SAPIENZA
UNIVERSITÀ DI ROMA

BEAM INJECTION OPTIMIZATION IN THE SPARC_LAB PLASMA ACCELERATOR

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Introduction

- In order to realize future experiments at SPARC_LAB, especially for plasma acceleration, is necessary a proper high brightness beam with low emittance, low energy spread and a proper focusing and compression.

- In order to do that, I did:
  1) Study and simulations for new focusing elements along the beam line
  2) Study and simulations for a new high gradient photoinjector able to produce beams with very low emittance and energy spread.

APPENDIX

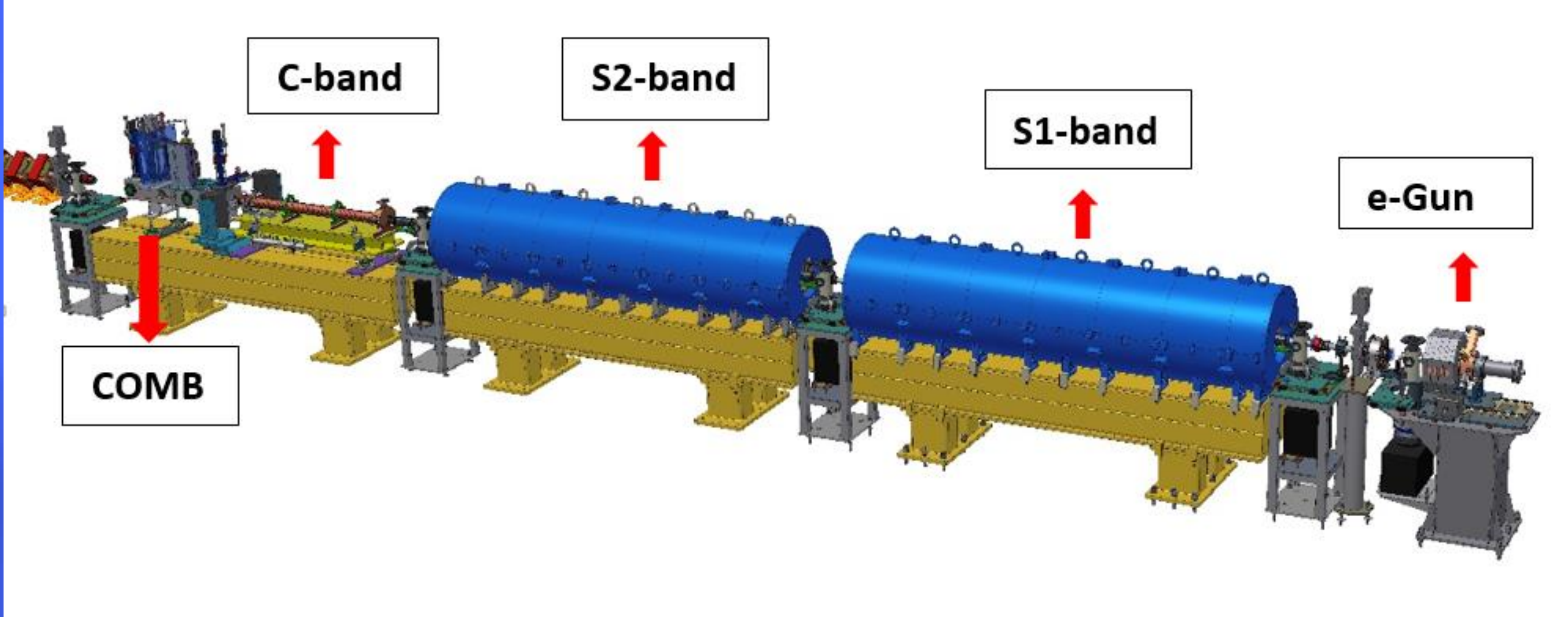
3) Study and simulations for the insertion of Printed Circuit (PC) skew quadrupoles inside the RF gun

4) Optimization of the existing focusing elements on the SPARC_LAB beam line

5) Experience with machine operations

The SPARC_LAB facility

S2E simulation with General Particle Tracer (GPT)

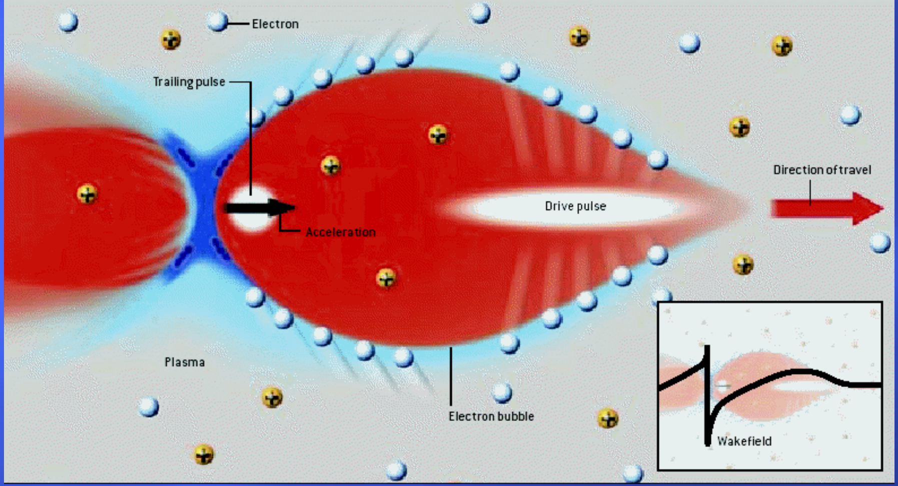


Linac:

$$\begin{cases} \boldsymbol{e^{-}Gun}: 1.6cells\ S-band, E_{peak} \approx 120\,\frac{MV}{m}, E_{exit} \approx 5{,}6\ MeV, \quad +\ Solenoid \\ \boldsymbol{S_1, S_2\ sections}:\ (f\sim 3GHz),\ \ L\sim 3\ m,\ \ E_{acc} \approx 20\,\frac{MV}{m}\ \ +\ \ Solenoids \\ \boldsymbol{C\ section}: (f\sim 6GHz),\ \ L\sim 1.4\ m,\ \ E_{acc} \approx 35\,\frac{MV}{m} \end{cases}$$

Beam Quality Parameters for Plasma Acceleration

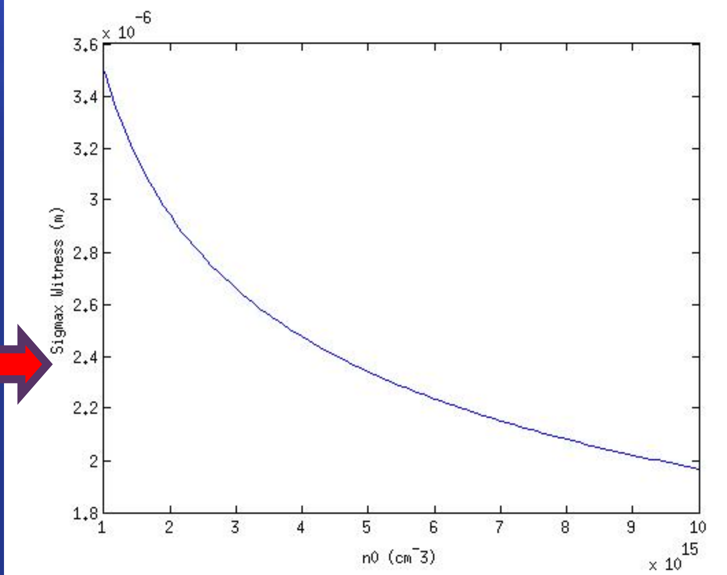
- High gradient acceleration in a plasma has been already demonstrated but with poor beam quality generation. The challenge is now to improve the quality of the accelerated beam. To this end one of the main concern is to satisfy the beam/plasma matching conditions.



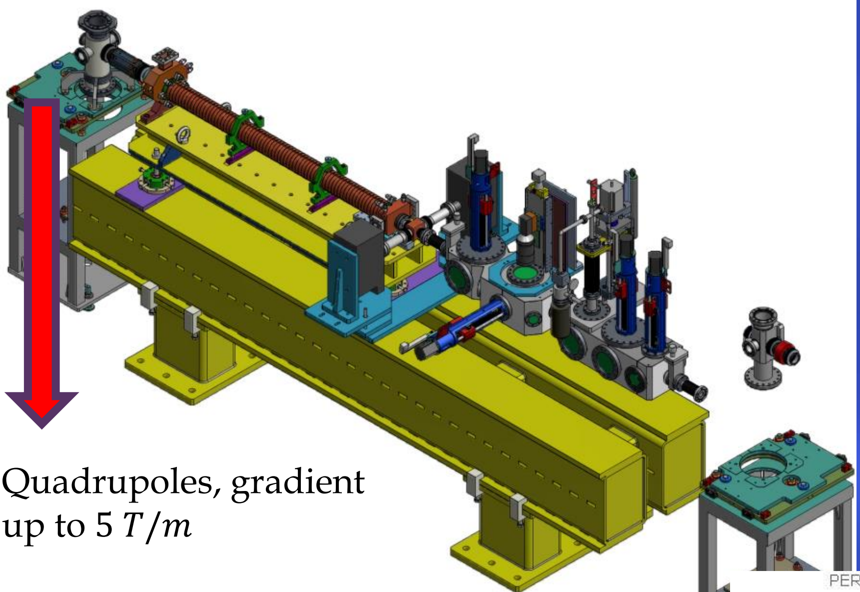
Driver pulse creates a perturbation that travel in the plasma with $v \approx c$.

$\lambda_p = 2\pi c\sqrt{\frac{\varepsilon_0 m}{n_0 e^2}}$ where n_0 is the plasma density

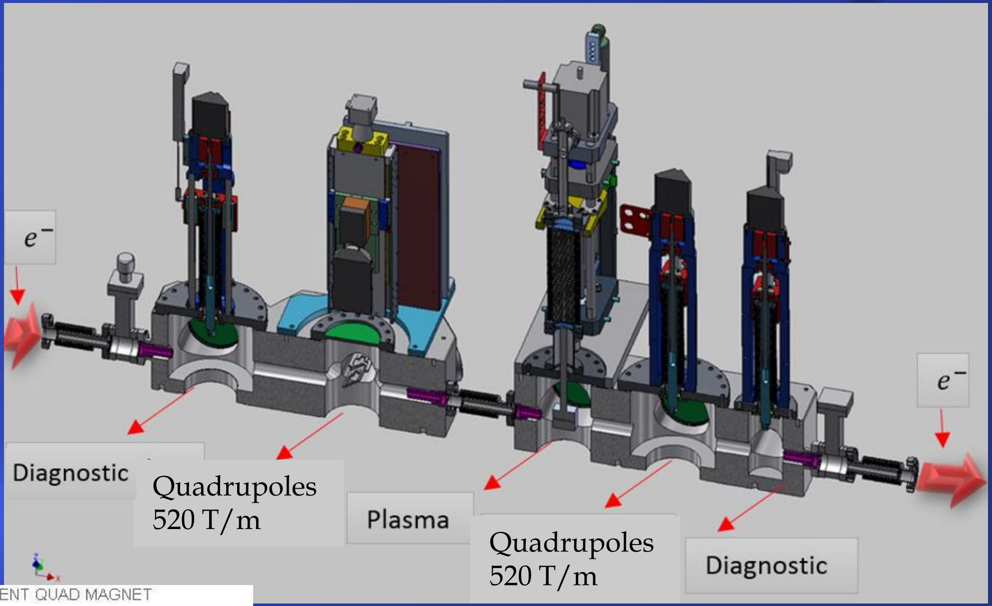
- Longitudinal matching conditions: $\sigma_z \ll \frac{\lambda_p}{2}$
- Energy spread: $\frac{\delta\gamma}{\gamma} = \frac{\sigma_z}{\lambda_p}$ Ultrashort bunches
- Optimal transverse conditions: $\sigma_x = \sqrt[4]{\frac{3(or\ 2)}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}}$
- Low emittance produces: $\beta_w = \frac{\sigma_0^2}{\varepsilon_{rms}}$

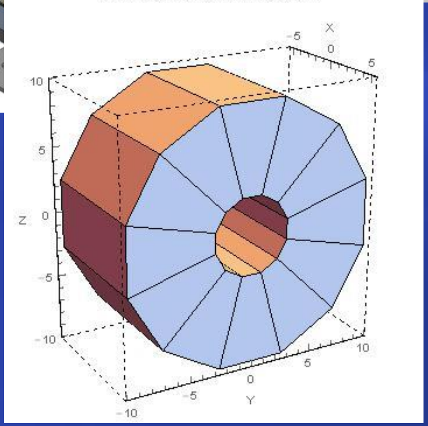


Interaction chamber and beam focusing

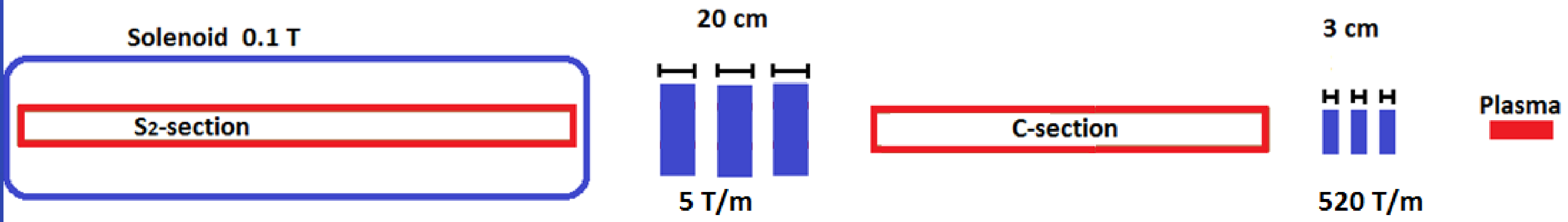


Quadrupoles, gradient up to 5 T/m



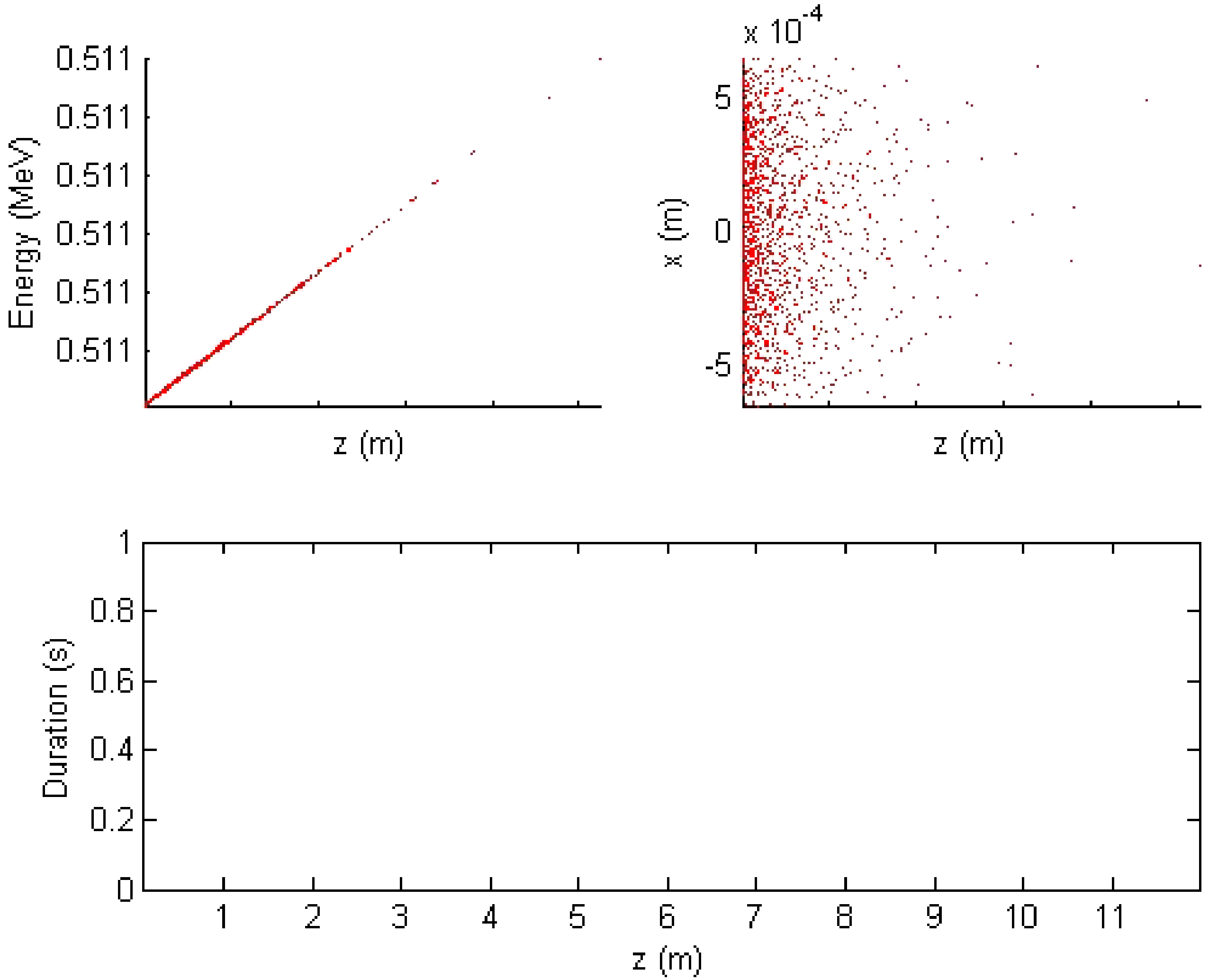


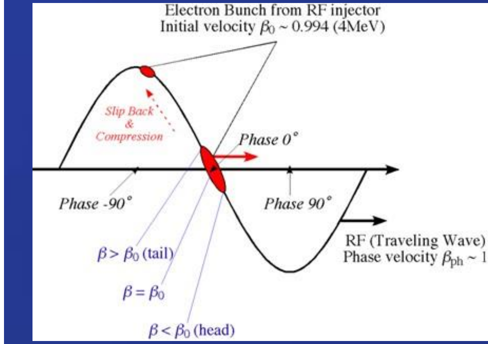
Focusing strenght: $\begin{cases} F_{x,sol} = \mp\left(\dfrac{qB_0}{2\gamma m_0 c}\right)^2 x \\ F_{x,quad} = \mp \dfrac{qB_0}{\gamma m_0 c} x \end{cases}$

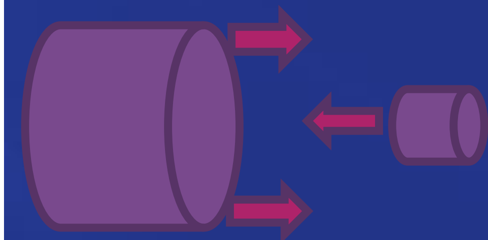


Configuration 1 Driver + 1 Witness beam

- 1 **Driver** (200pC) + 1 **witness** (20pC). Velocity Bunching
- **At the injection $\boldsymbol{\sigma_{z,D} = 54\ \mu m}$ (= 182 fs) $\boldsymbol{\sigma_{z,w} = 10.5\ \mu m}$ (= 35 $\boldsymbol{fs}$)**



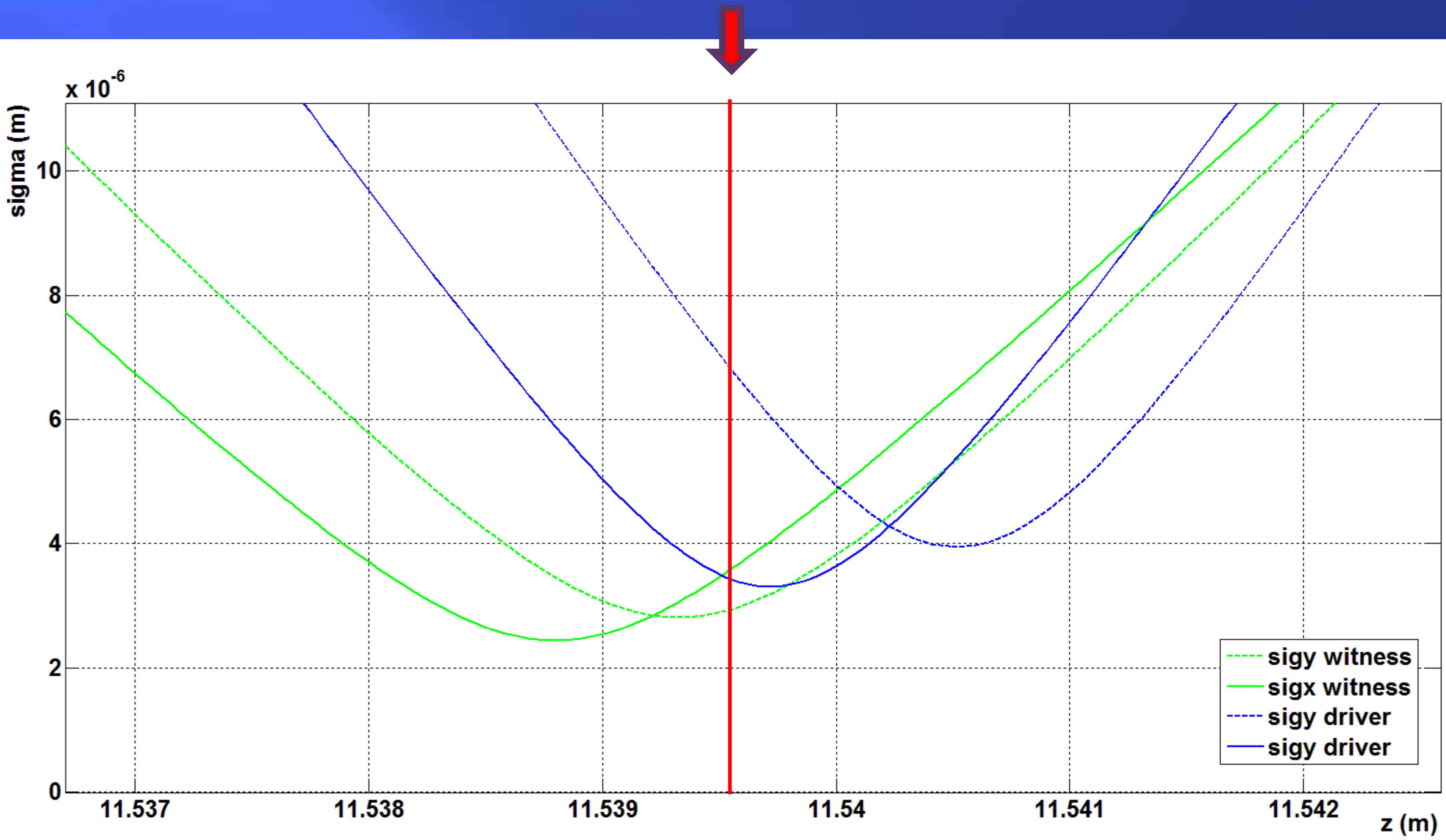




$$\sigma_{z,D} = 400fs$$
$$\sigma_{z,w} = 80fs$$

Spot Size at the injection

Start Plasma



Bunches parameters at the injection

DRIVER

- Betax=0.7mm
- Betay=2mm

- Sigmax=3.4um
- Sigmay=6.8um

- Emitx=4um
- Emity=5.1um

- Alphax=0,3
- Alphay=1.4

- E(spread)=115(0.19)MeV

- $\sigma_z = 54\ \mu m\ (= 182\ fs)$

WITNESS

- Betax=1.5mm
- Betay=0.8mm

- Sigmax=3.5um
- Sigmay=2.9um

- Emitx=1.9um
- Emity=2.4um

- Alphax=-1.1
- Alphay=-0.3

- E(spread)=115(0.11)MeV

- $\sigma_z = 10.5\ \mu m\ (= 35 fs)$

Next Generation High-Brightness beams using an Ultra-High Field C-Band Gun

- During plasma acceleration the beam can easily degrades its emittance. It is very important to have a good emittance at the injection, in order to preserve the brightness at the extraction for FEL experiments.

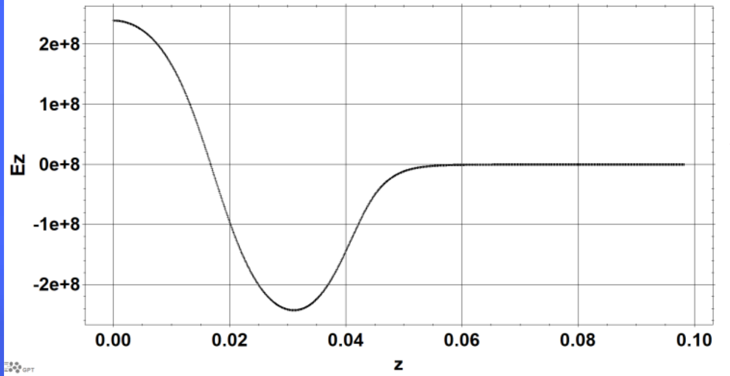
- In order to improve the beam emittance and the beam brightness of a factor 10 we can encrease the cathode peak field (control space charge, reduce the laser spot on cathode and intrinsic emittance).

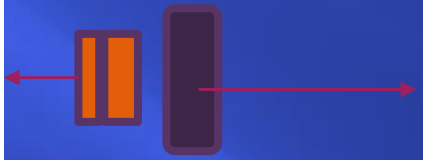
- In collaboration with UCLA-SLAC-LANL at SPARC_LAB we are optimizing a C-band gun able to reach up to 240 MV/m as a peak field.

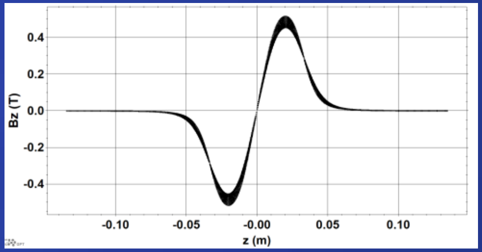
- A new scenario has been opened, and I worked in order to find a proper emittance compensation using and properly scaling the design of the new SPARC_LAB solenoid, able to reduce the residual field on the cathode up to 3.6 G @ 150 A in the S-band scenario.

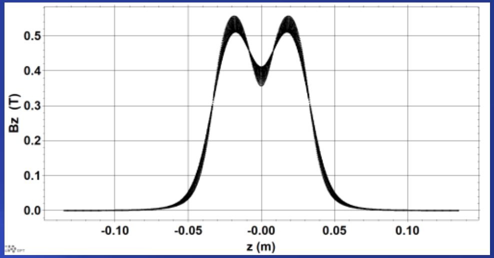
GUN LAYOUT

- In order to preserve the Ferrario scenario, I used a 1.6 cells C-Band gun with 240 MV/m. In this way $E_{final} \approx 5MeV$ like in the S-band 120 MV/m case.

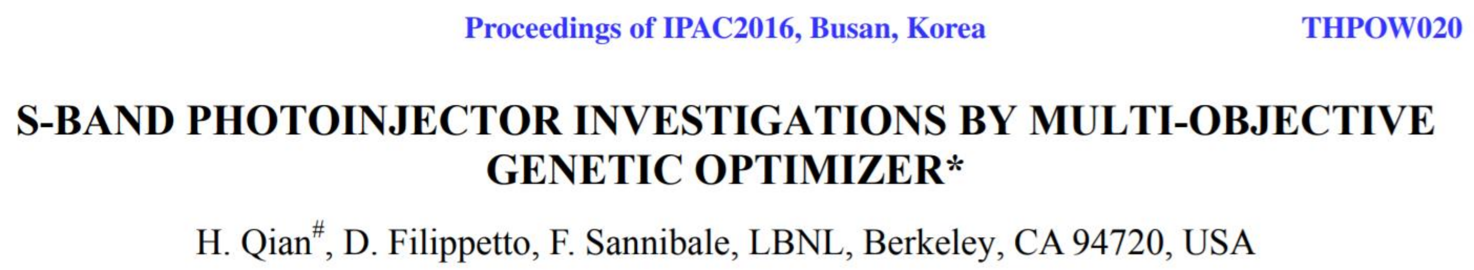








- Each lenghts was scaled by a factor 2 and each field was double respect to the S-Band scenario: the lenght of the solenoid was scaled by a factor 2 and the integrated magnetic field was double.
- With 100pC beam charge I used as a starting point the parameters scaled from:



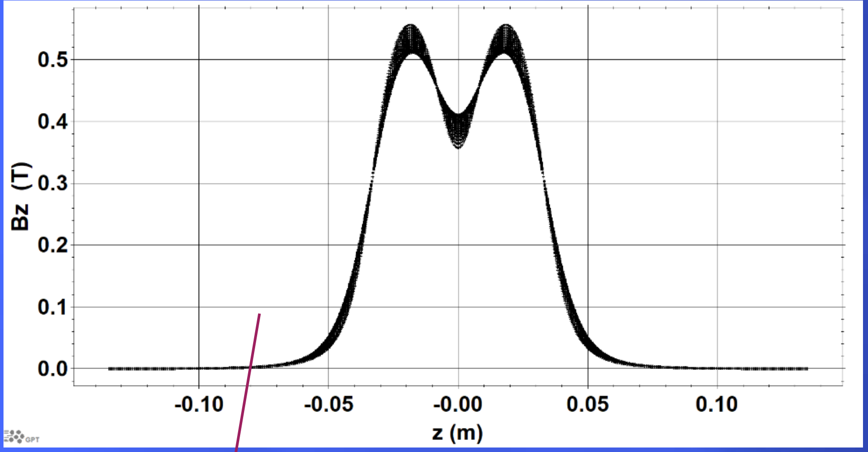
Proceedings of IPAC2016, Busan, Korea THPOW020

S-BAND PHOTOINJECTOR INVESTIGATIONS BY MULTI-OBJECTIVE GENETIC OPTIMIZER*

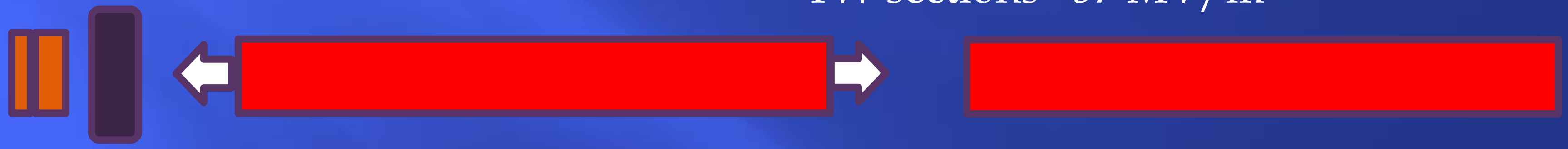
H. Qian[#], D. Filippetto, F. Sannibale, LBNL, Berkeley, CA 94720, USA

ASTRA 10k particles

LAYOUT



TW sections 57 MV/m



C-BAND
GUN +
SCALED
SOLENOID

C-BAND (on crest)

C-BAND (on crest)

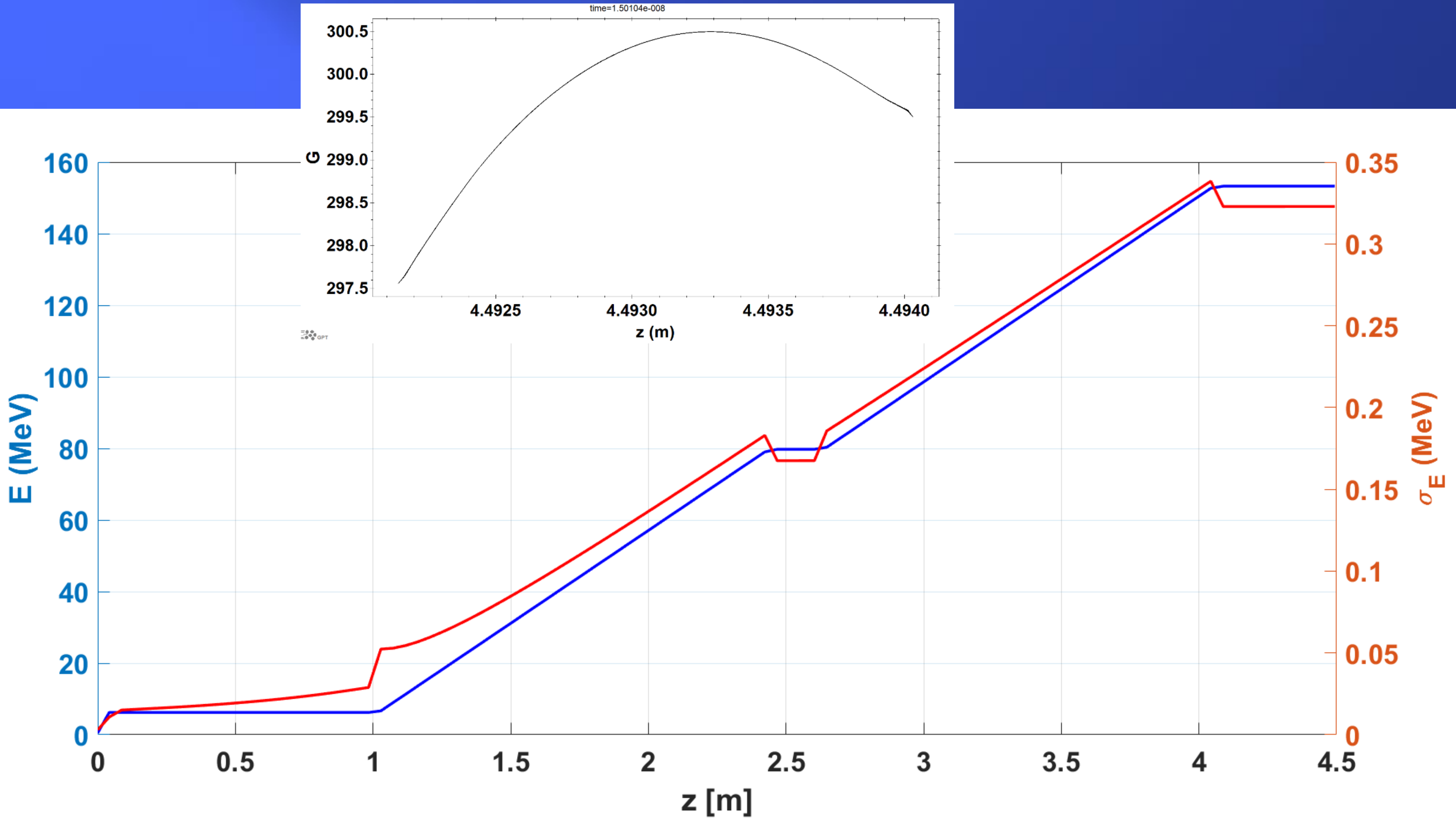
$$E_{final} \approx 150MeV$$
$$E_{spread} \approx 0{,}2\%$$

Using GPT the first linac position, the integrated magnetic field, the current in the coils, bunch parameters, magnetic field on the cathode (work in progress) were optimized. Initially scans with 35k particles was done, subsequently fine scans with 350k particles were performed.

GPT SIMULATION – Starting Parameters

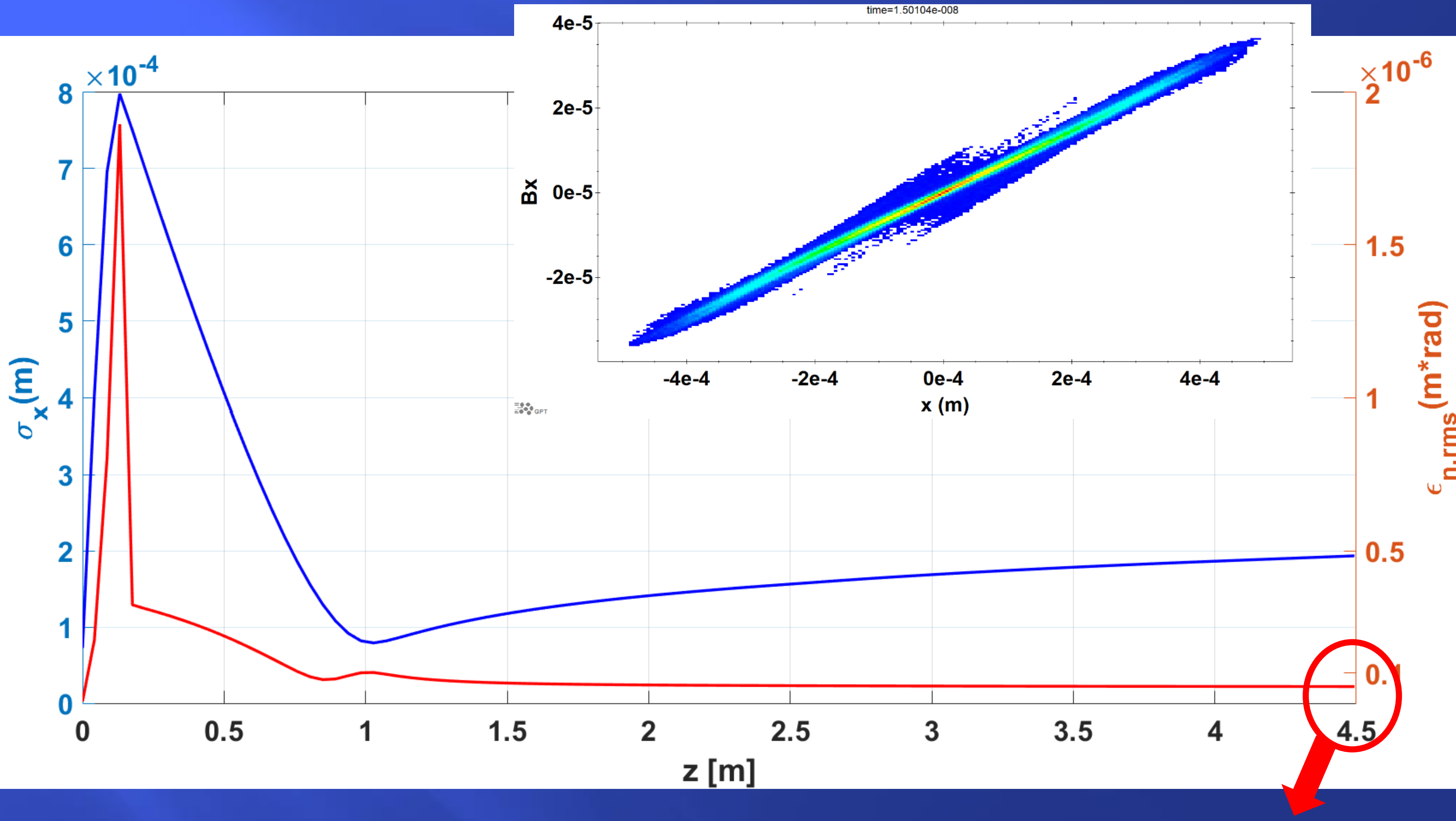
- GPT simulation with 350000 macro particles
- $Q = 100\,pC$
- Laser on cathode : $\begin{cases} \sigma_t = 5.8\,ps \;\; (uniform) \\ radius = 151\,\mu m\;(gaussian) \\ E = 4.66\,eV \text{ (corresponding to } \lambda = 266.7\,nm) \end{cases}$
  (Optimized)
- The field on the cathode is: $E_z = E_0 sin\phi_{launch}$. In this case $E_0 = 240 MV/m$ and $\phi_{launch} = 38°$ → $E_z \approx 145 MV/m$
- The field map of the new SPARC_LAB gun solenoid (2 coils powered with the same current) was used dividing the lenght and doubling the field by a factor 2.
- The starting intrinsic emittance was setted to: $\varepsilon_{int} = 25nm$.

ENERGY AND ENERGY SPREAD



$E_{final} \approx 150MeV$ $E_{spread} \approx 0,2\%$

SPOT AND EMITTANCE

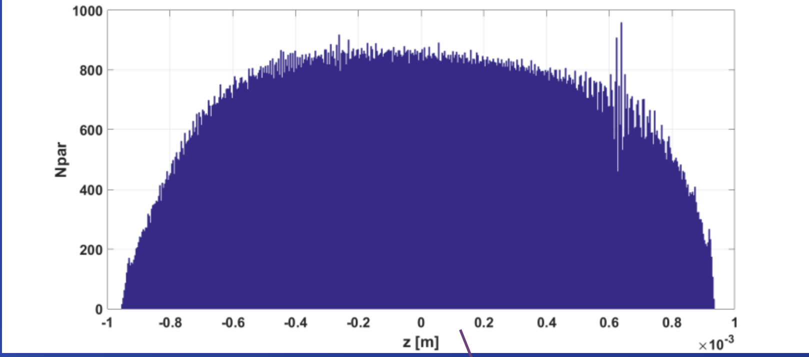


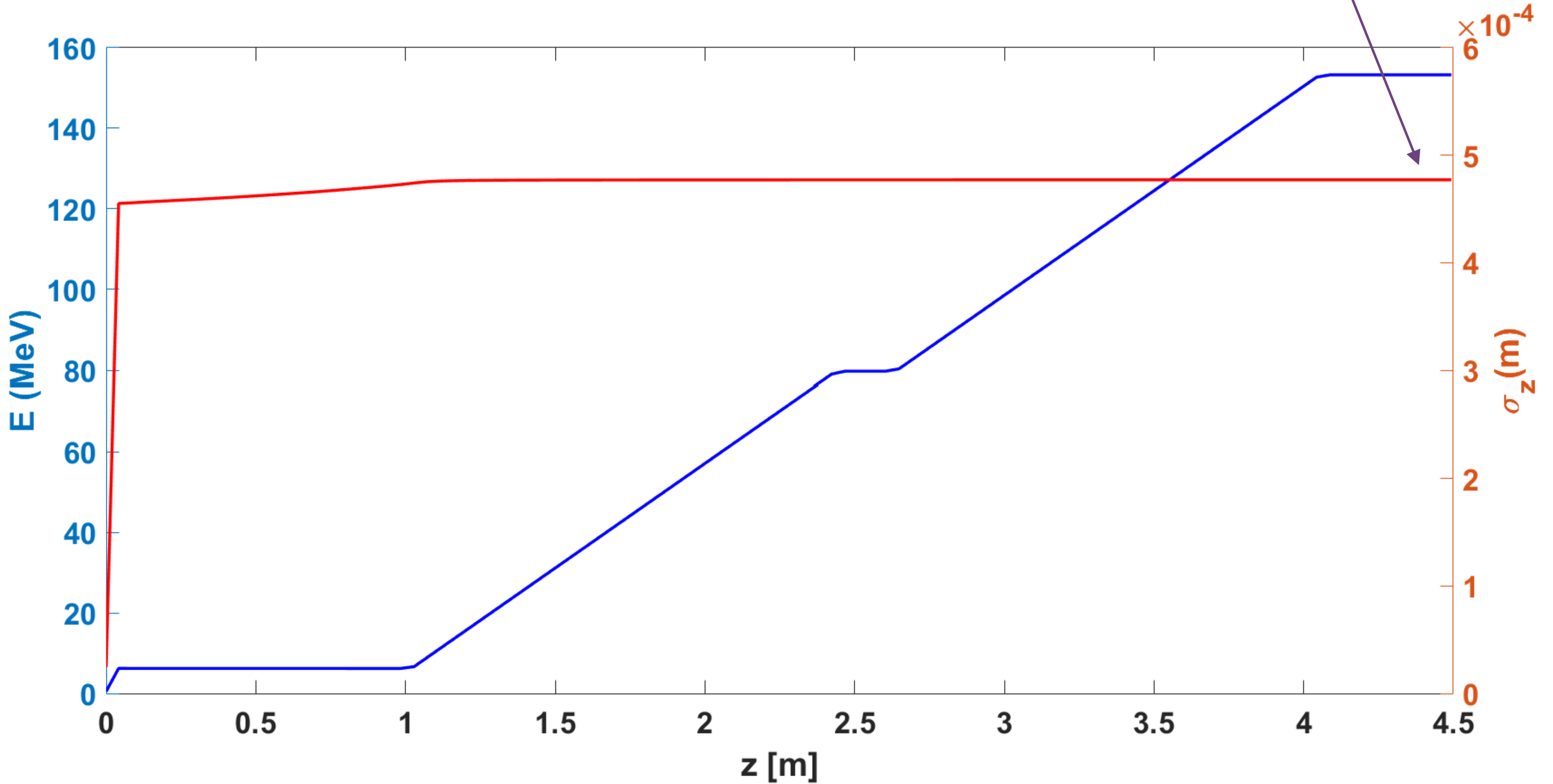
$\varepsilon_{final} \approx 55nm$

BUNCH LENGHT

$$\sigma_{z,rms} \approx 4.7\ x\ 10^{-4} m\ (1.5ps)$$

$$I \approx 64.1\ \text{A}$$





$$B = \frac{2I}{\varepsilon_n^2} \approx 4.2 \text{ x } 10^{16} \frac{A}{m^2} \qquad (5.1 \text{ x } 10^{16} \frac{A}{m^2} \text{ using } \sigma_{z,fwhm})$$

Magnetization emittance

- Busch's Theorem in order to estimate the magnetization emittance $\varepsilon_{n,mag}$
- When particles are emitted in a magnetic field they have a canonical angular momentum. This can be translated in an emittance contribution:

$$\varepsilon_{n,mag} \cong \frac{\sigma_{p\perp}}{m_0 c}\sigma_x \cong \frac{qB_0}{2m_0 c}\sigma_x^2 \quad \rightarrow \quad \varepsilon_{n,mag}(mm\ mrad) \cong 0.3B_0(mT)\sigma_x^2(mm^2)$$

- The scaled new SPARC_LAB solenoid has on the cathode a residual field $B_z = 0.83\ mT$ @ 177A that leads to:

$$\varepsilon_{n,mag} = 5.7\text{ nm}$$

- An optimization of the previous working point inserting a bucking coil in order to reduce the magnetization emittance was done leding to a final emittance value of $\boldsymbol{\varepsilon_{n,rms} \approx 54nm}$.

SUMMARY AND PERSPECTIVES

- High gradients acceleration in a plasma has been already demonstrated but with poor beam quality generation. The challenge is now to improve the quality of the accelerated beam and after send the beam to an FEL. To this end one of the main concern is to satisfy the beam/plasma matching conditions, and develop a new RF gun able to produce the next generation of Ultra-High brightness beams.

- By that work we have at SPARC_LAB a working point with new focusing elements along the beam line, thanks to which we will be able to produce high quality beams in the future SPARC_LAB plasma accelerator.

- In order to reach the impressive emittance value of $\boldsymbol{\varepsilon_{n,rms}} \approx \mathbf{55}\boldsymbol{nm}$ and a beam brightness of $\boldsymbol{B} \approx \mathbf{4.2\ x\ 10^{16}}\,\frac{\boldsymbol{A}}{\boldsymbol{m^2}}$, the layout and the beam dinamics of an Ultra-High peak field C-band gun has been optimized.

- We shared our Ultra-High beam brighntess beam with LANL (MARIE X-FEL), they are compressing the beam with a magnetic chi-cane. I am testing the possibility to use an RF compression system.

- A scan using cathode peak fields between 180-325 MV/m is starting. And a discussion on the RF technology able to reach these field has been opened.

Grazie

PRINTED CIRCUIT QUADRUPOLES

Insertion of PC skew quadrupoles in the photoinjector

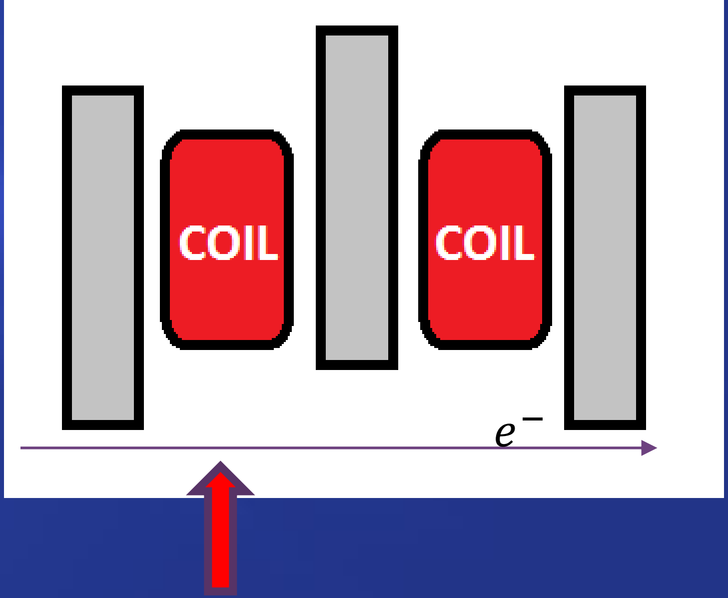
- Due to the gun solenoid misalignements, beam is ellipsoidal at the gun exit (different spots and emittances in x and y plane). In this way it is not possible to match the beam with plasma in both plane simultaneusly.

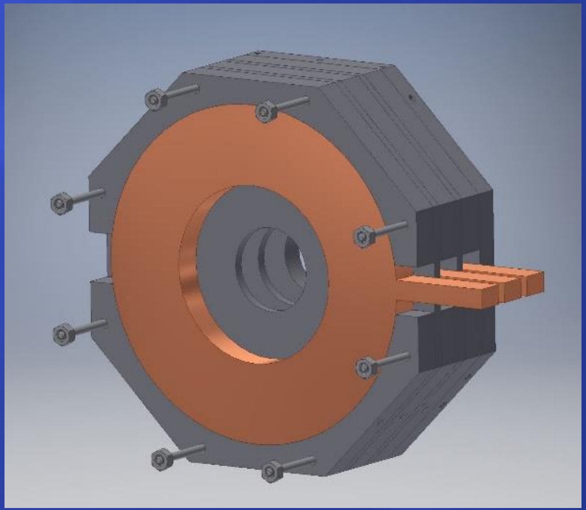
- In order to avoid ellipsoidal beam, I worked on the insertion of printed circuit skew quads inside the SPARC_LAB gun solenoid.

- I found the proper gradients, dimensions and positions for the current and future SPARC_LAB gun solenoid.

Insertion of PC skew quadrupoles in the photoinjector

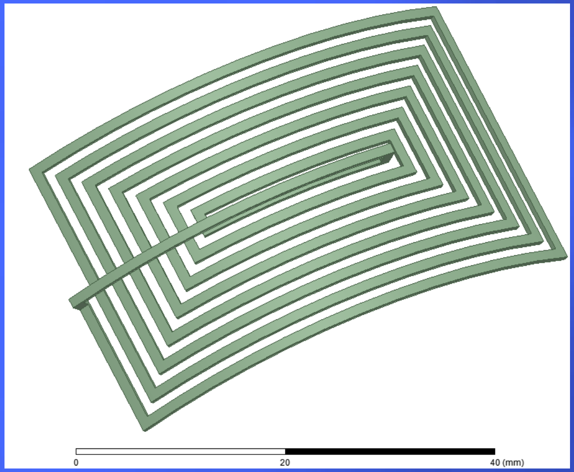
- Spot and emittances can be different in x and y planes due to: Laser and Gun solenoid misalignements. In this way it is not possible to match the beam with plasma in both plane simultaneusly.
- In order to avoid ellipsoidal beam, I worked on the insertion of printed circuit skew quads inside the SPARC_LAB gun solenoid.
- I found the proper gradients, dimensions and positions for the current and future SPARC_LAB gun solenoid.



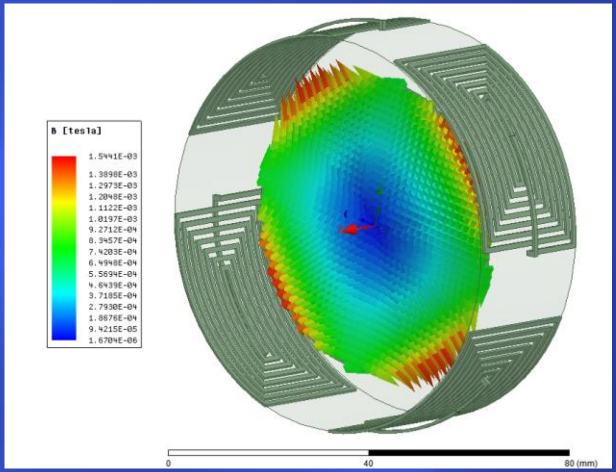


A possible position is inside the new solenoid on the first coil.
QUADS length 3*cm*.
Diameter=Unknown

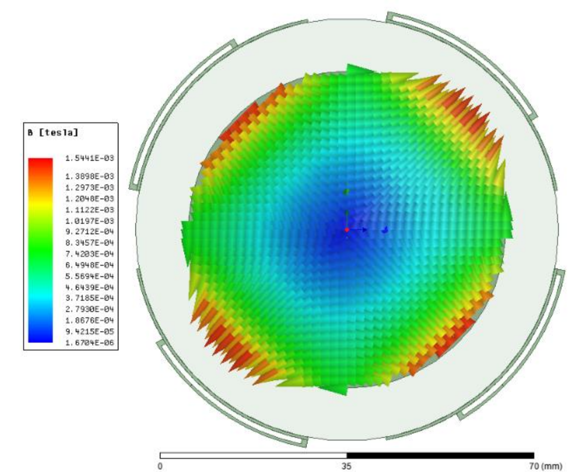
PRINTED CIRCUIT QUADRUPOLES



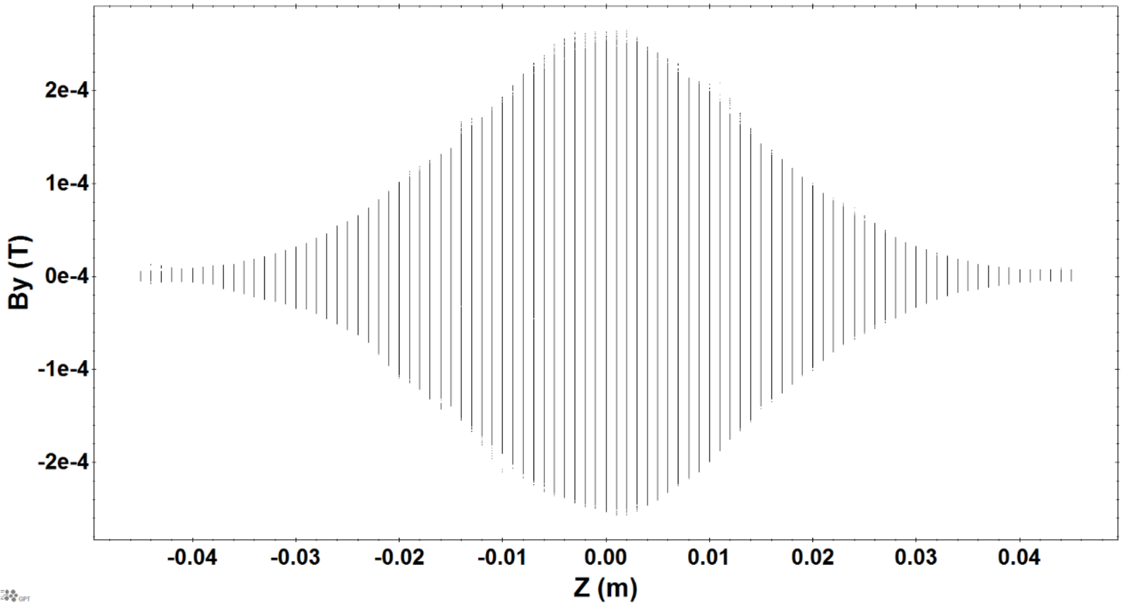
Section: $1mm^2$



Gradient: $2.1 \times 10^{-2}\, T/m$ @ 10 A



T~250°C

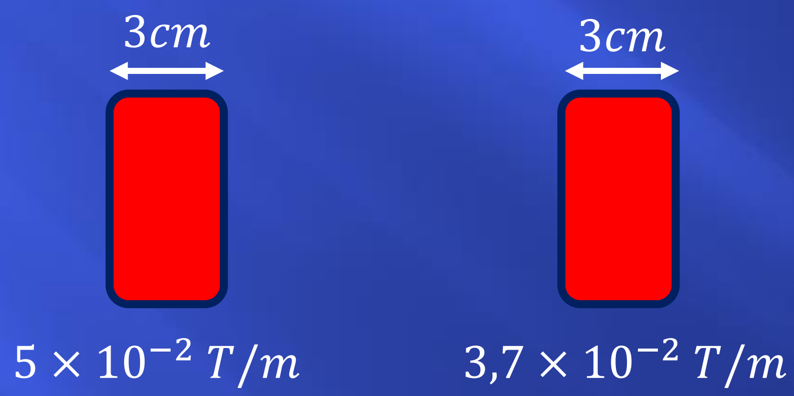


Courtesy of G.Castorina

GRADIENT OPTIMIZATION

- Starting with an ellipsoidal (~15%) laser on cathode, the diversity of σ_x and σ_y decreases at ~1% on AC1FLG, using two $3cm$ skew quadrupoles inside the Gun_Solenoid.

- Found Gradients:



$3cm$ $3cm$

$5 \times 10^{-2}\ T/m$ $3{,}7 \times 10^{-2}\ T/m$

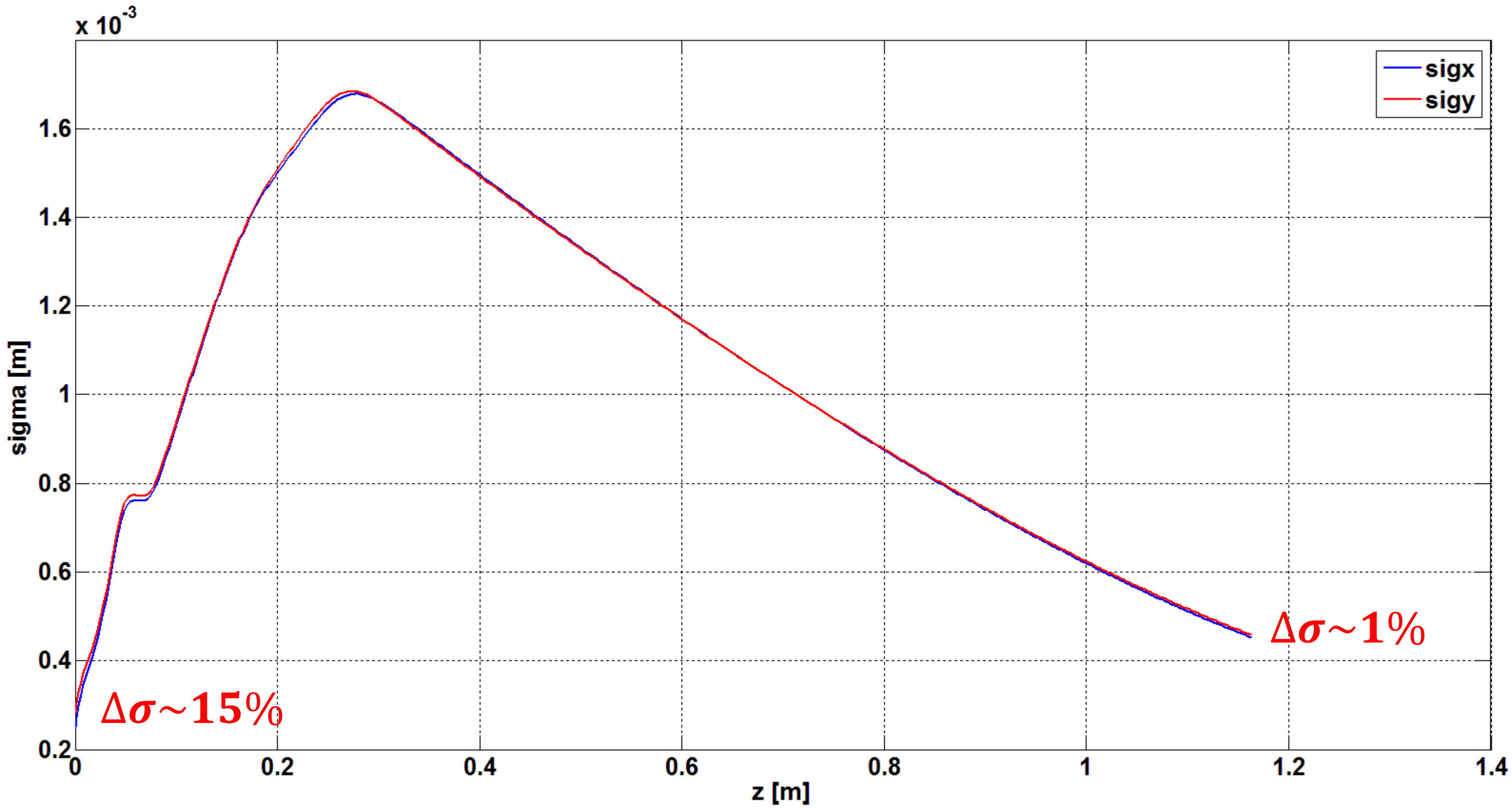
- In literature: $4.14 \times 10^{-2}\ T \cdot A/m$

GPT ELLIPSOIDAL BEAM

- STARTING beam: $Q = 100pC$

LASER PARAMETERS:

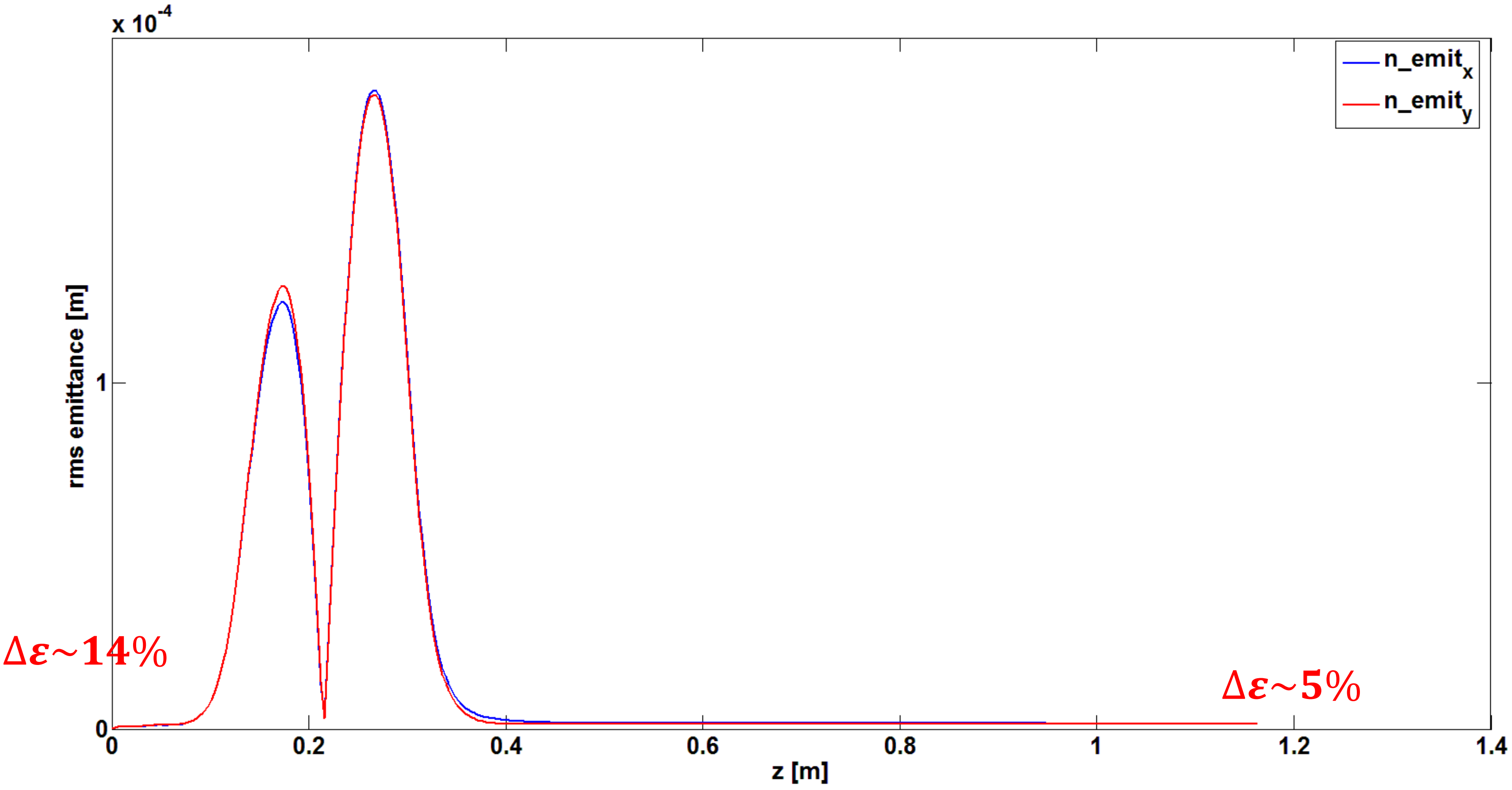
$$radius_x = 550\mu m$$
$$radius_y = 632\mu m \quad (\sim 15\%)$$
$$t_{length} = 600fs$$



$\Delta\sigma \sim 15\%$

$\Delta\sigma \sim 1\%$

EMITTANCE



$\Delta\varepsilon \sim 14\%$

$\Delta\varepsilon \sim 5\%$

OPEN PROBLEM: **Cooling. PC QUADS (section $1mm^2$) easily reach T > $200°C$**

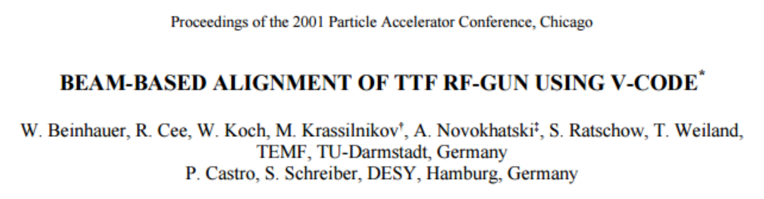
Gun Solenoid Alignement

Gun Solenoid Alignement at SPARC_LAB

- By the experiment at SPARC increasing the gun solenoid current I_{sol} we measure in a YAG flag before the first accelerating section a growing shift of the bunch centroid. This means that increasing I_{sol} (the B_{sol} field increases linearly) the bunch centroid perceives a growing kick due to solenoid misalignements.

- By a theoretical point of view, starting by the solenoid magnetic field B_{sol} and writing the equation of motion for a charged particle moving off axis, is possible to estimate the solenoid misalignements on x and y axis. Unfortunately this equation is unusable by a practical point of view (VERY long equation).

- Other techniques are well known in literaure for gun with coils powered with the same current



Proceedings of the 2001 Particle Accelerator Conference, Chicago

BEAM-BASED ALIGNMENT OF TTF RF-GUN USING V-CODE*

W. Beinhauer, R. Cee, W. Koch, M. Krassilnikov†, A. Novokhatski‡, S. Ratschow, T. Weiland,
TEMF, TU-Darmstadt, Germany
P. Castro, S. Schreiber, DESY, Hamburg, Germany

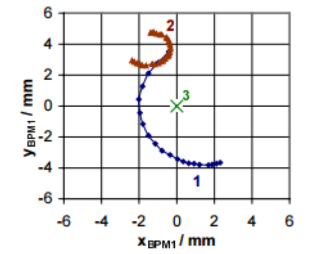
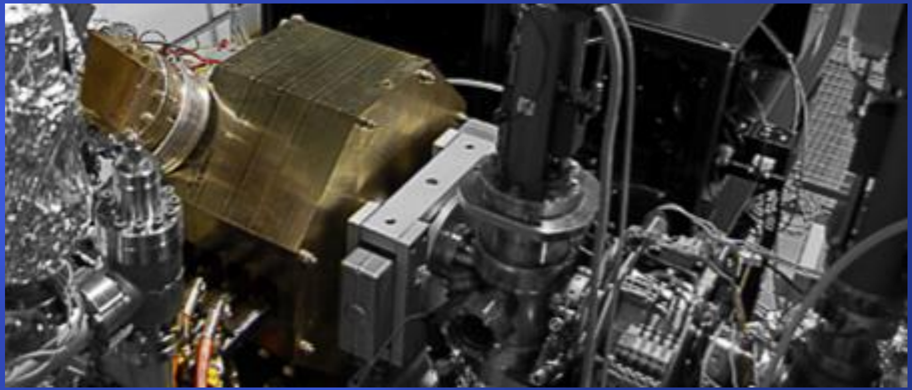


Figure 2: Measured beam position (X_{BPM1},Y_{BPM1}) dependence on: 1 – primary solenoid current (0A<I_{sol1}<400A, I_{sol2}=0A); 2 – secondary solenoid current (-290A<I_{sol2}<290A, I_{sol1}=0A). 3 – BPM1 center.

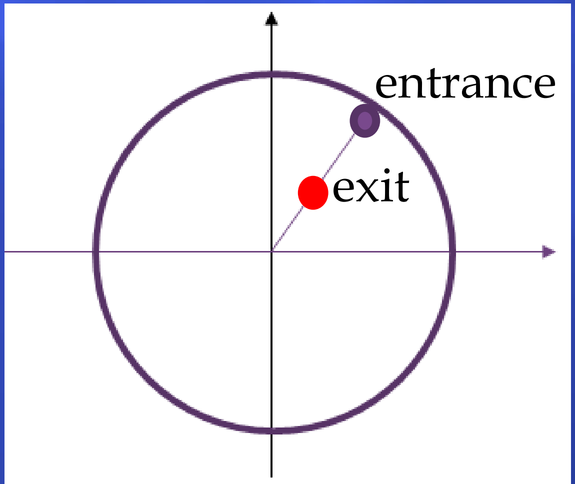
based on the study of the helix varying the solenoid current

Gun_Solenoid @ Sparc_Lab

- The Gun_Solenoid at Sparc_Lab is made up of 4 coils independently powered.



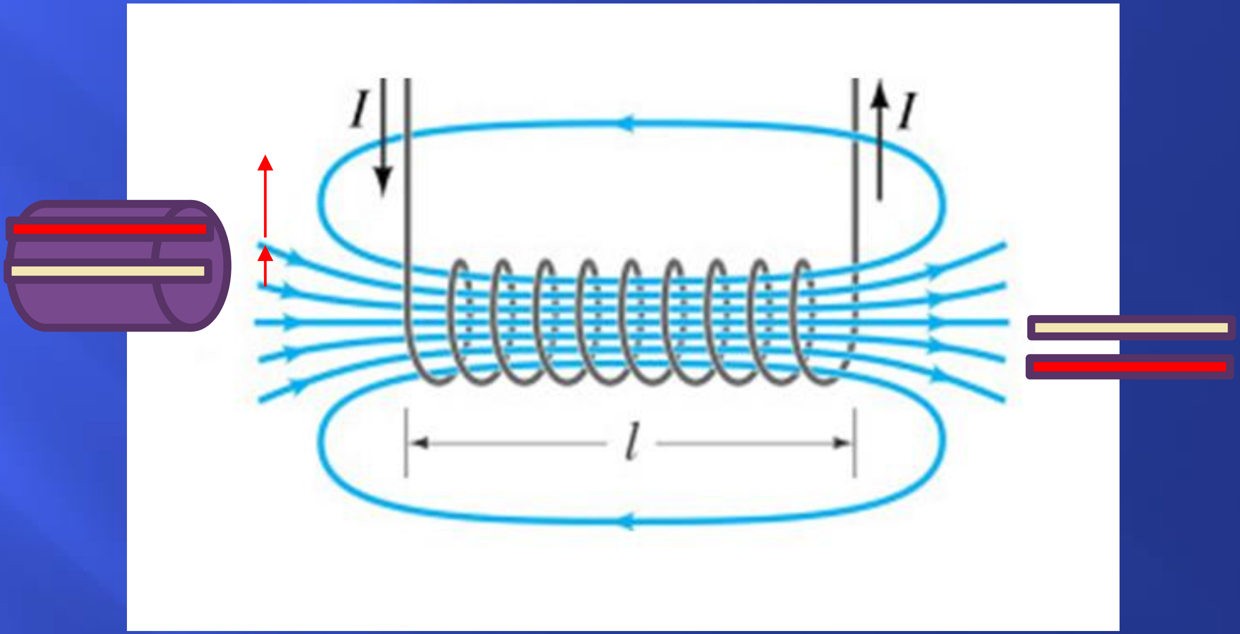
- One of the difference with the Desy Solenoid is that the first and the last 2 coils are powered with an opposite current. In this way the particles in the middle of the solenoid begin to reduce their rotation and do not rotate at the exit of the solenoid. At the end we do not perform an helix, but particles are focused.



In this way with a misalignement, encreasing the current the centroid do not move on an helix, but on a line. Increasing the current, a particle do not rotate at the exit but is focused. Increasing the current, the centroid of the bunch move on line.

Why the kick? A qualitative approach

- With a misalignement, **excluding the rotation effect**, every horizontal slice perceive a different $B_\perp$ of the fringe field, and subsequently a different coupling with B_z inside the solenoid.

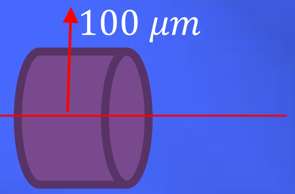


- The outer slices perceive an higher transverse field focus more than the internal one. At the end of the solenoid the result is a kick of the centroid, and a change of the bunch shape.

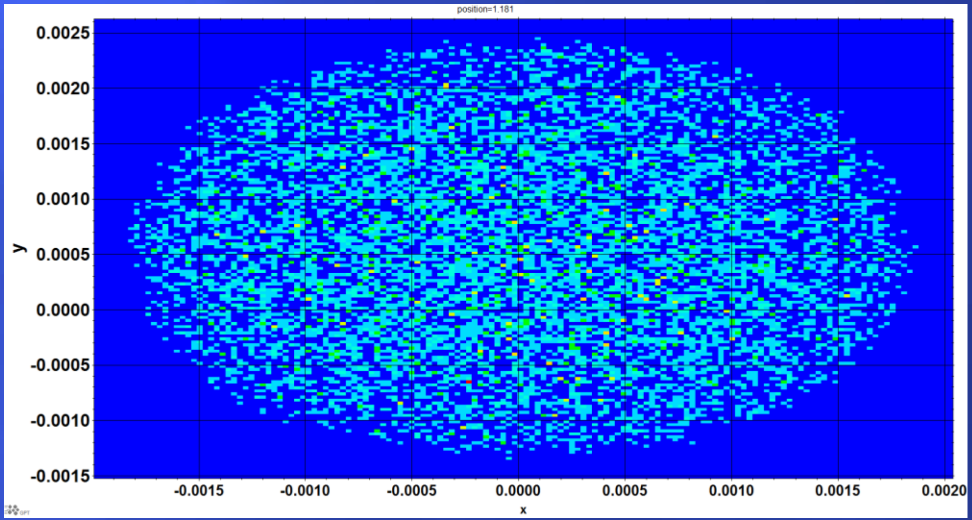
Beam-Based Alignement with GPT

- Possible kicks came from: Laser beam offset at the cathode, Solenoid misalignements, Solenoid Tilt. An evaluation of an initial kick effects due to errors on the solenoid was made with gpt:

Bunch of september run: $\varepsilon_{\,rms} = 0.9\ \mu m\ ; \sigma_z = 320\ \mu m\ ; \sigma_x = 500\ \mu m\ \ (UTL)$

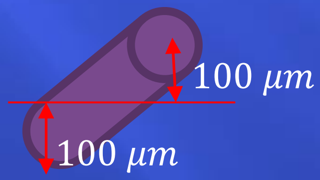


$I = 178\ A$

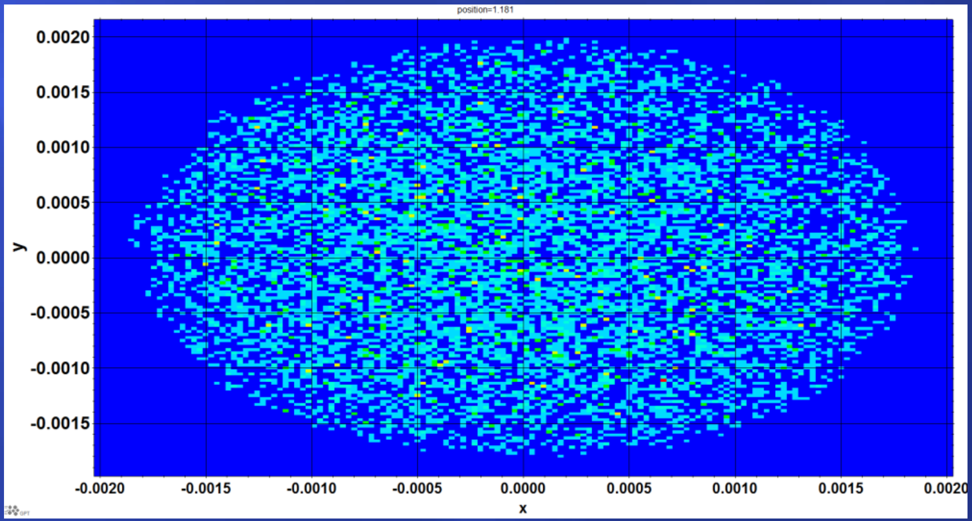


$x_c \approx cost$

$y_c = +600\ \mu m$



$I = 178\ A$

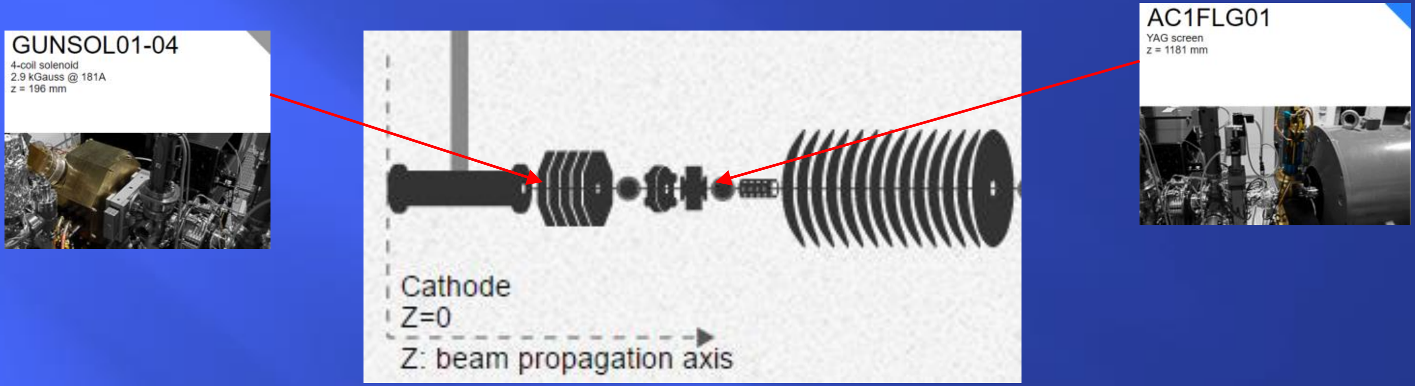


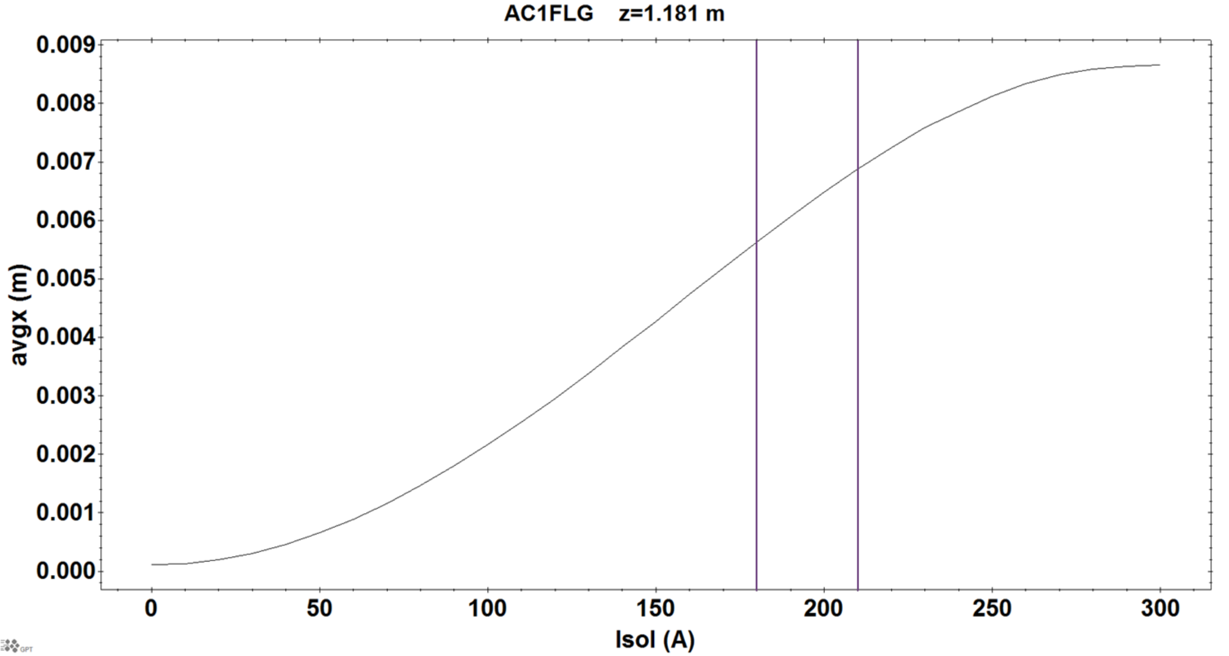
$x_c \approx cost$

$y_c = +100\ \mu m$

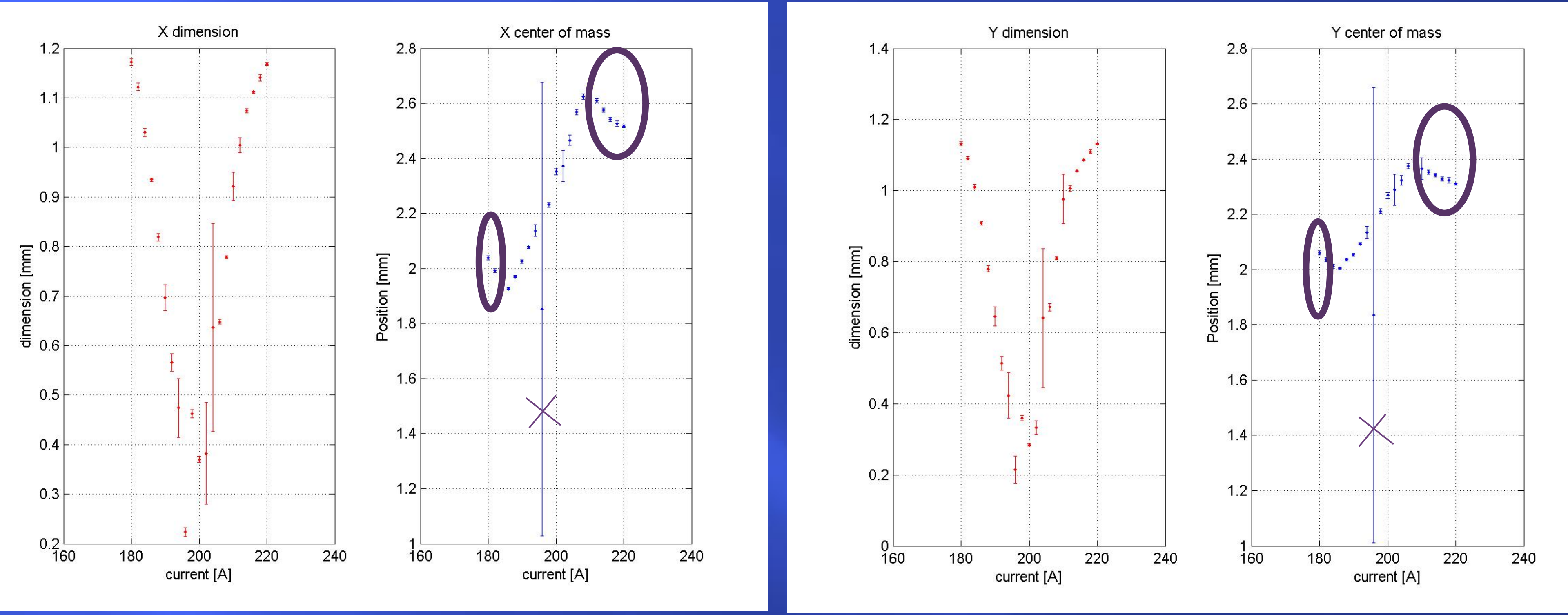
Beam-Based Alignement @ SPARC_LAB

- Solenoid Scan:



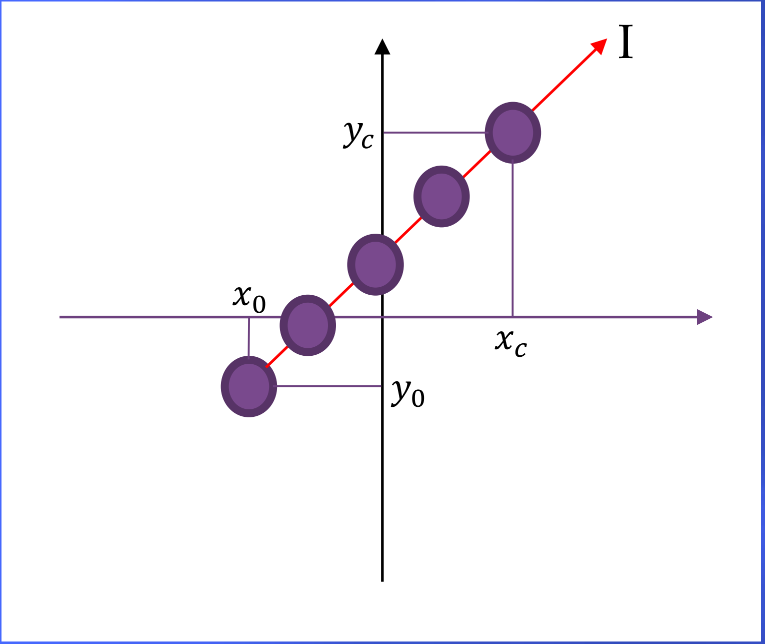


The linear increasing of the coordinate of the centroid $(x_c; y_c)$ was checked with GPT in the region in which we expect a linear growth of the field, varying the current from $0A$ to $300A$.



Fitting data we obtain, for $I = 0$, the coordinates of the centroid without solenoid perturbation:

$$x_0 = -3{,}91047\ mm \qquad (m_x = 0{,}031241)$$
$$y_0 = -1{,}50250\ mm \qquad (m_y = 0{,}018782)$$



Increasing the current I, we expect a linear increasing of the coordinate of the centroid $(x_c; y_c)$. Since the centroid $(x_0; y_0)$ for $I = 0$, is not centerd in (0;0), it is better to calculate the absolute value $(|x_0|+|x_c|;|y_0|+|y_c|)$ that are the real displacements obtained by increasing the current.

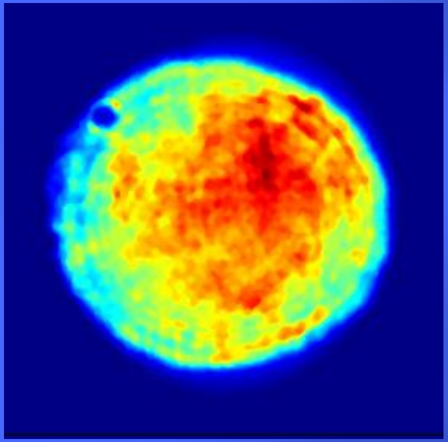
$ISOL\ (A)$	$x_c(mm)$	$y_c(mm)$	$x_0(mm)$	$y_0(mm)$	$\lvert x_0\rvert+\lvert x_c\rvert$	$\lvert y_0\rvert+\lvert y_c\rvert$
			$-3{,}91047$	$-1{,}5025$		
186	1,926638	2,004609			5,837105	3,507112
188	1,970898	2,03623			5,881365	3,538733
190	2,025531	2,053069			5,935998	3,555572
192	2,077063	2,093031			5,987530	3,595534
194	2,137242	2,134213			6,047709	3,636716
198	2,231432	2,211147			6,141899	3,71365
200	2,351545	2,267995			6,262012	3,770498
202	2,37206	2,289049			6,282527	3,791552
204	2,466206	2,322754			6,376673	3,825257
206	2,568433	2,37482			6,478900	3,877323

In order to find the solenoid misalignements in x and y directions, a GPT simulation has been performed, starting from the cathode $z = 0\ m$ up to AC1FLG $z = 1{,}181\ m$.

Using the centroid displacements obtained varying the current, the misalignements had been found by GPT solver, moving the solenoid in a range and trying to riproduce the displacement

GPT beam

Laser on cathode

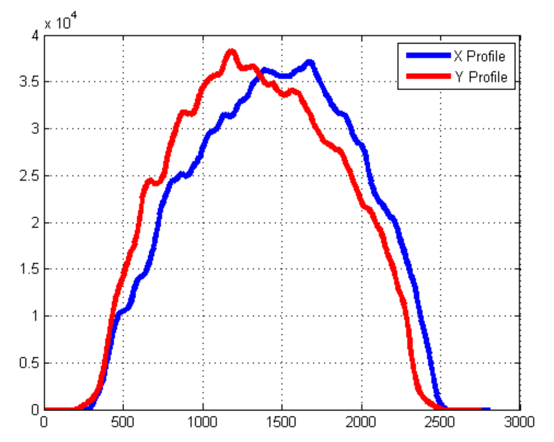


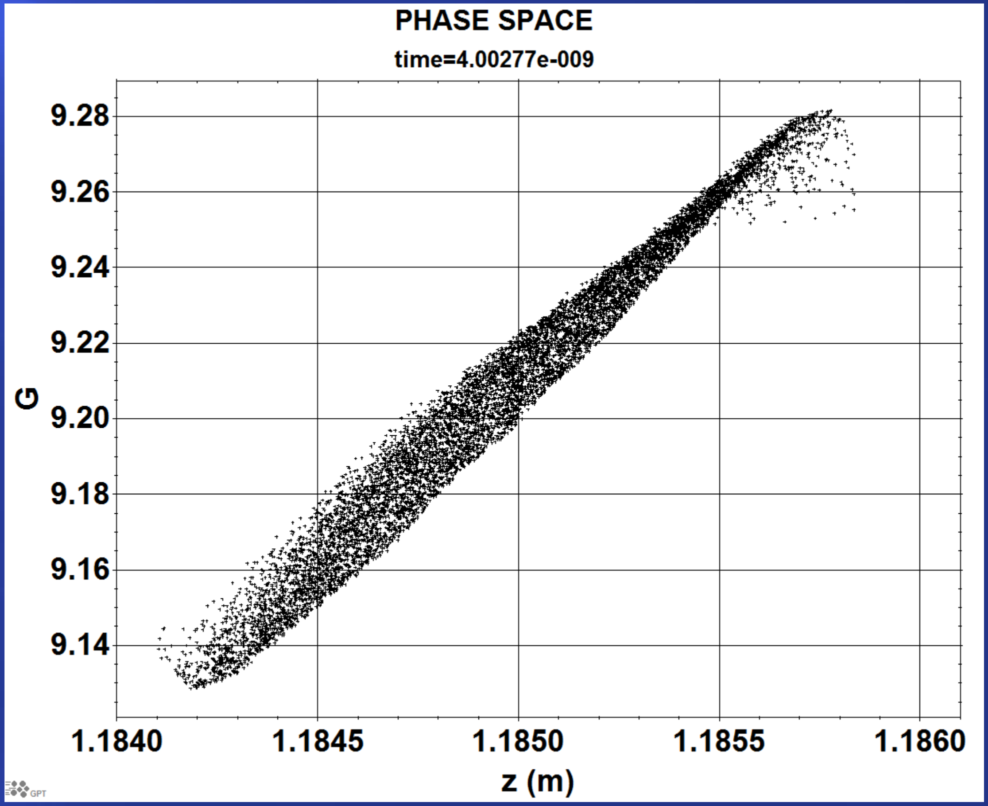
Lenght: $660fs$

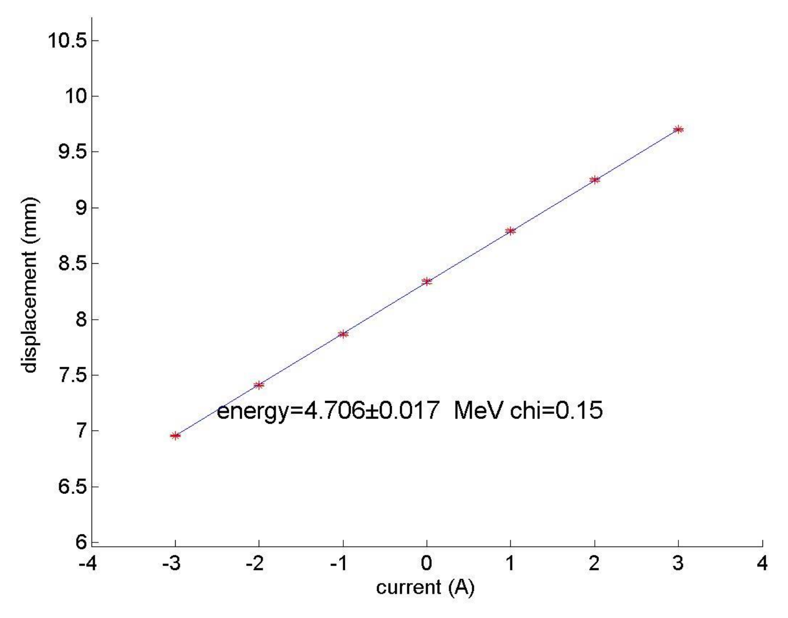
Spot: $\sigma_{x,rms} = 493\mu m$; $\sigma_{y,rms} = 481\mu m$

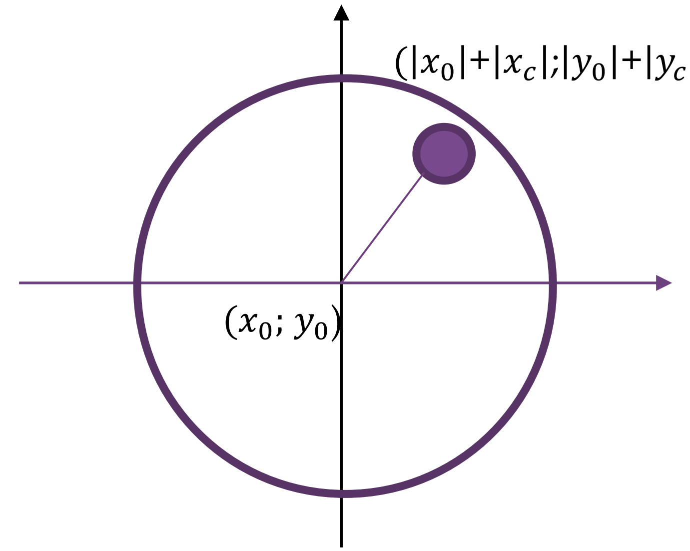
Thermal emittance: $0.7\mu m$

$Q = 100pC$









Solenoid $(x_0; y_0)$ was moved in x and y axis by GPT solver, in order to reproduce the bunch centroid $(|x_0|+|x_c|;|y_0|+|y_c|)$ measured at $I_{sol} = 186\ A$.

$ISOL\ (A)$	$|x_0|+|x_c|\ (mm)$	$|y_0|+|y_c|(mm)$	$\boldsymbol{Misx}(\boldsymbol{mm})$	$\boldsymbol{Misy}(\boldsymbol{mm})$	$Avgx(GPT)(mm)$	$Avgy(GPT)(mm)$	$deltax(mm)$	$deltay(mm)$
186	5,837105	3,507112	$\mathbf{0,927}$	$\mathbf{0,515}$	5,80251	3,49263	0,034595	0,014482

Solenoid Misalignment on x axis

Solenoid Misalignment on y axis

Aligning the solenoid to these values, we improve the centroid orbit shift to 99.4%

- Misalignments found with GPT for a solenoid current of 186A have been checked with other currents. Are also reported the differences with the experimental values.

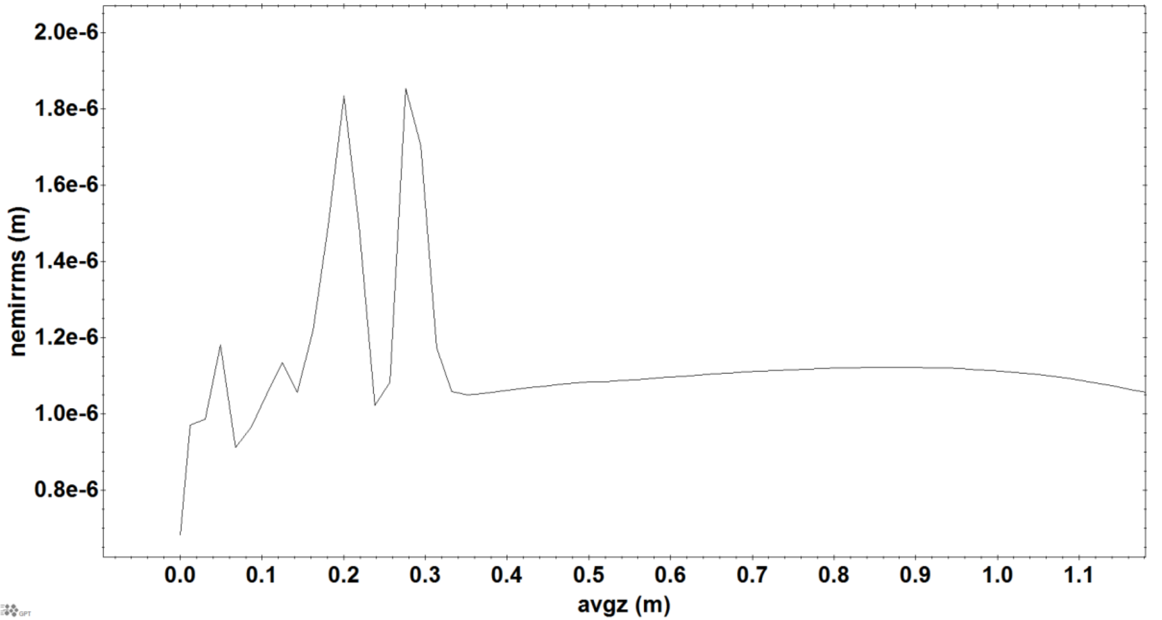
$ISOL\ (A)$	$\lvert x_0\rvert^{+}\lvert x_c\rvert\ (mm)$	$\lvert y_0\rvert^{+}\lvert y_c\rvert\ (mm)$	$\boldsymbol{Misx}\ (\mathbf{mm})$	$\boldsymbol{Misy}\ (\mathbf{mm})$	$Avgx(GPT)(mm)$	$Avgy(GPT)(mm)$	$\Delta_x\ (mm)$	$\Delta_y(mm)$
186	5,837105	3,507112	**0, 927**	**0, 515**	5,80251	3,49263	0,034595	0,014482
188	5,881365	3,538733			5,88227	3,52415	−0,0009	0,014583
190	5,935998	3,555572			5,95578	3,59244	−0,01978	−0,03687
192	5,987530	3,595534			6,06527	3,65916	−0,07774	−0,06363
194	6,047709	3,636716			6,14559	3,72954	−0,09788	−0,09282
198	6,141899	3,71365			6,31664	3,81466	−0,17474	−0,10101
200	6,262012	3,770498			6,3927	3,90247	−0,13069	−0,13197
202	6,282527	3,791552			6,44695	3,95908	−0,16442	−0,16753
204	6,376673	3,825257			6,50522	3,98656	−0,12855	−0,1613
206	6,478900	3,877323			6,62641	4,10475	−0,14751	−0,22743

- Has been tried with GPT a solenoid misalignement optimized at a current of 206 A. The results are very similar: $Misx\ = 0{,}902mm$ and $Misy\ (mm) = 0{,}517\ mm$, but Δ_x and Δ_y are worse.

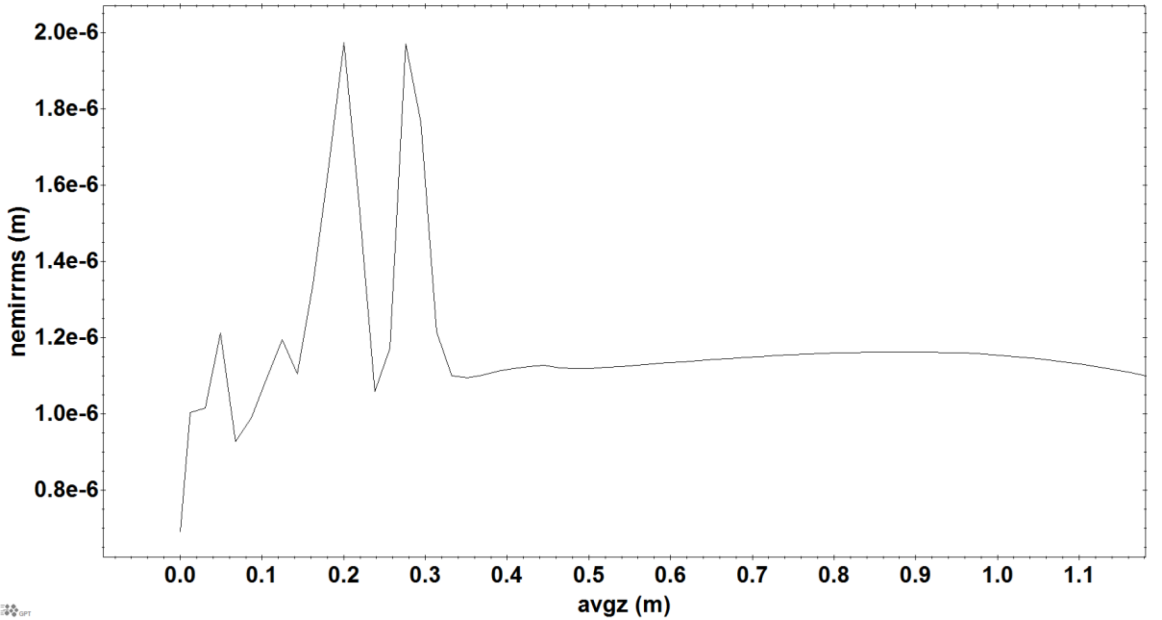
WITHOUT MISALIGNEMENTS

Emittance

- $I_{sol} = 157A$ waist at the entrance of S1 $z = 1.5m$



Without misalignement
emittance @ AC1FLG is:
$\varepsilon_{n,rms} = 1.06e^{-6}$



With misalignement
emittance @ AC1FLG is:
$\varepsilon_{n,rms} = 1.1e^{-6}$

Emittance degradation of 3.77%