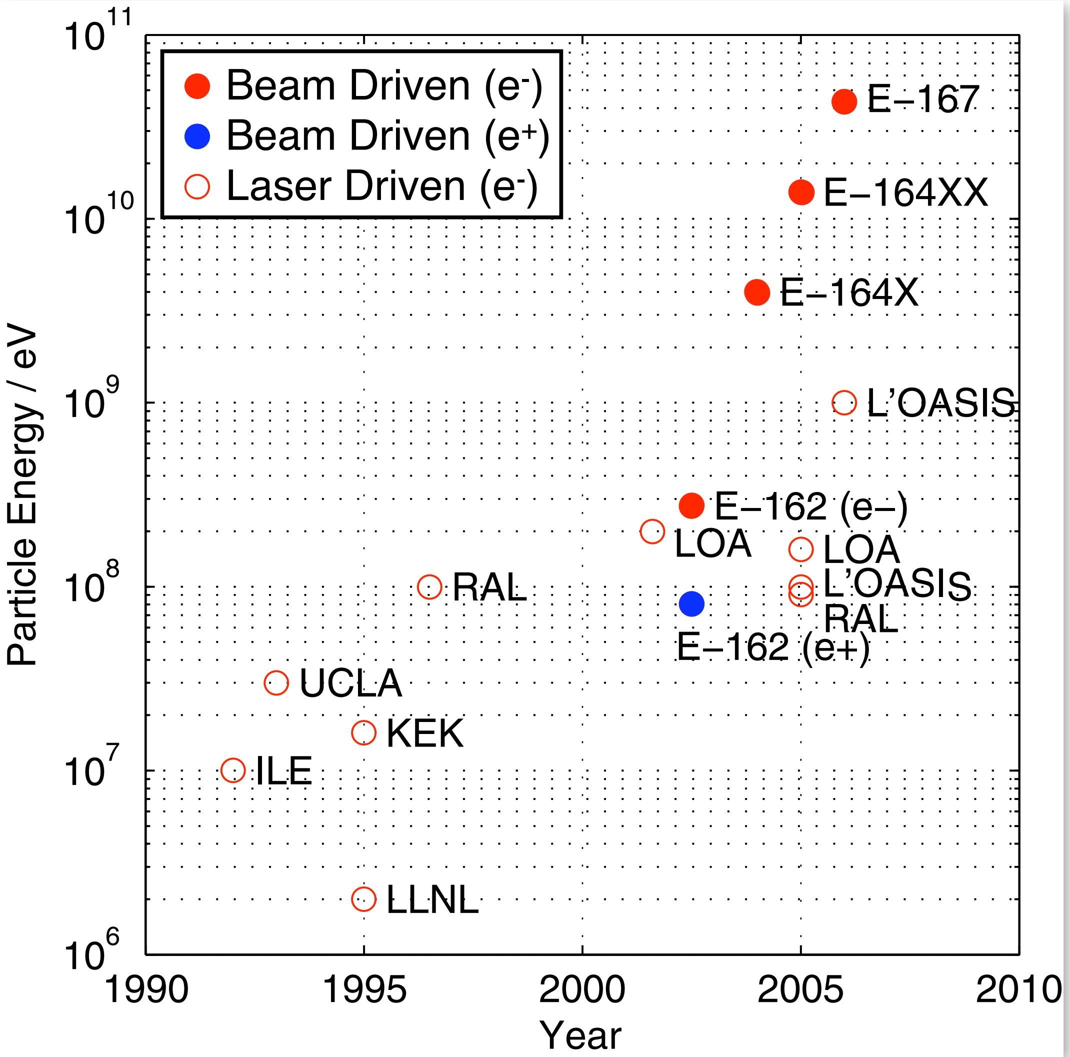
Beam Driven Plasmas and Linacs

Mark J. Hogan

(on behalf of the Duke, SLAC, UCLA, USC collaboration)

Robert H. Siemann Symposium and
ICFA Mini-Workshop on Novel Concepts for Linear Accelerators and Colliders
July 7-10, 2009

Plasma Acceleration has made tremendous progress in the last two decades



DOE HEP Office Of Science Issued CD-0 for Advanced Plasma Acceleration Facility February 2008

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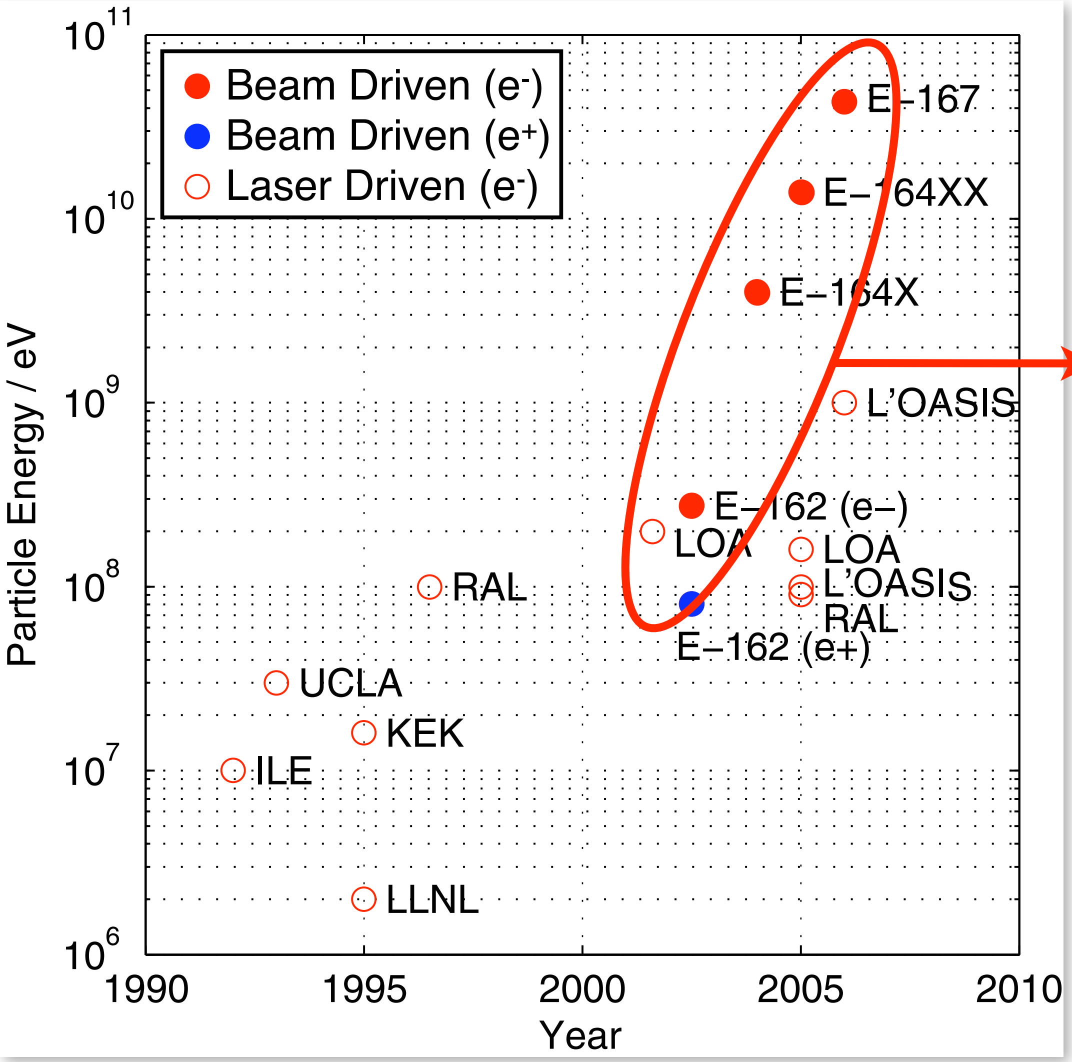

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Tremendous progress in beam driven concepts entirely the result of the the capability of the SLAC linac to provide high energy, high peak current, low transverse emittance electron beams

T. Tajima and J. M. Dawson
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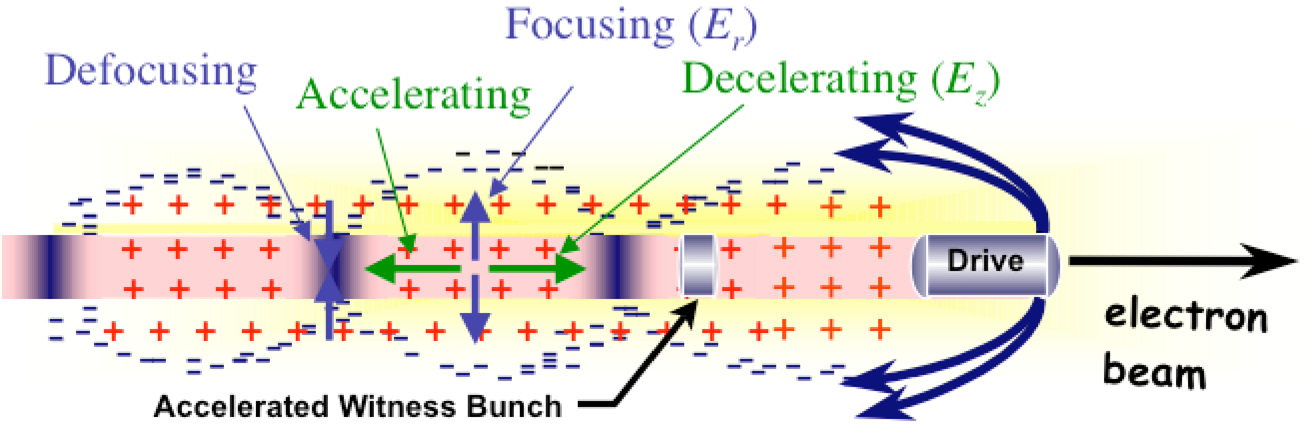
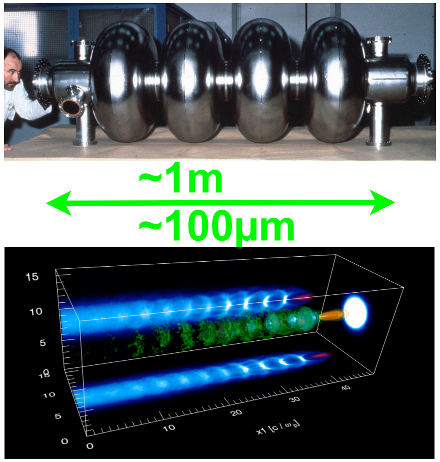
The Beam Driven Plasma Wakefield Accelerator

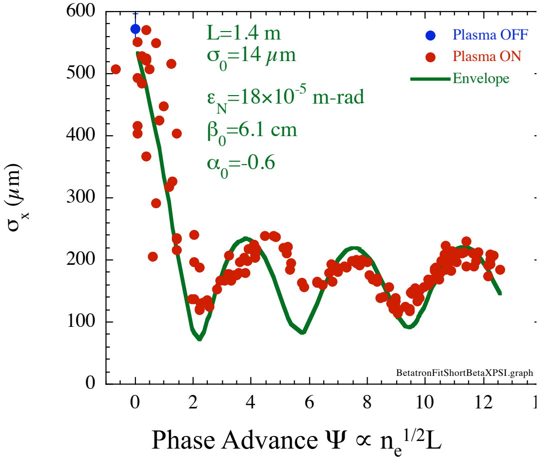




- Two-beam, co-linear, plasma-based accelerator
- Plasma wave/wake excited by relativistic particle bunch
- Deceleration, acceleration, focusing by plasma
- Accelerating field/gradient scales as $n_e^{1/2}$
- Typical: $n_e \approx 10^{17}$ cm^{-3}, $\lambda_p \approx 100$ µm, G>MT/m, E>10 GV/m
- High-gradient, high-efficiency energy transformer

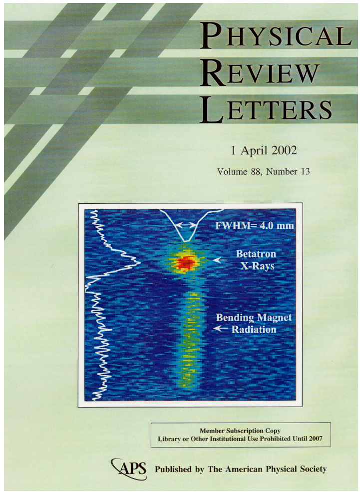
SLAC/UCLA/USC Experiments @ FFTB
Studied all aspects of beam-plasma interaction

Focusing & Matching e$^-$



Phys. Rev. Lett. **93**, 014802 (2004)

X-ray Generation



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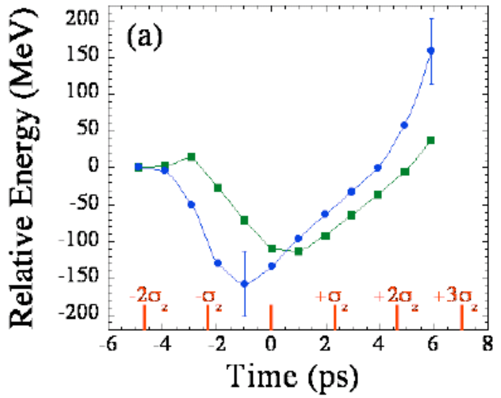
APS Published by The American Physical Society

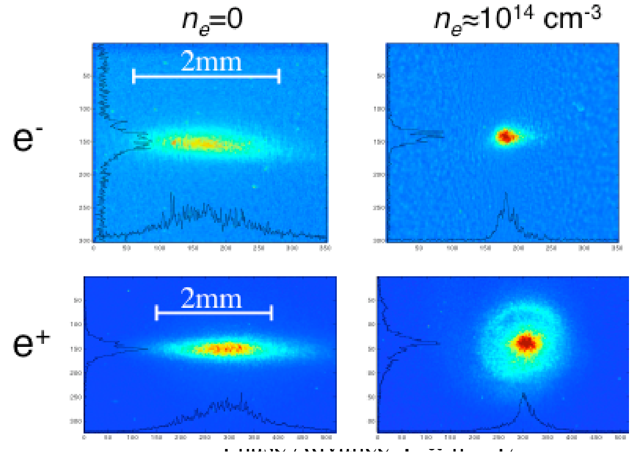
Phys. Rev. Lett. **88**, 135004 (2002)

Wakefield Acceleration e$^-$



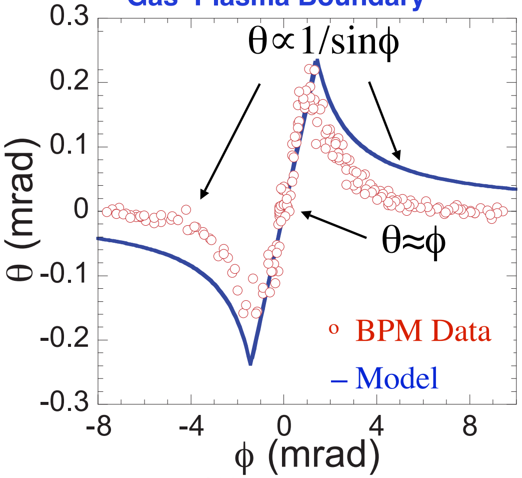
Phys. Rev. Lett. **93**, 014802 (2004)

Focusing & Halo Formation e$^+$



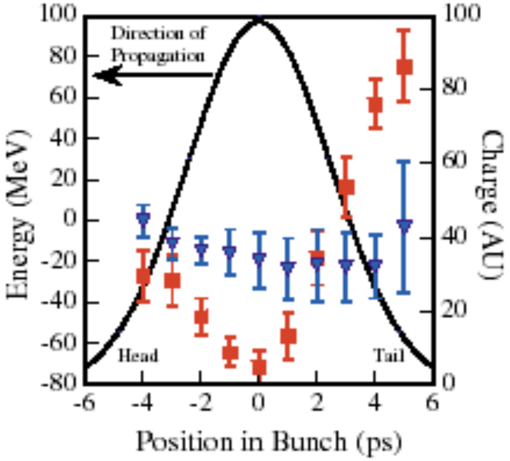
Phys. Rev. Lett. **101**, *055001 (2008)*

Electron Beam Refraction at the Gas–Plasma Boundary



Nature **411**, 43 (3 May 2001)

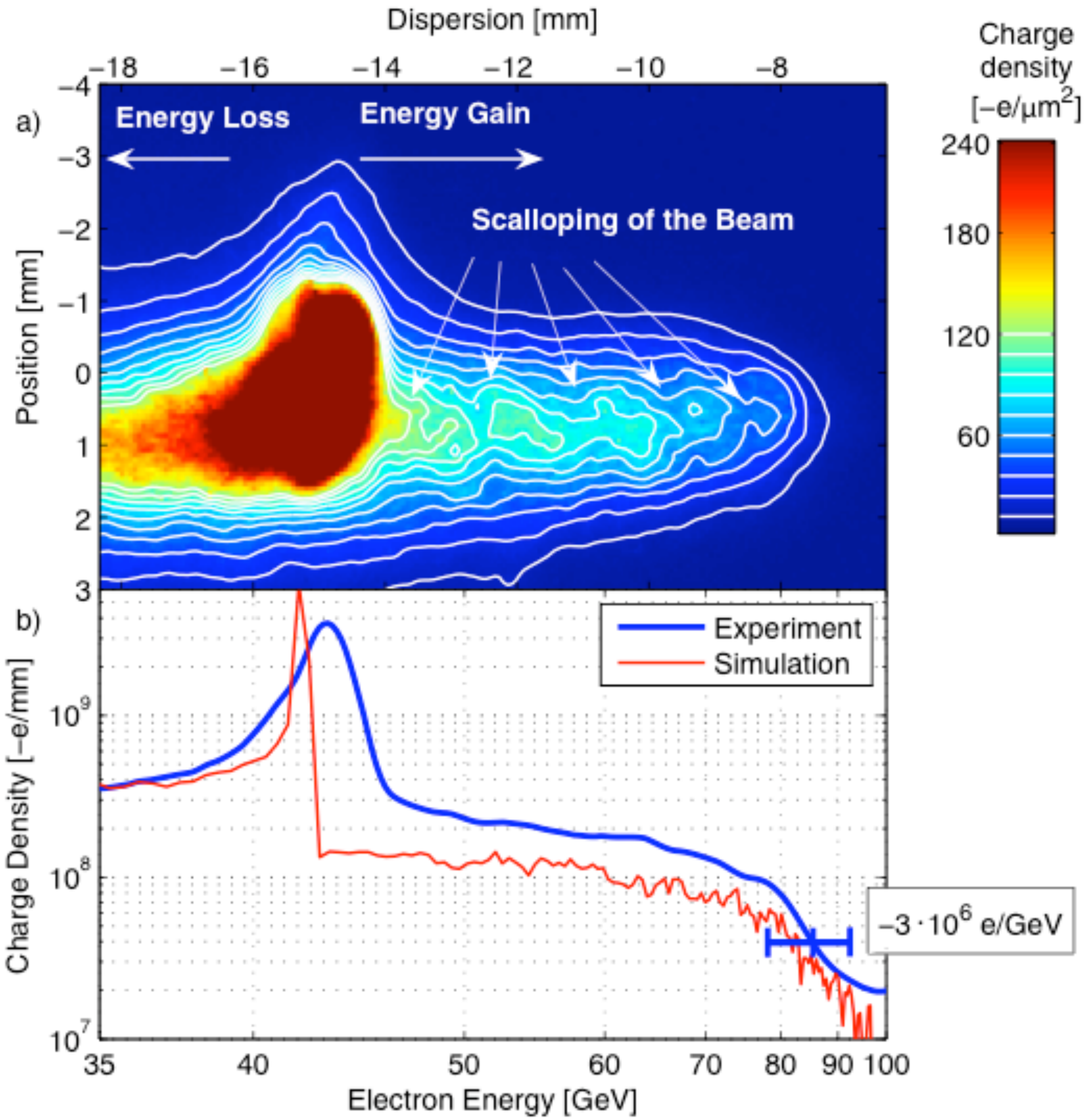
Wakefield Acceleration e$^+$



Phys. Rev. Lett. **90**, 214801 (2003)

E-167: Energy Doubling with a Plasma Wakefield Accelerator in the FFTB (April 2006)

- Acceleration gradients of ~50 GV/m (3000 x SLAC)
  - Doubled energy of 45 GeV beam in 1 meter plasma
  - Record Energy Gain
  - Highest energy electrons ever produced at SLAC
  - Significant advance in demonstrating the potential of plasma accelerators



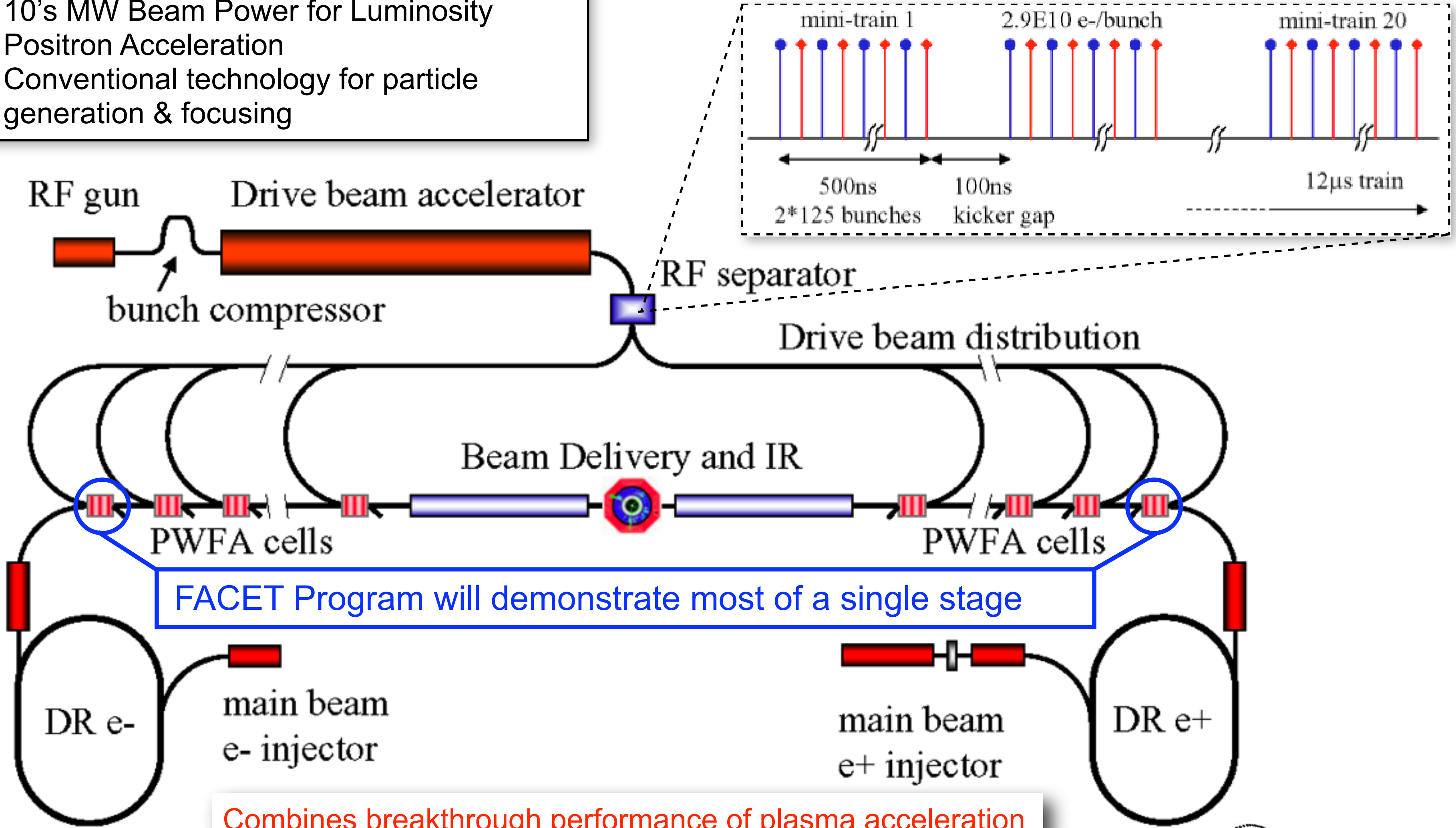
Nature *445 741 15-Feb-2007*

Approach to PWFA-LC concept

- Many ideas for plasma wakefield-based linear colliders
  - "Afterburner" double energy of a conventional rf linear collider just before the IP
  - Multi-stage afterburner
  - Proton driver (for e^-)
- Our present concept for a PWFA-LC:
  - Benefits from three decades of extensive R&D performed for conventional RF linear colliders
  - Possible to generate drive power extremely efficiently
  - Optimized to take advantage of the salient PWFA feature (gradient)
  - Reasonable set of R&D milestones that could be realized over the next ten years

A Concept for a Plasma Wakefield Accelerator Based Linear Collider

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



FACET Program will demonstrate most of a single stage

Combines breakthrough performance of plasma acceleration & wealth of 30+ yrs of LC development

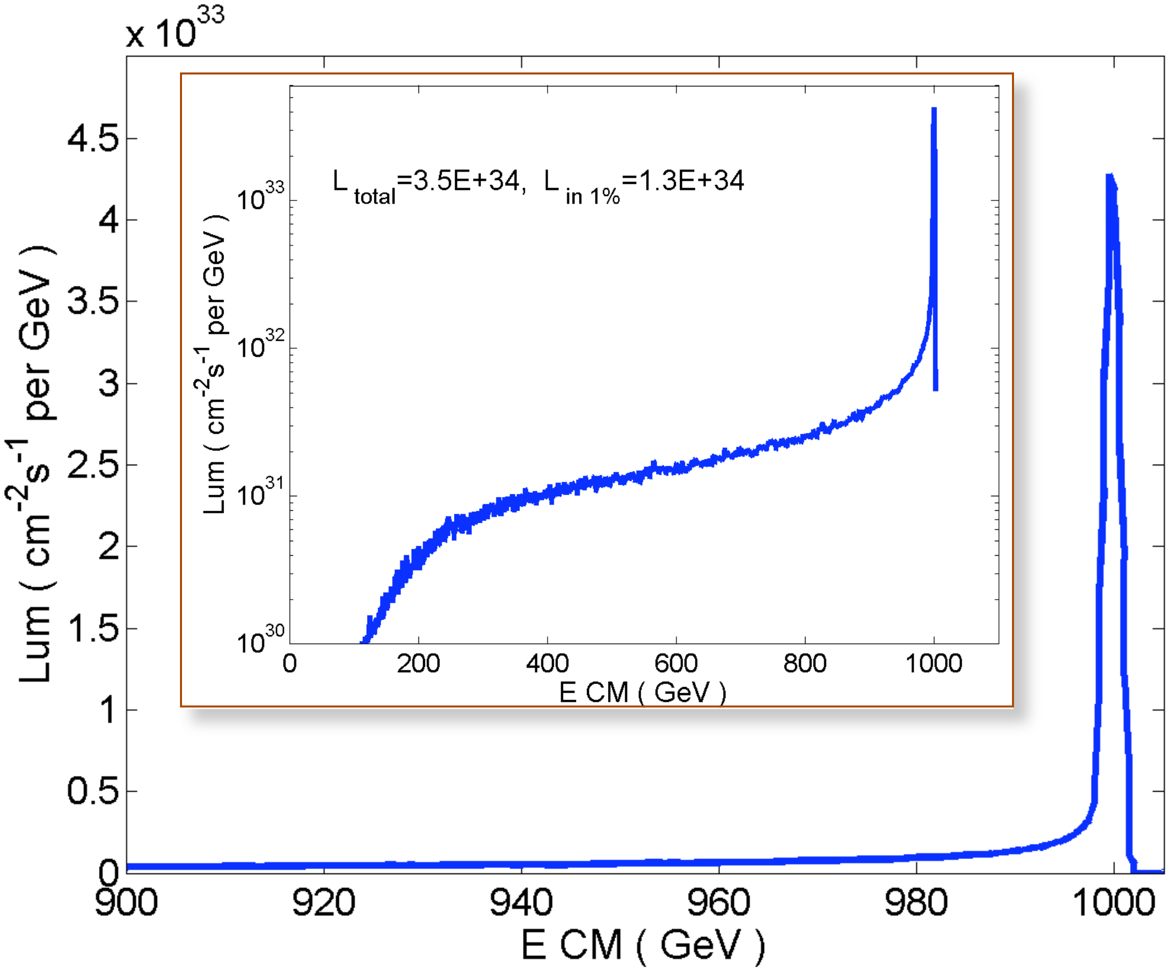
PWFA-LC main parameters

Luminosity	3.5×10^{34} cm^{-2}s^{-1}
Luminosity in 1% of energy	1.3×10^{34} cm^{-2}s^{-1}
Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Main beam emittances, $\gamma\varepsilon_x$, $\gamma\varepsilon_y$	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	140 nm, 3.2 nm, 10 μm
Plasma accelerating gradient, plasma cell length, and density	25 GV/m, 1 m, 1×10^{17}cm^{-3}
Power transfer efficiency drive beam=>plasma =>main beam	35%
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW

PWFA-LC Luminosity Spectrum

IP $\beta_{x/y}$=10/0.2mm, δ_B~30%, close to CLIC numbers

IP parameters and spectrum are close to those for CLIC, and moreover, the wealth of particle physics studies for the interaction region and detector design, background and event reconstruction techniques in the high beamstrahlung regime are all applicable to the PWFA-LC concept



Calculated w. beam-beam code Guinea-Pig [D.Schulte, ca.1995]

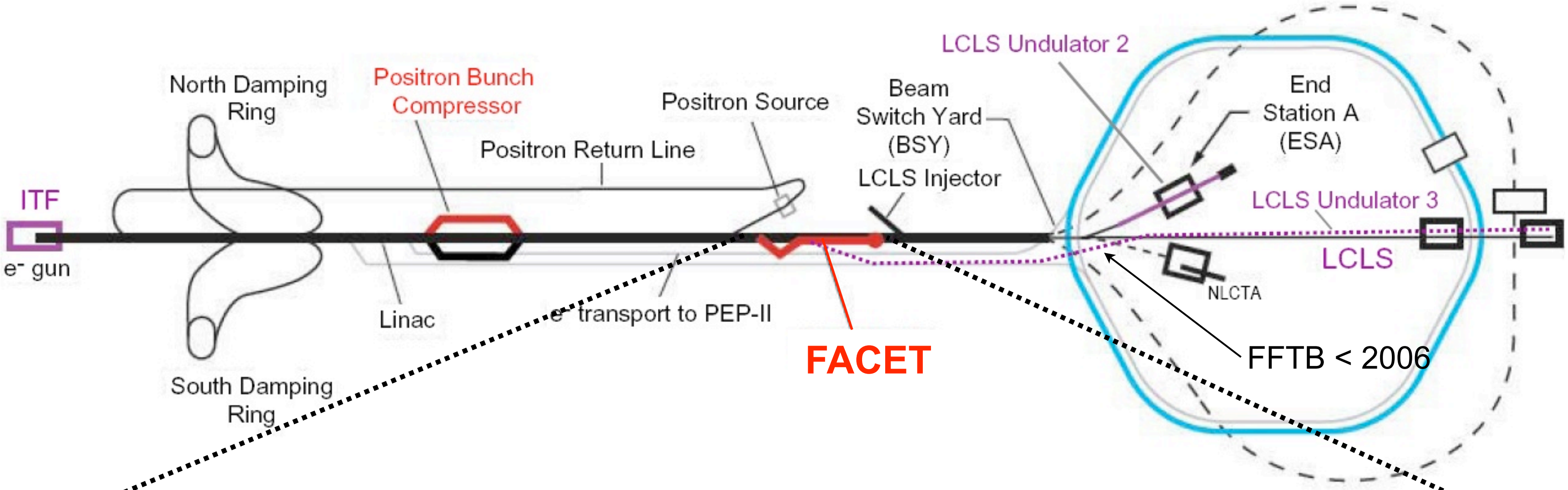
Key features of PWFA-LC concept

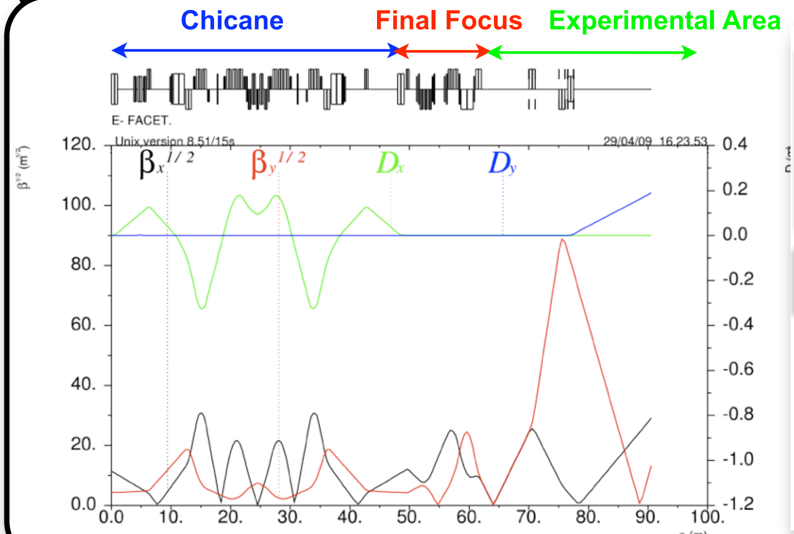
- Electron drive beam for both electrons and positrons
- High current low gradient efficient 25GeV drive linac
  - Similar to linac of CERN CTF3, demonstrated performance
- Multiple plasma cells
  - 20 cells, meter long, 25GeV/cell, 35% energy transfer efficiency
- Main / drive bunches
  - 2.9E10 / 1E10
- PWFA-LC concept will continue to evolve with further study and simulation
  - Bunch charge; Non-gaussian bunch profiles; Flat vs round beams; SC vs NC pulse format; ...
- Need a new facility to investigate and iterate these ideas through experiments

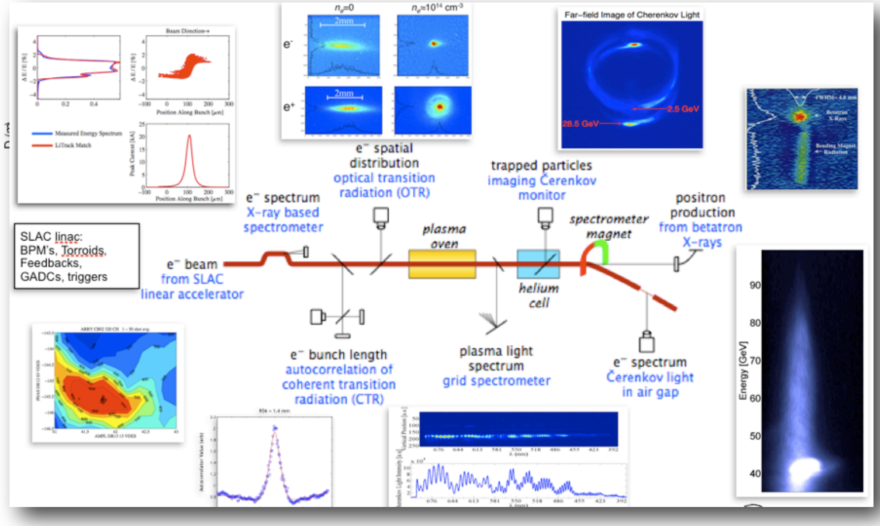
Primary Issues for any Plasma-based LC

- Need to understand acceleration of electrons & positrons
- Luminosity drives many issues:
  - High beam power (20 MW) → efficient ac-to-beam conversion
  - Well defined cms energy → small energy spread
  - Small IP spot sizes → small energy spread and small Δε
- These translate into requirements on the plasma acceleration
  - High beam loading of e+ and e- (for efficiency)
  - Acceleration with small energy spread
  - Preservation of small transverse emittances – maybe flat beams
  - Bunch repetition rates of 10's of kHz
- Multiple stages allow better beam control and use of drive-beam
  - possible to demonstrate single stage before full system test

A new facility to provide high-energy, high peak current e^- & e^+ beams for PWFA experiments





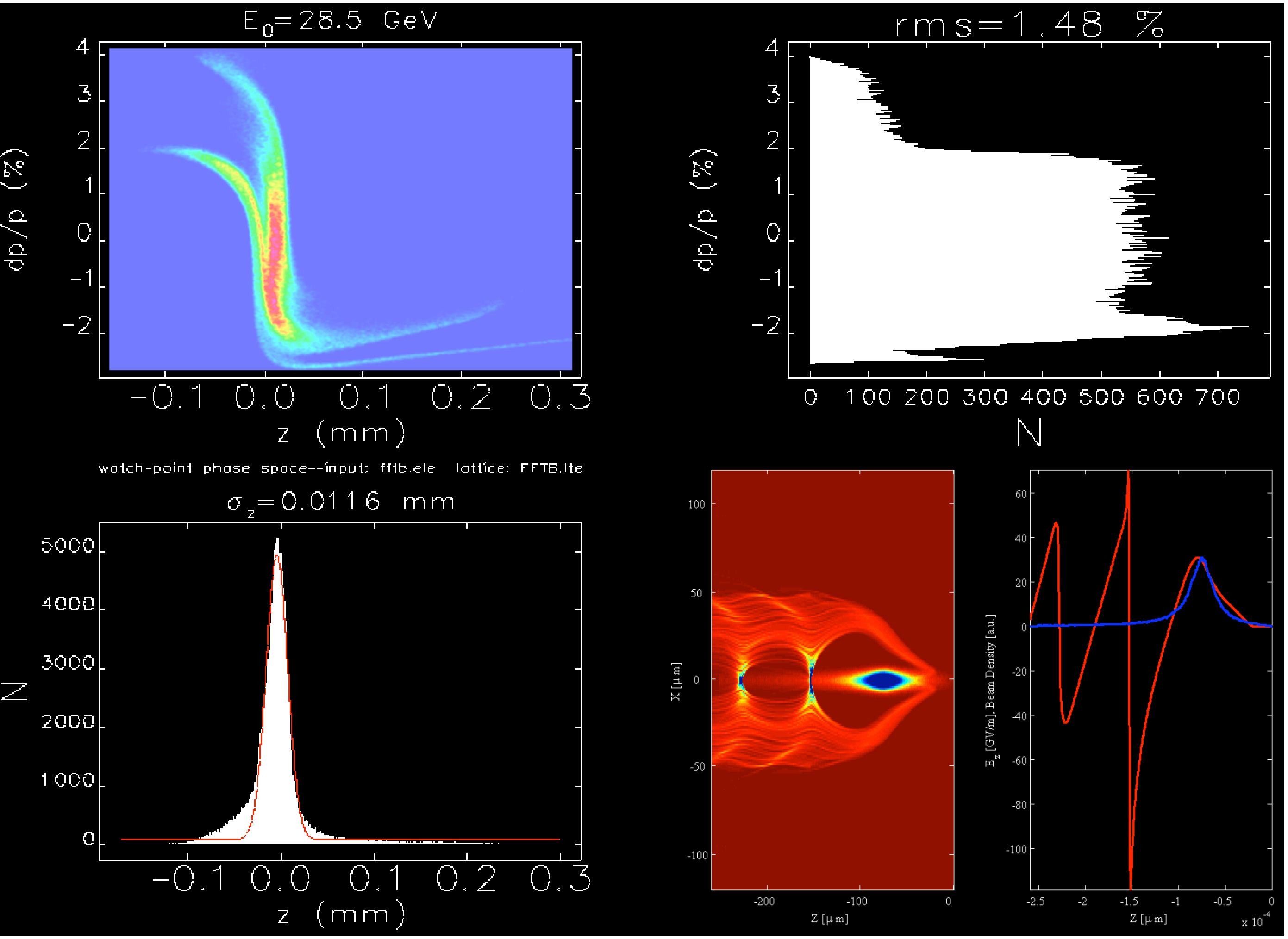


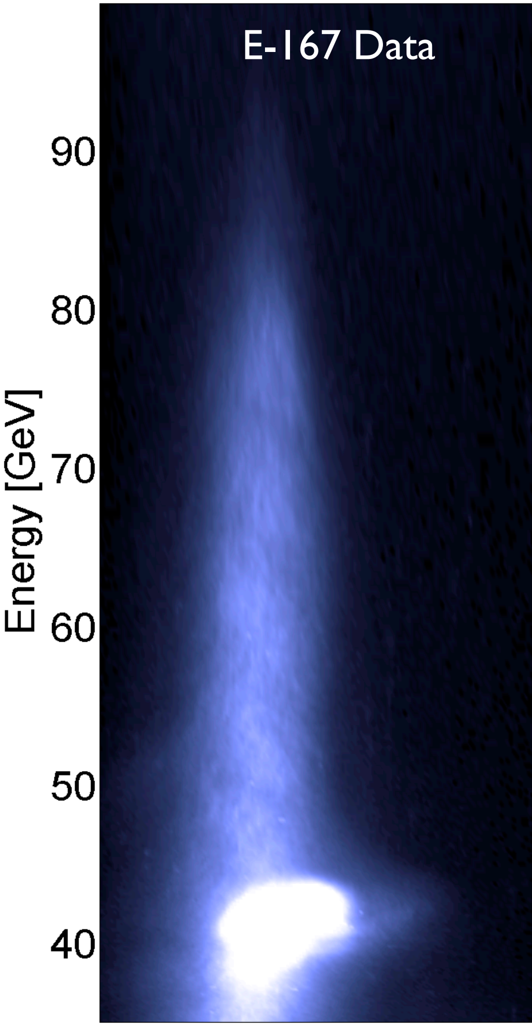
Plasma Acceleration Program and Challenges

- Accelerator physics: produce drive/witness bunches
  - For $n_p \sim 10^{17}$ cm^{-3}, need two bunches within 100μm!
- High Gradient Acceleation of witness bunch in ~ 1 m-long plasma
- Narrow energy spread & preserved emittance of the accelerated witness bunch

  particle acceleration ⟶ beam acceleration
- Beam loading of plasma wake, energy transfer efficiency
- Positrons in PWFA
- Plasma Stability and Tolerances
- Further developments in simulation tools

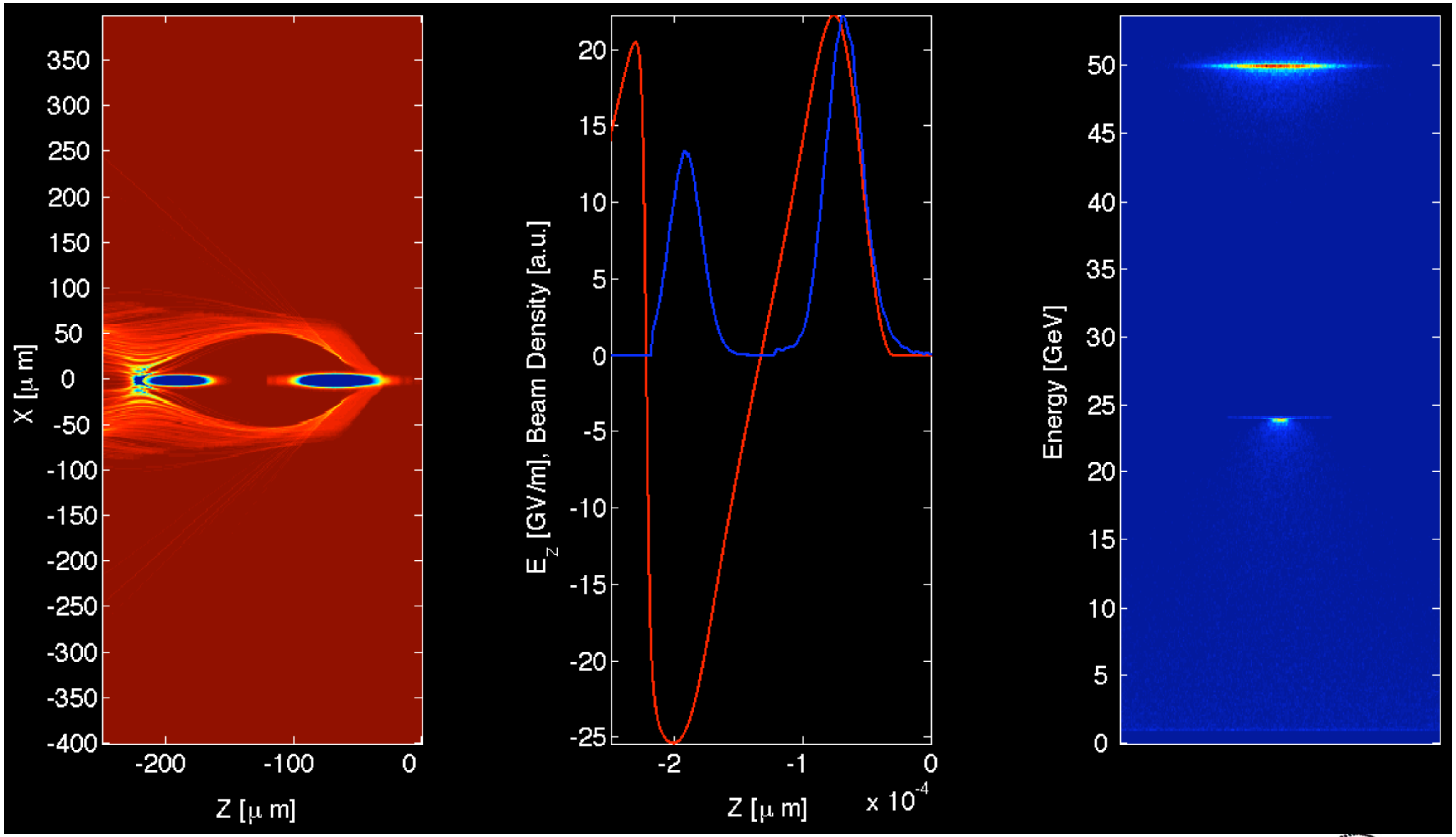
Single FFTB Bunch Sampled All Phases of the Wake Resulting in ~ 200% Energy Spread





FACET Experiments will accelerate a discrete bunch of particles with narrow energy spread

- Double Energy of a 25GeV Beam in ~1m
- Drive beam to witness beam efficiency of ~30% with small dE/E



Linear Collider Luminosity

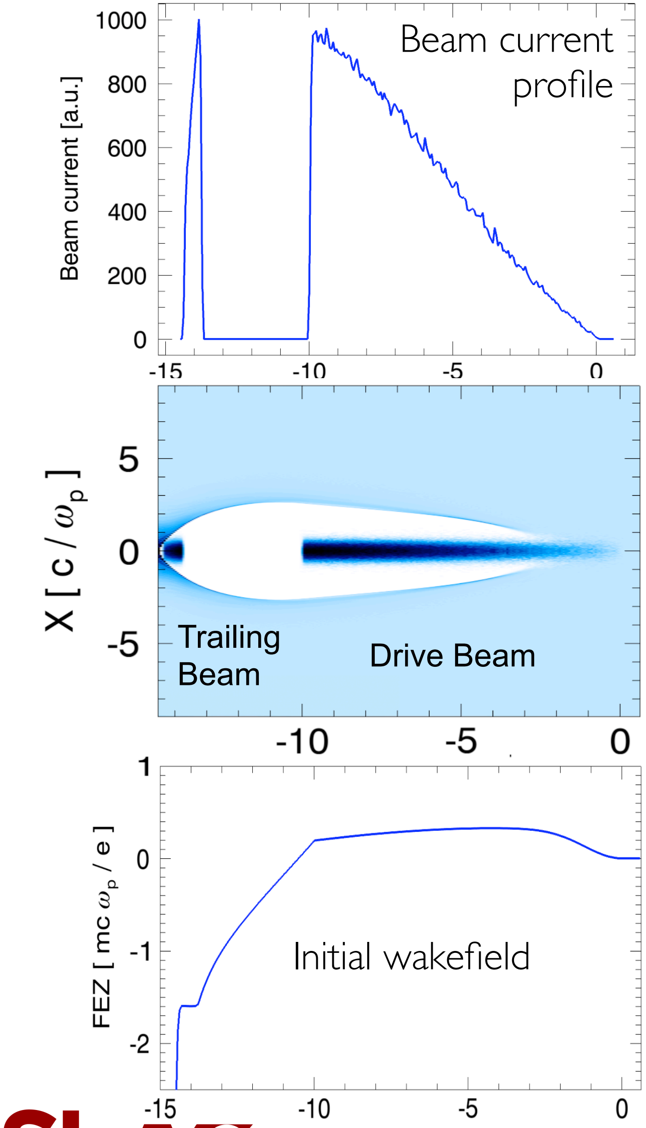
- Luminosity is critical in a linear collider
  - Physics studies have been based on ~1×10^{34} cm^{-2}sec^{-1}

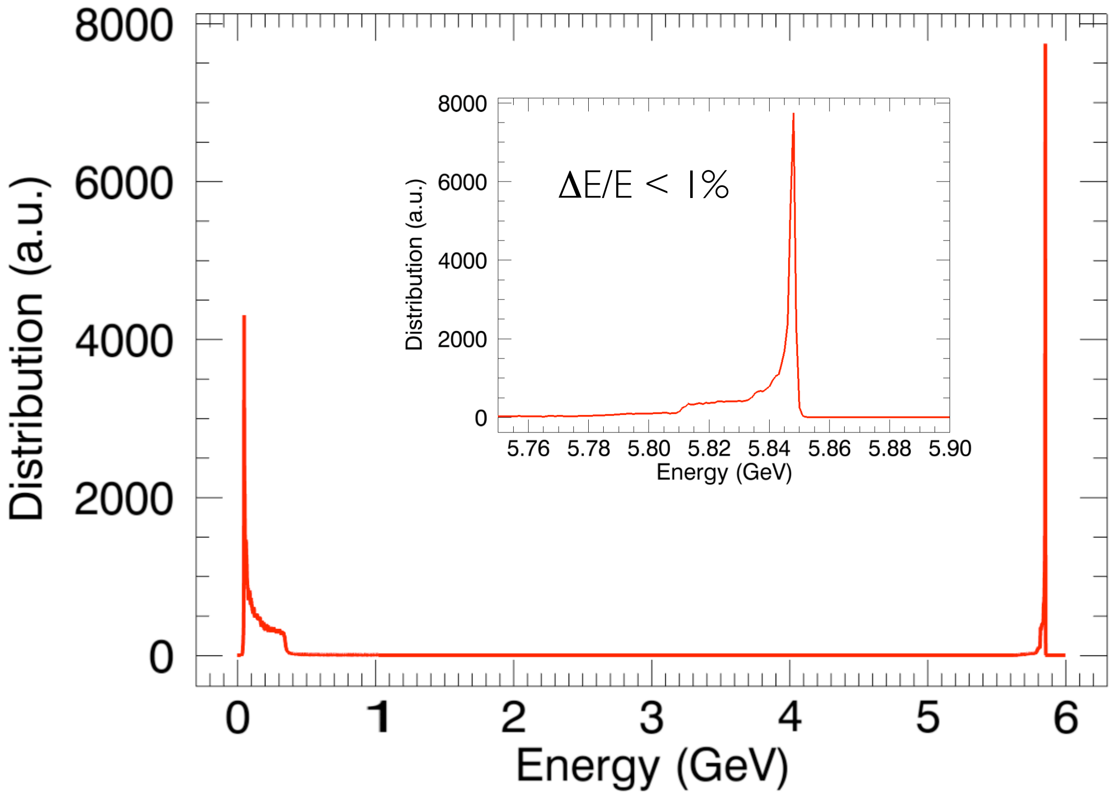
$$L = \frac{f_{rep}}{4\pi} \frac{N^2}{\sigma_x \sigma_y} \quad \Rightarrow \quad L = \frac{P_{beam}}{4\pi E_{beam}} \frac{N}{\sigma_x \sigma_y} H_D$$

- Need large beam powers, large bunch charges, and small spot sizes
  - For example, at 1 TeV:
    - 20 MW beam power, 10^{10} e+/e- per bunch, frep = 10 kHz, and σ_x/σ_y = 140 / 3 nm → 1×10^{34} cm^{-2}sec^{-1} within 1% of cms energy
- All parameters pushed beyond state-of-the-art
  - Choose set that minimizes the pain!

Simulation of PWFA with Transformer Ratio~5

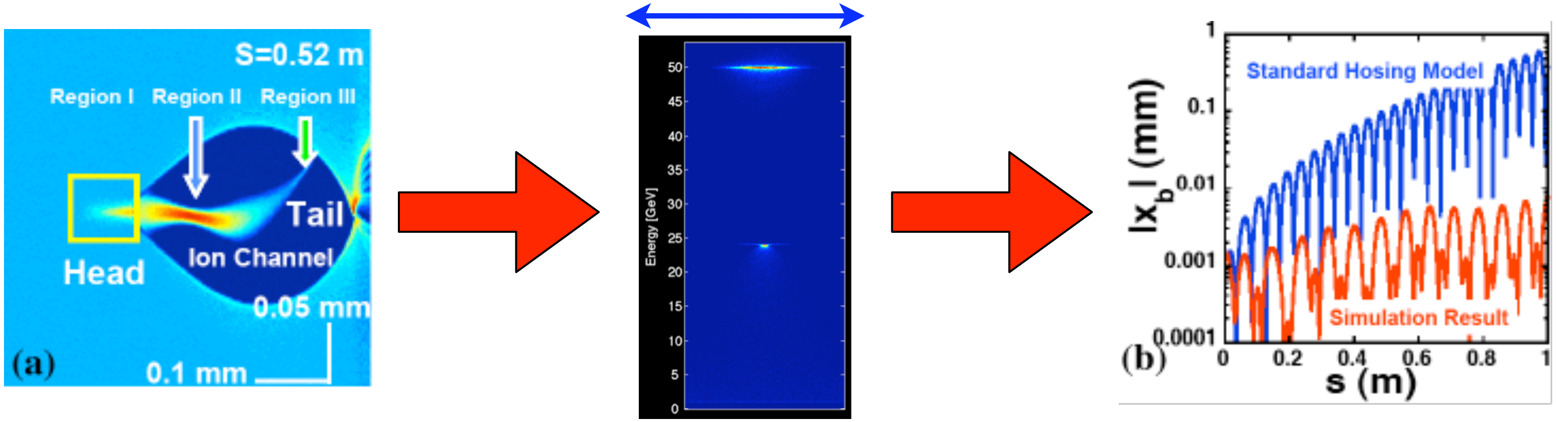
- Higher efficiencies possible with non-gaussian bunch profiles
- Applications beyond a PWFA-LC





FACET program will investigate emittance growth from several sources

- **Hosing**. Experimental signature is exponentially growing transverse displacement of accelerated bunch. Will excite through deliberate r vs. z correlation on drive bunch.



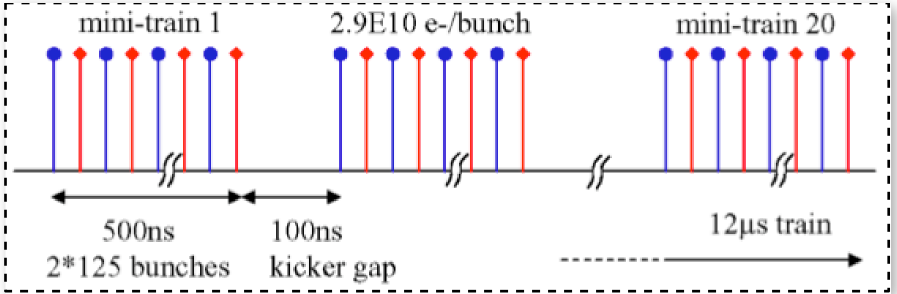
- **Ion motion**. Potentially an issue when $n_b/n_p \sim m_i/m_e$. Partially mitigated by using large emittance drive beam. FACET will attempt to quantify this for the first time by lowering the plasma density and measuring the emittance vs the ratio n_b/n_p.

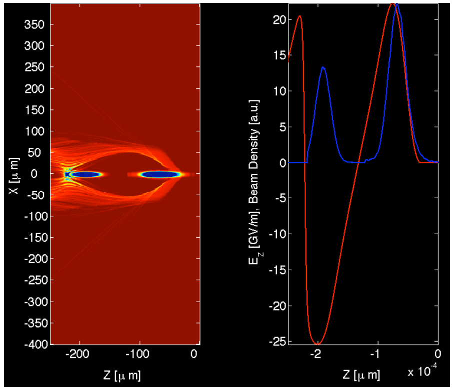
	Normalized Emittance [mm-mrad]	Sigma z [μm]	n_p	n_b/n_p
FFTB < 2005	>120 (x & y)	700	10^{14}	~10
FFTB > 2005	50 x 10	>12	10^{17}	~10
FACET	30 or 50 x 10*	>18	10^{14} -10^{17}	<10^4
PWFA-LC	D = 100, M = 2 x 0.05	D = 30, W= 10	10^{17}	100, 10^4

*Smaller emittance possible with upgrades

Plasma Stability & Cooling (1Hz to 1MHz)

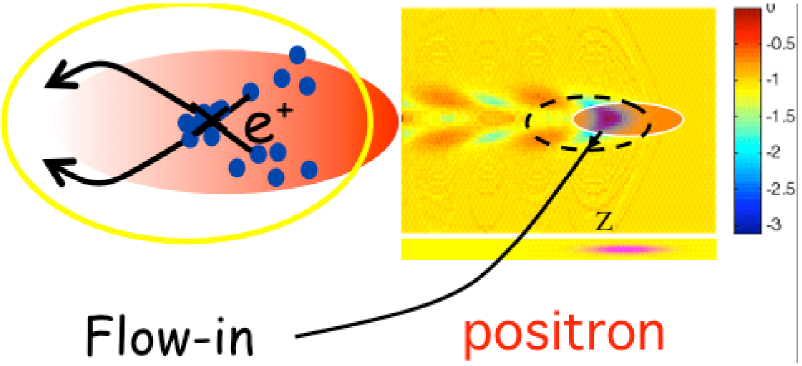
- Hollow plasma channels were mentioned as one area for plasma source development
- Warm conducting PWFA-LC concept maximizes efficiency with ~ns bunch spacing





- Plasma stability/reproducibility on ns time scales over several hundred shots has yet to be studied in plasma accelerators
- Proof of principle experiment possible by extracting several damping ring bunches at integer*5.6ns spacing
  - Energy spectrum vs shot number will indicate effective density

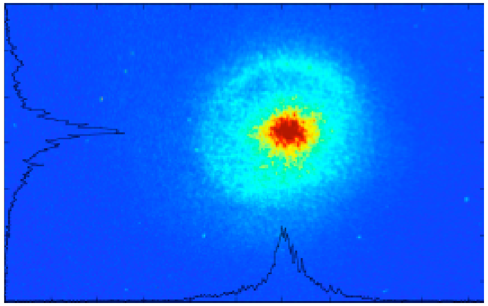
High Gradient Plasma Acceleration of Positrons

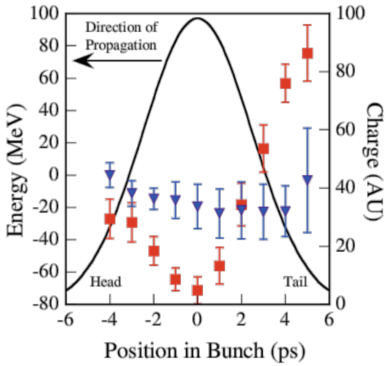


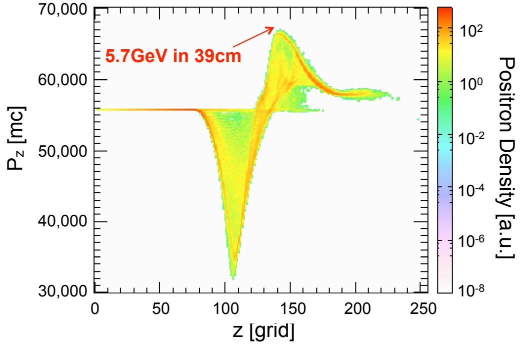
- * e+/plasma interaction much less studied than e-/plasma
- * Focusing force on e+ bunches is nonlinear

- * Emittance growth for single e^+ bunch in uniform plasma
- * Possible remedies include hollow plasma channel, linear wake

- * e^+ can be accelerated with in e^+ driven plasma wakes, but accelerating force is also nonlinear







Similar Physics with PD-PWFA

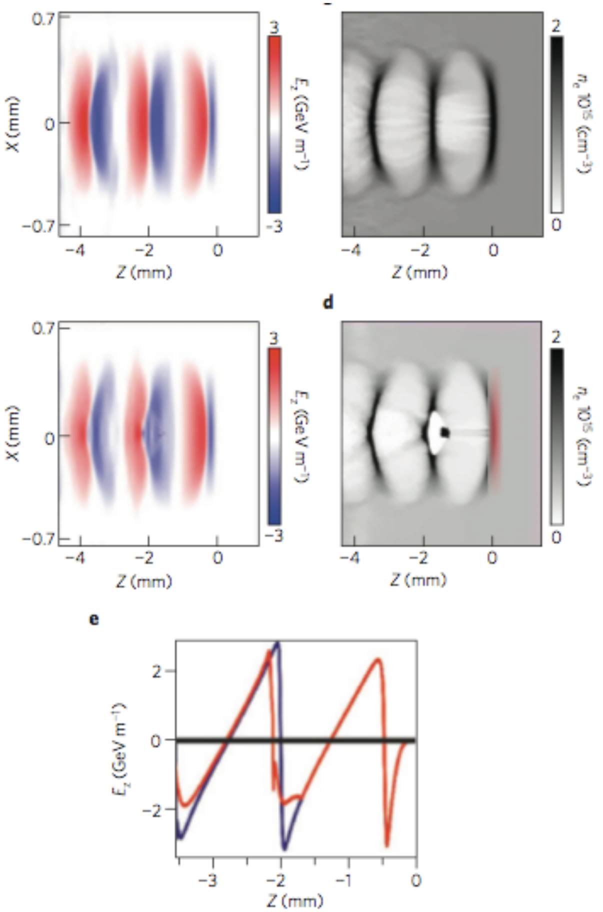
nature physics ARTICLES
PUBLISHED ONLINE: 12 APRIL 2009; CORRECTED ONLINE: 24 APRIL 2009 | DOI: 10.1038/NPHYS1248

Proton-driven plasma-wakefield acceleration

Allen Caldwell[1]*, Konstantin Lotov[2,3], Alexander Pukhov[4] and Frank Simon[1,5]

Table 1 | Table of parameters for the simulation.

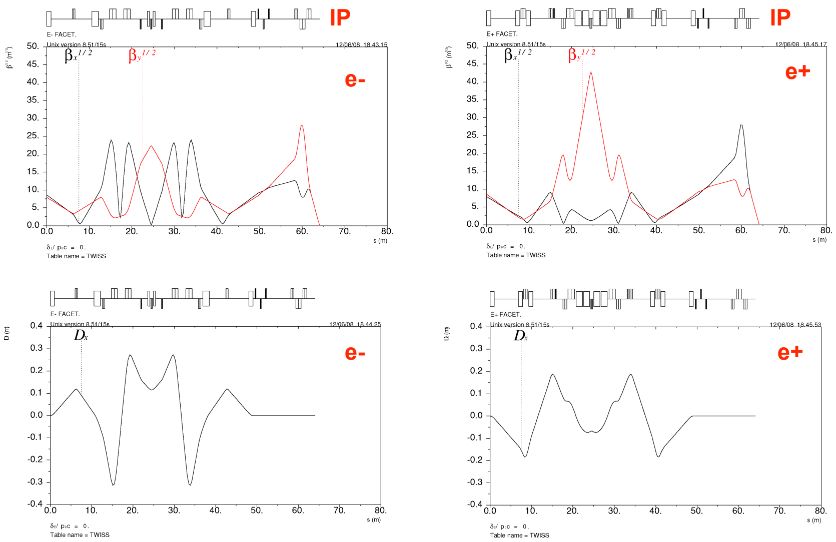
Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	$T\,m^{-1}$
Magnet length		0.7	m

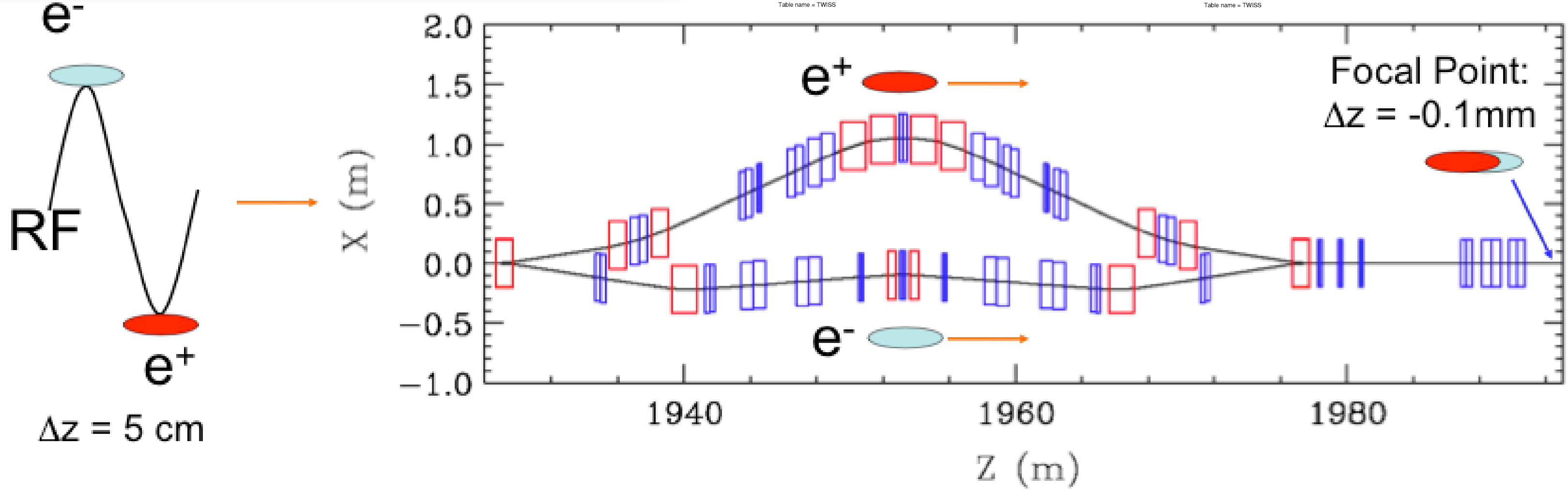


Sailboat Chicane Upgrade will enable full exploration of plasma acceleration of e^+ in e^- wakes

- Extract e- & e+ from damping rings on same linac pulse
- Accelerate bunches to sector 20 5cm apart
- Use 'Sailboat Chicane' to put them within 100μm at entrance to plasma
- Large beam loading of e^- wakes with high charge e^+ beams

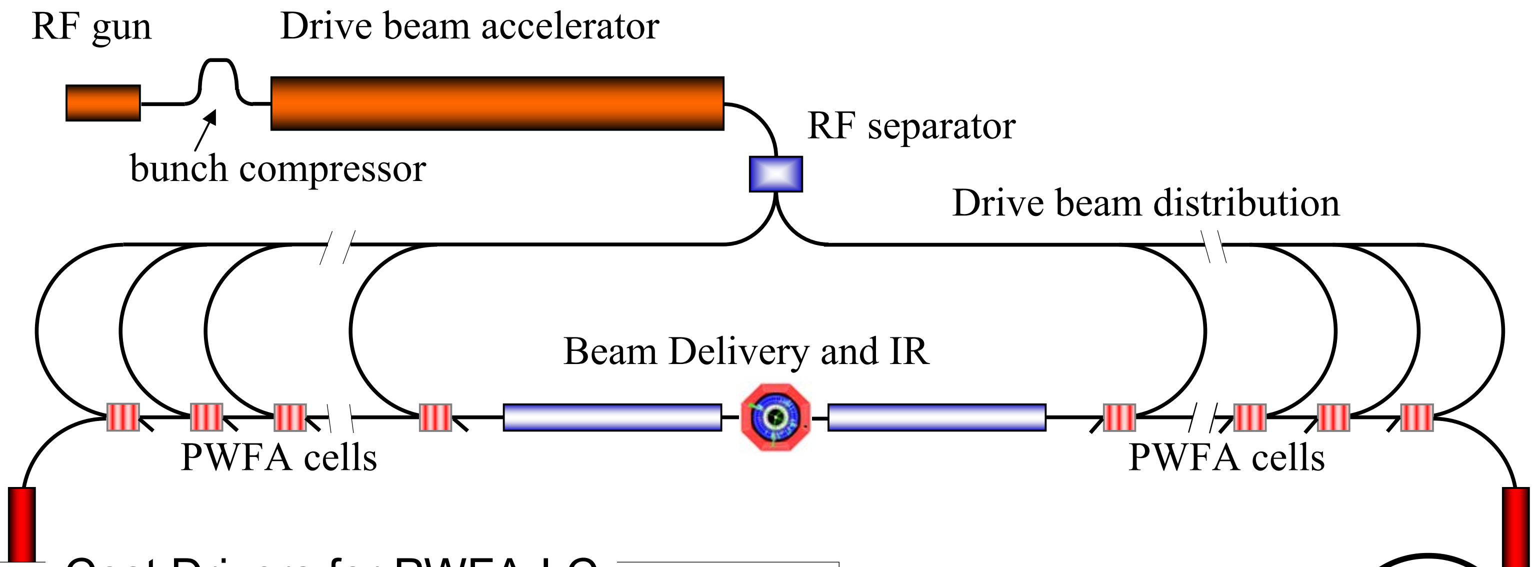
Beta functions and dispersion in chicanes and FF

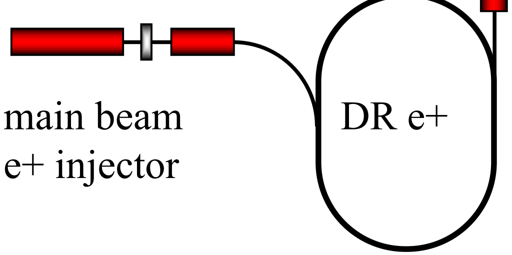




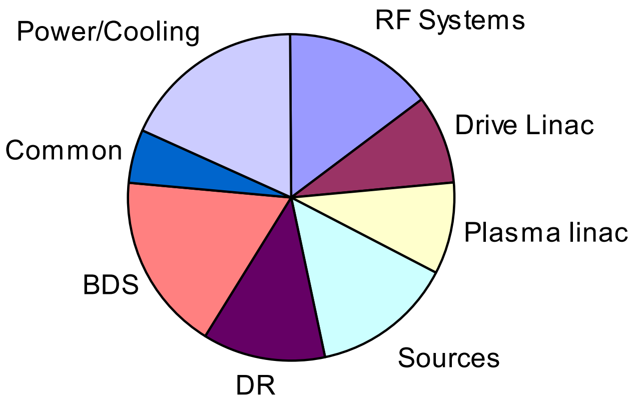
...other interesting applications as well!

Example: PWFA-LC Concept (Need detailed issues with model)





Cost Drivers for PWFA-LC

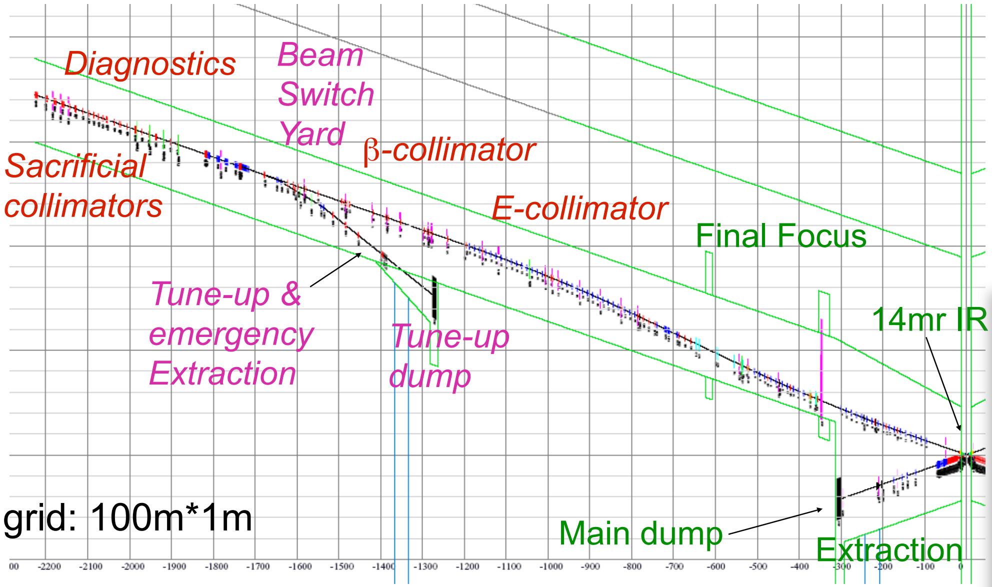


Areas for further improvement

- Superconducting drive linac
- Compact beam injection/extraction
- Shaped drive bunches
- Compact FFS and e- injectors

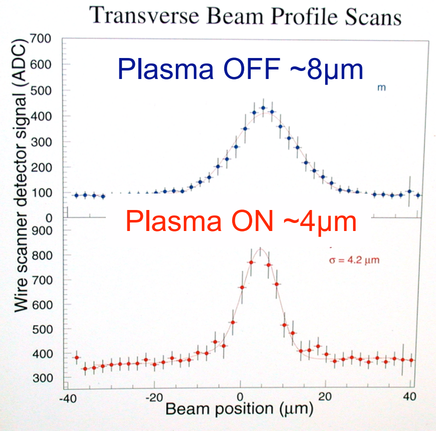
Opportunities Beyond Acceleration e.g. Beam Delivery & Plasma Lens

ILC Beam Delivery for 1TeV CM

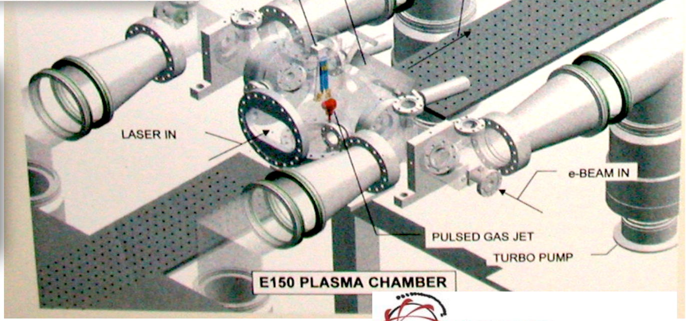


Early low-energy demonstration experiments in early to mid-nineties with electrons: FNAL (1990), JAPAN (1991), UCLA (1994)…

In 2001, E-150 Demonstrated plasma lensing of 28.5GeV electron *and* positron beams



Demagnification of 2
High Energy Beam with µm level spots

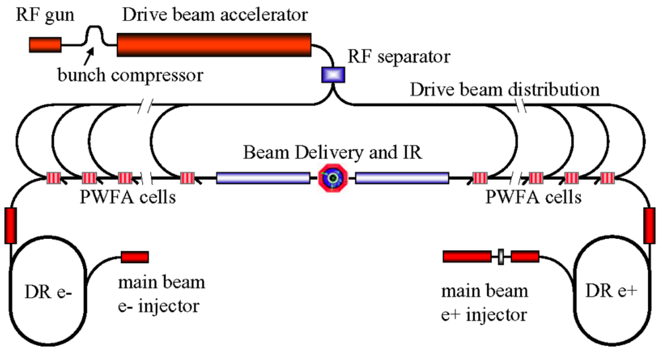


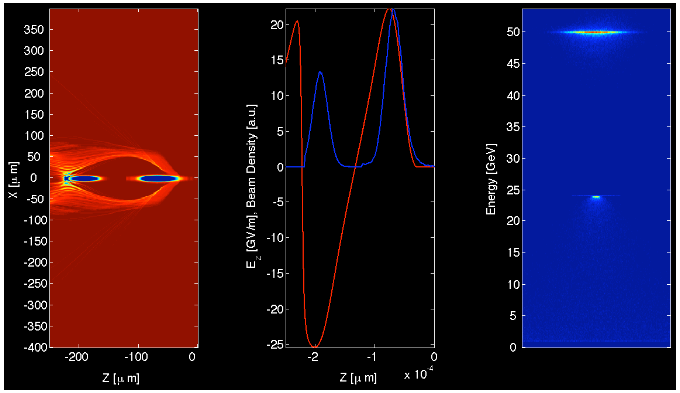
Plasma Potential:

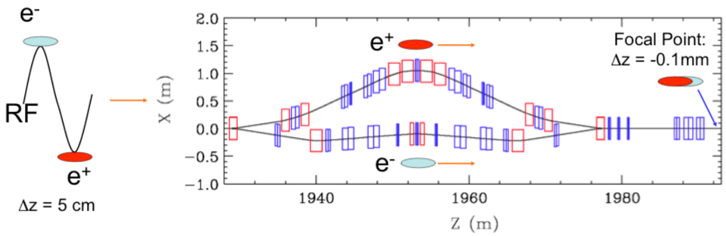
- > MT/m focusing to reduce the 600m final focus
- PWFA-LC design could re-distribute other functions

Summary

- Presented you a concept for PWFA-LC
  - Optimal use of Plasma Acceleration features
  - Experience of 30+ years of LC R&D to produce efficient design
  - Flexible concept, to allow changes resulting from FACET R&D
- FACET designed to address major issues of a PWFA -LC stage and lead to the next step
  - Accelerate a discrete bunch (not just particles)
    - With narrow dp/p, preserved emittance
  - Identify optimum method for e+ acceleration (e+ or e- driven wakes)
  - Study physics of PD-PWFA
- Successful completion of FACET
  - Define all parameters of PWFA-LC
- Experiments resume in early 2011!







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P. Tenenbaum	SLAC
J. Vollaire	SLAC
D. Walz	SLAC
X. Wang	USC
W. Wittmer	SLAC

Beams vs Lasers

- Physics:
  - Wakes and beam loading are similar for laser and beam driven plasmas
  - Driver propagation and coupling efficiency differ:
    - Lasers distort due to de-phasing, dispersion, photon deceleration, but to the plasma a 25GeV and 2GeV beam are nearly identical

      → Beams have higher coupling efficiency to wake (~2x)
    - Beams easily propagate over meter scales (no channel needed)

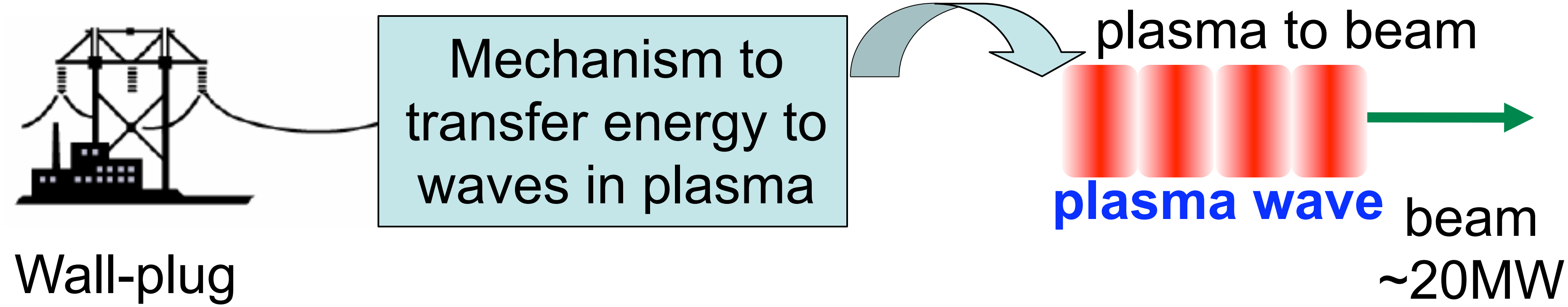
$$L_R \sim \pi\sigma^2/\lambda \sim \pi\sigma^2/1\mu \text{ vs } \beta^* \sim \pi\sigma^2/\varepsilon_v \sim \gamma\pi\sigma^2/1\mu$$

- Economics:
  - Lasers can more easily reach the peak power requirements to access large amplitude plasma wakes
    - $100K for a T^3 laser vs >$5M for even a 50MeV beam facility
  - However, need peak power AND average power (unlike DLA)
  - Average power costs sets the timescale for HEP applications
    - $$10^4$/Watt for lasers currently x 200MW ~ $2T driver. Much research on developing high power lasers but...
    - $10/Watt for CLIC-type RF x 100MW ~ $1B driver

$$L = \frac{P_{beam}}{4\pi E_{beam}}\frac{N}{\sigma_x\sigma_y}H_D$$

Plasma WF LC, Luminosity & Efficiency

- TeV collider call for P_{beam} ~10 MW of continuous power, small emittances and nanometer beams at IP



- An efficient approach to transfer several tens of MW of continuous power to plasma is to use drive beam

PWFA-LC drive beam linac

- Heavily loaded linac with high efficiency power transfer to the beam
  - High efficiency achieved by high peak current and low gradient
- Options for the design
  - CLIC drive linac has similar features and demonstrated 95% RF to beam efficiency without emittance growth (CTF3)
    - Slotted-iris, constant aperture (SICA) structure significantly reduces dipole Q and decouples dipole motion of the drive beam bunches
  - We used S-band structure: can take advantage of SLAC linac S-band klystrons if a prototype would need to be built and tested
    - Optimized to have 2.3 A peak current, 6.7 MV/m loaded gradient and 90% RF to beam efficiency
- Collaboration with CERN/CLIC colleagues on drive beam optimization for PWFA-LC would be most useful

PWFA-LC drive linac with S-band structures

- Conceptual design of structures for the drive linac:

RF frequency and structure operating mode	2856 MHz , $2\pi/3$
Structure Type	Slotted Iris – Constant Aperture (SICA)
Structure length	1.5m
Attenuation Factor & Filling Time	~0.17, 250 nsec
Fundamental Mode Q, Dipole Mode Q	~13000, ~20
Peak Current	2.3 A
Loaded gradient	6.7 MV/m
RF to Beam Efficiency	**90%**

[Shilun Pei, SLAC]

- Optimized for high efficiency and good damping of the dipole modes
- The structure optimized for S-band, which allowed, if needed, to perform structure tests with SLAC klystrons

Klystrons for PWFA-LC drive linac

- Klystron performance
  - SLAC 5045: 67MW at 3.5μs
  - Klystron of S-Band facility [DESY,ca.1995]: 150MW, 3μs

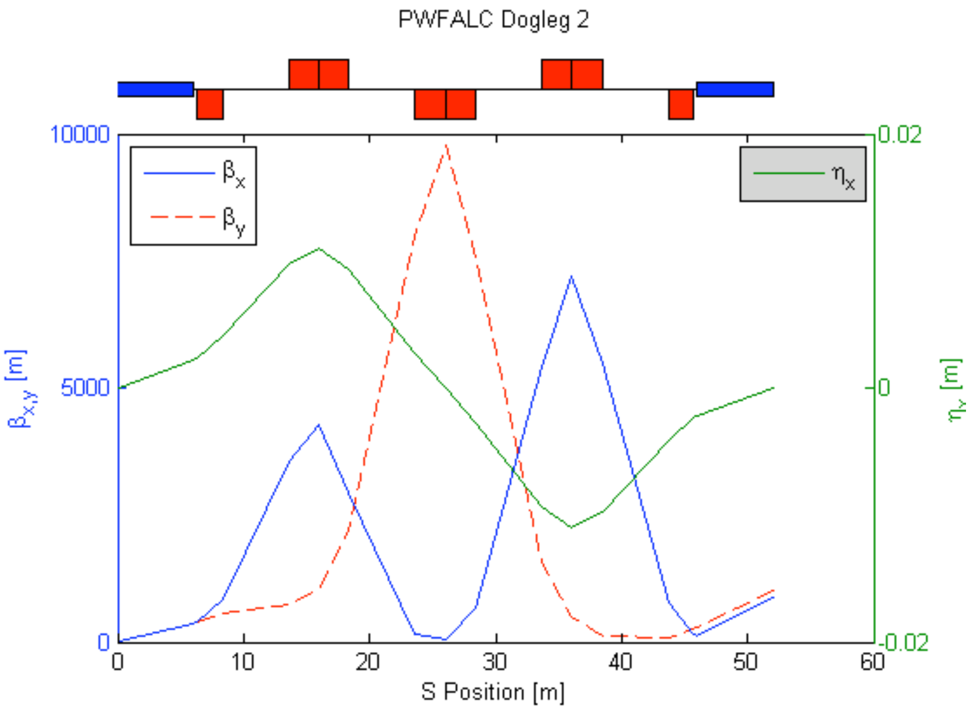
- Have proof-of-principle solution of using the SLAC 5045 klystron and modulator to produce
  - ~15-20MW, 0.1% duty (125Hz), ≥ 8μs pulse-width
    - Involves running with reduced voltage
  - Close to the specs of PWFA-LC demo, if it would be needed

[Daryl Sprehn,
Arnold Vlieks, SLAC]

- Guesstimate that an optimized multi-beam klystron will be 50~100 MW (similar average power to ILC MBK)
  - About ~600-1000 of klystrons would be required for the drive linac of 1TeV PWFA-LC

Isochronous magnetic combiner

- At the plasma cell, the main and drive beams are combined in a magnetic system, using their different energies
- Different challenges at different energies
  - High main beam energy: emittance growth from SR
  - Low main beam energy: separation tricky because of ~equal beam energies



Tentative 500 GeV/beam separator. First bend and quad separate drive and main beam in x (they have different E); combiner is same in reverse. System is isochronous to the level of ~1 μm R56. Emittance growth < 0.3 mm-mrad. Initial β_0=10cm.

IP parameters optimization

- Conventional <1TeV LC is typically in low quantum beamstrahlung regime (when $Y=2/3\ \omega_c\hbar/E<1$)
  - The luminosity then scales as $L \sim \delta_B^{1/2}\ P_{beam} / \varepsilon_{ny}^{1/2}$ (where δ_B is beamstrahlung induced energy spread)
- High beamstrahlung regime is typical for CLIC at 3TeV
- PWFA-LC at 1TeV is in high beamstrahlung regime
- Scaling and advantage of high beamstrahlung regime
  - $L \sim \delta_B^{3/2}\ P_{beam} / [\ \sigma_z\ \beta_y\ \varepsilon_{ny}\ ]^{1/2}$ and $\delta_B \sim \sigma_z^{1/2}$
  - short bunches allow maximizing the luminosity and minimizing the relative energy loss due to beamstrahlung
- Optimization of PWFA-IP parameters performed with high quantum beamstrahlung regime formulae and verified with beam-beam simulations

Other subsystems of PWFA-LC

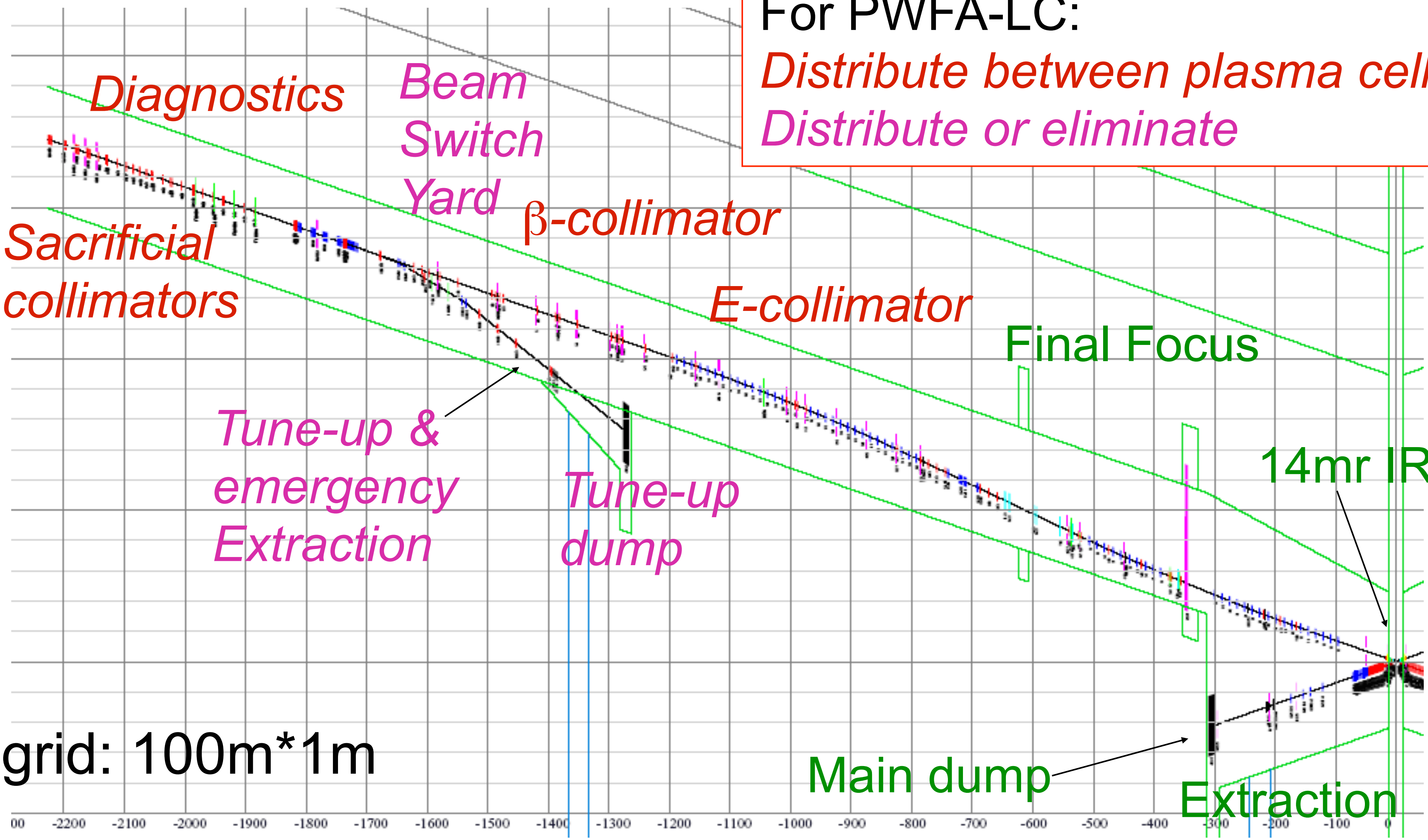
- Design of injectors, damping rings, bunch compressors, are similar to designs considered for LC and the expertise can be reused
  - Extensive tests of damping ring concepts at KEK ATF Prototype Damping Ring and the CESR-TA Test Facility
- Final focus system similar to conventional LC designs
  - Tested at Final Focus Test Beam and soon at the ATF2 at KEK
- Present design of Final focus and collimation has full energy acceptance of slightly greater than 2%
  - may need to deal with a factor of two larger energy spread for PWFA-LC
  - Further optimization of Final Focus and Collimation will need to be performed

ILC Beam Delivery for 1TeV CM

For PWFA-LC:

Distribute between plasma cells

Distribute or eliminate



FACET Systems in BDS for ILC and PWFA-LC

- * For ILC: expect very small emittance or dE/E growth in the linac:
  - → diagnostics and collimation only after the linac, included into the BDS
  - → Tune-up & emergency extraction dump (full power) after the linac, to keep DR and linac “warm” while BDS and detector is accessed and if dE/E or amplitude is larger than collimation acceptance
- * For PWFA: may need to collimate the beam after each plasma cell, and measure its properties
  - → distribute collimation and diagnostics from BDS to the optics between plasma cells
  - → Then the reason to have the emergency extraction in the BDS is also weakened, and may consider low power dump in between some plasma cells or eliminating the system
- → Then the length of BDS for PWFA-LC is ~700m per side
  - → However, if L* is decreased, even ~300m may be considered
  - → (Still not discussing any plasma length)

Emittance preservation

- Various phenomena were studied and found to be not limiting
  - Synchrotron radiation in plasma channel
  - Scattering in plasma (for low Z plasma)
- Issues which require further studies and parameter optimization
  - Ion motion is a potential issue, mitigating may require use of partially ionized plasmas, higher plasma atomic mass, lower plasma density (and lower gradient) and shorter bunches, tighter focusing at the IP and increasing the main beam power
  - If the main beam power to be increased, it would be beneficial to increase the PWFA efficiency by shaping the drive bunch. Plasma focusing may facilitate tighter focusing at the IP
  - Both the higher PWFA efficiency and plasma focusing studies are part of the FACET extended experimental program

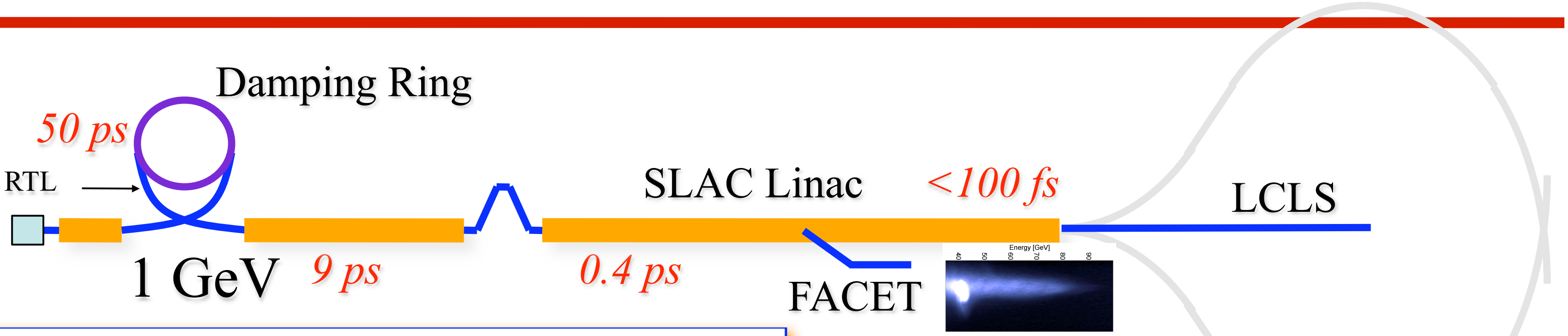
Plasma cells and flexibility of the concept

- Plasma cell is a heart of the PWFA-LC concept
  - The cell must provide acceleration with high throughput
- FACET will be able to produce a wide variety of beams to study the beam loading and acceleration with different plasmas
  - The initial tests will be done with lithium plasma
- In the PWFA-LC, the plasma in each cell needs to be renewed between bunches and stability of the plasma parameters is crucial
  - A high speed hydrogen jet is a possible candidate
- PWFA-LC concept is flexible:
  - bunch spacing presently assumed to be 4 ns
  - it can be doubled with the addition of RF separators and delay beamlines that can run along the drive linac
  - Increasing the bunch spacing by orders of magnitude could be done with a stretching ring, where the entire drive train would be stored and then bunches would be extracted one-by-one with fast rise kickers
  - Alternately could use a SC drive linac for very long spacing

Common CLIC-PWFA-LC topics

- Drive beam parameters, design, generation
  - frequency (1 or 3GHz)
  - energy (25GeV may be too high?)
  - RF system (and gaps in the train)
  - drive beam distribution system (isochronosity, compactness)
- Final focus and collimation
  - especially short bunch collimation survivability issues
- Drive bunch shaping
  - to allow increase of efficiency drive → witness to ~95%
  - and/or to allow higher transformer ratio ($E_{acc}/E_{decelerate}$)
    - may reduce number of stages but require larger charge/bunch

Short Bunches Bring Large Gradients and Long, Uniform High-Density Plasmas


Damping Ring

50 ps

RTL

SLAC Linac

<100 fs

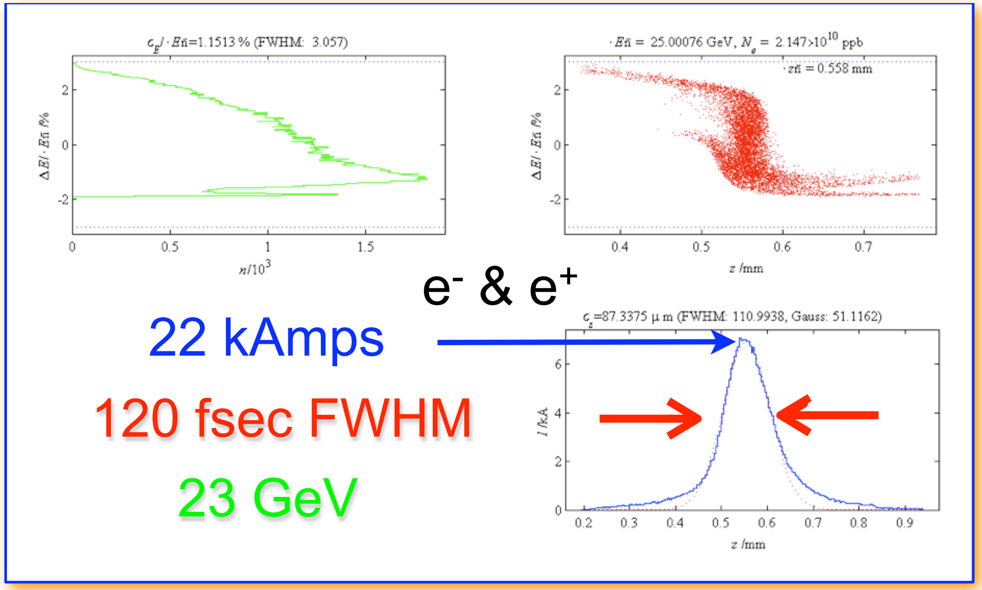
LCLS

1 GeV

9 ps

0.4 ps

FACET



e$^-$ & e$^+$

22 kAmps

120 fsec FWHM

23 GeV

Peak Field For A Gaussian Bunch:

$$E = 6GV/m \frac{N}{2x10^{10}} \frac{20\mu}{\sigma_r} \frac{100\mu}{\sigma_z}$$

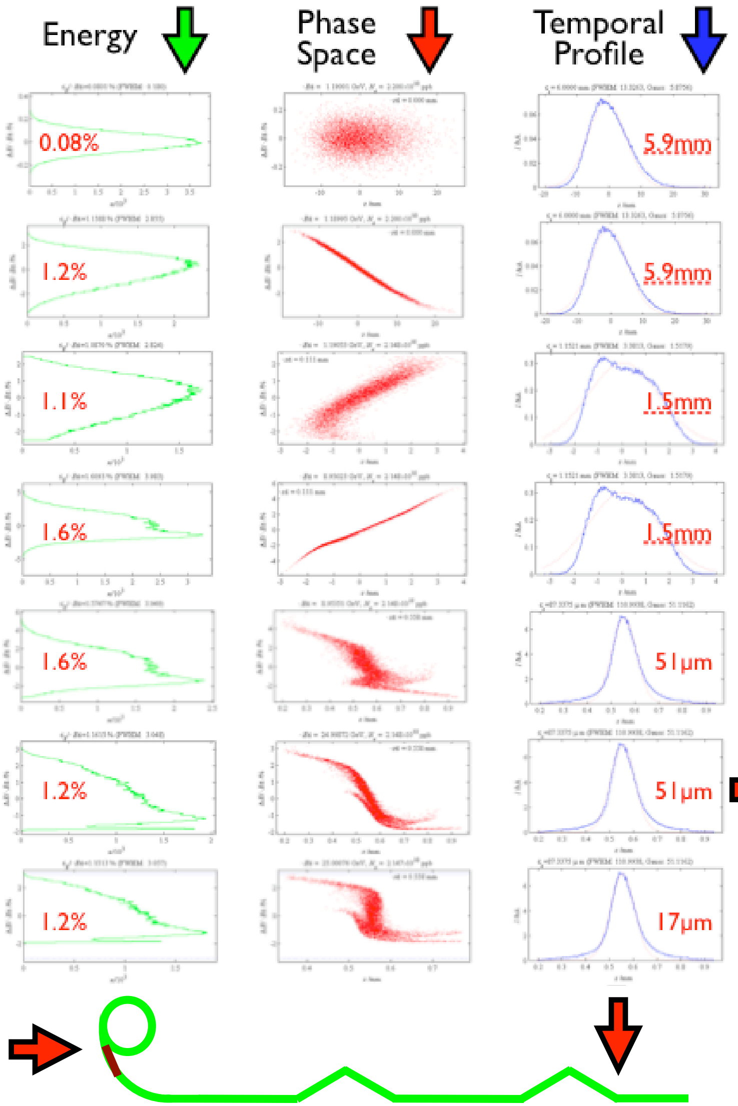
Ionization Rate for Li:

$$W_{Li}\left[s^{-1}\right] \approx \frac{3.60x10^{21}}{E^{2.18}\left[GV/m\right]} \exp\left(\frac{-85.5.}{E\left[GV/m\right]}\right)$$

See D. Bruhwiler et al, Physics of Plasmas 2003

Space charge fields tunnel ionize the vapor!
- No timing or alignment issues
- Long high-density plasmas now possible

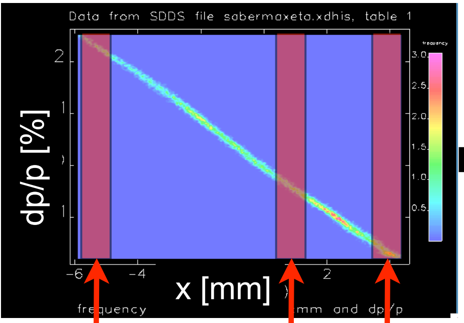
Generate Two Bunches by Selectively Collimating During Bunch Compression Process



Exploit Position-Time Correlation on e- bunch to create separate drive and witness bunch

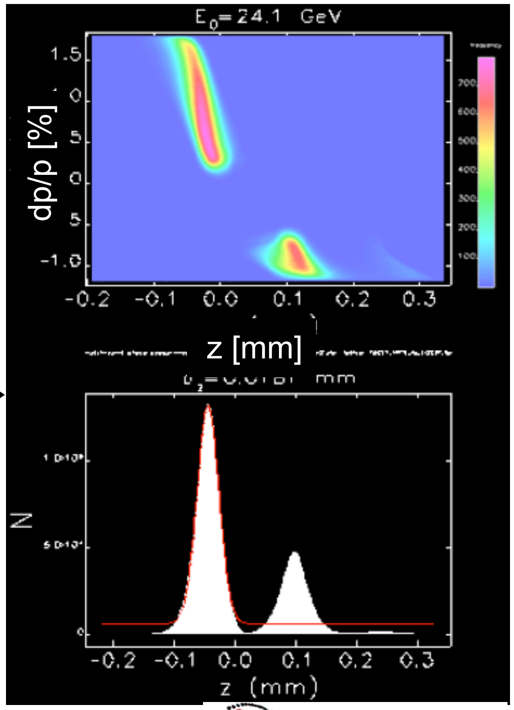
Disperse the beam in energy

$$x \propto \Delta E/E \propto t$$



...selectively collimate

Adjust final compression



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