EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

PWFA Construction Site at Frascati and its role as an LWFA Construction Site candidate

Massimo Ferrario (INFN) on behalf of the EuPRAXIA@SPARC_LAB team

EuPRAXIA Yearly Meeting 2019

DESY, October 17, 2019,

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

Laboratori Nazionali di Frascati

Istituto Nazionale di Fisica Nucleare

LNF is the largest and the oldest (since 1954) of INFN infrastructures: Personnel ~330 staff (1/3 scientists) + PhD & postdocs + 500 users (30% foreign)

Its main mission: accelerators for High Energy Physics (and not only) + fundamental physics: Main competences in electron/positron machines

Capabilities in designing, building and operate relatively large complex: Accelerator Division (~110 people) Technical Division (~30), Research Division (~150)

Main activities in accelerator technologies:

- Operation 24/24 **of DAFNE collider** (**up to 2019**)
- **R&D on plasma acceleration, 0.2 PW laser, FEL, THz sources (SPARC_LAB)**

Several other international collaborations:

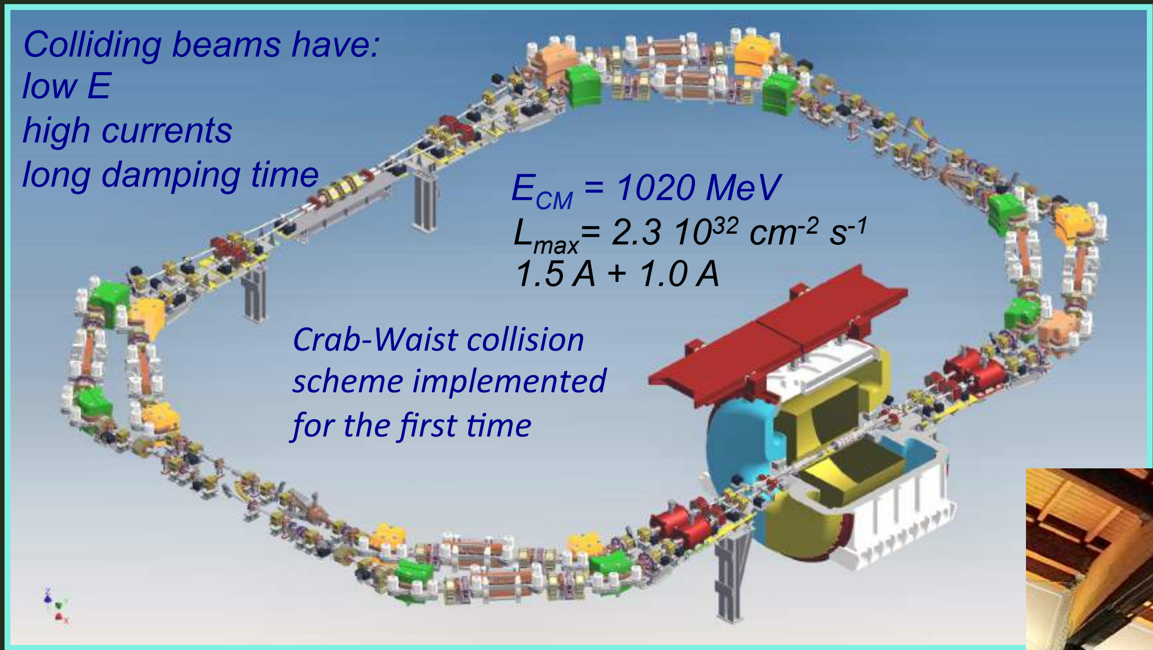
- CERN, ESRF Grenoble, KEK (Japan), ELI

Beam Test Facility also available (DAFNE Linac can be used parasitically)

Soft-X, UV, and infrared lines available around DAFNE ring (**DAFNE_Light**)

KLOE-2 data-taking closing ceremony

March 30th 2018 at 11:00 in the Bruno Touschek Auditorium



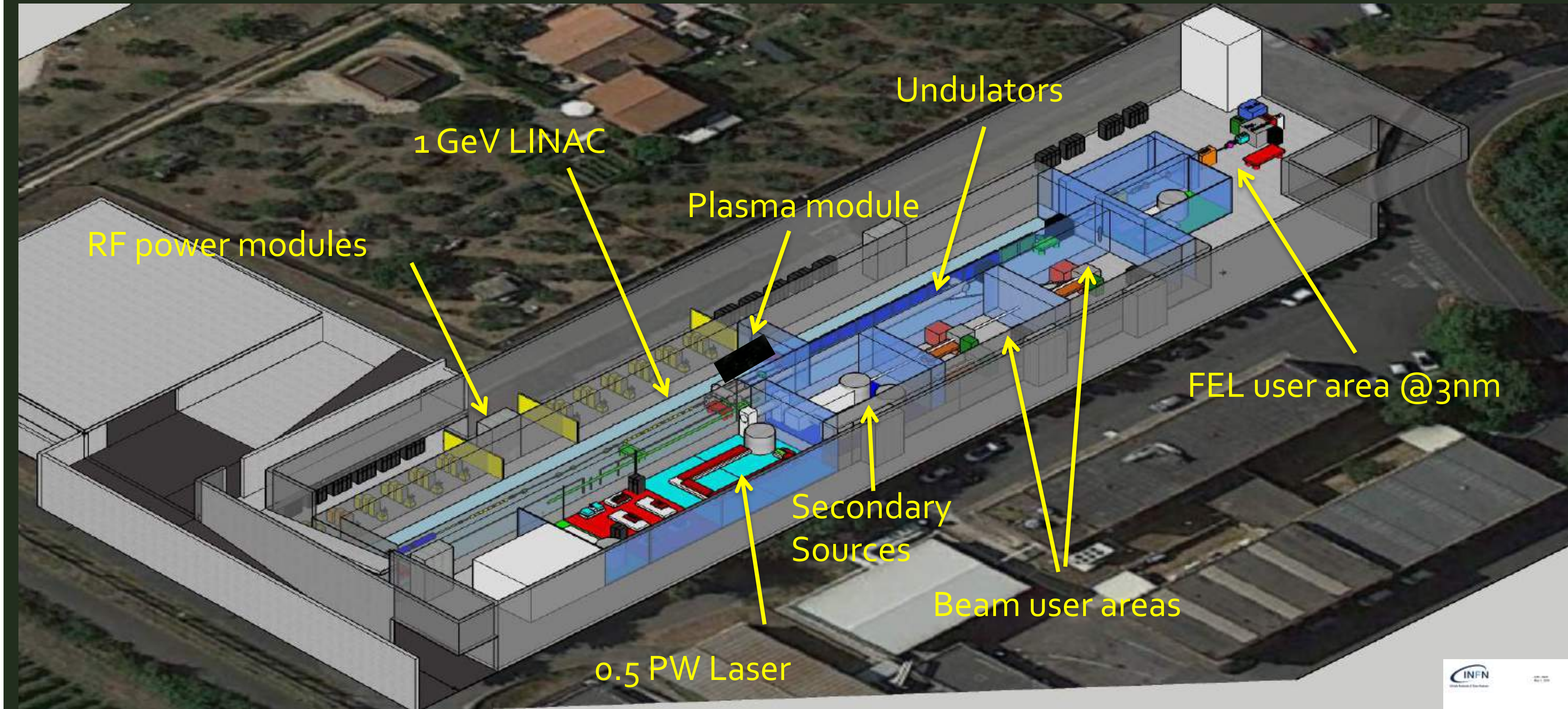
Research Activities at LNF

Internal Activities
External activities

EuPRAXIA@SPARC_LAB

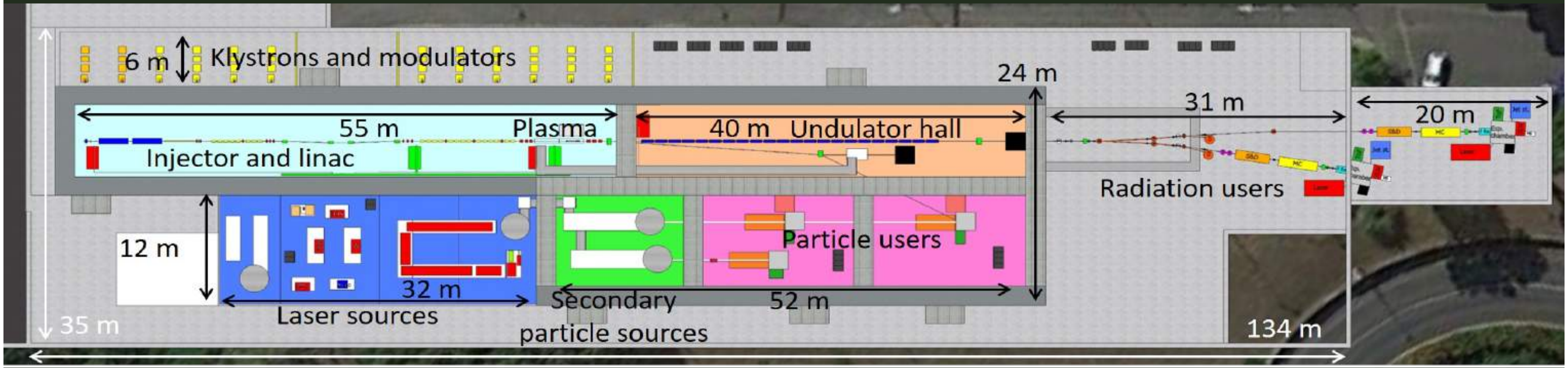
INFN
Istituto Nazionale di Fisica Nucleare

EuPRAXIA@SPARC_LAB



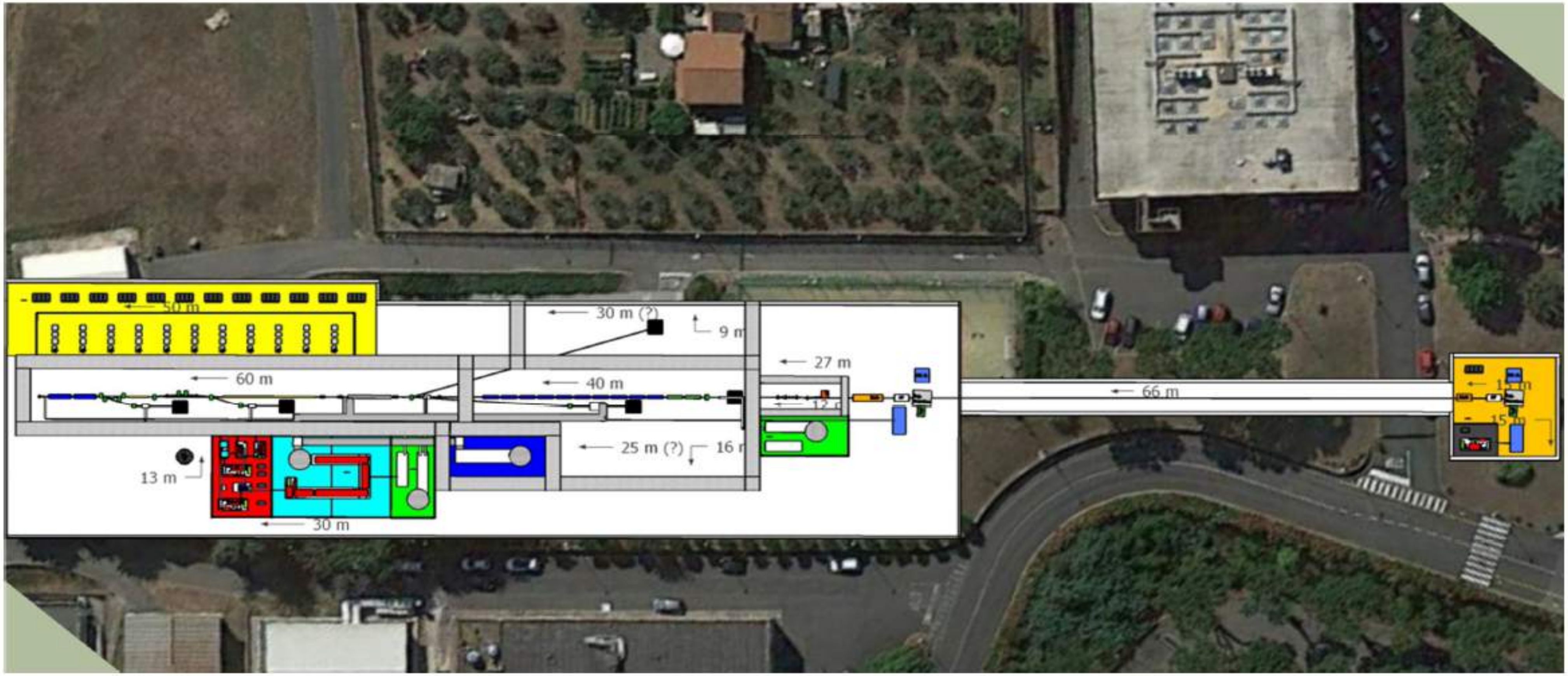
http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

- 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

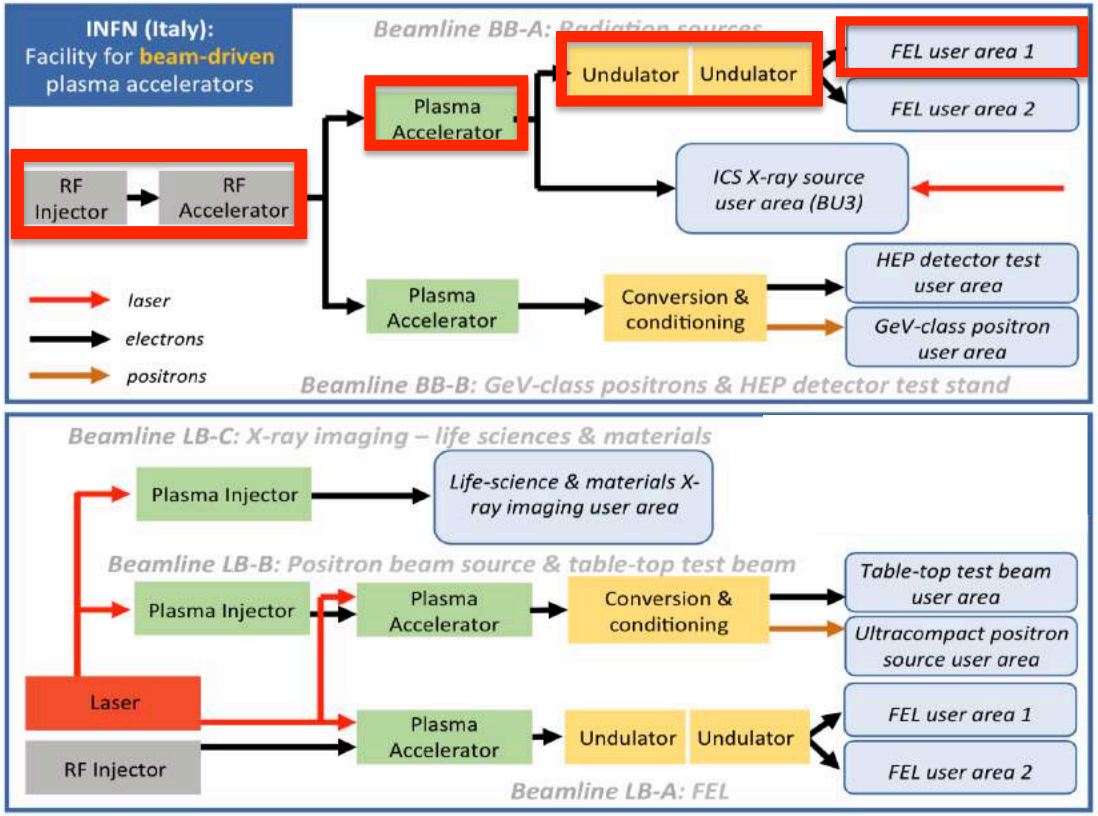
Possible building extension

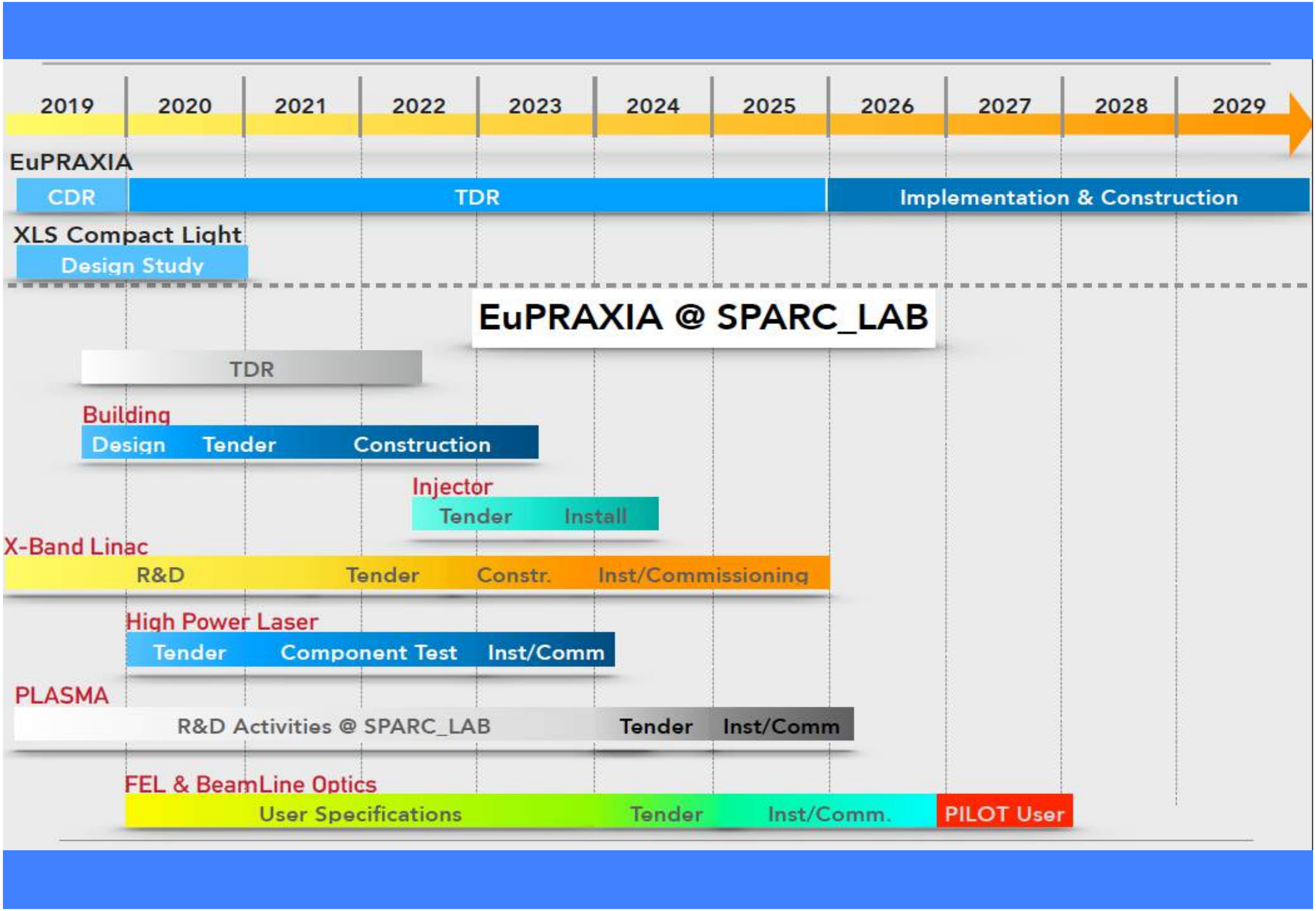


Phased Implementation of Construction Sites

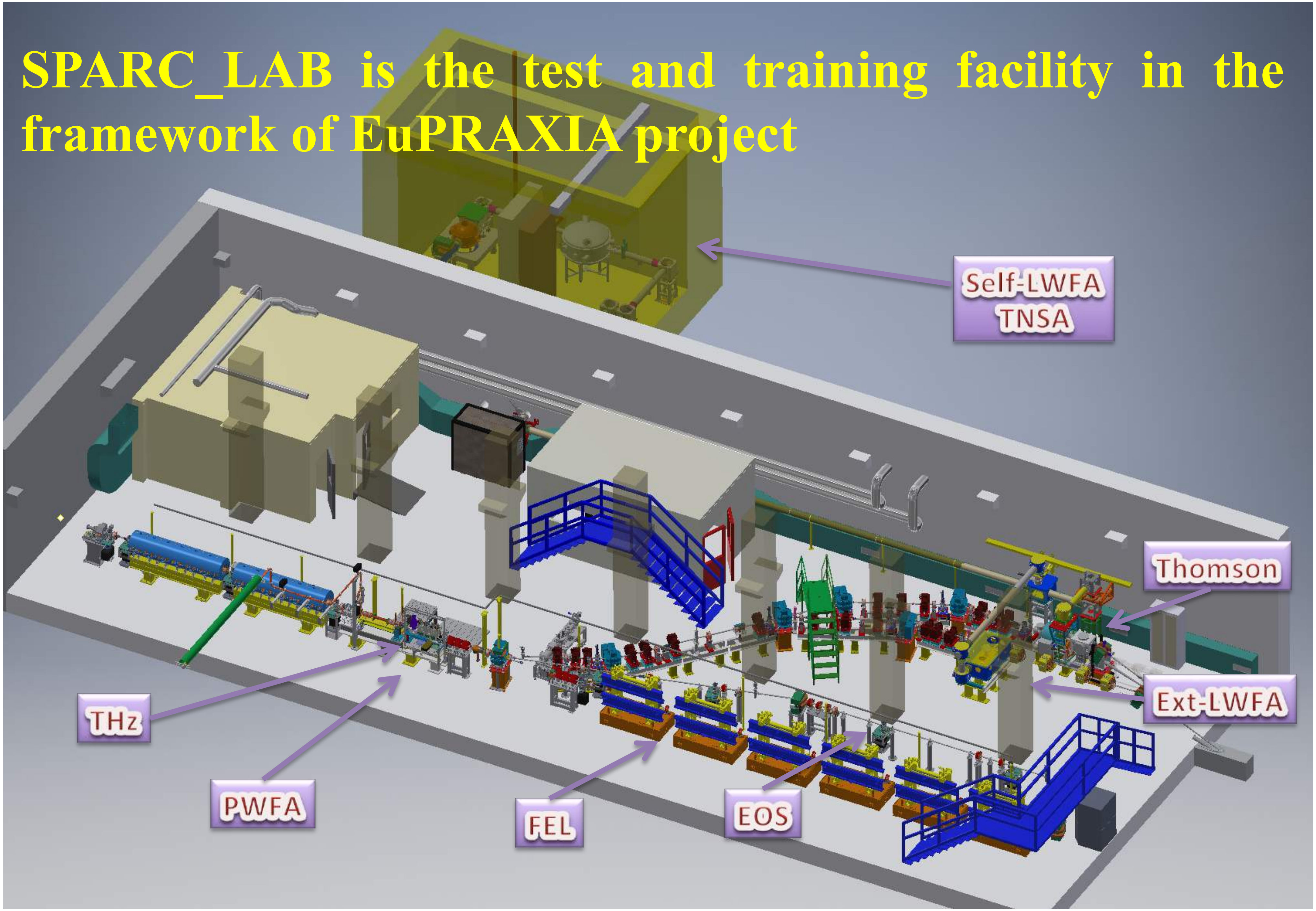
Phase 0

	INFN
Phase 1	✓ FEL beamline to 1 GeV + user area 1 ✓ GeV-class positrons beamline + positron user area
Phase 2	✓ ICS source beamline + user area ✓ HEP detector tests user area ✓ FEL user area 2 ✓ FEL to 5 GeV
Phase 3	✓ Medical imaging beamline / user area ✓ Other future developments




2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
EuPRAXIA
CDR
TDR
Implementation & Construction
XLS Compact Light
Design Study
EuPRAXIA @ SPARC_LAB
TDR
Building
Design
Tender
Construction
Injector
Tender
Install
X-Band Linac
R&D
Tender
Constr.
Inst/Commissioning
High Power Laser
Tender
Component Test
Inst/Comm
PLASMA
R&D Activities @ SPARC_LAB
Tender
Inst/Comm
FEL & BeamLine Optics
User Specifications
Tender
Inst/Comm.
PILOT User

SPARC_LAB is the test and training facility in the framework of EuPRAXIA project



SPARC_LAB activities related to the EuPRAXIA R&D

- Laser Comb technique
- S/C RF gun design and fabrication
- X-band test facility
- Velocity Bunching
- fs Synchronization
- Single shot diagnostics

- Capillary characterization
- Laser guiding
- Active Plasma Lens
- Plasma Dechirper
- PWFA acceleration experiments

- LWFA with external injection
- Plasma driven FEL test

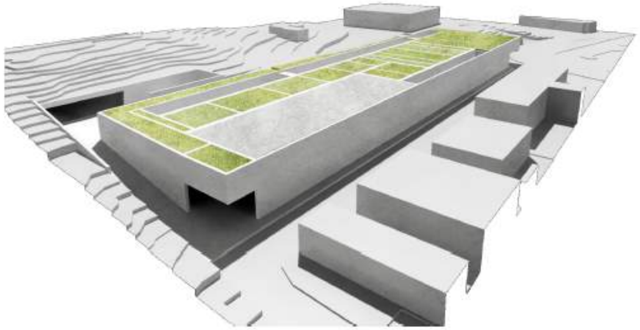
Conceptual Design Report Ready for the LNF site

INFN
Istituto Nazionale di Fisica Nucleare

LNF–18/03
May 7, 2018

EuPRAXIA@SPARC_LAB

Conceptual Design Report



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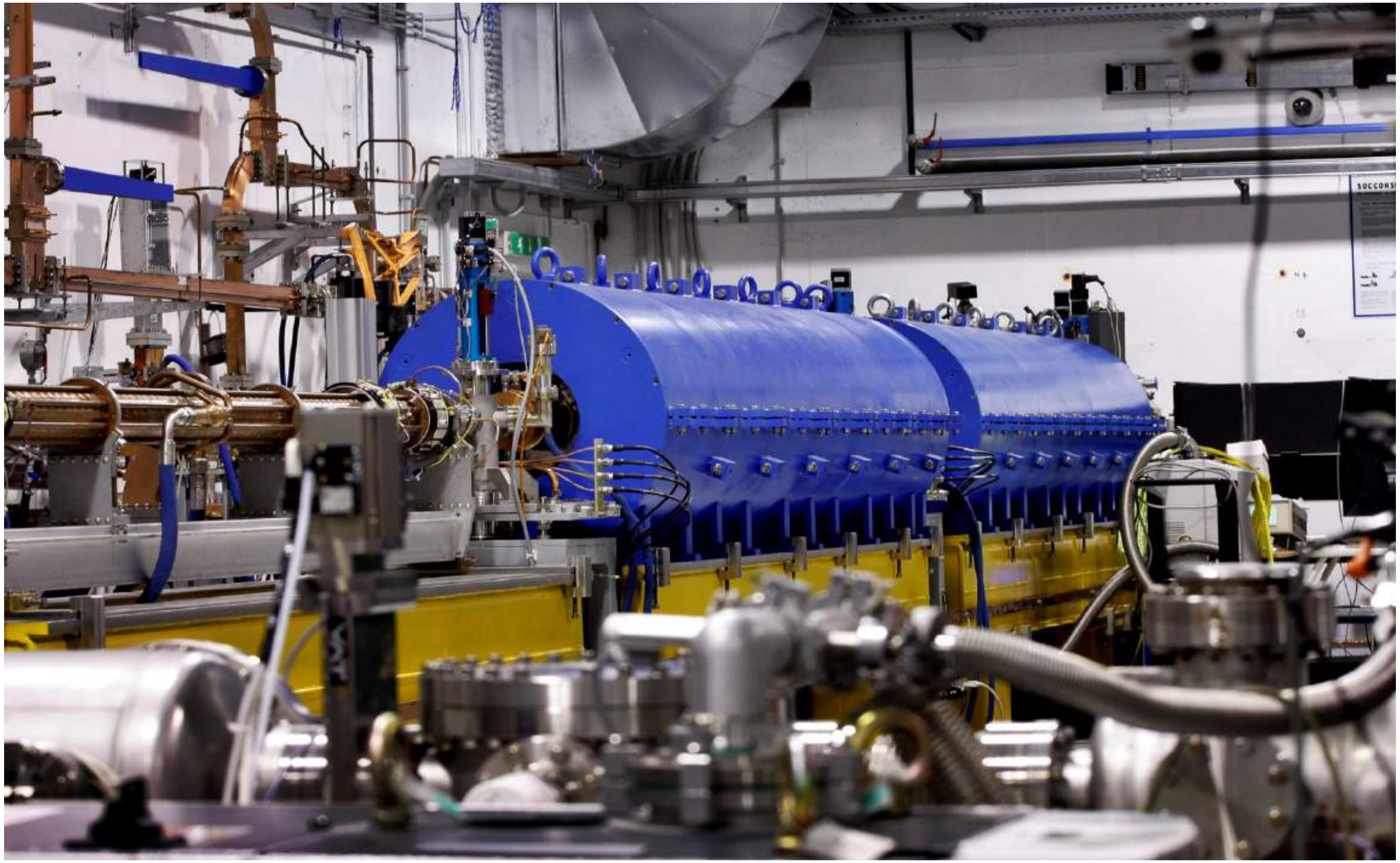
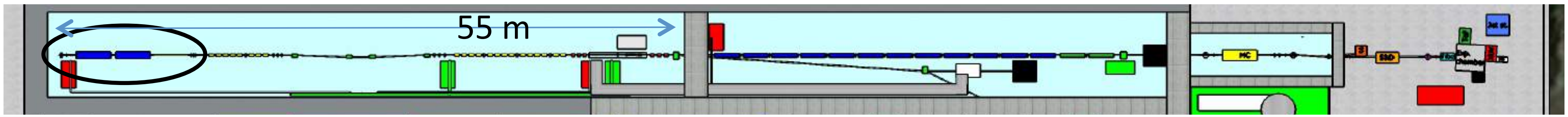
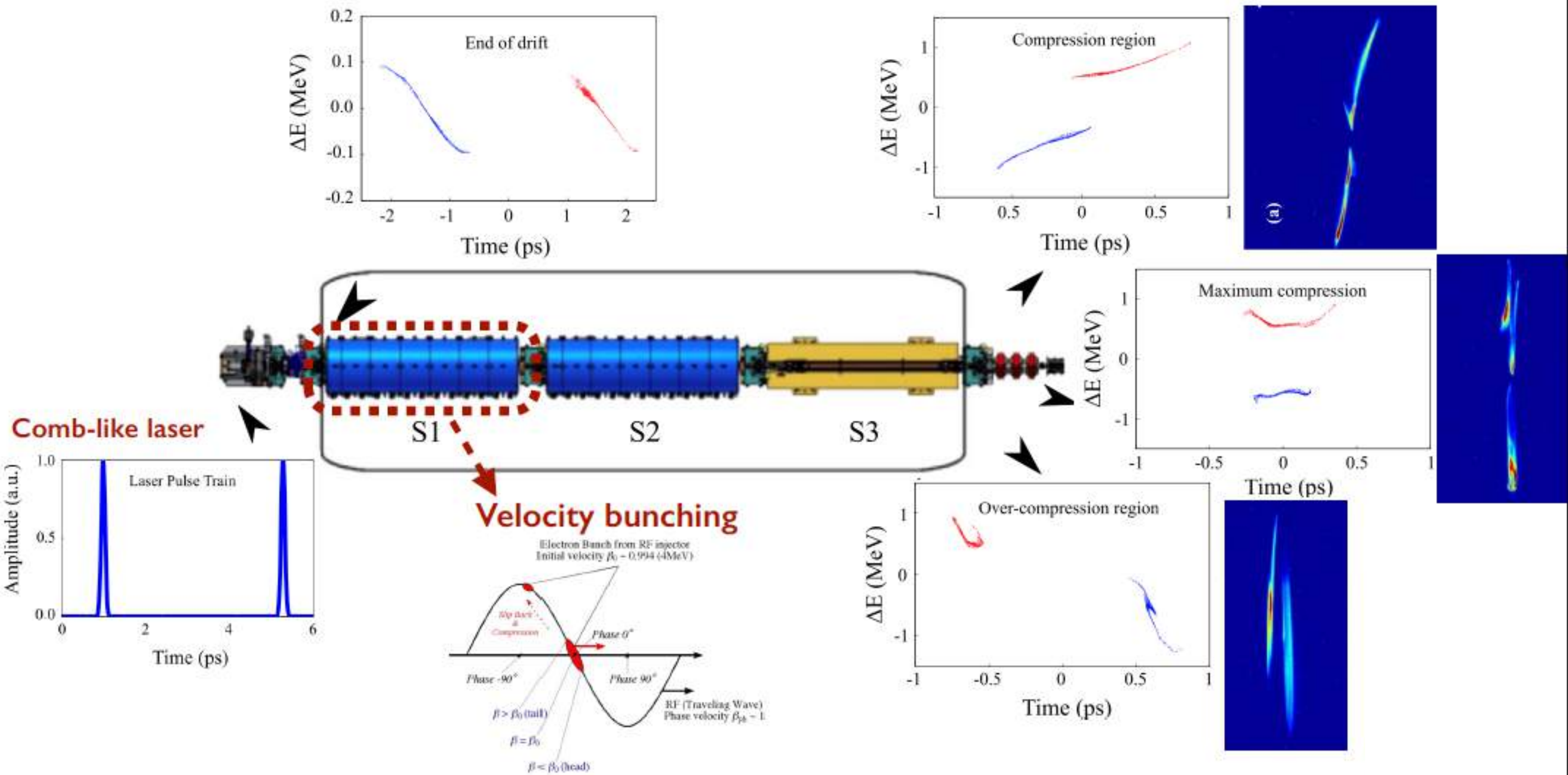
SPARC_LAB HB photo- injector

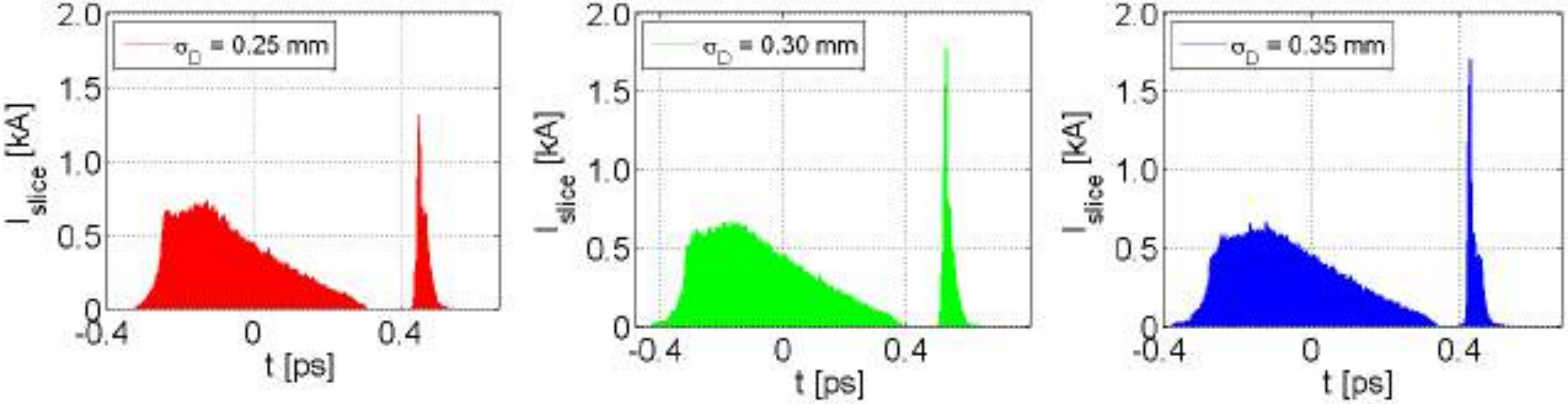




Generation of multi-bunch trains

Sub-relativistic electrons ($\beta_c < 1$) injected into a traveling wave cavity at zero crossing move more slowly than the RF wave ($\beta_{RF} \sim 1$). The electron bunch slips back to an accelerating phase and becomes simultaneously accelerated and compressed.

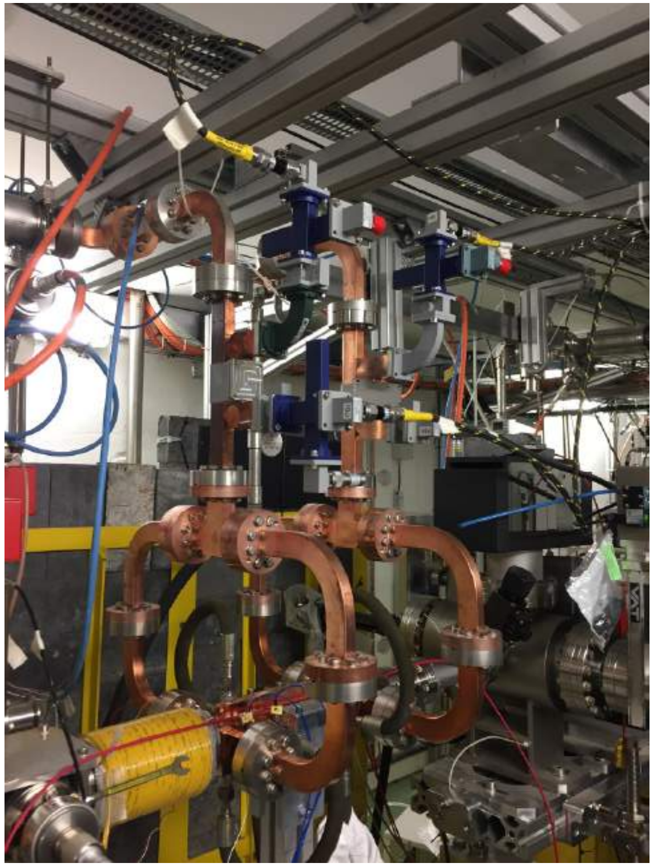


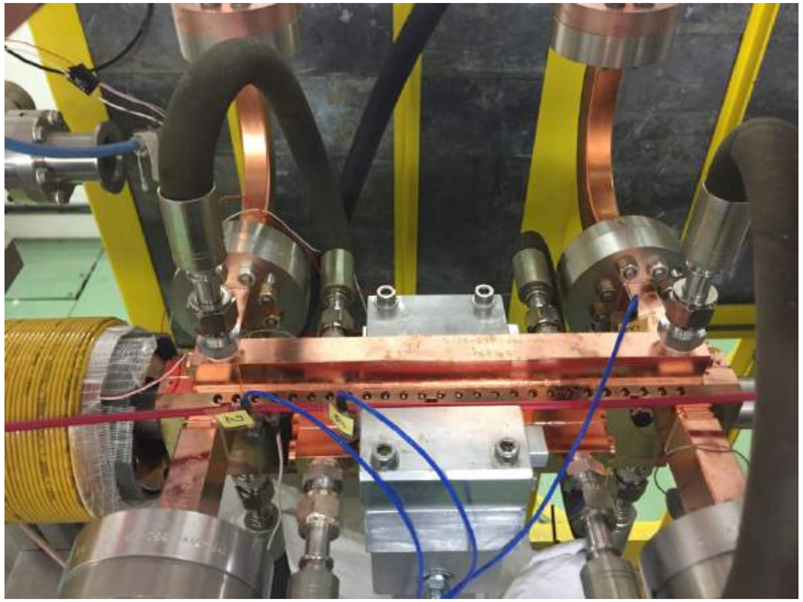


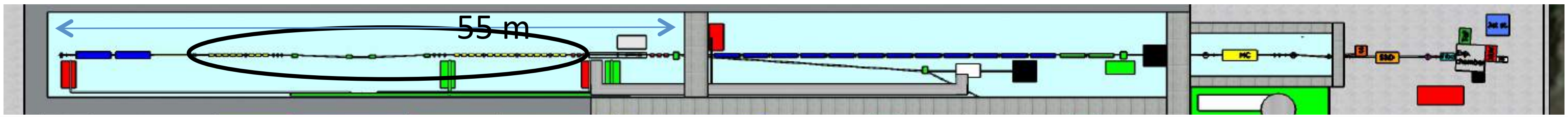
Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

Table 7.2: Driver and witness beam parameters at the end of photo-injector.

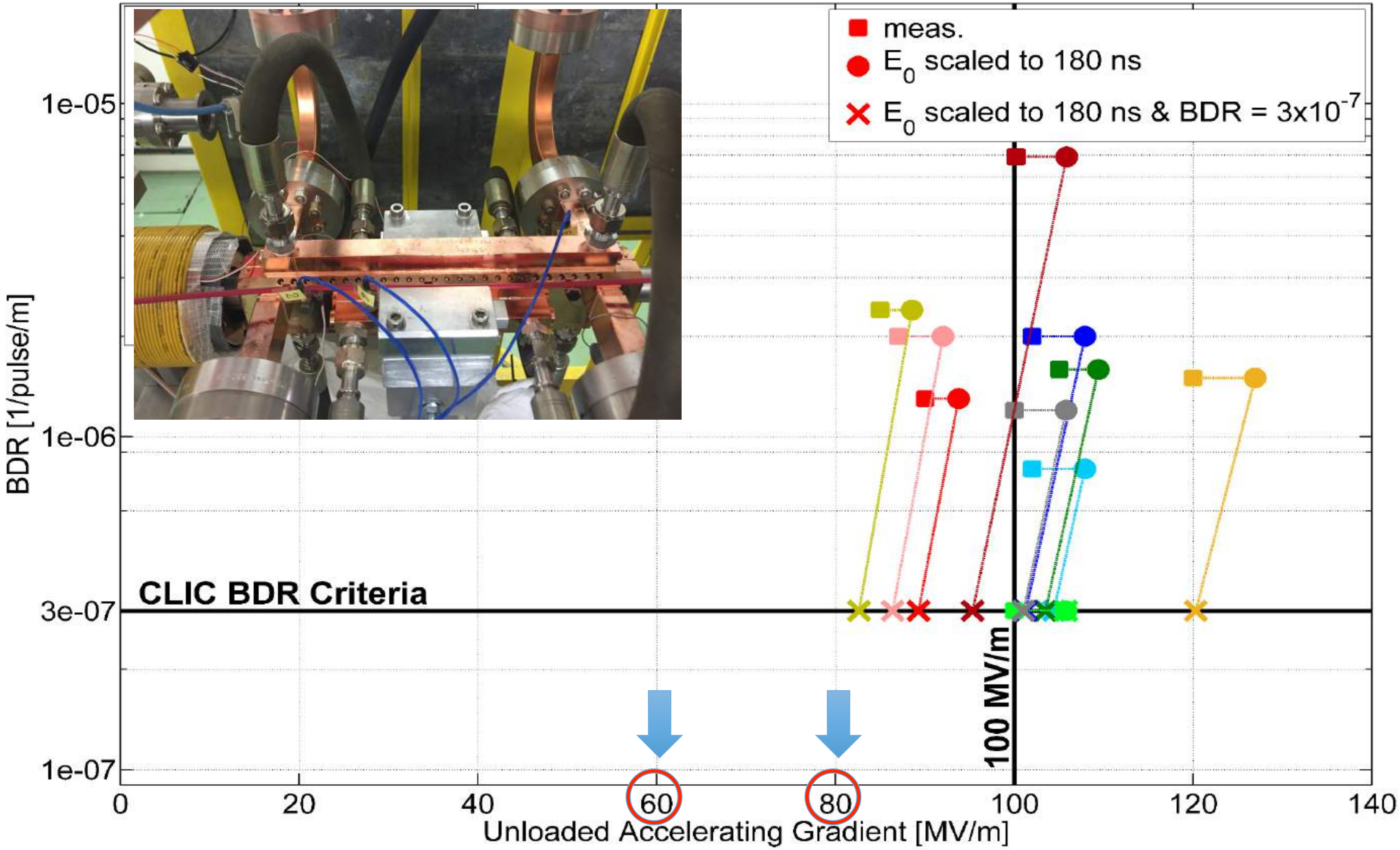
X-band Linac







X-band RF structures best performances



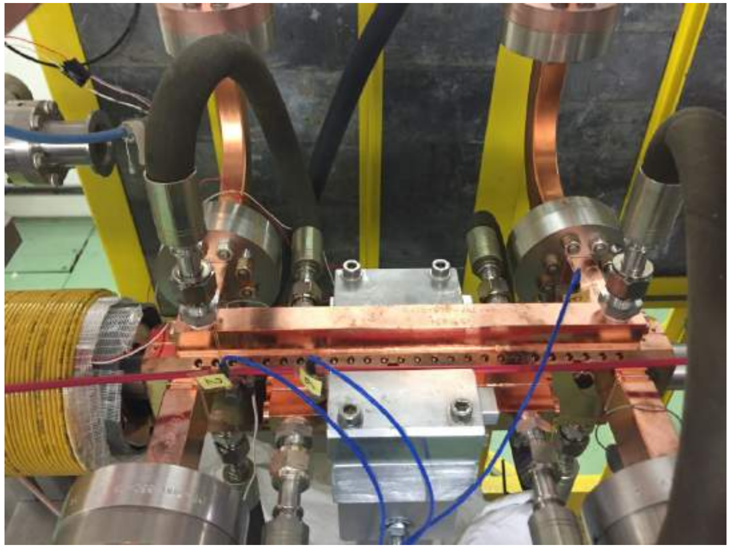
Compact

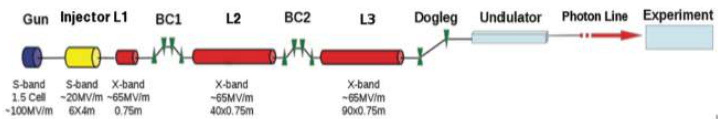
EU Design Study Approved

3 years – 3 MEuro

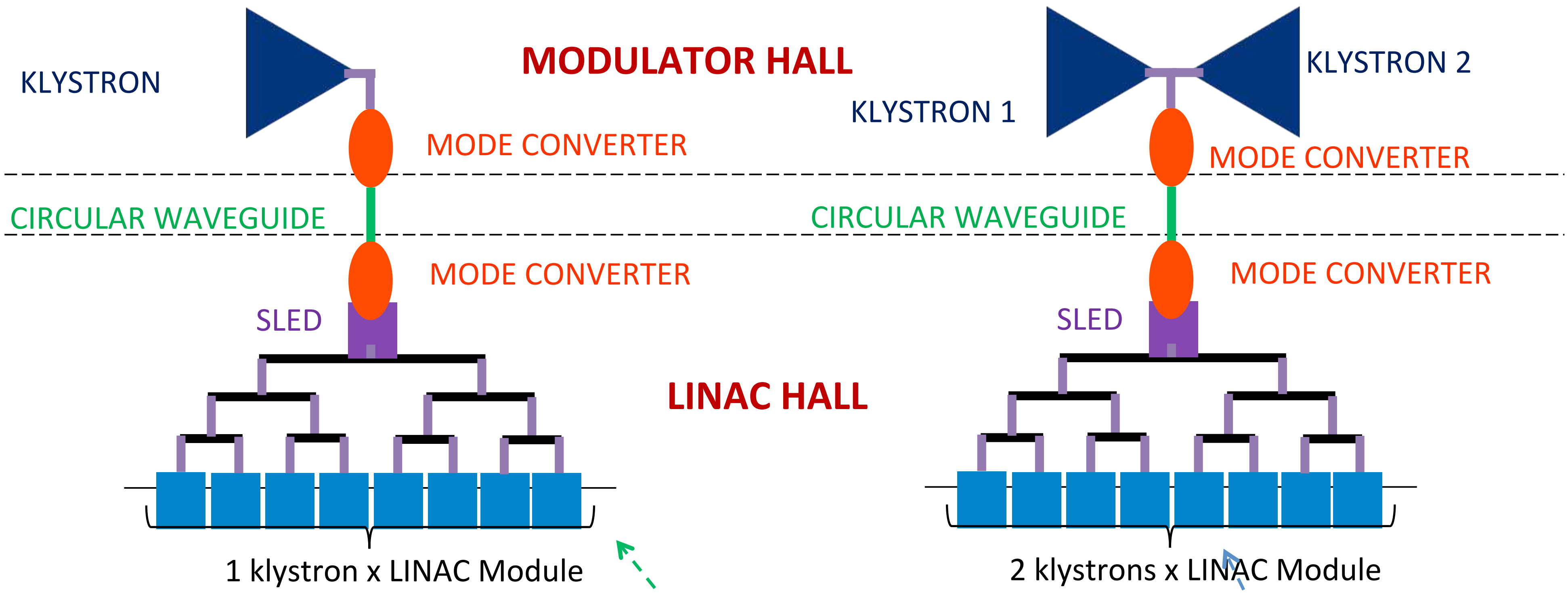
Coordinator: G. D'Auria (Elettra)

Focus on X-band technology



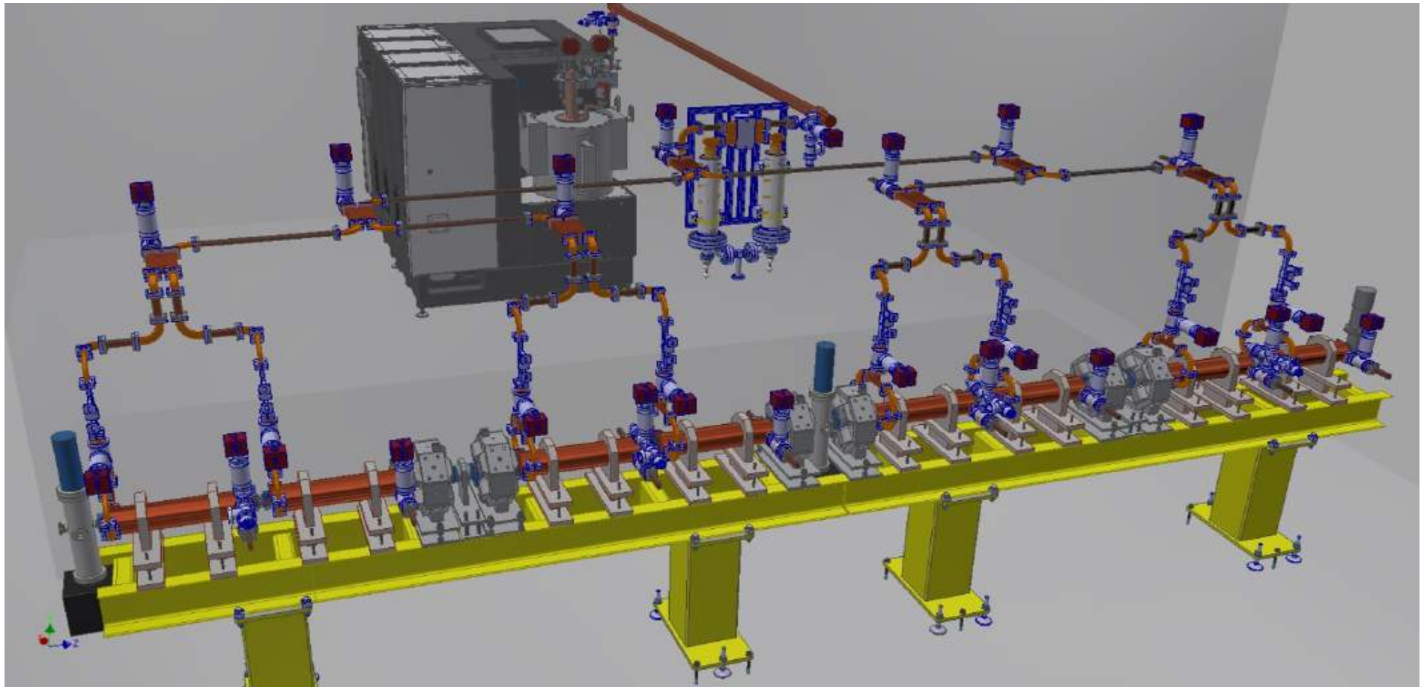


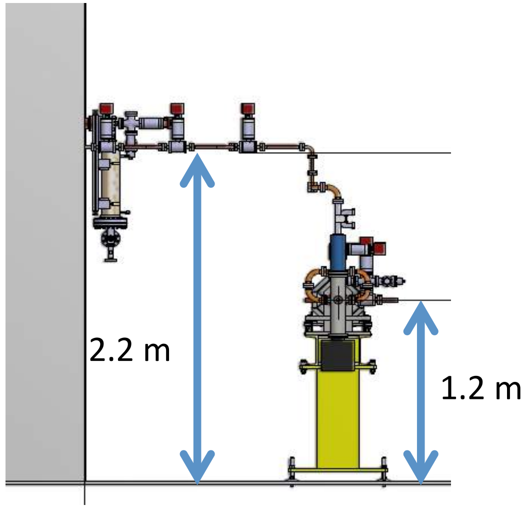
The key objective of the CompactLight Design Study is to demonstrate, through a conceptual design, the feasibility of an innovative, compact and cost effective FEL facility suited for user demands identified in the science case.



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)		
PWFA final energy	**1 GeV**	**5 GeV**	**> 5 GeV**
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

X-band Linac





Preliminary layout of the **RF module** (collaboration with CERN):
8 structures, 1 SLED, 1 or 2 Klystrons per module.

WR-90 total length [mm]	3758
WC-50 circular wg length [mm]	3674
WR-90 loss [dB]	-0.368
WC-50 loss [dB]	-0.0456
total loss [dB]	-0.414
total loss [%]	-9.09

Estimated **waveguide attenuation** (including circular waveguide): **10%**

INFN – CERN official partnership on X-band RF development

ADDENDUM No. KE3849/CLIC
to
FRAMEWORK COLLABORATION AGREEMENT KN3083
between
THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)
and
THE ISTITUTO NAZIONALE DI FISICA NUCLEARE ("INFN")

concerning

Collaboration on High Gradient Acceleration Studies in the framework of CLIC-CLEAR at CERN and EUPRAXIA@SPARC_LAB at LNF

CONSIDERING:

- The Framework Collaboration Agreement KN3083 (the "Agreement") concluded between CERN and INFN (individually the "Party" and collectively the "Parties") defining the framework applicable to collaboration between them in areas of mutual interest, including but not limited to the domains of particle and accelerator physics;
- Article 2.1 of the Agreement provides that each Party's contribution to a specific collaboration (the "Project") and all related details shall be set out in an Addendum to the Agreement;
- That the Parties have identified the Project set out below, which shall be covered by the provisions of this Addendum No.KE3849/CLIC (the "Addendum"). This Addendum shall be subject to the provisions of the Agreement, it being understood that in case of divergence the provisions of this Addendum shall prevail,
- That INFN shall execute its contribution to the Project through INFN-LNF,

THE PARTIES AGREE AS FOLLOWS:

1. Project

The Project comprises activities related to the research, development and application of high-gradient, X-Band linac systems in the framework of the CLIC high-gradient, CLEAR and EUPRAXIA@SPARC_LAB projects as described in Annex I.

4.1 CERN's contribution

4.1.1 CERN shall provide expertise and guidance through the sharing of knowledge, experience, data and documentation in:

- The design, construction and operation of high-gradient linac X-Band radio frequency systems; and
- Commercial procurement, cost estimation and industrialization of such radio frequency systems.

4.1.2 CERN shall provide on loan the components set out in Annex 2.

4.2.3 CERN shall make a cash contribution that not exceed EUR 500'000.00 (five hundred thousand) as per Annex 2. CERN's contribution shall be subject to receipt of a correct debit note. Payment details are set out in Annex 2.

4.2 INFN's contribution

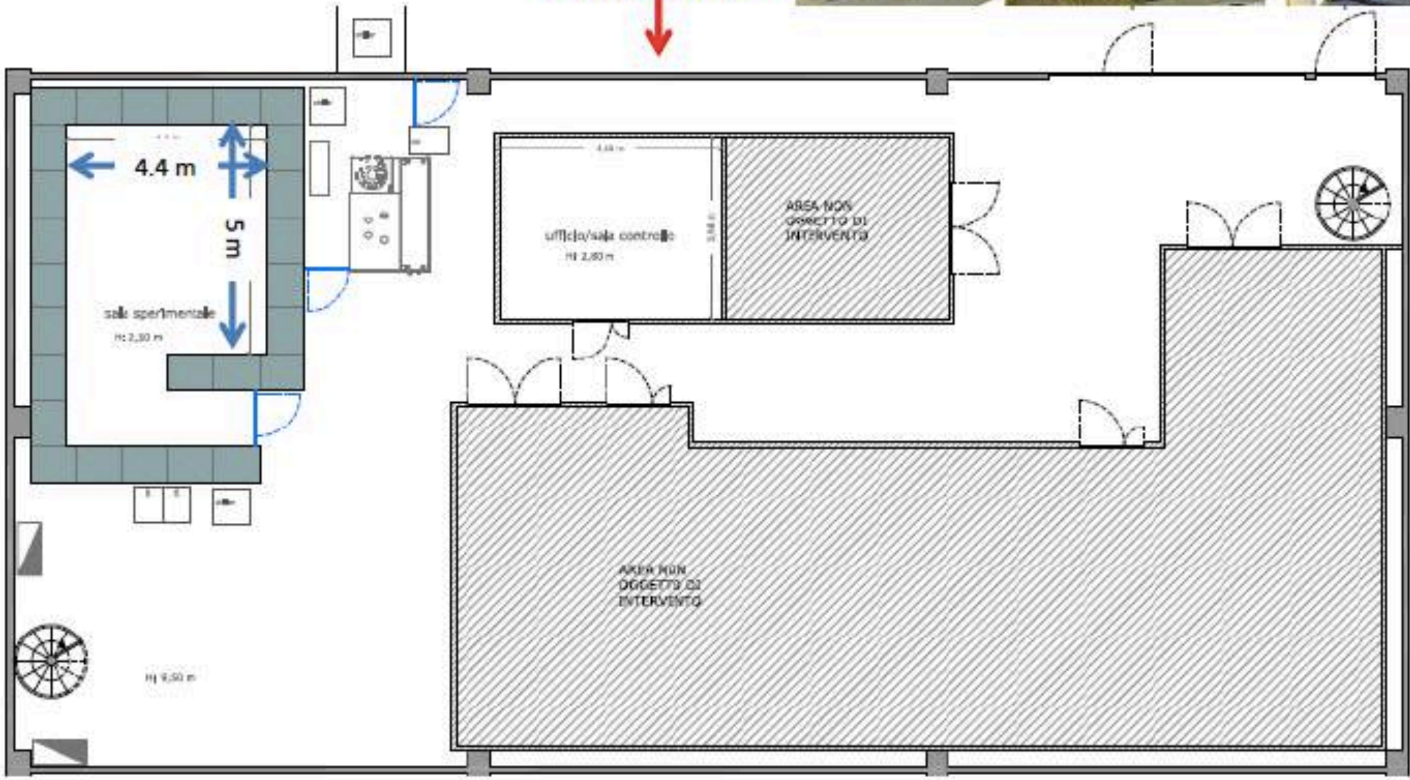
4.2.1 INFN shall:

- Through the elaboration of the EUPRAXIA@SPARC_LAB TDR, provide detailed documentation on the design, construction and industrialization of a medium scale high-gradient linac based on CLIC technology;
- Participate in the CLIC high-gradient testing program in particular through the installation and operation of a complete X-band test stand at INFN-LNF and the testing of CLIC accelerating structures by INFN-LNF experts;
- Provide experts to assist in the operation of the XBOX high-power test stands at CERN; and
- Develop and construct an electron injector for CLEAR.

Collaboration Agreement approved December 2017

LATINO project

The INFN Frascati X-box



it will be located in LNF building #7, very close to the SPARC_LAB area, formerly used for testing and conditioning of the DAFNE RF power plants and cavities

X-Band CERN-INFN collaboration

The INFN Frascati X-box

Pulsed Modulator: to be procured by INFN

OPERATIONAL PARAMETERS

		Unit	K2-3X	Notes
Pulse Output				
	Peak power to Klystron	MW	150.7	Peak power from Modulator
	Average power to Klystron	kW	17.3	Average power from Modulator
	Klystron Voltage range	kV	450	Nominal 410kV, see fig above
	Klystron Current range	A	335	Nominal 305A, see fig above
	Inverse Klystron Voltage	kV	<30	Reduced by the Solid State technology
	Pulse length	µs	1.5	Top of Klystron Voltage pulse
	Pulse length at 50%	µs	3,4	Of the Voltage Pulse
	RF duty cycle	%	0.0075	
	PRF range	Hz	1 - 50	
	Top flatness (dV)	%	<±0.25	Deviation from nominal voltage within the top of the pulse length
	Amplitude stability	%	<±0.1	
	Trig delay	µs	~1.2	See fig above
	Pulse to pulse jitter	ns	<6	
	Pulse length jitter	ns	<±10	
Filament Output				
	Klystron Max voltage DC	V	30	Nominal 10-30V
	Klystron Max current DC	A	30	Nominal 18-30A
	Kly. Fil. Current stability	%	<±1	
	Pre-heating period	min	60	Filament current is softly ramped to max value during pre-set time

VKX-8311A

X-band klystron: provided by CERN

Typical Operating Parameters		
Item	Value	Units
Beam Voltage	410	kV
Beam Current	310	A
Frequency	11.994	GHz
Peak Power	50	MW
Ave. Power	5	kW
Sat. Gain	48	dB
Efficiency	40	%
Duty	0.009	%

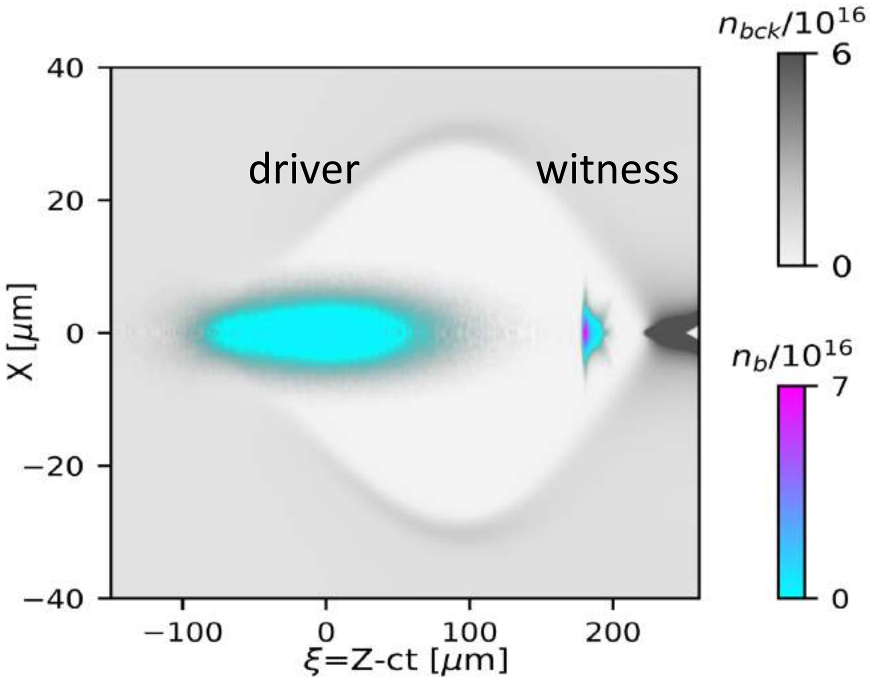
Pulse compressor: provided by CERN

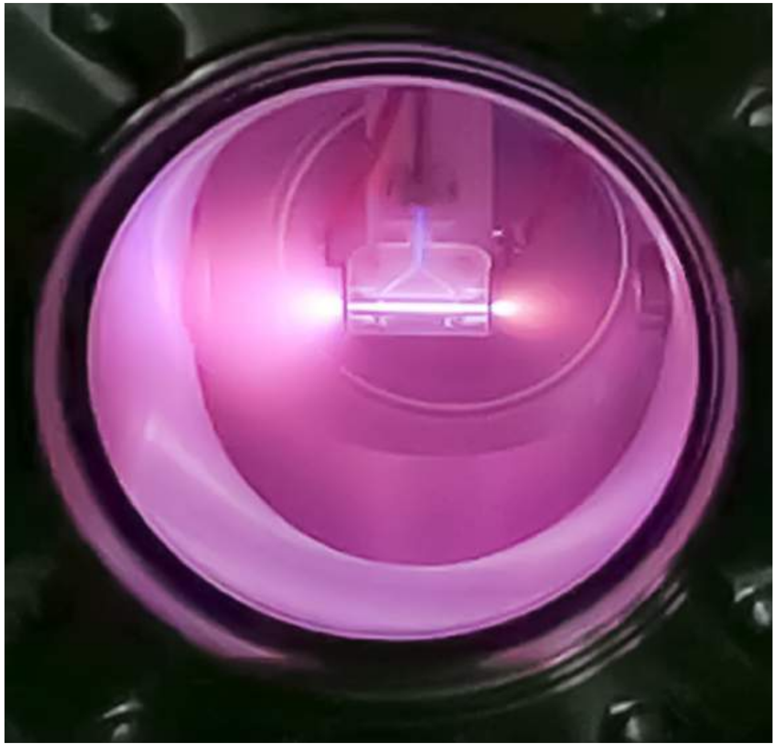
Other components:

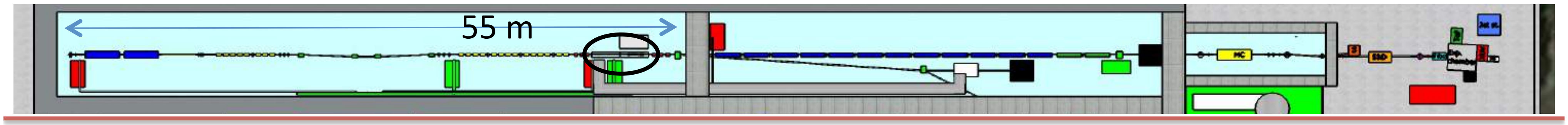
- Low level RF and controls;
- RF driver amplifier;
- Rectangular waveguides;
- Ceramic windows;
- Vacuum pumps and power supplies;
- ...

All components will be either provided by CERN or procured by INFN in full conformity with the original CERN X-box parts.

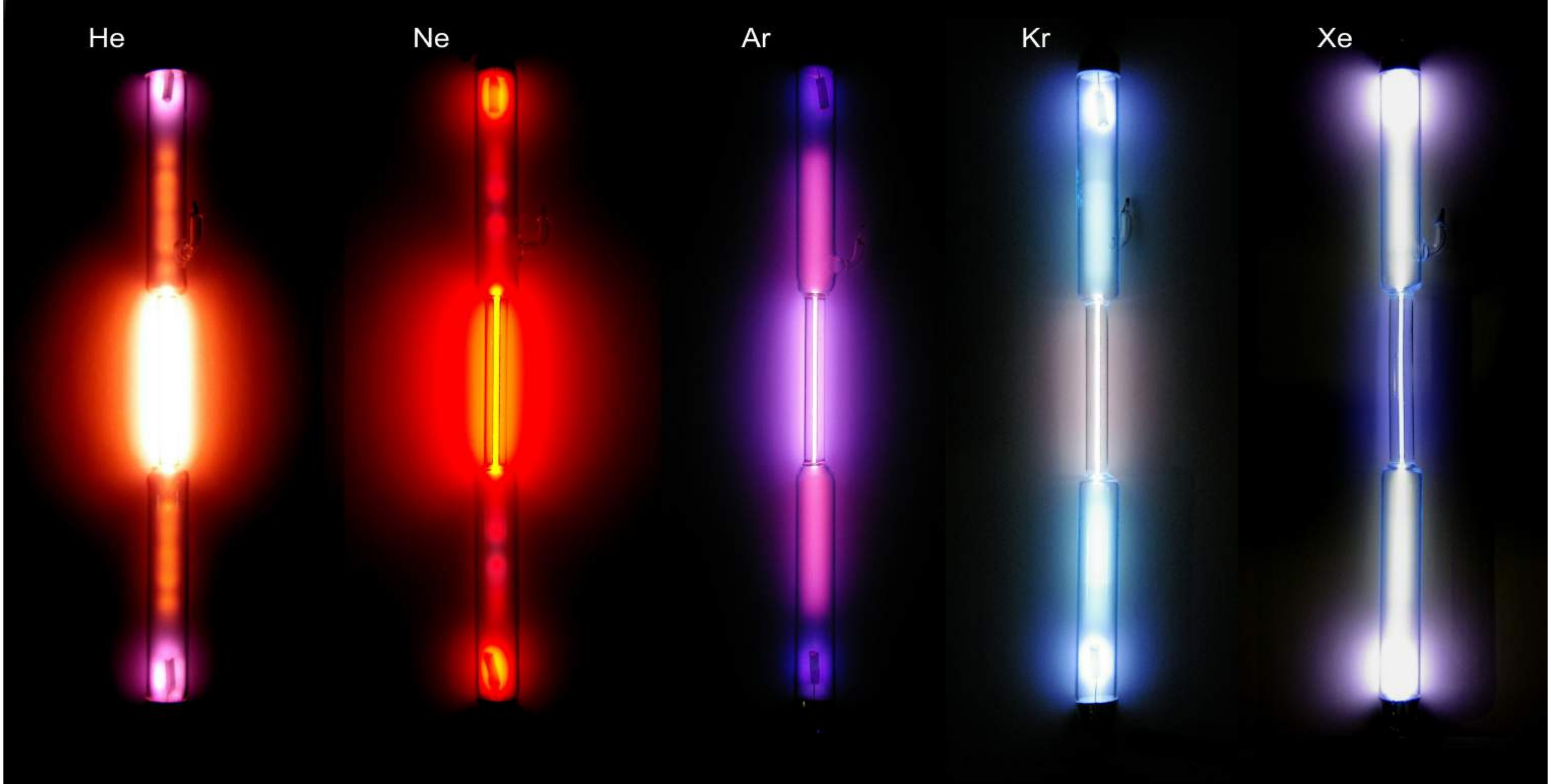
Plasma WakeField Acceleration – External Injection



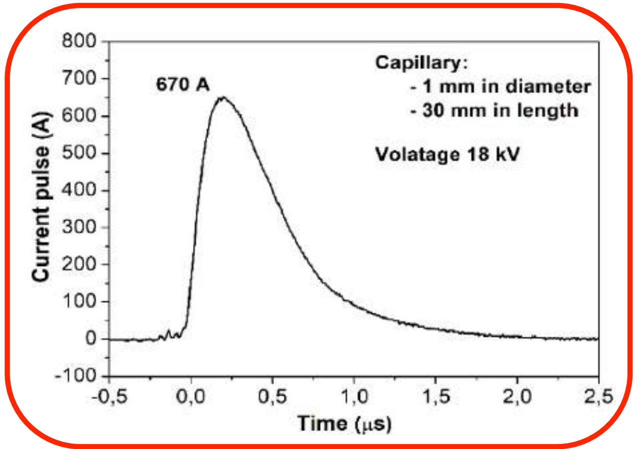

Capillary discharge at SPARC_LAB



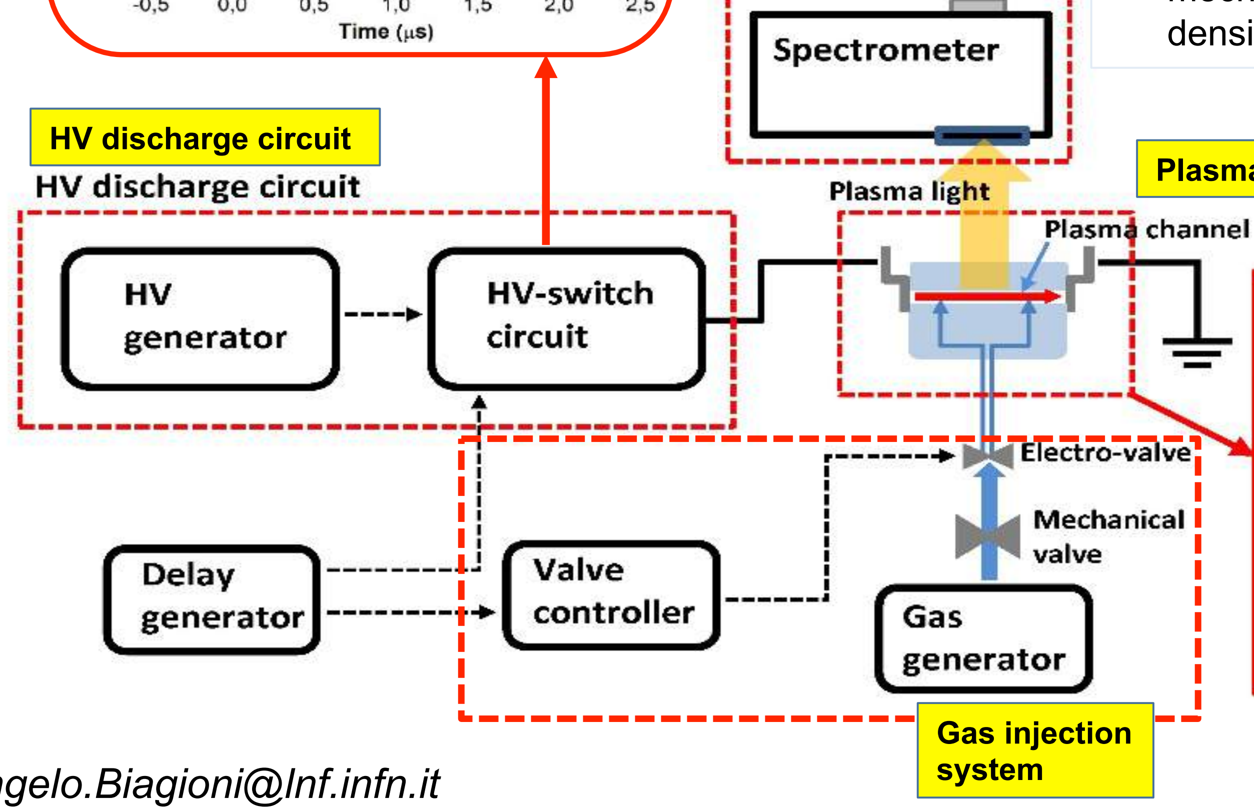
Plasma Lab

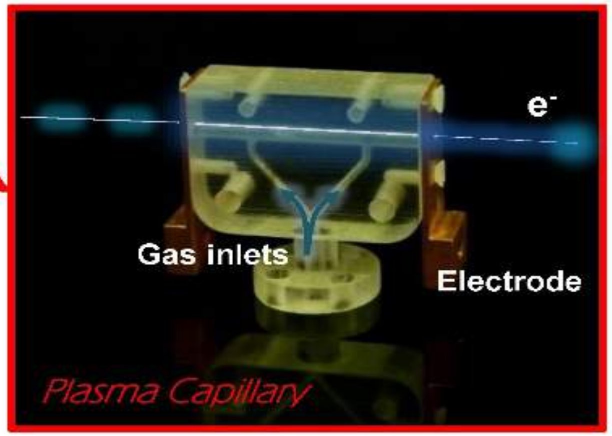


Plasma experimental setup



- ✓ Plasma within capillaries up to 10 cm-long with densities up to 10^{18} cm^{-3}
- ✓ Plasma current up to 700 A
- ✓ Stark broadening technique to measure both longitudinal and transverse density profiles
- ✓ Pulsed gas injection system (electro-valve and mechanical valve) to control the electron density





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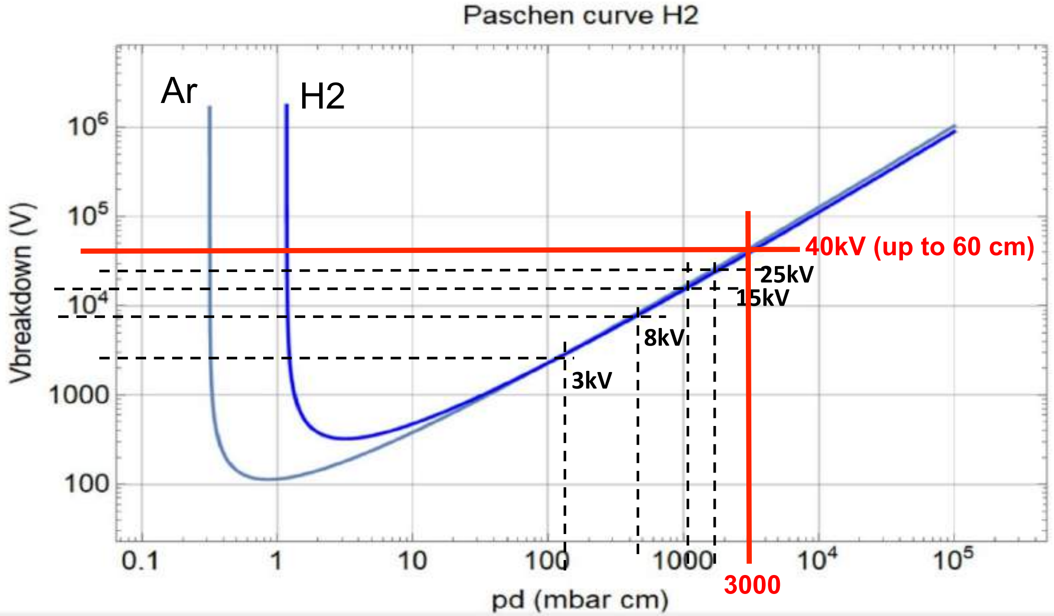
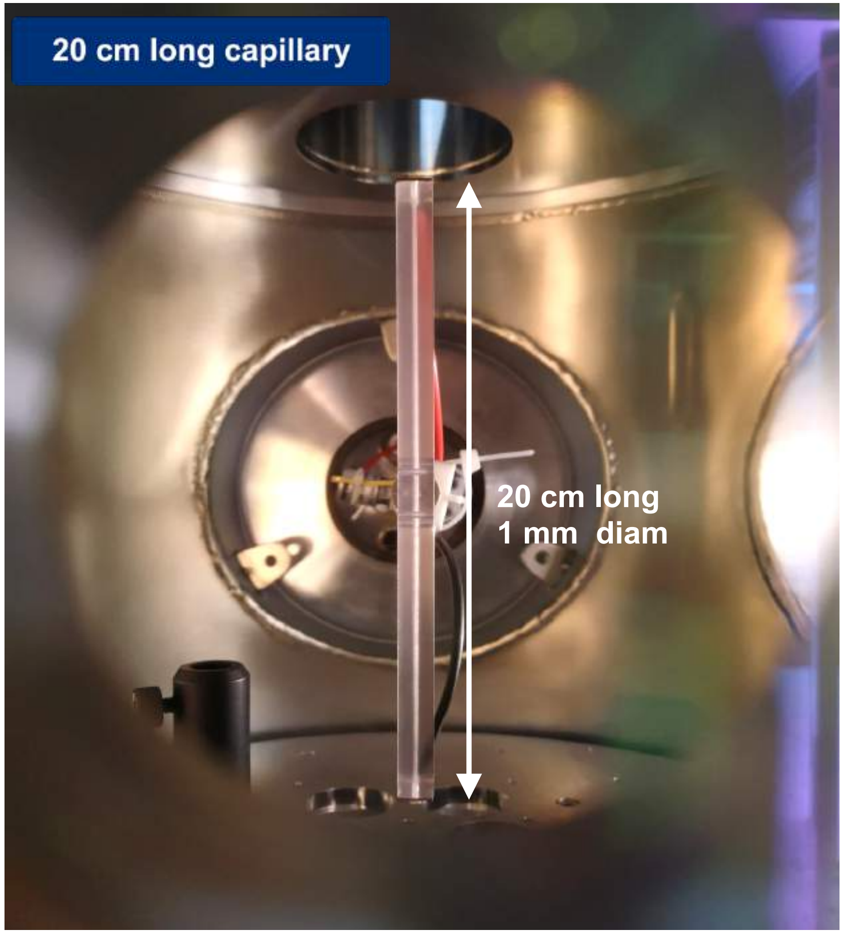
Plasma accelerator module: **EuPRAXIA case**

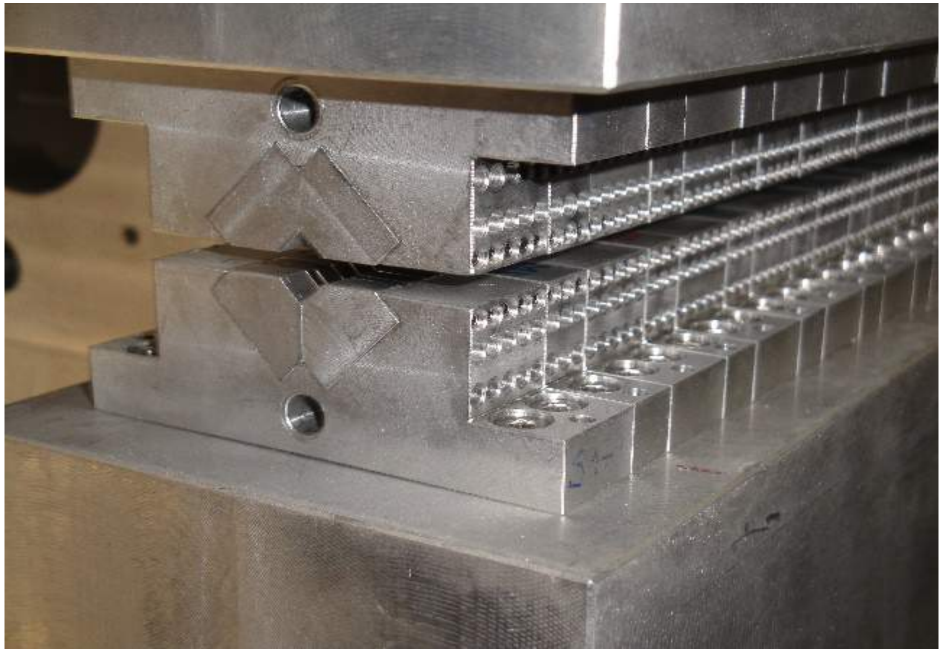
40 cm-long capillary (1.5 GV/m) (0.5 to 1.1 GeV case)
10^{16} cm^{-3} of the plasma density (E_0 ~ 13 GV/m)



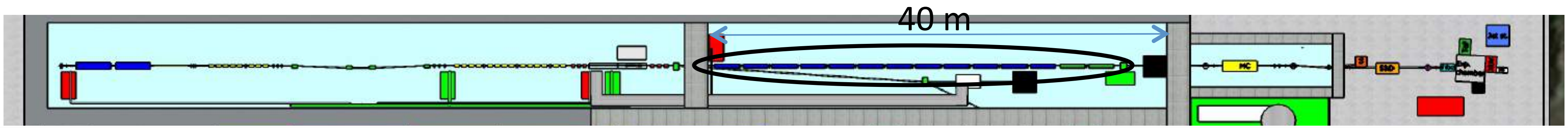


- We are going to test the EuPraxia case by using the plasma module at SPARC_LAB
- We have already tested 10 cm-long capillary and now we are working on 20-cm long capillary (14-15 kV), but we have to optimize the discharge/density
- We expect to reach around 60 cm at maximum voltage around 35-40kV

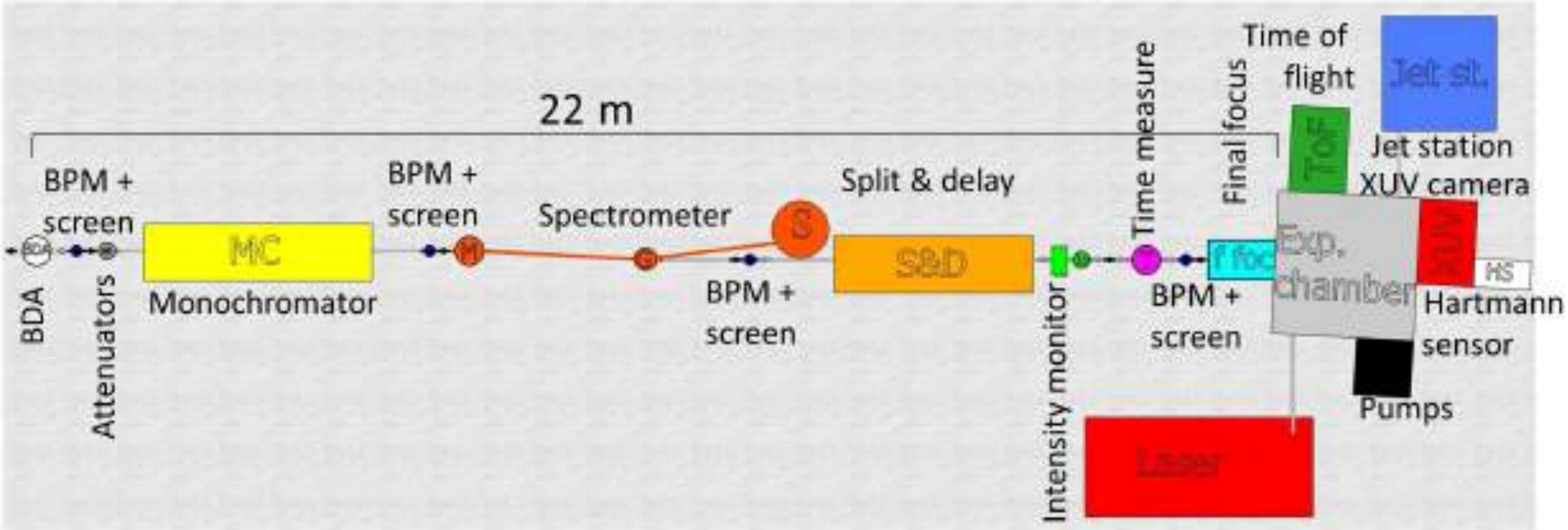
Undulators

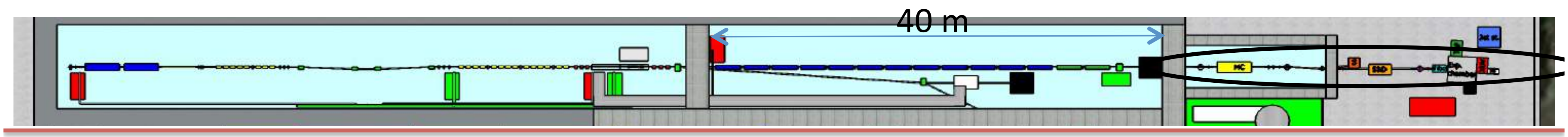


KYMA Δ udulator at SPARC_LAB: λ=1.4 cm, K1



Photon beam line



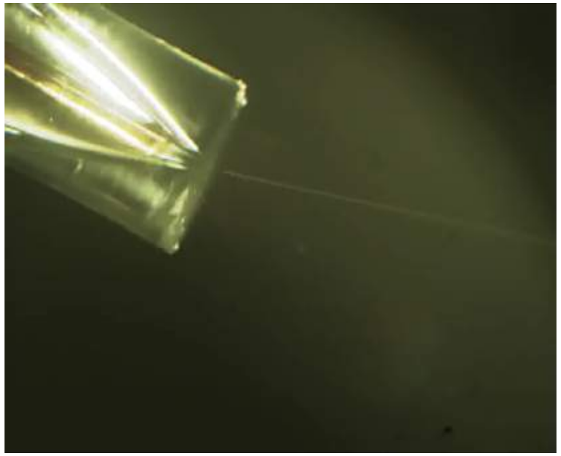


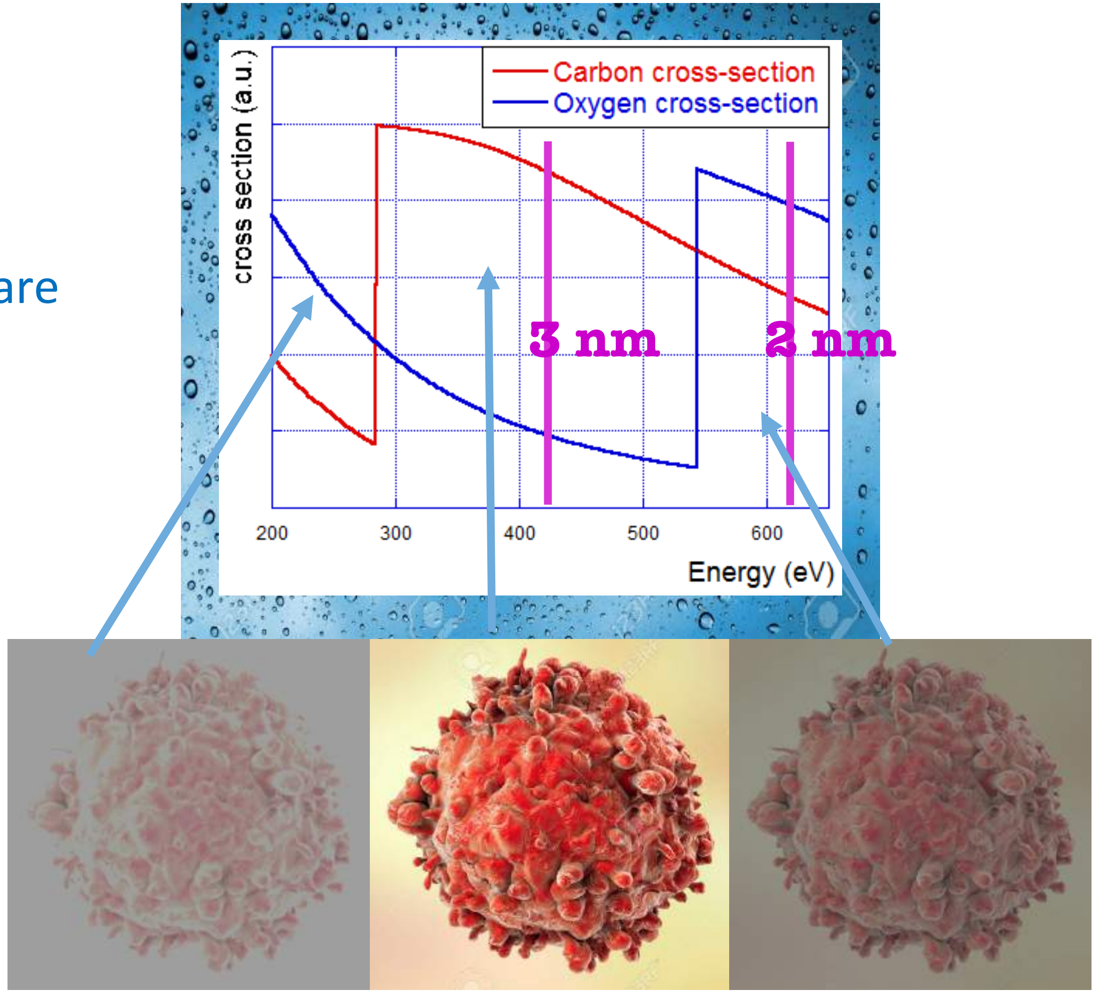
Water Window Coherent Imaging

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 living in their native state
Possibility to study dynamics
~10 [11] photons/pulse needed





Courtesy F. Stellato, UniToV

	Units	Full RF case	LWFA case	PWFA case
Electron Energy	GeV	1	1	1
RMS Energy Spread	%	0.05	2.3	1.1
Peak Current	kA	1.79	2.26	2.0
Bunch Charge	pC	200	30	30
RMS Bunch Length	µm (fs)	16.7 (55.6)	2.14 (7.1)	3.82 (12.7)
RMS normalized Emittance	mm mrad	0.5	0.47	1.1
Slice Length	µm	1.66	0.5	1.2
Slice Charge	pC	6.67	18.7	8
Slice Energy Spread	%	0.02	0.03	0.034
Slice normalized Emittance (x/y)	mm mrad	0.35/0.24	0.45/0.465	0.57/0.615
Undulator Period	mm	15	15	15
Undulator Strength $K(a_w)$		0.978 (0.7)	1.13 (0.8)	1.13 (0.8)
Undulator Length	m	30	30	30
Pierce parameter ρ **(1D/3D)**	$\times 10^{-3}$	1.55/1.38	2/1.68	2.5/1.8
Radiation Wavelength	nm (keV)	2.87 (0.43)	2.8 (0.44)	2.98 (0.42)
Photon Energy	µJ	177	40	6.5
Photon per pulse	$\times 10^{10}$	255	43	10
Photon Bandwidth	%	0.46	0.4	0.9
Photon RMS Transverse Size	µm	200	145	10
Photon Brilliance per shot	(s mm^2 mrad^2 bw(0.1%))$^{-1}$	1.4×10^{27}	1.7×10^{27}	0.8×10^{27}

Table 4.1: Beam parameters from start-to-end simulations for full RF and for plasma wakefield acceleration cases with electron (PWFA) or laser (LWFA) driver beam

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

…..+ its role as an LWFA Construction Site candidate

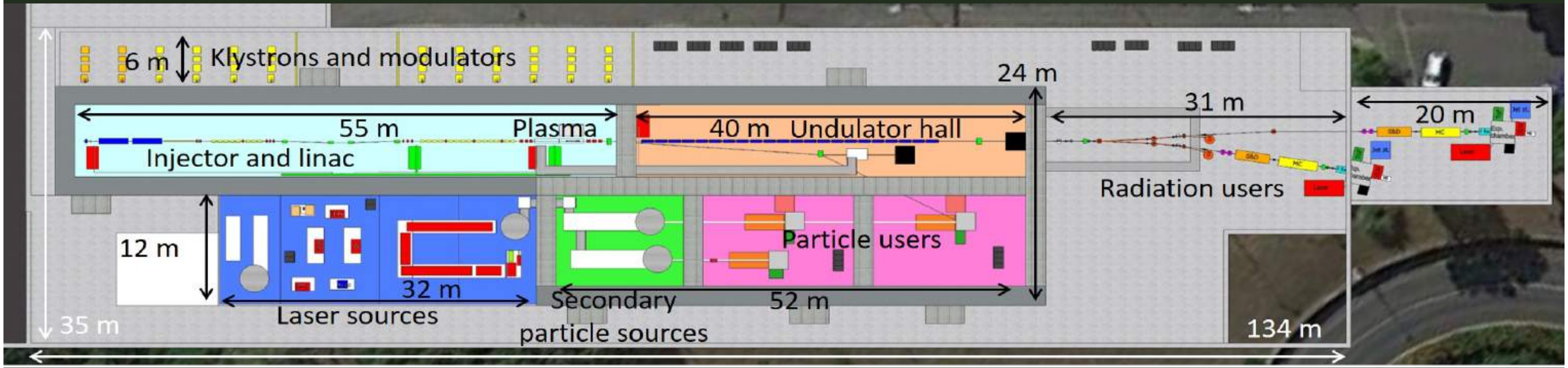
Massimo Ferrario (INFN) on behalf of the EuPRAXIA@SPARC_LAB team

EuPRAXIA Yearly Meeting 2019

DESY, October 17, 2019,

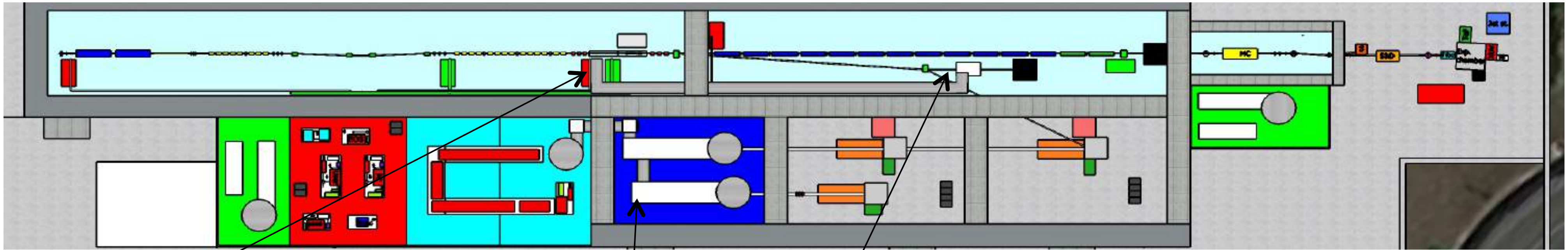
This project has received funding from the European Union's Horizon 2020
research and innovation programme under grant agreement No 653782.

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

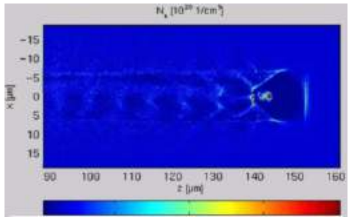


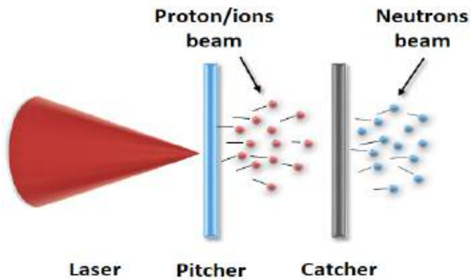
- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only
- Final goal compact 5 GeV accelerator

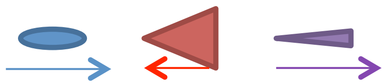
High power laser



- Laser wakefield acceleration in plasma
  - External injection
  - Self injection
- FEL source
- Secondary Prticles
- Compton scattering



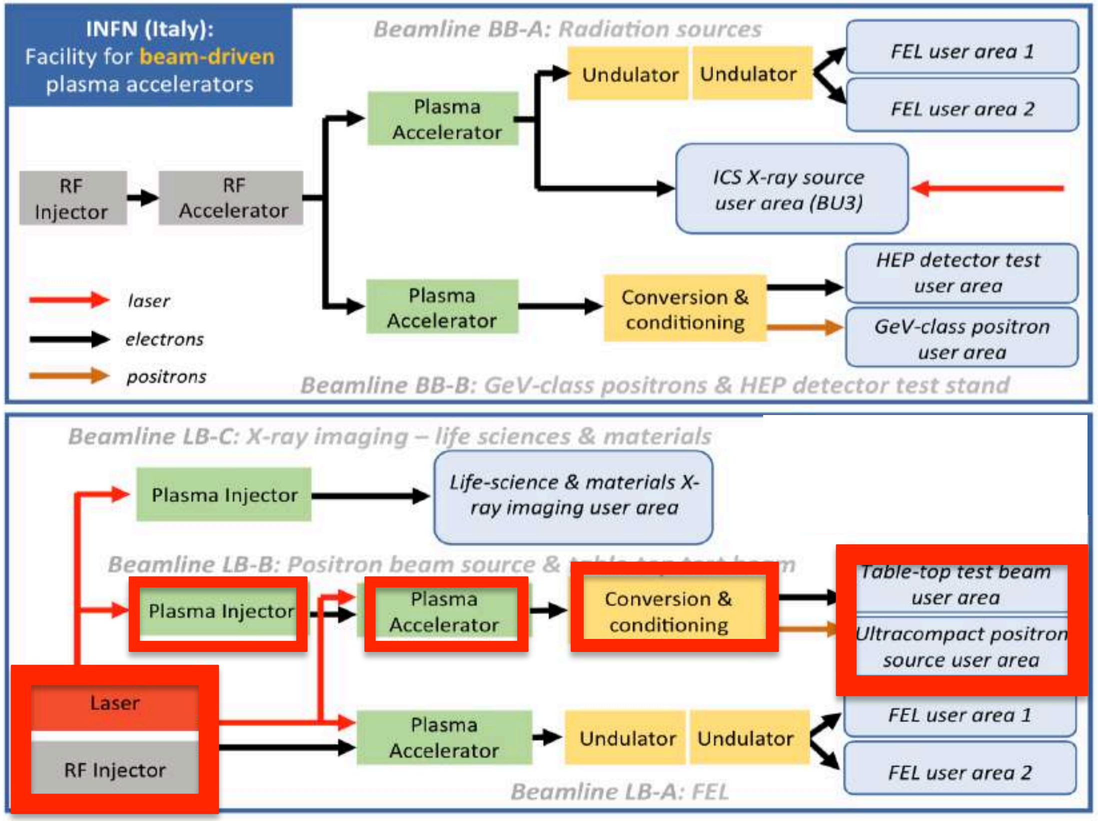




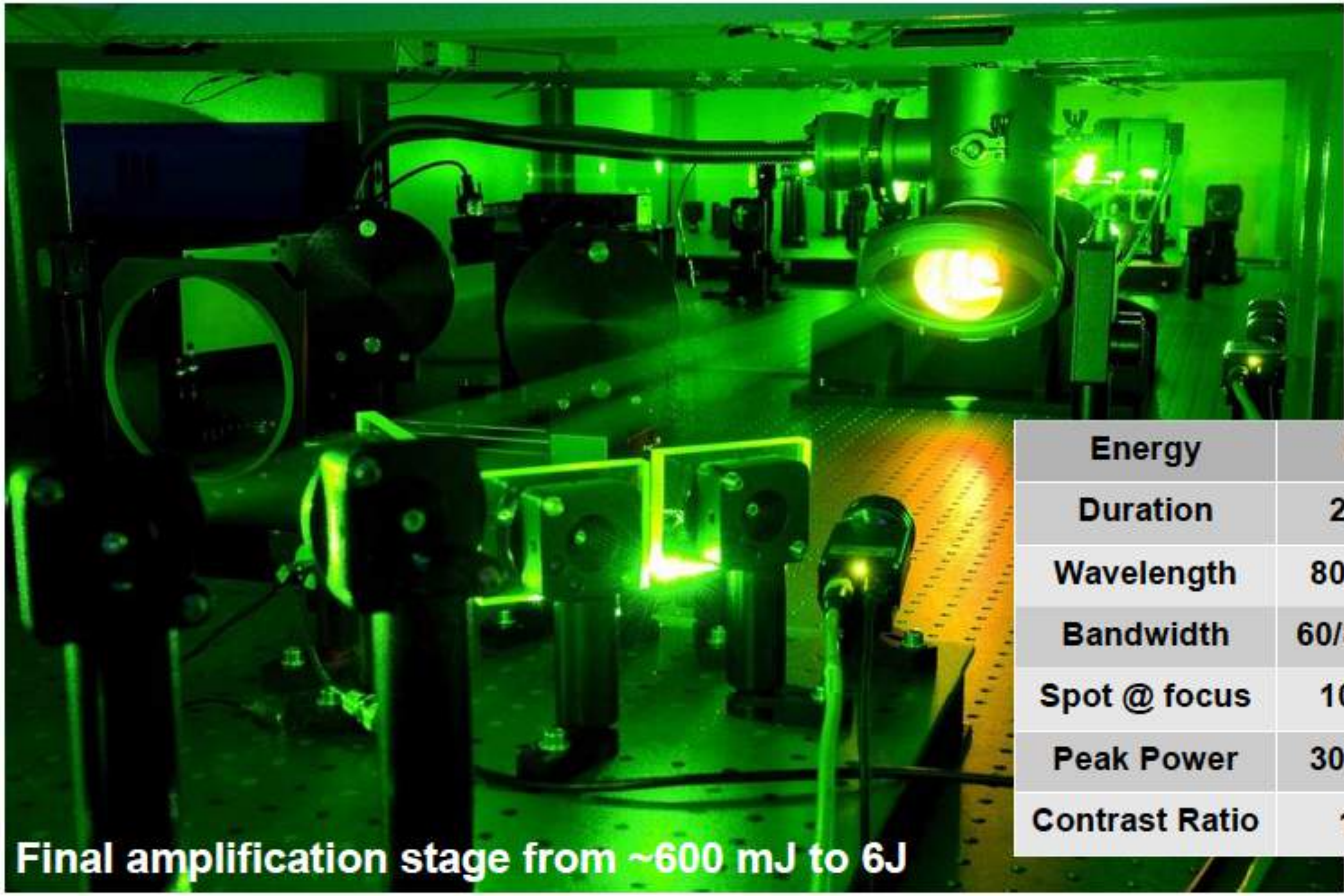
Phased Implementation of Construction Sites

Horizon 2020

	INFN
Phase 1	✓ FEL beamline to 1 GeV + user area 1 ✓ GeV-class positrons beamline + positron user area
Phase 2	✓ ICS source beamline + user area ✓ HEP detector tests user area ✓ FEL user area 2 ✓ FEL to 5 GeV
Phase 3	✓ Medical imaging beamline / user area ✓ Other future developments



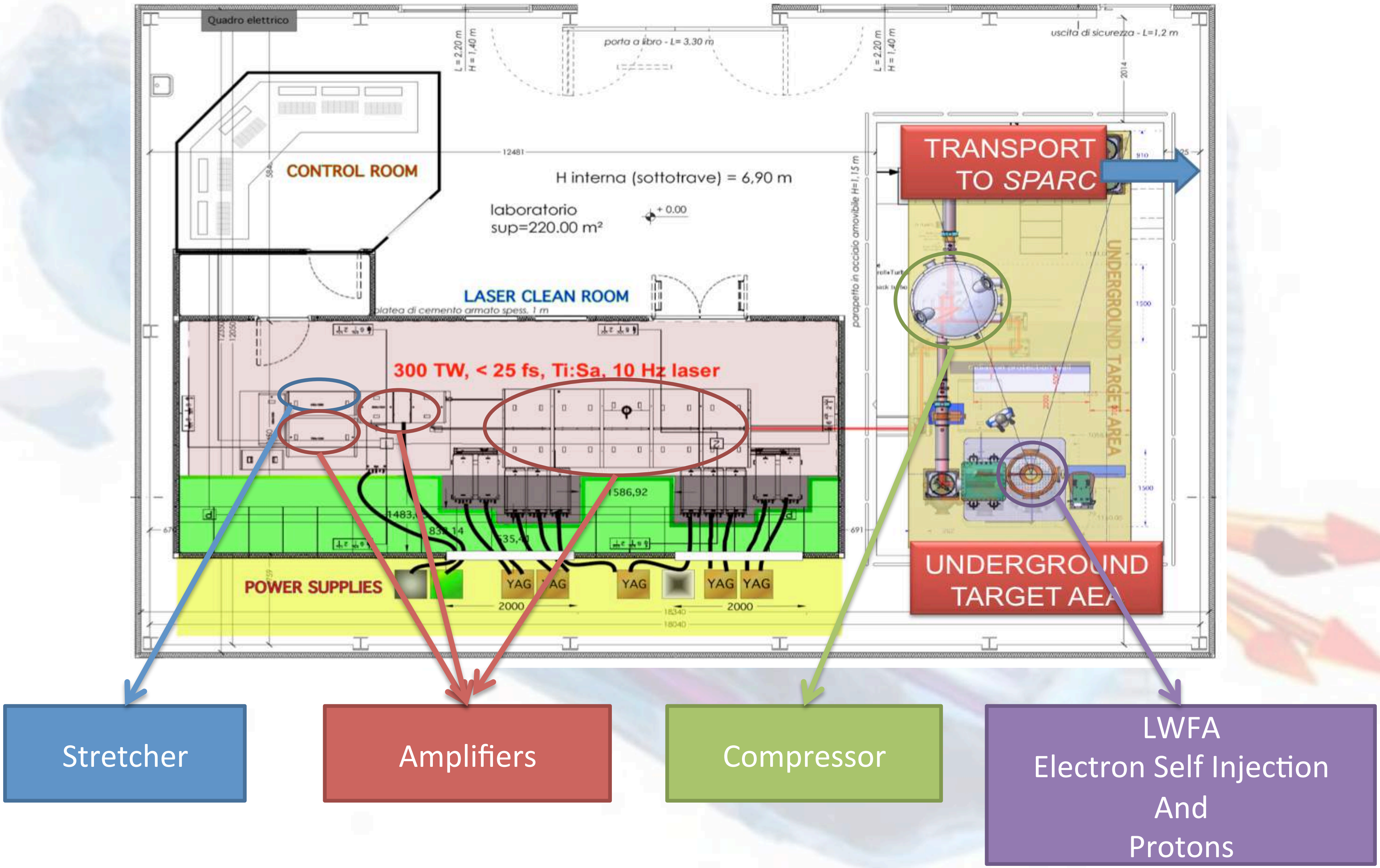
Ti:Sa FLAME laser



Final amplification stage from ~600 mJ to 6J

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}

Ti:Sa FLAME laser

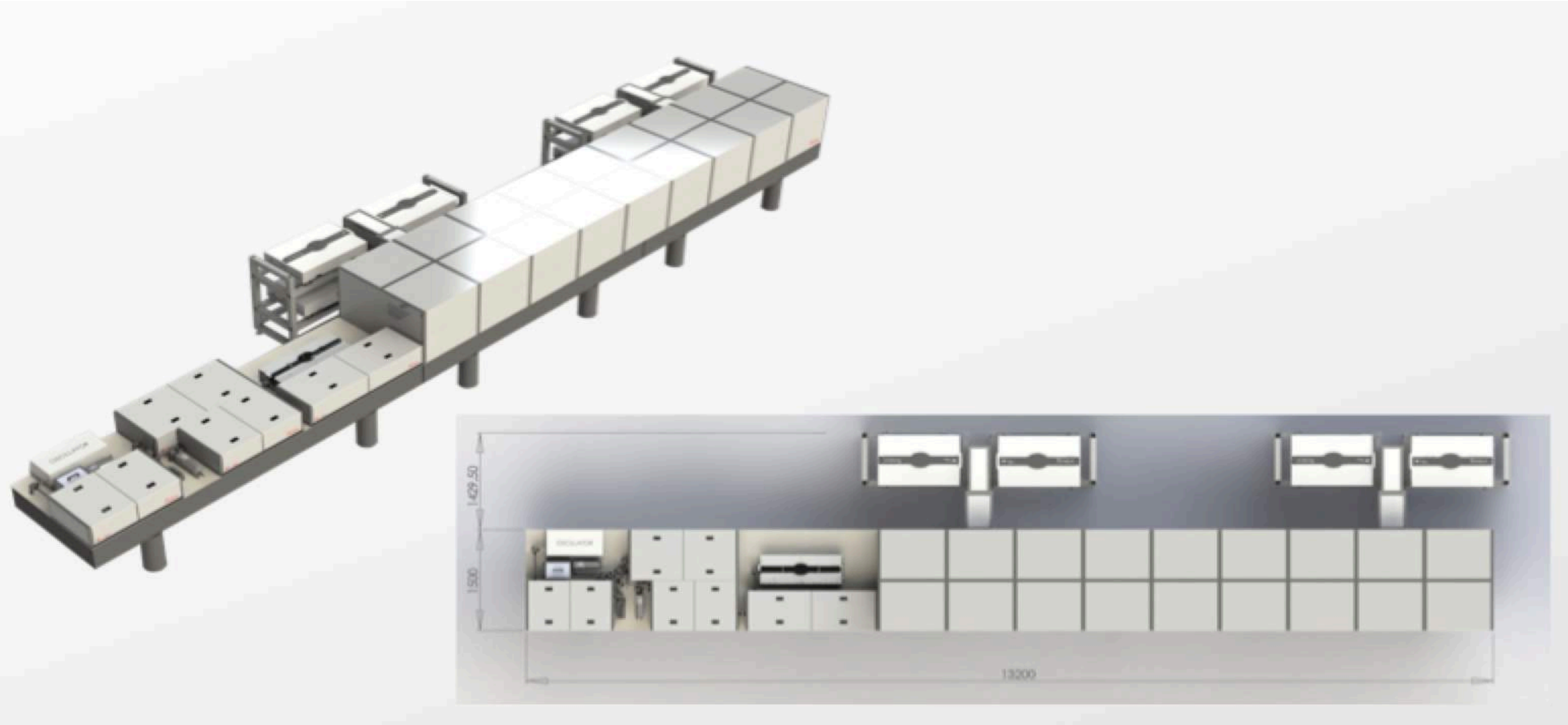


Parameters of the 500 TW laser

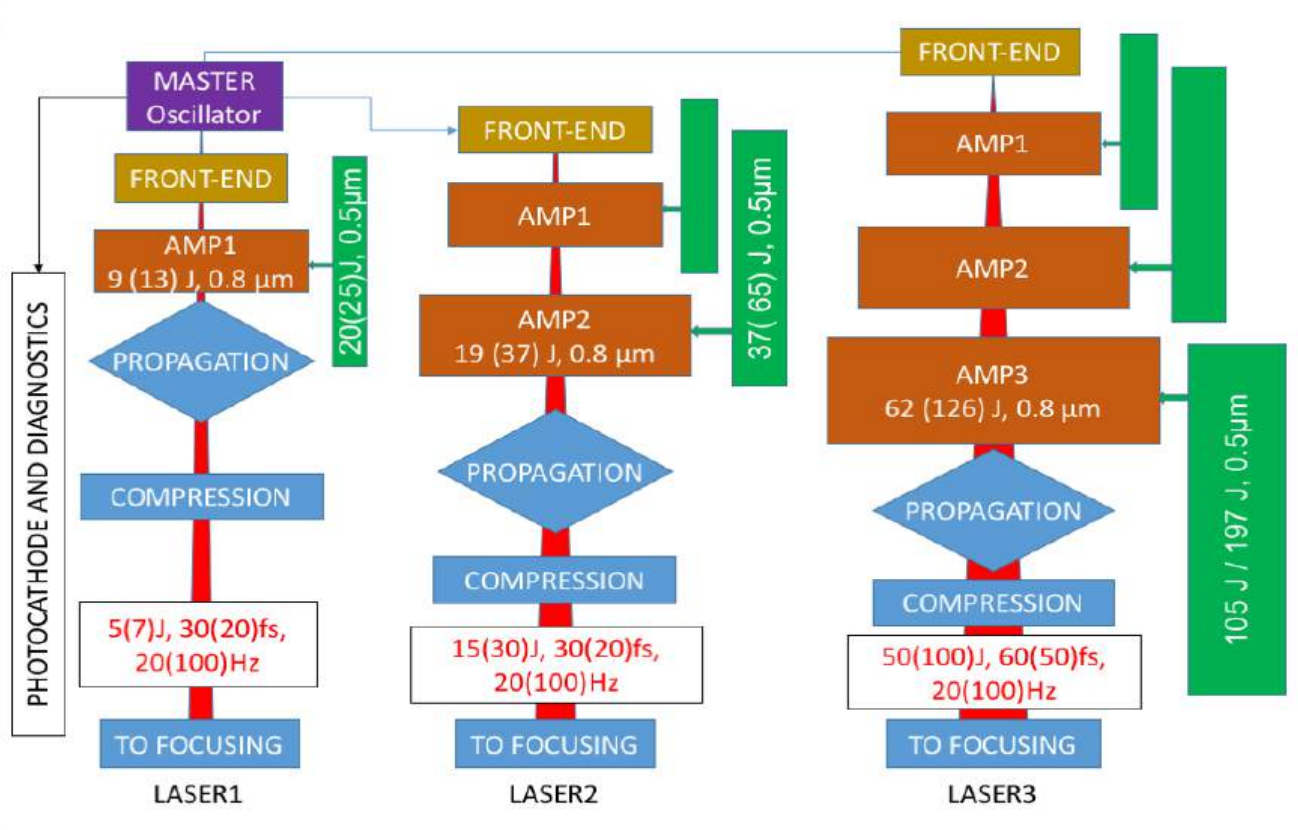
Parameters	FLAME today	FLAME upgrated
Wavelength [nm]	800	800
Bandwidth [nm]	60-80	60-80
Repetition rate [Hz]	10	1-5
Max energy before compression [J]	7	20
Max energy on target [J]	4	13
Min pulse length [fs]	25	25
Max power [TW]	250	500
Contrast ratio	10^{10}	10^{10}

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

The high power laser system: layout



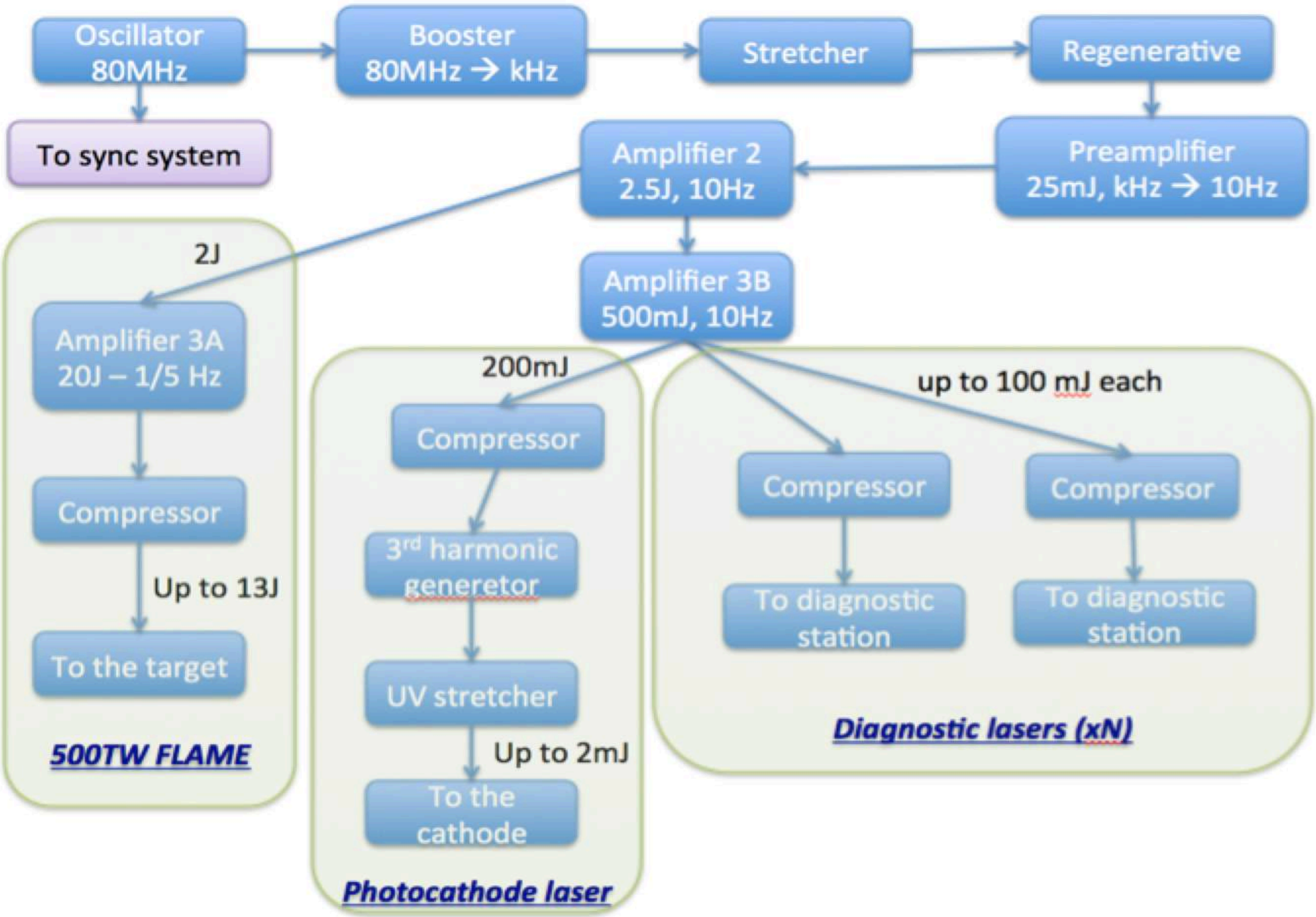
EuPRAXIA Design: 20 – 100 Hz Lasers



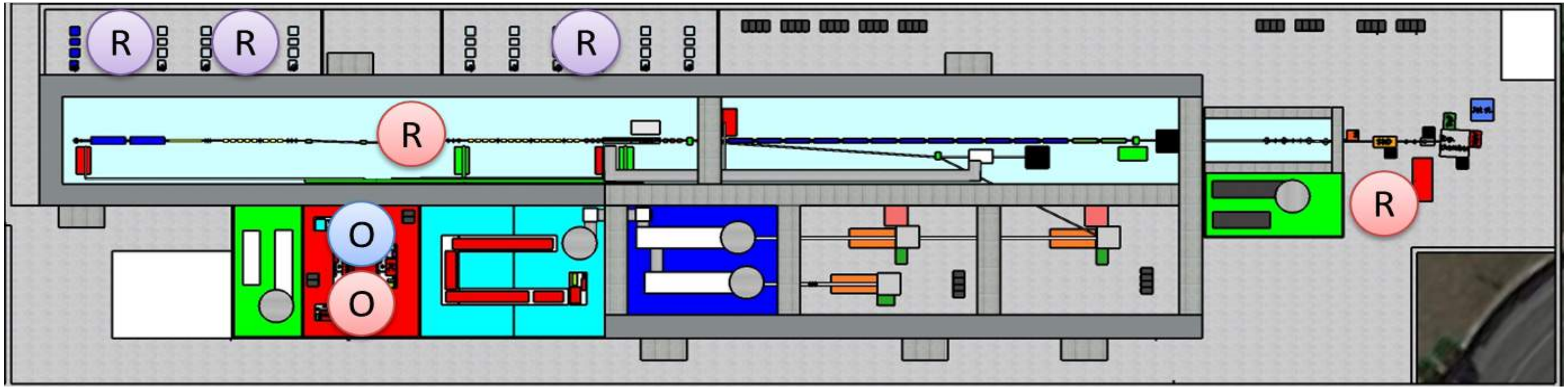
- **Three laser systems** for the laser-driven plasma accelerator facility
- Baseline: Start from lasers at present **state-of-the-art**, however, extended to 20 Hz and then to 100 Hz
- In parallel: **Development** of high efficiency, high average power lasers

Leo Gizzi, Francois Mathieu et al

The high power laser system: scheme of layout



Eupraxia@SPARC_LAB synchronization system



Synchronization system: A fine temporal alignment among all the relevant sub-system oscillators that guarantees temporal coherence of their outputs (**precision ~10fs**)

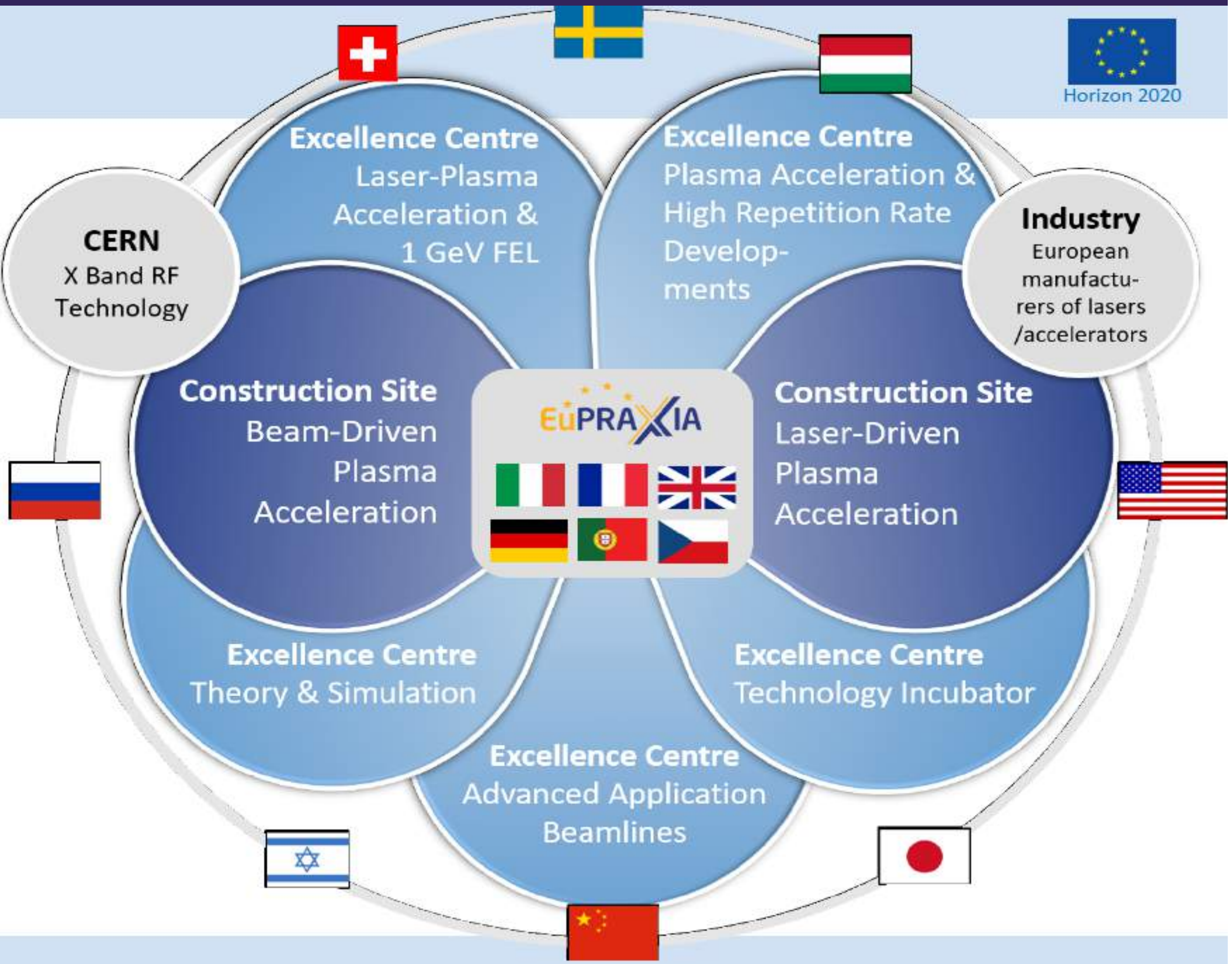
Tasks: triggers to sub systems (RF pulses, laser amplifiers, BPM, injection/extraction kickers), event tagging

Layout: 1 Electrical and 1 Optical Master Oscillator, 3 RF extractors, 2 optical link ends (diagnostics and users)

Excellence Sites

Located at existing major facilities in Europe, profiting from ongoing investments

- demonstration of major **critical principles**
- construction of **prototypes**
- testing and qualification of prototypes
- construction/testing of **components for construction site(s)**




Looking forward to seeing you all in Frascati!


1rst LEAPS Topical Conference
"LEAPS meets Quantum Technology"
24-29 May, 2020
Isola d'Elba
TALKS
BREAKFAST
COFFEE
MEALS
DISCUSSIONS
WAVE-BREAKING
https://agenda.infn.it/e/LEAPS2020


Thank for your attention