Advances in Beam-Driven Plasma Accelerators

IPAC 2013

Mark Hogan May 14, 2013

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Great Desire for Compact Access to High Energy Beams

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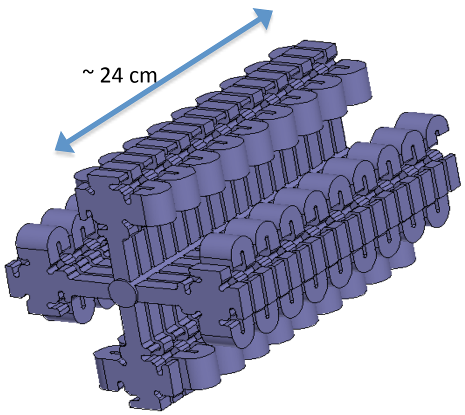
High energy particle accelerators are the ultimate microscopes

- Reveal fundamental particles and forces in the universe at the energy frontier
- Enable x-ray lasers to look at the smallest elements of life on the molecular level

Looking to beam driven concepts to shrink the size and cost of these accelerators by factors of 10-1000

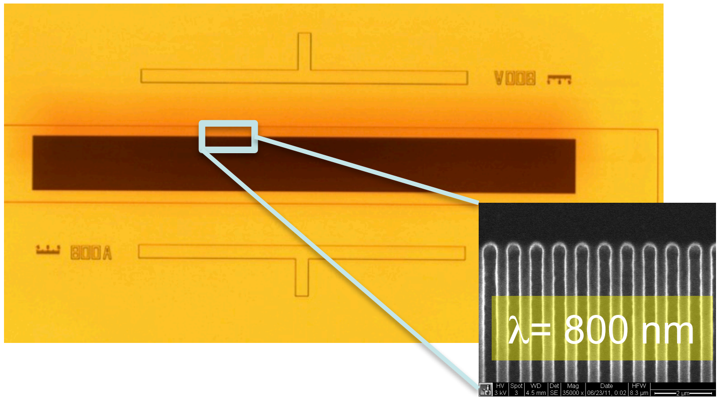
Combine efficient accelerator drivers with high-field dielectric and plasma structures to develop new generation of particle accelerators

~100MeV/m



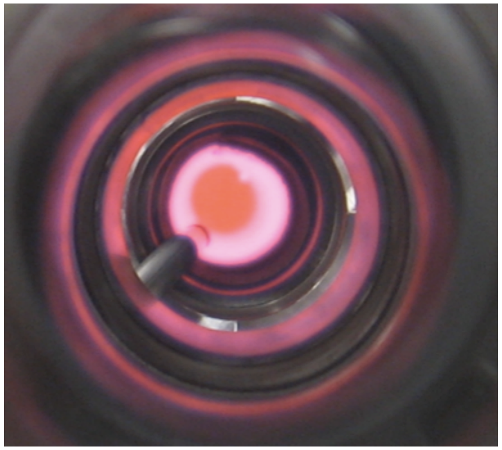
New designs and materials push metal structures to the limit

~1GeV/m



Telecom and Semiconductor tools used to make an 'accelerator on a chip'

~10GeV/m

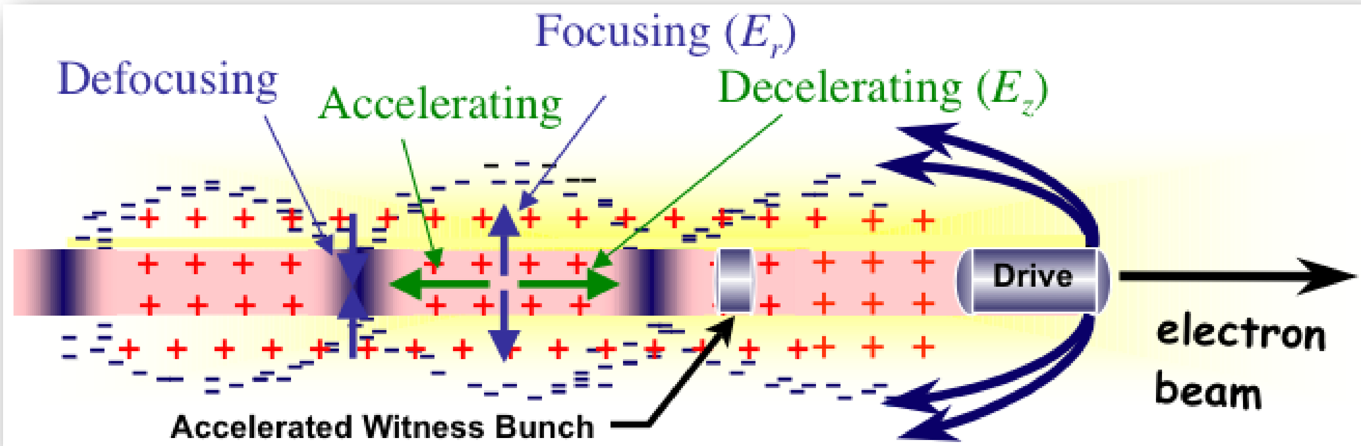


Extremely high fields in 1,000°C lithium plasmas have doubled the energy of the 3km SLAC linac in just 1 meter

A Beam Driven Plasma Wakefield Accelerator

A very high frequency structure acting as an energy transformer

- Accelerating structure is created anew every shot
- High gradients need high density plasmas
  - ~10^{17} e^-/cm^3
  - >10GeV/m acceleration
  - >MT/m focusing



For wake excitation need a beam matched to plasma dimensions:

- Individual bunches, or a bunch train, 100's fs apart (or use SMI for long bunches)
- Individual bunches small in all three dimensions
- High bunch charge for blow-out with large wake amplitude & good transport
- Need long, uniform high-density plasmas

Idea to Harness the Large Stored Energy in Proton Bunches to make High Energy Electrons

MAX-PLANCK-GESELLSCHAFT

nature physics

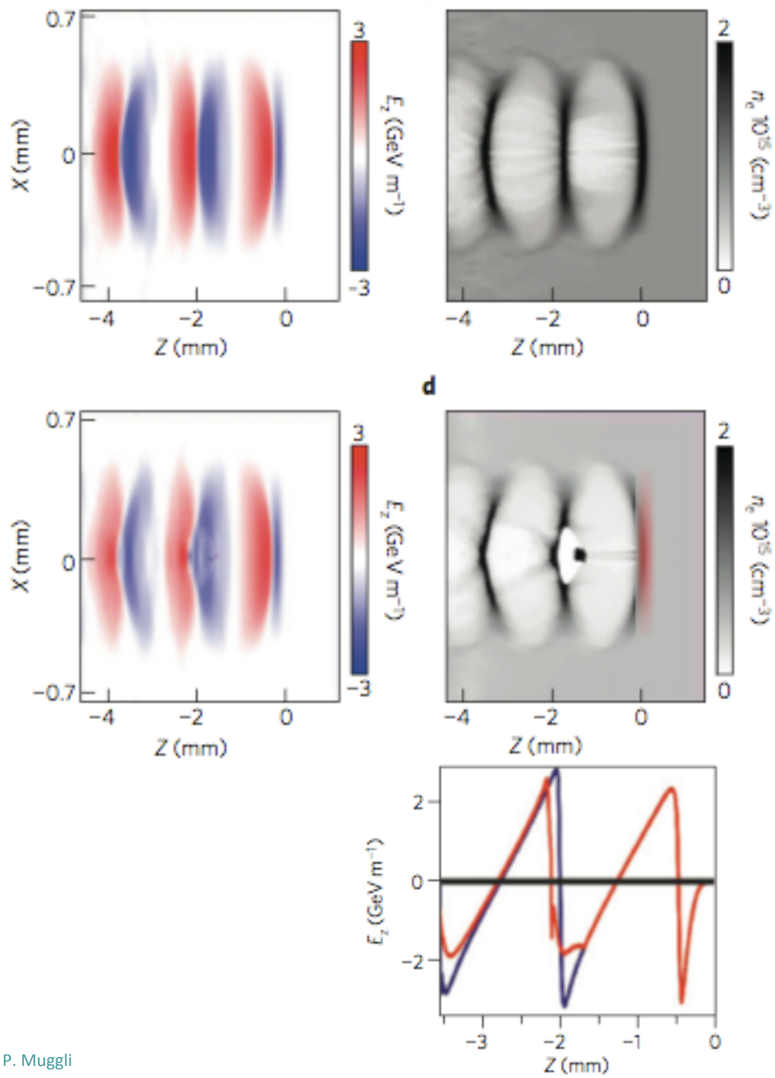
ARTICLES

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

AWAKE

Proton-driven plasma-wakefield acceleration

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

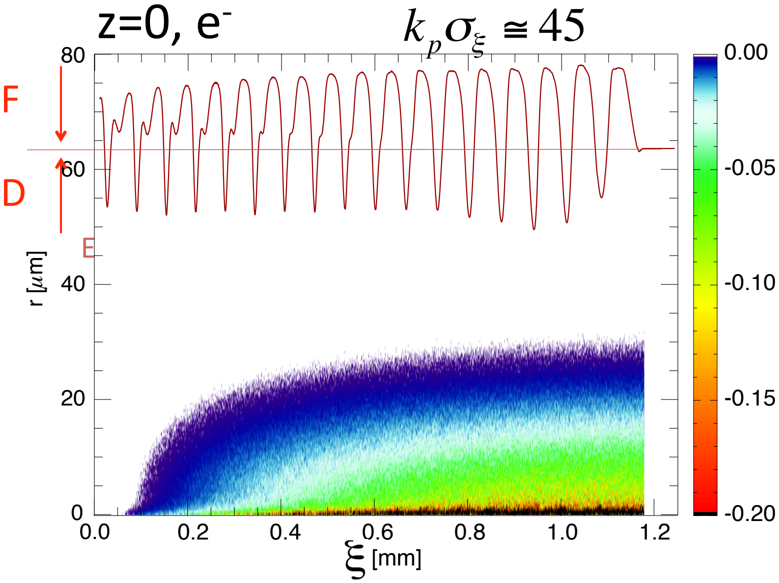


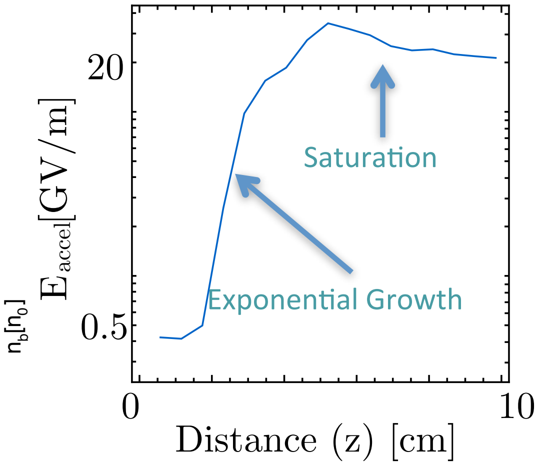
Goals of the AWAKE Collaboration:

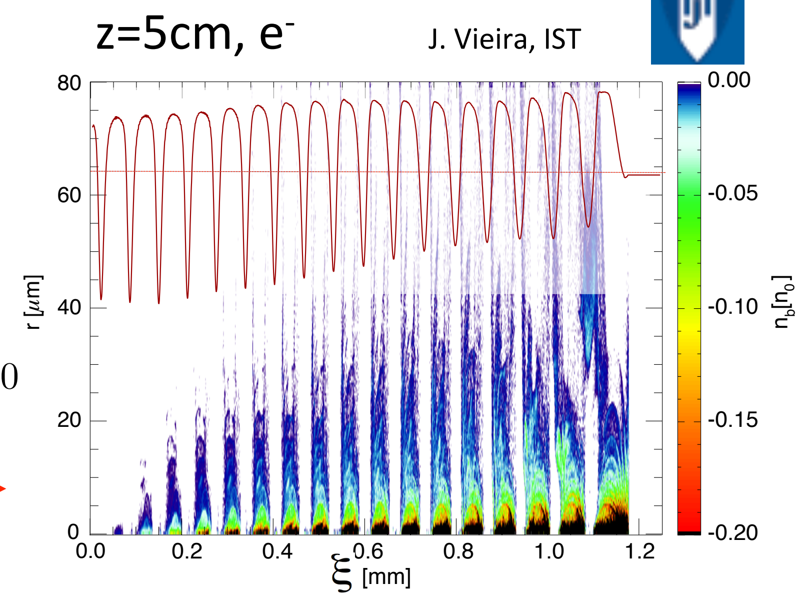
- >500 GeV e- in single long plasma cell (400m)!
- Requires short proton bunches (100µm vs 10 cm)
- Study physics of self-modulation of long p bunches
- Probe wakefields with externally injected e-
- Study injection dynamics for multi-GeV e-
- Develop long, scalable and uniform plasma cells
- Develop schemes for production and acceleration of short p bunches

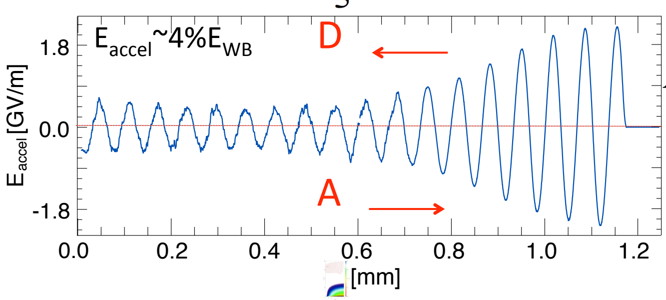
SELF-MODULATION INSTABILITY (SMI)

Kumar, PRL 104, 255003 (2010)



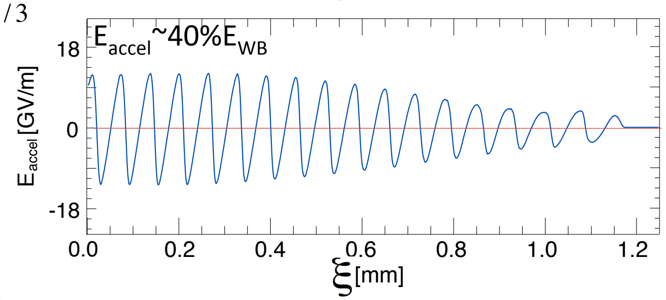






$$N_{exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{\gamma M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$

Grows along the bunch & along the plasma
Convective instability



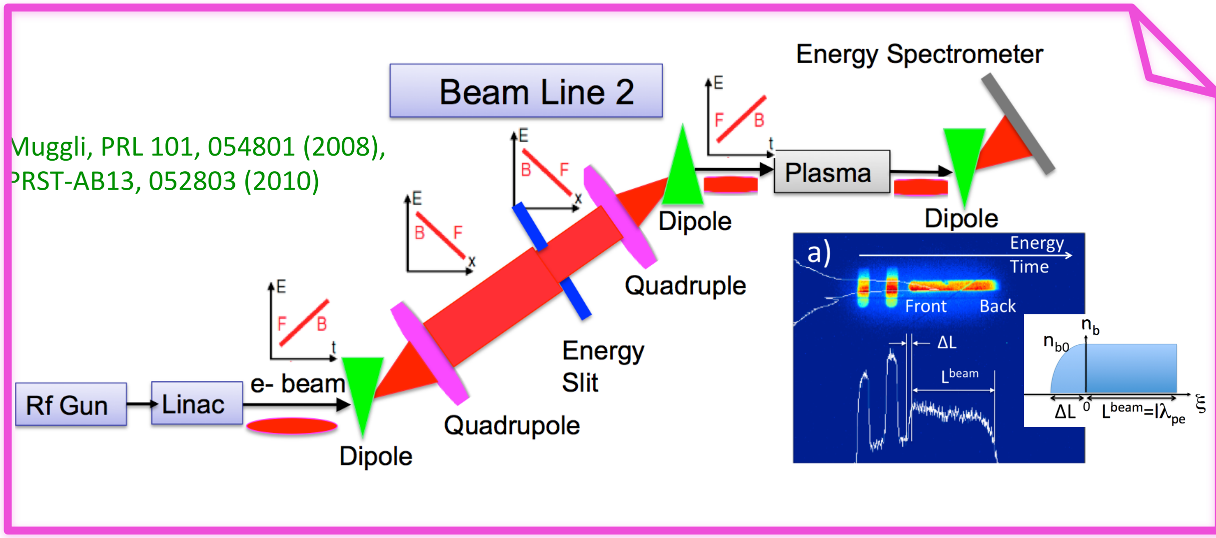
Pukhov, PRL 107, 145003 (2011)
Schroeder, PRL 107, 145002 (2011)

- Initial small transverse wakefields modulate the bunch density
- Associated longitudinal wakefields reach large amplitude through resonant excitation, similar to single bunch with total charge

Vieira, Phys. Plasmas 19, 063105 (2012)

SEEDING OF SMI

❒ Seeding of self-modulation instability (SMI) needed to shorten growth length to saturation, fix wakefields phase for external injection, suppress hose instability

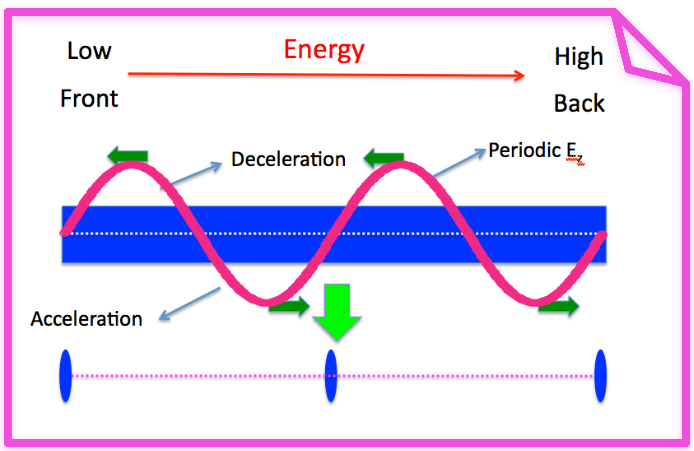


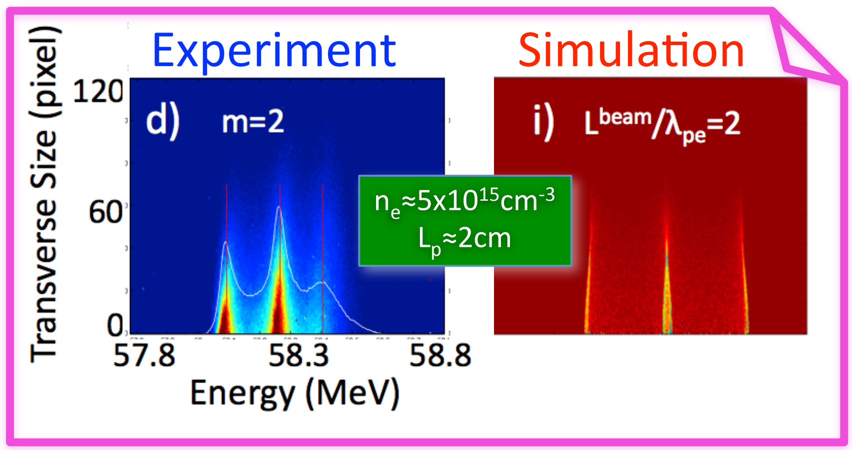
❒ Shape the bunch with "square" current profile

❒ The sharp ($<\lambda_{pe}$) rise time seeds the SMI by generating large wakefield amplitudes

❒ Seed wakefields lead to periodic energy bunching (FEL-like) with *m+1* peaks, $m=L^{beam}/\lambda_{pe}$

❒ With the low charge bunch (50pC) the energy modulation is visible in the experiment





❒ Shaped bunch generate linear wakefields for the seeding of the SMI

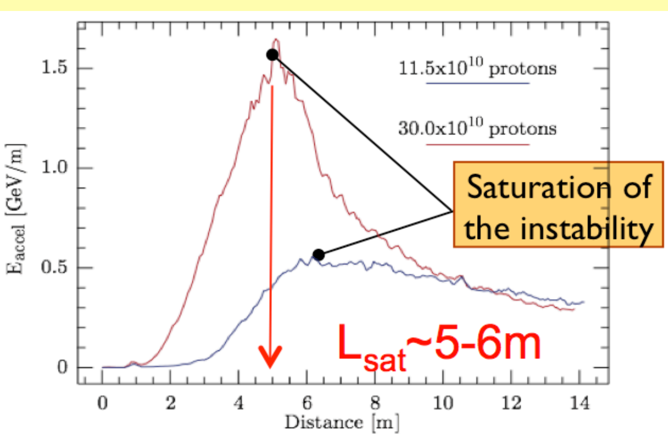
Work by Yun Fang, USC

SMI-PWFA PARAMETERS

❒ Experimental parameters determined by beam parameters

❒ CERN AWAKE

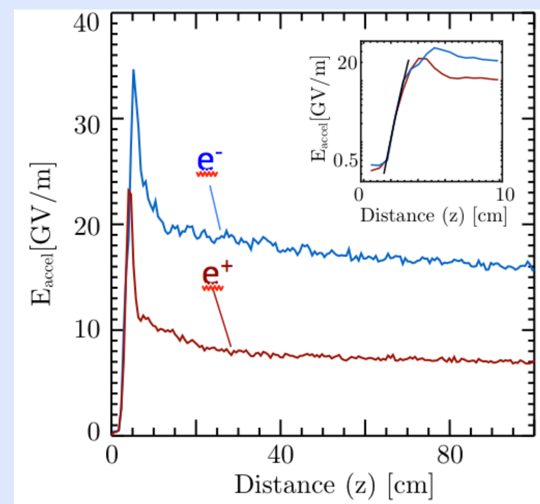
- p^+-driven
- SMI saturates in ~5m
- Study SMI or p^+-bunches
- Remain in ~linear PWFA regime
- ~GV/m over 10^+ m
- Externally inject e^-
- Accelerator experiments



Parameter	PDPWFA	PWFA
$n_e[\mathrm{cm}^{-3}]$	6×10^{14}	2.3×10^{17}
$f_{pe}[\mathrm{GHz}]$	220	4′300
$\sigma_r[\mu m]$	200	10
$\sigma_r[c/\omega_{pe}]$	0.9	0.9
$\sigma_\xi[\mathrm{cm}]$	12	5×10^{-2}
$\sigma_\xi[c/\omega_{pe}]$	553	45
σ_ξ/λ_{pe}	88	7
$E_0[\mathrm{GeV}]$	400	20.5
γ_0	426	40′000
N_{part}	30×10^{10}	2×10^{10}
n_b/n_0	2×10^{-2}	10^{-1}
$L^{\mathrm{plasma}}[\mathrm{m}]$	10	1
$L^{\mathrm{plasma}}[c/\omega_{pe}]$	46′056	90′173
$L^{\mathrm{plasma}}/\lambda_{pe}$	7′330	14′352
$\epsilon_N[\mathrm{mm}\cdot\mathrm{mrad}]$	3.83	50

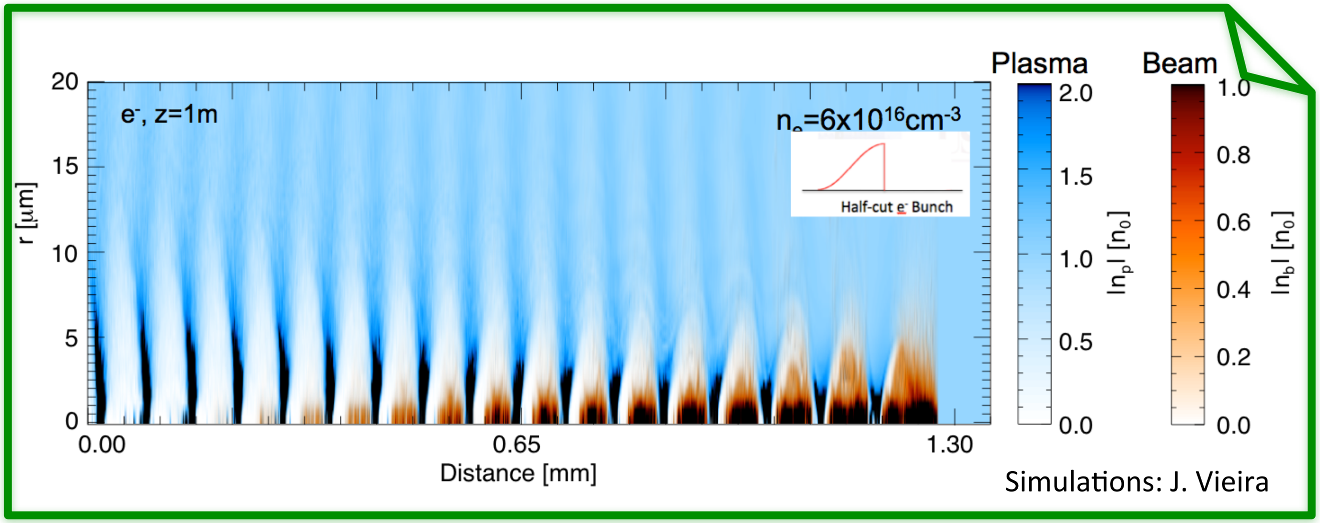
❒ SLAC E209

- e^-/e^+-driven
- SMI saturates in ~5cm
- Compare SMI of e^-/e^+ bunches
- Reaches nonlinear PWFA regime
- >10GV/m
- Multi GeV energy gain (drive particles) in ~1m
- SMI diagnostic

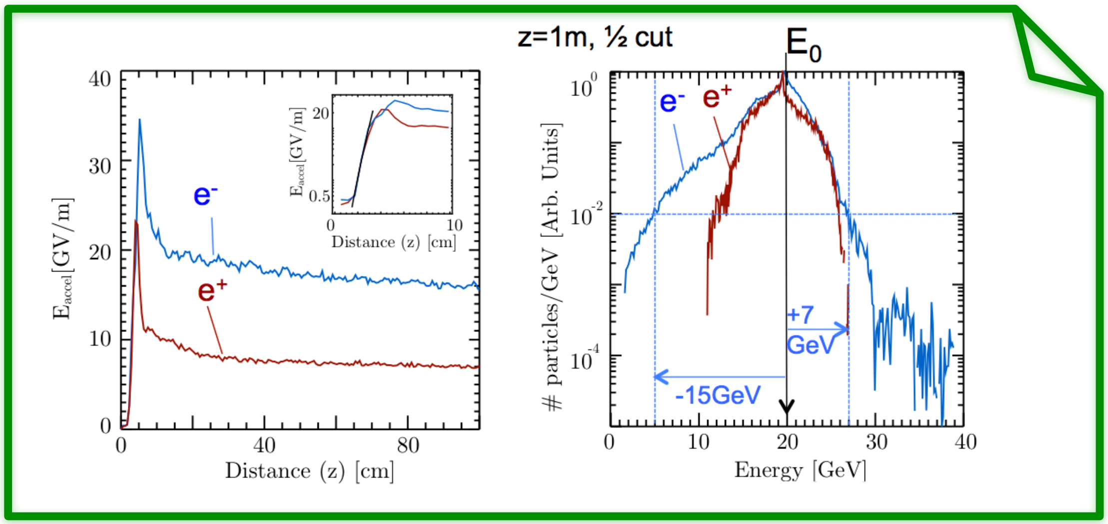


P. Muggli

LARGE AMPLITUDE WAKEFIELDS FROM SMI



- ❒ The SMI is seeded by shaping, "cutting", the bunch using a masking technique.
- ❒ The SMI of uncompressed FACET e^- and e^+ bunches forms a drive train
- ❒ The radial modulation period can be measured using transition radiation diagnostics

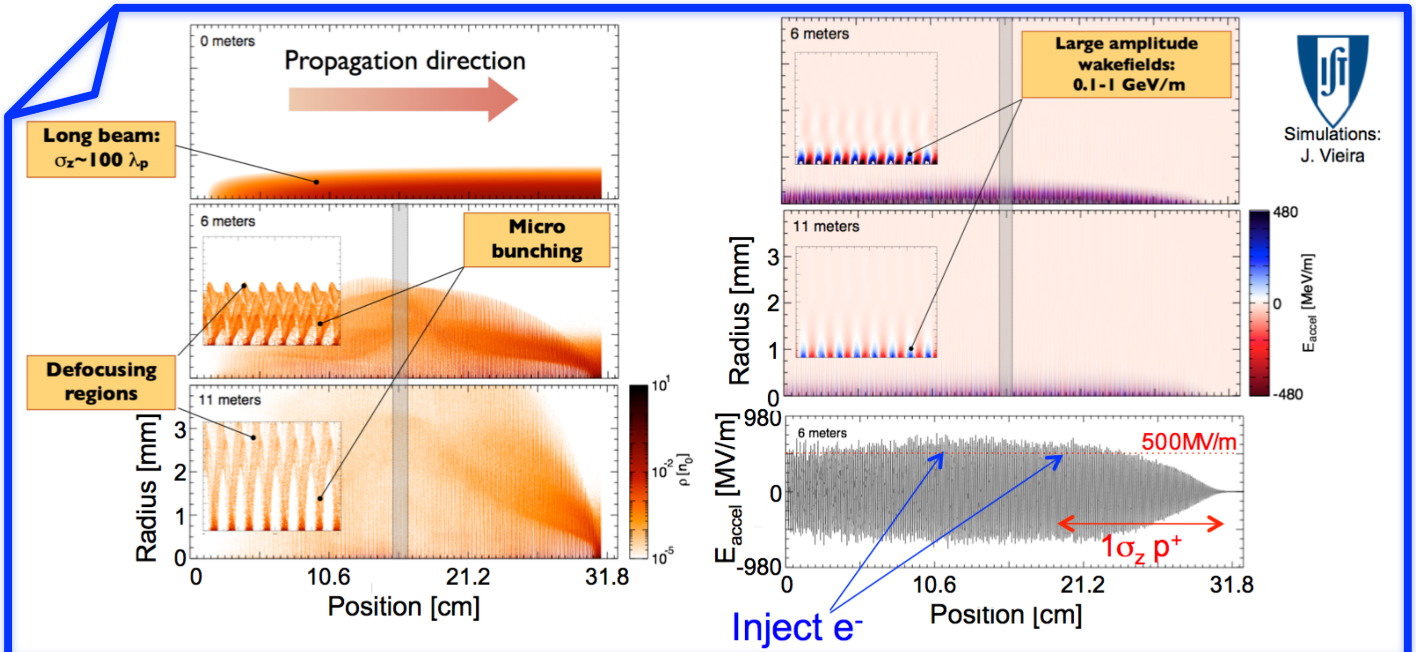


- ❒ The drive train resonantly drives accelerating fields to large amplitudes
- ❒ SMI saturates in ~5cm (~5m for p+)
- ❒ The drive bunch particles experience large energy loss/gain

- ❒ Differences between negatively (e^-) and positively (e^+, p^+) charged particle bunches can be studied
- ❒ SMI physics: SMI, seeding, radial modulation, competition with hosing …

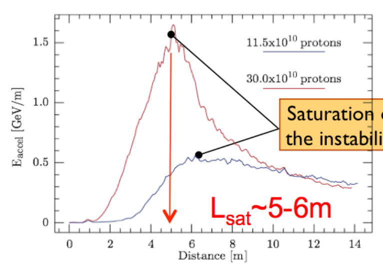
J. Vieira et al., Phys. Plasmas 19, 063105 (2012)

LARGE AMPLITUDE WAKEFIELDS FROM SMI



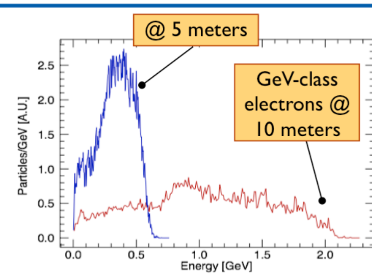
- Very long p^+ bunch: L^{beam}/λ_{pe}~100
- E_z peaks at ~$1\sigma_z$
- L_{plasma}=10m, n_e=1-10x10^{14}cm^{-3}
- SMI seeding with laser-created relativistic ionization front

Maximum accelerating gradients

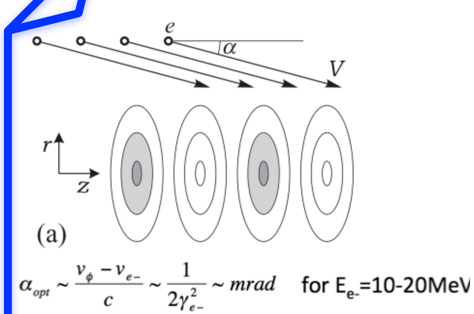


- Maximum fields achieved at 5 m of propagation
- GeV/m wakefields can be excited
- Wake phase velocity on the order of driver velocity (large dephasing lengths)

Test electron beam spectra using 3x10^{11} p^+

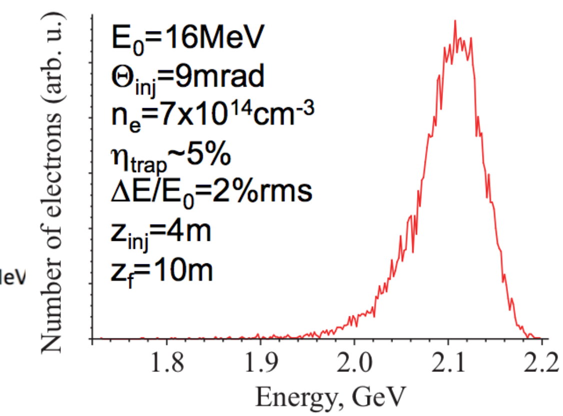


- Acceleration of external electrons to high energies
- High energies can be achieved (once the instability saturates lengths)



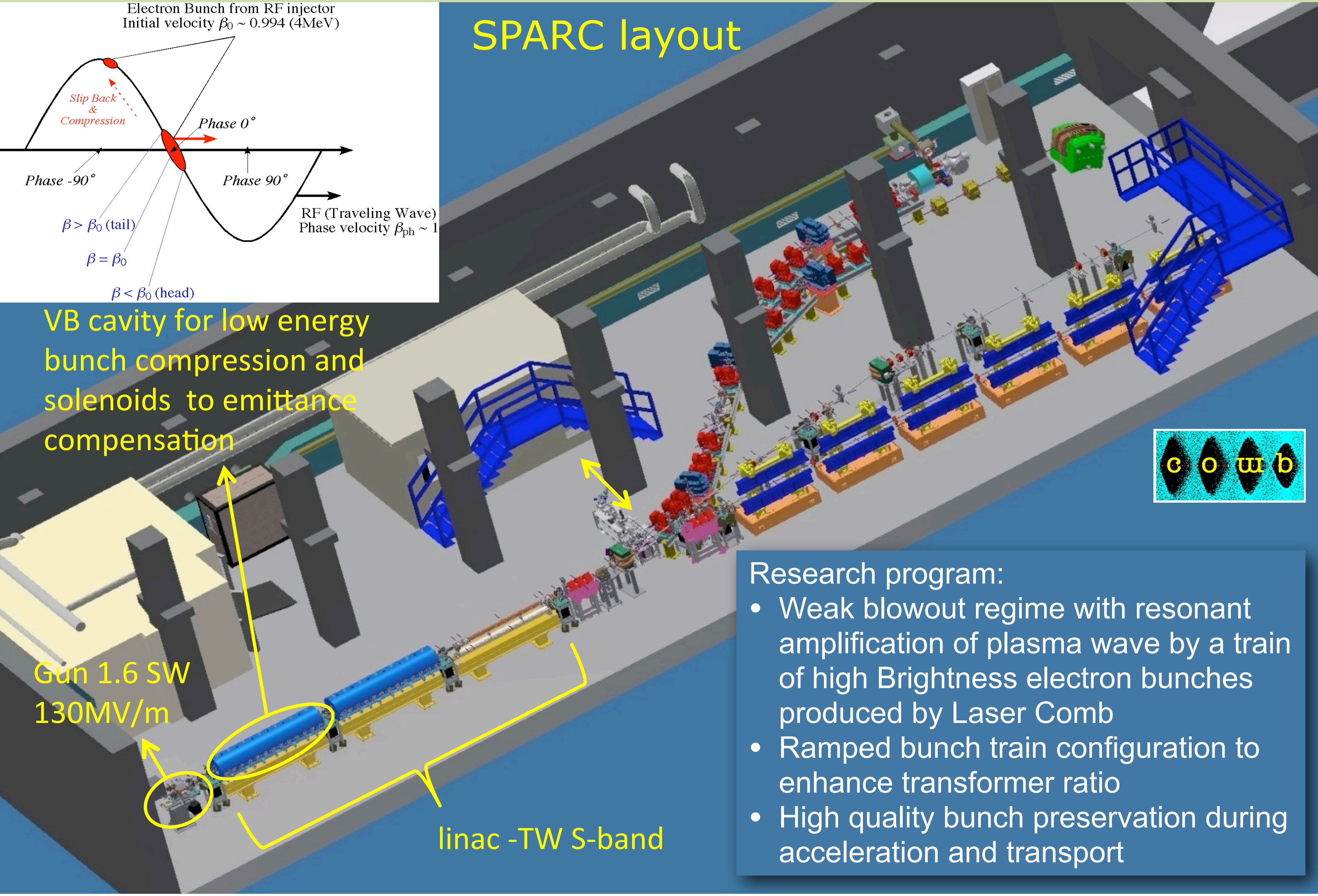
$$\alpha_{opt} \sim \frac{v_\phi - v_{e-}}{c} \sim \frac{1}{2\gamma_{e-}^2} \sim mrad$$ for E_{e-}=10-20MeV

Lotov, J. Plasma Phys. (2012)



- SMI saturates after 4-6m
- Witness electrons (10-20MeV) injected on axis gain up to 2GeV, road energy spectrum
- Witness electrons (10-20MeV) side-injected have a narrow energy spectrum

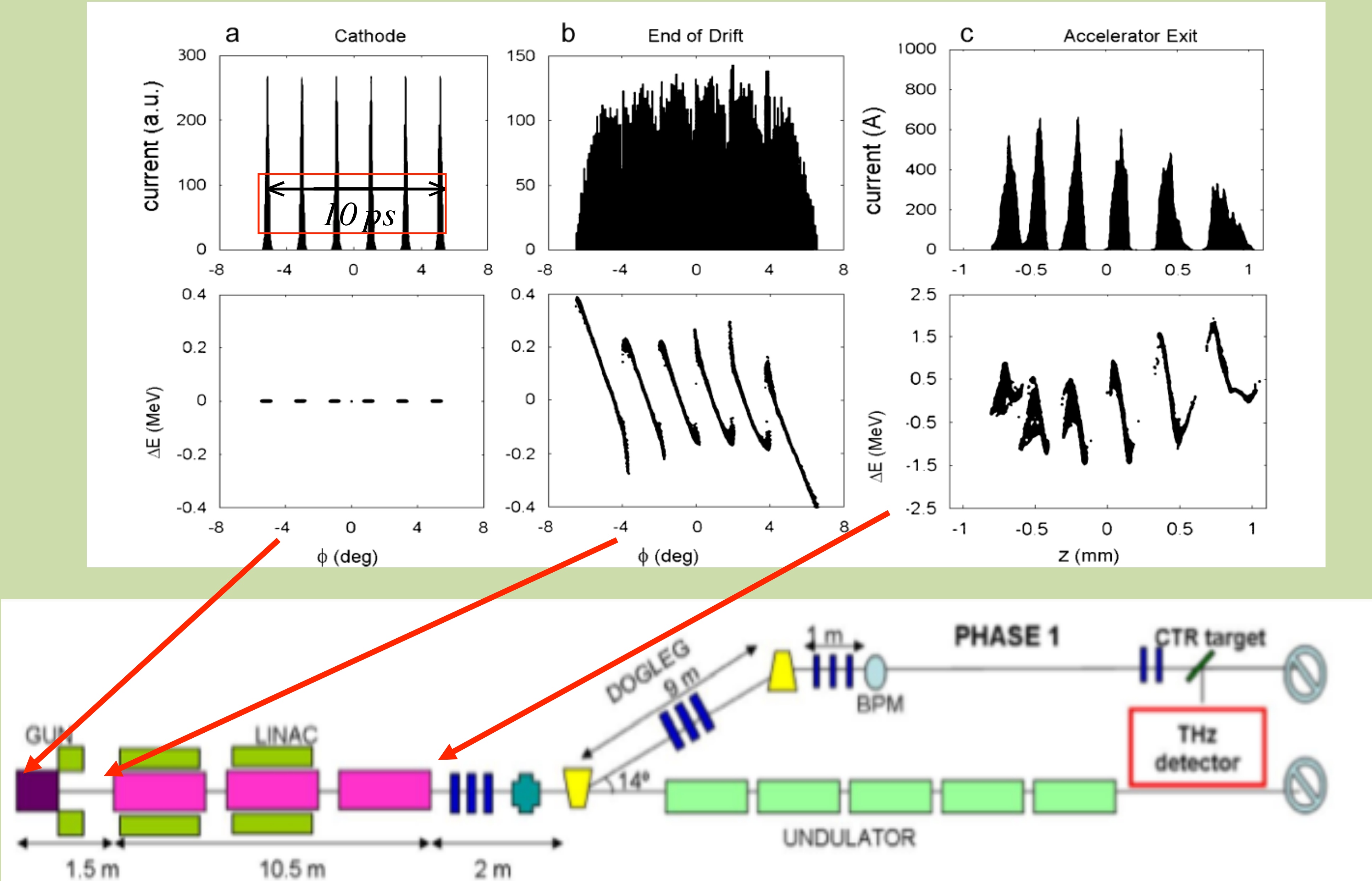
Resonant Plasma Oscillations by Multiple Electron Bunches at SPARC



Research program:

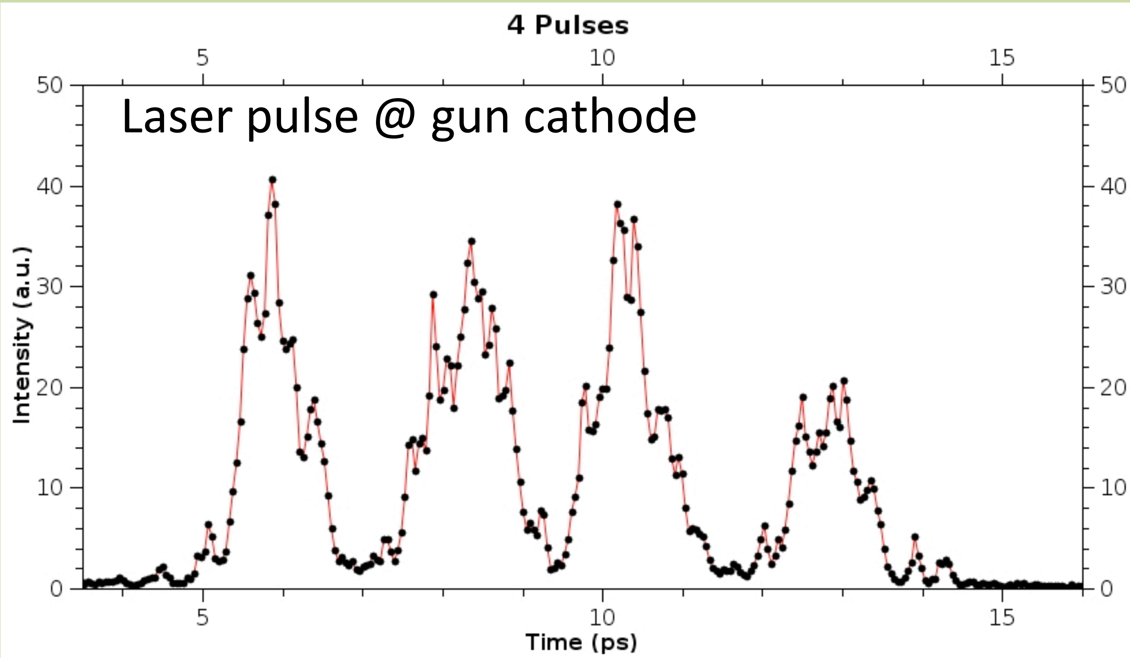
- Weak blowout regime with resonant amplification of plasma wave by a train of high Brightness electron bunches produced by Laser Comb
- Ramped bunch train configuration to enhance transformer ratio
- High quality bunch preservation during acceleration and transport

Laser Comb techniques: generation of a train bunches



- P.O.Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
- M. Ferrario. M. Boscolo et al., Int. J. of Mod. Phys. B, 2006 (Taipei 05 Workshop)

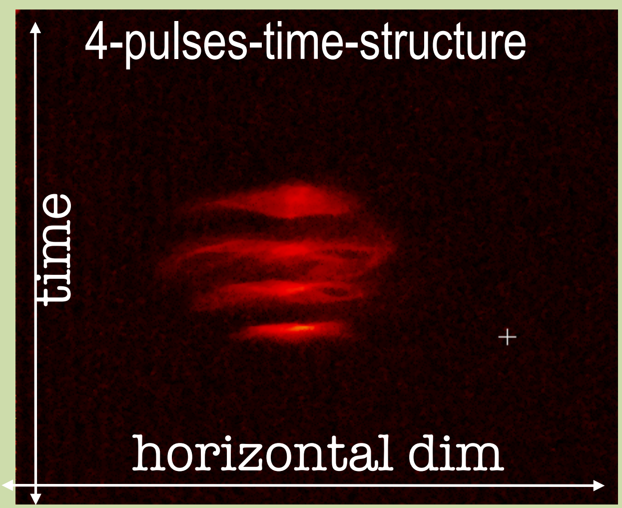
Four pulses structure observed at the SPARC linac exit (200 pC total charge – 1 ps separation – 3 mmmrad total rms emittance)



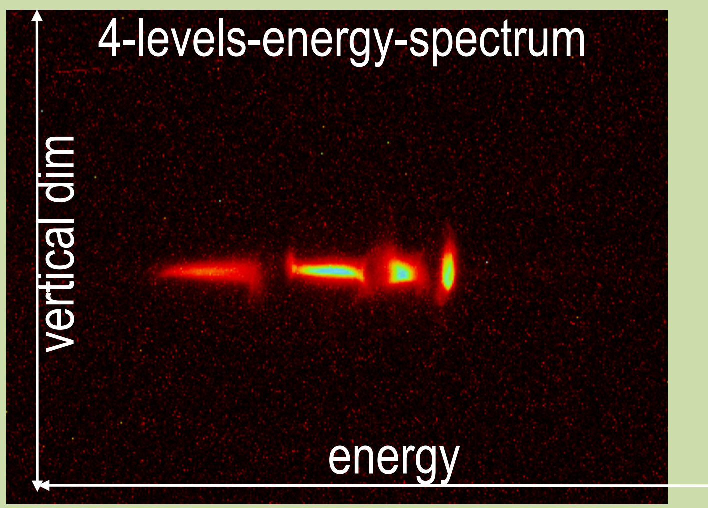
whole train length ≈ 9 ps

σ_t(per spike) ≈ 200 fs

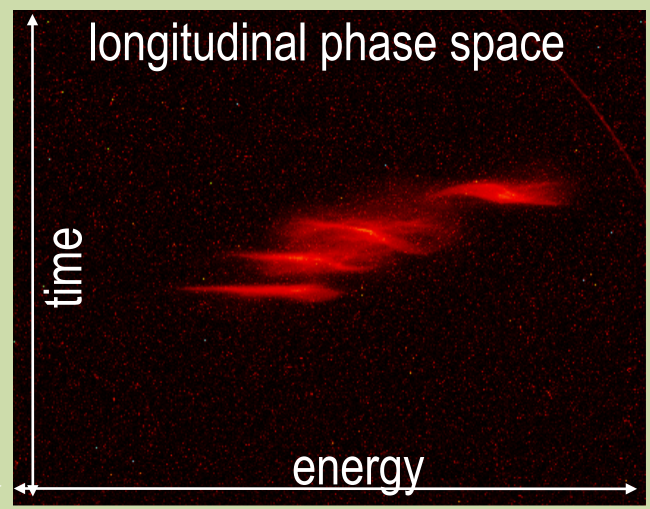
Downstream RF deflector



Downstream Dipole



Downstream RF deflector and Dipole

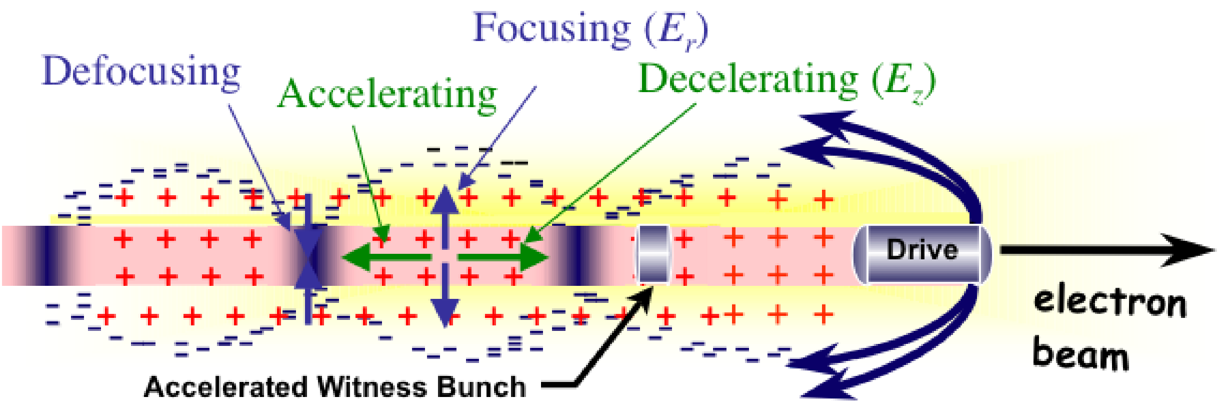


FACET Has a Multi-year Program to Study PWFA

- Demonstrate a single-stage high-energy plasma accelerator for electrons
- Meter scale, high gradient, preserved emittance, low energy spread, and high efficiency
  - Commission beam, diagnostics and plasma source (2012)
  - Produce independent drive & witness bunch (2012-2013)
  - Pre-ionized plasmas and tailored profiles to maximize single stage performance: total energy gain, emittance, efficiency (2013-2015)
- First experiments with compressed positrons
  - Identify optimum technique/regime for positron PWFA (2014-2016)

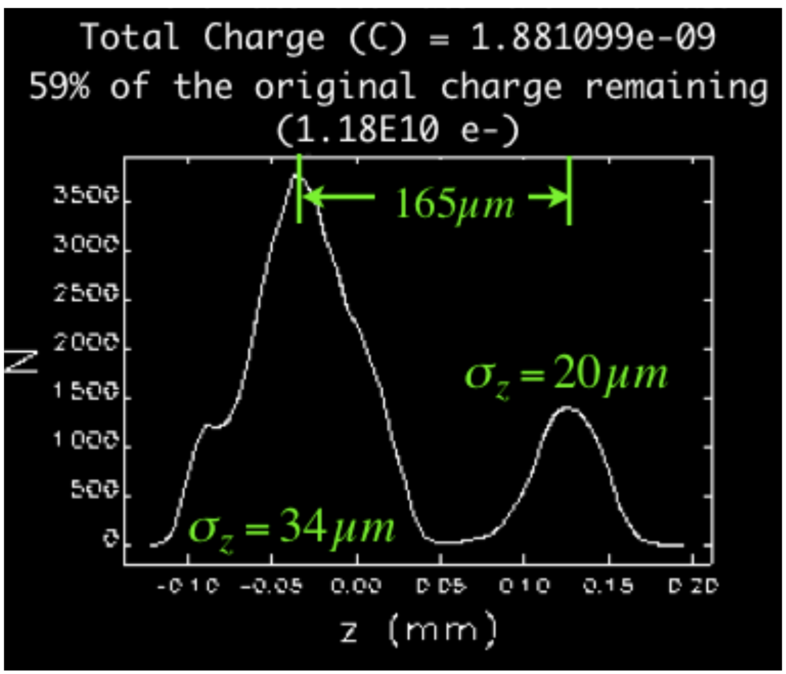
Primary Scientific Goal of FACET: Demonstrate a Single Stage Plasma Accelerator for Electrons

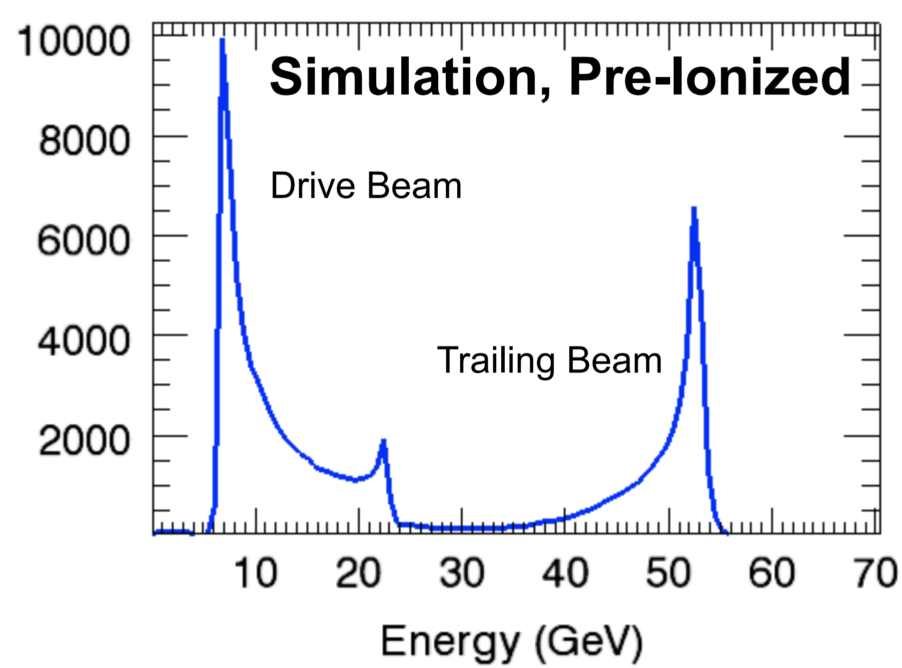
Collaboration between SLAC/UCLA/MPI



After 143 cm of 5 x 10^{16} plasma

- Energy Gain 30 GeV
- Energy Spread ~ 5%
- Energy Loss 17 GeV, Beam loading efficiency 64%





Two Bunches with Field Ionized and Pre-ionized plasma

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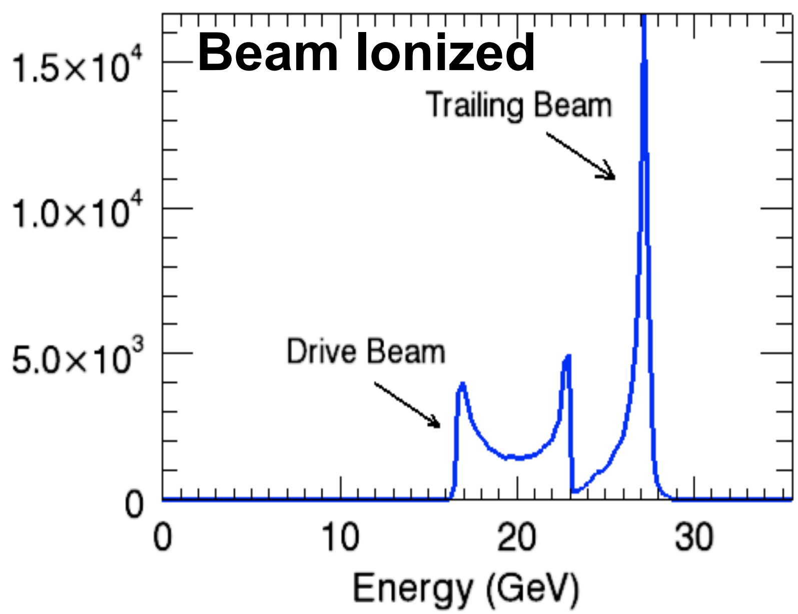
Simulations

After 88.5 cm of 3.7 x 10^{16} plasma

- Energy Gain 5 GeV
- Energy Spread ~ 3%
- Variable with plasma density, beam emittance, ionization potential



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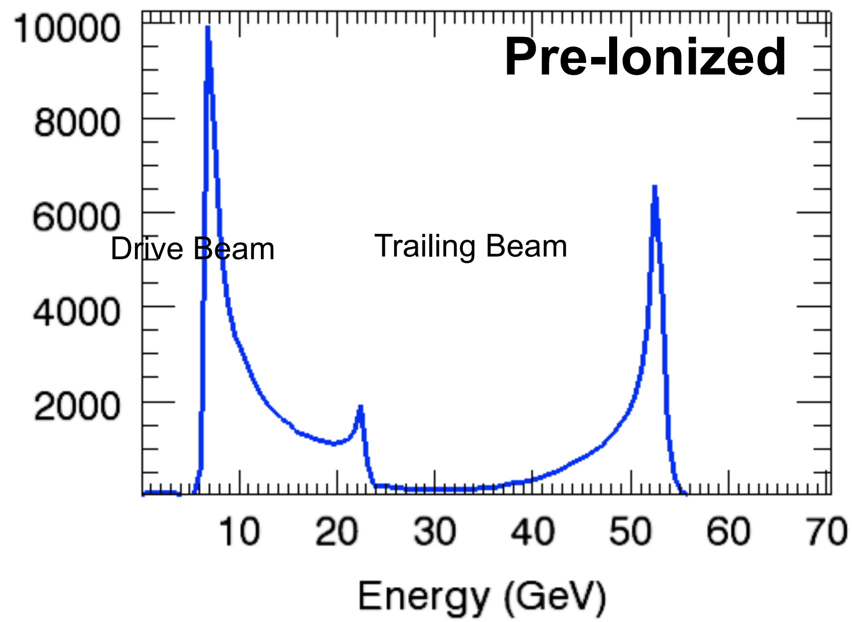

$$V[\mu m/m] = (3.6617 \cdot 10^4)\epsilon_i^{1.73}[eV]\frac{\epsilon_N[mm \cdot mRad]}{\gamma}\frac{1}{I^{3/2}[kA]}$$

Need a pre-ionized plasma to maximize single stage performance with two bunches

While commissioning systems for two-bunch experiments Investigate processes that limit single stage performance

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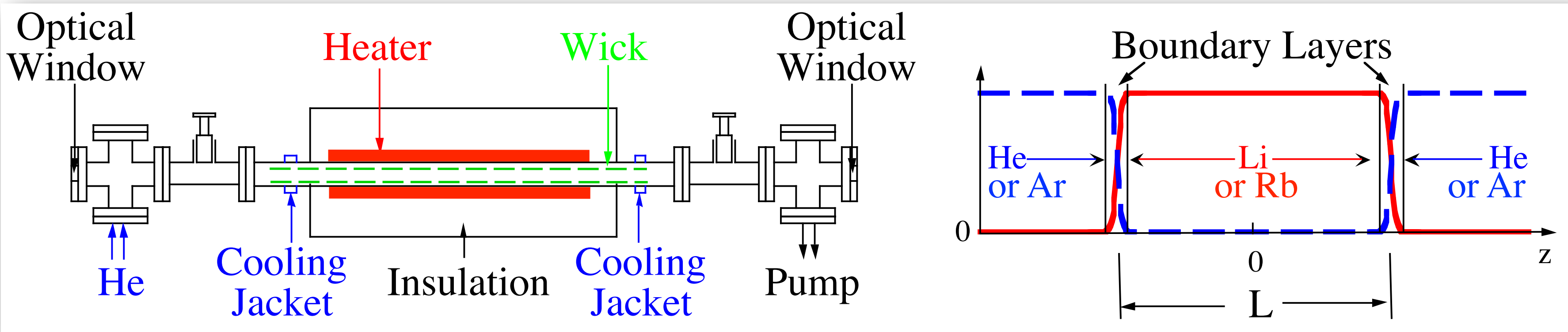
Plasma source starts with a heat pipe oven: Scalable, $n_0 = 10^{14}$-10^{17} e^-/cm^3, L = 20-200 cm



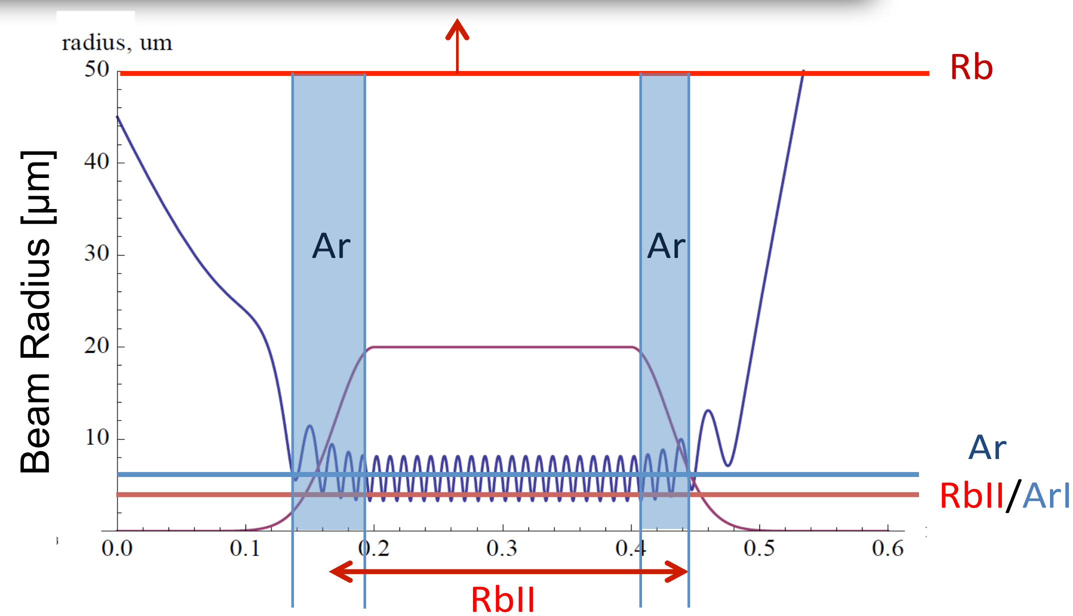
Peak Field For A Gaussian Bunch:

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

Ionization Rate for Li:

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

See D. Bruhwiler et al, Physics of Plasmas 2003



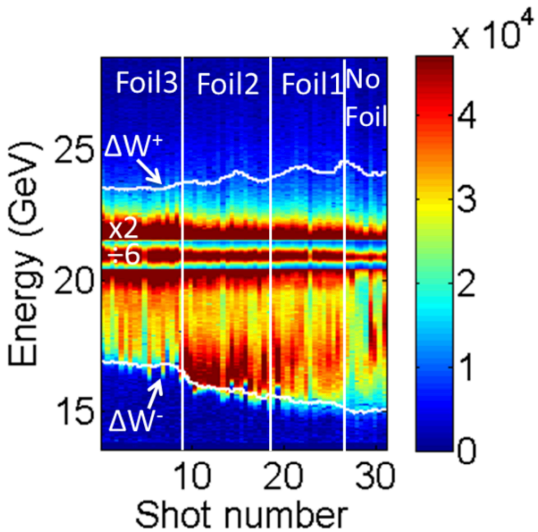
...but can suffer from Head Erosion

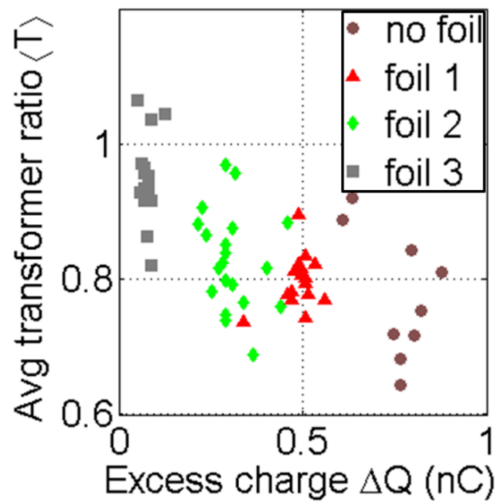
$$V[\mu m/m] = (3.6617 \cdot 10^4)\epsilon_i^{1.73}[eV] \frac{\epsilon_N[mm \cdot mRad]}{\gamma} \frac{1}{I^{3/2}[kA]}$$

Secondary ionization & dark current at pinches

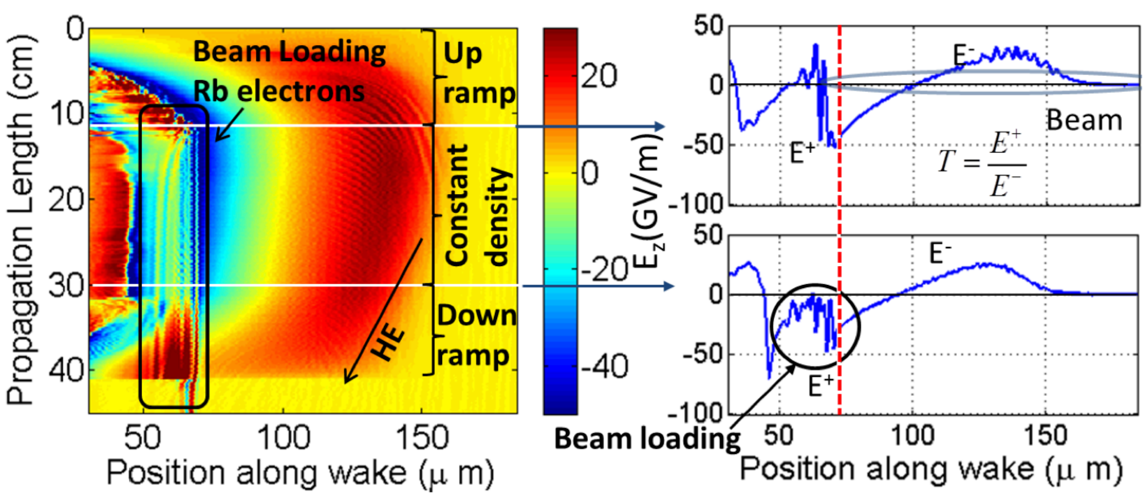
Head Erosion, Dark Current, Wake Loading and the Transformer Ratio

Change emittance (head erosion) with scattering foils:





Accelerating wake loaded by trapped Ar e$^-$



Has given rise to a new idea for mixed buffer gas experiments: controlled witness bunch injection through variable percentage of secondary buffer gas

Testing now!

Submitted for publication

Head Erosion, Dark Current, Wake Loading and the Transformer Ratio

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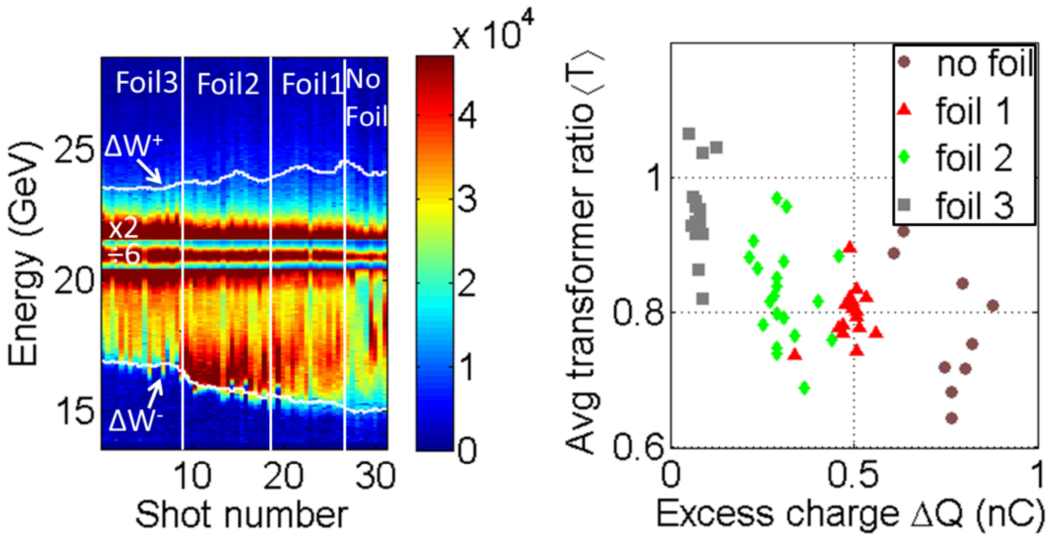
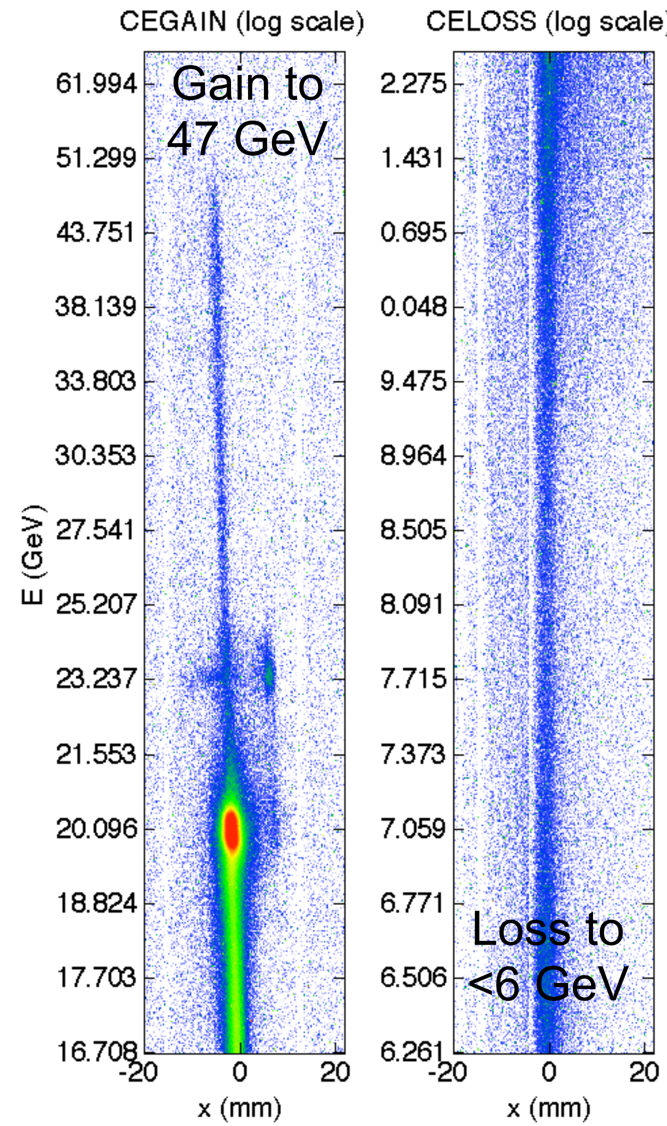
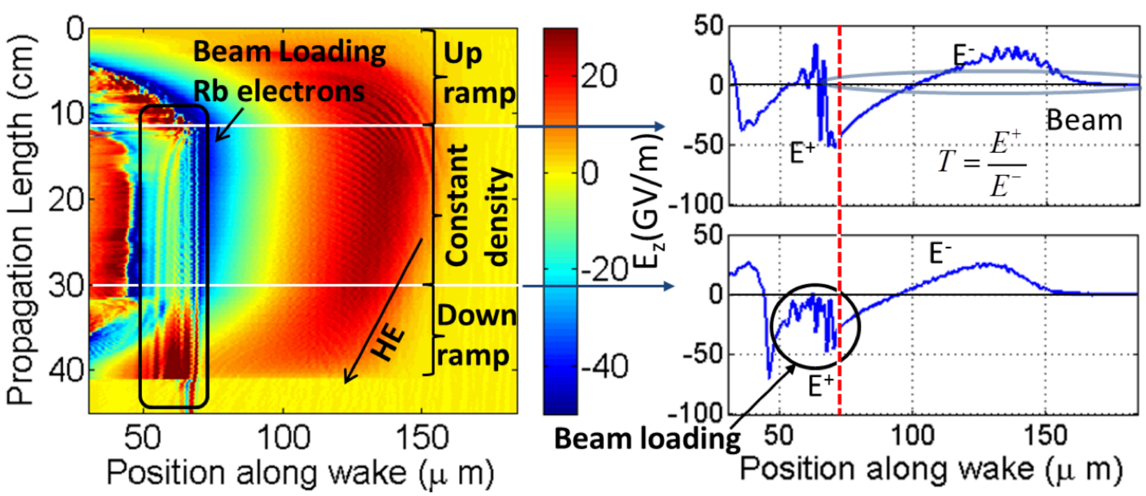
Change emittance (head erosion) with scattering foils:



Improved beam density in 2013 enough to ionize Ar and He without plasma lensing!



Accelerating wake loaded by trapped Ar e^-



Submitted for publication

New Diagnostics for Beam Matching and Radiation Generation

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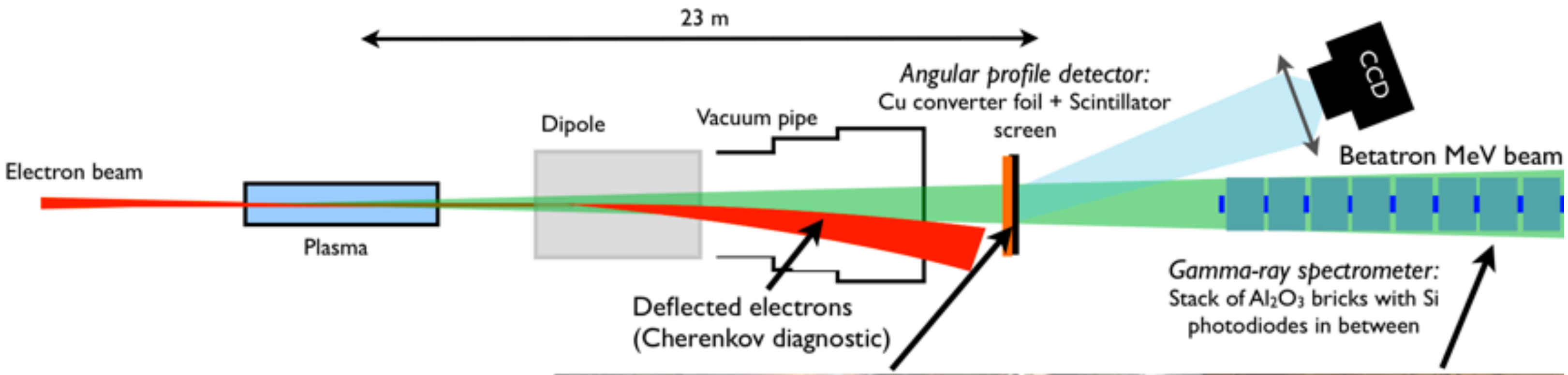
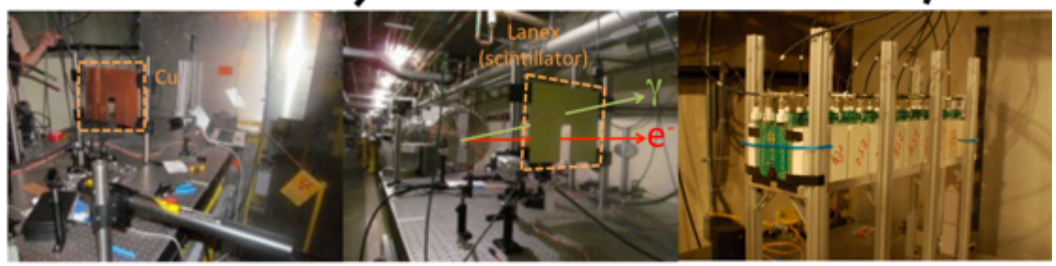
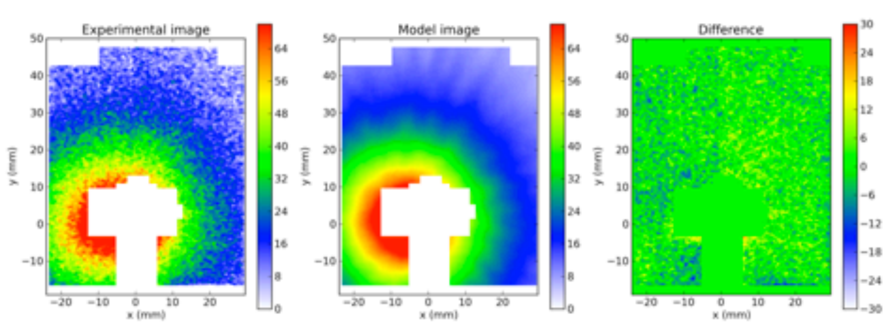


Measuring gamma-ray radiation reveals important information on the beam dynamics in the plasma.

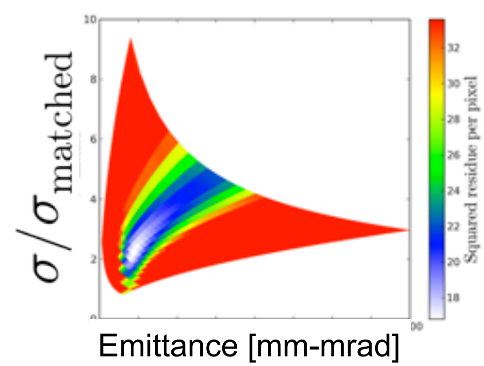
---> Assessing the matching of the beam in the plasma cavity.



Example of measured gamma-ray beam profile



Deduced beam parameters



---> Best fit for a 10 um beam size and 150 mm.mrad emittance (BMAG = 2.6)

Betatron radiation is a powerful tool to asses beam quality inside and after the plasma

Use a Notch Collimator to Create Drive-Witness Bunches

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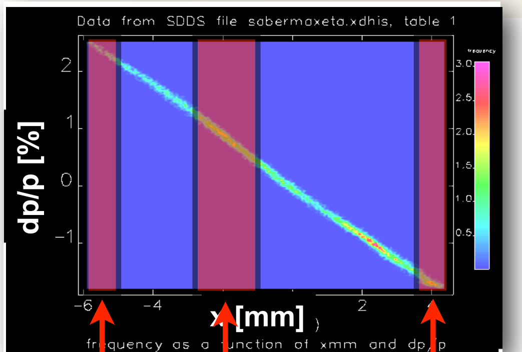


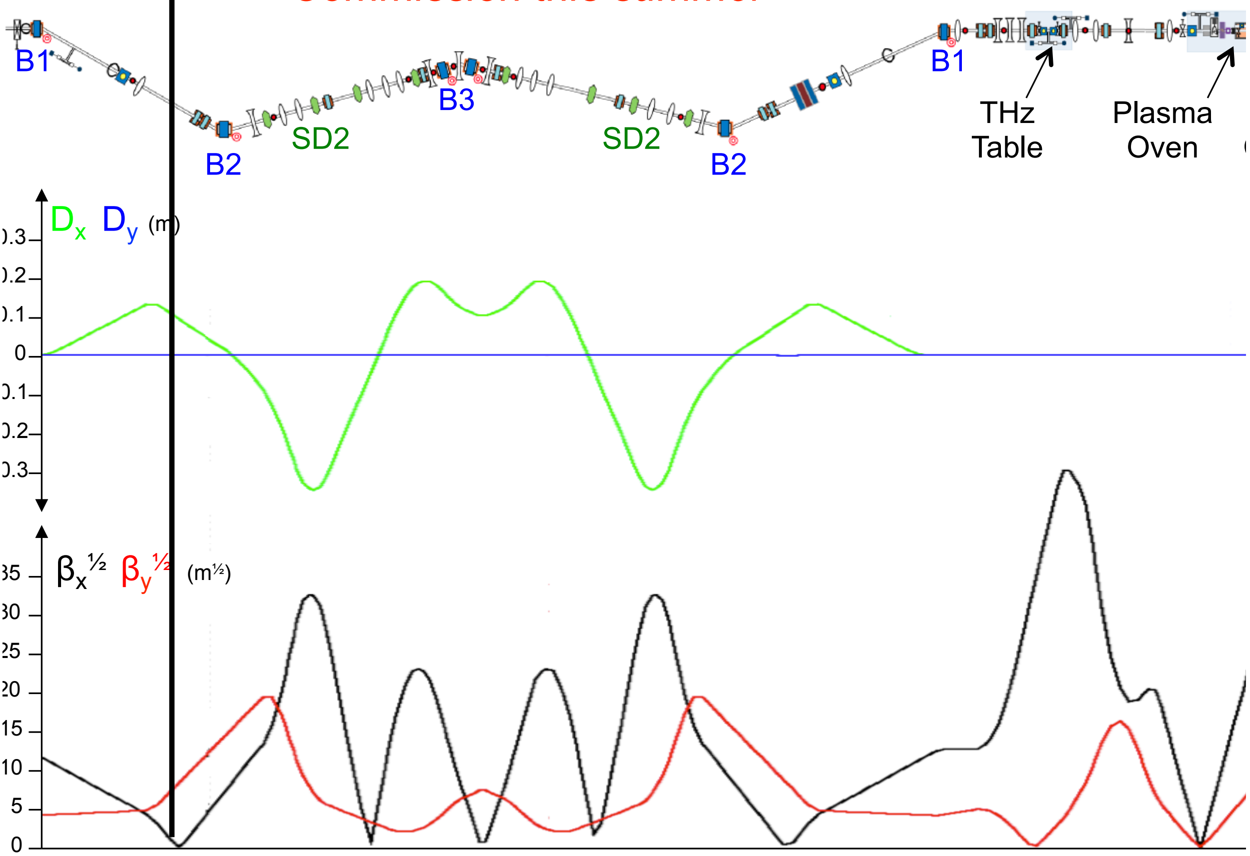
R56 = 10mm

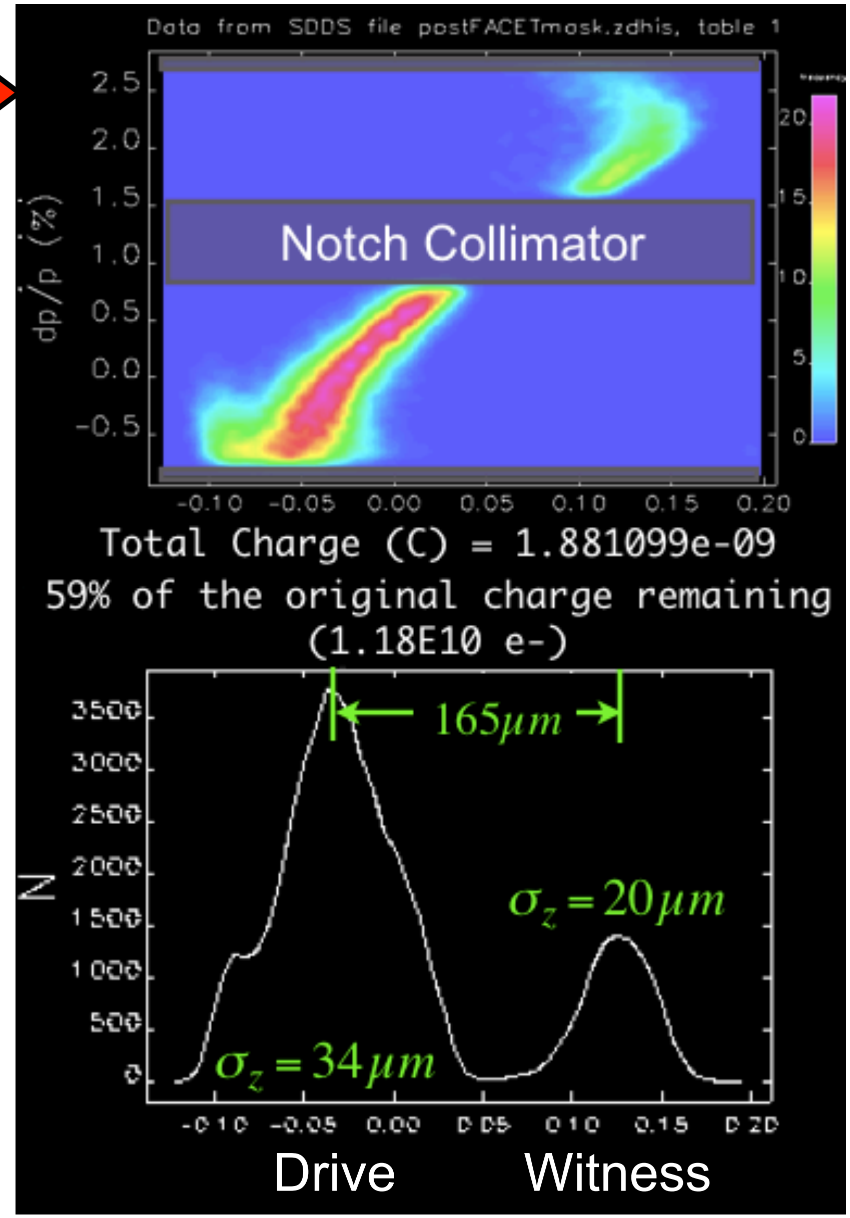
$$x \propto \Delta E/E \propto t$$

'Over-compressed'

...selectively collimate

Commission this summer

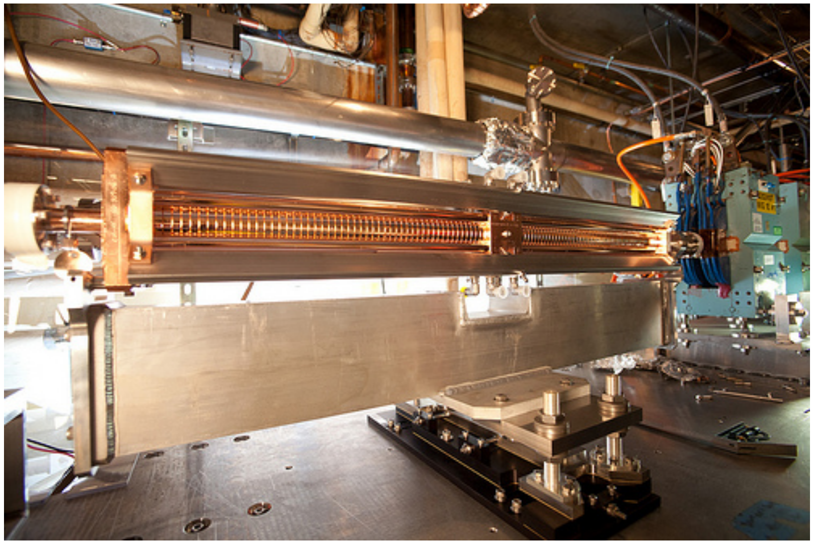


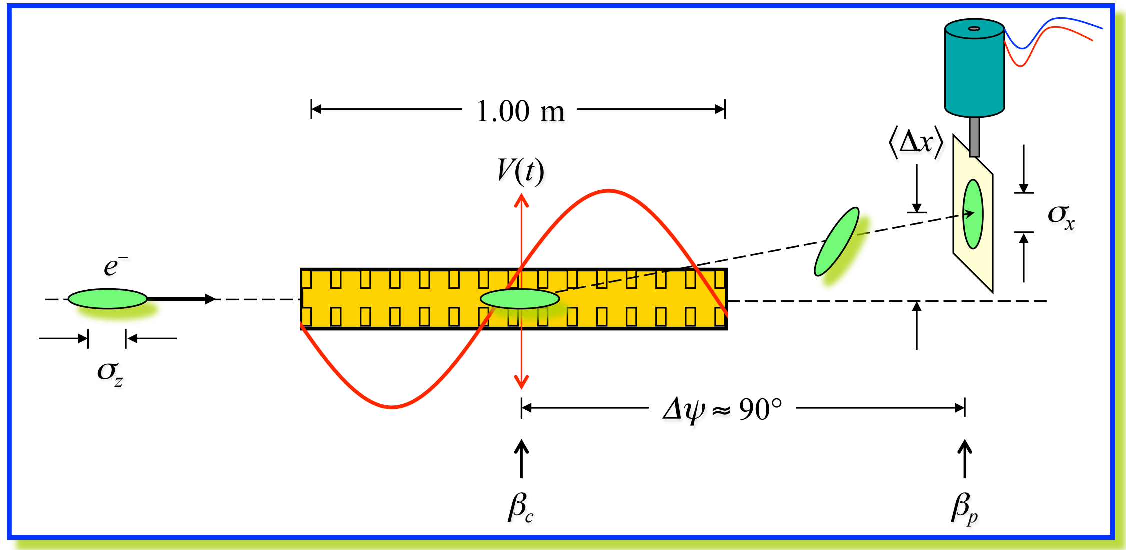


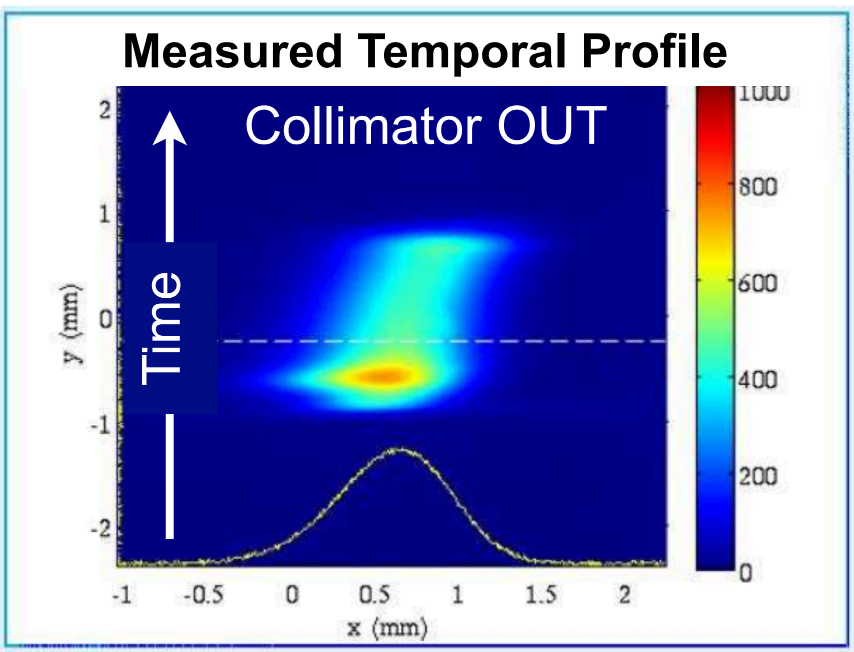
Now operating the tools to make and measure beams for the two bunch PWFA experiments

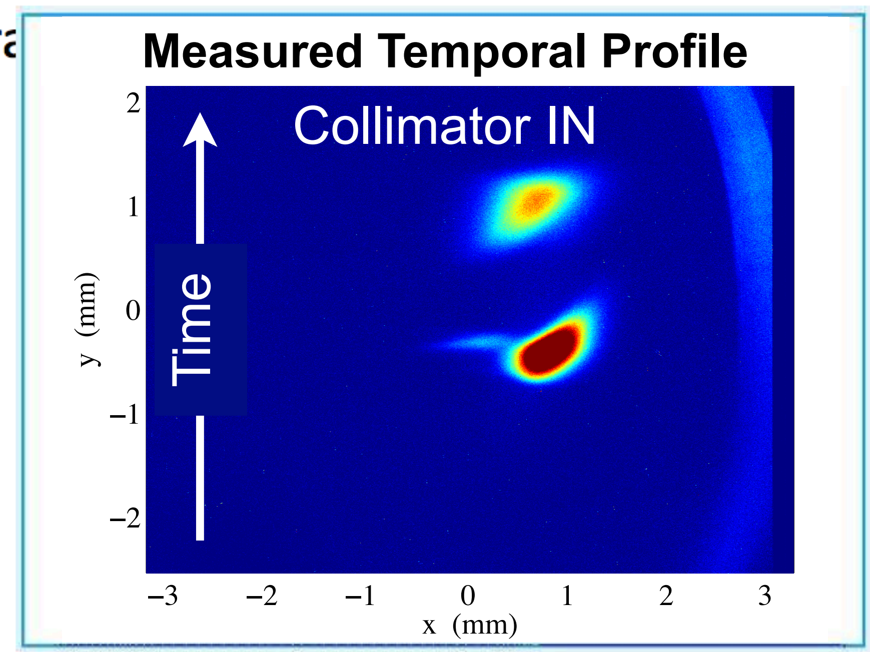
SLAC

X-band TCAV installed in Sector 20

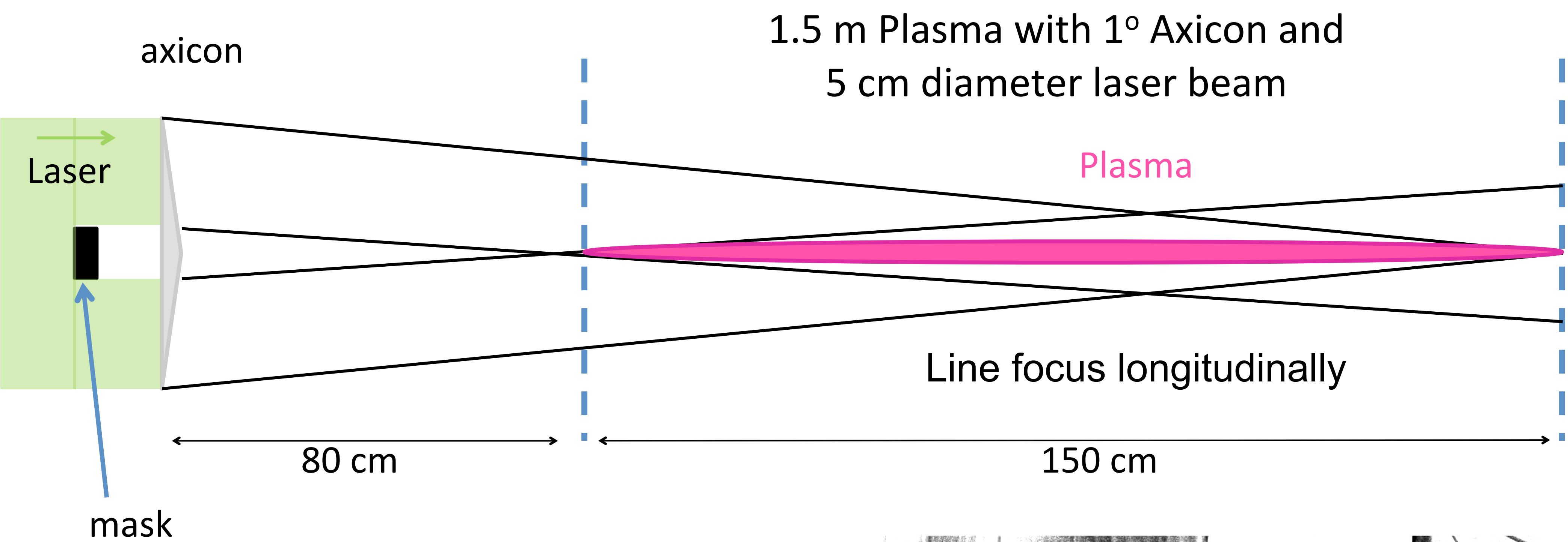




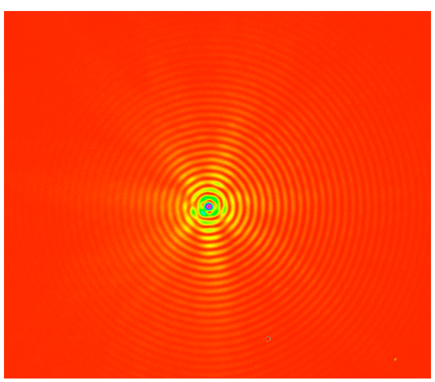


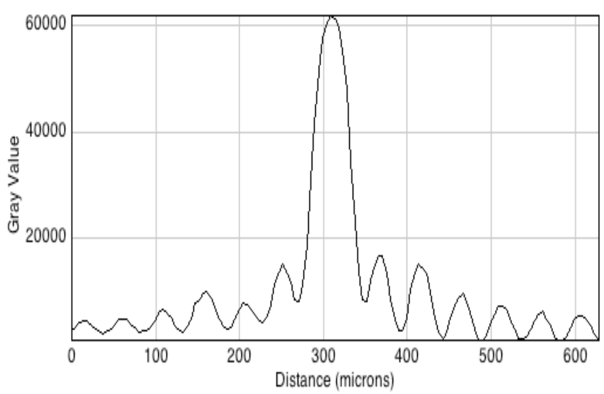


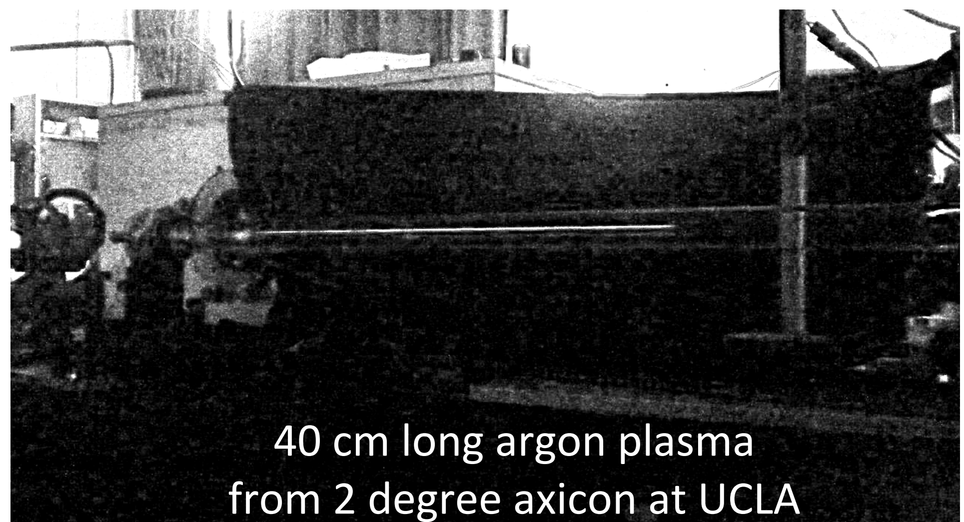
Use a Laser to Turn Lithium Vapor into a Plasma – Axicon Geometry Determines the Plasma Length



Bessel beam radial profile

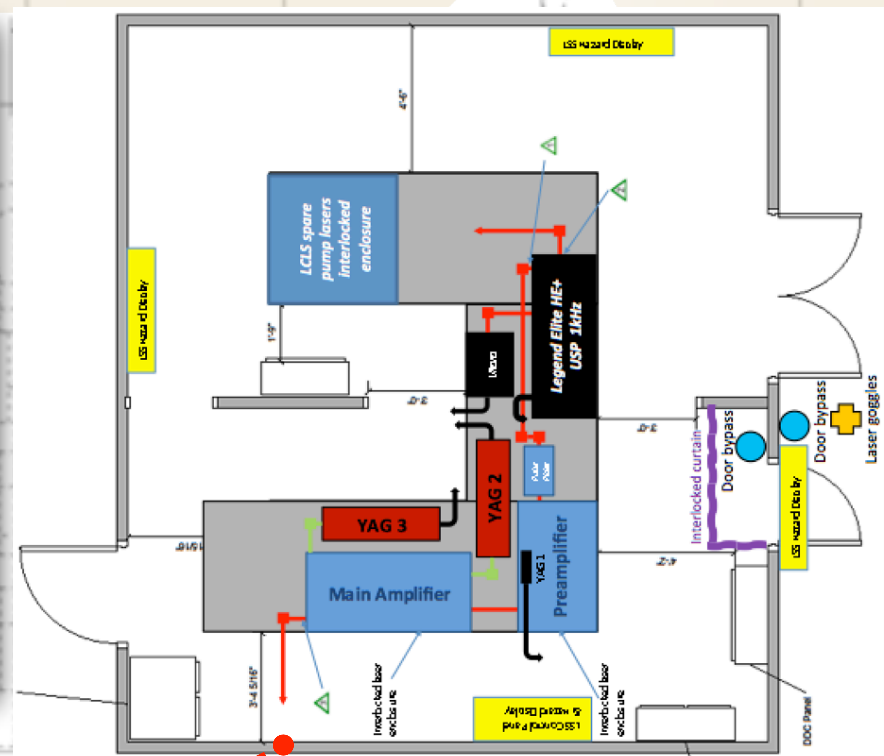


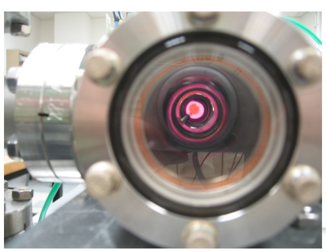


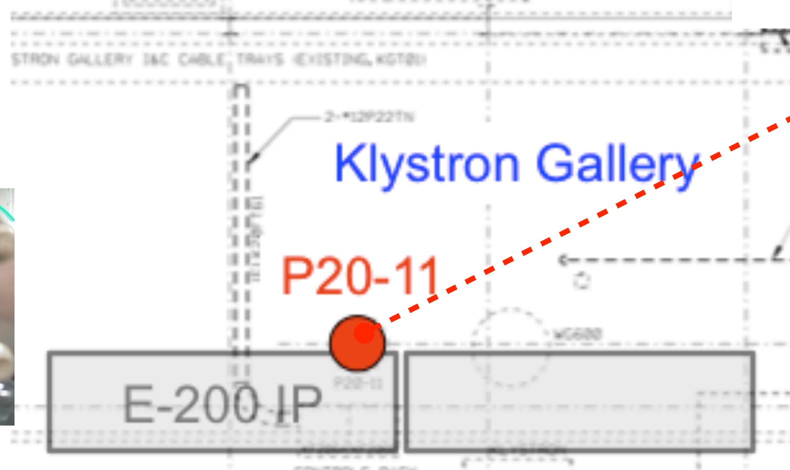


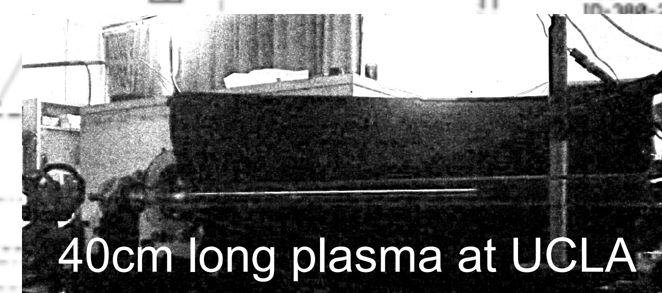
Installing 10TW Laser for Pre-ionized Plasma in 2013

- Laser room complete
- Laser system performing to specs
- Transport system installed
- Final high-power alignment ongoing
- Opens up many new experimental areas (Trojan Horse, Self-modulation, Plasma holography, THz pump-probe)









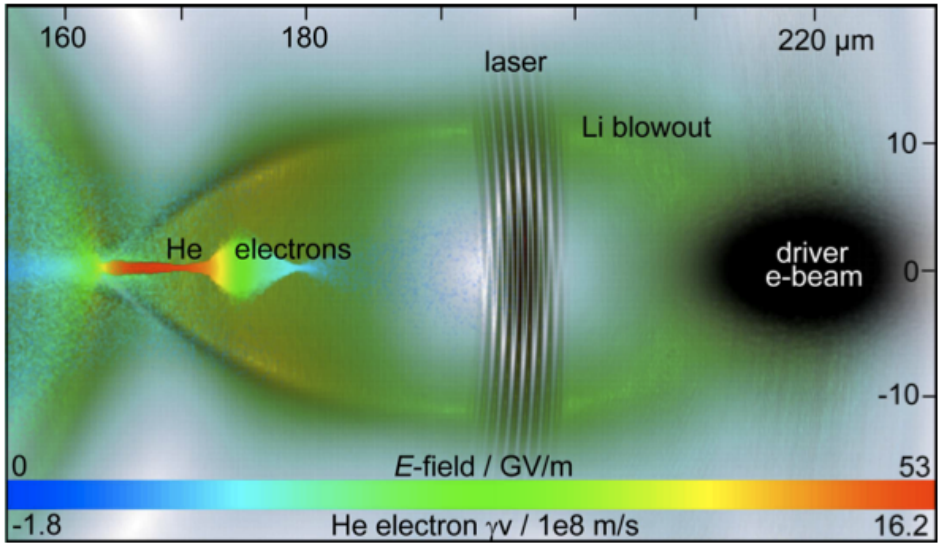
Will commission laser with beam over the next few weeks

Creating Ultra High-Brightness Beams with PWFA

SLAC

- Plasma bubble (wake) can act as a high-frequency, high-field, high-brightness electron source
- Ultra-high brightness beams for HEP & BES applications:
  - Unprecedented emittance (down to 10^{-9} m rad)
  - Sub-μm spot size
  - fs pulses
- Ingredients: electron & laser pulse (synchronized to fs level), plasma source with mixed ionization threshold
- Release laser pulse is strongly focused, needs 100 μJ, only, to ionize medium locally in focus at 10^{15} W/cm^2

Trojan Horse Technique



Leverages efficiency and rep rate of conventional accelerators to produce beams with unprecedented brightness for collider & XFEL applications

Summary

It is a very exciting time for beam driven plasma accelerators!

- Several groups looking at driving plasmas with electrons (single bunch, double bunch, trains), positrons and protons
- Optimistic we will see demonstration of high-gradient meter scale plasma stage within the next year with good beam quality and efficiency
- Coming years will build on this with injection and higher brightness beams paving the way for the first applications
- More information on all these topics in the poster sessions – see you there

Thank you to all my friends and colleagues for their contributions to this presentation!