EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

# Beam Manipulation with a Plasma Accelerator

**R. Pompili (LNF-INFN)**

On behalf of the EuPRAXIA@SPARC_LAB collaboration

This project has received funding from the European Union´s Horizon Europe research and innovation
programme under grant agreement
No. 101079773

# Particle accelerators

*A particle accelerator is a machine that uses electromagnetic fields to propel charged particles to very high speeds and energies, and to contain them in well-defined beams*

Wikipedia

According to the De Broglie hypothesis, larger is the particle **energy** better is the **spatial resolution** at which matter can be investigated

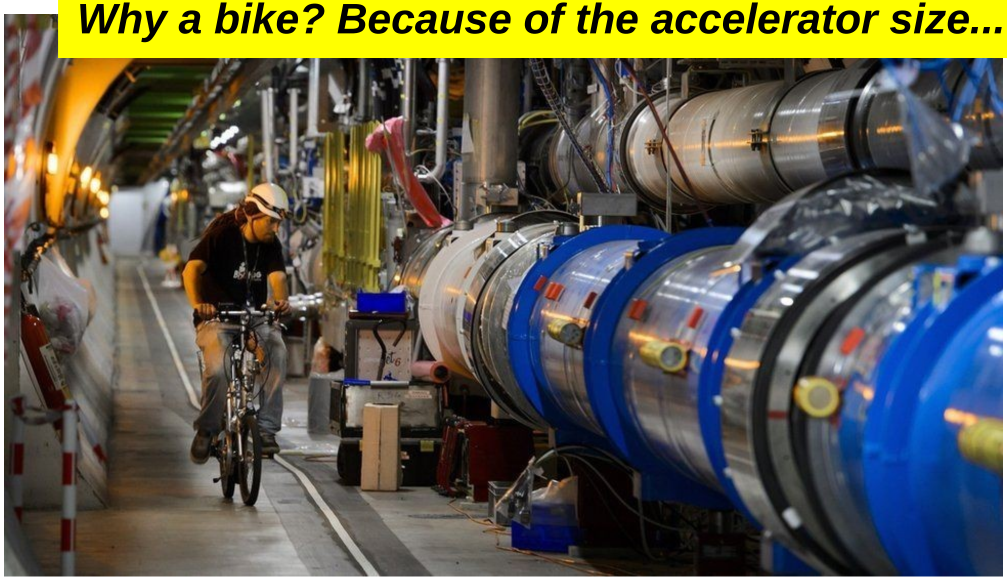
Today use of particle accelerators

High-energy and nuclear physics

Sources of synchrotron and FEL radiation

Medical/industrial applications

***Why a bike? Because of the accelerator size...***



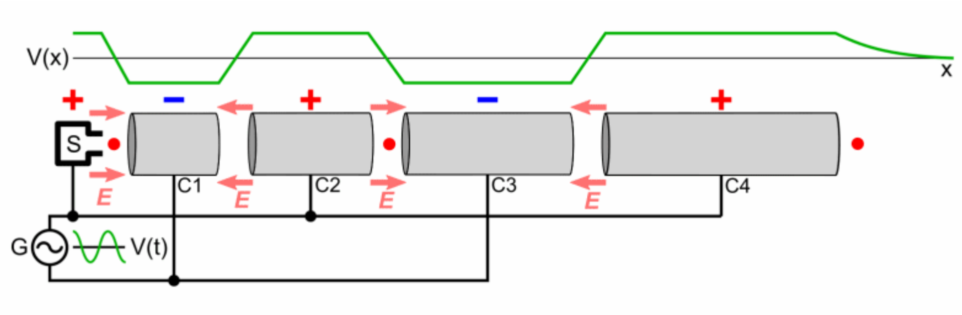
Microscope resolution

$$\lambda = \frac{h}{p}$$

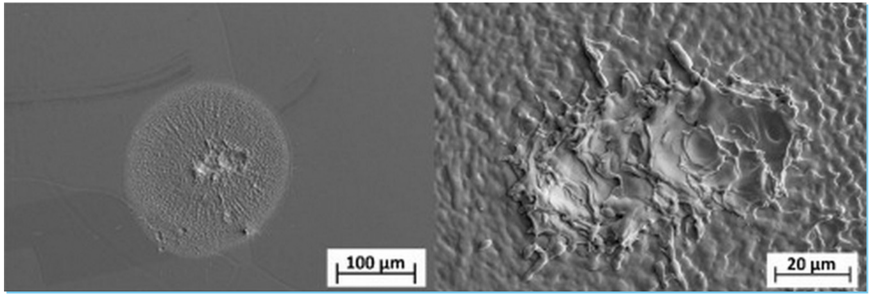
Planck constant

Particle momentum (~energy)

# Conventional RF technology



RF technology uses high power microwaves in resonant cavities with metallic walls.
Typical RF frequencies are in GHz range.
The cavities dimensions are of the order of the microwaves wavelength (1-60 cm)

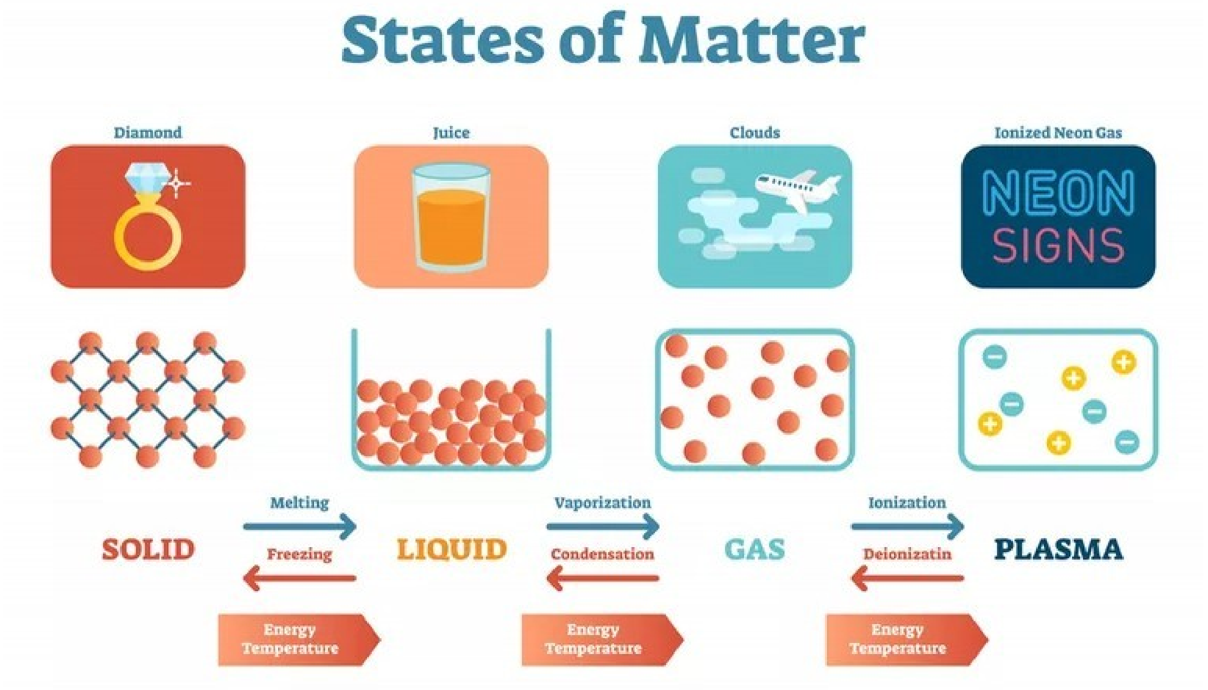


The power stored in the cavity cannot grow to infinite
**RF breakdown**: imperfections on the cavities can trigger sparks and damage the structure
There exists a maximum tolerable accelerating field

$$E_{max} \approx 150 \frac{MV}{m}$$

# Use of plasma to exceed RF limits

Funded by the European Union

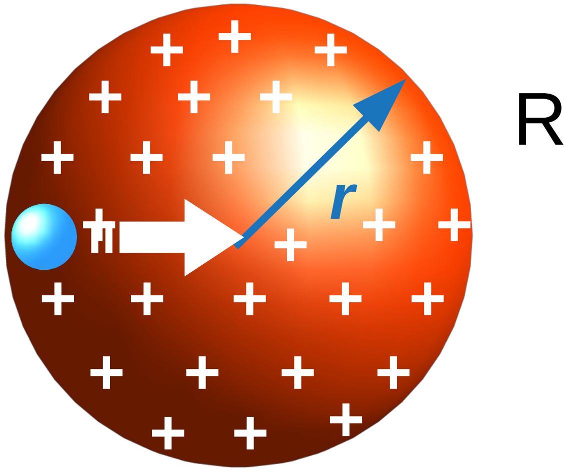


**Plasma** is the 4th state of matter and is made of free electrons and positively charged ions
It is typically made by heating a gas until its electrons have sufficient energy to escape from the (positive) nuclei
**Being already ionized, the plasma cannot be “damaged” by any spark and can thus sustain huge fields**

# Acceleration in a ionic bubble

From Maxwell’s equations, the electric field in a (positively) charged sphere with uniform density $n_i$ at location **r** is

$$\boxed{\vec{E}(r) = \frac{q_i n_i}{3\,\epsilon_0} r}$$



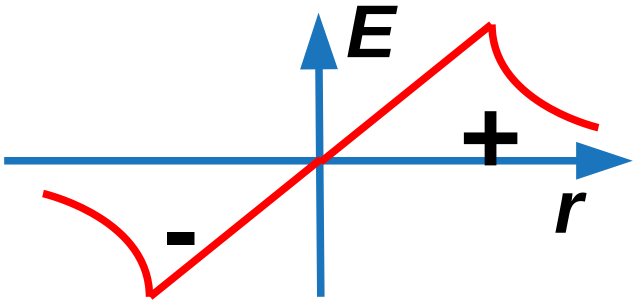
The field is **increasing** inside the sphere

Let’s put some numbers

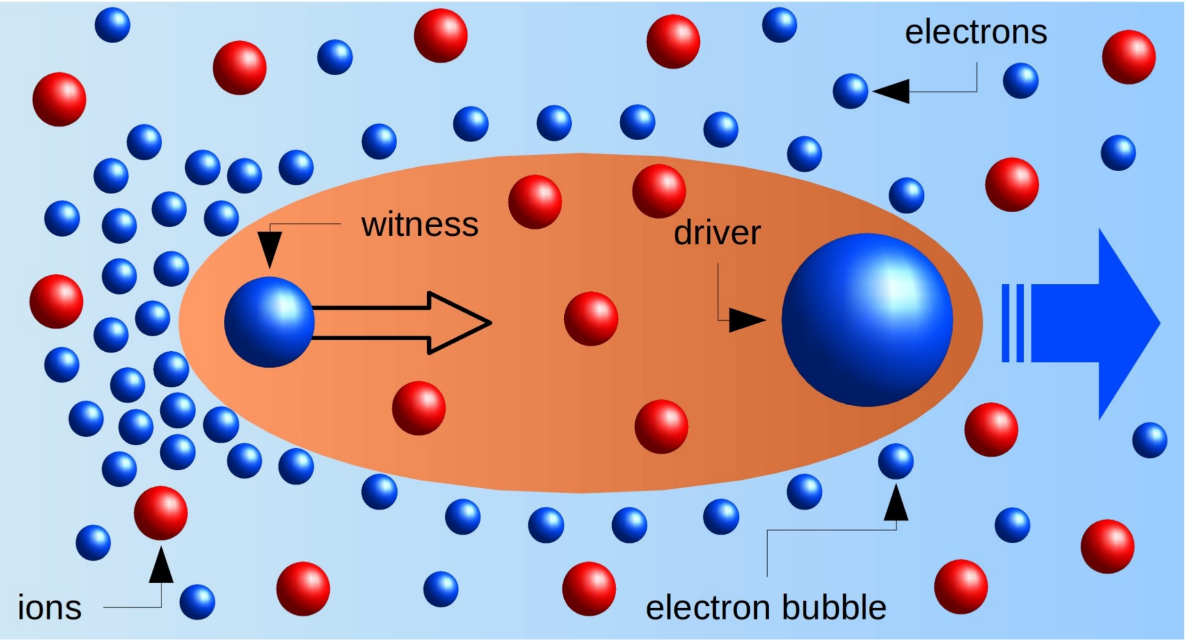
$n_i = 10^{16}\ cm^{-3}$

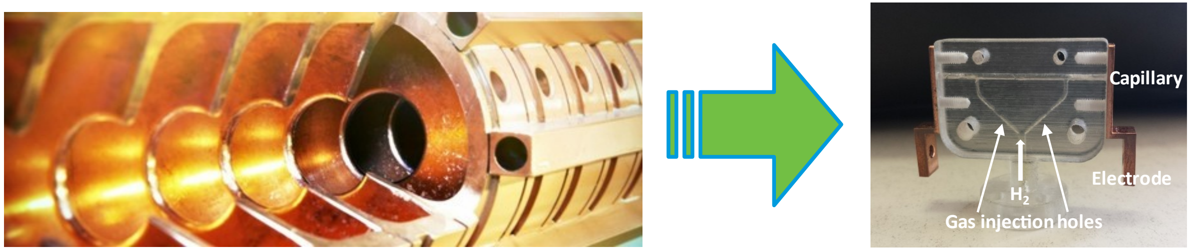
$R = 0.5\,\lambda_p = 150\ \mu m$

$$E \approx 10\,\frac{GV}{m}$$



# Plasma acceleration





$$\boxed{E_0 = \frac{m_e c \omega_p}{e} \simeq 96\sqrt{n_0\left(cm^{-3}\right)}}$$

$$\rightarrow E_0 \approx 10\frac{GV}{m} @ n_0 = 10^{16}\, cm^{-3}$$

The **driver** creates the positive sphere (or ***bubble***). It can be a

- *particle bunch (PWFA)*
- *laser pulse (LWFA)*

The **witness** can be

- *Self-injected*
- *Externally injected*

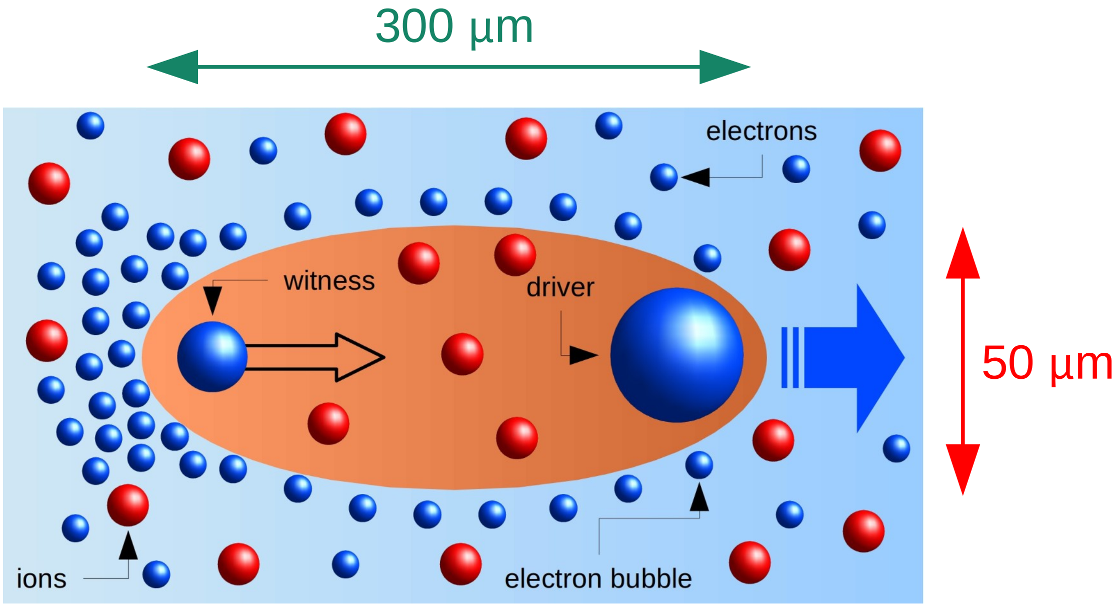
# Typical sizes

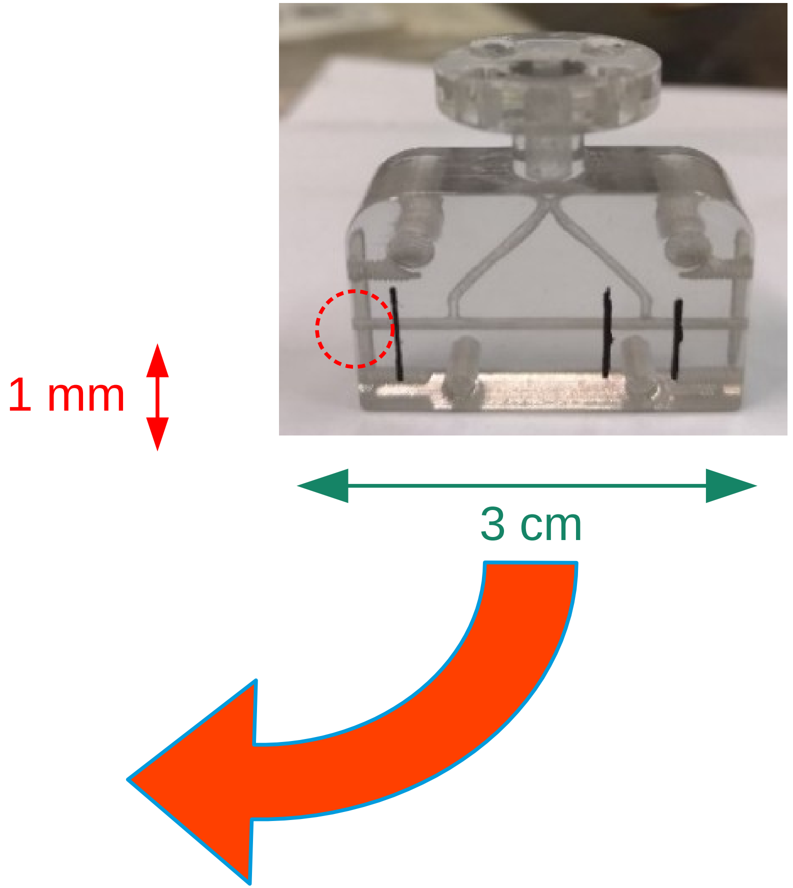
Funded by the European Union

The most critical part of a plasma-based accelerator is given by its typical size

*The bubble is tiny (tens/hundreds of micron scale)*

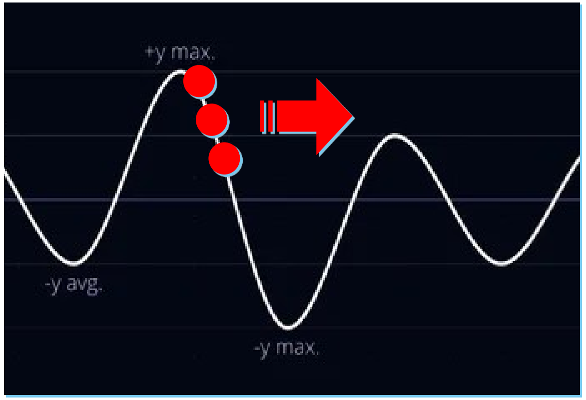
*The witness beam must be even smaller!!!*



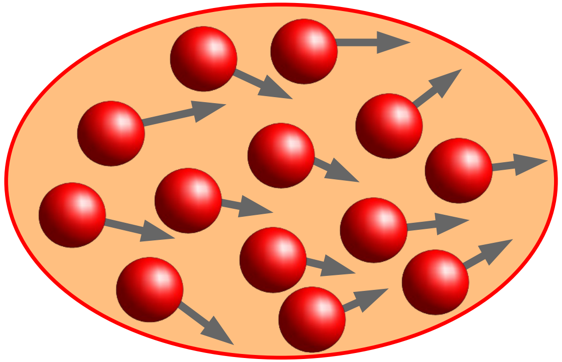


Funded by the European Union

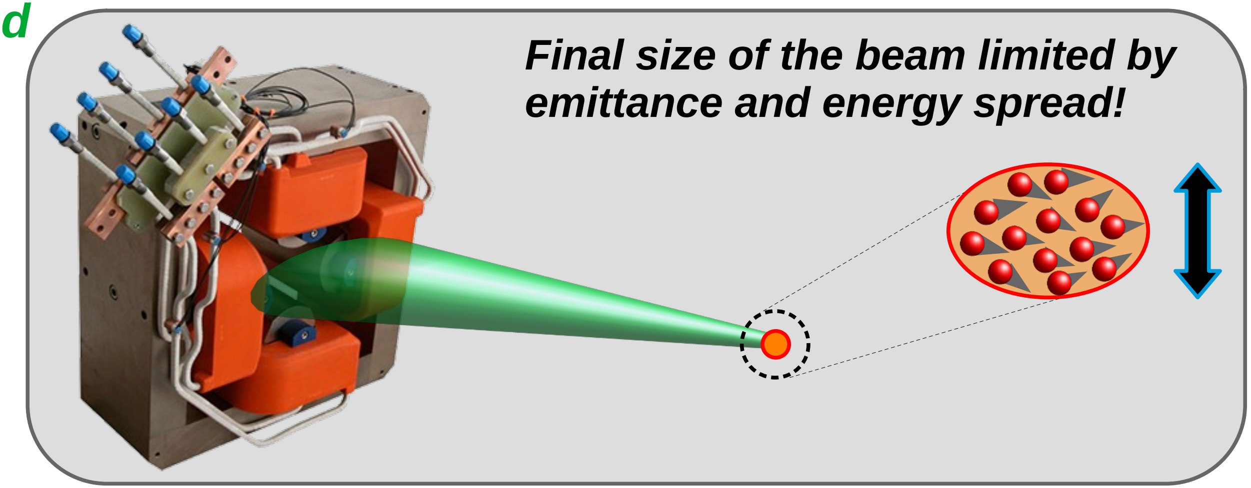
# Beam quality



Energy spread



Emittance

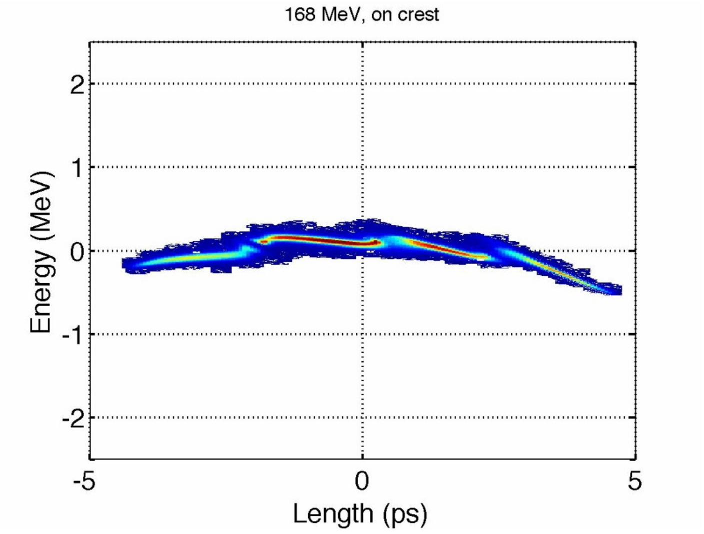


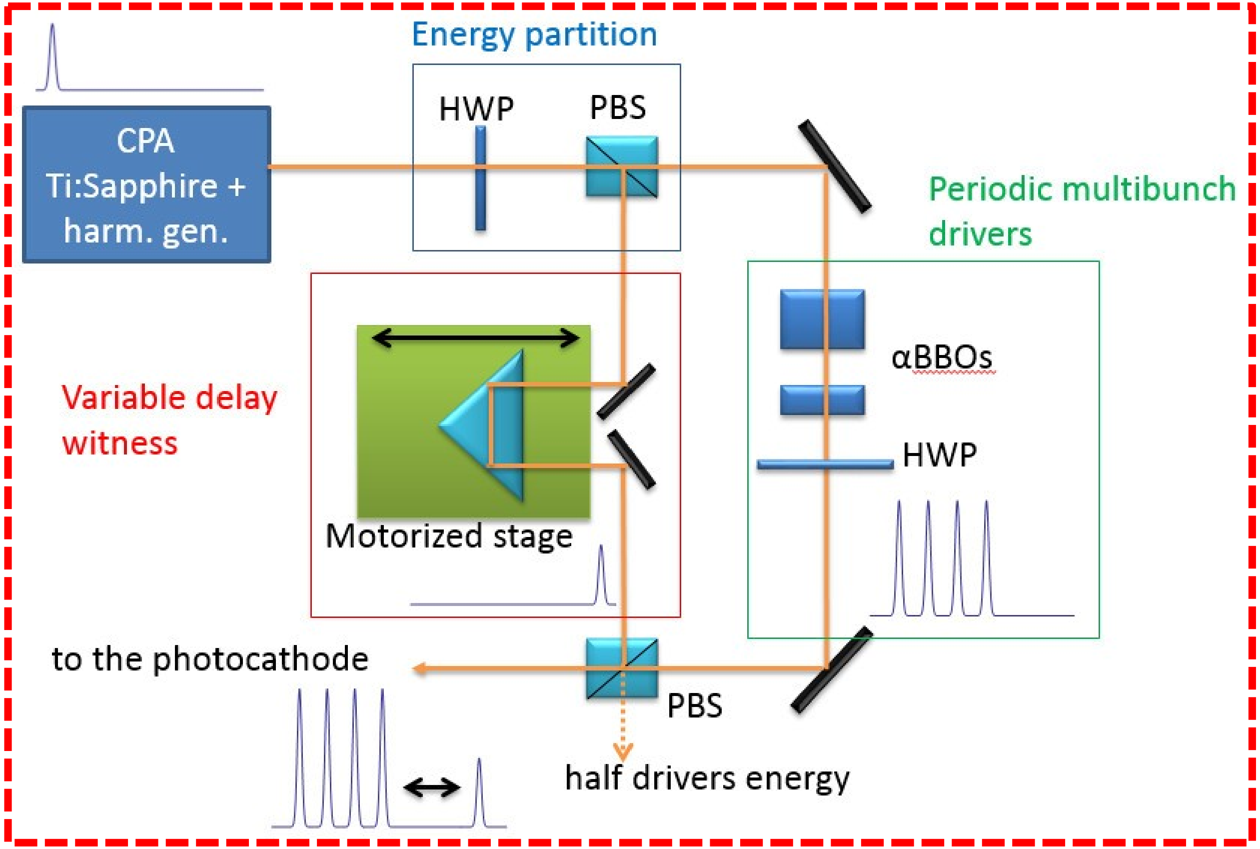
*Final size of the beam limited by emittance and energy spread!*

# Generation of multiple bunches

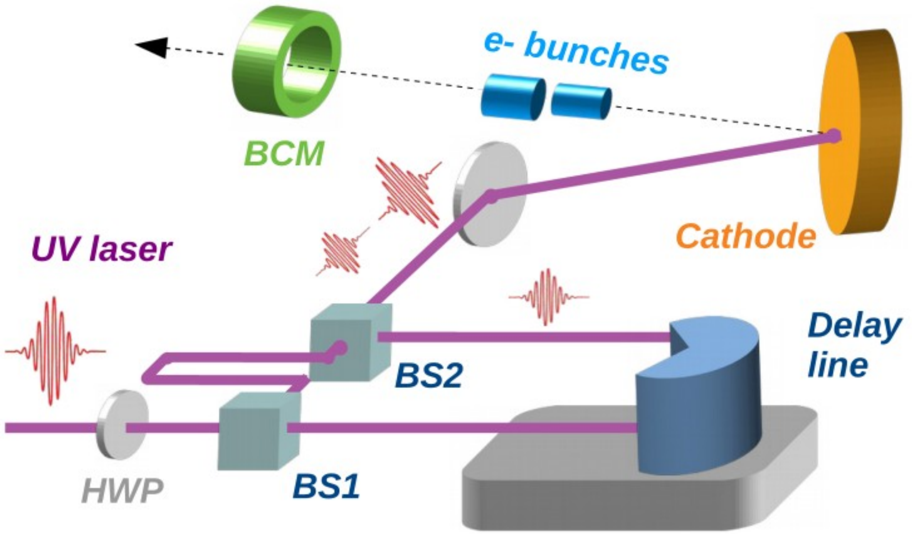
**Ferrario, M., et al.** "Laser comb with velocity bunching: Preliminary results at SPARC." NIM A 637.1 (2011): S43-S46.

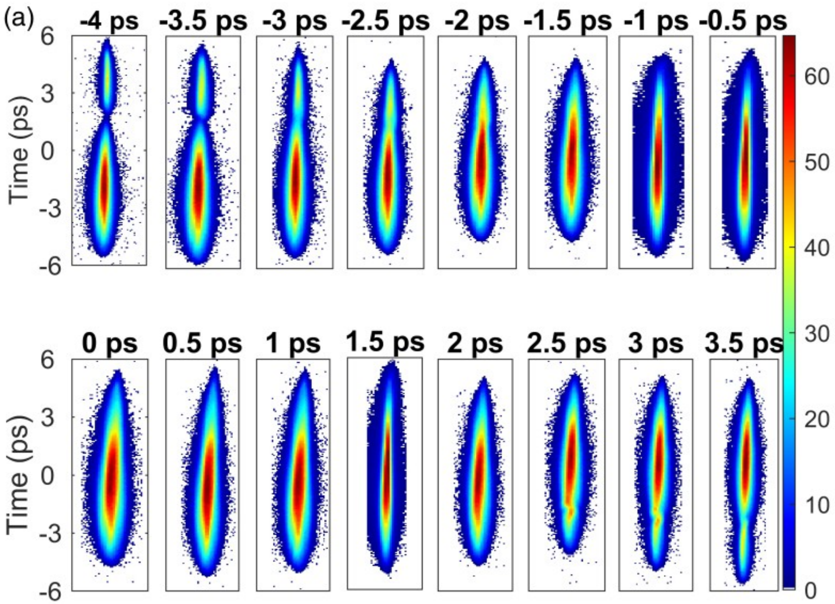
**Villa, F., et al.** "Laser pulse shaping for multi-bunches photo-injectors." NIM A 740 (2014): 188-192.



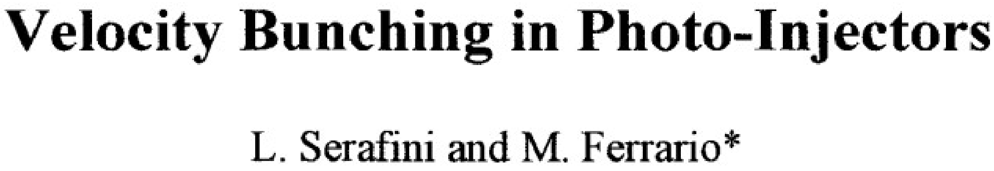


# Tuning of the photoemission process





# Compression with velocity-bunching



## Velocity Bunching in Photo-Injectors

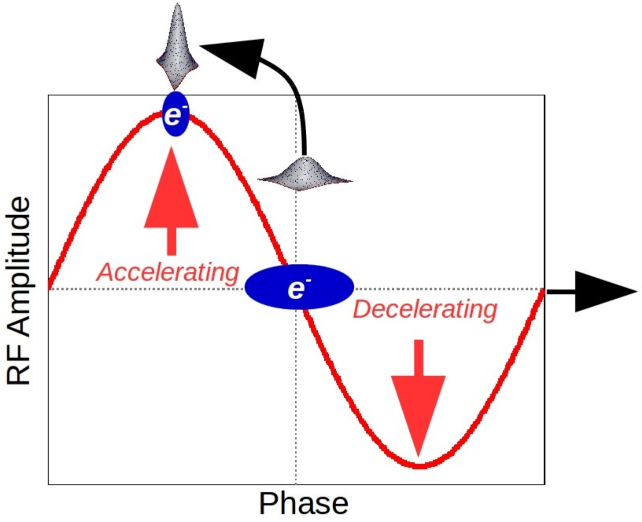
L. Serafini and M. Ferrario*

VB exploits the different fields felt by the beam head/tail to make compression

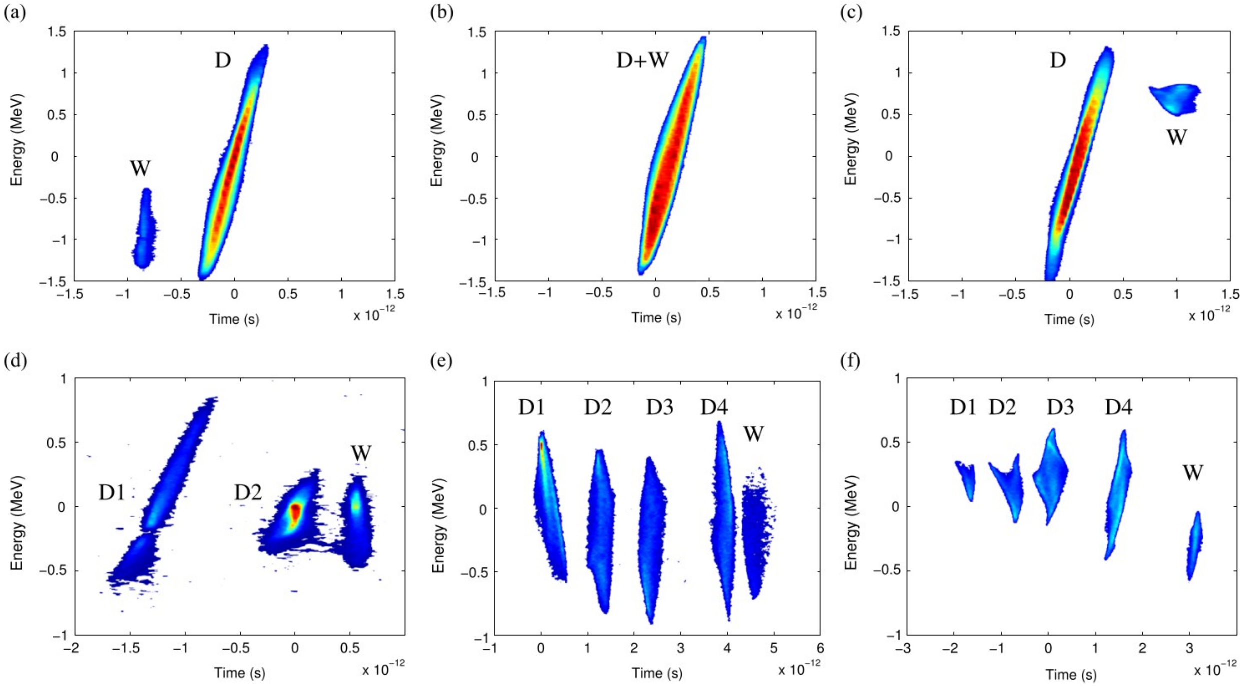
- *Simple, tunable and compact but can suffer from RF jitters (becoming intra-bunch jitters)*

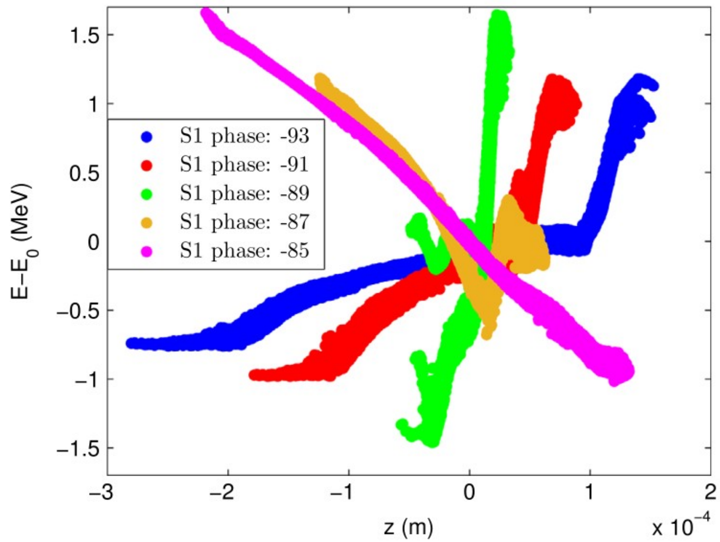
Compression is done in S1, where beams are not yet fully relativistic.

Shortest bunch measured @ SPARC was ~20 fs (20 pC). Largest peak current obtained for THz experiments (600 pC, 100 fs rms)

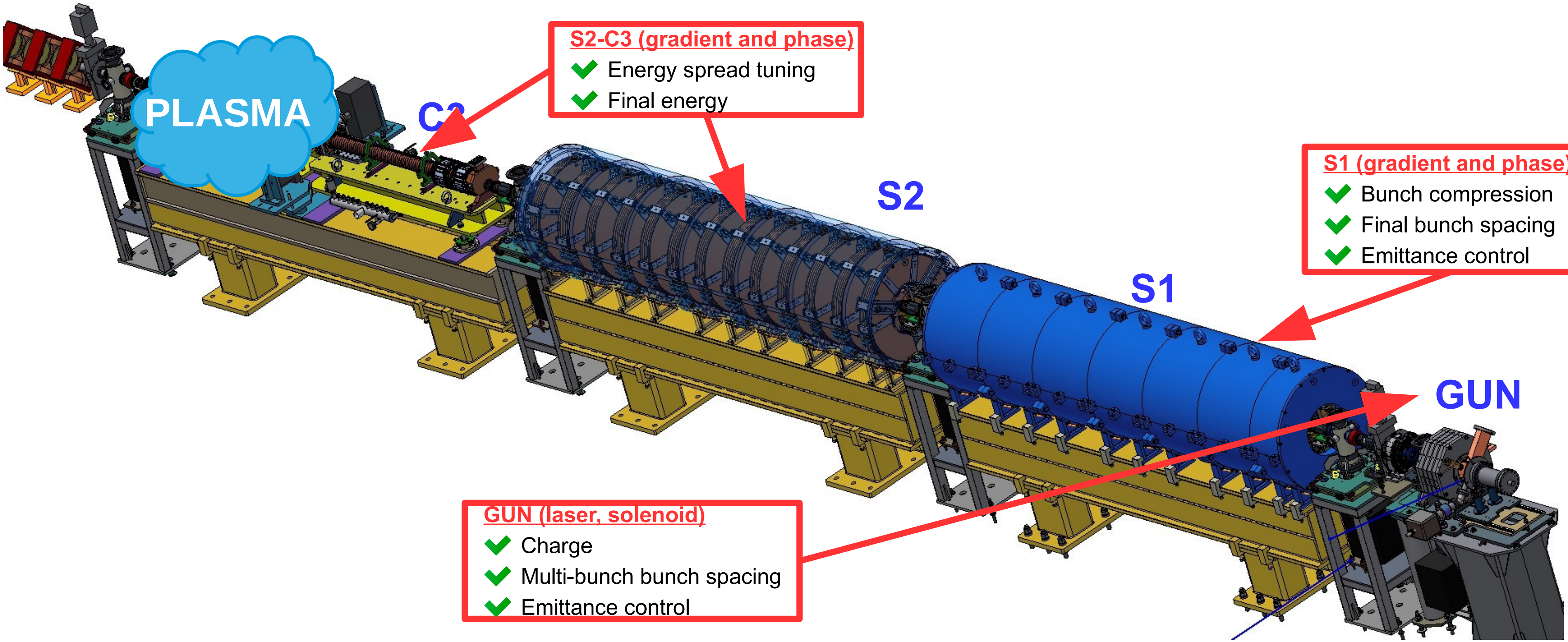


# LPS manipulation





# Tuning knobs



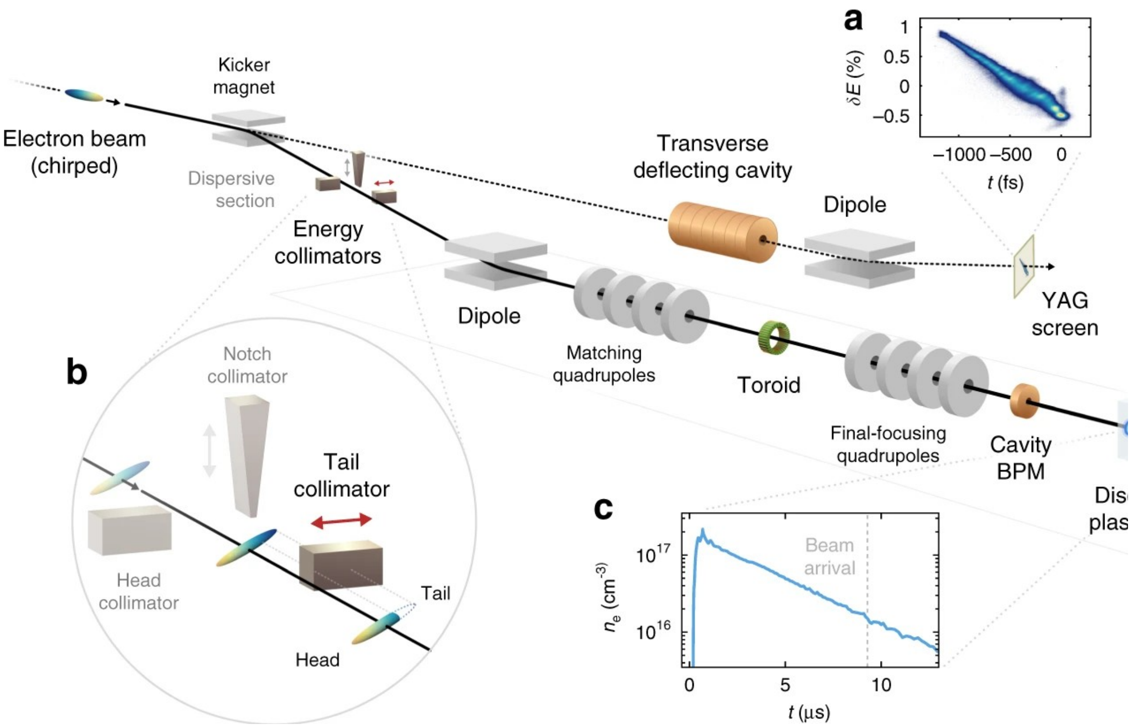
S2-C3 (gradient and phase)
- ✓ Energy spread tuning
- ✓ Final energy

S1 (gradient and phase)
- ✓ Bunch compression
- ✓ Final bunch spacing
- ✓ Emittance control

GUN (laser, solenoid)
- ✓ Charge
- ✓ Multi-bunch bunch spacing
- ✓ Emittance control

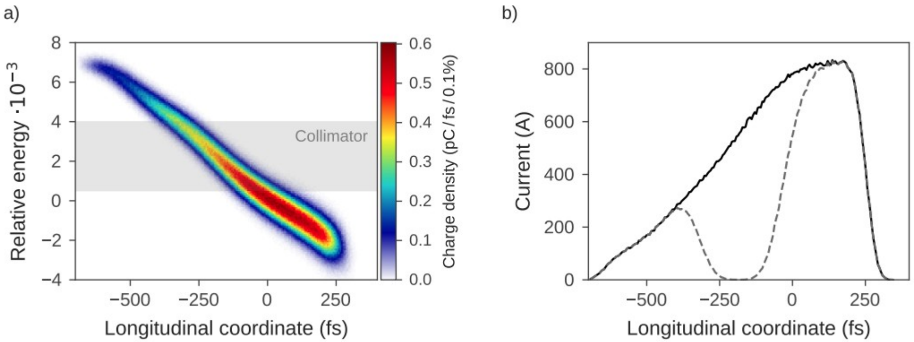
**Chiadroni, E., et al.** "Characterization of the THz radiation source at the Frascati linear accelerator." RSI 84.2 2013
**Mostacci, A., et al.** "Advanced beam manipulation techniques at SPARC."Proceedings of IPAC2011

# Alternative method: dispersive section



Propagate the beam in a dispersive section (e.g. dogleg, chicane)

Insert collimators to cut the beam in two or more bunches



Schröder, Sarah, et al. "High-resolution sampling of beam-driven plasma wakefields." Nature communications 11.1 (2020): 5984.

# Transverse matching

Focusing term

$$K \equiv -\frac{F_r}{\gamma r m_e v_b^2} \simeq \frac{2\pi r_e n_0}{\gamma} \quad \Longrightarrow \quad \sigma_r'' + K\sigma_r = \frac{\epsilon^2}{\sigma_r^3}$$

Envelope equation

Condition for transverse matching of the witness bunch

$$\boxed{\beta_{eq} = \sqrt{\frac{\gamma}{2\pi r_e n_p}}} \quad \Longrightarrow \quad \boxed{\sigma_{eq} = \sqrt{\frac{\beta_{eq}\epsilon_n}{\gamma}}}$$

N. Barov and J. B. Rosenzweig, Phys. Rev. E 49, 4407 (1994).

Focusing operated by a lens

$$\boxed{\beta_f = \frac{f^2}{\beta_i}}$$

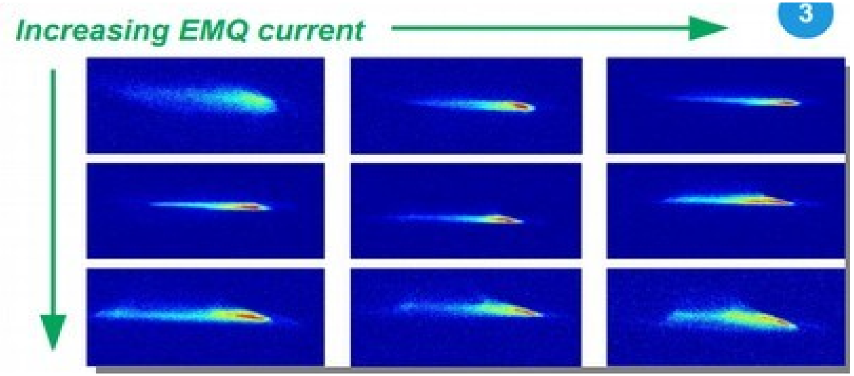
# First emittance measurement in PWFA

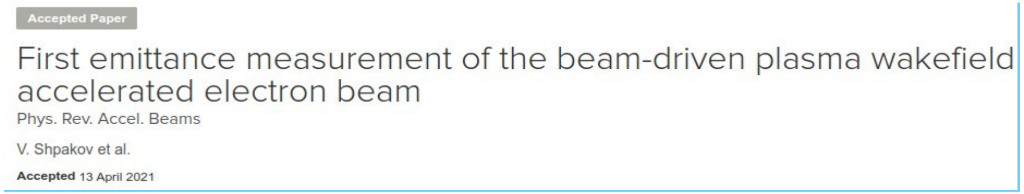
Funded by the European Union

PWFA characterization completed by measuring the witness emittance

*Measurement of its normalized emittance through quadrupole scan technique*

*We found emittance increase from 2.7 um to 3.7 um (rms) during acceleration*



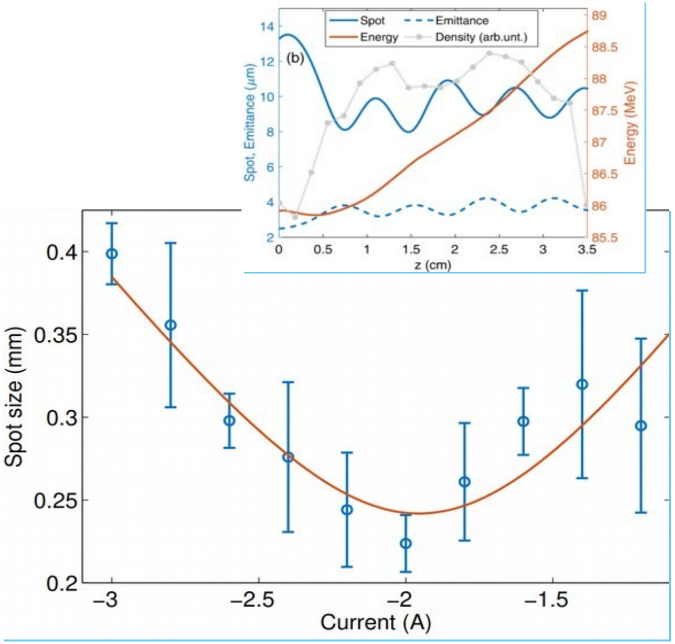

Accepted Paper

First emittance measurement of the beam-driven plasma wakefield accelerated electron beam

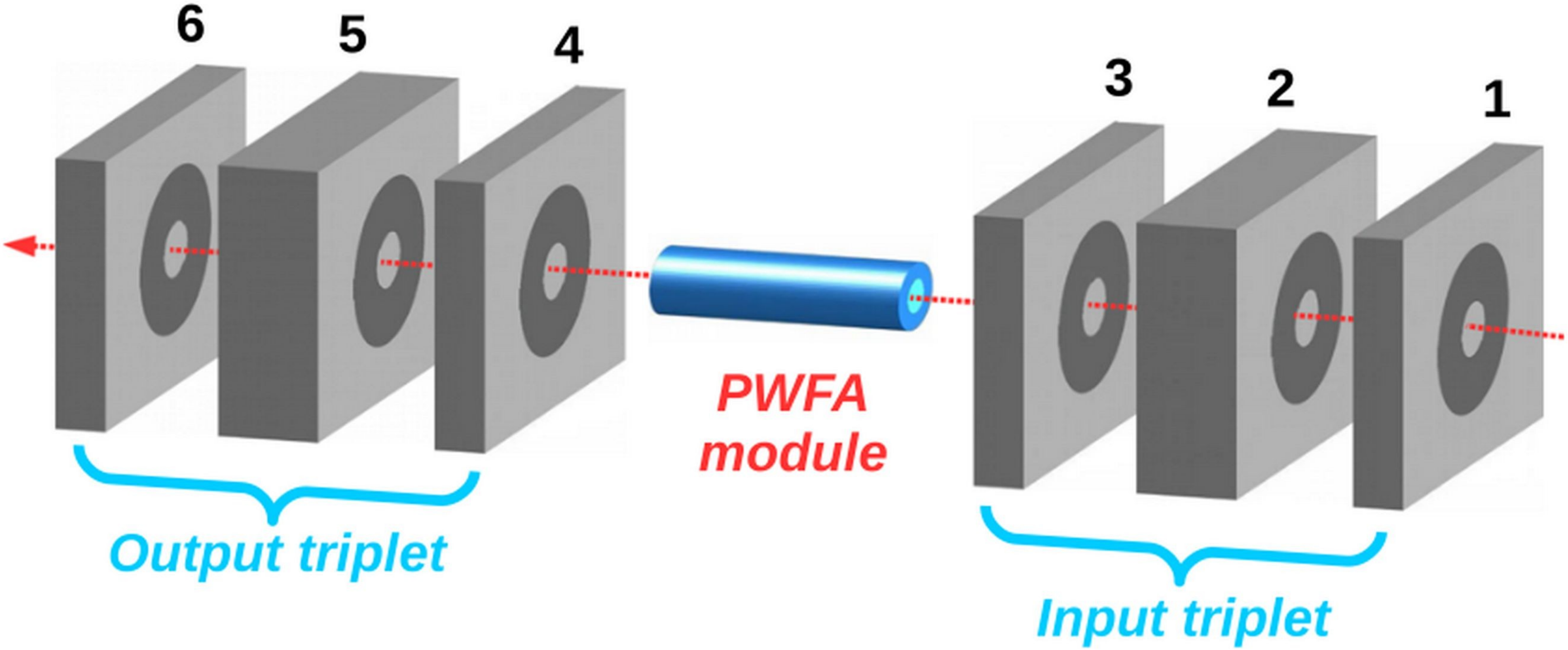
Phys. Rev. Accel. Beams

V. Shpakov et al.

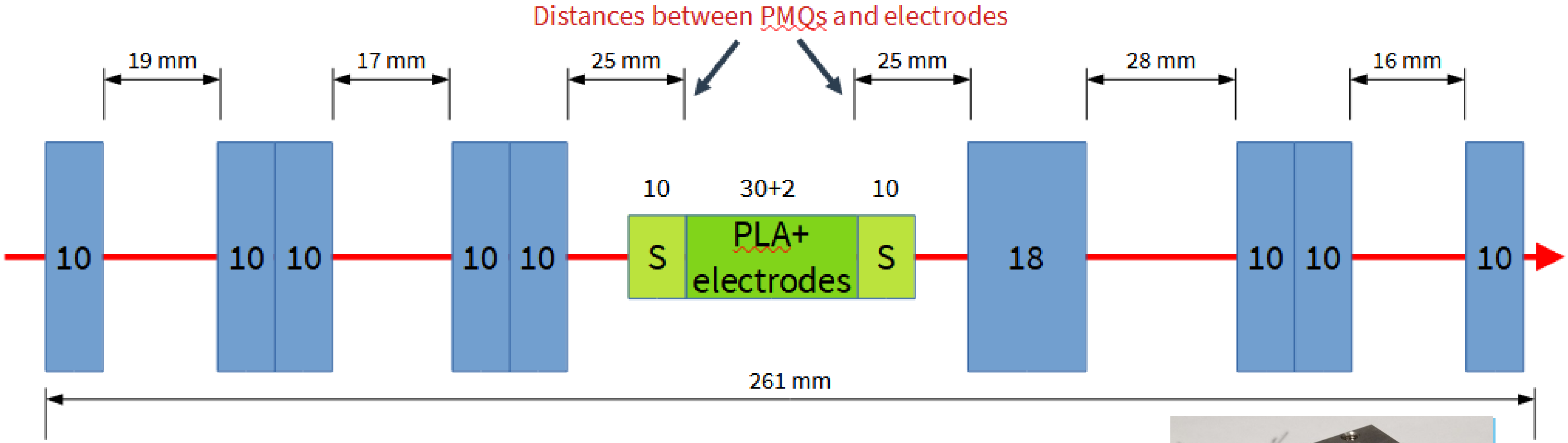
**Accepted** 13 April 2021

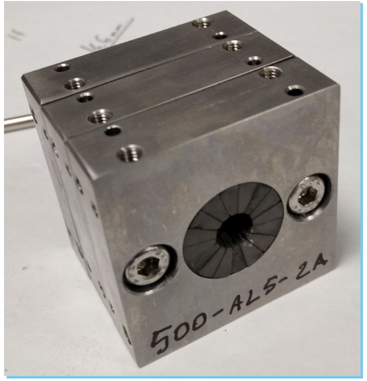


# Focusing optics (PMQ)



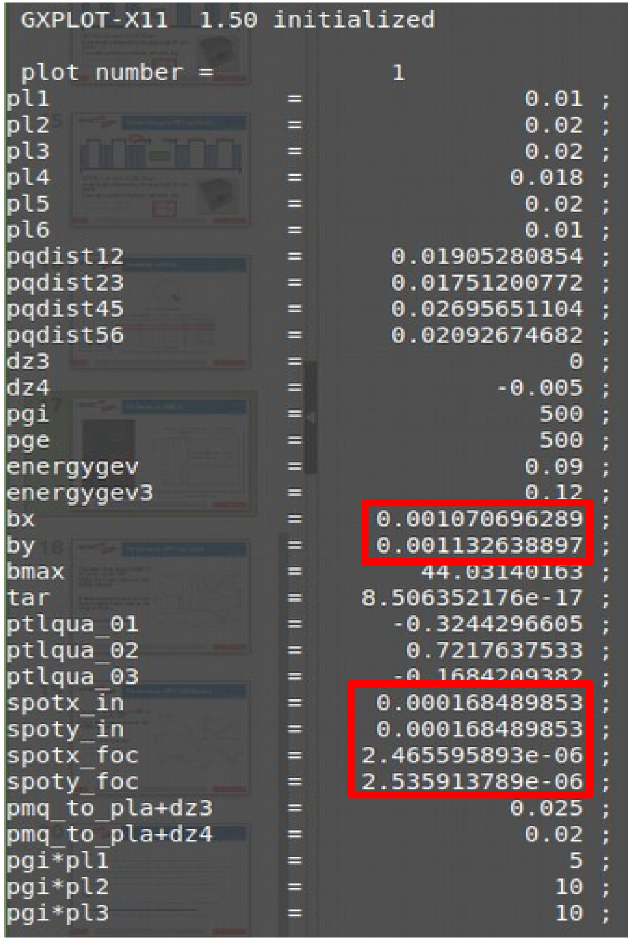
# Focusing optics (PMQ)





- PMQs should move by ±7 mm between them
- 500 T/m, r=3 mm, L=10,18,20 mm
- Obtained by merging single 10 mm pieces
- Currently available @ SPARC_LAB
- *1xAL6+1xAL4 = 4x18 mm*
- *2xAL5+2*AL3 = 8*10 mm*

# Example of matching



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pl2                    =                  0.02 ;
pl3                    =                  0.02 ;
pl4                    =                 0.018 ;
pl5                    =                  0.02 ;
pl6                    =                  0.01 ;
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pqdist23               =         0.01751200772 ;
pqdist45               =         0.02695651104 ;
pqdist56               =         0.02092674682 ;
dz3                    =                     0 ;
dz4                    =                -0.005 ;
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pge                    =                   500 ;
energygev              =                  0.09 ;
energygev3             =                  0.12 ;
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by                     =        0.001132638897 ;
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tar                    =       8.506352176e-17 ;
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ptlqua_02              =          0.7217637533 ;
ptlqua_03              =         -0.1684209382 ;
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spoty_in               =        0.000168489853 ;
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spoty_foc              =       2.535913789e-06 ;
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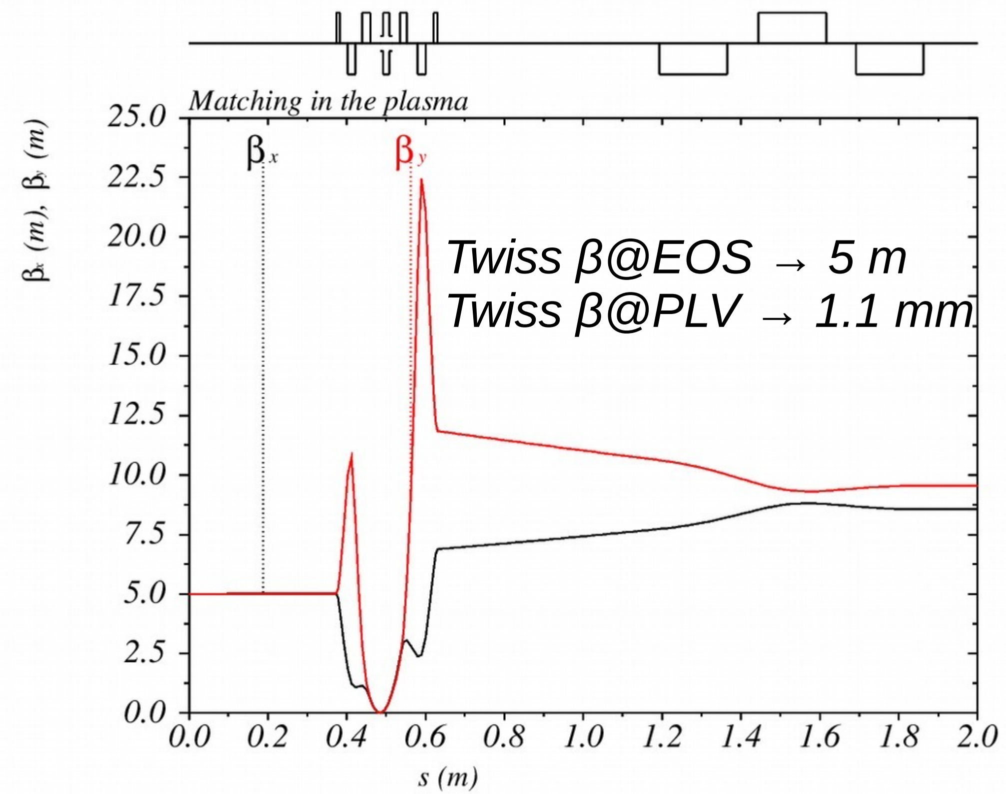
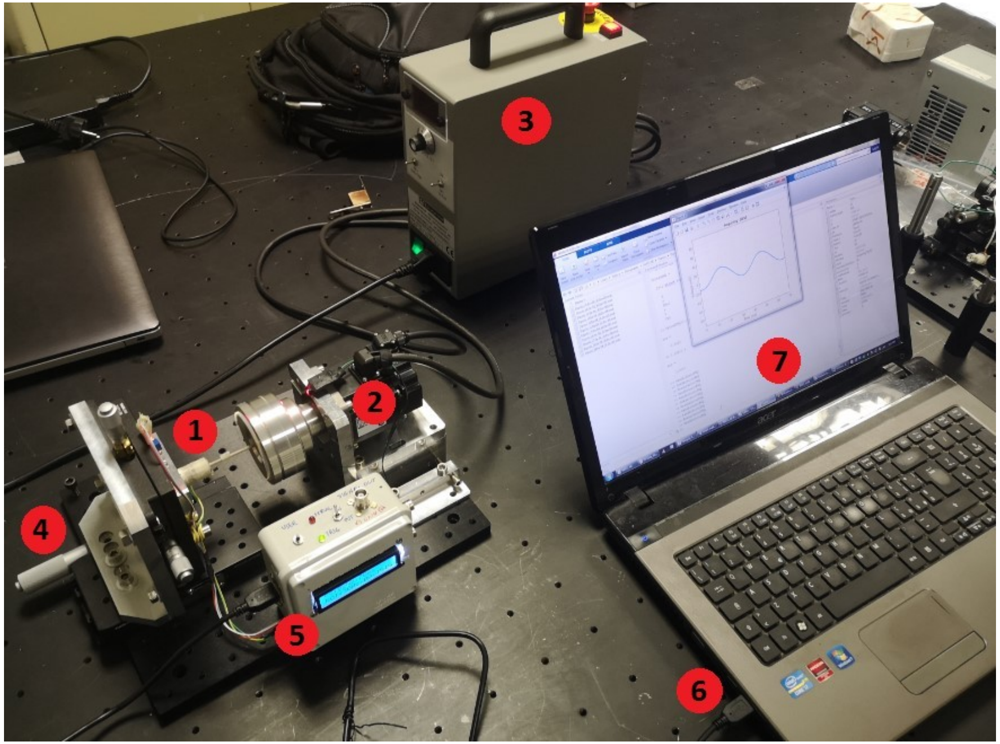
pmq_to_pla+dz4         =                  0.02 ;
pgi*pl1                =                     5 ;
pgi*pl2                =                    10 ;
pgi*pl3                =                    10 ;
```

*PMQs + 1 GV/m cavity* *PTL quads*

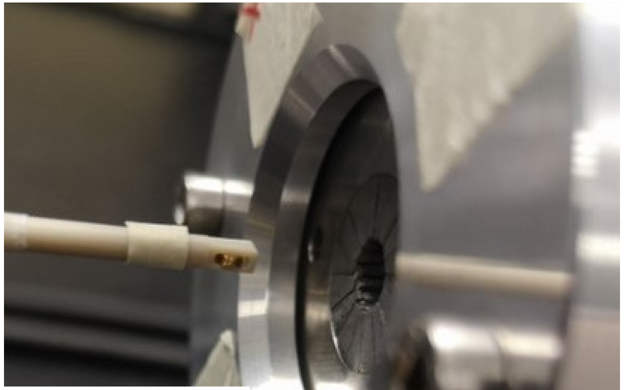


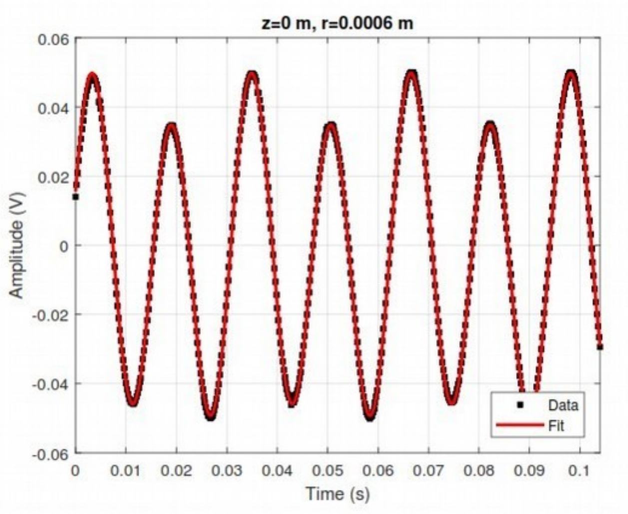
*Twiss β@EOS → 5 m*
*Twiss β@PLV → 1.1 mm*

# PMQ characterization

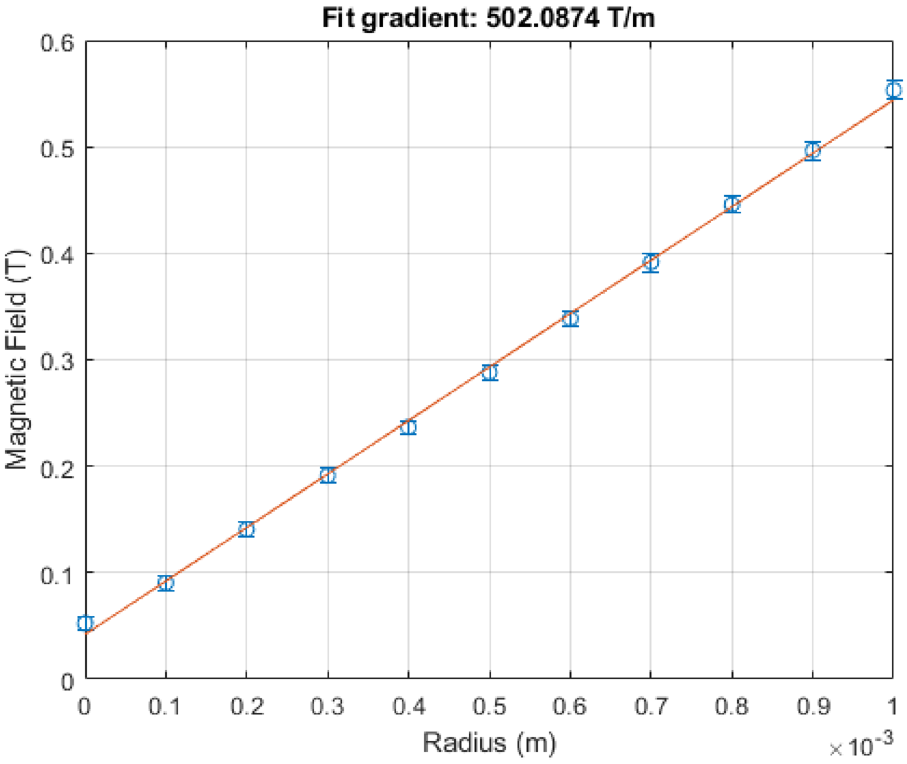


R Pompili, et al. Compact and tunable focusing device for plasma wakefield acceleration. Review of Scientific Instruments, 89(3):033302, 2018

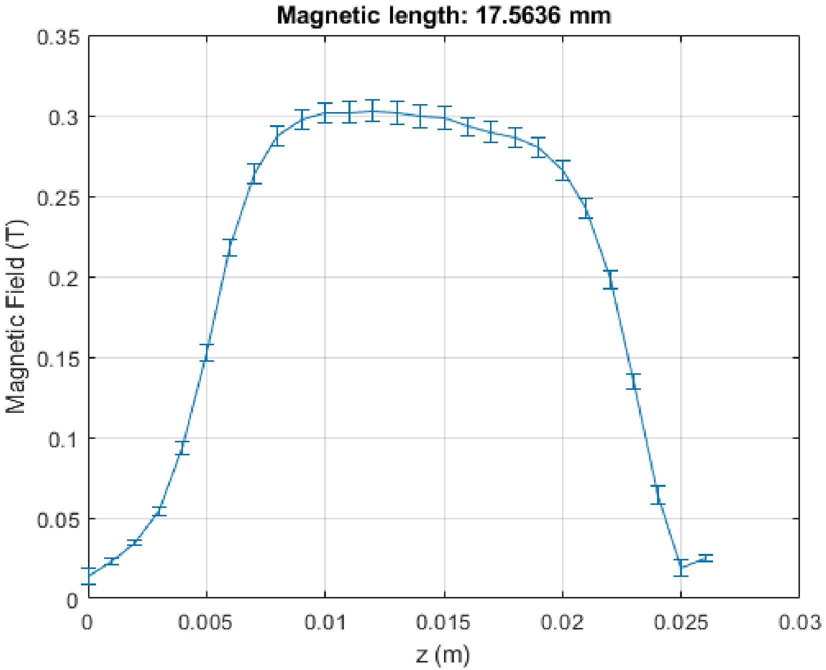




# PMQ characterization



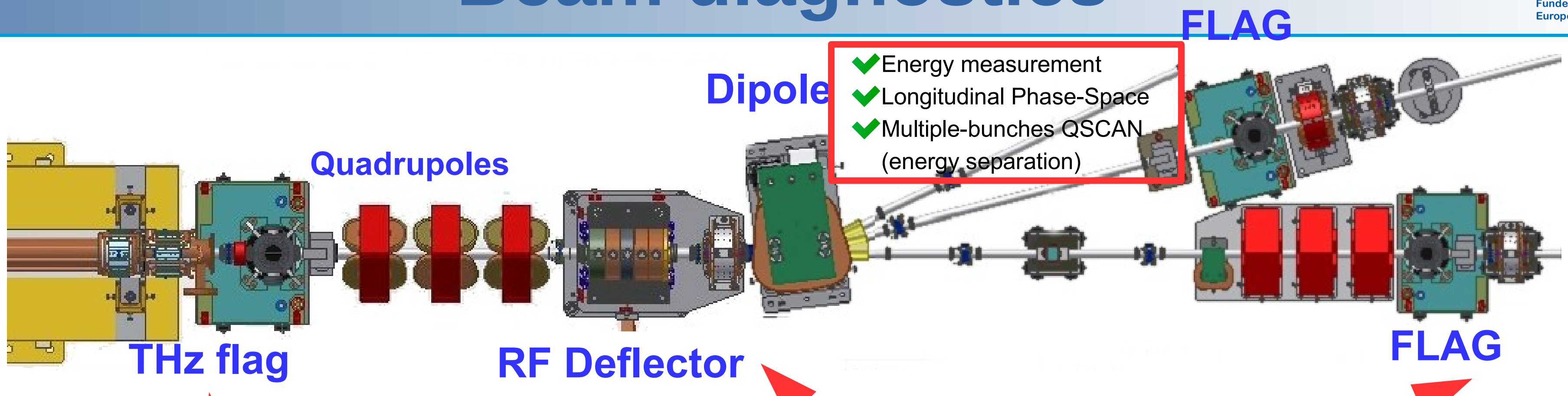
From KYMA
- 500 T/m
- 18 mm



Integrated field @ 0.5 mm
B*z=5.32 T*mm

# Beam diagnostics

**E O S**

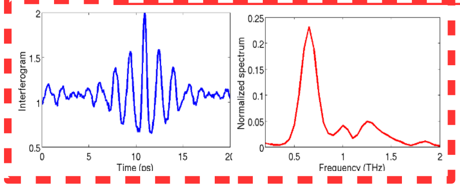


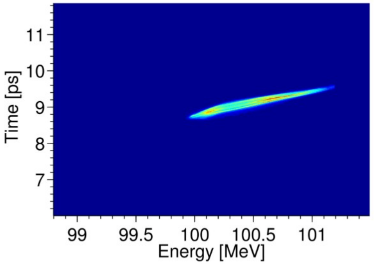
- ✓ Energy measurement
- ✓ Longitudinal Phase-Space
- ✓ Multiple-bunches QSCAN (energy separation)

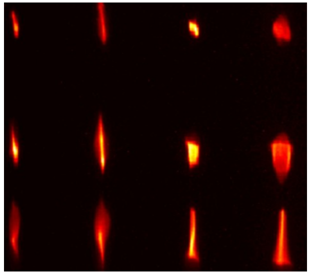
- ✓ CTR/CDR emission in THz range
- ✓ Longitudinal diagnostics
- ✓ THz radiation for user experiments

- ✓ Longitudinal diagnostics
- ✓ Phase-Space characterization

- ✓ Emittance (QSCAN)
- ✓ Multiple-bunches QSCAN (time separation) with RFD







**Cianchi, A. et al.** Six-dimensional measurements of trains of high brightness electron bunches. PRSTAB 18 082804.

# EuPRAXIA@SPARC_LAB

# A new high-tech user facility

Funded by the European Union

## European Plasma Research Accelerator With Excellence In Applications

“the first European project that develops a dedicated particle accelerator research infrastructure based on novel plasma acceleration concepts and laser technology”

- *Building a facility with very high field plasma accelerators, driven by lasers or beams*
- *1 – 100 GV/m accelerating field*
- *Shrink down the facility size*

- *Provide a practical path to more research facilities and ultimately to higher energies for the same investment in terms of size and costs*
- *Enable frontier science in new regions and parameter regimes*

FEATURE EuPRAXIA

**Surf’s up** *Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange).*

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

Ralph Assmann, Massimo Ferrario and Carsten Welsch describe the status of the ESFRI project EuPRAXIA, which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts.

Energetic beams of particles are used to explore the fundamental forces of nature, produce known and unknown particles such as the Higgs boson at the LHC, and generate new forms of matter, for example at the future FAIR facility. Photon science also relies on particle beams: electron beams that emit pulses of intense synchrotron light, including soft and hard X-rays, in either circular or linear machines. Such light sources enable time-resolved measurements of biological, chemical and physical structures on the molecular down to the atomic scale, allowing a diverse global community of users to investigate systems ranging from viruses and bacteria to materials science, planetary science, environmental science, nanotechnology and archaeology. Last but not least, particle beams for industry and health support many societal applications ranging from the X-ray inspection of cargo containers to food sterilisation, and from chip manufacturing to cancer therapy.

This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the path to an energy gain of several tens of MeV per metre. Very-high-energy accelerators were constructed with RF technology, entering the GeV and finally the TeV energy scales at the Tevatron and the LHC. New collision schemes were developed, for example the mini “beta squeeze” in the 1970s, advancing luminosity and collision rates by orders of magnitudes. The invention of stochastic cooling at CERN enabled the discovery of the W and Z bosons 40 years ago.

However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

**THE AUTHORS**

**Ralph Assmann** *DESY and INFN*, **Massimo Ferrario** *INFN*, **Carsten Welsch** *University of Liverpool/INFN.*

CERN COURIER MAY/JUNE 2023

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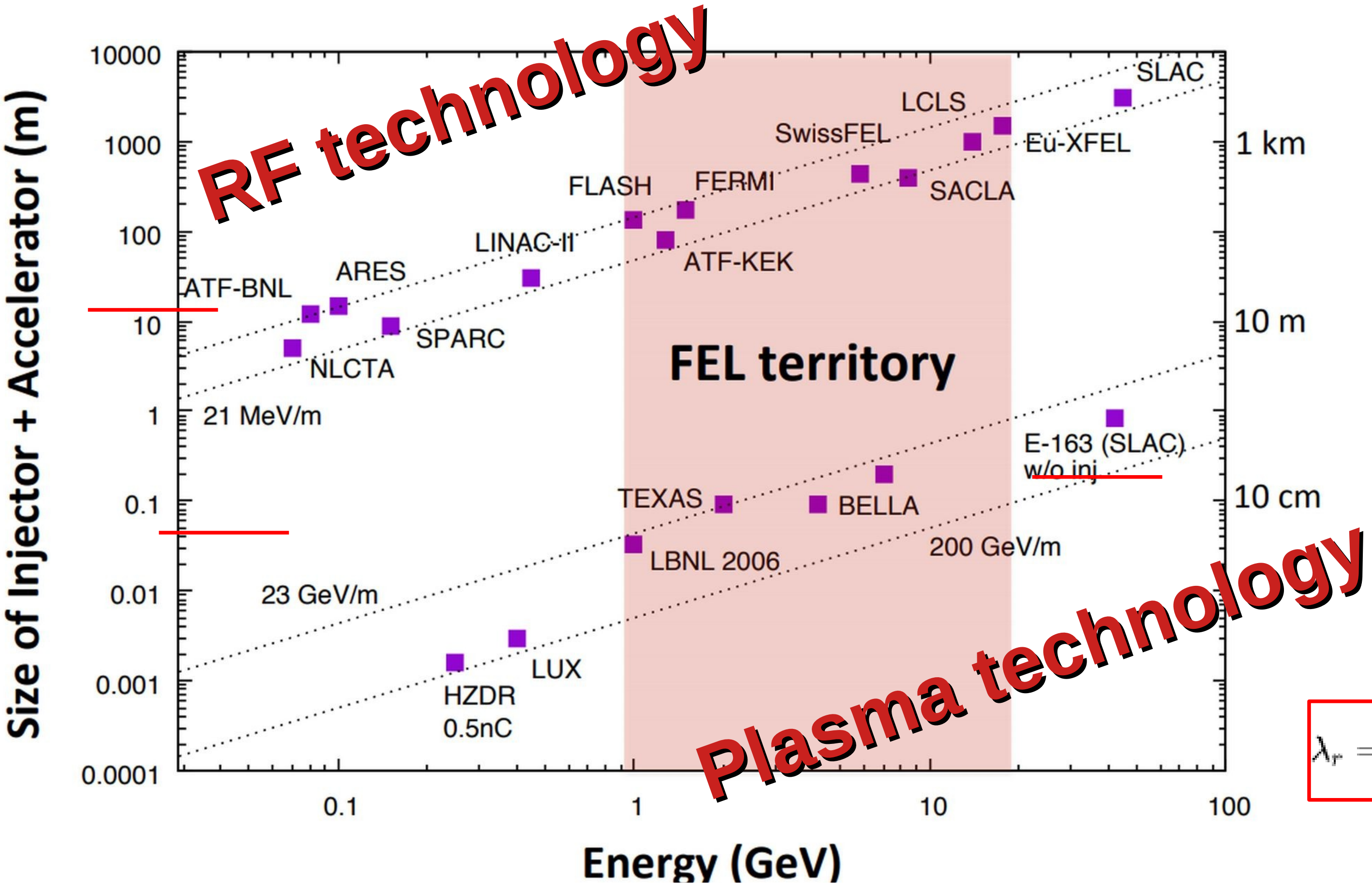
*https://cerncourier.com/a/europe-targets-a-user-facility-for-plasma-acceleration/*

# RF and Plasma technology

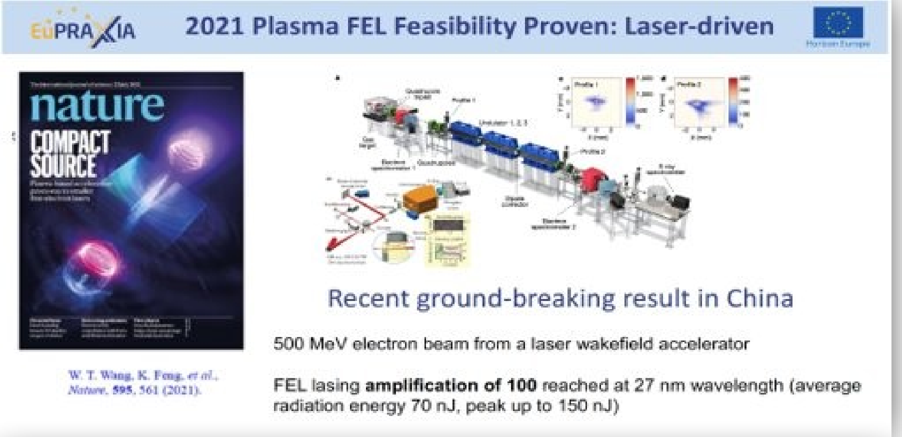


$$\boxed{\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)}$$

*R. Assmann*

# Pilot plasma-driven FELs experiments

Funded by the European Union



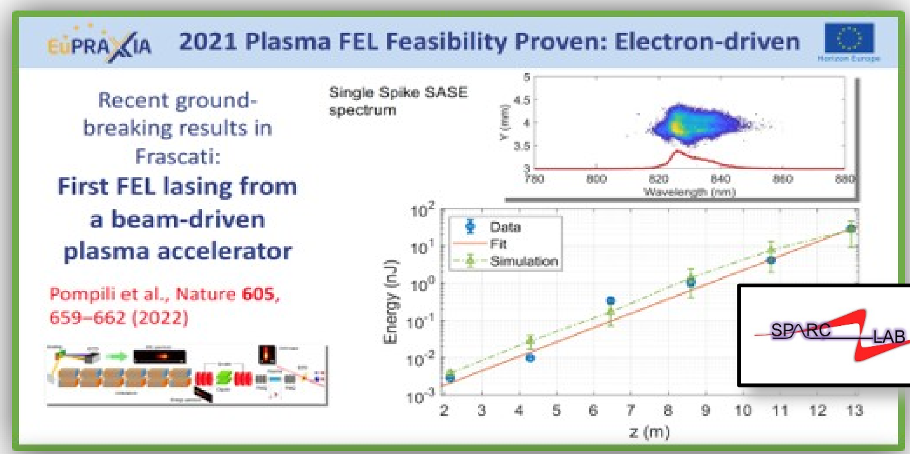
## 2021 Plasma FEL Feasibility Proven: Laser-driven

W. T. Wang, K. Feng, *et al.*, *Nature*, **595**, 561 (2021).

Recent ground-breaking result in China

500 MeV electron beam from a laser wakefield accelerator

FEL lasing **amplification of 100** reached at 27 nm wavelength (average radiation energy 70 nJ, peak up to 150 nJ)



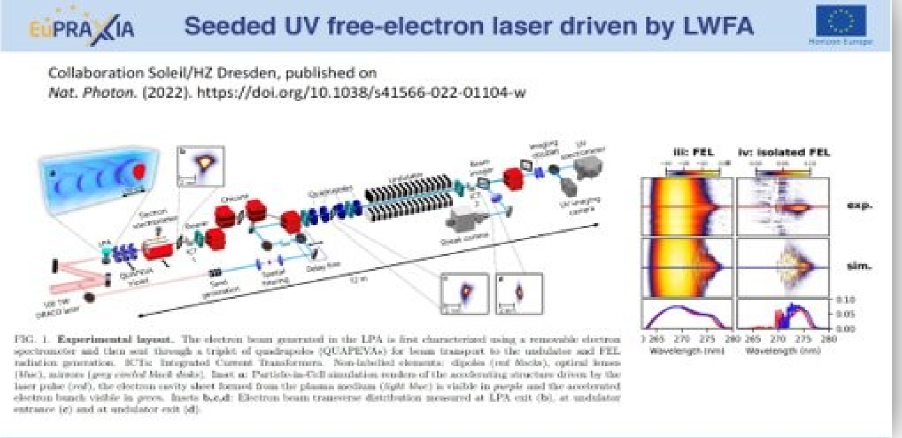
## 2021 Plasma FEL Feasibility Proven: Electron-driven

Recent ground-breaking results in Frascati:

**First FEL lasing from a beam-driven plasma accelerator**

Pompili et al., Nature **605**, 659–662 (2022)

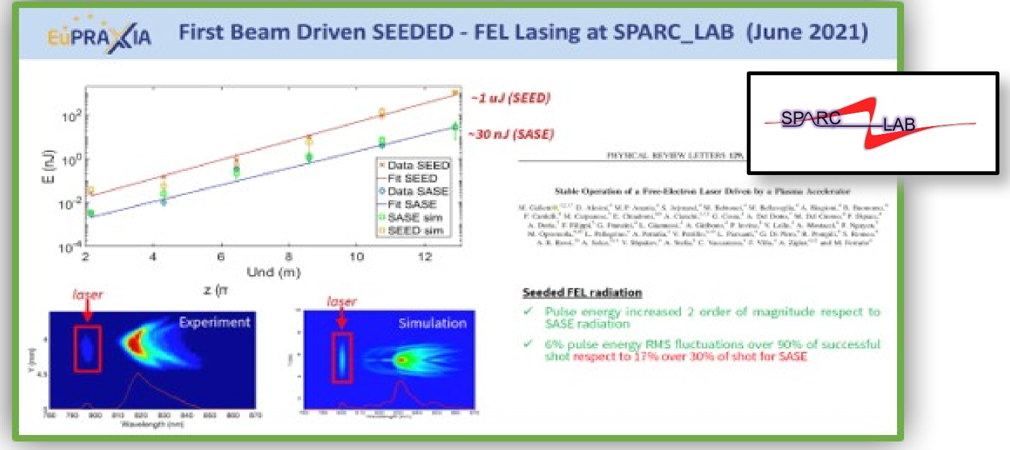
Single Spike SASE spectrum



## Seeded UV free-electron laser driven by LWFA

Collaboration Soleil/HZ Dresden, published on *Nat. Photon.* (2022). https://doi.org/10.1038/s41566-022-01104-w

FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTs: Integrated Current Transformers. Non-labelled elements: dipoles (red blocks), optical lenses (blue), mirrors (grey circled black disks). Inset a: Particle-in-Cell simulation renders of the accelerating structure driven by the laser pulse (red), the electron cavity sheet formed from the plasma medium (light blue) is visible in purple and the accelerated electron bunch visible in green. Insets b,c,d: Electron beam transverse distribution measured at LPA exit (b), at undulator entrance (c) and at undulator exit (d).

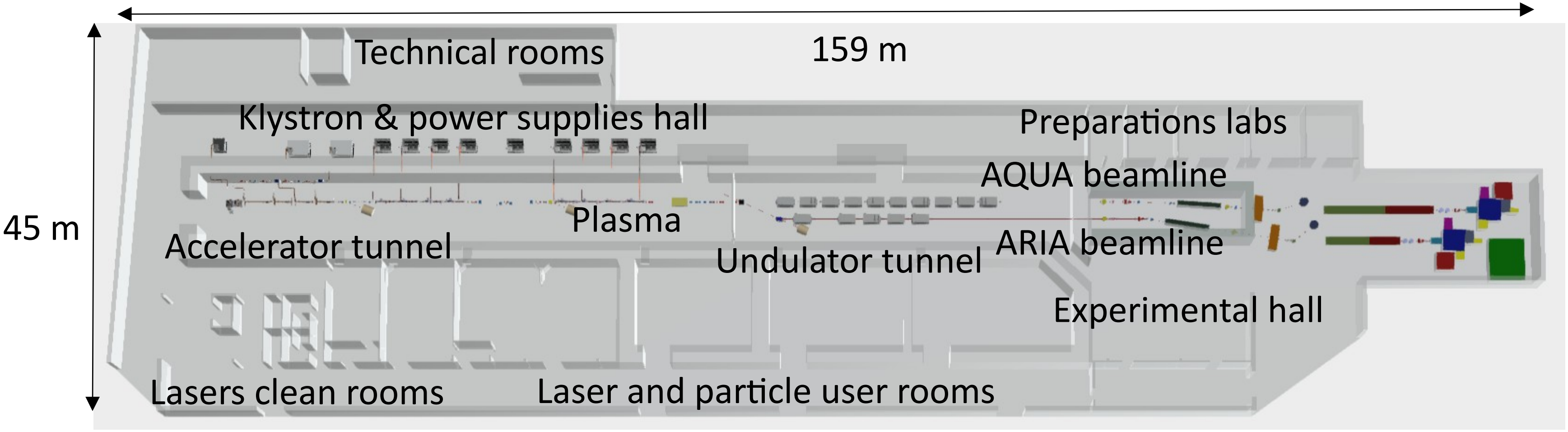


## First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)

**Seeded FEL radiation**

- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE

# EuPRAXIA@SPARC_LAB layout



~~Good~~ Excellent news first!

694

**MINISTERO DELLE INFRASTRUTTURE E DEI TRASPORTI**
PROVVEDITORATO IN[illegible]REGIONALE PER LE OO.PP. PER IL LAZIO, L'ABRUZZO, LA SARDEGNA
* * * * *
VIA MONZAMBANO, 10 – ROMA

**AVVISO**
**ai sensi dell'art. 29 del D.Lgs. 18 aprile 2016, n. 50**

**O[illegible]: C.[illegible] n. [illegible]4 - Realizzazione [illegible] un nuovo complesso edilizio EuSPARC per ospitare la facility EuPRAXIA presso i Laboratori Nazionali di Frascati INFN.**
**Am[illegible]one Proponente [illegible]N Istituto Nazionale di Fisica Nucleare**

Si com[illegible] ai sensi dell'art. 14-bis comma 5 della L. 241/90 e ss.mm. e ii., è da considerarsi acquisito l'assenso sul progetto in argomento da parte delle Am[illegible]razioni invitate alla Conferenza. Si **DICHIARA**, pertanto, sulla scorta degli atti acquisiti, perfezionata l'intesa per la localizzazione e realizzazione dell'opera indicata in [illegible]ggetto e, di conseguenza, **AUTORIZZATO** il relativo progetto definitivo.
**Gli atti del procedimento sono in visione presso la Segreteria dell'Ufficio Conferenze di Servizi di questo Provveditorato**

| IL DIRIGENTE | IL RESPONSABILE DEL PROCEDIMENTO | IL PROVVEDITORE |
|---|---|---|
| Dott. Ing. Carlo Guglielmi | Dott. Arch. Alessia Costa | Dott. Ing. Vittorio Rapisarda Federico |

Firmato digitalmente da CARLO GUGLIELMI

VITTORIO RAPISARDA FEDERICO
Ministero delle Infrastrutture e dei Trasporti
23.05.2023 11:37:37 GMT+01:00

Roma, lì ____________
PUBBLICATO ____________
RITIRATO ____________

APPROVED

A. Falone - TDR Review Committee – 15/06/2023

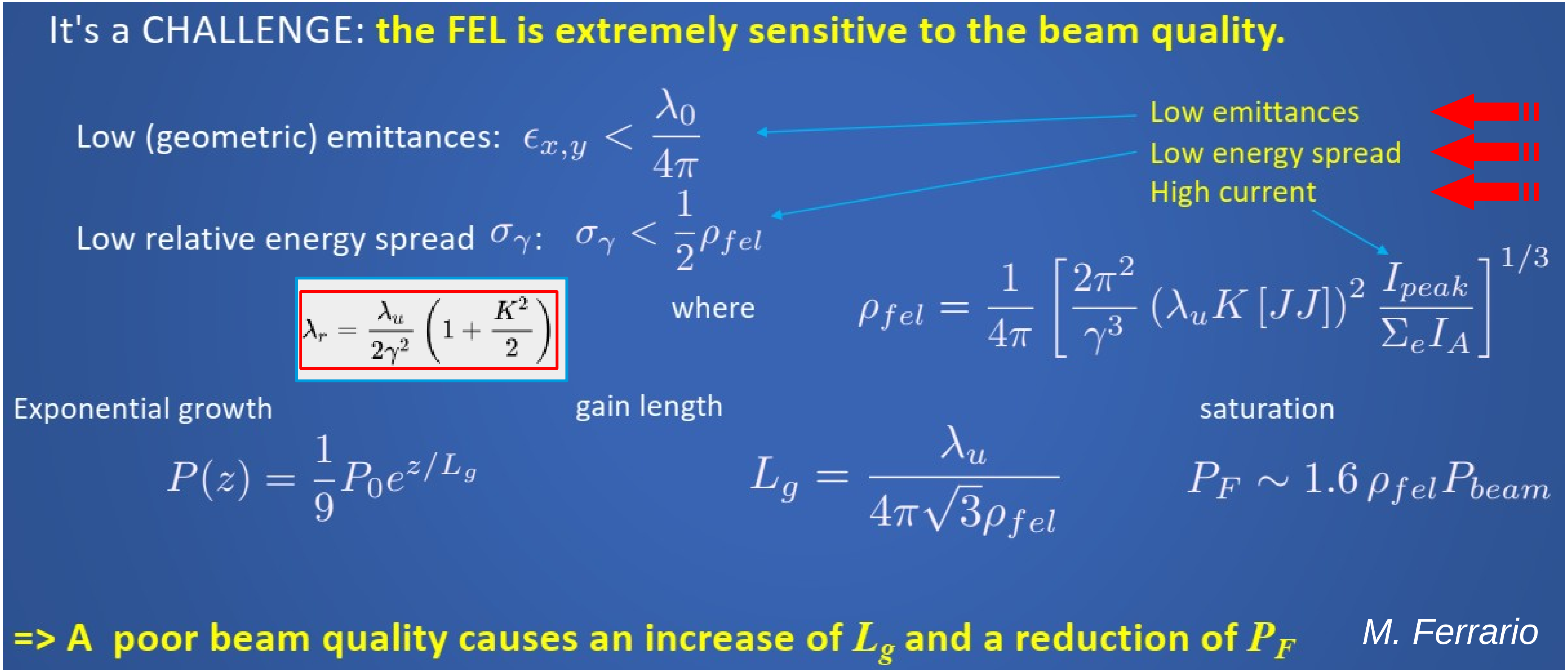
# Headquarters and Site 1

Credit: INFN and Mythos – consorzio stabile s.c.a.r.l.

Frascati’s future facility

- >130 M€ invest funding
- Beam-driven plasma accelerator
- Europe’s most compact and most southern FEL
- The world’s most compact RF accelerator

# FEL requirements



It's a CHALLENGE: **the FEL is extremely sensitive to the beam quality.**

Low (geometric) emittances: $\epsilon_{x,y} < \frac{\lambda_0}{4\pi}$

Low relative energy spread $\sigma_\gamma$: $\sigma_\gamma < \frac{1}{2}\rho_{fel}$

Low emittances

Low energy spread

High current

$$\boxed{\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)}$$

where $$\rho_{fel} = \frac{1}{4\pi}\left[\frac{2\pi^2}{\gamma^3}\left(\lambda_u K\left[JJ\right]\right)^2 \frac{I_{peak}}{\Sigma_e I_A}\right]^{1/3}$$

Exponential growth

$$P(z) = \frac{1}{9}P_0 e^{z/L_g}$$

gain length

$$L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho_{fel}}$$

saturation

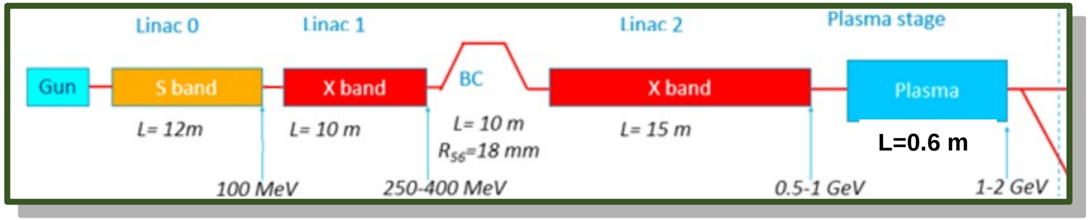
$$P_F \sim 1.6\,\rho_{fel} P_{beam}$$

**=> A poor beam quality causes an increase of $L_g$ and a reduction of $P_F$**

*M. Ferrario*

# Electron beam parameters

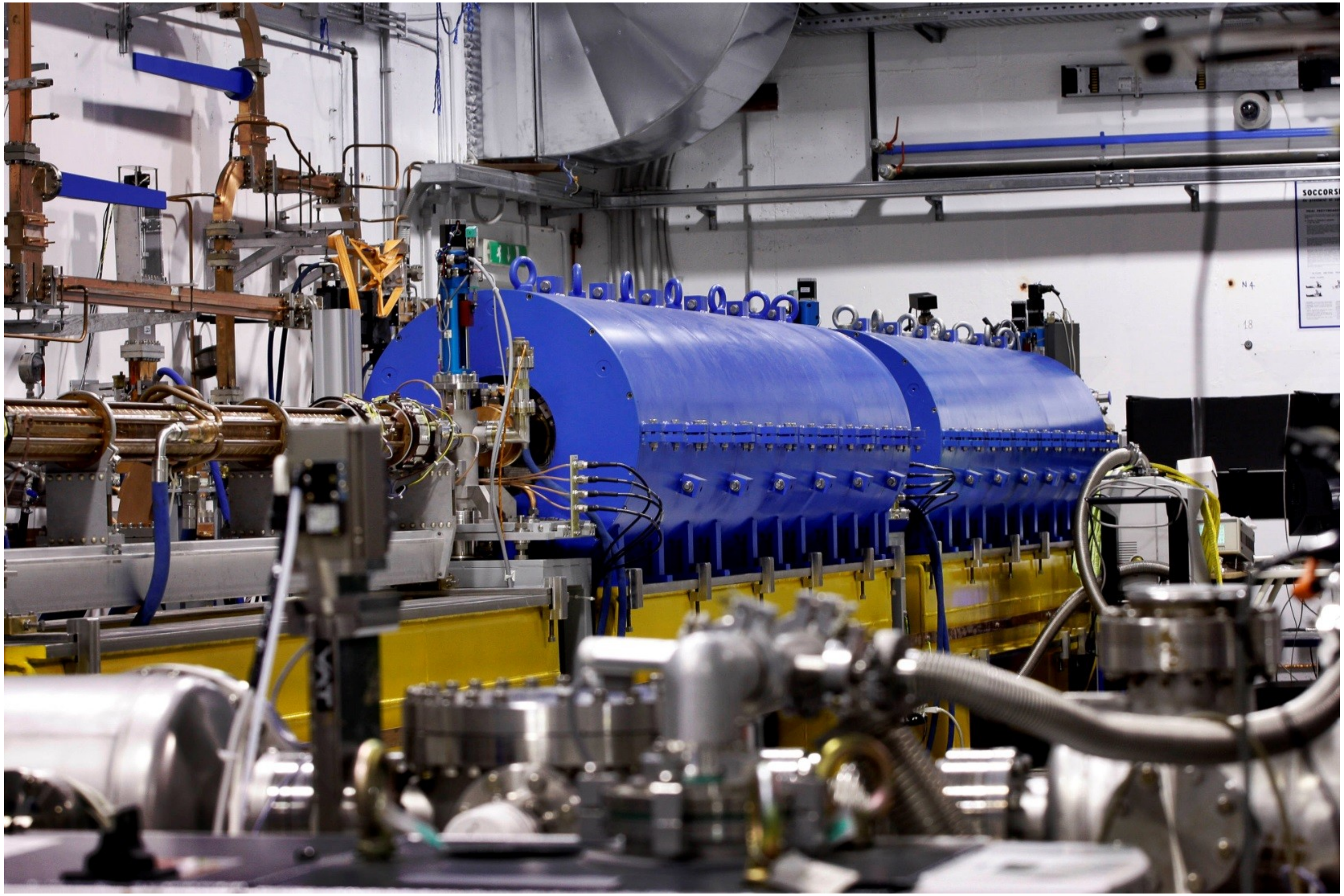
| **Parameter** | **Unit** | PWFA | X-band |
|---|---|---|---|
| Electron Energy | GeV | 1-1.2 | 1 |
| Bunch Charge | pC | **30-50** | **200-500** |
| Peak Current | kA | 1-2 | 1-2 |
| RMS Energy Spread | % | 0.1 | 0.1 |
| RMS Bunch Length | $\mu$m | **6-3** | **24-20** |
| RMS norm Emittance | $\mu$m | 1 | 1 |
| Slice Energy Spread | % | ≤0.05 | ≤0.05 |
| Slice norm Emittance | um | 0.5 | 0.5 |

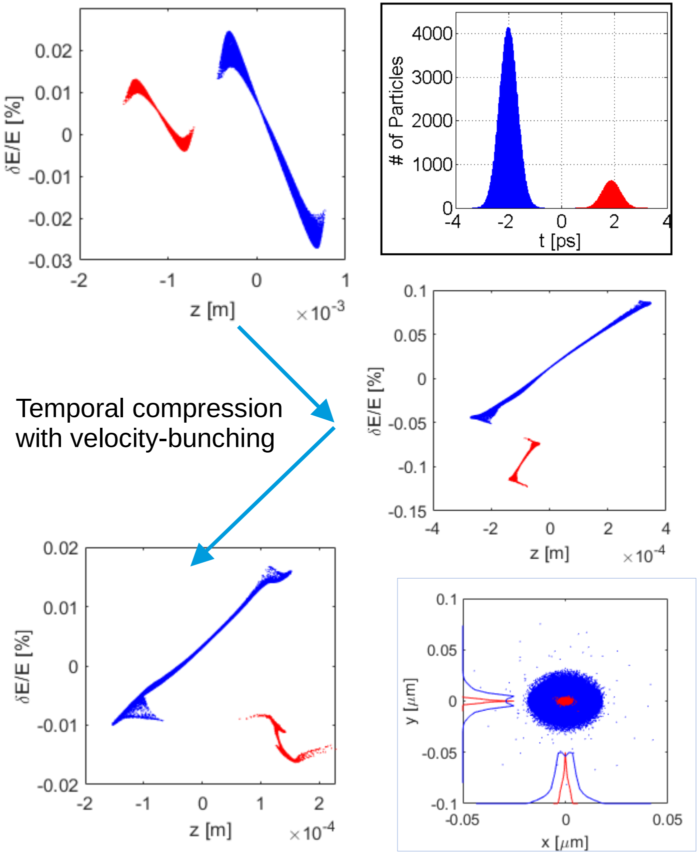


Two different configurations:

- 500 MeV beam from the X-band linac + 500 MeV from the compact plasma module
  - *Smaller accelerated charge*
  - *Shorter pulses*
  - *Final energy easily upgradable (up to 5 GeV) with similar building occupancy*
- 1 GeV beam from the X-band linac alone (requires additional RF power)
  - *Larger charge per bunch*
  - *Longer pulses*
  - *It exploits the largest RF field achievable with X-band technology*

# S-band Photo-injector



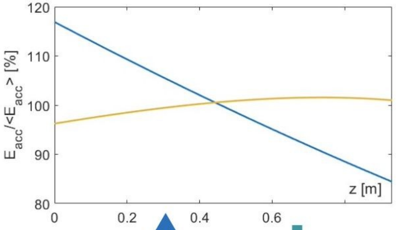


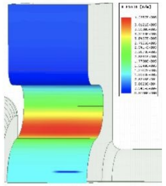
Temporal compression with velocity-bunching

E. Chiadroni, A. Giribono, C. Vaccarezza

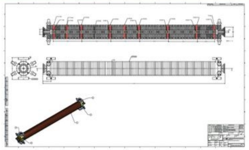
# X-band LINAC, tests @ TEX

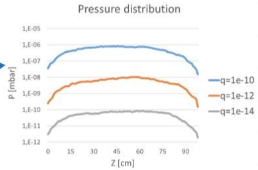
Funded by the European Union

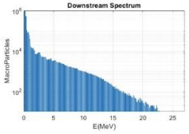




1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*







| PARAMETER | Value | |
|---|---|---|
| | with linear tapering | w/o tapering |
| Frequency [GHz] | 11.9942 | |
| **Average acc. gradient [MV/m]** | **60** | |
| Structures per module | 2 | |
| **Iris radius a [mm]** | **3.85-3.15** | **3.5** |
| Tapering angle [deg] | 0.04 | 0 |
| **Struct. length $L_s$ act. Length (flange-to-flange) [m]** | **0.94 (1.05)** | |
| No. of cells | 112 | |
| Shunt impedance R [MΩ/m] | 93-107 | 100 |
| Effective shunt Imp. $R_{sh\ eff}$ [MΩ/m] | 350 | 347 |
| Peak input power per structure [MW] | 70 | |
| Input power averaged over the pulse [MW] | 51 | |
| Average dissipated power [kW] | 1 | |
| $P_{out}/P_{in}$ [%] | 25 | |
| Filling time [ns] | 130 | |
| Peak Modified Poynting Vector [W/μm$^2$] | 3.6 | 4.3 |
| Peak surface electric field [MV/m] | 160 | 190 |
| Unloaded SLED/BOC Q-factor $Q_0$ | 150000 | |
| External SLED/BOC Q-factor $Q_E$ | 21300 | 20700 |
| **Required Kly power per module [MW]** | **20** | |
| **RF pulse [μs]** | **1.5** | |
| **Rep. Rate [Hz]** | **100** | |


TEX facility

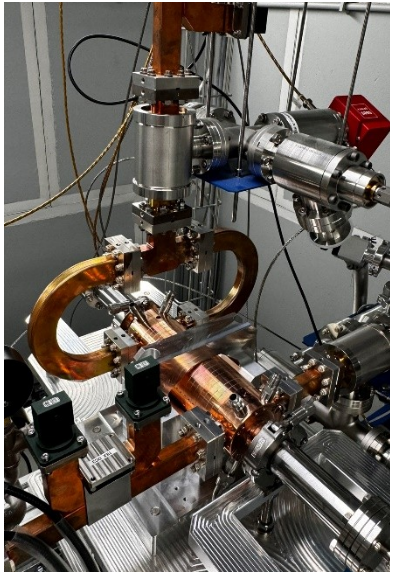
D. Alesini, F. Cardelli

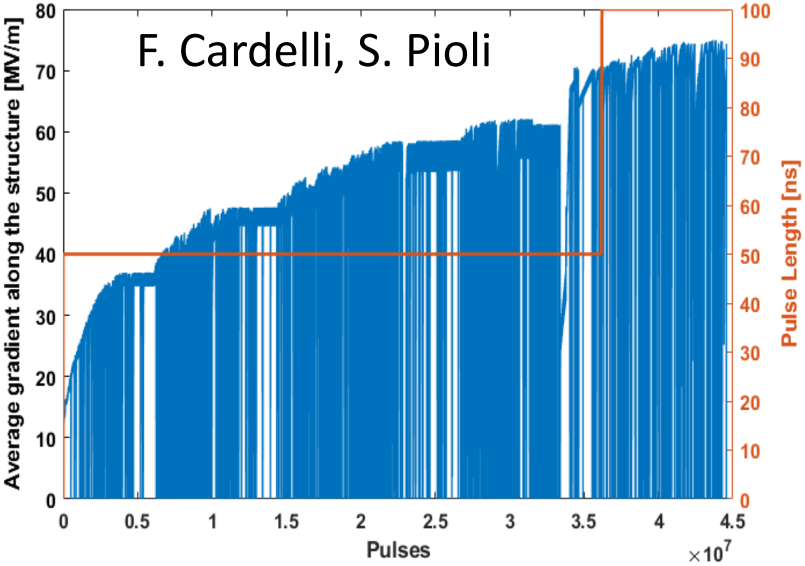
# 20 cells EuPRAXIA X-band tests

- From the 6th to the 17th of March we perform the high power test of the first EuPRAXIA@SPARC_LAB X-band structure prototype at **TEX**
- It is a 20 cells, constant impedance, RF prototype (the real structure will be 1 m long)
- In 10 days we reach an input pulse of 35 MW, 100 ns length at 50 Hz repetition rate, that correspond to an average gradient along the structure equal to 74 MV/m and a peak gradient at the structure input of 80 MV/m.

**Control Room**

**LLRF system**

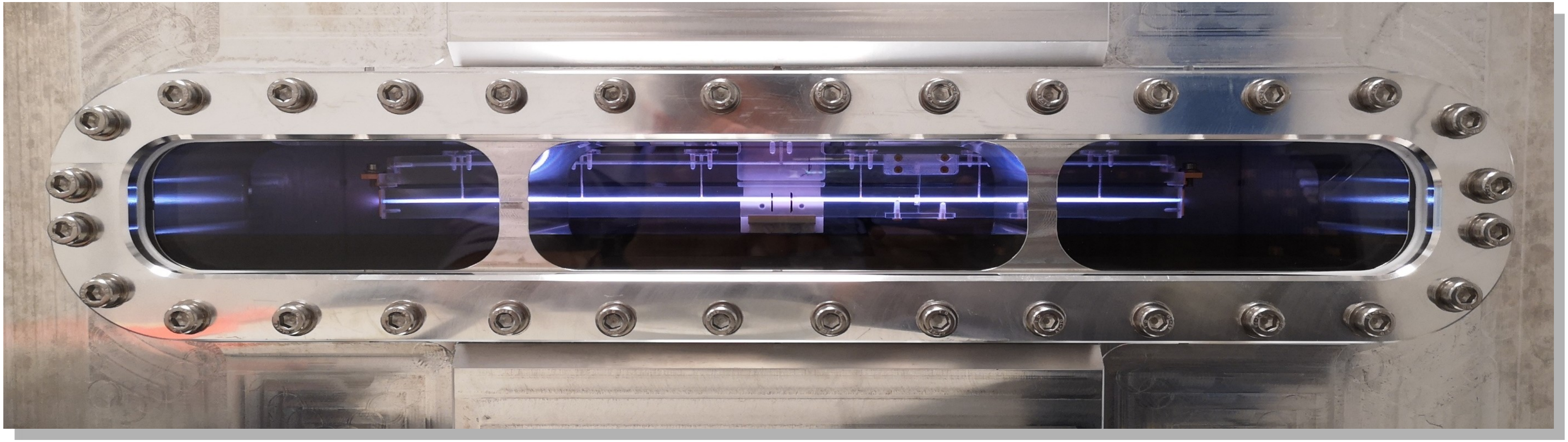




**RF Source**

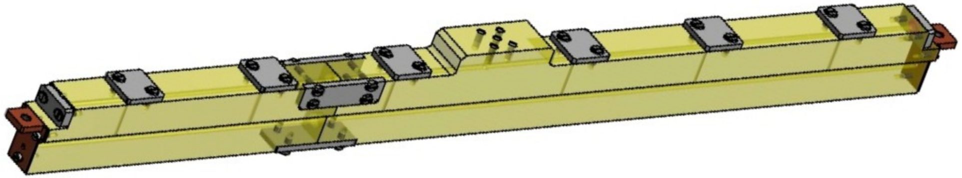
**VKX8311A Klystron**

# Plasma module



- 40 cm long capillary → $1^{st}$ prototype for the EuPRAXIA facility
  - *Made with special junction to allow negligible gas leaks ($<10^{-10}$ mbar)*
  - *Next step is to extend its length to 60 cm as required by last studies*
- Operating conditions
  - *1 Hz repetition rate (to be increased up to 100 Hz)*
  - *10 kV – 380 A minimum values for ionization*
  - *6 inlets for gas injection. Electro-valve aperture time 8-12 ms*

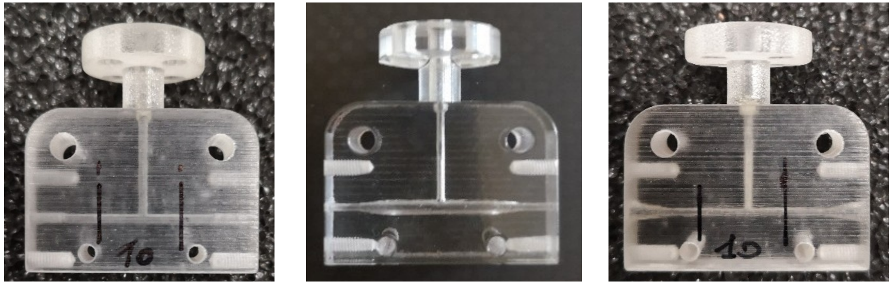
A. Biagioni, V. Lollo

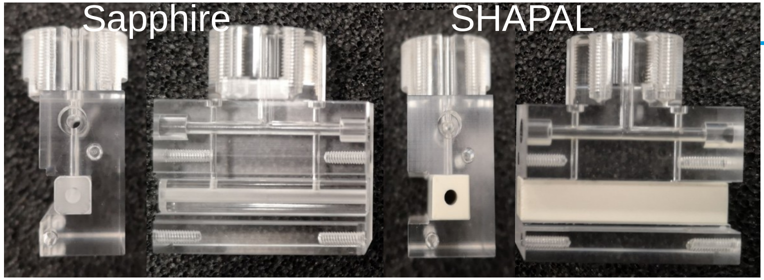


# R&D on plasma acceleration

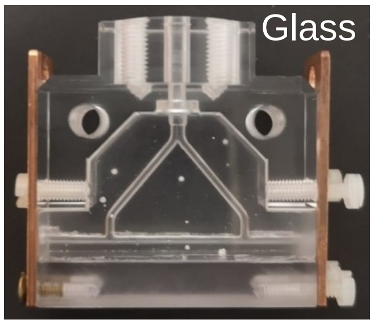
Funded by the European Union

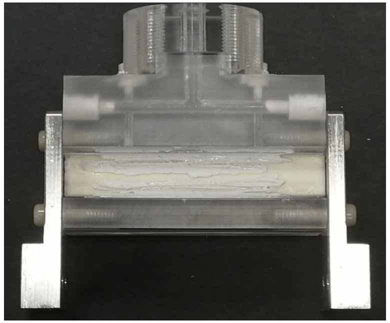
A. Biagioni, L. Crincoli

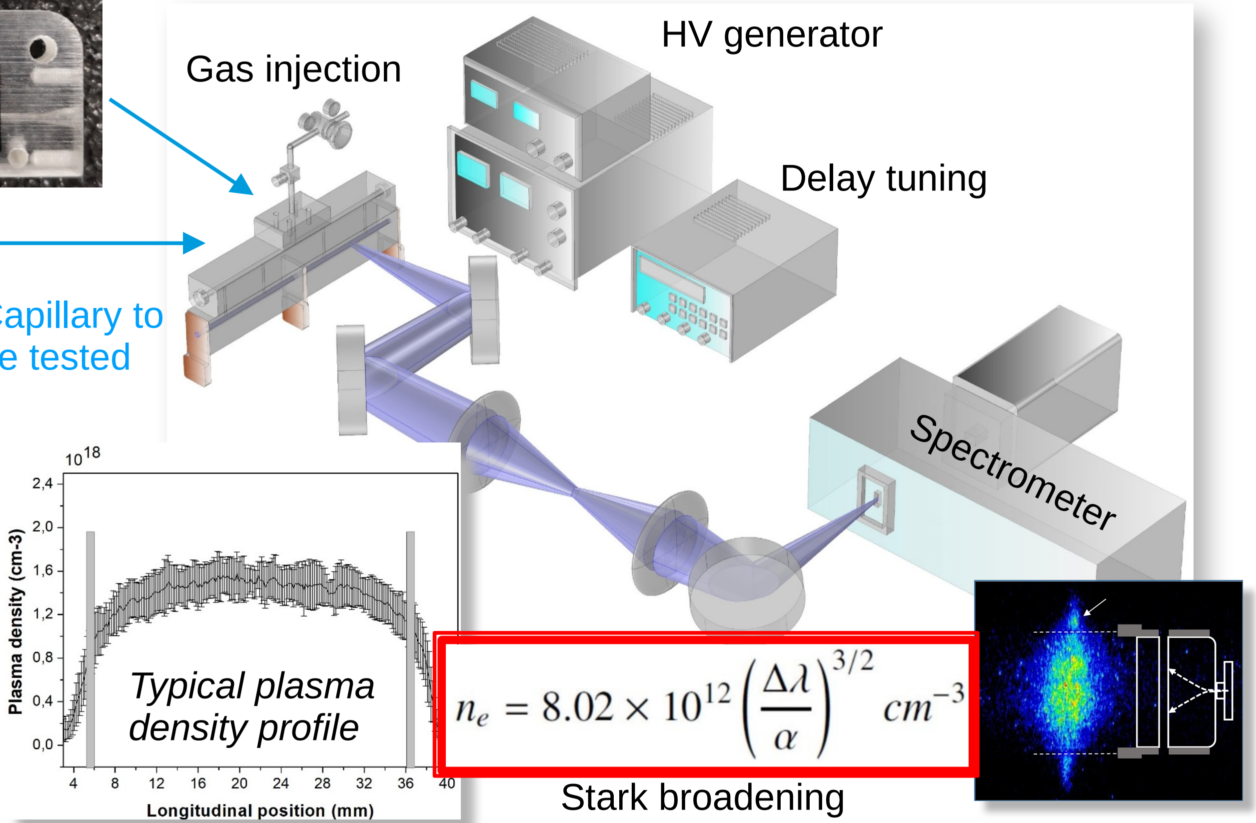




Capillary to be tested







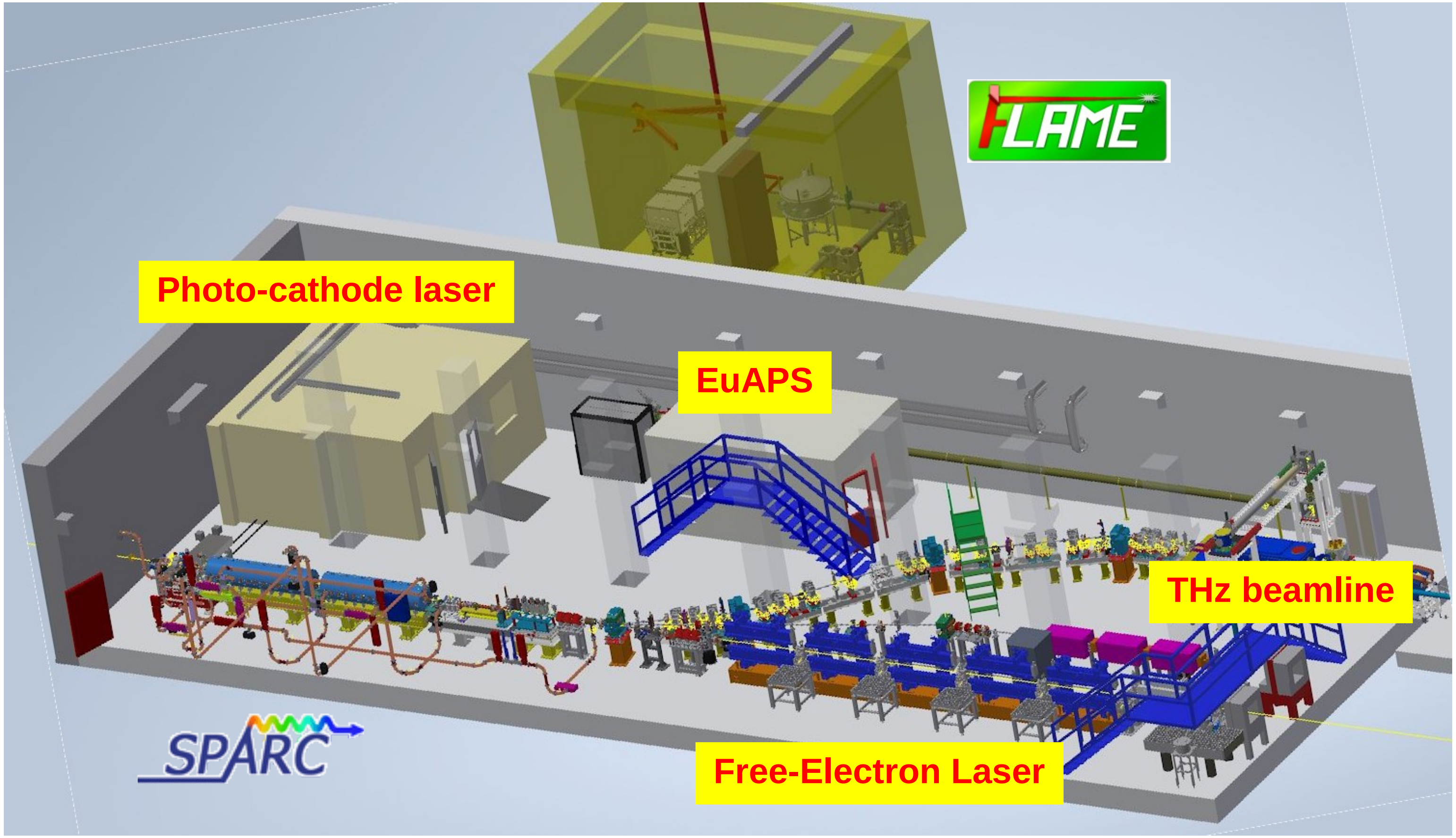
*Typical plasma density profile*

$$n_e = 8.02 \times 10^{12} \left( \frac{\Delta\lambda}{\alpha} \right)^{3/2} cm^{-3}$$

Stark broadening

# SPARC_LAB experience

# The SPARC_LAB facility



Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

# SPARC_LAB upgrade

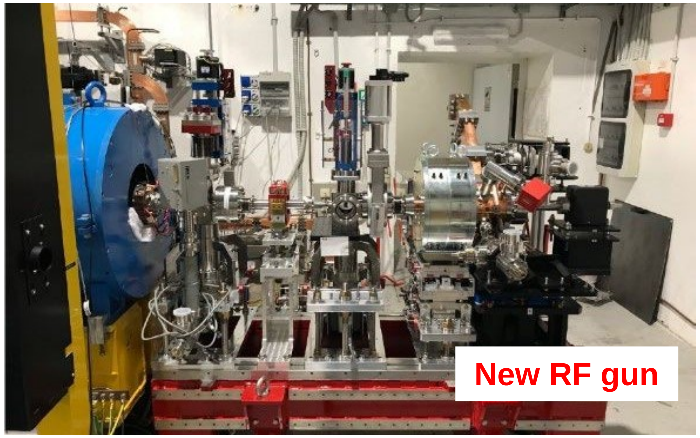
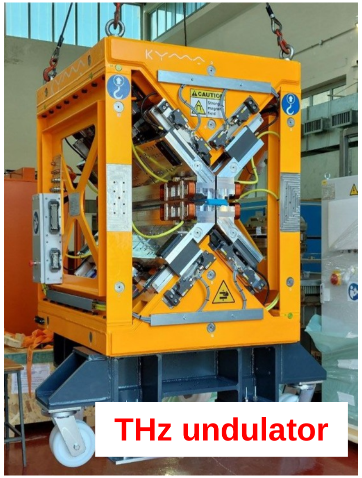

New RF gun

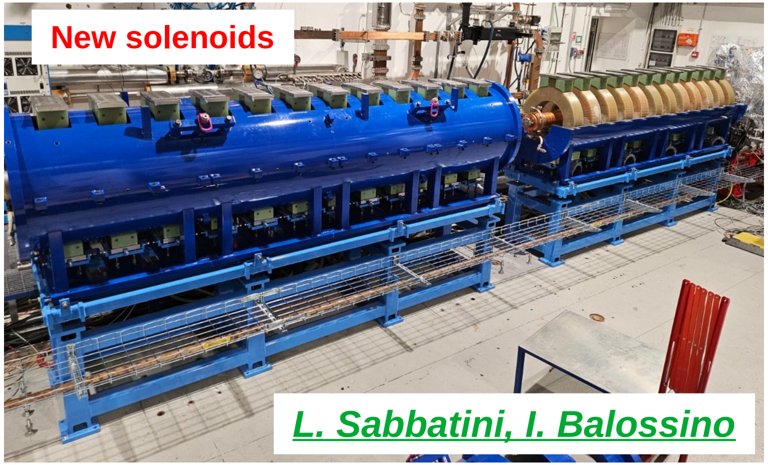

Photo-cathode laser


C-band modulator


Dry-cooler


LLRF


THz undulator

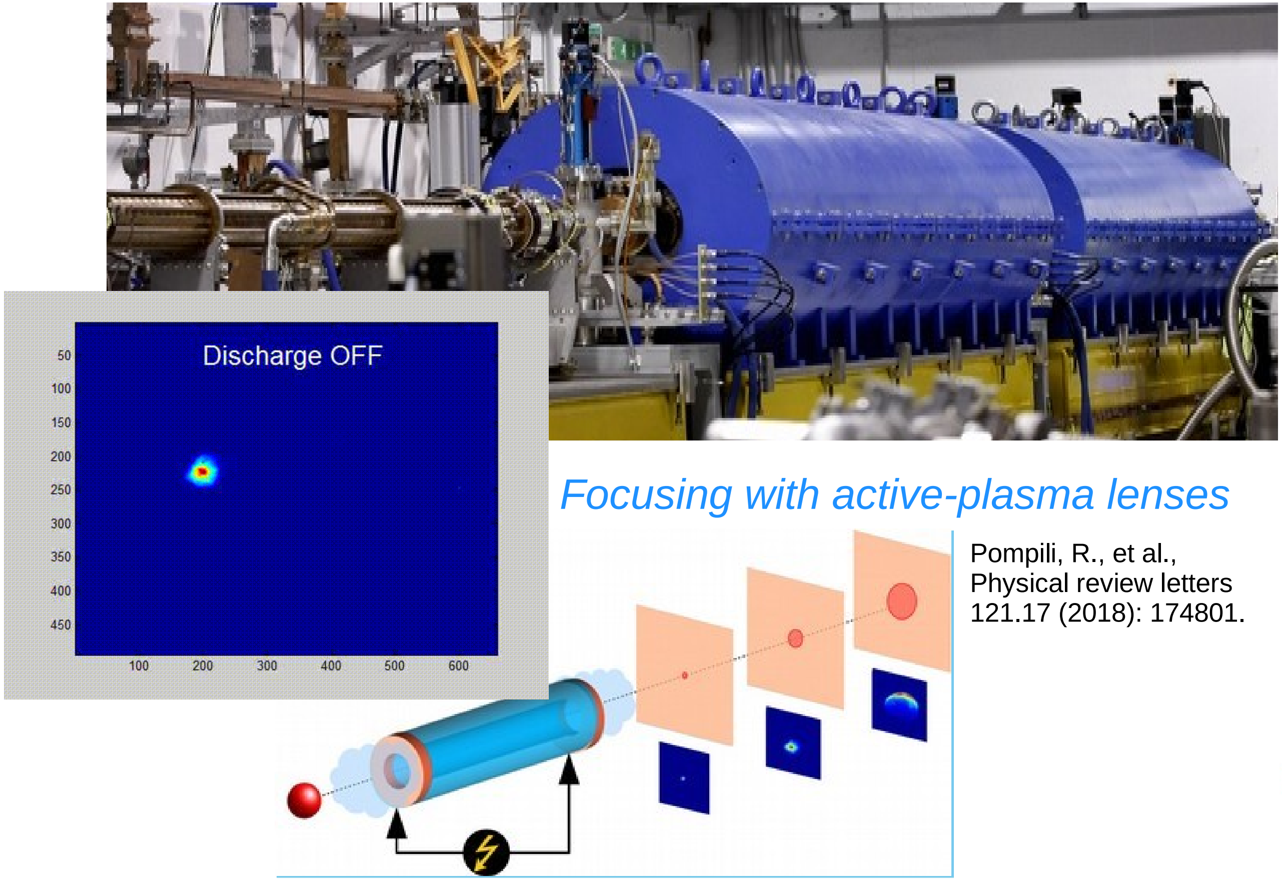

New solenoids

L. Sabbatini, I. Balossino

# Milestones

Funded by the European Union

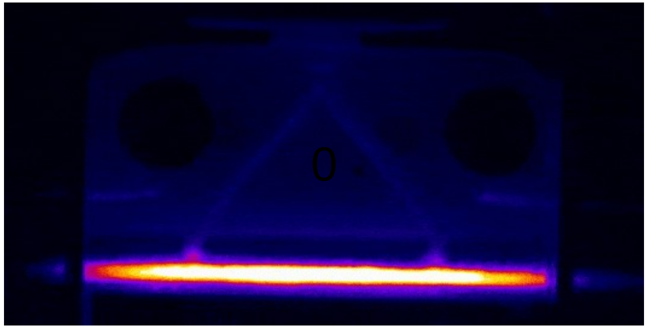
## *Activities with the high-brightness SPARC photo-injector*



## *Focusing with active-plasma lenses*

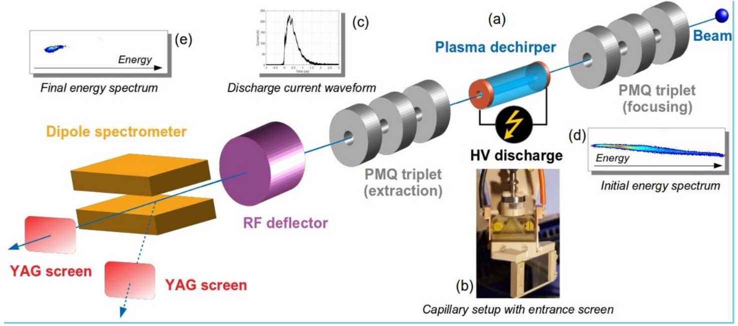
Pompili, R., et al., Physical review letters 121.17 (2018): 174801.

## *Plasma characterization*



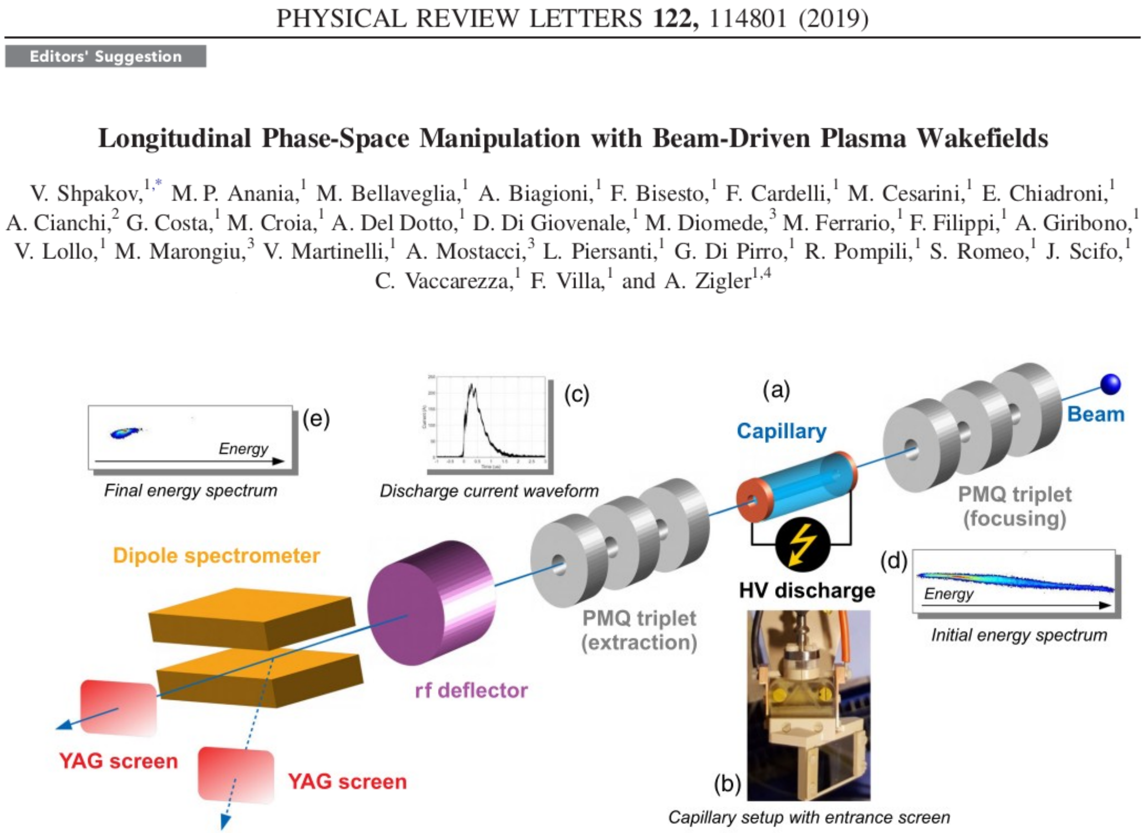
Biagioni, A., et al., Journal of Instrumentation 11.08 (2016)

## *Longitudinal phase-space manipulation*



V. Shpakov et al. Phys. Rev. Lett. 122, 114801 (2019)

# Plasma as a dechirper

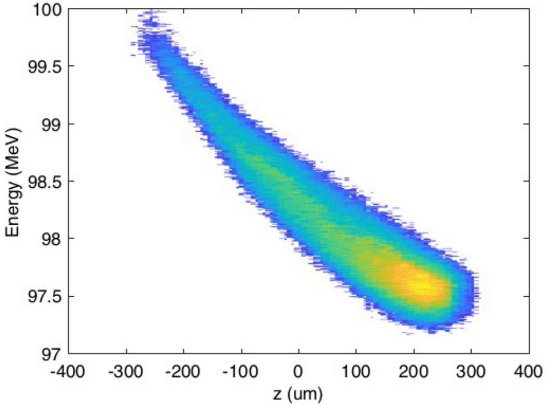


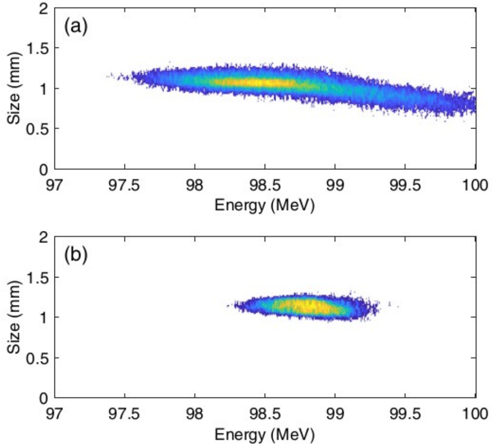
PHYSICAL REVIEW LETTERS **122,** 114801 (2019)

**Editors' Suggestion**

**Longitudinal Phase-Space Manipulation with Beam-Driven Plasma Wakefields**

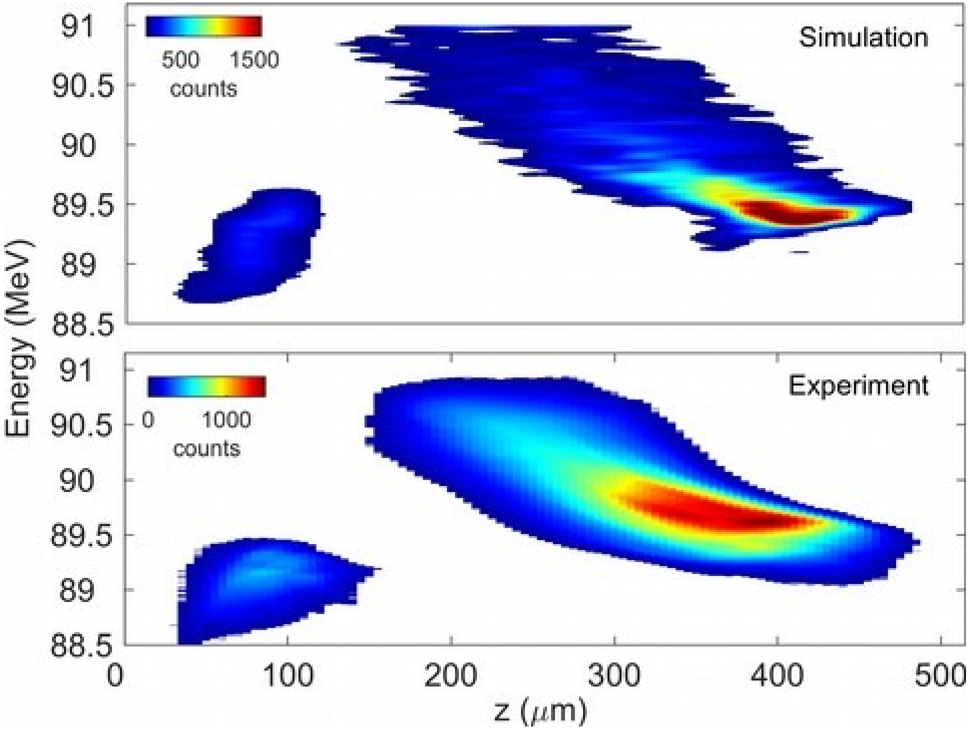
V. Shpakov,[1,*] M. P. Anania,[1] M. Bellaveglia,[1] A. Biagioni,[1] F. Bisesto,[1] F. Cardelli,[1] M. Cesarini,[1] E. Chiadroni,[1] A. Cianchi,[2] G. Costa,[1] M. Croia,[1] A. Del Dotto,[1] D. Di Giovenale,[1] M. Diomede,[3] M. Ferrario,[1] F. Filippi,[1] A. Giribono,[1] V. Lollo,[1] M. Marongiu,[3] V. Martinelli,[1] A. Mostacci,[3] L. Piersanti,[1] G. Di Pirro,[1] R. Pompili,[1] S. Romeo,[1] J. Scifo,[1] C. Vaccarezza,[1] F. Villa,[1] and A. Zigler[1,4]





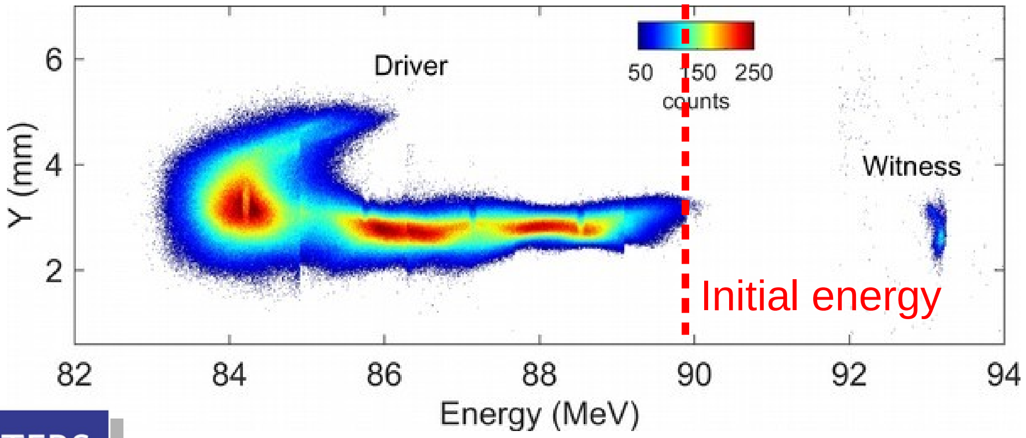
# Driver and witness at plasma entrance

Two-bunches configuration produced directly at the cathode with laser-comb technique
200 pC driver (charge increased up to 350 pC) followed by witness bunch (20 pC)
Ultra-short durations (200 fs + 30 fs)
Separation approximately equal to ¾ of the plasma wavelength (~1 ps)



# Control of the energy spread

4 MeV acceleration in 3 cm plasma with 200 pC driver
~133 MV/m accelerating gradient
2x$10^{15}$ cm$^{-3}$ plasma density
<u>Demonstration of projected energy spread compensation</u>
**Spread from 0.2% to 0.12%**

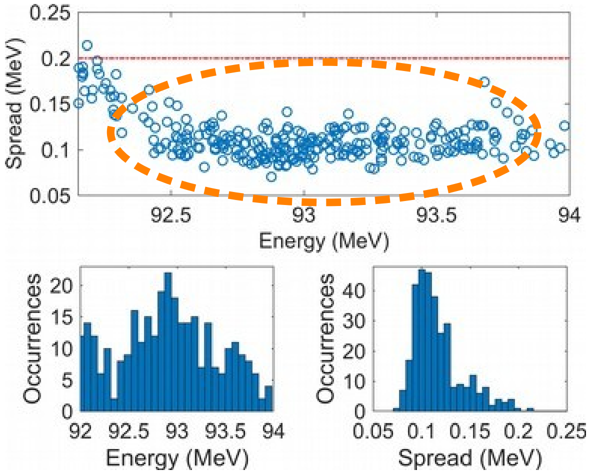



nature physics
LETTERS
https://doi.org/10.1038/s41567-020-01116-9

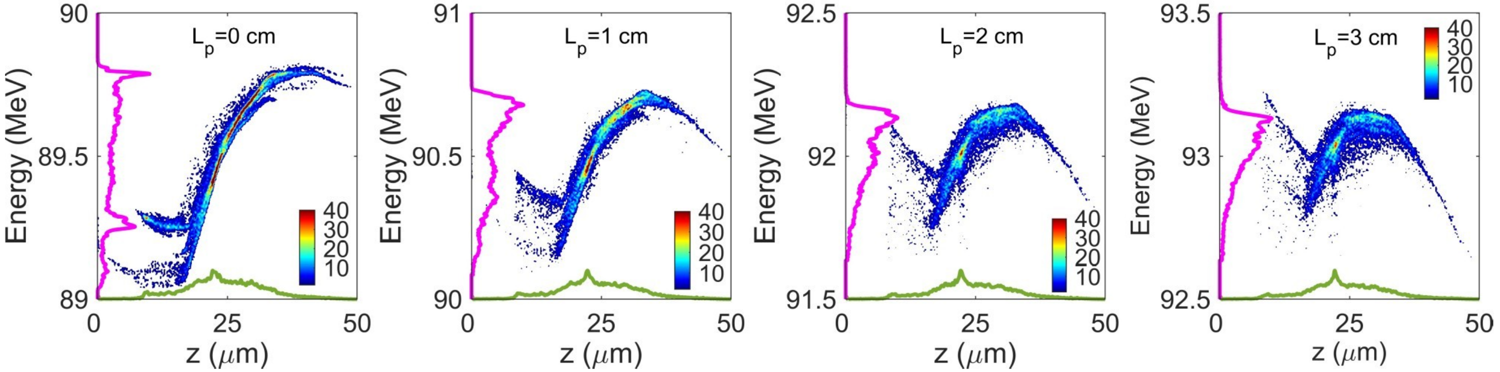
Check for updates

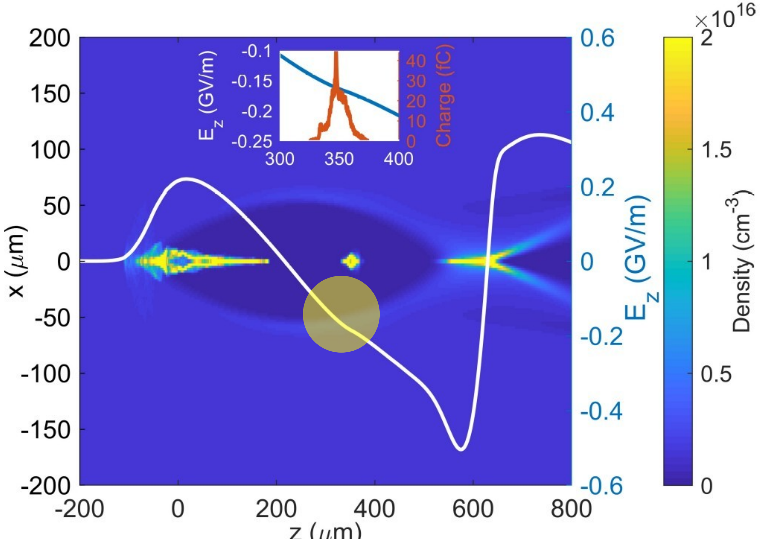
## Energy spread minimization in a beam-driven plasma wakefield accelerator

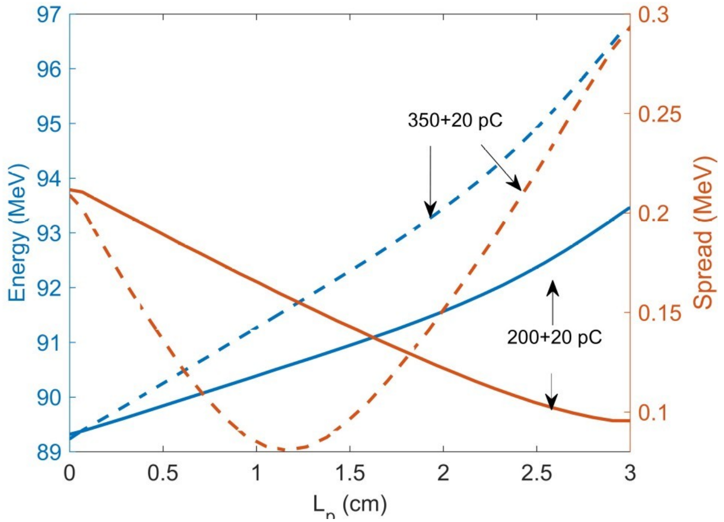
R. Pompili[1]✉, D. Alesini[1], M. P. Anania[1], M. Behtouei[1], M. Bellaveglia[1], A. Biagioni[1], F. G. Bisesto[1], M. Cesarini[1,2], E. Chiadroni[1], A. Cianchi[3], G. Costa[1], M. Croia[1], A. Del Dotto[1], D. Di Giovenale[1], M. Diomede[1], F. Dipace[1], M. Ferrario[1], A. Giribono[1], V. Lollo[1], L. Magnisi[1], M. Marongiu[1], A. Mostacci[2], L. Piersanti[1], G. Di Pirro[1], S. Romeo[1], A. R. Rossi[4], J. Scifo[1], V. Shpakov[1], C. Vaccarezza[1], F. Villa[1] and A. Zigler[1,5]



# Assisted beam-loading technique

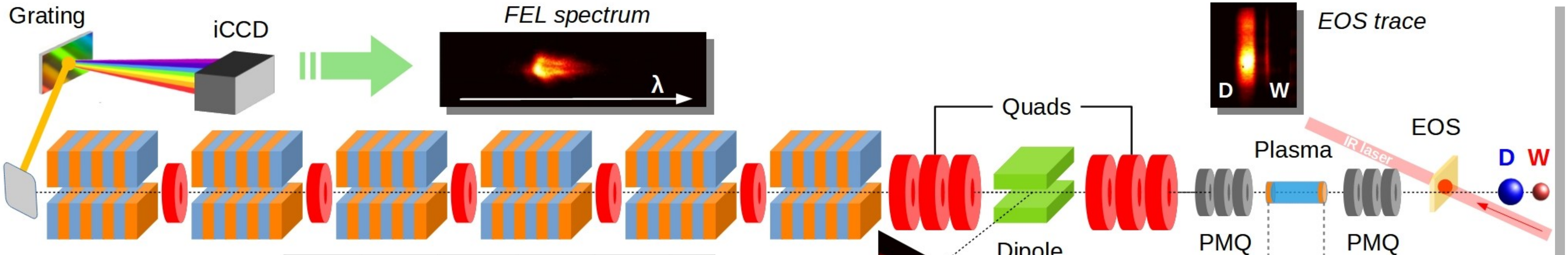


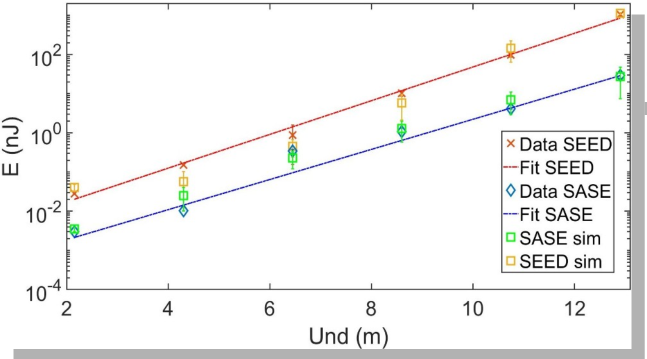




# First demonstration of FEL lasing

Funded by the European Union





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Article | Published: 25 May 2022

## Free-electron lasing with compact beam-driven plasma wakefield accelerator

R. Pompili, D. Alesini, … M. Ferrario + Show authors

*Nature* **605**, 659–662 (2022) | Cite this article

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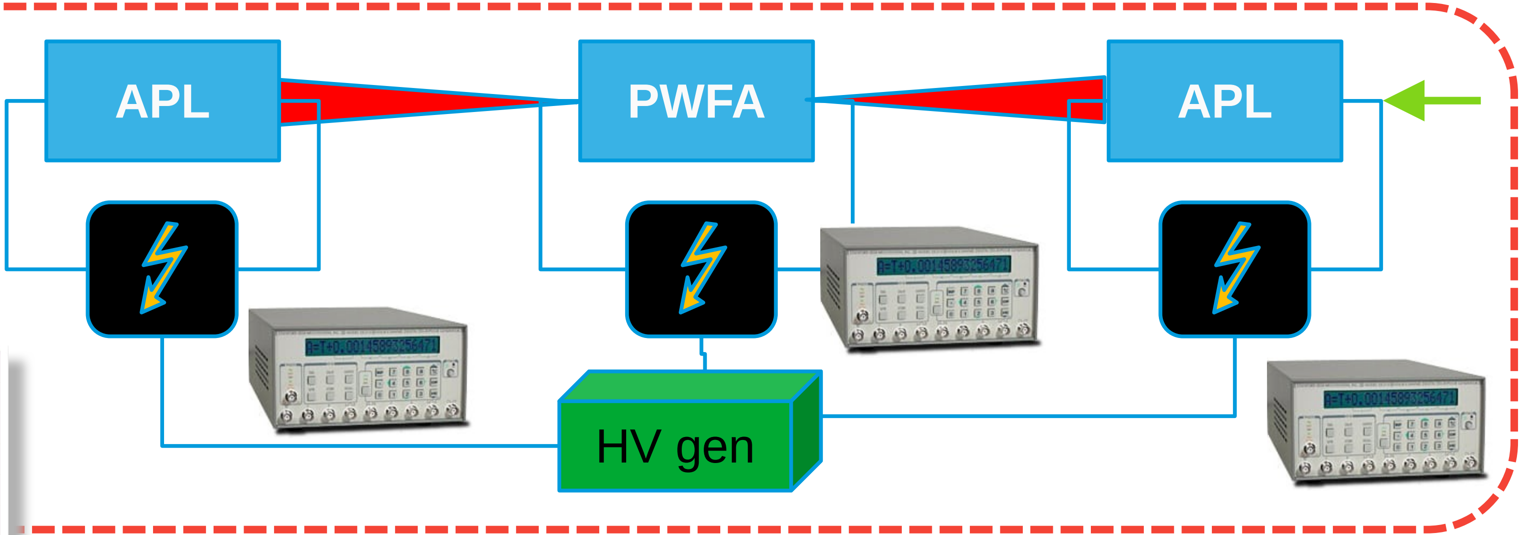
## Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

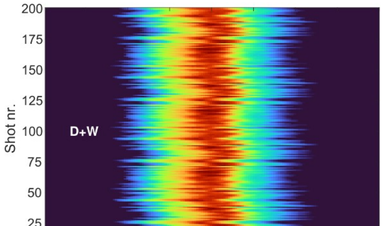
M. Galletti *et al.*

Phys. Rev. Lett. **129**, 234801 – Published 29 November 2022

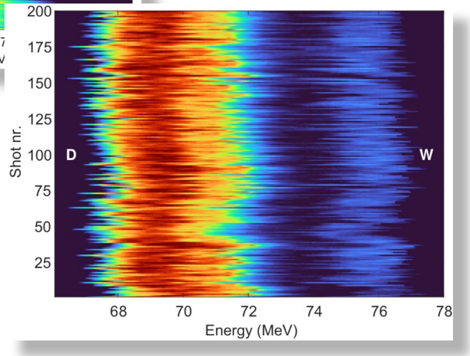
# “All-in-one” capillary

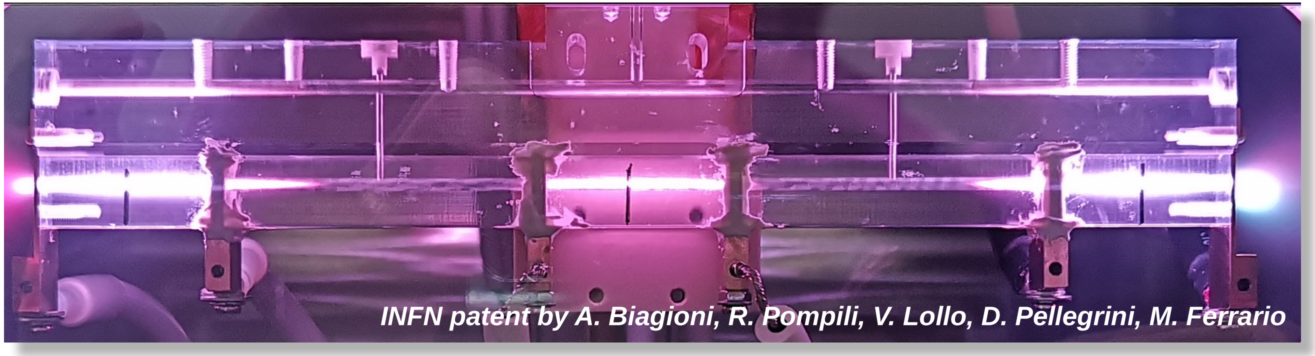


Lenses ON, Accelerator **OFF**



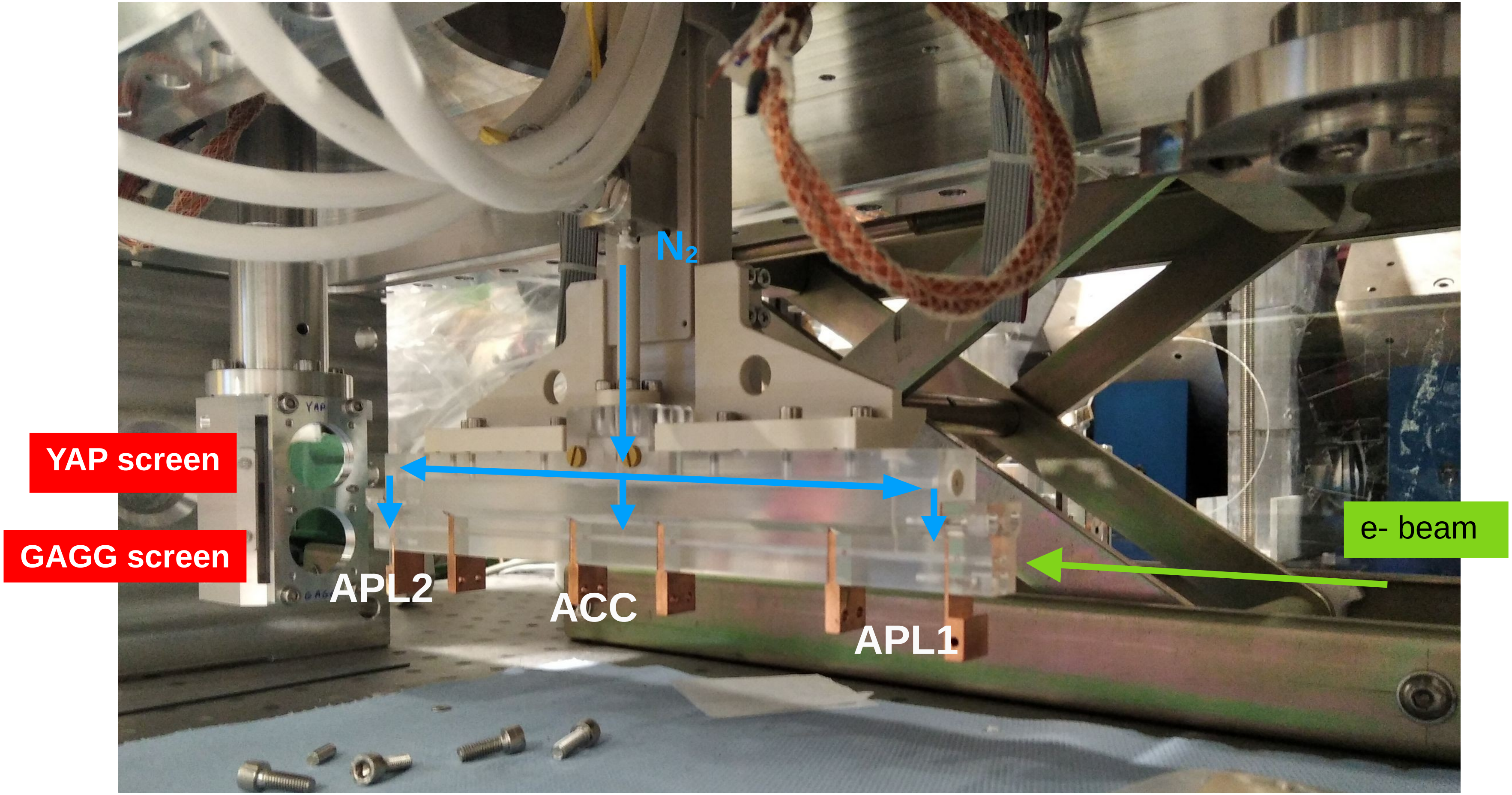
Lenses ON, Accelerator **ON**



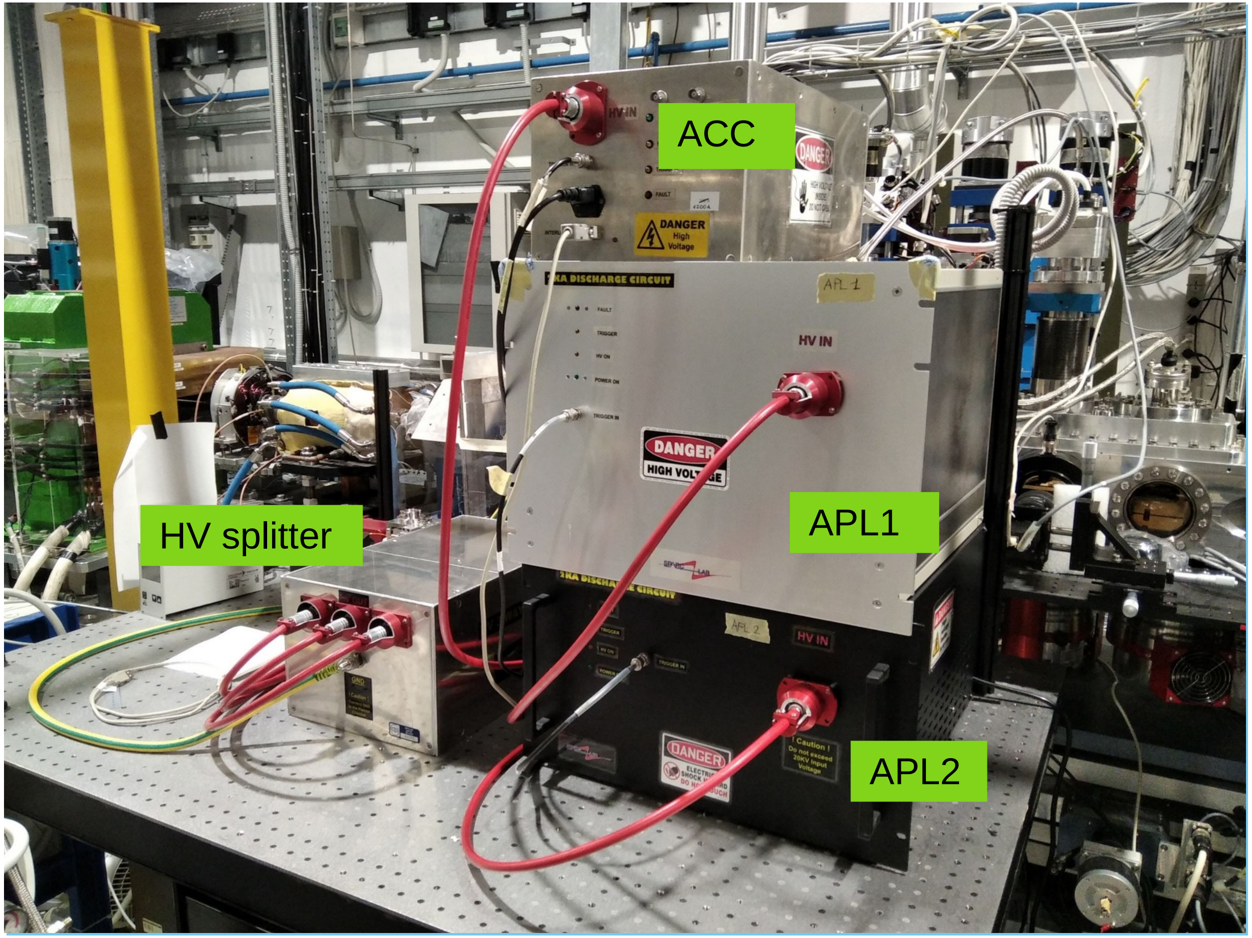


*INFN patent by A. Biagioni, R. Pompili, V. Lollo, D. Pellegrini, M. Ferrario*

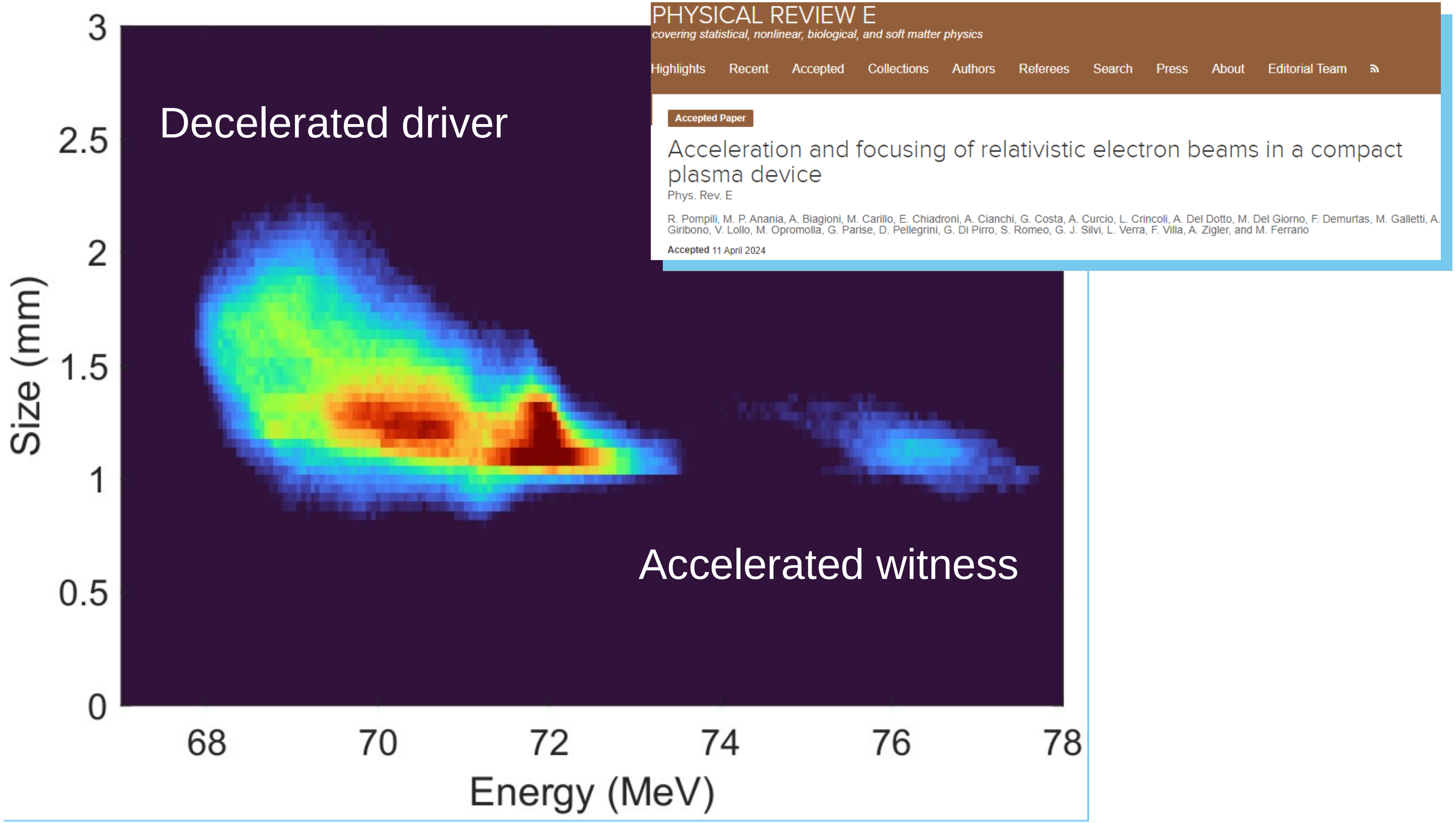
# Experimental setup



# HV setup



# Single-shot spectrum



Acceleration and focusing of relativistic electron beams in a compact plasma device

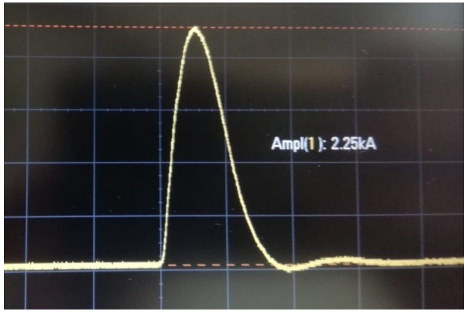
Phys. Rev. E

R. Pompili, M. P. Anania, A. Biagioni, M. Carillo, E. Chiadroni, A. Cianchi, G. Costa, A. Curcio, L. Crincoli, A. Del Dotto, M. Del Giorno, F. Demurtas, M. Galletti, A. Giribono, V. Lollo, M. Opromolla, G. Parise, D. Pellegrini, G. Di Pirro, S. Romeo, G. J. Silvi, L. Verra, F. Villa, A. Zigler, and M. Ferrario

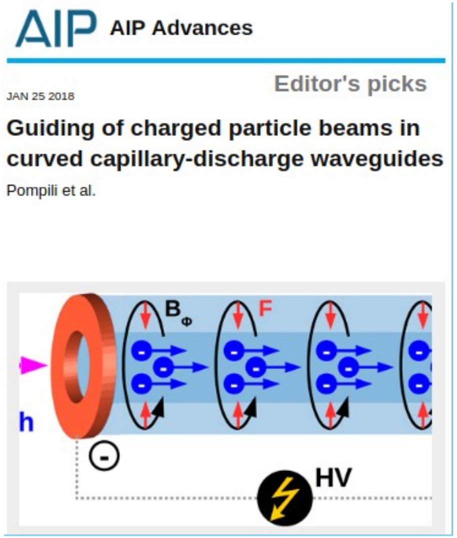
**Accepted** 11 April 2024

# Particle bending with plasma

- Yet another use of plasma
- The large magnetic fields produced in the plasma can be used to bend particles
  - *Compactness. Large deflection angles*
  - *Tunability. The bending is tuned by adjusting the discharge-current*
  - *Cheap solution*
  - *Tunable dispersion (dispersion-free also possible) by changing the discharge current*



D. Pellegrini, T. De Nardis, G. Grilli

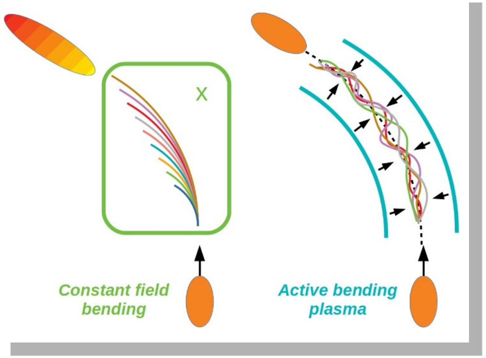

AIP AIP Advances

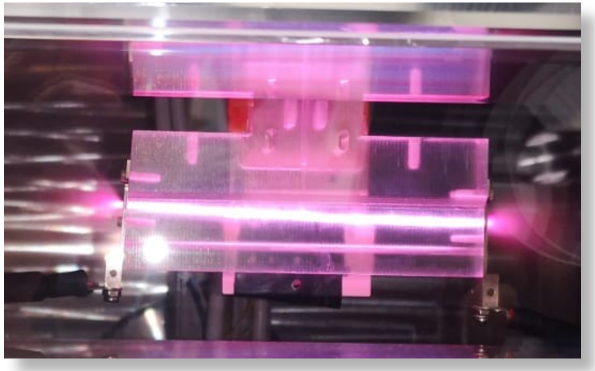
Editor's picks

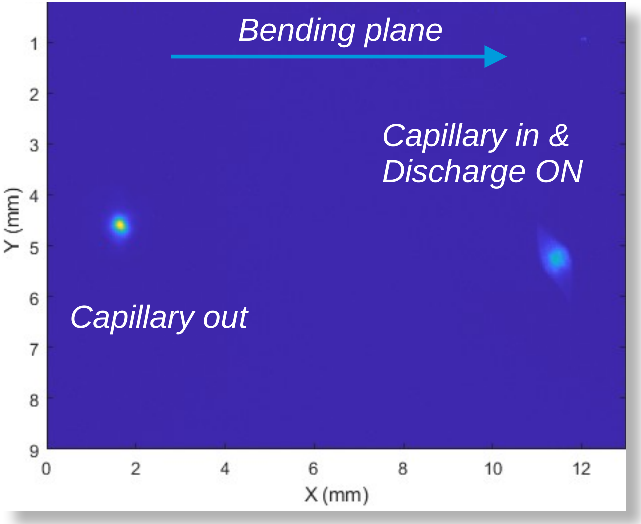
JAN 25 2018

**Guiding of charged particle beams in curved capillary-discharge waveguides**

Pompili et al.







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EXCELLENCE IN
APPLICATIONS

# Thanks!

**R. Pompili (LNF-INFN)**
On behalf of the EuPRAXIA@SPARC_LAB collaboration

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No. 101079773