# Overview of PWFA (WG2)

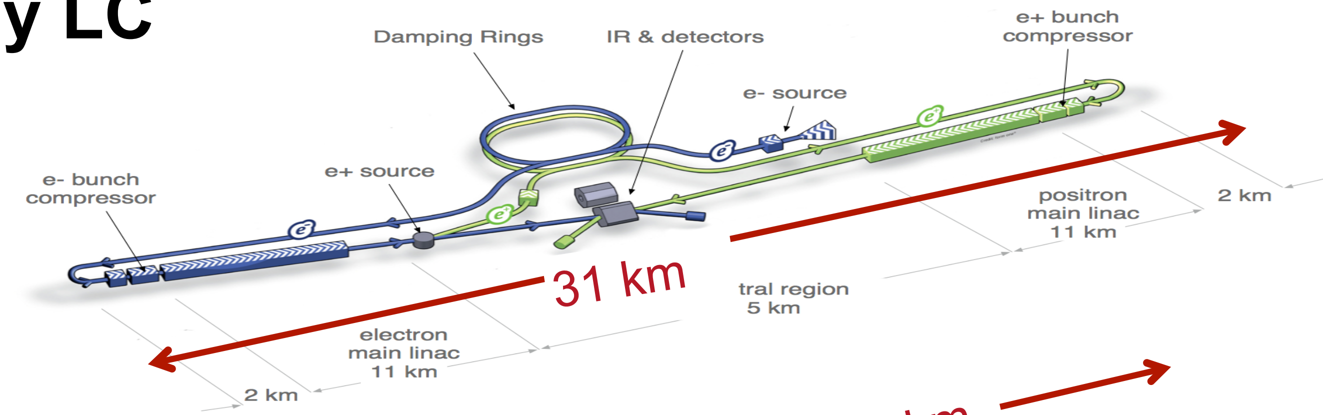
Mark J. Hogan
April 25, 2017 @ ANAR2017

U.S. DEPARTMENT OF ENERGY
Office of Science

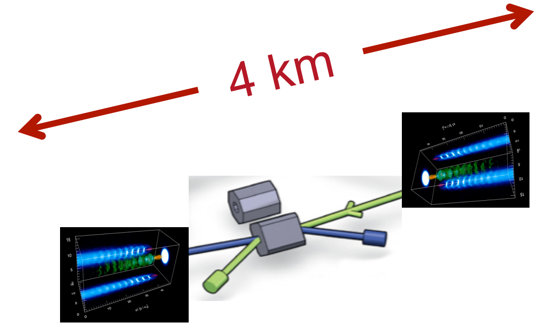
SLAC NATIONAL ACCELERATOR LABORATORY

# The Scale for a TeV Linear Collider

**Today's technology LC – a 31km tunnel:**




**Plasma Wakefield Technology LC:**




➡ GeV/m accelerating gradient

**The Luminosity Challenge:**

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

➡ High-efficiency, low emittance

…and must do it for positrons too!

# Accelerating Particles to Accelerating Beams → FACET

SLAC

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 Angele*

(Received 9 March 1979)

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

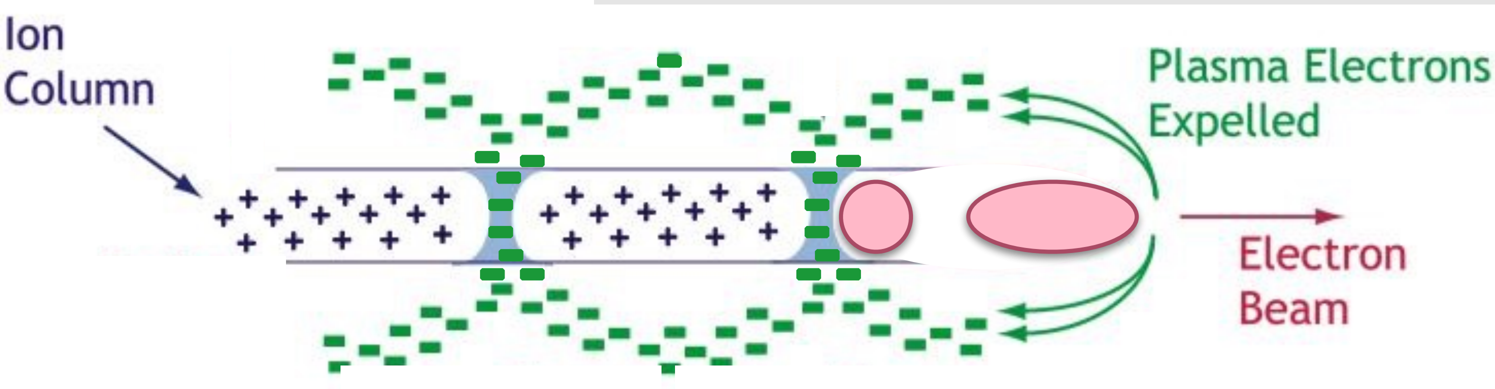
**Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma**

Pisin Chen[a]
*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305*

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas
*Department of Physics, University of California, Los Angeles, California 90024*

(Received 20 December 1984)




$$E_0 \sim 10\sqrt{\frac{n_0}{1\times10^{16}[\mathrm{cm}^{-3}]}}[\mathrm{GeV/m}]$$

- Two bunches externally injected
- Dimensions and spacing ~ $c/w_p$ ~ 20μm
- Blow-out when $n_b >> n_p$
- Plasma = highly efficient transformer
- No phase slippage – non-evolving wake

# 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)

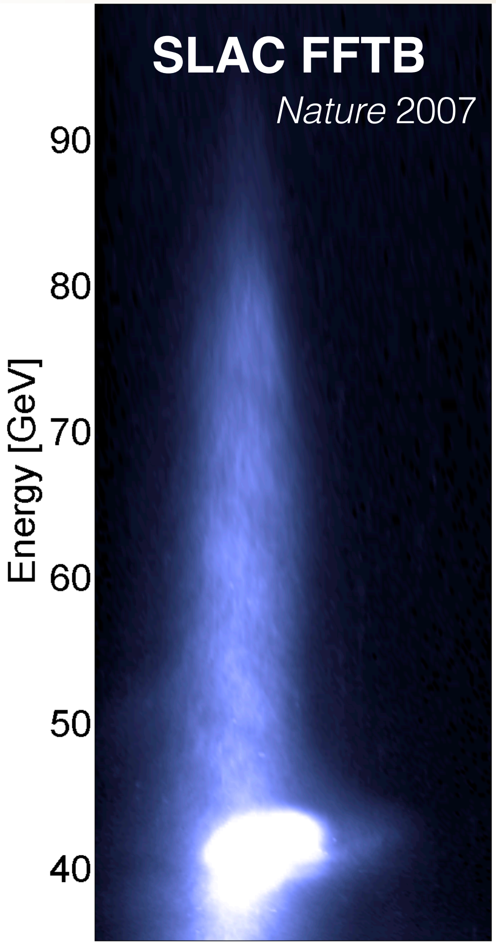
√First high-gradient $e^+$ PWFA (*Nature* **524**, Aug. 2015)

- Demonstrate required emittance, energy spread (FY16)

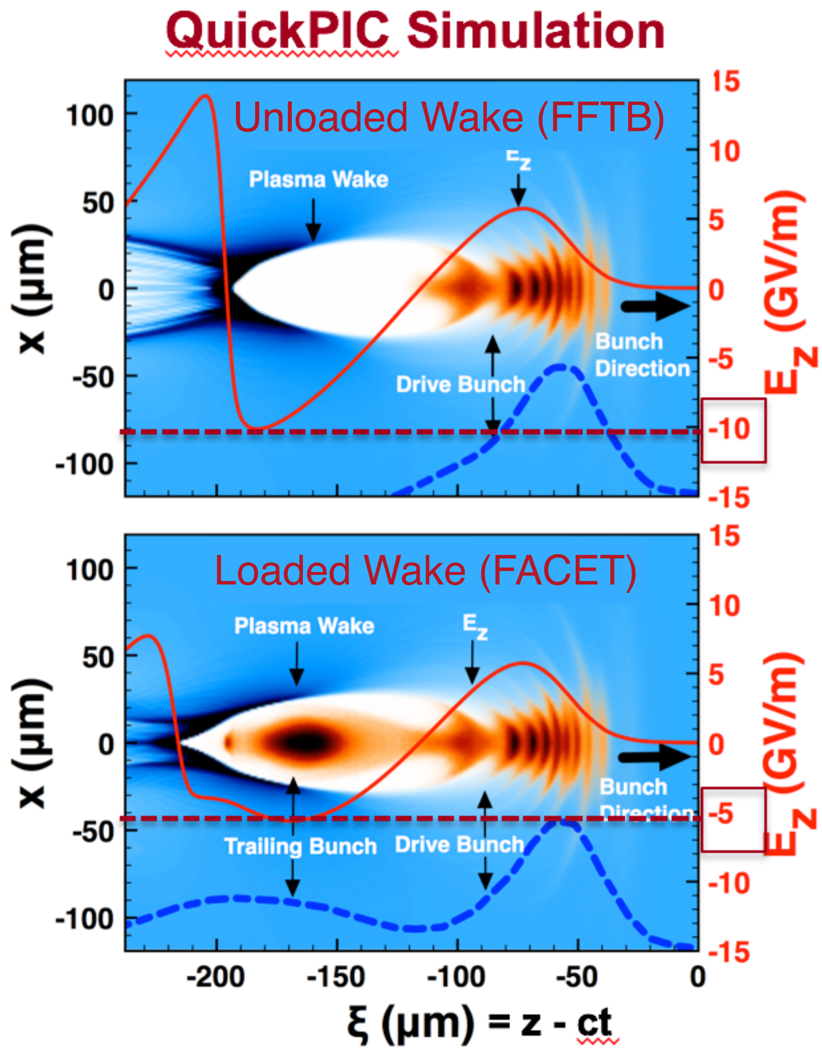
Premier R&D facility for PWFA: Only facility capable of e+ acceleration
Highest energy beams uniquely enable gradient > 1 GV/m

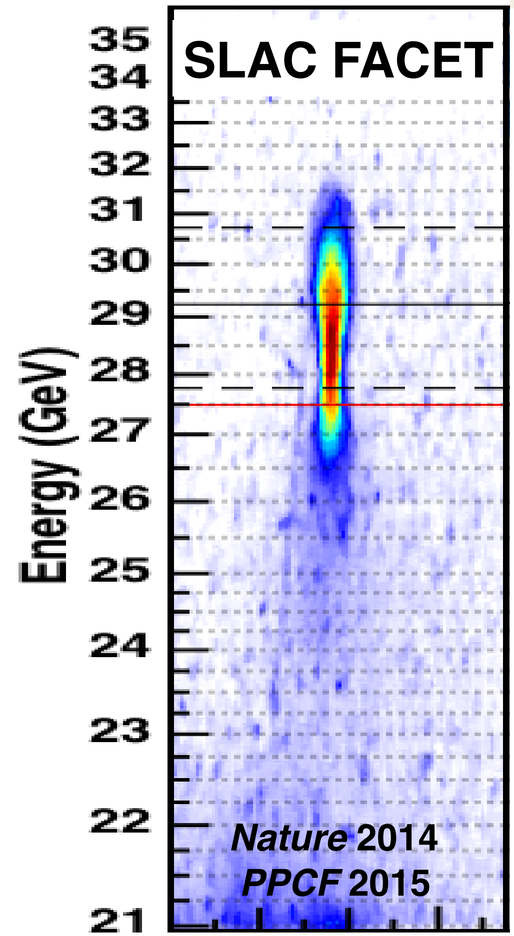
# Beam Loading Produces Narrow Energy Spread & High Efficiency

UCLA SLAC




43 GeV
Energy Gain




9 GeV
Energy Gain

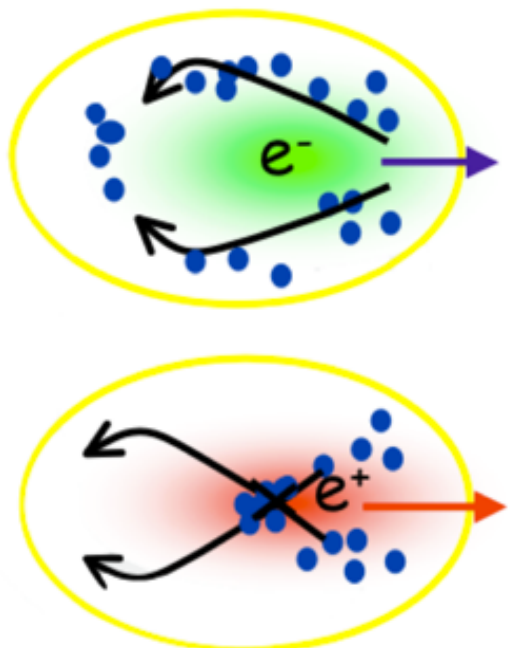
Narrow energy spread acceleration with high-efficiency has been demonstrated
Next decade will focus on simultaneously preserving beam emittance

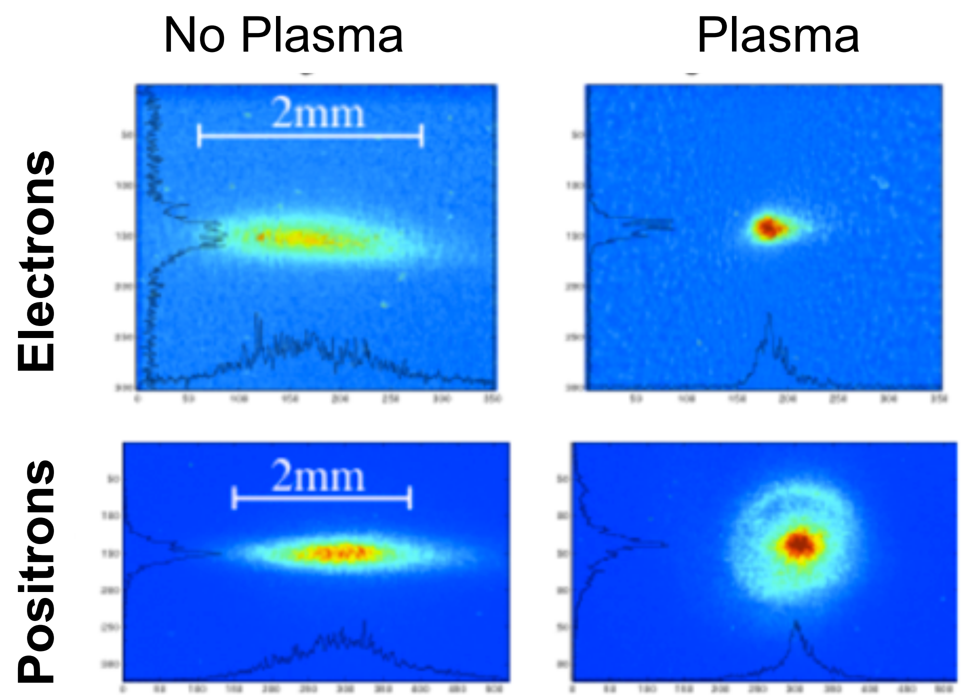
# Extending to Positrons is Not Trivial

Experiments at SLAC FFTB in 2003 showed that the positron beam was distorted after passing through a low density plasma.

**"Blow-out"**

**"Suck-in"**




*Phys. Rev. Lett.* **90**, 205002 (2003)

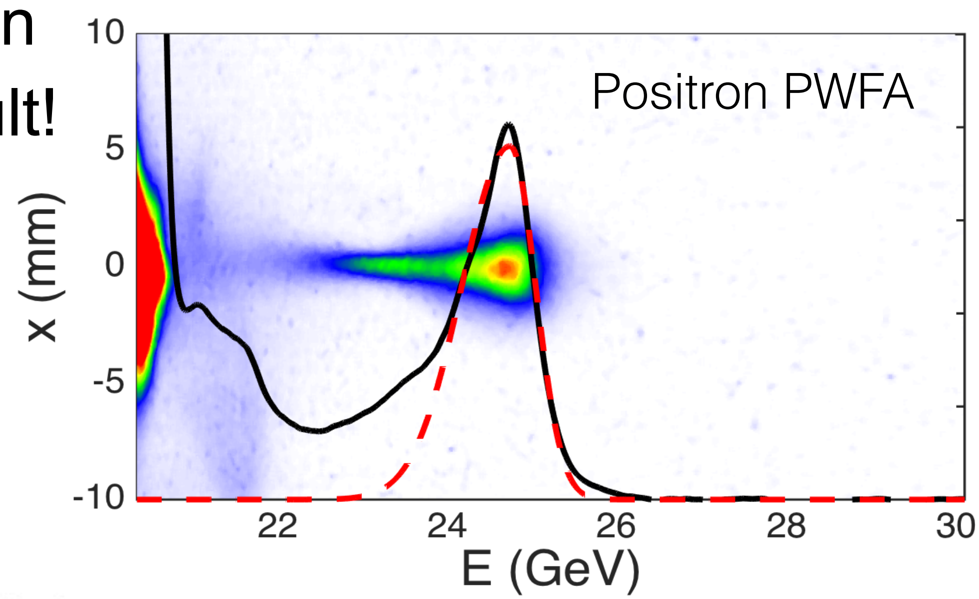
*Phys. Rev. Lett.* **101**, 055001 (2008)

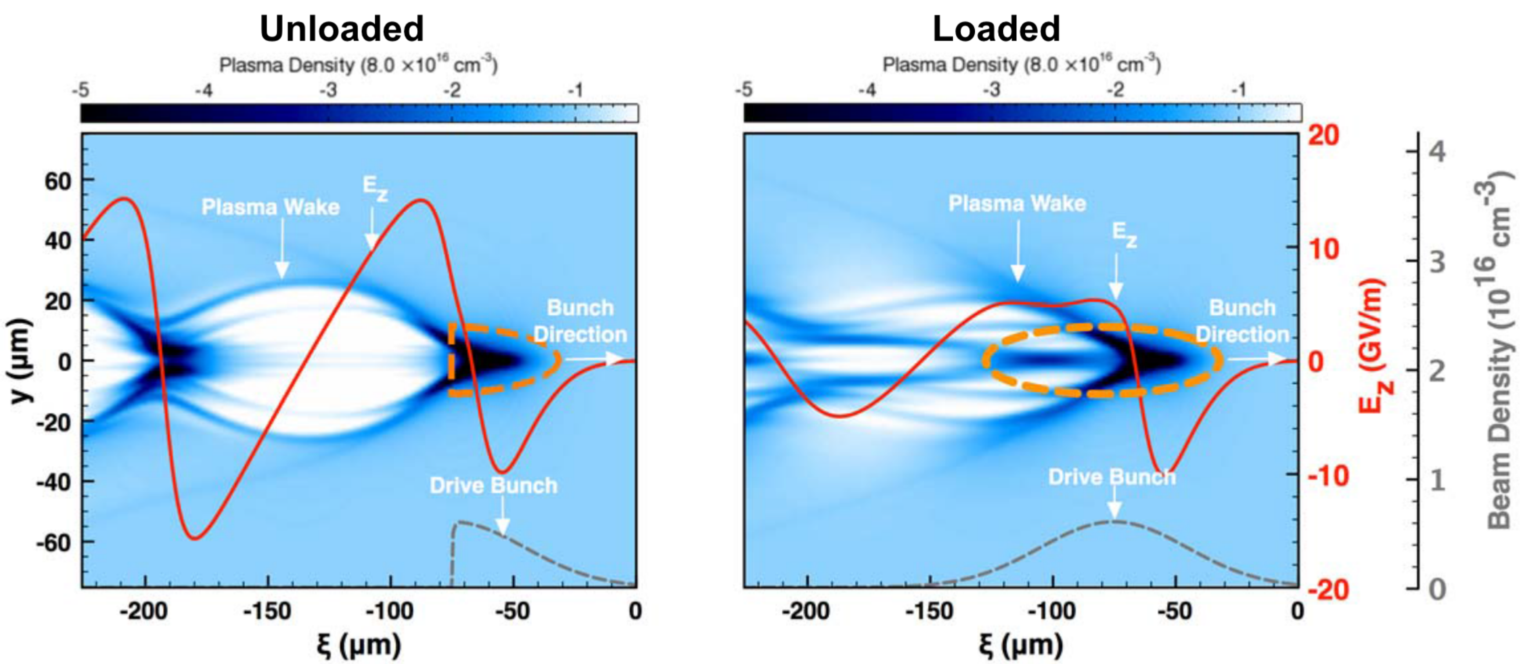
The nonlinear blowout regime will not work for positron PWFA

# Multi-GeV Acceleration of Positrons

Injecting a single high-intensity positron bunch produced a very surprising result!

- Energy gain 4 GeV in 1.3 meters
- 1.8% energy spread
- Low beam divergence
- No halo

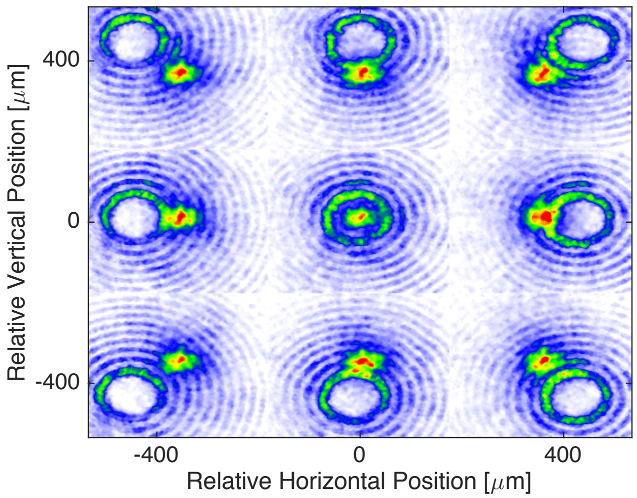


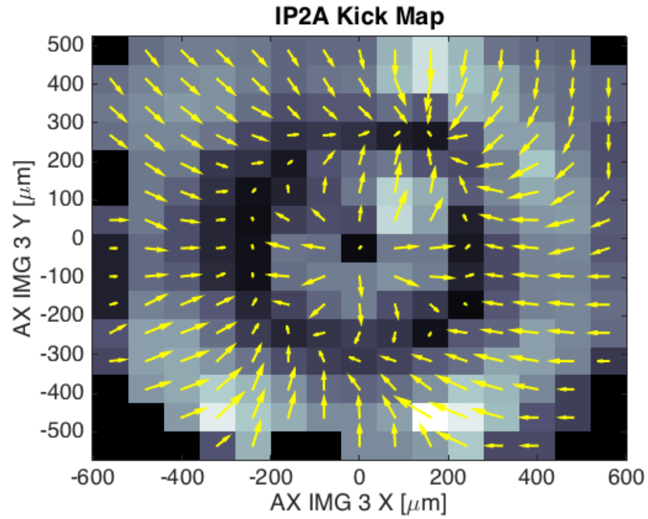



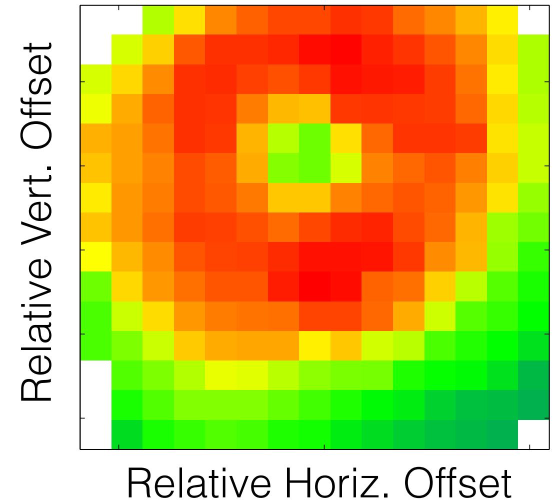

New PWFA regime warrants further exploration and development towards PWFA-LC application

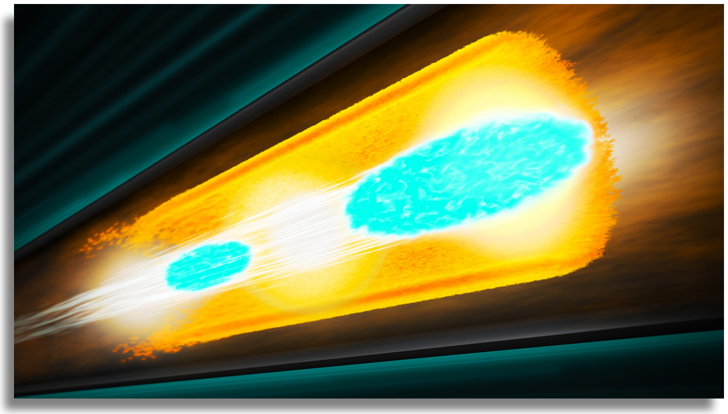
# Demonstration of Acceleration in Hollow Channel Plasmas

## Raster Scan of Beam-Channel Alignment
## Focusing Forces Minimized in Channel Center

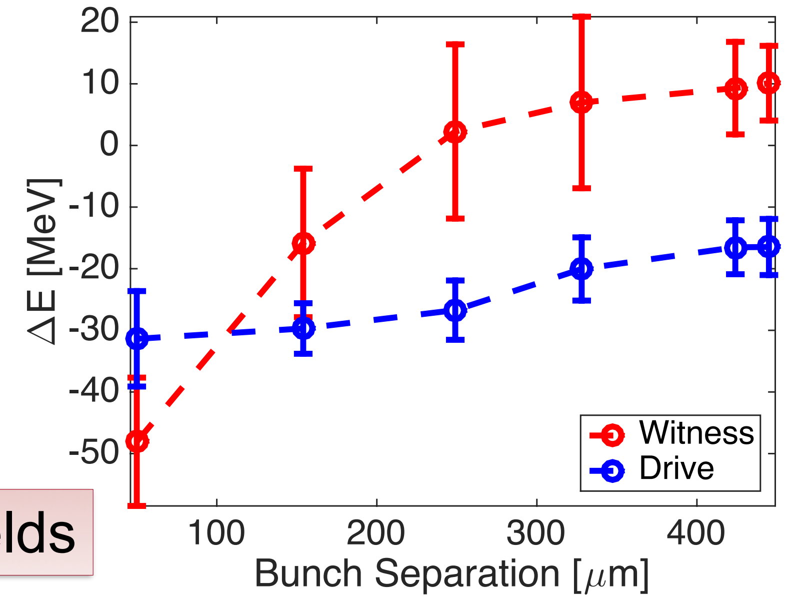


Change bunch spacing to map the longitudinal wakefield




**Engineer the Plasma Source to Control the Fields**

# Paths to a Linear Collider

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| | Advantages | Challenges | Open Questions |
|---|---|---|---|
| **Non-Linear Acceleration** | Extremely large gradients.<br><br>Simple experimental setup. | No known solution using an electron drive beam. | What are the optimal beam and plasma parameters for an afterburner application? |
| **Quasi-Linear Acceleration** | Very large gradients.<br><br>Works with a driving electron beam. | Scaling the plasma and drive beam parameters for an LC-quality witness bunch looks challenging. | Can the emittance of the witness beam preserved? |
| **Hollow Channel Acceleration** | Emittance preservation by precise alignment.<br><br>Works with a driving electron beam. | Modest accelerating gradients. | Can we increase the wake amplitude while maintaining the quality of the witness bunch? |

These are critical questions on the path to a plasma-based Linear Collider

# Beam Driven PWFA Parameters Achieved to Date

SLAC

**Energy**

| PWFA-LC | | | State of the Art | |
|---|---|---|---|---|
| **Parameter** | **Units** | **Value** | **Electrons** | **Positrons** |
| Final Energy | GeV | 3000 | 29 | 24.4 |
| Energy per Stage | GeV | 25 | 9 | 4.4 |
| Peak Gradient | GeV/m | 7.6 | 6.9 | 3.4 |
| Geographic Gradient | GeV/m | 1 | | |
| Transformer Ratio | | 1 | | |
| Number of Stages | | 60 | 1 | 1 |
| Plasma Length | meter | 3.3 | 1.3 | 1.3 |
| Plasma Density | e-/cc | 2E+16 | 5E+16 | 8E+16 |
| Heat Load | kW/m | 100 | | |

**Cost**

| PWFA-LC | | | State of the Art | |
|---|---|---|---|---|
| **Parameter** | **Units** | **Value** | **Electrons** | **Positrons** |
| Efficiency - Instantaneous | % | 50 | 30 | 34 |
| Efficiency - Total | % | | | |

**Performance**

| PWFA-LC | | | State of the Art | |
|---|---|---|---|---|
| **Parameter** | **Units** | **Value** | **Electrons** | **Positrons** |
| Charge per Bunch | nC | 1.5 | 0.03 | 0.207 |
| Rep Rate | Hz | 1E+04 | 1 | 1 |
| Normalized Emittance (H) | $\mu$m | 10 | 100 | |
| Normalized Emittance (V) | $\mu$m | 0.035 | | |
| Energy Spread [r.m.s.] | % | 1 | 4 | 1.8 |
| Polarization | % | 80 | | |
| Bunch Length (sigma) | $\mu$m | 20 | 50 | |
| Tolerances… | | | | |

Electrons:
Nature 515 (2014)
and http://arxiv.org/pdf/1511.06743v1.pdf
to be published in PPCF

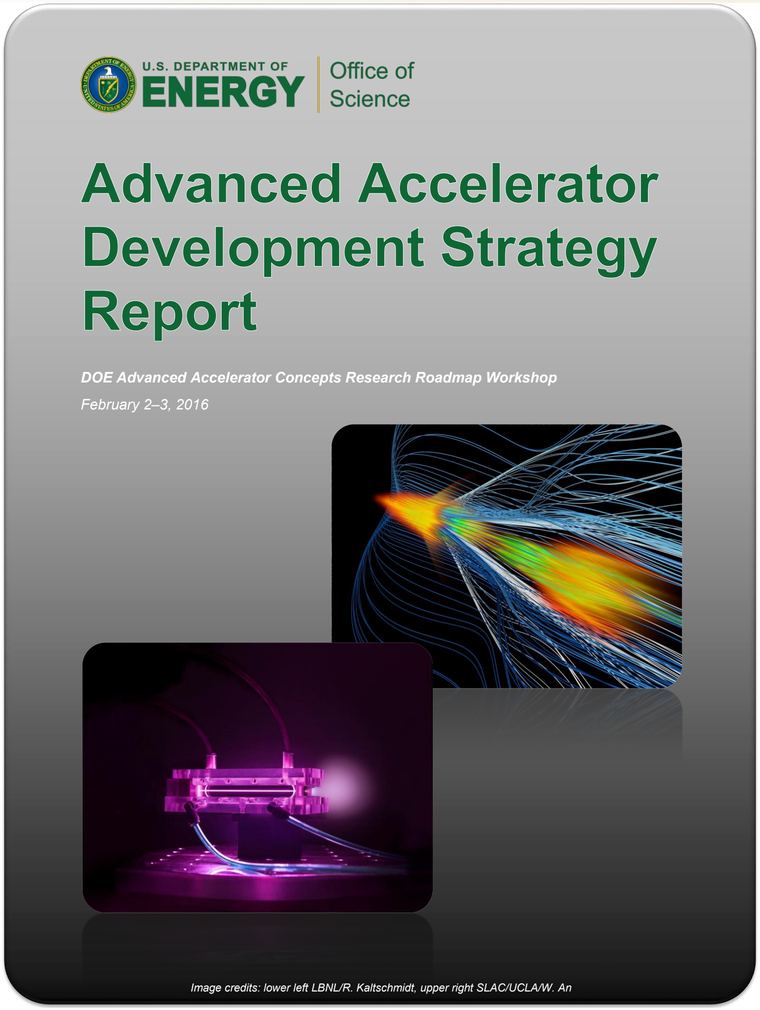
Positrons:
Nature 524 (2015)

Note: parameters are for single (best) cases/regimes. Individual parameters e.g. energy gain are not best of that quantity

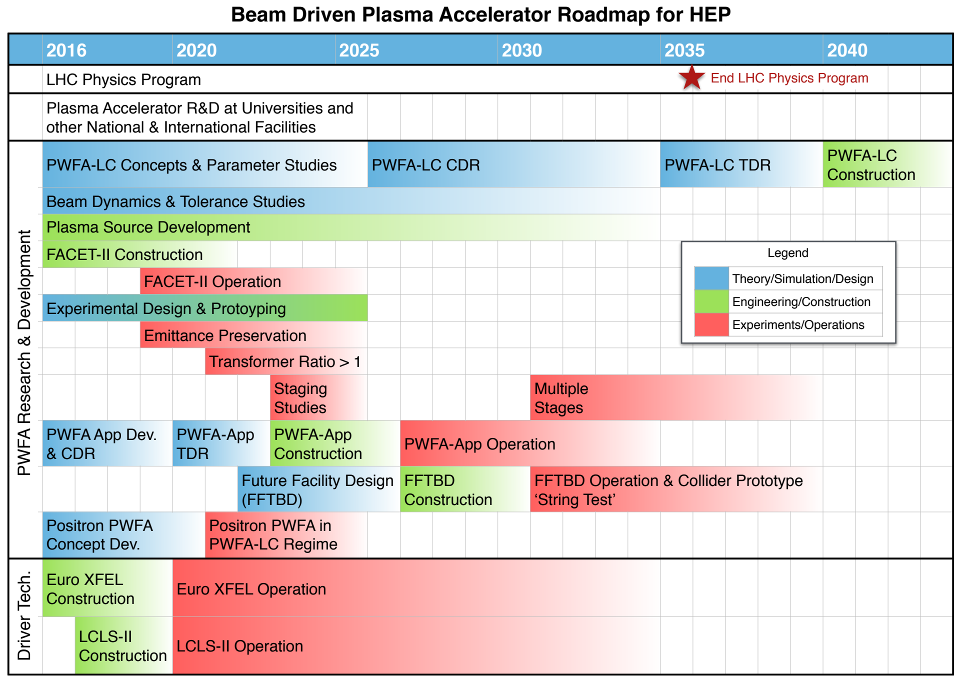
The parameters in above table are a self consistent set but it should be noted that a range of values has been measured for each quantity.

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

SLAC




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




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

# FACET-II Project Plan

SLAC


**Timeline:**

- ✓ **Nov. 2013, FACET-II proposal, Comparative review**
- ✓ **CD-0 Sep. 2015**
- ✓ **CD-1 Oct. 2015 *(ESAAB, Dec.2015)***
- ✓ CD-2/3A Sep. 2016
- CD-3B Sep. 2017
- CD-4 2022

***Experimental program (2019-2026)***

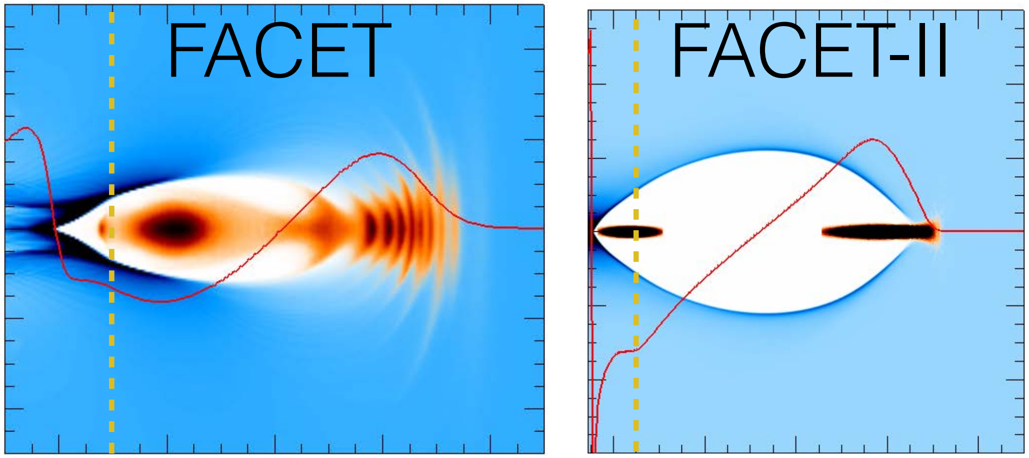
**Key R&D Goals:**

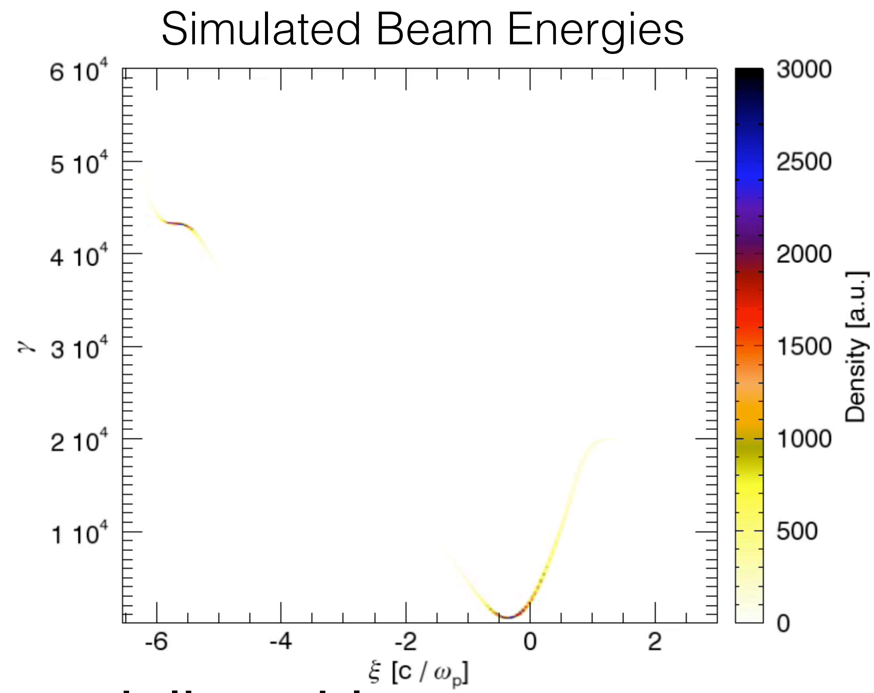
- Beam quality preservation, high brightness beam generation, characterization
- $e^+$ acceleration in $e^-$ driven wakes
- Staging challenges with witness injector
- Generation of high flux gamma radiation

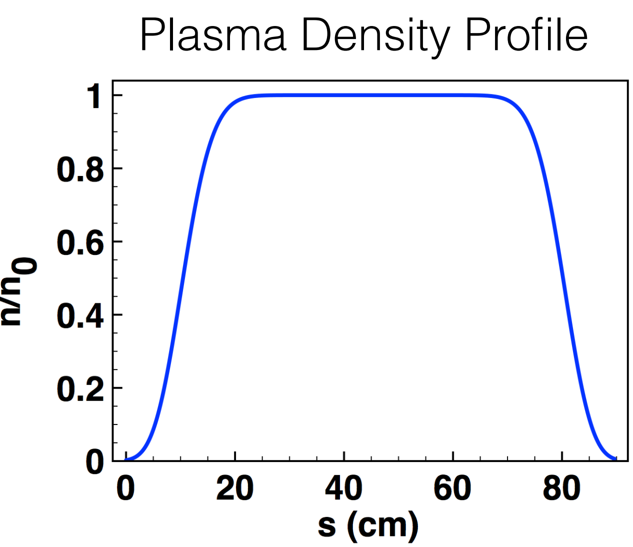
**Three stages:**

| | | |
|---|---|---|
| Photoinjector | (e- beam only) | FY17-19 |
| e+ damping ring | (e+ or e- beams) | FY18-20 |
| "sailboat" chicane | (e+ and e- beams) | |

FACET-II will operate as a National User Facility with an external program advisory committee reviewing proposals and recommending priorities for the experimental program



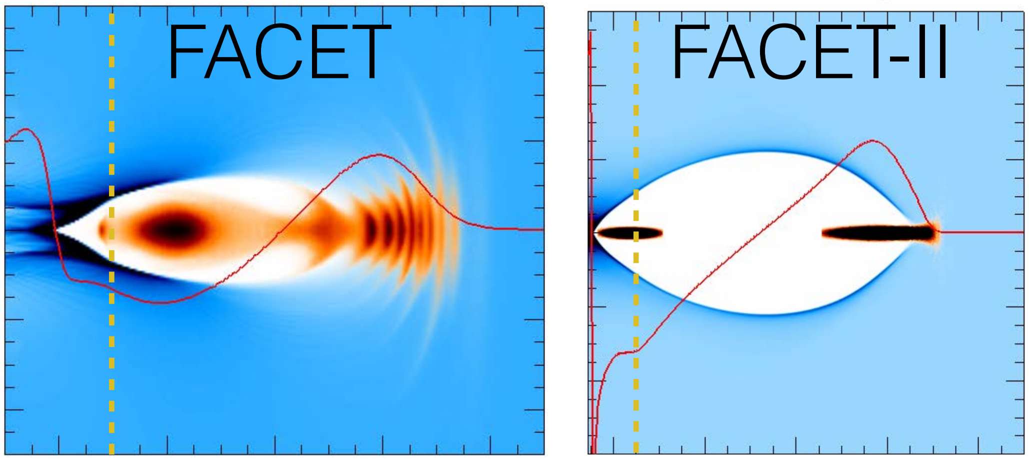



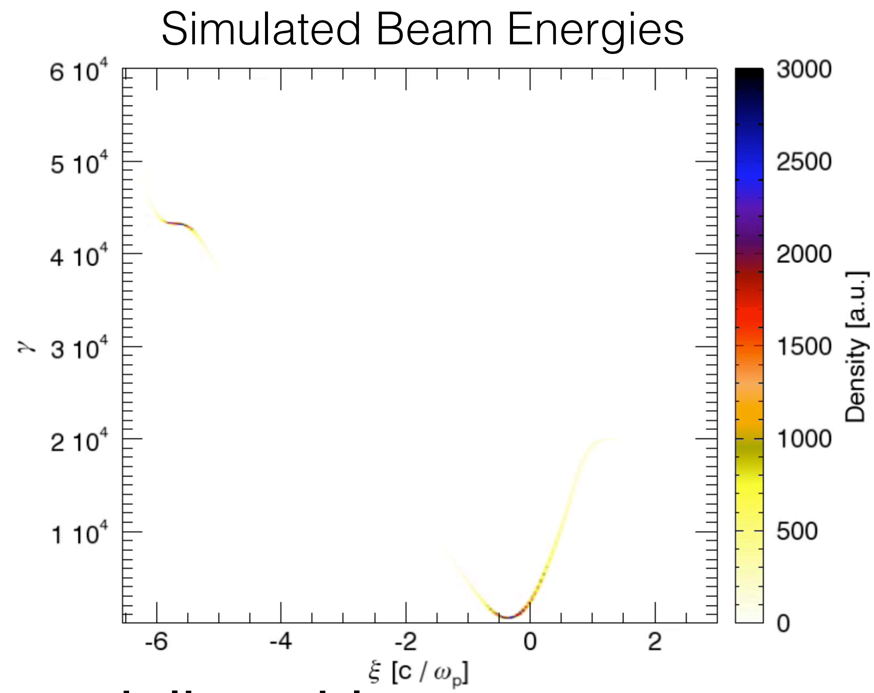

Illustrates science deliverables:

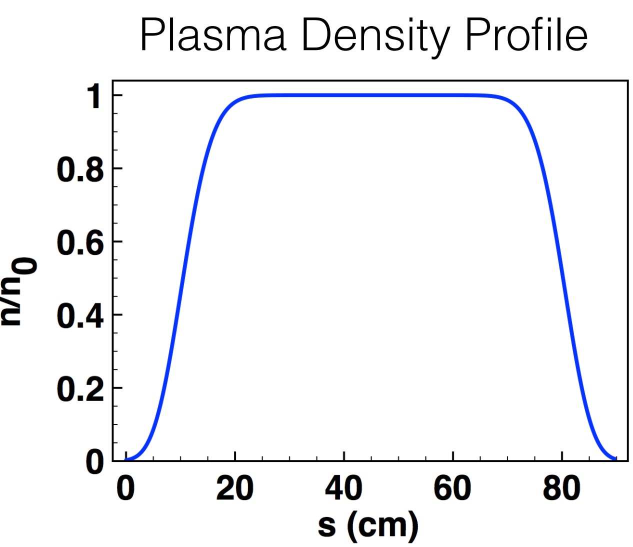
- Pump depletion of drive beam – Beam
- High efficiency & low energy spread – Beam
- Beam matching – Plasma source
- Emittance preservation – Diagnostics

Key upgrades (low emittance photo-injector beams, plasma source with optimized ramps, differential pumping)

# Design and QuickPIC Simulation of First Experiment

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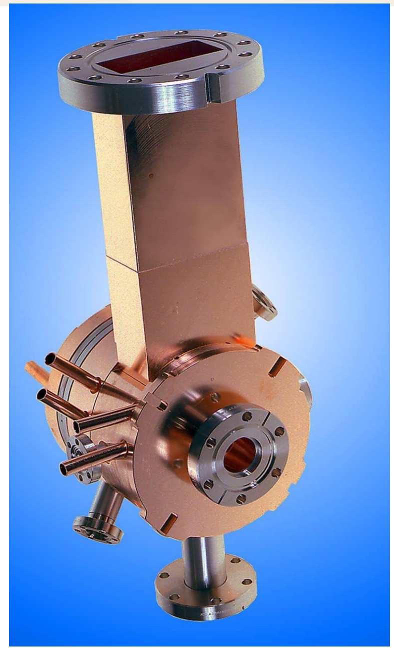
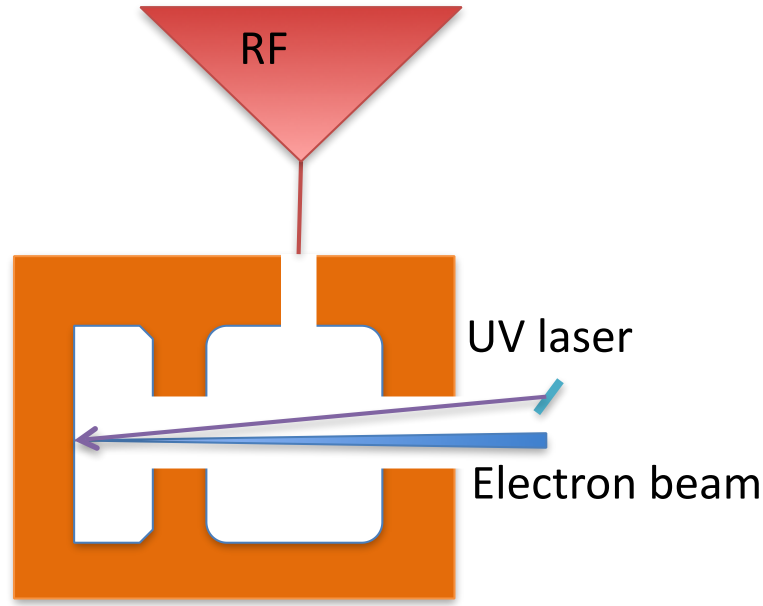
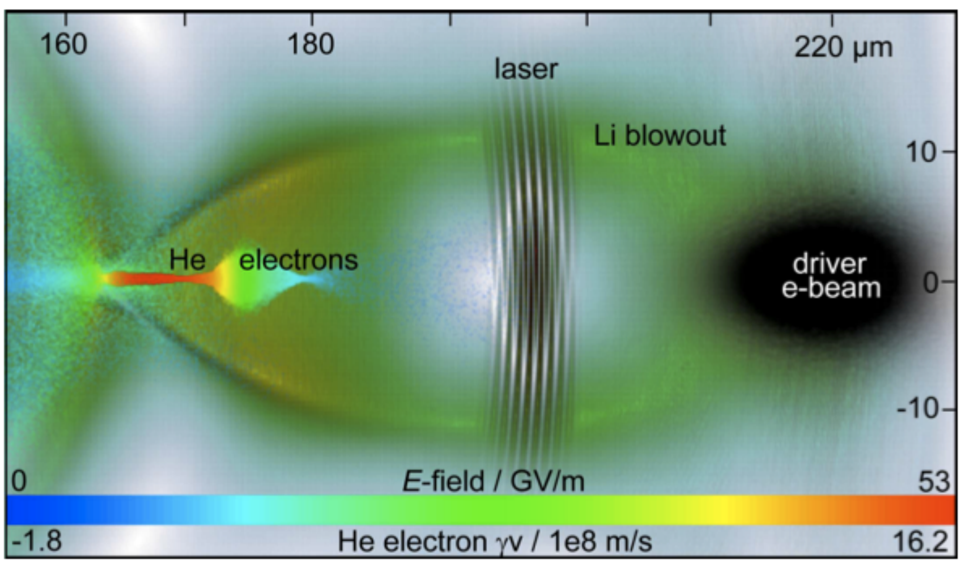
## LCLS Style Photoinjector

- 100MeV/m field on cathode
- Laser triggered release
- ps beams - multi-stage compressions & acceleration
  - Tricky to maintain beam quality (CSR, microbunching…)





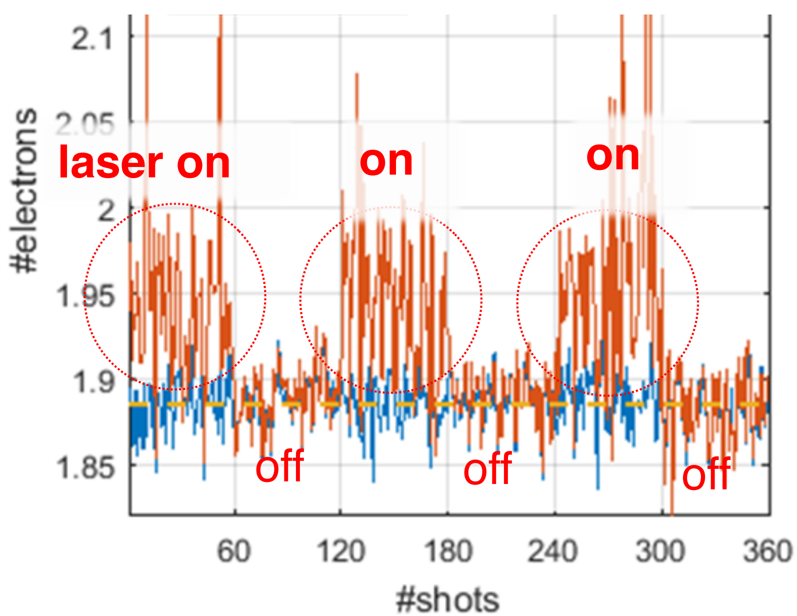



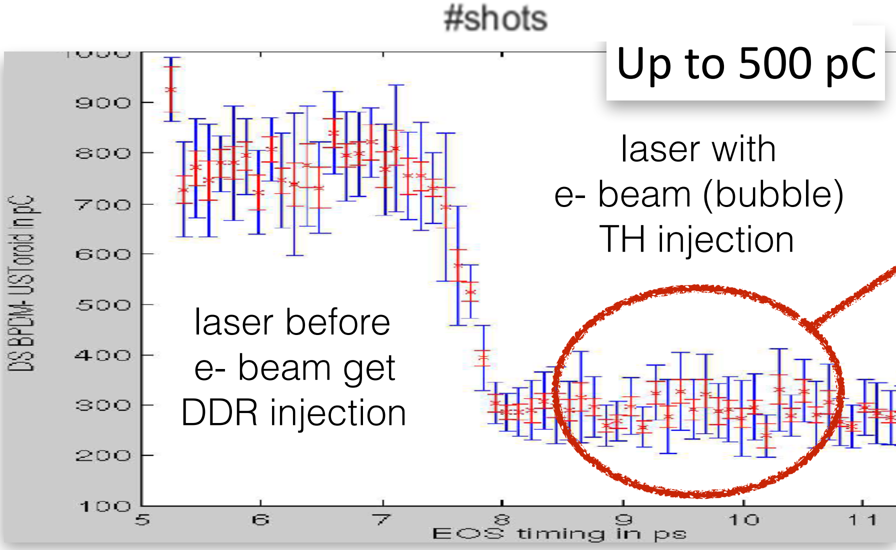

## Plasma Photoinjectors

- 100 GeV/m
- fs beams, µm size
- Promise orders of magnitude improvement in emittance
- Injection from: TH, Ionization, DDR, CP…

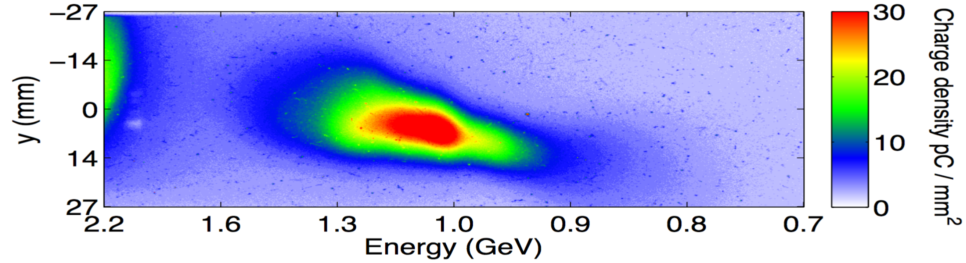
# Experimental Data from Trojan Horse Injection Experiment

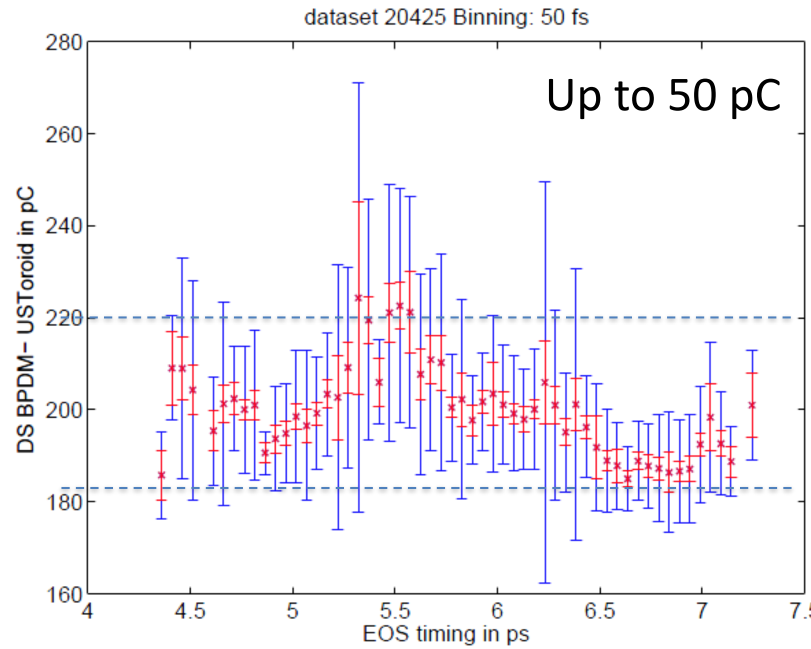
## Laser Triggered Charge

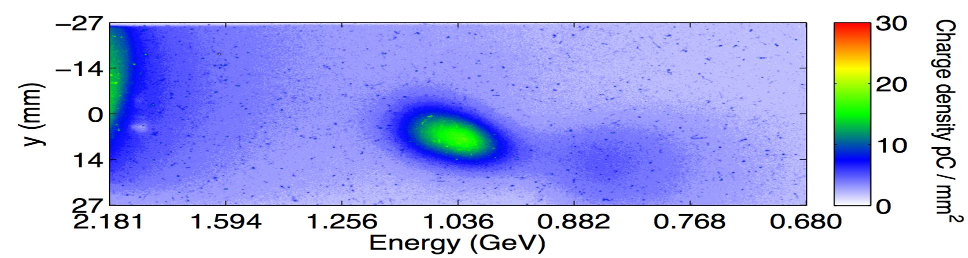



## Up to 4 GeV measured



# International Facilities Studying PWFA Are Coming Online Now and In Near Future

SLAC

EuroNNAC, DESY:

- Fully funded horizon 2020 proposal Eupraxia "European Plasma Research Accelerator with eXcellene In Applications"

CERN

- AWAKE Proton Driven Plasma

DESY

- The FLASHForward Project

INFN

- SPARC_LAB

Helmholtz VI, EAAC Workshops…

BNL

- ATF & ATF-II

# FLASHFORWARD▸▸

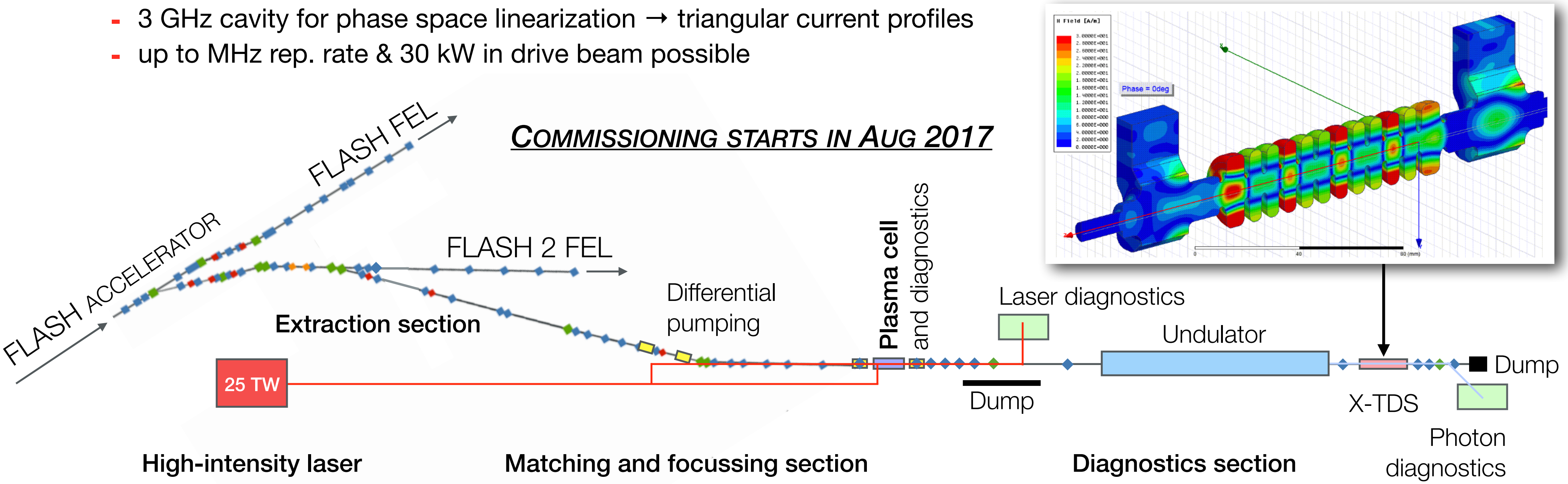
## FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

- ***a next-generation experiment for beam-driven plasma wakefield accelerator research***
- an extension beam line to the FLASH 1.25 GeV SCRF 1.3 GHz FEL facility
  → ~1 µm norm. emittance, ≲1 nC bunch charge, tunable few-fs to ps bunch duration
- to be operated simultaneously with FLASH FEL user facility
- facility goodies:
  - windowless steady-state-flow plasma target supporting $H_2$, $N_2$, and noble gases
  - X-band deflector post-plasma with ~1 fs resolution
  - 3 GHz cavity for phase space linearization → triangular current profiles
  - up to MHz rep. rate & 30 kW in drive beam possible

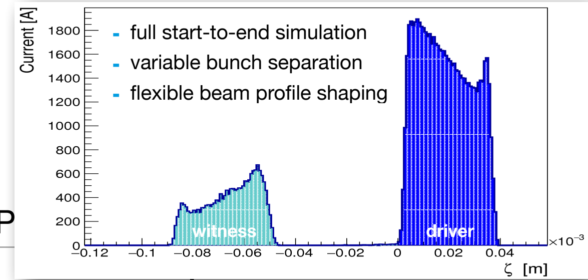
**Project lead:**
Jens Osterhoff (DESY)

**Scientific coordinator:**
Richard D'Arcy (DESY)

<u>*COMMISSIONING STARTS IN AUG 2017*</u>



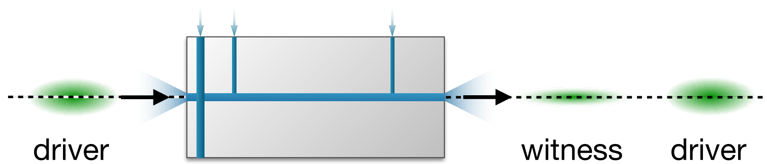
# FLASHForward▸▸ experiments




FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOP

## PHASE I FOCUS (2017 - 2020)

### X-1: PLASMA CATHODE FOR HIGH-BRIGHTNESS BEAMS

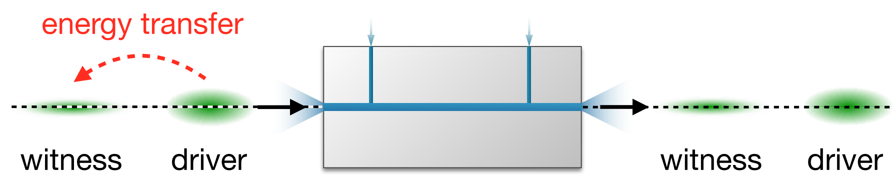



**GOALS:**

- > 1 GeV energy gain of in-plasma injected beams
- transverse normalized beam emittance ~100 nm
- peak current ≳ 1 kA
- femtosecond bunch duration

**> Beam generation for photon science applications**

### X-2: PLASMA BOOSTER AND BEAM-QUALITY CONSERVATION




**GOALS:**

- > 1 GeV energy gain of externally injected beam
- conserve initial beam energy spread
- conserve initial beam normalized transverse emittance
- deplete drive beam energy
- 10% energy extraction efficiency from drive to witness

**> Stage towards high-energy physics applications**

## PHASE II FOCUS (2020+)

**X-100: FEL-GAIN DEMONSTRATION**

+ [in PHASE I] X-10: Transformer ratio optimization, X-11: Hosing mitigation*, X-12: High rep.-rate operation, and many more. (incl. fs-resolution long. phase-space measurements, active plasma lens development, transverse plasma-wake imaging, ...)

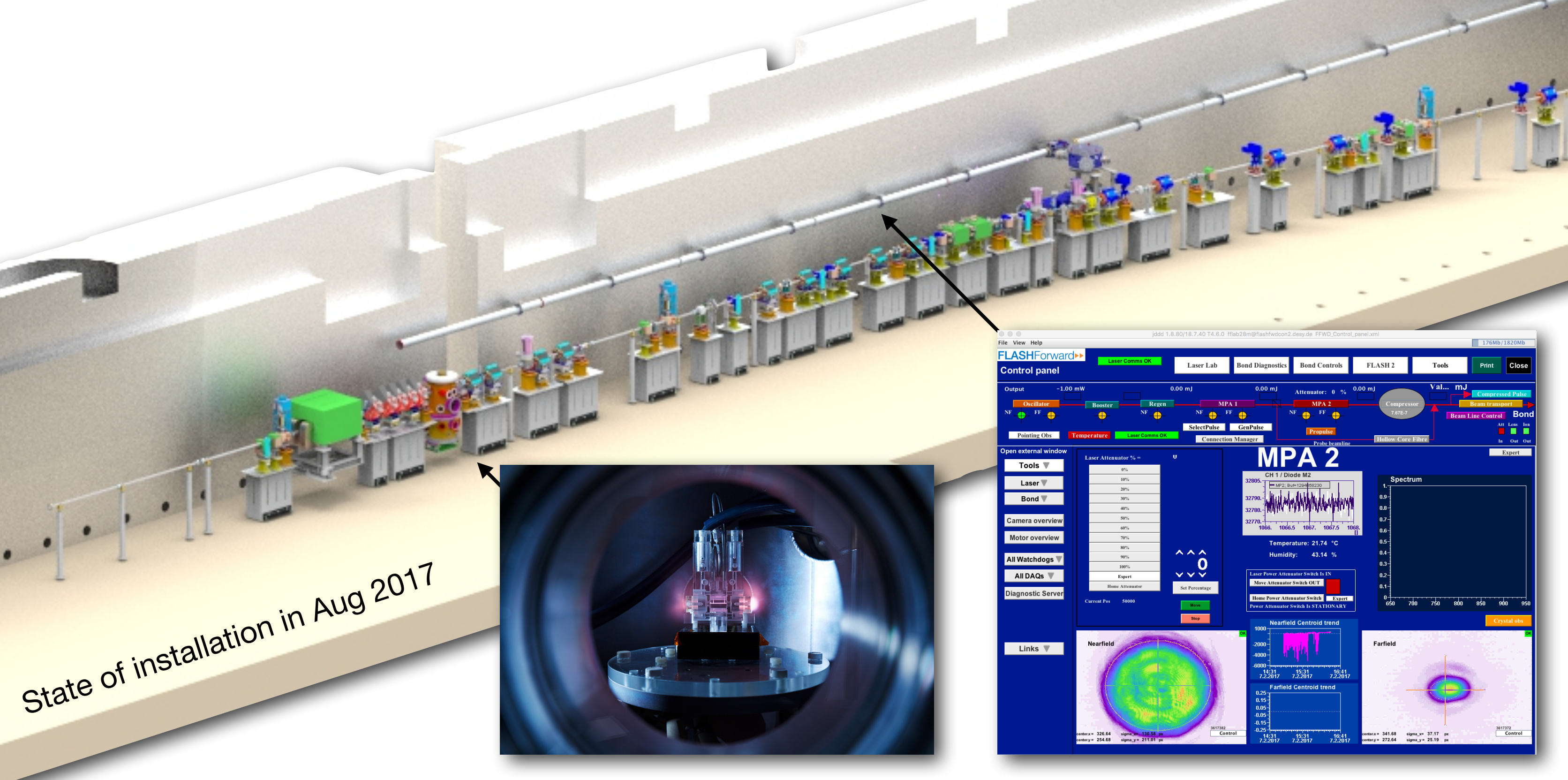
* T.Mehrling *et al.*, accepted for publication in Phys. Rev. Lett. (2017)

# FLASHFORWARD▸▸ into the future

## FUTURE-ORIENTED WAKEFIELD ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

HELMHOLTZ ASSOCIATION
VIRTUAL INSTITUTE
VH-VI-503

- Experimental access through open collaboration structure
- Call for proposals will be announced once facility in operation → stay tuned!




- 25 TW laser in operation since 2015
- plasma target and lens tests ongoing
- first PWFA experiments foreseen for 2017
- X-TCAV to be added in 2018
- undulator in 2020

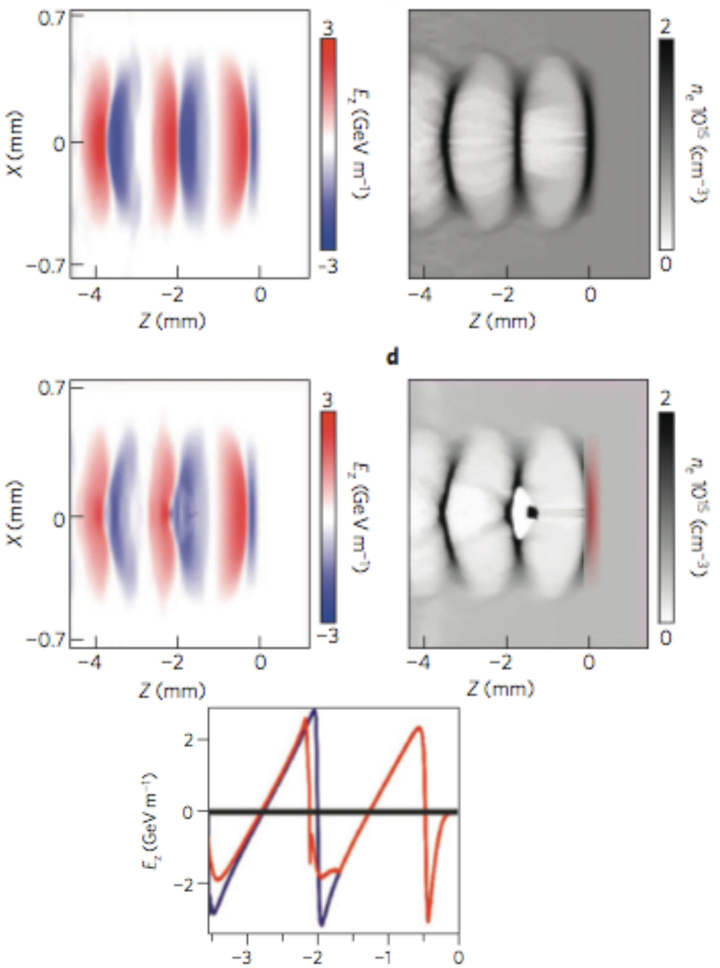
**>** For more info, get in touch with Jens Osterhoff (jens.osterhoff@desy.de) or subscribe through Twitter @FForwardDESY

# AWAKE Collaboration Will Study Proton Driven 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]

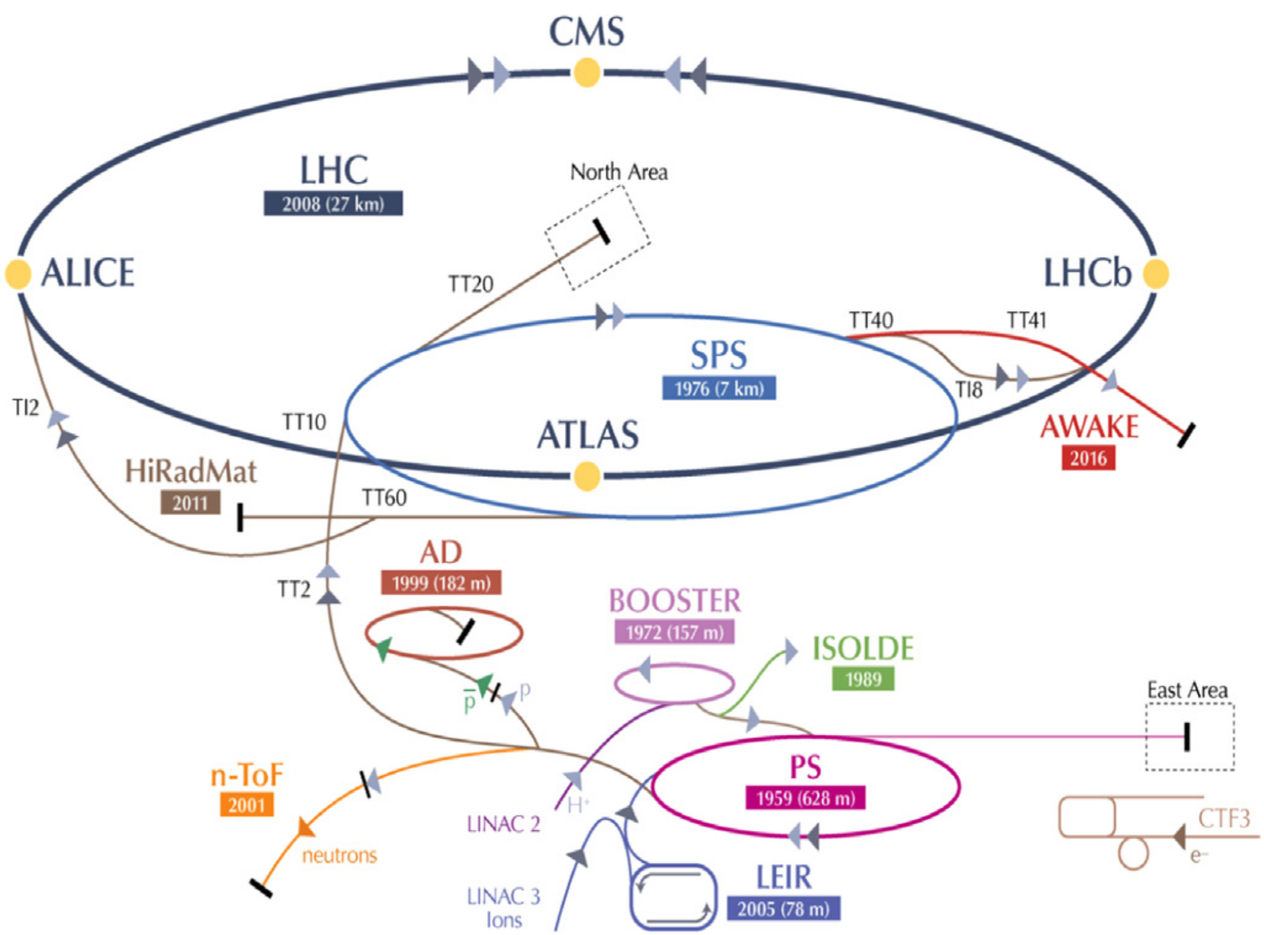



Idea to Harness the Large Stored Energy in Proton Bunches to make High Energy Electrons

### Goals of the AWAKE Collaboration:

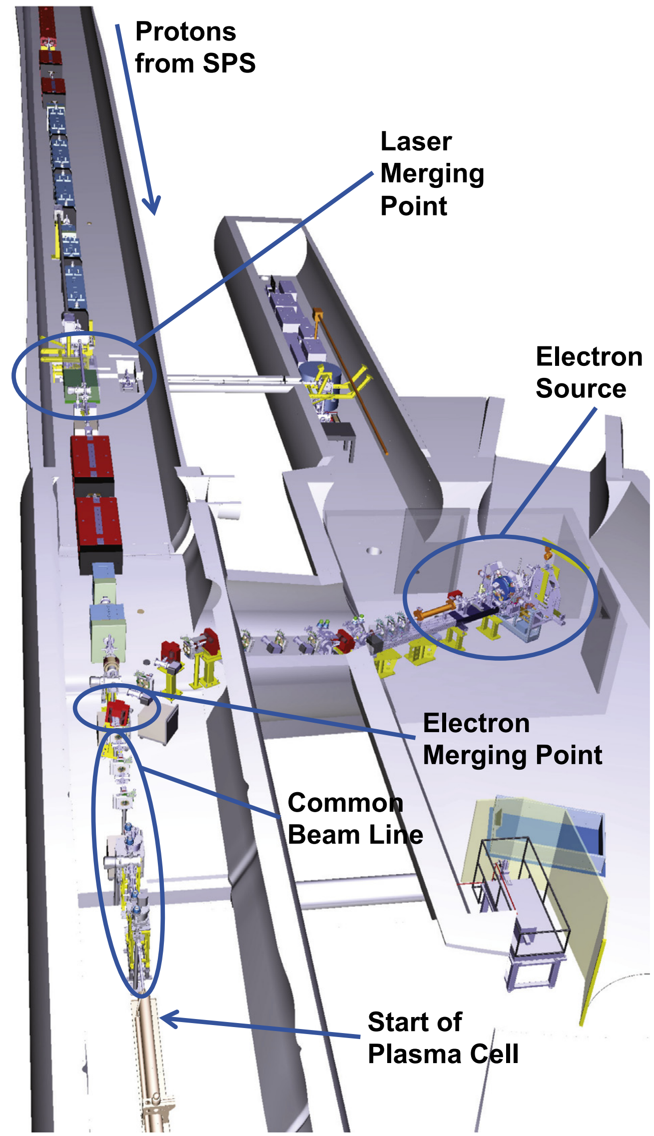
- >500 GeV e- in single long plasma cell (400m)!
- Requires short proton bunches (100µm vs 10 cm)
- Study physics of self-modulation of long p bunches
- Probe wakefields with externally injected e-
- Study injection dynamics for multi-GeV e-
- Develop long, scalable and uniform plasma cells
- Develop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

# The AWAKE Experiment at CERN




CERN Accelerator Complex

AWAKE Experimental Area

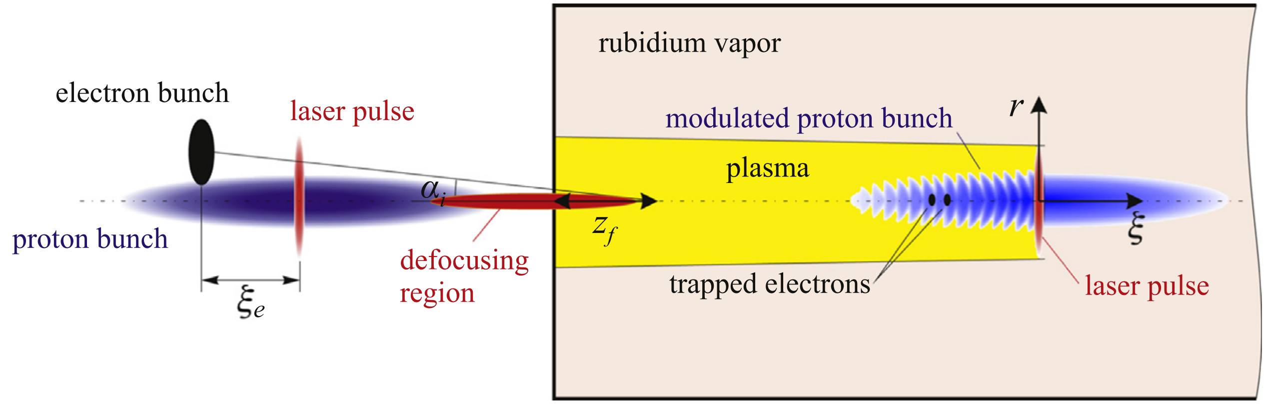


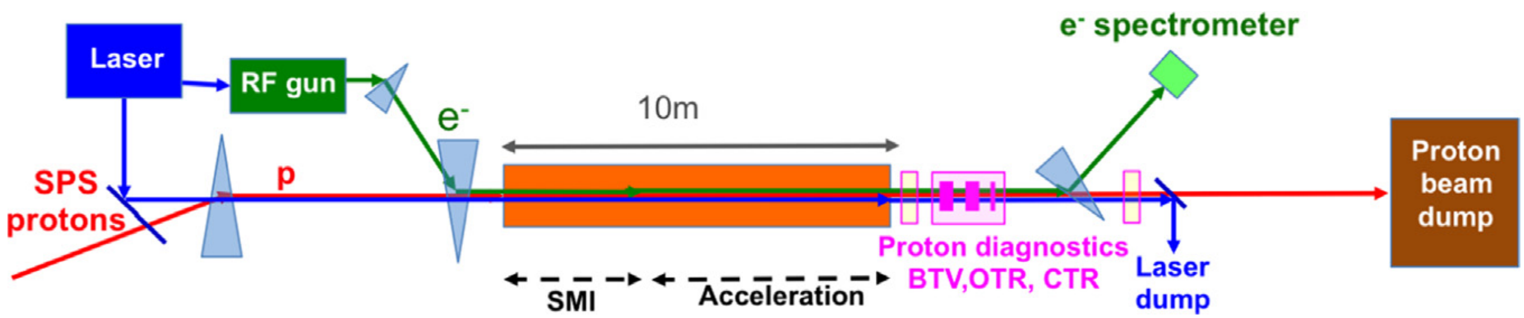
E. Gschwendtner et al. *N.I.M. A* 829 (2016)

# The AWAKE Experiment at CERN

Run1:

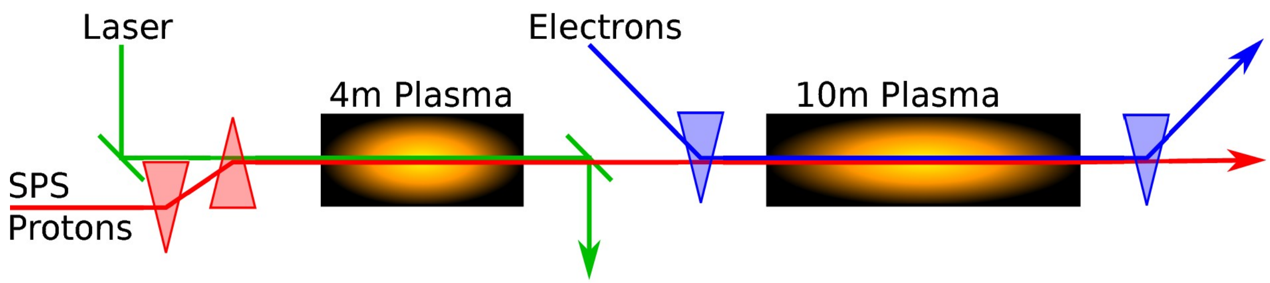
- 2016: SMI of long proton bunches in plasma
- 2017-2018: Externally injected long electron bunches




Run2 (after long LHC shutdown):

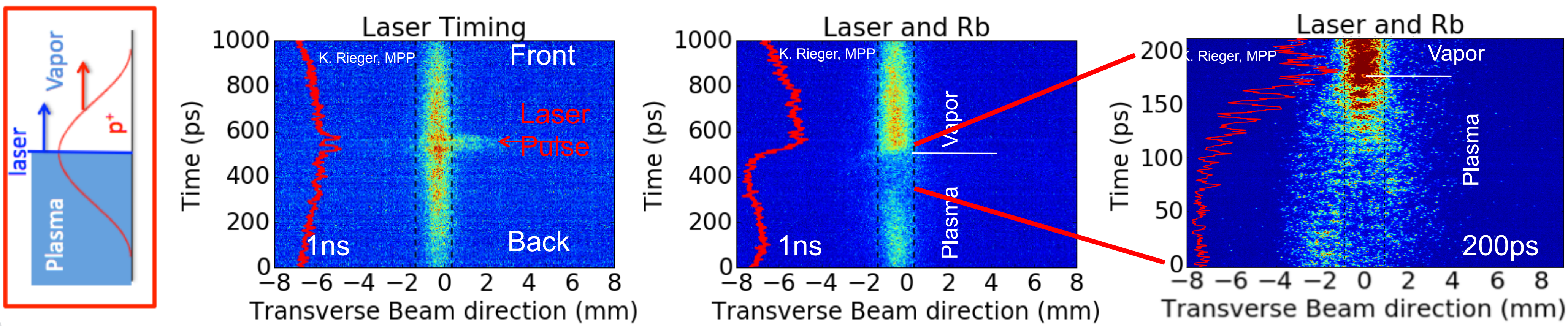
- Short e- bunches in wake of pre-modulated p bunch




*Proposed setup for AWAKE Run 2.*

# The AWAKE Experiment at CERN

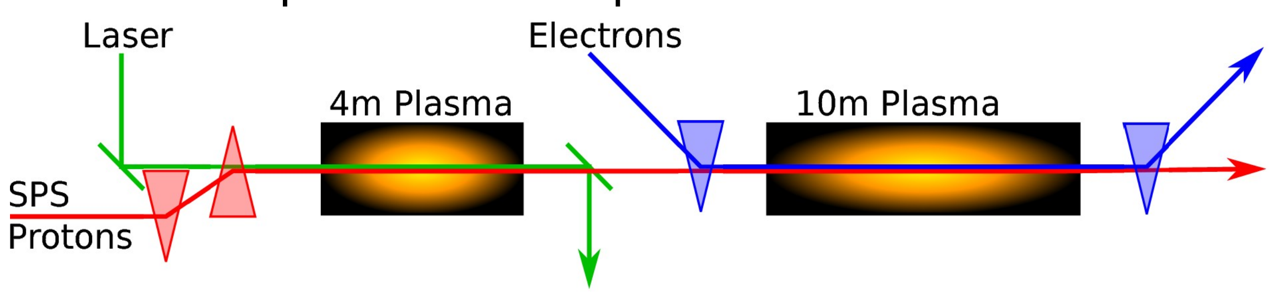
## Streak camera Images from Run 1!




*Courtesy of P. Muggli & K. Rieger, MPP*


Run2 (after long LHC shutdown):

- Short e- bunches in wake of pre-modulated p bunch

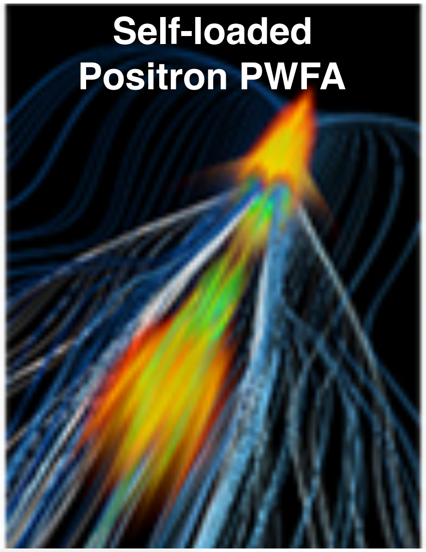


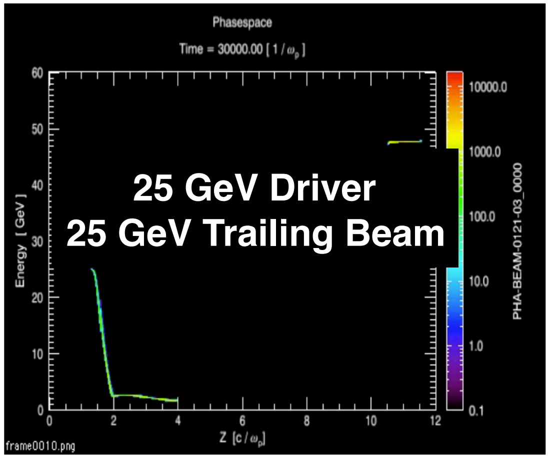

*Proposed setup for AWAKE Run 2.*

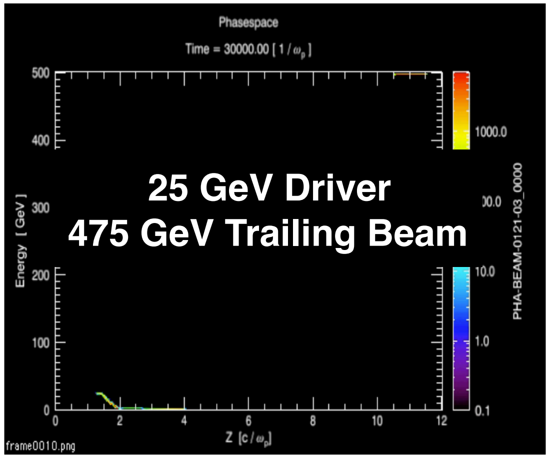
# Computation Has Been Essential Component of PWFA Science

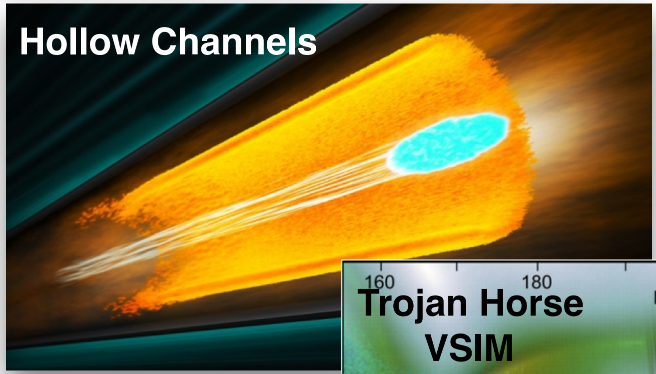
UCLA SLAC

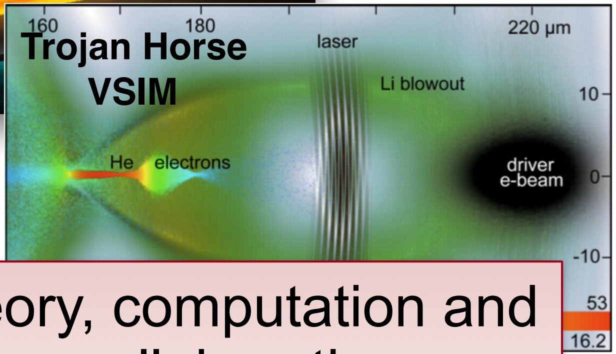
- QuickPIC, OSIRIS have been benchmarked against experiments at SLAC for the last 18 years
- Next generation e- & e+ experiments, plasma injectors, concepts using these beams, PWFA-LC studies…

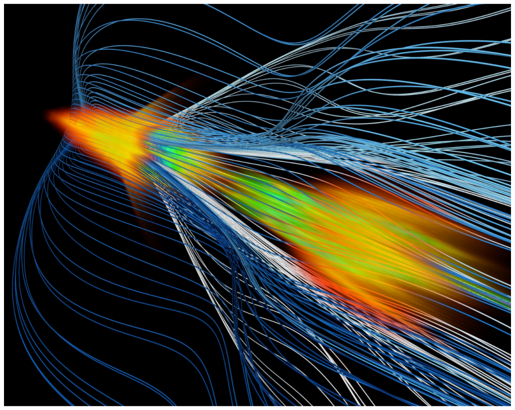



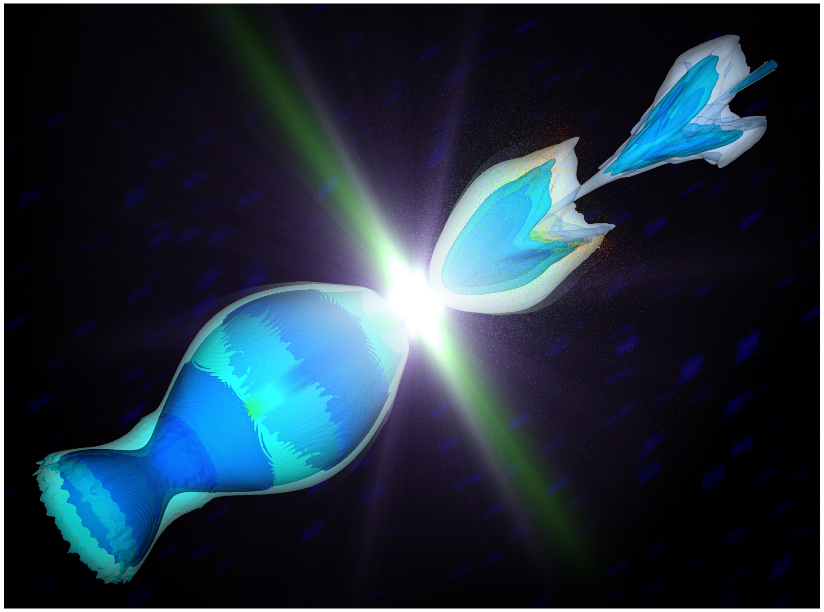

FFTB & FACET enjoyed strong connection between theory, computation and experiment – every major result benefited from strong collaborations

# 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



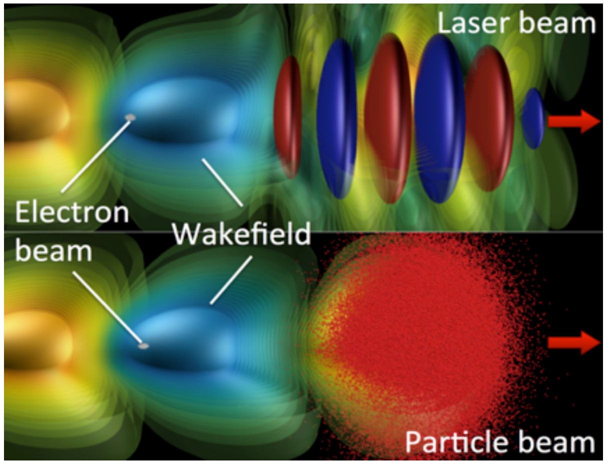
Another good opportunity to work together to develop common tools

# Exascale Computing to Support Detailed Collider Design

SLAC

## Exascale Modeling of Advanced Particle Accelerators

ECP EXASCALE COMPUTING PROJECT
NNSA U.S. DEPARTMENT OF ENERGY Office of Science




**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

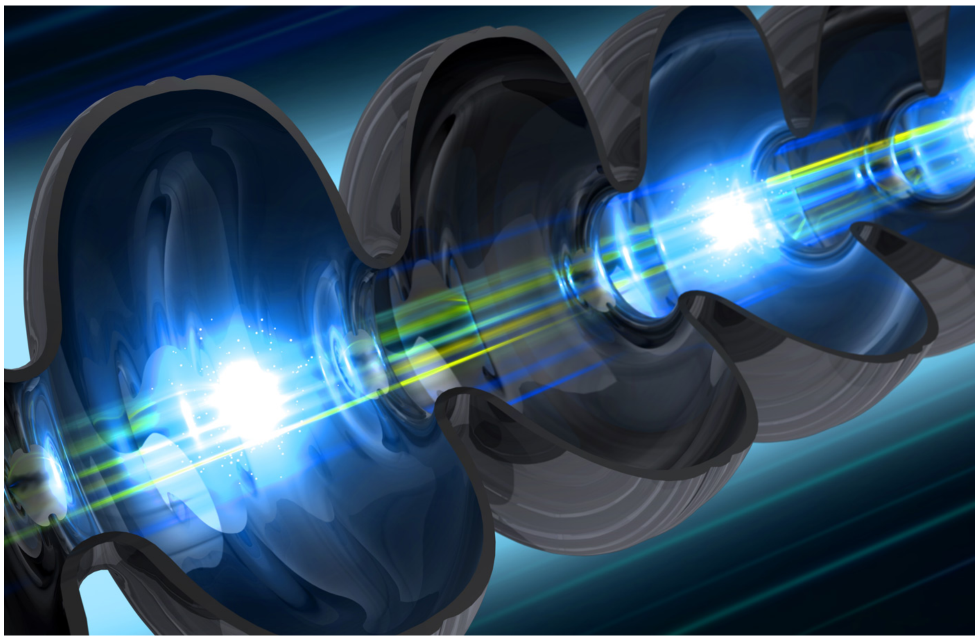
➔ Port to emerging architectures (Xeon Phi, GPU)

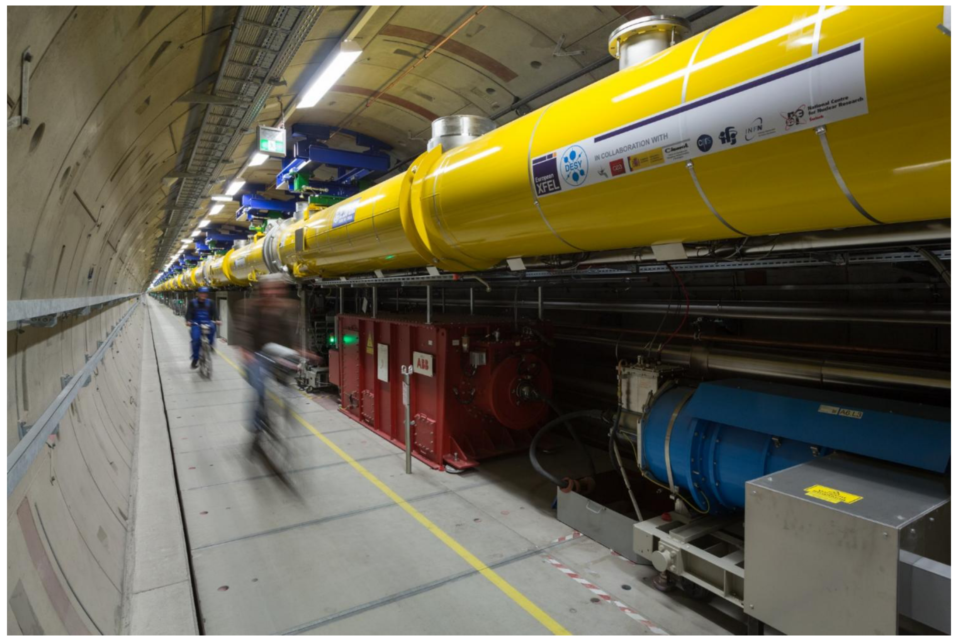
**Who:** **LBNL ATAP** (accelerators) + **LBNL CRD** (computing science) + **SLAC** + **LLNL**

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

# Drive Beam Technology

- Beam driven wakefield accelerators benefit from decades of 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

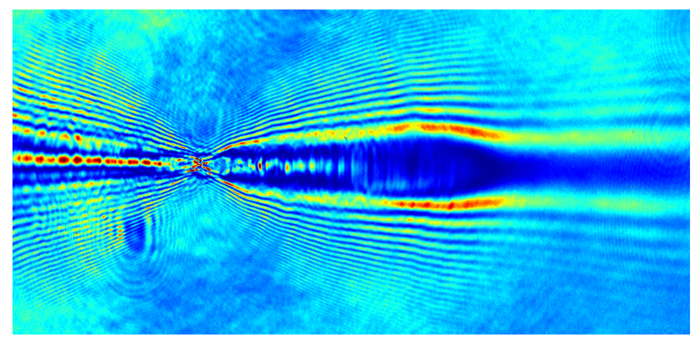
Colliders have very demanding requirements

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

# Summary

- There is tremendous optimism and tremendous progress in plasma acceleration around the world
- There is a healthy mix of competition and collaboration
- Need larger projects AND smaller R&D – "can't connect the dots looking forward"
- Plenty of room for new ideas (positrons, ultra-dense beams, kHz rep rates...)
- Need a bridge application on the way to HEP, likely photon science, maybe plasma based XFEL
- Stability, reliability won't get you the cover of Nature but they are crucial to a user facility so likely developed close to one
- Combine compelling scientific questions, University-Lab collaborations, and state of the art facilities and experienced experimentalists, powerful scientific apparatus and rapid scientific progress follow naturally from these three

***Thank you to all my colleagues who contributed material for this talk!***