LNF X-band test stand and linac plans

Alessandro Gallo

on behalf of the INFN LNF X-band Team

EUSPARC RF / X-band Team:

D. Alesini, M. Bellaveglia, B. Buonomo, F. Cardelli, M. Diomede, G. Di Raddo, M. Ferrario, L. Foggetta, A. Gallo, A. Ghigo, S. Incremona, L. Piersanti, S. Pioli

INFN – Laboratori Nazionali di Frascati

SUMMARY

- The EUSPARC project, a proposal for a new national facility as an expansion of the SPARC_LAB activities synergic with the EU EUPRAXIA and Compact Light design studies

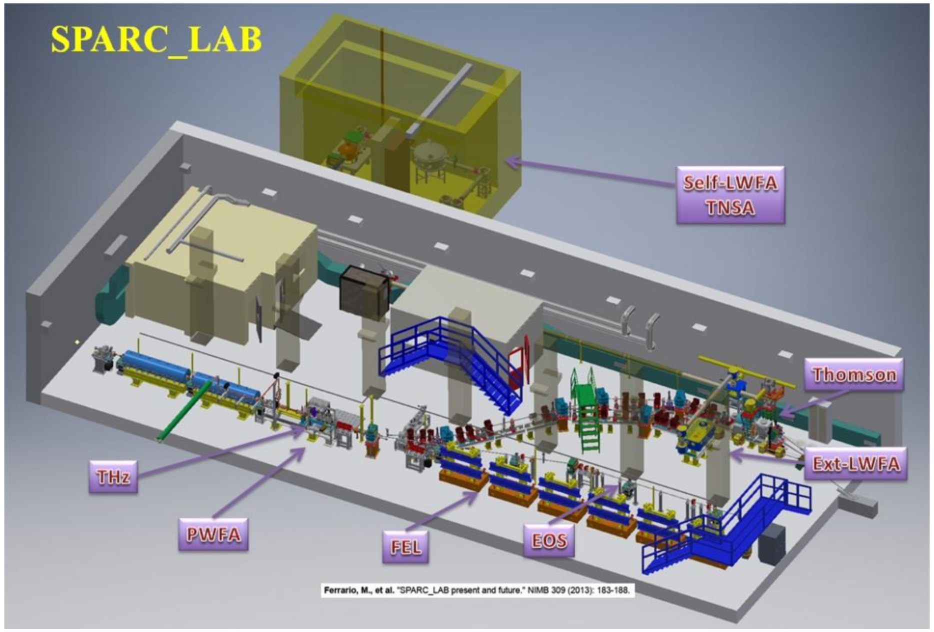
- The RF of the EUSPARC LINAC

- The Frascati X-band test stand, a facility for testing and conditioning the EUSPARC accelerating sections and the RF components

From SPARC_LAB to EUSPARC

SPARC_LAB is a multidisciplinary test facility of the INFN Frascati Labs based on 2 pillars: a conventional high brightness **RF photo-injector** (**SPARC**) and a **multi-hundred TW laser** system (**FLAME**). Several experiments have been performed and many others are in preparation using the photo-injector and the laser either independently or jointly. The experimental activities cover various fields such as FEL, THz radiation production, Thomson scattering, beam dynamics and beam diagnostics studies.

In the last years **plasma acceleration** research, in the self-injection and external injection (both particle and laser driven) modalities, has become a relevant part of the SPARC_LAB scientific program.

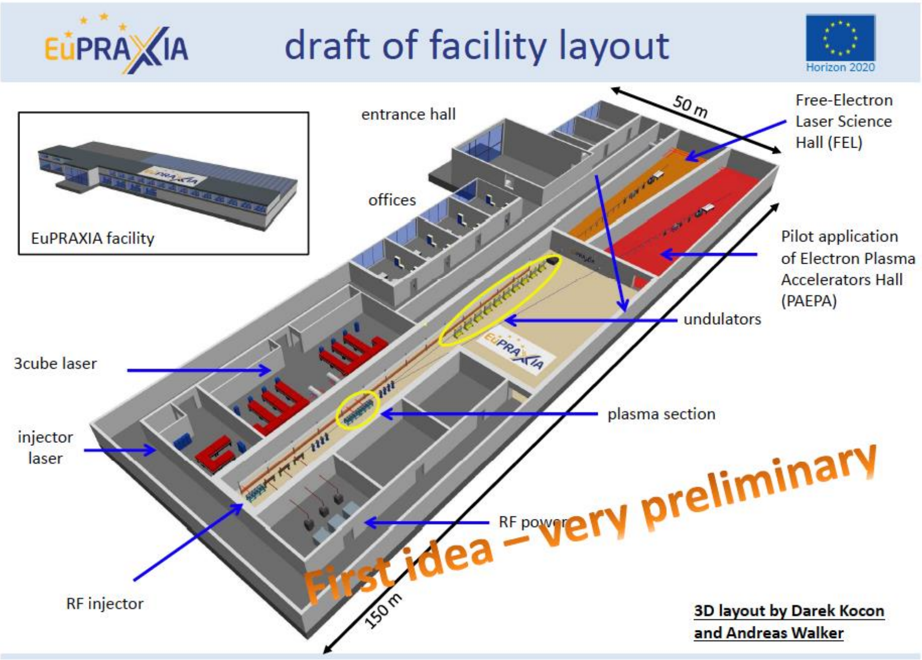


Energy	6 J
Duration	23 fs
Wavelength	800 nm
Bandwidth	60/80 nm
Spot @ focus	10 µm
Peak Power	300 TW
Contrast Ratio	10^{10}

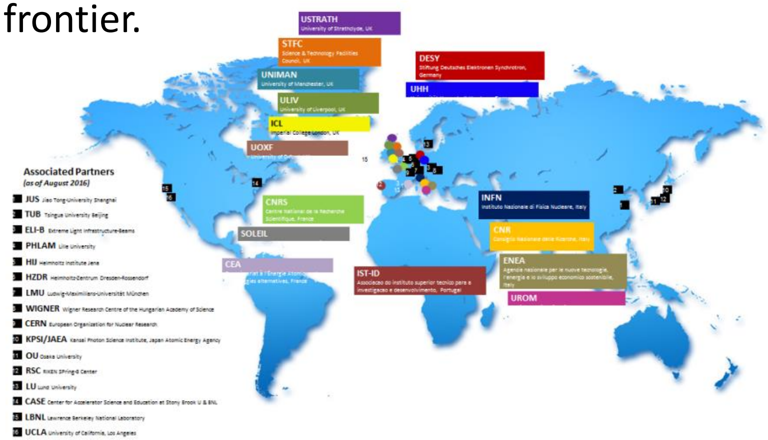
Capillary Discharge at SPARC_LAB

EuPRAXIA DESIGN STUDY

In the framework of the Horizon 2020, a **Design Study called EuPRAXIA** ("European Plasma Research Accelerator with eXcellence In Applications"), has been funded (3 M€ 16 laboratories and universities). Coordinator: Ralph Assmann (DESY)



The **goal of this project is to produce a CDR** for the worldwide first high energy **plasma-based accelerator** that can provide industrial beam quality and user areas. It is the important intermediate step between proof-of-principle experiments and ground-breaking, ultra-compact accelerators for science, industry, medicine or the energy frontier.



The **EuPRAXIA design study is site-independent**. It's final report will include various European **site options**.

EuPRAXIA parameters and site selection

Two different options under study:

- 1 PW Ti:Sa for **LWFA**
- 500 MeV electron beam for **PWFA**

MAIN APPLICATIONS

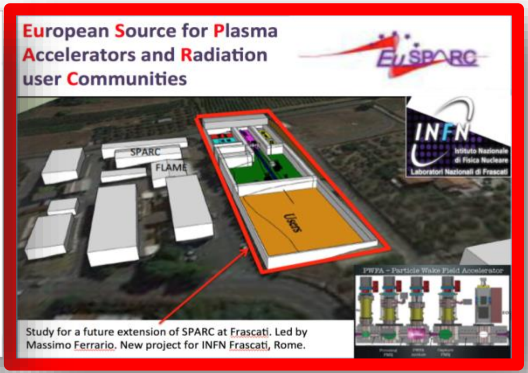
(1) FEL in the EUV to X-ray regime (1-15 nm)

(2) short electron pulses with high brightness for **HEP detector tests, material tests and other applications**.

EuPRAXIA PARAMETERS (From the proposal)

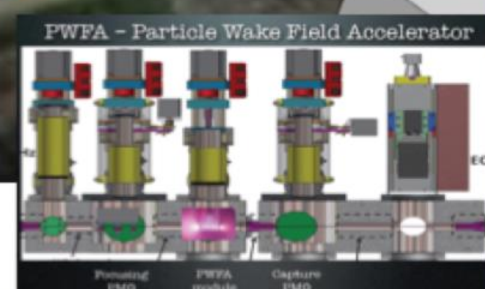
Beam Parameter	**Unit**	**Value**
Particle type	-	Electrons
Energy	GeV	1 – 5
Charge per bunch	pC	1 – 50
Repetition rate	Hz	10
Bunch duration	fs	0.01 - 10
Peak current	kA	1 – 100
Energy spread	%	0.1 – 5
Norm. emittance	mm	0.01 – 1
FEL wavelength	nm	1 - 15

The **EuPRAXIA design study is site-independent**. It's final report will include various European **site options**.



European Source for Plasma Accelerators and Radiation user Communities

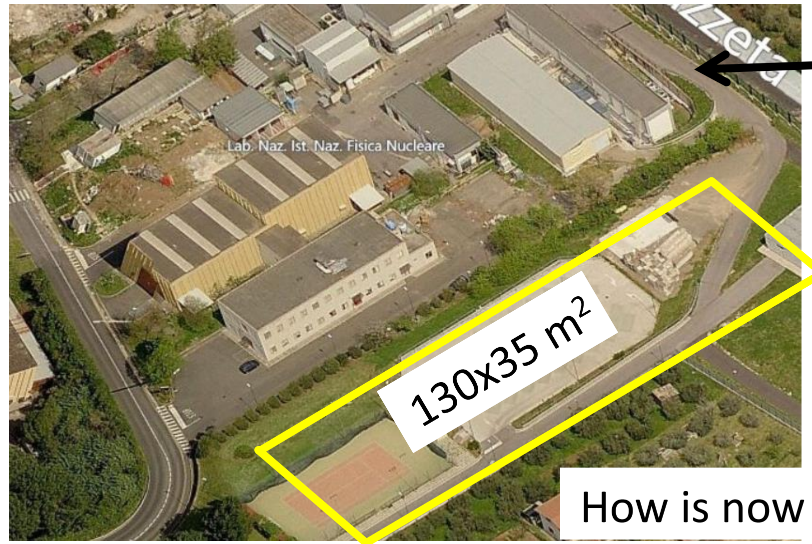
EuSPARC

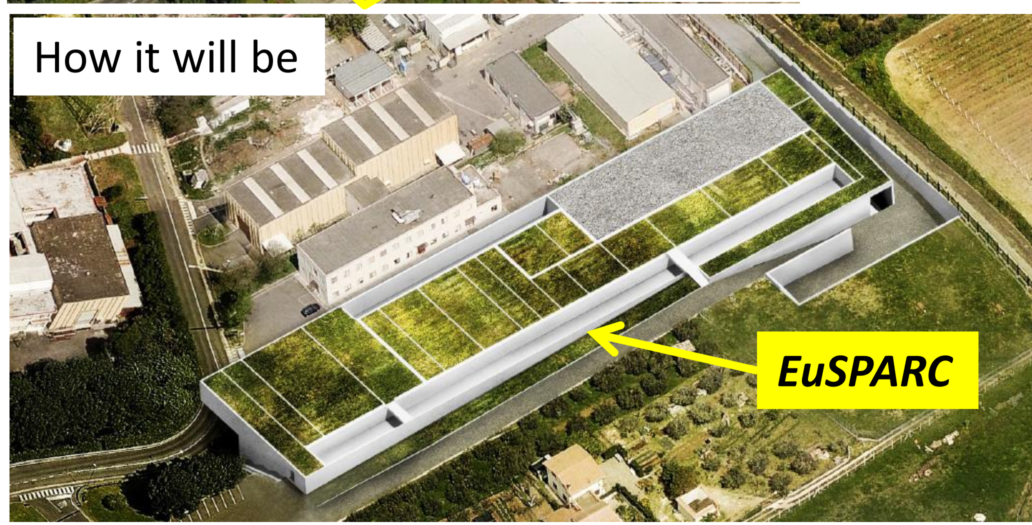


Study for a future extension of SPARC at Frascati. Led by Massimo Ferrario. New project for INFN Frascati, Rome.

- X-band RF technology implementation, CLIC collaborations
- Science with short wavelength Free Electron Laser (FEL)
- Physics with high powerlasers and secondary particle generation
- 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

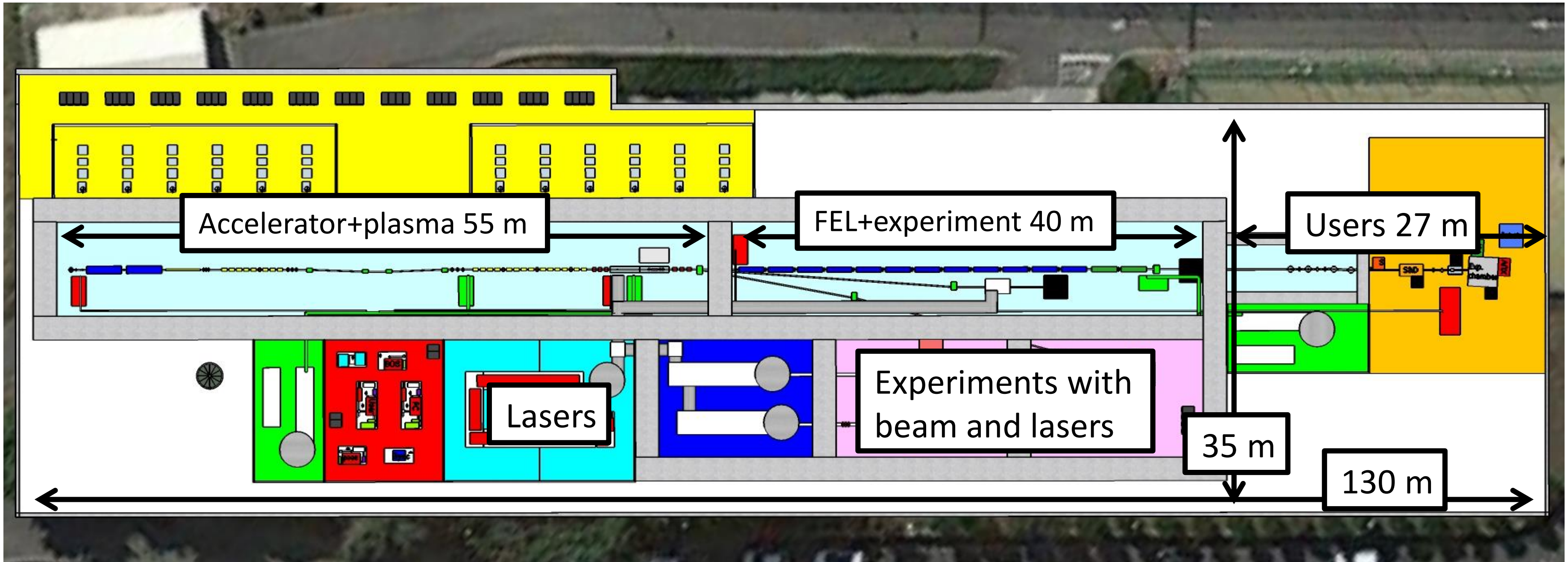
EuSPARC SITE@LNF





EuSPARC PRELIMINARY LAYOUT

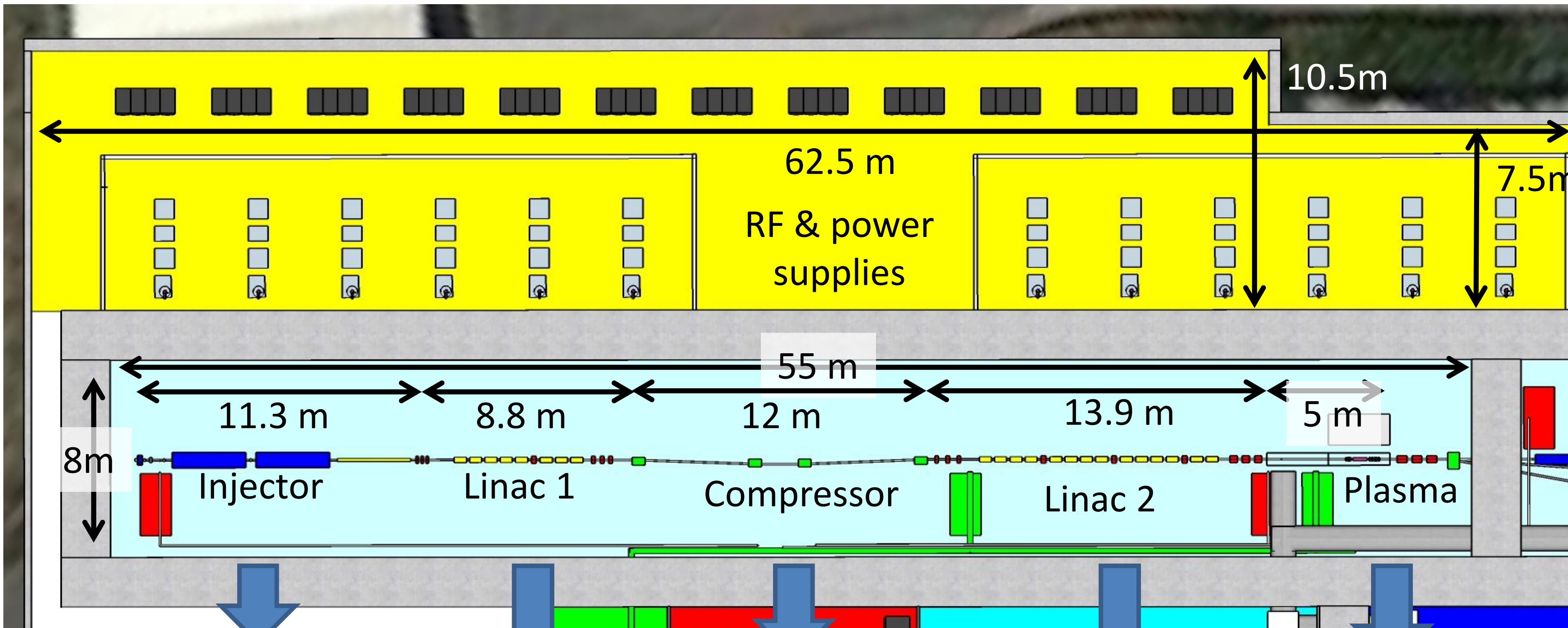
⇒ Candidate LNF to host EuPRAXIA (1-5 GeV)
⇒ FEL user facility (1 GeV – 3nm)
⇒ Advanced Accelerator Test facility (LC) + CERN (X-Band)



⇒ **500 MeV by RF Linac + 500 MeV by Plasma (EuPRAXIA@SPARC_LAB)**

⇒ **1 GeV by high gradient RF Linac only (EuSPARC)**

EuSPARC Accelerator (preliminary)



Injector:
S-Band photo-gun+solenoid
3x 3m TW S-band sectons

Linac 1:
8x 0.5m **X-band** sections, Matching Quads

Compressor:
2.19° deflection

Linac 2:
24 x 0.5m **X-band** sections, Matching Quads

Plasma:
PMQ matching 0.6 m capillary

EuSPARC PARAMETERS

(in progress)

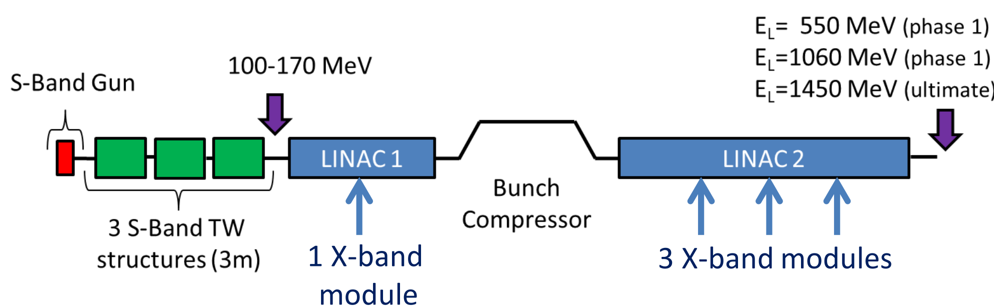
	Units	Eusparc Xband FEL-SASE 1 GeV	EuPRAXIA FEL-CDR 1GeV Witness bunch	PWFA 2 FEL-SASE 1 GeV 1 Driver
Linac parameters				
No. Bunches		1		1
Rep. rate	Hz	10 – 100	10	10
Injector energy	GeV	0,15	0,15	0,15
Xband Acc. Gradient	MV/m	> 70	> 70	> 70
Exit linac energy	GeV	1	0,5	0,5
Electron parameters after acceleration				
Rms Energy Spread	%	<1.	<1	< 1
Peak current	kA	2	3	1,8
Bunch charge	pC	100	30	200
Bunch length rms	μm (fs)	15 (50)	3 (10)	34 (112)
Rms norm. emittance	μm	< 1.	<1.5	< 2
Electron parameters at undulator start				
Electron energy	GeV	1	1	
Slice Length	μm	0,7	0,75	
Slice Charge	pC	4,5	7,5	
Slice Energy Spread	%	0,1	0,1	
Slice norm. emittance	μm	0,5	1	
Undulator parameters				
Undulator period	cm	1,5	1,5	
K		1	1	
rho	x 10^-3	1,2	1,1	
Saturation length	m	22	26	
FEL light parameters at undulator end				
Central wavelength tunability	nm (KeV)	3. (0.4)	3. (0.4)	
Bandwidth (Δλ/λ, rms)				
Energy/pulse	μJ	47	12	
Photons/pulse	x 10^10	70	17	

X-Band LINAC parameters				
L_t [m]	16			
	WP1	WP2	**WP3**	Ultimate
E_0 [MeV]	100	170	**170**	170
E_{gain} [MeV]	450	380	**890**	1280
<G> [MV/m]	20(L1)-36(L2)	20(L1)-27(L2)	**57**	80
E_L [MeV]	550	550	**1060**	1450

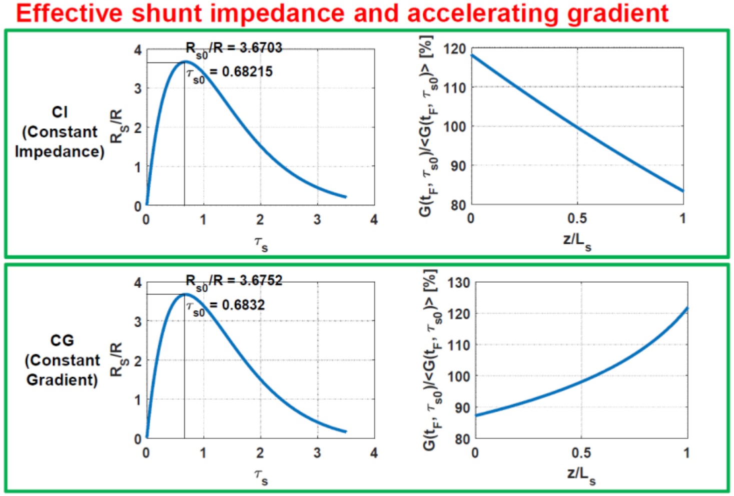
X-BAND LINAC DESIGN

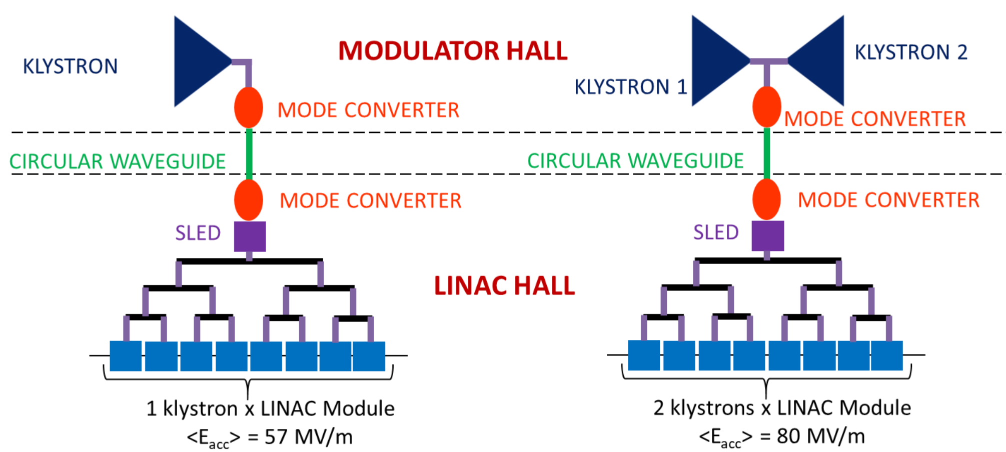
(based on A. Grudiev's calculations)

WP1: particle driven plasma acceleration
WP2: laser driven plasma acceleration
WP3: no plasma acceleration, only RF



Effective shunt impedance and accelerating gradient





INFN – CERN official partnership on X-band RF development

ADDENDUM No. KE3849/CLIC
to
FRAMEWORK COLLABORATION AGREEME...
between
THE EUROPEAN ORGANIZATION FOR NU...
and
THE ISTITUTO NAZIONALE ... ...")

Collaboratio... ... Studies in the framework of
CL... ...AXIA@SPARC_LAB at LNF

officially approved by INFN Board of Directors on Dec. 22, 2017

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.

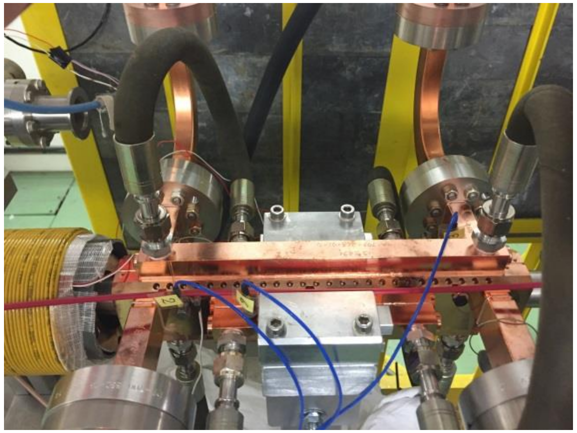
Other Synergies:

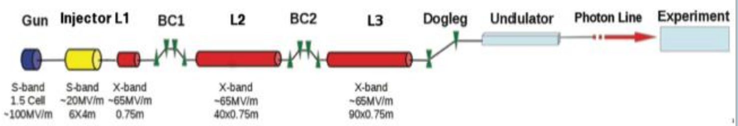
Compact

New EU Design Study Approved

3 years – 3 MEuro (→212 kEuro INFN)

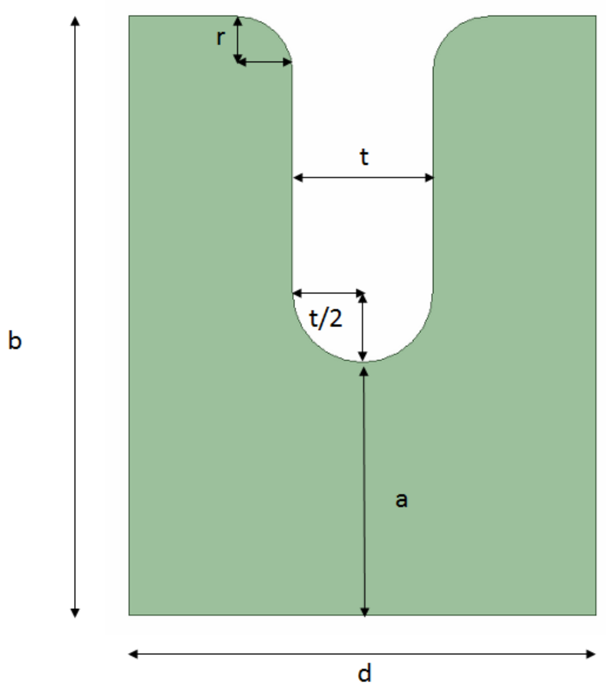
Coordinator: G. D'Auria (Elettra)



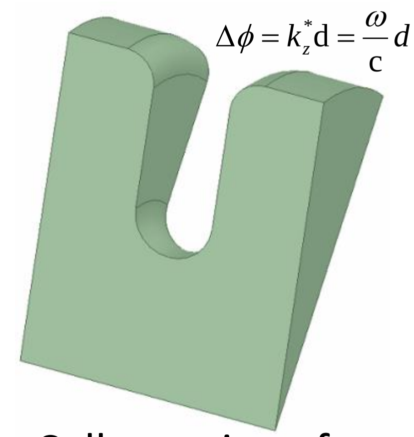


The key objective of the CompactLight Design Study is to demonstrate, through a conceptual design, the feasibility of an innovative, compact and cost effective FEL facility suited for user demands identified in the science case.

EuSPARC RF STRUCTURE DESIGN: Single-cell parametrization



A scan of the iris radius **from 2 mm to 5 mm** a has been performed with HFSS in order to obtain the single cell parameters **(R, v_g/c, Q, Sc_{max}/E^2_{acc})** as a function of the iris radius. Also the related polynomial fits have been derived.



Cell portion for HFSS simulations

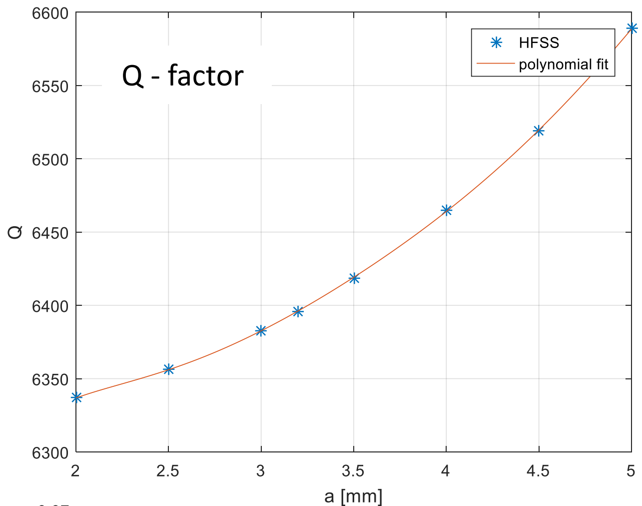
freq	11,9942 GHz
a	2 mm ÷ 5 mm
b	9.828 mm ÷ 10.917 mm
d	8.332 mm (2π/3 mode)
r	1 mm
t	2.5 mm

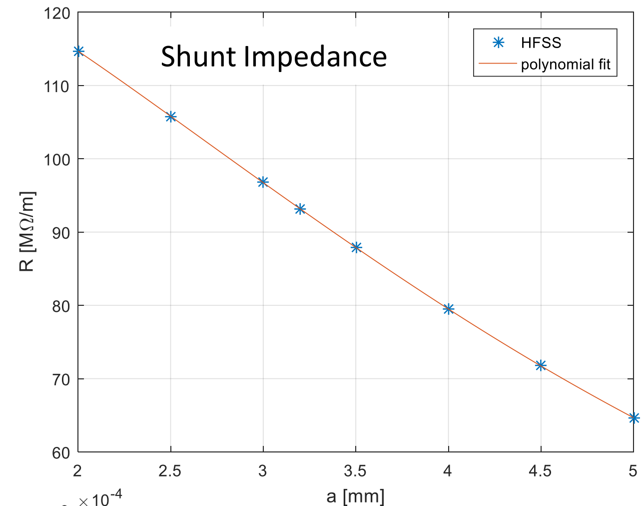
For more details on the RF structure design see:
M. Diomede et al. , arXiv:1801.00707 [physics.acc-ph]

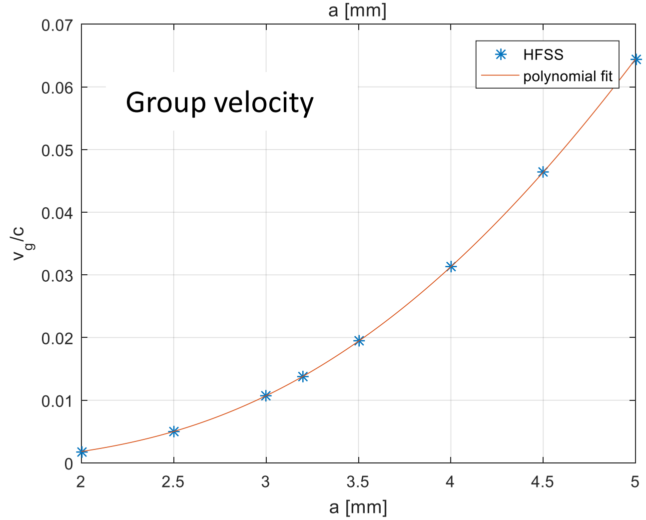
EuSPARC RF STRUCTURE DESIGN

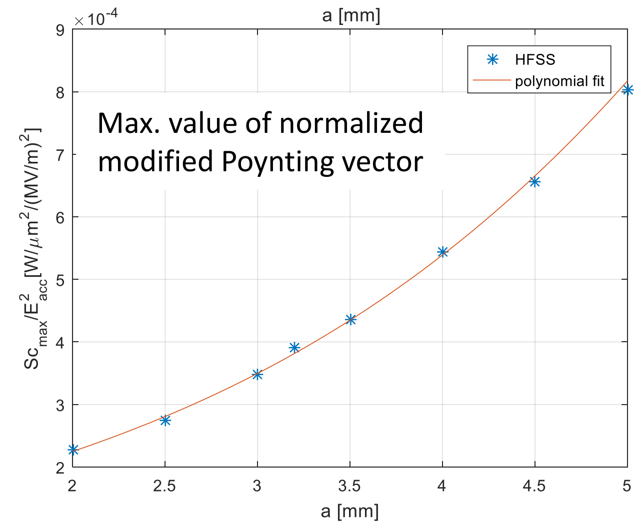
The **average iris radius <a>** has been fixed to **3.2 mm**, according to **beam dynamics calculations** (single bunch beam break up).

Single cell parameters (a=3.2 mm)	
b [mm]	10.139
R [MΩ/m]	93
v_g/c [%]	1.382
Q	6396
Sc_{max}/E^2_{acc} [A/V]	3.9×10^{-4}









EuSPARC RF STRUCTURE DESIGN

Analytical Optimization:

Computed assuming constant values for Q, R/Q, SLED Q_0 and klystron pulse duration.

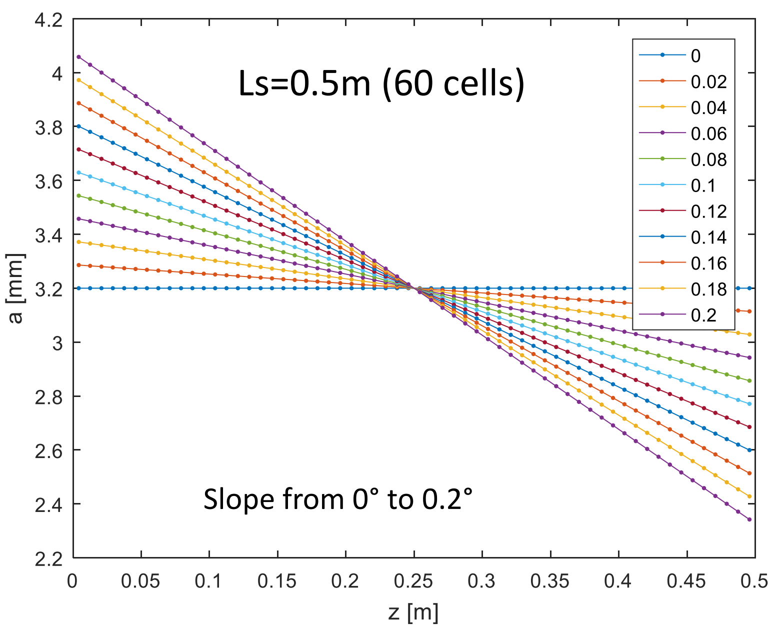
Constant Impedance parameters	
R_S [MΩ/m]	343
L_s [m]	0.474
t_f [ns]	114

Numerical Optimization:

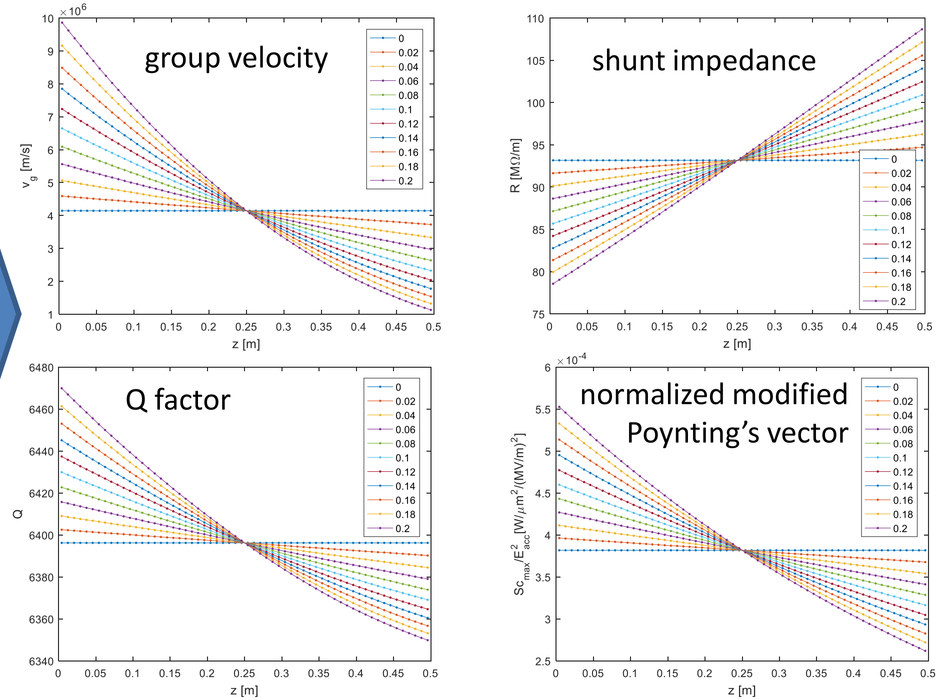
R/Q variation with iris aperture is not negligible. Constant gradient concept does not apply for not-flat RF pulses. For numerical optimization we assumed an average iris radius of 3.2 mm, different structure lengths and for each length different iris linear tapering slopes in order to find the highest effective shunt impedance.

Constant Gradient parameters	
R_S [MΩ/m]	344
L_s [m]	0.432
t_f [ns]	118

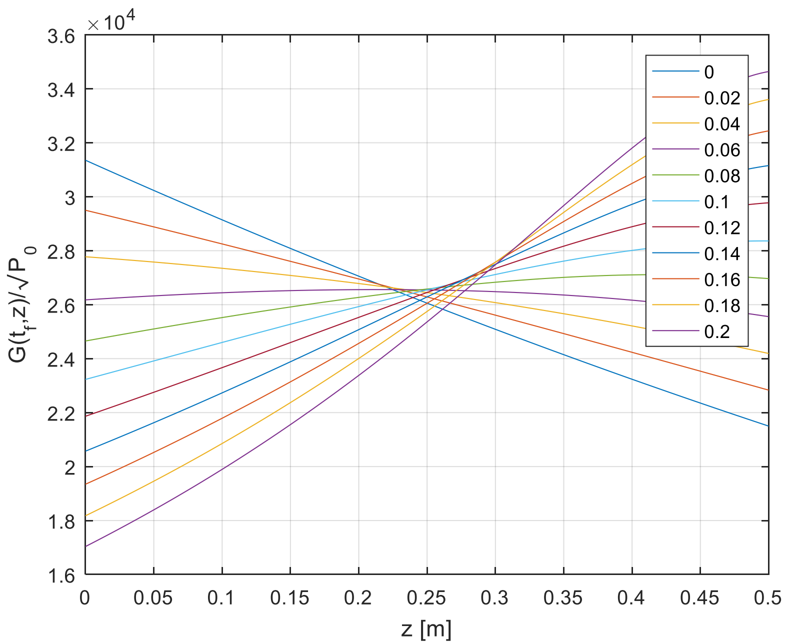
EuSPARC RF STRUCTURE DESIGN: Numerical Optimization



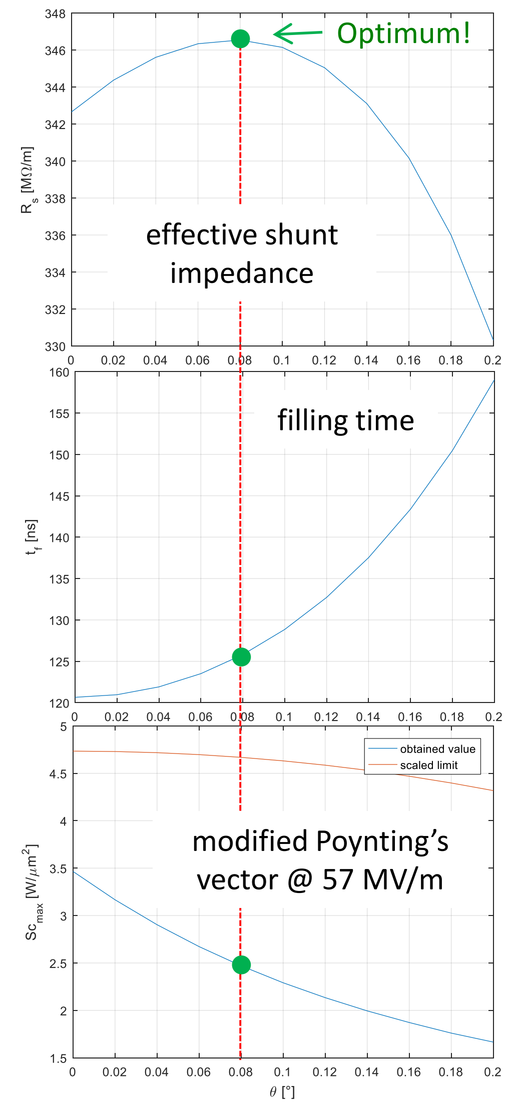
Various tapering slopes of the irises along the structure



EuSPARC RF STRUCTURE DESIGN: Numerical Optimization

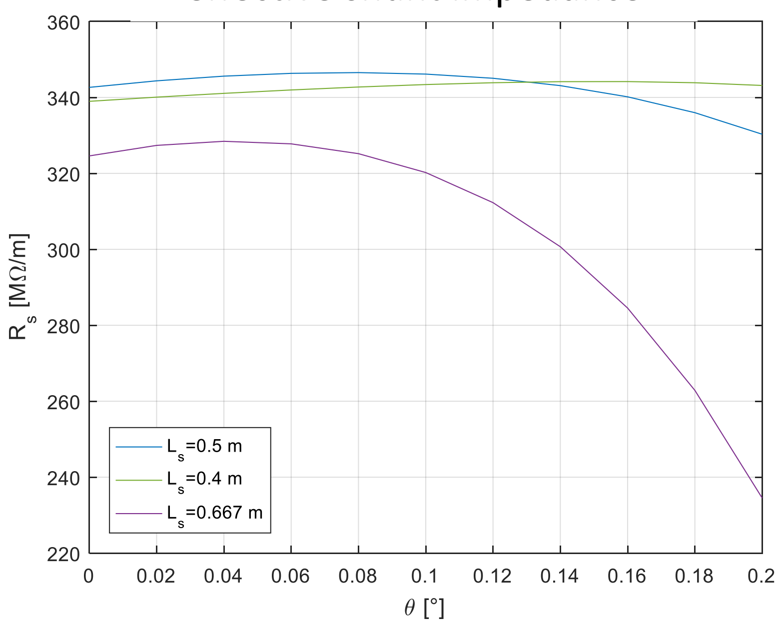


Accelerating field along the structure for various tapering slopes of the irises



EuSPARC RF STRUCTURE DESIGN: Numerical Optimization

effective shunt impedance

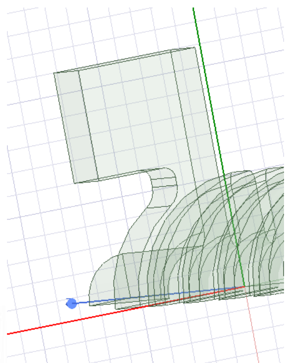


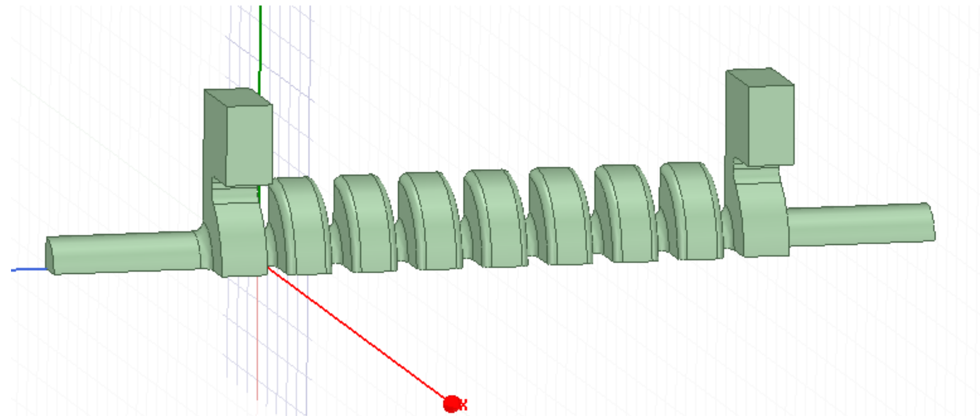
Same exercise for various structure lengths

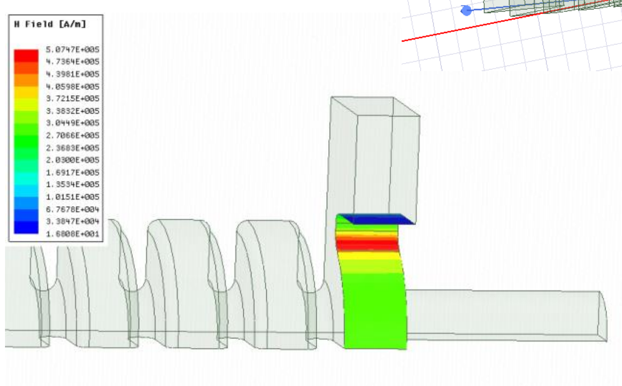
LINAC parameters		
<a> [mm]	3.2	
a first-last cell [mm]	3.636 – 2.764	
L_s [m] / N. of cells N_c	0.5 / 60	
L_t [m] / N. of structures N_s	16 / 32	
SLED Q_e	21800	
v_g/c [%]	2.2 – 0.78	
t_p [ns]	129	
R_S [MΩ/m]	346	
Available RF power / klystron	50 MW (@ klystron output) 40 MW (@ section input)	
	HG option	VHG option
<G> [MV/m]	57	80
W_{gain} [MeV]	912	1280
P_{RF} [MW]	150	296
No. of klystrons N_k	4	8

EuSPARC RF STRUCTURE DESIGN: Input coupler + 7 cells + output coupler

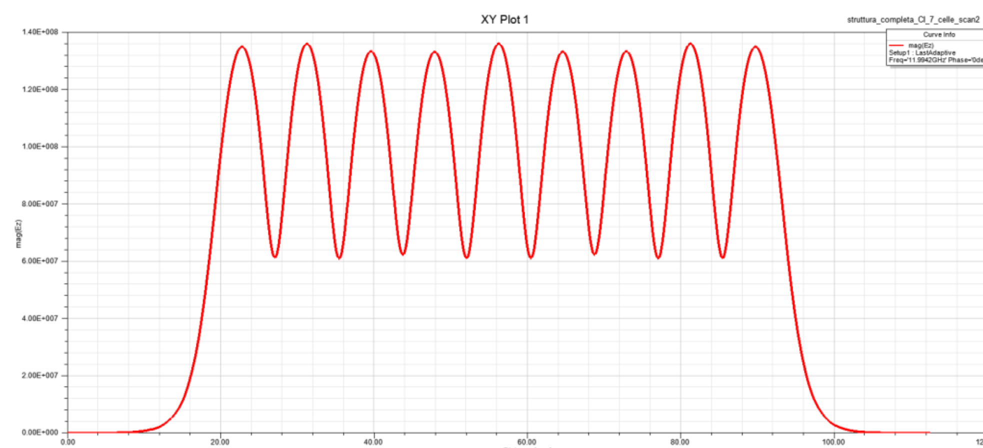
R_mc	9.73 mm
W_mc	8.224 mm
r1	1 mm
r2	2 mm







Input power (80 MV/m)	65.34/4 MW
H_surf_max	5.0747e5 A/m
deltaT	40.682°C



POSSIBLE WORPLAN FOR EuSPARC X-BAND LINAC DESIGN
(IN CLOSE COLLABORATION WITH CERN)

1) **Design of the X band structure and module** of acceleration for EuSPARC LINAC (under A. Grudiev supervision): cell type, iris aperture, thickness, couplers (J-type?, Integrated splitter?).
2) **Preliminary design/layout of the power distribution system**

Part of this work has been done already and will be included in the **EuSPARC CDR** in preparation

3) **Mechanical design of the cavity**. Different possibilities of realization can be explored (brazing w/o Tuning, PSI technique can be a good option).
4) **Design/layout of the power distribution system** (klystron + sled + waveguides, pumps, overmoded waveguides,…) according to the design of the **new building @LNF**.
5) **Design, realization and test at high gradient of prototypes** of structures (@LNF)
6) **Design, Realization and test of a full scale structure** to be tested at high power (@LNF)
7) **Realization of a complete module of acceleration** and possible test at high power (kly+sled+8 structures) (@LNF)

Implementation of an X-Box at LNF to test CLIC prototypes and EuSPARC cavities (MoU finalized)

The INFN Frascati X-box

X- band technology allows achieving **higher accelerating gradients** with respect to other industrially available technologies (L, S, C bands).

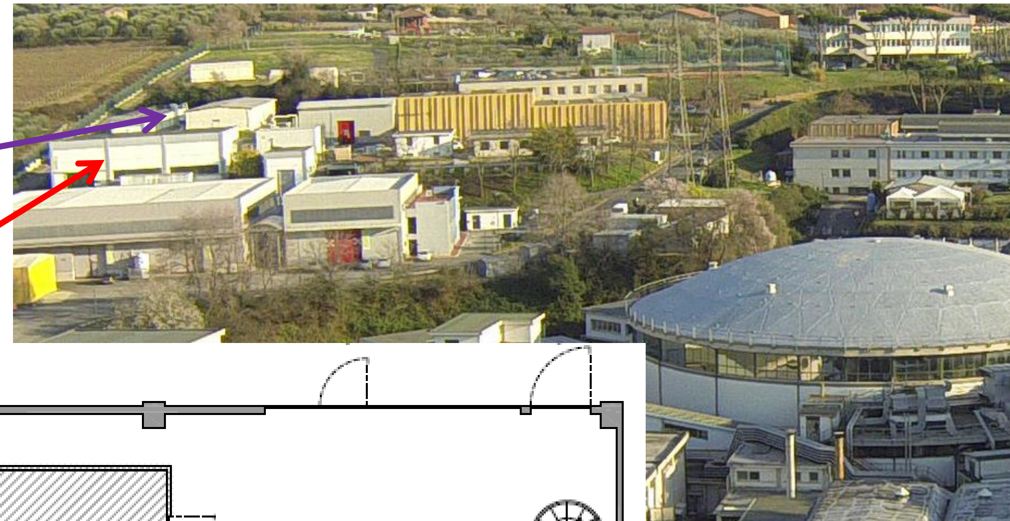
However, the maturation of the X-band as a reliable baseline for high gradient accelerators required a **huge technical effort** to establish the proper machining, cleaning and vacuum procedures, and to design and develop all the required RF components. It is in general **more critical** respect to the well established lower frequency bands.

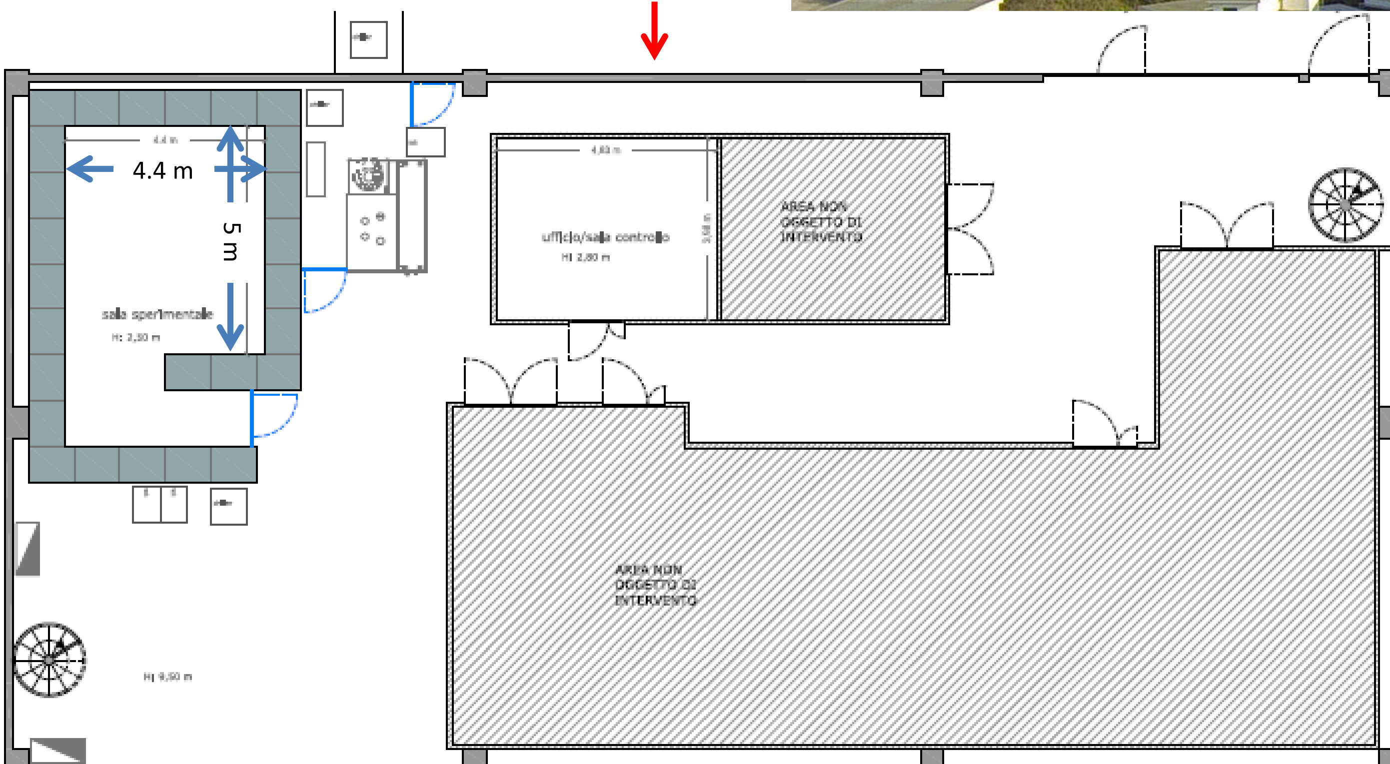
The INFN Frascati Labs have a long lasting experience on S-band acceleration, and a recent experience also on C-band (SPARC_LAB and ELI projects). Therefore in view of the EuSPARC project, the Frascati RF team need to **gain experience** and **expertise** in handling and operating X-band structures and power plants.

The **duplication of one of the CERN X-boxes** (X-box #2 is our reference) at the INFN Frascati Labs is a perfect opportunity to **establish and consolidate this kind of expertise**, and will provide a **strategic infrastructure** to the Labs for the development and optimization of the EuSPARC accelerating sections.

Finally, this activity allows activating a **strong synergy** and collaboration with the **CERN**.

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

LNF building #7: the old bunker

LNF building #7: inside view

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.

Workplan for the Frascati X-box realization

1)	**Choice of the area**	First clean-up, relocation of the stored material to recover the needed surface	**DONE**
2)	**MoU INFN-CERN**	Agreement to share material and expertise on injector design and X-band RF technology	**DONE**
3)	**Modulator procurement**	Acquisition from industry of a pulsed power supply to feed a 50 MW, 1.5 µs, 50 Hz X-band klystron	**Procedure ready to start, ≈ 15 months required**
4)	**Old bunker dismounting, new bunker design and construction**	Concrete blocks of the existing bunker can be reused together with new ones that need to be ordered, especially those needed for coverage	**Started ≈ 6 months required**
5)	**Services**	Electric and cooling services are already available in building #7. Distribution need to be adapted to the requirements of the new facility	**≈ 3 months required**
6)	**Waveguide network design and construction**	3D CAD model of the facility is needed to precisely define the waveguide path.	**CAD: 3 months required Fabrication: 6 months**
7)	**LLRF**	Hardware and software to precisely shape and control the RF drive signal for pulse compression, and to run the facility need to be acquired and installed	**15 months required**
…	**…**	…	…

CONCLUSIONS

- EuSPARC project will consolidate and expand the scientific program presently ongoing at SPARC_LAB, and will be one of the candidate to host the plasma acceleration based European infrastructure EUPRAXIA.
- To preserve the facility compactness, X-band RF technology has been chosen for the EuSPARC linac in view of the injection into the FEL undulators of a >1GeV beam accelerated only by RF.
- The X-band RF expertise of the CLIC RF team is a resource for the EuSPARC project. A collaboration agreement has been set for technical and scientific information exchange.
- The realization of a new test stand is one of the most relevant item of the agreement. The Frascati X-box construction has started, and will be completed in about 18 months.