Experiment to Measure Ramped Electron Bunches at the UCLA Neptune Laboratory Using a Transverse Deflecting Cavity

R. Joel England

J. B. Rosenzweig, B. O'Shea, G. Travish
UCLA Department of Physics and Astronomy
Particle Beam Physics Laboratory
Los Angeles, CA USA

D. Alesini
INFN Laboratori Nazionali di Frascati
Rome, Italy

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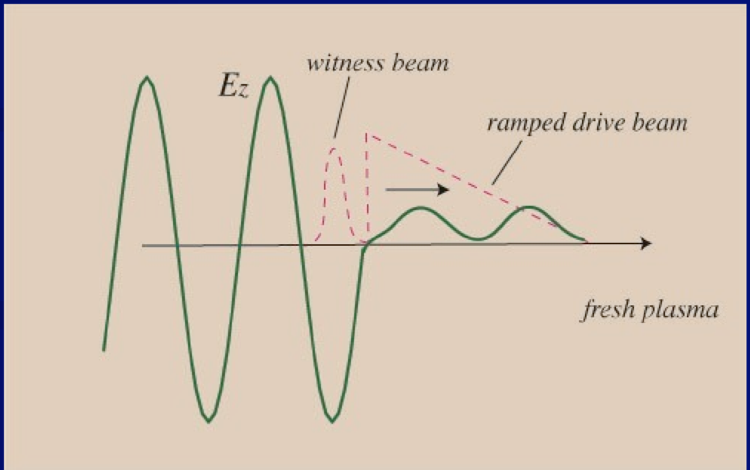
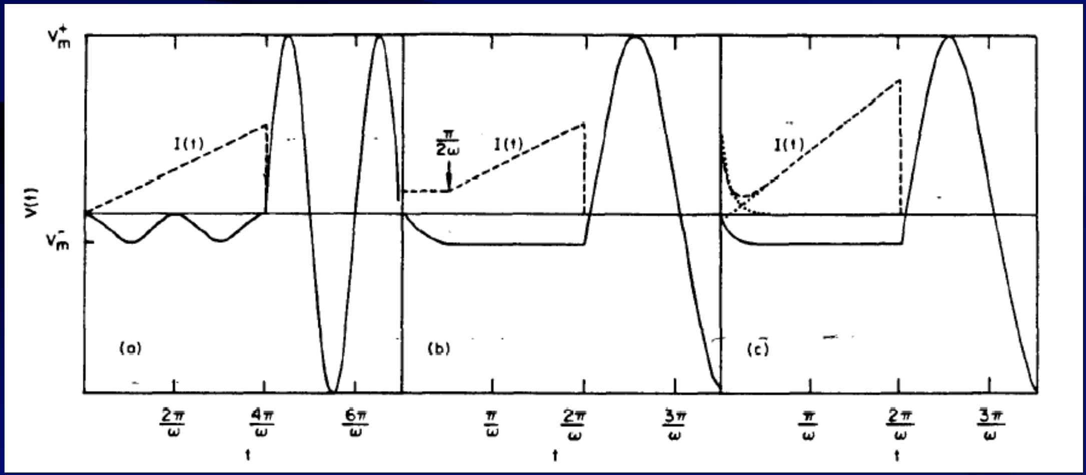
Optimal Drive Beam Profile for Blowout Regime of PWFA

- PWFA: plasma wakefield accelerator
- electron beam-driven plasma waves
- acc. fields on order of multi-GeV/m
- acceleration of drive tail or witness bunch



Chen, P., Su, J., and Dawson, J. SLAC PUB 3662 (1985).



triangle **doorstep** **ideal**

Transformer Ratio:

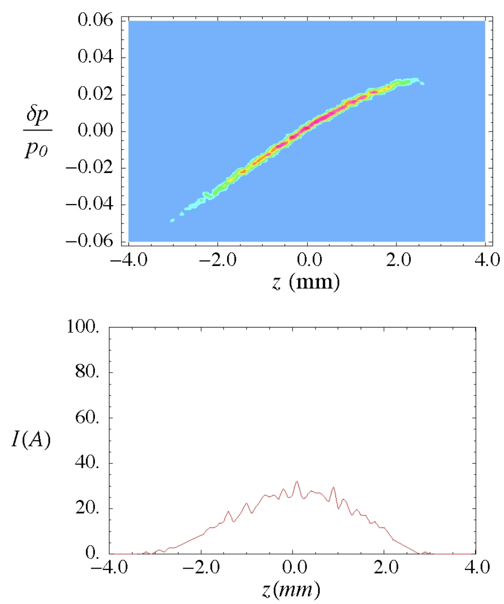
$$E_+ = acc.field; E_- = decc.field$$

$$R = E_+ / E_- = k_p L_z$$

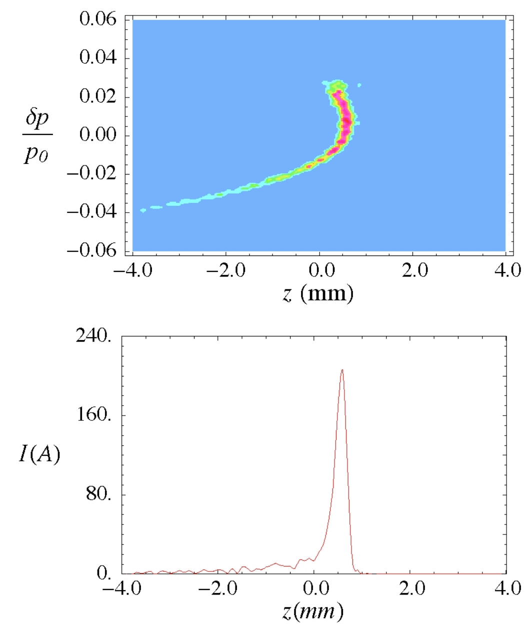
$$R > 2 \ \text{ if } \ L_z > 2k_p$$

Neptune Dogleg Compressor

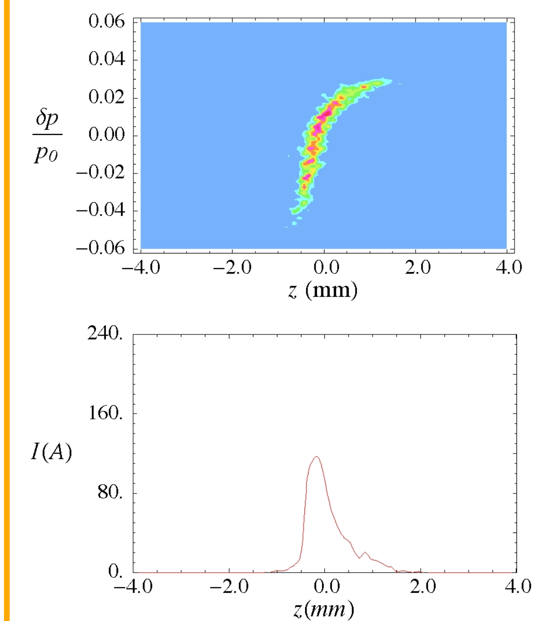
PARMELA Simulation Results: 1000 particles, 300pC



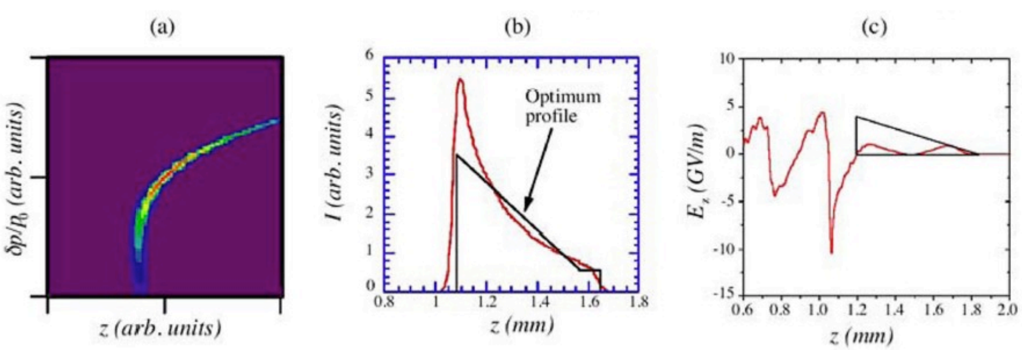
Initial



Final: Sextupoles Off



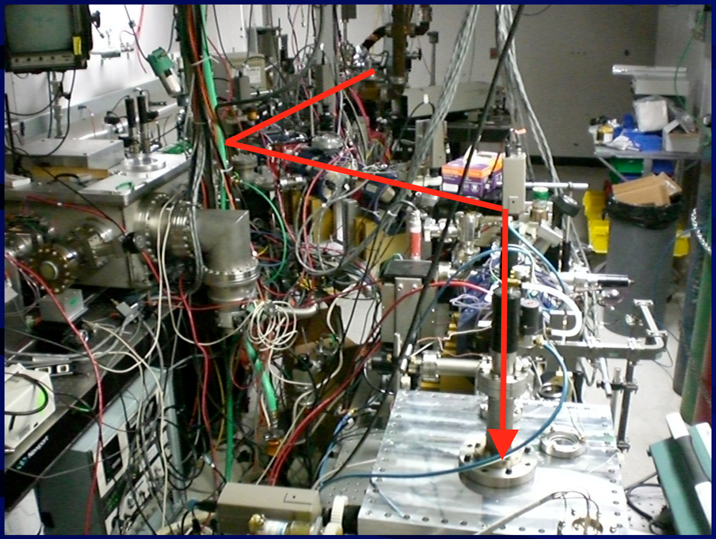
Final: Sextupoles On



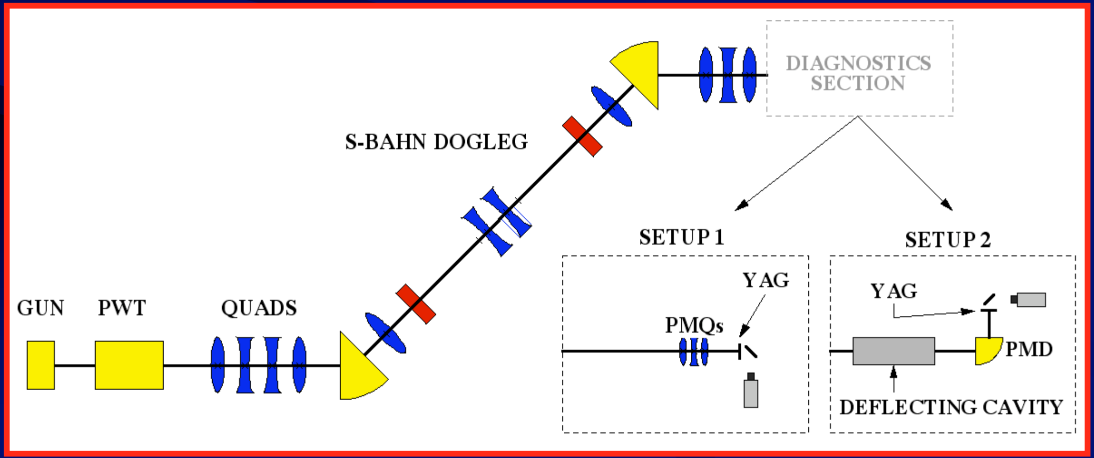
- 2D PIC Simulation
- 5 GeV/m gradients
- 6 nC drive beam w/ n_0=2e16 cm^{-3}

Neptune Dogleg Compressor

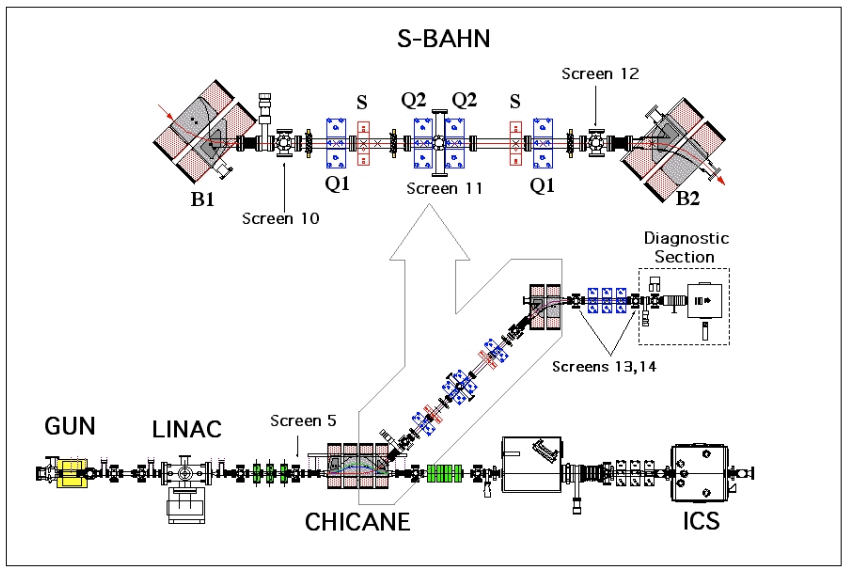
S-Bahn Compressor



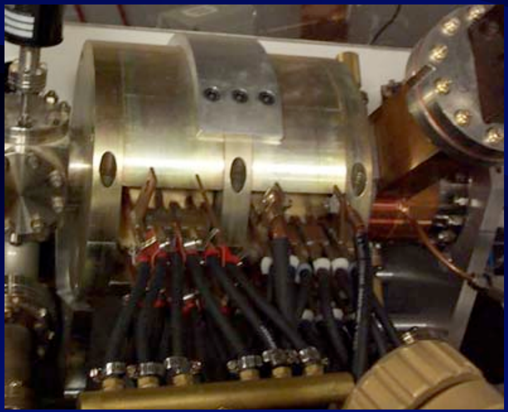
- Is a “dogleg” or dispersionless translating section.
- Half-chicane with focusing elements between the bends.
- Can be operated in a nondispersive mode with symmetric beta function and 2π betatron advance.
- Like a chicane, may be used as a bunch-length compressor.
- Nominal first order temporal dispersion (R_{56}=-5cm) is suitable for beam-shaping.
- Sextupoles required to compensate 2nd order longitudinal dispersion.



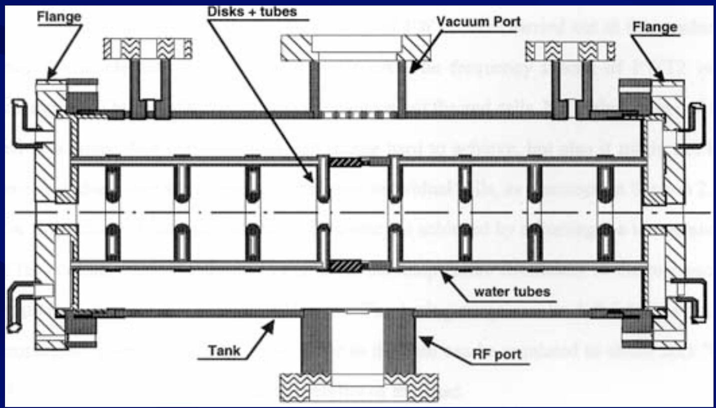
The UCLA Neptune Laboratory



Beam Charge:	100pC ---> 500pC
Beam energy:	up to 15 MeV
Emittance:	ε_N = 6 mm mrad
Power Source:	18 MW Klystron
RF Frequency:	2.856 GHz
Cathode laser:	60 μJ at λ = 266 nm
Laser pulse length:	5 ps RMS



1.6-Cell Photoinjector

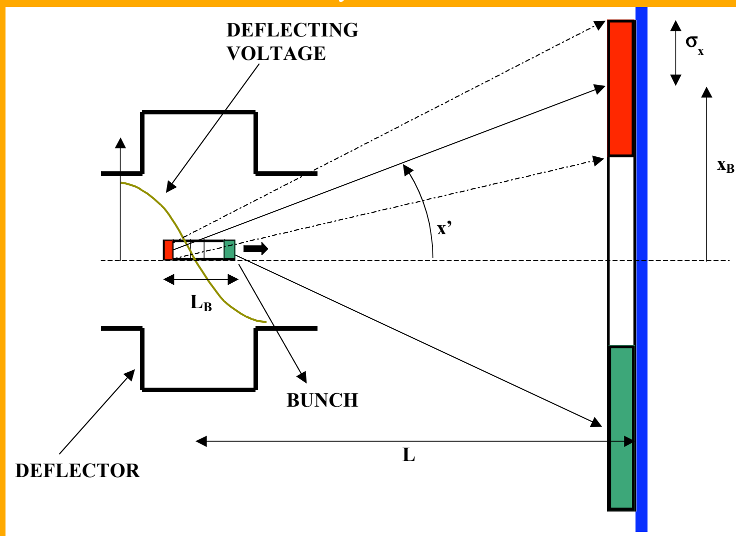


7&2/2 Cell PWT Linac

Temporal Bunch Shaping: Diagnostic

Deflecting Mode Cavity

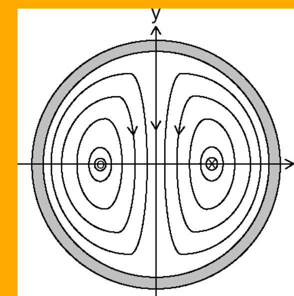
Courtesy of D. Alesini



Lowest dipole mode is TM_{110}
Zero electric field on-axis (in pillbox approx.)
Deflection is purely magnetic
Polarization selection requires asymmetry

$$x' = \frac{\pi f_{RF} L_B \sqrt{2 P_{RF} R_\perp}}{cE/e}$$

$$x_B = \frac{\pi f_{RF} L L_B \sqrt{2 P_{RF} R_\perp}}{cE/e}$$



J.D. Fuerst, et. al., DESY Report CDR98, 1998

Pillbox Fields

$$E_z = E_0 J_1(\kappa r) e^{i\phi};$$

$$B_r = B_0 \frac{J_1(\kappa r)}{\kappa r} e^{i\phi};$$

$$B_\phi = i B_0 J_1'(\kappa r) e^{i\phi};$$

on axis
$\kappa r = 0$

$$E_z = 0;$$

$$B_x = \frac{B_0}{2};$$

$$B_y = i\frac{B_0}{2};$$

Deflecting Cavity: Power & Resolution

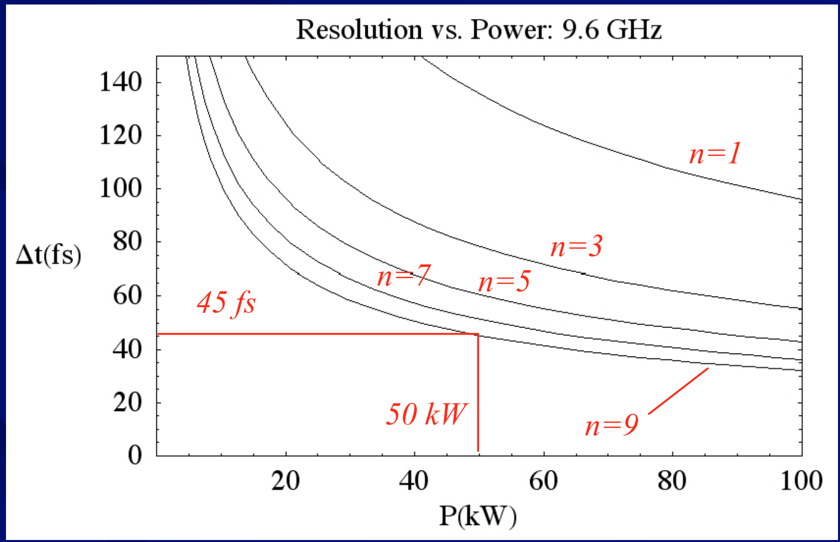
screen deflection: $\sigma_{x,f} = \sqrt{\sigma_{x,0}^2 + \sigma_{def}^2}$ $\sigma_{def} = 2\sigma_z L \dfrac{\pi V_\perp f}{cU/e}$

$$V_\perp >> V_{\min} = \frac{\sigma_{x,0} U/e}{L\pi\sigma_t f} \qquad \sigma_{t,\min} = \frac{\sigma_{x,0} U/e}{L\pi V_\perp f}$$

$$V_{\perp,design} = 3V_{\min} = 545\,kV \qquad \sigma_{t,\min} = 545\,fs$$

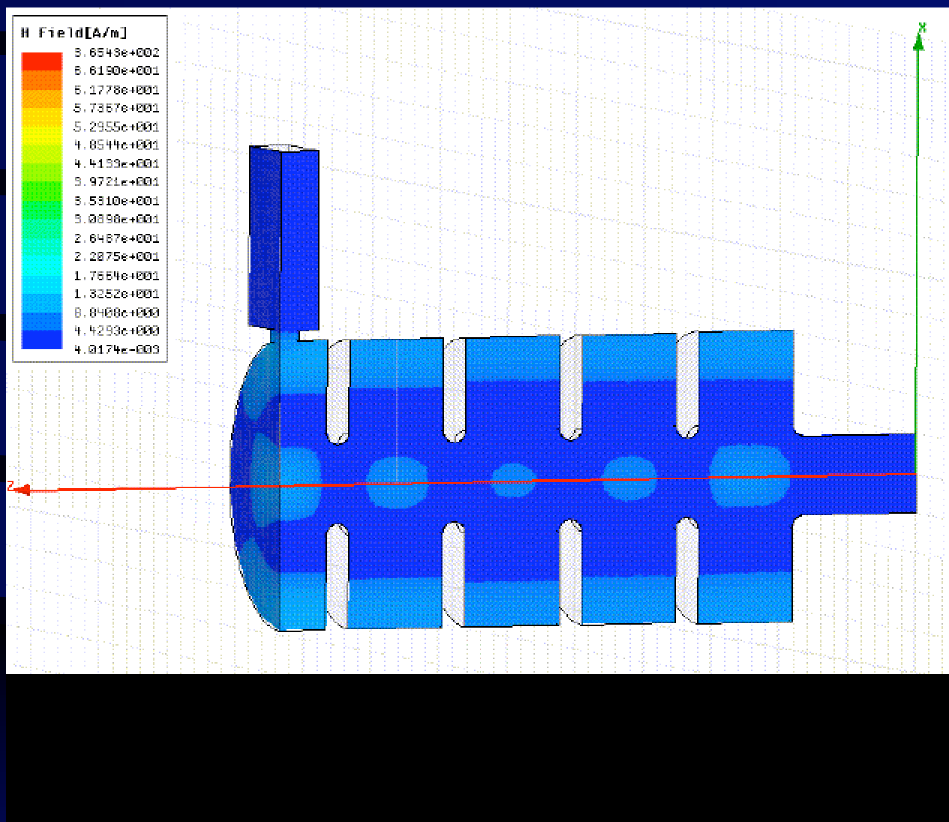
$$\Delta t = \frac{\Delta x\ U/e}{L\pi f R_\perp^{1/2}\sqrt{nP_{in}}}$$

- $\sigma_{x,f}$ = beam size at screen with deflector on;
- $\sigma_{x,0} = 0.3mm$ = beam size at screen with deflector off;
- $L = 43cm$ = drift from deflector to screen;
- $f = 9.6GHz$ = RF frequency;
- $V_\perp$ = deflecting voltage;
- $R_\perp = 820k\Omega$ = transverse shunt impedance per cell;
- P_{in} = input RF power;
- $U = 12\,MeV$ = electron beam energy;
- φ_0 = deflector injection phase = 0;
- $\sigma_{t,\min}$ = minimum resolvable rms bunch length;
- $\Delta x = 30\,\mu m$ = spatial resolution of screen & optics;
- Δt = effective temporal resolution of deflector;

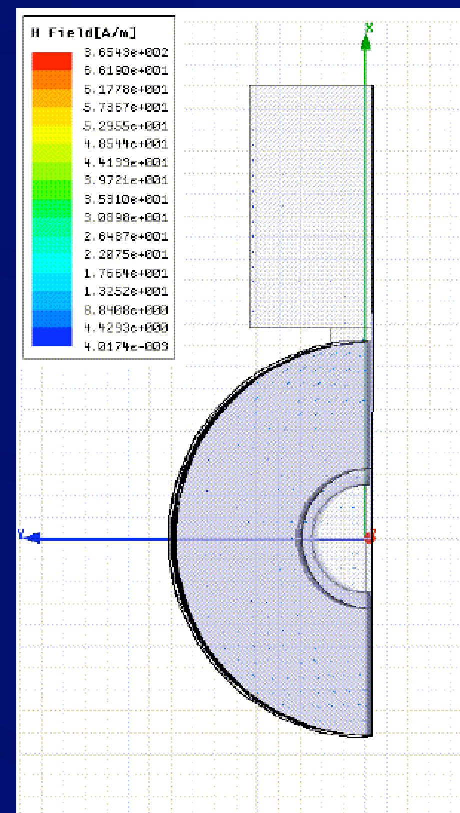


9 cells; 50 kW; 50 fs resolution

Deflecting Cavity TM110 Animations

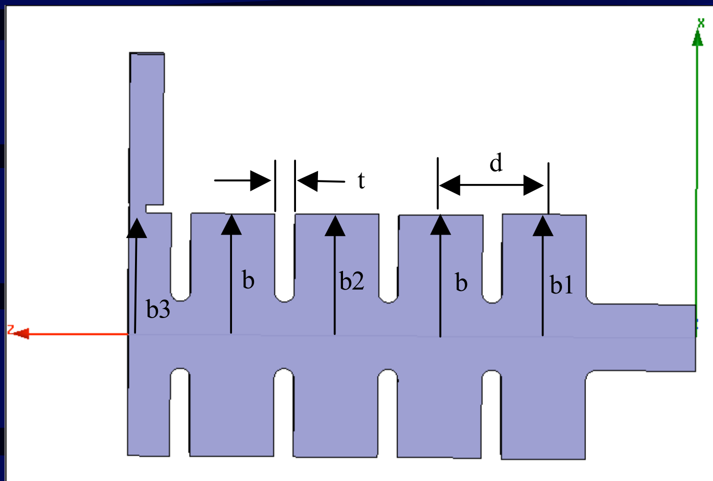


H-field complex magnitude



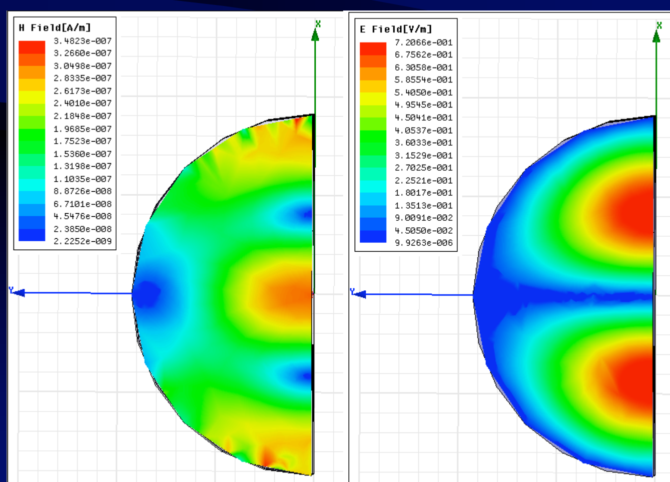
H-field vector plot

Deflecting Cavity: HFSS Design



HFSS Geometry of 1/2 structure

DIMENSION	VALUE [mm]
a	5
b	18.21
b1	18.44
b2	18.306
b3	18.21
t	3.0
d	15.62

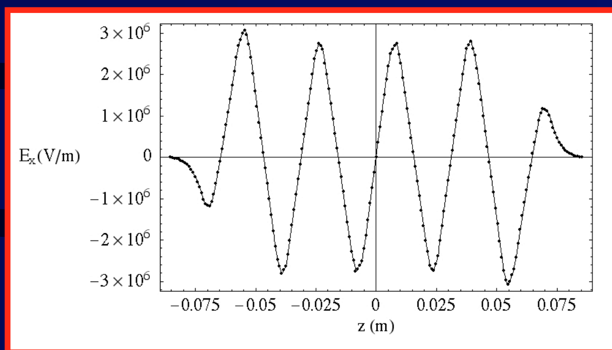


- X-Band, 9-cell design.
- Collaboration with INFL Frascatti.
- Will be built at UCLA; diffusion bonded at SLAC.
- Powered by a VA-24G X-Band klystron @ 50 kW.
- Frequency: 9.59616GHz

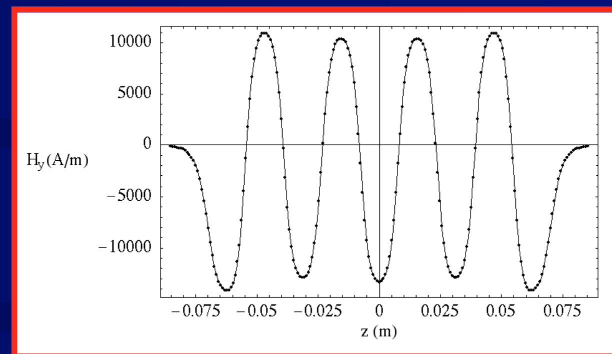
Deflecting Cavity: HFSS Design

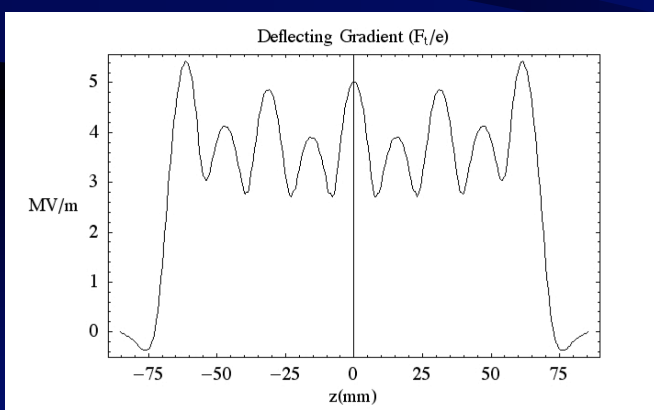
out of phase by 90°

E-field



H-field

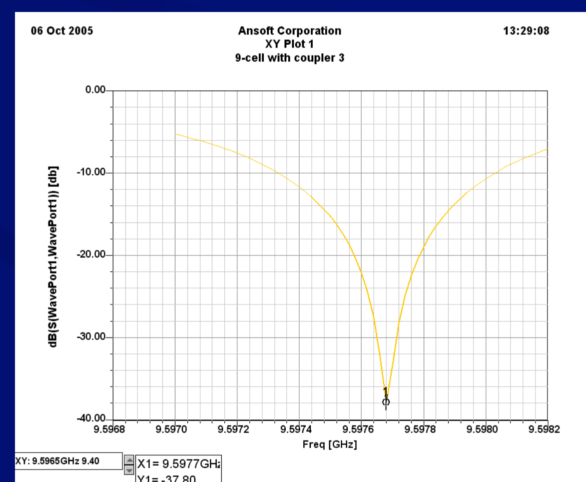




$$P_{in} = 50kW$$

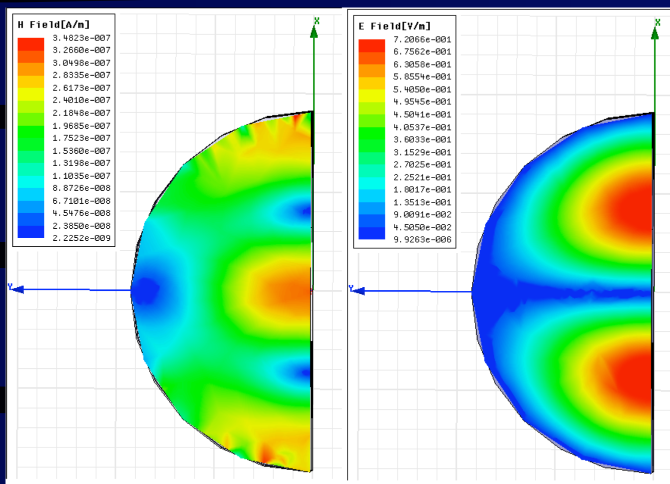
$$V_\perp = \tfrac{1}{e}\int F_\perp dz = 528kV$$

$$R_\perp = V_\perp^2 / P_{in} = 5.6M\Omega$$

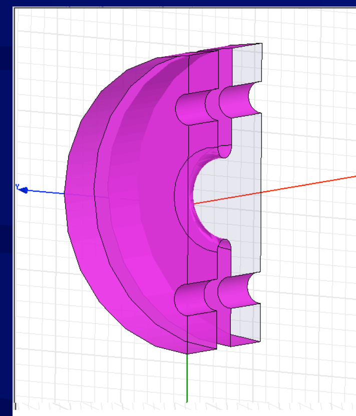


Resonance of the π-Mode

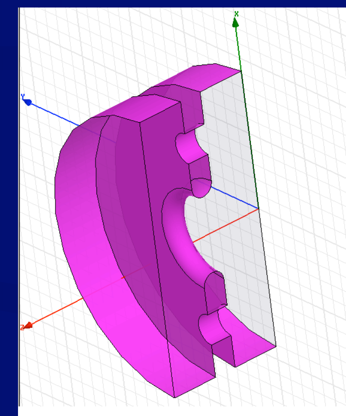
Deflecting Cavity: Polarization Separation



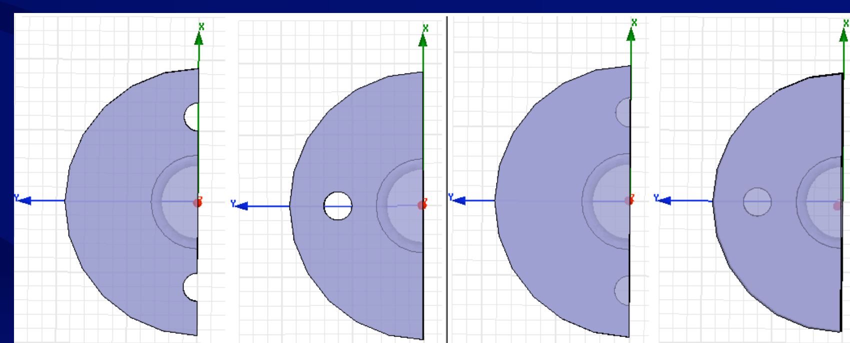
Rods



Holes

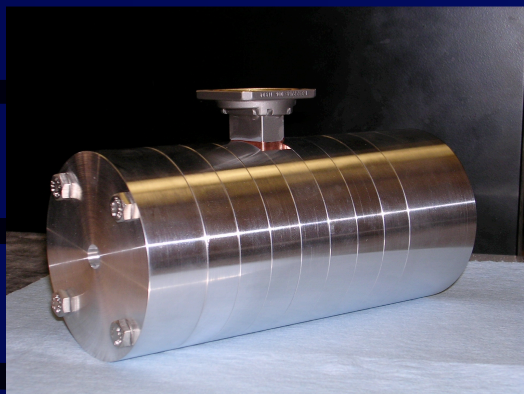
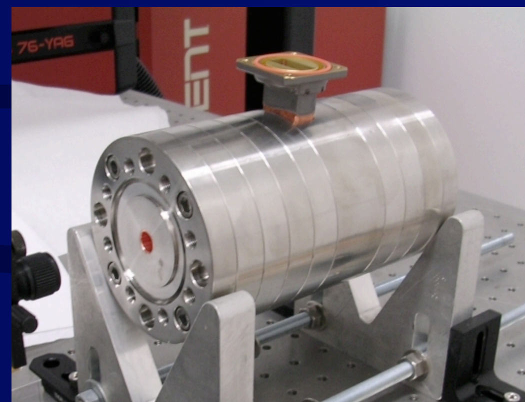
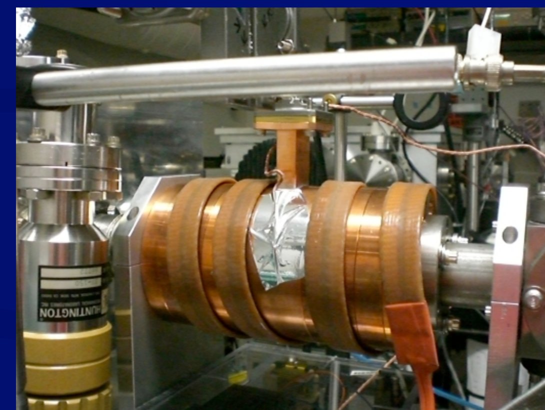


- Rods give greater better mode separation but shift the desired mode too much
- Holes give less mode separation (5 MHz) but only perturb desired mode by 2 MHz (within range of temperature tuning).
- Holes look like better option: 5 MHz is large compared to the resonance width



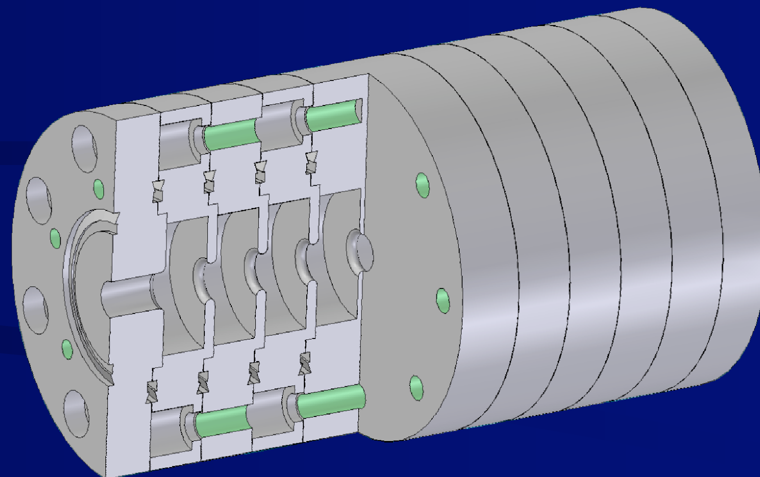
Undesired +1358 MHz | Desired +53 MHz | Undesired -7 MHz | Desired -2 MHz

Overview of Design Process

2004	2005	2006
		
cold test prototype	steel prototype	final design
Aluminum 9-cell 9.3 GHz cold-test only clamped no polarization separation	Steel with Cu coating 9-cell 9.5 GHz cold-test only cf flange design no polarization separation	GlidCop Al-15 9-cell 9.59616 GHz tested up to 70kW pp cf flange design EDM’ed polarization holes

Final Cavity Design

- 9-cell standing wave structure
- center-fed input RF
- reconditioned VA-24G klystron
- no brazing between cells
- cells are stacked CF vacuum flanges

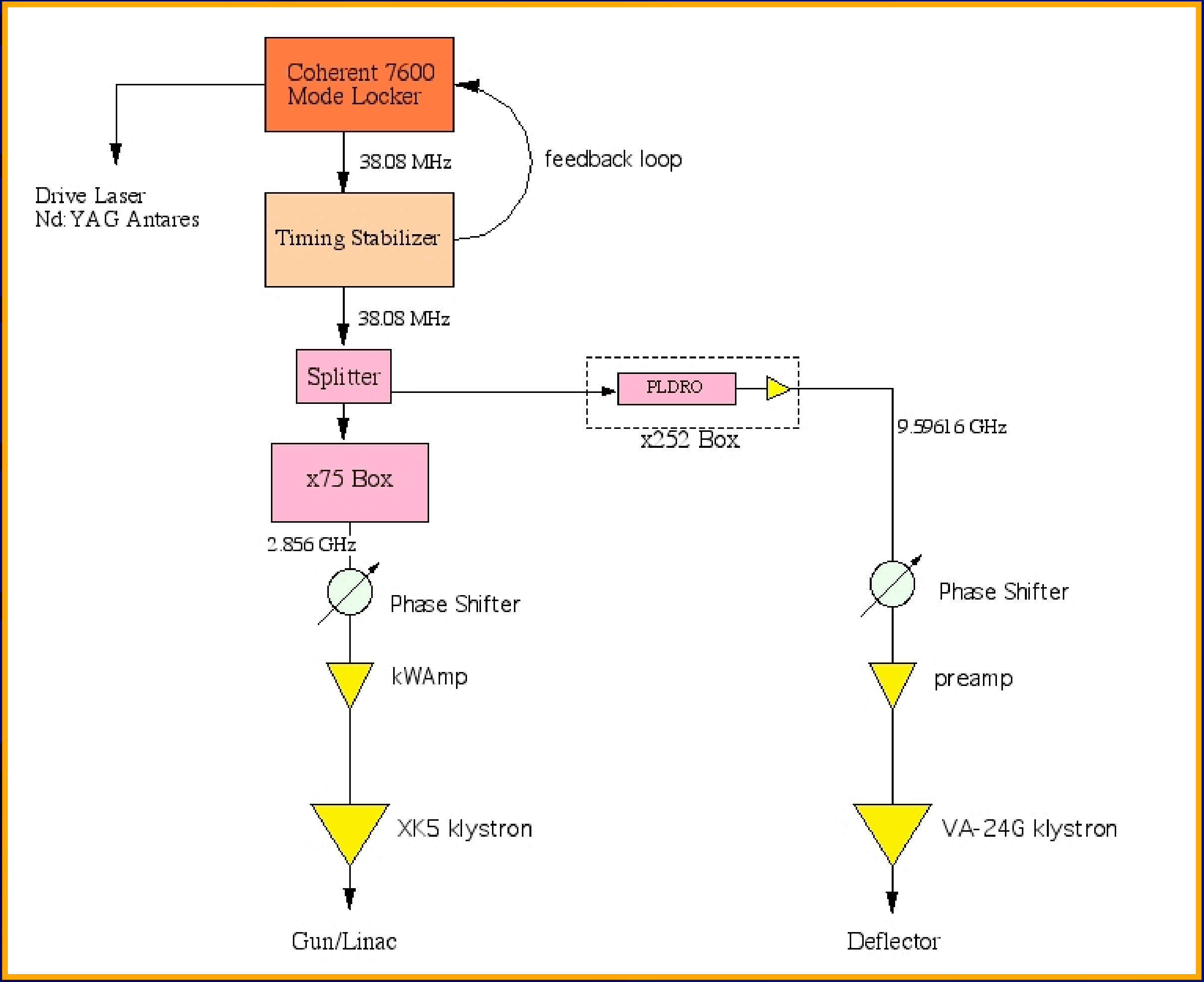


CAD drawing of stacked cells

x-band klystron (70 kW peak)

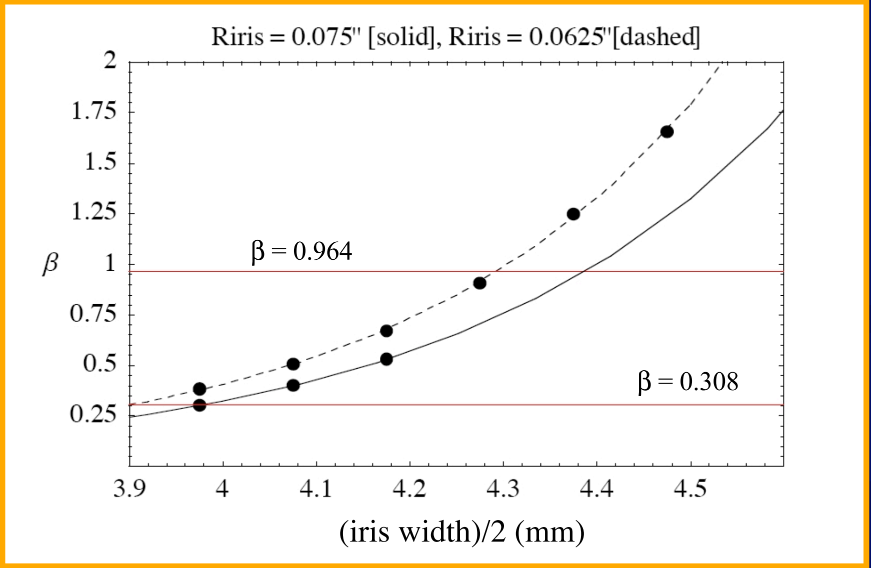
one cell with polarization holes

S-Band/X-Band RF System



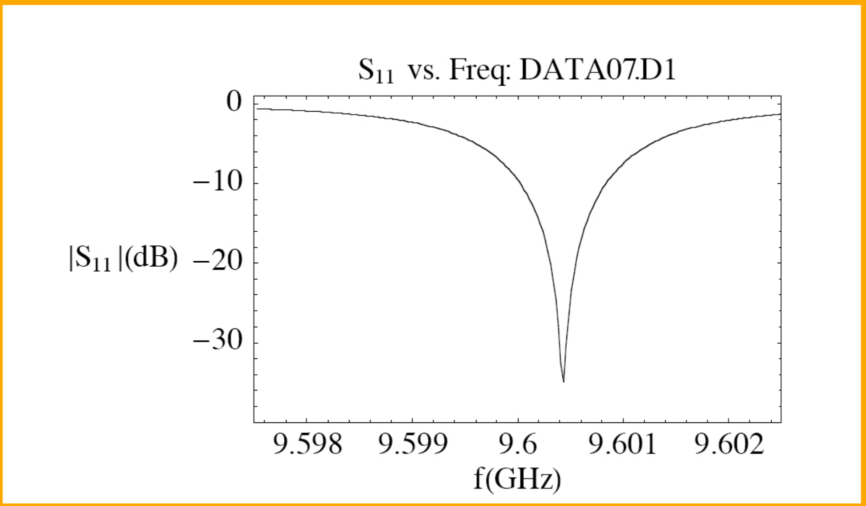
- S and X-Band frequencies are multiples of modelocker freq of drive laser
- Ensures phase stability of gun, linac, laser, and deflector

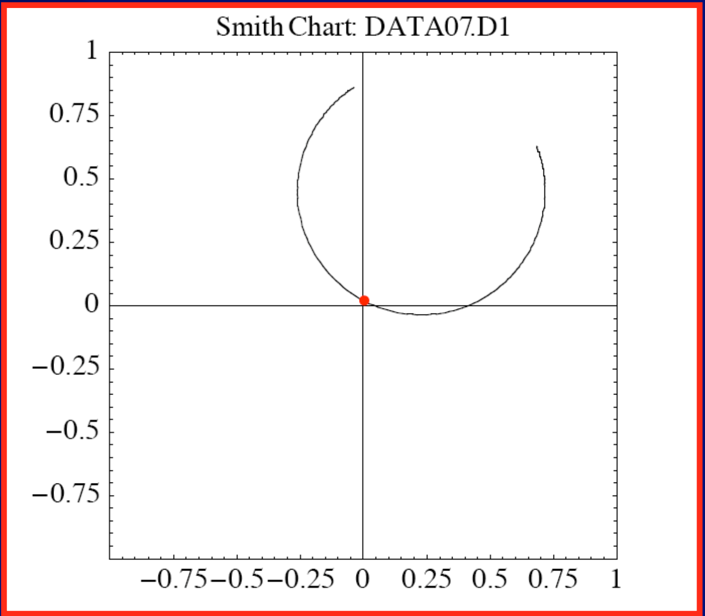
Input Coupler Tuning & Cold Test



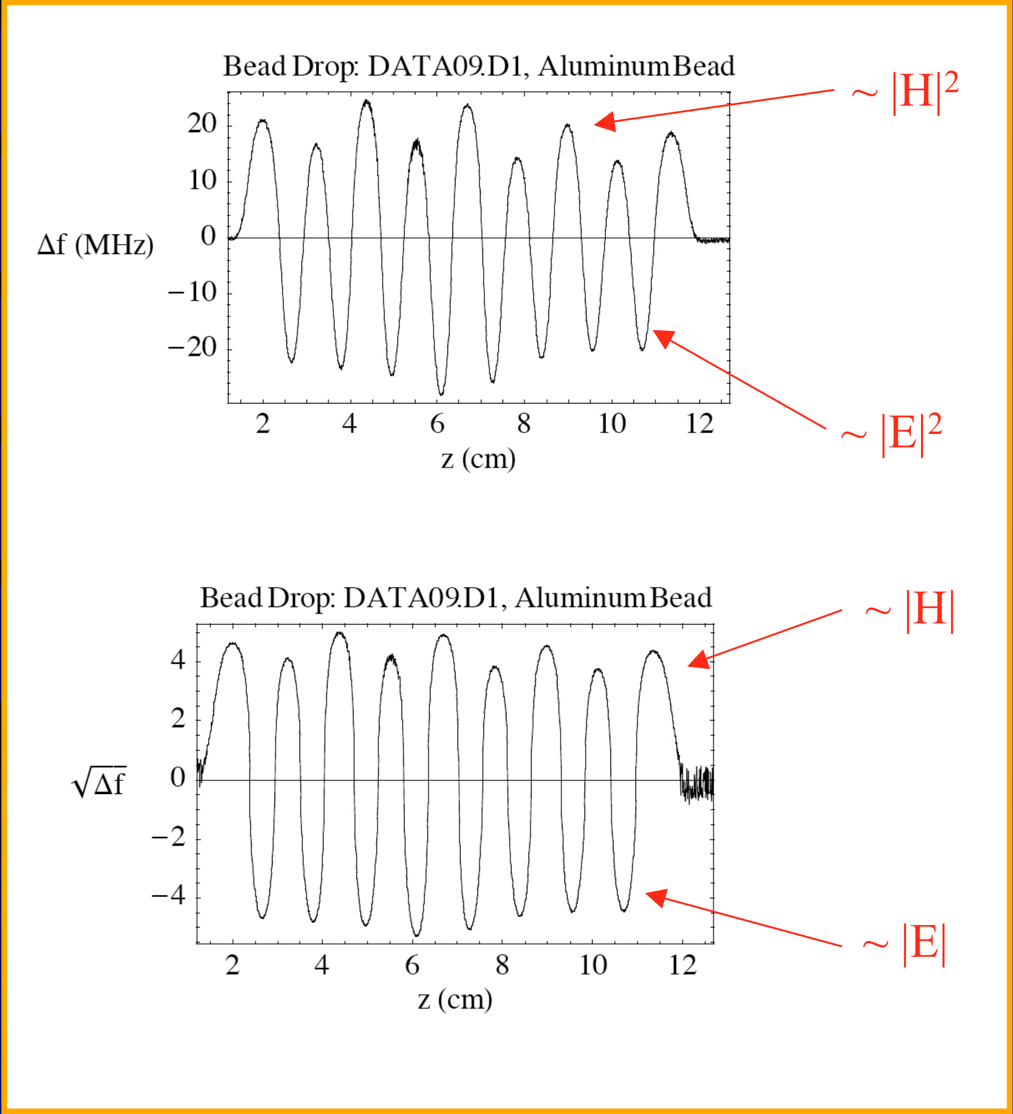
Tuning of input coupling iris:

- corner radii reduced to 1/16’’
- iris width increased by 0.585 mm
- dots: HFSS simulation data
- red lines: measured init & final beta values
- measured at room temp (24 ˚C)





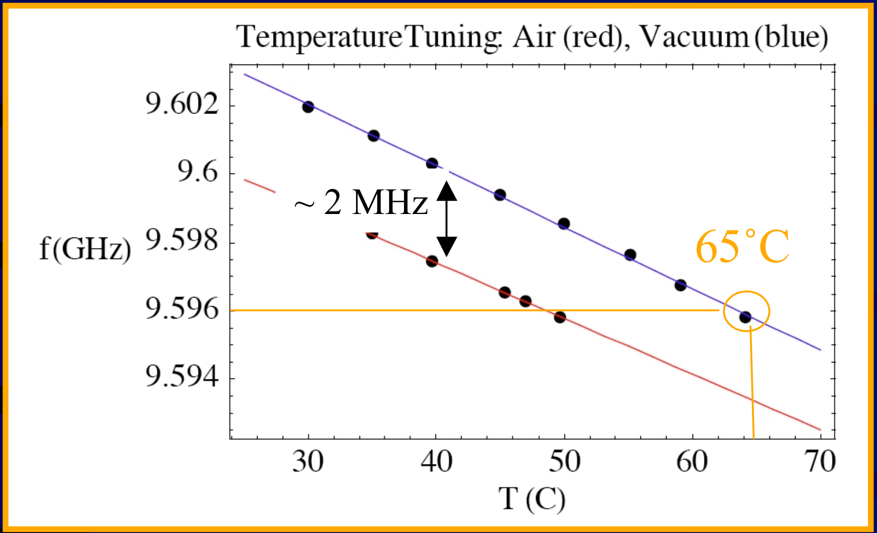
Bead Pull Results



- Bead pull using aluminum bead
- Data proportional to $|E|^2$ and $|H|^2$
- Field flatness ~ ±5%
- Data taken at room temp (24 C)

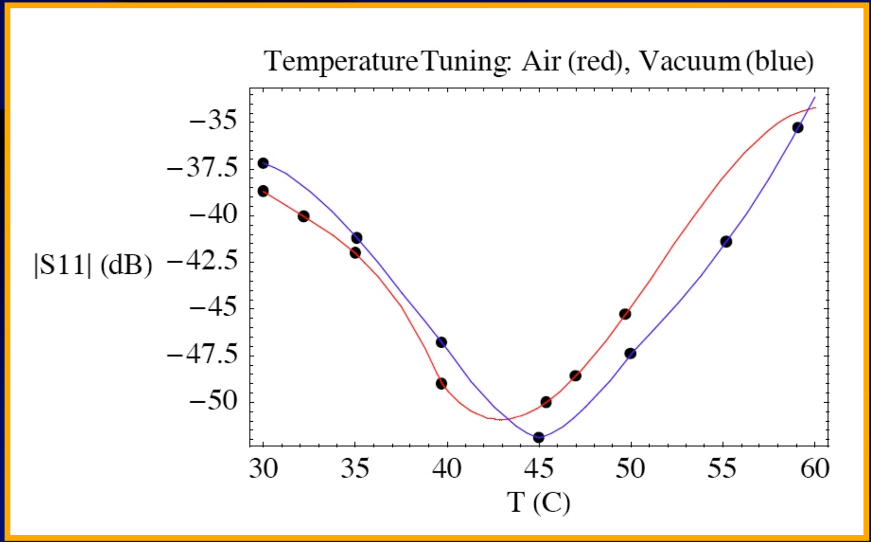
f_0 = 9.60043 GHz ; Δf = 1.5 MHz
β = 0.965 ; VSWR = 1.03637
Q_L = 6638 ; Q_0 = 13043 ; Q_e = 13517

Temperature Tuning



Frequency vs. Temperature

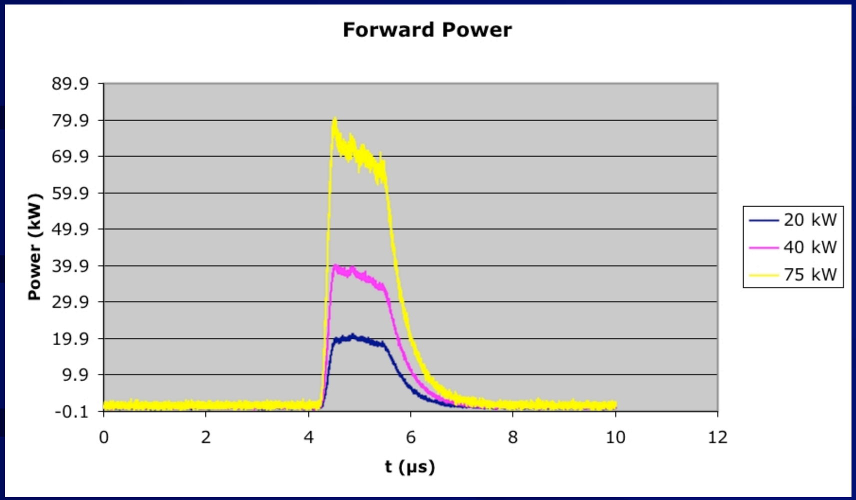
- using heater tape and thermocouple
- PID temperature feedback control
- dots are measured data
- solid lines are linear fits
- d*f*/d*T* = -179 kHz/˚C

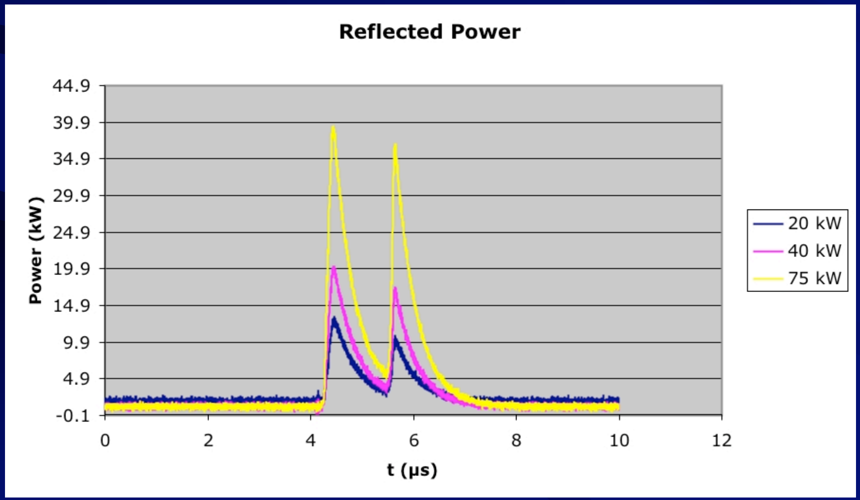


Reflectance vs. Temperature

- dots are measured data
- solid lines are interpolations
- at optimal freq in vacuum (9.59616 GHz), cavity is slightly <u>overcoupled</u> (-35 dB @ 62 C)
- therefore operating β = 1.036 in vacuum

High Power RF Measurements

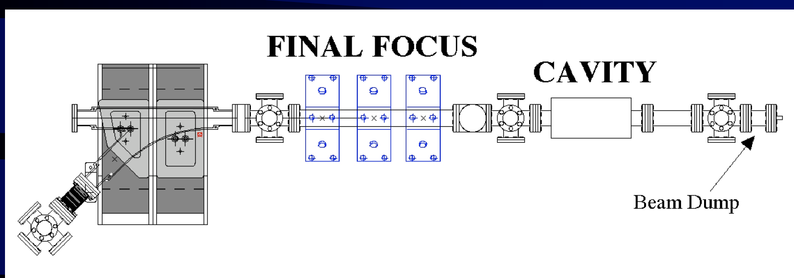


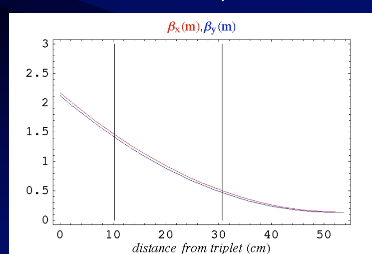


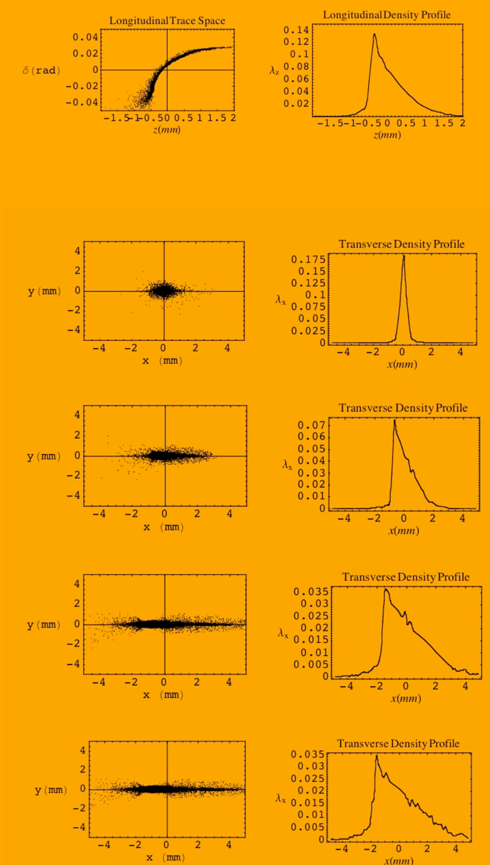
ELEGANT Simulations

ELEGANT Simulation Results

- Using RFDF element with 9 cells
- 10,000 macroparticles
- Shunt Impedance: $R_T = 6.12\ M\Omega$
- Power: $P = V_0^2/R_T$







Initial Current Profile

$V_0 = 0$; $P = 0$

$V_0 = 272$ kV ; $P = 12$ kW

$V_0 = 545$ kV ; $P = 48$ kW

$V_0 = 609$ kV ; $P = 61$ kW

* see e.g. Emma P, et al, SLAC report LCLS-TN-00-12 (2000).

ELEGANT Simulations

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- Using RFDF element with 9 cells
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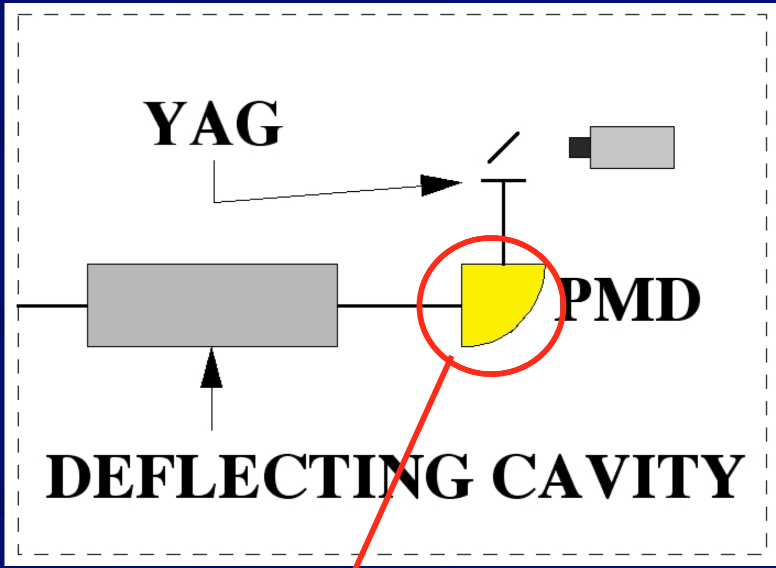

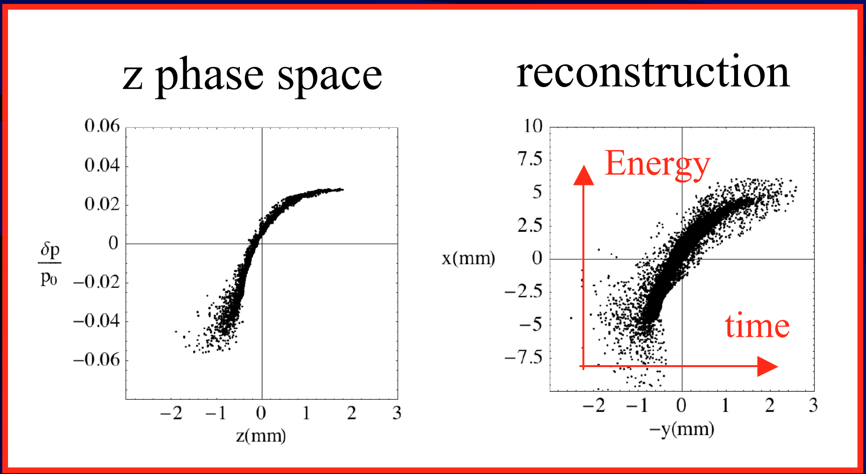

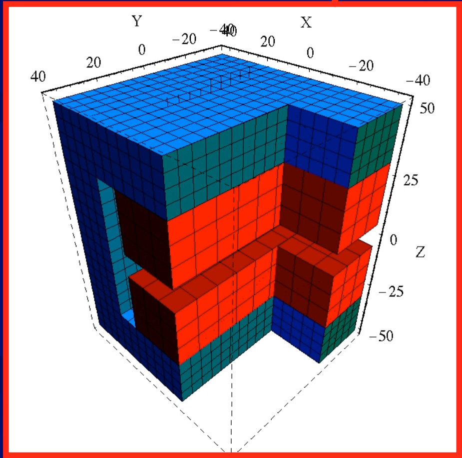

- Hybrid permanent magnet & iron dipole
- Designed in RADIA
- Built and ready for installation

Addition of dipole magnet permits full tomographic reconstruction.*

Conclusions

- Ramped bunch profile:
  - improved transformer ratio (R > 2) for PWFA applications
  - feasible using dogleg compression with sextupoles
  - deflecting cavity diagnostic (50 fs resolution)
- Status of deflecting cavity
  - final cavity design finalized using HFSS
  - cavity construction complete; cavity installed at Neptune
  - high power RF testing complete: no breakdown problems observed
- Near-term experiments:
  - test cavity with 12.5 MeV electron bunches
  - implement permanent magnet dipole for t-p phase space tomography
  - implement permanent magnet quadrupoles for high-brightness focus studies