Accélérateurs plasma dans le cadre de la stratégie européenne en physique des particules

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GdR APPEL
Accélérateurs Plasma PompÉs par Laser

Stratégie européenne en physique des particules

- Définir la R&D nécessaire à la construction des accélérateurs de particules et collisioneurs (après 2045)
- Révision tous les 5 ans
- Pilotée par le CERN
- Exercice consultatif, impliquant la communauté scientifique, puis synthèse et décision de priorités par le conseil du CERN
- Doit définir des livrables concrets ou des démonstrateurs pour la prochaine décennie
- Dernier exercice en 2019-2020

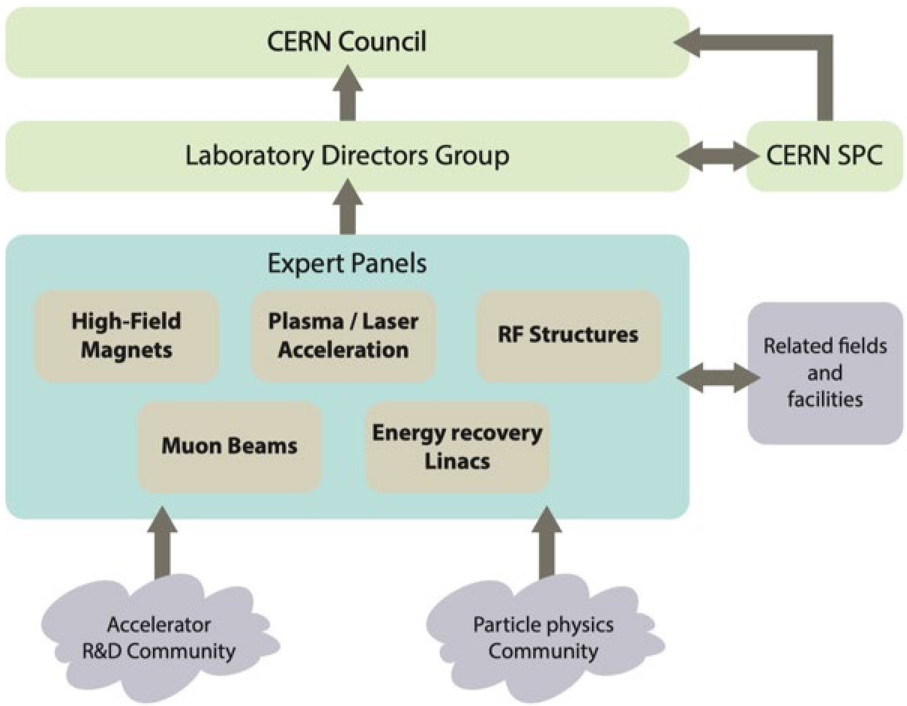
Update of the European Strategy for Particle Physics, June 2020

3. High-priority future initiatives

b) Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*

https://europeanstrategyupdate.web.cern.ch/

Organisation de la mise en place de l'ESPP



5 sujets de R&D en 5 groupes de travail

- 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.

Depuis 2020, discussions pour organiser la thématique des accélérateurs plasma

- Un groupe d'experts « plasma » a été constitué pour proposer une feuille de route et a rédigé un rapport préliminaire, coordonné par R. Assmann et E. Gschwendtner
- Quelles sont les actions prioritaires pour développer des accélérateurs plasma pour HEP?
- Wim Leemans (DESY) et Rajeev Patthatil (STFC RAL) ont été désignés pour organiser les travaux permettant de répondre à cette question

Méthode et calendrier

- Initier un effort collaboratif
- Identifier les objectifs principaux

- Définir plusieurs scénarios en fonction des moyens qui seront disponibles

Pas de financement dédié

Pas de choix de technology

R&D Coordination Panel: Plasma Accelerators

Objectif rédiger un « pre-CDR » pour Décembre 2025

Deliverable	Due by
Report: Electron High Energy Case Study (from 175GeV to 190GeV)	Jun-24

Exemple de paramètres à réaliser pour un module accélérateur plasma

Table 4.2: Specification for an advanced high energy accelerator module, compatible with CLIC [87]. Additional CLIC design values are listed for reference in the second part of the table.

Parameter	**Unit**	**Specification**
Beam energy (entry into module)	GeV	**175**
Beam energy (exit from module)	GeV	**190**
Number of accelerating structures in module	-	$\geq$2
Efficiency wall-plug to beam (includes drivers)	%	$\geq$10
Bunch charge	pC	833
Relative energy spread (entry/exit)	%	$\leq$0.35
Bunch length (entry/exit)	µm	$\leq$70
Convoluted normalised emittance ($\gamma\sqrt{\epsilon_h \epsilon_v}$)	nm	$\leq$135
Emittance growth budget	nm	$\leq$**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	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.5

R&D Coordination Panel: Plasma Accelerators

Objectif rédiger un « pre-CDR » pour Décembre 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

Définition d'un programme de R&D sur plusieurs décennies

Besoin d'intensifier la R&D pour les collisioneurs

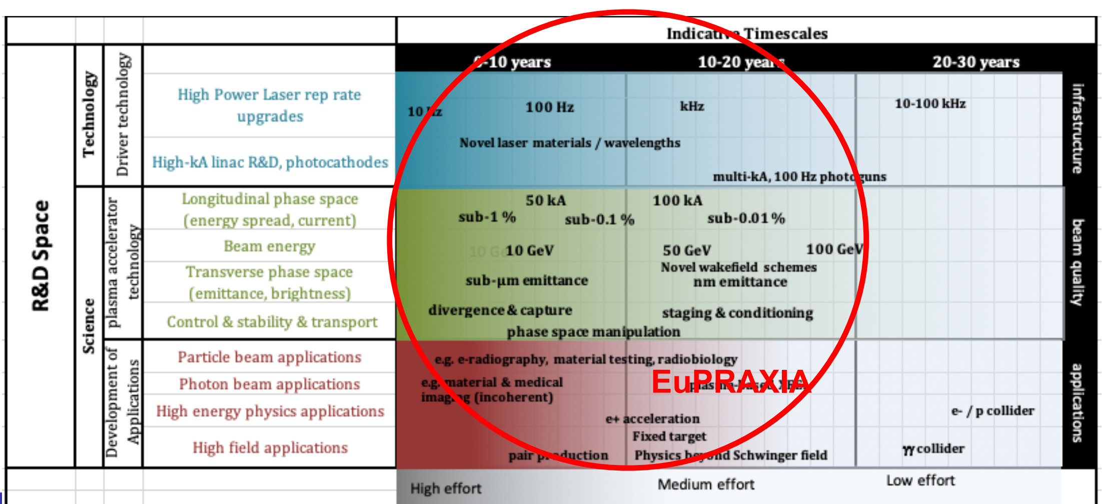
AWAKE

0-10 years	10-20 years	20-30 years
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

- Les recherches en cours LWFA et PWFA se concentrent sur la **qualité des faisceaux,** produits pour la génération de sources de lumière et leurs applications

- AWAKE a un programme de développement en lien avec la physique des hautes énergies.

LPA and e-PWFA Programs



Une R&D dédiée est indispensable pour une proposition de collisioneur plasma

Il faut un programme de travail le financement associé

Premières discussions pendant le workshop ALEGRO – March 2023

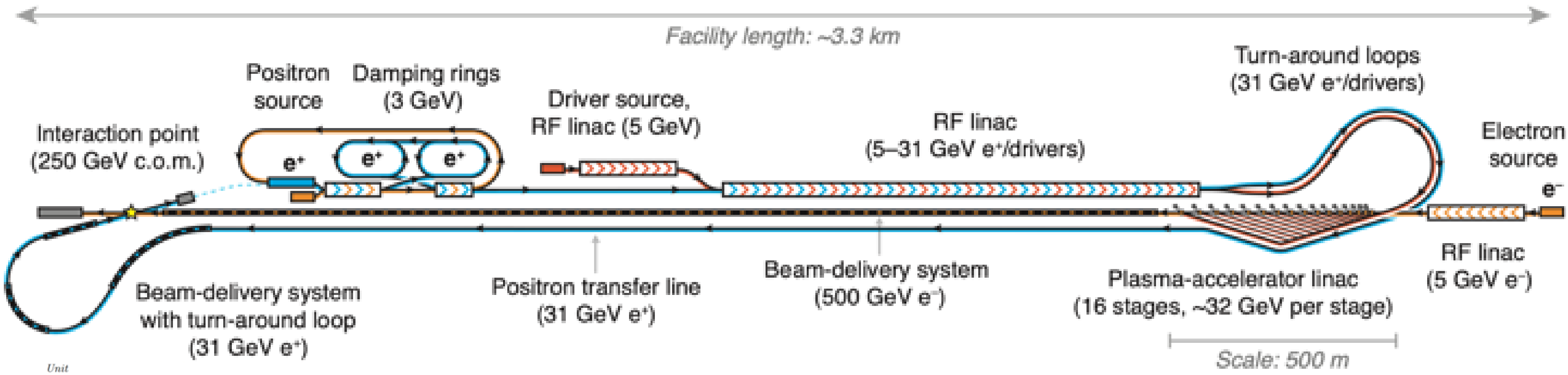
https://indico.cern.ch/event/1193719/

Première réunion de la communauté pour définir un programme de travail

- **Analyse d'un modèle préliminaire de collisioneur**
- **Analyse des éléments constitutifs :**
  - Injecteurs (electrons et positrons, polarisation de spin,…)
  - Etages accélérateurs
  - Transport de faisceaux et focalisation finale
  - Sources de puissance (laser et faisceaux)
- **Etudes expérimentales des concepts accélérateurs dans les plasmas pompés par faisceaux laser/electron/proton**
- **Concepts pour relever des défis de R&D : haute cadence** (plasma, laser, couplage entre étages)

Nouvelle proposition: HALHF – un schéma d'accélérateur plasma pour une usine à Higgs

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



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	$cm^{-2}\,s^{-1}$	0.81×10^{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)	μm	9	75
Bunch length at IP (rms)	μm	75	
Energy spread (rms)	%	0.15	
Horizontal emittance (norm.)	μm	160	10
Vertical emittance (norm.)	μm	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

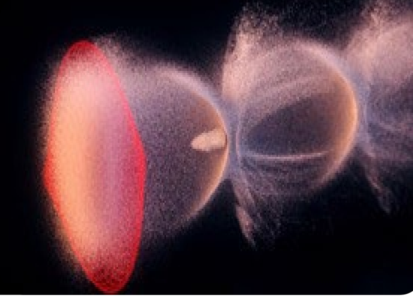
RF linac parameters		
Average gradient	MV/m	25
Wall-plug-to-beam efficiency	%	50
RF power usage	MW	47.5
Peak RF power per length	MW/m	21.4
Cooling req. per length	kW/m	20
PWFA linac parameters		
Number of stages		16
Plasma density	cm^{-3}	1.5×10^{16}
In-plasma acceleration gradient	GV/m	6.4
Average gradient (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)	μm	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).

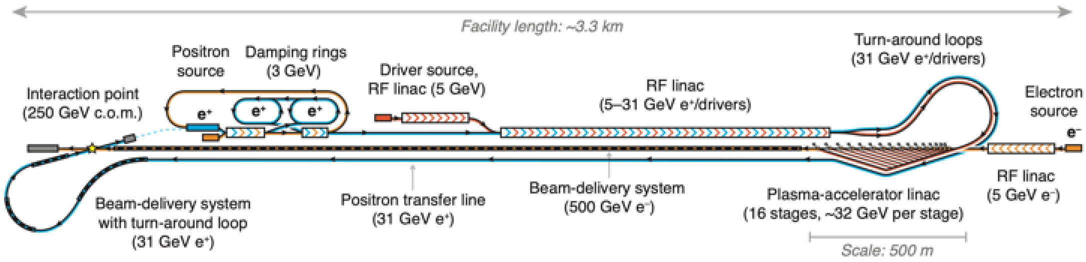
- Schéma préliminaire de collisioneur présenté par B. Foster, R D'Arcy and C. Lindstrøm
- Schéma de collisioneur e+e- assymétrique en énergie avec un bras 500GeV électrons et 31GeV positrons.
- Bras électrons PWFA et bras positrons basé sur un linac conventionnel.
- S'appuie sur les études faites pour CLIC

- Des études détaillées sont nécessaires pour définir les paramètres, tolérances, faisabilité etc. avec des simulations et des prototypes expérimentaux.

Opportunity to build a pre-CDR case around HALHF



- Higgs Factory at potentially **~1/4th of the cost**
- First generation: plasma accelerator arm of HALHF can be based on PWFA from a **technological readiness level (TRL) perspective.**
- **LPA plasma accelerator stages can be incorporated later,** as the technology matures, 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.

Préparation du pré-CDR organisée en groupes de travail

- **Etudes de faisabilité** (HALF, Laser driven Linac, positron acceleration, spin and polarization preservation)
- **Impact environnemental**
- **Développements technologiques** (plasmas haute cadence, démonstrations exp., lasers haute cadence)

WP No.	Workpackage
1.1	Overall collider concepts (Higgs Factory)
1.2	Beam driven electron linac – integrated simulations
1.3	Laser driven electron linac
1.4	Positron acceleration
1.5	Spin preservation
1.6	Final focus system
1.7	Sustainability analysis
2.1	High-repetition rate laser-driven plasma module (coordination)
2.2	High rep-rate laser drivers
2.3	High rep-rate targetry
2.4	LPA-experimental facility design (EPAC, CALA, ELI)
3.1	Electron-beam driven PWFA – experiment (FLASHForward/CLARA)
3.2	Proton-driven PWFA (at AWAKE)
4.1	Early High energy physics experiments

EuPRAXIA will be a major stepping-stone towards collider R&D

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

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

Conclusions

- Le rapport de stratégie 2020 a rendu les thématiques plasma visibles, la communauté doit maintenant s'organiser pour définir des concepts de machine
- La possibilité d'obtenir des ressources à la hauteur des défis n'est pas claire
- Des programmes en cours peuvent répondre à certaines questions (AWAKE, EuPRAXIA, FLASH FORWARD)
- Acknowledgement R. Patthatil EAAC2023 and further ref.

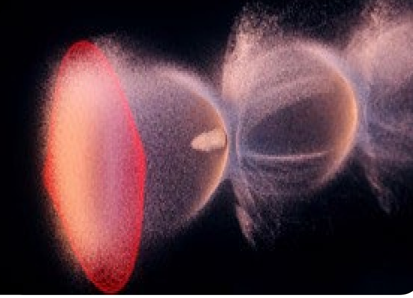
  https://agenda.infn.it/event/35577/timetable/#20230922.detailed

Plus d'information

- Présentation de Rajeev Patthatil à l'EAAC2023

https://agenda.infn.it/event/35577/timetable/#20230922.detailed

Plasma-based collider: Feasibility studies



Theory/simulation – based works

WP 1.3: Laser driven electron linacs
(Jorge Viera, Brigitte Cros, Maxence Thévenet, 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

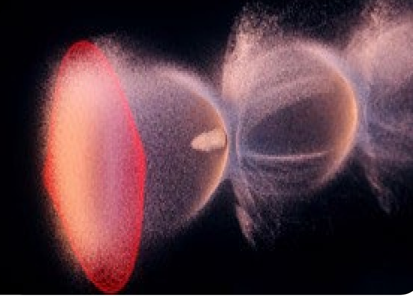
Start from the plasma stage
Full-physics 3D EM PIC simulation: Ion motion, collisions, radiation reaction, realistic parameters
Scale up in number of stages

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

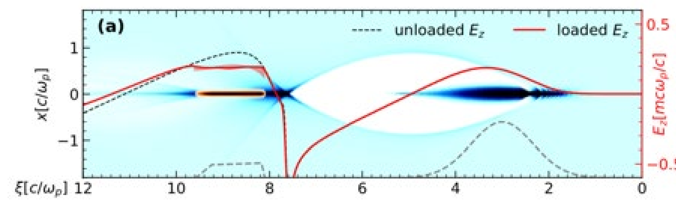
Plasma-based collider: Feasibility studies



Requires theory/simulations along with experimental verifications

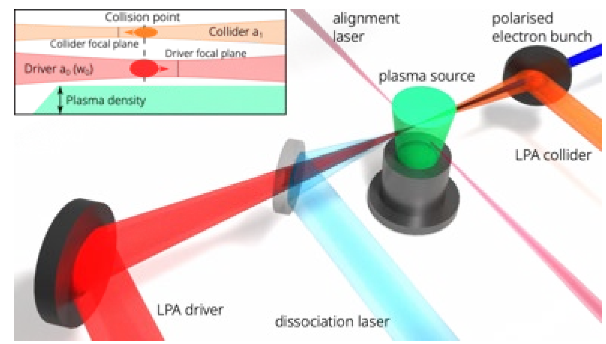
WP 1.4: Positron acceleration (Gianluca Sarri, Severin Dietrichs)

- 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:



WP 1.5: Spin and polarization preservation (Kristjan Põder)

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

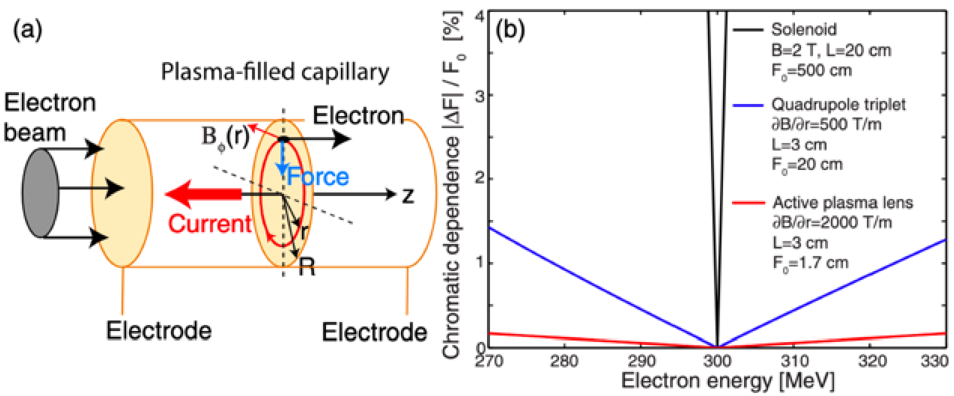


Plasma-based collider: Feasibility studies

Requires theory/simulations along with experimental verifications

1.6: Assess final-focus system concepts;

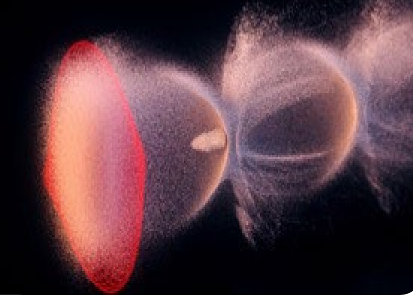
- Explore other technologies (eg. adiabatic plasma lens.) that could underpin future upgrades to HALHF



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

This might result in making HALHF upgrades more compact.

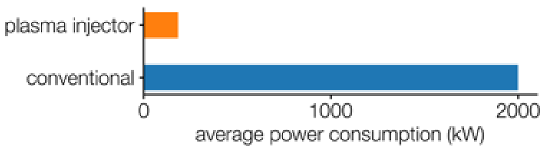
→ Need to find someone to lead this



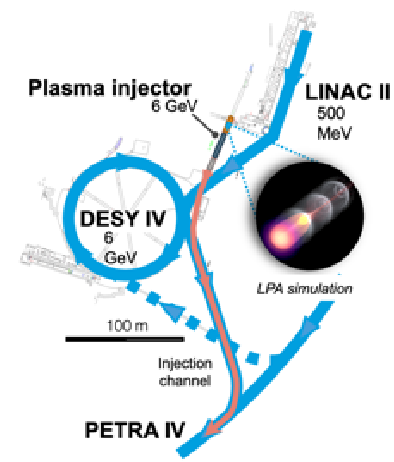
Sustainability and environmental impact study

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

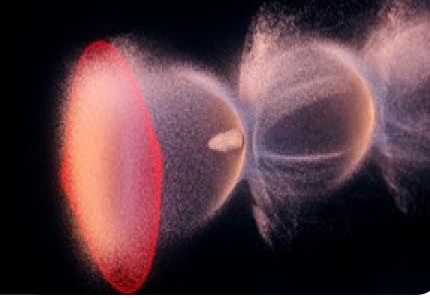
1. **Development of guidelines** that allow comparison of the environmental impact of the proposed HALHF and ILC Higgs-factory design.
   - Community input will assure incorporation of different stakeholder views, help prioritize guiding criteria and continuation of existing efforts.
   - Community outreach 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

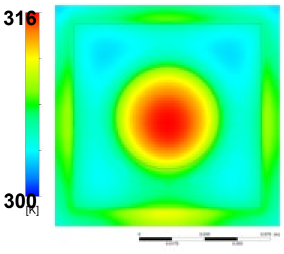
WP 2.1: High-repetition rate laser-driven plasma module (coordination) (Leo Gizzi, Andi Maier)

- 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)

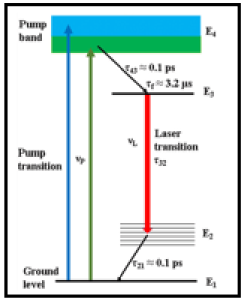
- Important for laser plasma accelerator developments and fusion drivers
- A lot of development towards industrial applications – need to channel this to our advantage

Potential synergy with laser-fusion drivers

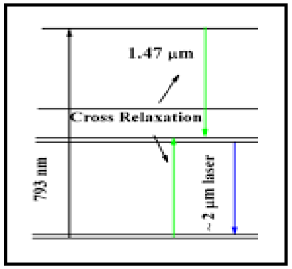


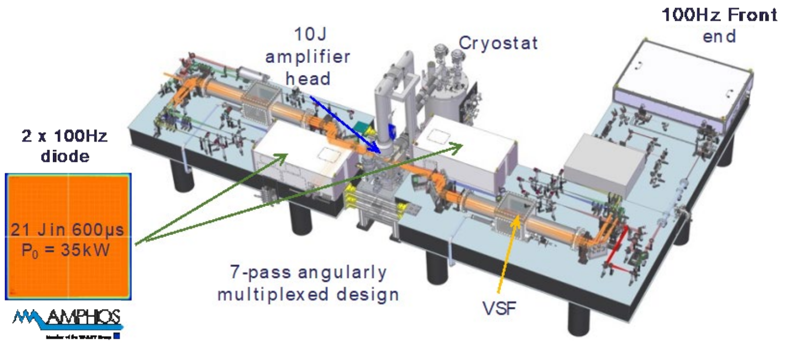
Gas-cooled clad Ti:Sa slab pumped at 1.4 kW @ 10 Hz

Ti:Sa

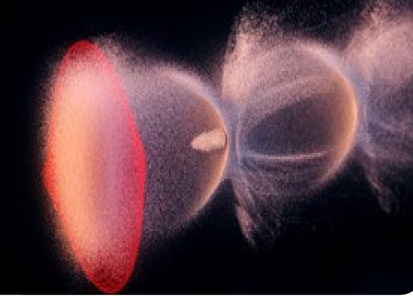


Tm:X (2µm)





Technology developments need to continue

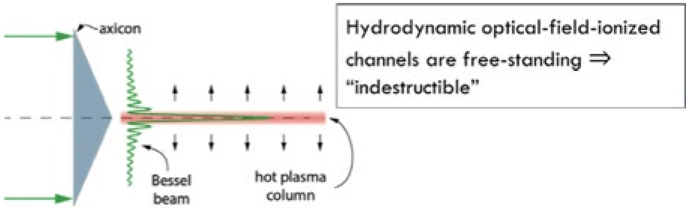


Can address major plasma accelerator challenges – need extra resources for aligning activities

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

Developing gas cells and HOFI channels – including PWFA-relevant targets

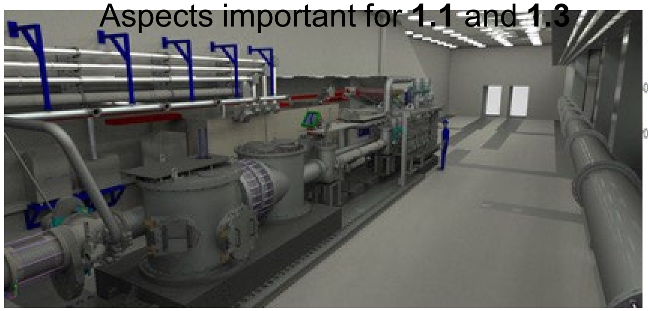
Solutions for heat load management in plasma sources and multi-time and length scale modeling aimed at pre- and post-driver interactions

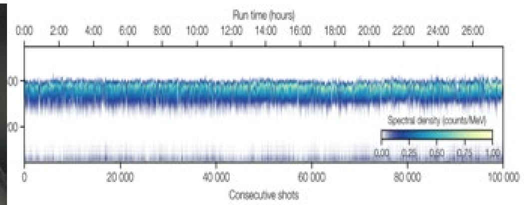


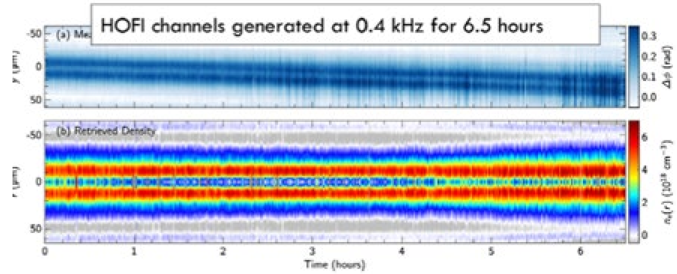
WP 2.4: Experimental LPA Facility Developments: (Dan Symes, Andreas Döpp)

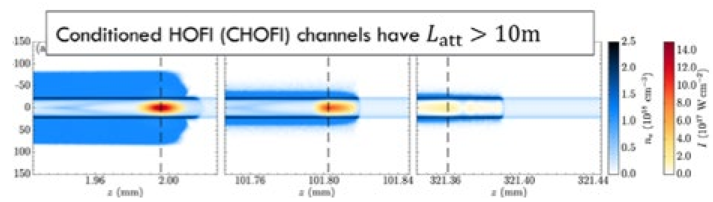
Experimental verifications and prototyping: beam manipulation and propagation, stability optimization and feedback control, plasma mirrors and driver removal, staging demonstrations

Aspects important for **1.1** and **1.3**









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