From SPARC_LAB to EuPRAXIA

Design Study of a ~1GeV Linac and its possible X-band option

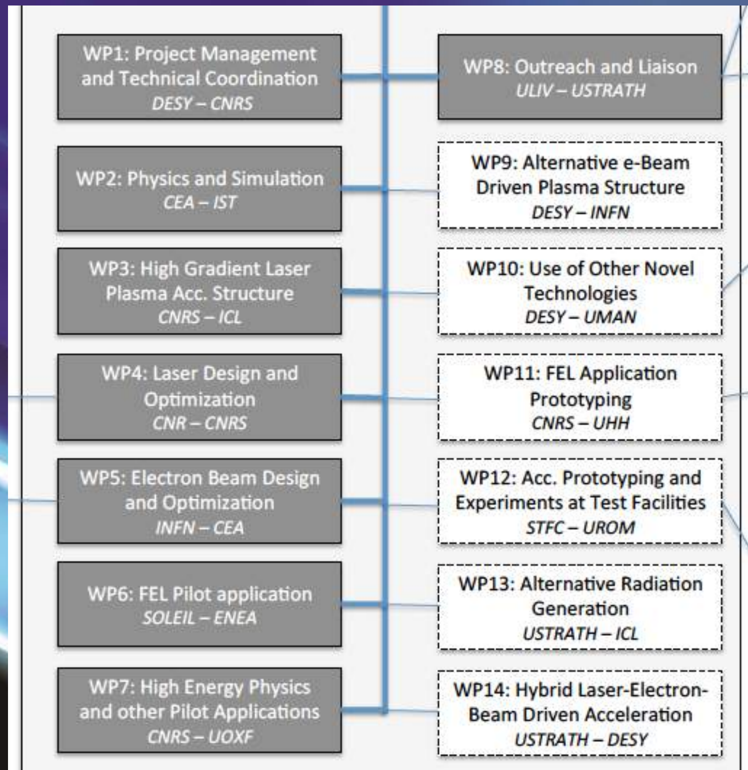
Massimo Ferrario
on behalf of the EuSPARC collaboration

CLIC Workshop – CERN, 9 March 2017

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

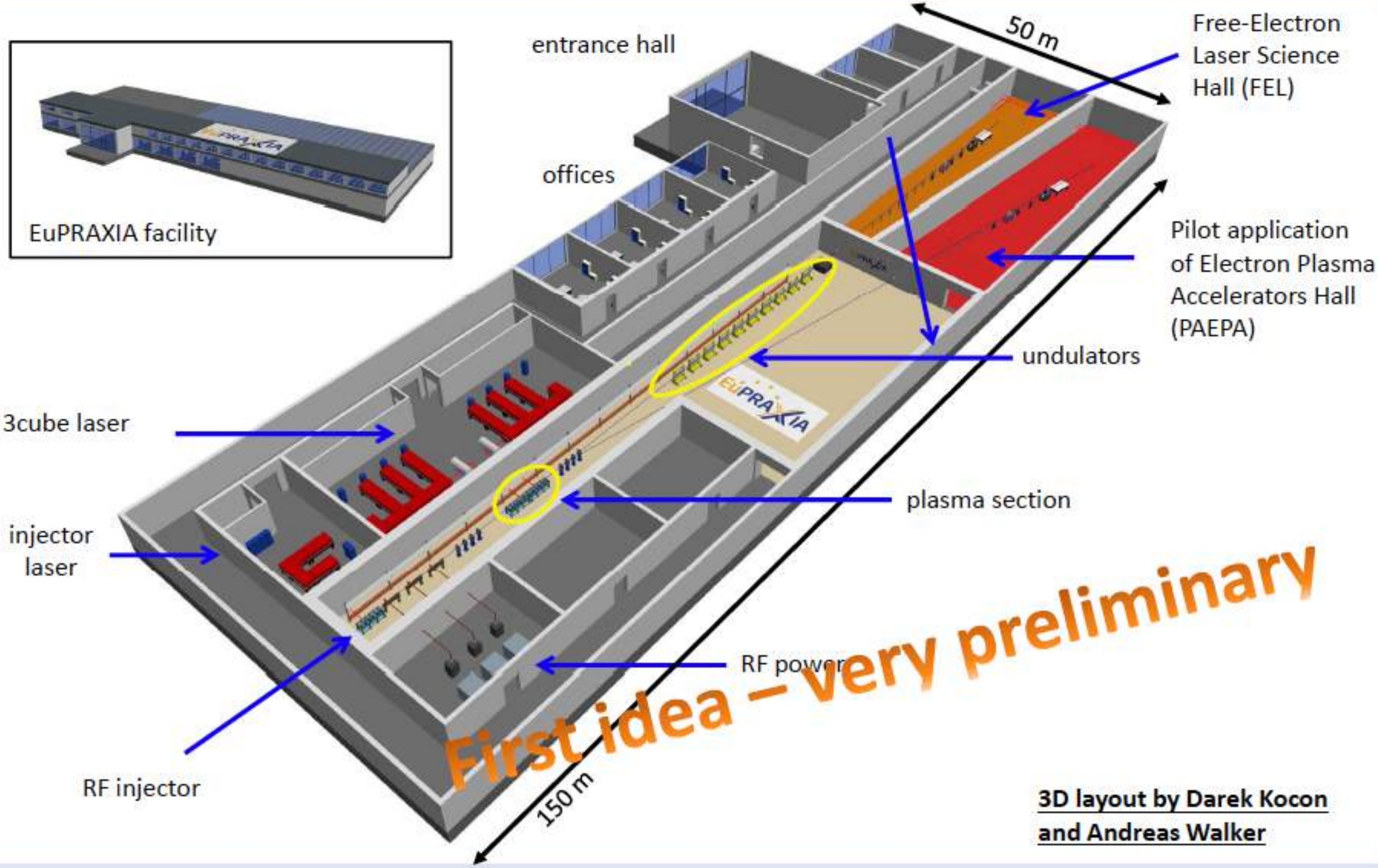
EuPRAXIA

Coord: Ralph Assmann (DESY)



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

draft of facility layout

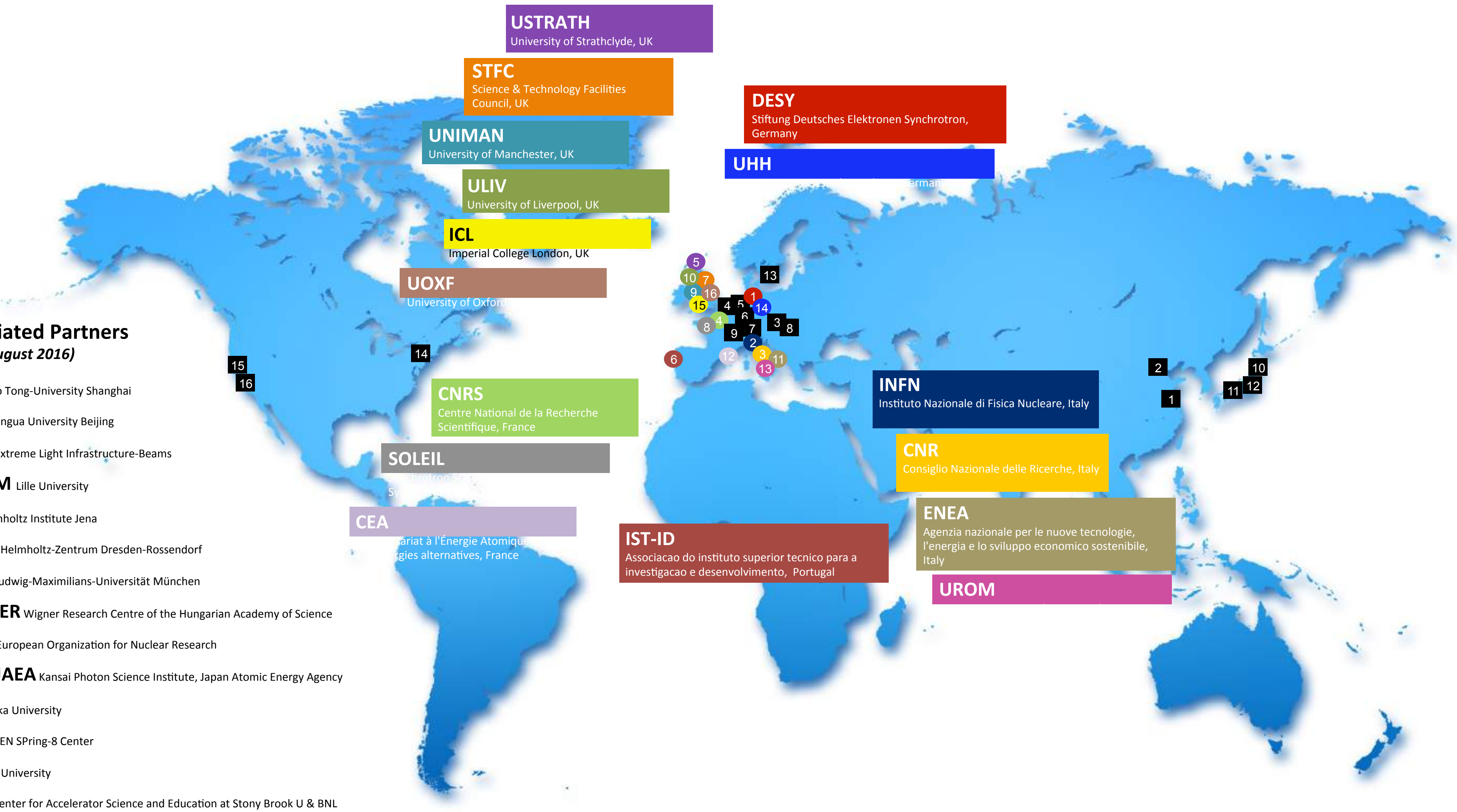


3D layout by Darek Kocon and Andreas Walker

EuPRAXIA

Participating Institutions

Horizon 2020



Associated Partners

(as of August 2016)

1 **JUS** Jiao Tong-University Shanghai

2 **TUB** Tsingua University Beijing

3 **ELI-B** Extreme Light Infrastructure-Beams

4 **PHLAM** Lille University

5 **HIJ** Helmholtz Institute Jena

6 **HZDR** Helmholtz-Zentrum Dresden-Rossendorf

7 **LMU** Ludwig-Maximilians-Universität München

8 **WIGNER** Wigner Research Centre of the Hungarian Academy of Science

9 **CERN** European Organization for Nuclear Research

10 **KPSI/JAEA** Kansai Photon Science Institute, Japan Atomic Energy Agency

11 **OU** Osaka University

12 **RSC** RIKEN SPring-8 Center

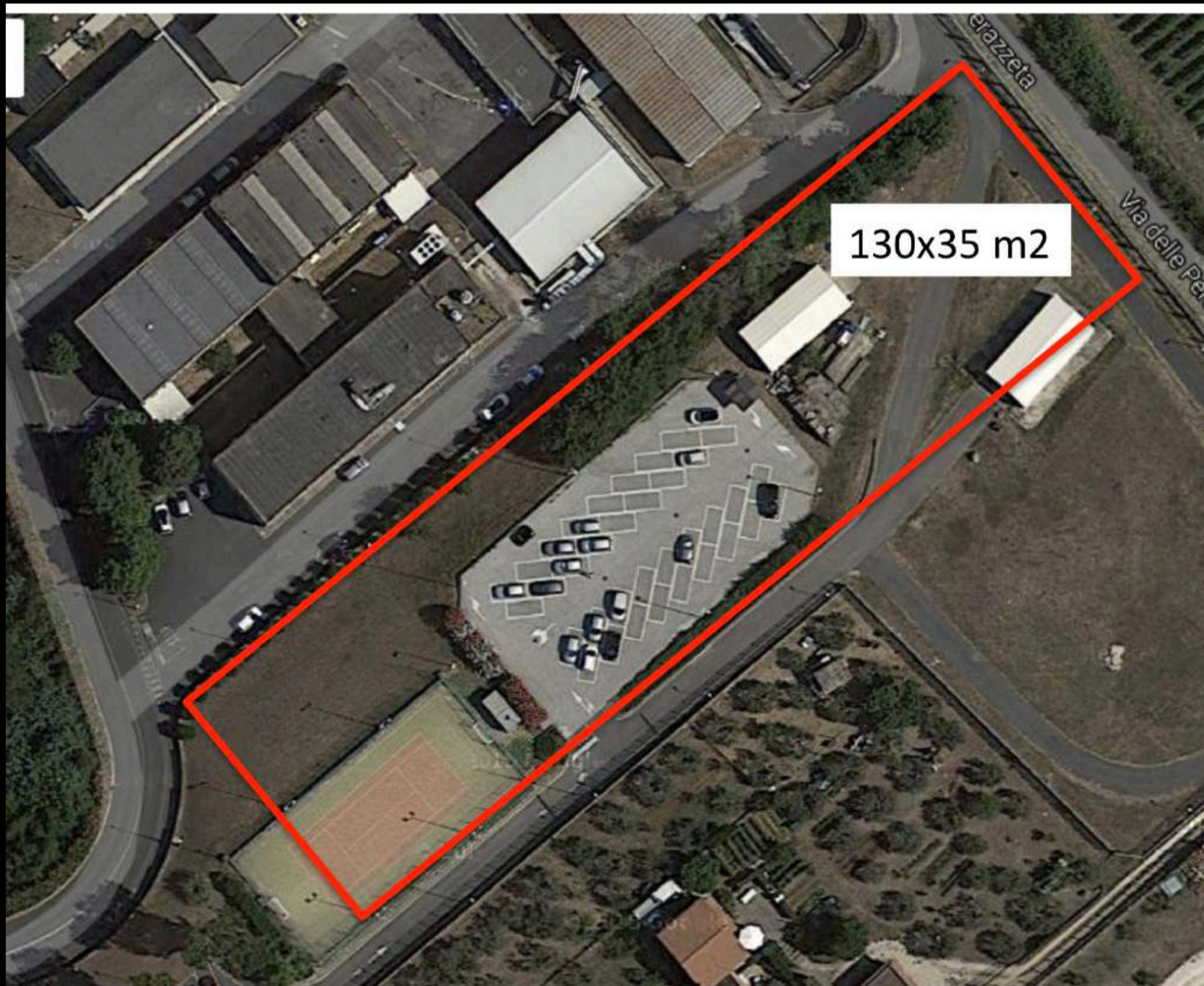
13 **LU** Lund University

14 **CASE** Center for Accelerator Science and Education at Stony Brook U & BNL

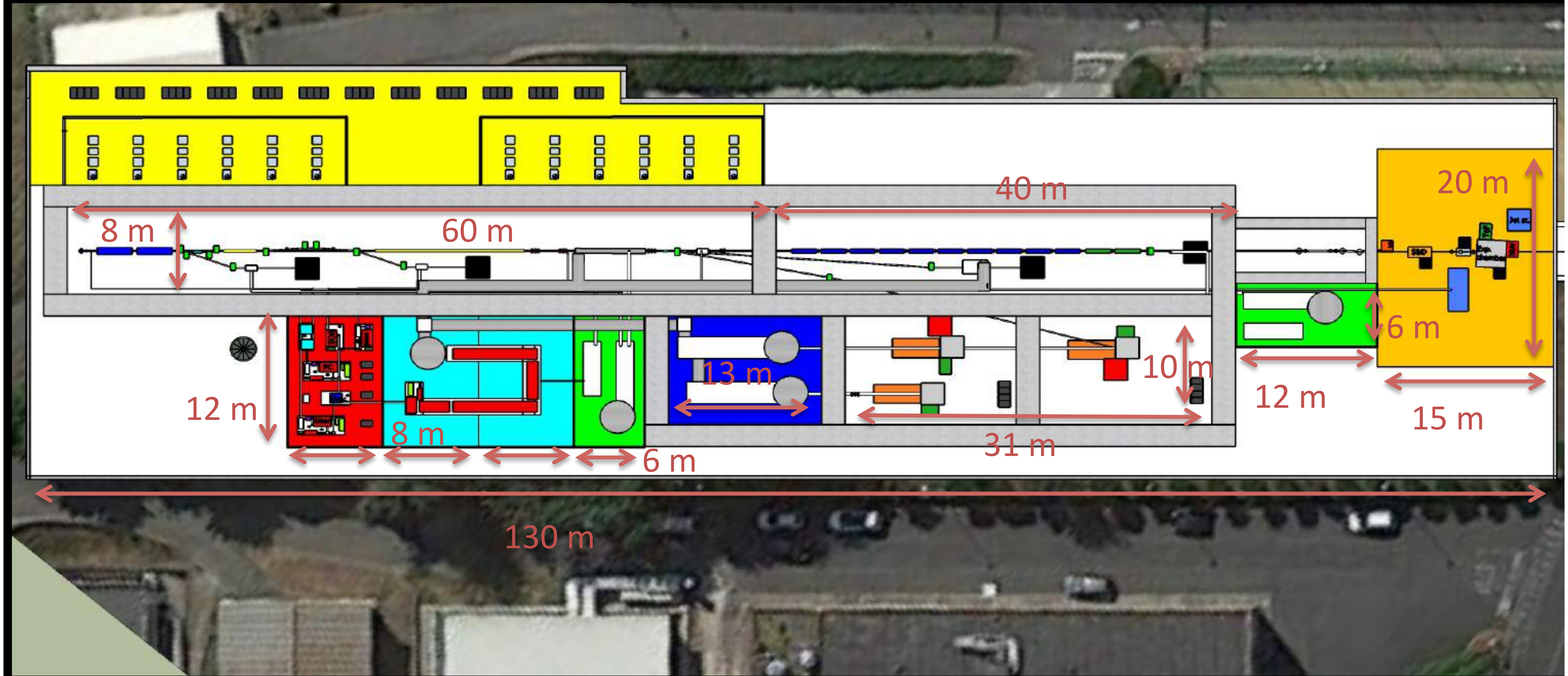
15 **LBNL** Lawrence Berkeley National Laboratory

16 **UCLA** University of California, Los Angeles

EuPRAXIA@SPARC_LAB



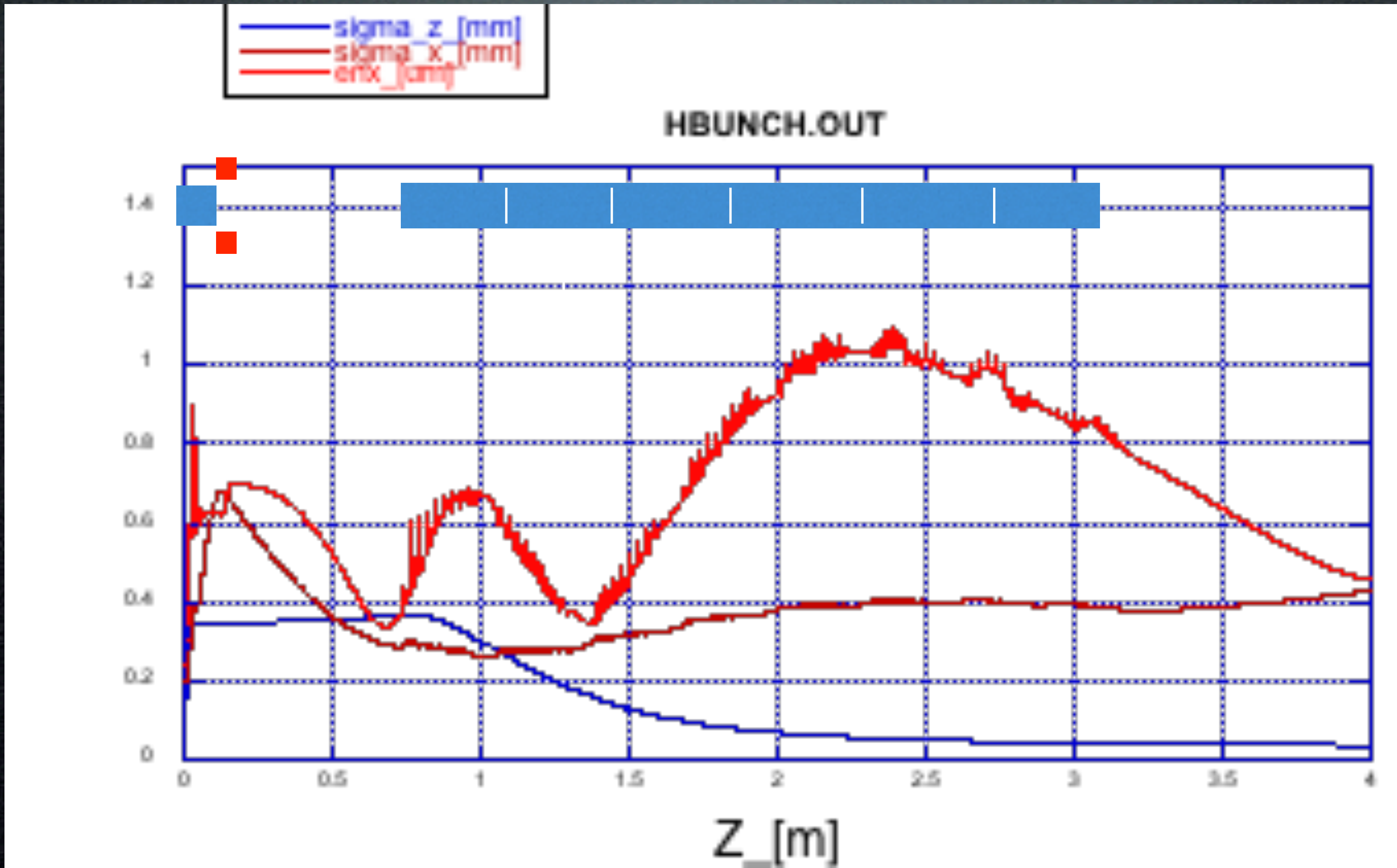
SPARC
FLAME
Users


40 m
20 m
8 m
60 m
6 m
12 m
13 m
10 m
12 m
8 m
15 m
31 m
6 m
130 m

Preliminary EuPRAXIA@SPARC_LAB Parameter List v2

	Units	Xband FEL-SASE 1 GeV	EuPRAXIA FEL-CDR 1 GeV Witness bunch		PWFA 2 FEL-SASE 1 GeV 1 Drive bunch	PWFA 5 FEL-SASE-COMB 1 GeV 4 Drive bunches			
No.bunches		1 – (maybe 2)			1	5			
Bunch separation	ps	(maybe 83)			1.	1.67			0.5
Rep. rate	Hz	10 – (100)	10		10	1			
Injector energy	GeV	0.15	0.15		0.15	0.15			
Xband Acc. Gradient	MV/m	> 70	> 70		> 70	>70			
Exit linac energy	GeV	1. – (1.5)	0.5		0.5	0.5			
			2016	**2017 ?**		B1	B2	B3	B4
Rms Energy Spread	%	<1.	<1	<1	< 1				
Peak current	kA	2.	3	1.5	1.8				
Bbunch charge	pC	100	30	10	200				
Bunch length rms	μm (fs)	15 (50)	3 (10)	2 (7)	34 (112)				
Rms norm. emittance	μm	< 1.	<1.5	<1	< 2				
Slice Length	μm	0.7	0.75	0.75					
Slice Charge	pC	4.5	7.5	3.7					
Slice Energy Spread	%	0.1	0.1	0.1					
Slice norm. emittance	μm	0.5	1	0.5					
Undulator period	cm	1.5	1.5	1.5					
K		1	1	1					
ρ	$x\ 10^{-3}$	1.2	1.1	1.1					
Radiation wavelength	nm (keV)	3. (0.4)	3. (0.4)	3. (0.4)					
Saturation length	m	22	26	27					
Saturation power	MW	940	1210	492					
Energy	μJ	47	12	3.3					
Photons/pulse	$x\ 10^{10}$	70	17.	4.8					

C-band Gun (250 MV/m peak on Cathode)
C-Band SW Velocity Bunching (50 MV/m acc.)



ε_n<0.5 μm

I>500 A

σ_z=40 μm

Linac Technology: C-band or **X-band** ?

C band: pros

- technology well established, background of various projects (SFEL, SPARC, ELI-NP, …);
- synergic with other internal activities;
- all components already industrialized, well known suppliers;
- medium gradients (50 MV/m) already demonstrated.
- linearization possible (X band)

C band: cons

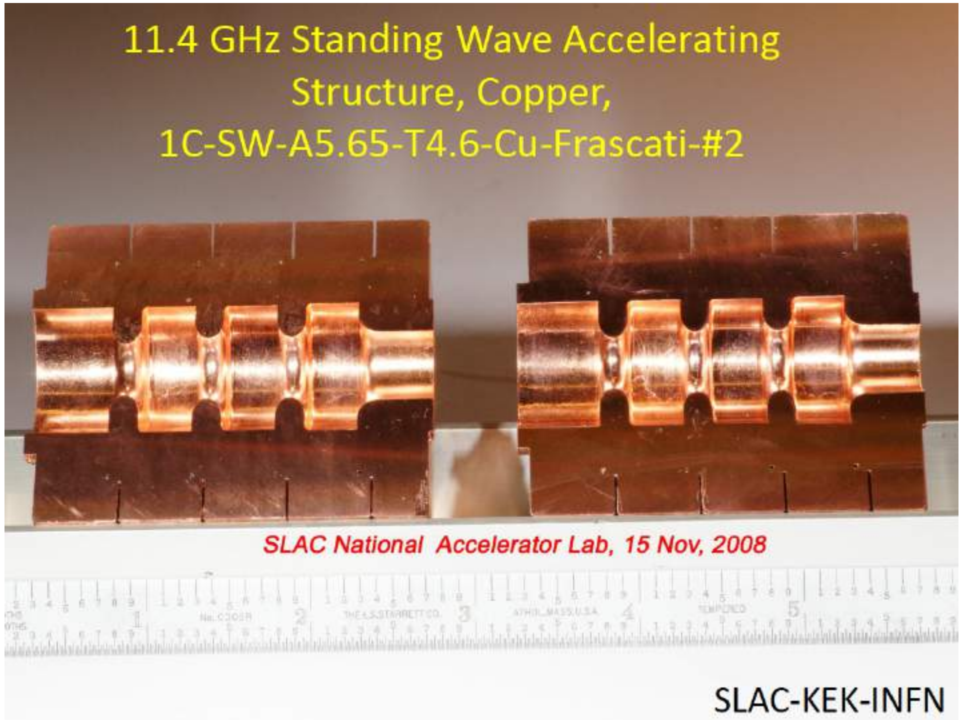
- relatively long pulses (300 – 400 ns);
- higher gradients require some R&D efforts;
- ultimate gradients realistically limited (< 80 MV/m)

X band: pros

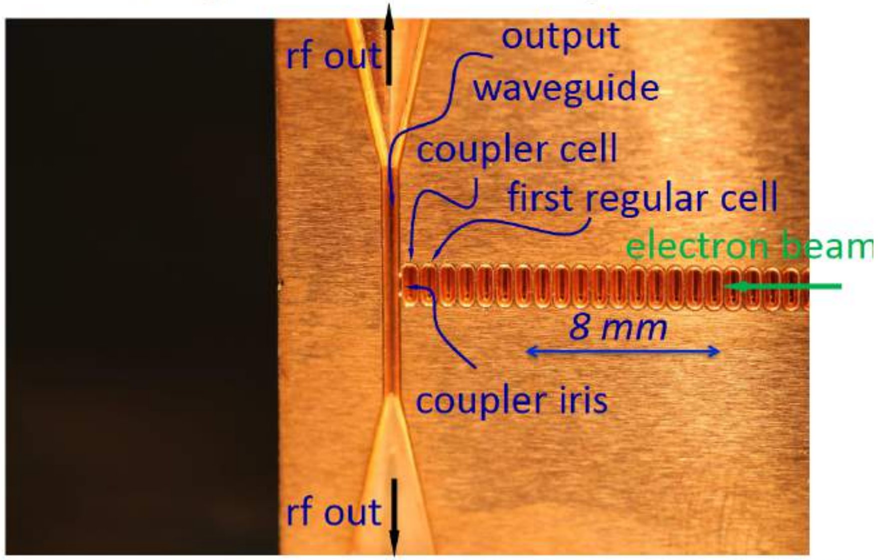
- short RF pulses (< 200 ns);
- about 40% larger efficiency;
- ultimate gradients in the > 100 MV/m range
- synergic with other european (CERN) and international efforts

X band: cons

- klystron availability and cost;
- more complicated pulse compressors;
- critical RF transport and distribution;
- not all components industrialized;
- no LLRF commercially available;
- in general any part of the system requires R&D effort and a lot of manpower



Output Part of the Open 100 GHz Copper
Traveling Wave Accelerating Structure



SLAC-INFN

Proceedings of FEL2015, Daejeon, Republic of Korea

THE X-BAND FEL COLLABORATION

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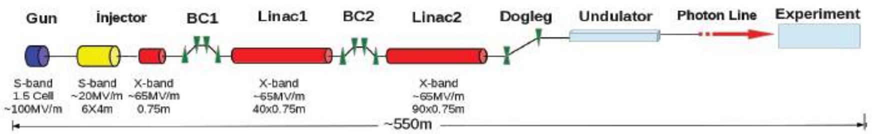
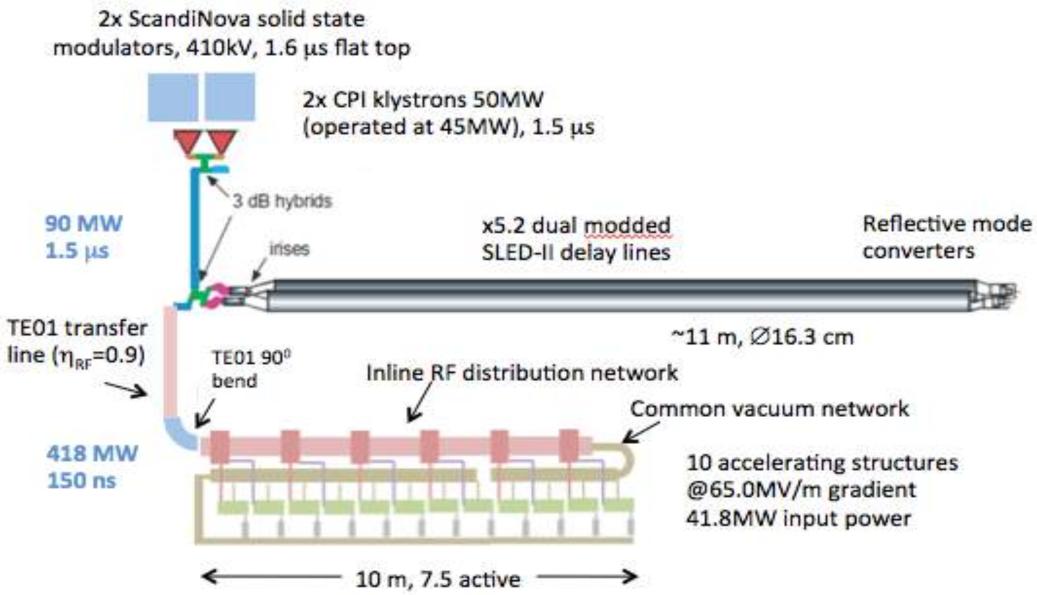
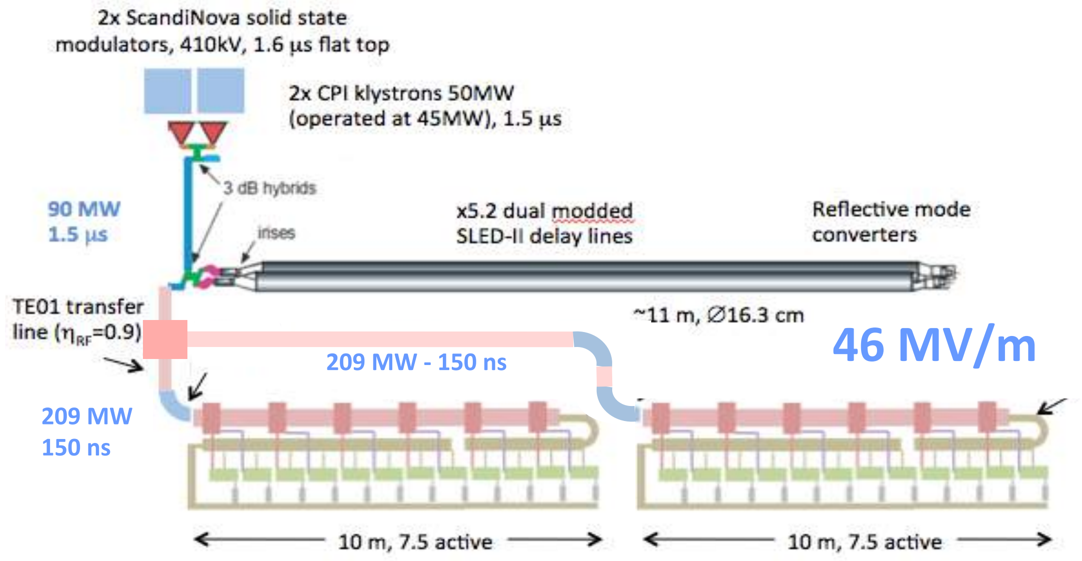




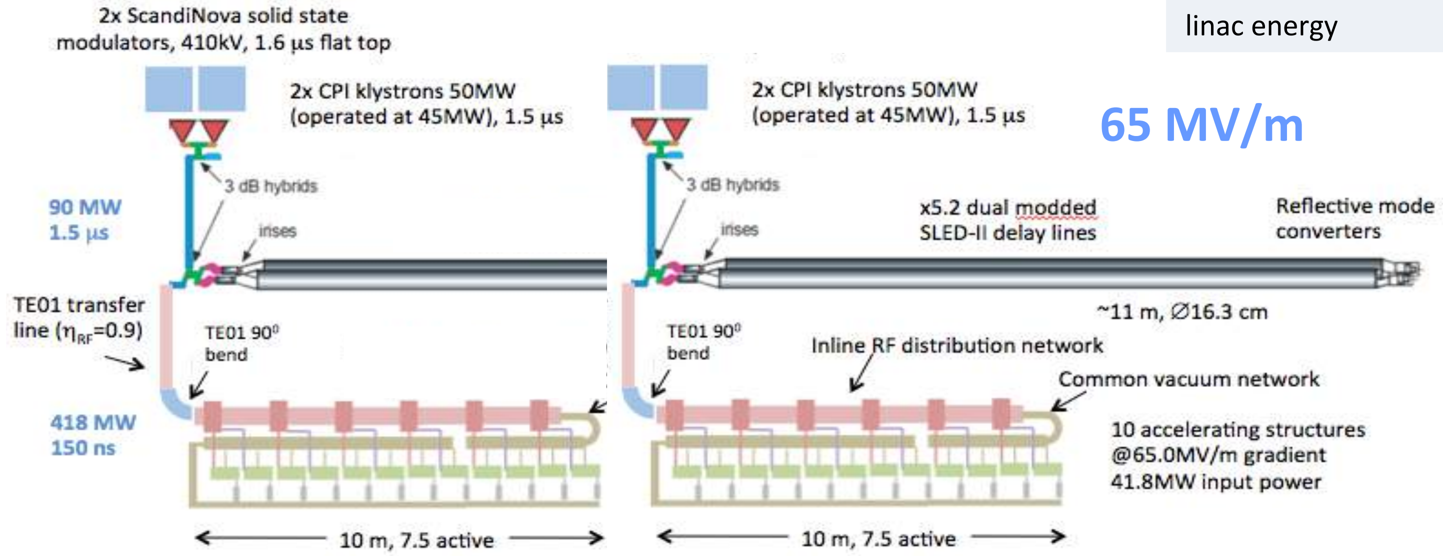
Parameter	CLIC-502		Optimum
Structures per RF unit	12	16	10
Klystrons per RF unit	2	2	2
Structure length (m)	0.23	0.23	0.75
a/λ	0.145	0.145	0.125
Operating gradient (MV/m)	77	67.5	65
Energy gain per RF unit (MeV)	213	248	488
RF units needed	27	23	12
Total klystrons	54	46	24
Linac active length (m)	74	84	88
Cost estimate (a.u.)	76.2	71.5	51.7

- No much info about this accelerating section (ever been prototyped and tested?). It might possibly be just an optimal scaling for the purpose.
- However the RF plant and the section properties fit the EUSPARC need, so the proposed RF basic block can be easily scaled to the EUSPARC case to draw some initial scenario.
- Filling factor is ≈ 75 %

EUSPARC scenario based on “X-band FEL collaboration” RF module



	Phase I	Phase II
RF gradient	46 MV/m	65 MV/m
# of sections	20	
# of modulators	1	2
# of klystrons	2	4
# of SLEDs	1	2
linac length	20 m (15 m active)	
section input power	21 MW	42 MW
linac energy	690 MeV	975 MeV

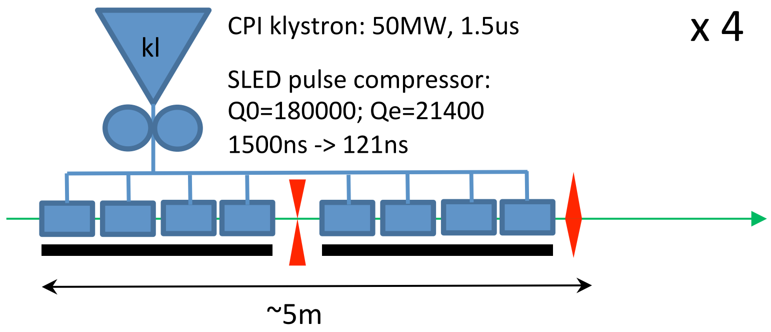


Higher Gradient layout
(A. Grudiev – CERN)

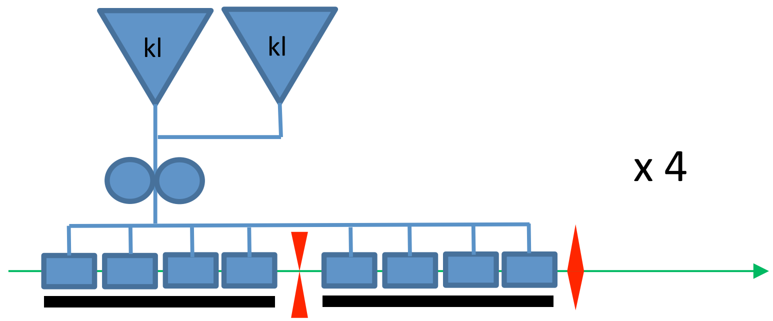
parameters			comments		
<a> [mm]	3.2				
d [mm]	2.5				
Ls [mm]	500				
Qe	21400				
vg/c [%]	2.5 – 0.77				
Tp [ns]	121				
R'_PC [MΩ/m]	350		$=G^2/(Pkl/L)$		
	Phase 1	Phase 2		**Phase 1**	**Phase 2**
Energy gain: Vt [MeV]	850	1350		**850**	**1350**
N structures	30	30		**32**	**32**
Total active length: Lt [m]	15	15		**16**	**16**
Total klystron power: Pt [MW]	138	347	On crest, No losses in WG	**129**	**325**
N klystrons	4	8		**4**	**8**

Does not fit together
⇒ N structures = 32
⇒ Lt = 16m

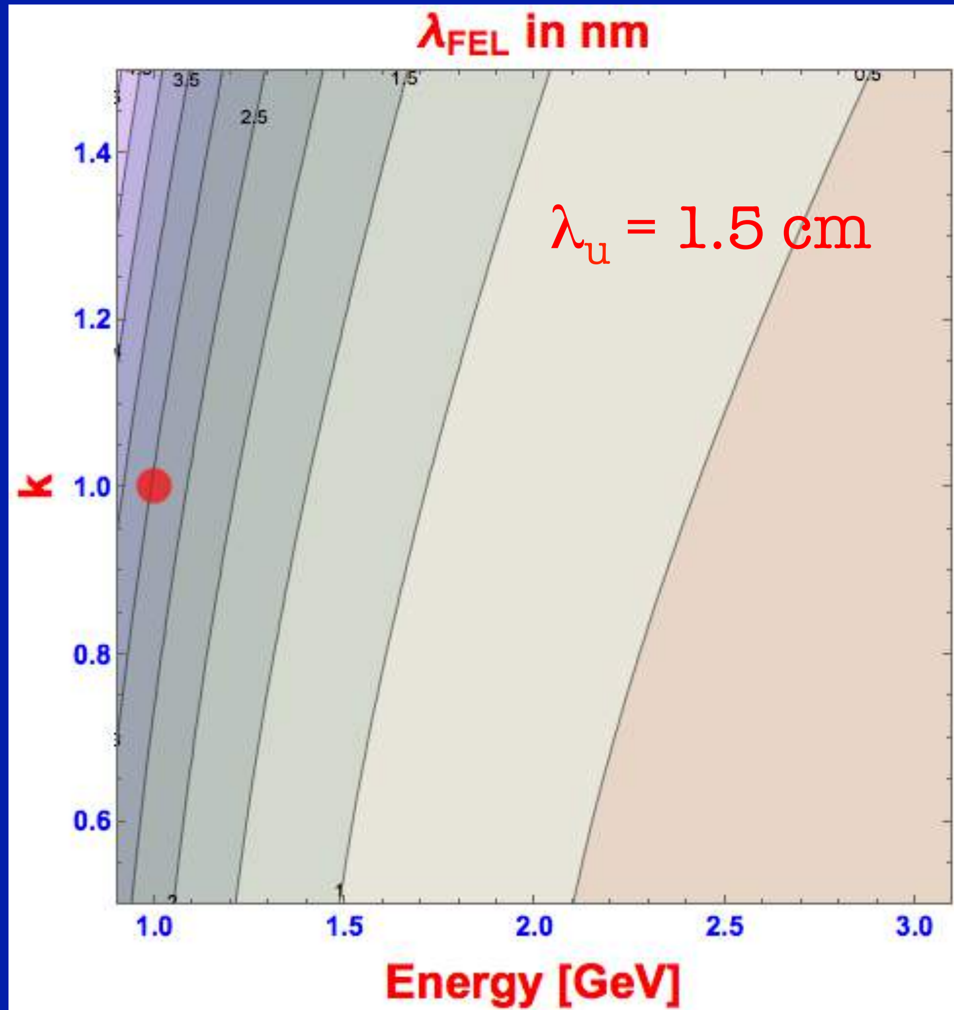
Layout Phase 1:

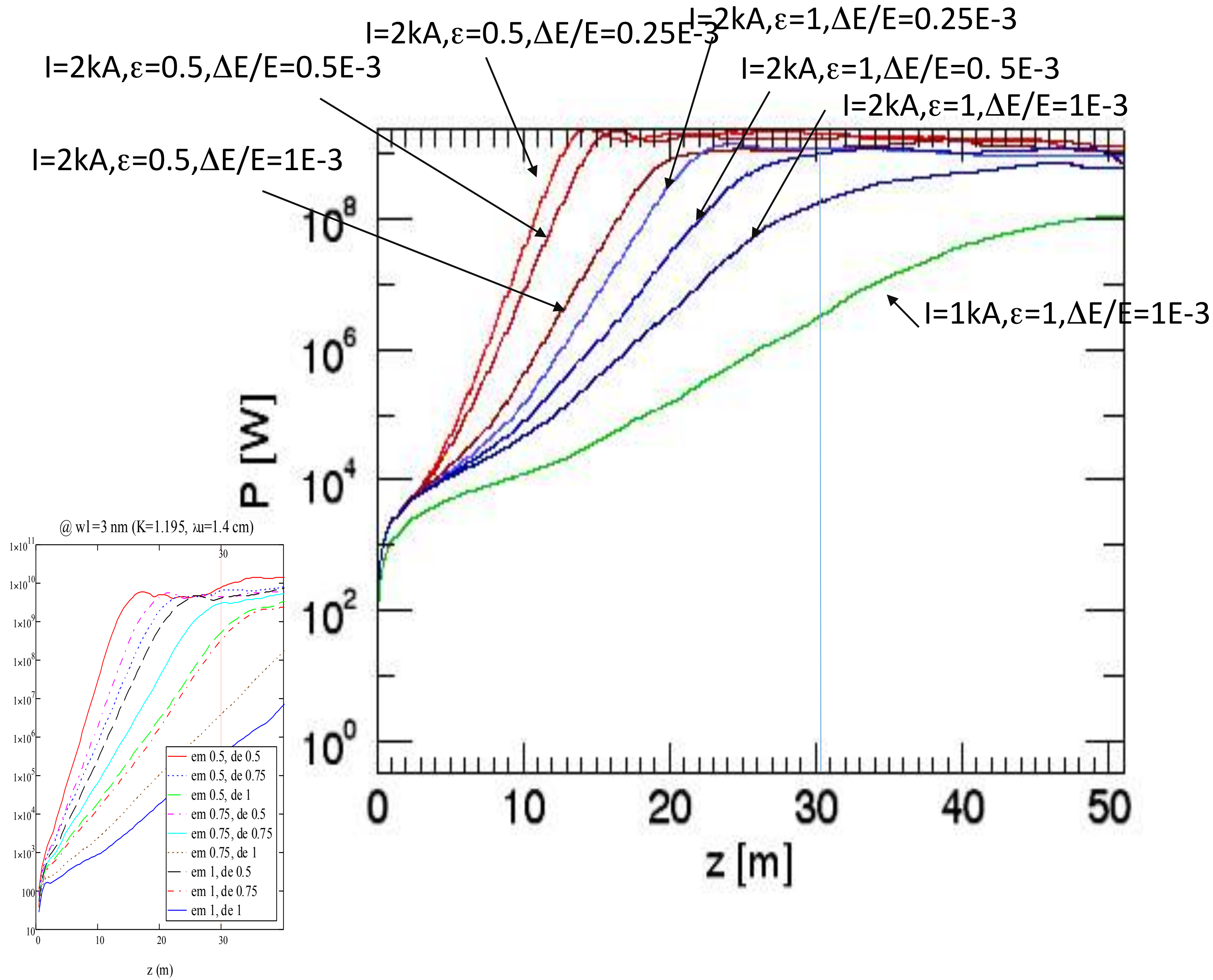


Layout Phase 2:



SASE FEL studies





I=2kA,ε=0.5,ΔE/E=0.25E-3
I=2kA,ε=1,ΔE/E=0.25E-3
I=2kA,ε=0.5,ΔE/E=0.5E-3
I=2kA,ε=1,ΔE/E=0. 5E-3
I=2kA,ε=1,ΔE/E=1E-3
I=2kA,ε=0.5,ΔE/E=1E-3
I=1kA,ε=1,ΔE/E=1E-3
P [W]
z [m]
@ wl=3 nm (K=1.195, λu=1.4 cm)
em 0.5, de 0.5
em 0.5, de 0.75
em 0.5, de 1
em 0.75, de 0.5
em 0.75, de 0.75
em 0.75, de 1
em 1, de 0.5
em 1, de 0.75
em 1, de 1
z (m)

WG 0 – Project Management

- 0.1 Executive summary (M. Ferrario)

WG 1 – Electron beam design and optimization

- 1.1 Advanced High Brightness Photo-injector (E. Chiadroni)
- 1.2 HB Linac technology, (A. Gallo)
- 1.3 Linac design and parameters (C. Vaccarezza)

WG 2 – Laser design and optimization

- 2.1 FLAME upgrade (M. P. Anania)
- 2.2 Advanced Laser systems (L. Gizzi)

WG 3 – Plasma Accelerator

- 3.1 PWFA beam line (A. Marocchino)
- 3.2 LWFA beam line (A. R. Rossi)
- 3.3 Plasma and Beam Diagnostics (A. Cianchi)

WG 4 – FEL pilot applications

- 4.1 Conventional and Plasma driven FEL (V. Petrillo)
- 4.2 Advanced FEL schemes (G. Dattoli)
- 4.3 Photon beam lines (F. Villa)
- 4.4 FEL user applications (F. Stellato)

WG 5 – Radiation sources and user beam lines

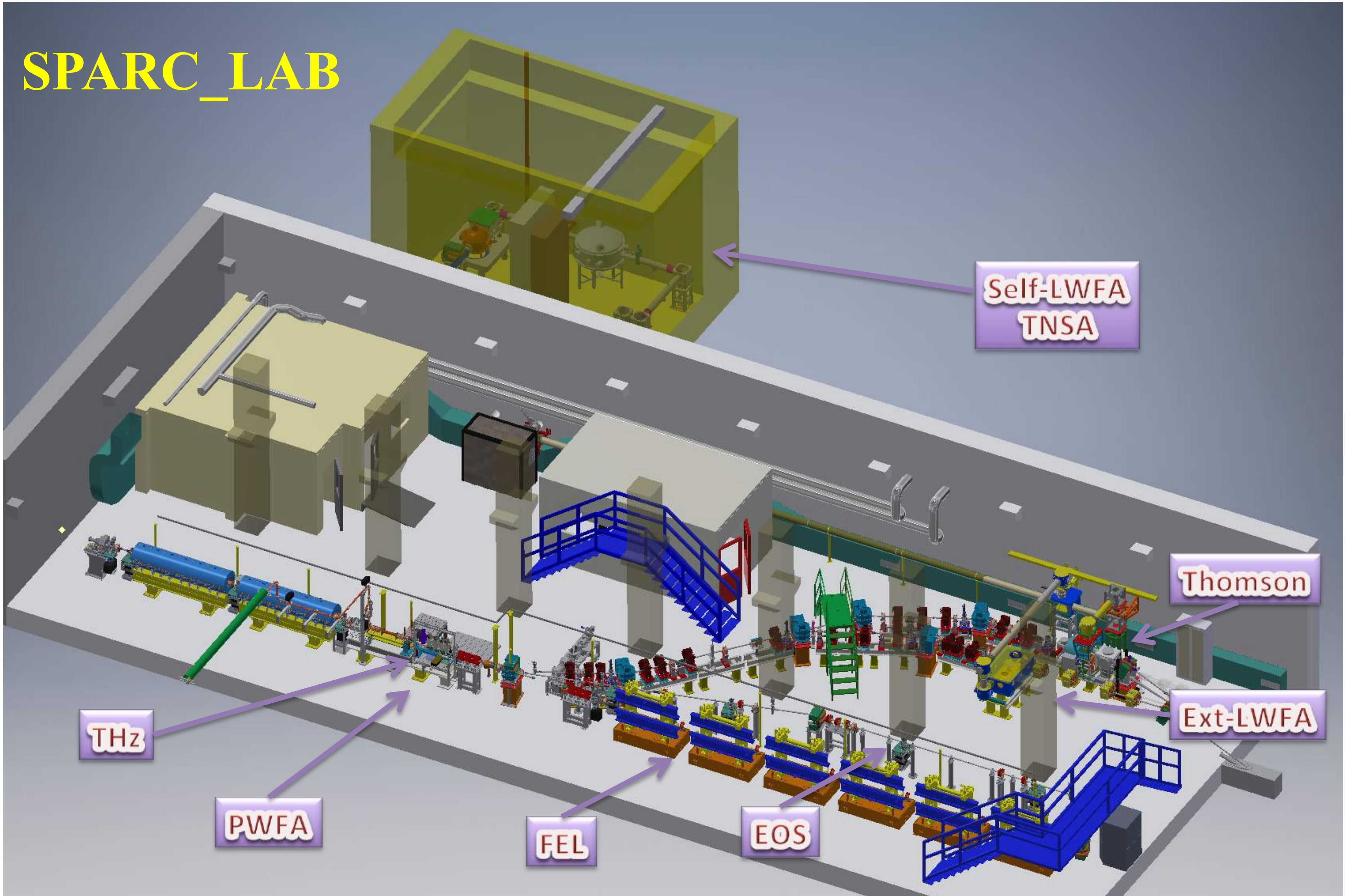
- 5.1 Advanced (dielectric) THz source (S. Lupi)
- 5.2 Compton source (C. Vaccarezza)
- 5.3 Secondary Particle Sources (LNS)?
- 5.4 Laser-driven neutron source (Cianchi)
- 5.4 User beam lines (P. Valente)

WG 6 – Low Energy Particle Physics

- 6.1 Advanced positron sources (A. Variola)
- 6.2 Fundamental physics experiments , LabAstro (C. Gatti)
- 6.3 Plasma driven photon collider (L. Serafini)

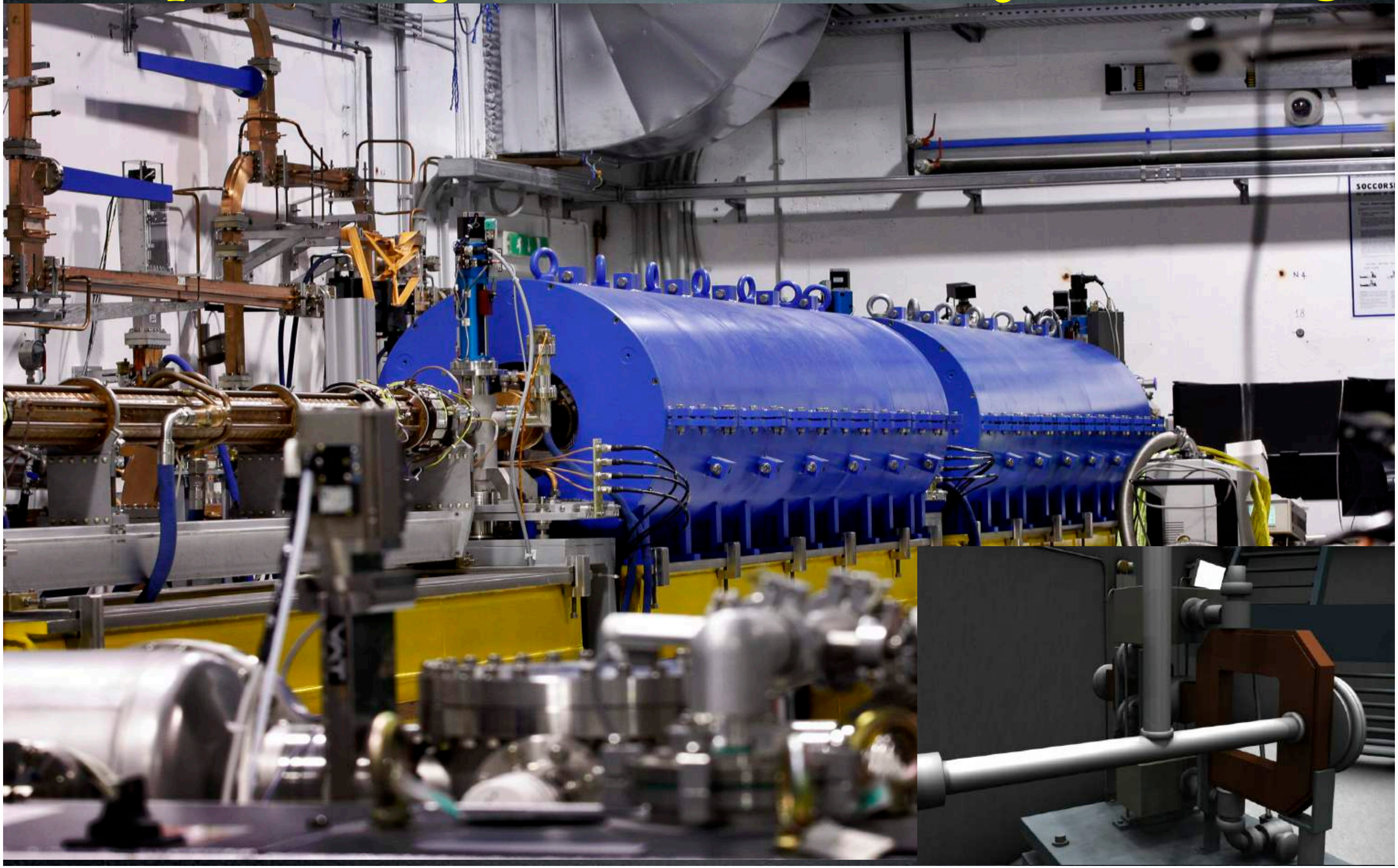
WG 7 – Infrastructure

- 7.1 Civil Engineering and conventional plants (U. Rotundo)
- 7.2 Control system (G. Di Pirro)
- 7.3 Radiation Safety (A. Esposito)
- 7.4 Machine layout

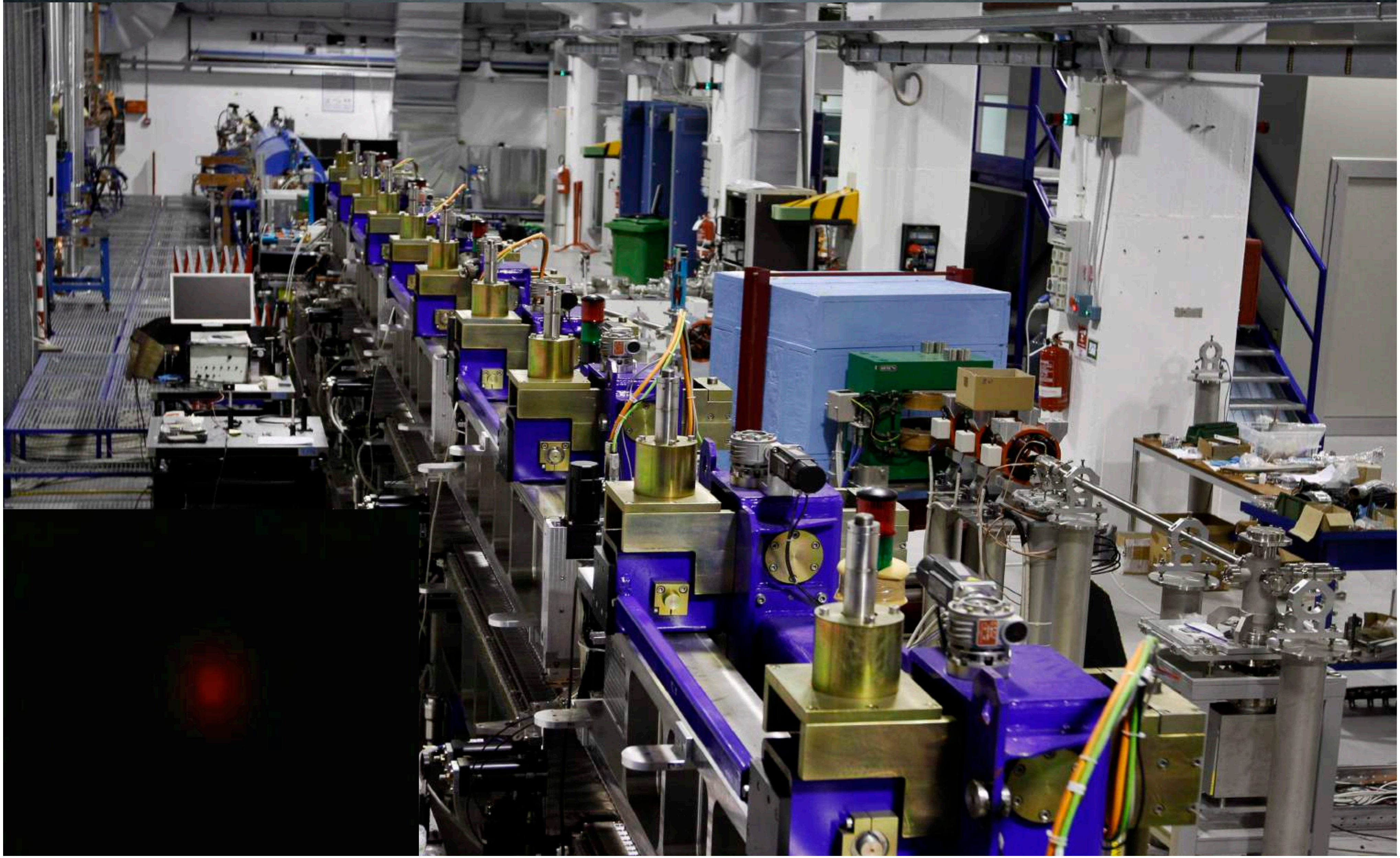


Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

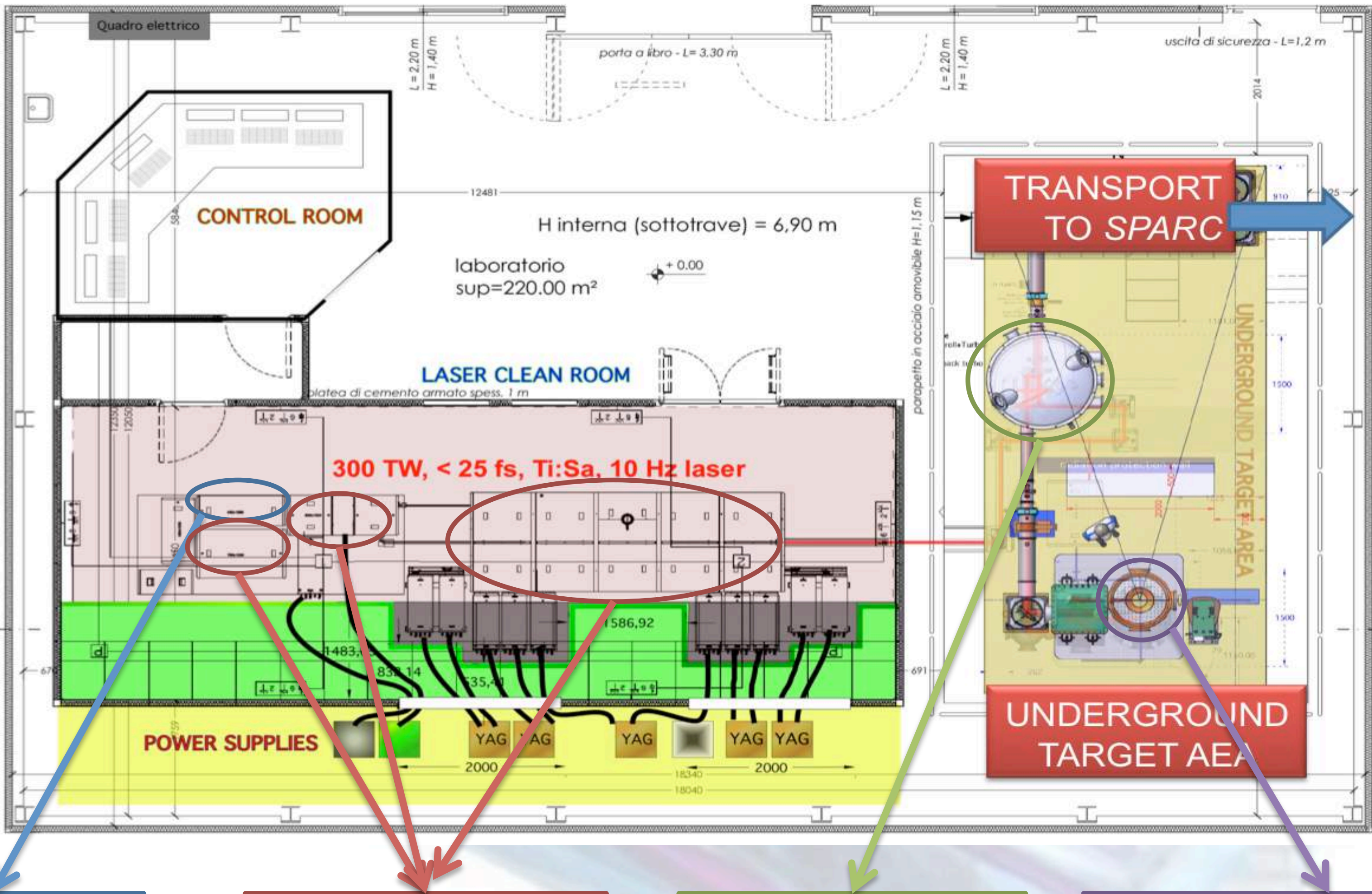
HB photo- injector with Velocity Bunching



Free Electron Laser



Ti:Sa FLAME laser



Stretcher

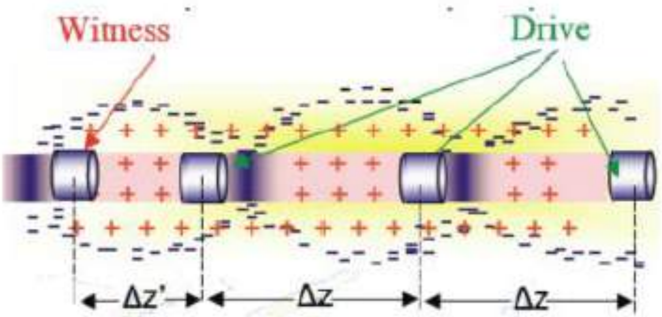
Amplifiers

Compressor

LWFA
Electron Self Injection
And
Protons

Plasma-based acceleration techniques

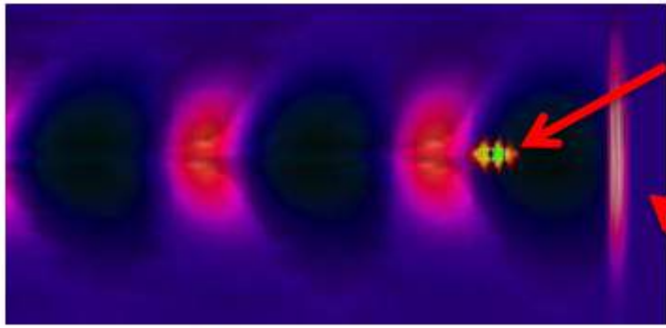
resonant-PWFA



•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 = 2x10^{16} cm^{-3}
λ_p = 300µm
Capillary 1mm
Hydrogen

external injection LWFA



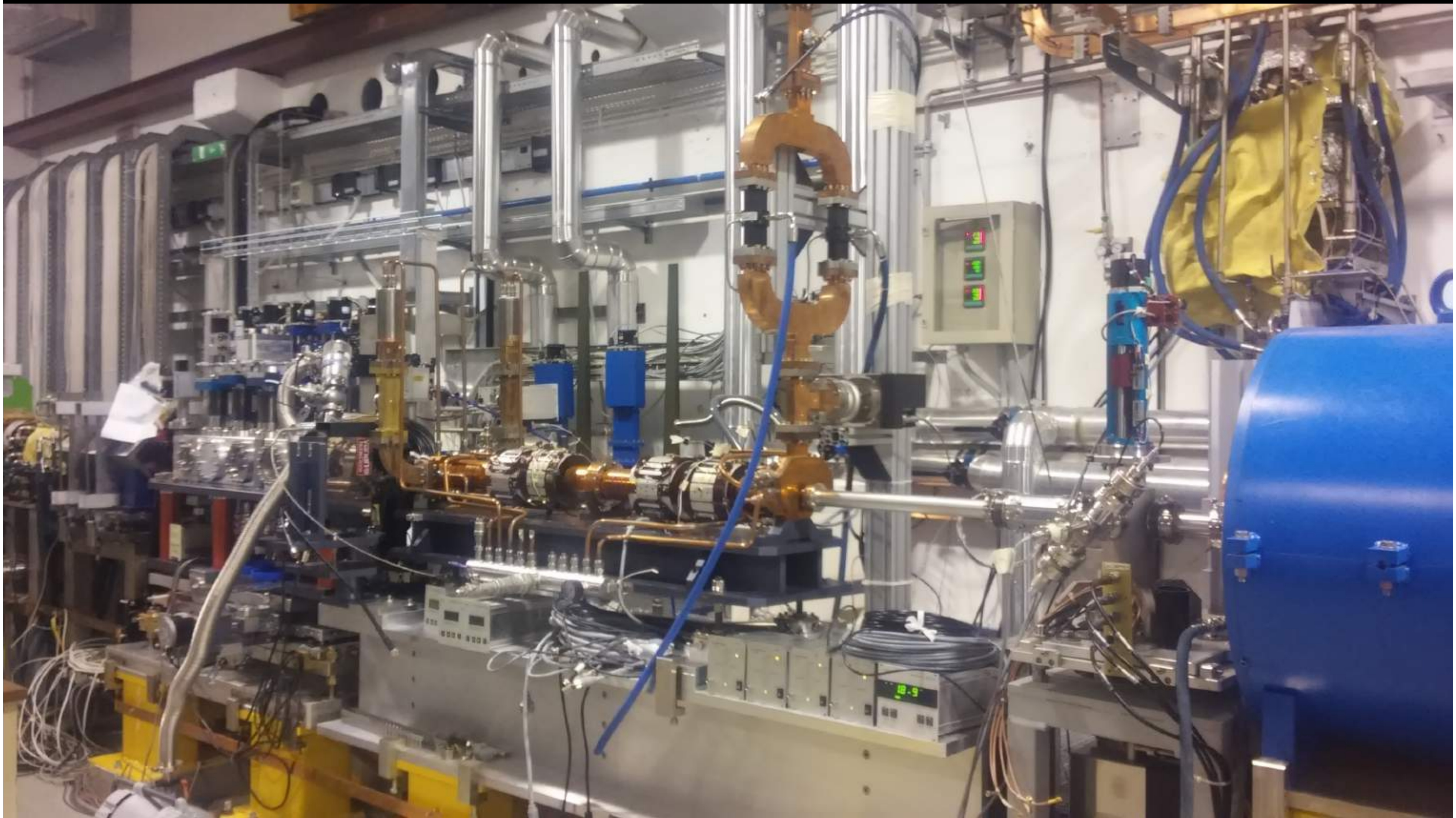
e-bunch

laser beam

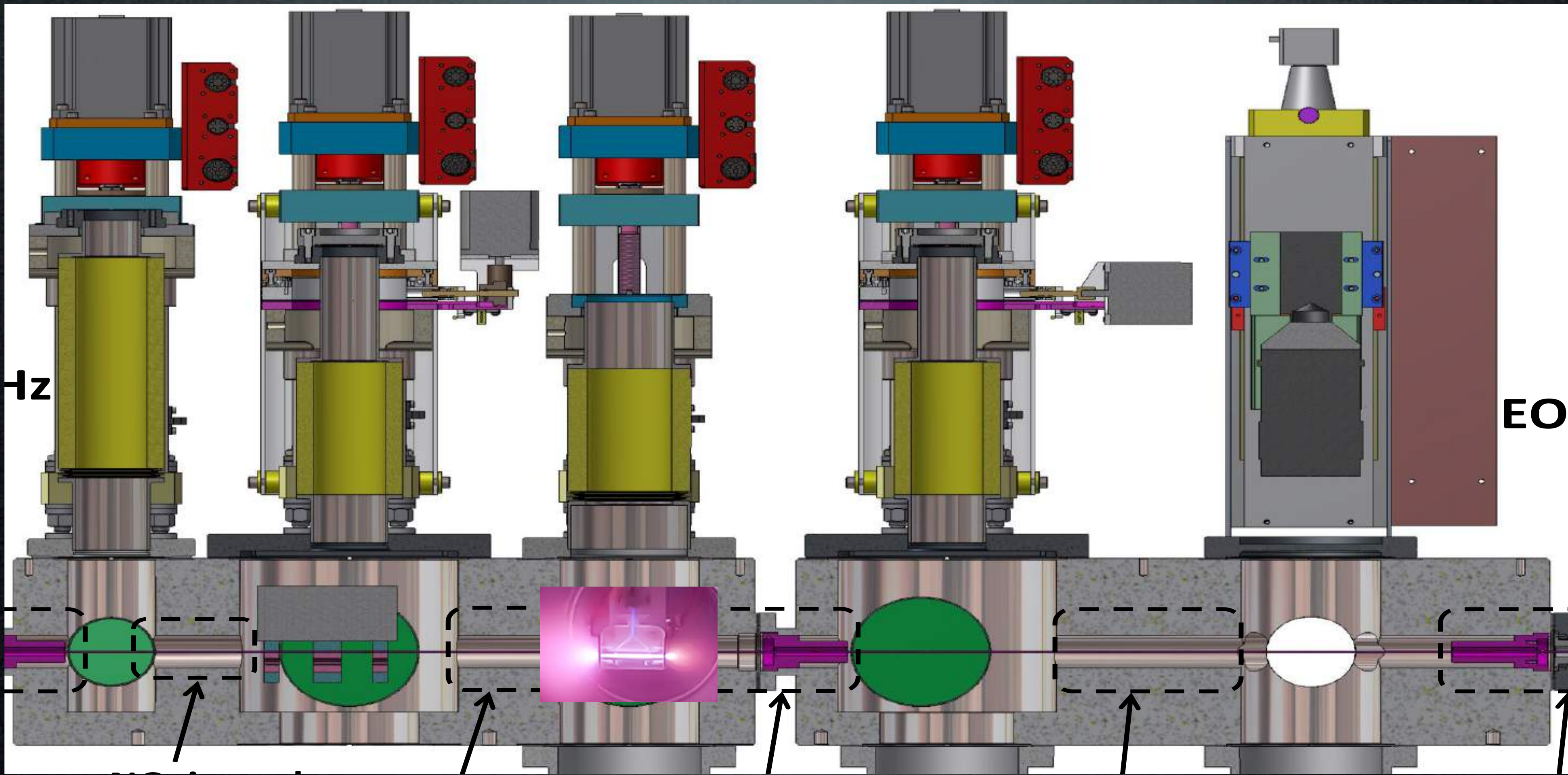
•A laser beam excites plasma waves in a capillary filled with gas
•A high brightness electron beam uses this wave to be accelerated

n_e = 1x10^{17} cm^{-3}
λ_p = 100µm
Capillary 100 µm
Hydrogen

C-Band accelerating structure and PWFA chamber



PWFA – Particle Wake Field Accelerator

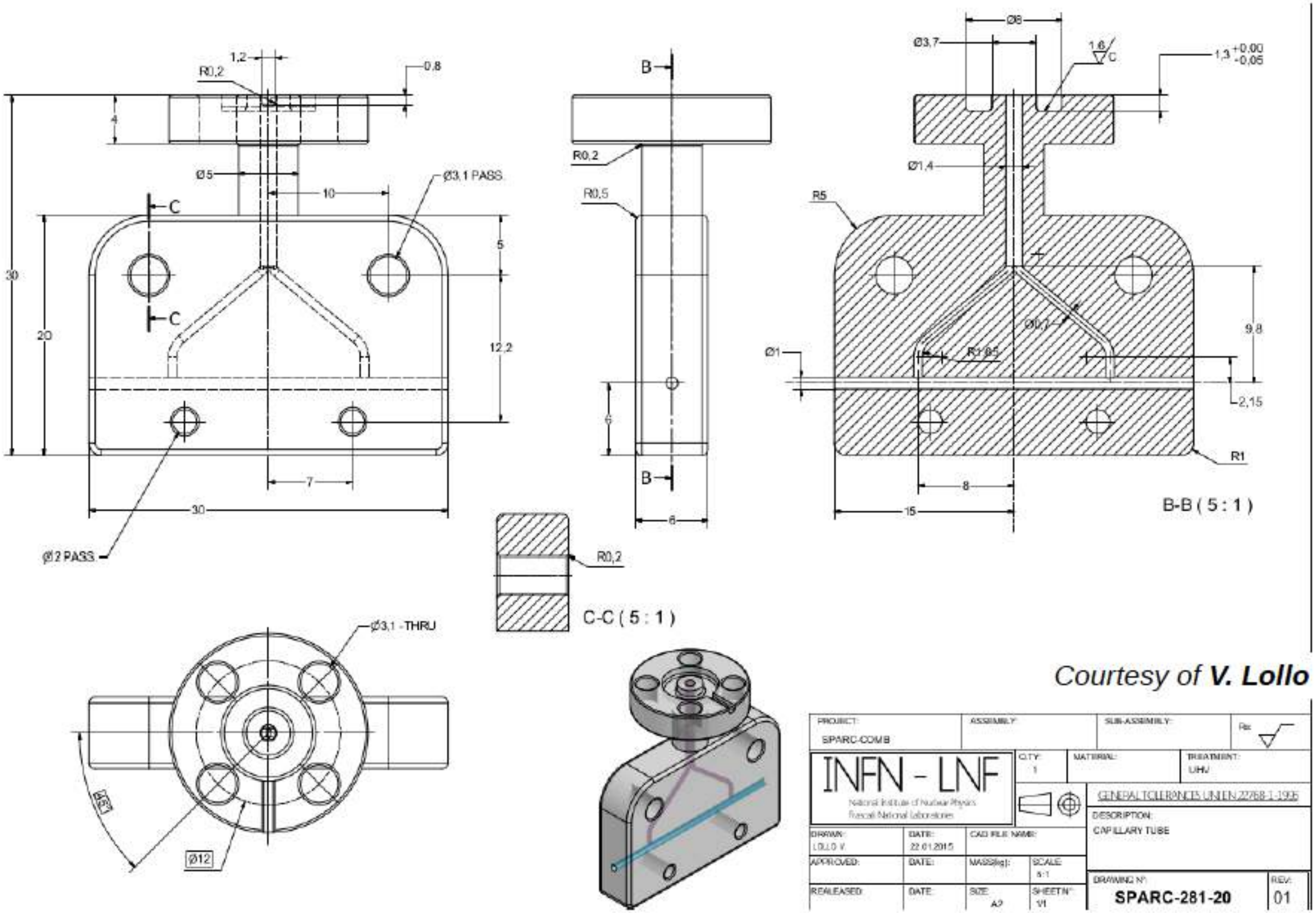


Focusing PMQ

PWFA module

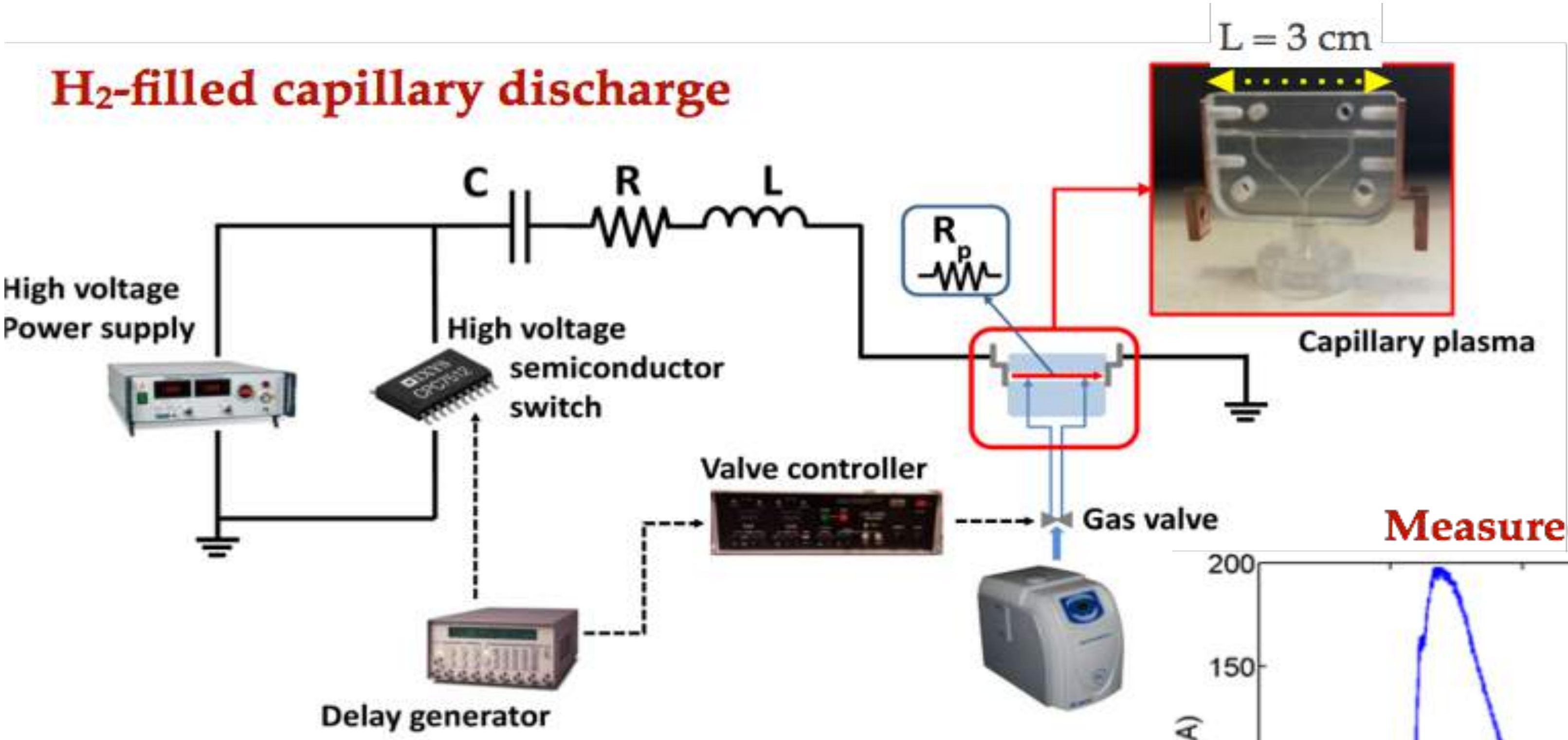
Capture PMQ

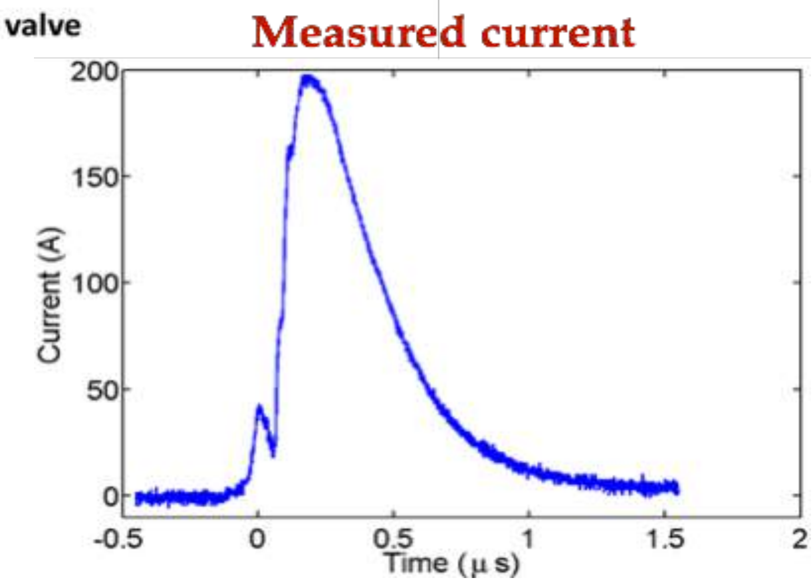
Plasma capillary



Courtesy of ***V. Lollo***

Plasma Source

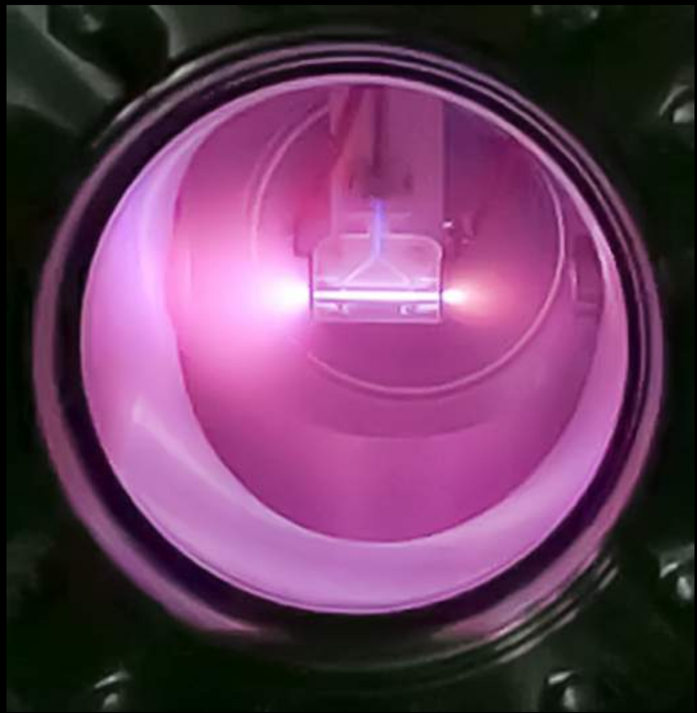




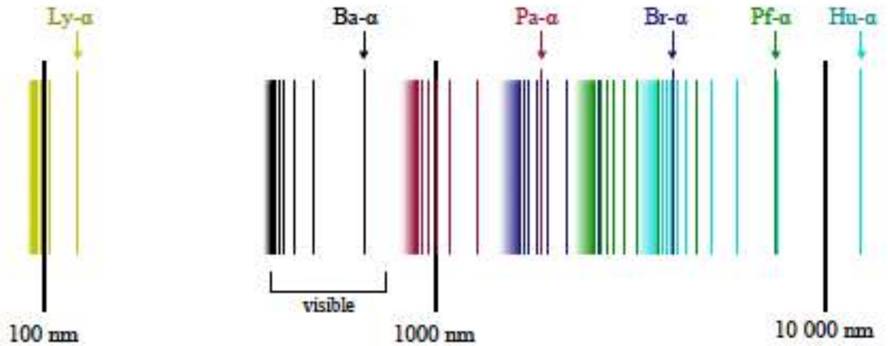
P_{H2} = 10 mbar
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

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

Capillary Discharge at SPARC_LAB



Stark broadening diagnostics

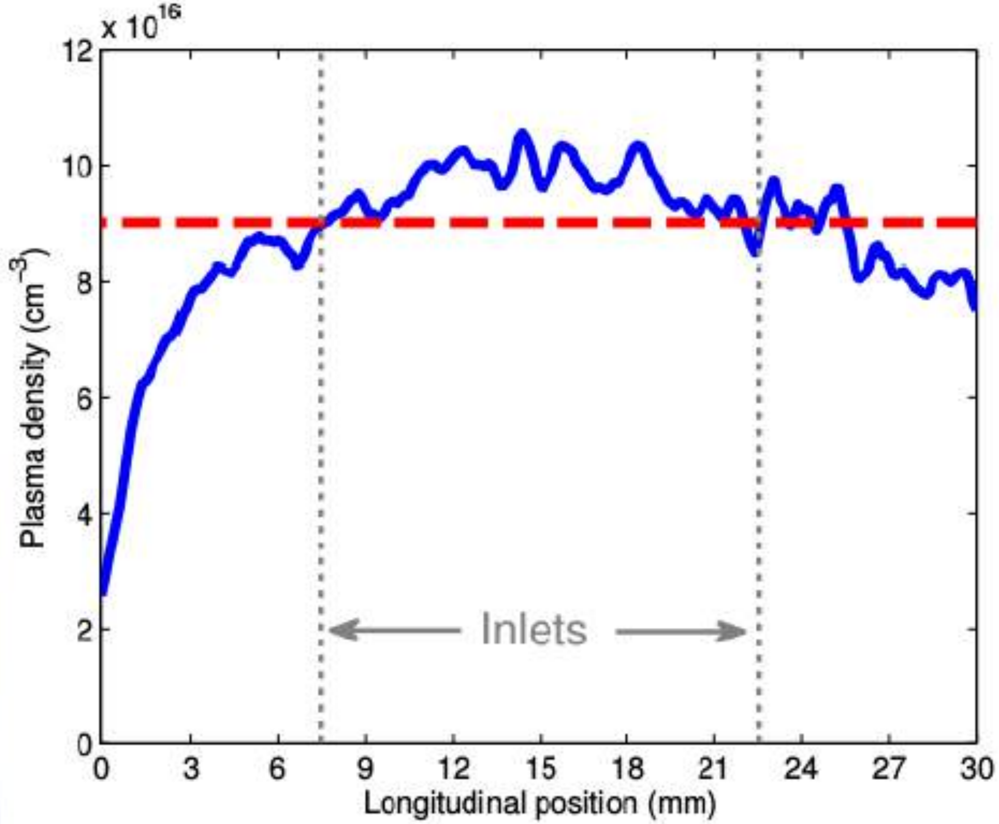


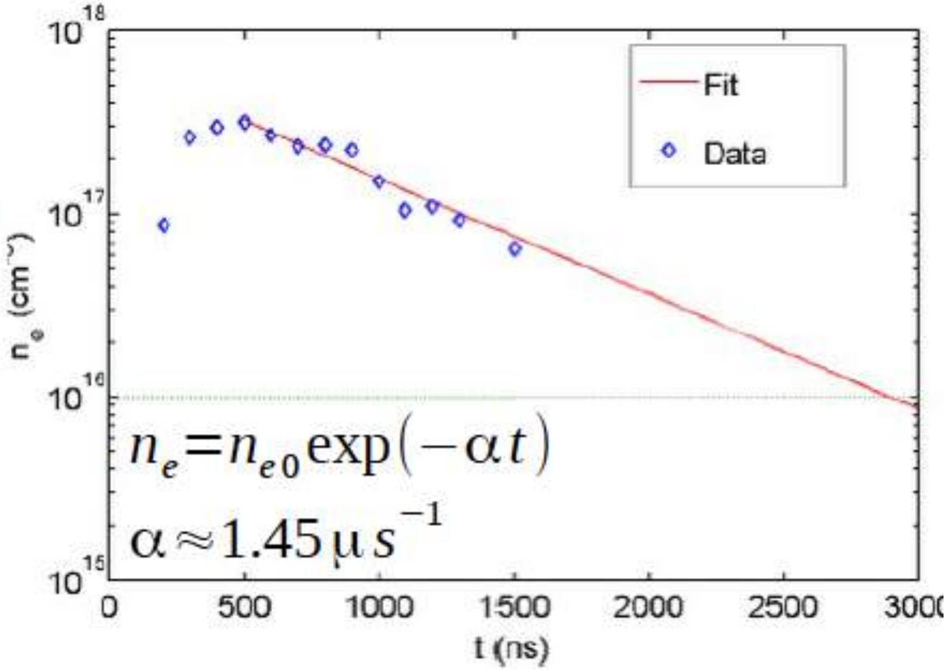
Hydrogen emission spectrum lines in the Balmer series

- Based on the **light emitted by plasmas** → measure of **electron plasma density**
- Plasma density can be determined by means of **Stark broadening effect**
  - *Spectral lines of Hydrogen are broadened as a result of the emitter interaction with the electric field produced by nearby ions.*
- The line-width is directly related to the plasma density → $\Delta\lambda \propto \alpha(T)\, n_0^{2/3}$
  - For Hydrogen, the H_β line (486 nm) is usually used → **α** is *less temperature dependent*.

Plasma characterization in capillary

Plasma density measurement from H_β Stark broadening





The plasma density is controlled through the delay after the discharge

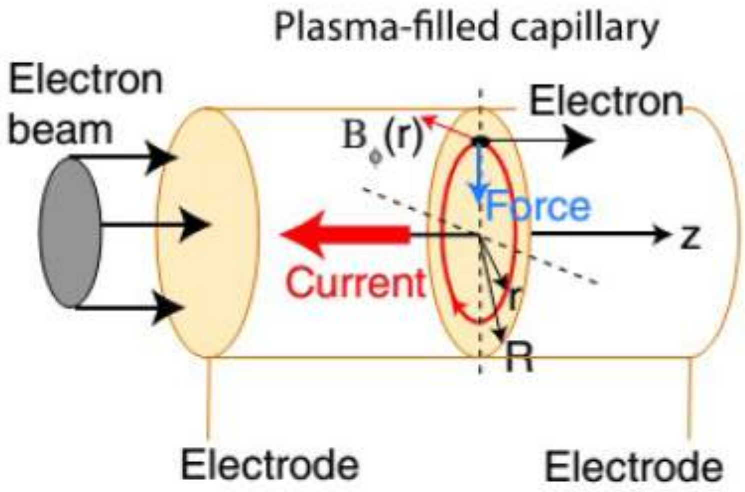
Beam Manipulation

Active plasma lens

- Focusing field produced by electric discharge in a plasma-filled capillary
  - *Focusing field produced, according to Ampere's law, by the discharge current*

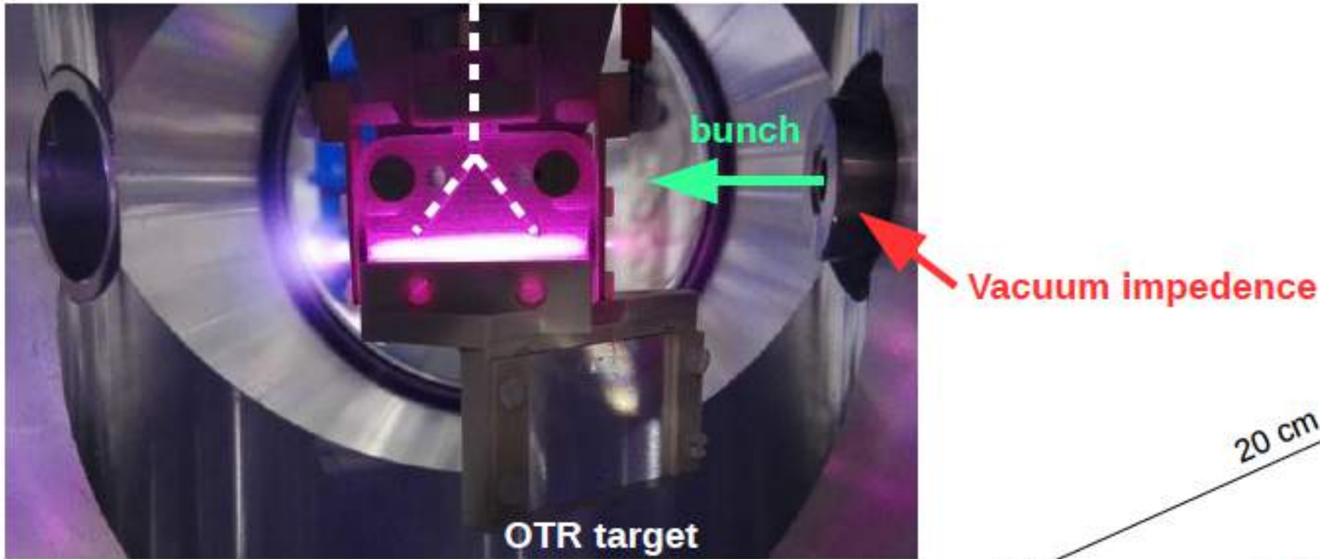
$$B_{\phi}(r)=\frac{1}{2}\int_{0}^{r}\mu_0 J(r')\,dr'$$

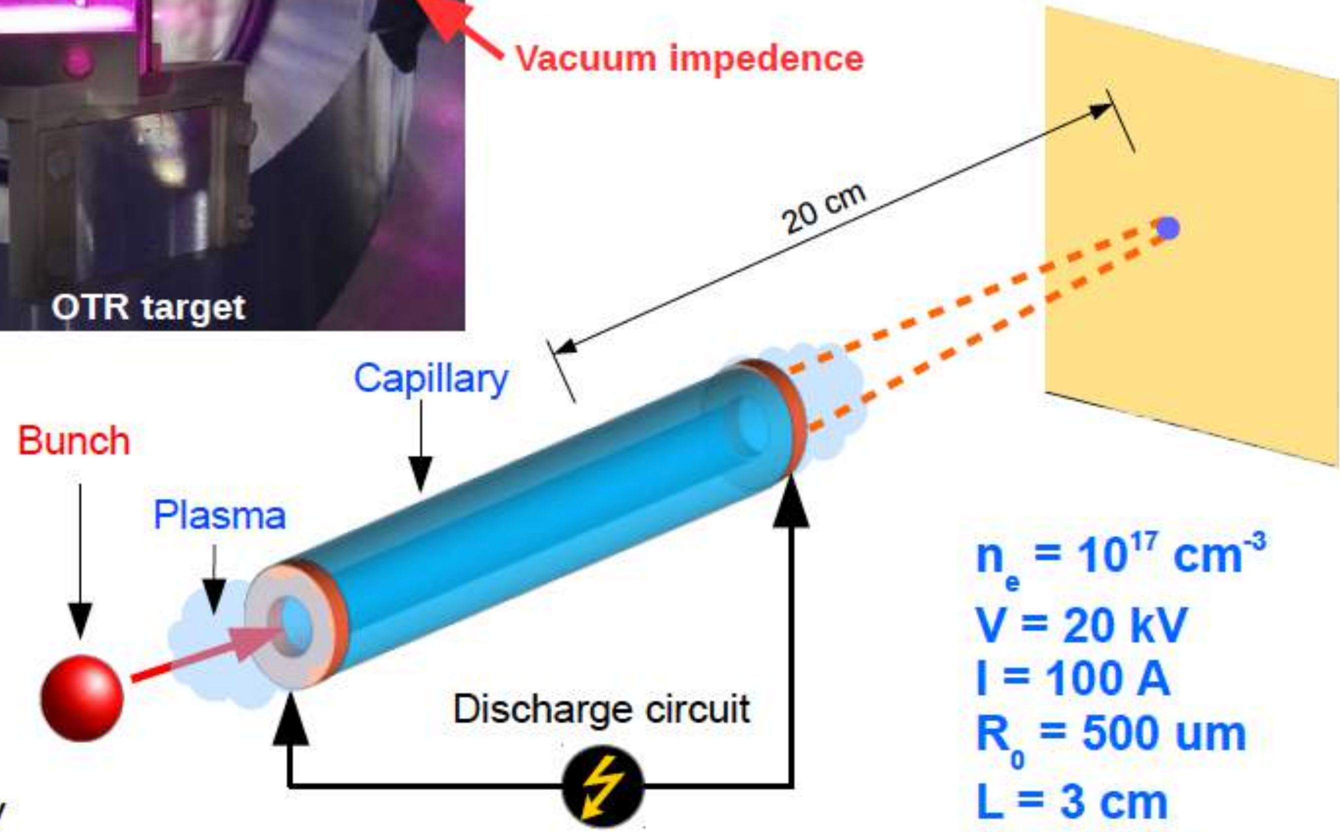
- ✔ Radial focusing
  - *X/Y planes are not dependent as in quads*
- ✔ Weak chromaticity
  - *Focusing force scales linearly with energy*
- ✔ Compactness
  - *Higher integrated field than quad triplets*
- ✔ Independent from beam distribution
  - *Not sensitive to longitudinal/transverse charge profile as in passive plasma lenses*



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

Experimental layout

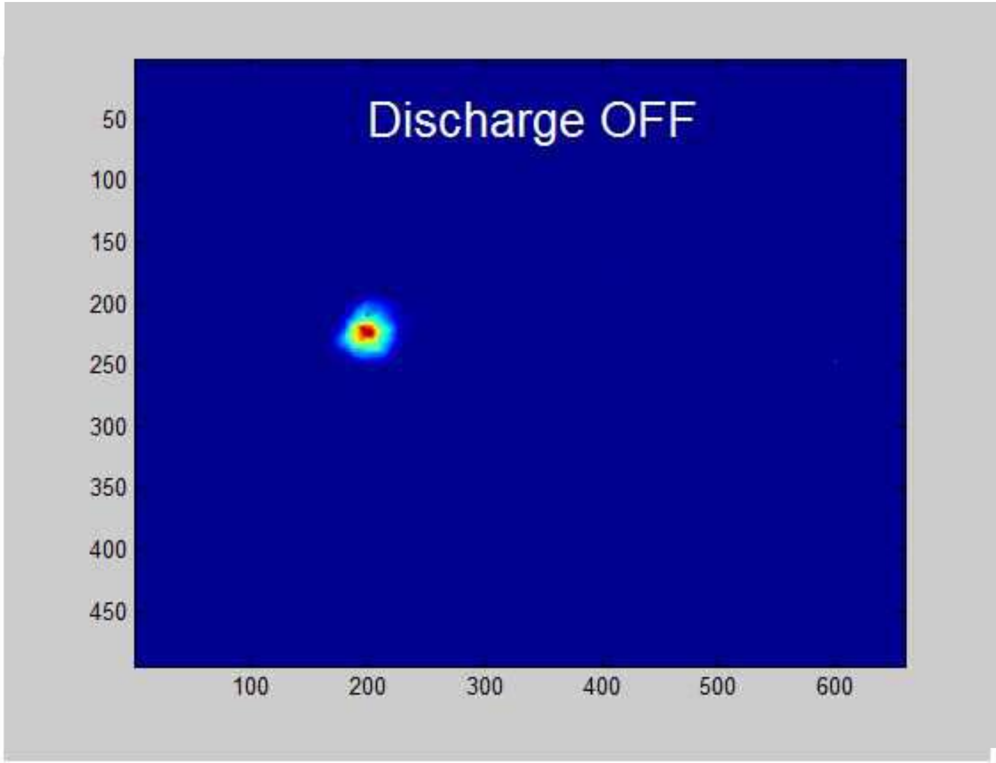


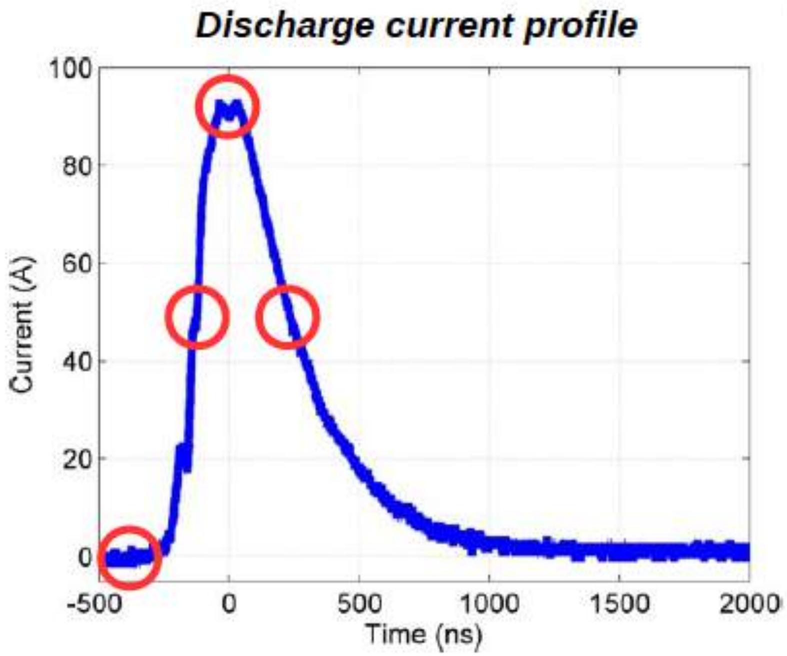


50 pC
1 ps
130 um
120 MeV
1 mm mrad

$n_e = 10^{17}$ 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

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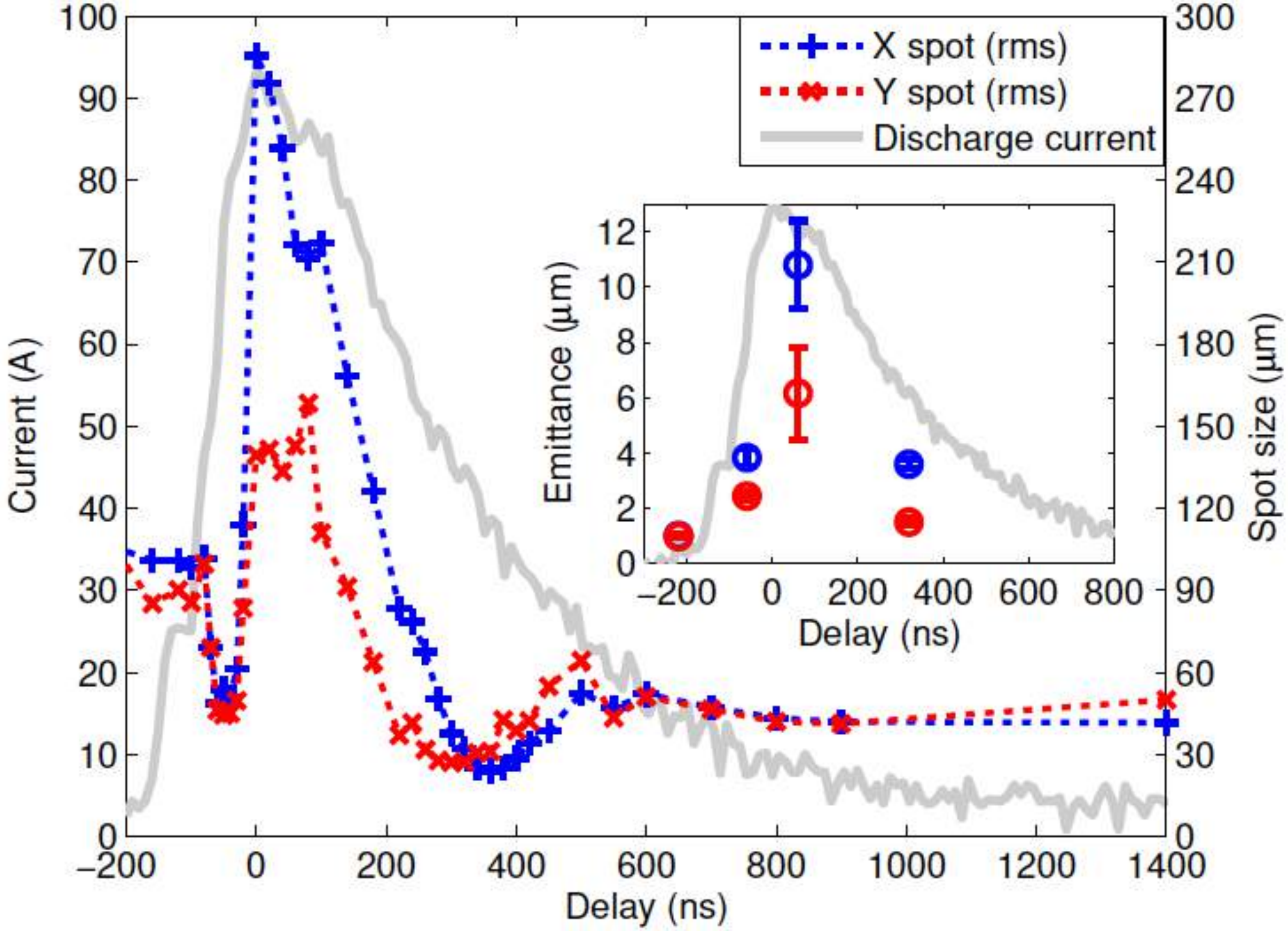
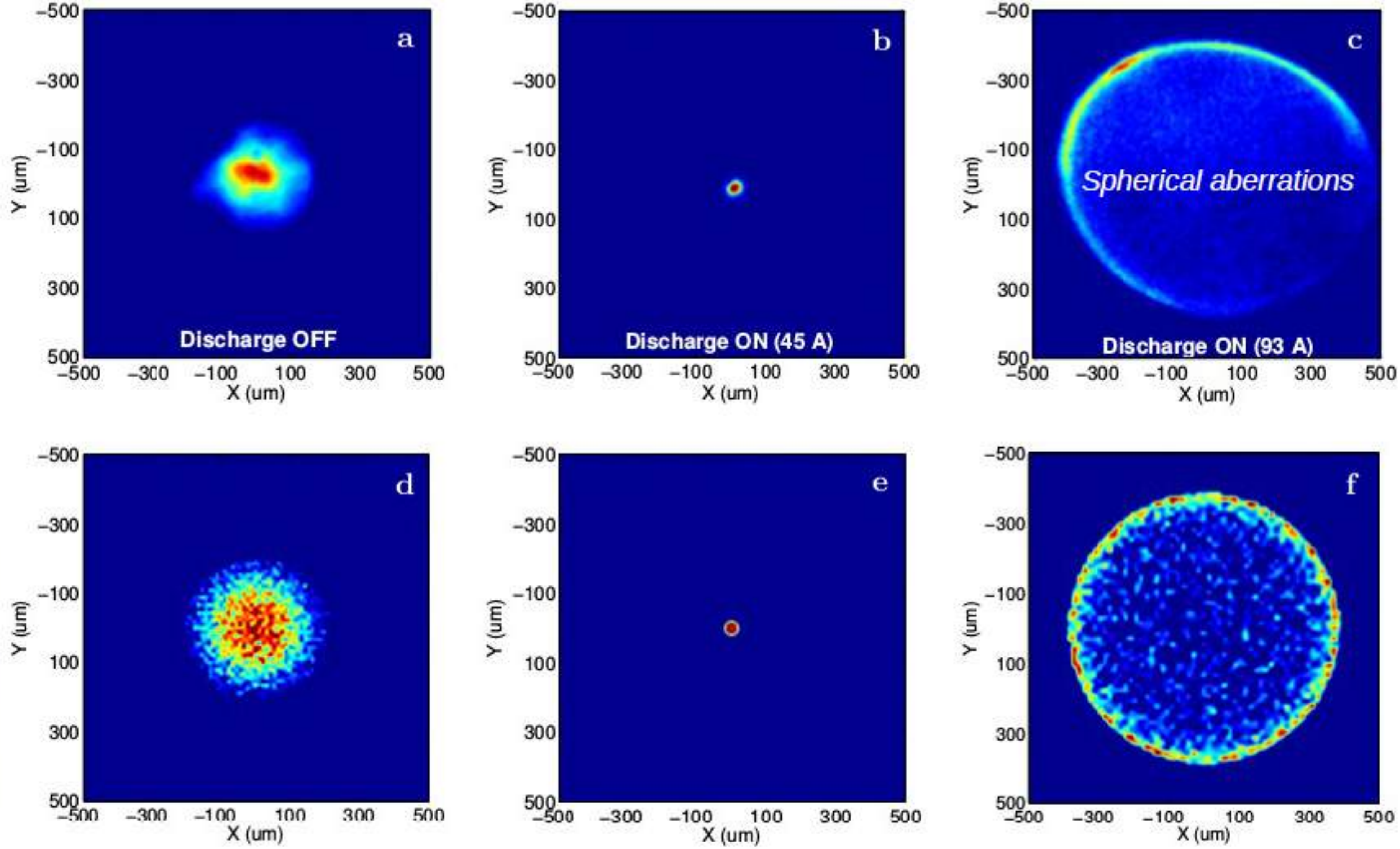
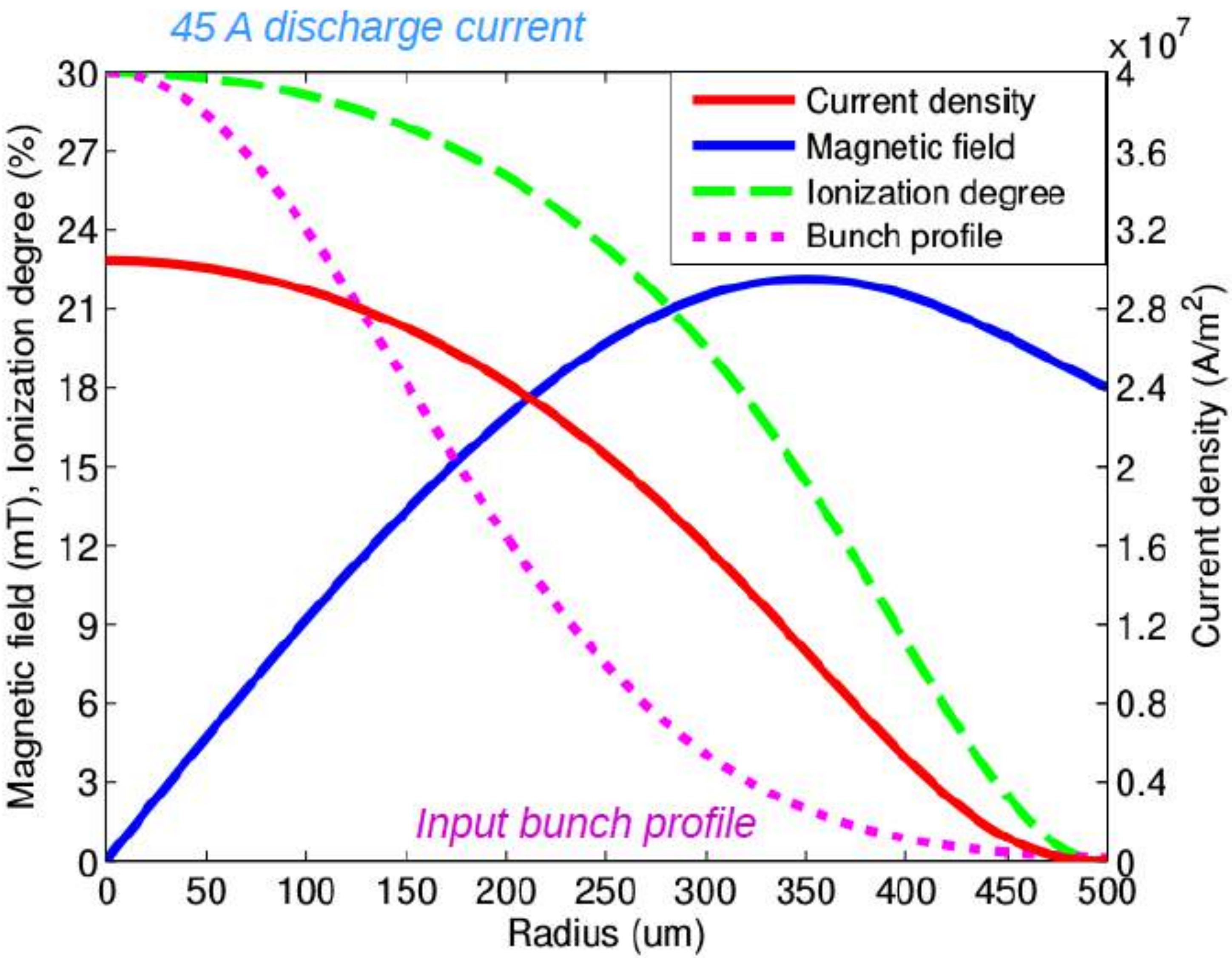
M. Ferrario,[1] F. Filippi,[1] A. Giribono,[4] V. Lollo,[1] A. Marocchino,[1] M. Marongiu,[4] A. Mostacci,[4]
G. Di Pirro,[1] S. Romeo,[1] A. R. Rossi,[5] J. Scifo,[1] V. Shpakov,[1] C. Vaccarezza,[1] F. Villa,[1]
and A. Zigler[6]



Results vs simulations

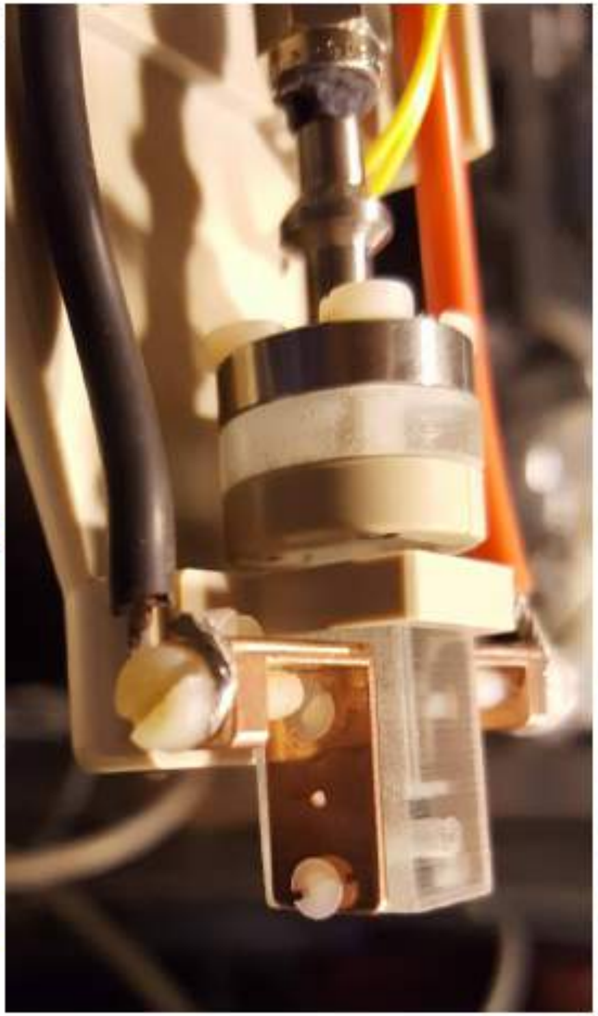


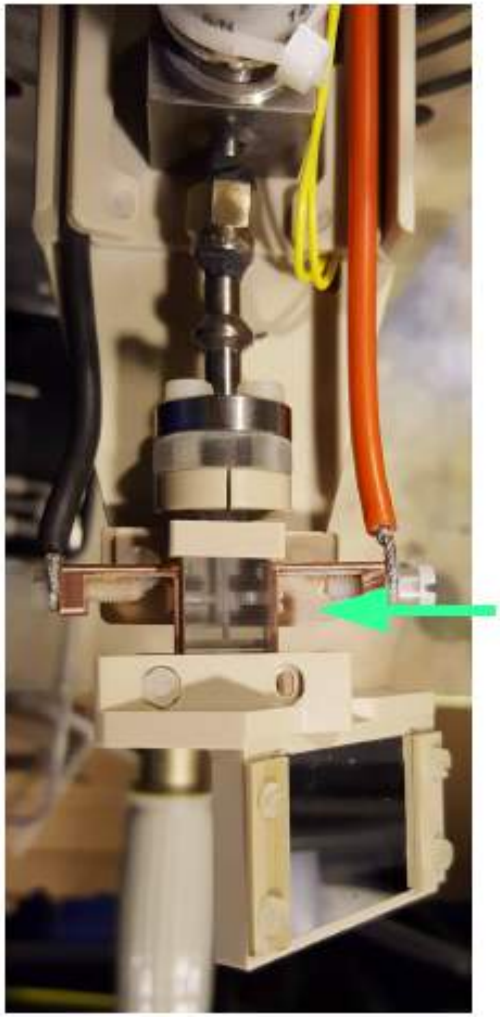
Nonlinear focusing field



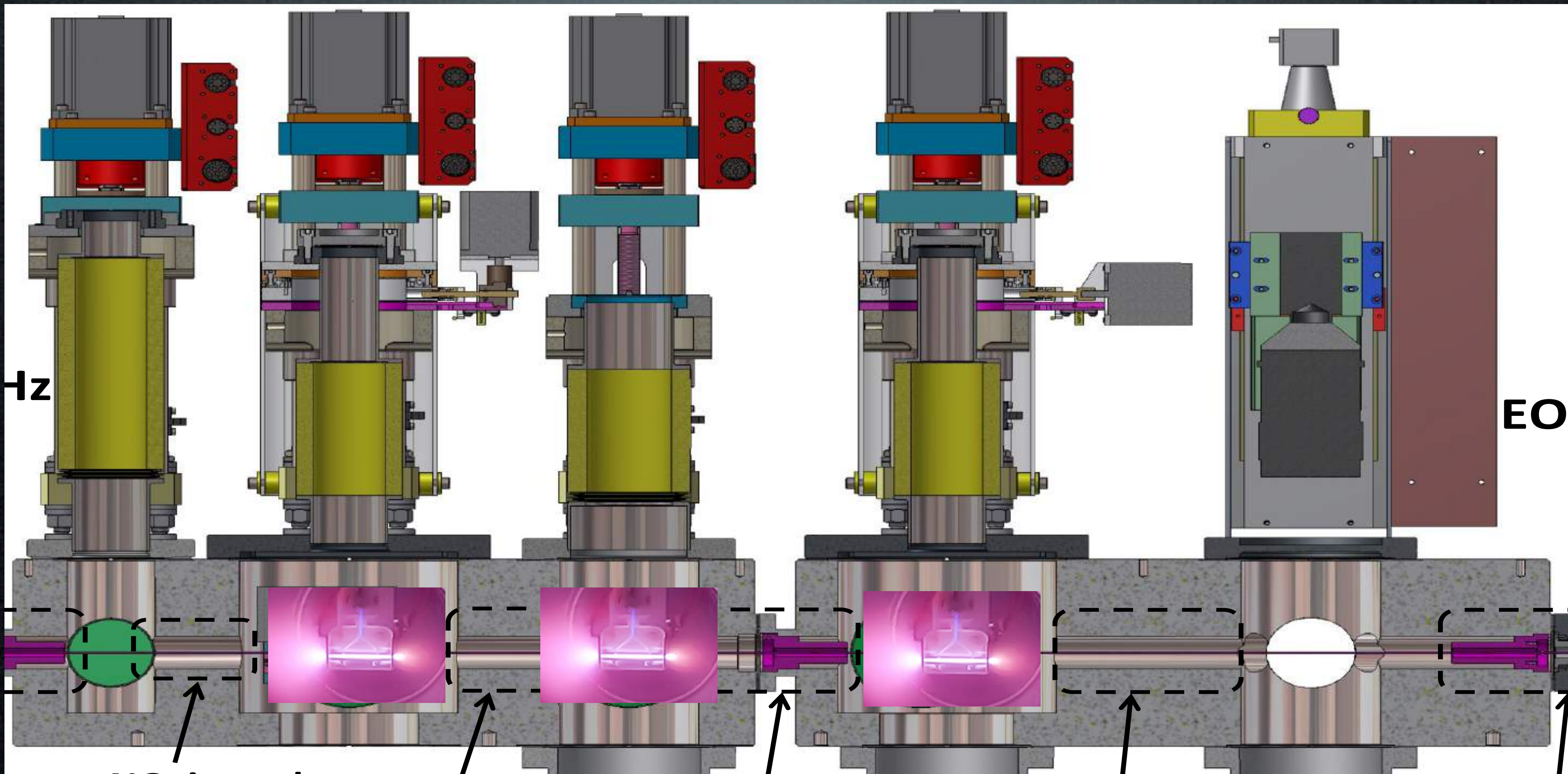
Preliminary results

- Preliminary results @ max focusing strength (140 A)
  - *Min spot size: 19-20 um*
  - *Normalized emittance: 1.5 um*
- First results show that the emittance after active lensing is still not preserved but much lower than before
  - *It indicates that the magnetic field felt by the beam is "more" linear*
- We will continue with tests on such setup and then move to the last configuration
  - *3 cm-long capillary*
  - *2 mm hole diameter to increase the linear region of the B field*





Plasma Driven FEL under investigation



Focusing Plasma Lens

PWFA module

Capture Plasma Lens


EAAC 2017
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TALKS
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