FACET-II Facility for Advanced Accelerator Experimental Tests

Plans at FACET-II Relevant to ALIC

ALEGRO 2019
March 26-29, 2019

Mark J. Hogan
FACET-II Project Scientist
Plasma Group Leader

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

One of the earliest examples:
“Towards a Plasma Wake-field Acceleration-based Linear Collider”, J.B. Rosenzweig, et al., Nuclear Instruments and Methods A 410 532 (1998).

J. Rosenzweig et al. / Nucl. Instr. and Meth. in Phys. Res. A 410 (1998) 532–543 539

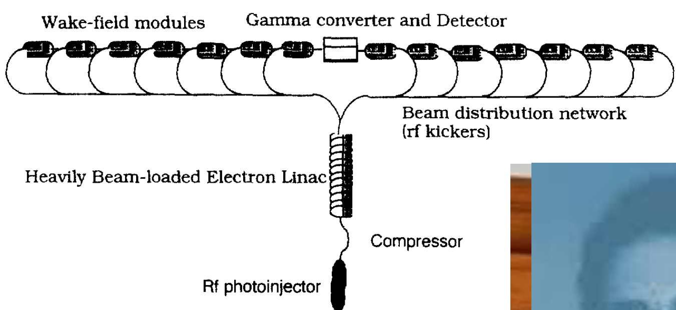


Fig. 6. Schematic of a γ–γ collider using a hardware transformer scheme. A large number o
linac fed by an RF photoinjector followed by a compressor. Seperate wake modules are c
a binary RF spliting scheme.

Table 1
Nominal drive beam and accelerating module parameters for the plasma wake-field accelerator-based collider shown in Fig. 4

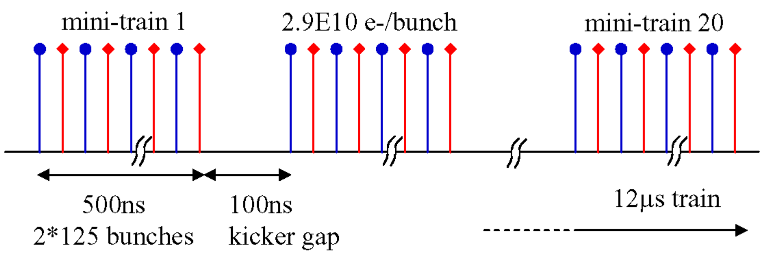
	L-band case	S-band case
Beam energy	3 GeV	3 GeV
Beam charge	20 nC	9 nC
Stored energy/bunch	60 J	27 J
Bunch length	0.8 mm	0.36 mm
Norm.emittance	50 mm mrad	23 mm mrad
Plasma density	2×10^{14} cm^{-3}	10^{15} cm^{-3}
Plasma wavelength	2.2 mm	1 mm
Deceleration wake	500 MeV/m	1.1 GeV/m
Accelerating wake	1 GeV/m	2.2 GeV/m
Wake module length	5.7 m	2.6 m
Intermodule drift	2.66 m	1.21 m

First SLAC Concept Developed with FACET Proposal < 2009

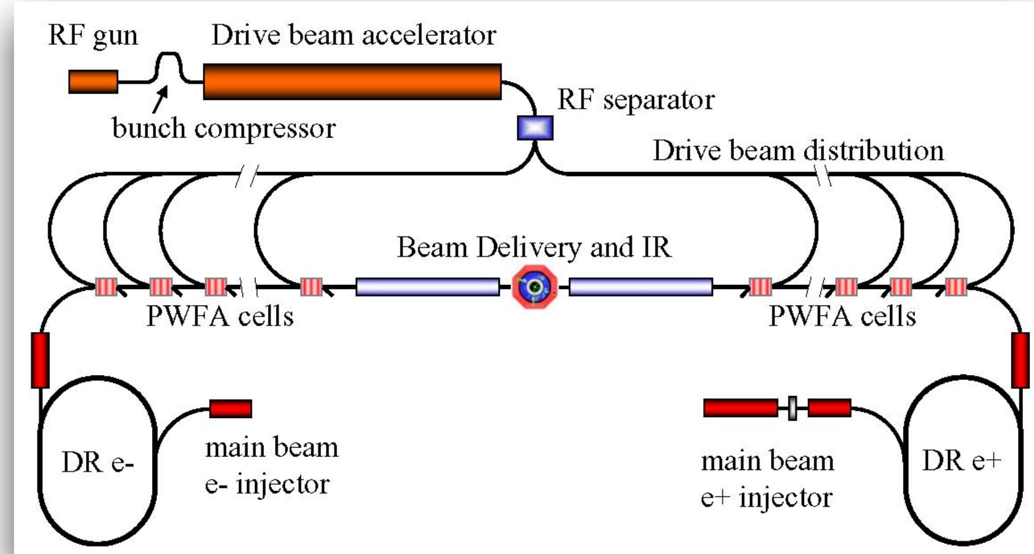
A CONCEPT OF PLASMA WAKE FIELD ACCELERATION LINEAR COLLIDER (PWFA-LC)*

SLAC-PUB-13766

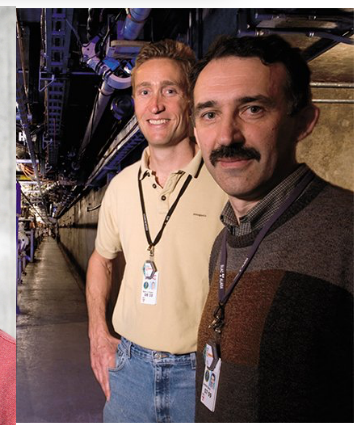
Andrei Seryi, Mark Hogan, Shilun Pei, Tor Raubenheimer, Peter Tenenbaum (SLAC), Tom Katsouleas (Duke University), Chengkun Huang, Chan Joshi, Warren Mori (UCLA, California), Patric Muggli (USC, California).



- 'Warm' Drive Linac
- 4ns bunch spacing
- Many turnarounds



Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Plasma density, accelerating gradient and plasma cell length	1×10^{17}cm^{-3}, 25 GV/m, 1 m
Power transfer efficiency drive beam=>plasma =>main beam	35%
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW
Main beam emittances, x, y	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	0.14, 0.0032, 10 μm
Luminosity	3.5×10^{34} cm^{-2}s^{-1}
Luminosity in 1% of energy	1.3×10^{34} cm^{-2}s^{-1}



Alternative SLAC Concept Developed Prior to CSS2013

SLAC

Proceedings of IPAC2014, Dresden, Germany THPRI013

A BEAM DRIVEN PLASMA-WAKEFIELD LINEAR COLLIDER FROM HIGGS FACTORY TO MULTI-TEV*

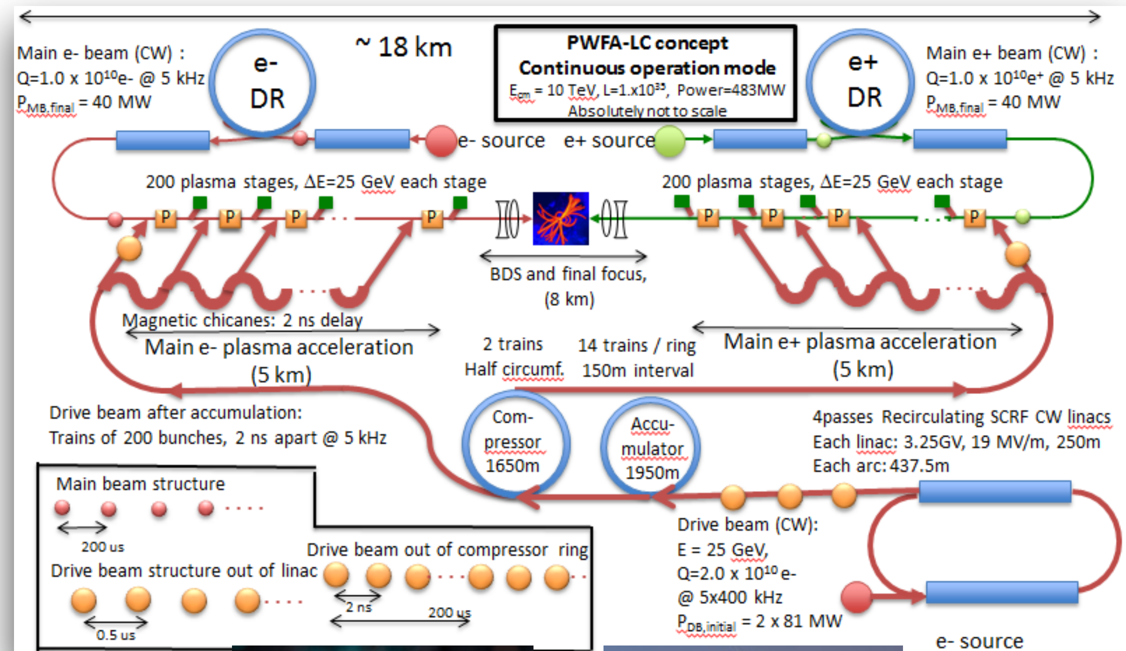
J.P. Delahaye, E. Adli, S.J. Gessner, M.J. Hogan, T.O. Raubenheimer, SLAC,
W. An, C. Joshi, W. Mori, UCLA

SLAC-PUB-15426
http://arxiv.org/abs/1308.1145
E. Adli *et al*, IPAC14

- ‘Cold’ Drive Linac
- 100μs bunch spacing
- Tricky delay chicanes

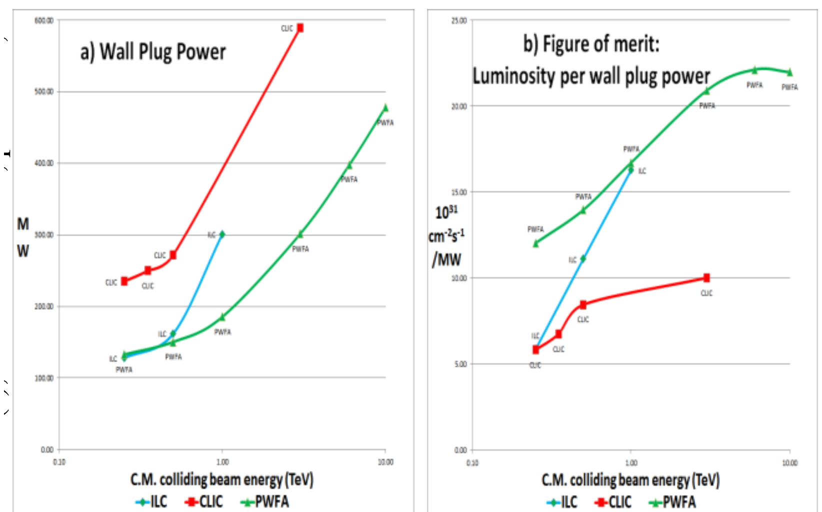
Table 1: Major PWFA-LC beam parameters

Colliding beam energy, CM	GeV	250	500	1000	3000	10000
N, experimental bunch		1.0E+10	1E+10	1.0E+10	1.0E+10	1.0E+10
Main beam bunches / train		1	1	1	1	1
Main beam bunch spacing,	nsec	3.33E+04	5.00E+04	6.67E+04	1.00E+05	2.00E+05
Repetition rate,	Hz	30000	20000	15000	10000	5000
n exp.bunch/sec,	Hz	30000	20000	15000	10000	5000
Beam power / beam at IP	W	6.0E+06	8.0E+06	1.2E+07	2.4E+07	4.0E+07
Effective accelerating gradient	MV/m	1000	1000	1000	1000	1000
Overall length of each linac	m	125	250	500	1500	5000
BDS (both sides)	km	2.00	2.50	3.50	5.00	8.00
Overall facility length	km	2.25	3.00	4.50	8.00	18.00
Drive beam						
Transfer efficiency drive to main	%	50	50	50	50	50
Drive beam power per beam	MW	12.2	16.2	24.3	48.6	81.0
Drive beam acceleration efficiency	%	39.9	42.0	44.3	45.0	45.3
Main beam acceleration efficiency	%	19.9	21.0	22.1	22.5	22.7
Wall plug to main beam efficiency	%	9.1	10.8	13.1	16.1	17.0
Total wall plug power	MW	132.9	150.4	185.5	301.3	477.9
IP Parameters						
Normalized horizontal emittance	m	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
Normalized vertical emittance	m	3.50E-08	3.50E-08	3.50E-08	3.50E-08	3.50E-08
Horiziontal beam size at IP (1σ)	m	6.71E-07	4.74E-07	3.35E-07	1.94E-07	1.06E-07
Vertical beam size at IP (1σ)	m	3.78E-09	2.67E-09	1.89E-09	1.09E-09	5.98E-10
Bunch length at IP (1σ)	m	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05
Disruption parameter, Y		8.44E-02	2.39E-01	6.75E-01	3.51E+00	2.14E+01
delta_B	%	2.75	6.66	12.76	23.10	29.88
ngamma		0.57	0.73	0.88	1.05	1.14
Geometric Lum ($cm^{-2} s^{-1}$)		9.41E+33	1.25E+34	1.88E+34	3.76E+34	6.27E+34
Total Luminosity ($cm^{-2} s^{-1}$)		1.57E+34	2.09E+34	3.14E+34	6.27E+34	1.05E+35
Luminosity in 1% top energy ($cm^{-2} s^{-1}$)		9.41E+33	1.15E+34	1.57E+34	2.51E+34	3.14E+34
Fig. merit:Luminosity/wall plug (10^{31}/MW)		11.8	13.9	16.9	20.8	21.9



Where do we begin?

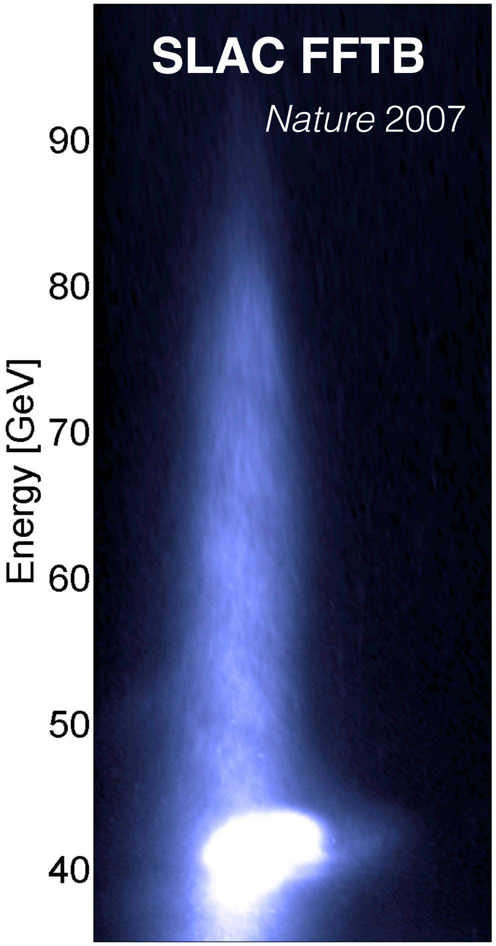
- Assume the decades of collider development (SLC/NLC/ILC/CLIC) made smart choices that we can start from for main beam and driver
- Focus on the accelerator module itself (the plasma)
- For luminosity – Power efficiency and beam quality are critical!
- Talk tomorrow on FACET-II studies of efficiency vs. transverse wakes
- Next iterations will benefit from more consideration of positron arm



Figures 2a and 2b: Linear colliders wall plug power consumption and figure of merit defined as the ratio of the wall plug power consumption to total luminosity

http://accelconf.web.cern.ch/accelconf/IPAC2014/papers/thpri013.pdf

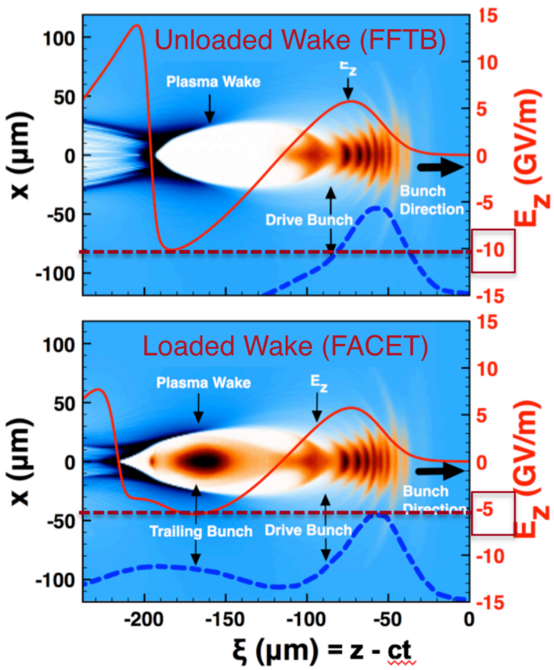
High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

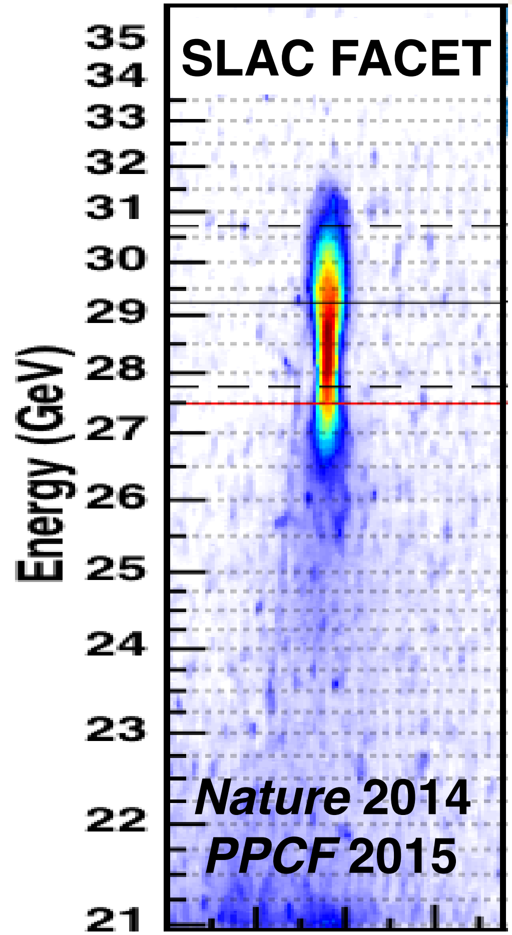


43 GeV
Energy Gain

Beam loading is key for: Narrow energy spread & high efficiency

QuickPIC Simulation



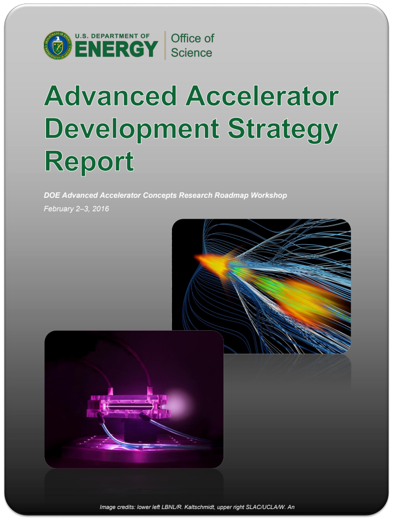


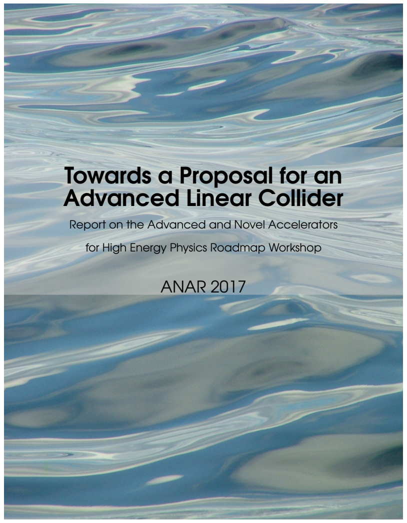
9 GeV
Energy Gain

Narrow energy spread acceleration with high-efficiency has been demonstrated
FACET-II experiments will focus on simultaneously preserving beam emittance

Roadmaps Have Been Developed
US in 2016 by DOE HEP and in Europe through ICFA ANAR2017

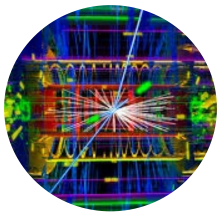
- Physics goals for various time horizons – 5, 10, 20 years
- Requires progress in theory, computation and experimentation
- Facilities (like FACET-II) are key for testing concepts discussed here
- ALIC aspirations and aligned with Roadmap and FACET-II priorities
  - Strong beam loading for narrow energy spread and high efficiency
  - Emittance preservation at μm and sub-μm levels
  - Matching in and out, mitigation of instabilities, ion motion
  - Knowledge of plasma dynamics at long timescales
  - Investigations of paths to positron acceleration comparable to electrons



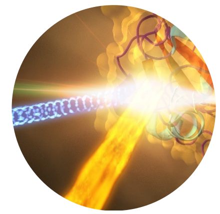


FACET-II: A National User Facility Based on High-energy Beams and Their Interaction with Plasmas and Lasers

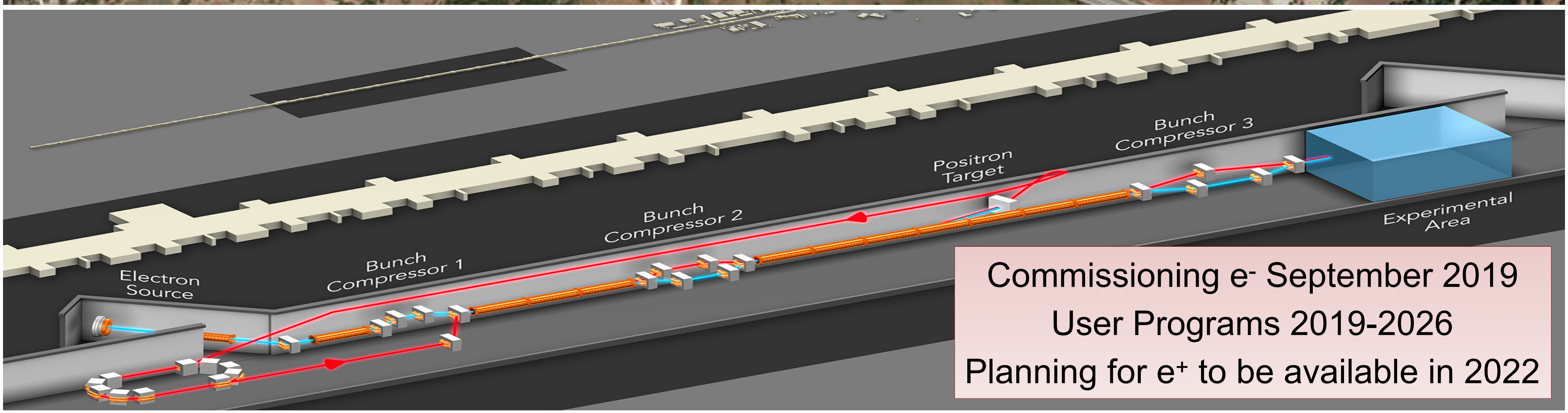
SLAC



Advance the energy frontier for future colliders



Develop brighter X-rays for photon science



FACET-II Layout and Beams

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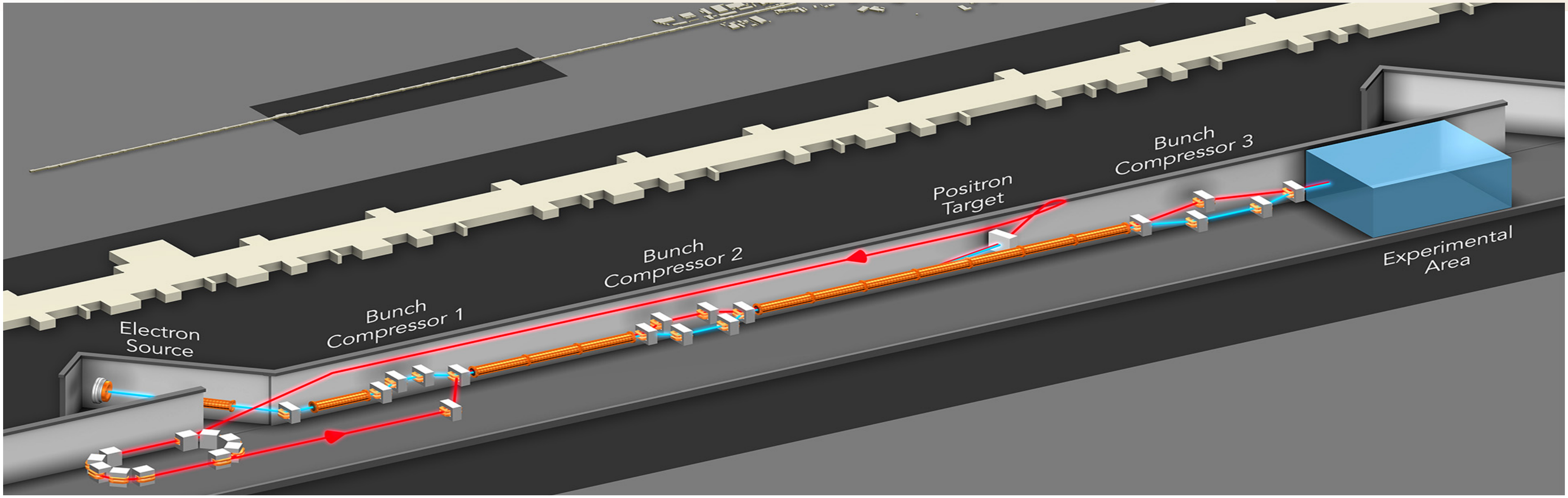
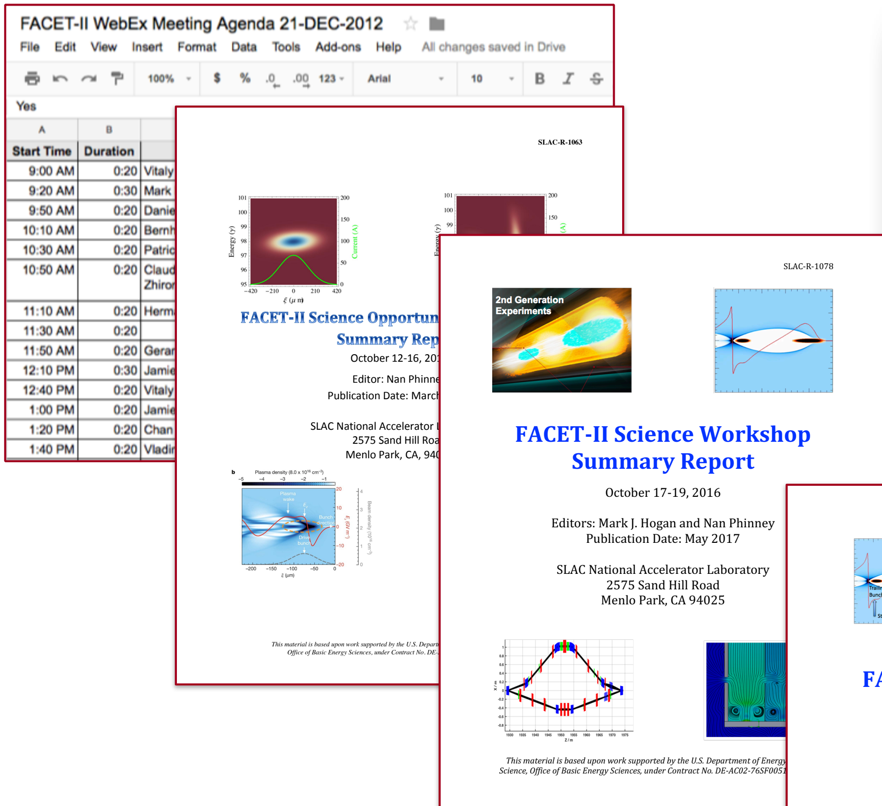
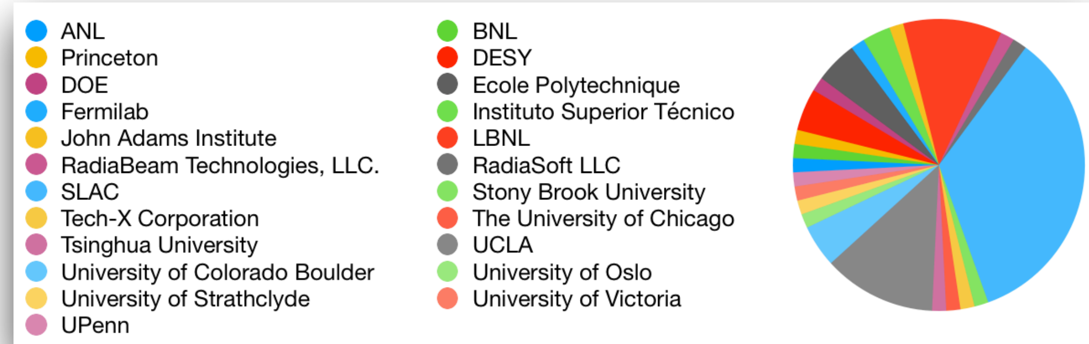


Electron Beam Parameter	Baseline Design	Operational Ranges
Final Energy [GeV]	10	4.0-13.5
Charge per pulse [nC]	2	0.7-5
Repetition Rate [Hz]	30	1-30
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19 [μm]	4.4, 3.2	3-6
Spot Size at IP $\sigma_{x,y}$ [μm]	18, 12	5-20
Min. Bunch Length σ_z (rms) [μm]	1.8	0.7-20
Max. Peak current I_{pk} [kA]	72	10-200

Positron Beam Parameter	Baseline Design	Operational Ranges
Final Energy [GeV]	10	4.0-13.5
Charge per pulse [nC]	1	0.7-2
Repetition Rate [Hz]	5	1-5
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19	10, 10	6-20
Spot Size at IP $\sigma_{x,y}$ [μm]	16, 16	5-20
Min. Bunch Length σ_z (rms)	16	8
Max. Peak current I_{pk} [kA]	6	12

FACET-II Annual Science Workshops
December 2012, October 2015, 2016, 2017…





- Call for proposals in June 2018
- Program Advisory Committee Meeting October 9-12, 2018

Next Science Workshop October 2019 to discuss:
- Beam quality in PWFA
- FEL applications
- Experiments with positrons
- Strong Field QED

User community is engaged with annual science workshops leading to strong proposals and excellent alignment with HEP Roadmap priorities

Flexibility of the photo-injector allows two bunches creation at the gun with order of magnitude better emittance and without collimation

Science deliverables:

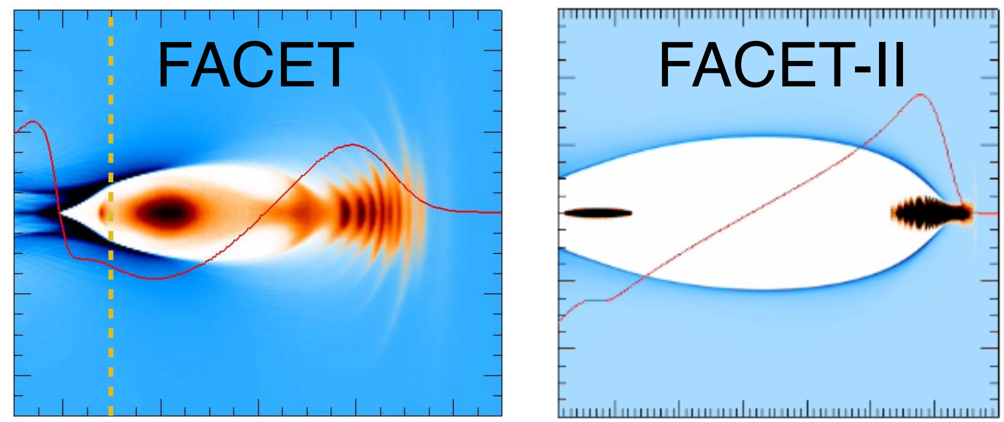
- Pump depletion of drive beam with high efficiency & low energy spread acceleration
- Beam matching and emittance preservation

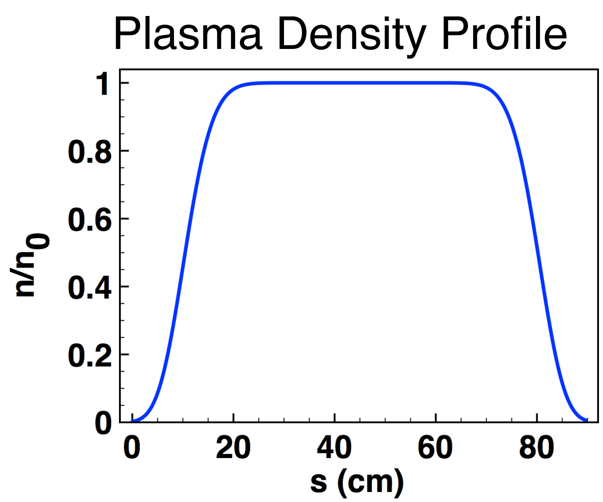
Key upgrades:

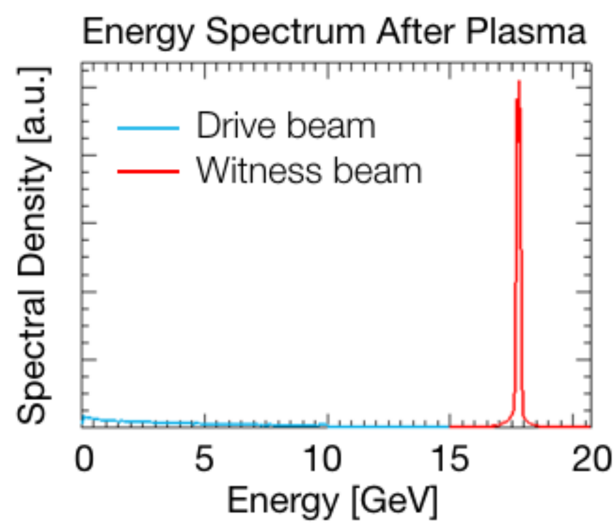
- Photoinjector beam
- Matching to plasma ramps
- Differential pumping
- Single shot emittance diagnostic

Plasma source development:

- Between 10-20μm emittance, beam expected to ionize He in down ramp
- Next step laser ionized hydrogen source in development at CU Boulder







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

PAC 'Excellent' rankings re-iterated that roadmap priorities are well developed in proposed experimental program

Community Coming Together Around Ideas for Testing Mechanisms That May Limit Beam Quality

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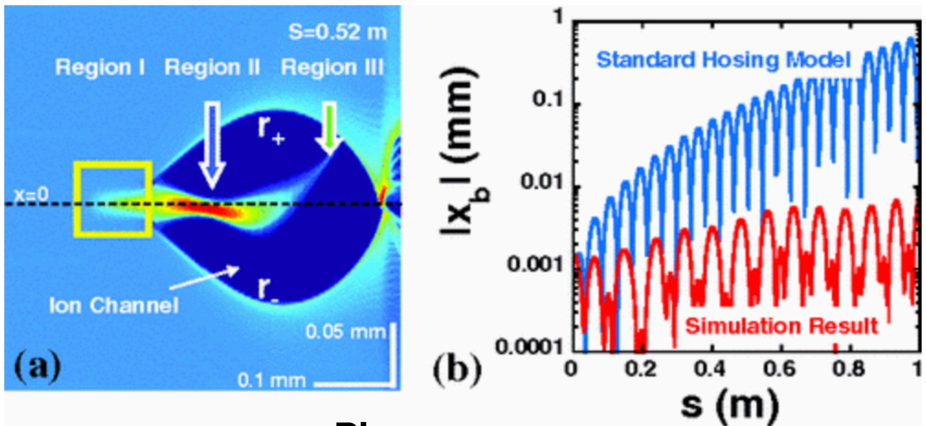
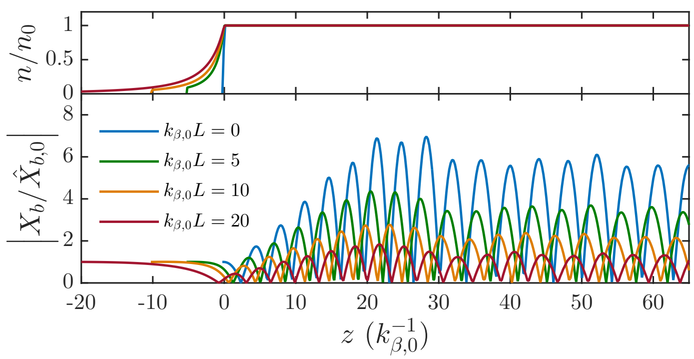


Many **mechanisms of emittance growth** have been put forward, e.g. ion motion, hosing…

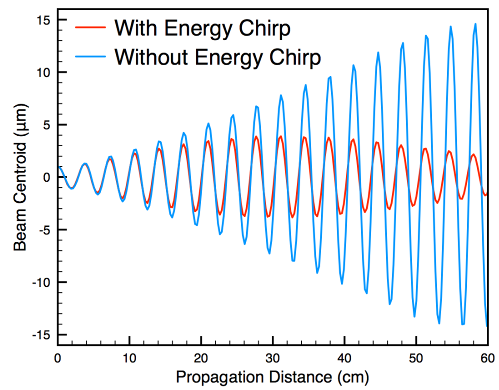
D. Whittum et al. PRL 67, 991 (1991) **LBNL/SLAC**
J. Rosenzweig et al., 95, 195002 (2005) **UCLA**
C. Huang et al., PRL 99, 255001 (2007) **UCLA**
V. Lebedev et al., PRST-AB 20, 121301 (2017) **FNAL**

Plamsa ramps

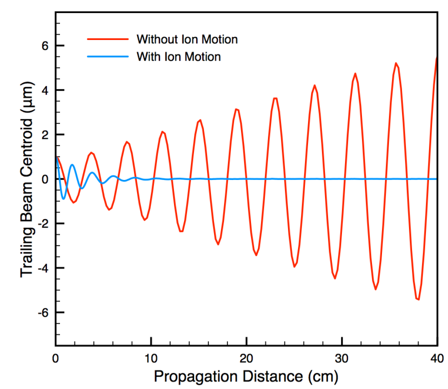


T. Mehrling et. al., PRL 118, 174801 (2017) **DESY/LBNL**

Energy Spread



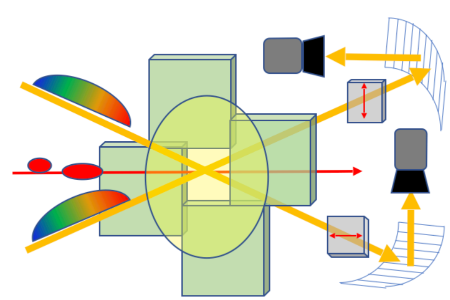
Ion Motion



W. An et al. PRL 118, 244801 (2017) **UCLA**

Proposed **techniques for mitigation** need to be tested experimentally

Quadrant EOS to measure r-t beam correlations



Goal is to measure correlation along ~1ps long bunch

Benchmarking theoretical and numerical predictions will be a strong component of FACET-II Program

M. Hogan "Plans on transverse wakefield measurements at FACET-II" Thursday 09:50-10:10

FACET Experiments Use Meter Scale Plasmas:
Laser or Beam Field Ionization, Alkali Metal Vapor or Hydrogen Gas

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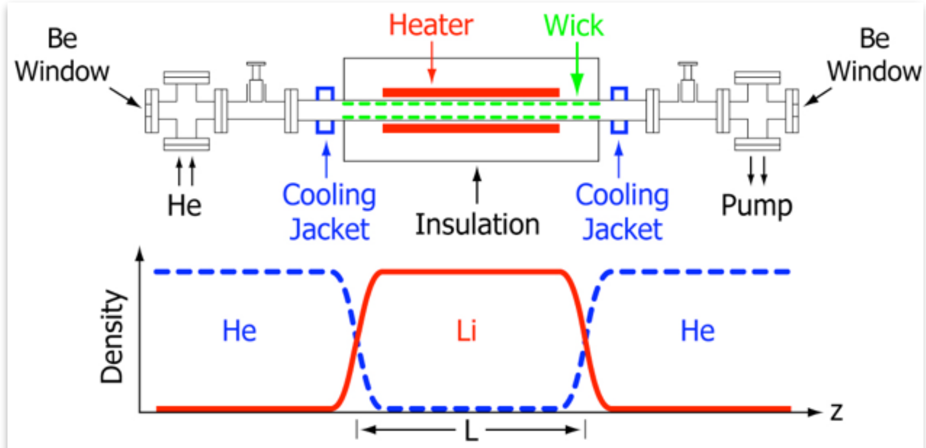
Lithium or Rubidium Vapor Produced in a Heat Pipe Oven:

- Scalable over wide range in density & length:
  - $n_0 = 10^{14}$-10^{17} e^-/cm^3, L = 20-200 cm
- 'Easy' first ionization:
  - e.g. Li 5.4 eV lessens ionization laser requirements
- Limited optical access for probe pulses and injection laser pulses (e.g. Trojan Horse)
- Developed in collaboration with UCLA, used in most acceleration experiments since 1998

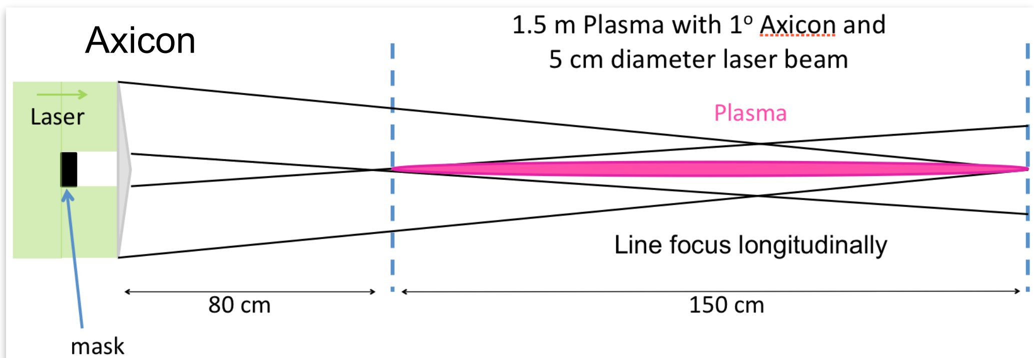


Hydrogen Gas Cells:

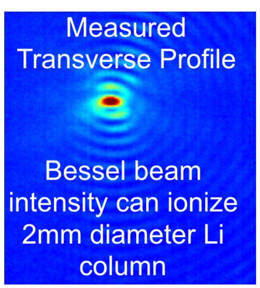
- Flexible optical access for visualization and injection

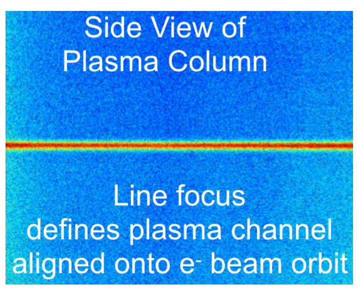
Ionization:

- Possible with beam fields directly for single compressed e- beams
- Pre-ionization laser pulse gives additional flexibility
- Specialized optics for uniform or hollow channel plasmas

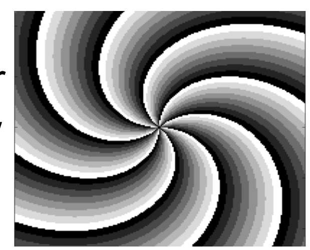


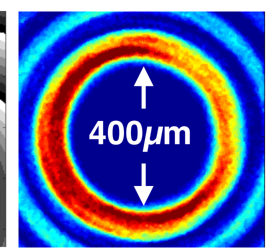
Axicon optic provides transversely uniform extended line focus for long, uniform plasmas for electron acceleration



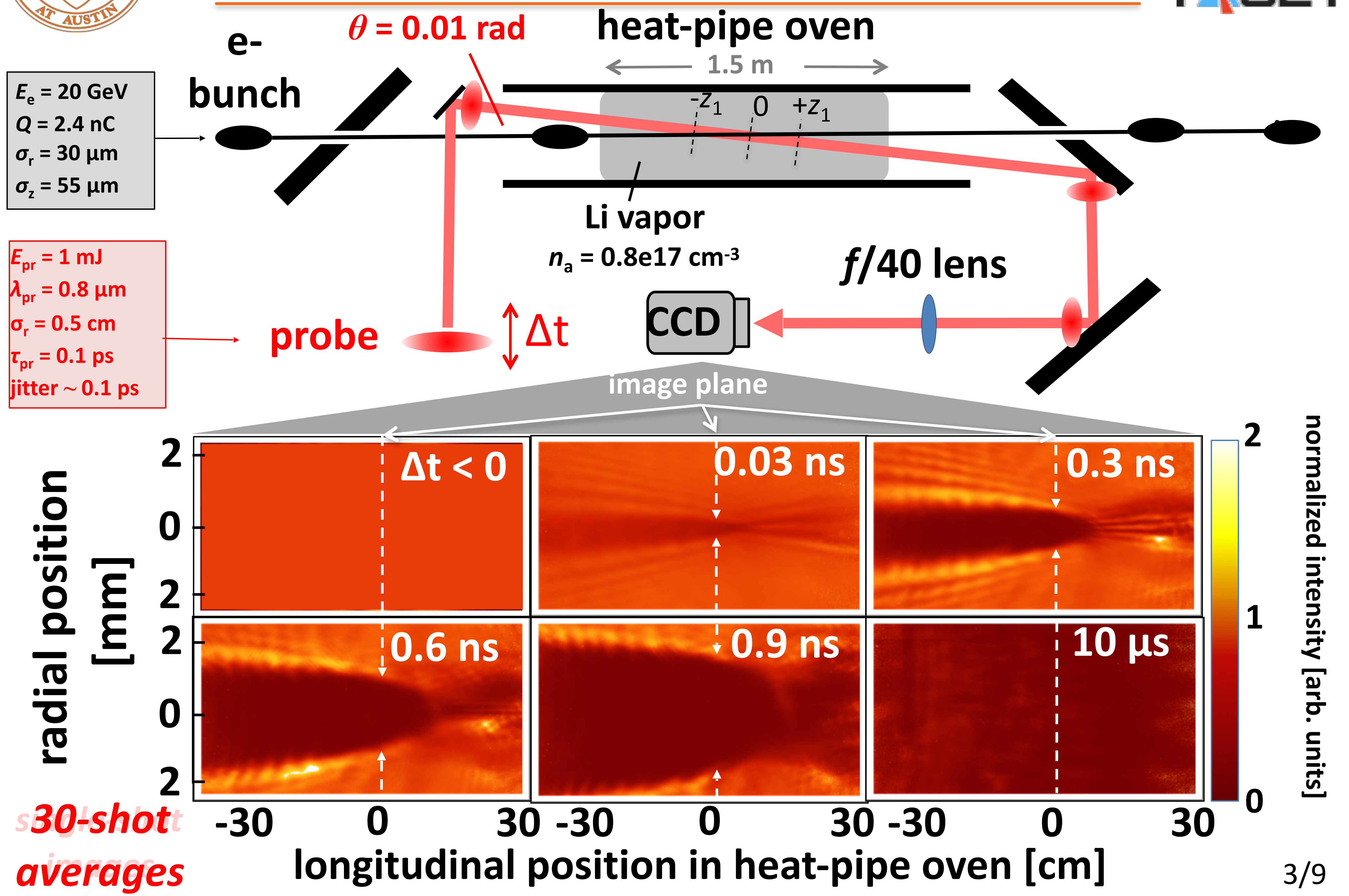


Spiral phase grating produces hollow laser beam to make hollow plasma channel for positron acceleration





In FACET-I, we imaged near-field diffraction patterns of an ion wake in a single shot



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SLAC FACET

CONCLUSIONS

- We reconstructed dissipation of a multi-GeV PWFA over 1 ns by analyzing probe diffractometry measurements with OSIRIS & LCODE simulations.

- SLAC e-bunch initially singly-field-ionizes neutral Li vapor ($n_a = 0.8 \times 10^{17}$ cm^{-3}) out to $r = 40$ µm & drives NL e-wake, depositing 2 J/cm.

- Periphery of plasma profile grows from r ~ 0 → 2 mm in 1 ns.

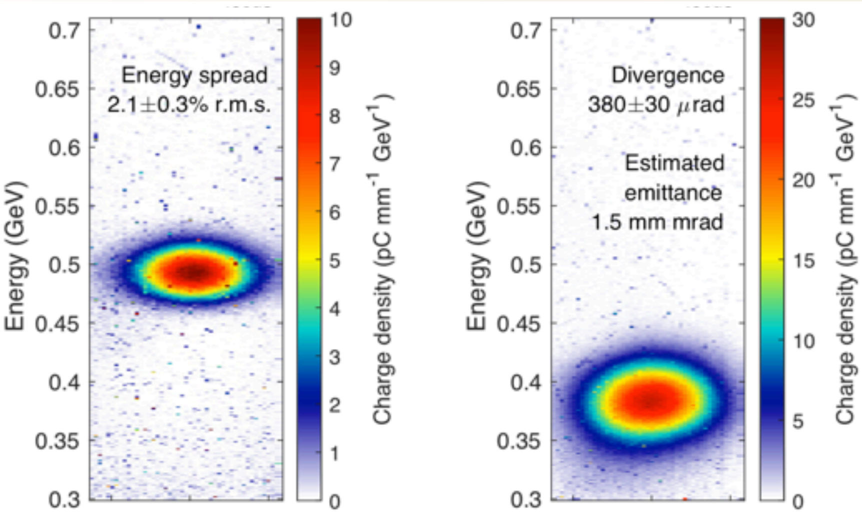
- 85% of deposited energy remains in plasma column for 1ns, driving:
  - outward radial ion motion
  - >60-fold multiplication of electron population by impact ionization in periphery, explaining its observed expansion.

- **FUTURE:** Probe plasma at steeper angles (.01 → .02 rad) available in FACET-II, to access internal structures (*e.g.* axial ion peak, NL e-wake).

Financial support: U. S. Department of Energy, U. S. National Science Foundation

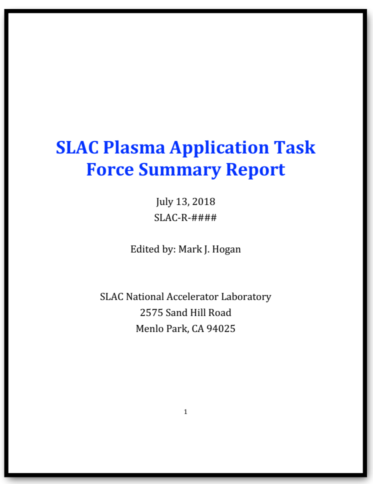
Prospects for Transformative Applications Based on Ultra-high Brightness Beams from Plasma Wakefield Accelerators

SLAC



A. Deng et al. *in Review* for E210 Collaboration

- FACET started high-brightness plasma wakefield injector research
- Demonstrating and optimizing different injection techniques (DDR, TH, CP) are important parts of FACET-II program
- Path to collider level 10-100nm emittance beams without damping rings



SLAC Plasma Application Task Force Summary Report

July 13, 2018
SLAC-R-####

Edited by: Mark J. Hogan

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2575 Sand Hill Road
Menlo Park, CA 94025

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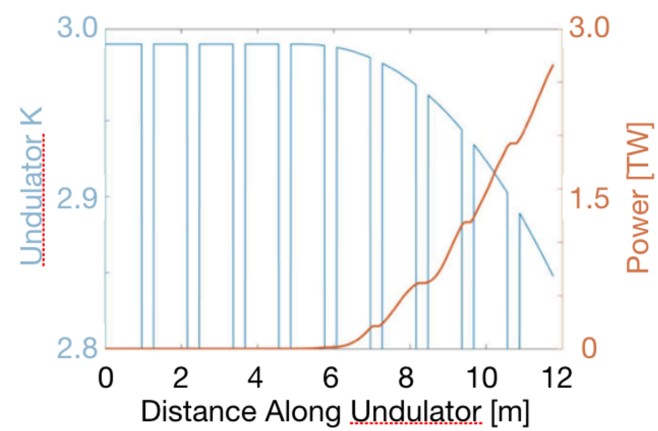
Example FEL Applications

- TerraWatt Peak Power
- Attosecond Pulses
- Photon Energies > 20keV

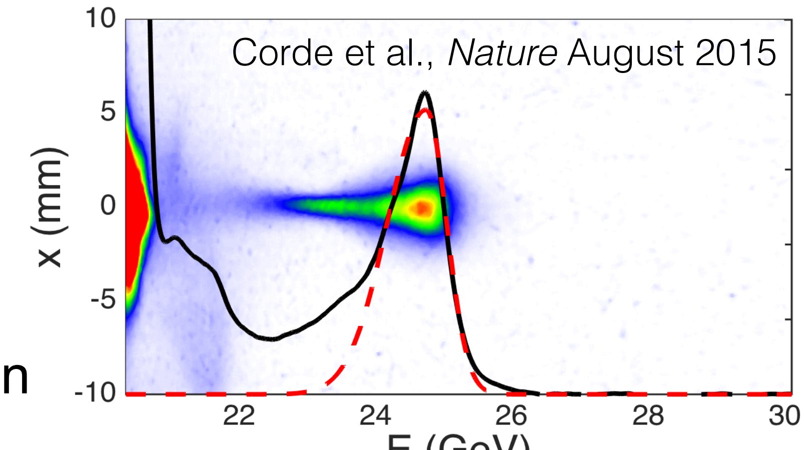


Results of FACET-II science program are needed to optimize the design of a future demonstration facility (systems engineering, reliability, tolerances…)

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

Multi-GeV Acceleration in **Non-linear wakes**

- New self-loaded regime of PWFA
- Energy gain 4 GeV in 1.3 meters
- Low divergence, no halo

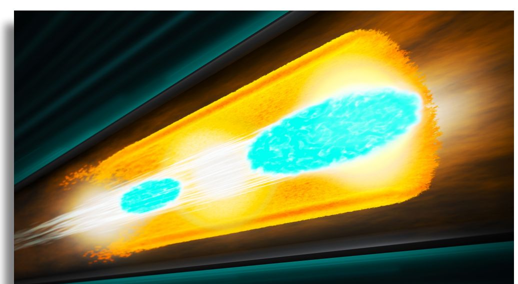


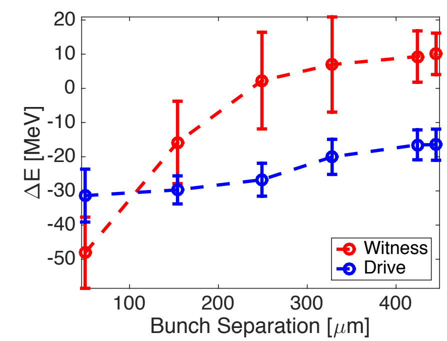
Corde et al., *Nature* August 2015

Hollow Channel Plasma Wakefield Acceleration

- Engineer Plasma to Control the Fields
- No focusing on axis
- Measured transverse and longitudinal wakefields

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

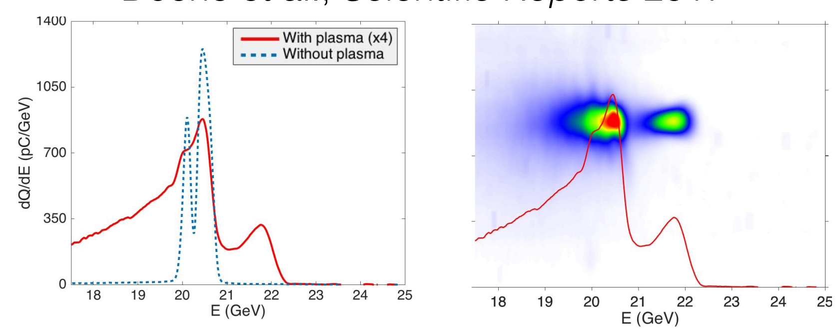




Quasi-linear Wakefield Acceleration

- > 1 GeV energy gain in 1.3 meters
- Of interest to both the PWFA and LWFA for linear collider applications
- This technique can be used to accelerate a positron witness beam in electron wake

Doche et al., *Scientific Reports* 2017



PWFA Research Priorities at FACET-II
Stage 1 Funded. Stage 2 & 3 will Fully Exploit the Potential of FACET-II

SLAC

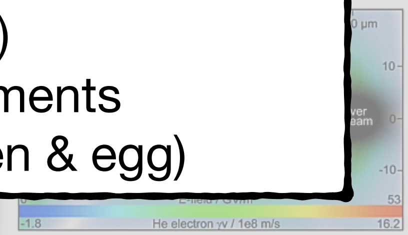
Emittance Preservation with Efficient Acceleration

- High-gradient … been demons…
- Full pump-dep… Emittance pre… at μm level pla… first experimen…

Stage 1

High Brightness Beam Generation & Characterization

…r collider apps
…d to first apps



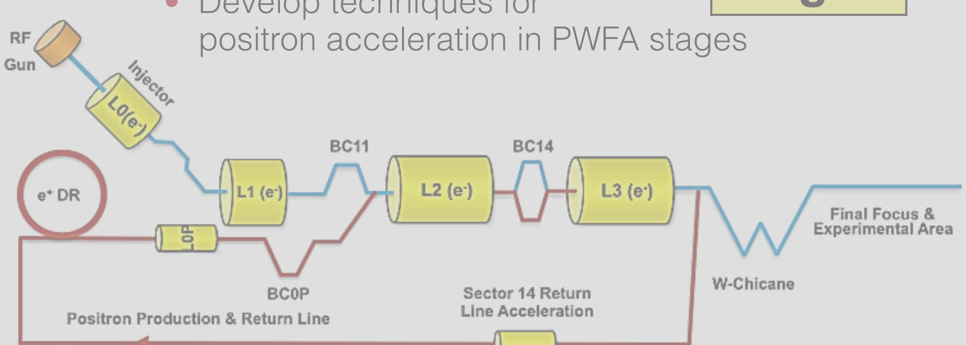
Stage 1

Possibility to add an independent witness injector has been studied:
- Independent control of drive & witness bunches
- More flexibility for shaping and higher transformer ratio studies
- Staging studies with independent beams (ins & outs)
- Incorporate lessons learned in double bunch experiments
- Requirements will follow experimental needs (chicken & egg)

Positron Acceleration
FY21-24

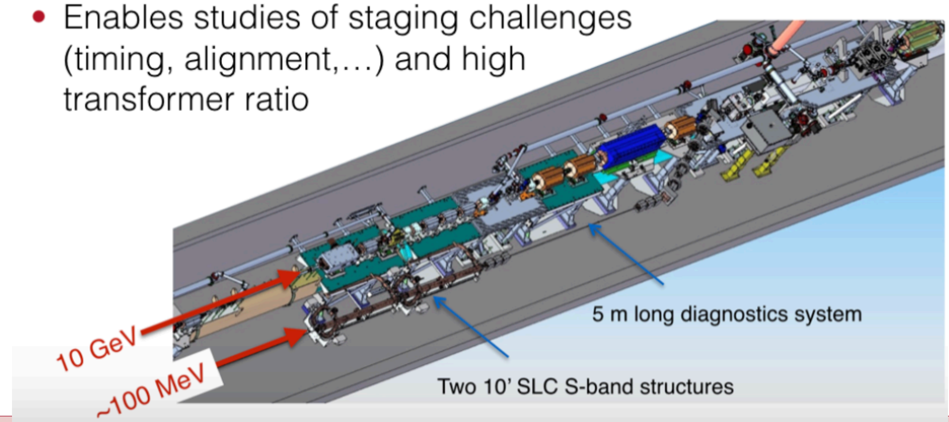
- Only high-current positron capability in the world for PWFA research will be enabled by Phase II
  - Develop techniques for positron acceleration in PWFA stages

Stage 2



Staging Studies
FY22-25

- Independent witness injector planned to be added to FACET-II as an AIP project
- Enables studies of staging challenges (timing, alignment,…) and high transformer ratio



User Community is engaged with annual science workshops. Gradual introduction of capabilities are aligned with User needs.

Concluding Thoughts

- FACET-II will commission electron beam this Fall
- User programs expected to run from 2019-2026
- FACET-II experimental collaborations have proposed many exciting and challenging experiments to address key physics issues on US Roadmap (and ANAR Roadmap)
- ALIC aspirations and aligned with FACET-II and Roadmap priorities
  - Strong beam loading for narrow energy spread and high efficiency
  - Emittance preservation at μm and sub-μm levels
    - Matching in and out, mitigation of instabilities, ion motion
  - Knowledge of plasma dynamics at long timescales
  - Investigations of paths to positron acceleration comparable to electrons
- Applying lessons learned to update collider designs will take motivated/dedicated personnel with time to do so