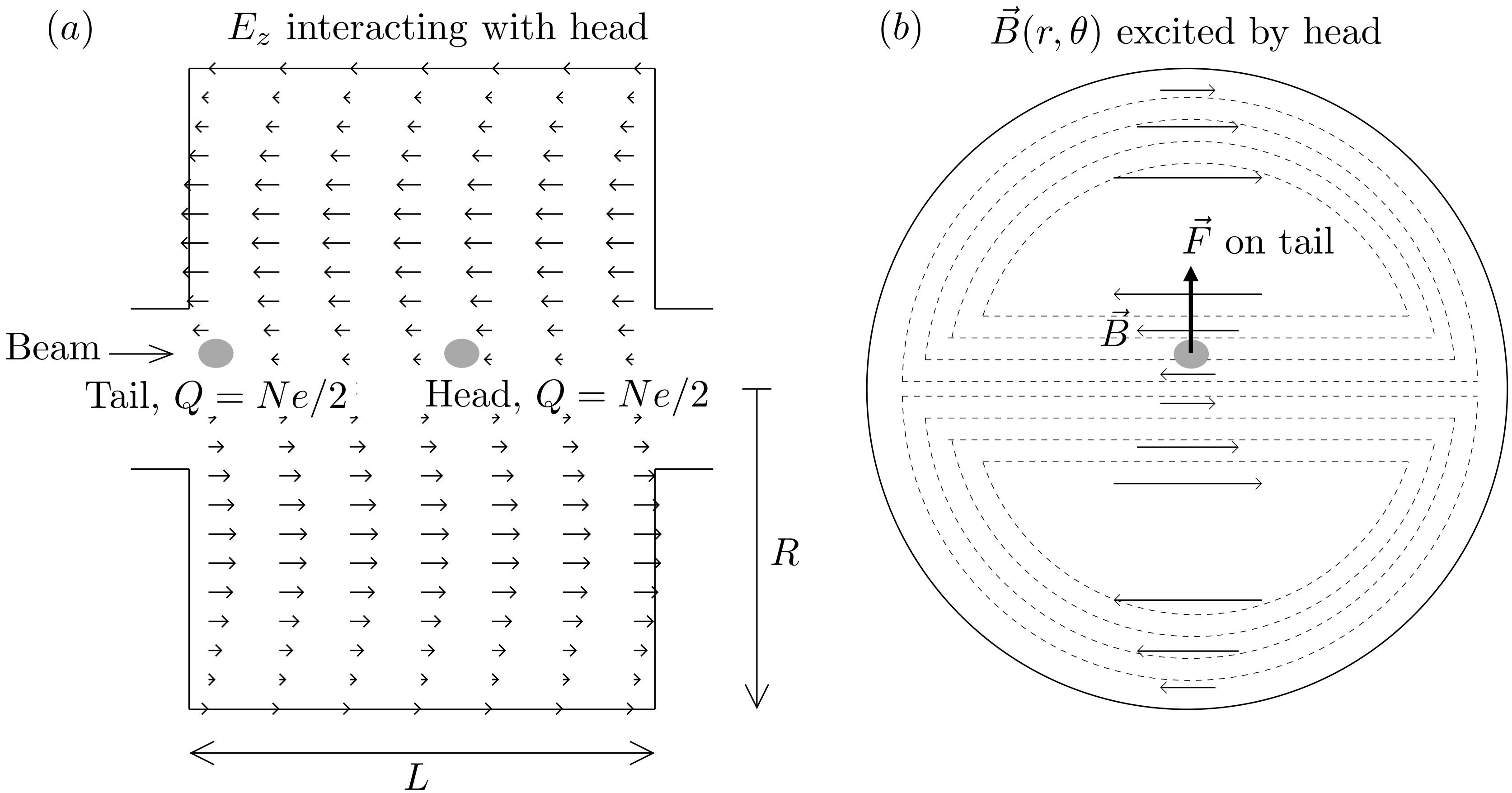
BBU Mechanism: TM110 mode





- Beam breakup RF cavity HOM
  - TM110 mode shown here: illustrates mechanism
- High Q HOM modes are most dangerous
  - Deposited power rings for longer time
  - More chance for unstable feedback loop with later beam

14.5: HOMs, BBU and BNS Damping



- Passing electron bunches can have transverse displacement
  - Interact with HOMs and deposit energy in cavity
  - Later beam at right phases can add energy constructively
  - Eventually field gets large enough to trip beam or trip RF control

Wakefield Formalism

- From Chao, the impulses (integrated forces) from a general order *m* wakefield are given by

$$\int_{-L/2}^{L/2} ds\, \vec{F}_\perp = -eI_m W_m(z) m r^{m-1}(\hat{r}\cos m\theta - \hat{\theta}\sin m\theta),$$

$$\int_{-L/2}^{L/2} ds\, F_\parallel = -eI_m W'_m(z) r^m \cos m\theta, \qquad (2.50)$$

- Here we only consider the first nontrivial transverse force wakefield with *m*=1:

$$\int_{-L/2}^{L/2} ds\, \vec{F}_\perp = -e\, I\, W_1(z)\, \hat{x} = -N\, e^2\, W_1(z)\, \hat{x}$$

- Averaging the integral over one cavity RF period gives

$$\vec{F}_{\perp,\mathrm{ave}} = -\frac{Ne^2}{2L} W_1(z)\, \hat{x}$$

$$F = \frac{dp_x}{dt} = \frac{dp_x}{ds}\frac{ds}{dt} = \frac{dp_x}{ds}\beta c \quad \Rightarrow \quad \frac{dp_x}{ds} = \frac{F}{\beta c}$$

$$x'' = \frac{dx'}{ds} = \frac{d}{ds}\frac{p_x}{p_0} = \frac{dp_x}{ds}\frac{1}{p_0} = \frac{1}{p_0}\frac{F}{\beta c} = \frac{F}{\beta^2\gamma mc^2} \approx \frac{F}{E}$$

14.5: BBU Formalism

$$x_{\text{head}}(s) \;=\; \hat{x}\cos(k_\beta s)$$

Regular betatron motion

Tail betatron motion is a driven harmonic oscillator:

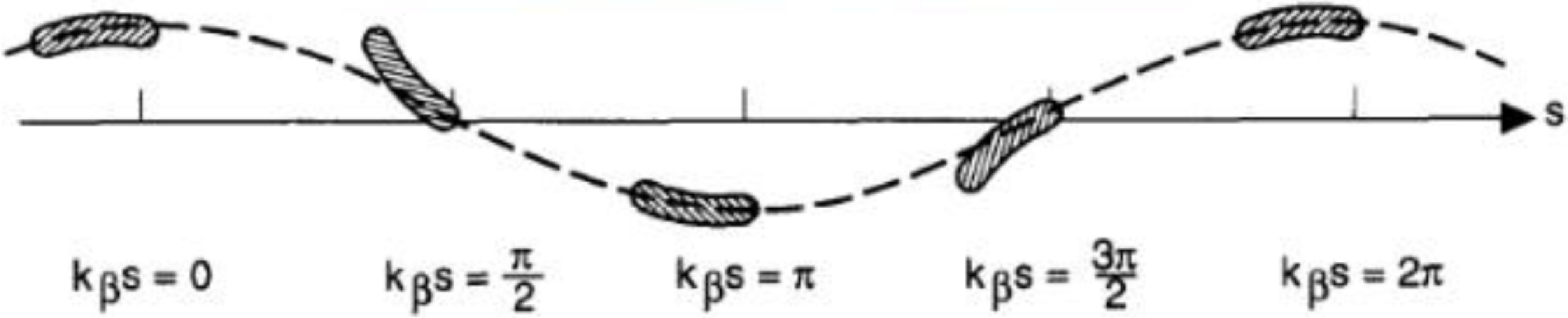
$$x''_{\text{tail}}(s) + k_\beta^2\, x_{\text{tail}}(s) \;=\; -\left(\frac{Ne^2 W_1(z)}{2EL}\right)\hat{x}\cos(k_\beta s) \qquad (14.23)$$

Solution of driven harmonic oscillator:

$$x_{\text{tail}}(s) \;=\; \hat{x}\cos(k_\beta s) - \left(\frac{Ne^2 W_1(z)}{4k_\beta EL}\right) s\,\hat{x}\,\sin(k_\beta s) \qquad (14.24)$$

- The tail sees an additional force from the RF wakefields driven by particles in the front (“head”) of the bunch
  - Solution grows linearly with s coordinate = distance along linac
  - A big problem for long linacs like the SLC
  - Establishes tight tolerance on beam alignment in RF cavities

BBU Illustrated



Tail amplitude grows over traversal of many cavities

From Chao textbook: https://www.slac.stanford.edu/~achao/wileybook.html

14.5: BBU Amelioration via BNS

- Plugging in realistic numbers (e.g. for SLAC linac)
  - Beam centering tolerance in RF cavities smaller than beam size! A tough sell!
- Instead, accelerate beam a little off crest
  - Tail has less energy than head, gets more betatron focusing

$$x''_{\text{tail}}(s) + (k_\beta + \delta k_\beta)^2 \, x_{\text{tail}}(s) \; = \; -\left(\frac{Ne^2 W_1(z)}{2EL}\right) \hat{x} \cos(k_\beta s) \qquad (14.25)$$

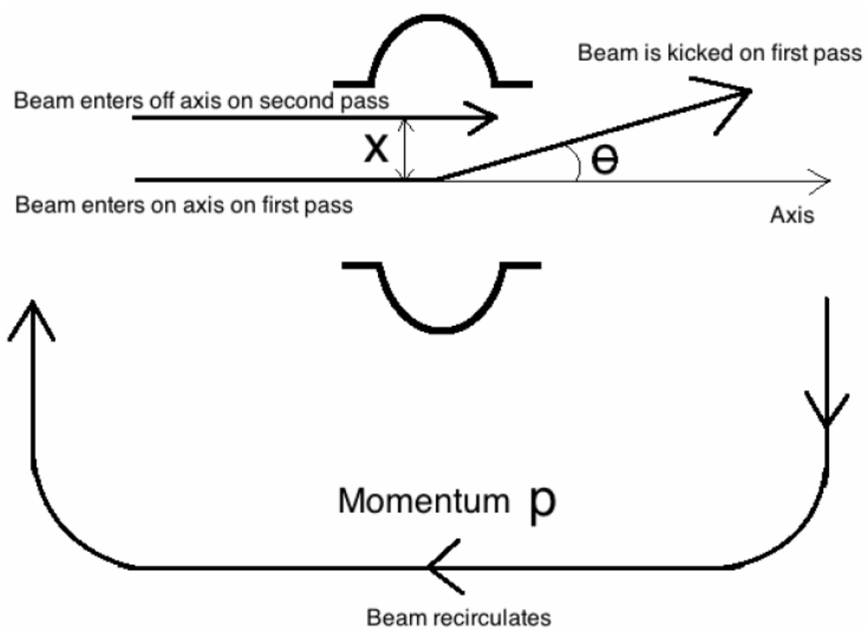
  - This can be safely kept stable if the additional betatron focusing is enough to satisfy the condition

$$\delta k_\beta \; = \; -\frac{Ne^2 W_1(z)}{4\, k_\beta \, EL}$$

  - This is called BNS damping, and it "rescued" the SLC
    http://accelconf.web.cern.ch/AccelConf/p85/PDF/PAC1985_2389.PDF

Regenerative Beam Breakup (BBU)

- Regenerative beam breakup
  - Positive feedback loop between beam power and higher order mode RF power
  - Couples through beam transport
  - Many RF higher order modes communicate with beam, each other in near-exponential complexity
  - Limits total beam current



Ilkyoung Shin dissertation

Regenerative BBU

- The threshold current for horizontal regenerative beam breakup is

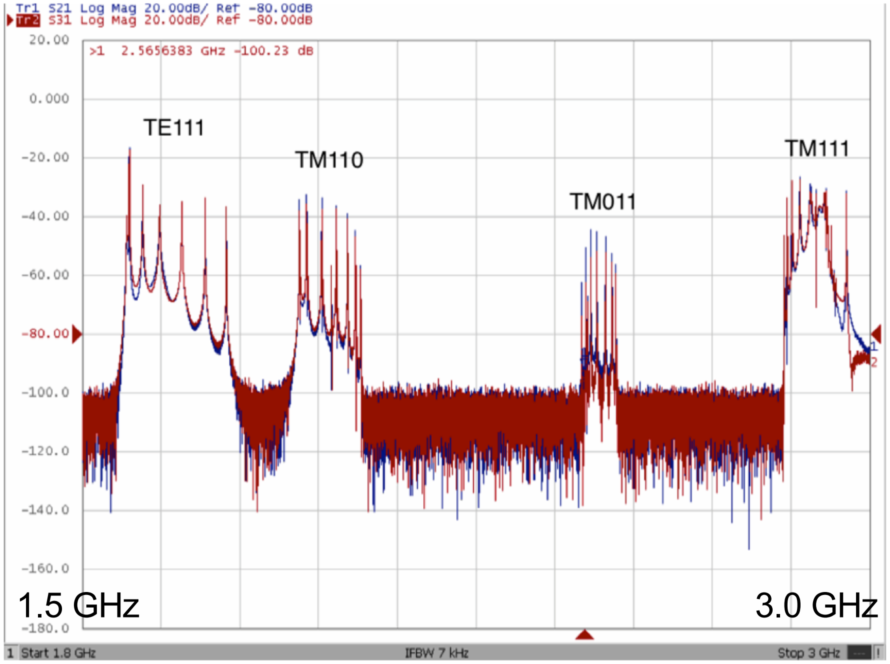
$$I_{\text{th}} \;=\; -\frac{2Ec}{e\omega\,(R/Q)Q\;M_{12}\,\sin(\omega T)} \tag{14.28}$$

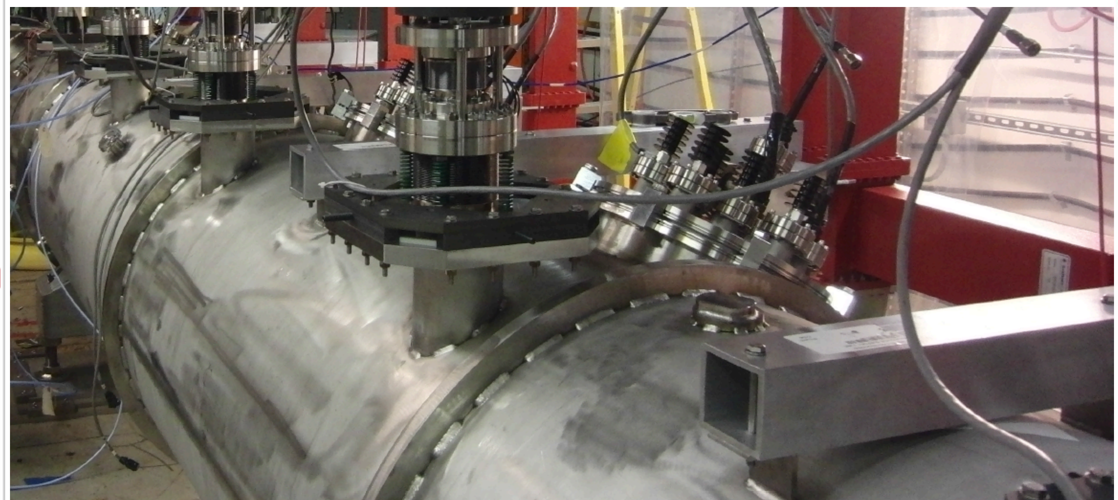
where E is the total beam energy, ω is the HOM frequency, Q and (R/Q) are properties of the HOM, M_{12} is the recirculation beam transport matrix element, and T is the recirculation time [45]. Instability is only possible if

$$M_{12}\,\sin(\omega T) \;<\; 0 \tag{14.29}$$

Otherwise the feedback loop damps the HOM, and the beam is predicted to remain stable at all currents. Regenerative BBU can be avoided for some HOMs by careful control of M_{12}. However, $\omega T \gg 1$ in realistic systems so stability cannot be assured for all HOMs.

BBU Measurements: C100 Warm HOM Loads





- C100 HOM, BBU experiment: Ilkyoung Shin's PhD thesis
- Surveyed HOMs using warm coupler ports in CMTF, tunnel
  - With and without beam loading, varying recirculation optics
- Based on techniques described in Chris Tennant's thesis
- HOM power and BBU measurements are accessible
- Can we drive BBU instability in ER@CEBAF with existing beam?