From Dreams to Reality
Prospects for Applying Advanced Accelerator Technologies to Next Generation Scientific User Facilities
Massimo.Ferrario@lnf.infn.it
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IPAC 2019, Melbourne (Australia), May 20, 2019
### Options towards higher energies

<table>
<thead>
<tr>
<th>Collider Type</th>
<th>Equation</th>
<th>Options/Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadron (p) circular collider</td>
<td>( p = e \cdot R \cdot B_y )</td>
<td>Increase bending field, SC bend magnet work (FCC-hh), increase radius = size (FCC-hh)</td>
</tr>
<tr>
<td>Lepton (e-,e+) circular collider</td>
<td>( p \propto E_0 \cdot \sqrt{\rho \cdot U_0} )</td>
<td>Increase supplied RF voltage (FCC-ee), increase mass of acc. particle (muon), increase radius = size (FCC-ee)</td>
</tr>
<tr>
<td>Lepton (e-,e+) linear collider</td>
<td>( p = L \cdot G_{acc} )</td>
<td>Increase accelerating gradient, (a) Pushing existing technology (ILC, CLIC), (b) New regime of ultra-high gradients (plasma, dielectric accelerators), increase length (ILC, CLIC)</td>
</tr>
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Options towards higher energies

**Hadron (p) circular collider**

\[ p = e \cdot R \cdot B_y \]

- Increase bending field
- SC bend magnet work (FCC-hh)
- Increase radius = size (FCC-hh)

**Lepton (e-, e+) circular collider**

\[ p \propto E_0 \cdot \sqrt[4]{\rho \cdot U_0} \]

- Increase supplied RF voltage (FCC-ee)
- Increase mass of acc. particle (muon)
- Increase radius = size (FCC-ee)

**Lepton (e-, e+) linear collider**

\[ p = L \cdot G_{acc} \]

- Increase accelerating gradient
- (a) Pushing existing technology (ILC, CLIC)
- (b) New regime of ultra-high gradients (plasma, dielectric accelerators)
- Increase length (ILC, CLIC)
Options towards higher energies

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## Options towards higher energies

### Hadron (p) circular collider

\[ p = e \cdot R \cdot B \]
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### Lepton (e-,e+) circular collider

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- Increase radius = size (FCC-ee)
- Increase mass of acc. particle (muon)

### Lepton (e-,e+) linear collider

\[ p = L \cdot G_{\text{acc}} \]
- Compact and Cost Effective...
- Increase length (ILC, CLIC)
Future accelerators will require also high quality beams:

=> High Luminosity & High Brightness,

=> High Energy & Low Energy Spread

\[ L = \frac{N_{e+} N_e f_r}{4\pi \sigma_x \sigma_y} \]

\[ B_n \approx \frac{2l}{\varepsilon_n^2} \]

- N of particles per pulse => 10^9
- High rep. rate \( f_r \) => bunch trains
- Small spot size => low emittance
- Short pulse (ps => fs)
- Little spread in transverse momentum and angle => low emittance
High Gradient Options

Metallic accelerating structures =>
$100 \text{ MV/m} < E_{\text{acc}} < 1 \text{ GV/m}$

Dielectrict structures, laser or particle driven =>
$E_{\text{acc}} < 10 \text{ GV/m}$

Plasma accelerator, laser or particle driven =>
$E_{\text{acc}} < 100 \text{ GV/m}$

Related Issues: Power Sources and Efficiency, Stability, Reliability, Staging, Synchronization, Rep. Rate and short (fs) bunches with small ($\mu$m) spot to match high gradients
A limit on the acceptable Break-Down Rate has been set at $< 3 \times 10^{-7}$ per pulse.

- A. Grudiev et al, PRST-AB 12, 102001 (2009)
The key objective is to demonstrate through a Conceptual Design, the feasibility of a compact and cost effective FEL facility driven by X-band RF technology eventually up to kHz repetition rate.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Soft X-ray</th>
<th>Hard X-ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy</td>
<td>keV</td>
<td>0.25 – 2.0</td>
<td>2.0 – 16.0</td>
</tr>
<tr>
<td>Wavelength</td>
<td>nm</td>
<td>5.0 – 0.6</td>
<td>0.6 – 0.08</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>Hz</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>fs</td>
<td>0.1 – 50</td>
<td>1 – 50</td>
</tr>
<tr>
<td>Polarization</td>
<td></td>
<td>Variable, selectable</td>
<td></td>
</tr>
<tr>
<td>Two-pulse delay</td>
<td>fs</td>
<td>±100</td>
<td>±100</td>
</tr>
<tr>
<td>Two-colour separation</td>
<td>%</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Synchronization</td>
<td>fs</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
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</table>
X-band from High Energy Physics to Industrial and Medical Applications

CLIC layout and power generation
Towards the TeV energy frontier

Radiology, Security, and X-ray analysis will benefit of cost and size reduction
The E.M. Spectrum of Accelerating Structures

Max accelerating field: \( \tau_{rf}^{-1/6} \)
Lower stored energy: \( f^{-3} \)
Dielectric Structures

The use of infrared lasers to power optical-scale lithographically fabricated particle accelerators is a developing area of research that has produced interesting results in recent years.

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<th>Si Single Grating</th>
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<tbody>
<tr>
<td>Electron Energy</td>
<td>8 MeV</td>
<td>30 keV</td>
<td>96.3 keV</td>
<td>86.5 keV</td>
</tr>
<tr>
<td>Relativistic β</td>
<td>0.998</td>
<td>0.33</td>
<td>0.54</td>
<td>0.52</td>
</tr>
<tr>
<td>Laser Energy</td>
<td>150 μJ</td>
<td>160 nJ</td>
<td>5.2 nJ</td>
<td>3.0 nJ</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>40 fs</td>
<td>110 fs</td>
<td>130 fs</td>
<td>130 fs</td>
</tr>
<tr>
<td>Interaction Length</td>
<td>~20 μm</td>
<td>11 μm</td>
<td>5.6 μm</td>
<td>5.6 μm</td>
</tr>
<tr>
<td>Peak Laser Field</td>
<td>8 GV/m</td>
<td>2.85 GV/m</td>
<td>1.65 GV/m</td>
<td>~1.1 GV/m</td>
</tr>
<tr>
<td>Max Energy Gain</td>
<td>30 keV</td>
<td>0.275 keV</td>
<td>1.22 keV</td>
<td>2.05 keV</td>
</tr>
<tr>
<td>Max Acc Gradient</td>
<td>~1.5 GV/m</td>
<td>25 MeV/m</td>
<td>220 MeV/m</td>
<td>370 MeV/m</td>
</tr>
<tr>
<td>$G_{\text{max}}/E_p$</td>
<td>~0.18</td>
<td>~0.01</td>
<td>~0.13</td>
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Laser pulses 180 degrees out of phase

Photonic band gap

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Dielectric Structures

A combination of DLA modules and optical undulator allows dreaming for a compact table top FEL.

DLA module can be built onto the end of a fiber-optic catheter and attached to an endoscope, allowing to deliver controlled, high energy radiation directly to organs, tumors, or blood vessels within the body.

Electrons with 1–3MeV have a range of about a centimeter, allowing for irradiation volumes to be tightly controlled.
All laser driven $\Rightarrow$ intrinsic attosecond synchr.,
1 Joule, 1 kHz Cryogenic Yb:YAG Laser
Laser-based THz generation
THz Linac, Optical undulator

E. Nanni et al., Nat. Comm. 6, 8486 (2015)
Dielectric Structures

Attoseconds X-ray Science Imaging and Spectroscopy

All laser driven => intrinsic attosecond synchr., 1 Joule, 1 kHz
Cryogenic Yb:YAG Laser
Laser-based THz generation
THz Linac, Optical undulator

E. Nanni et al., Nat. Commun. 6, 8486 (2015)

F.X. Kärtner et al., NIM A 829, 24 (2016)

Beam Driven exp. at FACET

GV/m fields in DWA
Principle of plasma acceleration
Principle of plasma acceleration

Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam
Principle of plasma acceleration

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Drive beam = high energy electron or proton beam

\[ n_o = 10^{16} \text{ cm}^{-3} \Rightarrow \lambda_p = 300 \text{ \mu m} \]

\[ \omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}} \]
Principle of plasma acceleration

Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

Break-Down Limit?
$\Rightarrow$ Wave-Breaking field:
$E_{wb} \approx 100\left[GeV / m\right]\sqrt{n_o\left[cm^{-3}\right]}$

$n_o = 10^{16} \, cm^{-3} \Rightarrow \lambda_p = 300 \, \mu m$

$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$
Principle of plasma acceleration

Driven by Radiation Pressure

\[ \left( \frac{\partial^2}{\partial t^2} + \omega_p^2 \right) n = \frac{c^2 \nabla^2 a^2}{2} \]

\[ a = \frac{eA}{mc^2} \propto \lambda J^{1/2} \]

Driven by Space Charge

\[ \left( \frac{\partial^2}{\partial t^2} + \omega_p^2 \right) n = -\omega_p^2 \frac{n_{\text{beam}}}{n_o} \]

\[ n_{\text{beam}} = \frac{N}{\sqrt{(2\pi)^3} \sigma_x \sigma_y \sigma_z} \]

LWFA limitations: Diffraction, Dephasing, Depletion
PWFA limitations: Head, Erosion, Hose
Principle of plasma acceleration

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LWFA limitations: Diffraction, Dephasing, Depletion

PWFA limitations: Head, Erosion, Hose
Figure 2: Non-exhaustive overview of laboratories working on (or with the capacity to work on) laser-driven (black) and particle beam-driven (green) plasma wakefield R&D. Based in part on the map of high-power laser laboratories produced by the International Committee on Ultra-high Intensity Lasers (ICUIL).21
**BELLA, Berkeley Lab, US**
Laser Driven Plasma Wakefield Acceleration Facility: Today: PW laser!

**Petawatt laser guiding** and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide


Laser heater added to capillary

→ path to 10 GeV with continued improvement of guiding in progress

**Multistage coupling** of independent laser-plasma accelerators

*S. Steinke, Nature 530, 190 (2016)*

Electron spectra, up to 6-8 GeV

Staging demonstrated at 100 MeV level.
FACET, SLAC, US
Premier R&D facility for PWFA: Only facility capable of e\(^+\) acceleration

- Timeline:
  - Commissioning (2011)
  - Experimental program (2012-2016)
- Key PWFA Milestones:
  - Mono-energetic e\(^-\) acceleration
  - High efficiency e\(^-\) acceleration
  - First high-gradient e\(^-\) PWFA
  - Demonstrate required emittance, energy spread

- Facility hosted more than 200 users, 25 experiments
- One high profile result a year
- Priorities balanced between focused plasma wakefield acceleration research and diverse user programs with ultra-high fields
- Unique opportunity to develop future leaders

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator
\(\Rightarrow\) gradient of 52 GV/m

High-Efficiency acceleration of an electron beam in a plasma wakefield accelerator, 2014
M. Litos et al., doi, Nature, 6 Nov 2014, 10.1038/nature 13882

70 pC of charge accelerated, 2 GeV energy gain, 5 GeV/m gradient \(\Rightarrow\) Up to 30% transfer efficiency, ~2% energy spread

9 GeV energy gain in a beam-driven plasma wakefield accelerator
Positron Acceleration, FACET

Positrons for high energy linear colliders: high energy, high charge, low emittance.

**First demonstration** of positron acceleration in plasma (FFTB)

**Energy gain of 5 GeV.** Energy spread can be as low as 1.8% (r.m.s.).

High-density, compressed positron beam for non-linear PWFA experiments. Energy transfer from the front to the back part of the bunch.

**Hollow plasma channel:** positron propagation, wake excitation, acceleration in 30 cm channel.

**Measurement of transverse wakefields in a hollow plasma channel** due to off-axis drive bunch propagation.

**Two-bunch positron beam:** First demonstration of controlled beam in positron-driven wake

**Emittance blow-up is an issue!** Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma. But then strong transverse wakefields when beams are misaligned.
AWAKE, CERN

AWAKE has demonstrated during Run 1 (2016-2018) that the seeded self-modulation is a reliable and robust process and that electrons can be accelerated with high gradients.

Seeded self-modulation of the proton bunch:

- **SSM process is reproducible, reliable and stable.**
- **Electrons accelerated to 2 GeV** in 10m.
- Energy is as expected from simulations

---


FLASHForward>>>, DESY

→ unique FLASH facility features for PWFA
  - FEL-quality drive and witness beams
  - up to 1 MHz repetition rate
  - 3rd harmonic cavity for phase-space linearization → tailoring of beam current profile
  - differentially pumped, windowless plasma sources
  - 2019: X-band deflector of 1 fs resolution post-plasma (collaboration with FALSH 2, SINBAD, CERN & PSI)
  - Future: up to 800 bunches (~MHz spacing) at 10 Hz macro-pulse rate, few 10 kW average power.

→ A. Aschke et al., NIM A 808, 175 (2016)

→ (12.3 ± 1.7) GV/m wakefield generated in 30 mm plasma cell
→ 12.7% total energy loss to plasma wakefield
SPARCLAB, Frascati, Italy

SPARC_LAB is the test and training facility for EuPRAXIA@SPARC_LAB

M. Ferrari et al., SPARC_LAB present and future, NIM B 309, (2013)

Main challenges addressed in this facility: beam quality, beam transport

- 150 MeV drive/witness beam
- FEL experiments
- Resonant PWFA
- LWFA with 200 TW laser

Plasma Lens Experiments:
Acceleration of high brightness beams and transport to the final application, while preserving the high quality of the 6D phase space

R. Pompili et al., PRL 121 (2018), 174801

BELLA, LBNL: J. van Tilborg et al., PRL 115 (2015), 184802
CLEAR, CERN: C.A. Lindstrom et al., PRL 121 (2018), 194801

Plasma dechirper:
Longitudinal phase-space manipulation with the wakefield induced in plasma by the beam itself.

From 0.6% to 0.1% energy spread

V. Shpakov et al., PRL 122 (2019), 114801

FLASHForward, DESY: R. D’Arcy et al., PRL 122 (2019), 034801
"Wake-up-call" to reality

\[ \epsilon_{n,rms} = \sqrt{\langle \gamma^2 \rangle \left( \sigma_{y}^2 \sigma_{x}^2 \sigma_{x'}^2 + \epsilon_{rms}^2 \right) } \]

M. Migliorati et al, Physical Review Special Topics, Accelerators and Beams 16, 011302 (2013)
K. Floettmann, PRSTAB, 6, 034202 (2003)
EuPRAXIA Design Study started on November 2015
Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€
Coordinator: Ralph Assmann (DESY)

http://eupraxia-project.eu
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 653782.
PRESENT PLASMA E- ACCELERATION EXPERIMENTS

Demonstrating 100 GV/m routinely
Demonstrating many GeV electron beams
Demonstrating basic quality

Engineering a high quality, compact plasma accelerator 5 GeV electron beam for the 2020’s
Demonstrating user readiness
Pilot users from FEL, HEP, medicine, ...

PLASMA ACCELERATOR PRODUCTION FACILITIES

Plasma-based linear collider in 2040’s
Plasma-based FEL in 2030’s
Medical, industrial applications soon

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 653782.
EuPRAXIA scientific goals
Compact Free Electron Laser Laser et al.

- Single and multi-stage acceleration of electrons to $1 - 5 \text{ GeV}$, transverse emittance of $1 \text{ mm-mrad}$, energy spread between $\%$ to $10^{-3}$
- Highly compact machine layout (factor 3 gain in floor space, up to factor 10)
- PW pulsed lasers developed together with industry and laser institutes. → Operation with high stability at $20 - 100 \text{ Hz}$.
- Compact beam driver based on X-band RF technology from CERN.
- Versatile user area

Other Related Talks at IPAC2019:
- Control of Laser Plasma Accelerated Electrons: A Route for Compact FELs – Marie-Emmanuelle Couprie (SOLEIL)
- Lasers for Novel Accelerators – Leonida Gizzi (INO-CNR)
Advanced methods to control beam quality

Colliding laser pulses: use the beating of 2 laser pulses to control the localized electron injection above wave-breaking threshold.

Advanced methods to control beam quality

Wake Field Induced Ionization: This mechanism exploits the electric wakefields to ionize electrons from a dopant gas and trap them in a well-defined region of the accelerating and focusing wake phase, Martinez de la Ossa et al., Phys. Rev. Lett. 111, 245003 (2013)

Colliding laser pulses: use the beating of 2 laser pulses to control the localized electron injection above wave-breaking threshold J. Faure et al., Nature 444, 737 (2006)
Wake Field Induced Ionization: This mechanism exploits the electric wakefields to ionize electrons from a dopant gas and trap them in a well-defined region of the accelerating and focusing wake phase, Martinez de la Ossa et al., Phys. Rev. Lett. 111, 245003 (2013).


Applications of plasma accelerators

- Free Electron Lasers
- Synchrotron sources
- Compton sources
- High Field Physics
- Positron Sources
- High Energy Physics

\[ E_s = 4\gamma^2 \hbar \omega \]

Betatron Radiation Source

Photon energy > 25 keV, investigating dense material, biological materials
Small source size (~ μm), intrinsically high resolution, exhibits spatial resolution
Small divergence (~ 10 mRad)
Short pulse (~10s fs), suitable for ultrafast dynamics
Bright (>10^9 photons per shot), suitable for single shot imaging
EuPRAXIA future

Two facilities will be proposed as the required intermediate step between proof of principle and user facility!

Beam-driven PWA facility

Laser-driven PWA facility

EuPRAXIA@SPARC_LAB

EuPRAXIA@SINBAD
**Conclusions**

- Accelerator-based High Energy Physics will at some point become practically limited by the size and cost of the proposed $e^+e^-$ colliders for the energy frontier.

- **Novel Acceleration Techniques and Plasma-based, high gradient accelerators open the realistic vision of very compact accelerators for scientific, commercial and medical applications.**

- The R&D now concentrates on **beam quality, stability, staging and continuous operation**. These are necessary steps towards various technological applications.

- The progress in advanced accelerators benefits from strong synergy with general advances in technology, for example in the laser and/or high gradient RF structures industry.

- A major milestone is an operational, 1 GeV compact accelerator. Challenges in repetition rate and stability must be addressed. This unit could become a stage in a high-energy accelerator.

- ➔ **PILOT USER FACILITIES Needed**
Acknowledgements:

Greatly appreciate slides from and discussions with: Ralph Assmann, Edda Gschwendtner, A. de La Ossa, D. Alesini And the EuPRAXIA, XLS, BELLA, FLASHFoward, SINBAD, AWAKE collaborations

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• Control of Laser Plasma Accelerated Electrons: A Route for Compact FELs – Marie-Emmanuelle Couprie (SOLEIL)
• 20 Years of Laser Ion Acceleration: Review and Recent Advances – Bjorn Hegelich (University of Texas at Austin)
• Lasers for Novel Accelerators – Leonida Gizzi (INO-CNR)
Thanks for your attention