Beam Shaping and Permanent Magnet Quadrupole Focusing with Applications to the Plasma Wakefield Accelerator

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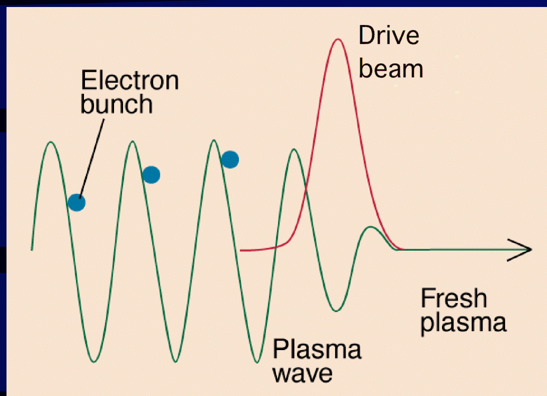
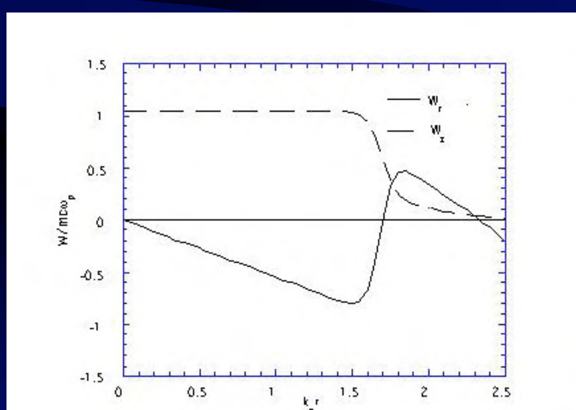
The Plasma Wakefield Accelerator (PWFA)



Bingham, R. Nature, **394**, 617 (1998).

Wake Fields in Blowout Regime



Rosenzweig, et al. PRA, **44**, R6189 (1991)

Overdense Plasma

$n_b < n_p$; $k_p \sigma_z > 1$ current neutralized

$n_b < n_p$; $k_p \sigma_r << 1$ self-focused

Underdense Plasma

$n_b/n_p > \gamma^2$ unfocused

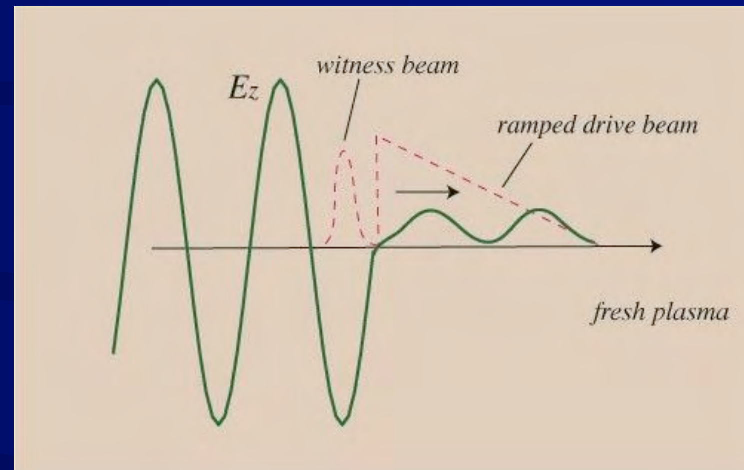
$\gamma^2 > n_b / n_p > 1$ ion focused (blowout)

Blowout Regime Mechanism:

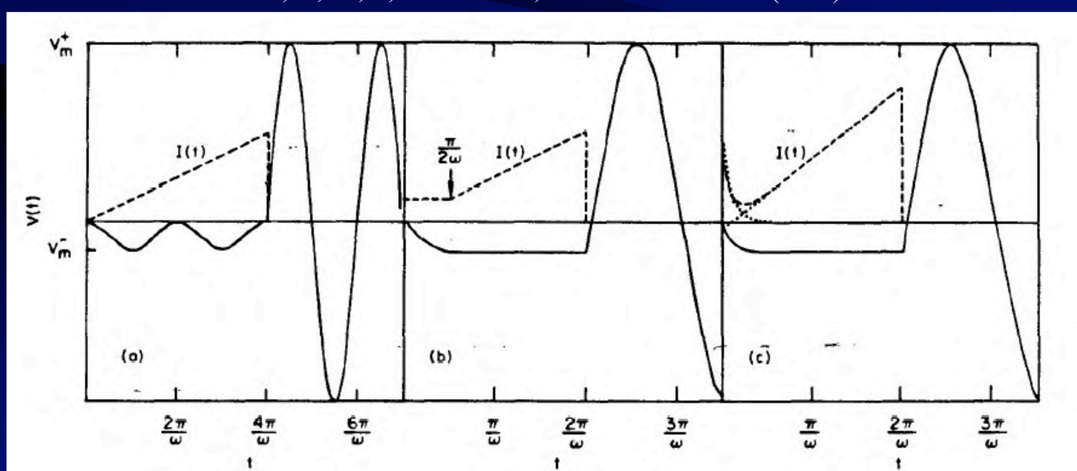
- Plasma electrons disturbed by drive beam.
- Longitudinal space-charge wave generated.
- Ion channel created, pulls electrons back.
- Ion focusing is linear in r.
- Accelerating electric field, $E_{acc} \approx n_0^{1/2}$ [V/cm]

Overview of Drive Beam Issues for Blowout Regime of PWFA

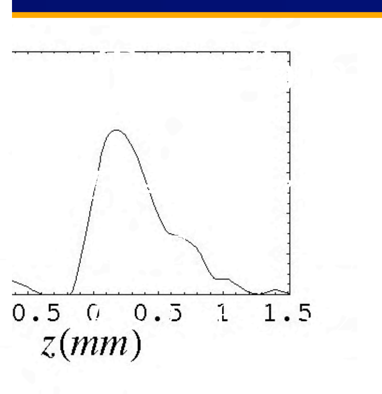
- **Longitudinal bunch shape**
- **High beam brightness**
  - **High charge**
  - **Strong Focusing**
  - **Betatron matching**
- **Creation of a Witness Bunch**



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



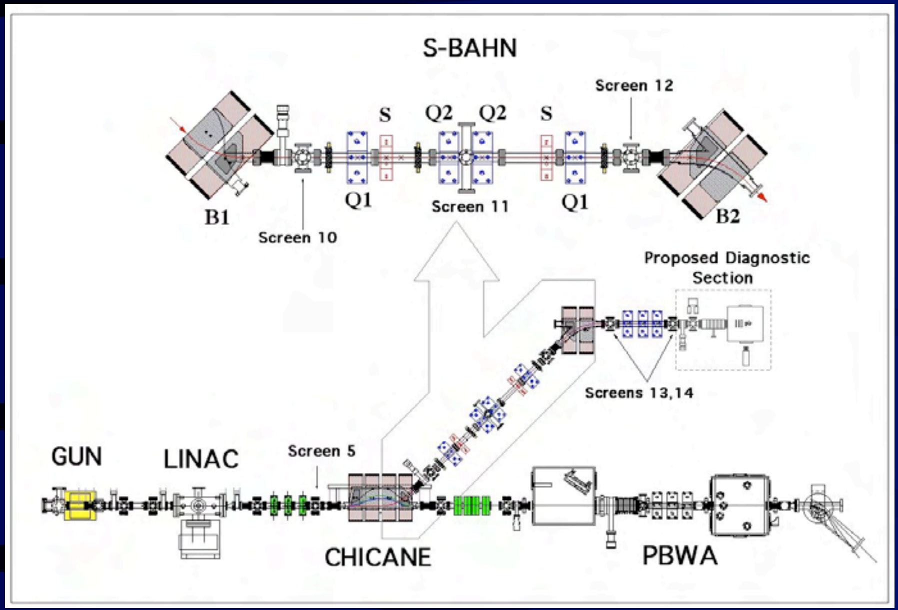
triangle **doorstep** **ideal**



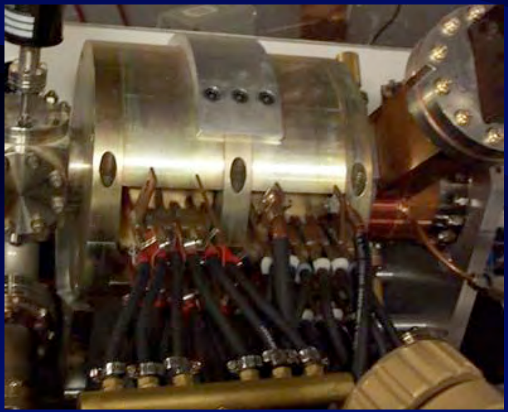
r Ratio:

= *decc.field*

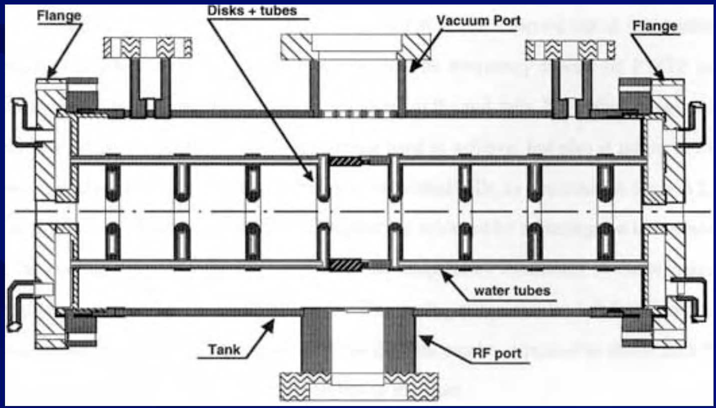
The UCLA Neptune Laboratory



Beam Charge:	100-300 pC
Beam energy:	up to 15 MeV
Emittance:	ε_N = 6 mm mrad
Power Source:	18 MW Klystron
RF Frequency:	2.856 GHz
Cathode laser:	60-80 μJ at λ = 266 nm
Laser pulse length:	5 ps RMS



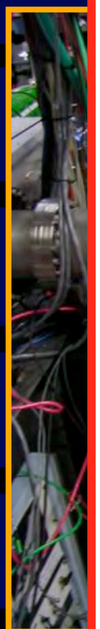
1.6-Cell Photoinjector

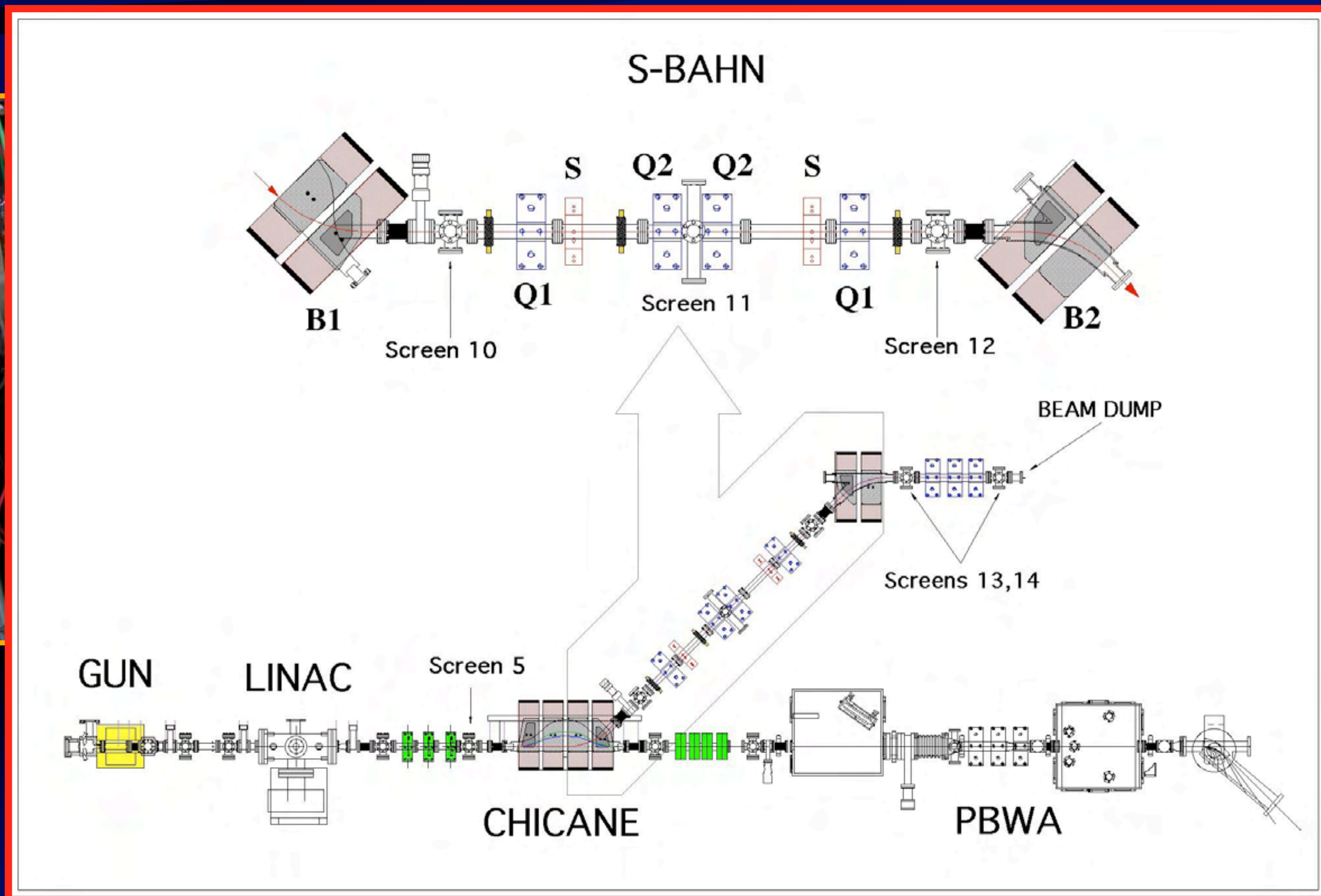


7&2/2 Cell PWT Linac

Neptune Dogleg Compressor

S-Bahn Compressor





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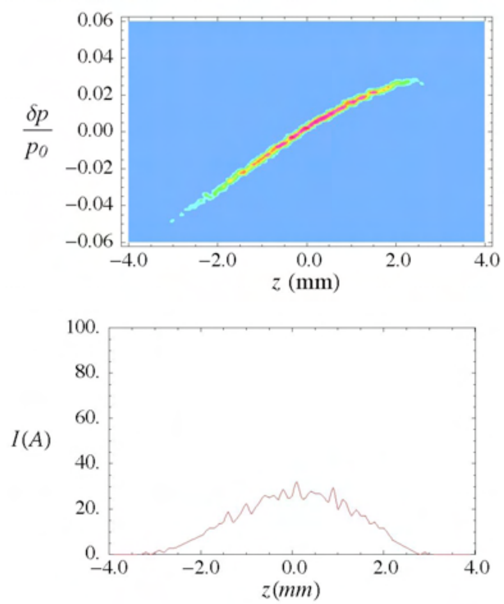
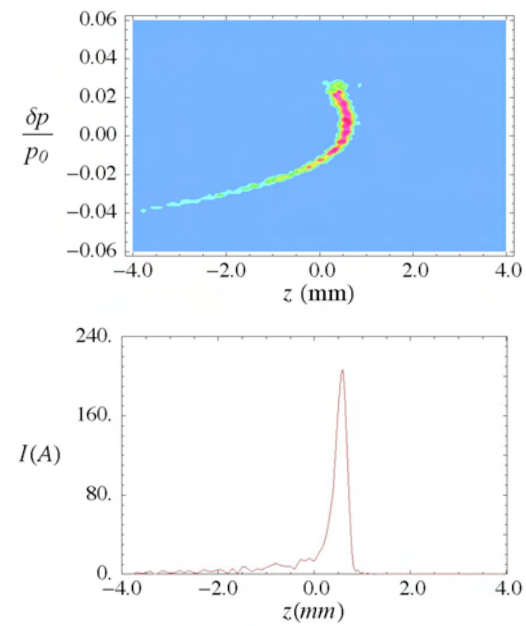
$_6$=-5cm)

Neptune Dogleg Compressor

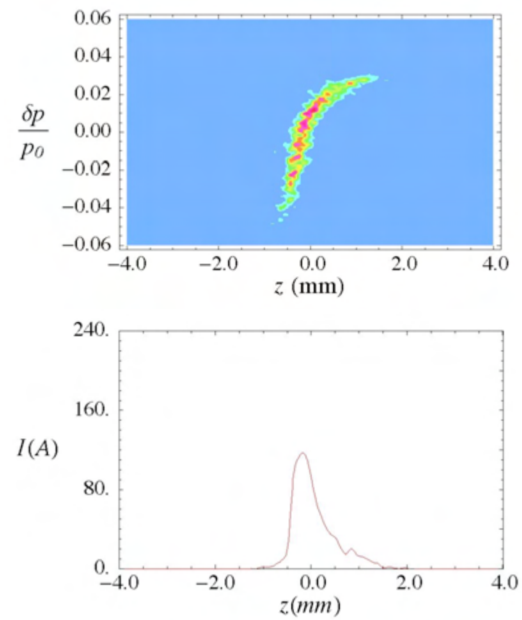
PARMELA Simulation Results: 1000 particles, 300pC



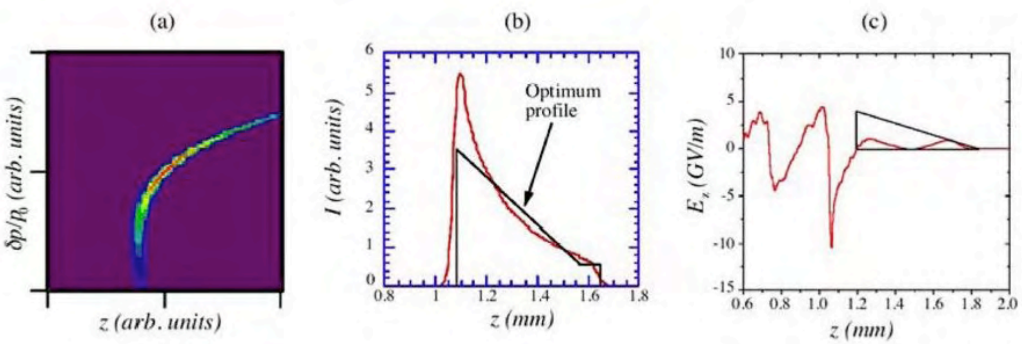
Initial



Final: Sextupoles Off



Final: Sextupoles On

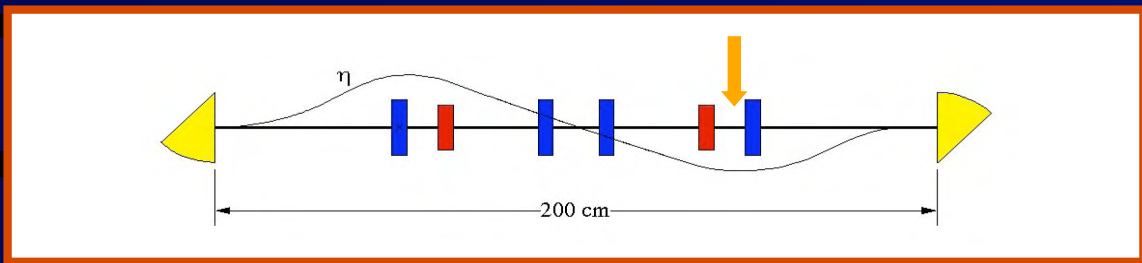


- 2D PIC Simulation
- 5 GeV/m gradients
- 6 nC drive beam w/ n_0=2e16 cm^{-3}

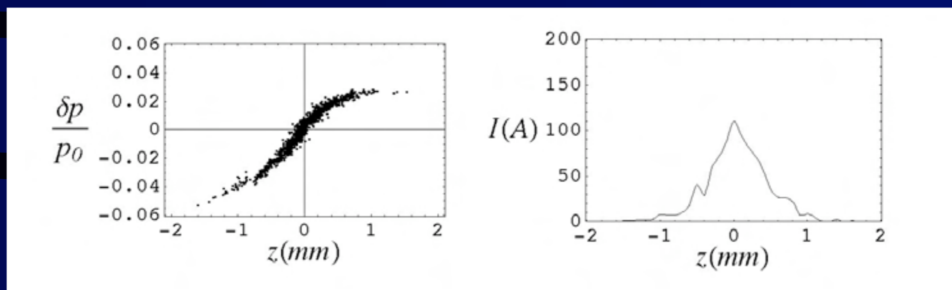
Neptune Dogleg Compressor

ELEGANT: Simulated Witness Beam

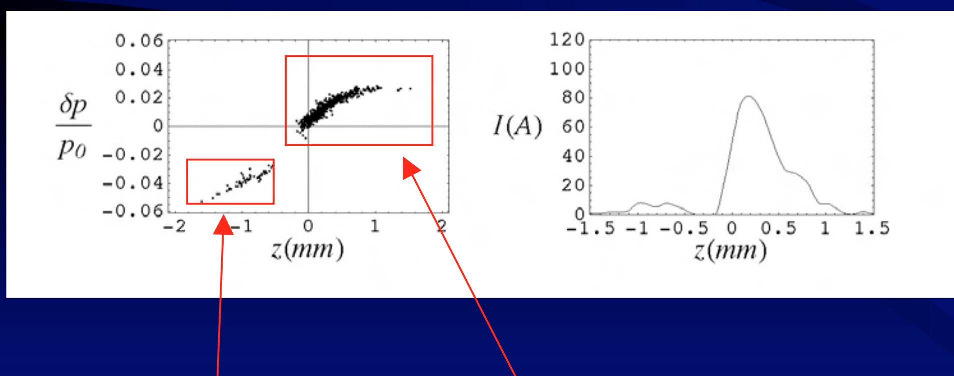
For PWFA application, drive beam needs a witness beam to accelerate.



Region of high dispersion in x
Strong correlation b/w x and z
Insert mask in x to **sever** beam in z



No mask inserted
Undercorrected with sextupoles to elongate profile



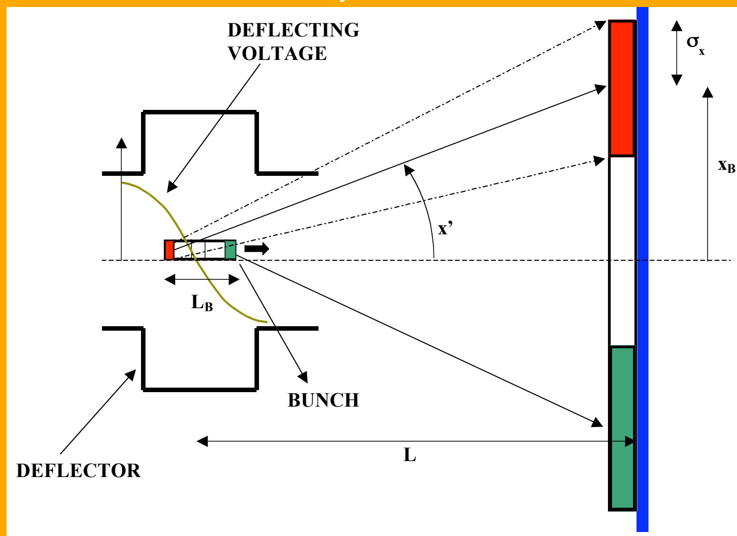
With 1cm mask inserted at above location

witness beam **ramped drive beam**

Temporal Bunch Shaping: Diagnostic

Deflecting Mode Cavity

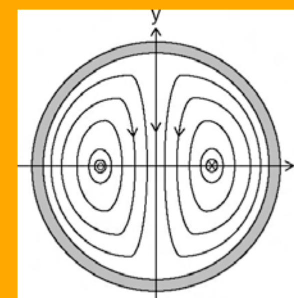
Courtesy of D. Alesini



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

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

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

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

$\sigma_{x,f}$ = 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;

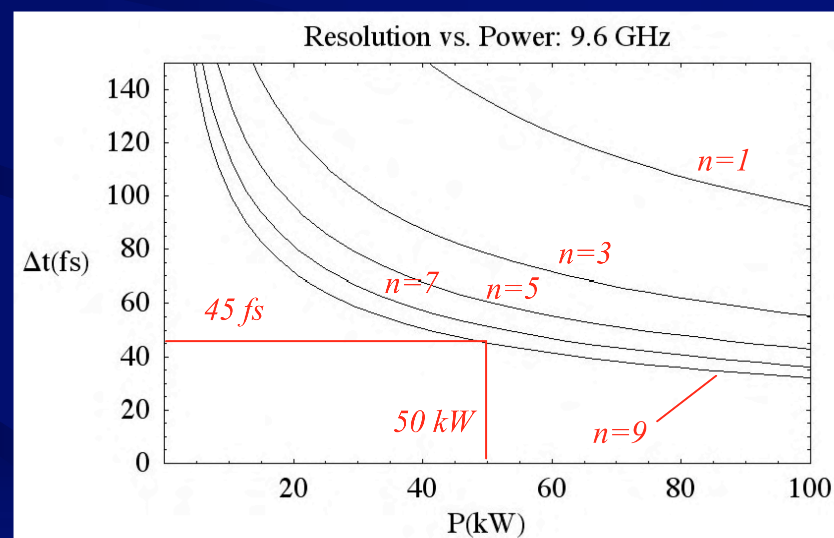
$U = 12MeV$ = electron beam energy;

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;

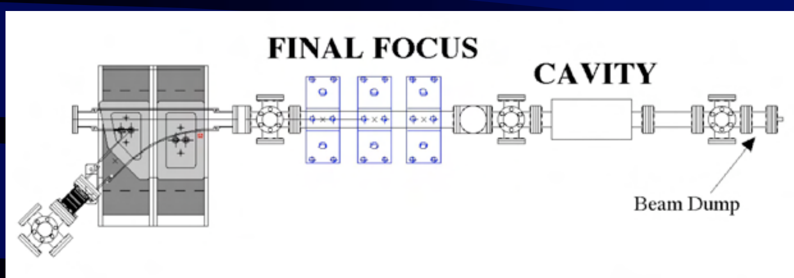


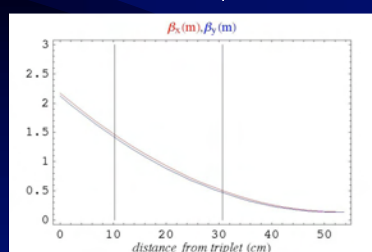
9 cells; 50 kW; 50 fs resolution

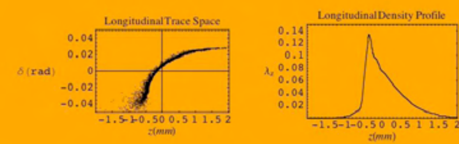
ELEGANT Simulations

ELEGANT Simulation Results

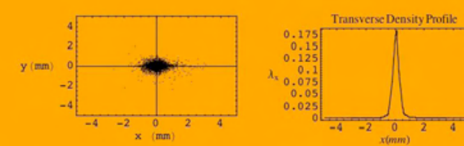
- Using RFDF element with 9 cells
- 10,000 macroparticles
- Shunt Impedance: $R_T = 6.12\ M\Omega$
- Power: $P = V_0^2/R_T$



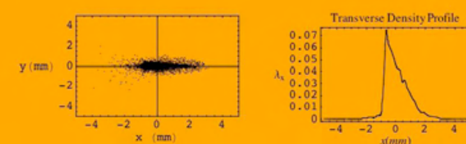




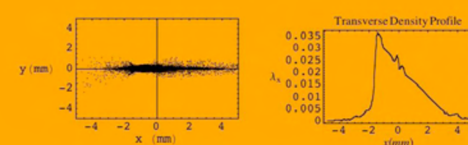
Initial Current Profile



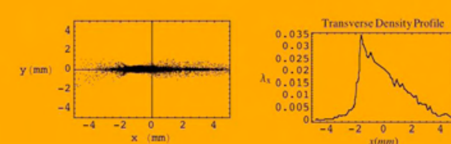
$V_0 = 0$; $P = 0$



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

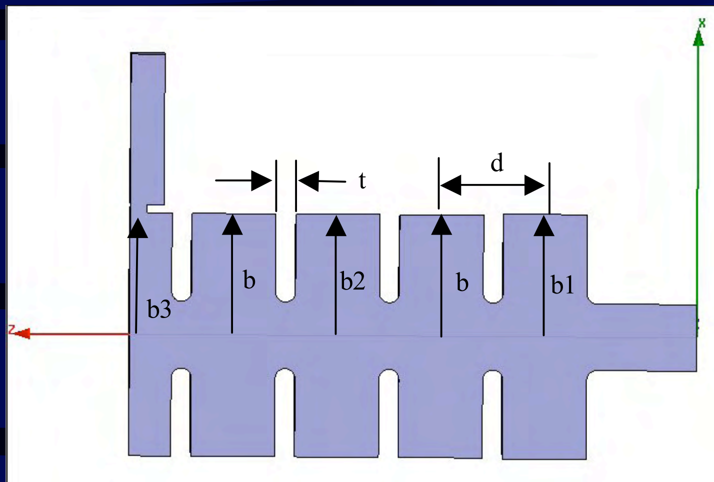


$V_0 = 545$ kV ; $P = 48$ kW



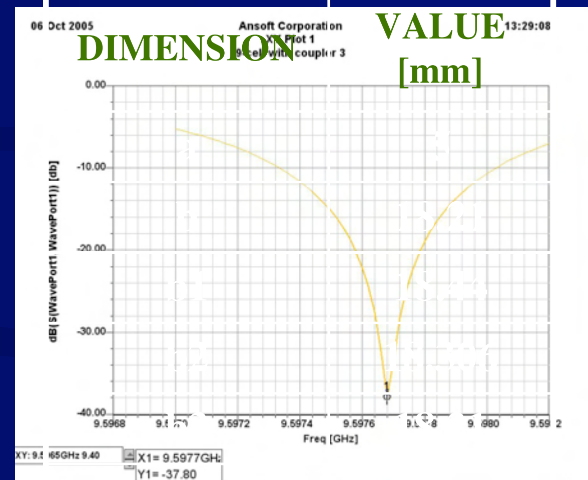
$V_0 = 609$ kV ; $P = 61$ kW

Deflecting Cavity: HFSS Design



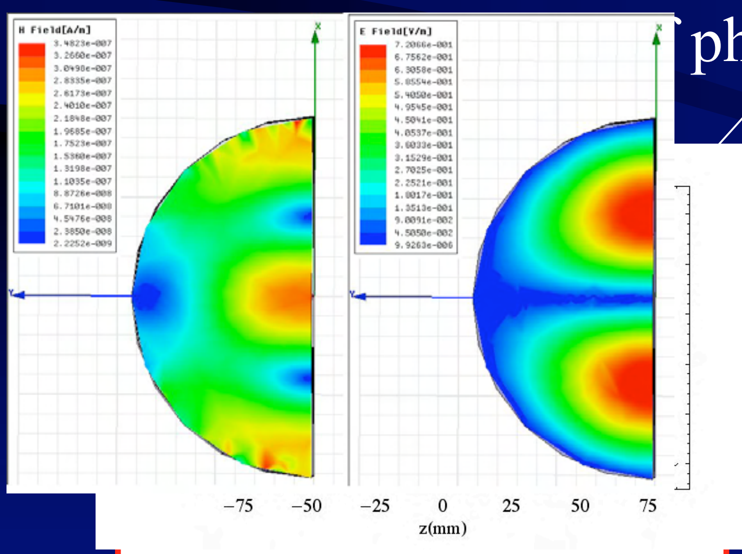
HFSS Geometry of 1/2 structure

DIMENSION	VALUE [mm]
t	3.0
d	15.62



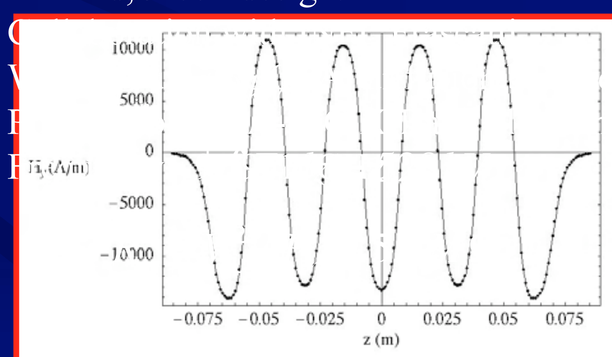
Resonance of the π-Mode

phase by 90°

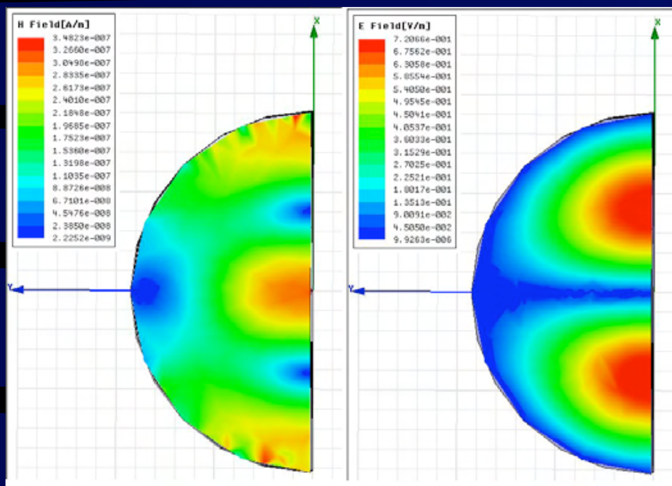


H-field

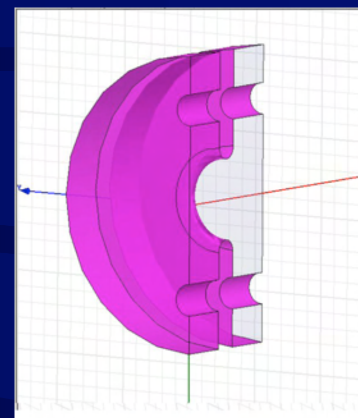
- X-Band, 9-cell design.
- at SLAC.
- @ 50 kW.



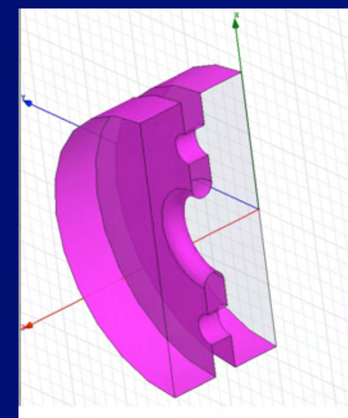
Deflecting Cavity: Polarization Separation



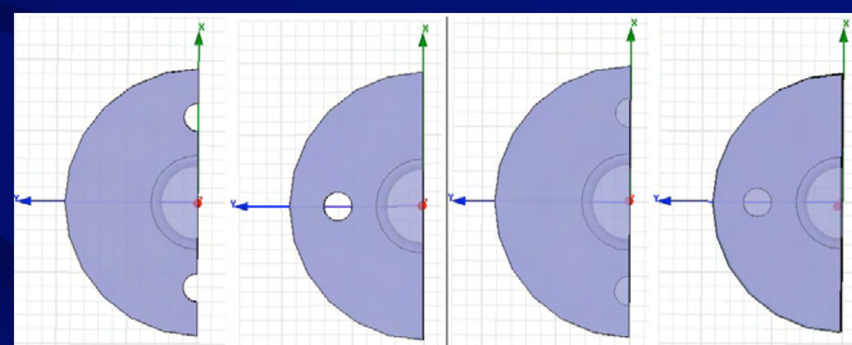
Rods



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



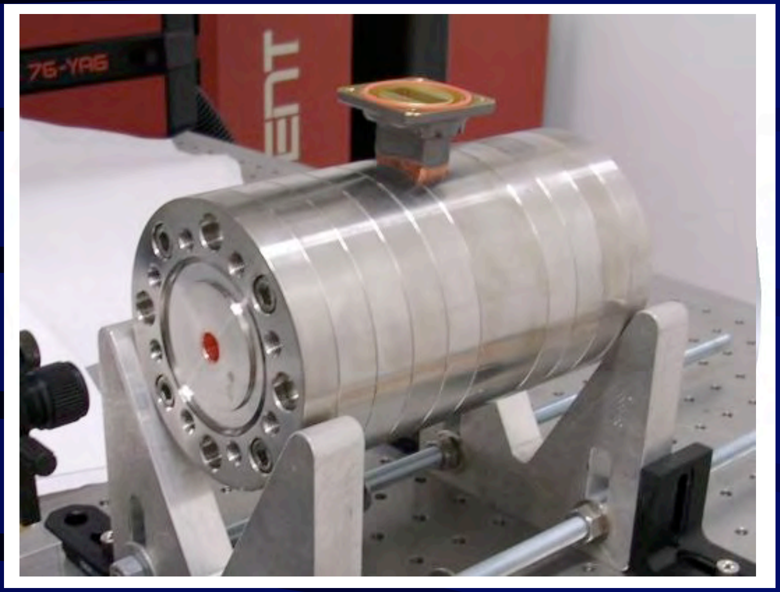
Undesired +1358 MHz

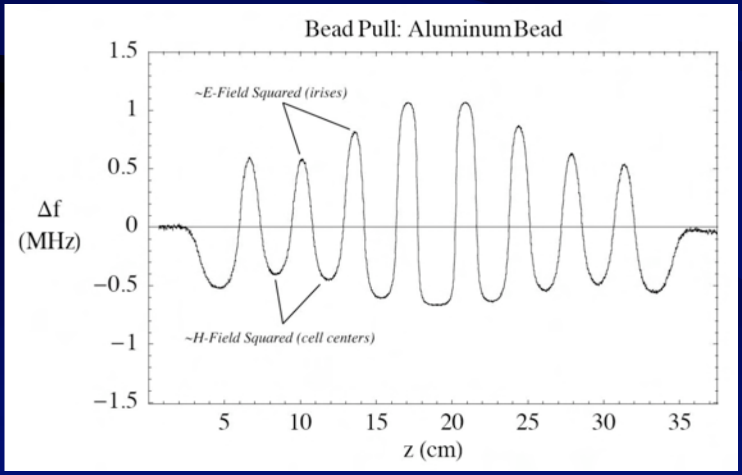
Desired +53 MHz

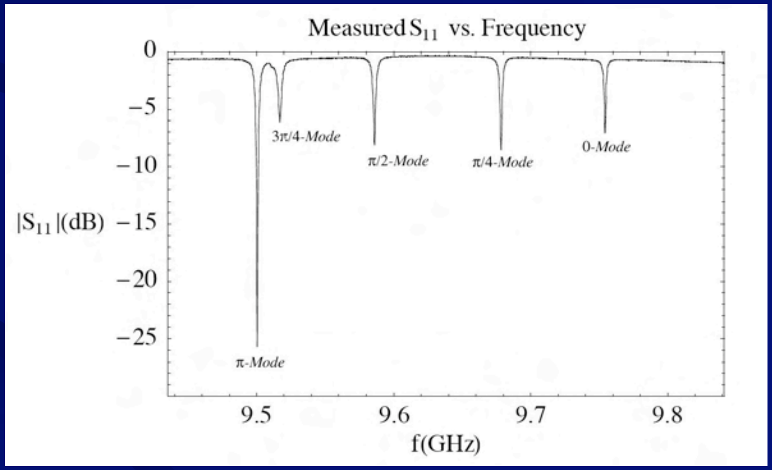
Undesired -7 MHz

Desired -2 MHz

Prototype Cavity







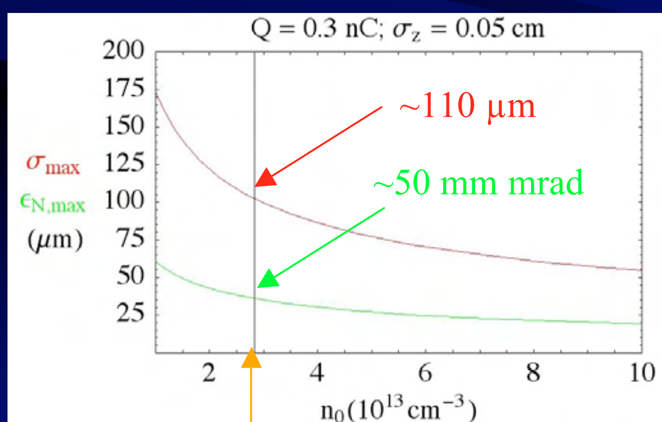
Constraints on Brightness & Emittance

blowout regime | transformer ratio | betatron matching

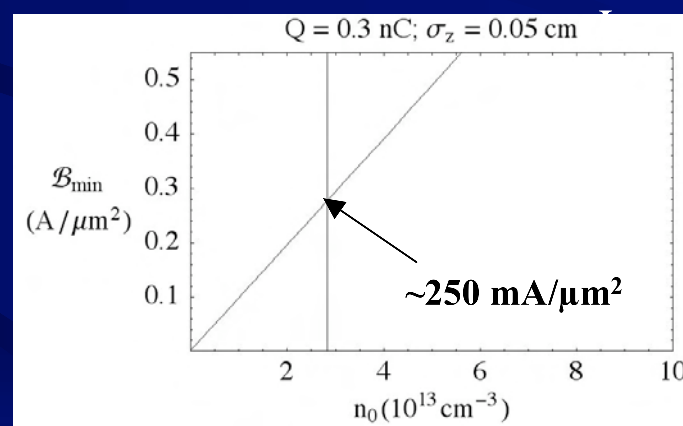
$$n_0 > \frac{mc^2}{\pi e^2 L} \qquad \sigma_r < \sigma_{\max} = \sqrt{\frac{Q/e}{4\pi n_0 \sigma_z}} \qquad \varepsilon_N < \varepsilon_{N\max} = \gamma\beta \frac{\sigma_{\max}^2}{\beta_{eq}} \qquad \mathcal{B} > \mathcal{B}_{min} = \frac{2I}{\varepsilon_N^2} = \frac{2cQ}{\varepsilon_{N\max}^2 \sigma_z}$$

Q=300 pC ; L=2mm; σ_z = 0.5 mm

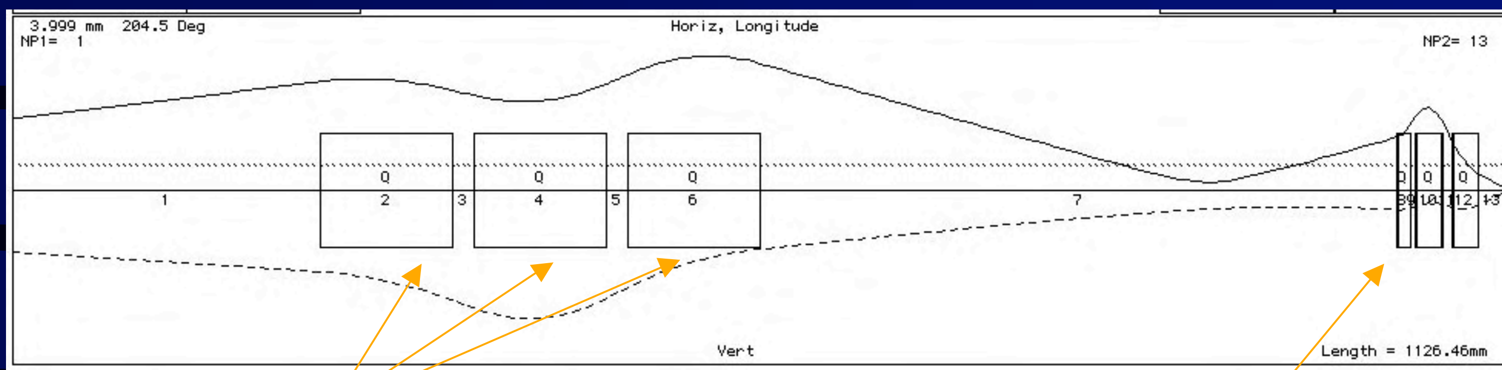
$n_b v \pi \sigma_r^2$



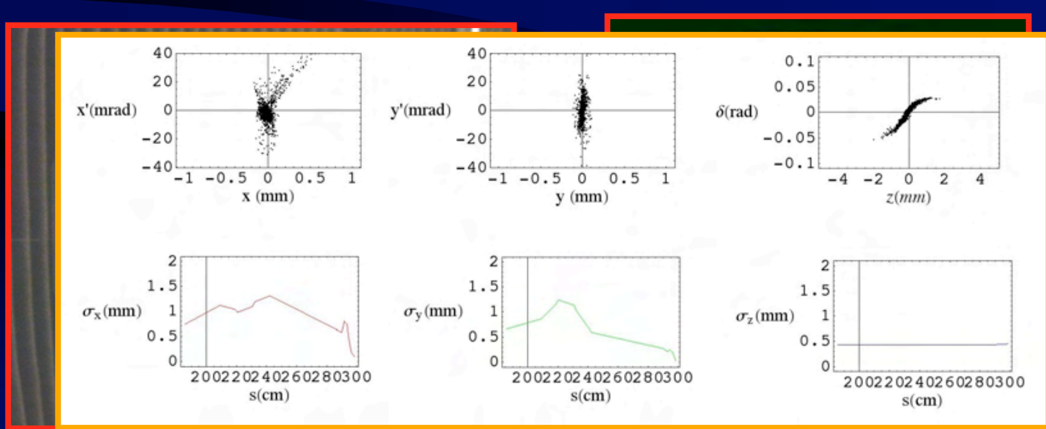
n_{0min} ~ 2.8×10^{13} cm^{-3}



Permanent Magnet Quad Focusing



PowerTrace 1.08 Simulation



- Hybrid Permanent Magnet and Iron
- Grey cubes are Alnico; M=1.175 T
- Field gradient:
  B′=110 T/m, B′′′=0.002 T/m²
- Bore diameter: 8mm
- Benefits: cheaper, better field profile
- Downsides: small bore; in-vacuum

ELEGANT Simulation Result

γ=25.7; E=13.13 MeV; Q = 300 pC

σ_x=130 μm; ε_x=41 mm mrad

σ_y=57 μm; ε_y=15 mm mrad

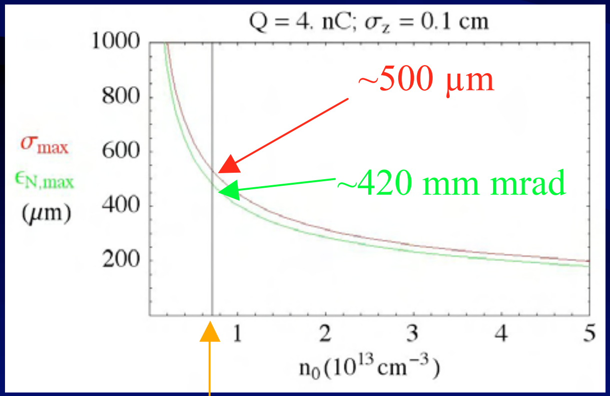
σ_z=0.51 mm; σ_δ=1.84%

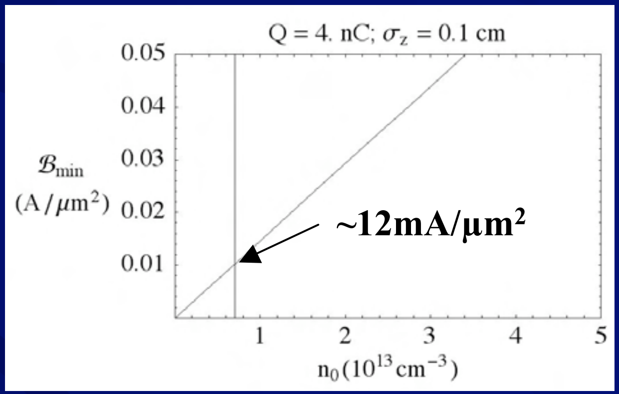
$$\mathcal{B} \approx \frac{2Q/\sigma_t}{\varepsilon_{N,x}\varepsilon_{N,y}} = 412 mA/\mu m^2$$

Scaling to Higher Charge: 4 nC

$$n_0 > \frac{mc^2}{\pi e^2 L} \qquad \sigma_r < \sigma_{\max} = \sqrt{\frac{Q/e}{4\pi n_0 \sigma_z}} \qquad \varepsilon_N < \varepsilon_{N\max} = \gamma\beta \frac{\sigma_{\max}^2}{\beta_{eq}} \qquad \mathcal{B} > \mathcal{B}_{min} = \frac{2cQ}{\varepsilon_{N\max}^2 \sigma_z}$$

Q=4 nC ; L=4mm; σ_z = 1 mm



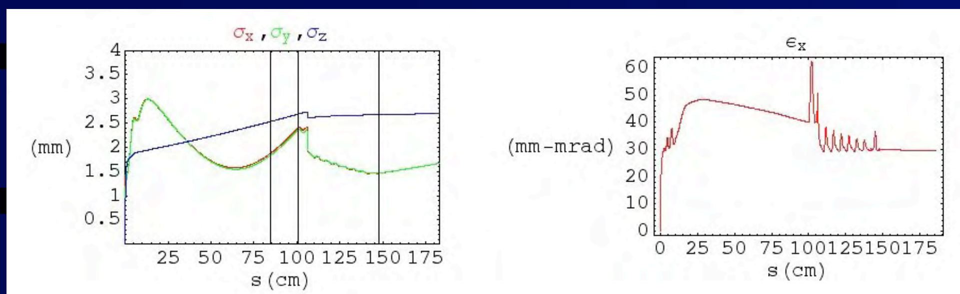


$n_{0min} \sim 0.8 \times 10^{13}\ cm^{-3}$

Scaling to Higher Charge: 4 nC

scaling applied to laser at cathode: $\sigma_x, \sigma_y, \sigma_t \propto Q^{1/3}$ $(Q : 300\,pC \rightarrow 4nC)$

Q = 4 nC; pt-to-pt space charge



UCLA-Parmela 2.0, 1000 particles

*** BEAM PARAMETERS AT END - SAVECOR6000 ***

Beam Energy:

γ= 25.4691, U= 13.0147 MeV, T= 12.5037 MeV, p_0/mc= 25.4494

X Twiss Paramters:

σ_x= 1.694 mm, α_x= -0.915558, β_x= 3.01018 m, ϵ_{xn}= 24.2613 mm mrad

Y Twiss Paramters:

σ_y= 1.69297 mm, α_y= -0.875431, β_y= 2.95505 m, ϵ_{yn}= 24.6839 mm mrad

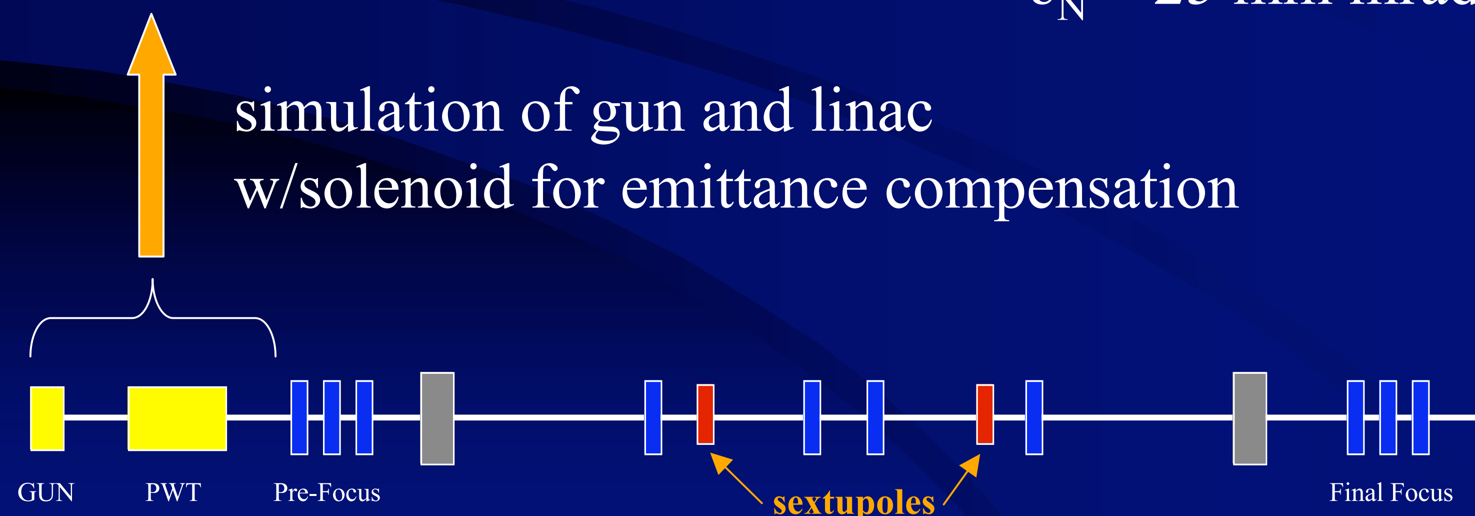
Z Phase Space Parameters:

σ_z = 2.70076 mm, σ_t = 9.01155 ps, σ_δ = 4.4692 %

N_{final} = 964 particles

$\varepsilon_N \sim 25$ mm mrad

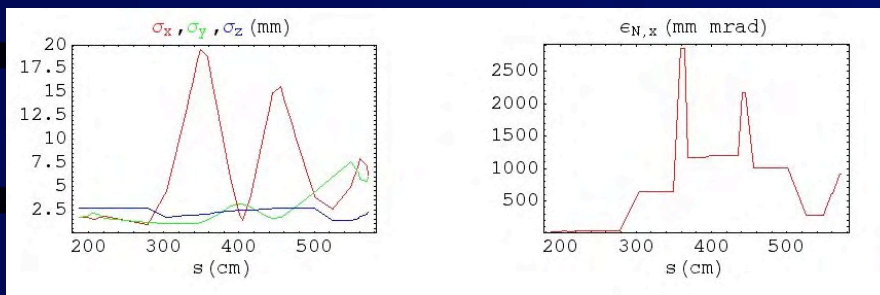
simulation of gun and linac
w/solenoid for emittance compensation



Scaling to Higher Charge: 4 nC

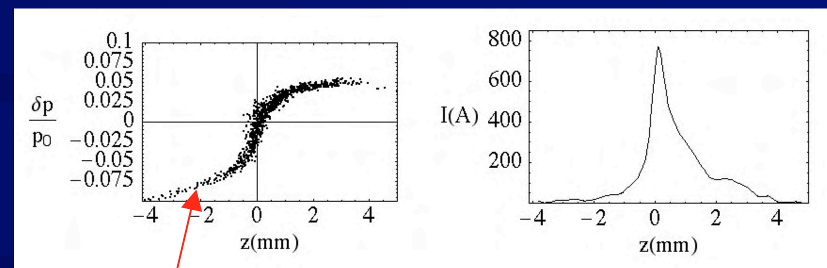
scaling applied to laser at cathode: $\sigma_x, \sigma_y, \sigma_t \propto Q^{1/3}$ $(Q: 300\,pC \rightarrow 4nC)$

dispersion killed to 1st Order



ELEGANT, 1000 particles

longitudinal ph. space and profile at end

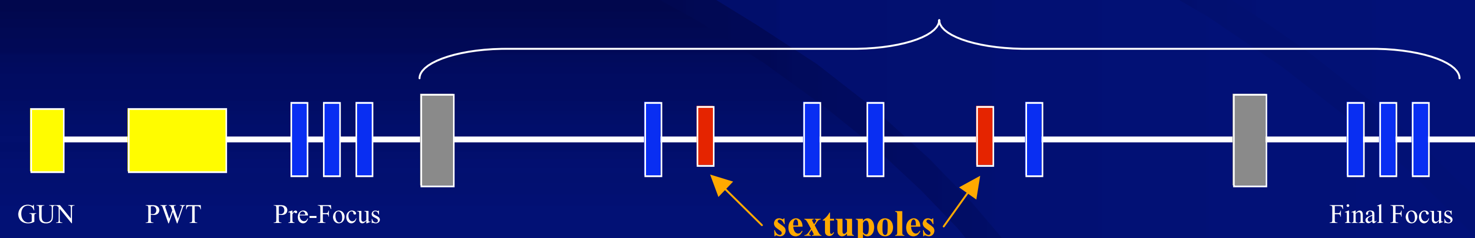


$\varepsilon_{N,x} = 742\ mm\ mrad$

$\varepsilon_{N,y} = 456\ mm\ mrad$

simulation of sbahn and final focus
horizontal dispersion killed to first order (R_{16},R_{26})
2nd order longitudinal dispersion T_{566} killed

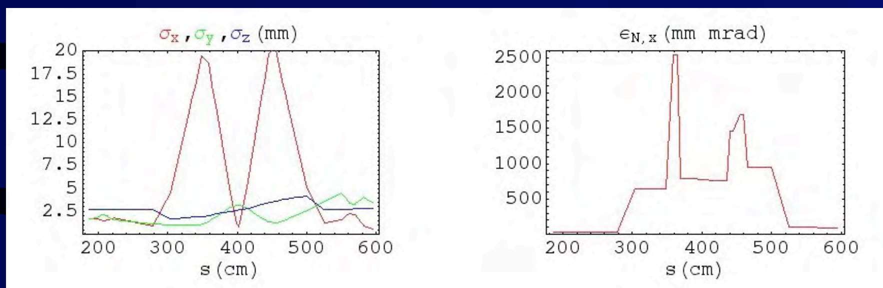
tail is 3rd order (U_{5666})
octupoles needed?



Scaling to Higher Charge: 4 nC

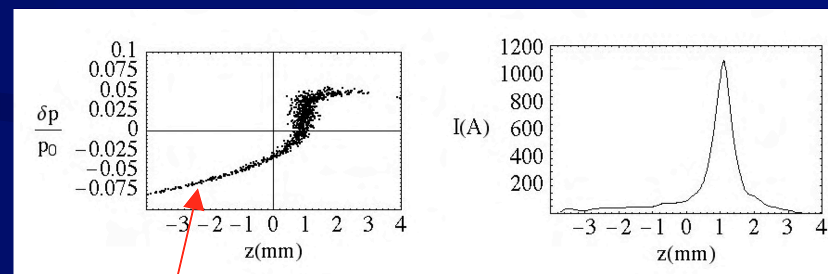
scaling applied to laser at cathode: $\sigma_x, \sigma_y, \sigma_t \propto Q^{1/3} \quad (Q: 300\,pC \rightarrow 4nC)$

dispersion killed to 2nd Order



ELEGANT, 1000 particles

longitudinal ph. space and profile at end

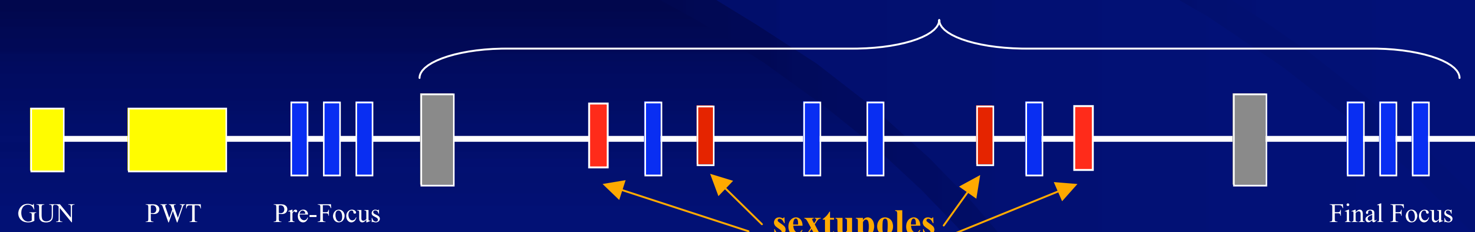


$\varepsilon_{N,x} = 96\ mm\ mrad$

$\varepsilon_{N,y} = 141\ mm\ mrad$

simulation of sbahn and final focus
horizontal dispersion killed to second order
2nd order longitudinal dispersion not killed

tail is 2nd **and** 3rd order
(T_{566}, U_{5666})



Conclusions

- PWFA drive issues: ramped profile, strong focus, high charge

- Ramped profile:
  - improved transformer ratio (R > 2)
  - feasible using dogleg compression with sextupoles
  - deflecting cavity diagnostic (50 fs resolution)
- Strong focus:
  - traditional EM quads + permanent magnet quadrupoles
  - adequate emittance and brightness (~ 100 µm, 450 mA/µm^2 @ 300 pC)
- High Charge:
  - scaling to high charge (~4 nC) at Neptune has some dilemmas
  - tradeoff between optimal profile and good emittance
  - extra sextupoles and octupoles may be required
  - beam sizes become bigger than the beam pipes
  - implies complete or partial redesign of the compressor