Gli acceleratori del futuro: EuPRA\textsc{XIA}

Massimo.Ferrario@lnf.infn.it

LNF Summer School - 19 Giugno 2020
Cosmic Accelerators
The graph illustrates the development of maximum beam energy over time, with key milestones and acceleration methods highlighted:

- **1940s**: Electron and positron storage rings
- **1960s**: Laser-driven electron plasma acceleration
- **1980s**: Electron and/or positron accelerators, including storage rings, linacs, and FELs
- **2000s**: Discovery and Free-Electron Lasers

Future goals include Higgs/Precision and Free-Electron Lasers.
LHC few data

- 27 km circumference
- ~100 m underground
- ~1300 magnets
- ~1.7 °K temperature
- 4 large experiments
Today FCC (Future Circular Collider) study

International collaboration to study:

- $pp$-collider ($FCC-hh$)
- $e^+e^-$ collider ($FCC-ee$) as potential intermediate step
- $p$-$e$ ($FCC-he$) as an option

$\sim 16 \, \text{T} \Rightarrow 100 \, \text{TeV}$ $pp$ in 100 km
$\sim 20 \, \text{T} \Rightarrow 100 \, \text{TeV}$ $pp$ in 80 km

FCC: 80-100 km infrastructure in Geneva area
Conventional RF accelerating structures
X-band RF structures – State of the Art

Max accelerating field: $\tau_{rf}^{-1/6}$

Stored energy: $f^{-3}$

- A. Grudiev et al, PRST-AB 12, 102001 (2009)
Laser Electron Accelerator

T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}$ W/cm$^2$ shone on plasmas of densities $10^{18}$ cm$^{-3}$ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen($^a$)

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas

Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.
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?
⇒ Wave-Breaking field:

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

$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_0 m_e}}$$

$$E_{wb} \approx 100 \left[ GeV / m \right] \sqrt{n_o \left[ cm^{-3} \right]}$$
Laser Pulse (200 TW, ~30 fs, $E_{\text{transv}} \sim TV/m$)

Plasma electrons
(plasma cell, $\sim 10^{19} \text{ cm}^{-3}$)
Plasma Wake-Acceleration
Plasma Wake-Acceleration

Bubble ($E_{long} \sim 100 \text{ GV/m}$)

Laser Pulse ($E_{transv} \sim TV/m$)

Plasma electrons (plasma cell, $\sim 10^{19} \text{ cm}^{-3}$)
This accelerator fits into a human hair!
Diffraction - Self injection - Dephasing – Depletion
**BELLA Facility:** state-of-the-art 1.3 PW-laser for laser accelerator science: >42 J in <40 fs (> 1PW) at 1 Hz laser and supporting infrastructure at LBNL

Critical HEP experiments:
- 10 GeV electron beam from <1 m LPA
- Staging LPAs
- Positron acceleration
Experiments at LBNL use the BELLA laser focused by a 14 m focal length off-axis paraboloid onto gas jet or capillary discharge targets.

Single shot spectra 30 MeV - 11 GeV

Magnetic spectrometer

CCD array

CCD

Calorimeter

Wedge with hole

ICT

Phosphor screen

FROG

Mode imager

Gas jet

Capillary discharge waveguide

Hydrogen

Capillary discharge

Big Laser In
4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J)

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012

Electron beam spectrum

- Laser (E=15 J):
  - Measured longitudinal profile (\(T_0 = 40\) fs)
  - Measured far field mode (\(w_0 = 53\) μm)
- Plasma: parabolic plasma channel (length 9 cm, \(n_0 \sim 6-7 \times 10^{17}\) cm\(^{-3}\))

<table>
<thead>
<tr>
<th></th>
<th>Exp.</th>
<th>Sim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>4.25 GeV</td>
<td>4.5 GeV</td>
</tr>
<tr>
<td>(\Delta E/E)</td>
<td>5%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Charge</td>
<td>~20 pC</td>
<td>23 pC</td>
</tr>
<tr>
<td>Divergence</td>
<td>0.3 mrad</td>
<td>0.6 mrad</td>
</tr>
</tbody>
</table>

W.P. Leemans et al., PRL 2014
Worldwide effort towards high quality plasma beams

Associated Partners
(as of December 2017)

1. Shanghai Jiao Tong-University, China
2. Tsinghua University Beijing, China
3. ELI Beamlines, International
4. PHLAM, Université de Lille, France
5. Helmholtz-Institut Jena, Germany
6. HZDR (Helmholtz), Germany
7. LMU München, Germany
8. Wigner Fizikai Kutatóközpont, Hungary
9. CERN, International
10. Kansai Photon Science Institute, Japan
11. Osaka University, Japan
12. RIKEN Spring-8, Japan
13. Lunds Universitet, Sweden
14. Stony Brook University & Brookhaven NL, USA
15. LBNL, USA
16. UCLA, USA
17. Karlsruher Institut für Technologie, Germany
18. Forschungszentrum Jülich, Germany
19. Hebrew University of Jerusalem, Israel
20. Institute of Applied Physics, Russia
21. Joint Institute for High Temperatures, Russia
22. Università di Roma ‘Tor Vergata’, Italy
23. Queen’s University Belfast, UK
24. Ferdinand-Braun-Institut, Germany

University of Strathclyde UK
STFC UK
University of Manchester UK
DESY Germany
INFN Italy
CNR Italy
CNRS France
University of Oxford UK
Imperial College London
University of Liverpool UK
Universität Hamburg Germany
SOLEIL France
CEA France
IST-ID Portugal
ENEA Italy
Università di Roma I and II Italy
Universitá di Roma I and II Italy
Queen’s University Belfast, UK
Ferdinand-Braun-Institut, Germany
EuPRAXIA Design Study started on November 2015
Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€
Coordinator: Ralph Assmann (DESY)
**Motivations**

**PRESENT EXPERIMENTS**

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

**EuPRAXIA INFRASTRUCTURE**

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

**PRODUCTION FACILITIES**

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

Courtesy R. Assmann
EuPRAXIA site studies:
- Design study is site independent
- Five possible sites have been discussed so far
- We invite the suggestions of additional sites
EuPRAxia@SPARCLAB
EuPRAAXIA@SPARC_LAB


**INFN - Laboratori Nazionali di Frascati**

- D. Cirrincione, A. Vacchi. **INFN - Sezione di Trieste**
- G. A. P. Cirrone, G. Cattone, V. Scudieri. **INFN - Laboratori Nazionali del Sud**
- L. Gizzi, L. Labate. **CNR - INO, Pisa**
- C. Andreani, A. Cianchi, G. Festa, V. Minicozzi, S. Morante, R. Senesi, F. Stellato. **Università’ degli Studi di Roma Tor Vergata and Sezione INFN**
- V. Petrillo, M. Rossetti. **Università’ degli Studi di Milano and Sezione INFN**
- G. Castorina, L. Ficcadenti, S. Lupi, M. Marongiu, F. Mira, A. Mostacci. **Università’ degli Studi di Roma Sapienza and Sezione INFN**
- M. Coreno, G. D’Auria, S. Di Mitri, L. Giannessi, C. Masciovecchio. **ELETTRA Sincrotrone Trieste**
- A. Ricci. **RICMASS, Rome International Center for Materials Science Superstripes**
Candidate LNF to host EuPRAXIA (1-5 GeV)

- FEL user facility (1 GeV - 3nm)
- Advanced Accelerator Test facility (LC) + CERN

- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only
- Final goal compact 5 GeV accelerator
SPARC_LAB HB photo-injector
Electron source and acceleration
X-band Linac
Plasma WakeField Acceleration

Capillary discharge at SPARC_LAB
KYMA Δ undulator at SPARC_LAB: $\lambda=1.4$ cm, K1
Long undulators chain
A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator.

\[
\lambda_{\text{rad}} \approx \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} + \gamma^2 \Theta^2 \right)
\]

(Tunability - Harmonics)
Beam separation
Photon beam line
Experimental hall (Single Protein Imaging)

http://lcls.slac.stanford.edu/AnimationViewLCLS.aspx
Atomic and molecular dynamics occur at the fsec-scale

J. Hajdu, Uppsala U.
Ultra-Small

Nature

Flea
Human hair ~30 μm wide
Red blood cells & white cell ~ 5 μm
Virus ~ 200 nm
DNA helix ~ 3 nm width
Water molecule
Atom

Technology

Head of a pin ~ 1 mm
Micro gears 10-100 μm diameter
DVD track
1 μm Electrodes connected with nanotubes
Carbon nanotube ~ 2 nm diameter
Atomic corral ~ 14 nm diameter

The Microworld

10⁻³ m
1 mm
10⁻⁶ m
1 μm
10⁻⁹ m
1 nm
0.1 nm

The Nanoworld

10⁻⁶ m
1 μm
10⁻⁹ m
1 nm
0.1 nm
Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV - 280 eV)
Water is almost transparent to radiation in this range while nitrogen and carbon are absorbing (and scattering)

Coherent Imaging of biological samples
protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10^{11} photons/pulse needed

Courtesy F. Stellato, UniToV
The average diameter of the virus particles is around 120 nm. The diameter of the envelope is ~80 nm and the spikes are ~20 nm long.
Light Source research on SARS-CoV-2

https://lightsources.org/2020/04/03/lightsource-research-and-sars-cov-2/

https://www.diamond.ac.uk/covid-19.html
The crystal structure of COVID-19 main protease in complex with an inhibitor N3

Electron density at the active site of the SARS-CoV-2 protease, revealing a fragment bound
https://lightsources.org/2020/03/14/lightsource-research-and-sars-cov-2/
Cell Membrane Proteins Imaged in 3-D

Using lanthanide-binding tags is possible to image proteins at the level of a cell membrane, opening new doors for studies on health and medicine.

Ultrabright x-rays revealed the concentration of **erbium** and **zinc** in a single E.coli cell expressing a lanthanide-binding tag and incubated with erbium.
SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)
PWFA vacuum chamber at SPARC_LAB
External Injection

\[ \Delta T_w = \left( R - \frac{q}{Q} \right) |\Delta T_D| \]

\[ R \approx 2 \]
Figura 2: fascio witness accelerato a SPARC_LAB. Immagine acquisita sulla targhetta a valle dello spettrometro magnetico. L’energia iniziale (senza plasma) è di 89.8 MeV. Accendendo il plasma, il witness guadagna 6 MeV lungo i 3 cm del capillare, arrivando a 95.8 MeV.

http://w3.lnf.infn.it/primi-elettroni-accelerati-con-plasma-a-sparc_lab/
Grazie per l’attenzione