Preparatory phase for X-band linac

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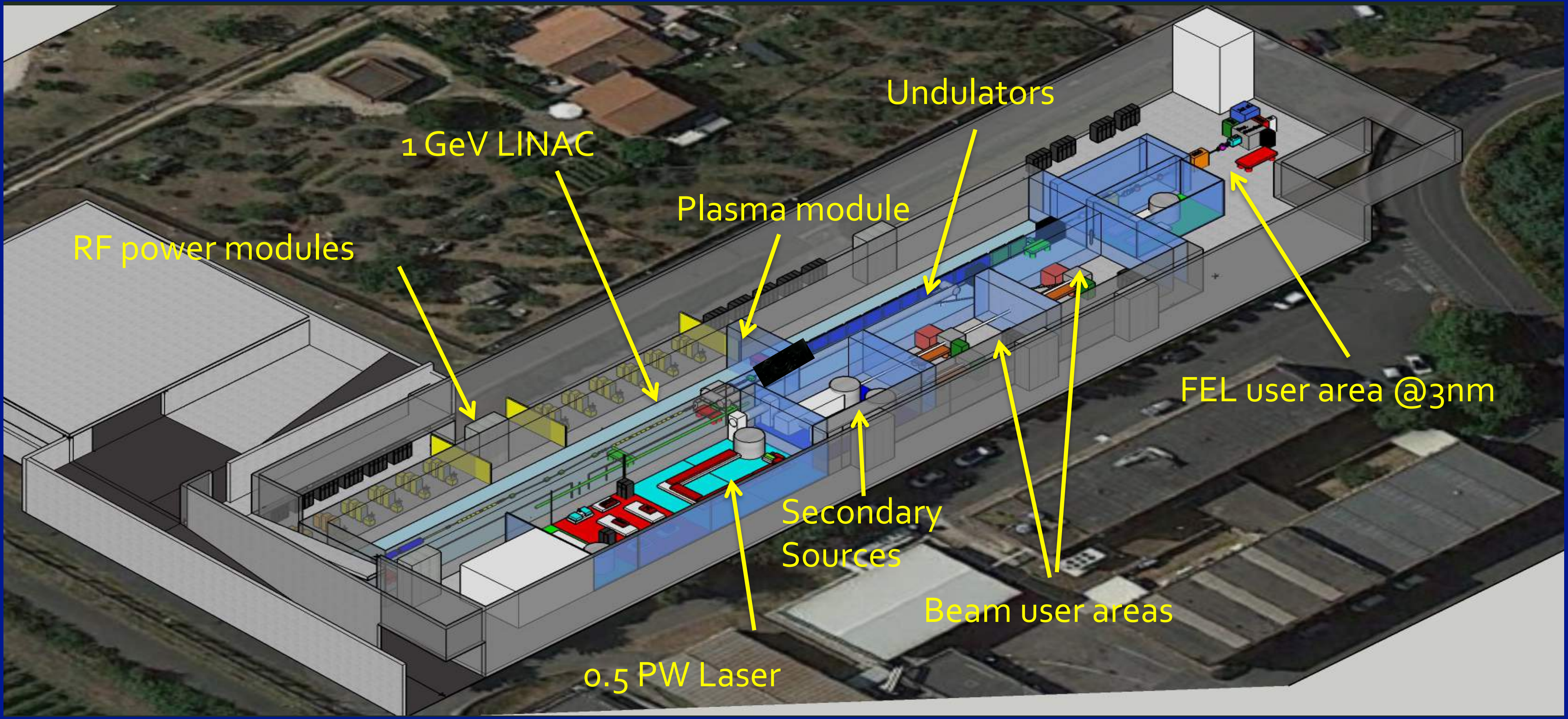
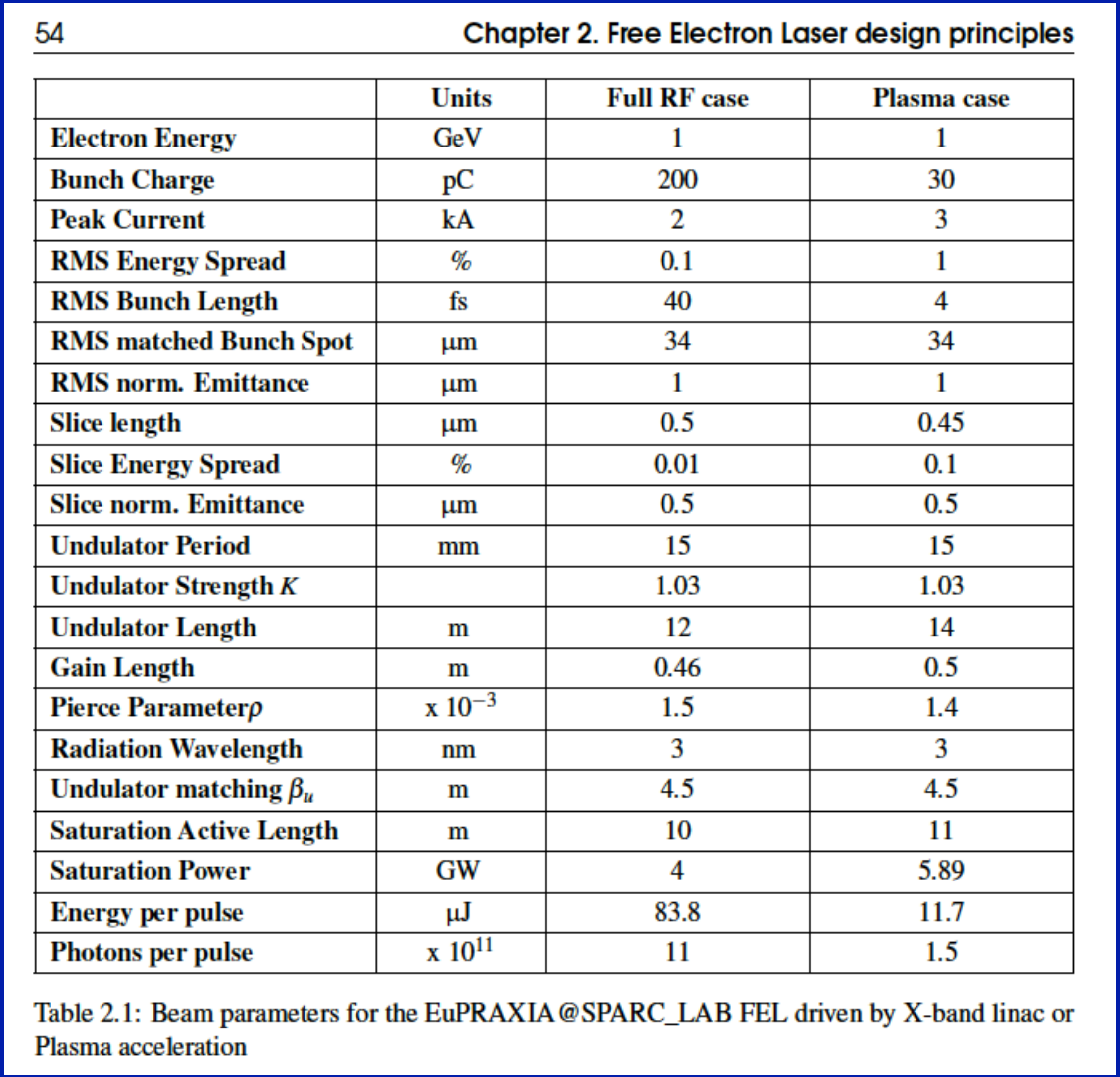
On behalf of the EuPRAXIA@SPARC_LAB team



CERN LNF bilateral meeting – November 26, 2020

Compact & User Facility



54 Chapter 2. Free Electron Laser design principles

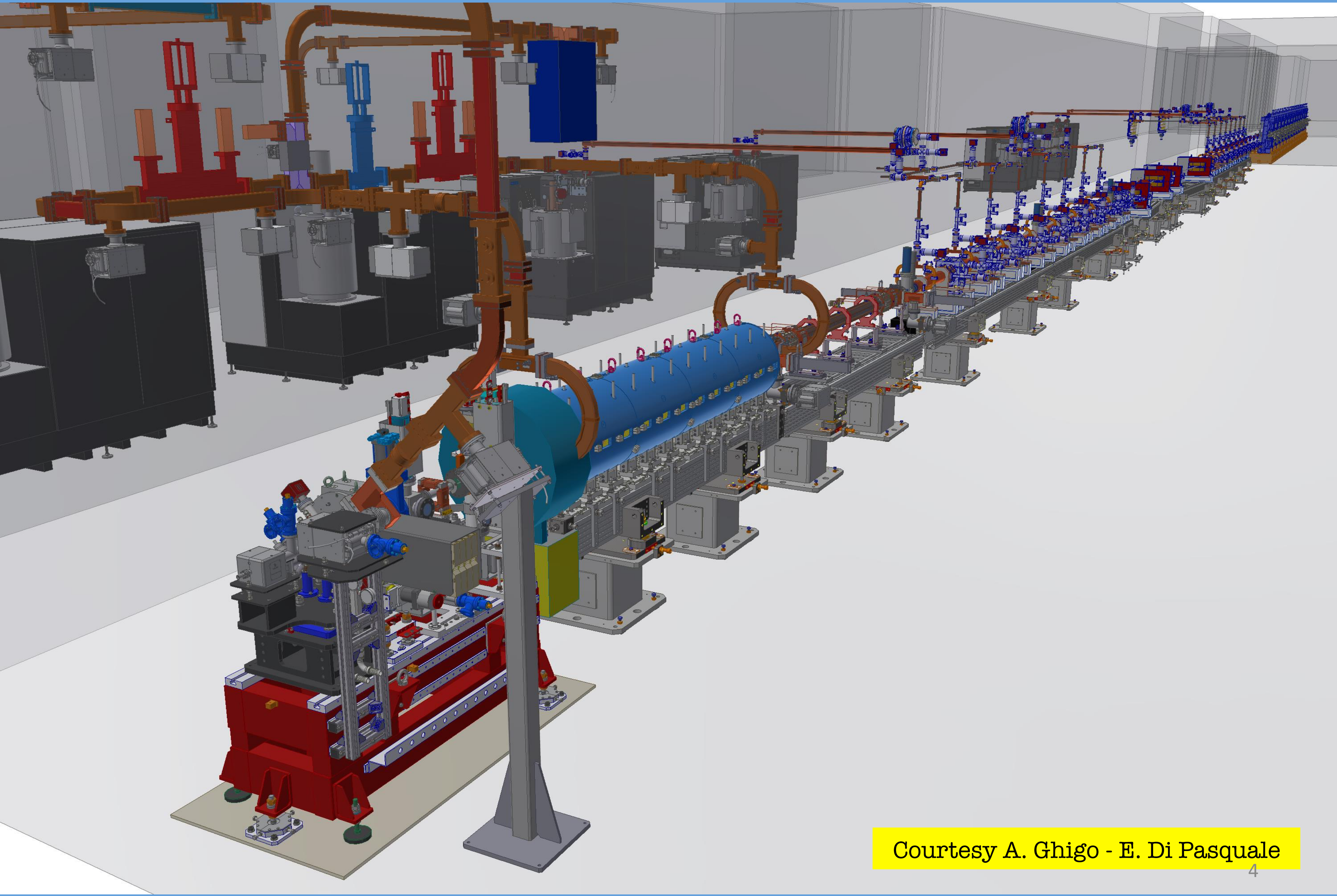
	Units	Full RF case	Plasma case
Electron Energy	GeV	1	1
Bunch Charge	pC	200	30
Peak Current	kA	2	3
RMS Energy Spread	%	0.1	1
RMS Bunch Length	fs	40	4
RMS matched Bunch Spot	µm	34	34
RMS norm. Emittance	µm	1	1
Slice length	µm	0.5	0.45
Slice Energy Spread	%	0.01	0.1
Slice norm. Emittance	µm	0.5	0.5
Undulator 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

$$\frac{\Delta\lambda}{\lambda}=\frac{1}{2}\frac{\Delta E}{E}\propto\rho\approx10^{-3}$$

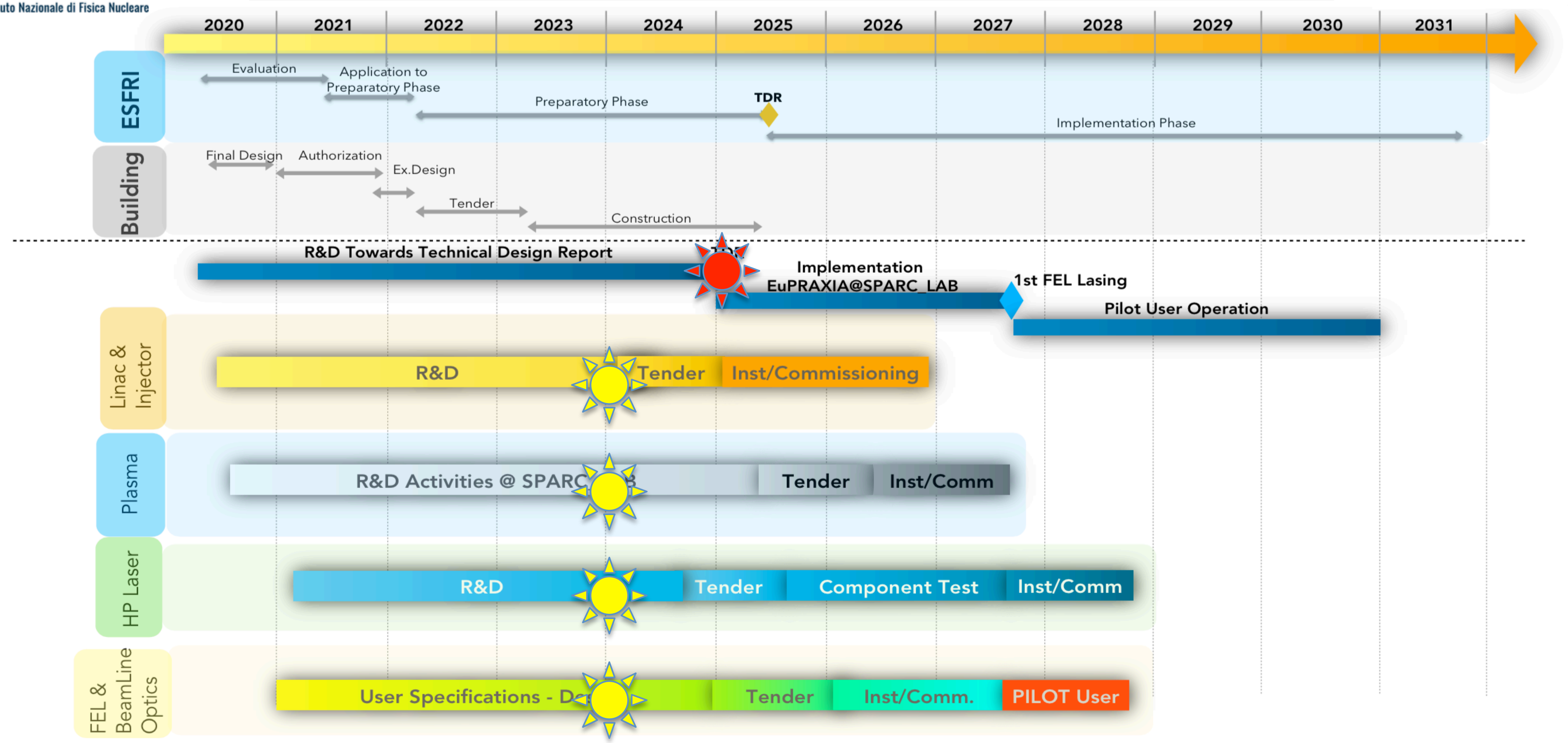
EuPRAXIA@SPARC_LAB building _ render

Courtesy S. Incremona – U. Rotundo



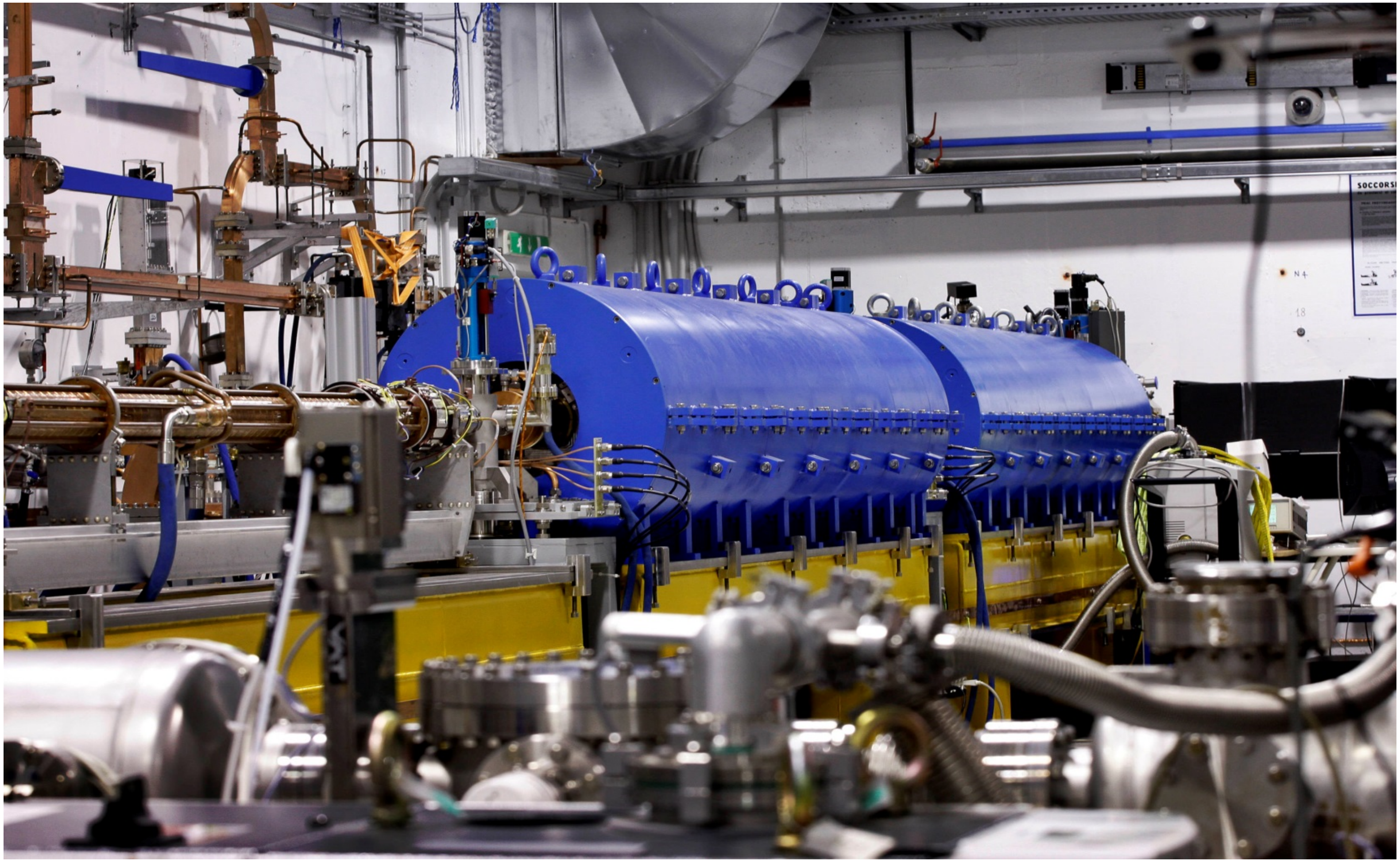
Courtesy A. Ghigo - E. Di Pasquale

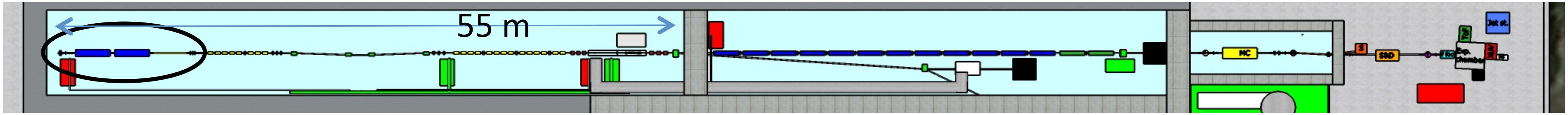
EuPRAXIA @ SPARC_LAB Master Schedule



Courtesy A. Falone

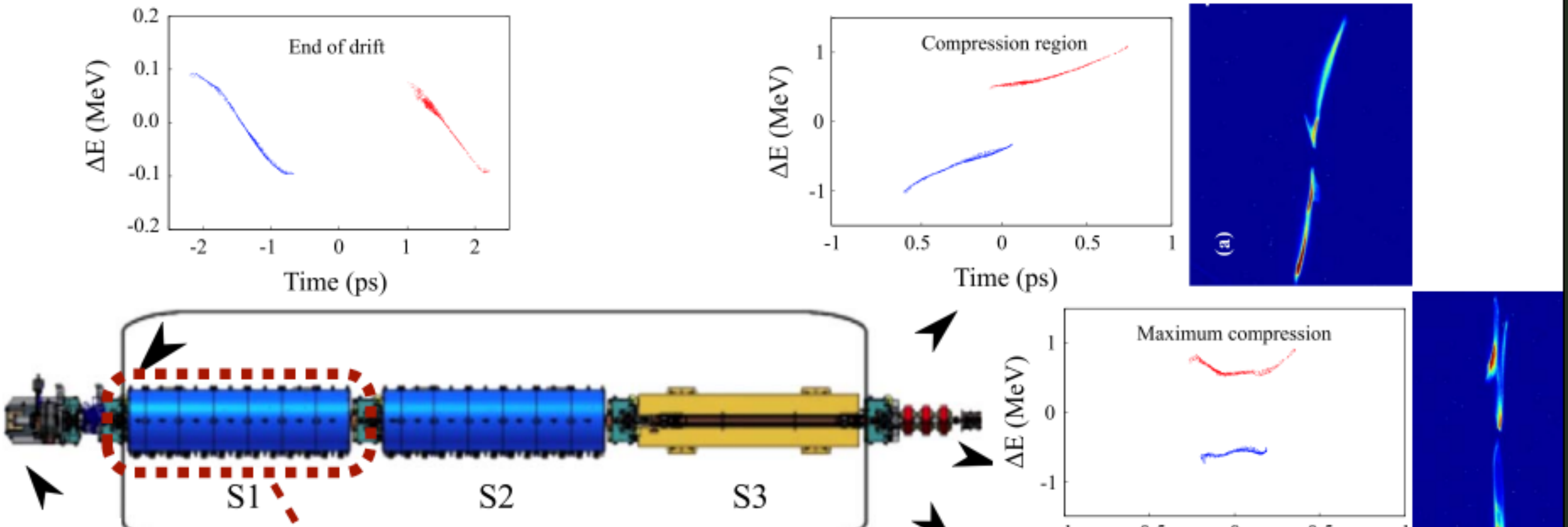
SPARC_LAB HB photo- injector

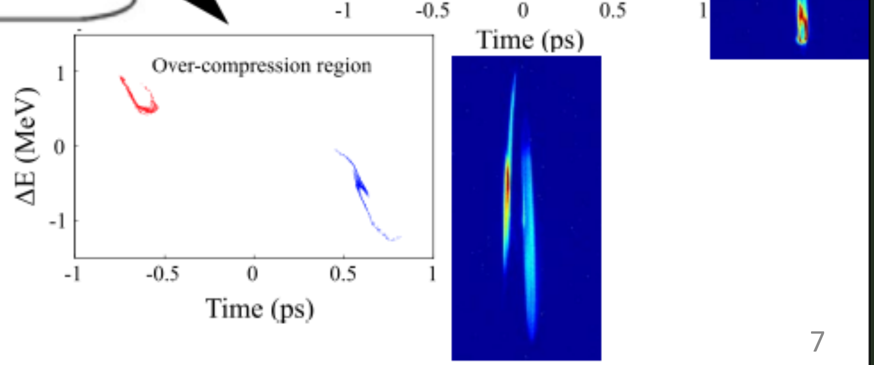




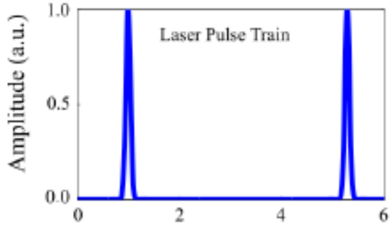
Generation of multi-bunch trains

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.



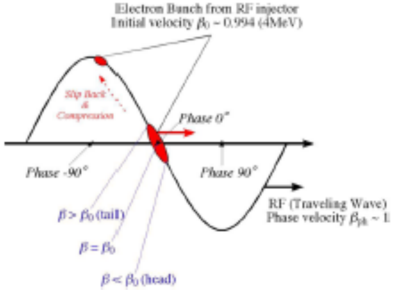


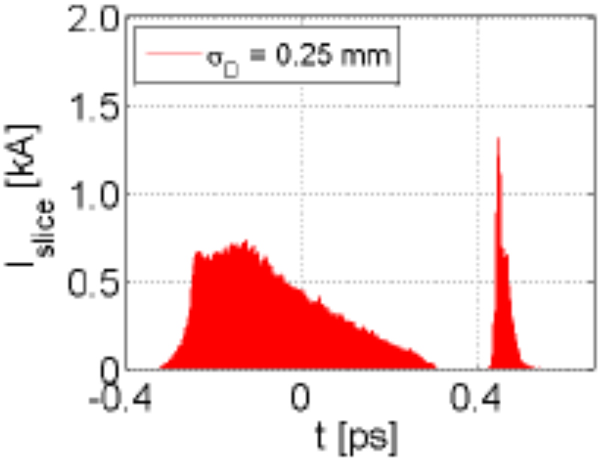
Comb-like laser

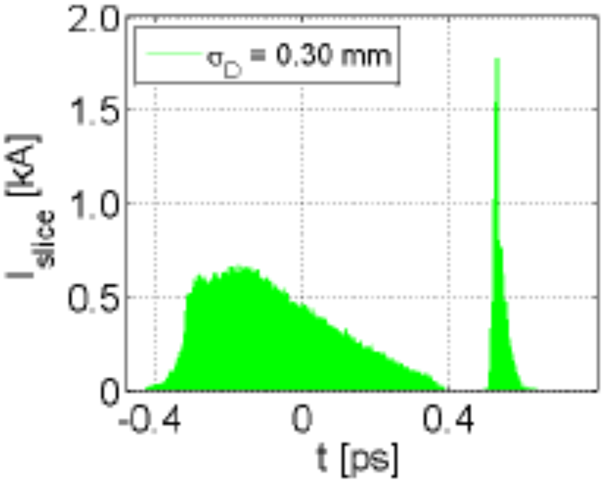


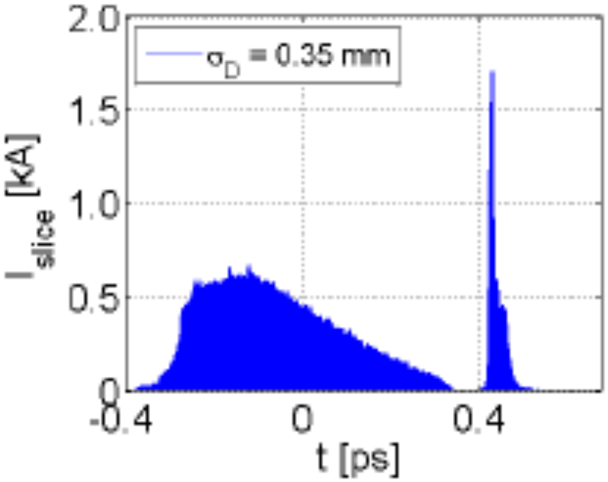
$$\Delta\phi_\infty = \frac{\sin\phi_0}{\sin\phi_\infty}\Delta\phi_0 + \frac{1}{2\alpha\gamma_0^2\sin\phi_\infty}\Delta\gamma_0 + \frac{1}{2}\left[\frac{\cos\phi_0}{\sin\phi_\infty} - \frac{\cos\phi_\infty\sin^2\phi_0}{\sin^3\phi_\infty}\right](\Delta\phi_0)^2.$$

Velocity bunching







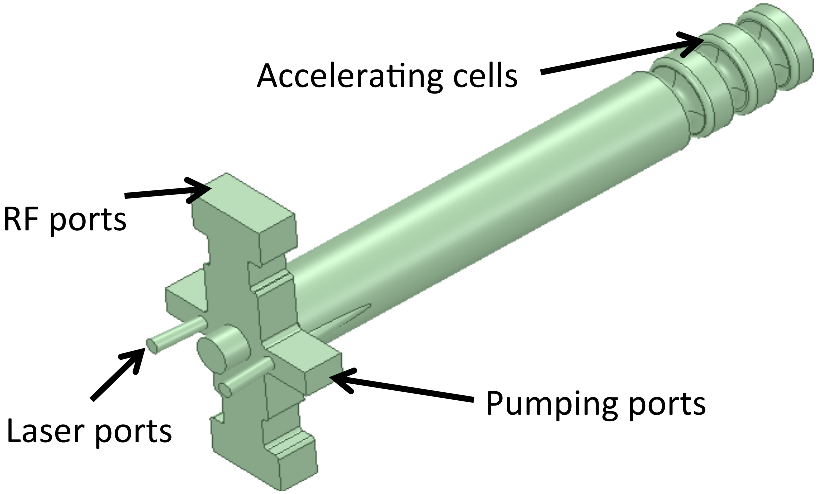


Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

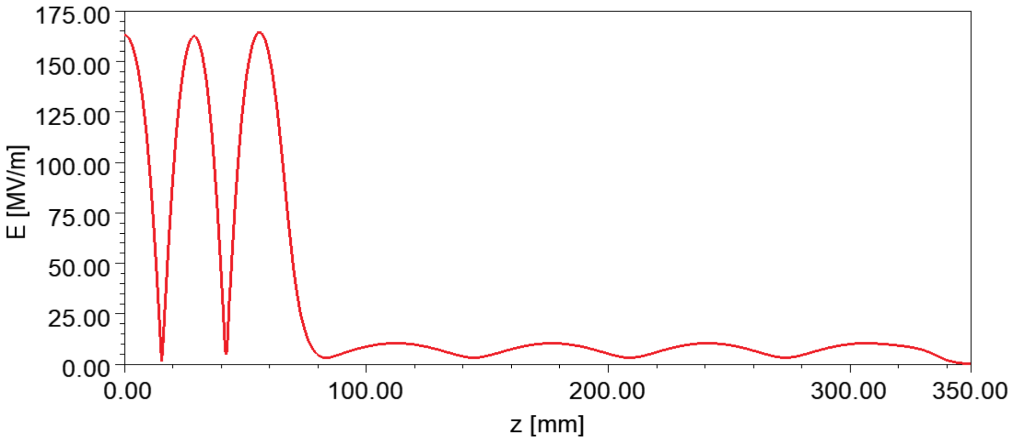
Table 7.2: Driver and witness beam parameters at the end of photo-injector.

POSSIBLE FUTURE UPGRADE:C-BAND GUN DESIGN

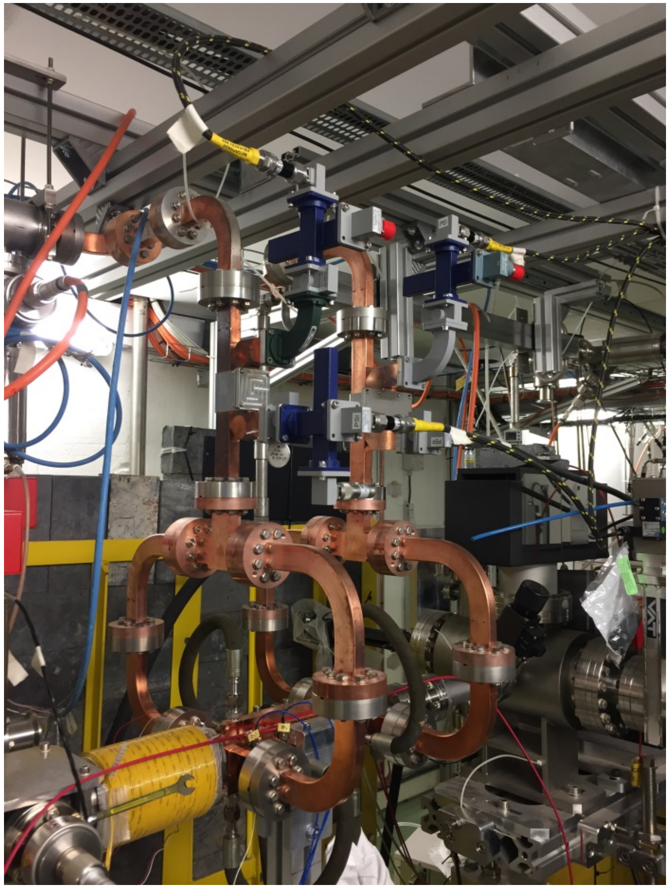
- ⇒ The e.m. design has been done both using **Superfish and ANSYS Electronics**
- ⇒ Two type of structures have been designed **1.5 and 2.5 cell**
- ⇒ In the context of the **EU project XLS Compact light, the C-band injector has been selected as the baseline injector (2.5 cell)**. The main advantage is to have the possibility to operate at repetition rates of 1 kHz with 160 MV/m cathode peak field.
- ⇒ **Beam dynamics calculations** (A. Giribono, M. Croia, C. Vaccarezza, M. Ferrario) and **dark current studies** (J.Scifo) have been done

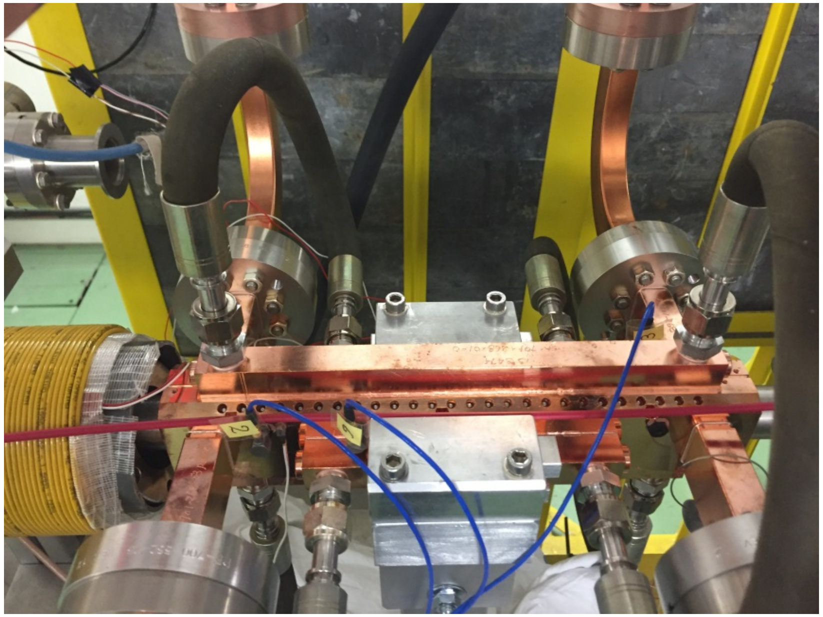


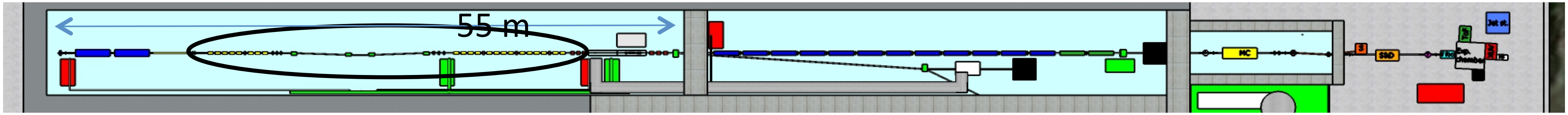
E_{cath}	160 => 250 MV/m
$\Delta f_{\pi/2-\pi}$	≈ 52 MHz
Q_0	11600
β	3
Filling time (τ_F)	160 ns
P_{diss} @160MV/m	9.7 MW
	34.2 [MV/m/(MW)$^{0.5}$]
Rep. Rate	1000 Hz
Peak Input power P_{IN}	18 MW
Pulsed heating (T_{puls})	<20 °C
RF pulse length (T_{RF})	350 ns
Av diss power (P_{av})	2300 W



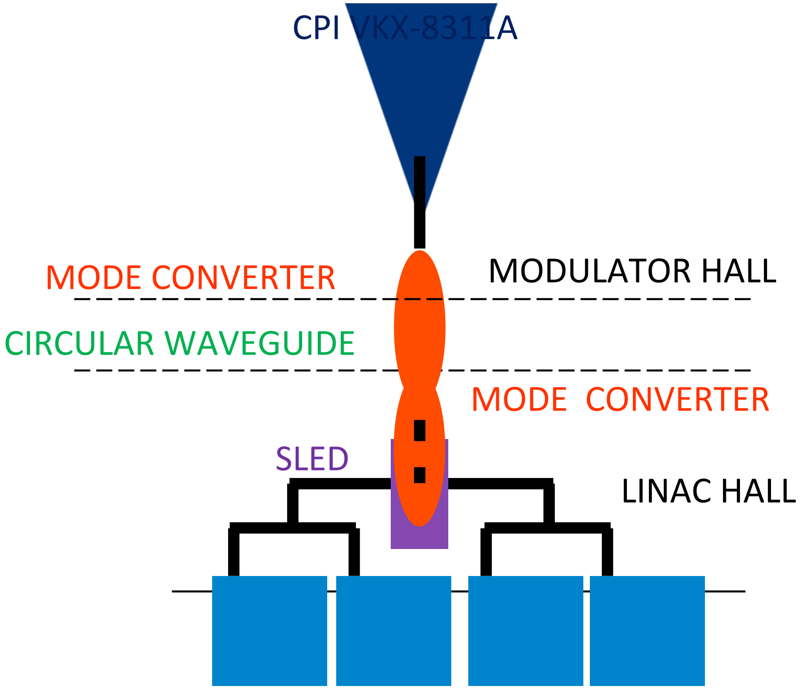
X-band Linac







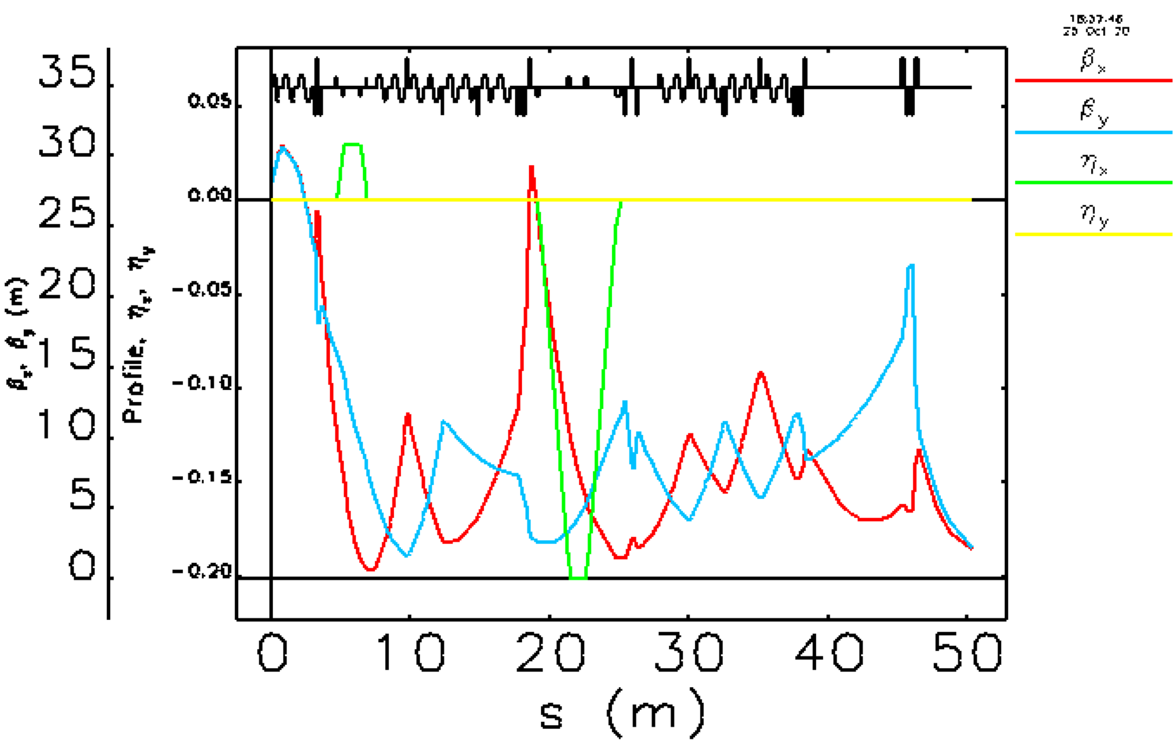
Compact



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]	65->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

Courtesy M. Diomede

A conservative value for the accelerating field in the accelerating sections is identified as **E_{acc}=60 MV/m**, corresponding to a 10% reduction of the RF power coming from the Klystron, i.e. 53.9 MV integrated for each X-band section, L=0.89856 m . With these premises and the old layout the maximum achievable energy at the Linac 2 end, turns out to be lower than 1 GeV, E_{max} = 0 .95 GeV



Twiss parameters for 200pC_1GeV_X_90cm_update_short_LH_4b_up_check_new_Oct_20

Courtesy C. Vaccarezza

WA 1 Summary:

HighLigths

- A layout update has been proposed based on a necessary safety margin for the maximum achievable Energy at the Linac end
- A first check has been performed on the feasibility of the emittance measurement at the end of the Linac

Actions

- The updated layout has to be verified for the COMB – WP
- The updated layout has to be verified with a 3D CAD (lattice file provided)
- The feasibility of the magnet according to the considered fields must be verified
- The X-band RFD position must be checked

Next

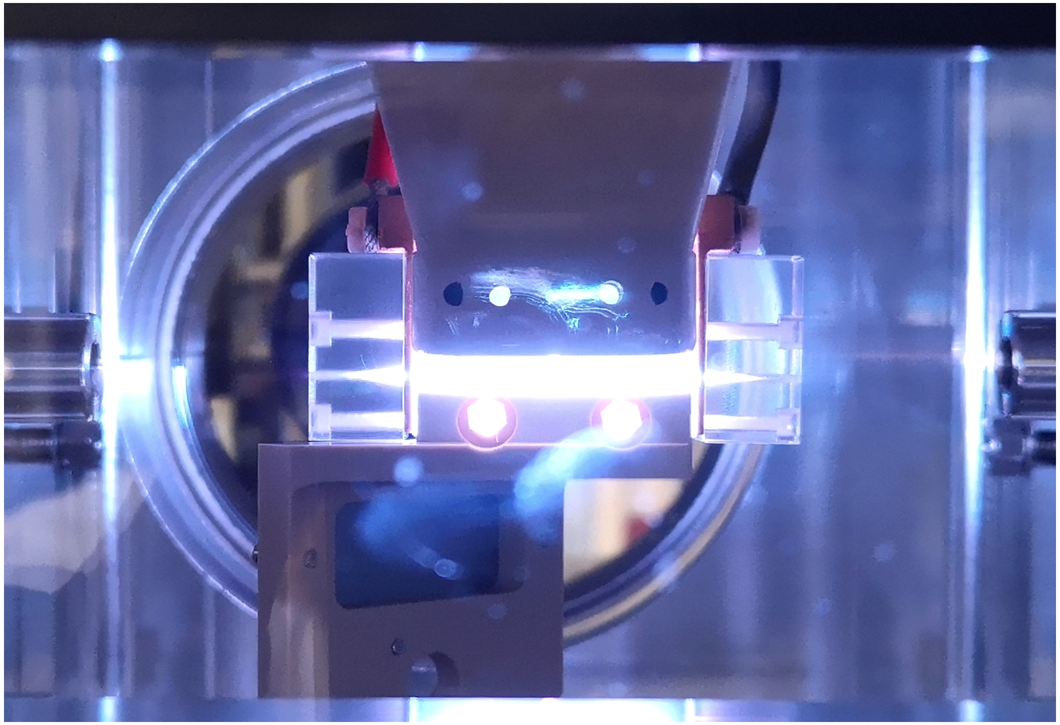
- WP2 on crest
- Study on the driver removal chicane
- More realistic diagnostic implementation
- Test of the optics for each diagnostic section
- Possible RFD insertion downstream the BC

Critical Issues

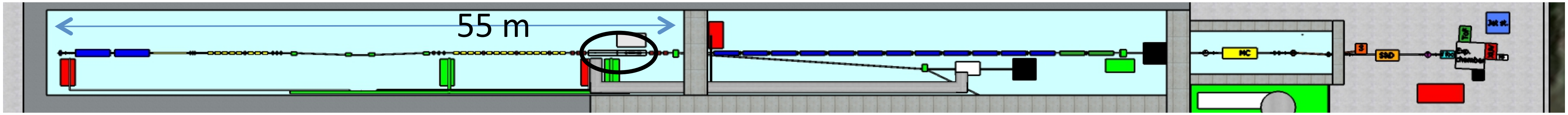
- The feasibility of the driver removal chicane
- Jitters Effects and Mitigation

Courtesy C. Vaccarezza

Plasma WakeField Acceleration



Capillary discharge at SPARC_LAB



Energy Stability

$$\frac{\Delta\lambda}{\lambda} = \frac{1}{2}\frac{\Delta E}{E} \propto \rho \approx 10^{-3}$$

FEL requirement

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

Plasma density

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

Bunch charge/length

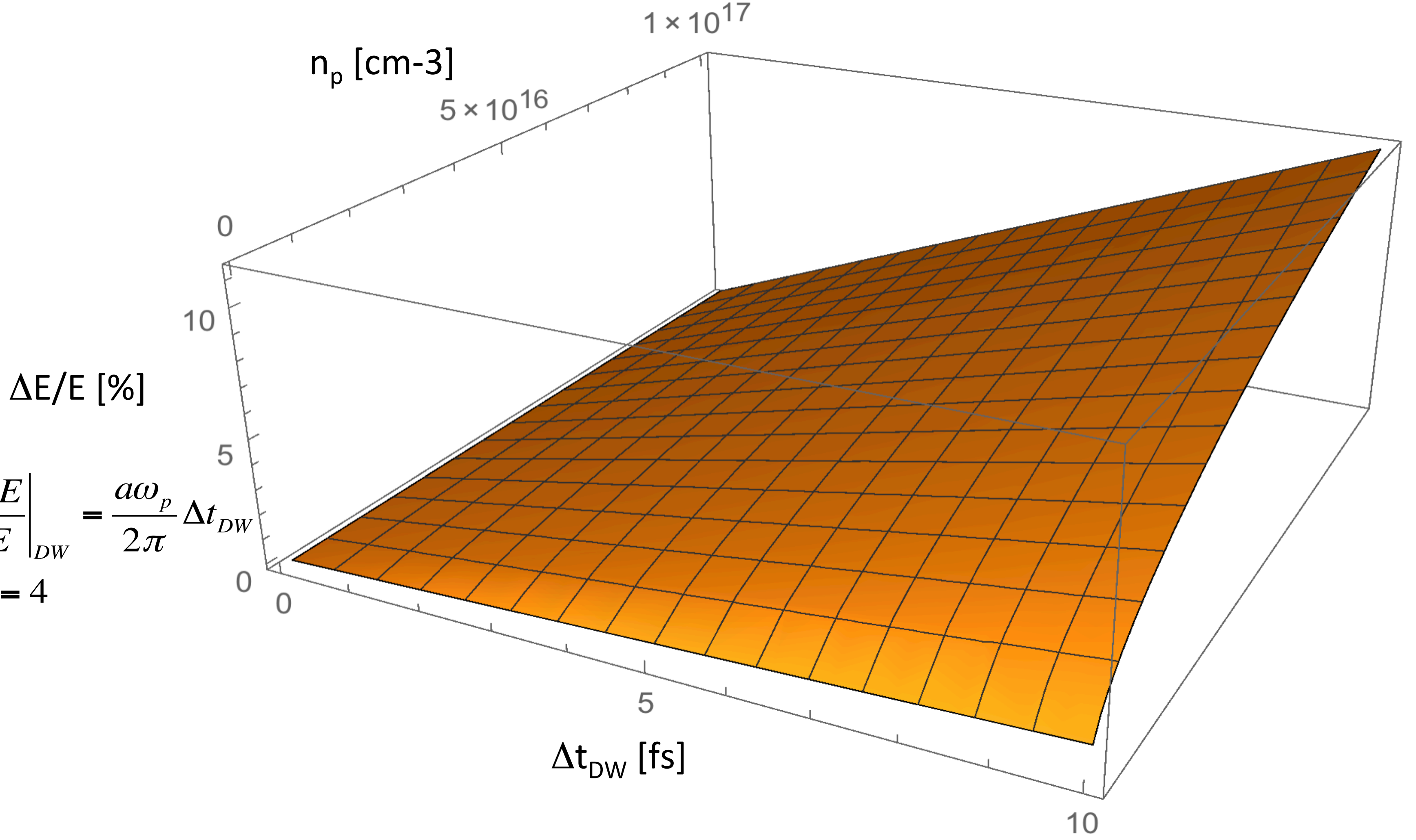
$$\left.\frac{\Delta E}{E}\right|_{DW} = \frac{a\omega_p}{2\pi}\Delta t_{DW}$$

$$2 \leq a \leq 4$$

Driver/Witness separation

Non Linear Regime - Energy Jitters

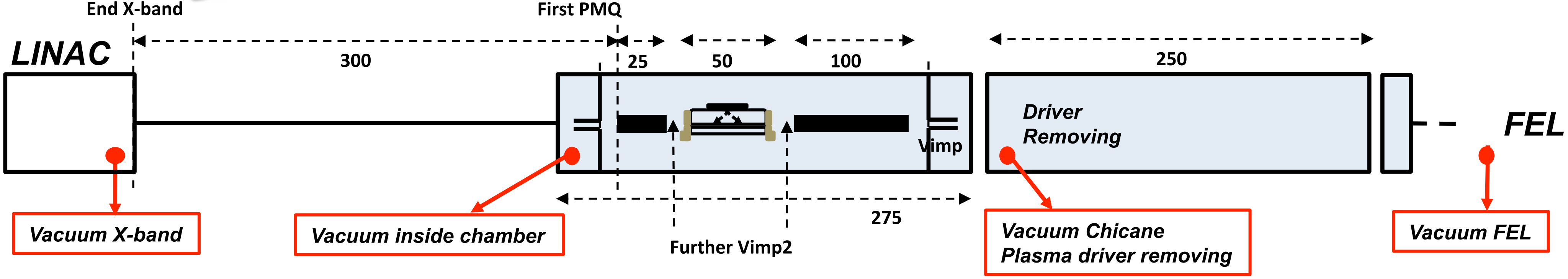
DE/E [%] versus plasma density n_p [cm-3] and D/W separation [fs]



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

$a = 4$

Plasma module layout



Vacuum X-band

Vacuum inside chamber

Vacuum Chicane
Plasma driver removing

Vacuum FEL

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 (cm^3)	*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* (cm^3)	*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

Conclusions

- **A Critical Review of the CDR is ongoing**
- A detailed **schedule and cost estimate** towards the completion of the TDR is in progress.
- 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**)

Thanks for your attention