SRF Cavities for High Current ERLs

Rama Calaga

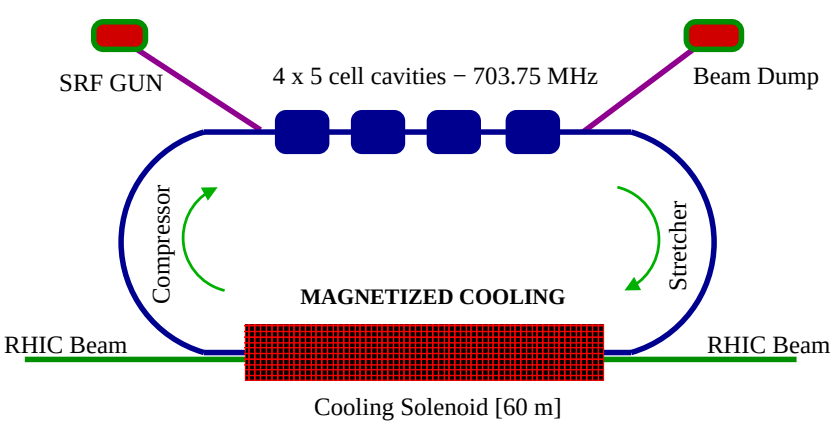
Brookhaven National Lab

January 23, 2006

ecooling@RHIC

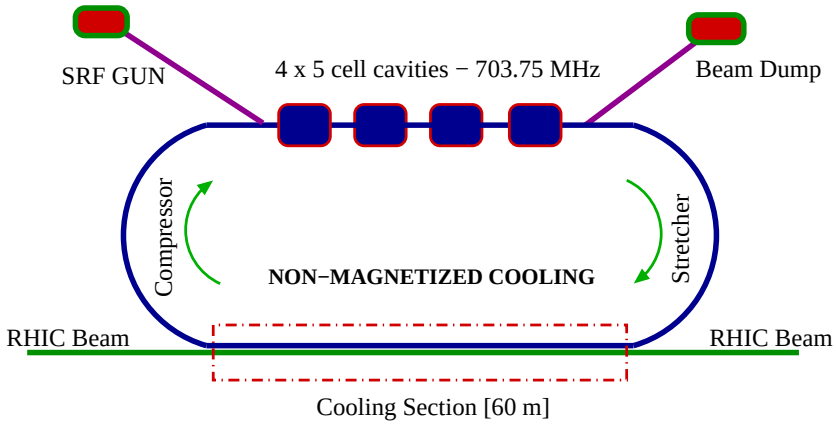
- Cooling Au beams at 100 GeV requires $\sim$ 54 MeV e^-
- $\frac{dCooling}{dt} \propto \gamma^{\frac{5}{2}}$
- Low $\epsilon_{x/y/z}$, High Current, and High Bunch Charge
- Replenish e^- every cycle - energy recovery linac

Previous Version



Average Current - 200 mA
Bunch Charge - 20 nC

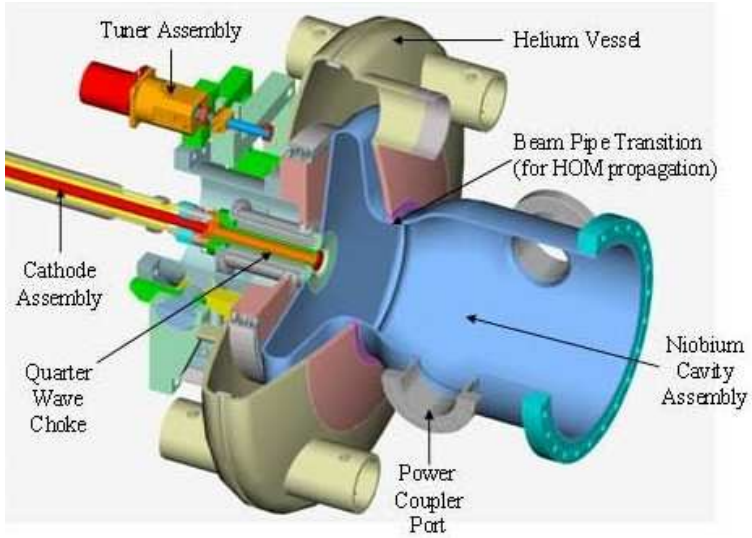
Current Version



Average Current - 50 mA
Bunch Charge - 5 nC

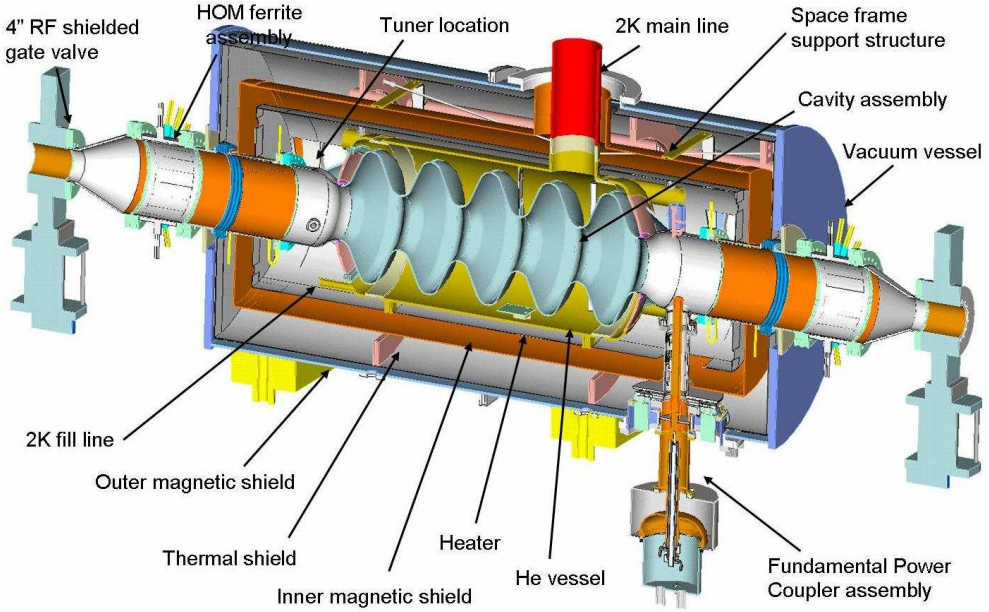
Outline

SRF Injector



- Generation of ampere class CW beam
- Low $\epsilon_{x/y}$ & $\delta E/E$
- Strong Coupling $Q_{ext} \sim 10^4$
- HOMs & Stability Criteria
- Cathode Issues and Isolation

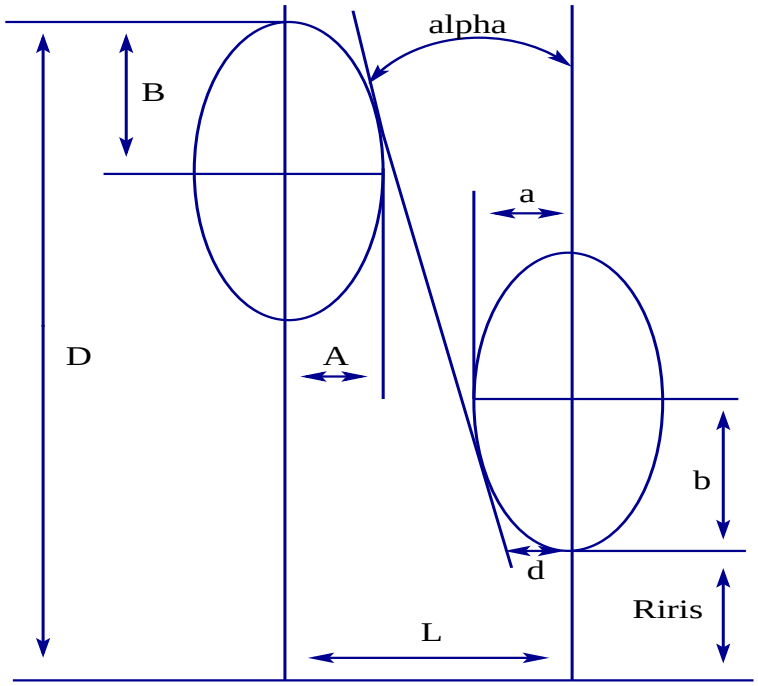
SRF Cavity



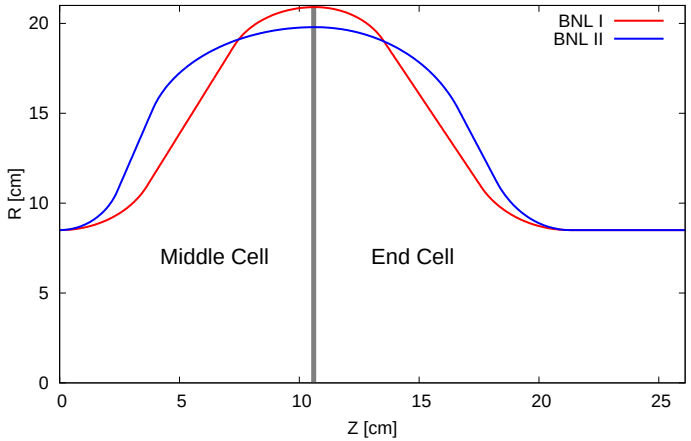
- Ampere Class LINAC
- HOM Power & Damping
- BBU (state-of-the-art)
- High Q_{ext} $\Rightarrow$ Lorentz force detuning & microphonics
- Q_0 & Gradient

Cavity Design & Fabrication

Cavity Design Criteria



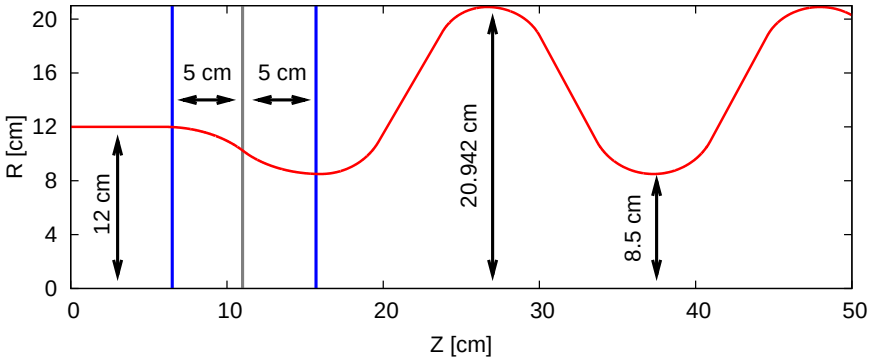
Iris Radius, R_{iris}	8.5 [cm]
Wall Angle, α	25 [deg]
Equatorial Ellipse, $R = \frac{B}{A}$	1.0
Iris Ellipse, $r = \frac{b}{a}$	1.1
Cav. wall to iris plane, d	2.5 [cm]
Half Cell Length, $L = \frac{\lambda\beta}{4}$	10.65 [cm]
$H = D - (R_{iris} + b + B)$	4.195 [cm]
Cavity Beta, $\beta = \frac{v}{c}$	1.0

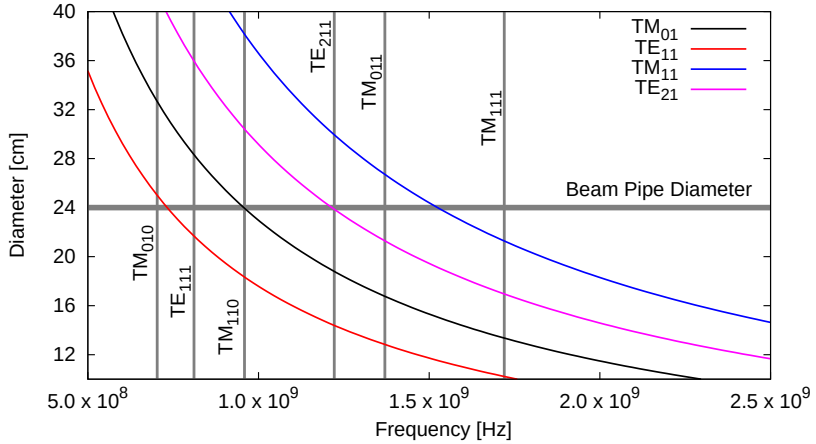


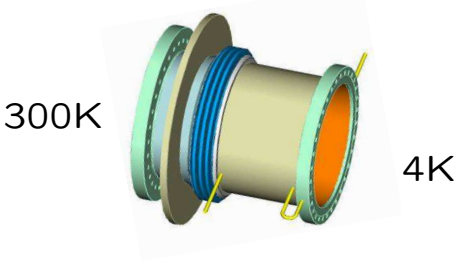
- Freq: 703.75 MHz
  - 25^{th} harmonic of RHIC
  - Lower Loss Factor ($k_{||}$, $k_{\perp}$)
  - CW power sources
  - Chemical treatment
- Five Cells
  - Fewer trapped modes
  - Field sensitivity factor: $\frac{N^2}{k_{cc}}$

Beam Pipe Transition

- Damping HOMs
  - **Enlarged BP (KEK, BNL, CORNELL)**
  - Flutes (CORNELL)
  - Loop couplers (TESLA, CEBAF)
- Minimize fundamental leakage ($< 10\ W$).
- Minimize FPC kick
  - Enlarged BP (KEK, BNL)
  - Symm. couplers (CORNELL)
- Cold to warm transition (Counter Flow of He)

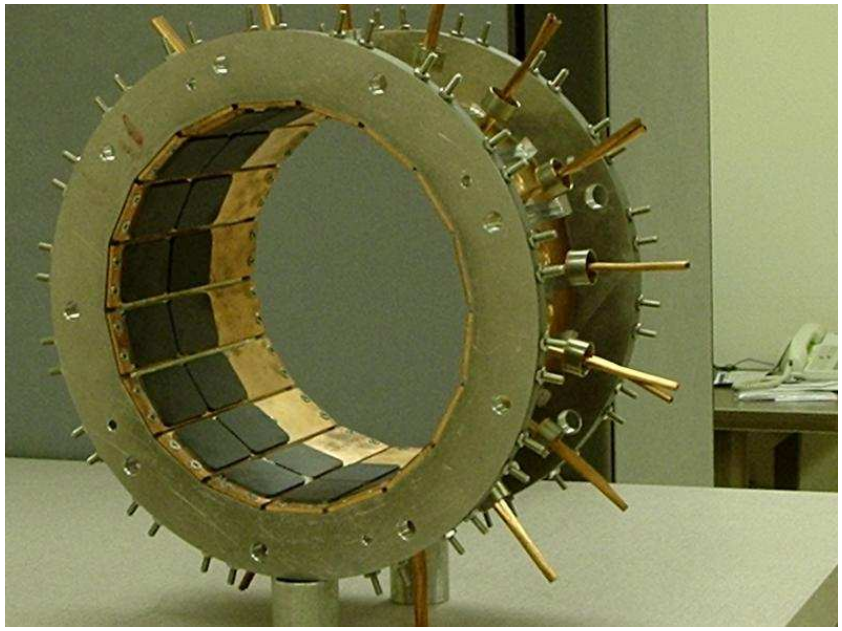




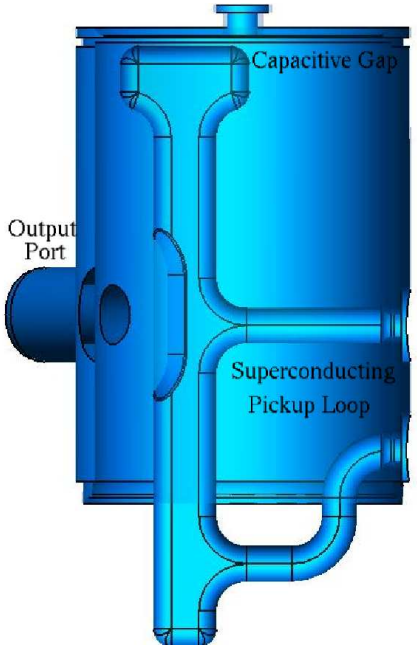


HOM Extraction & Damping

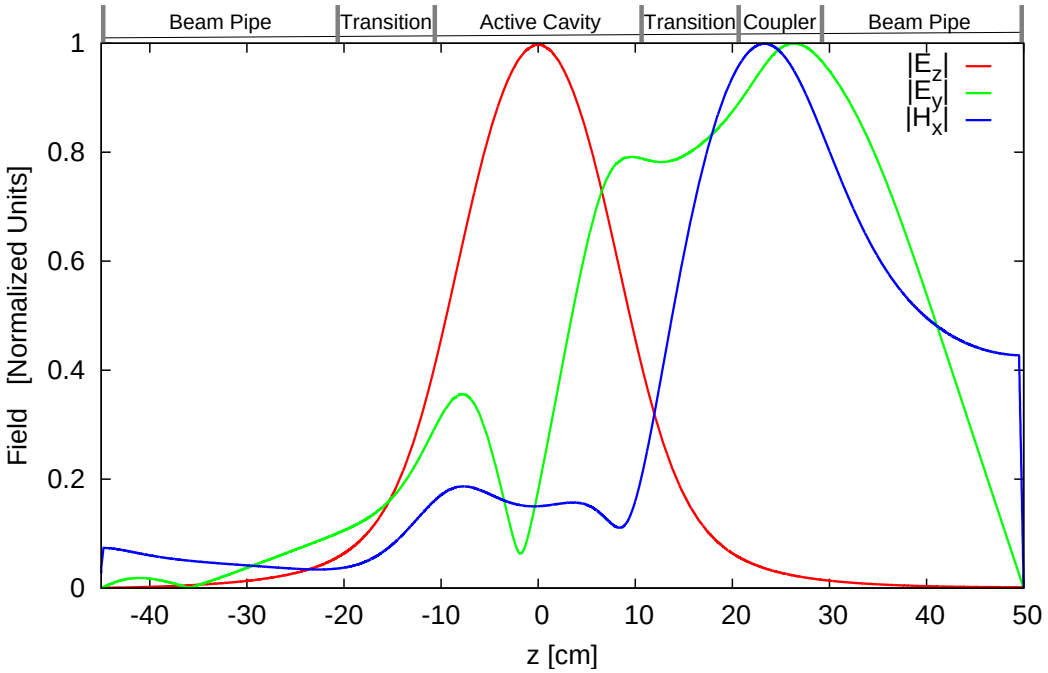
Ferrite Absorbers
Broadband (300 K)



Loop Couplers
Resonant Ciruit (2 K)



Coupler Kick



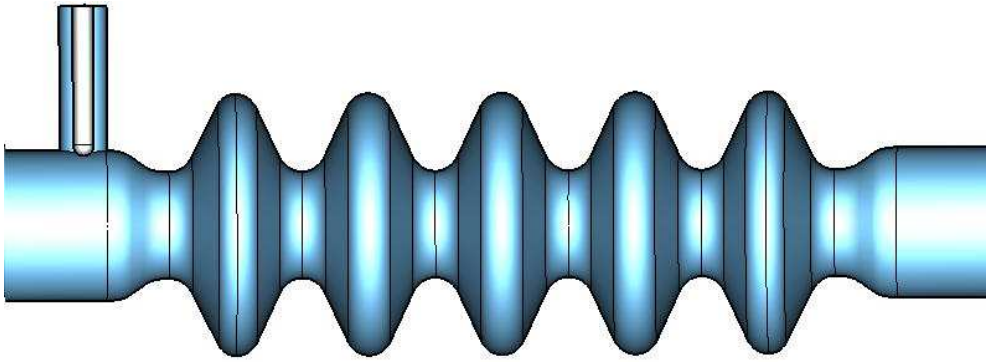
$$\delta_t = \frac{\int (E_y + cB_x)dz}{\int E_z dz}$$

	δ_t	Kick
Single Coupler	$(0.3 - 1.2i)\times 10^{-3}$	$\approx$ 0.27 mrad
Symmetric Couplers	$(5.3 - 8.7i)\times 10^{-5}\ mm^{-1}$	$\approx$ 48 μrad

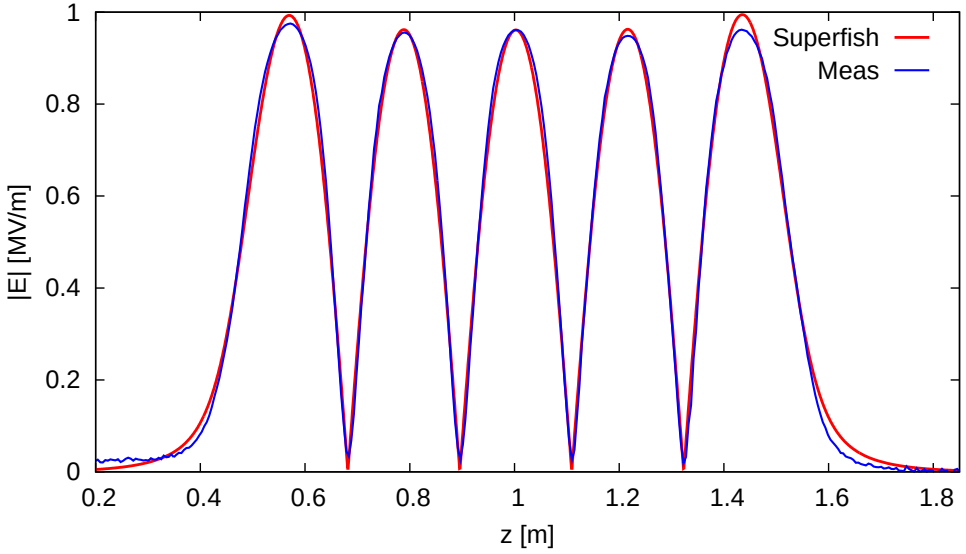
BNL High Current Cavity

Main Parameters:

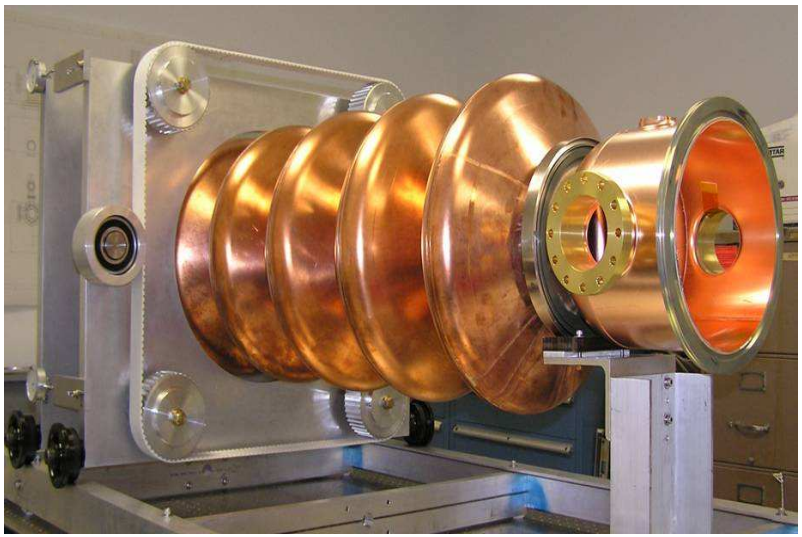
Frequency	703.75 [MHz]
RHIC Harmonic	25
Number of cells	5
Active cavity length	1.52 [m]
Iris Diameter	17 [cm]
Beam Pipe Diameter	24 [cm]
G (Ω)	225
R/Q	403.5 [Ω]
Q BCS @ 2K	4.5×10^{10}
Q_{ext}	3×10^{6}
E_p/E_a	1.97
H_p/E_a	5.78 [$mT/MV/m$]
cell to cell coupling	3%
Sensitivity Factor ($\frac{N^2}{\beta}$)	833
Field Flatness	96.5 %
Lorentz Detuning Coeff	1.2 [Hz/MV/m]
Lowest Mech. Resonance	96 [MHz]
$k_{\|\|}$ ($\sigma_z - 1cm$)	1.1 [V/pC]
$k_{\perp}$ ($\sigma_z - 1cm$)	3.1 [V/pC/m]
HOM Power (10-20 nC)	0.5-2.3 [kW]

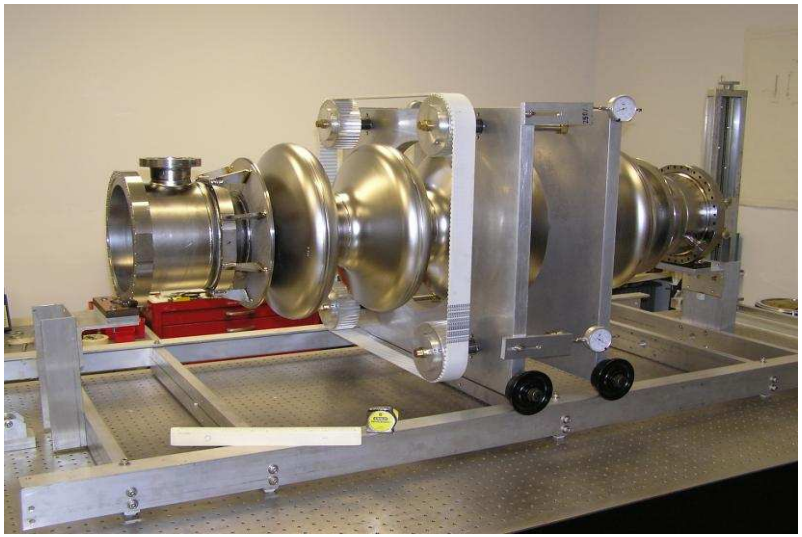


Field Flatness



Cu Prototype & Nb Cavity



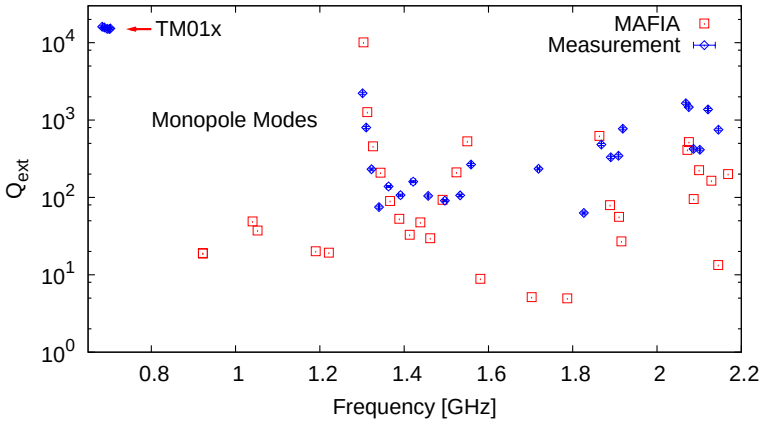


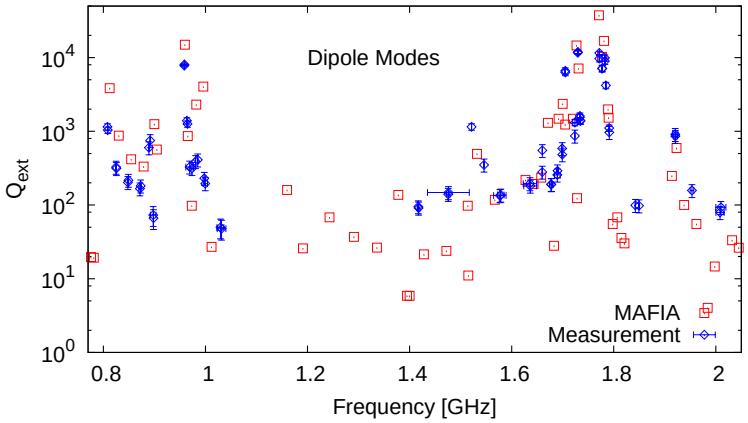
- Two Cu prototypes fabricated
- Measurement of fundamental and higher order modes completed
- Measurement of 2^{nd} cavity for statistics under progress
- Superstructure transition section to be developed and tested

- The cavity, BCP tooling and HPR system fabricated
- To be shipped to JLAB Jan 26^{th}, 2006
- Back to BNL May 18^{th}, 2006
- Cryostat assembly and cold testing BNL in Sept. 2006

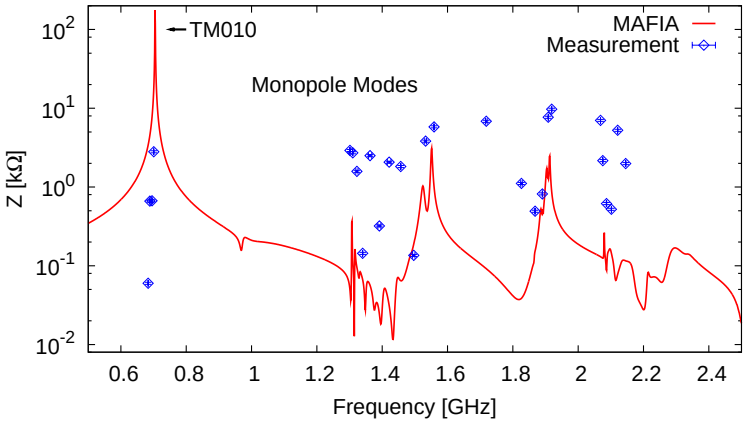
HOMs: Simulation & Measurements

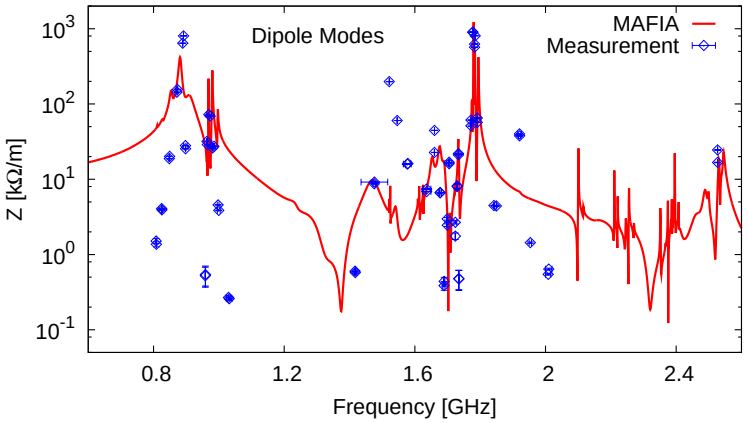
Frequency Domain





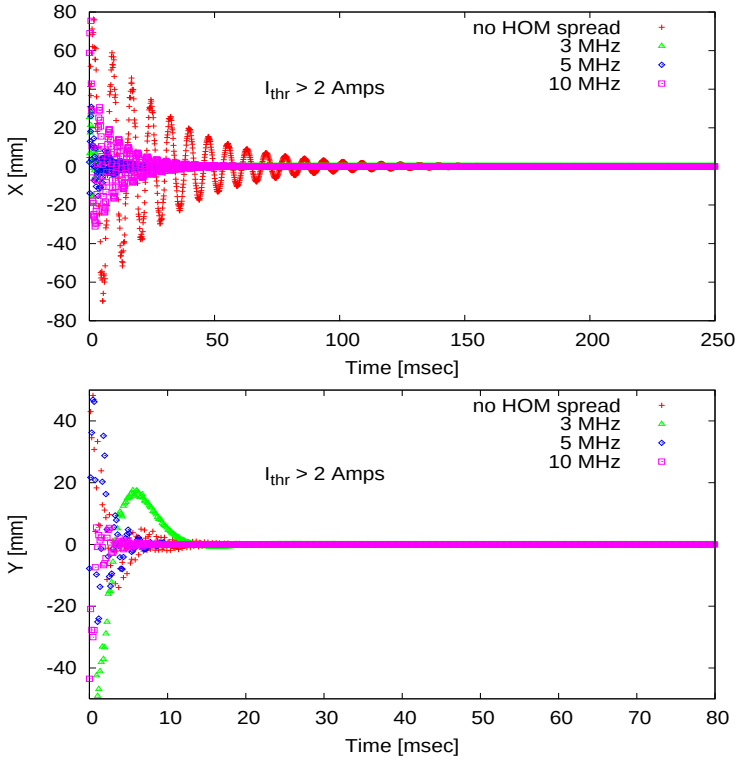
Time Domain



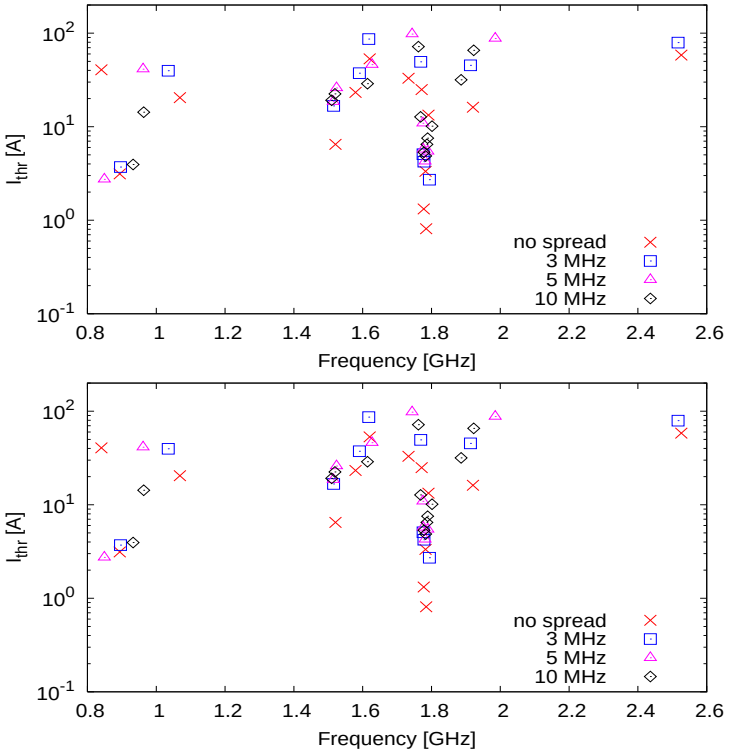


Multibunch Beam BreakUp

TDBBU



MATBBU



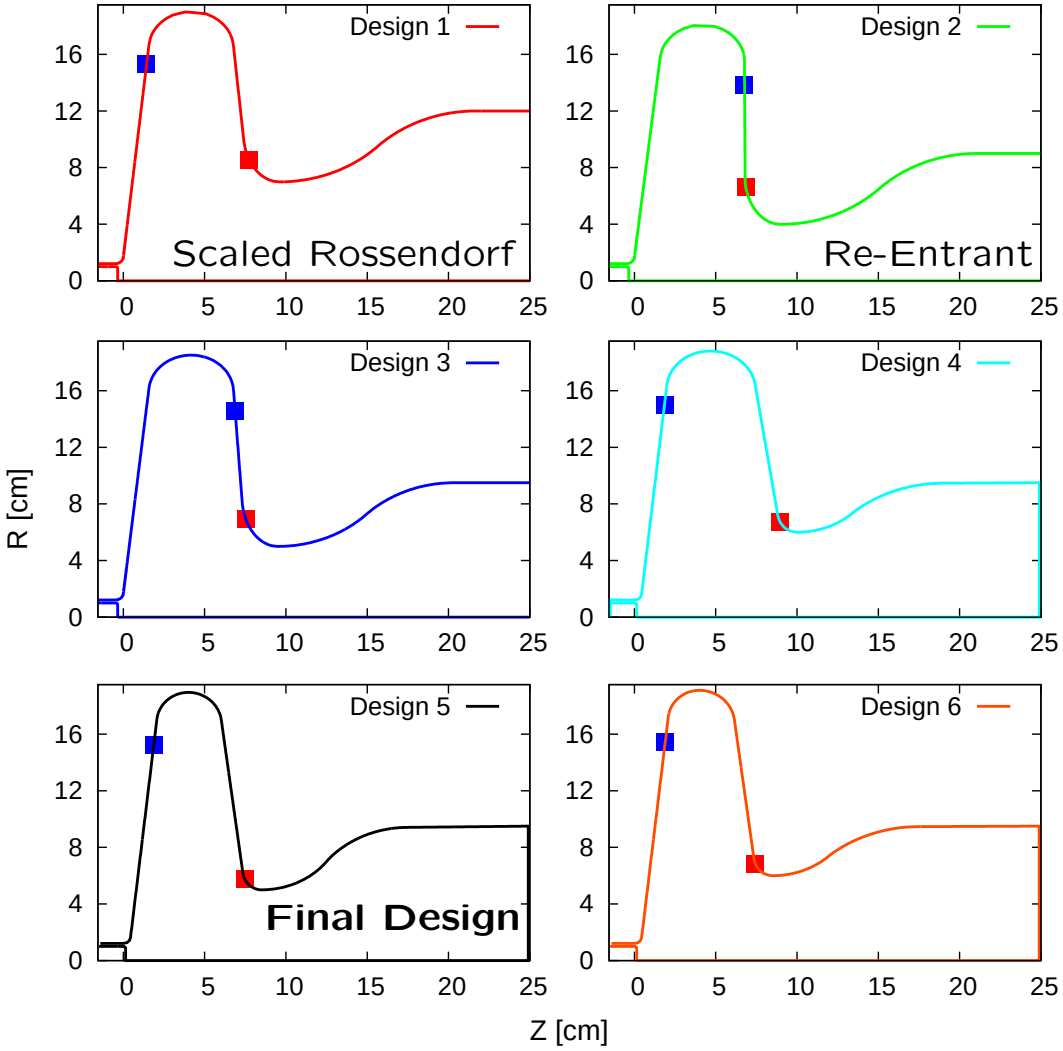
Threshold Current > 2 Amps

BNL eCooling Configuration - 4 Cavities - 54 MeV

(Numerical Codes from JLAB)

BNL 1/2 Cell Gun
ERL Prototype

SRF Gun Design

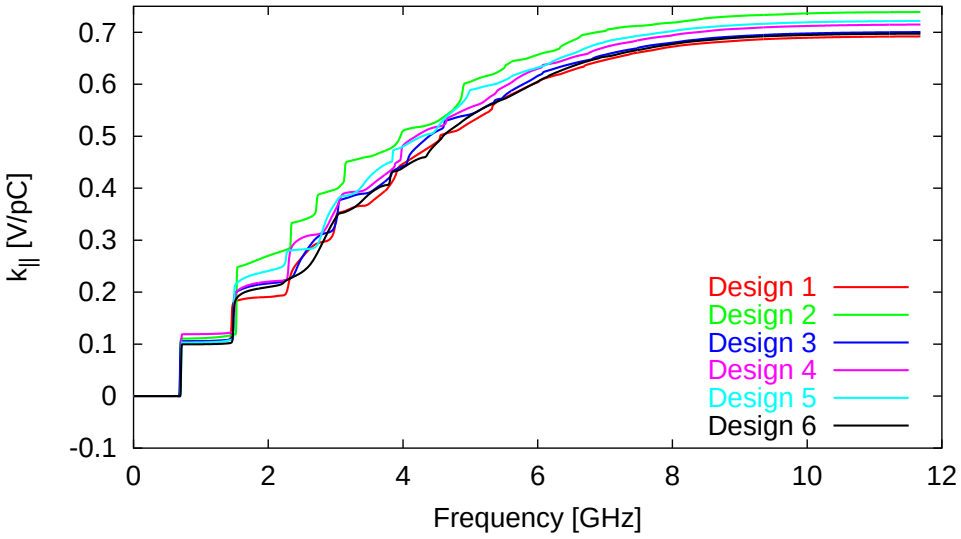


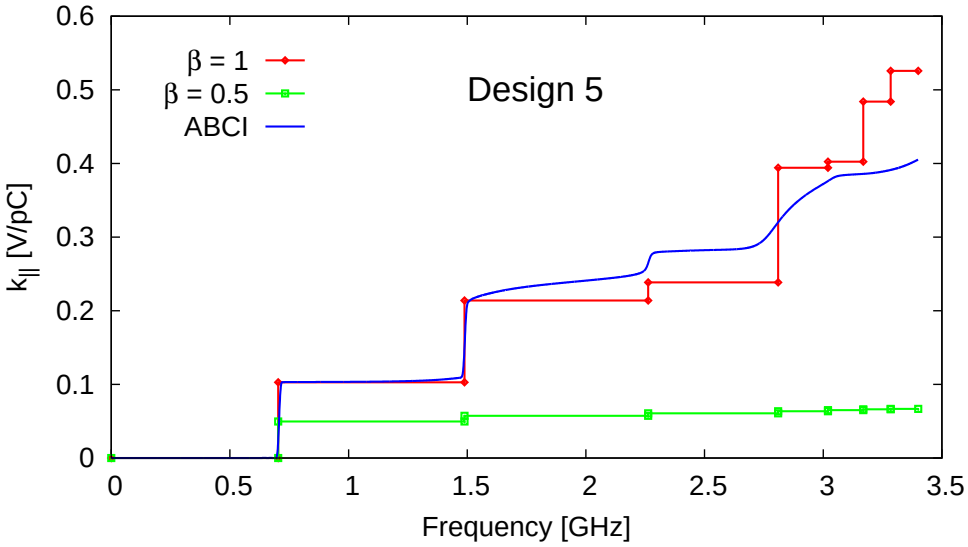
Some Comparisons

Shape	r/Q [Ω]	E_p/E_a	B_p/E_a $[\frac{mT}{(MV/m)}]$
Design 1	101	1.14	2.73
Design 2	105	1.39	2.97
Design 3	103	1.20	2.81
Design 4	112	1.33	2.69
Design 5	**95**	**1.42**	**2.96**
Design 6	92	1.42	2.87

Design 5	**Right Cell**
Frequency	703.75 MHz
Iris Radius, R_{iris}	5.0 cm
Wall Angle, α	6.5°
Equatorial Ellipse, $R = \frac{B}{A}$	1.1
Iris Ellipse, $r = \frac{b}{a}$	1.2
Cav. wall to iris plane,	1.0 cm
Active cavity Length, L	8.5 cm
Center to equator end	18.95 cm
Avg. Beta, $< \beta = \frac{v}{c} >$	0.587

Average HOM Losses





$$P_{HOM} = k_{||} Q_b I_b$$

For $\beta = 1$:

$$k_{||} = \frac{1}{\pi} \int_0^\infty ReZ_{||}(\omega) d\omega$$

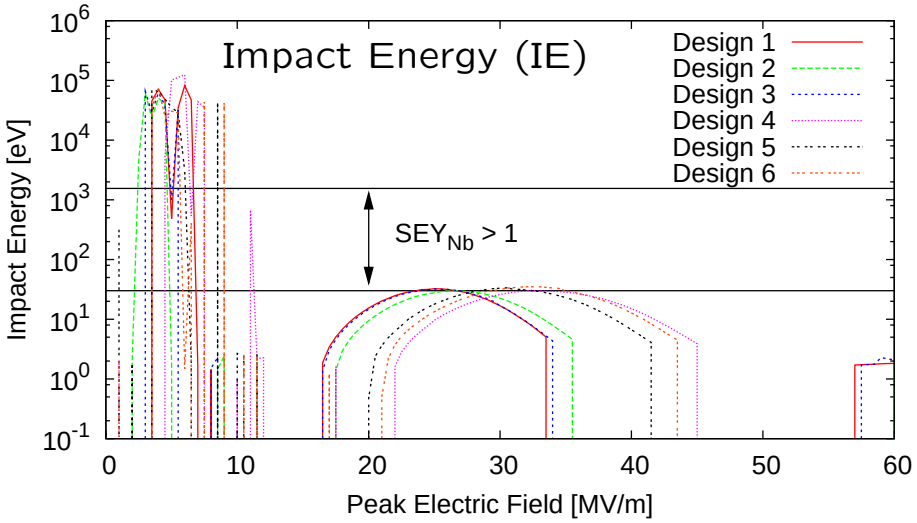
For $\beta < 1$:

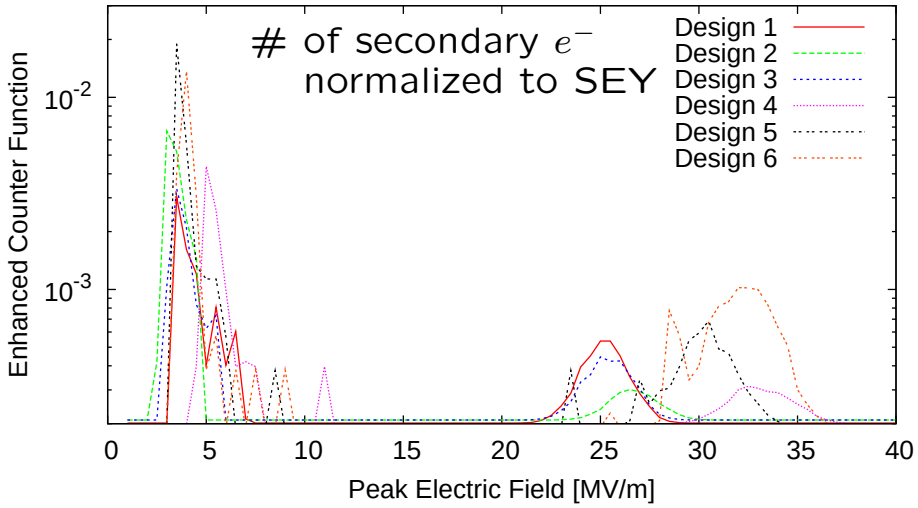
$$k(\beta, \sigma) = \sum_{n=1}^{n} \frac{\omega R_s(\beta)}{2Q_n} \; e^{-(\frac{\omega\sigma}{\beta c})^2}$$

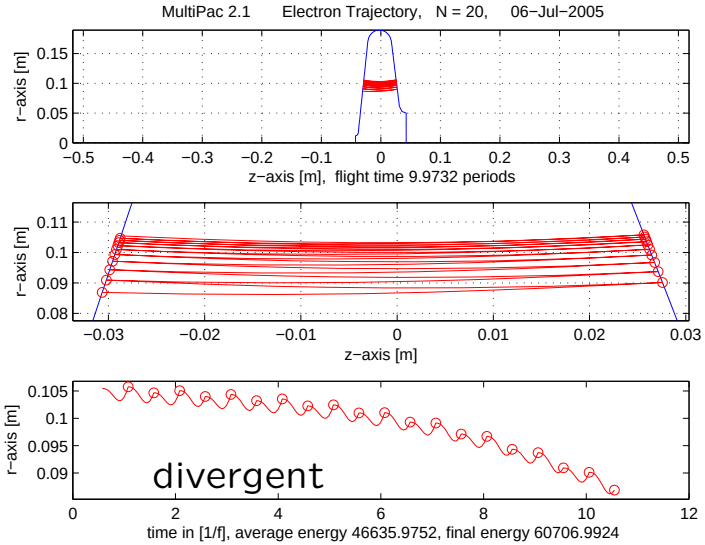
Avg. Power $\sim$ 175 W

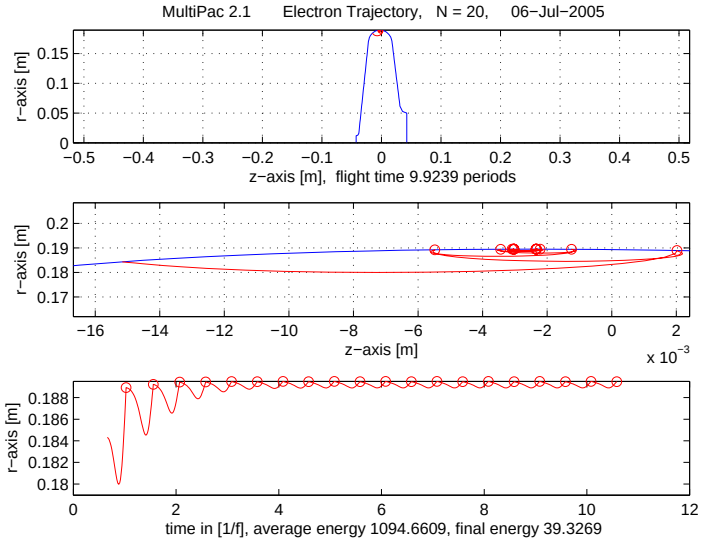
($Q_b = 5$ nC, $I_b = 50$ mA)

Multipacting



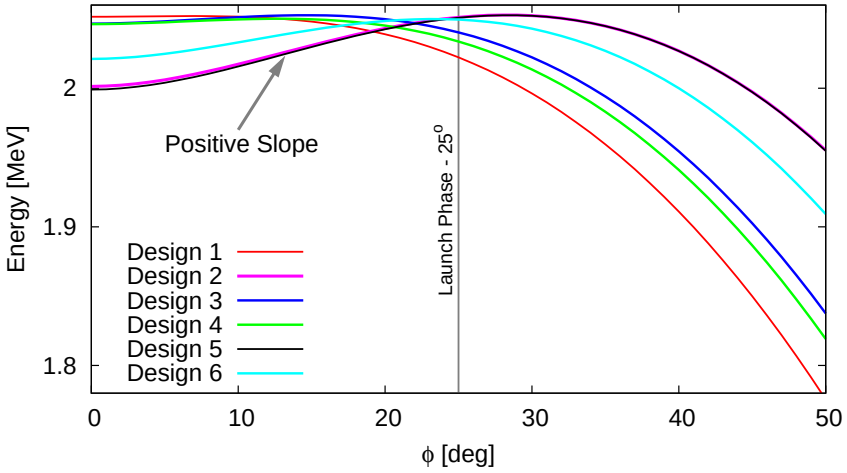




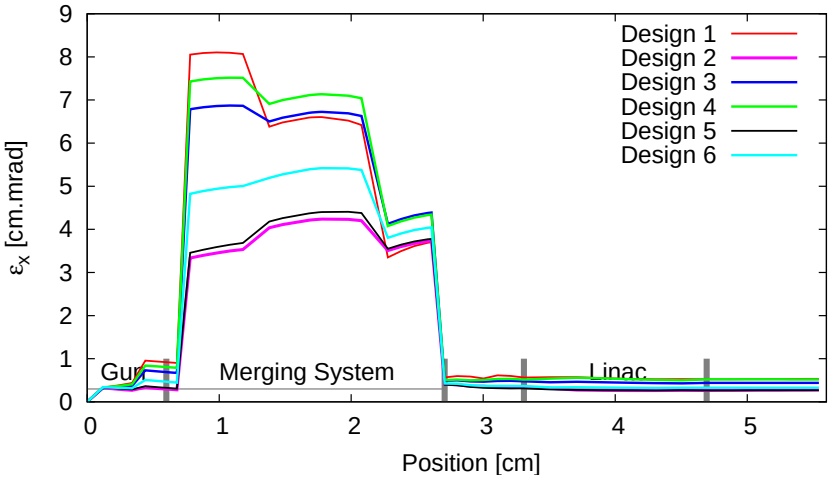


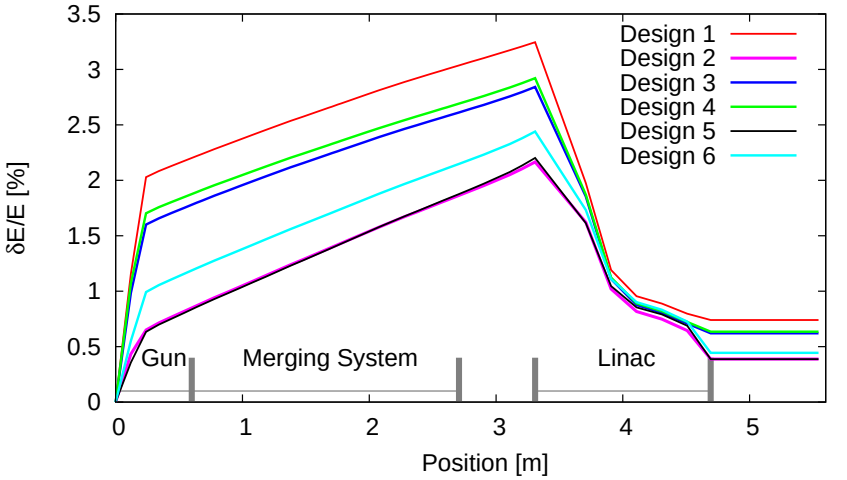
Energy Spread & Emittance

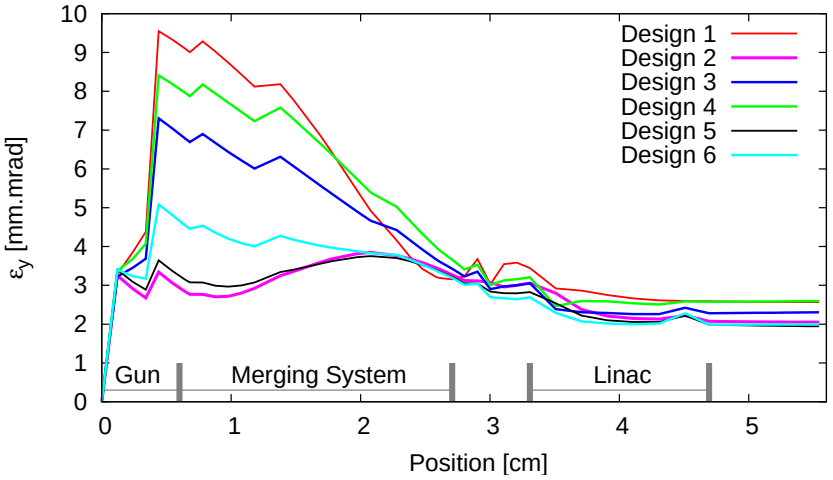
Longitudinal



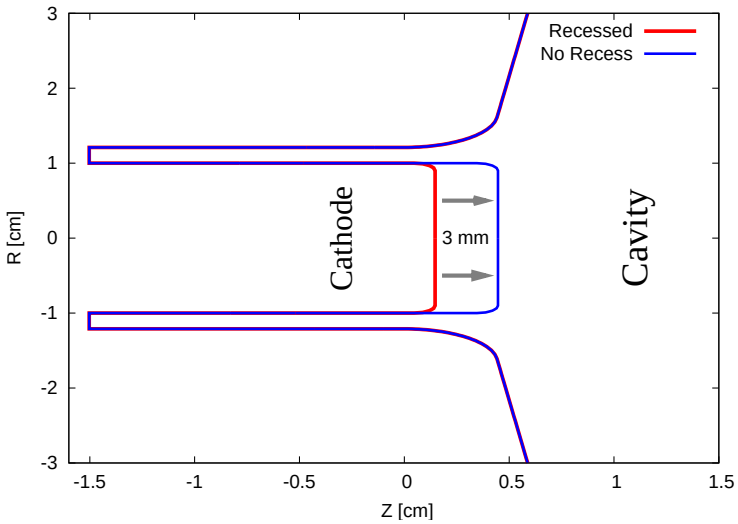
Transverse

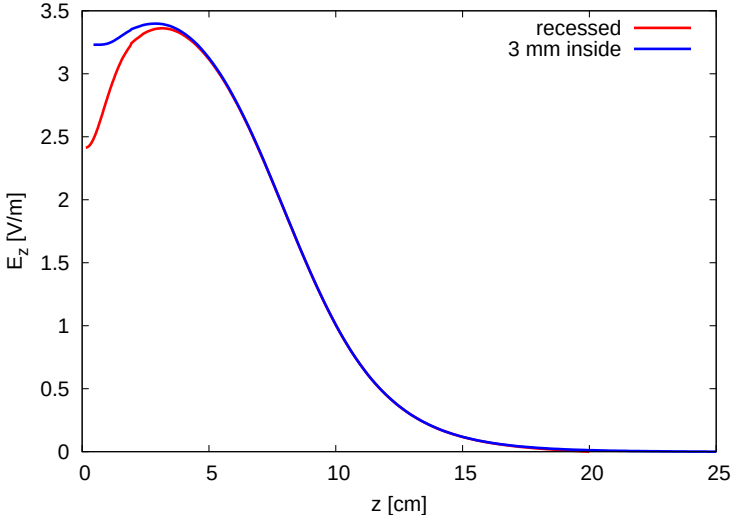


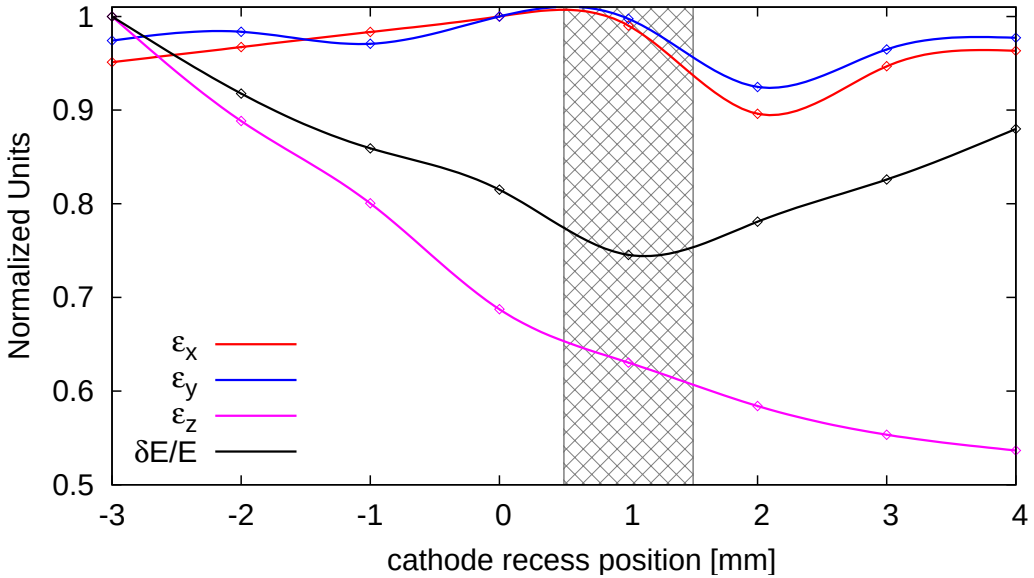




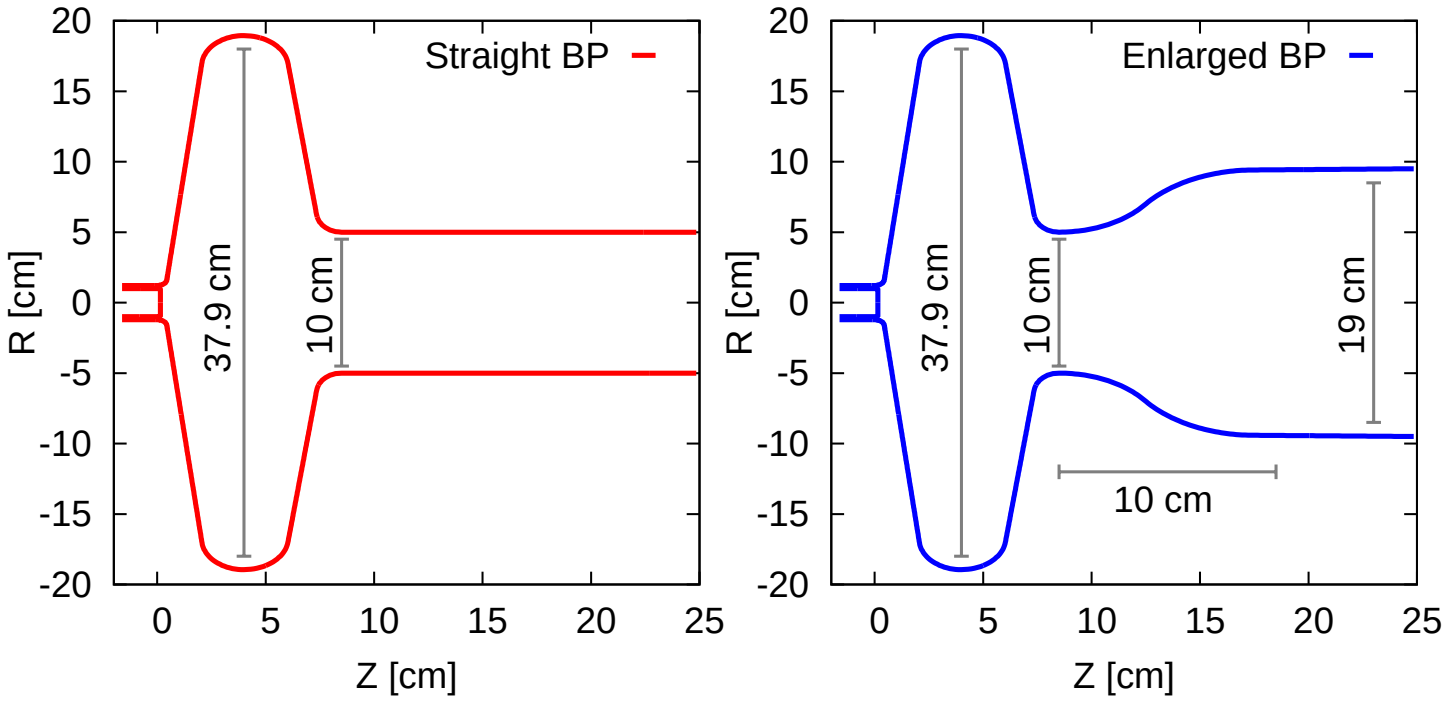
Cathode Recess





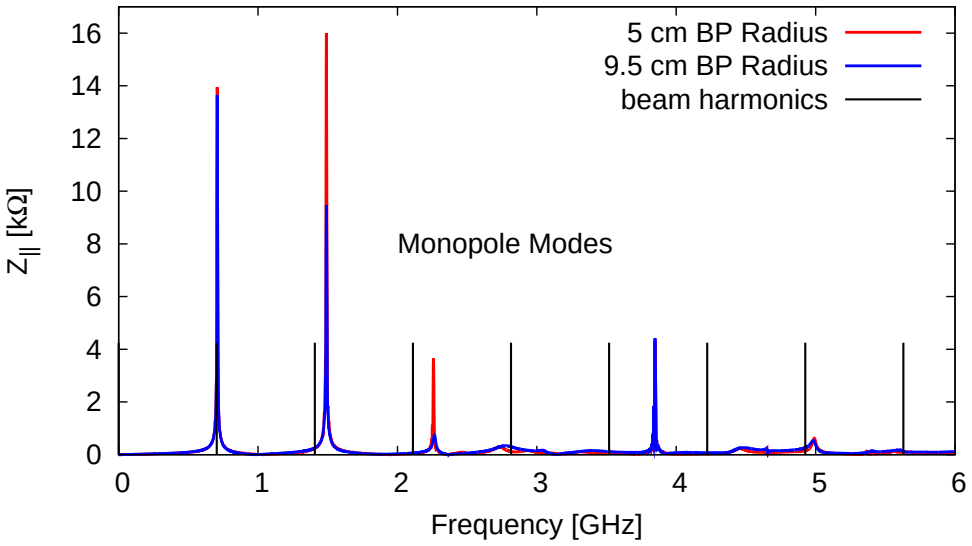


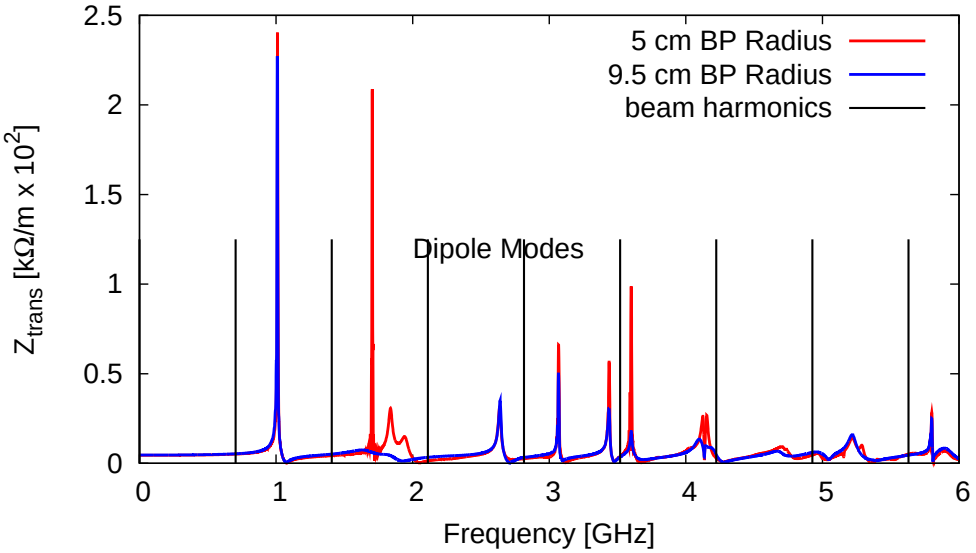
Beam Pipe Transition



- HOM Damping ☺
- FPC Coupling (field level $< 10^2 \rightarrow$ 10 cm away) ☹
- Mechanical Design (manufacturing, valves etc..) ☹

Impedance Spectrum & Laser Stability



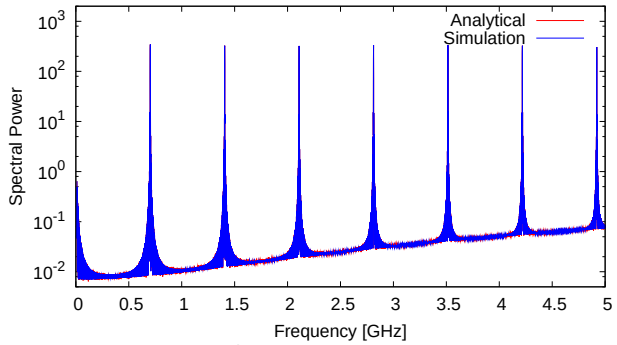


Phase Modulation:

$$I(t) = \sum_{n=-\infty}^{\infty} a_n \delta(t - nT_0 - \epsilon_n)$$

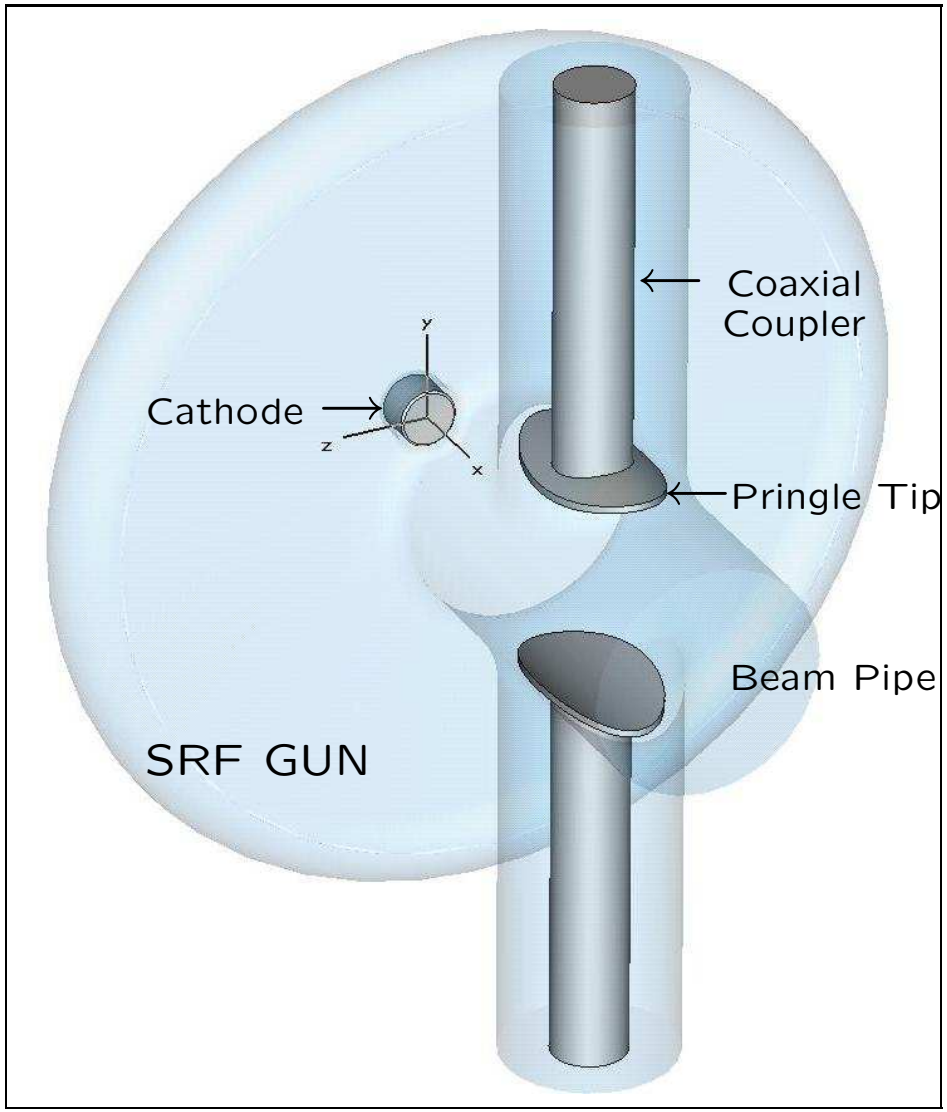
Spectral Power Density:

$$P(\omega) = \frac{2\pi}{T_0^2} \underbrace{\left[\frac{\sin(\sqrt{3}\omega\sigma_\epsilon)}{(\sqrt{3}\omega\sigma_\epsilon)}\right]^2}_{envelope} \sum_{m=-\infty}^{\infty} \underbrace{\delta\left(\omega - \frac{2\pi m}{T_0}\right)}_{harmonics} + \frac{1}{T_0} \underbrace{\left[\left(1 - \left[\frac{\sin(\sqrt{3}\omega\sigma_\epsilon)}{(\sqrt{3}\omega\sigma_\epsilon)}\right]^2\right) + \sigma_a^2\right]}_{baseline}$$



$\frac{V_{HOM}}{V_{acc}} \approx 9 \times 10^{-3}$ ($\sigma_a = 1\%$, $\sigma_\epsilon = 1$ ps)

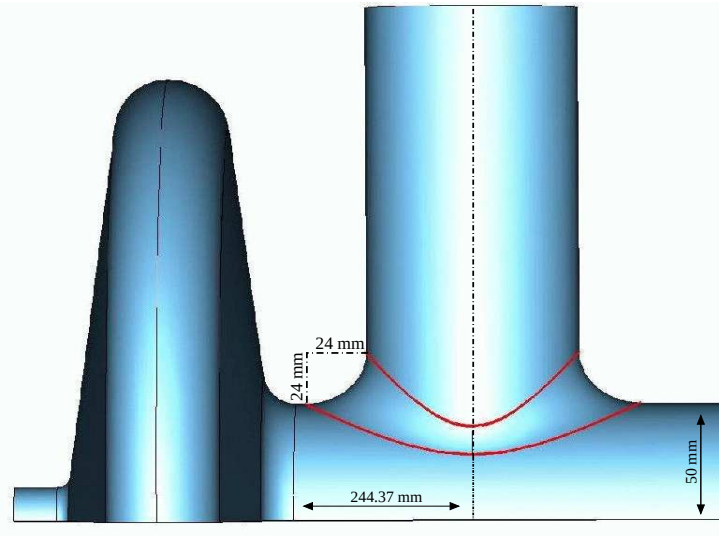
Coupling Fundamental Power



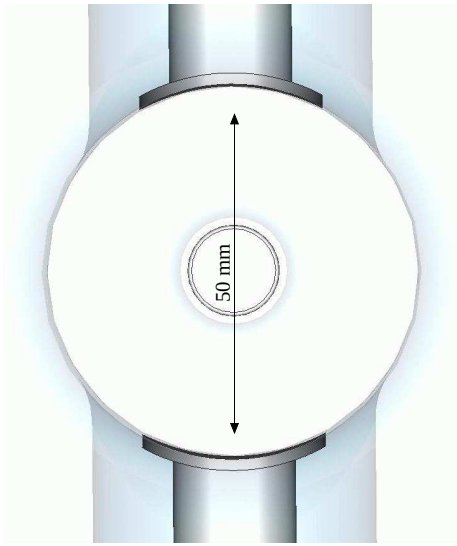
- Couple strongly: $Q_{ext} \sim 5 \times 10^4$
- Coupler kicks
- Reduce wakefields
- Engineering, alignments, etc..

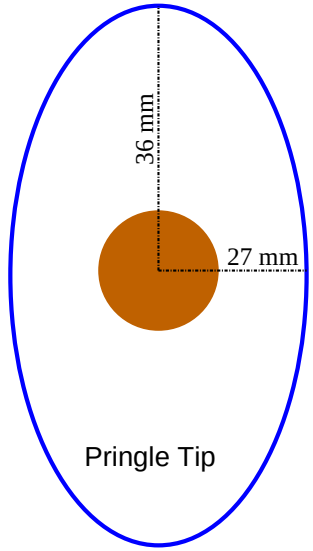
FPC Optimization

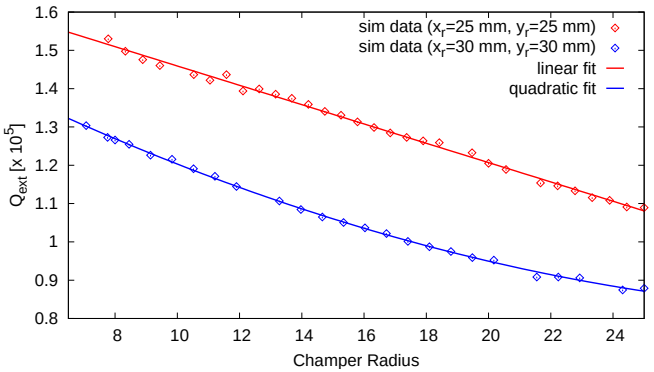
FPC - Beam Pipe Edge

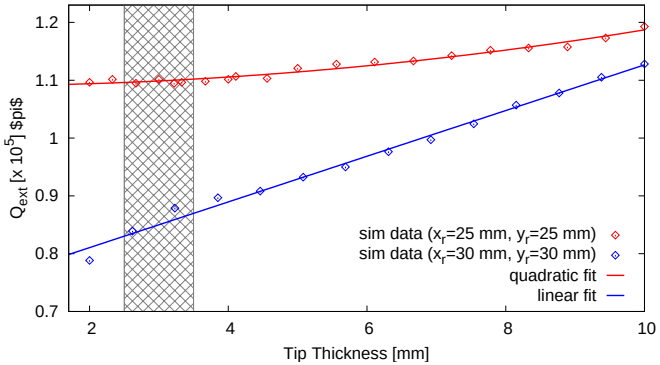


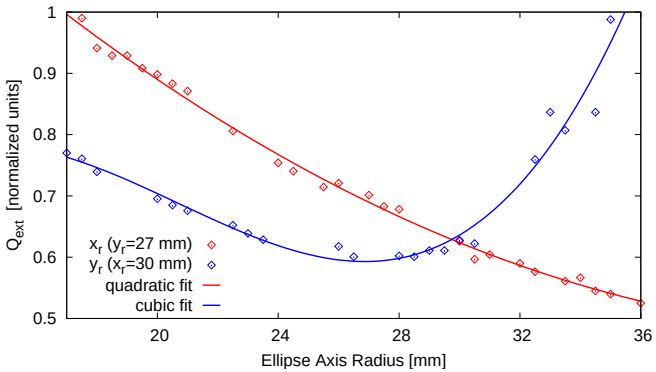
Pringle Tip Thickness



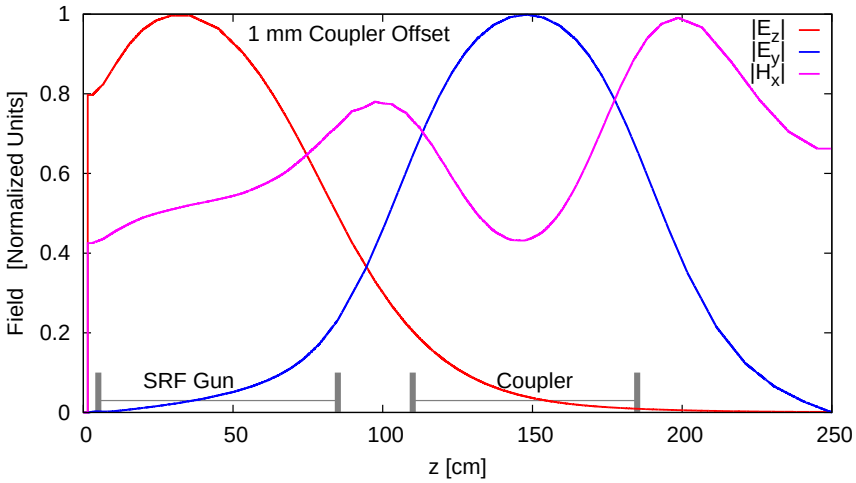


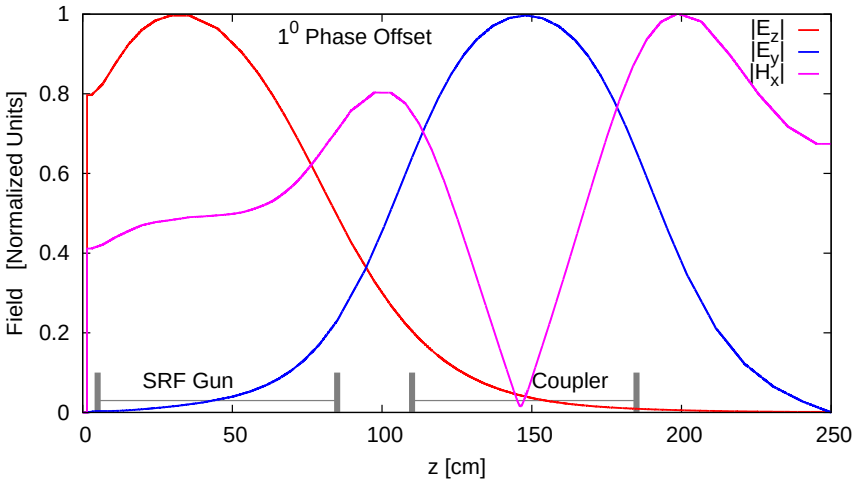






Coupler Kicks



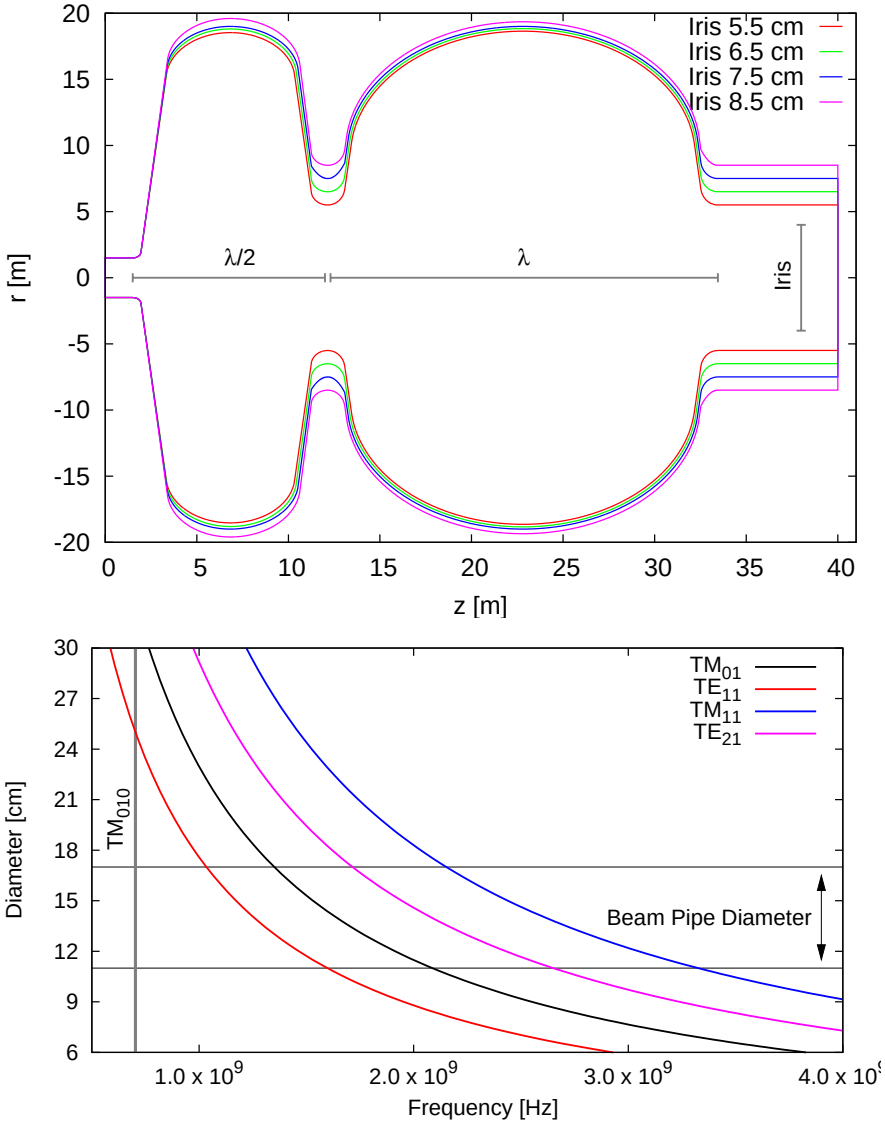


$$\delta_t = \frac{\int (E_y + v_z B_x) dz}{\int E_z dz}$$

$$d\epsilon_n = \sigma_t \frac{2\pi\sigma_z}{\lambda_{RF}} \frac{eV_{acc}}{E_0} \left| \mathrm{Re}(\delta_t) \sin\phi_0 + \mathrm{Im}(\delta_t) \cos\phi_0 \right|$$

Asymmetry	Kick	$d\epsilon_n/\epsilon_n$
Tip Penetration	$(-6.1 - 5.0i)\times 10^{-5}\ mm^{-1}$	$< 3\%$
Phase Offset	$(8.4 - 5.9i)\times 10^{-5}\ deg^{-1}$	$< 3\%$

eCooling 1.5 Cell Gun



- Optimize Iris Radius
  - f_{HOMs} & $f_{cut-off}$
  - Trapped Modes
- Beam pipe transition
  - HOM damping
  - FPC Coupling
- Optimize L_1 & L_2
  - Energy Vs. Phase Slope
  - Longitidinal Emittance
  - Transverse Emittance
- Optimize cavity ellipses
  - Peak fields, R/Q, etc...

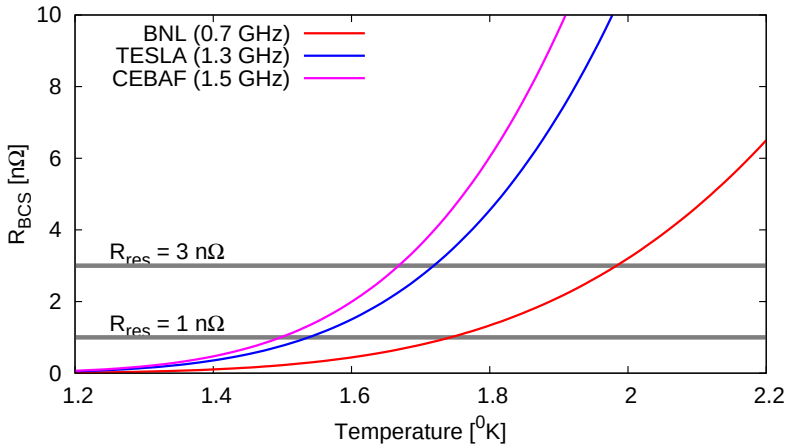
Conclusions and Outlook

- Final design review (1/2 Cell) - Dec 14^{th}, 2005
- SRF gun shape and FPC Coupler finalized
- Fabrication of prototype and Nb cavity underway

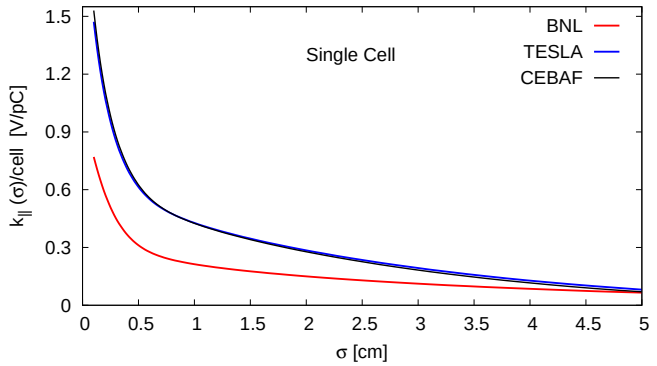
Extra Slides

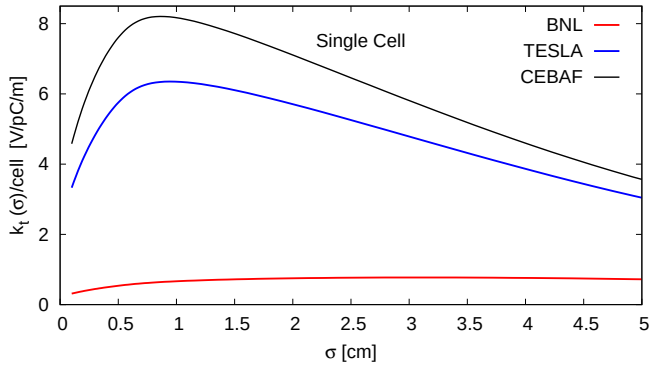
Design Criteria

- $\frac{E_{peak}}{E_{acc}}$ $(\downarrow)$, $\frac{H_{peak}}{E_{acc}}$ $(\downarrow)$
- $P_{cav} \propto \frac{Rs}{(R/Q)G}$ $(\downarrow)$
  - $R_s \propto \omega^2$ $(R_s = R_{BCS} + R_{res})$
  - $\frac{R}{Q}G \propto const.$ $(dim. \propto \omega)$
- Field sensitivity: $a \propto \frac{N^2}{k_{cc}}$ $(\downarrow)$

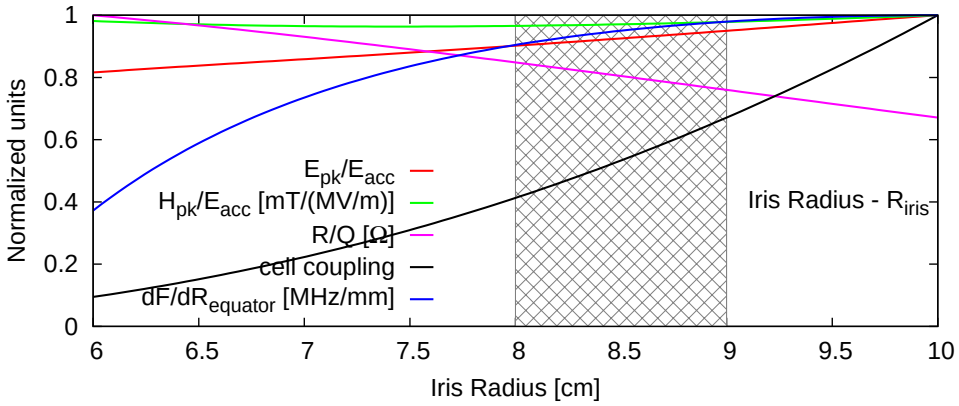


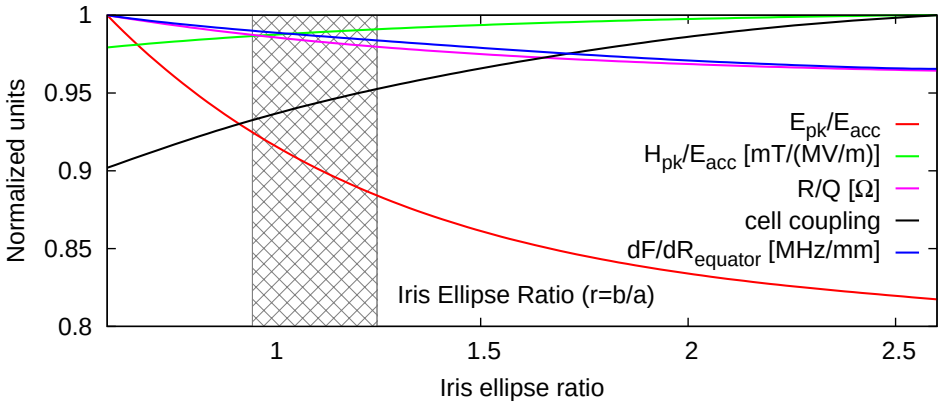
- $P_{avg} = 2k_{||}IQ$
- $k_{||} \propto \frac{1}{\mathbf{R_{iris}}}\sqrt{\frac{d}{\sigma_z}}\sqrt{N_c}$
- $k_{\perp} \propto \frac{1}{R_{iris}^3}\sqrt{d\sigma_z N_c}$

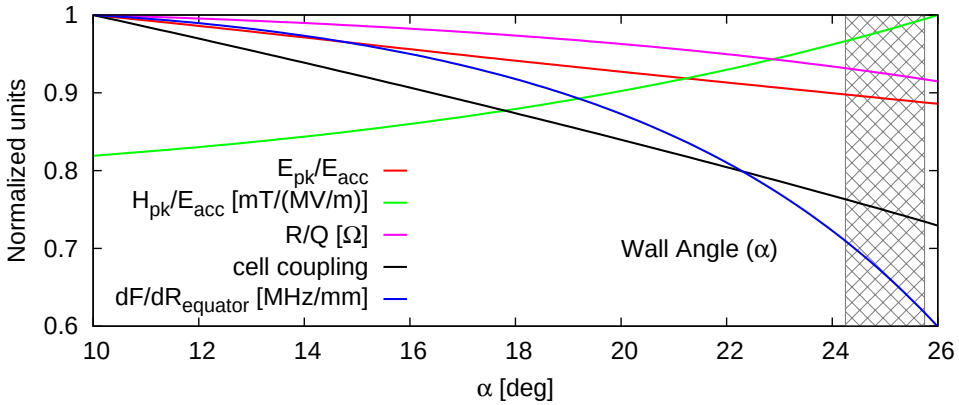


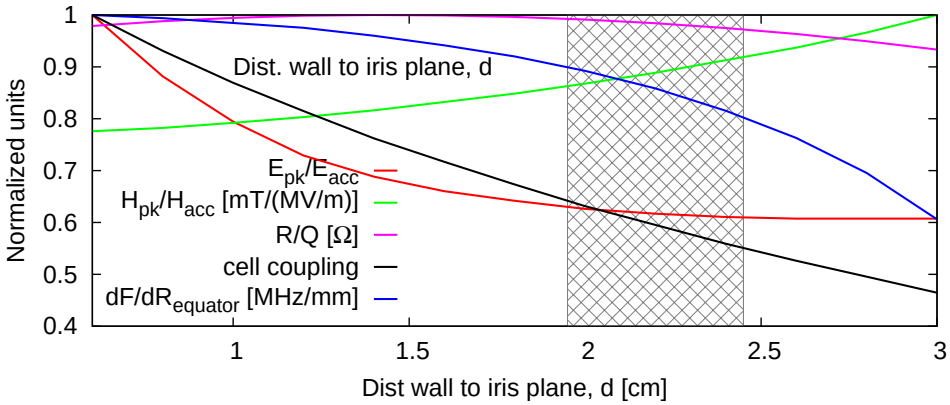


Cavity Design







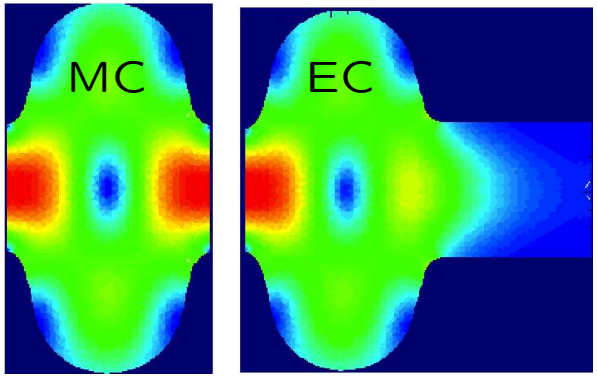


Cavity Comparisons

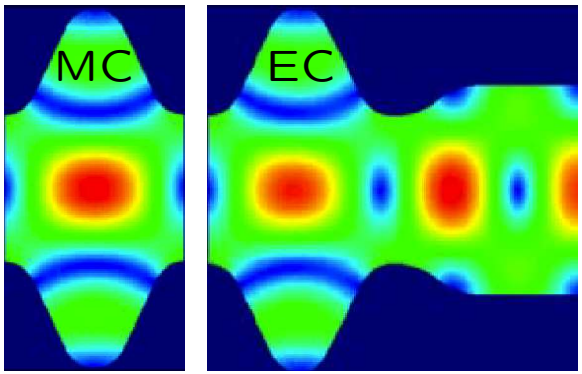
Par	BNL(HC)	CEBAF(HG)	TESLA(HG)
Freq. [MHz]	703.75	1497	1300
$\frac{R}{Q} * G$ [Ω^2]	9×10^4	2.1×10^5	2.8×10^5
E_p/E_a	1.97	1.96	1.98
H_p/E_a $[mT/MV/m]$	5.78	4.15	4.15
k_{cc}	3%	1.89%	1.87%
N_{cells}	5	7	9
$\frac{N^2}{\beta k_{cc}}$	8.3×10^2	2.6×10^3	4.1×10^3
Lorentz. Det. Coeff $[Hz/(MV/m)^2]$	1.2 (UnStiff)	2	1
$k_{\|\|}$ $(\sigma_z - 1mm)$ [V/pC]	4.25	10.71	13.14
$k_\perp$ $(\sigma_z - 1mm)$ [V/pC/m]	0.1	2.24	2.07
Q_{ext} (Dipole)	$10^2 - 10^4$	$10^3 - 10^6$	$10^3 - 10^7$

Design Criteria: Trapped Modes

Frequency Difference



$\Delta f = 30MHz$ (2.4 GHz)



$\Delta f = 13MHz$ (1.4 GHz)

Number of Cells