Roadmap towards Colliders:

Strategy in the USA

ANAR2017: Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop 2017

CERN; April 25-28, 2017

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Chair, U.S. High Energy Physics Advisory Panel

Thank you's to …

This presentation is based upon the *Advanced Accelerator Concepts Research Roadmap Workshop Report* (Feb. 2016).

Thank you to the participants in that workshop and its preparatory workshops.

Thank you also to those who provided me updates for this presentation:

Mark Hogan
Wim Leemans
John Power
Vitaly Yakimenko

Apologies:

- I'm an experimental particle physicist, not an accelerator scientist.
- Please forgive my misunderstandings and mistakes.

Thank you also to the ANAR2017 organizers for inviting me for this presentation.

Introduction

In the U.S., the advanced accelerator concepts research program is driven by the future needs of the particle physics research program.

- The future needs are outlined in the long-term vision articulated by the 2014 *Strategic Plan for U.S. Particle Physics in the Global Context*.
  - also known as the “P5 plan”.
- The other benefits of AAC research are appreciated and considered; however, the needs of HEP provide the essential motivation for funding.

Outline of this presentation:

- Introduction
- Background
  - The 2014 P5 Report
  - The 2015 ARD Subpanel Report
- Advanced Accelerator Concepts Research Roadmap Workshop
  - Workshop introduction
  - Common challenges
  - Roadmaps: LWFA, PWFA, DWFA
  - Synergies & Simulation
- Some updates since workshop (if time allows)
- Summary & Conclusions

BACKGROUND - I

The 2014 P5 Report

2014 P5 Report - 1

In the U.S., development of advanced acceleration concepts is supported by:

- DOE Office of High Energy Physics General Accelerator R&D program
- NSF Accelerator Science program
- (Note: There is also the potential for support via the DOE Office of Science Accelerator Stewardship program.)

In the U.S., the strategic plan is developed by a community-driven planning process that culminates in a report formulated by a Particle Physics Project Prioritization Panel (P5), which is a “subpanel” of the High Energy Physics Advisory Panel (HEPAP) that advises the U.S. DOE Office of High Energy Physics and the NSF Directorate for Mathematical and Physical Sciences.

- Note well: The P5 strategic plan prioritized U.S. particle physics activities. It did so in a global context; however, there is no intention for the P5 plan to serve as an international prioritization.

The 2014 P5 report: “Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context”

- P5 recognized in its report the critical role played by accelerators and the crucial need for accelerator R&D.

2014 P5 Report - 2

- P5 stated that *“The motivation for future-generation accelerators must be the science Drivers.”*
  - This statement was made in the context of a budget-driven prioritization of the activities across the field of particle physics.
- P5 listed future-generation accelerators in order of the strength of their physics cases:
  - Very high-energy proton-proton collider (~100 TeV)
    - *“the most powerful future tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window”* [the next 10 years]
    - Led to the recommendation that, *“… Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.”*
  - Multi-TeV *e+e-* collider collider
    - Could be based on CLIC or plasma-based wakefield technology
    - Could be an energy upgrade of the ILC or located elsewhere
  - Neutrino factory
  - Muon Collider
- Note: P5 did not consider ILC to be “future-generation”.
- Note: A push for a gamma-gamma collider did not emerge from the U.S. community study. I would say that, while a gamma-gamma collider offers special physics opportunities, the array of physics opportunities of a gamma-gamma collider does not match that of a VHEPP collider or a Multi-TeV lepton collider.

A Picture of Possible Future HEP Facilities

	HADRON COLLIDERS	LEPTON COLLIDERS	INTENSITY FRONTIER
CURRENT PROGRAM	LHC		PIP
	HL-LHC	ILC	PIP-II
NEXT STEPS			
	Very high-E p-p collider	~1 TeV ILC upgrade*	Multi-MW proton beam
POSSIBLE FURTHER FUTURE	* dependent upon how physics unfolds		
		Multi-TeV lepton collider*	Neutrino factory*

2014 P5 Report - 3

“The future of particle physics depends critically on transformational accelerator R&D to enable new capabilities and to advance existing technologies at lower cost.”

In recognizing the crucial importance of accelerator R&D, P5 recommended:

- *“Pursue accelerator R&D at levels consistent with budget constraints.*
- *Align the present R&D program with the P5 priorities and long-term vision, with an appropriate balance*
  - *among general R&D, directed R&D, and accelerator test facilities*
  - *and among short-, medium-, and long-term efforts.*
- *Focus on outcomes and capabilities that will dramatically improve cost effectiveness of mid-term and far-term accelerators.”*

P5 suggested a HEPAP subpanel on accelerator R&D to provide detailed guidance on implementation of accelerator R&D aligned with P5 priorities.

BACKGROUND - II

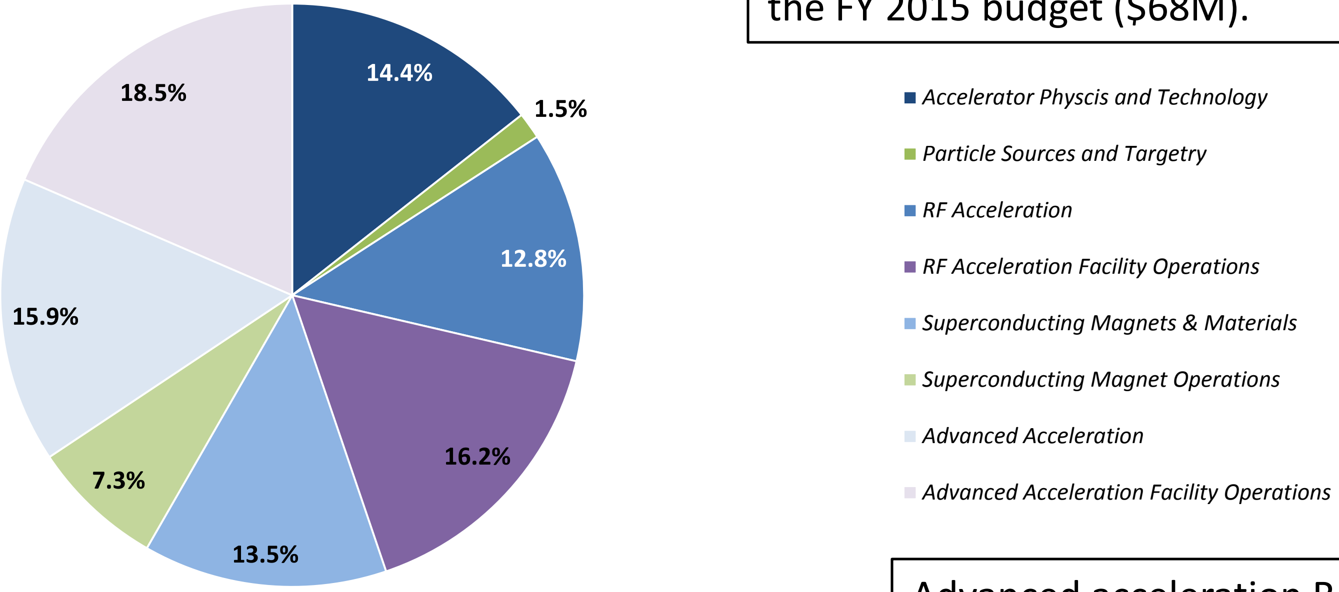
The 2015 ARD Subpanel Report

2015 ARD Subpanel Report - 1

Following P5's advice, DOE convened the HEPAP Accelerator R&D Subpanel.

- Recall the recommendation of P5 to:
  - Align the ARD program with P5 priorities and long-term vision.
  - Focus on outcomes that will dramatically improve cost-effectiveness.

Subpanel was charged to work within the FY 2015 budget ($68M).



Accelerator R&D thrusts within the GARD program.

Advanced acceleration R&D and its facilities operations is 1/3 of GARD. (Facilities construction is in addition.)

2015 ARD Subpanel Report - 2

In considering Advanced Acceleration R&D, the subpanel examined:

- Wakefield acceleration in plasmas
  - PWFA – beam-driven
  - LWFA – laser-driven
- Dielectric Wakefield Acceleration – DWFA
- Direct Laser Acceleration – DLA
  - With dielectric structures, or
  - Inverse free-electron laser (IFEL) mechanism

High-gradient NCRF & SRF were examined separately.

Target application for HEP = Multi-TeV *e+/e-* collider

Discussed a “stepping stone” demonstration project at a few-GeV

- Such as an ultra-compact FEL light source.
- An opportunity to explore beam quality and system feasibility issues.

2015 ARD Subpanel Report - 3

Major Advanced Acceleration R&D Facilities at U.S. National Labs:

On-campus university labs also exist.

- **FACET → FACET II - SLAC**
  - User facility
  - High-charge, short-pulse, small-emittance, ~10 GeV e+/e- beam
  - Focus of PWFA research; also DWFA research
  - (Note: report written as FACET operations were finishing and before FACET-II approval)
- **BELLA - LBNL**
  - Dedicated LWFA experiments and applications of LWFAs
  - >40J, 30fs, 1Hz for collider relevant studies, & 2 new 100 TW (3 J), 5 Hz lasers for FEL and for Thomson scattering γ-ray sources
  - Second beam-line on BELLA (requested) for staging, and k-BELLA concept for future kHz operations (requested)
- **AWA – Argonne Wakefield Accelerator**
  - Built to demonstrate two-beam acceleration (150-500 MV/m, 10-60 GHz range)
  - Expanding User Facility role to include PWFA, collinear wakefield acceleration, etc.
  - High-charge 75 MeV x 100nC drive beam; High Brightness 15 MeV witness beam; Longitudinal Bunch Shaping capability with emittance exchange beamline
- **ATF & ATF-II - BNL**
  - User facility
  - Supports research in novel acceleration techniques (DWFA, DLA, LWFA, etc.), high brightness radiation sources, ion generation/acceleration, beam manipulation/characterization, UED, etc.
  - 80 MeV high-brightness e- beams (up to 2nC), unique mid-IR TW-class laser beams, multiple experimental beam lines

Facilities operations cost (slightly) more than advanced acceleration R&D.

2015 ARD Subpanel Report - 4

The ARD Subpanel commented:

- *“For any of these approaches to advanced acceleration, the following facilities will likely be needed in order to make significant intermediate steps toward the eventual goal of a multi-TeV e+e- collider:*
  1. *a flexible, dedicated R&D facility, with a witness beam and a number of drive beams, either laser or particle as appropriate to the approach, for staging experiments; and*
  2. *a demonstration facility based upon the advanced acceleration approach, with beam characteristics scalable to future colliders.”*

The significant cost of R&D facilities strongly influences the roadmap for advanced accelerator R&D.

- Makes difficult (expensive) pursuit of multiple approaches in parallel.
- Drives early (too early?) down-selection of approaches.
- Cost strongly influenced the ARD Subpanel, which was charged to meet specific budget scenarios.
- An international AARD program, with some level of international coordination, is more capable of mounting the future facilities needed to explore multiple promising approaches.

2015 ARD Subpanel Report - 5

HEPAP Accelerator R&D Subpanel recommendations on Advanced Acceleration:

“Even with some relaxation of the present, tight budget constraints, some consolidation into joint test facilities would be required.
“Under the most constrained funding scenario, culling of the least promising approaches would be necessary.”

Recommendations:

- PWFA
    - *“Vigorously pursue particle-driven plasma wakefield acceleration of positrons at FACET in the time remaining for the operation of the facility.*
    - *“Between the closing of FACET and the operation of a follow-on facility, preserve the momentum of particle-driven wakefield acceleration research using other facilities.”*
- LWFA – *“Continue to support laser-driven plasma wakefield acceleration experiments at BELLA at the current level.”*
- DWFA – no recommendation
- DLA – *“Reduce funding for direct laser acceleration research activities.”*

  “The potential advantages of structure-based DLA have not been demonstrated.”

2015 ARD Subpanel Report - 6

Another recommendation (Recommendation 10):

- *“Convene the university and laboratory proponents of advanced acceleration concepts to develop R&D roadmaps with a series of milestones and common down-selection criteria towards the goal of constructing a multi-TeV e+e- collider.”*

This recommendation motivated the *DOE Advanced Accelerator Concepts Research Roadmap Workshop* (2-3 February 2016).

Under improved budget scenarios, an additional recommendation (#C1b):

- *“Develop, construct, and operate a next-generation facility for particle-driven plasma wakefield acceleration research and development, targeting a multi-TeV e+e- collider, in order to sustain this promising and synergistic line of research after the closure of the FACET facility.”*
  - Motivates FACET-II (although not specifically calling for that facility)
  - Does not directly favor PWFA over other approaches; speaks only to next pressing need for an R&D facility.

2015 ARD Subpanel Report - 7

R&D steps needed:

- To determine the most promising acceleration technique
- To further develop the techniques for a practical collider.

1. *“Continue studies of candidate techniques on existing facilities.*

2. *“Convene the advanced acceleration community to develop R&D roadmaps for each candidate technique, with common milestones to the extent possible, and to define criteria to be used in the down-selection of techniques.*

3. *“Based on successful results of R&D on existing facilities, build next-generation R&D facilities for selected candidate technologies.*
    a) *“The first next-generation R&D facility will be the successor to FACET for PWFA research. The need to move forward on this facility is immediate because of the impending closure of FACET.*
    b) *“A next-generation R&D facility for LWFA research is likely to be the next new facility needed after the next-generation PWFA facility. It will have higher repetition rate than BELLA in order to begin to understand plasma lifetime issues.*

(cont’d.)

2015 ARD Subpanel Report - 8

4. *“Down-selection should occur as early as possible after an adequate basis for the selection exists.*

   “The two facilities above are likely to be needed before the down-selection.

   “Down-selection to a single technique is desirable; however, an initial down-selection leaving two techniques may also be done.

5. *“Next-to-next-generation R&D facilities may be needed by one or more techniques before down-selection.*

   “For instance, if the currently proposed FACET-II is constructed as the next-generation R&D facility for PWFA, a successor facility will be needed to study staging of several plasma channels. Emittance preservation is the key concern in matching one channel to the next.

(cont’d.)

2015 ARD Subpanel Report - 9

6. *“After down-selection to a single technique, and when enough R&D has been performed that the technique can be developed for a multi-TeV collider, a demonstration facility based upon the selected acceleration technique should be constructed in order to demonstrate the technology on a scale that gives the confidence that further scaling can be done to the multi-TeV scale of the e+e- collider.*

   “This demonstration facility could perhaps be designed for an application for discovery science, for instance as a driver for an x-ray laser.

   “The demonstration facility should have beam characteristics scalable to future colliders.

7. The demonstration facility is the last step in the R&D program.

   “Following successful demonstration, one can then embark on the full technical design of a multi-TeV e+e- collider.”

2015 ARD Subpanel Report - 10

Membership of the HEPAP Acceleratory R&D Subpanel:

Bill Barletta (FNAL, MIT)
Ilan Ben-Zvi (BNL, Stony Brook)
Marty Breidenbach (SLAC)
Oliver Bruning (CERN)
Bruce Carlsten (LANL)
Roger Dixon (FNAL)
Steve Gourlay (LBNL)
Don Hartill (Cornell) - Chair
Georg Hoffstaetter (Cornell)
Zhirong Huang (SLAC)

Young-Kee Kim (Chicago)
Tadashi Koseki (KEK, J-PARC)
Geoff Krafft (JLab)
Andy Lankford (UCI) - *ex officio*
Lia Merminga (TRIUMF)
Jamie Rosenzweig (UCLA)
Mike Syphers (MSU)
Bob Tschirhart (FNAL)
Rik Yoshida (ANL)

(Listed institutions are as of time of report.)

Accelerating Discovery: A Strategic Plan for Accelerator R&D in the U.S.
(https://science.energy.gov/~/media/hep/hepap/pdf/Reports/Accelerator_RD_Subpanel_Report.pdf)

P5 accelerator experts:
Wim Leemans (LBNL)
Lia Merminga (TRIUMF)
Steve Peggs (BNL)

Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context
(https://science.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_Interactive_060214.pdf)

Advanced Accelerator Concepts Research Roadmap Workshop

AAC Roadmap Workshop

Advanced Accelerator Concepts Roadmap Workshop – February 2-3, 2016

- Convened by DOE
- Motivated by recommendation of HEPAP Accelerator R&D Subpanel
  - *“Convene the university and laboratory proponents of advanced acceleration concepts to develop R&D roadmaps with a series of milestones and common down-selection criteria towards the goal of constructing a multi-TeV e+e- collider.”*
- This workshop was preceded by a number of preparatory workshops.

Workshop outline:

- Presentation of individual roadmaps for PWFA, LWFA, DWFA.
- Talks on synergies between the roadmaps, and with global efforts
- Talks on potential early applications, diagnostic needs, simulation needs, and beam issues and challenges related to a collider.
- Discussion of individual roadmaps with emphasis on the next 5-10 years and common challenges.

Assumptions:

- The primary long-term goal is a multi-TeV *e+e-* collider.
  - The ideal timescale is set by a TDR in 2035-2040 timeframe, following the end of the LHC program.
- As an intermediate goal, a TDR for a potential early application, such as an XFEL or gamma-ray source.

Workshop report:

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

AAC Roadmap Workshop Attendees

Attendees:

- Expert proponents of PWFA, LWFA, DWFA
- Invited accelerator science experts from universities and laboratories

Invited participants:

Thomas Antonsen (Maryland)
Ilan Ben-Zvi (BNL, Stony Brook)
Jerry Blazey (NIU)
Yunhei Cai (SLAC)
Weiren Chou (FNAL)
Michael Downer (Texas-Austin)
Wei Gai (ANL)
Carl Schroeder (LBNL)
Mark Hogan (SLAC)
Chungguang Jing (ANL/Euclid)
Chan Joshi (UCLA)
Wim Leemans (LBNL)
Michael Litos (SLAC)
Sergei Nagaitsev (FNAL)
James Rosenzweig (UCLA)
Andrei Seryi (John Adams Inst.)
Bill Weng (BNL)

Other participants:

L.K. Len (DOE)
G. Crawford (DOE)
E. Colby (DOE)
A. Lankford (HEPAP)
J. Siegrist (DOE)
J. Boger (DOE)
K. Marken (DOE)
V. Lukin (NSF)

AAC Roadmap – Common Challenges

The workshop identified a set of common challenges as focus for next 10 years:

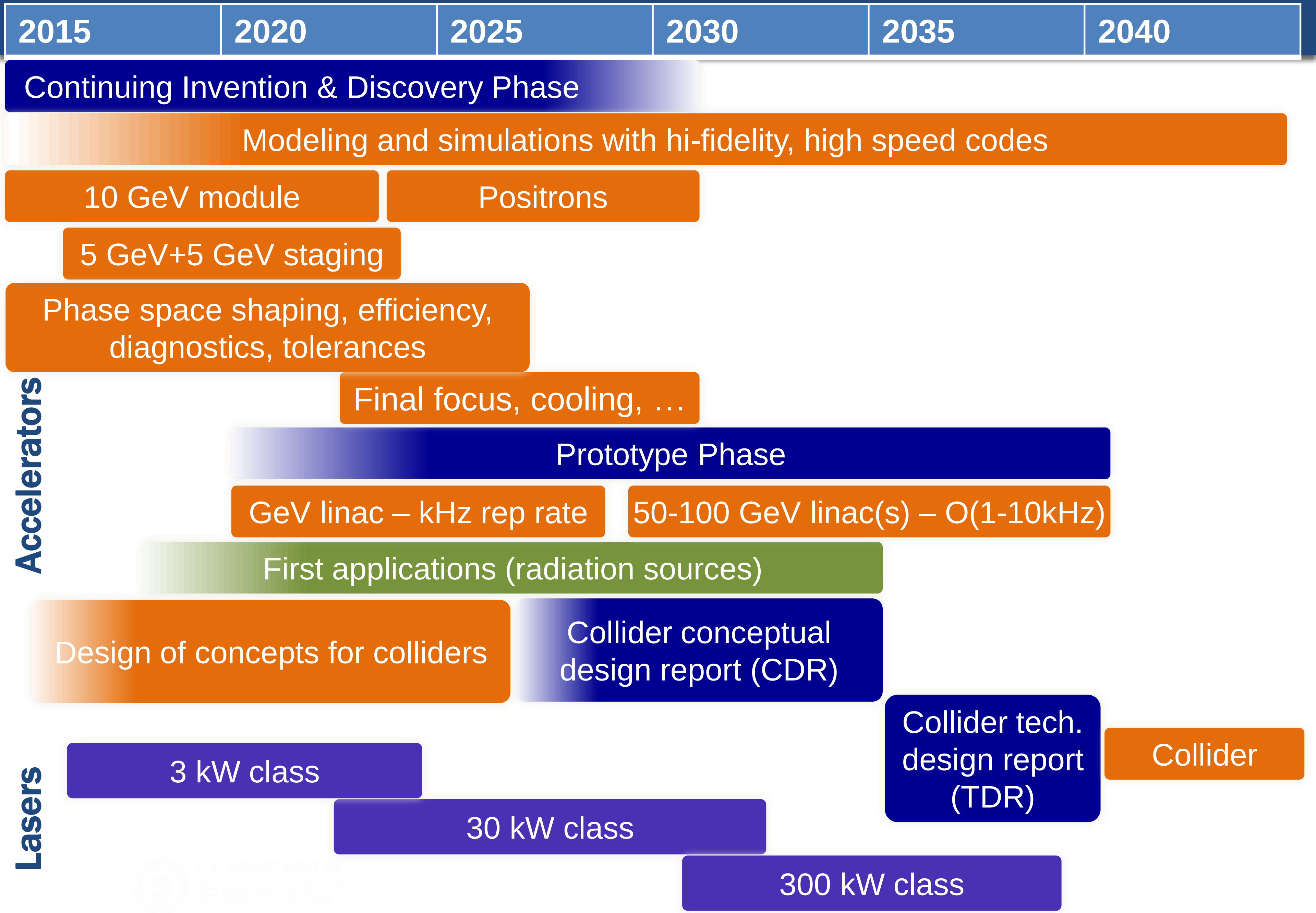
1. *Staging:*
   Higher energy staging of *e*- acceleration, with independent drive beams, equal energy, and 90% beam capture.

   (“Higher energy” means multi-GeV for LWFA & PWFA and multiple-100 MeV for DWFA.)
2. *Emittance:*
   Understanding mechanisms for emittance growth and developing methods for achieving emittances compatible with colliders.
3. *A complete e- acceleration stage:*
   Completion of a single *e*- acceleration stage at higher energy.
4. *Positron acceleration:*
   Demonstration and understanding of *e*+ acceleration.
5. *Collider parameter set:*
   Continuous, joint development of a comprehensive and realistic operational parameter set for a multi-TeV collider, to guide operating specifications for AAC.

Three-component program: Experiment + Theory + Modeling

LWFA Roadmap

Preliminary Roadmap for Laser Plasma Accelerators



2015 | 2020 | 2025 | 2030 | 2035 | 2040

Accelerators

Continuing Invention & Discovery Phase

Modeling and simulations with hi-fidelity, high speed codes

10 GeV module

Positrons

5 GeV+5 GeV staging

Phase space shaping, efficiency, diagnostics, tolerances

Final focus, cooling, …

Prototype Phase

GeV linac – kHz rep rate

50-100 GeV linac(s) – O(1-10kHz)

First applications (radiation sources)

Design of concepts for colliders

Collider conceptual design report (CDR)

Collider tech. design report (TDR)

Collider

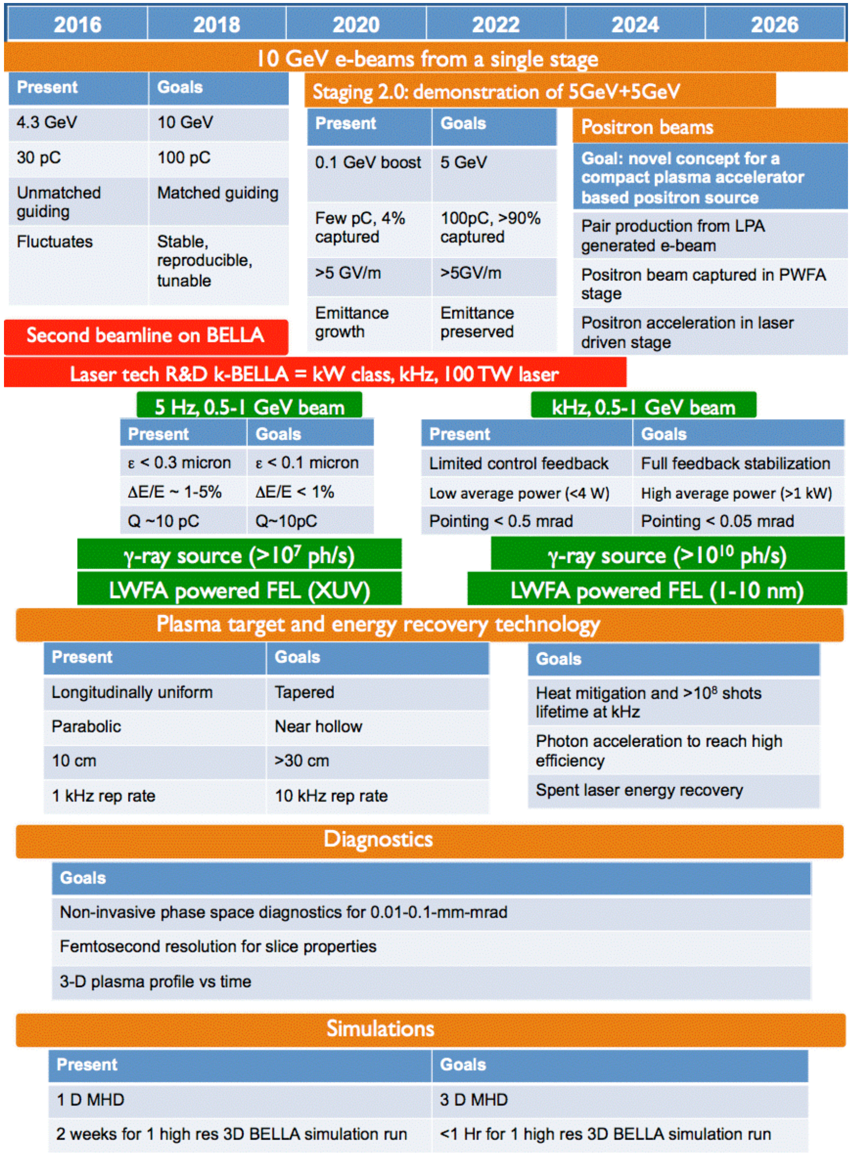
Lasers

3 kW class

30 kW class

300 kW class

LWFA roadmap for 1st 10 years



2016	2018	2020	2022	2024	2026

10 GeV e-beams from a single stage

Present	Goals
4.3 GeV	10 GeV
30 pC	100 pC
Unmatched guiding	Matched guiding
Fluctuates	Stable, reproducible, tunable

Second beamline on BELLA

Staging 2.0: demonstration of 5GeV+5GeV

Present	Goals
0.1 GeV boost	5 GeV
Few pC, 4% captured	100pC, >90% captured
>5 GV/m	>5GV/m
Emittance growth	Emittance preserved

Positron beams

Goal: novel concept for a compact plasma accelerator based positron source
Pair production from LPA generated e-beam
Positron beam captured in PWFA stage
Positron acceleration in laser driven stage

Laser tech R&D k-BELLA = kW class, kHz, 100 TW laser

5 Hz, 0.5-1 GeV beam

Present	Goals
$\varepsilon < 0.3$ micron	$\varepsilon < 0.1$ micron
$\Delta E/E \sim 1$-5%	$\Delta E/E < 1$%
Q ~10 pC	Q~10pC

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Present	Goals
Limited control feedback	Full feedback stabilization
Low average power (<4 W)	High average power (>1 kW)
Pointing < 0.5 mrad	Pointing < 0.05 mrad

γ-ray source (>10^7 ph/s)

LWFA powered FEL (XUV)

γ-ray source (>10^{10} ph/s)

LWFA powered FEL (1-10 nm)

Plasma target and energy recovery technology

Present	Goals
Longitudinally uniform	Tapered
Parabolic	Near hollow
10 cm	>30 cm
1 kHz rep rate	10 kHz rep rate

Goals
Heat mitigation and >10^8 shots lifetime at kHz
Photon acceleration to reach high efficiency
Spent laser energy recovery

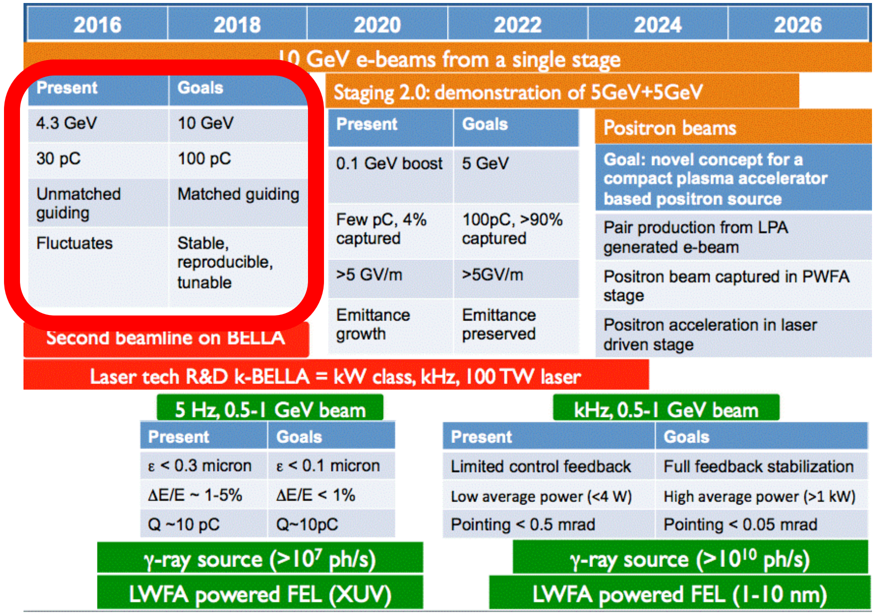
Diagnostics

Goals
Non-invasive phase space diagnostics for 0.01-0.1-mm-mrad
Femtosecond resolution for slice properties
3-D plasma profile vs time

Simulations

Present	Goals
1 D MHD	3 D MHD
2 weeks for 1 high res 3D BELLA simulation run	<1 Hr for 1 high res 3D BELLA simulation run

LWFA roadmap for 1st 10 years



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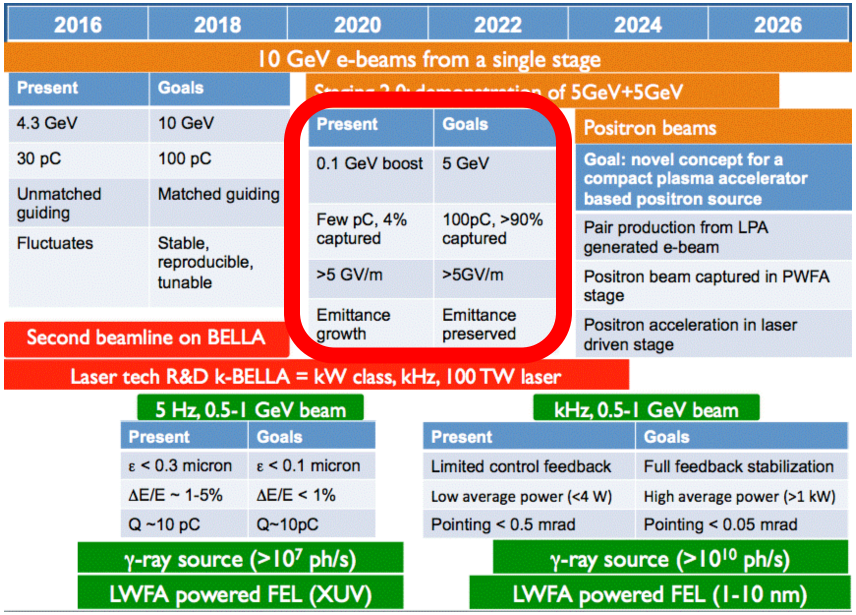

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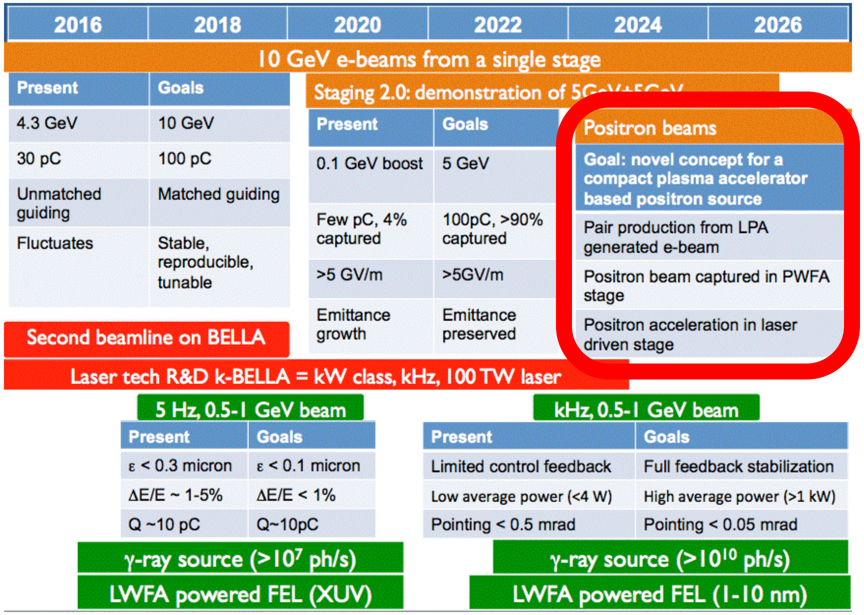
Staging: demo of 5 GeV + 5 GeV

- **Needs second beamline on BELLA**

LWFA roadmap for 1st 10 years



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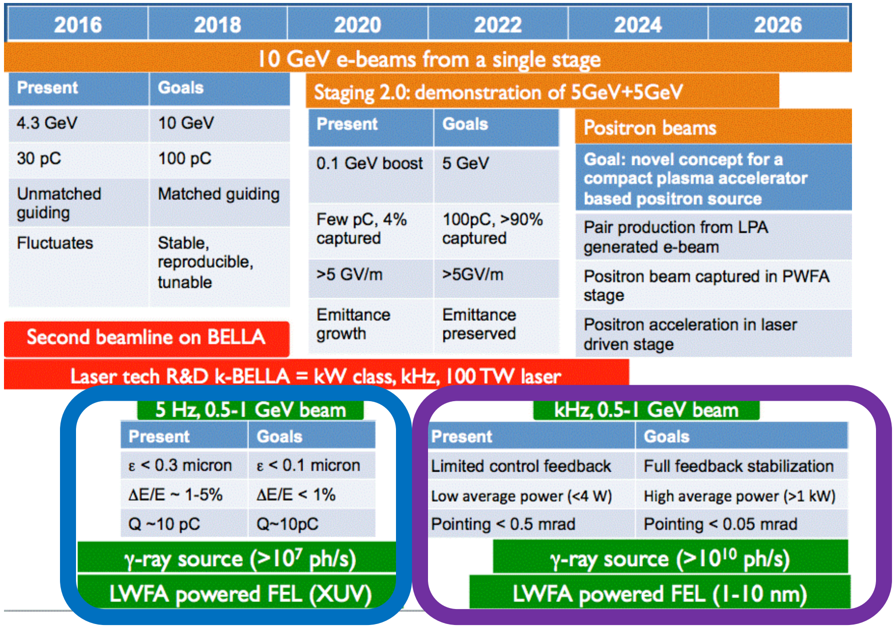

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γ-ray source (>10^{10} ph/s)

LWFA powered FEL (1-10 nm)

10 GeV *e-* beams from a single stage

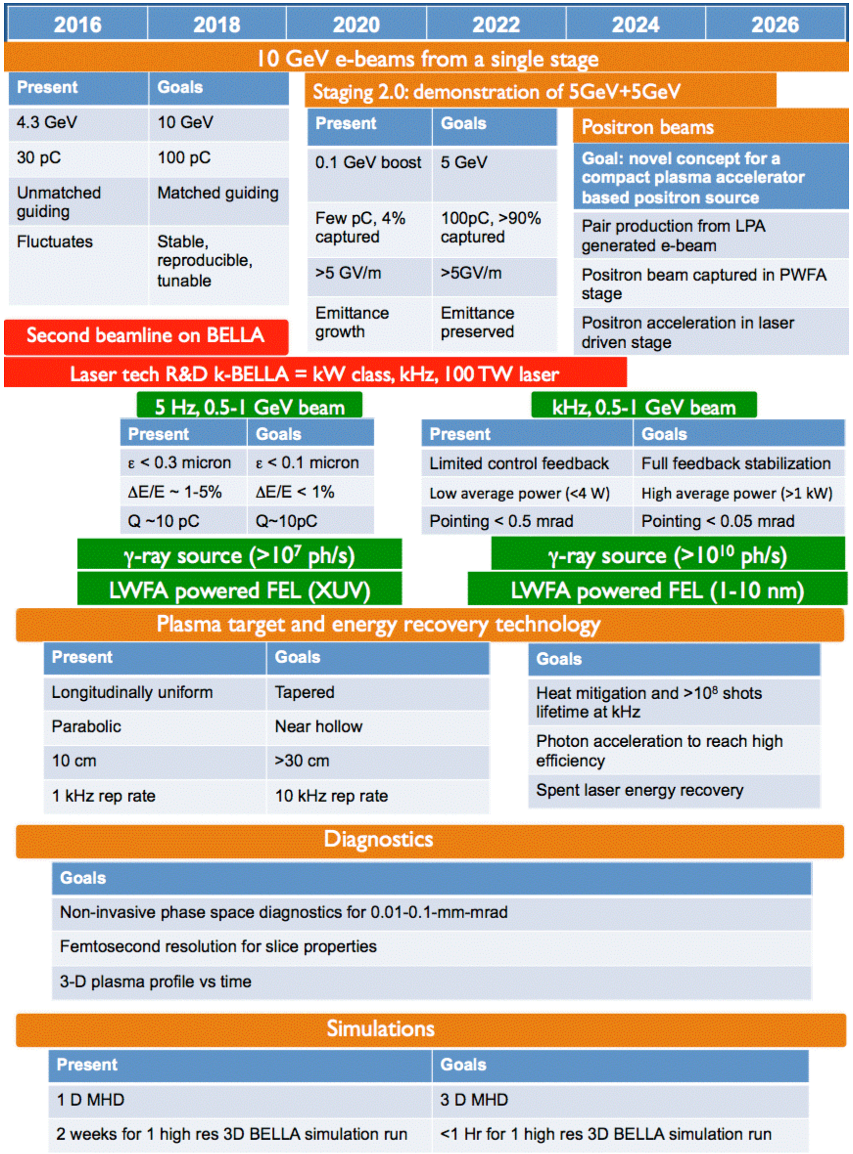
Staging: demo of 5 GeV + 5 GeV

Positron beams

Early application:

- LWFA-powered FEL (XUV)
- LWFA-powered FEL (1-10 nm)

LWFA roadmap for 1st 10 years



2016	2018	2020	2022	2024	2026

10 GeV e-beams from a single stage

Present	Goals
4.3 GeV	10 GeV
30 pC	100 pC
Unmatched guiding	Matched guiding
Fluctuates	Stable, reproducible, tunable

Staging 2.0: demonstration of 5GeV+5GeV

Present	Goals
0.1 GeV boost	5 GeV
Few pC, 4% captured	100pC, >90% captured
>5 GV/m	>5GV/m
Emittance growth	Emittance preserved

Positron beams

Goal: novel concept for a compact plasma accelerator based positron source
Pair production from LPA generated e-beam
Positron beam captured in PWFA stage
Positron acceleration in laser driven stage

Second beamline on BELLA

Laser tech R&D k-BELLA = kW class, kHz, 100 TW laser

5 Hz, 0.5-1 GeV beam

Present	Goals
ε < 0.3 micron	ε < 0.1 micron
ΔE/E ~ 1-5%	ΔE/E < 1%
Q ~10 pC	Q~10pC

kHz, 0.5-1 GeV beam

Present	Goals
Limited control feedback	Full feedback stabilization
Low average power (<4 W)	High average power (>1 kW)
Pointing < 0.5 mrad	Pointing < 0.05 mrad

γ-ray source (>10^7 ph/s)

LWFA powered FEL (XUV)

γ-ray source (>10^{10} ph/s)

LWFA powered FEL (1-10 nm)

Plasma target and energy recovery technology

Present	Goals
Longitudinally uniform	Tapered
Parabolic	Near hollow
10 cm	>30 cm
1 kHz rep rate	10 kHz rep rate

Goals
Heat mitigation and >10^8 shots lifetime at kHz
Photon acceleration to reach high efficiency
Spent laser energy recovery

Diagnostics

Goals
Non-invasive phase space diagnostics for 0.01-0.1-mm-mrad
Femtosecond resolution for slice properties
3-D plasma profile vs time

Simulations

Present	Goals
1 D MHD	3 D MHD
2 weeks for 1 high res 3D BELLA simulation run	<1 Hr for 1 high res 3D BELLA simulation run

10 GeV *e-* beams from a single stage

Staging: demo of 5 GeV + 5 GeV

Positron beams

Early application:

- LWFA-powered FEL (XUV)
- LWFA-powered FEL (1-10 nm)

Plasma target & energy recovery

Diagnostics

Simulations

LWFA Laser roadmap for 1st 10 years

2016	2018	2020	2022	2024	2026

k-BELLA: kW class, kHz, 100 TW laser

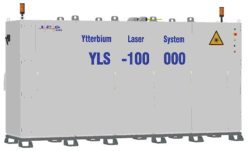
"Stepping stone": 30 kW class

▲ 100mJ/30fs/kW & contrast demo

Fiber Laser Technology

~1J & contrast demo ▲

Present	Goals: near term	Goals: mid term
1-5mJ	100mJ – >1J	30J
~500W	3kW	30kW
~300fs	~30fs	~100fs
Contrast: 10 - 20dB	Contrast 30 - >40dB	Contrast 50 - >60dB

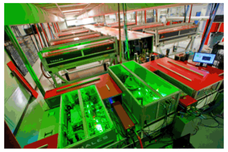


▲ Scaling to 3kW demo

Ti:sapphire

~80% WPE pump laser & power scaling demo ▲

Present	Goals
1-10Hz	1kHz
WPE: << 5 %	WPE: >15%
< 100W	>3kW



k-BELLA: kW class, kHz, 100 TW laser

"Stepping stone": 30 kW class

Common Technologies

▲ Ready for 30kW class laser demo

Goals		
>30kW mirrors and coatings	>30kW and broadband beam combiners	Contrast enhancing technology (e.g. plasma mirrors) operating at >1kHz
>30kW pulse compression gratings	>30kW adaptive optics	

Direct-CPA bulk

Goal: suitable diode-pumped solid-state material meeting pulse duration, energy, average power, and WPE requirement simultaneously

CO_2

100fs with ~25% WPE demo ▲

Goals: increase efficiency and reduce pulse duration simultaneously, increase system reliability and meet size requirements

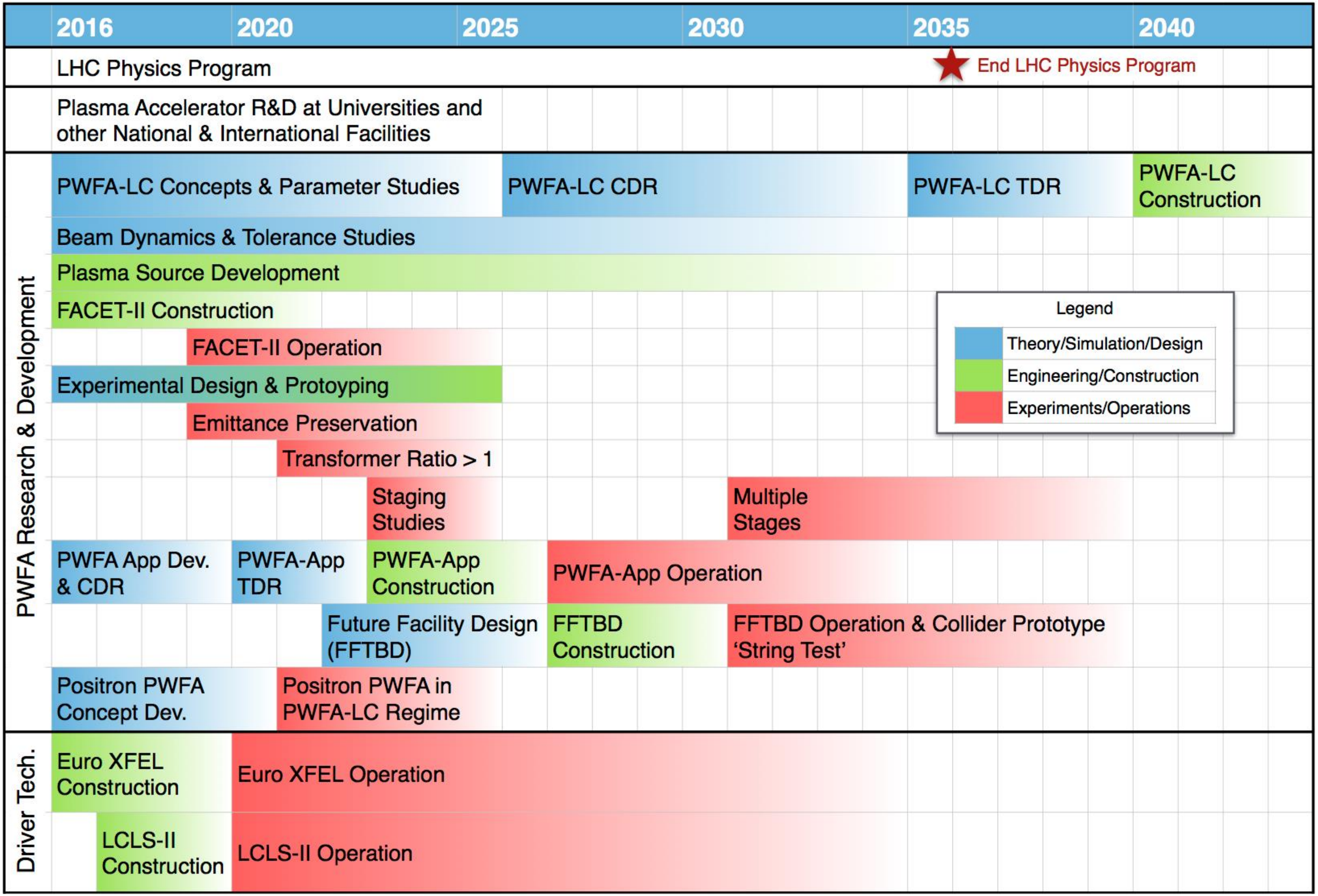
100fs with >25% WPE

OPCPA

Advances are needed in high-average power lasers.

PWFA Roadmap

Beam Driven Plasma Accelerator Roadmap for HEP



2016 2020 2025 2030 2035 2040

LHC Physics Program

End LHC Physics Program

Plasma Accelerator R&D at Universities and other National & International Facilities

PWFA Research & Development

PWFA-LC Concepts & Parameter Studies

PWFA-LC CDR

PWFA-LC TDR

PWFA-LC Construction

Beam Dynamics & Tolerance Studies

Plasma Source Development

FACET-II Construction

FACET-II Operation

Experimental Design & Protoyping

Emittance Preservation

Transformer Ratio > 1

Staging Studies

Multiple Stages

PWFA App Dev. & CDR

PWFA-App TDR

PWFA-App Construction

PWFA-App Operation

Future Facility Design (FFTBD)

FFTBD Construction

FFTBD Operation & Collider Prototype ‘String Test’

Positron PWFA Concept Dev.

Positron PWFA in PWFA-LC Regime

Driver Tech.

Euro XFEL Construction

Euro XFEL Operation

LCLS-II Construction

LCLS-II Operation

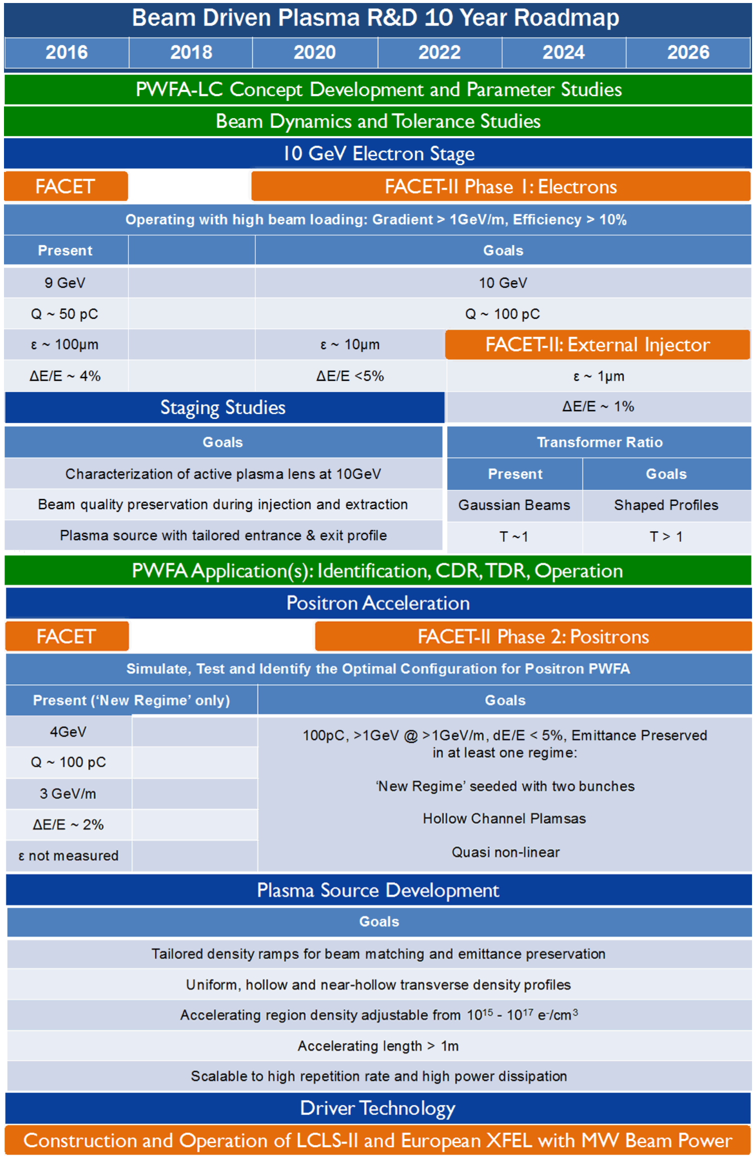
Legend

🟦 Theory/Simulation/Design

🟩 Engineering/Construction

🟥 Experiments/Operations

PWFA Roadmap for 1st 10 years



Beam Driven Plasma R&D 10 Year Roadmap

2016	2018	2020	2022	2024	2026

PWFA-LC Concept Development and Parameter Studies

Beam Dynamics and Tolerance Studies

10 GeV Electron Stage

FACET | FACET-II Phase 1: Electrons

Operating with high beam loading: Gradient > 1GeV/m, Efficiency > 10%

Present		Goals	
9 GeV		10 GeV	
Q ~ 50 pC		Q ~ 100 pC	
ε ~ 100μm		ε ~ 10μm	FACET-II: External Injector
ΔE/E ~ 4%		ΔE/E <5%	ε ~ 1μm
			ΔE/E ~ 1%

Staging Studies

Goals
Characterization of active plasma lens at 10GeV
Beam quality preservation during injection and extraction
Plasma source with tailored entrance & exit profile

Transformer Ratio

Present	Goals
Gaussian Beams	Shaped Profiles
T ~1	T > 1

PWFA Application(s): Identification, CDR, TDR, Operation

Positron Acceleration

FACET | FACET-II Phase 2: Positrons

Simulate, Test and Identify the Optimal Configuration for Positron PWFA

Present ('New Regime' only)		Goals
4GeV		100pC, >1GeV @ >1GeV/m, dE/E < 5%, Emittance Preserved in at least one regime:
Q ~ 100 pC		'New Regime' seeded with two bunches
3 GeV/m		Hollow Channel Plamsas
ΔE/E ~ 2%		Quasi non-linear
ε not measured		

Plasma Source Development

Goals
Tailored density ramps for beam matching and emittance preservation
Uniform, hollow and near-hollow transverse density profiles
Accelerating region density adjustable from 10^{15} - 10^{17} e^-/cm^3
Accelerating length > 1m
Scalable to high repetition rate and high power dissipation

Driver Technology

Construction and Operation of LCLS-II and European XFEL with MW Beam Power

Most pressing subjects:

- Emittance preservation
- Positron acceleration

Additional priorities:

- Beam loading
- Higher transformer ratios
- Beam dynamics & tolerances
- Plasma source development
- Staging
- First applications

Program is shaped by availability of facilities.

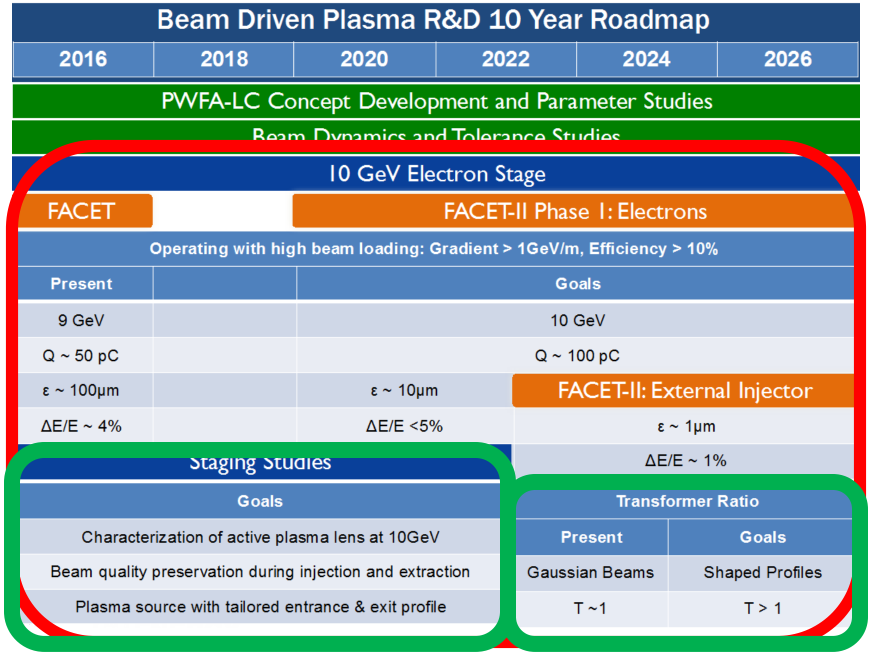
- FACET-II Phase 1 – electrons
- FACET-II Phase 2 – positrons
- FACET-II w/ external injector

Throughout the 10-years:

- LC concept development
- Beam dynamics & tolerance studies
- Early applications development

Program benefits from megawatt-class high-energy electron beams for LCLS-II & XFEL.

10-year PWFA Roadmap - 1



Beam Driven Plasma R&D 10 Year Roadmap

2016	2018	2020	2022	2024	2026

PWFA-LC Concept Development and Parameter Studies

Beam Dynamics and Tolerance Studies

10 GeV Electron Stage

FACET

FACET-II Phase I: Electrons

Operating with high beam loading: Gradient > 1GeV/m, Efficiency > 10%

Present		Goals	
9 GeV		10 GeV	
Q ~ 50 pC		Q ~ 100 pC	
ε ~ 100μm		ε ~ 10μm	FACET-II: External Injector
ΔE/E ~ 4%		ΔE/E <5%	ε ~ 1μm
			ΔE/E ~ 1%

Staging Studies

Goals
Characterization of active plasma lens at 10GeV
Beam quality preservation during injection and extraction
Plasma source with tailored entrance & exit profile

Transformer Ratio

Present	Goals
Gaussian Beams	Shaped Profiles
T ~1	T > 1

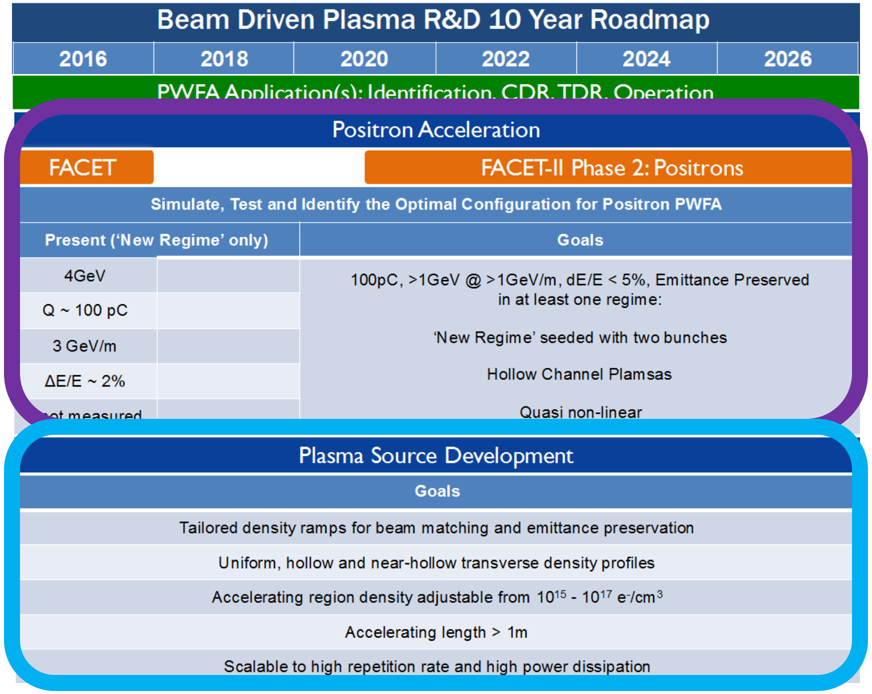
Complete 10-GeV electron stage

- FACET-II will enable next step in gradient and beam quality
- FACET-II external injector will enable further improvements (in emittance & energy spread)

Staging studies

- Independent witness beam injector

10-year PWFA Roadmap - 2



Beam Driven Plasma R&D 10 Year Roadmap

2016	2018	2020	2022	2024	2026

PWFA Application(s): Identification, CDR, TDR, Operation

Positron Acceleration

FACET

FACET-II Phase 2: Positrons

Simulate, Test and Identify the Optimal Configuration for Positron PWFA

Present ('New Regime' only)		Goals
4GeV		100pC, >1GeV @ >1GeV/m, dE/E < 5%, Emittance Preserved in at least one regime: 'New Regime' seeded with two bunches Hollow Channel Plamsas Quasi non-linear
Q ~ 100 pC		
3 GeV/m		
ΔE/E ~ 2%		
not measured		

Plasma Source Development

Goals
Tailored density ramps for beam matching and emittance preservation
Uniform, hollow and near-hollow transverse density profiles
Accelerating region density adjustable from 10^{15} - 10^{17} e^-/cm^3
Accelerating length > 1m
Scalable to high repetition rate and high power dissipation

Positrons

- FACET-II Phase 2 will enable next step in positron acceleration.

Plasma source development

DWFA Roadmap

DWFA Roadmap

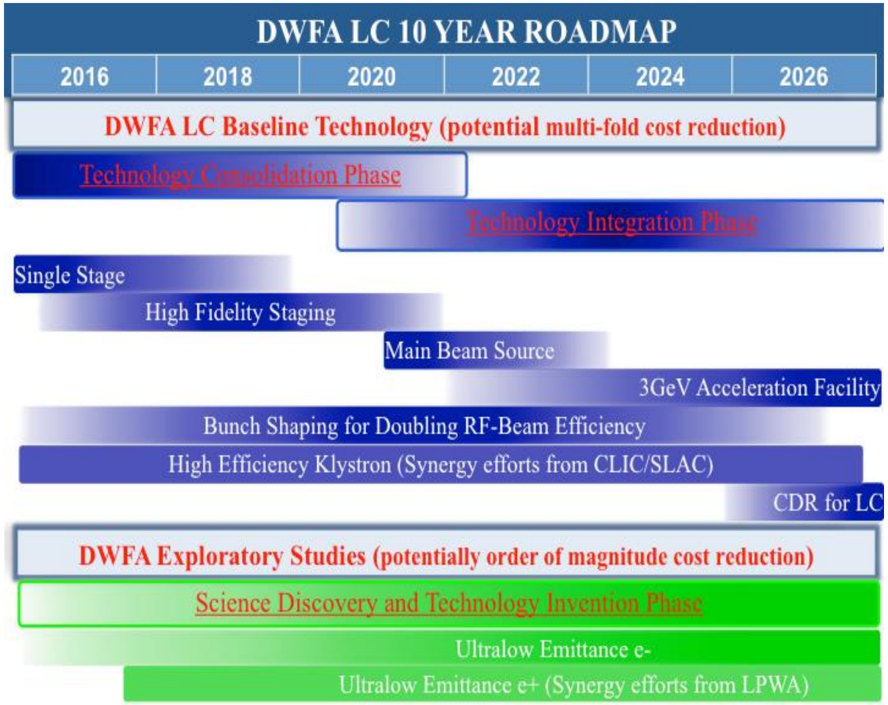
R&D primarily on dielectric two-beam acceleration:

- Several critical technology elements can draw upon CLIC or ILC designs:
  - Polarized *e+* and *e-* sources
  - Beam delivery system and appropriate main-beam parameters at IP
- The other critical technology elements are focus of current R&D:
  - Main (witness) beam acceleration
  - Drive beam power source
  - Staging of multiple accelerations structures to high energy

Goals:

- 300 MV/m gradient
- Low-cost dielectric structures
- Simple drive-beam based power source
- Main bunch shaping for high efficiency
- High-efficiency klystrons
- Multi-fold cost reduction compared to current LC technology

DWFA Roadmap



Note: the color fading is proportional to the effort. Timeline is subject to funding level. Cost reduction compared to current LC technology

2016-21 – Technology Consolidation Phase

2021-26 – Technology Integration Phase

2016-21 – Technology Consolidation Phase

- **Single stage**
- **High Fidelity Staging**

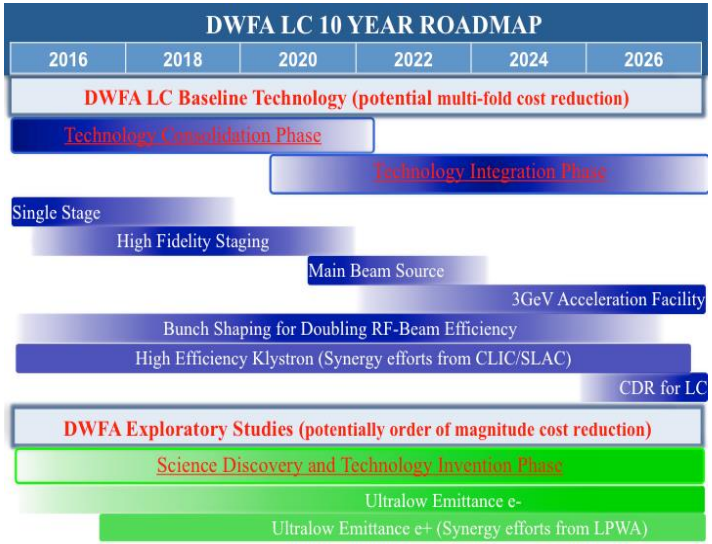
2021-26 – Technology Integration Phase

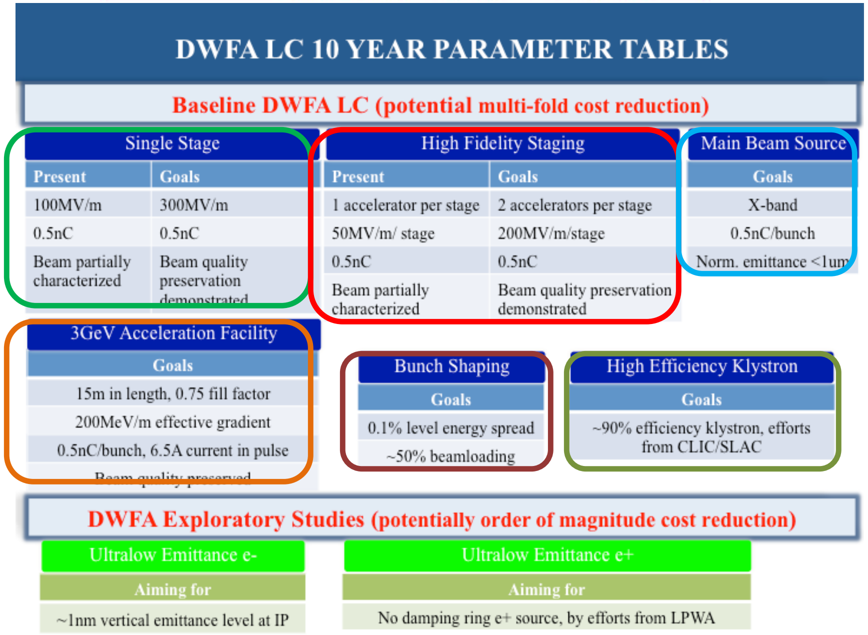
- **Main Beam Source**
- **3-GeV Acceleration Facility**

Ongoing:

- **Bunch Shaping**
- **High Efficiency Klystron**

DWFA Roadmap





DWFA LC 10 YEAR PARAMETER TABLES

Baseline DWFA LC (potential multi-fold cost reduction)

Single Stage	
Present	**Goals**
100MV/m	300MV/m
0.5nC	0.5nC
Beam partially characterized	Beam quality preservation demonstrated

High Fidelity Staging	
Present	**Goals**
1 accelerator per stage	2 accelerators per stage
50MV/m/ stage	200MV/m/stage
0.5nC	0.5nC
Beam partially characterized	Beam quality preservation demonstrated

Main Beam Source
Goals
X-band
0.5nC/bunch
Norm. emittance <1um

3GeV Acceleration Facility
Goals
15m in length, 0.75 fill factor
200MeV/m effective gradient
0.5nC/bunch, 6.5A current in pulse
Beam quality preserved

Bunch Shaping
Goals
0.1% level energy spread
~50% beamloading

High Efficiency Klystron
Goals
~90% efficiency klystron, efforts from CLIC/SLAC

DWFA Exploratory Studies (potentially order of magnitude cost reduction)

Ultralow Emittance e-
Aiming for
~1nm vertical emittance level at IP

Ultralow Emittance e+
Aiming for
No damping ring e+ source, by efforts from LPWA

2016-21 – Technology Consolidation Phase

- ○ Single stage
  - GW level RF power from drive beam
  - 300 MV/m in single stage
- ○ High Fidelity Staging
  - With beam kicker, RF delay lines, two TBA modules per stage

2021-26 – Technology Integration Phase

- ○ Main Beam Source
  - X-band
- ○ 3-GeV Acceleration Facility
  - High-fidelity, integrated test facility
  - High-gradient
  - Staging
  - LC quality beam

Bunch Shaping

- ○ Increase RF-beam efficiency

High Efficiency Klystron

- ○ Synergistic with CLIC (and SLAC)

Synergies
&
Simulation

Synergies

Many similarities and parallels in LWFA & PWFA roadmaps.

- Much physics and required R&D are independent of the driver.
- Examples:
  - Staging of 1-10 GeV modules
  - Mitigation of emittance growth due to collisions and ion motion
  - High-efficiency acceleration
  - Positron acceleration
  - Hollow plasma channels for positrons
  - Mitigation of transverse beam instabilities
- Similar timetables for advances
- Use of BELLA, FACET-II, ATF, and AWA as appropriate to each study will foster progress.
  - E.g.: positrons studies at FACET-II; staging and tolerances at BELLA; first studies of plasma lenses at ATF, moving to BELLA & FACET-II for higher energies; AWA for staging and bunch shaping.

Synergies of DWFA with CLIC

Simulation

A strong modeling program is a critical component of R&D progress.

Requirements:

- Development of personnel and of computational teams
- Development of new multi-scale models and algorithms
- Exploitation of new processor architectures

Addressing these requirement is itself a challenge.

Some Updates

from the last year

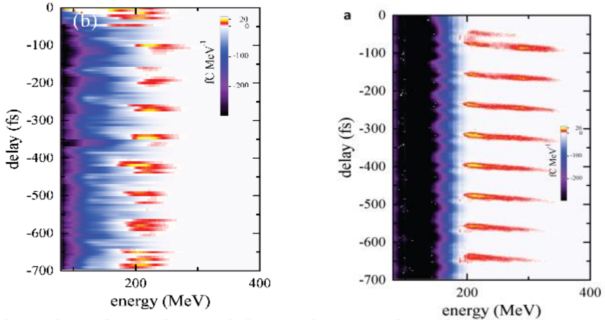
FY16-17 progress: Research Highlights for BELLA Center

Experiment

Staging of LPAs

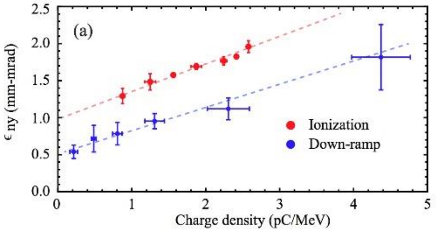
- Steinke et al., Nature (2016)

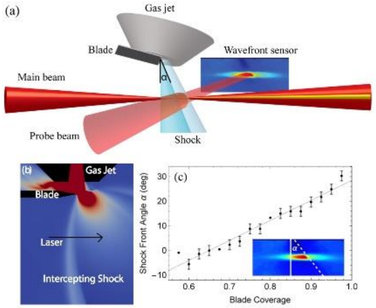
Comparison of experiment and simulation



Tunable injection in a jet with a sharp shock

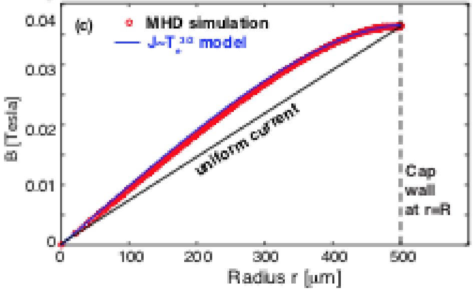
- Tsai et al., AAC 2016 proc.
- Swanson et al., submitted to PRAB
- Barber et al., PRL (in preparation)

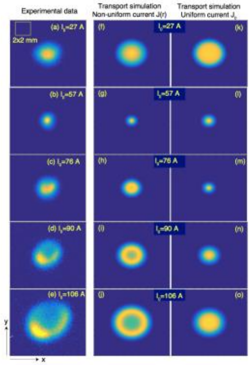




Active plasma lens

- van Tilborg et al., PRL (2015)
- van Tilborg et al, PRAB (2017)

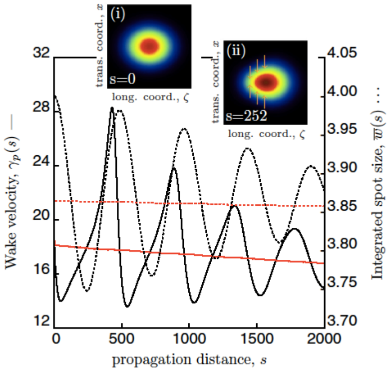




Theory

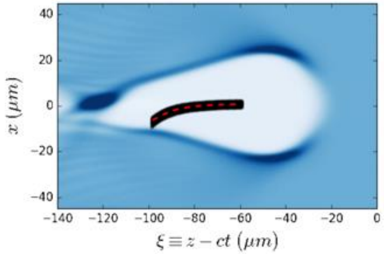
Laser depletion and wake phase velocity

- Benedetti et al., PRE (2016)



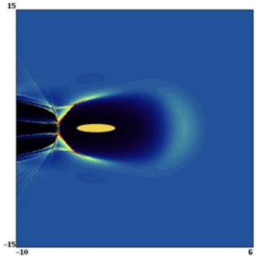
Beam Break-Up instability

- Penn et al., AAC 2016 proc.
- Lehe et al., in preparation



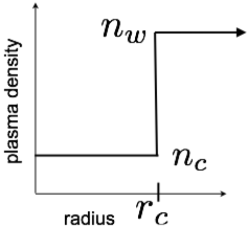
Ion motion induced by e-bunch

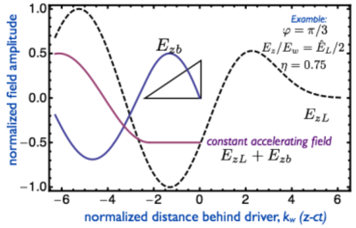
- Benedetti et al., in preparation



LPA colliders with near hollow channels

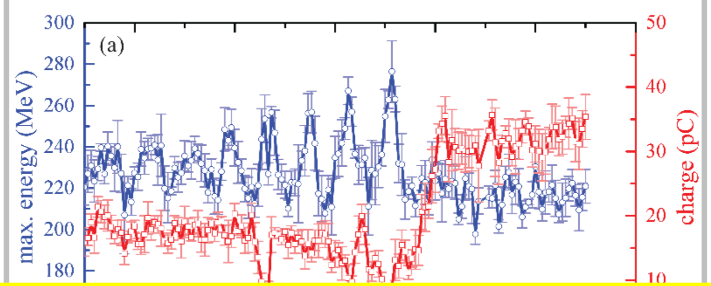
- Schroeder et al., in NIM (2016)

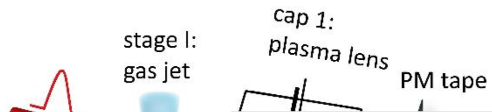




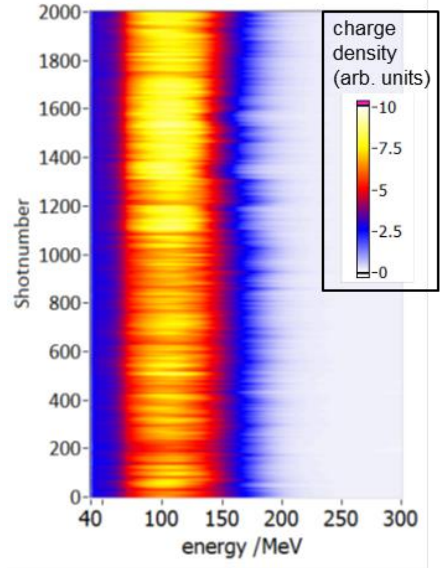
We demonstrated first independently powered staging of two consecutive laser plasma accelerators at BELLA Center of LBNL

Staging Result

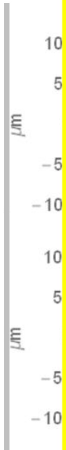




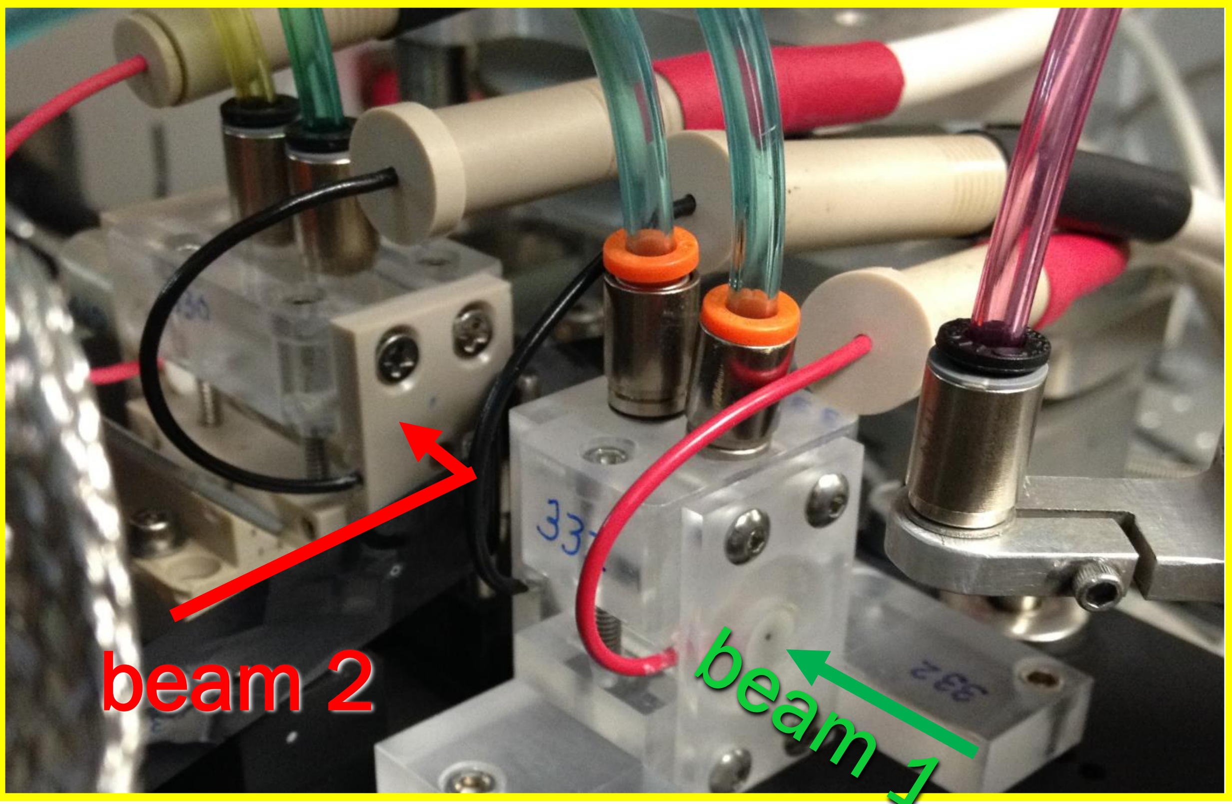
Stable Injector



Pla
Tra



J. van Tilborg et al., PRL 184802 (



These Experiments Were Made Possible by FACET Users

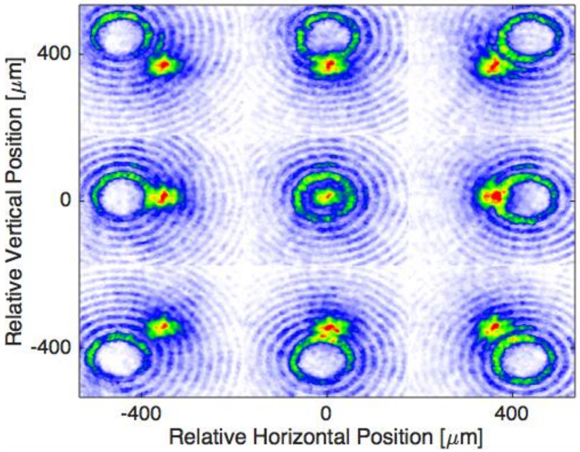
- 214 Scientists associated with 24 experiments and beam tests
  (82% of users are external to SLAC)
- 55% of these scientists working on the experiments are On-site Users
  (badged and trained for experimental work)
- 45% of the scientists involved in FACET experiments are from outside the US
- 52 Institutions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

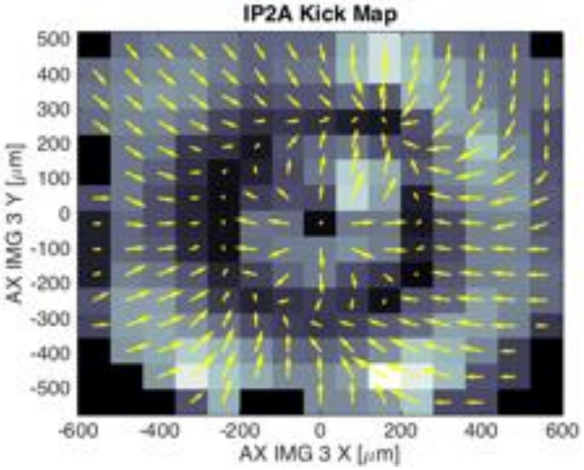
FACET Enabled a Broad User Community – User Community Enabled FACET Program

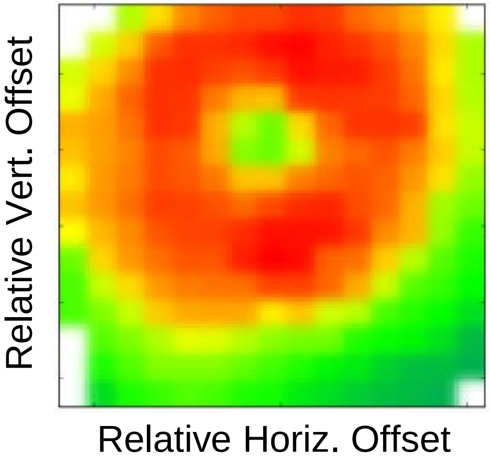
Gessner et al., *Nature Communications* June 2016

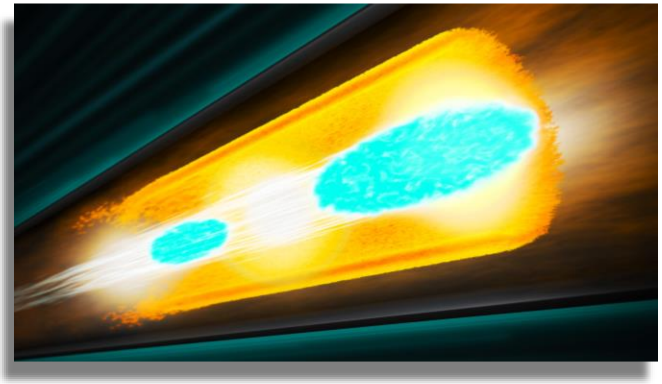
Demonstration of Acceleration in Hollow Channel Plasmas

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

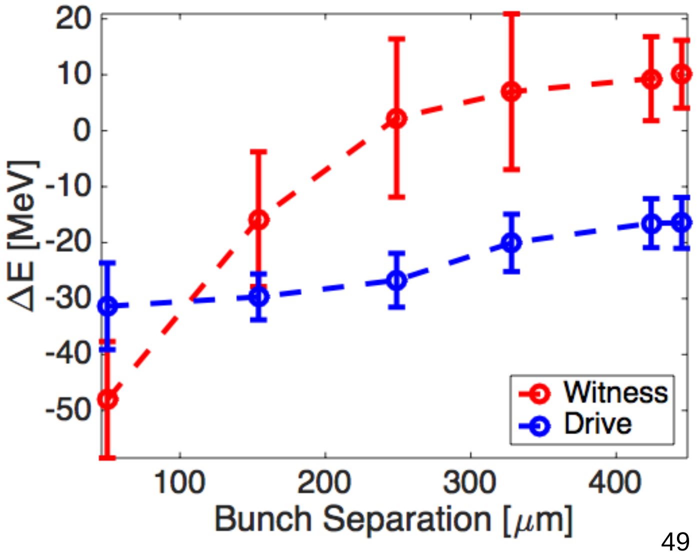








Change bunch spacing to map the longitudinal wakefield



FACET-II Project Plan


10GeV, 2nC, 10μm^3, e$^-$ & e$^+$

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:

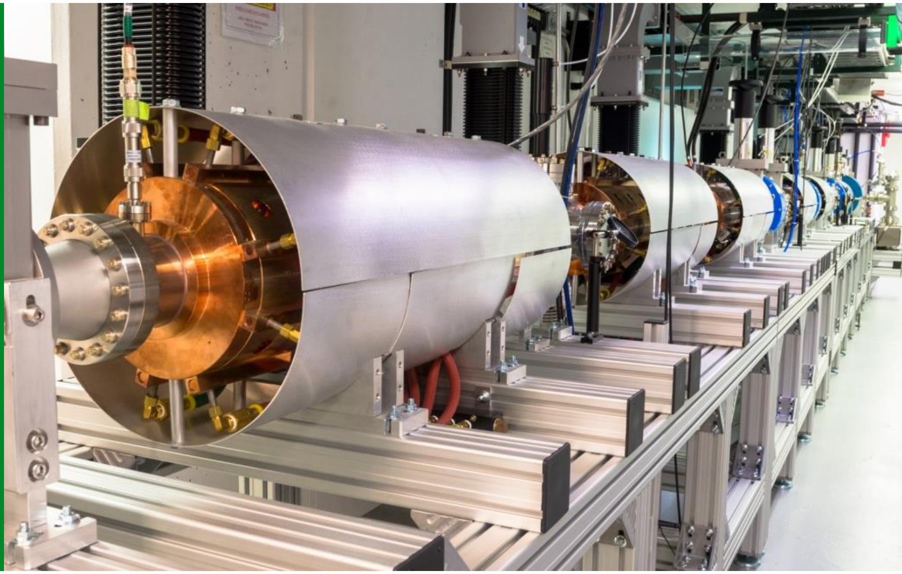
- Beam quality preservation, high brightness beam generation, characterization
- e$^+$ acceleration in e$^-$ driven wakes
- Staging challenges with witness injector
- Generation of high flux gamma radiation

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

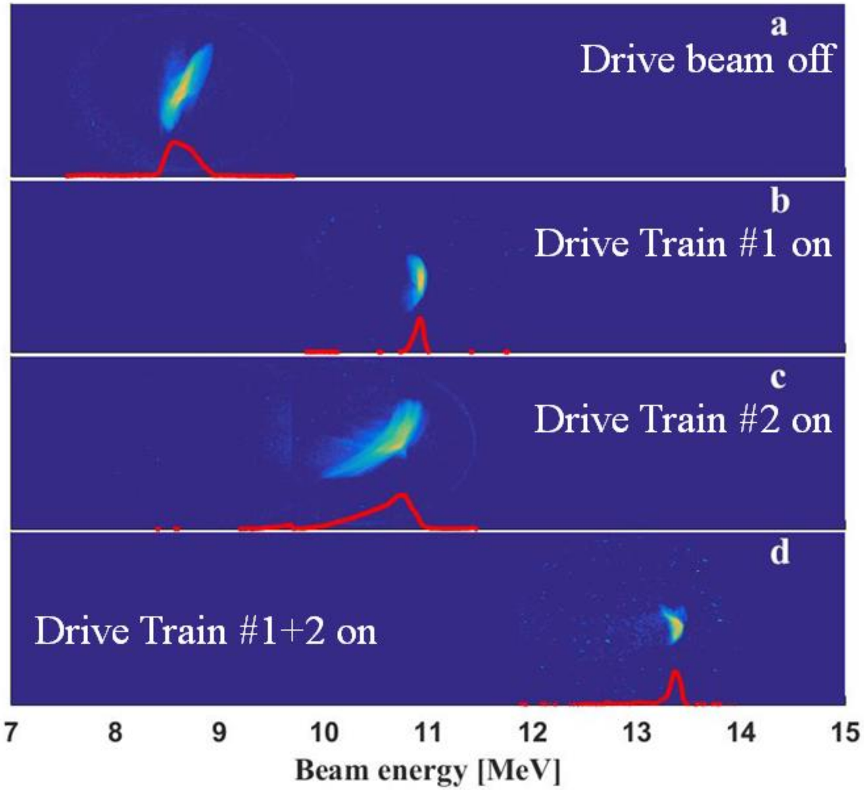
Progress on Dwa for collider since Feb.2016



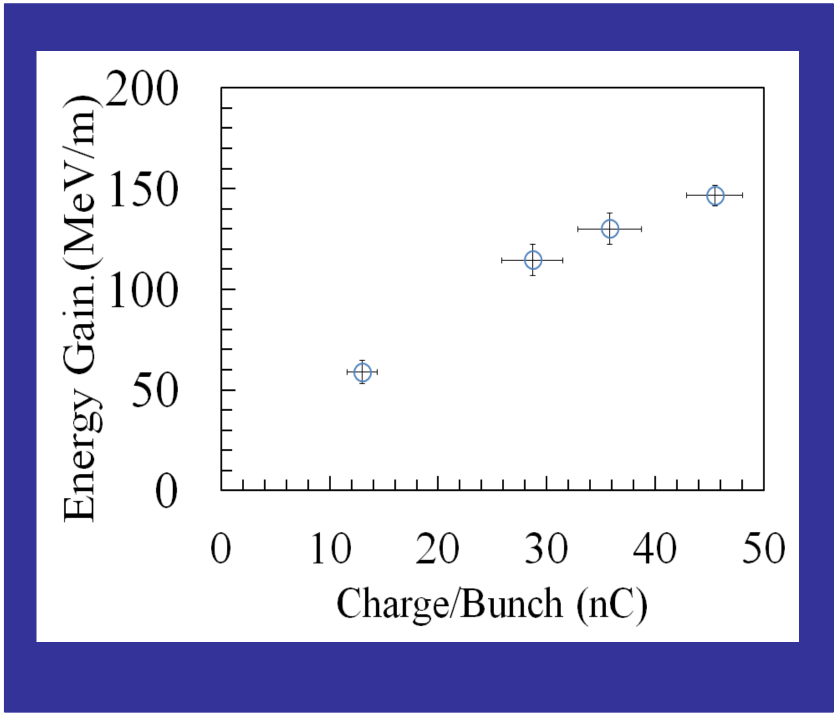
- ✓ Improved X-band Staging experiment with demonstration of ~100MV/m per stage
- ✓ Improved X-band Short pulse TBA with demonstration of 300MW rf power generation and 150MeV/m acceleration
- ✓ Demonstration of the 1st 26GHz full dielectric TBA with ~160MW rf generation and 50MeV/m acceleration
- ✓ Demonstration of the “near-ideal” main beam shaping using Micro Lens Array
- ✓ Construction of the drive beam kicking device is under way.

Technologies		**Intl. collaborators**
High Grad. & High Power Structures	⟷	CLIC and Tsinghua University
Advanced bunch shaping	⟷	Pohang Accelerator Laboratory, Korea
Advanced Positron Generation	⟷	Tsinghua University, China

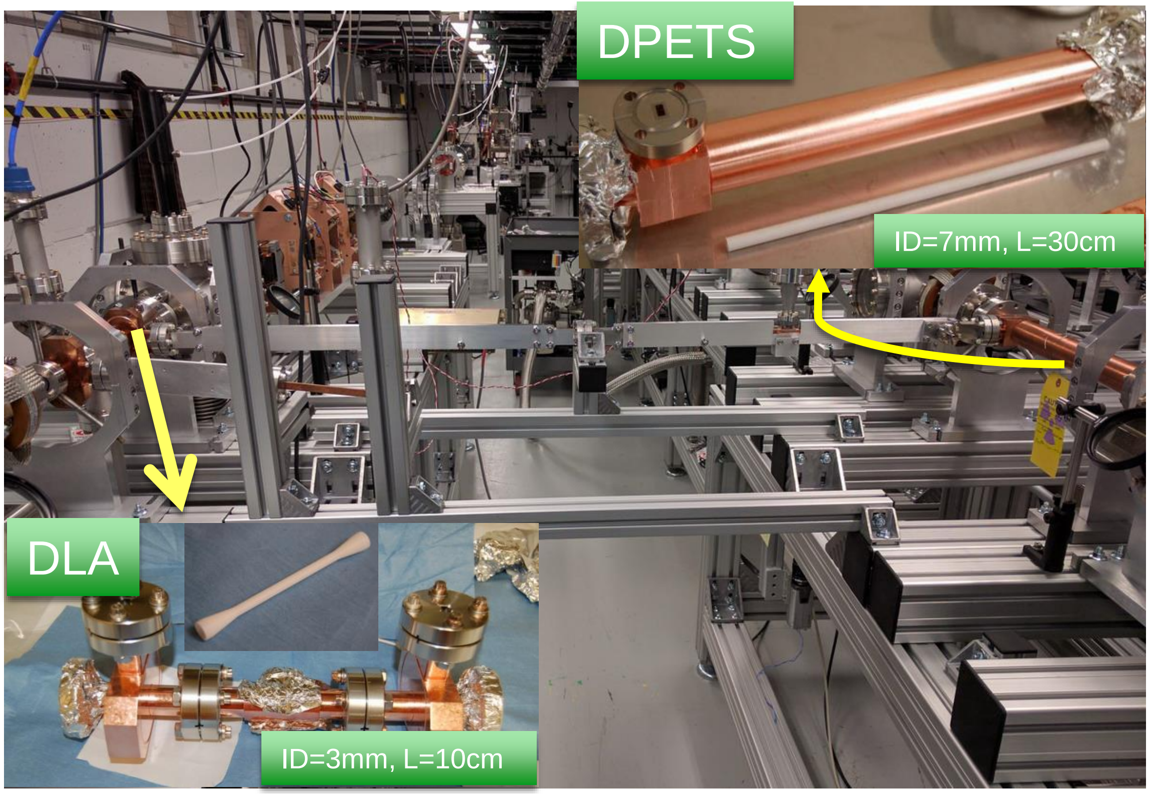
Improved Staging experiment (Feb.2016)



Improved Short pulse TBA (May 2016)



The 1st 26GHz Full Dielectric Short Pulse TBA Test (Feb.2017)



- ~4MeV deceleration was measured for each drive bunch which is aligned with ~160MW rf power output by a 4x22nC bunch train.

- ~1.8MeV acceleration of a 230pC witness beam transmitted through the dielectric accelerator, which is eqv. to ~50MV/m gradient.

Note: Gradient is lower than the ideal case due to the combination of RF loss in the waveguide, miss-match of the phase advance, and inefficient rf coupling, etc.

Summary

Summary and Conclusion

The U.S. R&D roadmap for Advanced Accelerator Concepts is driven by the science priorities set by the U.S. particle physics strategic plan.

Focuses on achieving a multi-TeV *e+e-* collider

at affordable cost,
with a TDR in the 2040 timeframe.

- The roadmap has several possible routes to the same destination.
  - We do not know which route will lead most directly or most quickly.
  - We do know that all routes are long and arduous.
  - In practice, we do not (yet) know how strong is the scientific motivation for our technical solution.
- Exploring all possible routes makes sense, provided all can be advanced at a technically limited pace.
  - Otherwise one needs to pick a favored route to explore more fully.
  - Because of the need for sophisticated (expensive) test facilities, being technically limited while pursuing all three options is unlikely.
- The arena of Advanced Accelerator Concepts is ripe for international collaboration and cooperation.
  - If we venture forward collaboratively to explore the range of possible solutions to the challenge of a multi-TeV *e+e-* collider, then we will all be winners when the goal is achieved and discovery science ensues.

Some Updates

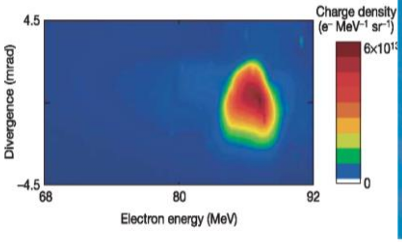
LWFA

from Wim Leemans (LBNL)

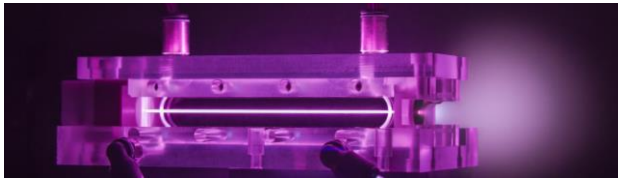
BELLA Center has an internationally recognized program in laser based advanced accelerators for High Energy Physics

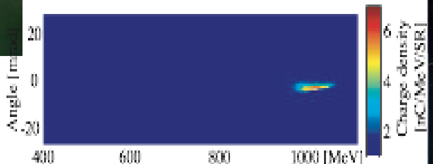
HEP

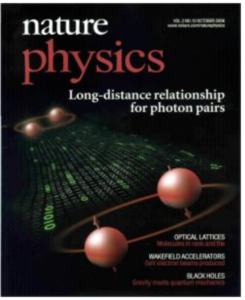
- BELLA Center (LOASIS)
- BELLA Operations/Facility



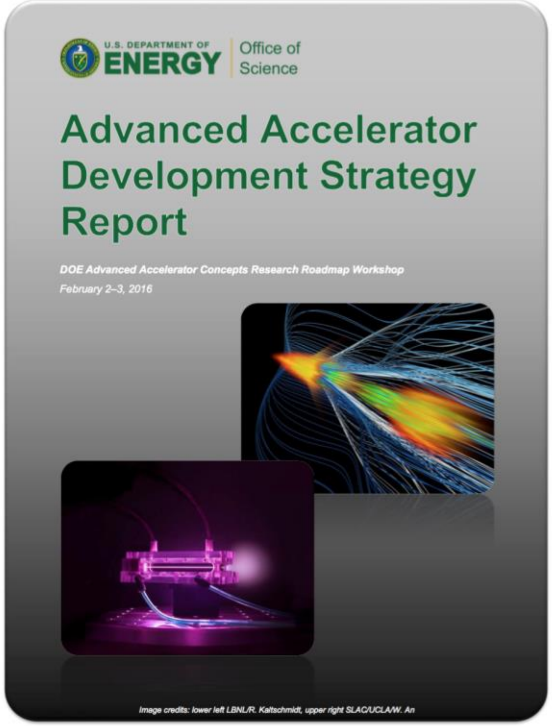
C.G.R. Geddes et al., Nature 2004







W.P. Leemans et al., Nature Physics 2006



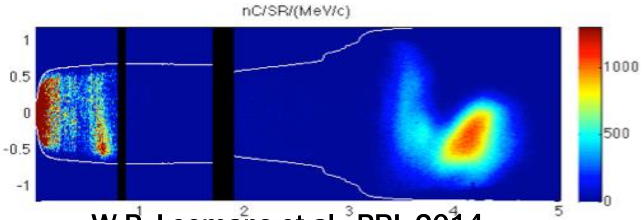
U.S. DEPARTMENT OF ENERGY | Office of Science

Advanced Accelerator Development Strategy Report

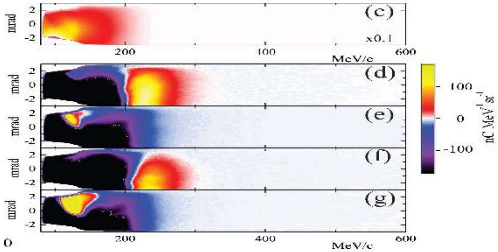
DOE Advanced Accelerator Concepts Research Roadmap Workshop

February 2–3, 2016

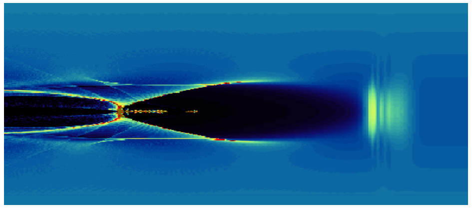
Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An



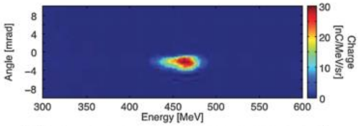
W.P. Leemans et al., PRL 2014

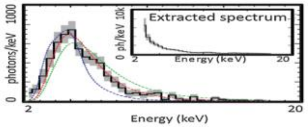


S. Steinke et al.,Nature 2016



C. Benedetti et al., Phys. Plasmas 2014
L.L. Yu et al., PRL 2014





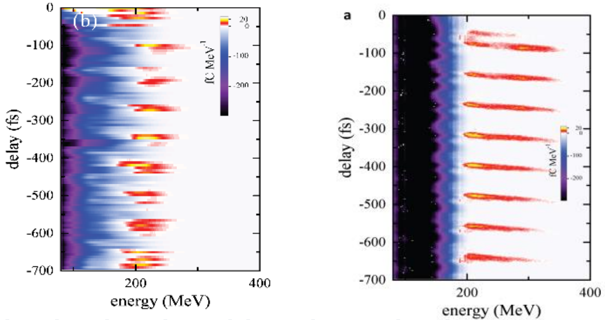
W.P. Leemans et al., PRL2003
L. Chen et al., PRL 2012
G. Plateau et al., PRL 2012

FY16-17 progress: Research Highlights for BELLA Center

Staging of LPAs

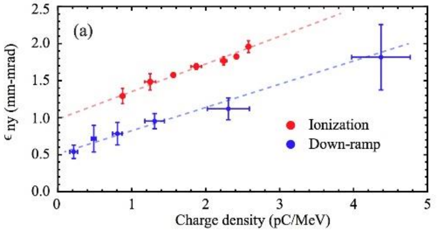
- Steinke et al., Nature (2016)

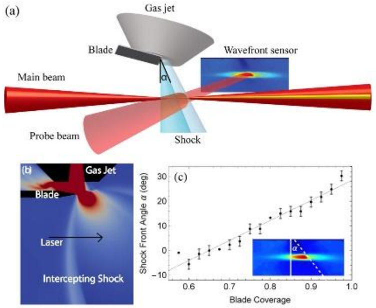
Comparison of experiment and simulation



Tunable injection in a jet with a sharp shock

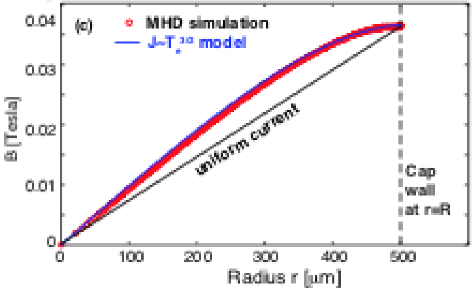
- Tsai et al., AAC 2016 proc.
- Swanson et al., submitted to PRAB
- Barber et al., PRL (in preparation)

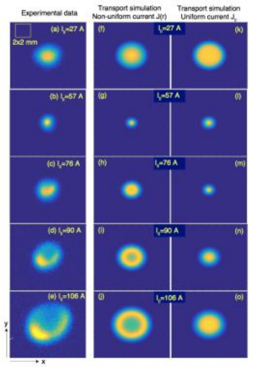




Active plasma lens

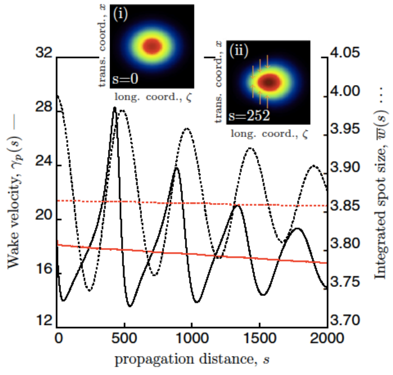
- van Tilborg et al., PRL (2015)
- van Tilborg et al, PRAB (2017)





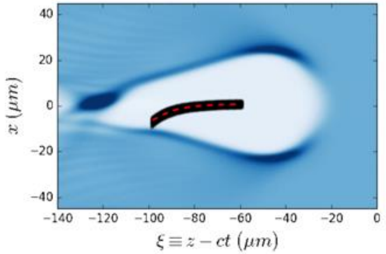
Laser depletion and wake phase velocity

- Benedetti et al., PRE (2016)



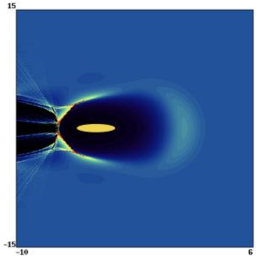
Beam Break-Up instability

- Penn et al., AAC 2016 proc.
- Lehe et al., in preparation



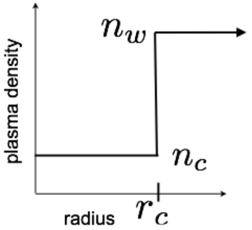
Ion motion induced by e-bunch

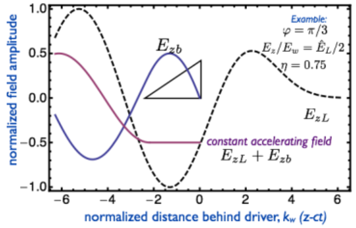
- Benedetti et al., in preparation



LPA colliders with near hollow channels

- Schroeder et al., in NIM (2016)

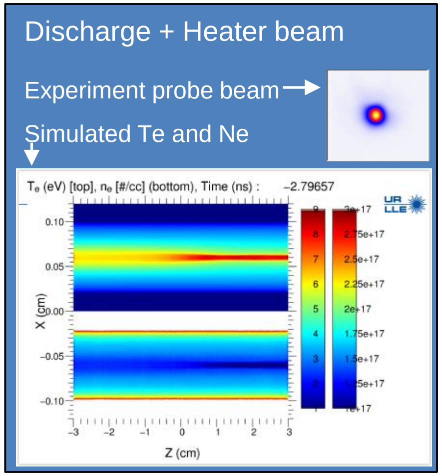




FY16-17 progress: BELLA experiments, modeling and concepts for the future

10 GeV module on BELLA

- Heater beam implemented
    - Daniels et al., in preparation (2017)

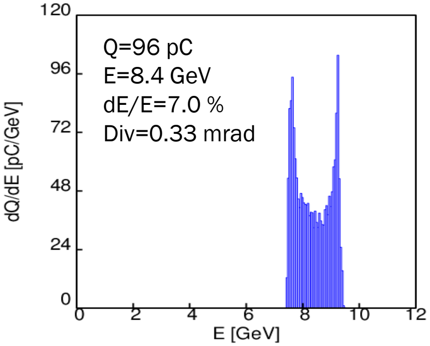


Discharge + Heater beam

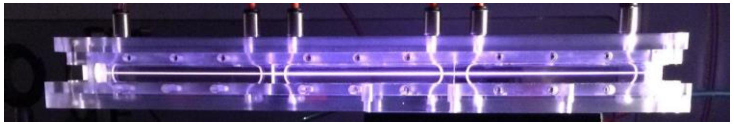
Experiment probe beam →

Simulated Te and Ne

INF&RNO 2016 simulations



- 20-40 cm capillary development



- 3D-Magneto-hydrodynamic capillary discharge modeling and measurements

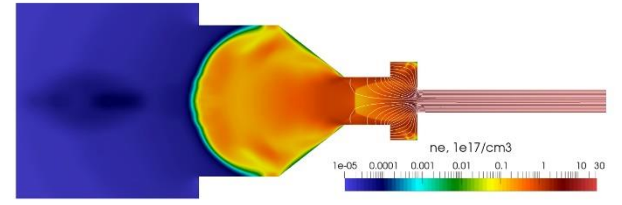
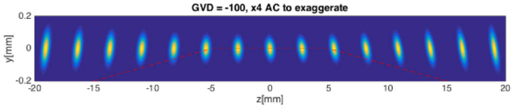
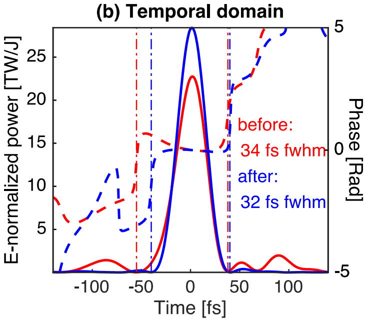


FIG. 5: Electron density distribution near the open end (color) together with the streamlines of current density (white lines) at $t = 200$ ns after discharge is started.

Pulse front tilt and electron beam steering

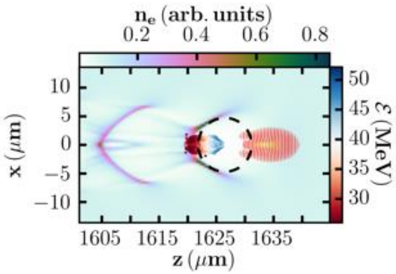
- Nakamura et al., submitted (2017)
- Mittelberger et al., in preparation (2017)





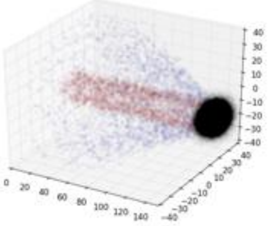
Dynamics of electrons in tailored density profile & injection

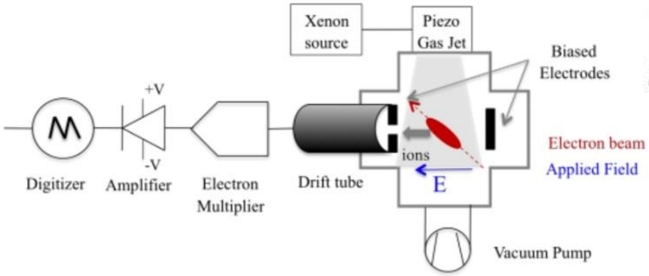
- P. Lee et al., PRAB (2016)
- P. Lee et al., NIMA 829 (2016)
- T. Audet et al., Phys. Plasmas 23 (2016)



Ionization based ultrafast charge density monitor

- Tarkeshian et al., in preparation
- Campaign during 2017

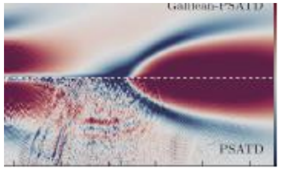




FY16-17 computational progress: new algorithms, numerical analyses & faster implementations

New “Galilean” solver cures numerical Cherenkov (collab. DESY)

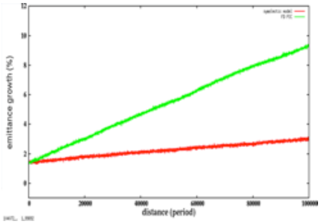
- R. Lehe et al, Phys. Rev. E 94, 053305 (2016)
- M. Kirchen et al, Physics Plasmas 23, 100704 (2016)



breakthrough

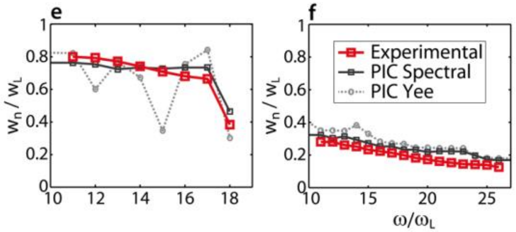
Fully symplectic tracking model reduces spurious emittance growth

- J. Qiang, to appear into PRAB



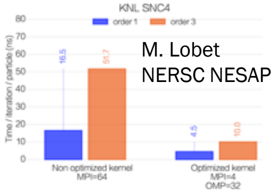
Pseudo-spectral methods with arbitrary order

- H. Vincenti et al., Comput. Phys. Comm., 200, 147 (2016)
- S. Jalas et al., submitted to Phys Plasmas
- A. Leblanc et al. submitted to PRL
- G. Blaclard et al., submitted to PRE



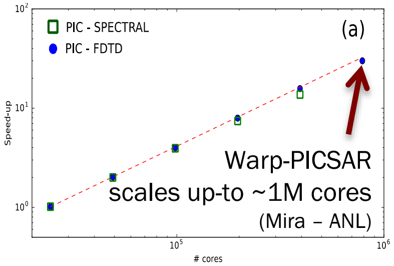
New PICSAR module implements fast Particle-In-Cell kernel

- Vincenti et al., Comput. Phys. Comm., 210, 145 (2017)
- D. Doerfler et al., Proceedings IXPUG



M. Lobet
NERSC NESAP

Speedup of 5 for PICSAR on a KNL.



Warp-PICSAR scales up-to ~1M cores
(Mira – ANL)

INCITE award 100,000 CPU-Hrs

Hybrid programming improves performance of BeamBeam3D

- J. Qiang
- (SciDAC)

Time(s)

OMP \ MPI	4	8	16	32	64	128	256	512	1024
1	268.26	161.22	109.41	93.91	41.57	50.48	68.93		
2	233.62	116.68	91.55	35.81	45.24	58.98	71.75		
4	107.86	85.53	33.93	34.1	35.77	51.2			
8	99.93	42.83	31.57	38.8	42.91				
16	43.49	34.41	33.93	39.03					
32	33.91	35.1	38.1						
64	44.83	46.51							

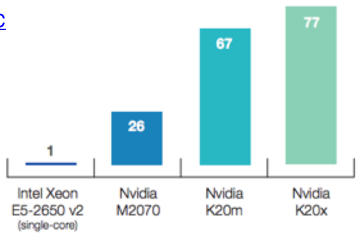
Total Memory(GB)

	4	8	16	32	64	128	256	512	1024
1	0.4	0.46	0.58	0.8	1.57	2.85	5.42		
2	0.41	0.46	0.59	0.95	1.58	2.85	5.4		
4	0.41	0.47	0.67	0.97	1.61	2.92			
8	0.42	0.46	0.69	1.02	1.72				
16	0.46	0.56	0.75	1.17					
32	0.5	0.62	0.86						
64	0.58	0.76							

New code FBPIC ported to GPU

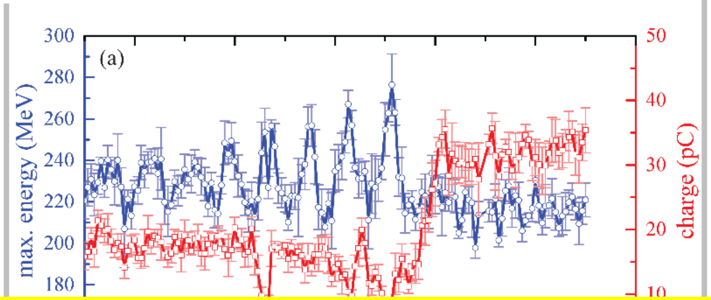
- Lehe et al, Comput. Phys. Comm. 203,66 (2016)
- Open source https://github.com/fbpic/fbpic

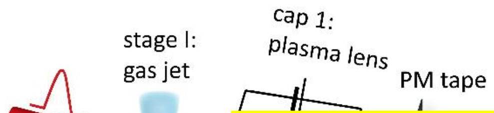
Speed-up on different Nvidia GPUs



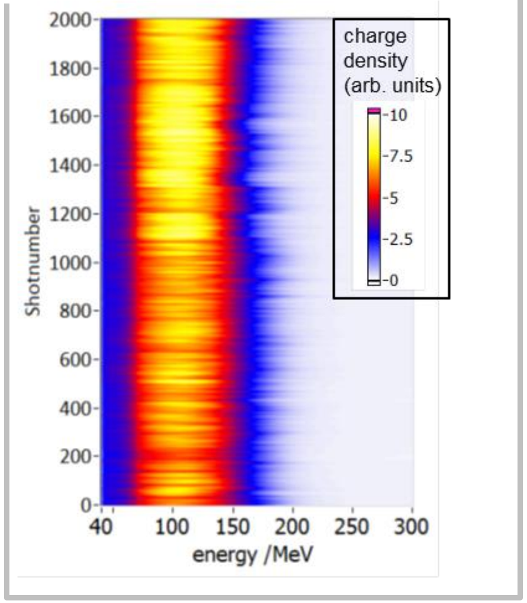
We demonstrated first independently powered staging of two consecutive laser plasma accelerators at BELLA Center of LBNL

Staging Result

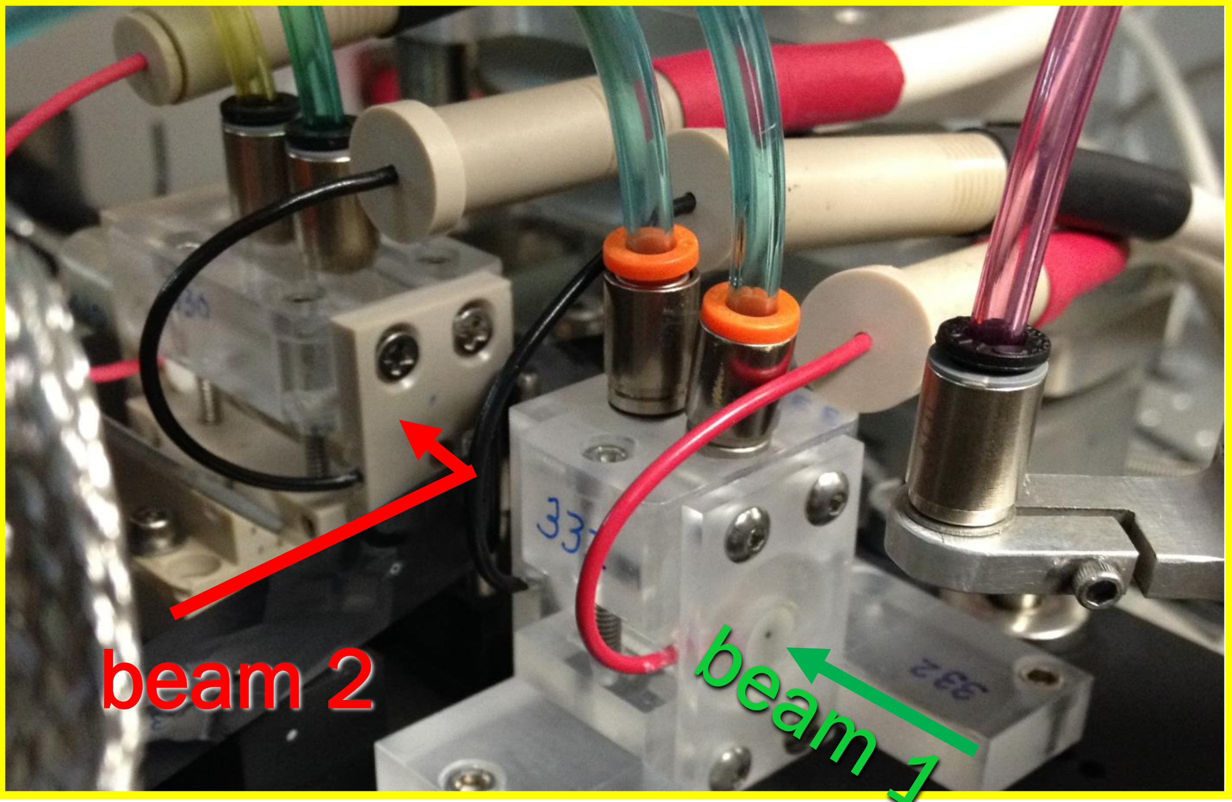




Stable Injector

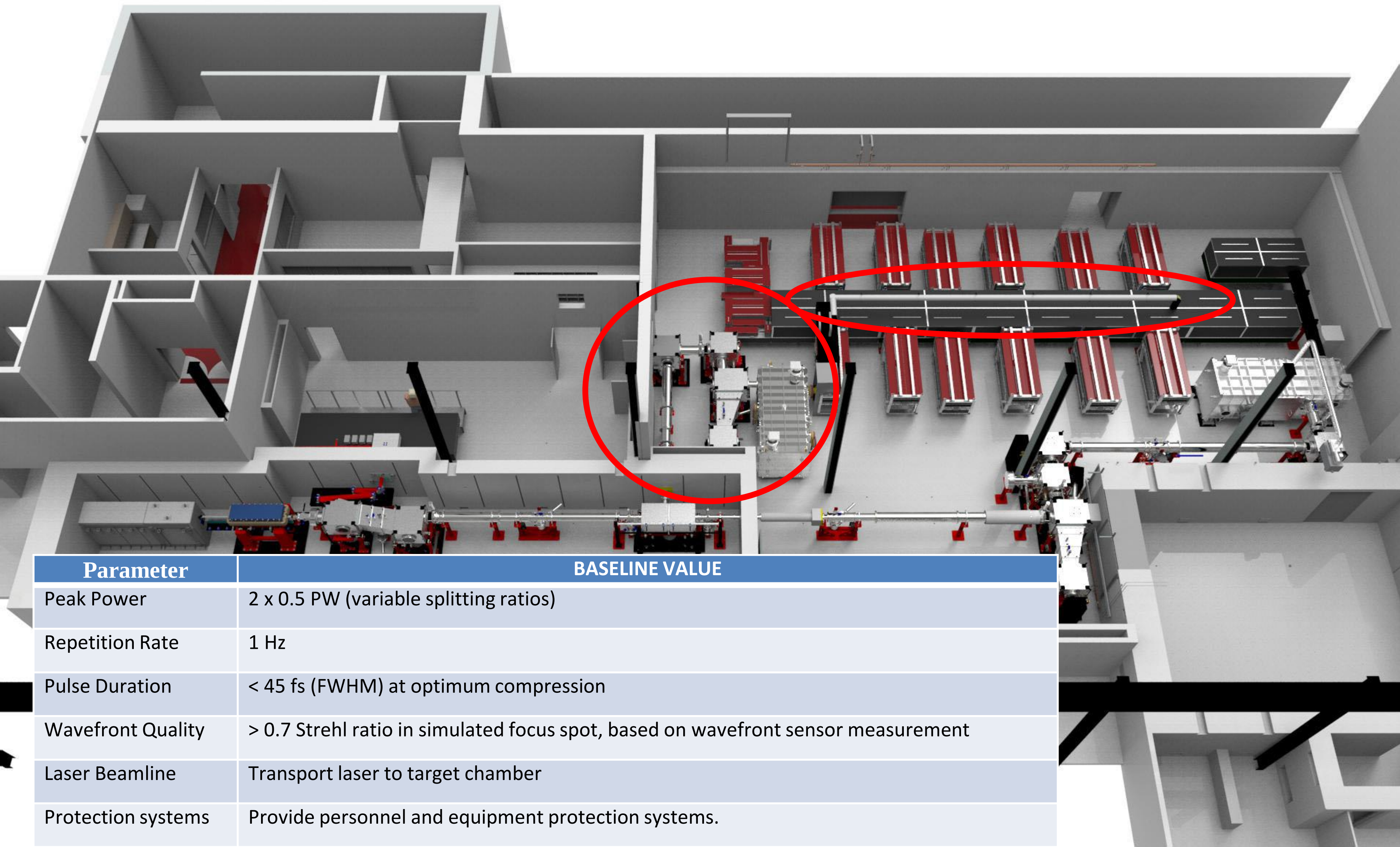


Pla
Tra



J. van Tilborg et al., PRL 184802 (

Executing the Roadmap Requires a Second Beamline on BELLA for 5 GeV+5GeV staging



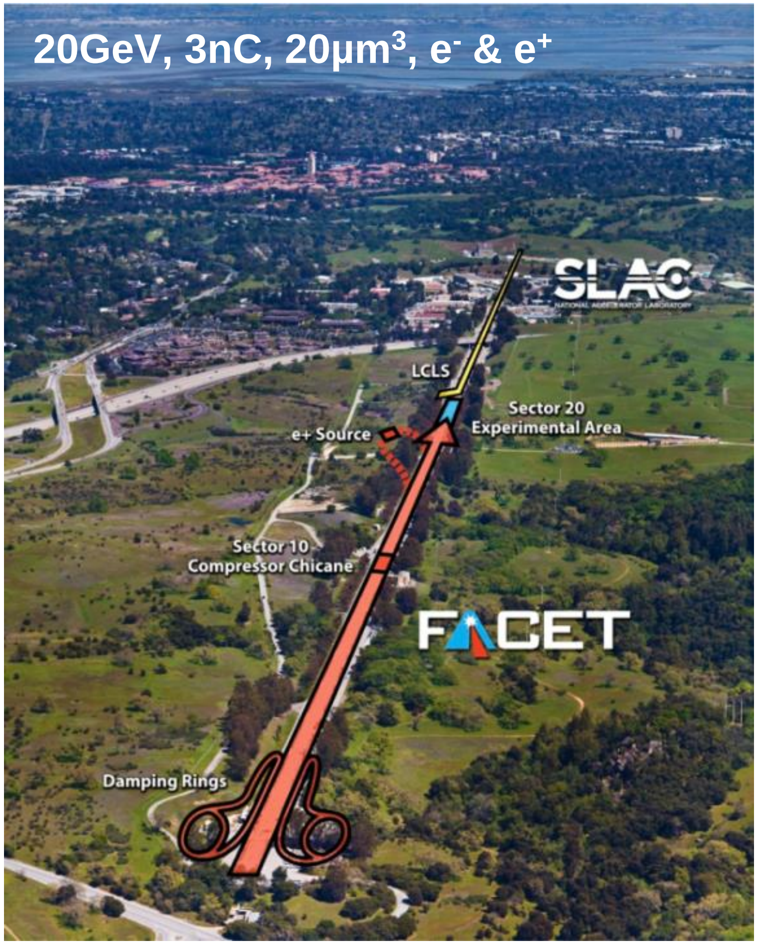
Parameter	BASELINE VALUE
Peak Power	2 x 0.5 PW (variable splitting ratios)
Repetition Rate	1 Hz
Pulse Duration	< 45 fs (FWHM) at optimum compression
Wavefront Quality	> 0.7 Strehl ratio in simulated focus spot, based on wavefront sensor measurement
Laser Beamline	Transport laser to target chamber
Protection systems	Provide personnel and equipment protection systems.

Some Updates

PWFA

from Mark Hogan
& Vitaly Yakimenko (SLAC)

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

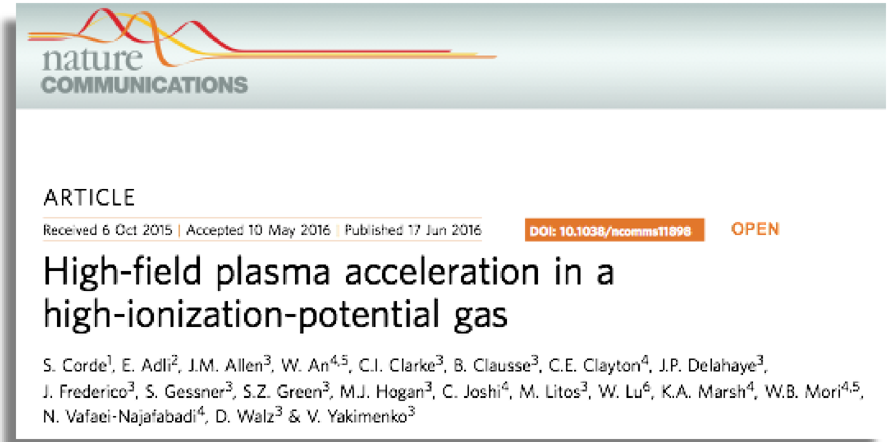
These Experiments Were Made Possible by FACET Users

- 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

Corde et al., *Nature Communications* June 2016

Physics of Head Erosion for PWFA Drive Beam



nature COMMUNICATIONS

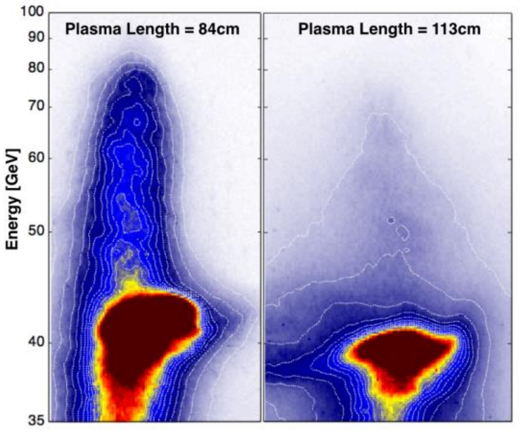
ARTICLE

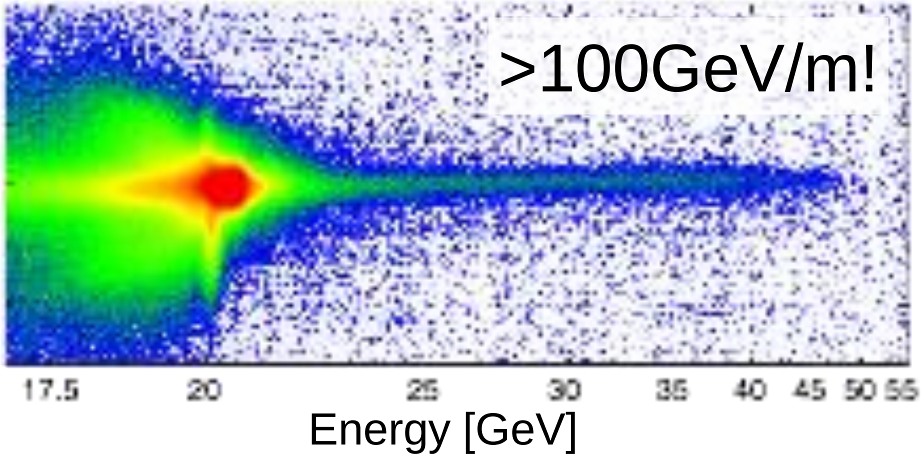
Received 6 Oct 2015 | Accepted 10 May 2016 | Published 17 Jun 2016 DOI: 10.1038/ncomms11898 OPEN

High-field plasma acceleration in a high-ionization-potential gas

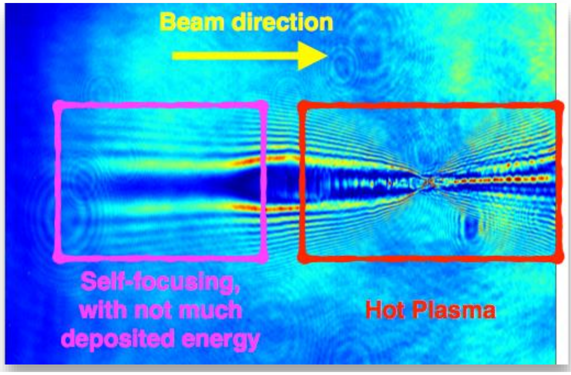
S. Corde[1], E. Adli[2], J.M. Allen[3], W. An[4,5], C.I. Clarke[3], B. Clausse[3], C.E. Clayton[4], J.P. Delahaye[3], J. Frederico[3], S. Gessner[3], S.Z. Green[3], M.J. Hogan[3], C. Joshi[4], M. Litos[3], W. Lu[6], K.A. Marsh[4], W.B. Mori[4,5], N. Vafaei-Najafabadi[4], D. Walz[3] & V. Yakimenko[3]

FFTB interactions in field ionized plasmas were limited by head erosion





>100GeV/m!



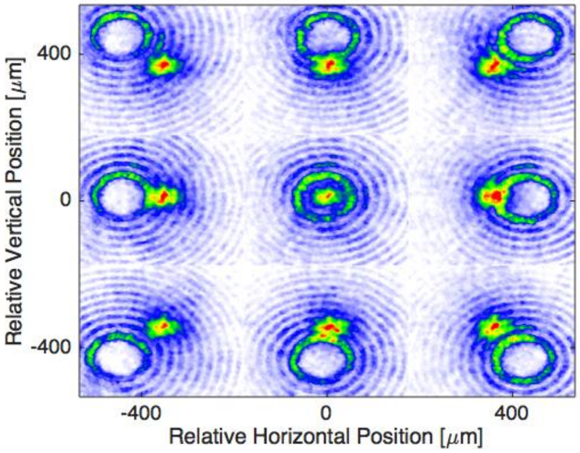
New insight into erosion mechanism and mitigation

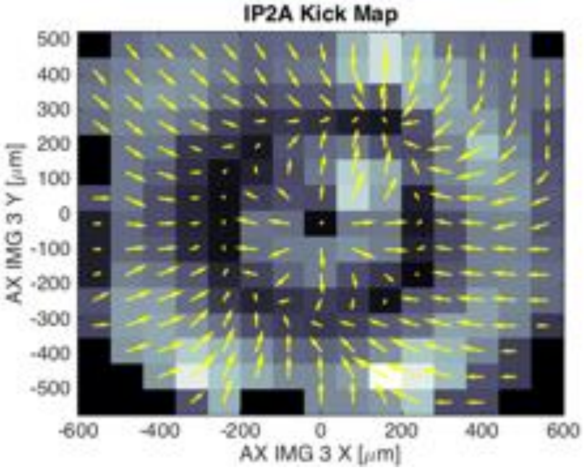
Breadth and depth: from proof-of-principle to fundamental physics

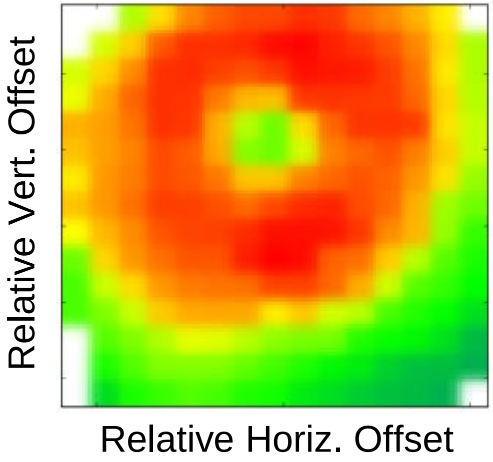
Gessner et al., *Nature Communications* June 2016

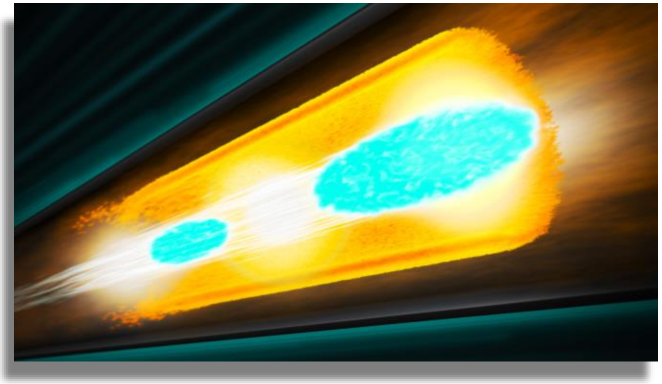
Demonstration of Acceleration in Hollow Channel Plasmas

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

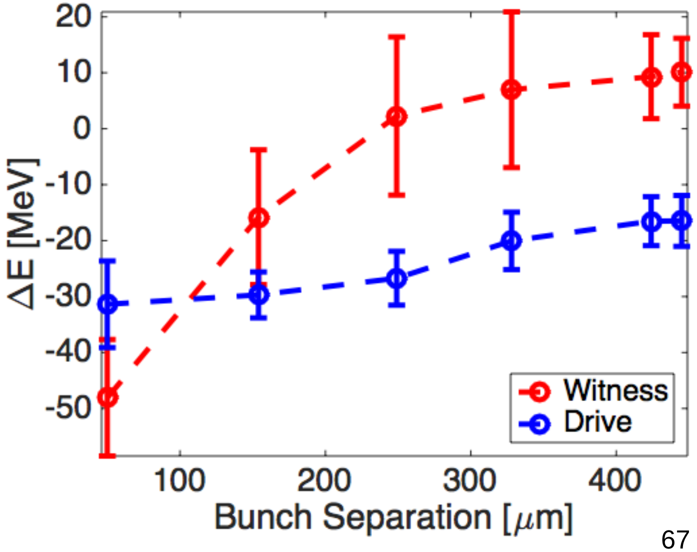








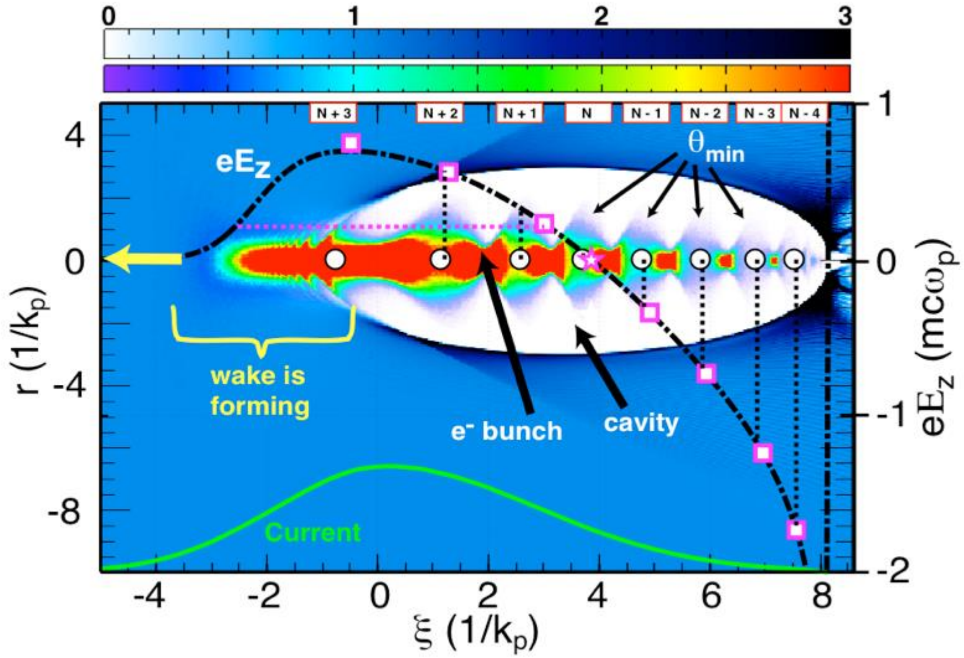
Change bunch spacing to map the longitudinal wakefield

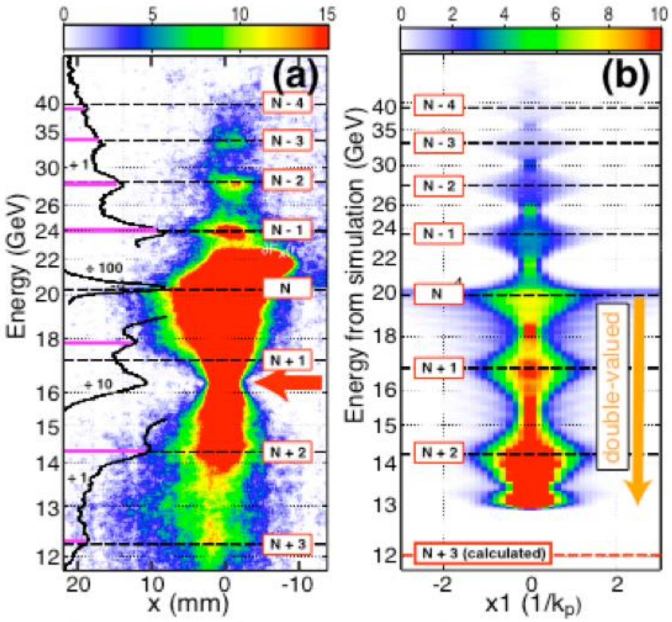


Clayton et al., *Nature Communications* August 2016

Self-Mapping the Longitudinal Field Structure

- Preservation of emittance of the accelerating beam is the next challenge for plasma-based accelerators
- Field structure of a highly nonlinear plasma wake is potentially suitable for this purpose but has not been yet measured



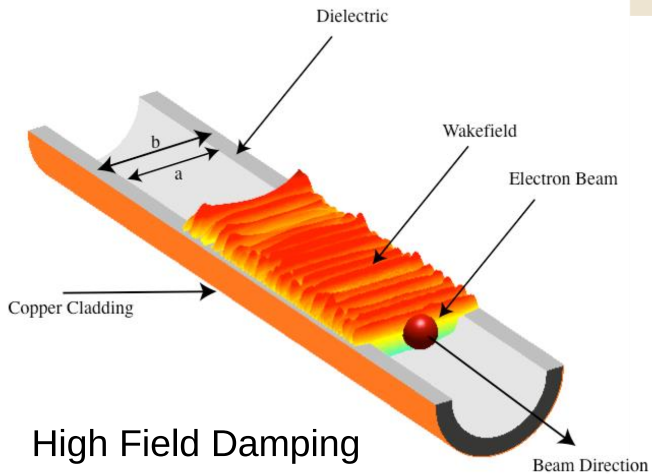


Data **Simulation**

Panofsky-Wenzel Theorem in a Plasma Wakefield Accelerator

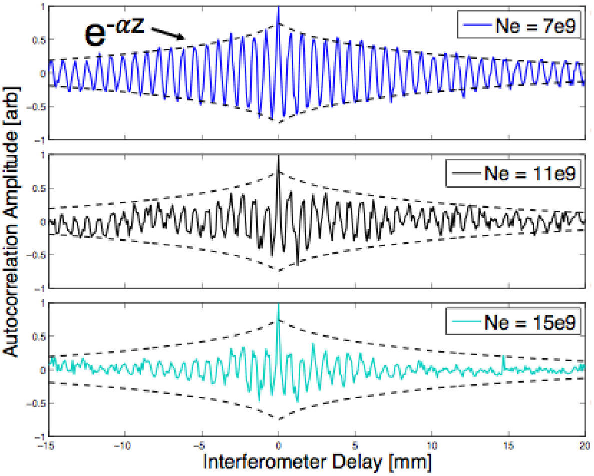
O’Shea et al., *Nature Communications* September 2016

Record Performance for Dielectric Wakefield Acceleration

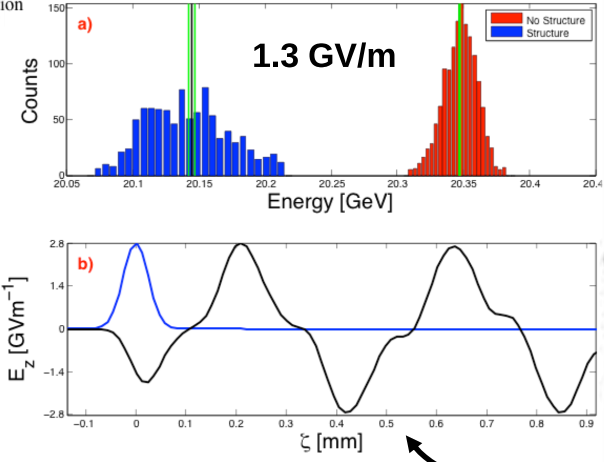


Quartz tubes
15cm long
300µm diameter

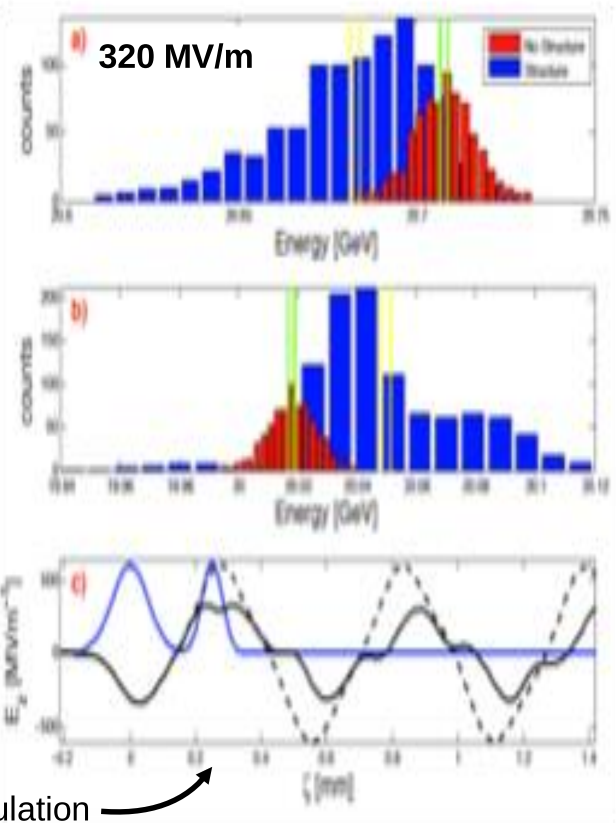
High Field Damping
(400/600) 3 cm



Single Bunch
(300/400) 15 cm



Two Bunch
(300/400) 10 cm



Simulation

Cross collaboration between DWFA and PWFA allowed measurement of highest accelerating gradient in a DWFA

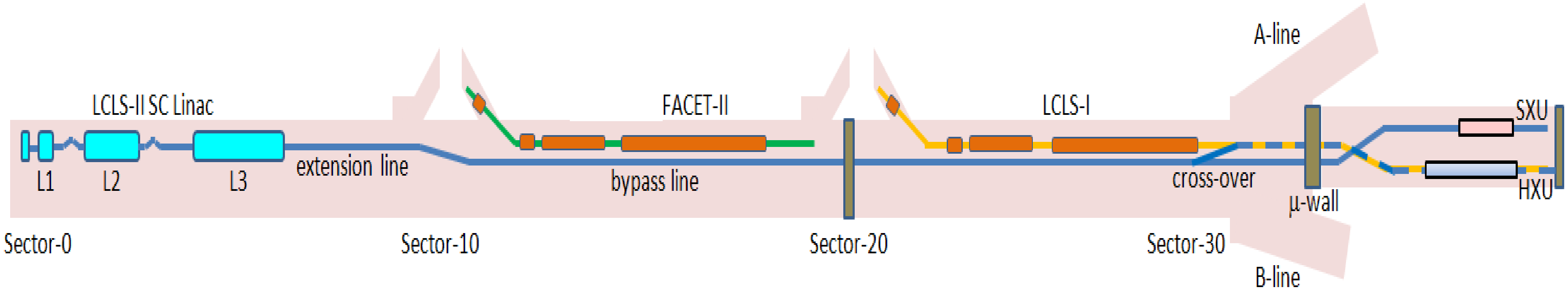
FACET Has a Unique Role in Addressing Plasma Acceleration of Positrons for Linear Collider Applications

	Advantages	Challenges	Open Questions
Non-Linear Acceleration	Extremely large gradients. 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. 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. Works with a driving electron beam.	Modest accelerating gradients.	Can we increase the wake amplitude while maintaining the quality of the witness bunch?

Results of FY16 studies at FACET are in preparation for publication

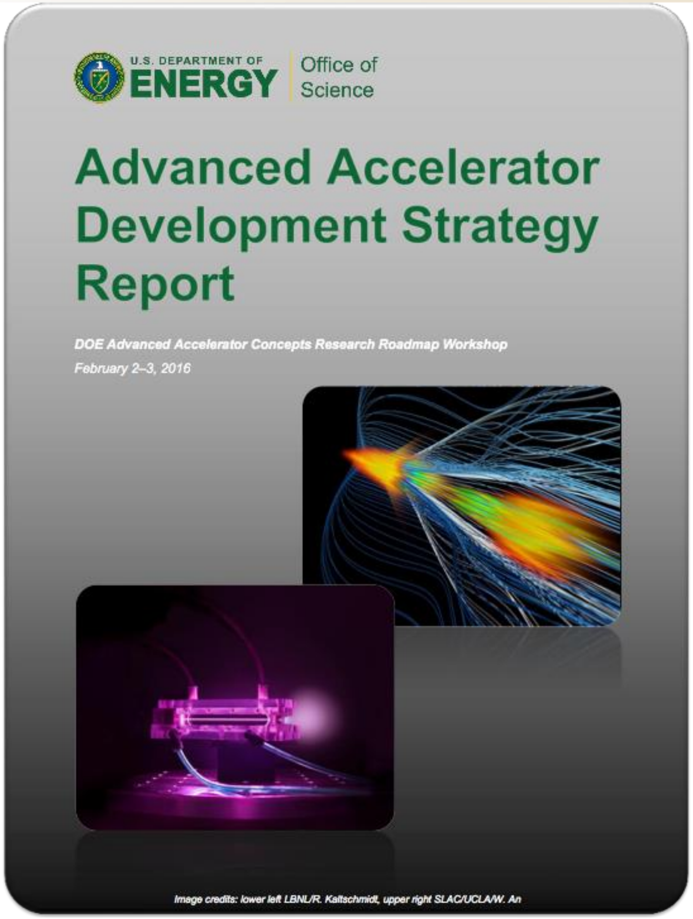
Planning for FACET-II as a Community Resource

- 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…)



FACET-II has been designed to address many of the R&D challenges of the Beam Driven Roadmap

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



U.S. DEPARTMENT OF ENERGY | Office of Science

Advanced Accelerator Development Strategy Report

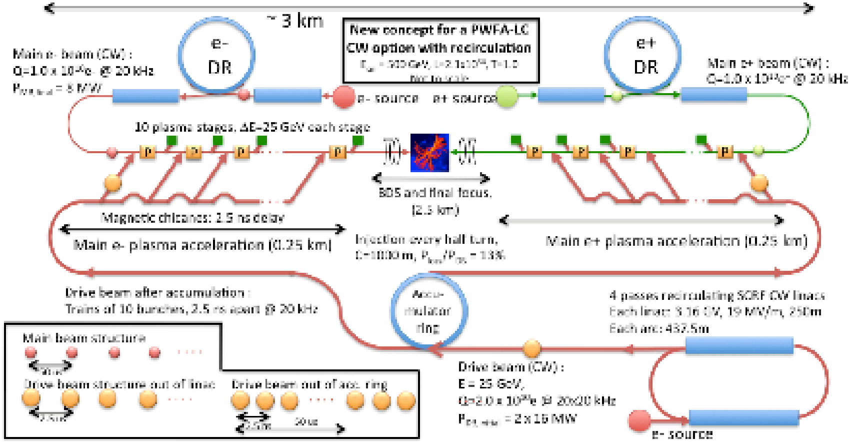
DOE Advanced Accelerator Concepts Research Roadmap Workshop

February 2–3, 2016

Image credits: lower left LBNL/R. Kaltschmidt, upper right SLAC/UCLA/W. An

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

FACET-II Project Plan

10GeV, 2nC, 10μm^3, e$^-$ & e$^+$

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)	

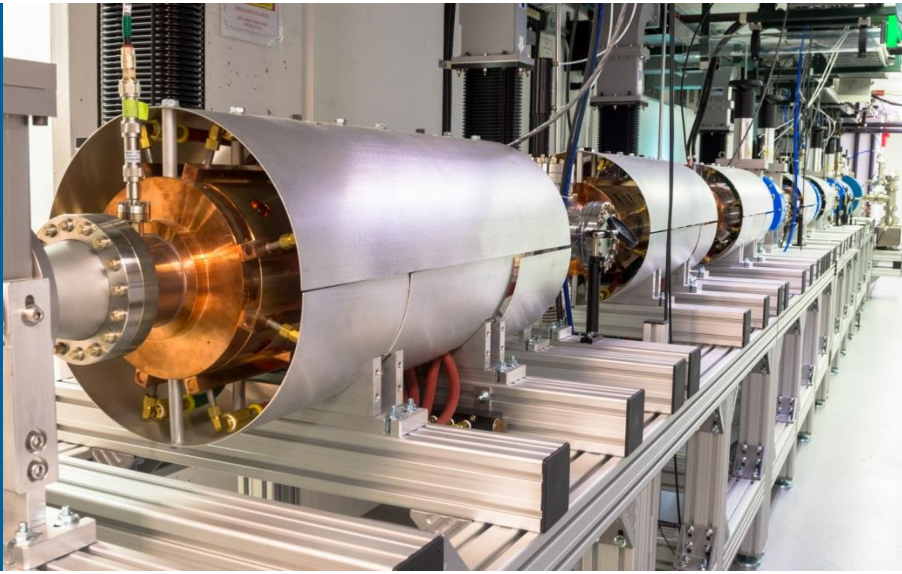
FACET-II will operate as a National User Facility with an external program advisory committee reviewing proposals and recommending priorities for the experimental program

Some Updates

DWFA

from John Power (ANL)

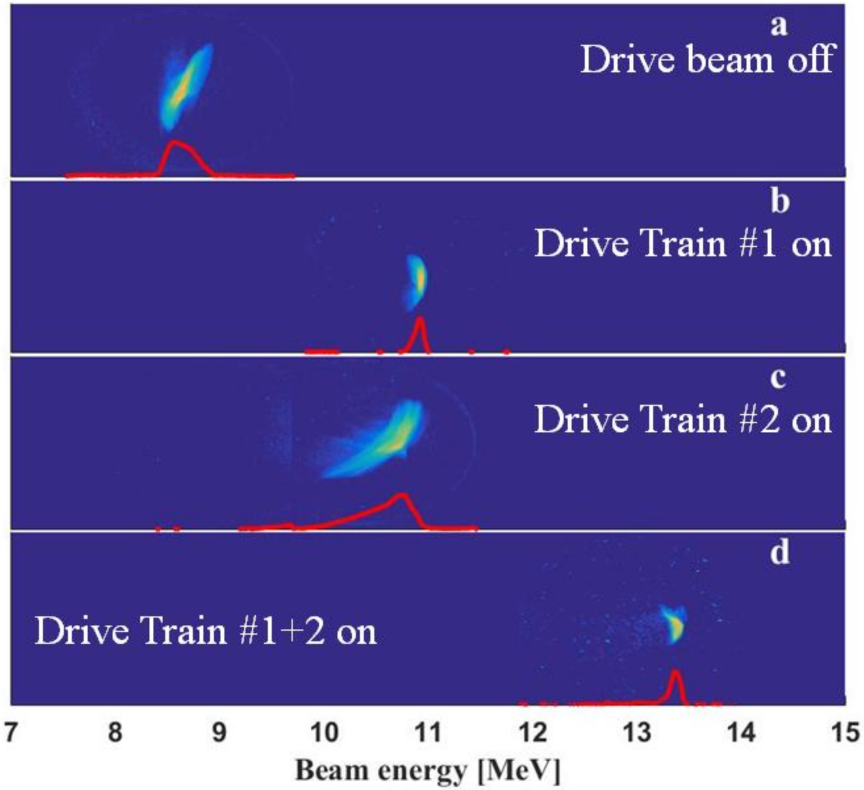
PROGRESS ON DWA FOR COLLIDER SINCE FEB.2016



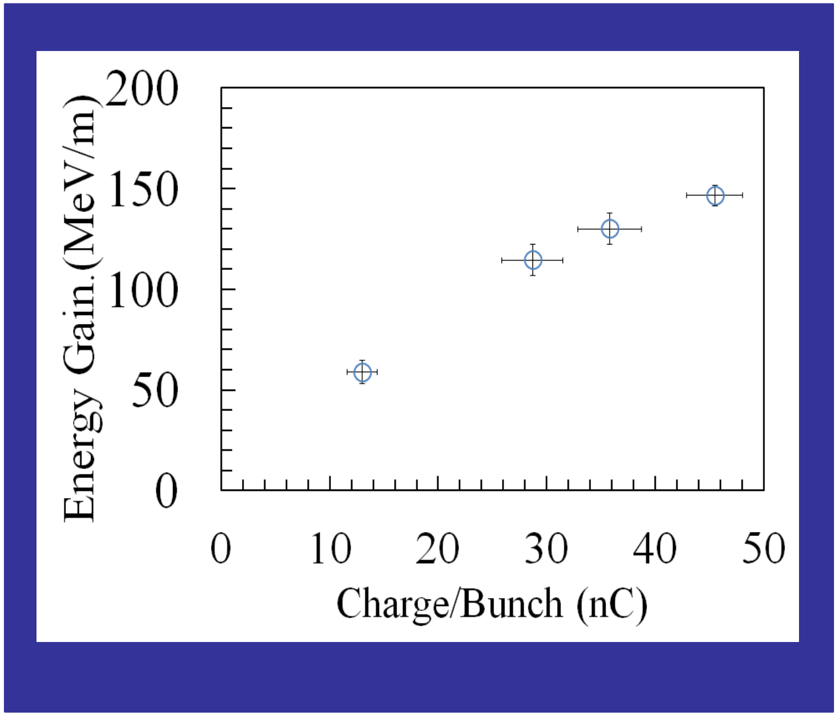
- ✓ Improved X-band Staging experiment with demonstration of ~100MV/m per stage
- ✓ Improved X-band Short pulse TBA with demonstration of 300MW rf power generation and 150MeV/m acceleration
- ✓ Demonstration of the 1st 26GHz full dielectric TBA with ~160MW rf generation and 50MeV/m acceleration
- ✓ Demonstration of the “near-ideal” main beam shaping using Micro Lens Array
- ✓ Construction of the drive beam kicking device is under way.

Technologies		Intl. collaborators
High Grad. & High Power Structures	↔	CLIC and Tsinghua University
Advanced bunch shaping	↔	Pohang Accelerator Laboratory, Korea
Advanced Positron Generation	↔	Tsinghua University, China

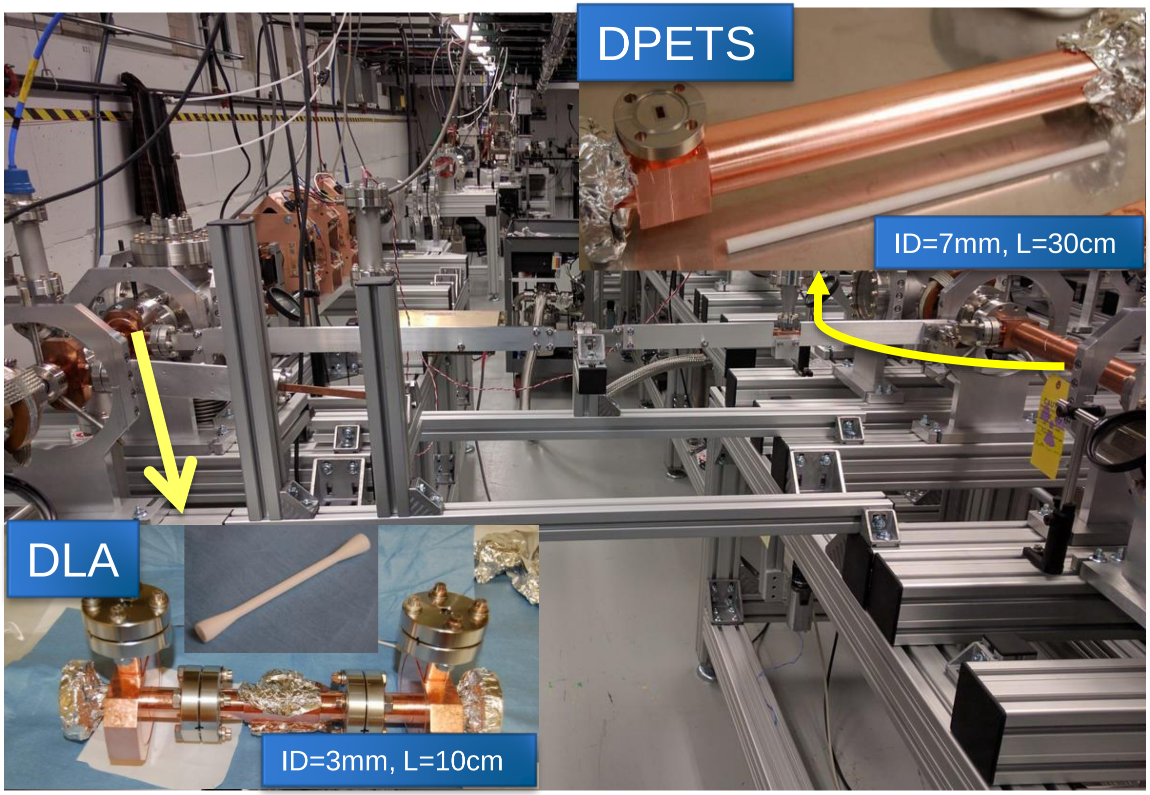
Improved Staging experiment (Feb.2016)



Improved Short pulse TBA (May 2016)



The 1st 26GHz Full Dielectric Short Pulse TBA Test (Feb.2017)

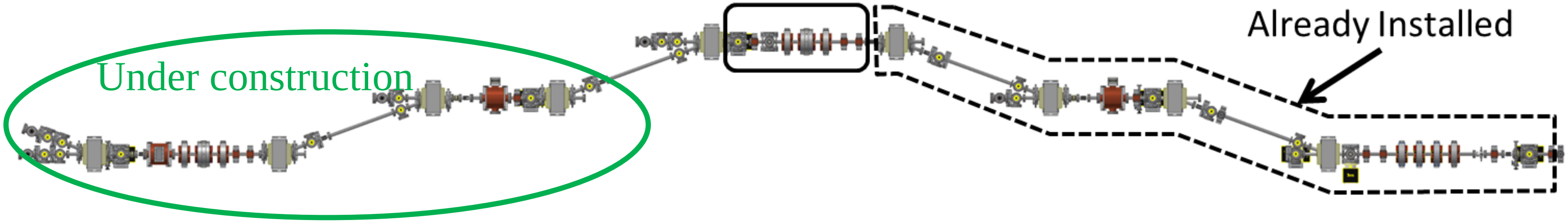


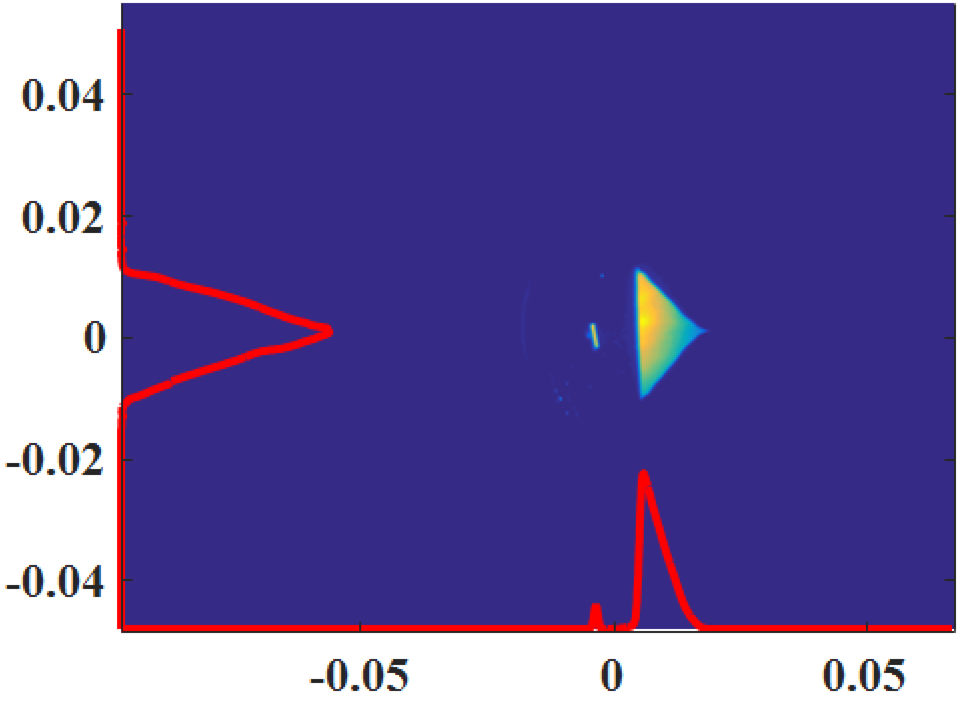
- ➢ ~4MeV deceleration was measured for each drive bunch which is aligned with ~160MW rf power output by a 4x22nC bunch train.

- •~1.8MeV acceleration of a 230pC witness beam transmitted through the dielectric accelerator, which is eqv. to ~50MV/m gradient.

Note: Gradient is lower than the ideal case due to the combination of RF loss in the waveguide, miss-match of the phase advance, and inefficient rf coupling, etc.

Arbitrary bunch shaper using EEX or DEEX (Jan.2017--present)





- Using Micro-Lens Array and mask produce the “ideal” transverse shaped bunch (Drive + witness bunches).

- Using Emittance Exchanger or Double Emittance Exchanger to transform the beam transverse profile to the current temporal profile.