RF linac optimization for FEL and Inverse Compton Scattering Radiation Sources

Anna Giribono
INFN-LNF

On behalf of ELI_NP and SPARC_LAB collaboration

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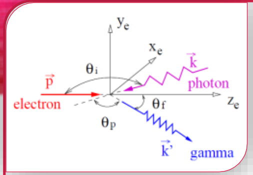
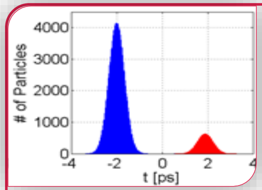


RF Linacs Driving Bright FEL and ICS radiation sources

- High brightness beams
- Radiation Sources under study at INFN_LNF
  1. ELI-NP GBS
  2. EuPRAXIA@SPARC_LAB

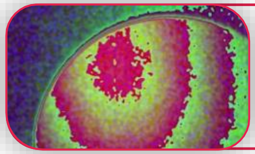
ELI-NP GBS RF Linac

- RF linac layout
- Start to end simulations
- Machine sensitivity studies



EuPRAXIA@SPARC_LAB RF linac

- EuPRAXIA@SPARC_LAB project
- Photoinjector Working Points (WPs)
- Start to end Simulations



Conclusions and Future Perspectives

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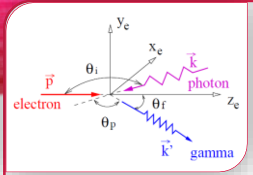

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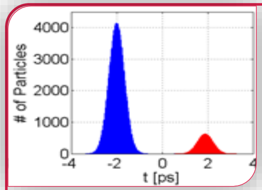

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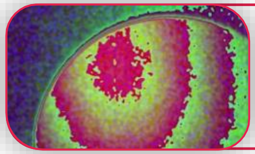


Conclusions and Future Perspectives

HIGH BRIGHTNESS BEAMS

- The production of high brightness electron beams has shown to be essential for radiation generation in the FELs and for the realization of bright Gamma-ray Compton sources.
- The characteristic brightness parameter B can be expressed as

Simplified formula

$$B \propto \frac{I}{\varepsilon_{nx}\varepsilon_{ny}\sigma_\gamma}$$

Peak current (I)

Transverse Normalised emittance ($\varepsilon_{nx}\varepsilon_{ny}$)

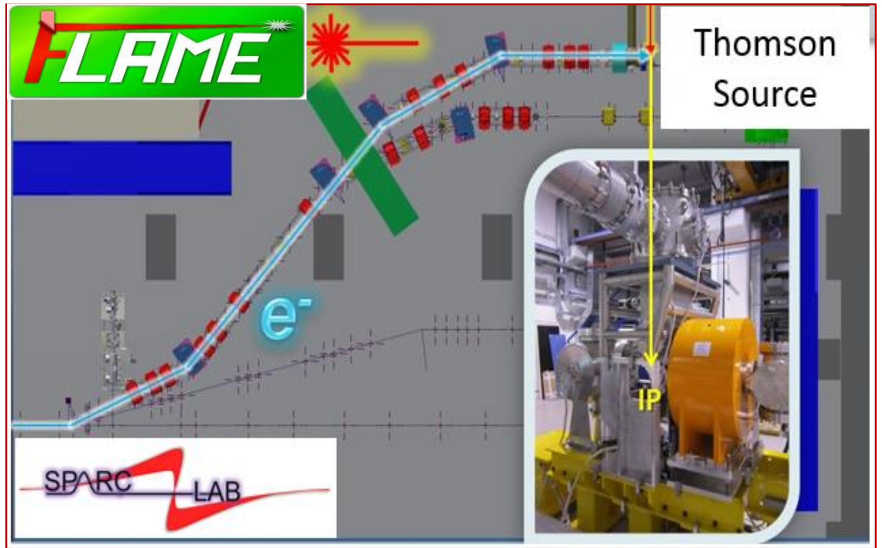
high brightness means high peak current and a small footprint in the transverse phase space

- *Noticeably*, for an ICS source these rms beam quality factors have to be evaluated *on projected (back-up slide) values* over the electron bunch, unlike in FEL's machines the so called *"slice" values* are mostly relevant for the high gain FEL process.
- These advanced radiation sources are based on high brightness accelerators (storage ring or linac)
- Both flux and brightness of the source can nowadays benefit from the linac-based configuration thanks to the *novel RF linac technology* that allows
  1. Generation of low energy spread and low emittance electron beams
  2. Generation of electron beams in a wide energy range → fast tuning of the emitted photon beam frequency
  3. Multi-bunch operation at high repetition rate (order of kHz) (where needed)

RADIATION SOURCES UNDER STUDY AT INFN_LNF

- The idea is to achieve these features for the electron beam adopting a hybrid scheme consisting in
  - RF high brightness photo-injector to generate the beam and to take care of its brilliance (*emittance and peak current*)
  - RF linac to boost the beam energy and to provide final beam compression and shaping. It will operate at higher frequency to compact the machine length.

High Brightness Photoinjector + Compact – High-gradient RF Linac



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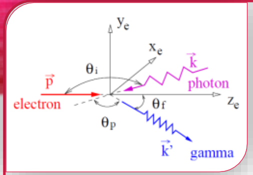
ELI-NP GBS

OUTLINE



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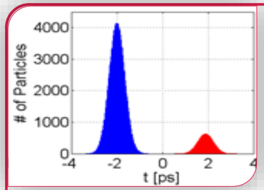

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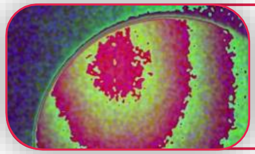
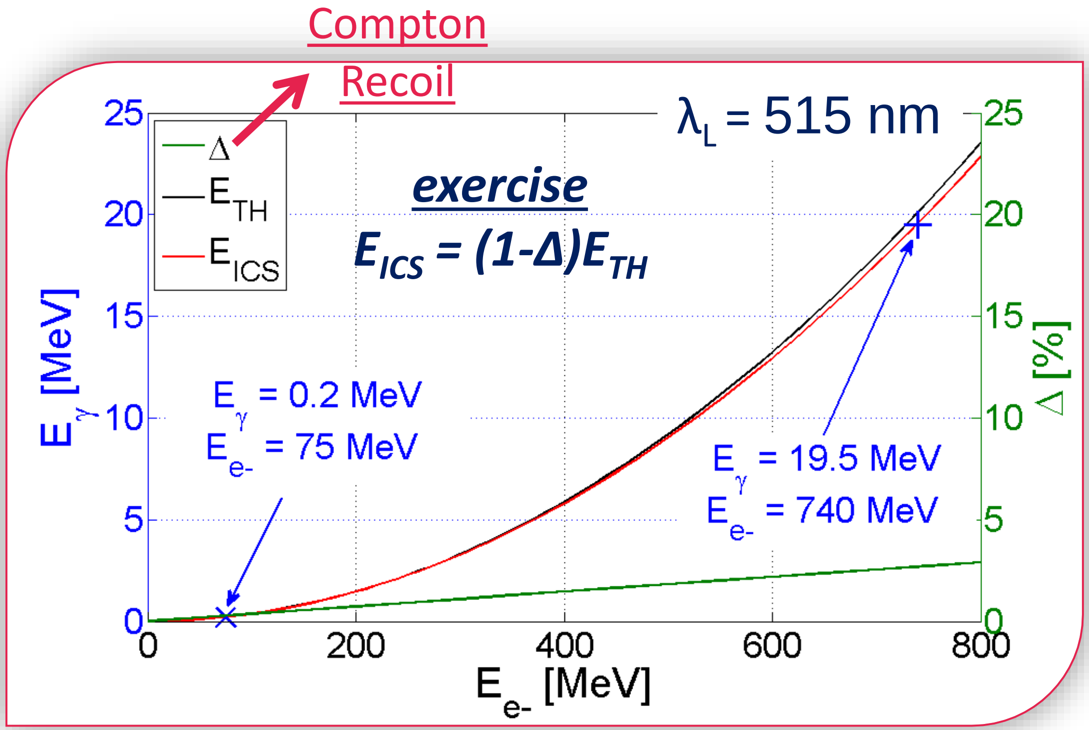


Conclusions and Future Perspectives

ELI-NP GBS RF LINAC

- Inverse Compton Scattering source, that will be installed at the Magurele site (close to Bucharest, Romania)
- One of the ***ELI project pillars*** whose main goal is to provide few femtosecond laser pulses (10-100 fs) with power up to 10 PW.
- The ELI-NP GBS γ Source peculiarities are
  1. Energy tunability in the range [0.2 –19.5] MeV
  2. Mono-chromaticity (BW_{rms}) ≤ 0.5%
  3. Peak brilliance > 10^{21} [N_{ph}/ s·mm²·mrad²·0.1%]
  4. SPD > 10^4 [ph / s·eV]



(*) **250 pC electron beam optimised parameters**

- 75 MeV ≤ Energy Tunability of Electron Beam ≤ 740 MeV
- 0.04% ≤ Energy Spread of Electron Beam (%) ≤ 0.1%
- 0.2 mm mrad ≤ ε_n ≤ 0.6 mm mrad
- 15 μm ≤ σ_t ≤ 30 μm
- 100 Hz Rep. Rate and up to 32 bunches (~ 3 kHz)

(*) L. Serafini et al., "Technical design report: Eurogammas proposal for the ELI-NP gamma beam system," Scientific Editor L. Serafini, 2014.

RF LINAC LAYOUT

HYBRID SCHEME CONSISTING IN A SPARC-LIKE S-BAND HIGH BRIGHTNESS PHOTOINJECTOR FOLLOWED BY A C-BAND RF LINAC

Simulation Tools

- S-band Photoinjector

Tstep, Astra include:

1. Space charge effects
2. Intrinsic emittance
3. Beam loading

- C-band RF linac

Elegant includes:

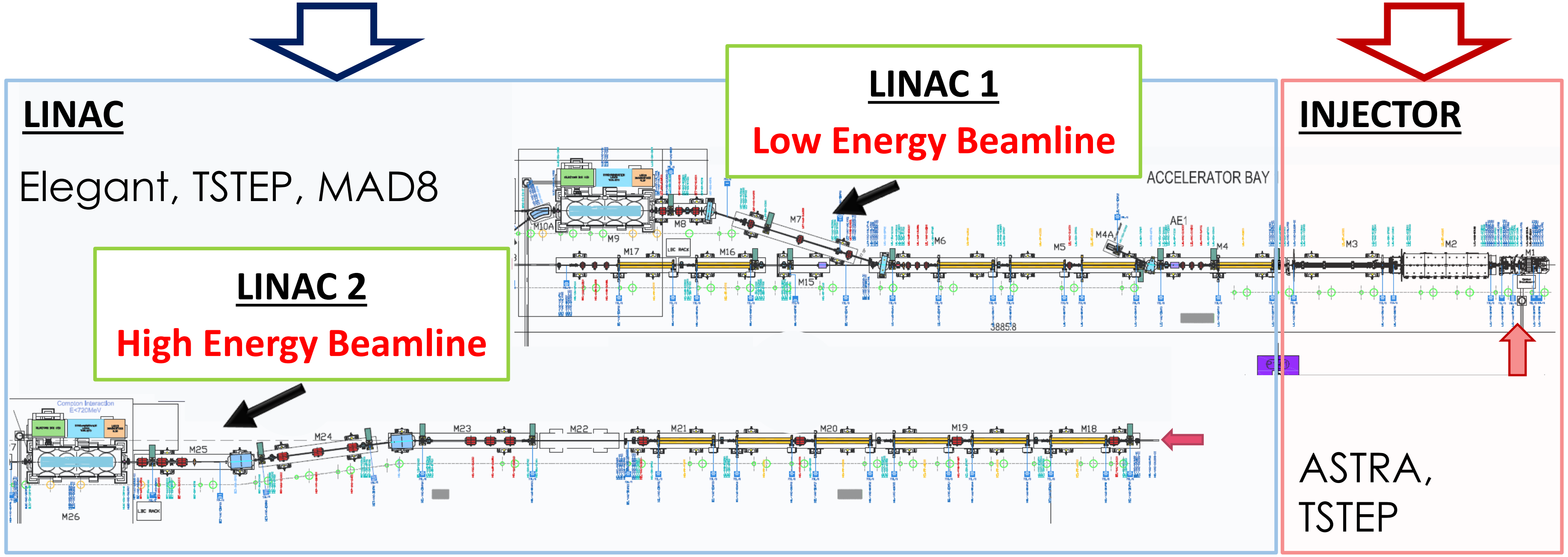
1. Wakefields in accelerating cavities
2. Longitudinal space charge
3. Coherent and incoherent synchrotron radiation in bending magnets

C-BAND RF LINAC

Higher accelerating gradients provided by the C-band accelerating sections in the rest of the linac allow to compact its length.

SPARC-LIKE S-BAND HIGH BRIGHTNESS PHOTOINJECTOR

In the RF gun a bunch long enough, $\sigma_z \approx 1$mm, is needed to reduce the emittance degradation in the space charge dominated regime.

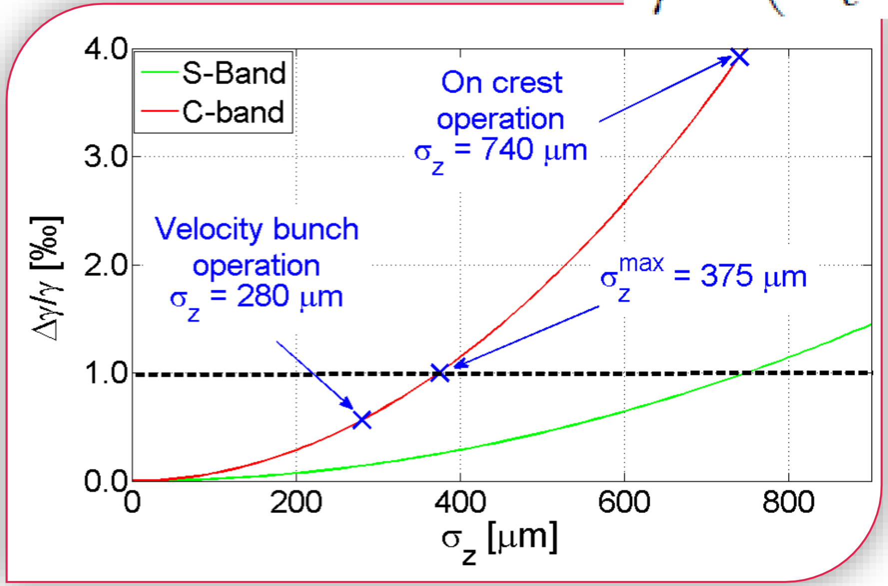


(*) $\varepsilon_t \approx 0.91 \pm 0.01$ [mm mrad]/[mm]•σ_r [mm rms]) a measured value for an S-band RF gun operating at Eacc = 120 MV/m [Y. Ding et al. PRL,vol. 102, no. 25 2009]

START TO END SIMULATIONS:
Working Point Optimisation

- BD simulations for several Working Points (WP) each corresponding to the main user required γ-photon beam energy.

$$\frac{\Delta\gamma}{\gamma} \approx 2\left(\frac{\pi f_{RF}\sigma_z}{c}\right)^2$$



- BD in the photoinjector:
  1. A σ_z < 280 μm must be injected in the C-band linac to avoid the energy spread dilution due to RF curvature degradation effects keeping Δγ/γ < 1 ‰
  2. Emittance compensation in the *velocity bunching scheme (**)*, according to the *invariant envelope criteria* (*)
  3. Nominal beam parameters at the injector exit:
     Q = 250 pC, E = 80 ± 10 MeV , σ_z = 280 μm , $\varepsilon_{nx,y}$ = 0.4 mm mrad

- BD in the C-band RF linac:
  1. Slightly off-crest operation to preserve the energy spread in the required energy range
  2. The beam transport line optics is matched to close the horizontal dispersion at each dogleg exit.
  3. Final focusing system to provide spot size in the range 10 - 25 μm at IP

(*) L. Serafini et al., "Envelope analysis of intense relativistic quasilaminar beams in rf photoinjectors: A theory of emittance compensation," Phys. Rev., vol.E55 1997
(**) M. Ferrario et al., "Experimental demonstration of emittance compensation with velocity bunching," Phys. Rev. Lett., vol. 104, p. 054801, 2010

START TO END SIMULATIONS: *Working Point Optimisation*

- Nominal electron beam parameters at IPs

  @LE-IP : E_{e-} = 234 MeV, σ_z = 270 μm , $\varepsilon_{nx,y}$ = 0.44 [mm mrad], $\sigma_{x,y}$ = 19.5 μm , Δγ/γ = 0.80 ‰ → *2.0 MeV γ-source*

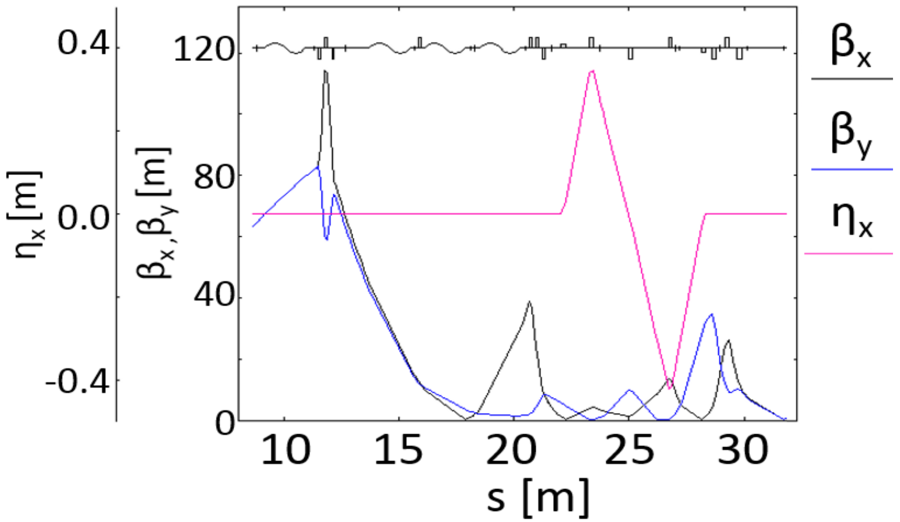
  @HE-IP: E_{e-} = 530 MeV σ_z = 270 μm , $\varepsilon_{nx,y}$ = 0.42 [mm mrad], $\sigma_{x,y}$ = 17.0 μm , Δγ/γ = 0.45 ‰ → *10.0 MeV γ-source*

	γ-source WP [MeV]	E_{e-} @IP [MeV]	E_{e-} @Inj Exit [MeV]	$^{\Delta\gamma}/_{\gamma}$ @ IP [‰]	σ_z @IP [μm]	$\varepsilon_{nx,y}$ [mm mrad]	$\beta_{x,y}$ [m]	$\sigma_{x,y}$ [μm]
LINAC 1	0.20	75	70.5	1.14	275	0.51	0.16	23.5
	1.00	165	80.5	0.86	274	0.44	0.43	20.0
	2.00	234	80.5	0.82	273	0.44	0.43	19.6
	2.85	280	80.5	0.78	275	0.45	0.50	19.5
	3.50	312	90.5	0.80	278	0.41	0.55	19.3
LINAC 2	10.00	530	80.5	0.45	272	0.44	0.71	17.5
	13.00	605	80.5	0.43	273	0.44	0.71	17.5
	19.50	740	90.5	0.48	278	0.41	0.95	16.5

(*) A. Giribono et al., "6D phase space electron beam analysis and machine sensitivity studies for eli-np gbs," NIMa, vol. A829 (2016)

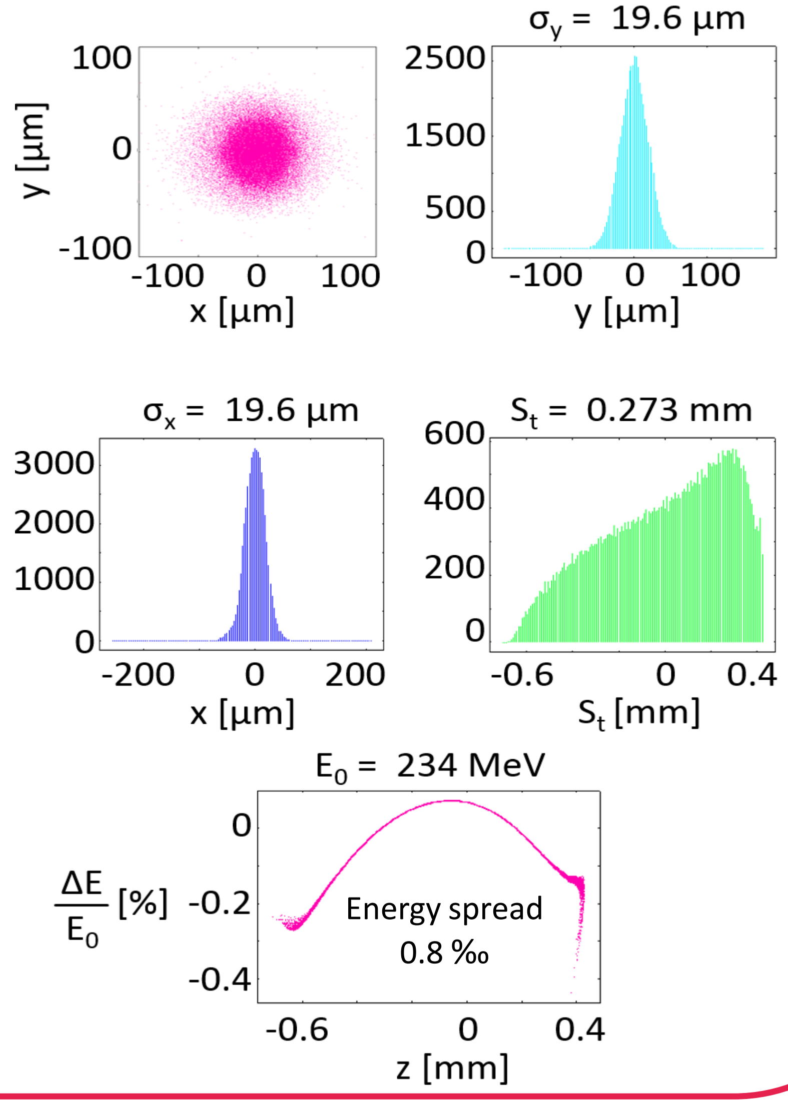
START TO END SIMULATIONS:
Working Point Optimisation (Nominal WP @ LE-IP)

Example: 2.0 MeV γ-source WP



234 MeV @LE IP (Ref. case)		
Energy	234.0	MeV
Energy spread	0.82	‰
Bunch length	273.0	µm
$\varepsilon_{n_{x,y}}$	0.44	mm mrad
Focal Spot	19.6	µm

@LE IP



START TO END SIMULATIONS:
A “real” machine model

- In view of the commissioning phase a machine model as much «real» as possible is needed.

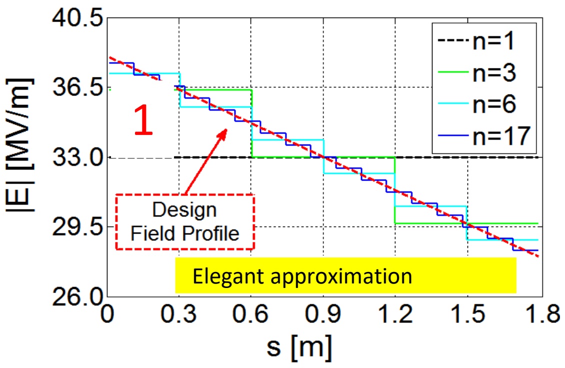
- The work has been focused on the aspects that are mostly involved in the robustness, operational reliability and active and passive element constraint specification as

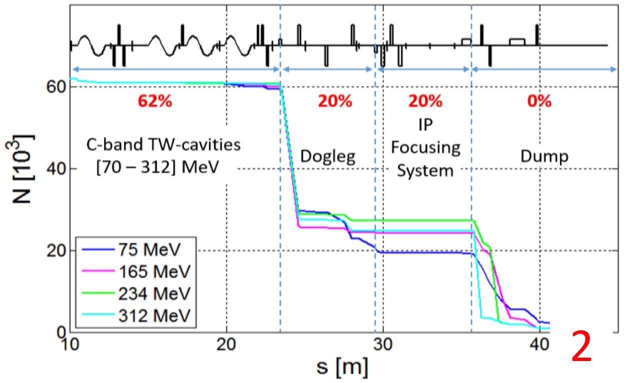
  1. Quasi constant gradient C-band cavities

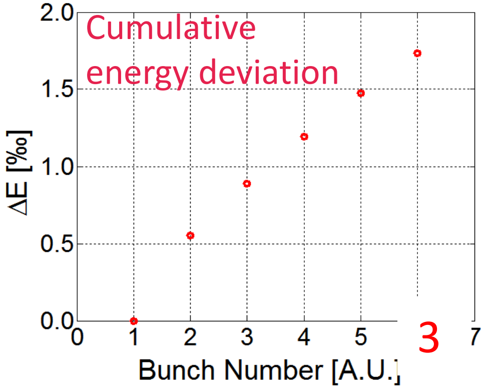
  2. Dark current evaluation

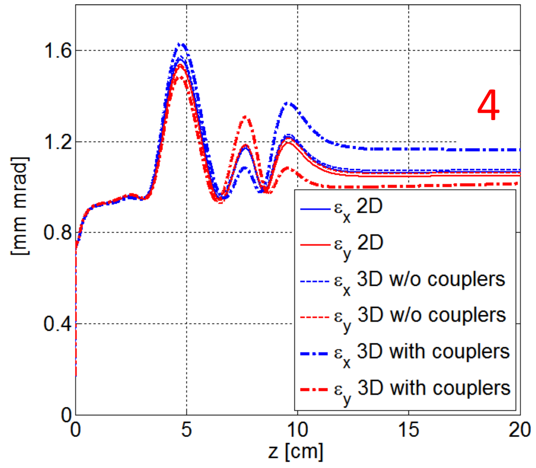
  3. Long-range wakefields in multi-bunch operation

  4. Insertion of measured field maps in tracking codes for RF gun and magnets. (on going)







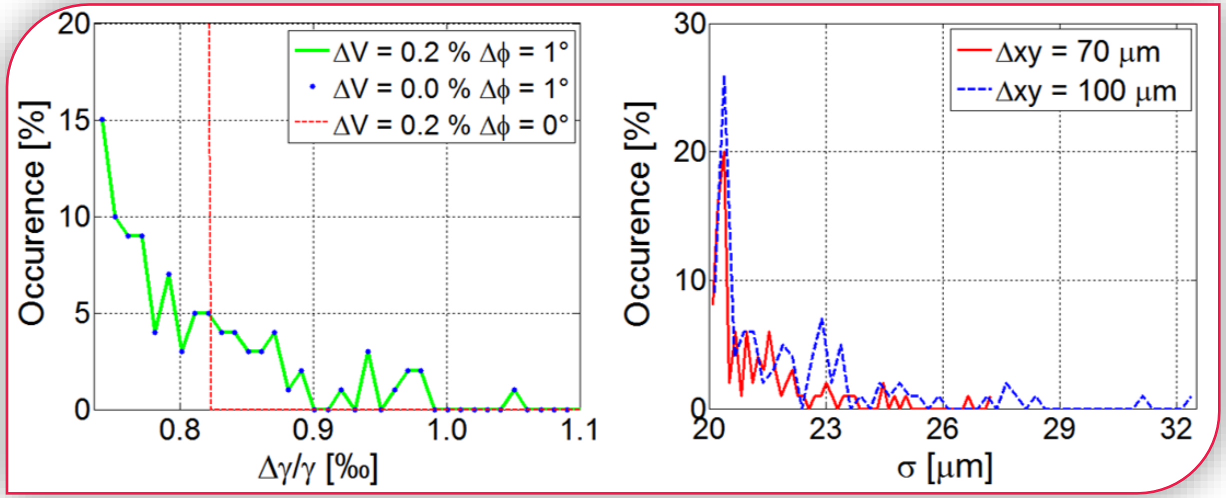


(*) A. Giribono, “6D Phase Space Optimisation for High Brightness Electron Beams in RF Linacs as Drivers for High Brilliance Inverse Compton Scattering X and g Ray Sources” PhD Thesis, http://hdl.handle.net/11573/1102634 (2017)

MACHINE SENSITIVITY STUDIES

The Method

- The study is in terms of e^- beam quality at IP.
- BD simulations over a sample of 100 machine runs aimed to:
  1. Test the robustness of the linac to any possible error
  2. Provide jitter and alignment specifications for accelerating structures and magnets.
- According to the previous results and the defined specifications, final BD simulations have been performed over an enlarged sample of 350 machine runs introducing the trajectory correction.



Linac Transfer Line Specifications		
C-band Accelerating Sections		
RF Voltage [ΔV]	< 2	‰
RF Phase [Δϕ]	< 1	deg
Alignment on transverse plane [Δxy]	< 70	μm
Quadrupoles		
Geometric strength [Δk]	< 3	‰
Alignment on transverse plane [Δxy]	< 70	μm
Tilt about incoming longitudinal axis [ΔΘ]	< 1	mrad
Dipoles		
Bend angle [ΔB]	< 1	‰
Tilt about incoming longitudinal axis [ΔΘ]	< 1	mrad
Steerers		
Strenght [Δk]	< 0.2	μrad
BPMs		
Resolution	< 20	μm
Cavity BPMs		
Resolution	< 5	μm

(*) A. Giribono et al., "6D phase space electron beam analysis and machine sensitivity studies for ELI-NP GBS" NIMa, vol. A829 (2016)

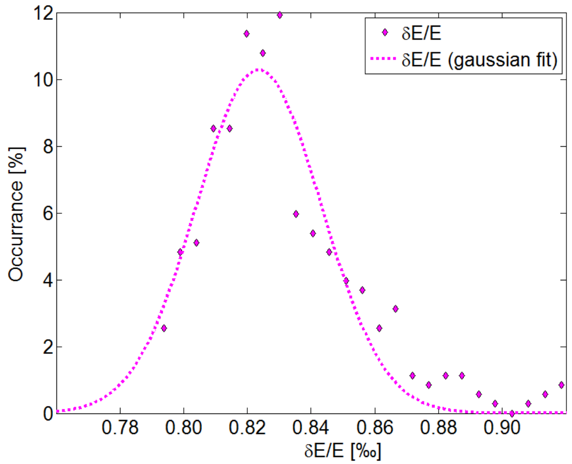
MACHINE SENSITIVITY STUDIES:
Nominal WP for the Low Energy Line

2.0 MeV γ-source WP

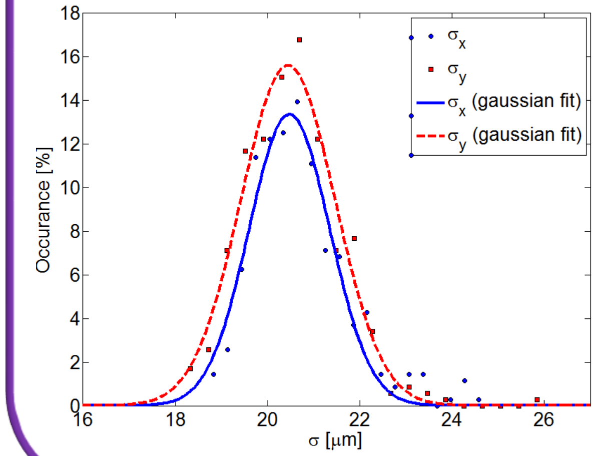
- The analysis has been in terms of electron beam quality at LE IP.
- Deviation from the reference values of few percents.
- The parameters are still in specifications.

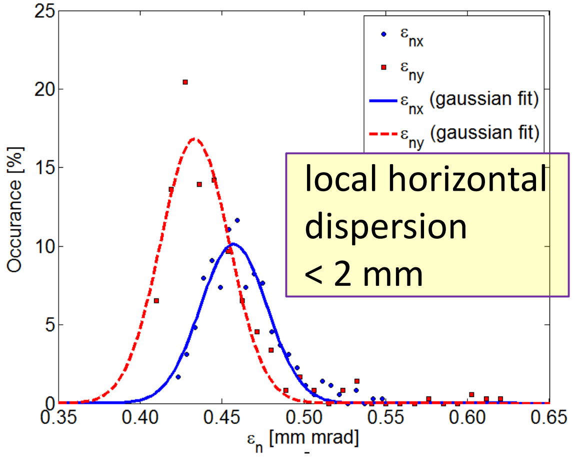
234 MeV @IP	Without errors	With errors	
Energy	234.0	234.3 ± 0.3	MeV
Energy spread	0.82	0.82 ± 0.02	‰
Bunch length	273.0	274.5 ± 6.0	μm
$\varepsilon_{n_{x,y}}$	0.44	0.46 ± 0.02	mm mrad
Focal Spot	19.6	20.5 ± 1.0	μm
$\Delta C_{x\text{-}y}$	0	0.2 ± 0.5	μm

Energy Spread **@IP**



@IP Transverse Spot Size and Normalised Emittance





MACHINE SENSITIVITY STUDIES:
Nominal WP for the High Energy Line

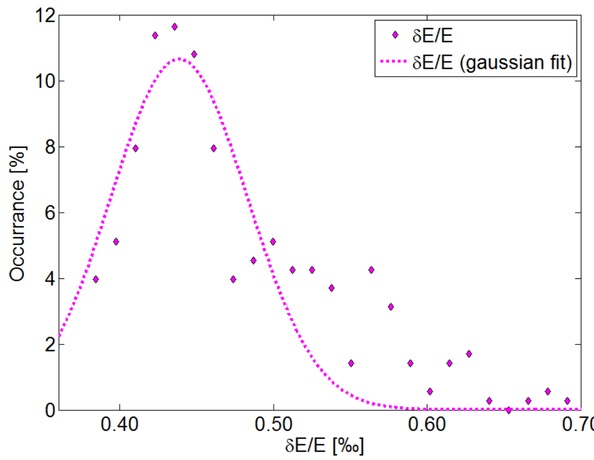
10.0 MeV γ-source WP

- The analysis has been in terms of electron beam quality at HE IP.
- Deviation from the reference values of few percents.
- The parameters are still in specifications.

530 MeV @IP	Without errors	With errors	
Energy	529.6	529.8 ± 0.5	MeV
Energy spread	0.45	0.44 ± 0.05	‰
Bunch length	272.0	272.1 ± 5.2	µm
$\varepsilon_{nx,y}$	0.44	0.47 ± 0.02	mm mrad
Focal Spot	17.3	17.8 ± 1.1	µm
ΔC_{x-y}	0	0.1 ± 0.5	µm

Energy Spread

@IP



@IP

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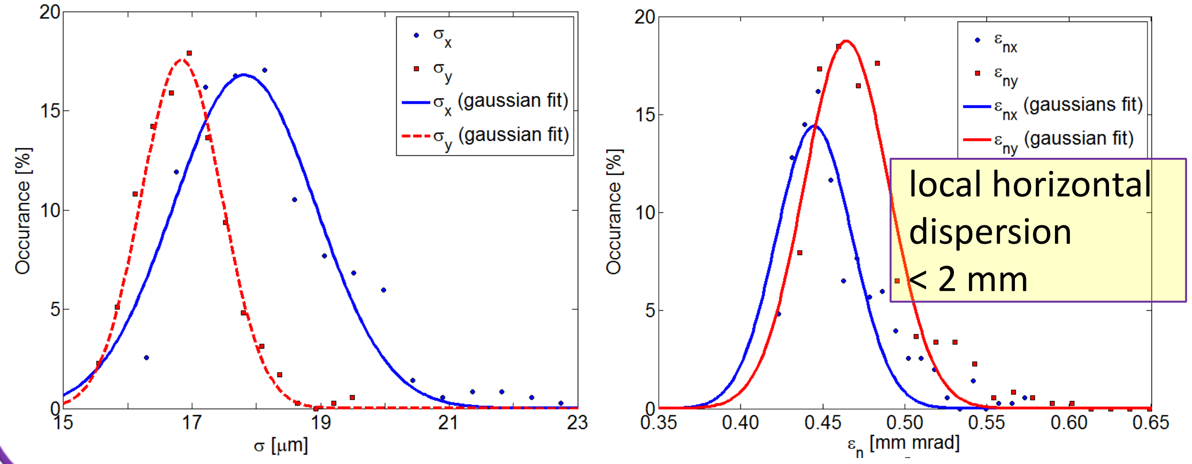

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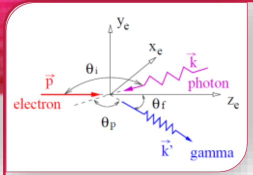

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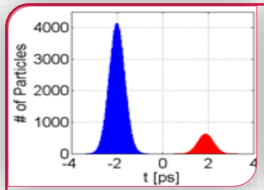

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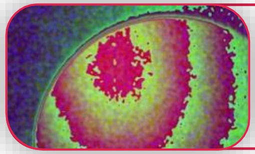
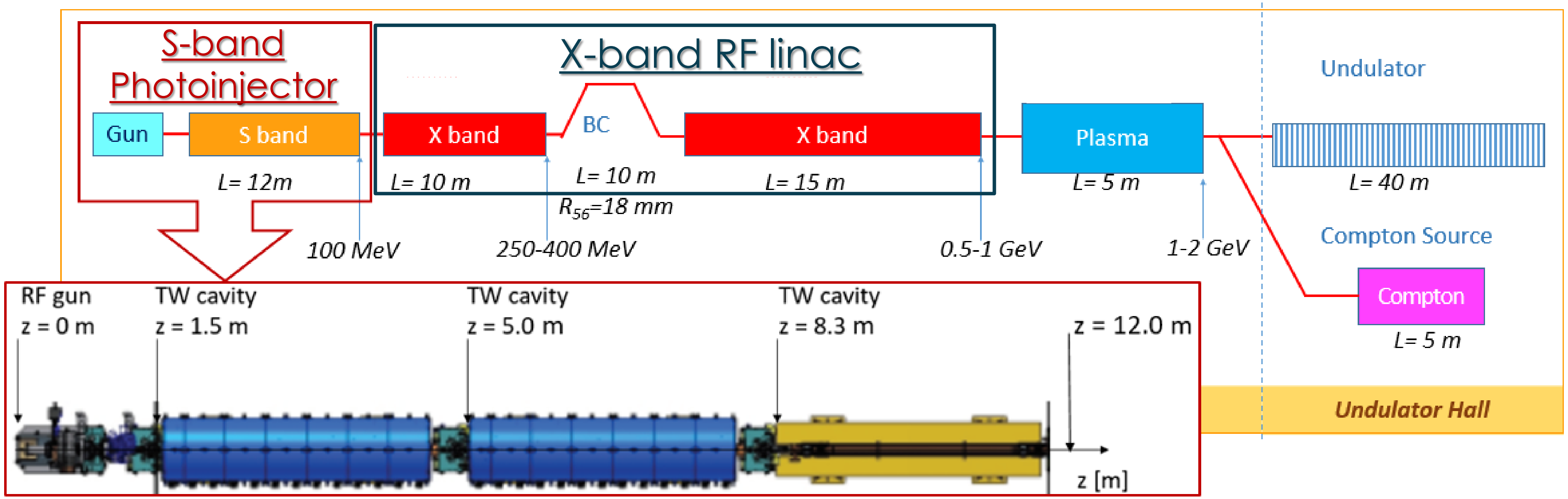


Conclusions and Future Perspectives

THE EUPRAXIA@SPARC_LAB PROJECT

- Design of a compact FEL source, equipped with user beam-lines at 3 nm wavelength, driven by a high gradient plasma-based accelerator (*).
- The project arises from the will to candidate the INFN-LNF Laboratories (Frascati, Italy) as host for the EuPRAXIA European Facility
- The electron beam is generated in an advanced compact RF injector coupled with a plasma-based accelerating stage operating in the external injection configuration.



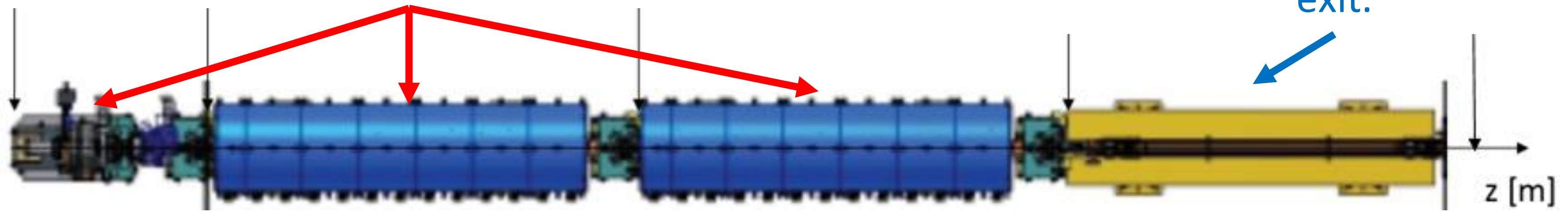
(*) M. Ferrario, EuPRAXIA@SPARC_LAB Design study towards a compact FEL facility at LNF (2018)

PHOTOINJECTOR WORKING POINTS (WPS)

- The *main challenge* for the RF injector comes from the request of producing ultra-short (<10 fs), high quality electron beams useful to cover a wide range of user applications, as fundamental physics oriented research and high social impact applications.
- *Two different configurations* have been studied to shorten the beam and reach peak current up to ~3kA:
  - a *fully RF compression* applying the velocity bunching scheme
  - a *hybrid compression* relying in an RF compression stage (at least a factor 3 from velocity bunching) followed by a magnetic one.
- Simulations performed with TStep that takes into account the space charge effects, relevant at very low energies, the thermal emittance and the beam loading.

The *emittance compensation* is obtained properly setting the gun solenoid and those surrounding the first and second S-band cavities in the velocity bunching scheme, according to the invariant envelope criteria

A slightly off-crest operation of the third S-band cavity *reduces the energy spread* at the injector exit.



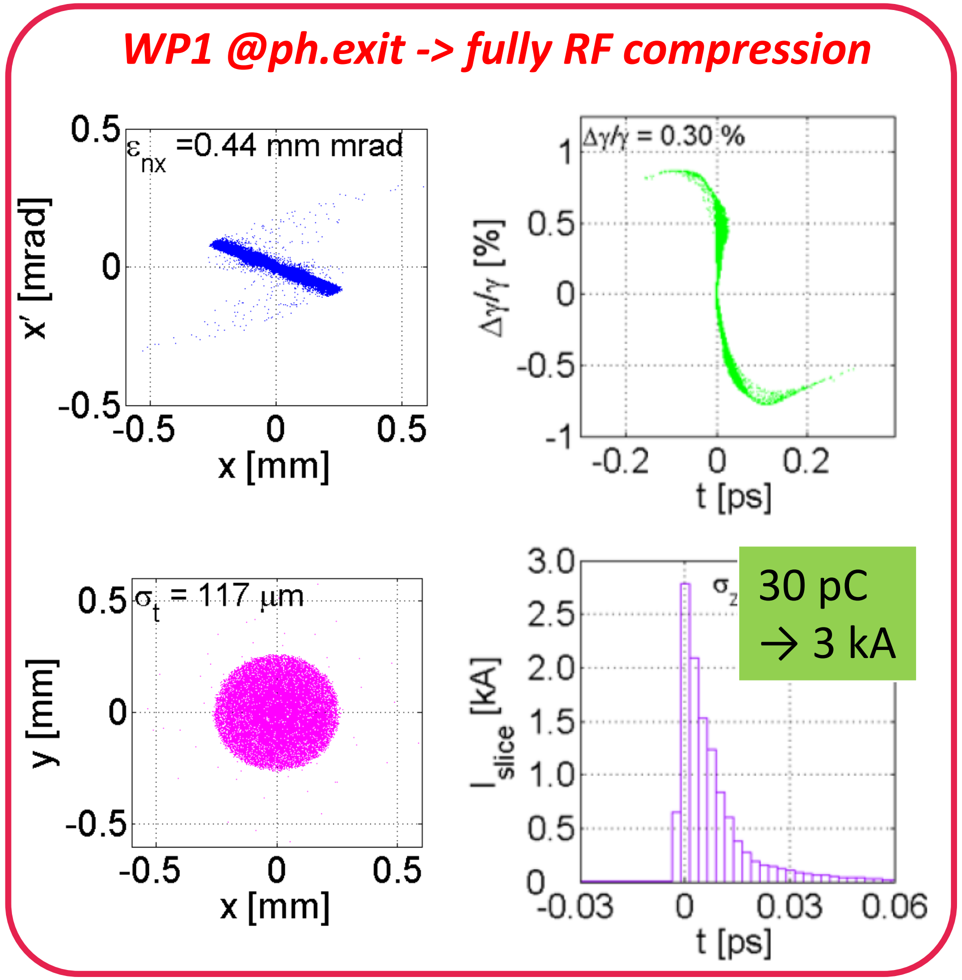
START TO END SIMULATIONS:
Photoinjector Working Points (WPs)

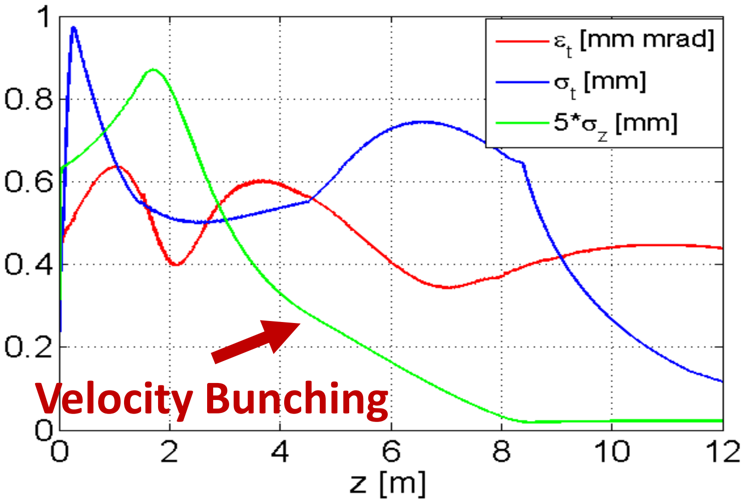
- **WP1: Low Charge-High Current** from the photoinjector: 30 pC-3kA (FWHM) per bunch, suitable both for Beam Driven and Laser driven acceleration in Plasma,
- **WP2: Low Charge-Low Current** from photoinjector: 30 pC-100A per bunch, coupled with a magnetic longitudinal compression stage in the chicane to reach the desired current I = 3kA (Hybrid scheme), suitable both for Beam Driven and Laser driven acceleration in Plasma,
- **WP3: High charge-Low Current (X–band RF based case)** from photoinjector: 200 pC-70 A, with and without the longitudinal bunch compression in the magnetic chicane to serve both the SASE-FEL, with peak current Ipk=2kA, and the Compton Source in the high flux operation scheme,
- **Comb operation: Low charge-High current trailing bunch + High charge driver bunch** from the Photoinjector: 30 pC-3kA (FWHM) trailing bunch + 200 pC driver bunch suitable for Beam Driven acceleration in Plasma.

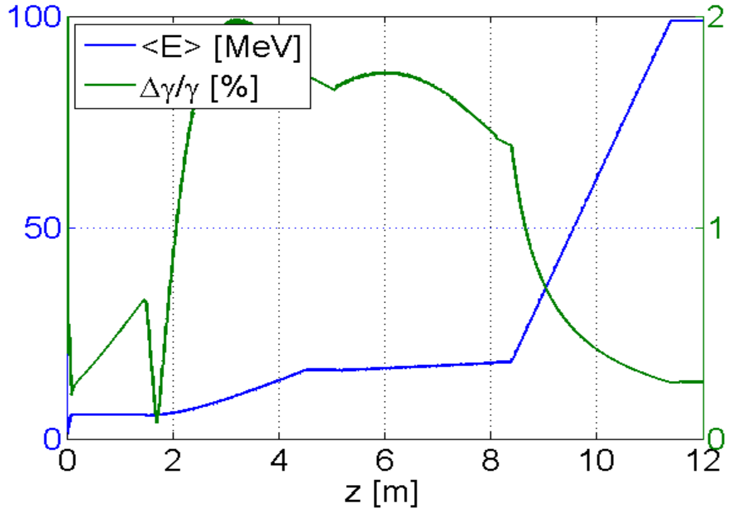
S2E results @ photo-injector exit	**Hybrid Compression**	**RF compression**			
	Single bunch operation			Comb beam operation	
	WP2	WP3	WP1	Witness	Driver
Q (pC)	30	200	30	30	200
E (MeV)	171.1	171.4	98.8	101.5	102.8
$\Delta\gamma/\gamma$ (%)	0.22	0.67	0.27	0.15	0.62
$\sigma_{r\text{-}rms}$ (μm)	104.0	390	117	99.0	89.0
$\varepsilon_{nx,y}$ (mm·mrad)	0.33	0.37	0.44	0.73	2.5
$\beta_{x,y}$ (m)	10.99	136.67	6.10	2.65	0.63
$\alpha_{x,y}$	2.96	-9.85	2.10	4	0.35
$\sigma_{z\text{-}slice}$ (μm)	0.75				
$\sigma_{z\text{-}rms}$ (μm)	37	112	5.6	6	42.1
$\sigma_{z\text{-}FWHM}$ (μm)			3	3	
$I_{peak\text{-}FWHM}$ (kA)			3	3	1.4
$I_{peak\text{-}slice}$ (kA)	0.14	0.51	3.8	1.5	0.5

START TO END SIMULATIONS
WP1: *low charge-high current*

- Best compromise in terms of *beam length* and *transverse normalised emittance*
- The *velocity bunching scheme* is applied to the first two S-band cavities to shorten the beam length from 350 down to ≅ 3 μm (FWHM).
- Current profile as naturally produced by the velocity bunching regime, i.e. a *spike-like distribution* with the charge gathered on the head of the bunch that is suitable in order to take profit of the beam loading.

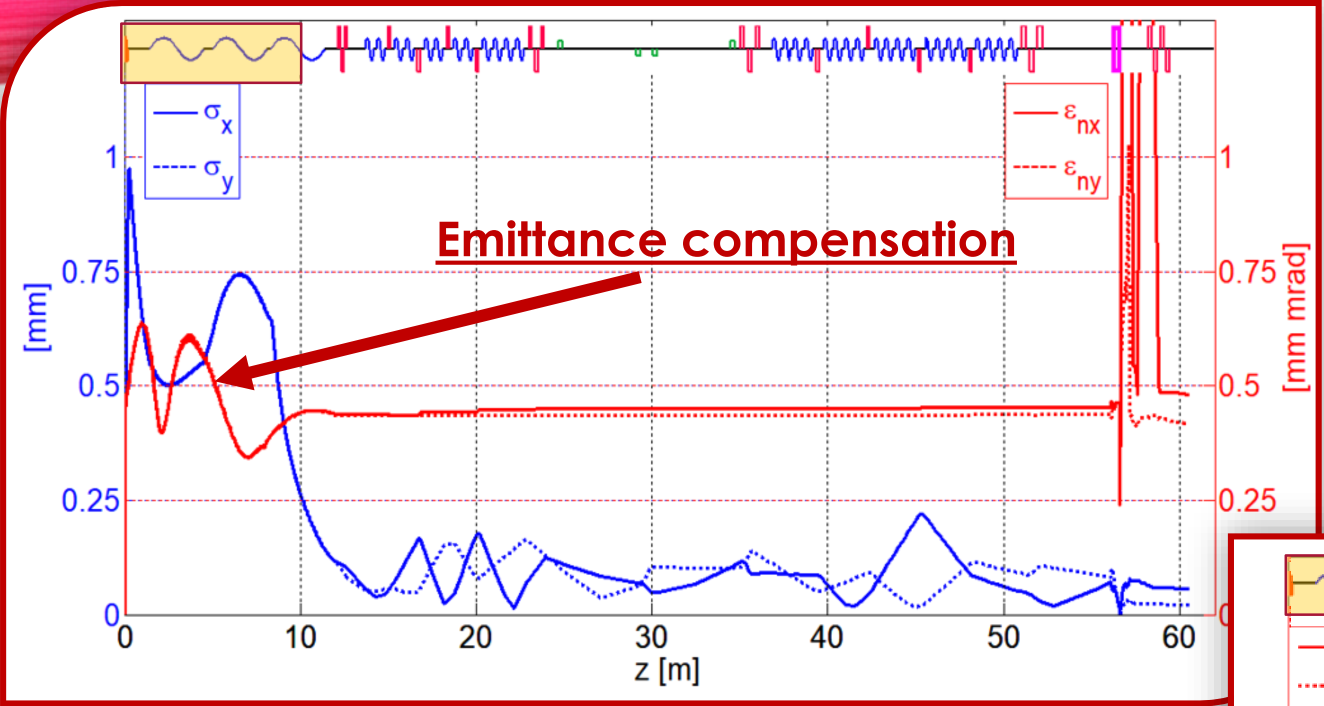


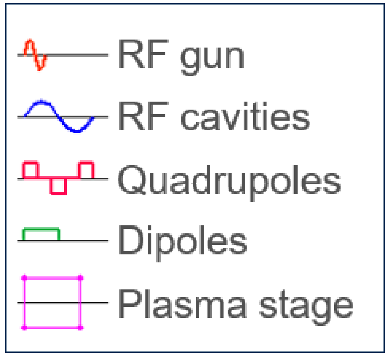


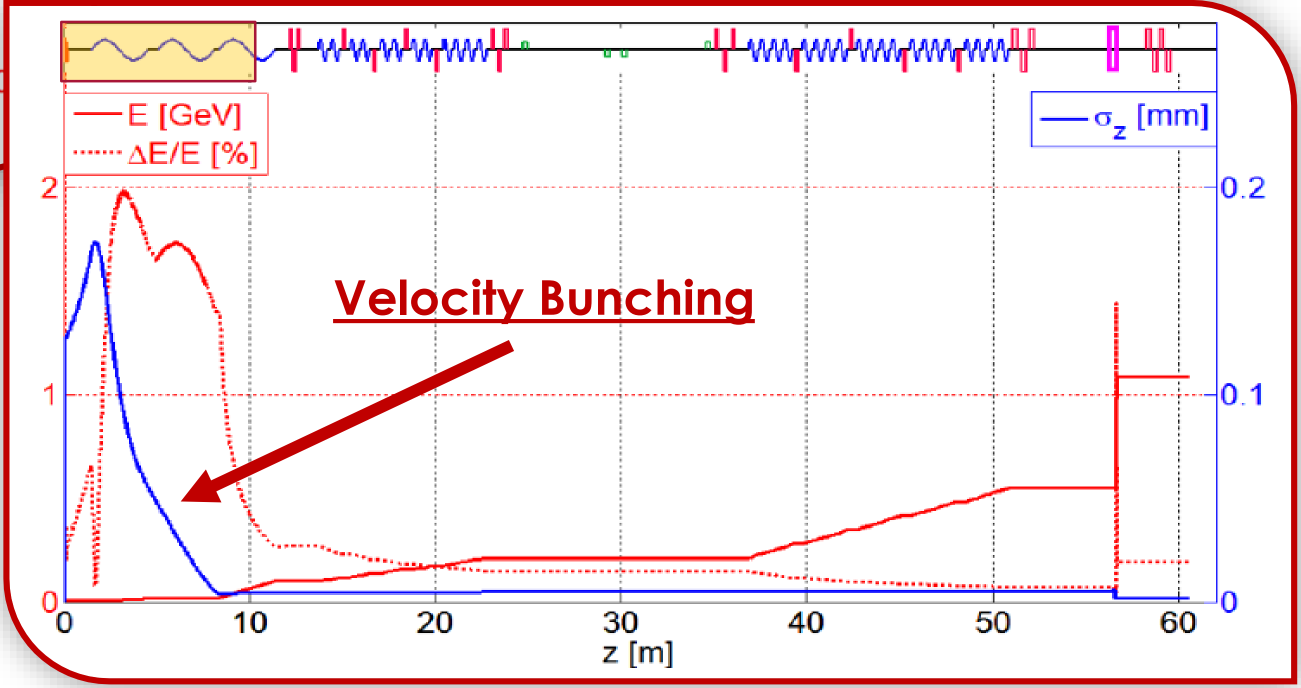


(*)A. Giribono, RF injector design studies for the witness beam for a plasma-based user facility, NIMA (2018)

START TO END SIMULATIONS
WP1: *low charge-high current*



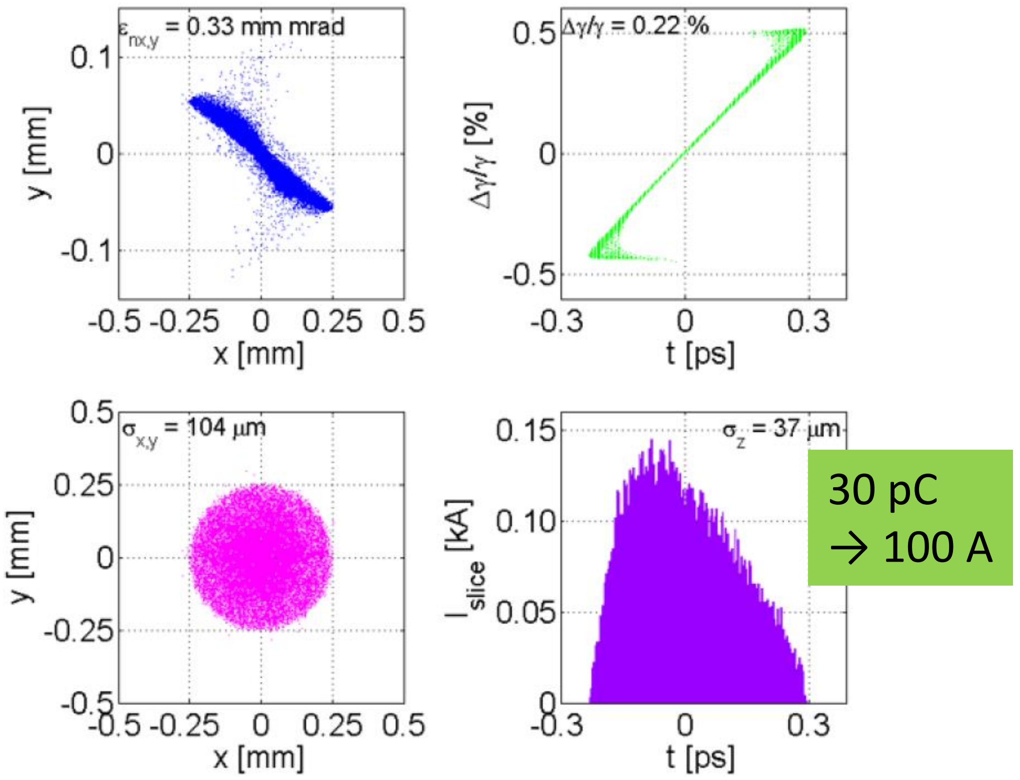




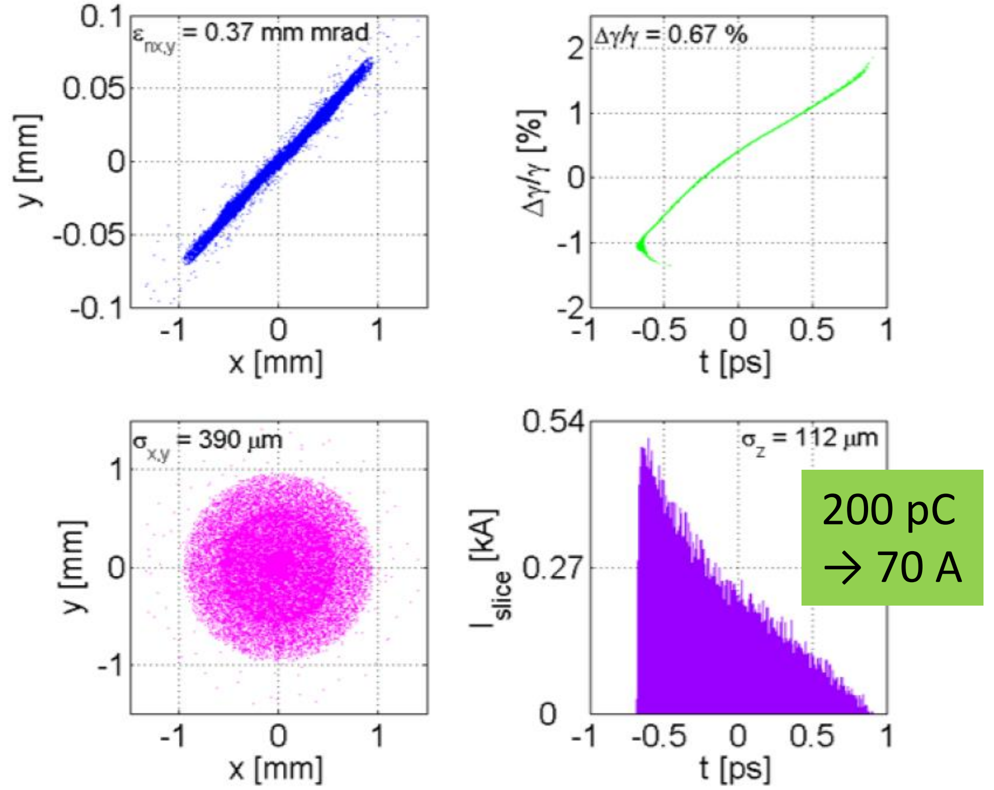
START TO END SIMULATIONS
WP2&3: *low&high charge-low current*

- Compression factor up to 3 with the velocity bunching to the first S-band cavity of the photoinjector
- Final compression in the magnetic chicane to get the required current at the FEL entrance

WP2 @ph. exit: compressed in the magnetic chicane to get the required 3 μm FWHM bunch length

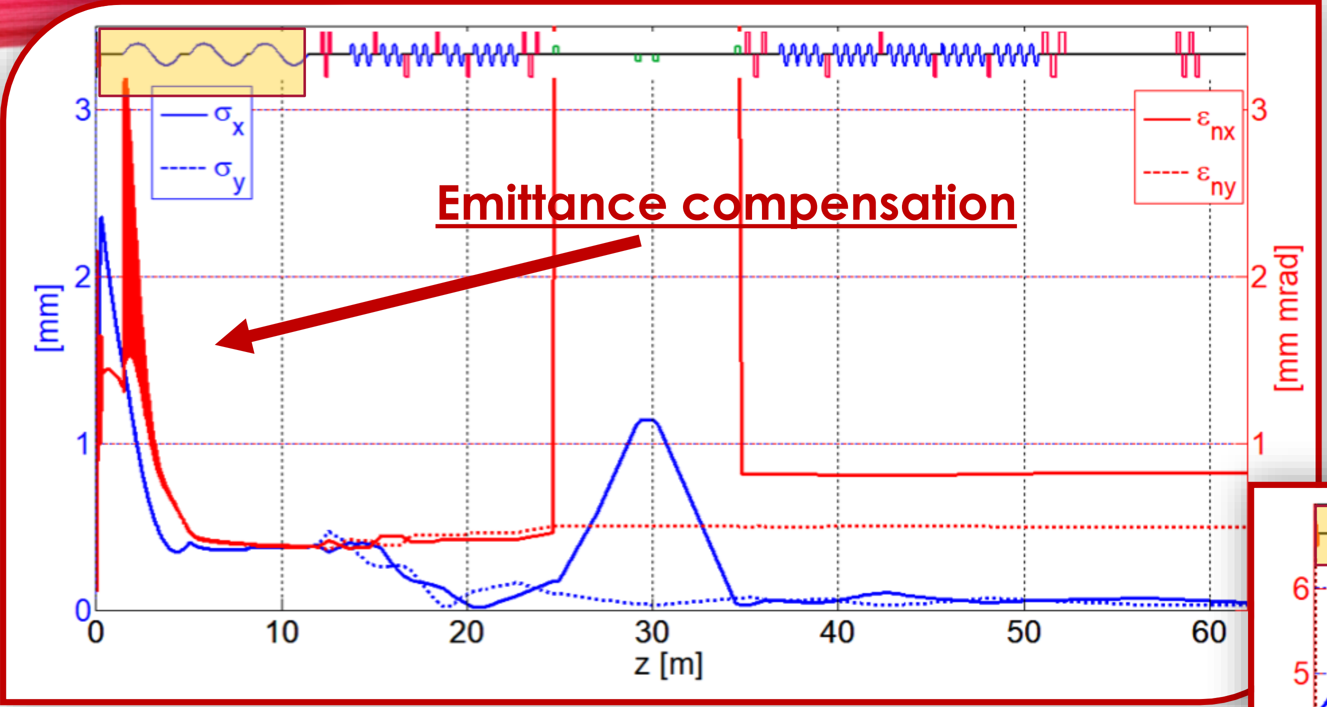


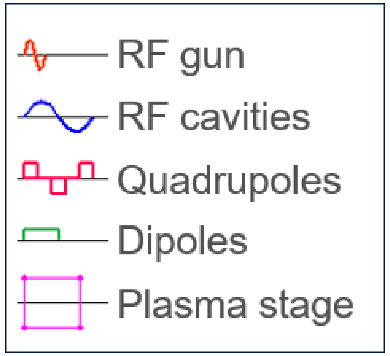
WP3 @ph.exit -> full X-band Rf based case: compressed in the magnetic chicane to get 2 kA peak current

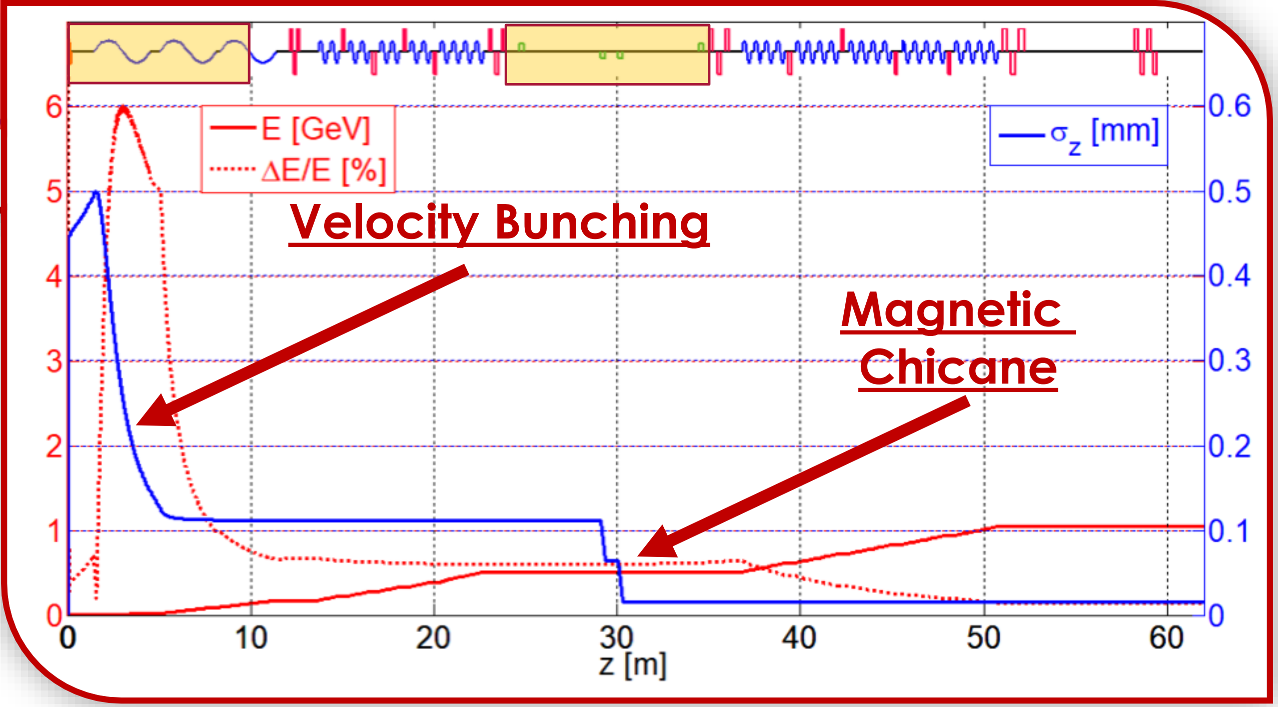


(*) A. Giribono, EuPRAXIA@SPARC_LAB: the high-brightness RF photo-injector layout proposal, NIMA (2018)

START TO END SIMULATIONS
WP3: *high charge-low current*







START TO END SIMULATIONS
Comb operation: 30 + 200 pC

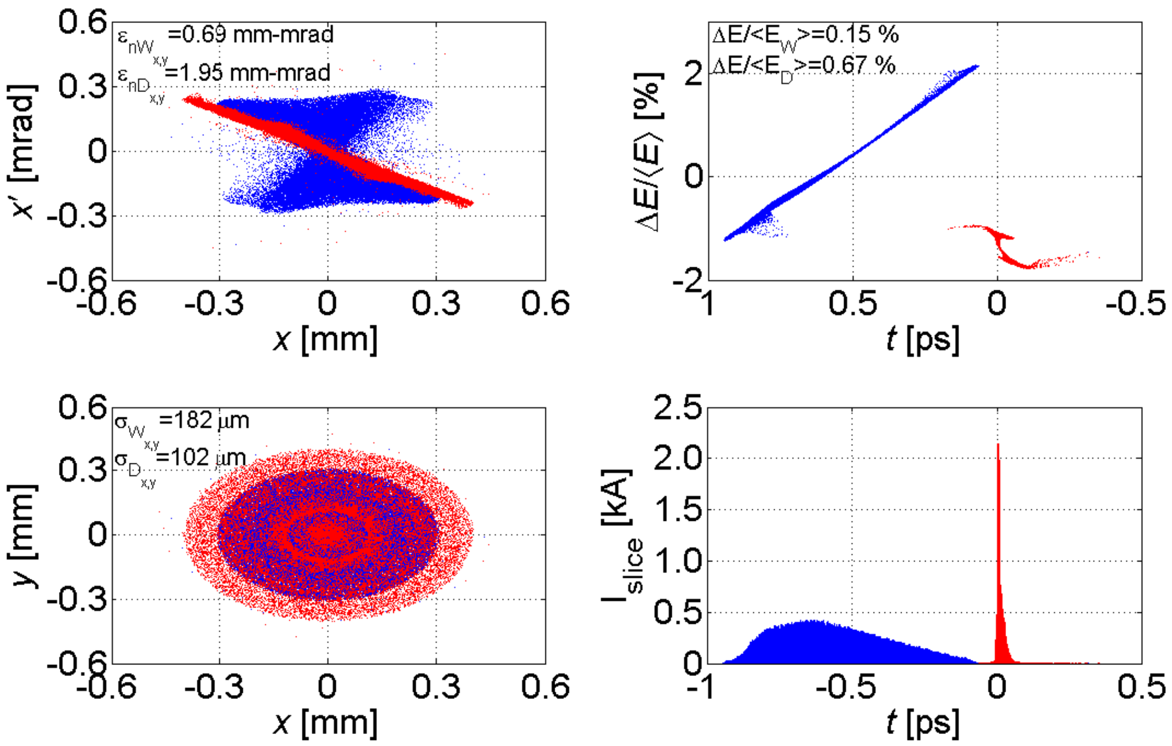
200 pC
→ 70 A

- Comb like configuration achieved by means of the laser-comb technique: *30 pC witness and 200 pC driver*

- Computational studies have been devoted to provide
  - $0.55 \cdot \lambda_p$ beam spaced (≈ 0.61 ps for $n_p = 10^{16}$ cm^{-3}), i.e. the accelerating and focusing region in the plasma bubble.
  - *witness with 3 kA-fwhm peak current*, minimising as much as possible the degradation of the transverse normalised emittance, that occurs because of the witness-driver crossing.
  - driver and witness transversally matched to the plasma (4 and 1 µm)

- Results have been obtained by
  - Appropriate shaping and relative spacing of the laser-comb pulses at the cathode surface
  - Fine tuning of phases of accelerating cavities and of magnetic fields of solenoids *starting from the optimised WP1*

COMB OPERATION @ph.exit -> starting from WP1



(*) A. Giribono, EuPRAXIA@SPARC_LAB: the high-brightness RF photo-injector layout proposal, NIMA (2018)

START TO END SIMULATIONS
Comb operation: 30 + 200 pC

- Best compromise in terms of final spacing and witness profile has been obtained with a laser-comb operation with two laser pulses spaced of $\Delta t = 4$ ps on the cathode

- *The driver spot size and beam-beam spacing on the cathode has been chosen looking at the witness quality, the witness emittance and longitudinal profile depending on it.*

- The driver spot size on the cathode is crucial for the control of
  - the witness emittance growth
  - the witness longitudinal distribution

- $r_D = 700$ µm is the optimal value for the driver spot size at the cathode surface

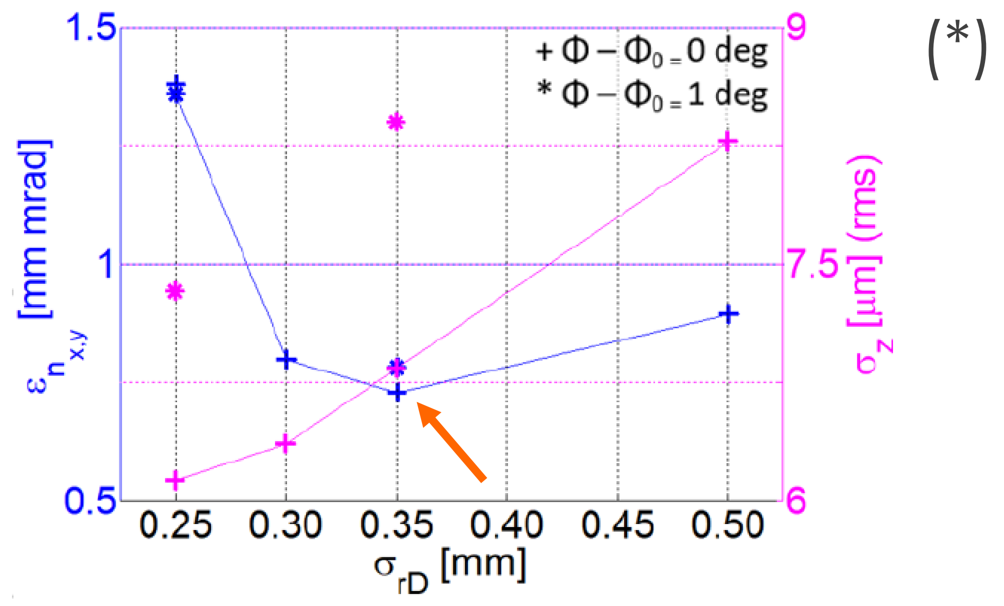


Figure 3: Witness RMS transverse normalised emittance and RMS length at the photo-injector exit as function of the driver spot size at the cathode (blue crosses are for nominal 2nd TW cavity RF phase, while magenta stars are for RF phase increased of 1 degree with respect to the nominal one.

(*) A. Giribono, EuPRAXIA@SPARC_LAB: the high-brightness RF photo-injector layout proposal, NIMA (2018)

START TO END SIMULATIONS
Comb operation: 30 + 200 pC

- In this configuration the *beam crossing* occurs in the second TW accelerating cavity and *a fine-tuning of the RF phases suffices to provide 0.55·λ_p spaced beams and the desired witness and driver longitudinal lengths*
- Adopting a r_D = 0.7 mm the FWHM witness length does not suffer lengthening and the fwhm peak current is preserved.
- Current profiles as naturally produced by the velocity bunching regime, i.e. a spike-like distribution with the charge gathered on the head of the bunch.

Optimal for the witness, but not for the driver and so further manipulation to increase the efficiency of the acceleration in the plasma stage are under investigation:

1. X-band linearizer
2. Beam shaping on the cathode
3. Etc…

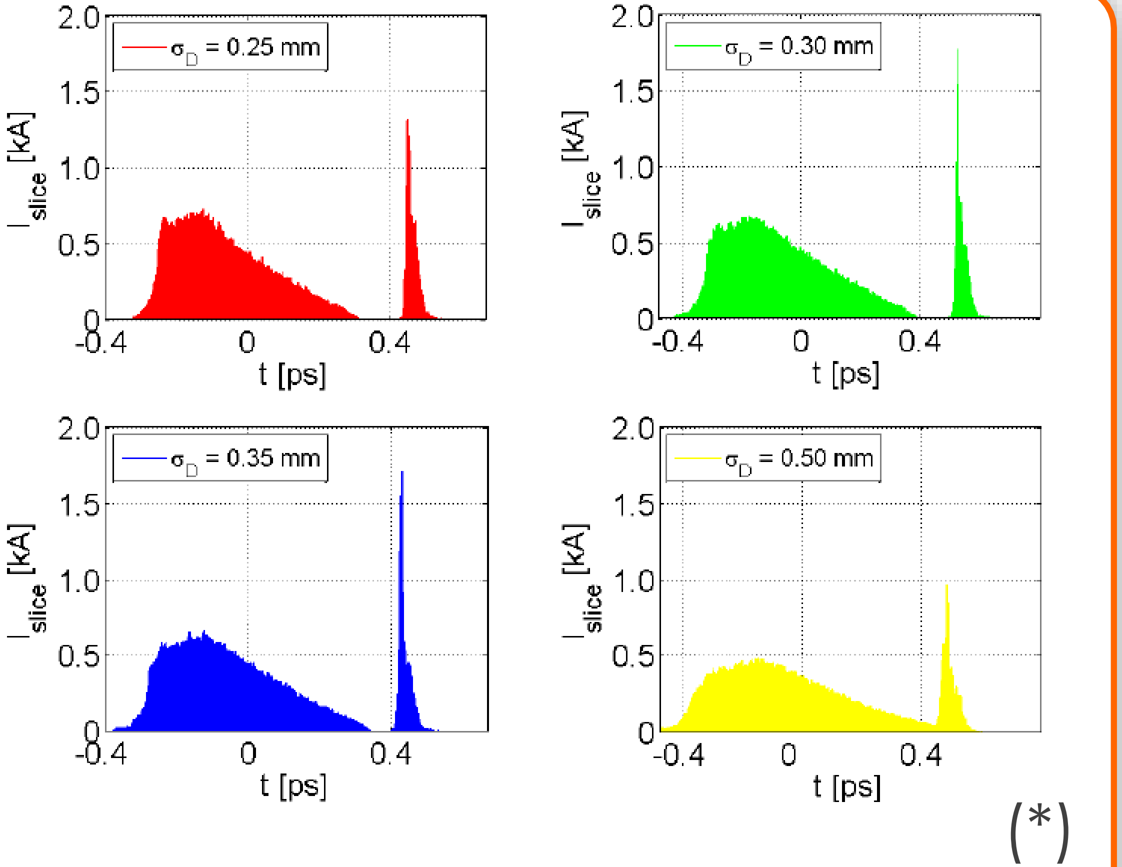
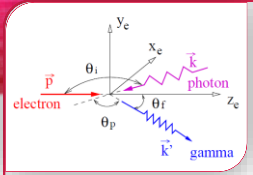


Figure 4: Longitudinal distribution of the comb-beam at the photo-injector exit for several driver spot size at the cathode. The beam is propagating from right to left with the driver arriving earlier that the witness.

(*) A. Giribono, EuPRAXIA@SPARC_LAB: the high-brightness RF photo-injector layout proposal, NIMA (2018)

OUTLINE

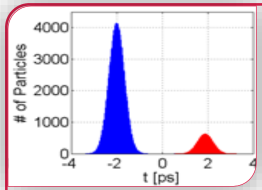


RF Linacs Driving Bright FEL and ICS radiation sources

- High brightness beams
- Radiation Sources under study at INFN_LNF
  1. ELI-NP GBS
  2. EuPRAXIA@SPARC_LAB

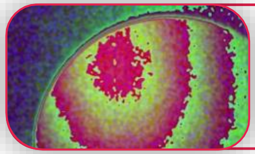
ELI-NP GBS RF Linac

- RF linac layout
- Start to end simulations
- Machine sensitivity studies



EuPRAXIA@SPARC_LAB RF linac

- EuPRAXIA@SPARC_LAB project
- Photoinjector Working Points (WPs)
- Start to end Simulations



Conclusions and Future Perspectives

CONCLUSIONS AND FUTURE PERSPECTIVES

- 6D phase space optimisation for high brightness electron beams in RF linacs have been described for advanced and high brilliance Inverse Compton Scattering and FEL radiation sources

- Expertise coming from high brightness linear accelerators enables reliable and demanding radiation sources that are today in the transition phase towards the era of *effective user facilities*

- The beam dynamics in the RF linac has been illustrated for the ELI-NP GBS and EuPRAXIA@SPARC_LAB facilties.

- Same studies have been performed for the EuPRAXIA European facility, whose proposed linac layout is very similar to the EuPRAXIA@SPARC_LAB one (*), and will be extended to the XLS Compact Light design study (FEL driven by X-band linac).

The practical experience coming from the ELI-NP GBS executive phase and from the experimental activity at SPARC LAB is playing an important role in view of the EuPRAXIA@SPARC_LAB TDR and of the ELI-NP machine future commissioning in Magurele.

(*)A. Giribono, RF injector design studies for the witness beam for a plasma-based user facility, NIMA (2018)

Thank you!!!