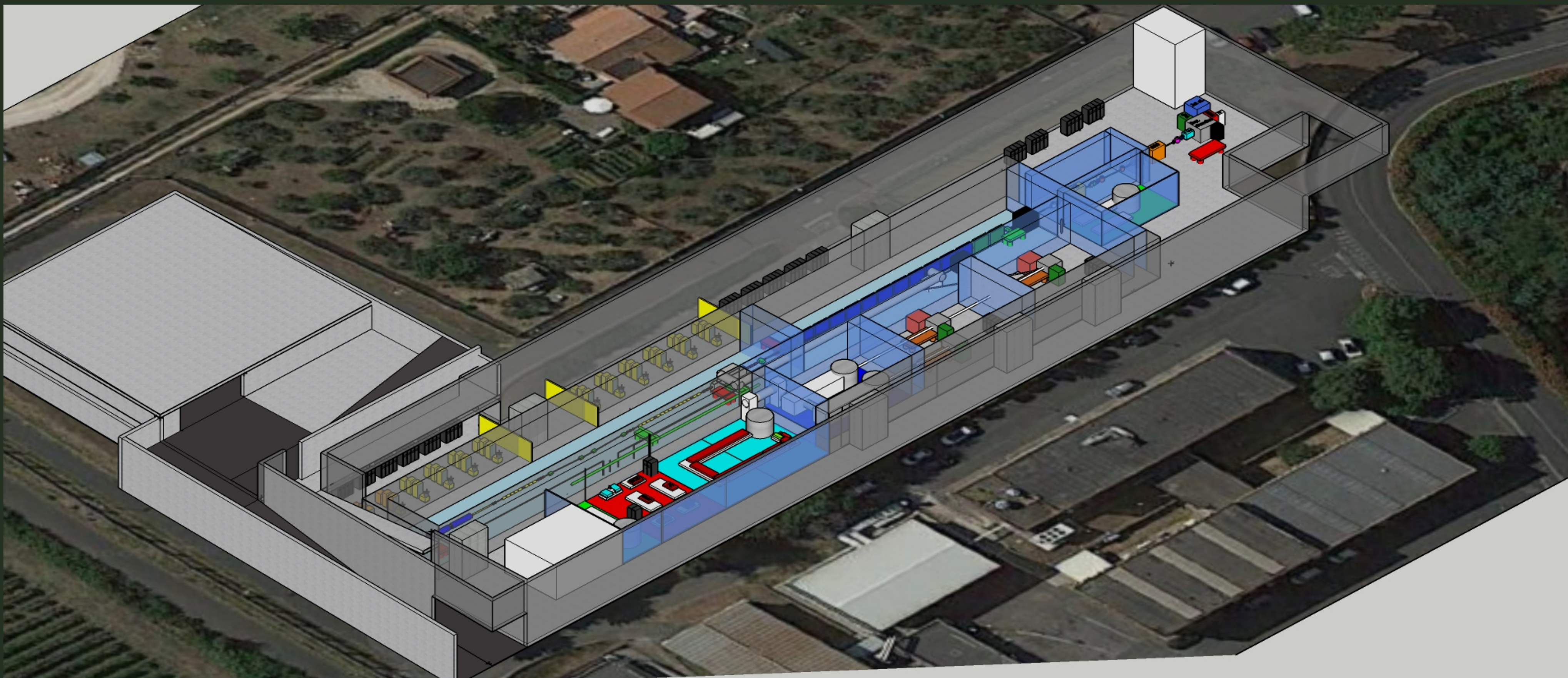
From SPARC_LAB to EuPRAXIA

Massimo.Ferrario@lnf.infn.it

On behalf of the design study team



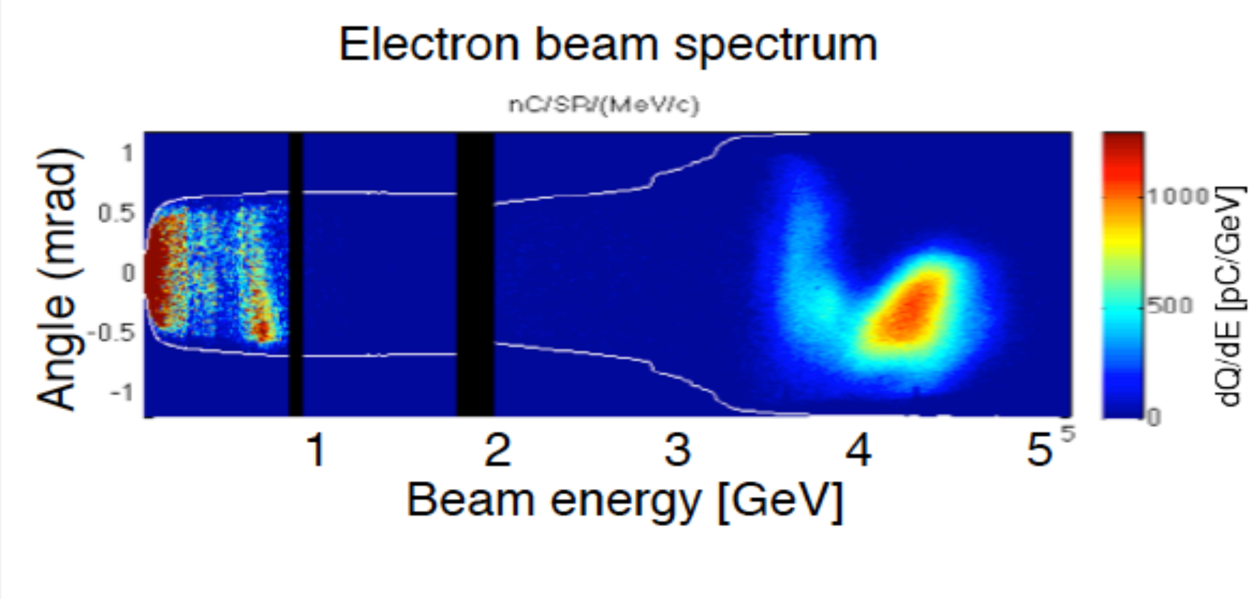
EuPRAXIA

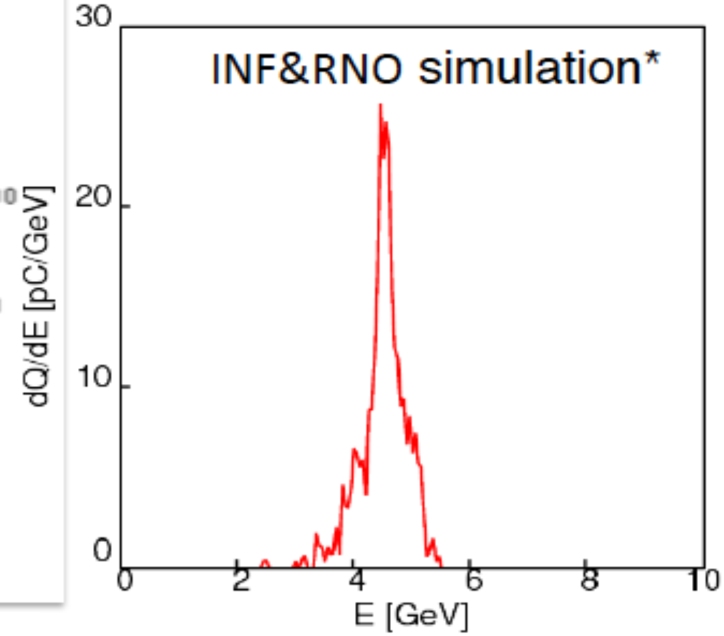
FLS 2018 - Shanghai, March 6

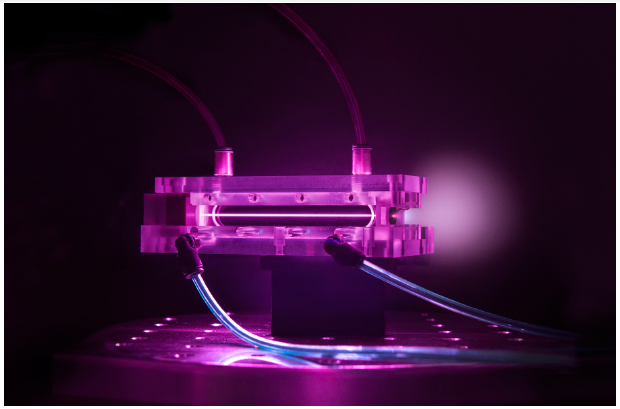
INFN Istituto Nazionale di Fisica Nucleare

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

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



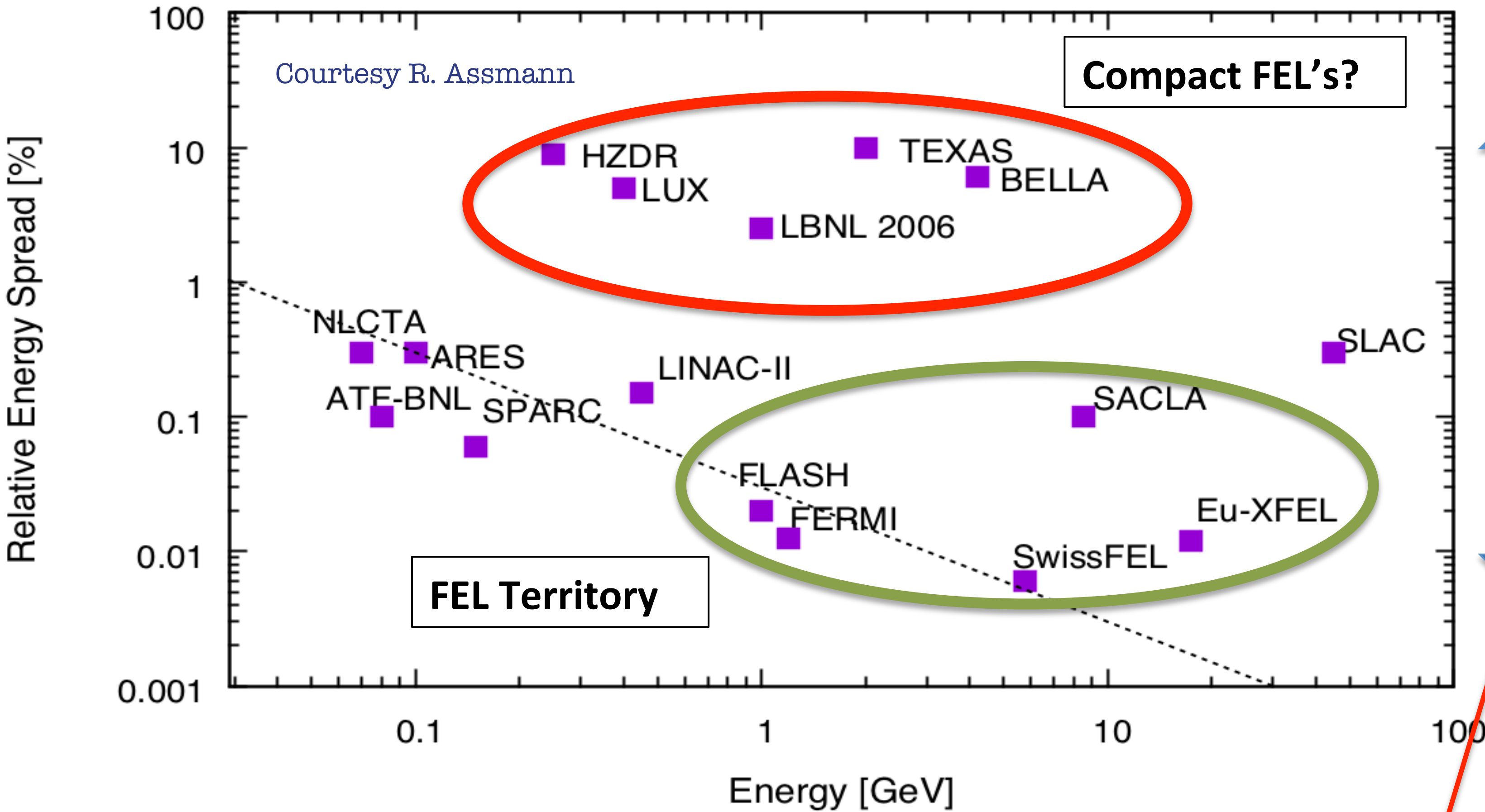




	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

W.P. Leemans et al.,PRL 2014

Quality: Example Energy Spread



Lower quality

$$\frac{\sigma_\gamma}{\gamma} = \frac{\sqrt{3}}{2} k_p^2 \sigma_z^2$$

$$\sin\varphi_w \propto \frac{q_w}{Q_d}$$

Higher quality

$$\varepsilon_{n,rms} = \sqrt{\langle\gamma^2\rangle\left(\sigma_\gamma^2\sigma_x^2\sigma_{x'}^2 + \varepsilon_{rms}^2\right)}$$

M. Migliorati et al, Physical Review Special Topics,Accelerators and Beams 16, 011302 (2013)
K. Floettmann, PRSTAB,6, 034202 (2003)

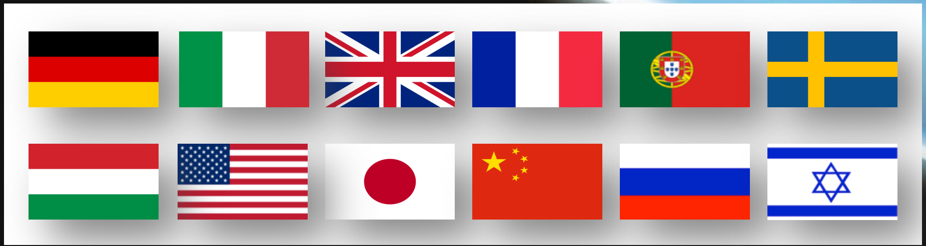
EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

EuPRAXIA Design Study started on Novemebr 2015

Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€

Coordinator: Ralph Assmann (DESY)



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

http://eupraxia-project.eu

Motivations

Horizon2020

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

FEL Electron Beam Requirements

Horizon 2020

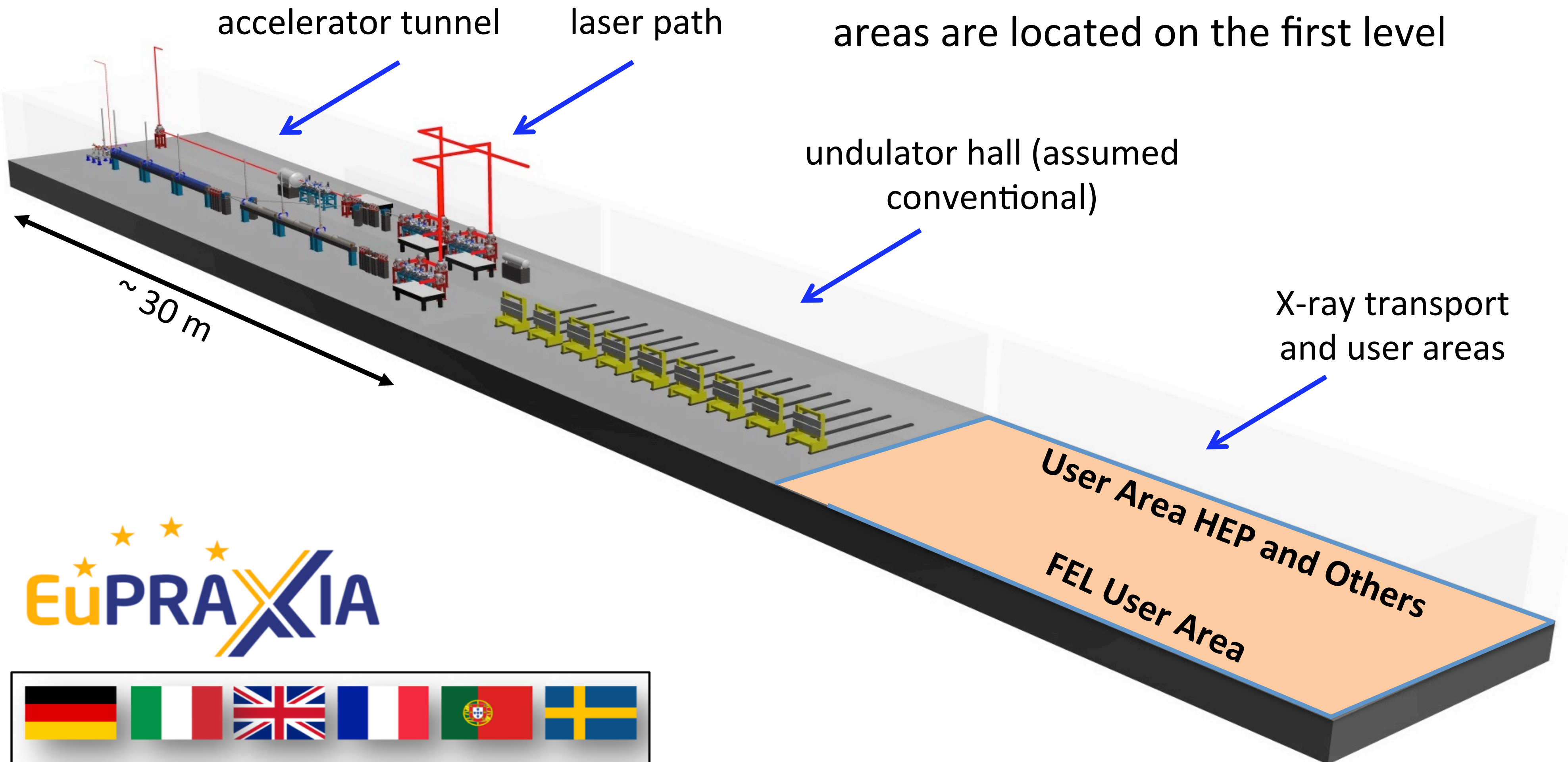
Electron beam parameters at the undulator

Quantity	Symbol [Unit of Meas.]	Target parameters
Energy	E [GeV]	1 - 5
Charge	Q [pC]	30
Bunch length (FWHM)	t_{FWHM} [fs]	10
Peak current	I [kA]	3
Repetition rate	f [Hz]	10
# of bunches	N	1
Transverse Norm. emittance	$\varepsilon_{n,x}, \varepsilon_{n,y}$ [mm mrad]	<1
Total energy spread	σ_E/E [%]	1
Slice Norm. emittance	$\varepsilon_{n,x}, \varepsilon_{n,y}$ [mm mrad]	<<1
Slice energy spread	$\sigma_{E,s}/E$ [%]	~0.1
Slice length	L_{Slice} [μm]	0.75 - 0.12

Overall layout status (ongoing)

Horizon 2020

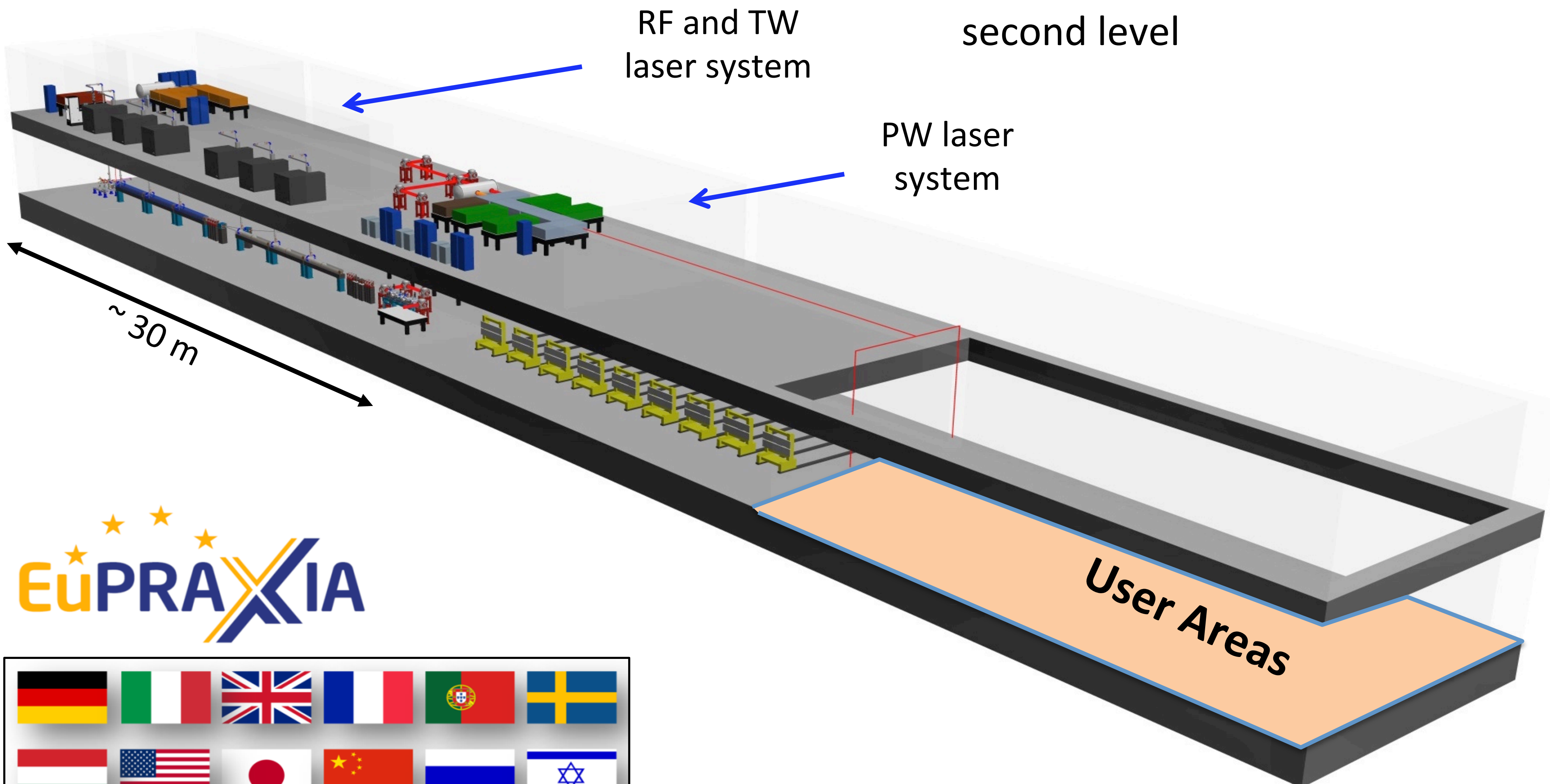
Accelerator research, undulators and user areas are located on the first level



Design by A. Walker (DESY) and Dariusz Kocoń (ELI-Beams)

… with 1st floor for laser infrastructure

RF and laser infrastructure on second level



Consortium

Horizon 2020

16 Participants

24 Associated Partners

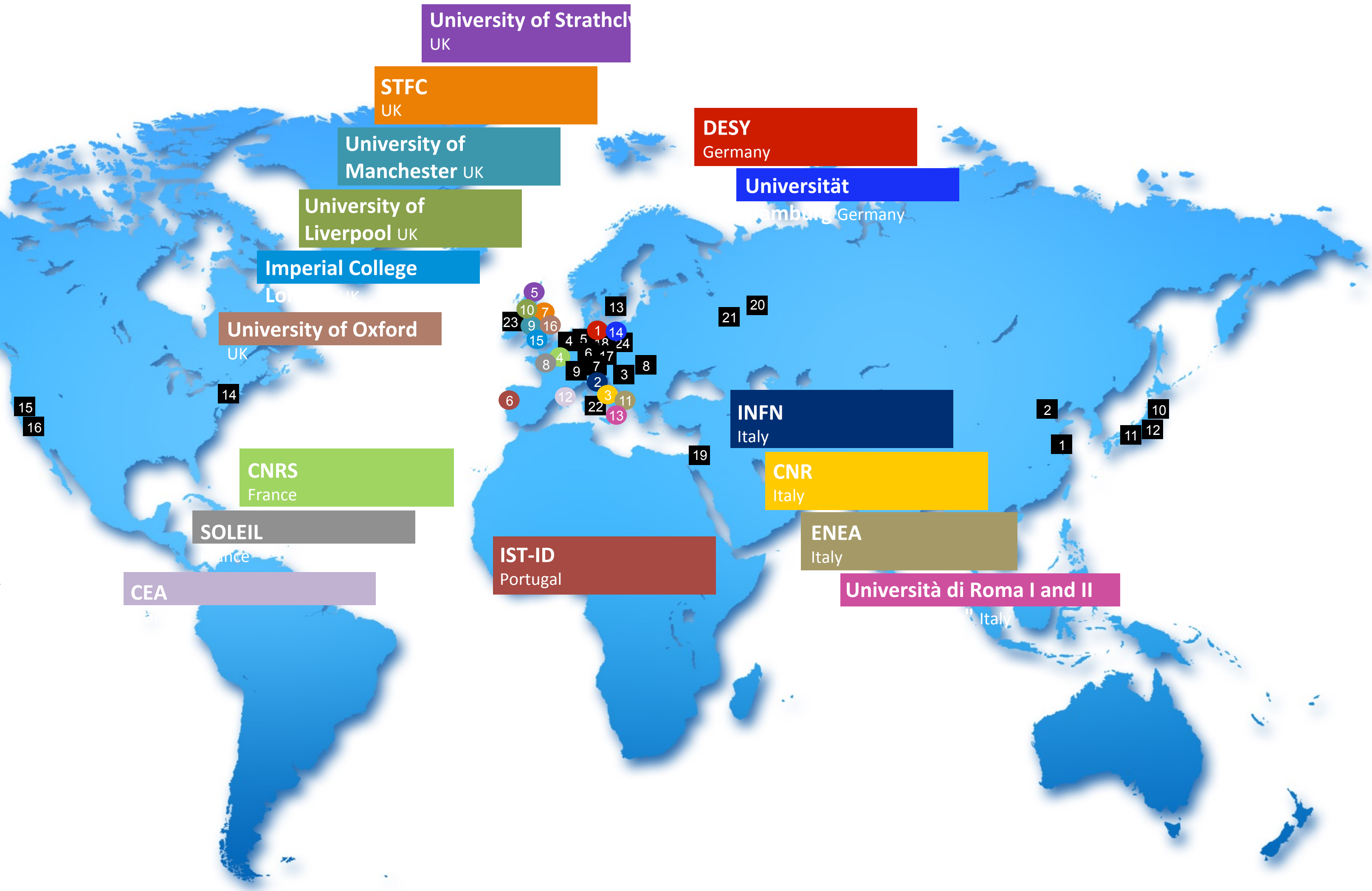
(as of December 2017)

Participating Institutions

Horizon 2020

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
193 **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



Industrial Participation

Industry: involved through workshops and Scientific Advisory Board

Contacts still evolving, several cooperations under discussion

Thales group (France): Number of employees: 62,194 (2015)
Sales 14.06 B€ (2015)

Amplitude (France): Number of employees: 80 (2015)
Sales 17.4 M€ (2015)

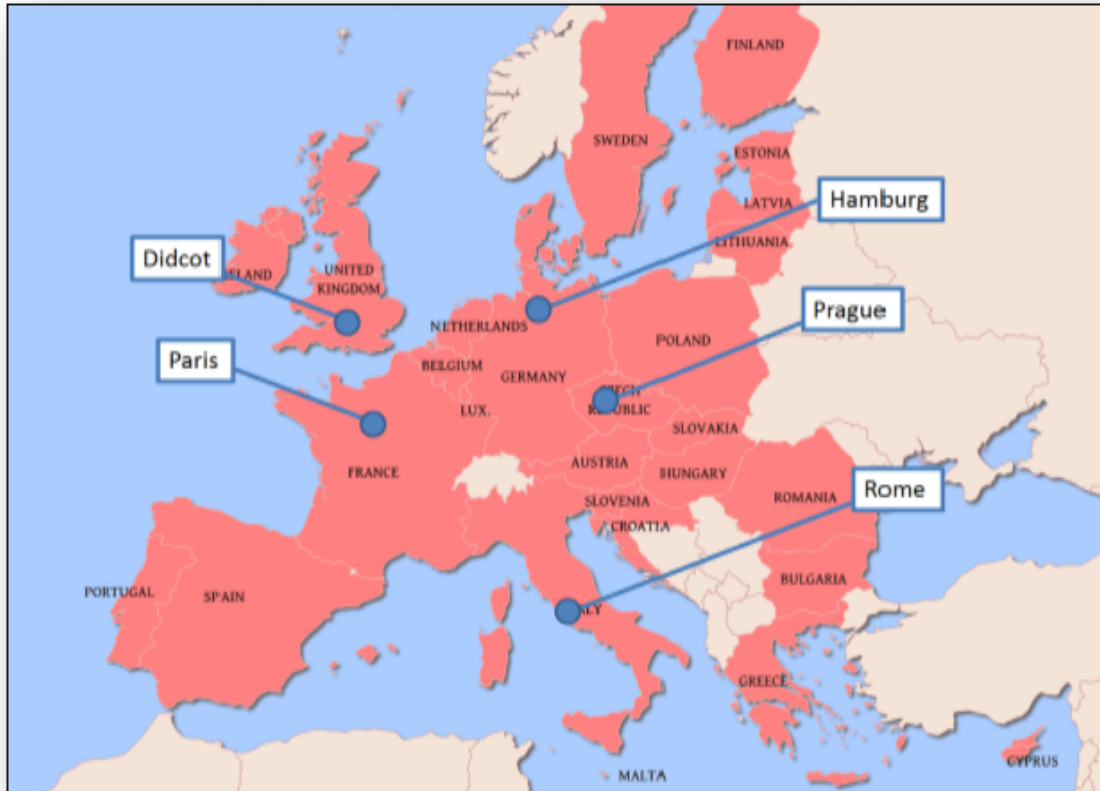
Trumpf group (Germany): Number of employees: 11,181 (2016)
Sales 2.81 B€ (2016)

Location of possible sites within EU

Horizon 2020

EuPRAXIA site studies:

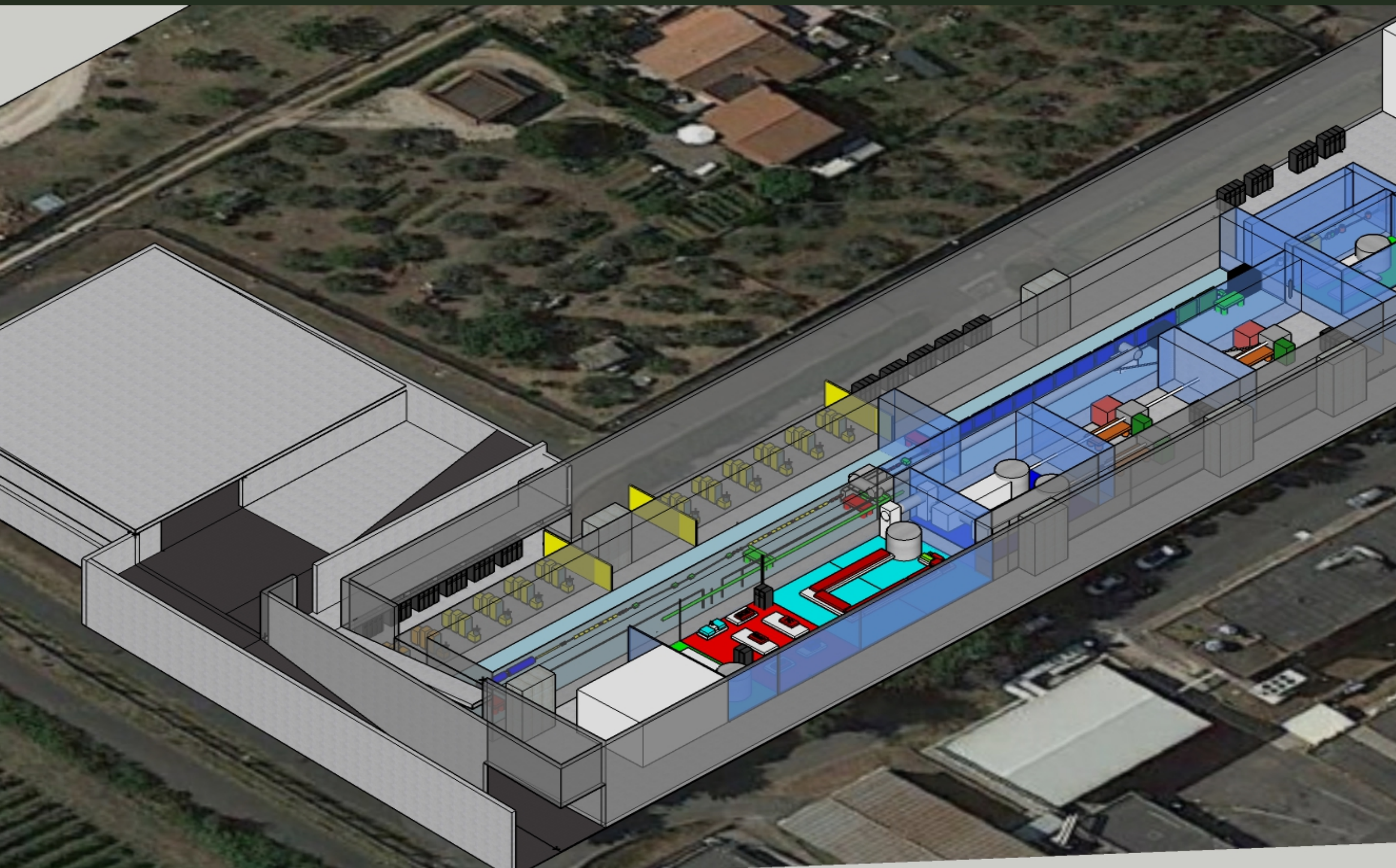
- Design study is site independent
- Five possible sites have been discussed so far
- We invite the suggestions of additional sites



Central Laser Facility
Didcot, United Kingdom

Eli Beamlines
Prague, Czech Republic

EuPRAXIA@SPARC_LAB

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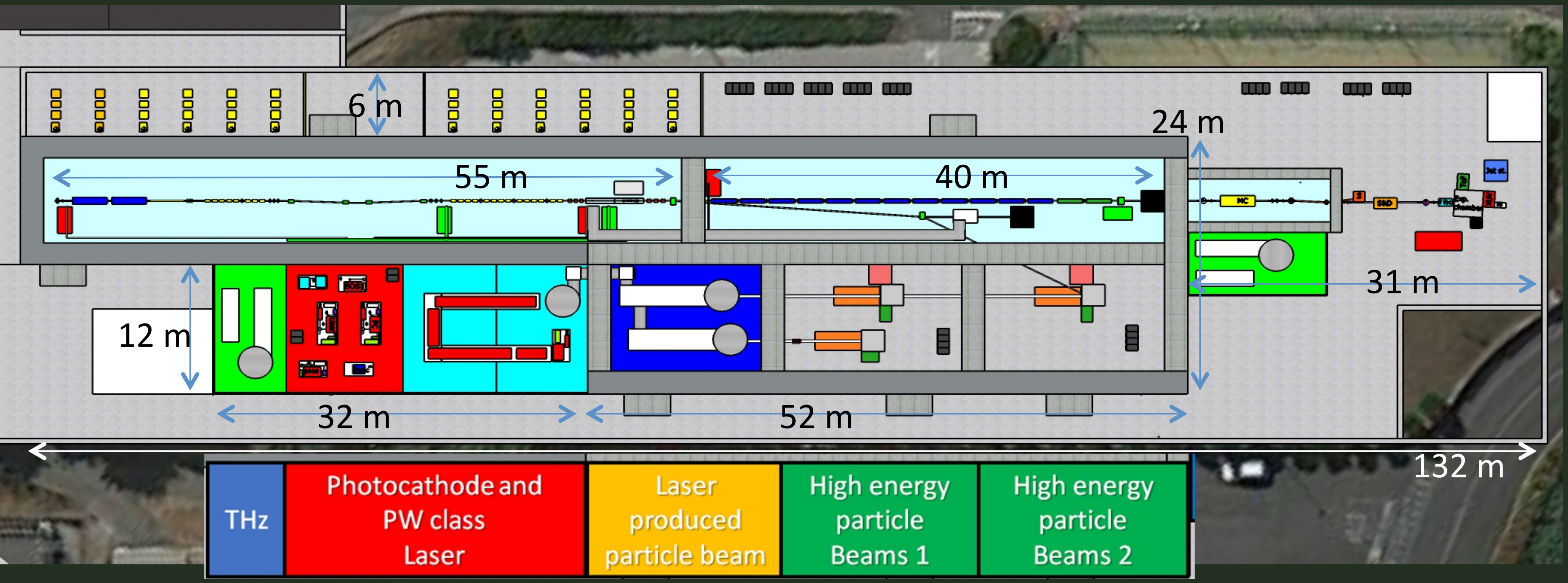
EuPRAXIA@SPARC_LAB

Conceptual Design Report

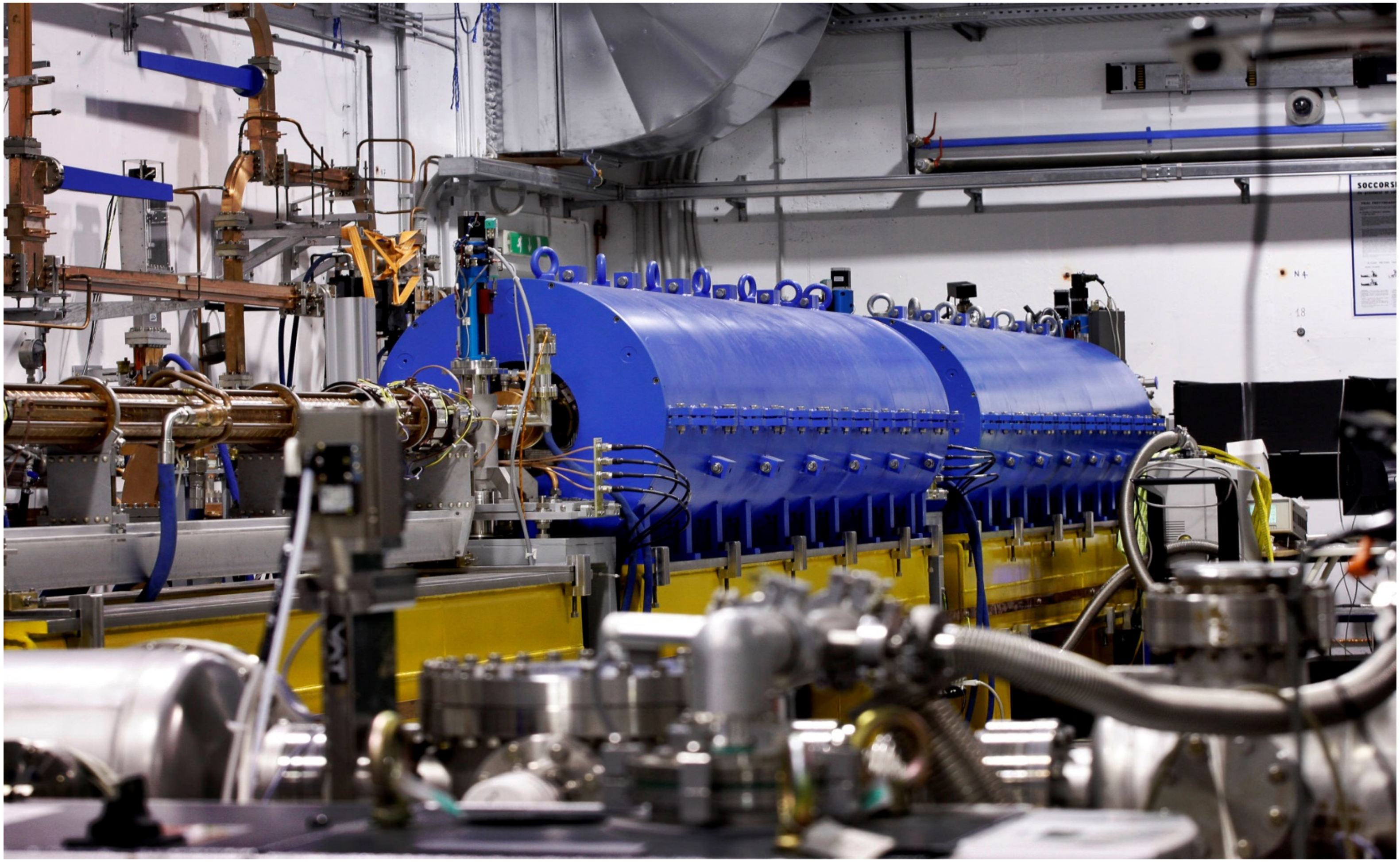
- D. Alesini, M. P. Anania, R. Bedogni, M. Bellaveglia, A. Biagioni, F. Bisesto, E. Brentegani, B. Buonomo, P.L. Campana, G. Campogiani, S. Cantarella, F. Cardelli, M. Castellano, E. Chiadroni, R. Cimino, R. Clementi, M. Croia, A. Curcio, G. Costa, S. Dabagov, M. Diomede, A. Drago, D. Di Giovenale, G. Di Pirro, A. Esposito, M. Ferrario, F. Filippi, O. Frasciello, A. Gallo, A. Ghigo, A. Giribono, S. Guiducci, S. Incremona, F. Iungo, V. Lollo, A. Marcelli, A. Marocchino, V. Martinelli, A. Michelotti, C. Milardi, L. Pellegrino, L. Piersanti, S. Pioli, R. Pompili, R. Ricci, S. Romeo, U. Rotundo, L. Sabbatini, O. Sans Plannell, J. Scifo, B. Spataro, A. Stecchi, A. Stella, V. Shpakov, C. Vaccarezza, A. Vannozzi, A. Variola, F. Villa, M. Zobov.
- **INFN - Laboratori Nazionali di Frascati**
- A. Bacci, F. Broggi, C. Curatolo, I. Debrot, A. R. Rossi, L. Serafini. **INFN - Sezione di Milano**
- D. Cirrincione, A.Vacchi. **INFN - Sezione di Trieste**
- G. A. P. Cirrone, G. Cuttone, V. Scudieri. **INFN - Laboratori Nazionali del Sud**
- M. Artioli, M.Carpanese, F.Ciocci, D.Dattoli, S.Licciardi, F.Nguyen, S. Pagnutti, A.Petralia, E. Sabia. **ENEA – Frascati and Bologna**
- L. Gizzi, L. Labate. **CNR - INO, Pisa**
- R. Corsini, A. Grudiev, N. Catalan Lasheras, A. Latina, D. Schulte, W. Wuensch. **CERN, Geneva**
- C. Andreani, A. Cianchi, G. Festa,V. Minicozzi, S. Morante, R. Senesi, F. Stellato. **Universita' degli Studi di Roma Tor Vergata and Sezione INFN**
- V. Petrillo, M. Rossetti. **Universita' degli Studi di Milano and Sezione INFN**
- G. Castorina, L. Ficcadenti, S. Lupi, M. Marongiu, F. Mira, A. Mostacci. **Universita' degli Studi di Roma Sapienza and Sezione INFN**
- S. Bartocci, C. Cannaos, M. Faiferri, R. Manca, M. Marini, C. Mastino, D. Polese, F. Pusceddu, E. Turco. **Università degli Studi di Sassari, Dip. di Architettura, Design e Urbanistica ad Alghero**
- M. Coreno, G. D'Auria, S. Di Mitri, L. Giannessi, C. Masciovecchio. **ELETTRA Sincrotrone Trieste**
- A. Ricci. **RICMASS, Rome International Center for Materials Science Superstripes**
- A. Zigler. **Hebrew University of Jerusalem** J. B. Rosenzweig. **University of California Los Aangeles**

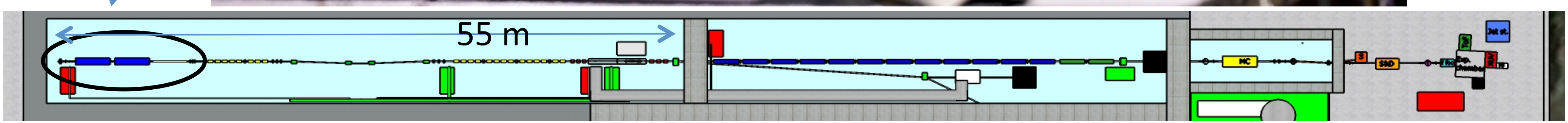
- Candidate LNF to host EuPRAXIA (1-5 GeV)
- FEL user facility (1 GeV – 3nm)
- Advanced Accelerator Test facility (LC) + CERN



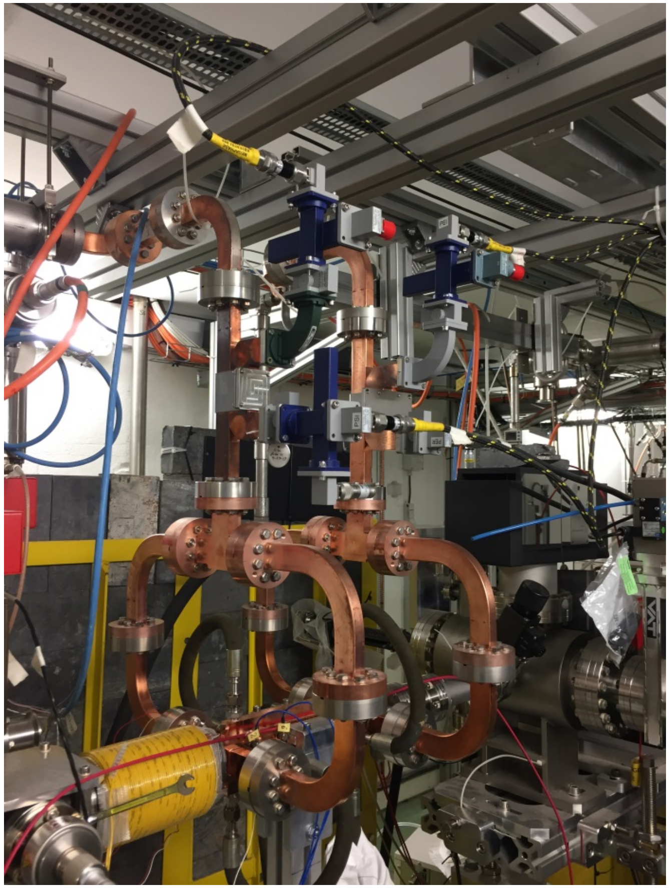
- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only
- Final goal compact 5 GeV accelerator

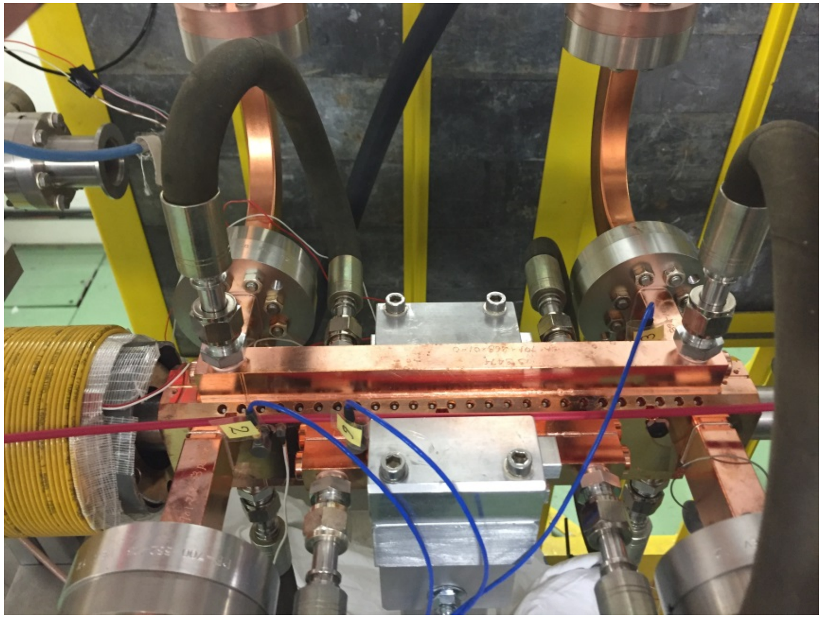
SPARC_LAB HB photo- injector

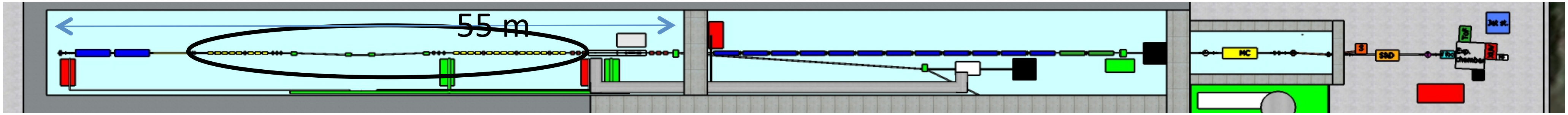


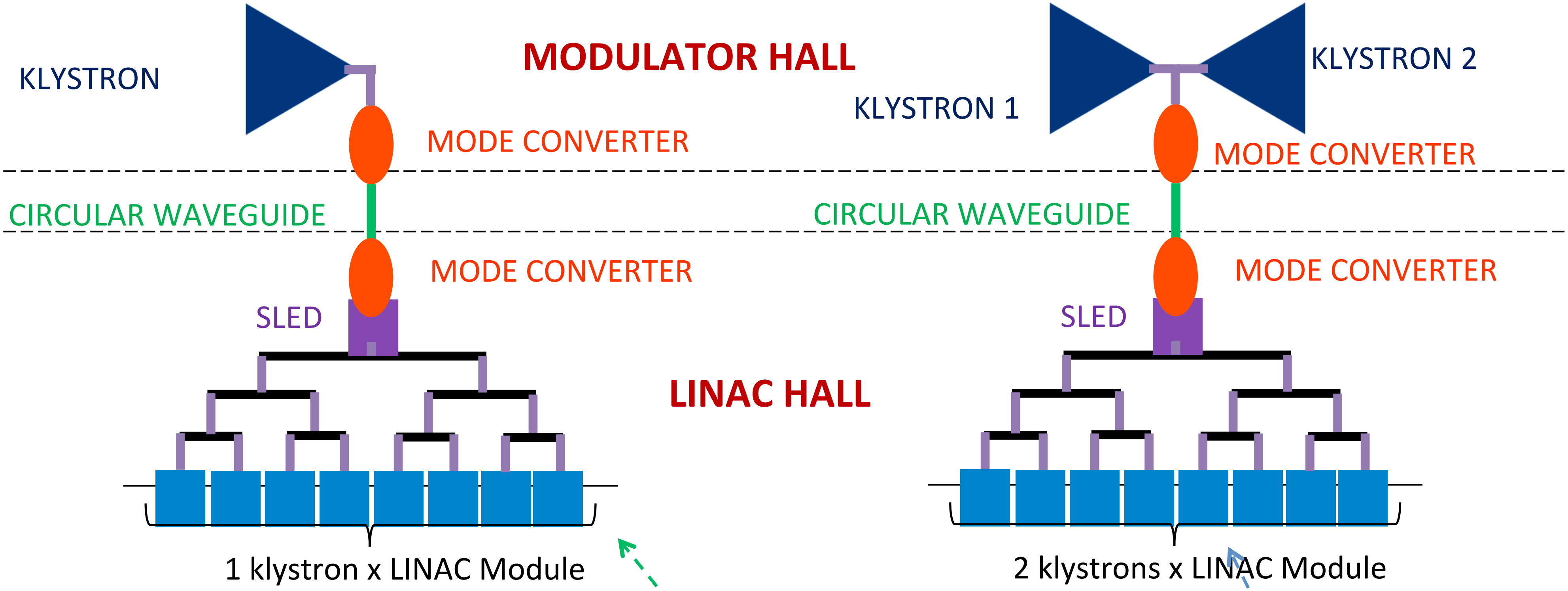


X-band Linac



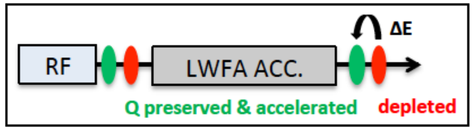


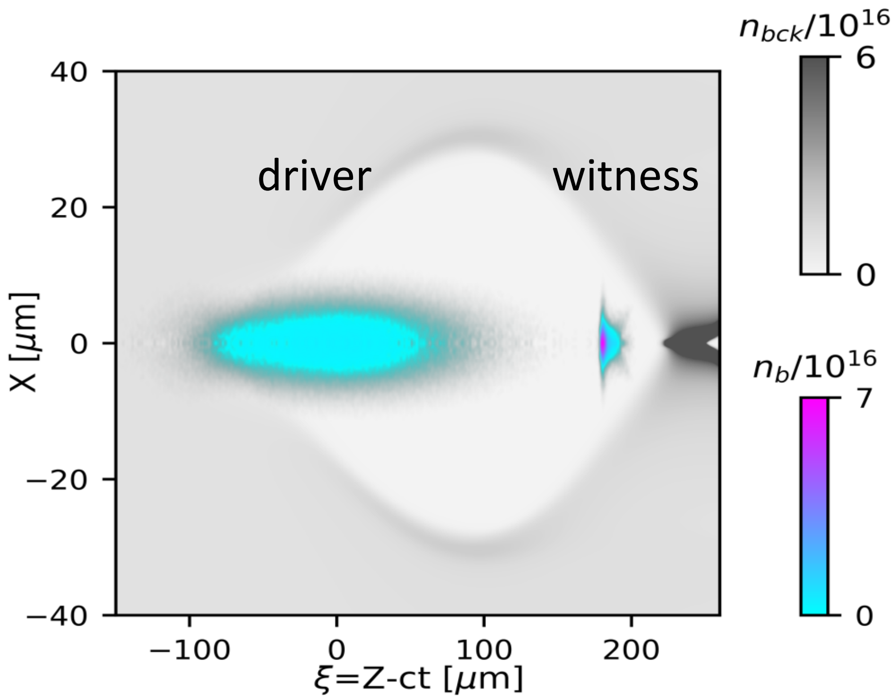


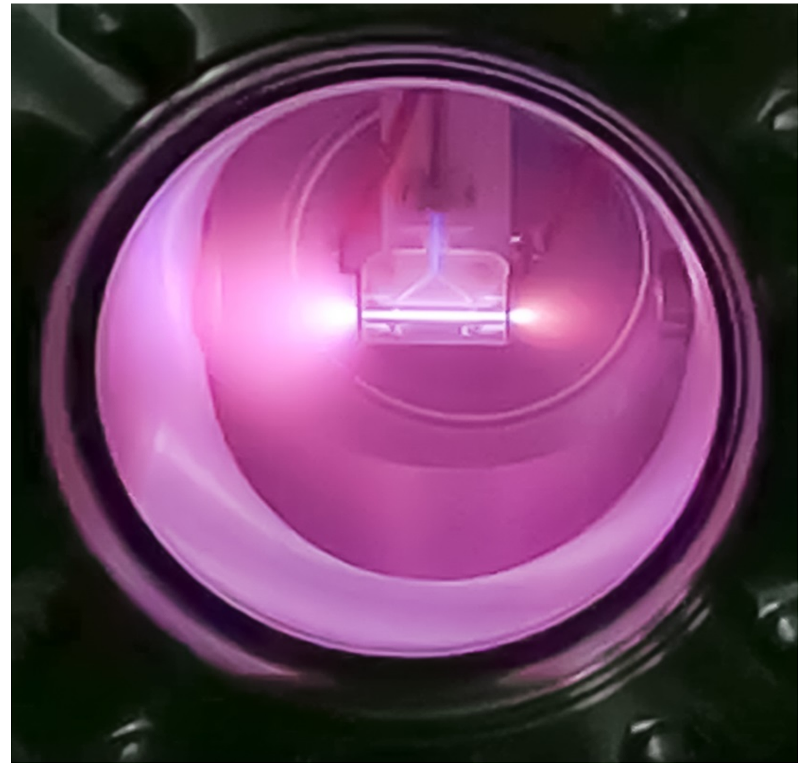


X-Band LINAC parameters			
total active length L_t	16 m		
Number of sections N_s	32 (4 modules x 8 sections)		
available RF power	50 MW (@klystron output coupler) 40 MW (@ section input couplers)		
	Injection in the plasma	Injection in the undulator	Ultimate
linac energy gain ΔW_{linac}	480 MeV	910 MeV	1280 MeV
average acc gradient $<E_{acc}>$	30 MV/m	57 MV/m	80 MV/m
total required RF power P_{RF}	44 MW	158 MW	310 MW

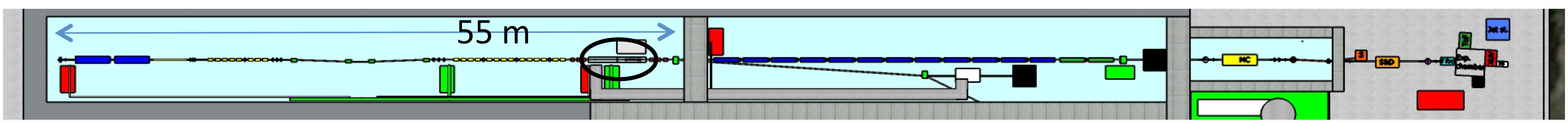
Plasma WakeField Acceleration – External Injection



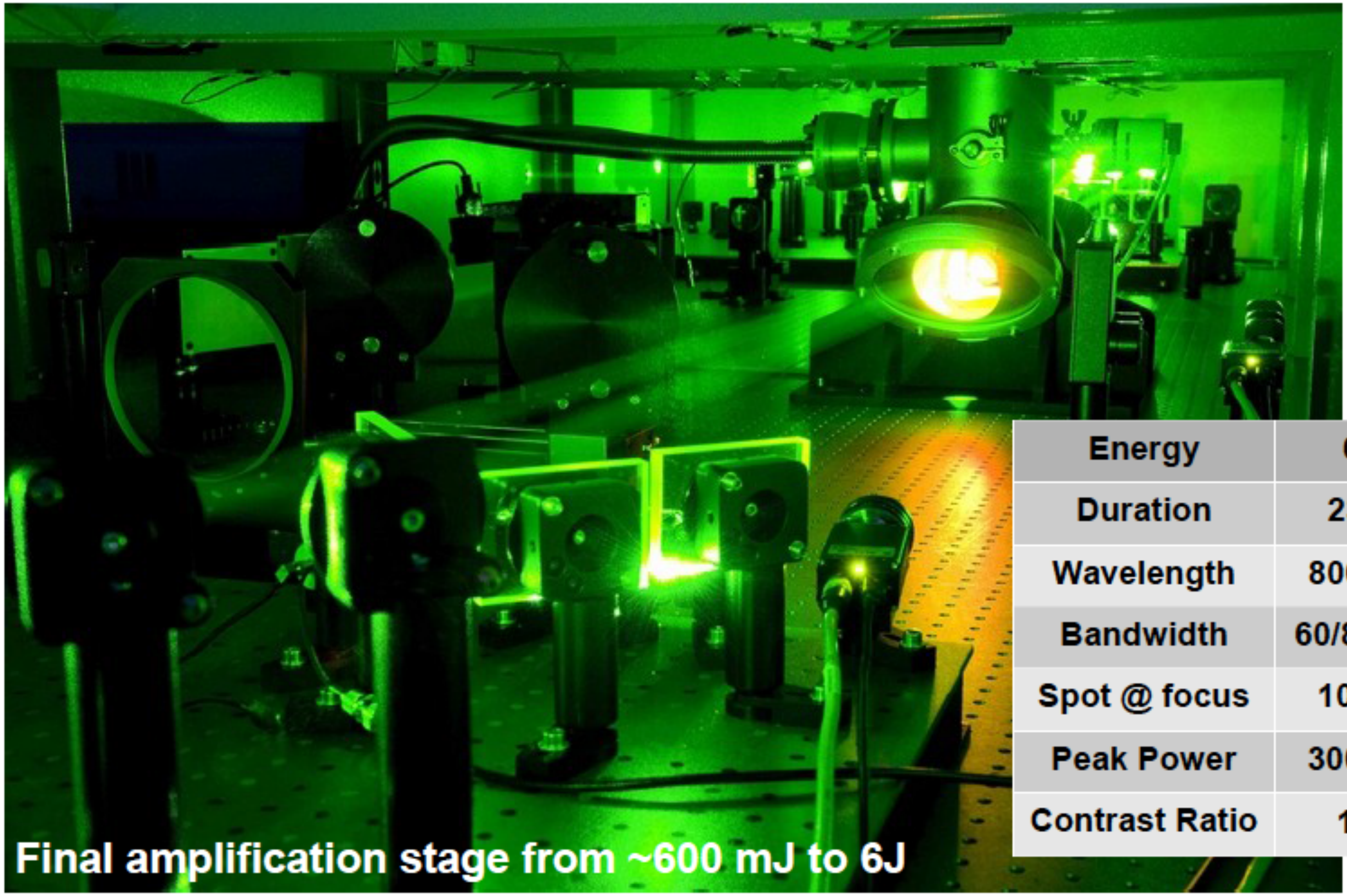




Capillary discharge at SPARC_LAB

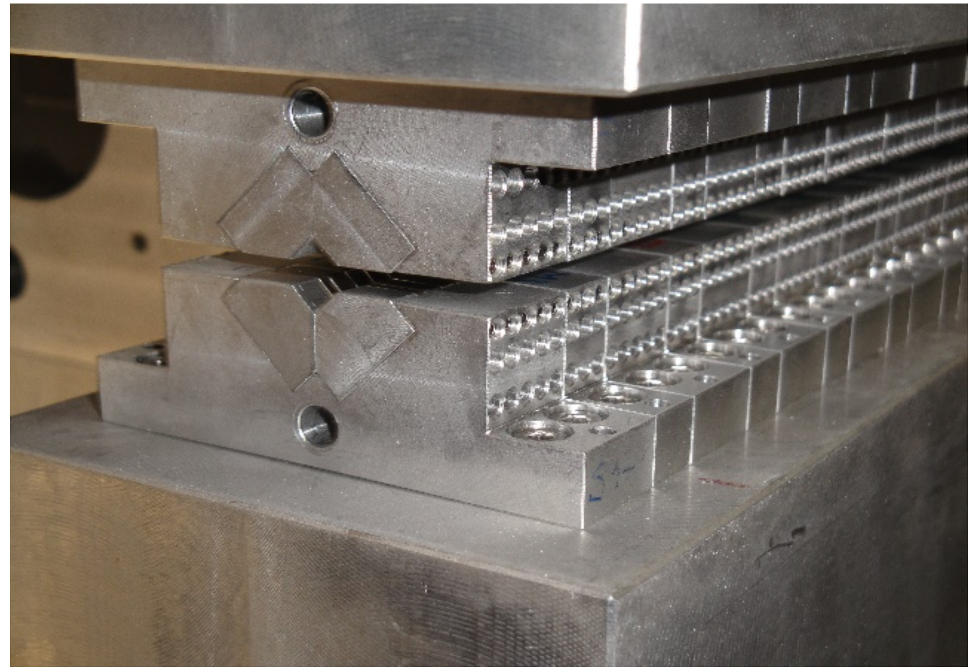


Ti:Sa FLAME laser

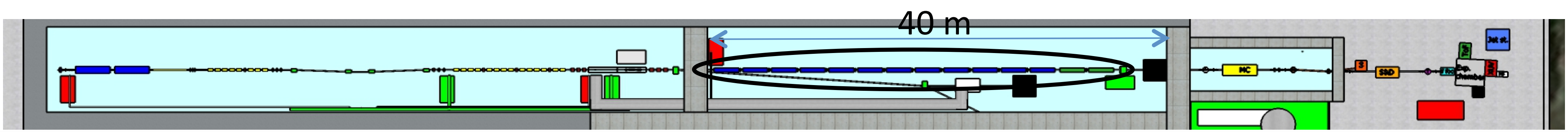


Energy	6 J
Duration	23 fs
Wavelength	800 nm
Bandwidth	60/80 nm
Spot @ focus	10 µm
Peak Power	300 TW
Contrast Ratio	10^{10}

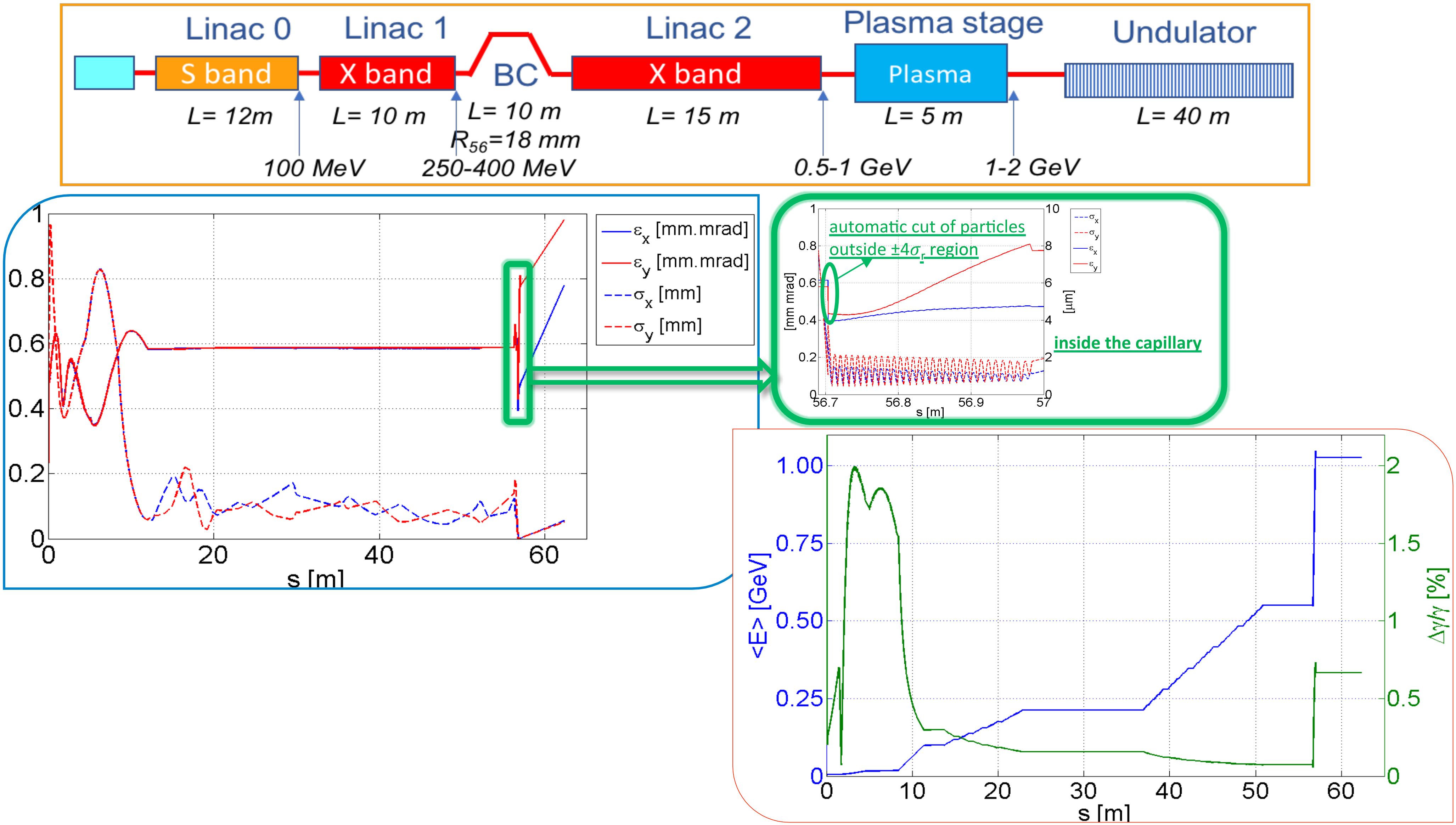
Undulators

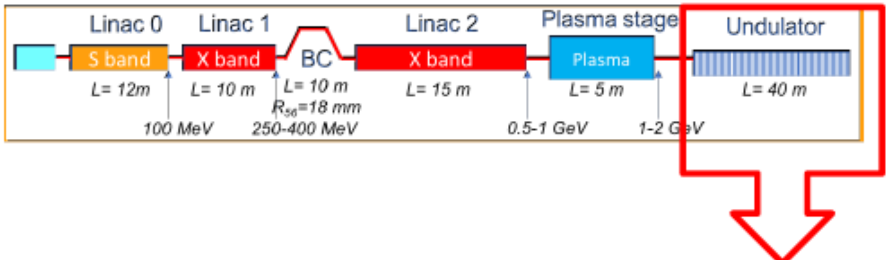


KYMA Δ udulator at SPARC_LAB: λ=1.4 cm, K1



30 pC beam Start To End Simulations

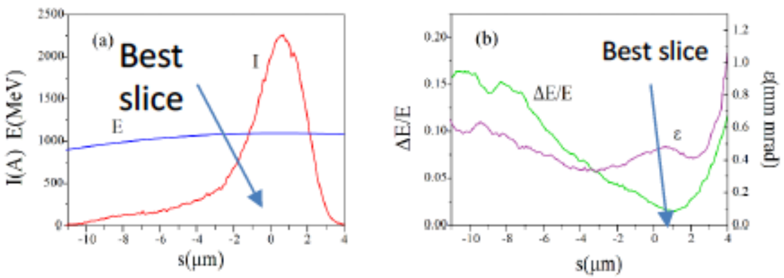




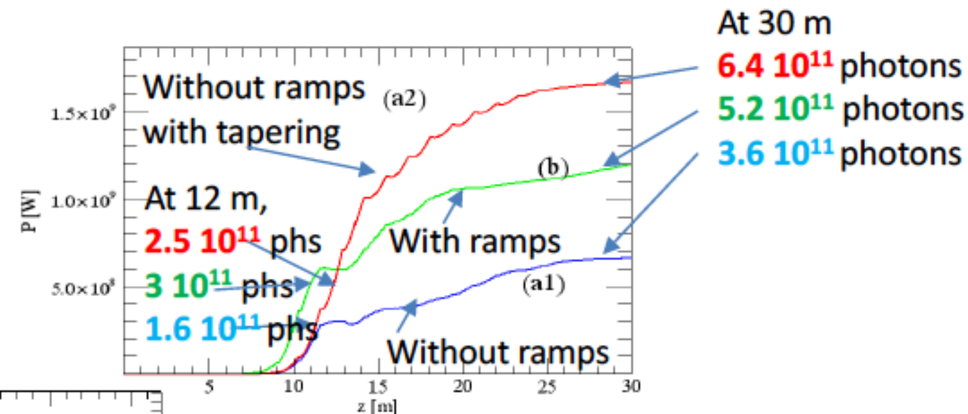
In the undulator

Undulator λ_u=1.5 cm, a_w=0.8

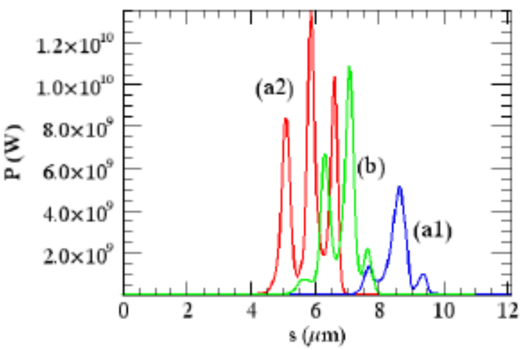
Radiation: λ=2.7 nm
E_{phot}=0.45 keV



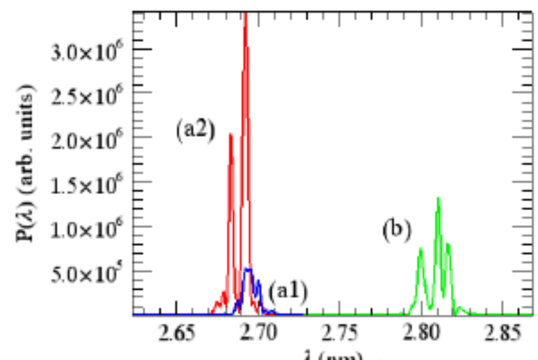
Characteristics of the electron beam, case a1



Growth of the radiation along the undulator



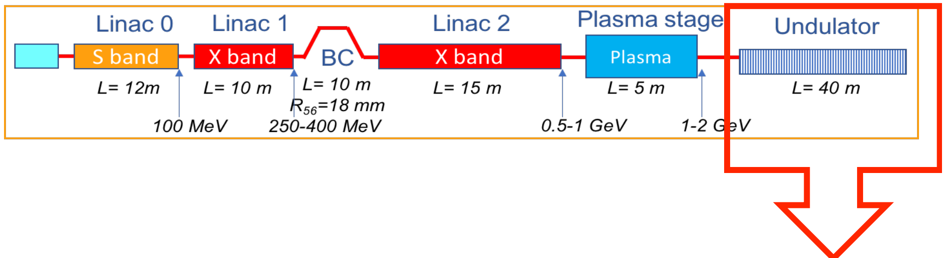
At 15 m, Power density
Quasi-single structure



At 15 m, Spectral density
Quasi-single spike structure

	(a)
Q(pC)	30
ε_x (mmmrad)	0.45
ε_y (mmmrad)	0.49
ΔE/E (10^{-4})	1.54
I_{peak}(A)	2258
z_1(m)	12
E(z_1) (µJ)	12
N_{phot}(z_1) (10^{11})	1.62
z_2(m)	30
E(z_2) (µJ)	27.
N_{phot}(z_1)(10^{11})	3.63
Bandwidth(%)	0.15
Divergence(µrad)	50
Rad. Size (µm)	155

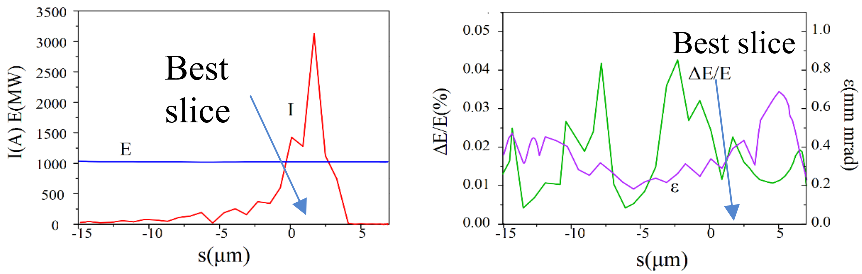
Courtesy of V. Petrillo



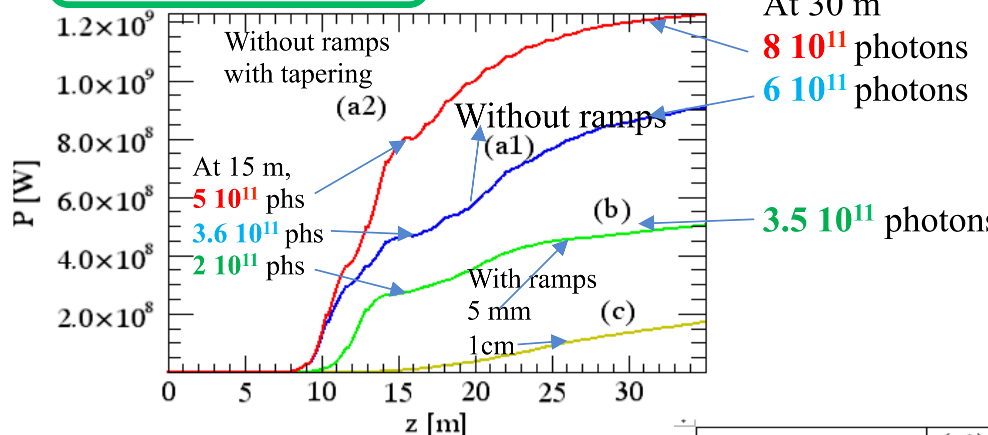
In the undulator

Undulator λ_u=1.5 cm, a_w=0.7

Radiation: λ=2.78 nm E_{phot}=0.44 keV

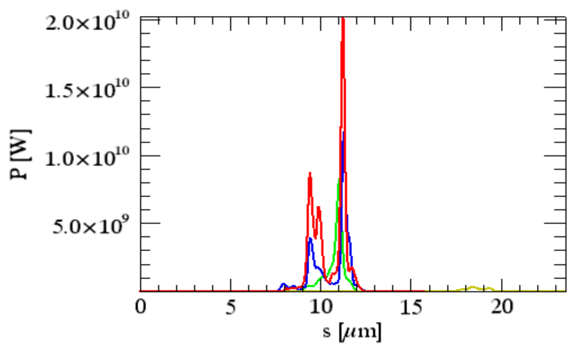


Characteristics of the electron beam

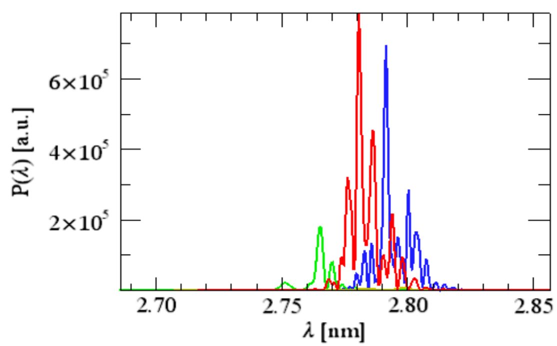


Growth of the radiation along the undulator

	(a1)
Q(pC)	30
ε_x (mmmrad)	0.39
ε_y (mmmrad)	0.309
ΔE/E (10^{-4})	2.49
I_{peak}(A)	3131
z_1(m)	15
E(z_1) (μJ)	25.8
$N_{phot}(z_1)$ (10^{11})	3.61
z_2(m)	30
E(z_2) (μJ)	43.9
$N_{phot}(z_1)$(10^{11})	6.1
Bandwidth(%)	0.15
Divergence(μrad)	40
Rad. Size (μm)	195



At 15 m, Power density
Quasi-single structure



At 15 m, Spectral density
Quasi-single spike structure

FEL driven by PLASMA

	Units	1 GeV PWFA with Undulator Tapering	1 GeV LWFA with Undulator Tapering
Bunch charge	pC	29	26.5
Bunch length rms	fs	11.5	8.4
Peak current	kA	2.6	3.15
Rep. rate	Hz	10	10
Rms Energy Spread	%	0.73	0.81
Slice Energy Spread	%	0.022	0.015
Average Rms norm. emittance	μm	0.6	0.47
Slice norm. emittance	μm	0.39-0.309	0.47
Slice Length	μm	1.39	1.34
Radiation wavelength	nm	2.79	2.7
ρ	x 10^{-3}	2	2
Undulator period	cm	1.5	1.5
K		0.987	1.13
Undulator length	m	30	30
Saturation power	GW	0.850-1.2	1.3
Energy	μJ	63	63.5
Photons/pulse		8.8 x 10^{11}	8.6 x 10^{11}
Bandwidth	%	0.35	0.42
Divergence	μrad	49	56
Rad. size	μm	210	160
Brilliance per shot	(s mm^2 mrad^{2}bw (‰))$^{-1}$	0.83 x 10^{27}	1.22 x10^{27}

FEL simulation with **linac accelerated electron beams, high flux case**

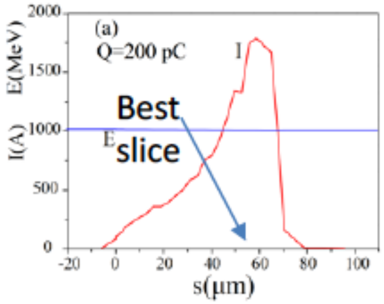
Case with 200 pC

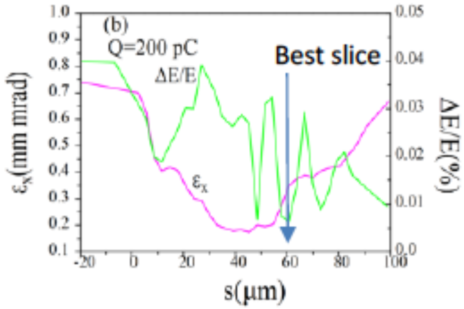
Undulator λ_u=1.5 cm, a_w=0.7

Radiation: λ=2.87 nm E_{phot}=0.43 keV

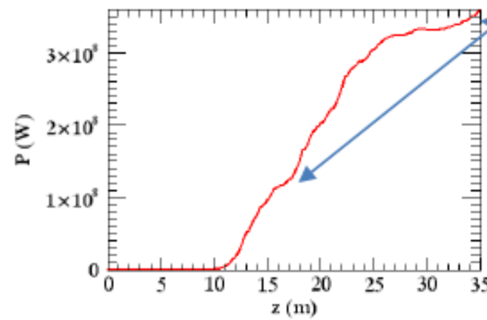
First saturation at 15 m with **9.1 10^{11}** photons

At 35 m, **2.7 10^{12}** photons

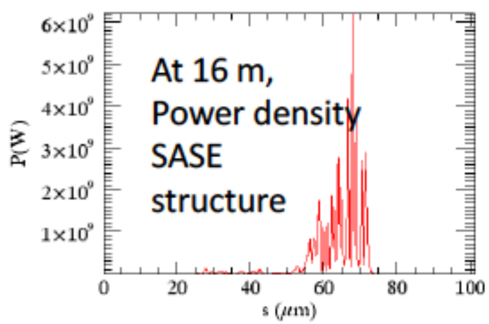


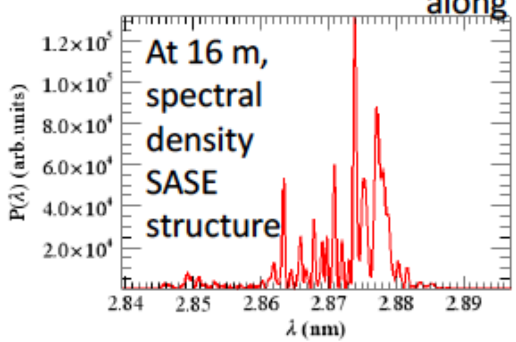


Characteristics of the electron beam



Growth of the radiation along the undulator



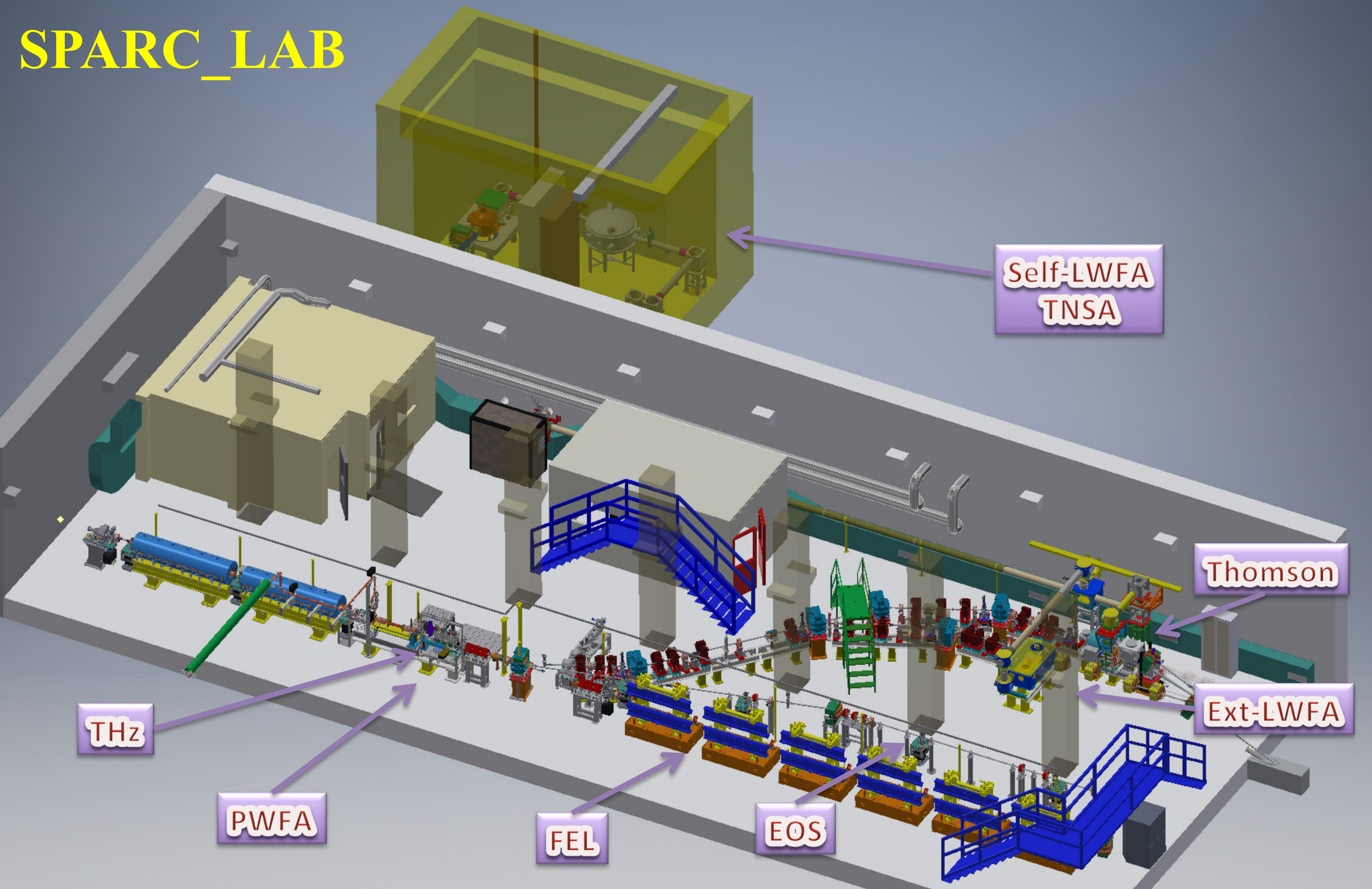


Courtesy of V. Petrillo

FEL driven by X-band linac only

	Units	1 GeV with X-band linac only 100 pC	1 GeV with X-band linac only 200 pC
Bunch charge	pC	100	200
Bunch length rms	fs	38.2	55.6
Peak current	kA	2.	1.788
Rep. rate	Hz	10	10
Rms Energy Spread	%	0.1	0.05
Slice Energy Spread	%	0.018	0.02
Average Rms norm. emittance	μm	0.5	0.5
Slice norm. emittance	μm	0.35-0.24	0.4-0.37
Slice Length	μm	1.25	1.66
Radiation wavelength	nm	2.4 (0.52 keV)	2.87(0.42 keV)
ρ	$x\ 10^{-3}$	1.9(1.7)	1.55(1.38)
Undulator period	cm	1.5	1.5
K		0.987	0.987
Saturation length	m	15-25	16-30
Saturation power	GW	0.361-0.510	0.120-0.330
Energy	μJ	48-70	64-177
Photons/pulse		$5.9\text{-}8.4\ x\ 10^{11}$	$9.3\text{-}25.5\ x\ 10^{11}$
Bandwidth	%	0.13-2.8	0.24-0.46
Divergence	μrad	17.5-16	28-27
Rad. size	μm	65-75	120-200

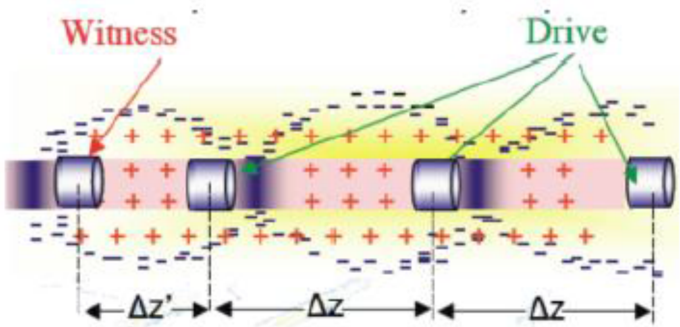
SPARC_LAB



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

Plasma-based acceleration techniques

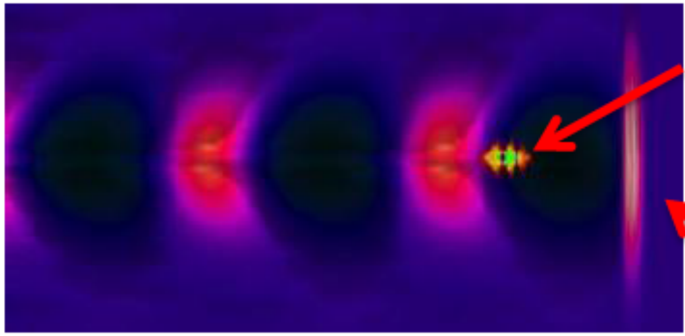
resonant-PWFA



•A train of three electron bunches (driver bunches) is sent through a capillary discharge
•A resonant plasma wave is then excited in plasma
•A fourth electron beam (witness beam) uses this wave to be accelerated

$n_e = 2\mathrm{x}10^{16}\ \mathrm{cm}^{-3}$
$\lambda_p = 300\mu\mathrm{m}$
Capillary 1mm
Hydrogen

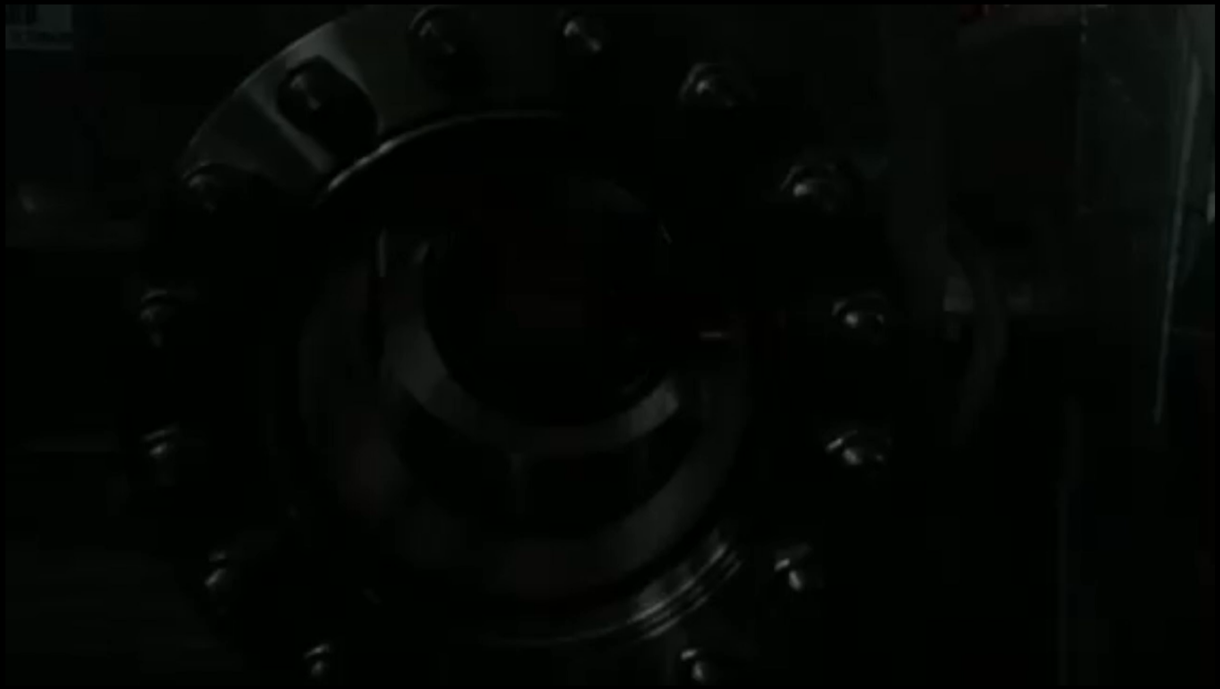
external injection LWFA

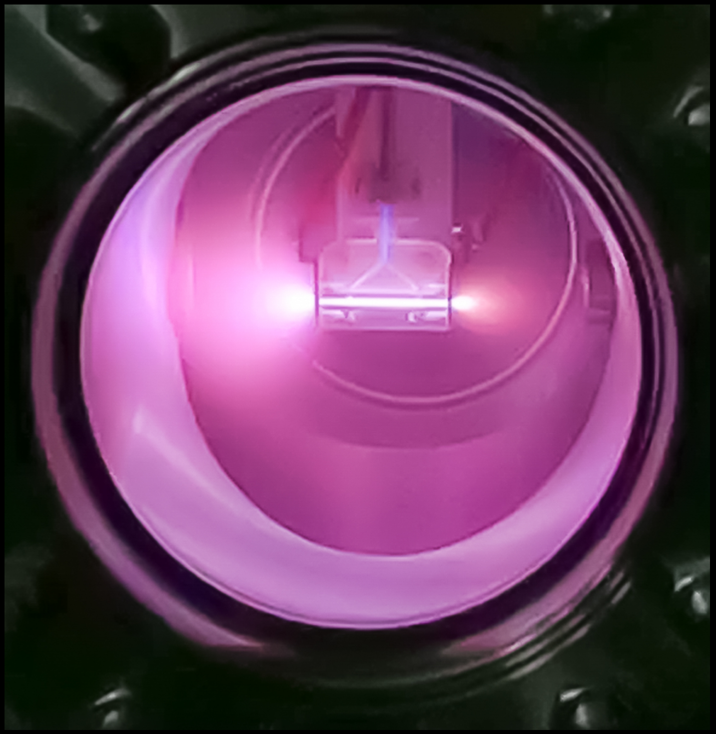


•A laser beam excites plasma waves in a capillary filled with gas
•A high brightness electron beam uses this wave to be accelerated

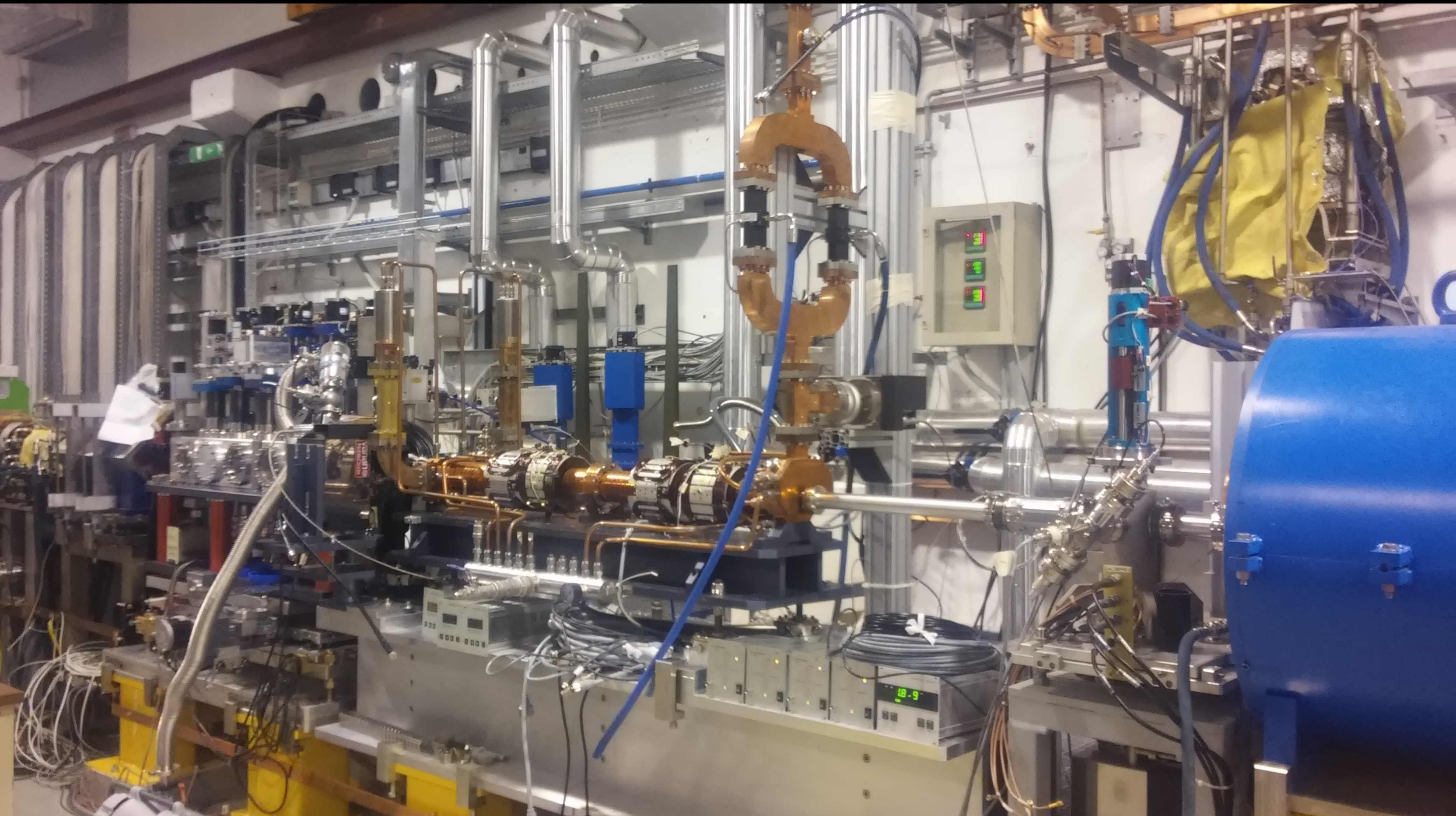
$n_e = 1\mathrm{x}10^{17}\ \mathrm{cm}^{-3}$
$\lambda_p = 100\mu\mathrm{m}$
Capillary 100 µm
Hydrogen

Capillary Discharge at SPARC_LAB

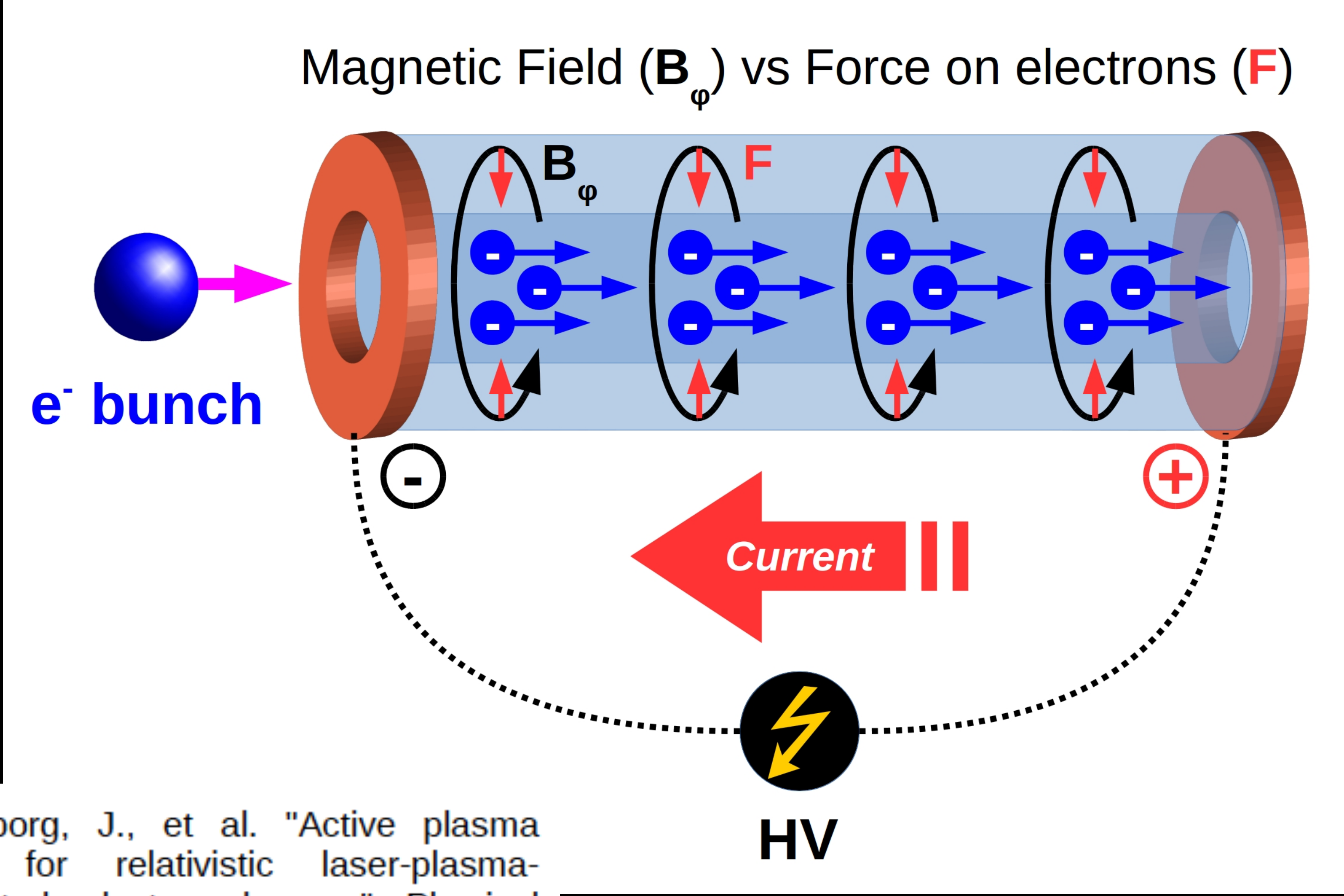




PWFA vacuum chamber at SPARC_LAB

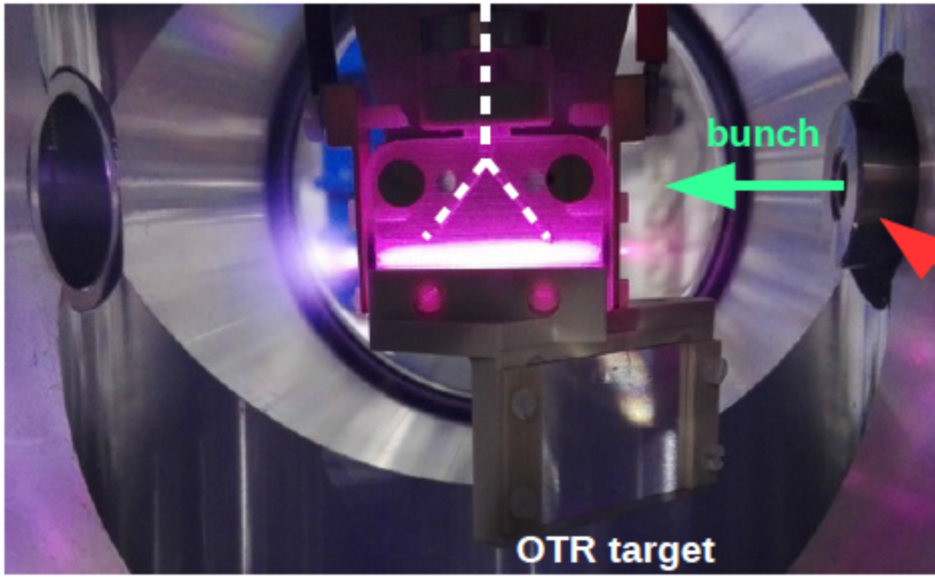


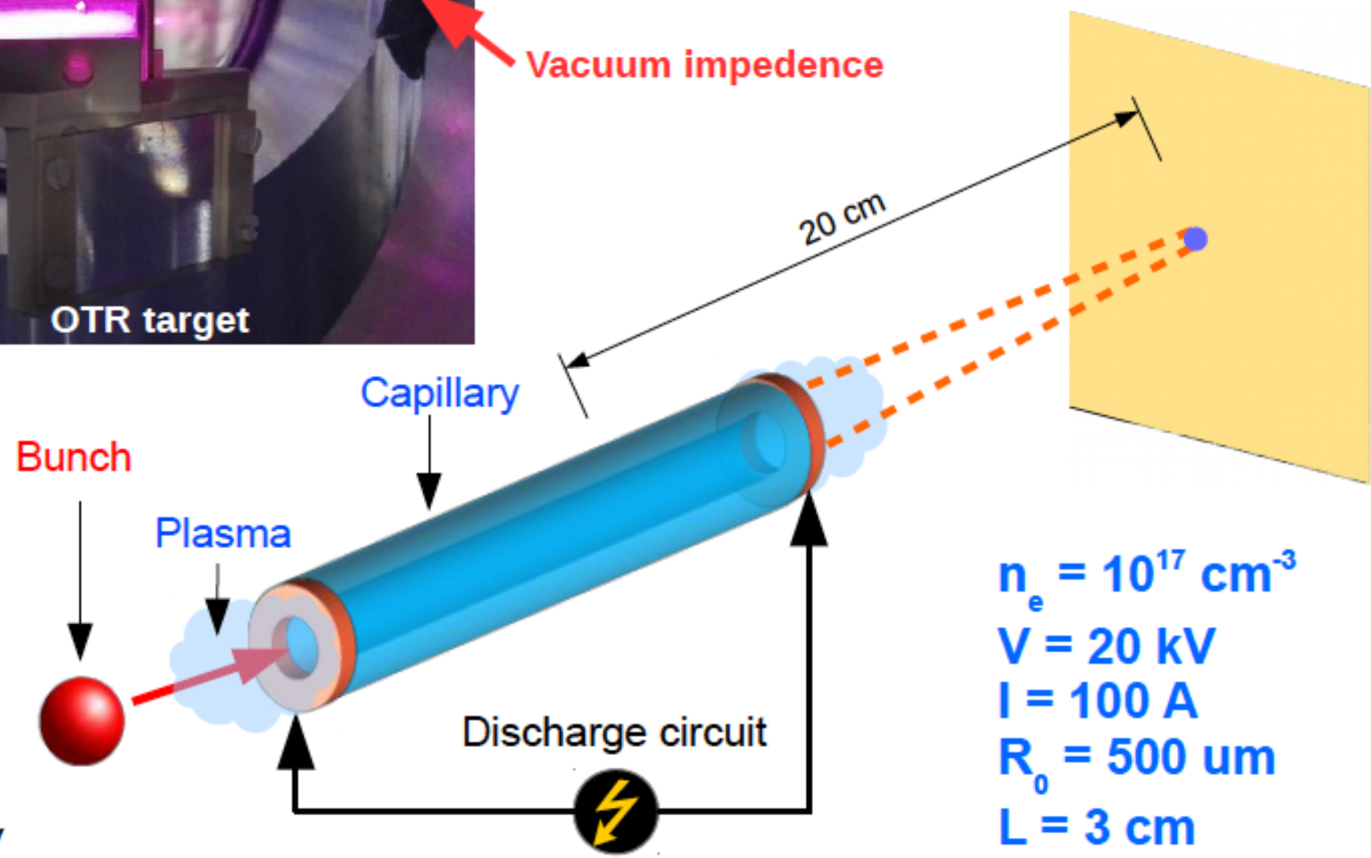
Active Plasma Lens



Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters 115.18 (2015): 184802.

Experimental layout

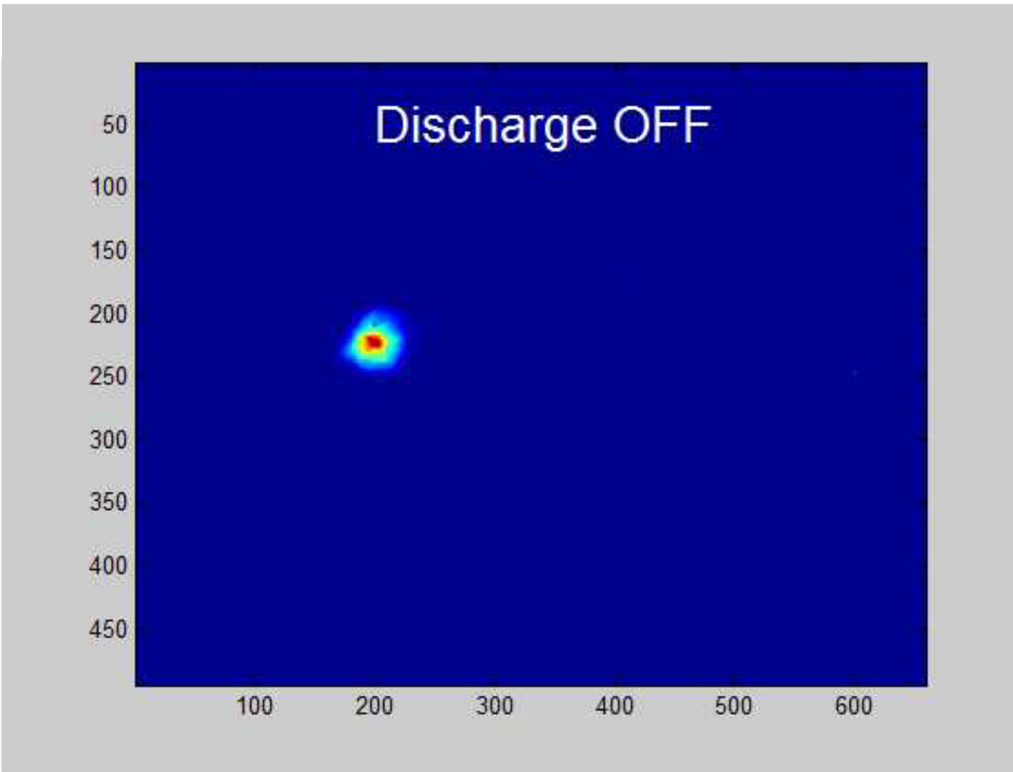


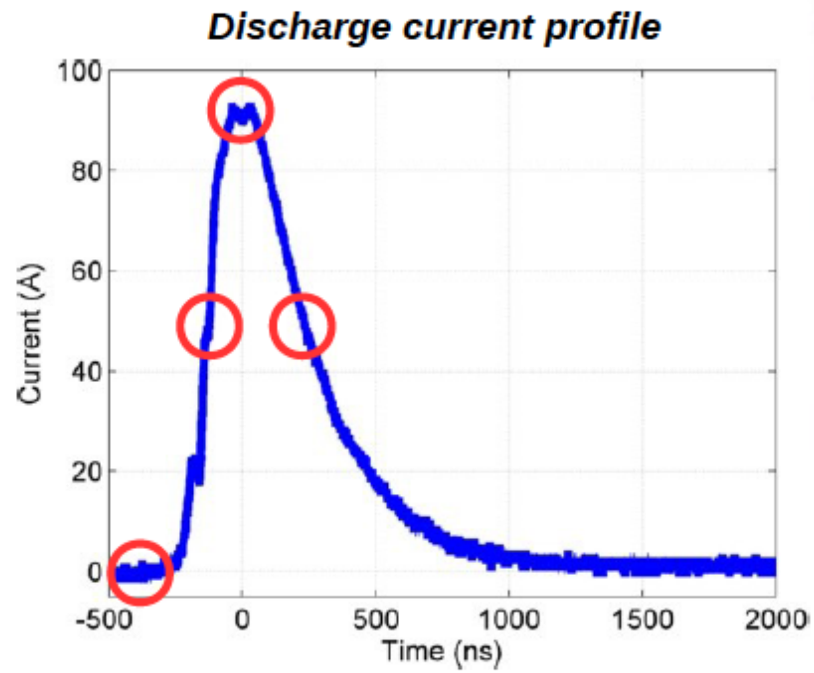


50 pC
1 ps
130 um
120 MeV
1 mm mrad

n_e = 10^{17} cm^{-3}
V = 20 kV
I = 100 A
R_0 = 500 um
L = 3 cm
Sapphire

Preliminary results

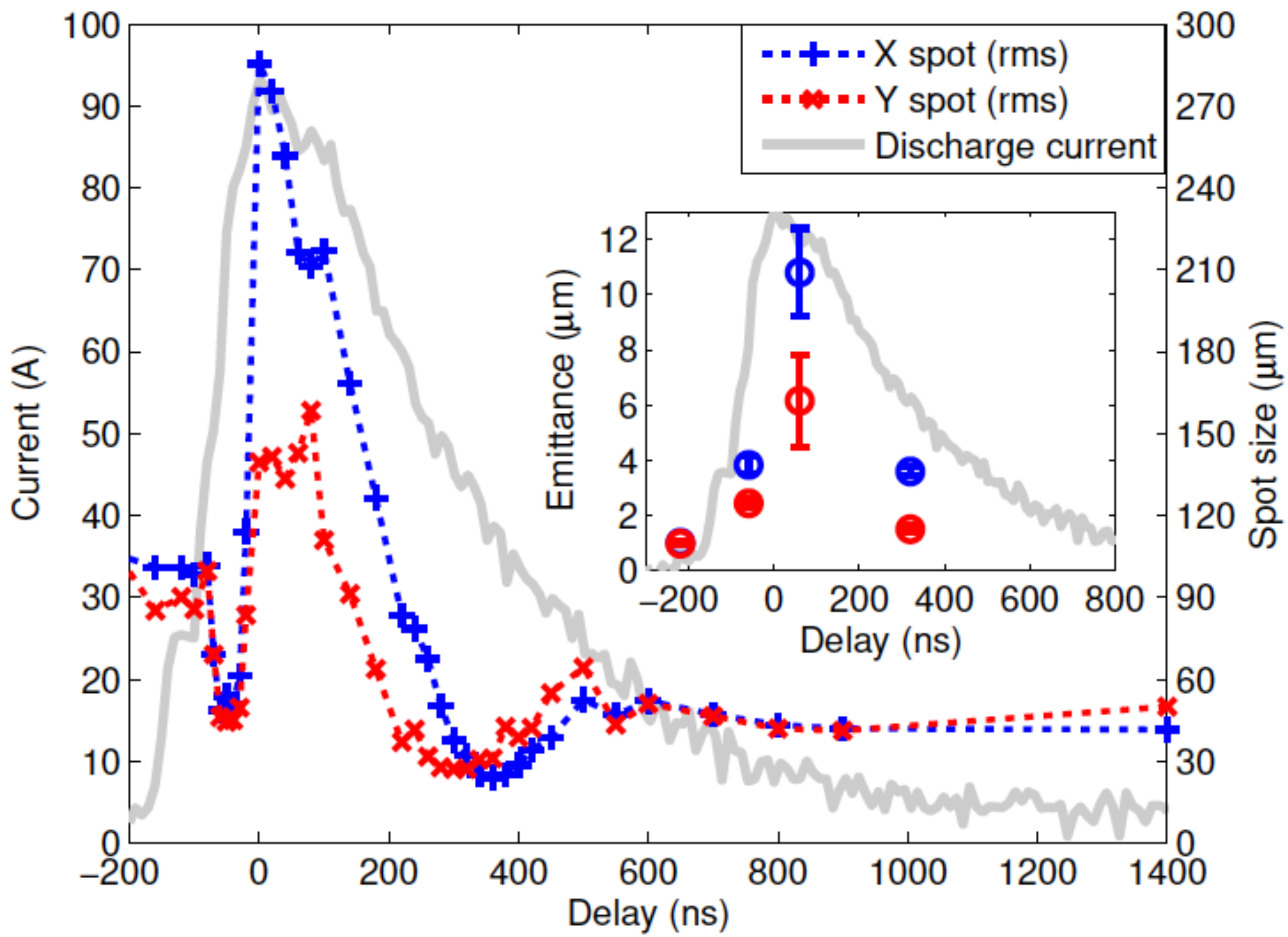




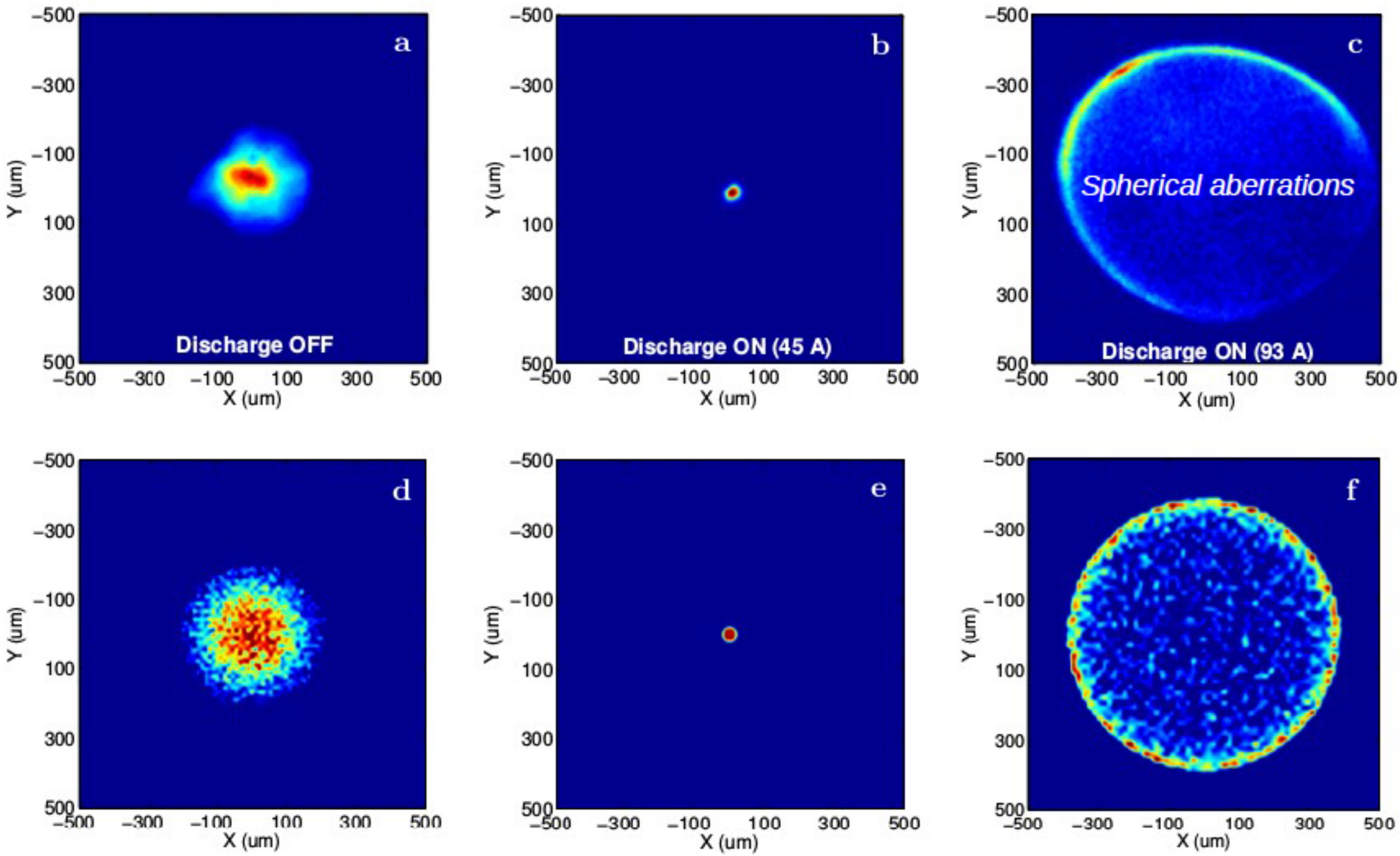
APPLIED PHYSICS LETTERS **110**, 104101 (2017)

Experimental characterization of active plasma lensing for electron beams

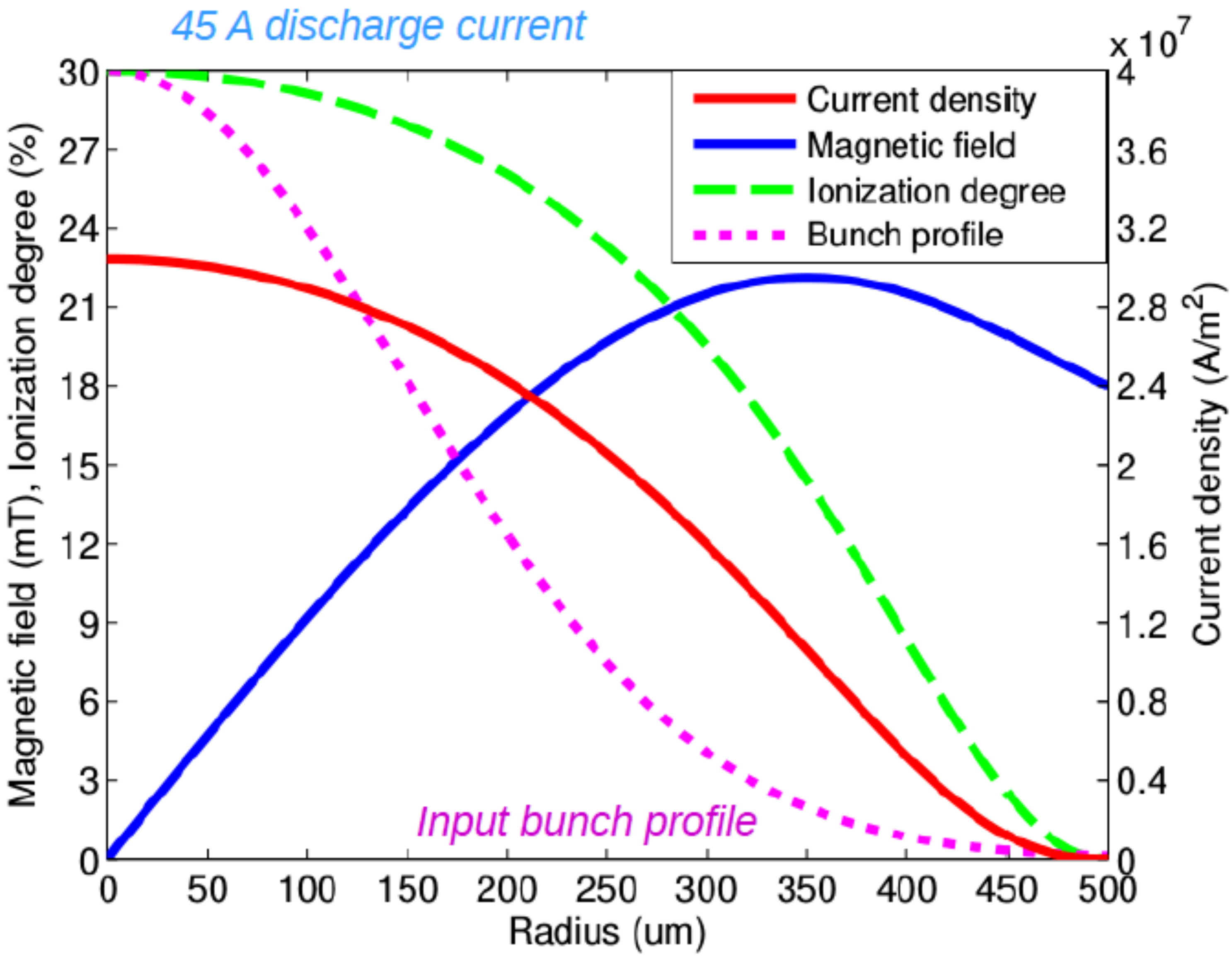
R. Pompili,[1,a)] M. P. Anania,[1] M. Bellaveglia,[1] A. Biagioni,[1] S. Bini,[1] F. Bisesto,[1] E. Brentegani,[1] G. Castorina,[1,2] E. Chiadroni,[1] A. Cianchi,[3] M. Croia,[1] D. Di Giovenale,[1] M. Ferrario,[1] F. Filippi,[1] A. Giribono,[4] V. Lollo,[1] A. Marocchino,[1] M. Marongiu,[4] A. Mostacci,[4] G. Di Pirro,[1] S. Romeo,[1] A. R. Rossi,[5] J. Scifo,[1] V. Shpakov,[1] C. Vaccarezza,[1] F. Villa,[1] and A. Zigler[6]



Results vs simulations



Nonlinear focusing field



Effects of plasma ramps

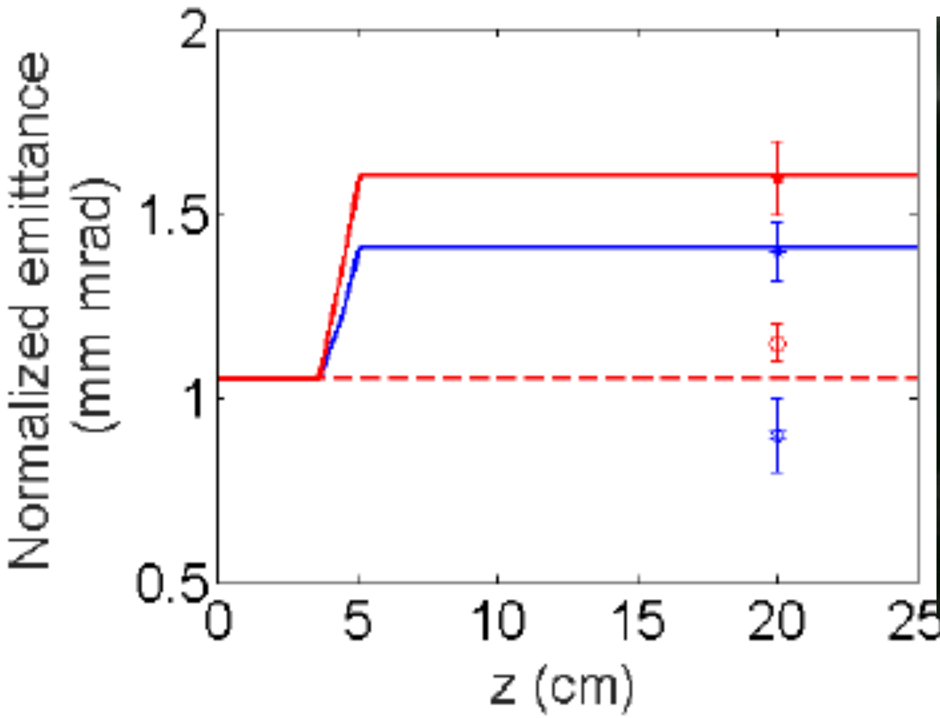
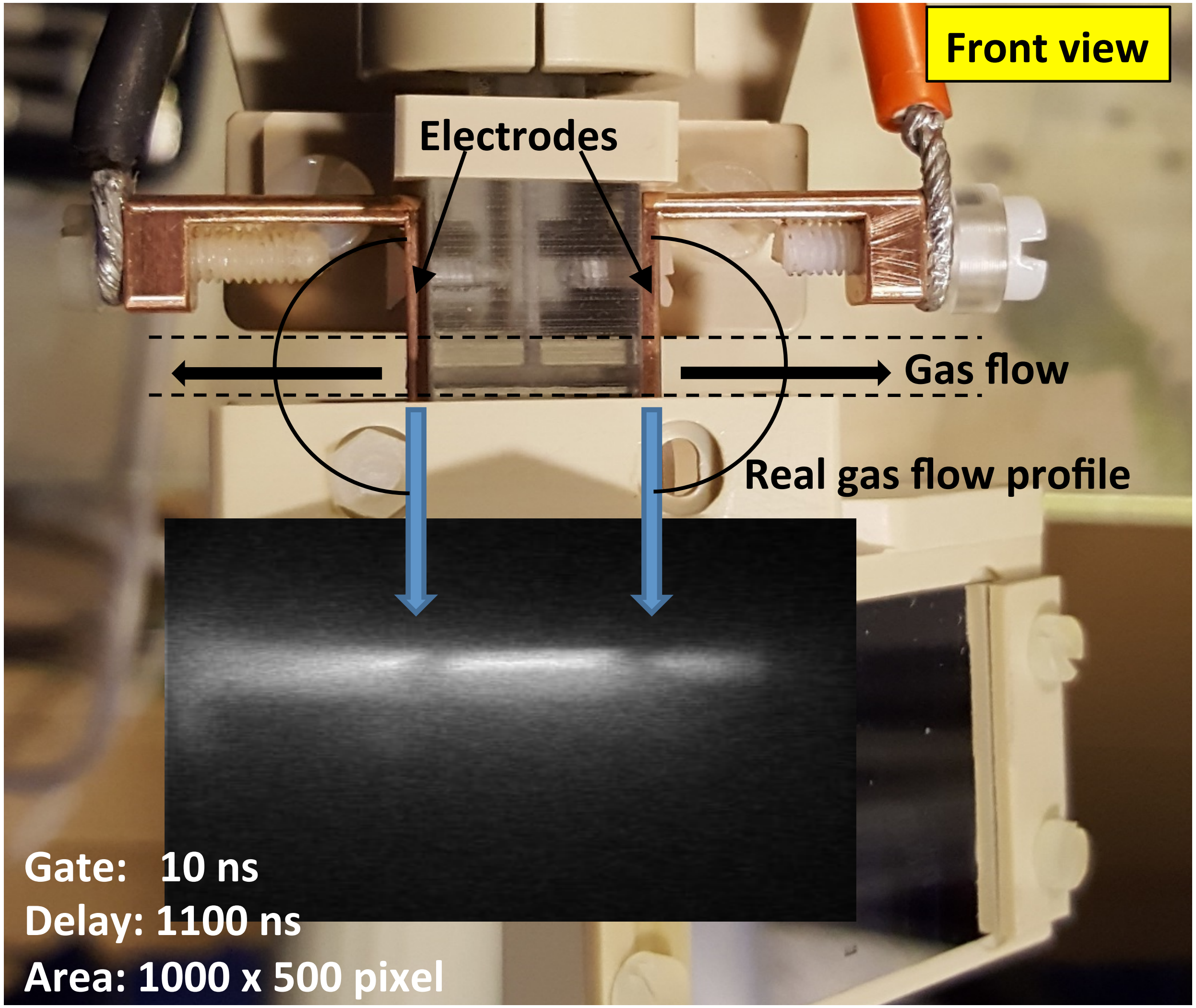
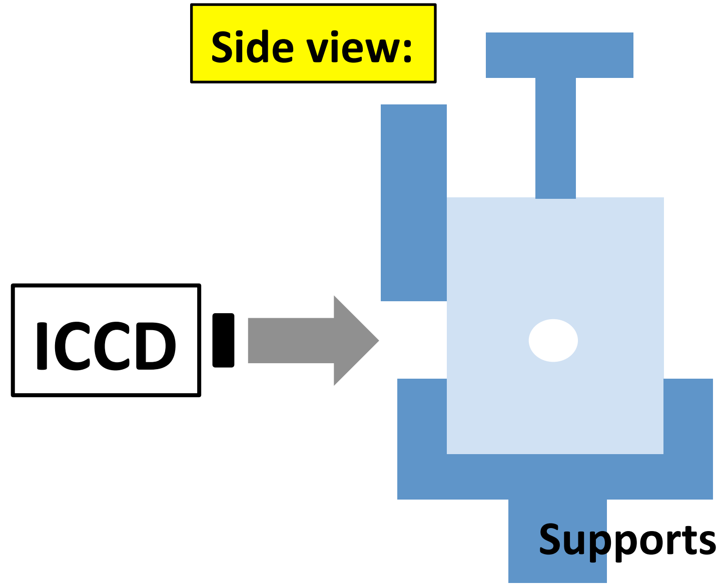


Figure 5: Normalized transverse emittance as function of z. The numerically computed emittance is plotted with solid lines, and the experimental values are overlapped with stars (ε_{nx}) and circles (ε_{ny}).

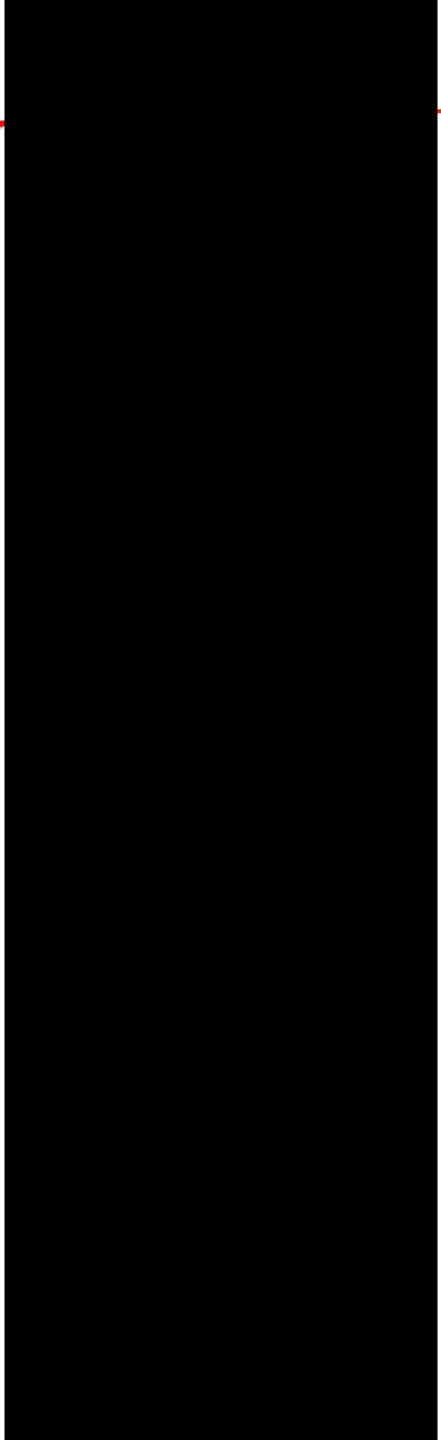
velocity of plasma

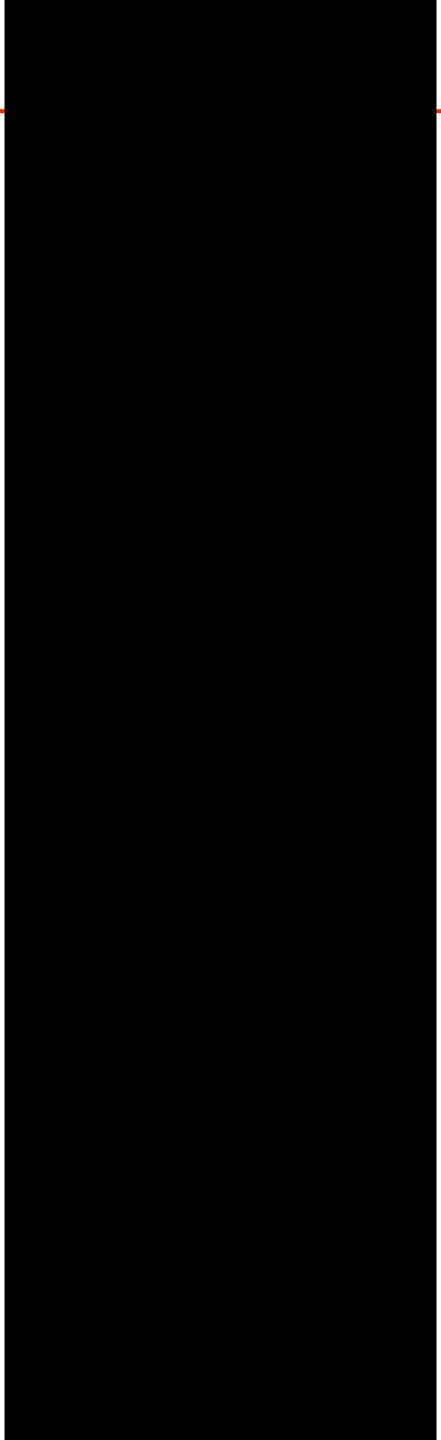


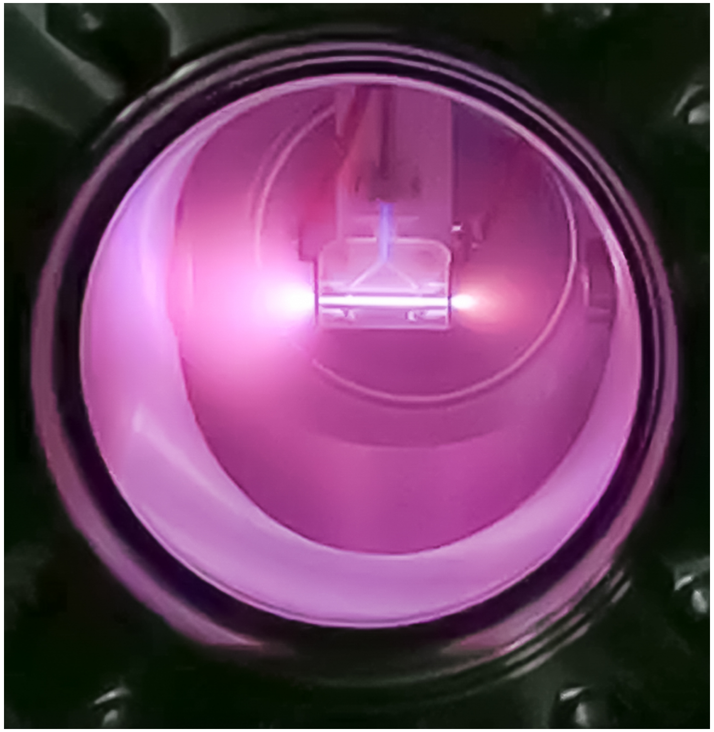


In order to see the real expansion of the plasma we have to mount the capillary of 3 cm length so that we will not see the cutting due to the supports

velocity of plasma





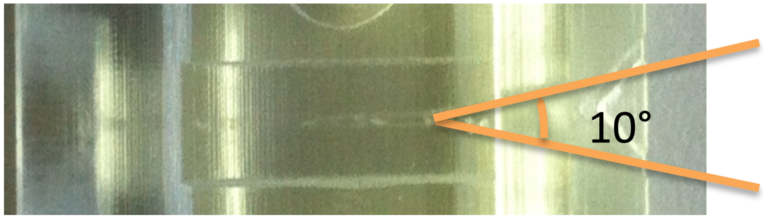


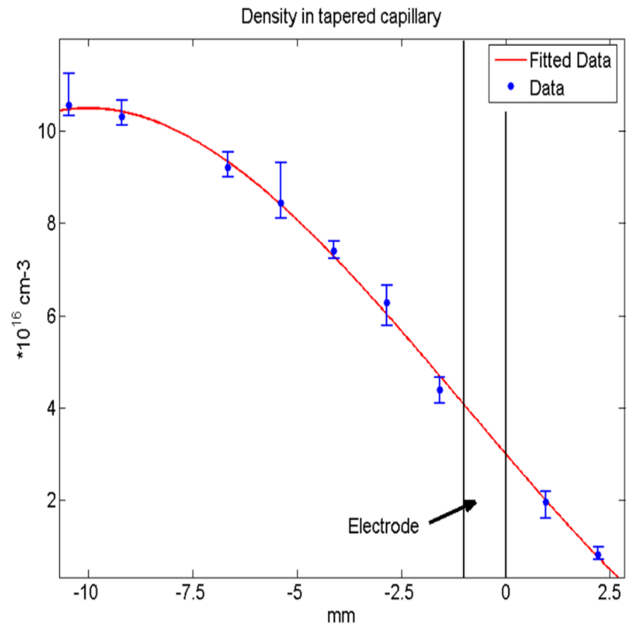
20 images separated by 100 ns => 2 μs
Gate: 10 ns
Area: 1000 x 500 pixel

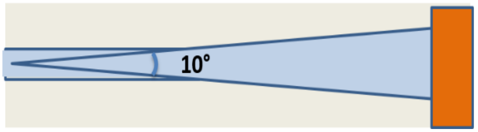
Tapered capillaries

Local control of the plasma density is required to match the laser/electron beam into the plasma. Tapering the capillary diameter is the easiest way to change locally the density.

By monotonically varying the radius of the capillary it is possible to change the density.







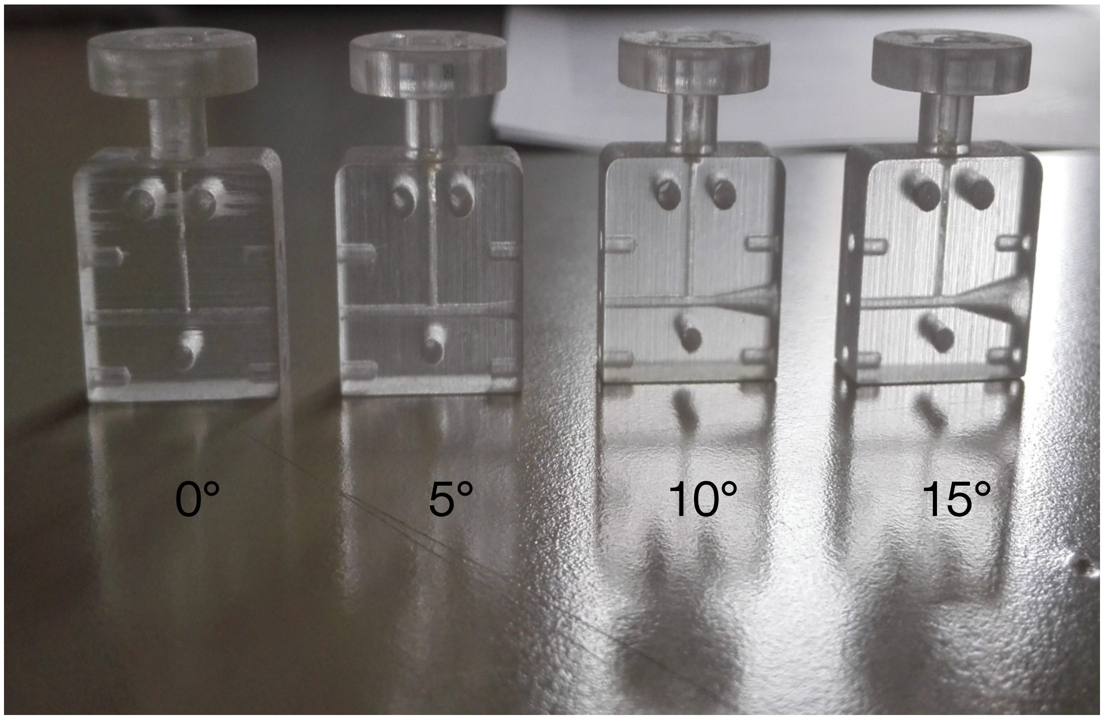
Kaganovich et al., Appl. Phys. Lett. 75, 772–774 (1999).

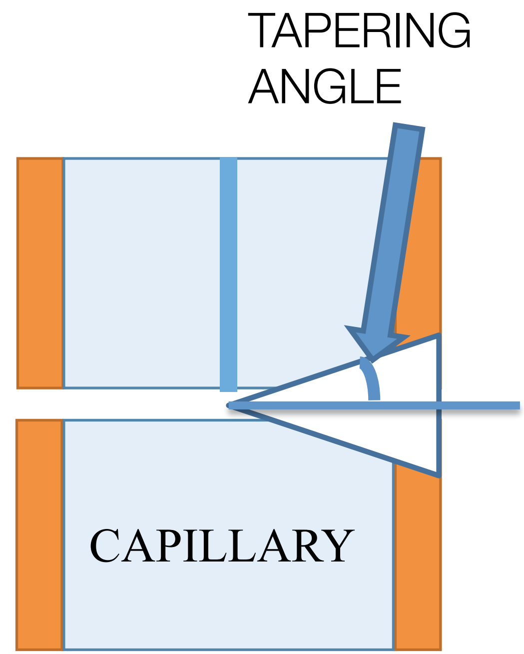
Studies on plasma tapering are currently in progress in the SPARC_LAB Plasma lab.

Tapered capillaries

Local control of the plasma density is required to match the laser/electron beam into the plasma. Tapering the capillary diameter is the easiest way to change locally the density.

TAPERING OF:





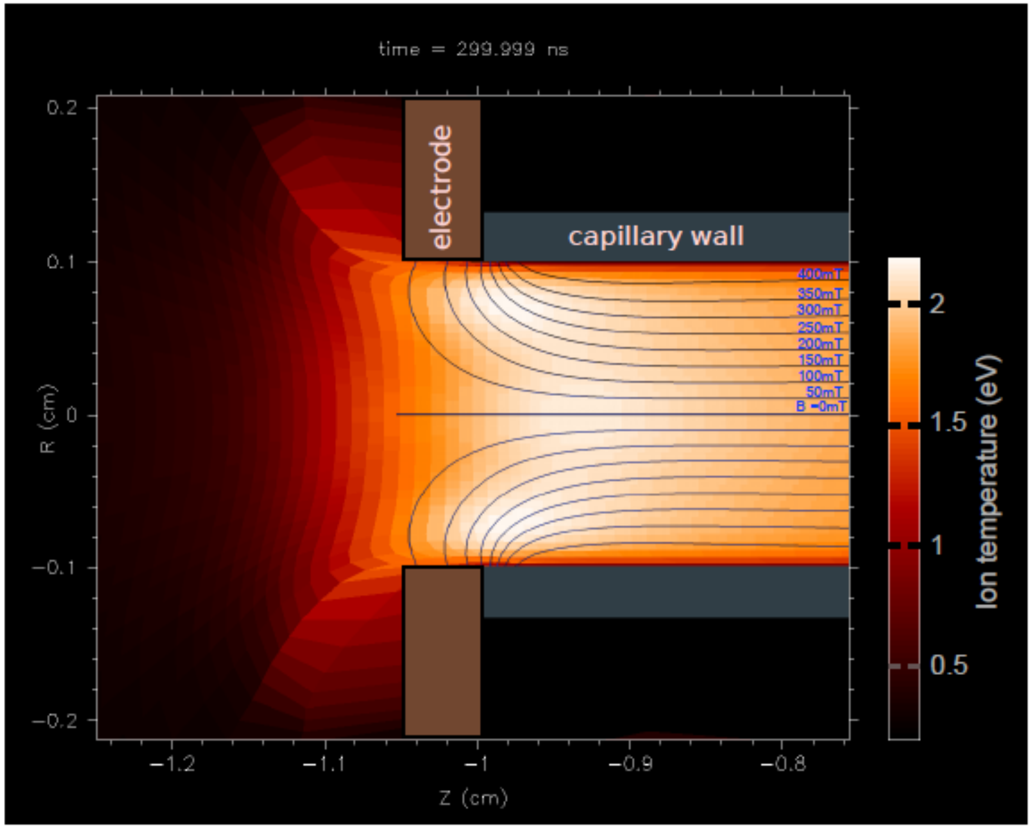


Figure: Particular of the plasma temperature (colored map) and azimuthal magnetic field (contour lines) in proximity of the left electrode at 300ns from the start of the discharge.

- It is possible to compute the magnetic field as post-processing
- Maps of other relevant quantities can be obtained
- The temperature reached by the plasma seems to be in qualitative agreement with what expected

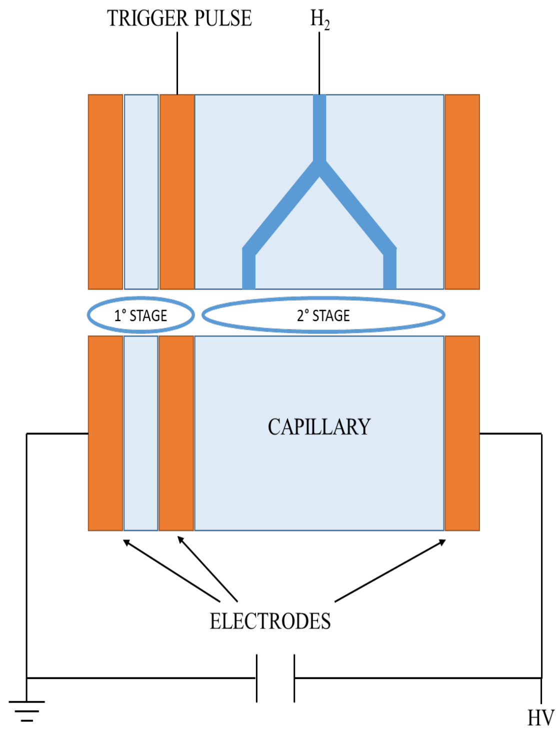
A hydrodynamic approximation can be employed, the current density is computed using the static current flow approximation and the ohmic heating term is added to the energy equation:

$$
\begin{cases}
\boxed{\begin{aligned}
&\frac{\partial}{\partial t}\rho + \nabla\cdot(\rho\vec{v}) = 0\\
&\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla p\\
&\frac{\partial}{\partial t}E + \nabla\cdot(E\vec{v}) = -\nabla\cdot(p\vec{v}) + \nabla\cdot\kappa\nabla T
\end{aligned}} + \eta\|\vec{J}\|^2\\
\nabla\cdot\vec{J} = 0,\ \vec{J} = -\eta\nabla V
\end{cases}
$$

Plasma source

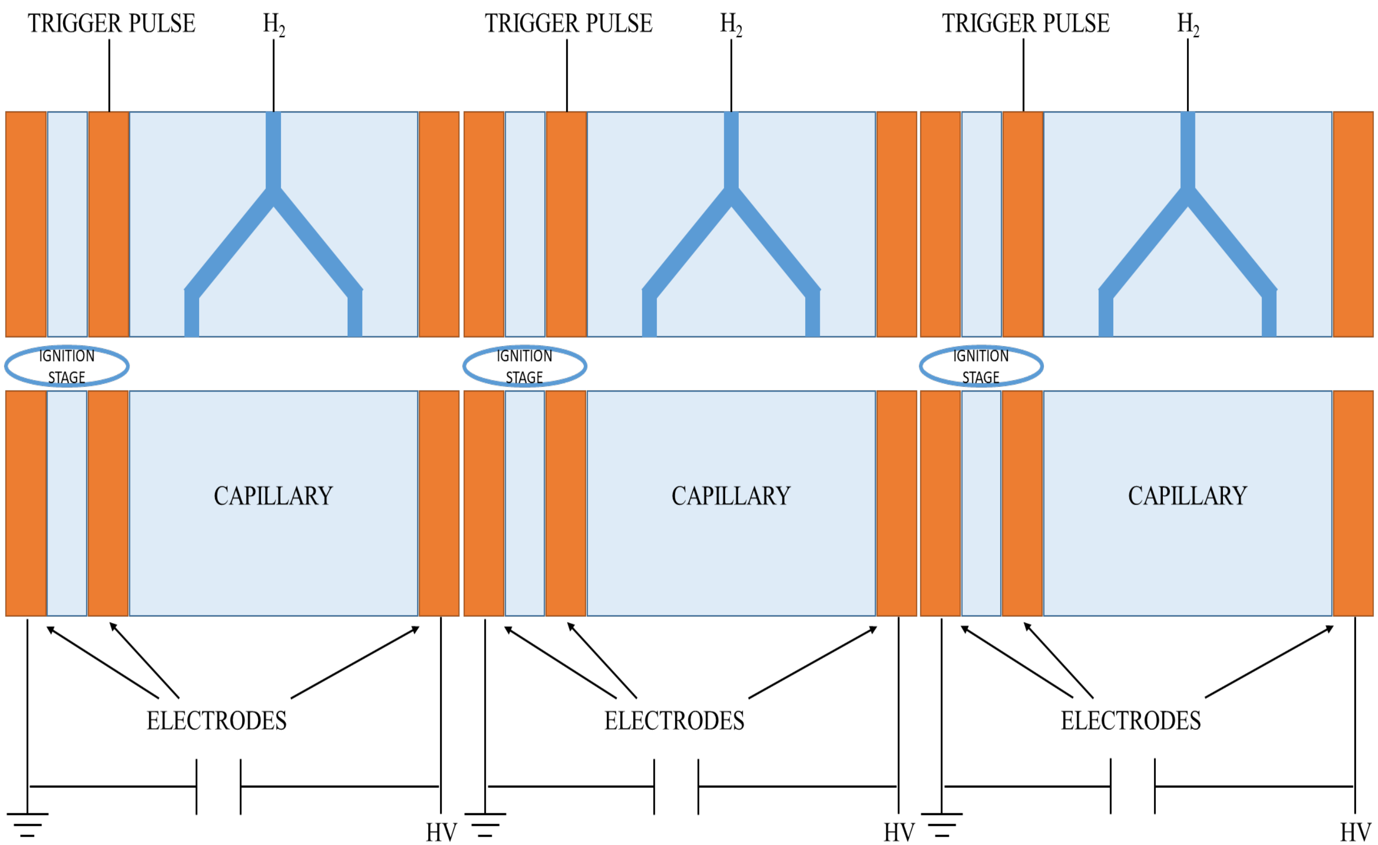
We preionize the capillary with a preformed plasma prior the main discharge. The initial plasma is formed in a short primary capillary by a high voltage pulse discharge. Part of this plasma and free electrons expanding into a long capillary that is connected to a high voltage capacitor. Since the discharge process follows the Paschen law, the breakdown threshold of the long capillary is lowered and the discharge can develop.

This strategy allow to ionize long capillaries with reasonable applied voltage in controlled and homogeneous way.



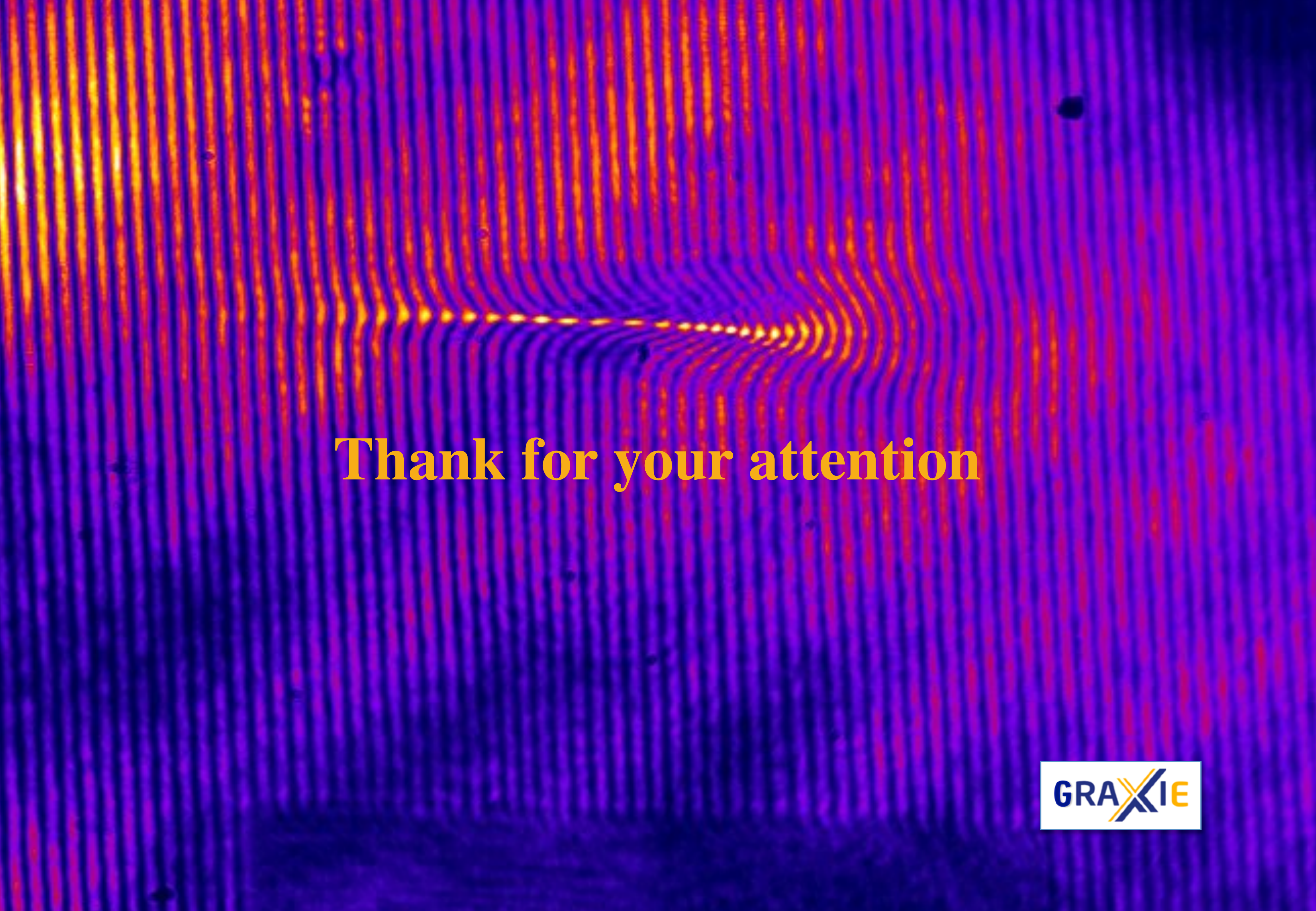
Plasma source

This scheme can be reproduced for tens-of-centimetre capillaries. This single unit can be integrated simply by adding more units obtaining up to tens of centimetre capillaries homogenously ionized and controlled independently one to each other, leading to the desired length of plasma (almost 30 cm) with the proper density (10^{17} cm^{-3}) required for this project.



EuPRAXIA@SPARC_LAB

- X-band RF technology implementation,➔ CompactLight
- Science with short wavelength Free Electron Laser (FEL)
- Physics with high power lasers and secondary particle source
- Compact Neutron Source
- R&D on compact radiation sources for medical applications
- Detector development and test for X-ray FEL and HEP
- Science with THz radiation sources
- Nuclear photonics with γ-rays Compton sources
- R&D on polarized positron sources
- R&D in accelerator physics and industrial spin – off


Thank for your attention
GRAXIE