EuPRAXIA@SPARC_LAB
and related R&D activities

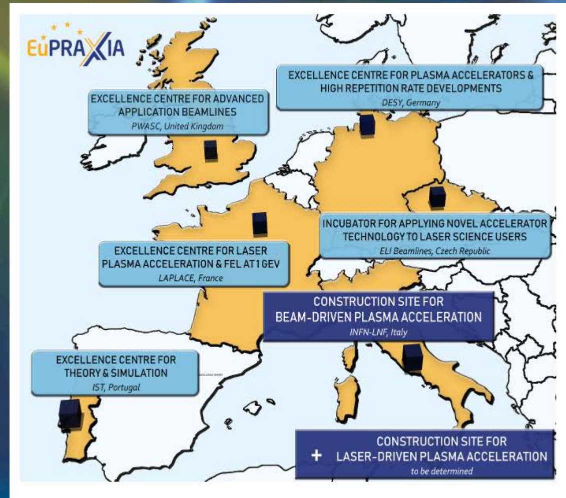
Massimo.Ferrario@LNF.INFN.IT

INFN, February 5

INFN
Istituto Nazionale di Fisica Nucleare

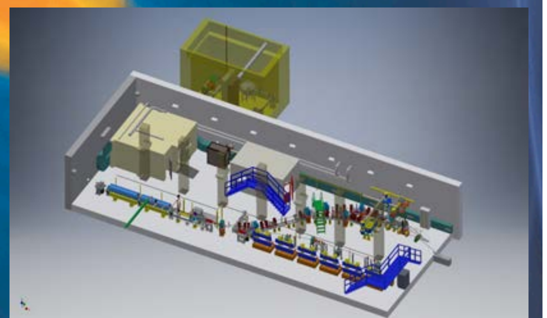
Outline

- EuPRAXIA as a Distributed Research Infrastructure



- EuPRAXIA@SPARC_LAB as a Pilot User Facility

- SPARC_LAB the R&D and training Facility



EuPRAXIA Conceptual Design: Complete

Conceptual design report submitted as planned to EU on November 1st

- **First ever international design of a plasma accelerator facility**
- Funded 2015-2019 by European Union (Horizon2020) with 3 Million Euro
- Coordinating lab: DESY (R. Assmann)
- Growing **consortium**: 32 → 41 labs, ELI, CERN, LBNL, Osaka, Shanghai, Russian labs
- **Industry**: Thales (France), Amplitude (France), Trumpf Scientific (Germany)
- EuPRAXIA envisions a beam energy of **1 to 5 GeV and a beam quality** (single pulse) equivalent to present RF-based linacs.

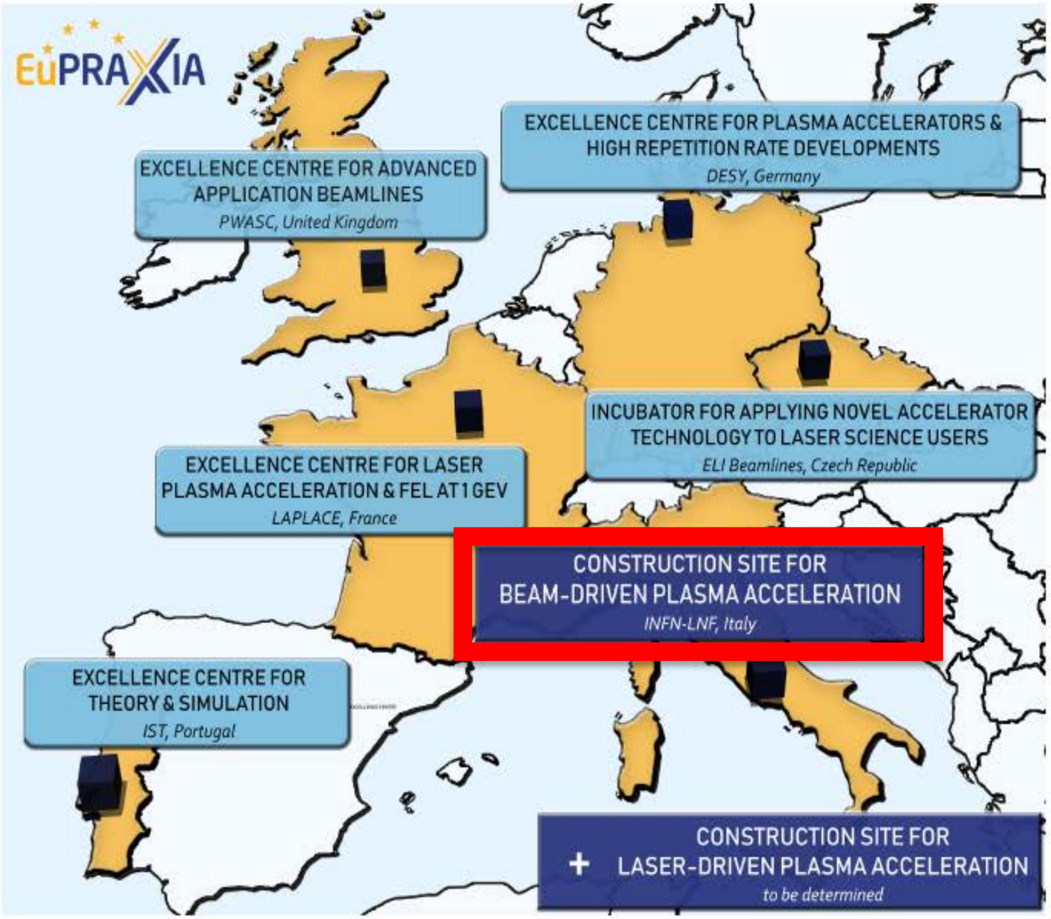
653 page CDR, 240 scientists contributed

http://www.eupraxia-project.eu/

… and Builds a European Distributed Facility

Position Europe as a Leader in the Global Context

1. Lean overall **EuPRAXIA management**
2. **Ten clusters:** Collaborations of institutes on specific problems, developing solutions, technical designs, driving developments with EuPRAXIA generated funding → **expertise of Helmholtz centers required - opportunities**
3. **Five excellence centers** at existing facilities: Using pre-investment, support tests, prototyping, production with EuPRAXIA generated funding → **DESY excellence center**
4. **One or two construction sites** at existing facilities with EuPRAXIA generated funding:
   - **Beam-driven** at Frascati (Italy).
   - **Laser-driven** at CLF/STFC (UK), CNR/ INFN (Italy) or ELI-Beamlines.

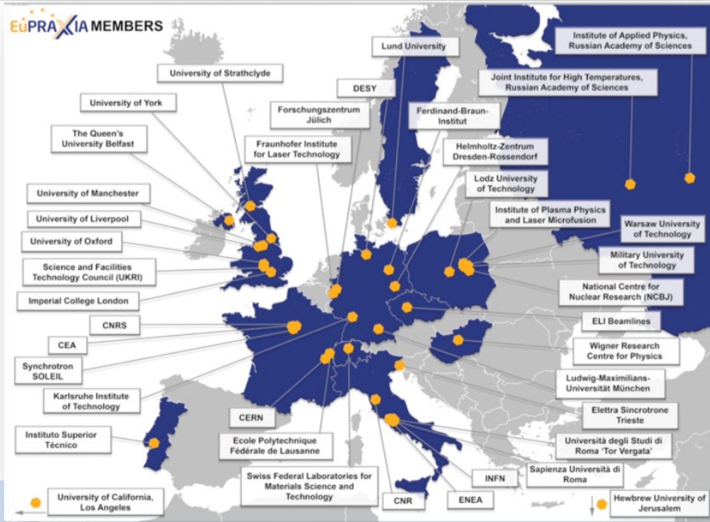


ESFRI Proposal: Submitted on September 9

Horizon 2020

- EuPRAXIA strongly supported in European research landscape, it is **timely**, it offers **highly attractive opportunities** for innovation with industry, novel applications and pilot users.
- **Lead Country**: **Italy (LNF/INFN)**
  Political and financial support letter sent to ESFRI by Italian Ministry
- **Political support letters** (at least two needed from countries):
  - **Hungary**
  - **Portugal**
  - **Czech Republic** (ELI))
  - **UK**
- Note: All operational costs covered by host countries.

From political landscape it is seen that both Czech Republic and UK would be excellent sites for the second leg of EuPRAXIA, connecting to existing facilities with laser expertise and few 100 million € pre-invest.



Recent (November 4) message from ESFRI Policy Officer:

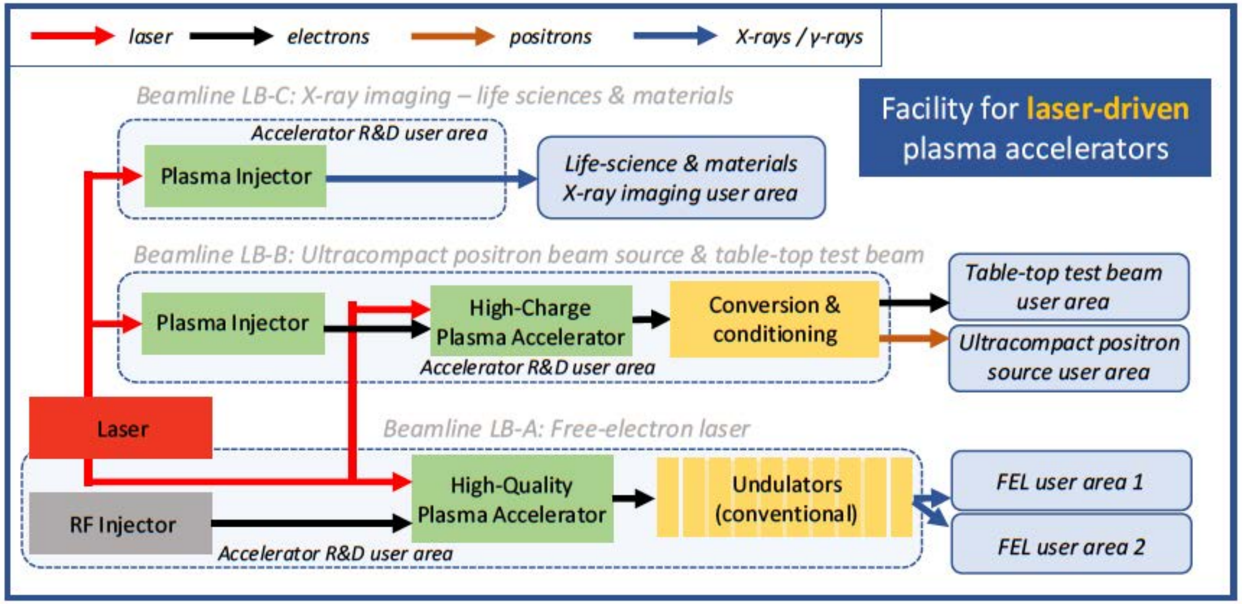
"We are glad to inform you that the proposal EuPRAXIA has been considered eligible and can now be assessed for entering the ESFRI Roadmap 2021."

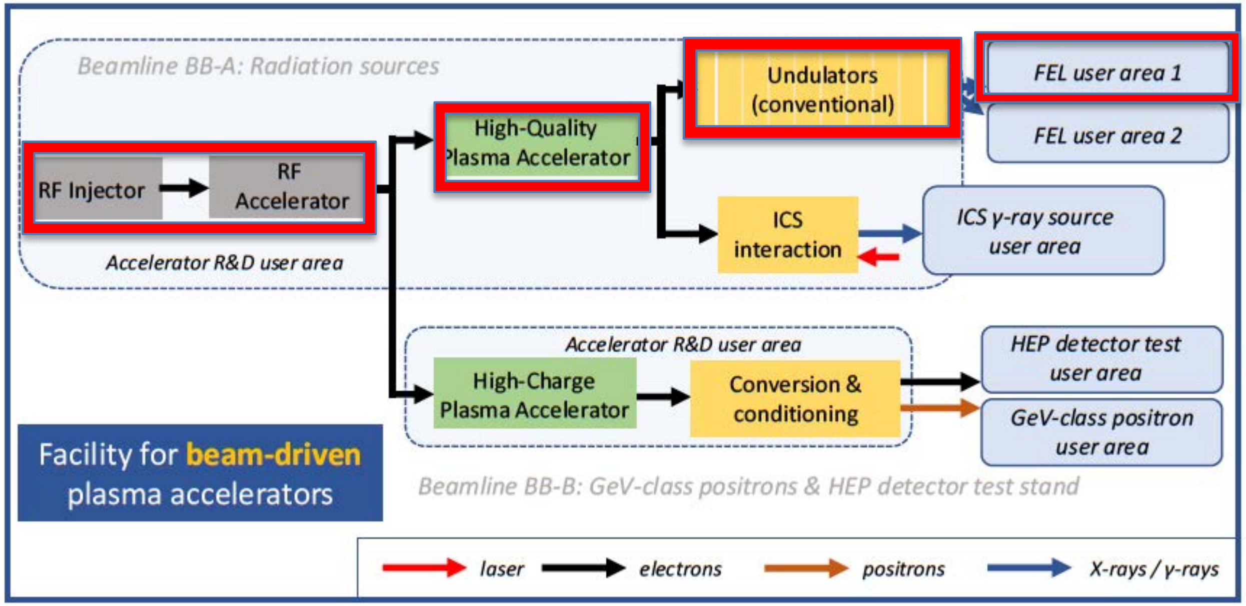
Next steps:

- Invitation for the hearing with list of critical questions: February-March 2021
- Hearing: April-May 2021

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.

Cost Estimate

1) **EuPRAXIA is a 569 M€** proposal under EU/ESFRI costing guidelines which is a full cost estimate. This includes CDR costs (already done), personnel cost, infrastructure cost (buildings), material costs, decommissioning costs.

Phase I: 388 M€ comprises the design, full preparation costs, (including laser technology), implementation of all excellence centres and the cost of construction at the site at INFN-LNF, Frascati, Italy. Personnel costs of 126 M€

Phase II: 53-181 M€ is the construction cost of the laser-driven EuPRAXIA leg (dependent on site choice) and termination costs. Personnel costs of 29 M€

Average Annual Operation Costs (covered by the local host institutes) : 30 M€ (PWFA 11.6 M€, LWFA 11.3 M€ , excellence centres 6.3 M€, RI management 0.8 M€)

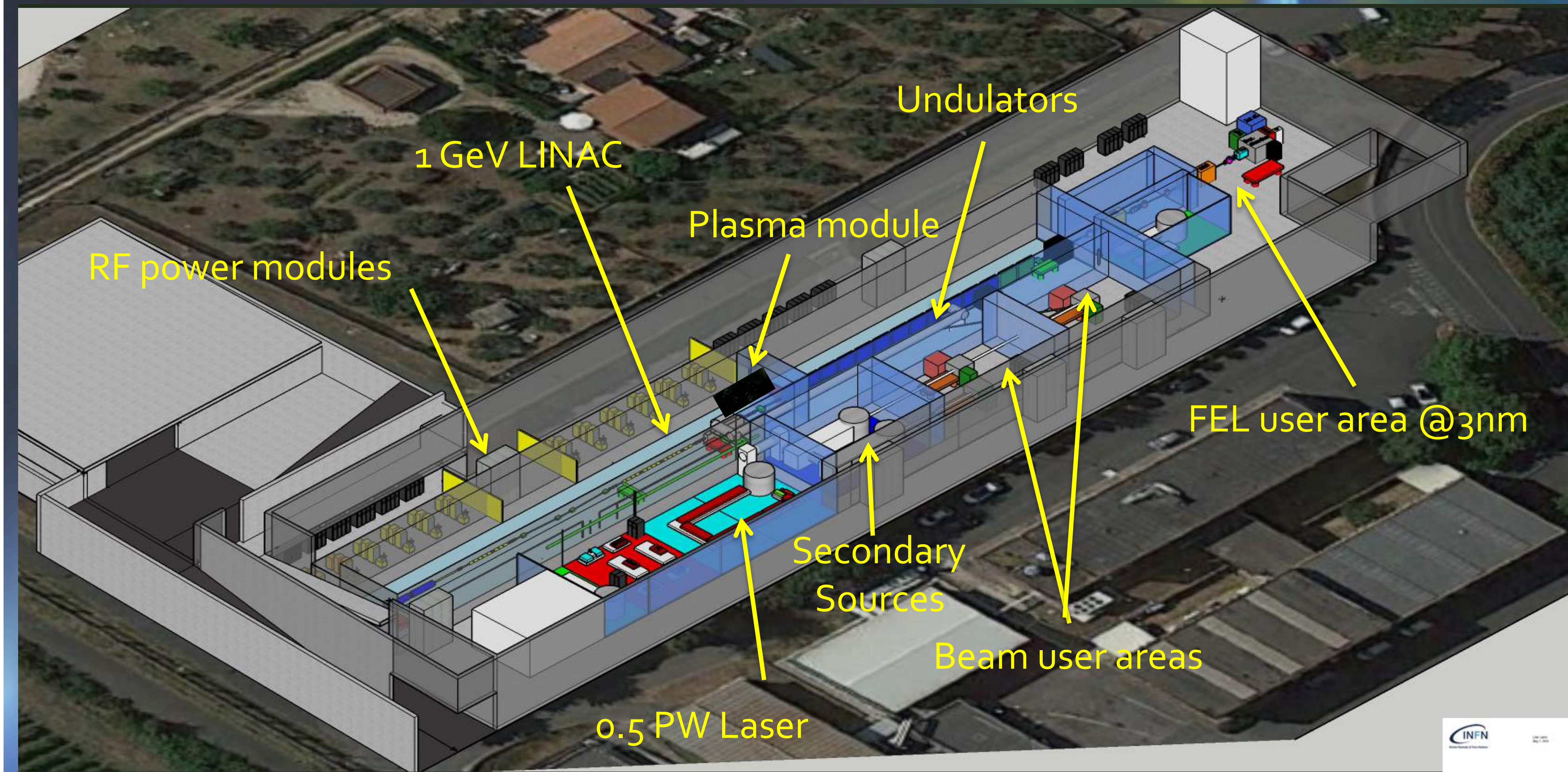
2**) We already have** binding commitments for more than **100 M€**, mainly through Italy.

3**) Lead country is Italy** which will also host the EuPRAXIA headquarters in the National Laboratory at Frascati**. Czech Republic** has provided a letter of financial and political support**. Portugal, Hungary and UK** have provided letters of political support .

4) EuPRAXIA has received **20 support letters** from industrial companies plus other from large representative bodies, including TIARA and LEAPS

5) Upcoming next will be the ESFRI review. Once we are on the roadmap we will have the preparatory phase for EuPRAXIA, during which we will finalise the preliminary studies and estimates from our CDR and from the ESFRI application.

EuPRAXIA@SPARC_LAB



http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

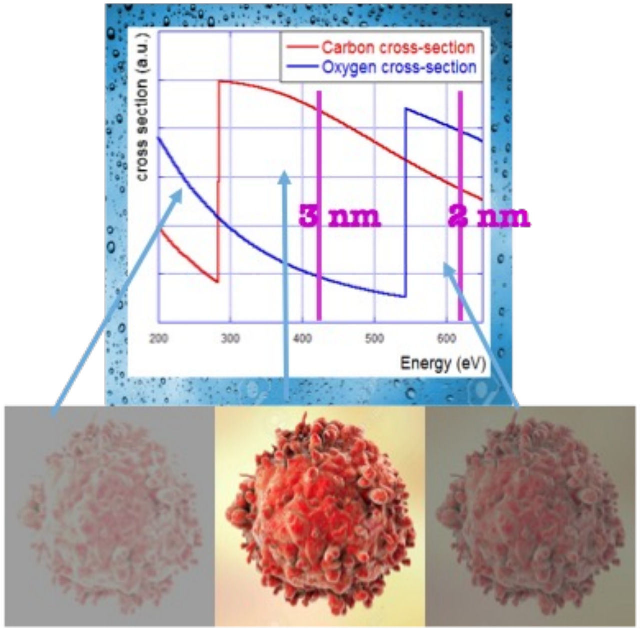
Expected SASE FEL performances

Horizon 2020

	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

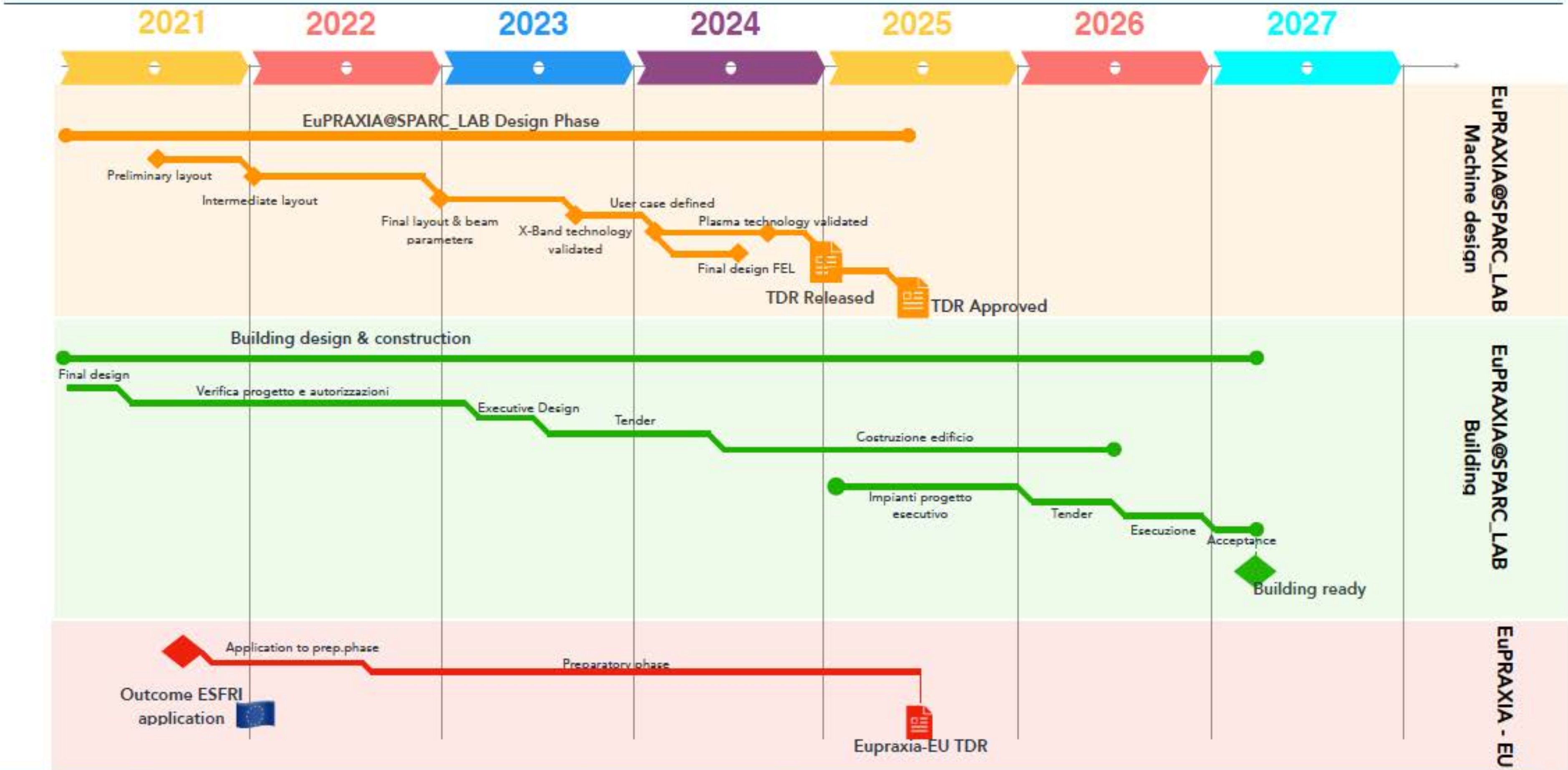
Energy region between Oxygen and
Carbon K-edge 2.34 nm – 4.4 nm
(530 eV -280 eV)
Water is almost transparent to radiation in this range while nitrogen and carbon are absorbing (and scattering)



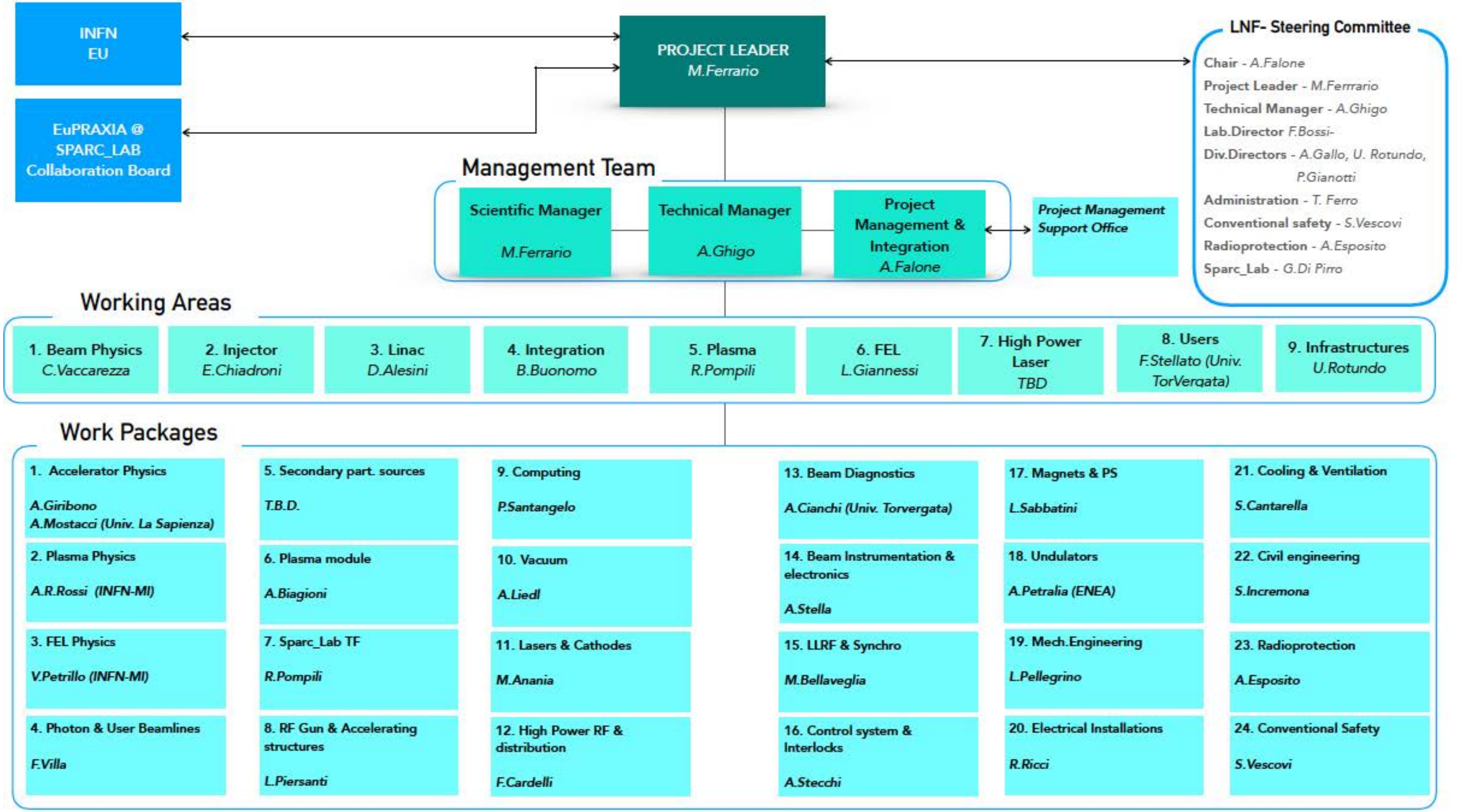
Coherent Imaging of biological samples
protein clusters, VIRUSES and cells
living in their native state
Possibility to study dynamics
~10^{11} photons/pulse needed

Courtesy F. Stellato, UniToV

Road map

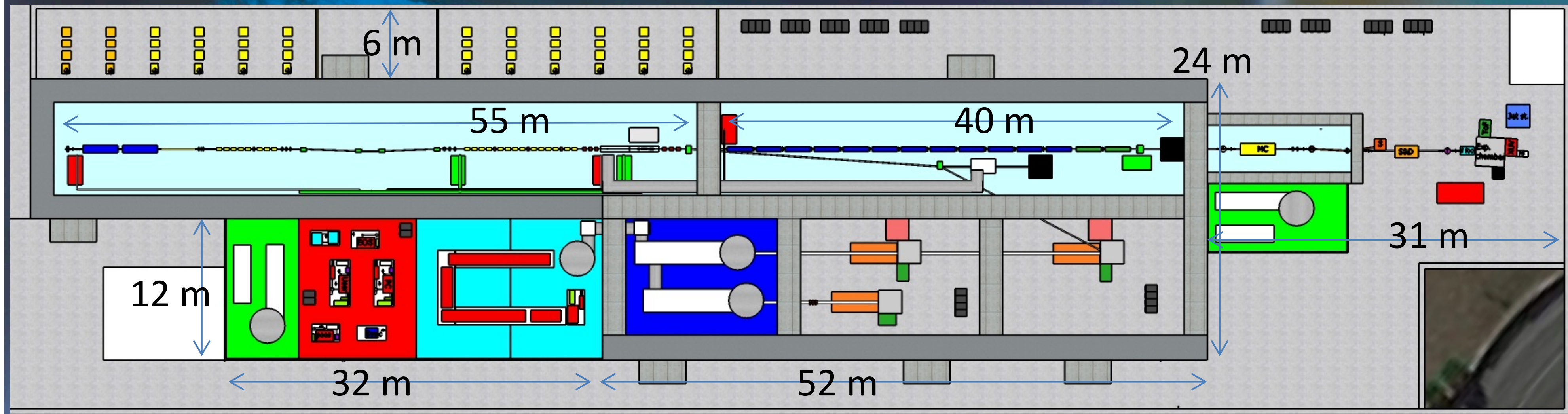


Courtesy A. Falone

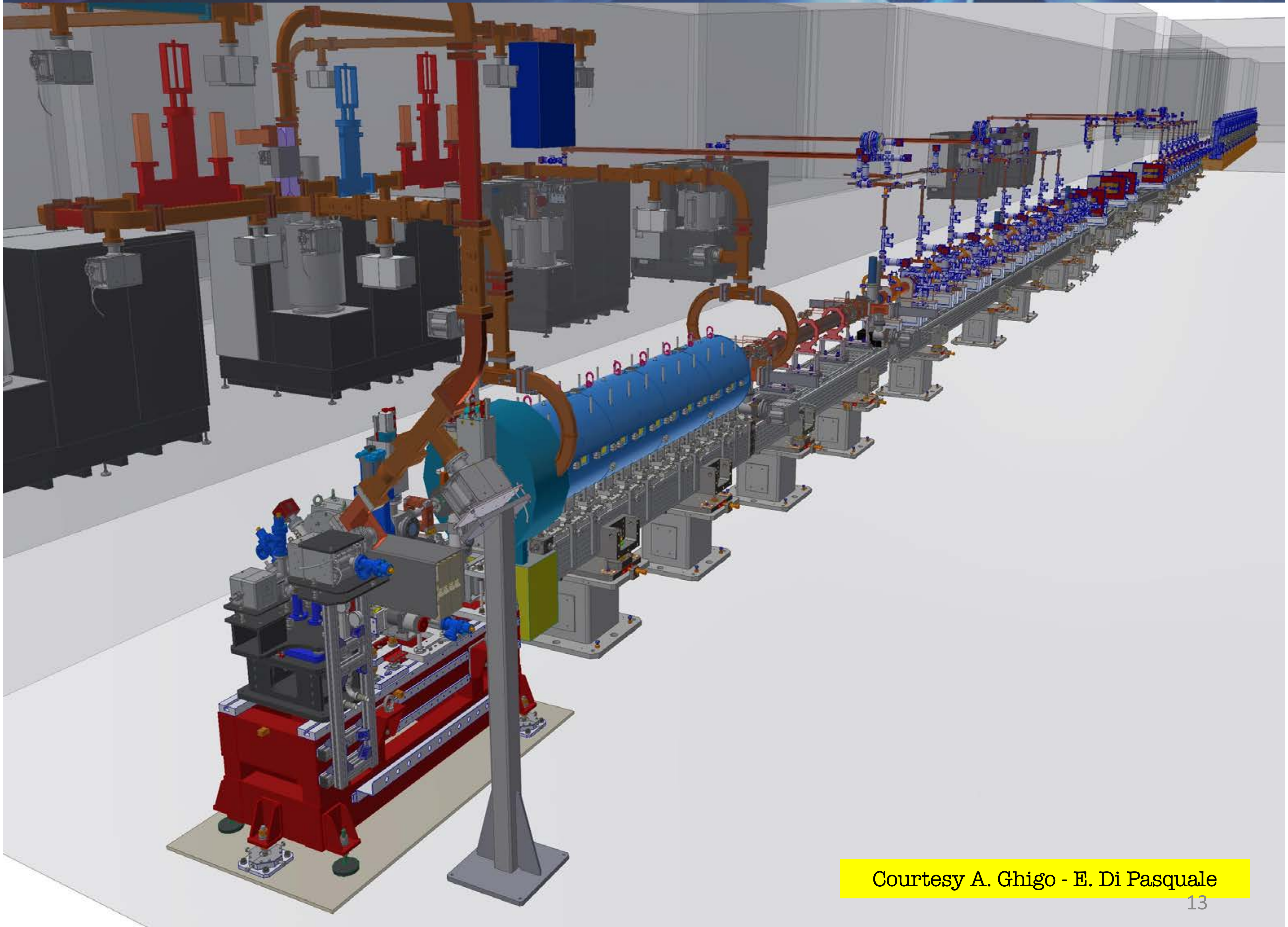

INFN
EU
EuPRAXIA @
SPARC_LAB
Collaboration Board
PROJECT LEADER
M.Ferrario
LNF- Steering Committee
Chair - A.Falone
Project Leader - M.Ferrrario
Technical Manager - A.Ghigo
Lab.Director F.Bossi-
Div.Directors - A.Gallo, U. Rotundo, P.Gianotti
Administration - T. Ferro
Conventional safety - S.Vescovi
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

Injector | Linac | Plasma | FEL | Users

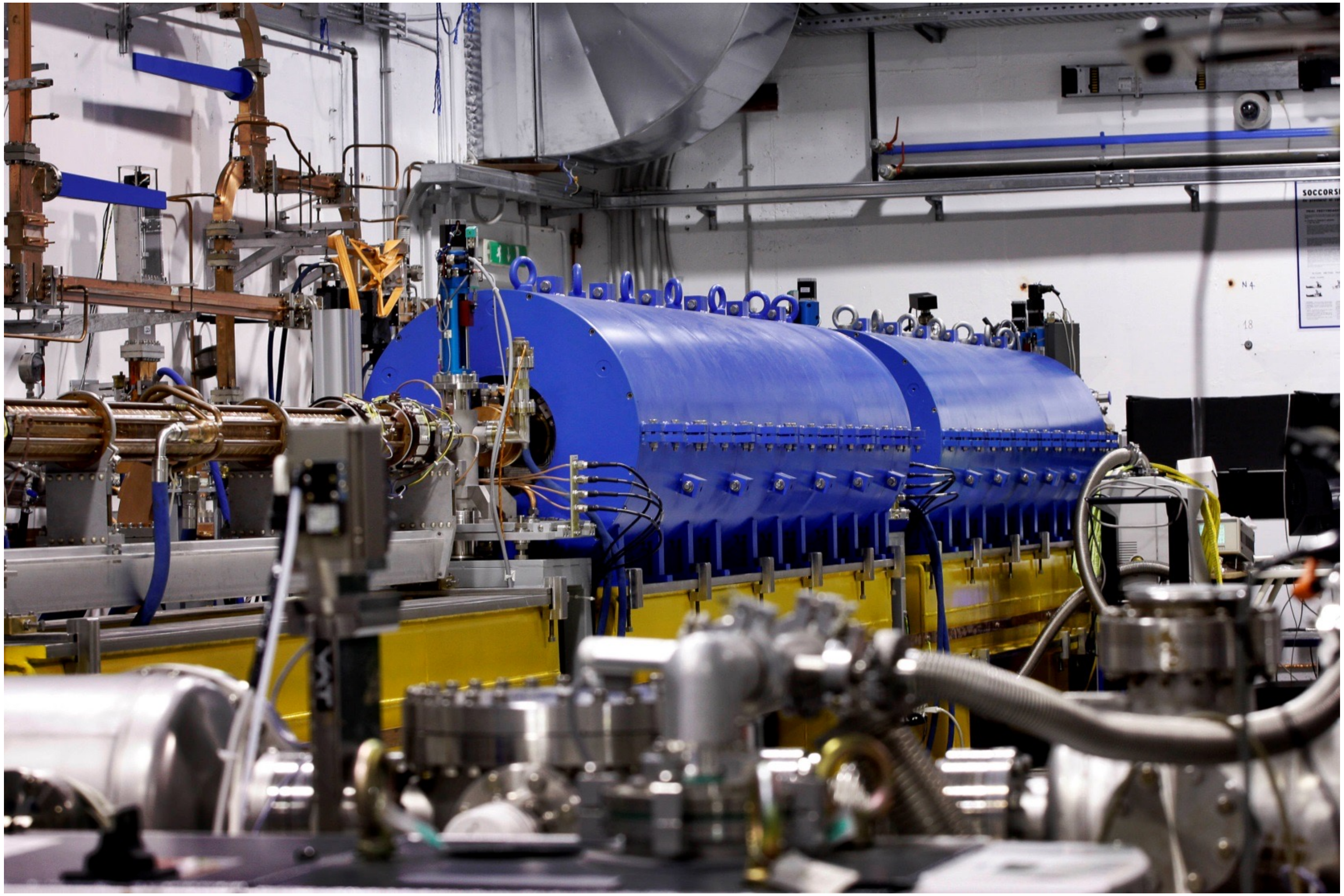


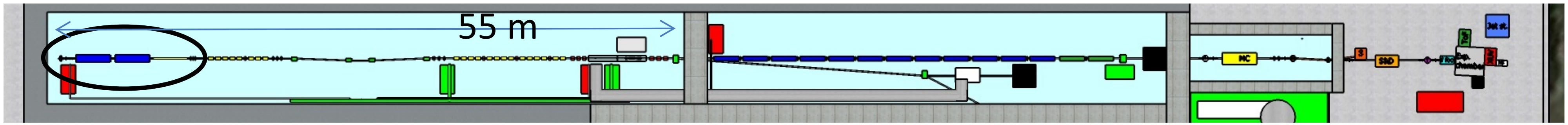
Beam Physics | Lasers | Integration | Infrastructures



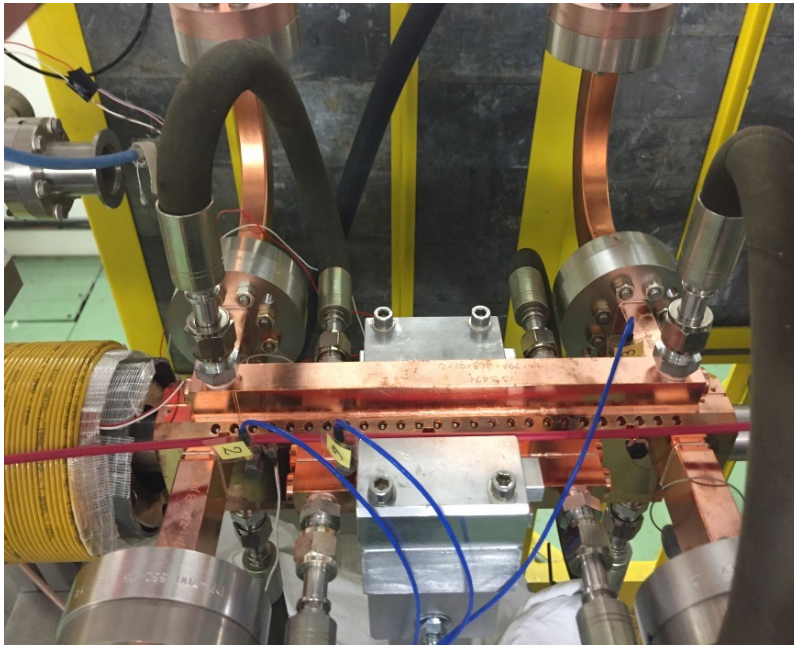
Courtesy A. Ghigo - E. Di Pasquale

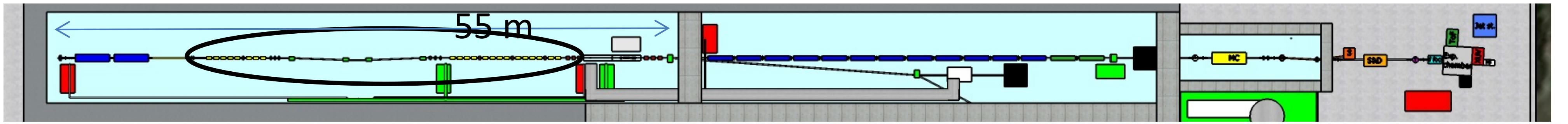
SPARC_LAB HB photo- injector



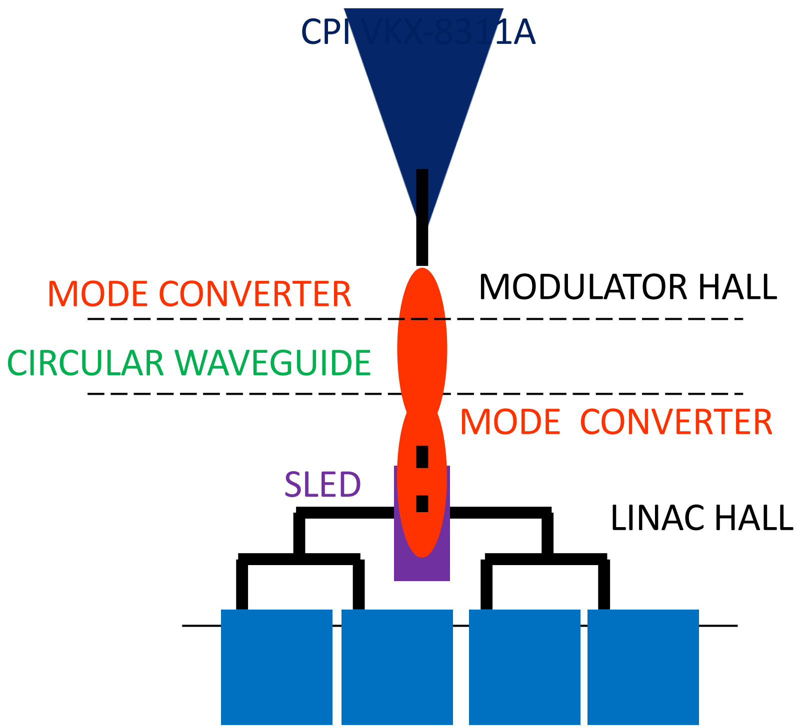


X-band Linac



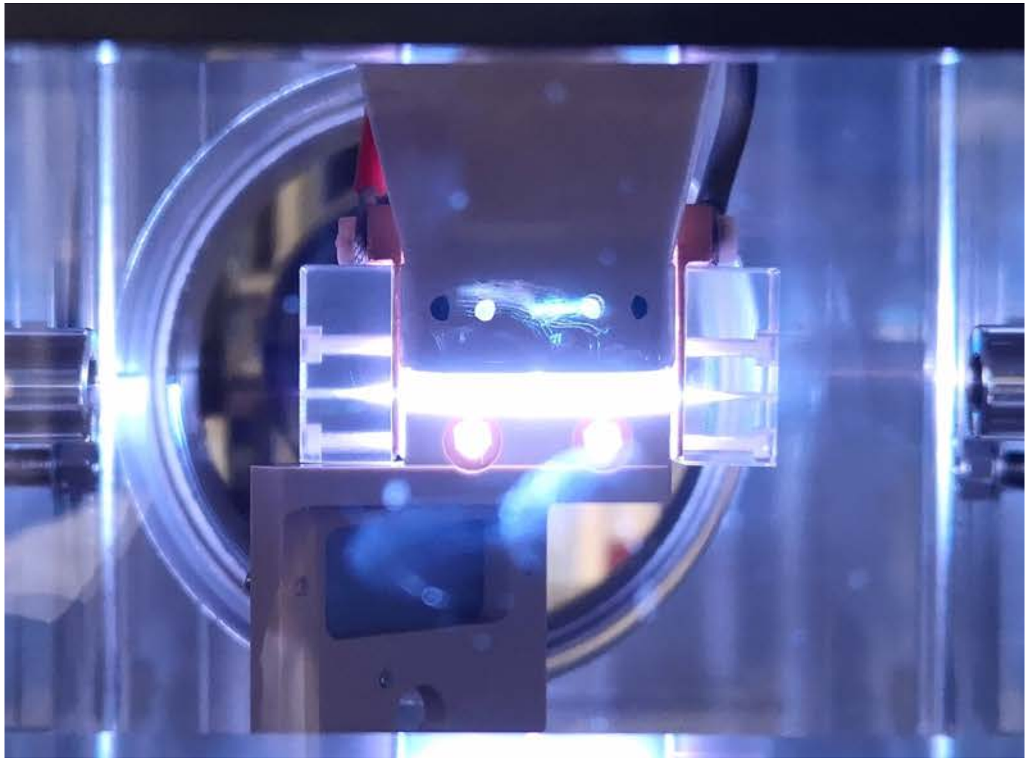


Compact

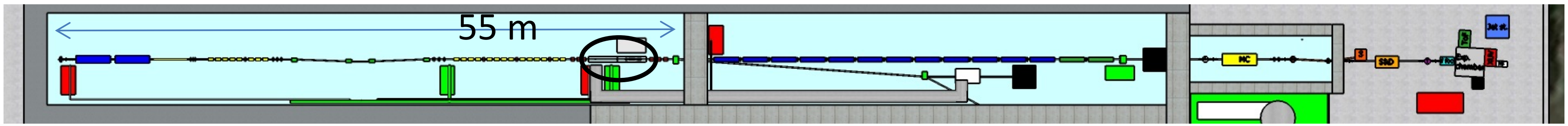


Parameter	Value
Frequency [GHz]	11.9942
RF pulse [μs]	1.5
Kly. power [MW]	50
Average iris radius <a>	3.5
Iris radius a [mm]	4.3-2.7
Average gradient <G> [MV/m]	60
Structure length L_s [m]	0.9
Linac active length L_{act} [m]	18
Unloaded SLED Q-factor Q_0	180000
External SLED Q-factor Q_E	23100
Shunt impedance R [MΩ/m]	85-117
Effective shunt Imp. R_s [MΩ/m]	356
Number of modules	5
Structures per module N_m	4
Klystron power per module Pk_m [MW]	43
Peak input power [MW]	74
Input power averaged over the pulse [MW]	48
Total number of structures N_{tot}	20
Total number of klystrons N_k	5

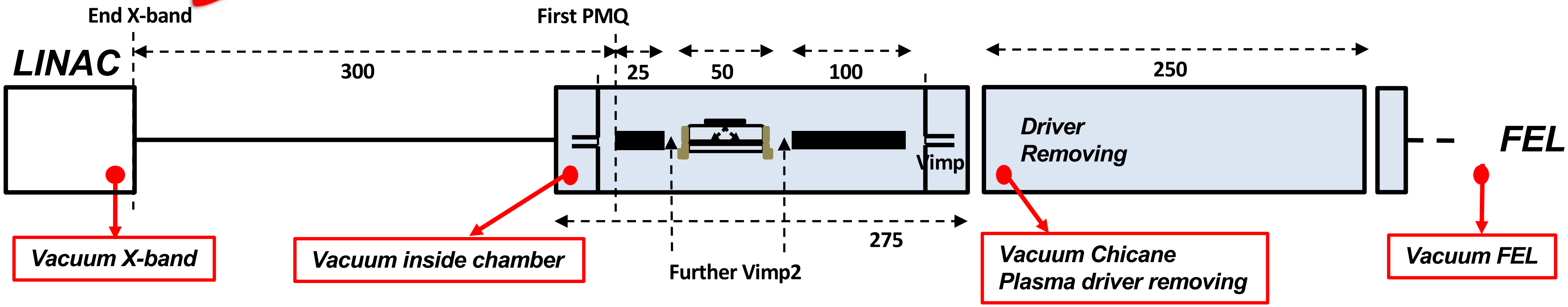
Plasma WakeField Acceleration



Capillary discharge at SPARC_LAB



Plasma module layout



1. *Chamber sizing depends on the vacuum constrains and capillary dimensions*
2. *Eupraxia chamber sizing starts from the current plasma chamber*
3. *Minimum length is 215 cm*
4. *Driver removing chamber properties depend on the technique used to remove the driver (Plasma or chicane)*
5. *Chamber/capillary factor is 5.5*
6. *New solutions will be studied to reduce the chamber/capillary factor by means of vacuum test and simulation*

3 cm-long capillary@ne = 10^{16} - 10^{17} cm^{-3}

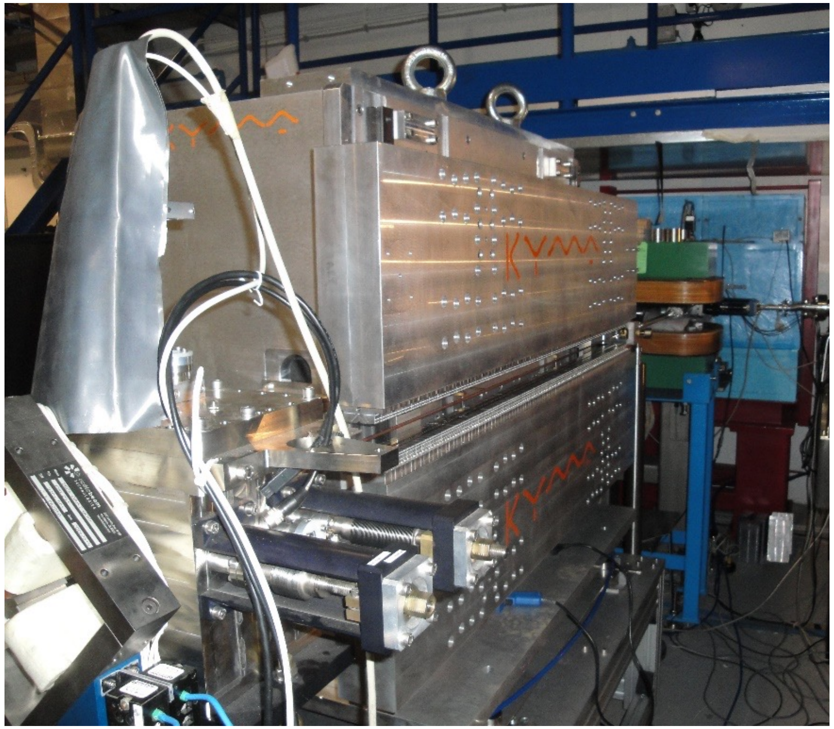
	Vgas (cm³)	*VimpEXT*	*VimpINT*	*Tpumps*	$V_{C\text{-}band}$	$V_{chamber}$	*Wtime*
1 Hz	0.0236	2 x 6mm/15cm	2 x 6mm/10cm	1780 l/s	10^{-7} mbar	10^{-8} mbar	No limits
10 Hz	0.236	2 x 6mm/15cm	2 x 6mm/10cm	1780 l/s	10^{-7} mbar	10^{-8} mbar	1 hour
100Hz	2.36						

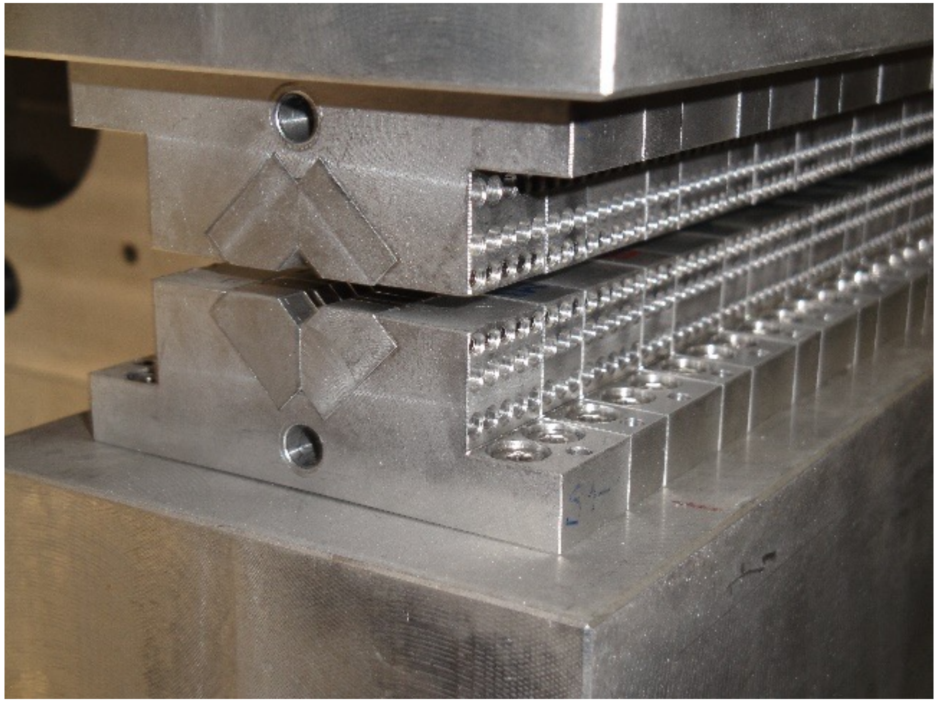
50 cm-long capillary@ne = 10^{16} - 10^{17} cm^{-3}

x15	*Vgas* (cm³)	*Vimp*	*Vimp2*	*Tpumps*	$V_{X\text{-}band}$	$V_{Chamber}$	*Wtime*
1 Hz	0.314	2 x 6mm/15cm	2 x 6mm/10cm	7000 l/s			
10 Hz	3.14	2 x 6mm/15cm	2 x 6mm/10cm	7000 l/s			
100Hz	31.4	x100					

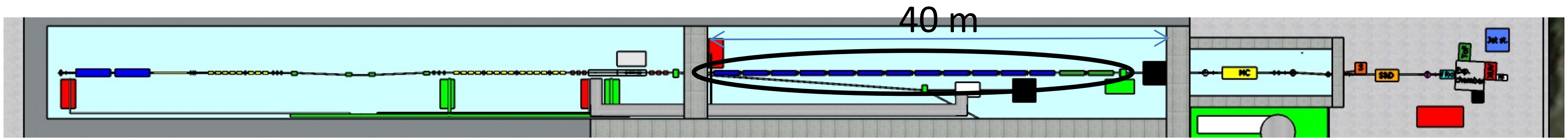
Courtesy R. Pompili , A. Biagioni

Undulators

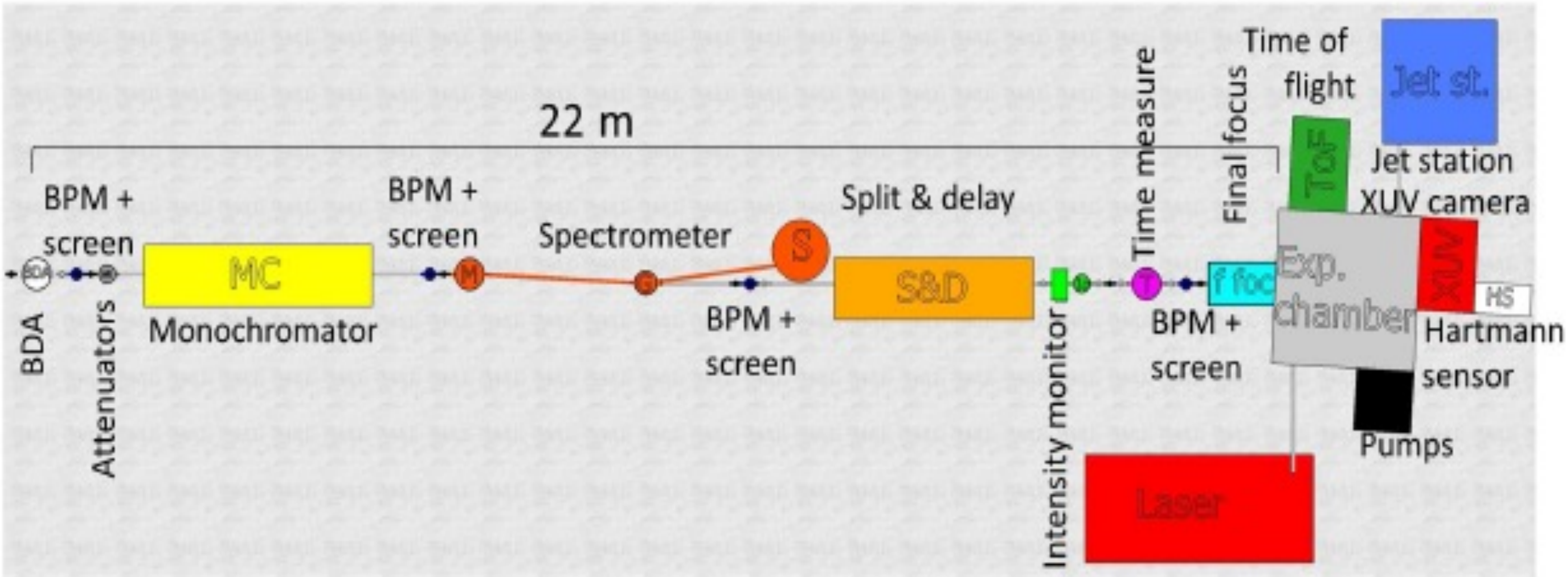


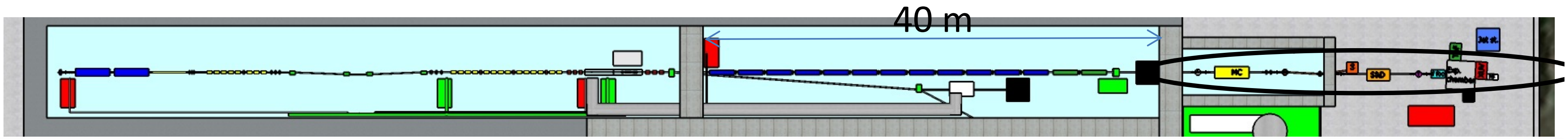


KYMA Δ udulator at SPARC_LAB: λ=1.4 cm, K1



Photon beam line





Water Window Coherent Imaging

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)

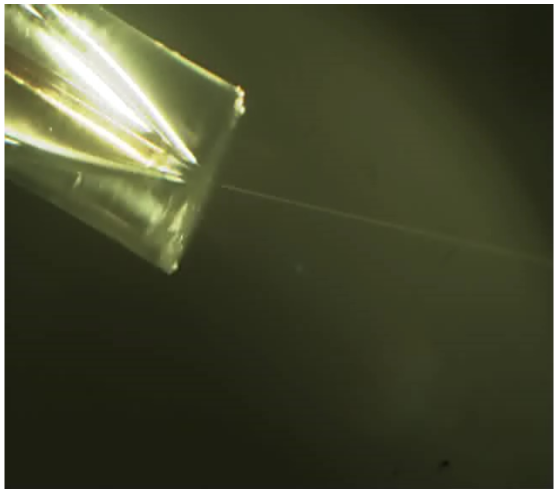
Coherent Imaging of biological samples

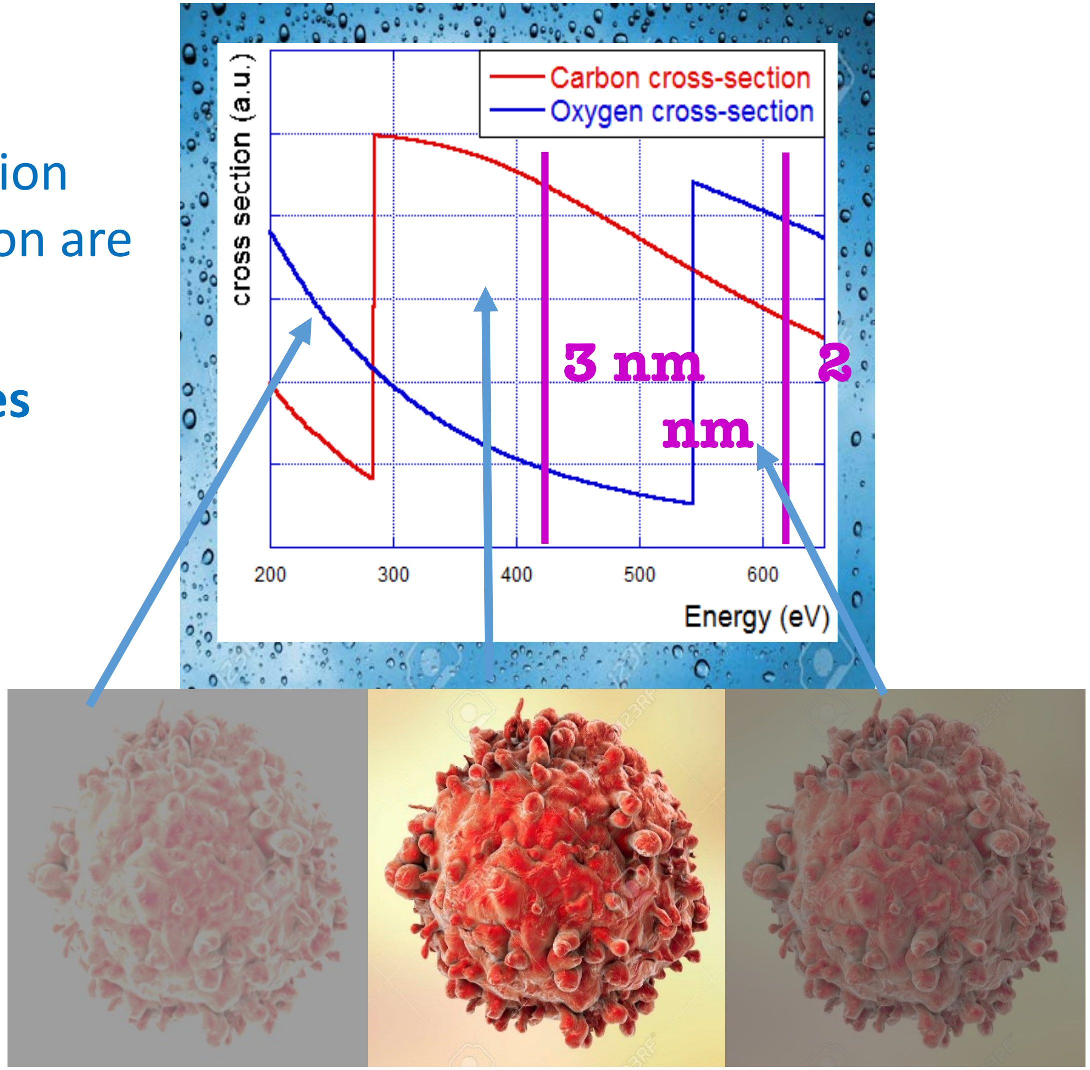
protein clusters, VIRUSES and cells

living in their native state

Possibility to study dynamics

~10^{11} photons/pulse needed

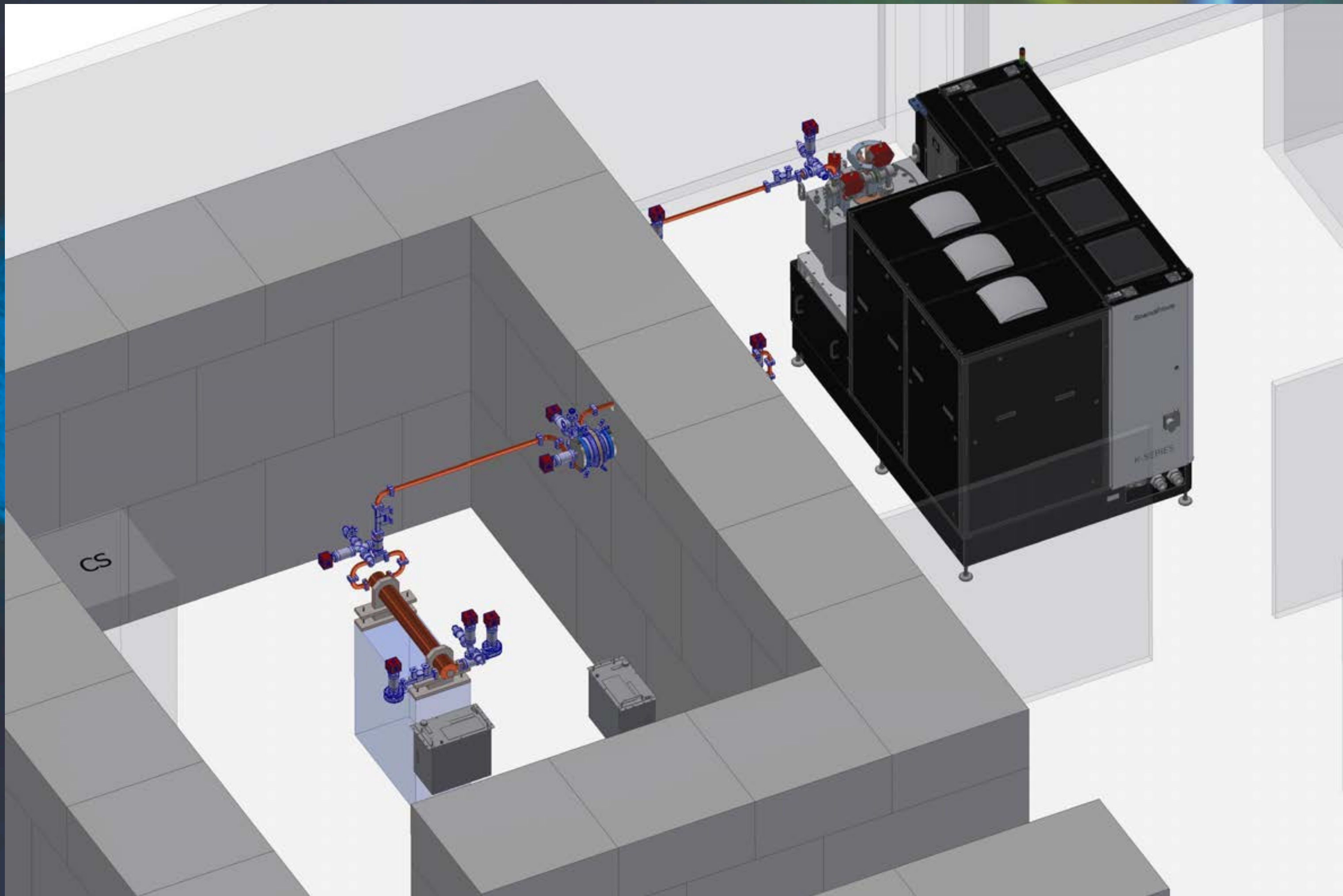




Courtesy F. Stellato, UniToV

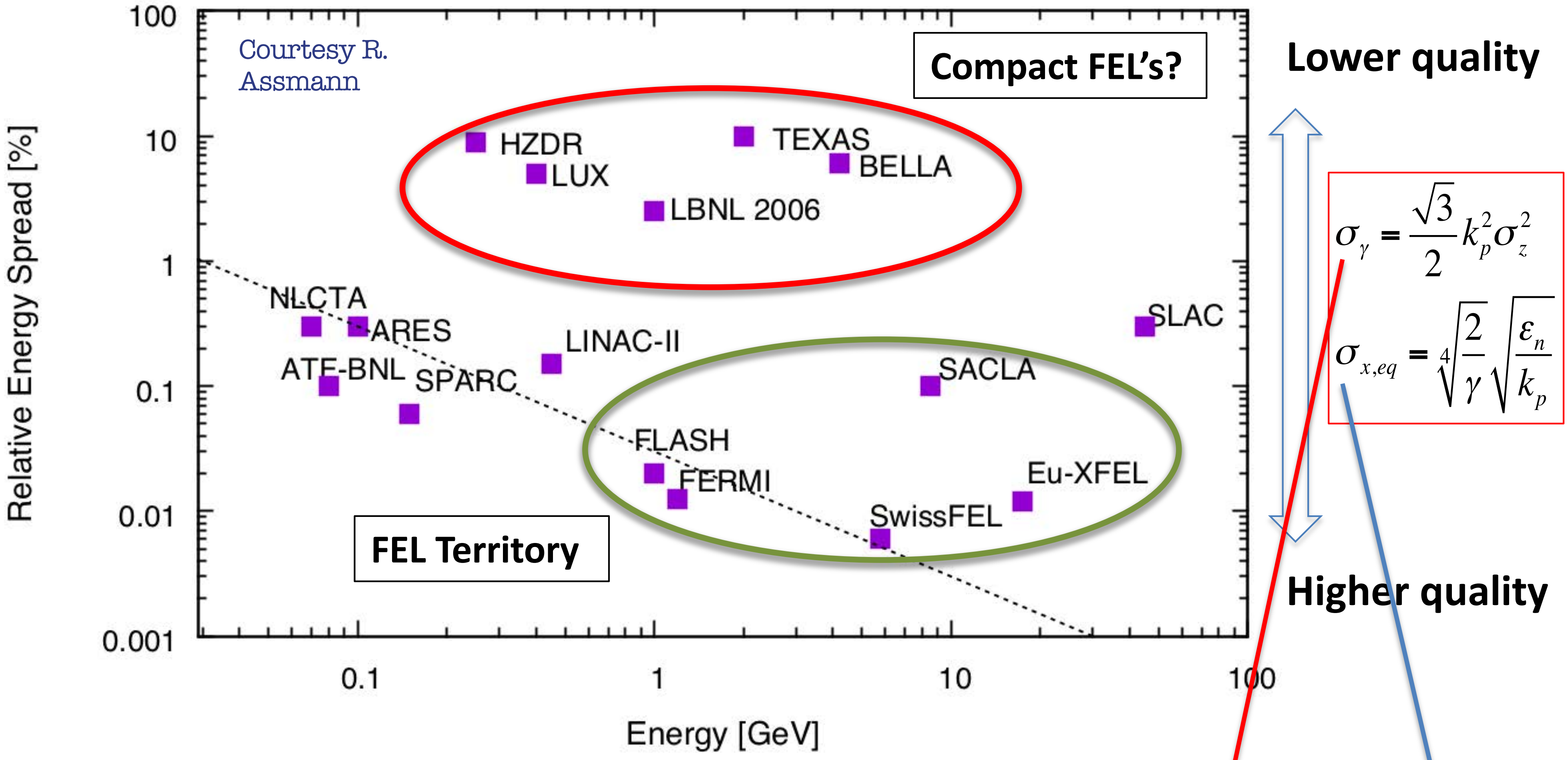
Open Problems and Required R&D for the TDR

TEX Facility



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

High Quality Beam



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

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

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

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)

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

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)

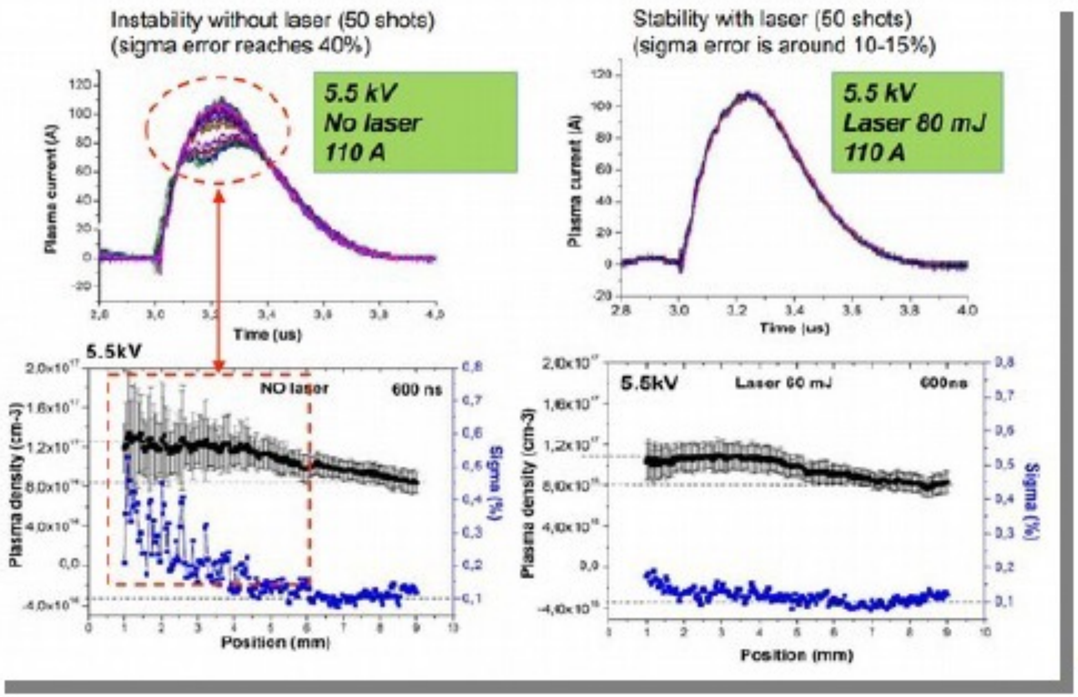
Plasma Characterization

Setup for plasma stabilization in Plasma_LAB has been replicated in the SPARC bunker

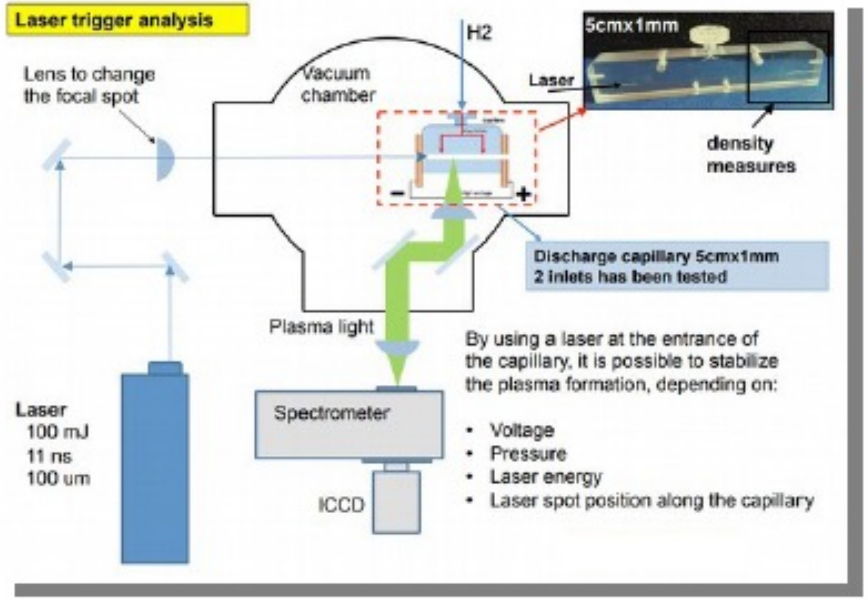
Measurements done in July 2020

We discovered that the LINAC dark current provides the same stabilization of the external laser

Analysis of experimental results (laser vs dark current) ongoing



M. Galletti, in preparation



A. Biagioni, in preparation

Plasma Density measured by observing Stark broadening of hydrogen emission lines

RF synchronization progress

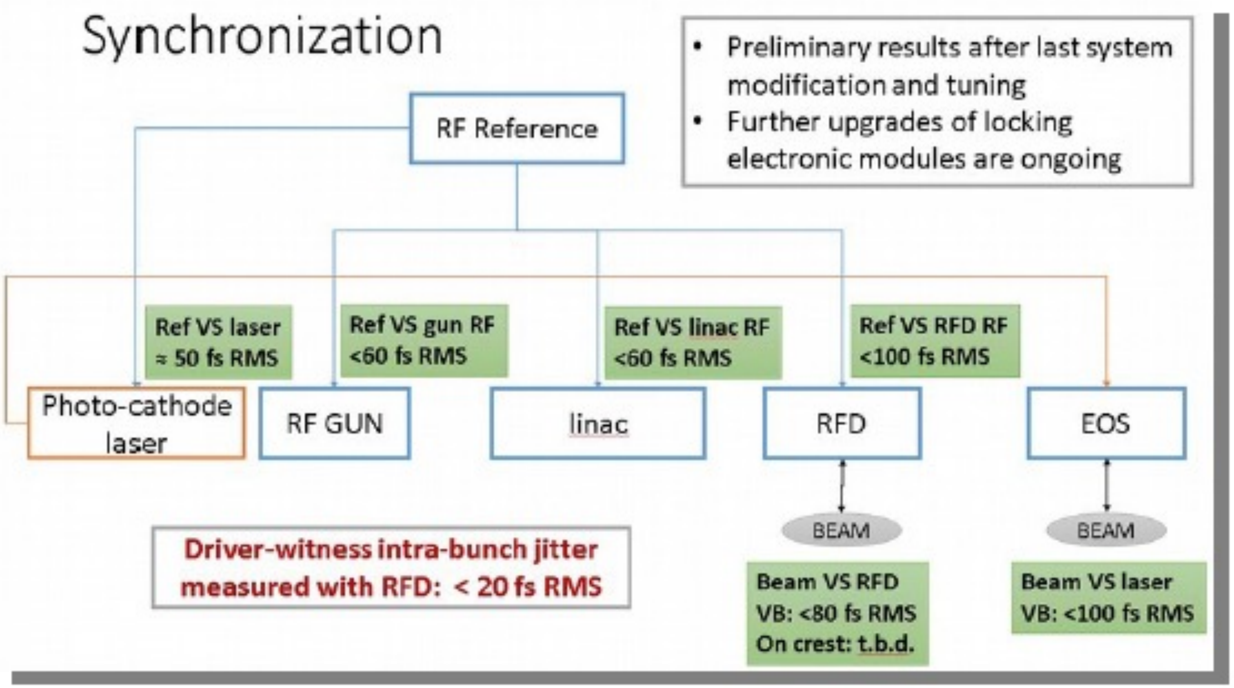
Recently we found rather large timing-jitters affecting the beam performances

*An **Electro-Optical Sampling (EOS)** station has been developed and allowed to estimate ~**300 fs** timing-jitter between the photo-cathode (PC) laser and the compressed beam*

*It translates in ~**70 fs** jitter in the distance between the driver-witness bunches → **MeV jitter with plasma!***

*Issue has been identified in the **photo-diode of the synchronization unit** that has been replaced*

*Last results show ~**80** fs bunch-PC laser jitter, giving ~**19 fs** jitter in the driver-witness distance → **expected lower energy jitter for the plasma accelerated bunch***

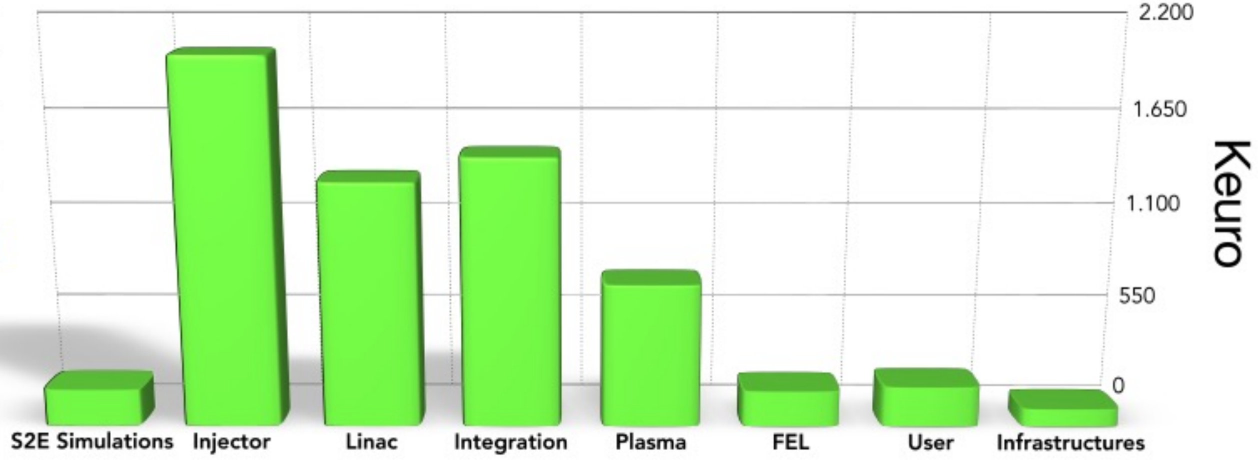


Stima costi TDR

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**

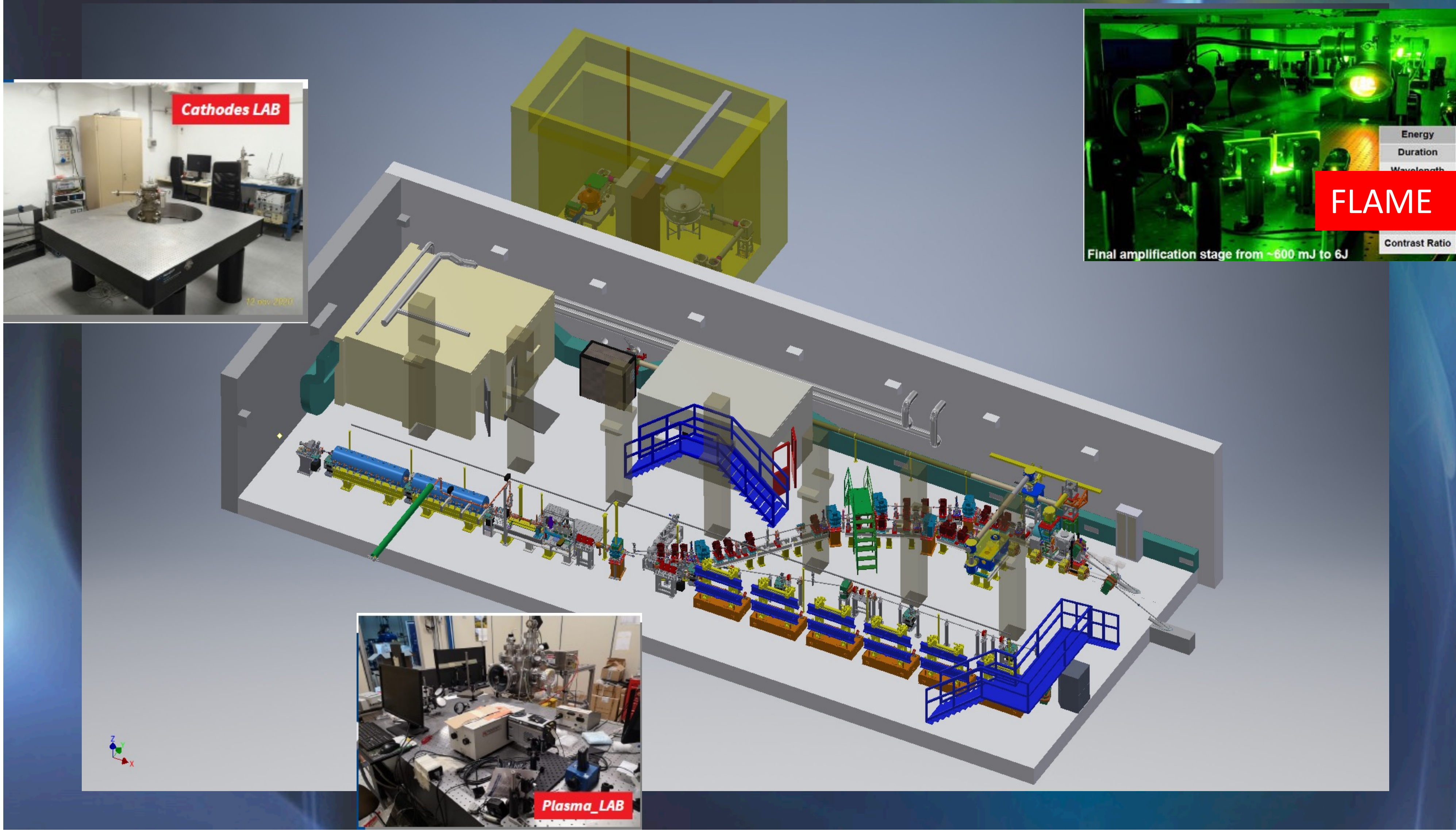
~6'500'000 € for the TDR

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

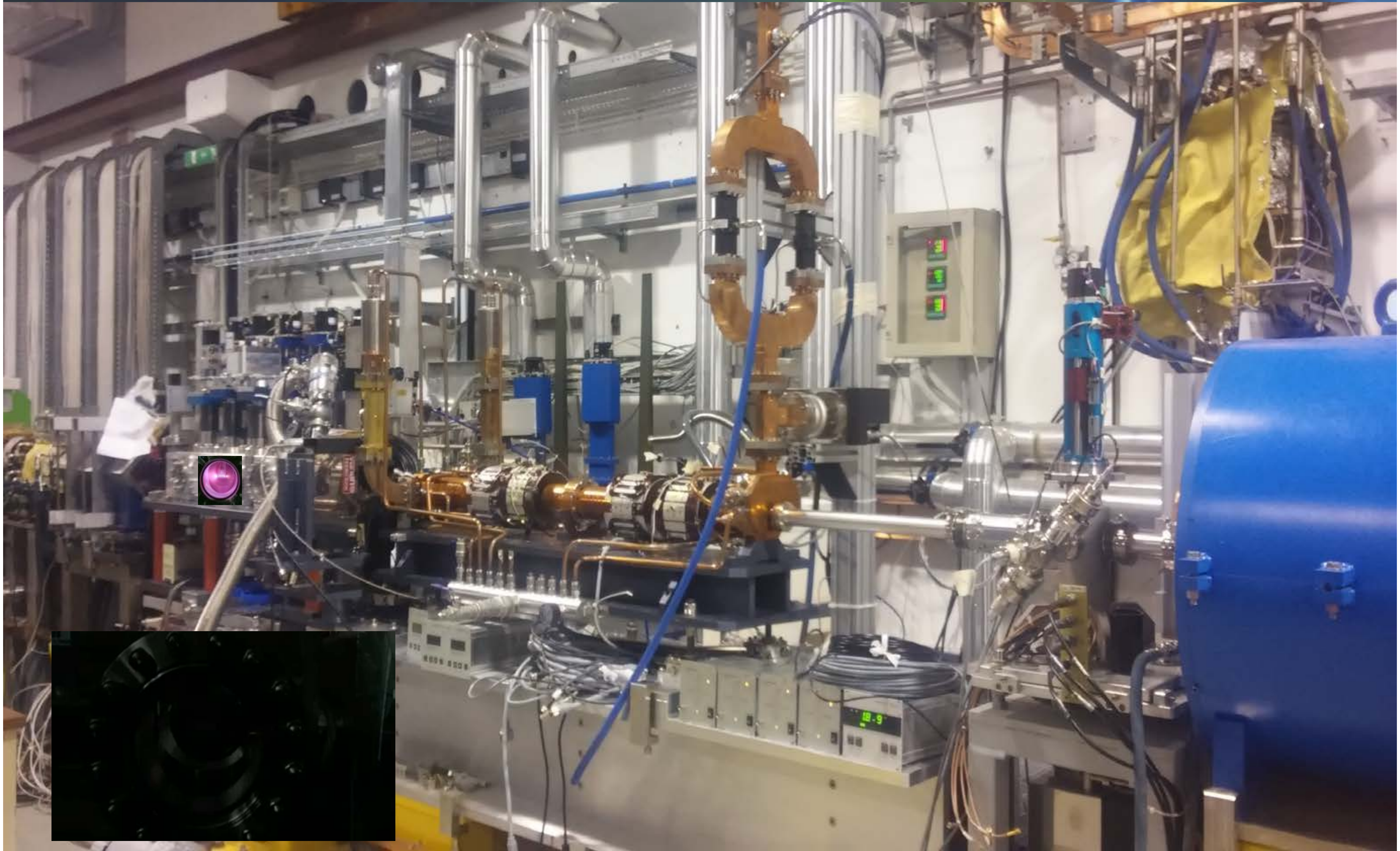


Investment per working area

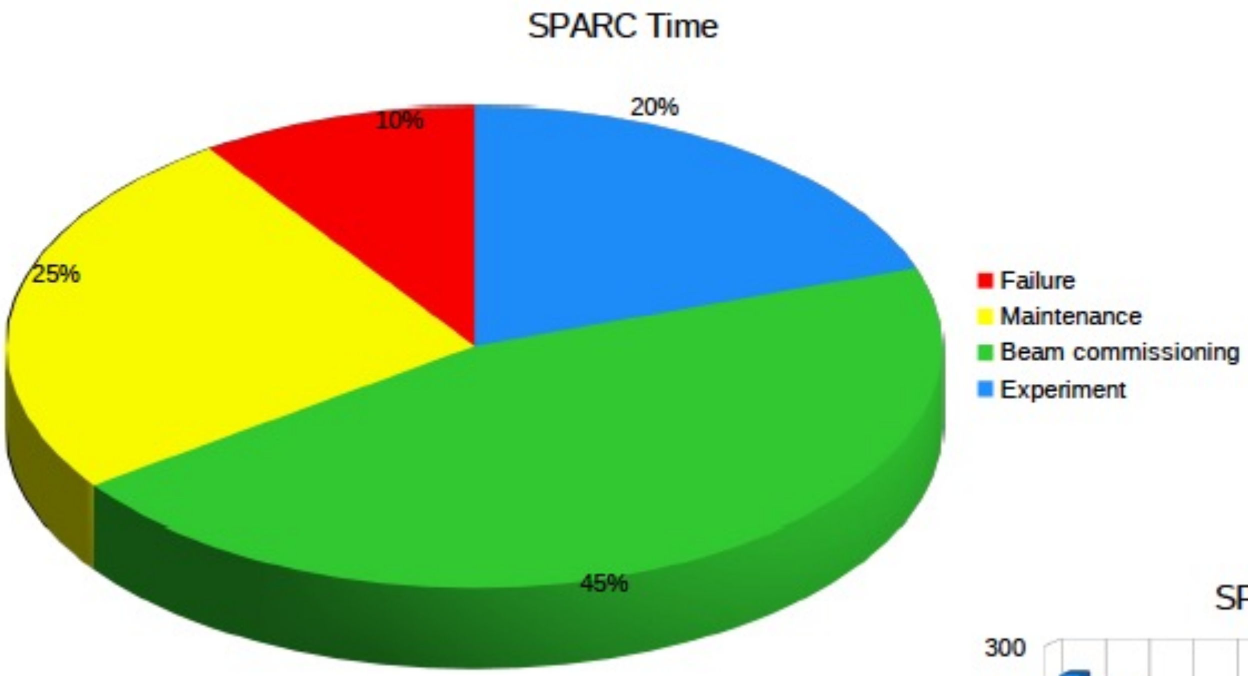
SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)



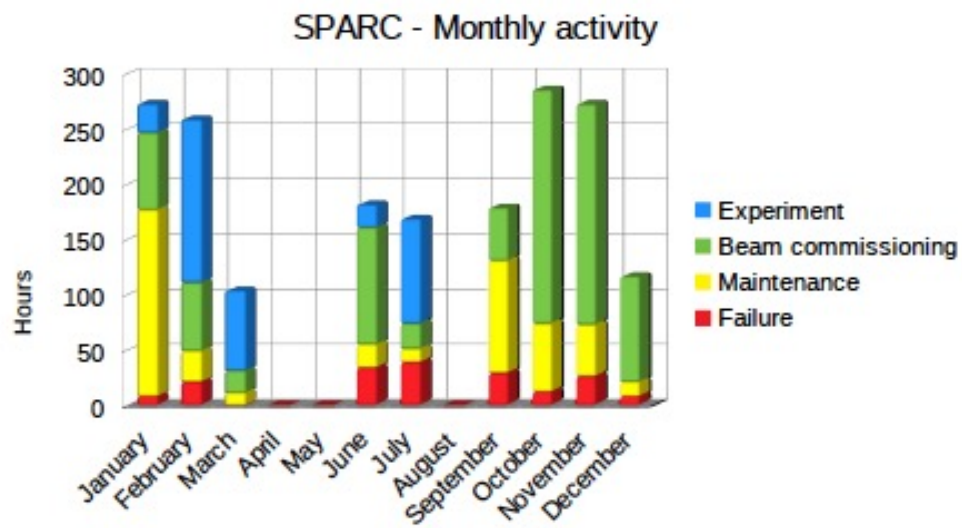
PWFA vacuum chamber at SPARC_LAB



SPARC up time (2020)

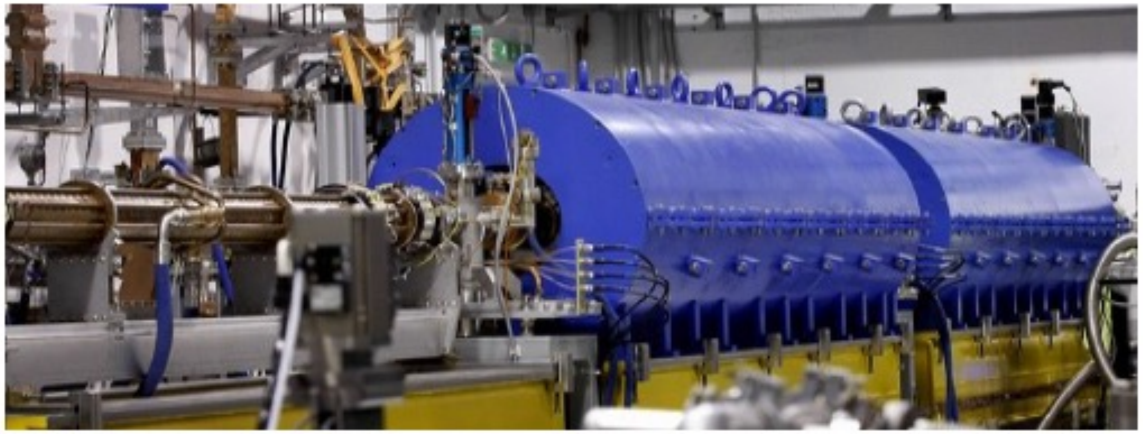


Total Up Time 65%

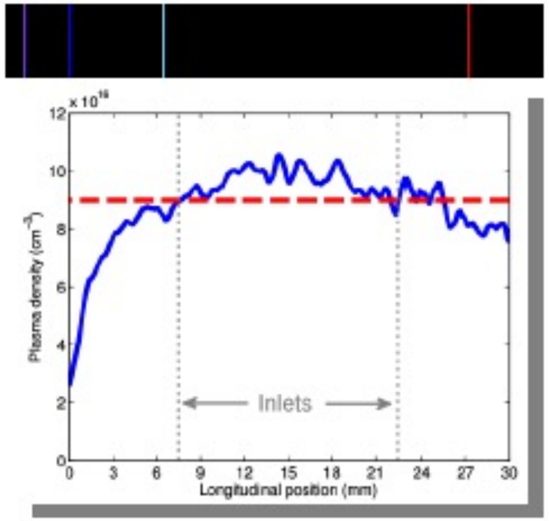


Previous Experimetal Results

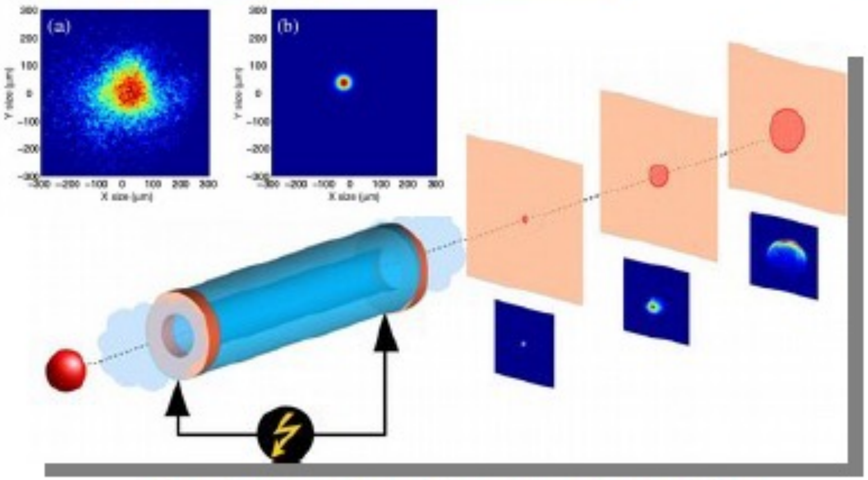
Activities with the high-brightness SPARC photo-injector



Plasma characterization

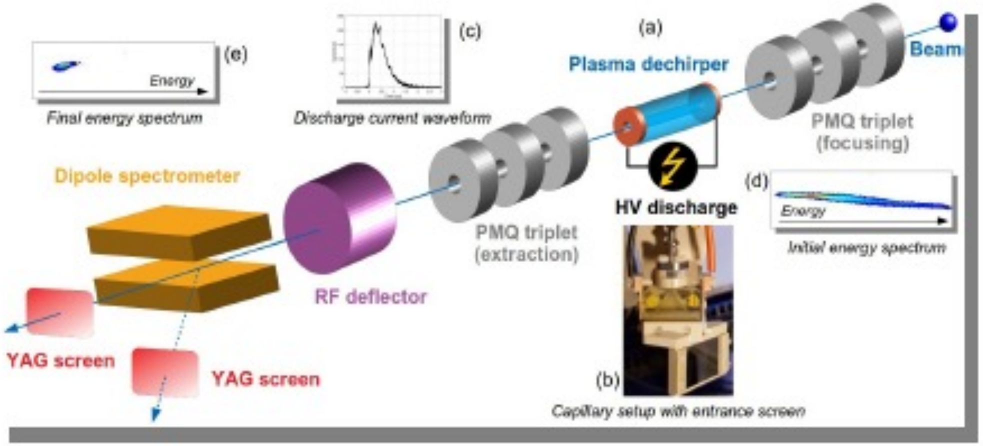


Biagioni, A., et al., Journal of Instrumentation 11.08 (2016): C08003.



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)

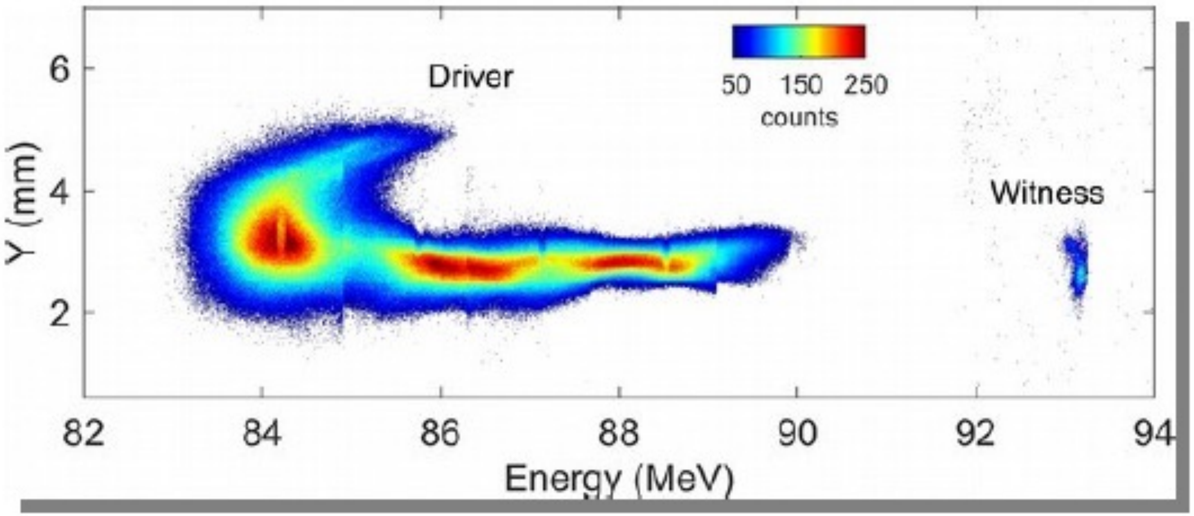
Assisted Beam Loading Energy Spread Compensation

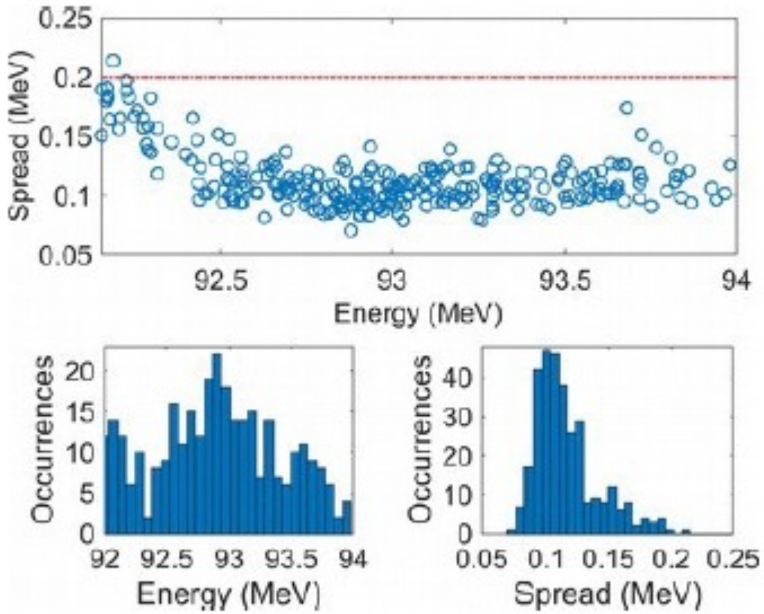
Achieved 4 MeV acceleration in 3 cm plasma with 200 pC driver

- *~133 MV/m accelerating gradient*
- *$2x10^{15}$ 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.

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

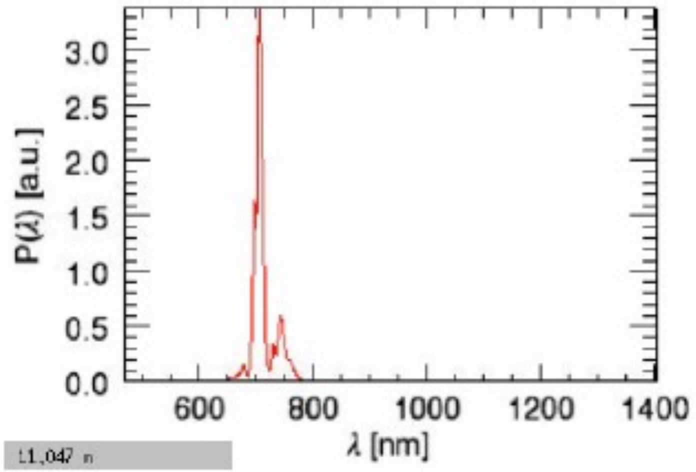
GENESIS 1.3 time-dependent simulations

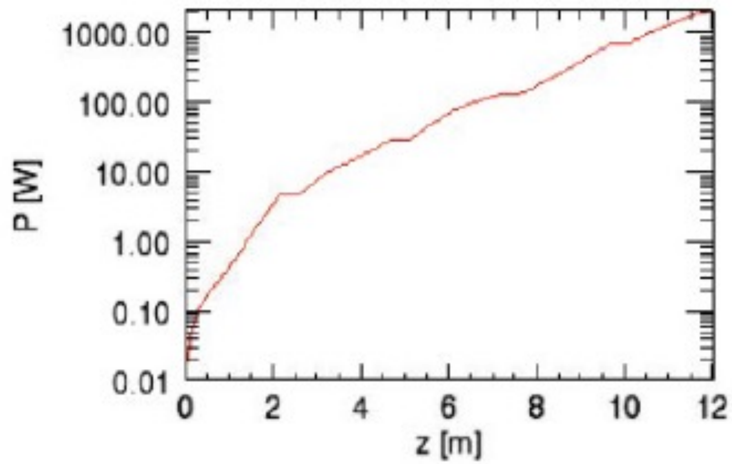
measurable growth of the FEL gain achieved

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





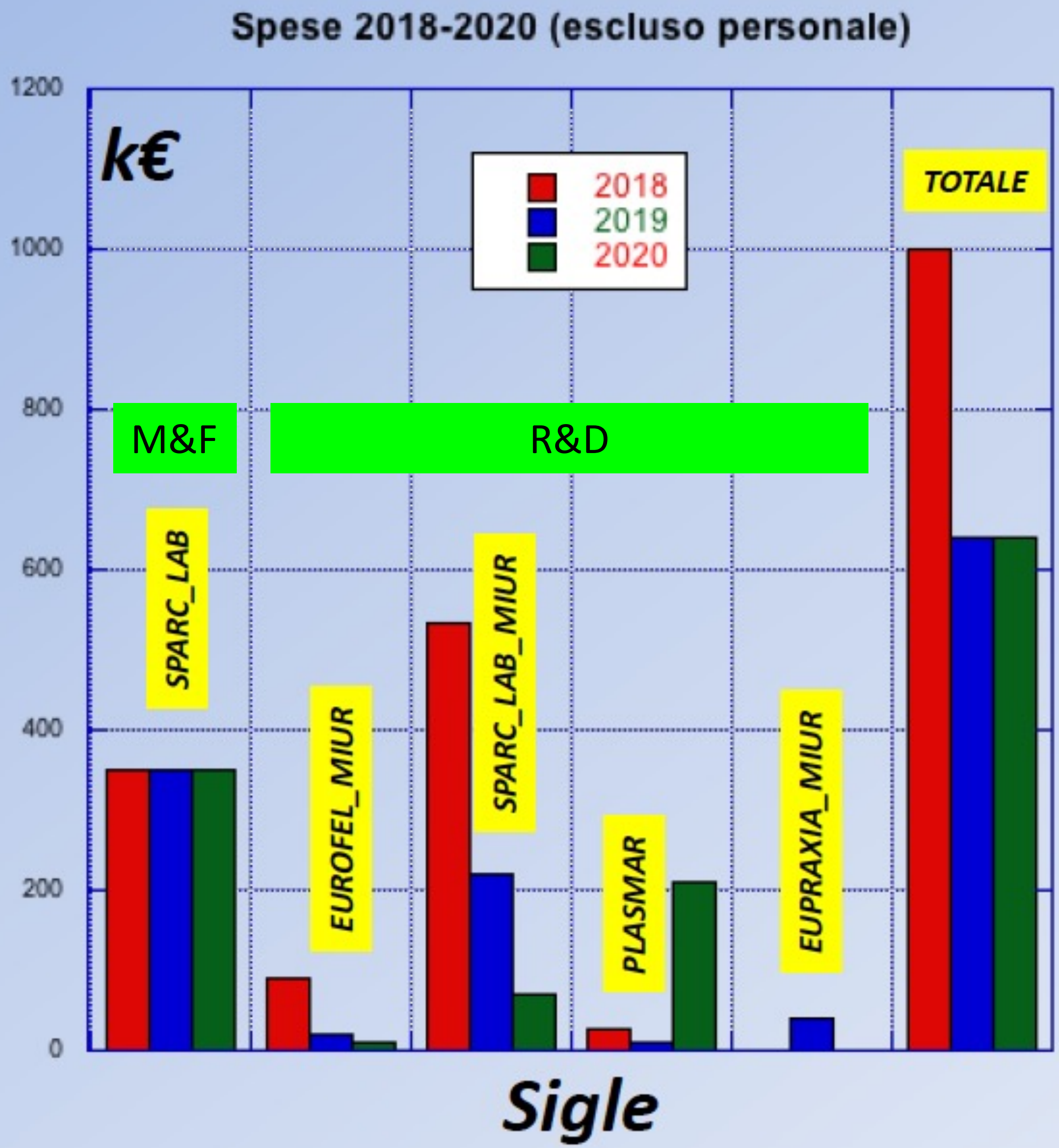
Facility: SPARC_LAB
Funding sources 2018-2020

- **SPARC_LAB** (fondi INFN, attivo dal 2012, **350 k€/anno**) – finanziamento annuale dell'INFN dedicato a "Manutenzione e Funzionamento della facility SPARC_LAB", generalmente assegnato tra Aprile e Luglio.
- **PLASMAR** (ex progetto Premiale MIUR, attivo dal 2017 al 2020, assegnati a LNF in totale **1 M€** di cui **0.5 M€** per personale): dedicato all'upgrade delle attività di accelerazione a plasma PWFA, lente a plasma, esperimento FEL pilotato da plasma, modularità della accelerazione a plasma, diagnostica e sistema di controllo.
- **EuPRAXIA_MIUR** (fondi FOE, attivo solo nel 2019, assegnati **600 k€** di cui **450 k€** per personale) dedicato alle attività di R&D per EuPRAXIA@SPARC_LAB. Disponibili residui.
- **SPARC_LAB_MIUR** (ex progetto Premiale MIUR, attivo dal 2014 al 2017, assegnati a LNF in totale **4 M€** di cui **1 M€** per personale): dedicato all'upgrade del sistema laser FLAME, delle relative linee sperimentali LWFA, della diagnostica ad alta risoluzione e del sistema di sincronizzazione. Disponibili residui.
- **EUROFEL_MIUR** (fondi FOE, attivo dal 2012 al 2016, assegnati a LNF circa **600 k€/anno**) dedicato allo sviluppo della sorgente FEL SPARC convenzionale. Praticamente esaurito (disponibili pochi k€).

SPARC_LAB

Funding sources

2018-2020



SABINA

SOURCE OF ADVANCED BEAM IMAGING FOR NOVEL APPLICATIONS

Avviso Pubblico Regione LAZIO

«Potenziamento delle Infrastrutture di Ricerca PNIR per elevare il tasso di innovazione del tessuto produttivo regionale» (*aka Infrastrutture per la Ricerca*)
http://www.lazioinnova.it/bandi-post/infrastrutture-la-ricerca/

POR-FESR 2014-2020d

Obiettivo: Potenziamento di SPARC

- Consolidamento degli impianti tecnologici
- Acquisizione nuova strumentazione (fotoiniettore, trasporto fascio, diagnostica, …)
- Creazione e messa in funzione di due facilities per utenti:
    1. Linea THz: analisi spettroscopiche su singolo punto, imaging, T variabile
    2. Laser di potenza FLAME: surface coating test nel verde, infrarosso, in vuoto

GOAL: aumentare uptime di SPARC (da 1200 a 2400 h/y)

Budget: circa **6.1 M€** (4.5 dalla Regione, 1.6 da INFN)

Durata: **18 mesi** (+6 proroga + 2 COVID): da agosto 2019 ad ottobre 2021

Status: entro dicembre 2020 (14 mesi dall'avvio) dovremmo avere 4.3M€ impegnati

COSTI PERSONALE SPARC_LAB AL 5/2/2021

	CONTRATTO	PROFILO	COSTO
FONDI EuPRAXIA_MIUR	ART. 15	COLL. AMMINISTRAZIONE 50%	19.212,50
	ASSEGNISTA	TECNOLOGO 50%	11.926,00
	ASSEGNISTA	RICERCATORE	30.000,00
	ASSEGNISTA	RICERCATORE	30.000,00
	ART. 7	COLLABORATORE	49.482,00
	ASSEGNISTA	TECNOLOGO	23.852,00
	ASSEGNISTA	TECNOLOGO	23.852,00
		TOT.	**188.324,50**
FONDI EUROFEL_MIUR	ART. 15	COLL. AMMINISTRAZIONE 50%	**19.212,50**
FONDI OVH LNF (residui EuPRAXIA H2020)	BORSISTA	NEODIPLOMATI	**13.020,00**
FONDI PLASMAR	ASSEGNISTA	TECNOLOGO	**23.852,00**
FONDI SPARC_LAB_MIUR	ASSEGNISTA	TECNOLOGO	**30.000,00**
FONDI MAECI_CAMEL	ASSEGNISTA	TECNOLOGO	**23.852,00**
		TOTALE COSTI PERSONALE	**298.261,00**

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 **do not include Manpower and the R&D** needed for the TDR. Additional funding must be found.
- Laser Heater/Magnetic Compressor optimization is in progress, including alternative schemes for Driver and Witness generation. **Energy Jitters investigation and mitigation 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).
- Plasma beam line optimized to **remove the driver** beam and preserve the the witness beam parameters .
- FEL Baseline and advanced configurations.
- Extend the Users Scientific Case including lower wavelength.
- **Demonstration of the main beam requirements at SPARC_LAB (spread, emittance, stability)**