Plasma Beam Modulator and Afterburner at FAST

FAST/IOTA Workshop

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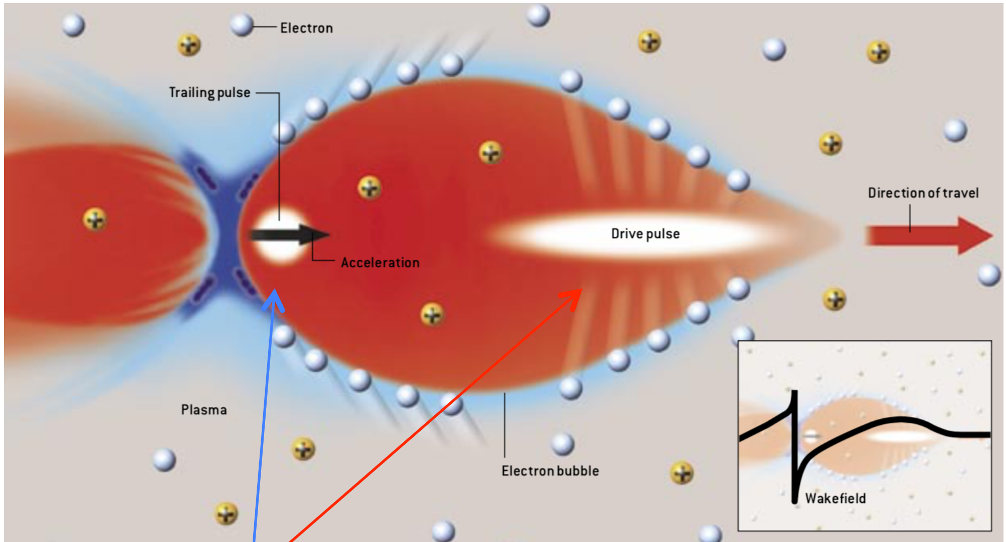
Plasma Accelerator Afterburner

- Compact plasma accelerator used to extend energy reach of existing (large, linear) accelerator
- Example applications: Nonlinear QED, ICS, FEL, Collider
- "Twice the energy, half the current"
- Need to use main beam for meaningful energy gain (required power too high for laser driver; inefficient)
- RF bucket spacing too large for beam-driven PWFA
- Dispersive bunch modulation no good at high energy
- Need linear bunch modulator – plasma!

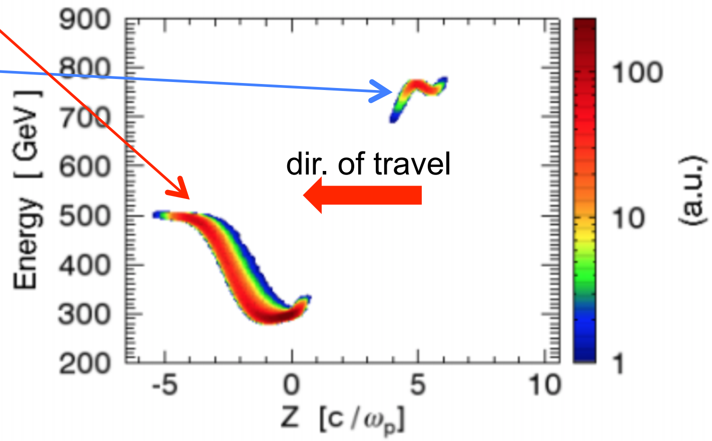
Beam-Driven PWFA



C. Joshi, Scientific American Feb. 2006

driver

witness



C. Huang, et al.,
PAC Proceedings 2005

- For minimum energy spread, need two-bunch structure
- Energy transferred from driver to witness
- Typical bunch separation: O(100 μm)
- Nominal loading in "blowout" PWFA:

$E_{acc.} = R\ E_{dec.}$
$Q_{wit}\ E_{acc.} \sim \eta\ Q_{drv}\ E_{dec.}$

R: trans. ratio (~1-2)
η: efficiency factor (~50%)

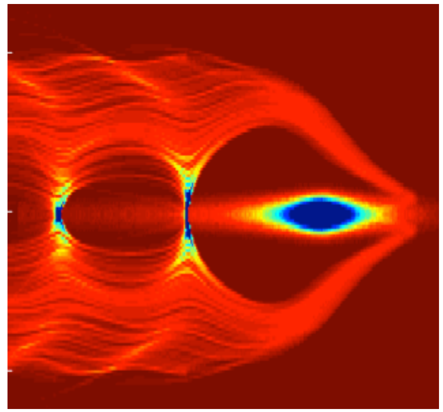
One Bunch vs. Two in Experiment

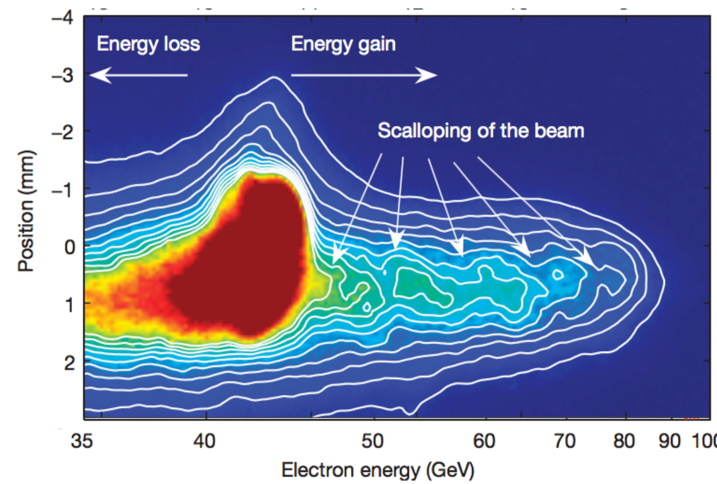
High-E PWFA in Experiment at SLAC

Bunches in Plasma – Sim.

Dispersed Bunches – Data

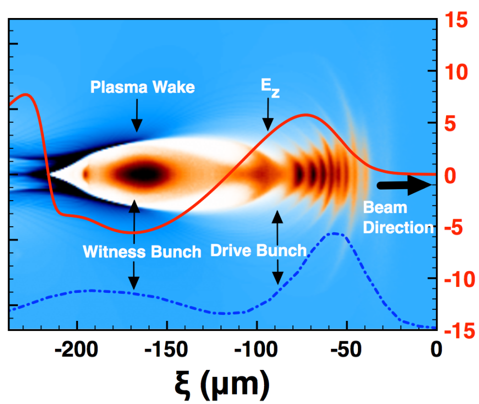
<u>FFTB in 2000s:</u>
- single bunch w/ long tail
- continuous E-spread
- low Q at highest E
- low E-transfer efficiency (wake-to-bunch)

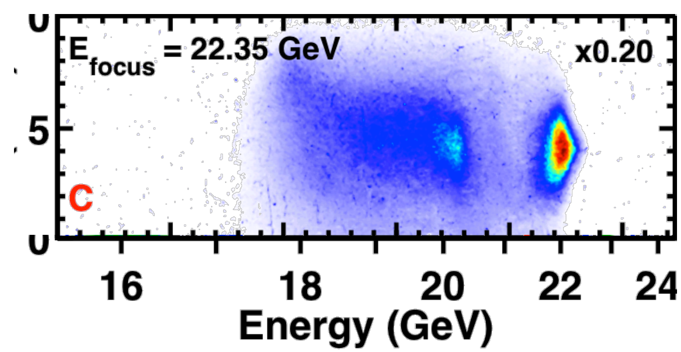




I. Blumenfeld, et al. *Nature* **445** 741 (2007)

<u>FACET in 2010s:</u>
- two-bunch beam
- low E-spread
- high Q at highest E
- high E-transfer efficiency (wake-to-bunch)

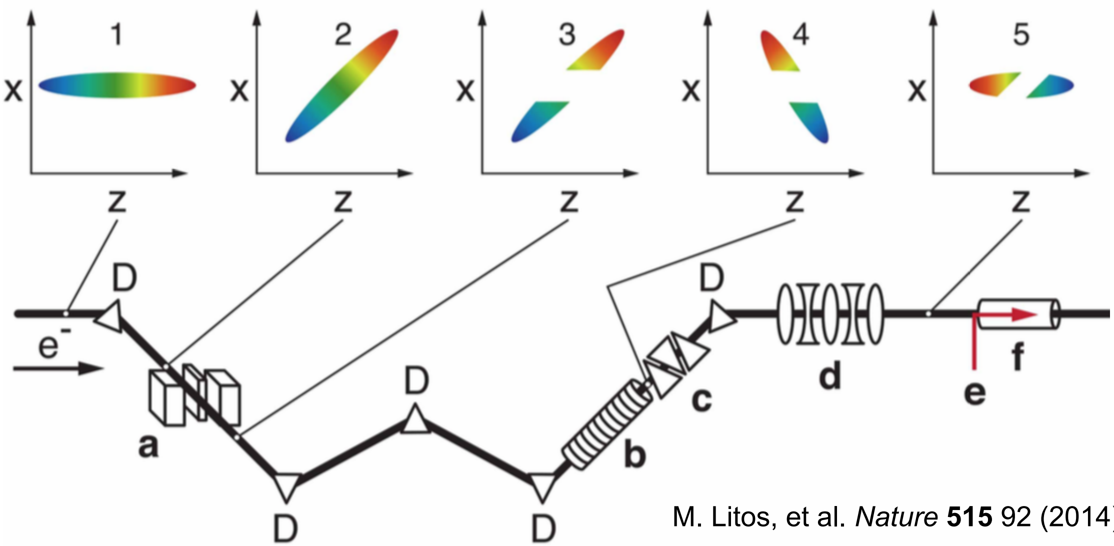




M. Litos, et al. *Nature* **515** 92 (2014)

Dispersive Beam Modulation

1. Chirp beam
2. Disperse beam
3. Spoil (notch) beam
4. Compress beam
5. Remove dispersion



M. Litos, et al. *Nature* **515** 92 (2014)

Significant issues at high energy and peak current:

- requires lots of space
- emittance growth from CSR & ISR in bends
- sensitive to many sources of jitter:
  centroid energy, energy spread, pointing, etc.
- notching blade heat issues at high avg. power

→ **Conclusion: Stiff beams need linear modulation**

Linear Plasma Wakefield Regime

Radial perturbation grows as ~e^N, where

$$N \simeq \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_p}(k_p\xi)(k_\beta z)^2\right)^{1/3}$$

Assumptions: long, narrow, cyl. symmetric flat-top bunch

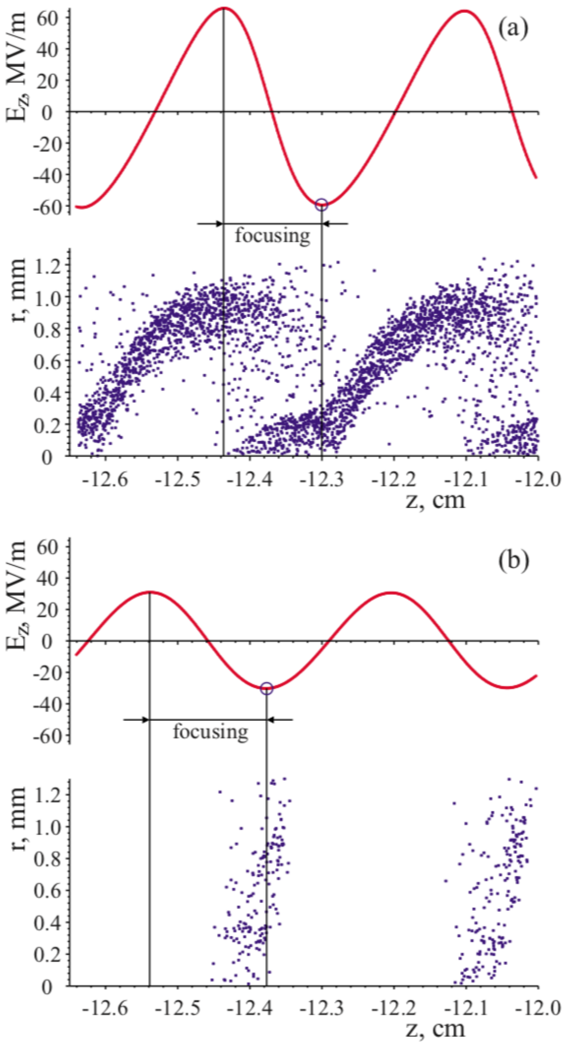
If bunch length L = 2λ_p, then modulation growth rate at mid-point $\xi = \lambda_p$ is

$$N \simeq 2.4\left(\frac{n_b}{n_p}\right)^{1/3}(k_\beta z)^{2/3}$$

If n_b/n_p ~ 1, then N reaches 10 in a few betatron periods
→ **Not many periods needed for strong modulation**

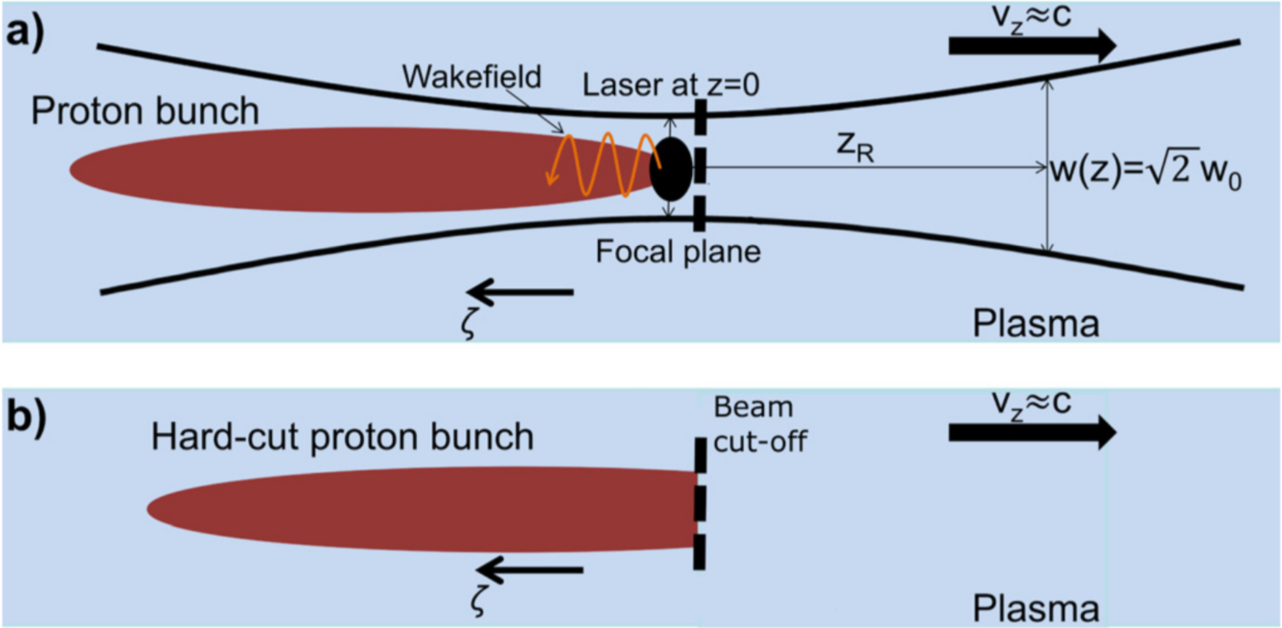
Modulation Instability

- Long, narrow bunch in linear regime ($L_b >> \lambda_p$, $k_p \sigma_r << 1$, $n_b < n_p$)
- Wake focuses and defocuses beam with period of plasma wavelength
- Stochastic process—must be seeded to control wake phase w.r.t. beam
- Seeding methods:
  - “hard cut” at front of bunch
  - density spike at front of bunch
  - high intensity laser pulse



K. V. Lotov, *Phys. of Plasmas* **18** 024501 (2011)

Seeding the Modulation Instability



C. Siemon, et al., *Phys. of Plasmas* **20** 103111 (2013)

Laser pulse can create equally strong modulation as "hard cut" if laser-induced radial velocity amplitude satisfies $$\frac{V_L}{\omega_\beta r_{b0}} \geq \frac{k_\beta z}{N}$$

→ Can be accomplished with a_0~0.1, w_0~300μm for beam & plasma conditions n_p~7x10^{14} cm^{-3}, k_β^{-1}~4.2 m (i.e. **reasonable**)

Wake Phase Velocity

Modulation phase velocity is not locked to the beam:

$$v_{\mathrm{ph}} = v_b\left[1 - \frac{1}{2}\left(\frac{\xi}{ct}\right)^{1/3}\left(\frac{n_b m}{2n_e m_p \gamma_b}\right)^{1/3}\right]$$

A. Pukhov, et al., Phys. Rev. Lett. **107** 145003 (2011)

This can be controlled by tapering the plasma density; i.e. increasing the density at just the right rate:

$$\hat{k}_p(z) \simeq 1 + \frac{3}{4|\hat{\zeta}_i|}\left[2\hat{k}_b^2(k_{p0}L_b)\right]^{1/3}\hat{z}^{2/3}$$

C. Schroeder, et al., Phys. Plasmas **19** 010703 (2012)

Density tapering should help preserve emittance and suppress hosing instability.

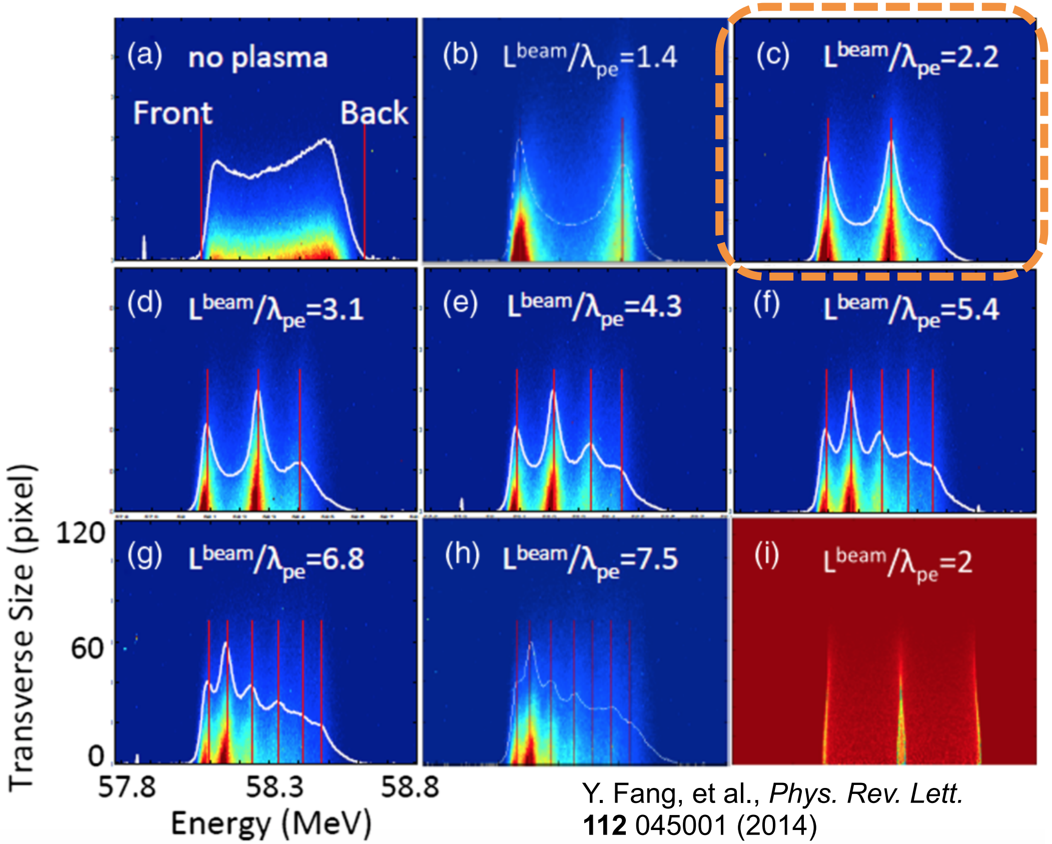
Experimental Concept for FAST

- Phase 1: Demonstrate “Bunch Splitter”
  - seed modulation instability
  - split bunch into driver and witness

- Phase 2: Couple two-bunch beam into PWFA
  - deplete energy of driver
  - vary relative charge b/w driver and witness

- Phase 3: Optimize final beam quality
  - minimize energy spread of witness
  - minimize emittance growth of witness
    → requires matching to plasma(s)

- Phase 4: Continue program with stiffer beams
  - FACET-II, LCLS/LCLS-II, elsewhere?
  - protons(?) or muons(??) at FNAL(???)

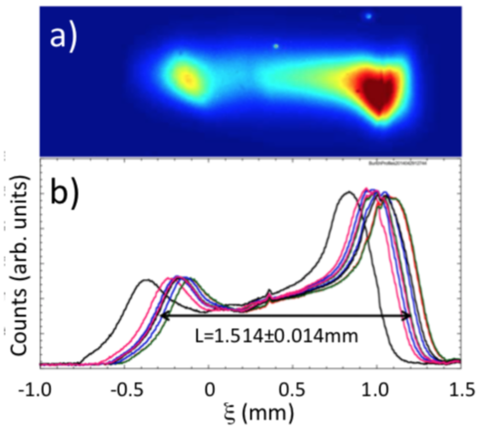


Y. Fang, et al., *Phys. Rev. Lett.* **112** 045001 (2014)

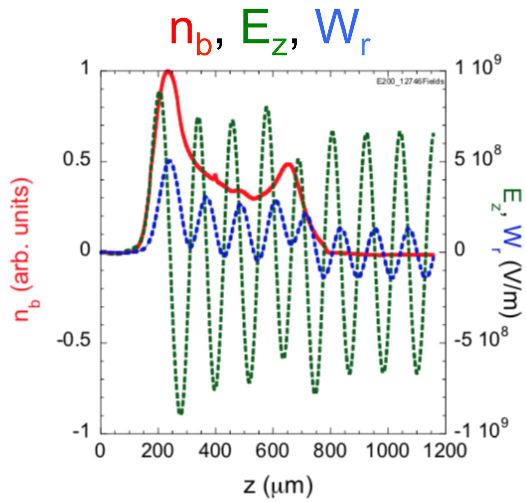
- Successful electron MI experiments at ATF
- Low number of segmentations in density-seeded modulation
- Tune plasma density until $L_{beam} = 2\ \lambda_{pe}$
- Tune seeding (laser timing) to optimize modulation
- Inset (c) in image is roughly the goal for afterburner

A "horned" beam structure would be optimal for charge conservation and seeding efficiency in longitudinal bunch modulator for afterburner.

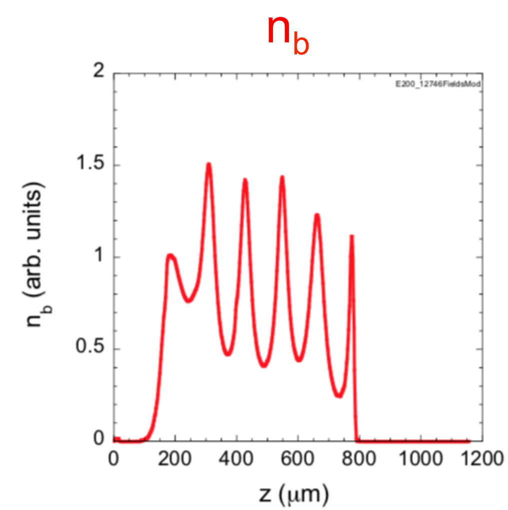
Horned Beam Used at FACET



(flip)



leads to



P. Muggli, et al., IPAC Proceedings 2014

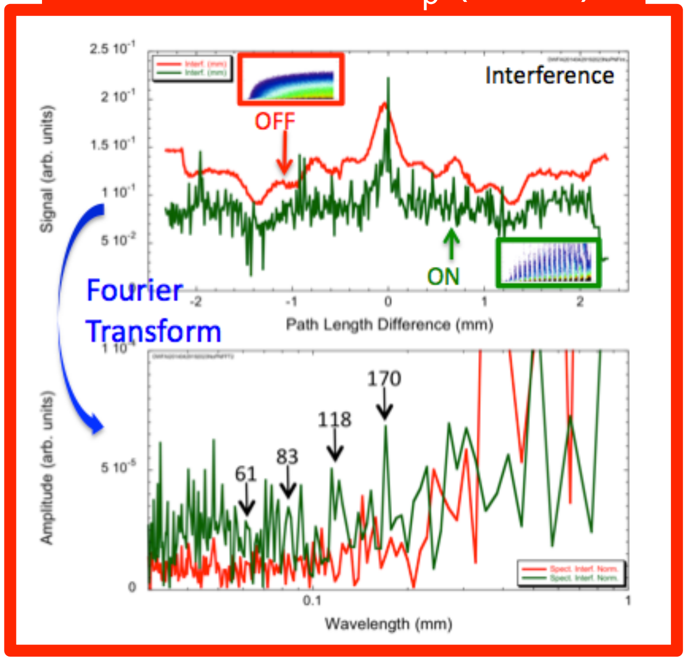
Long horned beam (left) used to good effect at FACET

Linear wakefield calculated from beam profile (middle)

Simulation of modulation (right) with small number of periods for this beam

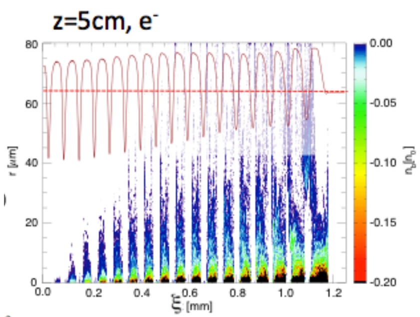
Electron and Positron Modulation at FACET

Modulation at λ_p (e^-, e^+)

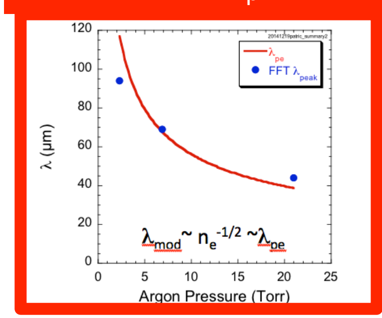


E. Adli, et al., Nucl. Inst. and Methods A **829** 334 (2016)

Simulation



Scaling as $n_p^{1/2}$ (e^+)



- Long e^- and e^+ bunches at FACET used as scaled experiment for AWAKE
- CTR interferometry shows bunching at λ_p intervals for both species
- Halo formation around core of beam seen on OTR monitor
- Bunching scaled as $n_p^{1/2} \sim \lambda_p$ as expected

Rough Experimental Parameters for FAST

Bunch Modulator Stage:

$E = 300$ MeV

$Q = 2$ nC

$L = 1.5$ mm

$\varepsilon = 3$ μm-rad

Require: $\lambda_p = L/2 \rightarrow \mathbf{n_p = 5\times10^{14}\ cm^{-3}}$

Require: $n_b \sim n_p \rightarrow \sigma_{r,m} = 55\ \mu m \rightarrow \boldsymbol{\beta \sim 60\ cm}$

PWFA Stage:

$\Delta z = \sim 1$ mm after modulation

Require: $\lambda_p \sim \Delta z = \sim 1\ mm \rightarrow \mathbf{n_p = 1\times10^{15}\ cm^{-3}}$

Require: $\beta_m = k_p^{-1}(2\gamma_b)^{1/2} \rightarrow \boldsymbol{\beta = 5.8\ mm}$

$\sigma_{r,m} = 5.4\ \mu m \ll c/\omega_p = 160\ \mu m \rightarrow$ narrow beam

$n_{drv} \sim 2 \times 10^{16}\ cm^{-3} \gg n_p = 1\times10^{15}\ cm^{-3} \rightarrow$ blowout regime

Experimental Challenges and Considerations

An inexhaustive list with potential solutions…

Challenge: Control of wake phase velocity in beam modulator

- Sol'n: seeding and plasma density ramp

Challenge: Transition from beam modulator to PWFA

- Sol'n: instantaneous transition?
- Sol'n: small vacuum gap
- Sol'n: strong lens (PMQ? Plasma?) between plasmas

Challenge: Hosing instability in beam modulator

- Sol'n: careful seeding, make modulation rate faster than hosing

Practical Experimental Considerations:

- Laser requirements (10 TW @ 10 Hz, or maybe 1 TW @ 1 kHz?)
- Plasma source (laser ionized gas? gas jet? discharge?)
- Diagnostics (CTR, spectrometer, TCAV, EOS)

Future Momentum of Research

Perform low-E modulator-afterburner experiments at FAST to prove concept, study physics, and learn lessons

Replicate concept at FACET-II with multi-GeV e^- beam
Replicate concept at FACET-II with multi-GeV e^+ beam

Study high rep. rate PWFA at FAST (not possible at FACET-II)

Medium-term aim: build functioning energy extender for nonlinear QED at high-rep. rate, high energy facility (LCLS-II?)

Long-term aim: build functioning energy extender for FEL

Longest-term aim: build functioning energy extender for HEP linear collider (ILC?)

Summary

- Plasma afterburner: extend energy at cost of current
- Two-bunch PWFA needed for small energy spread
- Stiff beams need linear current modulation
  → Plasma modulator seems well suited
- FAST could provide perfect test bed for low-E modulator-afterburner research
- Physics and lessons learned at FAST could inform modulator-afterburner research at high-E facilities

Thank you

Thanks!

Nonlinear QED

QED interaction strength parameter:

$$\chi_e = \frac{2\hbar}{m_e c^2}\omega_0\gamma_0 a_0$$

Near term experiments: $\chi_e \sim O(1)$

Future experiments: $\chi_e >> 1$

Scales linearly with γ_0
→ energy doubling matters!