RF Injector Design Studies for the Witness Beam for a Plasma-based User Facility

Anna Giribono

INFN-LNF

On behalf of SPARC_LAB collaboration

EuPRAXIA RF injector Design Studies

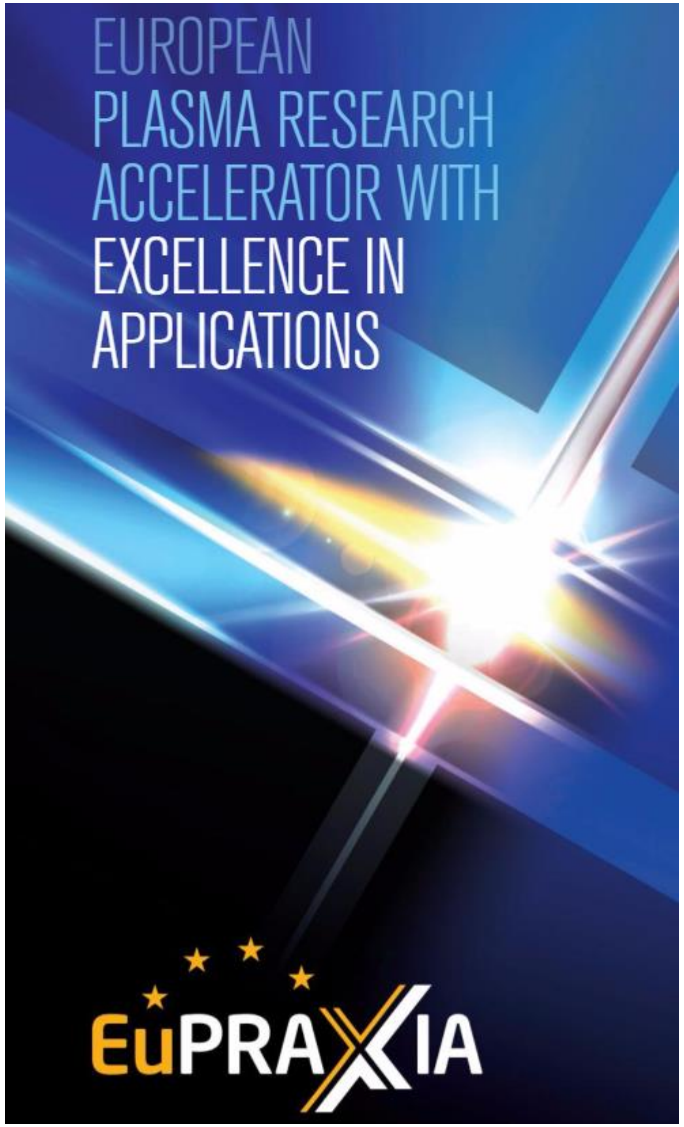
- The EuPRAXIA collaboration is preparing a conceptual design report for a multi-GeV plasma-based accelerator with outstanding beam quality [1] to drive a user facility for several applications (photon science, HEP, radiation sources, ...)

- Possible options for the EuPRAXIA facility foresee a plasma-wakefiled accelerator stage (LWFA or PWFA) with external injection from an RF-generated electron beam.

- The proposed injector scheme has been studied assuming that

  a) The successful operation of a plasma-based accelerator should not introduce any degradation of the beam quality but only boost of the energy.

  b) The beam parameters requested at the user beamline entrance are those at the plasma entrance, independently by the driving mechanism.



[1] P. A. Walker *et al.*, 'Horizon 2020 EuPRAXIA design study' - Journal of Physics: Conference Series 874, 1 (2017)

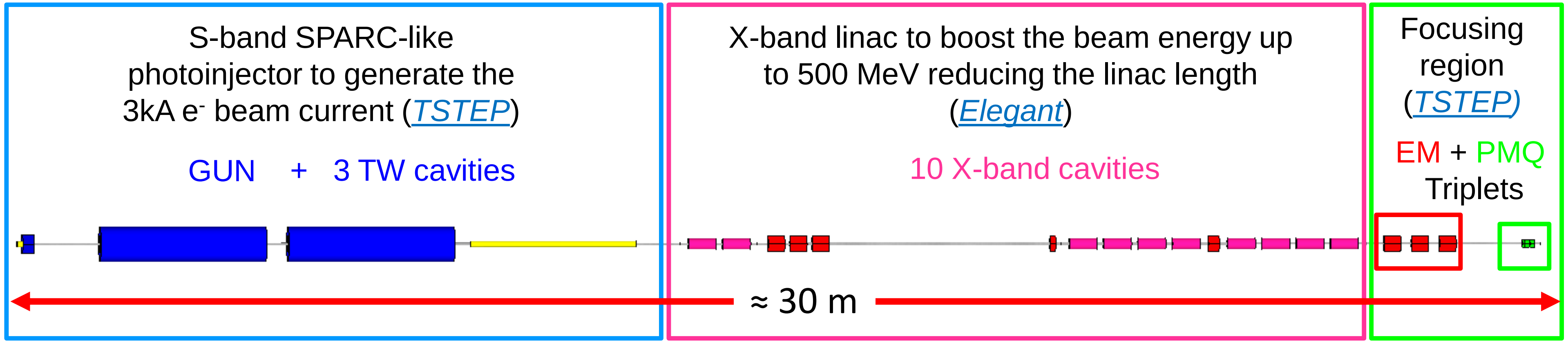
EuPRAXIA RF injector Layout

- The RF injector design is led by the e$^-$ beam quality needed for the operation of an X-ray FEL that is indeed *the most demanding for the electron beam in terms of brightness and quality*.
- A case of interest foresees a 1 GeV witness beam energy with less than 1 mm·mrad slice emittance and 30 pC in 10 fs fwhm, which turns into 3 kA peak current at the undulator entrance.
- **The study is focused on a witness beam at plasma entrance suitable for LWFA and PWFA: 30 pC, 3 kA, 500 MeV, 1 - 3 μm transverse spot size**
- The *EuPRAXIA RF injector proposal* is based on the combination of an S-band high-brightness photoinjector and an high-gradient X-band linac that can satisfy the request of high quality electron beams at the plasma stage entrance.

Simulation Tools *

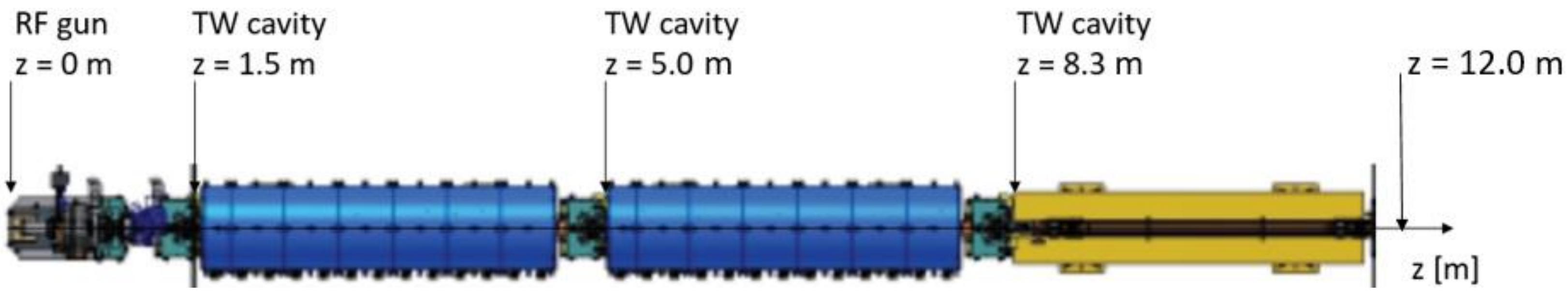
Tstep includes:
1. Space charge effects
2. Thermal emittance
3. Beam loading

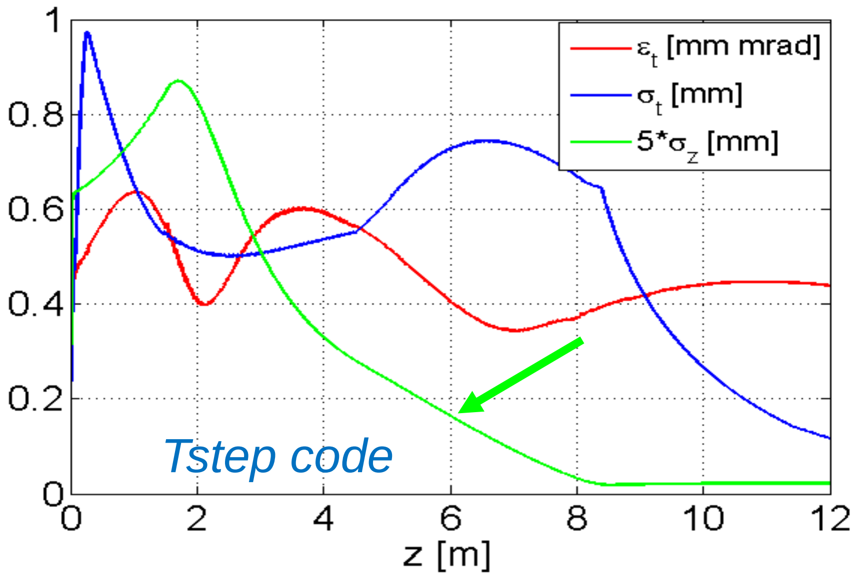
Elegant includes:
1. Wakefields in accelerating cavities
2. Longitudinal space charge
3. Coherent and incoherent synchrotron radiation in bending magnets

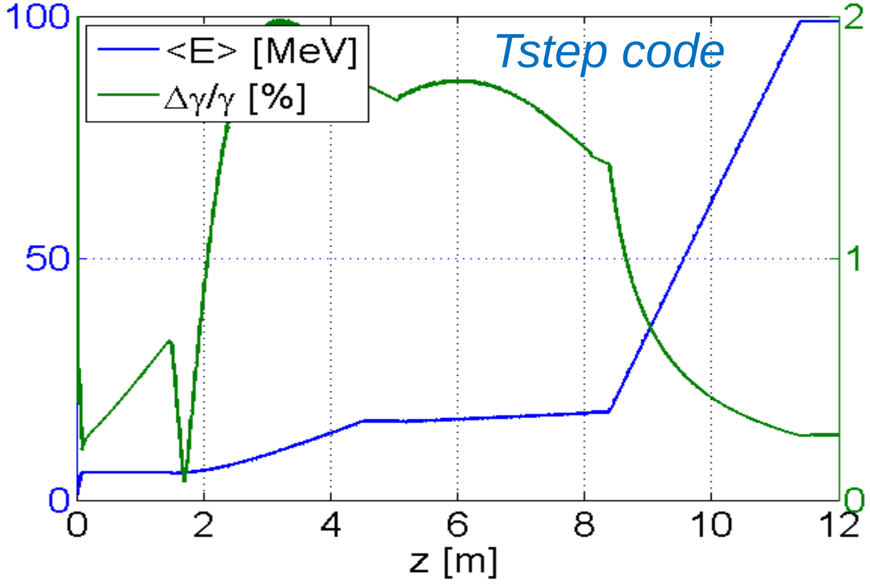


* *Used codes: Tstep, Elegant*

Beam Dynamics in photoinjector





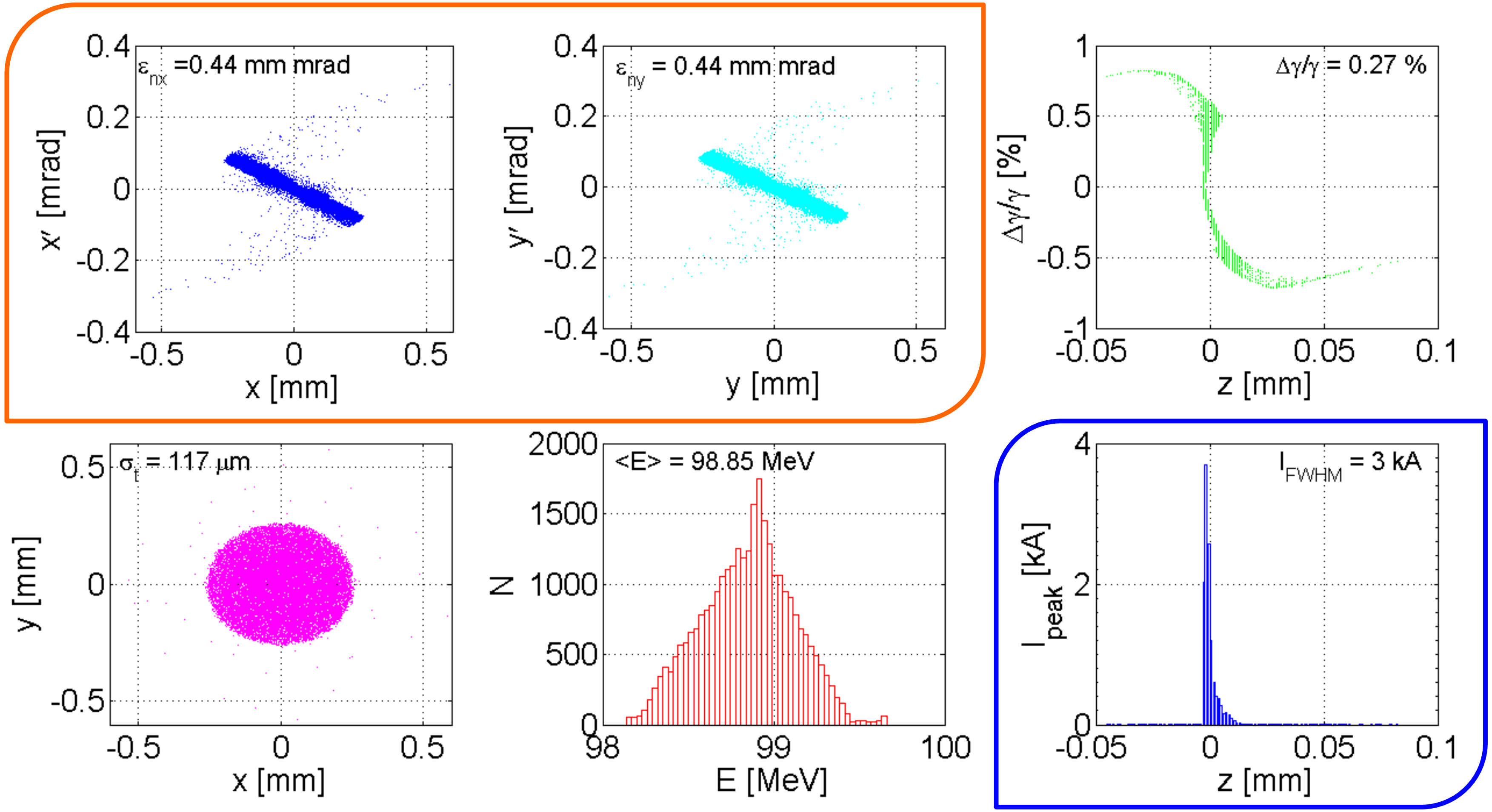


- BD and photoinjector layout optimised for the 30 pC witness beam in order to reach a peak current of ~3kA.
- The velocity bunching regime is applied to the first two S-band cavities to shorten the beam length from 350 to ≅ 3 μm (FWHM).
- The emittance minimisation is obtained properly setting the gun solenoid and those surrounding the first and second S-band cavities.
- A slightly off-crest operation of the third S-band cavity reduces the energy spread at the injector exit.
- Sensitivity studies have been performed and are detailed described in «**EuPRAXIA@SPARC_LAB: the high-brightness RF photoinjector layout proposal**» (Poster Session 2)

Beam Dynamics in photoinjector

- Best compromise in terms of beam length and transverse normalised emittance
- 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.

Beam parameters @Photoinj.Exit	
E [MeV]	**98.85**
$\varepsilon_{x,y}$ [mm mrad]	**0.44**
$\sigma_{z\text{-FWHM}}$ [µm]	**~ 3.0**
$\sigma_{z\text{-rms}}$ [µm]	**5.6**
ΔE/E [%]	**0.27**
$\sigma_{x\text{-rms}}$ [µm]	**117**
$\beta_{x,y}$ [m]	**6.1**
$\alpha_{x,y}$	**2.1**
$I_{peak\ [FWHM]}$ [kA]	**3**



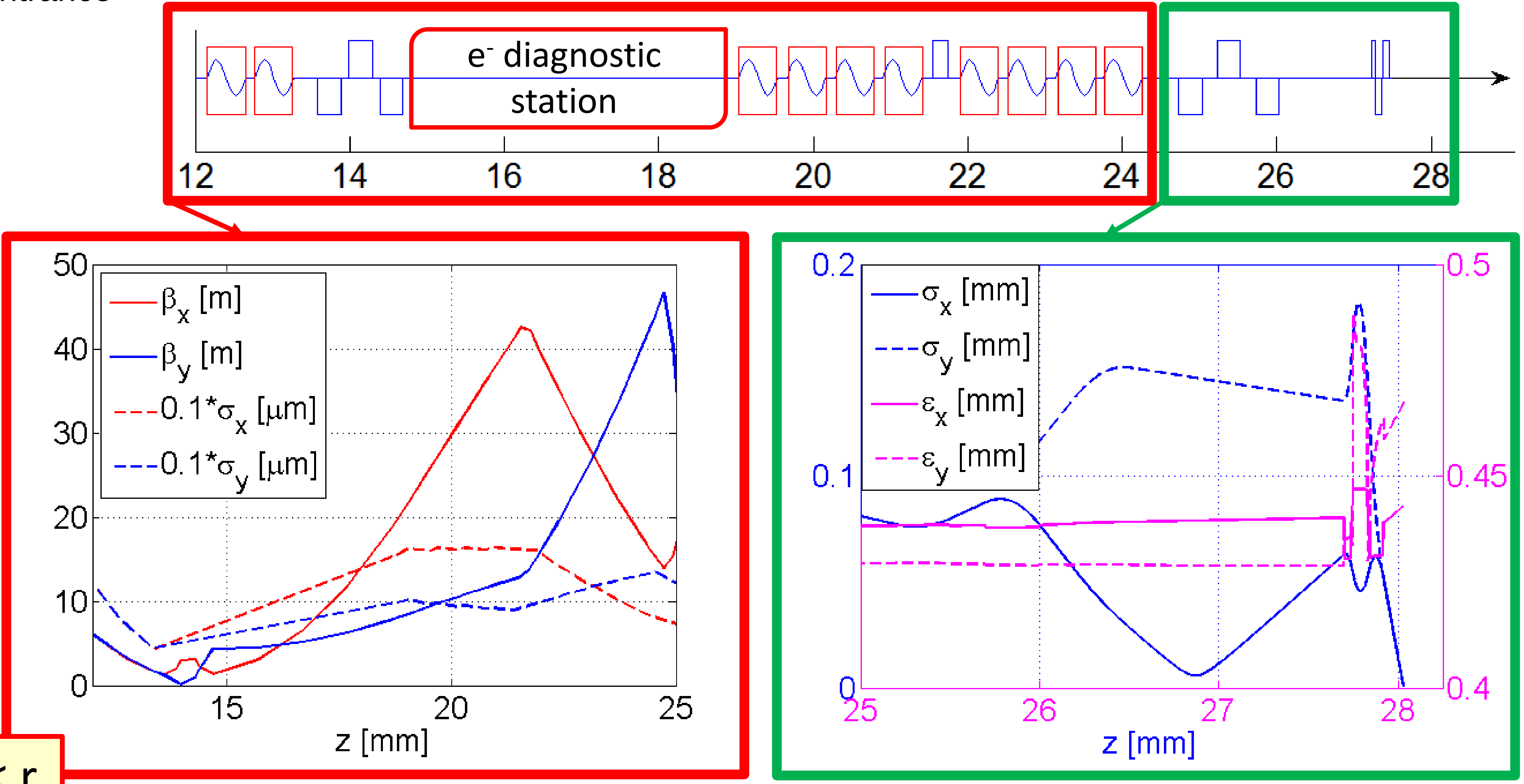
Beam Dynamics in the X-band linac

- Beam dynamics and X-band linac and focusing system optimised for the **30 pC witness beam** in order to
  1. boost the energy up to 500 MeV
  2. preserve the beam length and quality
  3. $\sigma_{t\text{-}rms} = 1\ \mu m$ @plasma entrance

- The beam line matching foresees to properly set magnetic elements and accelerating cavities

- Off crest operation to minimise the final beam energy spread.

The X-band accelerating structures are 0.5 m long and consist of 8.3 mm long cells with radius ranging between 2.4 - 3.5 mm on the Clic model (C. Vaccarezza's talk, M. Diomede's poster)

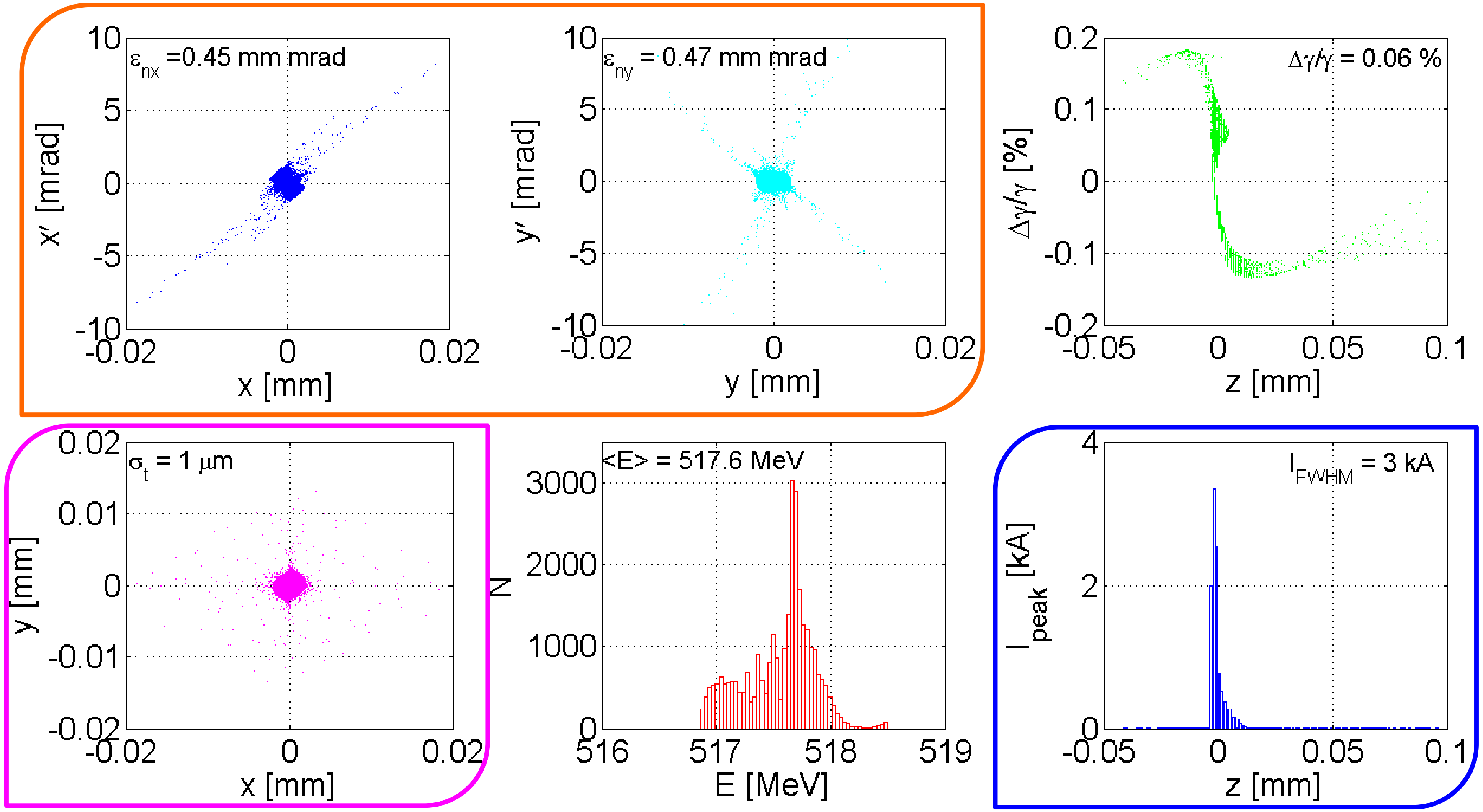


$10 \bullet \sigma_{x,y} < r$

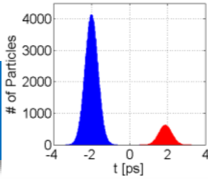
Witness Parameters @plasma entrance

1. Preservation of the witness length and transverse emittance in the X-band linac and in the focusing system
2. $\sigma_{t\text{-rms}}$ = 1 μm at plasma entrance

Beam parameters @Plasma Entrance	
E [MeV]	**517.6**
$\varepsilon_{x,y}$ [mm mrad]	**0.45 – 0.47**
$\sigma_{z\text{-FWHM}}$ [μm]	**~ 3.0**
$\sigma_{z\text{-rms}}$ [μm]	**6.0**
ΔE/E [%]	**0.06**
$\sigma_{t\text{-rms}}$ [μm]	**1.0**
$\beta_{x,y}$ [mm]	**2.0**
$\alpha_{x,y}$	**~ 0.0**
$I_{peak\ [FWHM]}$ [kA]	**3**



Comb-like configuration



- A "comb-like" configuration for the electron beam, consisting of a 200 pC driver followed by a 30 pC witness bunch, has been explored.

- First results have been obtained by
  - using the laser-comb technique, experimentally demonstrated at SPARC_LAB
  - appropriate shaping and relative spacing of the laser-comb pulses at the cathode surface
  - adopting a fine tuning of phases of accelerating cavities and of magnetic fields of solenoids ***starting from an optimised witness working point***

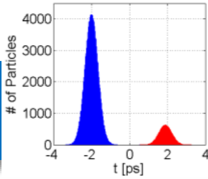
- Computational studies have been devoted to provide

  a) 0.55 ps beam spaced, corresponding to $\lambda_p/2$ (for $n_p = 10^{16}\ cm^{-3}$), i.e. the accelerating and focusing region in the plasma bubble.

  b) 3 µm (fwhm) witness length, and so 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.

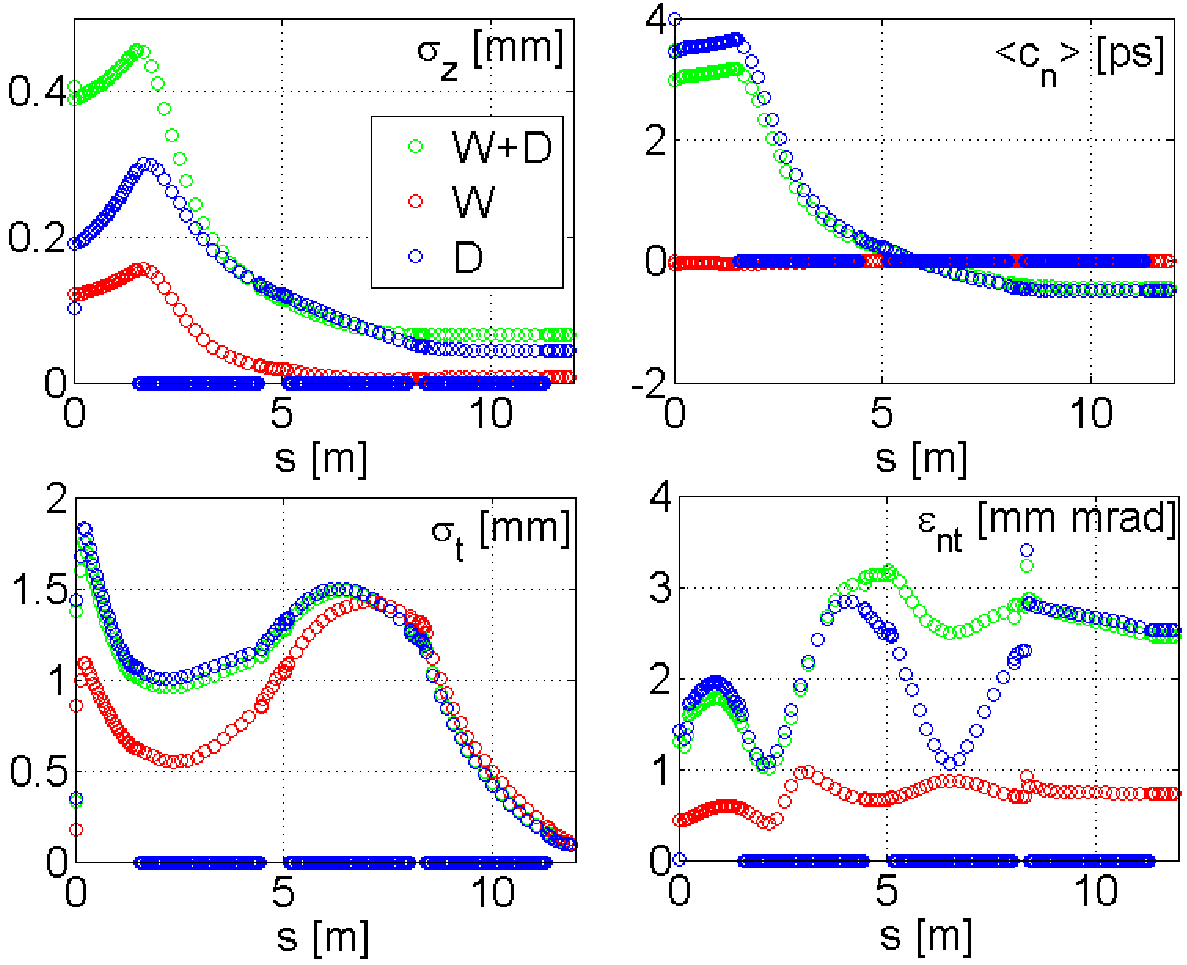
  c) driver and witness transversally matched to the plasma (4 and 1 µm)

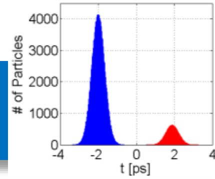
BD in the photoinjector



- Best compromise in terms of final spacing and witness profile has been obtained with a laser-comb operation with two laser pulses spaced of Δt = 4 ps on the cathode
- 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 ps spaced beams and the desired witness and driver longitudinal lengths
- The driver spot size on the cathode has been chosen looking at the witness quality, the witness emittance and longitudinal profile depending on it.

Beam parameters on the cathode		
	Driver	Witness
Charge [pC]	200	30
# of macroparticles	200k	30k
Transverse profile	Uniform	Uniform
Radius [μm]	500 - 700	350
Longitudinal profile	Gaussian	Gaussian
σ_z [μm]	120	120

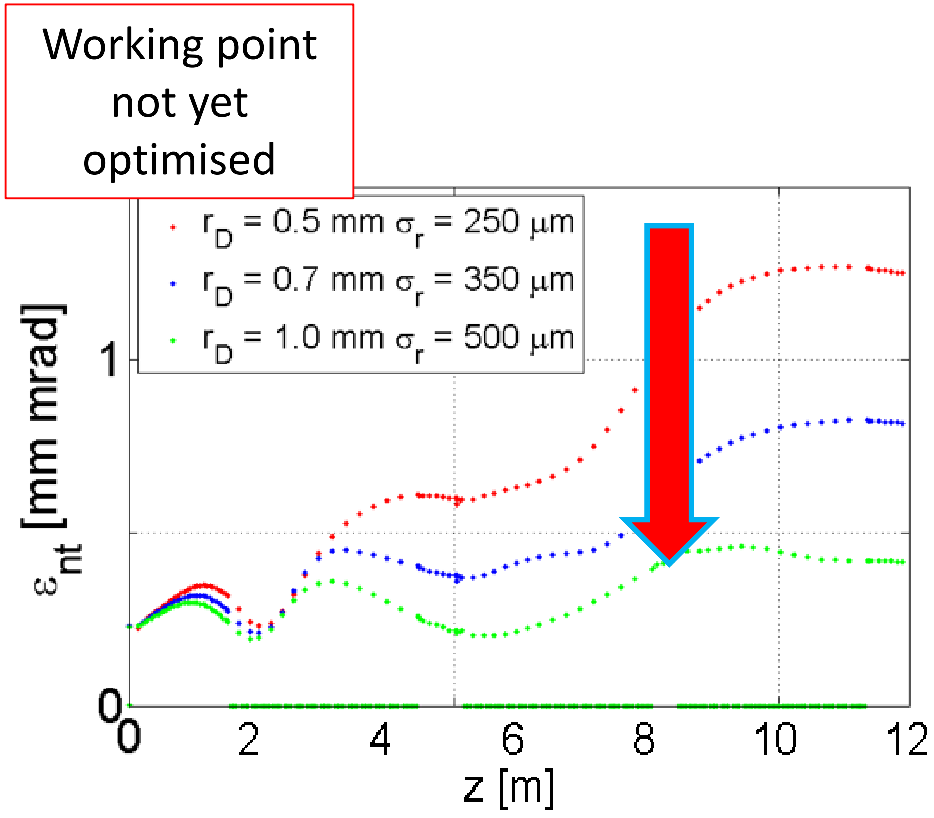


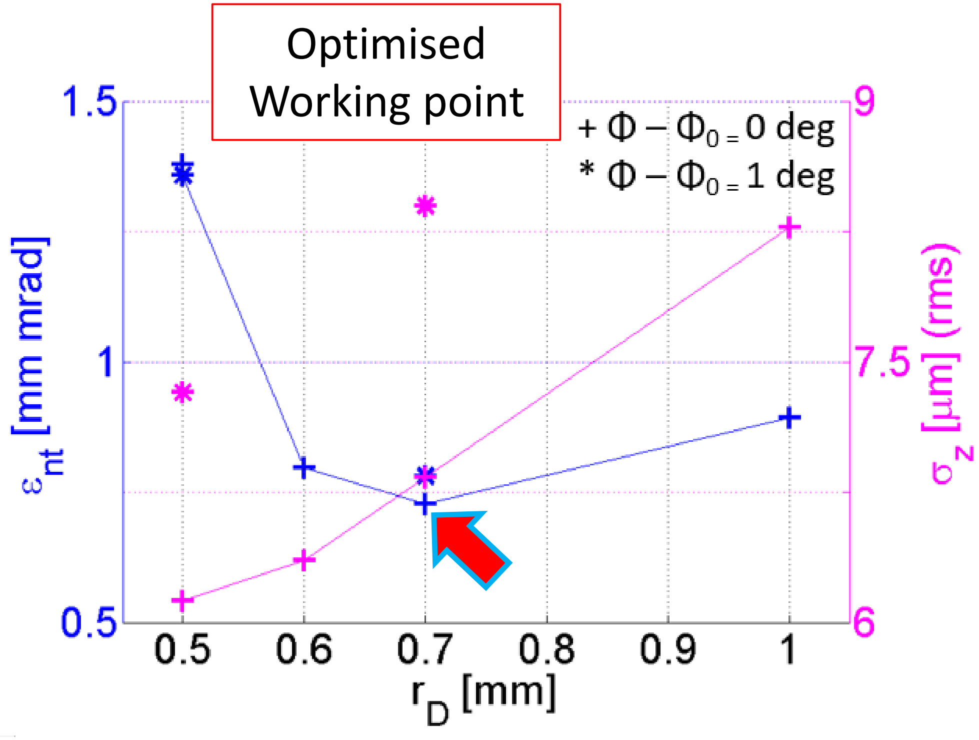


Transverse normalised emittance optimisation

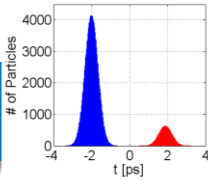
- The driver spot size on the cathode is crucial for the control of
  - a) the witness emittance growth
  - b) the witness longitudinal distribution

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





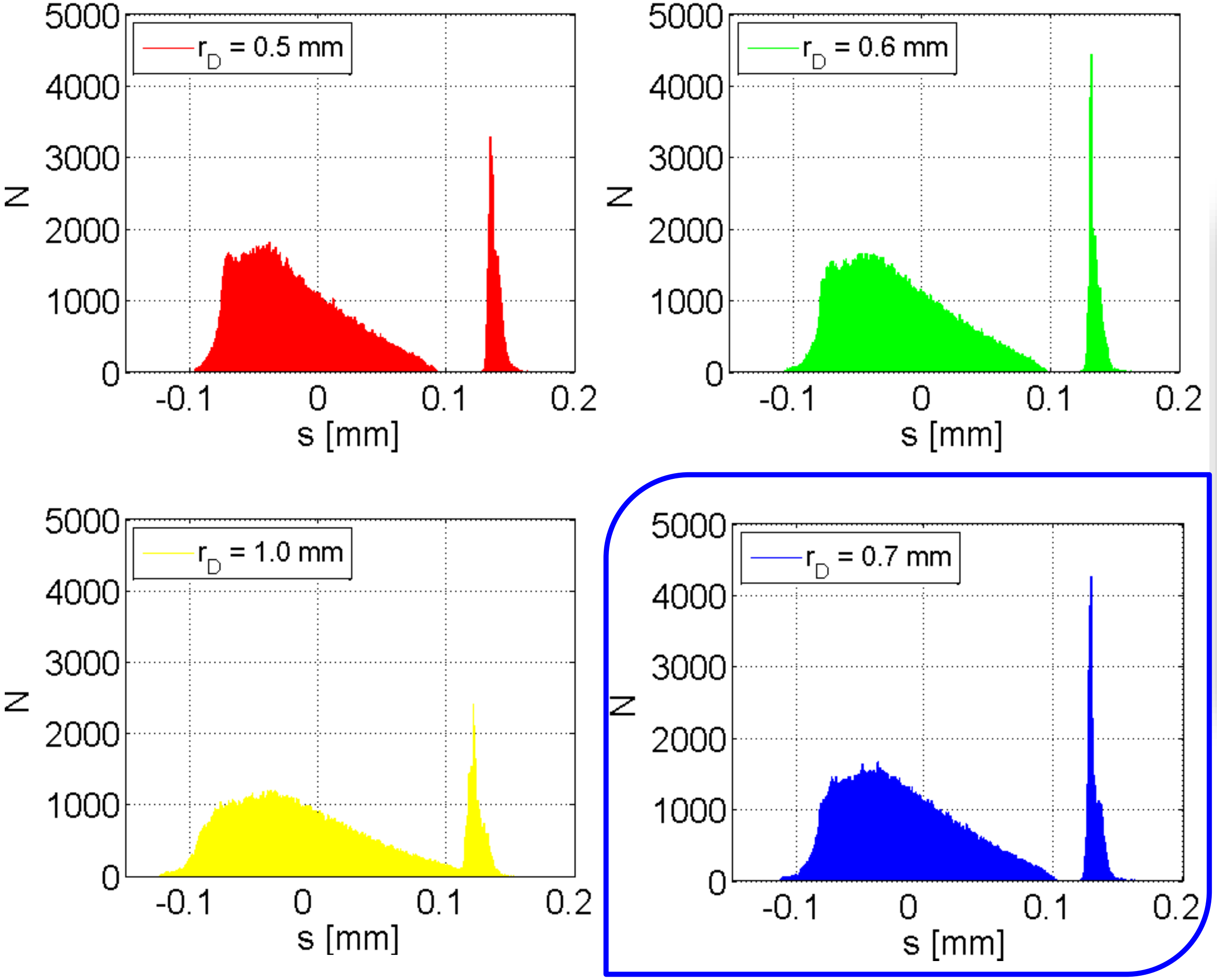
Longitudinal distribution optimisation



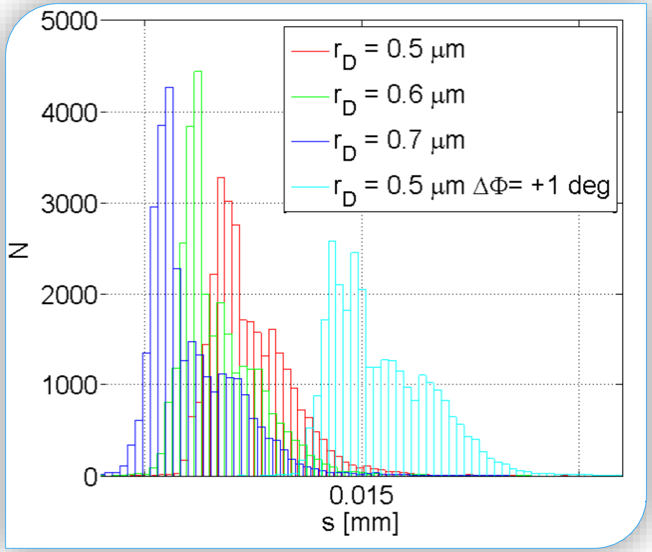
- Adopting a r_D = 0.7 mm the FWHM witness length does not suffer lengthening although the minimum rms witness length is obtained for r_D = 0.5 mm.

- 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.

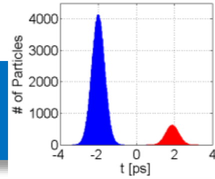
Further manipulation to increase the trasformer ratio



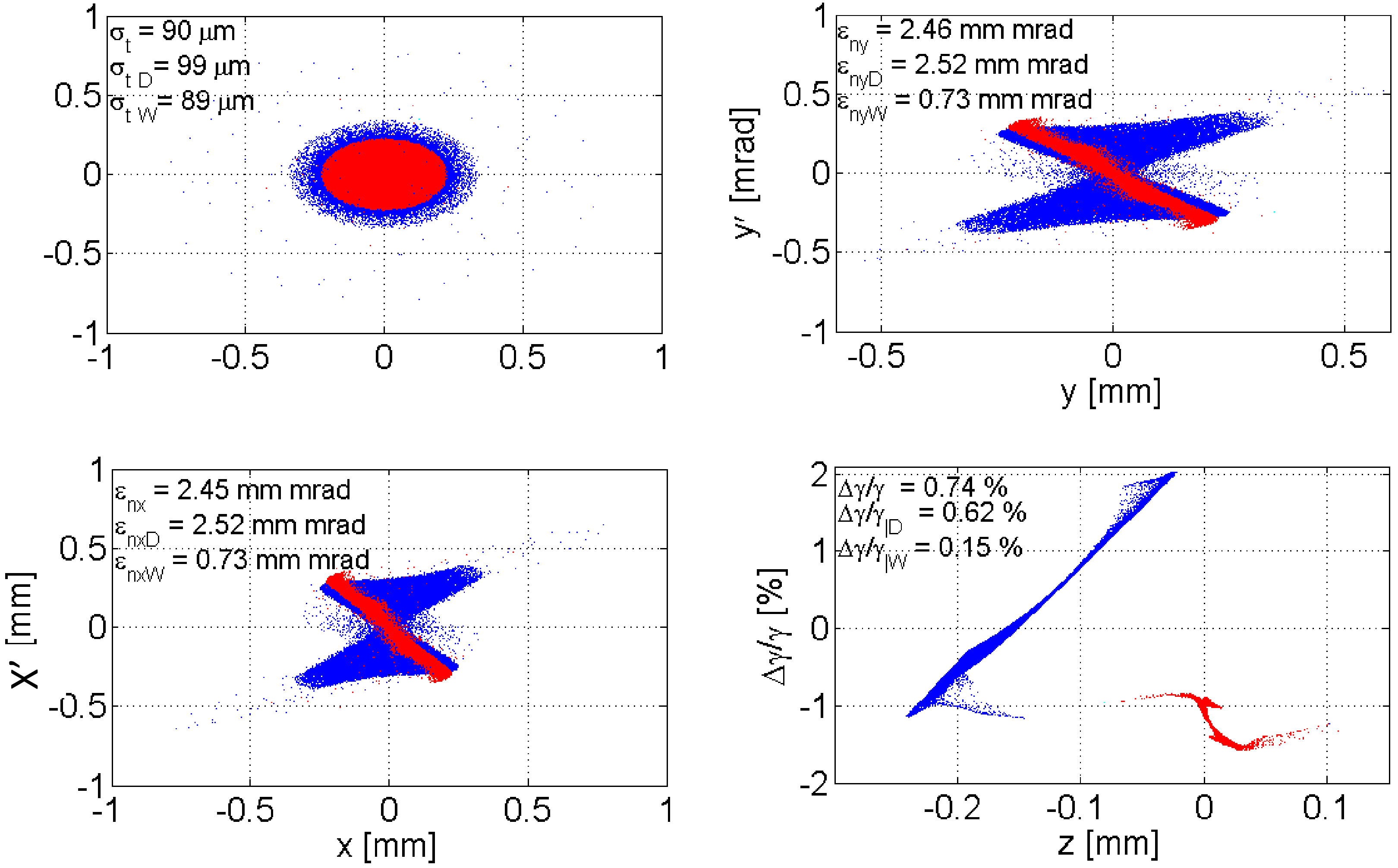
Detail of the witness longitudinal distribution

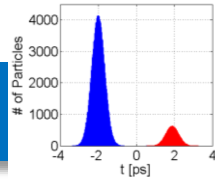


Phase space @Photoinjector exit



Witness parameters @Photoinj.Exit	
E [MeV]	**98.85**
$\varepsilon_{x,y}$ [mm mrad]	**0.73**
$\sigma_{z\text{-FWHM}}$ [μm]	**~ 3.0**
$\sigma_{z\text{-rms}}$ [μm]	**5.6**
ΔE/E [%]	**0.27**
$\sigma_{x\text{-rms}}$ [μm]	**117**
$\beta_{x,y}$ [m]	**6.1**
$\alpha_{x,y}$	**2.1**
$I_{peak\ [FWHM]}$ [kA]	**3**

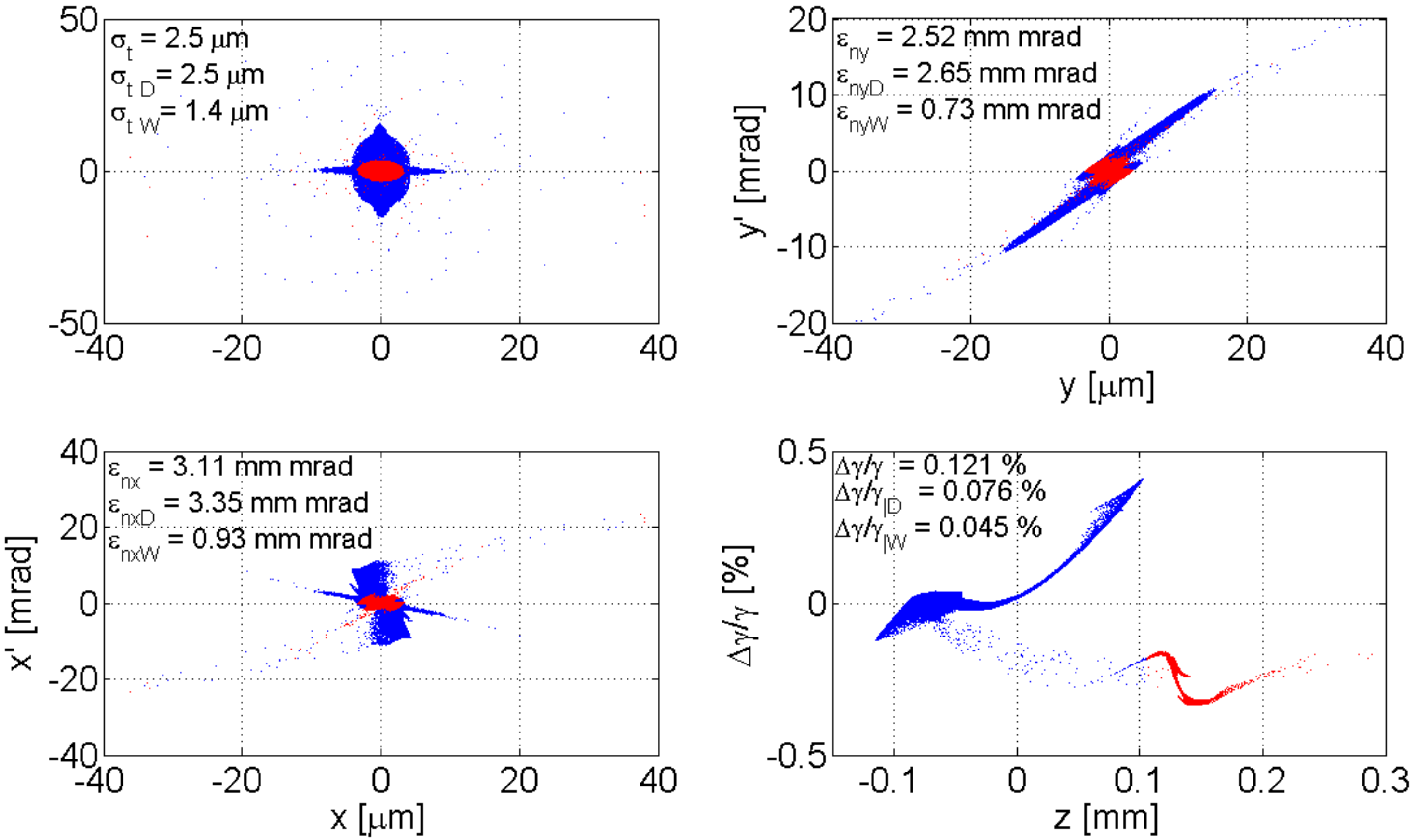




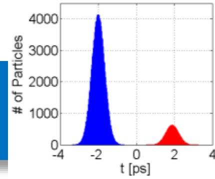
Phase space at plasma entrance

Very first results

Beam parameters @Plasma Entrance		
	Comb-like operation	
Q [pC]	**30**	**200**
E [MeV]	**499**	**500.4**
$\varepsilon_{x,y}$ [mm mrad]	**0.73 – 0.93**	**2.6 - 3.3**
$\sigma_{z\text{-FWHM}}$ [µm]	**~ 3.0**	**-**
$\sigma_{z\text{-rms}}$ [µm]	**6.0**	**42.1**
ΔE/E [%]	**0.05**	**0.07**
$\sigma_{x\text{-rms}}$ [µm]	**1.1**	**2 - 3**
$\beta_{x,y}$ [mm]	**2.0**	**-**
$\alpha_{x,y}$	**~ 0.0**	**-**
$I_{peak\ [FWHM]}$ [kA]	**3**	**-**

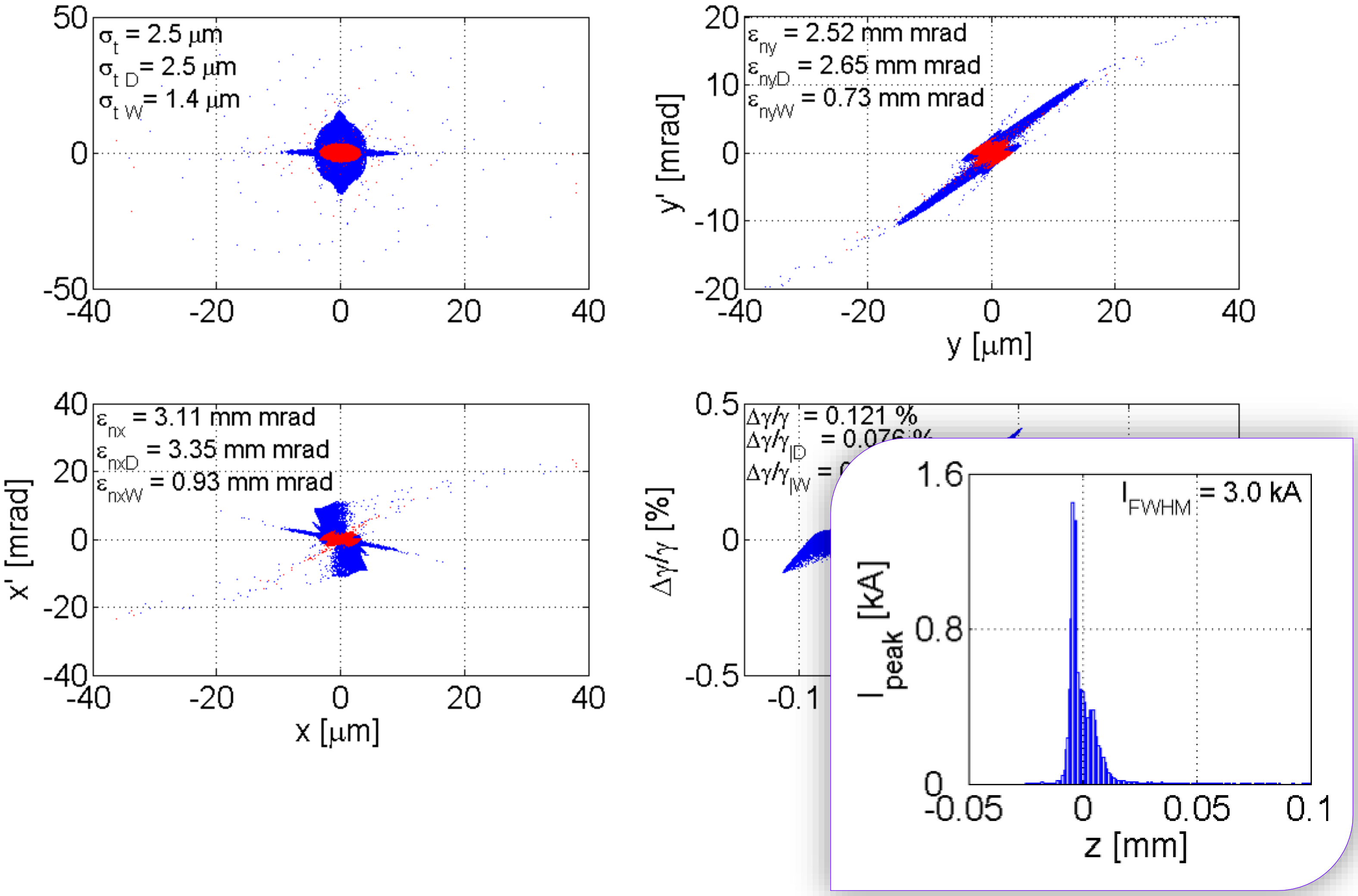


Phase space at plasma entrance



Very first results

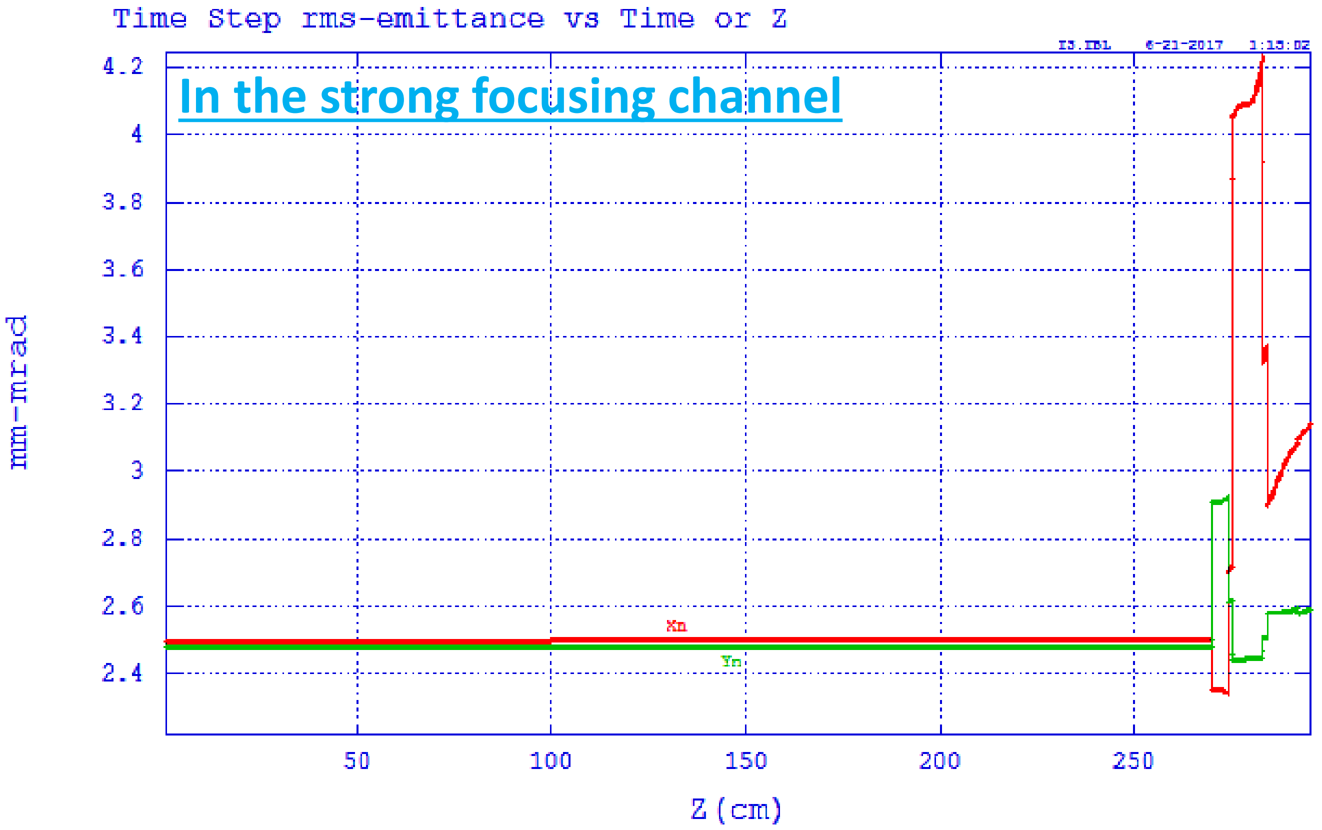
Beam parameters @Plasma Entrance		
	Comb-like operation	
Q [pC]	**30**	**200**
E [MeV]	**499**	**500.4**
$\varepsilon_{x,y}$ [mm mrad]	**0.73 – 0.93**	**2.6 - 3.3**
$\sigma_{z\text{-FWHM}}$ [μm]	**~ 3.0**	**-**
$\sigma_{z\text{-rms}}$ [μm]	**6.0**	**42.1**
ΔE/E [%]	**0.05**	**0.07**
$\sigma_{x\text{-rms}}$ [μm]	**1.1**	**2 - 3**
$\beta_{x,y}$ [mm]	**2.0**	**-**
$\alpha_{x,y}$	**~ 0.0**	**-**
$I_{peak\ [FWHM]}$ [kA]	**3**	**-**



BD in the strong focusing channel

- Some emittance dilution in the strong focusing region
- There is room for emittance preservation by optimizing the final strong focusing matching

Witness parameters	@ph. exit	@linac exit	@plasma entrance
E [MeV]	98.85	499	499
$\varepsilon_{x,y}$ [mm mrad]	0.73	0.73	0.73 – 0.93
$\sigma_{z\text{-FWHM}}$ [μm]	~ 3.0	~ 3.0	~ 3.0
$\sigma_{z\text{-rms}}$ [μm]	5.6	6.7	6.7
$\Delta E/E$ [%]	0.27	0.05	0.05
$\sigma_{x,y\text{-rms}}$ [μm]	117	67	1.4
$\beta_{x,y}$ [mm]	6.1	6 - 7	2.0
$\alpha_{x,y}$	2.1	-0.7 – -1.3	~ 0.0
$I_{peak\ [FWHM]}$ [kA]	3	3	3



CONCLUSIONS

- Injector scheme to provide a 3 kA witness beam at plasma injection has been optimised for the witness beam in the single bunch and comb-like configuration

- The witness beam has been successfully compressed down to 10 fs in a conventional SPARC-like photoinjector and boosted up to 500 MeV in an advanced high-gradient X-band linac reaching the plasma entrance with 3 kA peak current, 0.07% energy spread, 0.5 mm.mrad transverse normalised emittance and a focal spot down to 1 µm

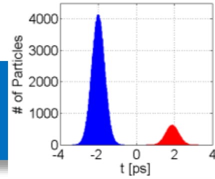
- A "comb-like" configuration for the electron beam, consisting of a 200 pC driver followed by a 30 pC witness bunch, has been also explored with promising results

- Even though the particle longitudinal distribution is suitable for the witness beam in order to take profit of the beam loading, it is not the optimum for the driver beam. Indeed, to increase the transformer ratio the opposite charge distribution, i.e. low charge on the head and maximum charge on the tail, is mandatory. At this regard, further manipulation of the longitudinal phase space is required for the driver.

- Further sensitivity studies are needed to check the actual robustness of the injector and in particular of the final focusing channel

THANK YOU!!!

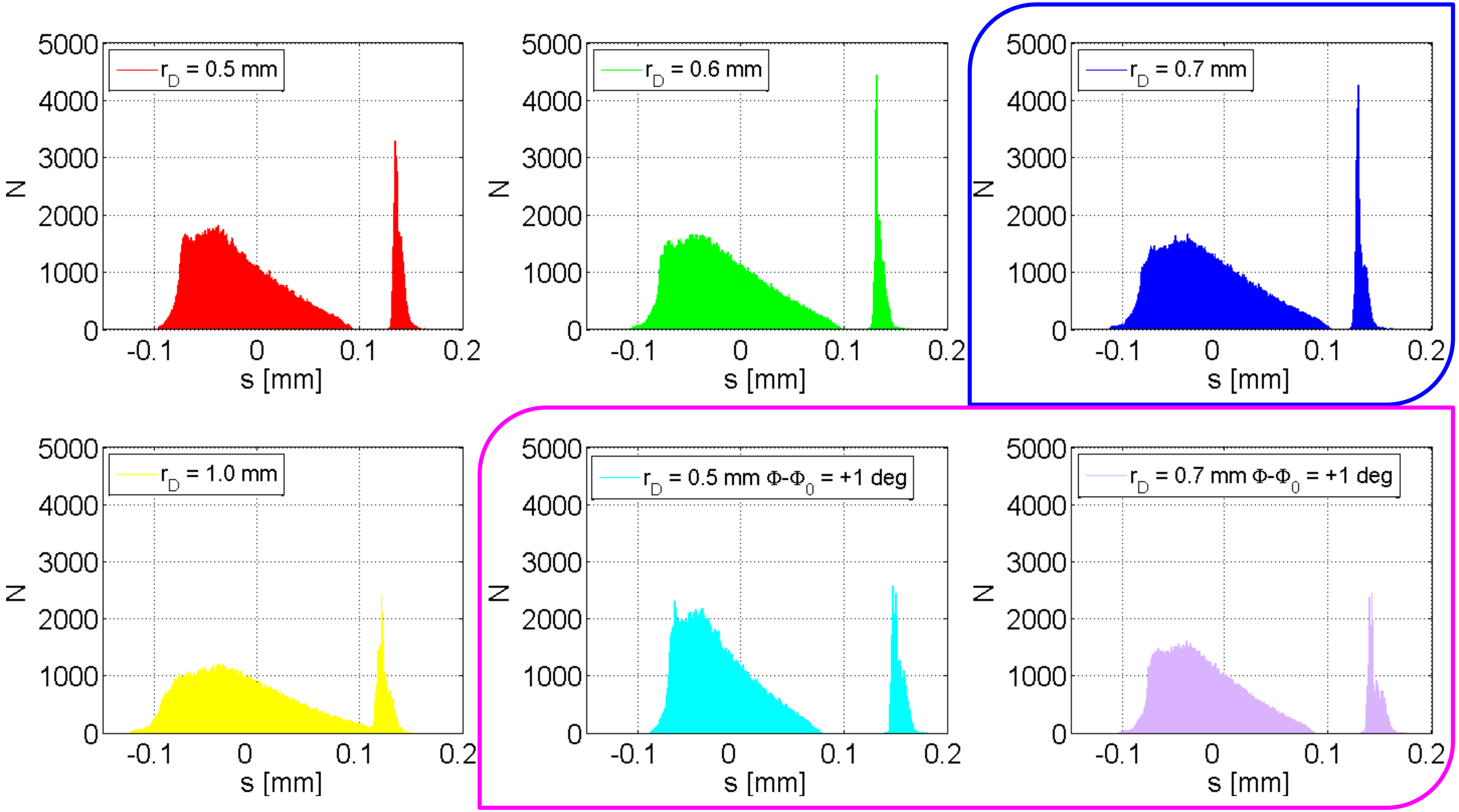
Longitudinal distribution optimisation



- Adopting a r_D = 0.7 mm the FWHM witness length does not suffer lengthening although the minimum rms witness length is obtained for r_D = 0.5 mm.

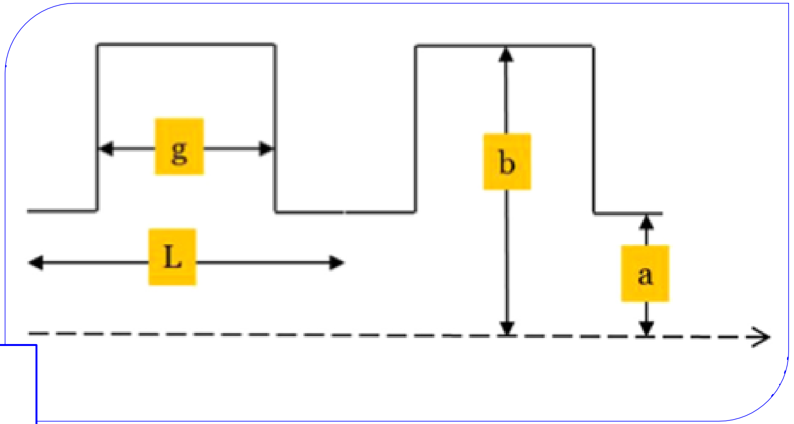
- Current profiles as naturally produced by the velocity bunching regime, i.e. a spike-like distribution with the charge gathered on the head of the bunch.

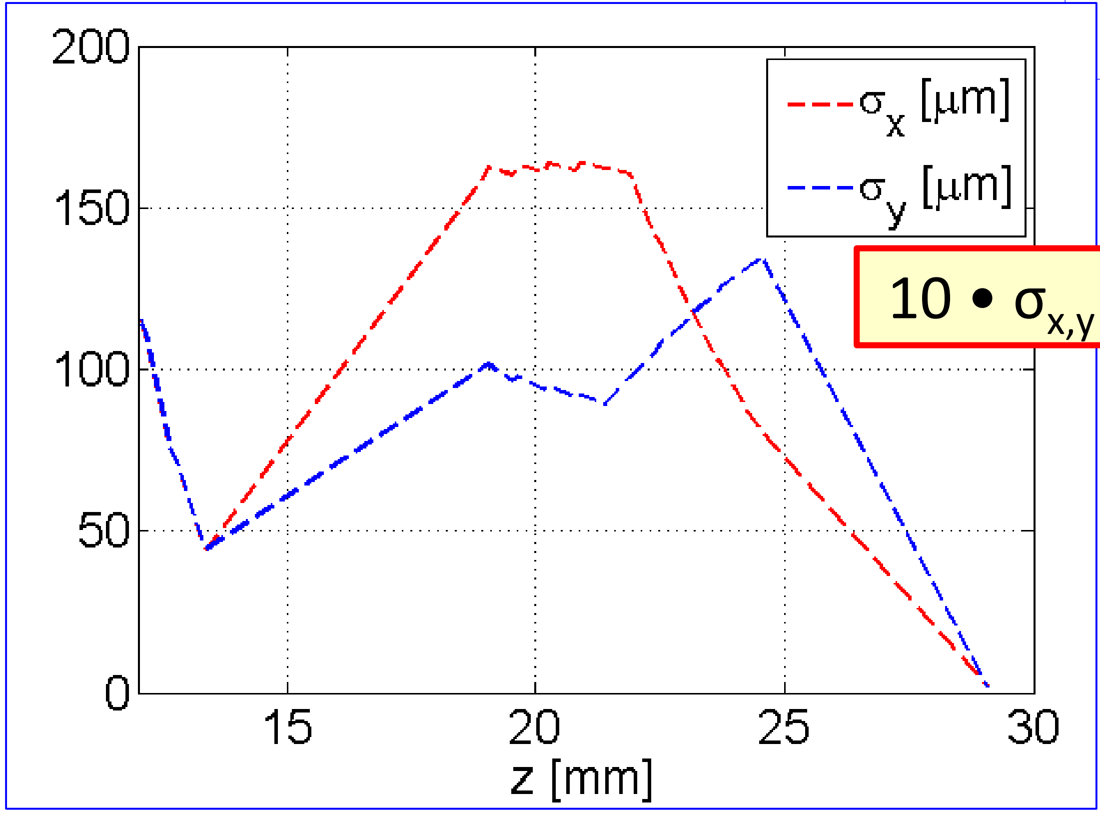
Further manipulation to increase the trasformer ratio



X-band linac optimisation studies

- The comb-like beam has been tracked through the X-band linac
- The cavity radius, r , ranges between 2.4 – 3.5 mm
- A check on the beam envelope along the X-band linac is mandatory due to the X-band cell iris radius





$10 \bullet \sigma_{x,y} < r$

The X-band accelerating structures are 0.5 m long and consist of 8.3 mm long cells on the Clic model (C. Vaccarezza's talk)

Beam parameters at plasma entrance

Beam parameters @Plasma Entrance			
	Single bunch operation	**Comb-like operation**	
Q [pC]	30	**30**	**200**
E [MeV]	517.6	**499**	**500.4**
$\varepsilon_{x,y}$ [mm mrad]	0.45 – 0.47	**0.73 – 0.93**	**2.6 - 3.3**
$\sigma_{z\text{-FWHM}}$ [μm]	~ 3.0	**~ 3.0**	**-**
$\sigma_{z\text{-rms}}$ [μm]	6.0	**6.0**	**42.1**
ΔE/E [%]	0.06	**0.05**	**0.07**
$\sigma_{x\text{-rms}}$ [μm]	1.0	**1.1**	**2 - 3**
$\beta_{x,y}$ [mm]	2.0	**2.0**	**-**
$\alpha_{x,y}$	~ 0.0	**~ 0.0**	**-**
$I_{peak\ [FWHM]}$ [kA]	3	**3**	**-**