6 Gev Linac As FEL Driver And Storage Ring Injector

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on behalf of the Task 4.4 Team

Eurizon 2020+ workshop
FEL linac driver and FEL physics applications
European XFEL
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European network for developing new horizons for RIs

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Linac as Injector for FEL and Storage Ring

- One of the Eurizon project goal is the definition of a 6 GeV injector useful for
  - high brightness soft Free Electron Laser
  - X-ray storage rings (top-up injection)
- The 6 GeV linac will be driven by two type of front-ends
  - RF gun (thermionic/photo cathode) for the injection into the storage ring
  - RF photogun for the injection into the FEL
- Several options have been study basing on the S and C band RF technology
  - **Full S-band RF linac** → RF gun + booster linac of Standing Wave Biperiodical Accelerating Structures (BAS)
  - **Hybrid RF linac** → S or C band Standing Wave RF gun + C-band Traveling Wave RF linac

The same injection scheme is used for SuperKEK-B and MAX-IV and is proposed for FCC-ee

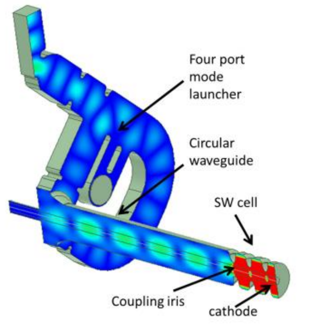

FIG. 13. Gun geometry with the circular wave-guide as result of ANSYS-HFSS simulations.

C-band photo-gun

S-band thermoionic gun

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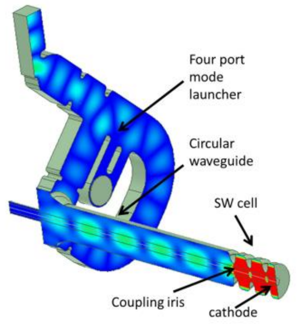
Definitive Proposal



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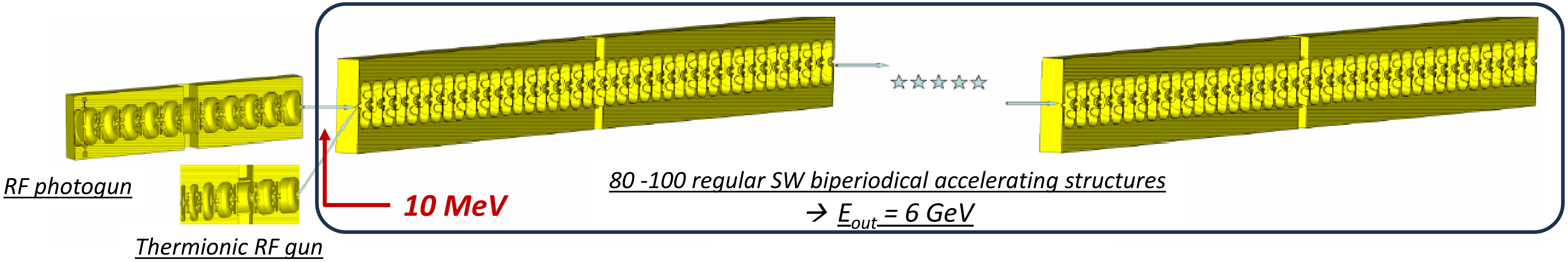
C-band photo-gun

S-band thermoionic gun

Full S-band RF linac *(previous proposal)*

- Beam dynamics analysis was done by using the BEAMDULAC-BL code [1] for both photo and thermionic cathode RF gun and for the booster linac [2,3,4]



Beam parameters from simulations	**Thermionic gun (250 mA)**	**Photo gun (250 pC)**
E (GeV)	6.0	6.3
<ε> (nm·rad)	1.5	0.3
<Bunch length> (ps)	25-34	0.01
<Energy spread> (%)	0.20 – 0.35	< 0.08
Current transmission coefficient (%)	46.5	99.5

[1] T. Bondarenko et al, "BEAMDULAC-BL code for 3d simulation of electron beam dynamics taking into account beam loading and Coulomb field", Prob.Atomic Sci.Technol. 2013 (2013) 6, 114-118.
[2] Yu. D. Kliuchevskaia, S. M. Polozov, 'Optimal rf-photogun parameters for the new injection linac for USSR project', RuPAC2021 proceedings, doi:10.18429/jacow-rupac2021-tupsb43
[3] I. A. Ashanin et al, 'Beam dynamics simulation in a linear electron accelerator – injector for the 4th generation specialized synchrotron radiation source USSR ', RuPAC2021 proceedings, doi:10.18429/jacow-rupac2021-mopsa08
[4] S. Polozov, et. al., Beam Dynamics Simulation Results in the 6 GeV Top-Up Injection Linac of the 4th Generation Light Source USSR, in Proc. of RuPAC2018, Protvino, Russia, Oct. 2018, paper WEPSB05

The RF Gun *(previous proposal)*

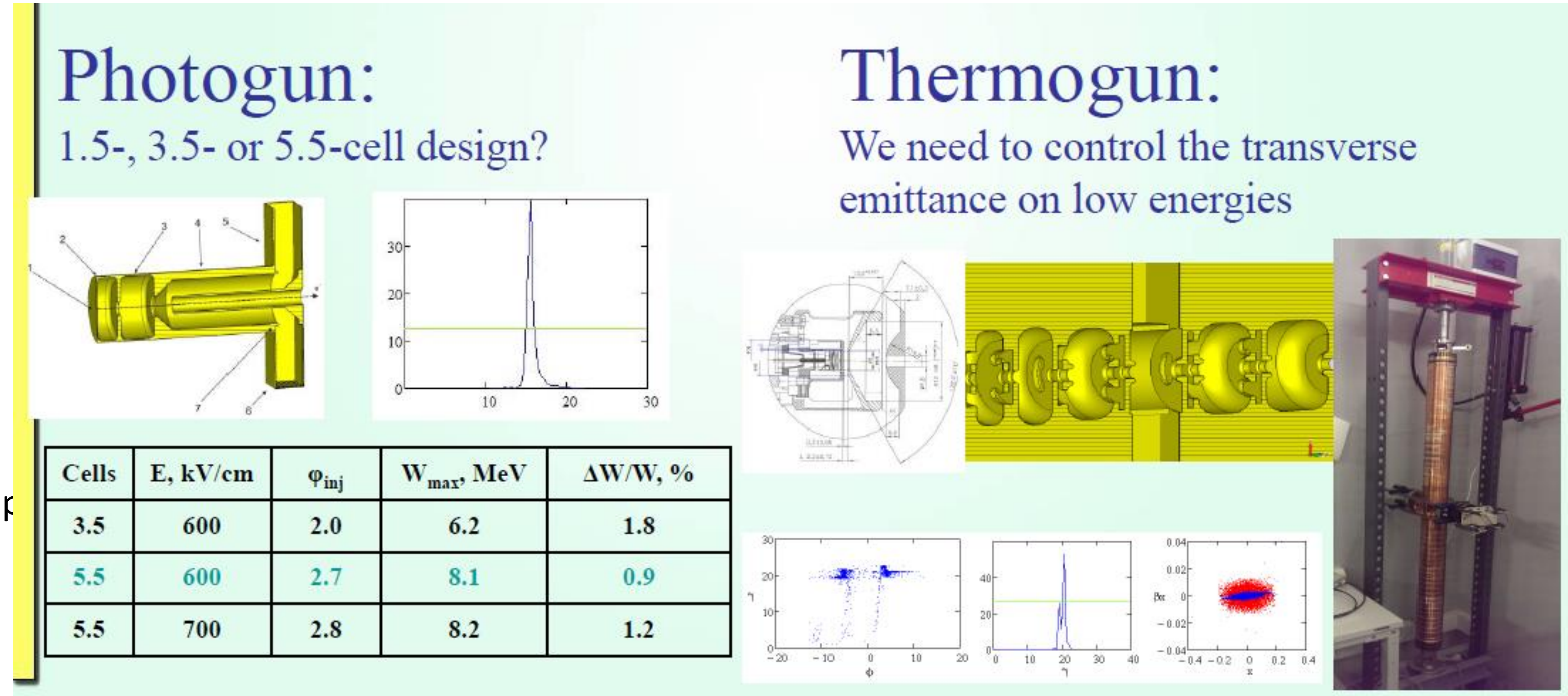
Several options have been investigated for both photo and thermionic gun that led to choose [4]

- ***Photo cathode gun*** → 5.5-cell accelerating structure with comparatively low accelerating gradient of 600 kV/cm
- ***Thermionic cathode*** → a classic adiabatic buncher consisting of 26 accelerating cells and 25 coupling cells. First 4 cells are the bunching cells and the phase velocity and the RF field amplitude growth here cell-to-cell. In the other 22 cells this parameters are constant

Table 1: Comparison of the RF-gun's Parameters

Parameter	Photogun	Thermogun
W_{inj}, keV	100	100-120
E_{acc}, kV/cm	450-600	150
W_{out}, MeV	10.5	10.3
Transmission coeff., %	100	85-90
FWHM, %	±1	±2 %
B, T	0.1	0.035

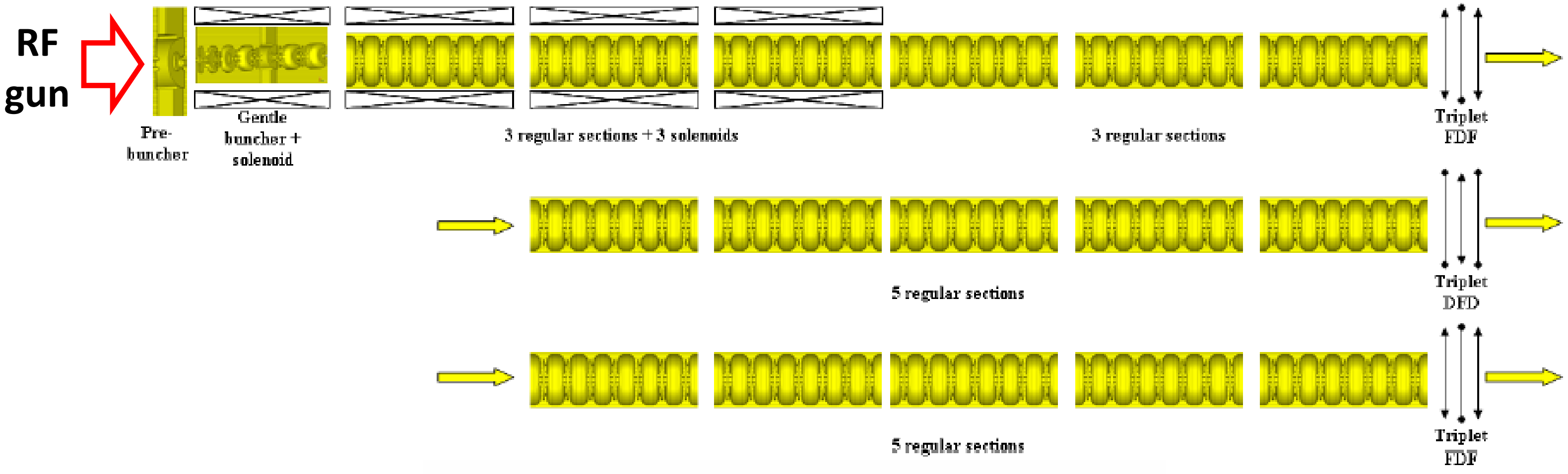
https://accelconf.web.cern.ch/rupac2021/papers/mopsa08.pdf

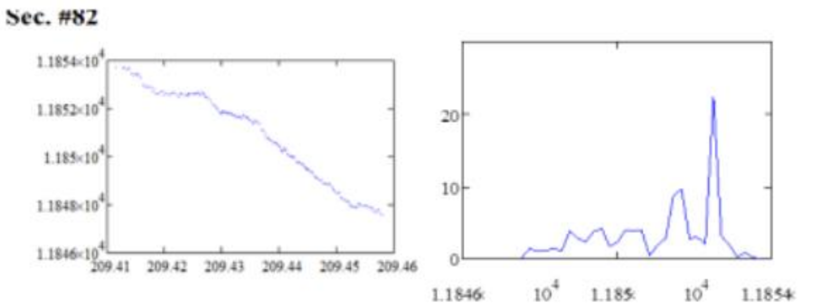


Cells	E, kV/cm	φ_{inj}	W_{max}, MeV	ΔW/W, %
3.5	600	2.0	6.2	1.8
5.5	600	2.7	8.1	0.9
5.5	700	2.8	8.2	1.2

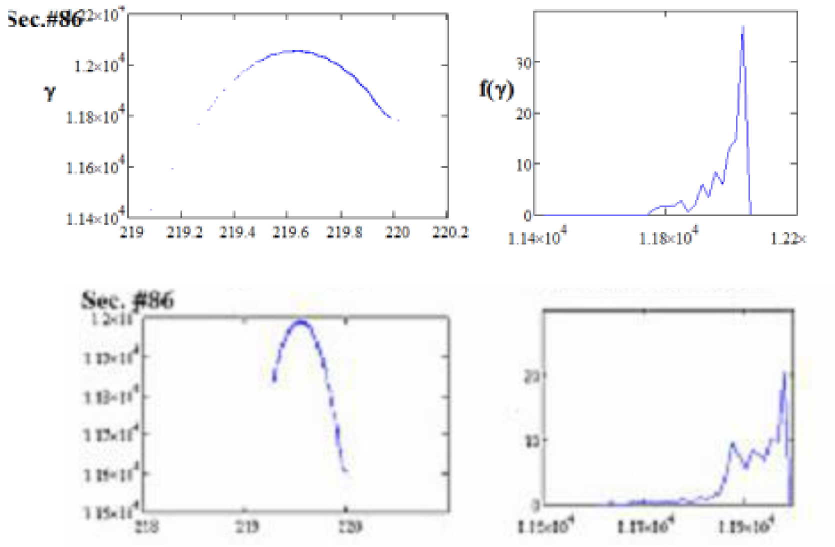
The energy booster [4] *(previous proposal)*

- The linac was made of
  - 80 to 100 SW *BAS* to boost the beam energy
  - A short klystron-type pre-buncher, operating on the half-frequency of 1428 MHz, and a gentle buncher to compress the bunch length and the decrease the bunch energy spectrum
- The beam focusing system consists of solenoids for energies up to 200 MeV, and triplets of quadrupole lenses for higher energies





Beam dynamics simulation results @6.3 GeV for the 250 pC bunch generated by photogun



Beam dynamics simulation results for 250 mA bunch generated by thermionic gun without (upper) and with (down) the pre-buncher

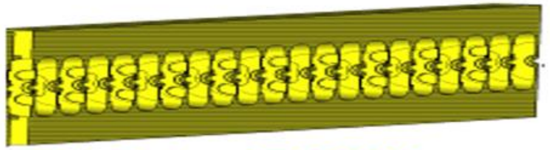
TW SLAC section and SW BAS [4]

- *TW SLAC section* have been also evaluated but excluded because
  - the energy spread and the transverse emittance at the injection were so high to lead to a low injection efficiency
  - comparatively lower energy spectrum was obtained in dynamics simulation of the beam at the output of SW BAS

Table 2: Comparison of the Beam Dynamics Simulation Results for Regular Part of Accelerator

Parameter	**TW SLAC**	**SW BAS**
Length, m	0.305	0.210
Energy gain, MeV/section	91	71
Number of sections	66	86
FWHM, %	±2.5	±0.9
Transverse emittance, nm·rad	1-5	0.3

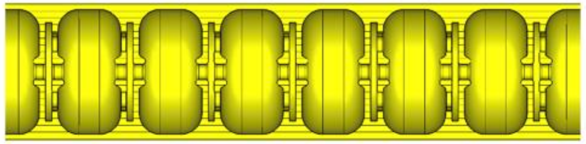
https://accelconf.web.cern.ch/rupac2021/papers/mopsa08.pdf



SLAC-type TW DLW:
3-m-length for 80MV/sec

-Low coupling coefficient
-Long RF pulse necessary
-High beam loading effect
-Wide spectrum

-Compression is possible!



Biperiodic Accelerating Structure (BAS) SW:
2-m-length for 75 MeV/sec

-High coupling coefficient
-Shorter RF pulse is necessary
-Lower beam loading effect
-Narrow spectrum

-Compression is theoretically possible but not realized!

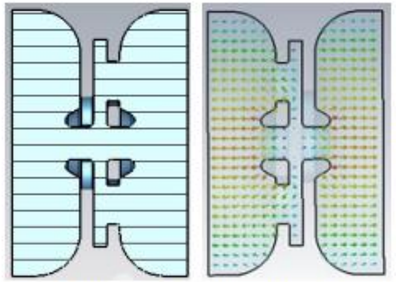


Figure 3: General view of regular section and electric field distribution.

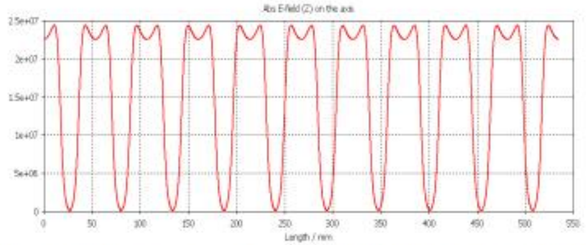
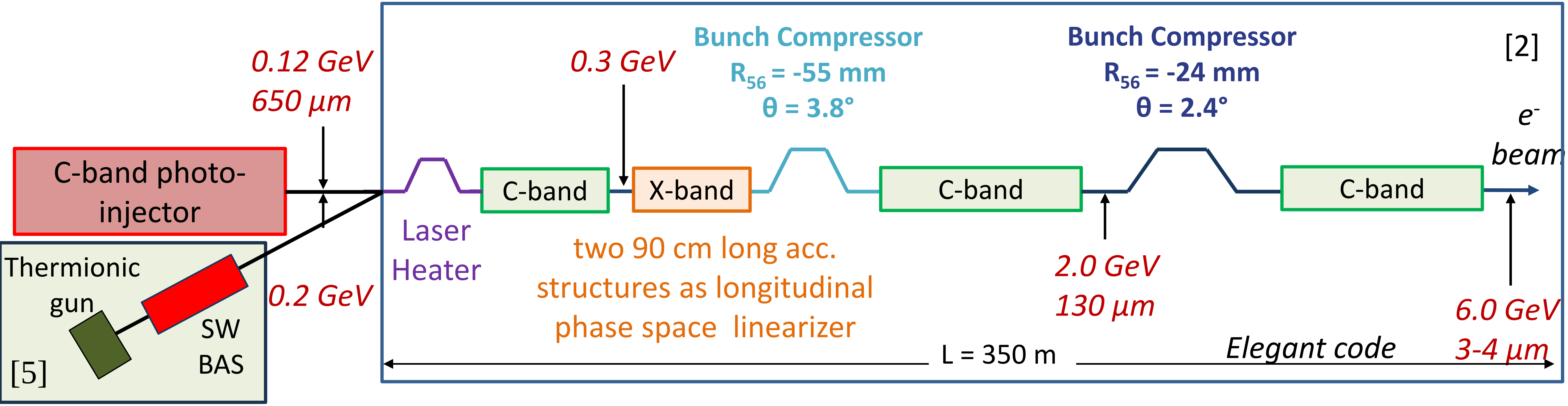


Figure 4: Electric field distribution of BAS structure consists of 10 sections.

The hybrid RF linac *(definitive proposal)*

- The hybrid solution integrates the described thermionic gun-based beamline and a C-band high brightness linac to feed both the storage ring and the FEL
- The integration takes place at ~ 200 MeV



- Beam dynamics simulations have been performed with
  - BEAMDULAC-BL code to study the thermionic gun-based injector [5]
  - ASTRA to study the space charge dominated part of the *photoinjector-based* beamline
  - Elegant to study the booster linac (emittance-dominated part of the *photoinjector-based* beamline)

[5] I. A. Ashanin, et. al., 200 MeV Linear Electron Accelerator – Pre-injector For A New Kurchatov Synchrotron Radiation Source, in Proc. of RuPAC2021, doi:10.18429/JACoW-RuPAC2021-MOPSA07

The FEL WP for Eurizon

- For the FEL a case of interest regards the emission of radiation at 4 nm and high brilliance
- Such parameters are achievable with e- beam parameters as

parameter	value [9]
energy	6 GeV
espread	2 MeV
peak current	5 kA
emittance, norm.	0.6 mm mrad
rms bunch length	6µm -> 20fs (250pC)

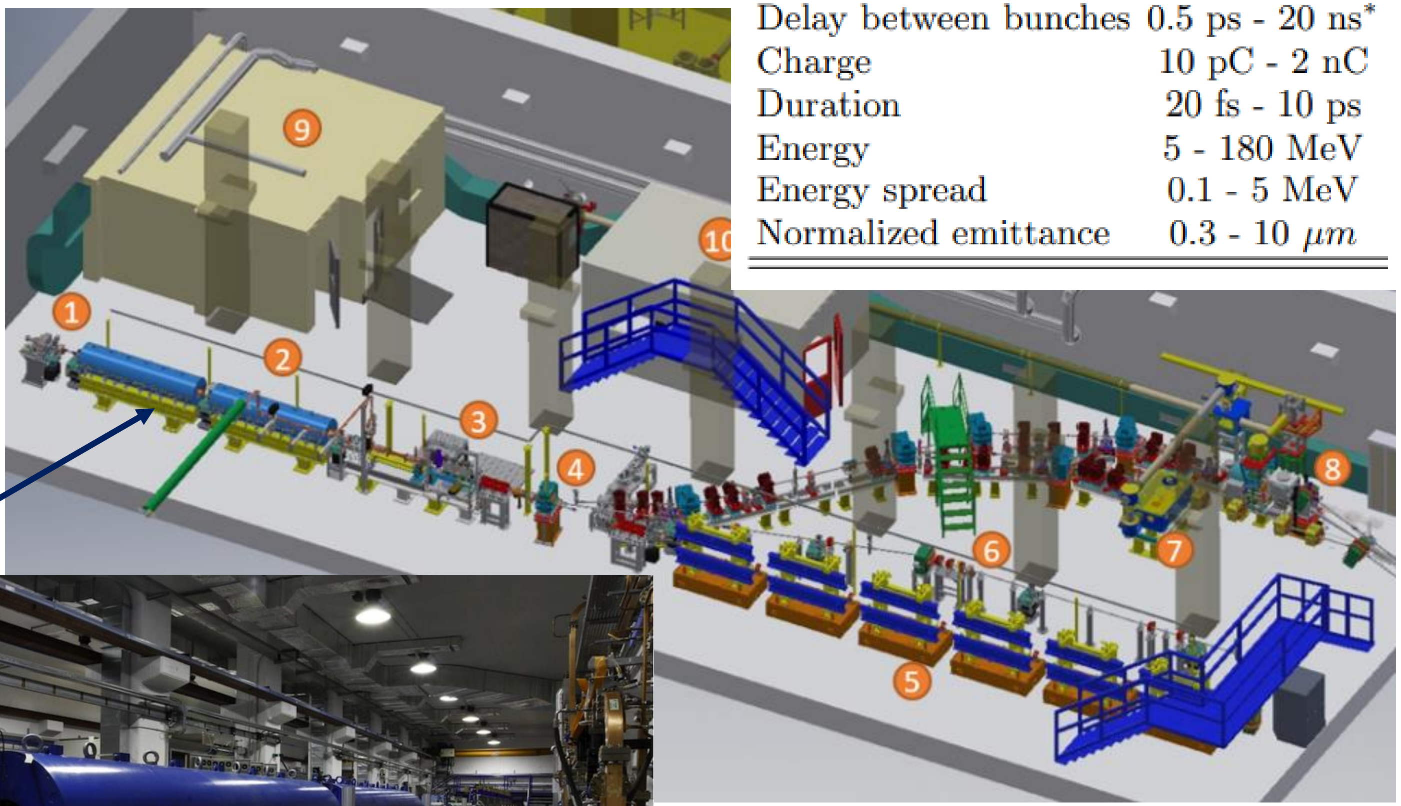
High brightness RF injectors designed at LNF with DESY and EuXFEL

[9] see Fabian Pannek talk at this Workshop

The INFN-LNF expertise: *high brightness photoinjectors*

- SPARC_LAB [1] is a test facility located at the **INFN National Laboratories in Frascati**
- The test facility hosts a 180 MeV ***high brightness photoinjector which feeds a 12 m long undulator***
- Main research activities regard the investigation of beam manipulation techniques and linac matching schemes useful for
  - linac-based radiation sources
  - new advanced acceleration concepts
    - plasma-based acceleration
    - S, C and X band technology

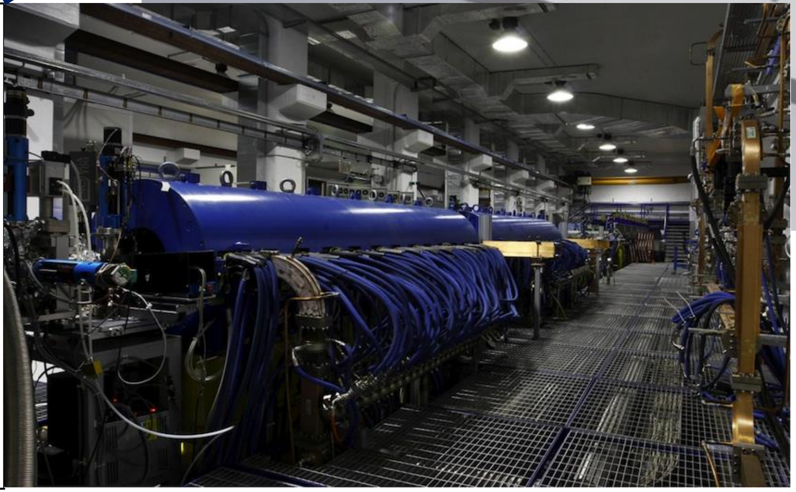
SPARC accelerator



Parameter	Value
Number of bunches	1 - 5
Delay between bunches	0.5 ps - 20 ns*
Charge	10 pC - 2 nC
Duration	20 fs - 10 ps
Energy	5 - 180 MeV
Energy spread	0.1 - 5 MeV
Normalized emittance	0.3 - 10 μm

The Photoinjector

The SPARC_LAB photoinjector is based on a 1.6 cell S-band RF gun which operates at ~120 MV/m peak on cathode. At the gun exit a solenoid is located for the emittance compensation and downstram two 3 m long S-band accelerating structures plus a 1.5 m C-band, are located providing a total energy of ~200 MeV on crest.



The INFN-LNF expertise: *high gradient accelerating structures at LNF*

- The INFN-LNF Accelerator Division is engaged in the development of high gradient normal conducting particle accelerator

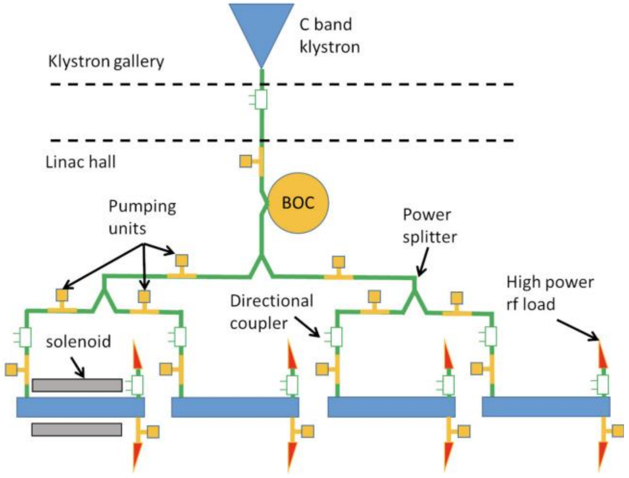


Figure 5.11.: Schematic layout of the C-band booster feeding system

Table 5.5.: Main parameters of the C-band structures.

Parameter	Unit	
Working Frequency	GHz	5.996
Phase advance per cell	rad	$2\pi/3$
Average iris radius $< a >$	mm	6.6
Iris radius **a**	mm	6.94-6.26
Number of cells per structure		120
Accelerating cell length	mm	16.67
Structure length $\mathbf{L}_s$	m	2
Shunt impedance **R**	MΩ/m	71 - 77
Effective shunt impedance $\mathbf{R}_s$	MΩ/m	190
Group velocity v_g/c	%	2.4-1.6
Filling time	ns	336
Average acceleration gradient	MV/m	15
Required input power per module	MW	9
Number of structure in the module		4

Table 5.6.: Main Parameters of the C-band Klystr

Parameter	Unit	Value
Operating frequency	GHz	5.996
Klystron pulse-length	μs	2
Klystron peak power	MW	15
Repetition Rate	Hz	1000
Q_0 of BOC		216000
Q_E of BOC		19100

Compact

*[6] Compact-Light Design Study (G. D'Auria et al, doi:*10.18429/JACoW-IPAC2019-TUPRB032)

[7] ELI-NP Gamma beam System

Technical Design Report
Final version
July 14th 2014

Table 16. Main parameters of the C-Band TW accelerating structures

Structure type	Constant impedance, TW
Working frequency (f_{RF})	5.712 [GHz]
Number of cells	102
Structure length	1.8 m
Working mode	TM_{01}-like
Phase advance between cells	c
Nominal RF input power (P_{IN})	40 MW
Average accelerating (E_{acc})	33 MV/m
Quality factor (Q_0)	8800
Shunt Impedance per unit length	67-73 MΩ/m
Phase velocity	c
Normalized group velocity	0.025-0.014 (v_g/c)
Filling time (τ)	310 ns
Structure attenuation constant	0.58 neper
Operating vacuum pressure (typical)	10^{-8}-10^{-9} mbar
Max RF input pulse length (τ_{IMP})	0.8 μs
Pulse duration for beam acceleration (τ_{BEAM})	<500 ns
Iris half aperture (a)	6.8-5.8 mm
Rep. Rate (f_{rep})	100 Hz
Average dissipated power	2.3 kW

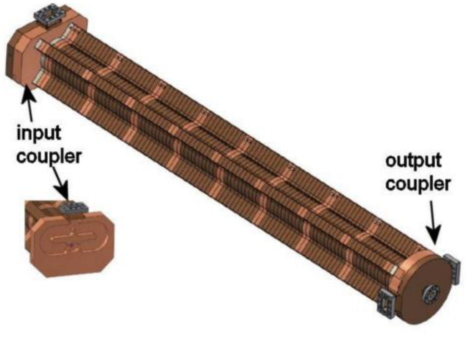


Fig. 66. Mechanical drawings of the C-band structure with details of couplers

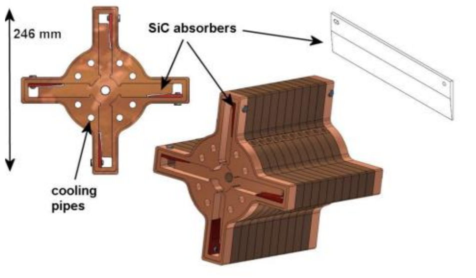


Fig. 67. Detail of the TW cell with absorbers

Headquarter and Site 1: EuPRAXIA@SPARC_LAB

Frascati`s future facility

- > 130 M€ invest funding
- Beam-driven plasma accelerator - ***PWFA***
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator **X band with CERN**

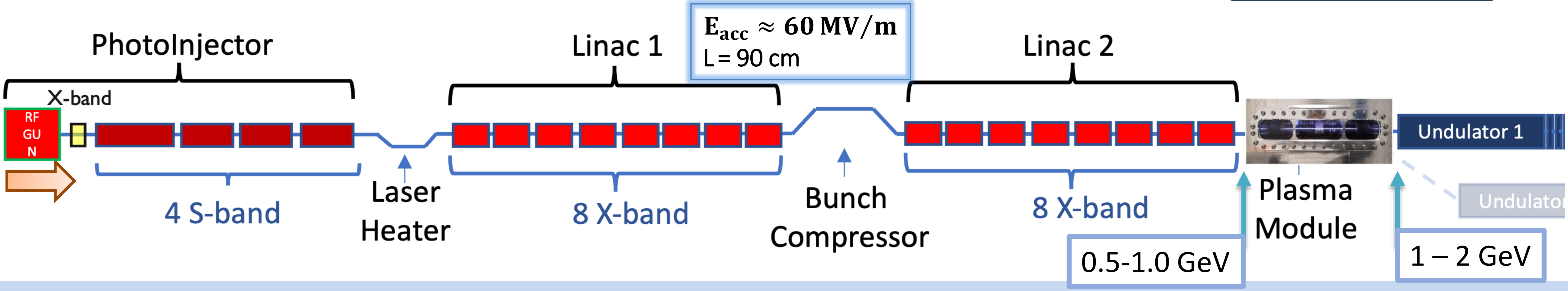
Credit: INFN and Mythos – consorzio stabile s.c.a.r.l.

A Beam-Driven Plasma Wake-field Accelerator

- **EuPRAXIA@SPARC_LAB** is a multi-GeV plasma-based accelerator with outstanding beam quality to drive a user facility whose main application concerns the operation of a soft X-ray FEL (3-5 nm)
- The FEL is driven by a 1 GeV high brightness electron beam, that turns into less than 1 mm-mrad emittance and up to 2 kAmps peak current.
- The accelerator is based on the unique combination of an **advanced high-brightness RF injector** and a **plasma-beam driven accelerator**

RMS e- beam parameters @plasma module entrance

	Single bunch (WoP2)	Comb beam operation (WoP1)	
		Witness	Driver
Q (pC)	200 - 500	30 -50	200 -500
E (GeV)	up to 1.0	Up to 0.650 GeV	
Δγ/γ (%)		< 0.10	
$\varepsilon_{nx,y}$ (mm·mrad)	< 1.0	0.5 - 1.0	2.0 -5.0
$\sigma_{z\text{-}rms}$ (μm)	20 - 50	< 6	< 65
$I_{peak\text{-}slice}$ (kA)	1.0 – 2.0	> 1.5	



High brightness electron beams

- High brightness electron beams have shown to be essential for the realization of brilliant radiation sources (FEL, inverse Compton sources or THz sources) as well as to guide novel acceleration and manipulation schemes based on high gradient wake-fields (plasma accelerators among others)

- The 6D brightness, B, is defined as:

$$B[\mathrm{A/m^2}] = \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}\sigma_t\sigma_\gamma},$$

- where

  Q is the beam charge
  ε_{nx} and ε_{ny} are the normalized transverse emittances
  σ_t is the bunch length
  σ_γ is the energy spread

- Thus, a high brightness beam results in a **large number** of **quasi-monochromatic electrons**, concentrated in very **short bunches**, with **small transverse size and divergence**, that is a *high particle density 6D phase space*

High brightness electron linac

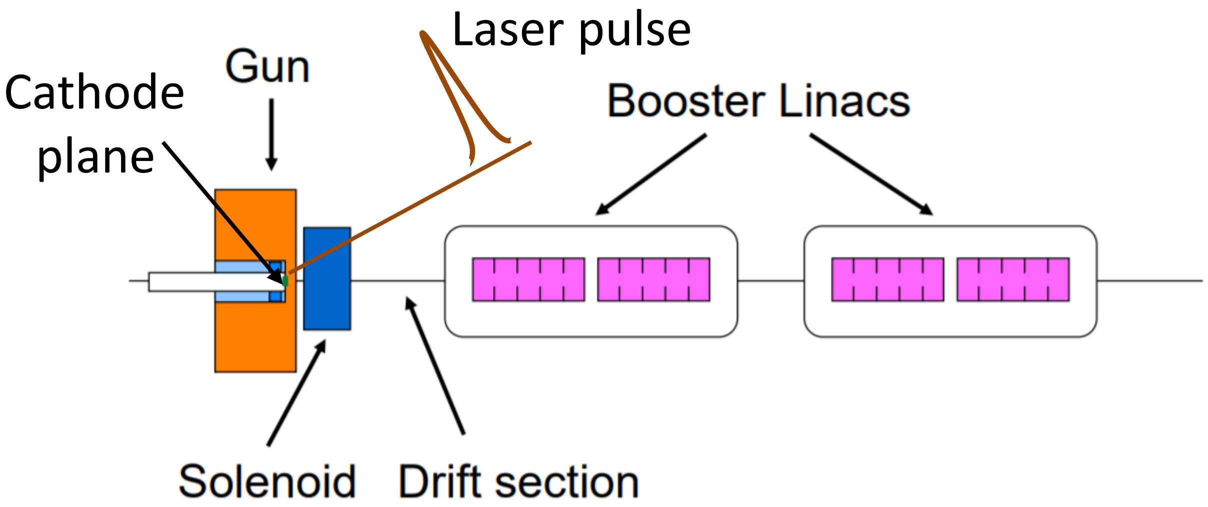
- The expertise acquired in the last decade on the combination of ***high brightness rf photoinjectors*** and ***high gradient booster linac*** has driven to established devices in the generation of high brightness electron beams

- The RF photoinjector, where the beam explores the collective effects at very low energy, plays a crucial role in the ***determination*** of the best transverse beam quality

- The high-gradient booster linac allows for few GeV electron beams in a relatively small footprint accelerator ***preserving*** the transverse beam quality or ***improving*** the ultimate 6D beam quality

High brightness photoinjectors

- A photoinjector consists of an RF gun, equipped with a laser driven photocathode system and a solenoid surrounding the gun, that can be followed by one or more accelerating structures as booster section.



- The strength of a photoinjector lies in opportunity to explore a wide range of working points in terms of beam parameters to drive very different kinds of devices → for a high brilliance radiation source as a free electron laser (FEL) one must optimise the peak brightness
- The main challenge for an RF high brightness photoinjector is generating electron beams with low transverse emittance (less than 1 mm mrad) and up to kA peak current

SPARC LAB

Transverse beam emittance

- In the photoinjector the electron beam is emitted from the cathode surface, illuminated by a laser pulse, when the applied RF accelerating field overcomes the electric field produced by the electron bunch itself—image and space charge fields.
- The properties of the photoelectrons arising from the cathode determine the beam intrinsic emittance that represents the ***lowest beam emittance value one can expect at the photoinjector exit***

$$\epsilon_{intrinsic} = \sigma_x \sqrt{\left(\frac{m^*}{m}\right)\left(\frac{\hbar\omega - \phi_{eff}}{3mc^2}\right)}$$

full width of the emitted electron energy spectrum

$$\phi_{eff} = \phi_w - \phi_{Schottky} = \phi_w - \alpha\sqrt{\beta E_{RF}} = \phi_w - e\sqrt{\frac{e}{4\pi\varepsilon_0}(\beta E_{RF})}$$

Cathode material	E_{RF}^{peak} [MV/m]	σ_{rms} [mm]	$\varepsilon_{n,int}$ [μm]	QE
Cu	240	0.17	0.12	10^{-5}-10^{-4}

Courtesy of J. Scifo Athens XLS meeting

- Once emitted, the electron beam experiences external and internal forces that degrade the beam quality as
  - strong self-fields → space charge emittance oscillations
  - fields in the accelerating cavities → emittance oscillations
  - fields of the transport optics → chromatic and geometric aberrations

$$\varepsilon = \sqrt{\varepsilon_{\text{int}}^2 + \varepsilon_{\text{roughness}}^2 + \varepsilon_{\text{rf}}^2 + \varepsilon_{\text{SC}}^2 + \varepsilon_{\text{solenoid}}^2}.$$

Beam emittance compensation

- It is possible to restore the initial transverse emittance value by
  - properly setting the magnetic field of the solenoid surrounding the gun to counteract the beam internal space charge forces and the external rf kick
  - pushing quickly the beam up to relativistic energy to freeze the beam transverse emittance
  - Applying the **invariant envelope** theory [7]: if a downstream booster section follows the gun, it is recommended to place it where the beam emittance exhibits its maximum and to set the gun solenoid so to let the emittance oscillations damp down to the intrinsic value; that way the beam is quickly pushed up to relativistic energy and the emittance oscillation can be frozen and reach its minimum at the exit of the accelerating section
- The laser pulse setup determines the emittance quality
  - **pancake beams** → very short beams, higher transverse emittance
  - **cigar beams** → pulse length in the mm range so to reduce the emittance degradation due to the transverse space charge forces before the beam becomes ultra-relativistic. This set point allows for an electron beam with sub mm mrad transverse emittance

$$F_x = \frac{e\hat{I}x}{8\pi\gamma^2\varepsilon_0\sigma_x^2\beta c}g(\zeta)$$

Space charge defocusing is primarily a non-relativistic effect and decreases as γ^{-2}

Envelope equation:

$$\sigma'' + \frac{\gamma'}{\gamma}\sigma' + \left(\frac{k}{\gamma}\right)^2\sigma = \frac{I}{2I_A\gamma^3\sigma} + \frac{\varepsilon_n^2}{\gamma^2\sigma^3}$$

Invariant envelope criteria:

- laminar envelope waist ($\sigma' = 0$)
- σ matched to the accelerating and focusing gradients to stay close to an equilibrium mode

$$\sigma = \frac{1}{k}\sqrt{\frac{I_0}{4\gamma_0 I_A}\left(1 + \sqrt{1 + \left(4\frac{\varepsilon_n\gamma_0 k I_A}{I_0}\right)^2}\right)}$$

[7] L Serafini and J B. Rosenzweig Phys. Rev. E **55, 7565** (1997)

The C-band photoinjector [8]

- The proposed C-band photoinjector, designed and simulated at Frascati National Laboratory (LNF), is the result of a long design study carried out in the framework of the CompactLight, EuPRAXIA@SPARC_LAB and IFAST projects.
- The C-band technology could represent a good compromise between the S and X-band ones

✓ it still allows for exploring a wide range in terms of beam charge and length

✓ it allows for a more compact beamline compared to S-band solution

✓ it enables high repetition rate operation with higher field compered to S-band solution

→ up to 160 MV/m peak field on cathode in the gun

→15 MV/m average field in TW sections

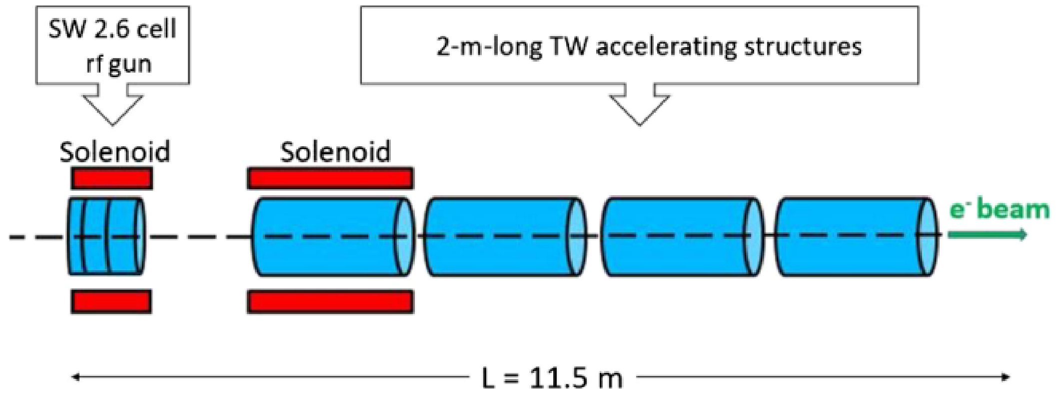


FIG. 1. The *C*-band photoinjector layout, designed and simulated at Frascati National Laboratory (LNF). It consists of a 2.6 cell standing wave gun, with an emittance compensation solenoid, followed by four traveling wave accelerating structures. The TW accelerating structures are 2 m long and can be powered up to 31 MV/m (at 100 Hz repetion rate); the first one is surrounded by a solenoid.

[8] Giribono et al. - Dynamics studies of high brightness electron beams in a normal conducting, high repetition rate C-band injector, PHYSICAL REVIEW ACCELERATORS AND BEAMS 26, 083402 (2023)

The 2.6 cell C-band gun

- The gun is a 2.6-cell standing wave (SW) structure operating with a peak field (E_{cath}) at the cathode of 160 - 180 MV/m.
- A four-port mode launcher with an on-axis coupling has been adopted to reduce the pulsed heating on the coupler and to perfectly compensate the dipole and quadrupole field components
- The insertion of the mode launcher has opened to an increased flexibility in positioning the input waveguide relative to the gun body that results in a more powerful cooling capability of the accelerating cells especially useful in the high repetition rate operation (1 kHz)

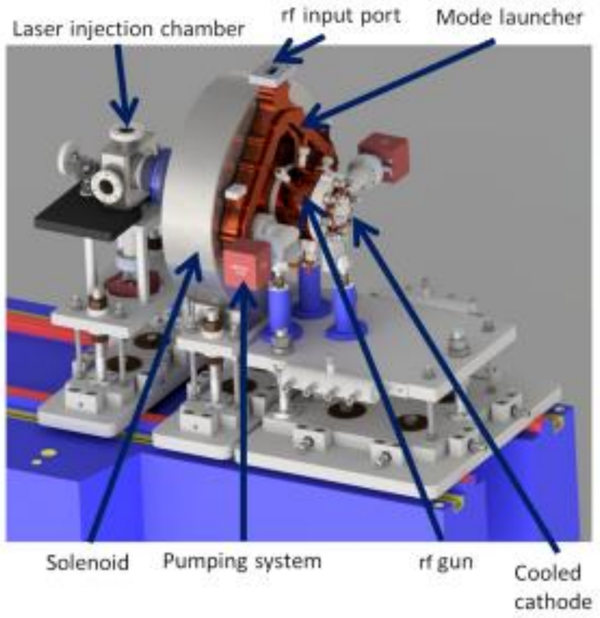
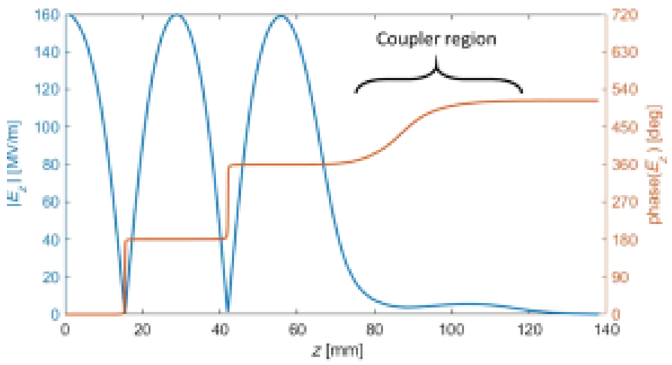


FIG. 8. Three dimension mechanical drawing of the entire gun region, also including essential components as the pumping system, the solenoid and the laser injection chamber.



IG. 7. Amplitude and phase of the longitudinal electric field long the beam propagation axis. The plot also includes the mode uncher region, where the field presents a traveling wave omponent (nonconstant phase) related to the power flow into ie gun.

Courtesy of D. Alesini et al.

TABLE II. Main gun parameters for the 100 Hz operation rate and for the 400 Hz repetition rate (in parenthesis), the latter being the maximum operation rate for available commercial klystrons [43].

Working frequency (GHz)	5.712
$E_{cath}/P_{diss}^{1/2}$ [MV/(mMW$^{1/2}$)]	51.4
rf input power (MW)	23 (18)
Cathode peak field (MV/m)	180 (160)
Cathode type	copper
Rep. rate (Hz)	100 (400)
Quality factor	11900
Filling time (ns)	166
Coupling coefficient	3
rf pulse length (ns)	300
E_{surf}/E_{cath}	0.96
Modified Poynting vector (W/μm^2)	3.2 (2.5)
Pulsed heating (°C)	20 (16)
Average diss. Power (W)	320 (1000)

The TW accelerating structures

- The C-band traveling wave module is made up of four 2 m long traveling wave accelerating structures fed by one klystron and one pulse compressor

ELI-NP dumped cells for multi-bunch operation (100 Hz)

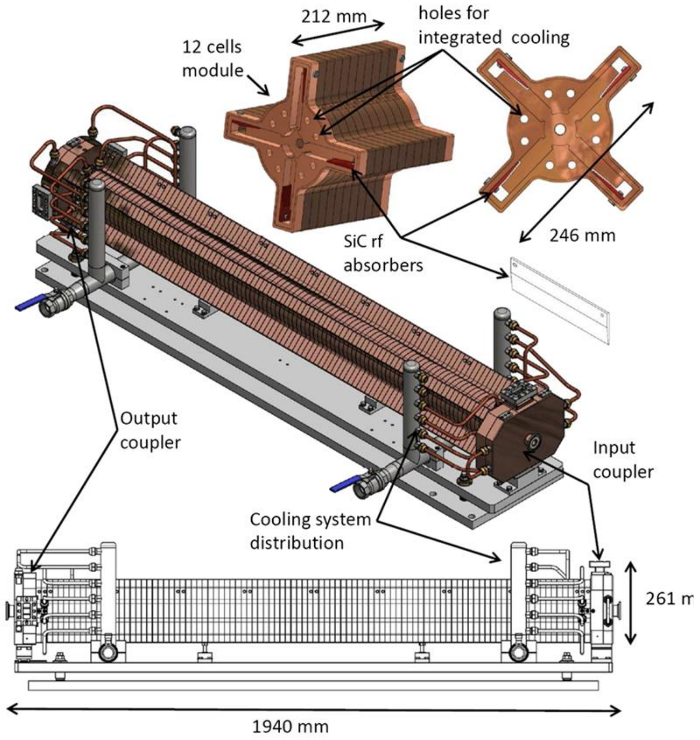


TABLE I. Main parameters of the ELI-NP accelerating structures.

Parameter	Value
Working frequency (f_{rf})	5.712 GHz
Cell phase advance	$2\pi/3$
Number of cells	102
Structure length	1.8 m
Iris aperture radius	6.8–5.78 mm
Repetition rate	100 Hz
Average quality factor	8850
Average accelerating field	33 MV/m
Shunt impedance	67–74 MΩ/m
Group velocity (v_g/c)	0.025–0.015
Filling time	313 ns
rf input power (P_{in})	40 MW
Output power (P_{out})	$0.29P_{in}$
Pulse duration for beam (τ_{beam})	<512 ns
Pulsed heating (input coupler)	<21 °C
Average wall-loss power	2.3 kW
Working temperature	30 °C

D. Alesini *et al*,0.1103/PhysRevAccelBeams.23.042001

Compact Light TW cells for high rep rate (100 -400 Hz)

TABLE IV. Main parameters of the *C*-band structures (in parenthesis we have reported the 400 Hz repetition rate case).

Working frequency (GHz)	5.712
Phase advance per cell (rad)	$2\pi/3$
Average iris radius $\langle a \rangle$ (mm)	6.6
Iris radius **a** (mm)	6.94-6.26
Number of cells per structure	120
Accelerating cell length (mm)	16.67
Structure length $\mathbf{L}_s$ (m)	2
Shunt impedance **R** (MΩ/m)	71–77
Effective shunt impedance $\mathbf{R}_s$ (MΩ/m)	190
Group velocity v_g/c (%)	2.4–1.6
Filling time (ns)	336
Average acceleration gradient (MV/m)	31 (15)
Required input power per module (MW)	41 (9)
Number of structure in the module	4

Solenoids

Courtesy of A. Vannozzi et al.

- Axial symmetric 2D simulations have been performed with Poisson Superfish

Gun solenoid

The gun solenoid is a 12 cm long device consisting in a single coil with a bore radius of 3 cm

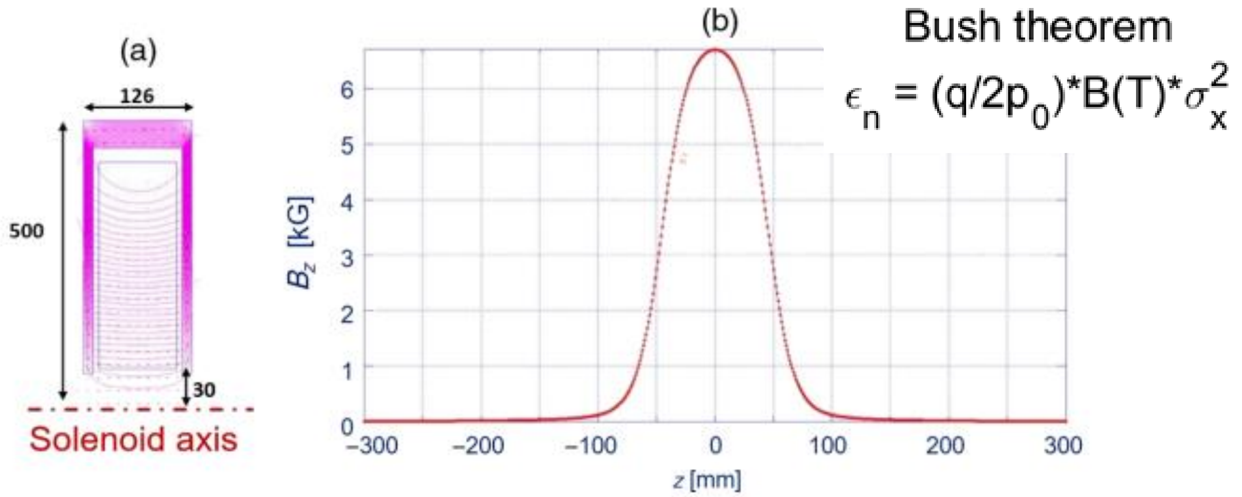


FIG. 9. (a) Solenoid geometry (dimensions are in mm) and (b) the on-axis magnetic field as obtained by means of Poisson-Superfish simulations.

TW acc. Solenoid

The solenoid around the first accelerating structure is composed of four coils embedded in an iron shielding

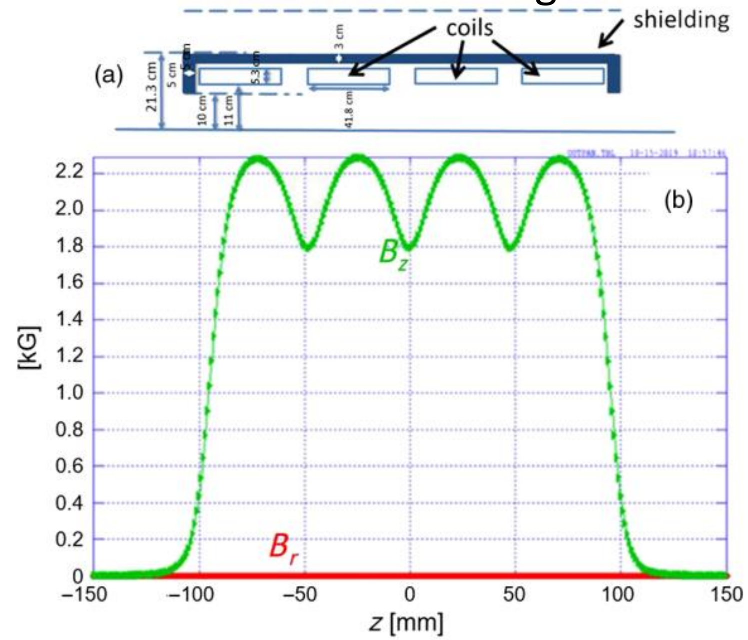


FIG. 11. (a) Geometry of the *C*-band solenoid simulated with Poisson-Superfish (dimensions are in mm); (b) longitudinal (B_z) and radial (B_r) magnetic field on axis.

Beam Dynamics Studies

- A wide set of working points has been explored in terms of beam charge and bunch length looking at the requirements of the recently proposed European FEL user facilities, such as CompactLight (XLS) or EuPRAXIA@SPARC_LAB (E@S), and of the state of the art ones, taking as reference the SwissFEL performances.
- The common issue lies in the production of electron beams with brightness of the order of 10^3 TAm^2 that turns in transverse emittance lower than 1 mm mrad and final kA peak current

TABLE I. List of the working points described in this paper.

	Low charge		Medium charge			High charge		Units
Charge	75	75	200	200	200	500	500	pC
Average energy	125	105	125	250	200	200	125	MeV
Transverse normalized emittance (100%—rms)	0.15	0.18	0.25	0.25	0.37–0.69	1.3	0.65	mm mrad
Transverse normalized emittance (95%—rms)	0.11	0.13	0.18	0.16	0.25–0.45	0.80	0.44	mm mrad
Length (rms)	380	100	500	500	280–55	55	720	μm
Peak current	20	85	40	40	70–500	1000	70	Ampere
rf compression	off	on	off	off	on	on	off	
Repetition Rate	high	high	high	low	low	low	high	
Peak field @cathode	160	160	160	180	180	180	160	MV/m
TW structure accelerating field	15	15	15	31	31	31	15	MV/m

[8] Giribono et al. - Dynamics studies of high brightness electron beams in a normal conducting, high repetition rate C-band injector, PHYSICAL REVIEW ACCELERATORS AND BEAMS 26, 083402 (2023)

Beam Dynamics Studies – Medium charge WP

- The beam dynamics has been studied to generate a 200 pC beam with a variable length in the range 55–500 µm.
- In details, four beam lengths have been investigated
  - 55 µm of interest as driver of a particle wake field acceleration accelerator
  - 100 and 280 µm representing the maximum lengths to avoid distortions of the longitudinal phase space in a downstream X or C-band booster linac, respectively
  - 500 µm → the on-crest operation with performances very close to the SwissFEL facility considering both the high and low repetition rate

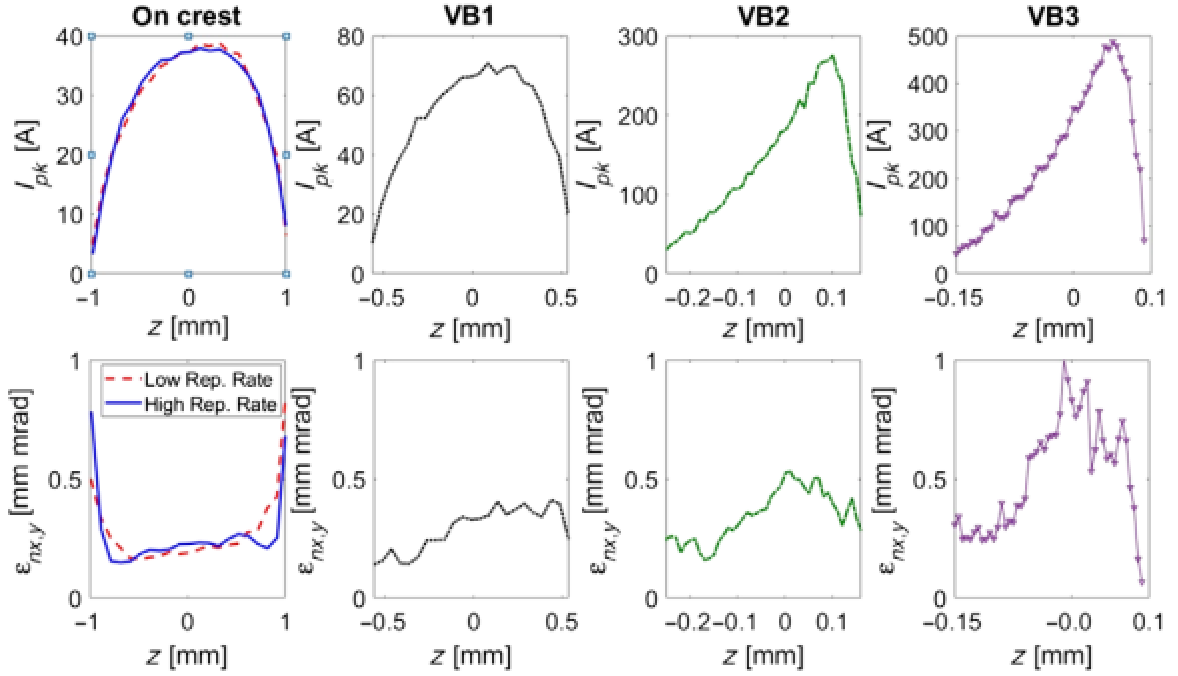
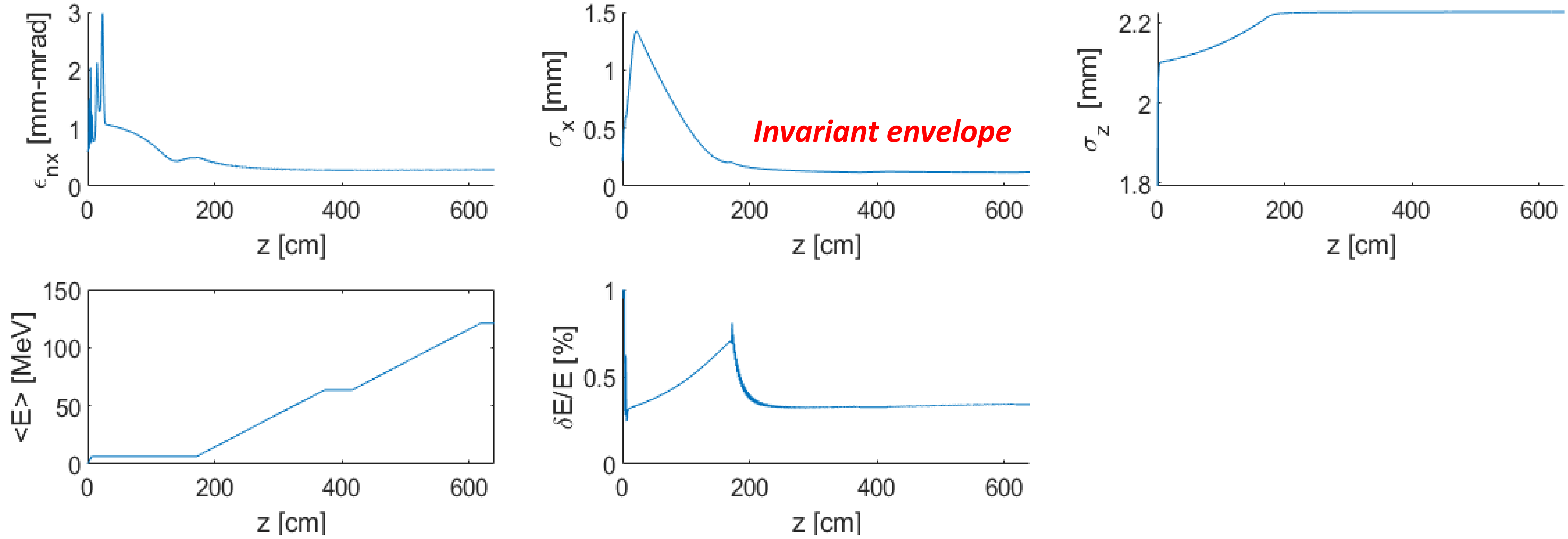


FIG. 5. Slice analyses of the transverse normalized emittance and of the peak current for different compression factors in case of velocity bunching operation. The VB 1 to 3 are related to the case of final beam length of 280, 100, and 50 µm, respectively.

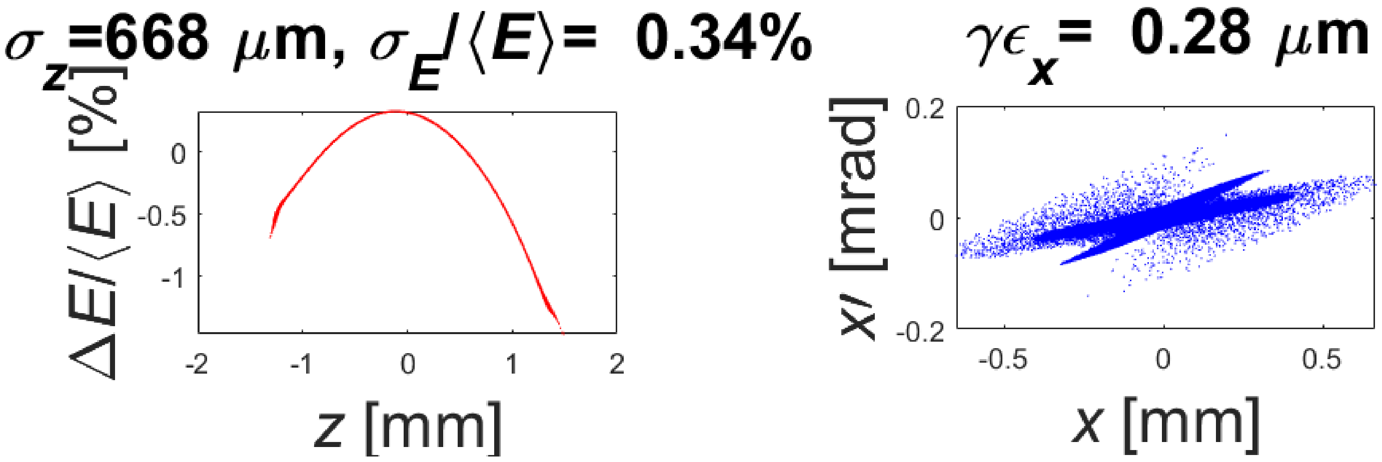
Beam Dynamics Studies – Eurizon WP

- **The beam dynamics has been studied by means of simulations with the *ASTRA* code**
- A 250 pC beam is used as reference working point
  - The beam distribution at the cathode has been chosen looking at the beam quality at the photoinjector exit
    - Flat-top 8.5 ps fwhm
    - Transverse uniform profile with 170 μm rms beam size
  - The photoinjector is sets **on-crest** to obtain as much as possible low transverse emittance @ph.exit

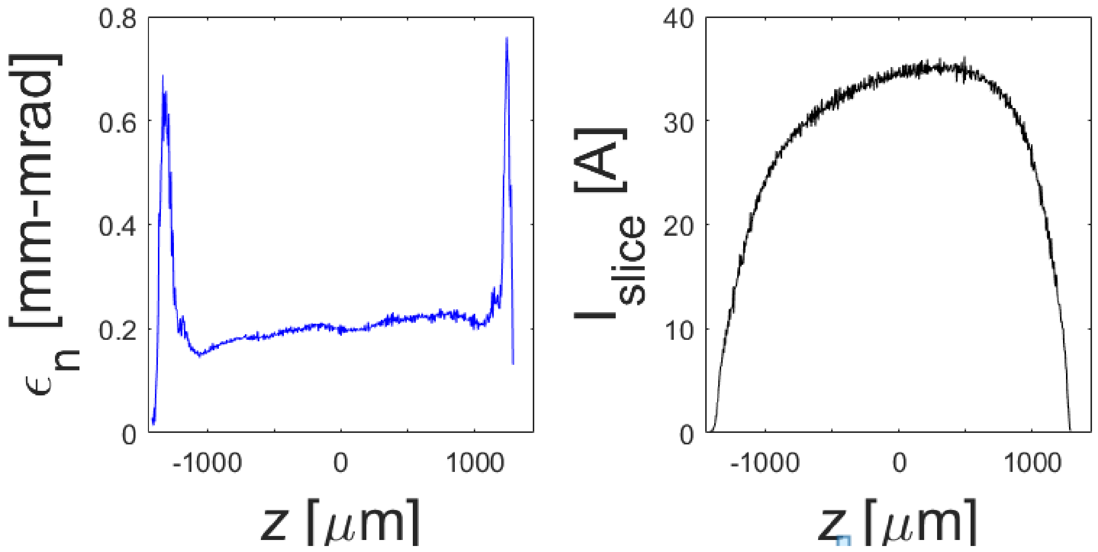


Beam Dynamics Studies – Eurizon WP

6D phase space @ph. exit



Slice emittance (5 µm slice width) @ph. exit



Parameters @ph. exit	Sim. results	units
Q	250	pC
E	122	MeV
$\boldsymbol{\sigma_E/E}$	0.34	%
$\epsilon_{n,rms}$	0.28	μm
$\boldsymbol{\sigma_z}$	670	μm
$\boldsymbol{I_{peak}}$	35	A

The booster linac

- The booster linac design started from the Swiss FEL CDR

Fig. 2.1.1: Schematic of the SwissFEL Accelerator and FEL with the simulated beam parameters for the 200 pC operating mode.

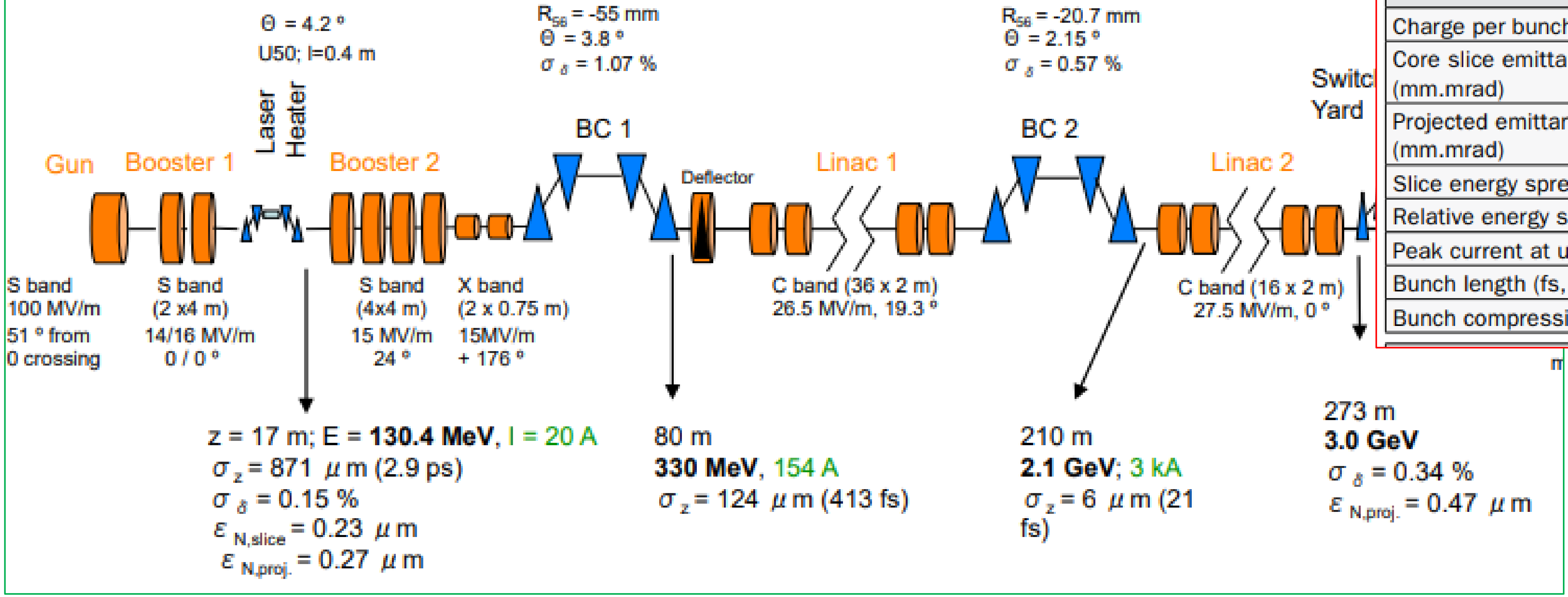


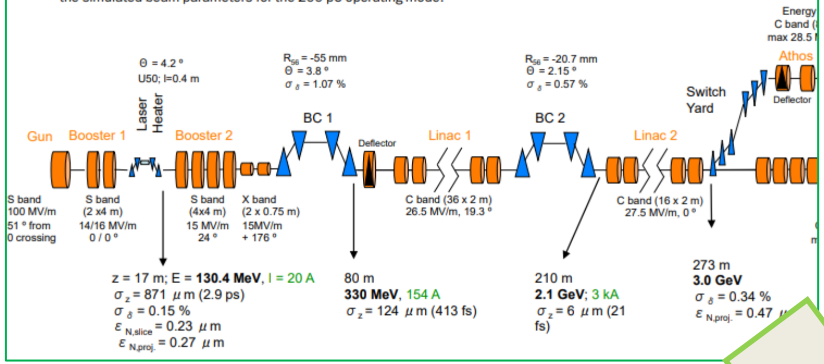
Table 1.4.2 Expected Performance of Linac, Aramis and Athos lines. Performances for different operation regimes are detailed in Chapter 2.

Design parameters for the electron beam	Operation Mode	
	Long Pulses	Short Pulses
Charge per bunch (pC)	200	10
Core slice emittance (mm.mrad)	0.43	0.18
Projected emittance (mm.mrad)	0.65	0.25
Slice energy spread (keV, rms)	350	250
Relative energy spread (%)	0.006	0.004
Peak current at undulator (kA)	2.7	0.7
Bunch length (fs, rms)	25	6
Bunch compression factor	125	240

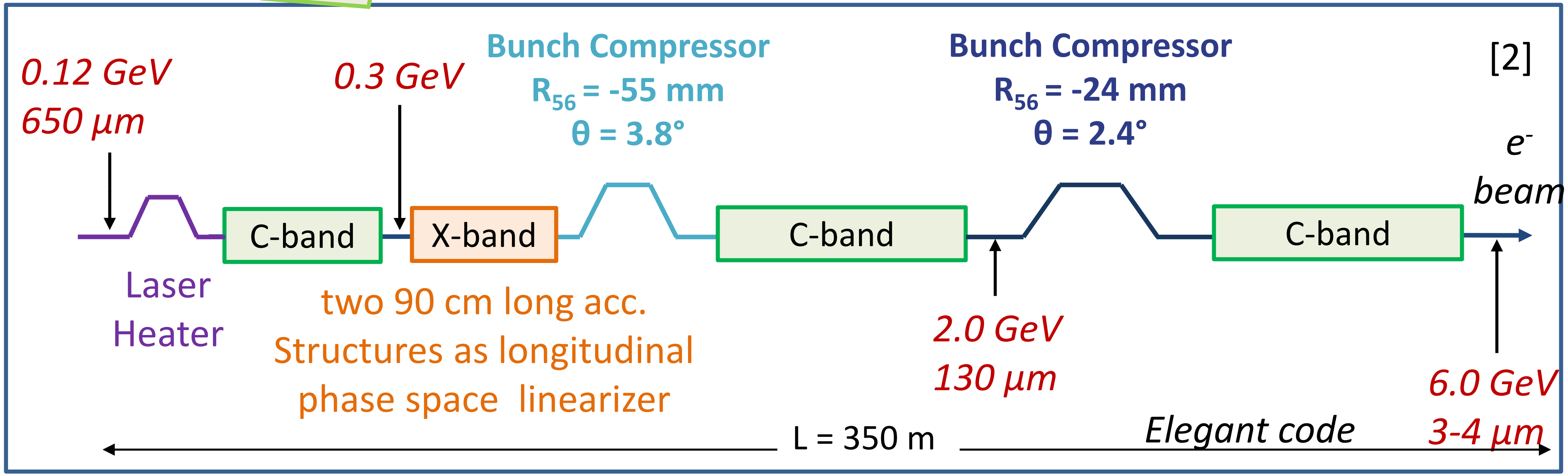
[9] https://www.psi.ch/sites/default/files/import/swissfel_old/CurrentSwissFELPublicationsEN/SwissFEL_CDR_V20_23.04.12_small.pdf

Beam dynamics in the Eurizon booster linac

Fig. 2.1.1: Schematic of the SwissFEL Accelerator and FEL with the simulated beam parameters for the 200 pC operating mode.



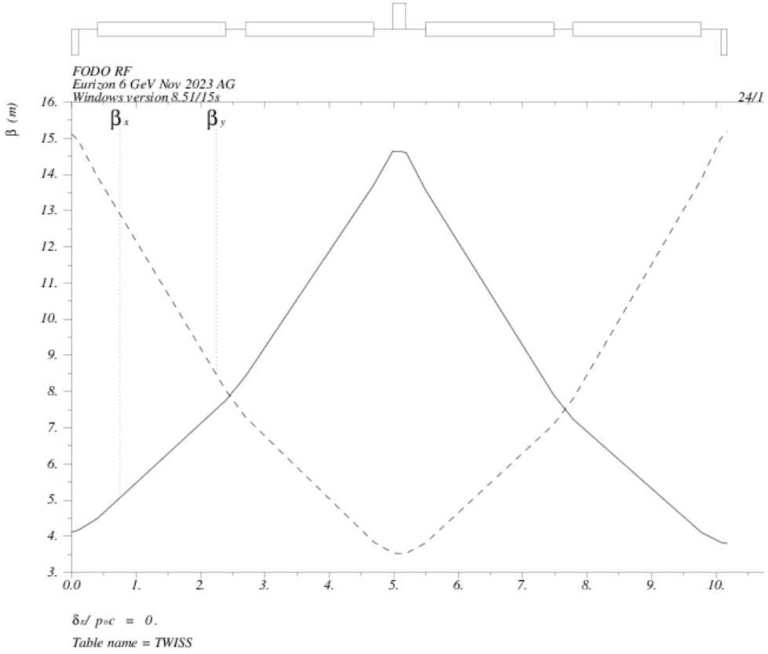
- The booster linac has been simulated with the Elegant code considering longitudinal space charge, CSR and wakefields
- It is operated off-crest to
  - Set the desired energy spread at chicane entrances
  - Minimize of the final beam energy spread
- A certain number of matching quadruples and steering have been used to carry the beam at the FEL entrance and to proper match the beam at the LH, BC1 and BC2 entrance (no emittance dilution)



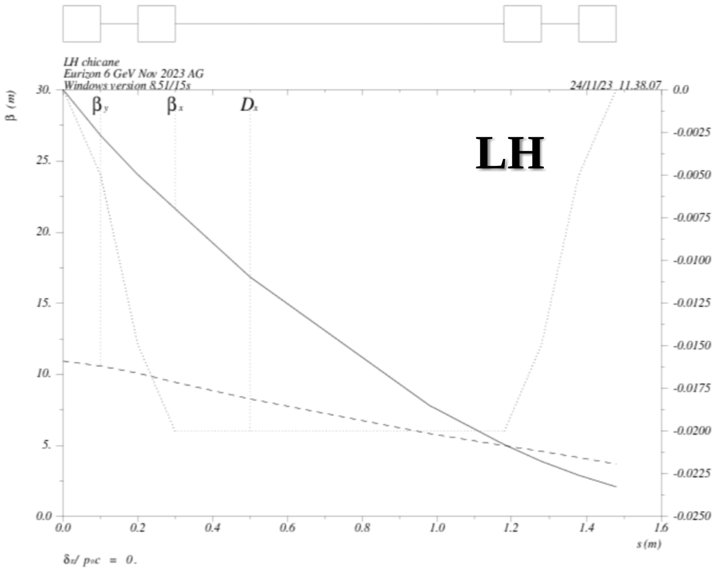
Beam dynamics in the Eurizon booster linac

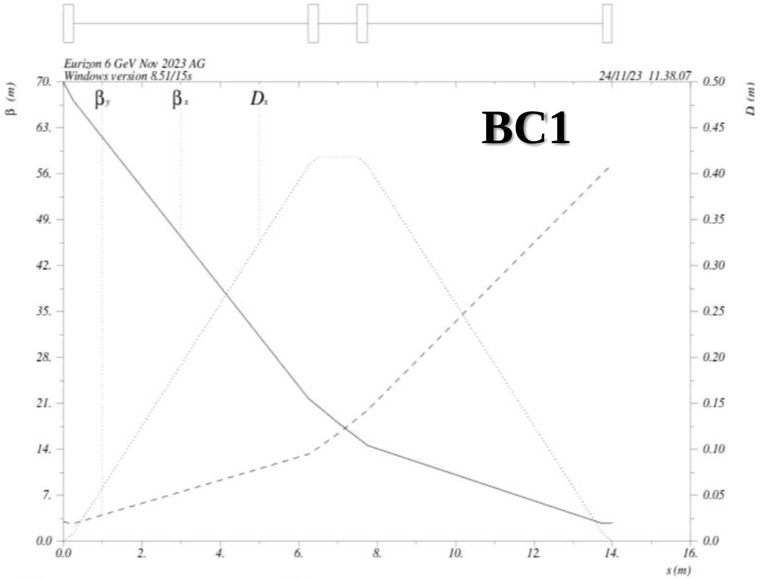
A simple matching has been adopted to proper match the beam at

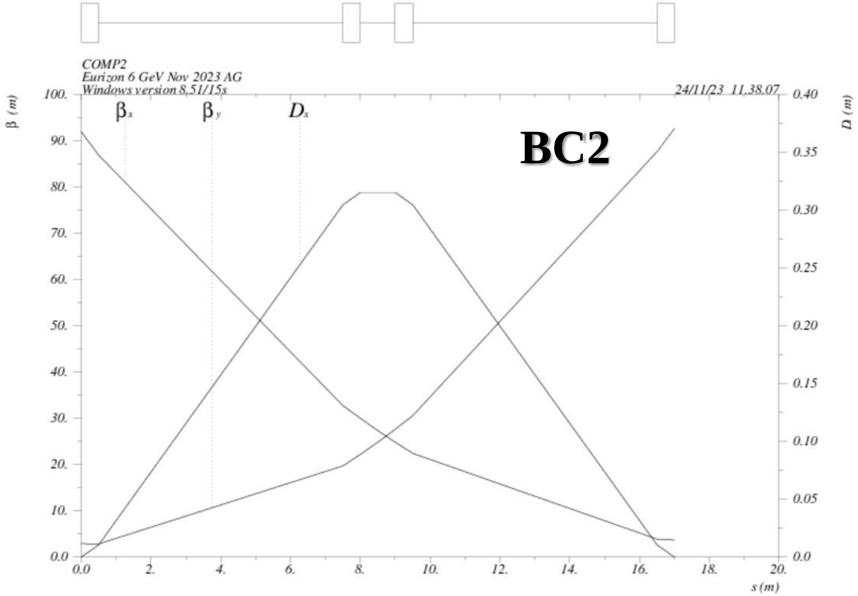
the Linac section entrance to transport it through the linac



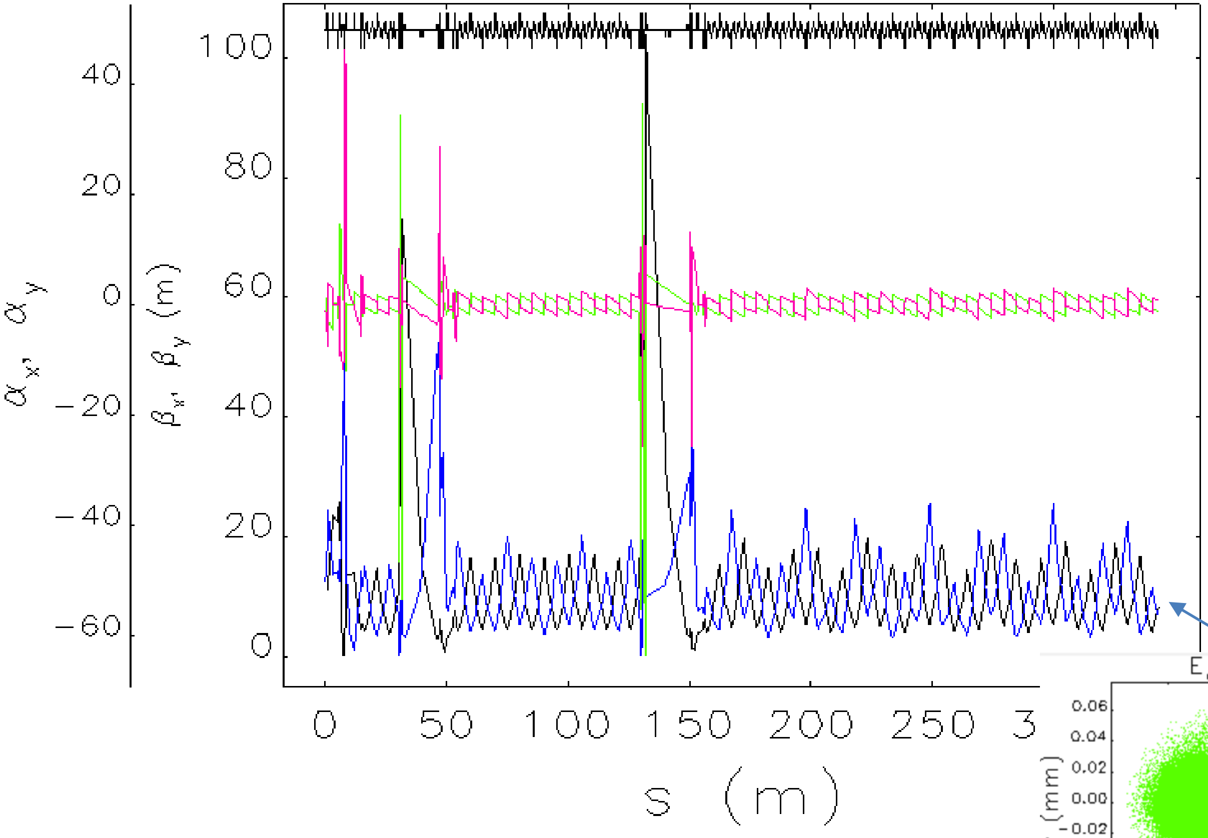
the LH, BC1 and BC2 entrance (no emittance dilution)

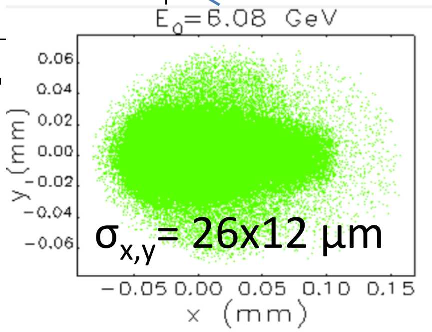


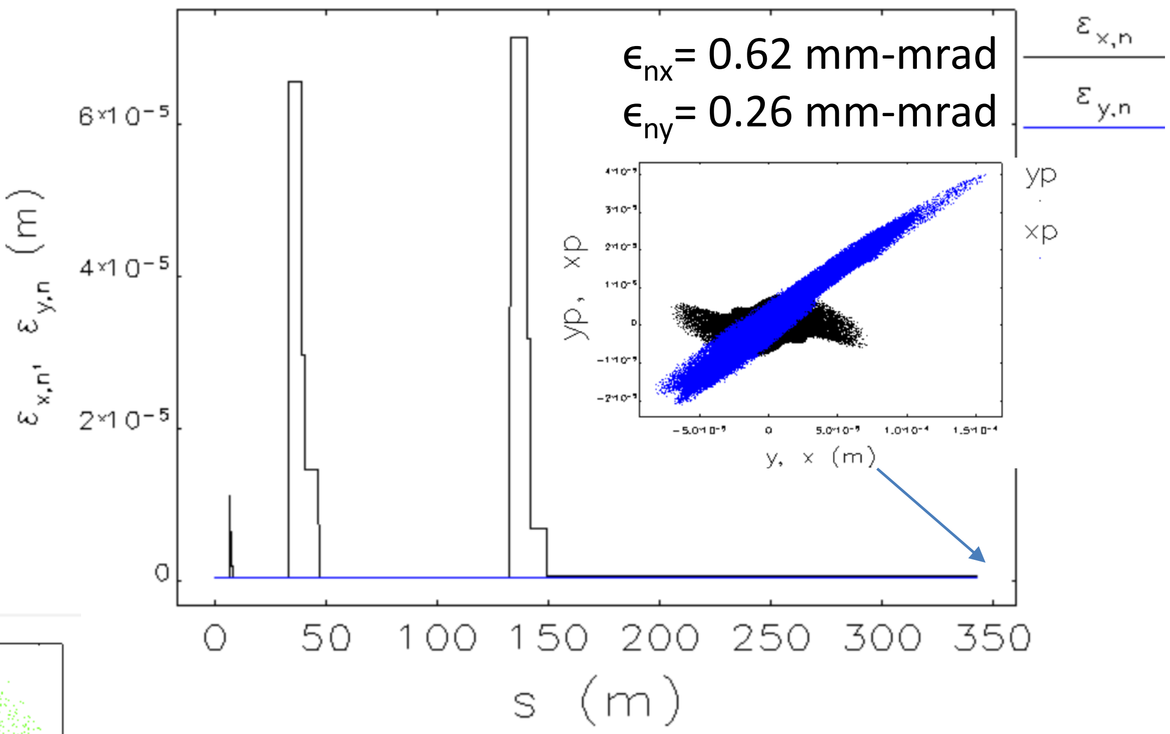




Tracking results: transverse phase space





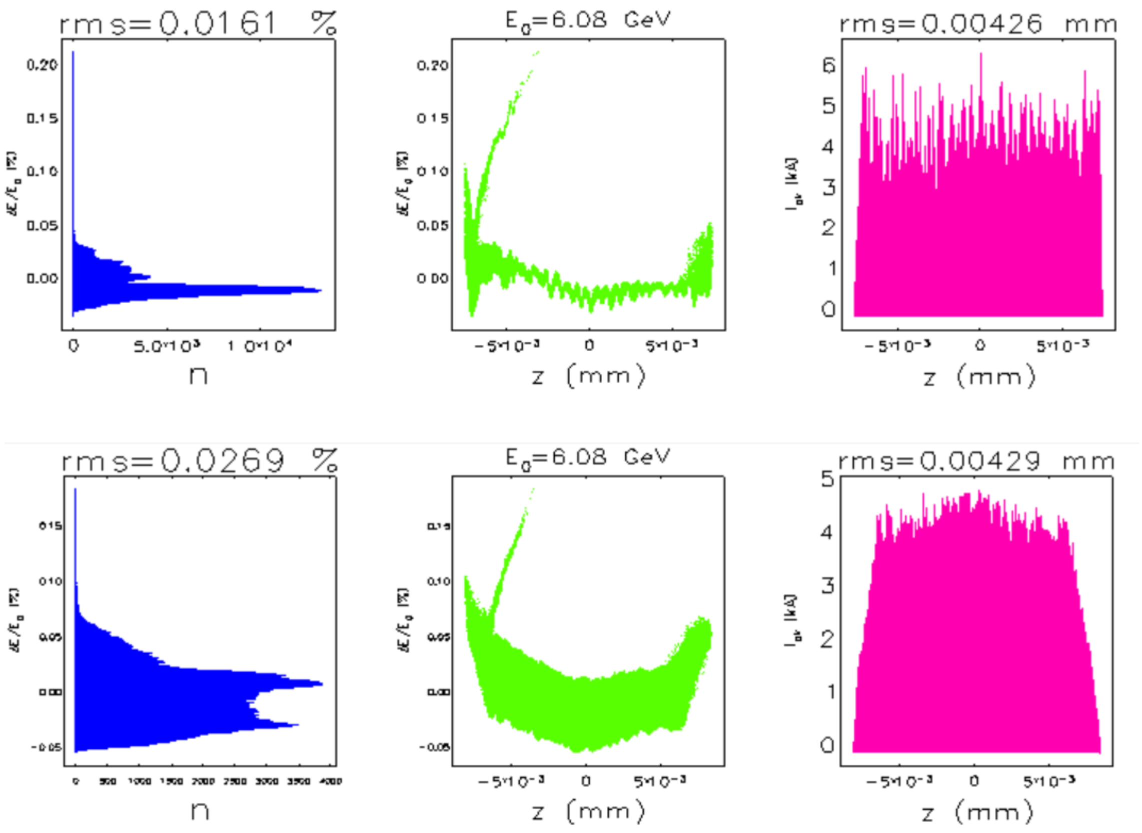


Twiss function along the C-band booster linac

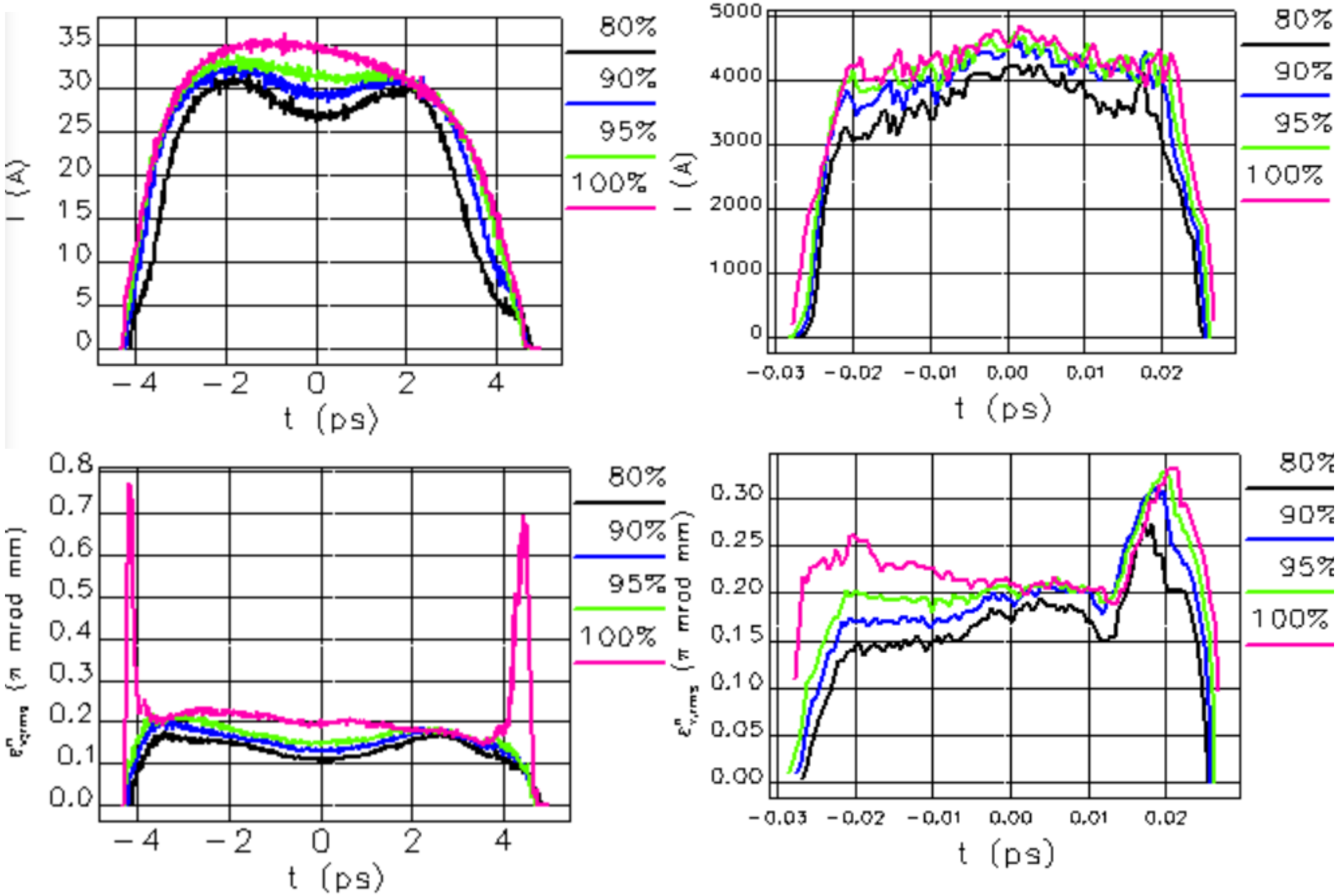
Emittance along the C-band booster linac

Tracking results: longitudinal phase space

- The beam is boosted in energy and longitudinally compressed to obtain a 5kA peak current, less than 0.6 mm-mrad slice emittance and less than 2 MeV slice energy spread (<0.04%)



LPS analyses at 6 GeV with the laser heater switched off (up) and on (down)



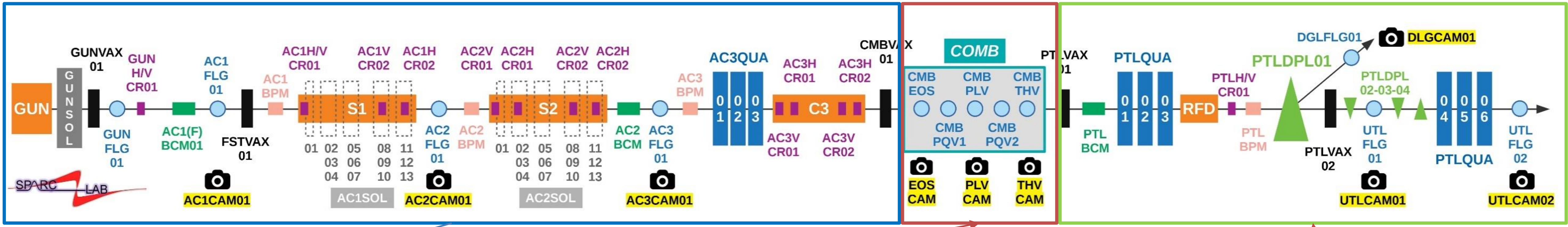
Slice analyses at the photoinjector (left) and booster linac (right LH on) exit

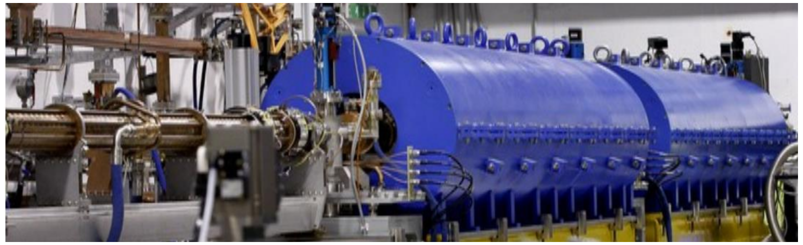
Conclusions

- The Eurizon collaboration has finalized a proposal for a 6 GeV injector useful for
  - high brightness soft Free Electron Laser
  - X-ray storage rings (top-up injection)
- The 6 GeV linac will be driven by two type of front-ends
  - RF gun (thermionic/photo cathode) for the injection into the storage ring
  - RF photogun for the injection into the FEL
- Both a full S-band linac and a hybrid S-C band linac solutions have been explored by means of simulations → the hybrid linac has been chosen as definitive layout
  - Start to end simulations for the top-up injector have been performed from the cathode to the booster linac entrance. A dogleg beamline will carry the beam up to the storage ring
  - Start to end simulations have been performed for the FEL scientific case from the cathode to the FEL entrance


THANK YOU!!!

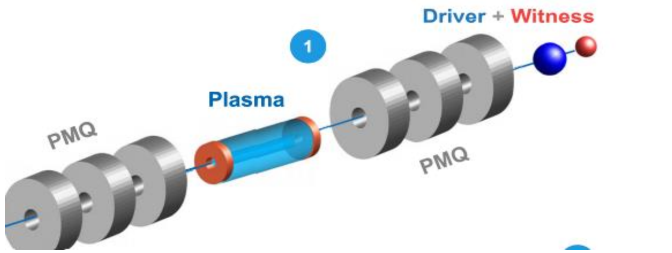
The SPARC_LAB accelerator

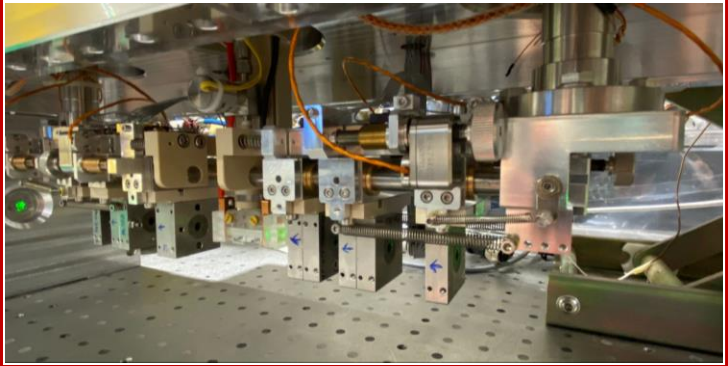


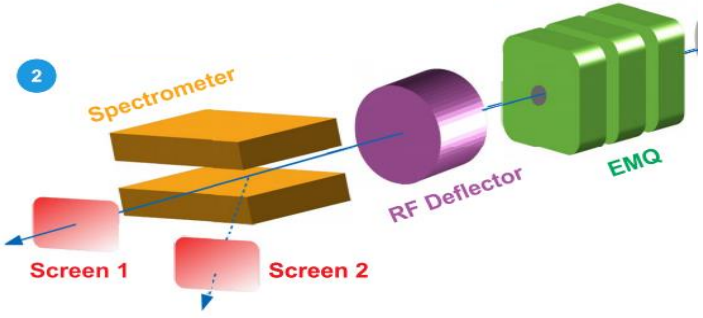


Parameter	Value
Number of bunches	1 - 5
Delay between bunches	0.5 ps - 20 ns*
Charge	10 pC - 2 nC
Duration	20 fs - 10 ps
Energy	5 - 180 MeV
Energy spread	0.1 - 5 MeV
Normalized emittance	0.3 - 10 μm

e- beam parameters @Photoinjector exit



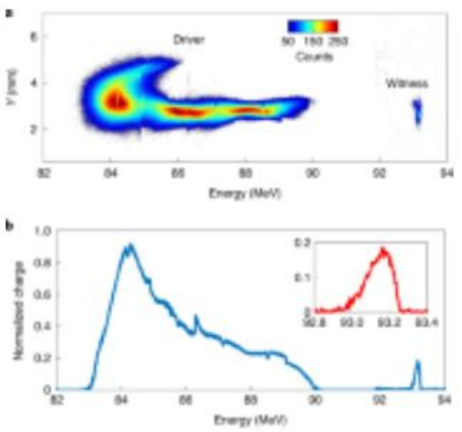


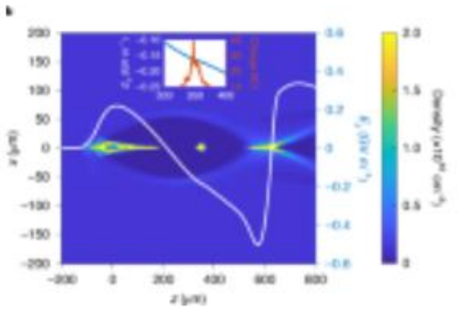


Diagnostic beamline

The SPARC_LAB experience

Energy spread minimization in a beam-driven plasma wakefield accelerator

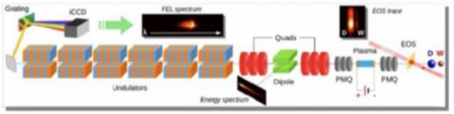


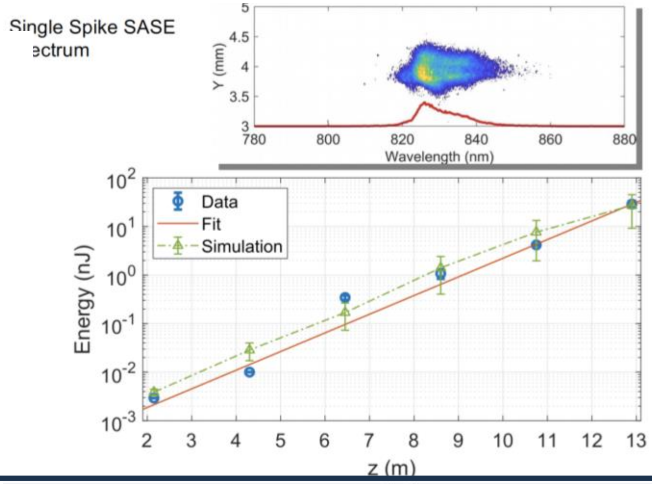


Nature Physics 17, 499-503
R. Pompili et al. (2021)

Free-electron lasing with compact beam-driven plasma wakefield accelerator

First FEL lasing from a beam-driven plasma accelerator

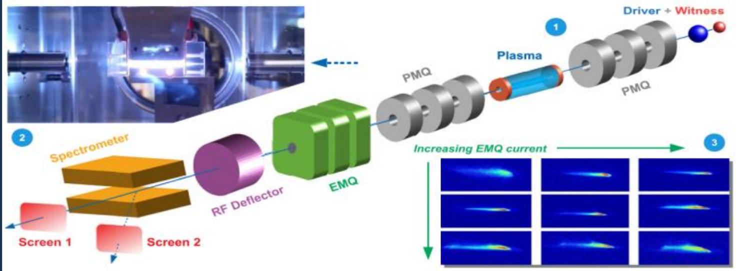


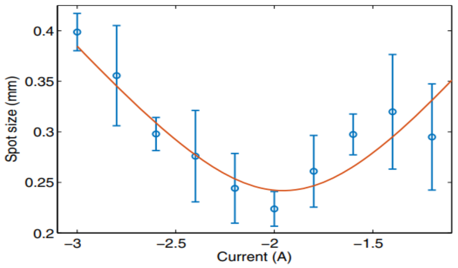


Nature 605, 659-662
R. Pompili et al. (2022)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 051301 (2021)

First emittance measurement of the beam-driven plasma wakefield accelerated electron beam

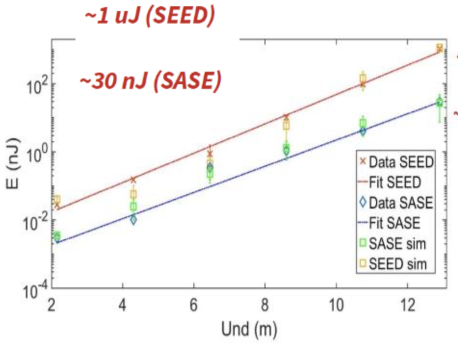




PRAB 24, 051301 V. Shpakov et al. (2021)

PHYSICAL REVIEW LETTERS **129,** 234801 (2022)

Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator



Seeded FEL radiation

- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE

PRL, 129 234801 M.Galletti et al. (2022)