FACET-II Facility for Advanced Accelerator Experimental Tests

Roadmap towards linear colliders based on plasma accelerators

2019 FACET-II Science Workshop

Mark J. Hogan

October 31, 2019

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

For context - what might a plasma based collider look like?

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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

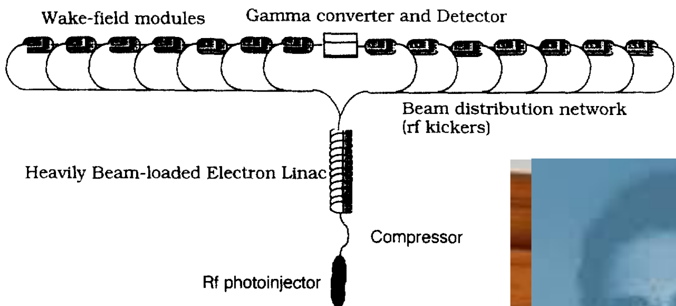

Fig. 6. Schematic of a γ–γ collider using a hardware transformer scheme. A large number o
linac fed by an RF photoinjector followed by a compressor. Seperate wake modules are c
a binary RF spliting scheme.

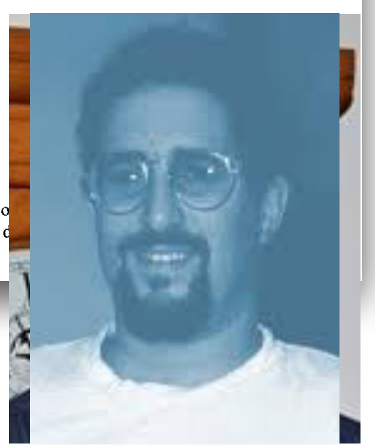

Table 1
Nominal drive beam and accelerating module parameters for the plasma wake-field accelerator-based collider shown in Fig. 4

	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

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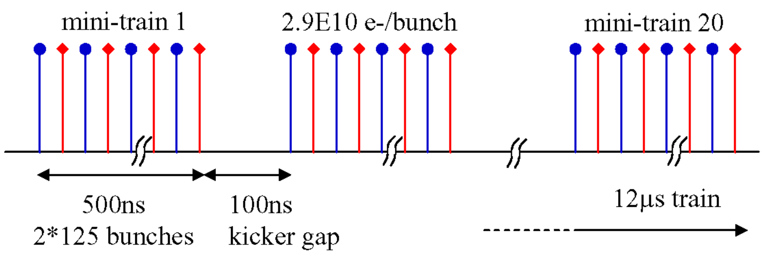
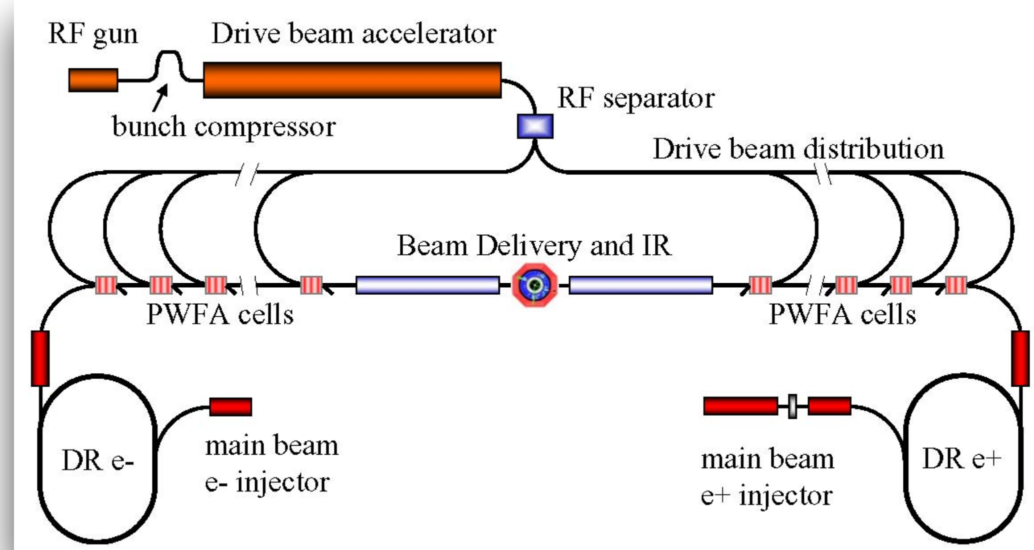
A CONCEPT OF PLASMA WAKE FIELD ACCELERATION LINEAR COLLIDER (PWFA-LC)*

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).

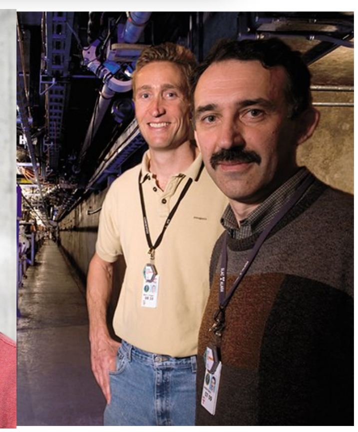
SLAC-PUB-13766



- ‘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

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Proceedings of IPAC2014, Dresden, Germany THPRI013

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

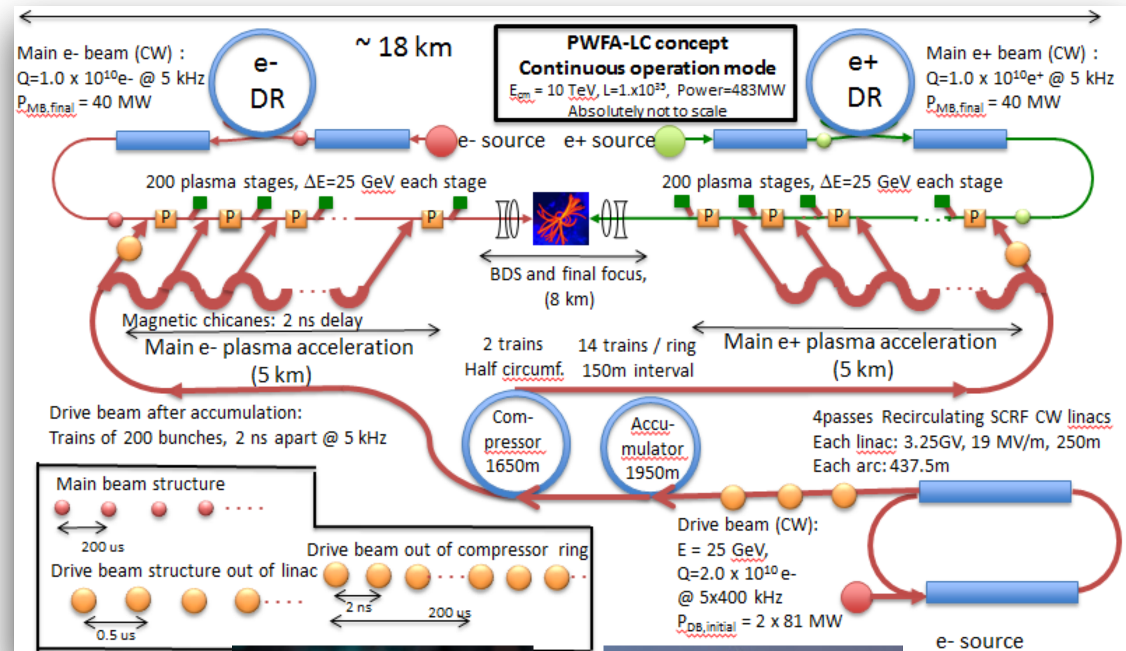
J.P. Delahaye, E. Adli, S.J. Gessner, M.J. Hogan, T.O. Raubenheimer, SLAC,
W. An, C. Joshi, W. Mori, UCLA

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



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

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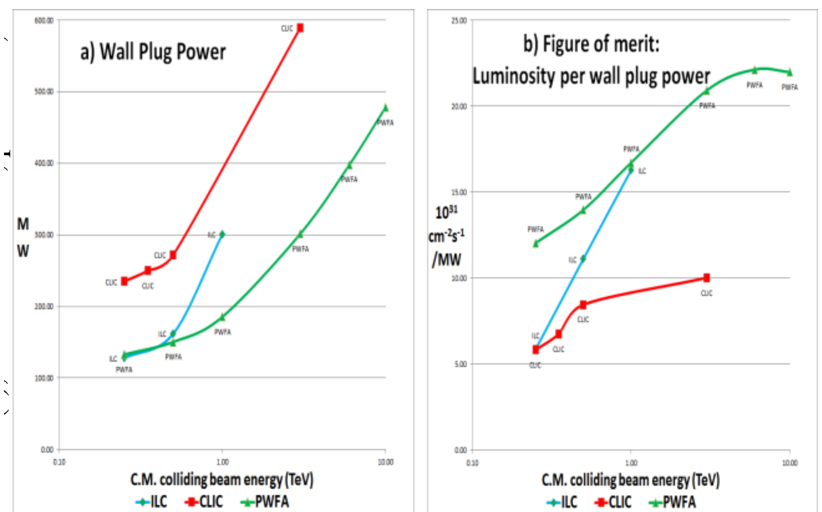
- Assume the decades of collider development (SLC/NLC/ILC/CLIC) made smart choices that we can start from for main beam and driver
- Focus on the accelerator module itself (the plasma)
- For luminosity – Power efficiency and beam quality are critical!
- Next iterations will benefit from more consideration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

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

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

To be discussed: table of beam parameters for a plasma-based e-/e+ collider

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ALEGRO process looking at designs for ALIC at 10+ TeV

electron beam parameters

(assumes 4x times better interstage wrt Lindstrøm apochromatic design: 10 m instead of 40 m at 500 GeV)

Drive beam		Main beam	
Energy	100 GeV	Final energy	10 TeV
Charge	2 nC	Charge	1 nC
Normalized Emittance	<10 mm.mrad	Normalized emittance	<0.1 mm.mrad
Energy spread	<1%	Energy spread	<1%

Accelerator parameters	
Accelerating field	10 GV/m
Wall plug efficiency	1-10 %
Repetition rate	10-1000 kHz
Plasma stage length	10 m
Number of stages	100
Total interstage length	3 km
Total plasma linac length	4 km
Tolerances	<10-100 nm, <0.1-1 urad

positron beam parameters

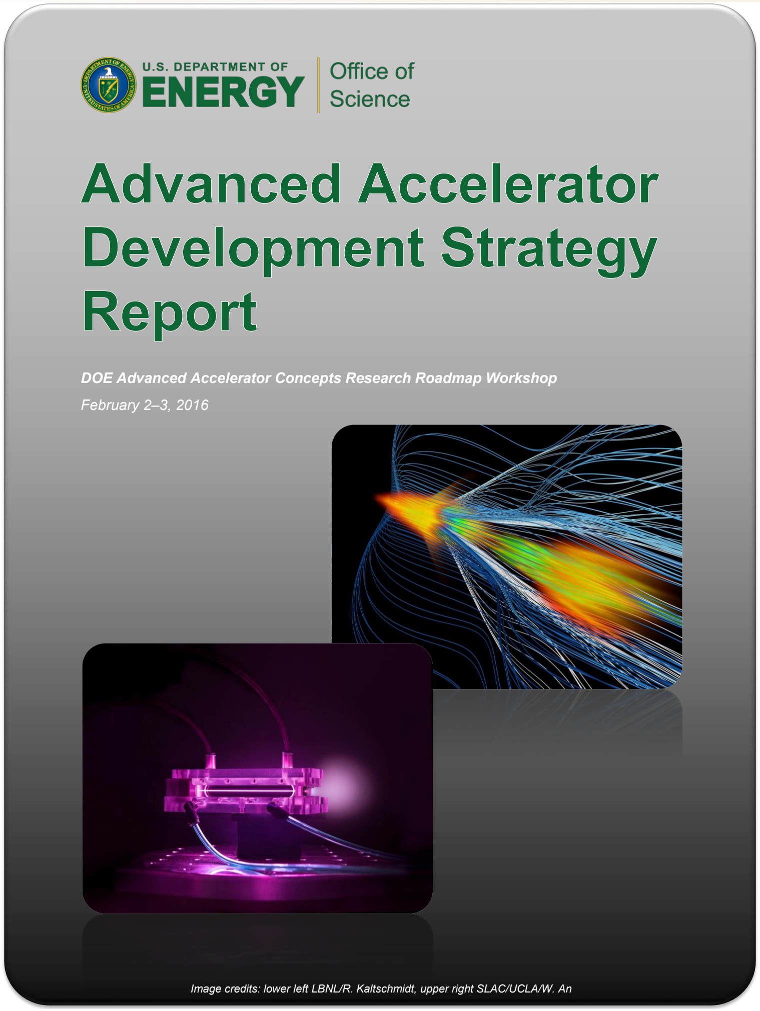
(assumes hollow channel with 1T pole external focusing)

Drive beam		Main beam	
Energy	100 GeV	Final energy	10 TeV
Charge	10 nC	Charge	5 nC
Normalized Emittance	<10 mm.mrad	Normalized emittance	<0.1 mm.mrad
Energy spread	<1%	Energy spread	<1%

Accelerator parameters	
Accelerating field	1 GV/m
Wall plug efficiency	1-10 %
Repetition rate	10-1000 kHz
Plasma stage length	100 m
Number of stages	100
Total interstage length	3 km
Total plasma linac length	13 km
Tolerances	<10-100 nm, <0.1-1 urad

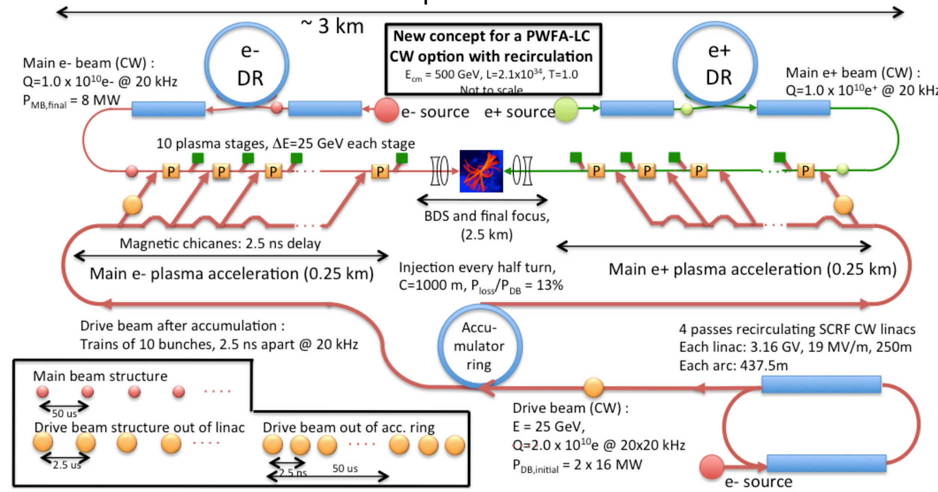
S. Corde, M. Hogan, S. Gessner, C. Lindstrøm

PWFA Experimental Program at FACET-II is Motivated by Roadmap for Future Colliders Based on Advanced Accelerators



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 the next decade:

- Beam quality – focus on emittance preservation at progressively smaller values
- Positrons – use FACET-II positron beam identify optimum regime for positron PWFA
- Injection – ultra-high brightness sources, staging studies with external injectors

Beam Driven Plasma Accelerator Roadmap for HEP

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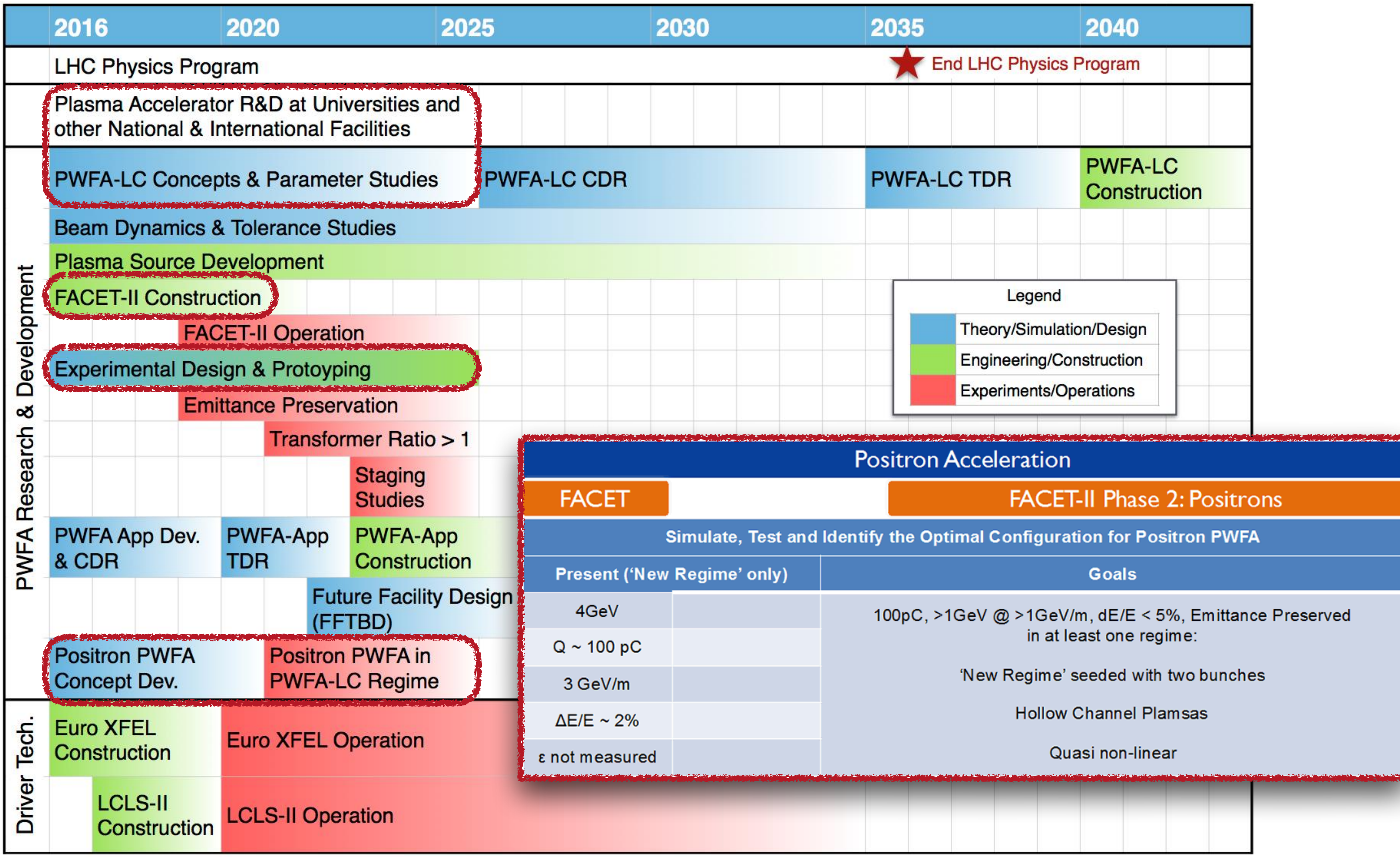
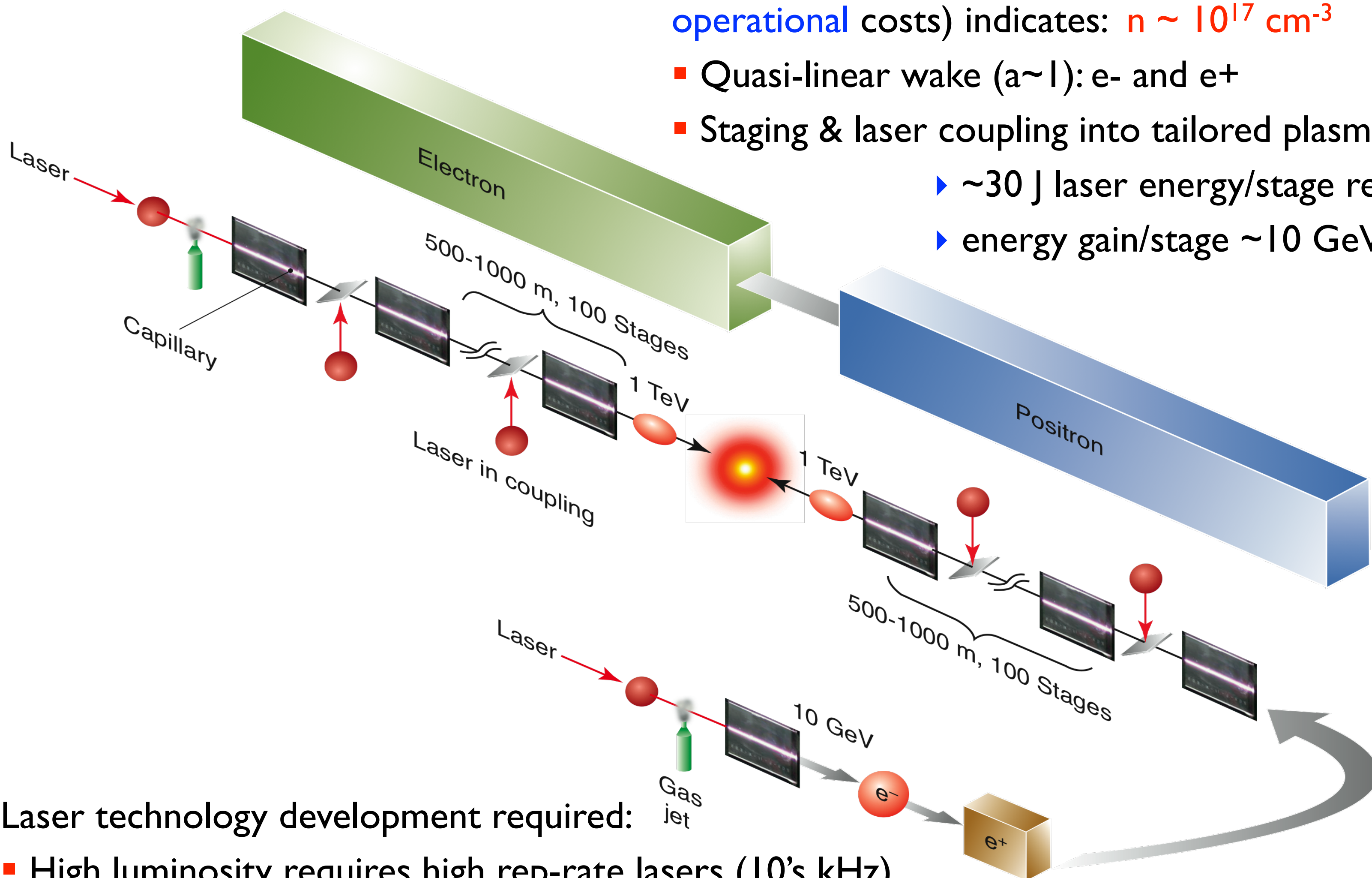


Laser-plasma Accelerator Based Collider Concept

Leemans & Esarey, Physics Today (2009)

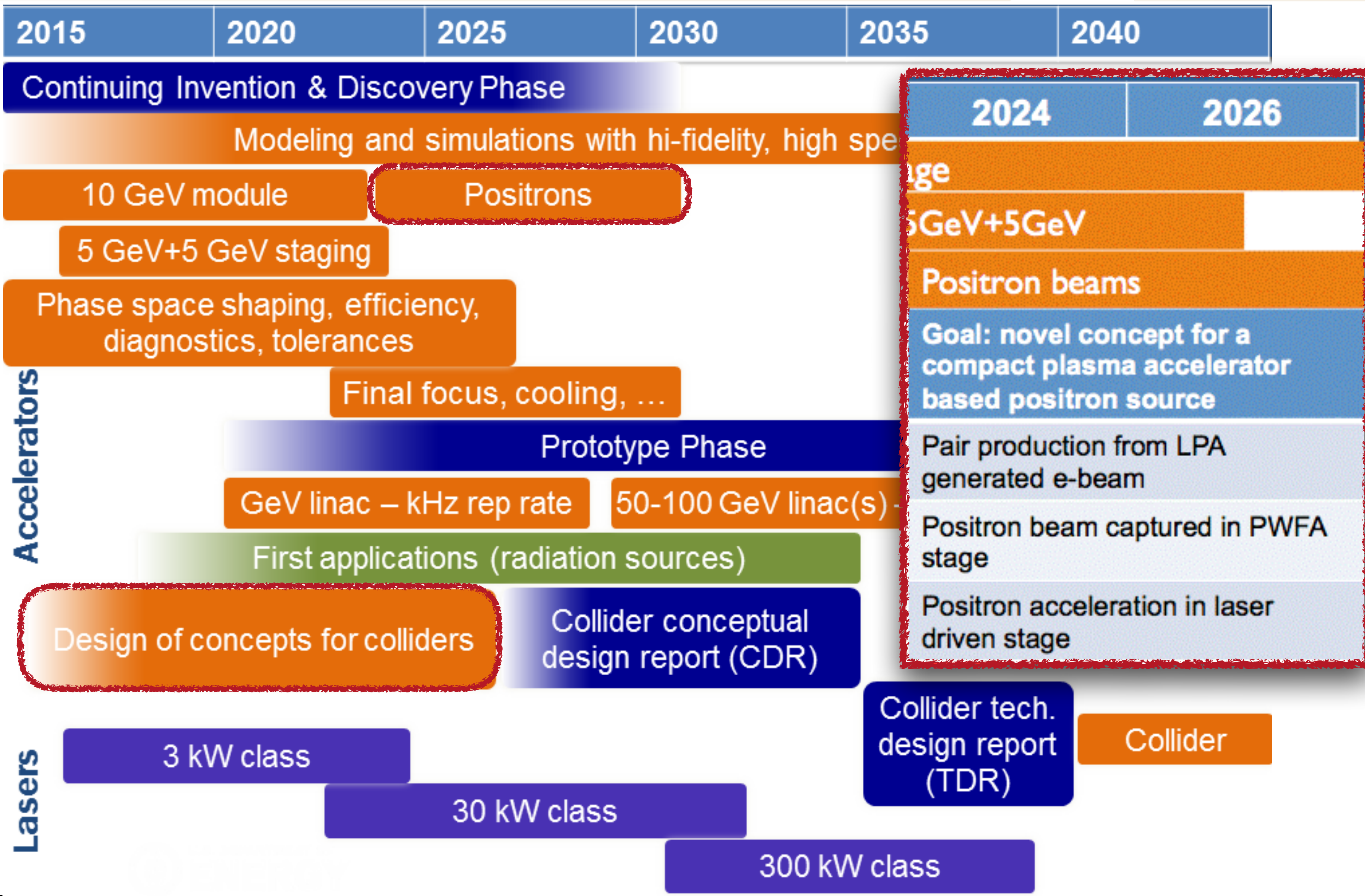


- Plasma density scalings (minimize construction and operational costs) indicates: $n \sim 10^{17}$ cm^{-3}
- Quasi-linear wake (a~1): e- and e+
- Staging & laser coupling into tailored plasma channels:
  - ~30 J laser energy/stage required
  - energy gain/stage ~10 GeV in ~1m

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 %)

Laser Driven Plasma Accelerator Roadmap for HEP



Overall Timescale and Common Challenges: "Demonstration and understanding of positron acceleration"

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Synergies

Extensive collaboration among the three LWFA, PWFA, and DWFA concepts over the next ten years would be highly beneficial to all AAC programs in DOE. As discussed below, the technical overlap between LWFA and PWFA suggests a number of collaborative avenues. In addition, the facilities supporting DWFA research and development can inform many of the issues facing future wake-field colliders.

The roadmaps for the plasma-based approaches, LWFA and PWFA, contain many similarities and parallels, since much of the physics and required R&D are independent of the driver. These parallels include the multiple staging of ~1-10 GeV level modules, the preservation of beam quality throughout multiple stages, mitigation of emittance growth due to collisions and ion motion, high efficiency acceleration, the difficulty of accelerating positrons with nonlinear plasma waves, the use of hollow plasma channels for positron acceleration, and the mitigation of transverse beam instabilities. The overarching goals of the plasma-based R&D roadmaps include: a) solving the outstanding physics issues through experimental investigations and simulations so that the potential of plasma–based colliders can be realistically considered; b) addressing through experiments and computer simulations engineering issues such as tolerances; c) continuously refining a collider design based on the latest data from experiments and simulations; and d) developing driver technologies that will enable the demonstration of a real multi-stage plasma accelerator at the requisite repetition rate. The plasma-based roadmaps show that there is a considerable agreement between the proponents of LWFA and PWFA as to what the outstanding physics issues are and a rough timetable for the required R&D. Progress may be faster if some of these issues were addressed at either the BELLA or the FACET-II facility as appropriate as long as they are common to both schemes. For instance, developing various ideas for high quality positron acceleration may in the next five years be better suited for

High-efficiency, high-gradient positron acceleration of low emittance beams in plasma is recognized as an opportunity for collaboration

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

See presentation by Spencer Gessner 9:45AM Thursday

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

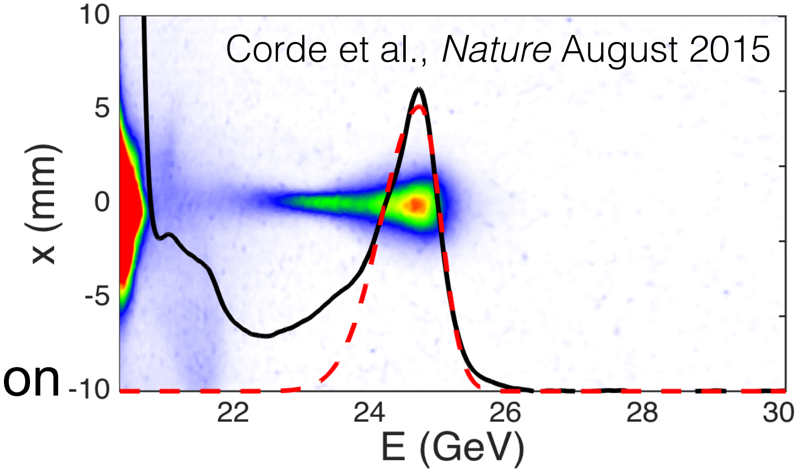
- New self-loaded regime of PWFA
- Energy gain 4 GeV in 1.3 meters
- Low divergence, no halo

Hollow Channel Plasma Wakefield Acceleration

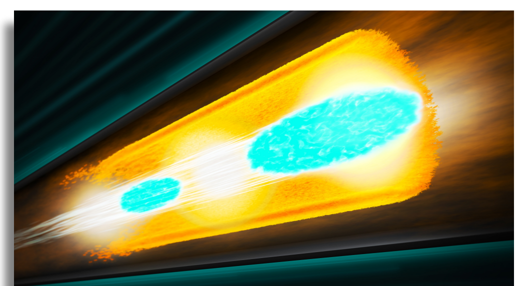
- Engineer Plasma to Control the Fields
- No focusing on axis
- Measured transverse and longitudinal wakefields

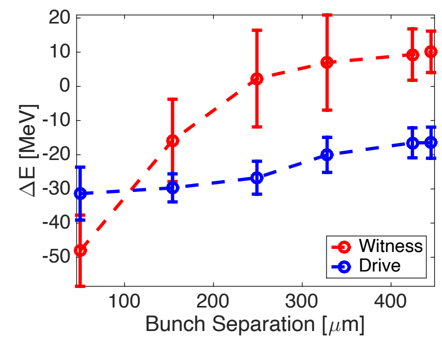
Quasi-linear Wakefield Acceleration

- > 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

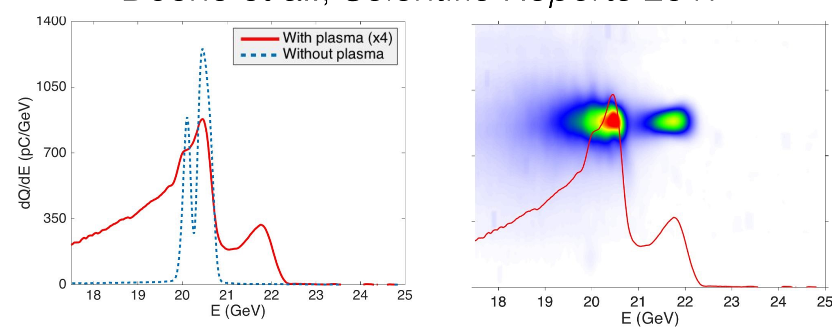


Gessner et al., *Nature* Communications 2016
Lindstrom et al., *Phys. Rev. Lett.* 2018





Doche et al., *Scientific Reports* 2017



FACET-II Layout and Beams

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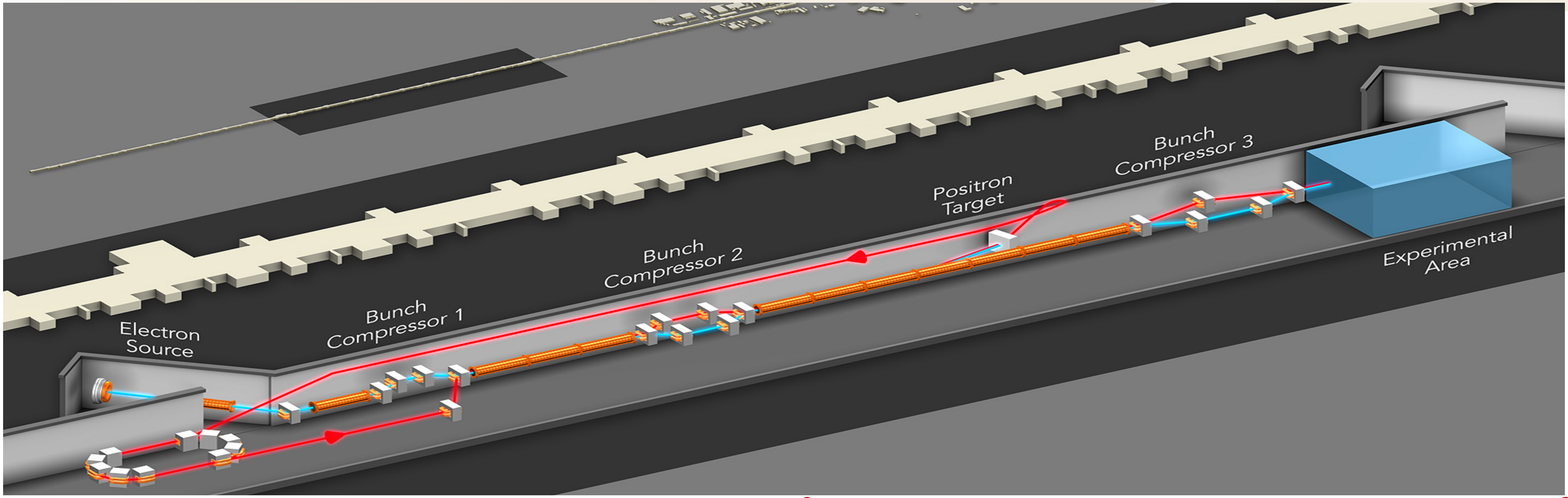
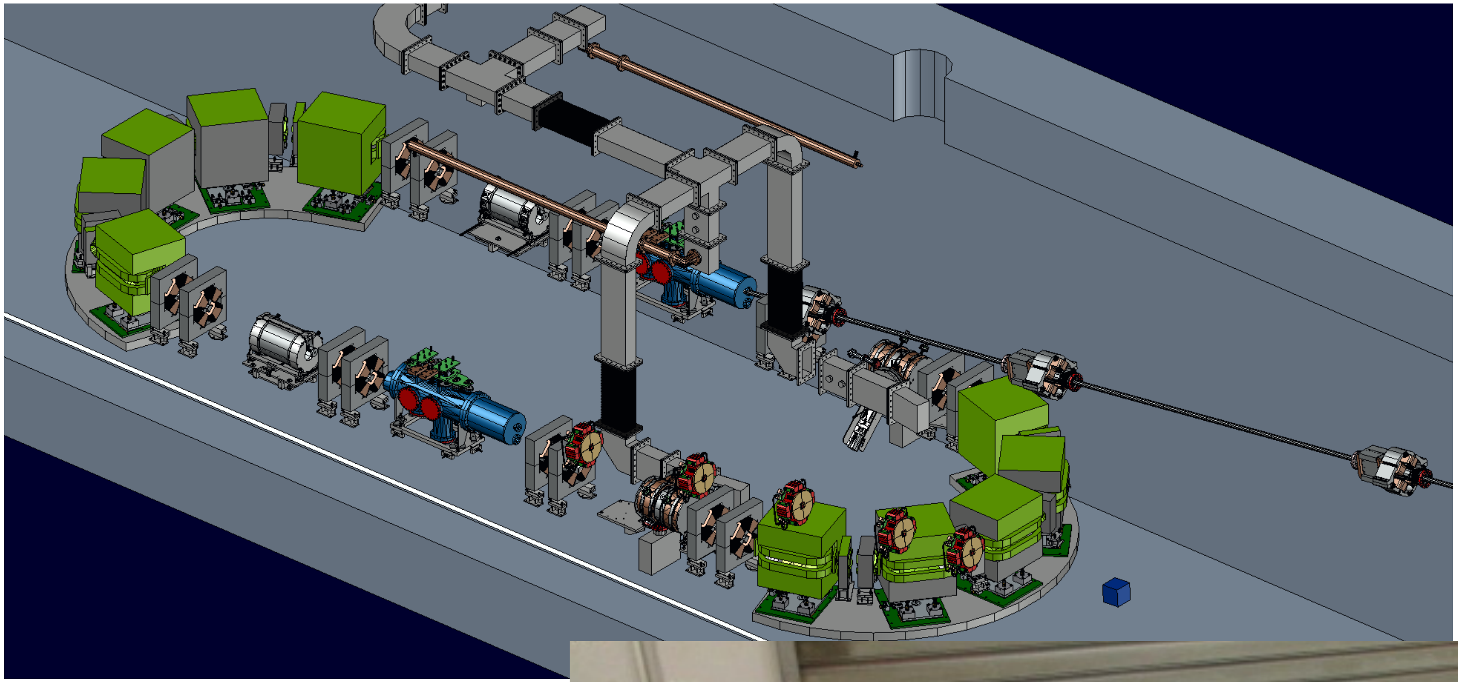
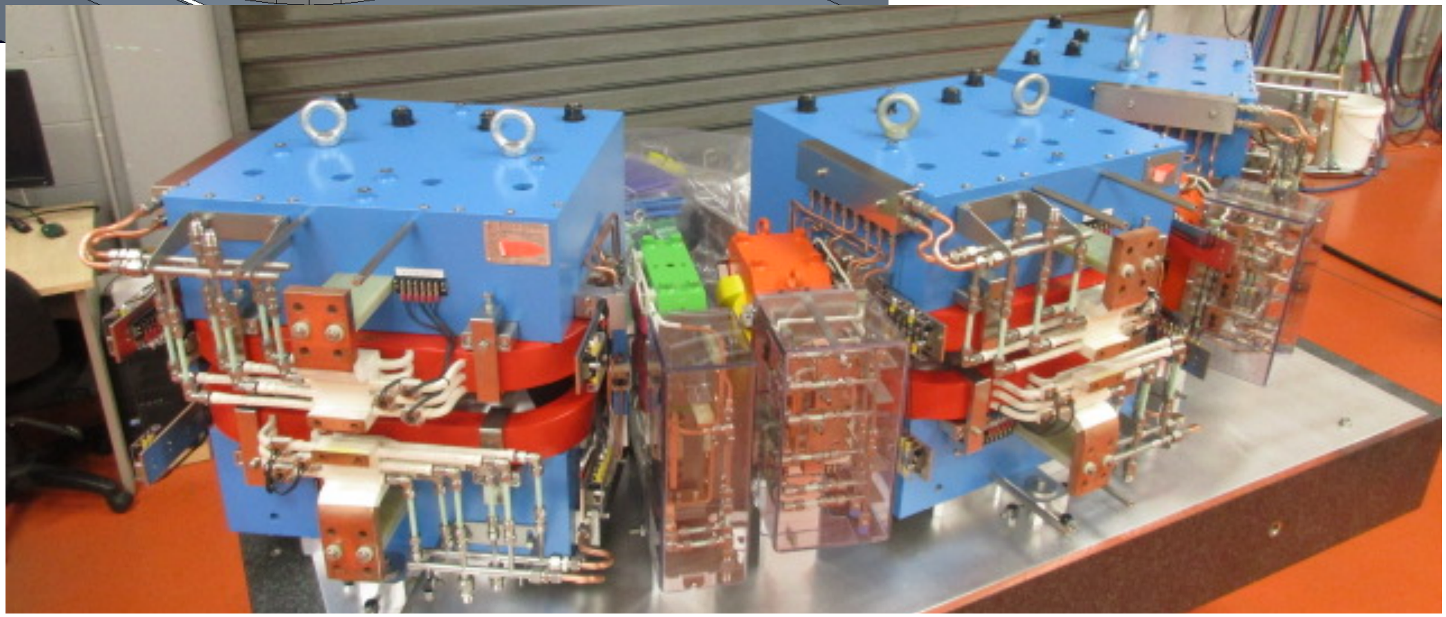


Electron Beam Parameter	Baseline Design	Operational Ranges
Final Energy [GeV]	10	4.0-13.5
Charge per pulse [nC]	2	0.7-5
Repetition Rate [Hz]	30	1-30
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19 [μm]	4.4, 3.2	3-6
Spot Size at IP $\sigma_{x,y}$ [μm]	18, 12	5-20
Min. Bunch Length σ_z (rms) [μm]	1.8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

Positron Capability is Designed and Prototyped





Positron capability expected to be restored on 2022 timeframe

Worldwide Theoretical Studies on Positron PWFA are Focused on Beam Parameters Anticipated at FACET-II

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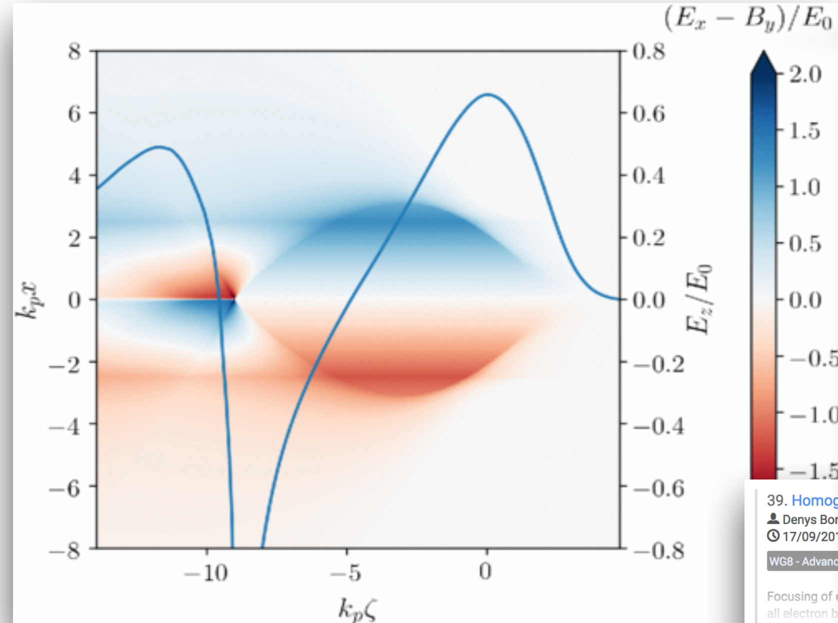


New regime for positron PWFA being proposed

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

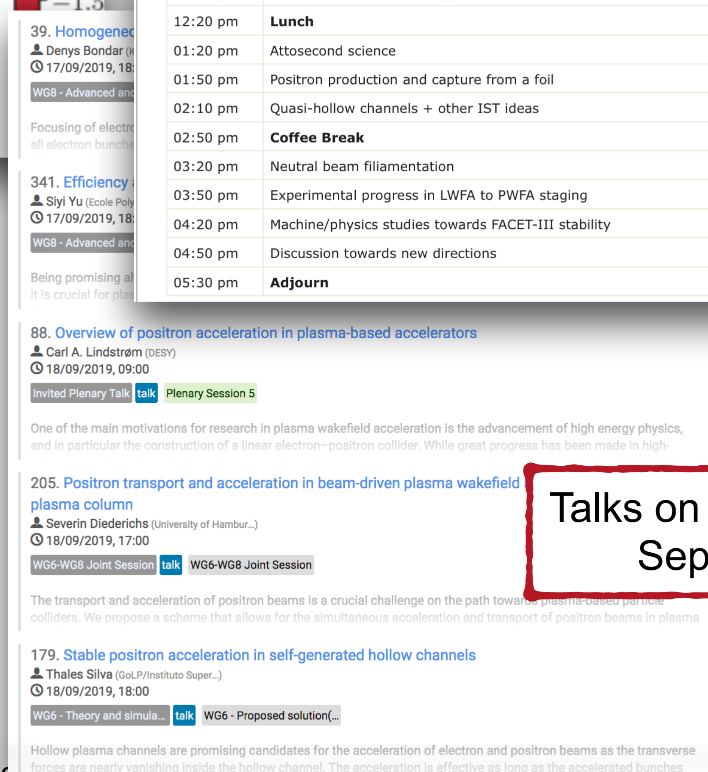
Positron PWFA Agenda at 2019 FACET-II Science Workshop

Tuesday | Wednesday | Thursday | Friday

Developing the science case for positrons and other upgrades: On the third day, the first goal is to clarify the science case for positrons. The second goal is to discuss ideas for new experiments and to understand the match to FACET-II capabilities. We hope through discussions to see an evolution of the experimental needs that improve chances for a positive review of potential proposals at the next Program Advisory Committee Meeting.

To listen in via zoom meeting: **https://stanford.zoom.us/j/514840095**

Start Time	Presentation	Presenter	Affiliation
09:00 am	**Summary of FNAL Crystal Workshop & Opportunities @ FACET-II**	Vladimir Shiltsev	FNAL
09:30 am	Roadmap towards linear colliders based on plasma accelerators	Mark Hogan	SLAC
09:45 am	New directions in positron acceleration research	Spencer Gessner	SLAC
10:30 am	**Coffee Break**		
11:00 am	Transversely tailored plasmas	Severin Diederichs	LBNL/DESY
11:30 am	Transversely tailored plasmas	Shiyu Zhou	UCLA
12:00 pm	Non-linear hollow channel plasmas	Spencer Gessner	SLAC
12:20 pm	**Lunch**		
01:20 pm	Attosecond science	Agostino Marinelli	SLAC
01:50 pm	Positron production and capture from a foil	Hiroki Fuji	UCLA
02:10 pm	Quasi-hollow channels + other IST ideas	Thales Silva	IST
02:50 pm	**Coffee Break**		
03:20 pm	Neutral beam filiamentation	Frederico Fiuza	SLAC
03:50 pm	Experimental progress in LWFA to PWFA staging	Sebastien Corde	Ecole Polytechnique
04:20 pm	Machine/physics studies towards FACET-III stability	Claudio Emma	SLAC
04:50 pm	Discussion towards new directions		
05:30 pm	**Adjourn**		



Talks on Positron PWFA at EAAC September 16-20, 2019

Positron Acceleration in Plasma Doesn't Have to Be a Spooky Subject…