EuPRAXIA@SPARC_LAB

design study towards a new compact FEL facility at LNF

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On behalf of the study group

EAAC 2017

Isola d'Elba, 27 September 2017

INFN Istituto Nazionale di Fisica Nucleare

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- G. Castorina, L. Ficcadenti, S. Lupi, M. Marongiu, F. Mira, A. Mostacci. **Universita' degli Studi di Roma Sapienza and Sezione INFN**
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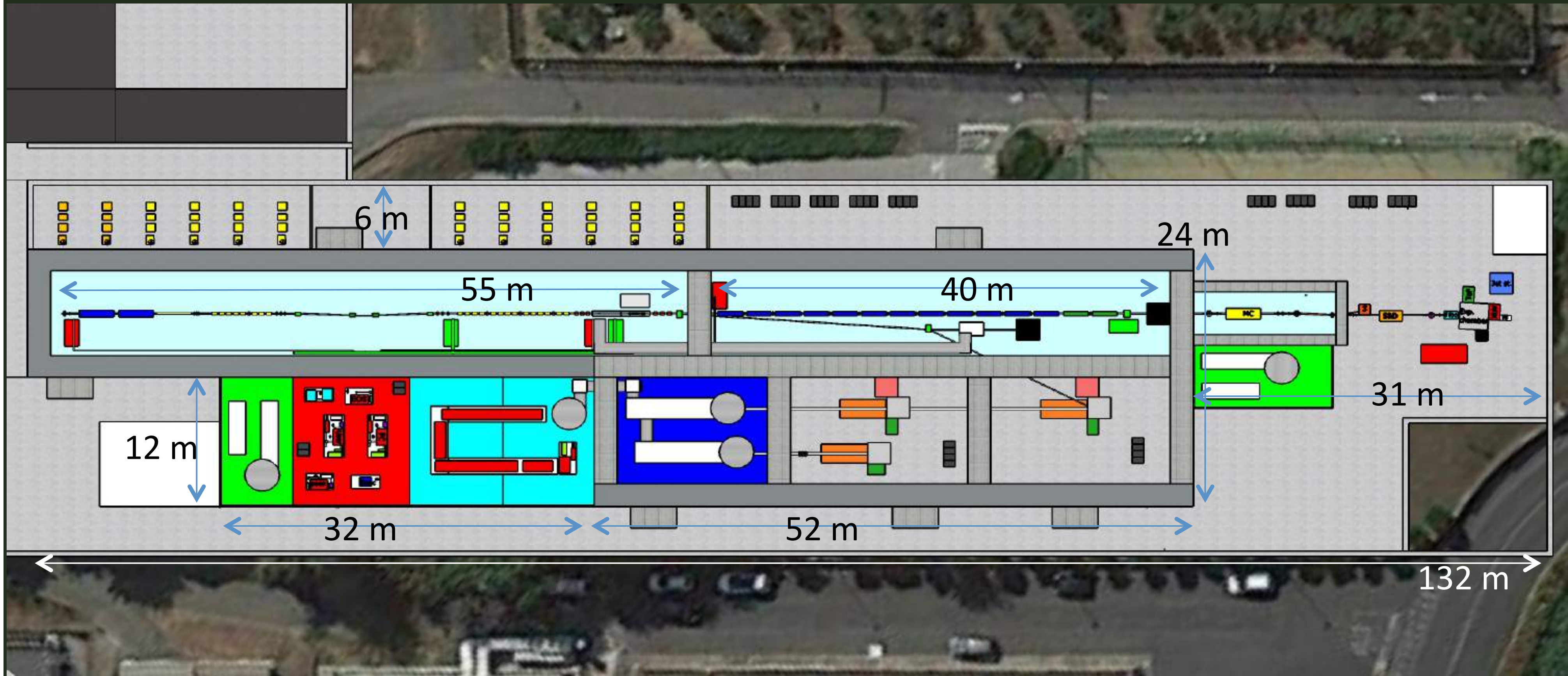
- A. Ricci. **RICMASS, Rome International Center for Materials Science Superstripes**
- A. Zigler. **Hebrew University of Jerusalem** J. B. Rosenzweig. **University of California Los Aangeles**

- Candidate LNF to host EuPRAXIA (1-5 GeV)
- FEL user facility (1 GeV – 3 nm)
- 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

CDR.1 delivery expected by Autumn

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)

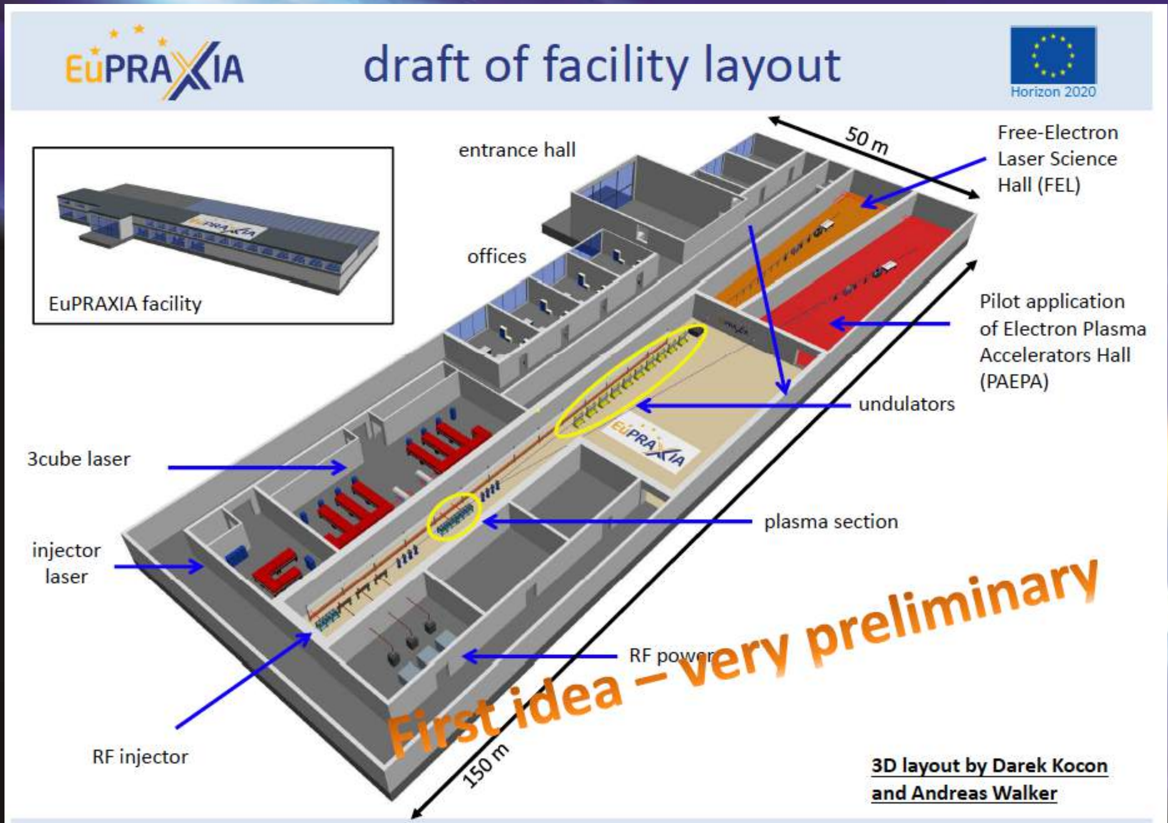
WG 4 – FEL pilot applications
- 4.1 Conventional and Plasma driven FEL (V. Petrillo)
- 4.2 Advanced FEL schemes (G. Dattoli)
- 4.3 Photon beam lines (F. Villa)
- 4.4 FEL user applications (F. Stellato)

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)

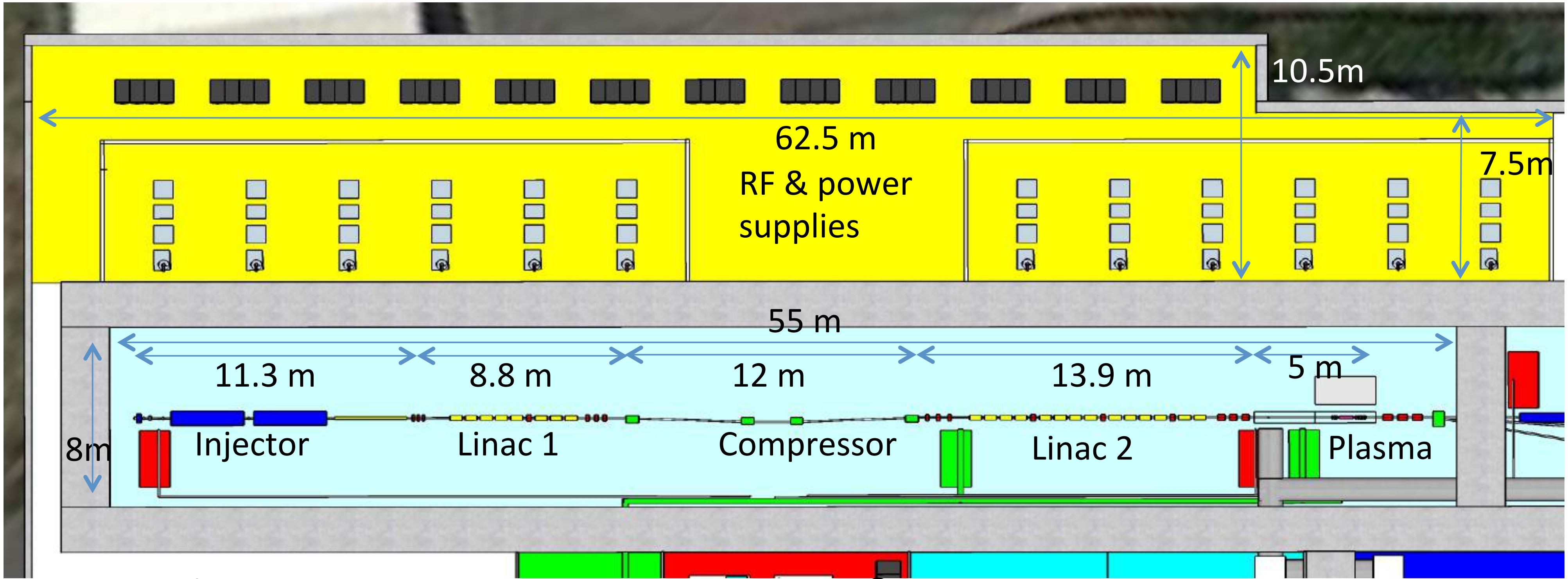
WG 7 – Infrastructure
- 7.1 Civil Engineering and conventional plants (U. Rotundo)
- 7.2 Control system (G. Di Pirro)
- 7.3 Radiation Safety (A. Esposito)
- 7.4 Machine layout

EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS



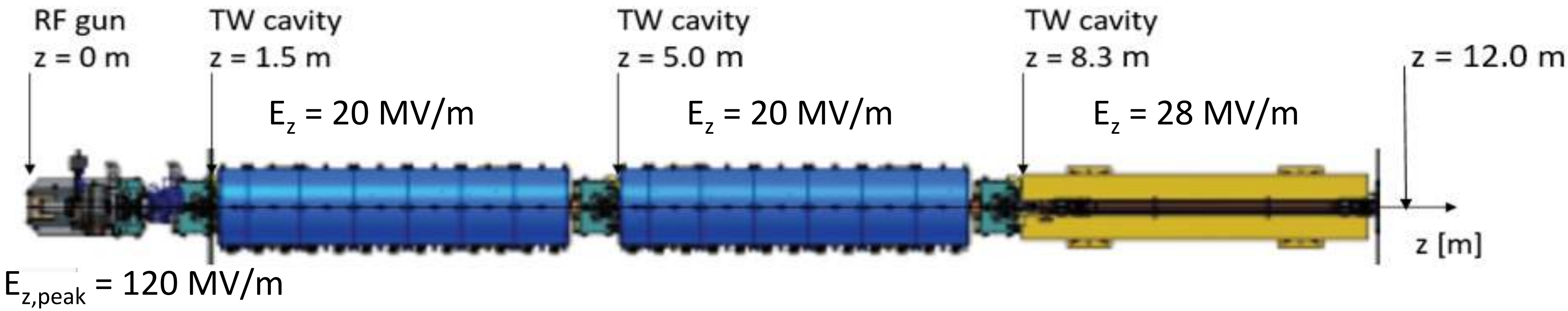
See R. Assmann talk tomorrow

Accelerator (X-band EU frequency – 100 Hz?)



- Injector:
  - Gun+solenoid
  - 3x 3m s-band sectons
- Linac 1:
  - 8x 0.5m x-band sections
  - Matching Quads
- Compressor:
  - 2.19° deflection
- Linac 2:
  - 14x 0.5m x-band sections
  - Matching Quads
- Plasma:
  - PMQ or Plasma Lens matching
  - 0.6 m capillary

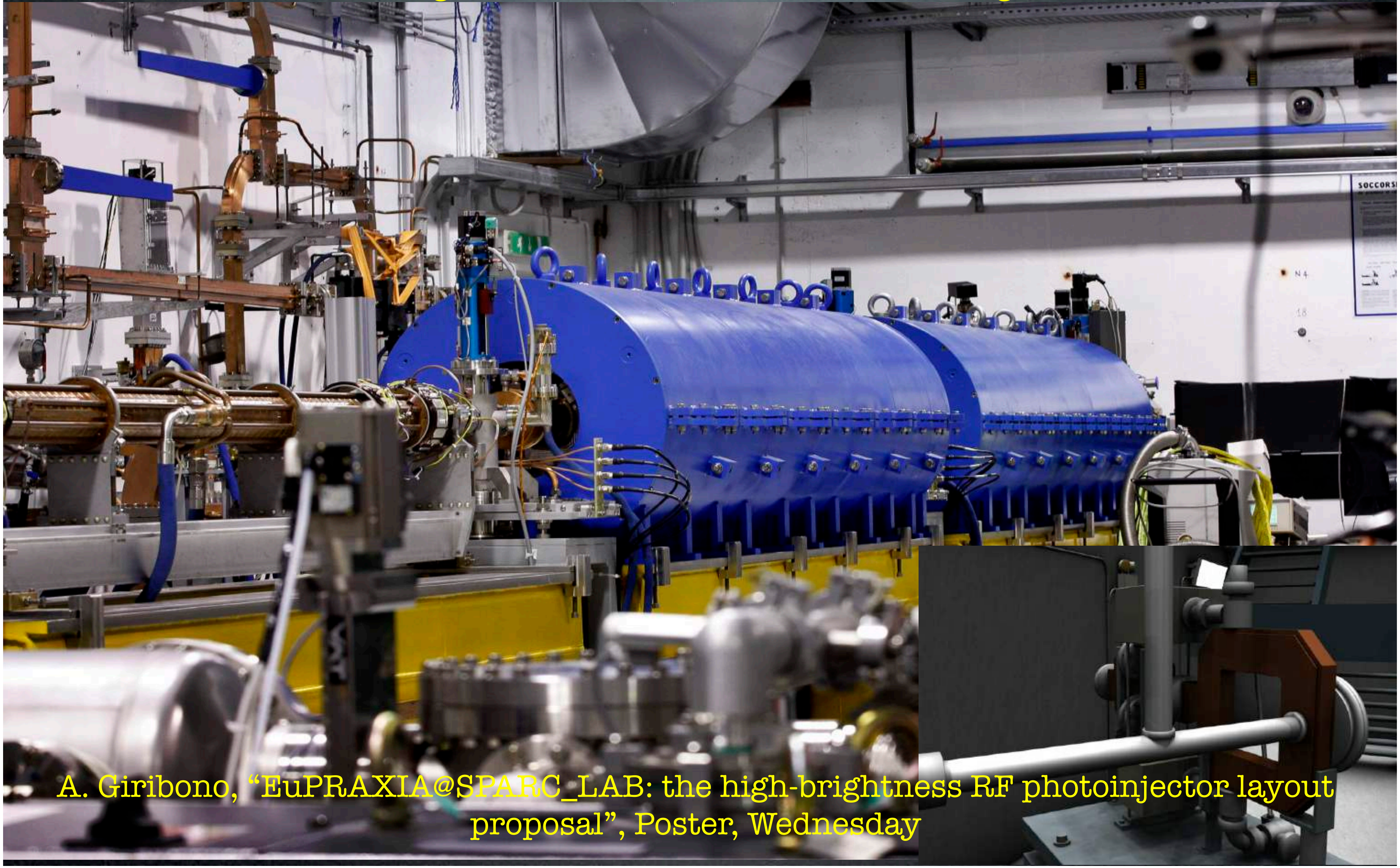
Photo-injector layout



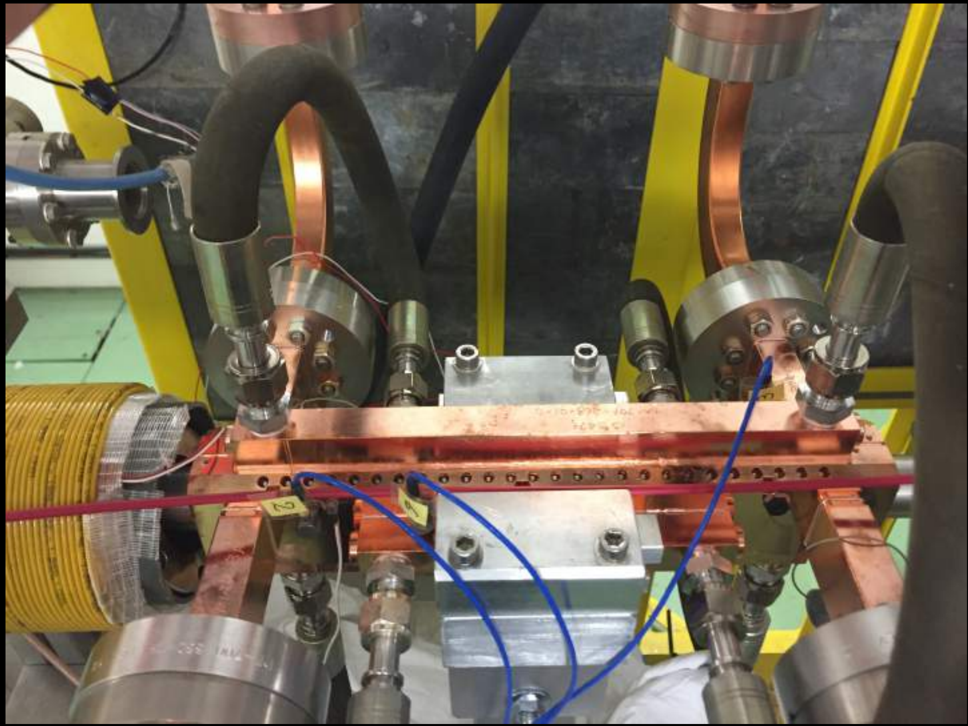
SPARC-like design: S-band photoinjector consisting of 1.6 cell UCLA/BNL type SW RF gun, equipped with a copper photo cathode and an emittance compensation solenoid, followed by three TW SLAC type sections; other two compensation solenoids surround the first and the second S-band cavities for the operation in the velocity bunching scheme

Beam dynamics simulations have been performed by means of **TSTEP** to take into account space charge degradation effects **in the photo-injector.**

HB photo- injector with Velocity Bunching



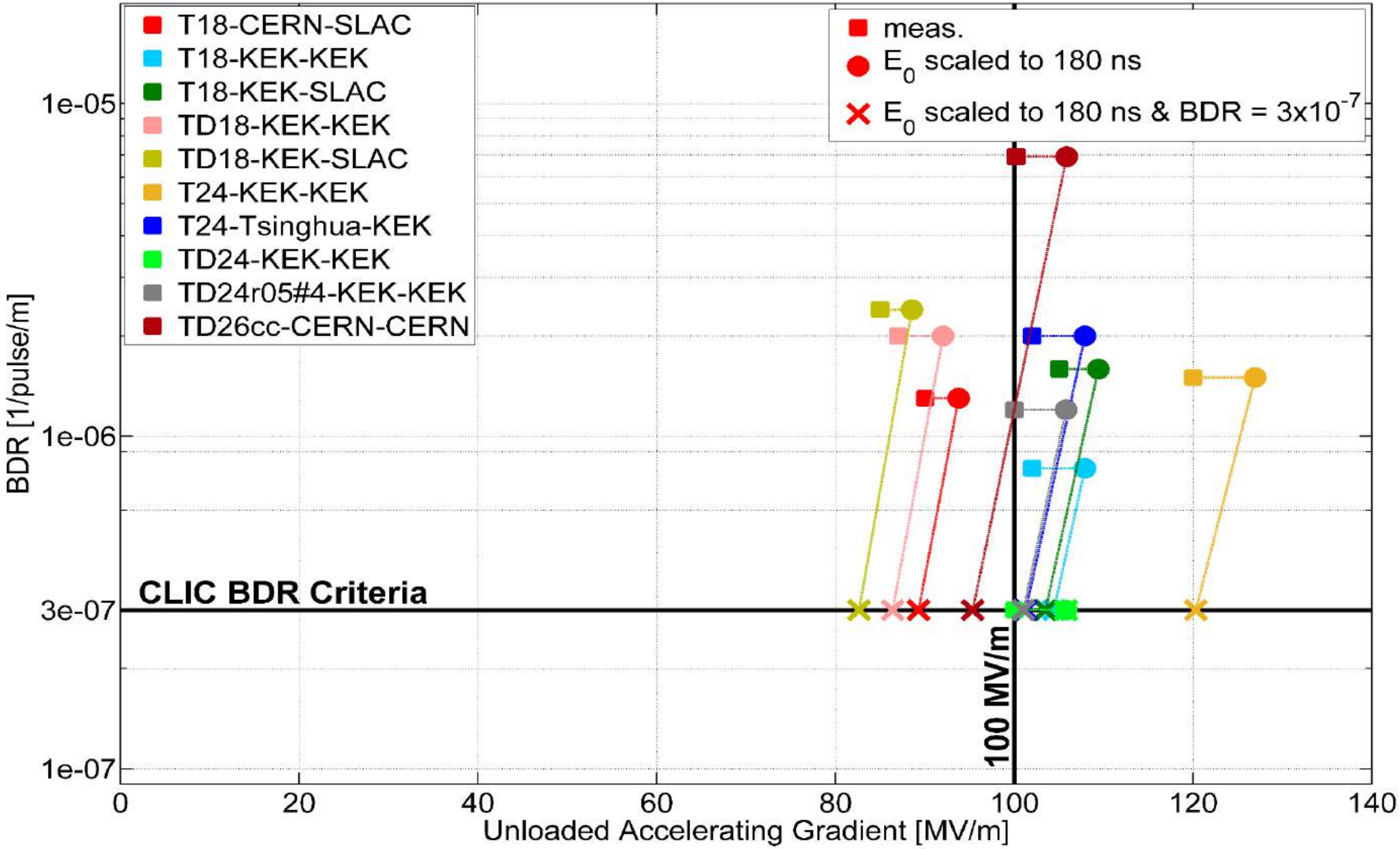
A. Giribono, “EuPRAXIA@SPARC_LAB: the high-brightness RF photoinjector layout proposal”, Poster, Wednesday

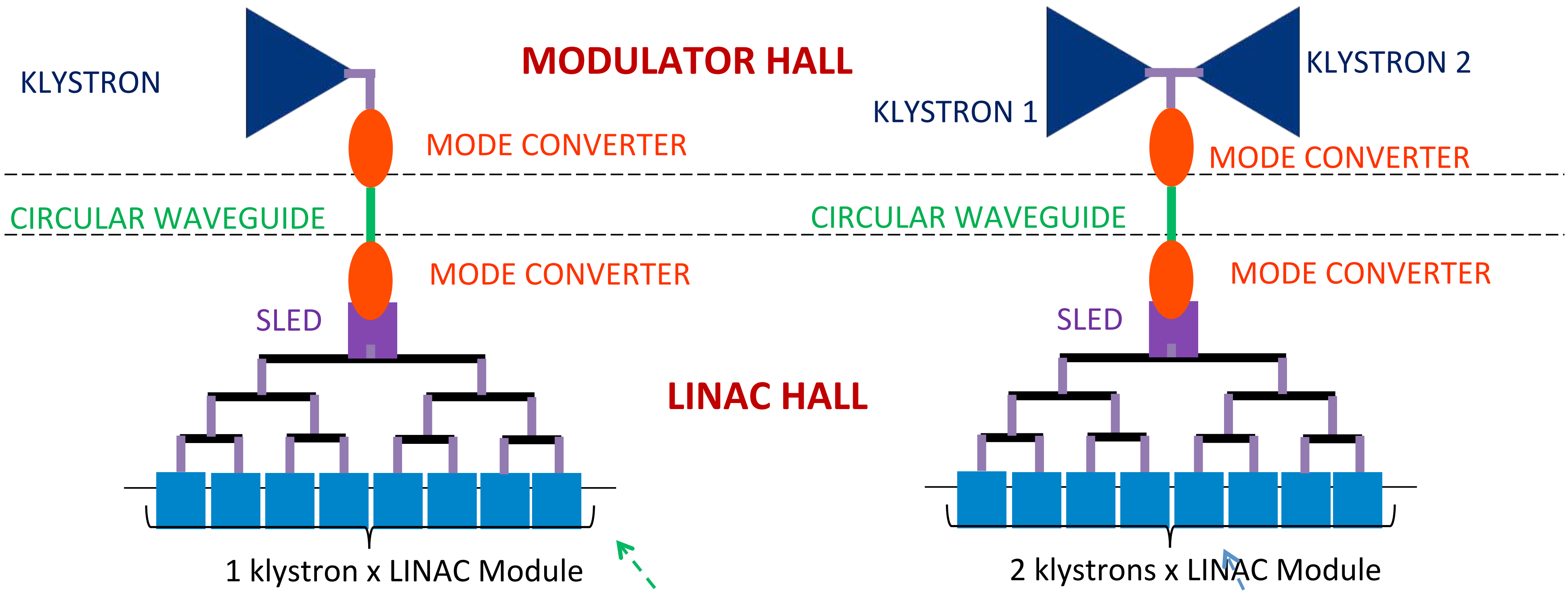


M. Diomede, "Preliminary RF design of an X-Band LINAC for the EuPRAXIA@SPARC_LAB project", Poster, Monday

C. Vaccarezza, "EUPRAXIA at SPARC_LAB: Beam Dynamics studies for the X-band Linac, WG4, Today

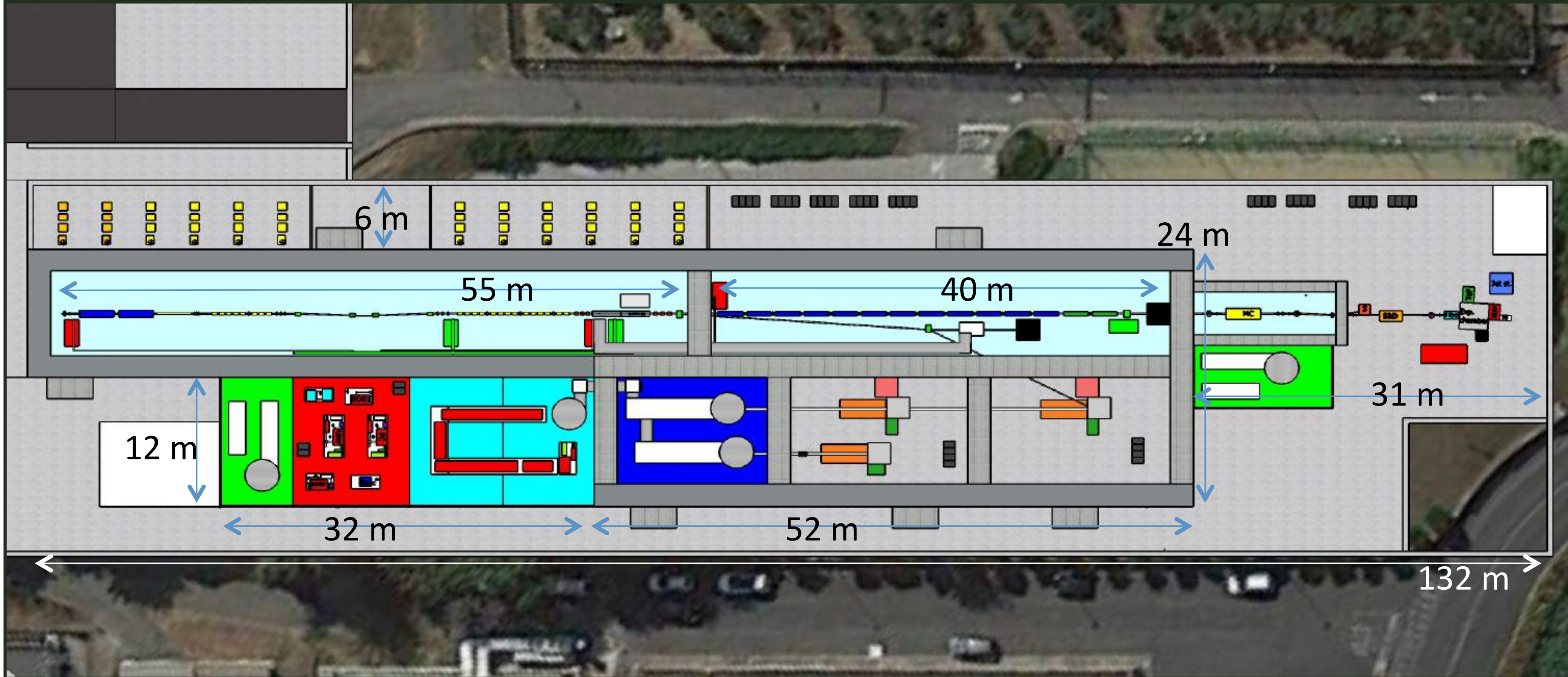
Performance summary at CLIC specifications



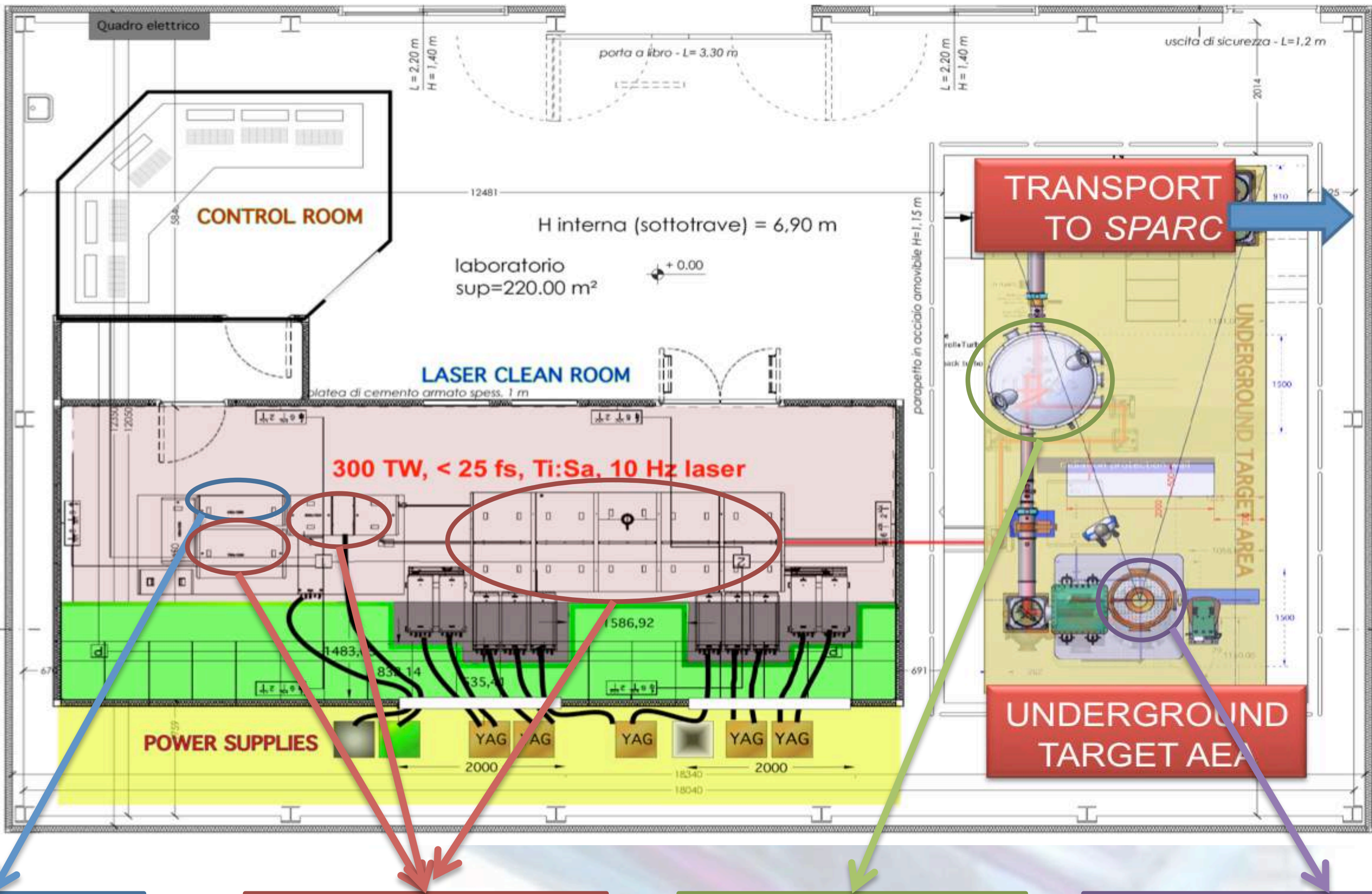


X-Band LINAC parameters			
total active length L_t	16 m		
Number of sections N_s	32 (4 modules x 8 sections)		
available RF power	50 MW (@klystron output coupler) 40 MW (@ section input couplers)		
	Injection in the plasma	Injection in the undulator	Ultimate
linac energy gain ΔW_{linac}	480 MeV	910 MeV	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

- The High Power Laser system



Ti:Sa FLAME laser



Stretcher

Amplifiers

Compressor

LWFA
Electron Self Injection
And
Protons

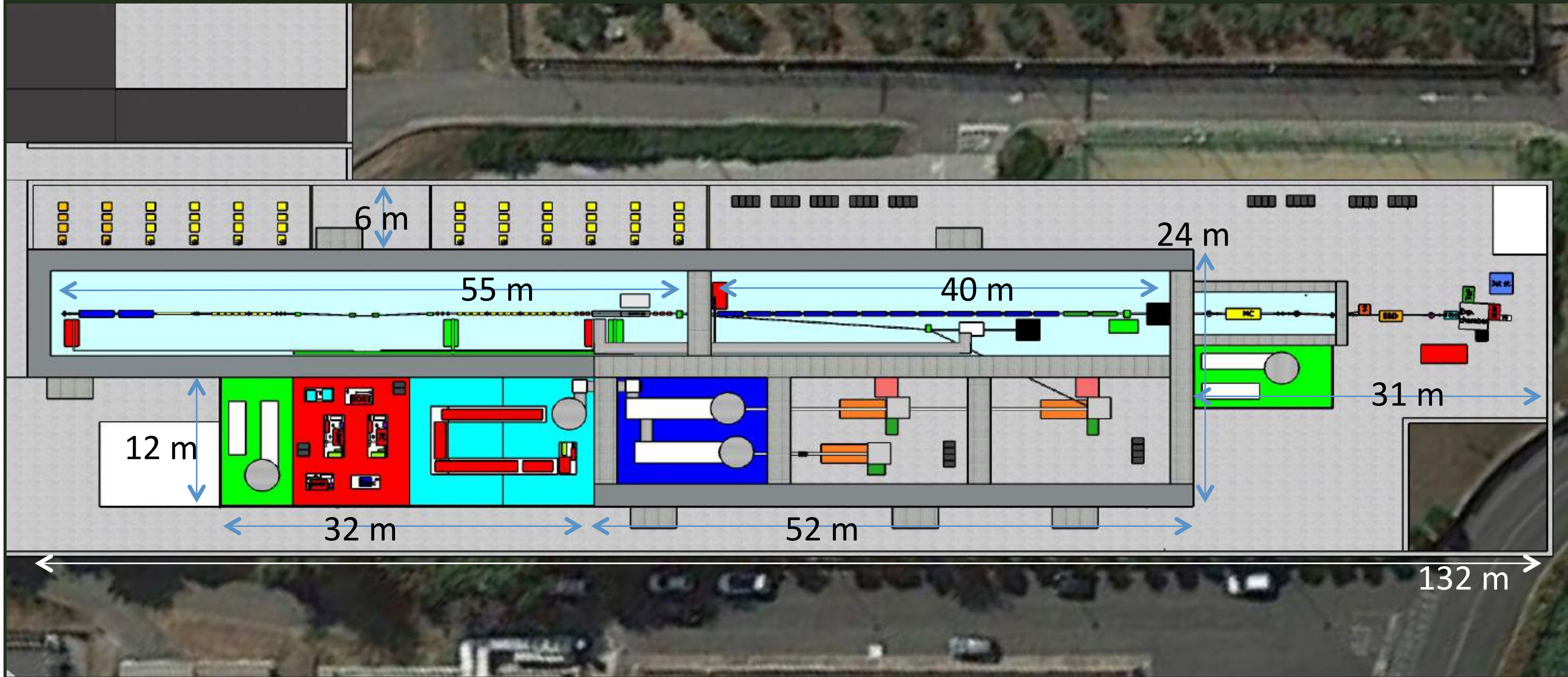
Parameters of the 500 TW laser

Parameters	FLAME today	FLAME upgraded
Wavelength [nm]	800	800
Bandwidth [nm]	60-80	60-80
Repetition rate [Hz]	10	1-5
Max energy before compression [J]	7	20
Max energy on target [J]	4	13
Min pulse length [fs]	25	25
Max power [TW]	250	500
Contrast ratio	10^{10}	10^{10}

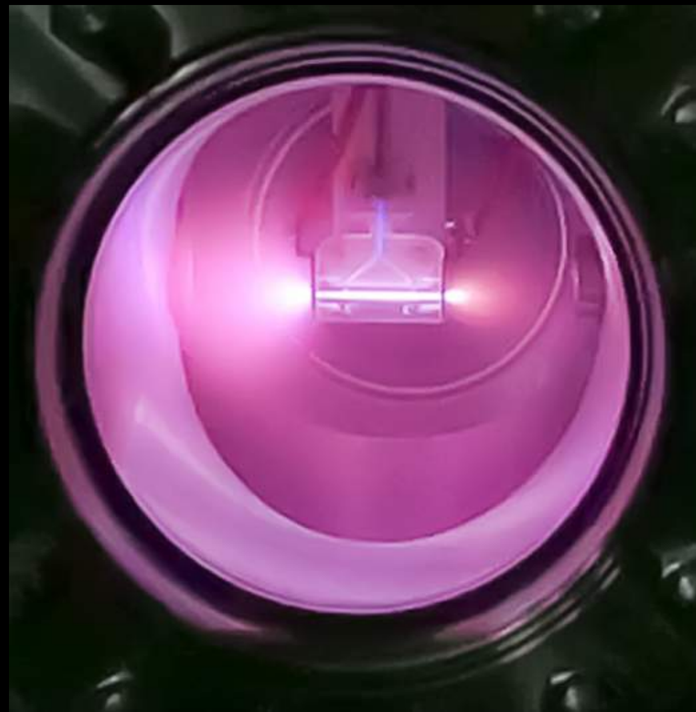
Comparison between the parameters of the actual FLAME system and the upgraded FLAME system.

M.P. Anania, The FLAME laser at SPARC_LAB, WG7, Monday

- The Plasma Accelerator Complex

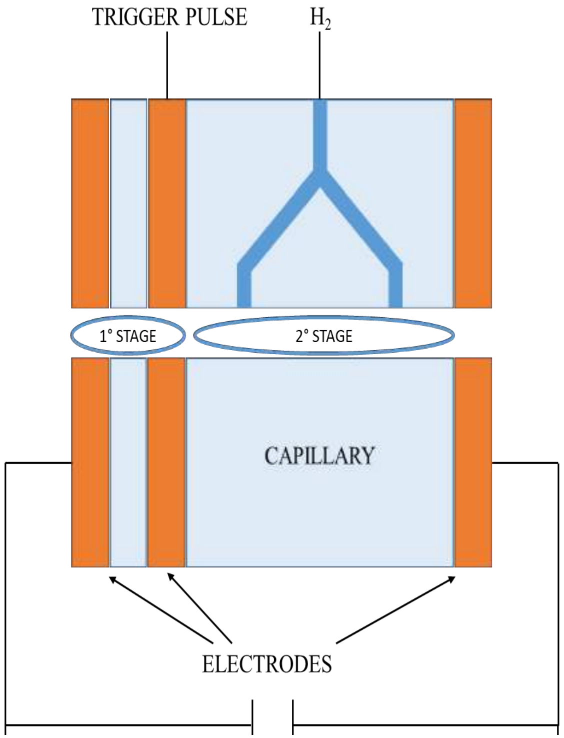


Capillary Discharge at SPARC_LAB



Plasma source

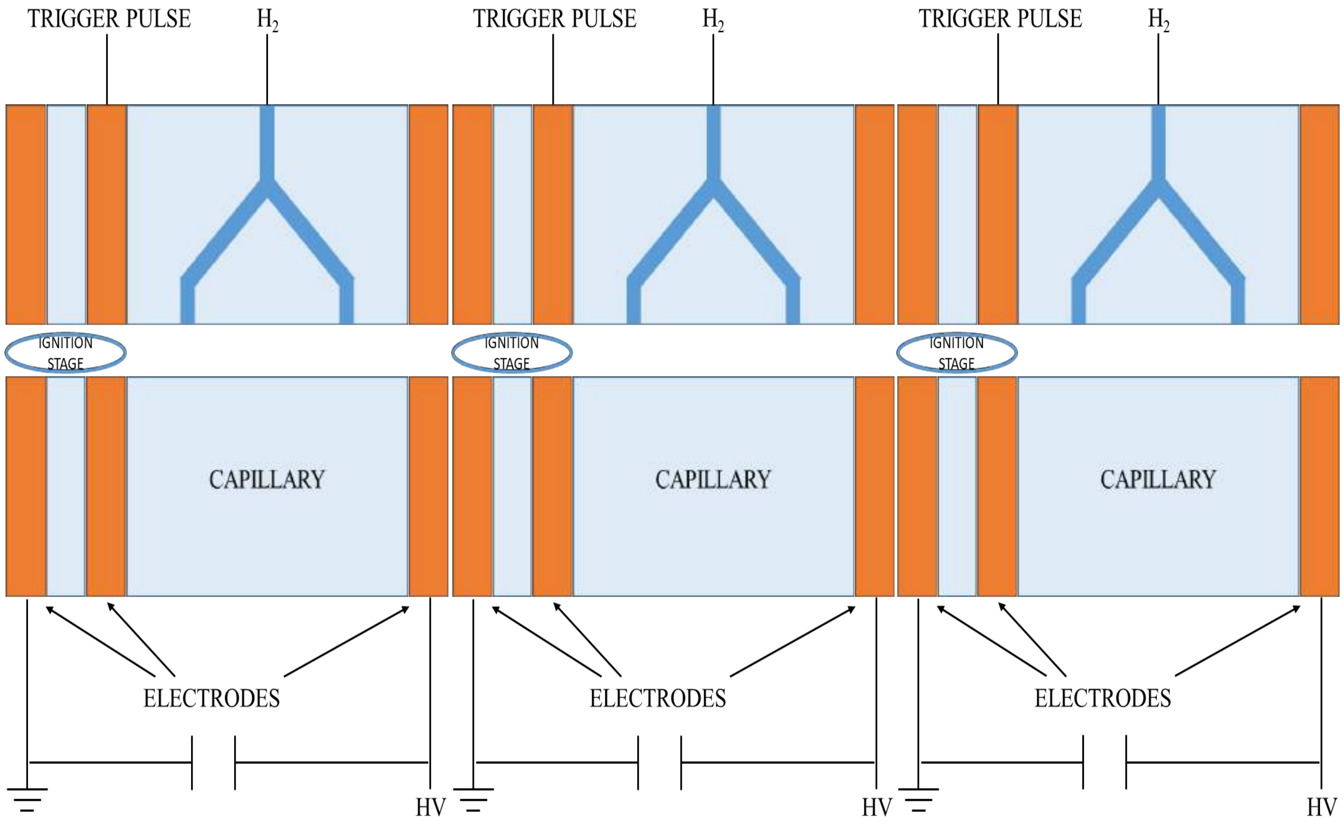
We preionize the capillary with a preformed plasma prior the main discharge. The initial plasma is formed in a short primary capillary by a high voltage pulse discharge. Part of this plasma and free electrons expanding into a long capillary that is connected to a high voltage capacitor. Since the discharge 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.



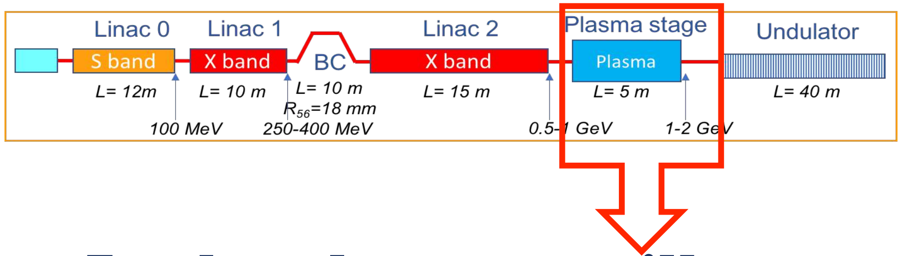
F. Filippi, "Gas-filled capillary discharge for tens-centimetre long plasma channel", Poster, Today

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.



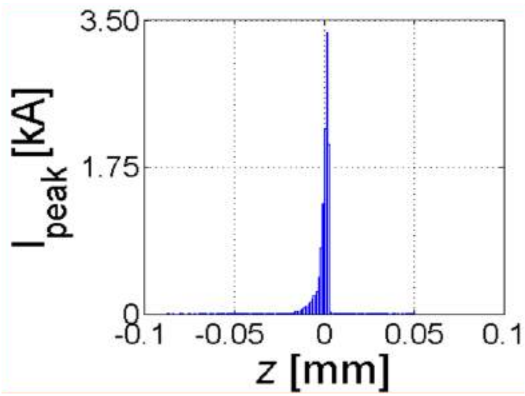
F. Filippi, "Gas-filled capillary discharge for tens-centimetre long plasma channel", Poster, Today



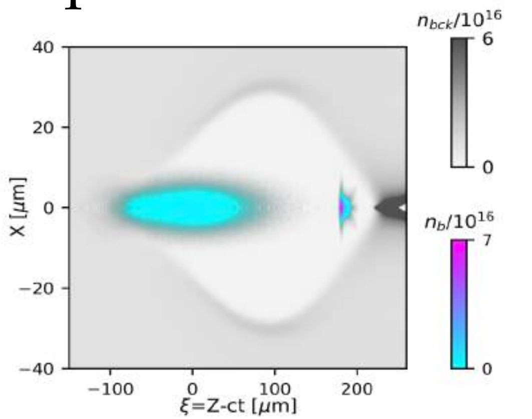
Architect simulations for particle driven plasma accelerated electron

In the plasma capillary

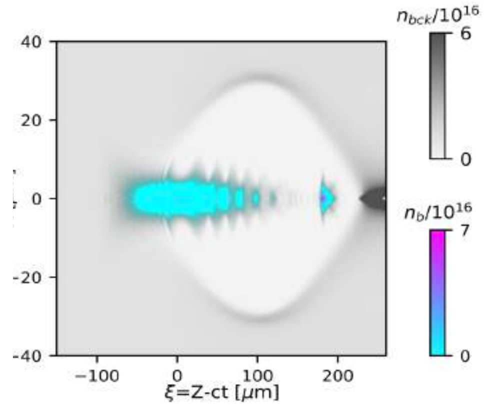
T-Step: hist (witness)



at plasma entrance

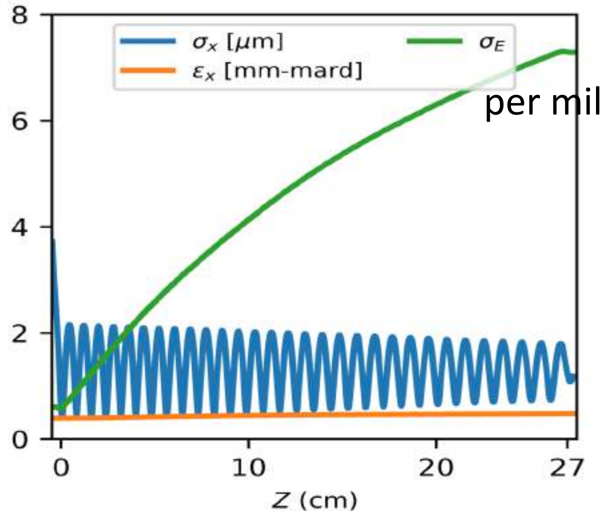


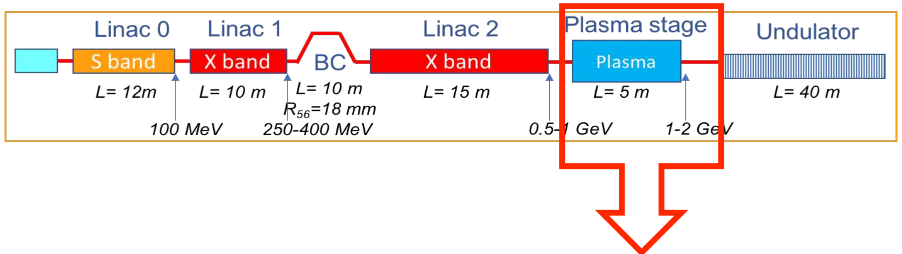
at exit



witness parameters	Trailing bunch	Trailing bunch End Capillary
Q (pC)	29	29
σ_x (μm)	0.73	1.2
σ_y (μm)	1.3	1.2
σ_z (μm)	3.5	3.3
ε_x (μrad)	0.4	0.48
ε_y (μrad)	0.4	0.81
σ_E (%)	0.06	0.73
E (GeV)	0.5	1

witness evolution



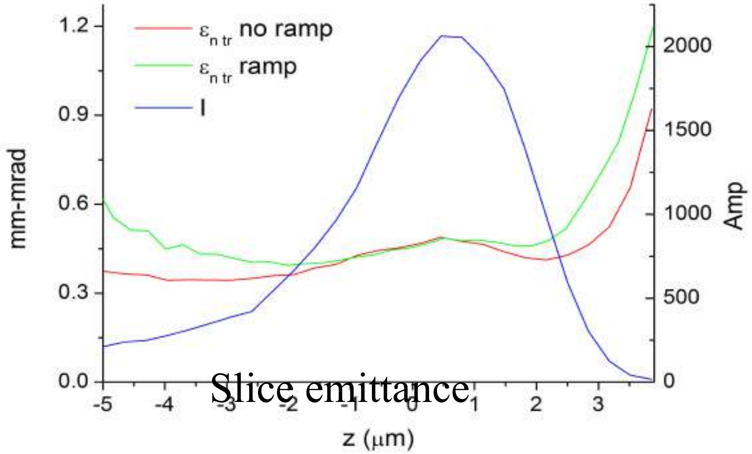


Q-Fluid simulations of LWFA external injection

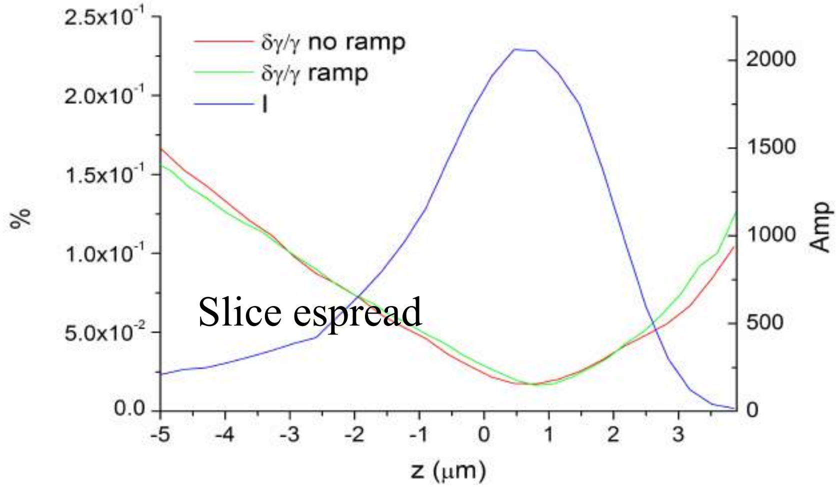
In the plasma capillary

- Simulations with QFluid[1]
- Plasma density: 10^{17} cm^{-3}
- Plasma plateau length: 6 cm
- Exponential ramp with characteristic length $\lambda_r = 2.5$ mm
- Ramps span from 10^{14} to 10^{17} cm^{-3} for a total length $L_r = 1.75$ cm
- Effective accelerating gradient: 9 GV/m
- $\varepsilon_{n\,tr} = (\varepsilon_{n\,x}{}^2 + \varepsilon_{n\,y}{}^2)^{1/2}$

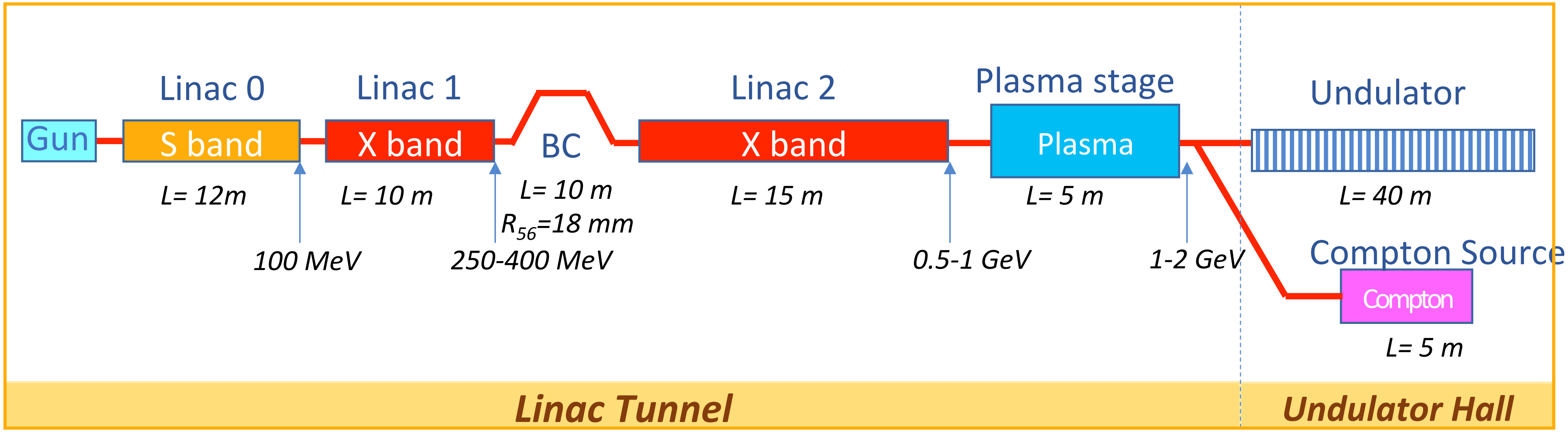
	Input	Output w/o ramp	Output with ramp
E [MeV]	536	1060	1035
ΔE/E	$7\ 10^{-4}$	$1.2\ 10^{-2}$	$7\ 10^{-4}$
$I_{peak\ FWHM}$ [kA]	1,8	1,8	1,8
Q [pC]	30	27	27
$\sigma_{z\ rms}$ [µm]	3,7	3,3	3,3
$\sigma_{z\ FWHM}$ [µm]	3,3	3,2	3,2
$\varepsilon_{n\ tr}$ [mm-mrad]	0,44	0,47	0,47
$I_{peak\ slice}$ [kA]	2,1	2,1	2,1



A. Rossi, "High brightness, plasma boosted beams for driving a Free Electron Laser", WG1, Monday



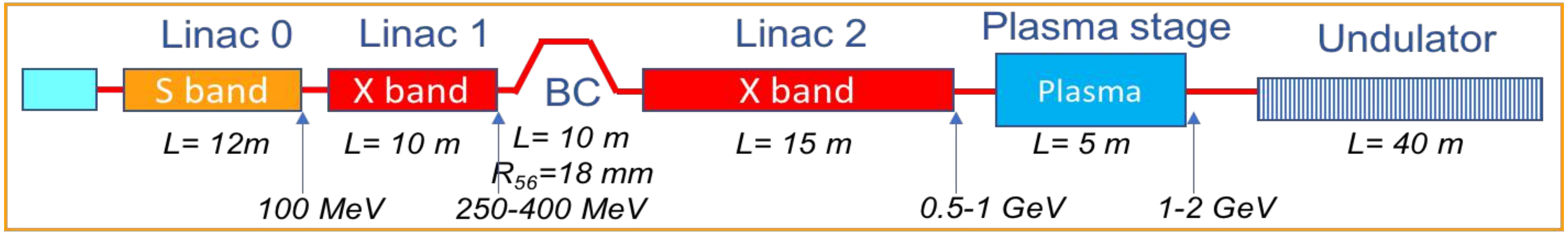
EuPRAXIA@SPARC_LAB: S2E results

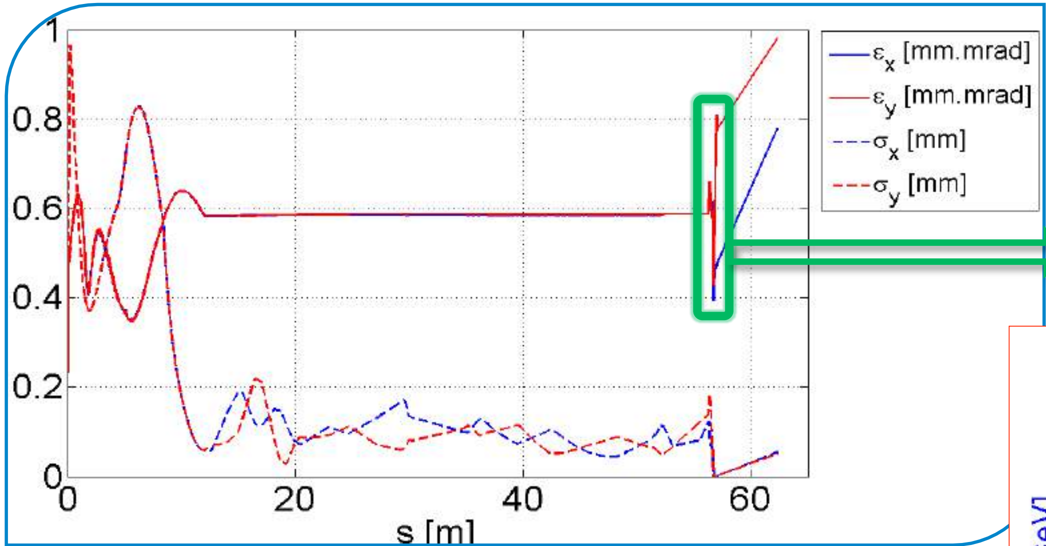


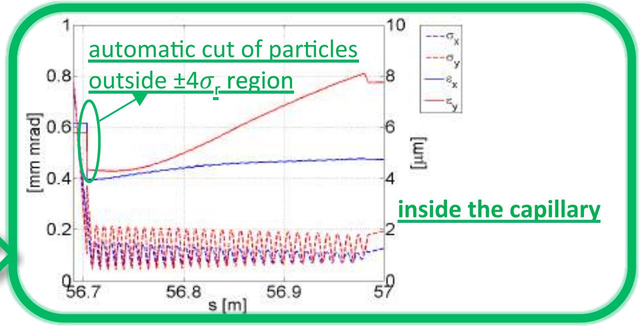
- **WP1: Low Charge-High Current** from the Photoinjector: 30 pC-3KA FWHM per bunch with only velocity bunching, suitable both for Beam Driven and Laser driven acceleration in Plasma,

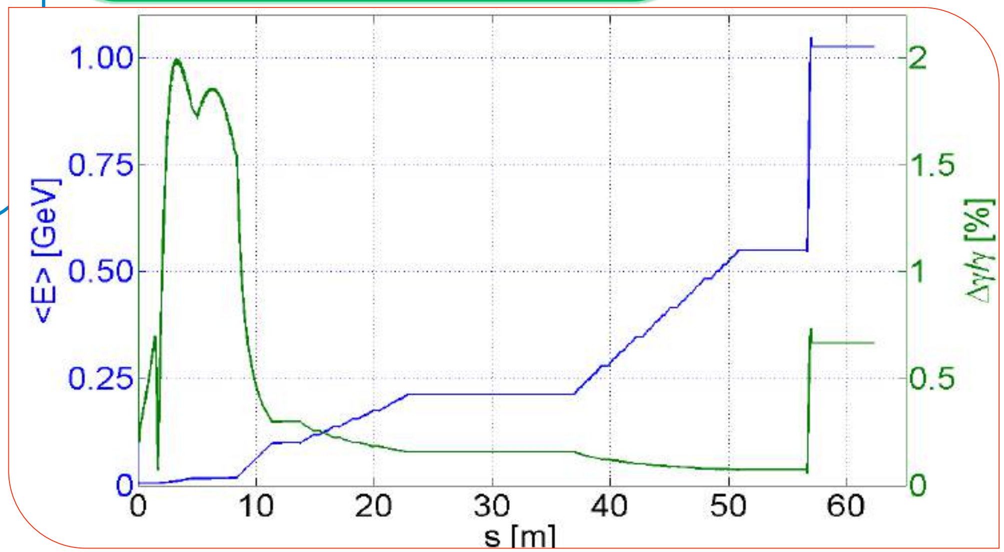
Beam Parameter	Unit	L1			L2		
		WP1	WP2	WP3	WP1	WP2	WP3
Initial energy	GeV	0.10	0.17	0.17	.21	.28	.51
Final energy	GeV	0.21	0.28	.55	.55	0.55	1.06
Active Linac length	m		6.0			10.0	
Accelerating Gradient	MV/m	20.0	20.0	57.0	36.0	26.8	57.0
RF phase (crest at 0)	deg	-20.0	-20.0	-12.0	-19.5	0	+15.0
Initial rms energy spread	%	0.30	0.22	0.67	0.15	0.22	0.47
Final rms energy spread	%	0.15	0.22	0.47	0.07	0.06	0.09
rms bunch length	mm	0.006	0.020	0.112	0.006	0.004	0.020

WP1 case: 30 pC beam evolution from Cathode to Undulator

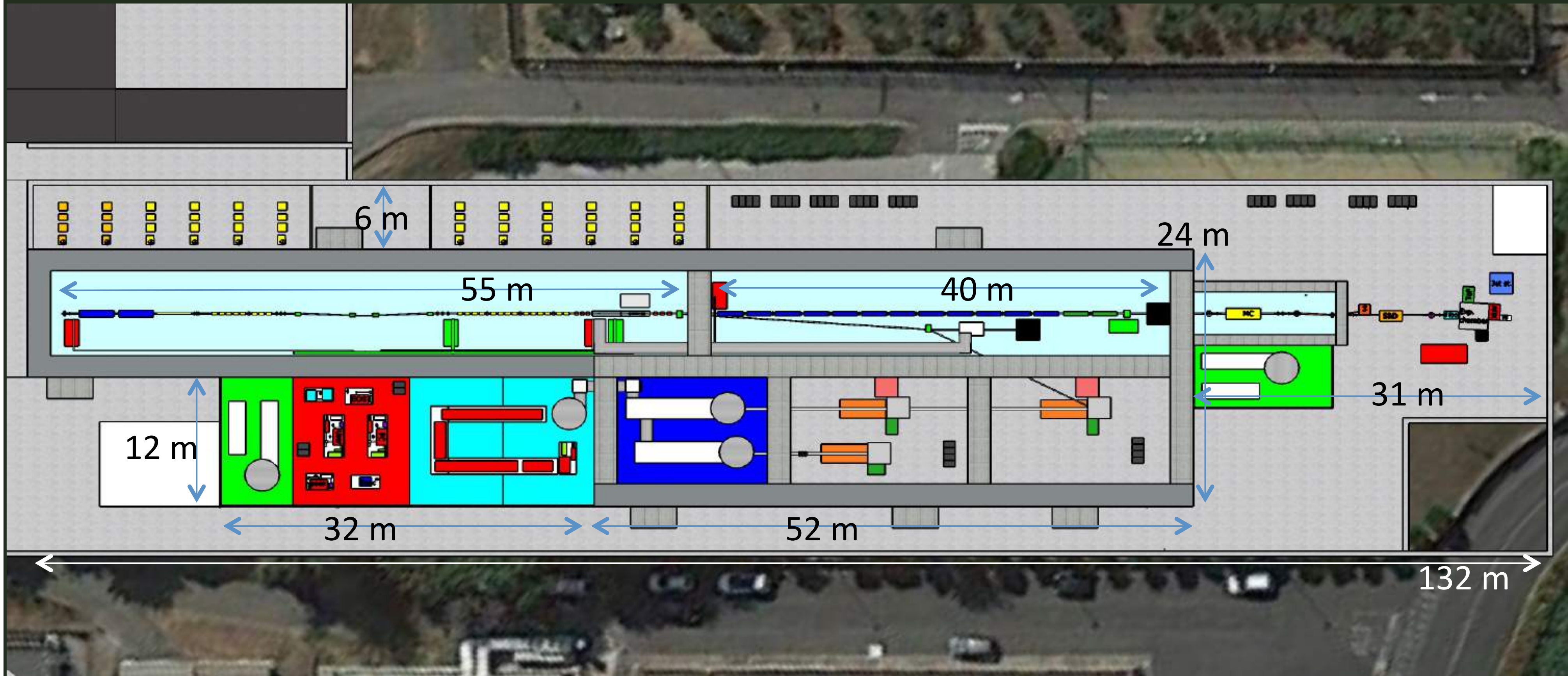








- The FEL

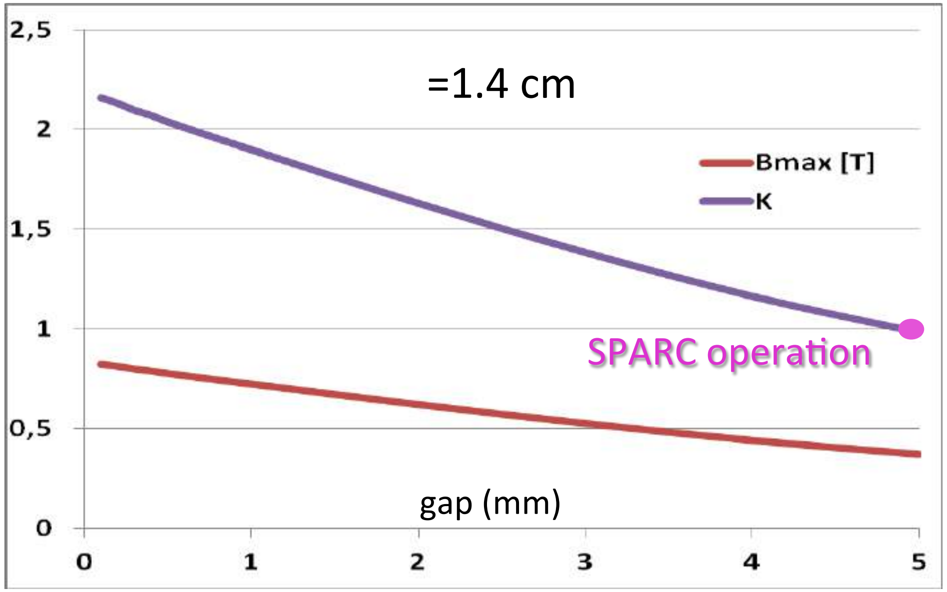


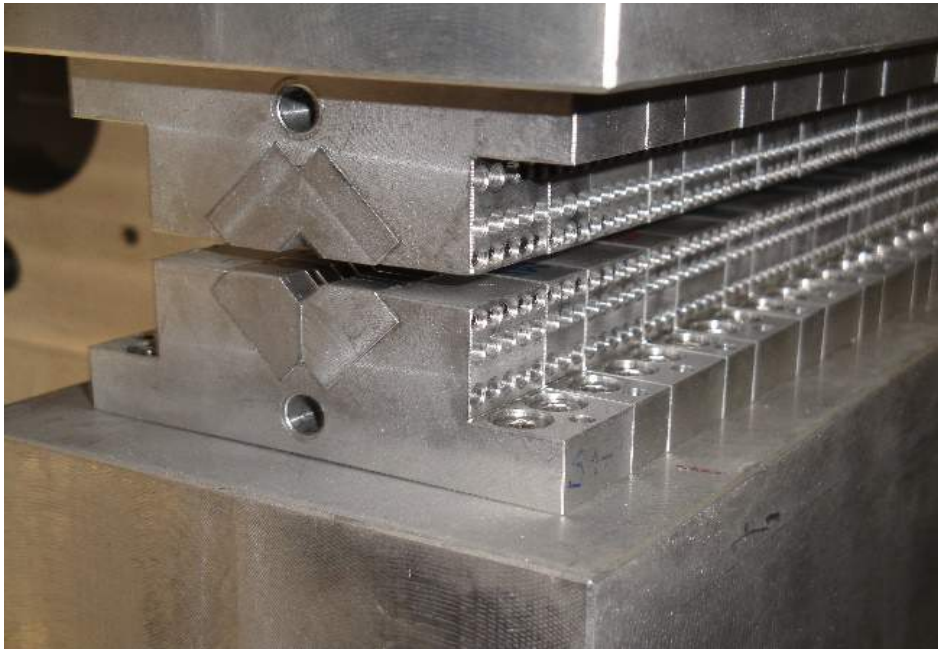
- 500 MeV by RF Linac + 500 MeV by Plasma
- 1 GeV by RF Linac only (EuSPARC)

KYMA Δ undulator:
designed by ENEA Frascati,
constructed by Kyma Trieste,
tested on beam at SPARC_LAB

- DELTA like undulator
  λ_u = 1.4 cm, gap g = 5mm, Br = 1.22T.

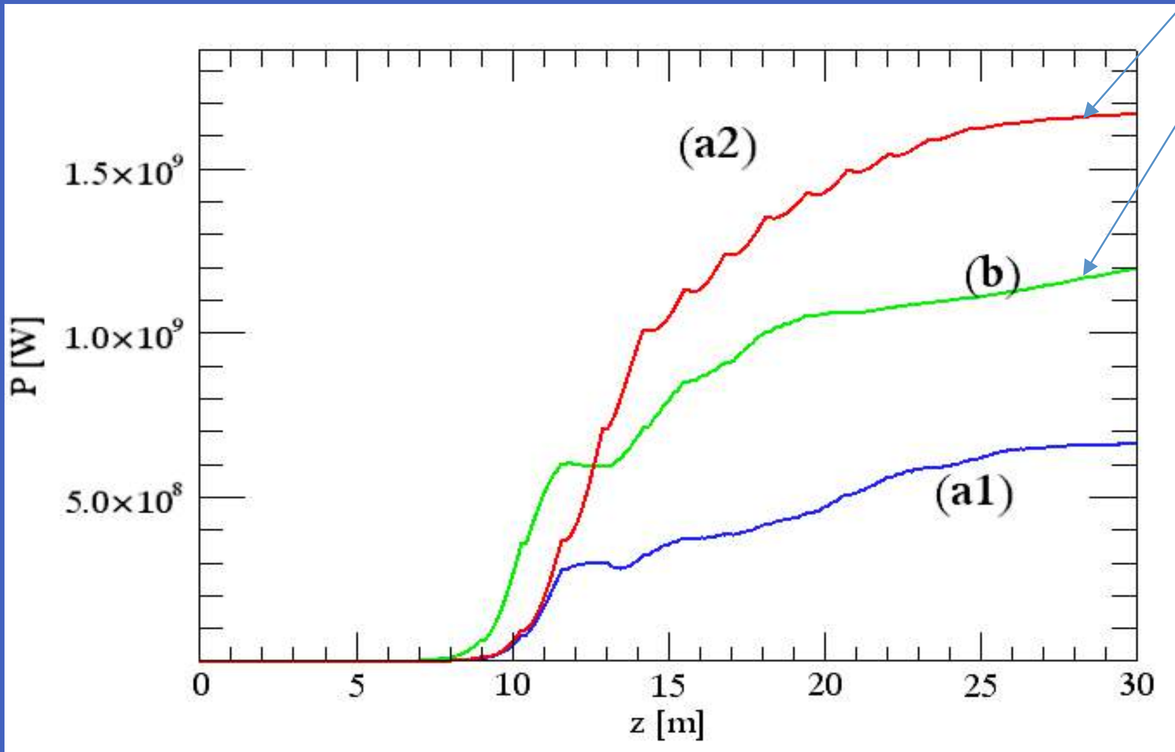
Undulator tested in two stage SASE-FEL:
630nm to 315 nm





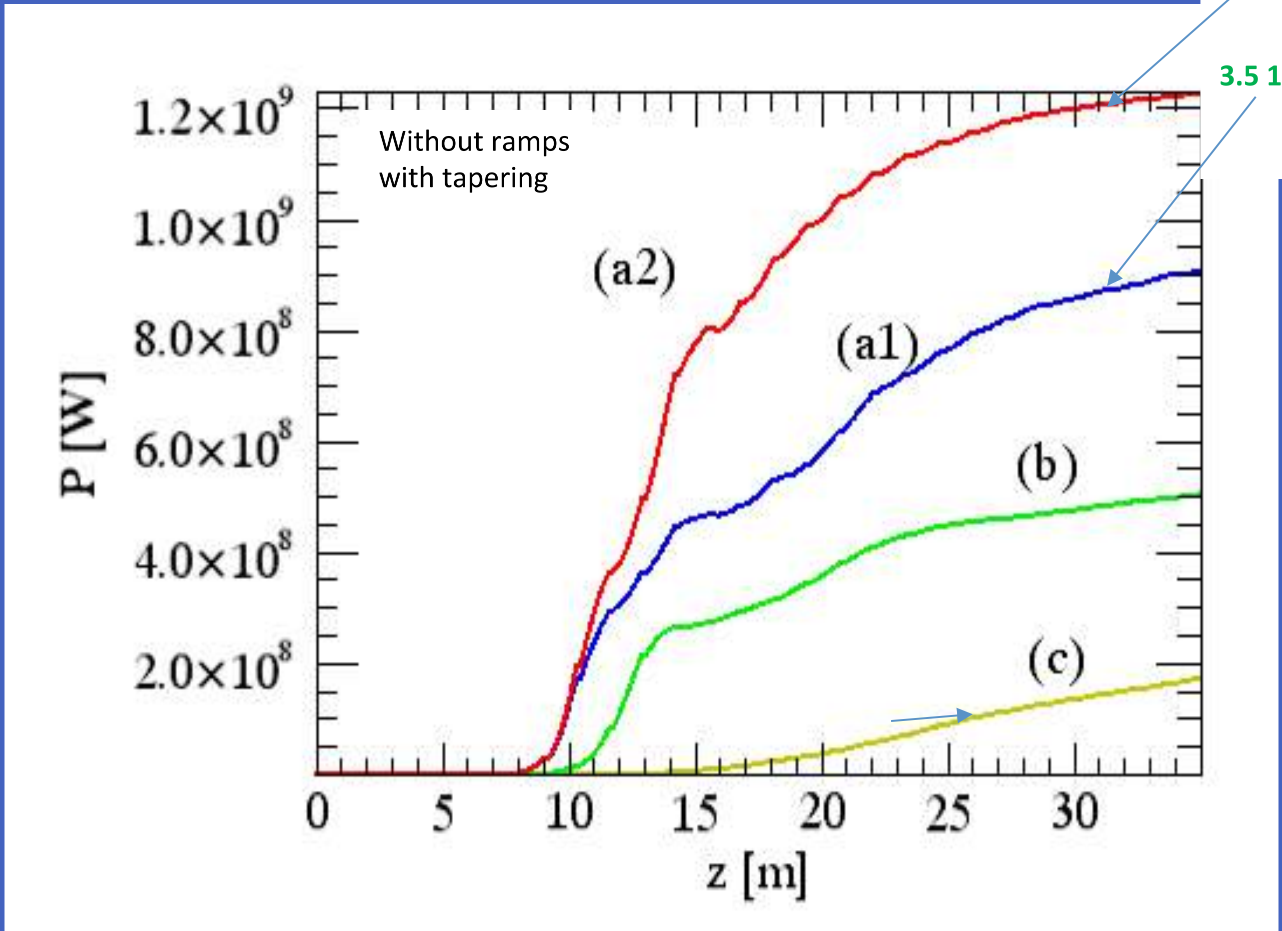
FEL driven by LWFA

At 30 m
6.4 10^{11} photons
5.2 10^{11} photons
3.6 10^{11} photons



Growth of the radiation along the undulator

FEL driven by PWFA



At 30 m
8 10^{11} photons
6 10^{11} photons
3.5 10^{11} photons

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 driven by X-band 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	$\times 10^{-3}$	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		$5.9\text{-}8.4 \times 10^{11}$	$9.3\text{-}25.5 \times 10^{11}$
Bandwidth	%	0.13-2.8	0.24-0.46
Divergence	μrad	17.5-16	28-27
Rad. size	μm	65-75	120-200
Brilliance per shot	$(\text{s mm}^2\ \text{mrad}^2 \text{bw}(‰))^{-1}$	$\text{Fx}3.8\text{-}2.2\ 10^{28}$	$\text{Fx}2.5\text{-}1.4\ 11^{27}$

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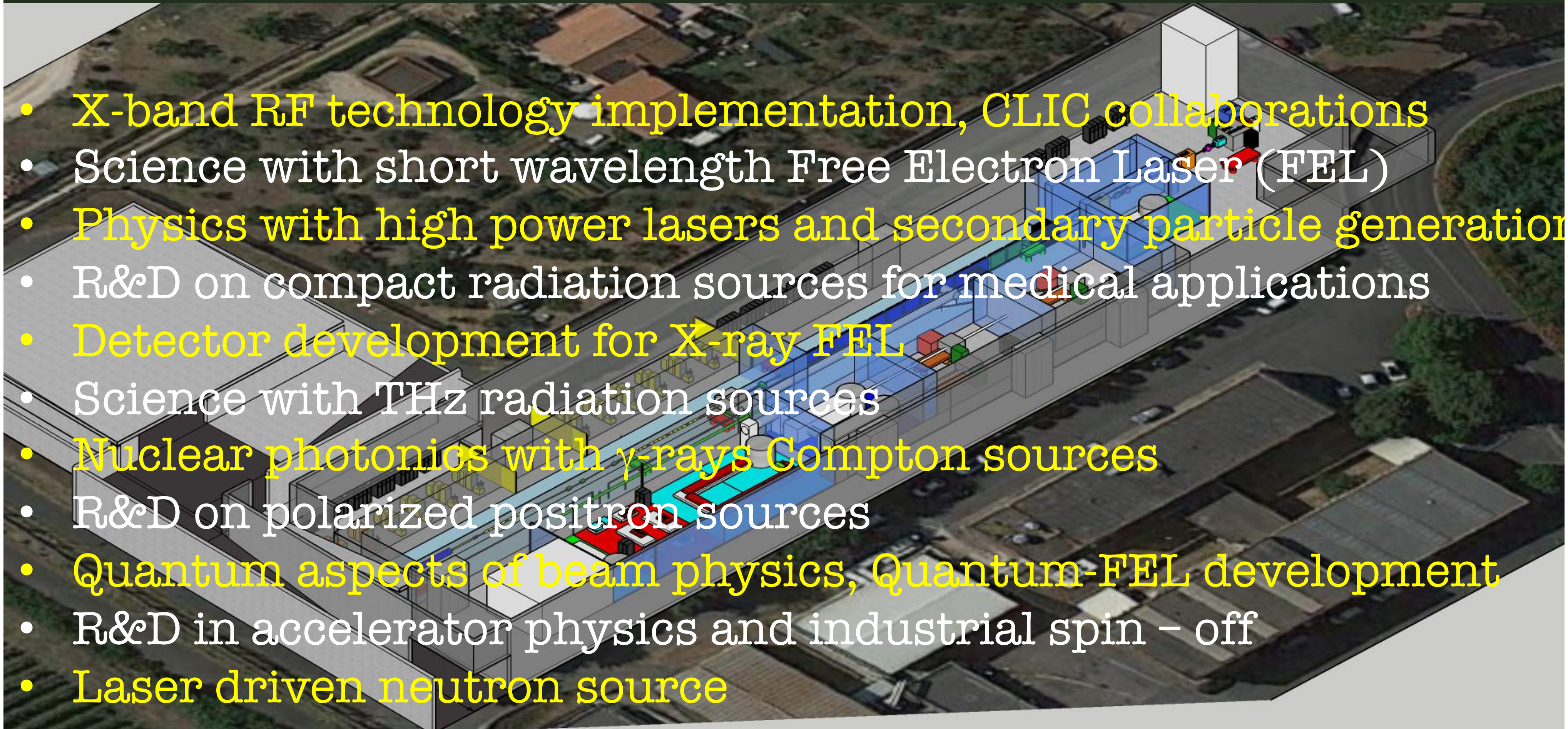

- X-band RF technology implementation, CLIC collaborations
- Science with short wavelength Free Electron Laser (FEL)
- Physics with high power lasers and secondary particle generatio
- R&D on compact radiation sources for medical applications
- Detector development for X-ray FEL
- Science with THz radiation sources
- Nuclear photonics with γ-rays Compton sources
- R&D on polarized positron sources
- Quantum aspects of beam physics, Quantum-FEL development
- R&D in accelerator physics and industrial spin – off
- Laser driven neutron source