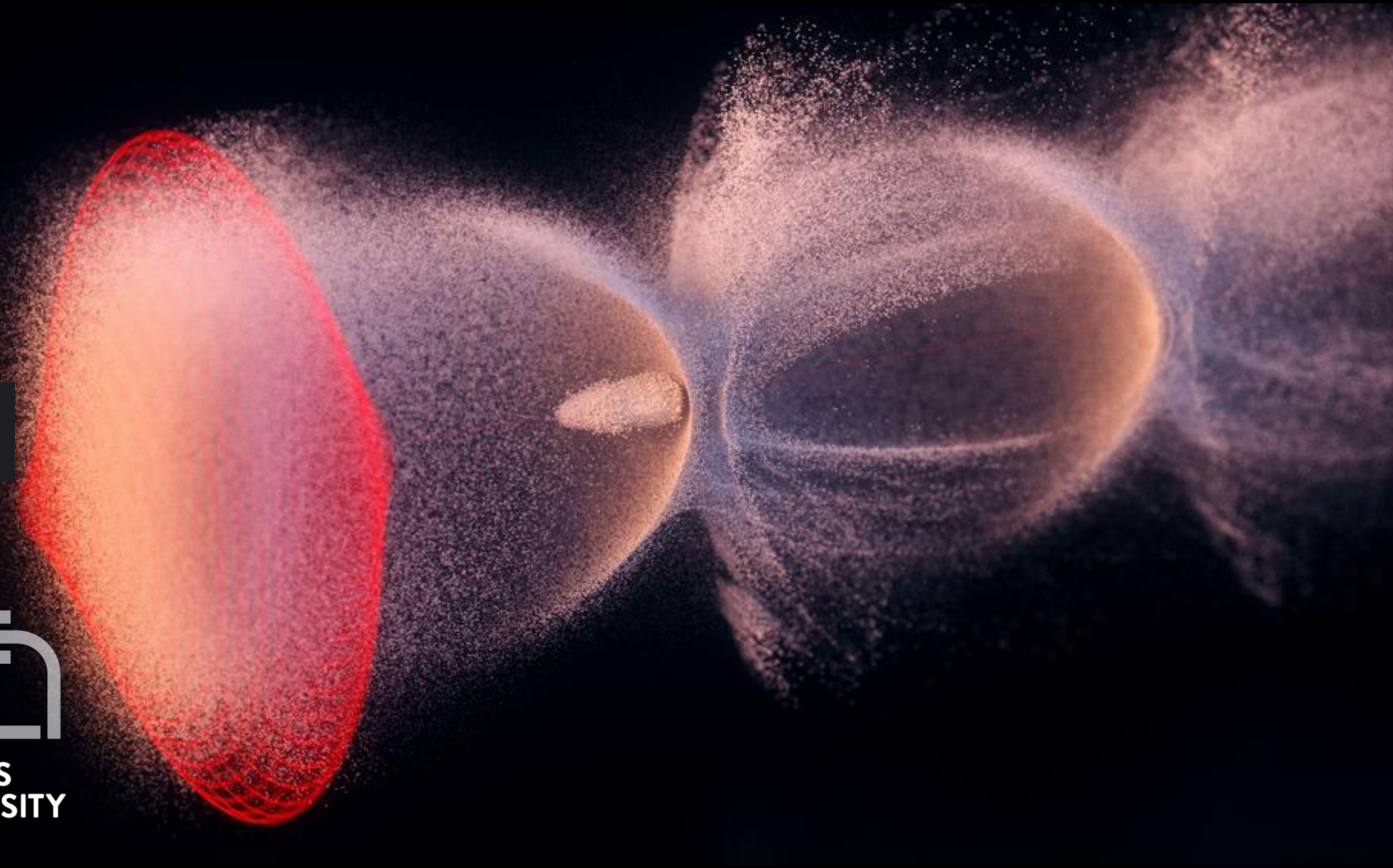
ESPP Feedback

Wim Leemans (DESY)
Rajeev Pattathil (RAL)



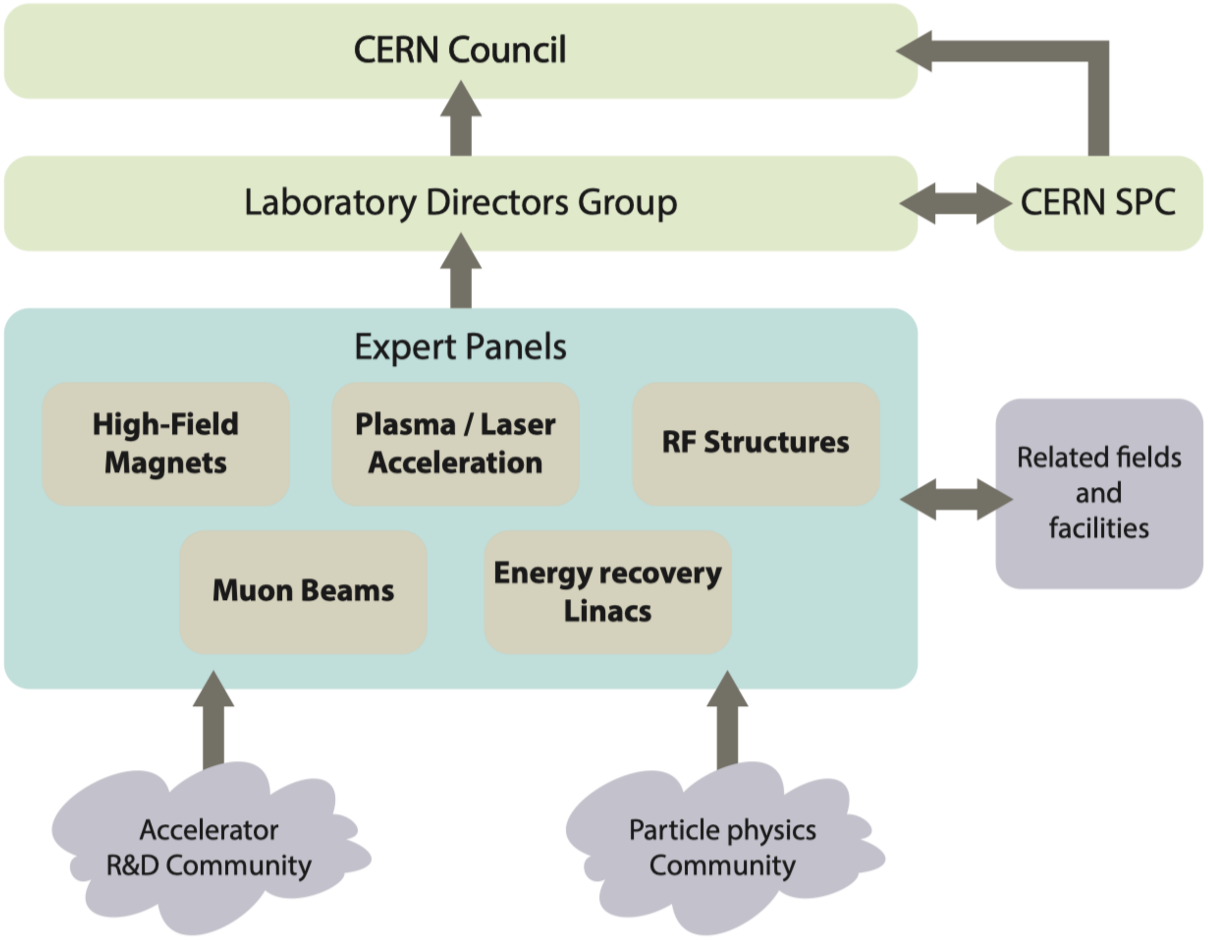
ESPP Roadmap

- Develop R&D for the next generation of particle accelerators and colliders (beyond 2045)
- Commissioned by Lab Directors' Group – CERN
- To provide an agreed structure for a coordinated and intensified programme
- Develop in consultation with the community and expert panels
- Coordinate with international activities
- Specify a series of concrete deliverables, including demonstrators, over the next decade

ESPP Roadmap

Identified 5 topics for R&D – 5 panels

- Further development of high-field superconducting magnet technology.
- Advanced technologies for superconducting and normal-conducting radio-frequency (RF) accelerating structures.
- Development and exploitation of laser / plasma acceleration techniques.
- Studies and development towards future bright muon beams and muon colliders.
- Advancement and exploitation of energy-recovery linear accelerator technology.

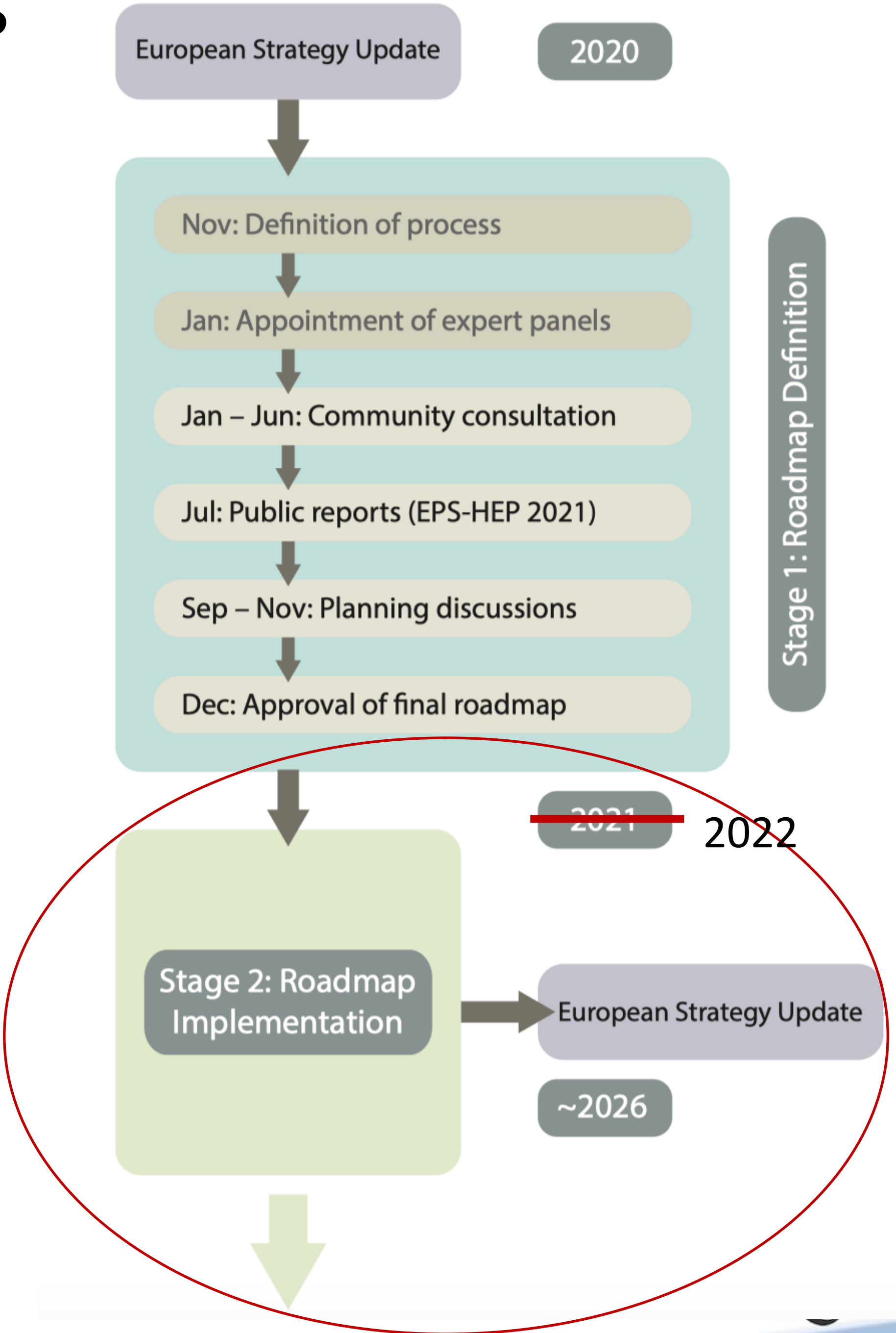


ESPP Roadmap – Process & Timescales

- A significant collaborative effort through expert panels
- Identifying key R&D objectives
- Weighted under indicative funding scenarios:
  - ‘minimal’ scenario: achieved with restricted resources (only if current activities already align)
  - ‘nominal’ scenario: extra funding conditions continue
  - ‘aspirational’: significant additional funding

Doesn’t identify a ring-fenced funding pot

Doesn’t provide recommendations between technologies (i.e. no prioritization)



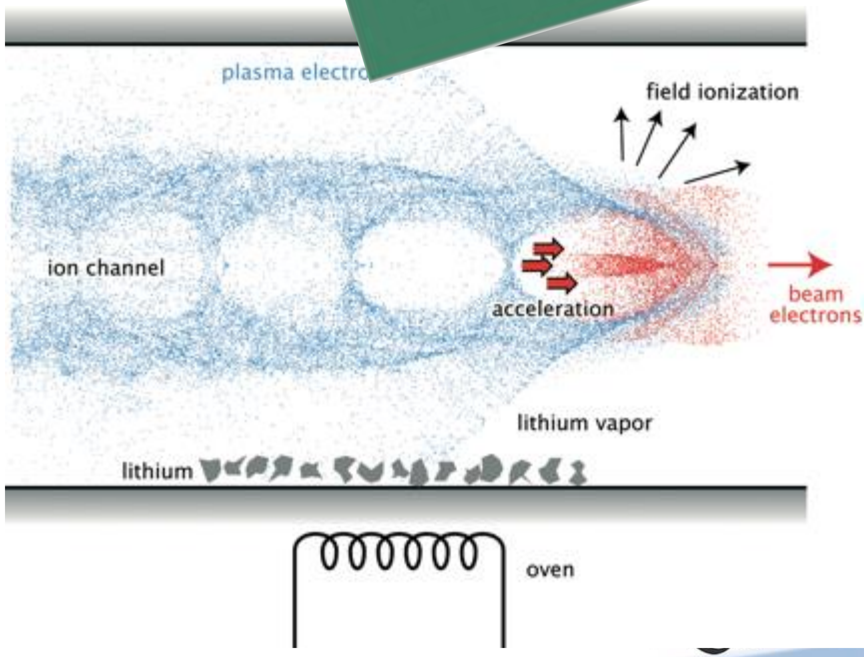
Science and Technology Facilities Council

R&D Coordination Panel: Plasma Accelerators

Major deliverables

Deliverable	Due by
Report: Electron High Energy Case Study (from 175GeV to 190GeV)	Jun-24
Report: Positron High Energy Case Study (similar to above)	Jun-25
Report: Spin-Polarised Beams in Plasma Accelerators	Dec-25
Report: Physics Case of an Advanced Collider	Jun-24
Report: Low Energy Study Cases for Electrons and Positrons (15-50GeV)	Jun-25
Report: Pre-CDR and Collider Feasibility Report	Dec-25
Experiment: High-Repetition Rate Plasma Accelerator Module (kHz)	Dec-25
Experiment: High-Efficiency, Electron/Proton-Driven Plasma Accelerator Module with High Beam Quality	Dec-25
Report/prototyping: Scaling of DLA/THz Accelerators	Dec-25

Agreed with LDG a reduced scope (will concentrate on plasma-based concepts)



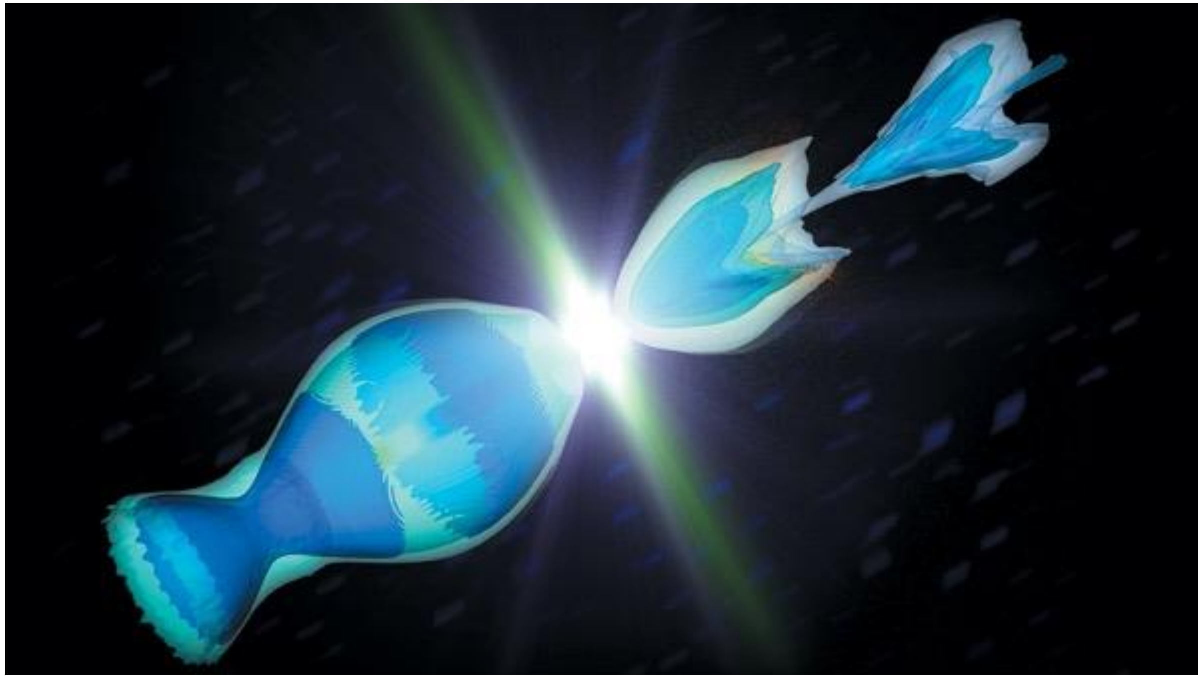
Science and Technology Facilities Council

DESY.

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

Main activities

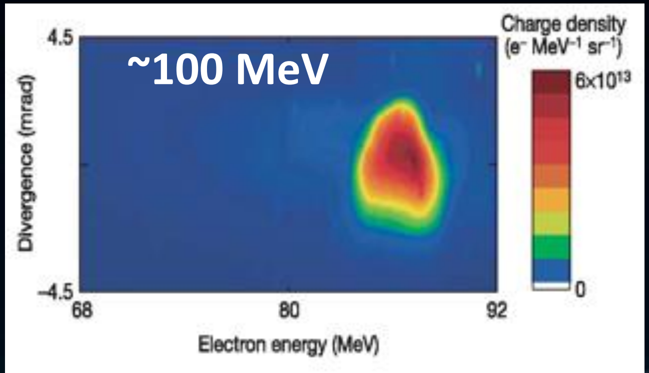
- Evaluating the state of the art in detail and providing an assessment on its suitability
- Determining theoretical limits and scalability, extrapolating experimentally achieved parameters for collider-relevant aspects: Luminosity, energy gain, energy gradient, bunch charge, emittance and energy efficiency.
- 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



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

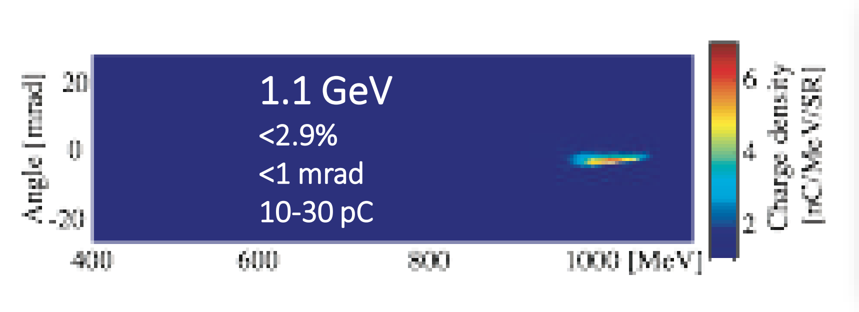
2004-2019: A success story

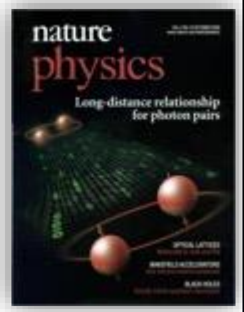
2004 result: 10 TW laser, mm-scale plasma



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

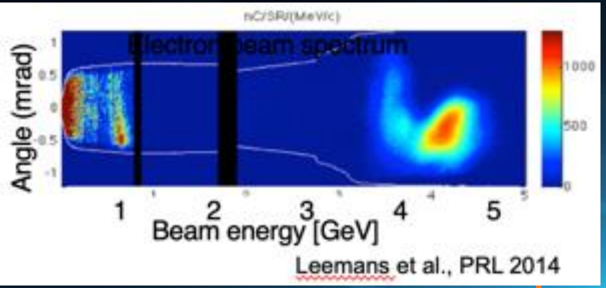




W.P. Leemans *et al.*, Nature Physics 2, p696 (2006)

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

Experiment (spectrum)



2004

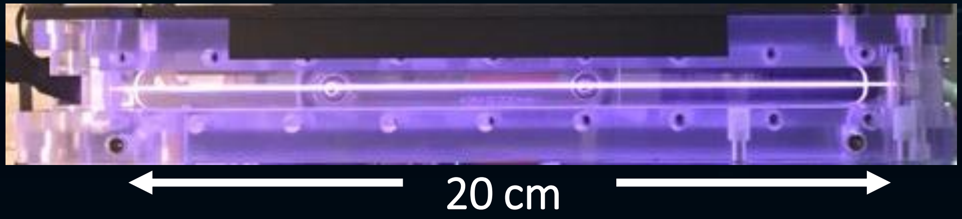
2006

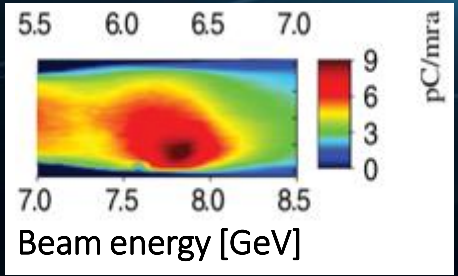
2014

2019

Gonsalves *et al.*, PRL 2019

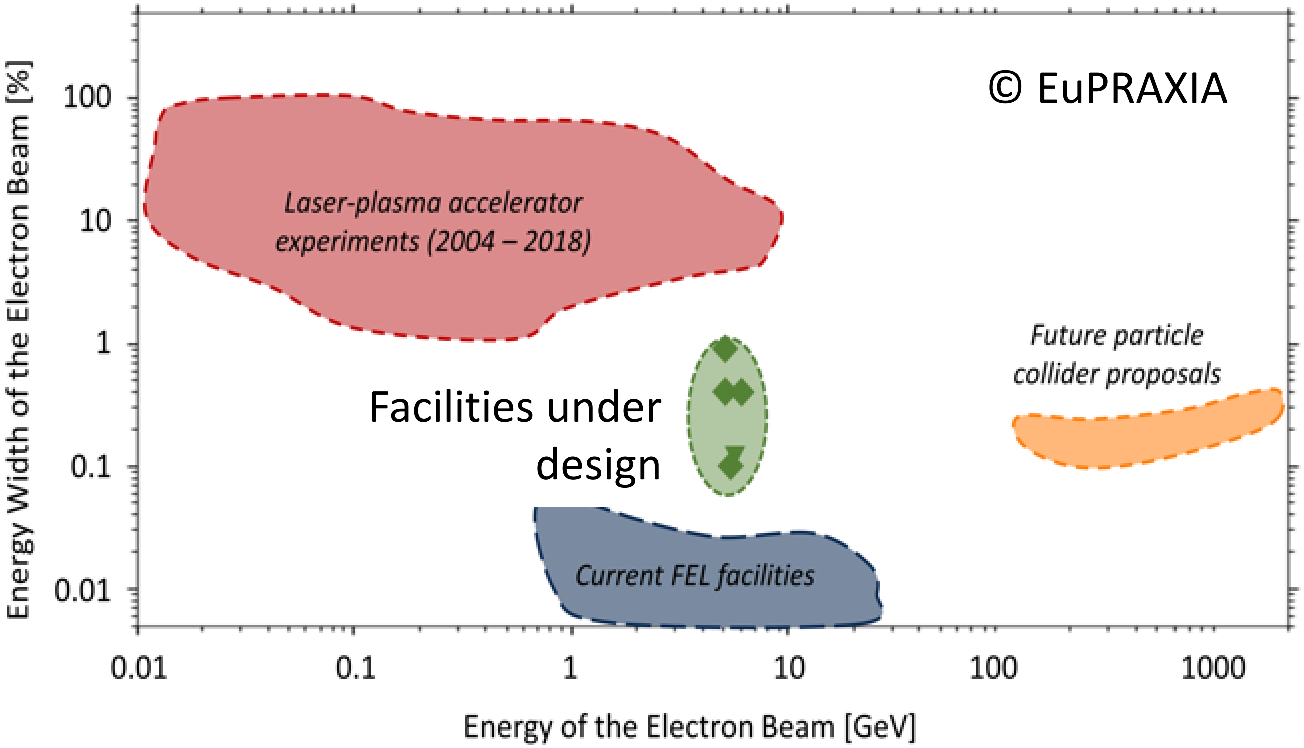
2019 result: 1 PW laser, 20 cm-scale plasma





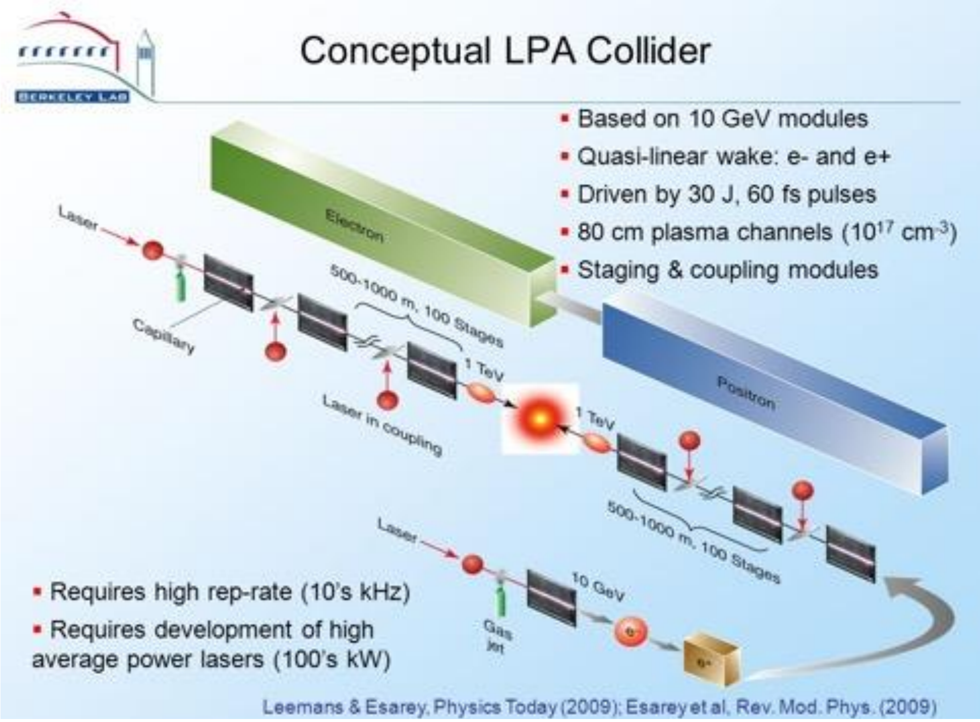
Main challenges in laser-plasma accelerators

- 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



Main themes for feasibility study

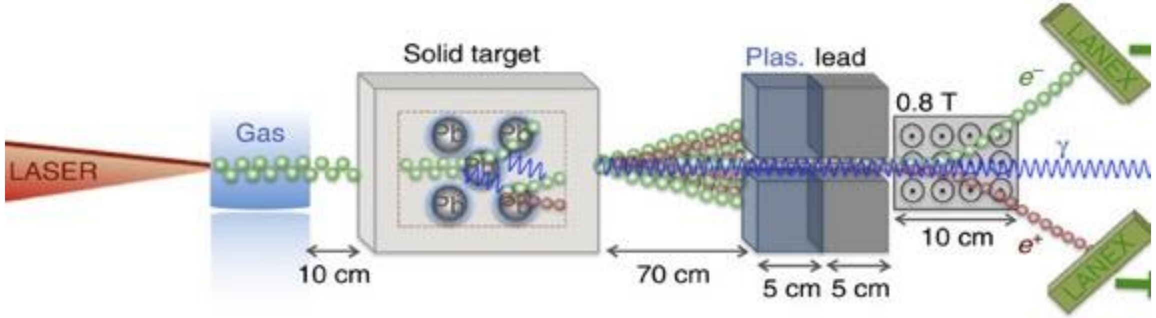
- Simulations on pathways to generate beams with particle-physics relevant parameters - simultaneous realisation of nC charge, 0.1% energy spread @ 100-200 GeV levels
- Small Beam Emittance preservation schemes, maintaining other critical parameters
- Staging of multiple accelerator modules
- Detailed analysis of failure modes and mitigation methods



Parameter	Unit	Specification
Beam energy (entry into module)	GeV	**175**
Beam energy (exit from module)	GeV	**190**
Number of accelerating structures in module	-	≥2
Efficiency wall-plug to beam (includes drivers)	%	≥10
Bunch charge	pC	833
Relative energy spread (entry/exit)	%	≤0.35
Bunch length (entry/exit)	µm	≤70
Convoluted normalised emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm	≤135
Emittance growth budget	nm	≤**3.5**
Polarization	%	80 (for e^-)
Normalised emittance h/v (exit)	nm	900/20
Bunch separation	ns	0.5
Number of bunches per train	-	352
Repetition rate of train	Hz	50
Beamline length (175 to 190 GeV)	m	**250**
Efficiency: wall-plug to drive beam	%	58
Efficiency: drive beam to main beam	%	22
Luminosity	$10^{34}cm^{-2}s^{-1}$	1.5

Science and Technology Facilities Council

Main themes for feasibility study

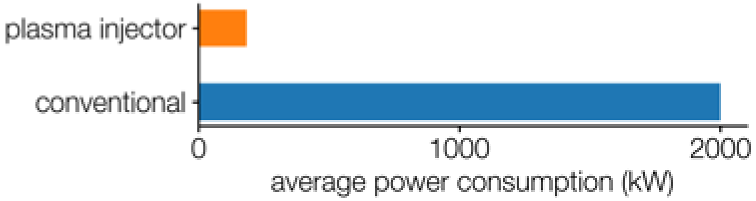


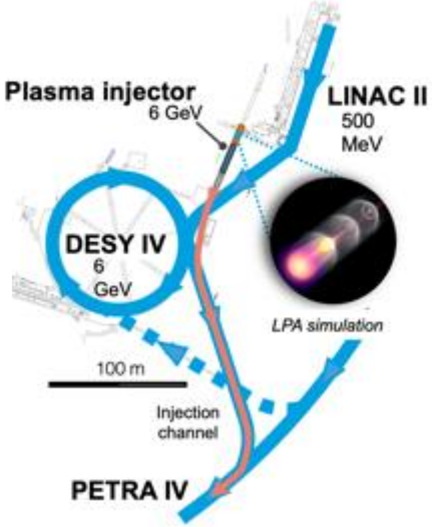
Electron-positron plasma

- 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

- Sustainability – realistic wall-plug efficiency, power requirements, carbon footprint





185 kW (estimate)

Organization of the team

Work package leaders are expected to organize how they want to carry out the work

Topic 1: Feasibility and pre-CDR Study on Plasma Based Accelerators for Particle Physics (Simulations-Analysis - Paper studies)

- **1.1: Overall collider concepts (Higgs factory, multi-TeV)**
  - Assessment of what the particle physics community requires for these two classes of machines
  - Can be combined with Topic 4 (later in the talk)
- **1.2: Beam driven electron linac**
  - Conceptual design of a linac that can deliver the beam power and quality to reach the required luminosity
  - Simulations and theory based. Q: Are there simulation tools missing?
  - Validate concept as much as possible against already demonstrated experimental observations
  - Identify the research that is needed and the key bottle necks

Organization of the team

Work package leaders are expected to organize how they want to carry out the work

Topic 1: Feasibility and pre-CDR Study on Plasma Based Accelerators for Particle Physics (Simulations-Analysis - Paper studies)

- **1.3: Laser driven electron linac**
  - Conceptual design of a linac that can deliver the beam power and quality to reach the required luminosity
  - Simulations and theory based. Q: Are there simulation tools missing?
  - Validate concept as much as possible against already demonstrated experimental observations
  - Identify the research that is needed and the key bottle necks
- **1.4: Positron arm**
  - What is the state-of-the-art in positron generation, capture, acceleration in plasmas?
  - What are the key challenges to build a plasma based positron linac that can be demonstrated in the next 5-10 years?
  - What are the challenges in using a conventional linac based systems for positrons?

Organization of the team

Work package leaders are expected to organize how they want to carry out the work

Topic 1: Feasibility and pre-CDR Study on Plasma Based Accelerators for Particle Physics (Simulations-Analysis - Paper studies)

- **Joint questions for Topics 1.2 and 1.4:**
  - What tools do we have (experimental, theory/simulation) and what are we missing and needs development?
  - What can we test/develop in the next three years that allows us to increase the TRL level?
  - How much of our theory/simulation tools have been developed and have been benchmarked against one another and against experiments?
  - What experimental capabilities do we have and what tests/experiments can we do to answer some key questions?

Organization of the team

Work package leaders are expected to organize how they want to carry out the work

- **Topic 1 (continued): Feasibility and pre-CDR Study on Plasma Based Accelerators for Particle Physics (Simulations-Analysis - Paper studies)**
  - 1.5: Spin and polarization preservation:
    - What are potential concepts? Are there proof-of-principle experiments that can be proposed? What is the state of the art in simulation tools and do we need more?
  - 1.6: Assess final-focus system concepts; are there experiments conceivable at existing facilities? Open area: adiabatic plasma lens.
  - 1.7: Sustainability analysis: can plasma based colliders be more energy efficient and more sustainable (e.g., usage of rare earths)? What needs to happen to achieve the goal of being more sustainable than conventional technology?
-

Topic 1: Organisation of Workpackages

Topic 1		Feasibility and pre-CDR Study on Plasma Based Accelerators for Particle Physics - paper studies			
		Work Package	**WP coordinators**		**Potential consultants**
	1.1	Collider concepts (Higgs factory, multi-TeV)	Carl Lindstrøm (Oslo)	Zulfikar Najmudin (Imperial)	Carl Schroeder (LBNL) - consult
	1.2	Beam-driven electron linac (paper study)	Eric Adli (Oslo)	Carl Lindstrøm (Oslo)/Brigitte Cros (CNRS)	
	1.3	Laser-driven electron linac (paper study)	Jorge Viera (IST)	Maxence Thevenet (DESY)	
	1.4	Positron arm (Simulation Results - Comparisons)	Gianluca Sarri (QUB)	Severin Diedrichs	
	1.5	Spin and Polarization preservation	Kristjan Põder (DESY)		Spencer Gessner (SLAC) - consult
	1.6	Final focus system/Interaction	Arnd Specka?		
	1.7	Sustainability analysis	Denise Völker (CERN)		Marlene Turner (LBNL) - consult

Science and Technology Facilities Council

Please approach them if you are willing to contribute

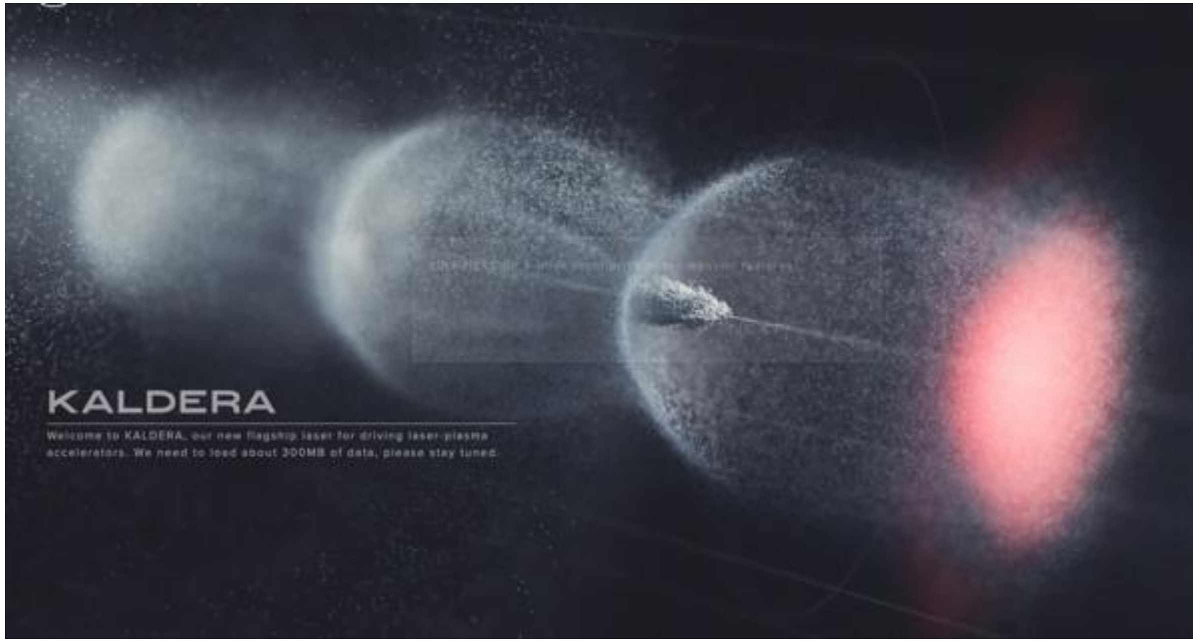
Topic 2: High repetition rate LWFA demonstration

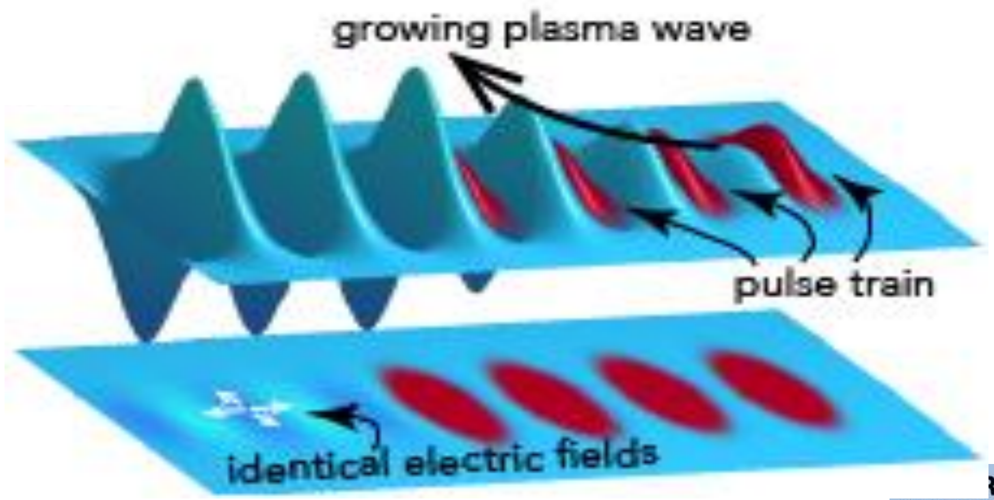
Main activities

- 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)

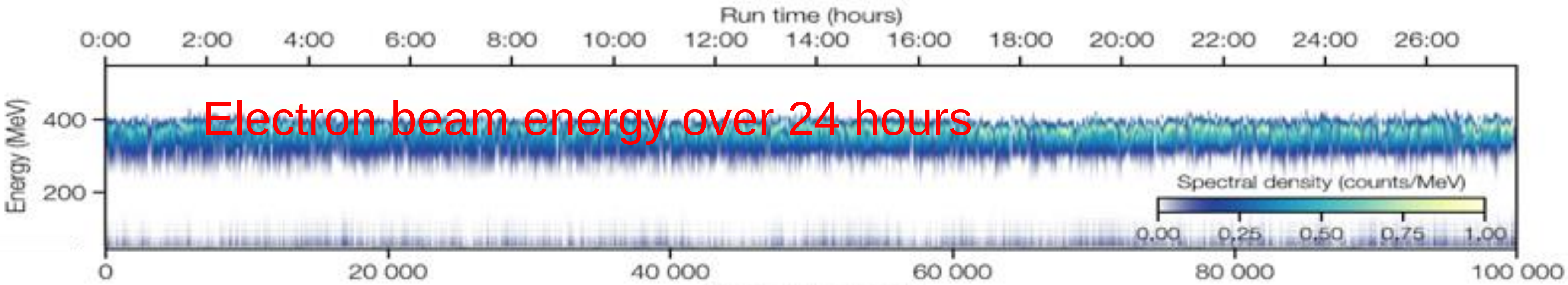




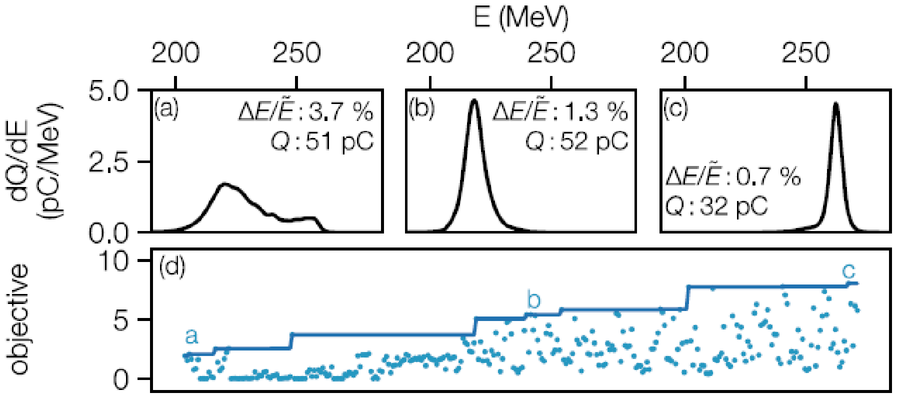
Science and Technology Facilities Council

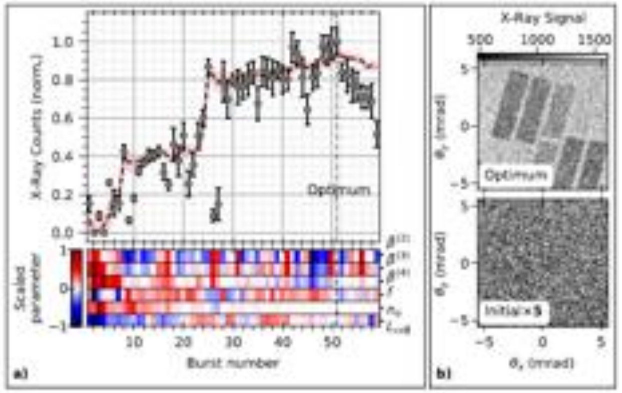
DESY.

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)

Extreme Photonics Applications Centre

- A new £88M UK facility for applications of laser-driven plasma accelerators
- Wiill 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 centres in the UK

pwasc.org.uk

Building completed; installations ongoing; first operations in 2025-26

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

Science and Technology Facilities Council

DESY.

Organization of the team

Work package leaders are expected to organize how they want to carry out the work

- **Topic 2:Laser driver based accelerators (experiments/prototypes)**
  - **2.1:** What are the critical questions we need to address and can address in the next three years?
    - What experiments are doable today at existing facilities that would get us insight into critical questions?
    - What are potential concepts? Are there proof-of-principle experiments that can be proposed?
    - What is required to carry out a high capture efficiency staging experiment?
  - **2.2:** What is the path towards high rep rate, high performance, and high efficiency lasers for colliders? What can/must we test in the next 3 years? What technology will allow high rep rates?
  - **2.3:** What are the options for plasma sources that allow high repetition rate?
  - **2.4:** What would a facility look like at the different stages of R&D to address key questions (beyond what we have today) and what would a collider facility look like? This ties into WP 1.1.
-

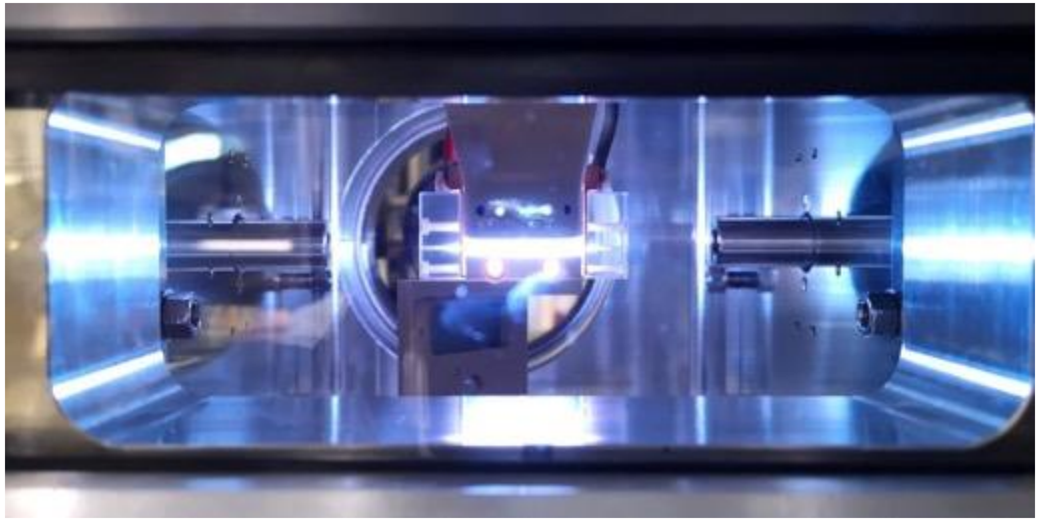
Topic 2: Organisation of Workpackages

Topic 2		***Experimental demonstration: High-Repetition Rate Plasma Accelerator Module***		
	2.1	Coordination of modules	Leo Gizzi (CNR)	Andi Maier (Hamburg/DESY)
	2.2	High rep lasers (100 Hz-kHz)	Andi Maier (Hamburg/DESY)	Paul Mason (RAL)
	2.3	High rep plasma targets	Simon Hooker (Oxford)	Brigitte Cros (CNRS)
	2.4	Facility/Delivery	Dan Symes (RAL)	Andreas Dopp (CALA)

Please approach them if you are willing to contribute

Topic 3: High Repetition Rate Particle-driven Wakefield Accelerators

- Electron-driven (FLASHForward, CLARA/FEBE)
- Proton-driven (AWAKE)



Plasma accelerator @ SPARC Lab – EuPRAXIA - INFN

Main R&D themes

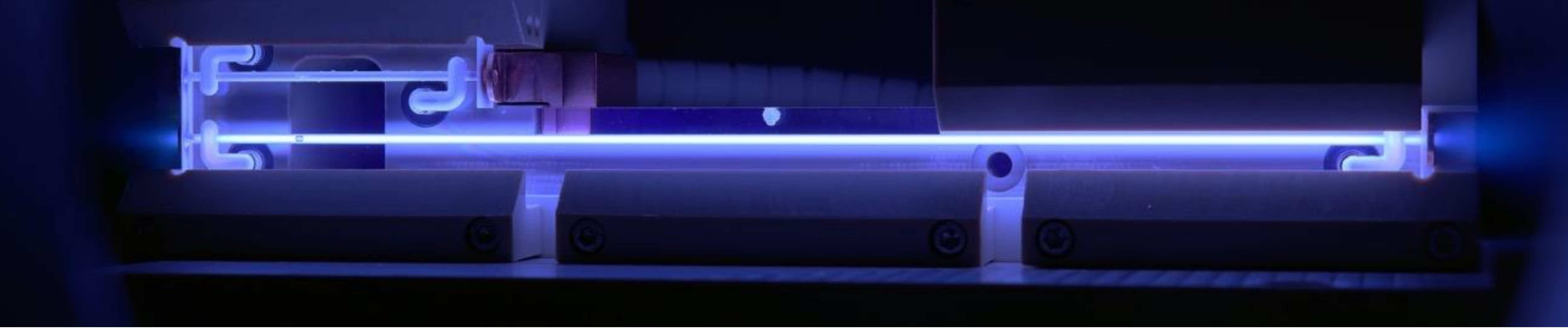
- Emittance preservation
- High Transformer Ratio
- Efficiency

FLASHForward @ DESY

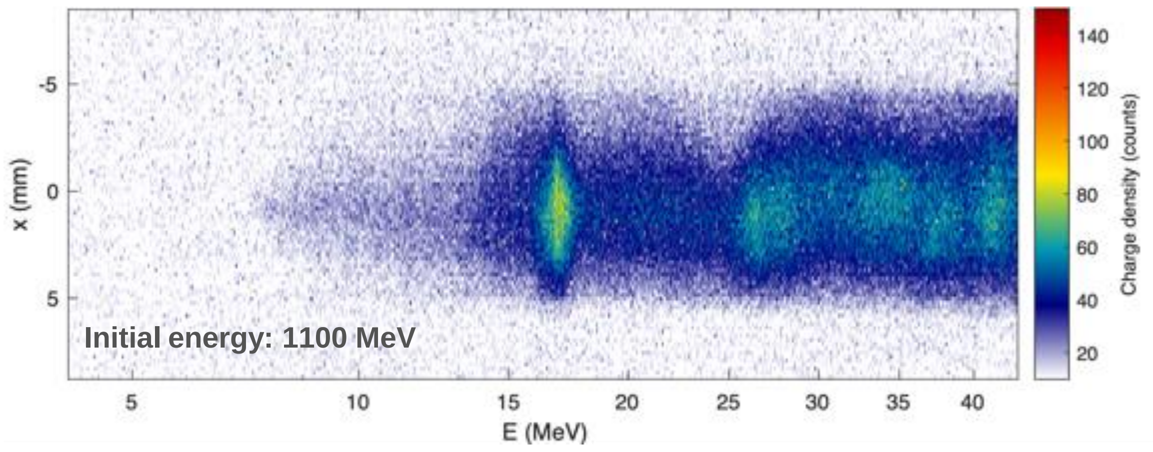
1.1 GeV energy gain and loss achieved in a 195 mm plasma accelerator cell

First experiments with long source

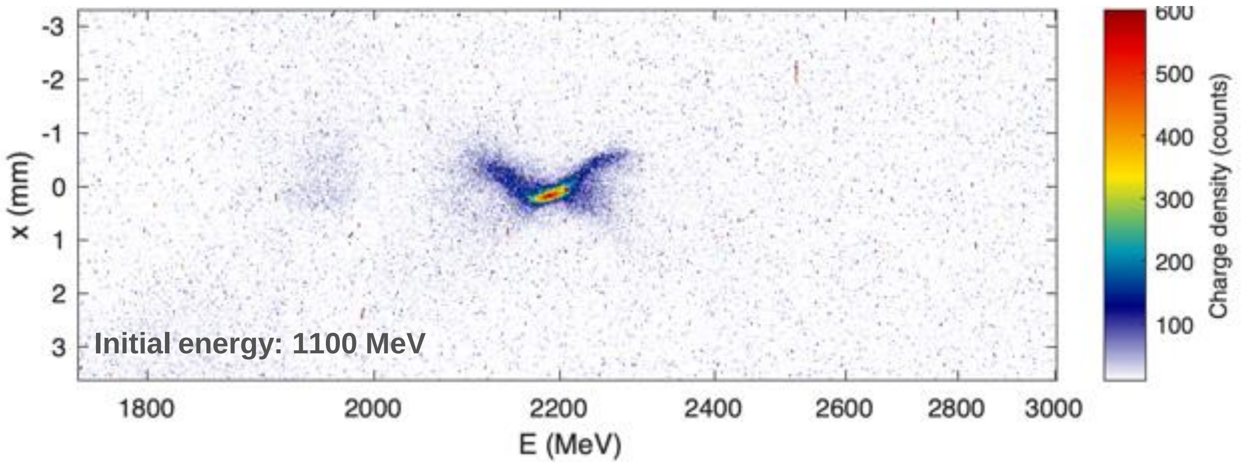
FLASHFORWARD▸▸ plasma capillaries



Energy depletion ➞ active plasma beam dump

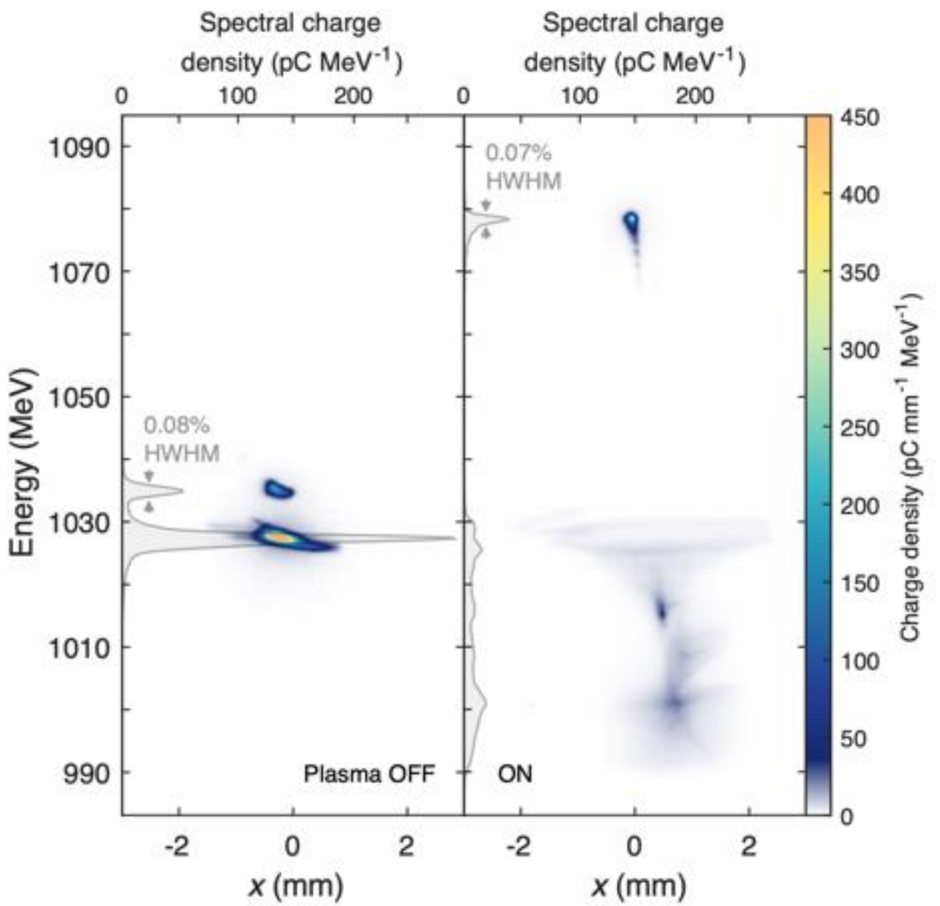


Energy doubling to 2.2 GeV ➞ plasma booster

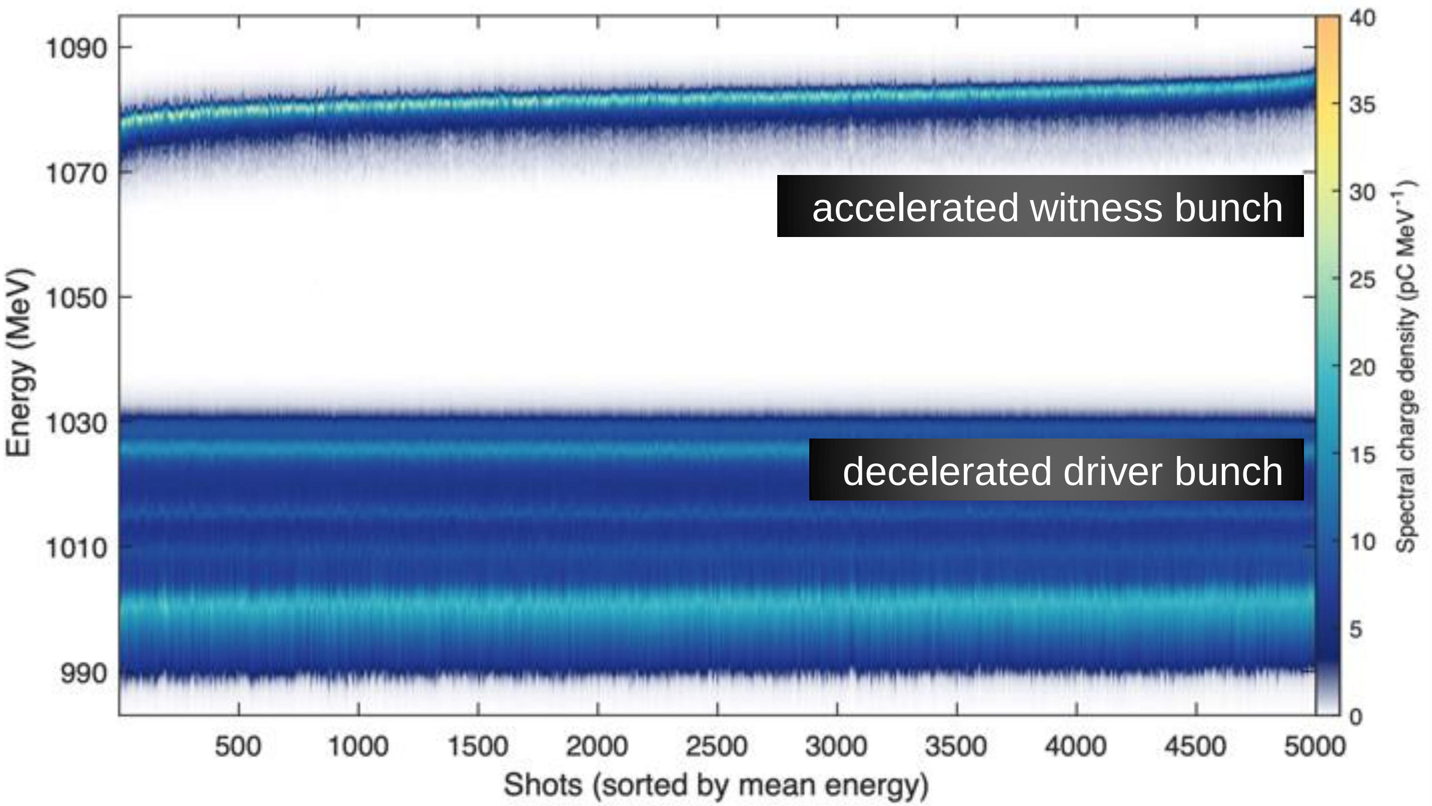


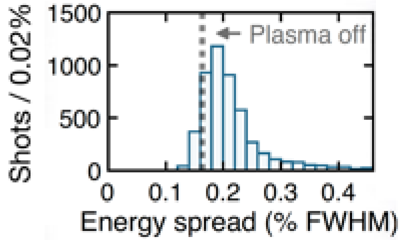
High-quality, efficient acceleration for sustainable applications

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

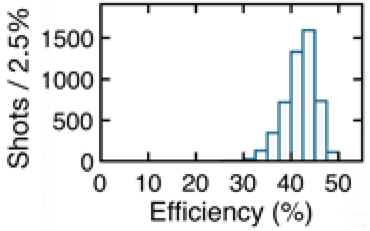


C.A. Lindstrøm *et al.,* Phys. Rev. Letts. **126**, 014801 (2021)





> 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

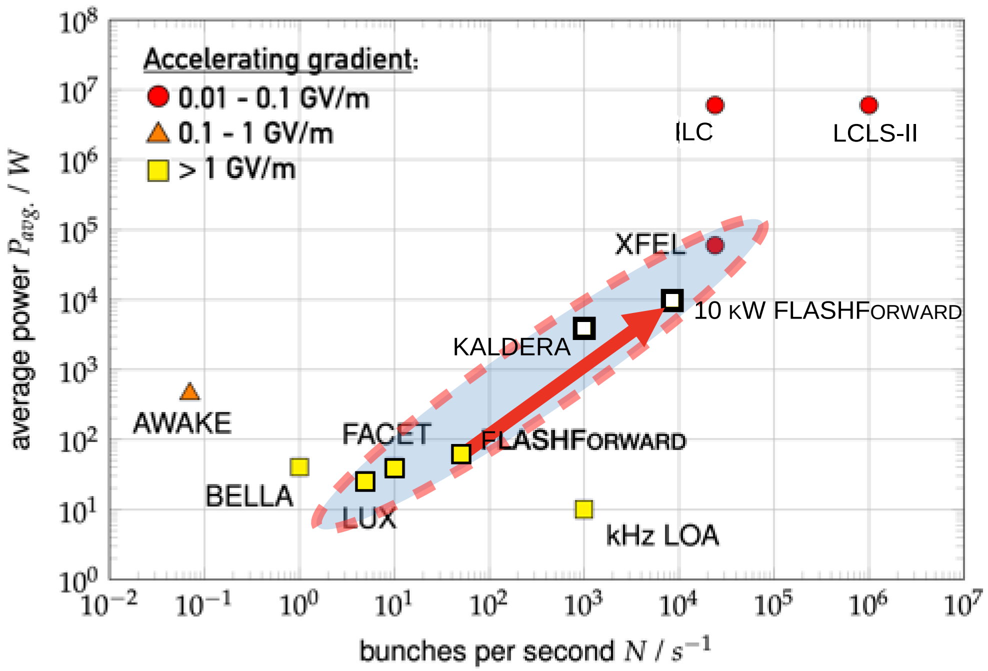
10 kW stage with 40% efficiency & beam quality conservation

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

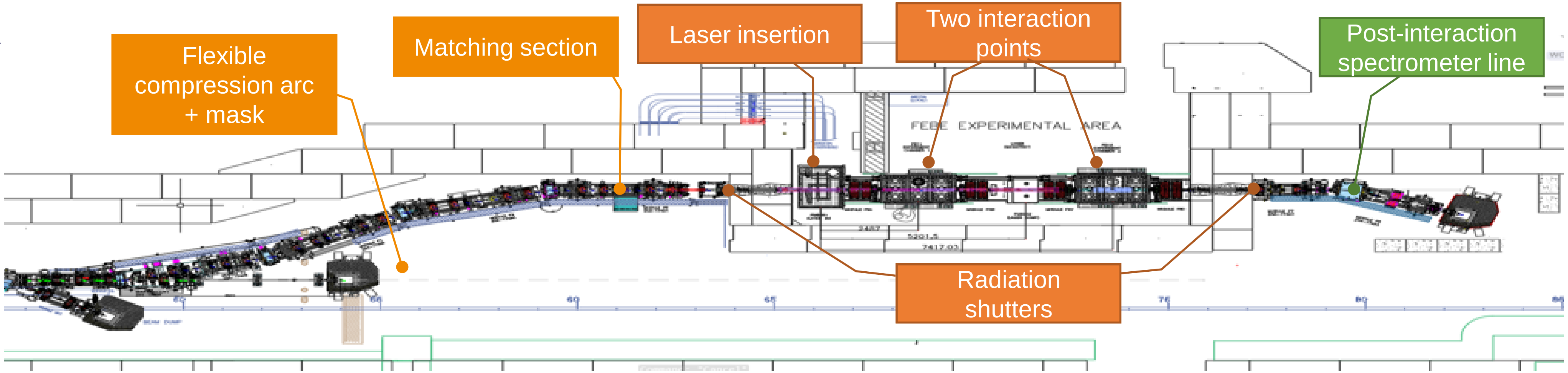
complete

planned

DESY.



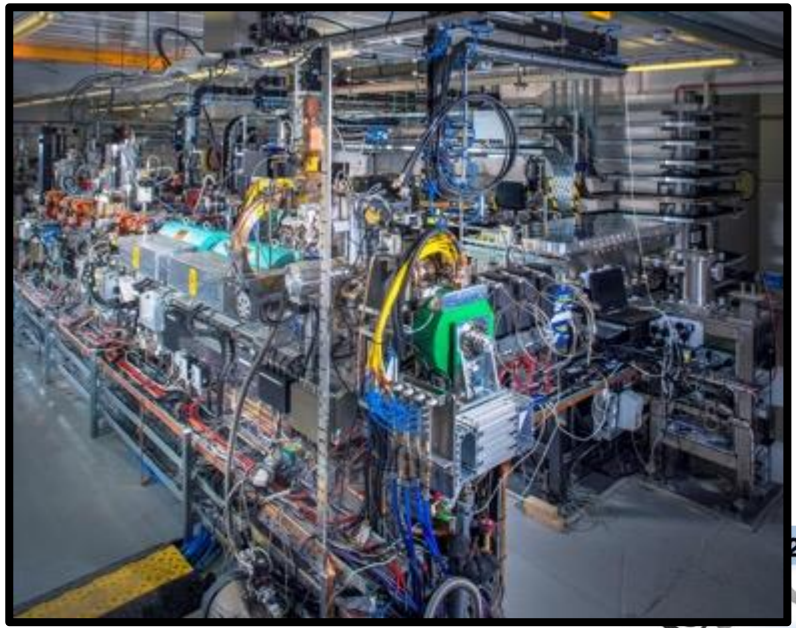
Novel acceleration with Full Energy Beam Exploitation (FEBE) @CLARA



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

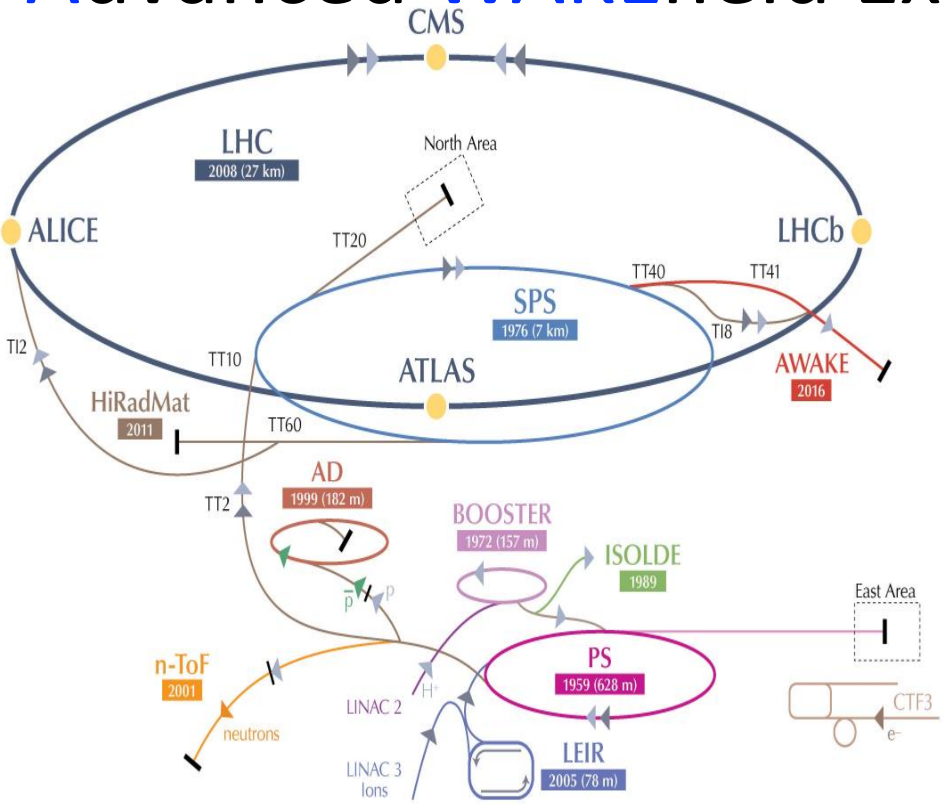
Collaborative research

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



Science and Technology Facilities Council

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):

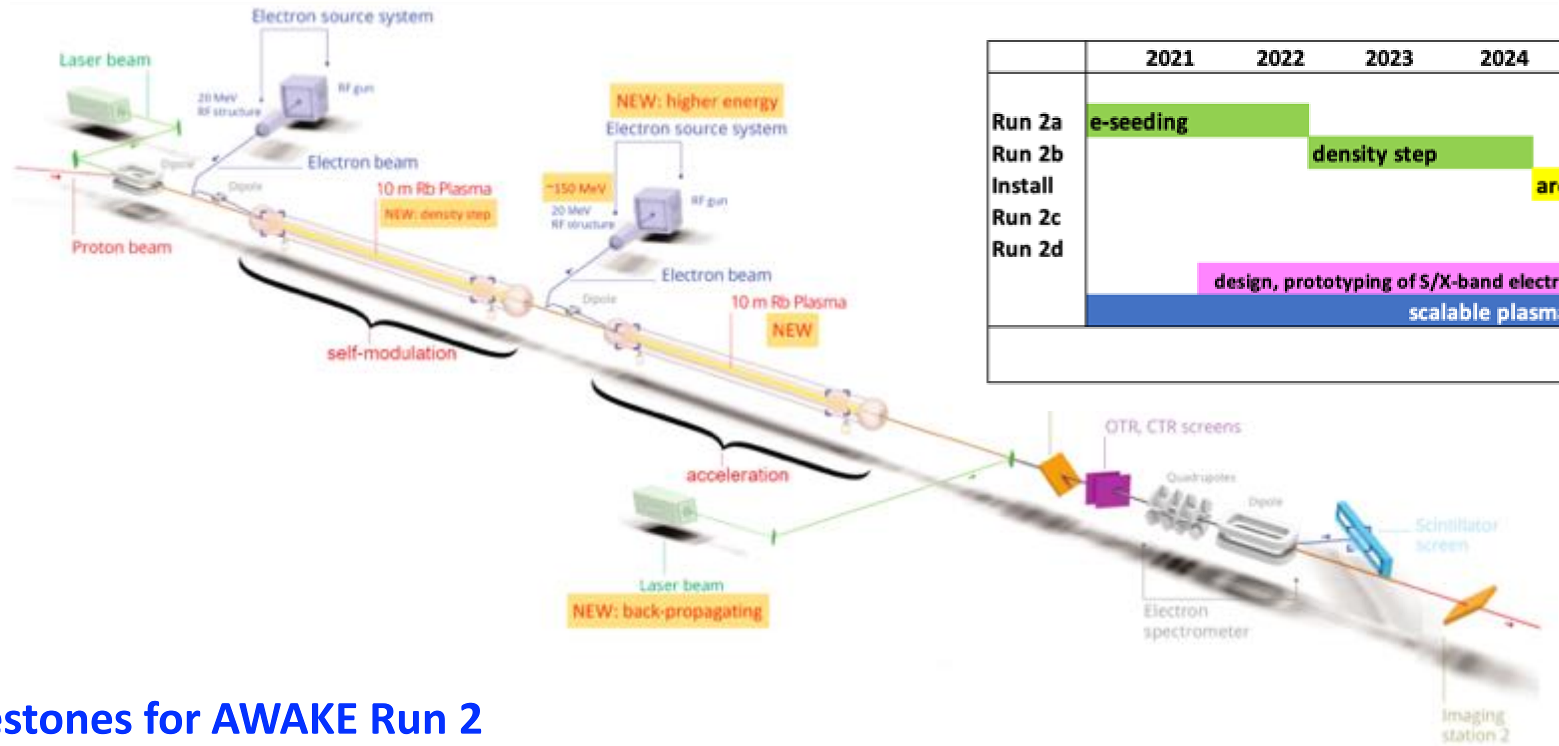
- ✓ 1st milestone: Demonstrated seeded self-modulation of the proton bunch in plasma (2016/17)
- ✓ 2nd milestone: Demonstrated electron acceleration in plasma wakefield driven by a self-modulated proton bunch. (2018)

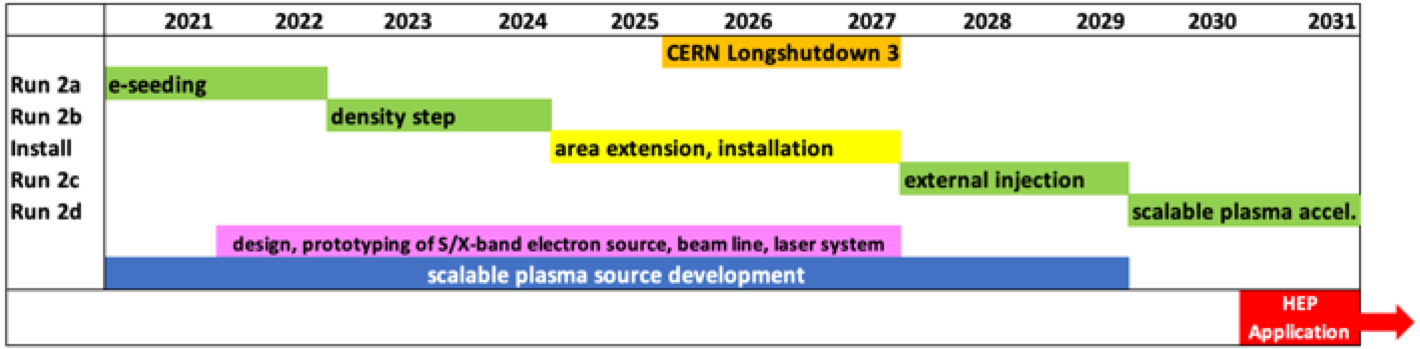
AWAKE Run 2 (2021 – ~2030):

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.

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!**

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

Organization of the team

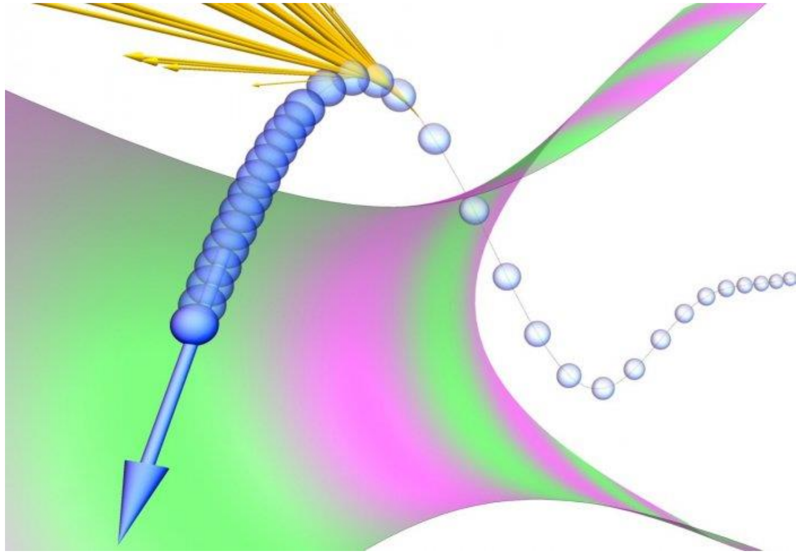
Work package leaders are expected to organize how they want to carry out the work

- **Topic 3: Particle driver based accelerators**
  - **3.1:** What are the critical questions we need to address and can address in the next three years with electron based driver facilities (e.g., FFWD, FACET II,…)?
  - **3.2:** What are the critical questions we need to address and can address in the next three years with proton based driver facilities (AWAKE)?

Topic 3	3.1 (Electron Driven)	Electron-Driven Plasma Accelerator Module with High beam Quality	Jens Osterhoff (DESY)	Richard d'Arcy (Oxford)
	3,2 (Proton – Driven)	AWAKE	Edda Gschwendtner (CERN)	Patrick Muggli (Max-Plank)

Please approach them if you are willing to contribute

Topic 4: Early Particle Physics Experiments



Radiation Reaction

[Phys. Rev. X **8**, 031004 (2018)](#)

[Phys. Rev. X 8, 011020 (2018)](#)

Early particle physics with advanced accelerators

4.1: What early experiments can we envision that would engage the particle physics community into a plasma based facility (e.g., Non-linear QED using plasma mirrors, fixed target experiments,…)

Are there suggestions for potential experiments in planning now or in the next few years?

…

Topic 4	Early particle physics experiments and test facilities	Maria Vranic (IST)	Matt Zepf (Jena)	Brian Foster (Oxford), Stuart Mangles (Imperial)

Please approach them if you are willing to contribute

Present Status

- Work Packages setup for major activities
- Almost all main WP leaders have been assigned
- Involving most of the major labs/groups across Europe
- Two sessions in the morning tomorrow (23rd) to look at the programme

Time	Short Description	Speakers	Wo
9:00-9:15	Coordination Plasma Accelerators for Particle Physics	Wim Leemans/Rajeev Pattathil	
TOPIC 1: Feasibility and pre-CDR Study on Plasma Based Accelerators for Particle Physics (Simulations-Analysis - Paper studies)			
9:15-9:25	Overall collider concepts (Higgs factory, multi-TeV)	Carl Lindstrom/Zulfikar Najmudin (Carl Schrc	
9:25-9:35	Beam-driven electron linac	Eric Adli	
9:35-9:45	Laser-driven electron linac	Jorge Viera/Maxence Thevenet/Brigitte Cros	
9:45-10:00	Other considerations (Positrons, spin/polarisation presearvation/final focus	Gianluca Sarri/Severin Diedrichs/Kristjan Poder/Arnd Specka	
10:00-10:10	Sustainability analysis	Denise Völker	
10:10-10:45	Discussion	All	
10:45-11:15	Coffee break		
TOPIC 2 Laser driver based accelerators (Experiments/prototypes)			
11:15-11:25	High-Repetition Rate Plasma Accelerator Module: vision for the next 10 years	Leo Gizzi/Andi Maier	
11:25 -11:35	High rep rate laser driver developments (100 Hz-kHz)	Andi Maier/Paul Mason	
11:35 - 11:45	High rep plasma targets	Simon Hooker/Brigitte Cros	
11:45-11:55	Facility/Delivery requiremnts	Dan Symes/Andreas Dopp	
TOPIC 3 Particle driver based accelerators (Experiments/prototypes)			
11:55-12:05	Experimental demonstration: High-Efficiency,Electron-Driven Plasma Accelerator Module with High beam Quality: vision and milestones for next 10 years	Jens Osterhoff/Richard d'Arcy	
12:05-12:15	Experimental demonstration: Proton driven experiments at AWAKE: roadmap-related activities	Edda Gschwendtner/Patrick Muggli	
TOPIC 4: Early particle physics with advanced accelerators			
12:15 -12:25	Early particle physics experiments and test facilities	Brian Foster/Maria Vranic/Matt Zepf/Stuart Mangles	
12:25 - 13:00	Discussion -- next steps	All	

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
- Opportunity to get other countries involved – STEM training
- Potential funding route for some activities in the UK
  - Accelerator R&D call (closed 2nd March)
  - Submitted a consortium proposal - ~ £1M/year

Funding challenges

We are working on a plan and need everyone's ideas to make it a must-do proposition

- **Approach:**
  - Provide a compelling list of goals and activities that we aim at achieving in the next three years
  - Discuss how the new activities are leveraged by at times very significant in-house activities
- **Key position:**
  - If this roadmap exercise is desired, funding is needed to support it
    - Each workpackage lead and deputy requires a postdoc (or PhD student?)
    - We need to secure funding for ~20-25 postdocs (some WPs may be merged)
    - Without funding it will not be possible to carry out this work.
- **Discuss with LDG, CERN management and national funding agencies how to proceed**
  - If funding is not made available for this study then we need to rethink

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

- Close alignment with ALEGRO programme – detailed discussions tomorrow