ACCELERATOR GROUP
European Physical Society

IPAC23

14th International Particle Accelerator Conference

IPAC '23

7 - 12 May 2023

VENICE, ITALY

Hosting institutions

Elettra Sincrotrone Trieste

INFN
Istituto Nazionale di Fisica Nucleare

Student Tutorials 5,6 May

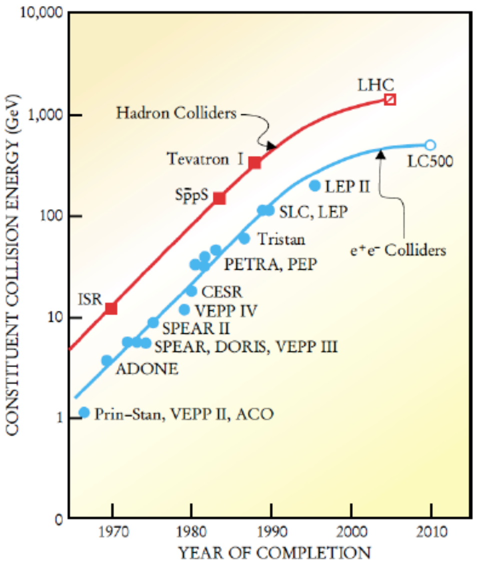
IPAC23

Challenges of plasma cell-based accelerators

Enrica Chiadroni
(SBAI Dept. Sapienza University of Rome and INFN-LNF)

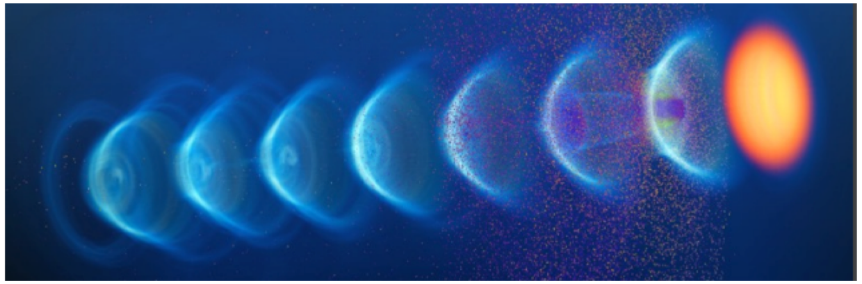
Outline

- Saturation of conventional accelerators technology

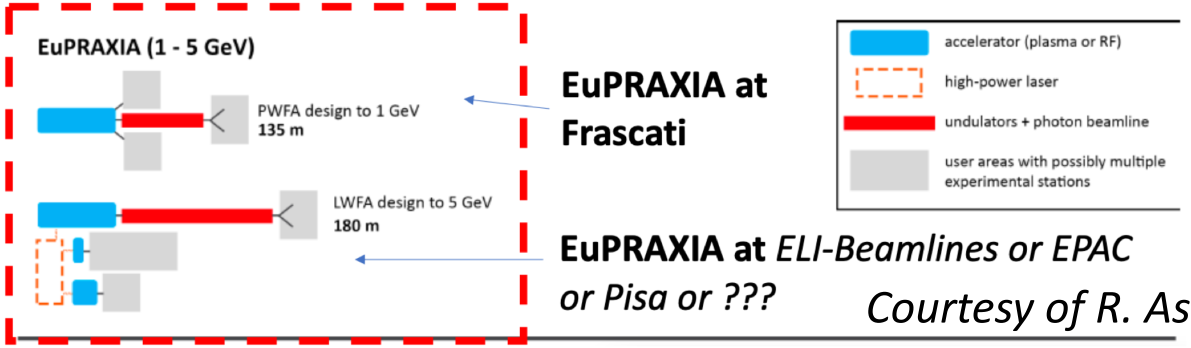


M. Tigner, DOES ACCELERATOR-BASED PARTICLE PHYSICS HAVE A FUTURE? *Phys. Today* (2001)

- Novel acceleration techniques
  - Plasma-based accelerators driven either by laser or particle beams



- Towards compact facilities for High Energy Physics studies and novel radiation sources production



EuPRAXIA (1 - 5 GeV)

PWFA design to 1 GeV
135 m

LWFA design to 5 GeV
180 m

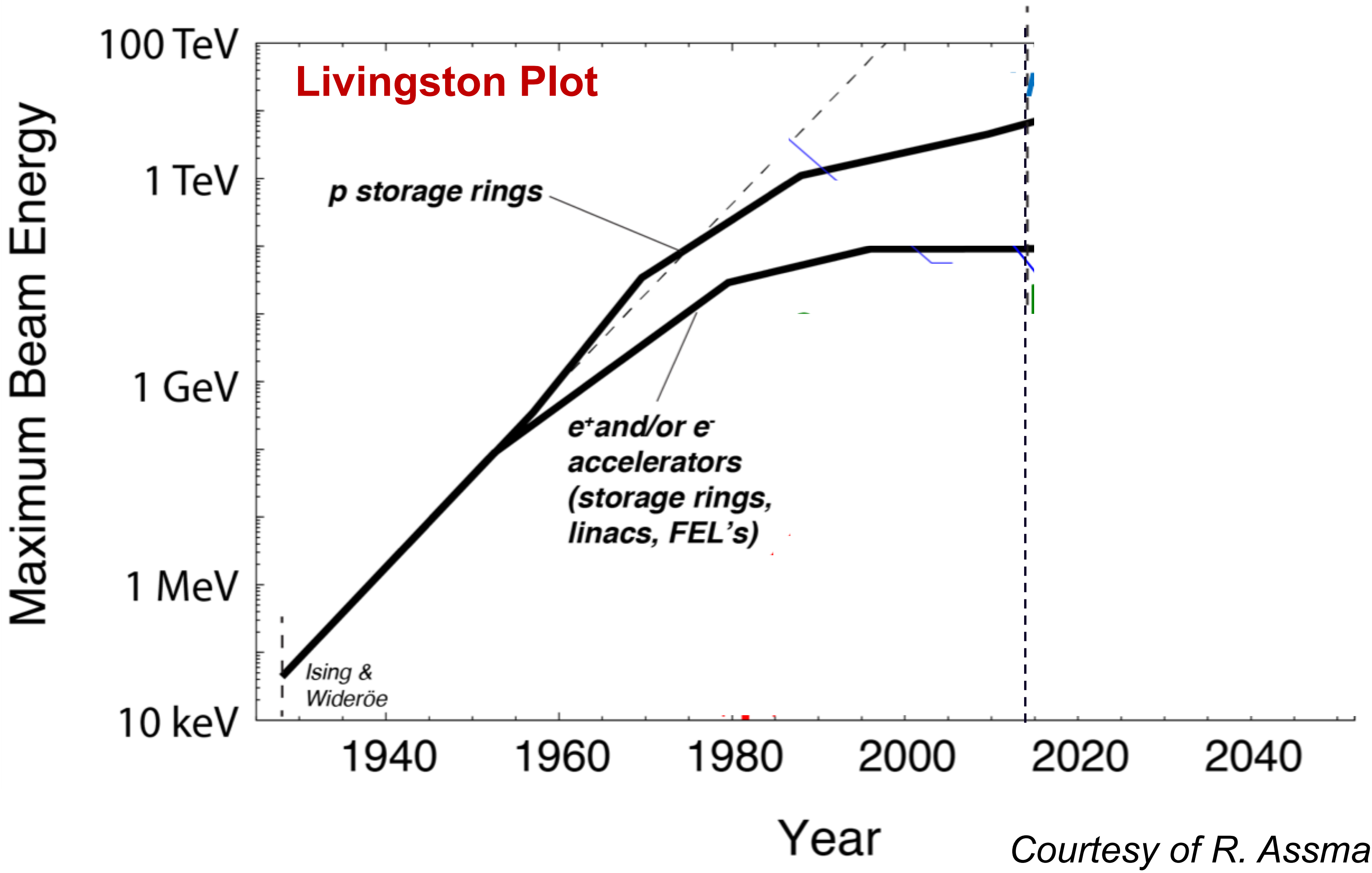
EuPRAXIA at Frascati

EuPRAXIA at ***ELI-Beamlines or EPAC or Pisa or ???***

🟦	accelerator (plasma or RF)
▭	high-power laser
🟥	undulators + photon beamline
⬜	user areas with possibly multiple experimental stations

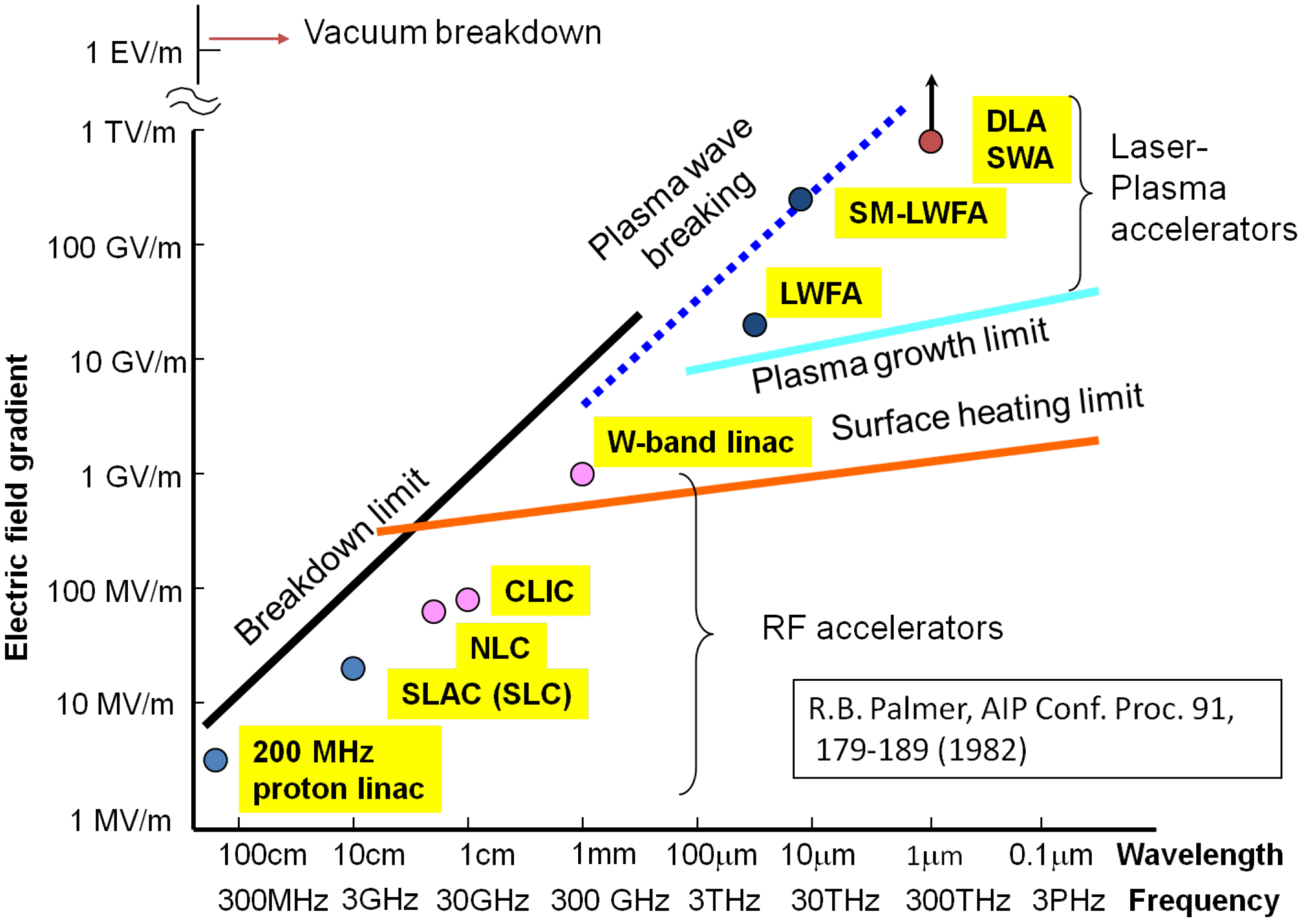
Courtesy of R. Assmann

Saturation of Accelerator Technology



Courtesy of R. Assmann, EAAC 2015, 9/2015

Accelerating Field Limits



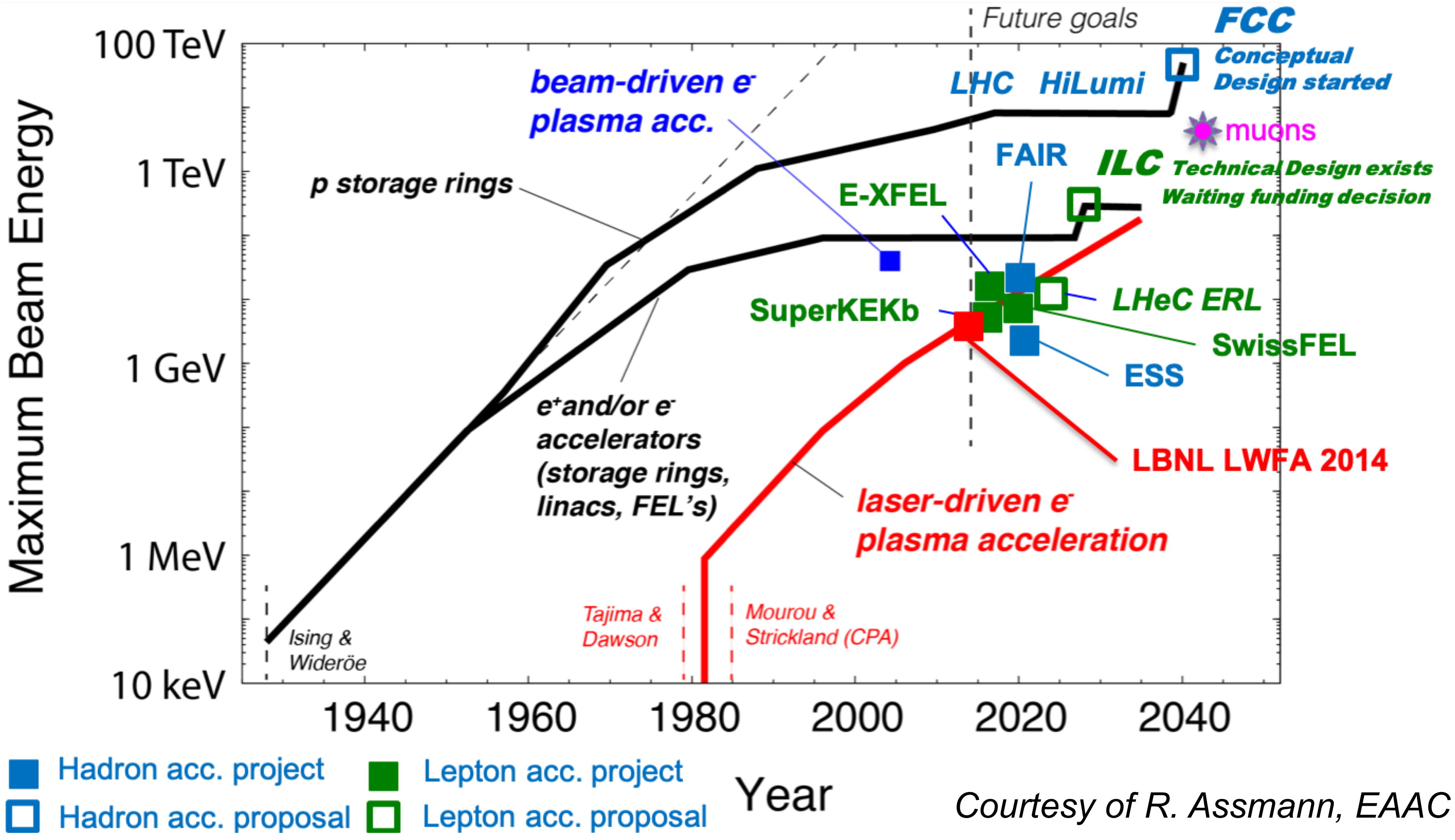
R.B. Palmer, AIP Conf. Proc. 91, 179-189 (1982)

- **Gradient limited by material breakdown**
    - e.g. X-band demonstration around 120 MV/m)
- **High-gradient field => reduction of operating wavelength**, from RF to the THz

$$E_s(MV/m) = 220[f(GHz)]^{1/3}$$

- Challenges in power generation
    - ***new paradigma in the excitation of accelerating waves***

Updated Livingston Plot

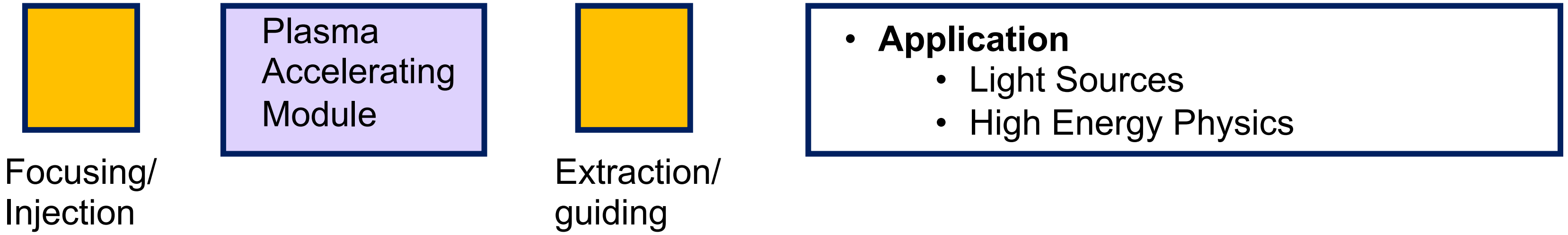


Courtesy of R. Assmann, EAAC 2015, 9/2015

Towards Compact Facilities

- ***Multi GeV*** acceleration ***in cm scale*** plasma structures

- Acceleration of high brightness electron beams and their transport up to the final application, preserving the high quality of the 6D beam phase space



Focusing/ Injection

Plasma Accelerating Module

Extraction/ guiding

- **Application**
  - Light Sources
  - High Energy Physics

- Injection and matching to plasma accelerating module
- Extraction and guiding to final application

International Scenario

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, ...

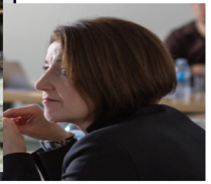
PRODUCTION FACILITIES

Plasma-based **linear collider** in 2040's

Plasma-based **FEL** in 2030's

Medical, industrial applications soon

Courtesy R. Assmann



High Gradient Options

- **RF** accelerating structures, **from X-band to K-band**

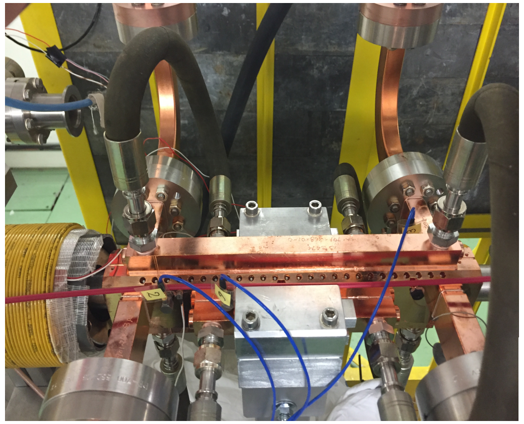
  $100\ \mathrm{MV/m} < E_{acc} < 1\ \mathrm{GV/m}$

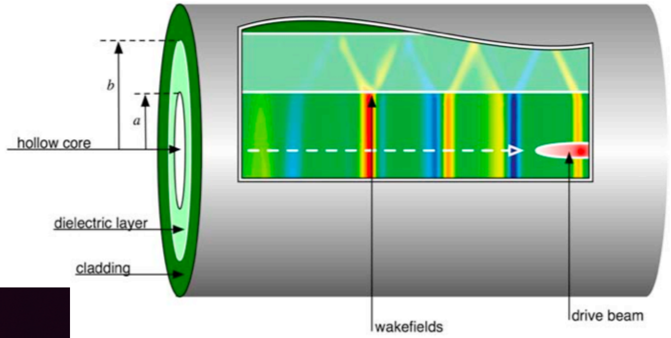
- Dielectrict structures, laser or particle driven

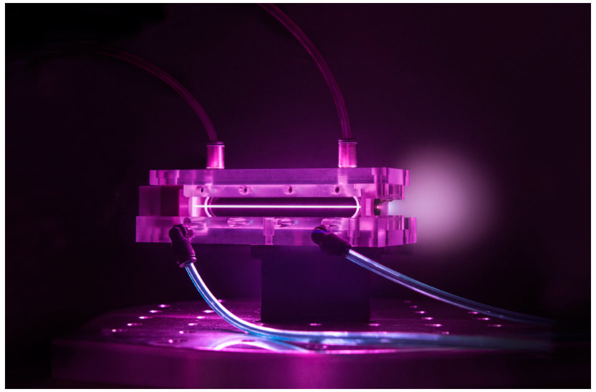
  $1\ \mathrm{GV/m} < E_{acc} < 5\ \mathrm{GV/m}$

- Plasma accelerator, laser or particle driven

  $1\ \mathrm{GV/m} < E_{acc} < 100\ \mathrm{GV/m}$







Acceleration in Vacuum

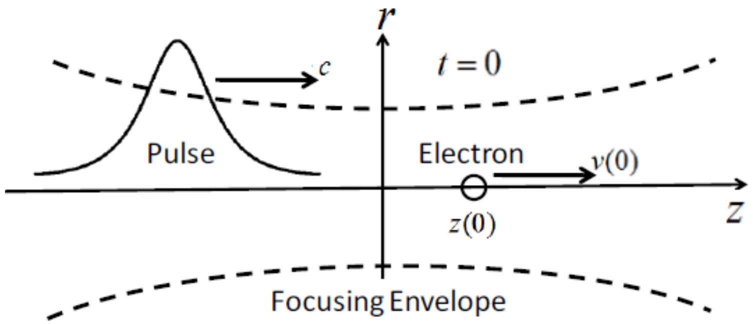
In vacuum, the motion of an electron in a laser field $\vec{E}(\vec{r},t) = \vec{E}_s(\vec{r},t)\cos(\omega t)$ is determined by the Lorentz force equation

"direct" laser acceleration

$$\frac{d\vec{p}}{dt} = -e\left[\vec{E} + \frac{1}{c}\left(\vec{v}\times\vec{B}\right)\right]$$

"ponderomotive" laser acceleration

Let consider an electron initially (t=0) on the beam axis of the laser at z = z(0), moving in the longitudinal direction with velocity $\vec{v}(0) = v(0)\hat{z}$



Acceleration in Vacuum

When a laser field propagating along the *z* axis is focused in vacuum, the laser spot size and intensity, assuming a fundamental Gaussian mode, evolve as

$$r_s = r_0\sqrt{1+\frac{z^2}{Z_R^2}} \qquad I = I_0\frac{r_0{}^2}{r_s{}^2}e^{-\frac{2r^2}{r_s{}^2}}$$

$$Z_R = \frac{kr_0{}^2}{2}$$ Rayleigh length

The finite laser spot size implies the existence of an axial component of the laser electric field via

$$\nabla\cdot\vec{E}=0,\ \text{i.e.}\ E_z \approx \frac{1}{kr_0}E_\perp$$

The amplitude of the axial field can be very large: the axial field might be directly used for laser acceleration.

However, $v_{ph} > c$ and near the focus is $\frac{v_{ph}}{c} \cong 1+\frac{1}{kZ_R}$

Since $v_{ph} > c$, **electrons** with $v_z < c$ **will phase slip with respect to the accelerating field and decelerate**.

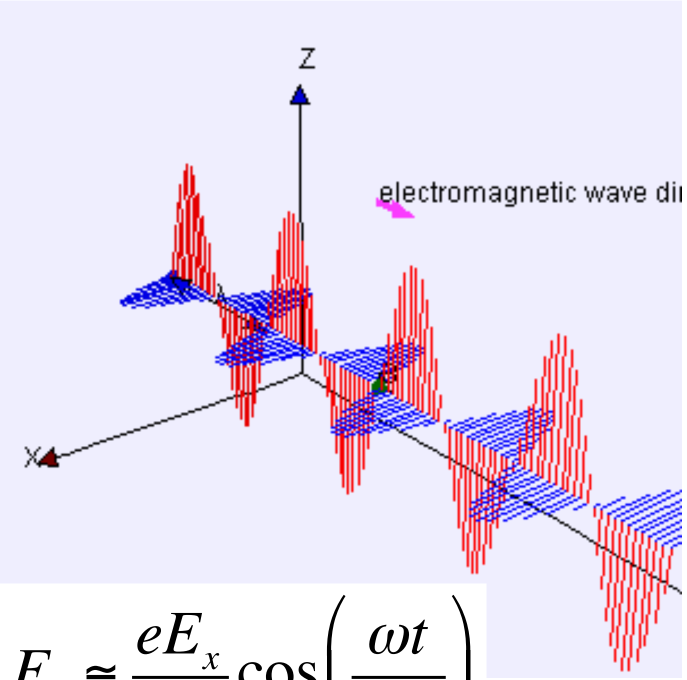
Lawson-Woodward Theorem

The net energy gain of a relativistic electron interacting with an electromagnetic field **in vacuum** is zero

The theorem assumes that
(i) the em field is in vacuum **with no walls or boundaries present**
(ii) the electron is highly relativistic ($v \approx c$) along the acceleration path
(iii) no static electric or magnetic fields are present
(iv) the region of interaction is infinite
(v) ponderomotive effects (nonlinear forces, e.g. **v** x **B** force) are neglected

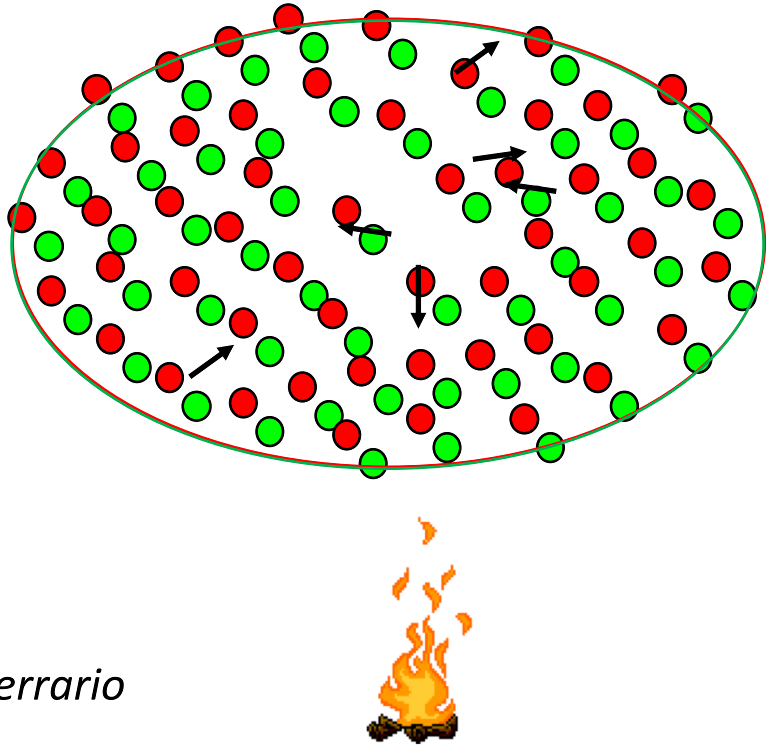
Acceleration mechanism must violate the Lawson-Woodward theorem

J.D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217, 1979
P.M. Woodward, J. Inst. Electr. Eng. 93, 1554, 1947



$$F_\perp \cong \frac{eE_x}{2\gamma^2}\cos\left(\frac{\omega t}{2\gamma^2}\right)$$

Plasma Model

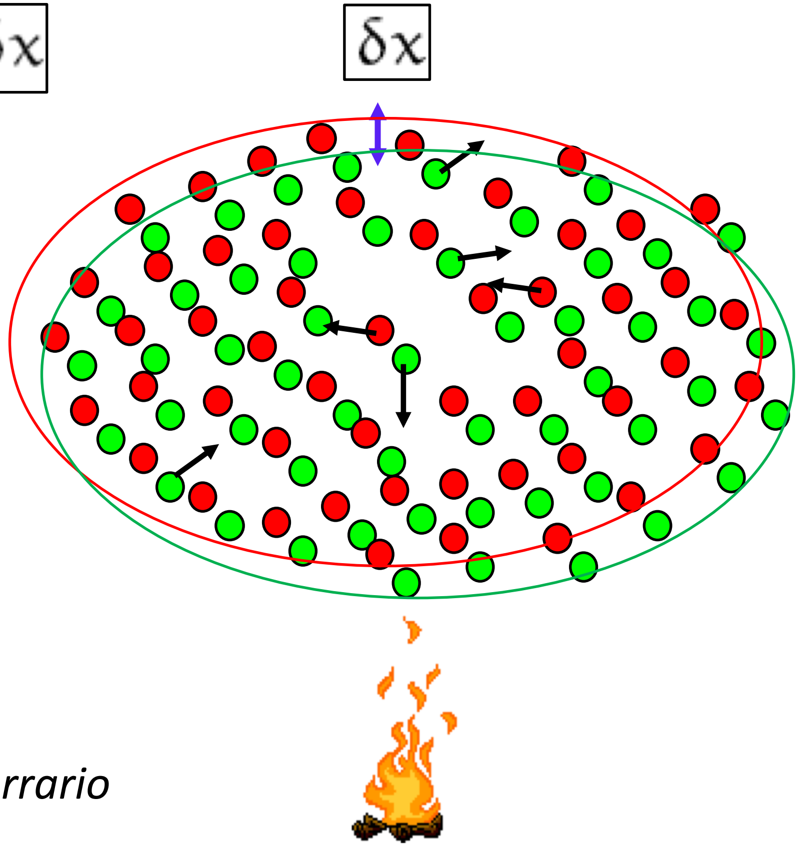


Courtesy of M. Ferrario

Plasma Model

Surface charge density

$$\sigma = e n \delta x$$

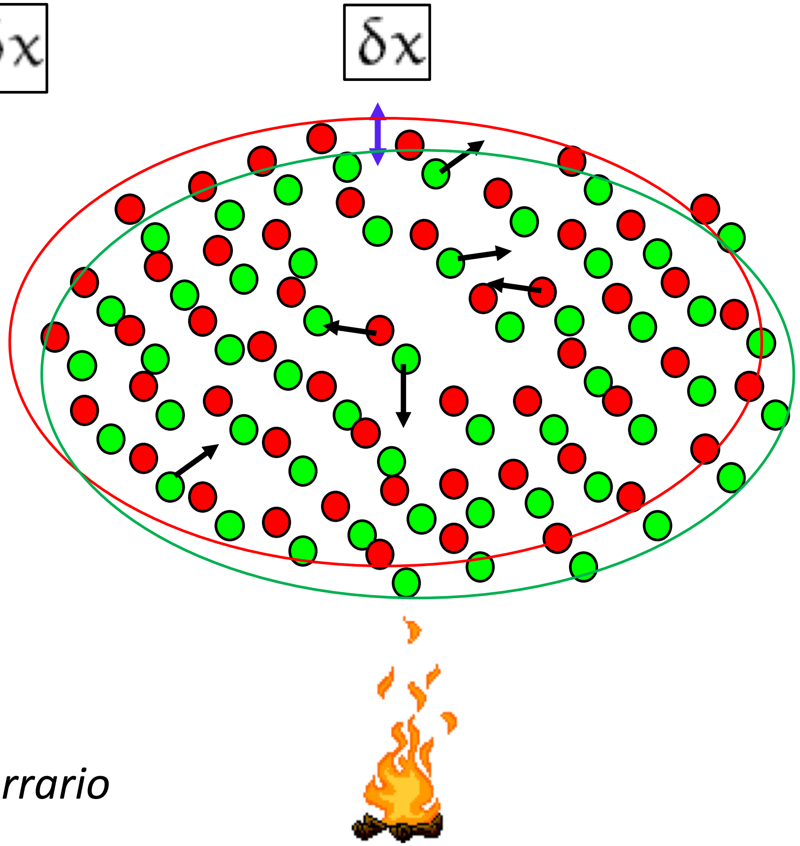


Courtesy of M. Ferrario

Plasma Model

Surface charge density

$$\boxed{\sigma = e\,n\,\delta x}$$



Courtesy of M. Ferrario

Surface electric field

$$E_x = -\sigma/\epsilon_0 = -e\,n\,\delta x/\epsilon_0$$

Restoring force

$$m\frac{d^2\delta x}{dt^2} = e\,E_x = -m\,\omega_p{}^2\,\delta x$$

Plasma oscillations

$$\delta x = (\delta x)_0 \cos(\omega_p t)$$

Plasma frequency

$$\boxed{\omega_p{}^2 = \frac{n\,e^2}{\epsilon_0\,m}}$$

Collective behavior !!

Plasma Definition

- A partially or completely ionized gas, globally neutral, is a plasma if it exhibits a **collective behavior**
  - Coulomb shielding
    - Dimensions >> Debye length

$$\lambda_D = \sqrt{\frac{kT\varepsilon_0}{ne^2}}$$

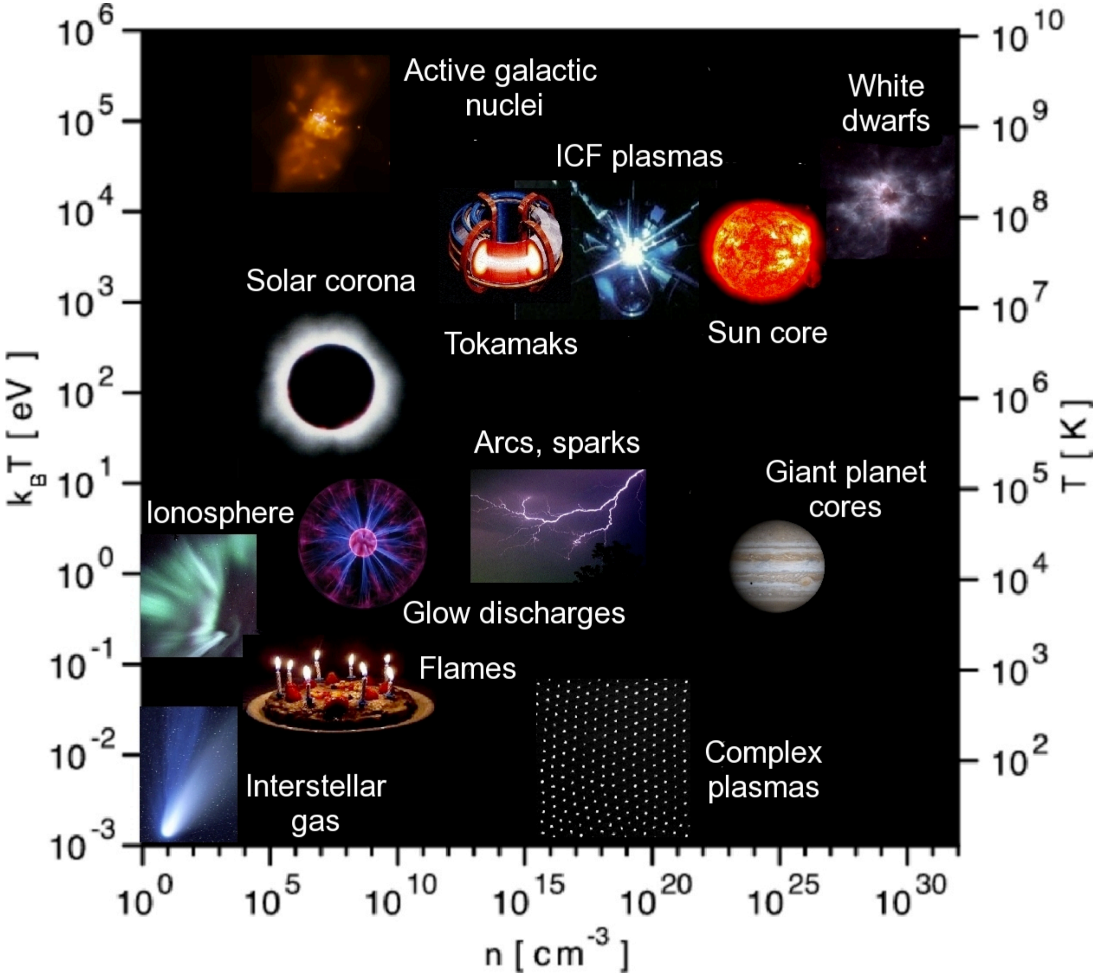
  - Plasma Oscillations
    - Temporal response >> ω_p^{-1}

$$\omega_p = \sqrt{\frac{ne^2}{m\varepsilon_0}}$$

- The large electric fields a plasma can sustain are supported by collective motion of plasma electrons, forming a **space charge disturbance** moving at a speed slightly smaller than *c*

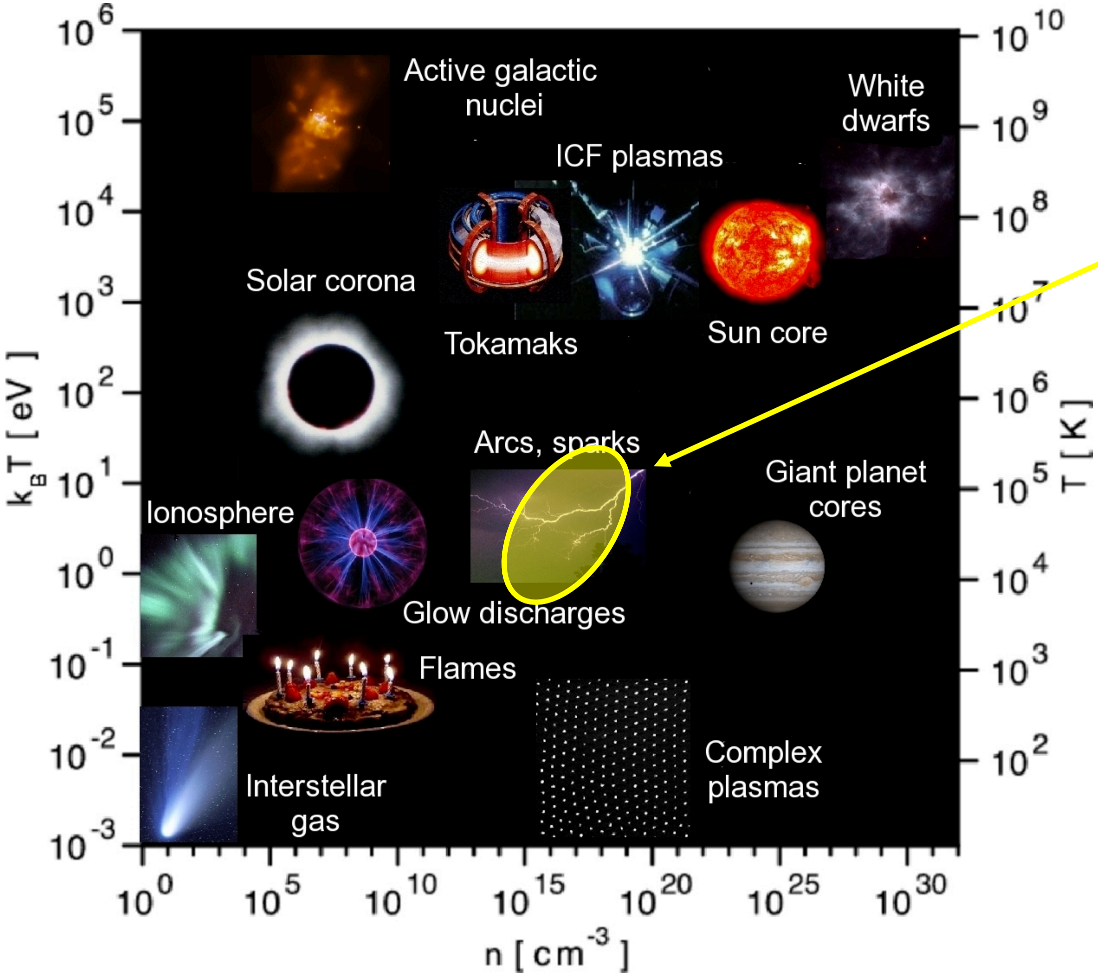
Plasma States

In Nature and in Laboratory



Plasma for Accelerators

In Nature and in Laboratory



Plasma-based accelerators

Laser-driven Plasma Wakefield Acceleration (LWFA)

Let us consider a **charge q in an oscillating electric field with a non-uniform envelope**

$$\vec{E}(\vec{r},t) = \vec{E}_s(\vec{r},t)\cos(\omega t)$$ Laser Field (**LWFA**)

Hypotheses

1. Slowly varying envelope approximation (**SVEA**): $\vec{E}_s(\vec{r},t) \approx \vec{E}_s(\vec{r})$

2. **Non relativistic** equation of motion $m\frac{d\vec{v}}{dt} = q\left[\vec{E}(\vec{r},t) + \vec{v}\times\vec{B}(\vec{r},t)\right]$

$\vec{v}\times\vec{B}(\vec{r},t) \ll \vec{E}(\vec{r},t)$ but not negligible (**II order theory**)

3. Position of q = "**slow**" drift + "**fast**" oscillation

$$\vec{r}(t) = \vec{r}_0(t) + \delta\vec{r}_1(t)$$

$$\delta\vec{r}_1(t) \ll \vec{r}_0(t) \qquad |\vec{v}_0| \ll |\vec{v}_1| \qquad \left|\frac{d\vec{v}_0}{dt}\right| \ll \left|\frac{d\vec{v}_1}{dt}\right|$$

Let's first neglect the **B** field and Taylor expand the **E** field around: $\vec{r}_0(t)$

$$m\frac{d\vec{v}}{dt} = m\frac{d\vec{v}_0}{dt} + m\frac{d\vec{v}_1}{dt} = q\left[\underbrace{\vec{E}_s(\vec{r}_0) + (\delta\vec{r}_1\cdot\nabla)\,\vec{E}_s(\vec{r}_0)}_{\approx \vec{E}_s(\vec{r}_0)}\right]\cos(\omega t)$$

Hyp. III

$$m\frac{d\vec{v}_1}{dt} \approx q\vec{E}_s(\vec{r}_0)\cos(\omega t)$$

$$\Downarrow$$

$$\vec{v}_1 = \frac{q}{m\omega}\vec{E}_s(\vec{r}_0)\sin(\omega t)$$

$$\delta\vec{r}_1 = -\frac{q}{m\omega^2}\vec{E}_s(\vec{r}_0)\cos(\omega t)$$

...

Moreover from III Maxwell equation:

$$\nabla \times \vec{E} = \left[\nabla \times \vec{E}_s(\vec{r}_0)\right] \cos(\omega t) = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{B}(\vec{r}_0, t) = -\frac{1}{\omega}\left[\nabla \times \vec{E}_s(\vec{r}_0)\right] \sin(\omega t)$$

Then, the particle motion equation $m\frac{d\vec{v}}{dt} = q\left[\vec{E}(\vec{r},t) + \vec{v} \times \vec{B}(\vec{r},t)\right]$

$$m\frac{d\vec{v}}{dt} = m\frac{d\vec{v}_0}{dt} + m\frac{d\vec{v}_1}{dt} = q\vec{E}_s(\vec{r}_0)\cos(\omega t) + \left[\overbrace{\frac{-q^2}{m\omega^2}\left(\vec{E}_s(\vec{r}_0)\cdot\nabla\right)\vec{E}_s(\vec{r}_0)\cos(\omega t)^2}^{q\,(\delta\vec{r}_1\cdot\nabla)\,\vec{E}_s(\vec{r}_0)\cos(\omega t)}\right.$$

$$\left. - \frac{-q^2}{m\omega^2}\underbrace{\vec{E}_s(\vec{r}_0)\times\left(\nabla\times\vec{E}_s(\vec{r}_0)\right)\sin(\omega t)^2}_{q\vec{v}_1\times\vec{B}(\vec{r},t)}\right]$$

Then, the particle motion equation $m\frac{d\vec{v}}{dt} = q\left[\vec{E}(\vec{r},t) + \vec{v}\times\vec{B}(\vec{r},t)\right]$

$$m\frac{d\vec{v}_0}{dt} = \frac{-q^2}{m\omega^2}\left[\left(\vec{E}_s(\vec{r}_0)\cdot\nabla\right)\vec{E}_s(\vec{r}_0)\cos(\omega t)^2 + \vec{E}_s(\vec{r}_0)\times\left(\nabla\times\vec{E}_s(\vec{r}_0)\right)\sin(\omega t)^2\right]$$

$$\left\langle m\frac{d\vec{v}_0}{dt}\right\rangle_T = \frac{-q^2}{2m\omega^2}\left[\underbrace{\left(\vec{E}_s(\vec{r}_0)\cdot\nabla\right)\vec{E}_s(\vec{r}_0) + \vec{E}_s(\vec{r}_0)\times\left(\nabla\times\vec{E}_s(\vec{r}_0)\right)}_{\frac{1}{2}\nabla\left[E_s(\vec{r}_0)^2\right]}\right]$$

Ponderomotive Force

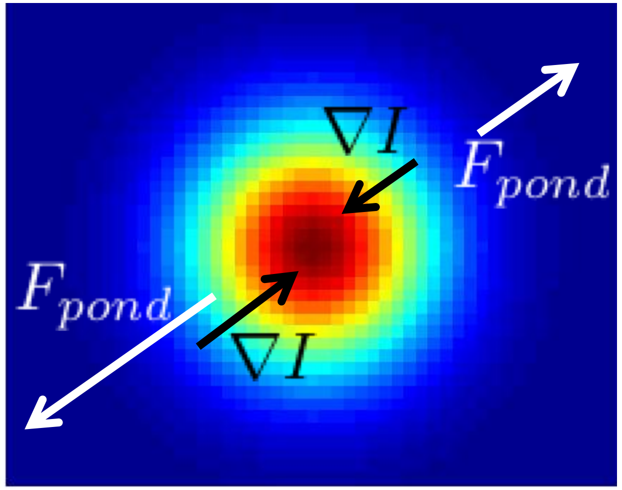
$$\left\langle m\frac{d\vec{v}}{dt}\right\rangle_T = \left\langle m\frac{d\vec{v}_0}{dt}\right\rangle_T = \frac{-q^2}{4m\omega^2}\nabla\left[\vec{E}_s(\vec{r}_0)^2\right]$$

Ponderomotive force

Ponderomotive force per unit volume

$$n\frac{-q^2}{4m\omega^2\epsilon_0}\nabla\left[\epsilon_0 E_s(\vec{r}_0)^2\right] = -\frac{\omega_p^2}{\omega^2}\nabla\left[\frac{\langle\epsilon_0 E^2\rangle}{2}\right]$$

$$F_{pond} \propto -q^2\frac{\nabla(\text{wave intensity})}{m} = -q^2\frac{\nabla I}{m}$$



Any charge escapes from the region of greater radiation intensity, like under a pressure ...

Electrons undergoes to a greater force than ions (force depends on the mass, ... **pondus**)

Limits to Acceleration Length

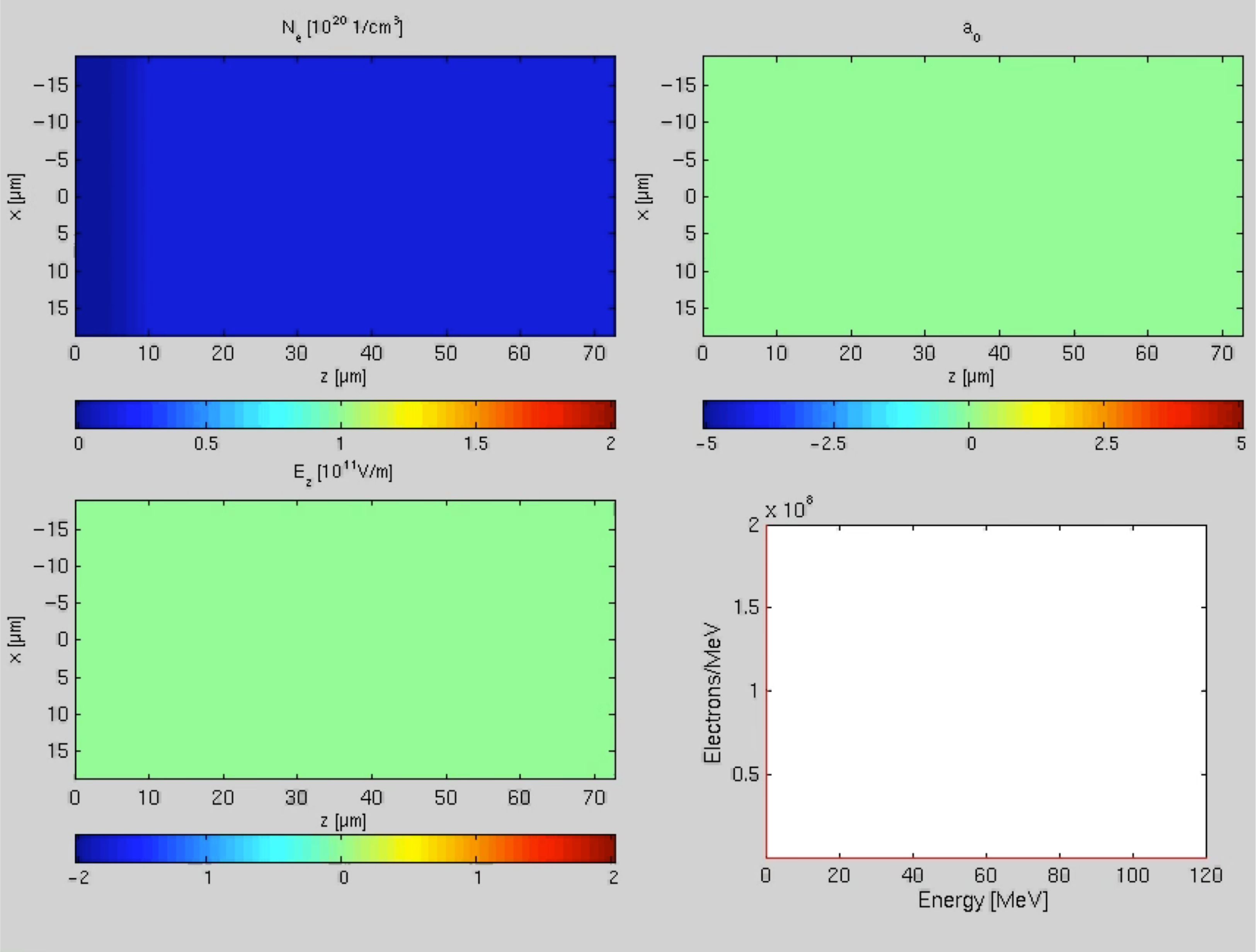
- Laser pulse diffraction
  - Limits laser-plasma interaction length to ~ Rayleigh range
    - **SOLUTION**: transverse plasma density tailoring => guiding capillary
- Electron dephasing
  - Slippage between e-beam and plasma wave

$$L_{\text{dephase}} = \lambda_p/2(1-\beta_p) \approx \lambda_p^3/\lambda^2$$

    - **SOLUTION**: longitudinal plasma density tailoring => tapered density or capillary

- Laser pulse energy depletion
  - Rate of laser energy deposition into plasma wave excitation
    - **SOLUTION**: Staging

$$L_{\text{deplete}} \propto n^{-3/2}\lambda^{-2}$$



N_e [10^{20} 1/cm^3]
a_0
x [μm]
−15
−10
−5
0
5
10
15
0
10
20
30
40
50
60
70
z [μm]
0
0.5
1
1.5
2
−5
−2.5
0
2.5
5
E_z [10^{11}V/m]
−2
1
0
1
2
x 10^8
Electrons/MeV
0.5
1
1.5
2
0
20
40
60
80
100
120
Energy [MeV]

The Dawn of Compact Accelerators

September 2004

Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]

A laser–plasma accelerator producing monoenergetic electron beams

J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]

30 September 2004

International weekly journal of science

nature

www.nature.com/nature

Dream beam

The dawn of compact particle accelerators

Offshore tuna ranches
A threat to US waters?

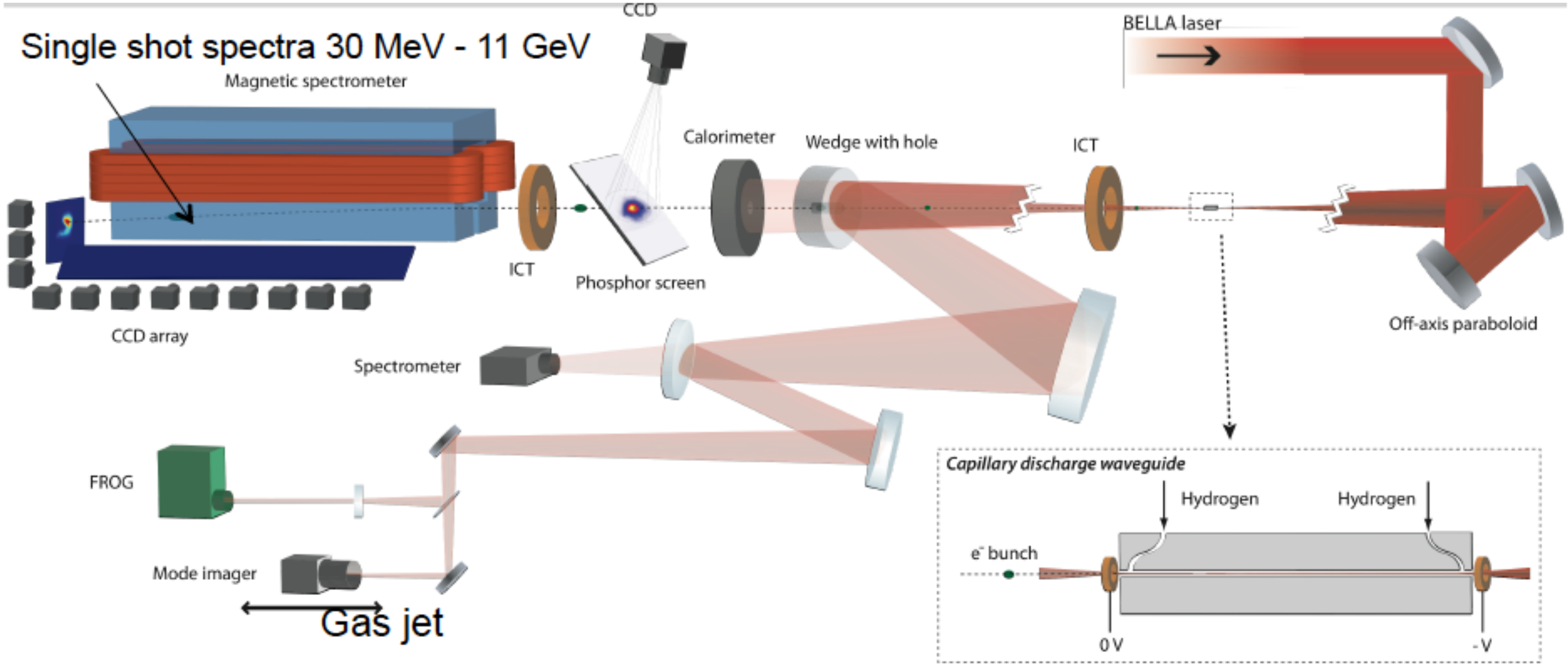
The Earth's hum
Sounds of air and sea

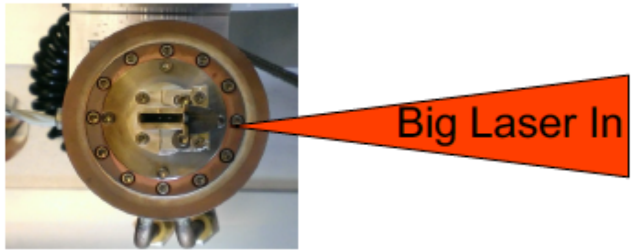
Protein folding
Escape from the ribosome

Human ancestry
One from all and all from one

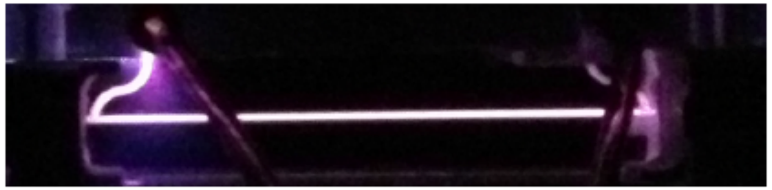
technology feature RNA interference

Experiments at LBNL



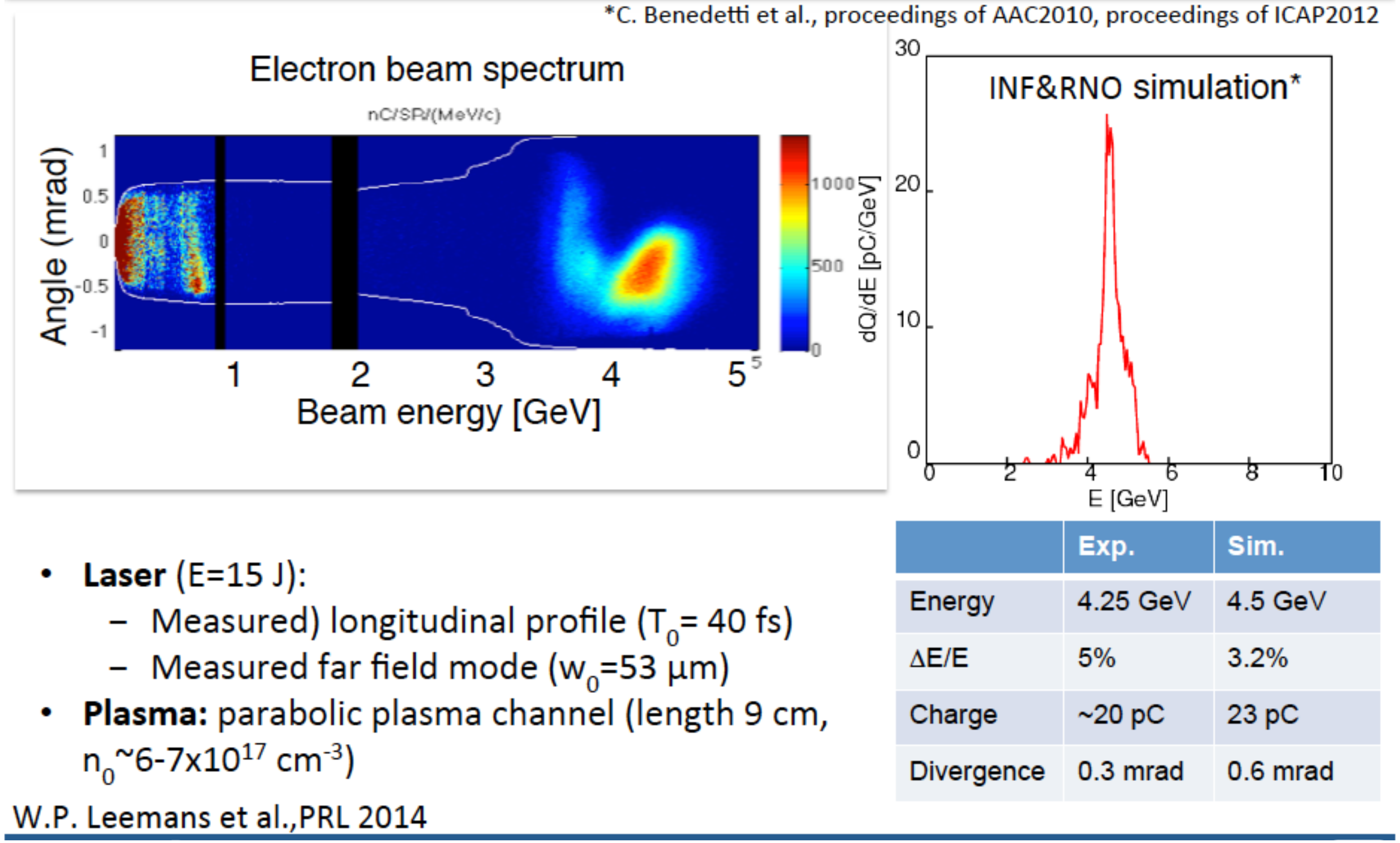


Capillary discharge



The BELLA laser was focused by the 14 m focal length off-axis parabola onto a gas jet or capillary discharge targets

Experiments at LBNL



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

- **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_0~6-7x10^{17} cm^{-3})

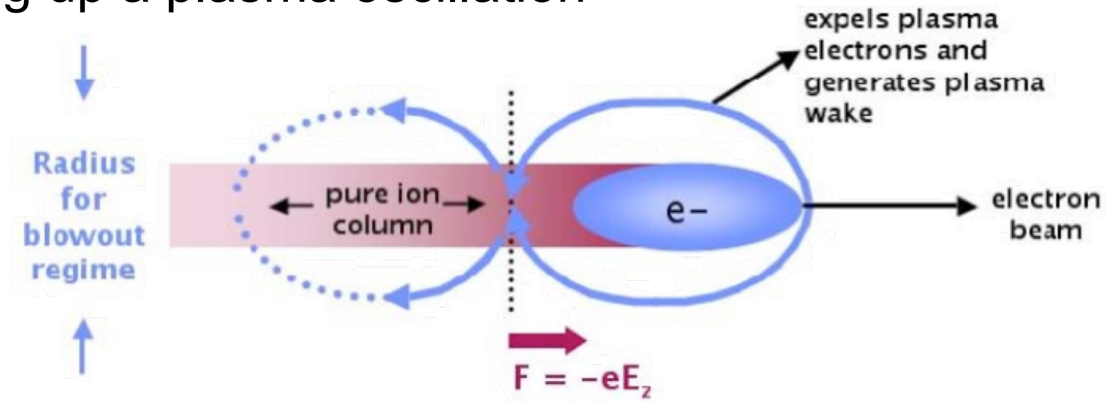
	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

W.P. Leemans et al.,PRL 2014

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

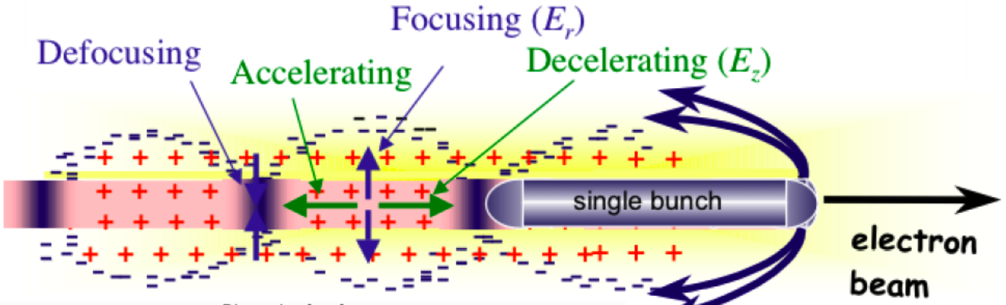
Particle-driven Plasma Wakefield Acceleration (PWFA)

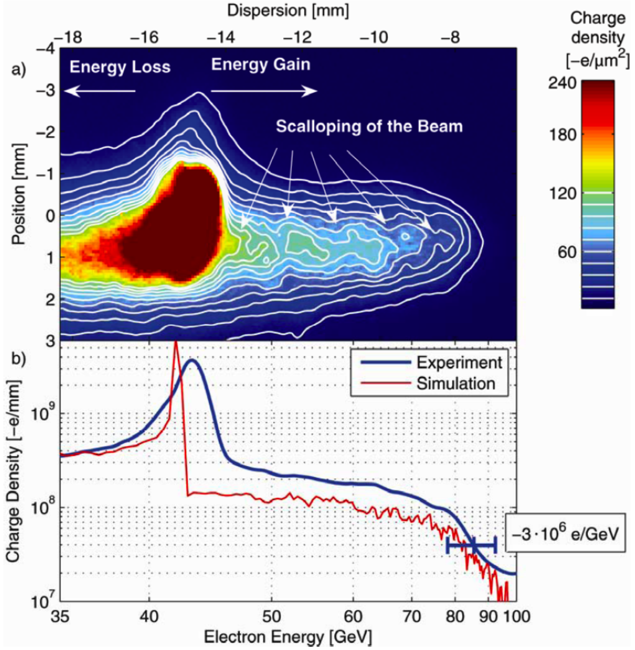
- The high-gradient wakefield is driven by an intense, high-energy charged particle beam as it passes through the plasma.
- The **space-charge** of the electron bunch **blows out plasma electrons which rush back in and overshoot** setting up a plasma oscillation



- First demonstration of the excitation of a wakefield by a relativistic beam in the linear regime, i.e. beam density typically less than the plasma density => J. Rosenzweig et al., Phys. Rev. Lett. 61, 98 (**1988**)
- Peak acceleration gradient ~ 1.6 MeV/m, but the experiment clearly showed the wakefield persisting for several plasma wavelengths.

Particle-driven Plasma Wakefield Acceleration (PWFA)

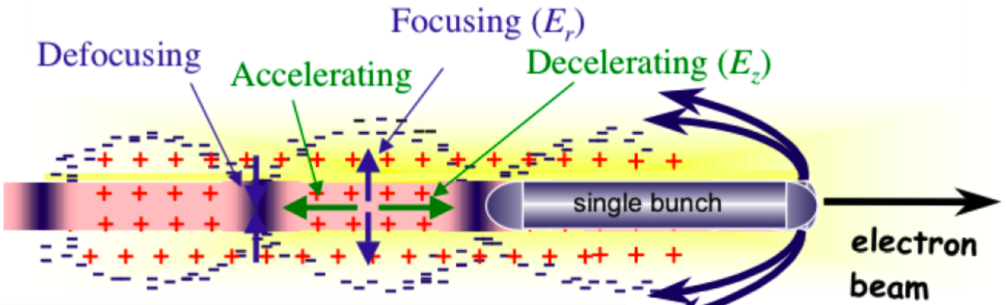


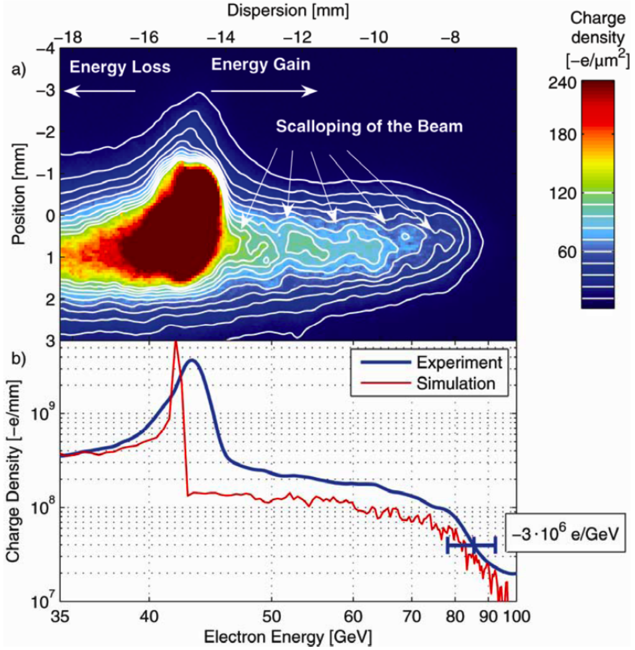


Energy doubling in a meter scale

Blumenfeld, I. et al. **Nature** 445, 741–744 (2007).

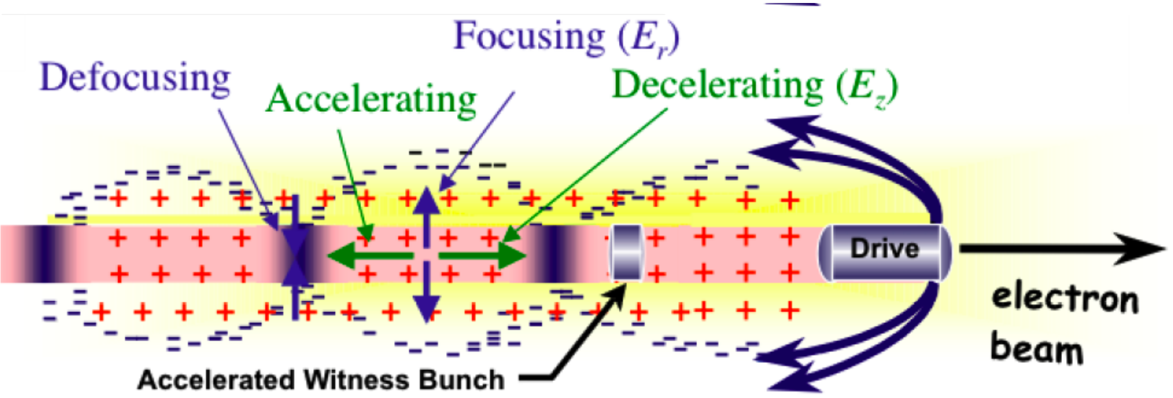
Particle-driven Plasma Wakefield Acceleration (PWFA)

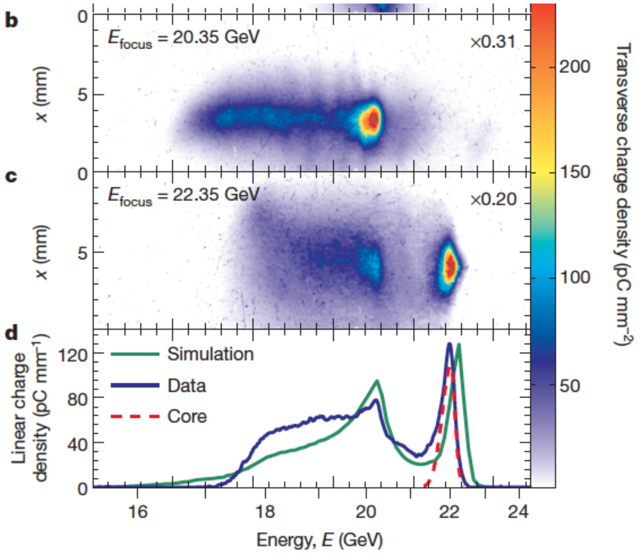




Energy doubling in a meter scale

Blumenfeld, I. et al. **Nature** 445, 741–744 (2007).

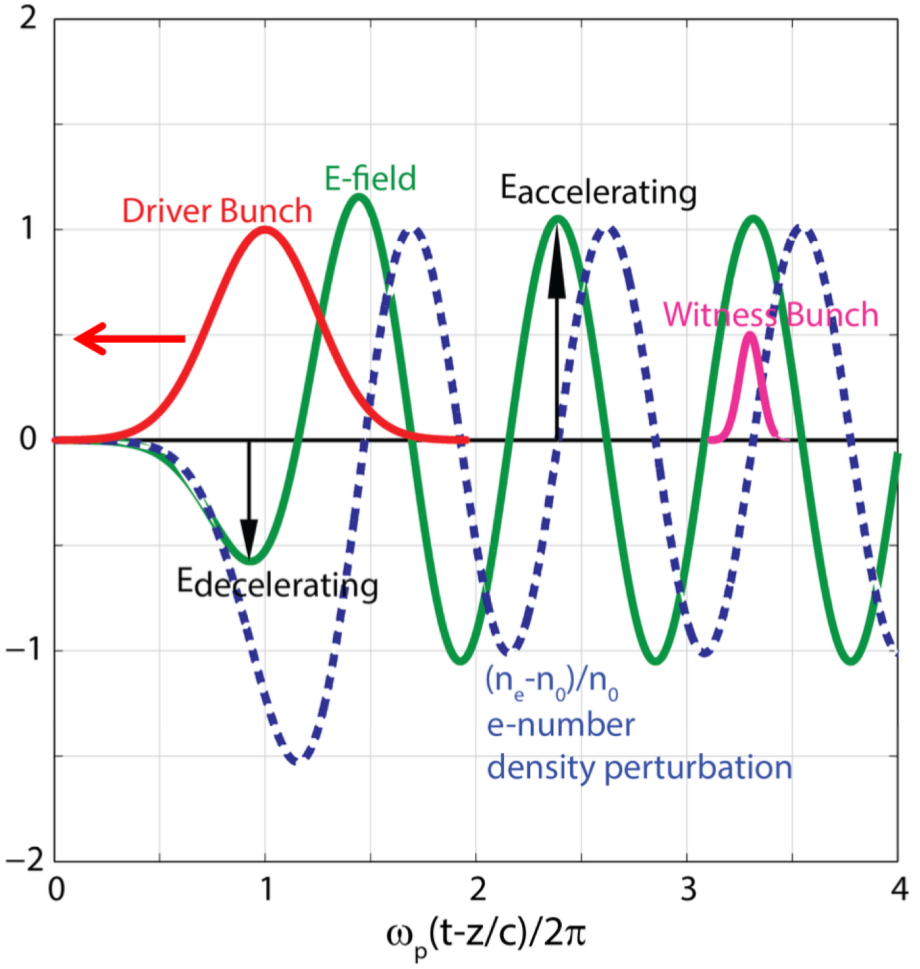




High-efficiency acceleration

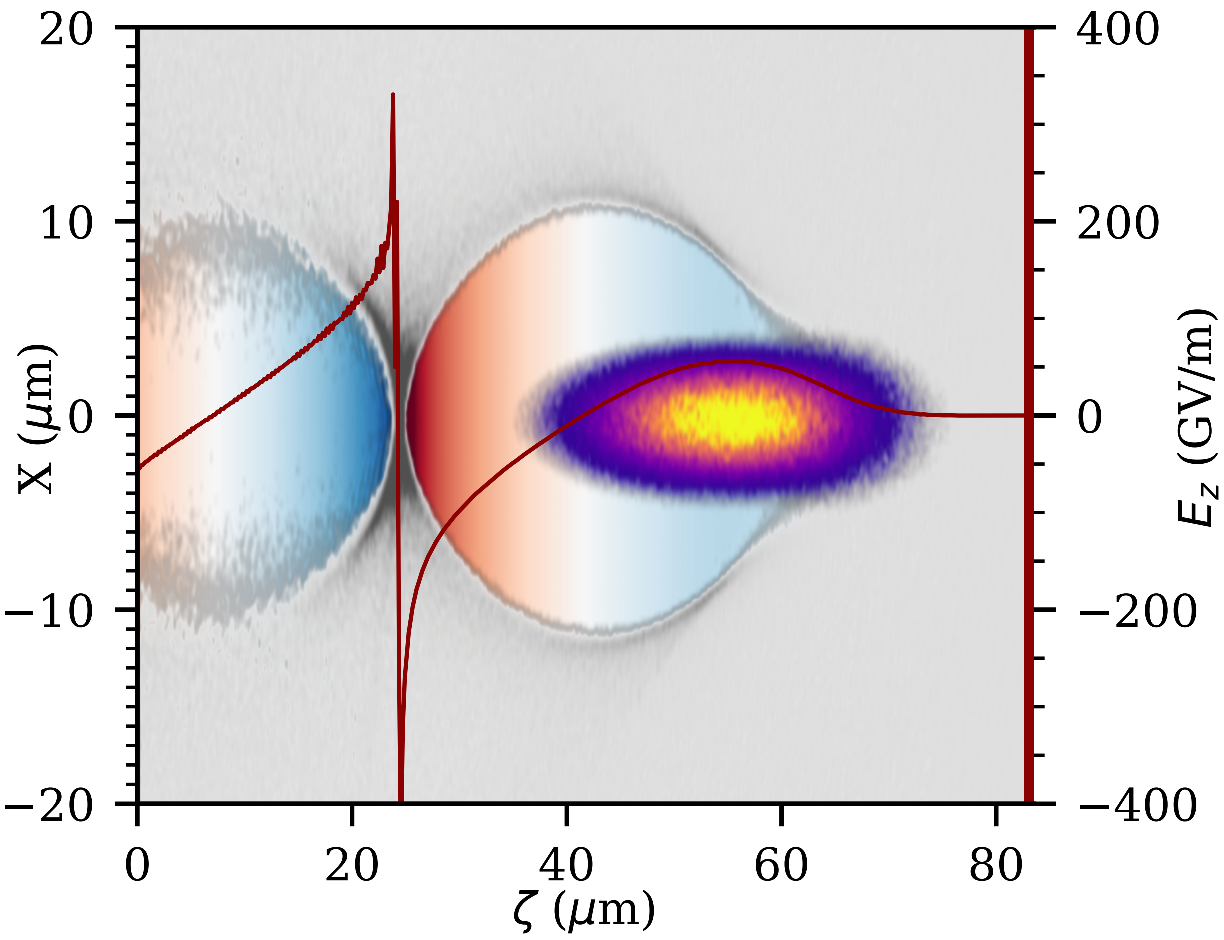
Litos, M. et al. **Nature** 515, 92–95 (2014).

From Linear Regime …



Note:
Focusing force is sinusoidal

… to Quasi Linear and Non Linear Regime

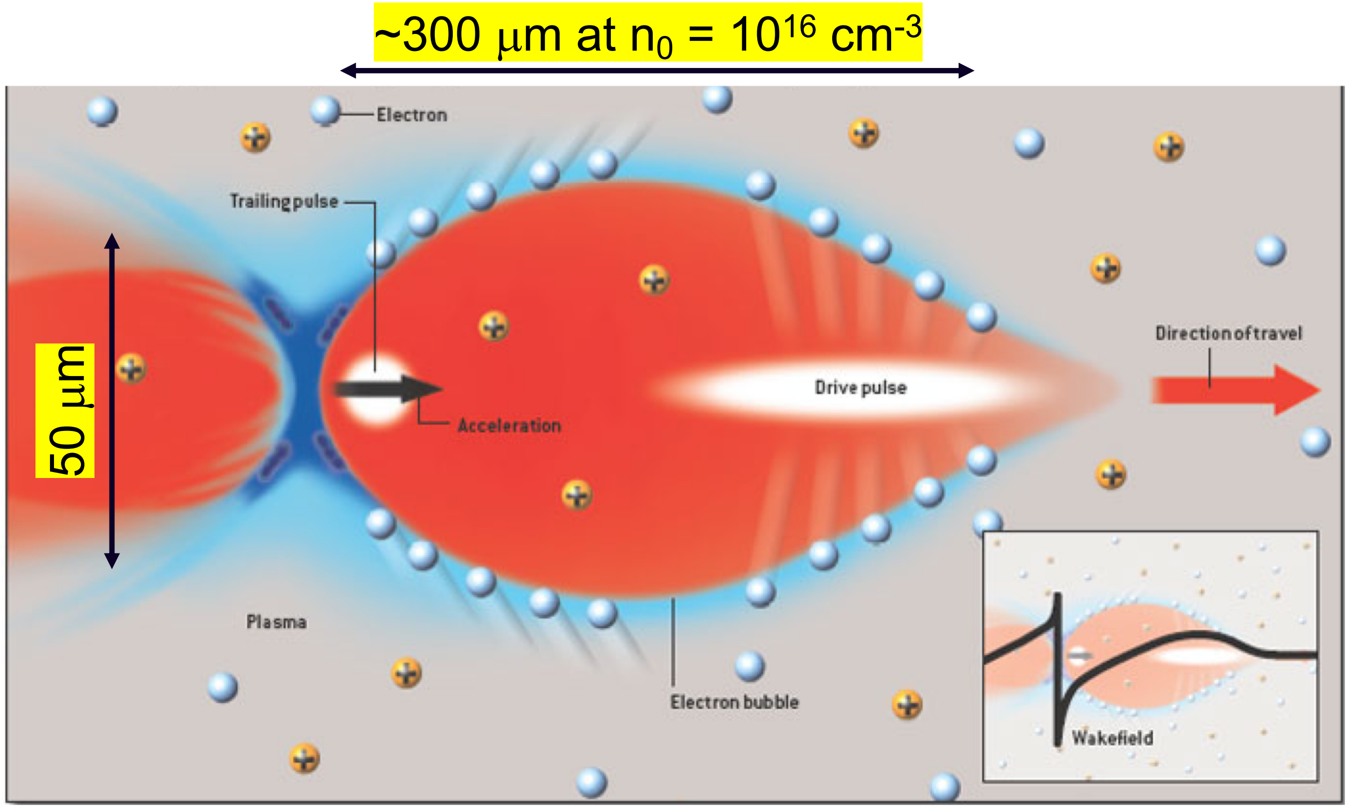


Breakdown Limit

- The **ionized plasma** in a gas-filled discharge capillary, a gas cell or a gas jet **can sustain** accelerating gradient 2-3 orders of magnitude larger than in conventional RF-based accelerators

- Maximum accelerating field a plasma can sustain: **Wave breaking field**

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$



~300 μm at $n_0 = 10^{16}$ cm^{-3}

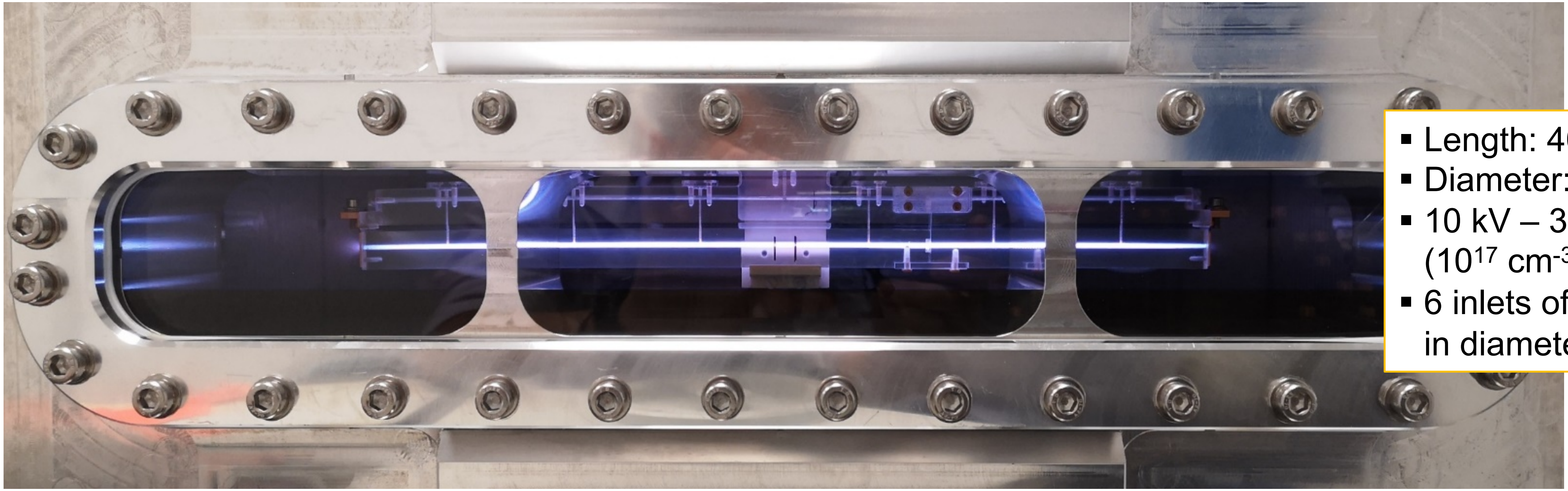
50 μm

- **Characteristic scale length** of the accelerating field, i.e. the plasma wake, is the plasma wavelength,

$$\lambda_p(\mu m) \approx \frac{3.3 \cdot 10^{10}}{\sqrt{n_0(cm^{-3})}}$$

Gas-filled Discharge Capillary

First EuPRAXIA plasma source enabling **1.1 GeV** (1.5 GV/m) in **40 cm** length capillary (n = 10^{16} cm^{-3})



- Length: 40 cm
- Diameter: 2 mm
- 10 kV – 380 A (10^{17} cm^{-3})
- 6 inlets of 1 mm in diameter

Courtesy of A. Biagioni (INFN-LNF)

High Quality Beams

$$\uparrow \quad L = \frac{N_{e+} N_{e-} f_r}{4\pi\sigma_x\sigma_y}$$

- –N of particles per pulse => 10^9
- –**High rep. rate** f_r=> bunch trains

- –Small spot size => **low emittance**

$$\uparrow \quad B_n \approx \frac{2I}{\varepsilon_n^2}$$

- –**Short pulse** (ps to fs)

- –Little spread in transverse momentum and angle => **low emittance**

Towards the Applications

- Extraction from plasma accelerating module
  - plasma fields stronger than in conventional accelerators

$$G(MT/m) = \frac{F_r}{ecr} \approx 3n(10^{17}\ cm^{-3})$$

  - beams experience huge transverse size variation when propagating from the plasma outer surface to the conventional focusing optics

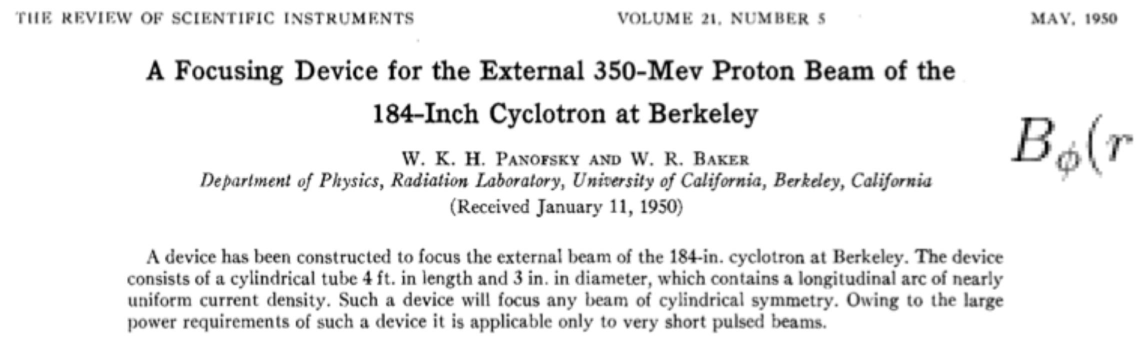
$$\sigma_x \sim \mu m \qquad\qquad \sigma_{x'} \sim mrad$$

  - the particle transverse motion becomes extremely sensitive to energy spread
  - the beam angular divergence has to be reduced and the transverse spot size increased to limit the chromatic induced emittance degradation in vacuum

$$\varepsilon_n^2 =< \gamma >^2 (\sigma_E^2 \sigma_x^2 \sigma_{x'}^2 + \varepsilon^2) \approx < \gamma >^2 (\sigma_E^2 \sigma_{x'}^4 s^2 + \varepsilon^2)$$

M. Migliorati et al., PRST AB ***16****, 011302 (2013)*

Active Plasma Lens Device



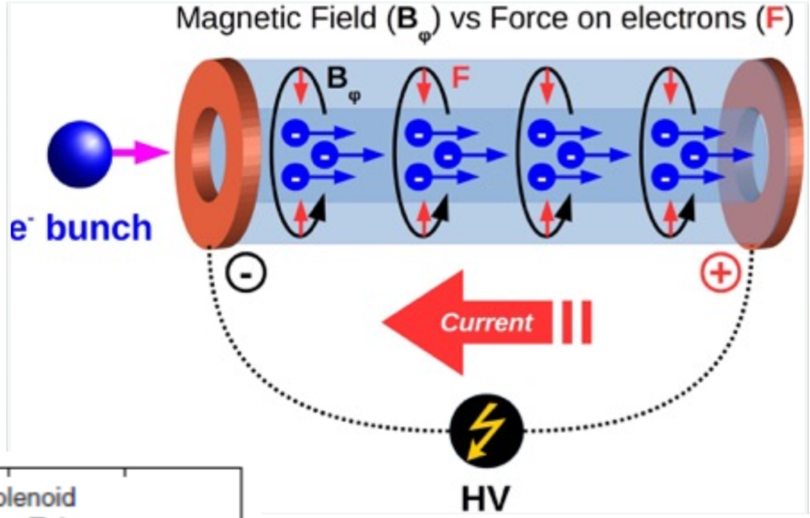
THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 21, NUMBER 5 MAY, 1950

A Focusing Device for the External 350-Mev Proton Beam of the 184-Inch Cyclotron at Berkeley

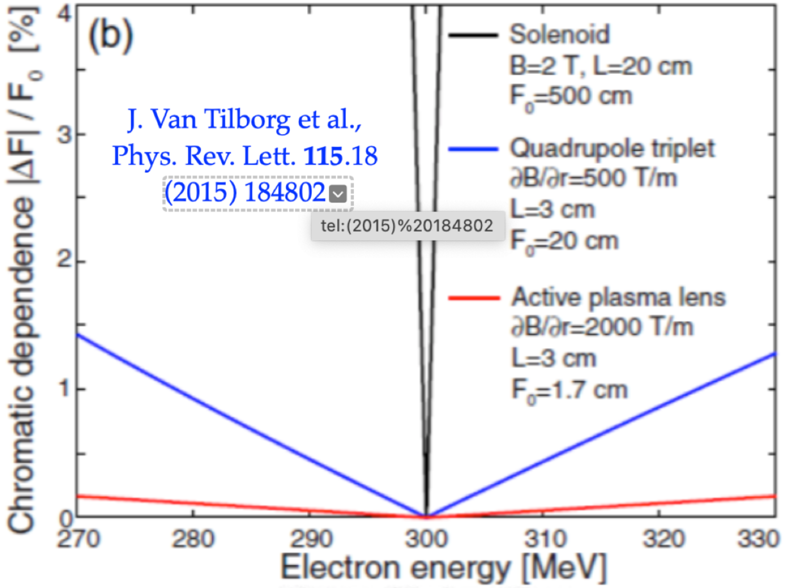
W. K. H. Panofsky and W. R. Baker
Department of Physics, Radiation Laboratory, University of California, Berkeley, California
(Received January 11, 1950)

A device has been constructed to focus the external beam of the 184-in. cyclotron at Berkeley. The device consists of a cylindrical tube 4 ft. in length and 3 in. in diameter, which contains a longitudinal arc of nearly uniform current density. Such a device will focus any beam of cylindrical symmetry. Owing to the large power requirements of such a device it is applicable only to very short pulsed beams.

$$B_\phi(r) = \frac{\mu_0}{r}\int_0^r J(r')r'dr'$$



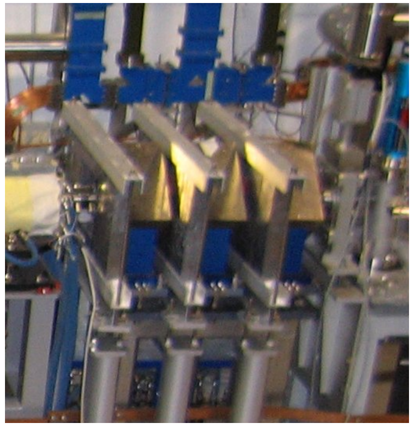
- Cylindrical symmetry
  - purely radial focusing effect
- Tunability
- Focusing strength ∝ γ^{-1}
- High focusing gradient ~ kT/m
  - short focal length
    - weak chromaticity

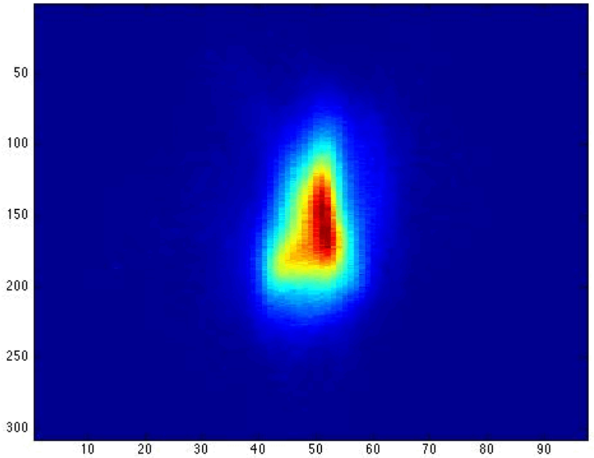


J. Van Tilborg et al., Phys. Rev. Lett. **115**.18 (2015) 184802

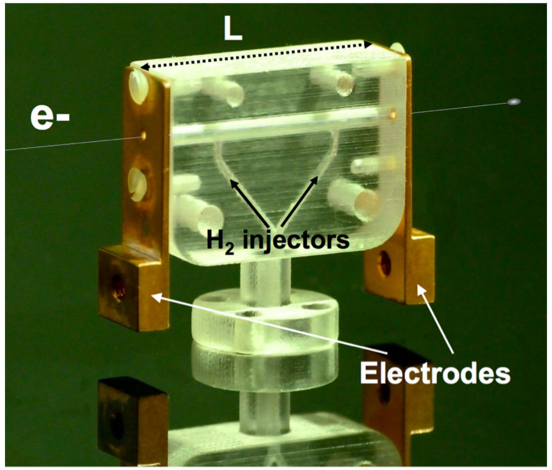
Plasma vs Convetional Focusing

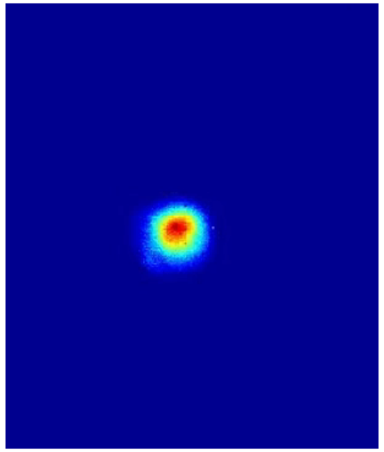
Single
Quadrupole
Magnet





Single
Plasma Lens





Experimental measurements
at SPARC_LAB (INFN-LNF)

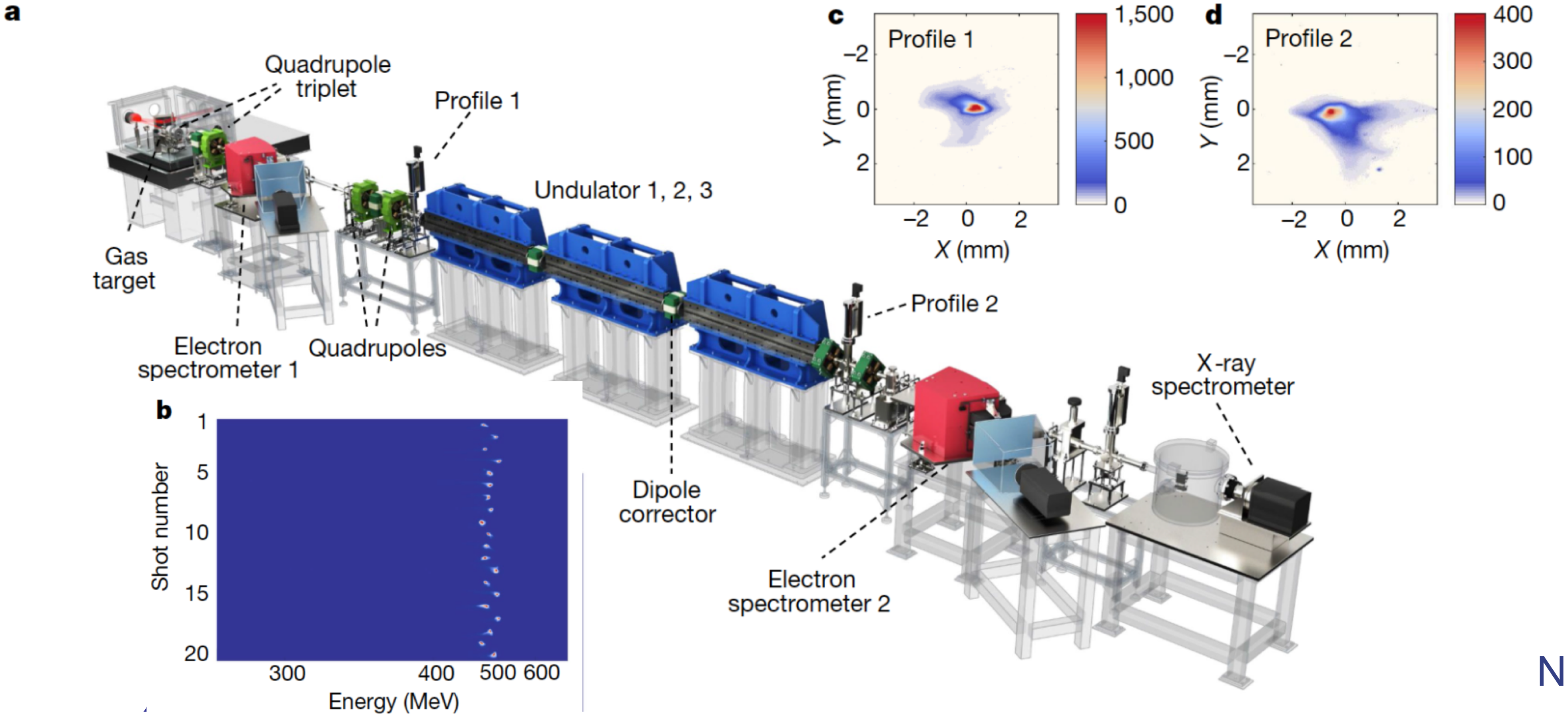
Solving Beam Quality Issues

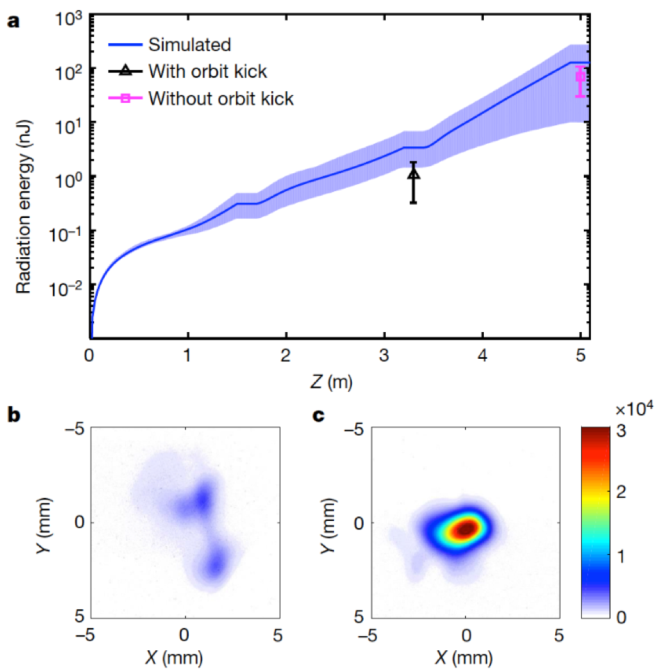
- Several key challenges facing plasma-based facility operation **under control**
  - **stabilization and control of the acceleration process** (R. Pompili et al., *Energy spread minimization in a beamdriven plasma wakefield accelerator*, Nat. Physics **17**, no. 4, pp. 499-503, 2021; Ferran-Pousa et al., PRL 123, 054801, 2019)
    - energy spread mitigation, normalized emittance preservation, overall stability gain

- **Improvements still needed** to guarantee continuous operation
  - sub-percent to sub-per-mille energy spread and **mm mrad to sub-mm mrad emittances**
  - increase of the **repetition rate** from a few hertz to kilohertz (R. D Arcy et al., *Recovery time of a plasma-wakefield accelerator*, Nature **603**, pp. 58–62, 2022)
  - improvement of **shot-to-shot stability**

Preliminary Feasibility Proofs

First SASE FEL lasing **from a laser-driven plasma accelerator** at **SIOM** (Shangai)

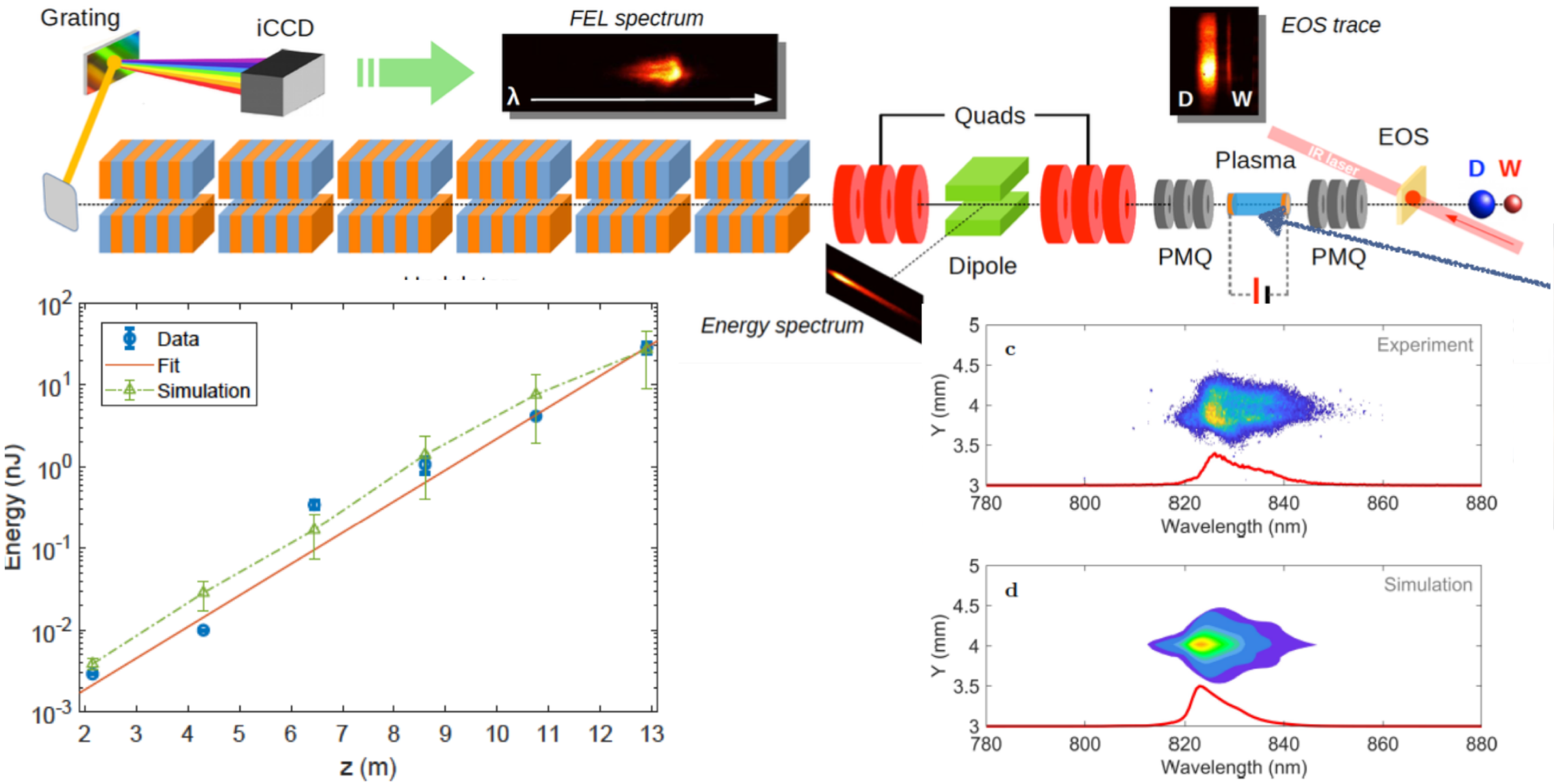


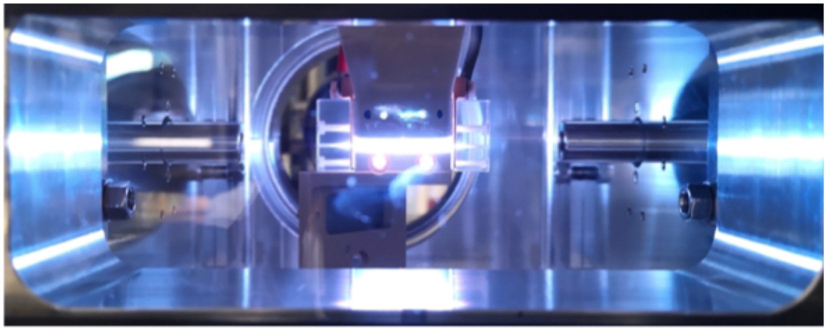


Nature **595**, pp. 516–520 (2021)

Preliminary Feasibility Proofs

First SASE FEL lasing **from a beam-driven plasma accelerator** at **SPARC_LAB** (INFN, Frascati)

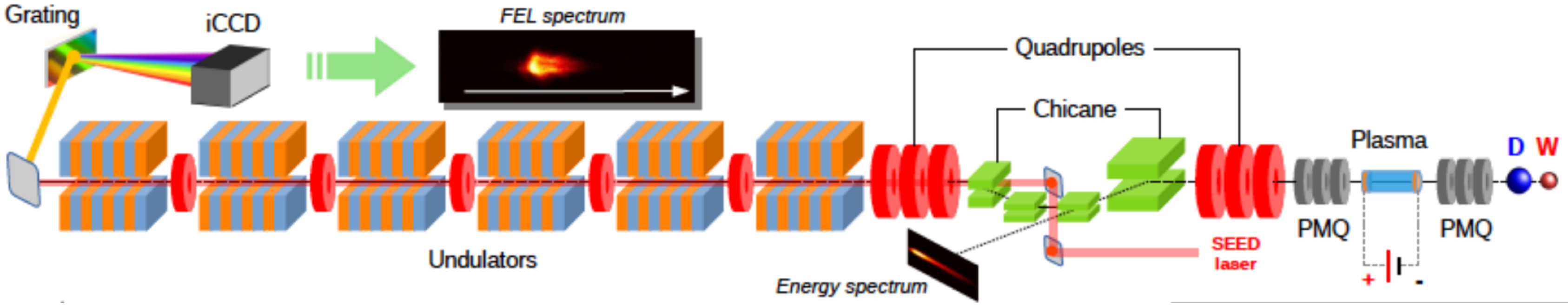


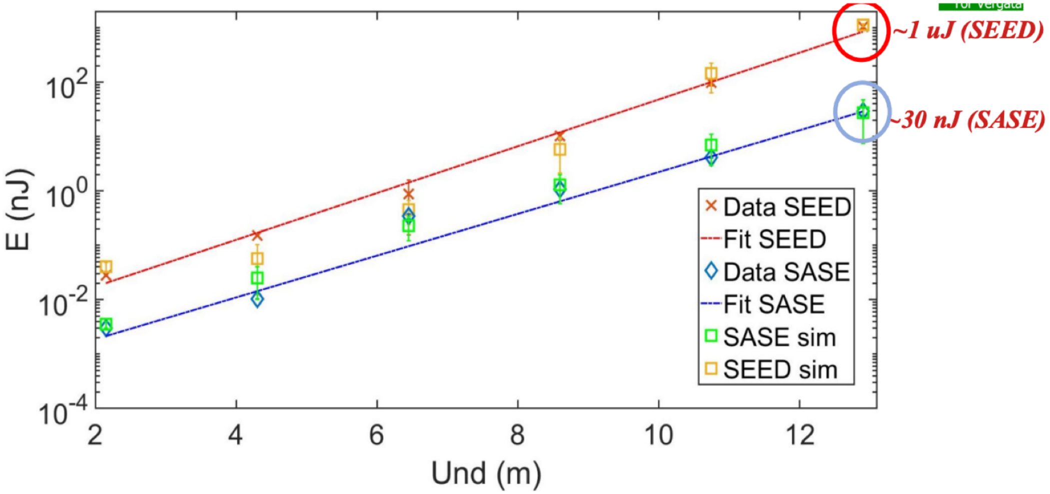


Nature **605**, 659–662 (2022)

Preliminary Feasibility Proofs

First Seeded FEL lasing **from a beam-driven plasma accelerator** at **SPARC_LAB** (INFN, Frascati)





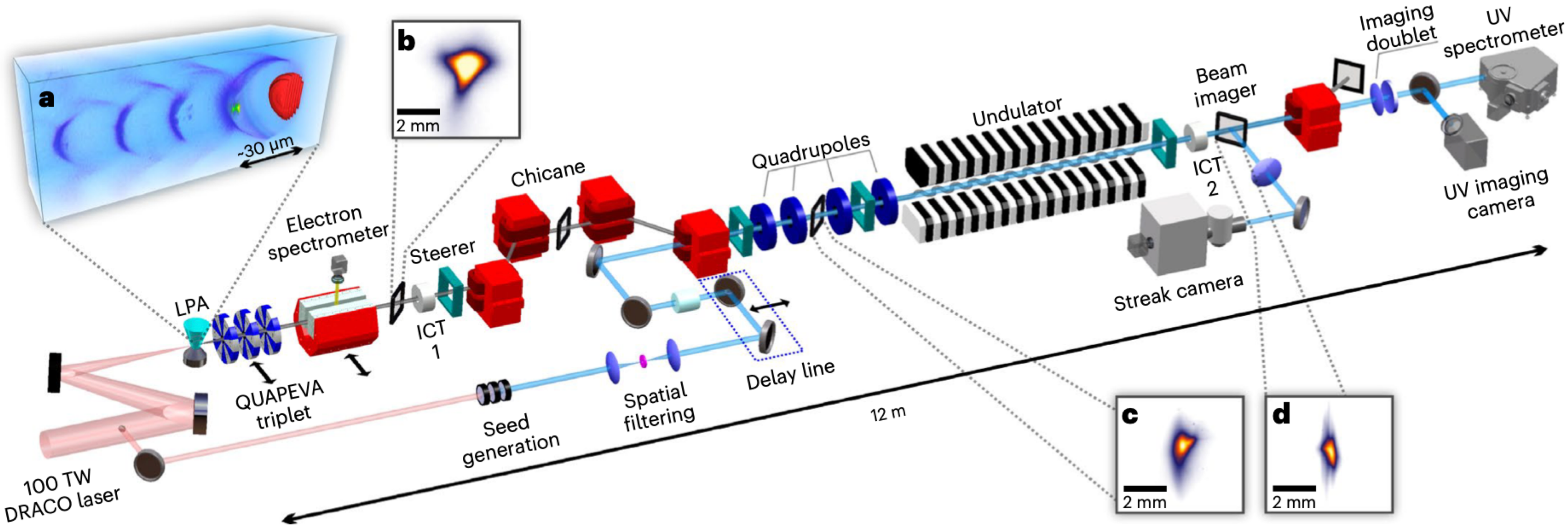
Seeded FEL Radiation

- Part of the EOS laser used as seed
- Seed laser ~ 795 nm, FEL peak 827 nm
- Pulse energy increase from 30 nJ up to 1 μm
- Increased stability of emitted radiation

Phys. Rev. Lett. **129**, 234801 (2022)

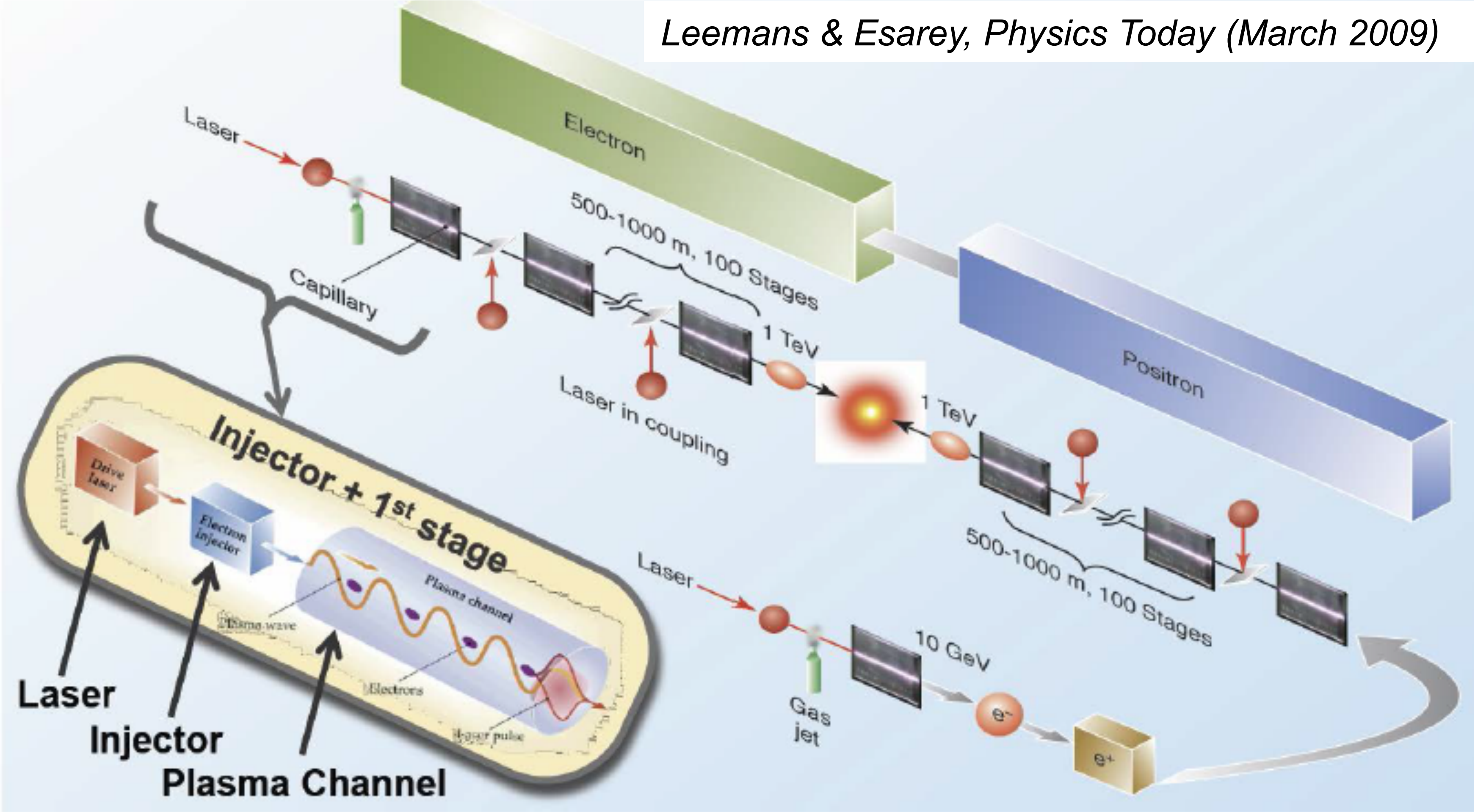
Preliminary Feasibility Proofs

First Lasing of the COXINEL Seeded FEL driven **by** the HZDR **Laser Plasma Accelerator** (Dresden)



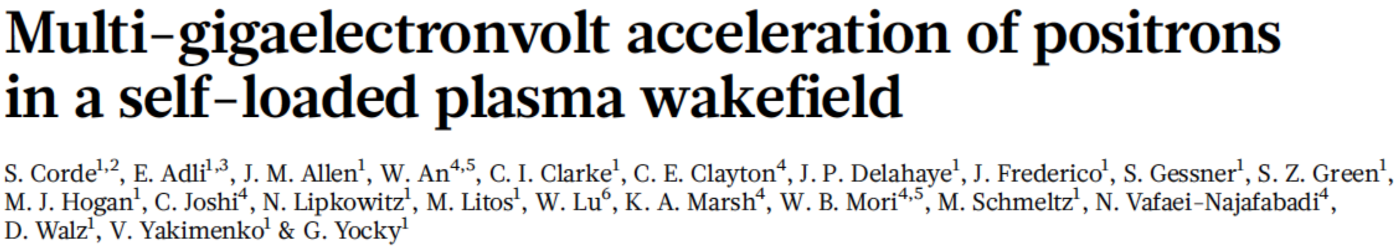
Nature Photonics **17**, 150–156 (2023)

LWFA-based Linear Collider



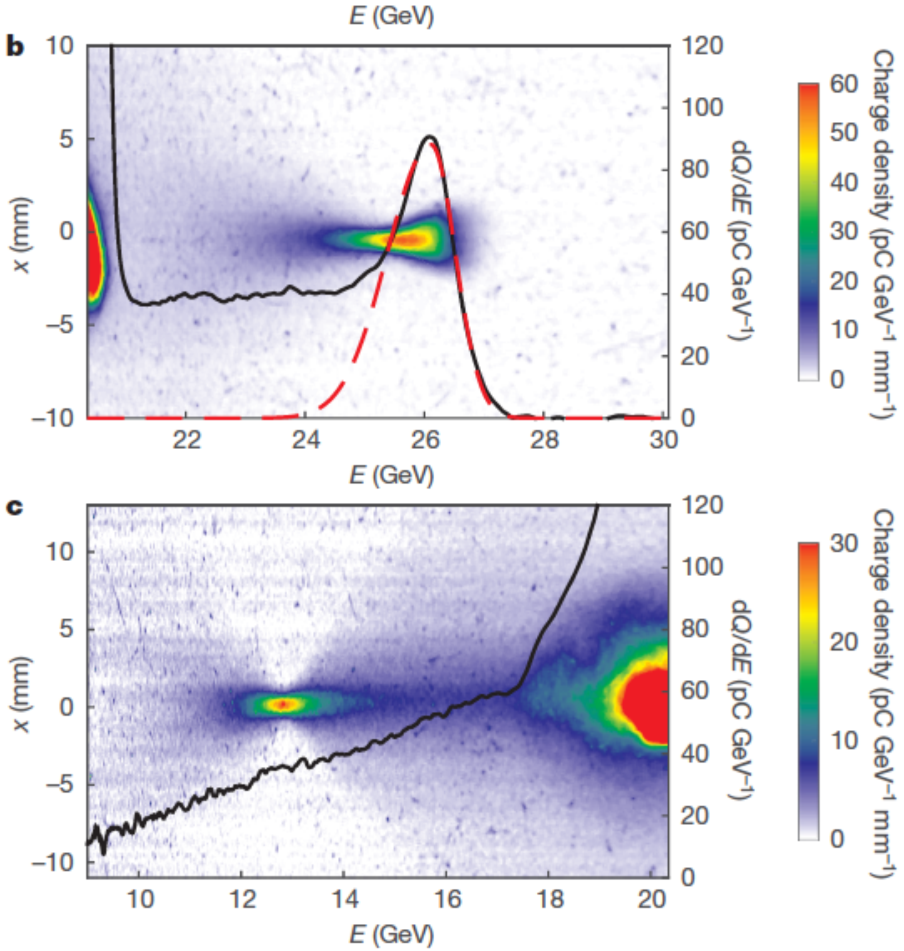
Leemans & Esarey, Physics Today (March 2009)

Acceleration of Positrons in Plasma Wakefield



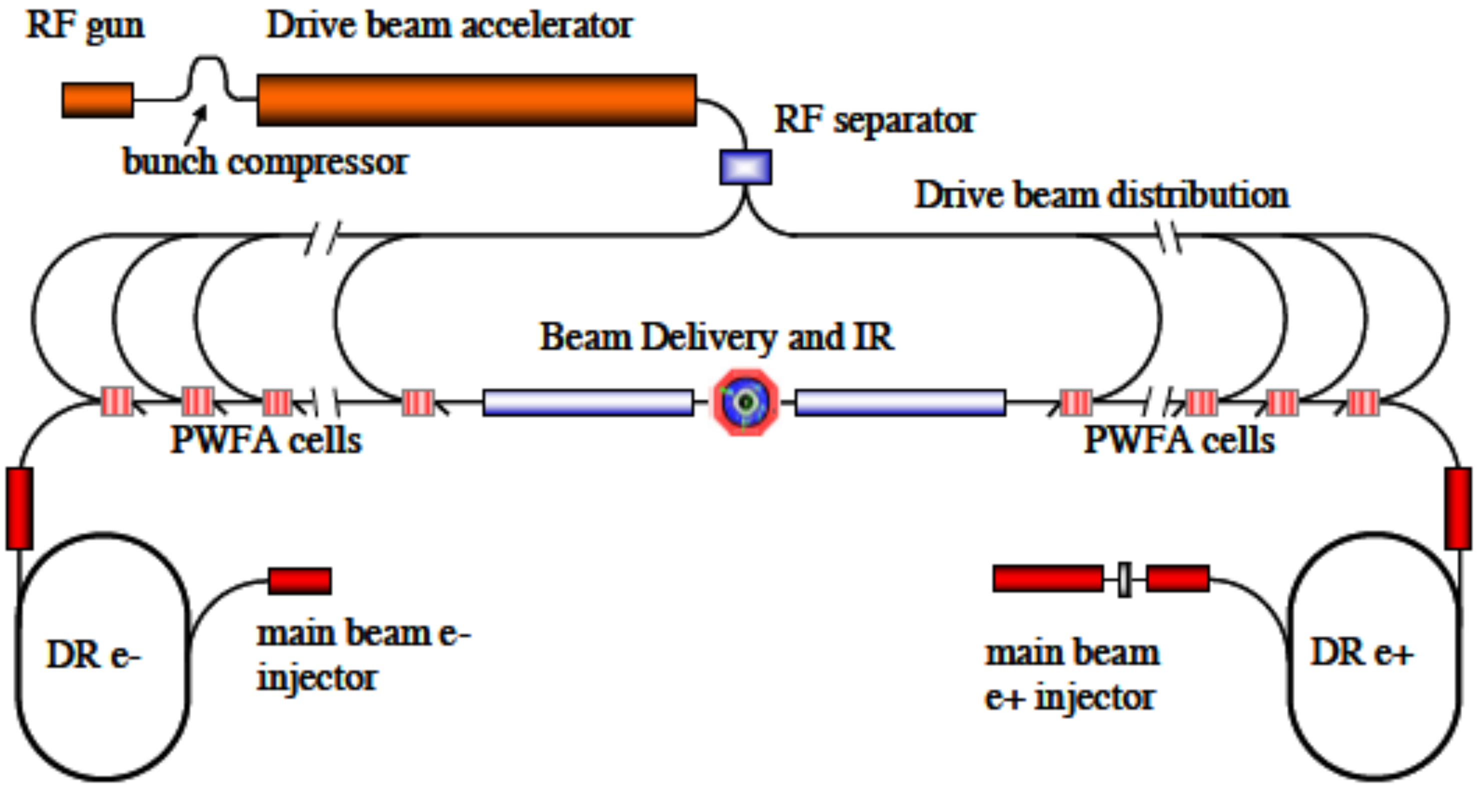
Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield

S. Corde[1,2], E. Adli[1,3], J. M. Allen[1], W. An[4,5], C. I. Clarke[1], C. E. Clayton[4], J. P. Delahaye[1], J. Frederico[1], S. Gessner[1], S. Z. Green[1], M. J. Hogan[1], C. Joshi[4], N. Lipkowitz[1], M. Litos[1], W. Lu[6], K. A. Marsh[4], W. B. Mori[4,5], M. Schmeltz[1], N. Vafaei-Najafabadi[4], D. Walz[1], V. Yakimenko[1] & G. Yocky[1]



Nature **524,** pages 442–445 (2015)

PWFA-based Linear Collider

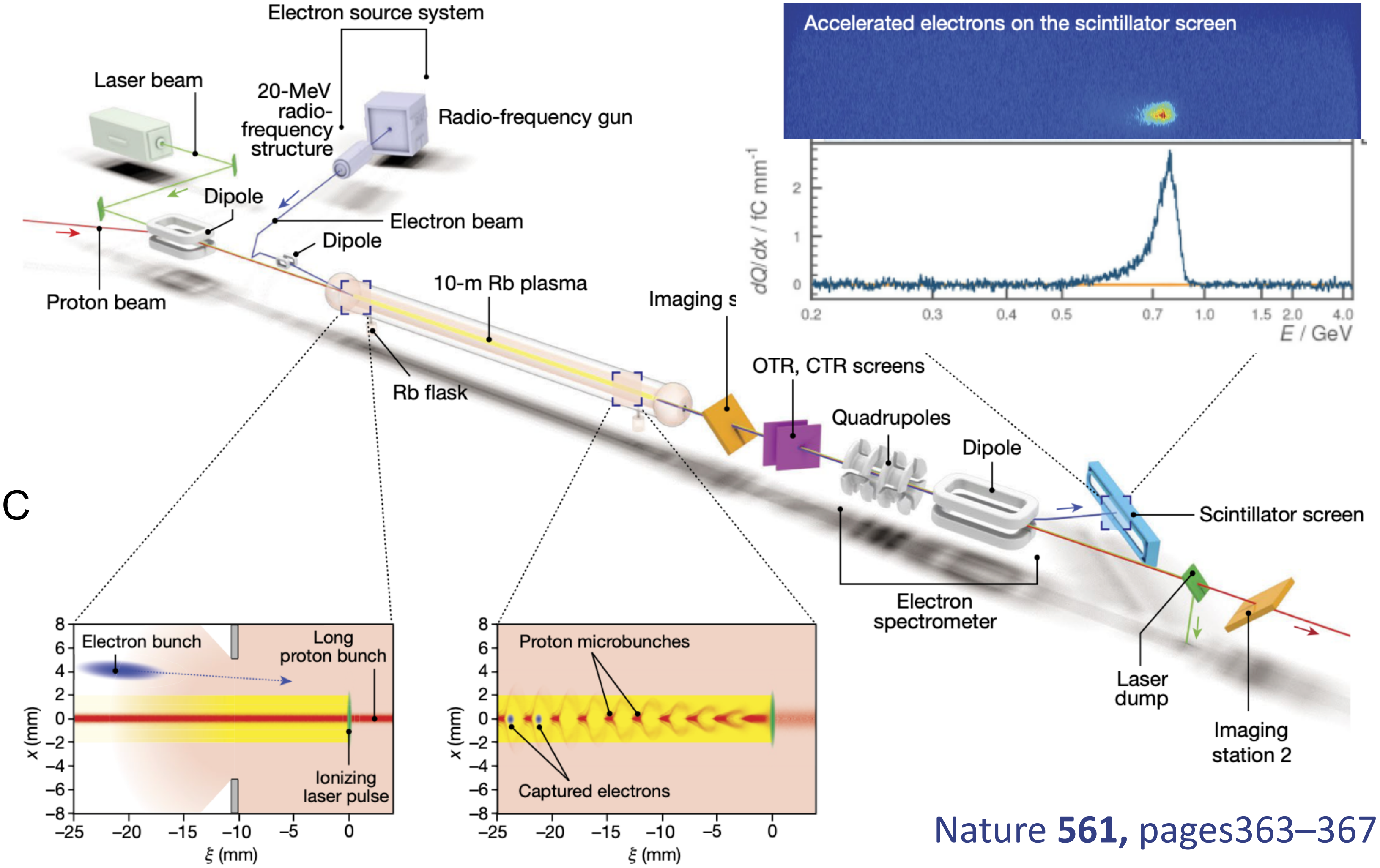


CONCEPTUAL DESIGN OF THE DRIVE BEAM FOR A PWFA-LC*

S. Pei[#], M. J. Hogan, T. O. Raubenheimer, A. Seryi, SLAC, CA 94025, U.S.A.
H. H. Braun, R. Corsini, J. P. Delahaye, CERN, Geneva

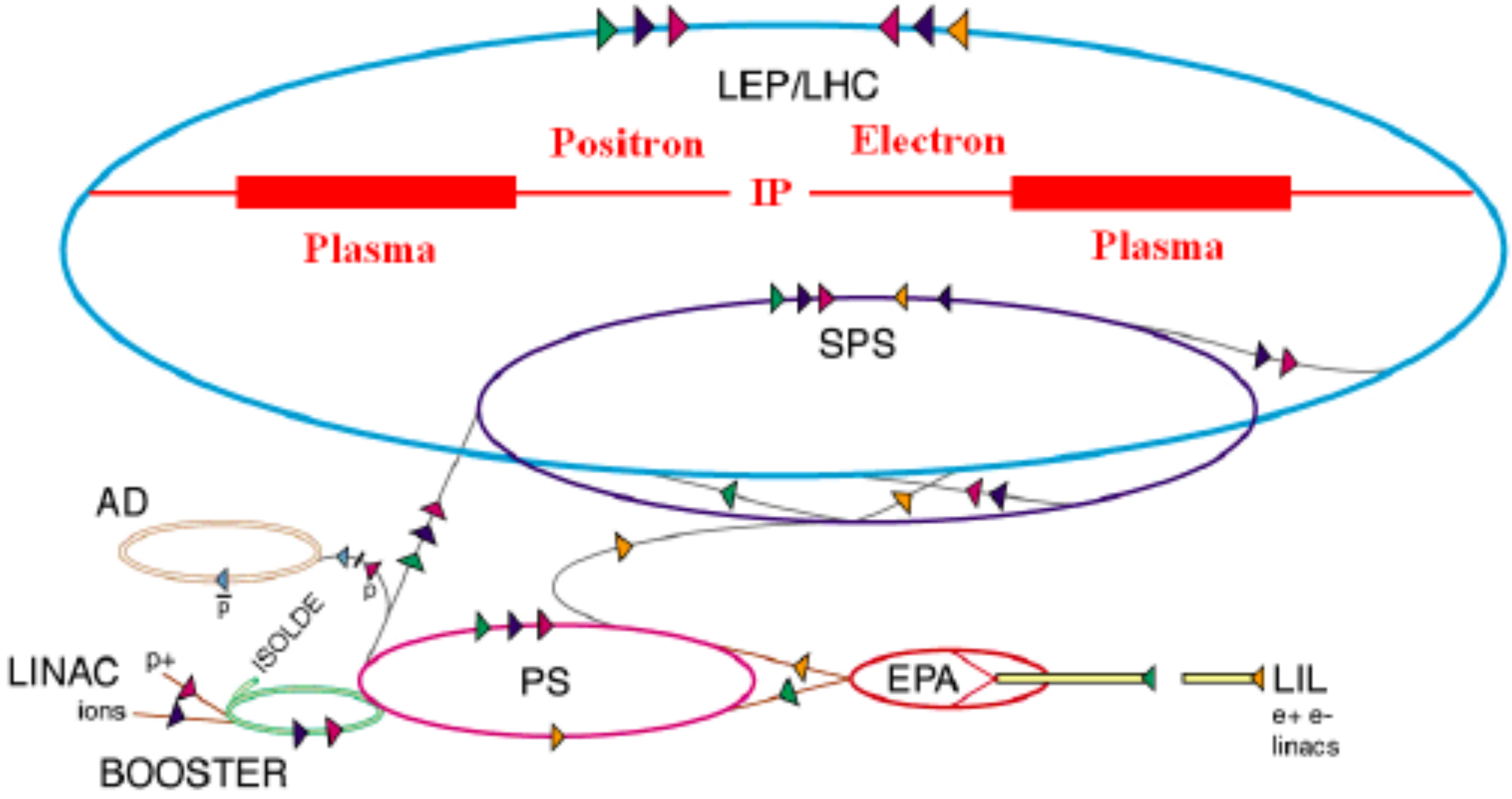
Proton-driven PWFA: AWAKE

- Mean energy: 800 ± 40 MeV,
  => E_{acc}~150 MV/m
- FWHM of 137.3 ± 13.7 MeV
  => Spread >10%
- Total charge: 0.249 ± 0.074 pC
  => Low charge trasmission



Nature **561,** pages363–367 (2018)

Idea of a Linear Collider based on a Modulated p+ driven PWFA



Conclusions

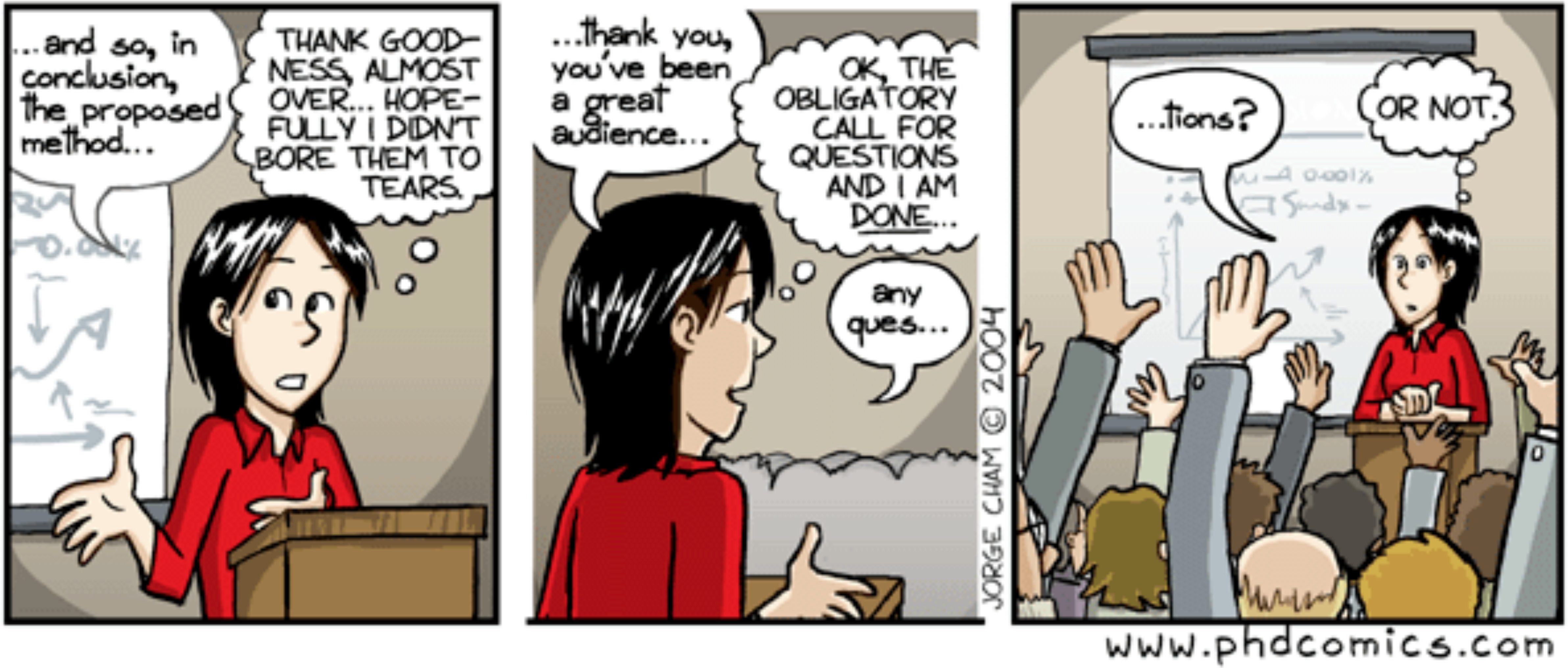
- Plasma-based acceleration techniques have demonstrated accelerating gradients up to 3 orders of magnitudes beyond presently used RF technologies
- Plasma-based acceleration techniques have provided solid feasibility proofs of FEL lasing under different configurations
  - Successful efforts on improving beam quality
- The R&D now concentrates on **beam stability, staging and continuous operation**, as necessary steps towards the realization of compact plasma-based accelerator facilities
  - **A major milestone is an operational, 1 GeV compact accelerator**
  - **Challenges in high repetition rate**
- **Plasma-based, ultra-high gradient accelerators therefore open the realistic vision of very compact accelerators for scientific, commercial and medical applications**

MC3 – Novel Particle Sources and Acceleration Techniques at IPAC23

- Towards COXINEL Seeded FEL Using Laser Plasma Accelerator at HZDR – **Marie Emmanuelle Couprie, SOLEIL**
- EuPRAXIA and its Italian Construction Project – **Massimo Ferrario, INFN**
- Laser-Plasma Acceleration beyond the Diffraction and Dephasing Limits – **Cedric Thaury, Laboratoire d’Optique Appliquée**
- Fabrication and testing of corrugated Waveguides for a Collinear Wakefield Accelerator – **Alexander Zholents, Argonne National Laboratory**

References

- Tajima & Dawson, Phys. Rev. Lett. **43**, 267 (1979)
- Esarey, Schroeder, Leemans, Rev. Mod. Phys. **81**, 1229 (2009)
- … and papers in the slides



Thank You for the attention!