# Lecture 5: Photoinjector Technology

J. Rosenzweig
UCLA Dept. of Physics & Astronomy

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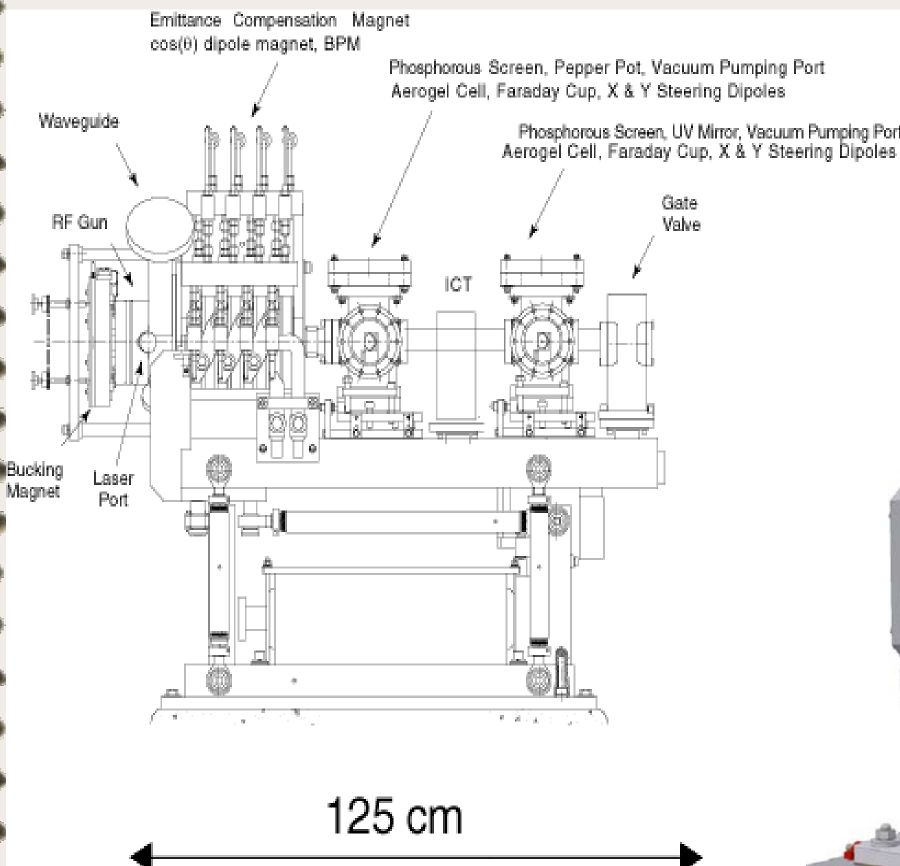
# Technologies

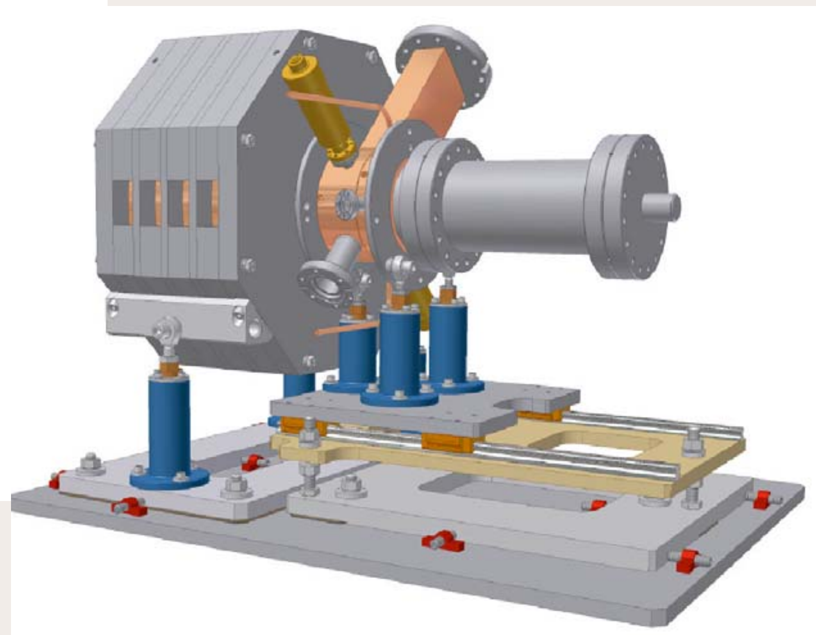
- Magnetostatic devices
  - Computational modeling
  - Map generation
- RF cavities
  - 2 cell devices
  - Multicell devices
  - Computational modeling: map generation
- Short pulse lasers
- Diagnosis of electron beams

# The photoinjector layout

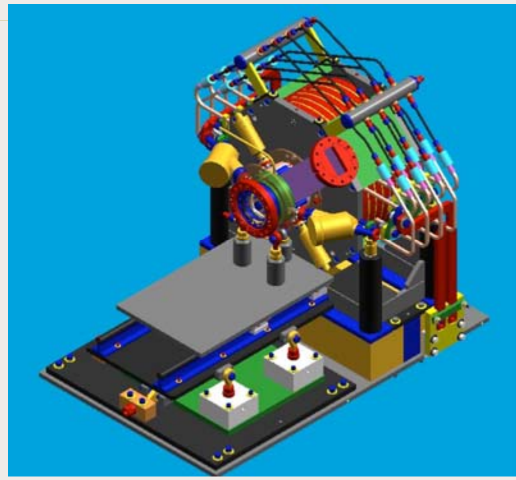



ORION gun side view

SPARC gun and solenoid

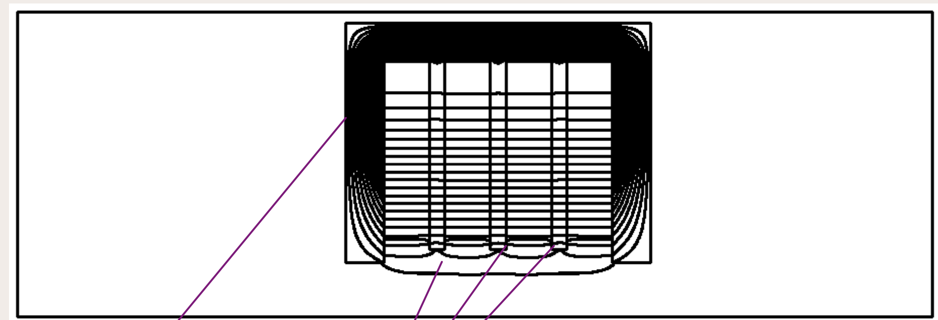


# Solenoid Design



ORION design has all coils in series

SPARC design has four independent coils

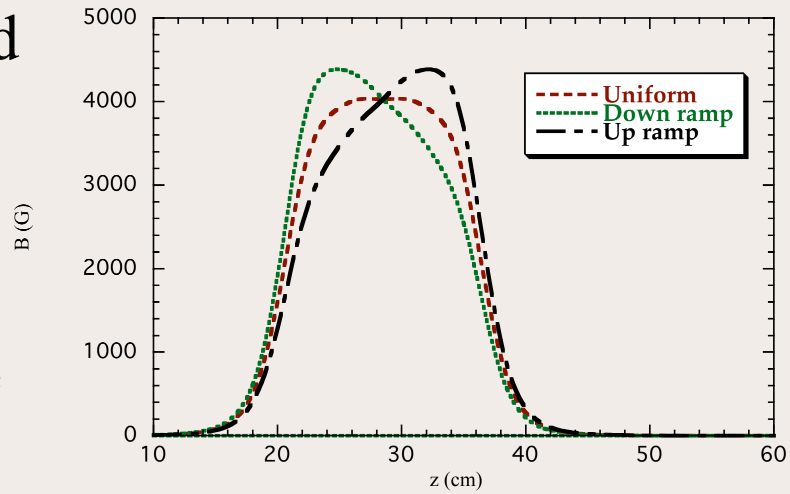


- Electromagnet with iron yoke and field stiffeners/dividers
- Iron acts as magnetic equipotential.
- Use of magnetic circuit analogy for dipole gives field strength

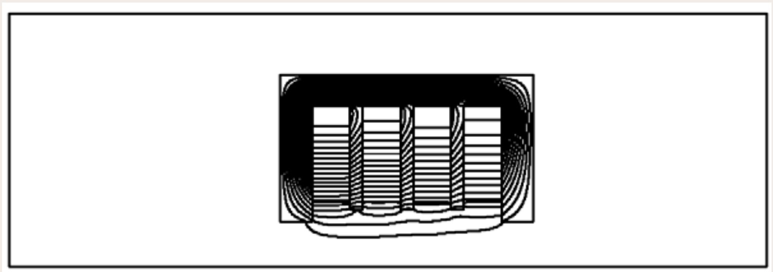
$$\oint \vec{H} \bullet d\vec{l} = I_{enc} \longrightarrow \frac{B_0}{\mu_0} L_{sol} + \frac{1}{\mu} \int_{Fe} \vec{B} \bullet d\vec{l} = I_{enc} \longrightarrow B_0 \cong \mu_0 NI / L_{sol}$$

# Solenoid field tuning

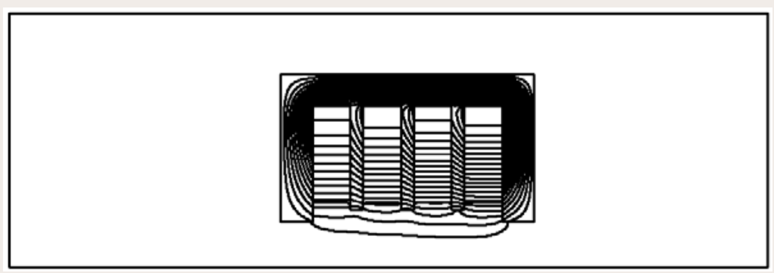
- No motion of heavy solenoid
- Uniform field possible
- Tune centroid of emittance compensation lens by asymmetric excitation of the four coils
- Simulation indicates 8 G field at cathode.




Maps available for HOMDYN

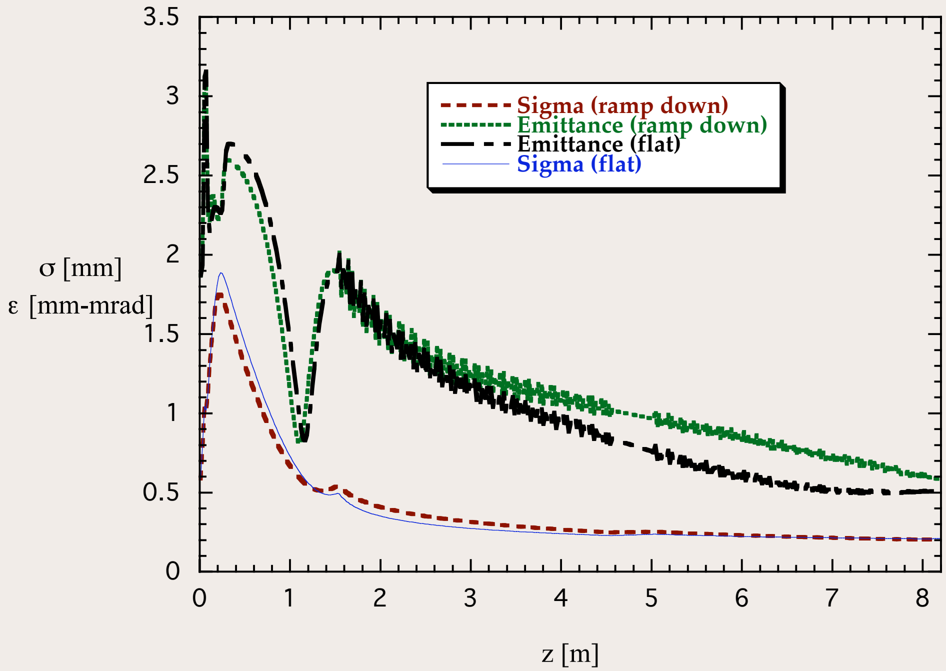


Ramp up field



Ramp down field

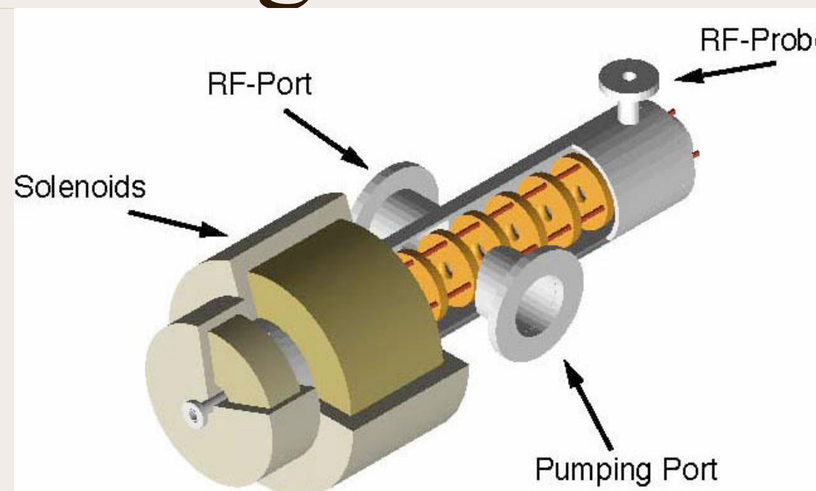
# Effect of solenoid tuning on beam dynamics

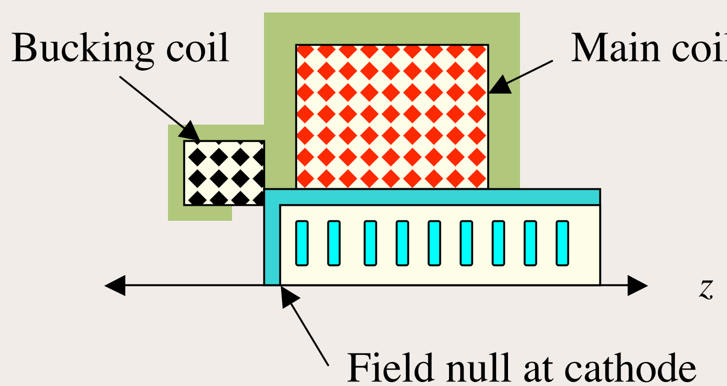



- Beam dynamics studied with HOMDYN
- SPARC/LCLS design surprisingly robust, may be fine-tuned using this method

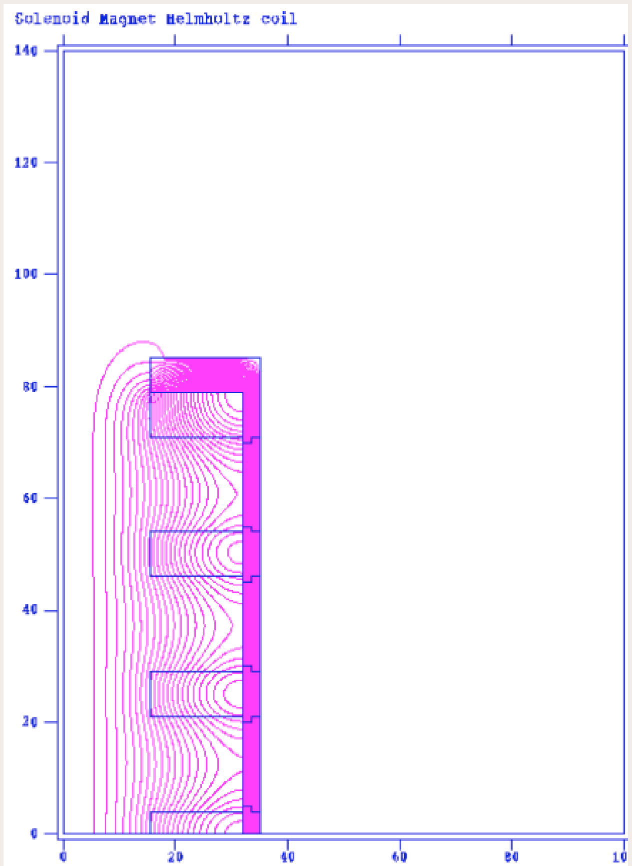
# Other emittance compensation solenoid designs

- Lower gradients are possible for integrated photoinjectors
- Lower magnetic focusing fields as well
- Fields closer to the cathode for beam control
- “Bucking” coil needed
- Example: PEGASUS PWT injector



# Other solenoids: linac emittance compensation




SPARC linac solenoid,
From LANL POISSON

- In TW linac, second order RF focusing is not strong

$\eta = 1$ (pure SW),

$\eta = 0$ (pure TW), $\eta = 0.4$ (SLAC TW)

- Generalize focusing in envelope equation

$$\eta \Rightarrow \eta + 2b^2, \quad b = cB_0 / E_0$$

- Example: for 20 MV/m TW linac,

$$\text{for } b^2 = 1, \; B_0 = 1.1 \text{ kG}$$

# Some practical considerations

- Power dissipation limited. Limit is roughly 700 A/cm$^2$ in Cu

$$\frac{dP}{dV} = \frac{J^2}{\sigma_c} \approx 1 \text{ W/cm}^3 \qquad \left(\sigma_c = 5.8\times10^5 \ (\Omega\cdot\text{cm})^{-1}\right)$$

- Yoke saturation: avoid fields above 1 T in the iron

$$\Phi = \iint_{pole} \vec{B}\bullet d\vec{A} \qquad A_{Fe} >> A_{pole}\frac{B_{pole}}{B_{sat}}$$

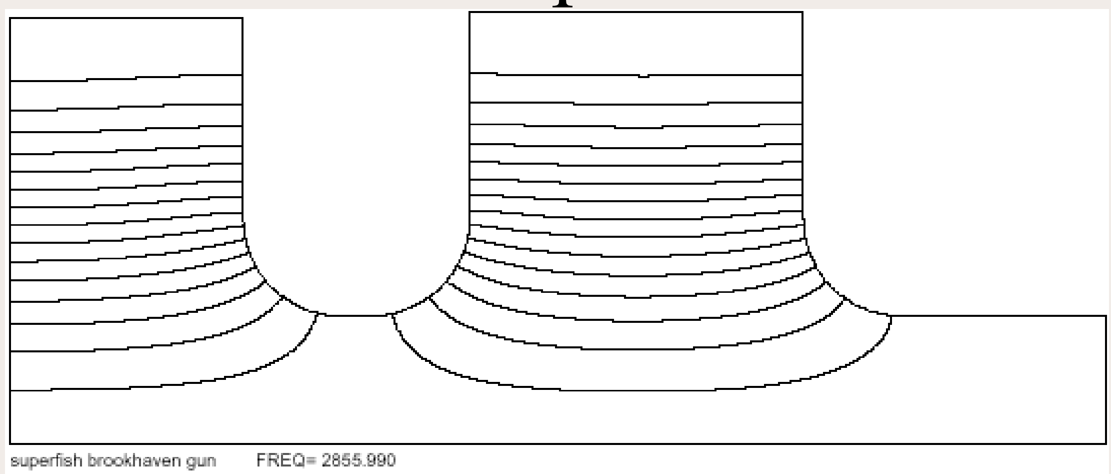
# RF structures

- Photoinjectors are based on high gradient standing wave devices
- Need to understand:
  - Cavity resonances
  - Coupled cavity systems
  - Power dissipation
  - External coupling
- Simple 2-cell systems to much more elaborate devices…

UCLA photocathode gun with cathode plate remove

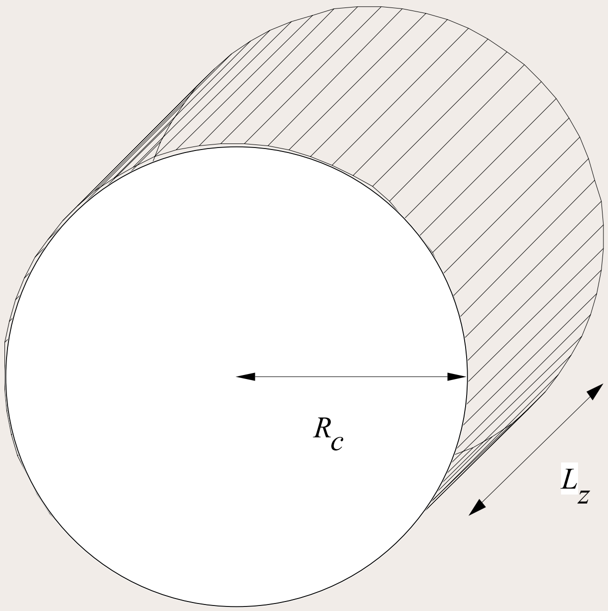
# The “standard” rf gun

- Concentrate on simplest case




- π-mode, full (λ/2) cell with 0.6 cathode cell
- Start with model

# Cavity resonances




- Pill-box model approximates cylindrical cavities
- Resonances from Helmholtz equation analysis

$$\left[\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial}{\partial\rho}\right) - k_{z,n}^2 + \frac{\omega^2}{c^2}\right]\tilde{R} = 0$$

No longitudinal dependence in fundamental $\omega_{0,1} \cong \dfrac{2.405c}{R_c}$

- Fields:

$$E_z(\rho) = E_0 J_0\left(k_{\rho,0}\rho\right)$$

$$H_\phi(\rho) = \frac{\omega\varepsilon_0}{k_{\rho,0}} E_0 J_1\left(k_{\rho,0}\rho\right) = c\varepsilon_0 E_0 J_1\left(k_{\rho,0}\rho\right)$$

- Stored energy

$$U_{EM} = \tfrac{1}{4}\varepsilon_0 L_z E_0^2 \int_0^{R_C} \left[J_0^2\left(k_{\rho,0}\rho\right) + J_1^2\left(k_{\rho,0}\rho\right)\right]\rho\, d\rho$$

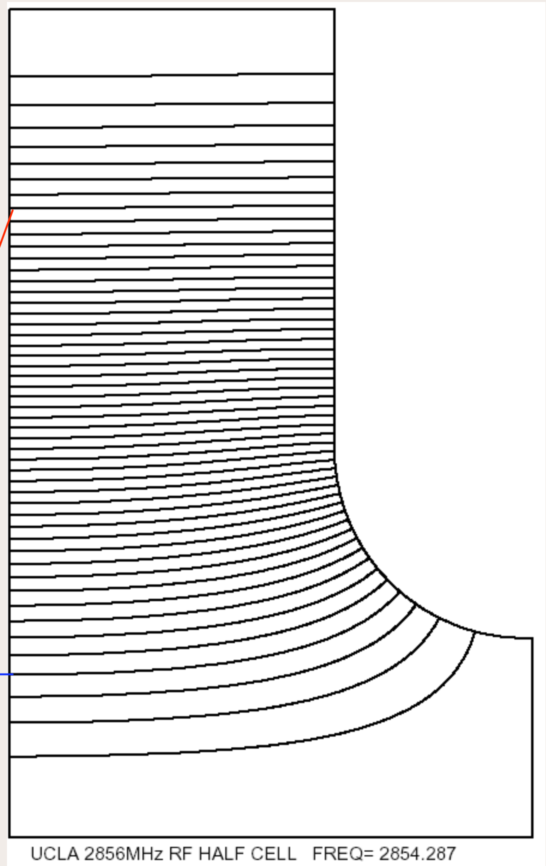
$$= \tfrac{1}{2}\varepsilon_0 L_z E_0^2 R_c^2 J_1^2\left(k_{\rho,0}R_C\right)$$

# A circuit-model view

- Lumped circuit elements may be assigned: *L*, *C*, and *R*.
- Resonant frequency

$$\omega \cong \frac{1}{\sqrt{LC}}$$

- Tuning by changing inductance, capacitance
- Power dissipation by surface current (*H*)




Contours of constant flux in 0.6 cell of gun

# Cavity shape and fields

- Fields near axis (in iris region) may be better represented by spatial harmonics

$$E_z(\rho,z,t) = E_0 \,\mathrm{Im} \sum_{n=-\infty}^{\infty} a_n \exp\left[i\left(k_{n,z} z - \omega t\right)\right] I_0\left[k_{\rho,n}\rho\right] \qquad k_{\rho,n} = \sqrt{k_{n,z}^2 - \left(\omega / c\right)^2}$$

- Higher (no speed of light) harmonics have nonlinear (modified Bessel function) dependence on $\rho$.
  - Energy spread
  - Nonlinear transverse RF forces
- Avoid re-entrant nose-cones, etc.

# Power dissipation and $Q$

- Power is lost in a narrow layer (skin-depth) of the wall by surface current excitation

$$\frac{dP}{dA} = -\frac{K_s^2}{4\delta_s\sigma_c} = -\frac{K_s^2}{4}\sqrt{\frac{\omega\mu_0}{2\sigma_c}} = -\frac{K_s^2}{2}R_s,$$

$$R_s \equiv \frac{1}{2}\sqrt{\frac{\omega\mu_0}{2\sigma_c}}$$ Surface resistivity

$$K_s = \left|\vec{H}_{\parallel}\right| = \mu_0\left|\vec{B}_{\parallel}\right|$$ Surface current

- Total power

$$\langle P\rangle = \pi R_s\left(c\varepsilon_0E_0\right)^2\left[R_cL_zJ_1^2\left(k_{\rho,0}R_c\right) + 2\int_0^{R_c} J_1^2\left(k_{\rho,0}\rho\right)\rho d\rho\right]$$

$$= \pi R_s\left(c\varepsilon_0E_0\right)^2 R_cJ_1^2\left(k_{\rho,0}R_c\right)\left[L_z + R_c\right]$$

- Internal quality factor

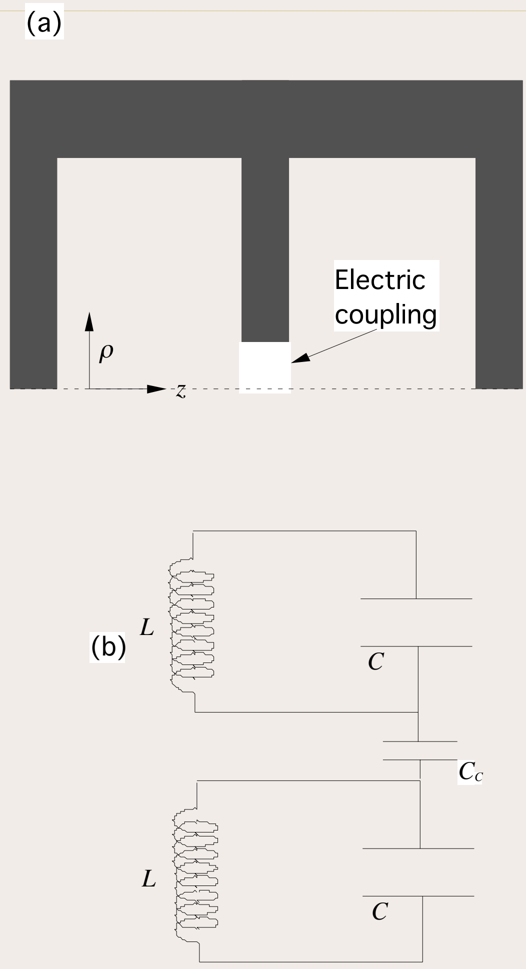
$$Q \equiv \frac{\omega U_{EM}}{\langle P\rangle} = \frac{Z_0}{2R_s}\frac{2.405L_z}{\left(R_c + L_z\right)}$$

$$Z_0 = 377\Omega$$

- Other useful interpretations of $Q$

$$Q = \omega\tau_f = \frac{\omega}{\Delta\omega_{1/2}} = \frac{L}{R}$$

# Cavity coupling




- Circuit model allows simple derivation of mode frequencies

$$\frac{d^2 I_1}{dt^2} + \omega_0^2 (1-\kappa_c) I_1 = -\kappa_c \omega_0^2 I_2$$
$$\frac{d^2 I_2}{dt^2} + \omega_0^2 (1-\kappa_c) I_2 = -\kappa_c \omega_0^2 I_1$$

- Solve eigenvalue problem

$$\omega = \omega_0 \text{ (0 - mode) and } \omega = \omega_0 \sqrt{1+2\kappa_c} \text{ } (\pi \text{ - mode})$$

- Mode separation is important

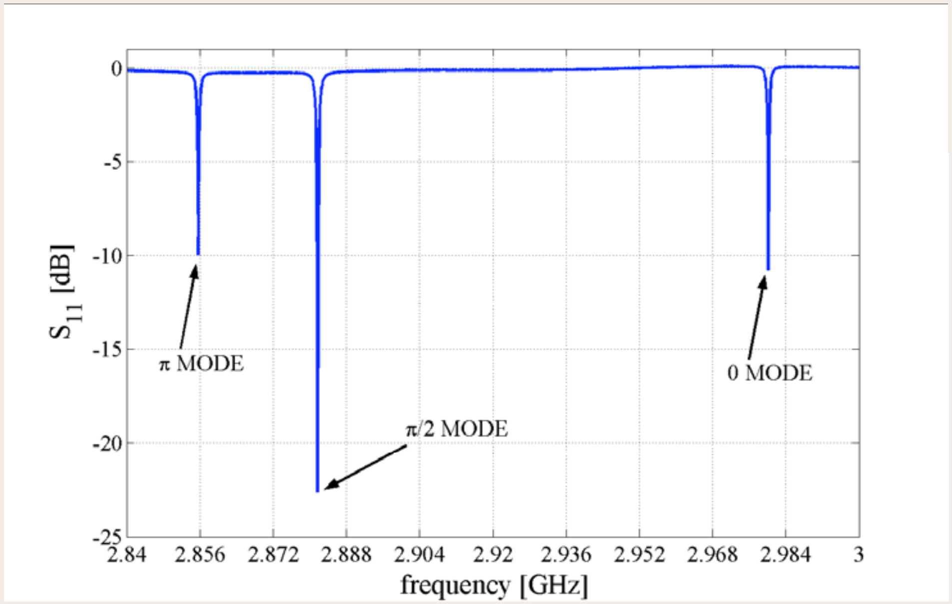
$$\Delta\omega \approx \kappa_c >> \omega_0 / Q$$

- In 1.6 cell gun

$$\Delta f = 3.3 \text{ MHz}, \; f_\pi = 2856 \text{ MHz}, \; Q = 12{,}000$$

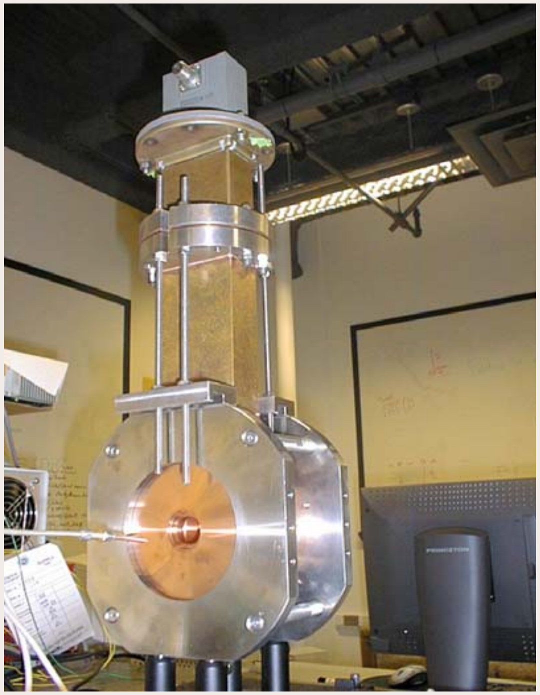
# Measurement of frequencies

- Frequency response can be measured on a network analyzer
- Resonance frequencies of individual cells and coupled modes
- Tuning via Slater's theorem guide $\frac{\delta\omega_0}{\omega_0} = \frac{\delta V_c}{U_{EM}}\left[\frac{1}{2}\varepsilon_0\vec{E}^2 - \frac{1}{2}\mu_0\vec{H}^2\right]$

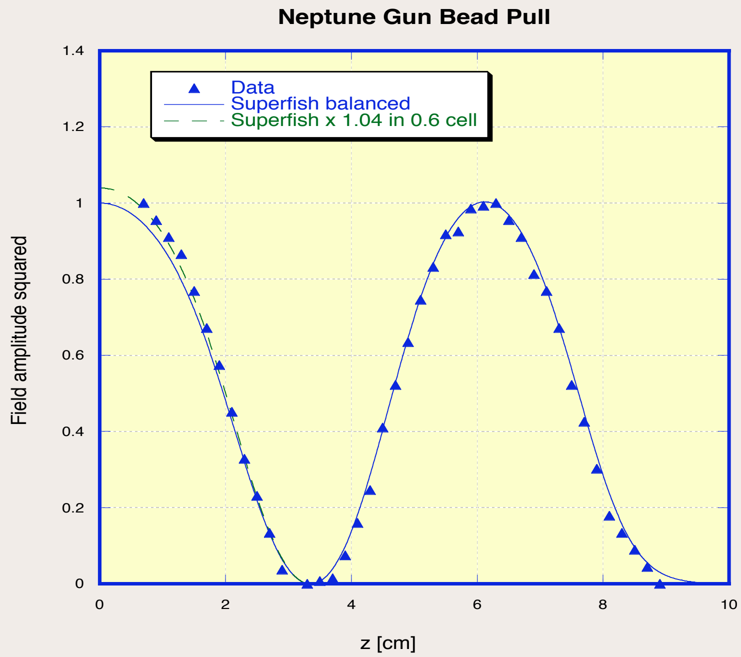



Reflection measurement $S_{11}$
(5-cell deflection mode cavity)

Width of resonances measures Q.



# Measurement of fields

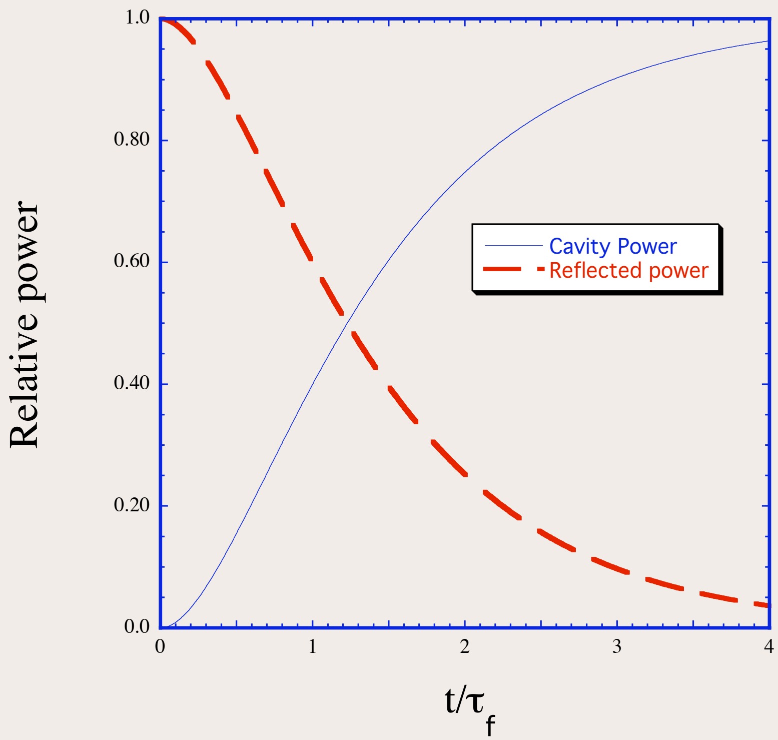



- Use so-called “bead-pull” technique
- Metallic of dielectric bead (on optical fiber)
- Metallic bead on-axis gives negative frequency shift (electric field energy displaced)

$$|E_z| \propto \sqrt{-\delta\omega}$$

- More complex if one has magnetic fields (deflector)

# Temporal response of the cavity




- Standing wave cavity fills exponentially

  $$E \propto 1 - \exp(-\omega / 2Q)$$

- Gradual matching of reflected and radiate power ($E^2$) from input coupler
- In steady-state, all power goes into cavity (critical coupling)
- Ideal *VSWR* is 1 (no beam loading)

# Reading references

- Magnets: Chapter 6, section 2
- RF cavities: Chapter 7, sections 2-8