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, for example plasma acceleration, is necessary a proper high brightness beam with low emittance, low energy spread and a proper focusing and longitudinal compression scheme.

- In order to do that, I did:

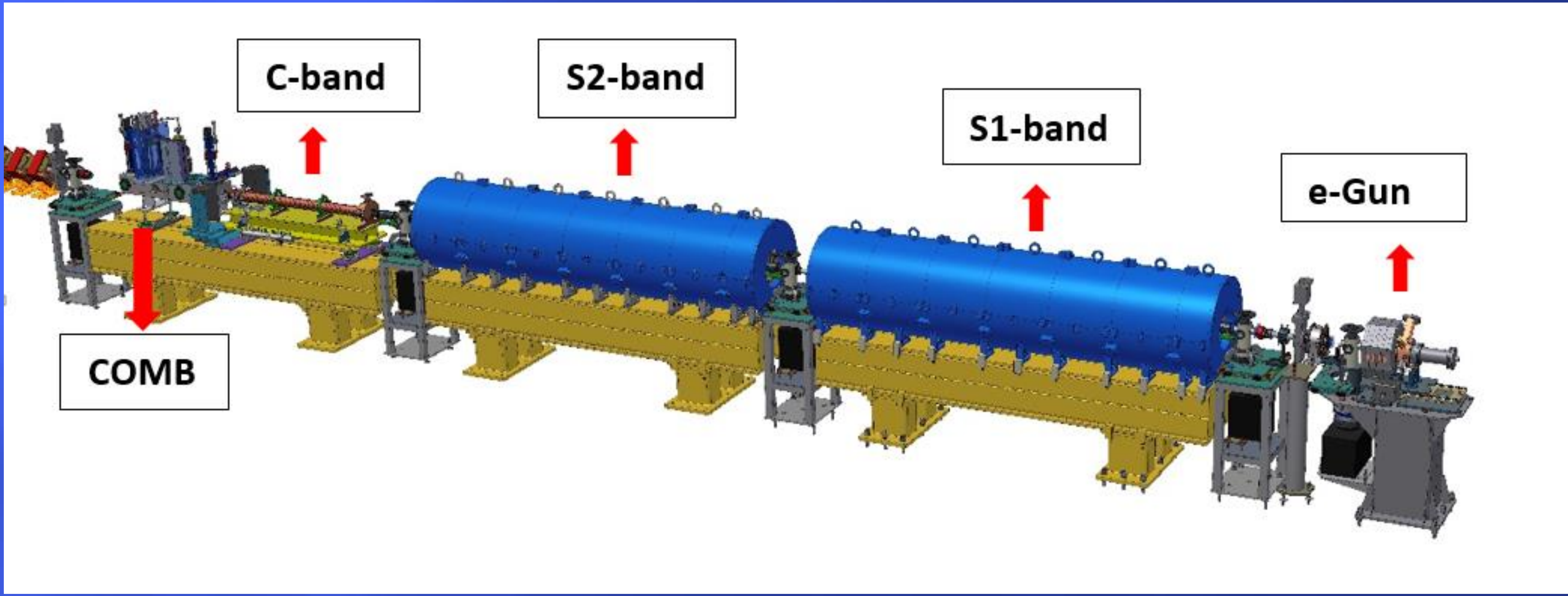
1) Study, simulations and project of new focusing elements

2) Optimization of the existing focusing elements on the SPARC beam line

3) Study and simulations of a new ultra cold photoinjector with very low emittance and energy spread.

The SPARC_LAB facility

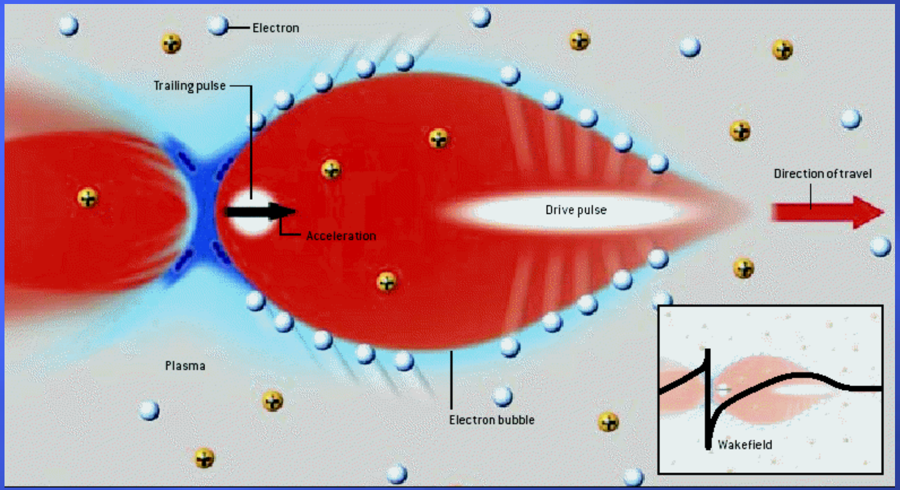
S2E simulation with General Particle Tracer (GPT)



$$\text{Linac:}\begin{cases} \boldsymbol{e^{-}Gun}: \; 5{,}6\,MeV, \quad L = 10\,cm \; + \; Solenoid\ 0.3\,T \\ \boldsymbol{S_1, S_2\ sections}: \; (f \sim 3GHz), \; L \sim 3\,m, \; E_{acc} \approx 20\,\frac{MV}{m} \; + \; Solenoids\ 0.1\,T \\ \boldsymbol{C\ section}: (f \sim 6GHz), \; L \sim 1.4\,m, \; E_{acc} \approx 35\,\frac{MV}{m} \end{cases}$$

Beam Quality Parameters for Plasma Acceleration

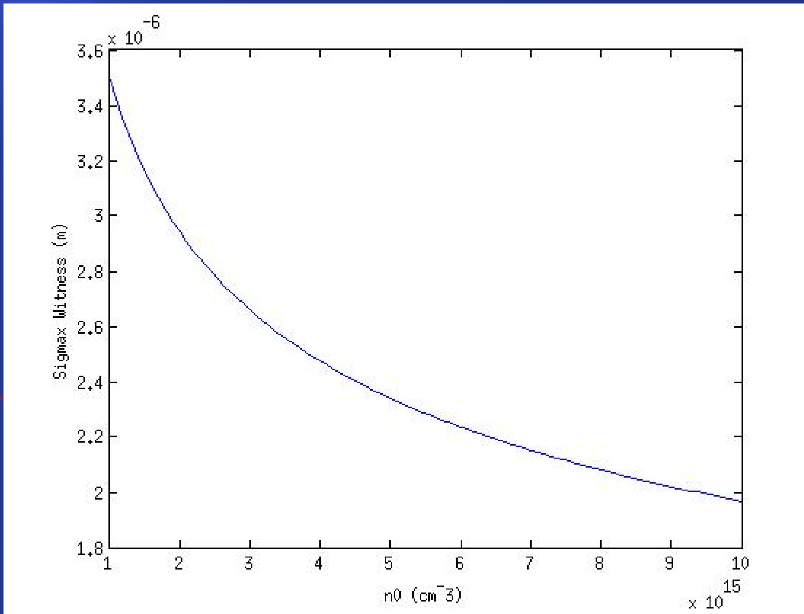
- High gradient acceleration in a plasma has been already demonstrated but with poor beam quality generation. The challenge is now to improve the quality of the accelerated beam. To this end one of the main concern is to satisfy the beam/plasma matching conditions.



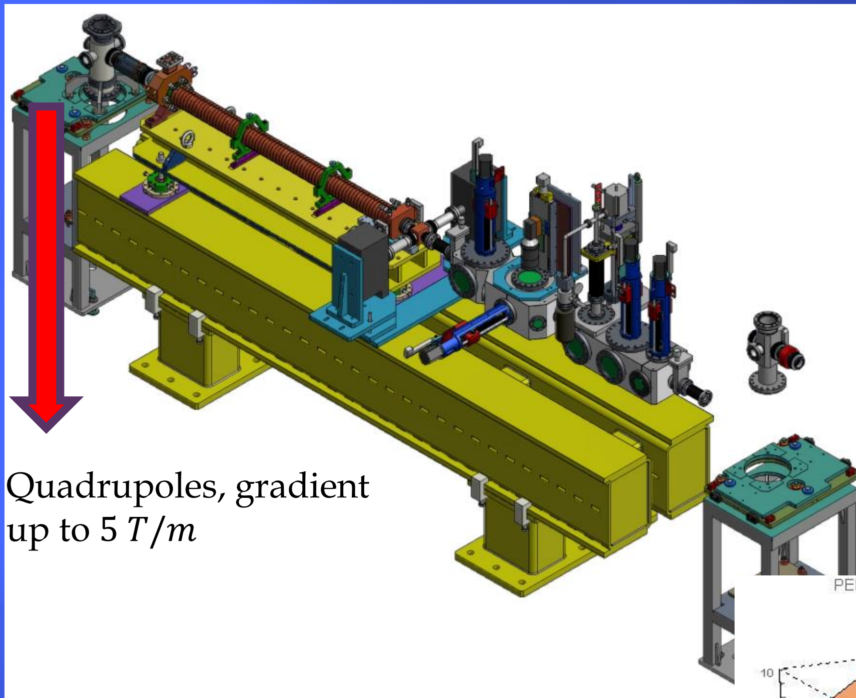
Driver pulse creates a perturbation that travel in the plasma with $v \approx c$.

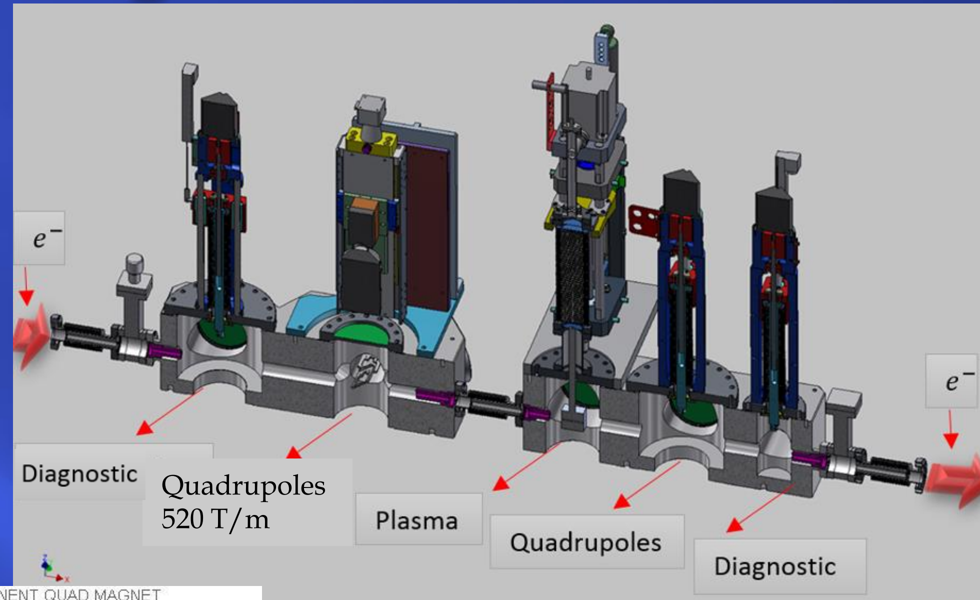
$\lambda_p = 2\pi c\sqrt{\frac{\varepsilon_0 m}{n_0 e^2}}$ where n_0 is the plasma density

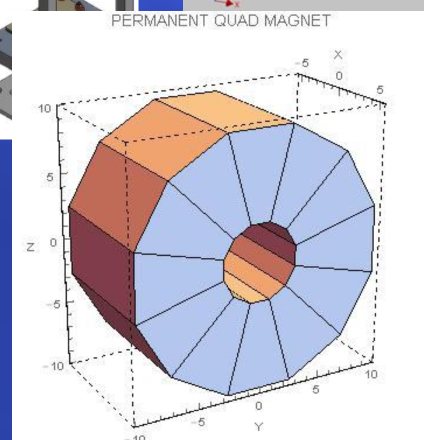
- Longitudinal matching conditions: $\sigma_z \ll \frac{\lambda_p}{2}$
- Energy spread: $\frac{\delta\gamma}{\gamma} = \frac{\sigma_z}{\lambda_p}$ Ultrashort bunches
- Optimal transverse conditions: $\sigma_x = \sqrt[4]{\frac{3}{\gamma}}\sqrt{\frac{\varepsilon_n}{k_p}}$
- Low emittance produces: $\beta_w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



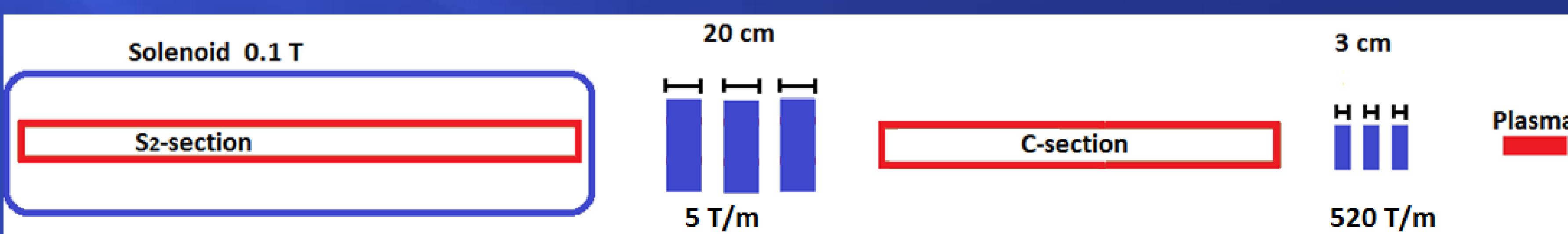
New focusing scheme





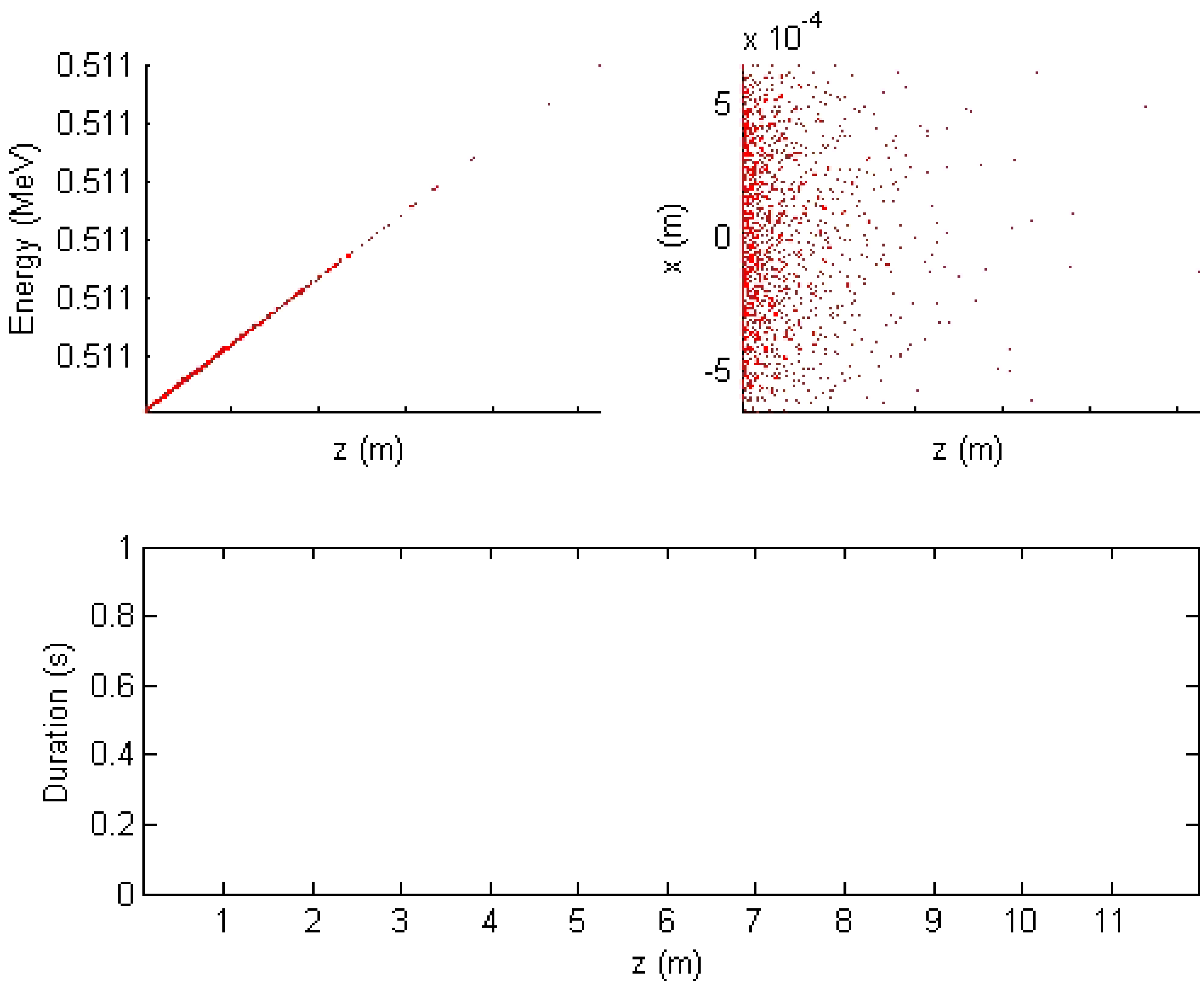


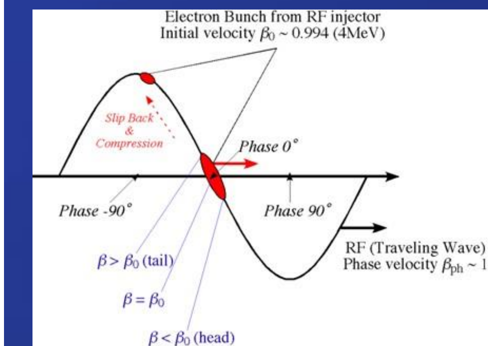
Focusing strenght:
$$\begin{cases} F_{x,sol} = \mp\left(\dfrac{qB_0}{2\gamma m_0 c}\right)^2 x \\ F_{x,quad} = \mp\dfrac{qB_0}{\gamma m_0 c} x \end{cases}$$

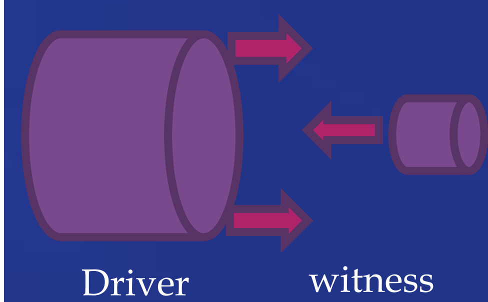


Configuration 1 Driver + 1 Witness beam

- 1 **Driver** (200pC) + 1 **witness** (20pC) yet simulated
- **At the injection $\boldsymbol{\sigma_z = 54\ \mu m}$ (= 182 fs) $\boldsymbol{\sigma_z = 10.5\ \mu m\ (= 35 fs)}$**



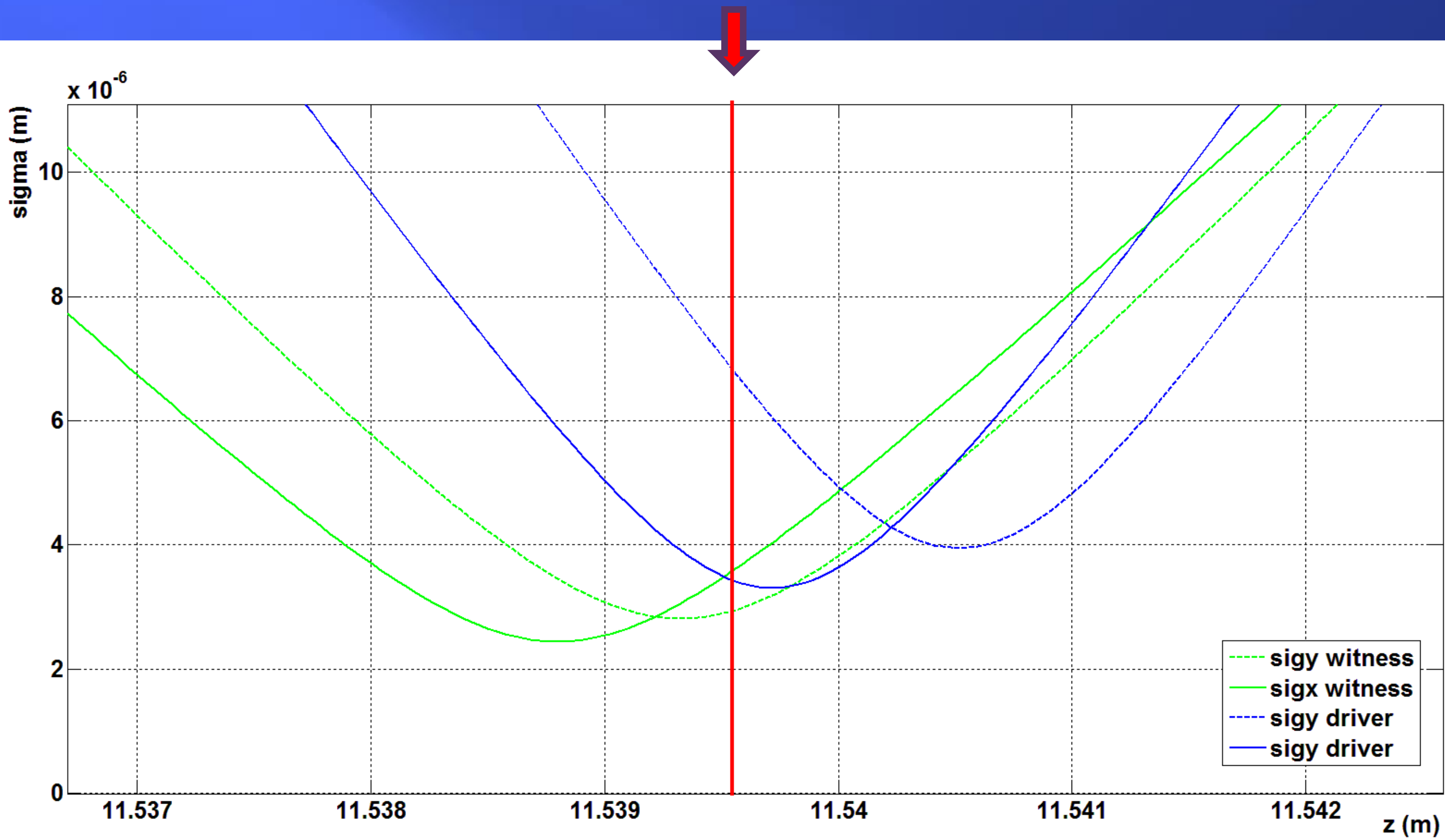




Thanks to R.Pompili

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

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

Donut beam configuration

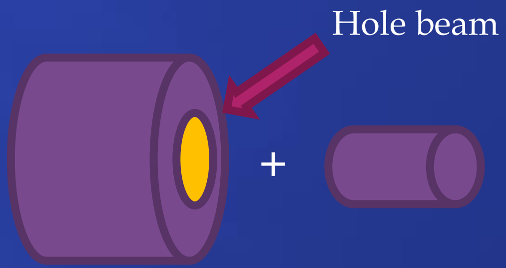
- Hollow Driver can preserve the witness emittance during the velocity bunching

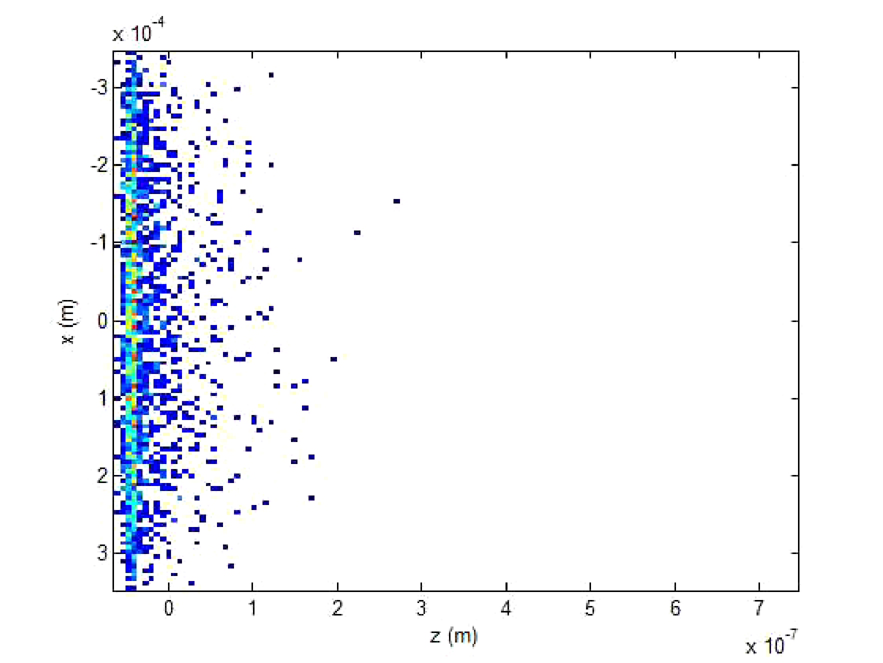
Advantages

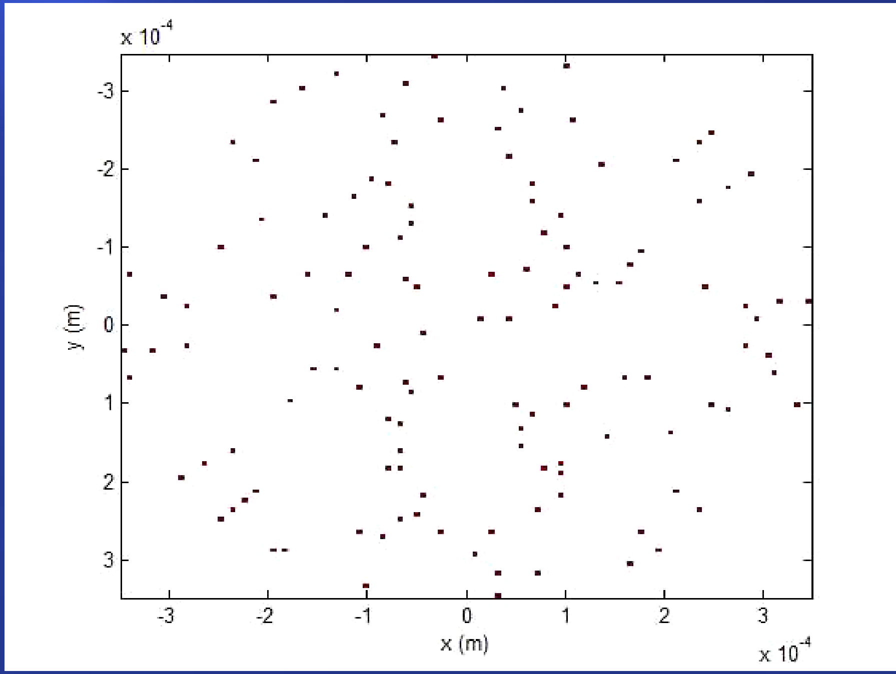
- Smaller witness emittance $0.6\ \mu m$
- Shorter witness: $7\mu m\ (23fs)$
- Hollow driver can be stopped with a proper holed target after plasma acceleration

Disadvantages

- Large driver emittance $20\mu m$







Insertion of PC skew quadrupoles in the gun solenoid

- Due to the gun solenoid misalignements, the 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 the plasma in both plane simultaneusly.

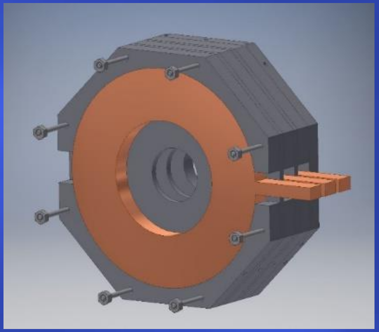
- In order to avoid ellipsoidal beam, I am now working on the insertion of Printed Circuit (PC) skew quads around the SPARC gun solenoid.

- I found the proper gradients, dimensions and positions for the present SPARC gun solenoid.

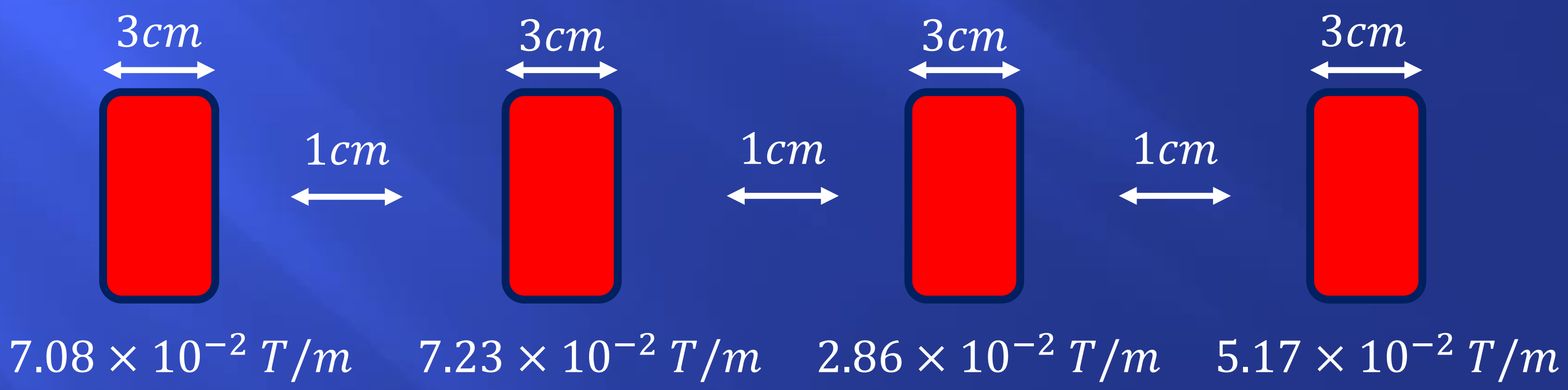
- I am searching for the proper gradients, dimensions and positions for a future upgrade of the SPARC photoinjector.

GRADIENTS OPTIMIZATION

- Starting with an ellipsoidal (~40%) laser on cathode, the diversity of σ_x and σ_y decreases at ~4% on AC1FLG, using four $3cm$ skew quadrupoles inside the Gun_Solenoid.

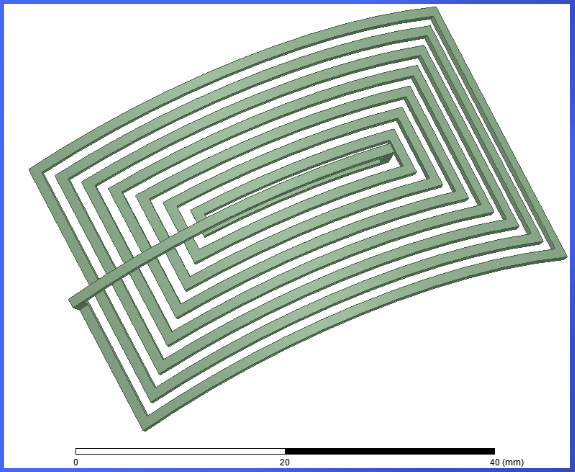


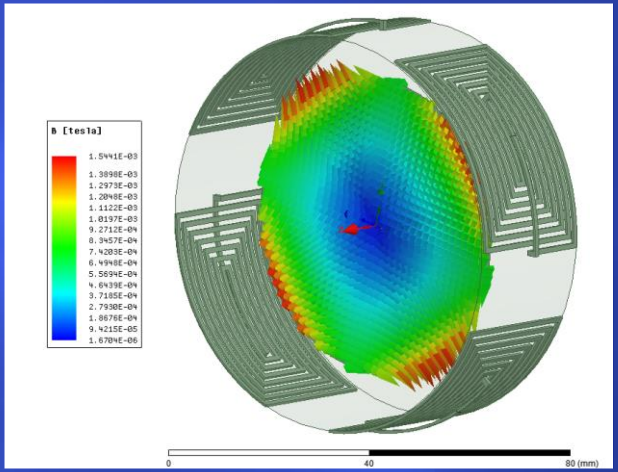
- Found Gradients:

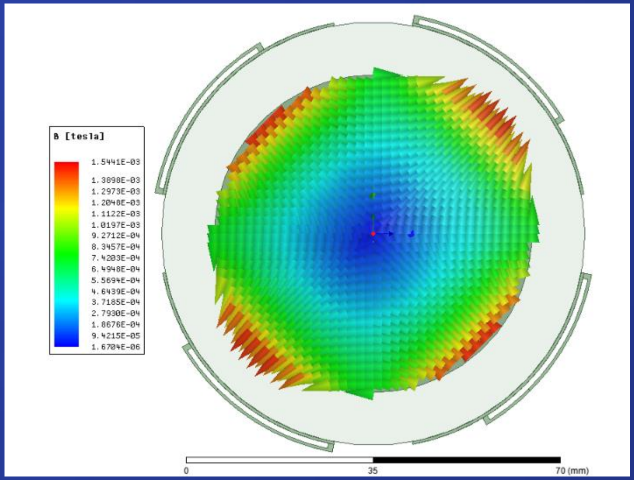


- In literature: $4.14 \times 10^{-2}\ T \cdot A/m$

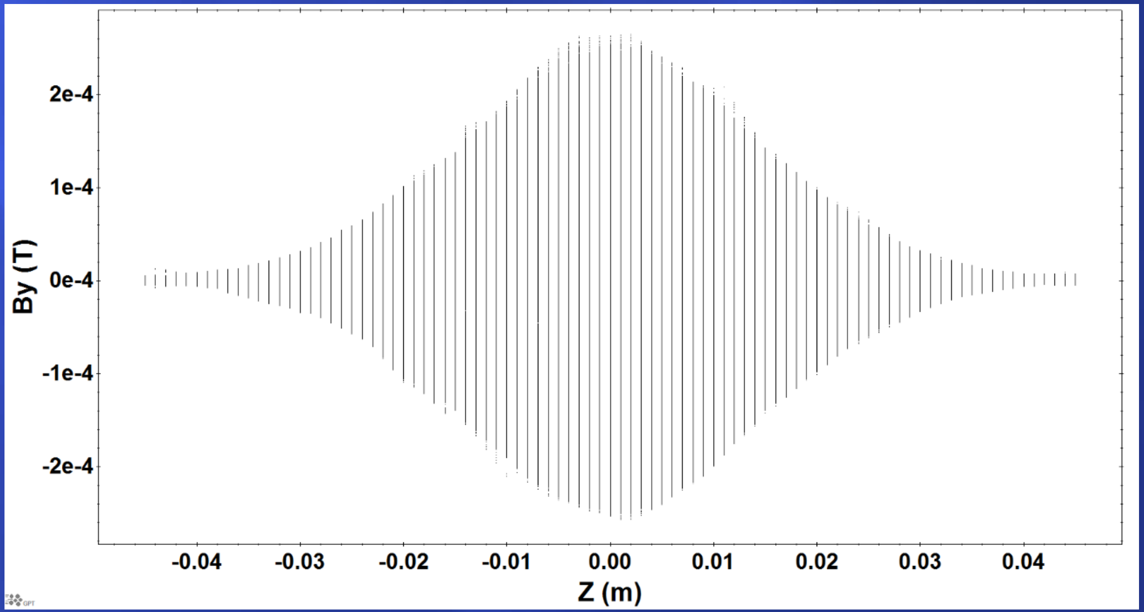
PRINTED CIRCUIT QUADRUPOLES







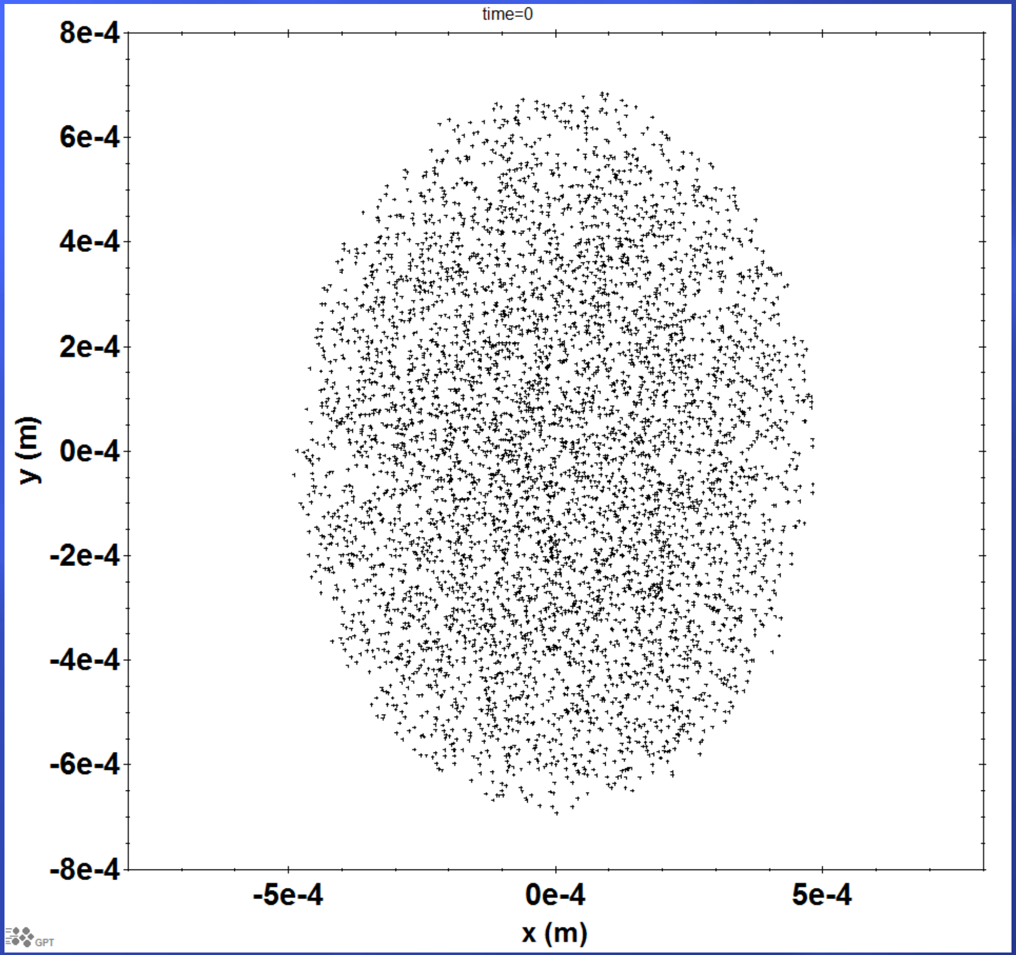
Section: $1mm^2$ Gradient: 2.1×10^{-2} @ 10 A T~250°C



Thanks to G.Castorina

GPT ELLIPSOIDAL BEAM

- STARTING beam: $Q = 100pC \quad \varepsilon_{rms} = 0.7\mu m$

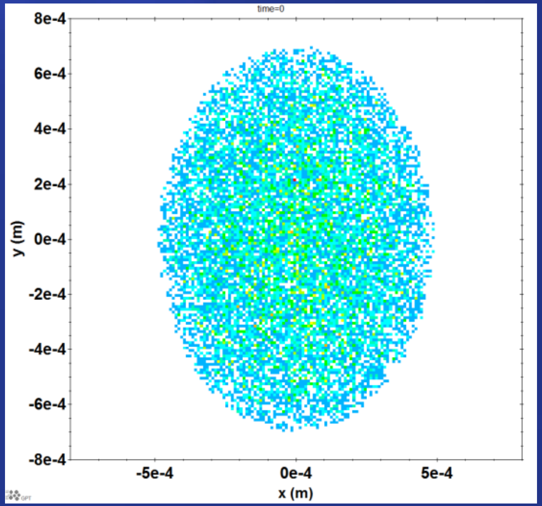


LASER PARAMETERS:

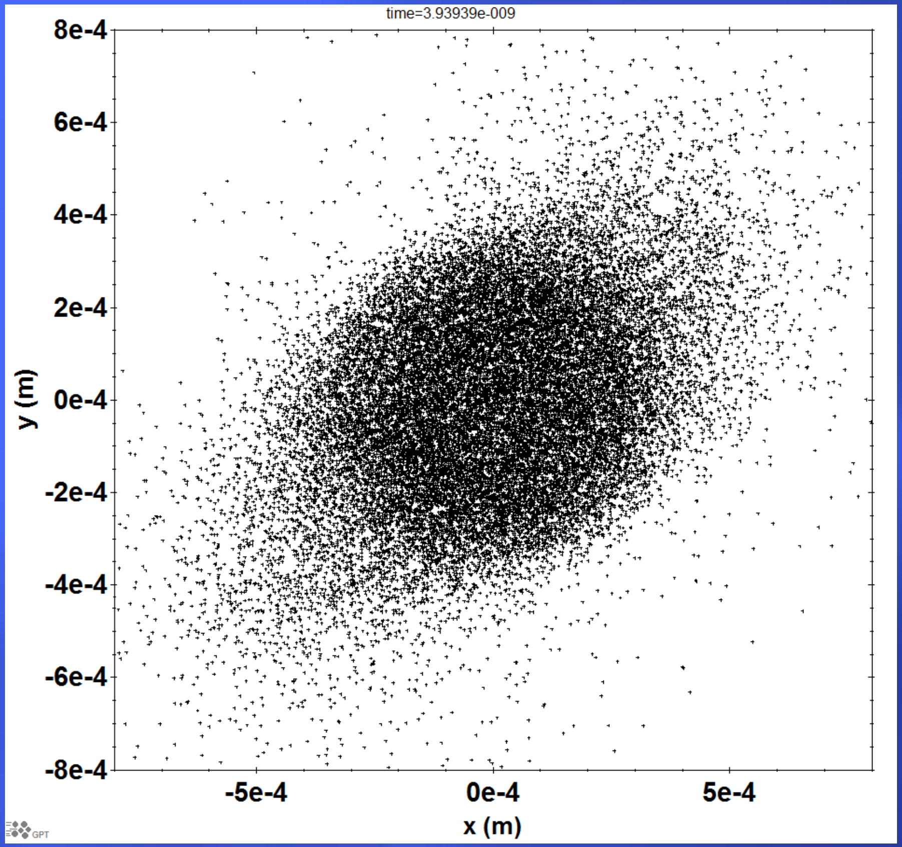
$radius_x = 490\mu m$

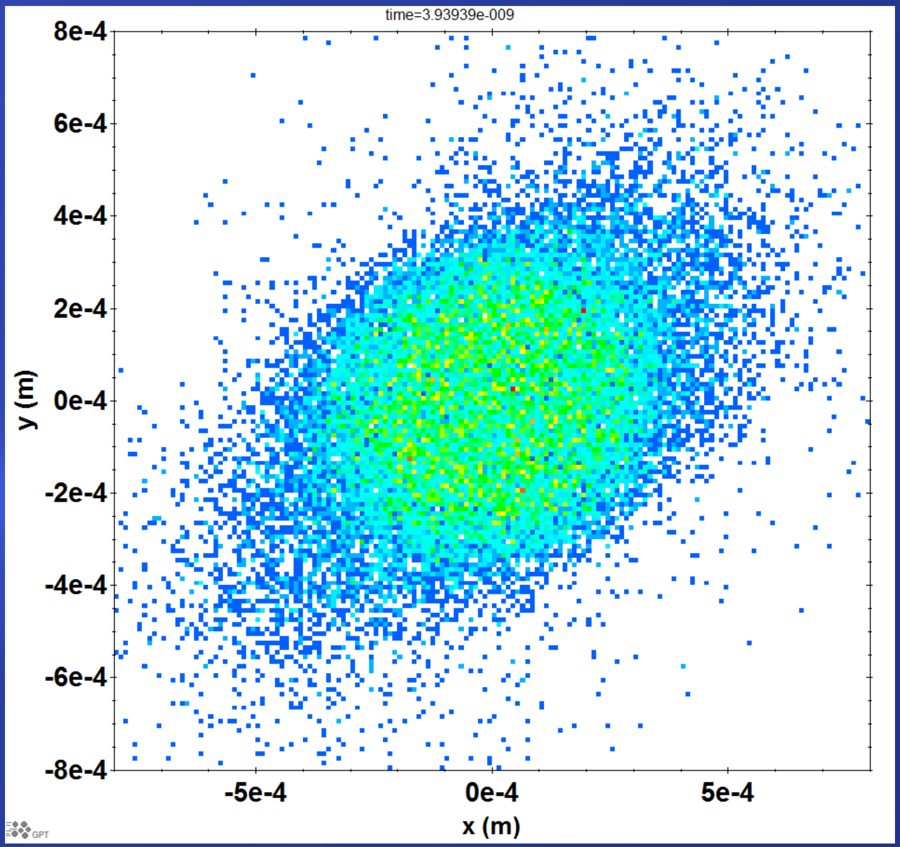
$radius_y = 700\mu m \ (\sim 40\%)$

$t_{length} = 600fs$



BEAM @ AC1FLG (Z= 0.181m)





GPT QUADS

$\sigma_x = 2.3 \times 10^{-4} m$

$\sigma_y = 2.2 \times 10^{-4} m$ $\sim 4\%$

FIELD MAPS

$\sigma_x = 2.2 \times 10^{-4} m$

$\sigma_y = 2.1 \times 10^{-4} m$ $\sim 4\%$

$\varepsilon_{x,rms}(start) = 0.75(0.15)\mu m$

$\varepsilon_{y,rms}(start) = 0.73(0.2)\mu m$ $\sim 3\%$ (33%)

Open/Solved Problems

- Cooling. PC QUADS (section $1mm^2$) easily reach $\mathrm{T} > 200°C$. Power to be dissipated is around 40/50 Watt for one PC quad.

- The current gun does not have space for a water cooling.

- A new SPARC photoinjector is under project, with the insertion of this PC QUADS.

Gun Solenoid Alignement at SPARC_LAB

- By the experiment at SPARC increasing the current I_{sol} of the gun solenoid, 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 magnetic field of the solenoid B_{sol} and writing the equation of motion for a charged particle moving off axis, it 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 literature for gun solenoids 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

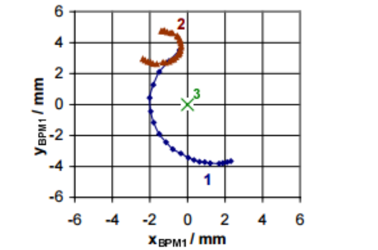
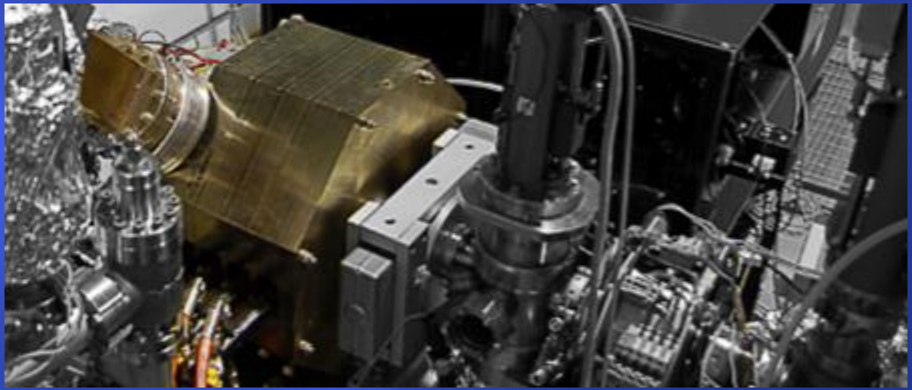


Figure 2: Measured beam position (X_{BPM1},Y_{BPM1}) dependence on: 1 – primary solenoid current ($0A<I_{sol1}<400A$, $I_{sol2}=0A$); 2 – secondary solenoid current ($-290A<I_{sol2}<290A$, $I_{sol1}=0A$). 3 – BPM1 center.

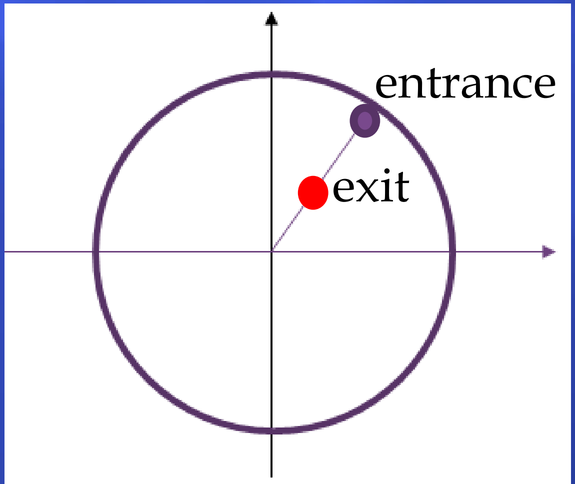
based on the study of the helix varying the solenoid current

Gun_Solenoid @ Sparc_Lab

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



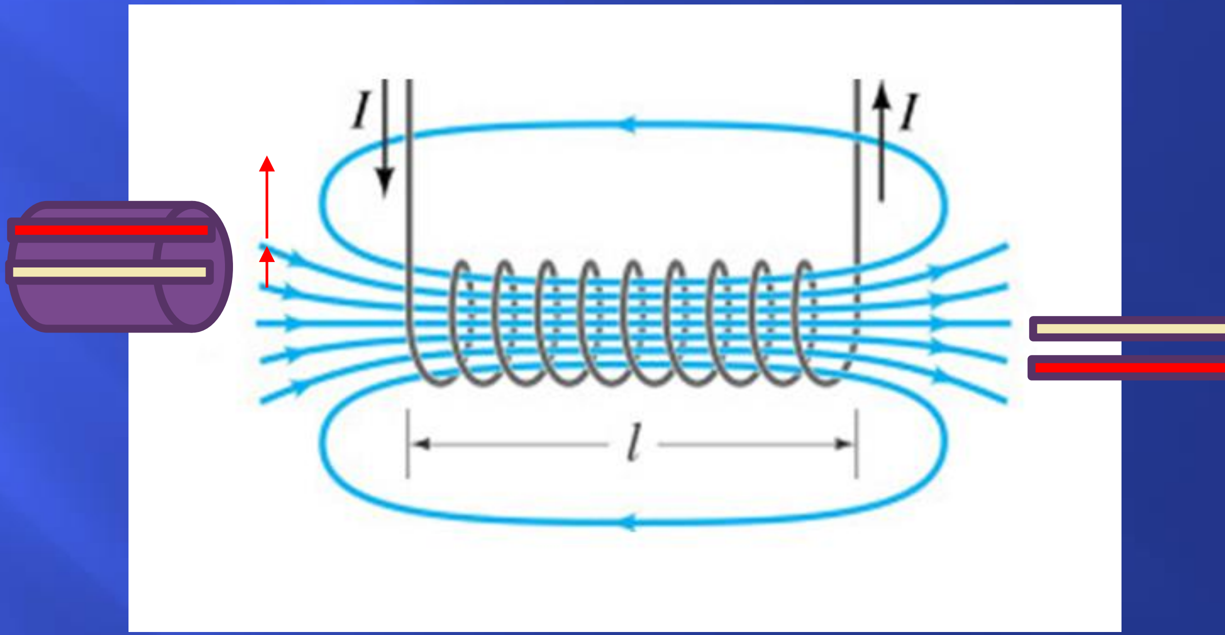
- One of the difference with the Desy Solenoid is that the first and the last 2 coils are powered with an opposite current. In this way the particles in the middle of the solenoid begin to reduce their rotation and do not rotate at the exit of the solenoid. At the end centroids do not perform an helix,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



In this way with a misalignement increasing 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 moves on line.

Why the kick? A qualitative approach

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

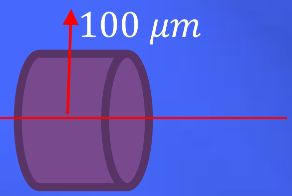


- The outer slices perceive an higher transverse field and focus more than the internal one. At the end of the solenoid the result is a kick of the centroid, and a change of the bunch shape.

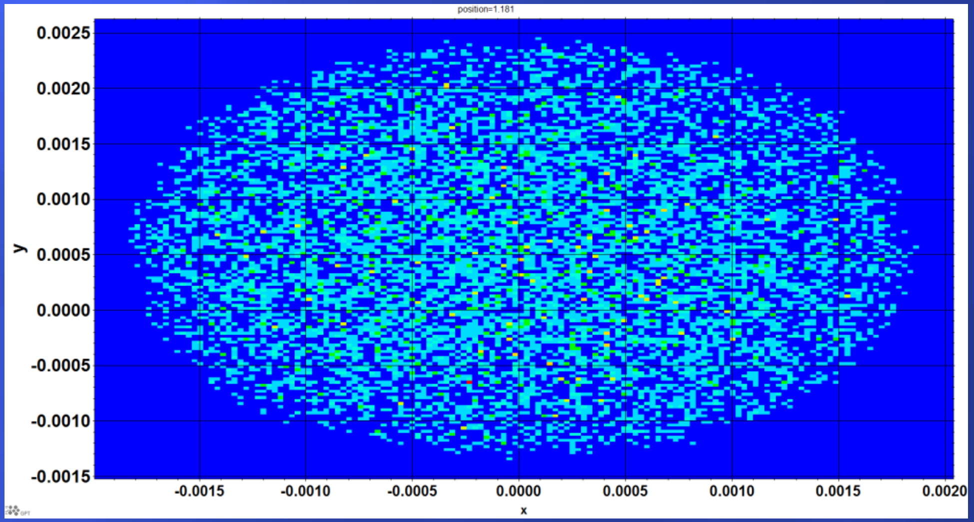
Beam-Based Alignement with GPT

- 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 a run: $\varepsilon_{rms} = 0.9\ \mu m\ ;\ \sigma_z = 320\ \mu m\ ;\ \sigma_x = 500\ \mu m\ \ (UTL)$

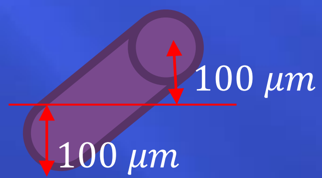


$I = 178\ A$

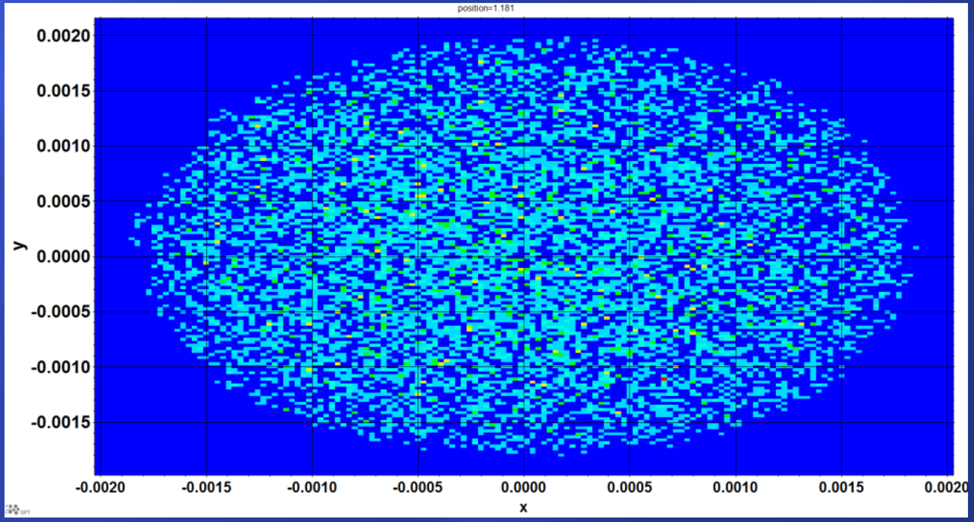


$x_c \approx cost$

$y_c = +600\ \mu m$



$I = 178\ A$

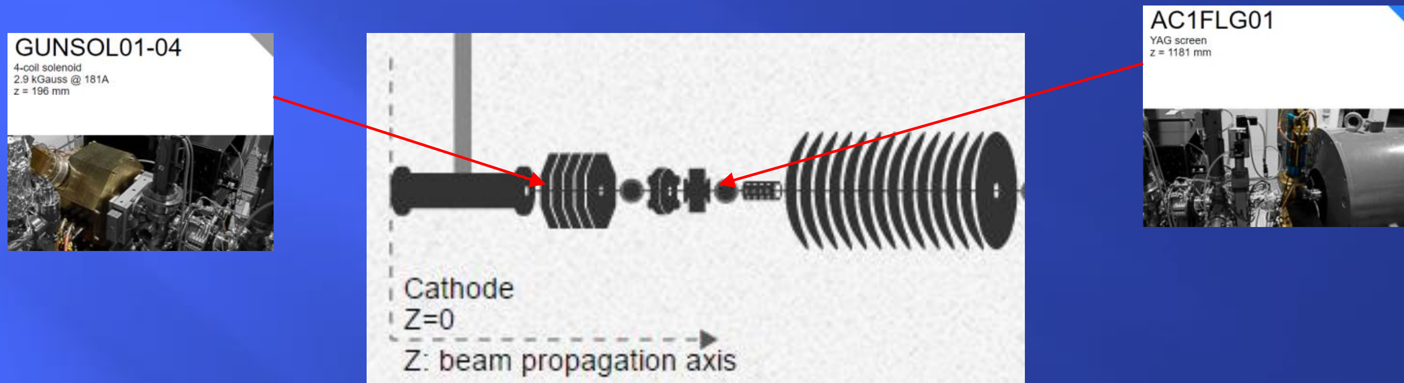


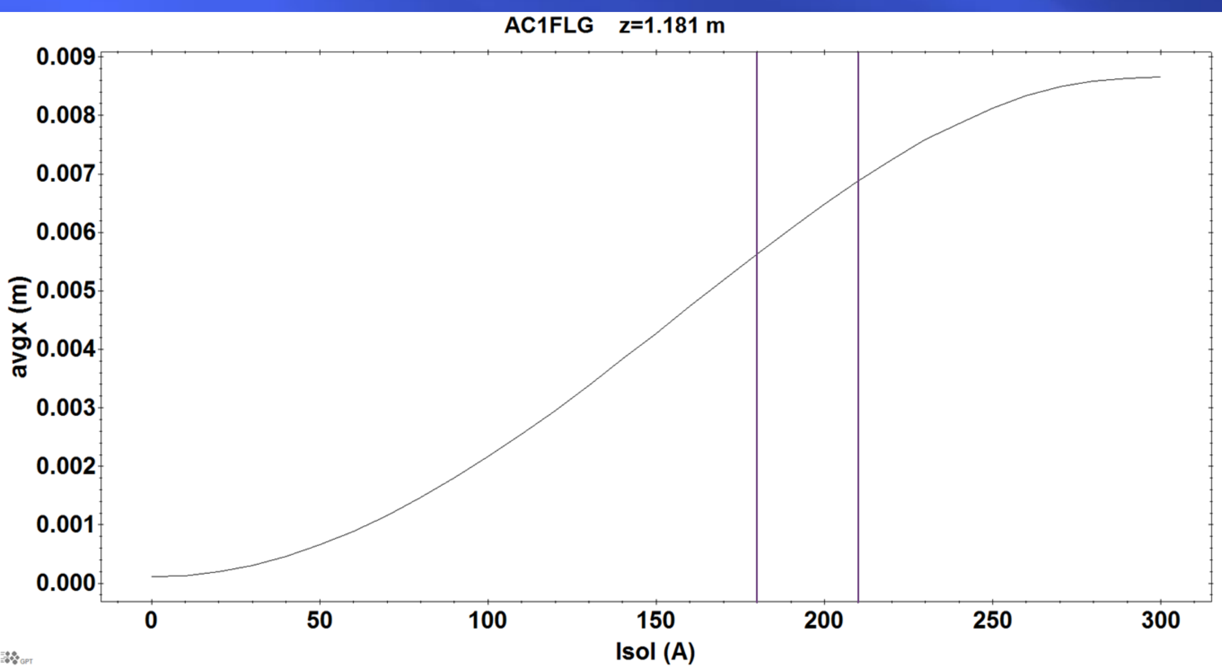
$x_c \approx cost$

$y_c = +100\ \mu m$

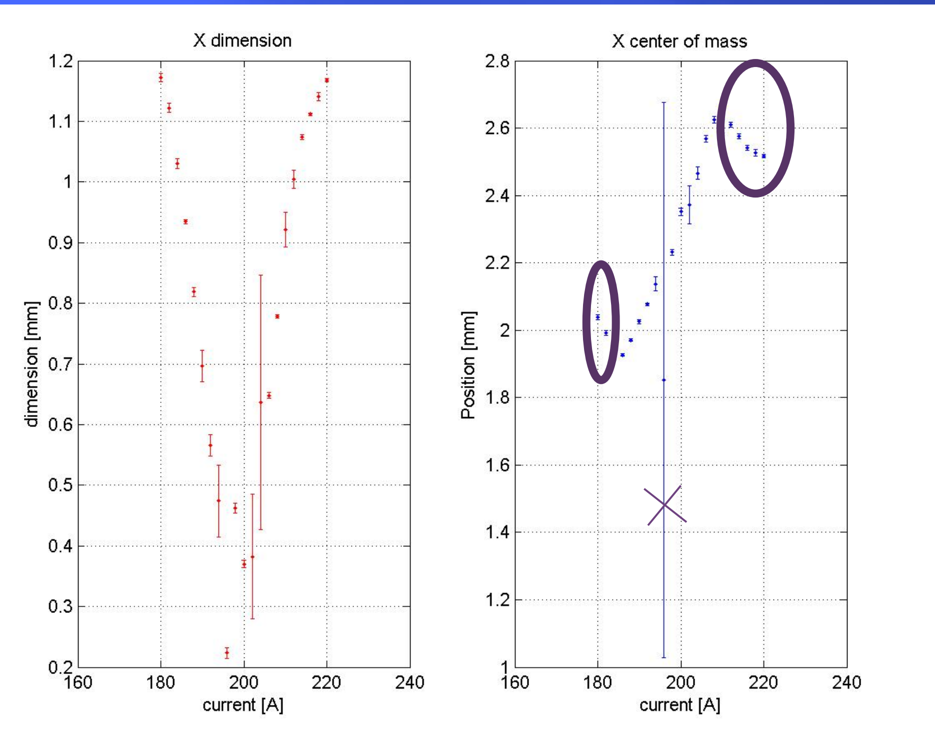
Beam-Based Alignement @ SPARC_LAB

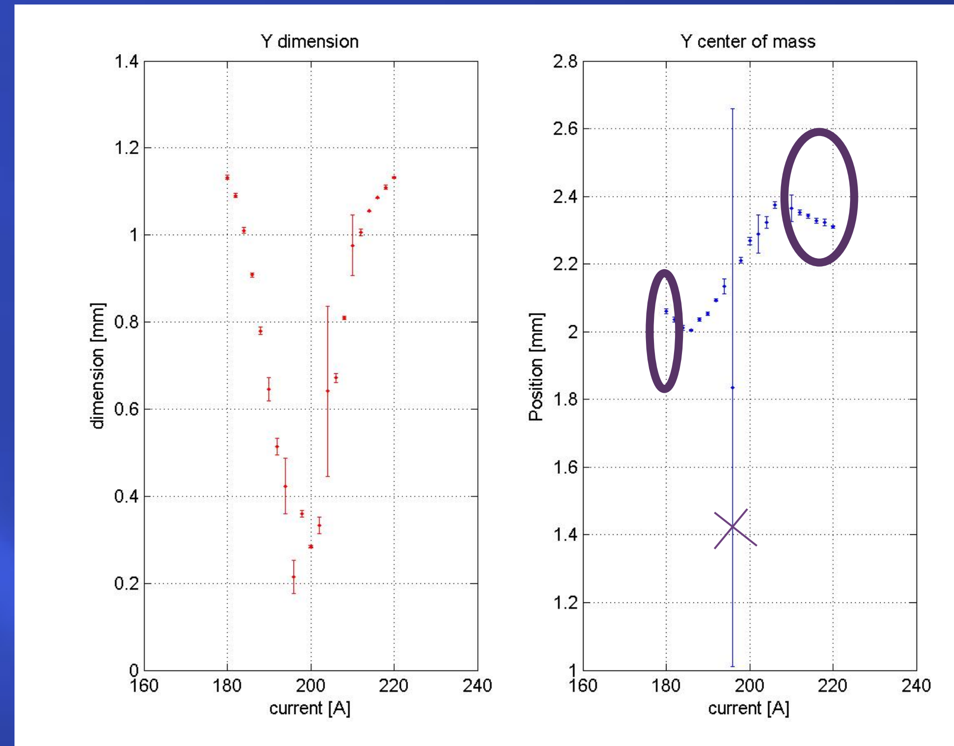
- Solenoid Scan:





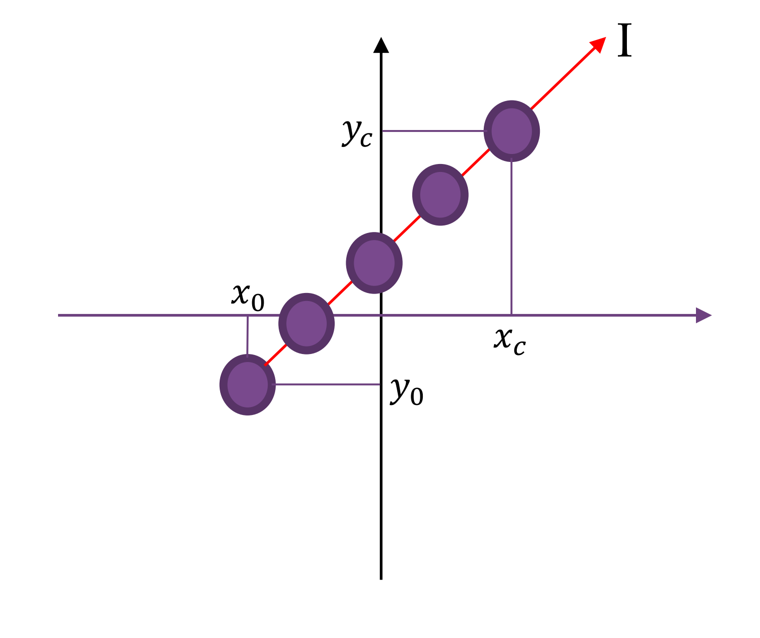
The linear increase of the coordinate of the centroid $(x_c; y_c)$ was checked with GPT in the region in which we expect a linear growth of the field, varying the current from $0A$ to $300A$.





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 increase 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 values $(|x_0|+|x_c|;|y_0|+|y_c|)$ that are the real displacements obtained by increasing the current.

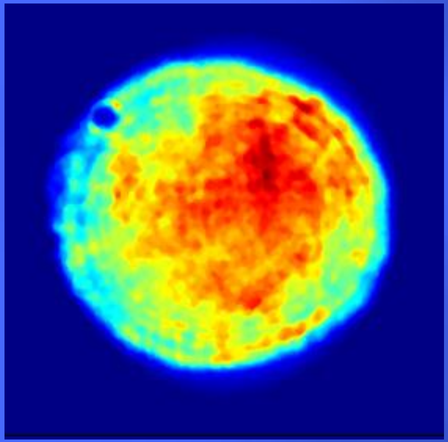
$ISOL\ (A)$	$x_c(mm)$	$y_c(mm)$	$x_0(mm)$	$y_0(mm)$	$\|x_0\|+\|x_c\|$	$\|y_0\|+\|y_c\|$
			−3,91047	−1,5025		
186	1,926638	2,004609			5,837105	3,507112
188	1,970898	2,03623			5,881365	3,538733
190	2,025531	2,053069			5,935998	3,555572
192	2,077063	2,093031			5,987530	3,595534
194	2,137242	2,134213			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 misalignements of the solenoid 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 displacements of the centroid obtained varying the current, the misalignements were found by GPT solver, moving the solenoid in a range and trying to riproduce the displacement

GPT beam

Laser on the cathode

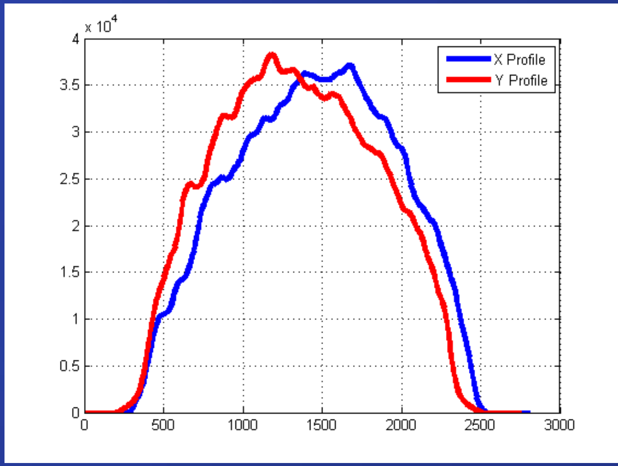


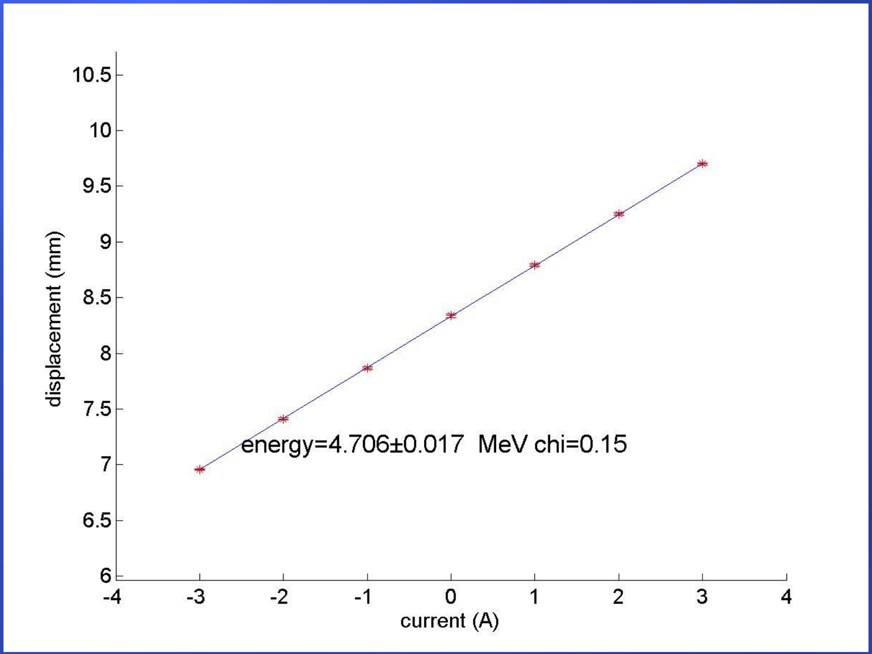
Lenght: $660fs$

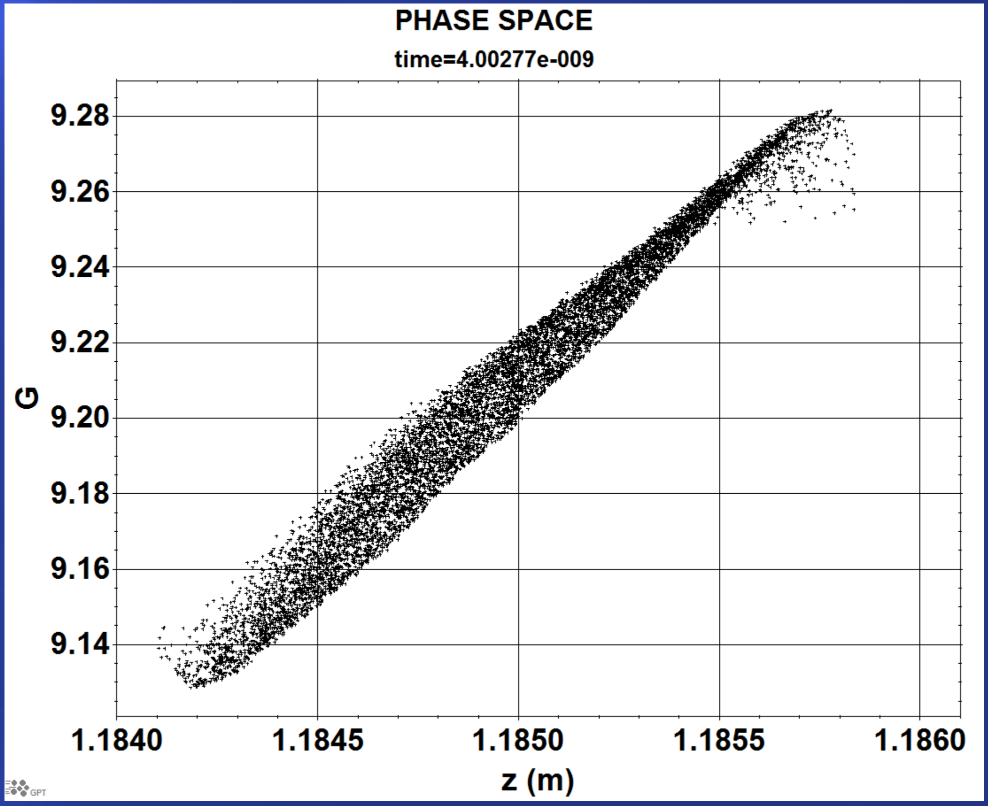
Spot: $\sigma_{x,rms} = 493\mu m$; $\sigma_{y,rms} = 481\mu m$

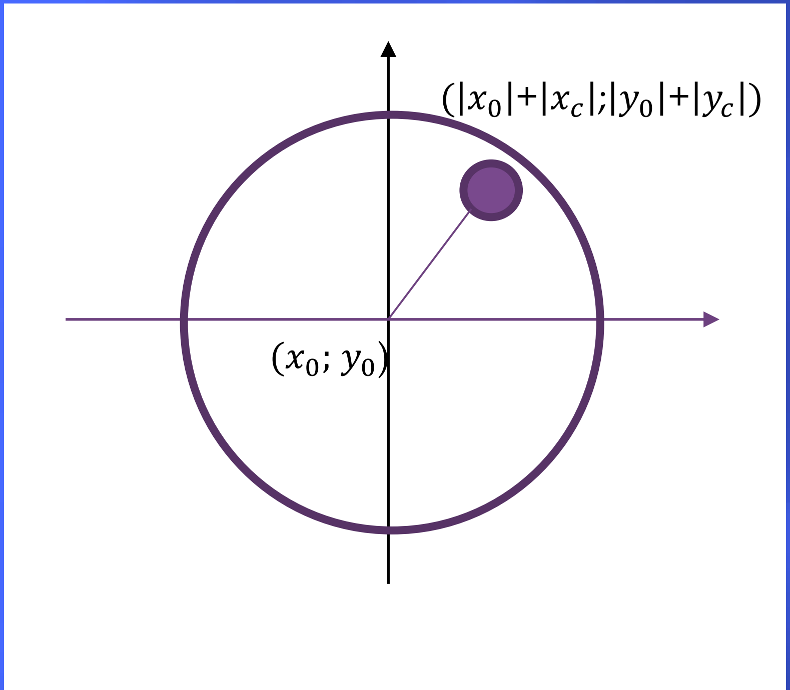
Thermal emittance: $0.7\mu m$

$Q = 100pC$









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 Misalignement on x axis

Solenoid Misalignement on y axis

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

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

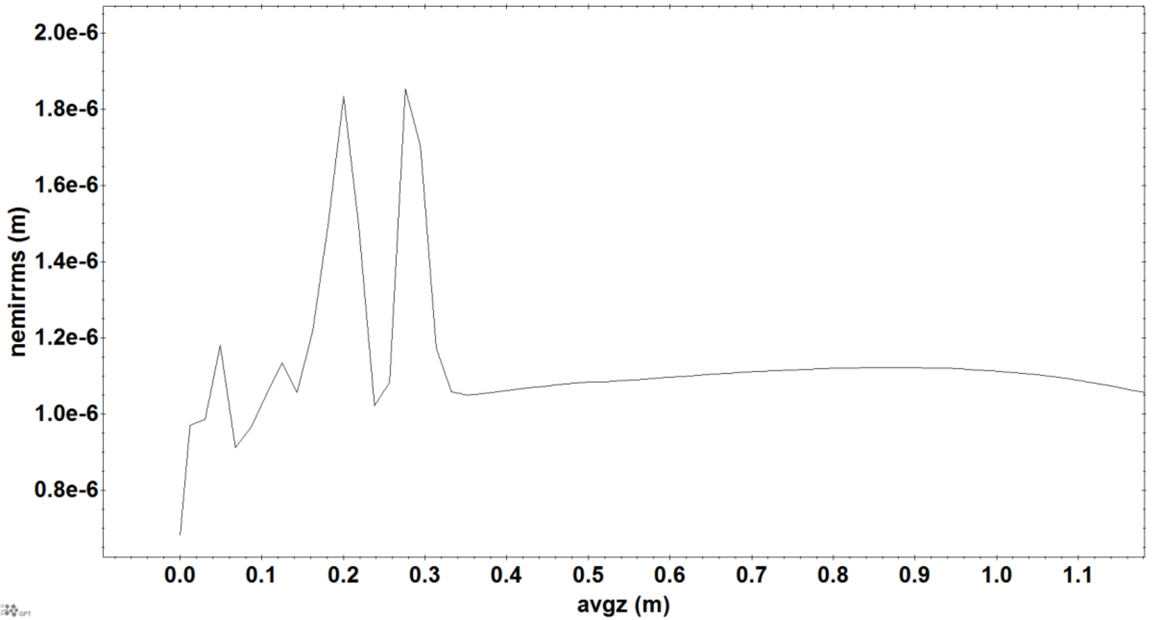
$ISOL\ (A)$	$\|x_0\|+\|x_c\|\ (mm)$	$\|y_0\|+\|y_c\|\ (mm)$	$\boldsymbol{Misx}\ (\boldsymbol{mm})$	$\boldsymbol{Misy}\ (\boldsymbol{mm})$	$Avgx(GPT)(mm)$	$Avgy(GPT)(mm)$	$\Delta_x\ (mm)$	$\Delta_y (mm)$
186	5,837105	3,507112	$\mathbf{0,927}$	$\mathbf{0,515}$	5,80251	3,49263	0,034595	0,014482
188	5,881365	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 misalignement of the solenoid, 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.

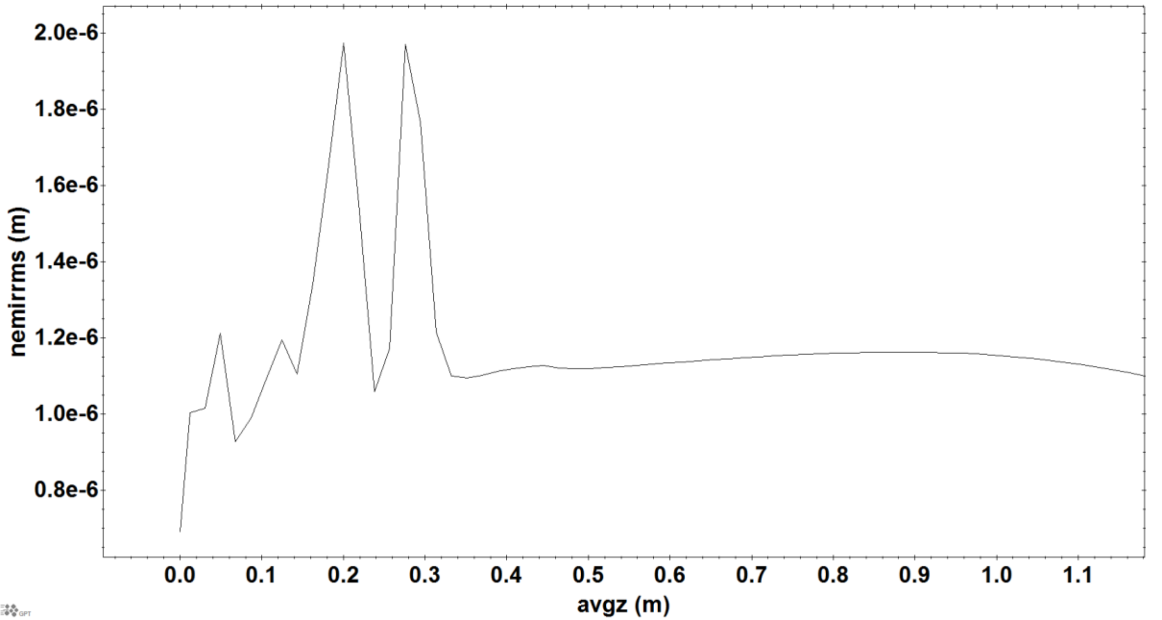
WITHOUT MISALIGNEMENTS

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%

Next generation of cryogenics rf photo-injector

- In order to realize future experiment on: Plasma Acceleration, FEL and QFEL, I am testing the possibility to upgrade the RF photo-injector with an ultra cold ($T = 27 - 40K$) one. One of the main advantages of this ultra cold gun is the possibility to create a beam with very low emittance. Thanks to the low temperature it is possible to enhanche the accelerating field up to 250 MV/m, creating rapidly a relativistic beam.

- I am optimizing a working point for a future QFEL experiment, with very low charge Q=0.1pC and low emittance.

- I added in GPT a new injector after the ultra cold photo-injector made of 2 accelerating structure S-band embedded in solenoids: ($f \sim 3GHz$), $L \sim 3\ m$, $E_{acc} \approx 20 \frac{MV}{m}$ + Solenoids of $0.3\ T$.

Cryogenics gun for QFEL

Table I:			
		THEORETICAL REQUEST	GPT SIMULATION
E-beam energy	γ	51.98	**59**
Charge in an electron bunch	$Q(pC)$	0.1 (Changeable)	**0.1**
Normalized emittance	$\varepsilon_n(\mu m)$	0.01	**0.01**
E-beam rms radius	$\sigma(\mu m)$	0.63	10
E-beam current (peak current)	$I(A)$	10	4
E-beam rms bunch length	$L_b(\mu m)$	3.0 (Changeable)	**3.1**
E-spread	$\Delta\gamma/\gamma$	$\sim 10^{-5}$	$\sim 10^{-2}$