Beam Driven Plasma Acceleration for γγ Collider (FACET)

ICFA Mini-Workshop on Future gamma-gamma Collider

Mark J. Hogan
April 23, 2017

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Plasma Acceleration and the Birth of AAC

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles
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Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

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Department of Physics, University of California, Los Angeles, California 90024
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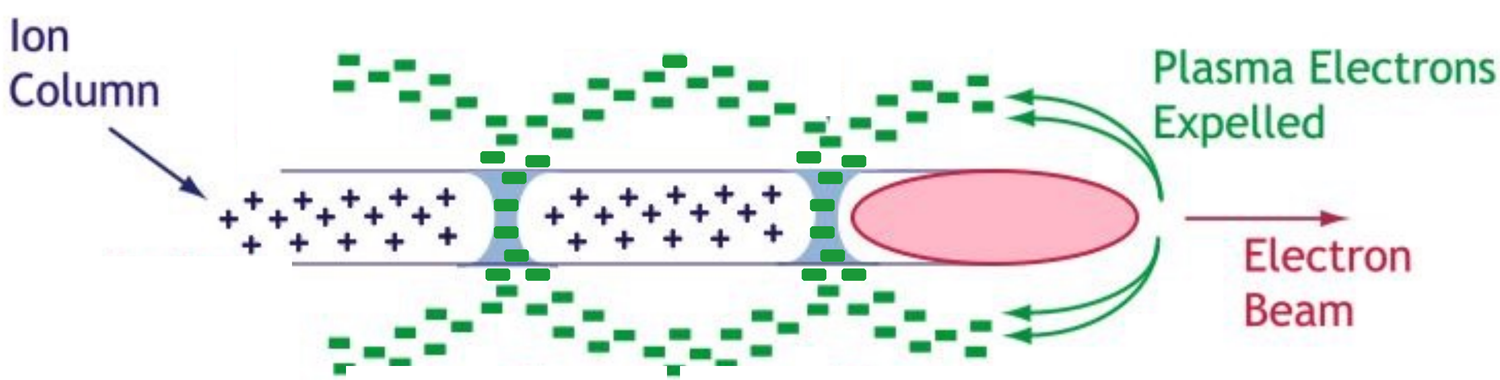

- Blow-out when $n_b >> n_p$
- Large accelerating gradients ~ GeV/m
- Strong ideal focusing ~ MT/m
- Relativistic driver, no de-phasing

$$E_0 \sim 10\sqrt{\frac{n_0}{1\times 10^{16}[\mathrm{cm}^{-3}]}}[\mathrm{GeV/m}]$$

Accelerating Particles to Accelerating Beams → FACET

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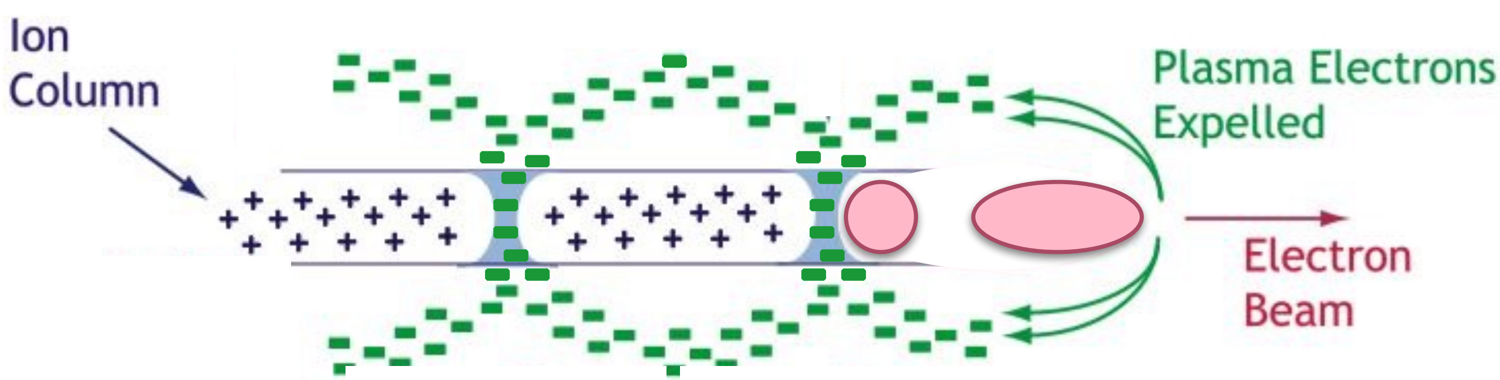
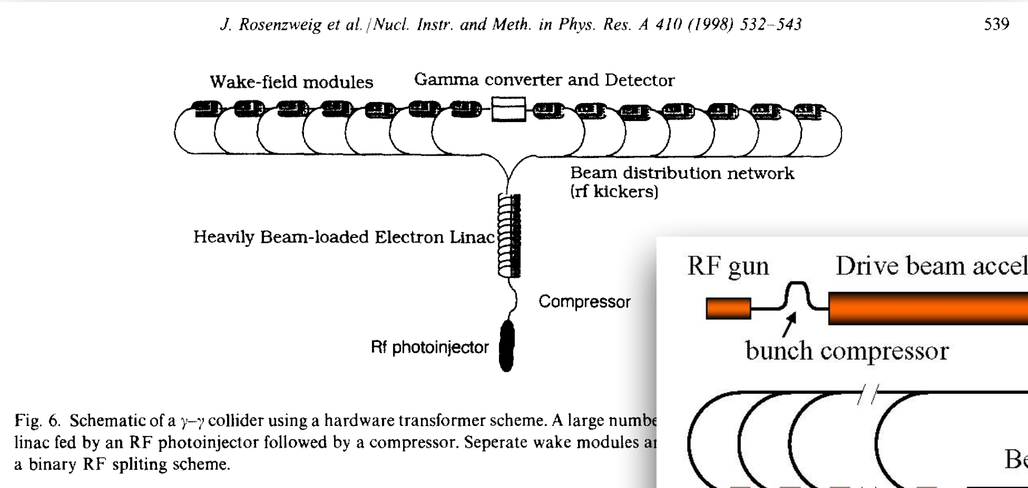


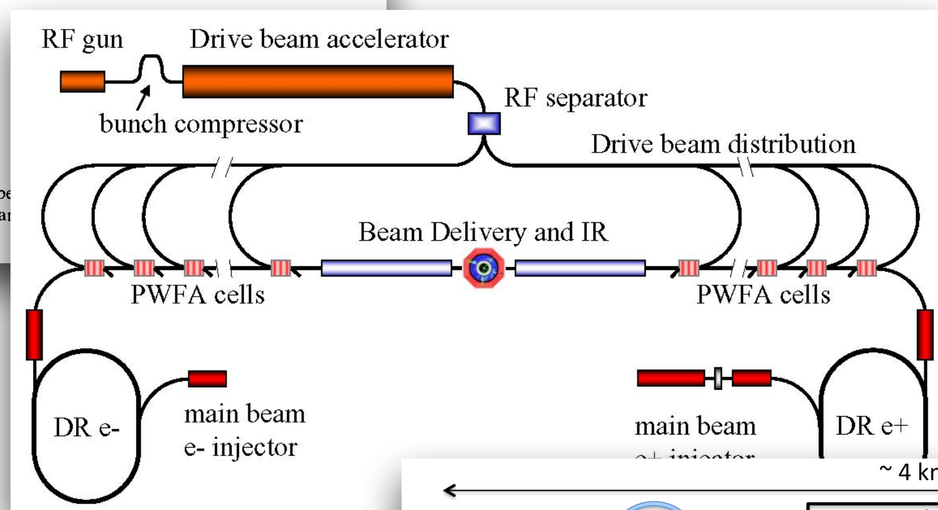
$$E_0 \sim 10\sqrt{\frac{n_0}{1\times 10^{16}[\mathrm{cm}^{-3}]}}[\mathrm{GeV/m}]$$

- Two bunches externally injected
- Dimensions and spacing ~ c/w_p ~ 20µm
- Blow-out when $n_b >> n_p$
- Plasma = highly efficient transformer

PWFA Research Roadmap:
Goal is to Get To A TeV Scale Collider for High Energy Physics

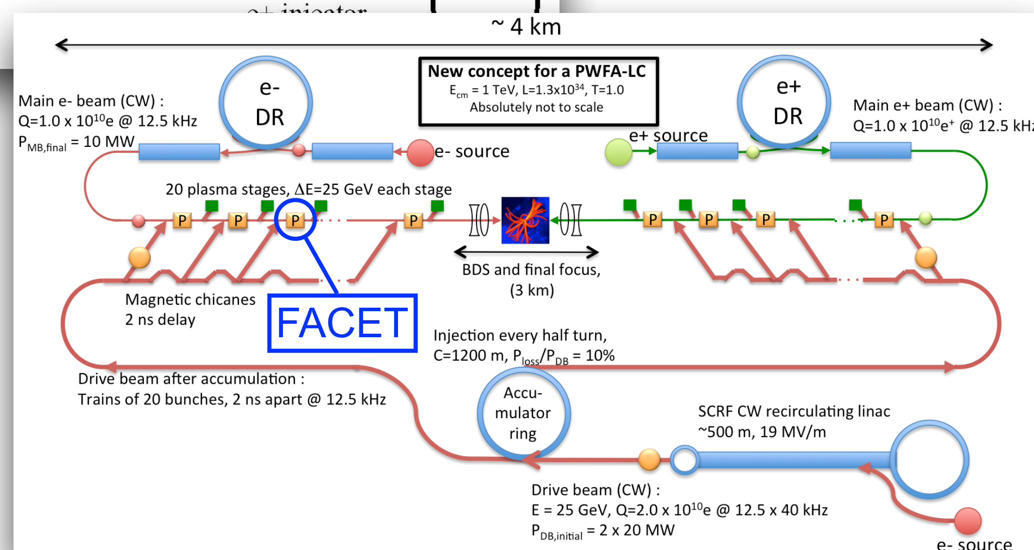


Rosenzweig *et al* (1998)



Seryi *et al* (2008)

Adli *et al* (2013)



PWFA-LC concepts highlight key issues and help us prioritize our research programs e.g. gradient, efficiency, and emittance preservation

FACET Project History

Primary Goal:

- Demonstrate a single-stage high-energy plasma accelerator for electrons

Timeline:

- CD-0 2008
- CD-4 2012, Commissioning (2011)
- Experimental program (2012-2016)

A National User Facility:

- Externally reviewed experimental program
- >200 Users, 25 experiments, 8 months/year operation

Key PWFA Milestones:

√ Mono-energetic e- acceleration

√ High efficiency e^- acceleration (*Nature* **515**, Nov. 2014)

√ First high-gradient e^+ PWFA (*Nature* **524**, Aug. 2015)

- Demonstrate required emittance, energy spread (FY16 in preparation for *Nature*)

Premier R&D facility for PWFA: Only facility capable of e+ acceleration
Highest energy beams uniquely enable gradient > 1 GV/m

A Roadmap for Future Colliders Based on Advanced Accelerators Contains Key Elements for Experiments and Motivates FACET-II

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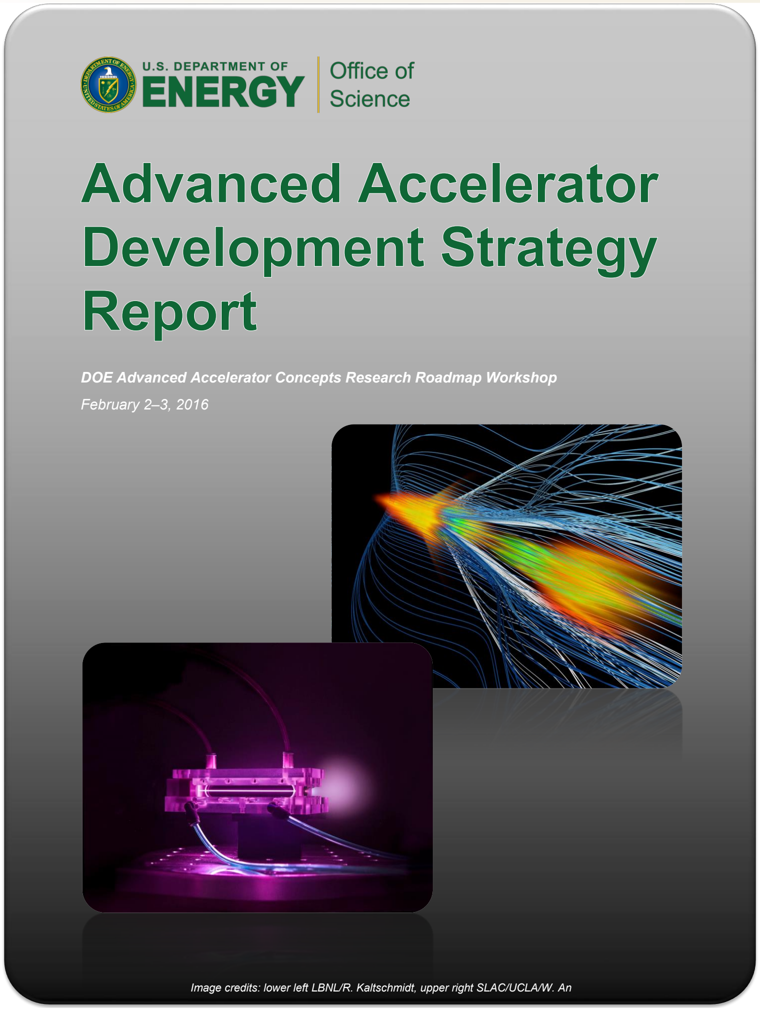
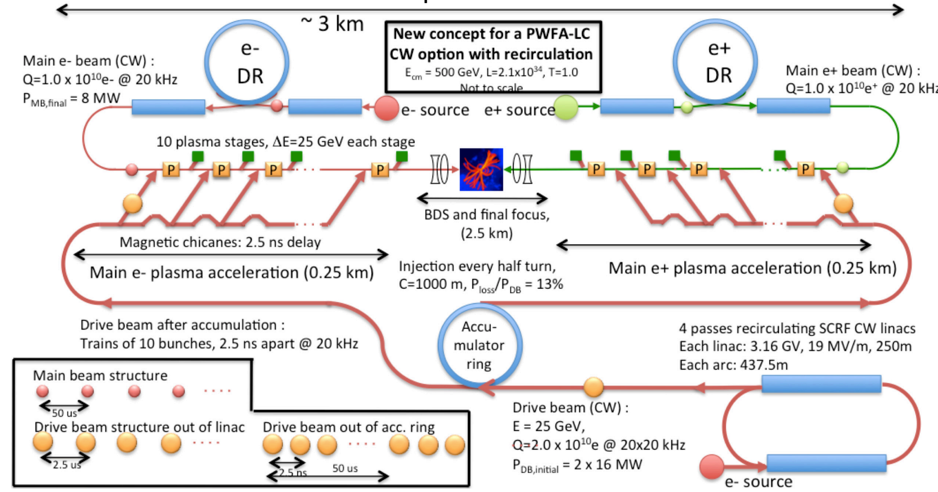


http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf

A Conceptual PWFA-LC



E. Adli et al., ArXiv 1308.1145
J. P. Delahaye et al., Proceedings of IPAC2014

Key Elements for PWFA over next decade:

- Beam quality – build on 9 GeV high-efficiency FACET results with focus on emittance
- Positrons – use FACET-II positron beam identify optimum regime for positron PWFA
- Injection – ultra-high brightness sources, staging studies with external injectors

Roadmap Can Be Broadly Distilled into a List of Key R&D Challenges

- Emittance preservation
- Positrons
- Beam loading
- Higher transformer ratios
- Beam dynamics & tolerances
- Plasma source development
- Staging
- Offramp's & First applications

Key R&D Challenges

- **Emittance preservation**
- Positrons
- Beam loading
- Higher transformer ratios
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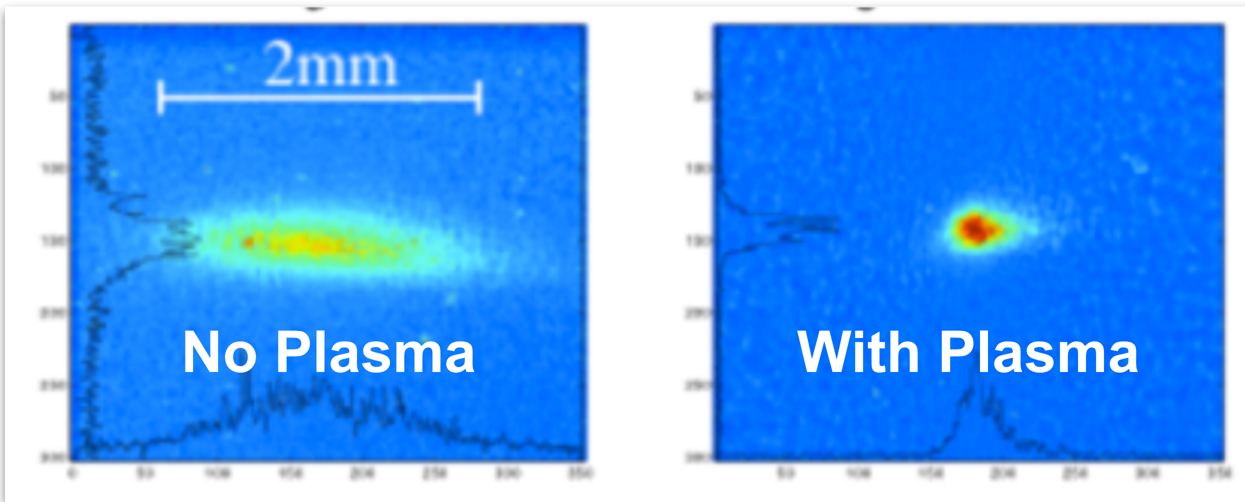
- **Plasma source development**
- Staging
- Offramp's & First applications

Must Understand and Control Plasma Focussing to Preserve Beam Emittance

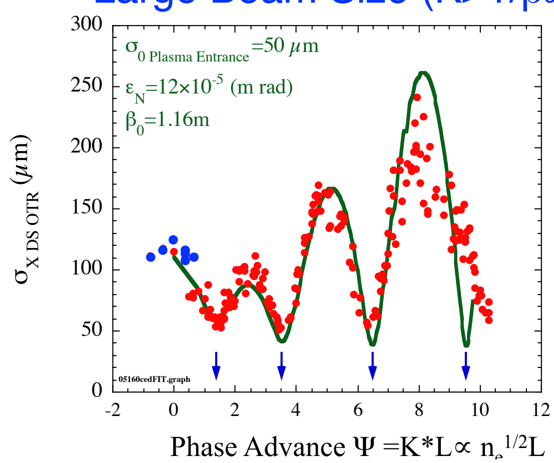
UCLA SLAC



- Ion column will focus and guide beam over length of the plasma
- Ideal lens free of geometric aberration

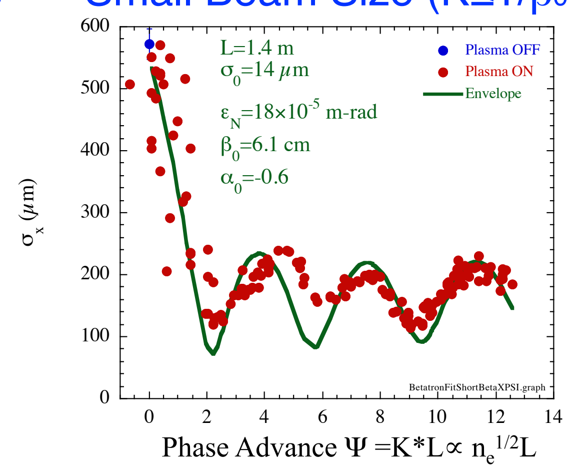
- Increase the density/focusing
- Focusing >1,000 larger than beamline magnets
- Ion column well described by simple model
- Multiple foci within the plasma

Large Beam Size ($K>1/\beta_0$)



Phys. Rev. Lett. **88**, 154801 (2002)

Small Beam Size ($K\leq1/\beta_0$)



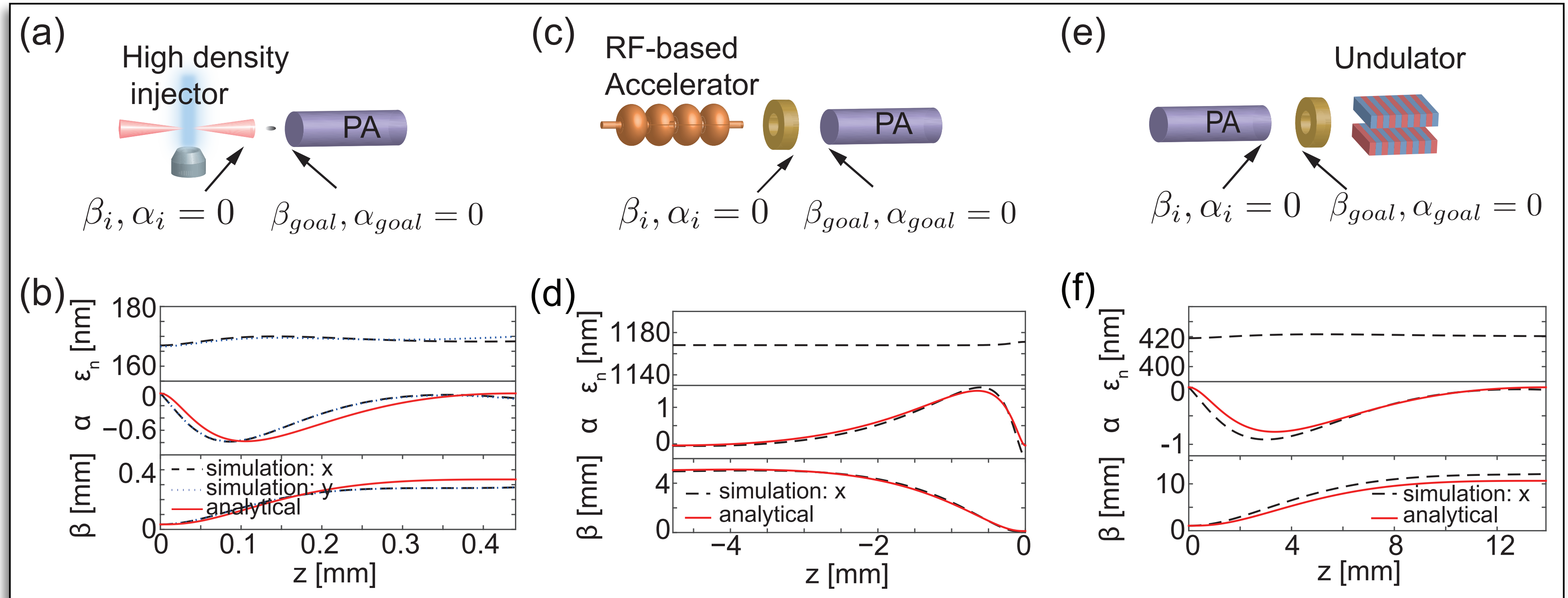
Phys. Rev. Lett. **93**, 014802 (2004)

Need to match the beam into and out of the plasma focusing channel to preserve emittance

Plasma Source Development
Critical for Preserving Emittance In and Out of the Plasma

- Analytic framework developed at UCLA/Tsinghua
- Match beams with finite energy spread in & out of plasma stages

X. Xu Phys. Rev. Lett. 116.124801 (2016)

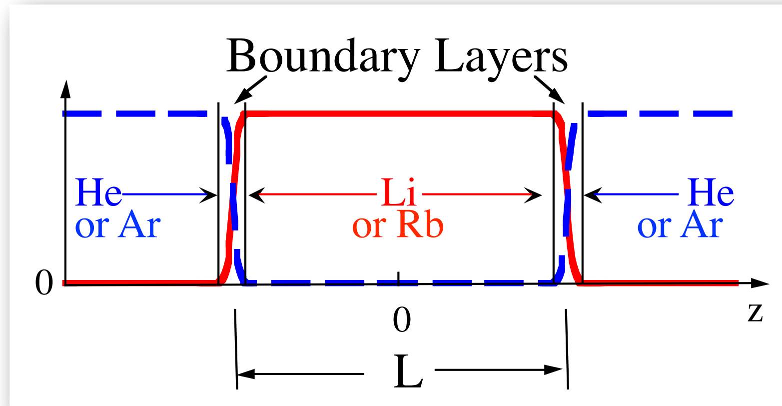


Roadmap emphasizes need to continue meter scale plasma source development with emphasis on emittance preservation

Plasma Sources in Use Today

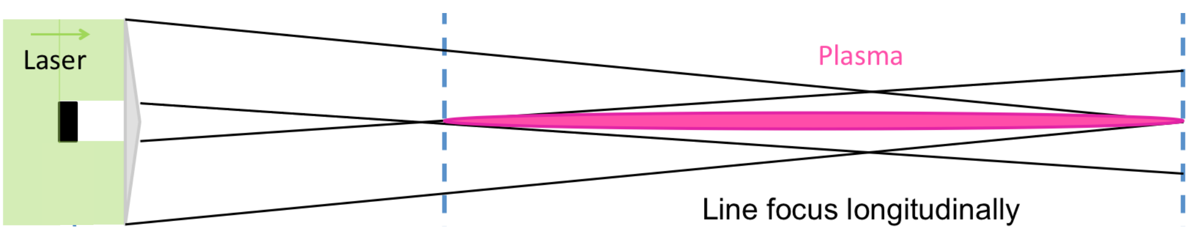
Metal vapor heat-pipe ovens

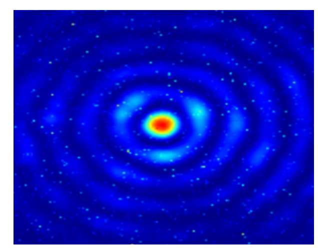
- Uniform vapor column, scalable, $n_0 = 10^{14}$-10^{17} e^-/cm^3, L = 20-200 cm
- 10m long variant will be used at CERN AWAKE
- Adiabatic transition/focusing at boundaries

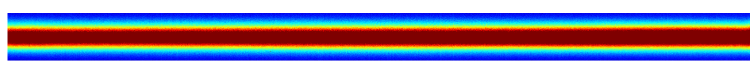


Laser ionized hydrogen development

- Plasma profile conforms to laser intensity
- Axion, Axilens, Kinoform + masks for control of transverse & longitudinal profile





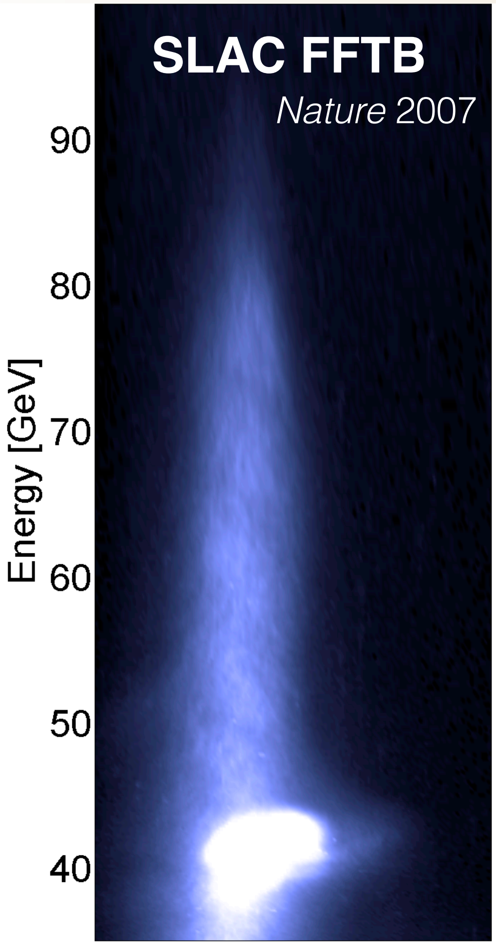


Future plasma sources will require even greater control (needed for both beam and laser driven concepts) and techniques to dissipate power

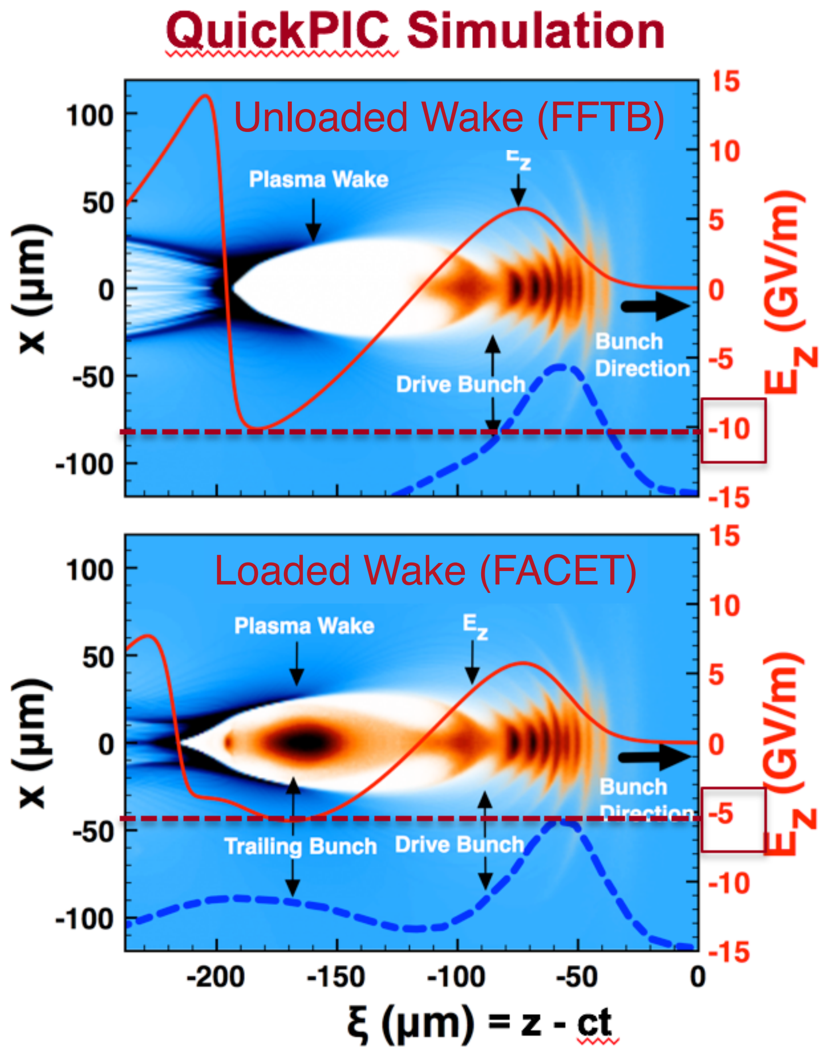
Key R&D Challenges

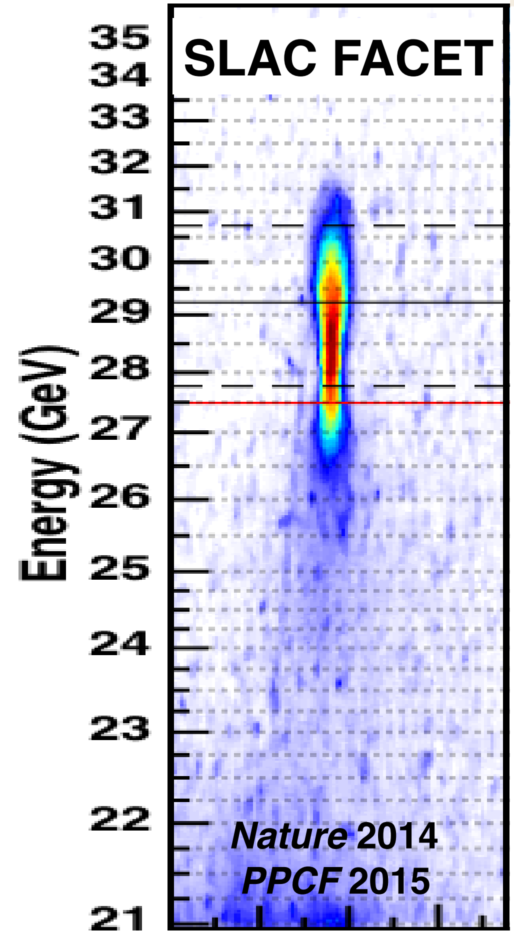
- Emittance preservation
- Positrons
- **Beam loading**
- **Higher transformer ratios**
- Beam dynamics & tolerances
- Plasma source development
- Staging
- Offramp's & First applications

Beam Loading Produces Narrow Energy Spread & High Efficiency



43 GeV
Energy Gain



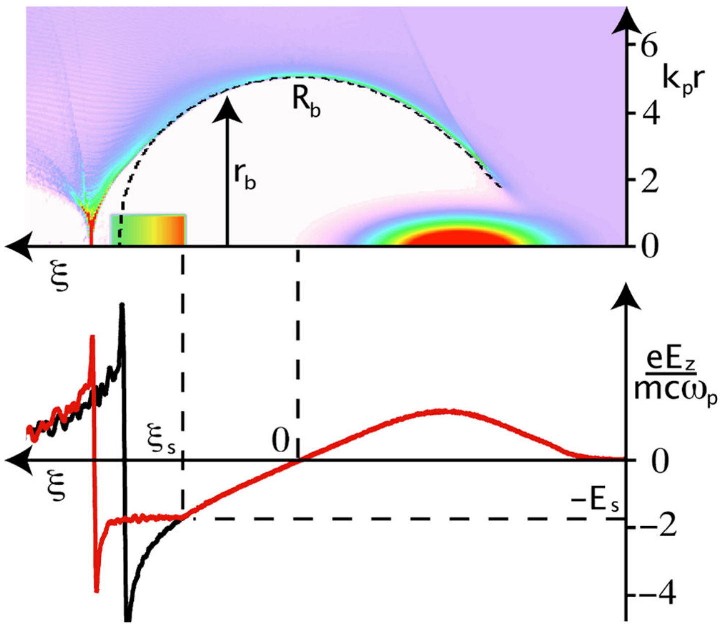


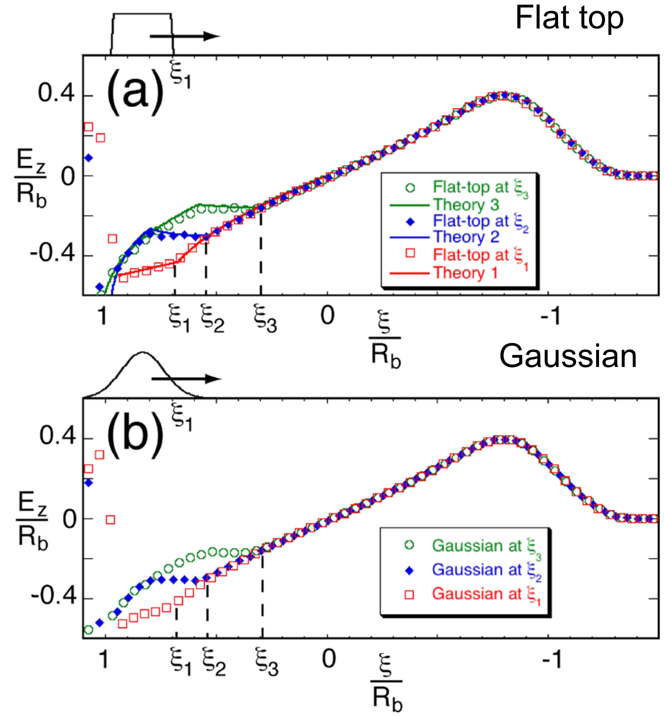
9 GeV
Energy Gain

Narrow energy spread acceleration with high-efficiency has been demonstrated
Next decade will focus on simultaneously preserving beam emittance

Beam Loading in Non-linear Wakes

Theoretical framework, augmented by simulations, provides a recipe



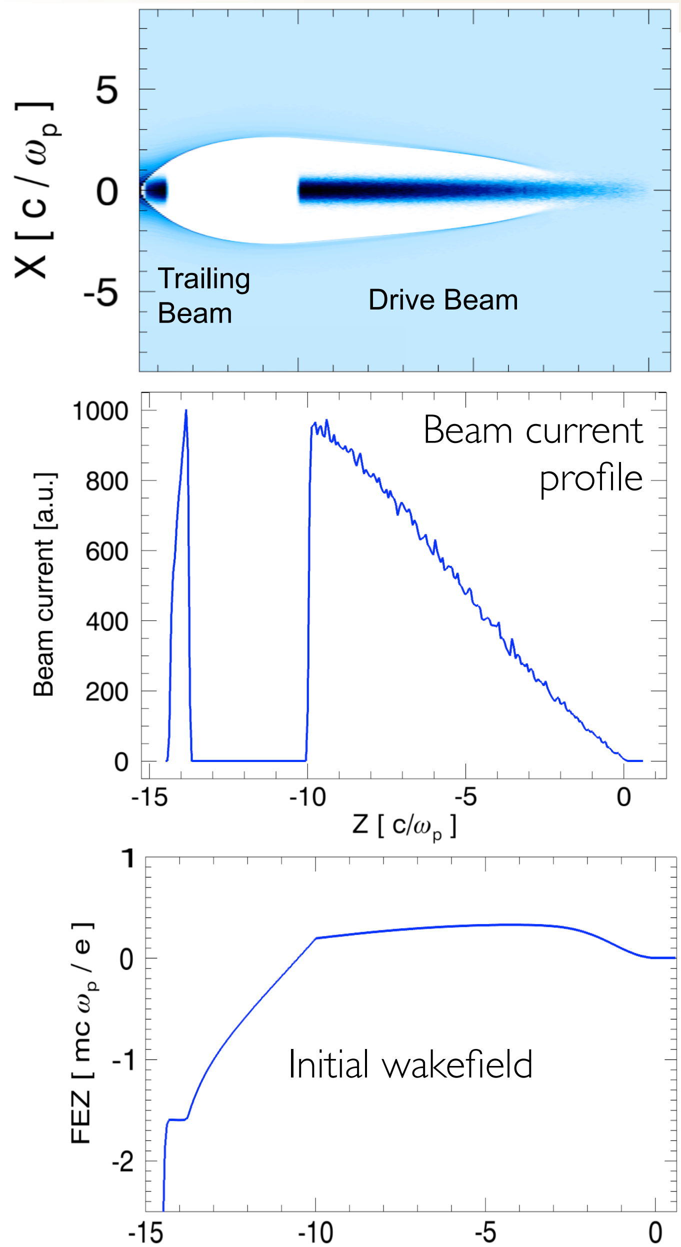


Roadmap emphasizes the need to answer the question: How strongly can the witness beam load the longitudinal wake without strong transverse wakes and BBU?

- Relativistic Beams provide a non-evolving wake
- Possible to nearly flatten accelerating wake – even with Gaussian beams
- Gaussian beams provide a path towards ΔE/E ~ 10^{-2} - 10^{-3}
- Applications requiring narrower energy spread, higher efficiency or larger transformer ratio → Shaped Bunches

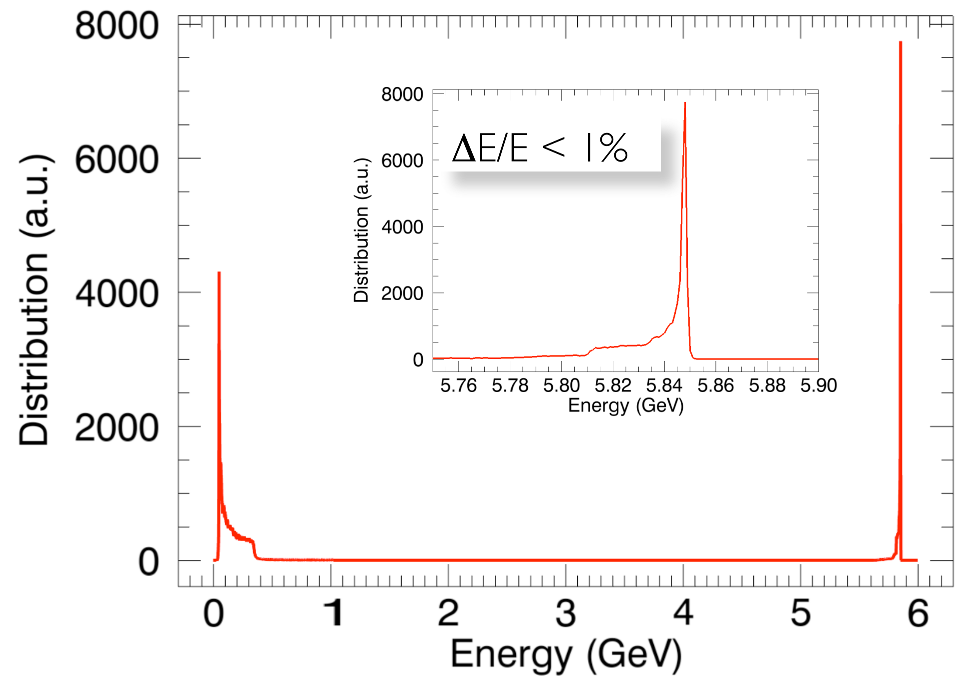
$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

Higher Transformer Ratios – Lower Drive Beam Energy, Fewer Stages and Higher Efficiency



Shaped bunches have many benefits:

- Reduced energy spread
- Maximizes energy boost from a single stage
- Different source & emittance for drive/witness



Need to investigate maximum transformer ratio that still preserves beam quality, e.g. with T = 5 and 20GeV driver can get 100GeV for gg in single stage

Key R&D Challenges

- Emittance preservation
- Positrons
- Beam loading
- Higher transformer ratios
- **Beam dynamics & tolerances**
- Plasma source development
- **Staging**
- Offramp's & First applications

Staging and/or High Transformer Ratios Will Be Required to Reach Very High Energies

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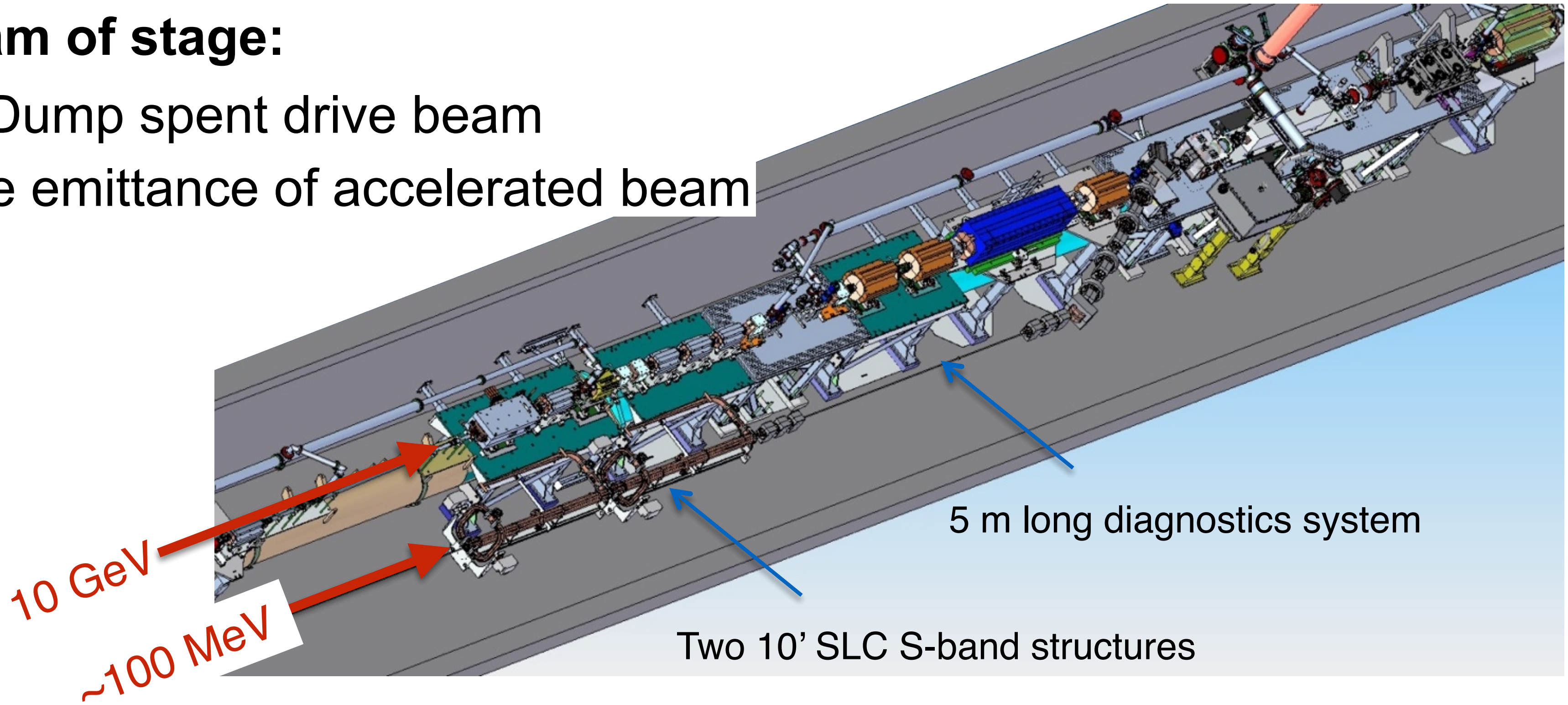
Upstream of stage:

- Inject high-brightness witness bunch from independent source
- Tailored current profiles for maximum efficiency
- Investigate tolerances on timing, alignment

Downstream of stage:

- Extract/Dump spent drive beam
- Preserve emittance of accelerated beam

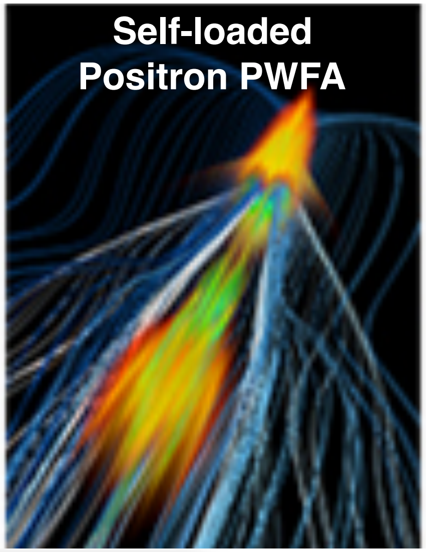


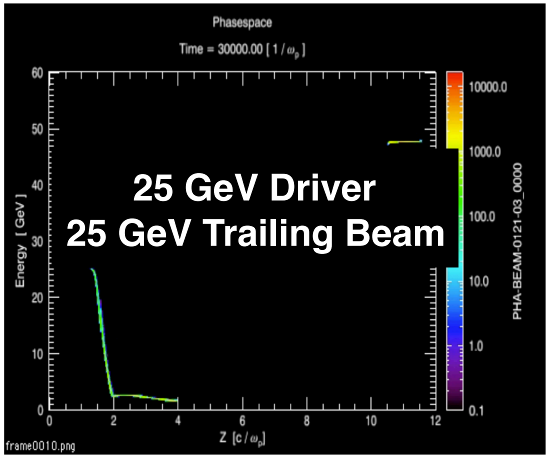
Witness bunch injector concept, a possible solution for staging studies and high transformer ratio experiments, is compatible with FACET-II design

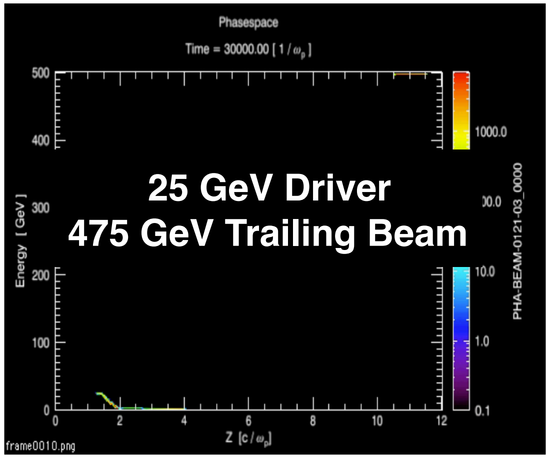
Computation Has Been Essential Component of FACET Science

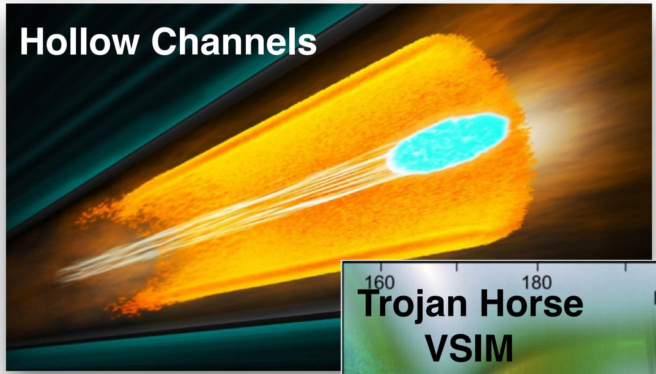
UCLA SLAC

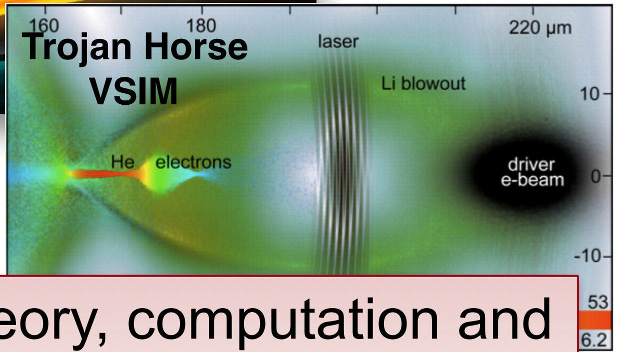
- QuickPIC, OSIRIS have been benchmarked against experiments at SLAC for the last 18 years
- Next generation e- & e+ experiments, plasma injectors, concepts using these beams, PWFA-LC studies…









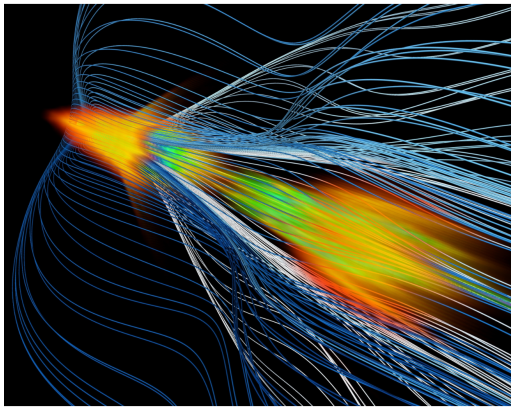


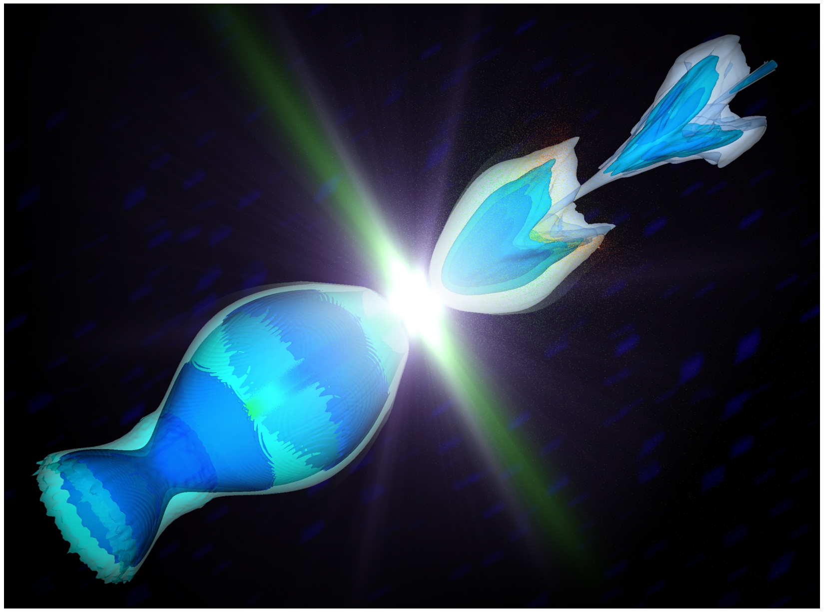
FFTB & FACET enjoyed strong connection between theory, computation and experiment – every major result benefited from strong collaborations

Simulation Development

Collider modeling, tolerance studies and optimization need advances in simulation capabilities

- Speed, resolution…more, more, more
  - Need more than a few time steps (BBU, positrons)
  - Collider level emittance means very small grids (adaptive mesh?)
- Physics:
  - Radiation loss
  - Ion motion
  - Scattering
  - All ionization models
  - Arbitrary beam and plasma profiles
  - Polarization
- Integration with accelerator and FEL codes



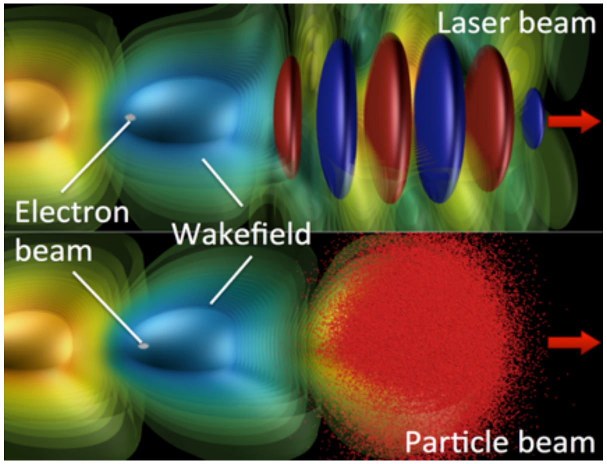


Another good opportunity to work together to develop common tools

Exascale Computing to Support Detailed Collider Design

Exascale Modeling of Advanced Particle Accelerators

Goal (4 years): Convergence study in 3-D of 10 consecutive multi-GeV stages in linear and bubble regime, for laser- & beam-driven plasma accelerators.



How: ➔ Combination of most advanced algorithms

➔ Coupling of Warp+BoxLib+PICSAR

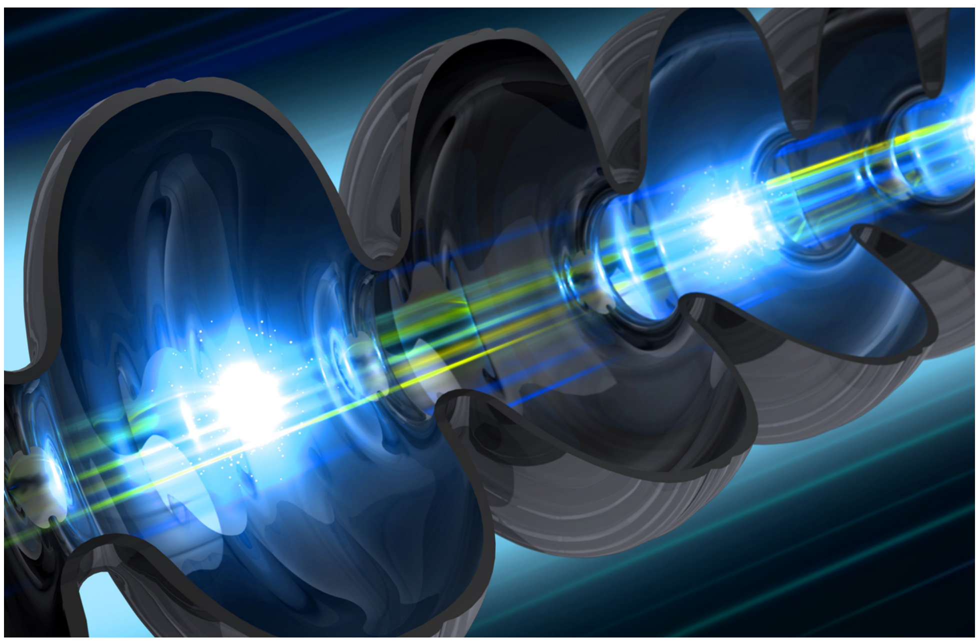
➔ Port to emerging architectures (Xeon Phi, GPU)

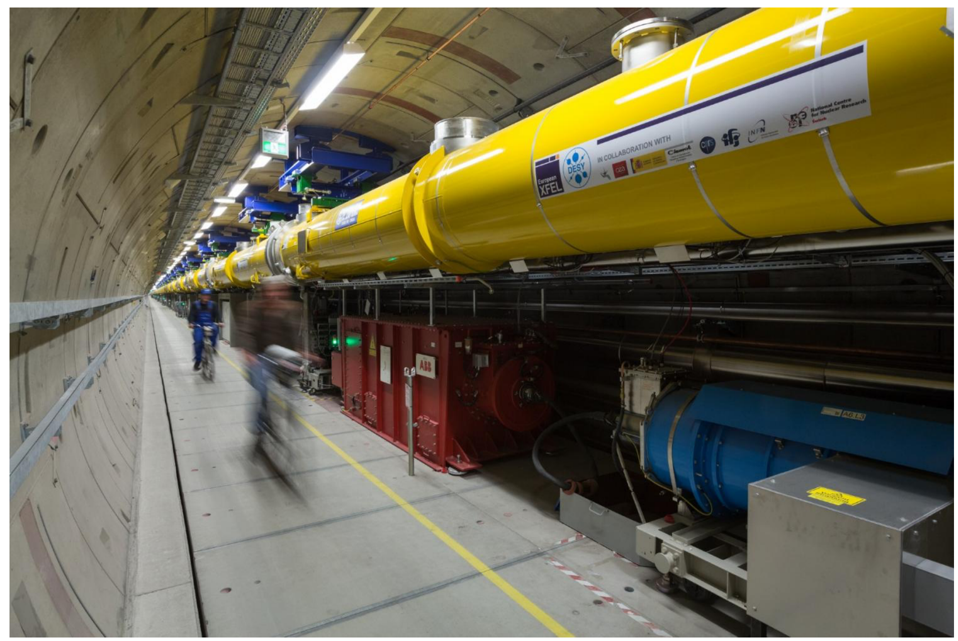
Who: **LBNL ATAP** (accelerators) + **LBNL CRD** (computing science) + **SLAC** + **LLNL**

Ultimate goal: enable modeling of 100 stages by 2025 for 1 TeV collider design!

Drive Beam Technology

- Beam driven wakefield accelerators benefit from 30 years of linear collider research and development
- Now benefitting from large free electron laser projects that will be operating within next 5 years
- Leverage experience from existing projects with multi-GeV, MHz repetition rate electron beams





LCLS-II, LCLS-II HE, European XFEL driving industrialization and experience with superconducting linacs

Diagnostic Development

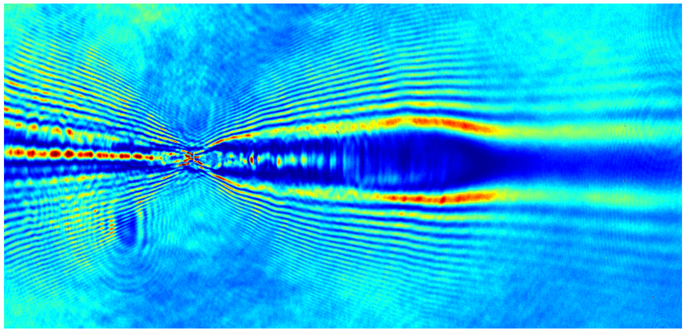
Colliders have very demanding requirements

Diagnostics can help understand the physics without the need to design all sub-systems to collider level tolerances

- Vary and measure every beam parameter single shot, every shot
  - Orbit, charge, bunch length, emittance, energy spectrum, phase space…
- Measure plasma parameters
  - Density, length, column width and evolution
- Plot correlations and ascertain range of acceptable inputs

These are very challenging measurements

- Femtosecond time resolution
- Sub-micron spatial resolution
- Benefit from XFEL community (ps to fs to as…)



Advanced Accelerator community has a history of innovation in this area and this is a good opportunity to work together to develop common techniques

Planning for FACET-II as a Community Resource

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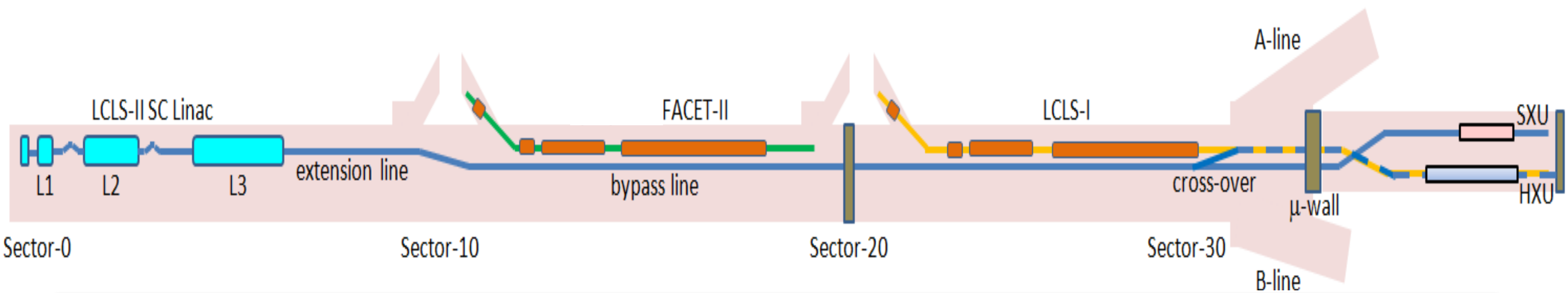
- FACET stopped running in April 2016 to begin LCLS-II construction
- Over the next few years FACET-II will add new capabilities:
  - LCLS style photoinjector with state of the art electron beam
  - Flexibility e.g. low-charge mode or 'two color' operation for two-bunch PWFA
  - Nominal **e⁻** parameters: 10GeV, 2nC, 15kA, 30Hz (**2019**) → Beam quality
  - Nominal **e⁺** parameters: 10GeV, 1nC, 6kA, 5Hz (**2021**) → Positron Acceleration
  - External injection → Staging studies, ultra-bright sources
- Continue to plan experimental program with **Science Workshops** (October 2015, 2016…)



Premier R&D facility for PWFA: Only facility capable of e+ acceleration
Highest energy beams uniquely enable gradient > 1 GV/m

These Experiments Were Made Possible by FACET Users

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- 214 Scientists associated with 24 experiments and beam tests (82% of users are external to SLAC)
- 55% of these scientists working on the experiments are On-site Users (badged and trained for experimental work)
- 45% of the scientists involved in FACET experiments are from outside the US
- 52 Institutions are involved in FACET
- Majority of scientists come from universities

FACET Enabled a Broad User Community – User Community Enabled FACET Program

Summary

- The U.S. community has come together at a series of workshops and developed a high level roadmap for beam-driven plasma acceleration
- Priorities include emittance preservation, beam loading, higher transformer ratios, beam dynamics & tolerances, plasma source development, staging studies
- Continued progress will need powerful test facilities such as FACET-II, advanced computer simulation capabilities and diagnostic development
- Many common themes and research areas have been identified as opportunities for collaboration
- Next decade will see worldwide progress on key R&D challenges

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