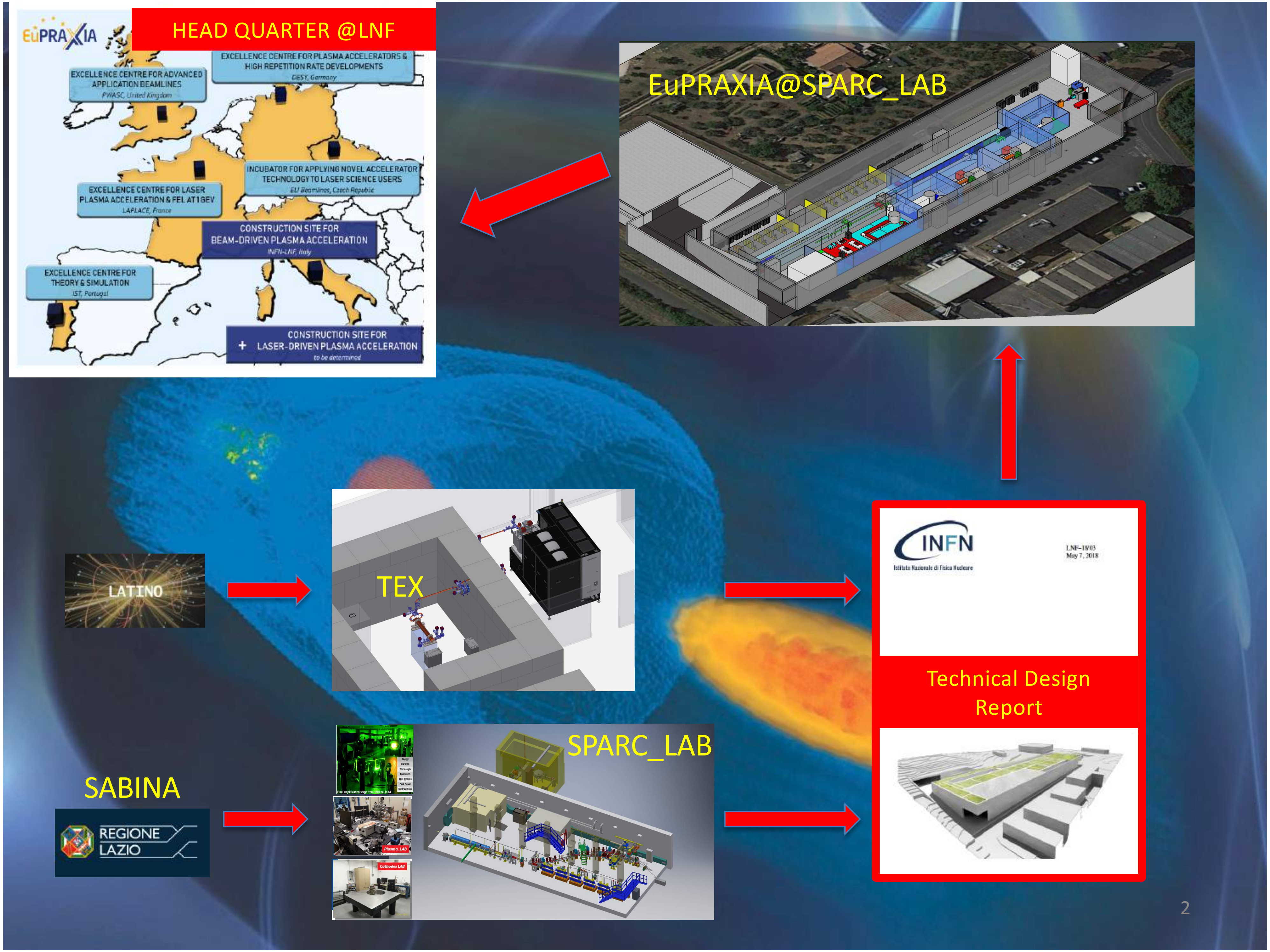
EuPRAXIA@SPARC_LAB
and related R&D activities

Massimo.Ferrario@LNF.INFN.IT

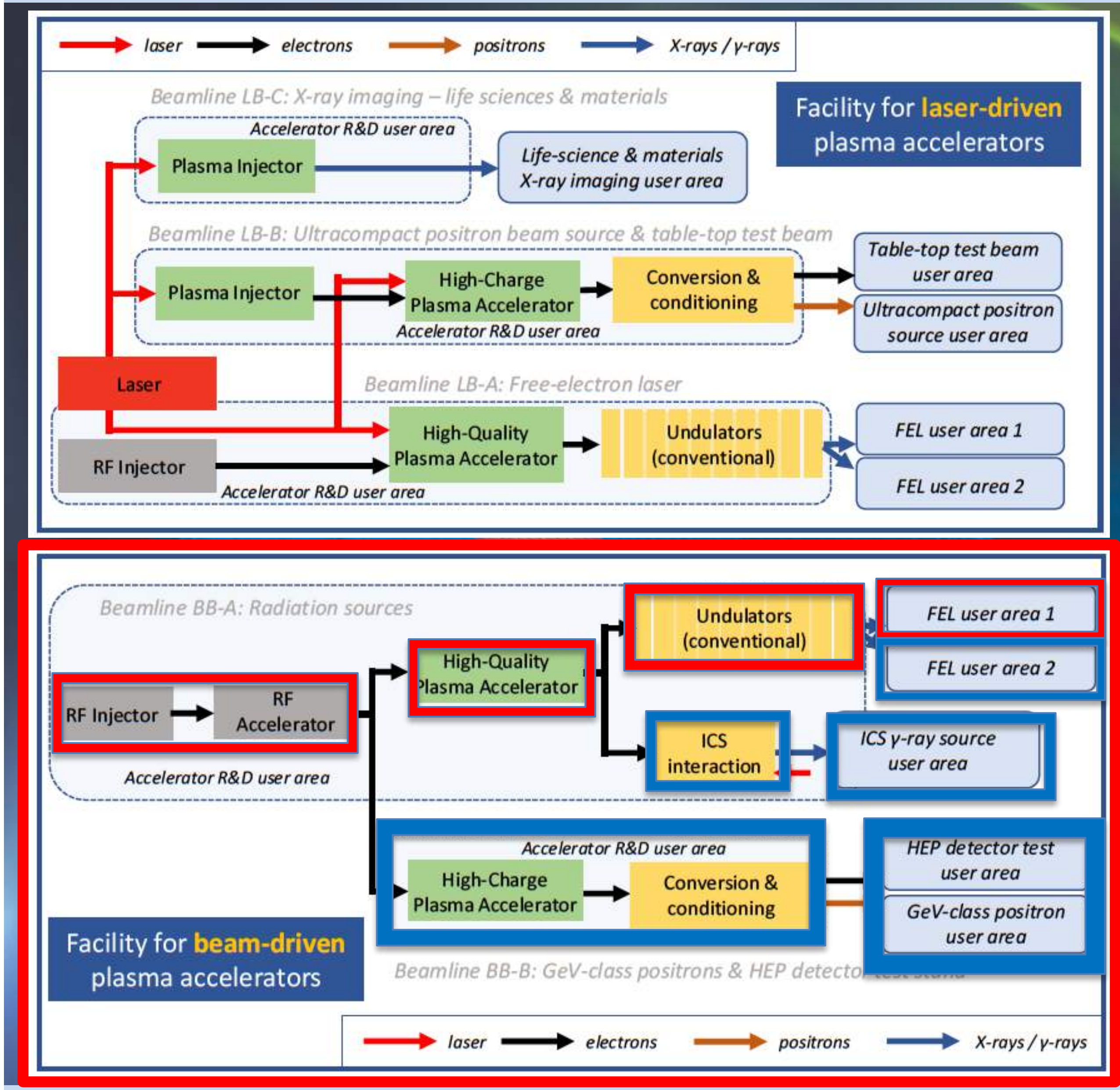
First TDR Review Committee Meeting, Zoom, February 22, 2021

Istituto Nazionale di Fisica Nucleare


HEAD QUARTER @LNF
EuPRAXIA
EXCELLENCE CENTRE FOR PLASMA ACCELERATORS & HIGH REPETITION RATE DEVELOPMENTS
DESY, Germany
EXCELLENCE CENTRE FOR ADVANCED APPLICATION BEAMLINES
PWASC, United Kingdom
INCUBATOR FOR APPLYING NOVEL ACCELERATOR TECHNOLOGY TO LASER SCIENCE USERS
ELI Beamlines, Czech Republic
EXCELLENCE CENTRE FOR LASER PLASMA ACCELERATION & FEL AT 1 GEV
LAPLACE, France
CONSTRUCTION SITE FOR BEAM-DRIVEN PLASMA ACCELERATION
INFN-LNF, Italy
EXCELLENCE CENTRE FOR THEORY & SIMULATION
IST, Portugal
+ CONSTRUCTION SITE FOR LASER-DRIVEN PLASMA ACCELERATION
to be determined
EuPRAXIA@SPARC_LAB
LATINO
TEX
INFN
Istituto Nazionale di Fisica Nucleare
LNF–18/03
May 7, 2018
Technical Design Report
SABINA
REGIONE LAZIO
SPARC_LAB

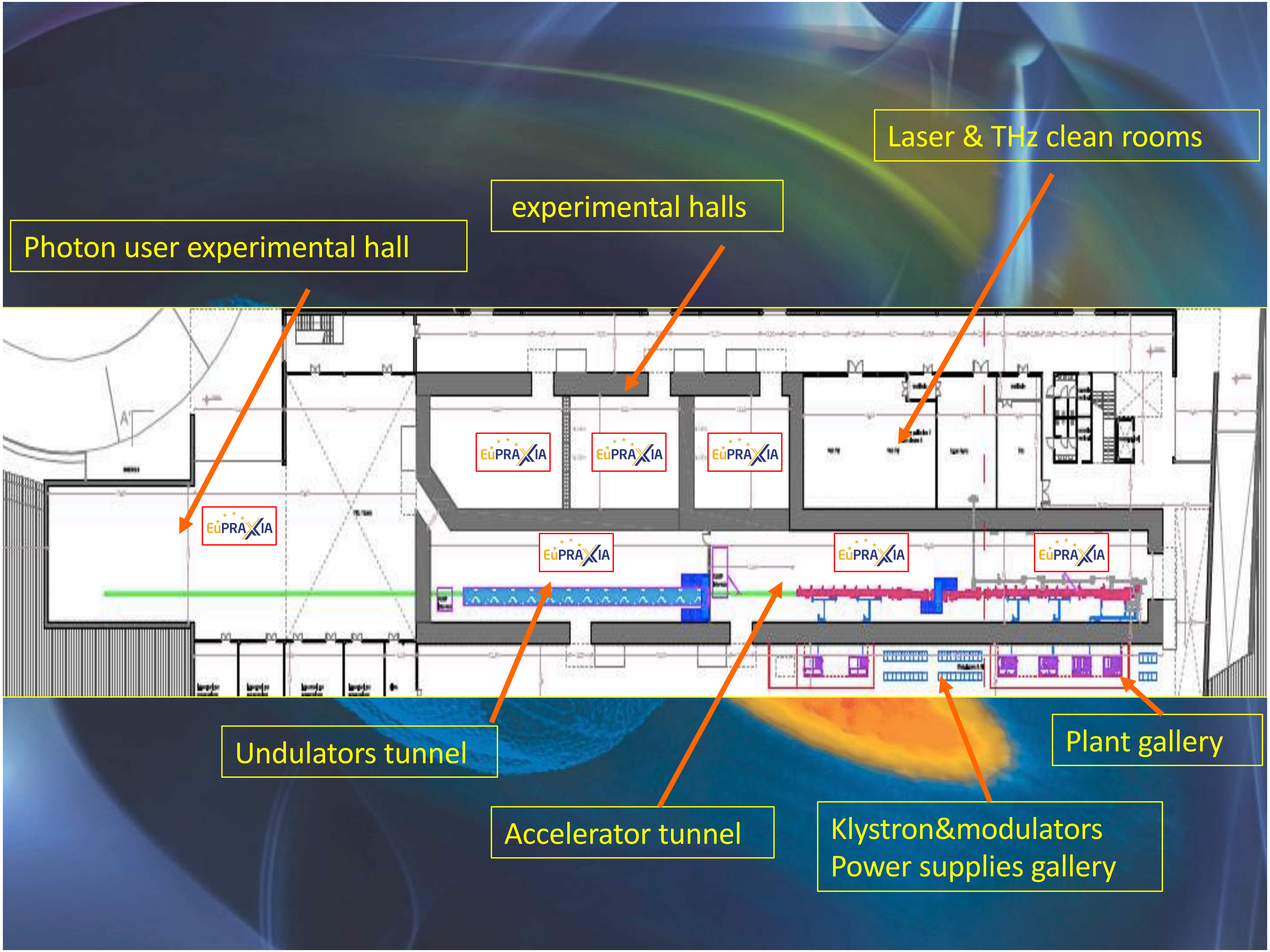
EuPRAXIA Conceptual Layout

Horizon 2020



EuPRAXIA **lasers** will operate with high stability at 20 to 100 Hz, a modest advancement of a factor 2 to 10 over the current state of the art. In parallel, R&D activities will be pursued on the development of laser that can operate at kHz repetition rates and deliver peak-power at 100 TW or more.

EuPRAXIA also includes the development and construction of a compact **X-band RF accelerator** based on technology from CERN with up to 100 MV/m gradients to realise a beam-driven plasma accelerator.


Laser & THz clean rooms
experimental halls
Photon user experimental hall
Undulators tunnel
Accelerator tunnel
Klystron&modulators
Power supplies gallery
Plant gallery

EuPRAXIA@SPARC_LAB TDR Review Committee (RC) Mission

- The RC is expected to Assess and Monitor on the following topics:
  - the EuPRAXIA@SPARC_LAB team effort towards the delivery of the Technical Design Report (2024),
  - the required R&D program,
  - the consistency with the financial plan for implementation and R&D,
  - the implementation of management activities,
  - possible upgrades and future options (consistency with the future evolution of EuPRAXIA).

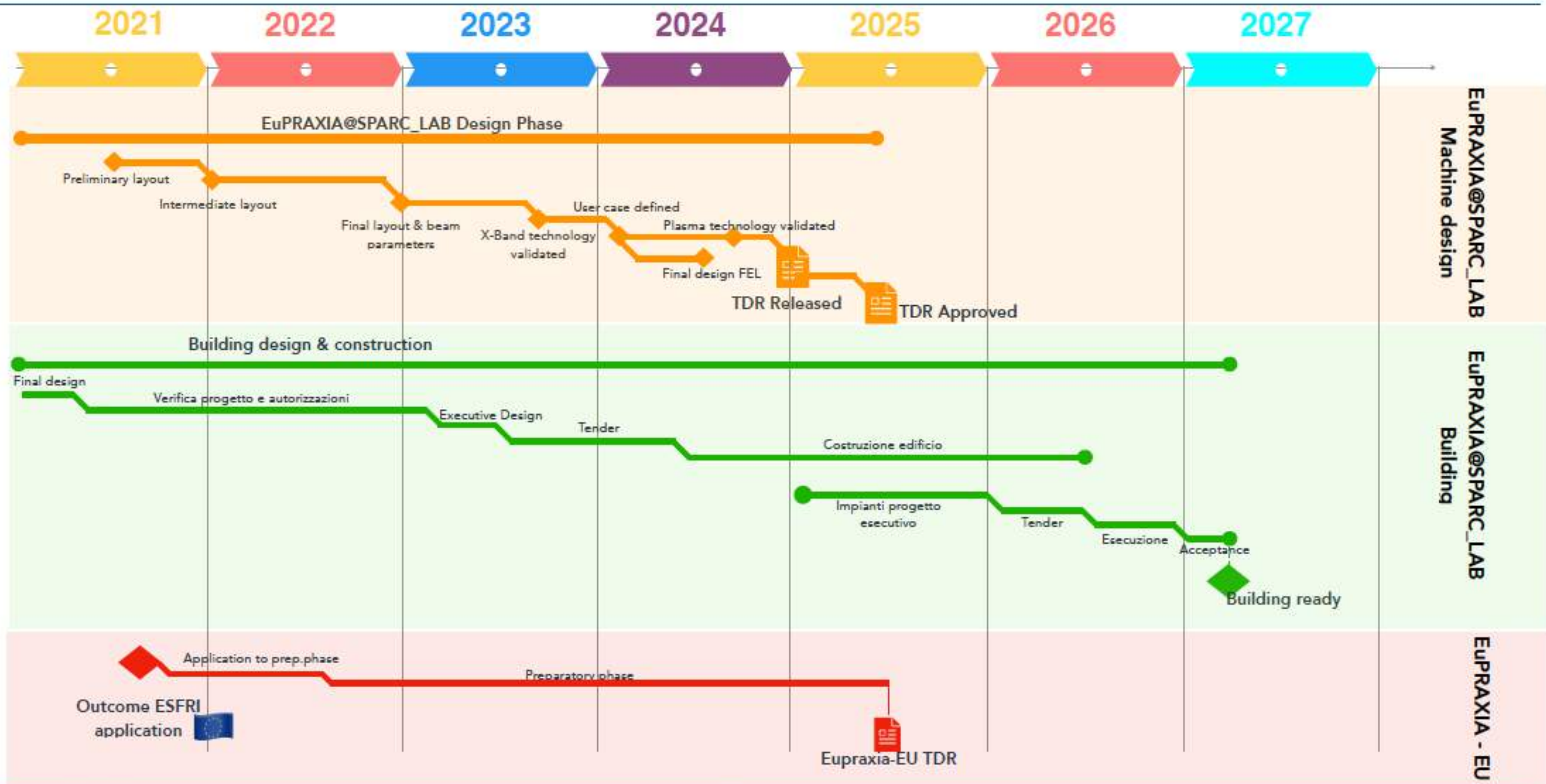
- The RC is expected to evaluate also the Photon Transport and the Users beamlines including the Scientific Program. This assignment could require the inclusion of more dedicated experts in the RC.

- The RC will convene 2 times/year (October and April ?)

The RC Mission does not include:

- The European EuPRAXIA project that will be assessed by a dedicated RC.
- The SPARC_LAB operation that is currently monitored by the INFN-MAC and the LNF Scientific Committee.

Road map



Courtesy A. Falone

INFN
EU

EuPRAXIA @ SPARC_LAB Collaboration Board

PROJECT LEADER
M.Ferrario

LNF- Steering Committee

- Chair - *A.Falone*
- Project Leader - *M.Ferrrario*
- Technical Manager - *A.Ghigo*
- Lab.Director *F.Bossi-*
- Div.Directors - *A.Gallo, U. Rotundo, P.Gianotti*
- Administration - *T. Ferro*
- Conventional safety - *S.Vescovi*
- Radioprotection - *A.Esposito*
- Sparc_Lab - *G.Di Pirro*

Management Team

- Scientific Manager — *M.Ferrario*
- Technical Manager — *A.Ghigo*
- Project Management & Integration — *A.Falone*

Project Management Support Office

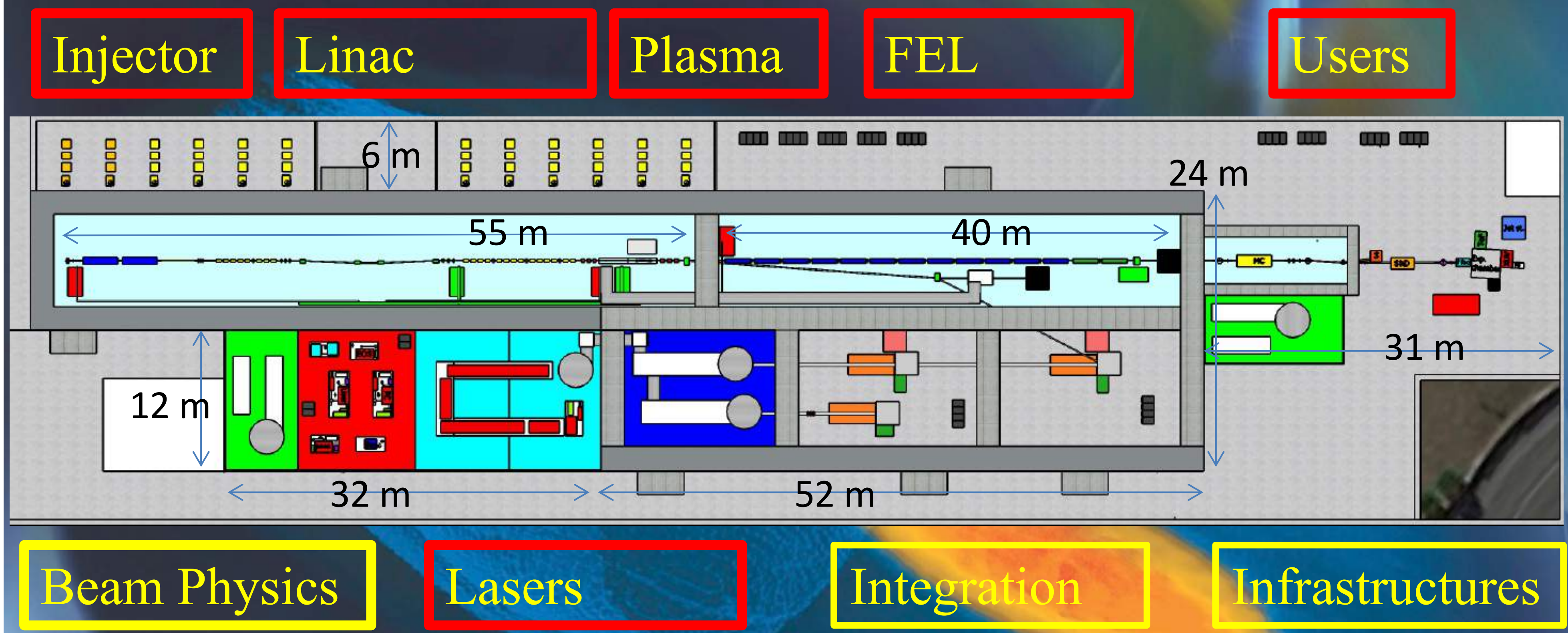
Working Areas

1. Beam Physics — *C.Vaccarezza*
2. Injector — *E.Chiadroni*
3. Linac — *D.Alesini*
4. Integration — *B.Buonomo*
5. Plasma — *R.Pompili*
6. FEL — *L.Giannessi*
7. High Power Laser — *TBD*
8. Users — *F.Stellato (Univ. TorVergata)*
9. Infrastructures — *U.Rotundo*

Work Packages

1. Accelerator Physics — *A.Giribono*, *A.Mostacci (Univ. La Sapienza)*
2. Plasma Physics — *A.R.Rossi (INFN-MI)*
3. FEL Physics — *V.Petrillo (INFN-MI)*
4. Photon & User Beamlines — *F.Villa*
5. Secondary part. sources — *T.B.D.*
6. Plasma module — *A.Biagioni*
7. Sparc_Lab TF — *R.Pompili*
8. RF Gun & Accelerating structures — *L.Piersanti*
9. Computing — *P.Santangelo*
10. Vacuum — *A.Liedl*
11. Lasers & Cathodes — *M.Anania*
12. High Power RF & distribution — *F.Cardelli*
13. Beam Diagnostics — *A.Cianchi (Univ. Torvergata)*
14. Beam Instrumentation & electronics — *A.Stella*
15. LLRF & Synchro — *M.Bellaveglia*
16. Control system & Interlocks — *A.Stecchi*
17. Magnets & PS — *L.Sabbatini*
18. Undulators — *A.Petralia (ENEA)*
19. Mech.Engineering — *L.Pellegrino*
20. Electrical Installations — *R.Ricci*
21. Cooling & Ventilation — *S.Cantarella*
22. Civil engineering — *S.Incremona*
23. Radioprotection — *A.Esposito*
24. Conventional Safety — *S.Vescovi*

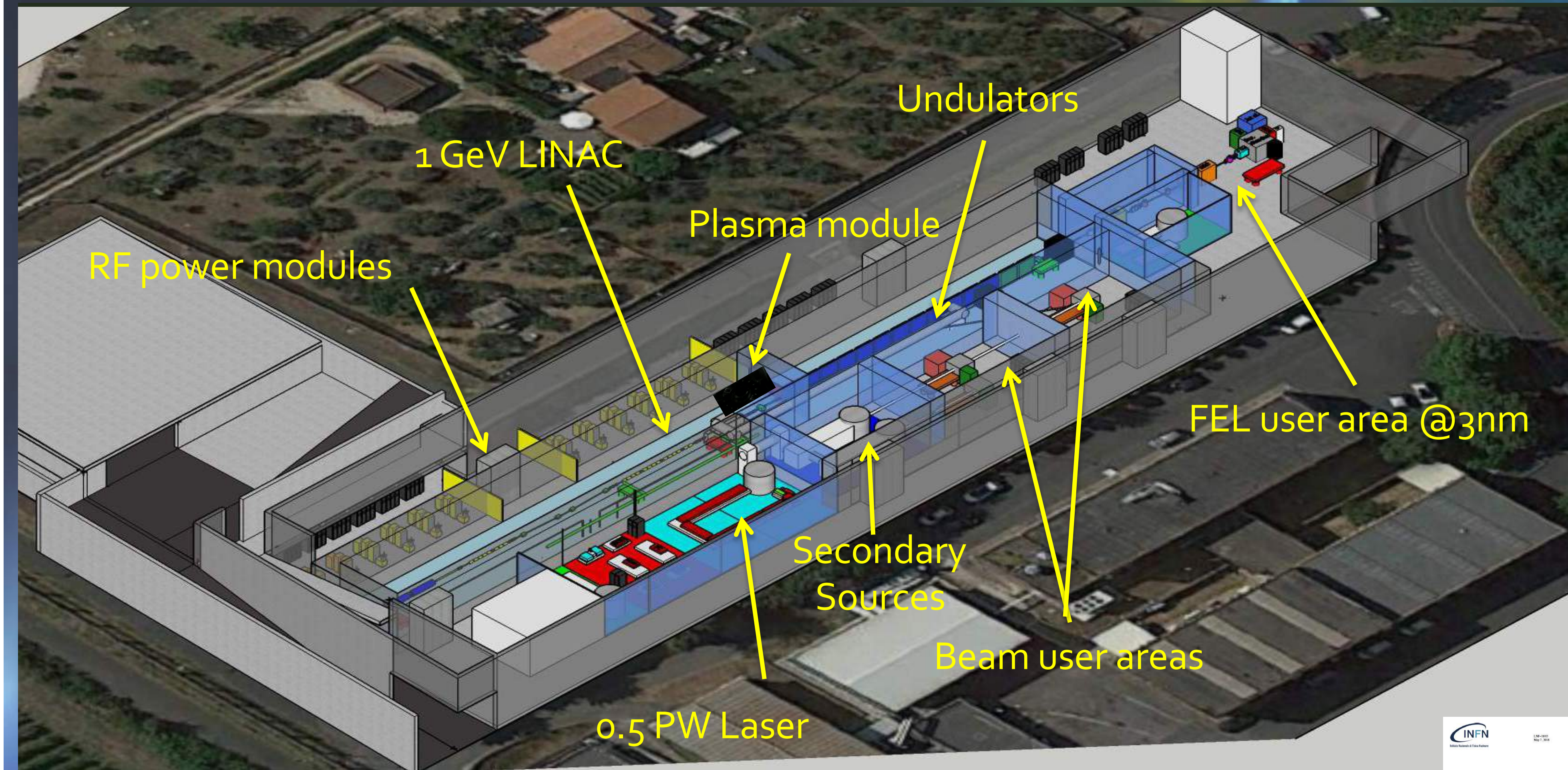
- EuPRAXIA@SPARC_LAB and Macro-Areas



Interface Working Areas vs Work-Packages - Responsibility Assignment Matrix

		WA 1	WA 2	WA 3	WA 4	WA 5	WA 6	WA 7	WA 8	WA 9
		Beam Physics	Injector	Linac	Integration	Plasma	FEL	High Power Laser	Users	Infrastructure
WP 1	Accelerator Physics	x	x	x		x	x	x		
WP 2	Plasma Physics	x				x		x		
WP 3	FEL Physics	x					x	x		
WP 4	Photon & User Beamlines	x					x	x	x	
WP 5	Secondary Part.Source							x	x	
WP 6	Plasma module	x				x		x		
WP 7	Sparc_lab TF					x				
WP 8	RF Gun & Acc.Structure	x	x	x						
WP 9	Computing	x								
WP 10	Vacuum		x	x	x	x		x		
WP 11	Laser & Cathodes		x					x		
WP 12	High Power RF & Distribution		x	x	x					
WP 13	Beam Diagnostics	x	x	x	x	x	x		x	
WP 14	Beam Instrumentation & Electronics		x	x	x					
WP 15	LLRF & Synchro		x	x	x					
WP 16	Control system & Interlocks	x	x	x	x	x	x	x	x	x
WP 17	Magnets & PS	x	x	x	x		x			
WP 18	Undulators						x			
WP 19	Mech.Engineering		x	x	x					x
WP 20	Electrical Installation				x					x
WP 21	Cooling & Ventilation		x	x	x					x
WP 22	Civil Engineering									x
WP 23	Radioprotection									x
WP 24	Conventional Safety									x

EuPRAXIA@SPARC_LAB

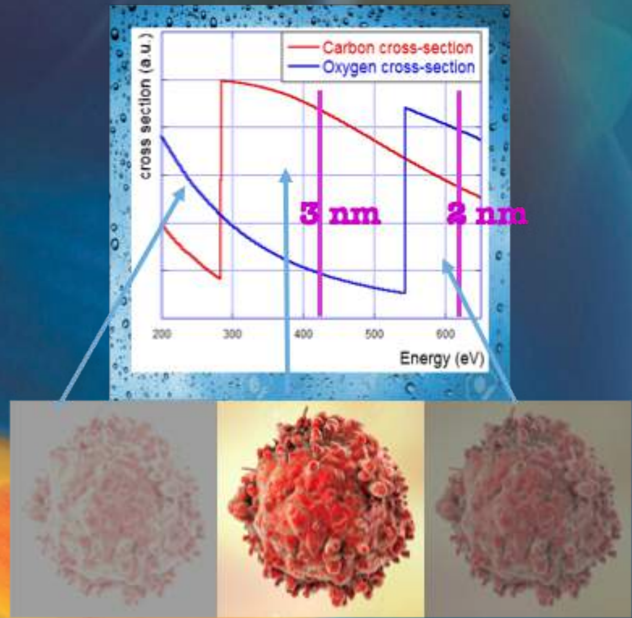


Expected SASE FEL performances

	Units	Full RF case	Plasma case
Electron Energy	GeV	1	1
Bunch Charge	pC	200	30
Peak Current	kA	2	3
RMS Energy Spread	%	0.1	1
RMS Bunch Length	fs	40	4
RMS matched Bunch Spot	µm	34	34
RMS norm. Emittance	µm	1	1
Slice length	µm	0.5	0.45
Slice Energy Spread	%	0.01	0.1
Slice norm. Emittance	µm	0.5	0.5
Undulator Period	mm	15	15
Undulator Strength K		1.03	1.03
Undulator Length	m	12	14
Gain Length	m	0.46	0.5
Pierce Parameter ρ	x 10^{-3}	1.5	1.4
Radiation Wavelength	nm	3	3
Undulator matching β_u	m	4.5	4.5
Saturation Active Length	m	10	11
Saturation Power	GW	4	5.89
Energy per pulse	µJ	83.8	11.7
Photons per pulse	x 10^{11}	11	1.5

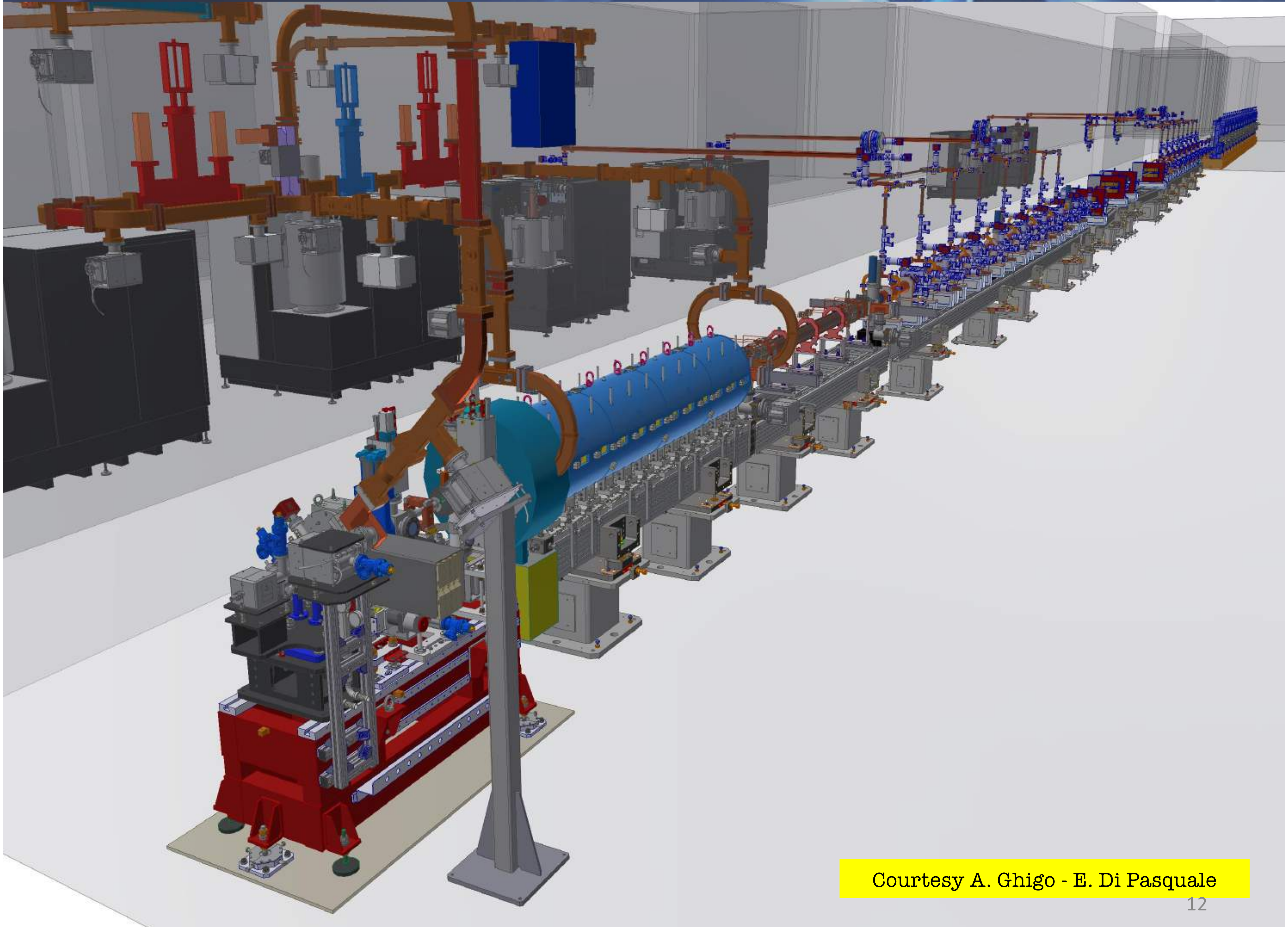
Table 2.1: Beam parameters for the EuPRAXIA@SPARC_LAB FEL driven by X-band linac or Plasma acceleration

Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV)
Water is almost transparent to radiation in this range while nitrogen and carbon are absorbing (and scattering)



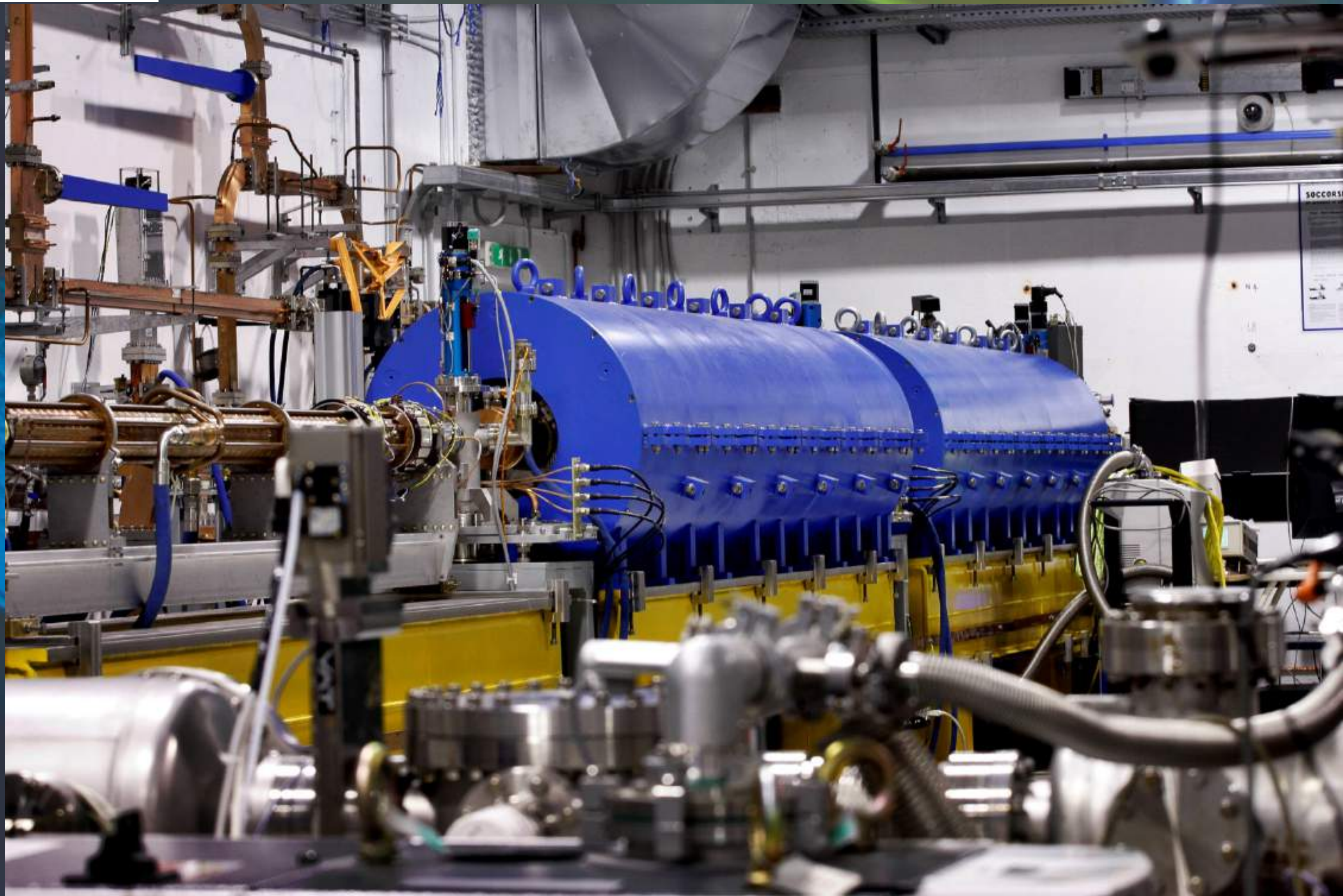
Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10^{11} photons/pulse needed

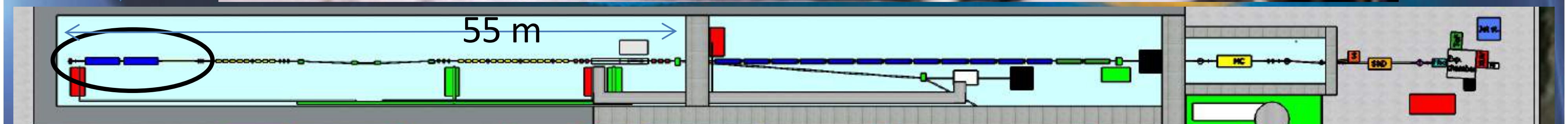
Courtesy F. Stellato, UniToV



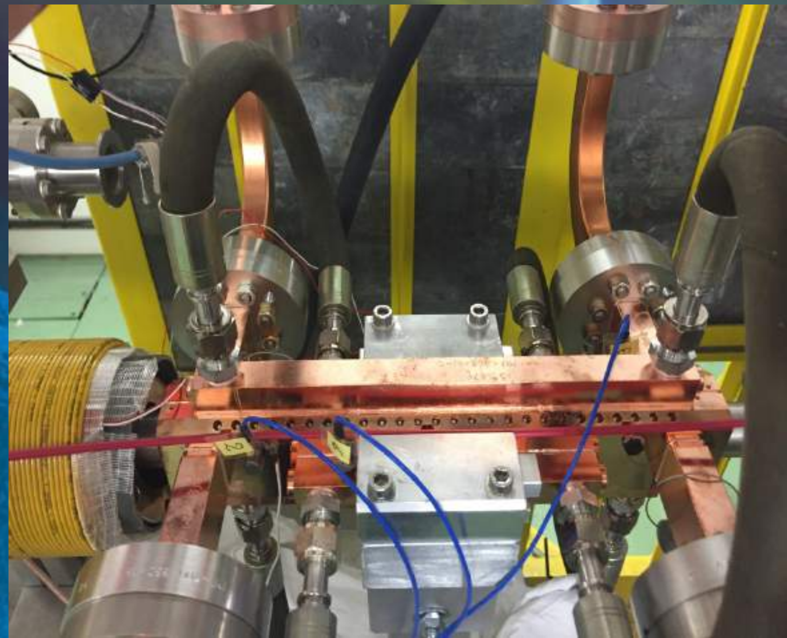
Courtesy A. Ghigo - E. Di Pasquale

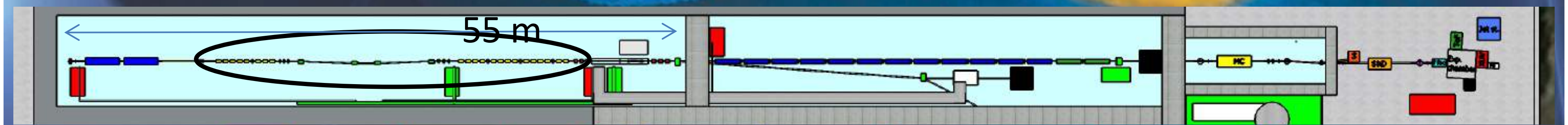
SPARC_LAB HB photo- injector



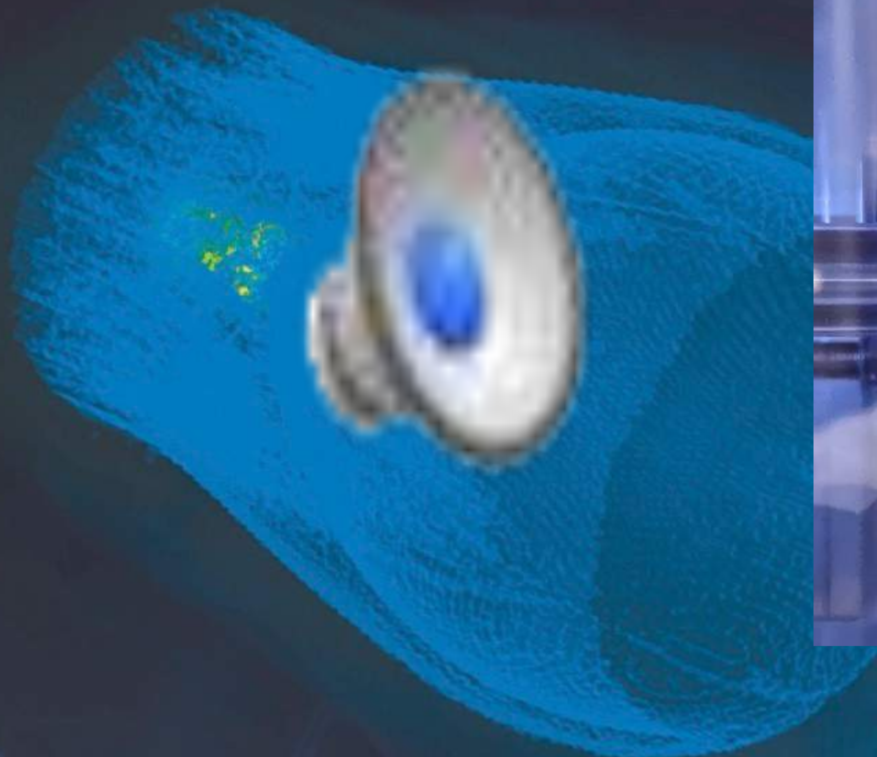


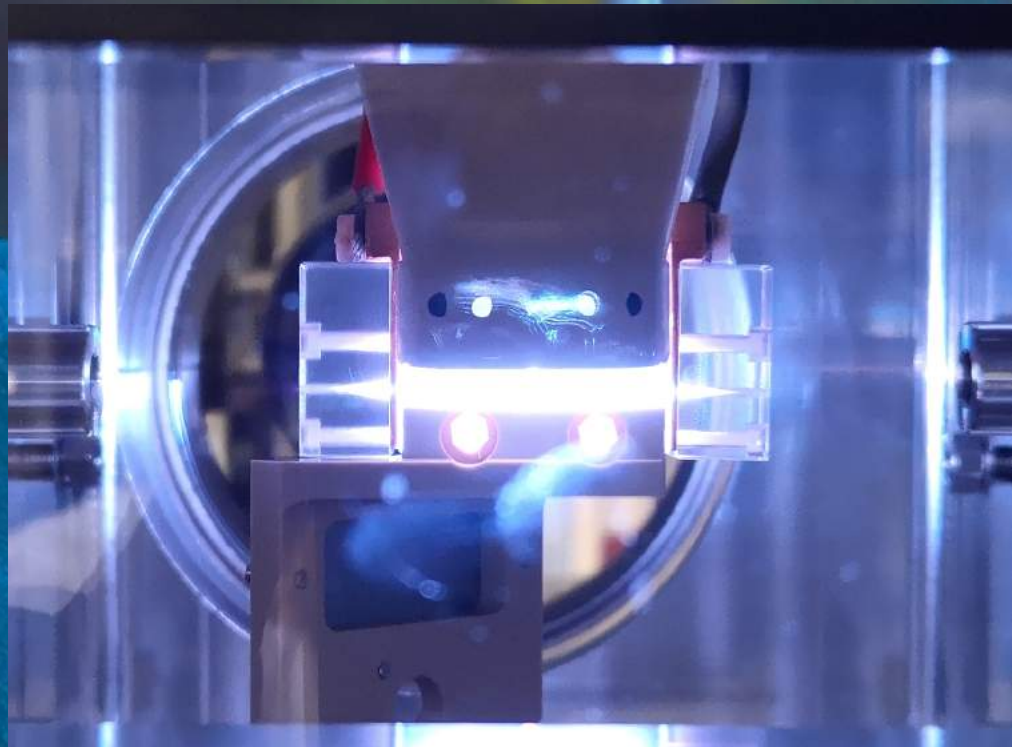
X-band Linac



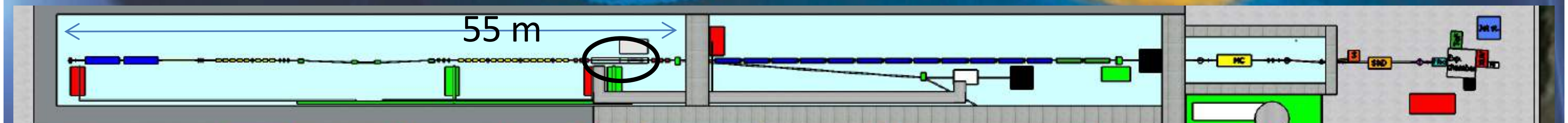


Plasma WakeField Acceleration

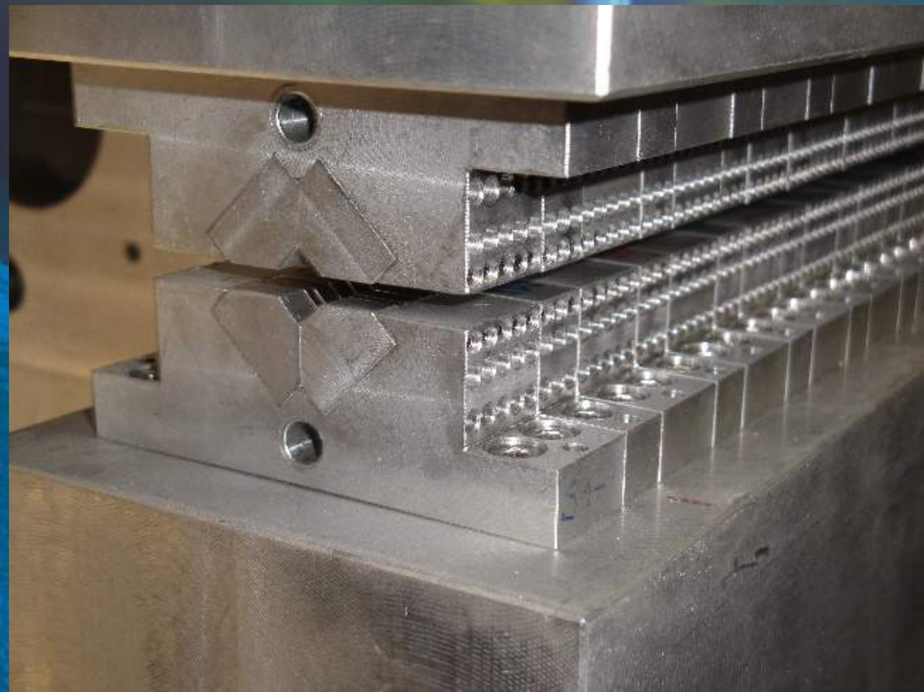




Capillary discharge at SPARC_LAB

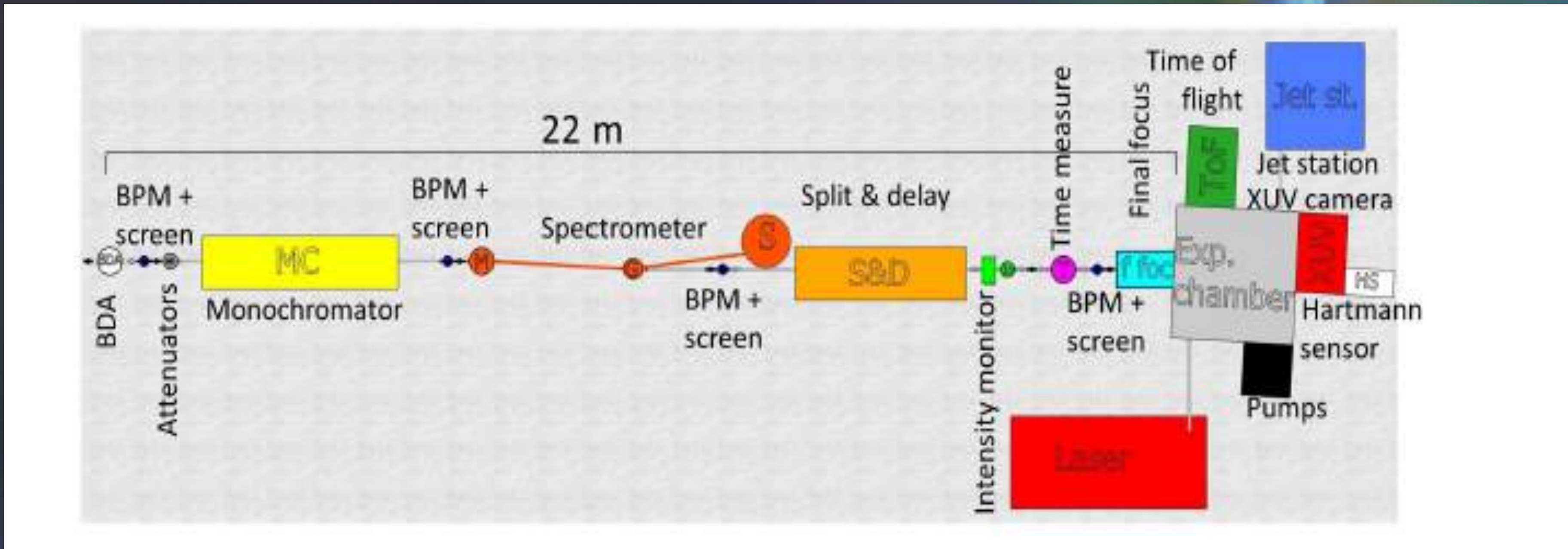


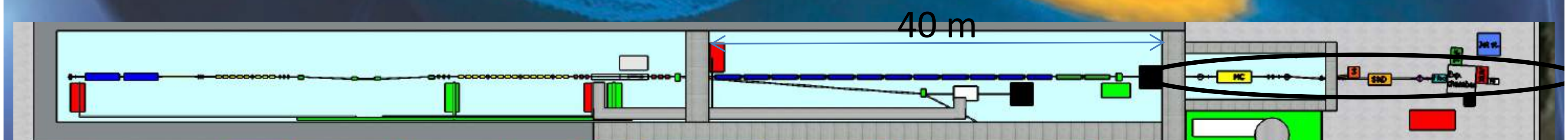
Undulators



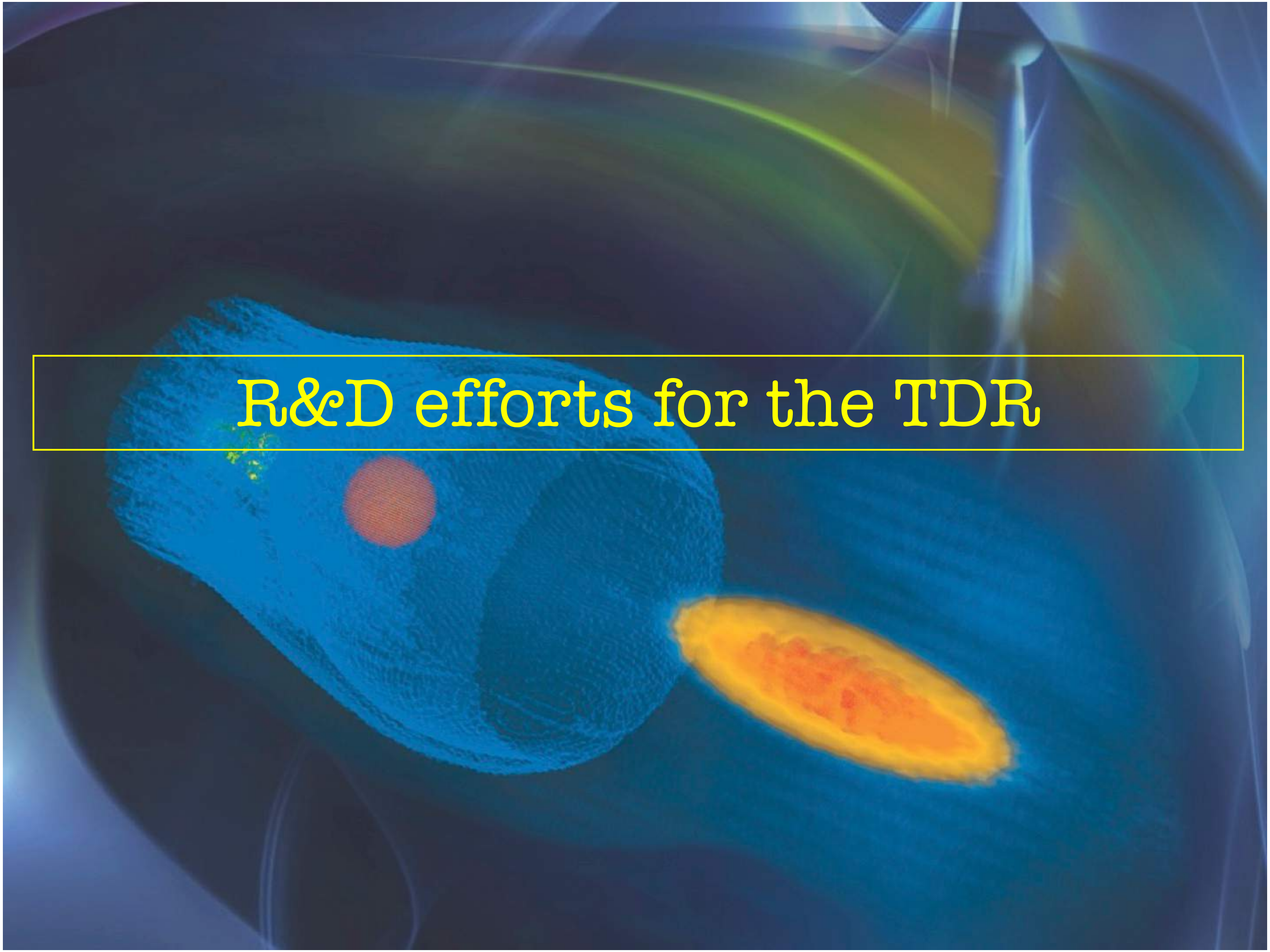
KYMA Δ udulator at SPARC_LAB: λ=1.4 cm, K1

Photon beam line

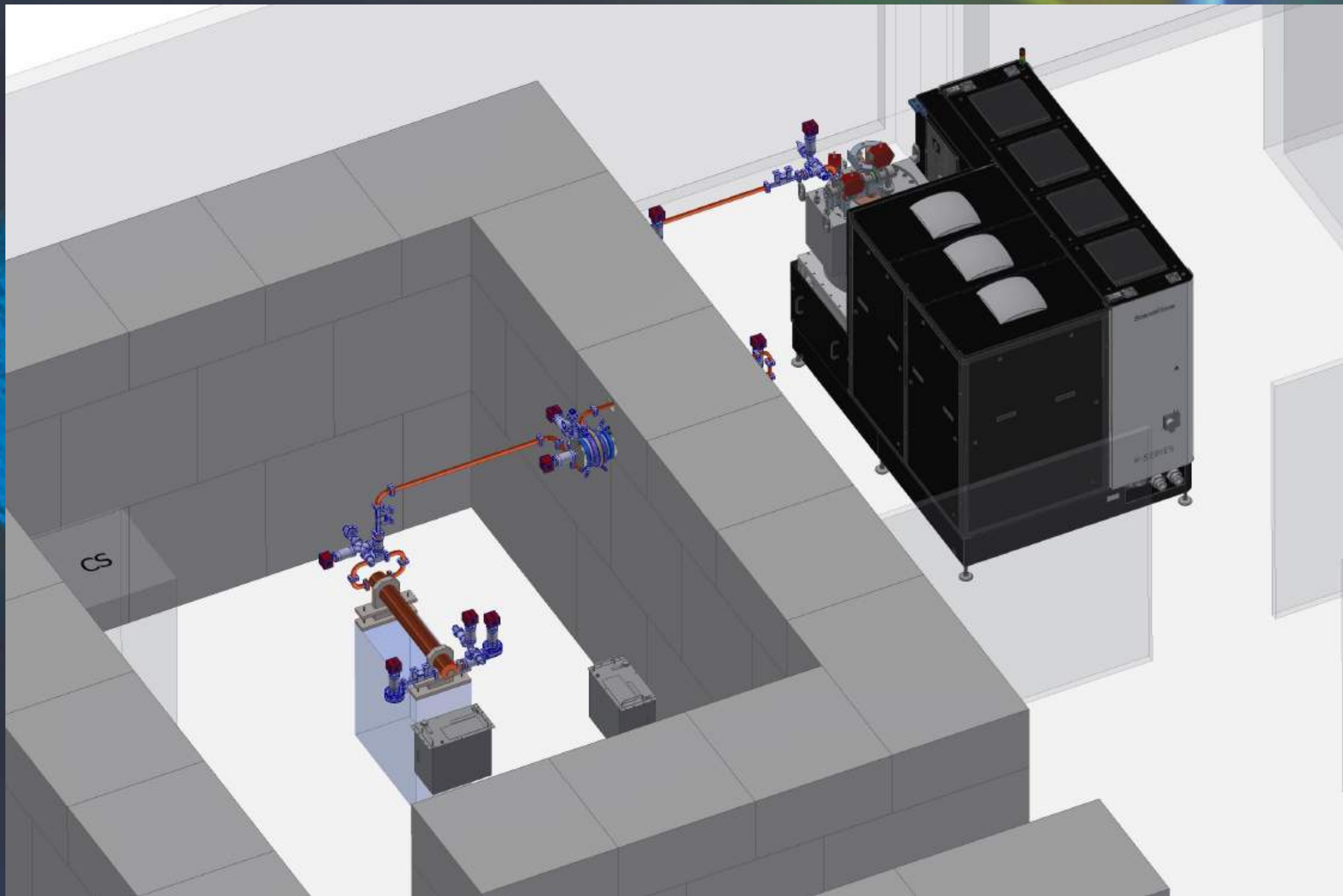




R&D efforts for the TDR

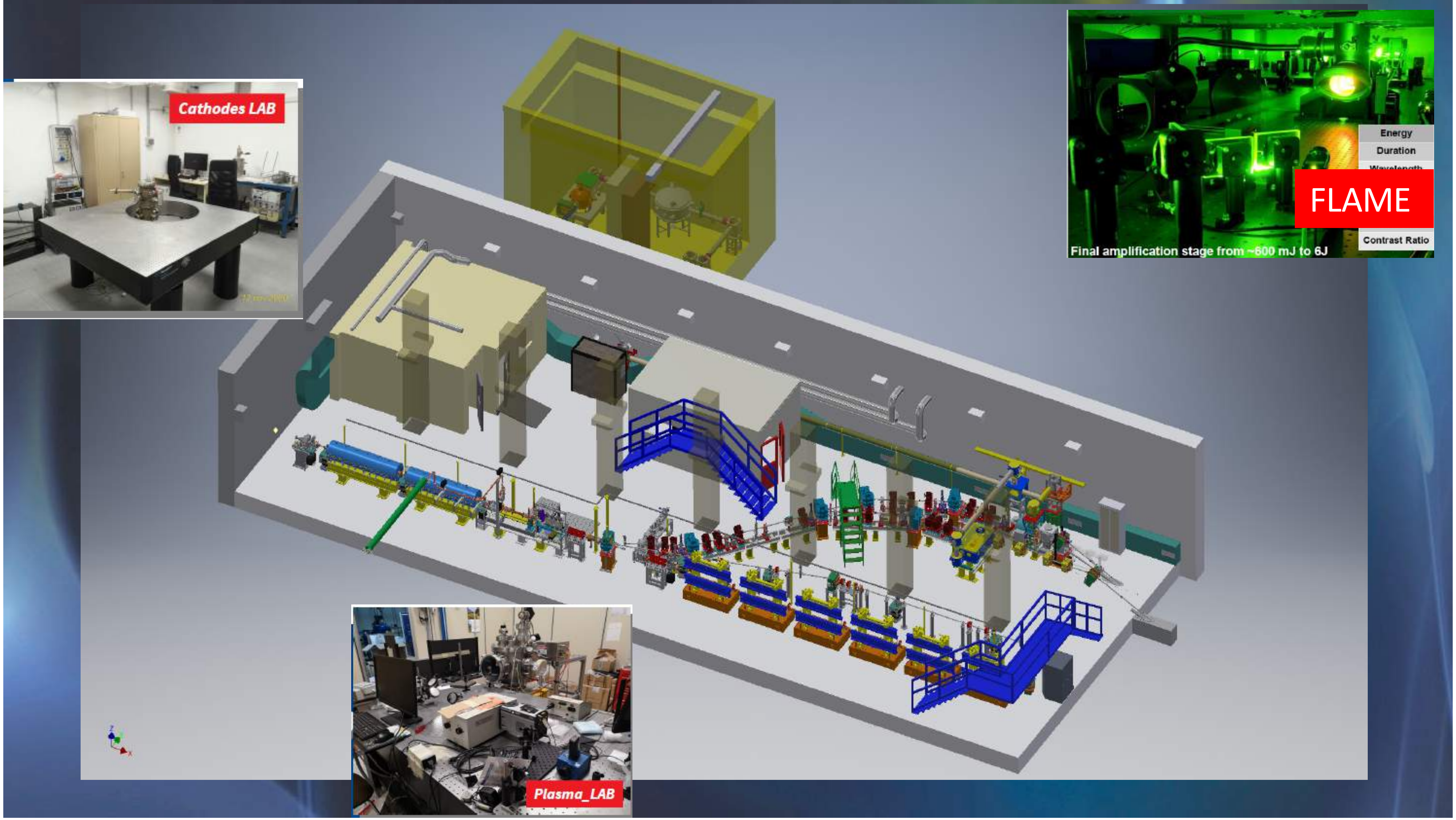


TEX Facility



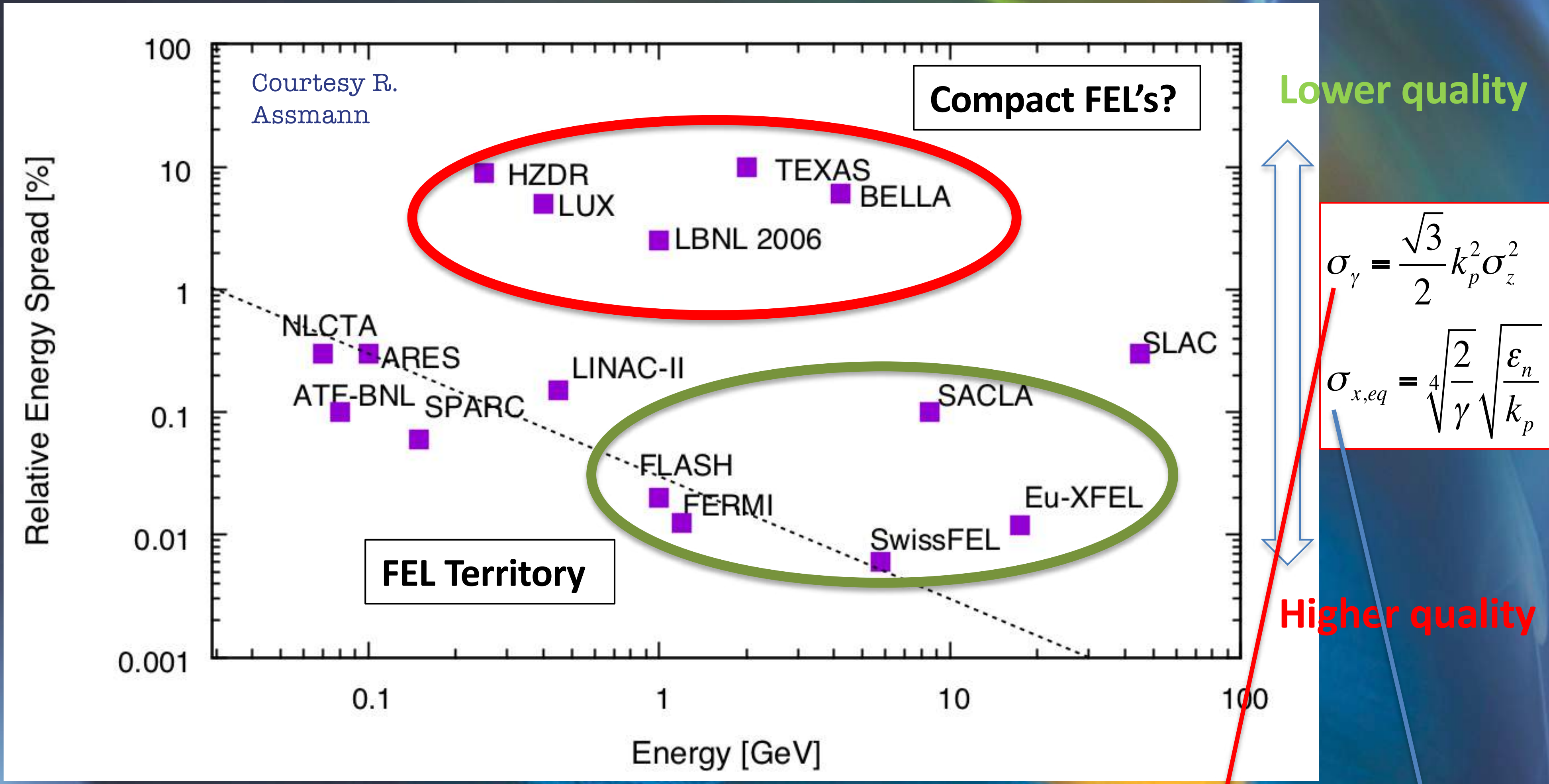
INFN – CERN official partnership on **X-band RF development**, with the contribution of the LATINO project funded by Regione Lazio

SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)



High Quality Beam

Horizon 2020



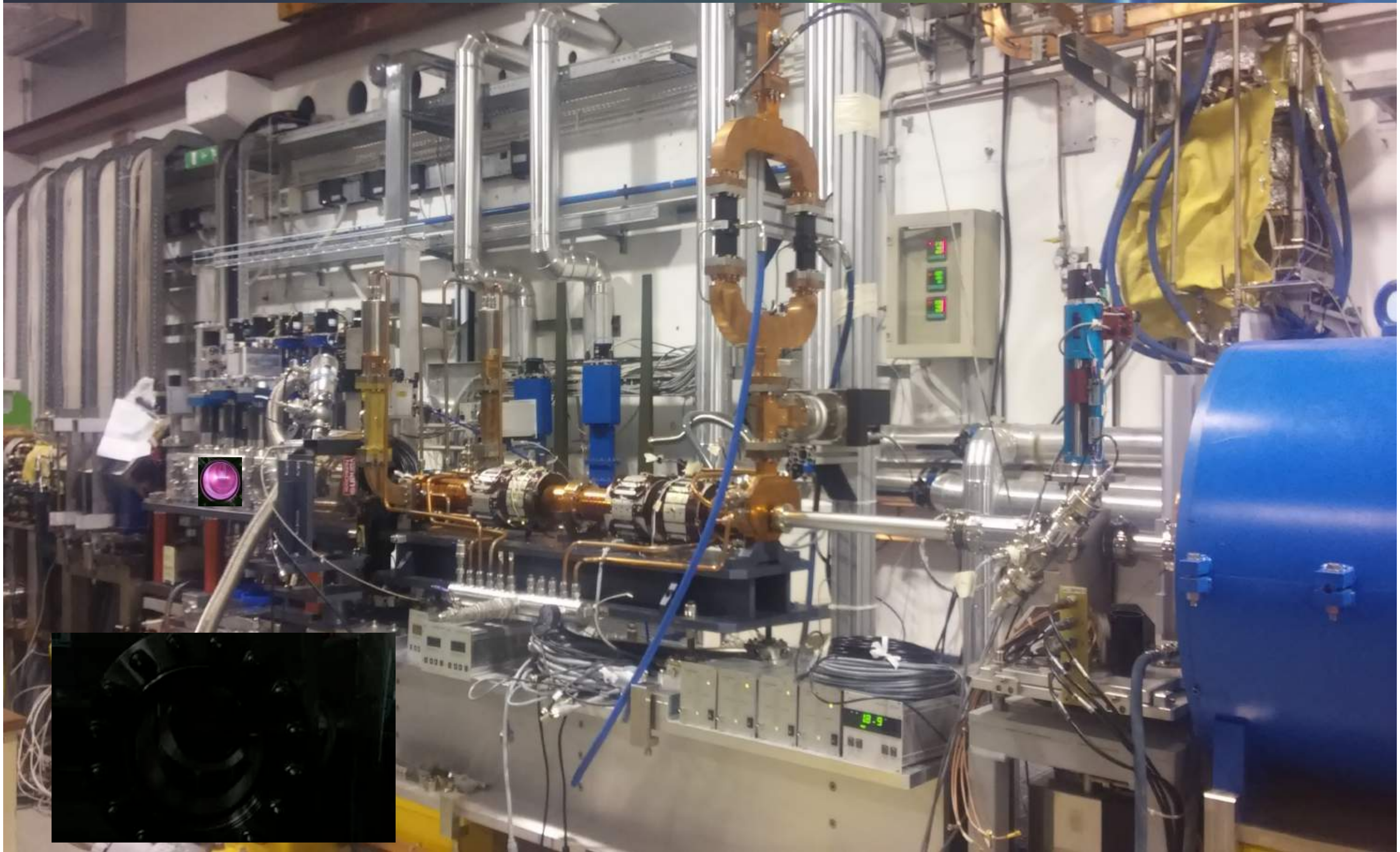
$$\sigma_\gamma = \frac{\sqrt{3}}{2} k_p^2 \sigma_z^2$$

$$\sigma_{x,eq} = \sqrt[4]{\frac{2}{\gamma}} \sqrt{\frac{\varepsilon_n}{k_p}}$$

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

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

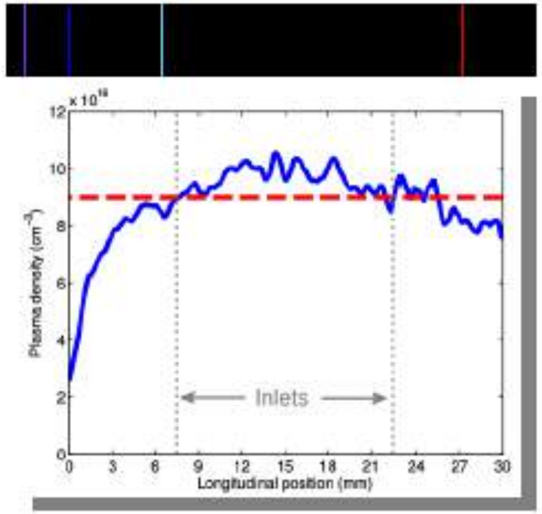
PWFA vacuum chamber at SPARC_LAB



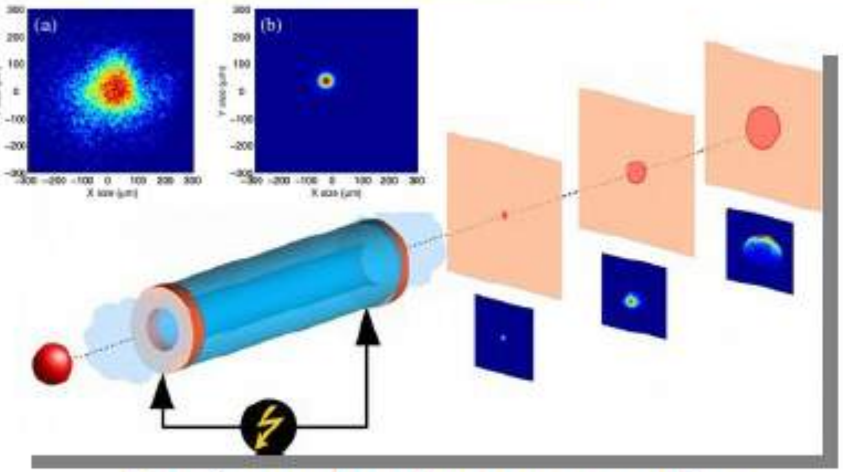
Previous Experimetal Results

Activities with the high-brightness SPARC photo-injector

Plasma characterization

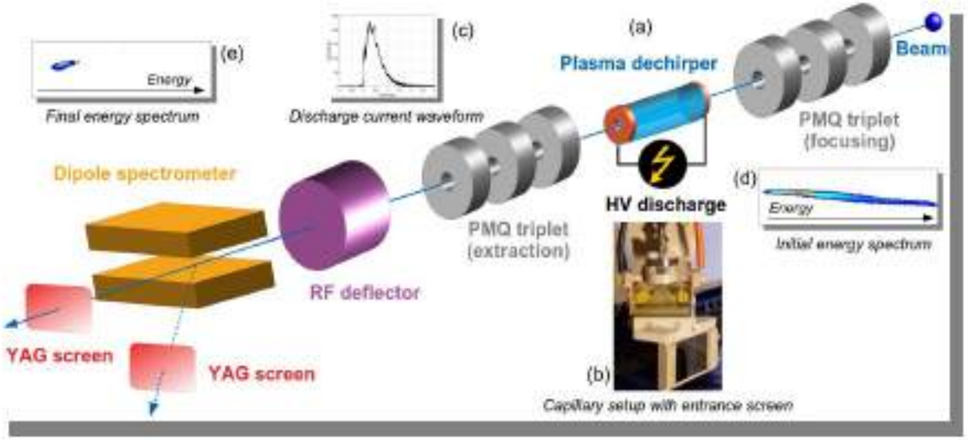


Biagioni, A., et al., Journal of Instrumentation 11.08 (2016): C08003.



Focusing and emittance preservation with active-plasma lenses

Pompili, R., et al., Physical review letters 121.17 (2018): 174801.
Pompili, R., et al., Applied Physics Letters 110.10 (2017): 104101.



Plasma-dechirper

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

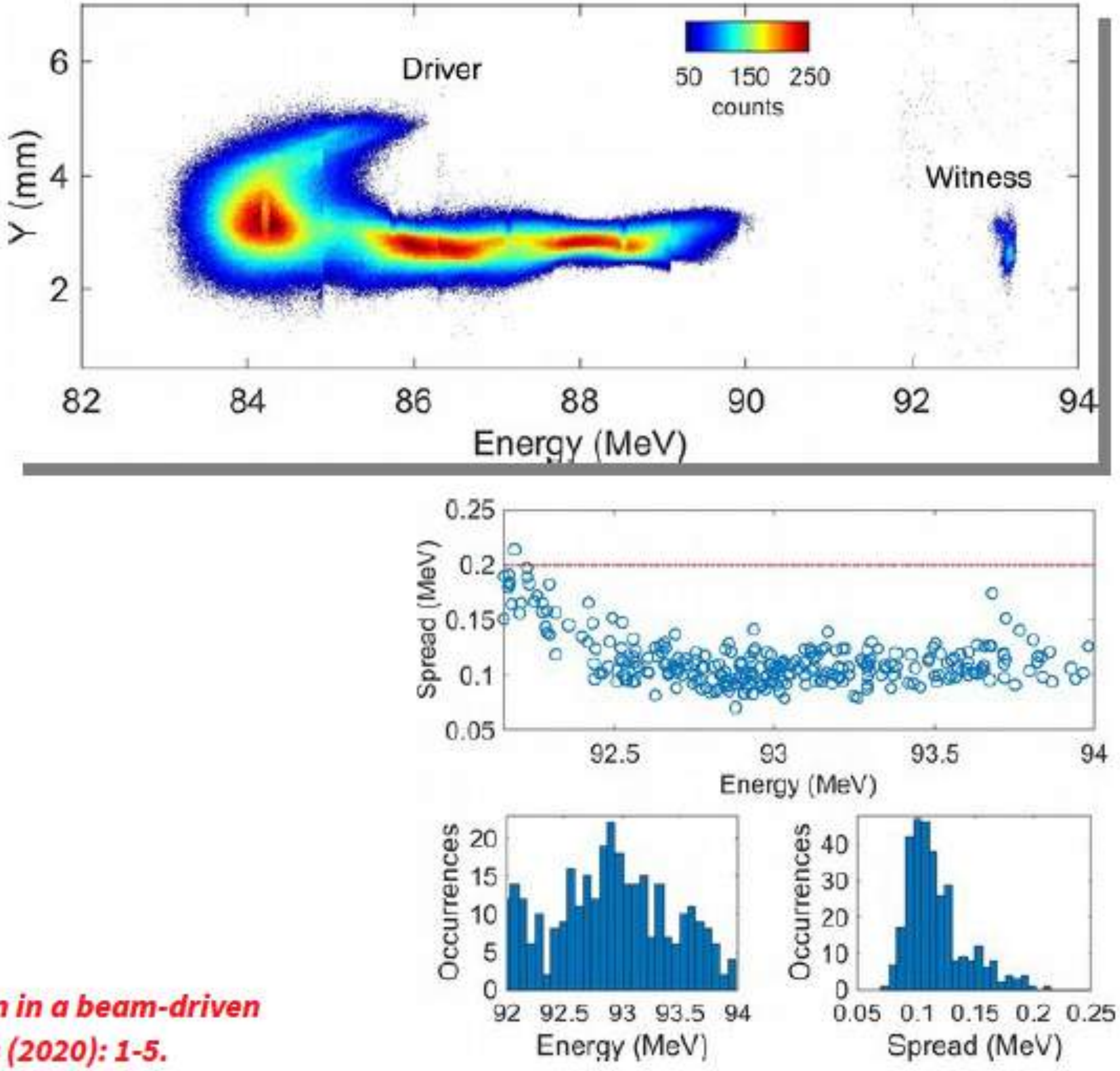
Assisted Beam Loading Energy Spread Compensation

Achieved 4 MeV acceleration in 3 cm plasma with 200 pC driver

- *~133 MV/m accelerating gradient*
- *2x10¹⁵ cm⁻³ plasma density*

→ demonstration of energy spread compensation during acceleration

- *Energy spread reduced from 0.2% to 0.12%*
- *99.5% energy stability*



Pompili, R., et al. "Energy spread minimization in a beam-driven plasma wakefield accelerator." Nature Physics (2020): 1-5.

Ongoing FEL activity (SL_COMB2FEL)

The experimental beam parameters measured in the PWFA experiment have been used as input for a preliminary evaluation of FEL performances

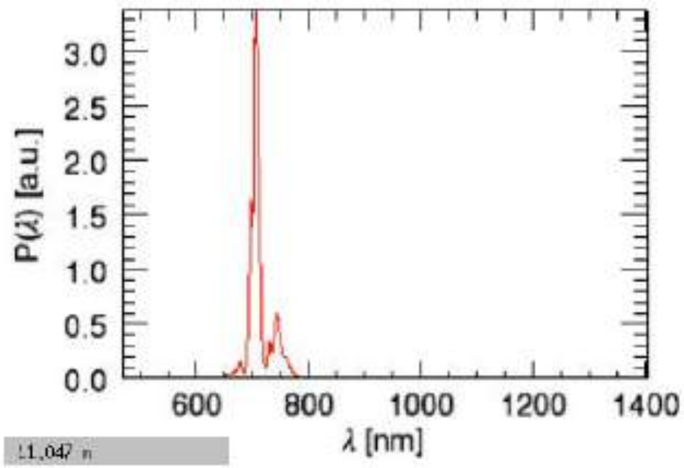
GENESIS 1.3 time-dependent simulations

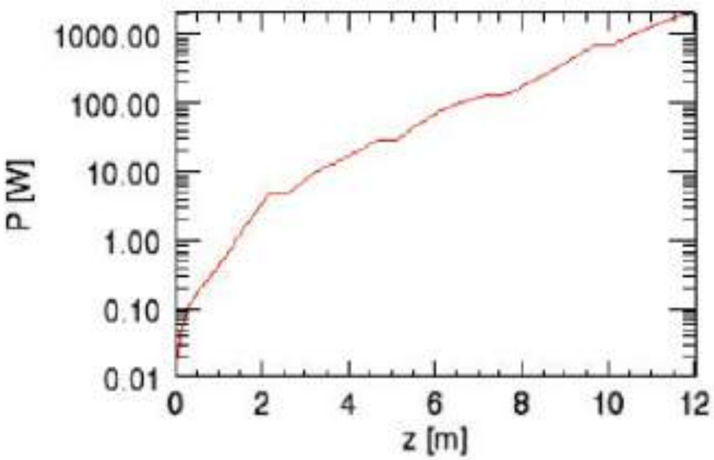
measurable growth of the FEL gain achieved

E. Chiadroni (LNF)
F. Nguyen (ENEA)

Witness beam parameters		Undulator parameters	
γ	174	λ_u (cm)	2.8
$\Delta E/E$ (%)	0.28*	K_{rms}	0.72
$\varepsilon_{nx,y}$(mm mrad)	3.5**	FODO β function (m)	1.6
Q (pC)	20	λ_r (nm)	700
I_{peak} (A)	214		

*It is the rms energy spread
**projected emittance





High Quality Facility

$$\frac{\Delta\lambda}{\lambda} \propto \frac{\Delta E}{E} \propto \rho \approx 10^{-3}$$

FEL requirement
(Undulators - Optics)

$$\left.\frac{\Delta E}{E}\right|_p = \frac{\Delta n_p}{n_p}$$

Plasma density
(Long Capillary – Diagnostics)

$$\left.\frac{\Delta E}{E}\right|_Q = \frac{\Delta I_d}{2(I_d)} + \frac{\Delta I_w}{2(I_w)}$$

Bunch charge/length
(Cathodes – Laser – Injector)

$$\left.\frac{\Delta E}{E}\right|_{DW} = \frac{a\omega_p}{2\pi}\Delta t_{DW}$$

$$2 \leq a \leq 4$$

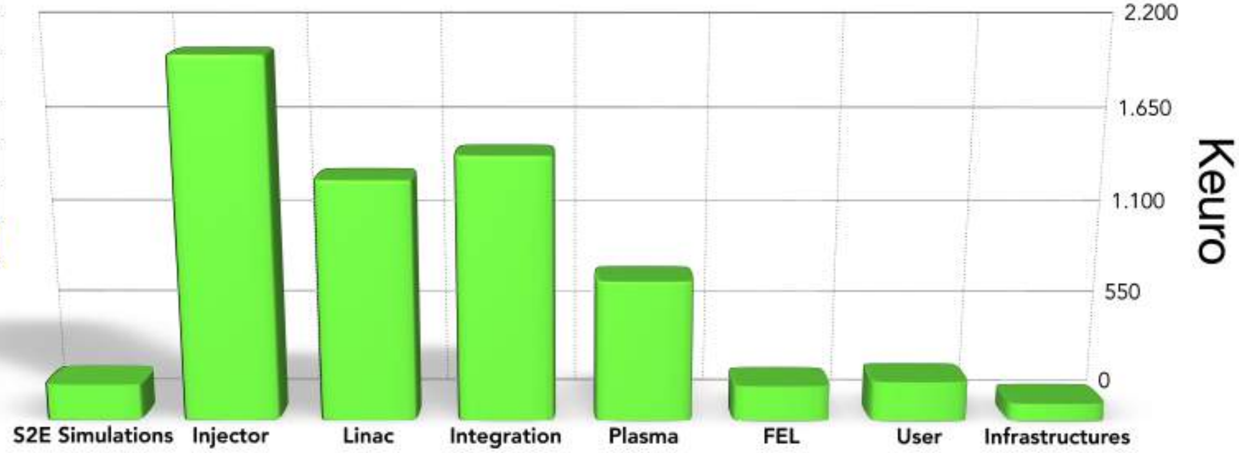
Driver/Witness timing
(Compressors - Synchronization)

Stima costi TDR

ID	AREA	Amount (k€)	%
WA1	S2E Simulations	205	3,18
WA2	Injector	2045	31,75
WA3	Linac	1365	21,20
WA4	Integration	1500	23,29
WA5	Plasma	800	12,42
WA6	FEL	200	3,11
WA8	User	225	3,49
WA9	Infrastructures	100	1,55
	Budget At Completion	**6440**	**100,00**

~6'500'000 € for the TDR

This does **NOT** include
- Manpower
- High Power Laser activities
- Running cost
- Travels
- Conference fee
- PCs
- Maintenance TEX & SPARC_LAB



Investment per working area

Conclusions

- **A Critical Review of the CDR is ongoing**
- The technology readiness level of the main components is high but it requires **additional R&D effort** (with particular emphasis to the **stability, reproducibility** and **quality** of the accelerated electron beam) to have a fully proven engineering design of the X-band Linac and Plasma Module.
- The current funding **does not include Manpower and the R&D** needed for the TDR. Additional funding must be found (In progress).
- **Adjust the optimal energy/wavelength for FEL operation** with and without Plasma compatible **with realistic accelerating gradients** (X-band 60 MV/m, Plasma 1 GV/m) **and undulator technology** (PM or SC).
- Plasma beam line optimized to **remove the driver** beam and preserve the the witness beam parameters .
- Extend the Users Scientific Case including lower wavelength.
- **Demonstration of the main beam requirements at SPARC_LAB (spread, emittance, stability)**