Laser Plasma Acceleration

State-of-the-Art and Perspectives

Brigitte Cros

Laboratoire de Physique des Gaz et des Plasmas, Orsay

GDR APPEL: Accélérateurs Plasma Pompés par Laser

GdR APPEL Accélérateurs Plasma PompÉs par Laser

cnrs

université PARIS-SACLAY

LPGP

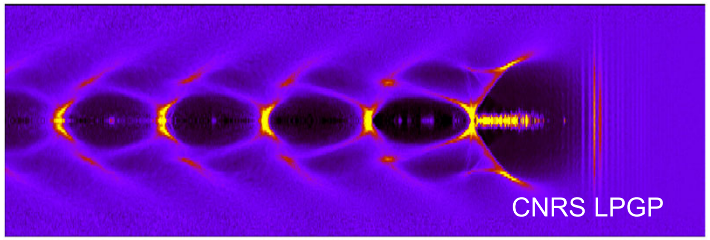
LWFA is a promising concept for the development of compact accelerators

- Laser plasma acceleration: Laser WakeField Acceleration (LWFA) provides accelerating fields in the range 1-100 GV/m:
- An e-e+ collider in the TeV range would be 100 km long using an accelerating field < 50 MV/m with conventional technology

cavity scaling:

~ 0.1 m

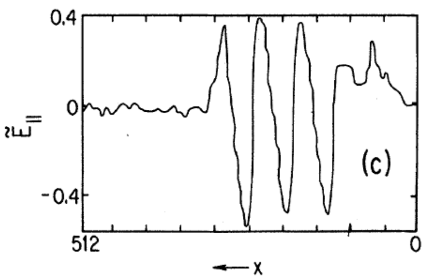
~ 0.1 mm



- **The properties of LWFA have attracted the interest of a large community since the achievements of GeV electrons over a length of 3 cm in 2006**

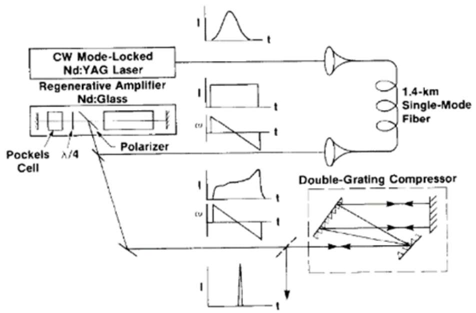
LWFA associates new concepts to innovative technology

Tajima et Dawson, Phys. Rev. Lett. 1979



- A plasma wave can be associated to very high accelerating gradients
- Concept of laser wakefield to excite a relativistic plasma wave

Strickland et Mourou, Opt. Comm. 1985



- Concept of laser system using laser chirped pulse amplification
- Short and intense laser pulse facilities have become available at the beginning of the 1990s

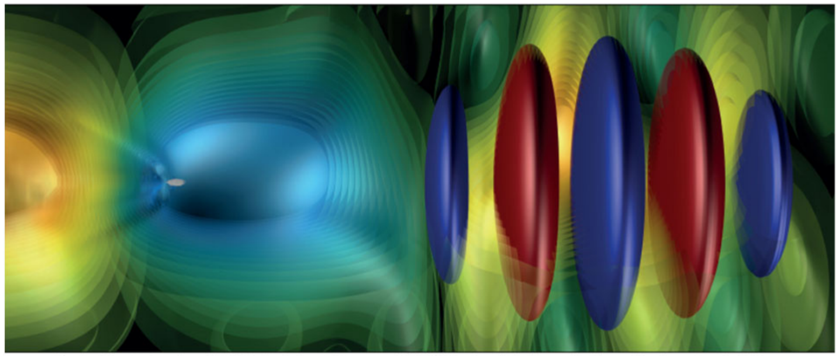
Laser wakefield studies are now in full growth

Outline

- **Basic physics of LWFA**
- **Main achievements**
- **Perspective**

Advanced accelerators

Charting a course for advanced accelerators



Simulated excitation of a wakefield behind a laser driver using the WARP code, with the laser pulse depicted in alternating dark-blue and dark-red spheroids. Yellow/white areas have more plasma electrons, blue/green more plasma ions. (Image credit: J-L Vay/LBNL.)

Applying next-generation plasma acceleration techniques to high-energy physics requires a global effort by the accelerator community.

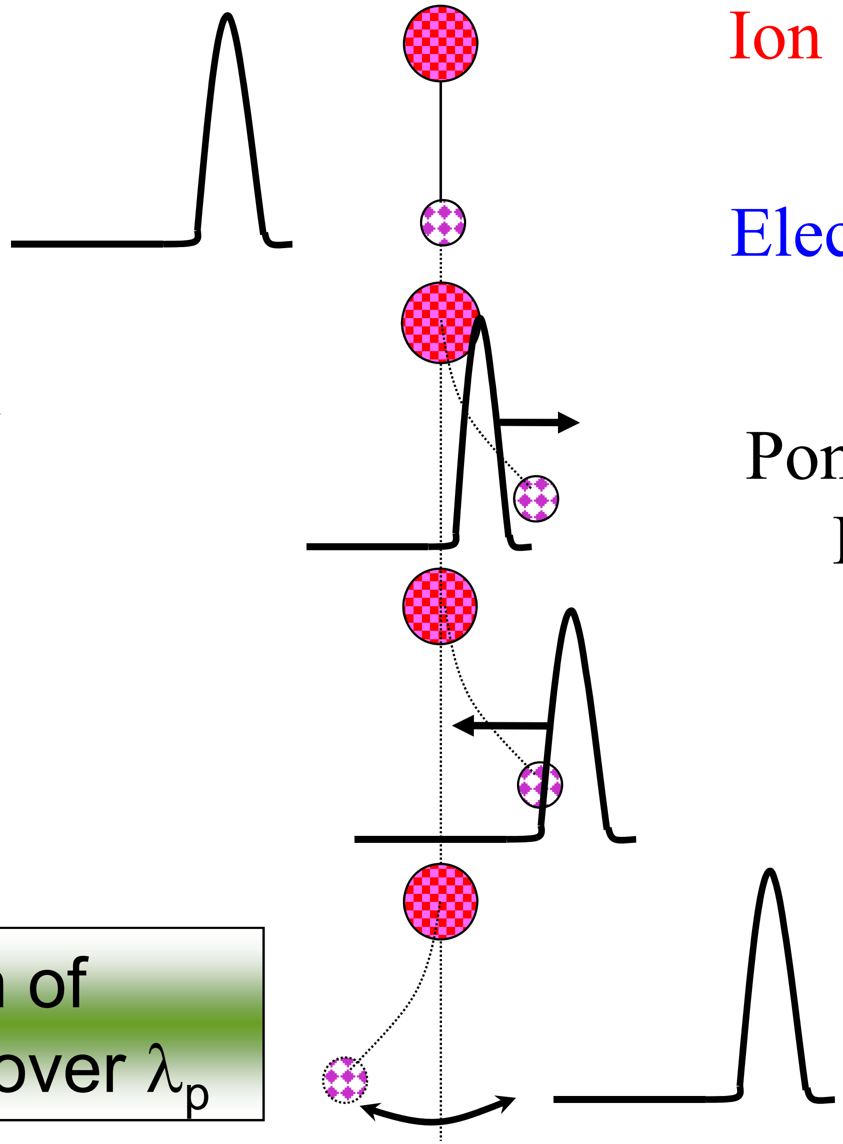
Progress in experimental particle physics is driven by advances in accelerators. The conversion of storage rings into colliders in the 1970s is one example, another is the use of superconducting magnets and RF structures that allow higher energies to be reached. of operating with an accelerating gradient larger than 1 GV/m, advanced and novel accelerators (ANAs) could reach energies in the 1–10 TeV range in much more compact and efficient ways. The technological challenge is huge and the timescales are long, but the eventual goal is to have a linear electron–positron or an electron–proton collider at the energy frontier. Such a machine would have a smaller footprint than conventional collider designs and promises energies that otherwise are technologically extremely difficult and expensive to reach.

The first Advanced and Novel Accelerators for High Energy Physics Roadmap (ANAR) workshop took place at CERN in

How to create a plasma wave ?

Electrons move under the action of the ponderomotive force

Driving laser pulse
L=cτ



Ion

Electron

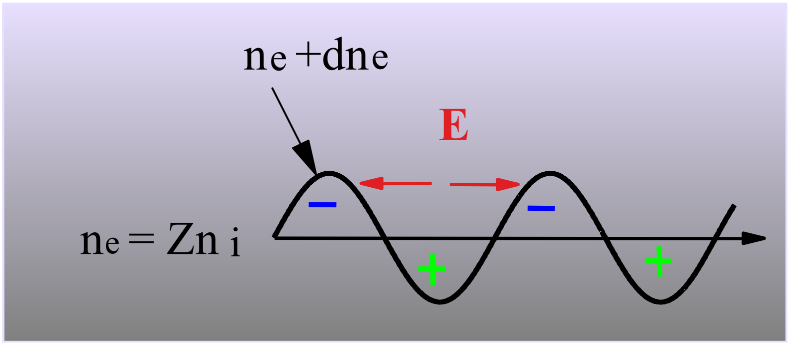
Ponderomotive force
F ∝ -∇ Energy

Oscillation of electrons over λ_p

Large longitudinal electric field associated to a plasma wave

Accelerating fields > 1 GV/m

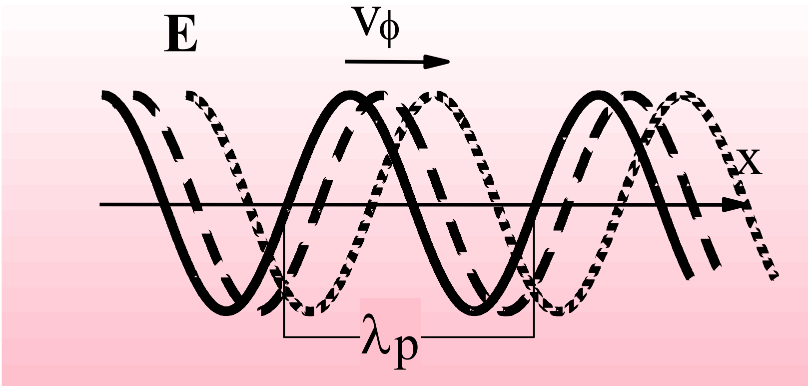
$$E_z\,[\mathrm{GV/m}] \sim 96\ (n_e\,[10^{18}\,\mathrm{cm}^{-3}])^{1/2}\, dn_e/n_e$$



- Space charge field and plasma wave

  $\lambda_p[\mu m] \sim 33\ (n_e[10^{18} cm^{-3}])^{1/2}$

- **$\lambda_p \sim 33 \mu m \rightarrow$ pulse duration~55 fs**

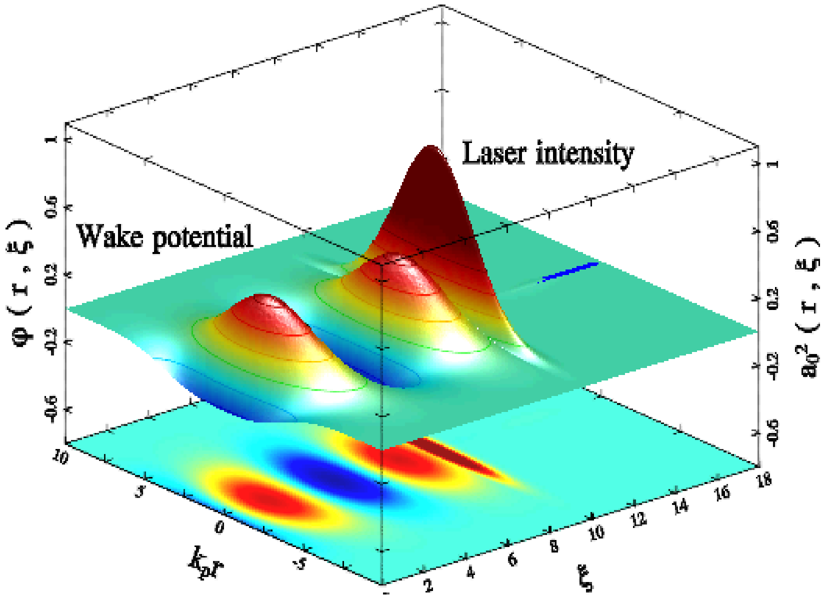


- Relativistic wave:

  phase velocity of the order of the laser group velocity

$$v_g = \frac{\partial \omega}{\partial k} = c\sqrt{1 - \frac{\omega_P^2}{\omega^2}},$$

Laser wakefield in the quasi-linear regime



- Laser strength parameter

  $a \sim eA/mc^2$

normalized laser vector potential

- Peak value

  $a_0 \sim 8.5 \times 10^{-10}\, \lambda_0[\mu m]\, I_0^{1/2}[Wcm^{-2}]$

- Quasilinear regime or weakly relativistic regime

  $a_0 \sim 1$

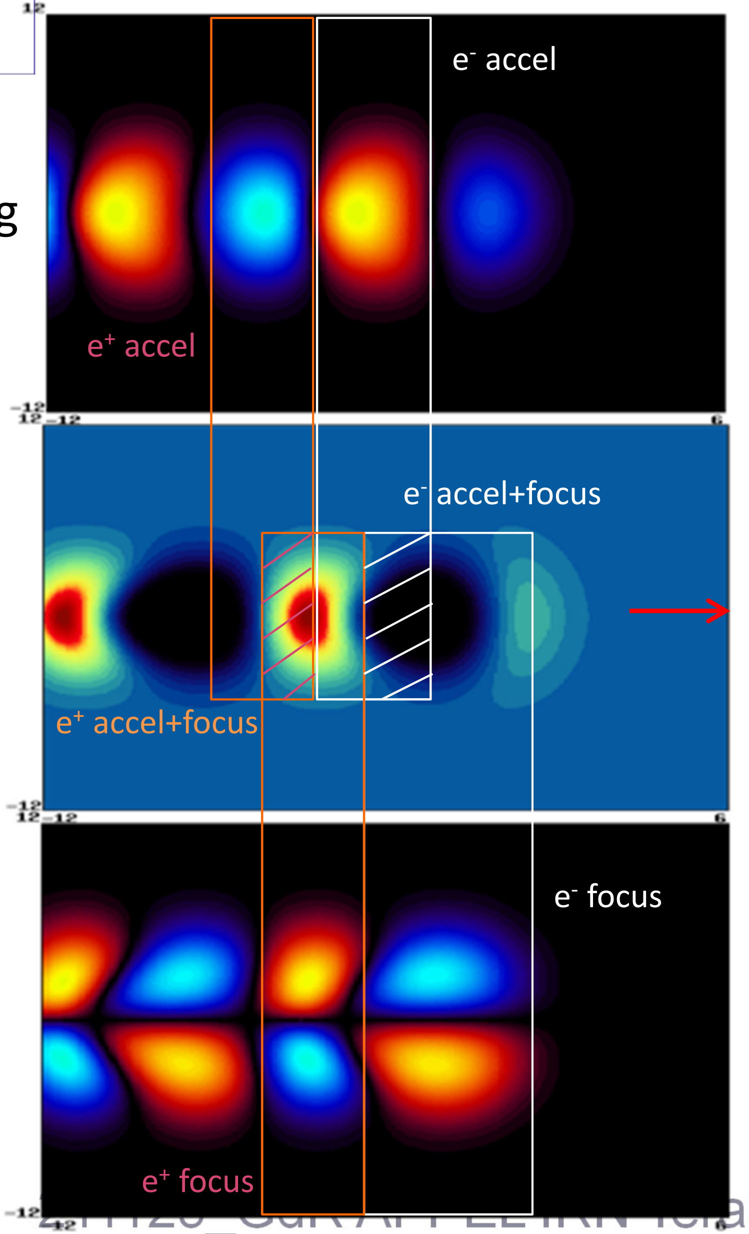
Courtesy N.E. Andreev

Linear e- or e+ focusing and acceleration, Independent control of acceleration and focusing

Accelerating field

Plasma density

Focusing field



Courtesy C. Schroeder

Quasi-linear regime, $a_0 \sim 1$

- Accelerating field: 1-10 GV/m

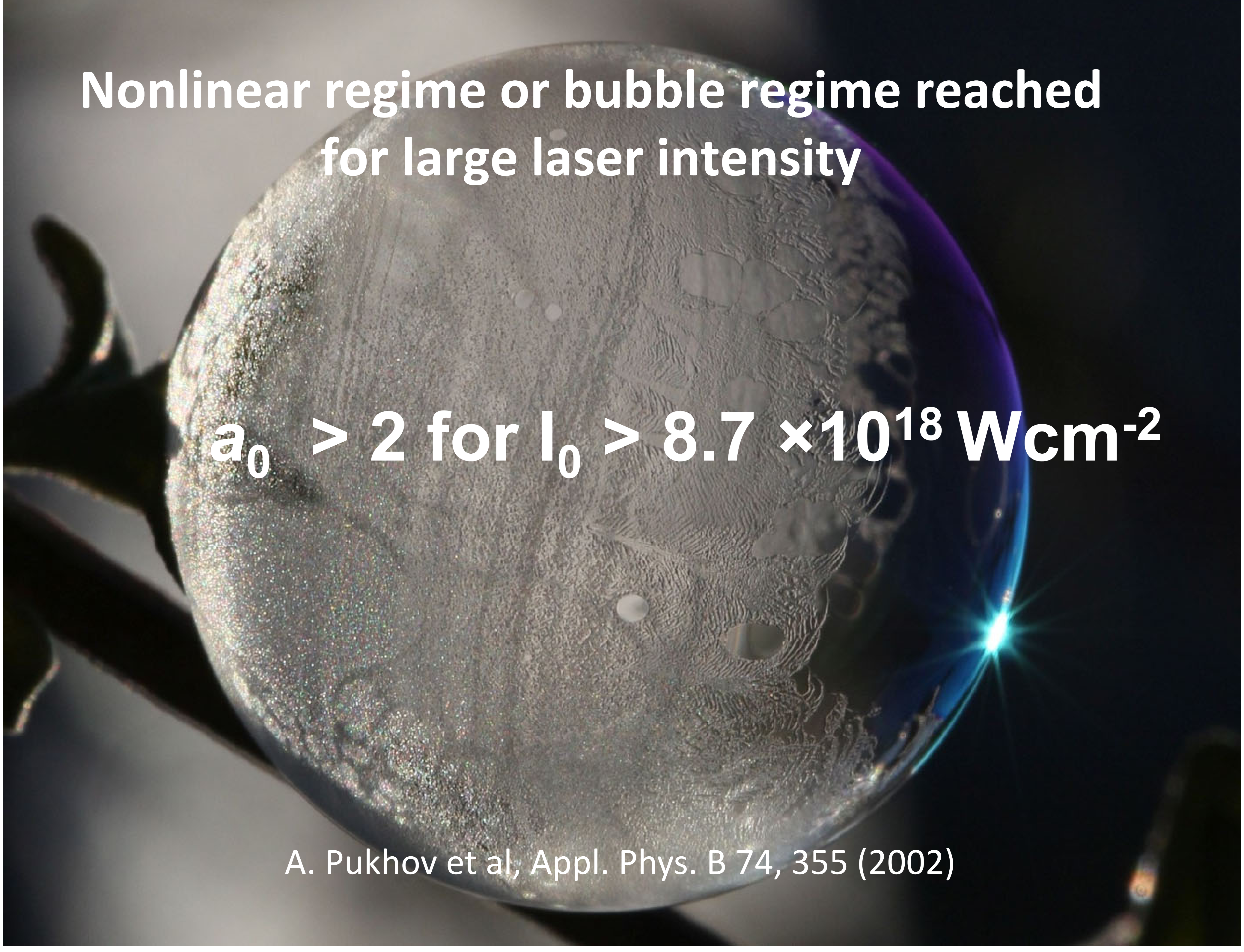
Transverse fields : focusing or defocusing, driver transverse profile can be shaped :

Cormier-Michel et al., PR ST-AB (2011)

$$F_\perp \propto \nabla_\perp a^2$$

- Electrons or other relativistic particles produced by an external source can be accelerated

E_z [GV/m]=1.35 10^{-18} I_{max}[Wcm^{-2}](λ[μm]$)^2/\tau$[ps]

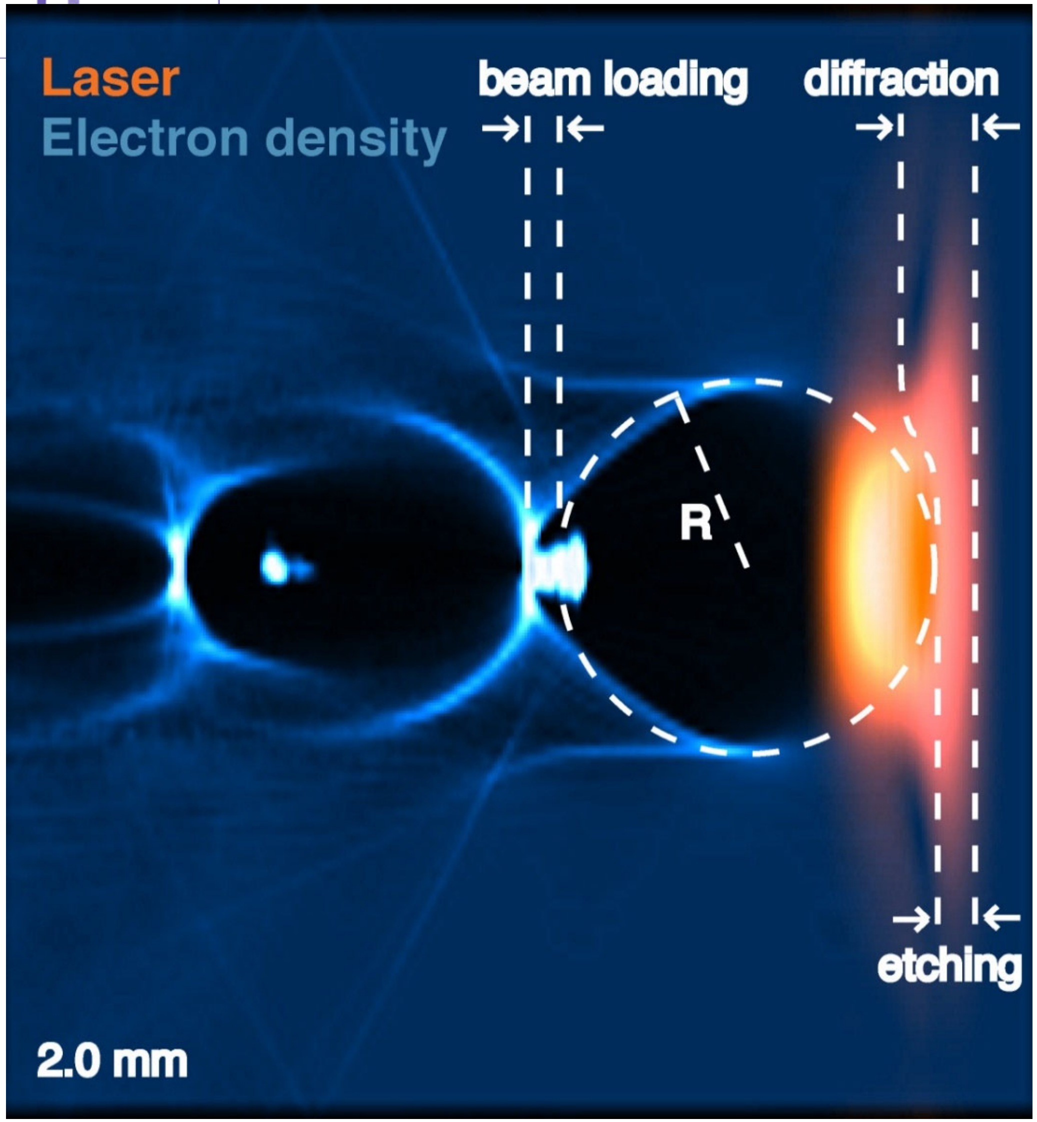


Nonlinear regime or bubble regime reached for large laser intensity

$a_0 > 2$ for $I_0 > 8.7 \times 10^{18}$ $\mathrm{Wcm^{-2}}$

A. Pukhov et al, Appl. Phys. B 74, 355 (2002)

Non linear wakefield with self-injection of electrons



W. Lu PRSTAB, 10, 061301 (2007)

- Compression and self-focusing of the pulse
- Expulsion of electrons: creation of a bubble (ions)
- Electrons self-injected at the back of the bubble by accelerating and focusing fields
- Injected electrons modify the back of the bubble (beam loading)
- Generation of betatron radiation

Maximum energy gain in a laser plasma accelerator

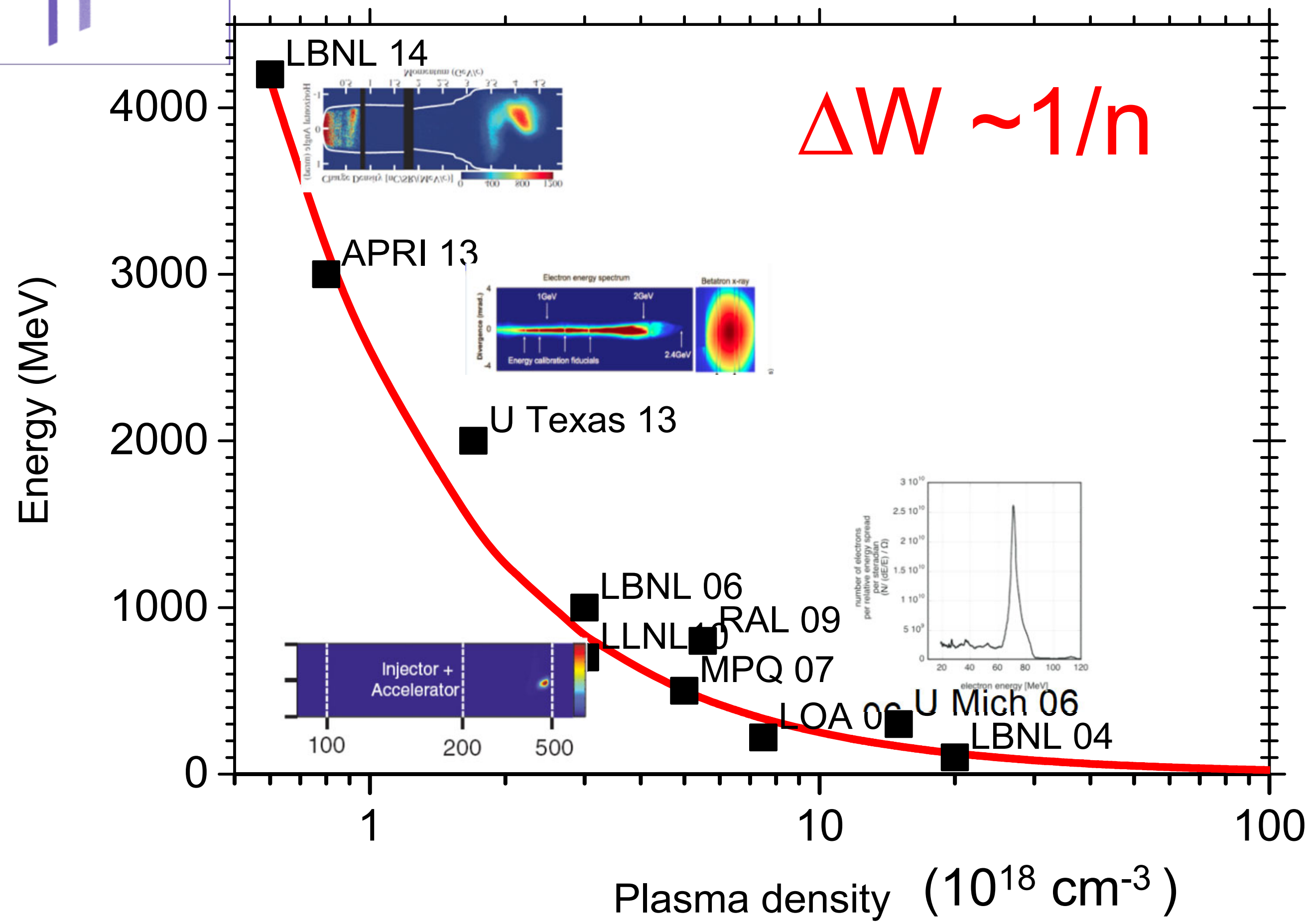
$$\Delta W = e\, E_p\, L$$

- The length of acceleration is determined by
  - Laser diffraction
  - Dephasing of electrons (entering a decelerating phase of the plasma): $L_{deph} \propto 1/\ n_e^{3/2}$
  - Damping of laser energy $L_{am} \propto 1/\ (a_0^2\ n_e^{3/2})$
- Optimum length: $L_{deph} \sim L_{am}$ and $a_0 \sim 1$

$$\Delta W \propto 1/n_e$$

- **To increase energy gain requires**
  - **To lower electron density**
  - **To increase interaction length**

Experimental results since 2004 follow the scaling law for the energy gain



Non Linear regime with injection of plasma electrons

Energies above GeV reached for PW laser power: UTexas13, APRI13: 2 gaz jets

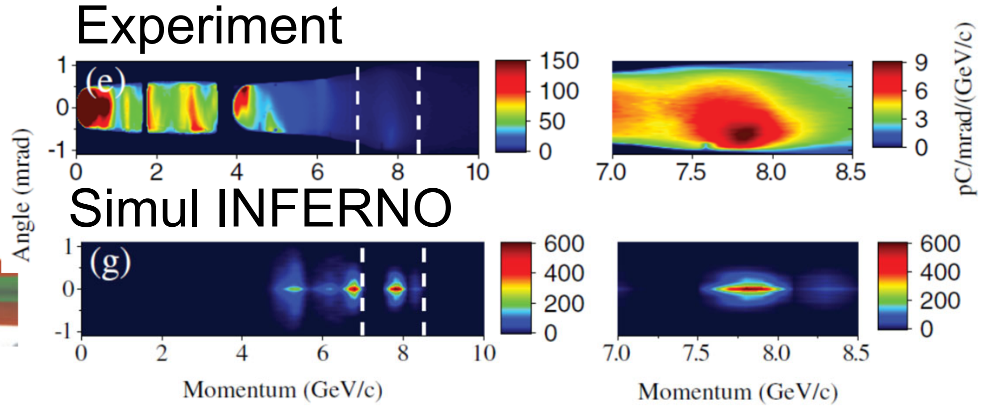
LBNL14 also includes channel guiding

- Energy increases for lower plasma density
- At low enough density, self-injection stops, additional laser power or external injection should be used

Recent breakthrough for accelerator R&D

10GeV accelerator module

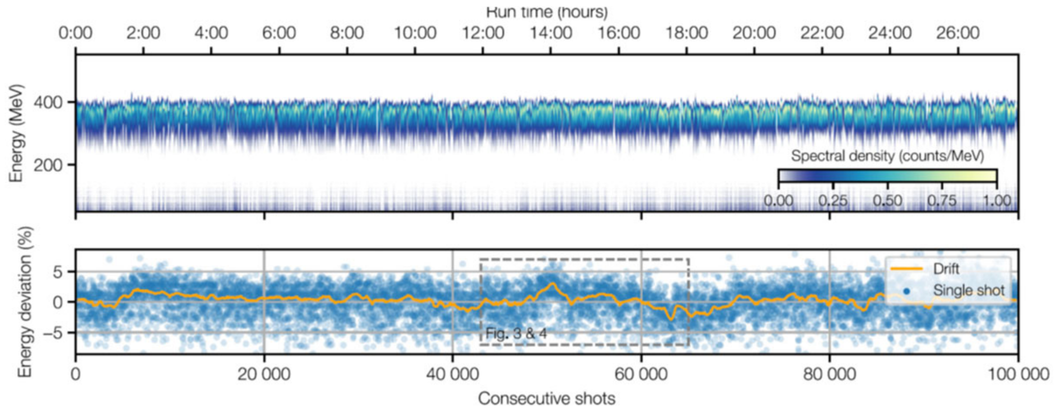
LBNL, laser guiding in 20cm long cap discharge waveguide



PRL 122, 084801 (2019)

24 hour operation

DESY, LUX Laser plasma accelerator

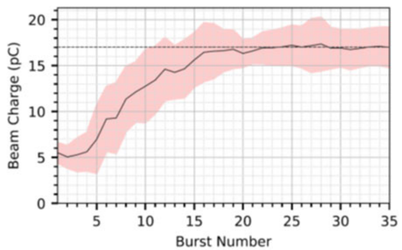


PRX 10, 031039 (2020)

PRL 126, 104801 (2021)

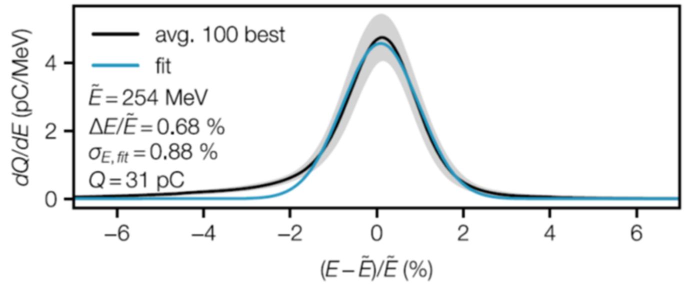
Automated optimisation

Shalloo et al, Nat comm (2020) 11:6355



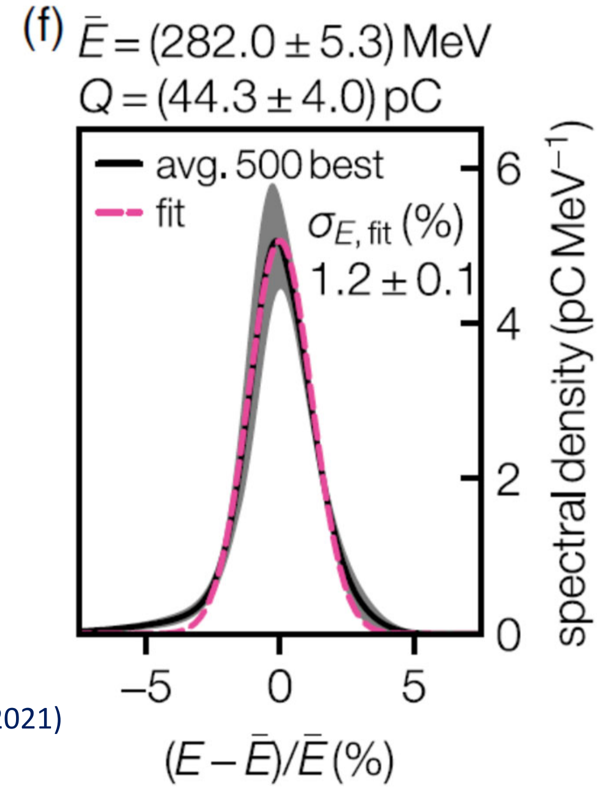
Optimised for charge

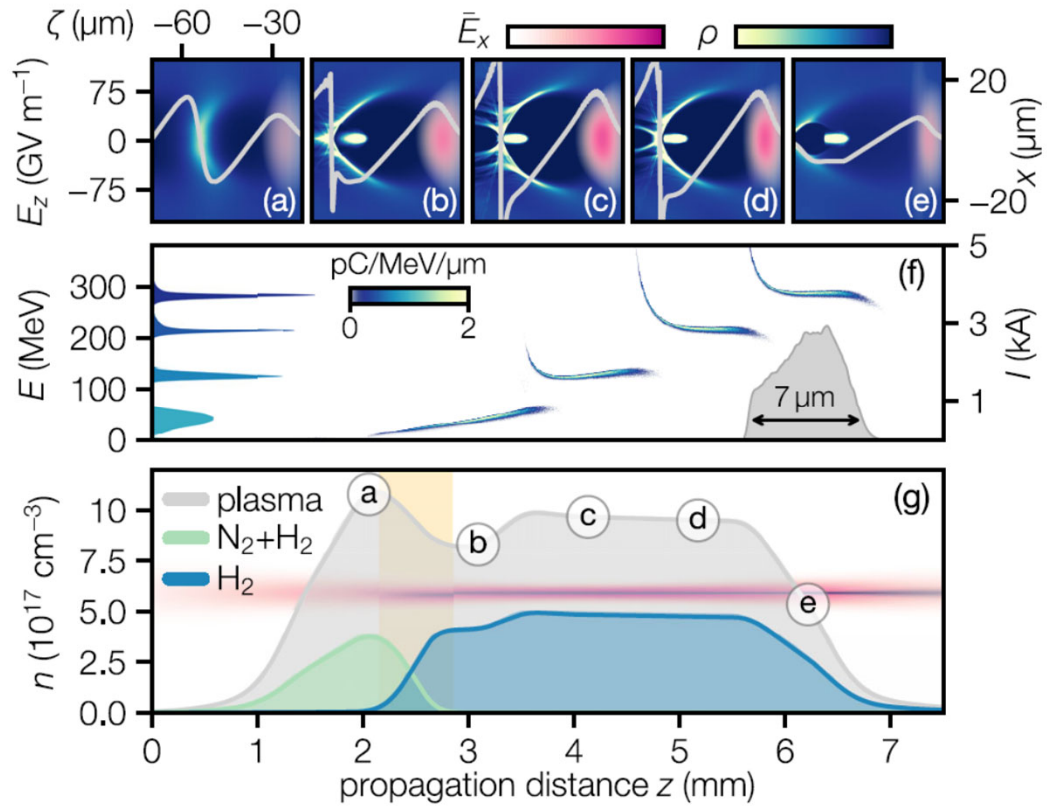
Optimised for small energy spread



Optimisation of electron beam properties assisted by machine learning

- Best beam properties demonstrated so far at DESY
- Agreement with simulations (injection and acceleration in the plasma)





PRL 126, 174801 (2021)

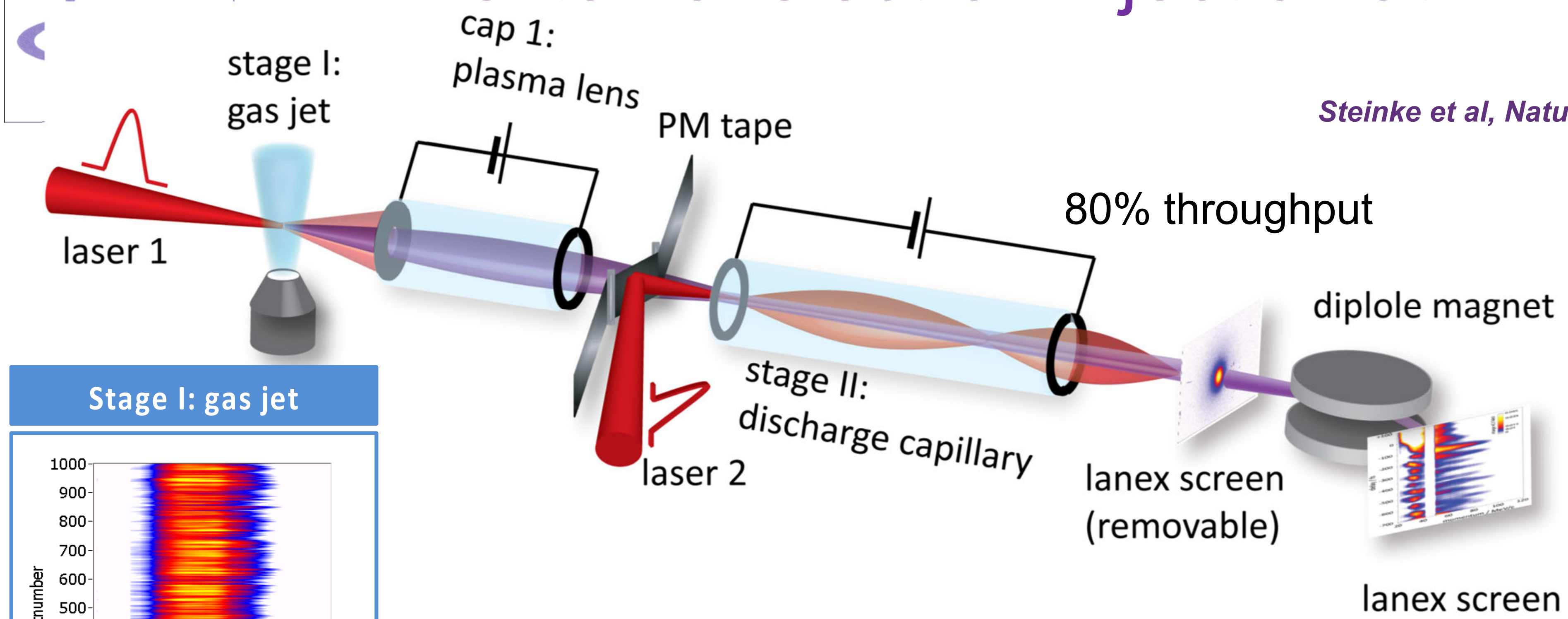
- Good agreement with simulations: strong basis for accelerator design

Next steps: multi-stage schemes to achieve multi-GeV reliable beams

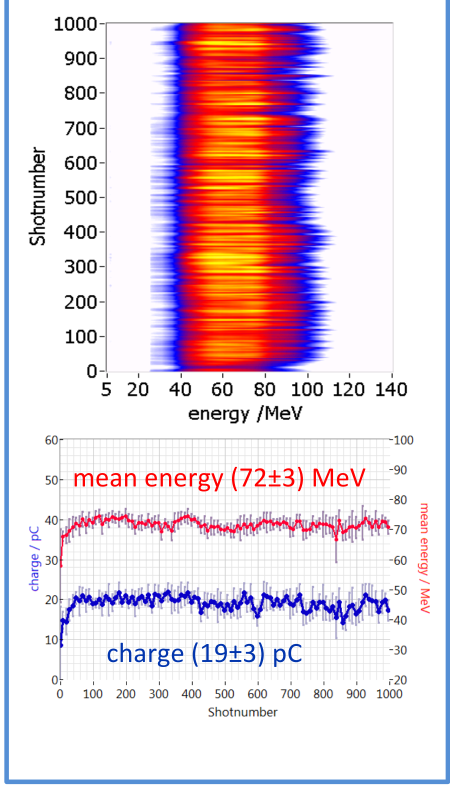
- **Objective of multi-stage:** control the properties of the accelerated beams and increase their energy
  - Optimisation of the beam properties (energy spread, emittance, reliability) in the range 100MeV -1GeV
  - Control the emitted radiation
  - Increase the energy: feasability studies for an accelerator scalable to high energy (multi-stages)
- **Main challenges**
  - Laser reliability and performance (average power, stability, quality)
  - Increase acceleration length
  - Inject electrons in the accelerating structure in a precise and controlled way

Preliminary test of external electron injection at LBNL

Steinke et al, Nature (2016)

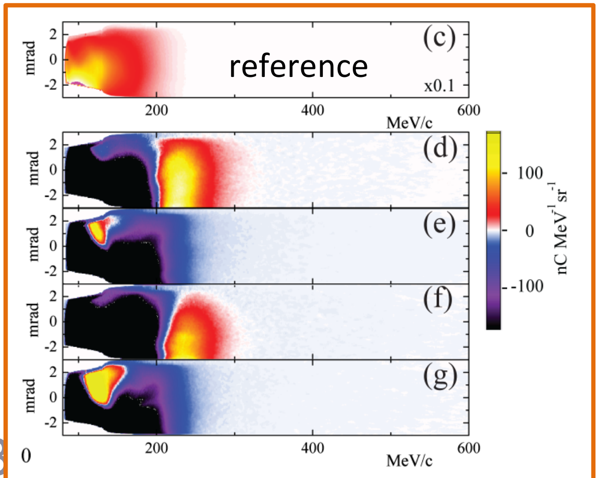


Stage I: gas jet



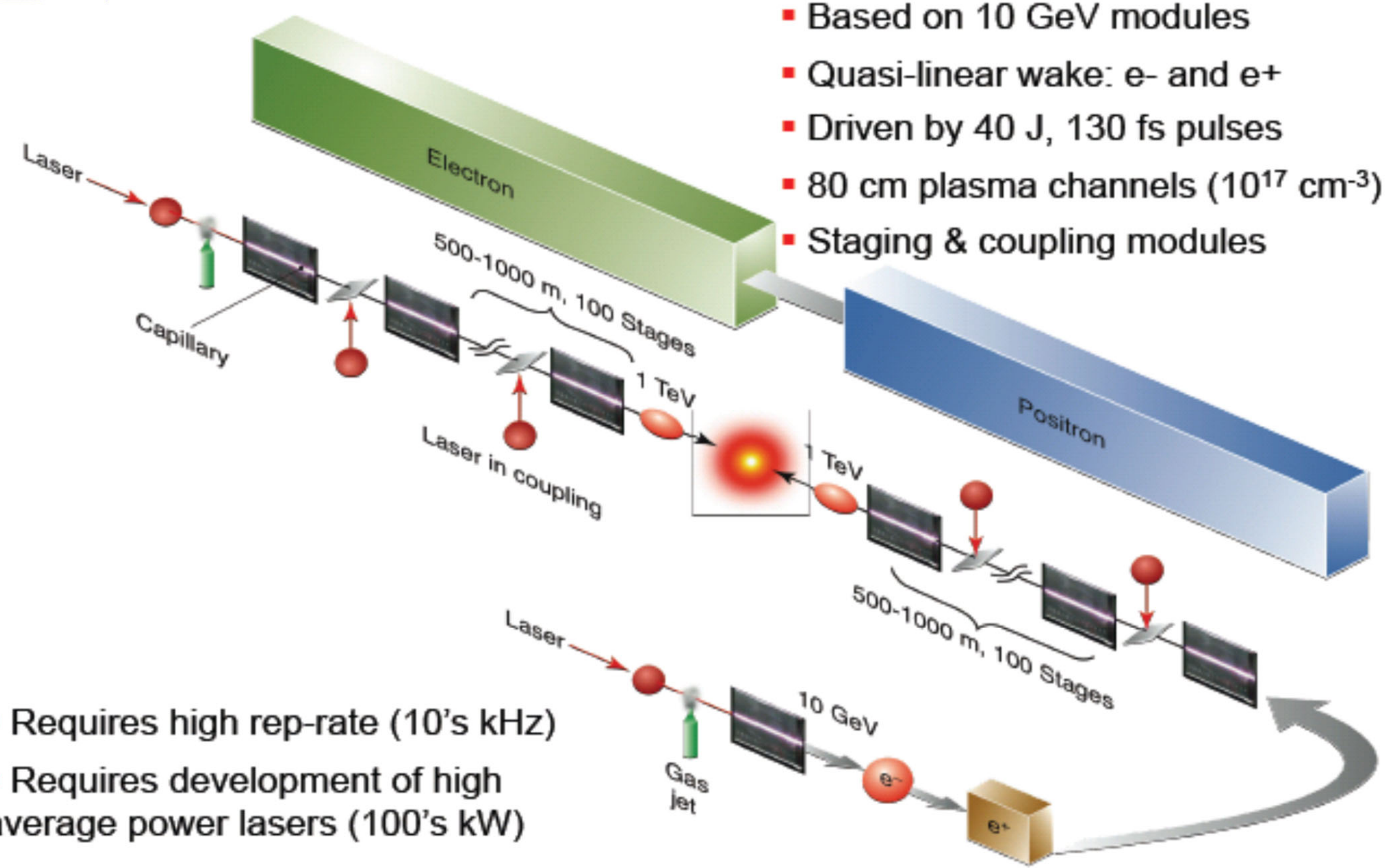
➡ Emphasizes the need to achieve a good beam quality for coupling the electron beam to the plasma

Stage I + II



Laser plasma collider concept

- Based on 10 GeV modules
- Quasi-linear wake: e- and e+
- Driven by 40 J, 130 fs pulses
- 80 cm plasma channels (10^{17} cm^{-3})
- Staging & coupling modules



- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

Leemans & Esarey, Physics Today, March 2009

Perspective of LWFA

Coordination towards accelerator development happens at different levels

- **National coordination** (GdR APPEL) and roadmaps (UK, De Helmoltz)
- **European projects** : Eupraxia has fostered accelerator development (pilot application to FEL, overlaps GeV range requirement for future collider)
- **International coordination** :ALEGRO, ICFA
- **Input for last ESPP** lead to a mention of plasma R&D in strategic recomendations and expert panel on plasma and laser has been created to propose a roadmap for advanced concepts

National coordination towards laser plasma accelerators

- GdR APPEL in France
- Brings together laser plasma physicists and accelerator community (INP, IN2P3)
- Input from particle physicists most welcome for brainstorming and collaboration

GdR APPEL
Accélérateurs Plasma PompÉs par Laser

- Brigitte Cros, Nicolas Delerue
- contact@gdr-appel.fr

http://gdr-appel.fr/

European coordination: Eupraxia has fostered accelerator development

The EuPRAXIA Project

Horizon 2020

- First ever international design of a **plasma accelerator facility.**
- Challenges addressed by EuPRAXIA since 2015:
  - How **can plasma accelerators produce usable electron beams**?
  - **For what can we use those beams** while we increase the beam energy towards HEP and collider usages?
- **CDR for a distributed research infrastructure** funded by EU Horizon2020 program. Completed by 16+25 institutes end 2019.
- Formed **next phase consortium** with 40 partners, 10 observers.
- **Applied to ESFRI roadmap update 2021** with government support in Sep 2020.
- **On the ESFRI roadmap since July 2021** ew.

653 page CDR
240 scientists contributed

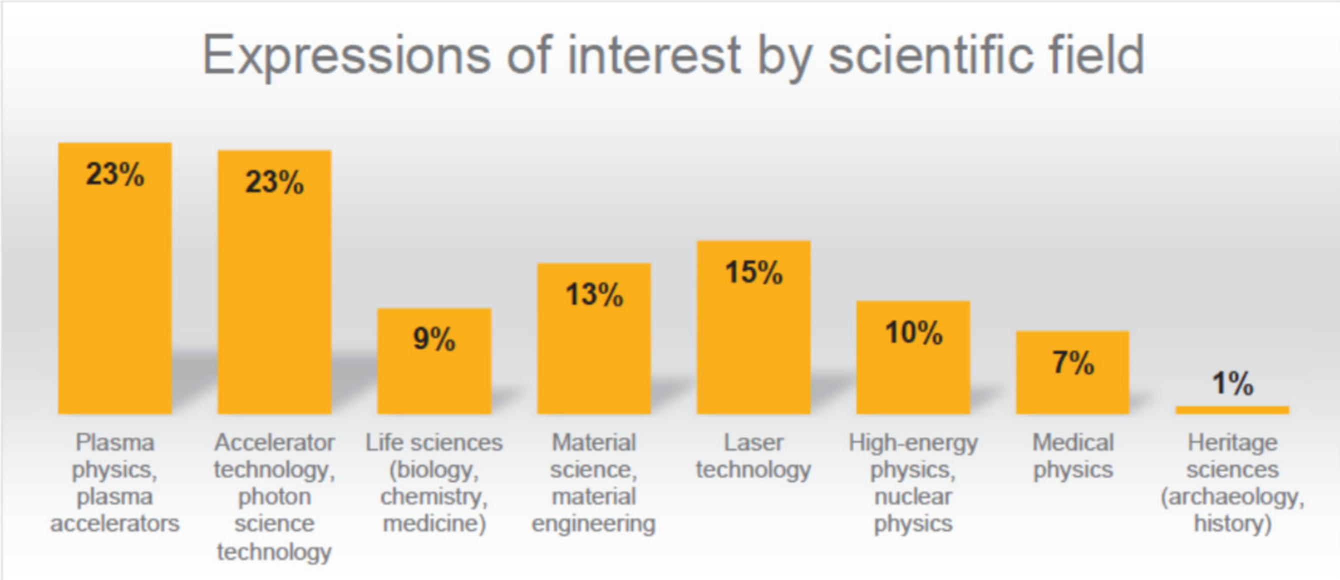
http://www.eupraxia-project.eu/

EuPRAXIA - R. Assmann, ECFA - 11/2020

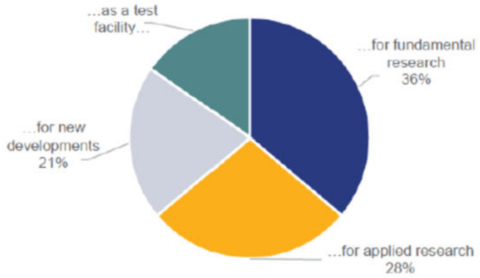
EuPRAXIA Deliverables and User Interests

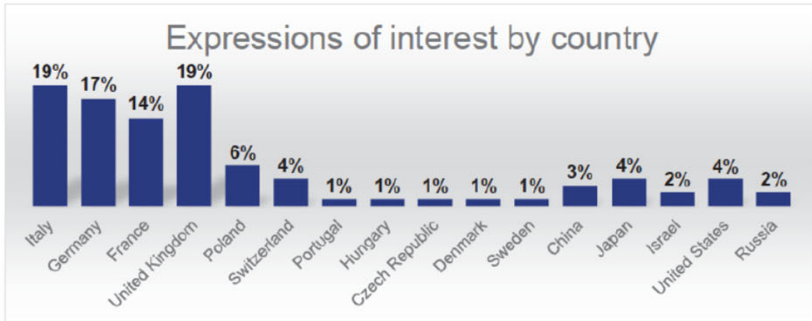
Horizon 2020

EuPRAXIA is designed to deliver at 10-100 Hz ultra-short pulses of
- Electrons (0.1-5 GeV, 30 pC)
- Positrons (0.5-10 MeV, 10^6)
- Positrons (GeV source)
- Lasers (100 J, 50 fs, 10-100 Hz)
- Betatron X rays (5-18 keV, 10^{10})
- FEL light (0.2-36 nm, 10^9-10^{13})



Expressions of interest from **95 research groups** representing several thousand scientists in total.

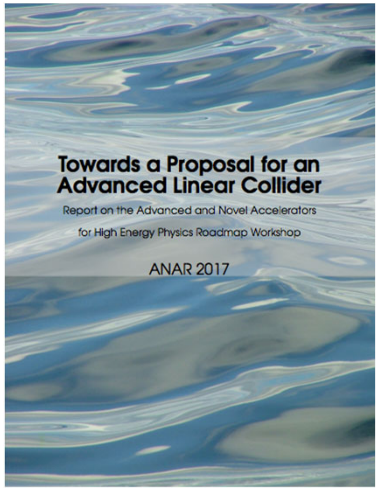




International coordination ICFA , ALEGRO

- Advanced and Novel Accelerator panel of ICFA (International Committee for Future Accelerators) has initiated a **study group** for advanced linear Collider
- **Challenging question for ANAs**: Can we envisage the delivery of an Advanced Linear Collider **design** at >1TeV (30 TeV) in 2035?
  - Electron- positron Collider at the energy frontier
  - Parameters defined for/by HEP (Luminosity)
- **Discussions towards multi TeV range have started in 2017 (ALEGRO):** input from physicists (theory and exp) needed to define scientific case and parameters for test facilities
- Workshops in 2017 (CERN), 2018 (JAI Oxford), 2019(CERN)
  http://www.physics.ox.ac.uk/confs/alegro2018/index.asp
  https://indico.cern.ch/event/732810/
- Submitted a contribution to ESPP update
  https://arxiv.org/abs/1901.08436
  https://arxiv.org/abs/1901.10370

ALEGRO
Advanced LinEar collider study GROup



Towards a Proposal for an Advanced Linear Collider Report on the Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop, CERN, Geneva, April 2017 - CERN Document Server

http://www.lpgp.u-psud.fr/icfaana/

Prospective parameters for multi-TeV colliders: single stage LWFA

Table 2.4: LWFA single stage parameters operating at a plasma density of $n_0 = 10^{17}$ cm^{-3}.

Plasma density (wall), n_0[cm^{-3}]	10^{17}
Plasma wavelength, λ_p[mm]	0.1
Plasma channel radius, r_c[μm]	25
Laser wavelength, λ[μm]	1
Normalized laser strength, a_0	1
Peak laser power, P_L[TW]	34
Laser pulse duration (FWHM), τ_L[fs]	133
Laser energy, U_L[J]	4.5
Normalized accelerating field, E_z/E_0	0.14
Peak accelerating field, E_L[GV/m]	4.2
Plasma channel length, L_c[m]	2.4
Laser depletion, η_{pd}	23%
Bunch phase (relative to peak field)	$\pi/3$
Loaded gradient, E_z[GV/m]	2.1
Beam beam current, I[kA]	2.5
Charge/bunch, $eN_b = Q$[nC]	0.15
Length (triangular shape), L_b[μm]	36
Efficiency (wake-to-beam), η_b	75%
e^-/e^+ energy gain per stage [GeV]	5
Beam energy gain per stage [J]	0.75

- Plasma stage driven by laser, **based on order of magnitude scaling laws,**
- and efficiencies (laser to plasma and plasma to beam) that could be obtained in principle.

arXiv:1901.10370 **[physics.acc-ph]**

Prospective parameters for multi-TeV colliders

Table 2.5: Example parameter sets for 0.25, 1, 3, 30 TeV center-of-mass LWFA-based colliders.

Energy, center-of-mass, $U_{\rm cm}$[TeV]	0.25	1	3	30
Beam energy, $\gamma mc^2 = U_b$[TeV]	0.125	0.5	1.5	15
Luminosity, $\mathcal{L}[10^{34}\ {\rm s}^{-1}{\rm cm}^{-2}]$	1	1	10	100
Beam power, P_b[MW]	1.4	5.5	29	81
Laser repetition rate, f_L[kHz]	73	73	131	36
Horiz. beam size at IP, σ_x^*[nm]	50	50	18	0.5
Vert. beam size at IP, σ_y^*[nm]	1	1	0.5	0.5
Beamstrahlung parameter, Υ	0.5	2	16	2890
Beamstrahlung photons, n_γ	0.6	0.5	0.8	2.8
Beamstrahlung energy spread, δ_γ	0.06	0.08	0.2	0.8
Disruption paramter, D_x	0.07	0.02	0.05	3.0
Number of stages (1 linac), $N_{\rm stage}$	25	100	300	3000
Distance between stages [m]	0.5	0.5	0.5	0.5
Linac length (1 beam), $L_{\rm total}$[km]	0.07	0.3	0.9	9.0
Average laser power, $P_{\rm avg}$[MW]	0.3	0.3	0.6	0.17
Efficiency (wall-to-beam)[%]	9	9	13	13
Wall power (linacs), $P_{\rm wall}$[MW]	30	120	450	1250

- **Very preliminary estimation, needs:**
- A full simulation study,
- Experimental demonstrations,
- Development of plasma and driver technology.

arXiv:1901.10370 **[physics.acc-ph]**

Update of the European Strategy for Particle Physics in 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/

Laser and Plasma Expert Panel general considerations

- Advanced accelerators have made **important progress in demonstrating key aspects** of those technologies: energy and quality for laser/electron/proton driven
- **Rapid progress** in underlying technologies, e.g. lasers, feedbacks, nano-control, manufacturing, …
- Various roadmaps in EU (EuroNNAc), US (DOE) and internationally (ALEGRO), defining R&D needs for having a collider at the end of the 2030`s or in the 2040`s → **slipping schedule due to missing funding** for particle physics oriented R&D in novel accelerators.
- **Feasibility of a collider remains to be proven:**
  - E.g. scheme for positrons in plasma accelerators still to be demonstrated on paper.
  - Staging designs for high energy remain to be calculated in detail and with all elements, including tolerances, length and cost scaling.
  - Repetition rate issues and efficiency approach to be investigated in detail.

A plan for feasibility assessment by 2025 of advanced accelerator development is under discussion

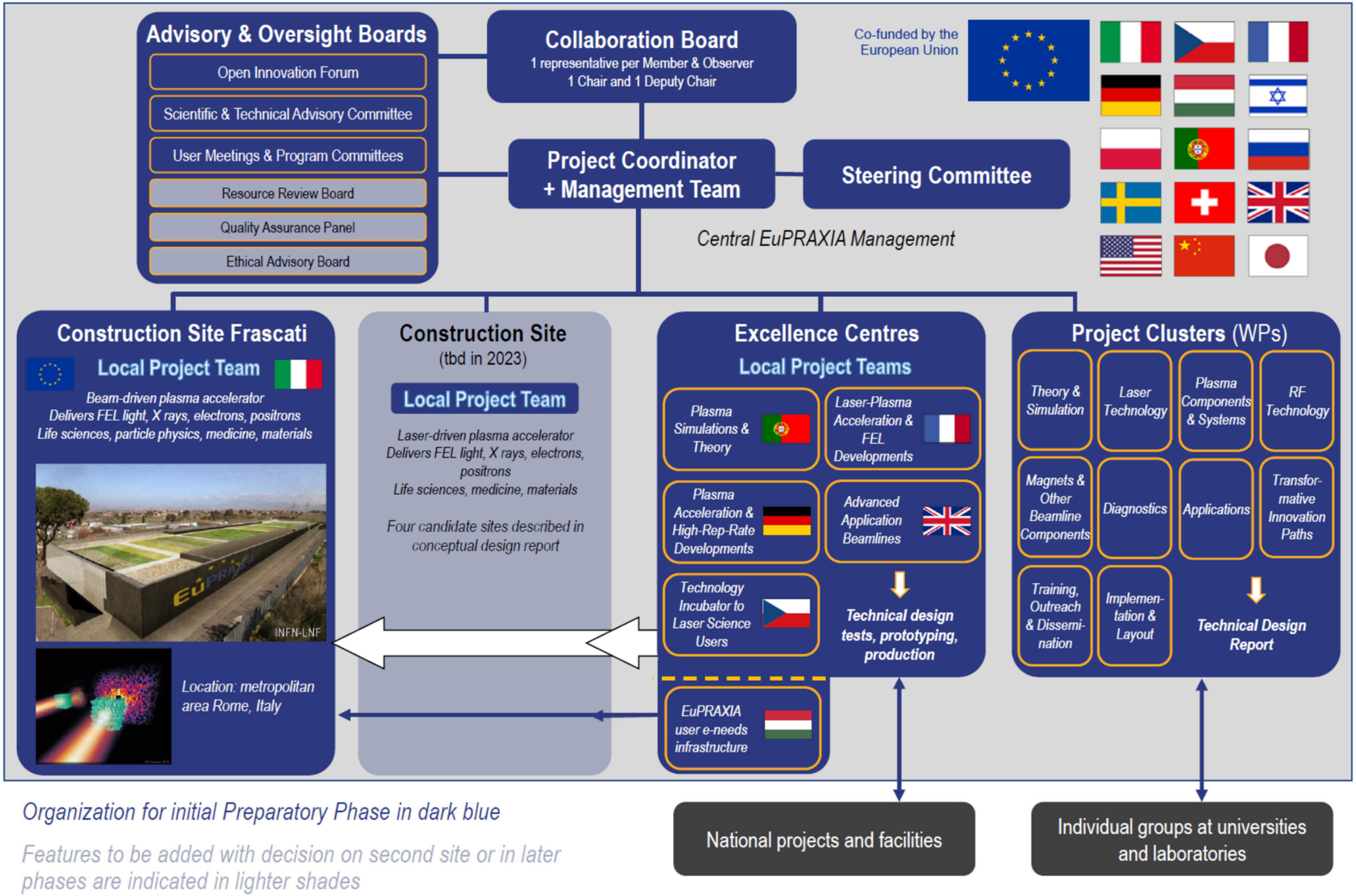
2024 – **electron high energy** case study	**Multi-stage electron accelerator from 175 GeV to 190 GeV**, including full lattice, in/out-coupling, all magnetic elements, correctors, diagnostics, collective effects, synchrotron radiation, estimate of **realistic performance**, estimate of realistic footprint, **estimate of realistic benefits in cost and size**, understanding of **scaling with beam energy for different technologies** (laser-driven, electron-driven, proton-driven, DLA/THz).
2024 – **Physics Case of an Advanced Collider**	Report from **common study group with particle physicists on physics cases of interest at the energy frontier (e+e- collider, gg) and at lower beam energies (e- g collider, dark matter search, …)**
2025 - **positron high energy** case study	Equivalent to 2024 study on electron accelerator **(see above).**
2025 – **low energy study cases** for electrons and positrons	Assessing the **low energy regime** around 15-50 GeV, achievable performance, foot print and cost, **schemes and designs for first particle physics experiments** with novel accelerators, needed R&D demonstration topics for low energy design and needed test facilities

Summary

- Tremendous progress has been achieved since the seminal idea and over the last 10 years in LWFA
- LWFA is a promising technology for facilities with significantly reduced size that may be an alternative path to multi-TeV scale e+e- colliders
- It is timely to push forward plasma accelerator R&D and strengthen the physics case
- Roadmaps are under discussion at several levels and new projects should emerge within the next 10 years

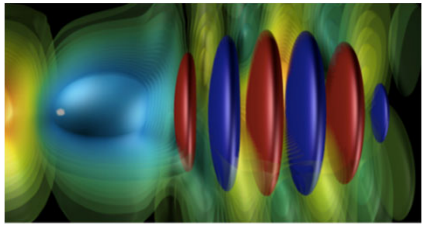
Additional slides

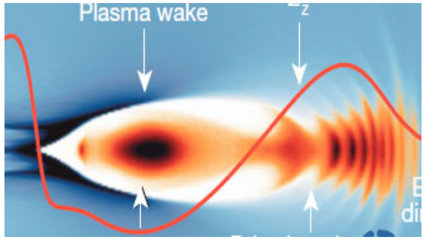
Eupraxia organisation

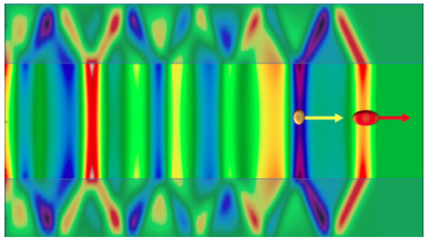


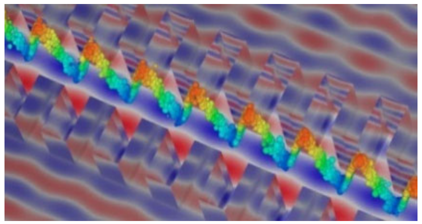
Advanced and Novel Accelerator concepts (ANAs): definition

Acceleration gradients larger then 1GV/m





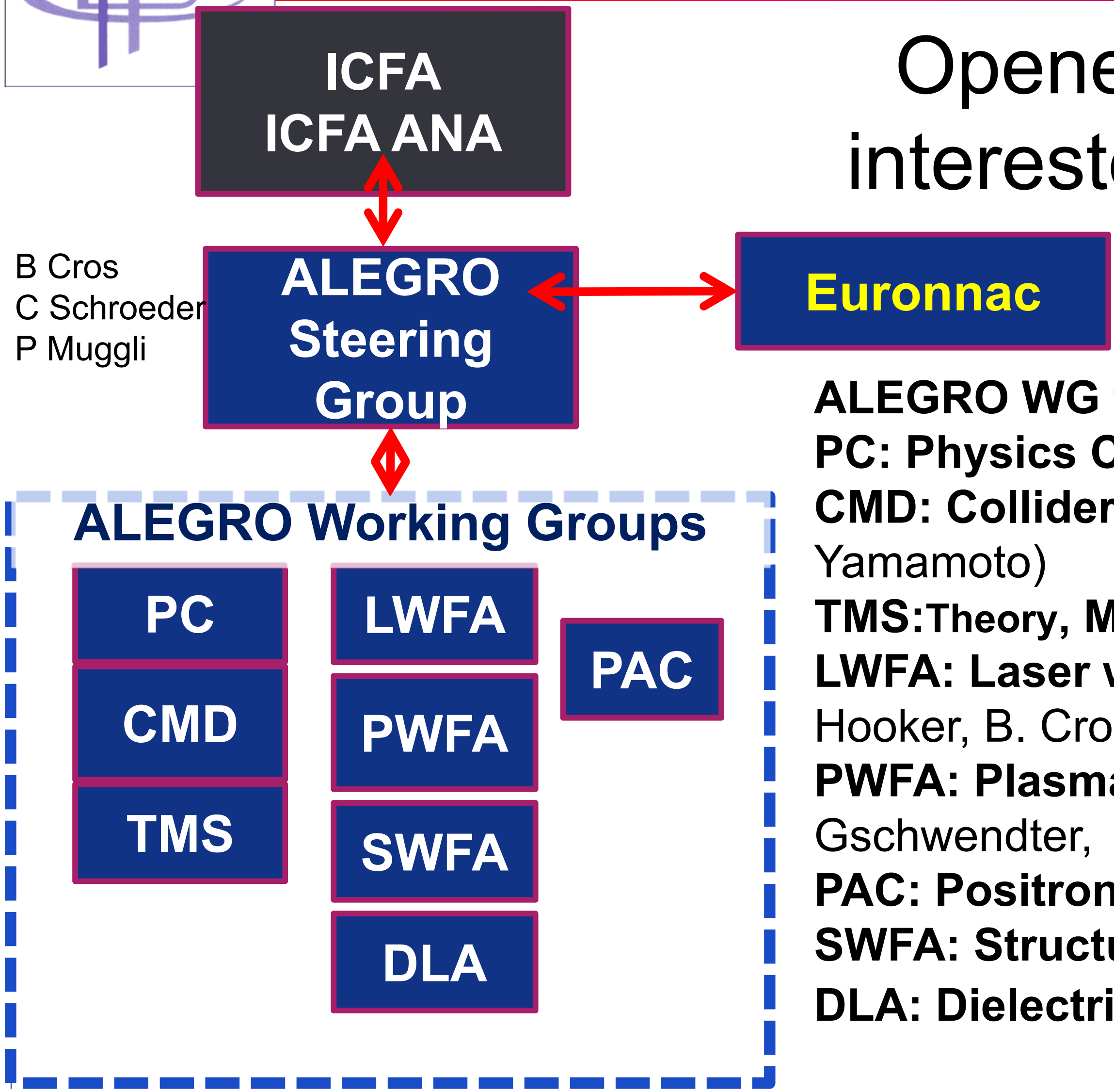




- Wakefields driven in **plasma** by **intense** laser beams : **LWFA**
- Wakefields driven in **plasma** by **particle** beams: **PWFA**
- Wakefields driven in **structures** (e.g.dielectric tubes) by **particle** beams: **SWFA**
- Wakefields driven in **dielectric structures** by **short-pulse** lasers: **DLA**

Advanced LinEar collider study GROup: organisation

Opened to contributions from interested scientists worldwide



ALEGRO WG titles and leaders:

PC: Physics Case (M Peskin, J Tian)

CMD: Collider Machine Design (A Seryi, D Schulte, H Yamamoto)

TMS:Theory, Modelling, Simulations (JL Vay, J. Vieira)

LWFA: Laser wakefield Accelerators (C. Schroeder, S. Hooker, B. Cros)

PWFA: Plasma wakefield Accelerators (J Osterhoff, E Gschwendter, P Muggli)

PAC: Positron acceleration (S. Gessner, S. Corde)

SWFA: Structure wakefield accelerator (P Piot, J Power)

DLA: Dielectric laser accelerator (J England, B Cowan)

http://www.lpgp.u-psud.fr/icfaana/ana-publications-2017