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EuPRAXIA Preparatory Phase

Status of the EuPRAXIA@SPARC_LAB Technical Design Report-Part 1

C. Vaccarezza INFN-LNF

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

Outline

- WP15:
  - D15.2 Mid-term report on TDR status for EuPRAXIA@SPARC_LAB
  - M15.2 Workshop on “EuPRAXIA@SPARC_LAB machine upgrade and additional beam lines“ (moved from M20, June 2024)
- Technical Design Report General Overview & Contents
- Timeline update
- Some Chapters details:
  - Civil Infrastructures
  - Machine Layout
  - Beam Physics
  - RF X-band Linac
  - Plasma Module
  - FEL & Undulator
- Conclusions

TDR General Overview

Since February 2021 the preparation of the EuPRAXIA@SPARC_LAB Technical Design Report has been submitted to the Review Committee evaluation. The RC meets twice a year (May-Jun/Dec-Nov) till completion of the TDR document.

Current Review Committee Members:

- Deepa Angal-Kalinin (UKRI STFC, UK)
- Majed Chergui (EPFL, Switzerland)
- Patric Muggli (MPP, Germany, chair)
- Marco Pedrozzi (PSI, Switzerland)
- Luigi Scibile (CERN, Switzerland)

Editorial Board (July 2024) Members

- Massimo Ferrario
- Alessandro Gallo
- Anna Giribono
- Riccardo Pompili
- Fabio Villa

TDR Contents

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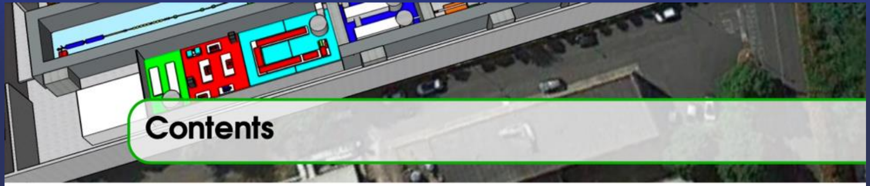
INFN

Istituto Nazionale di Fisica Nucleare

LNF – xx/xx
Jun 16th, 2024

EuPRAXIA@SPARC_LAB

Technical Design Report

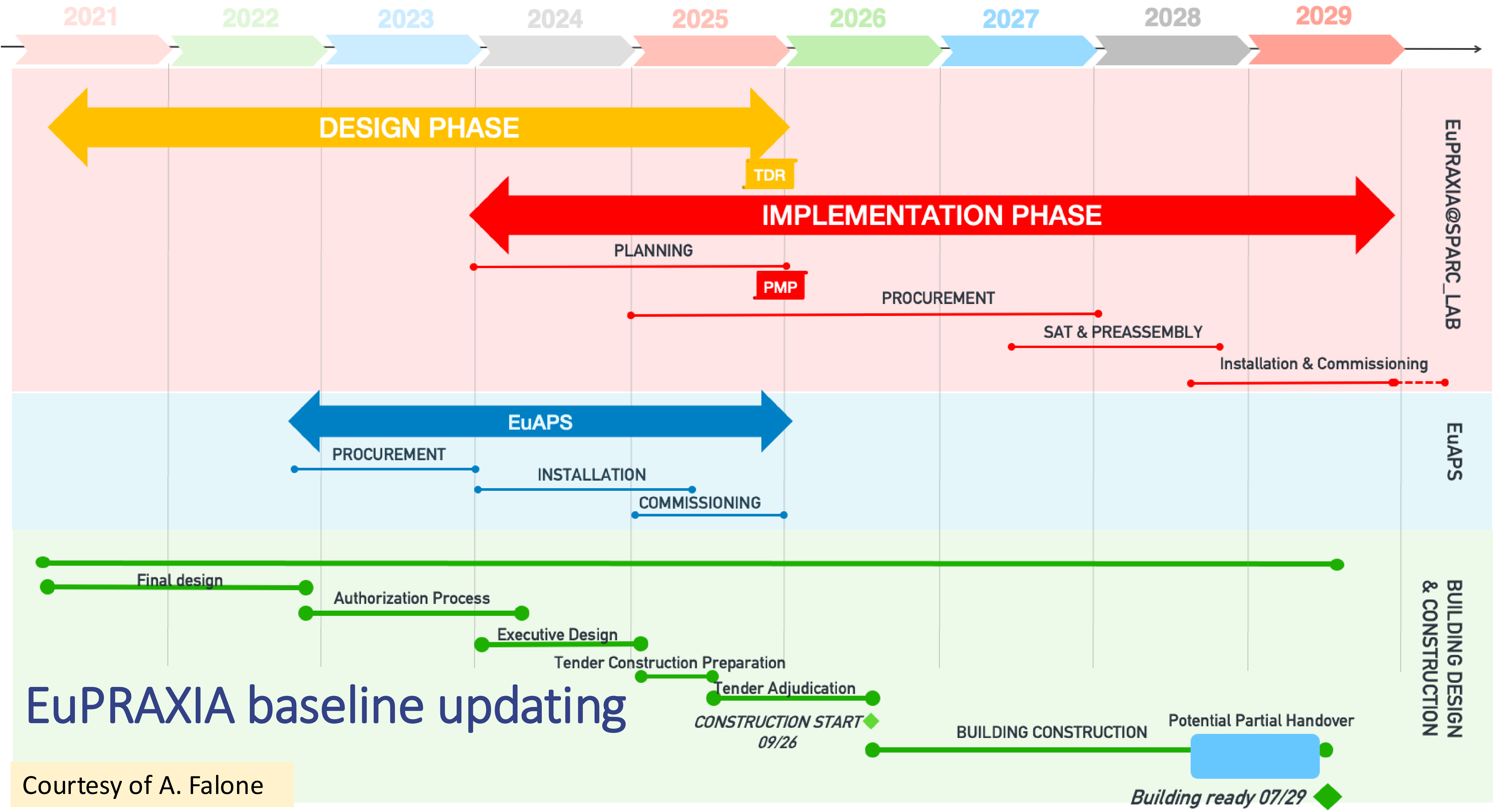


Contents

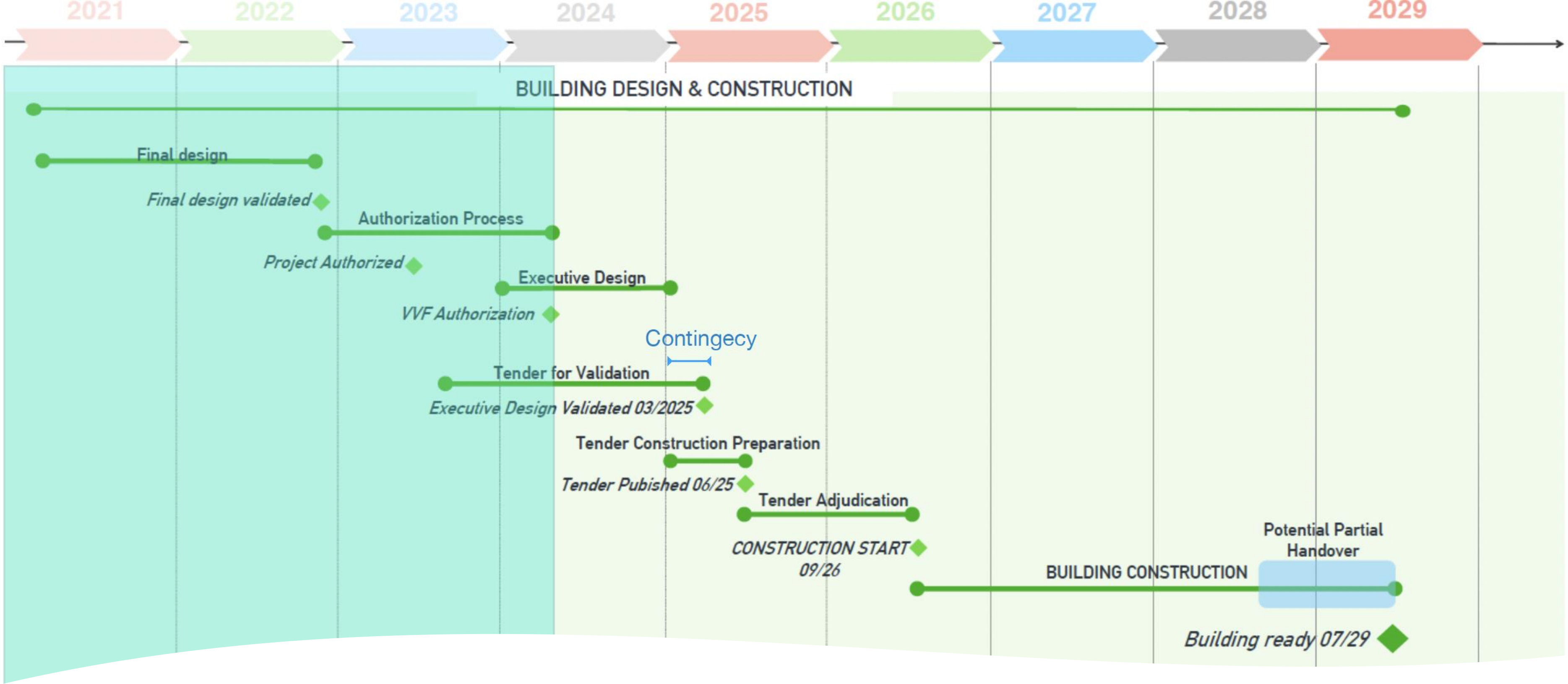
27 Chapters now under redaction (around 30% ready).

To be finalized by first half 2025.

EuPRAXIA baseline updating



Courtesy of A. Falone



Facility building timeline details

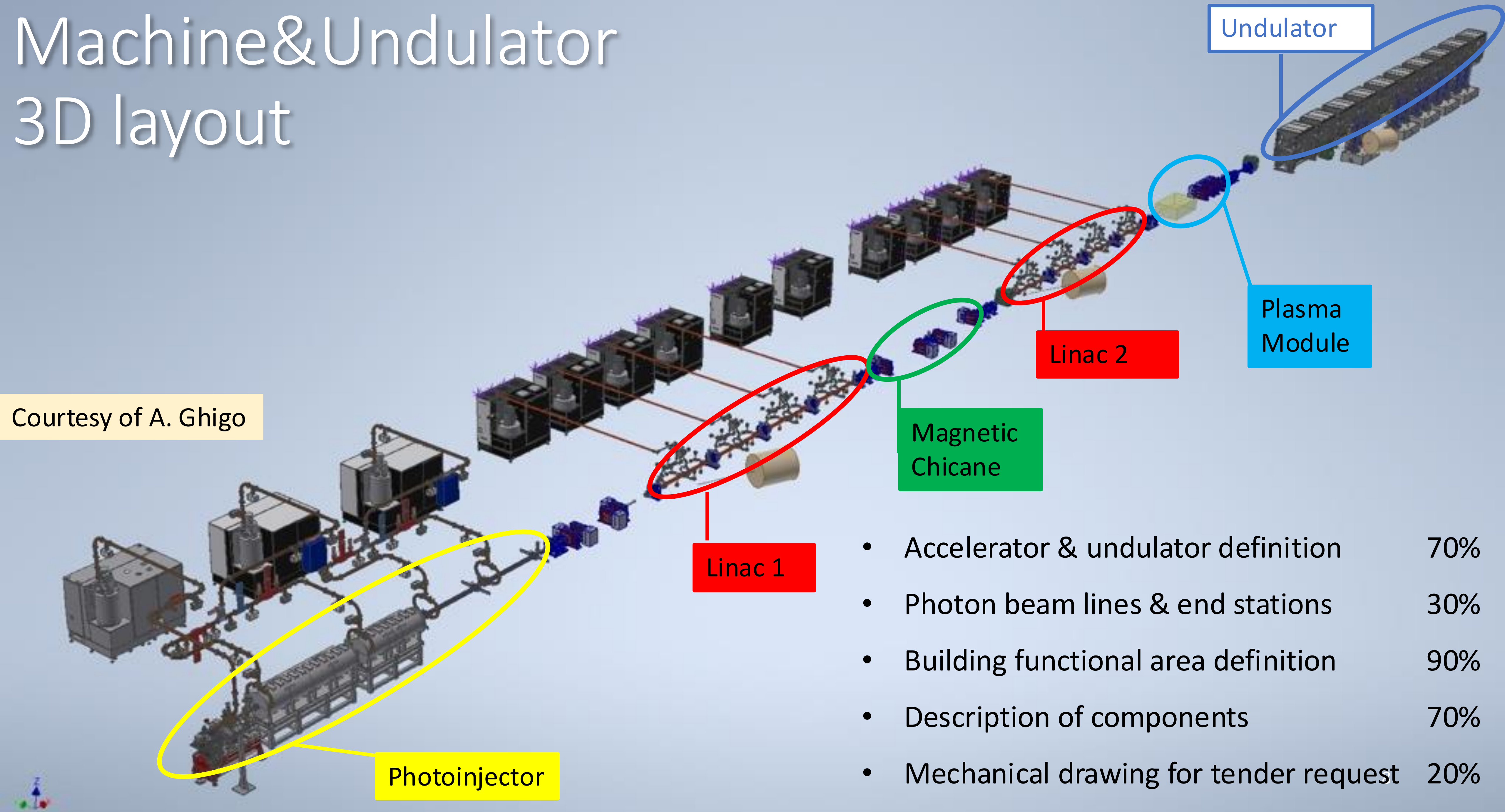
- Executive Design almost completed
- Draft delivered in June 2024
- Authorization from Fire Brigade - approved.
- Tender for the verification on going to be awarded in September (3months for the execution of the verification according to the contract).
- Tender for construction to be prepared starting from the end of the year.

Courtesy of A. Falone

Final Design

Courtesy of S. Incremona

Machine&Undulator 3D layout



- Accelerator & undulator definition 70%
- Photon beam lines & end stations 30%
- Building functional area definition 90%
- Description of components 70%
- Mechanical drawing for tender request 20%

- Reference Plasma Working point:
  - $E = 1\ GeV, \lambda_r = 4nm, Q = 30 - 50\ pC,$ Comb scheme w plasma module
- X-band Linac Working point
  - $E = 1\ GeV, \lambda_r = 4nm, Q = 250\ pC,$ Single bunch

The Basic Layout

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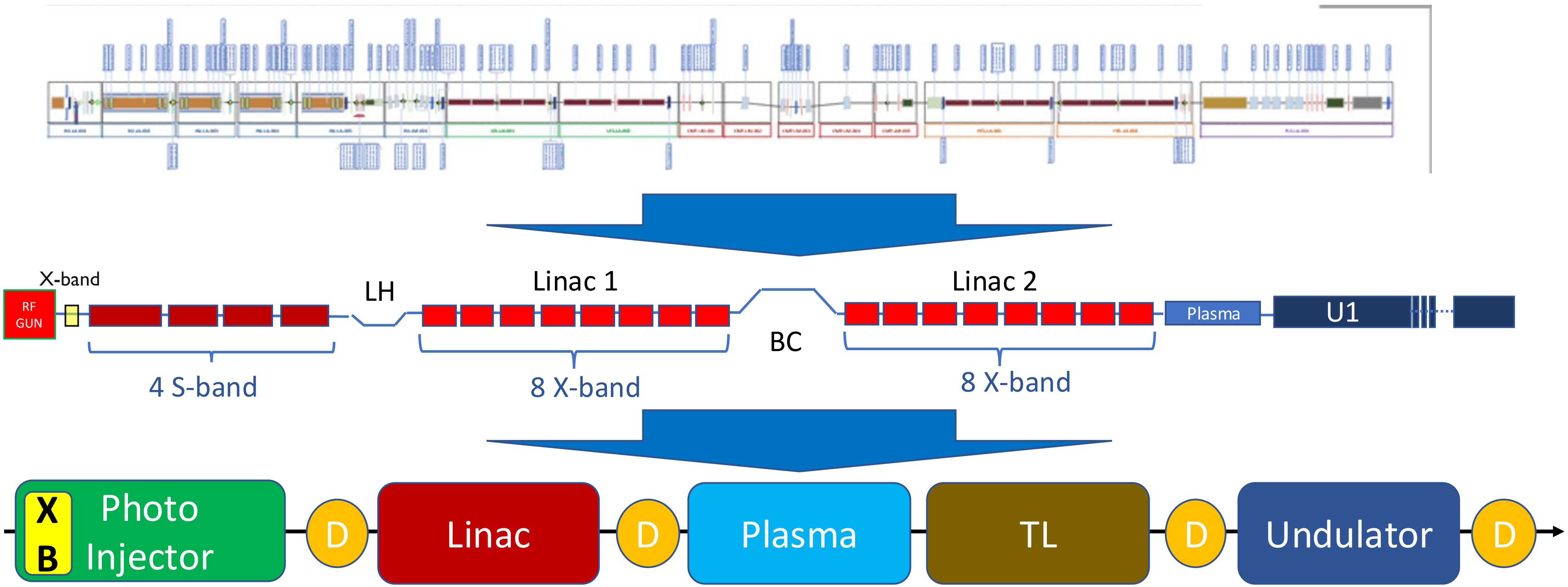
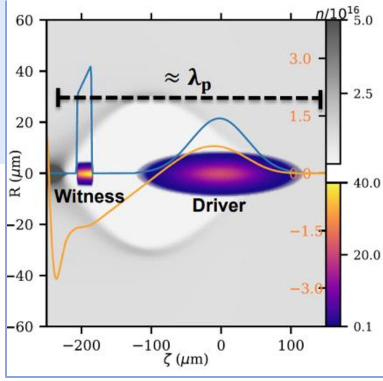


- **Baseline : Plasma acceleration operation scheme = WoP1**
- **Suitable for the High Charge Single Bunch operation boosted by an All-RF Linac up to 1 GeV = WoP2**

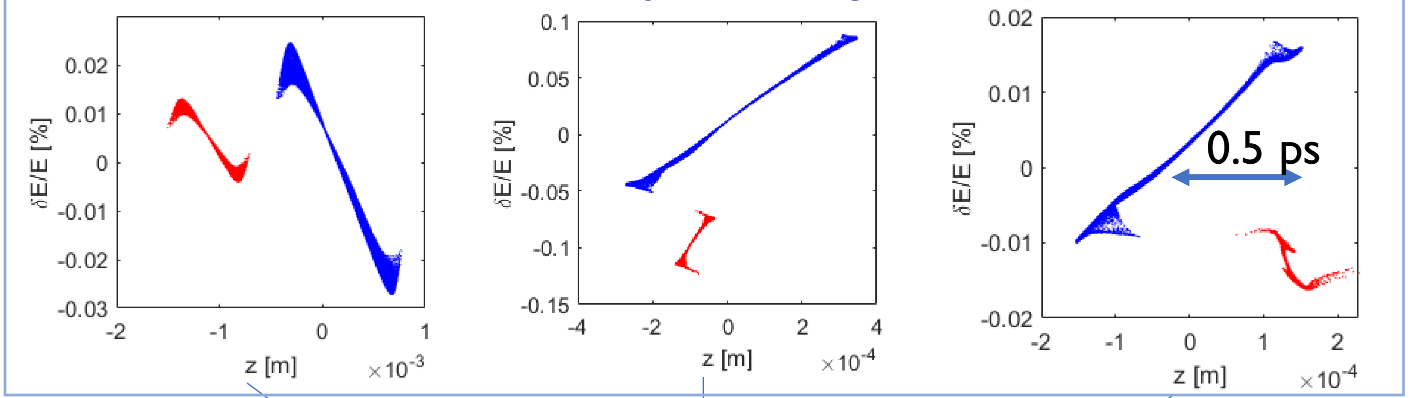
Reference Working point Beam Dynamics



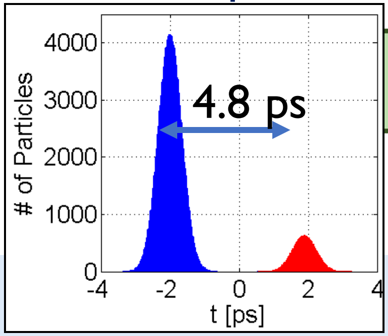
- Based on the FEL specifications, the <u>reference working point</u> has been determined by the plasma module
  - At least 500 MeV energy gain (in less than 1 m)
  - Weakly non-linear regime (bubble with resonant behaviour)

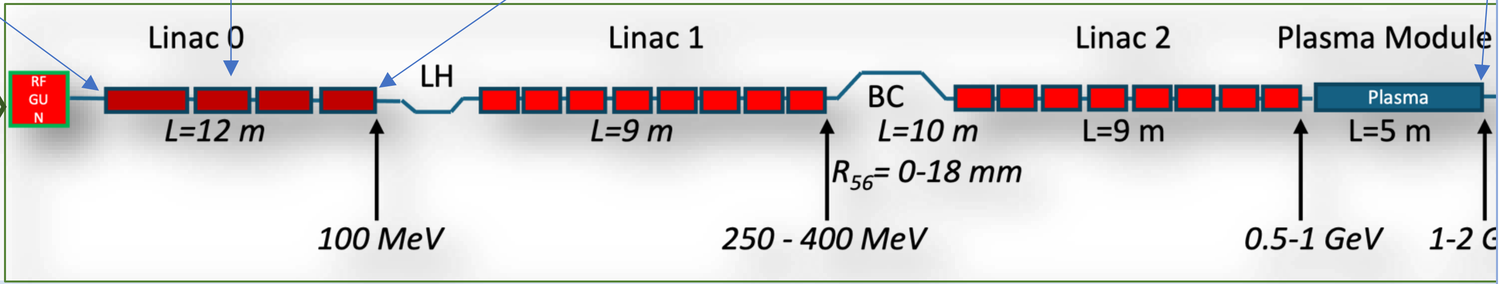
1. 200 pC driver + 30 pC witness
2. plasma density of the order of $10^{16} cm^{-3}$ (λ_p = 334 μm)
3. Driver-witness separation of around 0.5 ps (i.e. λ_p /2)
4. Driver and witness bunches of 200 fs and 10 fs rms
5. Driver and witness spot size of 4 and 1 μm with α=1

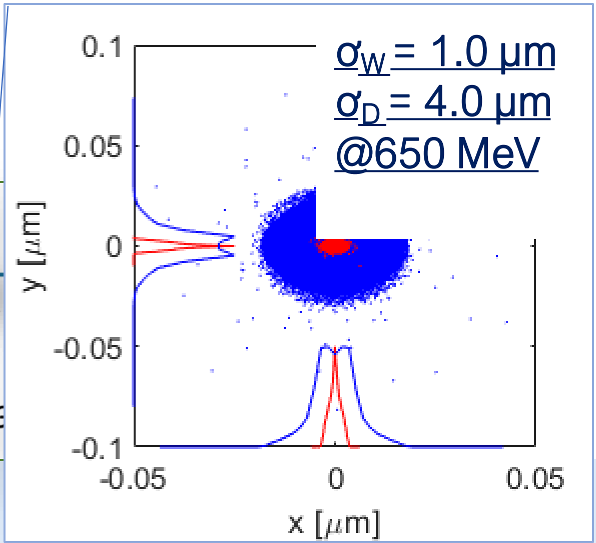
<u>Velocity bunching technique</u>



<u>Laser comb technique</u>







Nominal Working Point parameter list

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- Driver and Witness beam are separated in a magnetic chicane downstream the plasma module.
- A short matching transfer line follows to inject the beam in the undulator

parameter	Units	
Charge before cut	pC	28.3
Charge after cut (a.c.)	pC	26.5
Peak current (a.c.)	kA	3
Emittance projected a.c. (x,y)	mm mrad	0.7
Emittance slice a.c. (x,y)	mm mrad	0.7
Energy spread a.c (relative)		$1.7x10^{-3}$
Energy spread slice a.c.		$3x10^{-4}$
Rho	X10^-3	1.6
Rho_3d	X 10^-3	1.5
Energy emitted (25 m)	microJ	13.2
Photon emitted (25 m)	X 10^11	2.5
Saturation length	m	20
Wavelength	nm	4
Bandwidth (25 m)	%	0.2
Size	micron	120
Divergence	microrad	19

A. Del Dotto, A. Giribono, M. Opromolla, V. Petrillo, S. Romeo, A.R. Rossi

Current Activity: Jitter contribution studies

RF Gun (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
S-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
X-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.10	*deg*
Cathode Laser System (max)		
Charge [ΔQ]	± 1	%
Laser time of arrival [Δ*t*]	± 0.02	fs
Laser Spot size [Δσ]	± 1	%

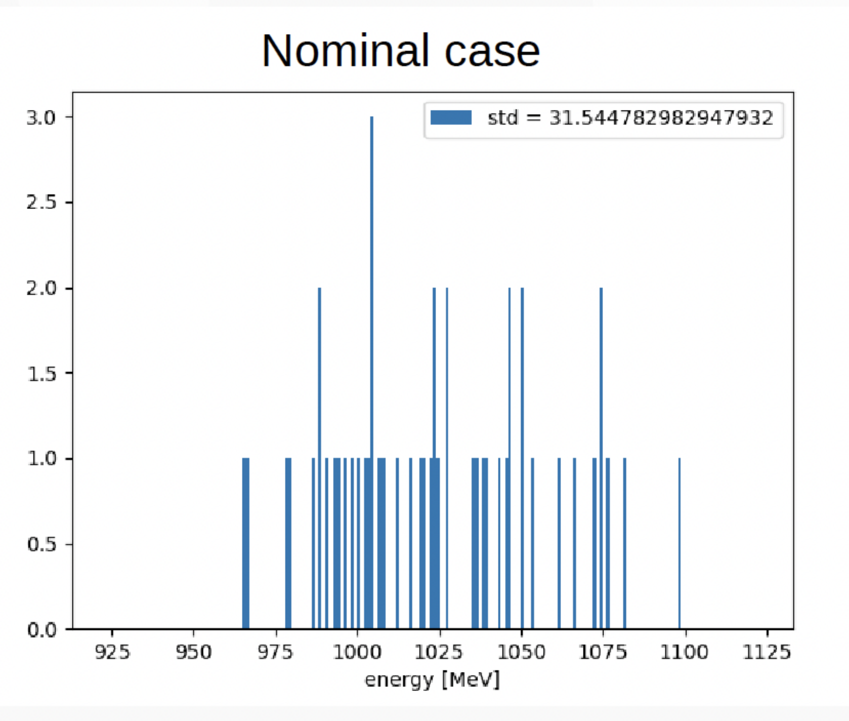
end of 2023 data

	Witness		Driver		
	Without errors	With errors	Without errors	With errors	
Charge	30.00	30.00 ± 0.33	200.00	200.00 ± 2.00	pC
Energy	537.18	537.19 ± 0.31	539.29	539.29 ± 0.30	MeV
Energy spread	0.712	0.711 ± 0.003	0.92	0.92 ± 0.001	‰
Bunch length	19.88	19.97 ± 0.32	205.87	205.55 ± 0.87	fs
I_{peak}	1873	1643 ± 99	-	-	kA
Δt	0.494	0.494 ± 0.044	-	-	fs
$\varepsilon_{n x,y}$	0.562	0.562 ± 0.007	4.18	4.22 ± 0.15	mm mrad
$\sigma_{x,y}$	1.5	1.52 ± 0.18	5.85	5.89 ± 1.07	μm
$\beta_{x,y}$	4.3	4.5 ± 1.1	8.8	9.1 ± 3.3	mm
$\alpha_{x,y}$	1.2	1.2 ± 0.25	1.65	1.65 ± 0.30	

- Errors are intended as rms quantities
- Driver & Witness numerically separated on the longitudinal axes

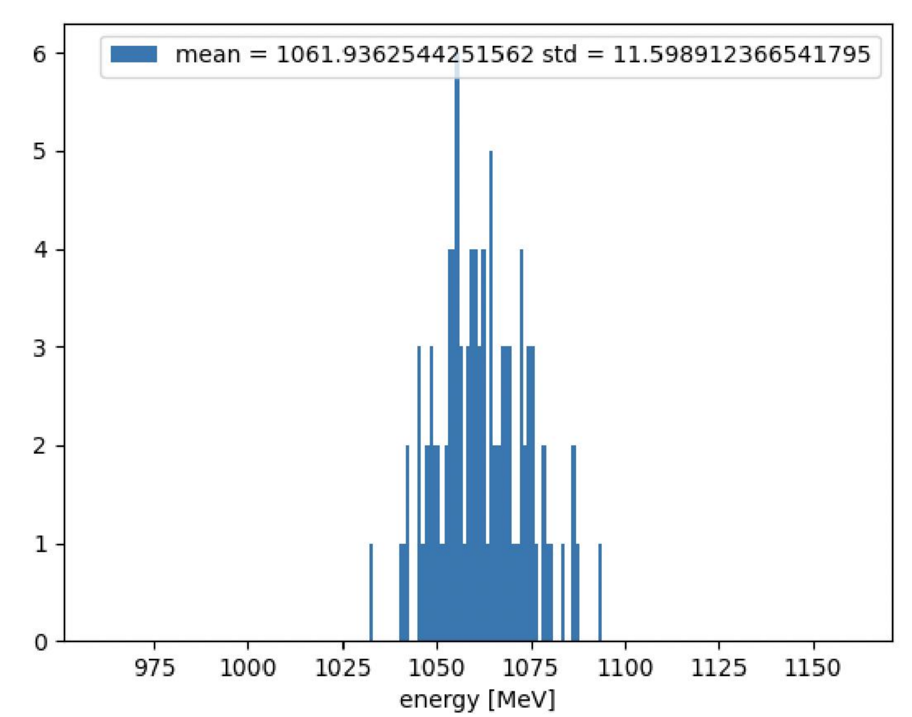
Example: energy stability shot to shot at the plasma exit

End of 2023 results: ~ 3%



- through continuous work to optimize the working point for Linac and plasma module
- to be finalized in the next 1-2 months to be compliant with the TDR delivery schedule

Sep 2024 results: ~ 1%



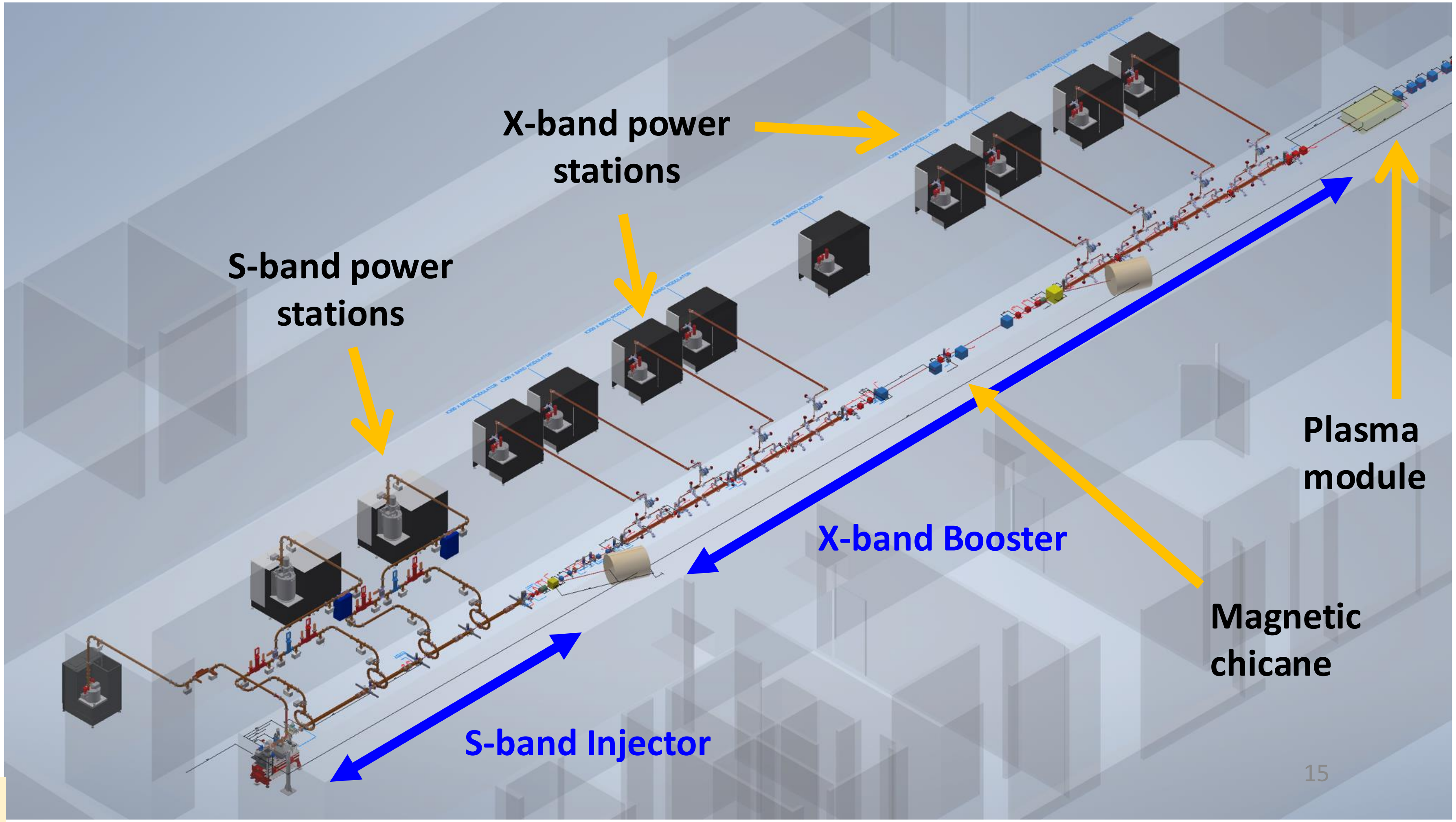
RF X-BAND LINAC

⇒ High brightness electron beam up to **1 GeV**, at **100 Hz** repetition rate (baseline) with a possible future upgrade at 400 Hz, single bunch;

⇒ **S-band (2.856 GHz) injector** composed by a photocathode 1.6 cells SW RF Gun and 1x 3m TW S-band structure and 3x 2m TW S-band structures;

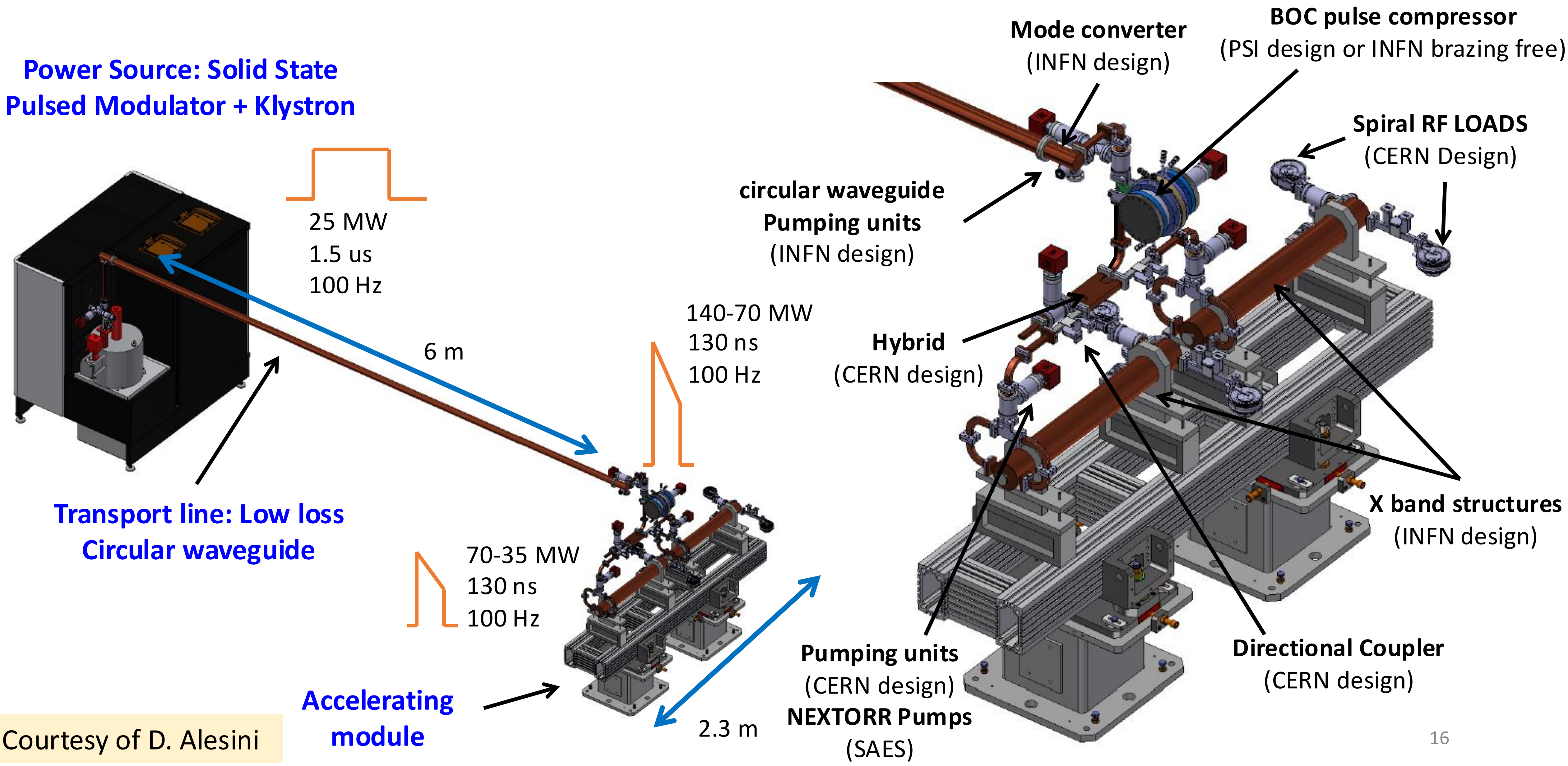
⇒ **X-band (11.994 GHz) booster** composed by **16xTW, 0.9 m accelerating structures** with a nominal gradient of **60 MV/m, 8 X band power station (25 MW, 1.5us, up to 400 Hz)**

⇒ **Magnetic chicane**



Courtesy of D. Alesini- E. Di Pasquale

X-BAND RF MODULE



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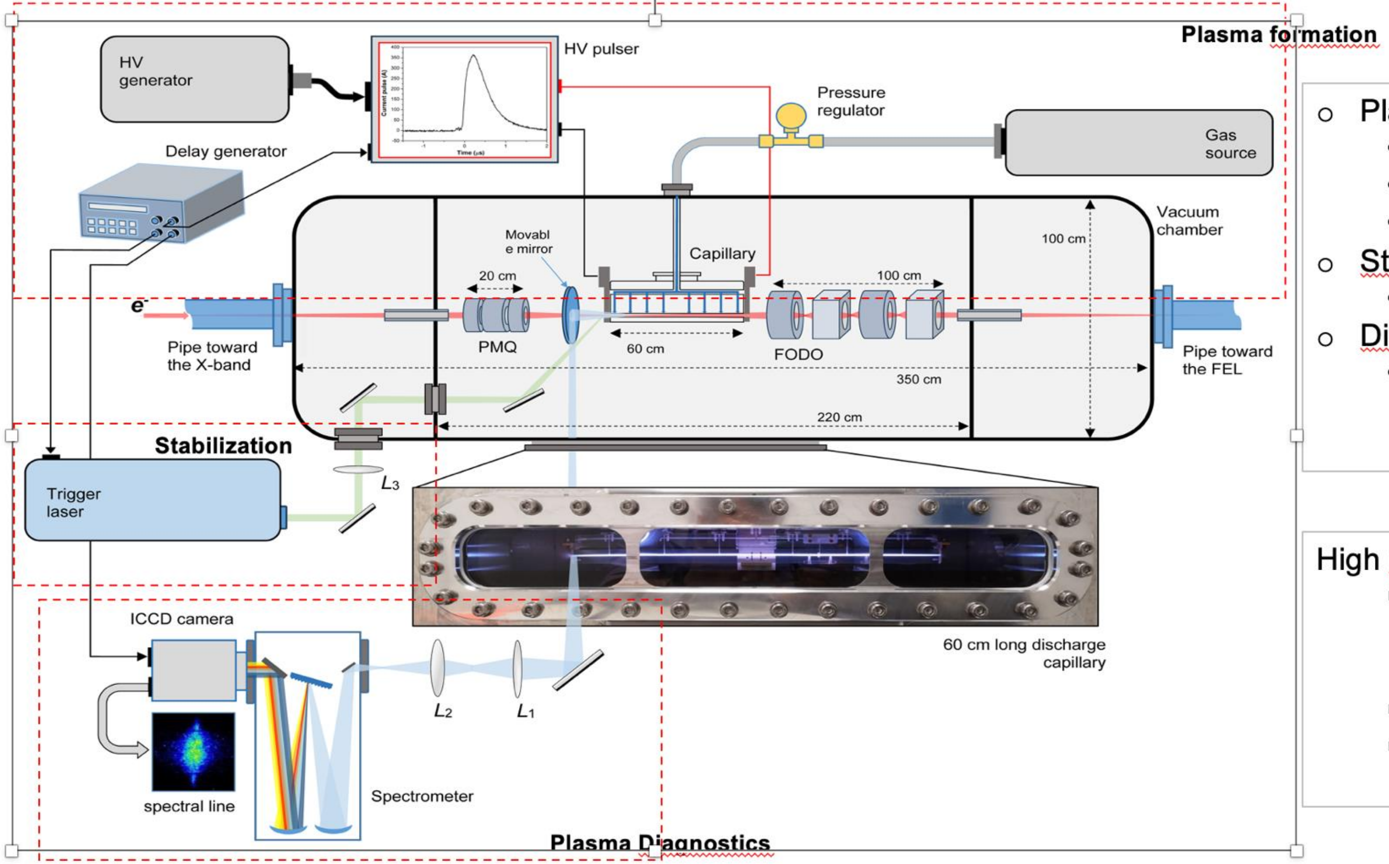
Plasma Source

Plasma accelerating module	Technical design (83%)
10.1 Introduction	100%
10.2 Plasma module design	
10.2.1 Plasma sources	70%
10.2.2 HV-sources for plasma creation	100%
10.2.3 Plasma discharge stabilizaiton	100%
10.3 Plasma chamber design	20%
10.3.1 Focusing and extraction systems	**Beam physics**
10.3.2 Capillary supports and handling	70%
10.4 Vacuum pumping system	60%
10.5 Diagnostics	
10.5.1 Plasma diagnostics	100%
10.5.1.1 Stark broadening technique	100%
10.5.1.2 Interferometric techniques	100%
10.5.2 Beam diagnostics	**Beam diagnostics**
10.6 High repetition rate plasma sources	80%
10.7 Future developments	
10.7.1 Segmented capillary	100%
10.7.2 All-in-one capillary	100%
10.7.3 APL collimator system	70%
10.8 Plasma module safety system	80%

Courtesy of A. Biagioni

Plasma Accelerating Module



- Plasma formation:
  - Gas-filled discharge capilary
  - HV sources
  - Gas source/Vacuum system
- Stabilization:
  - Laser trigger
- Diagnostics:
  - Stark broadening (ICCD/Spectrometer/Optics)

High repetition rate operations

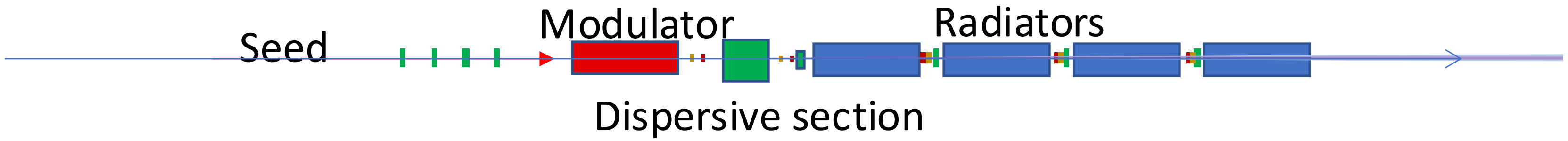
- Plasma source design
  - Walls material
  - 60 cm long
- HV source
- Vacuum system/Gas source

Courtesy of A. Biagioni

EUPRAXIA FELs

- **ARIA**

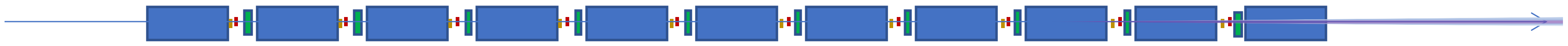
VUV seeded HGHG FEL



Focus on the AQUA line

- **AQUA**

Soft-X ray SASE FEL – optimized for 4 nm

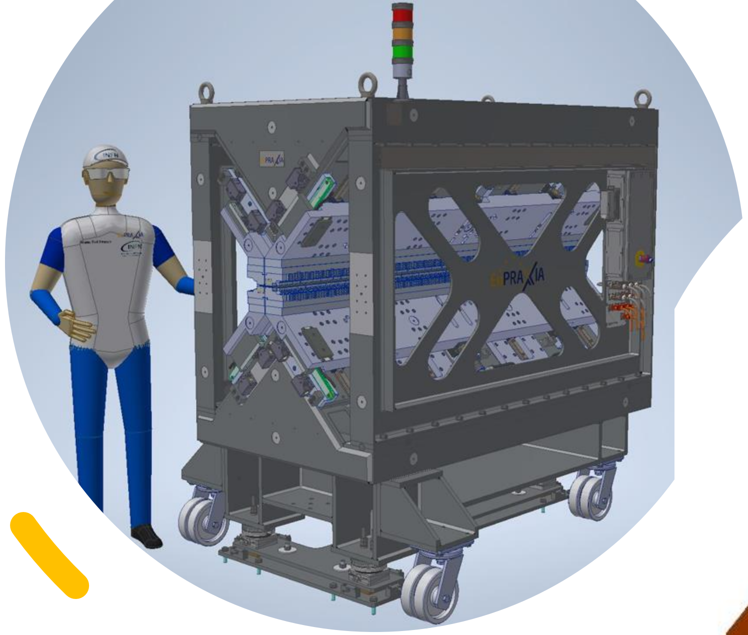


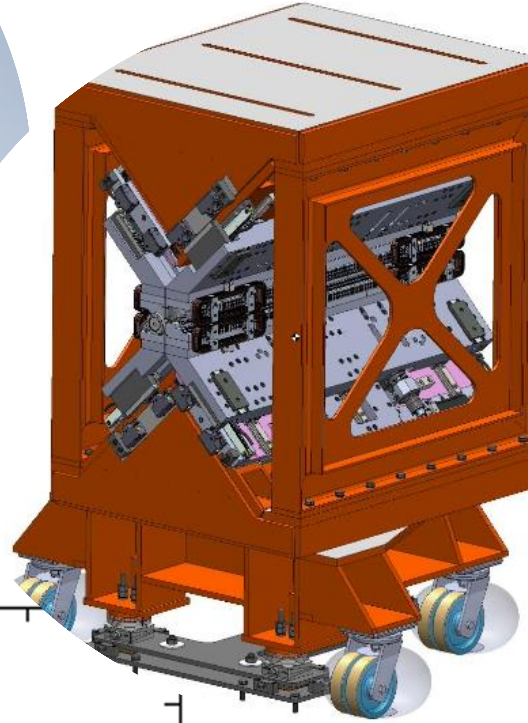
Courtesy of L. Giannessi

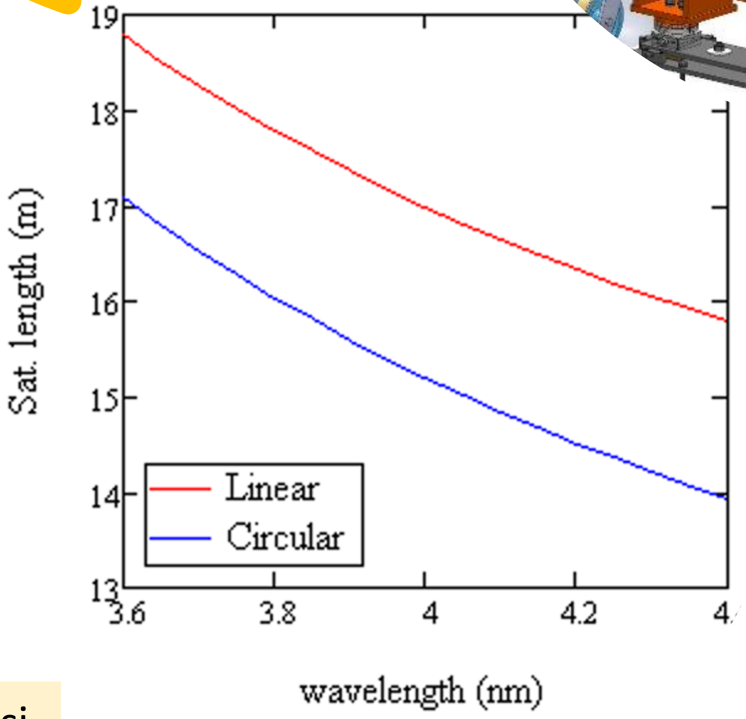
EUPRAXIA AQUA Undulator Model (derived from SABINA)

- The total undulator magnetic length considered is 20 m, i.e. 10 modules 2 m each.
- **Period length:** provide sufficient tuning range at fixed energy which allows the FEL to reach carbon and eventually nitrogen K-edge (at higher peak current/beam energy) is 18 mm.
- **Polarization:** variable polarization is an asset as it fits with the requests from the scientific case. Circular polarization ensures higher gain (about 2 m = 1 module)
- **Apple X type:** Substantially higher field at comparable undulator aperture = extended tuning range. Tuning range independent of polarization.
- Experience from the SABINA Undulator at LNF (KYMA).
- The target photon energy range is extended toward lower photon energies by
    - Small gap aperture (thin UV chamber walls – Apple X design)
    - High undulator remanent field (high remanent field magnets are assumed – Br=1.35 T)
    - Tuning the electron beam energy

Fully symmetric (K_{max} independent of polarization)







Courtesy of L. Giannessi

Conclusions

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- The updated timeline for the EuPRAXIA@SPARC_LAB Technical Design Report foresees its delivery by the end of 2025 that means the complete version ready for revision by June 2025.
- Since 2021 the activity has been followed by the Review Committee and more recently the Editorial Board has been charged with coordinating and harmonising the TDR document
- The readiness of the technical content is around 70-80%
- The activity is now deeply focused on the drafting of the chapters of the document