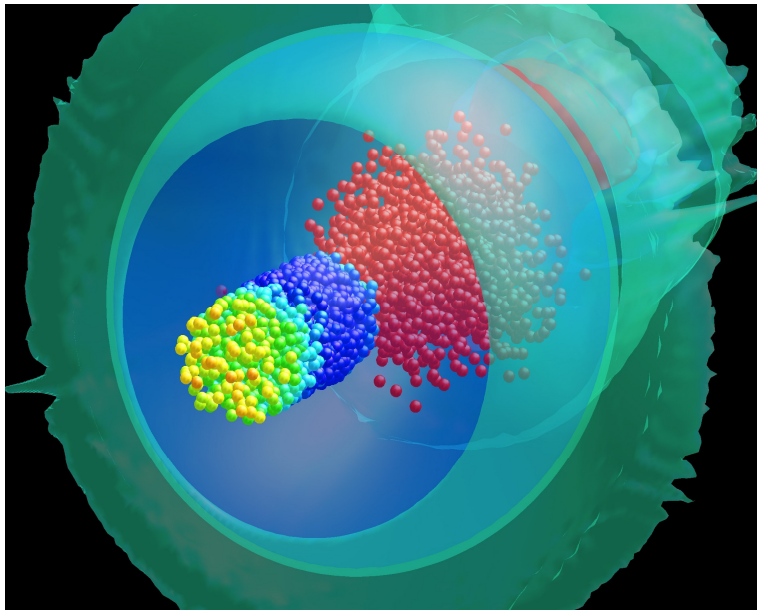
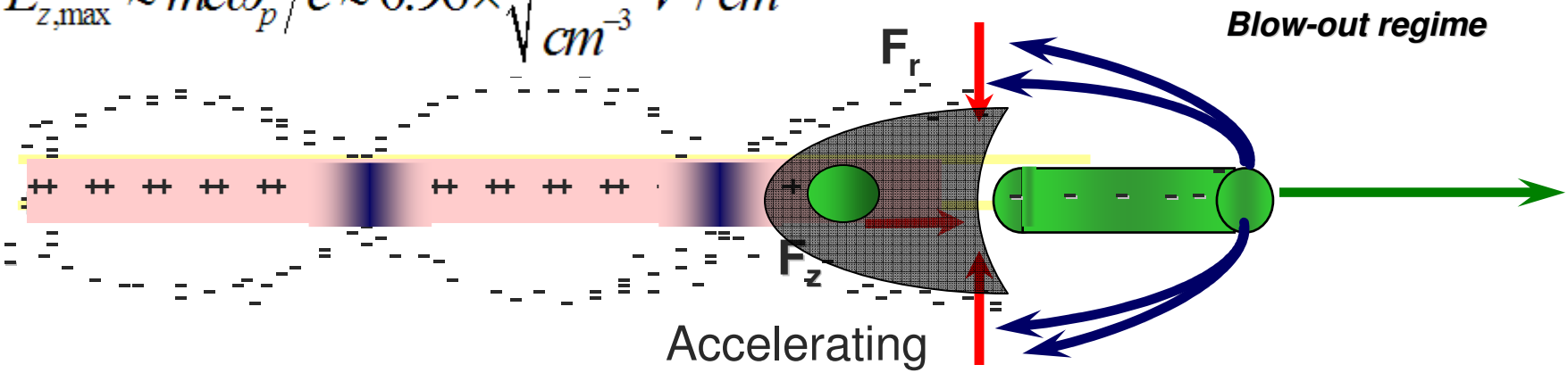
Challenges and results on modeling pwfa: current experiments and a collider

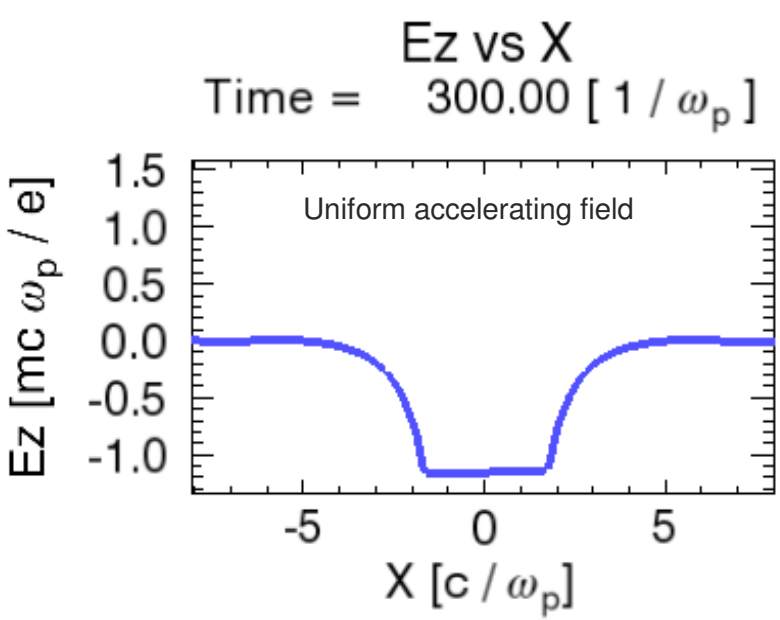
Chengkun Huang, I. Blumenfeld,
C. E. Clayton, F.-J. Decker,
M. J. Hogan, R. Ischebeck, R. Iverson,
C. Joshi, T. Katsouleas, N. Kirby,
W. Lu, K. A. Mash, W. B. Mori,
P. Muggli, E. Oz, R. H. Siemann,
D. Waltz, M. M. Zhou

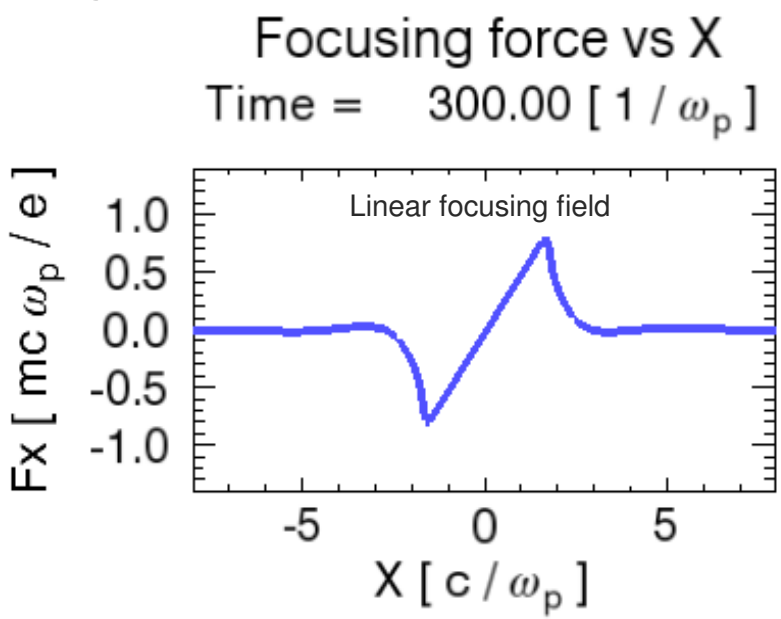


Plasma Wakefield Acceleration

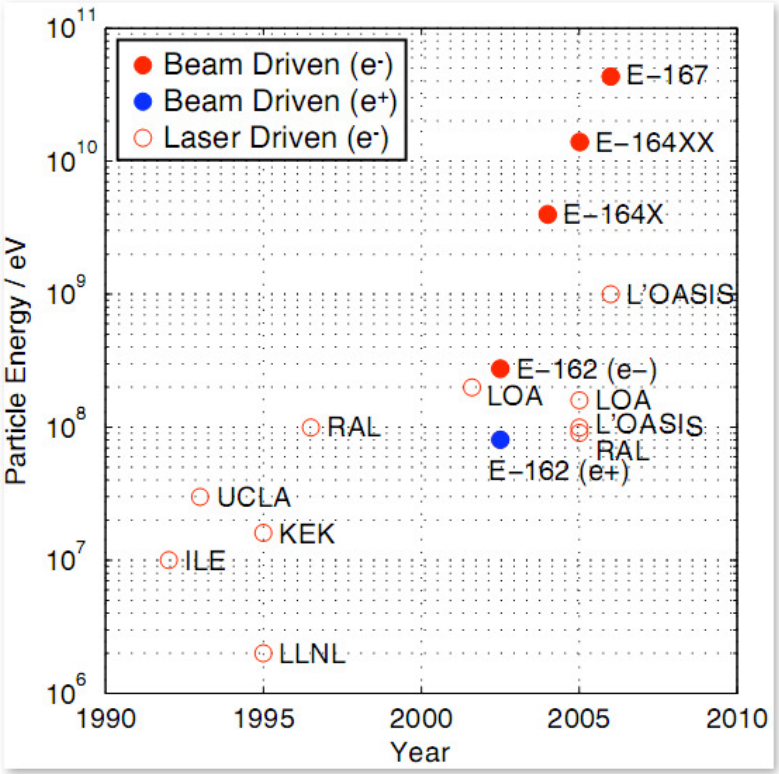
$$E_{z,\max} \approx mc\omega_p / e \approx 0.96 \times \sqrt{\frac{n}{cm^{-3}}}\, V/cm$$



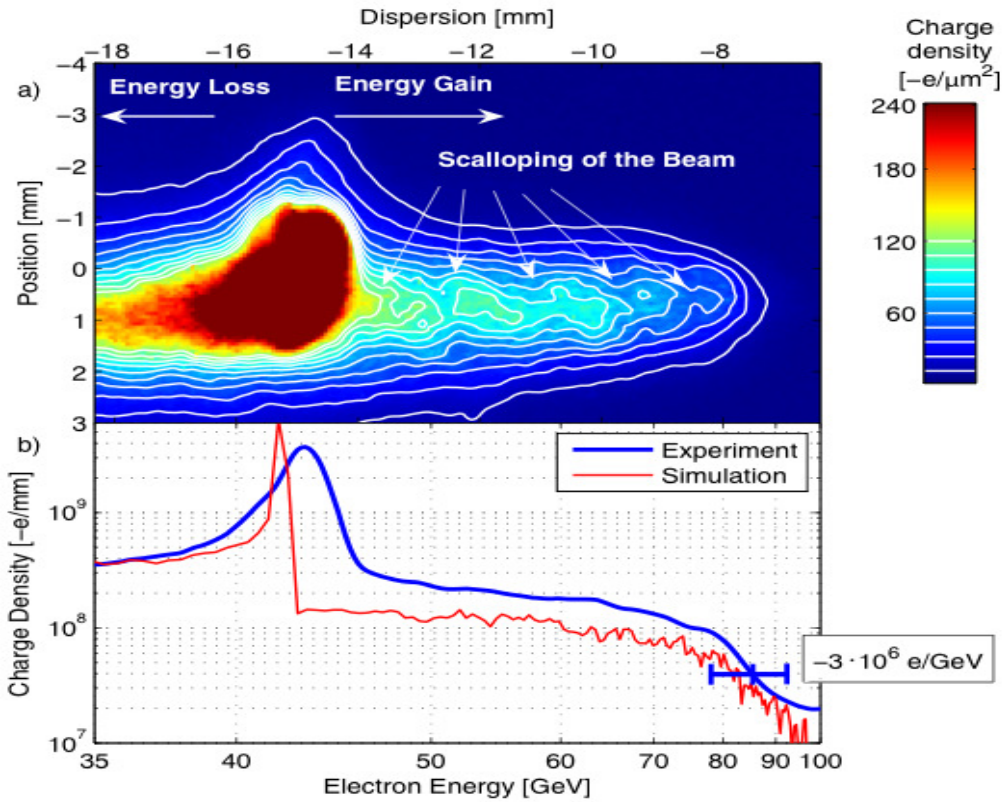




Energy doubler



The Energy Doubling Experiment



Blumenfeld et. al. Nature (2007)

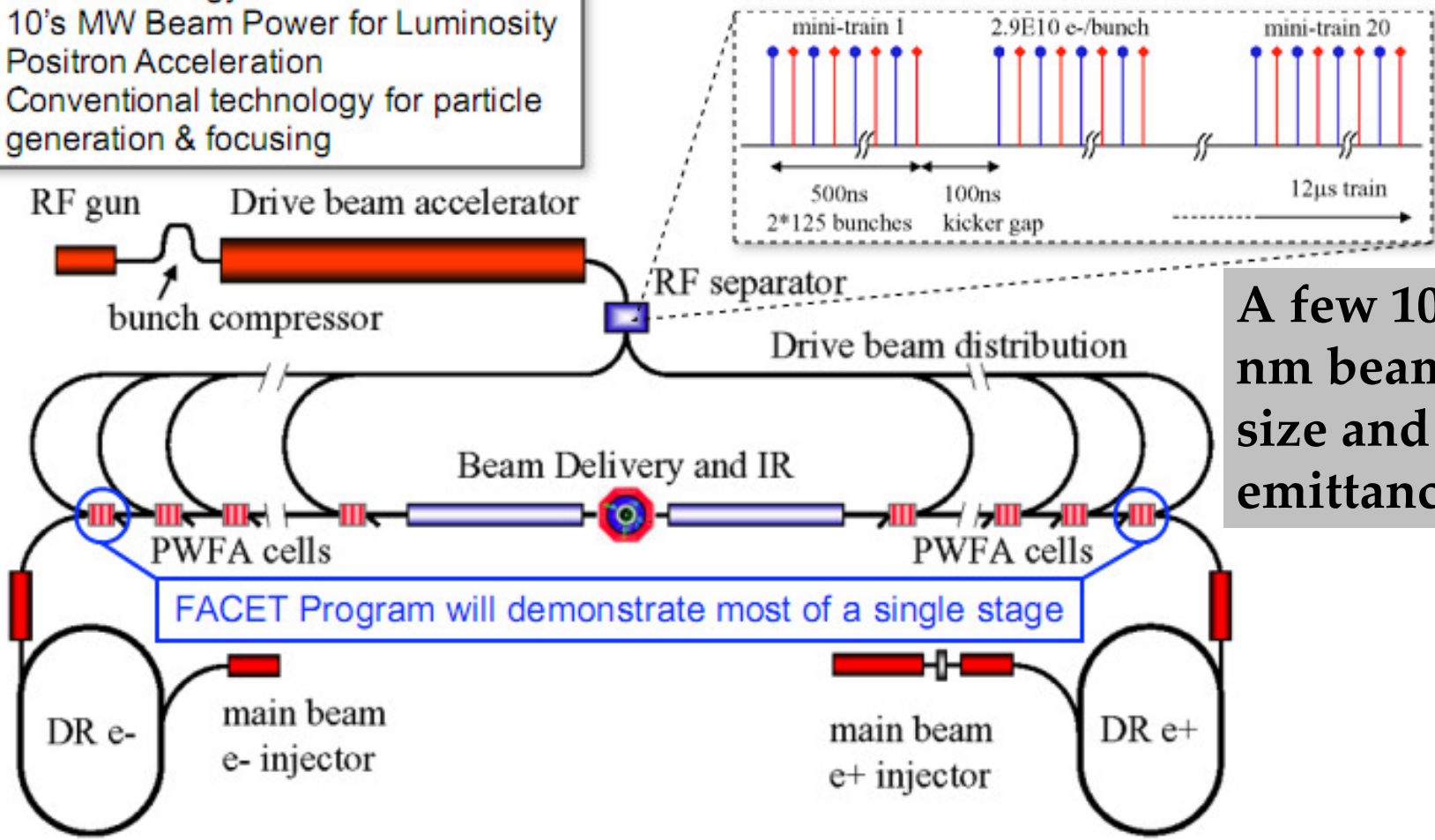
Particles, not beam yet!
Next step: demonstrate high quality beam acceleration

$$42GeV, N_b = 1.7\times10^{10}, \sigma_r = 10\mu m$$

$$\sigma_z = 15\mu m, n_p = 2.7\times10^{17} cm^{-3}$$

PWFA-based collider concept

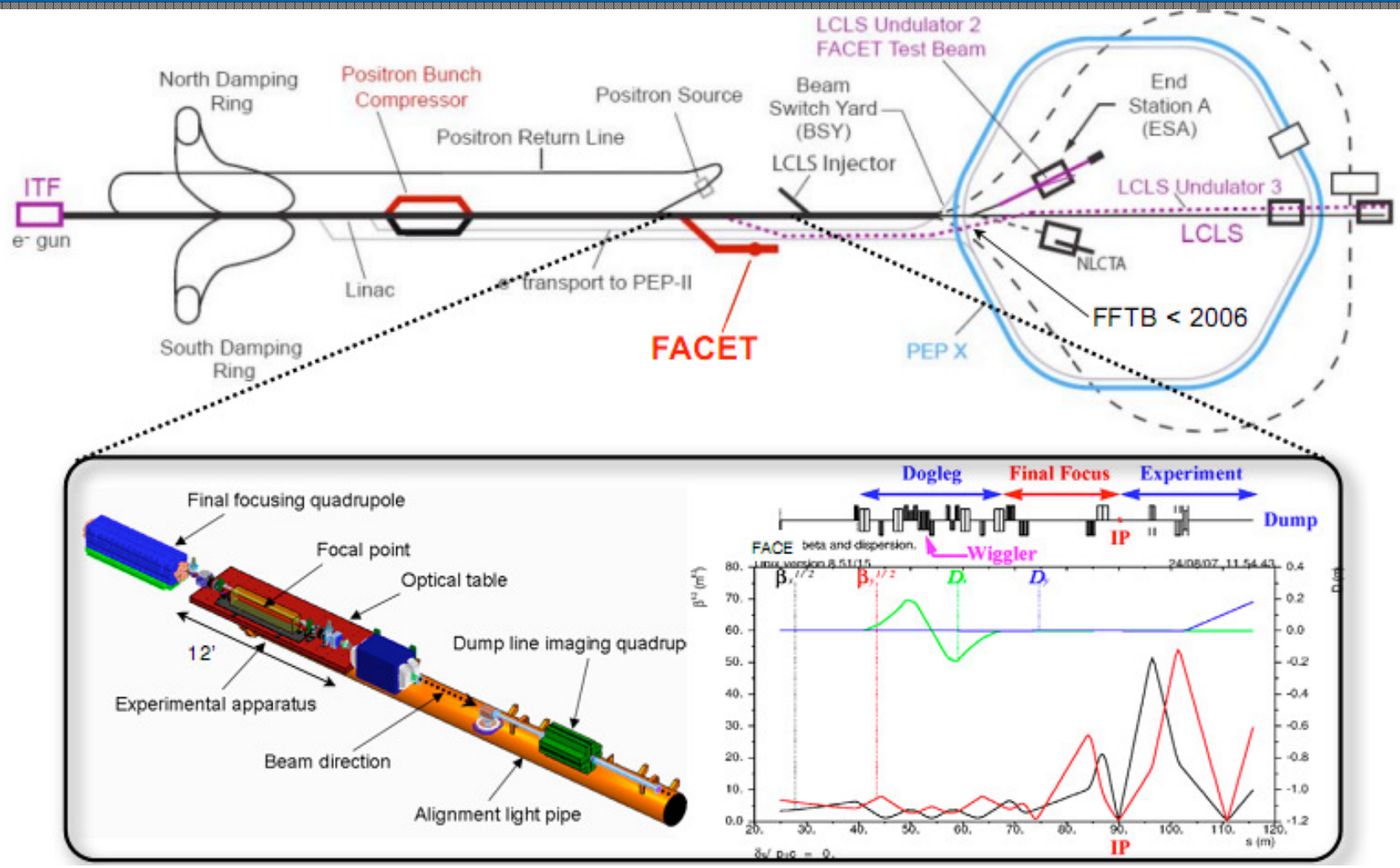
- TeV CM Energy
- 10's MW Beam Power for Luminosity
- Positron Acceleration
- Conventional technology for particle generation & focusing



A few 10s nm beam size and emittance

a 19 Stages PWFA-LC with 25GeV energy gain per stage

Facilities for ACcelerator science and Experimental Test Beams

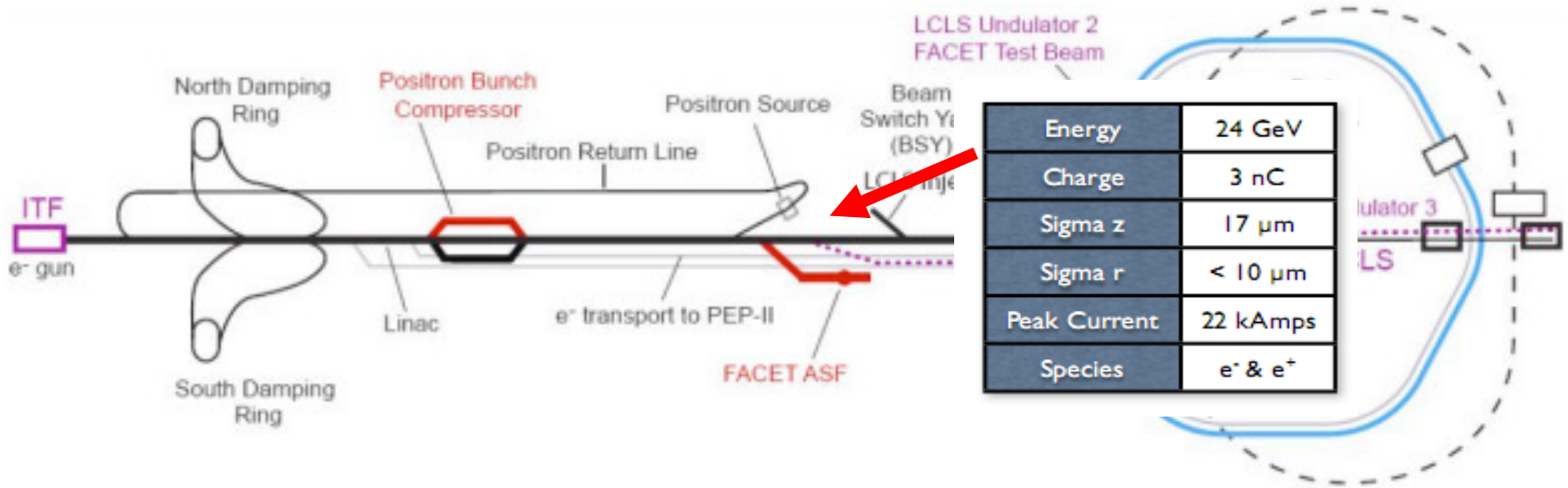


FACET is a new facility to provide high-energy, high peak current e^- & e^+ beams for PWFA experiments at SLAC

PWFA research @ FACET

The PWFA-LC concept illustrates the key questions that must be answered:

* High beam loading with both electrons and positrons (required for high efficiency)
* Small energy spreads (required to achieve luminosity and luminosity spectrum),
* Small emittances and small emittance dilution (required to achieve luminosity),
* Average bunch repetition rates in the 10's of kHz (required to achieve luminosity)
* Multiple plasma stages to achieve the desired energy.



Energy	24 GeV
Charge	3 nC
Sigma z	17 μm
Sigma r	< 10 μm
Peak Current	22 kAmps
Species	e^- & e^+

Plasma Acceleration Research Program at FACET will focus on the first three

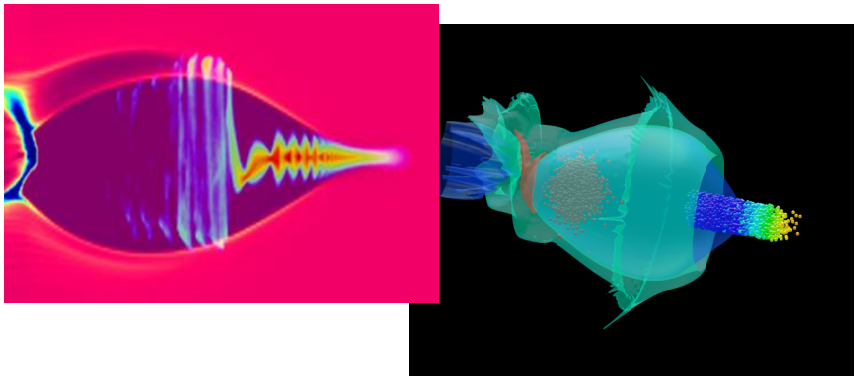
Simulation needs

- Meter long plasma + highly relativistic beam, there is clear separation of time scales, well suited for reduced PIC code.
- 3D effects such as hosing and asymmetric beam sizes are important, 3D simulation model required.
- Spotsizes are extremely tight for a electron positron collider, the transverse resolution has to be extremely high which means very strict time step requirement for a full PIC model.
- For example, beam size in next linear collider is 600x6 nm^2, simulation box size is 200x200 micron^2, needs 600x60000x500 grids, time step < 0.7 fs, # of time step ~ 1E7 for one 25 GeV stage.

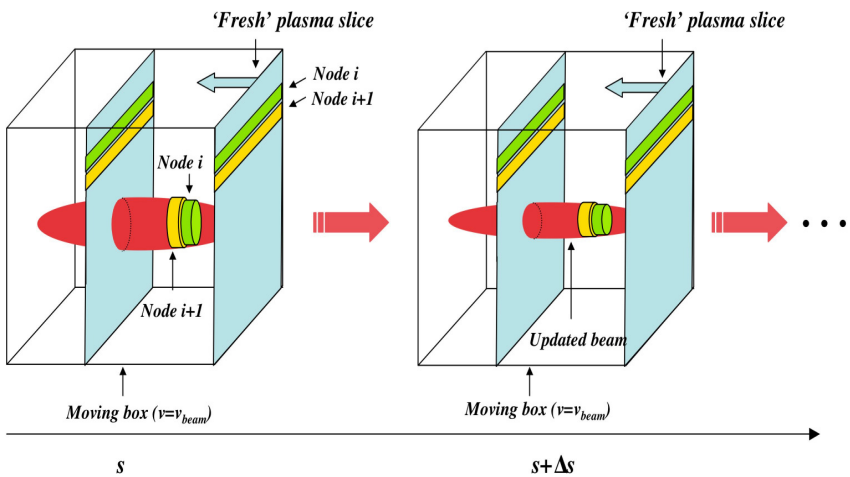
Quisa-static PIC model appears to be a good choice for modeling PWFA-LC.

Quasi-static PIC code QuickPIC

- **3D Quasi-static model + Ponderomotive guiding center + envelope model + ADK model**
- **Can be 100+ times faster than conventional PIC with good accuracy**
- **Examples of applications**
  - Simulations for PWFA experiments, E157/162/164/164X/167 (Including Feb. 2007 Nature)
  - Study of electron cloud effect in LHC.
  - Plasma afterburner design up to TeV
  - Beam loading study using laser/beam drivers
- **Development institutions**
  - UCLA, IST and U. Maryland

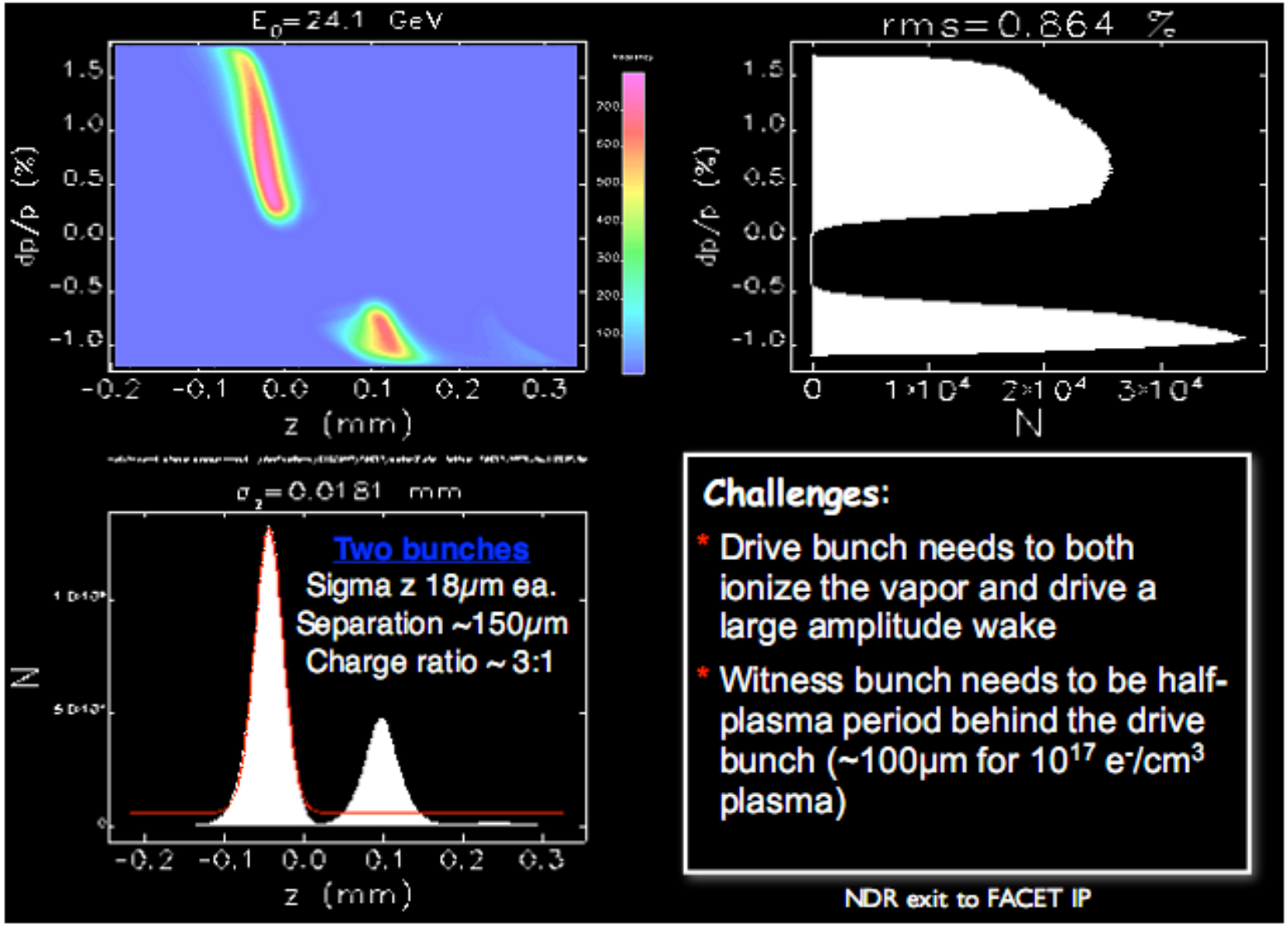


Quasi-static model

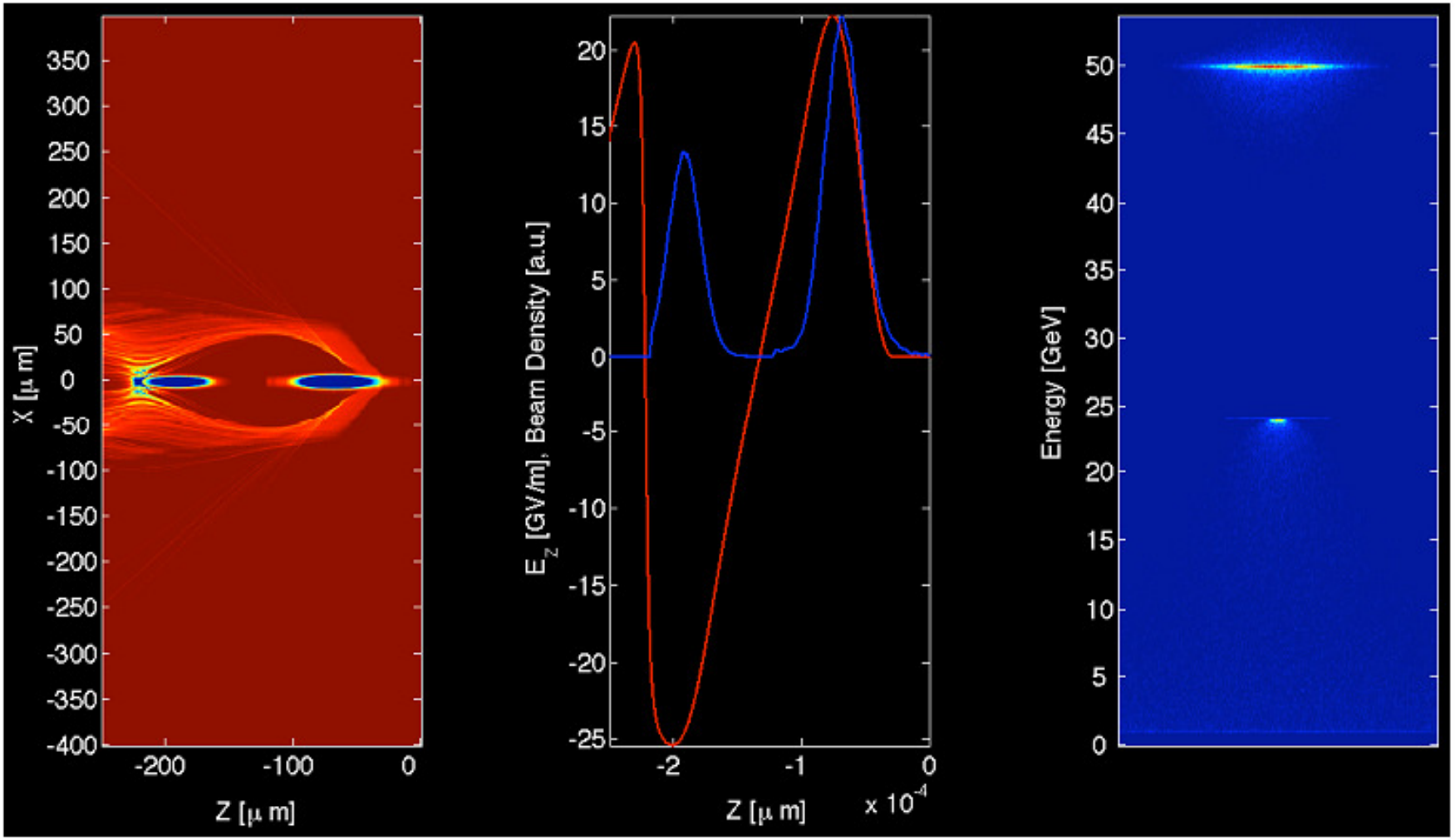


The driver evolution can be calculated in a 3D moving box, while the plasma response can be solved for slice by slice with the longitudinal index being a time-like variable.

2 beams generation in FACET



Simulation of proposed FACET experiment



PWFA-LC design exercise

- Focus on first/last PWFA stage
- Use theoretical framework to guide our designs
- Explore design options
- Test design with simulation
- Not an optimized or final design

Why nonlinear physics is important ?

We start from :

$$n_b = \frac{N}{(2\pi)^{3/2}\sigma_r^2\sigma_z}$$

High luminosity, beam loading efficiency requires N ~ $1x10^{10}$

Emittance preservation requires matched beams :

$$\Rightarrow \sigma_r^2 = \sqrt{\frac{2}{\gamma}}k_p^{-1}\varepsilon_N^{-1}$$

In addition, in order to limit the energy spread :

$$\sigma_z \sim \alpha\frac{c}{\omega_p}$$

Therefore,

$$\frac{n_b}{n_0} = 7x10^3\frac{N}{1x10^{10}}\frac{\mu m - rad}{\sqrt{\varepsilon_{Nx}\varepsilon_{Ny}}}\sqrt{\frac{Energy}{250\ GeV}}\frac{1}{\alpha}$$

Therefore, narrow beams which violate linear theory are required in the trailing beam for either PWFA or LWFA

Basic parameters

In the blow-out regime:

Dimensionless beam current:

$$\Lambda = k_p^2 \sigma_r^2 n_b / n_p = 2I_{peak} / I_A \text{ (for gaussian beam; for round beam, } r_b = \sigma_r / \sqrt{2})$$

$$I_A = mc^3/e = 17kA \text{ (Alfven current, } 3.5\times10^8 e/\mu m)$$

Size:

$$L \propto n_p^{-1/2}$$

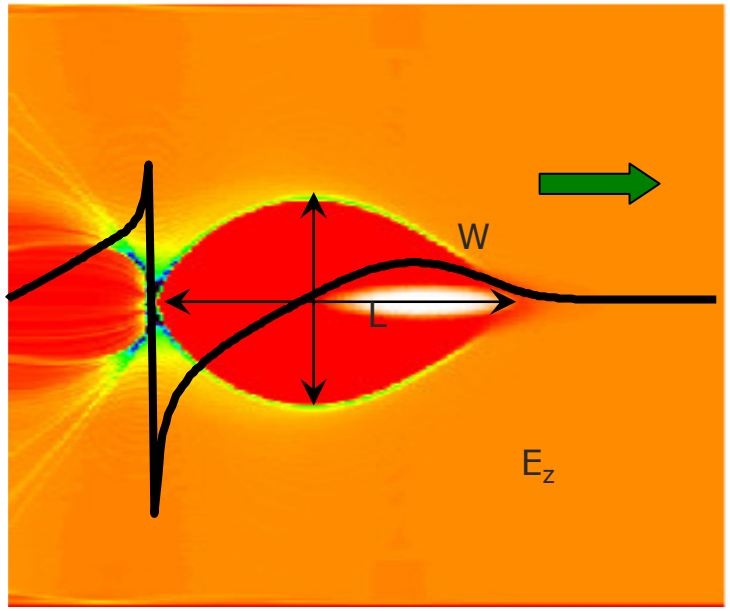
$$W \propto \sqrt{\Lambda} \cdot k_p^{-1} = \sqrt{\sigma_r^2 n_b / n_p}$$

Accel. Gradient:

$$E_z = 1.3\Lambda \ln\left(\frac{10}{\Lambda}\right)^{1/2} \times \frac{mc\omega_p}{e}$$

Accel. Length:

$$s = \gamma k_p^{-1} \text{ or } k_\beta s = \frac{\gamma}{\sqrt{2\gamma}} = \sqrt{\frac{\gamma}{2}}$$



Practical parameters:

Beam : ~1E10 e^-

Plasma : 1E14 cm^{-3} ~ 1E18 cm^{-3}

(Ez = 1~100 GeV/m)

To blow-out (W/2=1~3), bunch length 3 ~ 30 micron

Synchrotron radiation

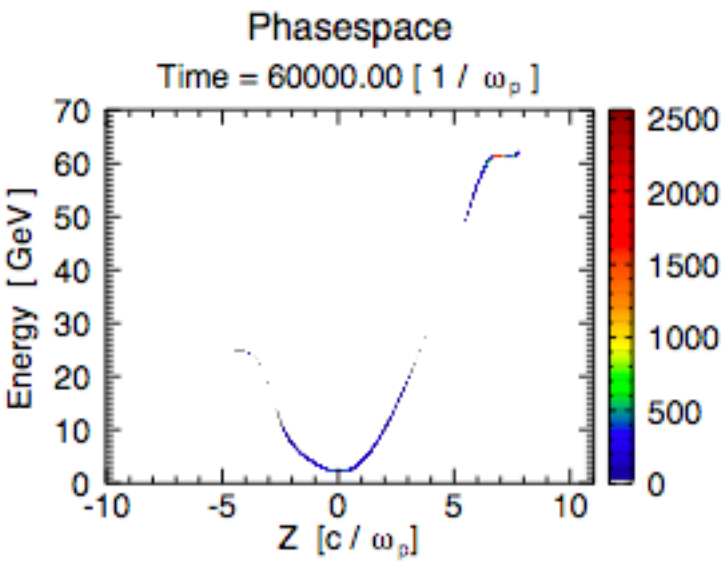
$$P_{loss} = \frac{2}{3}\frac{e^2}{c}\gamma^6\left(\left[\dot{\vec{\beta}}\right]^2 - \left[\vec{\beta}\times\dot{\vec{\beta}}\right]^2\right)$$

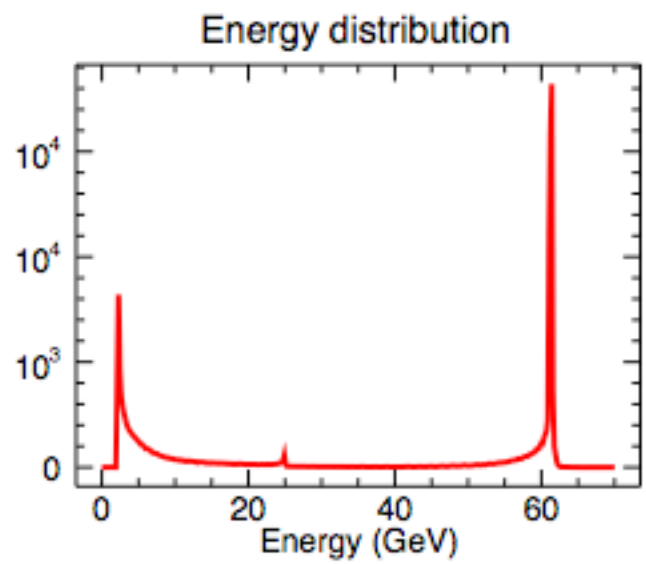
$$\frac{\varepsilon_r}{\varepsilon_{loaded}} = \frac{1}{\varepsilon_{loaded}} 1.5x10^{-5}\left(\frac{\mathrm{E}}{50GeV}\right)^2\left(\frac{n}{10^{16}}\right)^{3/2}\left(\frac{r}{1\mu m}\right)^2$$

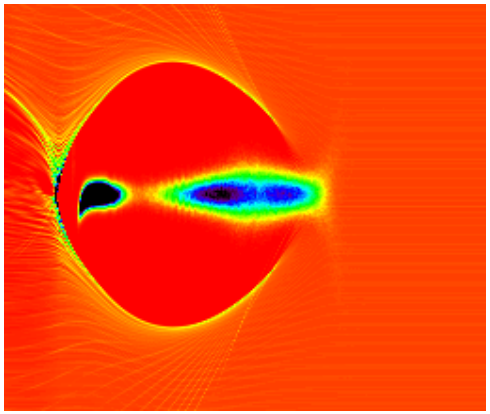
For a matched beam this can be rewritten as:

$$\frac{\varepsilon_r}{\varepsilon_{loaded}} = \frac{1}{\varepsilon_{loaded}} 3.75x10^{-3}\left(\frac{\mathrm{E}}{250GeV}\right)^{3/2}\left(\frac{n}{10^{16}}\right)\left(\frac{\varepsilon_n}{10^{-6}m}\right)$$

Nominal 25 GeV Preionized PWFA stage







n_p= $1\times10^{17}cm^{-3}$
N_{driver} = 2.9×10^{10}, σ_r= 3 μ, σ_z = 30 μ, Energy = 25 GeV
$N_{trailing}$ = 1.0×10^{10} , σ_r= 3 μ , σ_z = 10 μ, Energy = 25 GeV
Spacing=110 μ
R_{trans} = $-E_{acc}/E_{dec}$ > 1 (Energy gain exceeds 25 GeV per stage)
1% Energy spread
Efficiency from drive to trailing bunch ~48%!

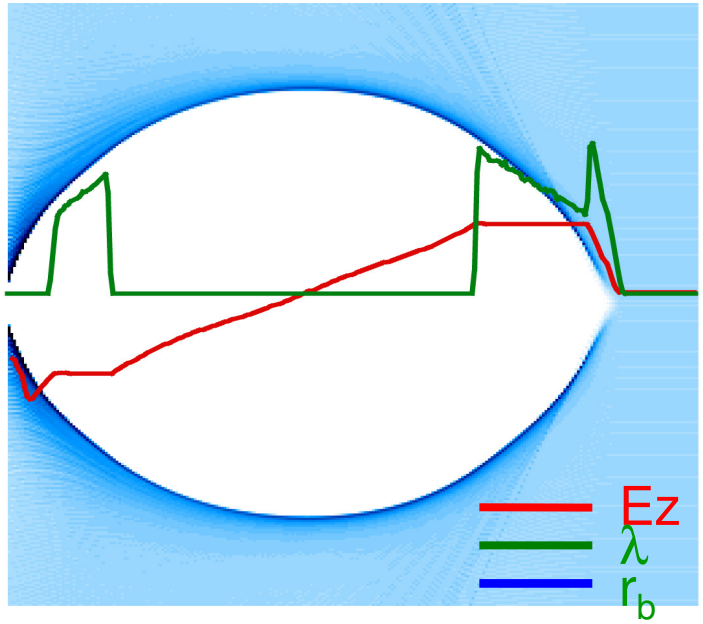
Beam profile design

To achieve the smallest energy spread of the beam, we want the beam-loaded wake to be flat within the beam.

Formulas for designing flat wakefield in blow-out regime (Lu et al., PRL 2006; Tzoufras et al, PRL 2008):

$$A(r_b,\beta)\frac{d^2 r_b}{d\xi^2}+B(r_b,\beta)r_b\left(\frac{dr_b}{d\xi}\right)^2+C(r_b,\beta)r_b=\frac{\lambda(\xi)}{r_b}$$

$$\begin{cases} r_b\dfrac{d^2 r_b}{d\xi^2}+2\left(\dfrac{dr_b}{d\xi}\right)^2+1=4\dfrac{\lambda(\xi)}{r_b^2} & (k_p R_b >> 1) \\ E_z=\dfrac{1}{2}r_b\dfrac{dr_b}{d\xi} & (when\ sheath\ width \approx 0) \end{cases}$$



We know when $r_b=r_{b,max}$, $E_z=0$, $dE_z/d\xi=-1/2$. Integrating E_z from this point in +/- ξ using the desirable E_z profile yield the beam profile.

$$\lambda(\xi)=E_z(\xi)^2+\int E_z(\xi)d\xi+r_b(\lambda=0)^2/4 \quad \left(when\ \frac{dE_z}{d\xi}=0\right)$$

For example, $R_b=5$, $E_{z,acc}=-1$, $\Lambda=6.25-(\xi-\xi_0)$

PWFA-LC simulation setup

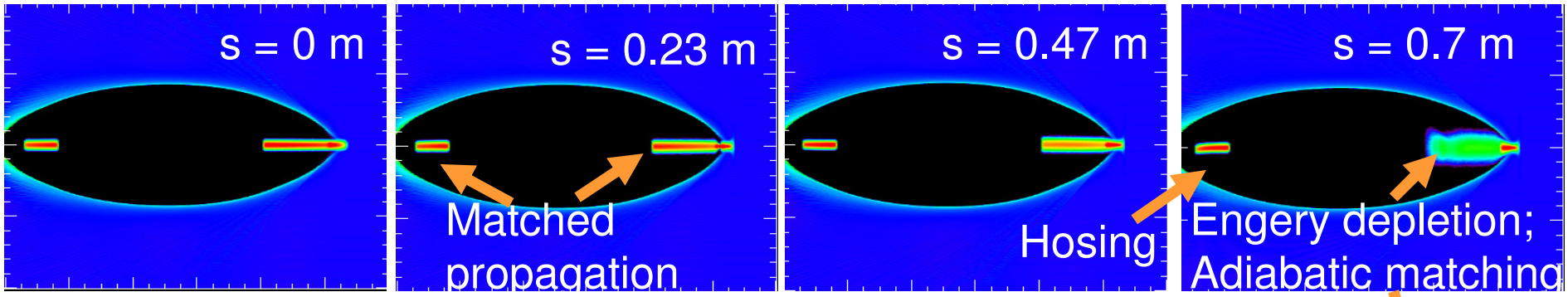
Simulation of the first and the last stages of a 19 stages 0.5TeV PWFA

Physical Parameters	Drive beam	Trailing beam
Beam Charge (1E10e^{-})	0.82 + 3.65	1.62
Beam Length (micron)	13.4 + 44.7	22.35
Emittance (mm mrad)	10 / 62.9	62.9
Plasma density (1E16 cm^{-3})	5.66	
Plasma Length (m)	0.7	
Transformer ratio	1.2	
Loaded wake (GeV/m)	45 GeV/m	

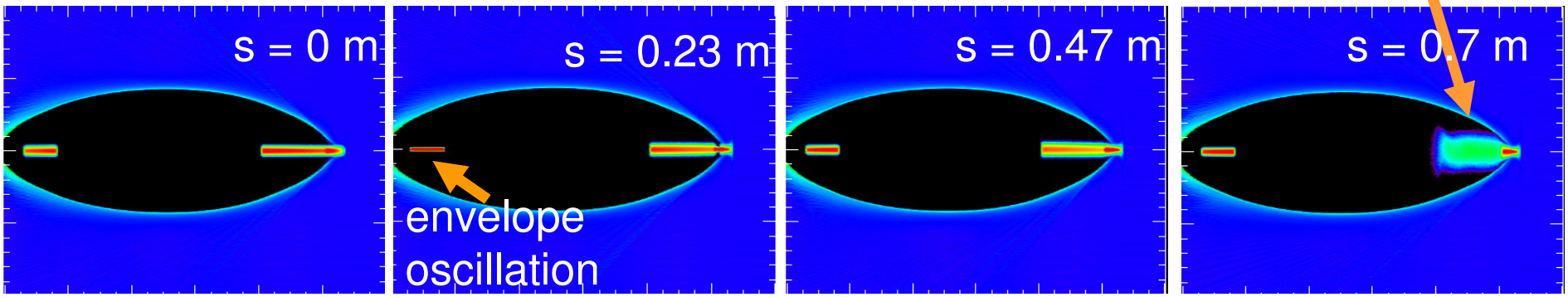
Numerical Parameters	
Box size	1000x1000x272
Grids	1024x1024x256
Plasma particle	4 / cell
Beam particle	8.4 E6 x 3
Time step	60 k_p^{-1}
Total step	520

Simulation of 25/475 GeV stages

25 GeV stage

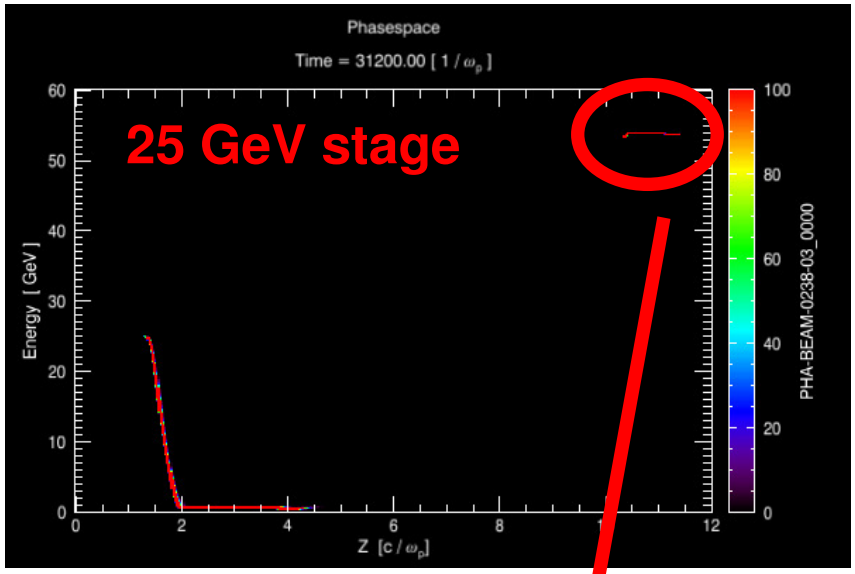


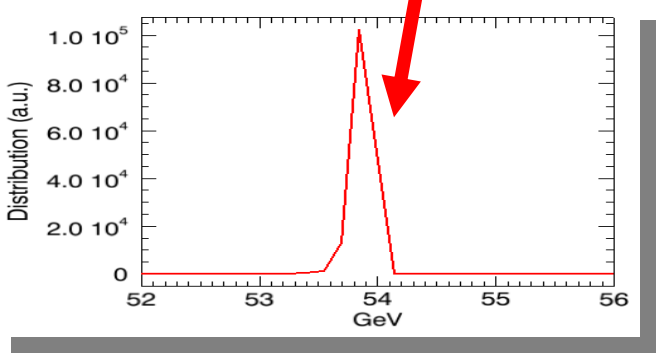
475 GeV stage



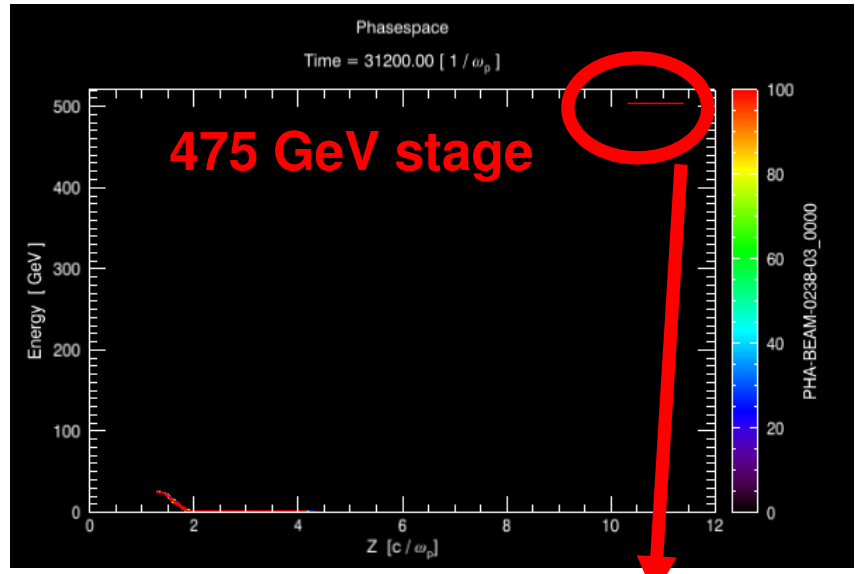
Simulation of 25/475 GeV stages

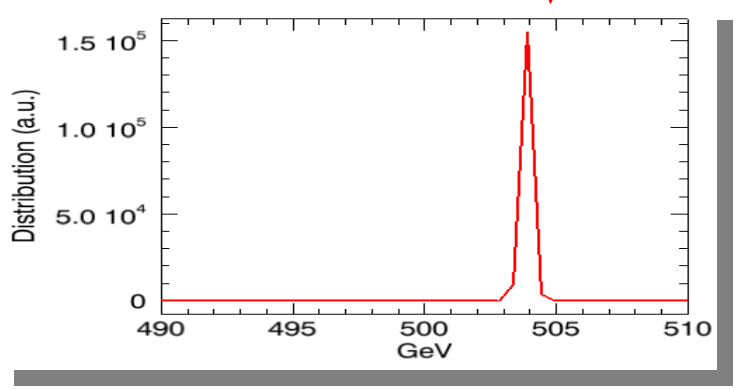
longitudinal phasespace





Energy spread = 0.7% (FWHM)



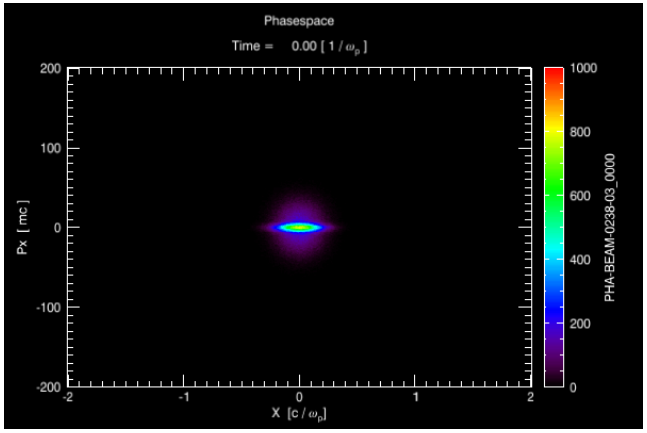


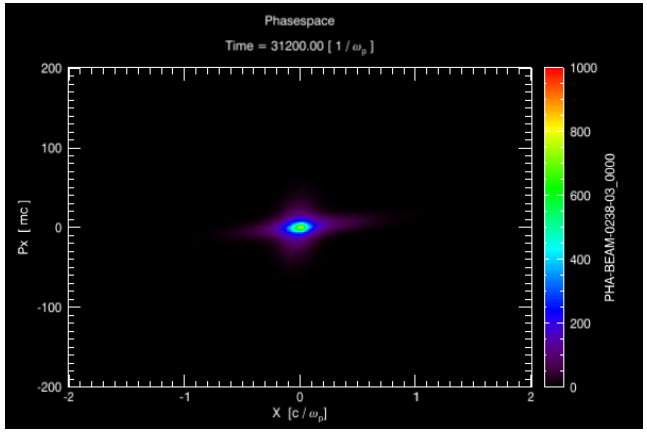
Energy spread = 0.2% (FWHM)

Simulation of 25/475 GeV stages

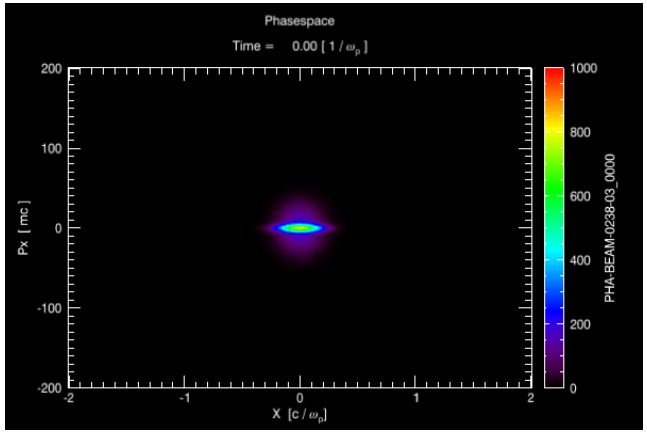
Transverse phasespace

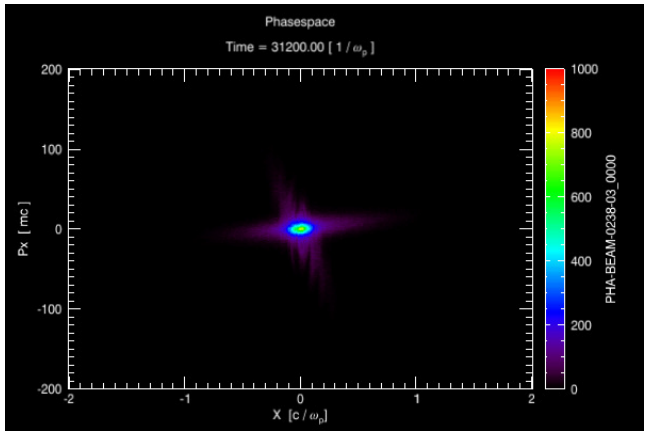
25 GeV stage





475 GeV stage





Ion motion

- Ion motion when

$$n_b > n_o \frac{M_i}{m_e}$$

- Matched beam spot size shrinks at large γ, low ε_n

$$n_b \propto \sigma_x^{-1}\sigma_y^{-1} = \frac{1}{\sqrt{\varepsilon_{nx}\varepsilon_{ny}}}\sqrt{\frac{\gamma}{2}}\frac{\omega_p}{c}$$

- For future collider
  - ε_{ny} down by 10^2 (e.g., 10nm-rad)
  - γ up by 10+
  - n_b up by 10^2
  - Ion motion must be included in design/models

Ref. S. Lee et al., AAC Proc (2000); J. Rosenzweig et al., PRL (2006)

Summary

• PWFA experiment has shown sustained acceleration of electrons over meter-long plasma. Quasi-static model enables full-scale simulations that reveal the underlying physics.

• Designing PWFA-LC for TeV collider scenario is challenging, we attempt to investigate the problem in an integrated approach, where relevant physics such as beam-loading, hosing, head erosion and radiation loss are taken as design constraints. Theoretical understanding of the blow-out regime and beam-loading makes it possible to reduce energy spread of the accelerated beam.

• Simulation of 2 beams PWFA experiment in the proposed FACET facility shows that high quality beam can be accelerated.

• Preliminary simulations are conducted to explore the possibility of a 19 stages PWFA-LC.