S-band Photoinjector

Beam dynamics studies with and without velocity bunching

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On behalf of SPARC_LAB collaboration

Outline

- The S-band photoinjector option
- Beam dynamics in the photoinjector
  - Working points
- Tstep-ASTRA-GPT validation
  - WP1 (reference case)
  - Code benchmark results

The S-band photoinjector option

- In the photoinjector the beam is generated at the cathode in the RF gun with its own intrinsic emittance, that represents the lowest possible emittance.
- Among other, having a bunch long enough at the cathode allows to reduce the emittance degradation due to the space charge contribution in the gun region

From [1] scaling with RF frequency
$\sigma_x \; \alpha \; \lambda_{RF}$, $\sigma_z \; \alpha \; \lambda_{RF}$, $Q \; \alpha \; \lambda_{RF}$ (A= σ_x/σ_z costant)
(@cathode surface)

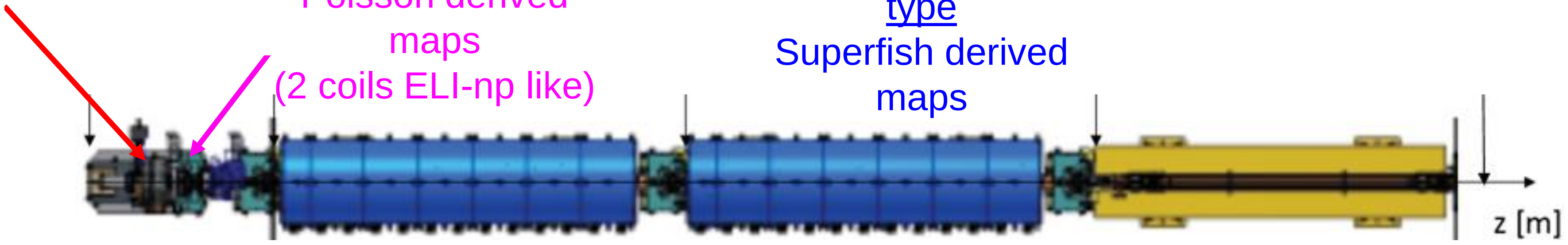
The S-band option, based on a state of the art technology, well known, reliable and stable, allows to explore a very wide range of working points in terms of beam parameters.

SPARC-like S-band photoinjector

RF gun
Superfish derived maps

Gun Solenoid
Poisson derived maps
(2 coils ELI-np like)

S-band TW SLAC type
Superfish derived maps



[1] J. Rosenzweig, E. Colby - Charge and Wavelength Scaling of RF Photoinjector Designs (1994)

Beam Dynamics in the Photoinjector

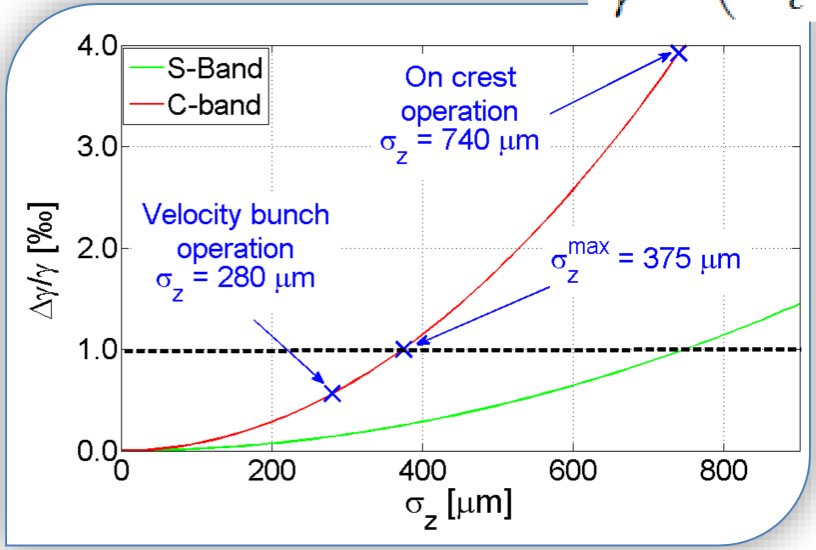
- The main challenge for the RF photoinjector comes from the request of generate and transport low emittance electron beams ($\varepsilon_{nx,y}$ < 20 mm-mrad) with charges ranging between 20 – 100 pC → *emittance preservation is the goal!*

- In the RF gun the beam undergoes RF and space charge forces that induce emittance oscillations. The emittance compensation down to the intrinsic emittance is obtained properly setting the gun solenoid and those surrounding the S-band cavities according to the invariant envelope theory (also dumping the emittance oscillations).

- In the meanwhile the beam can be shortened in the S-band cavities downstream the gun by means of the velocity bunching method so to achieve the required high peak current. → The beam is compressed inside an RF structure and if integrated in the emittance compensation process one can provide the desired beam brightness preventing from energy spread dilution in the downstream linac.

- Two different configurations have been studied
  1. On crest operation
  2. Velocity bunching operation

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



Energy spread dilution in the downstream linac vs the beam length at the linac entrance

Working Points

- WP a) - w/o velocity bunching

From S. Di Mitri minutes of WG3/6 meetings

  - Charge (50 : 100) pC
  - bunch length of about 500 fs
  - emittance of about 0.5 mm-mrad

- WP b) - with velocity bunching

From Summary_WG3.doc (M. Ferrario)

  - Charge 100 pC
  - bunch length of about 120 fs
  - emittance of about 0.4 mm-mrad

- WP c) – with and w/o velocity bunching

From HX FEL – F. Nguyen (18 Oct.'18): with and without RF compression (VB)

- charge ranging between 20 and 100 pC → 75 pC chosen as reference
- bunch length from photoinjector that enables needed emittances
- emittance of about 0.2 mm-mrad

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Even if these are not the final WPs, they shown us the «limits». In both cases we need short bunches at the cathode leading to nonlinear effects at low energy and so not well compensated emittance, the VB case showing better perfomances.

1. WPa) 600- 775 fs length and ≈ 0.3 mm-mrad emittance.
2. WPb) 95 fs length and 0.32 mm-mrad emittance (σ_z= 10µm at maximum compression).

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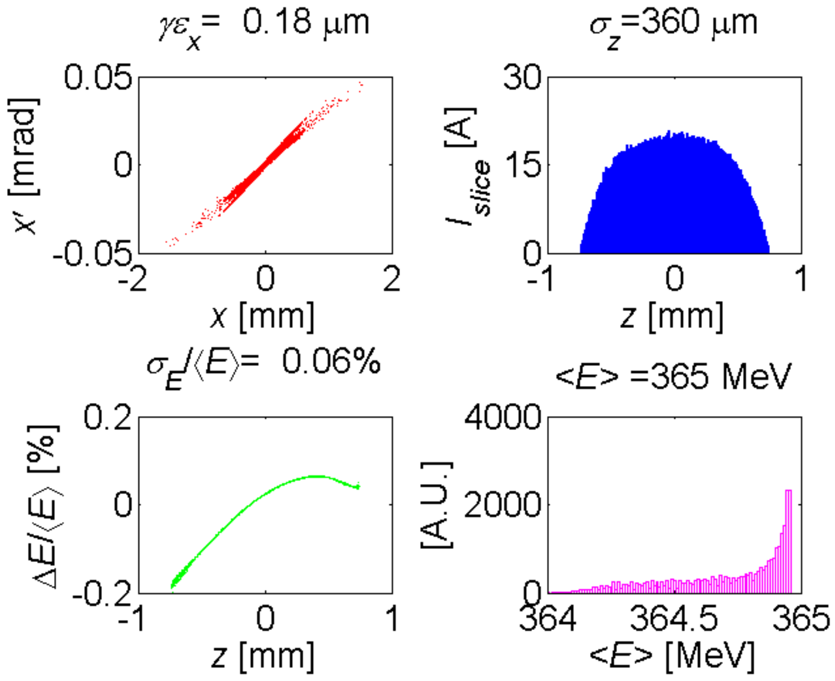
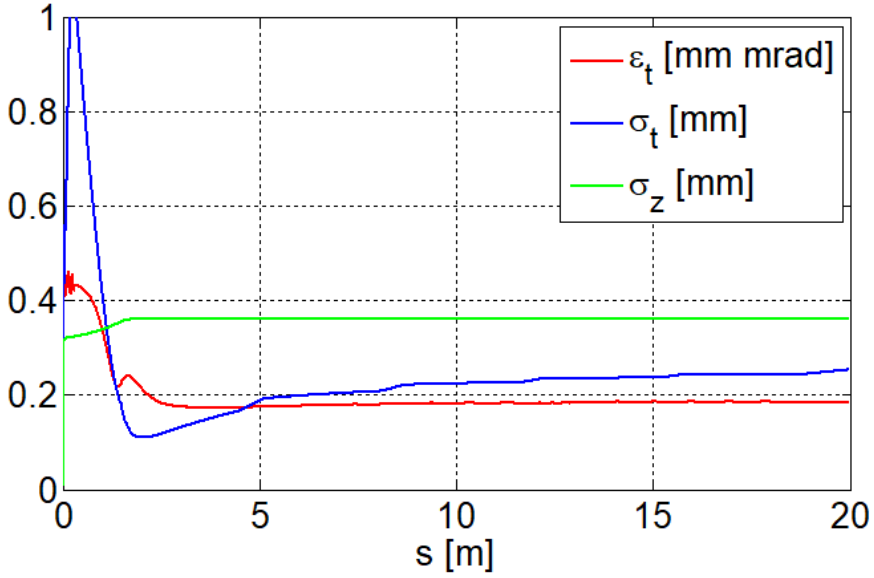
In the following the lowest reachable emittance is limited by the intrinsic emittance that is of the order of 0.15 mm-mrad → On going studies to lower this value and reach 0.12 mm-mrad emittance.

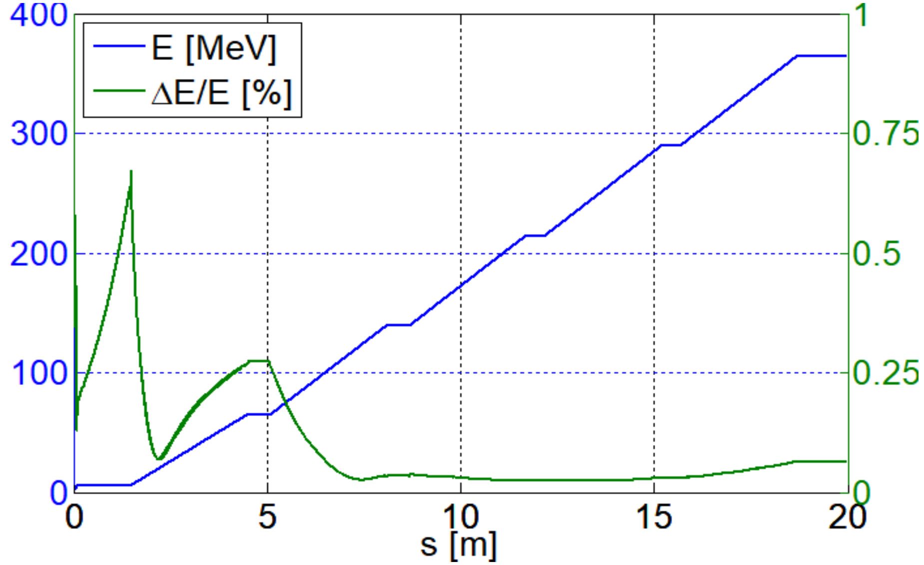
0.12 mm-mrad reached with about 2 ps beam exiting the photoinjector

WP c) – w/o velocity bunching

- From HX FEL – F. Nguyen (18 Oct.'18): with and without RF compression (VB)
  - charge ranging between 20 and 100 pC → 75 pC chosen as reference
  - emittance less than 0.2 mm-mrad
- 0.2 mm-mrad allowed for bunch length at cathode in the ps range → final bunch length higher than 310 μm (≈1 ps).







WP c) – with velocity bunching

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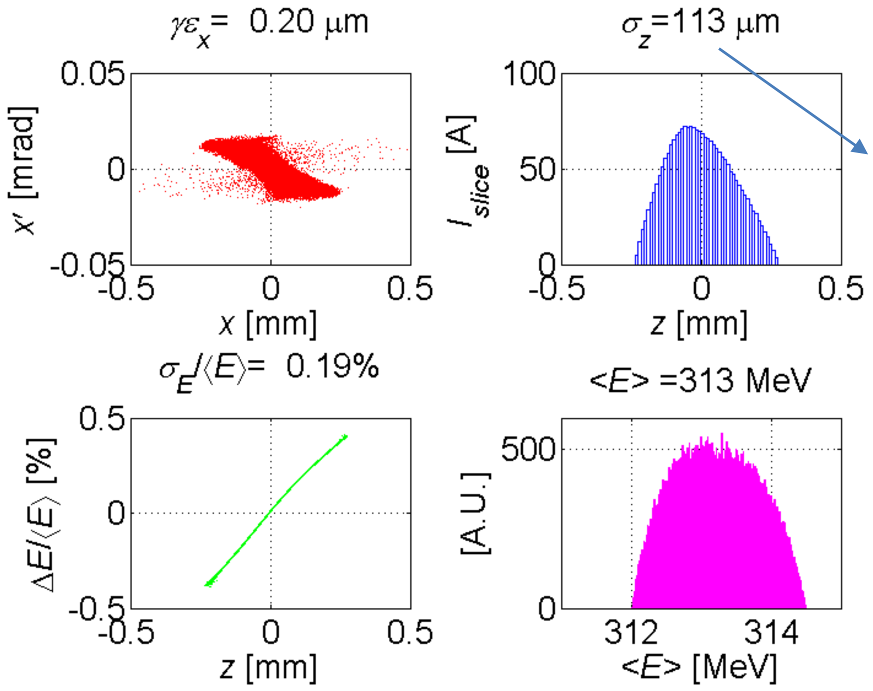
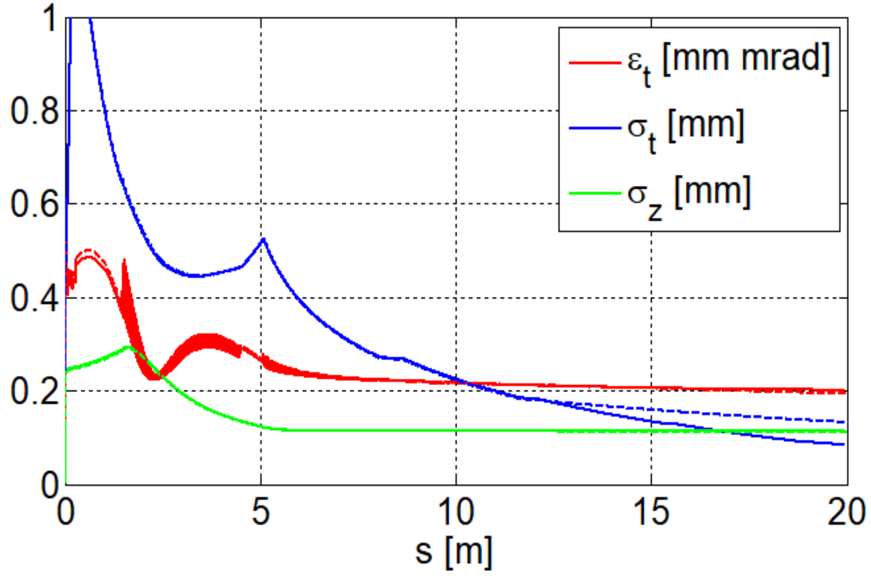
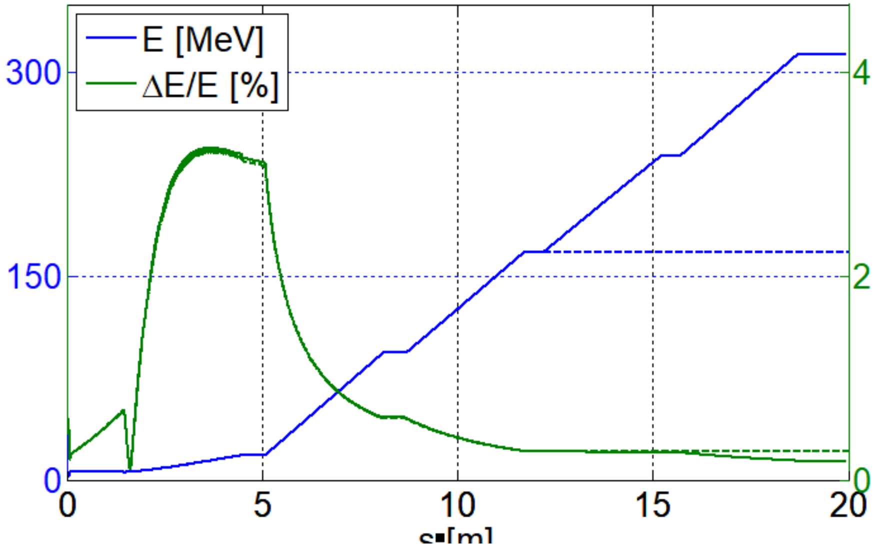
  - charge ranging between 20 and 100 pC → 75 pC chosen as reference
  - emittance less than 0.2 mm-mrad
- 0.2 mm-mrad allowed for bunch length at cathode in the ps range → final bunch length of about 113 μm (≈0.3 ps).



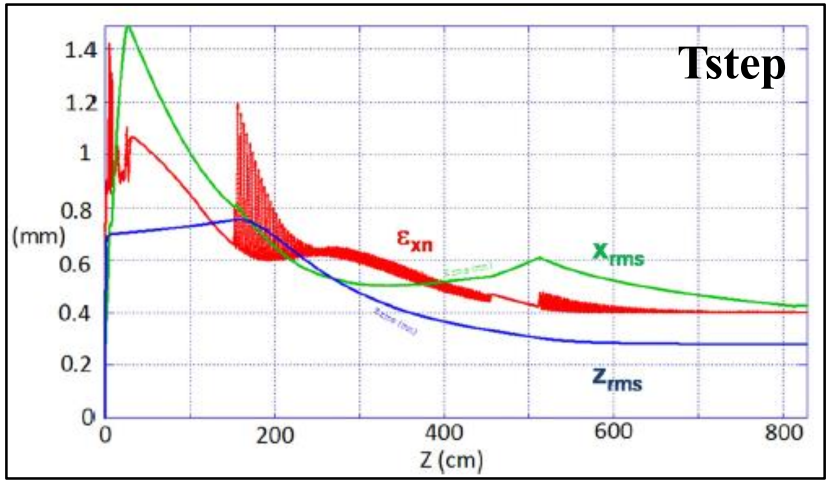
Helps to avoid energy spread dilution in X-band linac

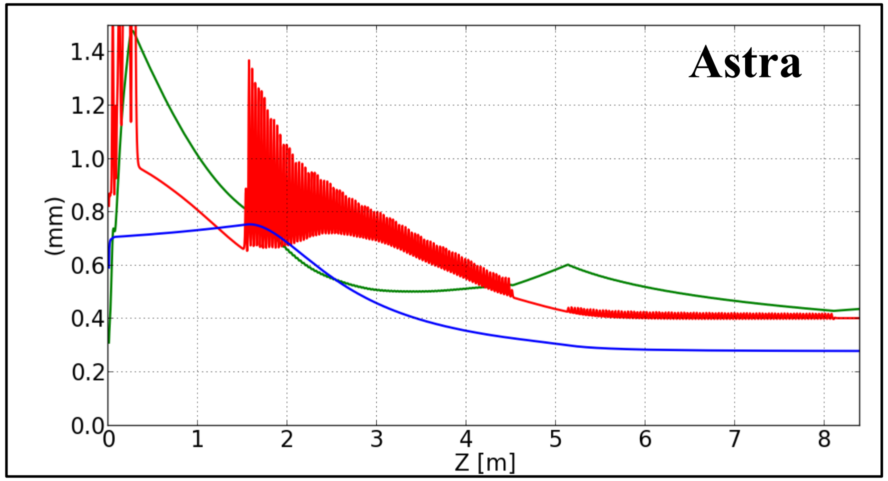




TStep-ASTRA-GPT validation

- Simulations have been performed with the multi-particles code Tstep, an updated version of Parmela. It takes into account space charge forces, beam loading and CSR.
- It is routinely cross-checked with experimental measurements and other codes (GPT and Astra) for all our projects (SPARC,ELI-NP, etc..).
- For example: beam dynamics studies illustrated in the ELI-NP GBS Technical Design Report were made by using the tracking code Tstep. Then the results have been tested with a second tracking code Astra [2].





From ELI-NP internal discussion courtesy of A. Bacci and C. Ronsivalle

[2] A. Giribono - 6D Phase Space Optimisation for High Brightness Electron Beams in RF Linacs as Drivers for High Brilliance Inverse Compton X and g Ray Sources, Cap.3.4 (PhD thesis) (2017)

TStep-ASTRA-GPT validation

- A huge effort has been done in the past to verify and validate these tracking codes

- Some references:
  1. C. Limborg et al., Code comparison for simulations of photo-injectors - PAC03, Portland, USA, DOI: 10.2172/833072 (2003)
  2. Nr. Neveu et al., Benchmark of RF photoinjector and dipole using ASTRA, GPT, and OPAL - THPOA46 PAC2016, Chicago, ISBN 978-3-95450-180-9 (2016)
  3. C. Ronsivalle et al., Simulations of the emittance compensation in photoinjectors and comparison with SPARC measurements, EPAC08, Genoa, italy (2008)
  4. Ivan Bazarov, Xiangyun Chang, Massimo Ferrario, Bob Garnett, Dmitry Kayran, Sergey Kurennoy, John Lewellen, Ji Qiang, Dave Sutter, Xijie Wang "Summary of working group a: injector design" for Workshop on high average power & high brightness beams november 8 - 10, 2004 → simulation codes verification and validation
  5. and so on and so forth…

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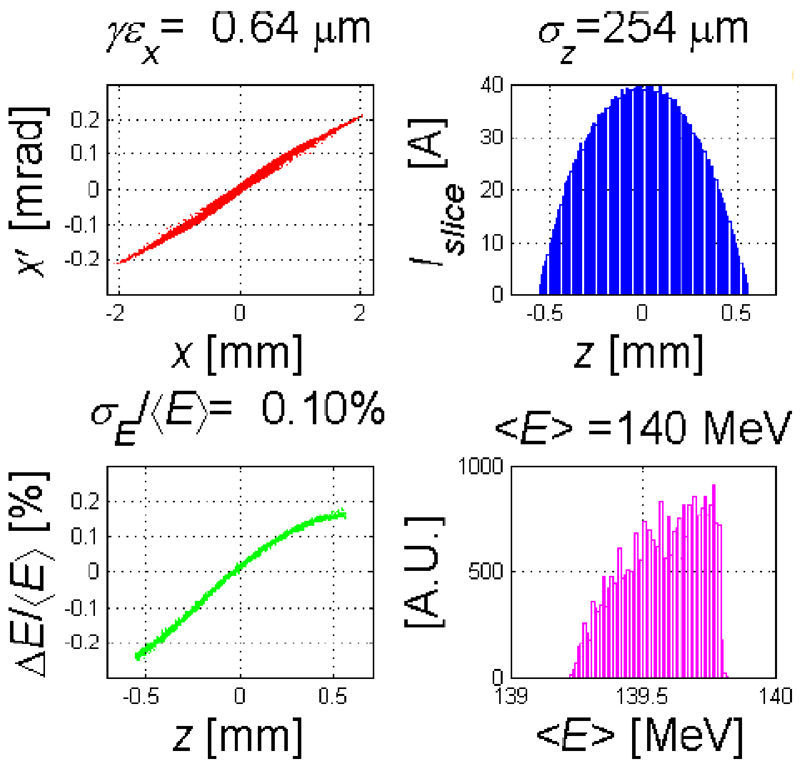
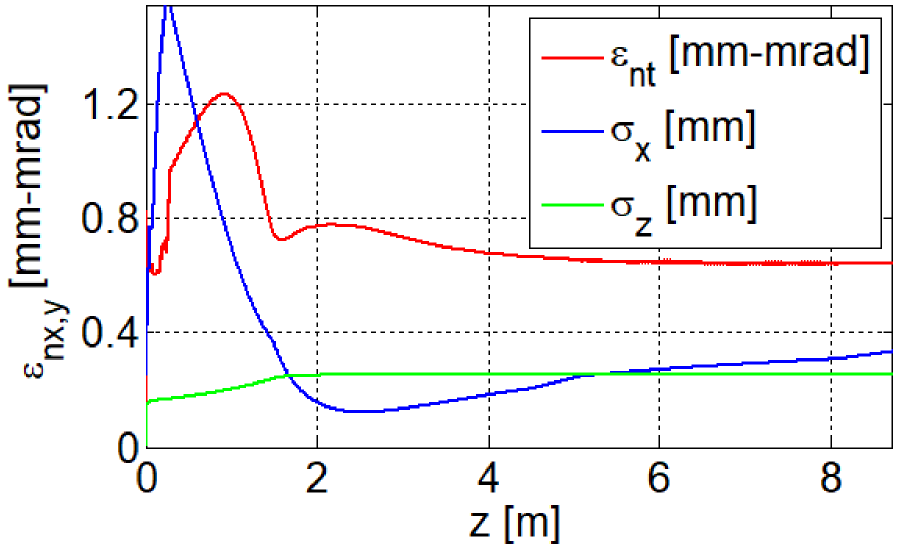
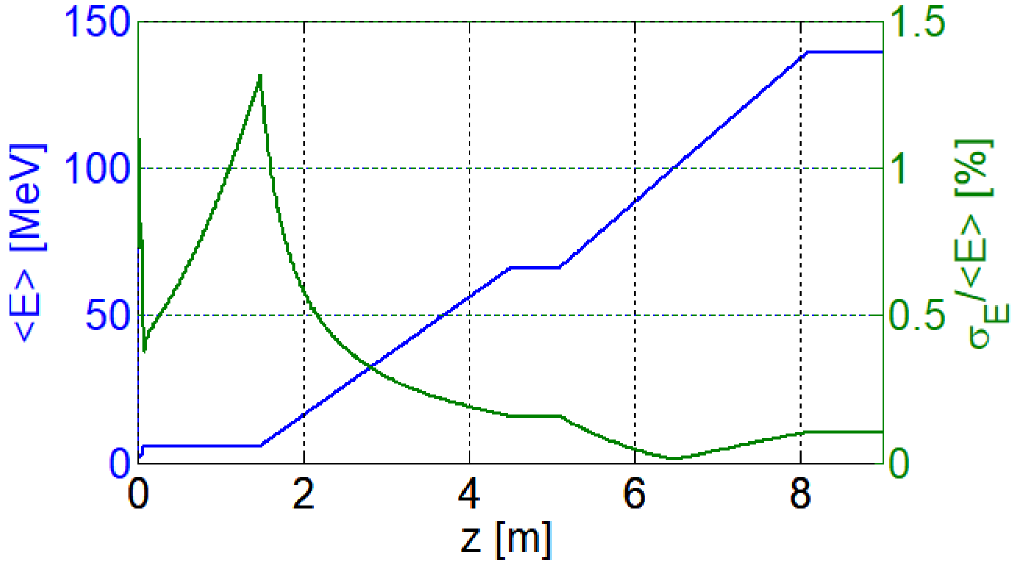
Code Name	Dim.	Wake field	Sp. charge Model	Parallel	Doc.	Source
Astra	2 1/2d	no	2d ring ?	No	Yes	No?
GPT	2 1/2d - 3d	no?	pt-2-pt + 3d mesh	Yes	Yes	Half?
Impact-T	3d	no	pt-2-pt + 3d mesh	Yes	Und. Const.	Yes
Parmela	2d – 3d	yes	2d ring + 3d mesh + pt-2-pt	No	Yes	Wld. be
Homdyn	3d envelope	yes	Analytical	No	Yes	Not yet

WPa) (reference case)

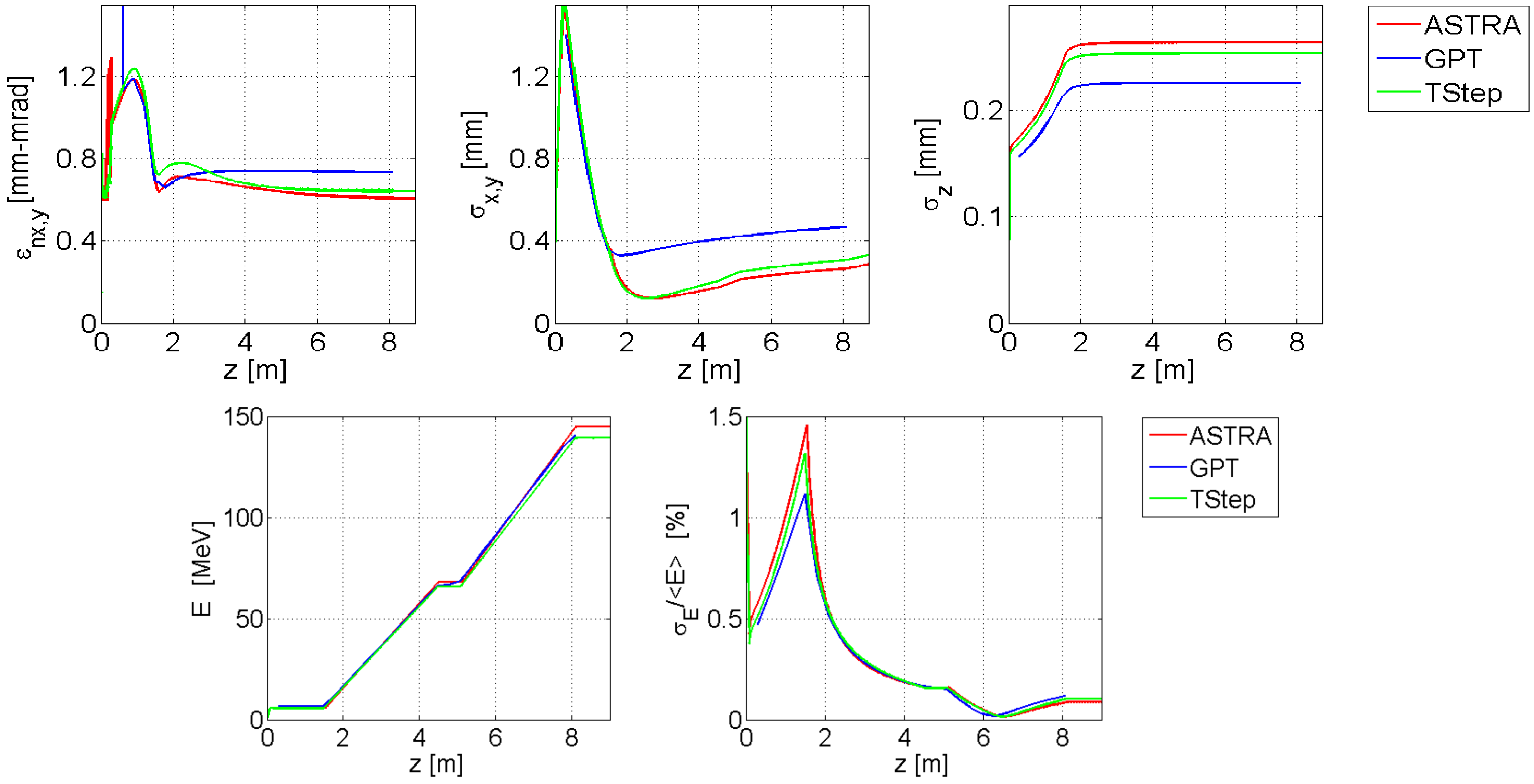
- Tstep studies cross-checked with GPT (E. Marin) and Astra (A. Giribono) for WPa) with uniform radial distribution and gaussian longitudinal distribution.
- As you will see the codes are quite well aligned







First results – parameters evolution



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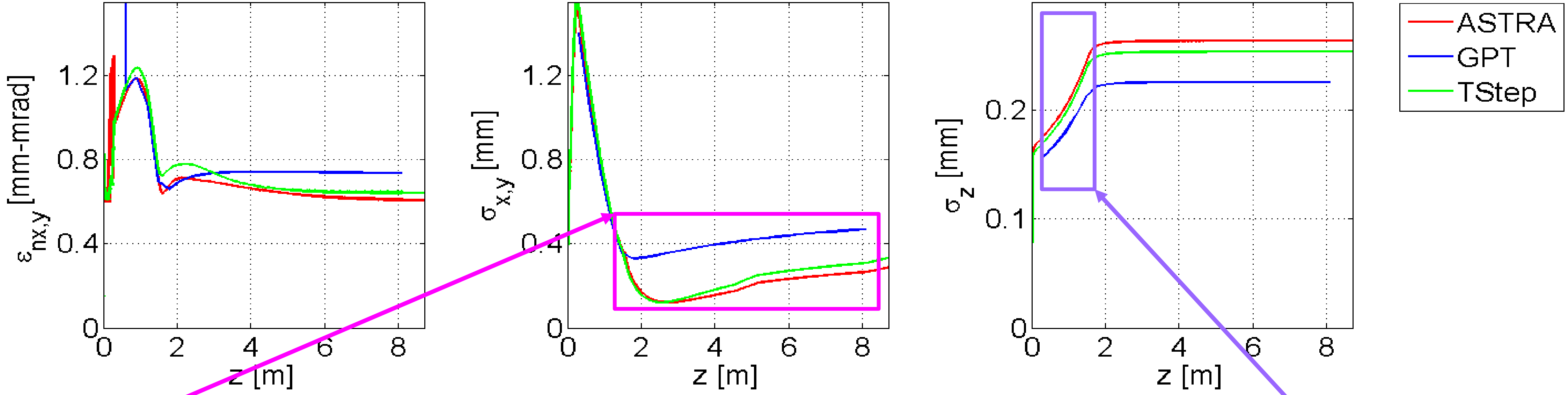
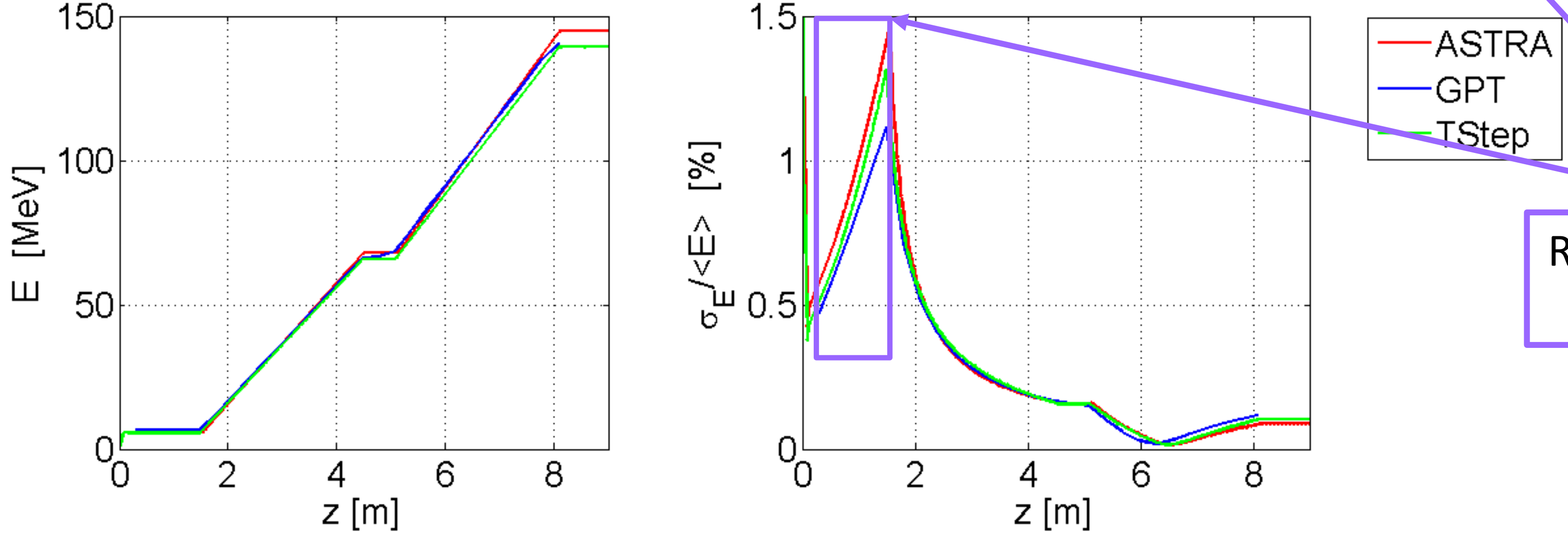




TW sections region

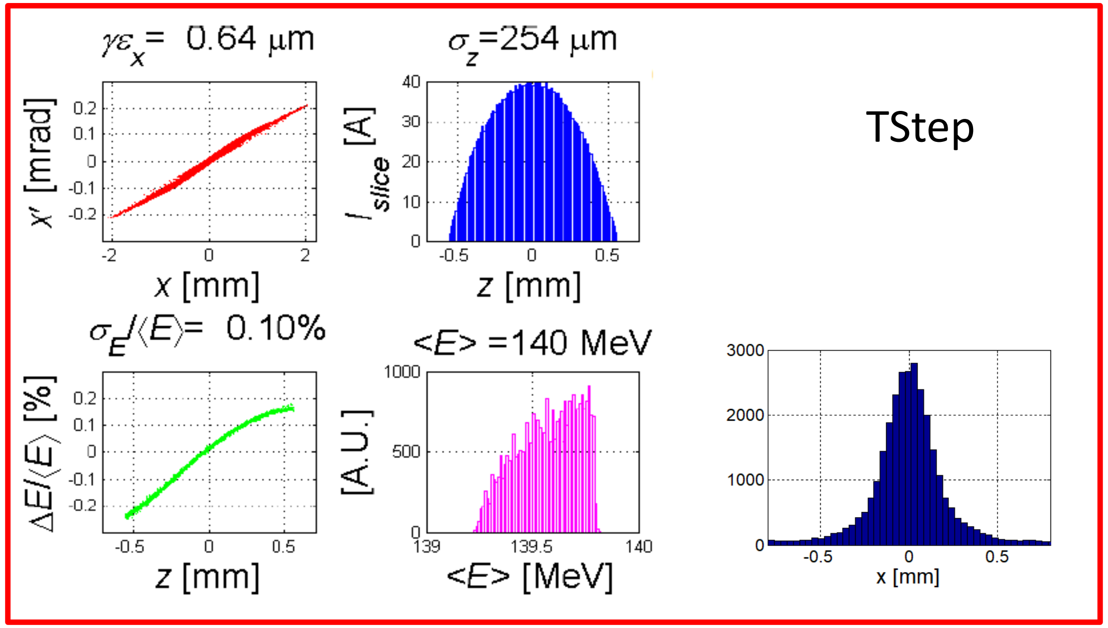
<u>TW sections model</u>

RF gun+solenoid+drift region

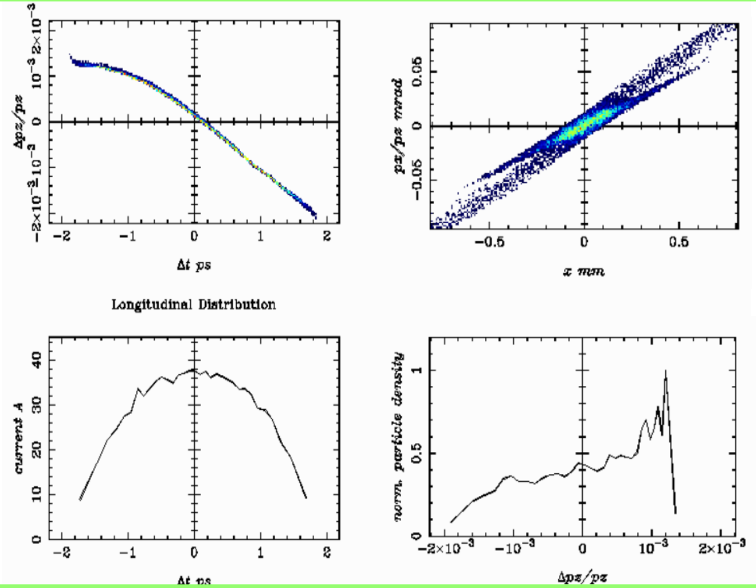
<u>RF gun phase tuning</u>

First results – Phase spaces

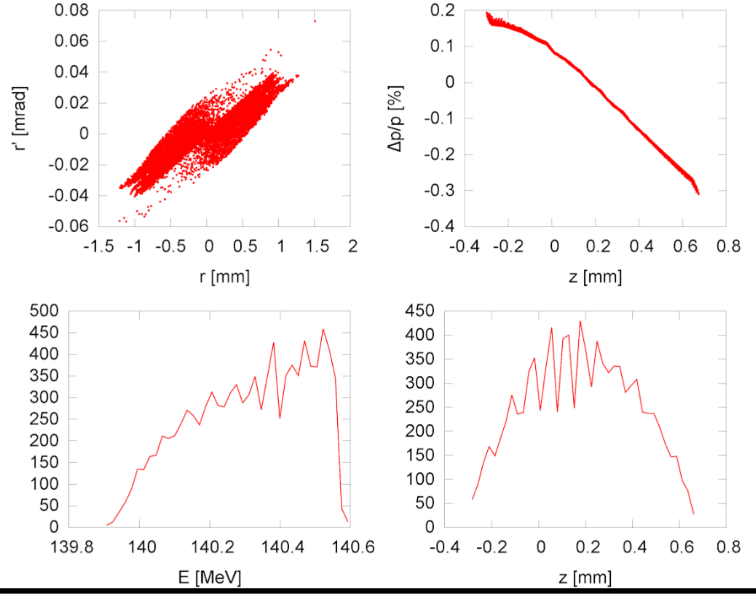
Parameter	Tstep (WP1)	GPT	ASTRA
Charge [pC]	100	100	100
Energy [MeV]	139.6	140.3	145.0
Dp/p [%]	0.10	0.11	0.09
σ_z (rms) [mm]	0.254	0.226	0.264
σ_r (rms) [mm]	0.375	0.47	0.325
e_{nx} (rms) [mm mrad]	0.64	0.76	0.60



ASTRA



GPT



NEXT STEPS

- Perform simulations with field maps of an optimised XLS RF gun → higher peak field at the cathode (>120 MV/m)
- Extend the study to different beam charges
- Understand the range of parameter tunability and stability
- Discussion on the limit between RF photo-injector and RF-linac. Maybe we can introduce X-band cavities to freeze the beam phase space compacting the machine length → M. Ferrario proposes 300 MeV as threshold
- Benchmark has to be completed understanding the differences in the TW cavity model between codes.

THANK YOU!!!

S-band RF Photoinjector Layout

[1]

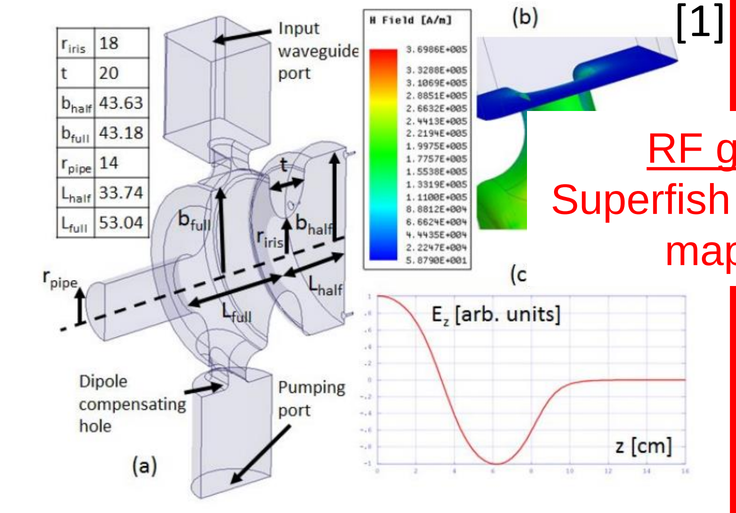
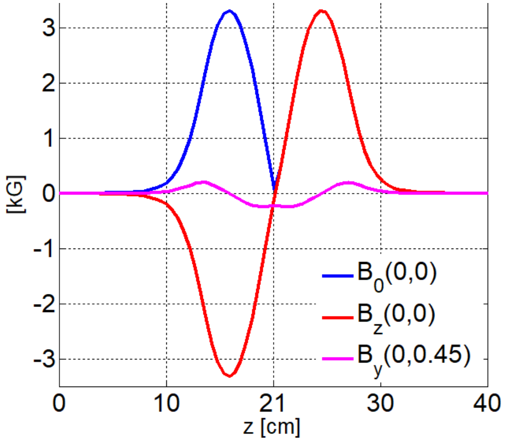


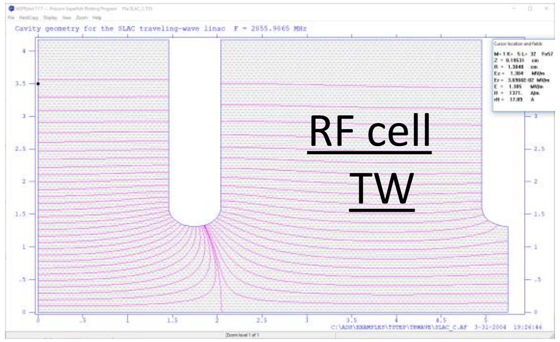
Figure 1: (a) HFSS geometry of the gun; (b) H field in the coupler region; (c) longitudinal accelerating field profile.

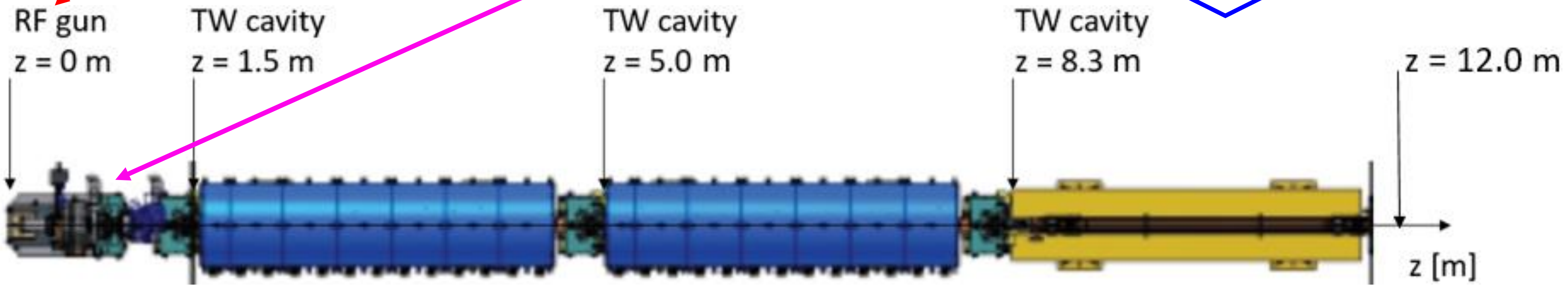
RF gun
Superfish derived maps

Gun Solenoid Poisson derived maps
(2 coils ELI-np like)



S-band TW SLAC type
Superfish derived maps



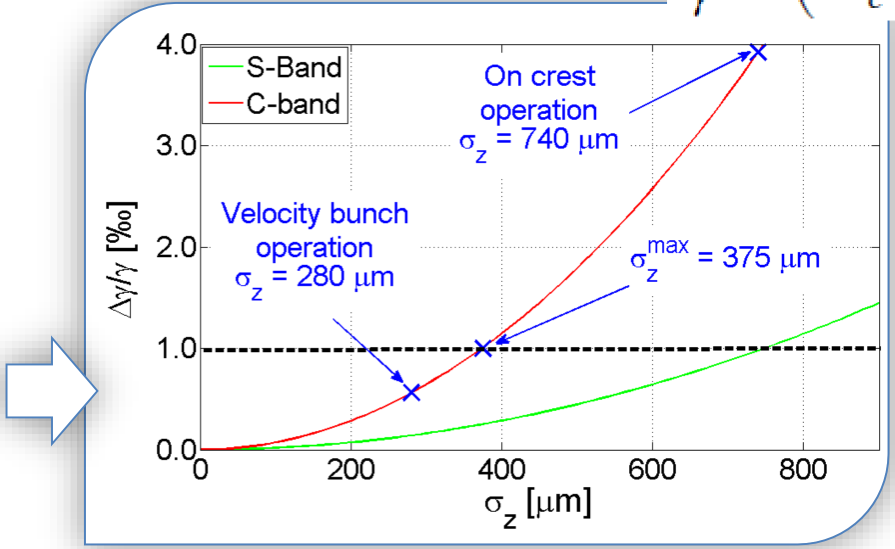


[1] D. Alesini et al. - High Power Test Results Of The ELI-NP S-band Gun Fabricated With The New Clamping Technology, IPAC17 (THOBB1)

Beam Dynamics in the Photoinjector

- The main challenge for the RF photoinjector comes from the request of generate and transport low emittance electron beams ($\varepsilon_{nx,y}$ < 20 mm-mrad) with charges ranging between 20 – 100 pC → *emittance preservation is the goal!*
- In the RF gun the beam undergoes RF and space charge forces that induce emittance oscillations. The emittance compensation down to the intrinsic emittance is obtained properly setting the gun solenoid and those surrounding the S-band cavities according to the invariant envelope theory (also dumping the emittance oscillations).
- In the meanwhile the beam can be shortened in the S-band cavities downstream the gun by means of the velocity bunching method so to achieve the required high peak current. → The beam is compressed inside an RF structure and if integrated in the emittance compensation process one can provide the desired beam brightness
  - with the advantage of compactness of the machine and absence of Coherent Synchrotron Radiation (CSR) effects present in a magnetic compressor
  - With shortened beam length avoiding energy spread dilution due to RF curvature degradation.

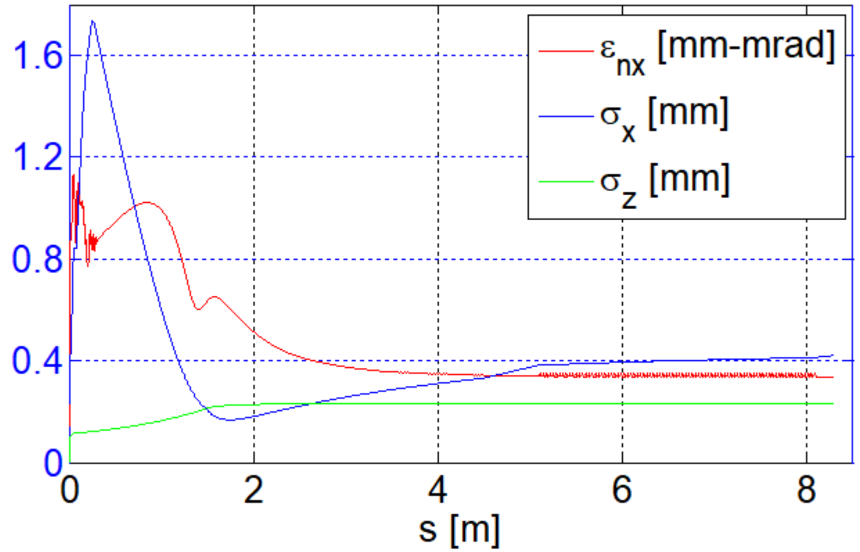
$$\frac{\Delta\gamma}{\gamma} \approx 2\left(\frac{\pi f_{RF}\sigma_z}{c}\right)^2$$

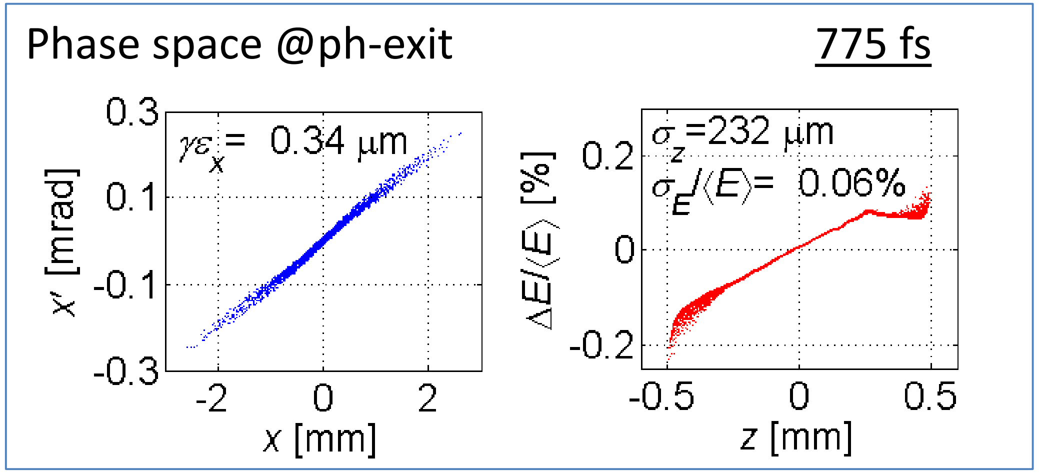


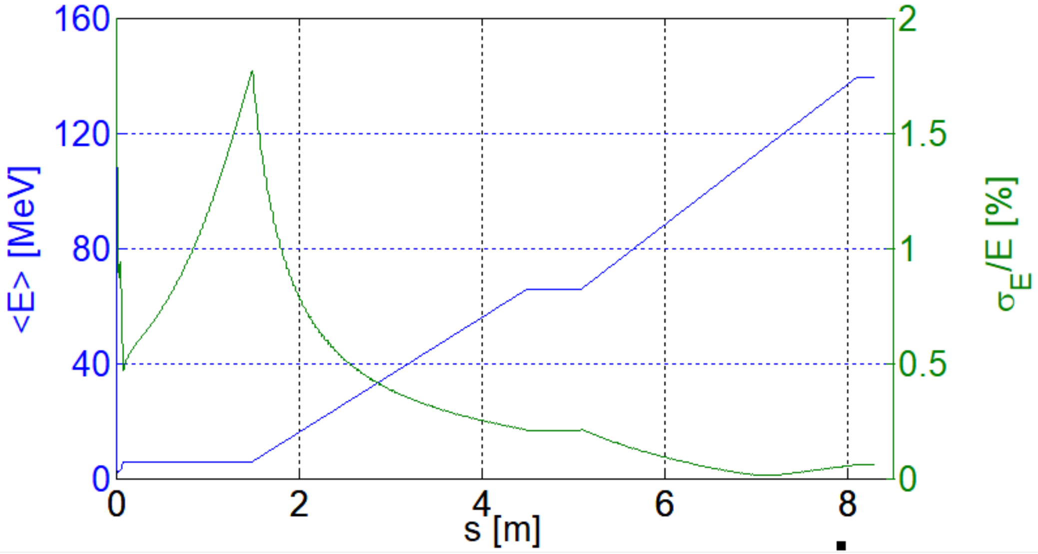
- Two different configurations have been studied
  1. On crest operation
  2. Velocity bunching operation

WP a) - w/o velocity bunching

- From S. Di Mitri minutes of WG3/6 meetings: **on crest operation** for (50 : 100) pC beam with
  - bunch length of about 500 fs
  - emittance of about 0.5 mm-mrad
- In order to get 500 fs bunch without compression we need to start with short bunches at the cathode leading to not optimized emittance compensation scheme → better emittances elongating the beam
- 50 pC, 0.3 mm-mrad, 600 fs

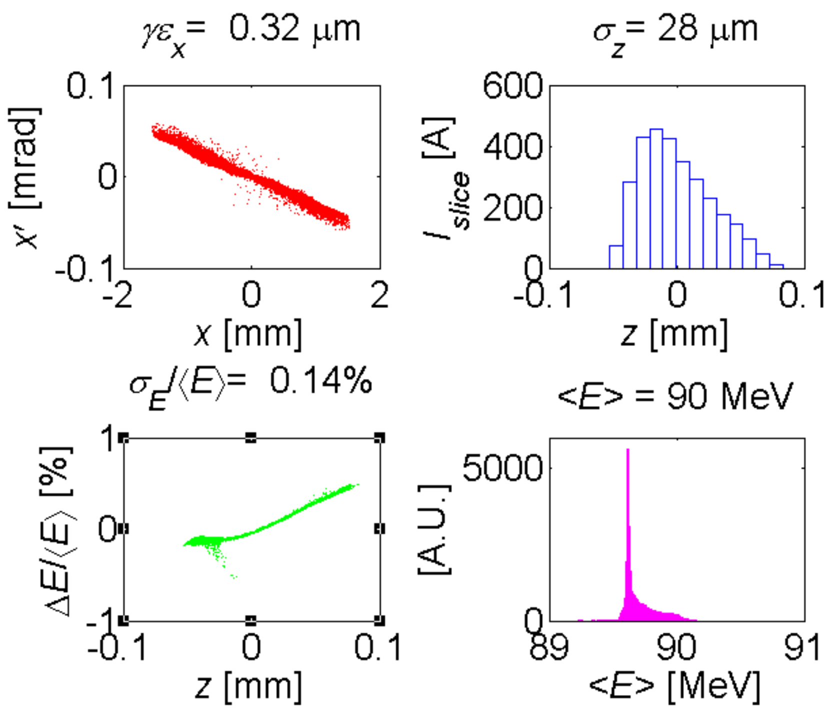


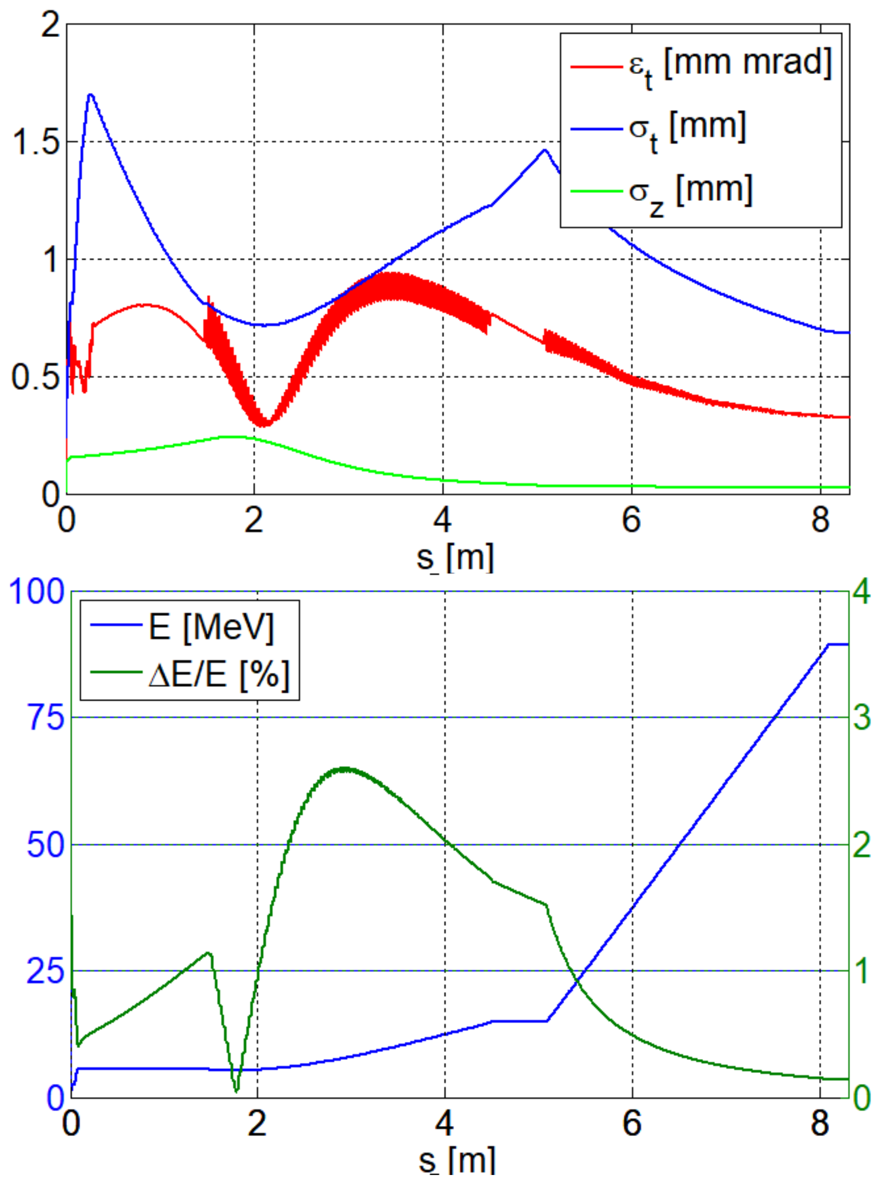




WP b) - with velocity bunching

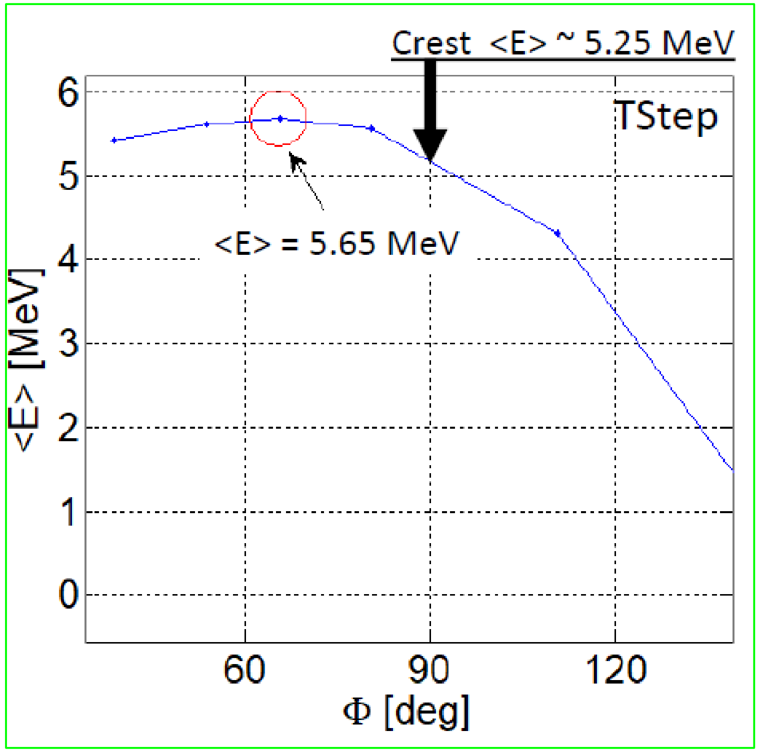
- From Summary_WG3.doc (M. Ferrario): RF compression (**VB**) for 100 pC beam with
  - bunch length of about 120 fs
  - emittance of about 0.4 mm-mrad
- In order to reach the 120 fs bunch length avoiding emittance degradation due to too high RF compression factor, the beam starts at the cathode in sub-ps range (at maximum compression σ_z= 10μm)

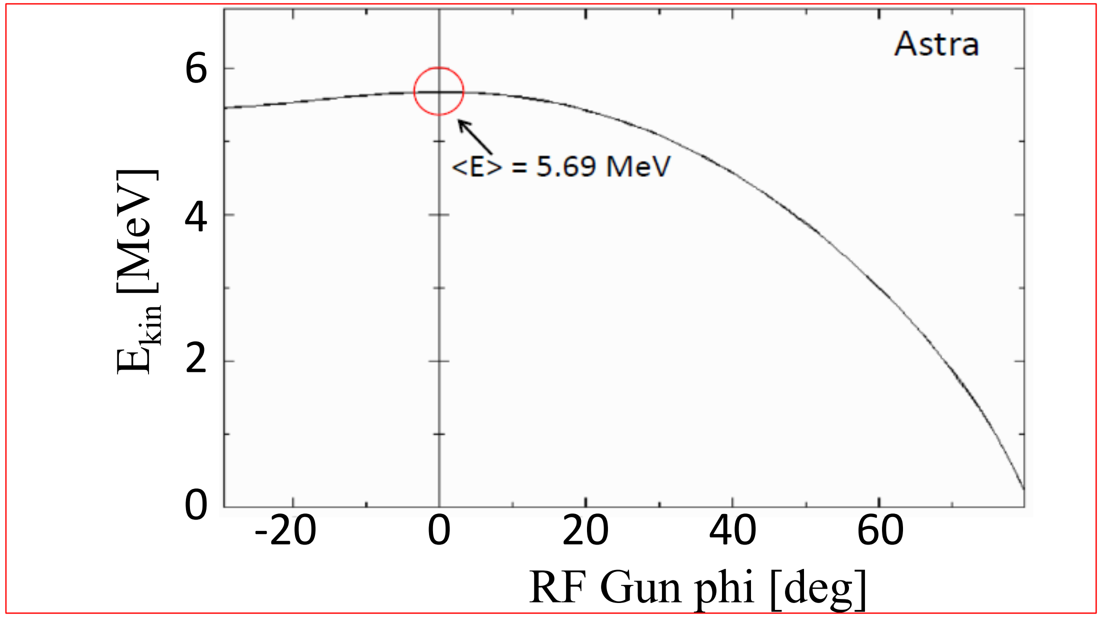


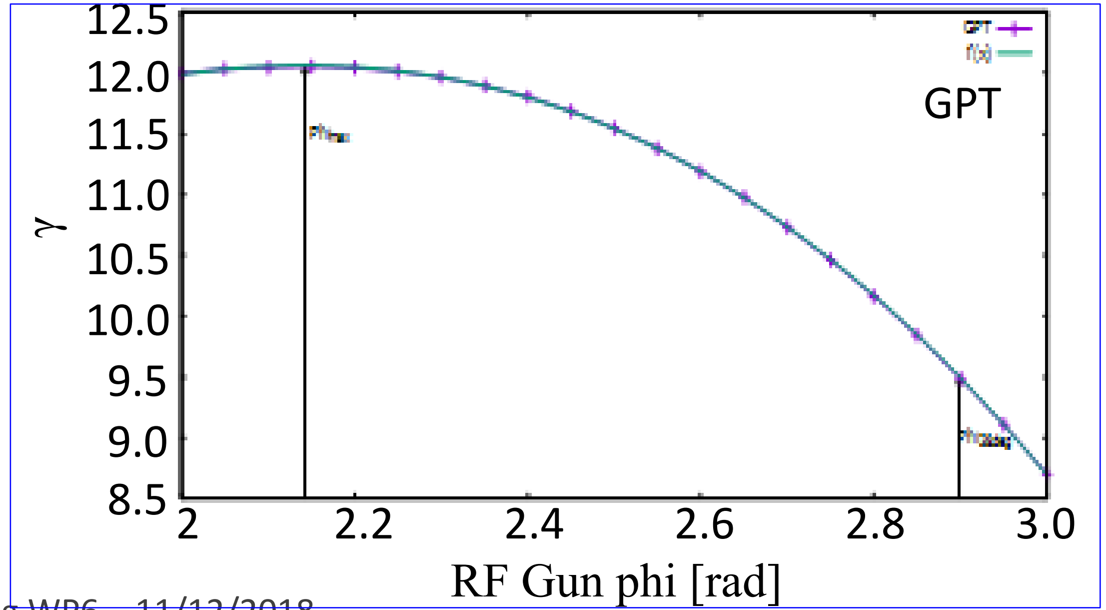


First results – RF gun: energy gain vs injection phase

- The curves reproduce analytical calculations
- WP1 foresees 120 MV/m at cathode and -24.4deg injection phase (α_{RF} ≈1.96)







RF gun+solenoid+drift region