Low Energy RHIC e-Cooler:
Electron beam transport and dynamics

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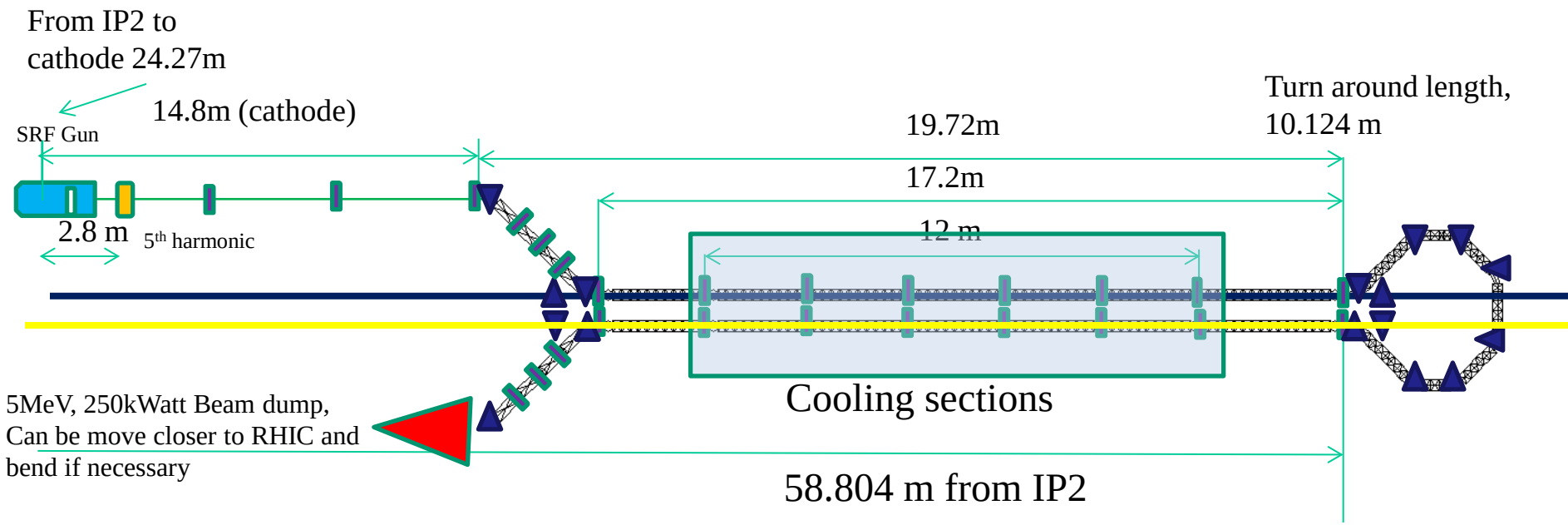
Outline

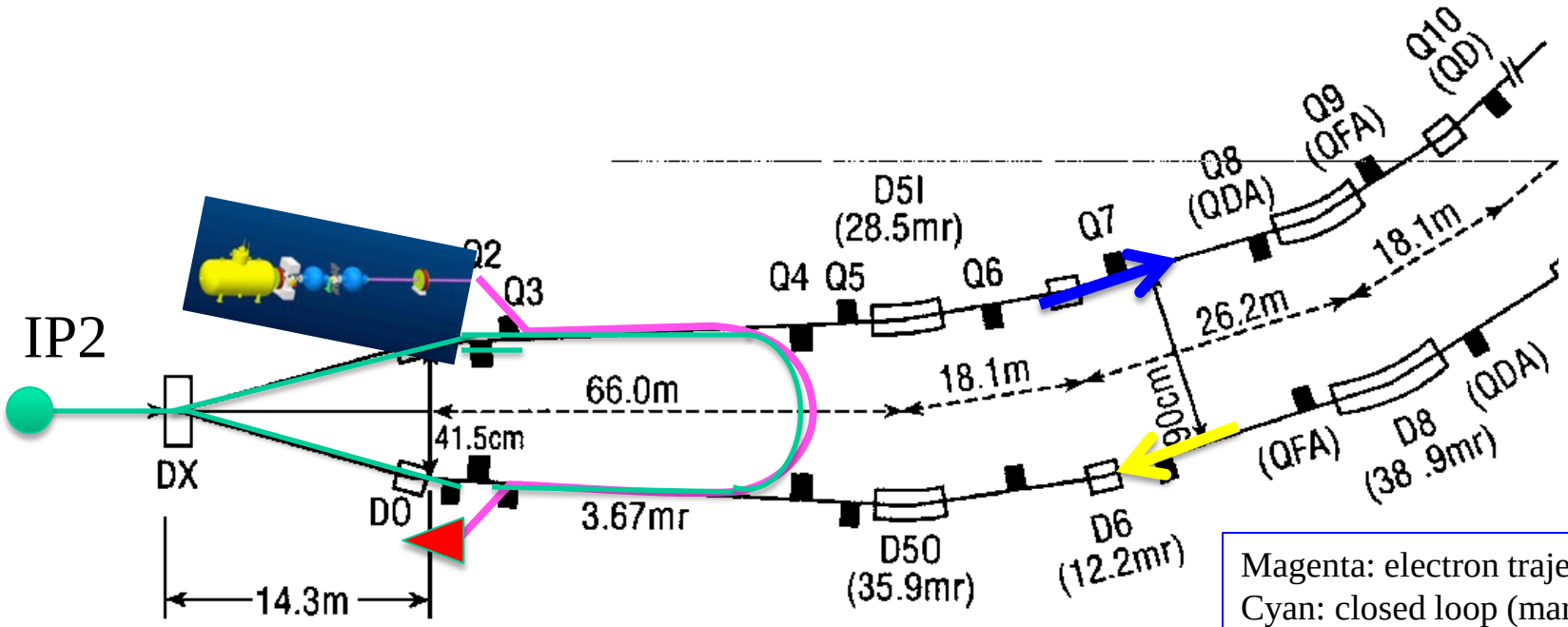
- General layout and main components of beam transport
- Beam dynamics during acceleration
- Beam dynamics in cooling section
- Summary

Low Energy RHIC e-cooler schematic layout



- The relatively long electron bunch (~700 psec) is generated in 100 MHz SRF gun by KCs2Sb photocathode and accelerated by the RF field in the gun to 2.5 MeV.
- 2nd 100 MHz SRF cavity is used to bust the e-beam energy to 5 MeV in order to cover full range of energies of low energy RHIC program. Both cavities are installed in common cryo-module.
- Then 500 MHz cavity is used to compensate the RF induced curvature
- Then electron beam is merged with ion beam in blue ring by set of dipoles and quadrupole/solenoids magnets.
- In cooling section 12 m e-beam interacts with ion beam
- Every 2 m there is a solenoid to compensate the transvers space charge defocusing to the beam
- After interaction with ion beam in blue ring the electron beam is turned around and merge back to the RHIC into yellow ring
- After interaction with ion beams the electron beam extract to the beam dump

Same electron beam is used for cooling both ion beams



Magenta: electron trajectory
Cyan: closed loop (marker)
Black: blue and yellow RHIC rings

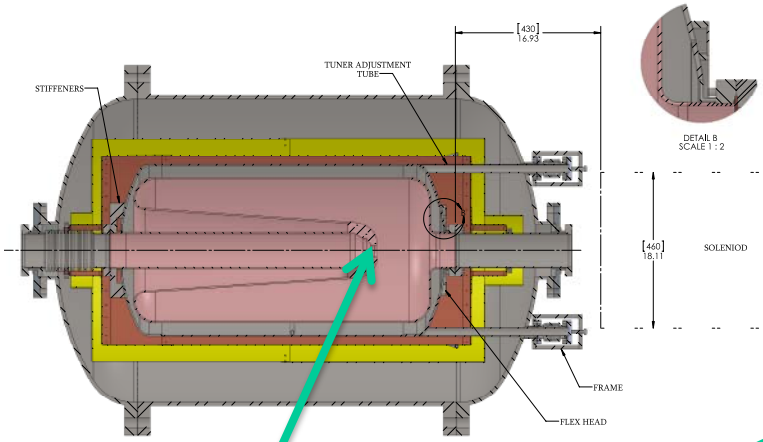
Closed loop from IP through RHIC rings, e-bunch turn around and back to the IP (cyan color) has to be integer number of RHIC bunches distance (63.9m corresponds to 60 bunches in each RHIC ring L_{RHIC}=3834 m)

Beams parameters

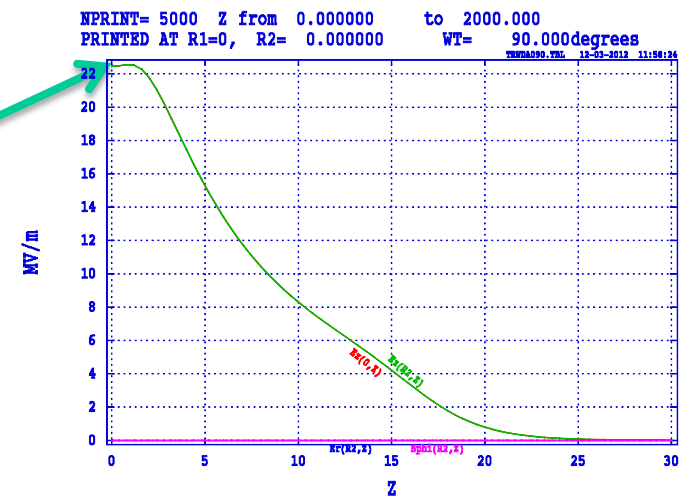
Ion beam parameters		
Gamma	4.1	10.7
RMS bunch length	5.8 m	4.2 m
N_{au}	0.75e9	3e9
I_peak	0.2 A	1 A
Frequency	4.55 MHz	4.67 MHz
Beta function@cooling	30 m	30 m
RMS bunch size	4.3 mm	2.7 mm
RMS angular spread	140 urad	90 urad

Electron beam cooler requirement		
Cooling sections	2x12 m	2x12 m
Charge per ion bunch	4 nC (9x0.44nC)	7 nC (5x1.4 nC)
RMS norm. emittance	< 2.5 um	<2 um
Average current	18.2 mA	32.7 mA
RMS energy spread	<5e-4	< 4e-4
RMS angular spread	<150 urad	<90 urad

Low frequency SRF Gun*



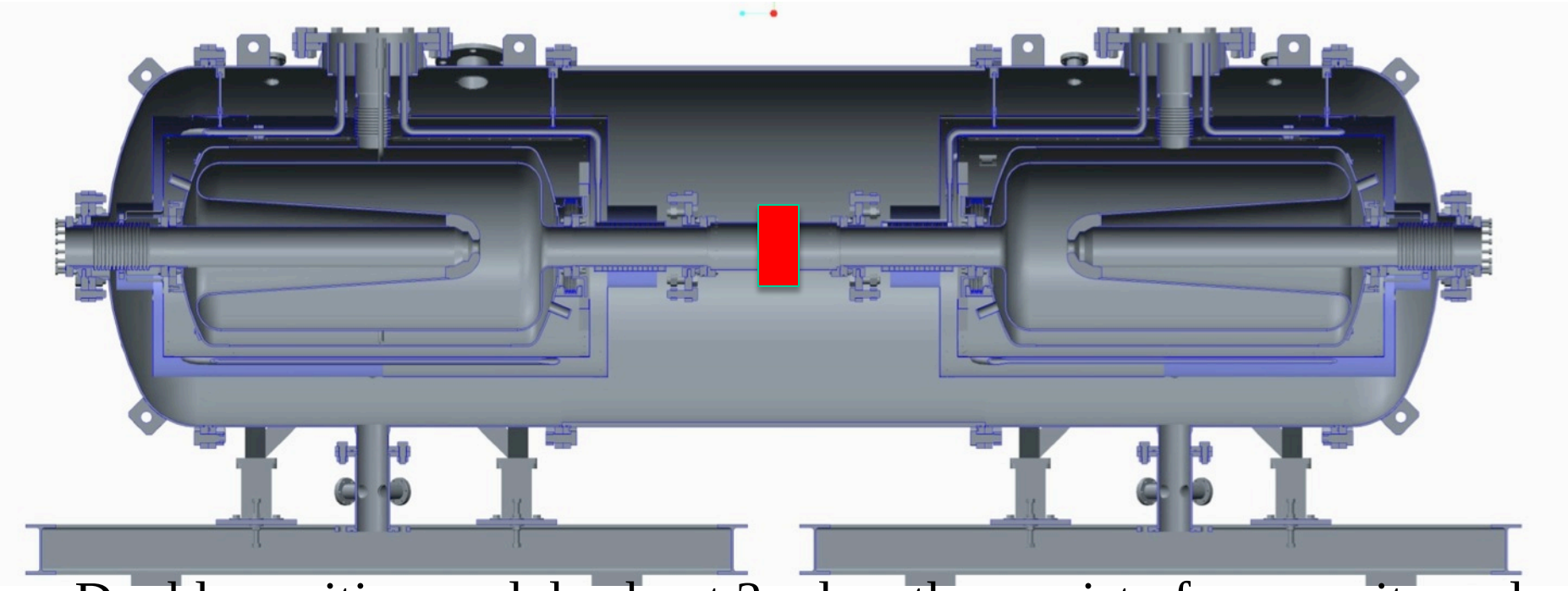
Cross-section of original 112 MHz SRF gun.
New cavity 100MHz will be very similar



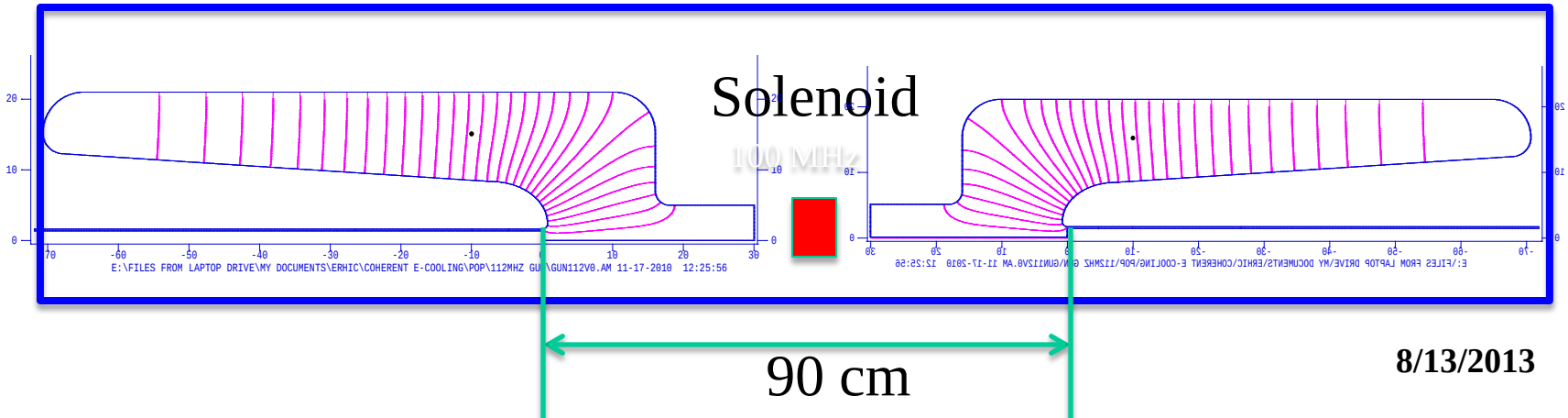
- Photocathode is located in a high electric field.
- Immediate acceleration of the electrons to a high energy reduces emittance degradation caused by a strong non-linear space charge forces.
- The low RF frequency of the gun reduces the RF curvature effect to the beam.

[*] S. Belomestnykh et al, “Design and First Cold Test of BNL Superconducting 112 MH QWR for Electron Gun Applications” TUP051, PAC’11

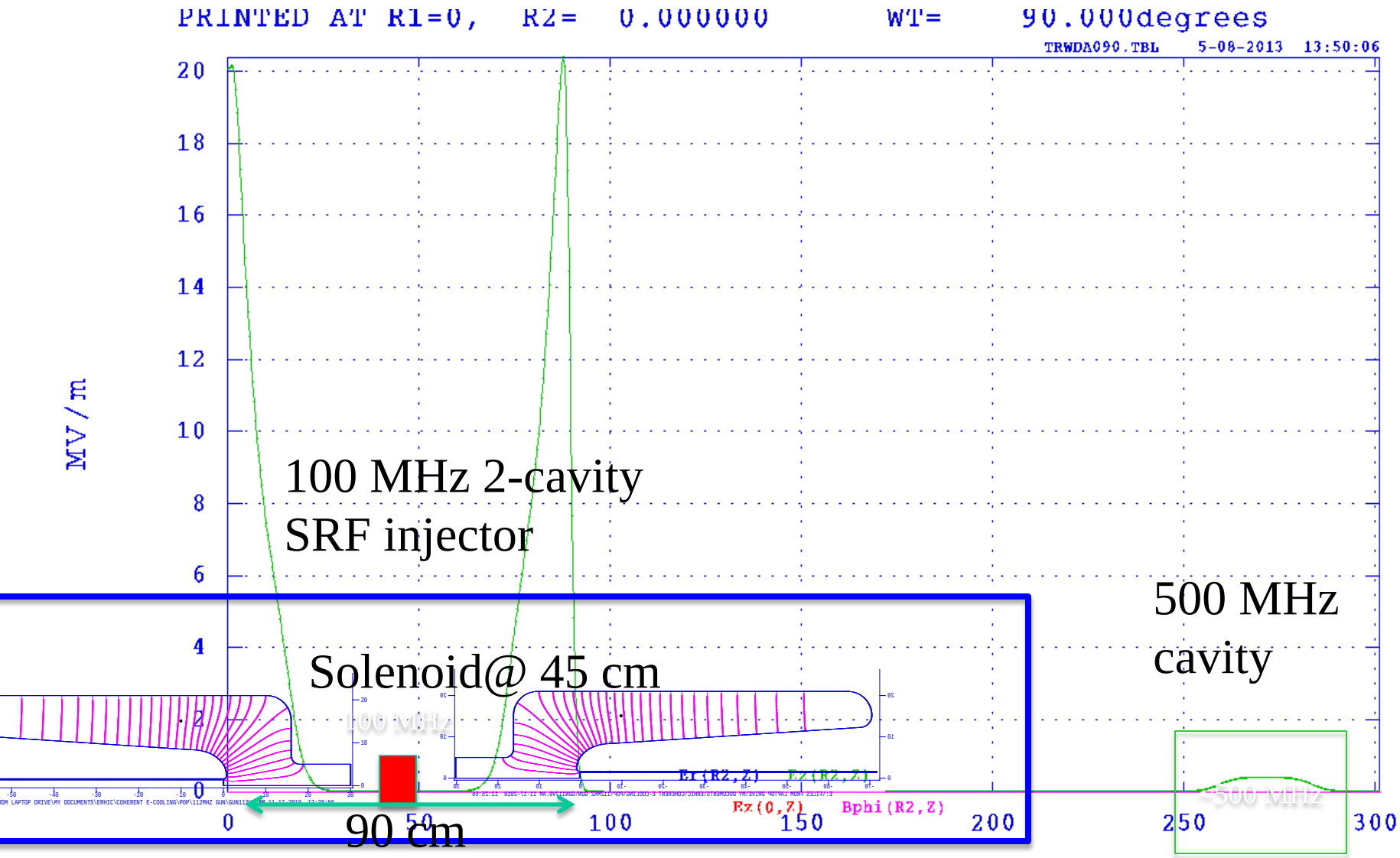
SRF injector up to 5 MeV



Double cavities module about 3m length: consist of gun cavity and booster cavity with solenoid between



5 MeV accelerator based on 2x100 MHz SRF cavities followed by 5th harmonic NC cavity (1/25 of main voltage)



Energy spread due to RF curvature

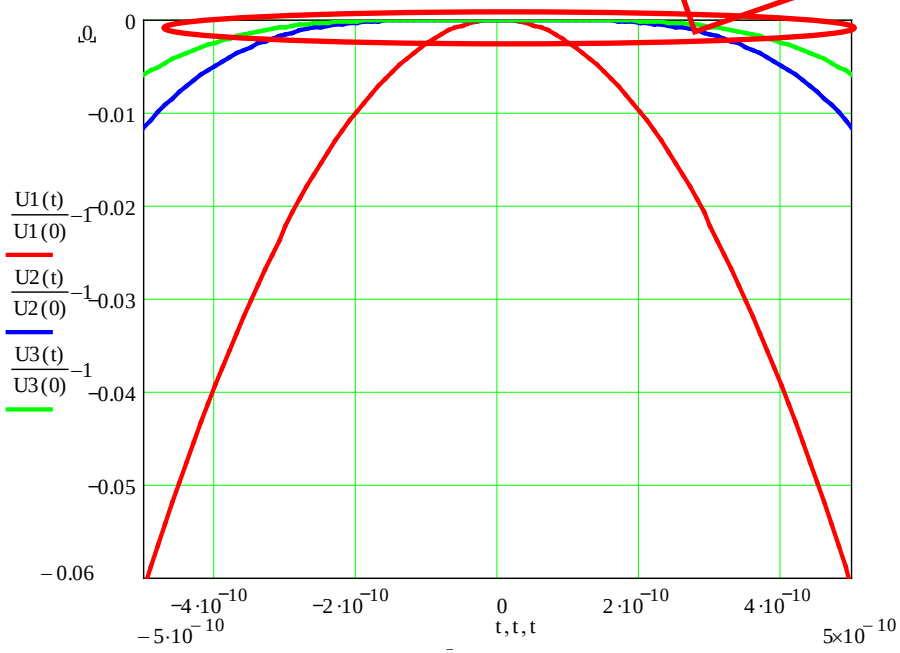
Gun frequency: 100 MHz

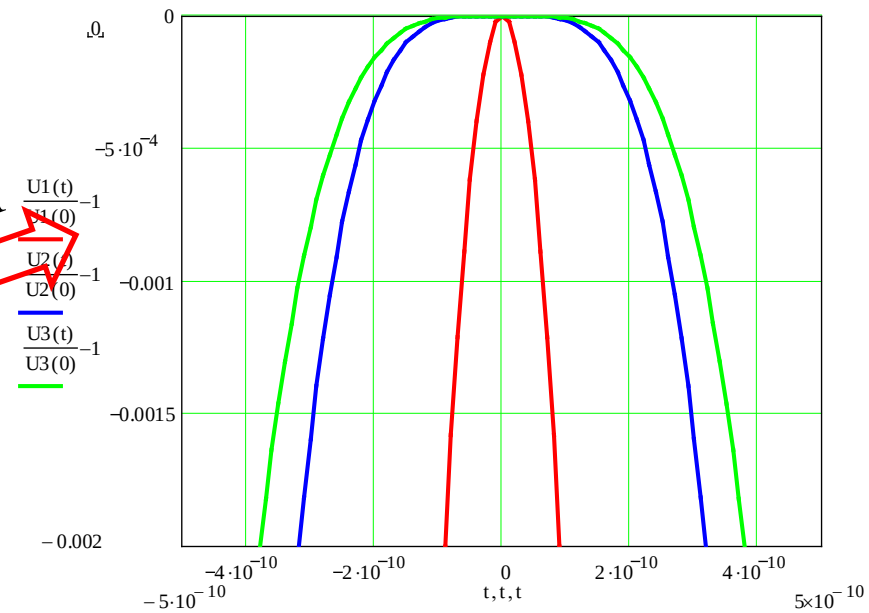
Bunch length: 1 nsec

a) RF corrector frequency: 500 MHz

b) RF corrector frequency: 300 MHz

Zoom in



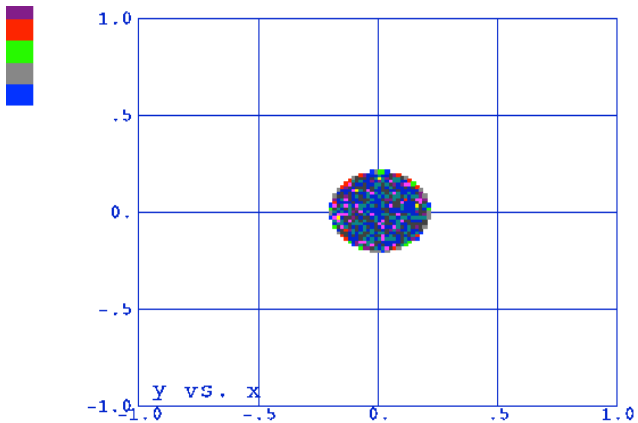


Without RF correction to satisfied e-cooler requirement maximum bunch length 0.1 nsec (very short)

With RF correction bunch length can be relaxed upto 0.7-0.8 nsec. (more reasonable)

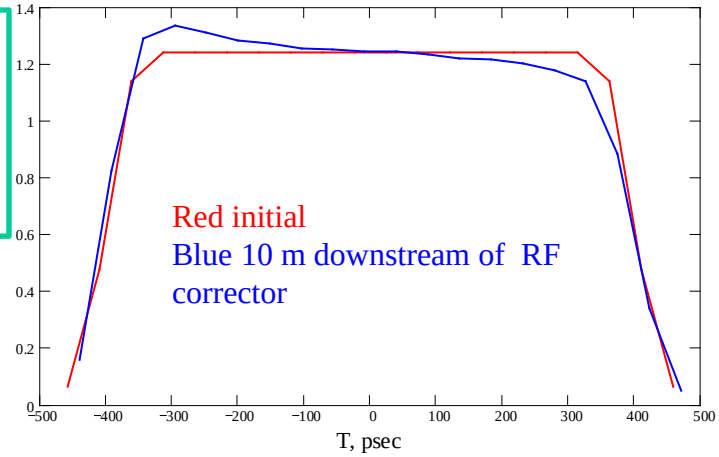
Longitudinal dynamics

Initial beam

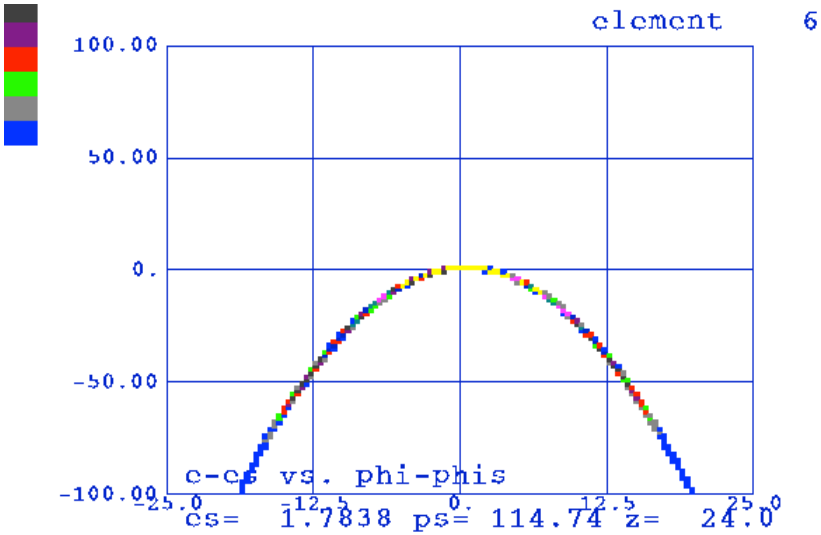


Q=1 nC
T_FWHM=0.75 nsec
R_cathode=2 mm
Final energy: 2.1 MeV

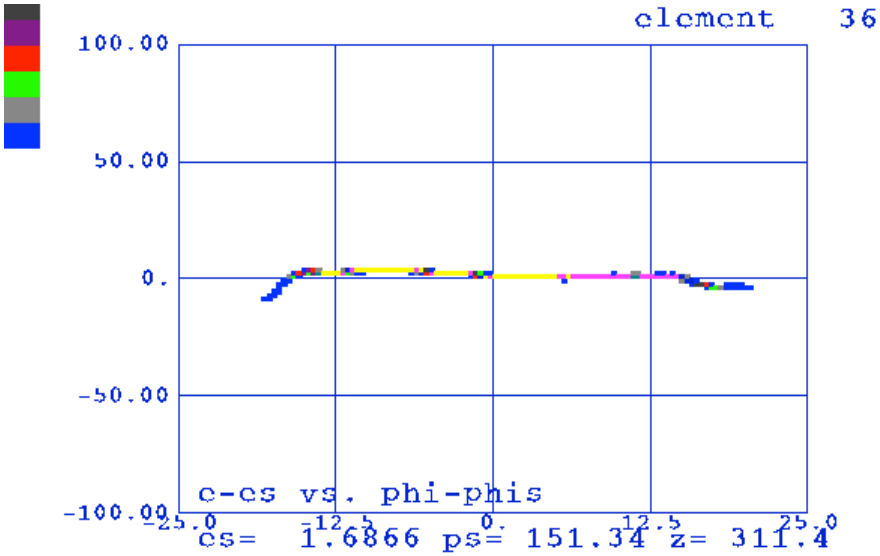
Current distribution



After the gun



After the 5th hormonics correction



Summary beam dynamics in accelerator *PARMELA* simulation

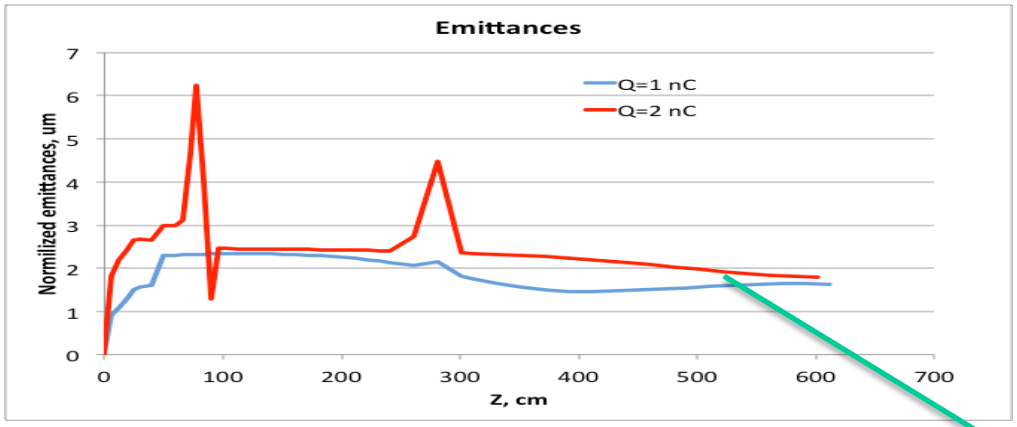
SRF Gun
Vmax=2.5M

SRF buster cavity
Vmax=2.5M

5th hormonic, RF corrector ~1/25 of Gun, V~80kV

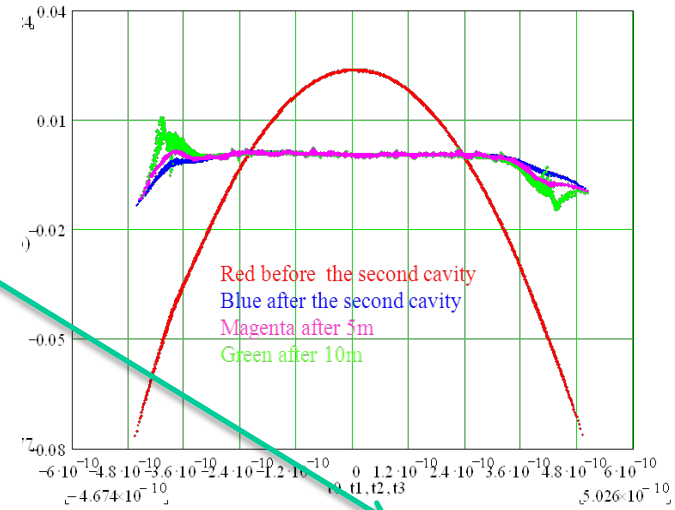
Solenoid

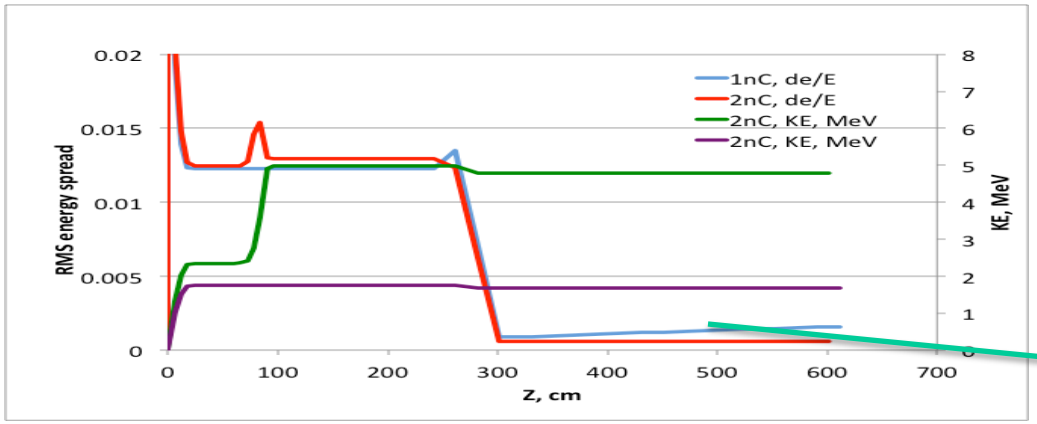
Q=1,2 nC
T_FWHM=0.75 nsec
R_cathode=2 mm
Final energy: 2.1-5 MeV



RMS normilized emittance for Q=1nC gamma 4.1 and Q=2nC gamma 10.7

Longitudinal phase space (gamma=4.1):

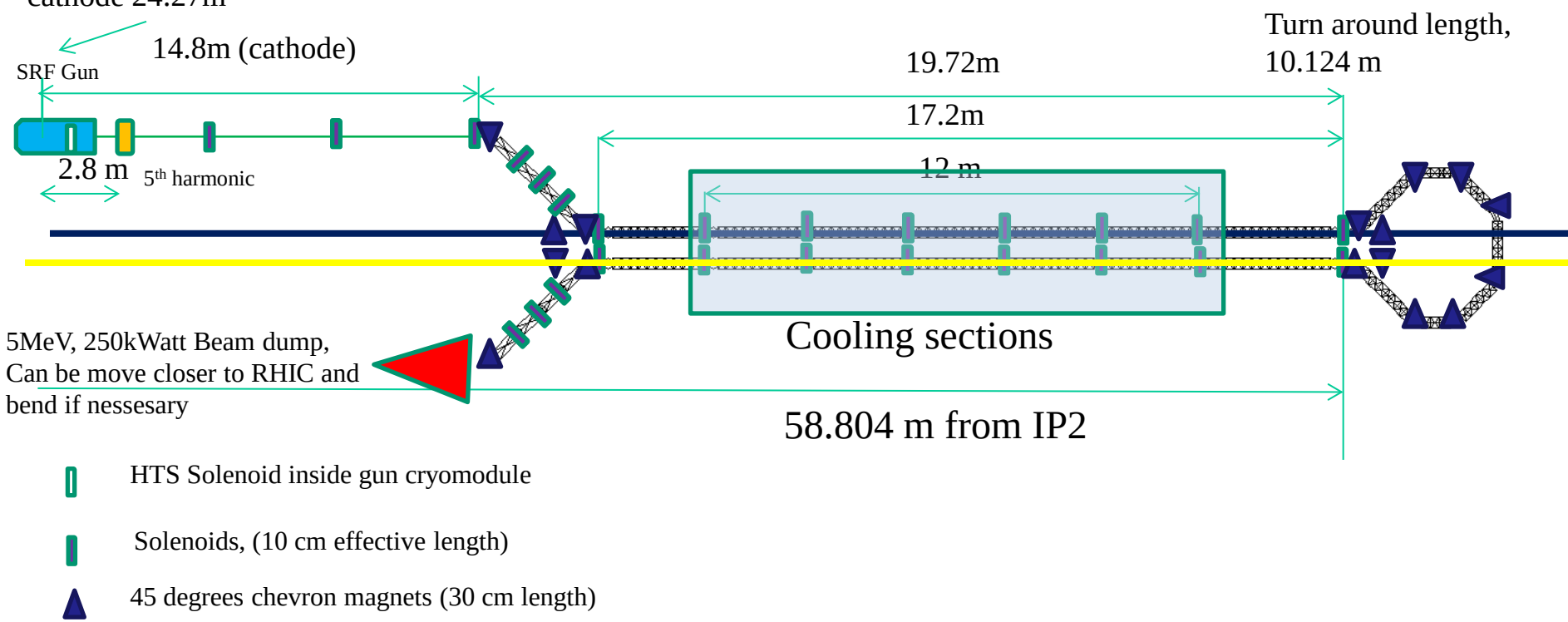




RMS energy spread: for Q=1nC gamma 4.1 and Q=2nC gamma 10.7

γ	Q, nC	ε, um	de/E
4.1	1	1.8	7e-4
10.7	2	2.1	5e-4

eBeam transport layout



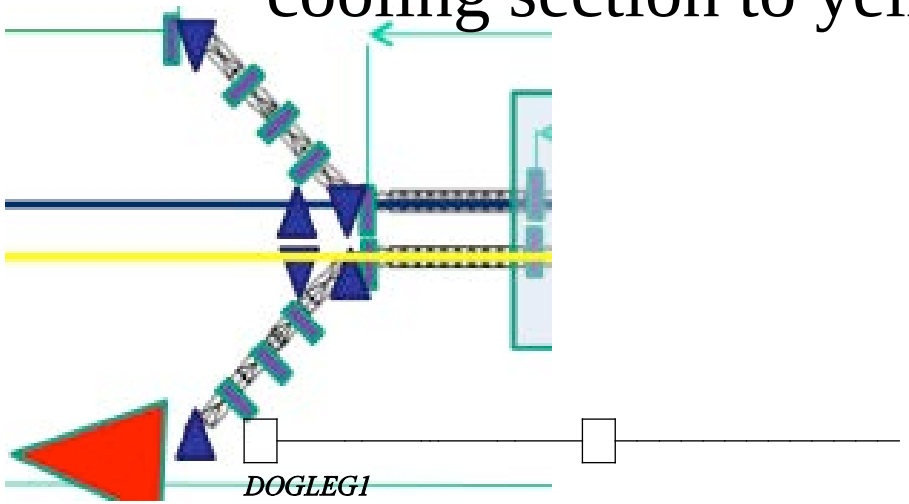
HTS Solenoid inside gun cryomodule

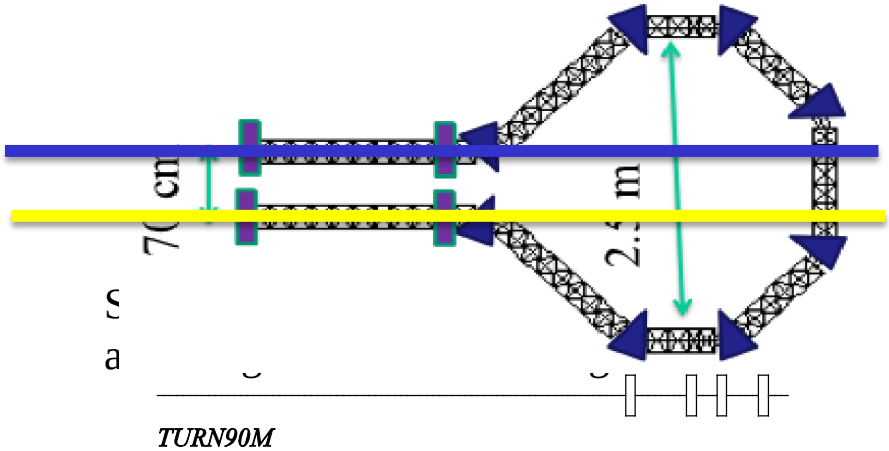
Solenoids, (10 cm effective length)

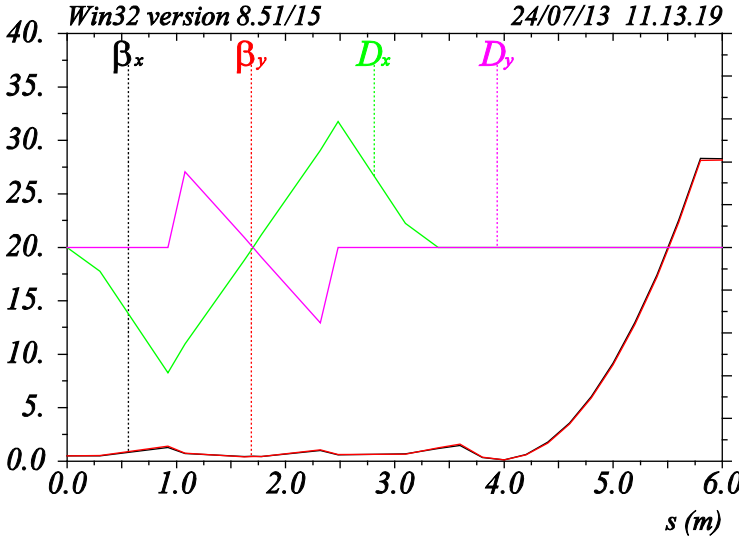
45 degrees chevron magnets (30 cm length)

- 11 m transport line from the accelerator to cooling section includes solenoids for matching beta functions.
- Then there is dog-leg merger to the RHIC blue ring consist of 2 45° chevron type dipole magnets with two solenoids between (triplet of quadupoles can be considered as well).
- First 2 meters of cooling section is used for matching e-beam (telescope: based on two solenoids 2 meters apart) with cooling section (beta 30 m).
- After 12m of cooling section there is turn around transport (consist of two telescopes for matching with 2 solenoids each and 8 45° chevron type dipole magnets.
- After the yellow cooling section there is 2 m matching section and then extraction dipole.

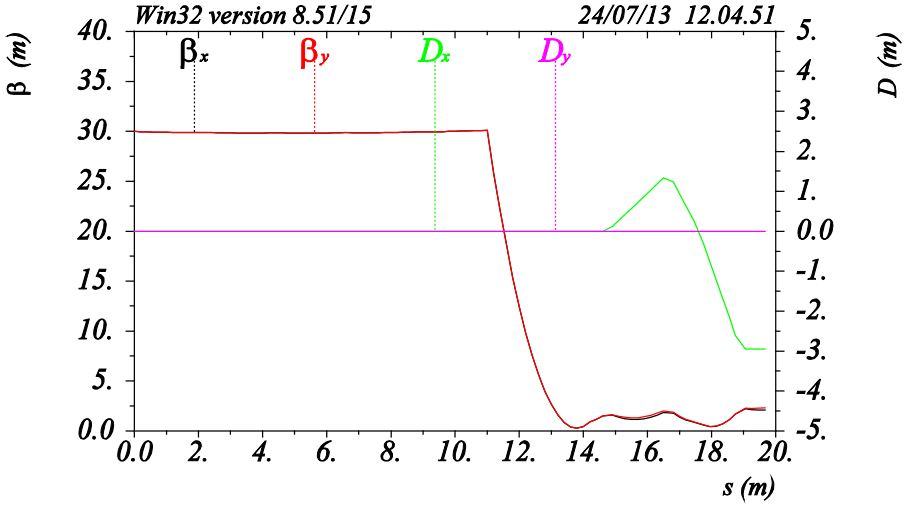
Dog bone turn around transport line from blue ring cooling section to yellow ring cooling section







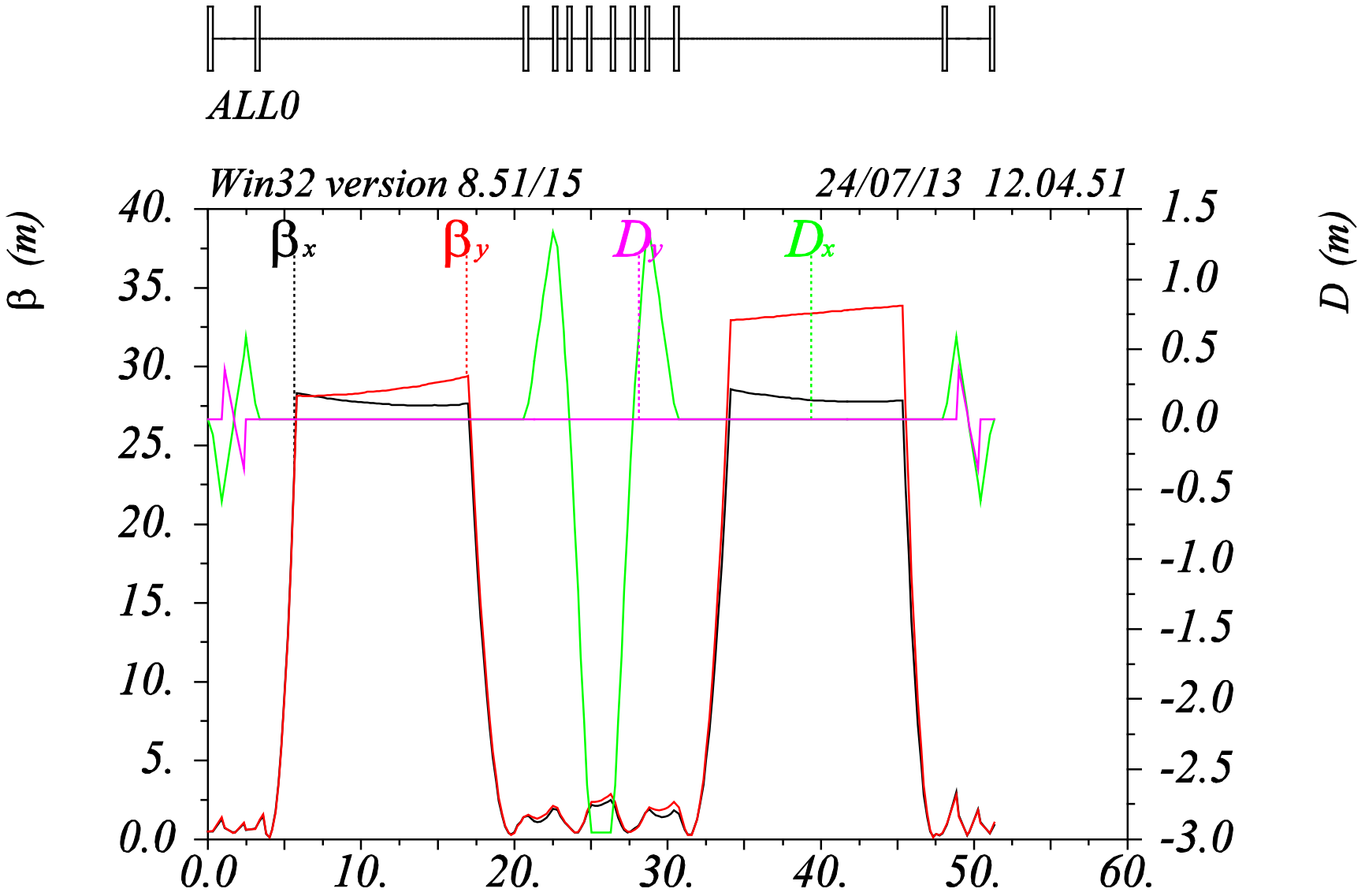
Lattice of dog leg and matching section



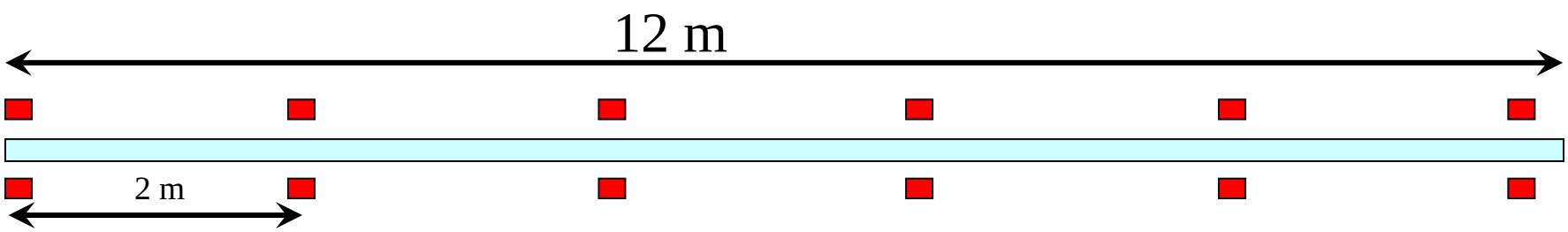
Lattice, Cooling section and half of the U-turn.

After 14m of cooling section there is turn around transport (dog bone) consist of two telescopes for matching with 2 solenoids each and 8 45° chevron type dipole magnets.

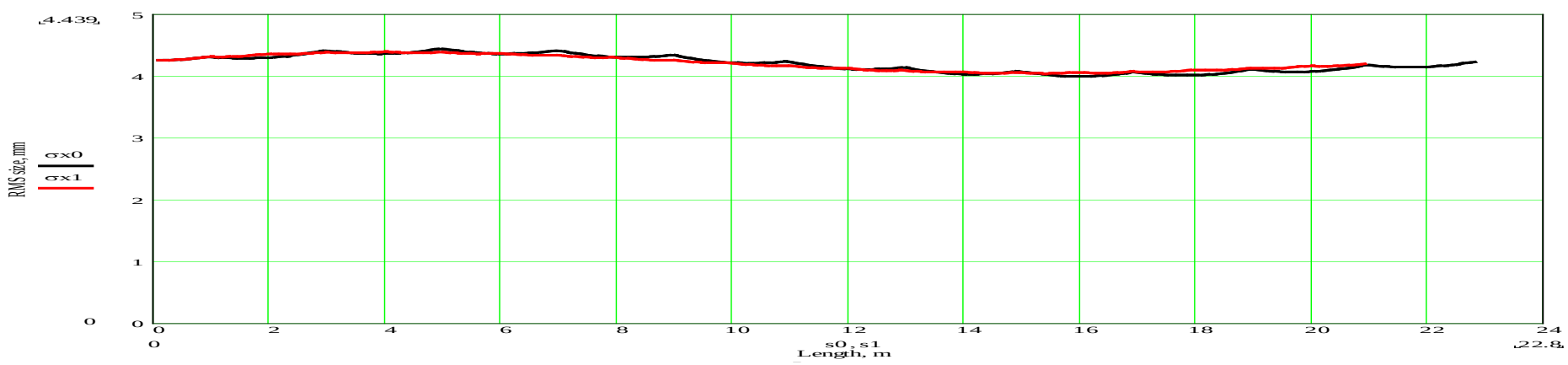
Lattice : injection cooling section blue, turn around, cooling section yellow, extraction



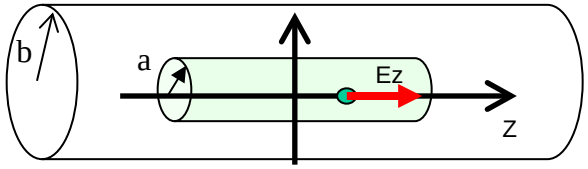
Cooling section with solenoids



RMS Bunch size, rms ~4.2mm

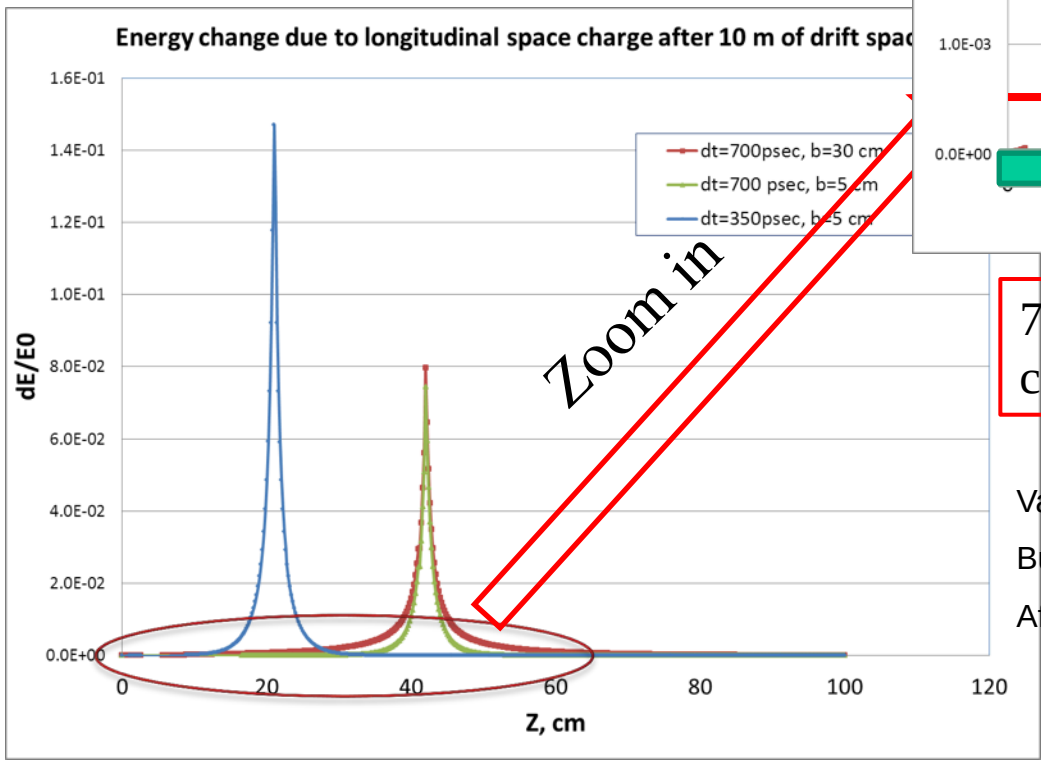


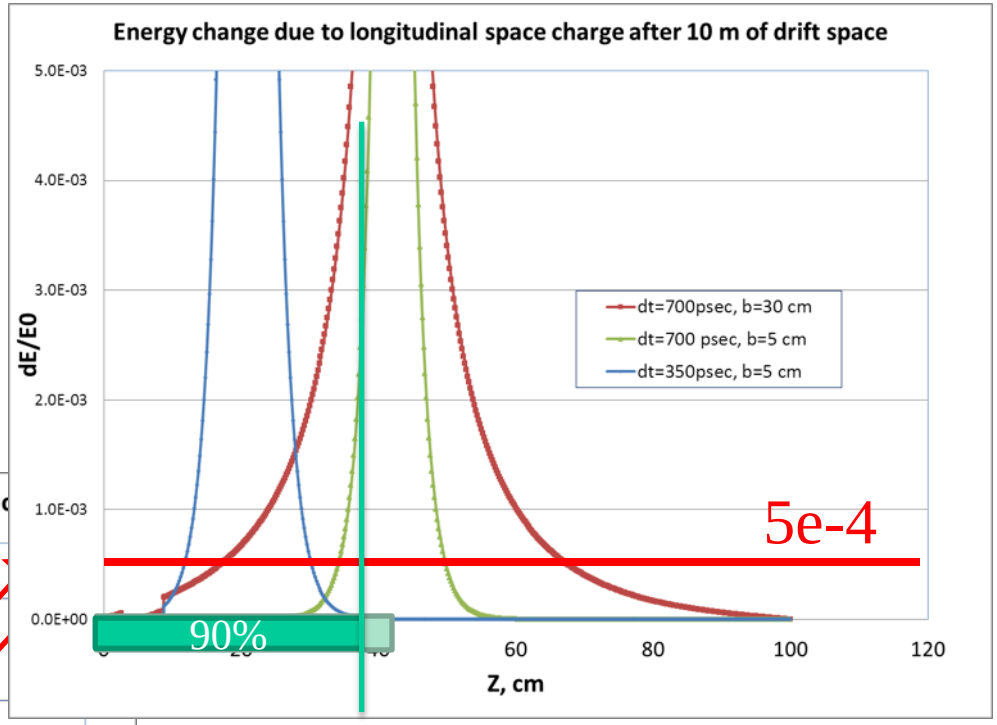
Electric field for cylindrical electron bunch inside the vacuum chamber (in beam frame)



Q=1nC, a=8.6 mm, γ=4.1, b=5 cm

$$E(z) := 2\cdot\frac{Q}{L0\cdot a^2}\cdot\begin{cases}\operatorname{sign}(z)\cdot L0-\sqrt{a^2+\left(\frac{L0}{2}+z\right)^2}+\sqrt{a^2+\left(\frac{L0}{2}-z\right)^2} & \text{if } |z|\ge\frac{L0}{2}\\ 2\cdot z-\sqrt{a^2+\left(\frac{L0}{2}+z\right)^2}+\sqrt{a^2+\left(\frac{L0}{2}-z\right)^2} & \text{otherwise}\end{cases}$$

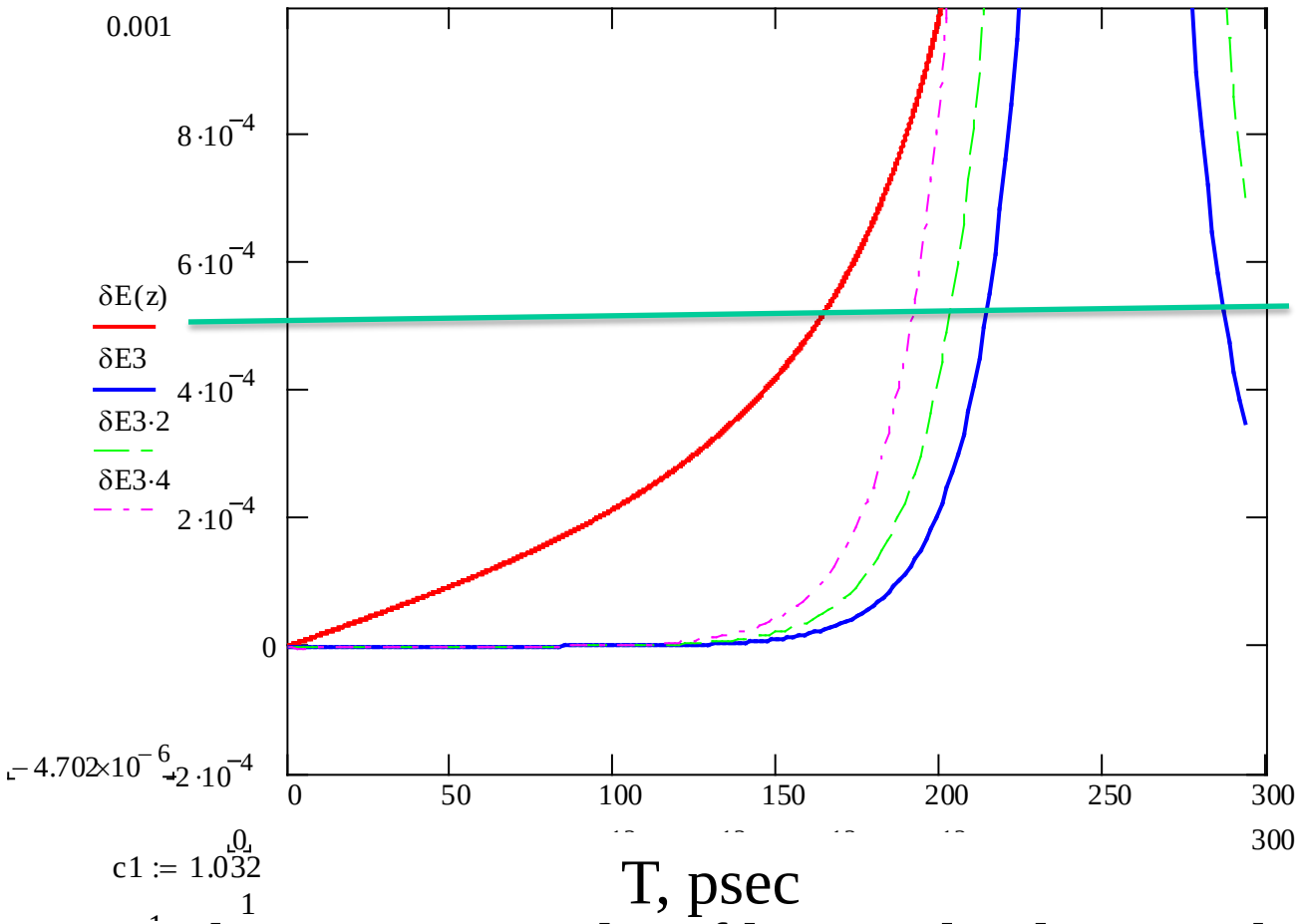




700 psec bunch inside 5cm vacuum chamber

Vacuum chamber:	~free space	5cm	5cm
Bunch length:	0.7ns	0.7 ns	0.35 ns
After 10m 90% $\sigma_{\Delta E/E}$:	4.4e-4	1.4e-4	2.7e-3

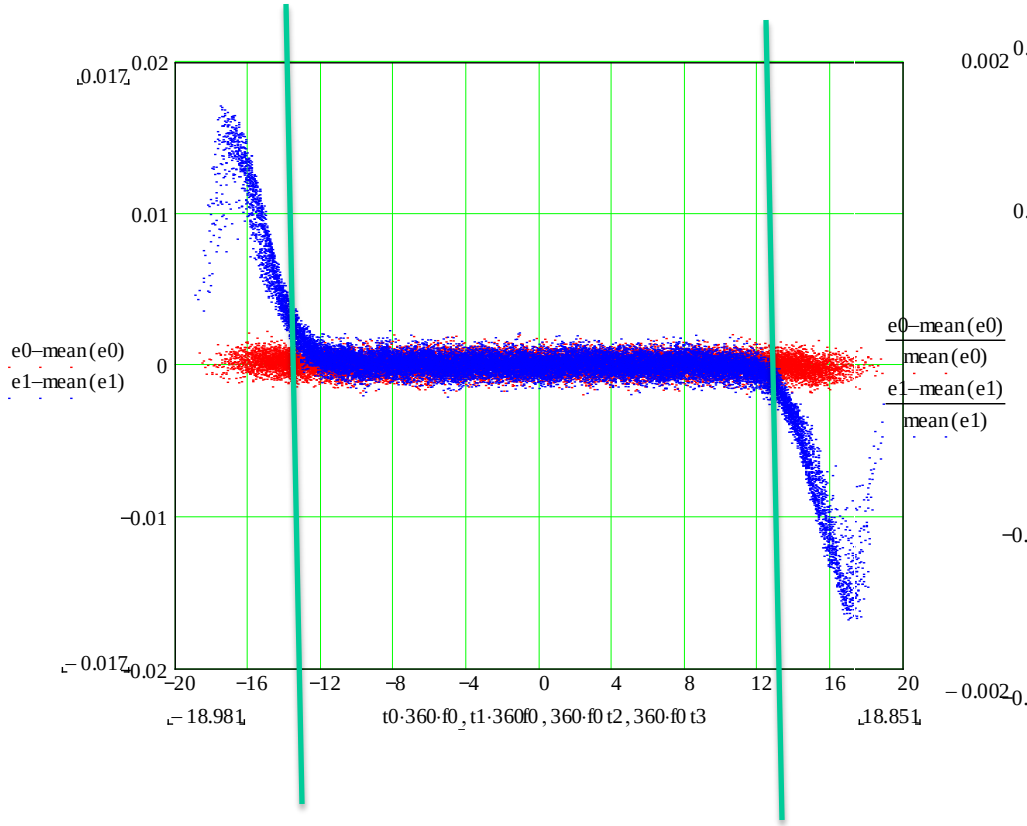
Shielding longitudinal space charge by the vacuum chamber

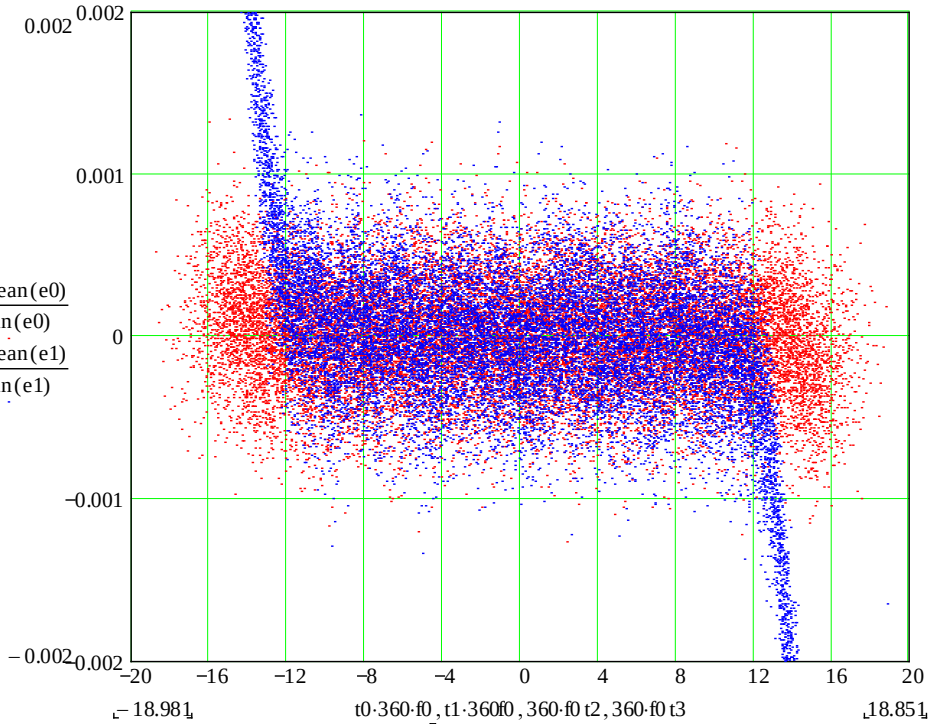


Energy change as a results of longitudinal space charge after 20 m of drift space for 500 psec cylindrical bunch.

Red: free space 1nc bunch, Blue, green, magenta: round vacuum chamber r=6 cm for different charge per bunch 1,2,4 nC

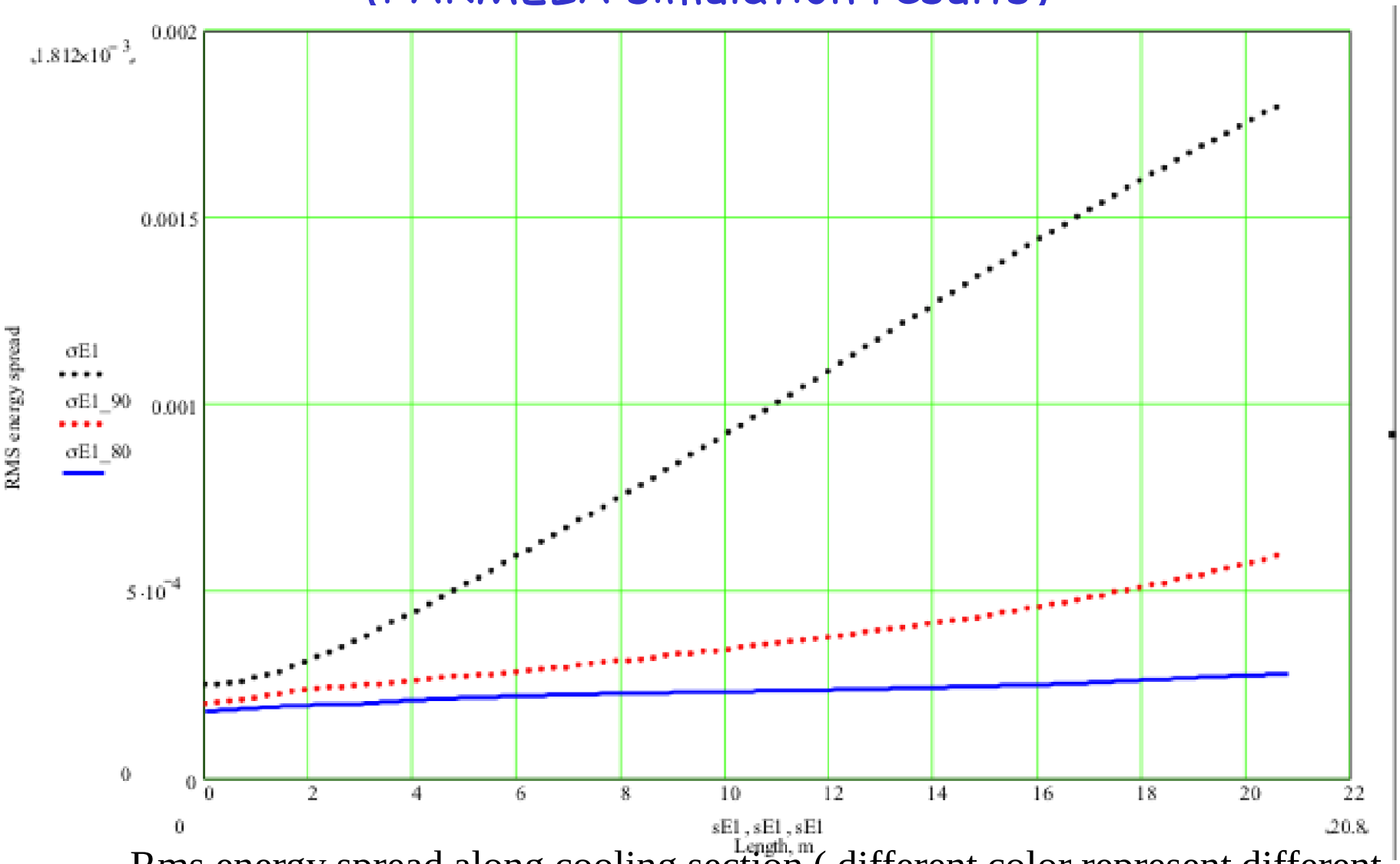
Longitudinal phase space before and after 20 m cooling section simulation results





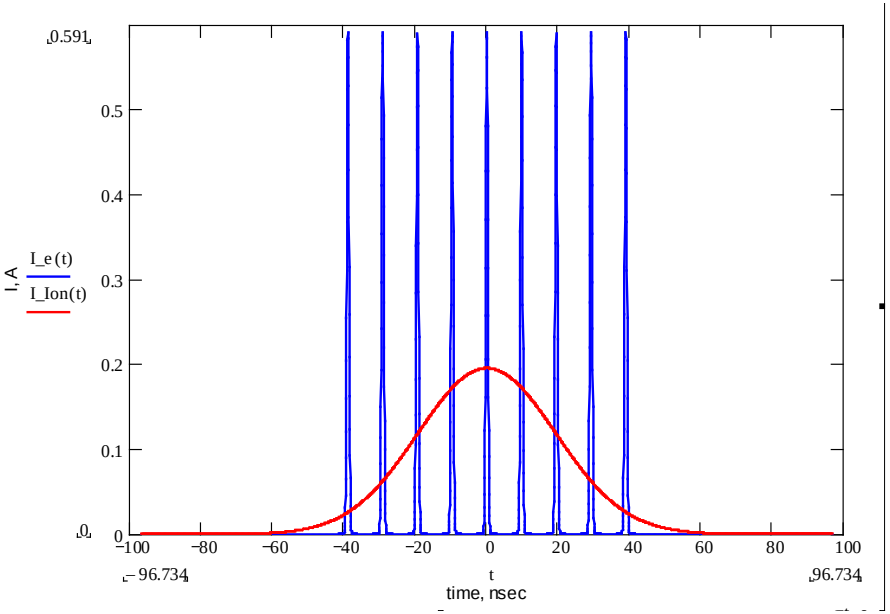
80% of charge no visible energy spread degradation

RMS Energy spread along 20 m cooling sections (PARMELA simulation results)

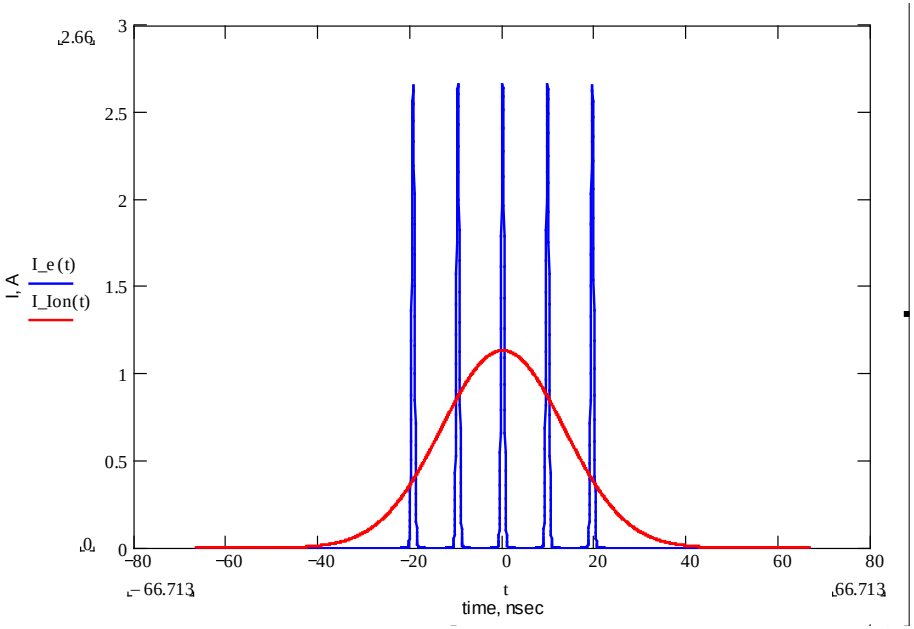


Rms energy spread along cooling section (different color represent different portion of the beam: black 100%, red 90%, blue 80%).

Using train of electron bunches for cooling each ion bunch.



.45 nC , Flat Length=0.75 nsec,
I_peak=0.6A, 2.92 m (9.7 nsec) apart



2nC , Flat Length=0.75 nsec,
I_peak=2.5A, 2.92 m (9.7 nsec) apart

- Electron cooling will be provided with a train of electron bunches place on single ion bunch
- For ion bunches at lowest energies with 4.5 MHz RF we can place up to 9 electrons bunches on a single ion bunch.
- For highest energy of g=10.7 we can place 5 electron bunches on a single ion bunch.
- The laser will produce the bunch pattern needed.

Linear part of transverse space charge effect

Effective defocus straight of space charge force:

$$Ksc := \frac{2Ie0}{Ia\cdot(\gamma\cdot\beta)^3\cdot(a)^2}$$

Ia = 17000A

Focus straight of solenoid:

$$\left(\frac{eBsol}{2pc}\right)^2 Lsol$$

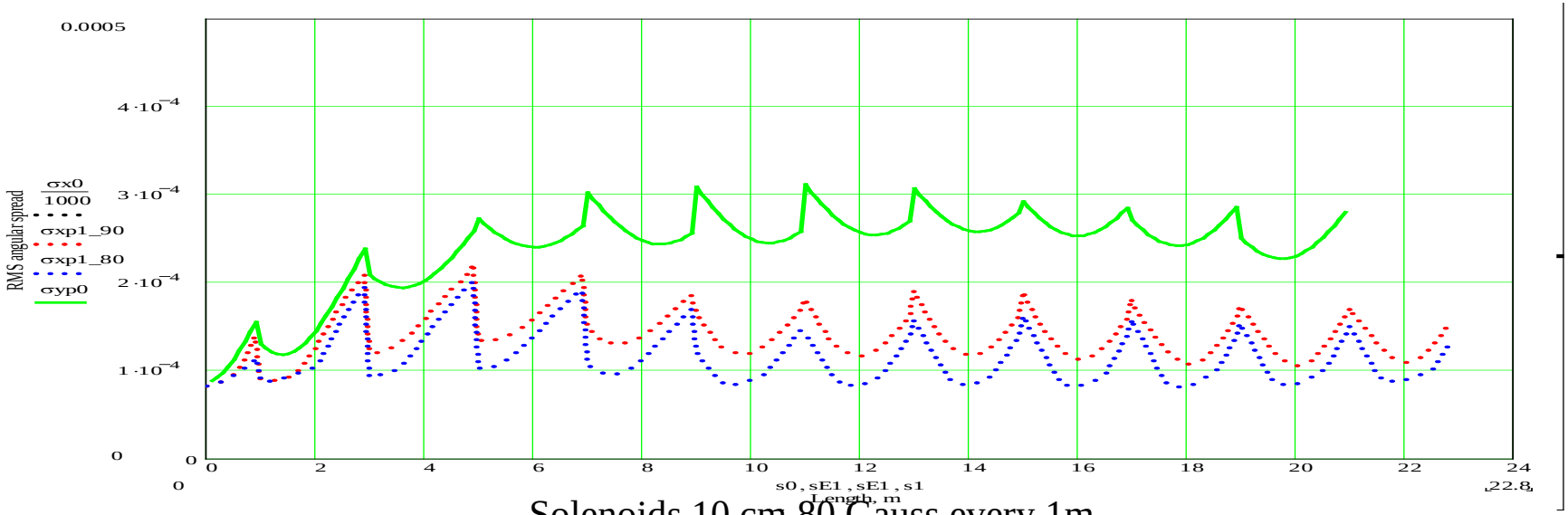
γ=4.1	γ=10.7
Q=1nC	Q=2nC
I = 1.2 A	I = 2.8 A
L = 20 m	L = 20 m
a=8.6 mm	a=5.2 mm

Angular spread increase due to transverse space charge

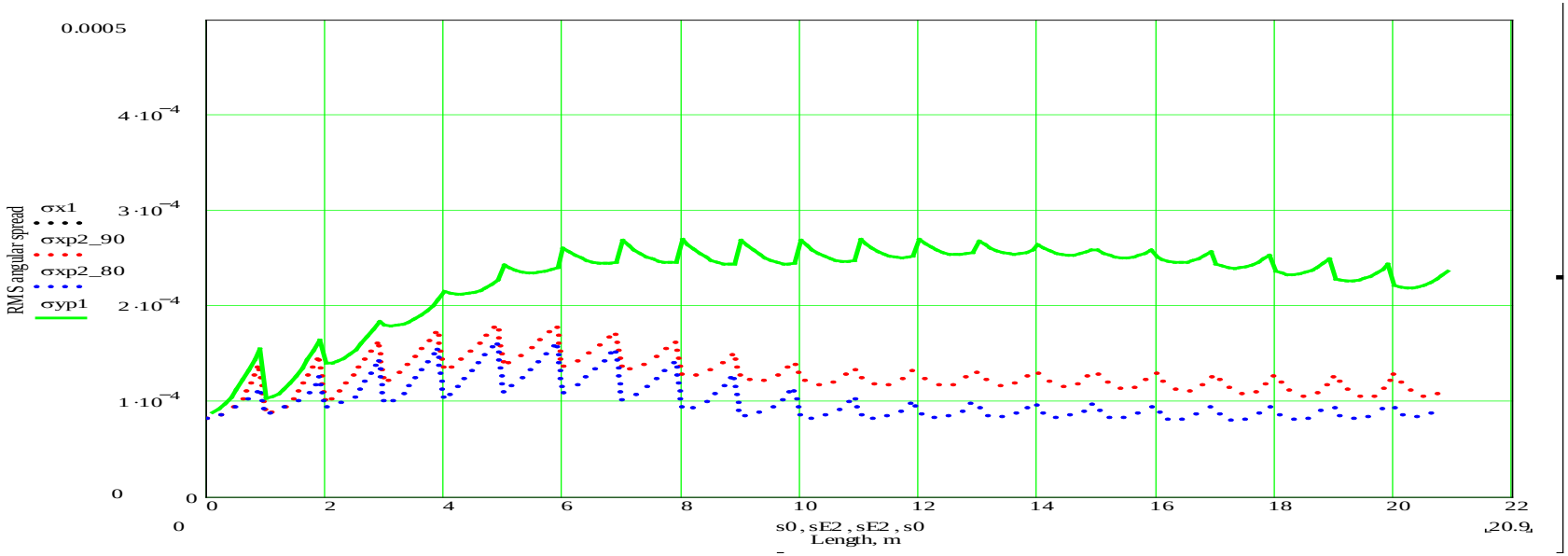
after 2 m: ~115 urad (req. <150 urad)	after 2 m: ~53 urad (req. <90urad)
↓	↓
Continues solenoid:	Continues solenoid:
Lsol=20m	Lsol=20m
Bsol= 25 Gauss	Bsol= 37 Gauss
Solenoids every L=2m;	Solenoids every L=2m;
Lsol=10 cm ;	Lsol=10 cm ;
Bsol= 115G ;	Bsol= 164G ;

Rms angular spread in cooling section (no ion beam) 100%,90% 80%

Solenoids 10 cm 113 Gauss every 2m

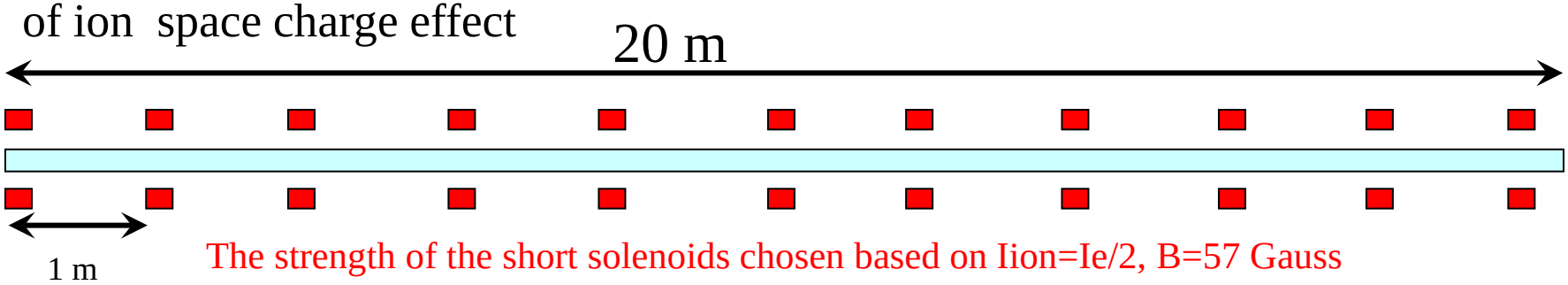


Solenoids 10 cm 80 Gauss every 1m



Ion space charge focusing effect

Long solenoid with the same focusing strength can be use to represent linear part of ion space charge effect



The strength of the short solenoids chosen based on Iion=Ie/2, B=57 Gauss

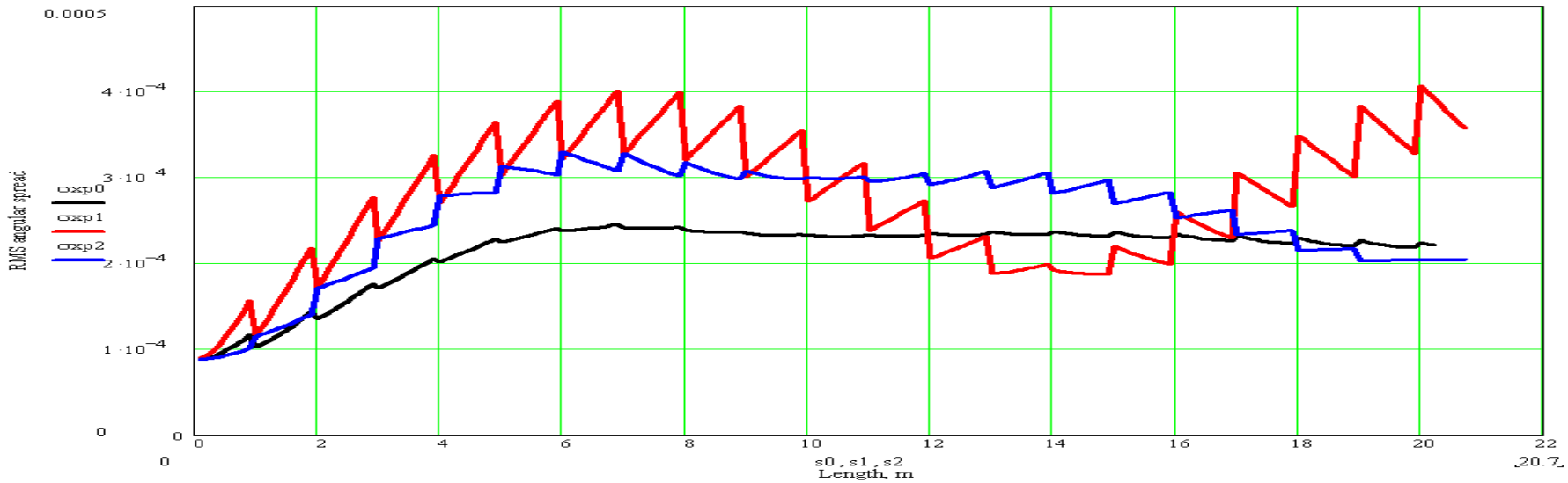
Linear part

$$\frac{I_{ion} * Lcool}{Ia * (\gamma\beta)^3} \frac{1}{\sigma^2} \left(\frac{eBsol}{2pc}\right)^2 Lsol$$

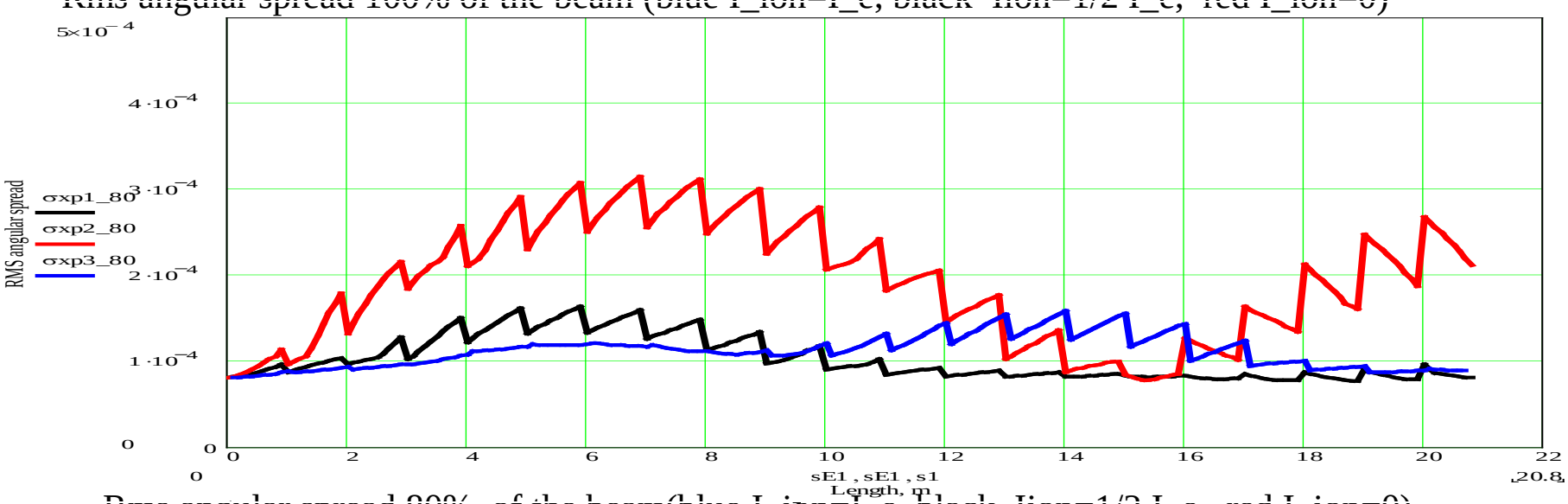
	Effective long solenoid (Lsol=Lcooler)
I_ion	
I_e/2	B=17 Gauss
I_e	B=24 Gauss
0	B=0 Gauss

Ion space charge focusing effect

Angular spread for different Ion current and constant lumped solenoid field Bs=57Gauss



Rms angular spread 100% of the beam (blue I_ion=I_e, black Iion=1/2 I_e, red I_ion=0)

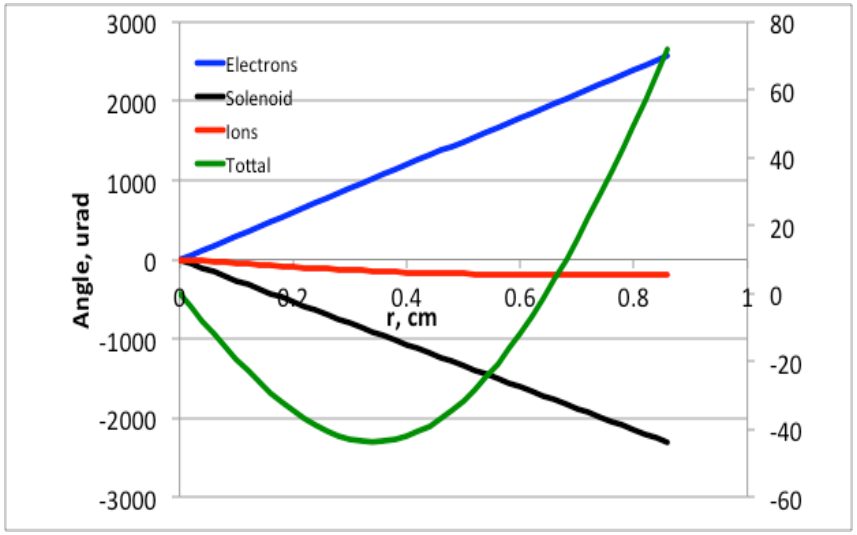


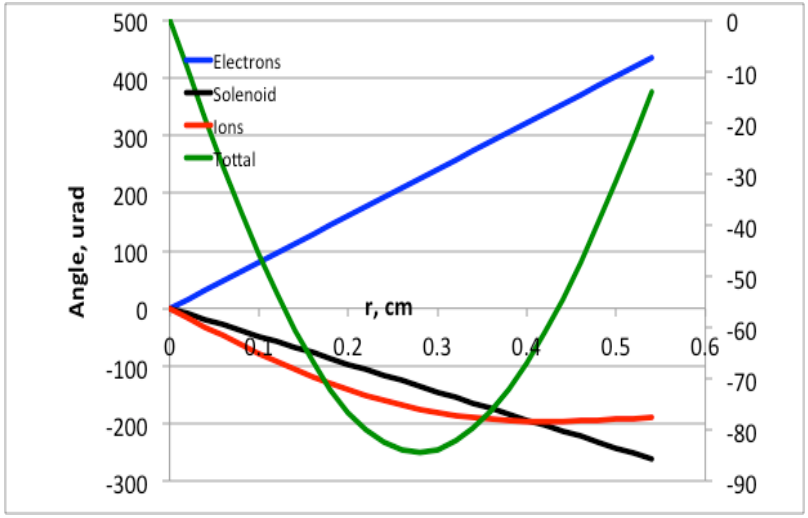
Rms angular spread 80% of the beam(blue I_ion=I_e, black Iion=1/2 I_e, red I_ion=0)

Non linear ion space charge effects

$$\frac{2 * I_{ion} * Lcool}{Ia * (\gamma\beta)^3} \frac{1}{r}\left(1 - e^{\frac{-r^2}{2\sigma^2}}\right)$$

After 12 m of cooling section angle gain along e-bunch radius:
Blue: Electron space charge (Uniform), Black: Linear compensation by solenoid,
Red: Ion space charge (Gaussian), Green: Total angle due to non-liner ion focusing,





Gamma 4.1,Qe=1nC, I_ion=0.2A,
rms angular spread <50 urad

Gamma 10.7, Qe=2nC, I_ion=1A,
rms angular spread <30 urad

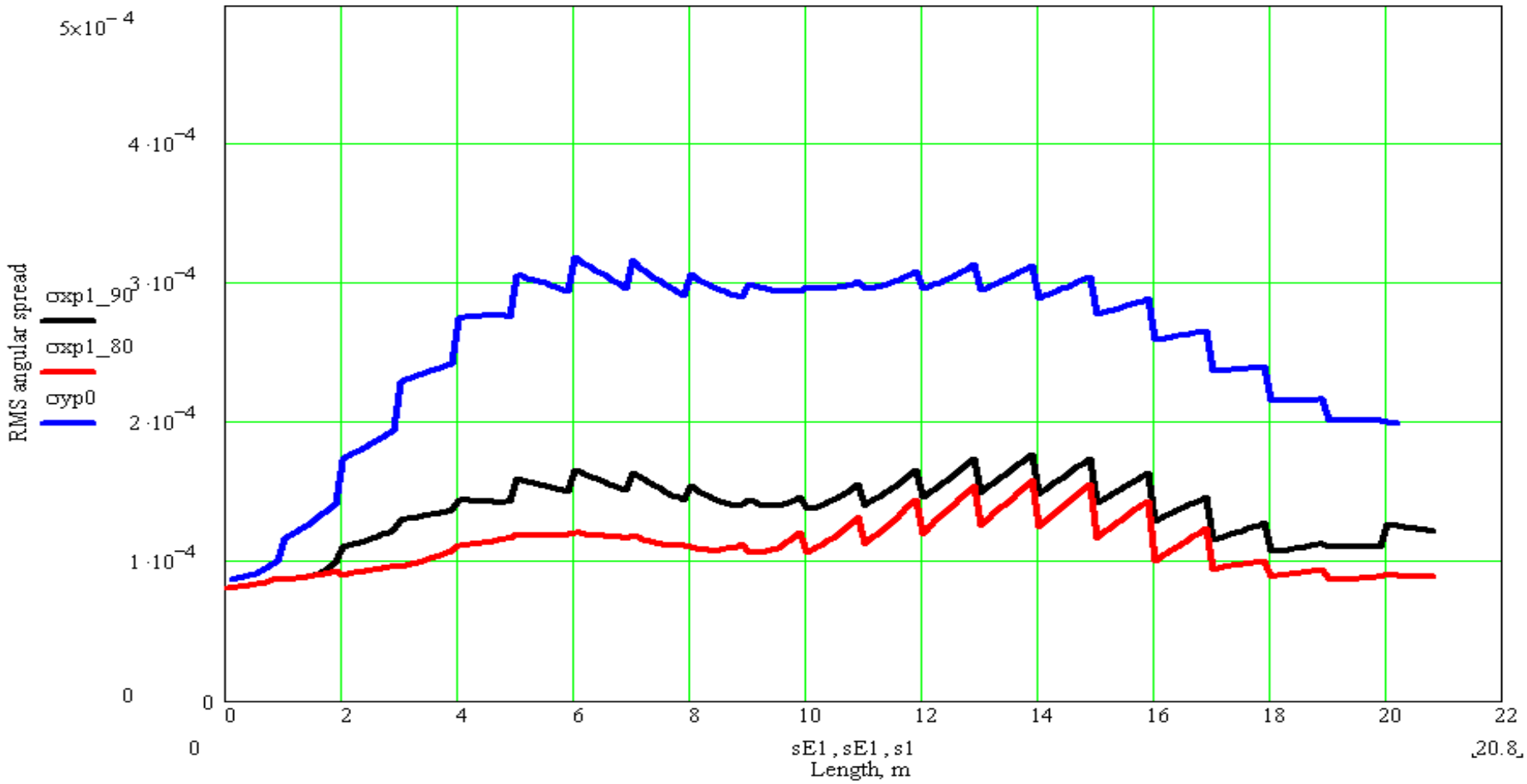
Summary

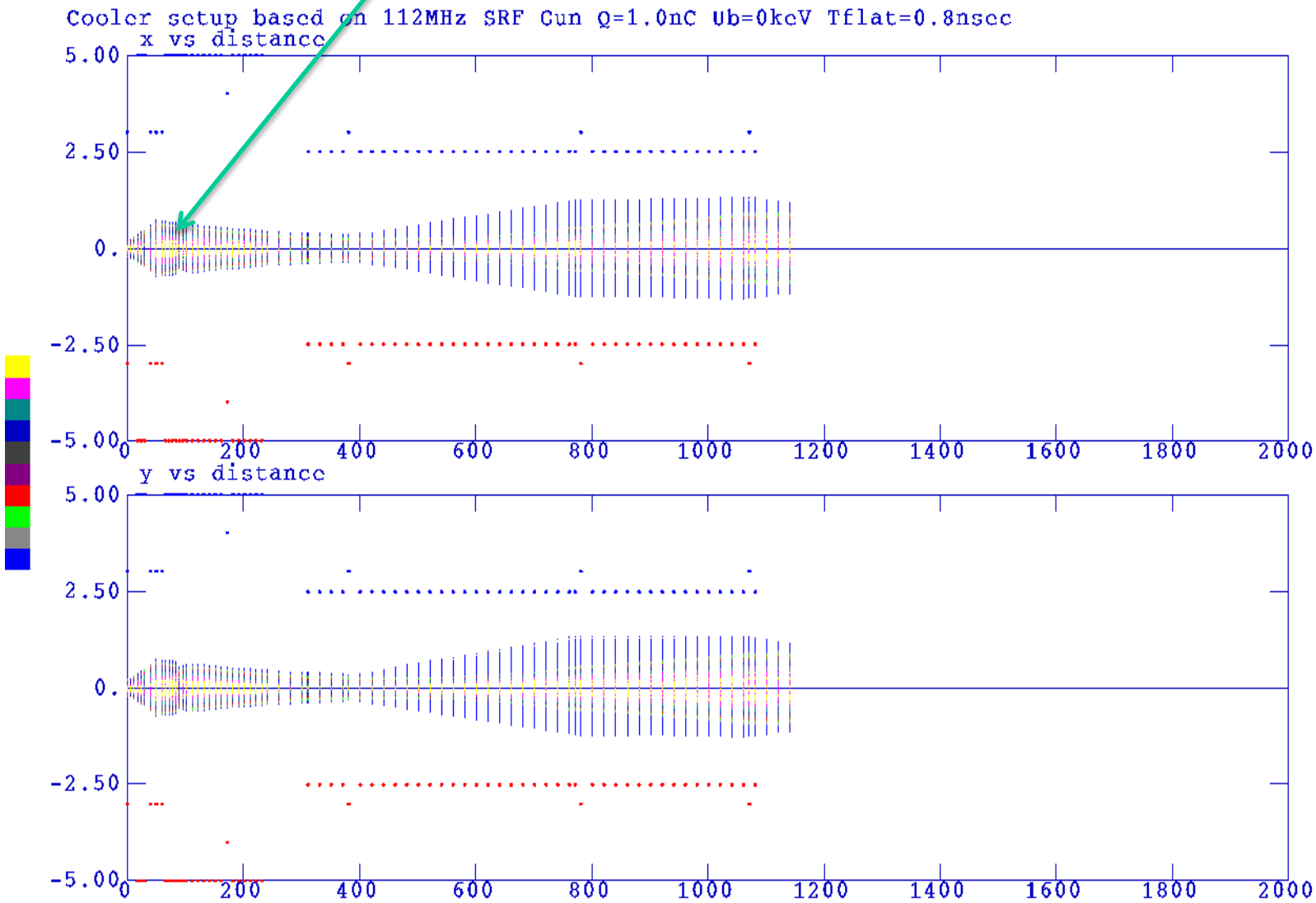
- Based on simulations and models:
  - Injection system based on low frequency gun can provide required e-beam parameters
  - Preliminary lattice design of beam transport is completed.
  - By design the lattice is flexible for final tuning in order to match ion and electron beams envelopes when/if it's required.
  - Beam quality doesn't degrade in cooling section with and without ion beam.
  - Long bunches and longitudinal space charge screening due to vacuum chamber essential part of beam quality preservation.

- More simulation/optimization will be required using full 3D field profiles then design of RF elements and magnets are finalized.

Back up

Iion=Ie, Bs=57Gauss



Rms angular spread in cooling section (blue 100%, black 90%, red 80%)

Q=1 nC, dt=750psec, gamma=4.1, Solenoid 700 Gauss between Gun and booster