C-band gun simulations

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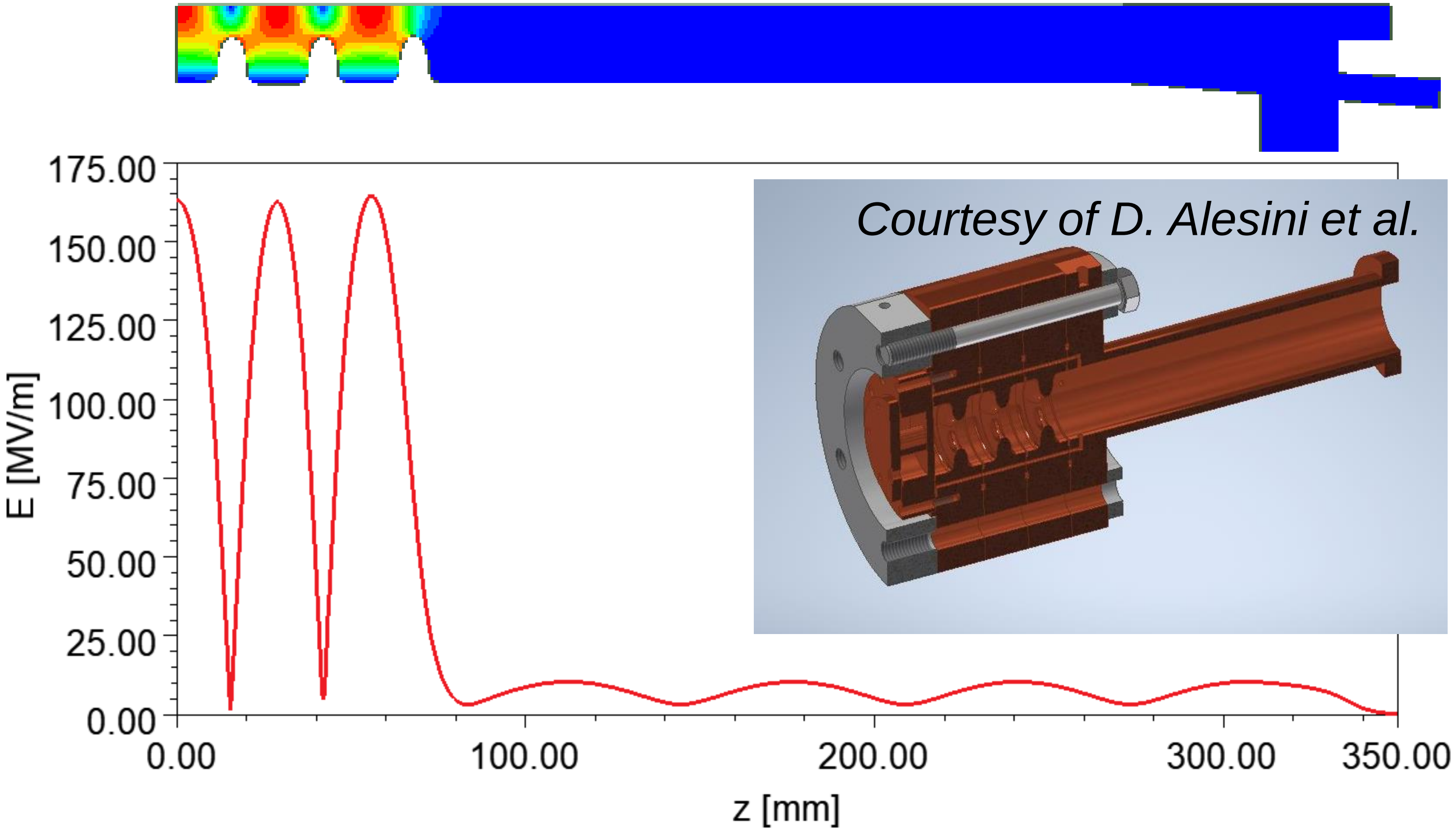
On behalf of the WP3 XLS team

Outline

- Description of the 2.5 cell C-band gun
- Beam dynamics considerations
- WP validation with ASTRA
- Conclusions and hints for next future

The 2.5 cell C-band gun

- The XLS photoinjector proposal relies on a **2.5 cell C-band gun** followed by *four* 2 m long C-band TW structures
- The **2.5 cell gun** has been chosen because it allows higher energy gain and so to allocate the proper distance between the cathode and the first TW structure useful for the *beam characterization before entering the linac.*



Courtesy of D. Alesini et al.

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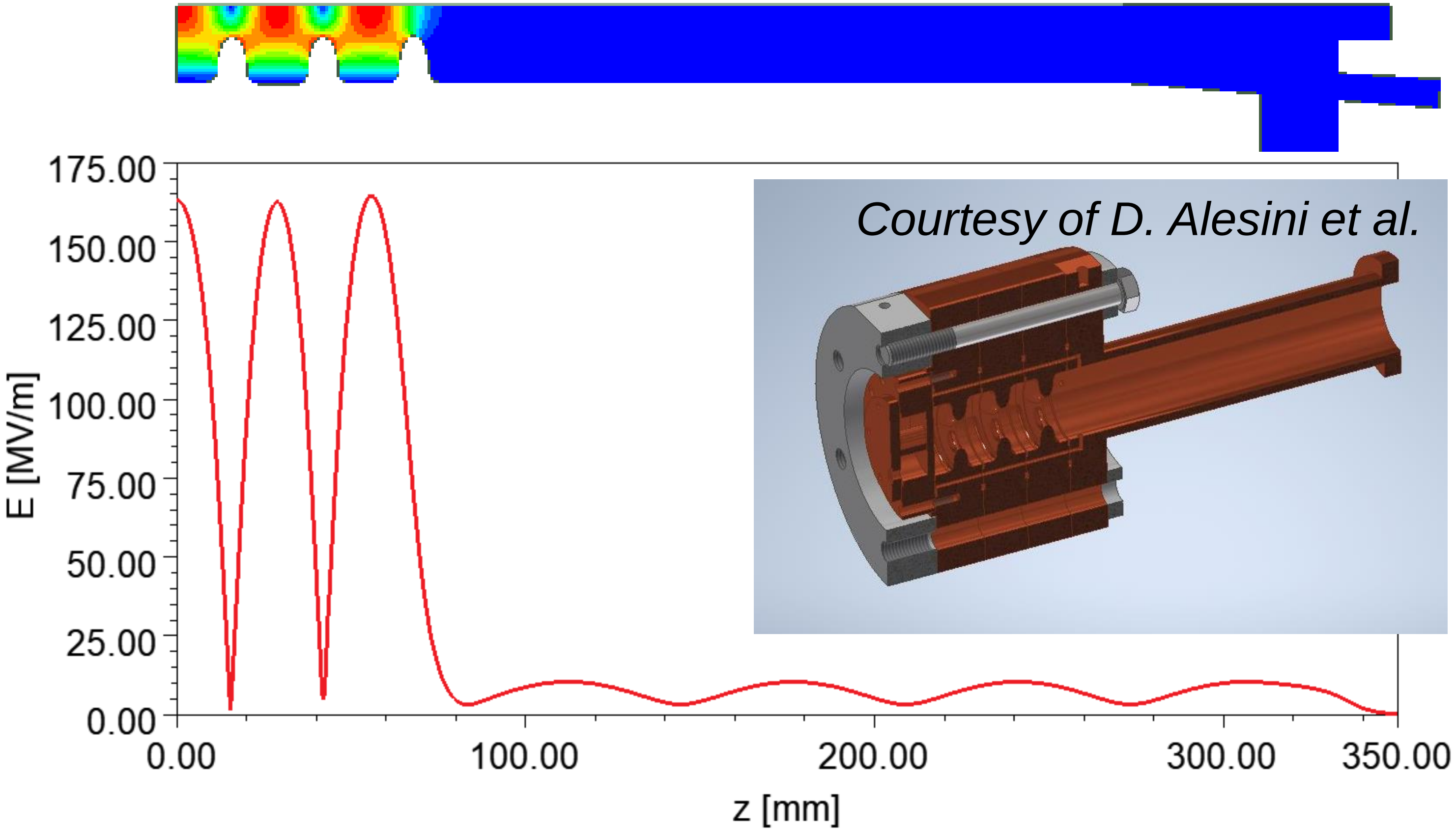
- In details, the gun will be powered using a mode launcher

Advantages:

- Increased flexibility in positioning the input waveguide relative to the gun body → more powerful cooling capability of the accelerating cells especially useful for the high repetition rate operation
- Lowered pulsed heating on the gun cell surface

Disadvantages:

- Field tails in the mode launcher region that can affect the beam quality
- More challenging design for the gun solenoid requiring a bigger bore and the introduction of a bucking coil to zero the field at the cathode



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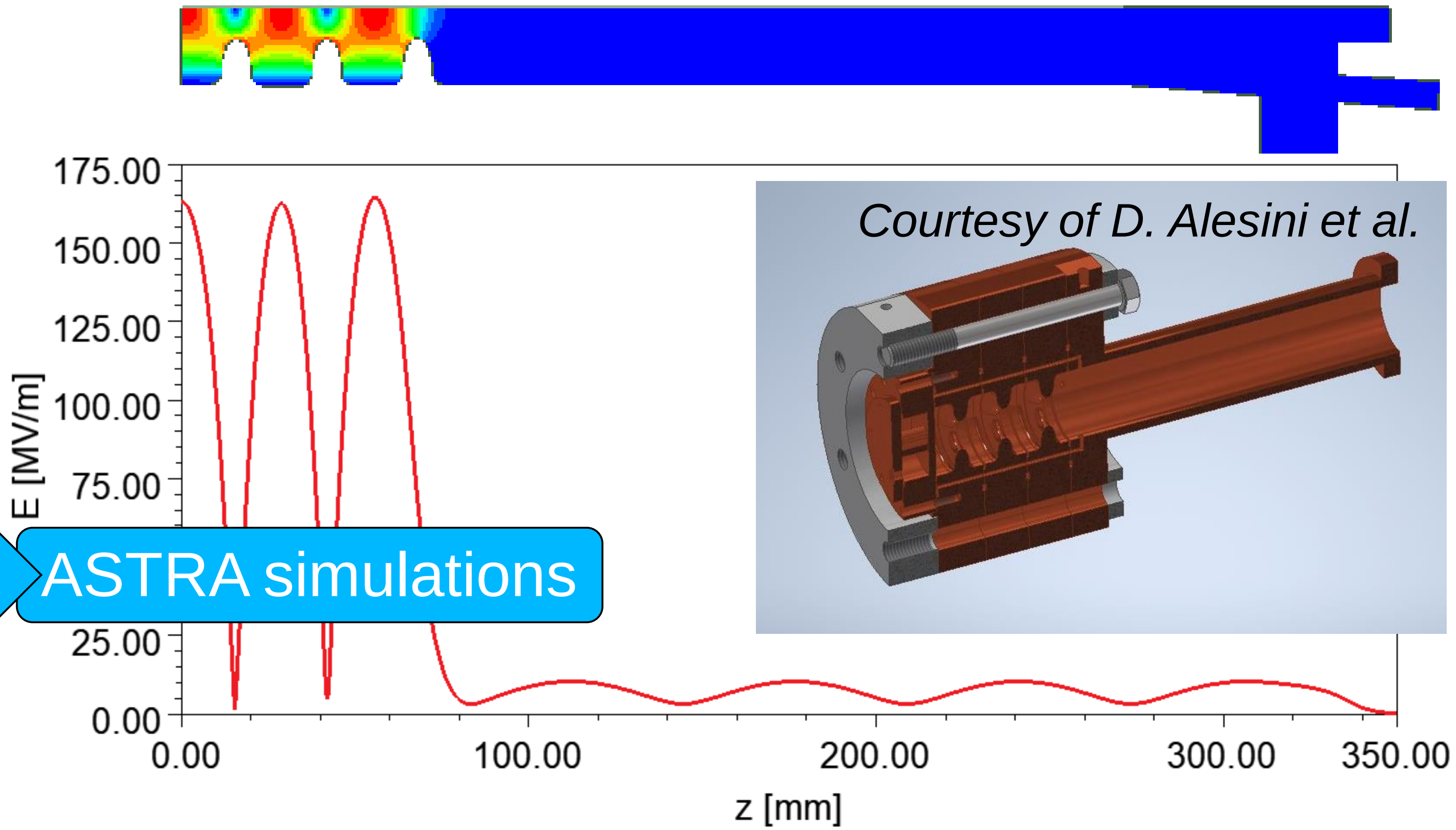
ASTRA simulations



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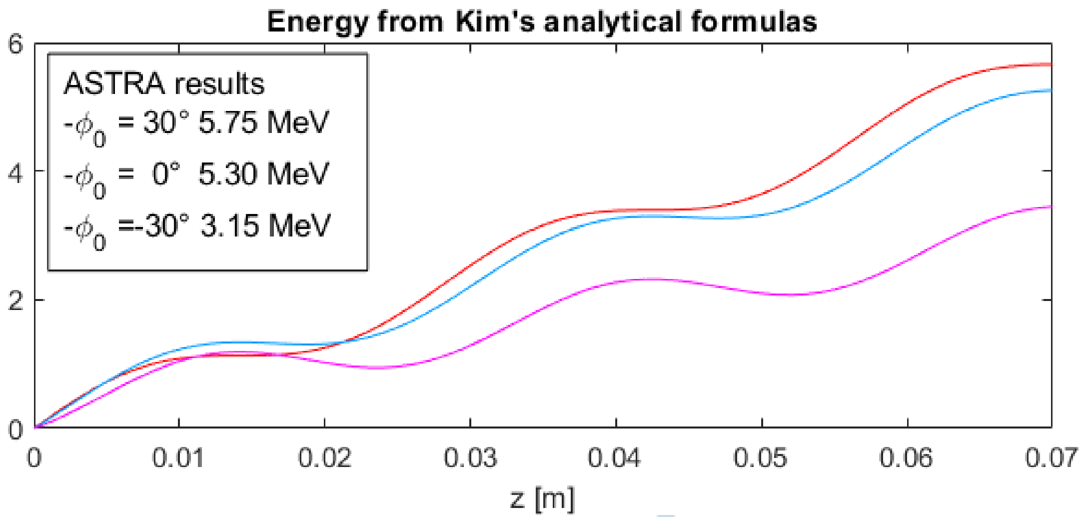
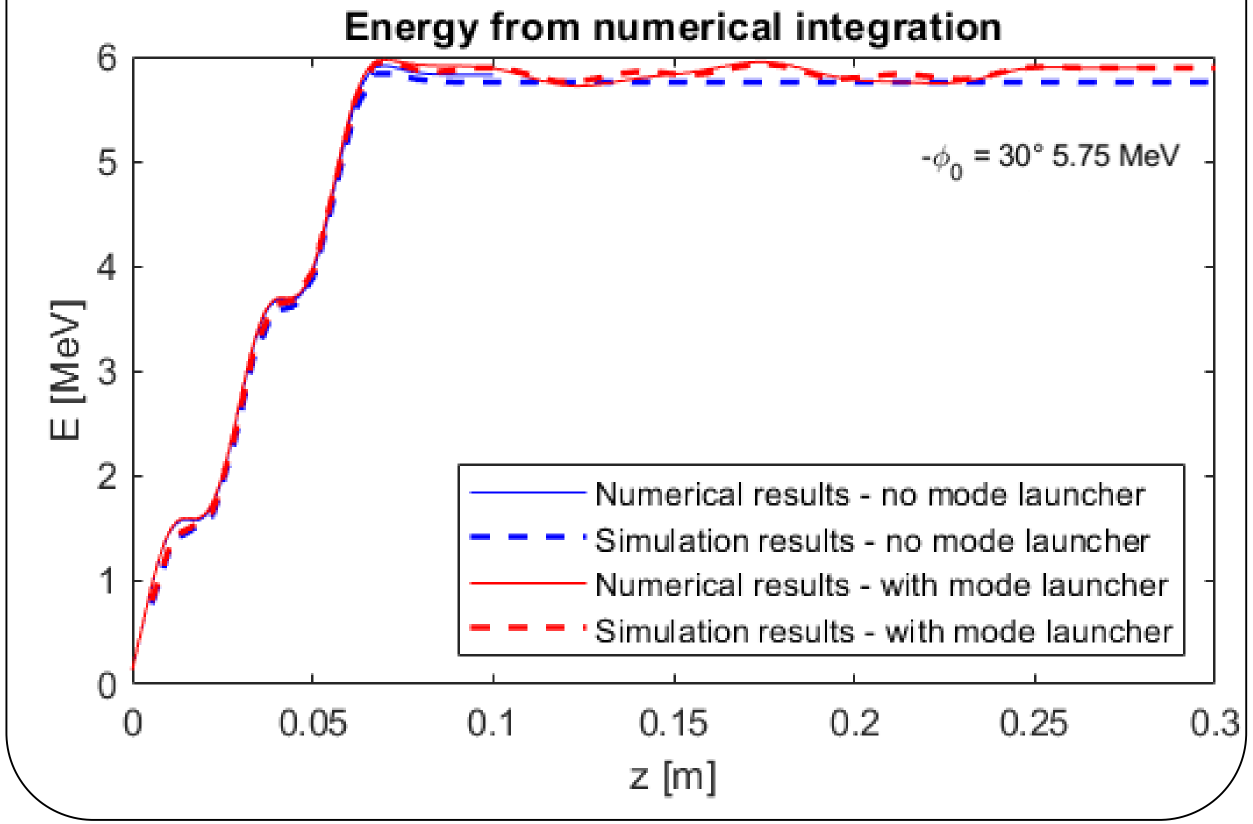
Longitudinal beam dynamics

- The main difference for the beam dynamics comes from the mode launcher region where the field presents fluctuations before going zero
- Beam dynamics simulations have been cross-checked with Kim’s analytical formulas and numerical integration method
- The result is an energy modulation around a mean value with a final energy slightly higher than ideal case

Ideal field in the gun without any coupler



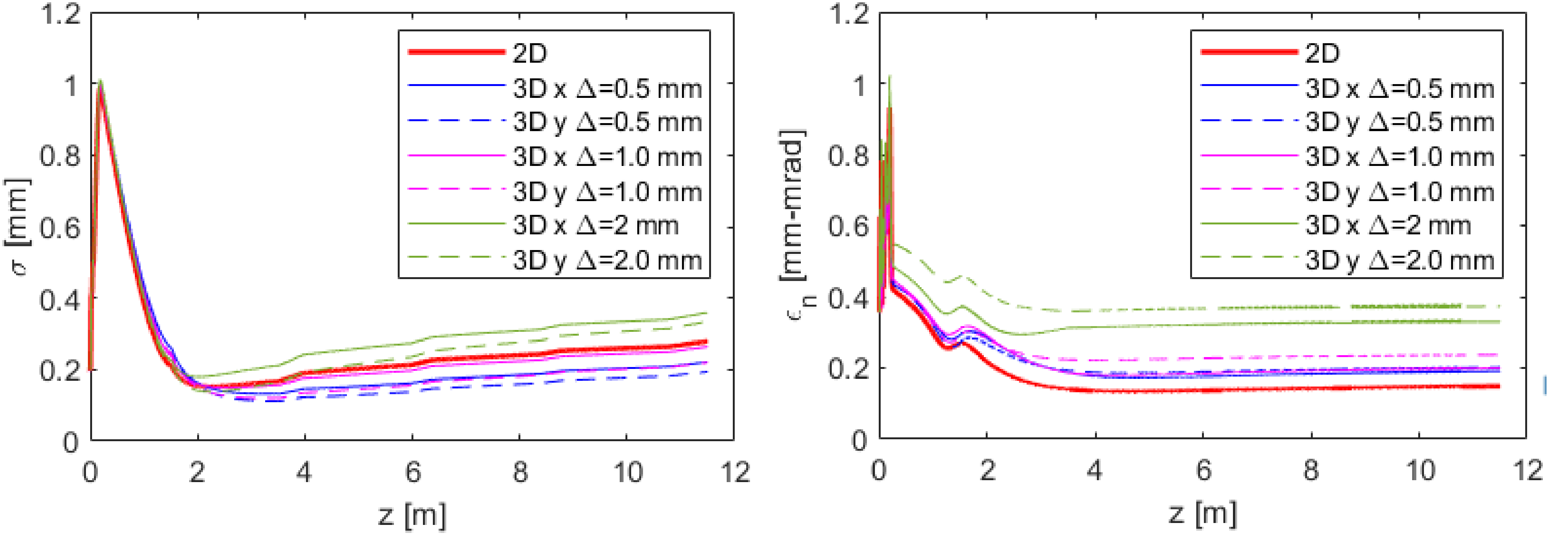
Simulations and numerical integration of field-beam interaction with and without the coupler



Transverse dynamics – Gun w/o mode launcher

- To avoid assumption on the cylindrical symmetry of the mode launcher we used 3D field maps
- As known, when one uses 3D maps also introduces fictitious contributions to the beam quality
- In order to distinguish it from physical contribution to the beam quality we first studied the case of a *cylindrical symmetric gun without mode launcher*

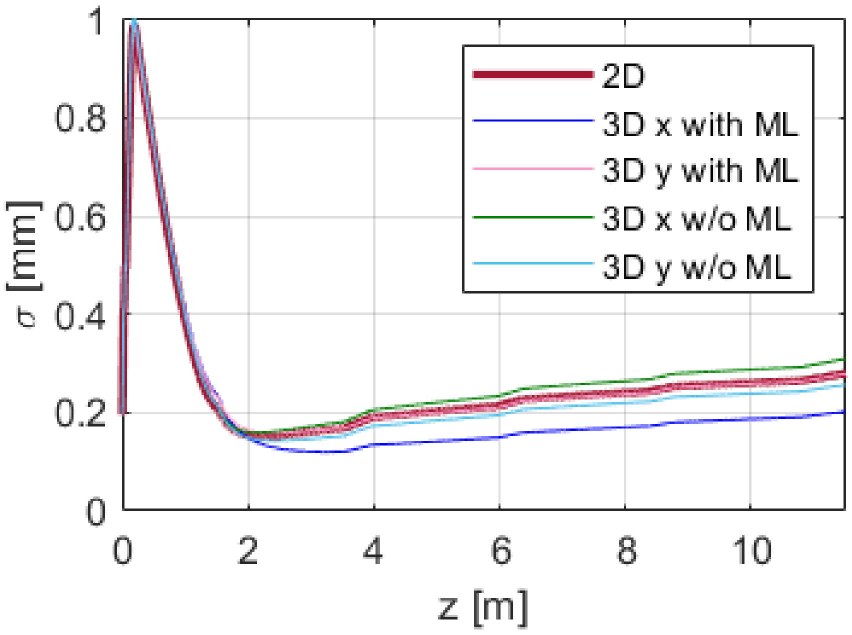
Results for various HFSS setting (*Δ = tetrahedra edge size)

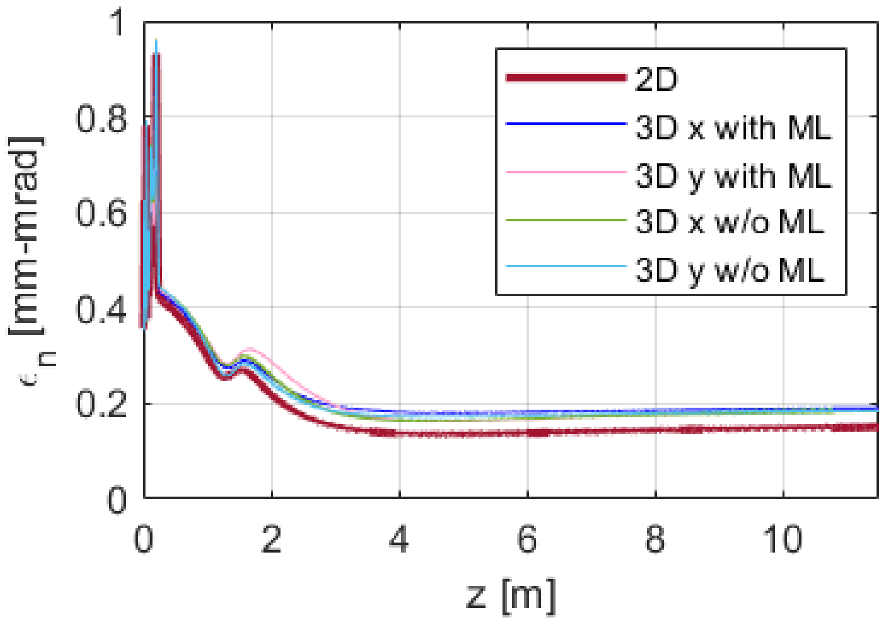


- The simulation is very sensitive to field map numerical noise. Indeed there is any physical explanation for the observed emittance increase, while acting on the tetrahedra edge size Δ in HFSS helps in reducing artificial asymmetry
- **The case Δ = 0.5 mm is chosen as reference for further studies**

Beam dynamics simulations – Gun with mode launcher

- Then we proceeded with a *cylindrical symmetric gun with coaxial mode launcher described by a 3D field map*



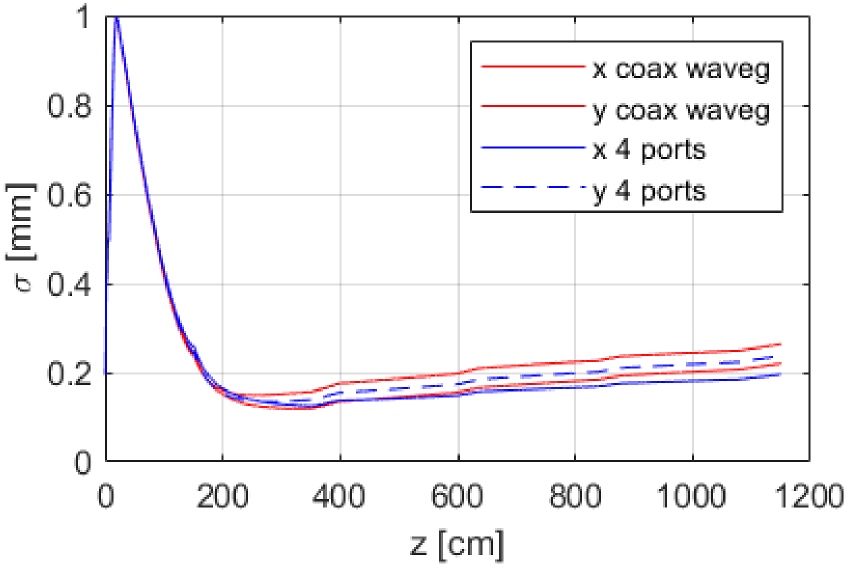


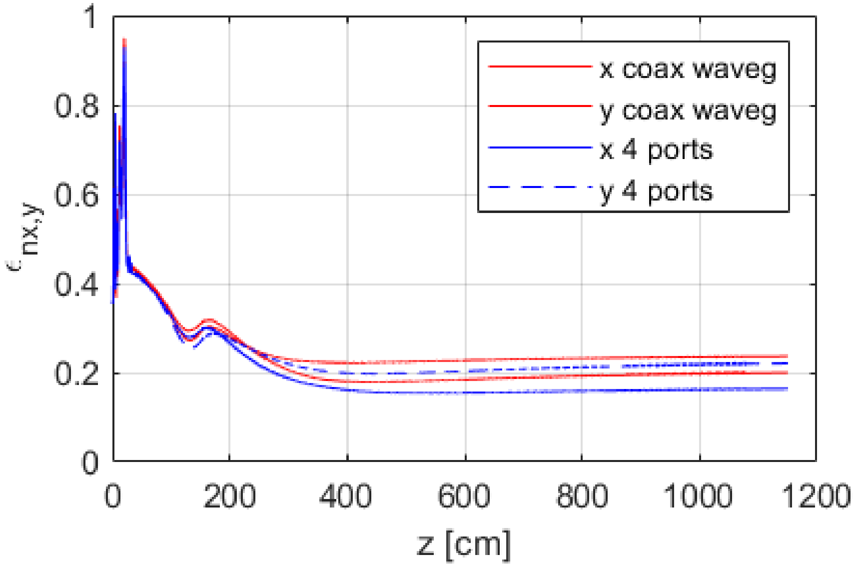
Field tails of the mode launcher for the C-band gun don't affect negatively nor transverse nor longitudinal beam quality

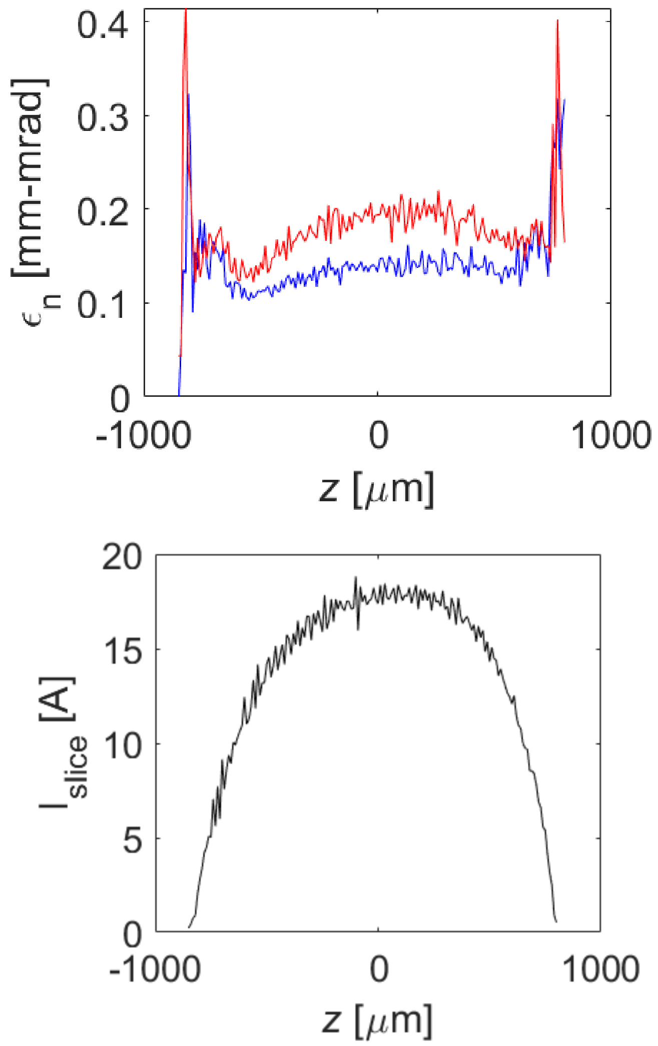
Different configurations have been considered for the mode launcher: 2 and 4 ports waveguide mode launcher

Gun mode launcher: 4 port configurations

- We decided for a fully symmetric four port waveguide coupler so to avoid quadrupole component insertions would arise from a 2 ports solution
- We report here the comparison of beam evolution in case of coaxial and 4 ports waveguide couplers with HFSS tetrahedra size 1 mm.
- The effect on the quality is negligible, and we account for a complete recovery of the beam quality by working on the HFSS simulation setting and/or inserting skew quadrupoles, if still needed.







Slice analysis @laser hater entrance for 4 ports coupler

WP validation with ASTRA

Courtesy of
J. Scifo

- The studies related to the mode launcher started from a WP optimised with TStep → the results described up to now comes from an ASTRA input file defined by *J. Scifo*
- The main difference between ASTRA and TStep regards the photo-emission process treatment *: ASTRA implements the photo-emission process from the cathode when a Fermi-Dirac beam distribution impinges on the cathode and it is the only code that explicitly foresees the treatment of the Schottky effect

The photo-emission process determines the beam intrinsic emittance at the cathode, a key parameter that represents the lowest emittance value one can get at the FEL injection

FERMI-DIRAC distribution

The particles emerging from the cathode at room temperature have an intrinsic velocity spread and so an intrinsic emittance described as:

$$\varepsilon_{x,y}^{\text{intrinsic}} = \sigma_{x,y}\sqrt{\frac{E_{\text{phot}} - \Phi_{\text{eff}}}{3m_0c^2}}$$

where $\sigma_{x,y}$ is the rms laser beam size, Φe_{ff} is the effective work function and E_{phot} is the photon energy.

ISOTROPIC distribution

The beam distribution emerges from the cathode with isotropic emission angles into a half sphere over the cathode according to with the intrinsic emittance being:

$$\varepsilon_{x,y}^{\text{intrinsic}} = \sigma_{x,y}\sqrt{\frac{2E_{\text{kin}}}{3m_0c^2}}$$

where $\sigma_{x,y}$ is the rms laser beam size and E_{kin} represents the beam kinetic energy.

* XLS Deliverable D6.1 3

WP validation with ASTRA

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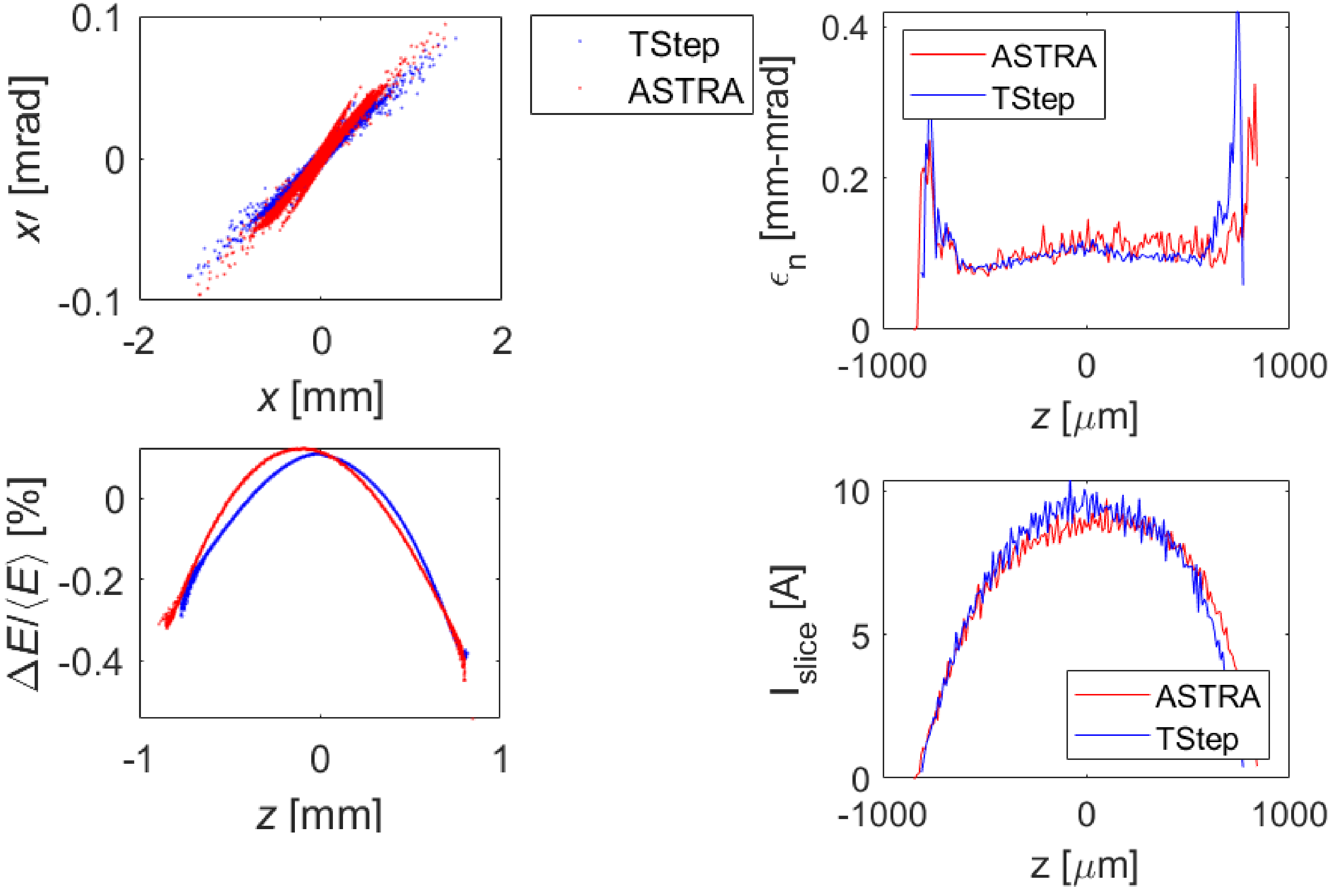
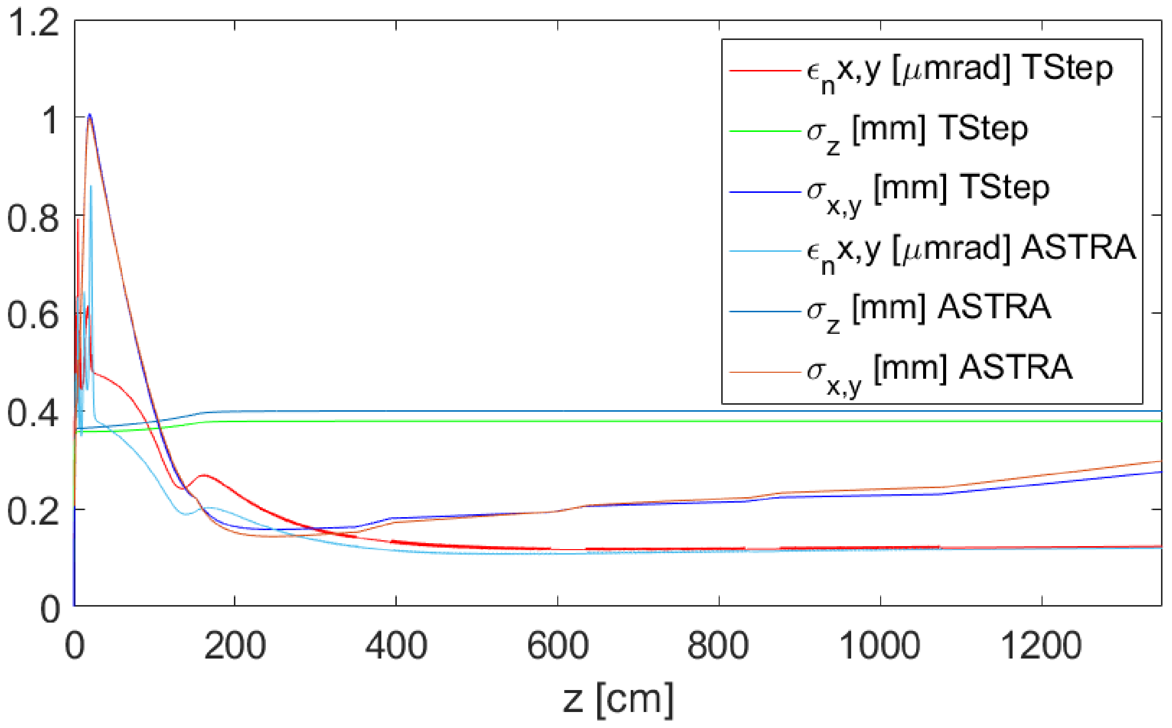
Parameters before BC1	Sim. results	Target	units
Q	75		pC
Rep. rate	1000		Hz
E	126	125	MeV
σ_E/E	0.11	0.5	%
$\epsilon_{n,rms}$	0.12	0.15	μm





Conclusions

- *The mode launcher for the C-band gun presents "field tails" whose effect on the beam dynamics has been studied*
- *Beam dynamics studies have been performed to evaluate the effect of non cylindrically symmetric waveguide for the mode launcher (2 and 4 ports). The choice is for a 4 port waveguide coupler with negligible effects on beam quality. In the following the insertion of skew quadrupole will be considered if needed*
- *The WP proposed in Glasgow meeting (June2020) has been validated with ASTRA and a more accurate treatment for the photo-emission has been introduced and discussed. Also simulation files have been provided to the XLS community for further benchmarking.*

The C-band photoinjector proposal

- We propose a **C-band** photoinjector relying on a **2.5 cell gun** followed by *n* 2 m long TW structures
- 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

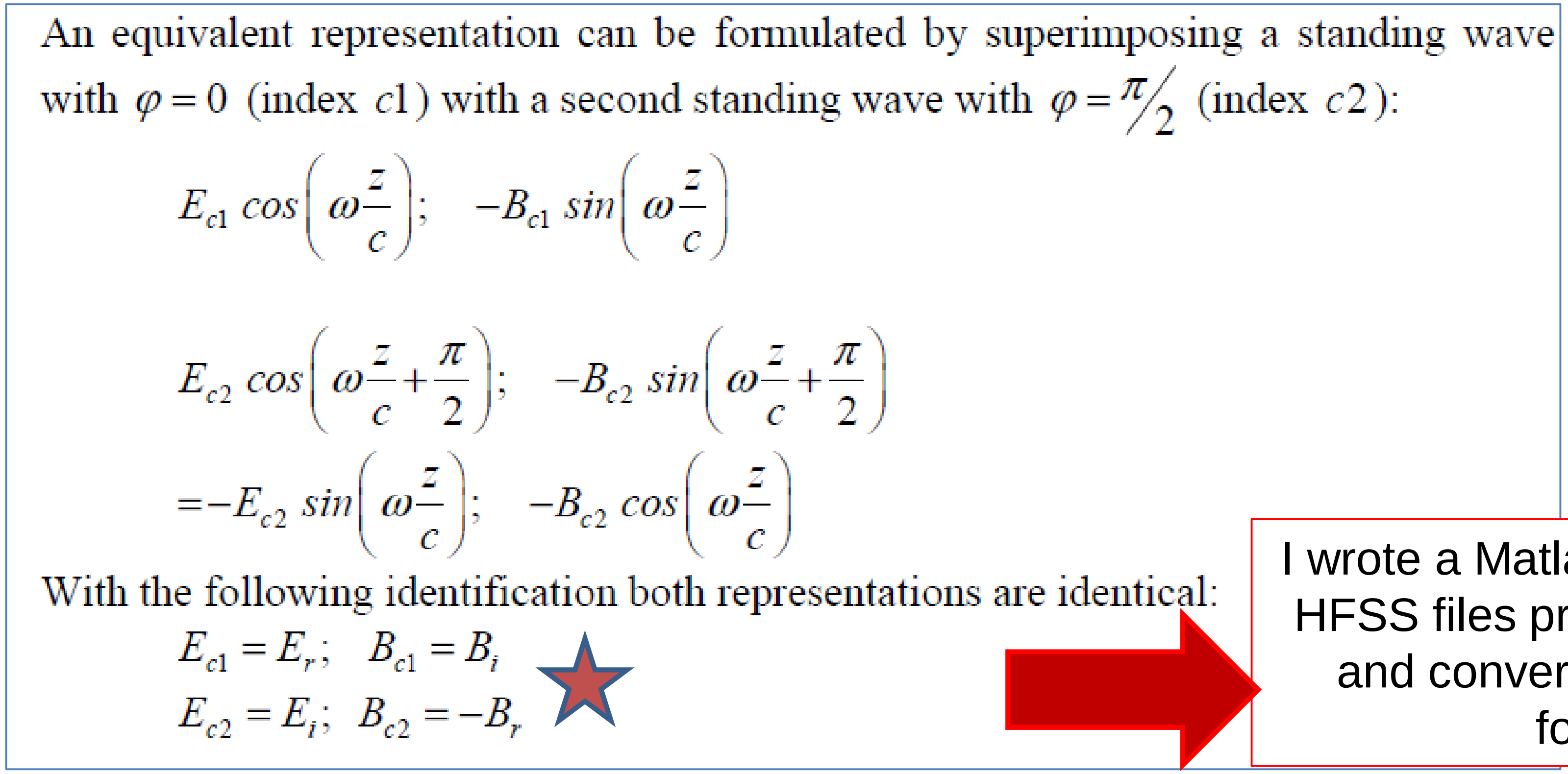
→ up to 160 MV/m peak field on cathode in the gun

→15 MV/m average field in TW sections

- The **2.5 cell gun** allows to at least double the space for *beam characterization after the gun* → *150 cm drift from WP8*

Building up the 3D gun model in ASTRA

- Beam dynamics simulations have been performed by means of ASTRA code
- ASTRA supports both 3D space charge tracking and 3D modeling of static and EM elements
- In particular, the user can provide both real and imaginary parts of the e.m. fields and so one can define a custom element with any assumption on the field temporal evolution (nor TW nor SW).
- In general one can build any the field by superimposing two standing wave. From ASTRA manual:



An equivalent representation can be formulated by superimposing a standing wave with $\varphi = 0$ (index $c1$) with a second standing wave with $\varphi = {}^{\pi}/_{2}$ (index $c2$):

$$E_{c1}\ cos\left(\omega\frac{z}{c}\right); \quad -B_{c1}\ sin\left(\omega\frac{z}{c}\right)$$

$$E_{c2}\ cos\left(\omega\frac{z}{c}+\frac{\pi}{2}\right); \quad -B_{c2}\ sin\left(\omega\frac{z}{c}+\frac{\pi}{2}\right)$$

$$= -E_{c2}\ sin\left(\omega\frac{z}{c}\right); \quad -B_{c2}\ cos\left(\omega\frac{z}{c}\right)$$

With the following identification both representations are identical:

$$E_{c1} = E_r; \quad B_{c1} = B_i$$

$$E_{c2} = E_i; \quad B_{c2} = -B_r$$

I wrote a Matlab routine that reads HFSS files provided by D. Alesini and converts them to ASTRA formalism

ASTRA-HFSS interfacing

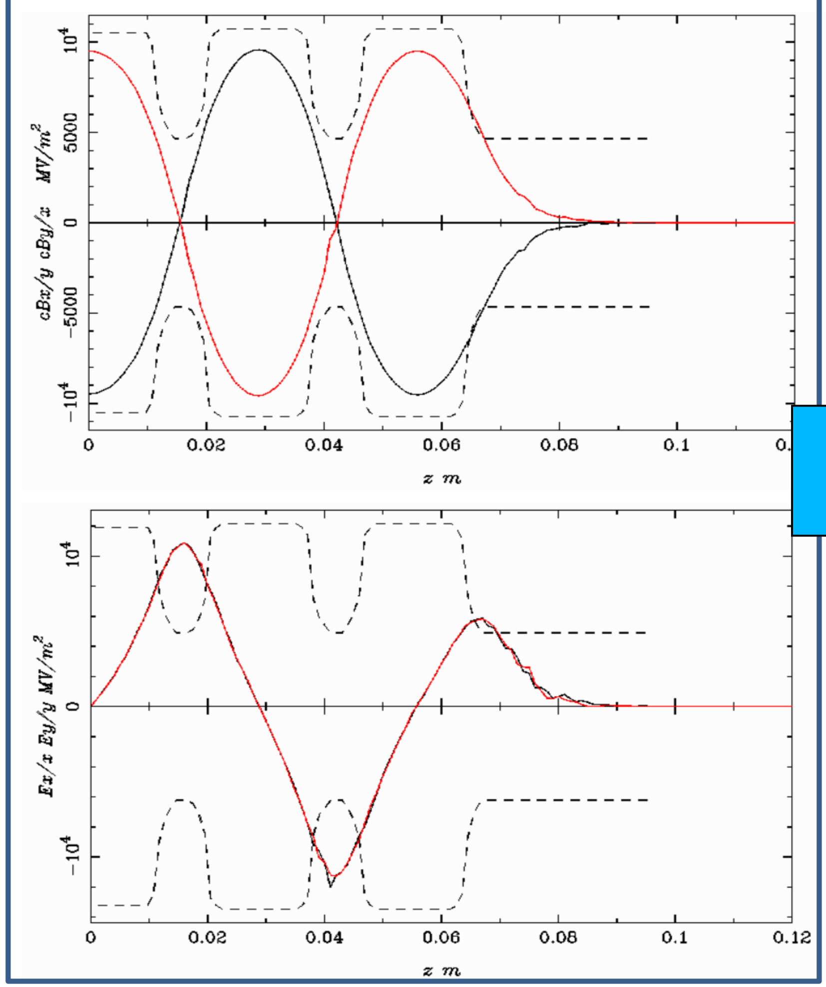
- First, we worked with a 3D map version of the gun without any mode launcher and we used it as reference for other cases
  - We worked on the field maps in order to control numerical effects that corrupt beam dynamics simulation results
  - We identified to numerical effect sources:
    - map discontinuities rising from HFSS resolution routine → step size, tetrahedra edge
    - map numerical noise → HFSS functions that help in suppressing the noise

- Then we proceeded with the 3D map of a gun with cylindrical waveguide → indeed introducing 3D maps we have anymore pure cylindrical beam dynamics and so we need to separate physical from numerical noise beam dynamics effects.
- Finally we studied the case of the gun with the mode launcher as it comes from EM and mechanical drawings

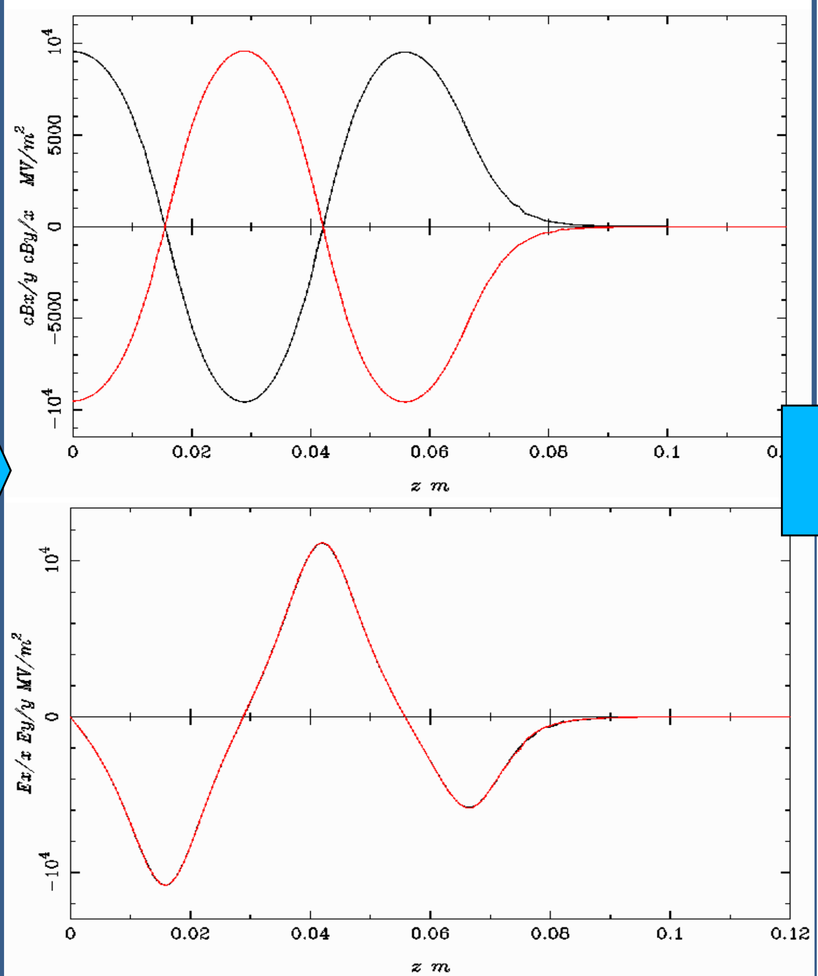
	tetrahedra edge size Δ [mm]	**(x,y) step size ε [mm]**	**z step size [mm]**	**Smooth Function**
2D		ASTRA routine	0.9773	
3D w/o ML	0.5 – 1.0 – 2.0	0.5	1	ON - OFF
3D with cylindrical ML	1.0 – 2.0	0.5	1	ON - OFF

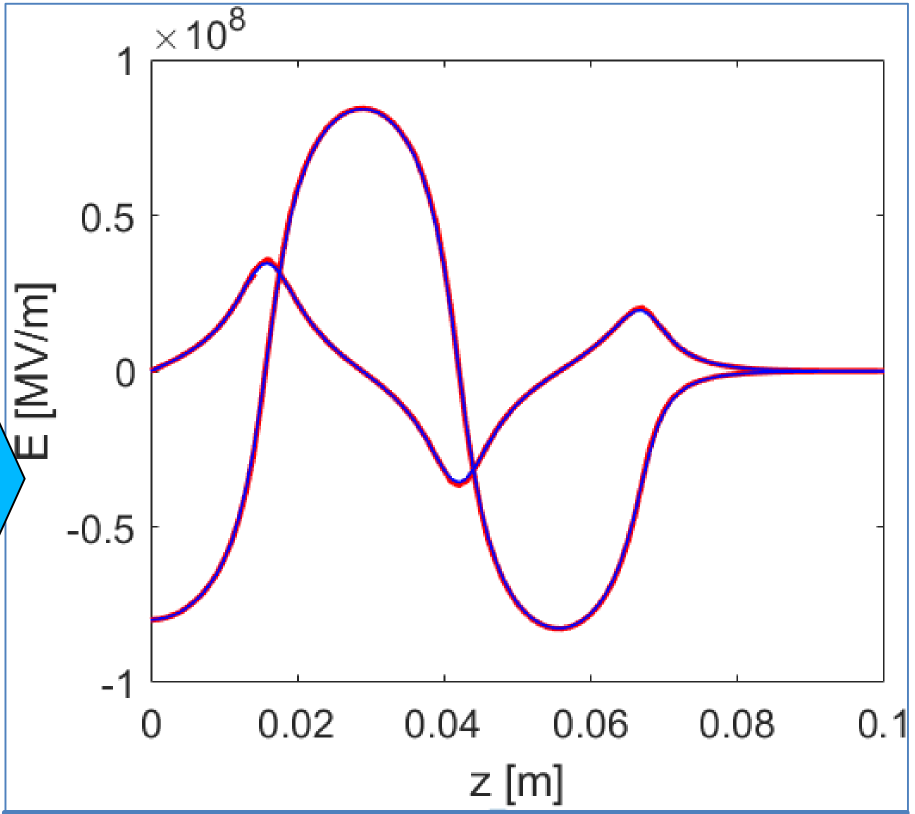
ASTRA-HFSS interfacing – Suppressing the noise

ASTRA: W/o HFSS smoothing



ASTRA: with HFSS smoothing





Plus Matlab smoothing