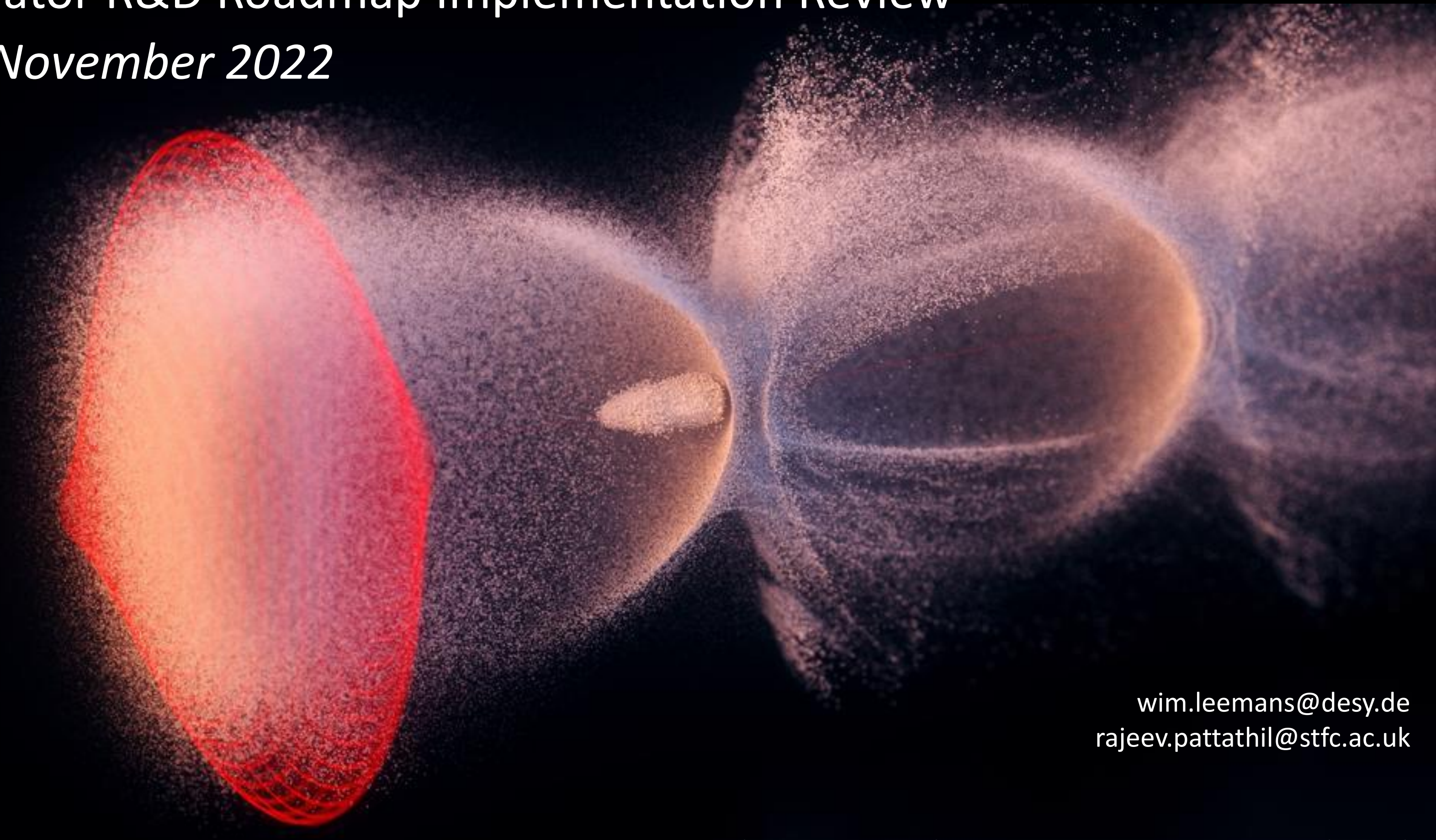
Plasma Accelerators

Report from R&D Coordination Panel

1st Accelerator R&D Roadmap Implementation Review

CERN, 21 November 2022



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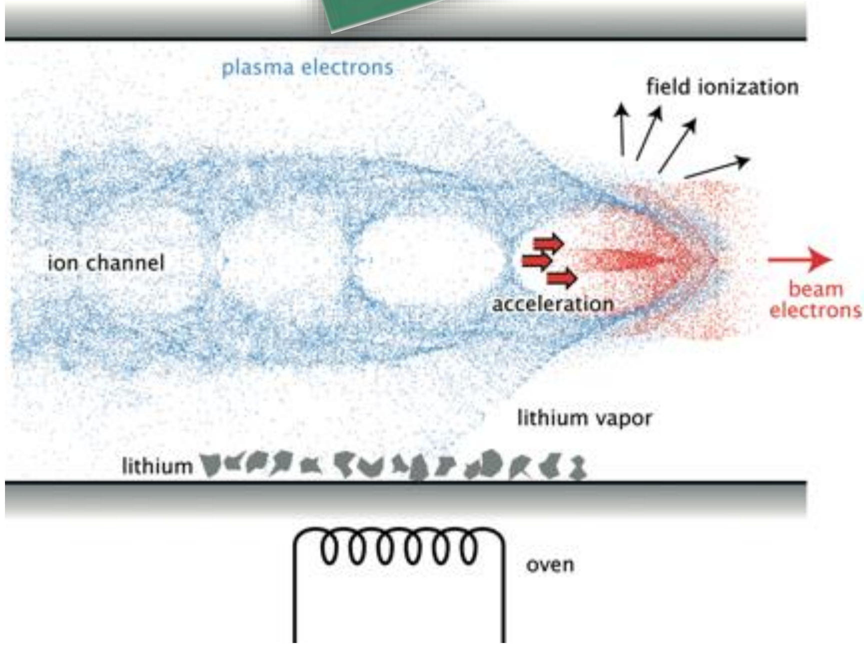
Wim Leemans, Jens Osterhoff (both DESY) and Rajeev Pattathil (RAL)

R&D Coordination Panel: Plasma Accelerators

Major milestones/deliverables

Deliverable	Due by
Report: Electron High Energy Case Study	Jun-24
Report: Positron High Energy Case Study	Jun-25
Spin-Polarised Beams in Plasma Accelerators	Dec-25
Physics Case of an Advanced Collider	Jun-24
Report: Low Energy Study Cases for Electrons and Positrons	Jun-25
Pre-CDR and Collider Feasibility Report	Dec-25
High-Repetition Rate Plasma Accelerator Module	Dec-25
High-Efficiency, Electron-Driven Plasma Accelerator Module with High Beam Quality	Dec-25
Scaling of DLA/THz Accelerators	Dec-25



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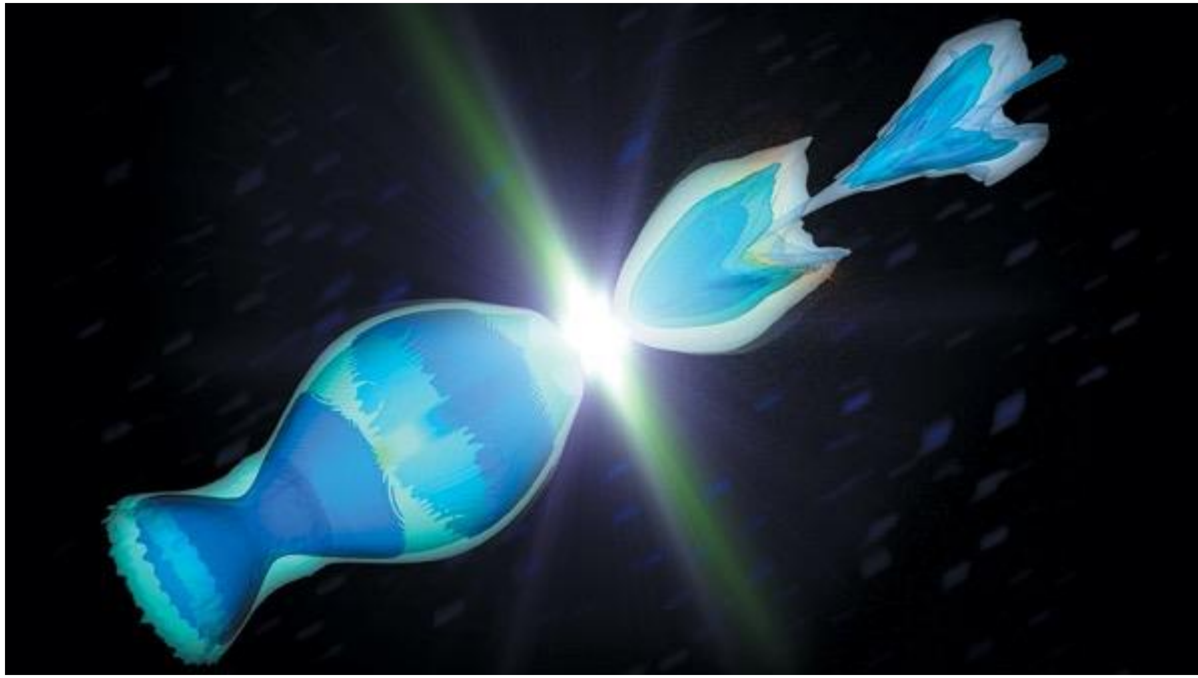
Topic 1: A feasibility study: Plasma Accelerators and their particle physics reach

Main activities

- Evaluating the state of the art in detail and providing an assessment on its suitability
- Determining theoretical limits and scalability, extrapolating experimentally achieved parameters for collider-relevant aspects: Luminosity, energy gain, energy gradient, bunch charge, emittance and energy efficiency.
- End-to-end simulations, with scalable parameters relevant for HEP.
- Establish a common set of parameters across the board for consistency
- Physics Case for plasma-accelerator-based HEP and preliminary particle physics experiments
- Sustainability analysis



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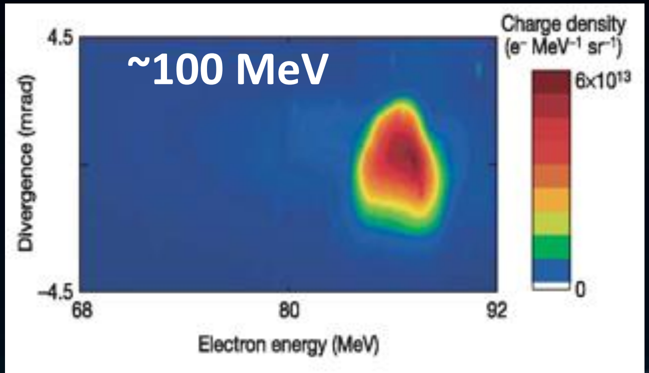
Laser-plasma accelerators go from 100 MeV to 8 GeV in a decade and half

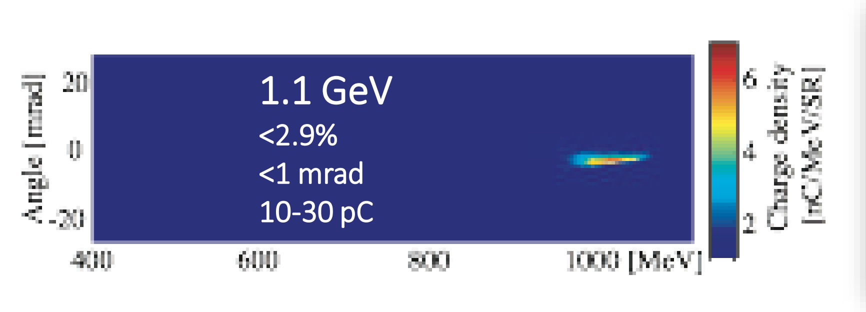
2004-2019: A success story

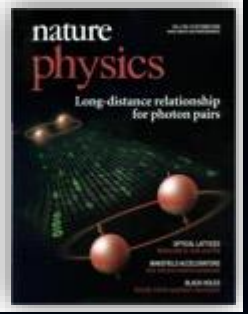
2004 result: 10 TW laser, mm-scale plasma



C. G. R. Geddes *et al.*, Nature,431, p538 (2004)
*S. Mangles *et al.*, Nature 431, p535 (2004)
*J. Faure *et al.*, Nature 431, p541 (2004)

2006 result: 40 TW laser, cm-scale plasma

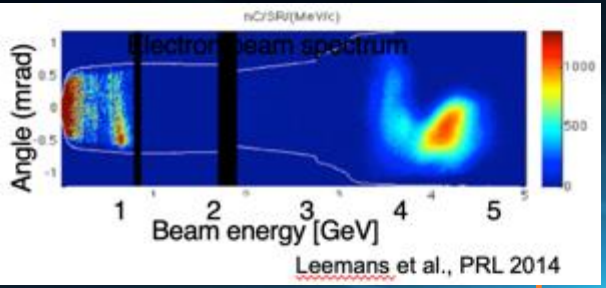




W.P. Leemans *et al.*, Nature Physics 2, p696 (2006)

2014 result: 310 TW laser, 9 cm-scale plasma

Experiment (spectrum)



2004

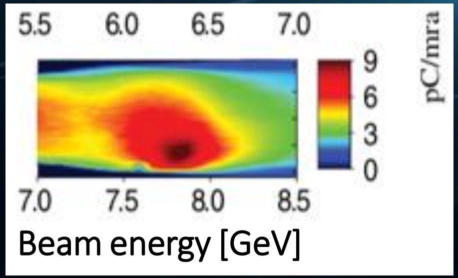
2006

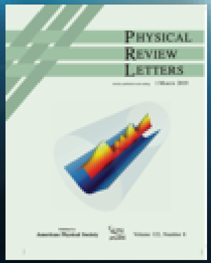
2014

2019

2019 result: 1 PW laser, 20 cm-scale plasma

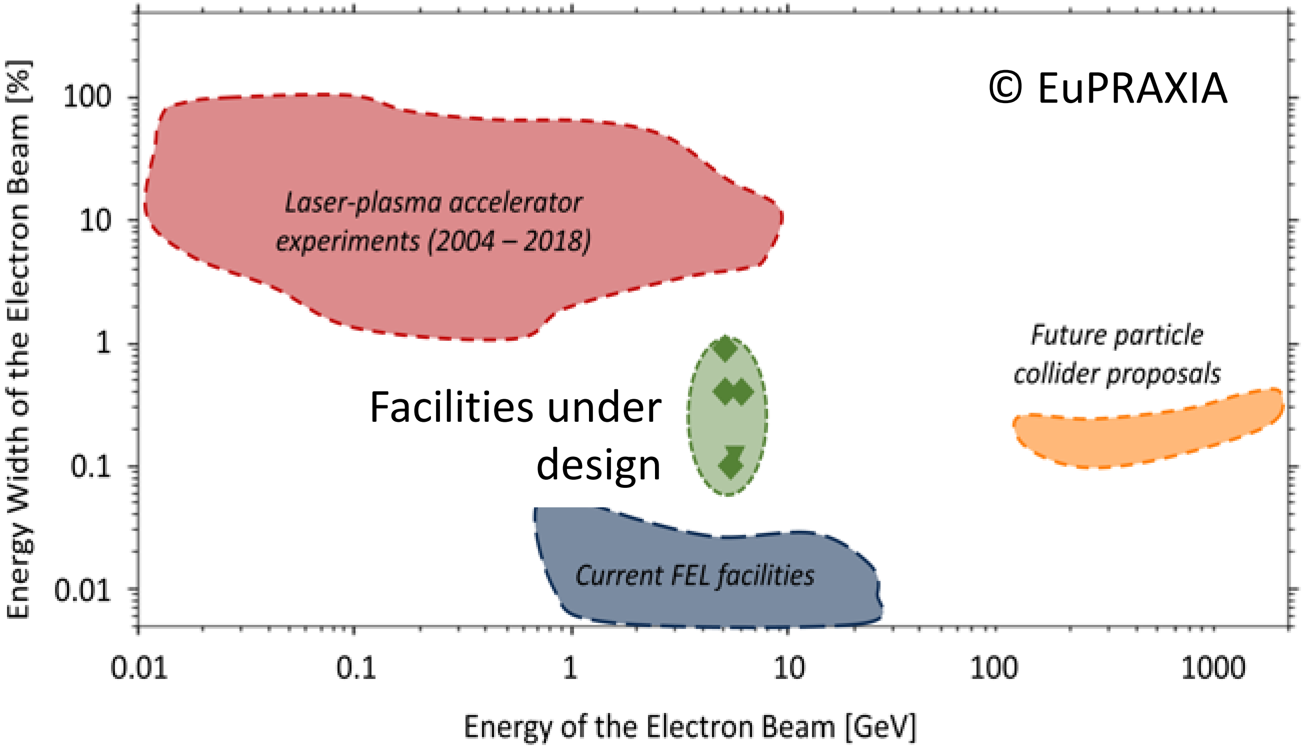
Gonsalves *et al.*, PRL 2019





Main challenges in laser-plasma accelerators

- LWFA has produced Multi-GeV energies and 1% energy spread but not simultaneously
- Schemes to produce 6D- bright, high-energy physics relevant electron beams at 100's of GeV range(low emittance, low energy spread, high brightness)
- Repetition rates beyond kHz and high wall-plug efficiency – high luminosity
- Stable beams over long periods and beam control
- Staging multiple accelerator modules
- Accelerating positron beams



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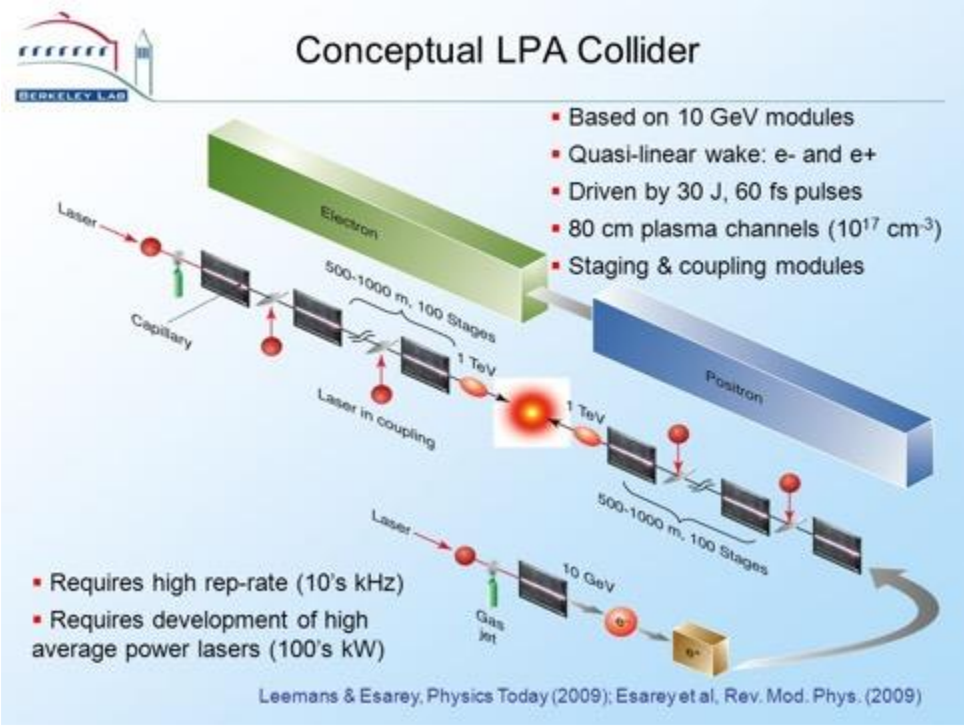
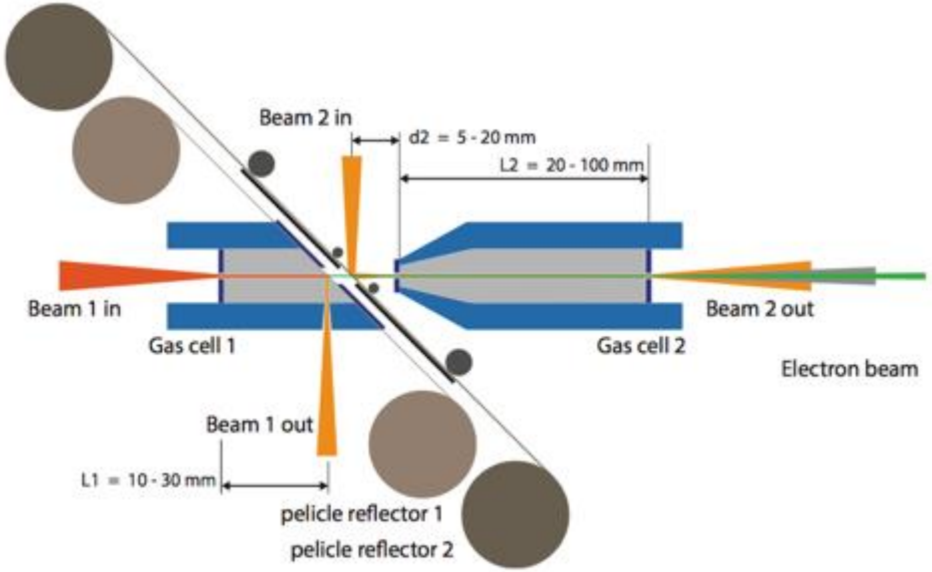
Main themes for feasibility study

- Simulations on pathways to generate beams with particle-physics relevant parameters - simultaneous realisation of nC charge, 0.1% energy spread @ 100's of GeV –TeV
- Small Beam Emittance preservation schemes, maintaining other critical parameters
- Staging of multiple accelerator modules
- Detailed analysis of failure modes and mitigation methods





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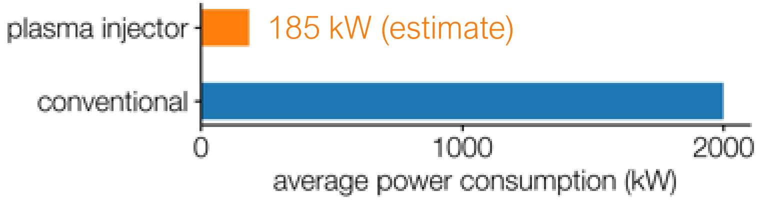
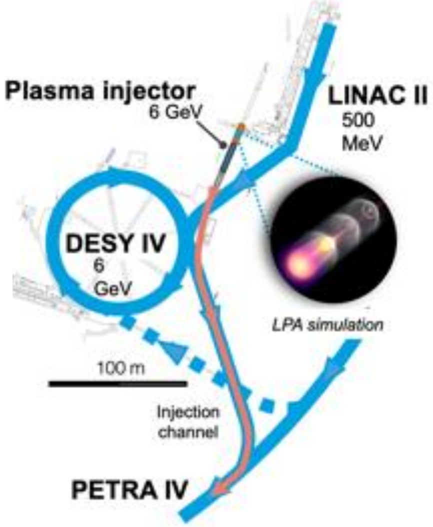
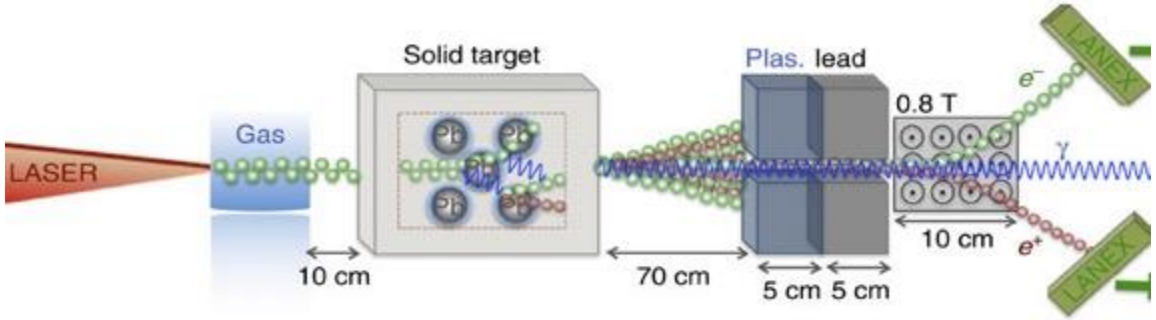
Main themes for feasibility study

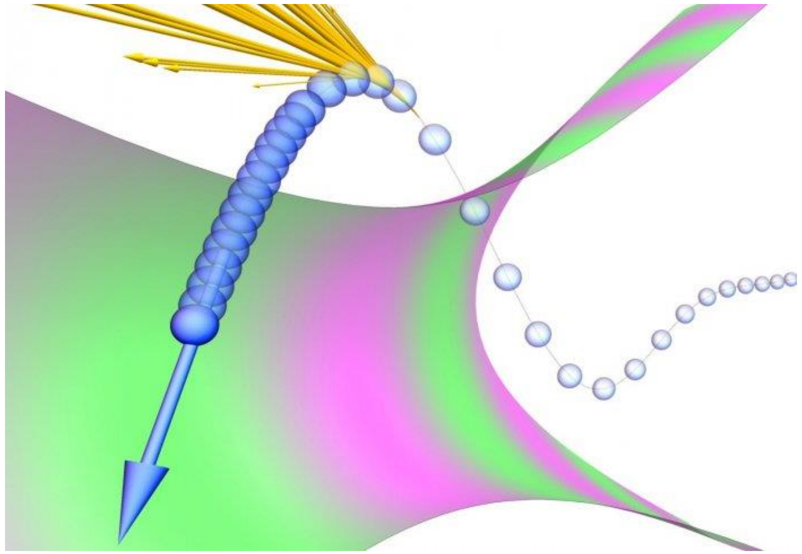
- Accelerating positrons beams : A viable and efficient acceleration mechanism to low emittance GeV and multi-GeV energies that's scalable.
- Final focusing scheme for colliders
- Early Particle-physics relevant experiments
- Sustainability – realistic wall-plug efficiency, power requirements, carbon footprint







Electron-positron plasma



Radiation Reaction

Phys. Rev. X **8**, 031004 (2018)

Phys. Rev. X 8, 011020 (2018)

Topic 1: Organisation of Work packages

FEAS		**Feasibility and pre-CDR Study on Plasma and Laser Accelerators for Particle Physics**			
	FEAS.1	Electron Beam Performance and scaling (Simulations/ Results - Comparisons)	Jorge Viera (IST)	Maxence Thevenet (DESY)	
	FEAS.2	Positron Beam Performance and scaling (Simulation/ Results - Comparisons)	Severin Diedrichs (DESY)	Gianluca Sarri (QUB)	Carl Schroeder (LBNL) - tbc
	FEAS 3	Accelerator Design, Staging	Carl Lindstrøm (Oslo)	Zulfikar Najmudin (Imperial)	
	FEAS.4	Spin and Polarization preservation	Kristjan Põder (DESY)		
	FEAS.5	Final focus system- physics at interaction point	Arnd Specka (Ecole Polytechnique)		Spencer Gessner (SLAC) - tbc
	FEAS.6	Conceptual integration (e+/e- pathways inc g-g collider)	Eric Adli (Oslo)	Brigitte Cros (CNRS)	
EFFICIENCY	EFFS.1	Sustainability analysis	Denise Völker (DESY)	Erik Jensen (CERN)	Marlene Turner (LBNL) - tbc
PHYS	PHYS.1	Study WG: Particle Physics with Advanced Accelerators	Brian Foster (Oxford)		
	PHYS.2	Intermediate steps, early particle physics experiments and test facilities	Maria Vranic (IST)	Matt Zepf (Jena)	Stuart Mangles (Imperial)

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Considering

Potential consultants

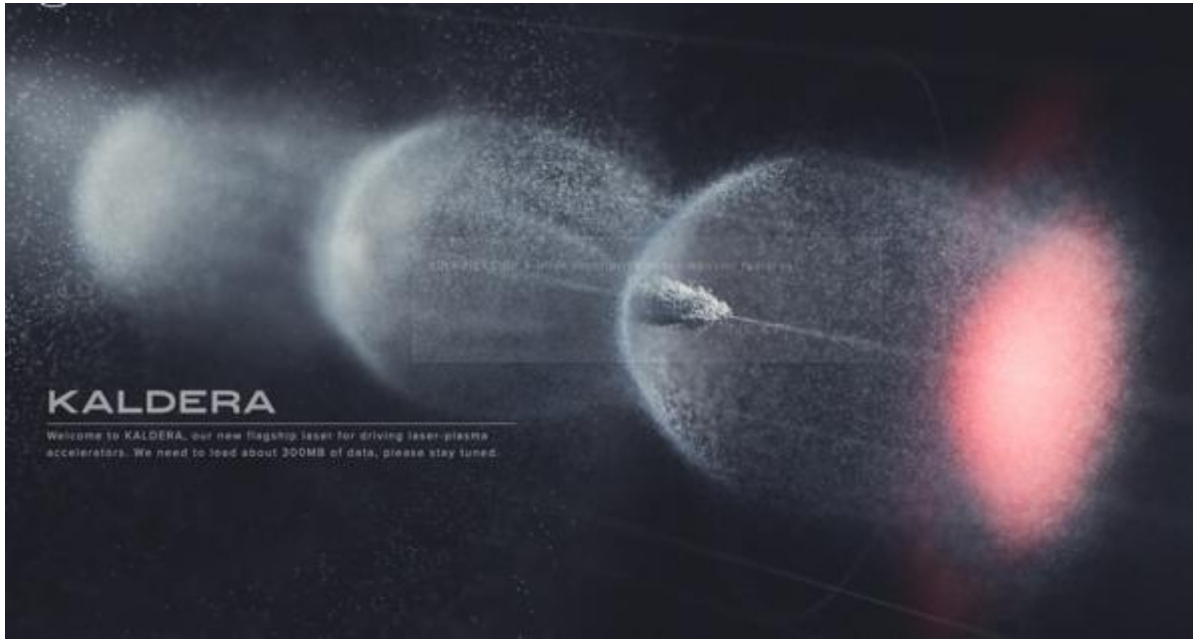
Topic 2: High repetition rate LWFA demonstration

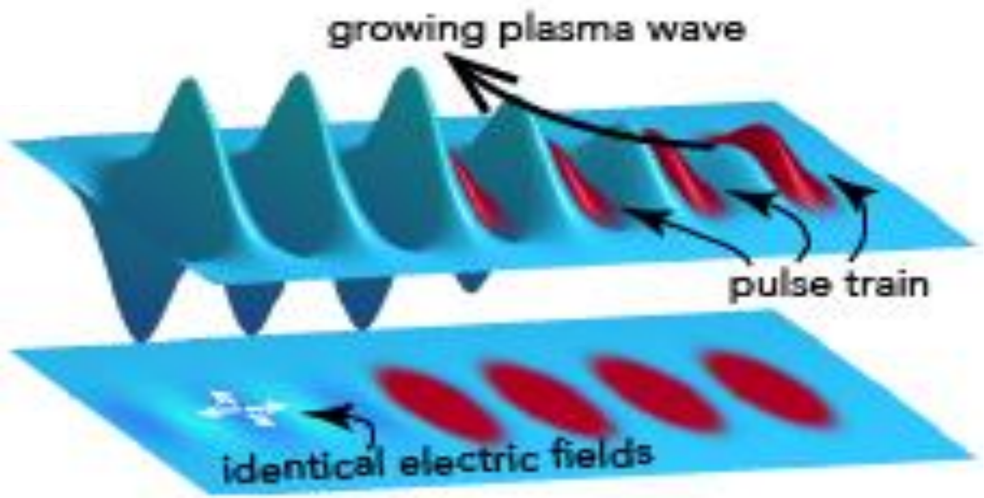
Main activities

- Demonstration of 100Hz-kHz plasma accelerator KALDERA (Germany), CALA (Germany) k-BELLA (USA), DiPOLE-s (UK)
    - Development of appropriate laser driver
    - Plasma targetry
    - Machine learning control

- Demonstration of routine, long-term operation of a plasma accelerator without losing beam quality

- Novel excitation and injection schemes – multi-pulse wakefield, REMPI etc. – for increasing rep.rate beyond kHz
- Emittance preservation and Low-emittance schemes (eg. Trojan Horse)





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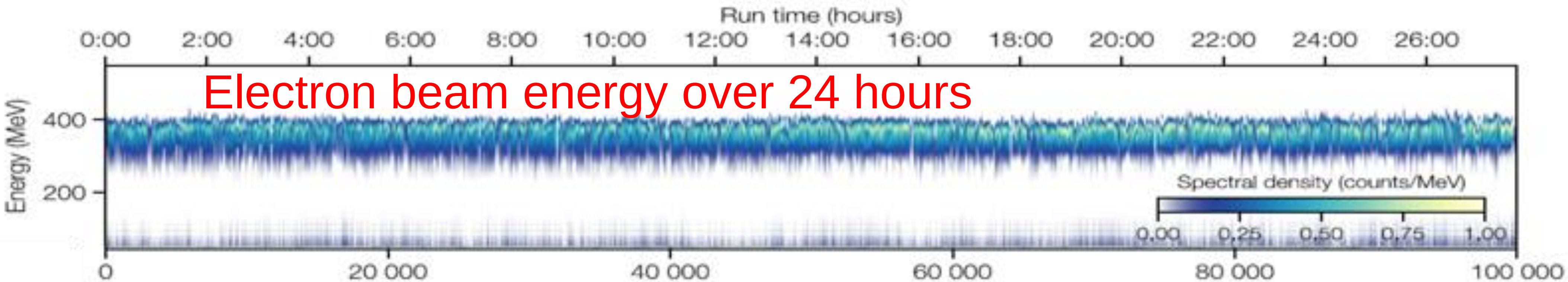
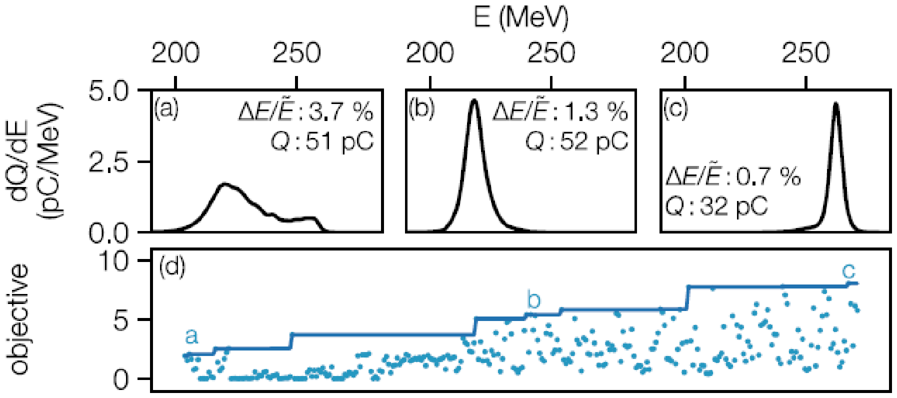
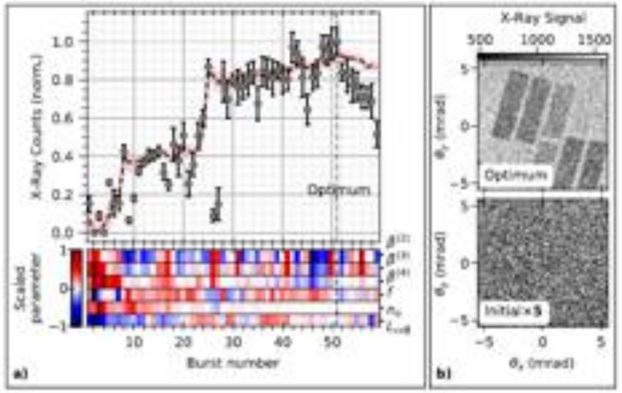
Stable LPA operation over extended periods



They can be optimized with Machine Learning loops





6-dimensional LWFA optimisation

Laser pulse shaping and varying gas target parameters optimises the specified property
(e.g. electron energy, x-ray flux etc)

Maier et al PRX **10**, 031039 (2020);
Jalas et al PRL **126**, 104801 (2021)

Shalloo Nature Comm. 11, 6355 (2020)

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Extreme Photonics Applications Centre

- A new £88M UK facility for applications of laser-driven plasma accelerators
- Will produce LWFA driven beams at 1PW, 10Hz: Expected up to 10GeV electron beams
- Will play a major role in the Laser Plasma Accelerator development, along with SCAPA and other centers in the UK

pwasc.org.uk

Building completed; installations ongoing; first operations in 2025

Additional space for future laser and experimental areas (eg. a 100Hz system under development)

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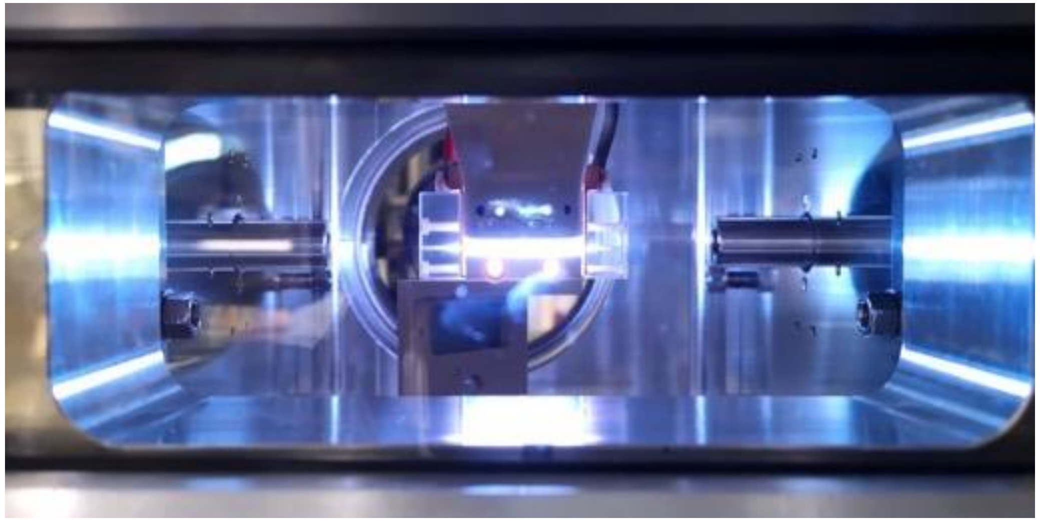
Topic 2: Organisation of Work packages

HRRP		***Experimental demonstration: High-Repetition Rate Plasma Accelerator Module***		
		Coordination	Leo Gizzi (CNR)	Andi Maier (Hamburg/DESY)
	HRRP1	High rep lasers (100 Hz-kHz)	Andi Maier (Hamburg/DESY)	Paul Mason (RAL)
	HRRP2	High rep plasma targets	Simon Hooker (Oxford)	Brigitte Cros (CNRS)
	HRRP3	Facility/Delivery	Dan Symes (RAL)	Andreas Dopp (CALA)

Topic 3: High Repetition Rate Particle-driven Wakefield Accelerators

Main activities

- Emittance preservation
- High Transformer Ratio
- Efficiency



Plasma accelerator @ SPARC Lab – EuPRAXIA - INFN

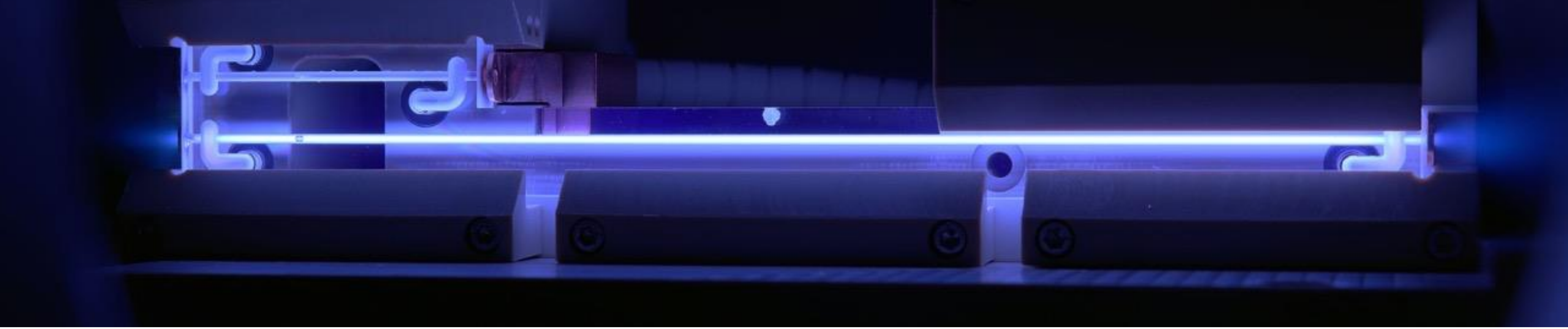
HEFP	Electron-driven	Electron-Driven Plasma Accelerator Module with High beam Quality	Jens Osterhoff (DESY)	Richard D'Arcy (Oxford)
	Proton - Driven	AWAKE	Edda Gschwendtner (CERN)	Patric Muggli (Max-Planck)

FLASHForward @ DESY

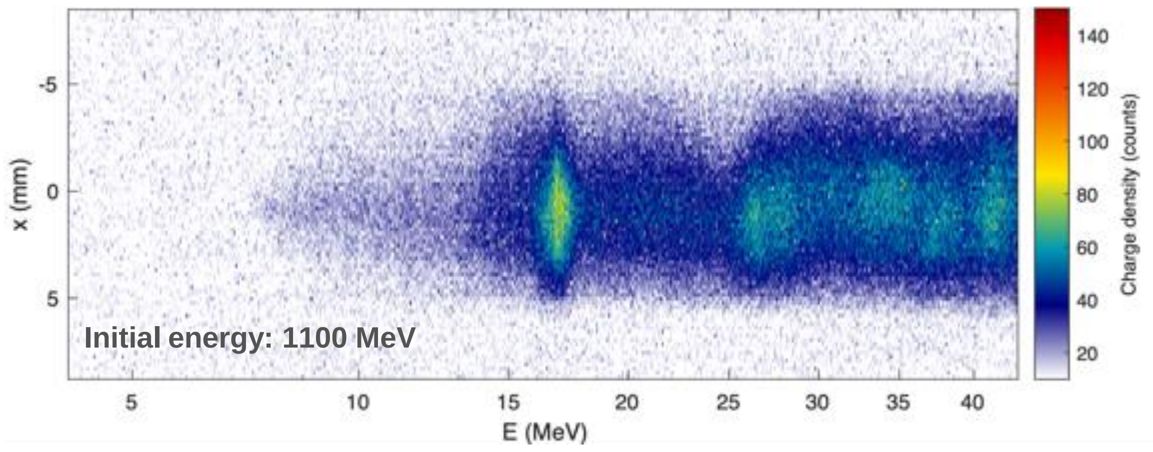
1.1 GeV energy gain and loss achieved in a 195 mm plasma accelerator cell

First experiments with long source

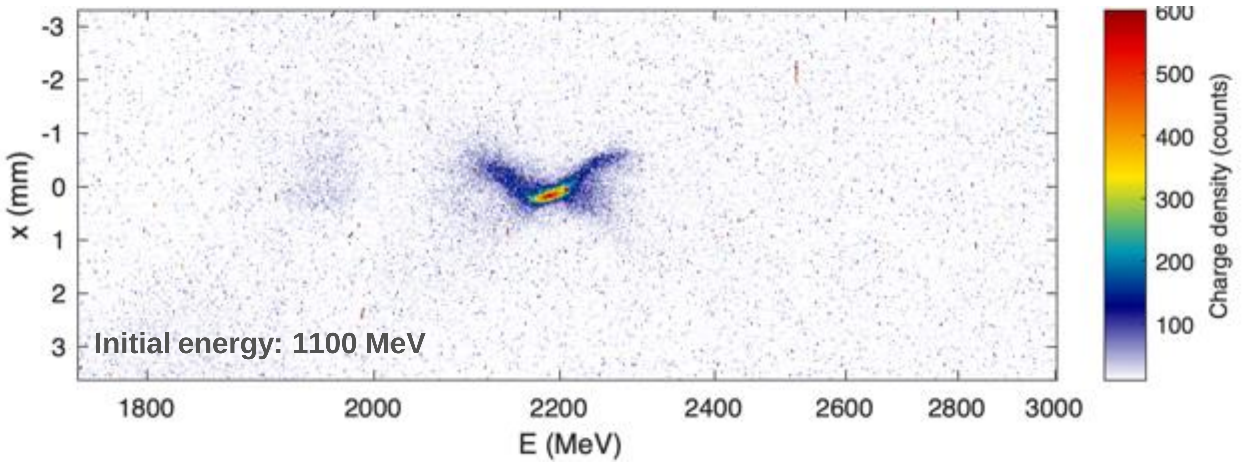
FLASHFORWARD▸▸ plasma capillaries



Energy depletion ➞ active plasma beam dump



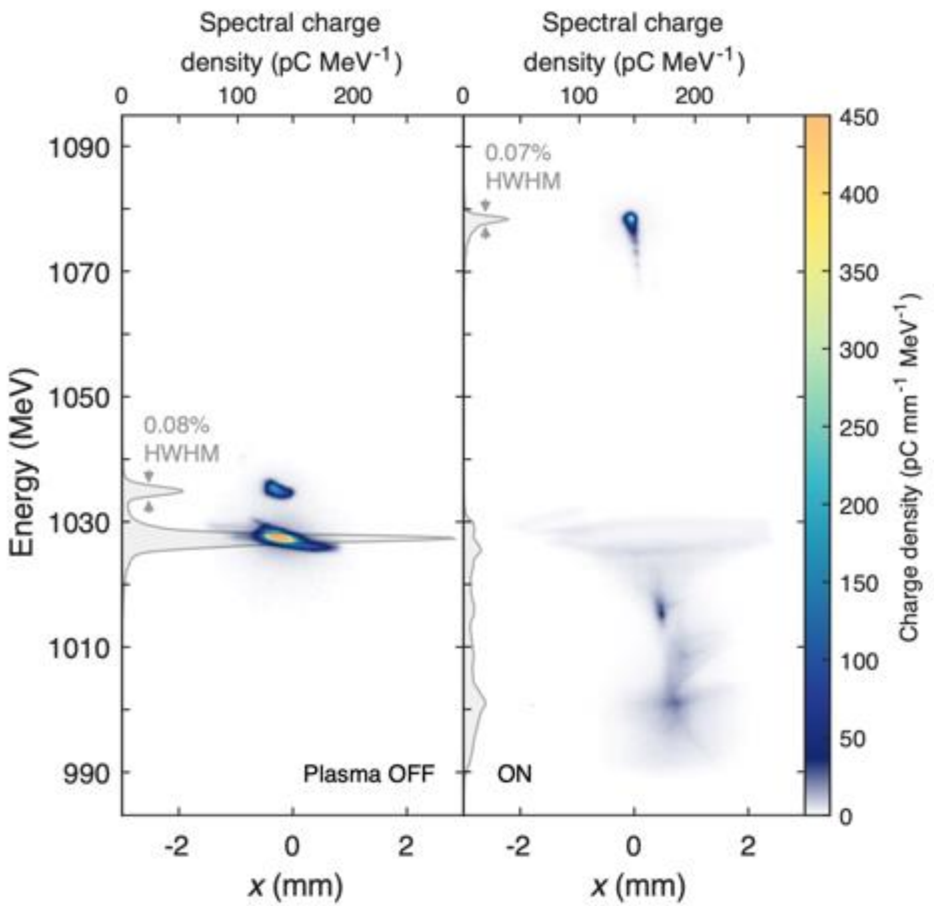
Energy doubling to 2.2 GeV ➞ plasma booster

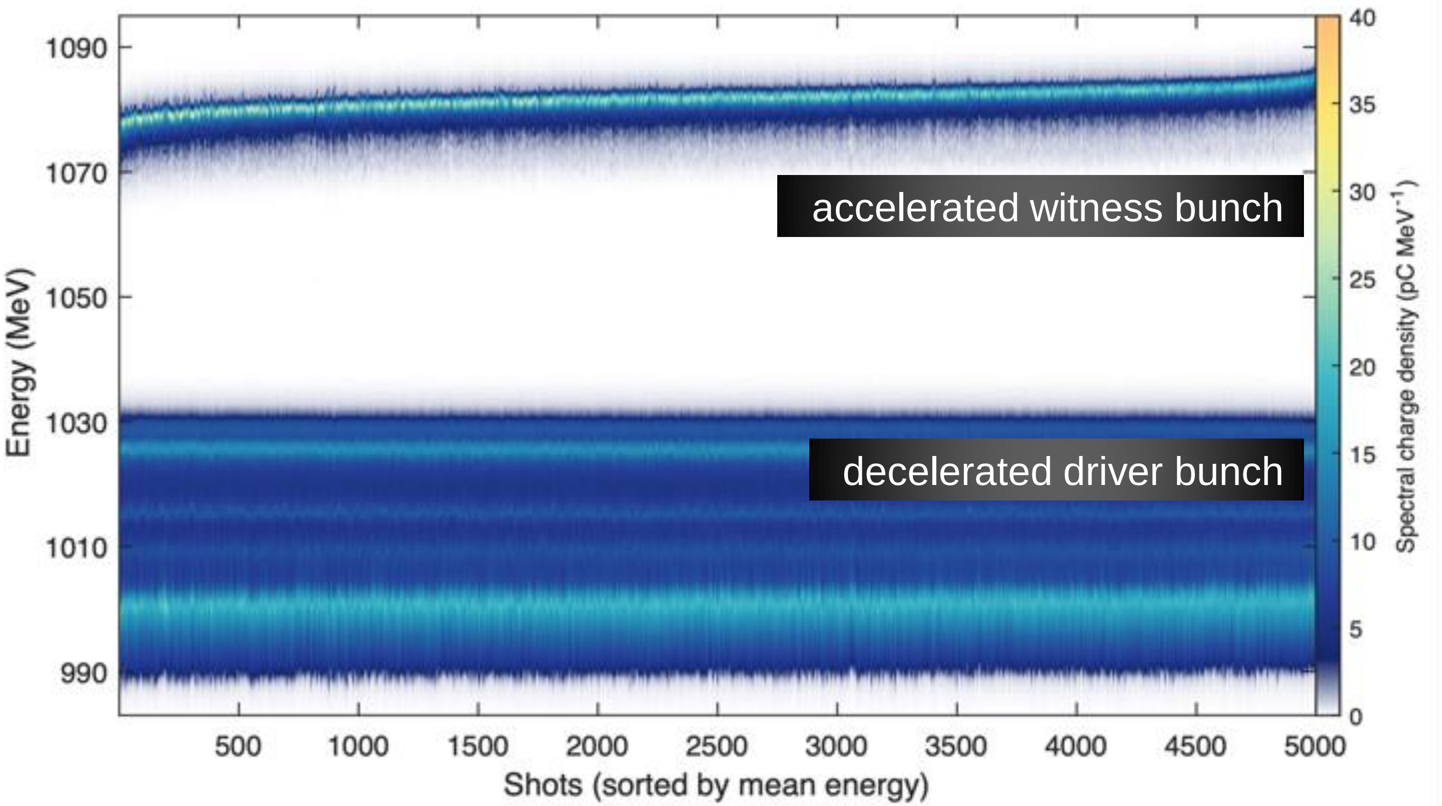


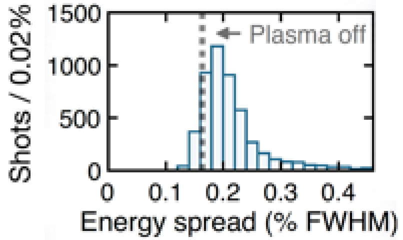
High-quality, efficient acceleration for sustainable applications

Optimizing beam loading facilitates near 50% energy-transfer efficiency and 0.1% energy spread

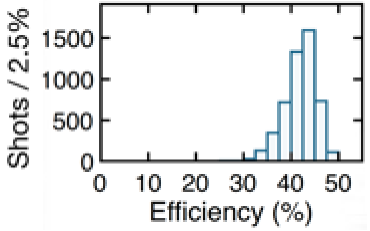
C.A. Lindstrøm *et al.,* Phys. Rev. Letts. **126**, 014801 (2021)







> 0.1% energy spread (input 0.08%)
(improvement by factor 10 over state-of-the-art)



> 42% avg. energy transfer efficiency
(improvement by factor 3 over state-of-the-art)

FLASHFORWARD▸▸ roadmap aims at 10 kW with high beam quality

Plan covers major plasma accelerator challenges

2018 **Plasma dechirper**
- D'Arcy *et al.*, PRL 122, 034801 (2019)

2019 **Energy depletion and energy doubling**

Wakefield sampling
- Schröder *et al.*, Nat. Commun. 11 5984 (2020)

2020 **Energy spread preservation by beam loading control**
- Lindstrøm *et al.*, PRL 126, 014801 (2021)

Emittance preservation
- Lindstrøm *et al.*, submitted (2022)

2022 **High gain and overall efficiency for sustainable operation**

kHz-to-GHz plasma response
- D'Arcy *et al.*, Nature 603, 58 (2022)

2024 **10 kW avg. power operation**

2026

2030

10 kW stage with 40% efficiency & beam quality conservation

→ FLASH: increase FEL energies, access oxygen K-edge at 2.33 nm wavelength

complete

planned

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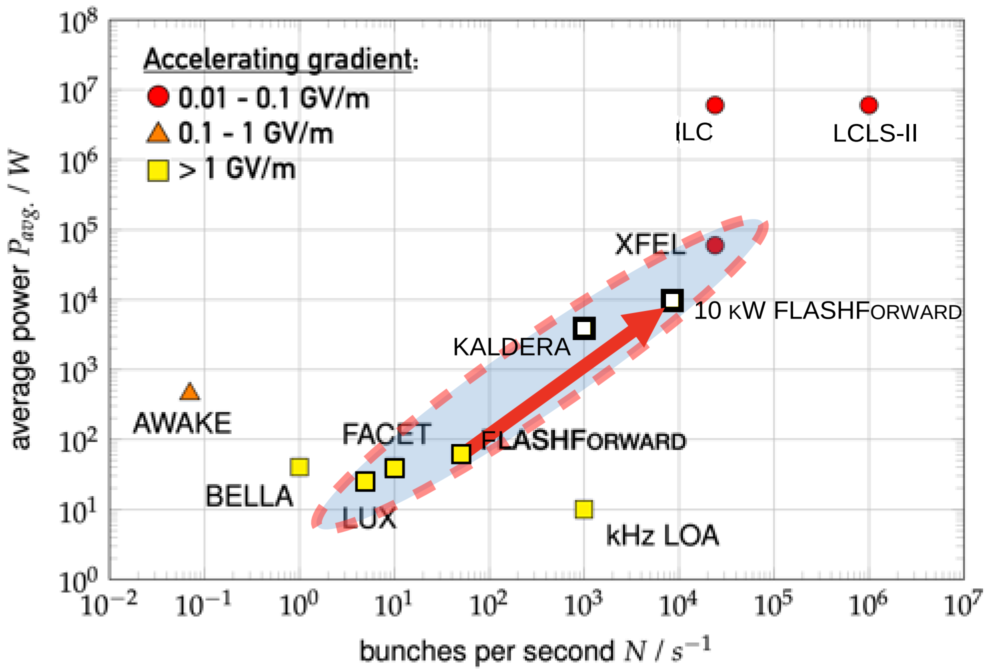
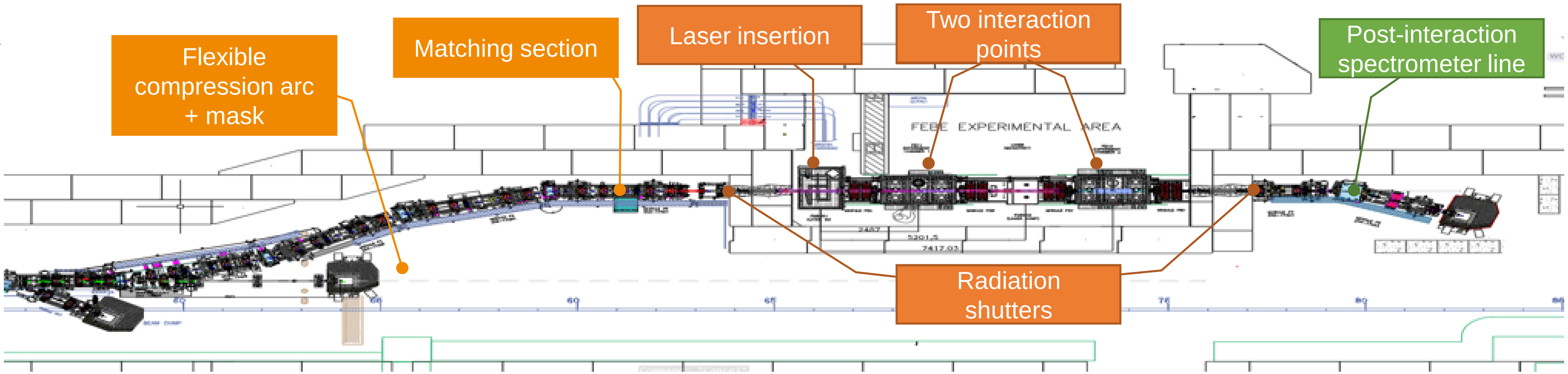


Novel acceleration with Full Energy Beam Exploitation (FEBE) @CLARA

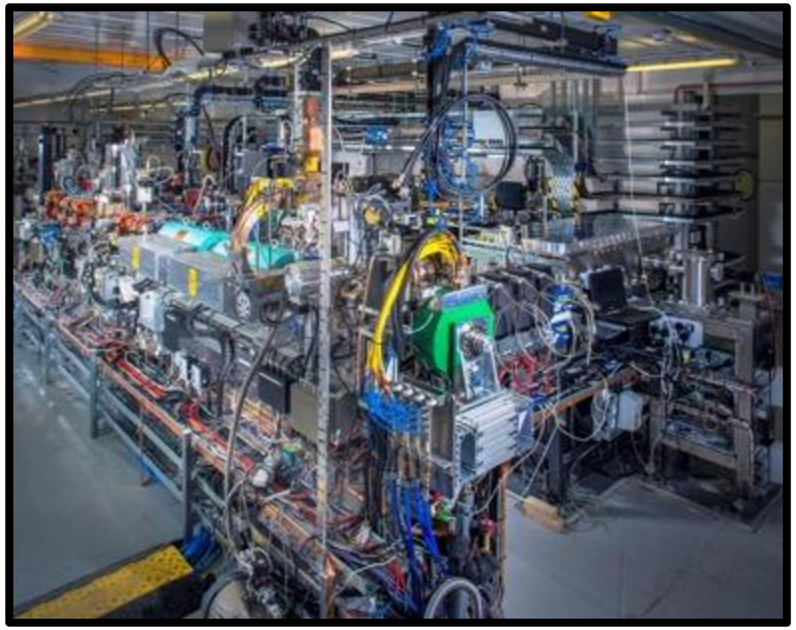


CLARA is an ultrabright, electron beam test facility under development at STFC Daresbury Laboratory

FEBE will combine CLARA with a Plasma Wakefield Accelerator stage driven by a 100TW laser

Collaborative research

- Electron beam-driven PWFA/Plasma photocathode
- Plasma source development/plasma-based beam diagnostics
- External injection LWFA, Trojan Horse,…



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EuPRAXIA

A flagship international research facility for propelling laser-driven plasma accelerators to transformative real-world applications

EuPRAXIA will drive plasma accelerators producing 10GeV electron beams at 100 Hz that can drive sources with unprecedented properties for industrial and medical applications

This is now on ESFRI roadmap

EuPRAXIA will have two sites:

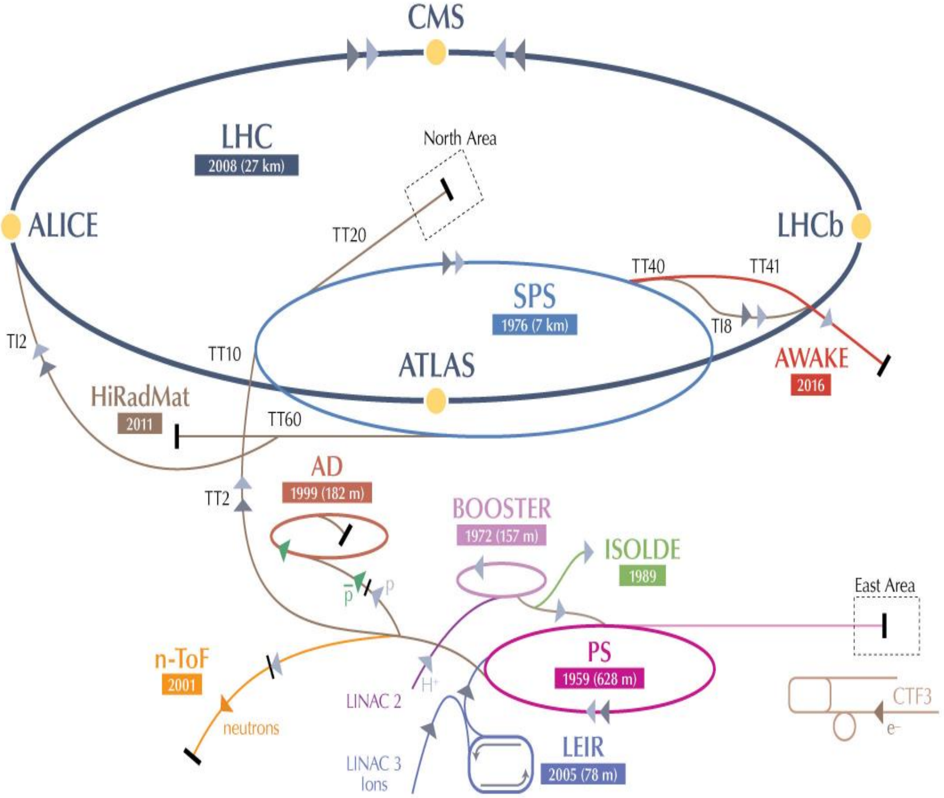
- Total estimated costs ~ 600M€
- The beam-driven arm will be based in INFN, Frascati
- The site for the laser-driven arm is yet to be decided - four short-listed sites
- Decision on the 2nd site to be made by 2024

The preparatory phase is funded (3.5M€)

This phase (Nov22– Oct 26) will choose the 2nd EuPRAXIA site and develop a pre-TDR

EuPRAXIA Preparatory Phase

Advanced WAKEfield Experiment



Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
Collaboration of 23 institutes world-wide.

➔A clear scientific roadmap towards first particle physics applications within the next decade

➔Many studies relevant for concepts that are based on plasma wakefield acceleration.

AWAKE Run 1 (2016-2018):

- ✓ 1st milestone: Demonstrated seeded self-modulation of the proton bunch in plasma (2016/17)
- ✓ 2nd milestone: Demonstrated electron acceleration in plasma wakefield driven by a self-modulated proton bunch. (2018)

AWAKE Run 2 (2021 – ~2030):

Accelerate an electron beam to high energies (gradient of 0.5-1GV/m) while preserving the electron beam quality and demonstrate scalable plasma source technology.

Once AWAKE Run 2 demonstrated: **First application of the AWAKE-like technology:** Particle physics experiments for e.g. dark photon search.

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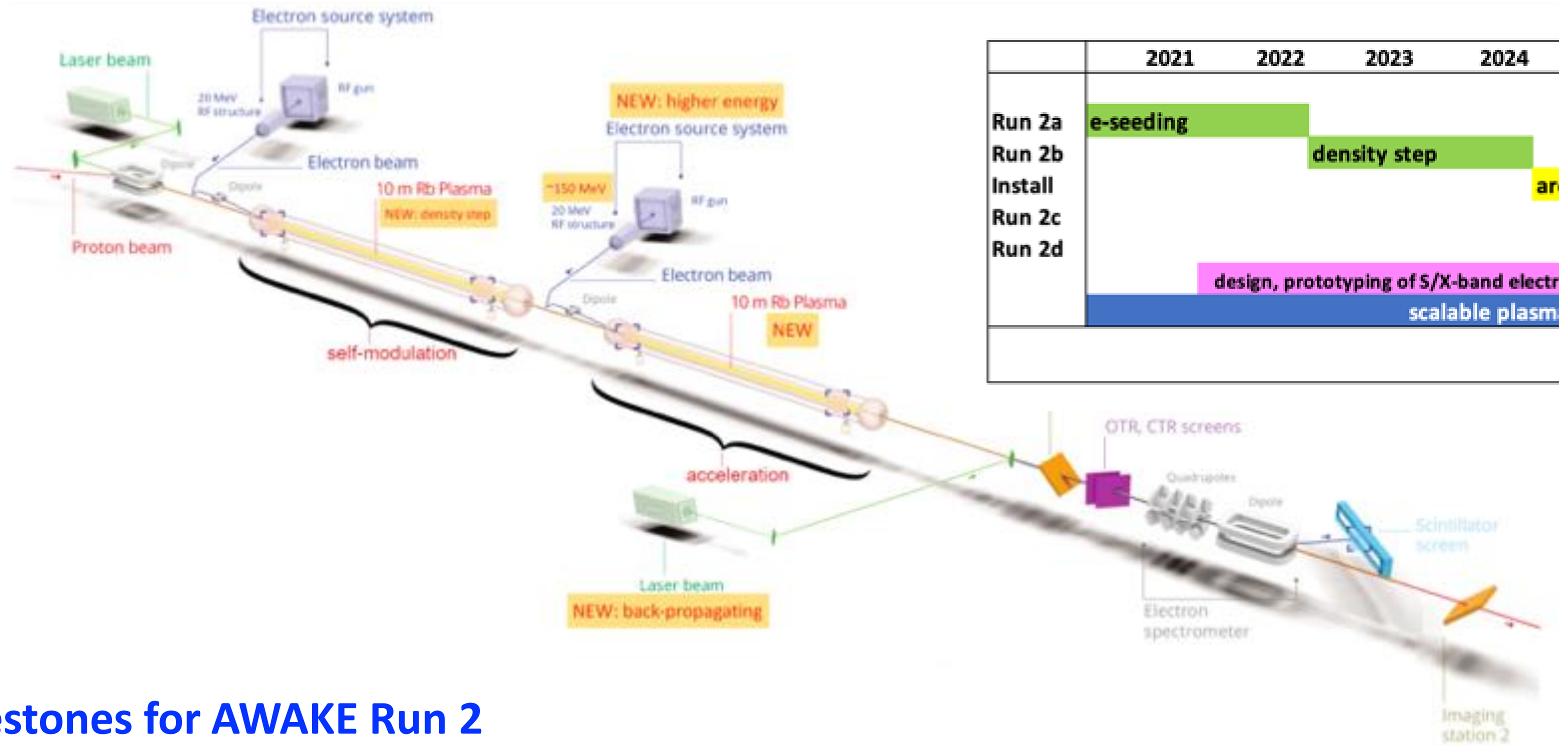
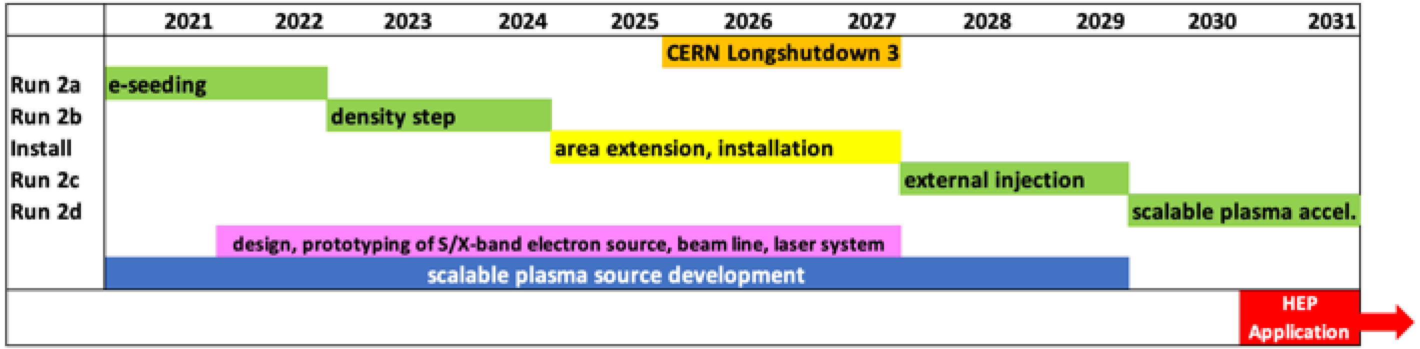
AWAKE Run 2 (2021 – 2030): Towards an Accelerator





L. Verra et al. (AWAKE Collaboration), Phys. Rev. Lett. 129, 024802 (2022)

Milestones for AWAKE Run 2

✓ Run 2a: **demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch**
- Run 2b: maintain large wakefield amplitudes over long plasma distances by introducing a step in the plasma density
- Run 2c: demonstrate electron acceleration and emittance preservation of externally injected electrons.
- Run 2d: development of scalable plasma sources to 100s meters length with sub-% level plasma density uniformity.

➔ **Propose first applications for particle physics experiments with 50-200 GeV electron bunches!**

Present Status

- Work Packages setup for major activities
- Almost all main WP leaders have been assigned – most have accepted
- Involving most of the major labs/groups across Europe
- Informal discussions with most WP leaders during the EuroNNAC special topics workshop (19-25th September)
- BUT…

WP	Task	Short Description	WP coordinator/Task leader	Deputy
COOR		Coordination Plasma and Laser Accelerators for Particle Physics	Wim Leemans	Rajeev Pattathil
FEAS		Feasibility and pre-CDR Study on Plasma and Laser Accelerators for Particle Physics		
	FEAS.1	Electron Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)	Jorge Viera	Maxence Thevenet
	FEAS.2	Positron Beam Performance Reach of Advanced Technologies (Simulation Results - Comparisons)	Severin Diedrichs	Gianluca Sarri
	FEAS 3	Accelerator Design, Staging	Carl Lindstrom	Zulfikar Najmudin
	FEAS.4	Spin and Polarizationpreservation	Kristjan Poder	
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HEFP	Electron-driven	Experimental demonstration: High-Efficiency, Electron-Driven Plasma Accelerator Module with High beam Quality	Jens Osterhoff	Richard d'Arcy
	Driven	AWAKE	Edda Gschwendtner	Patrick Muggli

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Funding is required for progress

- Different labs and university groups have their own strategy – may not align with the roadmap
- Funding required to ensure extra effort for filling gaps and alignment
- Buying back time of senior academics is required to ensure commitment
- All WP leaders' agreements are "in principle" – subject to funding – some tbc until funding is available
- Opportunity to get other countries involved – STEM training
- Potential funding route for some activities in the UK

Summary and Next Steps

- Plasma accelerators provide an opportunity to realize high-gradient accelerator stages, with the potential to reduce size and cost of future accelerators

- Although the technology is progressing, several key challenges remain

- Hybrid meeting with WP leaders to agree the programme (likely to be in 2nd week of January 2023)

- Close alignment with ALEGRO programme – discussing with Community at the next ALEGRO workshop – March 2023

ALEGRO
Advanced LinEar collider study GROup

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