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Compact

X-band RF electron gun injector design

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Index

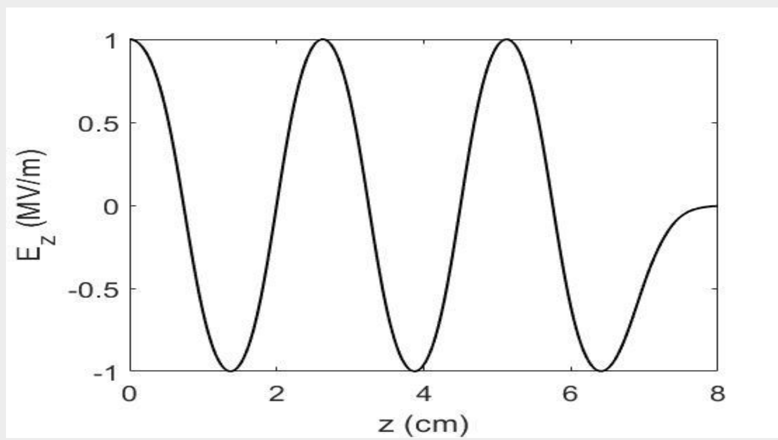
- RF design
- RF breakdown risk
- RF pulse heating
- Multipactor analysis in the coaxial coupler
- RF power system
- Beam dynamics

RF design

Main characteristics of the X-band RF photoinjector:

- It consists of a 5.6 cell structure operating in Standing Wave (SW) with the π-mode
- Fed by a coaxial coupler (preserves the rotational symmetry of the gun)
- RF design made with SUPERFISH (2D software, allows to obtain the cavity modes)
- Cavity irises with elliptical shape to reduce the superficial electric field (to prevent RF breakdown)

Results for the first design



RF electric field maximum flatness is better than 99%

$f = 11.993996\ GHz$

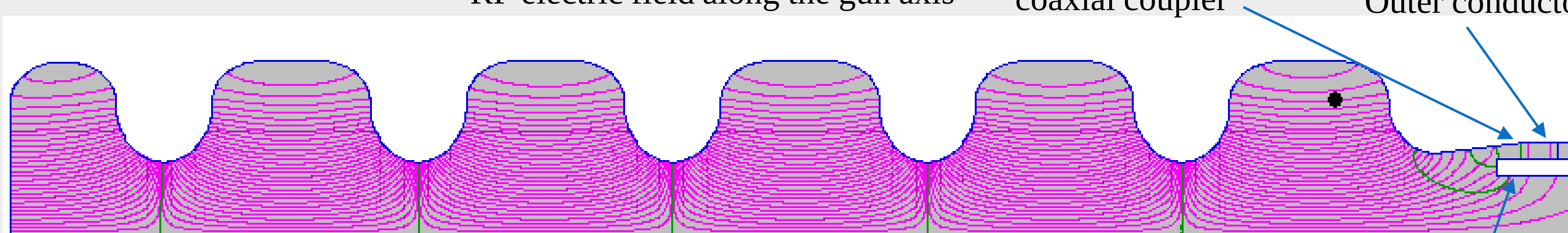
$\beta = 1.005$

$\Delta f = 27.1\ MHz$

RF electric field along the gun axis

coaxial coupler

Outer conductor



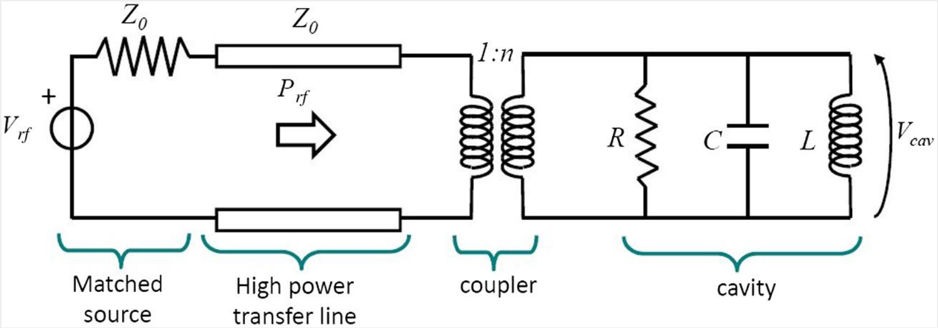
Inner conductor

Scheme of a 5.6 cell RF gun with a coaxial coupler

RF design

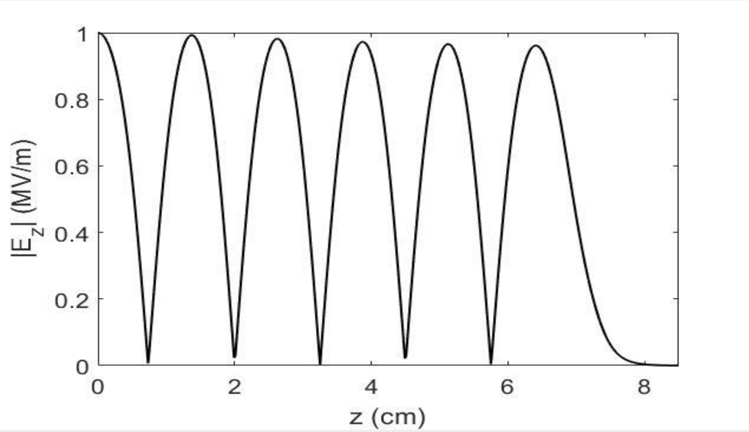
- For the first design, only the π-mode was considered and later on it was observed a slight distortion on the RF electric field pattern due to the presence of the neighbor modes
- Thus, a re-optimization of the RF gun taking into account the neighbor modes was performed
- An equivalent circuital model was employed to take into account the excitation of these neighbor modes[1]

mode	f_m (GHz)	$Q_{L,m}$	β_m	α_m ($Vm^{-1}W^{-0.5}$)
π	11.993996	4238.51	1.00477	42207.155
1	11.9669	2927.36	1.816202	60021.928
2	11.896	3411.46	1.405519	63107.831
3	11.809	4447.77	0.8362	66482.625
4	11.730	6115.44	0.3414	35850
5	11.681	7924.16	0.0722	48378.9

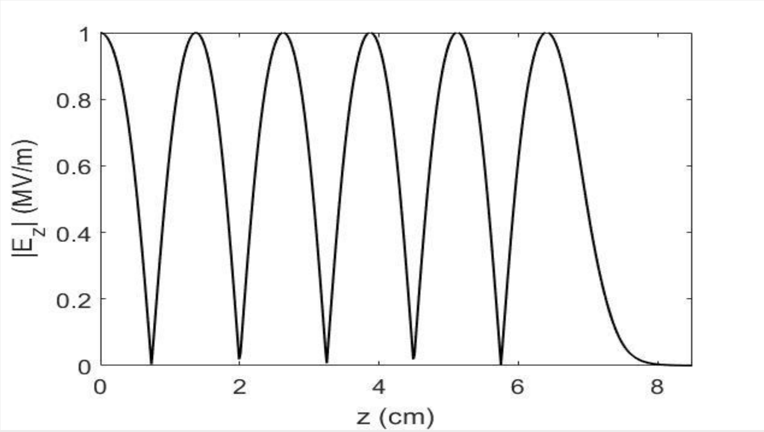


Equivalent circuit describing the RF generator, coupler and gun cavity (extracted from ref. 1)

First design (with neighbor modes)



Second design (with neighbor modes)



$$f = 11.9940380\,GHz$$
$$\beta = 1.027$$
$$\Delta f = 27.1\ MHz$$

$$\max(E_{sup}) = 0.988\ MV/m$$
(for 1 MV/m at cathode axis)

RF electric field maximum flatness is better than 99%

[1] D. Alesini et al., "Design, realization, and high power test of high gradient, high repetition rate brazing-free S-band photogun", Physical Review Accelerators and Beams. 21, 112001 (2018)

RF breakdown

- The risk of RF breakdown in the component is assessed by means the breakdown rate (BDR), which is obtained by computing the modified Poynting vector[1]

$$BDR \equiv \frac{number\ of\ breadowns}{pulse \cdot 1m\ structure\ length}$$

Complex Poynting vector $\vec{S} = \frac{1}{2}\vec{E} \times \vec{H}^*$

Modified Poynting vector $S_c = |Re\{\vec{S}\}| + g_c|Im\{\vec{S}\}|$ typically $g_c = 1/6$

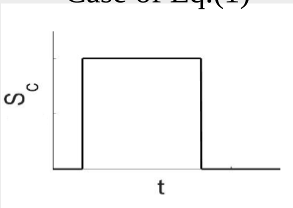
The BDR follows the next empirical law: $BDR = \frac{S_c^{15} t_{on}^5}{C}$ (1)

t_p is the pulse length
C is a constant

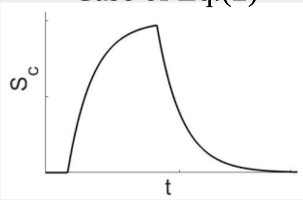
According to ref. (1), C= 9.765625×10^{27} $W^{15} \cdot ns^5 \cdot m \cdot \mu m^{-7.5} bpp^{-1}$

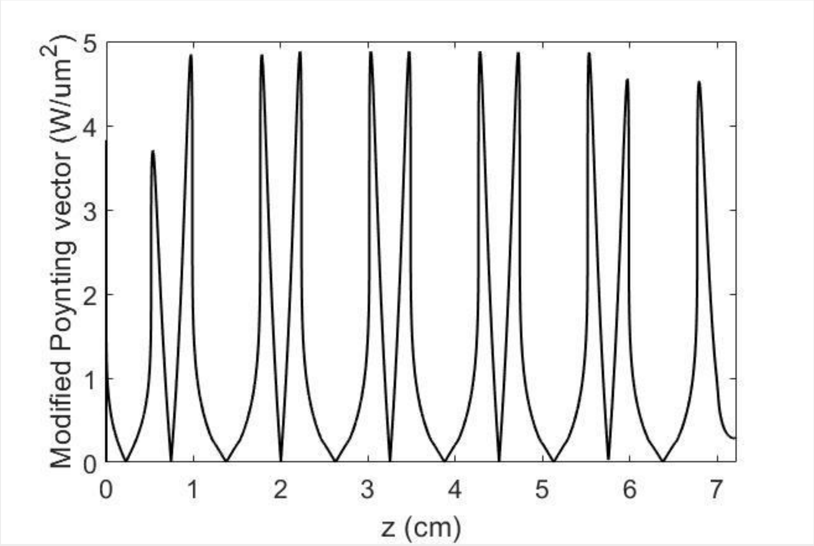
For the case with transient ⟶ $BDR_{pulse} = \frac{5}{C}\int_0^{t_{on}} S_c^{15}(t)\, t^4 dt$ (2)

Case of Eq.(1)

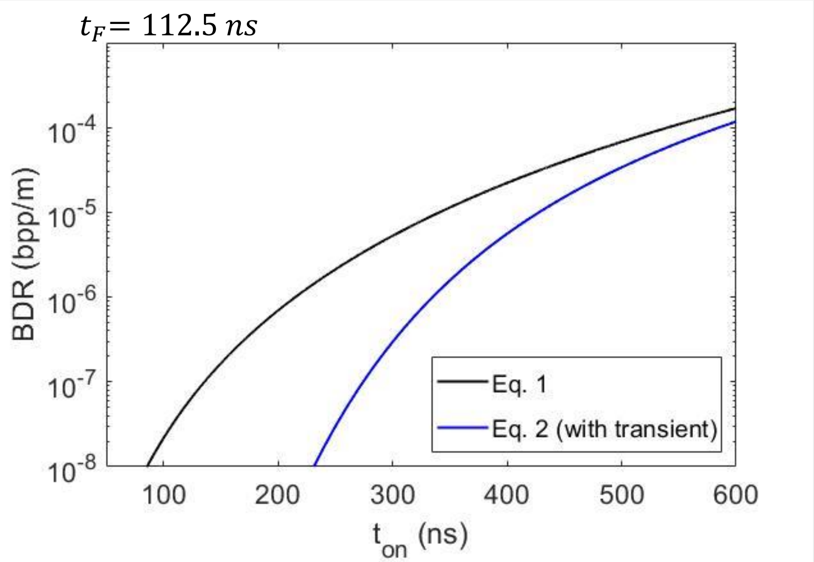


Case of Eq.(2)





Modified Poynting vector at the RF gun surfaces as a function of the axial position, for 200 MV/m at cathode

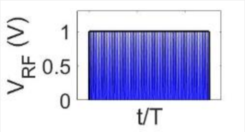


Maximum BDR as a function of the pulse duration, for 200 MV/m at cathode

[1]A. Grudiev et al., "New local field quantity describing the high gradient limit of accelerating structures", Physical Review Special Topics –Accelerators and Beams, 12, 102001 (2009).

RF pulse heating

- The RF pulse heating in the metallic walls of the device has been analyzed solving the heat transfer differential equation using a 1D model

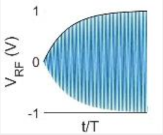


Temperature rise (approximation)[1] ⟶

$$\Delta T = \frac{|H_{||}|^2 \sqrt{t_{on}}}{\sigma\delta\sqrt{\pi\rho C_\epsilon k}}$$

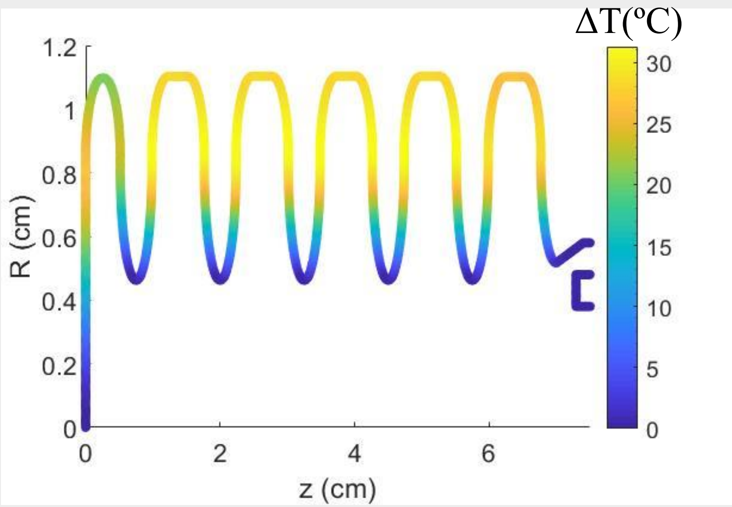
$$u_0(t) = \frac{g_0}{2}\left[t + t_F\left(2e^{-\frac{t}{t_F}} - \frac{1}{2}e^{-\frac{2t}{t_F}} - \frac{3}{2}\right)\right]$$

$$u_n(t) = \frac{g_n\left(1 - e^{-\frac{t_{on}}{t_F}}\right)^2}{\left(\frac{\pi a n}{L}\right)^2}\left[e^{-\frac{2t}{t_F}} - e^{-\left(\frac{\pi a n}{L}\right)^2 t}\right] \qquad g_n = \frac{2}{L}\int_0^L g(\xi)\cos\left(\frac{\pi n \xi}{L}\right) d\xi$$

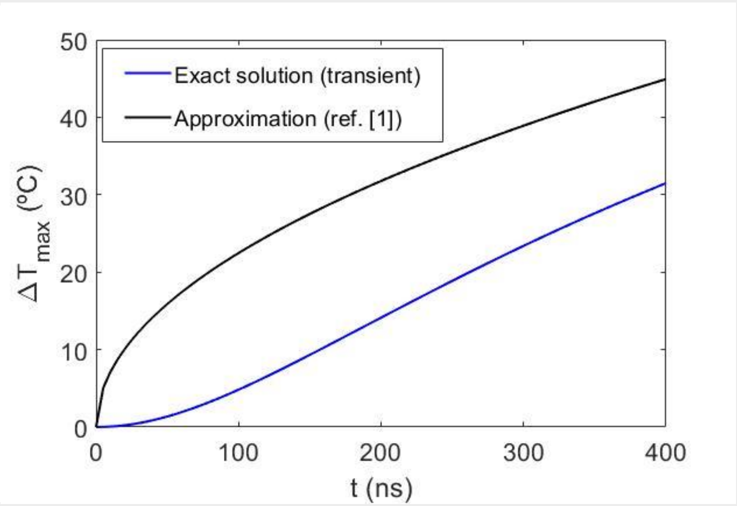


Temperature rise with transient (exact solution) ⟶

$$\Delta T(x,t) = u_0(t) + \sum_{n=1}^{\infty} u_n(t)\cos\left(\frac{\pi n x}{L}\right), \qquad 0 \le t \le t_{on}$$



Temperature rise along the RF gun surfaces (t_{on} = 400 ns and 200 MV/m at cathode)



Maximum Temperature increase as a function of time

- The maximum temperature increase is 31 ºC for a pulse length of 400 ns and 200 MV/m cathode field
- This value is below 50ºC, which is the maximum temperature rise suggested by Avni

$H_{||}$ is the magnetic field parallel to the surface
t_p is the RF pulse length
σ is the electric conductivity
ρ is the density
C_ϵ is the specific heat
k is the thermal conductivity
ω is the angular frequency
μ_0 is the magnetic permeability of vacuum
T is the temperature
L is the wall length

$$a = \sqrt{\frac{k}{\rho C_\epsilon}} \qquad \delta = \sqrt{\frac{2}{\sigma \mu_0 \omega}}$$

[1] D. P. Pritzkau, "RF Pulsed Heating", SLAC-Report-577 , Ph.D. Dissertation, Stanford University, 2001.

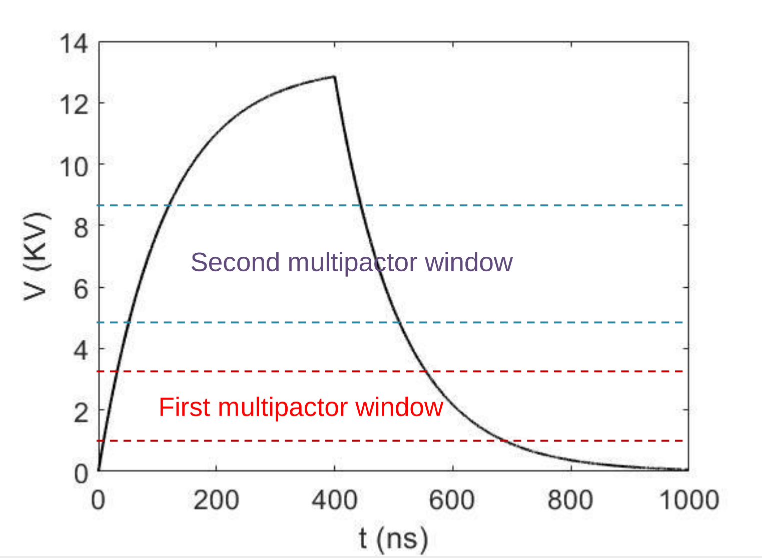
Multipactor analysis in the coaxial coupler Compact

- Multipactor risk in the coaxial coupler was assessed by means of numerical simulations using our in-house developed code

Numerical simulations were launched at several RF voltage values up to the maximum RF voltage reached at the coaxial coupler, finding two multipactor zones:

Multipactor zones →

Multipactor window	P (MW)	V(kV)
1	0.035-0.56	0.891-3.565
2	1.20-3.10	5.219-8.388



Coaxial voltage amplitude during the RF pulse

- Multipactor can be suppressed provided that a strong enough magnetic field is applied along the coaxial axis[1]

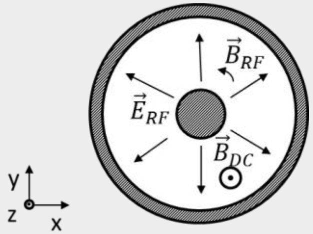
As an approximate rule, the minimum magnetic field to mitigate the discharge is given by

$$f_c \approx f \qquad f_c = \frac{1}{2\pi}\frac{e}{m}B_{dc}$$

f is the RF frequency
B_{dc} is the external magnetic field
m is the electron mass

f_c is the cyclotron frequency
$-e$ is the electron charge

In our case, the above condition gives $B_{dc} = 428.5\ mT$



coaxial line transverse cross section

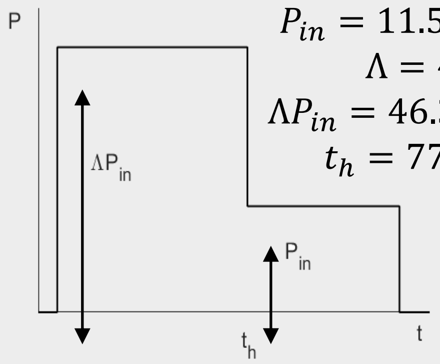
- ✓ Numerical simulations support that no multipactor discharge is expected with such external magnetic field
- ✓ In fact, it is found that a $B_{dc} = 360\ mT$ is enough to suppress the discharge, according to the numerical simulations

[1]D. González-Iglesias et al., "Multipactor Mitigation in Coaxial Lines by Means of Permanent Magnets", IEEE Transactions on Electron Devices, vol. 61, no. 12, pp. 4224-4231, Dec. 2014.

RF power system

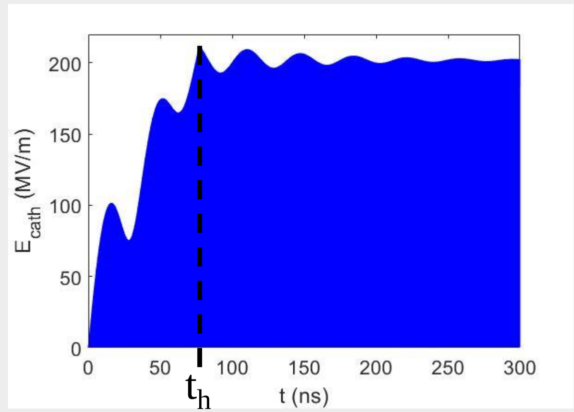
- The reflected power from the cavity during the transient can damage the klystron and there no available circulators for X-band operation, hence, to protect the klystron: i) an extra length L has been added between the klystron and the gun, and ii) the pulse has been shortened

- The klystron pulse shape has been modified to fill the cavity in a shorter time[1]

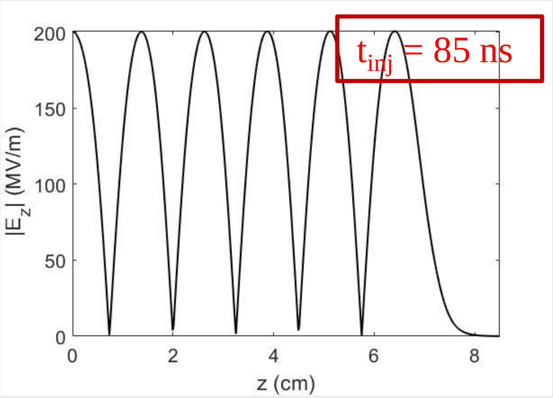


$$P_{in} = 11.58\ MW$$
$$\Lambda = 4$$
$$\Lambda P_{in} = 46.32\ MW$$
$$t_h = 77.2\ ns$$

Scheme of the klystron RF pulse



RF Electric field at cathode



Axial RF Electric field along the gun axis

- For a pulse length of t_{inj} = 85 ns the required extra length is L =10.67 m, to compensate the power losses in the extra length the klystron is required to deliver $\mathbf{P_{klystron}}$ **= 60. 7 MW**

- We propose a RF power system layout similar to that existing in the Xbox 3 at CERN[2], which is composed of:
  - Four combined Toshiba E37113 klystrons
  - SLED pulse compressors

Each klystron can provide 6 MW with 4-5μs

↓ combining the four klystrons

Combined pulse with 24 MW and 4-5μs

↓ pulse compression with factor between 3 and 4

Output pulse with 70-80 MW and 300 ns, and a max repetition rate of 400 Hz

[1] D. Alesini et al., "Design, realization, and high power test of high gradient, high repetition rate brazing-free S-band photogun", Physical Review Accelerators and Beams. 21, 112001 (2018)
[2] B. J. Woolley, "High Power X band RF Test Stand Development and High Power Testing of the CLIC Crab Cavity", PhD Thesis, 2015

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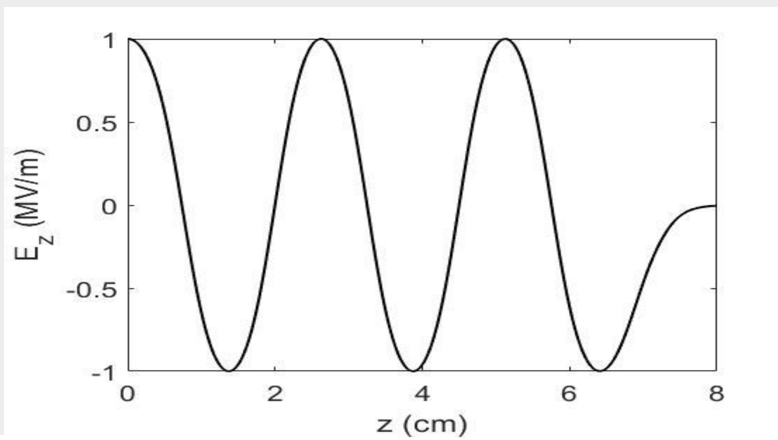
Beam dynamics simulations

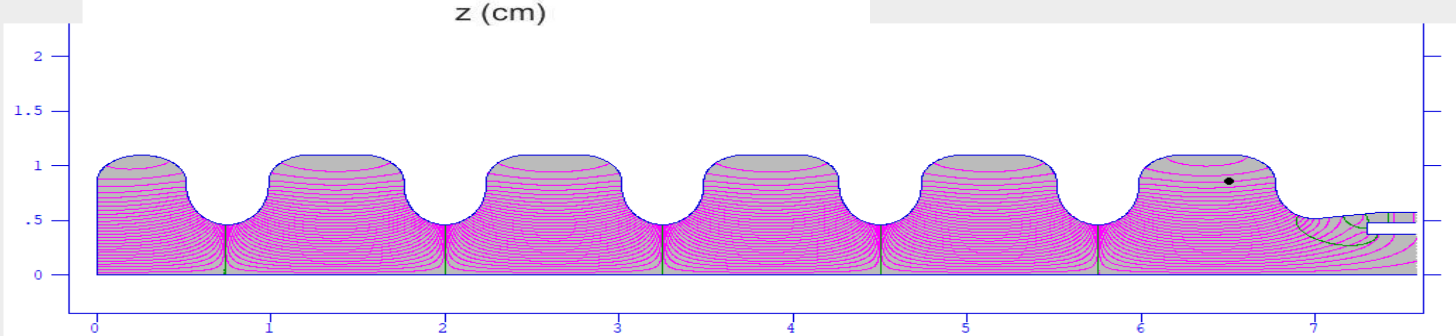
- The objective is to perform beam dynamics simulations for the X-band photoinjector in order to achieve the XLS CompactLight design goals in terms of beam quality

- To reach this aim, a solenoid must be designed in order to compensate the space charge forces during the early stages of the beam acceleration

- The solenoid will be designed with Poisson/Superfish, whilst the beam dynamics simulations will be carried out with GPT

	Goal
Charge (Q)	75 pC
Beam energy (E_{avg})	300 MeV
rms bunch length (σ_t)	350 fs
rms energy spread ($\Delta E/E_{avg}$)	0.5 %
Peak current ($Q/\mathrm{sqrt}(12)\ \sigma_t$)	60 A
rms norm. emittance	0.2 mm mrad

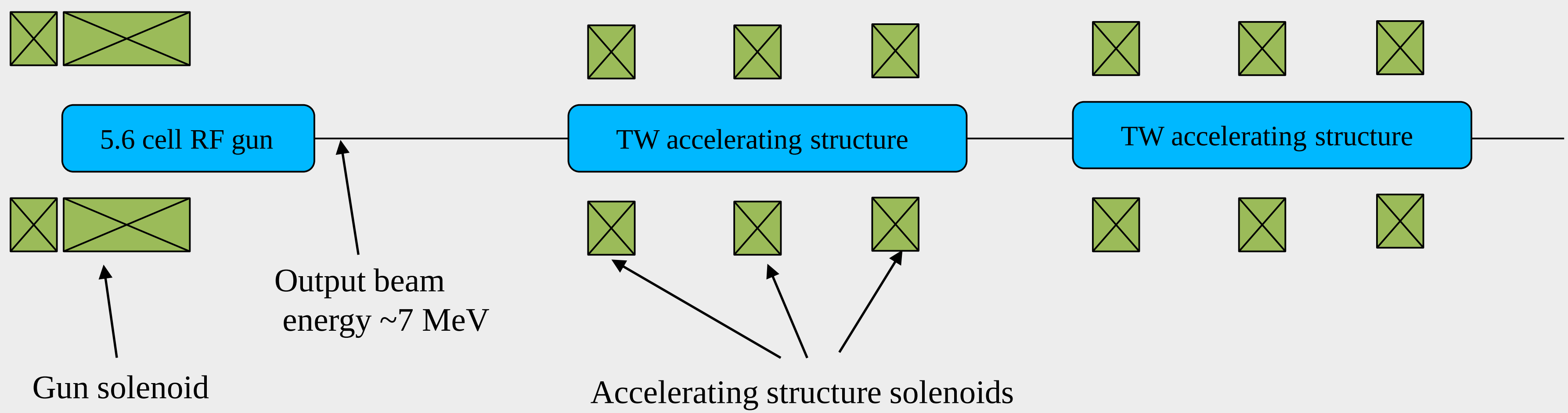




Scheme of the 5.6 cell X-band RF photoinjector

RF injector layout

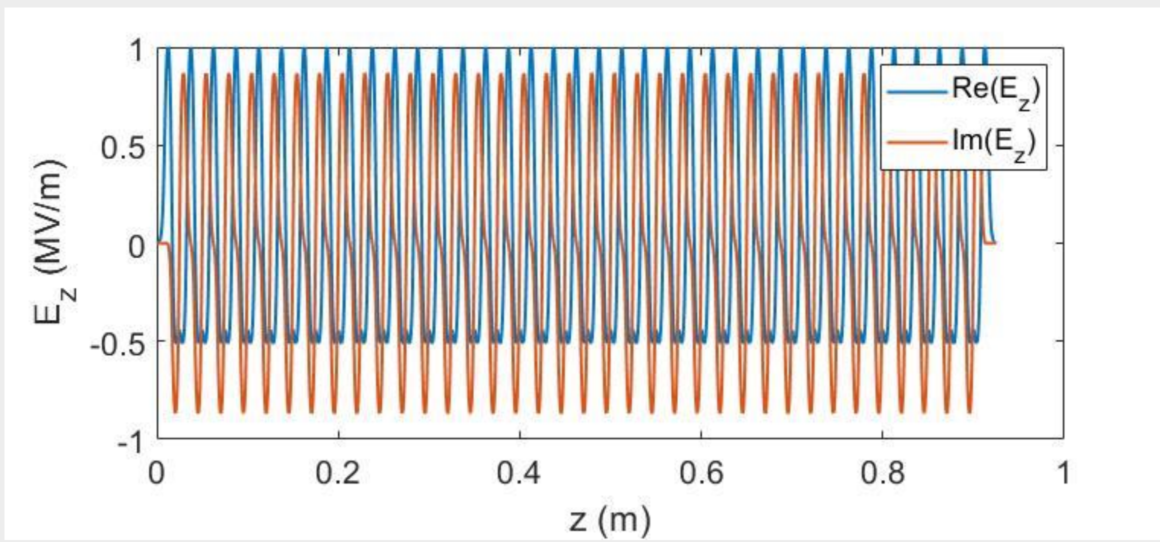
- The following layout is proposed for the injector scheme



- Several X-band TW accelerating structures are added downstream the gun to accelerate the beam up to the final target of 300 MeV

Parameter	Value
Frequency	12 GHz
Average gradient	65 MV/m
Total length	0.9 m
Number of cells	108
Advance phase per cell	2π/3

TW accelerating structure module (from WP4)



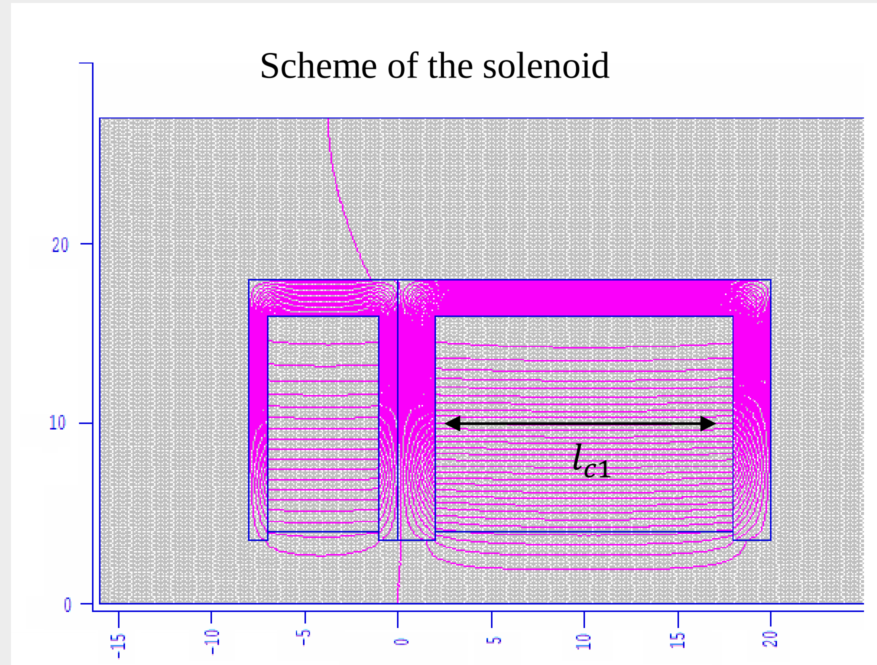
RF gun solenoid

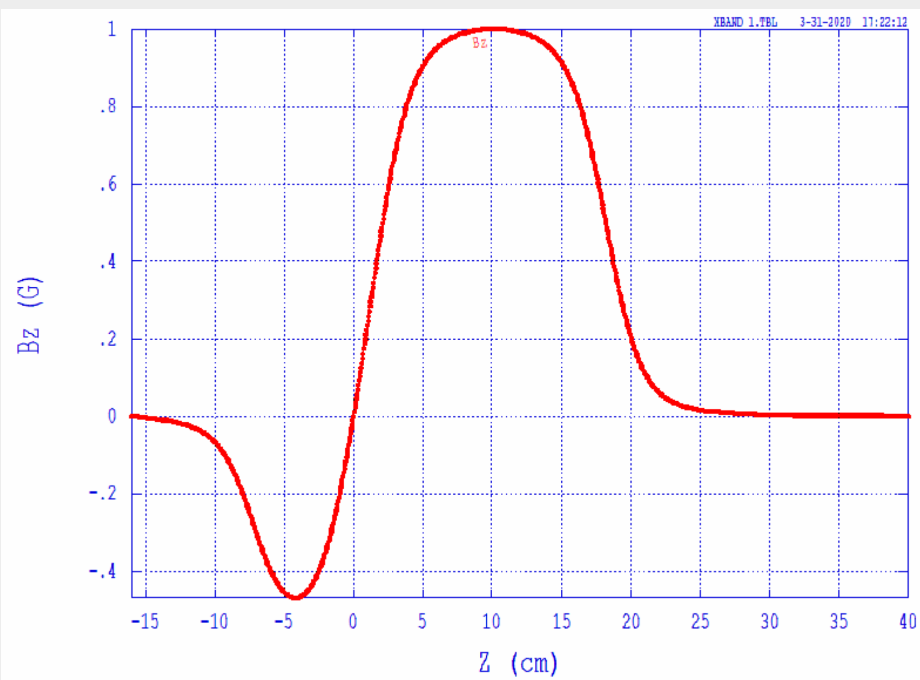
- The RF gun solenoid for emittance compensation will be designed with the 2D software Poisson/Superfish, taking as a reference the model provided by Avni

- It consists of two coils fed by opposite polarity electric currents, each coil is surrounded by a ferromagnetic material yoke

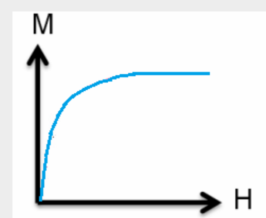
- The junction point between the two coils is aligned with the RF gun cathode plane

- The secondary coil has the purpose of zeroing the magnetic field at cathode, in order to avoid the increase of the initial beam emittance





Axial magnetic field along the gun axis (cathode at z=0)



Magnetization curve for ferromagnetic material

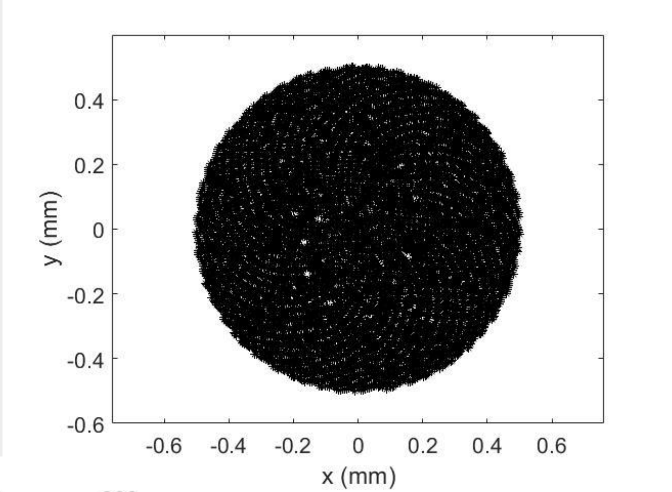
- For the yoke material, we choose a low carbon steel with $\mu_r = 250$ (at B = 2mT)

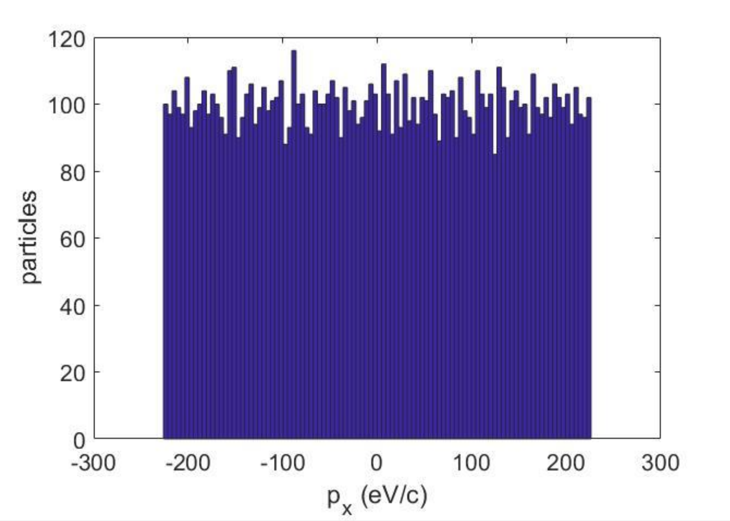
Initial particle distribution

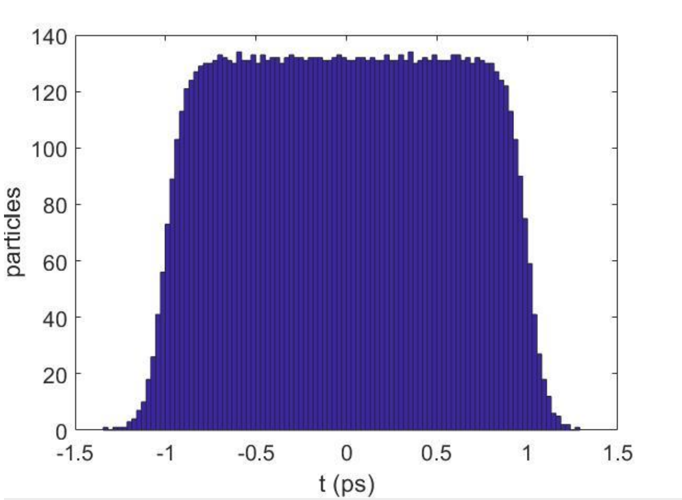
- Prior to simulations, it is required to stablish the initial particle distribution properties for the beam simulations (only bunch charge is specified by the CompactLight goals chart)
- The remaining properties will be chosen to match with the employed by Avni on his simulations. Those are extracted from the file “part_10k_2ps_0.25mm.dat”, containing ASTRA initial particle distribution
- The analysis of such file allows to get information about the particle distribution:

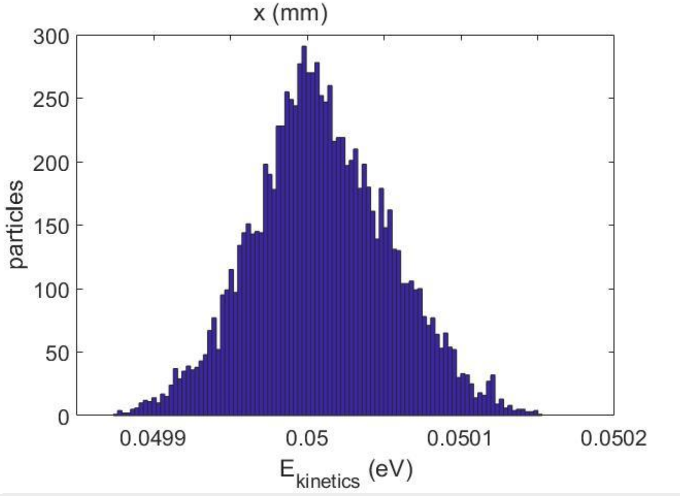
Avni’s distribution:

$N_{particles}$=10000
<$E_{kinetics}$>= 0.05 eV
$\varepsilon_{x,y}$ = 0.06 mm·mrad
Time distribution → “Plateau” with σ_t (FWHM)= 2 ps
x-y distribution → Radial uniform with $\sigma_{x,y}$ = 0.25 mm
p_x-p_y distribution → 1D uniform with σ_{px} (FWHM)= 200 eV/c









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Initial particle distribution

Compact

- Then, an equivalent initial particle distribution is implemented in GPT for our simulations

Avni's distribution (ASTRA):

$N_{particles}$=10000

$\varepsilon_{x,y}$ = 0.06 mm·mrad

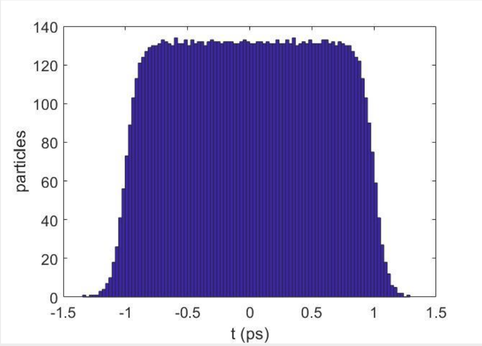
x-y distribution → Radial uniform with $\sigma_{x,y}$ = 0.25 mm;

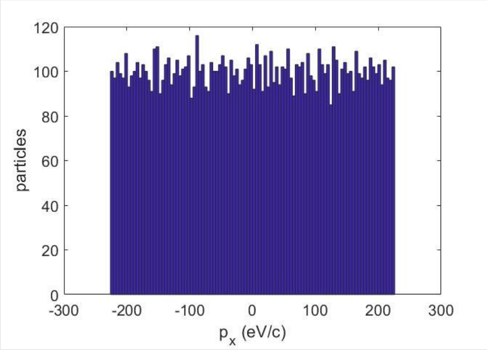
$<E_{kinetics}>$= 0.05 eV

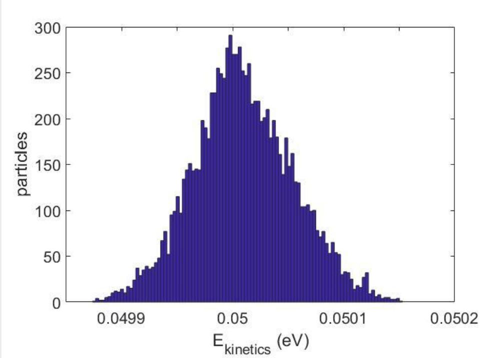
Time distribution → "Plateau" with σ_t (FWHM)= 2 ps

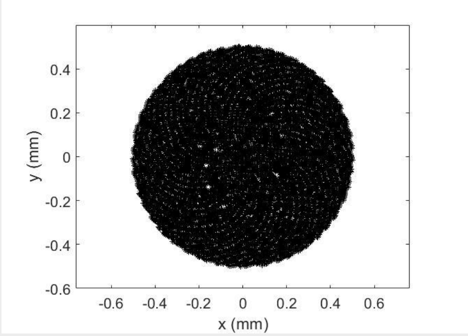
p_x-p_y distribution → 1D uniform with σ_{px} (FWHM)= 200 eV/c

ASTRA

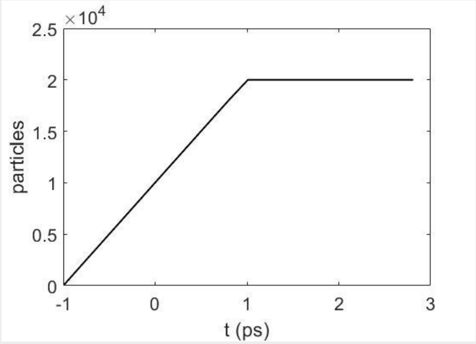


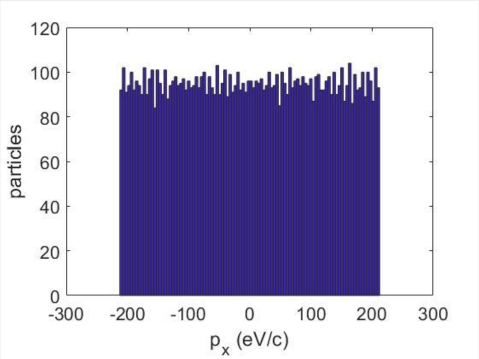


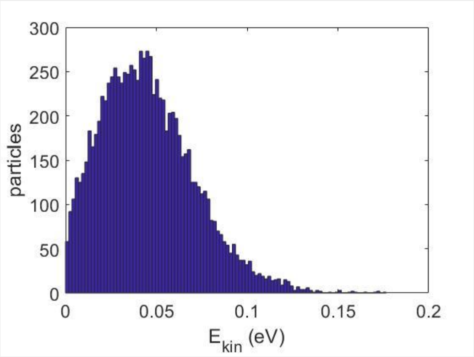


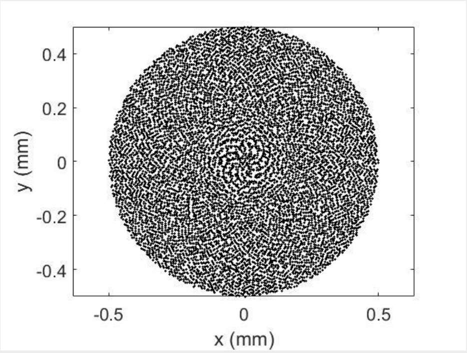


GPT





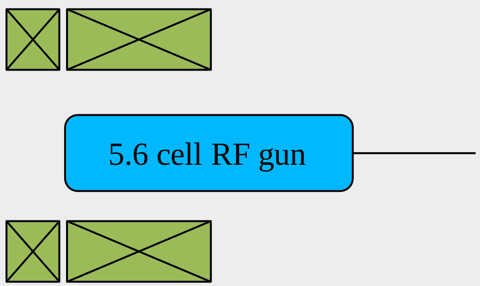


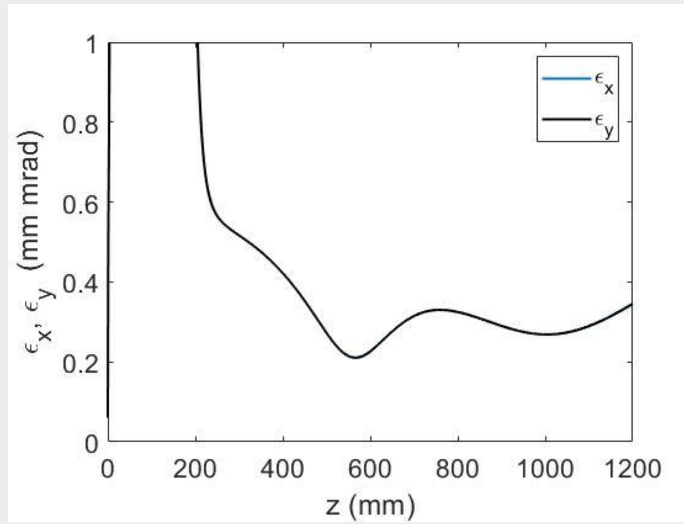


In GPT, $N_{particles}$= 20000 ensures reasonable convergence of the results

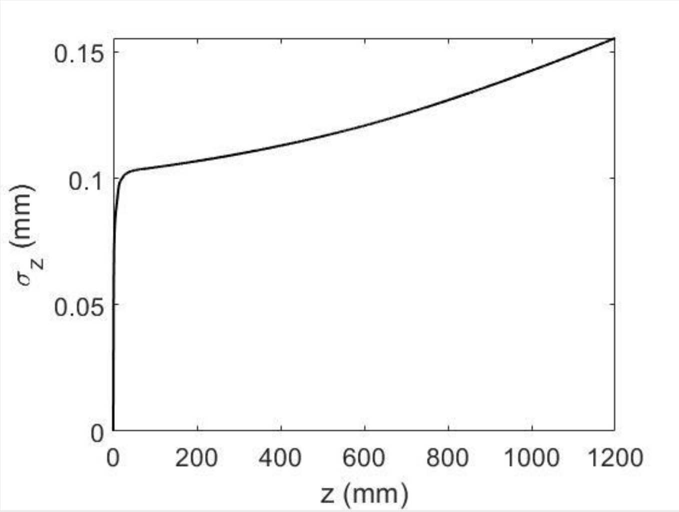
Beam simulations of the RF gun

- First, the solenoid is optimized for minimizing the emittance at the exit of the 5.6 cell RF gun (l_{c1} = 13.5 cm , B_0 = 465 mT)

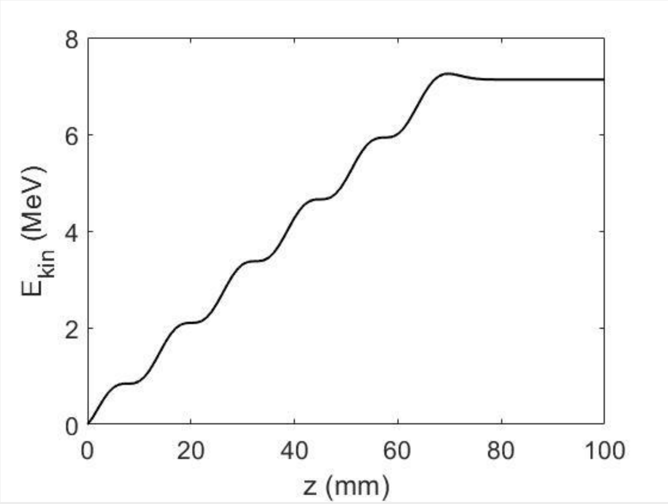




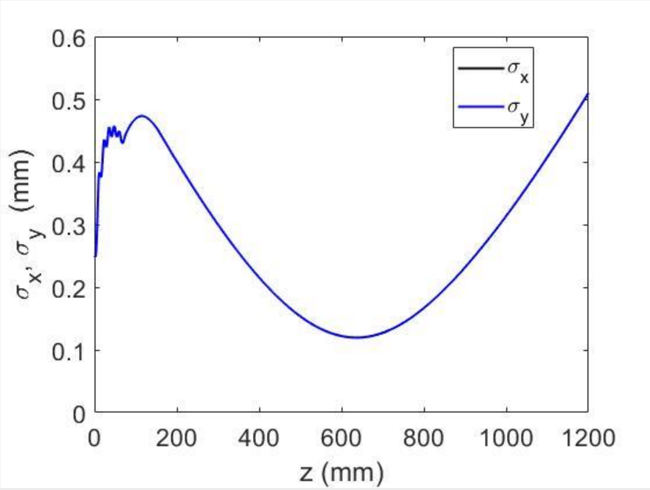
Beam emittance along axis



Longitudinal standard deviation along axis



Average beam kinetic energy along axis



Transversal standard deviation along axis

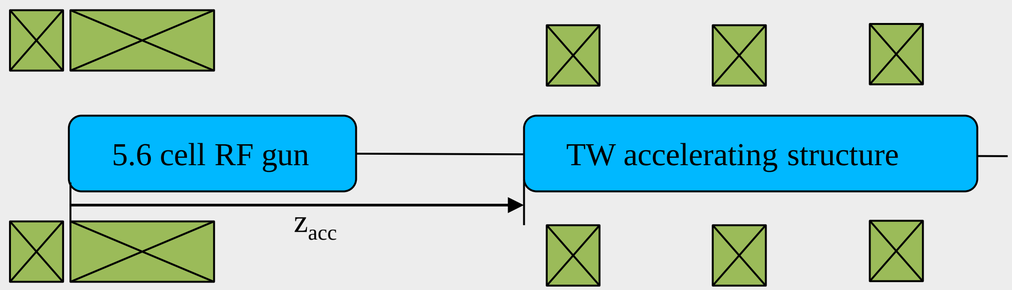
Beam parameters at the gun output:

- Average kinetic energy: 7.1 MeV
- Minimum beam emittance: 0.21 mm mrad
- Minimum beam transversal size: 0.12 mm at z = 0.640 m

The next step is to add the TW structures to accelerate the beam up to the required 300 MeV

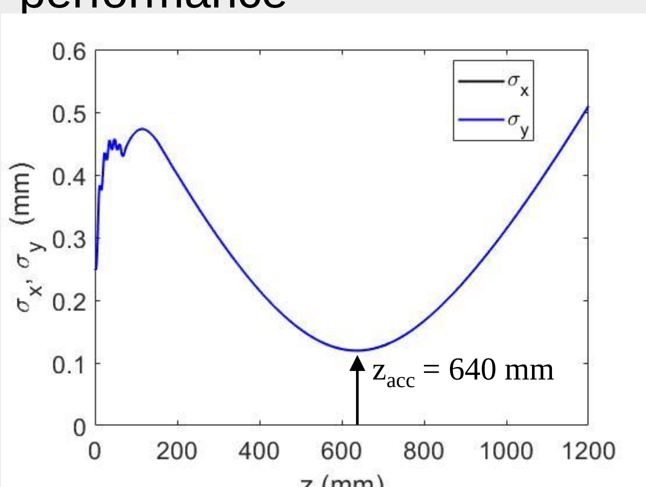
Beam simulations of the RF gun

- Next, it is added an X-band TW accelerating structure after the RF gun

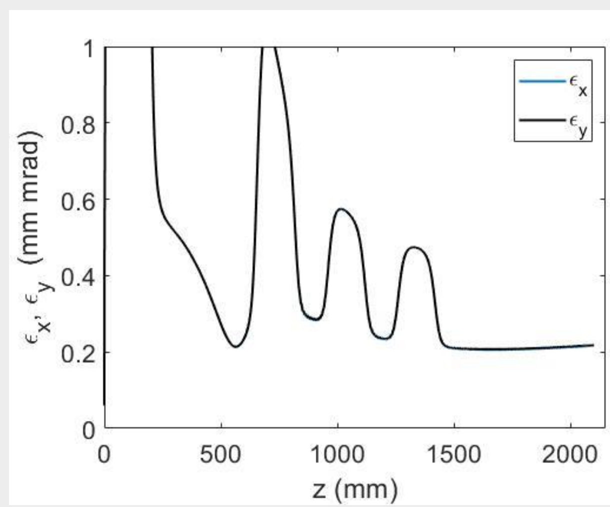


Parameter	Value
Frequency	12 GHz
Average gradient	65 MV/m
Total length	0.9 m
Number of cells	108
Advance phase per cell	2π/3

- The TW accelerating structure is defined mainly by two parameters: its axial position with regard the gun cathode plane, z_{acc}; and the initial phase of the RF fields, ϕ_{TW}
- According to the Ferrario working point[1], the beam must be a waist in the entrance of the TW structure in order to minimize the emittance
- Then, the remaining parameter ϕ_{TW} has to be adjusted to obtain a good beam performance

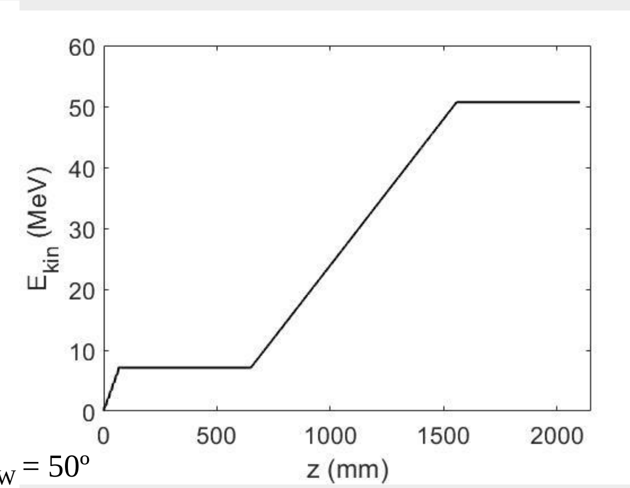


Transversal standard deviation along axis (without accelerating structure)



Beam emittance along axis

ϕ_{TW} = 50º

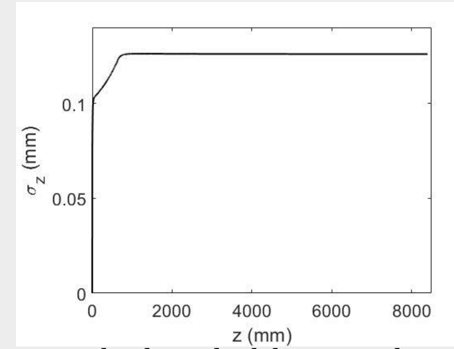


Average beam kinetic energy along axis

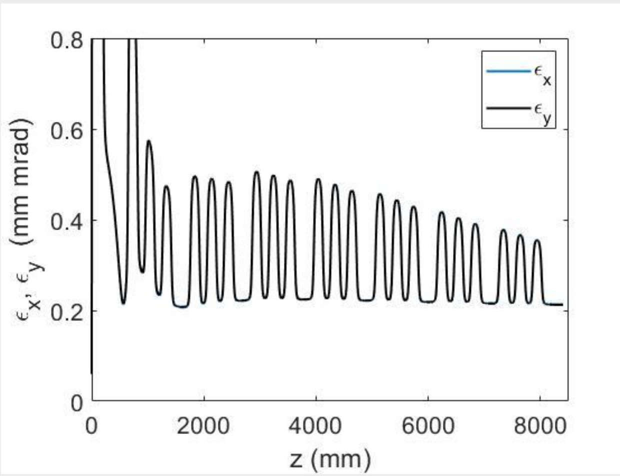
[1] M. Ferrario et al., "HOMDYN Study for the LCLS RF Photo-Injector", The Physics of High Brightness Beams, pp. 534-563 (2000)

Beam simulations of the RF gun

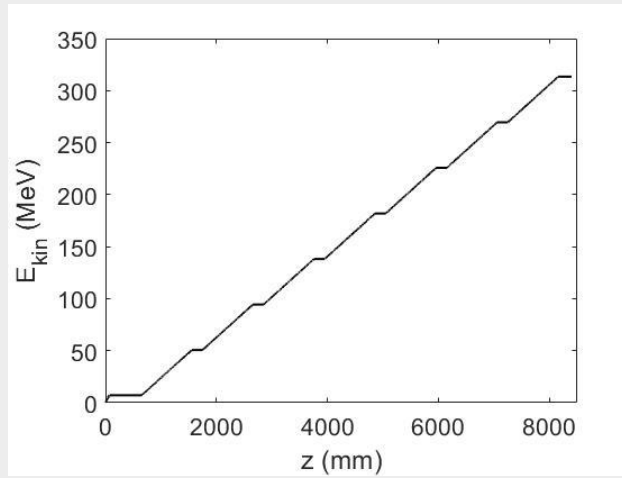
- Finally, additional accelerating structures are included to accelerate the beam up to 300 MeV



Longitudinal standard deviation along axis



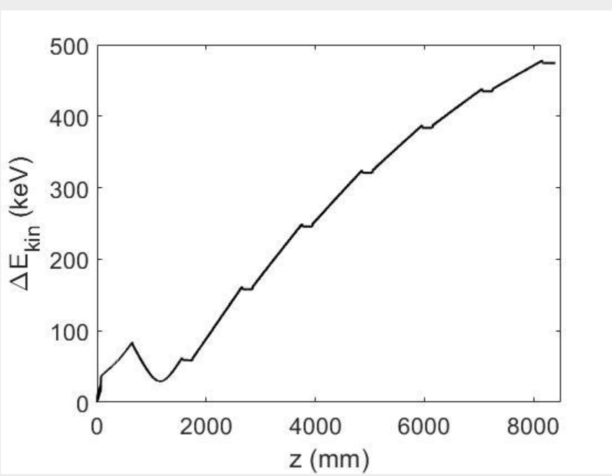
Beam emittance along axis



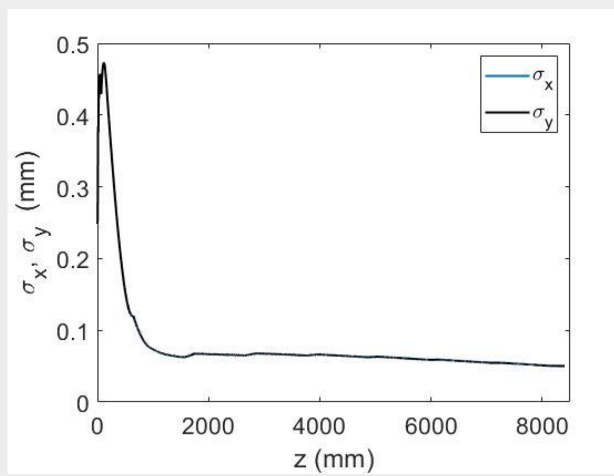
Average beam kinetic energy along axis

Beam parameters at photoinjector output

	X-band injector	Goal
Charge (Q)	75 pC	75 pC
Beam energy (E_{avg})	313 MeV	300 MeV
rms bunch length (σ_t)	420 fs	350 fs
rms energy spread ($\Delta E/E_{avg}$)	0.15 %	0.5 %
Peak current (Q/sqrt(12) σ_t)	52 A	60 A
rms norm. emittance	0.21 mm mrad	0.2 mm mrad
Transverse size (σ_x, σ_y)	0.05 mm	-
Total length	8.2 m	-
Num. of acc. TW structures	7	-



Standard deviation of kinetic energy



Transversal standard deviation along axis

All the beam parameters goals are fulfilled but the rms bunch length

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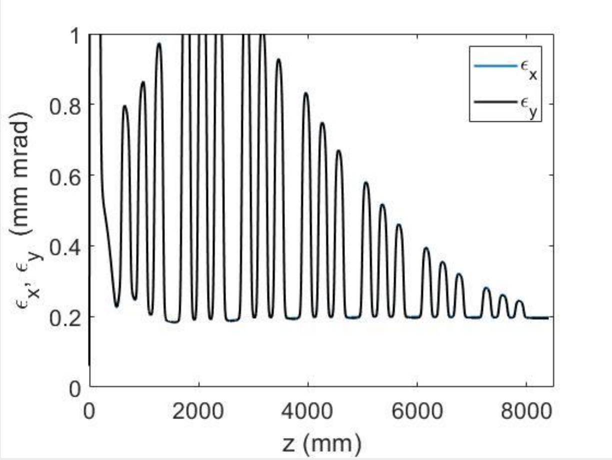
Beam simulations of the RF gun

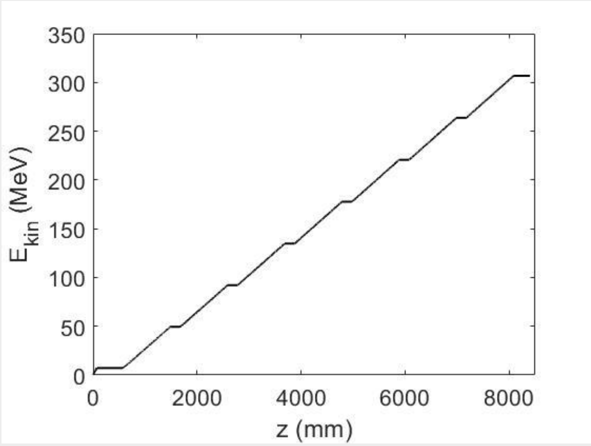
Compact

- According to Avni's suggestion, the initial time distribution was shortened from 2000 fs to 300 fs, with the aim of fulfill the final rms bunch length goal of CompactLight (some re-optimization was needed):

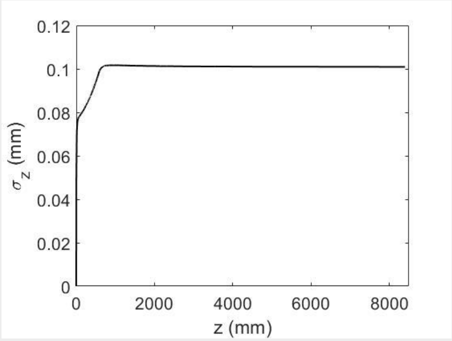
B_0 = 480 mT, l_{c1} = 13.5 cm, z_{acc} = 0.568 m, ϕ_{TW} = 0º



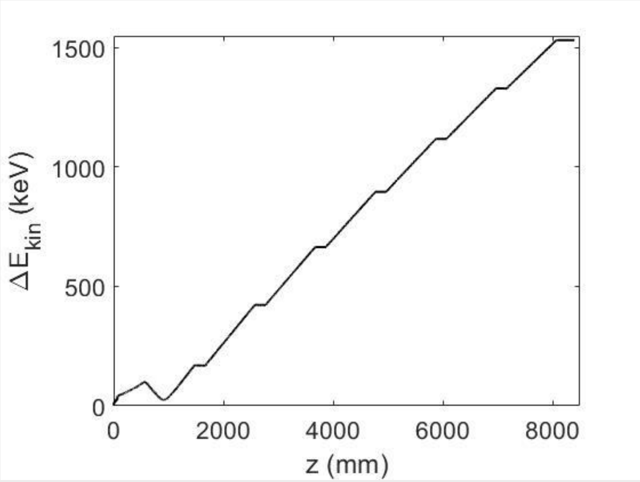
Beam emittance along axis



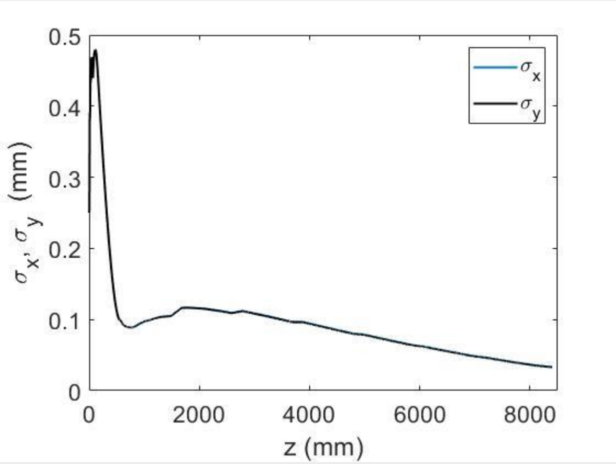
Average beam kinetic energy along axis



Longitudinal standard deviation along axis



Standard deviation of kinetic energy



Transversal standard deviation along axis

Beam parameters at photoinjector output

	X-band injector	Goal
Charge (Q)	75 pC	75 pC
Beam energy (E_{avg})	307 MeV	300 MeV
rms bunch length (σ_t)	337 fs	350 fs
rms energy spread ($\Delta E/E_{avg}$)	0.5 %	0.5 %
Peak current (Q/sqrt(12) σ_t)	64 A	60 A
rms norm. emittance	0.20 mm mrad	0.2 mm mrad
Transverse size (σ_x, σ_y)	0.03 mm	-
Total length	8.2 m	-
Num. of acc. TW structures	7	-

Now all the goals are satisfied with this new design

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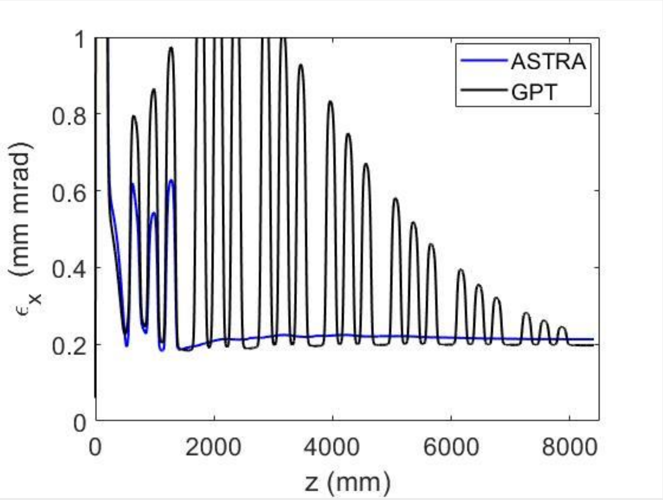
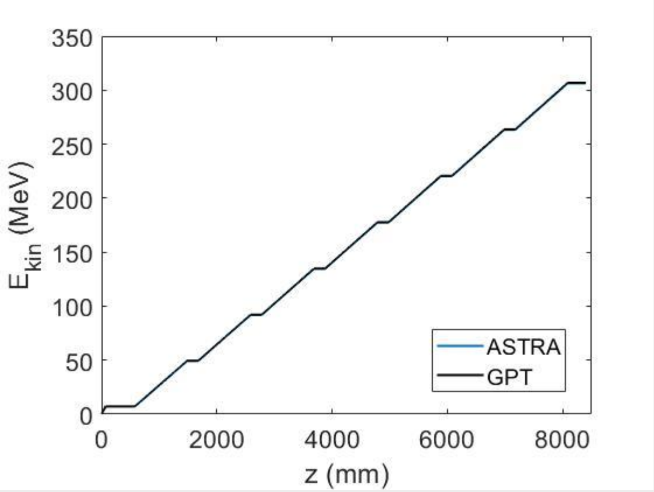
Benchmarking of codes

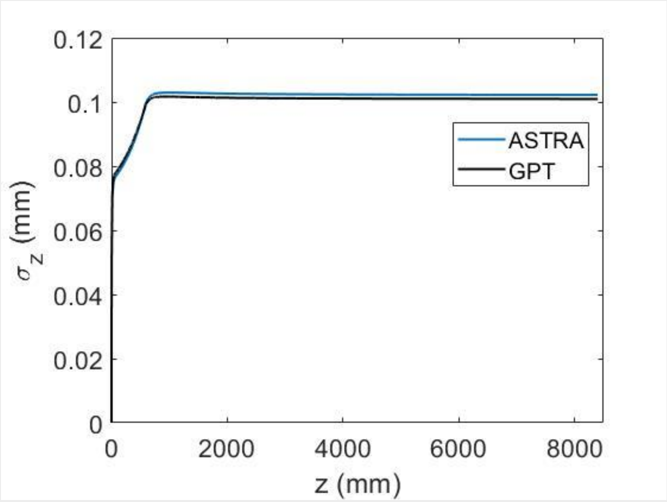
➢ GPT simulations are benchmarked with the ASTRA code:



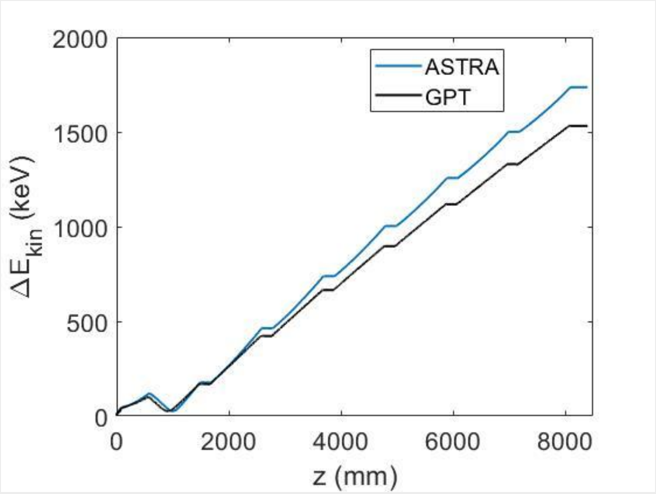
Beam emittance along axis



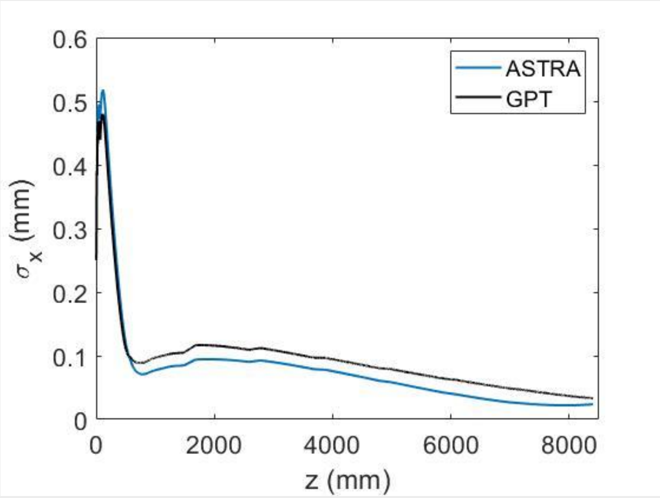
Average beam kinetic energy along axis



Longitudinal standard deviation along axis



Standard deviation of kinetic energy



Transversal standard deviation along axis

Beam parameters at photoinjector output

	GPT	ASTRA
Beam energy (E_{avg})	307 MeV	306 MeV
rms bunch length (σ_t)	337 fs	341 fs
rms energy spread ($\Delta E/E_{avg}$)	0.5 %	0.56 %
Peak current (Q/sqrt(12) σ_t)	64 A	64 A
rms norm. emittance	0.20 mm mrad	0.21 mm mrad
Transverse size (σ_x, σ_y)	0.03 mm	0.02 mm

Good agreement is found between both codes

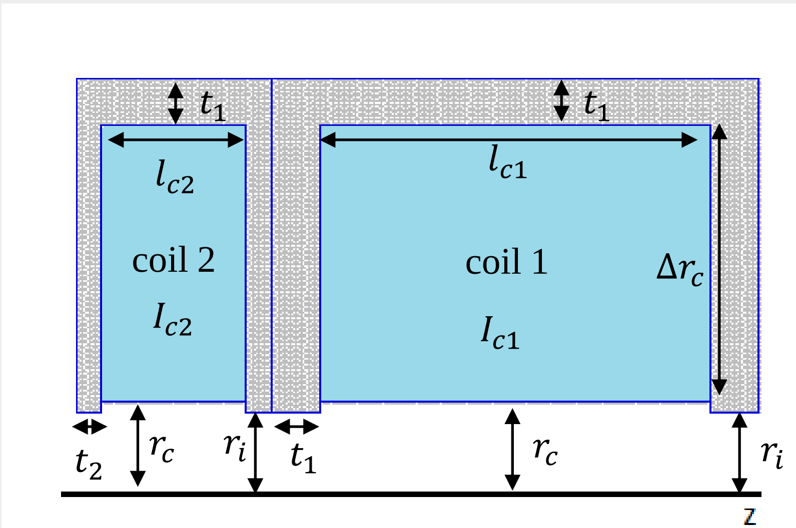
Comparison of the results

- For comparison, the other injector options of the CompactLight project are summarized on the following table:

	Units	Goal	X-band injector	DC	S vb	S mc	C vb	S/X
Charge (Q)	pC	75	75	10	75	75	75	75
Beam energy (E_{avg})	MeV	300	307	270	313	280	346/341	300
rms bunch length (σ_t)	fs	350	337	700	367	300	232/350	113-350
rms energy spread ($\Delta E/E_{avg}$)	%	0.5	0.5	0.2	0.2	0.3	0.3/0.4	0.3
Peak current ($Q/\mathrm{sqrt}(12)\ \sigma_t$)	A	60	64	4	57	60	62/62	65-162
rms norm. emittance	mm mrad	0.2	0.20	0.25	0.2	0.2	0.23/0.15	0.13
Transverse size (σ_x ,σ_y)	mm	-	0.03	-	-	-	-	-
Total length	m	-	8.2	11.3	<15	<15+8	10	8.6
Num. of acc. TW structures	-	-	7	-	-	-	-	-

RF gun solenoid design

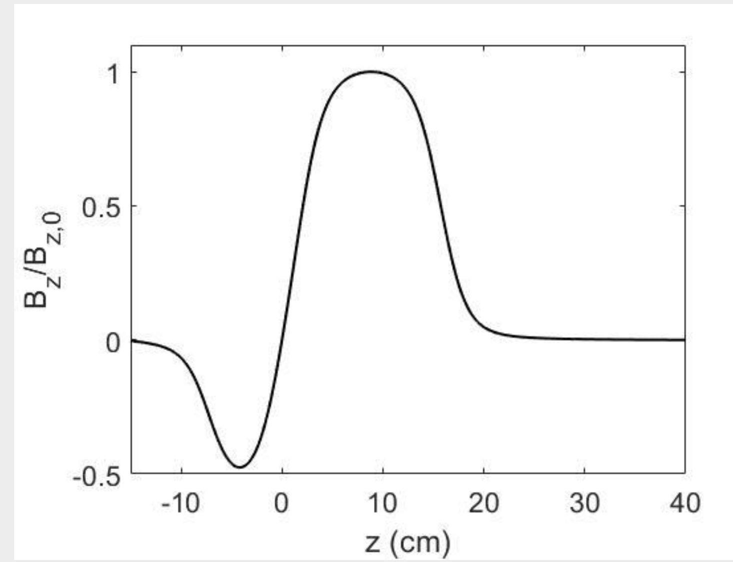
➢ The following dimensions and magnetic field amplitude are found to optimize the beam dynamics performance:



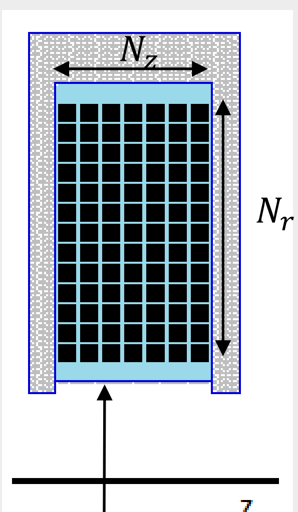
Scheme of the gun solenoid

Parameter	Value
l_{c1}	13.5 cm
l_{c2}	6.0 cm
t_1	2.0 cm
t_2	1.0 cm
Δr_c	12.0 cm
r_i	3.5 cm
r_c	4.0 cm
B_0	480 mT
I_{c2}/I_{c1}	-0.2806

Yoke material: low carbon steel (μ_r = 250)

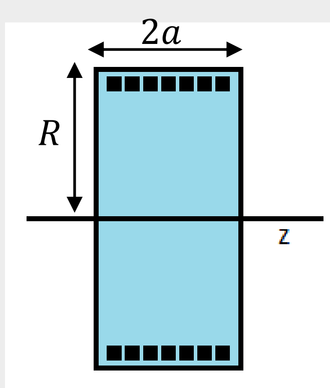


Axial magnetic field along the gun axis



Conductor is assumed to be square-shaped

N_z : turns along axis;
N_r : turns along radius



Scheme of a simple axial coil with N turns

$$B_z(0) = \frac{\mu_0 NI}{2R}\frac{1}{\sqrt{1+\left(\frac{a}{R}\right)^2}}$$

I is the electric current

- In Poisson, it is set the total "effective" current of the coil, i.e., NI
- For our case, when N_1I_{c1}= 1 A and N_2I_{c2}=-0.2806 A, then $B_{z,0}$ = 8.769 × 10^{-3} mT
- Then, as $B_{z,0}$ depends linearly with NI, for $B_{z,0}$ = 480 mT, it is required: N_1I_{c1}= 54738.28 A and N_2I_{c2}=-15359.56 A
- For coil 1, the conduction dimensions are 6 × 6 mm, then the maximum number of turns along the axis is 135 mm / 6 mm width per turn ≈ 22 turns. Similarly, along radial direction 120 mm/6 mm width per turn = 20 turns. It will be chosen N_z = 22 and N_r = 17, so N = N_z N_r = 374 turns. Thus, it results in I_{c1}= 146.4 A.
- For coil 2, the conductor dimensions are 2 × 2 mm, it will be chosen N_z = 30 and N_r = 55, so N = N_z N_r = 1650 turns. Thus, it results in I_{c2}= -9.3 A

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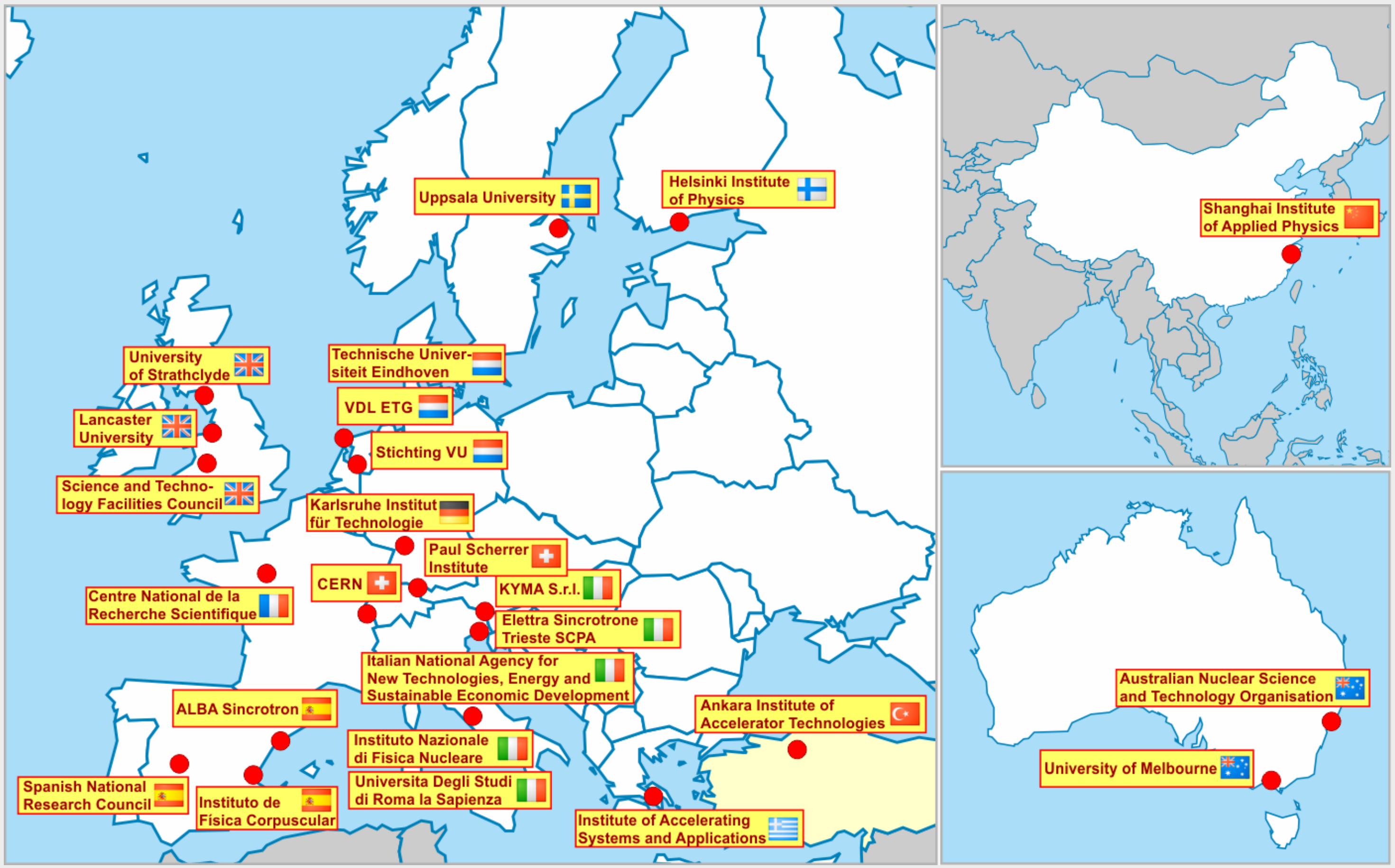
Thank you!

CompactLight@elettra.eu www.CompactLight.eu



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