Acceleration in Plasma Wakefield Driven by Beams

ECFA Meeting, 14 November 2019, CERN

Edda Gschwendtner, CERN

Beam-Driven Wakefield Acceleration Facilities

Outline:

- State of the Art of Current Beam Driven PWFA Facilities
- Status and Goals towards HEP Colliders
- Key Challenges Addressed in Planned Beam Driven PWA Facilities
- Summary

Facilities relevant for HEP

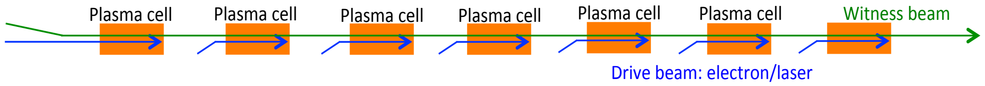
Facility	Where	Drive (D) beam	Witness (W) beam	Start	Goal
FACET/FACET II	SLAC, Stanford, USA	20/10 GeV **electrons** and **positrons**	Two-bunches (e^-/e^+ and e^--e^+ bunches)	2012/ 2019	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of **positrons**
FLASHForward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2018	- Acceleration of witness bunch with high quality and efficiency - **High repetition rate**
SPARC Lab	Frascati, Italy	150 MeV **electrons**	Several bunches	On going	- Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (20 MeV)	2016	- Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme. - **Application for HEP** (e.g. fixed target, e/p collider)

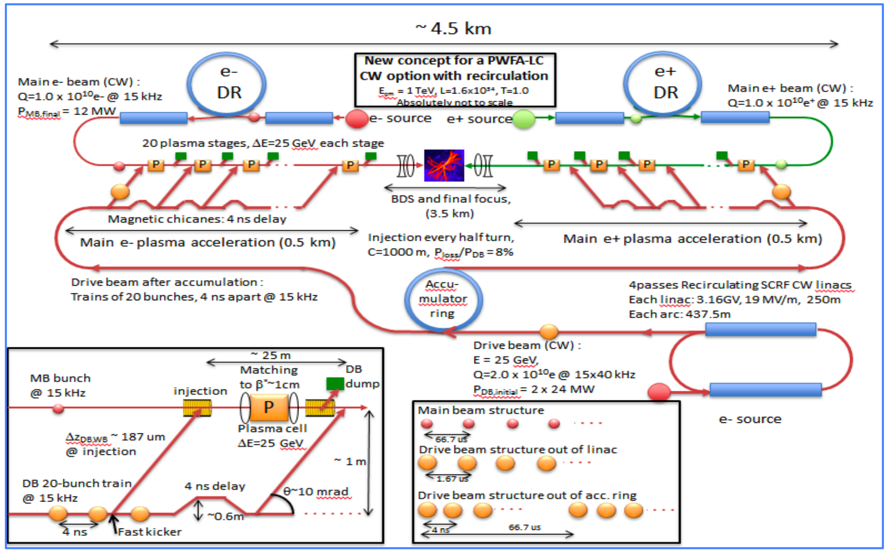
Acceleration to HEP Energies in PWA

Drive beams:
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams:
Electrons: 10^{10} particles @ 1 TeV ~few kJ

- **Electron driven PWA**: need several stages
  - effective gradient reduced because of long sections between accelerating elements….

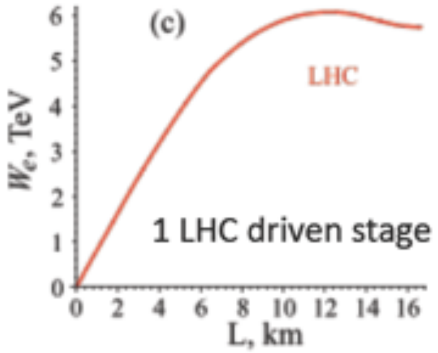




E. Adli et. al.,arXiv:1308.1145 (2013)

- **Proton driven PWA**: large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.

Dephasing:
SPS: ~70 m
LHC: ~few km
FCC: ~ ∞



A. Caldwell and K. V. Lotov, Phys. Plasmas ***18,*** *103101 (2011)*

State of the Art

Where are we with respect to the main objectives for a high energy physics collider applications?

MAiN OBJECTiVES

- ✧Single acceleration stage with collider parameters (e^-)
- ✧Staging of two stages with average gradient and collider parameters
- ✧Reliability and reproducibility of the acceleration process
- ✧High-repetition rate operation
- ✧Acceleration of e^+ bunch
- ✧Demo facility(ies)
- ✧Global collider concept
- ✧Theory and simulations

P. Muggli

First Beam Driven Acceleration

Theoretical paper for beam driven PWFA 1985

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

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

Pisin Chen[a]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
and
J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

→ towards ✧Single acceleration stage with collider parameters (e^-)

Gradient ✔

First beam driven plasma wakefield acceleration 1988

VOLUME 61, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1988

Experimental Observation of Plasma Wake-Field Acceleration

J. B. Rosenzweig, D. B. Cline,[a] B. Cole,[b] H. Figueroa,[c] W. Gai, R. Konecny, J. Norem, P. Schoessow, and J. Simpson
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 21 March 1988)

Argonne National Lab

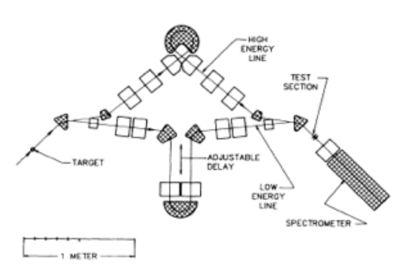


FIG. 1. Schematic of Argonne National Laboratory AATF layout.

- Drive beam: 21 MeV, witness beam: 15 MeV σ_z = σ_r = 2.4mm, charge: 2-3nC
- DC plasma source, Argon, n_e= 0.7-7x10^{13}cm^{-3}

→ Result: **Wakefields of order 1 MV/m**

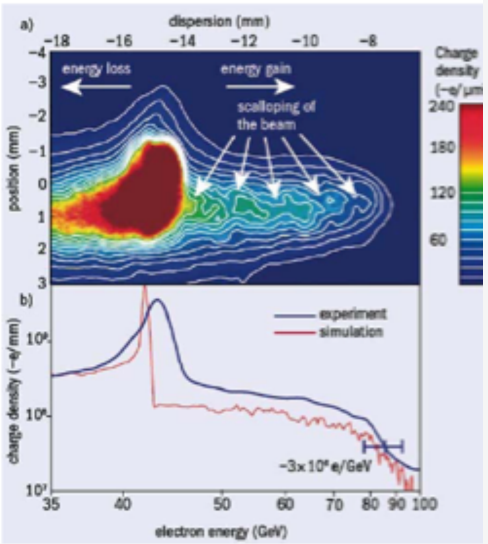
Breakthrough

*I. Blumenfeld et al, Nature 455, p 741 (**2007**)*

Gaussian electron beam with 42 GeV, 3nC @ 10 Hz,
σ_x = 10µm, 50 fs
85cm Lithium vapour source, 2.7x10^{17}cm^{-3}

→ Accelerated electrons from 42 GeV to 85 GeV in 85 cm.

→ Reached accelerating gradient of **52 GeV/m**



Final Focus Test Beam Facility, **FFTB** at SLAC

FACET, SLAC, US

Premier R&D facility for PWFA: **Only facility capable of e^+ acceleration**

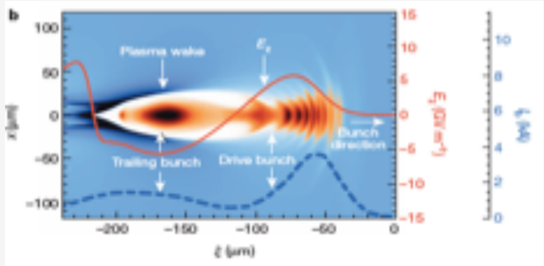
- **Timeline:**
  - Commissioning (2011)
  - Experimental program (2012-2016)
- **Key PWFA Milestones:**
  - ✓ Mono-energetic electron acceleration
  - ✓ High efficiency electron acceleration
  - ✓ First high-gradient positron PWFA
  - ✓ Demonstrate required emittance, energy spread

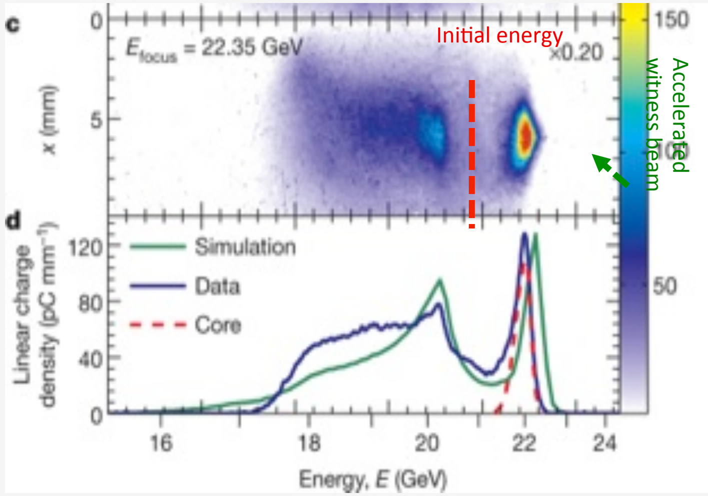
- Facility hosted more than 200 users, 25 experiments
- One high profile result a year
- Priorities balanced between focused plasma wakefield acceleration research and diverse user programs with ultra-high fields
- Unique opportunity to develop future leaders

High Efficiency, High Energy Acceleration, FACET

High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator, 2014

*M. Litos et al., doi, Nature, 6 Nov **2014**, 10.1038/nature 13882*



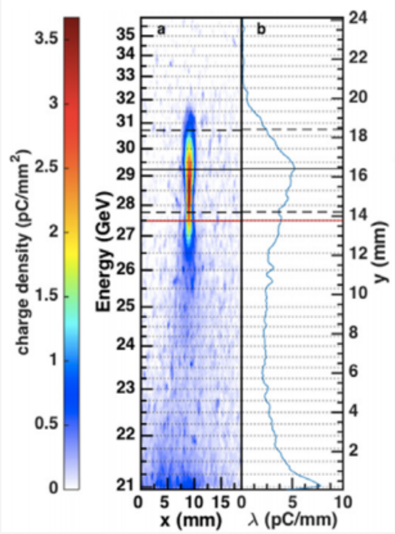


70 pC of charge accelerated, 2 GeV energy gain, 5 GV/m gradient

➔ Up to **30% transfer efficiency, ~2% energy spread**

9 GeV energy gain in a beam-driven plasma wakefield accelerator

*M Litos et al **2016** Plasma Phys. Control. Fusion 58 034017*



➔ towards ✧Single acceleration stage with collider parameters (e^-)

Positron Acceleration, FACET

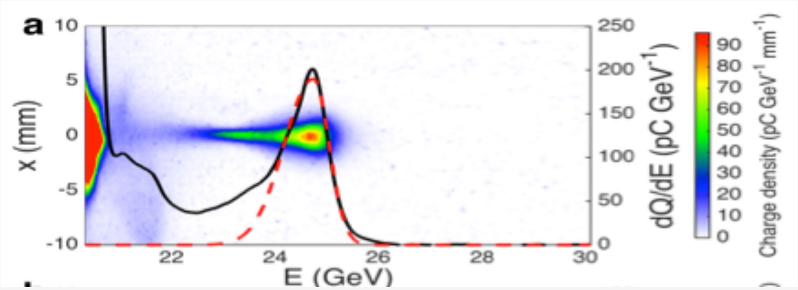
Positrons for high energy linear colliders: **high energy, high charge, low emittance**.

First demonstration of positron acceleration in plasma (FFTB)

*B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (**2003**)*
M. J. Hogan et. al. Phys. Rev. Lett. 90 205002 (2003).

Energy gain of 5 GeV. Energy spread can be as low as **1.8%** (r.m.s.).

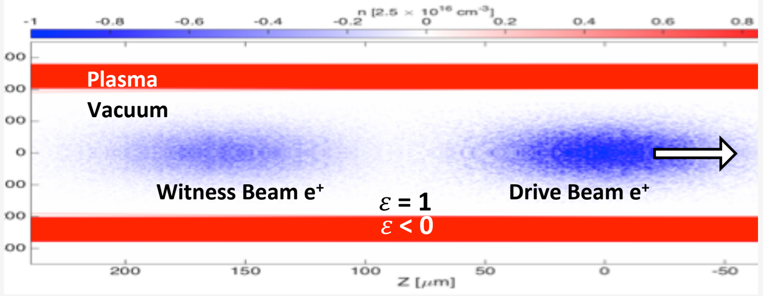
*S. Corde et al., Nature **524**, 442 (2015)*



High-density, compressed positron beam for non-linear PWFA experiments. Energy transfer from the front to the back part of the bunch.

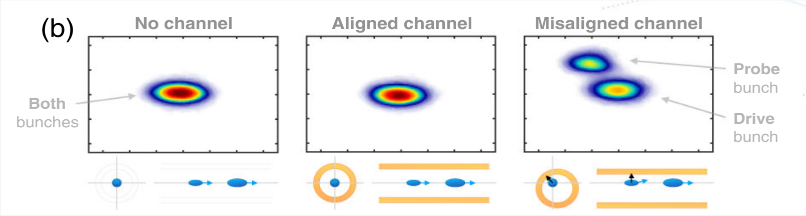
Two-bunch positron beam: First demonstration of controlled beam in positron-driven wake
S. Doche *et al.*, Nat. Sci. Rep. 7, 14180 (2017)

Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.
S. Gessner et. al. Nat. Comm. 7, 11785 (2016)



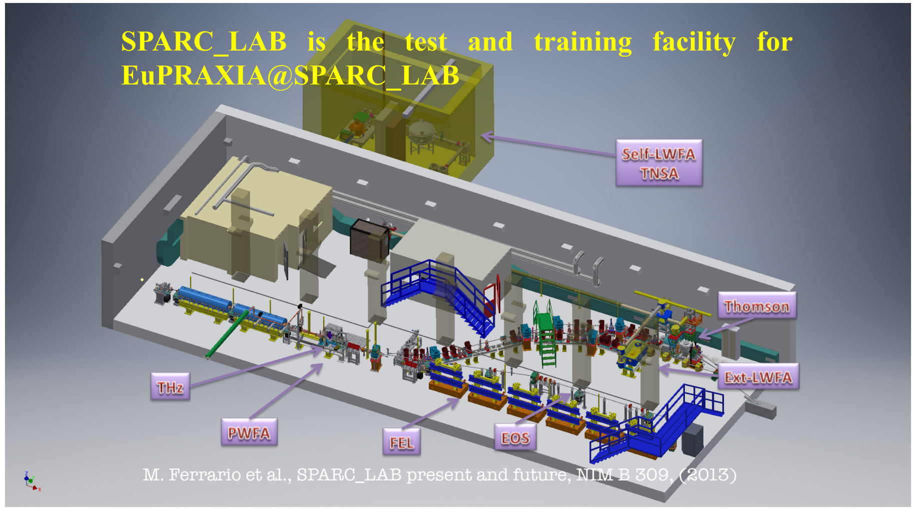
Measurement of **transverse wakefields in a hollow plasma** channel due to off-axis drive bunch propagation.

*C. A. Lindstrøm et. al. Phys. Rev. Lett. 120 124802 (**2018**).*



➔ towards ✧Acceleration of e$^+$ bunch: e$^+$ acceleration demonstrated, but issue: emittance blow-up

SPARCLAB, Frascati, Italy



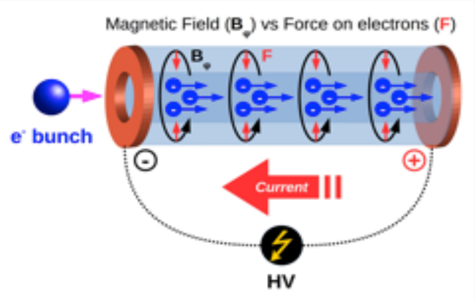
- 150 MeV drive/witness beam
- FEL experiments
- Resonant PWFA
- LWFA with 200 TW laser

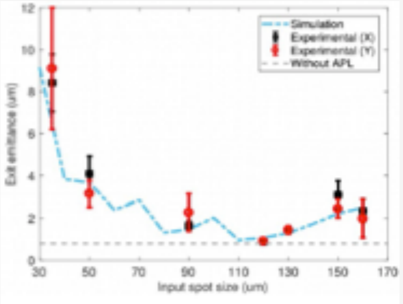
SPARC_LAB: **EuPRAXIA** Site for beam driven plasma accelerator
EuPRAXIA Design Study started in November 2015, 4 years,
Goal: Engineering of a high quality, compact plasma accelerator, 5 GeV electron beam for 2020's, demonstrate user readiness, Pilot users from FEL, HEP, medicine

➔ See R. Assmann's talk

Plasma Lens Experiments:

Acceleration of high brightness beams and transport to the final application, while preserving the high quality of the 6D phase space



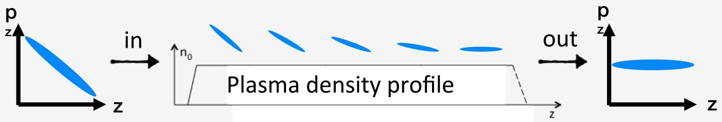


R. Pompili et al., PRL 121 (2018), 174801

BELLA, LBNL: *J. van Tilborg et al., PRL 115 (2015), 184802*
CLEAR, CERN: *C.A. Lindstrom et al., PRL 121 (2018), 194801*

Plasma dechirper:

Longitudinal phase-space manipulation with the wakefield induced in plasma by the beam itself.



From 0.6% to 0.1% energy spread

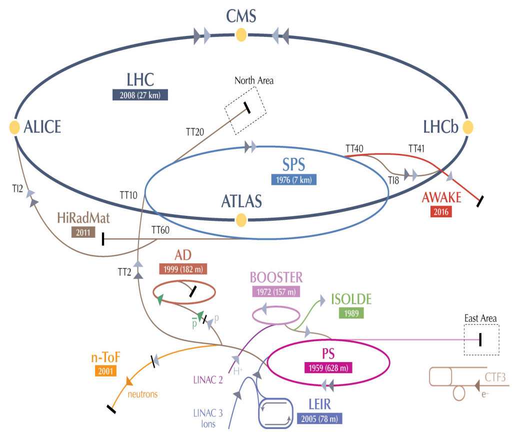
V. Shpakov et al., PRL 122 (2019), 114801

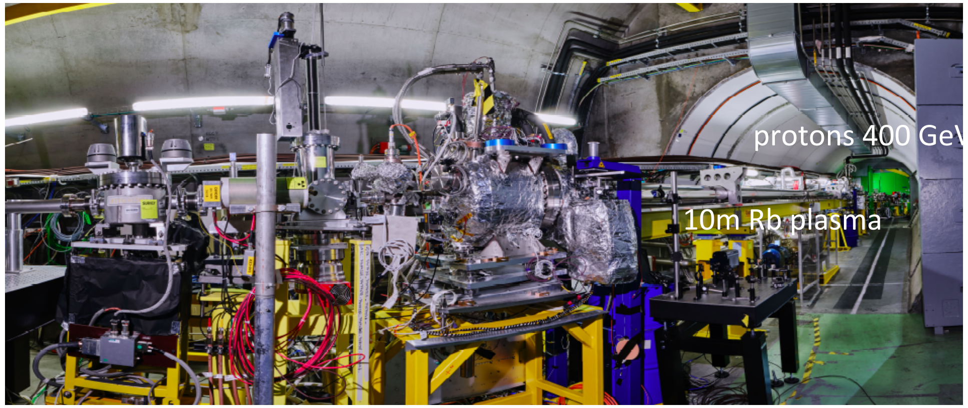
FLASHForward, DESY: *R. D'Arcy et al., PRL 122 (2019), 034801*

➔ towards ✧Staging of two stages with average gradient and collider parameters

AWAKE, CERN

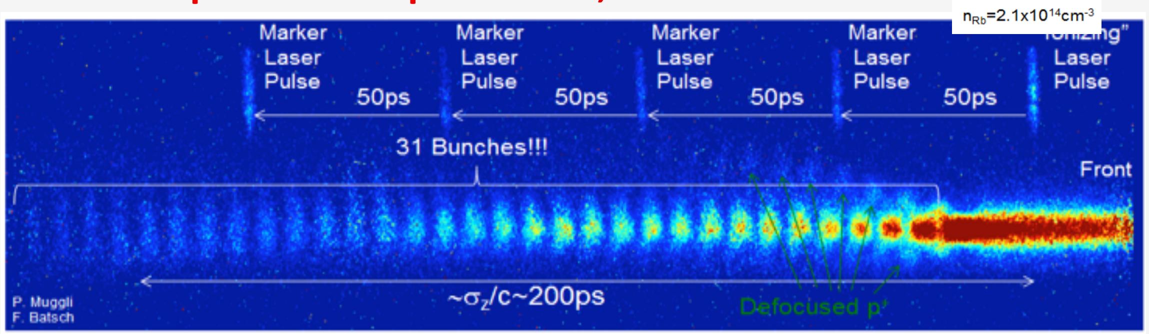
AWAKE has demonstrated during Run 1 (2016-2018) that the proton beam can be used as drive beam, that the seeded self-modulation is a reliable and robust process and that externally injected electrons can be accelerated with high gradients .



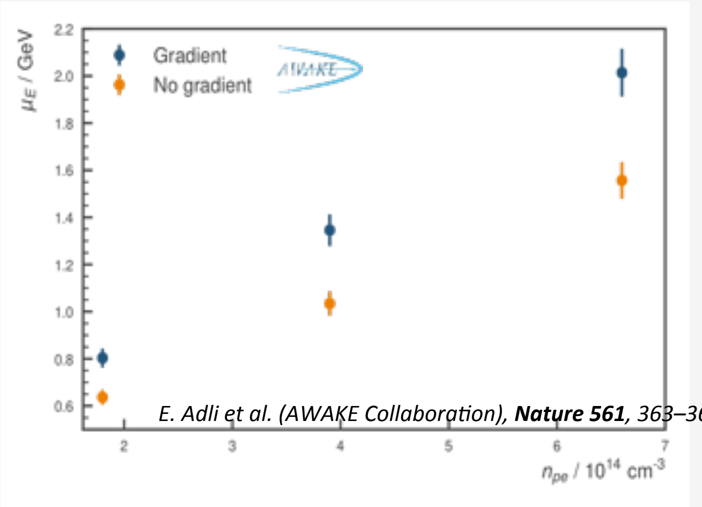


Seeded self-modulation of the proton bunch:

➔ SSM process is reproducible, reliable and stable.



*E. Adli et al. (AWAKE Collaboration), **Phys. Rev. Lett. 122, 054802 (2019).***
*M. Turner et al. (AWAKE Collaboration) **PRL, 122, 054801 (2019).***



*E. Adli et al. (AWAKE Collaboration), **Nature 561**, 363–367 (2018)*

➔ Electrons accelerated to 2 GeV in 10m plasma.
➔ Energy is as expected from simulations

➔ towards ✧Reliability and reproducibility of the acceleration process

Status of Today and Next Goals towards Collider Application

Beam Driven PWFA	Current	Next Goals
Charge (nC)	0.1	1
Energy (GeV)	9	10
Energy spread (%)	2	0.5
Emittance (um)	>50-100 (PWFA)	<0.5
Staging	single	multiple
Beam to beam efficiency (%)	20	40
Rep Rate (Hz)	1	10^{3-4}
Acc. Distance (m)/stage	1	1-5
Positron acceleration	acceleration	emittance preservation
Proton drivers	SSM, acceleration	Emittance control
Plasma cell (p-driver)	10 m	100s m
Simulations	days	Improvements by 10^3

Note: Current parameters have not been achieved at the same time!

We need facilities that address the collider application goals as well as the different components relevant for high energy physics colliders.

Facility characteristics:

- Continuous operation, high availability
- Repetition rate > 1Hz
- e- driven: ~1m plasma, 2-20 GeV drive electron beam
- > 100 MeV witness electron beam
- Diagnostics
- Positron bunch source

Collider facility:

- > 2 stages
- High repetition rate (kHz)
- Emphasis on continuous operation, quality efficiency,
- Redundancy of systems

⬇

See J. Osterhoff's talk

FACET-II, SLAC

FACET-II: 10 GeV, 2 nC, 30 Hz, µm emittance, I_{peak}>10kA

SLAC

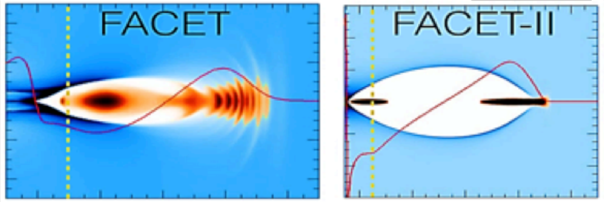
Emittance Preservation with Efficient Acceleration

FY19-21

- High-gradient high-efficiency (instantaneous) acceleration has been demonstrated @ FACET

Stage 1

- Full pump-depletion and Emittance preservation at µm level planned as first experiment
- Beam matching to plasma
- Alignment tolerances

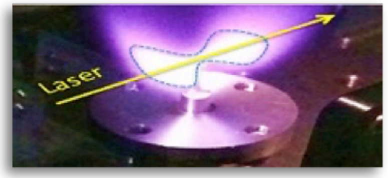


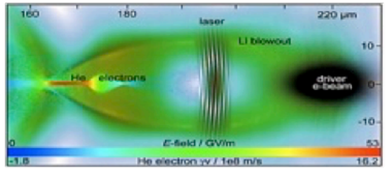
High Brightness Beam Generation & Characterization

FY20-22

- 10's nm emittance preservation is necessary for collider apps
- Ultra-high brightness plasma injectors may lead to first apps

Stage 1





FACET-II, SLAC

FACET-II: 10 GeV, 2 nC, 30 Hz, µm emittance, I_{peak}>10kA

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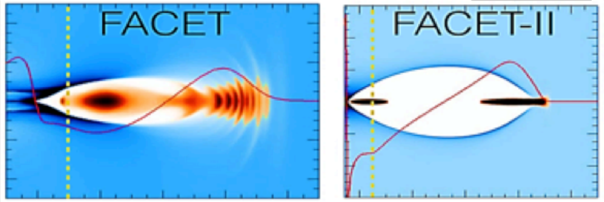

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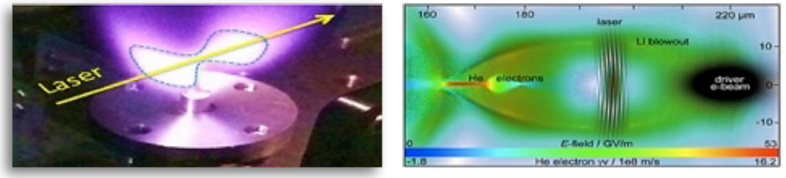


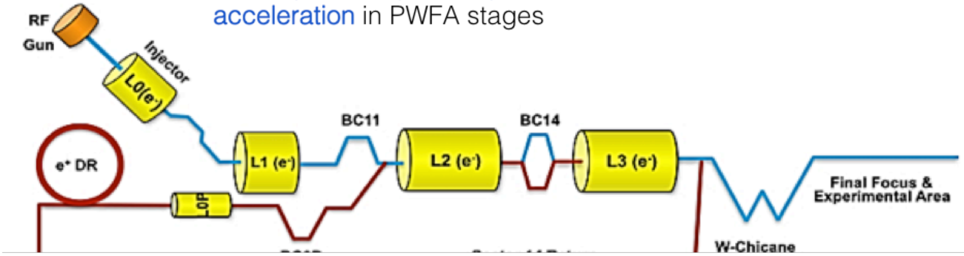
Positron Acceleration

FY21-24

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

Stage 2

- Develop techniques for positron acceleration in PWFA stages

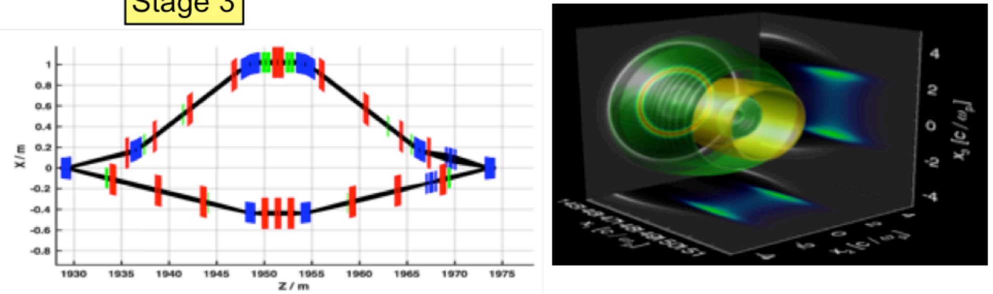


Simultaneous Deliver of Electrons & Positrons

FY22-25

- Positron Acceleration on Electron Beam Driven Wakefields

Stage 3



→ Addresses important aspects of staging (alignment, beam matching), but no staging

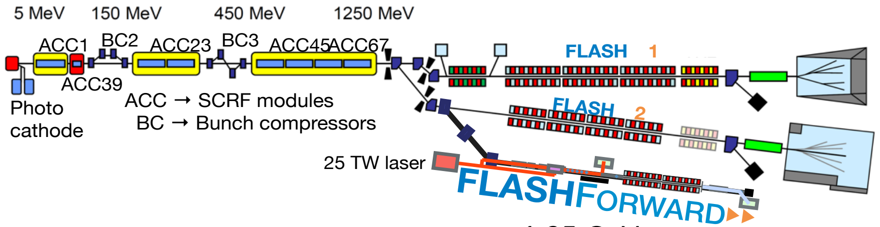
→ Only **positron** capability in the world (not approved yet)

FLASHForward>>, DESY

→ unique FLASH facility features for PWFA

now

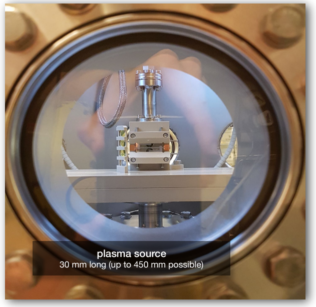
- FEL-quality drive and witness beams
- up to 1 MHz repetition rate
- 3rd harmonic cavity for phase-space linearization
  → tailoring of beam current profile
- differentially pumped, windowless plasma sources
- X-band deflector with 1 fs resolution post-plasma
- up to 10 kW average power (up to 800 bunches, ~MGz spacing, at 10 Hz)
- 15 m of FLASH 1 type undulators

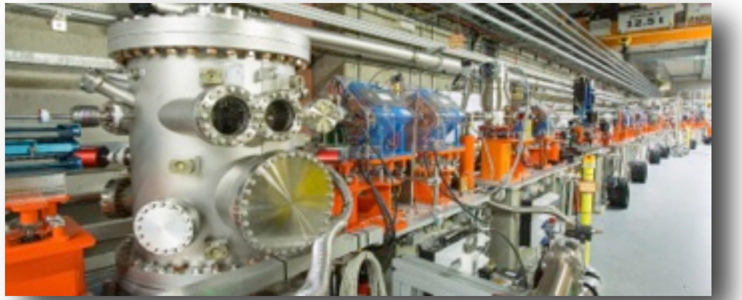


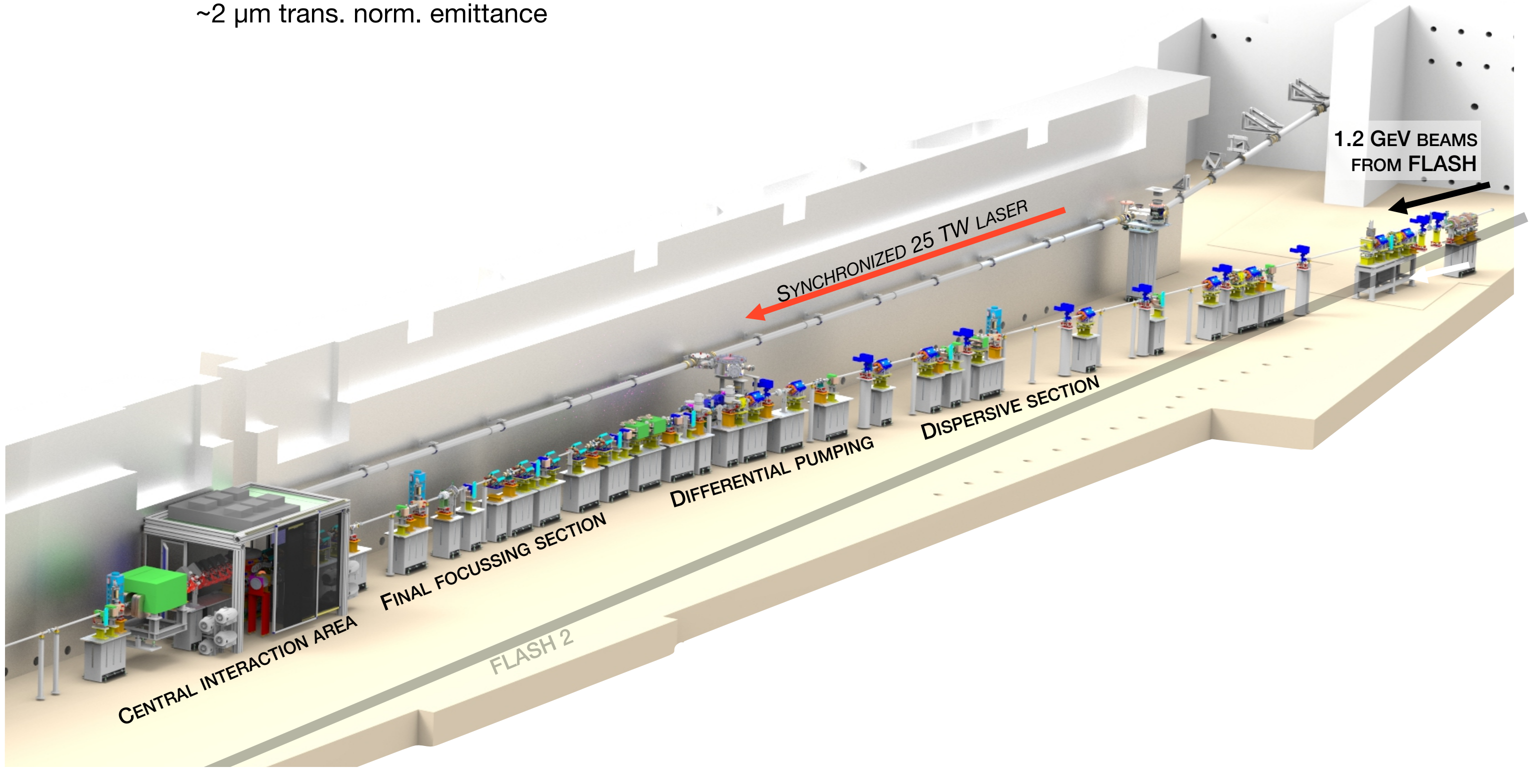
1.25 GeV

≲ **1.25 GeV energy** with a few **100 pC at ~100 fs** rms bunch duration, ~2 μm trans. norm. emittance

→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)







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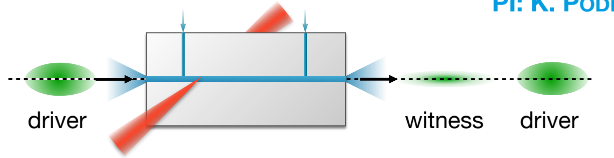
FLASHForward>>, DESY

CORE STUDY I — X-1: PLASMA CATHODE

2019-2020

PI: K. PÕDER



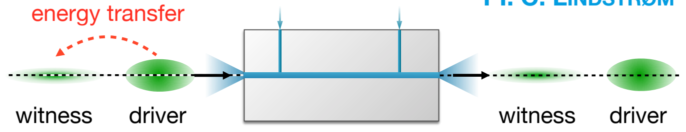
GOALS:
- 1 GeV energy gain of in-plasma injected beam
- transverse normalised beam emittance ~ 100 nm
- peak current ≳ 1 kA
- femtosecond bunch duration

> Beam generation for collider final focus

CORE STUDY II — X-2: PLASMA BOOSTER

2019-2021

PI: C. LINDSTRØM

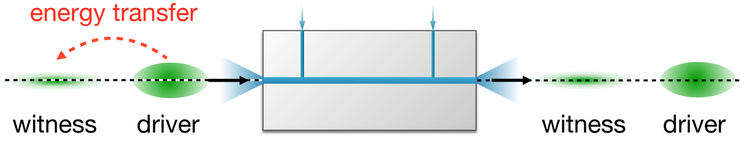


GOALS:
- 1 GeV energy gain
- conserve beam energy spread
- conserve beam normalised transverse emittance
- deplete drive beam energy
- 20% energy extraction efficiency from drive to witness

> Energy boosting section for collider staging

CORE STUDY III — X-3: HIGH-AVERAGE POWER PWFA

PI: R. D'ARCY



x *MHz*

2019-2025

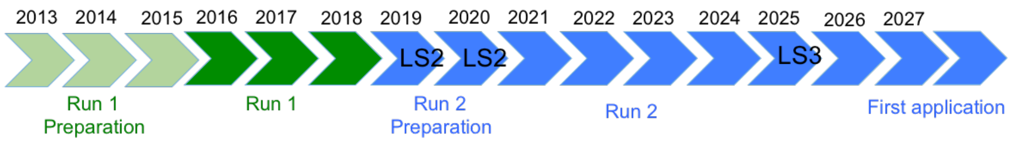
GOALS:
- GeV energy gain, beam quality preservation, depletion @ MHz
- plasma relaxation studies
- investigation into multi-discharge plasma recovery time
- MHz thermal management
- driver-witness beam separation

> Test bed to address high-average-power challenges

➔ Addresses **high-average-power** challenges

AWAKE Run 2, CERN

➔ **PWA experiment dedicated to high energy physics applications!**
➔ **International Collaboration:** 22 collaborating institutes, 3 associate institutes



Goal:

Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

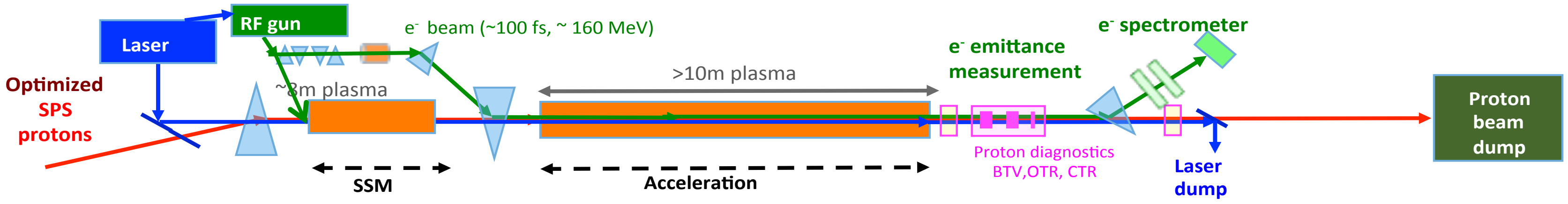
Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

Demonstrate scalable plasma source technology (e.g. helicon prototype)

➔ Freeze the modulation with **density step** in first plasma cell

➔ For emittance control: need to work in **blow-out regime** and do **beam-loading**

➔ R&D on different **plasma source technologies**



➔ Addresses aspects of staging (external electron injection) and energy scaling
➔ Scalable plasma cell development

➔ **Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, AWAKE technology could provide particle physics application in mid-term future!**

➔ See J. Osterhoff's talk

Summary

Remarkable progress has been done in beam driven plasma wakefield acceleration and many of the challenges important for a collider design have been demonstrated.

Current and planned beam driven plasma wakefield acceleration facilities explore different advanced and novel accelerator concepts and proof-of-principle experiments and **include challenges of HEP applications**, however, **not necessarily at the same time.**

In order to **advance towards HEP applications** we need:

- **Dedicated plasma wakefield facilities** where all components are optimized for HEP R&D
- Facility with **positrons**
- Facility with **staging**
- **Global coordination** towards HEP applications
- **Stronger collaboration between high energy and plasma acceleration** to work out a reliable collider concept
- **Commitment** from the big laboratories is essential in order **to advance in the same speed** as with conventional technologies