LNF - LNGS "Operazione di Acceleratori di elettroni e positroni"
Laboratori Nazionali del Gran Sasso , 21-22 Giugno 2018

From SPARC_LAB to EuPRAXIA

Enrica Chiadroni
(INFN-LNF)
on behalf of the collaboration

Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

Motivation

- The quality of beams in particle accelerators is driven by applications
  - **Applied Science**
    - Novel sources (e.g. FELs, THz, Thomson, etc…) for material science, biology, …
  - **Fundamental research**
    - Particle physics: Build multi-stages compact colliders

- **Conventional RF structures** reached a **practical limit**
  - they cannot sustain accelerating gradients larger than ~100 MV/m (X-band structures) due to **breakdown** on the wall surfaces
- **Ultra-high gradients** require structures to sustain high fields
  - **Plasma-filled structures**
    - Maximum accelerating field a plasma can sustain: **Wave breaking field**

$$E_{Max}[V/m] = \frac{m_e c \omega_p}{e} \approx 100\sqrt{n_0[cm^{-3}]}$$

The **frontier** in modern accelerator physics is based on R&D towards **compacts accelerators**.

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Plasma Acceleration

✓ Multi-GeV in *cm scale* plasma structures

- J. Rosenzweig et al., Phys. Rev. Lett. **61**, 98 (1988): *First experimental demonstration of PWFA*
- Mangles, Geddes, Faure et al., Nature **431**, (2004): *The dream beam*
- W. P. Leemans, Nature Physics vol. **2**, p.696-699 (2006): *GeV electron beams from a centimetre-scale accelerator*
- I. Blumenfeld et al., Nature **445**, p. 741 (2007): *Doubling energy in a plasma wake*
- P. Muggli et al, in Proc. of PAC 2011, TUOBN3: *Driving wakefields with multiple bunches*

➡ Acceleration, extraction and transport of stable and reliable high brightness electron beams

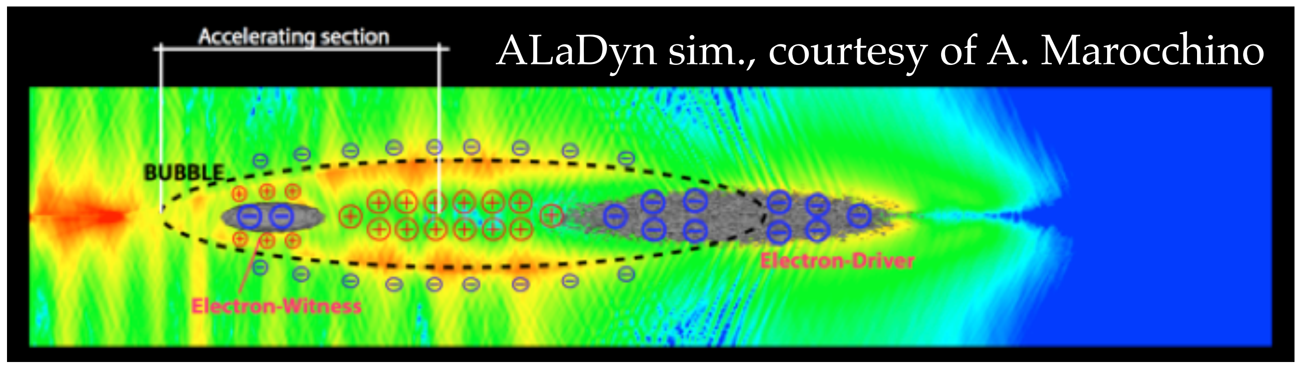
- M. Litos et al., Nature **515**, 92 (2014): *High efficiency acceleration in the driver-trailing bunches*
- S. Steinke et al., Nature **000** (2016) doi:10.1038/nature16525: *Multi-stage coupling*

➡ Plasma-based user facility

- H2020 EuPRAXIA Design Study
- EuPRAXIA@SPARC_LAB

Towards a Plasma-based Facility

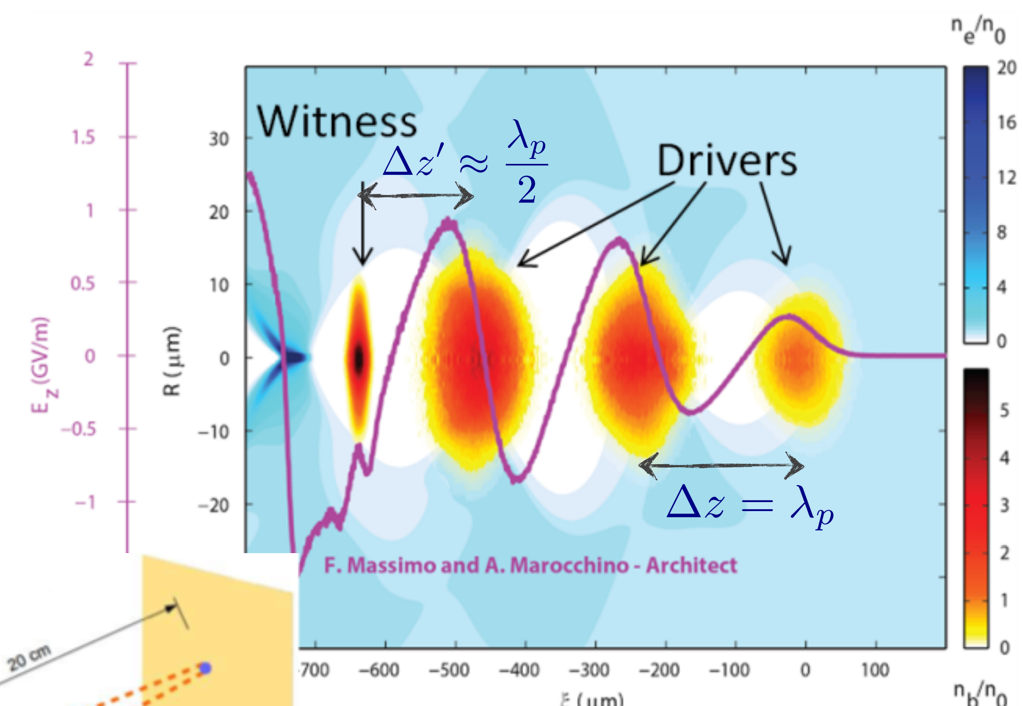
- **High quality** $\varepsilon_n \ll 1mm\ mrad, I_{peak} \sim kA, \frac{\Delta\gamma}{\gamma} \ll 1\%$
  - External injection of high brightness electron beams



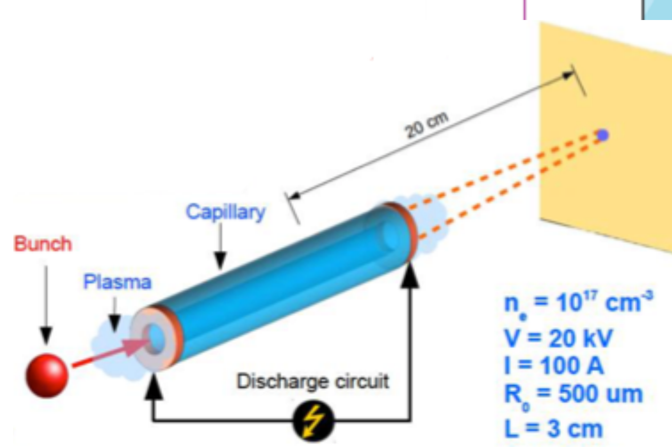
$\lambda_p(\mu m) \approx 3.3 \cdot 10^{10} n_p^{-1/2}(cm^{-3})$

$\lambda_p \approx 330\mu m\ @\ n_p = 10^{16} cm^{-3}$

- **High efficiency** $\Delta\gamma \sim R\gamma_d$
  - **Increase the transformer ratio** $R = \frac{|E_{+,max}|}{|E_{-,max}|} > 2$
    - Tailoring longitudinal current profile such that all longitudinal slices lose energy at the same rate
      - **multiple ramped bunch trains**, overcome this limit



- **Compactness**
  - Plasma lenses for injection and extraction



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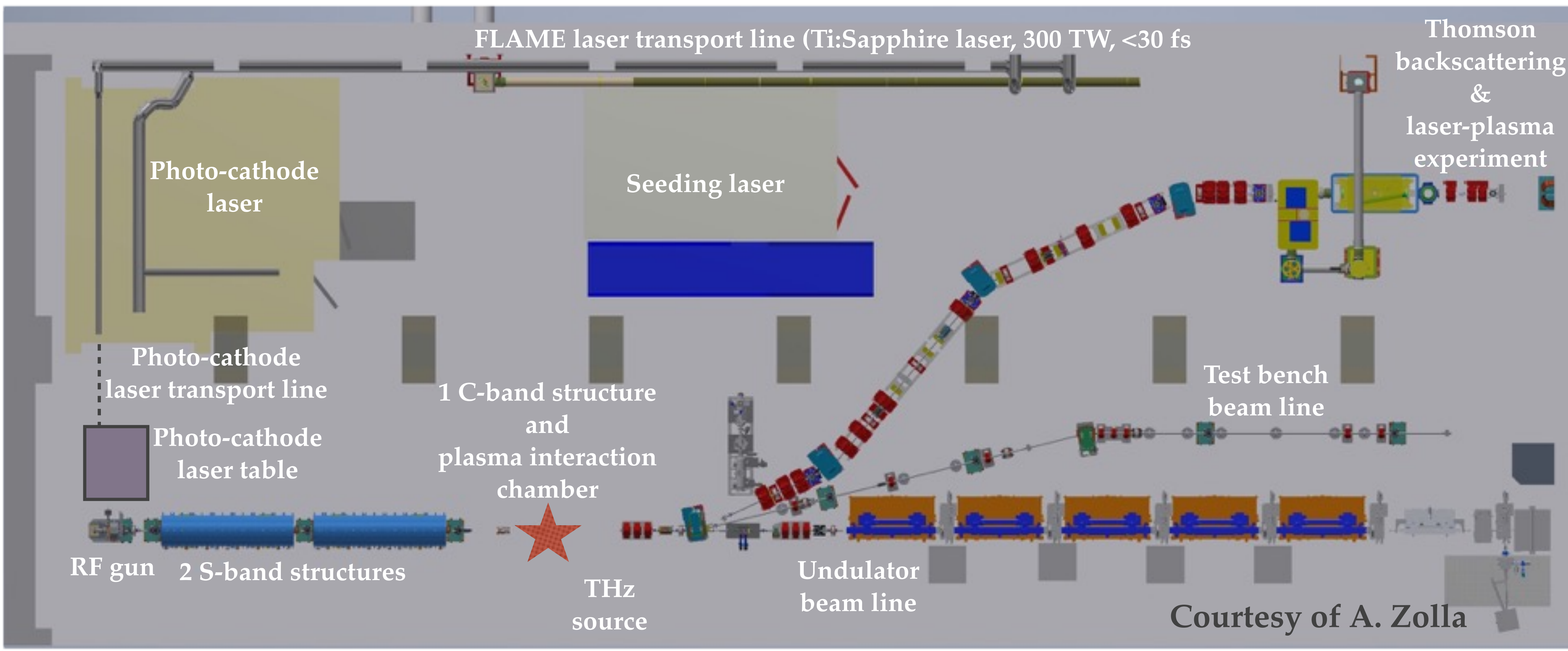
SPARC_LAB Test Facility

SPARC_LAB (**S**ources for **P**lasma **A**ccelerators and **R**adiation **C**ompton with **L**asers **A**nd **B**eams) is a **Test Facility** consisting in a **High Brightness photo-injector** able to deliver high quality electron beams to drive a **FEL**, a **plasma-based accelerator** and high intensity **advanced radiation sources**, e.g. THz and Thomson ones.



https://www.google.it/maps/@41.8231995,12.6743967,3a,69.7y,130.68h,76.68t/data=!3m6!1e1!3m4!1sYyB35yaBMxJgQ92-wp3oYQ!2e0!7i13312!8i6656?hl=en

M. Ferrario et al., *SPARC_LAB present and future*, NIM B **309**, 183–188 (2013)

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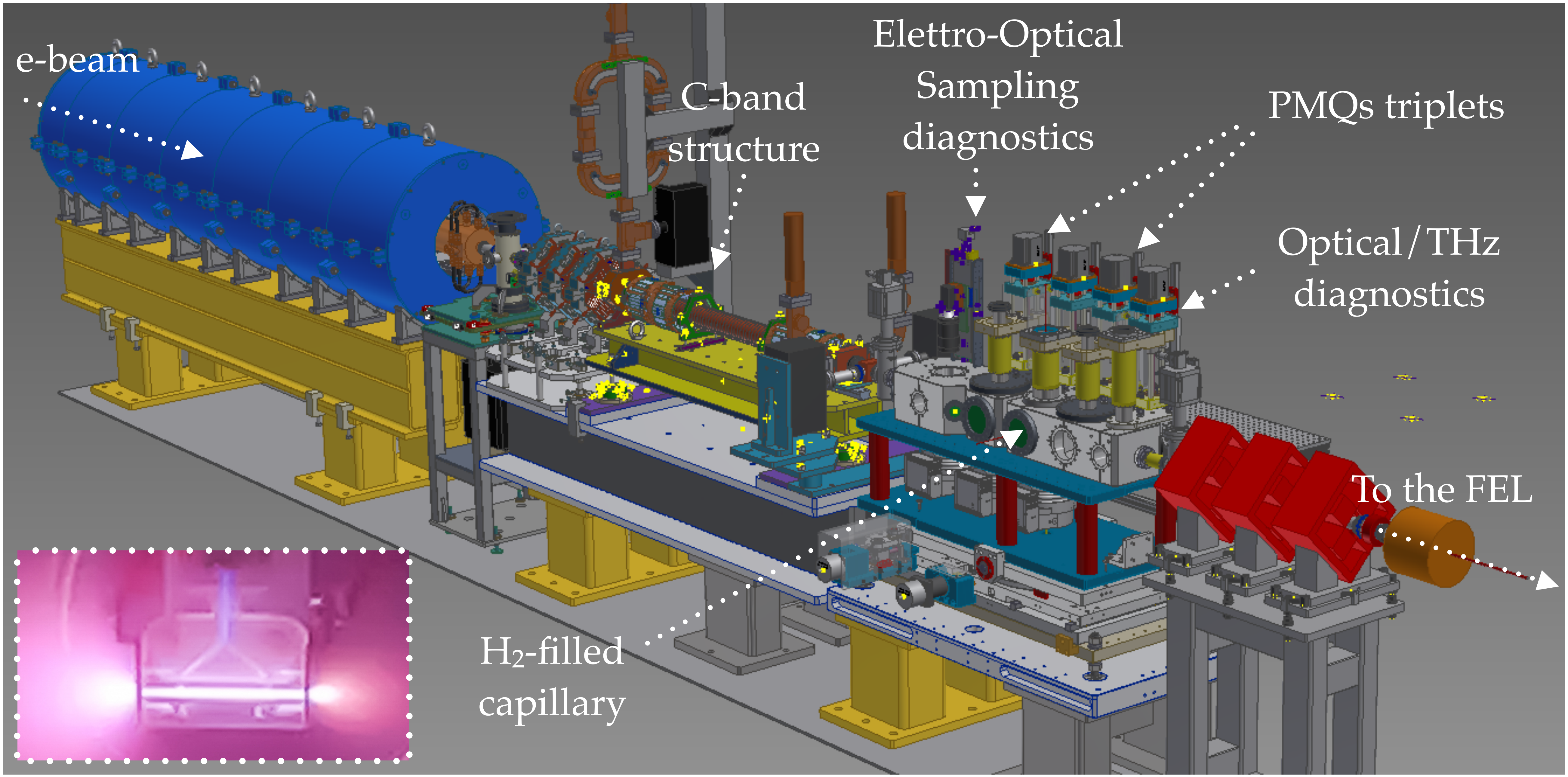
C-band and Plasma Interaction Chamber

H_2 generation and injection system

- Electrolytic generator (1 l of water → 1.4 m^3 Hydrogen)
- Pressure reduction system (300 mbar → 10 mbar in capillary)
- Electro-valve triggered by the HV discharge with tunable aperture (3 ms) and delay time (10 μs before discharge)



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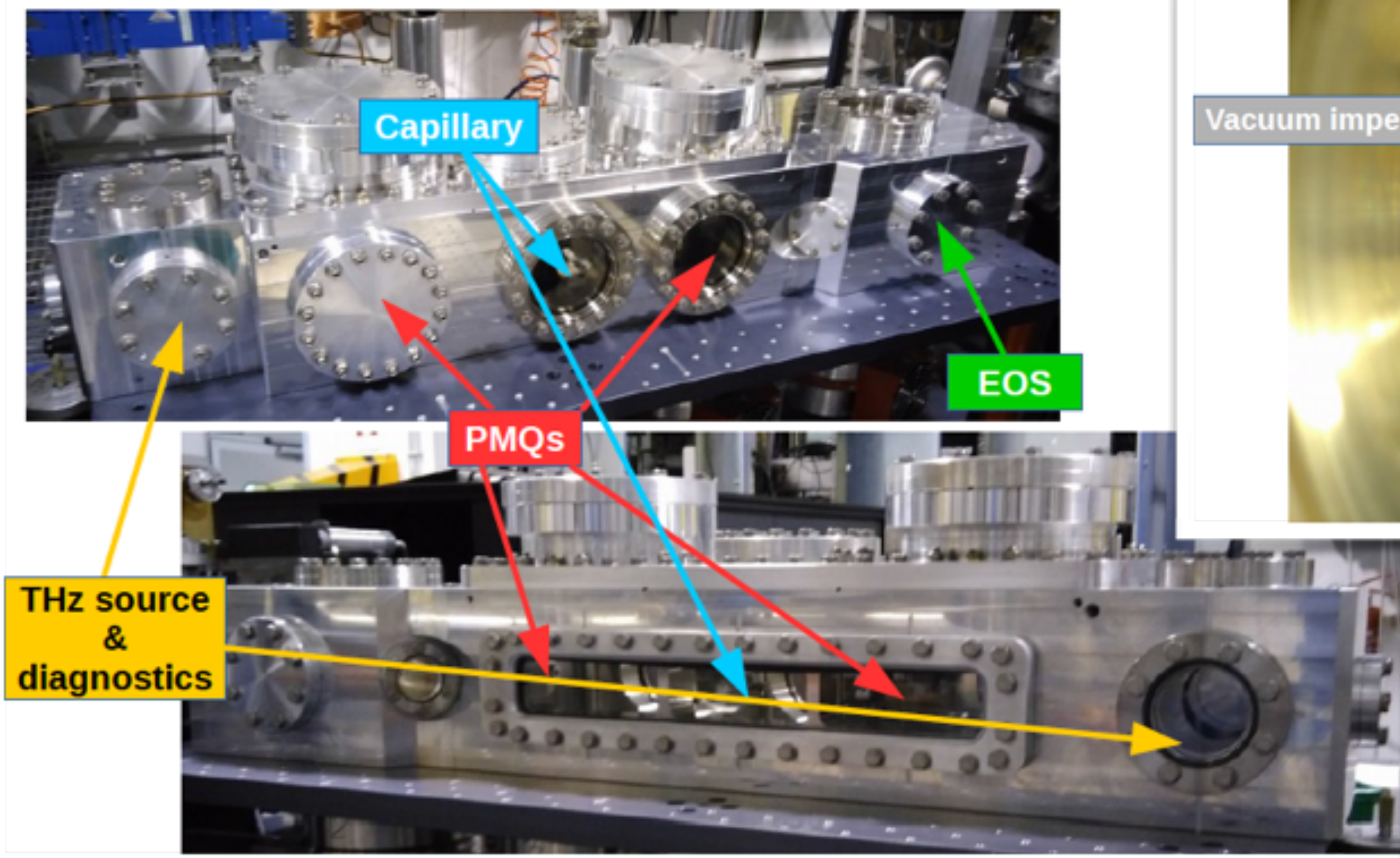
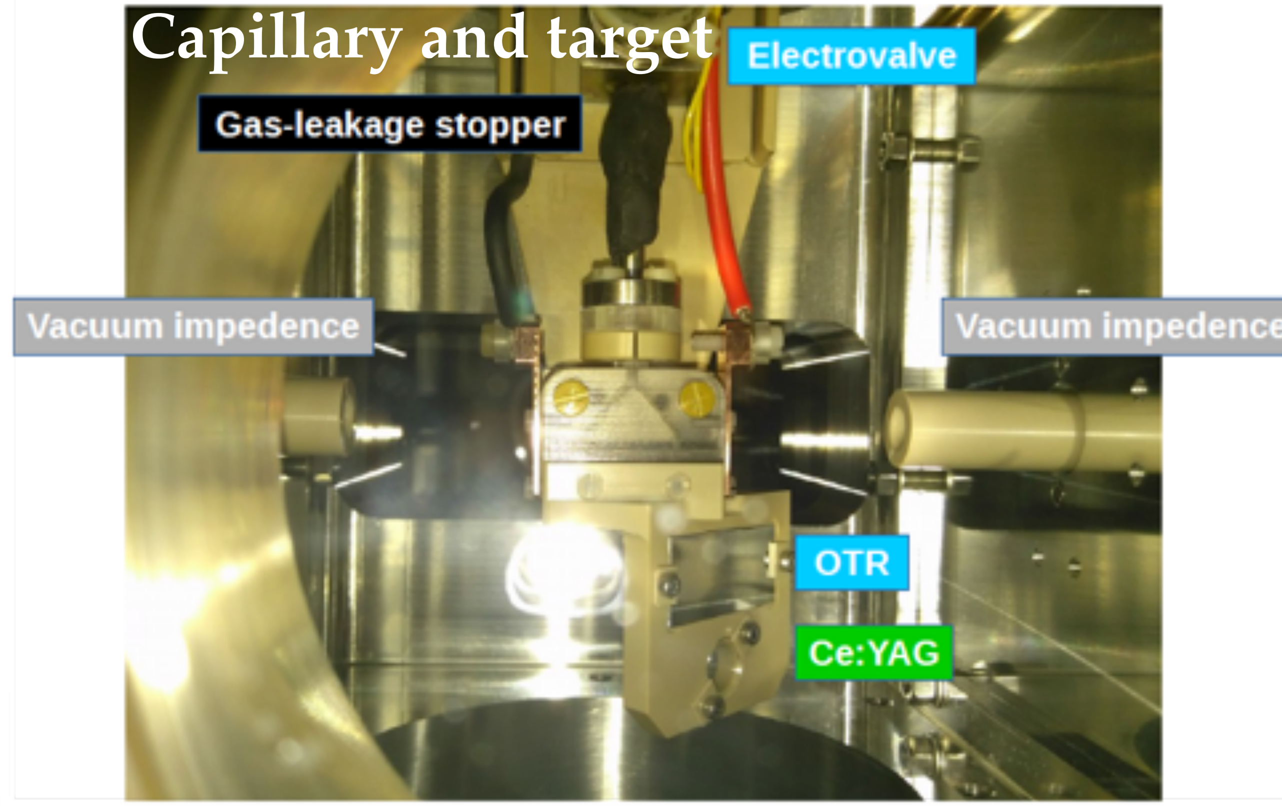
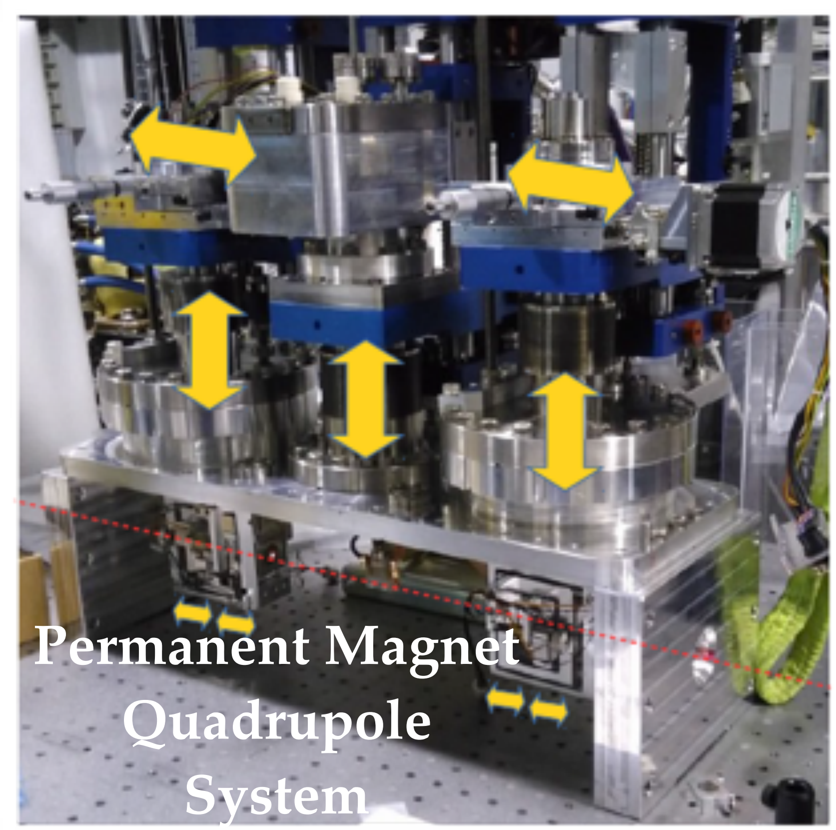
New Plasma Interaction Chamber







Courtesy of V. Lollo

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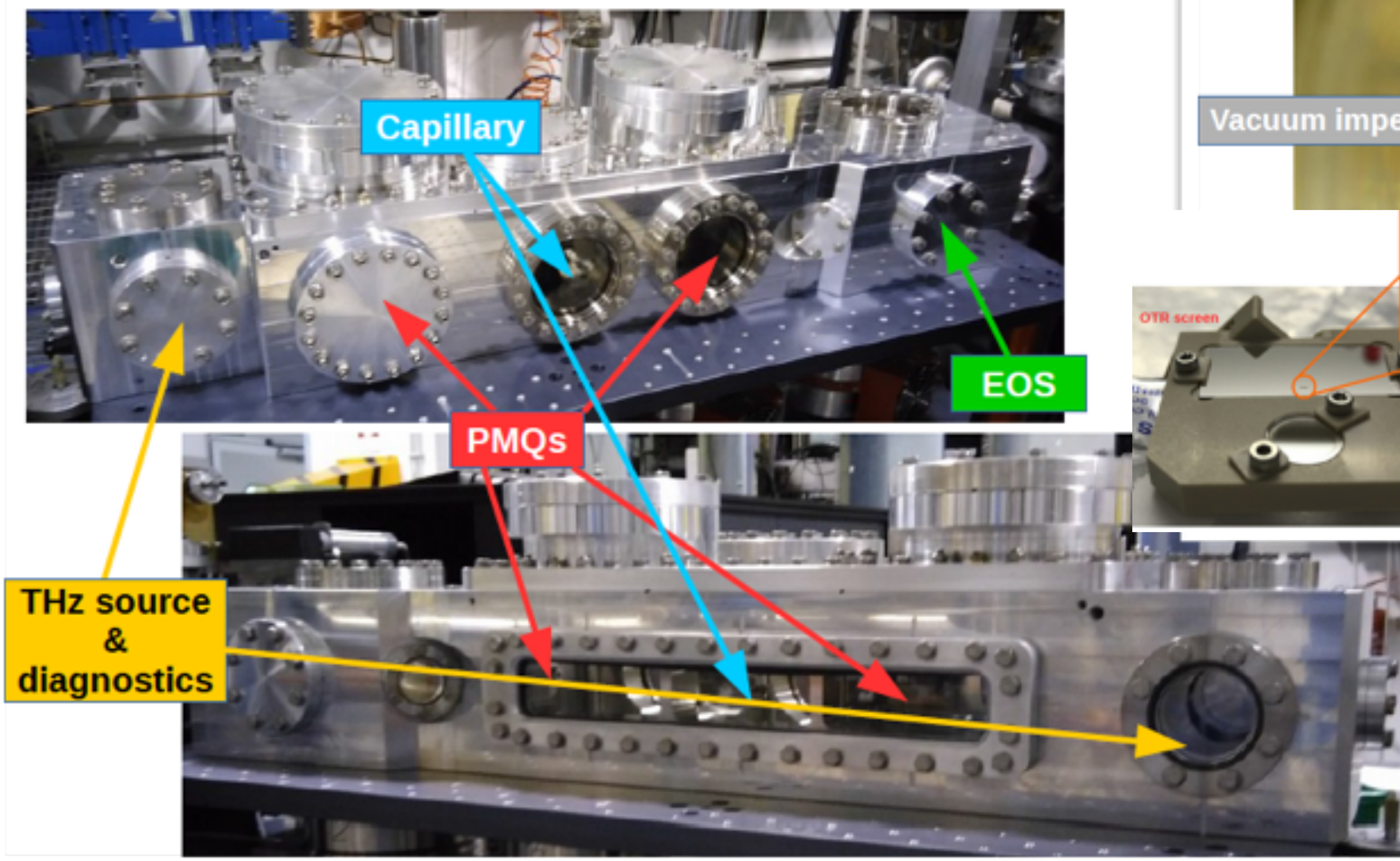

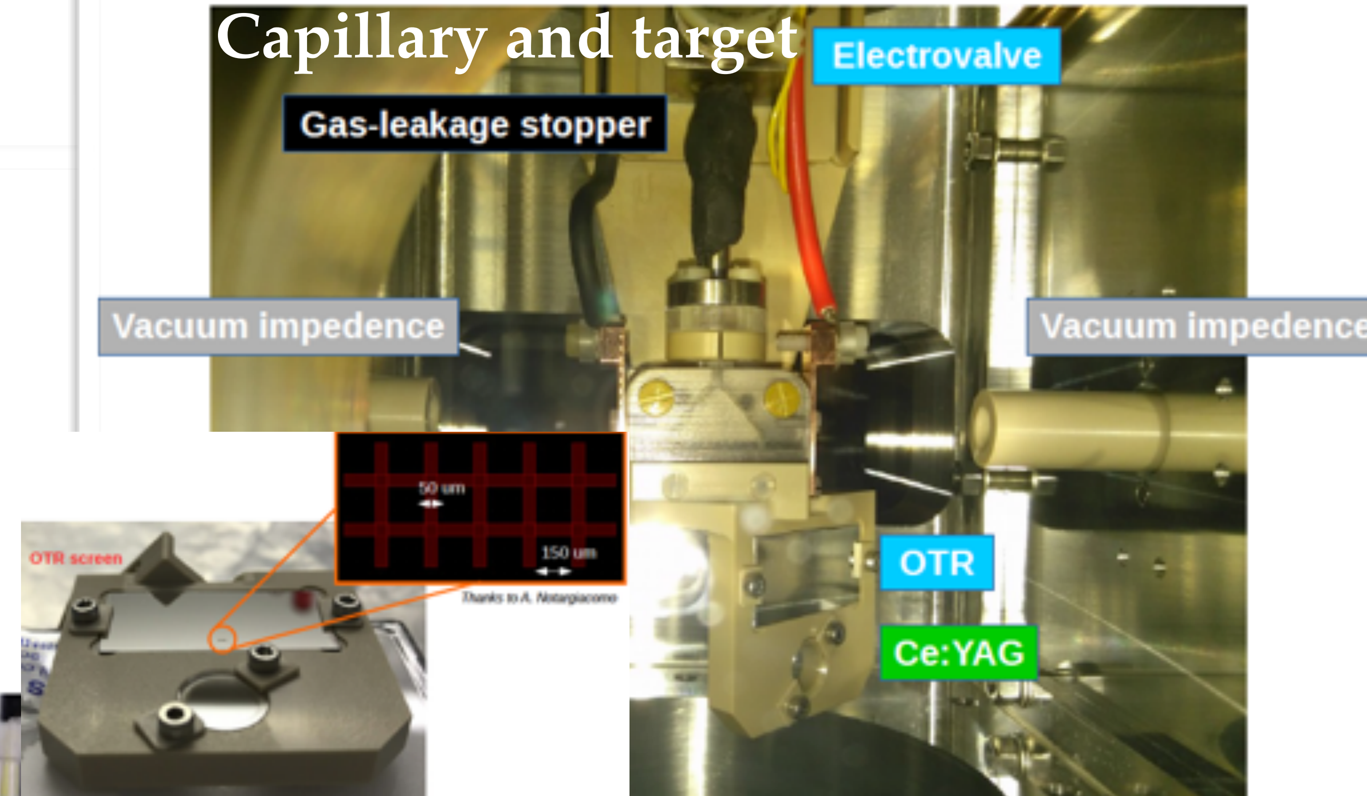

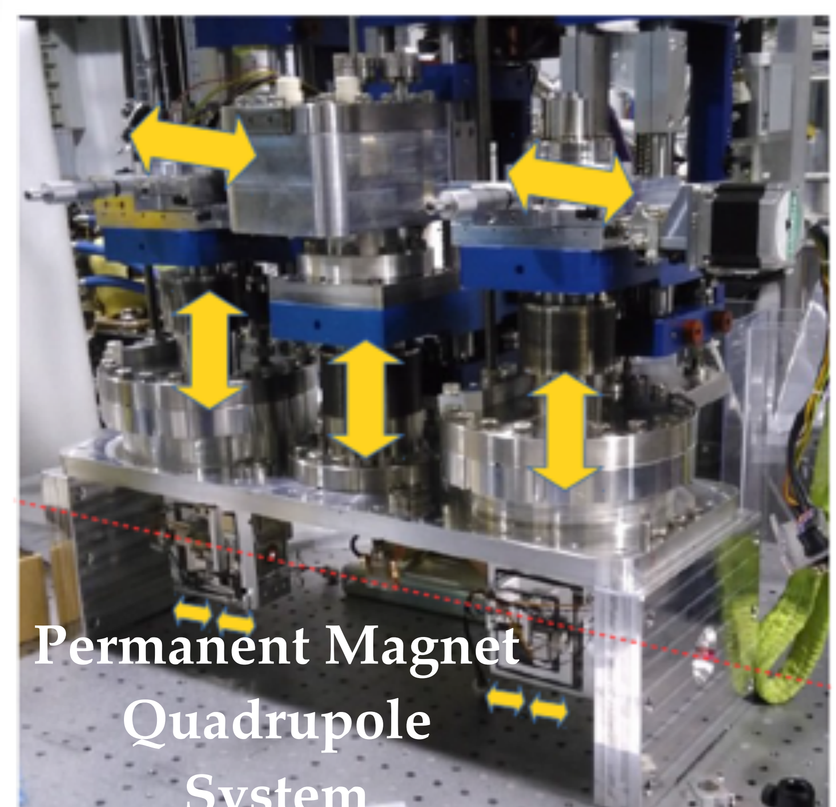

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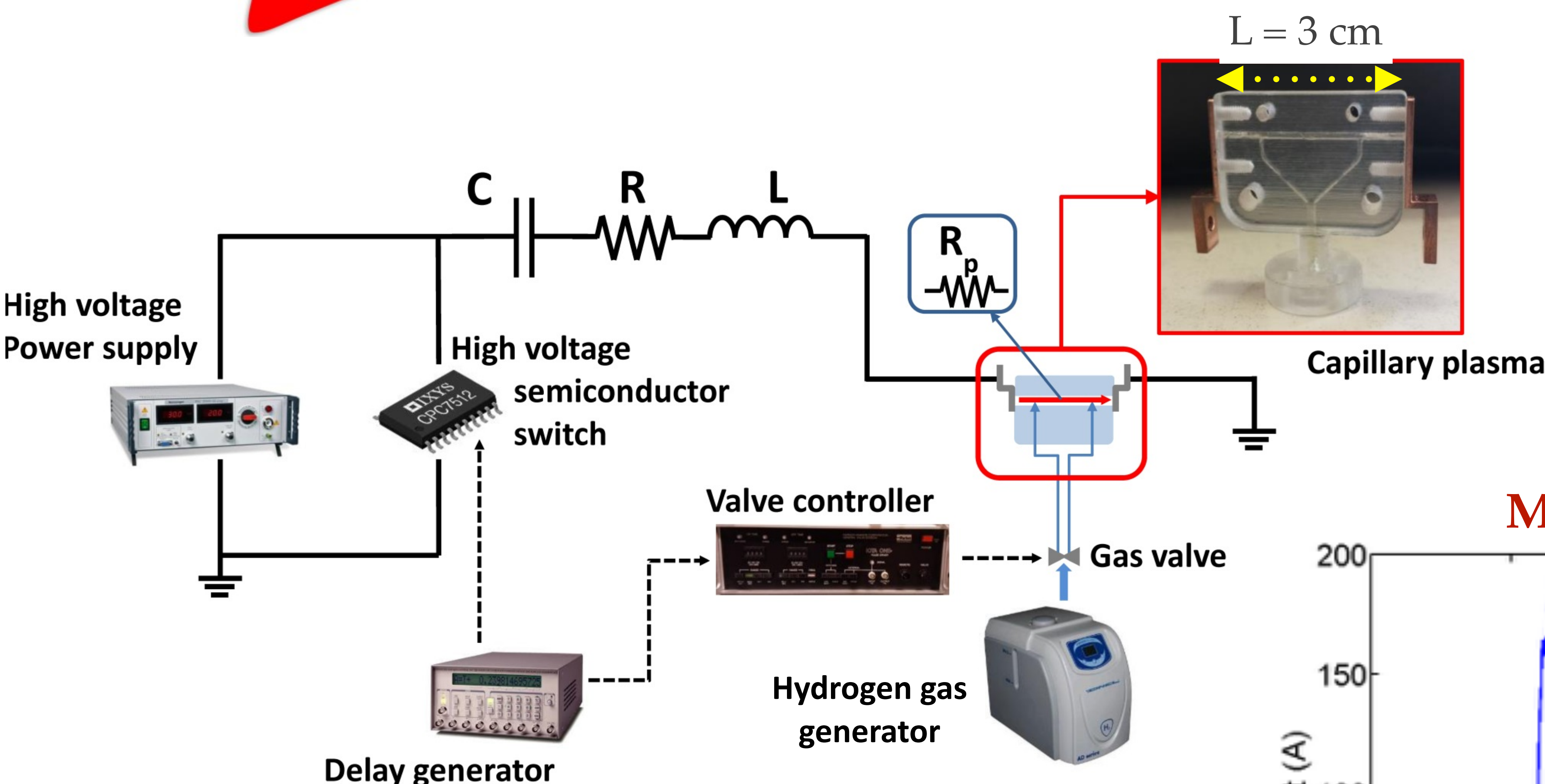
Plasma Source



P_{H2} = 10 mbar

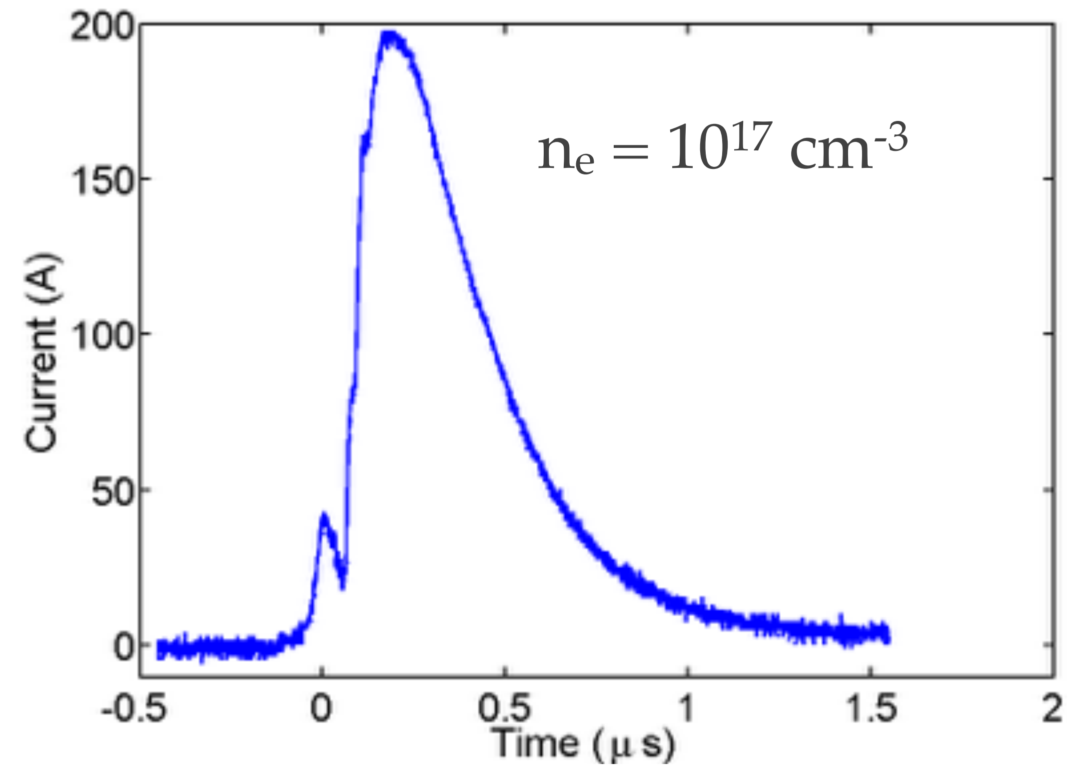
Total discharge duration :800 ns

Voltage : 20 kV

Peak current : 200 A

Capacitor : 6 nF

Measured current



Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella

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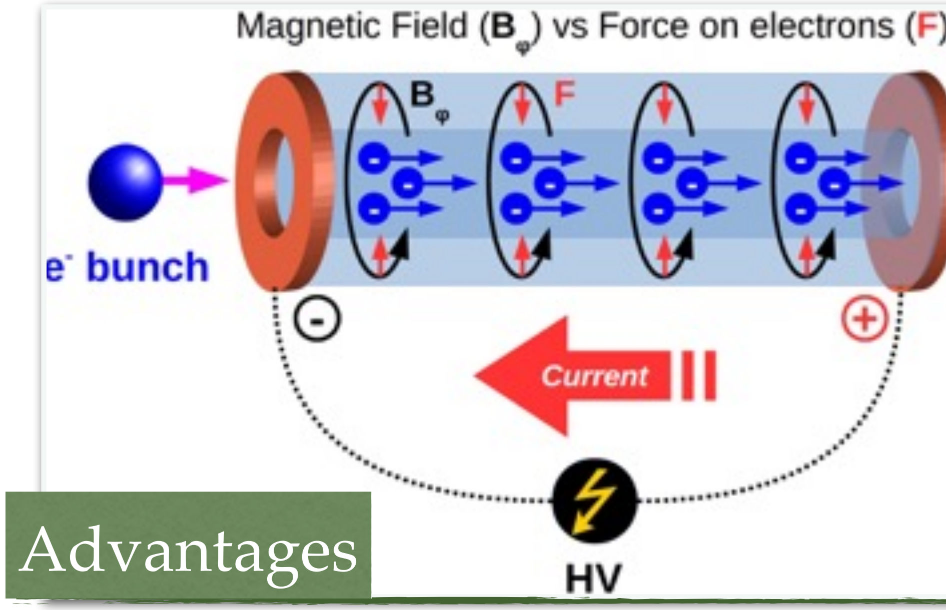
Plasma Lenses Studies

- Discharge current in gas-filled capillary
  - the bunch is focused by the azimuthal magnetic field generated by the discharge current density



Advantages

- Cylindrical symmetry
  - purely radial focusing effect
- Tunability
- Focusing strength
- High focusing gradient ~ kT/m
  - short focal length
    - weak chromaticity

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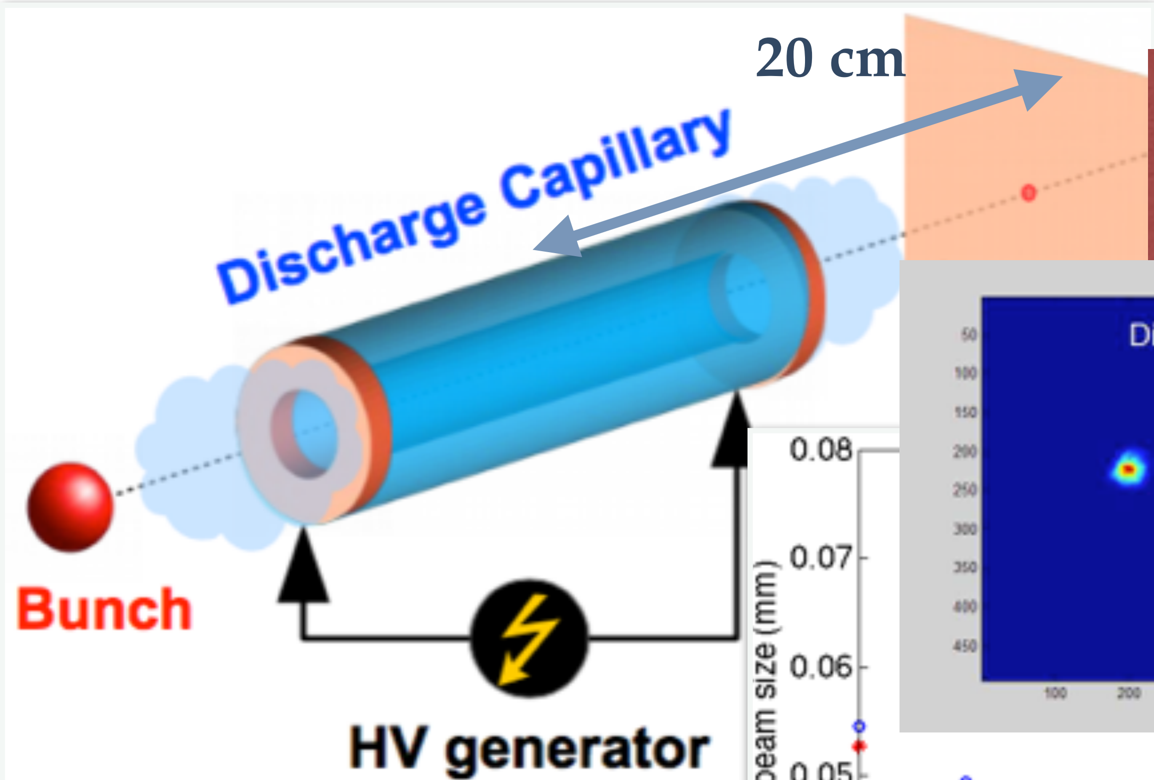
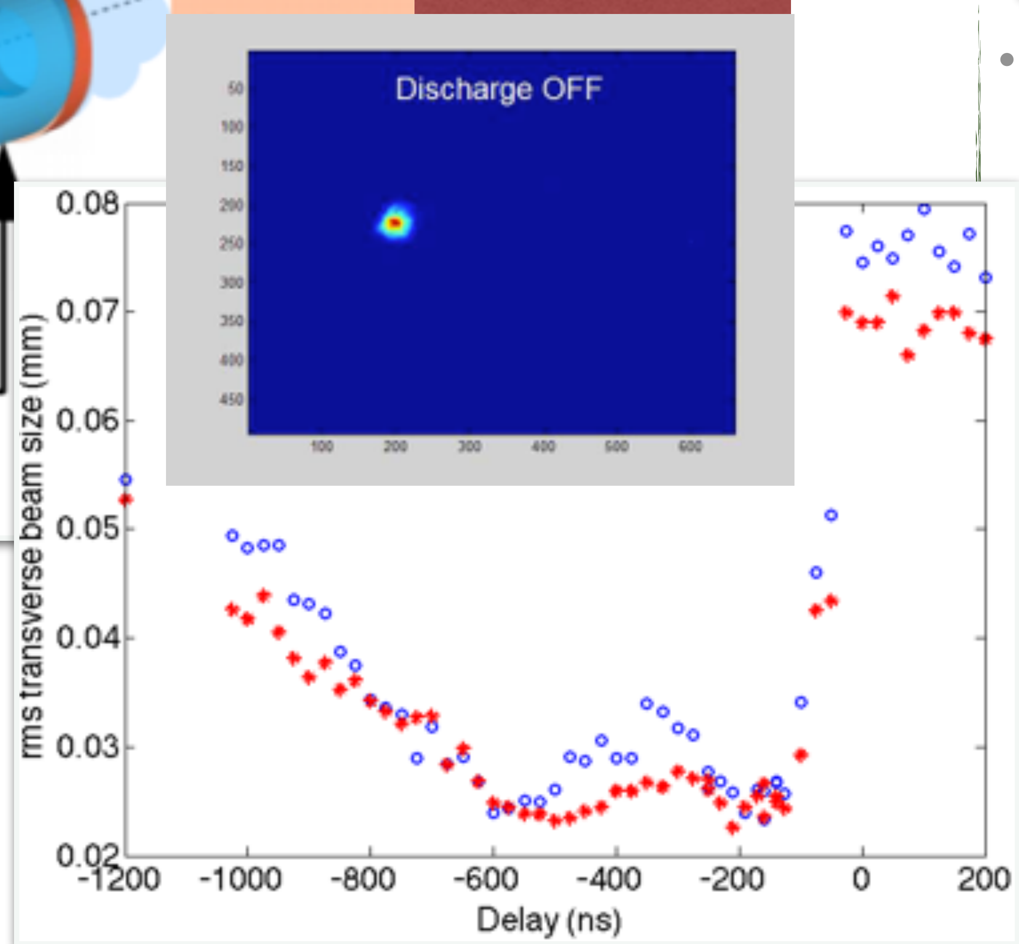
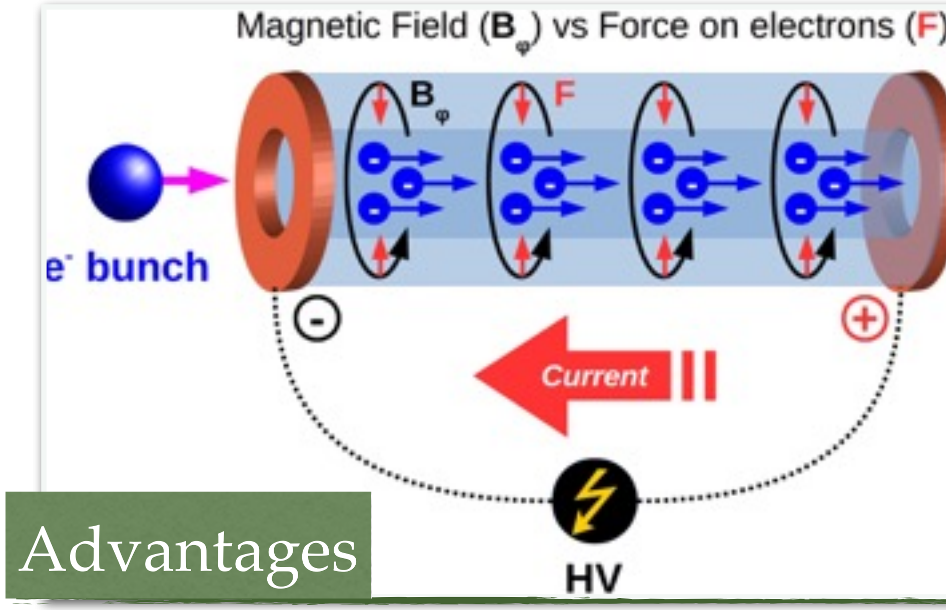


Measured beam size on the YAG screen





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R. Pompili et al., Appl. Phys. Lett. **110**, 104101 (2017)
E. Chiadroni et al., NIM A, https://doi.org/10.1016/j.nima.2018.02.014

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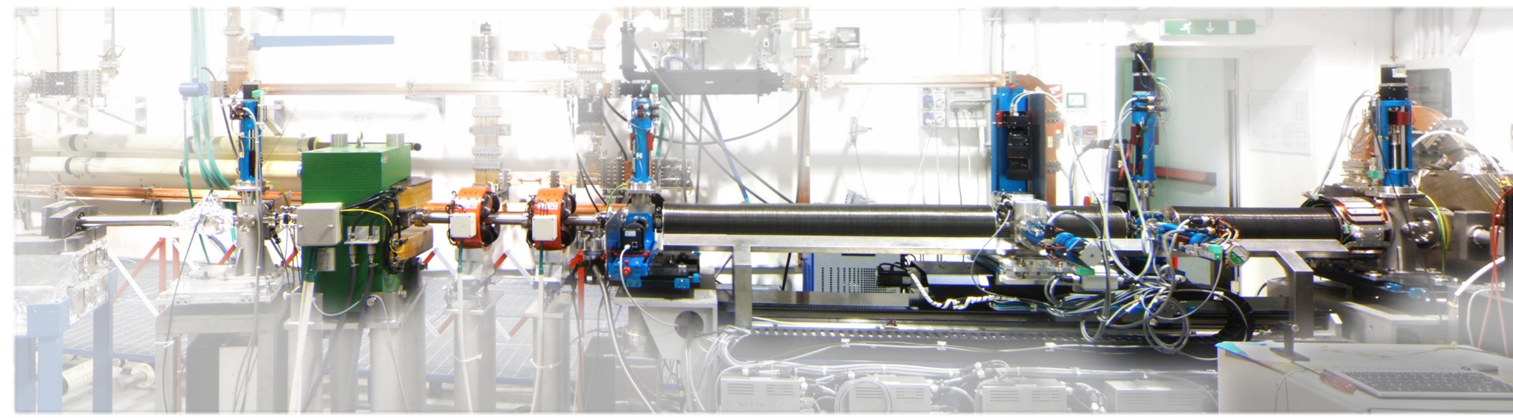
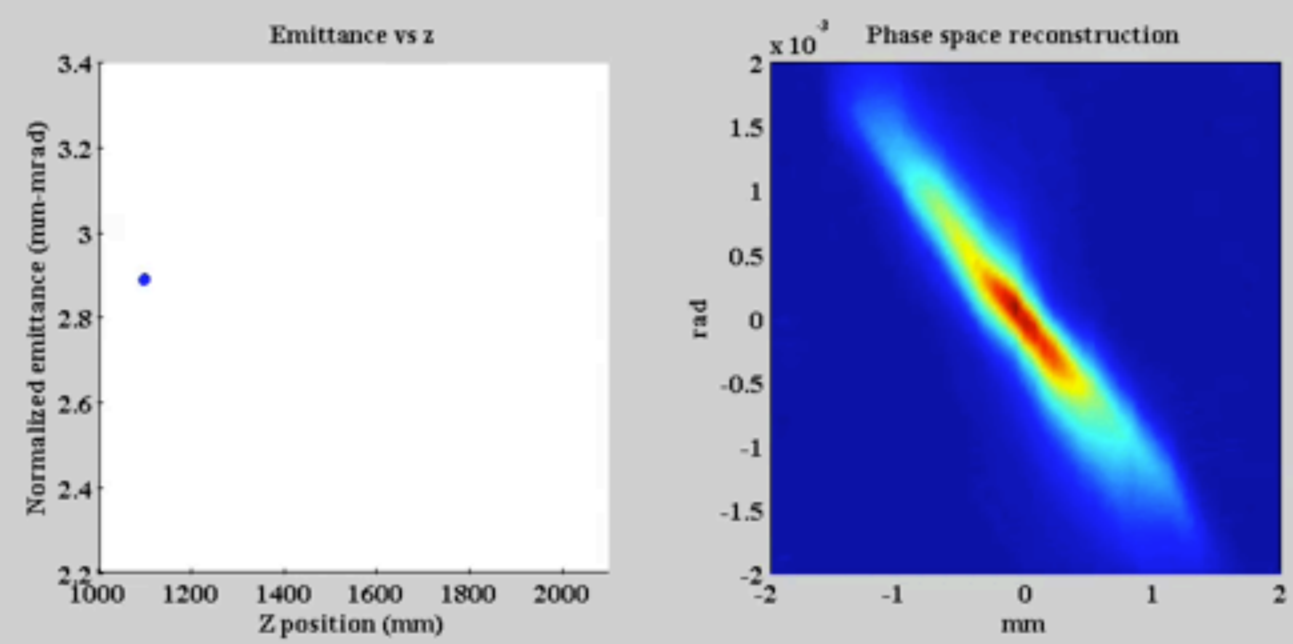
SPARC_LAB Achievements

- **First experimental observation of emittance oscillation** in a drift at low energy
  - Working point adopted in many photo-injector based user facilities
    - *Ferrario's working point*





M. Ferrario et al., PRL **99**, 234801 (2007)

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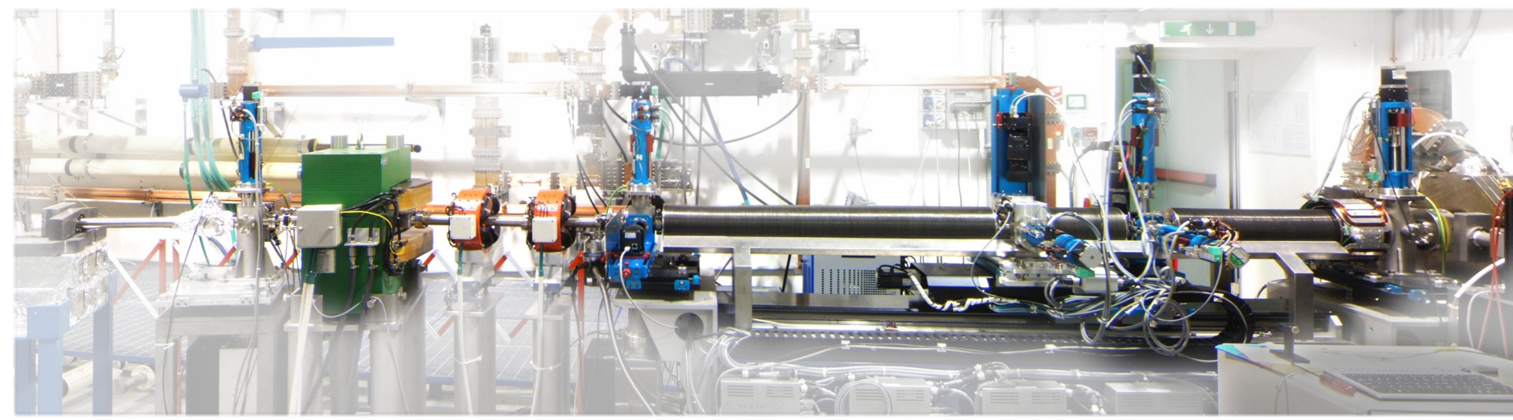

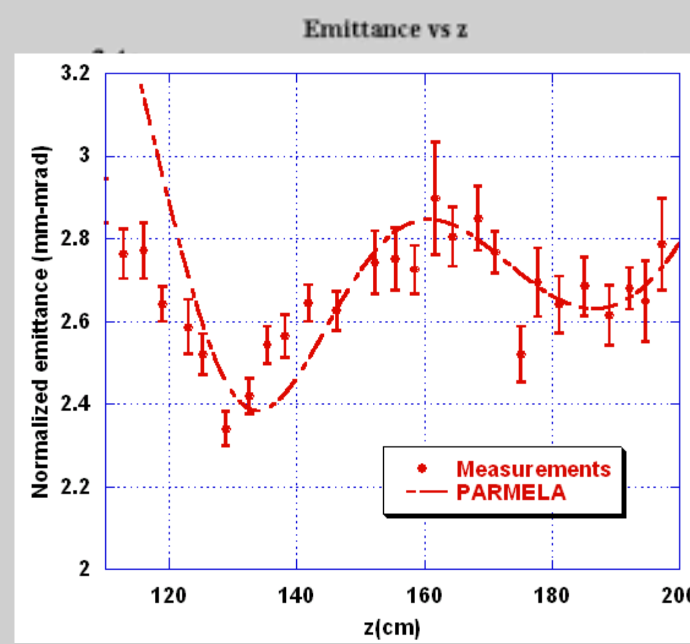

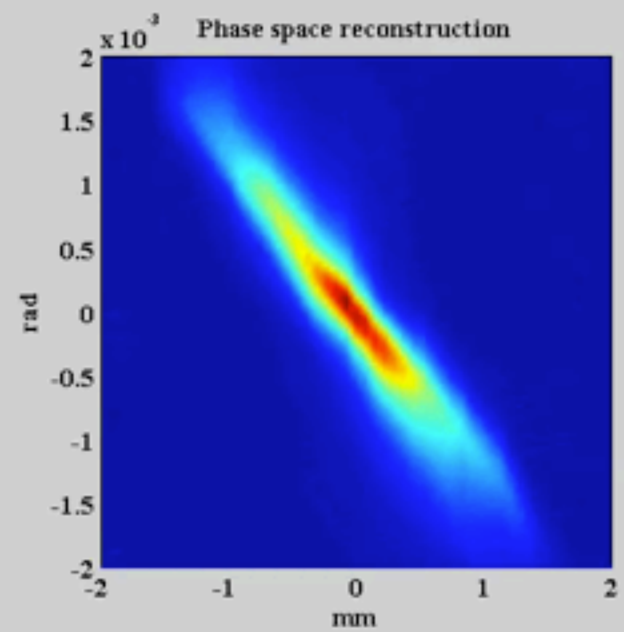

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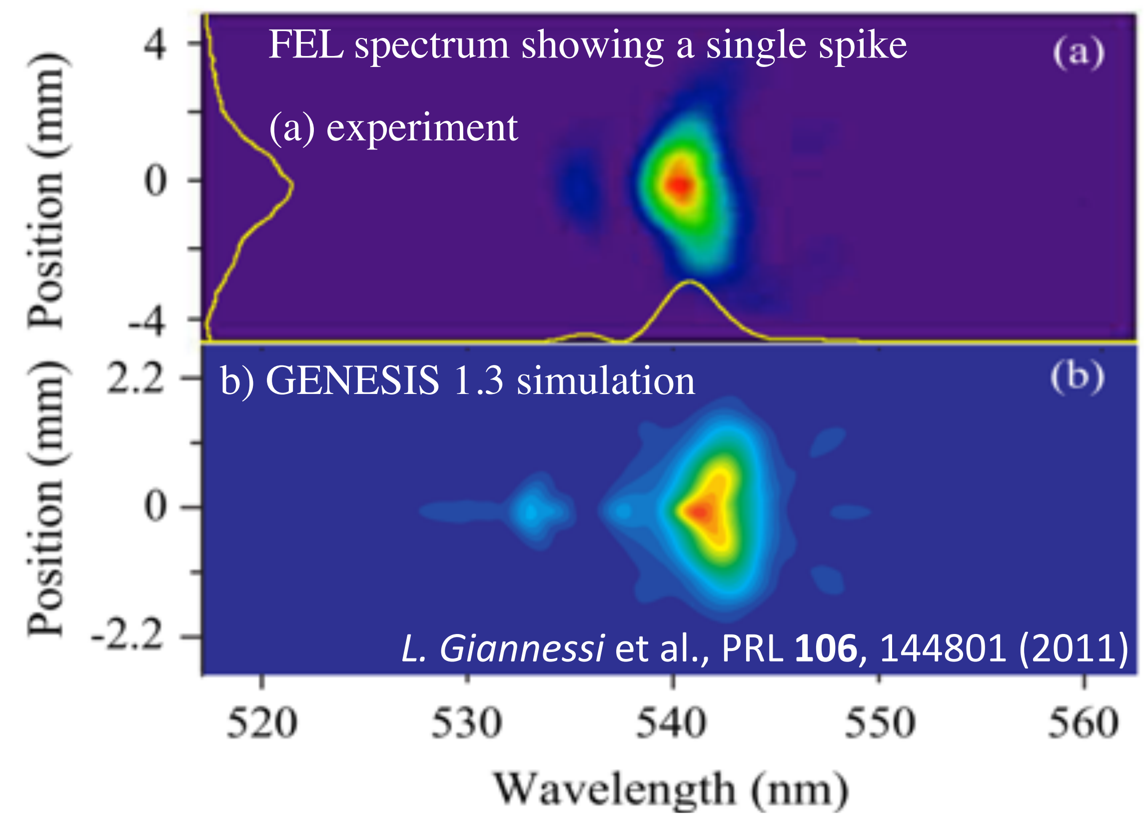
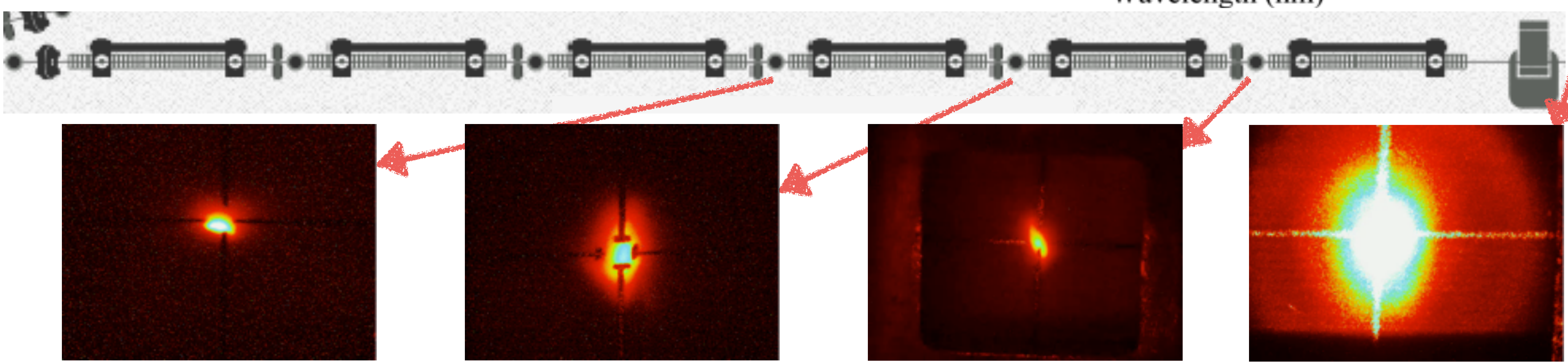
- **SASE FEL exponential gain in single spike**





Electron beam image on view screens while the gap is closing. Weak FEL radiation already after the third module.

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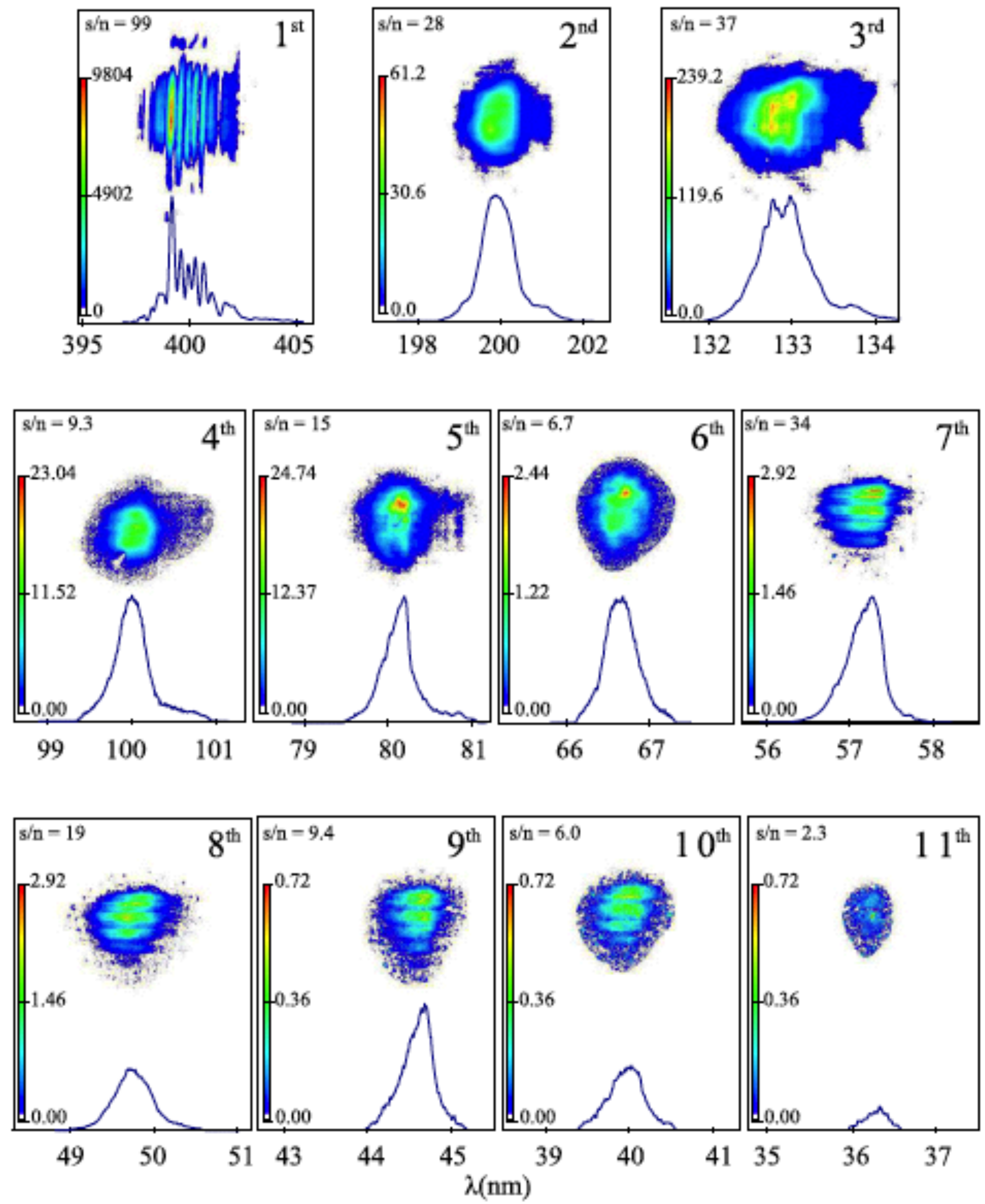
  - **FERMI@Elettra Seeded FEL user facility**



High order harmonic generation in a seeded FEL

L. Giannessi et al., PRL **108**, 164801 (2012)

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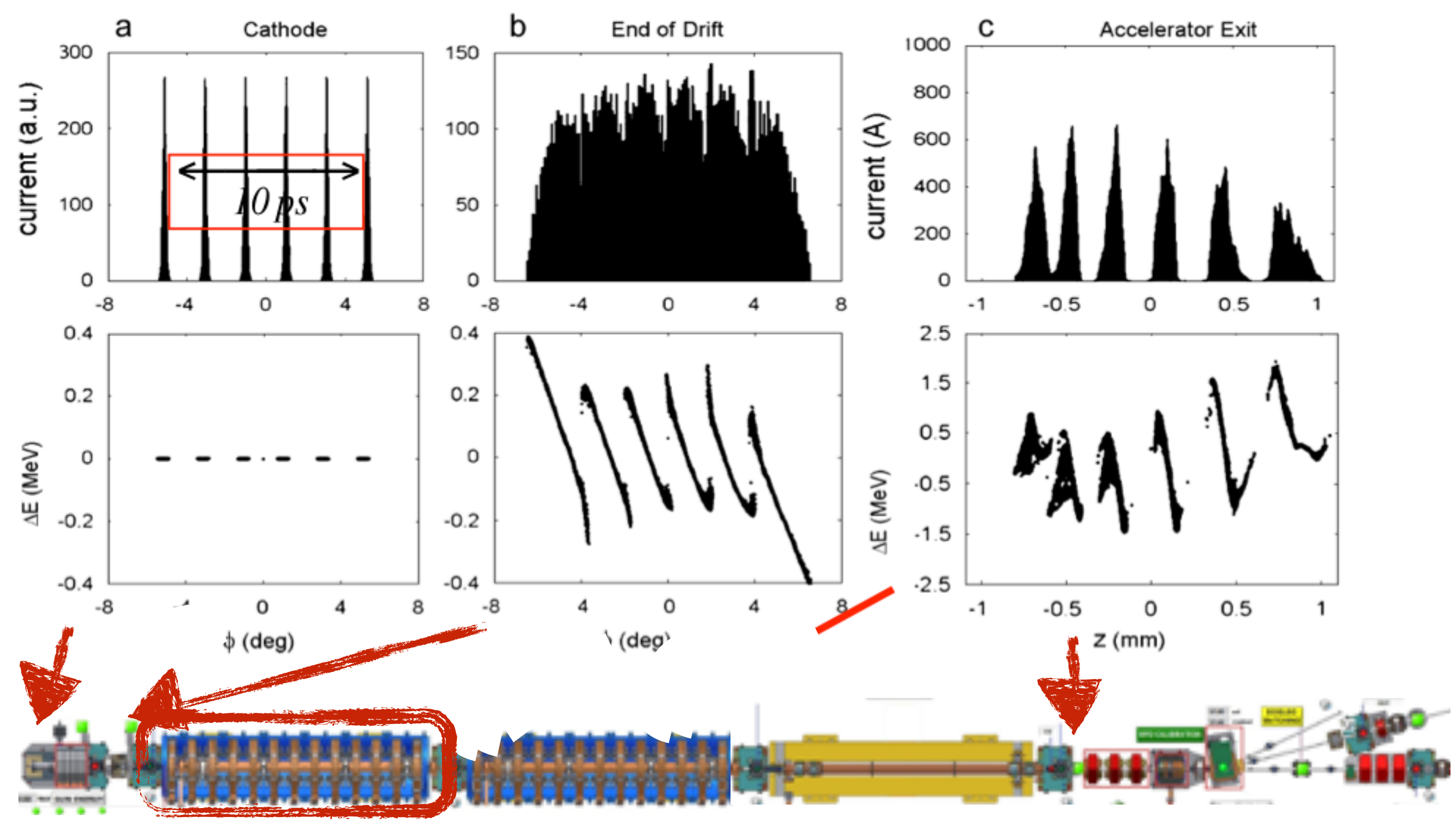
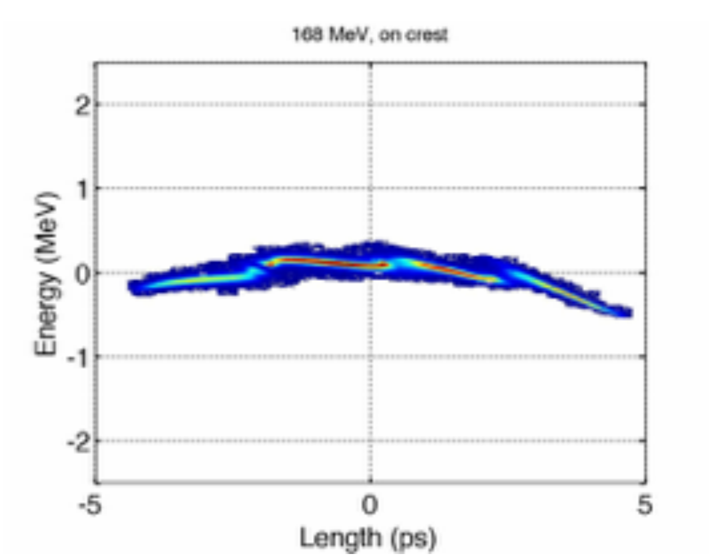
  - Laser comb technique
    - Two-color FEL radiation
    - Narrow band tunable THz radiation
    - Particle-driven wakefield acceleration



P. O. Shea et al., Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
M. Ferrario et al., Int. J. of Mod. Phys. B, 2006



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Resonant PWFA => SL_COMB

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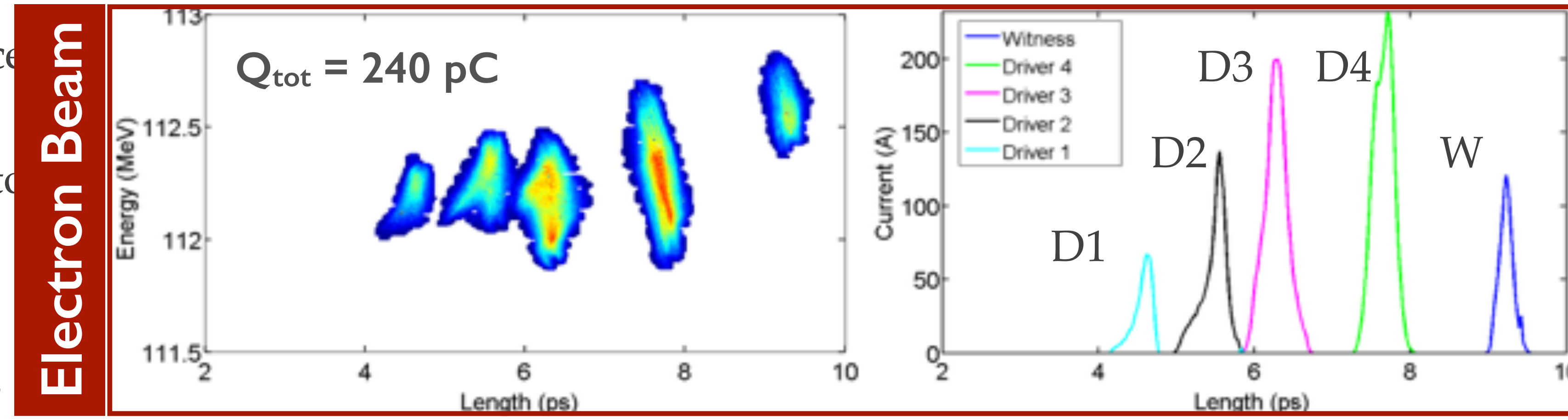

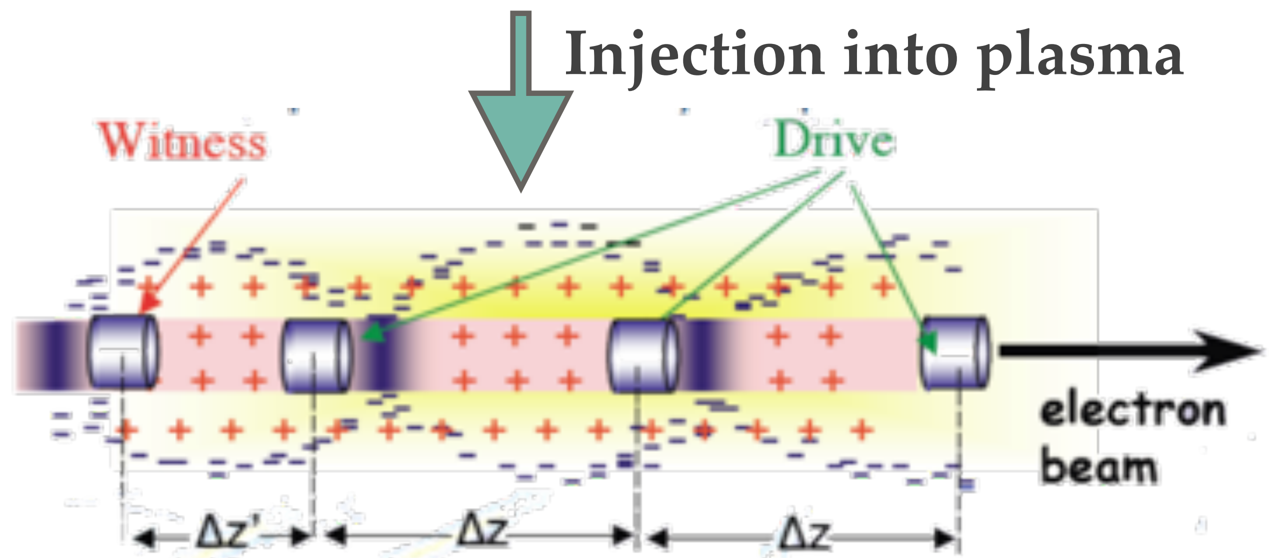

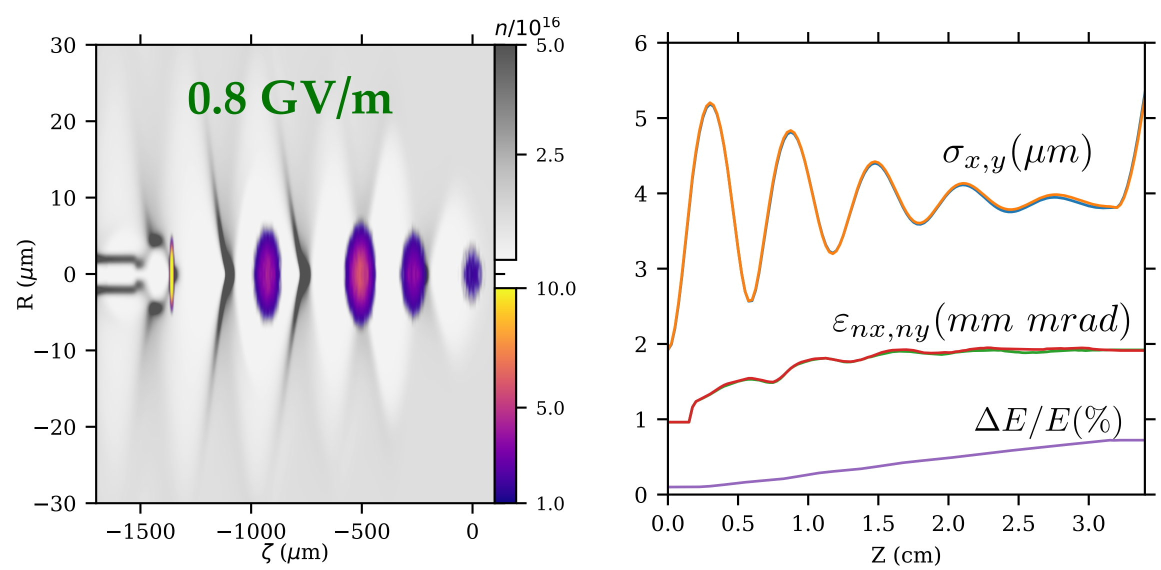

Architect sim., courtesy of A. Marocchino

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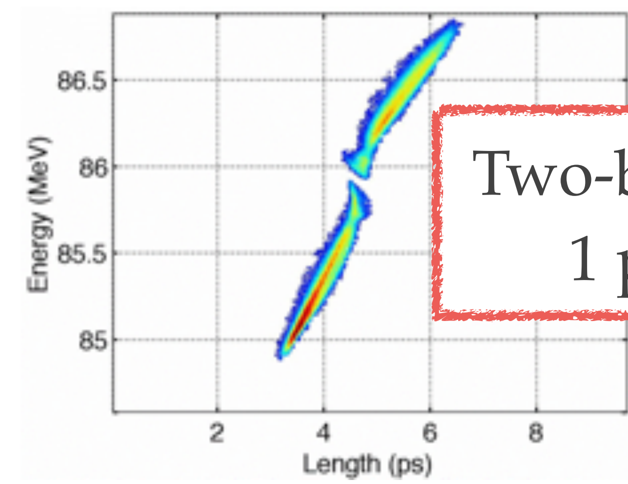
  - LCLS scaling at X-rays to drive user experiments



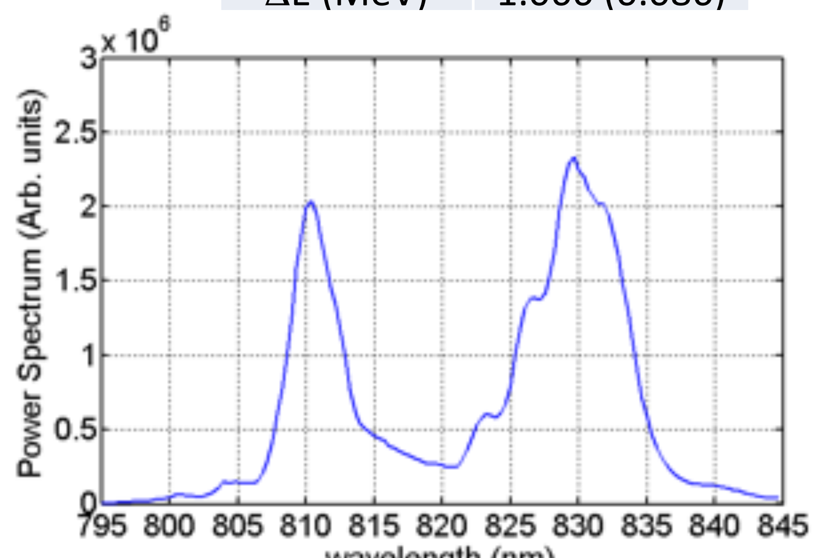
Two-bunch beams
1 ps spaced

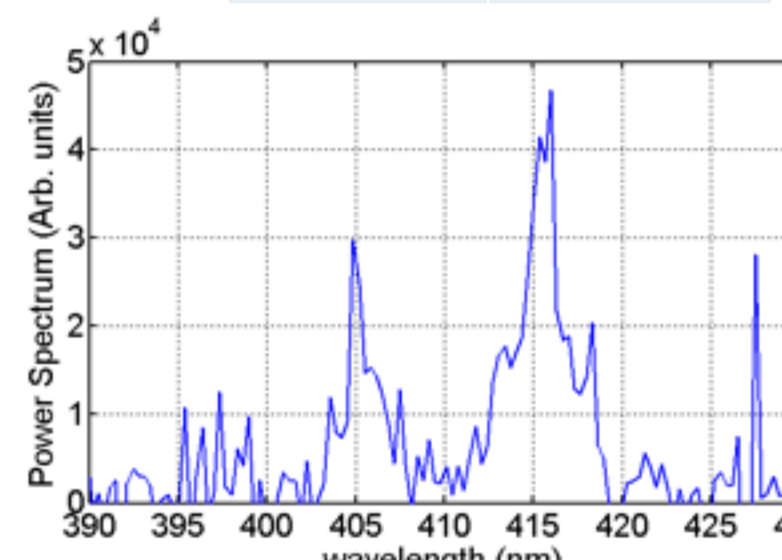
1st harm

λ_{min} (nm)	809.8 (2.1)
$BW_{\lambda min}$ (%)	0.6
λ_{Max} (nm)	830.5 (1.8)
$BW_{\lambda Max}$ (%)	0.8
$\Delta\lambda$ (nm)	20.7 (1.7)
ΔE (MeV)	1.066 (0.086)

2nd harm

λ_{min} (nm)	404.78 (0.63)
$BW_{\lambda min}$ (%)	0.7
λ_{Max} (nm)	415.48(0.60)
$BW_{\lambda Max}$ (%)	0.9
$\Delta\lambda$ (nm)	10.7 (0.5)
ΔE (MeV)	1.10 (0.05)





C. Ronsivalle et al., New Journal of Physics **16** (2014) 033018

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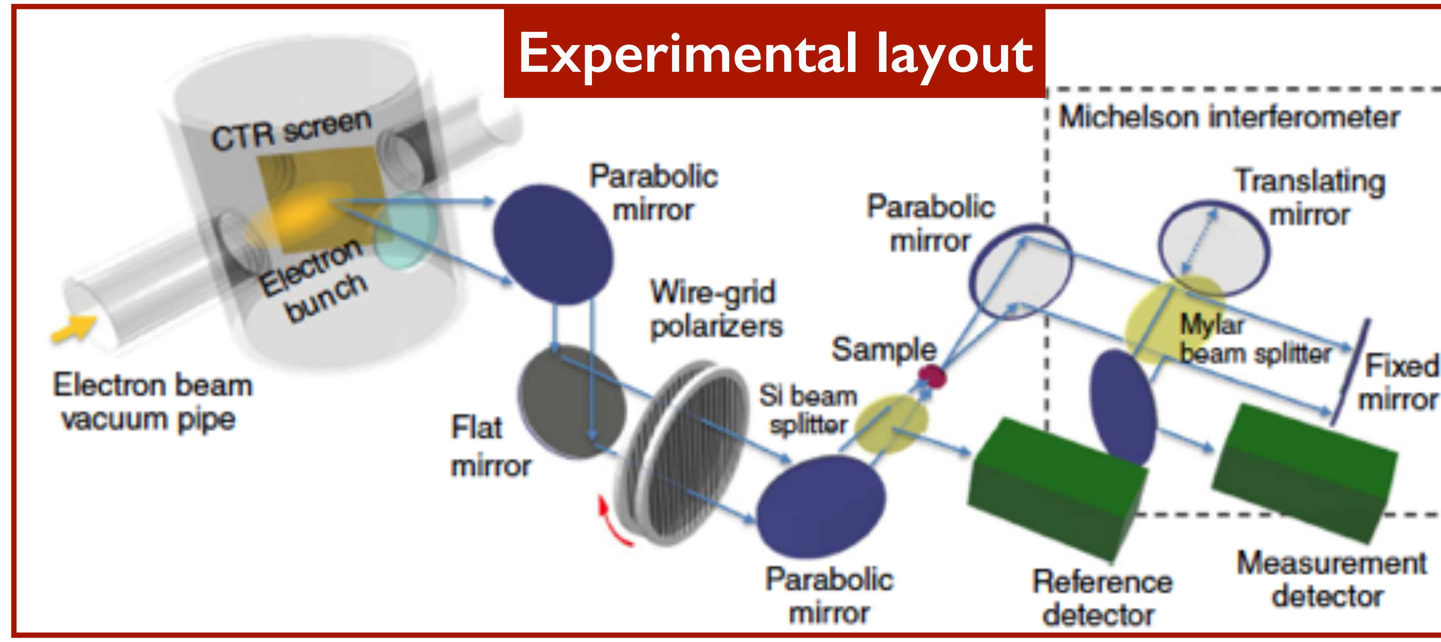
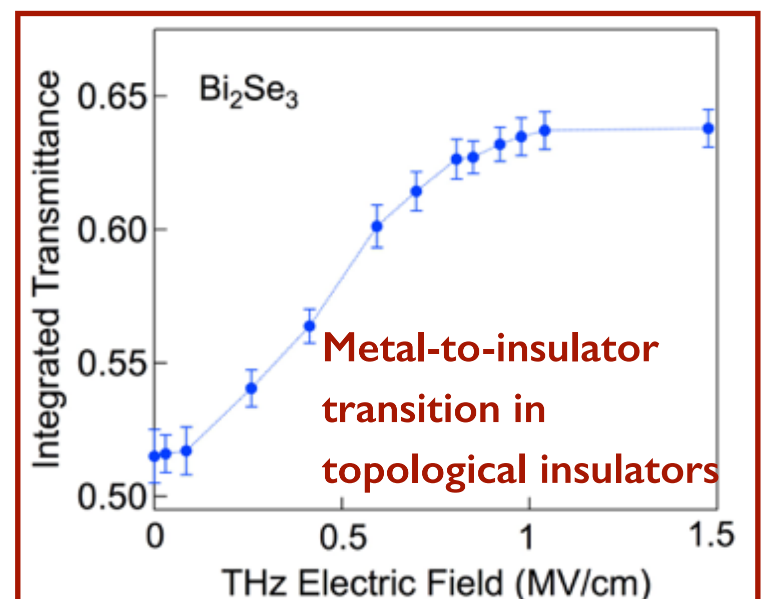
- **First user experiment with high peak power THz radiation and first observation of metal-to-insulator transition in topological insulator**
  - High technological applications





F. Giorgianni *et al.*, Nature Communications **7**:11421 (2016)

Collaboration with TeraLab group leaded by Prof. S. Lupi (Univ. of Rome *La Sapienza*)

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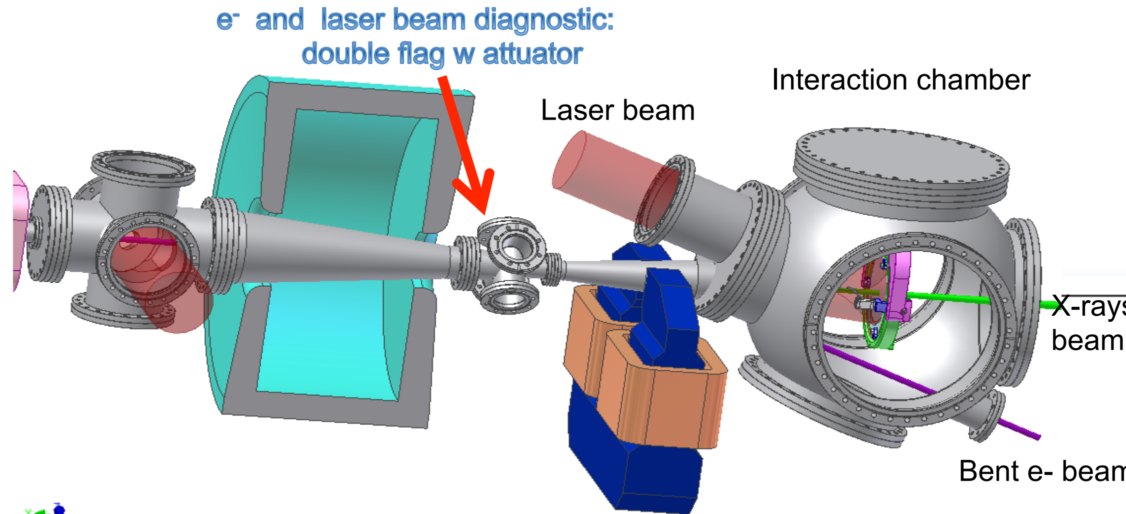
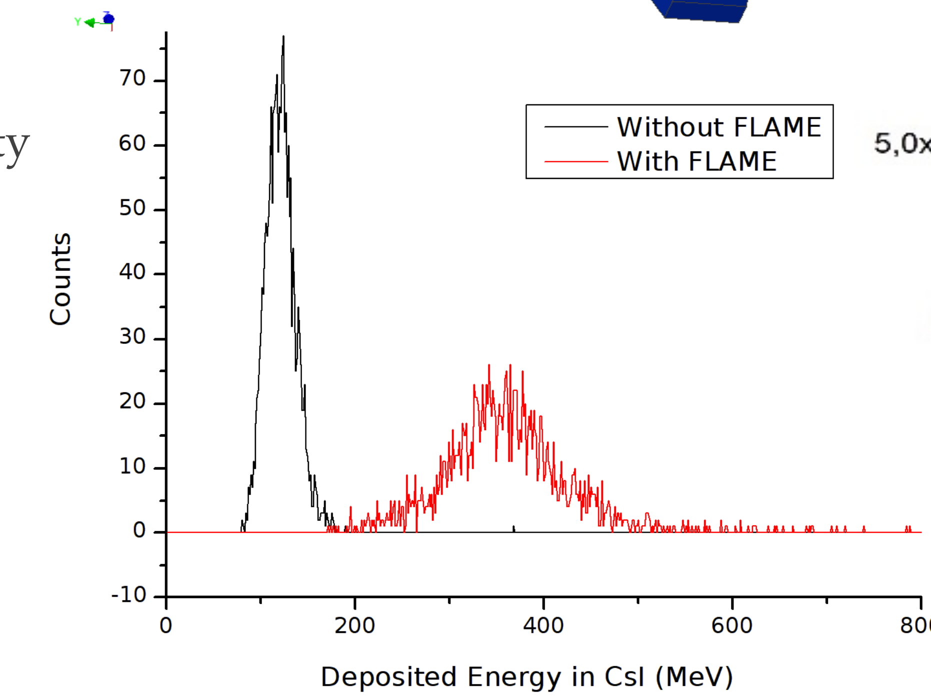
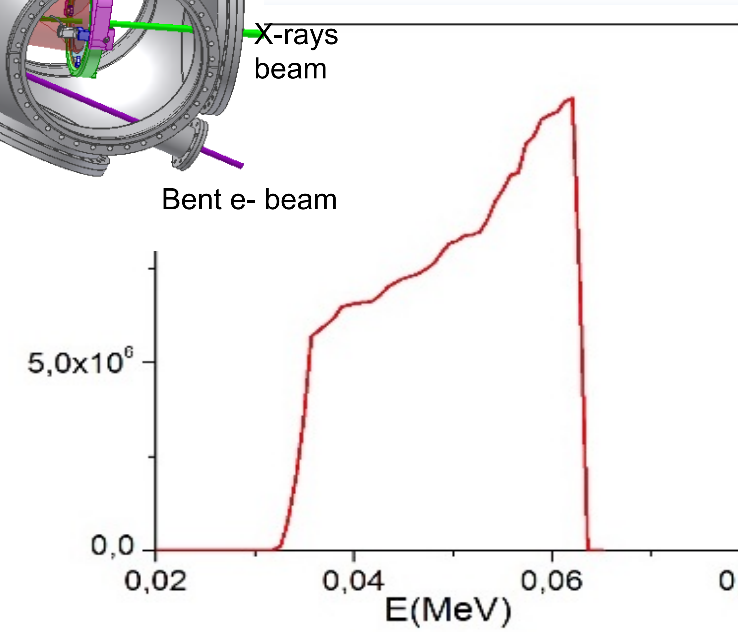
- First user experiment with high peak power THz radiation
  - Implicazioni tecnologiche
- **γ-rays through Thomson-backscattering**
  - STAR project
  - ELI-NP





Thomson x-rays signal in red, in black the electron background signal (without FLAME laser), integrated over 120 s (1200 pulses).

The number of photons per each pulse, coming from poor overlap conditions, and interacting with the detector sensitive area, is in average **6.7x10³**.



Spectral density S (MeV^{-1}) versus photon energy.

(50 MeV electron beam, with 200 pC charge, 5 mm mrad of emittance, 150 mm of rms beam transverse dimension, colliding with the laser with 500 mJ and 30 mm of waist, gives a number of photons of 2×10^5 in a bandwidth of about 19%.

The photon energy edge, given by $E_p \sim 4E_L\, g^2$, is about **63 keV.**

C. Vaccarezza et al., NIM A **829** (2016) 237–242

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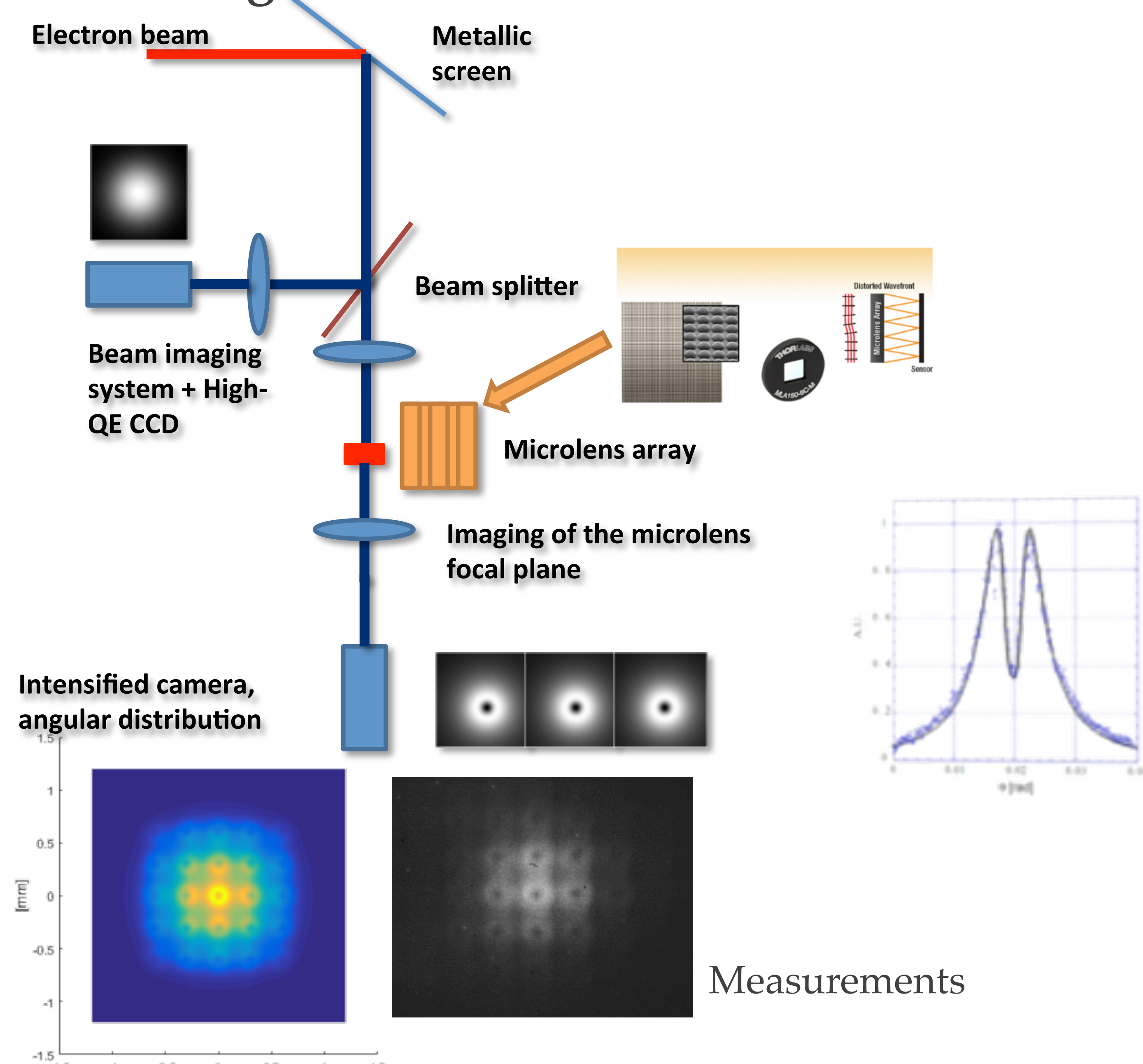
- **Test bench of novel diagnostics**

Single shot emittance measurement



Cianchi, A., et al. "Transverse emittance diagnostics for high brightness electron beams." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 865 (2017): 63-66.

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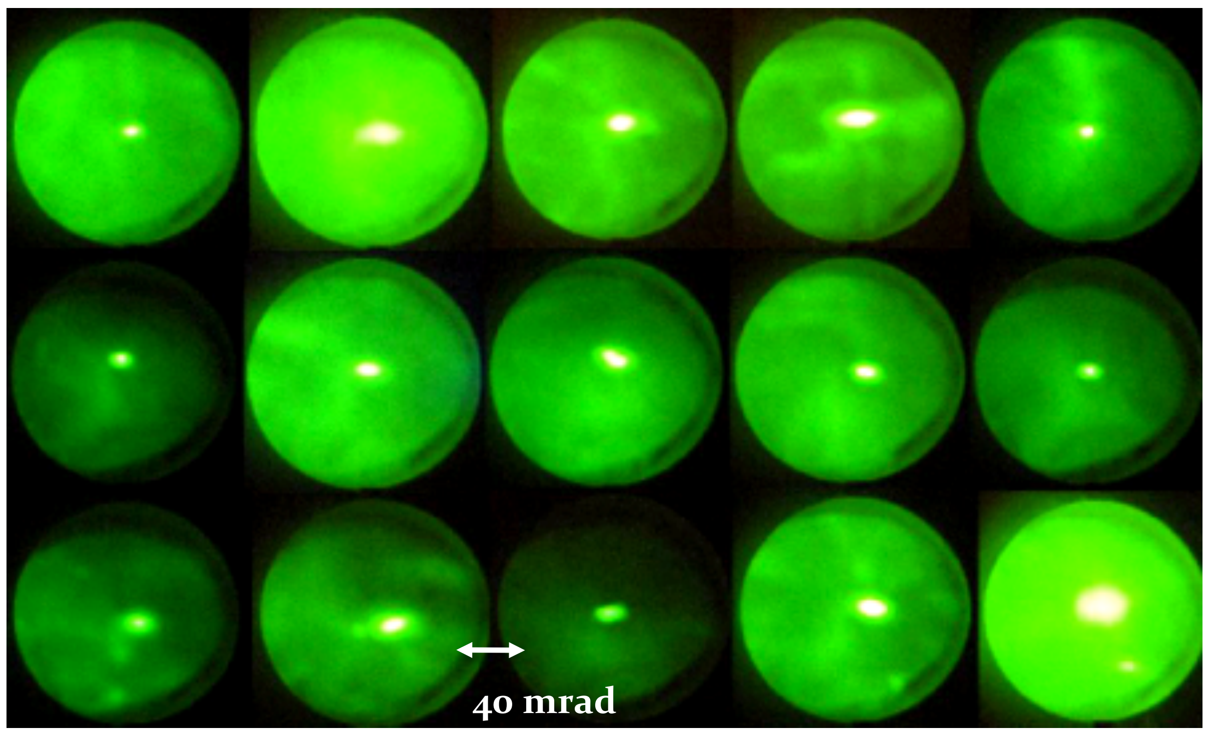
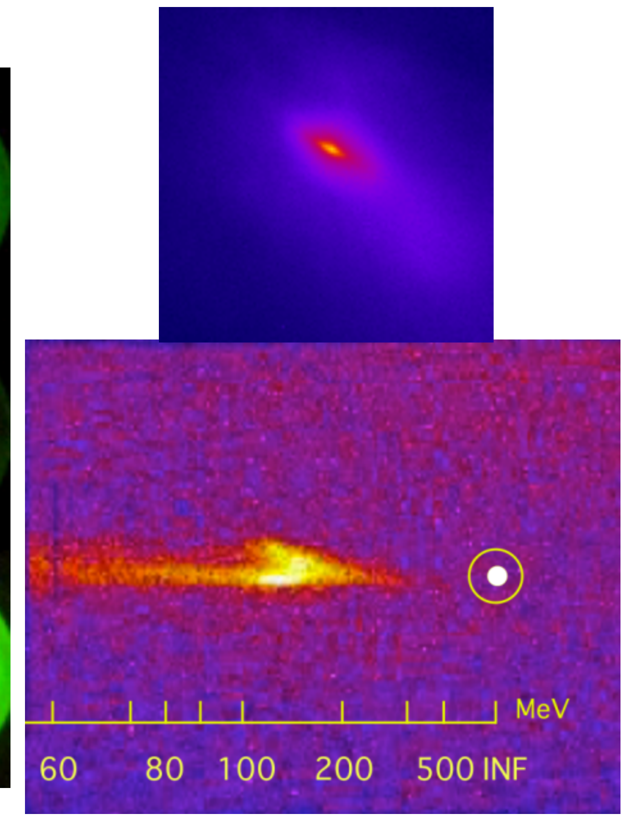
Self-injection acceleration with FLAME

Typical electron bunches accelerated by laser-plasma interaction observed at SPARC_LAB





Collimated and reproducible electron bunches have been generated. 200 MeV energy electron bunches have been measured by using only 25% of the nominal laser power.

G. Grittani et al, **SPIE proceeding, 740** (2013)

EuPRAXIA European Design Study

…to drive the first plasma-based user facility for nm FEL radiation and high energy physics applications!

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

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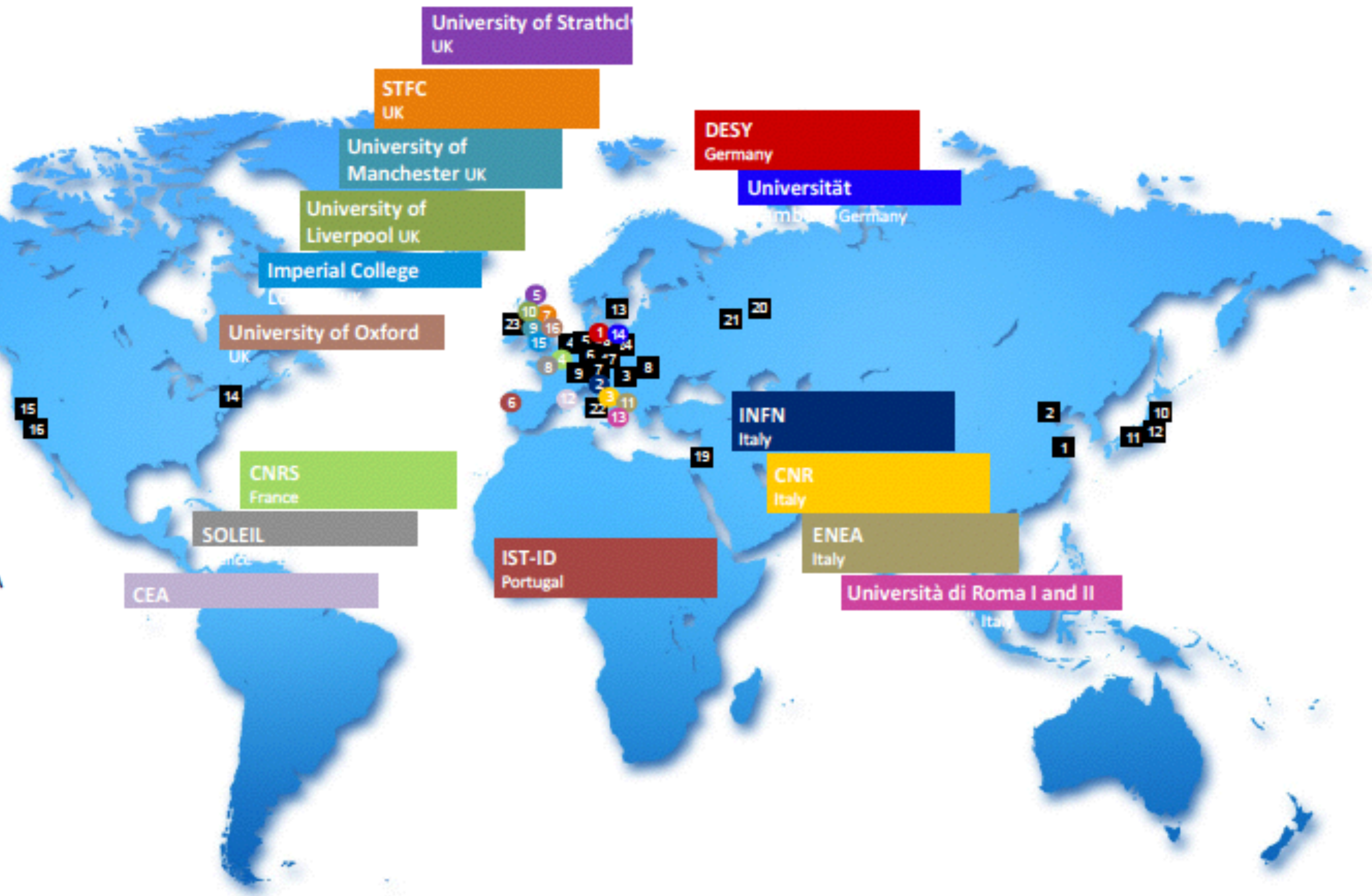
Worldwide effort towards high quality plasma beams

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



Consortium

16 Participants

24 Associated Partners

(as of December 2017)

Industrial participation

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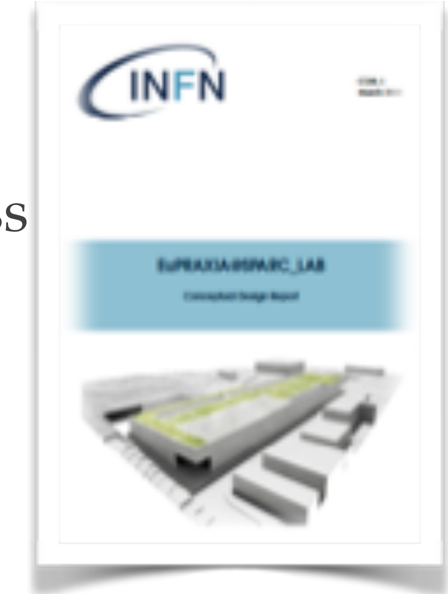
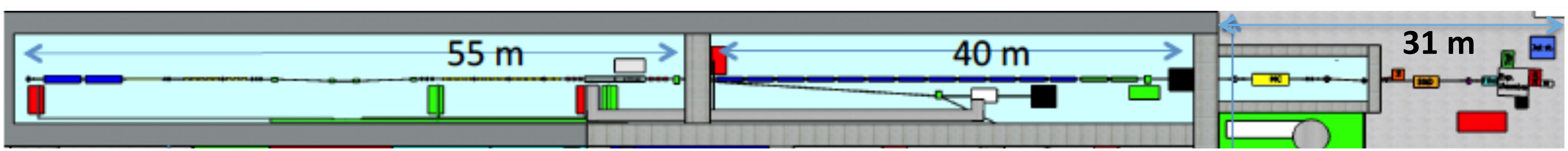
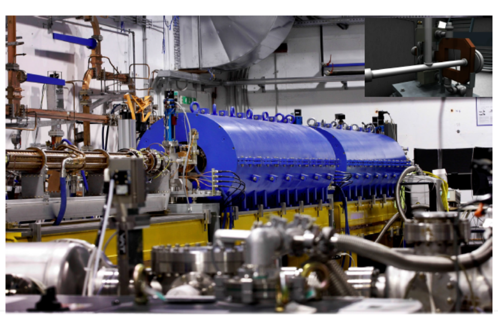
EuPRAXIA@SPARC_LAB



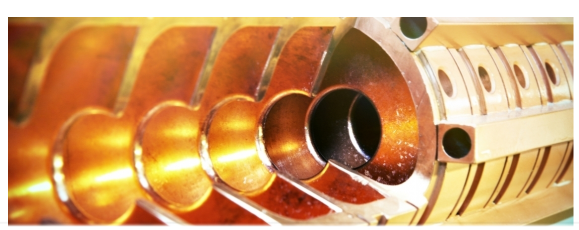
- **Candidate LNF to host EuPRAXIA (1 - 5 GeV)**
- The EuPRAXIA@SPARC_LAB Test User Facility will produce high brightness electron beams either by a **500 MeV X-band RF linac plus 500 MeV plasma** accelerator or by a **1 GeV X-band RF linac only** to drive
  - FEL user facility: 1 GeV – 3 nm
  - Advanced Accelerator Test Facility (LC + CERN)
  - Novel radiation sources facility, e.g. *THz radiation, γ-rays, neutron sources*



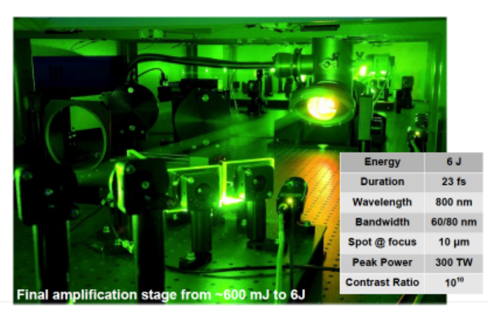
SPARC High Brightness Photo-injector



X-band linac

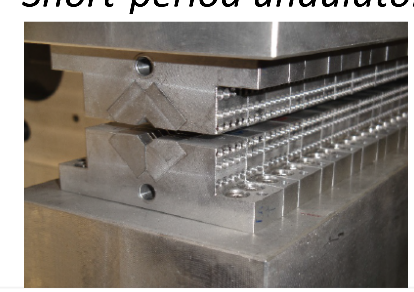


High power laser



Plasma-discharge capillary

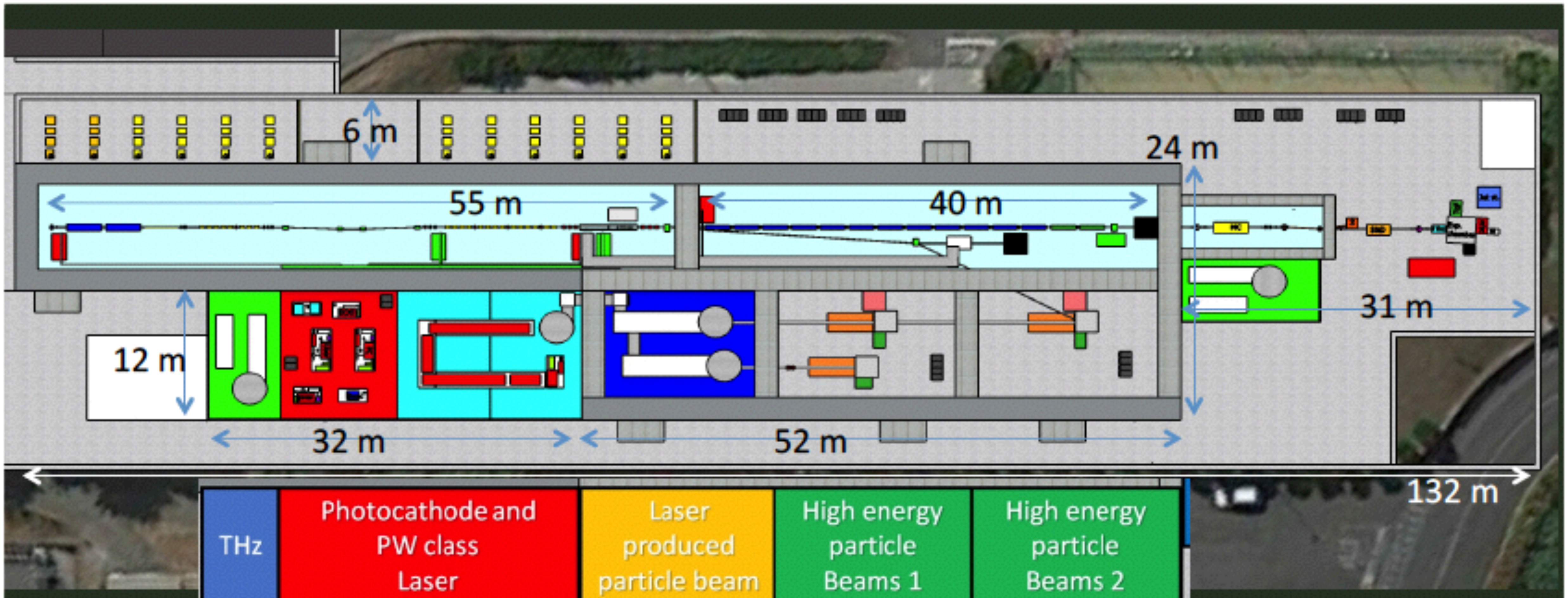
Short-period undulator



EuPRAXIA@SPARC_LAB Conceptual Design Report is publicly available and can be downloaded from
http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

enrica.chiadroni@lnf.infn.it

EuPRAXIA@SPARC_LAB Layout



- 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

EuPRAXIA@SPARC_LAB Site

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Thank You for the attention!

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