EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

Contributions to the CDR about the PWFA option

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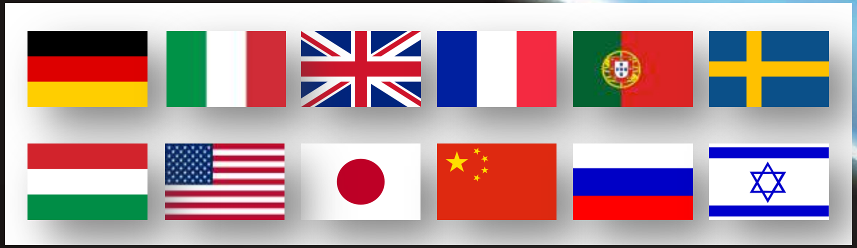
Retreat in the Alps, February 27, 2019, Hotel am Badersee, Grainau



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

Why beam driven?

- Beam/Plasma wave dephasing is negligible,
- Driver/Witness energy transfer efficiency ~20%,
- Timing and synchronization are rather mitigated issues (D/W from the same source),
- State of the art RF electron linacs can achieve repetition rates as high as GHz in pulsed mode in NC linacs or MHz even in CW operation in SC linacs,
- Compact and cheap…..
- Many existing conventional electron linacs in research laboratories and universities can benefit of a PWFA booster (ex: XFEL, Swiss_FEL, ILC)

Critical issues

- generation of ultralow emittance and energy spread,
- damping of instabilities, ex: hose instability, head erosion
- development of optimized plasma module
- optimization of the driving beams.
- Staging

Long term impact on LC

CLIC-like **Linear Collider** schemes from the Higgs energy up to TeV range

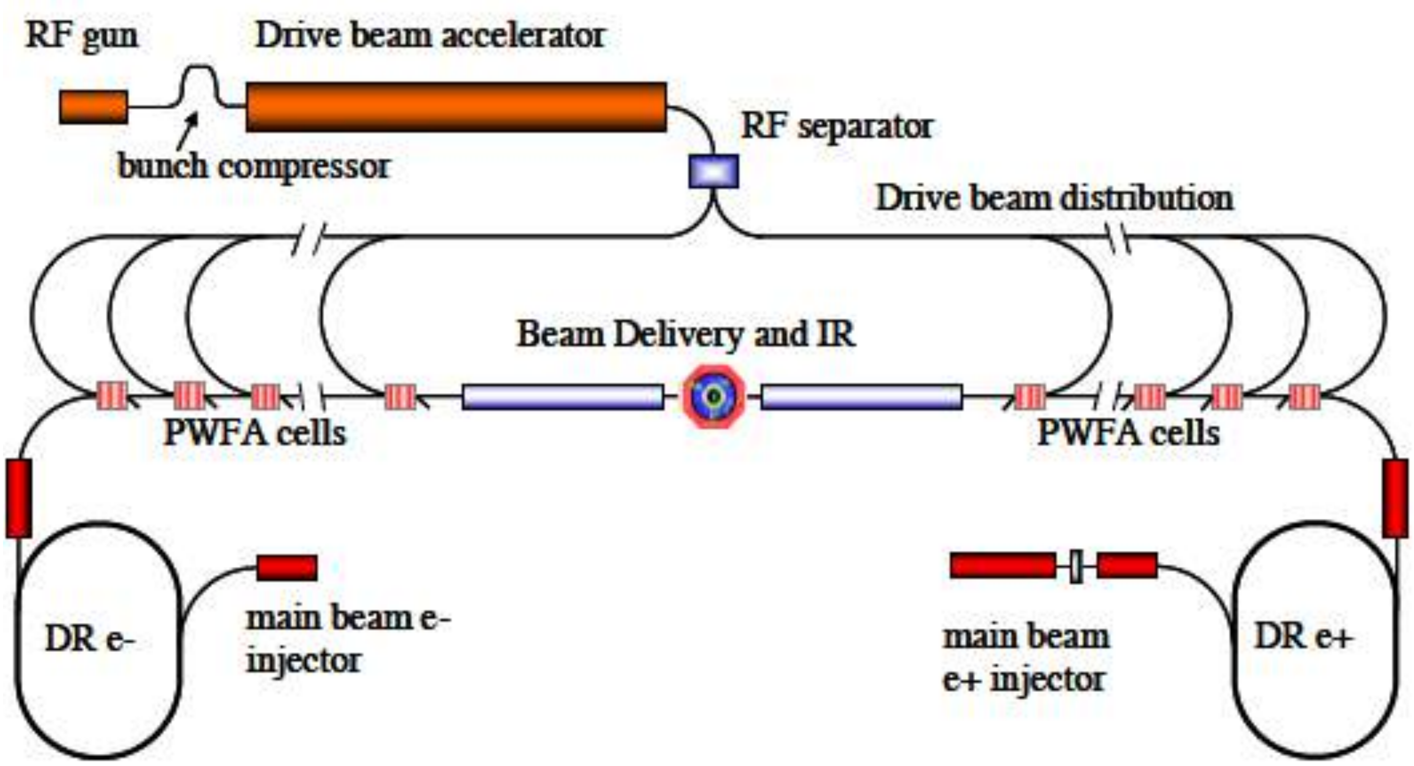


Fig. 1: Concept for a multi-stage PWFA Linear Collider.

→ A. Aschikhin *et al.*, NIM A **806**, 175 (2016)

FLASHForward▸▸

Future-oriented wakefield accelerator research and development at FLASH

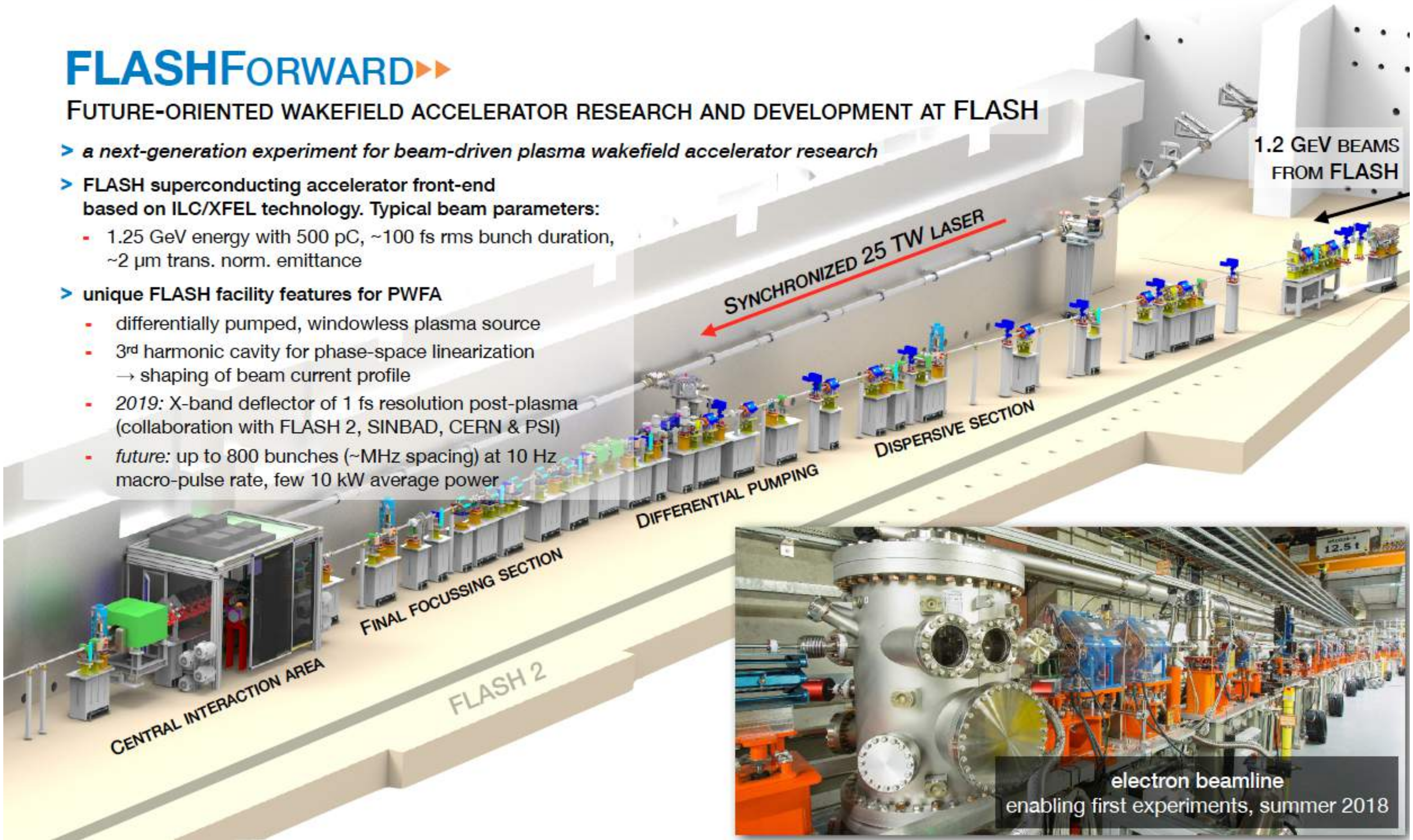
> ***a next-generation experiment for beam-driven plasma wakefield accelerator research***

> **FLASH superconducting accelerator front-end based on ILC/XFEL technology. Typical beam parameters:**

- 1.25 GeV energy with 500 pC, ~100 fs rms bunch duration, ~2 µm trans. norm. emittance

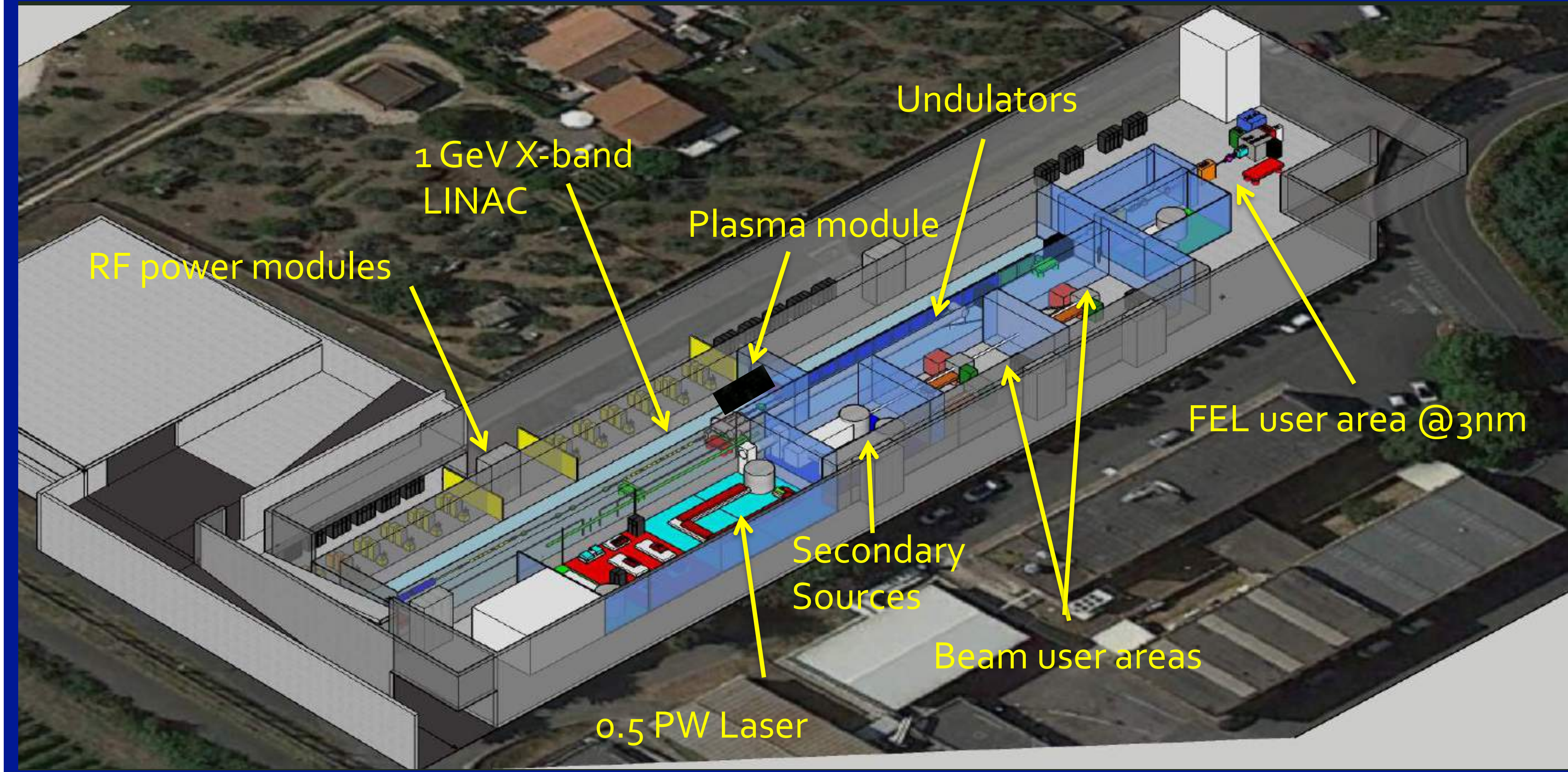
> **unique FLASH facility features for PWFA**

- differentially pumped, windowless plasma source
- 3rd harmonic cavity for phase-space linearization → shaping of beam current profile
- *2019:* X-band deflector of 1 fs resolution post-plasma (collaboration with FLASH 2, SINBAD, CERN & PSI)
- *future:* up to 800 bunches (~MHz spacing) at 10 Hz macro-pulse rate, few 10 kW average power



electron beamline
enabling first experiments, summer 2018

EuPRAXIA@SPARC_LAB



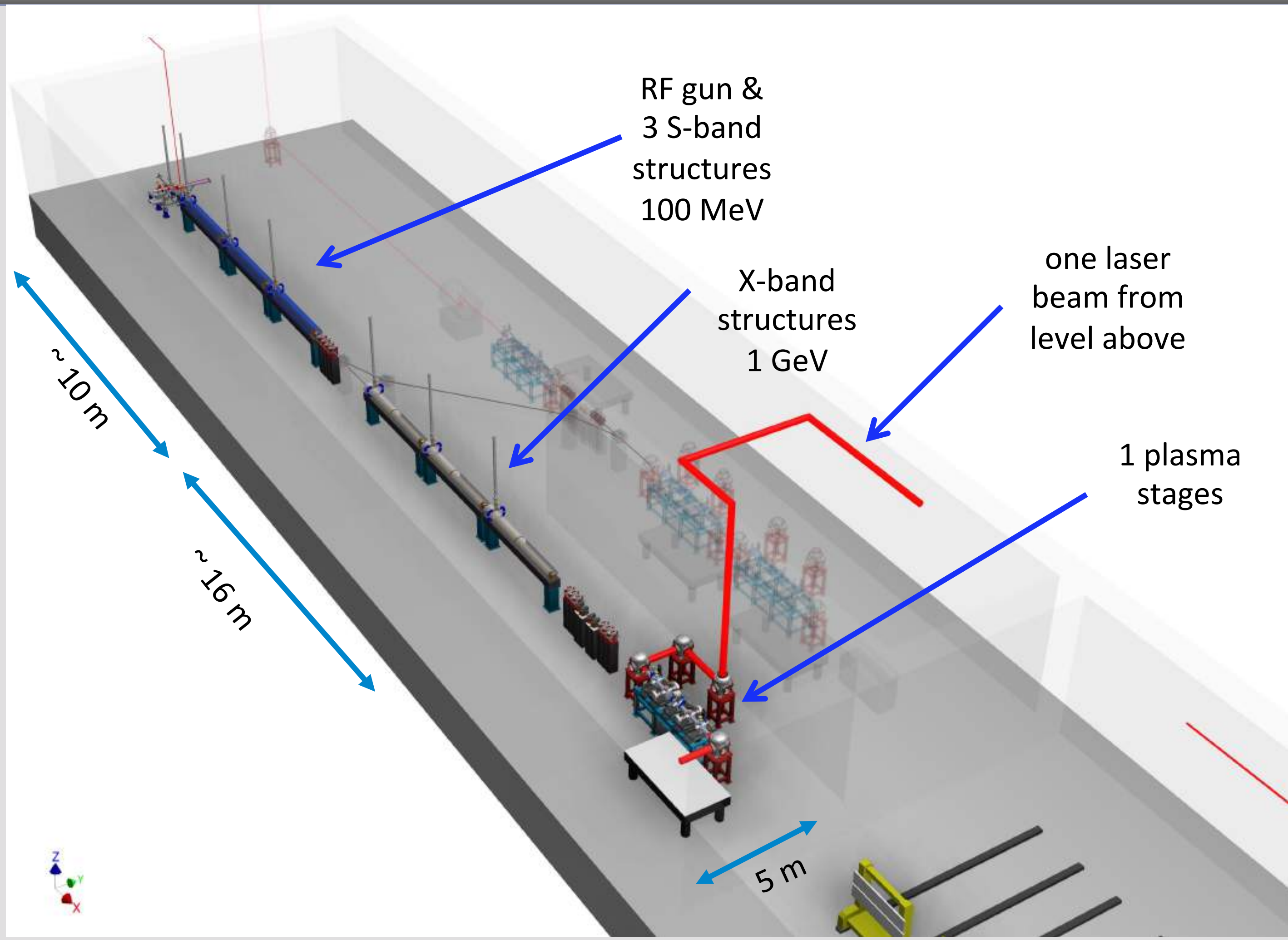
Possible EuPRAXIA Beam Driven layout

Horizon 2020

PWFA up to 5 GeV

RF structures consist of S-band injector and high gradient X-band

Laser needed for pre-ionization of plasma



A = 45 x 5 m² = 225 m²

3D layout by Dariusz Kocoń and Paul Andreas Walker

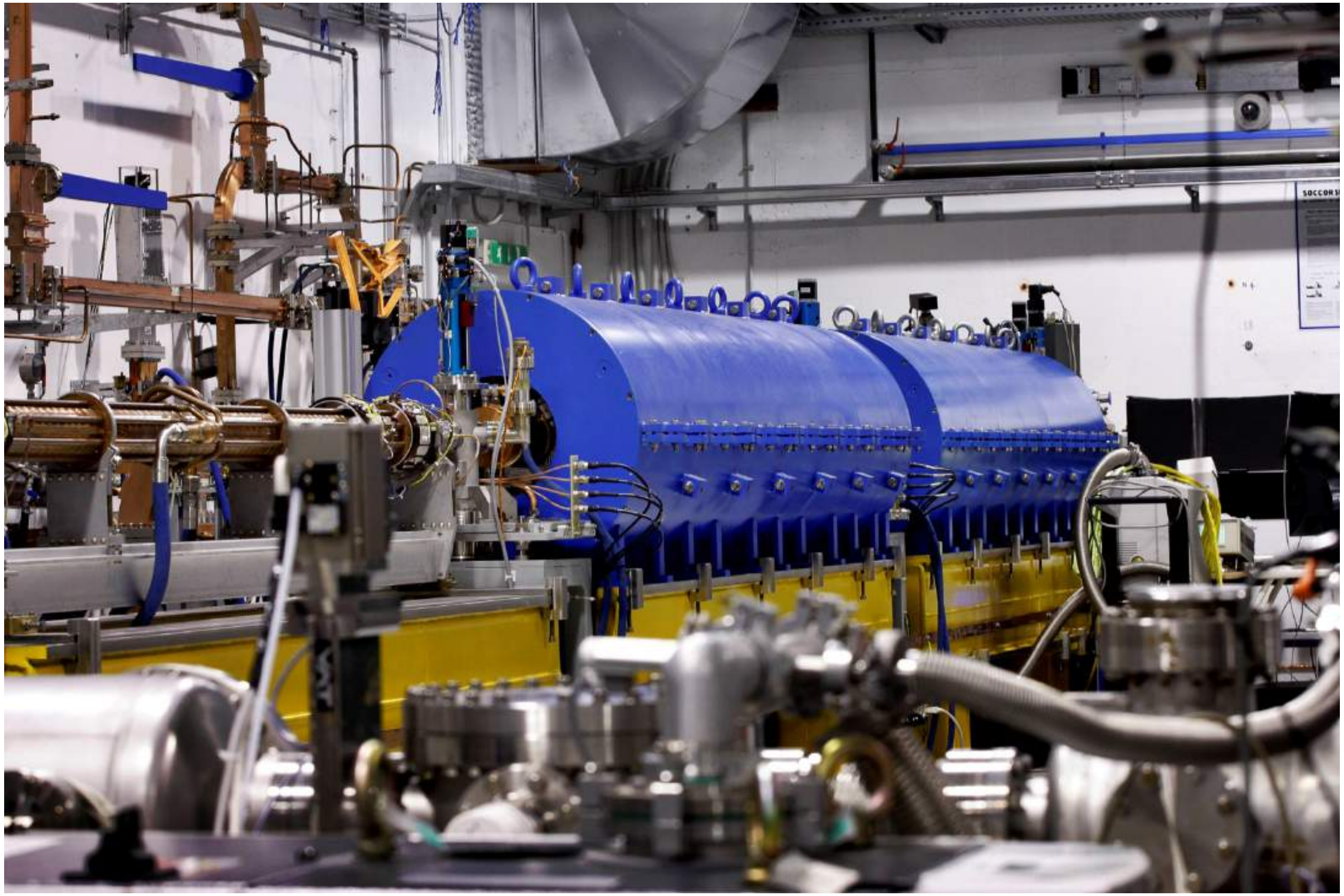
FEL Electron Beam Requirements

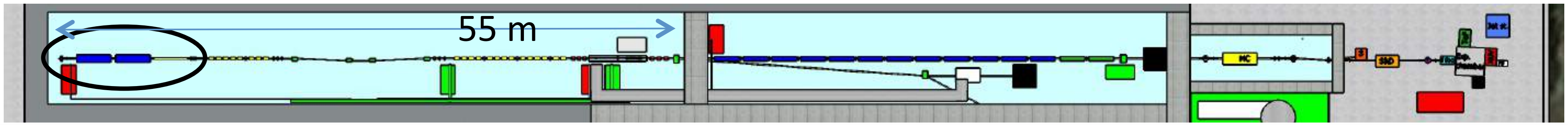
Horizon 2020

Electron beam parameters at the undulator

Quantity	Symbol [Unit of Meas.]	Target parameters
Energy	E [GeV]	1 - 5
Charge	Q [pC]	30
Bunch length (FWHM)	t_{FWHM} [fs]	10
Peak current	I [kA]	3
Repetition rate	f [Hz]	10
# of bunches	N	1
Transverse Norm. emittance	$\varepsilon_{n,x}, \varepsilon_{n,y}$ [mm mrad]	<1
Total energy spread	σ_E/E [%]	1
Slice Norm. emittance	$\varepsilon_{n,x}, \varepsilon_{n,y}$ [mm mrad]	<<1
Slice energy spread	$\sigma_{E,s}/E$ [%]	~0.1
Slice length	L_{Slice} [μm]	0.75 - 0.12

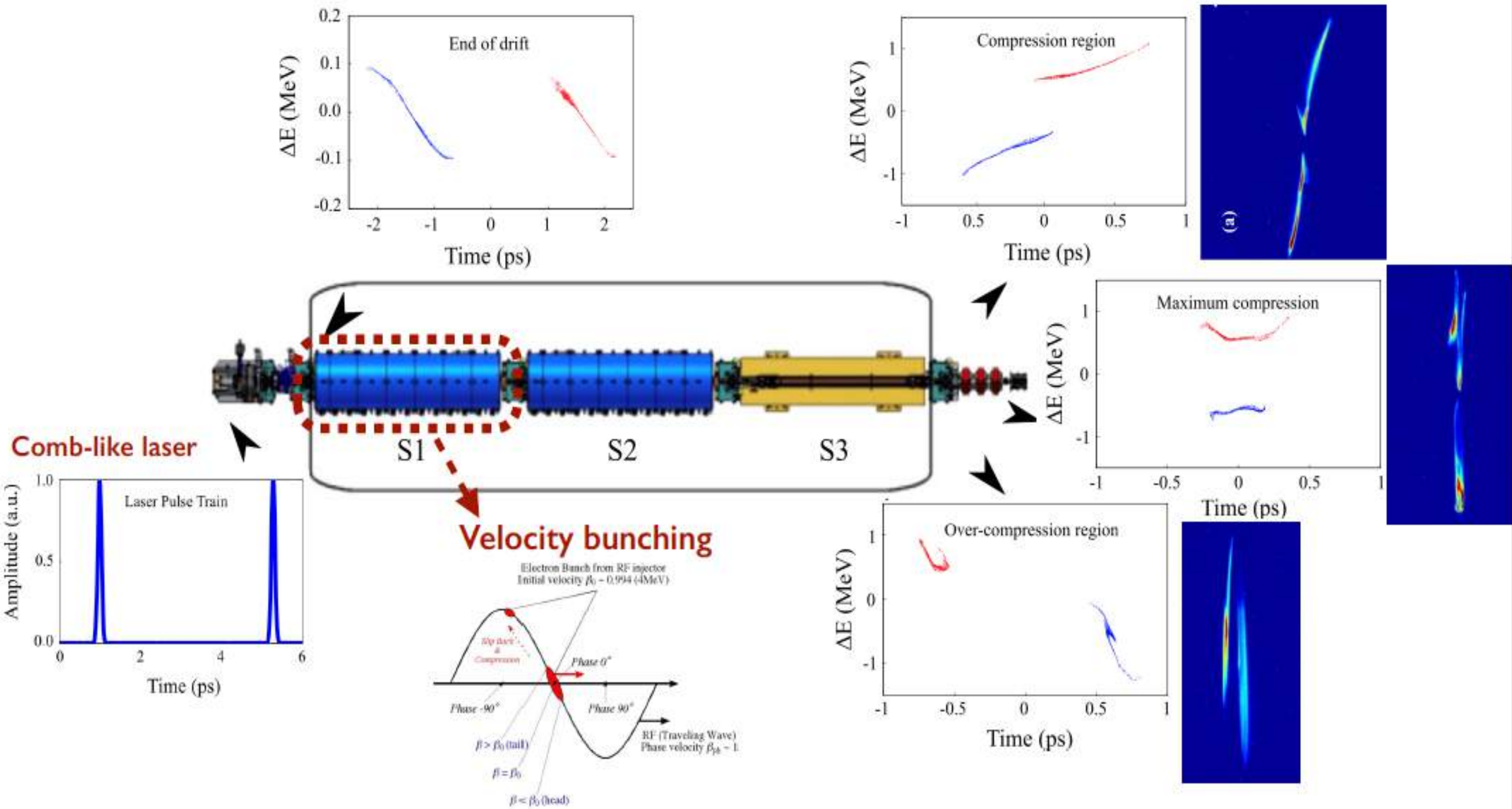
SPARC_LAB HB photo- injector

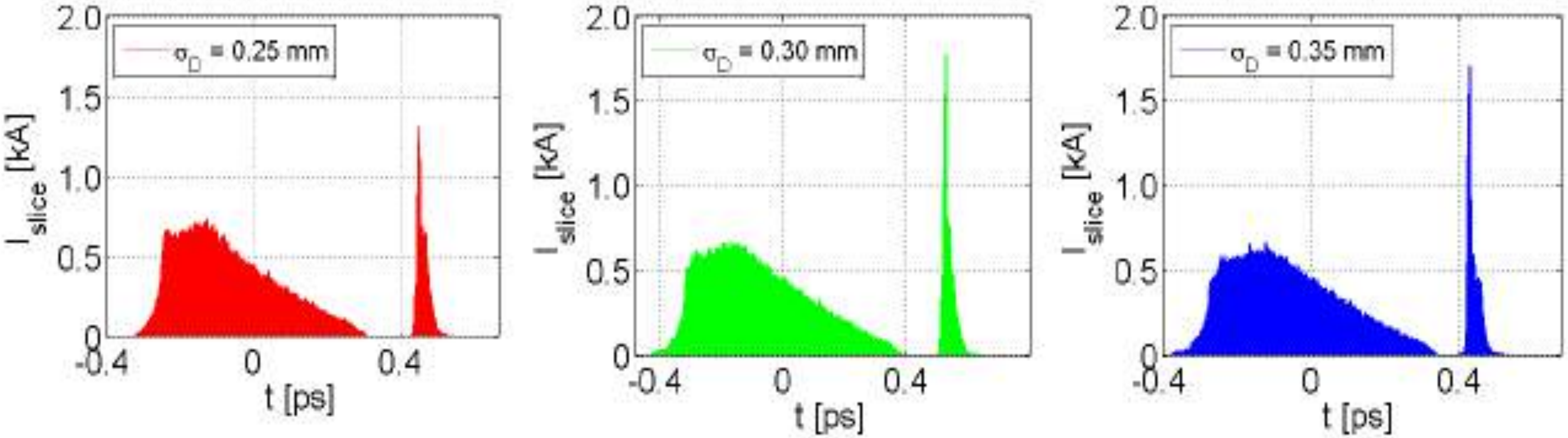




Generation of multi-bunch trains

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.

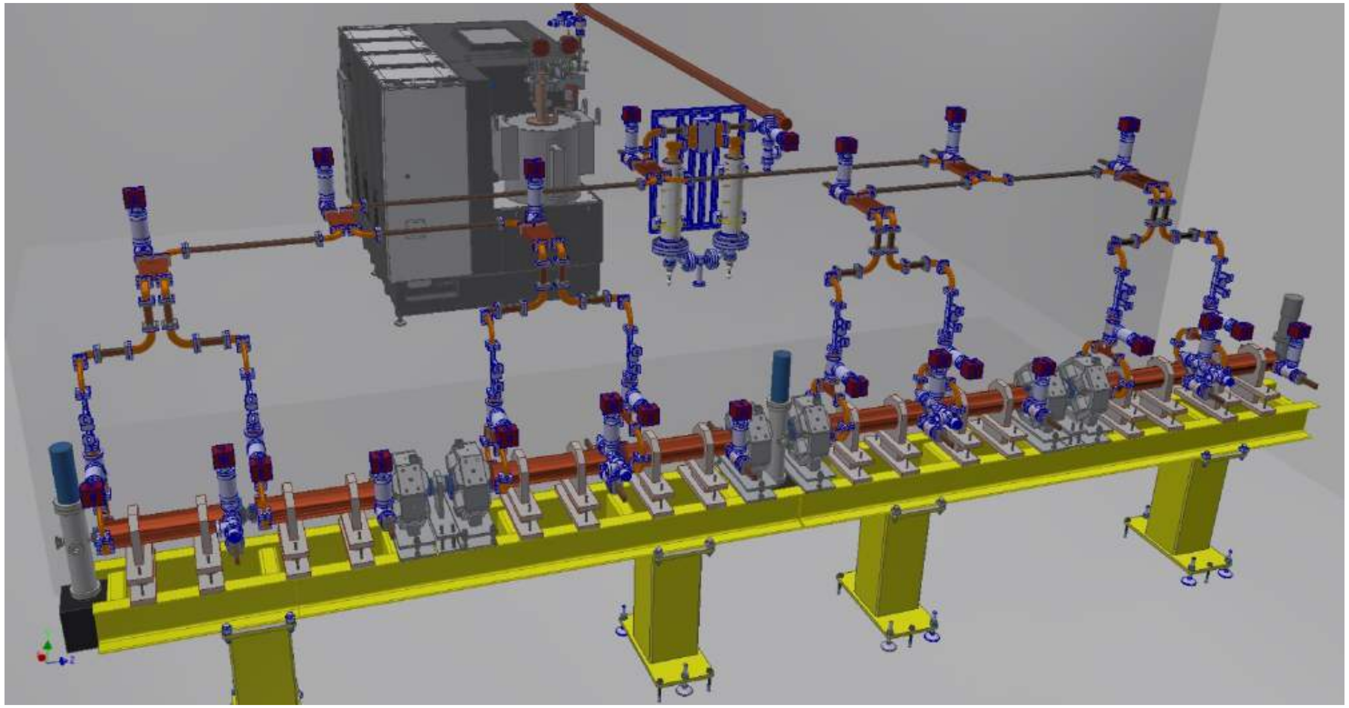


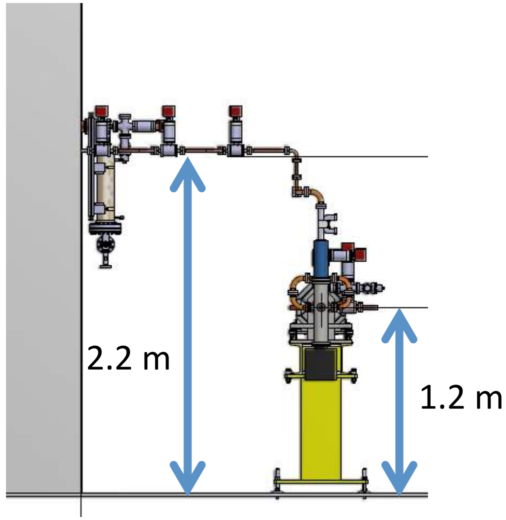


Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

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

X-band Linac

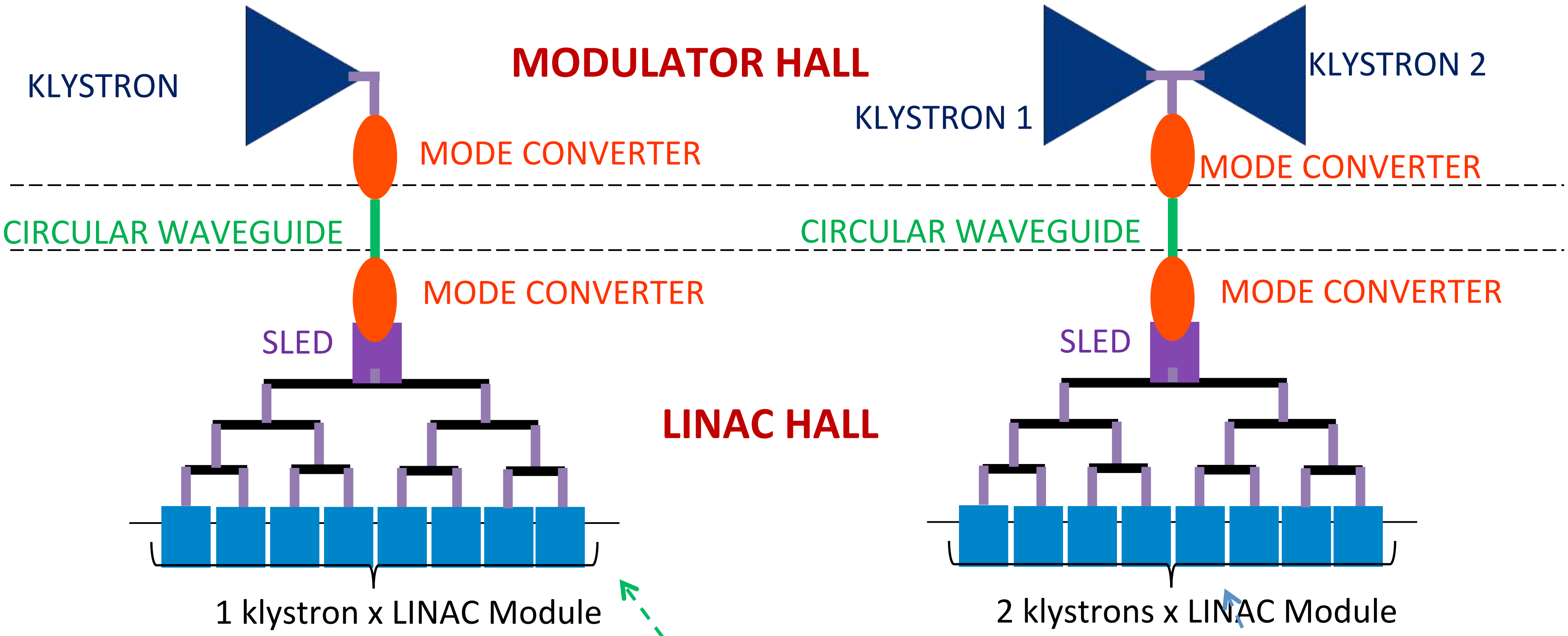




Preliminary layout of the **RF module** (collaboration with CERN):
8 structures, 1 SLED, 1 or 2 Klystrons per module.

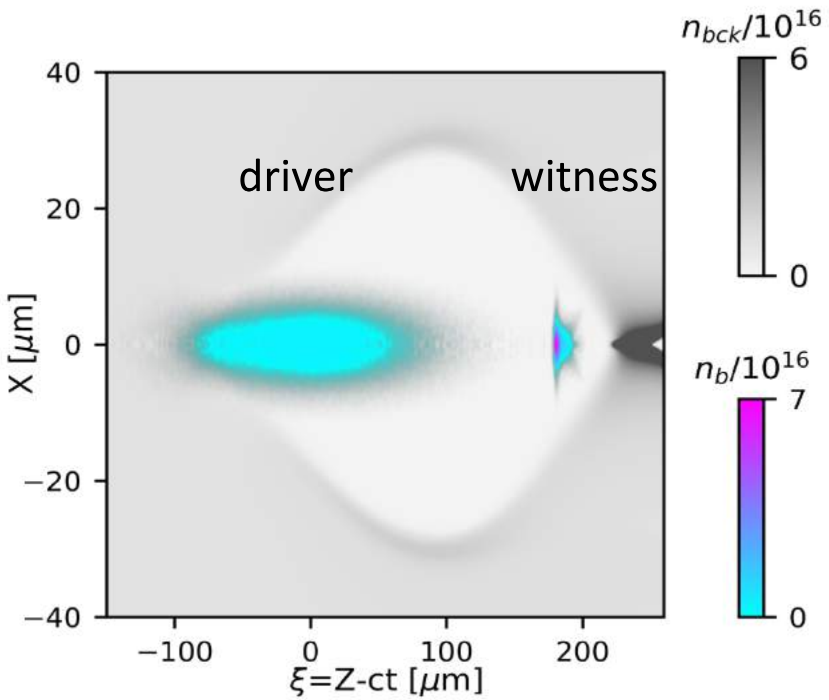
WR-90 total length [mm]	3758
WC-50 circular wg length [mm]	3674
WR-90 loss [dB]	-0.368
WC-50 loss [dB]	-0.0456
total loss [dB]	-0.414
total loss [%]	-9.09

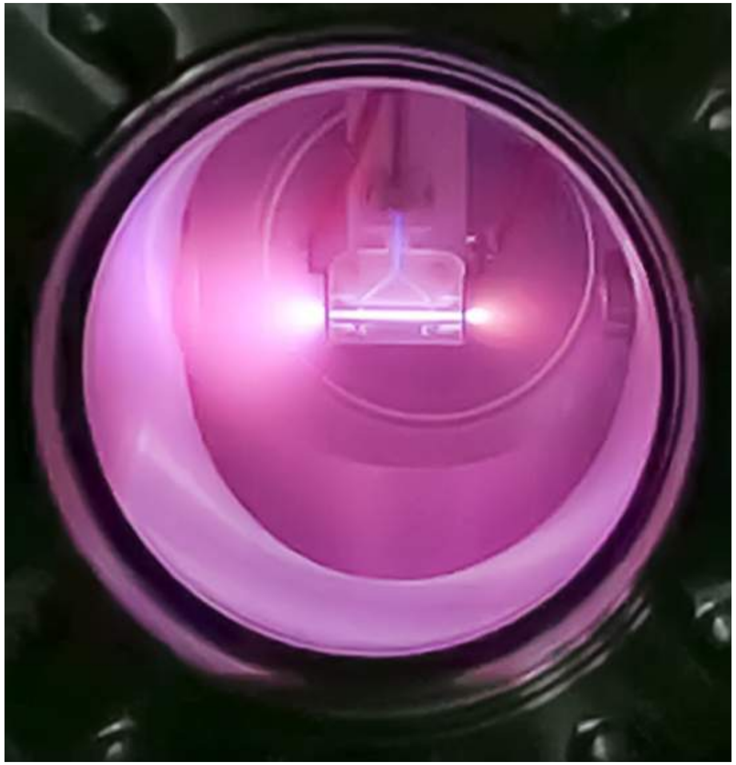
Estimated **waveguide attenuation** (including circular waveguide): **10%**



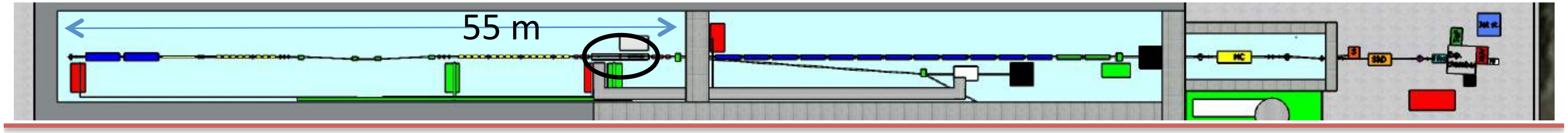
X-Band LINAC parameters			
total active length L_t	16 m		
Number of sections N_s	32 (4 modules x 8 sections)		
available RF power	50 MW (@klystron output coupler) 40 MW (@ section input couplers)		
PWFA final energy	**1 GeV**	**5 GeV**	**> 5 GeV**
linac energy gain ΔW_{linac}	480 MeV	910 MeV	1280 MeV
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

Plasma WakeField Acceleration

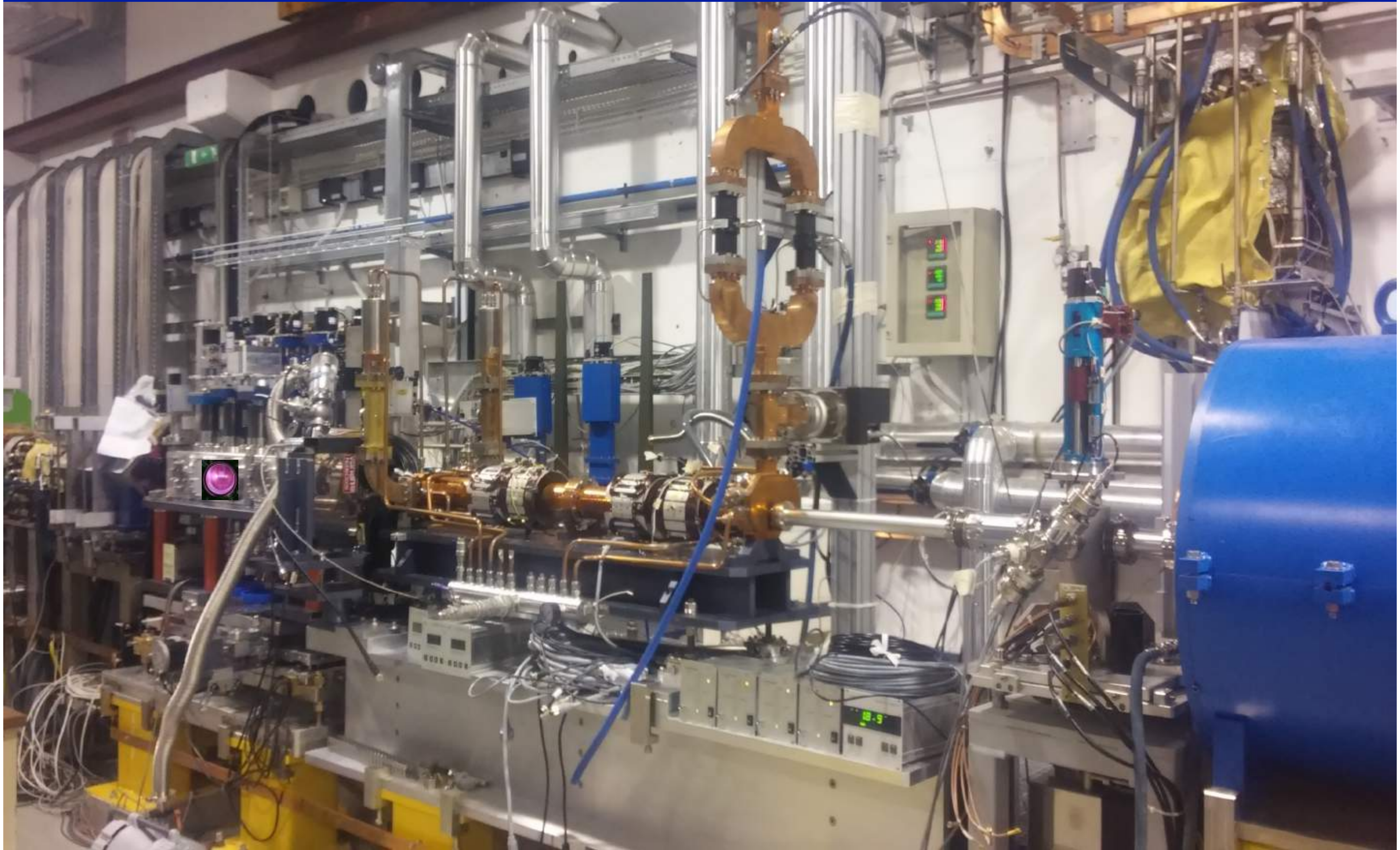




Capillary discharge at SPARC_LAB

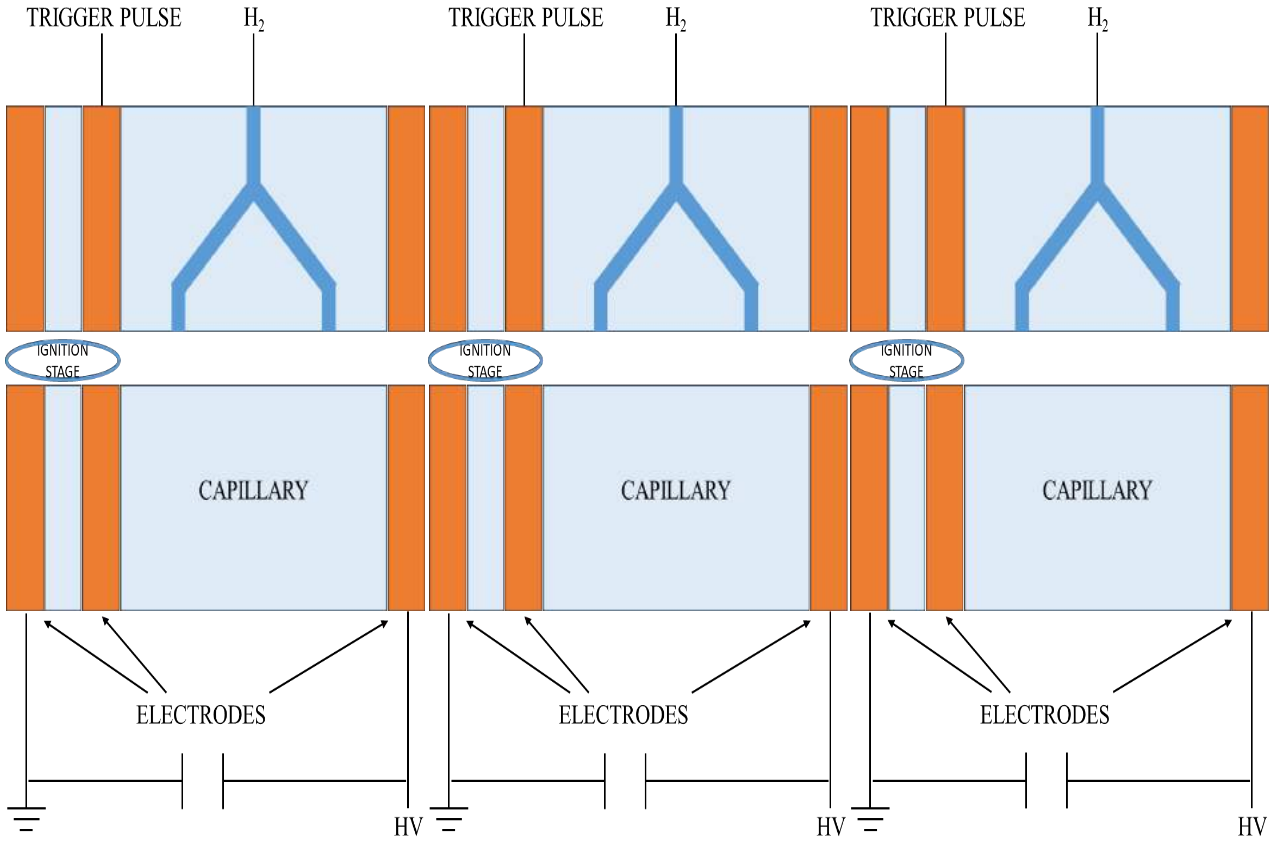


PWFA vacuum chamber at SPARC_LAB



Plasma module

This scheme can be reproduced for tens-of-centimetre capillaries. This single unit can be integrated simply by adding more units obtaining up to tens of centimetre capillaries homogenously ionized and controlled independently one to each other, leading to the desired length of plasma (almost 30 cm) with the proper density (10^{17} cm^{-3}) required for this project.



Driver S2E

Bunch parameters				
bunch	Q [pC]	σ_x [µm]	σ_z [µm]	ε_x [mm mrad]
Driver	200	4	75	3
Witness	25–30	1.5	6	1

Plasma parameters		
n_0 [cm^{-3}]	λ_p [µm]	k_p [µm $^{-1}$]
10^{16}	334	0.02

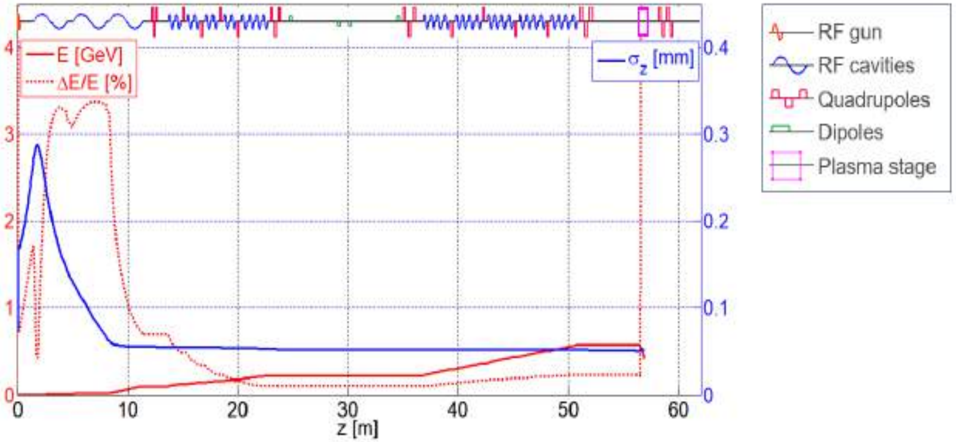
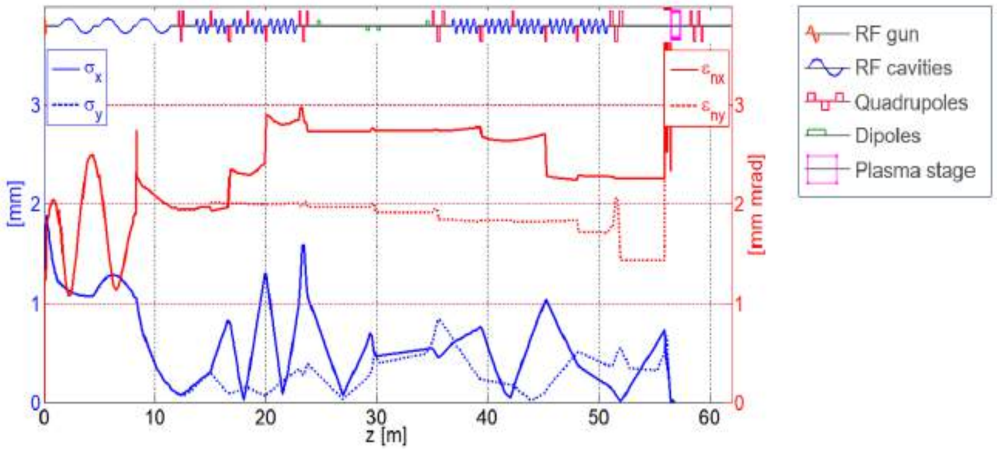


Figure 4.7: Start to end simulation results for the driver bunch for the PWFA case: evolution along the injector of the energy (E red line) and energy spread ($\Delta E/E$ red dotted-line) and longitudinal bunch length (σ_z blue line).



Witness S2E

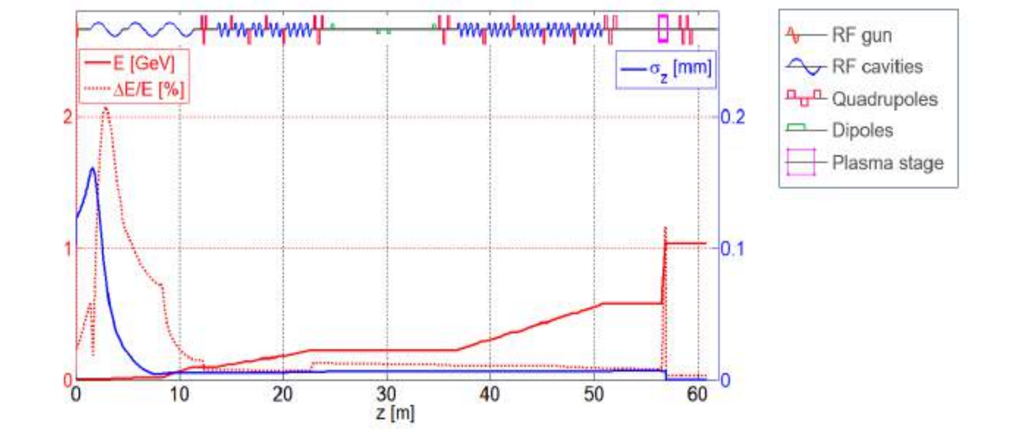
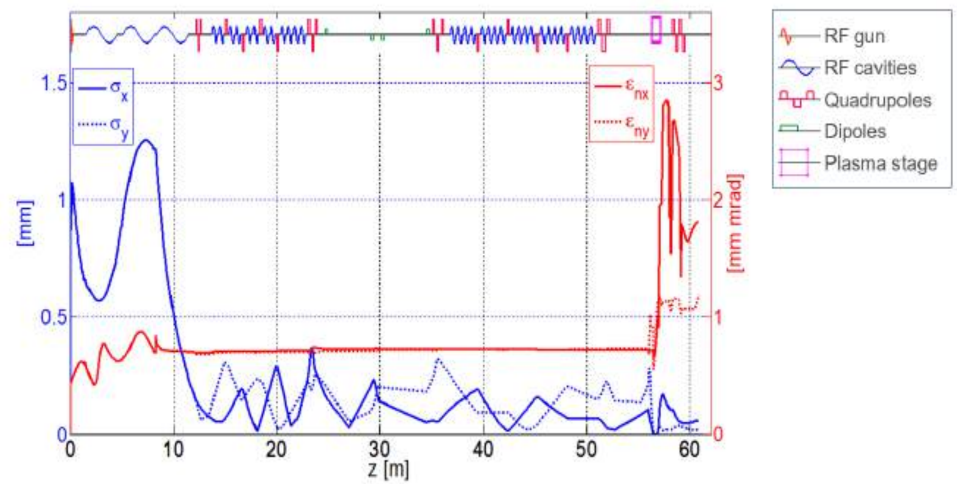
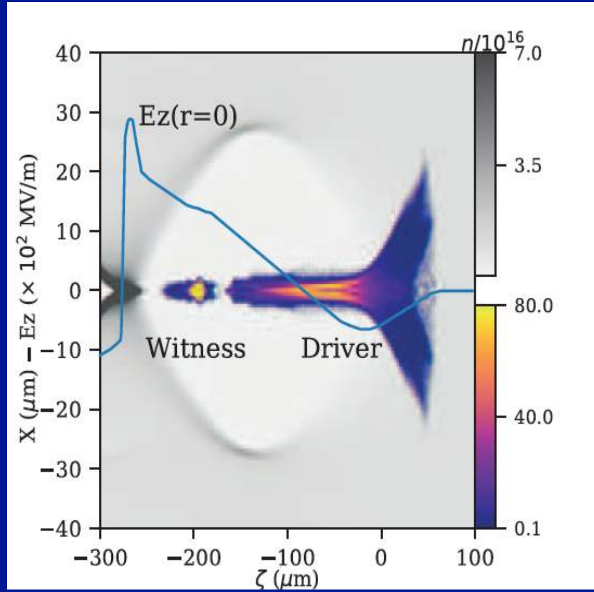
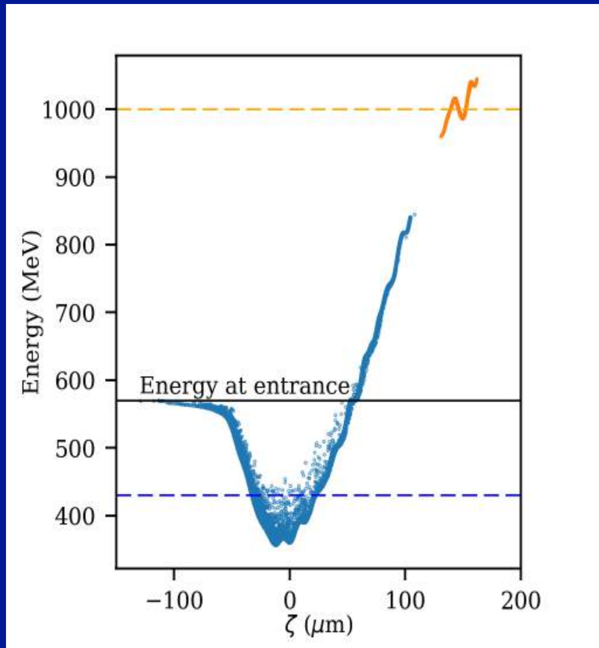


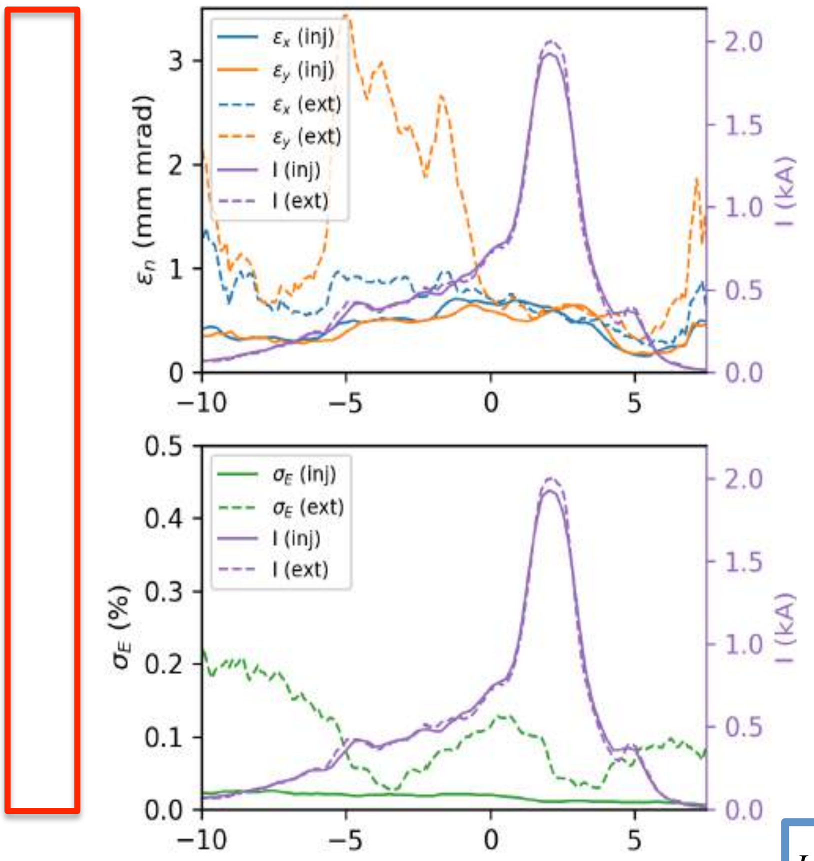
Figure 4.5: Start to end simulation results for the trailing bunch for the PWFA case: evolution along the injector of the energy (E red line) and energy spread ($\Delta E/E$ red dotted-line) and longitudinal bunch length (σ_z blue line).







Plasma Exit: Rolling Slice analysis



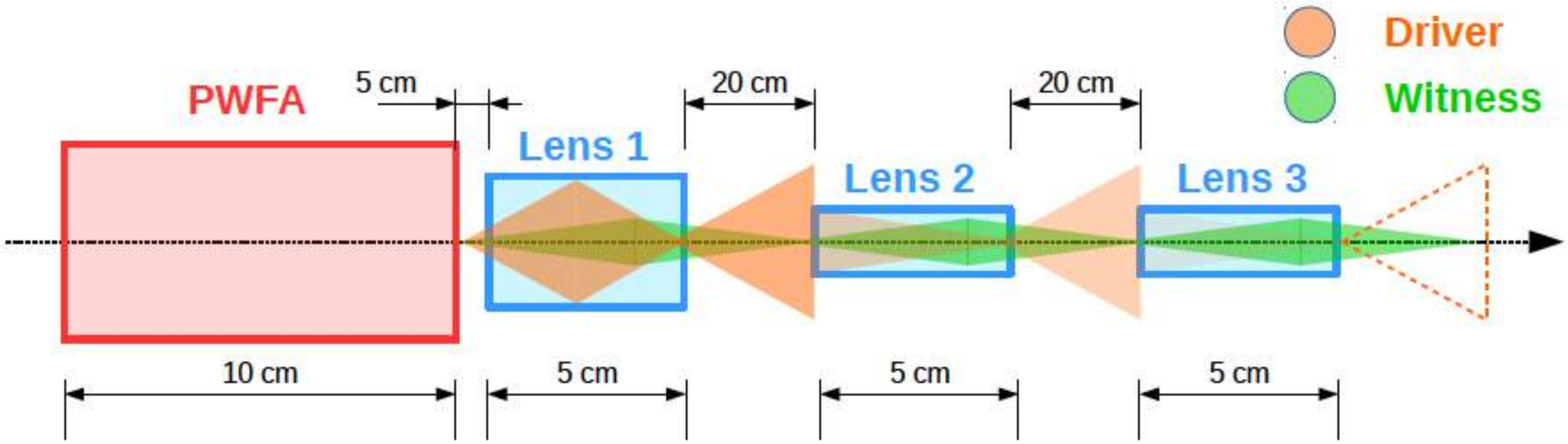
$$L_s = \frac{\lambda_r}{2\sqrt{3}\rho} \approx 1\ \mu\text{m}$$

Figure 7.12: Rolling slice analysis for the witness bunch at plasma input, dashed line, and at plasma exits, solid line. The top panel report the emittance in both transverse plane and the current. The bottom panel plots the energy spread together with the current. The corresponding current axis is the left y axis.

Beam	units	Driver-IN	Driver-OUT	Witness-IN	Witness-OUT
Charge	pC	200	200	30	30
σ_x	µm	8	6.4	1.47	1.42
σ_y	µm	3.1	10	3.17	1.4
σ_z	µm	52	50	3.85	3.8
ε_x	mm mrad	2.56	4.1	0.6	0.96
ε_y	mm mrad	4.8	11.4	0.55	1.2
σ_E	%	0.2	20	0.07	1.1
E	MeV	567	420	575	1030
Best Slice					
current	kA			2	2.0
ε_x	mm mrad			0.59	0.57
ε_y	mm mrad			0.58	0.62
σ_E	%			0.011	0.034

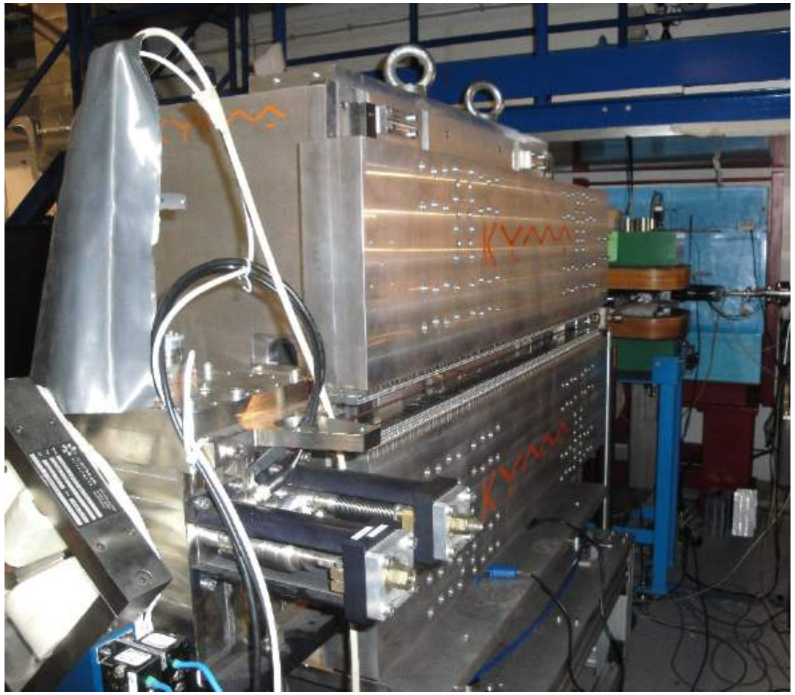
Table 7.3: PWFA bunch parameters at plasma entrance and at plasma exit. The best slice value is also reported.

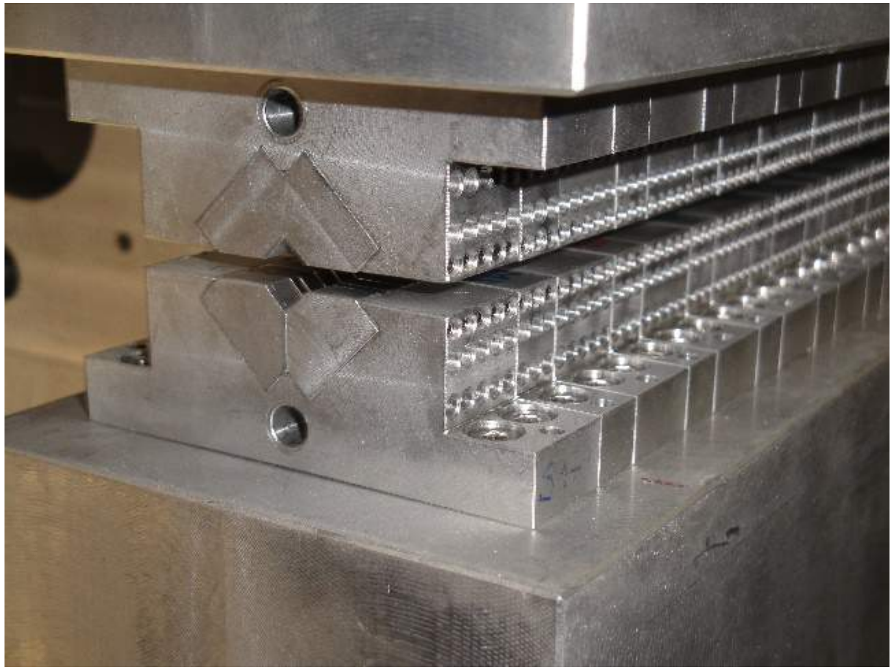
Layout of the extraction system



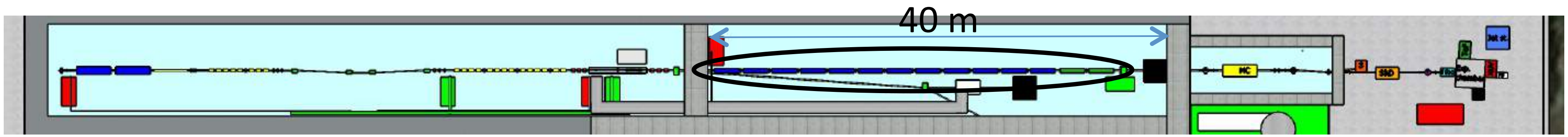
- Downstream the plasma accelerator a system of 3 plasma lenses is used
  - *Capture and matching of witness bunch, avoiding emittance degradation due to its large angular divergence @ acceleration capillary exit*
  - *Destroy the driver bunch*
- 1st plasma lens contains the witness widening and overfocuses the driver.
  - *200 um radius to keep the witness emittance (avoid nonlinear focusing)*
- 2nd and 3rd plasma lenses transport the witness while acting as collimators for the driver.
  - *100 um radius to destroy as much as possible the driver particles*

Undulators





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



FEL Simulations (Genesis)

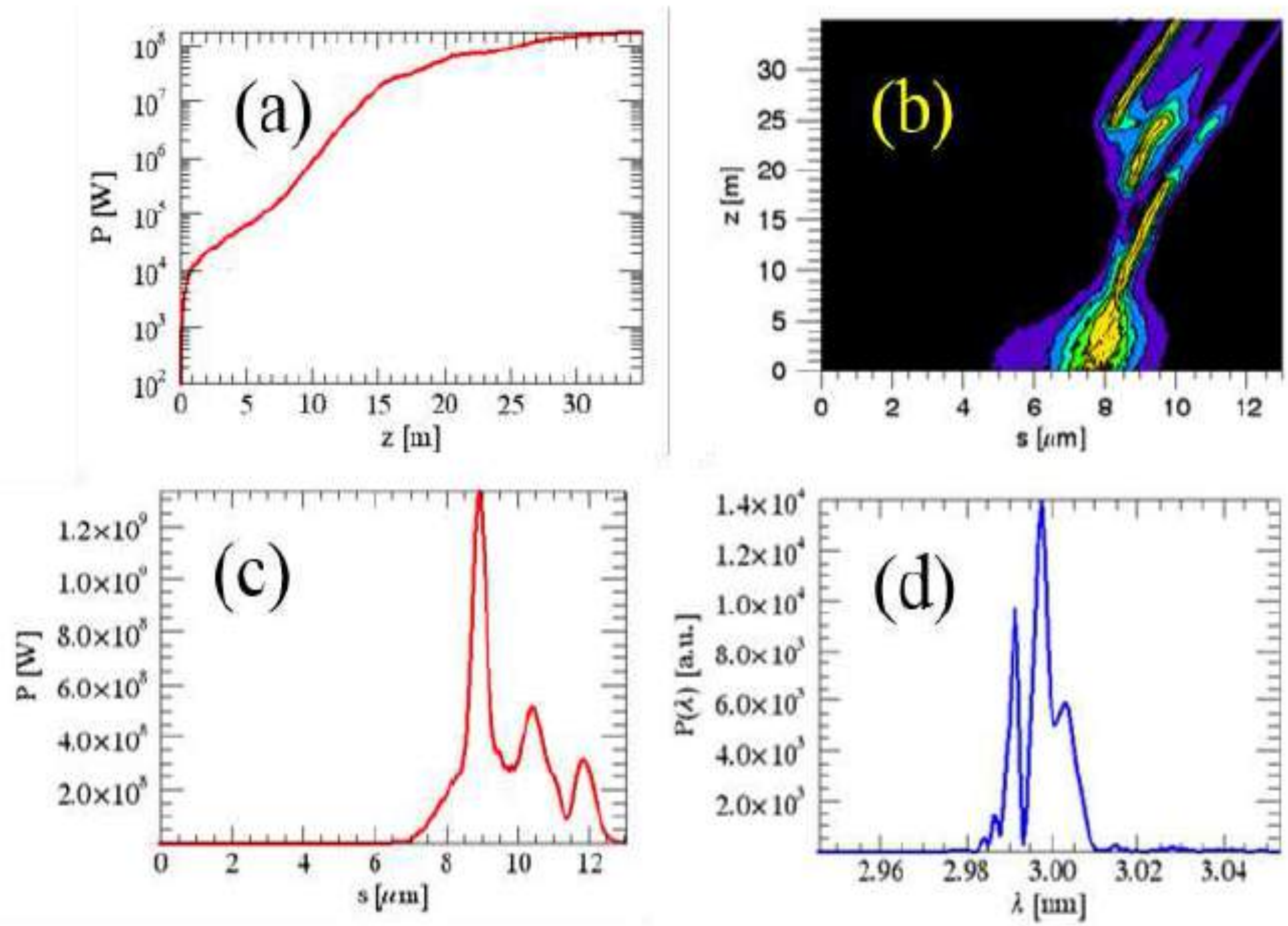
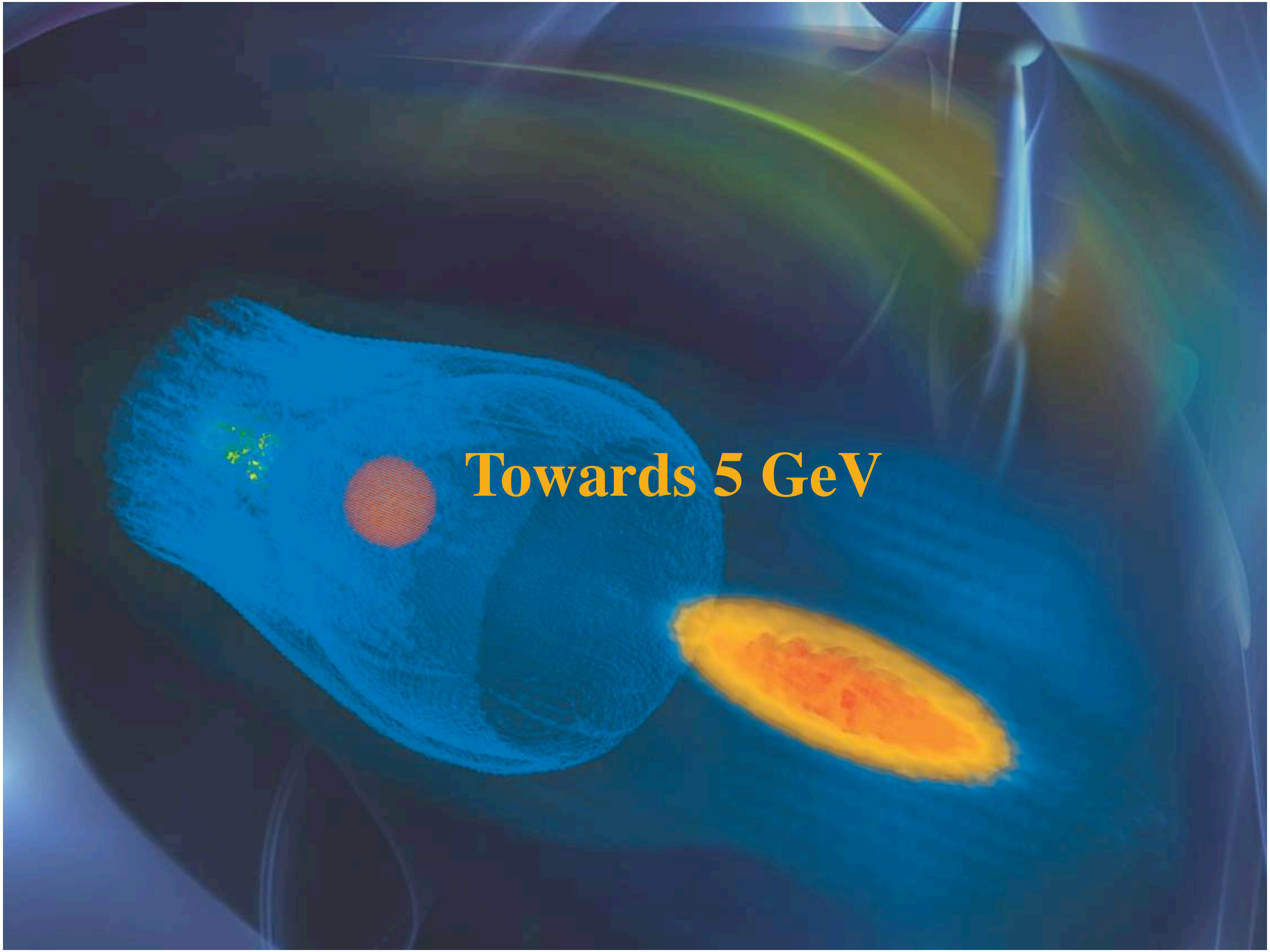


Figure 7.18: Particle driven acceleration: (a) Radiation growth along the undulator coordinate z(m). (b): Contour plot of the power P in the plane (s,z). (c) Power and (d) spectrum of the radiation at 30 m.

	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	$(\text{s mm}^2\ \text{mrad}^2\ \text{bw}(0.1\%))^{-1}$	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

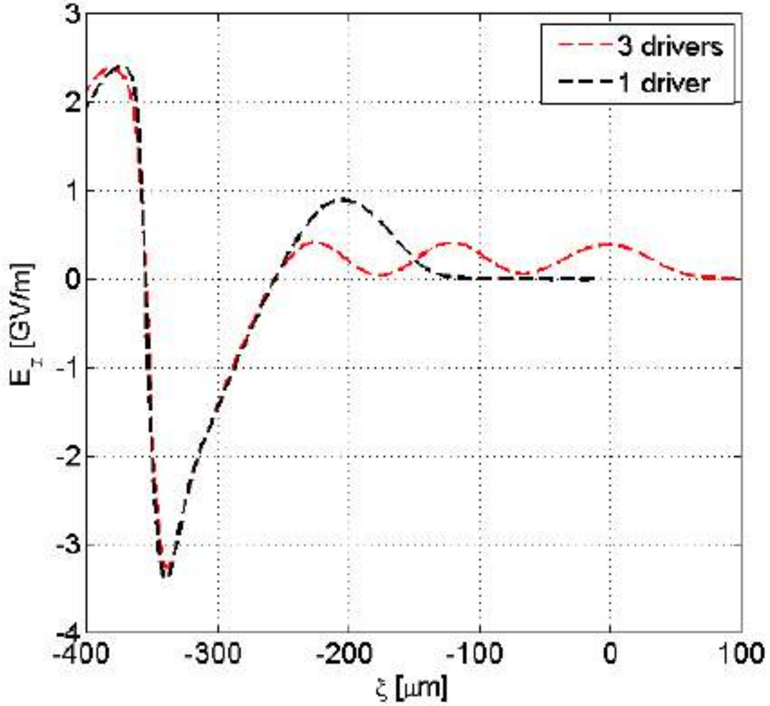

Towards 5 GeV

Driver parameters choice

$k_p \sigma_r \ll 1$	Efficient nonlinear wake excitation
$\beta_m = \frac{\sqrt{2\gamma}}{k_p}$	Transverse matching condition
$k_p \sigma_z = 1$	Maximum accelerating wakefield

$$n_p = 2.5 \cdot 10^{16} \mathrm{cm}^{-3}$$
$$\gamma = 2348$$
$$\varepsilon_{n(x,y)} = 1 \mathrm{mm\ mrad}$$
$$\sigma_z = 33 \mu\mathrm{m}$$

$$\sigma_{x,y} = \sqrt[4]{\frac{2}{\gamma}} \sqrt{\frac{\varepsilon_n}{k_p}} \Rightarrow \sigma_{x,y} = 1 \mu\mathrm{m}$$



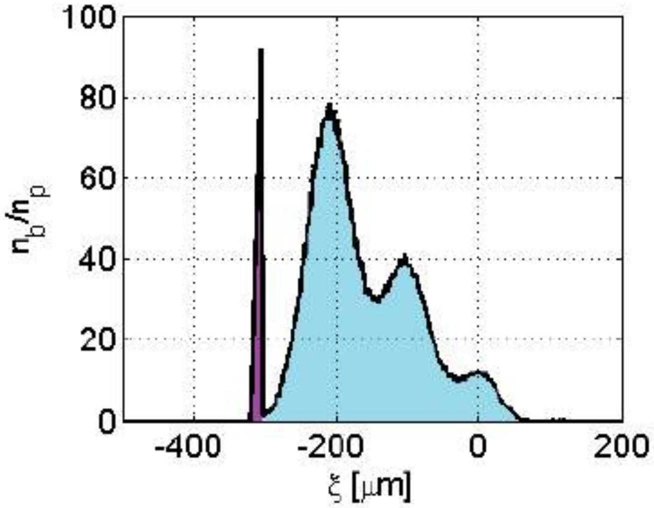
$\tilde{Q} = N_b \frac{k_p^3}{n_p}$	For the single bunch we choiced Q in order that $\tilde{Q} = 1$

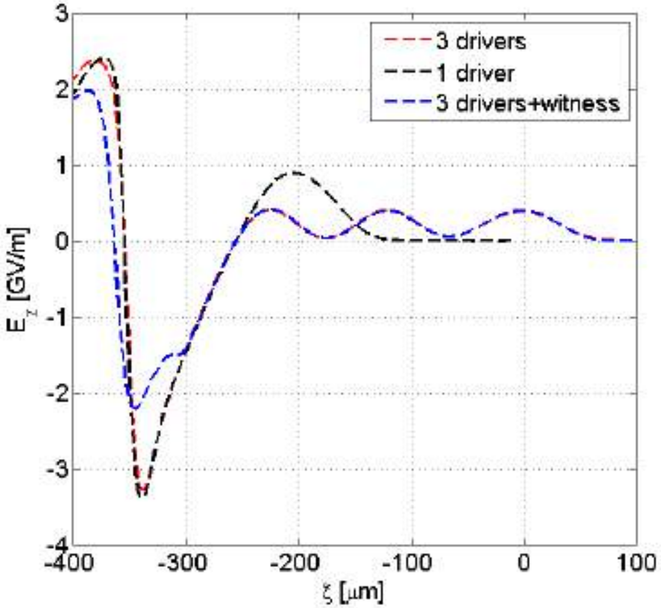
We arranged the charges of the 3 drivers in order to mantain the accelerating field and to have the same maximum decelerating field acting on every driver

$$Q_{tot} = 40 + 140 + 270 \mathrm{pC}$$

With this 3 bunch scheme we have $E_{z,max} = 3.3 \mathrm{GV/m}$ and $R_T \approx 8$

3 driver + witness





Witness:

- Triangular shape
- 3 kA peak current
- Length 16μm (3.8 rms)
- Emittance 0.7 μ m

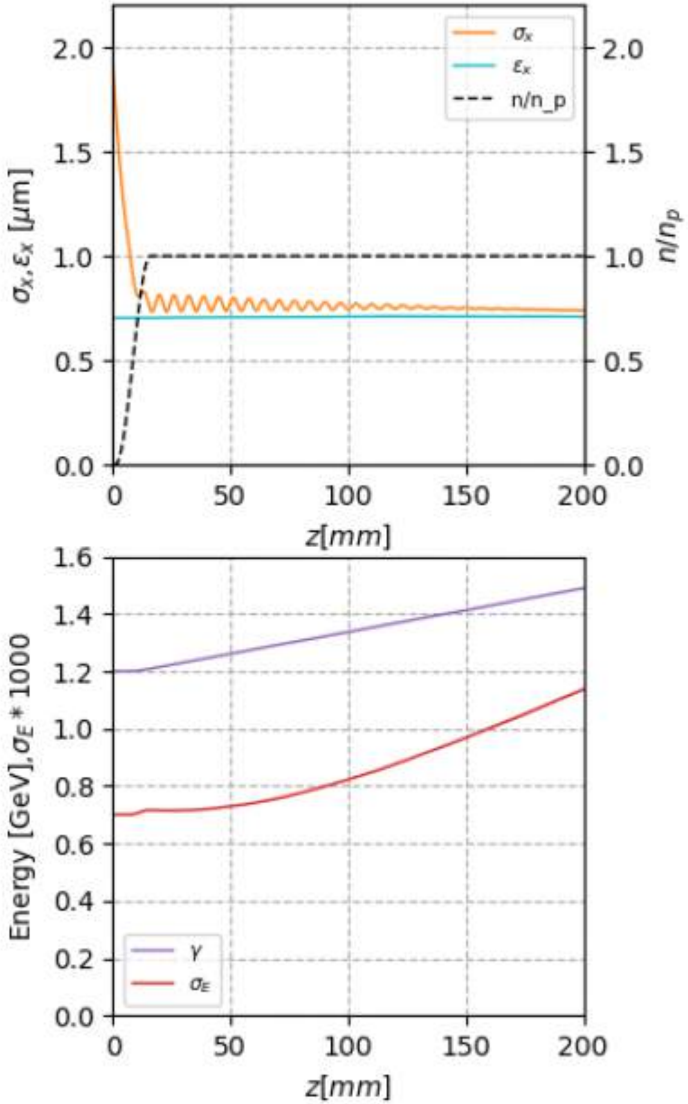
The high current of witness slightly decreases the accelerating field and the transformer ratio of a factor 2

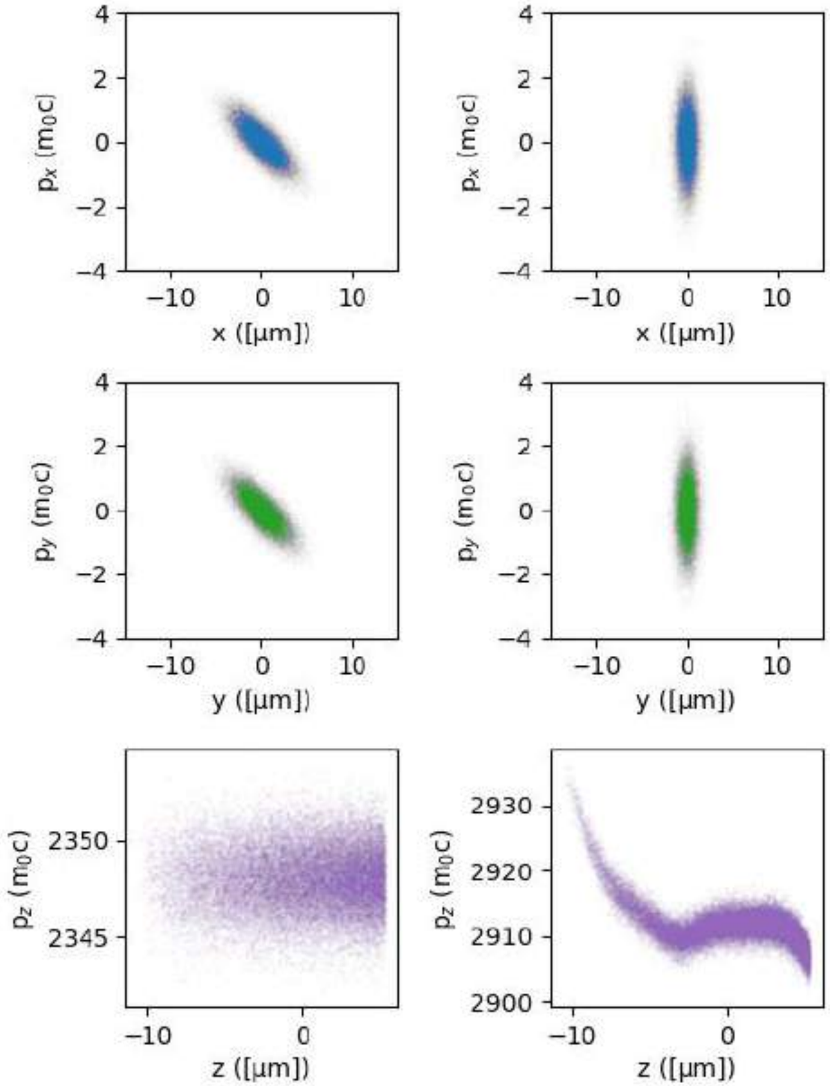
With this 3 bunch scheme we have $E_{z,max} = 1.5 GV/m$ and R_T =3.25

Final Final energy with the S-band inj. + X-band configuration $E_{fin} = 5.1\ GeV$

Expected energy spread $\sigma_E < 1\%$

Witness evolution (20 cm)





PWFA Cost estimate - 5 GeV

Components Phase 1	Cost k€	Partial Cost k€
S-band Injector	4,000	
4 X-band Linac modules	11,000	
Beam diagnostics	1,500	
LLRF & Synch.	1,400	
Control System	600	
Total RF Linac		**17,100**
Plasma module and diagnostics	500	
Plasma beam line	500	
Total plasma module		1,000


Thank for your attention