FACET-II Facility for Advanced Accelerator Experimental Tests

# Cross Cutting Connections of ABP with Plasma Acceleration


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*With input from*

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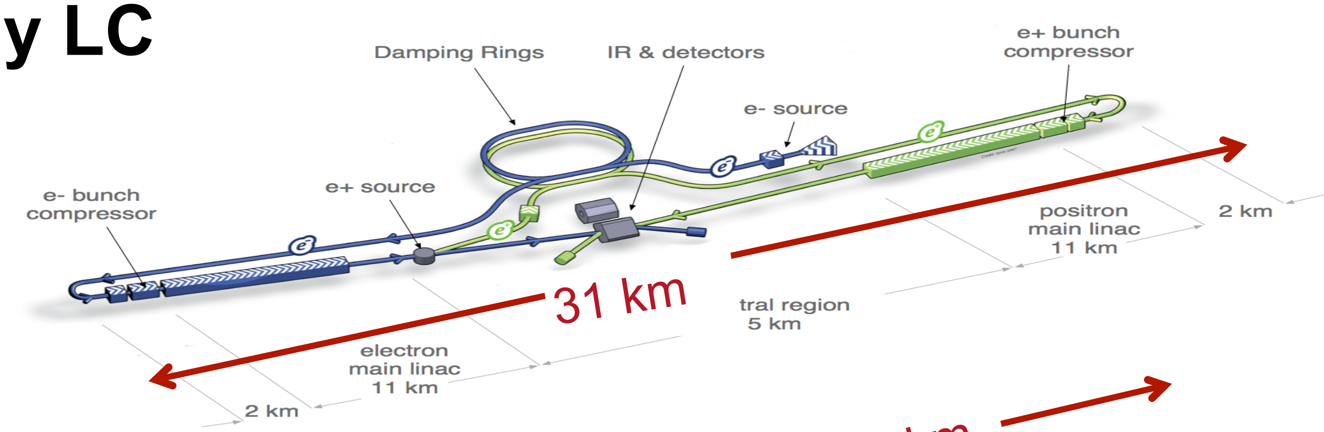
December 10, 2019


U.S. DEPARTMENT OF ENERGY Office of Science

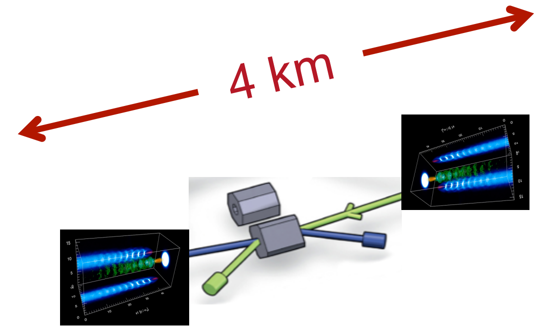
SLAC NATIONAL ACCELERATOR LABORATORY

# The Scale for a TeV Linear Collider

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




**Plasma Accelerator Technology LC:**




➔ GeV/m accelerating gradient

**The Luminosity Challenge:**

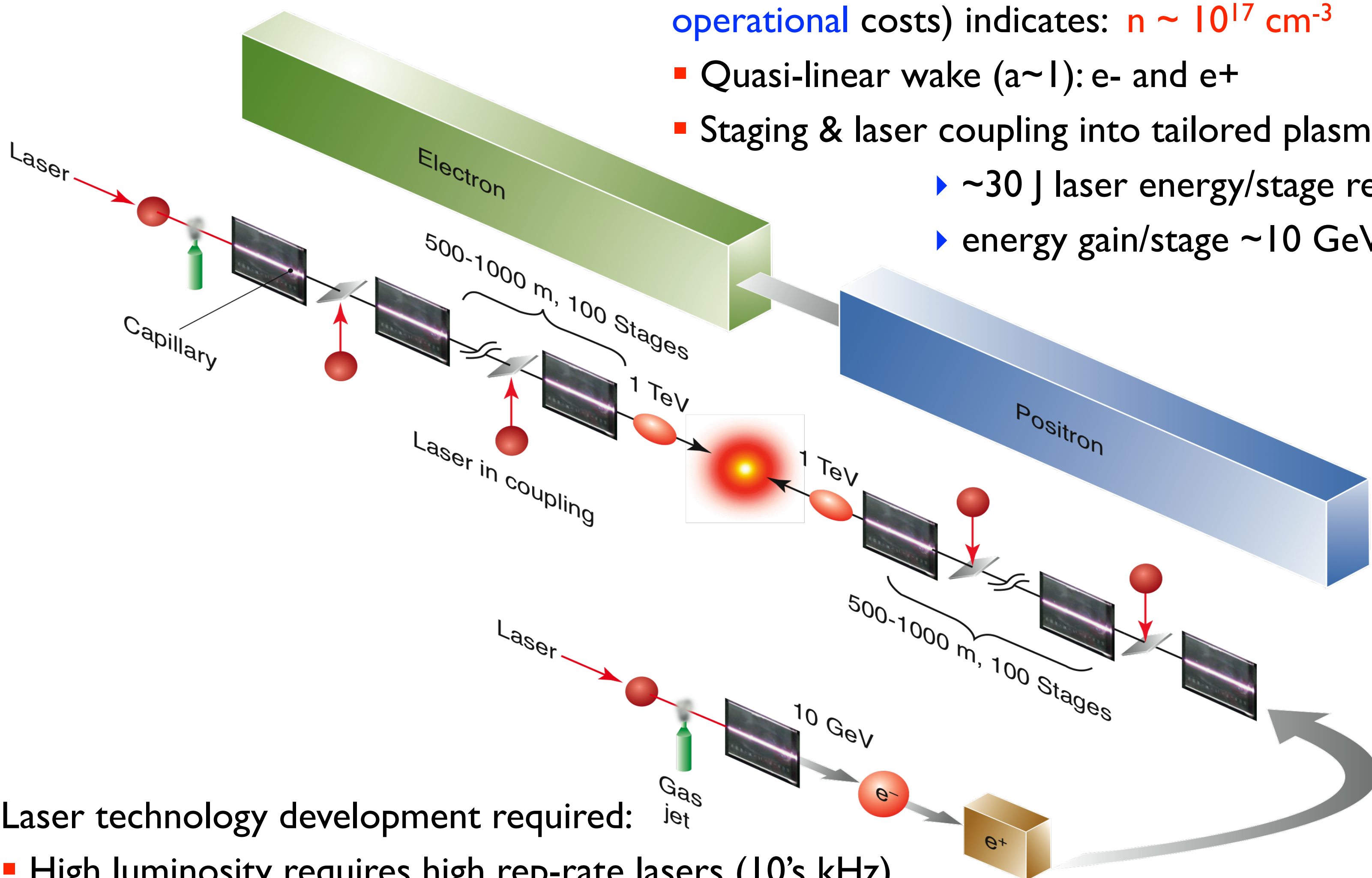
$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)$$

➔ High-efficiency

…and must do it for positrons too!

# Laser-plasma Accelerator Based Collider Concept

Leemans & Esarey, Physics Today (2009)




- Plasma density scalings (minimize construction and operational costs) indicates: n ~ $10^{17}$ $cm^{-3}$
- Quasi-linear wake (a~1): e- and e+
- Staging & laser coupling into tailored plasma channels:
  - ~30 J laser energy/stage required
  - energy gain/stage ~10 GeV in ~1m

Laser technology development required:

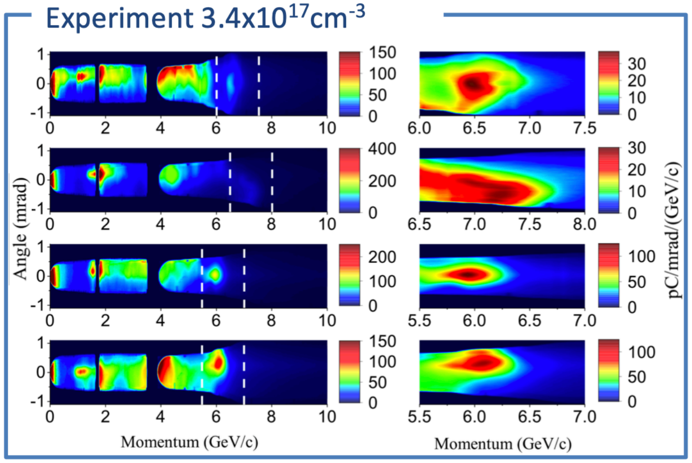
- High luminosity requires high rep-rate lasers (10's kHz)
- Requires development of high average power lasers (100's kW)
- High laser efficiency (~tens of %)

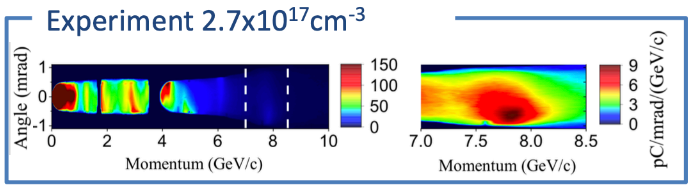
# State of the Art:
# BELLA Laser at Lawrence Berkeley Lab (LBNL)

BERKELEY LAB
Lawrence Berkeley National Laboratory

## Petawatt laser at 1Hz (40J/40fs)

State of the art: 8GeV, 10-100pC, <10% Efficiency, 1-10% dE/E, ~mm-mrad emitt.

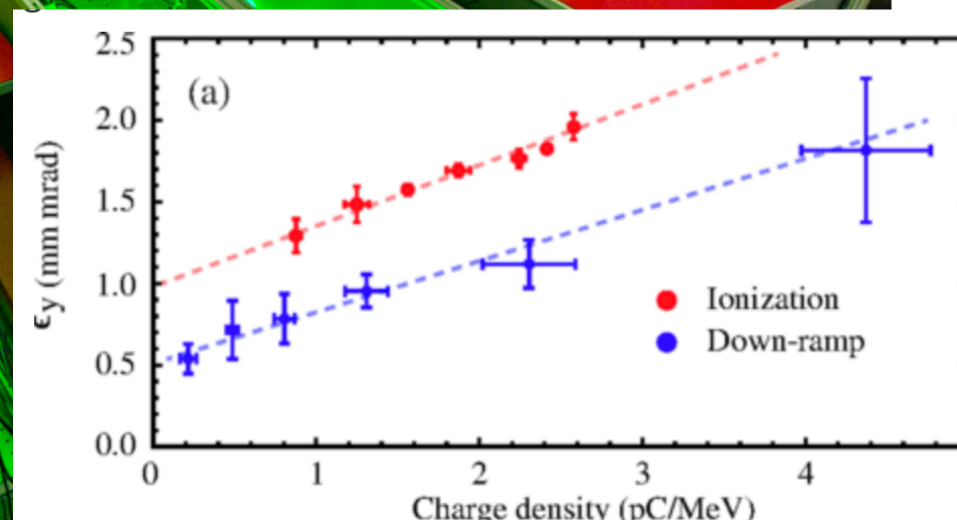



- Non-localized injection produces large energy spread
- Up to 60pC (of >200pC) in 6 GeV peaks
- Highest energy bunches dE/E~10%
- 0.5-1 joule energy in e beam

A. J. Gonsalves et al.. "Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide" Phys. Rev. Lett. **122**, 084801 (2019)

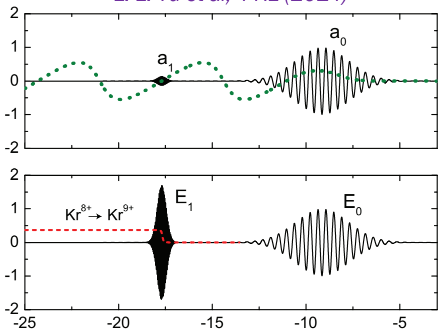
S. Barber et al.. "Measured Emittance Dependence on the Injection Method in Laser Plasma Accelerators" Phys. Rev. Lett. 119, 104801 (2017)

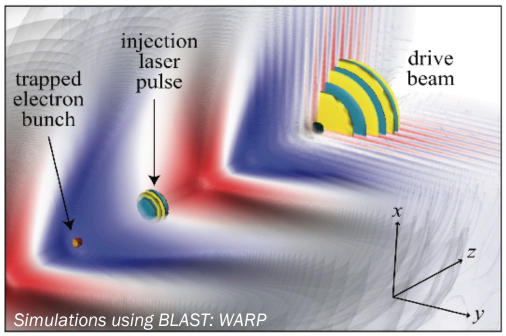


# Next Steps in LWFA

- Compact multi-GeV LWFA staging with 100% capture
- Laser-triggered injection for high brightness electron beam generation

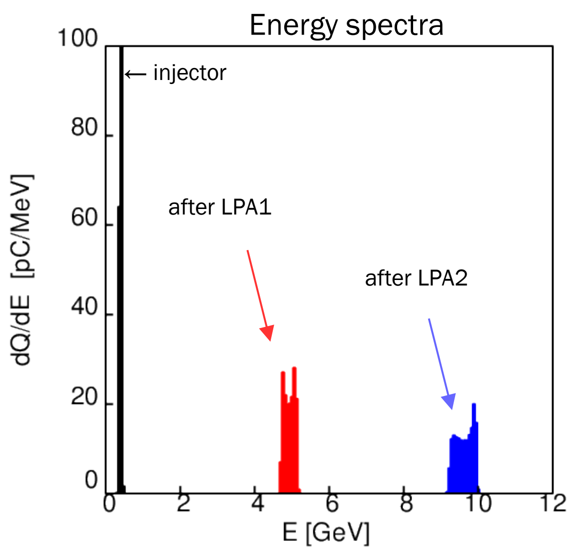
*L.-L. Yu et al, PRL (2014)*



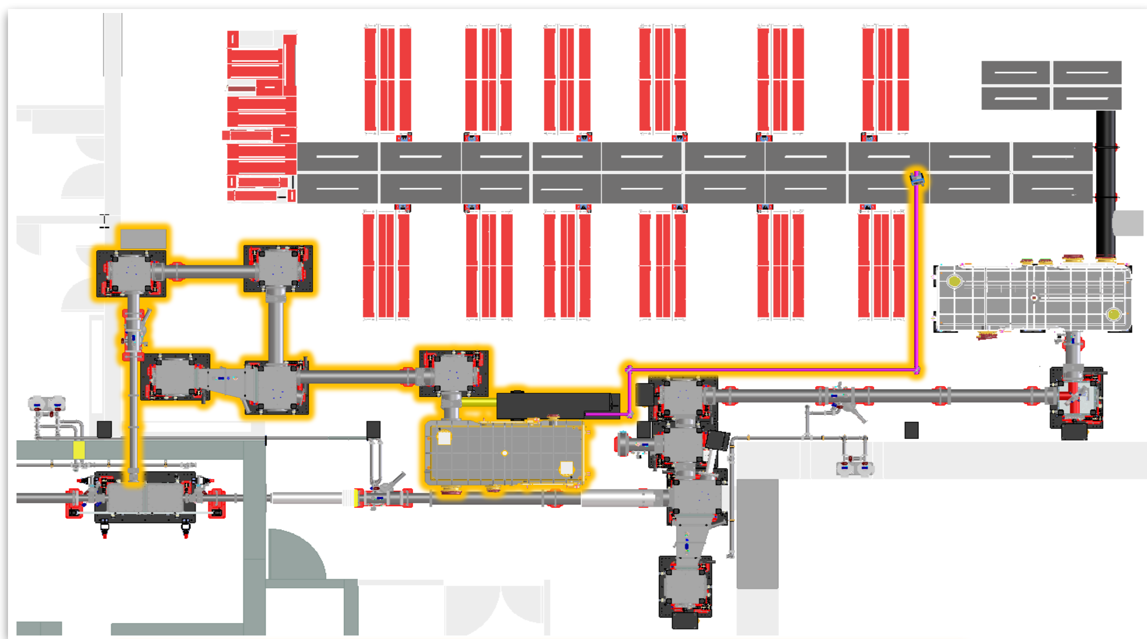




L.-L. Yu et al., "Two-Color Laser-Ionization Injection", Phys. Rev. Lett. 112, 125001 (2014)

S. Steinke et al., "Staging of laser-plasma accelerators" Physics of Plasmas **23**, 056705 (2016)




**BELLA 2nd Beamline – Installation 2020:**



**Longer term – kHz rep rate @ kBELLA**

# Beam Driven Plasma Accelerator Based Collider Concepts

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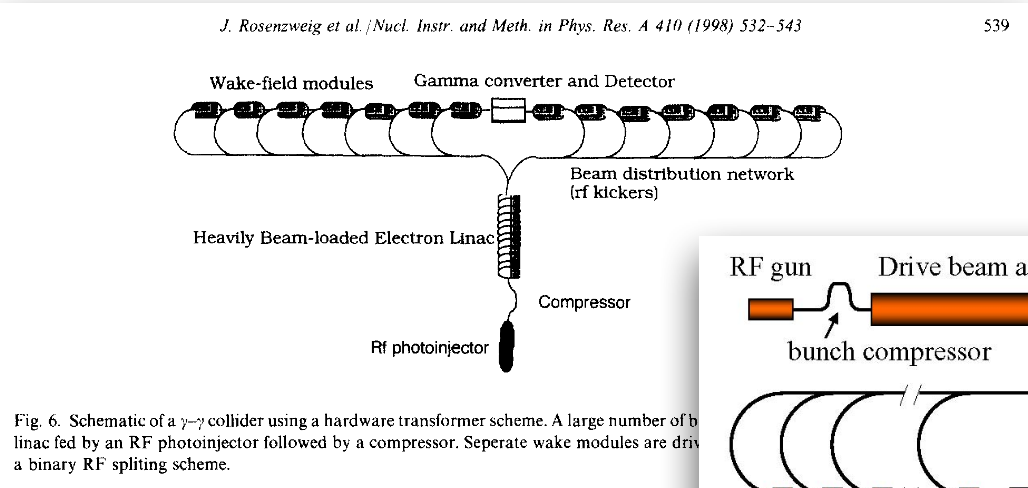
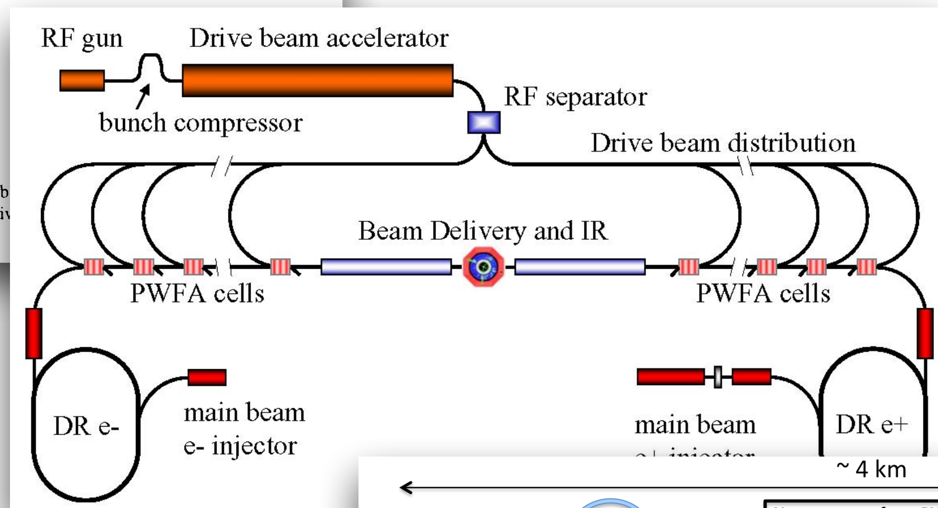
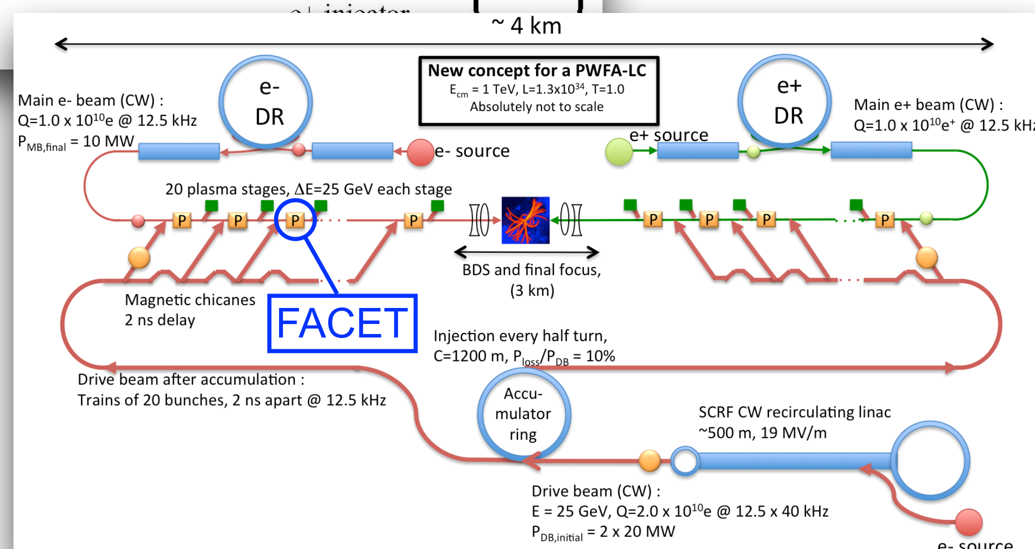



Rosenzweig *et al* (1998)




Seryi *et al* (2008)




Adli *et al* (2013)

- Assume SLC/NLC/ILC/CLIC made smart choices that we can start from for main beam and driver
- Focus on the accelerator module itself (the plasma)
- For luminosity – Power efficiency and beam quality are critical!

# State of the Art:
# E-200/E-210 Experiments @ FACET National User Facility

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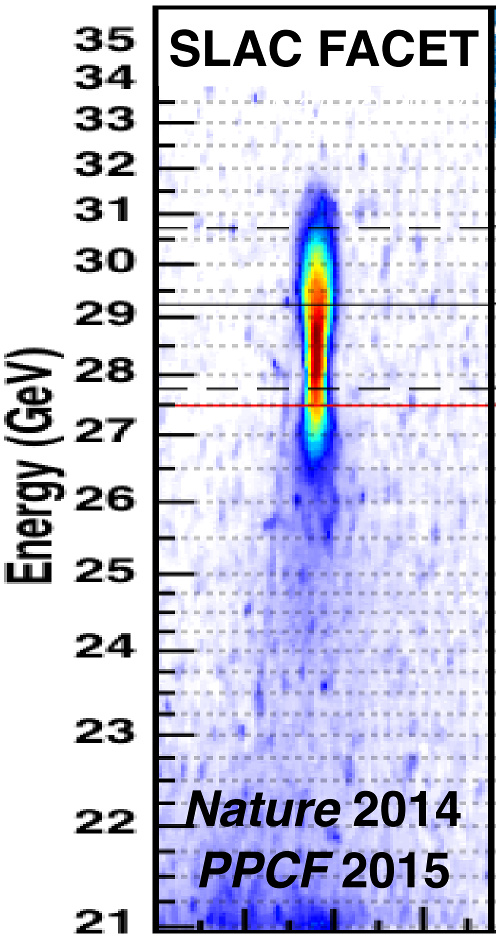
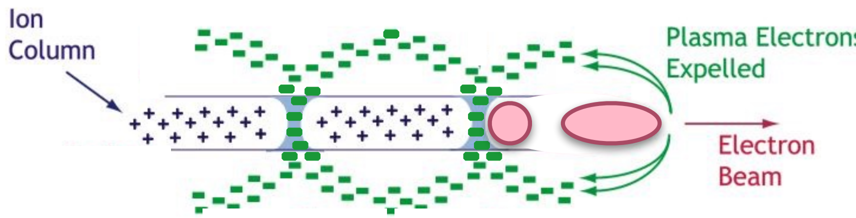
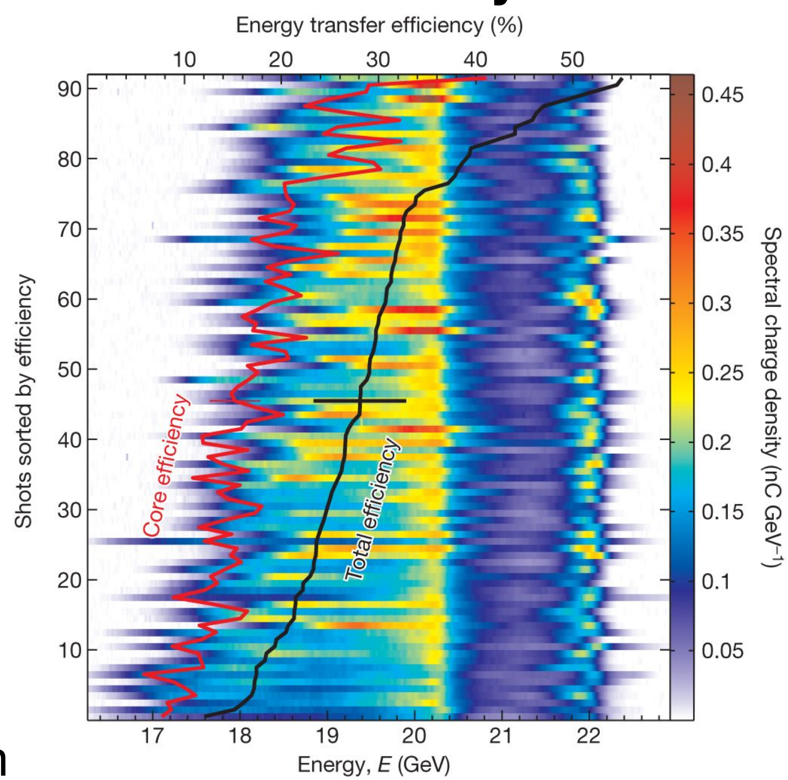
**Energy**



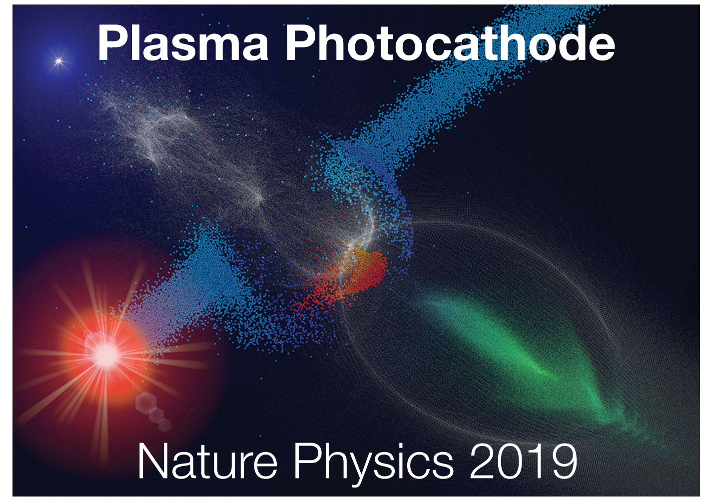

9 GeV
Energy Gain in 1.3m

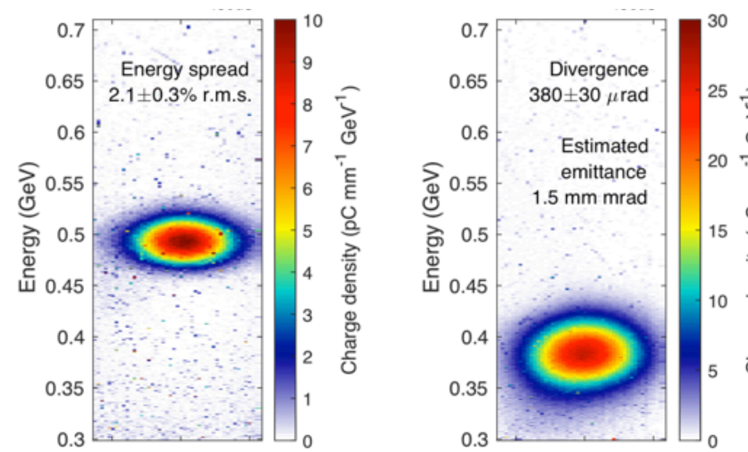



**Efficiency**




**Injection**



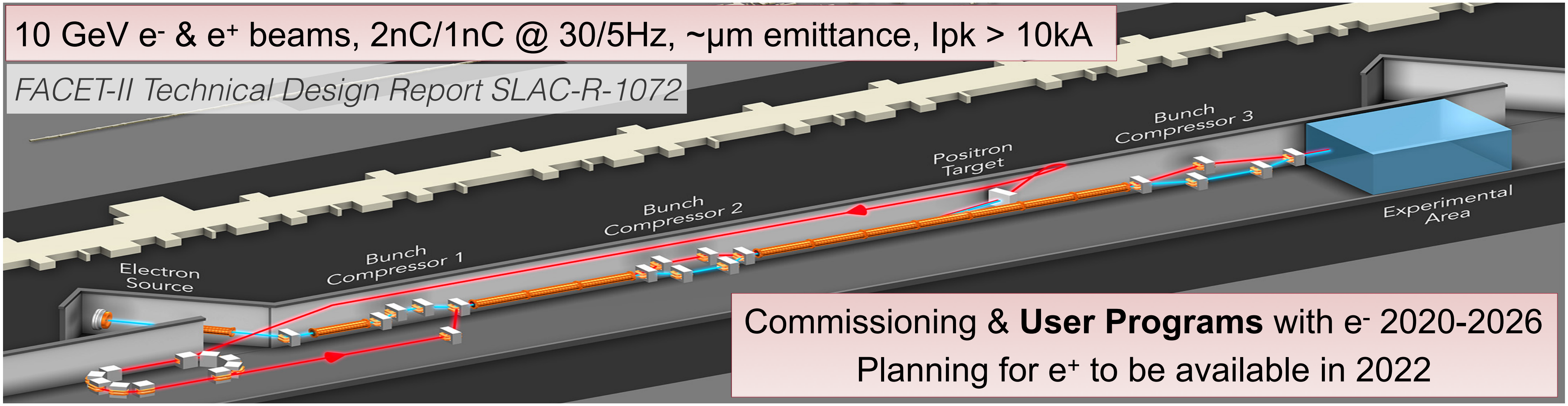

9GeV, ~30% instantaneous efficiency, 2% dE/E, ~100μm emittance.
Deflection and betatron motion have been observed but never observed hosing

*C Joshi et al 2018 Plasma Phys. Control. Fusion 60 034001*

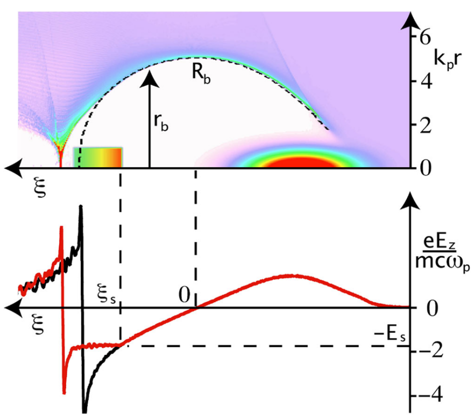
# Next Steps in PWFA: Simultaneously achieve pump depletion, high-efficiency, narrow energy spread and preserved emittance

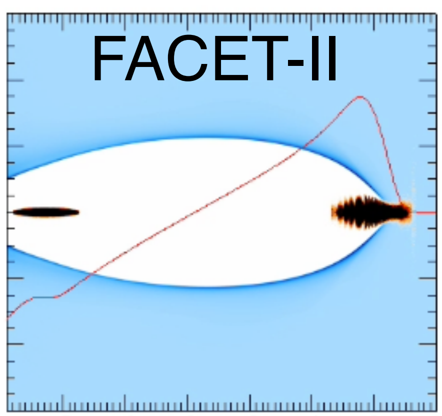
10 GeV e⁻ & e⁺ beams, 2nC/1nC @ 30/5Hz, ~μm emittance, Ipk > 10kA

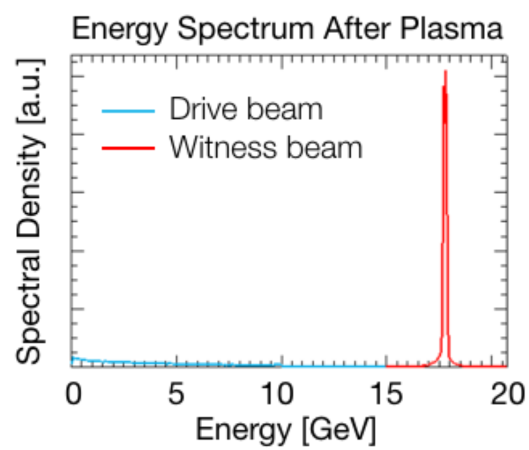
*FACET-II Technical Design Report SLAC-R-1072*




Commissioning & **User Programs** with e⁻ 2020-2026
Planning for e⁺ to be available in 2022



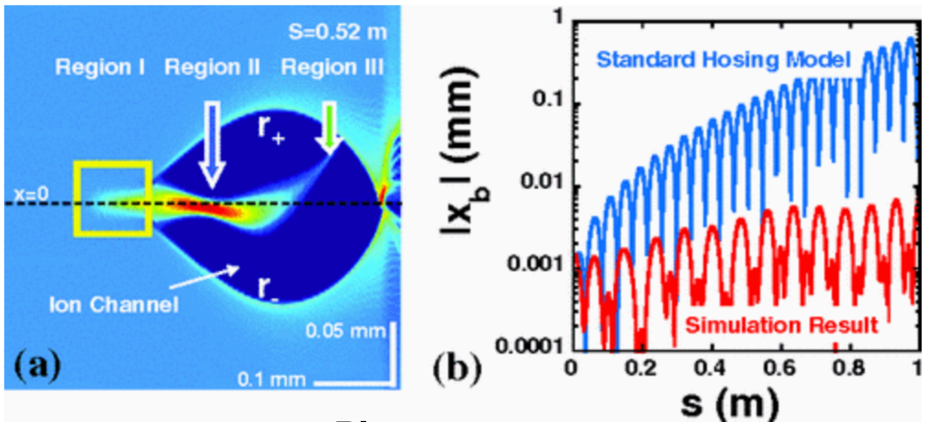

Photoinjector for ~mm-mrad emittance and plasma injectors longer term as proxy for DR level emittance beams

$$\eta_t \approx \frac{\eta_P^{\,2}}{4\left(1-\eta_P\right)}, \qquad \frac{r_{t2}}{R_b} \le 0.7$$

Answer the question: Is it possible to strongly load the longitudinal wake without strong transverse wakes and BBU?

*See: M. Tzoufras et al, Phys. Plasmas* ***16****, 056705 (2009); W. Lu et al., Phys. Rev. Lett.* ***96****, 165002 (2006), V. Lebedev et al., PRST-AB 20, 121301 (2017) and References therein*

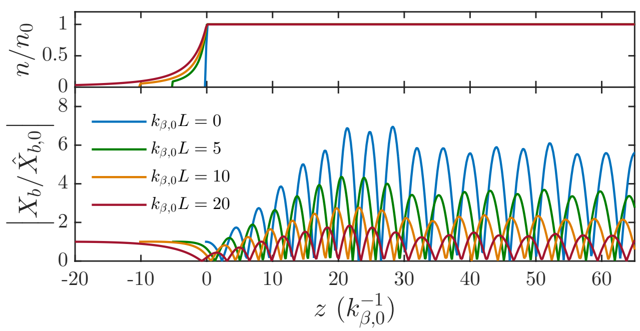
# E-302: Transverse Wakefields and Instabilities in Plasma Wakefield Accelerators (physics common for accelerated beams)




Many **mechanisms of emittance growth** have been put forward, e.g. ion motion, hosing…

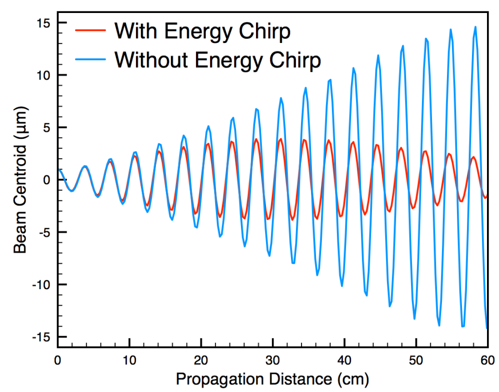
D. Whittum et al. PRL 67, 991 (1991) **LBNL/SLAC**
J. Rosenzweig et al., 95, 195002 (2005) **UCLA**
C. Huang et al., PRL 99, 255001 (2007) **UCLA**
V. Lebedev et al., PRST-AB 20, 121301 (2017) **FNAL**

**Plamsa ramps**

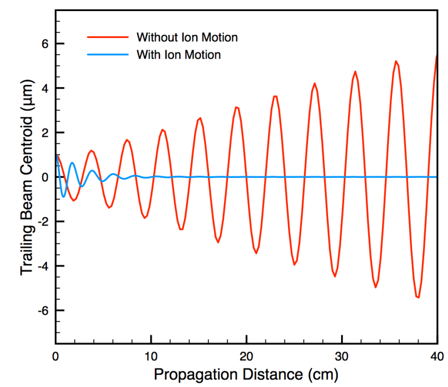



T. Mehrling et. al., PRL 118, 174801 (2017) **DESY/IST**
T. Mehrling et. al., PRL 121, 264802 (2018) **LBNL**

**Energy Spread**

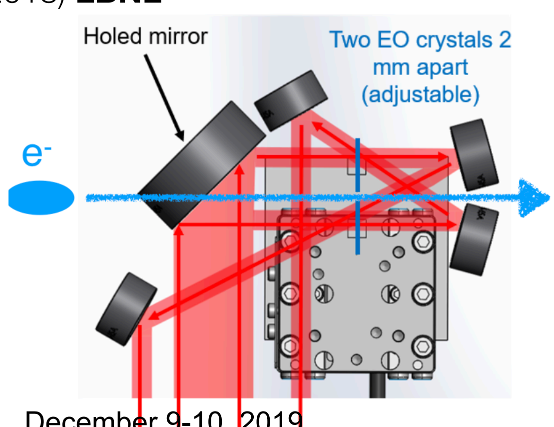



**Ion Motion**




W. An et al. PRL 118, 244801 (2017) **UCLA**
A. Burov et al., arXiv:1808.03860 **FNAL**

Benchmark theoretical and numerical predictions and testing mitigations will be an important part of upcoming experimental programs




Note – requires generations of new diagnostics capable of characterizing individual bunches with μm position and fs resolution, slice emittance etc..

# Accelerator Physics Topics in An AAC-based Linear Collider

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Acceleration issues

- Beam loading for efficiency and % level energy spread
- Longitudinal beam shaping to maximize transformer ratio (minimize number of stages)
- Transverse shaping for quasi-linear regime or positrons
- Precise timing to provide acceleration in many sections
- Interstage optics designs to maximize average gradient
- Positron acceleration (plasma concepts) – see next slide

Emittance preservation

- CSR (and inter bunch correlation) suppression
- Section by section alignment, corrections and feedbacks
- Inter-stage focusing, dispersion control
- Applicability of plasma lenses
- Multiple Coulomb Scattering, ion motion, mismatch…
- Transverse/longitudinal drive beam jitter <1um (same reqs as for main beam)

IP: Control of head-on collision < 1 nm for single bunch

- Ground motion, vibrations (jitter in beam position)
- Flat beams collision

Technical issues:

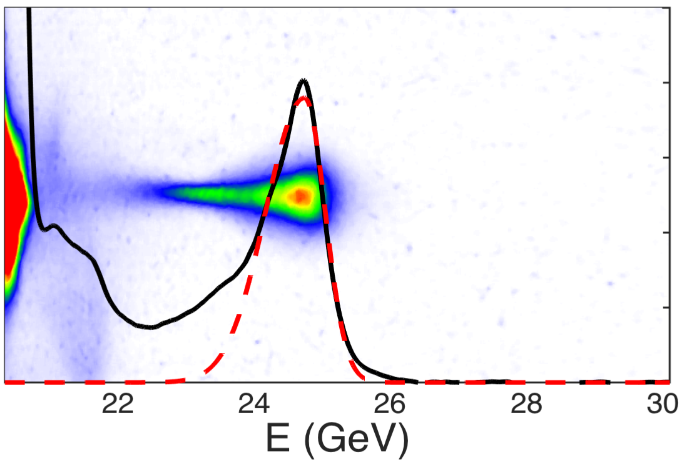
- Plasma response time and heat removal, Synchrotron Radiation and activation

More holistic view beginning to be discussed in presentations and some publications, e.g. C. Lindstrom PhD Thesis "Emittance Growth and Preservation in a plasma-based linear collider" https://www.duo.uio.no/handle/10852/66134

# FACET/FACET-II Have a Unique Role in Addressing Plasma Acceleration of Positrons for Linear Collider Applications

**Non-linear wakes** (4 GeV energy gain)

- New self-loaded regime of PWFA

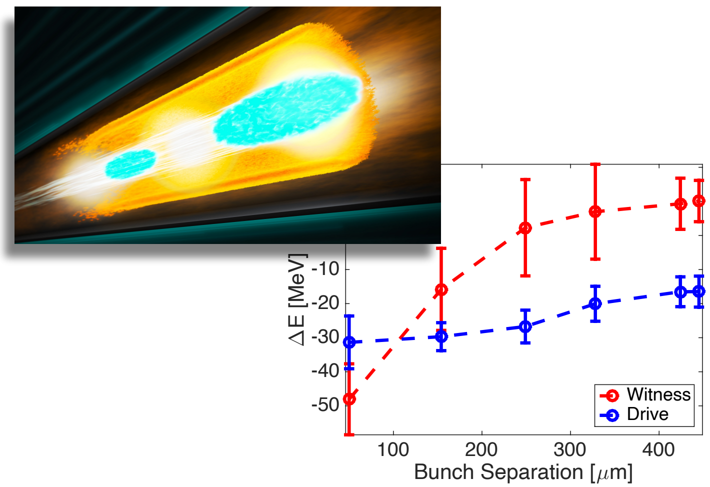



Corde et al., ***Nature*** August 2015

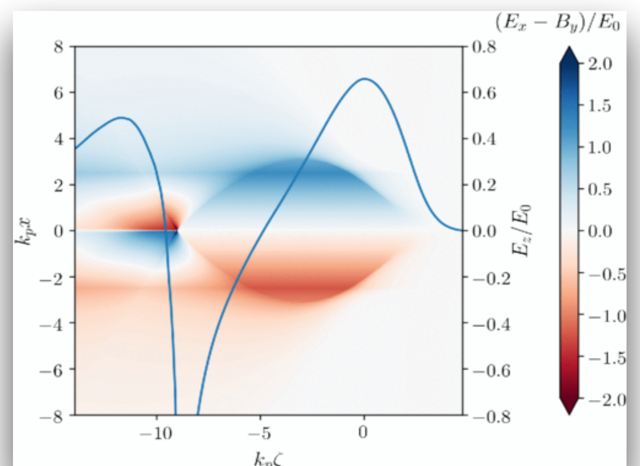
New regime for positron PWFA has been proposed

- Finite-channel plasmas are predicted to preserve emittance
- Concepts are testable at FACET-II
- LBNL, DESY and SLAC collaboration

**Hollow Channel Plasma** Wakefield Acceleration



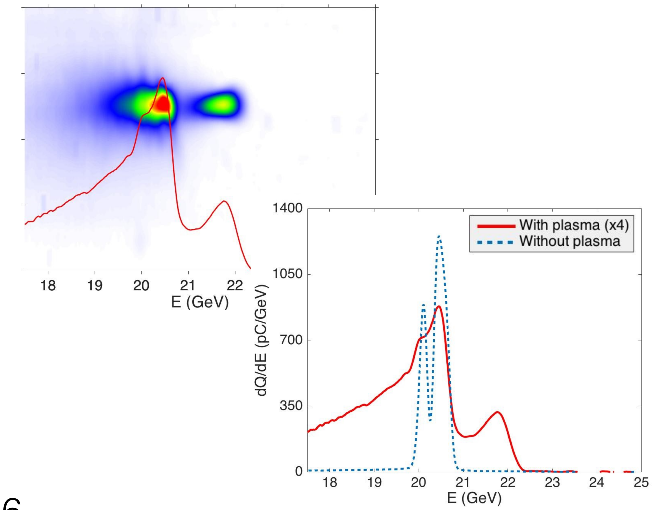

Gessner et al., ***Nature* Communications** 2016
Lindstrom et al., ***Phys. Rev. Lett.*** 2018




S. Diederichs et al., Phys. Rev. Accel Beams 22, 081301 (2019)

**Quasi-linear** Wakefield Acceleration

- > 1 GeV energy gain




Doche et al., ***Scientific Reports*** 2017

Worldwide theoretical studies focused on beam parameters that will be achievable at FACET-II: e.g. see talks at EAAC2019 and 2019 FACET-II Science Workshop

# Addressing Elements of the Grand Challenges But Not Yet Pushing to the Extremes Mentioned (e.g. quantum degeneracy)

**Grand Challenge #2: Beam quality**

- Pushing on brightness and quality preservation during acceleration and hope to demonstrate order(s) of magnitude improvement in next few years

**Grand Challenge #3: Beam control**

- Beam shaping for high-transformer ratios and better beam loading
- Transverse shaping for accelerated beams in LWFA collider concepts in quasi-linear regime and certain positrons acceleration concepts

**Grand Challenge #4: Beam prediction**

- Need for better code integration between beams and plasma PIC
- Beam codes need validation of CSR models (hosing seed) and effects at low emittance and high-peak currents (see Glen White talk)
- Reduced models work well when appropriate (e.g. quasi-static in QuickPIC, HighPACE)
- Codes that scale to Exascale for modeling multiple stages and parameter scans (Warp-X Exascale development)

# Addressing ABP Challenges for Plasma Acceleration Will Enable Synergistic Applications for non-HEP Agencies

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**HEP (non-Linear Collider)**

- Injector for CEPC (softer targets for emittance etc)

**BES**

- All optical LWFA FEL e.g. Jeroen ECA @ LBNL, efforts in Europe (EuPRAXIA, Angus, Apollon)
- PWFA injector as brightness transformer (e.g. PLEASE concepts at SLAC)
  - Attosecond science, TW peak power, Harder X-ray photons

**FES**

- LWFA betatron source for X-ray pump at MEC instrument @ LCLS

**DOE-NNSA**

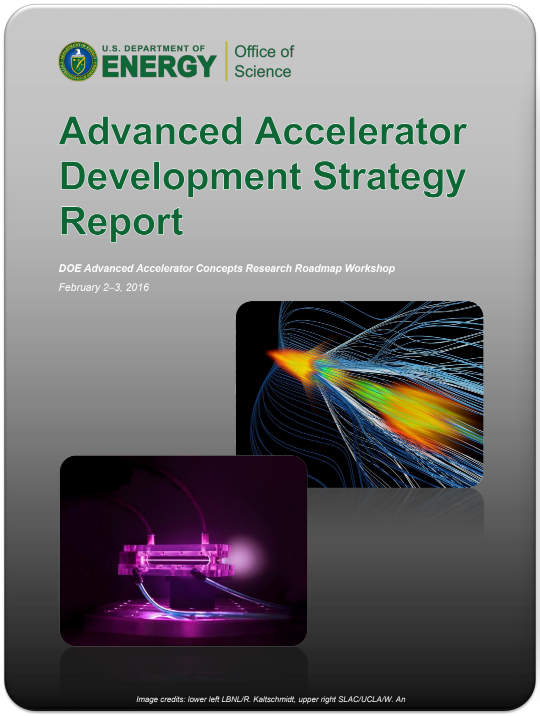
- LWFA ICS gamma ray source at LBNL

**HEP-FES**

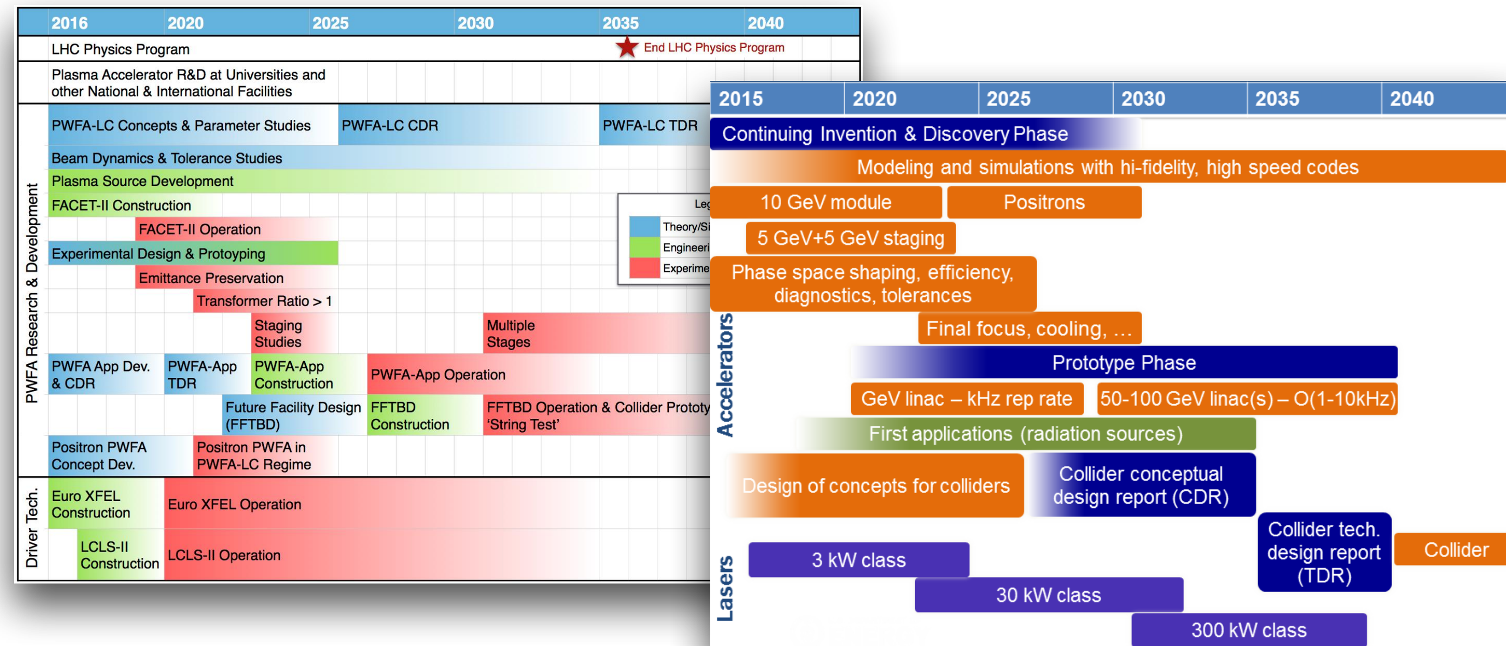
- Exploration of bunch compression techniques for plasma injectors synergistic with push to mega-Amp SFQED collider concepts

# Timeline, Milestones and Roadmap

- Milestones for LWFA, PWFA and DWFA defined in 2016 roadmaps
- ABP issues will be addressed hand in hand with experiments in interactive process
- Capability to test theories drives progress, e.g. positrons




## Beam & Laser Driven Plasma Acceleration Roadmaps




Community representatives from universities and laboratories organized workshops and summarized priorities in the report

https://www.osti.gov/biblio/1358081-advanced-accelerator-development-strategy-report-doe-advanced-accelerator-concepts-research-roadmap-workshop

# Who is working in this now? Are current facilities adequate?

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## PWFA R&D:

- US: Collaborations @ **FACET/FACET-II** National User Facility (CU Boulder, Ecole Polytechnique, Fermilab, University of Oslo, SLAC, UCLA, UT Austin, University of Strathclyde)
- Europe: FLASHForward @ DESY, AWAKE @ CERN (protons)
- Asia: Tsinghua University

## LWFA R&D:

- US: **LBNL BELLA**, Michigan, Rochester, LLNL, UCLA, Texas, NRL, BNL, Nebraska, …
- Europe: ELI Beamlines, RAL, Oxford, Strathclyde, DESY, MPQ, HZDR, Jena, Ecole Polytechnique, Apollon, INFN, IST-Lisbon,…
- Asia: Shanghai Jiao Tong University, SIOM, Tsinghua U., Kansai Photon Science Institute, CoReLs-GIST, …

Programs will need increased collaboration, coordination and targeted investments in facilities to remain competitive as financial underdogs.

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# Backup

Mark J. Hogan
December 10, 2019