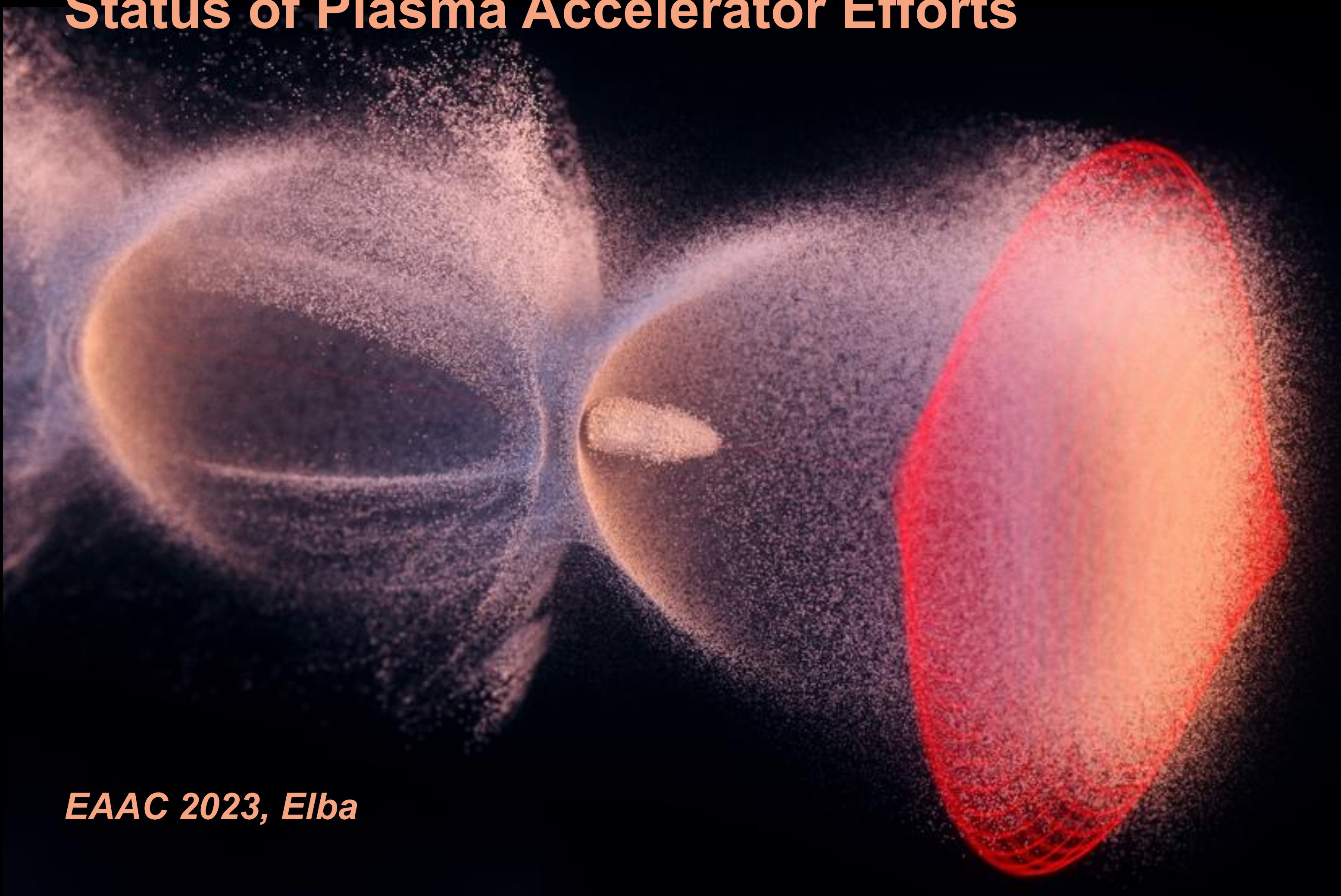
# ESPP Roadmap Update – Plasma Accelerators

## Status of Plasma Accelerator Efforts



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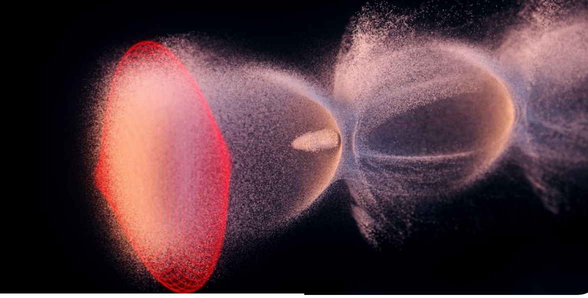
*EAAC 2023, Elba*

# ESPP Roadmap



## European Strategy for Particle Physics - Accelerator R&D Roadmap

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**Introduction & conclusion**

*Author:* D. Newbold[h,*]

**High-field magnets**

*Panel members:* P. Védrine[b,†] (Chair), L. García-Tabarés[k] (Co-Chair), B. Auchmann[g], A. Ballarino[a], B. Baudouy[b], L. Bottura[a], P. Fazilleau[b], M. Noe[o], S. Prestemon[p], E. Rochepault[b], L. Rossi[q], C. Senatore[r], B. Shepherd[s]

**High-gradient RF structures and systems**

*Panel members:* S. Bousson[c,‡] (Chair), H. Weise[e] (Co-Chair), G. Burt[d], G. Devanz[b], A. Gallo[f], F. Gerigk[a], A. Grudiev[a], D. Longuevergne[c], T. Proslier[b], R. Ruber[t]

*Associated members:* P. Baudrenghien[a], O. Brunner[a], S. Calatroni[a], A. Castilla[d], N. Catalan-Lasheras[a], E. Cenni[b], A. Cross[u], D. Li, F. Montesinos, G. Rosaz, J. Shi, N. Shipman, S. Stapnes[a], I. Syratch…, S. Tantawi[w], C. Tennant[x], A.-M. Valente[x], M. Wenskat[e], Y. Yamamoto[y]

**High-gradient plasma and laser accelerators**

*Panel members:* R. Assmann[e,f,**] (Chair), E. Gschwendtner[a] (Co-Chair), K. Cassou[c], S. Corde[z], L. Corner[i], B. Cros[aa], M. Ferrario[f], S. Hooker[bb], R. Ischebeck[g], A. Latina[a], O. Lundh[cc], P. Muggli[dd], P. Nghiem[b], J. Osterhoff[e], T. Raubenheimer[w,ee], A. Specka[ff], J. Vieira[gg], M. Wing[hh]

*Associated members:* C. Geddes[p], M. Hogan[w], W. Lu[v], P. Musumeci[ii]

**Bright muon beams and muon colliders**

*Panel members:* D. Schulte[a,††] (Chair), M. Palmer[jj] (Co-Chair), T. Arndt[o], A. Chancé[b], J. P. Delahaye[a], A. Faus-Golfe[c], S. Gilardoni[a], P. Lebrun[a], K. Long[h,kk], E. Métral[a], N. Pastrone[ll], L. Quettier[b], T. Raubenheimer[w,ee], C. Rogers[h], M. Seidel[g,mm], D. Stratakis[nn], A. Yamamoto[y]

**Energy-recovery linacs**

*Panel members:* M. Klein[i,‡‡] (Chair), A. Hutton[x] (Co-Chair), D. Angal-Kalinin[qq], K. Aulenbacher[rr], A. Bogacz[x], G. Hoffstaetter[ss,jj], E. Jensen[a], W. Kaabi[c], D. Kayran[jj], J. Knobloch[tt,uu], B. Kuske[uu], F. Marhauser[x], N. Pietralla[vv], O. Tanaka[y], C. Vaccarezza[f], N. Vinokurov[ww], P. Williams[qq], F. Zimmermann[a]

*Associated members:* M. Arnold[vv], M. Bruker[x], G. Burt[d], P. Evtushenko[xx], J. Kühn[uu], B. Militsyn[qq], A. Neumann[uu], B. Rimmer[x]

*Sub-Panel on CERC and ERLC:* A. Hutton[x] (Chair), C. Adolphsen[w], O. Brüning[a], R. Brinkmann[e], M. Klein[i], S. Nagaitsev[nn], P. Williams[qq], A. Yamamoto[y], K. Yokoya[y], F. Zimmermann[a]


**The FCC-ee R&D programme**

*Authors:* M. Benedikt[a,γ], A. Blondel[yy,r,δ], O. Brunner[a], P. Janot[a], E. Jensen[a], M. Koratzinos[zz], R. Losito[a], K. Oide[y], T. Raubenheimer[w,ee], F. Zimmermann[a,ϵ]

**ILC-specific R&D programme**

*Authors:* S. Michizono[y,ζ], T. Nakada[mm], S. Stapnes[a]

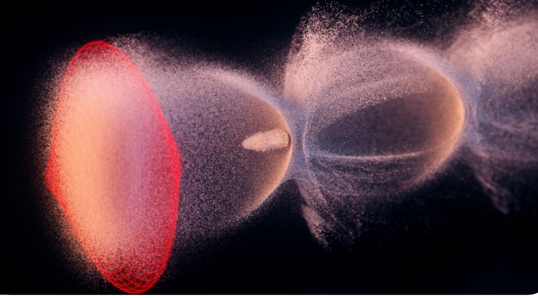
**CLIC-specific R&D programme**

*Authors:* P. N. Burrows[bb], A. Faus-Golfe[c,η], D. Schulte[a], S. Stapnes[a]

**Sustainability considerations**

*Authors:* T. Roser[jj,α], M. Seidel[g,mm,β]

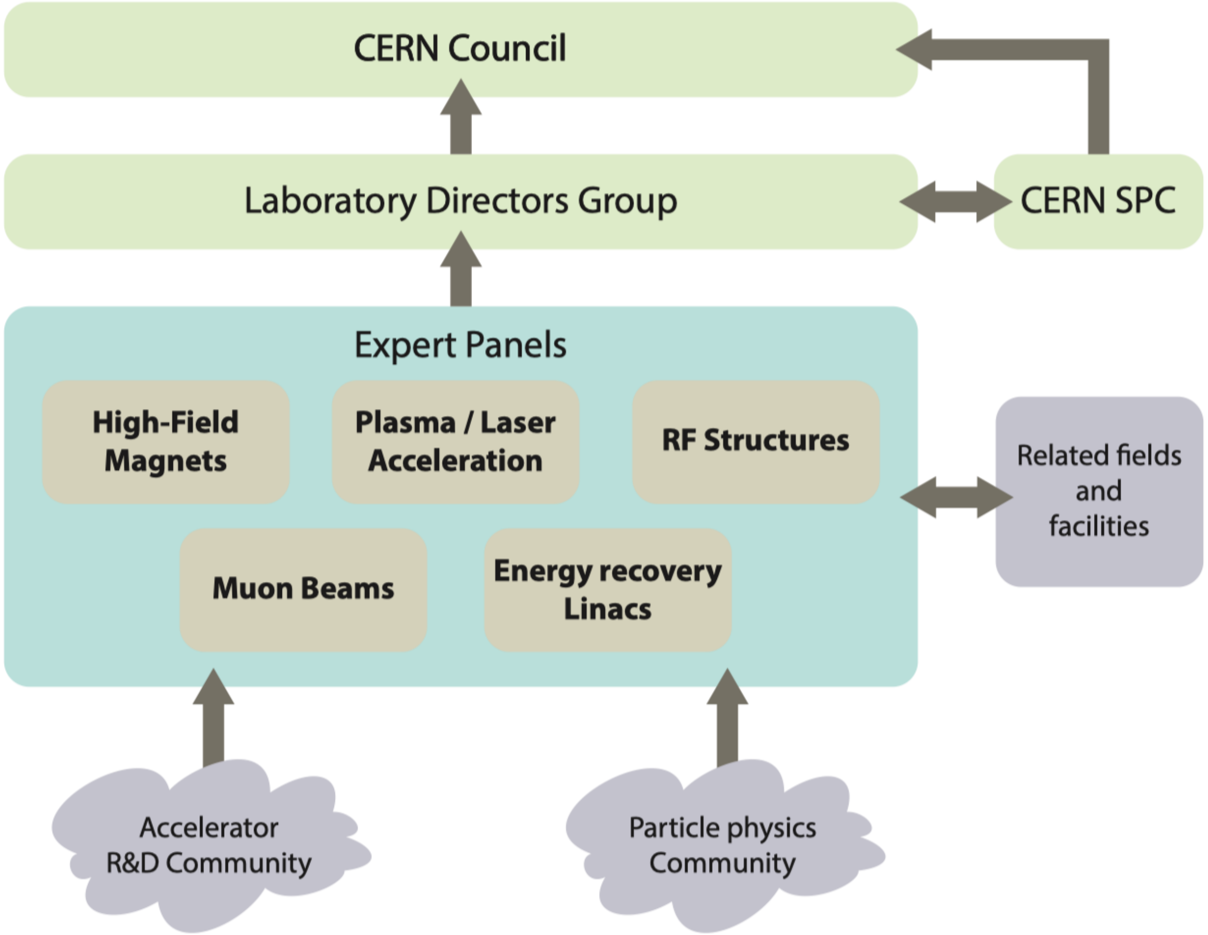
# ESPP Roadmap



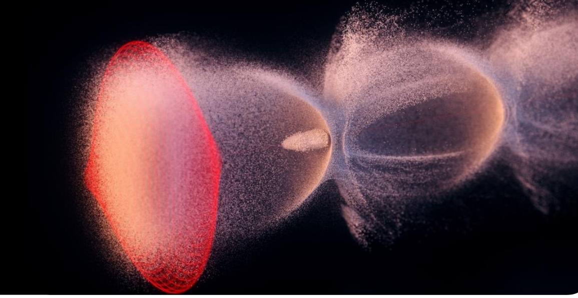
- To develop R&D for the next generation of particle accelerators and colliders (beyond 2045)
- Commissioned by Lab Directors’ Group – CERN
- To provide an agreed structure for a coordinated and intensified programme
- Develop in consultation with the community and expert panels
- Coordinate with international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

# ESPP Roadmap

- 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



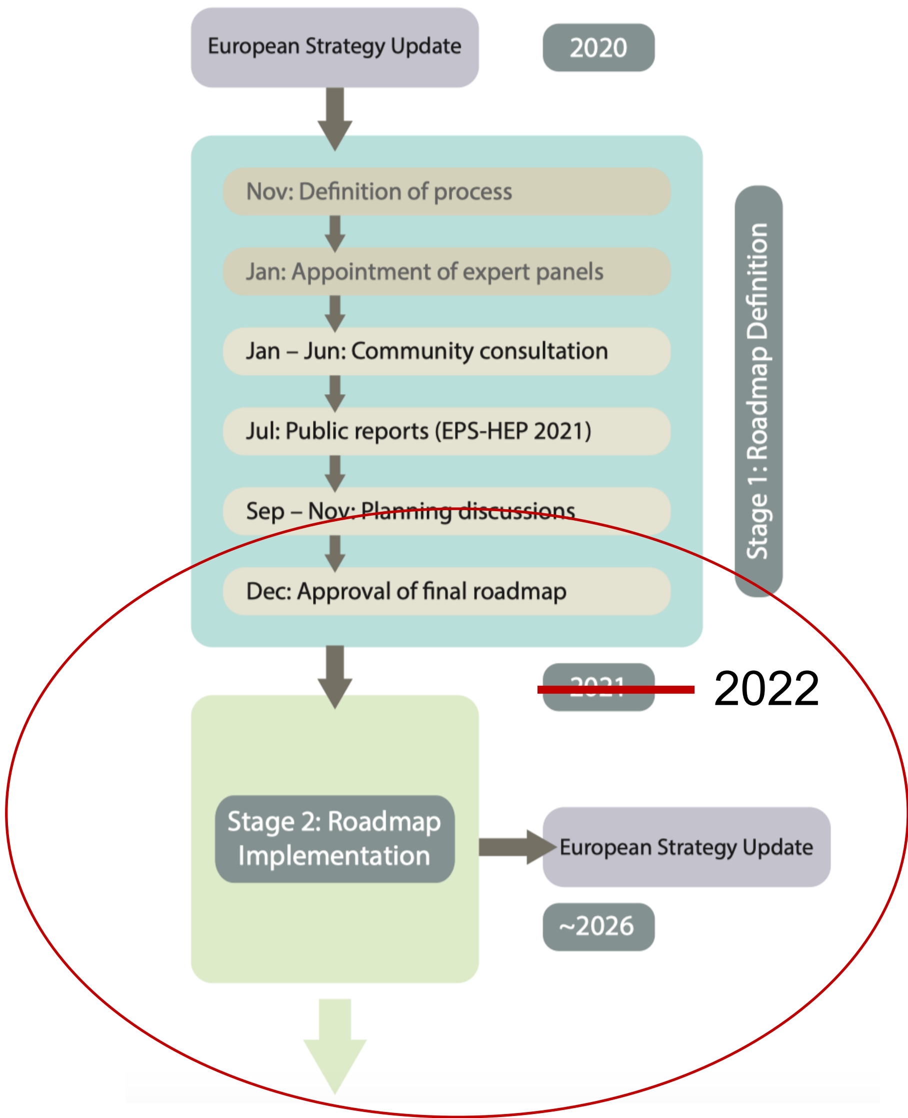
- Identifying key R&D objectives

- Weighted under indicative funding scenarios:

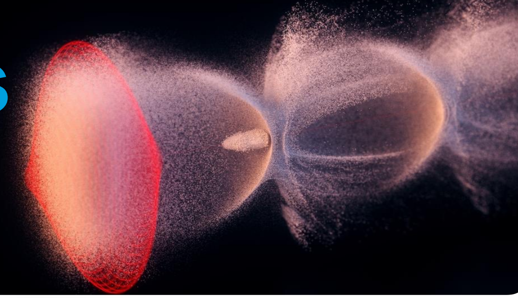
    - ‘minimal’ scenario: achieved with restricted resources (only if current activities already align)
    - ‘nominal’ scenario: extra funding conditions continue
    - ‘aspirational’: significant additional funding

**Doesn’t identify a ring-fenced funding pot**

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

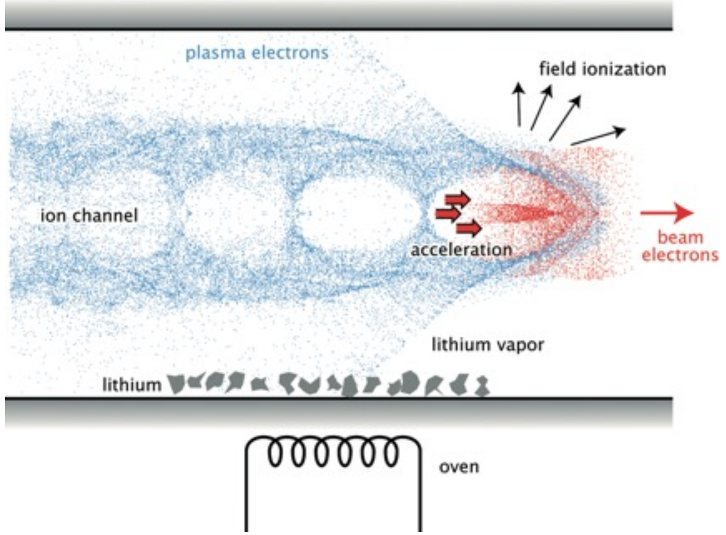


# R&D Coordination Panel: Plasma Accelerators

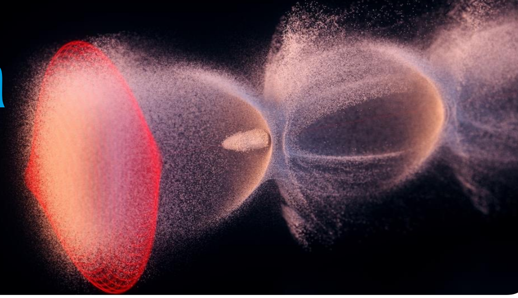


## EPPS Roadmap exercise aims at delivering a pre-CDR study by December 2025

| 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 (Laser) Plasma Accelerator Module (kHz) | Dec-25 |
| Experiment: High-Efficiency, Electron/Proton-Driven Plasma Accelerator Module with High Beam Quality | Dec-25 |

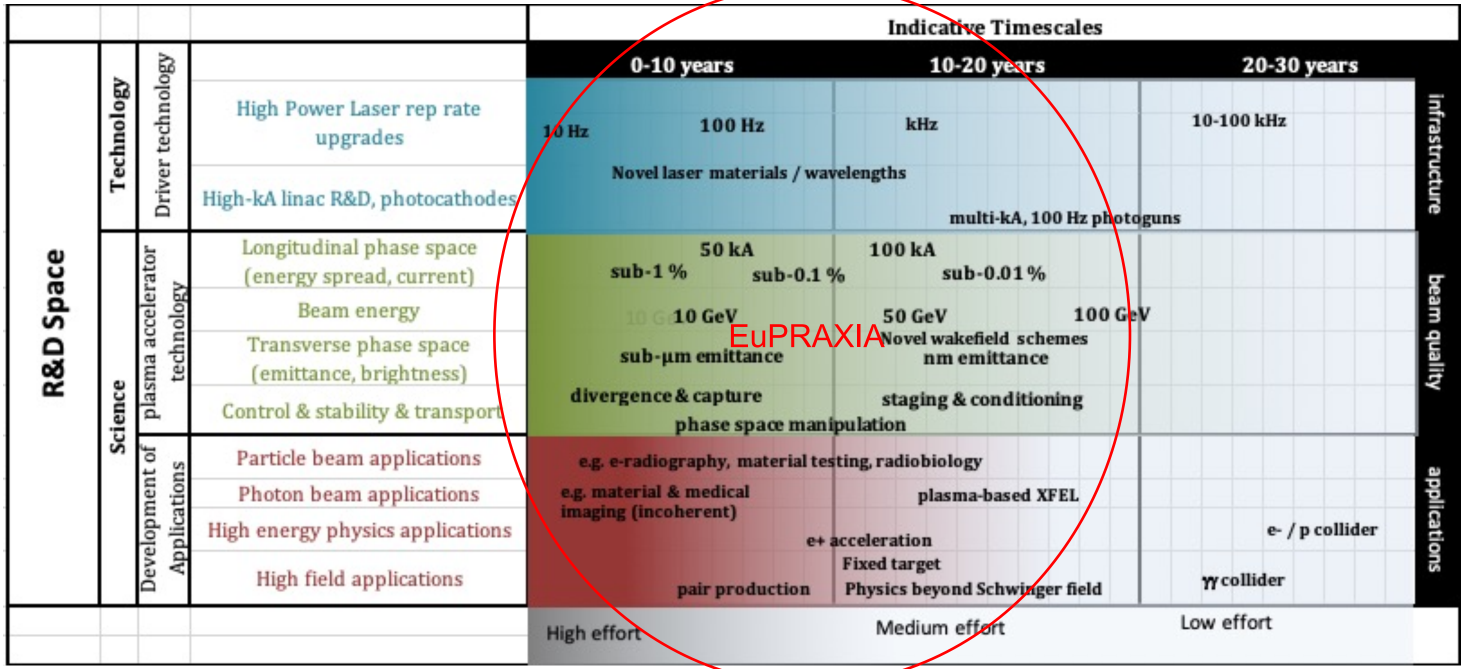
# Shaping a multi-decadal program towards plasma based colliders and experiments



- Current research in LPA and e-PWFA concentrated on producing high-quality beams for light sources and their applications
- AWAKE has a programmatic path towards HEP relevant energies
- Dedicated R&D is critical for a future plasma-based collider
- Need a program (and funding)

| | 0-10 years | 10-20 years | 20-30 years |
|---|---|---|---|
| AWAKE | **Demonstration of:** Preserved beam quality, acceleration in very long plasmas, plasma uniformity | **Fixed-target experiment (AWAKE)** Dark-Photon search, strong-field QED etc, (50-200GeV $e^-$) | |
| | | **Demonstration of:** Use of LHC beams, TeV acceleration, beam delivery | **Energy-frontier collider** 10 TeV c.o.m. electron-proton collider |

LPA and e-PWFA Programs




PWASC Roadmap 2019

# Kick-off meeting at ALEGRO – March ‘23

## First Community Meeting to put together a program of work


- **Analysis of a pre-conceptual (straw-person) model of a collider and fixed target experiments**
- **Collider building block analysis:**
  - Injector (electron and positron, spin-polarized,….)
  - Accelerator stages
  - Beam transport and final focus
  - Power sources (laser and/or particle drivers)
- **Experimental studies on laser/electron/proton-driven plasma accelerator concepts towards solving some key R&D Challenge**

**Goal: Prepare for start of a CDR in second half of the decade**

- Two dedicated sessions for ESPP
- Representation from almost all work packages
- Brief presentations on proposed activities and resources

https://indico.cern.ch/event/1193719/

**ESPP Roadmap Process - DESY Lecture Hall (09:00 - 10:45)**

| time | [id] title | presenter |
|---|---|---|
| 09:00 | [22] Coordination: Plasma Accelerators for Particle Physics | PATTATHIL, Rajeev<br>LEEMANS, Wim |
| 09:15 | [23] Overall collider concepts (Higgs factory, multi-TeV) | LINDSTRØM, Carl A.<br>SCHROEDER, Carl<br>NAJMUDIN, Zulfikar |
| 09:25 | [24] Beam-driven electron linac | ADLI, Erik |
| 09:35 | [25] Laser-driven electron linac | CROS, Brigitte<br>VIERA, Jorge<br>THEVENET, Maxence |
| 09:45 | [26] Positron arm / Spin and polarisation preservation / Final-focus system | |
| 10:00 | [27] Sustainability analysis | VÖLKER, Denise |
| 10:10 | [28] Discussion | |

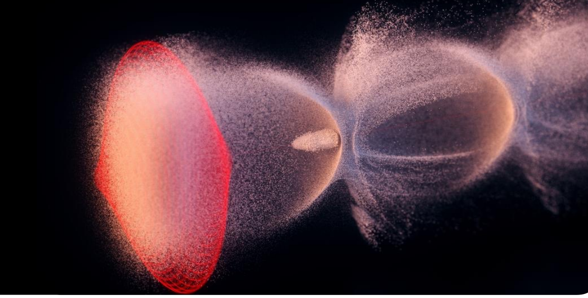
**Coffee break - DESY Lecture Hall (10:45 - 11:15)**

**ESPP Roadmap Process - DESY Lecture Hall (11:15 - 13:00)**

| time | [id] title | presenter |
|---|---|---|
| 11:15 | [29] High-rep.-rate plasma-accelerator module: 10 yr vision | MAIER, Andreas<br>GIZZI, Leonida |
| 11:25 | [30] High-rep.-rate laser-driver development | MAIER, Andreas<br>MASON, Paul |
| 11:35 | [31] High-rep.-rate plasma targets | CROS, Brigitte<br>HOOKER, Simon |
| 11:45 | [32] Facility/Delivery requirements | DÖPP, Andreas<br>SYMES, Daniel |
| 11:55 | [33] High-efficiency, beam-quality-preserving electron-driven plasma module: 10 yr vision | OSTERHOFF, Jens<br>D'ARCY, Richard |
| 12:05 | [34] Proton-driven experiments at AWAKE | GSCHWENDTNER, Edda<br>MUGGLI, Patric |
| 12:15 | [35] Early particle physics experiments and test facilities | FOSTER, Brian<br>VRANIC, Maria<br>ZEPF, Matt<br>MANGLES, Stuart |
| 12:25 | [36] Discussion - next steps | |

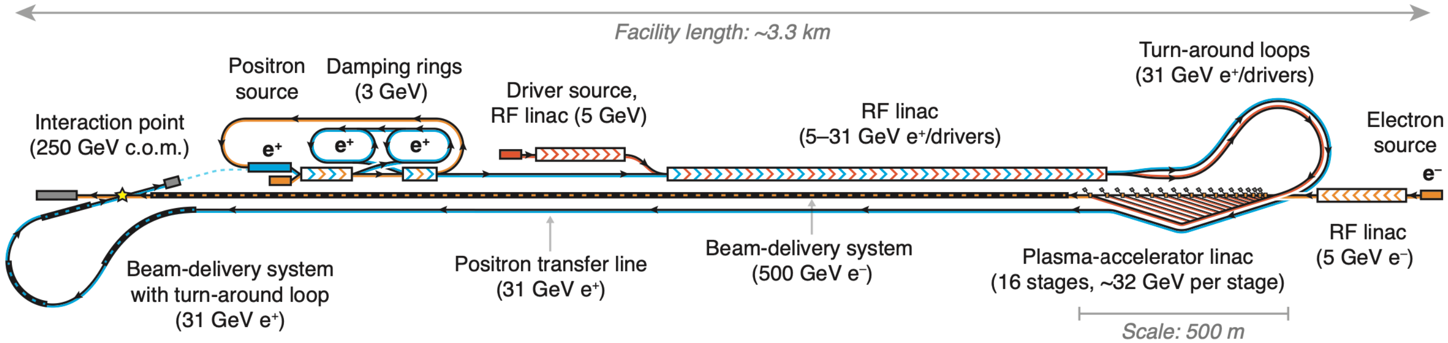
**Lunch Break - DESY Lecture Hall (13:00 - 14:00)**

# A new proposal: HALHF – a plasma accelerator scheme for a Higgs Factory



- An end-to-end preliminary collider design presented by Brian Foster, Richard D'Arcy and Carl Lindstrøm
- Asymmetric energy e+e- collider design with a 500GeV electron arm and a 31GeV positron arm.
- Plasma-accelerator driven electron arm and a positron-arm based on conventional linac
- Credible, yet novel (asymmetric) design concept with some key parameters required for colliders
- Parameters, tolerance levels, technical feasibility etc. need to be scrutinized through extensive modelling and simulations (and experimental prototypes)

**Previous Talk by Carl Lindstrøm**




| *Machine parameters* | *Unit* | |
|---|---|---|
| Center-of-mass energy | GeV | 250 |
| Center-of-mass boost | | 2.13 |
| Bunches per train | | 100 |
| Train repetition rate | Hz | 100 |
| Collision rate | kHz | 10 |
| Luminosity | $cm^{-2}\,s^{-1}$ | $0.81 \times 10^{34}$ |
| Peak luminosity (in top 1%) | | 57% |
| Estimated total power usage | MW | 100 |

| *Beam parameters* | | $e^-$ | $e^+$ |
|---|---|---|---|
| Beam energy | GeV | 500 | 31.25 |
| Bunch population | $10^{10}$ | 1 | 4 |
| Bunch length in linac (rms) | $\mu$m | 9 | 75 |
| Bunch length at IP (rms) | $\mu$m | 75 | |
| Energy spread (rms) | % | 0.15 | |
| Horizontal emittance (norm.) | $\mu$m | 160 | 10 |
| Vertical emittance (norm.) | $\mu$m | 0.56 | 0.035 |
| IP horizontal beta function | mm | 3.3 | |
| IP vertical beta function | mm | 0.1 | |
| IP horizontal beam size (rms) | nm | 729 | |
| IP vertical beam size (rms) | nm | 7.7 | |
| Average beam power delivered | MW | 8 | 2 |
| Average beam current | mA | 0.016 | 0.064 |

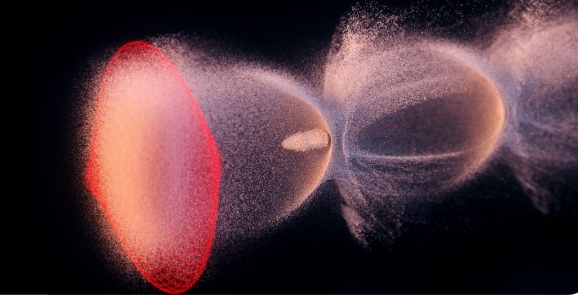
| *RF linac parameters* | | |
|---|---|---|
| Average gradient | MV/m | 25 |
| Wall-plug-to-beam efficiency | % | 50 |
| RF power usage | MW | 47.5 |
| Peak RF power per length | MW/m | 21.4 |
| Cooling req. per length | kW/m | 20 |

| *PWFA linac parameters* | | |
|---|---|---|
| Number of stages | | 16 |
| Plasma density | $cm^{-3}$ | $1.5 \times 10^{16}$ |
| In-plasma acceleration gradient | GV/m | 6.4 |
| Average gradient (incl. optics) | GV/m | 1.2 |
| Length per stage[a] | m | 5 |
| Energy gain per stage[a] | GeV | 31.9 |
| Initial injection energy | GeV | 5 |
| Driver energy | GeV | 31.25 |
| Driver bunch population | $10^{10}$ | 2.7 |
| Driver bunch length (rms) | $\mu$m | 27.6 |
| Driver average beam power | MW | 21.4 |
| Driver-to-wake efficiency | % | 74 |
| Wake-to-beam efficiency | % | 53 |
| Driver-to-beam efficiency | % | 39 |
| Wall-plug-to-beam efficiency | % | 19.5 |
| Cooling req. per stage length | kW/m | 100 |

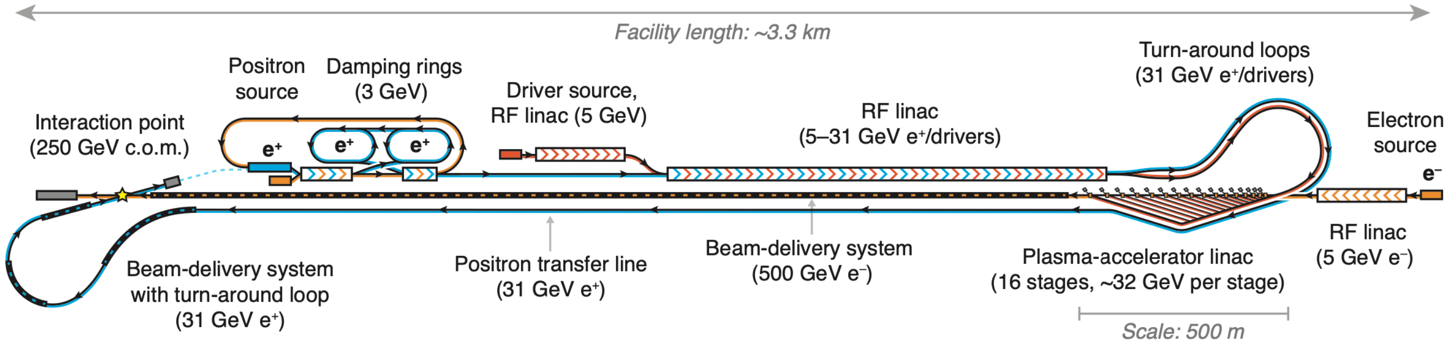
[a] The first stage is half the length and has half the energy gain of the other stages (see Section V. 4).

https://arxiv.org/pdf/2303.10150.pdf

# Opportunity to build a pre-CDR case around HALHF



- Higgs Factory at potentially ~1/4$^{th}$ of the cost
- Plasma accelerator arm of HALHF can be beam-driven or laser-driven
- First generation to consider PWFA from a technological readiness level (TRL) perspective and LPA stages can be incorporated later, providing an even more compact architecture
- Many synergies between all plasma accelerator technologies (laser-, electron-, and proton-driven), and all will contribute to the pre-CDR.

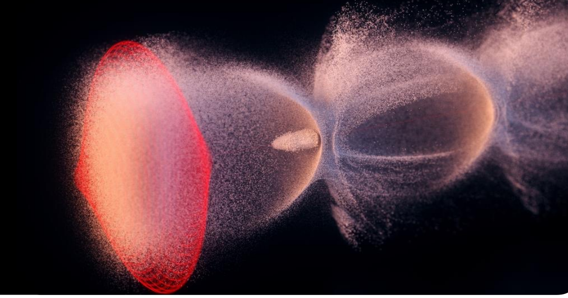



| Subsystem | Original cost (MILCU) | Comment | Scaling factor | HALHF cost (MILCU) | Fraction |
|---|---|---|---|---|---|
| Particle sources, damping rings | 430 | CLIC cost [69], halved for $e^+$ damping rings only[a] | 0.5 | 215 | 14% |
| RF linac with klystrons | 548 | CLIC cost, as RF power is similar | 1 | 548 | 35% |
| PWFA linac | 477 | ILC cost [47], scaled by length and multiplied by 6[b] | 0.1 | 48 | 3% |
| Transfer lines | 477 | ILC cost, scaled to the ∼4.6 km required[c] | 0.15 | 72 | 5% |
| Electron BDS | 91 | ILC cost, also at 500 GeV | 1 | 91 | 6% |
| Positron BDS | 91 | ILC cost, scaled by length[d] | 0.25 | 23 | 1% |
| Beam dumps | 67 | ILC cost (similar beam power) + drive-beam dumps[e] | 1 | 80 | 5% |
| Civil engineering | 2,055 | ILC cost, scaled to the ∼10 km of tunnel required | 0.21 | 476 | 31% |
| | | | Total | 1,553 | 100% |

**ALL plasma accelerator concepts, and associated technologies should continue to be developed to ensure that synergies can be leveraged**

**Potential upgrade paths for HALHF remain open.**

# Plasma-based collider: Feasibility studies



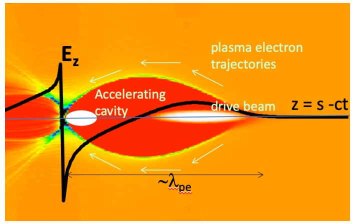
## Theory/simulation – based works

**WP 1.1: Overall collider concepts (Carl Lindstrøm, Brian Foster, Richard D'Arcy) + Zulfikar Najmudin**

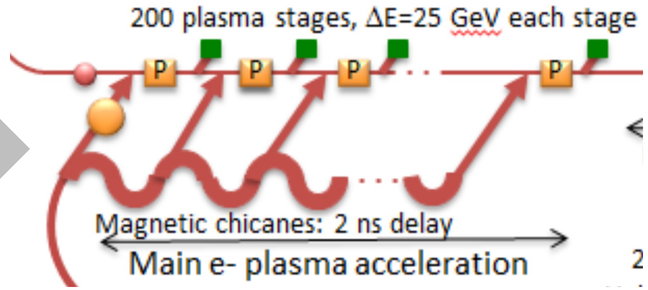
- Provides crucial input to the development of HALHF into pre-CDR

**WP 1.2: Beam driven electron linacs (Erik Adli, Carl Lindstrøm)**

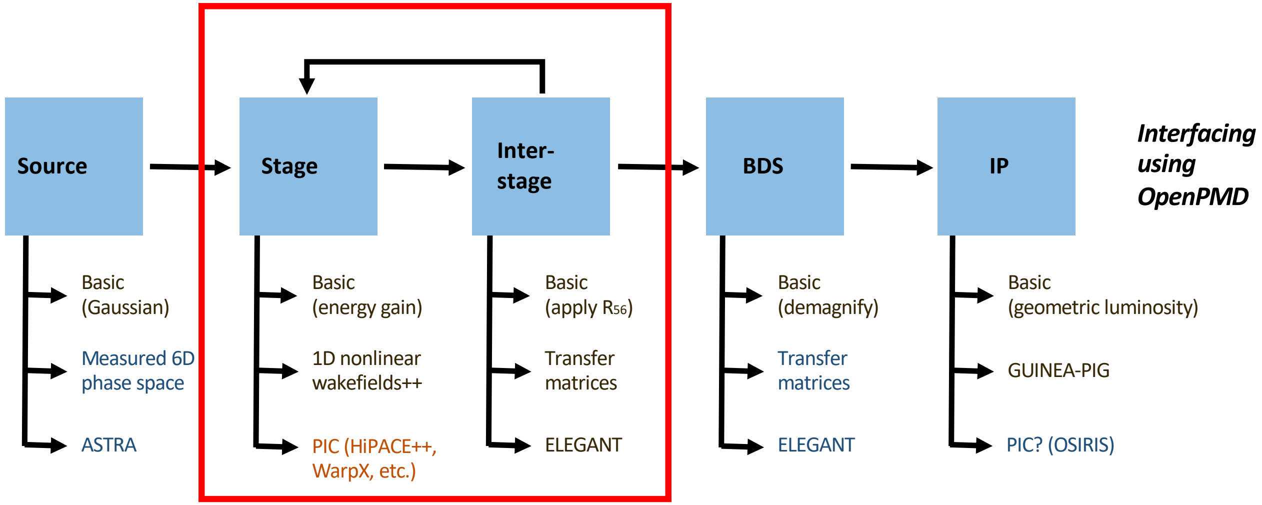
- Simulations to underpin HALHF design
- Develop single stage and interstage models with all the relevant physics needed
- Tolerance checks/self-correction concepts




Single-stage physics

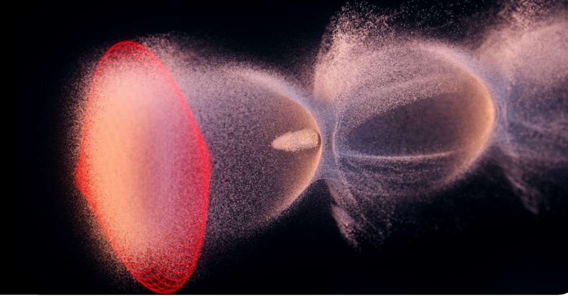



Drive beam generation and distribution




Talks in WG10 yesterday

# Plasma-based collider: Feasibility studies



## Theory/simulation – based works

**WP 1.3: Laser driven electron linacs (Jorge Viera, Maxence Thévenet, Brigitte Cros, Zulfikar Najmudin)**

- Looking out for fundamental show-stoppers
- Improving reduced models with additional physics
- Simulate 2 stages, starting with reduced model & coupling and confirm with full-3D simulation
- Could underpin future plasma-based collider designs/upgrades to HALHF
- Experimental verification via **2.4** and in-kind contributions at LPA facilities

**Start from the plasma stage**

Full-physics 3D EM PIC simulation: Ion motion, collisions, radiation reaction, realistic parameters

*Scale up in number of stages*

**Start from the collider design**

Reduced model to simulate a section

Axisymmetric, quasi-static, reduced models

*Scale up in accuracy/physics*

**Shake hands: ensembles of start-to-end accurate simulations**

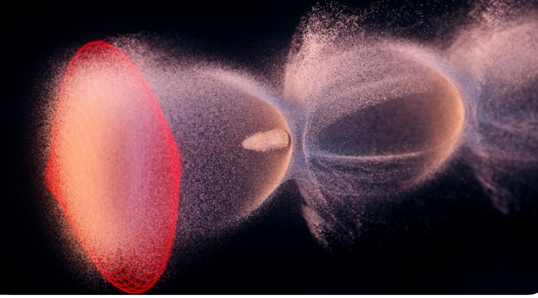
Next steps:

- Improve reduced models with additional physics
- Simulate 2 stages (e.g. 150 GeV - 190 GeV), starting reduced model & coupling
- Confirm with full-3D simulation

**Common topics:**

- Pre- and post-driver plasma modeling
- Multi-time and length scales
- Radiation and mass transport
- Ionization and MHD
- Heat management

# Plasma-based collider: Feasibility studies



**Requires theory/simulations along with experimental verifications**

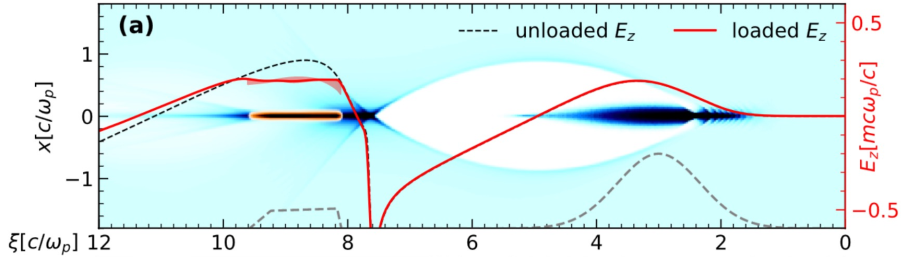
**WP 1.4: Positron acceleration (Gianluca Sarri, Severin Diederichs)**

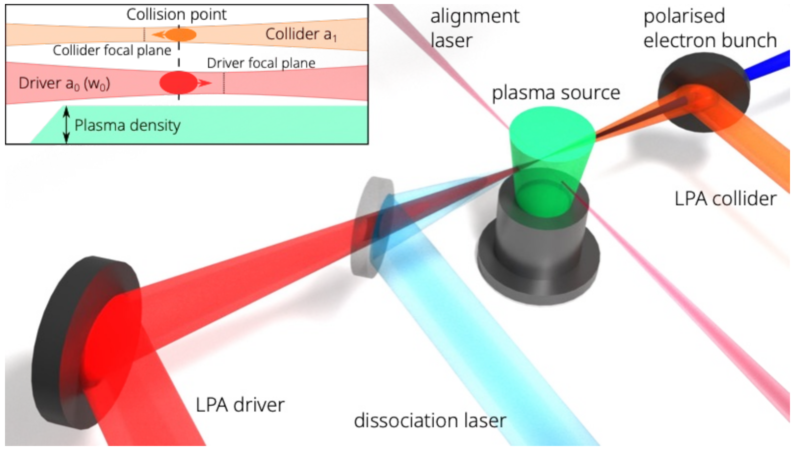
- Important to continue effort. A few potential schemes have recently emerged – need to investigate tolerances etc. before experimental realisation
- Development of experimental areas where positron wakefield acceleration can be studied
- Systematic simulation studies and improvements of simulation codes:

S. Diederichs – Wed
Spencer Gessner – Thurs
Sébastien Corde - Thurs

**WP 1.5: Spin and polarization preservation (Kristjan Põder)**

- Important to continue effort
- A few potential schemes – need experimental realisation (eg. LEAP project)



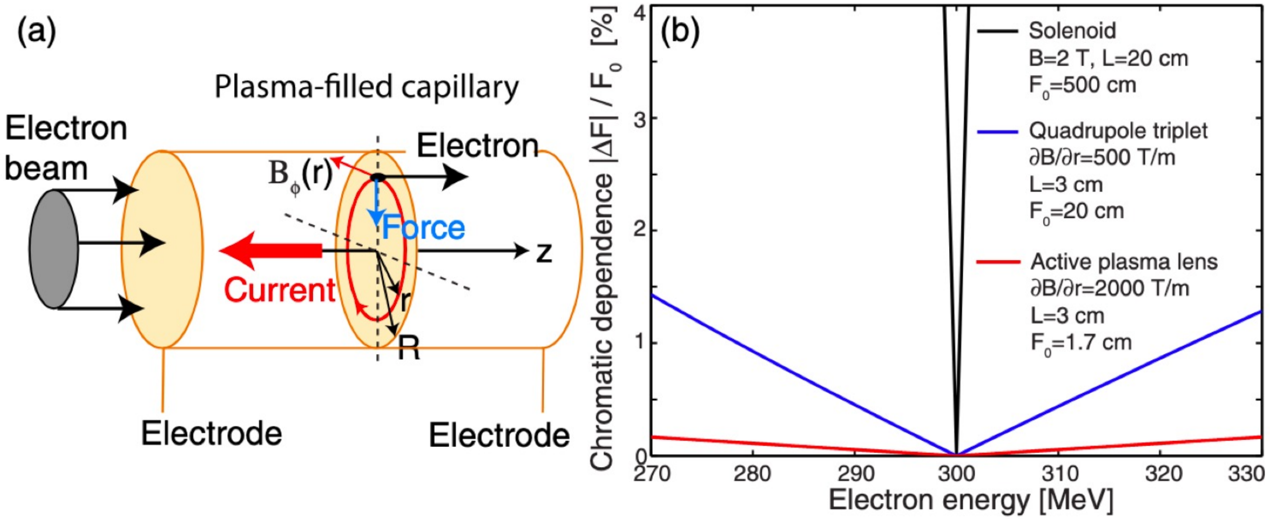



# Plasma-based collider: Feasibility studies

## Requires theory/simulations along with experimental verifications

**1.6: Assess final-focus system concepts**;

- Explore other technologies (eg. adiabatic plasma lens.) that could underpin future upgrades to HALHF

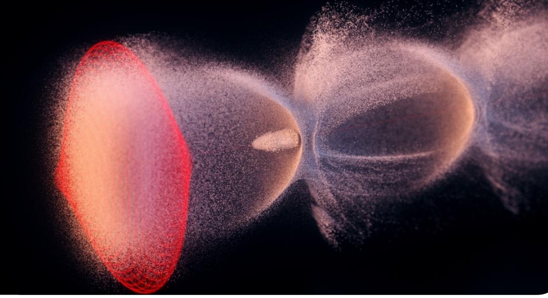



Active plasma lenses can work independent of beam shape
Both for electrons and positrons

**This might result in making HALHF upgrades more compact.**

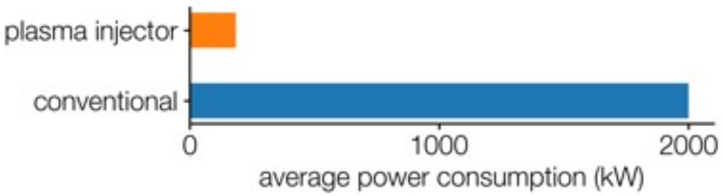
**→ Need to find someone to lead this**

# Sustainability and environmental impact study

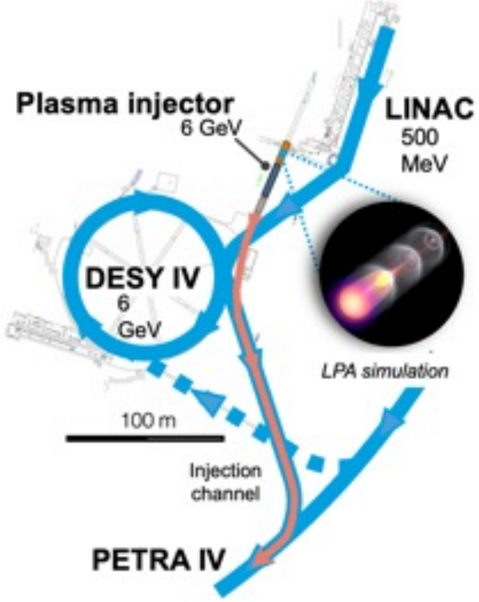


## WP 1.7 Coordinated by D. Voelker (DESY) & M. Turner (CERN)

1. **Development of guidelines** that allow comparison of the environmental impact of the proposed HALHF and ILC Higgs-factory design.
   - Community input will assure incorporation of different stakeholder views, help prioritize guiding criteria and continuation of existing efforts.
   - Community outreach will help gathering reliable data from similar previous projects and synergistic efforts (e.g. CLIC efforts, iFAST,...).
   - External consultancy will ensure conformity with European legislation and industry standards in methods and criteria.
2. **Application of the developed guidelines** for the environmental impact comparison of the HALHF and ILC Higgs-factory proposal.
3. **A facility-wide energy consumption assessment for electron, proton and laser drivers.**
4. **Communicate, share and spread analysis results.** Establish platforms that enable networking, exchanges and cooperation between accelerator physics, other scientific areas and industry.
5. **Identify highest impact R&D** that would allow to reduce the environmental footprint of future accelerators.

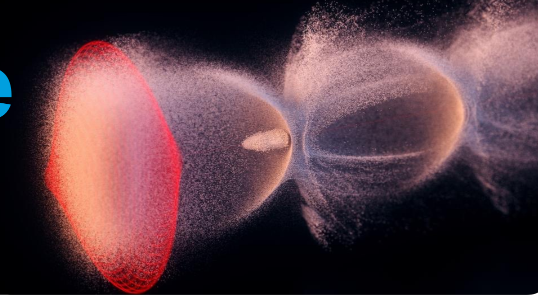



225 kW (estimate)



# Technology developments need to continue

## Can address major plasma accelerator challenges – need extra resources for aligning activities



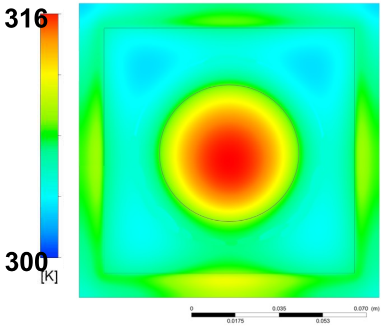
**WP 2.1: High-repetition rate laser-driven plasma module (coordination) (Leo Gizzi, Andi Maier)**

- Plan a joint workshop to develop concepts and carry out R&D (lasers, plasma targets, facility aspects)
- Focus on inter-stage technology R&D

**WP 2.2: Development of high-rep rate, high-efficiency lasers (Paul Mason, Andi Maier)**

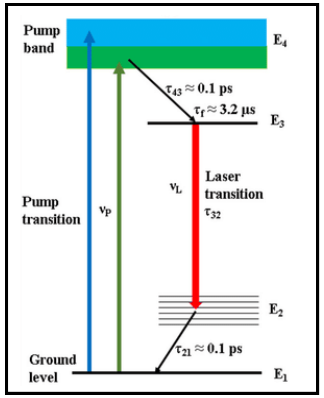
- Important for laser plasma accelerator developments and fusion drivers
- A lot of development towards industrial applications – need to channel this to our advantage

**Potential synergy with laser-fusion drivers**

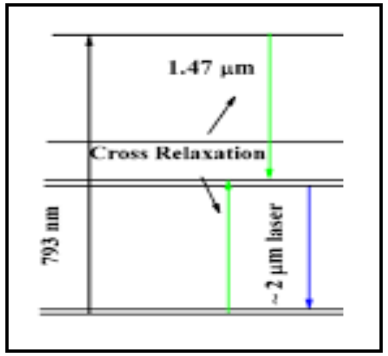


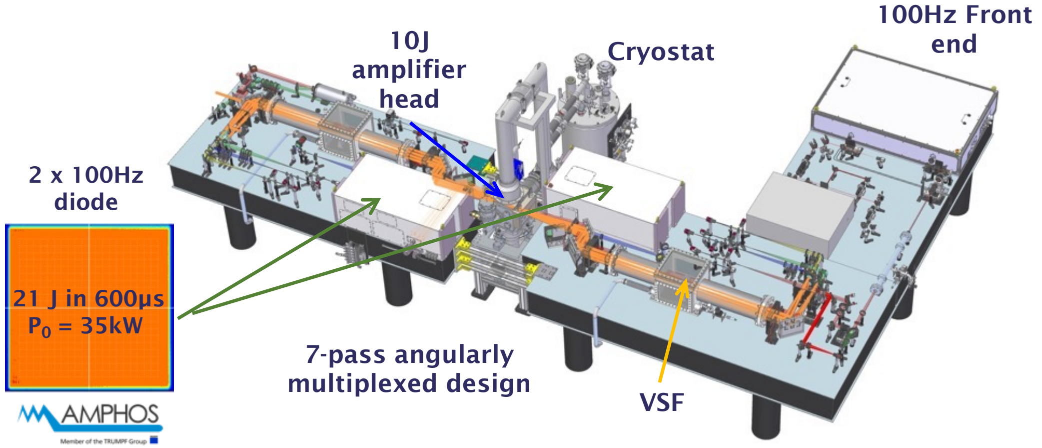

Gas-cooled clad Ti:Sa slab pumped at 1.4 kW @ 10 Hz

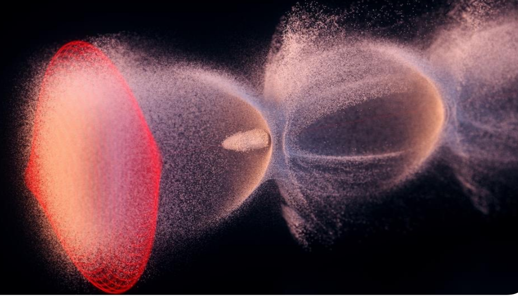
Ti:Sa




Tm:X (2µm)





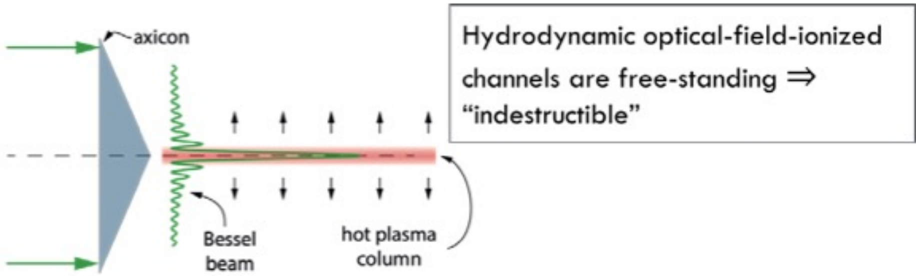
# Technology developments need to continue

## Can address major plasma accelerator challenges – need extra resources for aligning activities

**WP 2.3: Plasma source technology (Simon Hooker, Brigitte Cros)**

Developing gas cells and HOFI channels – including PWFA-relevant targets
Solutions for heat load management in plasma sources and multi-time and length scale modeling aimed at pre- and post-driver interactions

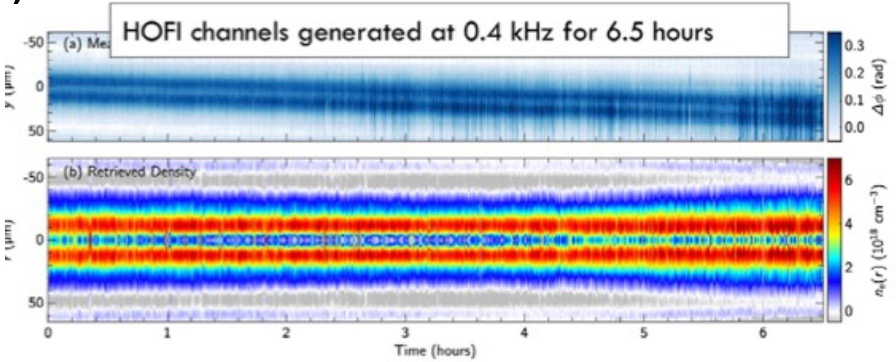
Aaron's talk - Monday

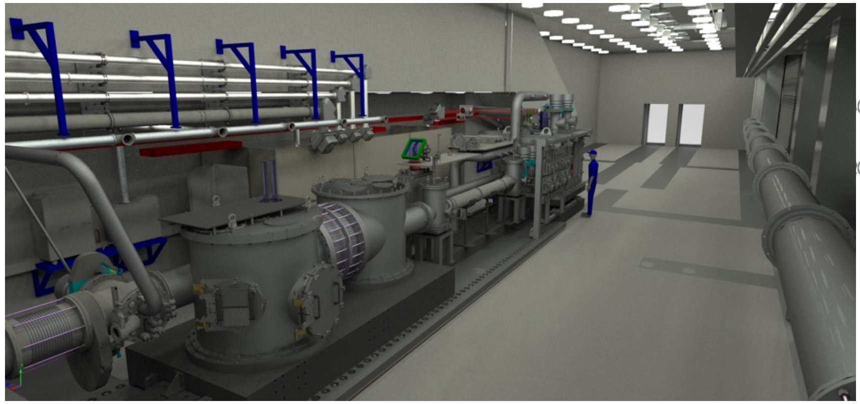


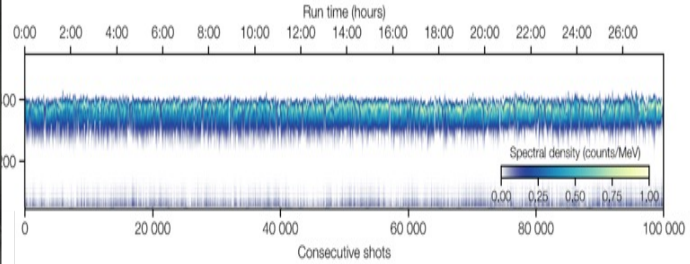

**WP 2.4: Experimental LPA Facility Developments: (Dan Symes, Andreas Döpp)**

Experimental verifications and prototyping: beam manipulation and propagation, stability optimization and feedback control, plasma mirrors and driver removal, staging demonstrations
Aspects important for **1.1** and **1.3**

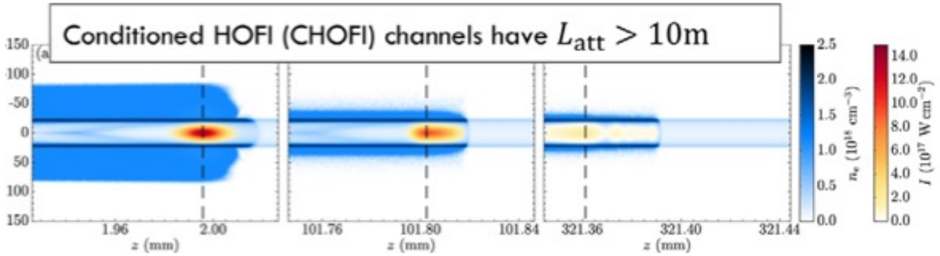
Andreas' talk - Monday



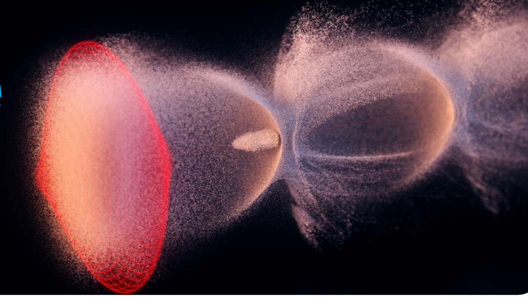



LPA-based facilities are under construction – requires resources to align with the CDR



# Technology developments need to continue

## Can address major plasma accelerator challenges – need extra resources for aligning activities



kHz, multi-GeV accelerators are already under development based on novel schemes

Simon Hooker, Monday

## P-MoPA: Plasma-Modulated Plasma Accelerators

*A route to efficient, kHz repetition-rate, multi-GeV, laser-driven accelerator stages*

**Further reading**

O. Jakobsson *et al.*, *Phys. Rev. Lett.* **127** 184801 (2021)
J. J. van de Wetering *et al.*, *Phys. Rev. E* — *accepted*

**Step 1: Plasma modulator**

- ☑ Drive & seed pulses guided in HOFI channel
- ☐ Spectrum of drive pulse modulated by wake driven by seed pulse

**Step 2: Train generation**

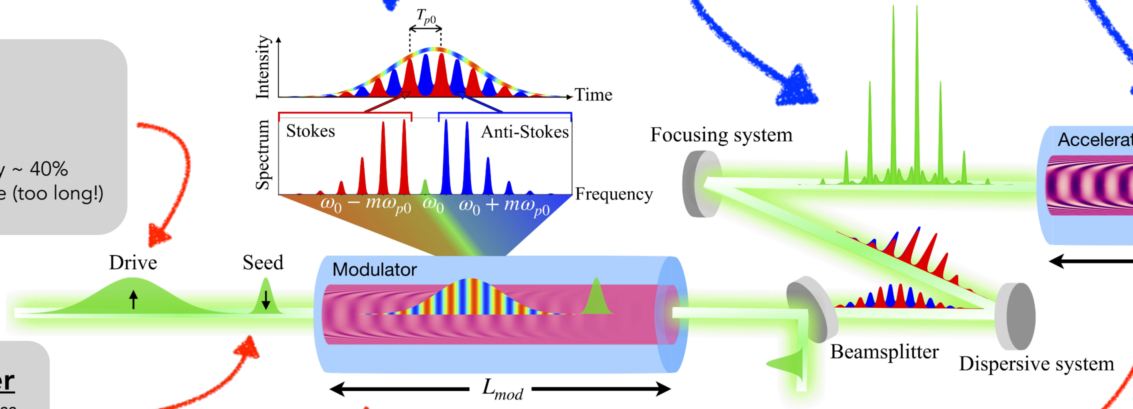
- ☐ Spectrally-modulated drive pulse converted to pulse train by dispersive system

**Step 3: Accelerator**

- ☑ Resonant wake excitation by pulse train guided in HOFI channel
- ☐ Acceleration of injected electrons to multi-GeV energies @ kHz rep. rate

**Drive laser**

- ✓ Industrial-class
- ✓ Multi-joule
- ✓ Multi kilohertz
- ✓ Optical efficiency ~ 40%
- ✗ Picosecond pulse (too long!)




**Seed laser**

- ✓ Industrial-class
- ✓ ~ 100 mJ
- ✓ Multi kilohertz

**HOFI plasma channel**

- ✓ Low loss
- ✓ > 100 mm guiding
- ✓ kHz rep. rate

**kPAC**

kHz Plasma Accelerator Consortium

University of Oxford, Central Laser Facility, LMU Ludwig-Maximilians-Universität München, TRUMPF

**Key**

- ☑ Concept demonstrated
- ☐ To be demonstrated

S.M. Hooker, University of Oxford

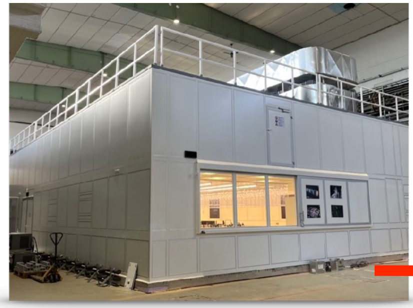
# KALDERA LaserLab @DESY completed, and laser development has started

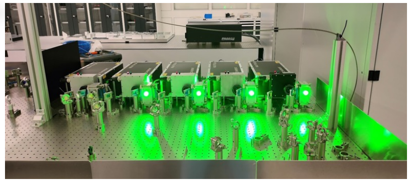
HI-ACTS | Helmholtz Innovation Platform for Accelerator-based Technologies and Solutions

## KALDERA

**Science Case:**
- Active Stabilization
- Competitive Technology
- Technology Demonstrat

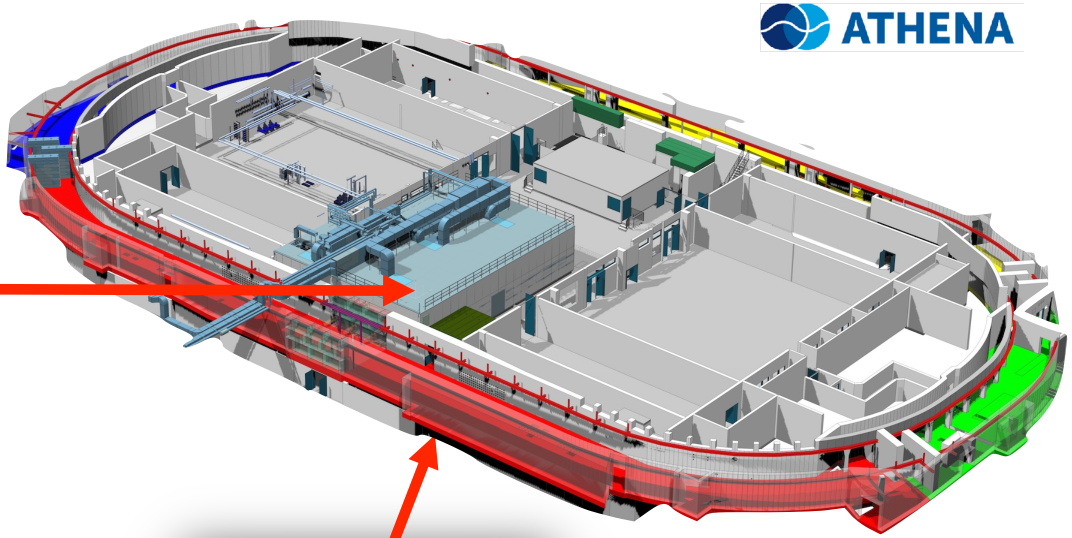
**Specifically**
- New LPA Drive Laser
- 100 TW at 1 kHz rep rat
- Goal: FEL-quality electr

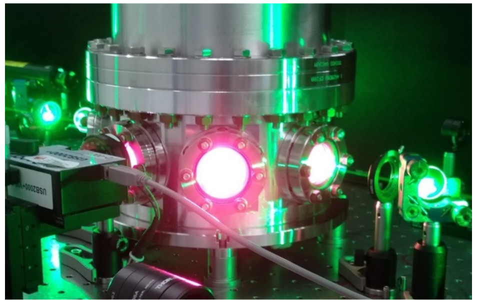




**Laser Lab**
- 400m² ISO5/6 clean room
- 0.1° temperature stability
- Lab completed end 2022

ATHENA

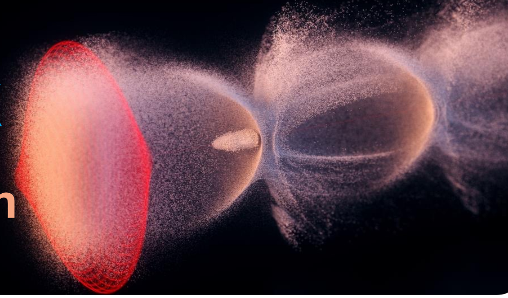




**Laser**
- Setting up seed laser, stretcher, and preamp in parallel
- Finalizing concept for main amplifier, including compressor and pump laser
- Developing feedback mechanism also as part of HI-ACTS innovation plattform

**KALDERA Tunnel**
- Generic infrastructure for experiments (many different experiments over time)
- Supports up to 1GeV @ 1kHz
- Started installation of interlock systems, new venting, IT and electricity

# Strategies of PWFA facilities align with pre-CDR work



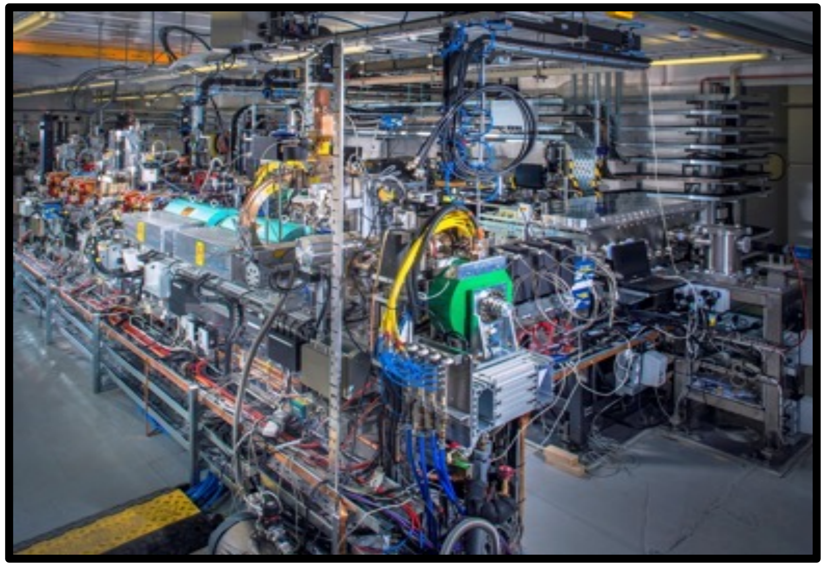
**Plan covers major plasma accelerator challenges – need extra resources for coordination**

- 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
- FLASHForward at DESY explores high energy, high power PWFAs
- Frascati (INFN) explores PWFA based light sources and applications (EuPRAXIA)

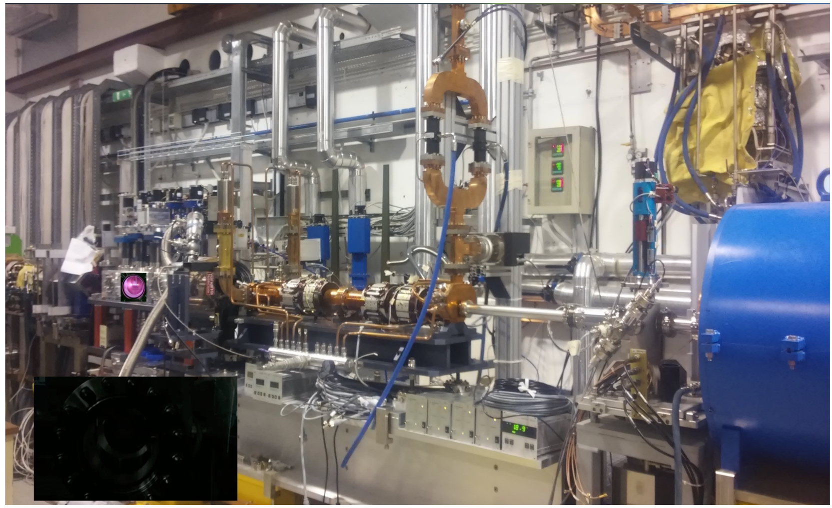
## Contributing to

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

CLARA beamline



INFN PWFA chamber



# Strategies of PWFA facilities align with pre-CDR work

## Plan covers major plasma accelerator challenges – need extra resources for coordination

FLASHFORWARD

- complete
- planned

**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)

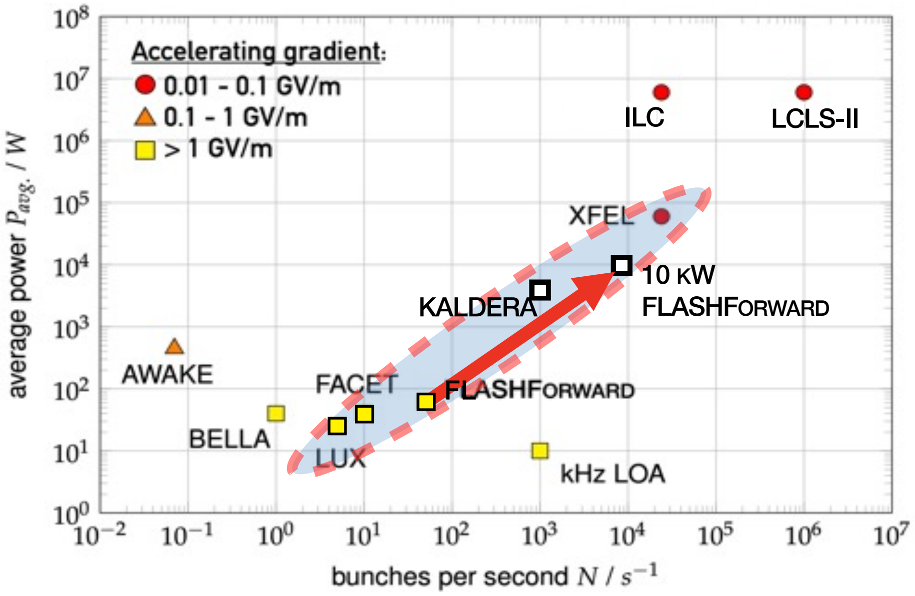
**2022** — **High gain and overall efficiency for sustainable operation**

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

**2024** — **10 kW avg. power operation**

**2026** — **10 kW stage with 40% efficiency & beam quality conservation**

**2030**
→ FLASH: increase FEL energies,
access oxygen K-edge at 2.33 nm wavelength



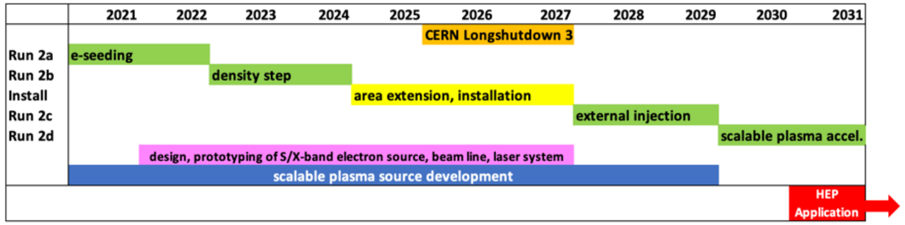

F. Peña) Wed

**WP 3.1** Electron-beam driven PWFA experiments
(Jens Osterhoff, Richard D'Arcy)
Scaling to HALHF-relevant energies and parameters

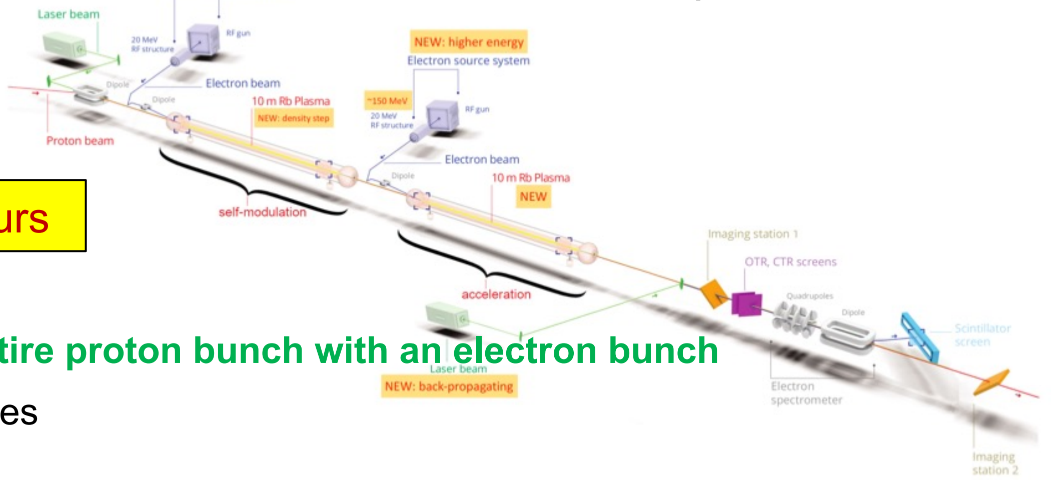
# Strategies of PWFA facilities align with pre-CDR work

## Plan covers major plasma accelerator challenges – need extra resources for coordination

- ➔ **CERN is committed to AWAKE and included in the Mid Term Plan**
- ➔ **AWAKE Has developed a clear scientific roadmap towards first particle physics applications within the next decade!**
- ➔ **AWAKE achieved all milestones so far. Many general issues are studied, which are relevant for concepts that are based on plasma wakefield acceleration *(external electron injection, scalable plasma sources, emittance control, etc.)***




Edda's talks: Tue, Thurs




### Milestones for AWAKE Run 2

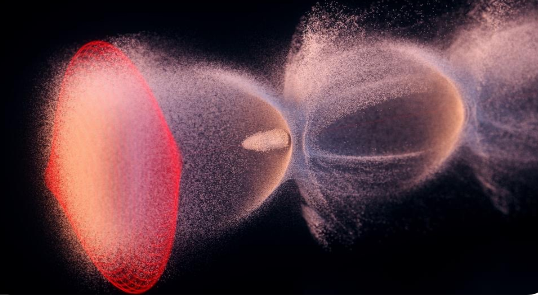
✔ **Run 2a (2021-2022): demonstrate the seeding of the self-modulation of the entire proton bunch with an electron bunch**

- Run 2b (2023-2024): maintain large wakefield amplitudes over long plasma distances
- LS3: CNGS dismantling, installation of Run 2c
- Run 2c (2028-2029): demonstrate electron acceleration and emittance preservation of externally injected electrons.
- Run 2d (2021- ): 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!**

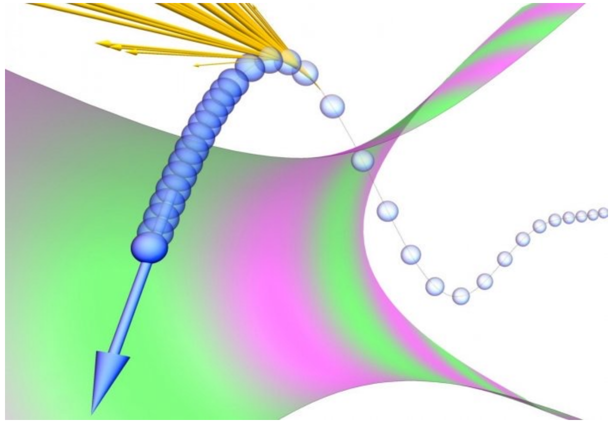
**WP 3.2** Proton-beam driven PWFA – AWAKE (Edda Gschwendtner, Patric Muggli)

# Early Particle Physics-relevant experiments are already being planned



## 4.1 Early particle physics with advanced accelerators (Matt Zepf, Brian Foster, Stuart Mangles, Marija Vranic)

- Non-linear QED using plasma mirrors: EPAC, CALA, ELI, DESY,…
- Fixed target experiments – AWAKE
- Some experiments are already planned

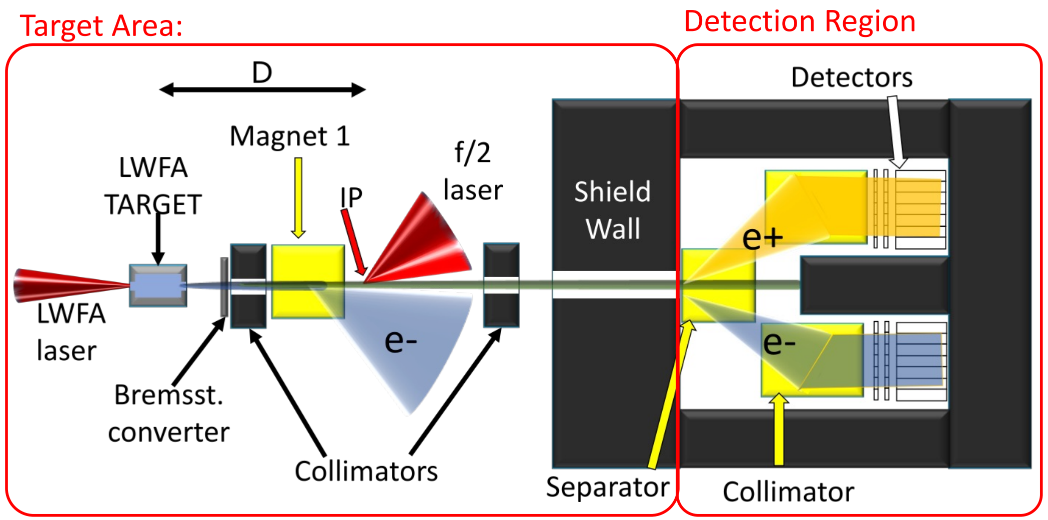


Radiation Reaction

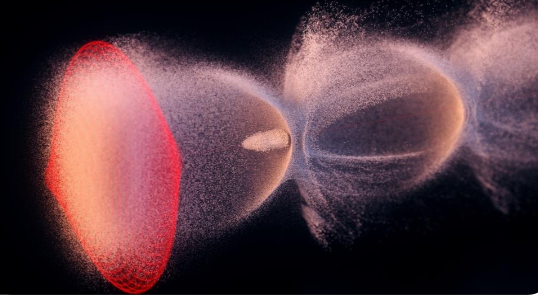
Phys. Rev. X **8**, 031004 (2018)

Phys. Rev. X 8, 011020 (2018)

Detection region construction at CALA




# Work packages aim to address some of the major R&D challenges towards future colliders



- Some of the key R&D challenges for future plasma-based colliders will be addressed by the laser-, electron- and proton-driven schemes
- Work packages aim to address a number of them
- The CDR will exploit the synergies amongst these developments
- Some key developments will be beyond the scope of this roadmap

| R&D required for future colliders | Demonstrable in Single Stage | | | Demonstrable in Multi-stage | |
|---|---|---|---|---|---|
| | Proton-driven | Electron-driven | Laser-driven | Electron-driven | Laser-driven |
| Electron beams with HEP relevant energies | 3.2 | | | 1.1, 1.2 | 1.3 |
| Acceleration in very long plasma | 3.2 | | | | |
| Plasma uniformity (long. & trans.) | 3.2 | 3.1, 2.3 | 2.3, 2.4 | | |
| Preserving injected beam quality: emittance, charge, energy spread, spin polarisation | | 3.1 | 1.5, 2.4 | 3.1 | 1.5, 2.4 |
| Stabilisation (active and passive) | | 3.1 | 2.4 | 3.1 | 2.4 |
| Ultra-low emittance beams | | | 2.4 | | 2.4 |
| Advanced beam-delivery systems | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| External injection and timing | | 3.1 | 2.4 | 3.1 | 2.4 |
| Positron beams for collider | 1.4 | 1.4 | 1.4 | | |
| High rep-rate targetry with heat management | | 2.3, 3.1 | 2.1, 2.3, 2.4 | | |
| Facility sustainability | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| Temporal plasma uniformity & stability | 3.2 | | | | |
| Driver removal | | 3.1 | 2.4 | 3.1 | 2.4 |
| High rep-rate, high wall plug efficiency drivers | | | 2.1, 2.2 | | 2.1, 2.2 |
| Inter-stage beam coupling and timing | | | | 3.1 | 2.4 |
| Driver coupling and removal (plasma mirrors) | | | | 3.1 | 2.4 |
| Total system design with end-to-end simulations | | | | 1.1, 1.2 | 1.3 |

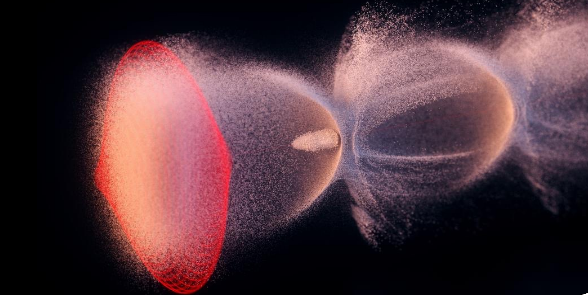
Not applicable

Not feasible

Not part of the program

Technically feasible

# Timelines for R&D on plasma-based colliders



| Single-stage accelerators (proton-driven) | Timeline (approximate/aspirational) 0-10 years | 10-20 years | 20-30 years |
|---|---|---|---|
| | **Demonstration of:** Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse) | **Fixed-target experiment (AWAKE)** Dark-photon searh, strong-field QED experiment etc. (50-200 GeV e-) | |
| | | **Demonstration of:** Use of LHC beams, TeV acceleration, beam delivery | **Energy -frontier collider** 10 TeV c.o.m electron-proton collider |

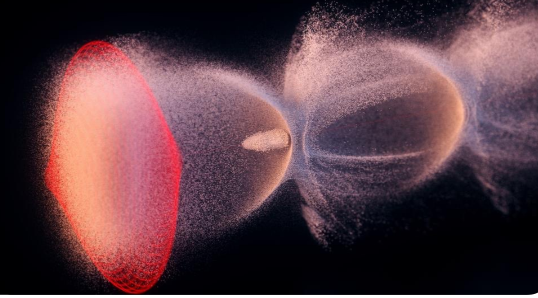
Legend: R&D (exp & theory); HEP facility

| Multi-stage accelerators (Electron-driven or laser-driven) | Timeline (approximate/aspirational) 0-5 years | 5 - 10 years | 10-15 years | 15-25 years | 25+ years |
|---|---|---|---|---|---|
| | **Pre-CDR (HALHF)** Simulation study to determine self-consistent parameters (demonstration goals) | **Demonstration of:** scalabe staging, driver distribution, stabilisation (active and passive) | **Multistage tech demonstrator** Strong-field QED experiment (25-100 GeV e-) | Facility upgrade | |
| | | **Demonstration of:** High wall-plug efficiency(e- -drivers), preserved beam quality & spin polarization, high rep.rate, plasma temporal uniformity & cell cooling | | **Higgs Factory (HALHF)** Asymmetric, plasma-RF hybrid collider (250-380 GeV c.o.m) | Facility upgrade |
| | | **Demonstration of:** Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser-drivers), ultra-low emittances, energy recovery schemes, compact beam delivery systems | | | |

Legend: *Feasibility study*; *R&D (exp & theory)*; *HEP facility (earlist start of construction)*

This is the eventual scenario but not the full picture

# Timelines for R&D on plasma-based colliders: how does the other HALF fit in?



| | Timeline (approximate/aspirational) | | |
|---|---|---|---|
| | 0-10 years | 10-20 years | 20-30 years |
| Single-stage accelerators (proton-driven) | Demonstration of: Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse) | Fixed-target experiment (AWAKE) Dark-photon searh, strong-field QED experiment etc. (50-200 GeV e-) | |
| | | Demonstration of: Use of LHC beams, TeV acceleration, beam delivery | Energy -frontier collider 10 TeV c.o.m electron-proton collider |

Legend: R&D (exp & theory); HEP facility

| | 0-10 years |
|---|---|
| Single/multi-stage accelerators for light sources (electron & laser-driven) | Demonstration of: ultra-low emittances, high rep-rate/high efficiency e-beam and laser drivers, Long-term operation, potential staging, positrons (EuPRAXIA) |

R&D on EuPRAXIA will de-risk HALHF and other plasma-based collider concepts considerably

| | Timeline (approximate/aspirational) | | | | |
|---|---|---|---|---|---|
| | 0-5 years | 5 - 10 years | 10-15 years | 15-25 years | 25+ years |
| Multi-stage accelerators (Electron-driven or laser-driven) | Pre-CDR (HALHF) Simulation study to determine self-consistent parameters (demonstration goals) | Demonstration of: scalabe staging, driver distribution, stabilisation (active and passive) | Multistage tech demonstrator Strong-field QED experiment (25-100 GeV e-) | Facility upgrade | |
| | | Demonstration of: High wall-plug efficiency(e- -drivers), preserved beam quality & spin polarization, high rep.rate, plasma temporal uniformity & cell cooling | | Higgs Factory (HALHF) Asymmetric, plasma-RF hybrid collider (250-380 GeV c.o.m) | Facility upgrade |
| | | Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser-drivers), ultra-low emittances, energy recovery schemes, compact beam delivery systems | | | |

Legend: *Feasibility study*; *R&D (exp & theory)*; *HEP facility (earlist start of construction)*

# EuPRAXIA could be a major stepping-stone towards this

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

EuPRAXIA will drive plasma accelerators producing multi-GeV electron beams at 100 Hz

This is now on ESFRI roadmap – has/will attract funding

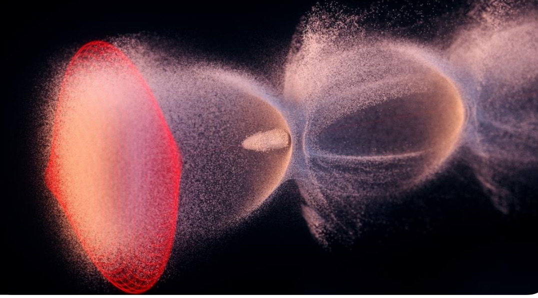
Will address some of the key issues regarding the suitability of plasma accelerators for future colliders

- Low emittance beams
- Reliable facility-mode operation – 24/7
- Staging/positron beams etc.

Energy upgrades limited only by funding

EuPRAXIA Preparatory Phase

# Funding required for activities



| WP No. | Workpackage | Postdocs | Other Resources required |
|---|---|---|---|
| 1.1 | Overall collider concepts (Higgs Factory) | 1 | Buying time of coordinators<br>Access to computing resources |
| 1.2 | Beam driven electron linac – integrated simulations | 2 | Buying time of coordinators<br>Access to computing resources |
| 1.3 | Laser driven electron linac | 3 | Funding for joint meetings<br>Access to computing resources |
| 1.4 | Positron acceleration | 1 | Experimental consumables<br>Access to computing resources |
| 1.5 | Spin preservation | 1 | Experimental consumables<br>Access to computing resources |
| 1.6 | Final focus system | 1 | TBD |
| 1.7 | Sustainability analysis | 1 | TBD |
| 2.1 | High-repetition rate laser-driven plasma module (coordination) | 1 | Funding for joint meetings |
| 2.2 | High rep-rate laser drivers | 4 | Resource for prototypes |
| 2.3 | High rep-rate targetry | 2 | Resources for testing concepts, Facility Access |
| 2.4 | LPA-experimental facility design (EPAC, CALA, ELI) | 2 | Resources for testing concepts, Facility Access |
| 3.1 | Electron-beam driven PWFA – experiment (FLASHForward/CLARA) | 2 | 2 postdocs to realize/approximate HALHF-relevant parameters in today's operational test experiments |
| 3.2 | Proton-driven PWFA (at AWAKE) | 2 | Continued funding |
| 4.1 | Early High energy physics experiments | 2 | Access to computing resources |

## Opportunity:

- We have a compelling list of goals and activities that we aim at achieving in the next 2 years but time is ticking…
- New activities are leveraged by at times very significant in-house activities by major labs

## Key challenge:

- We need to secure funding on the order of 3M€/a to do everything
- Will sufficient, suitably qualified students/post-docs be available?

STFC Visions

Exploring funding options via STFC, Helmholtz…

European Commission
Horizon Europe 2021-2027

Workshop on developing HALHF concept: 23rd October - DESY