Electron Cooling
Expected Performance &
Construction

Electron Cooler Parameters

Momentum (MeV/c)	35	13.7
β	0.037	0.015
Electron beam energy (eV)	355	55
Electron current (mA)	5	2
Electron beam density (m^{-3})	1.38×10^{12}	1.41×10^{12}
Bgun (G)	1000	
Bdrift (G)	100	
Expansion factor	10	
Cathode radius (mm)	8	
Electron beam radius (mm)	25	
Twiss parameters (m)	β_h=2.103, β_v=2.186, D=1.498	

Why These Parameters?

Constraints imposed by the machine design:

- Available space
- Machine lattice
- Perturbation to the ring

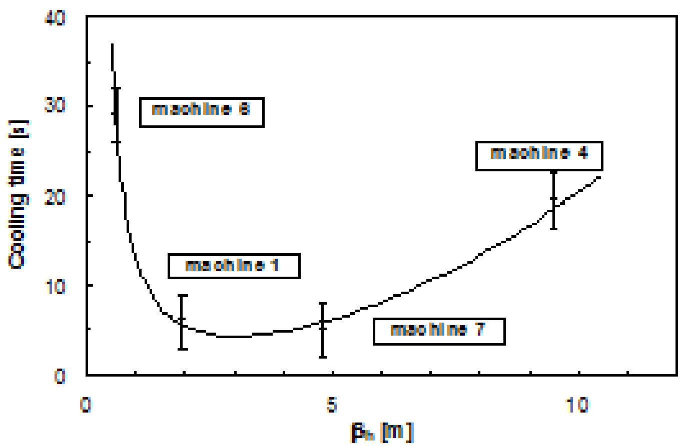
Experience obtained designing, operating and optimising electron coolers

- >30 years on LEAR/LEIR and AD
- Experience from other labs (Kyoto, MPI Heidelberg…)

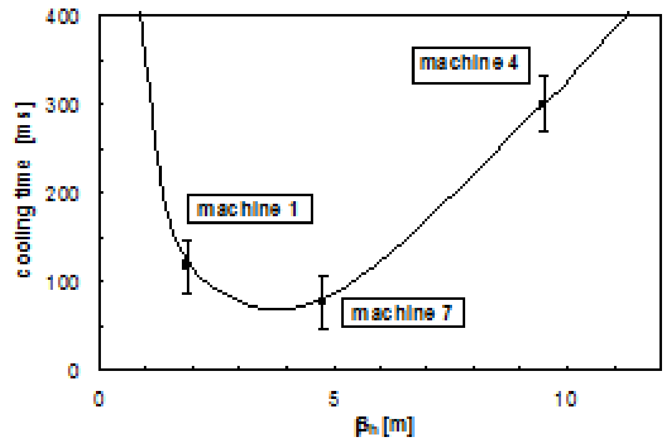
Theory/simulations

- Evaluation of the cooling time
- Identify any limitations
- Betacool simulations

“Optimum” Lattice Parameters

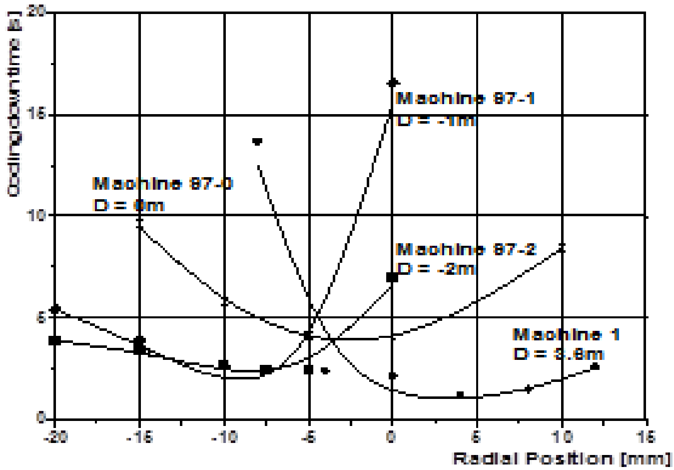


Plot of the cooling down time for 50 MeV protons as a function of the horizontal beta function in the cooler.



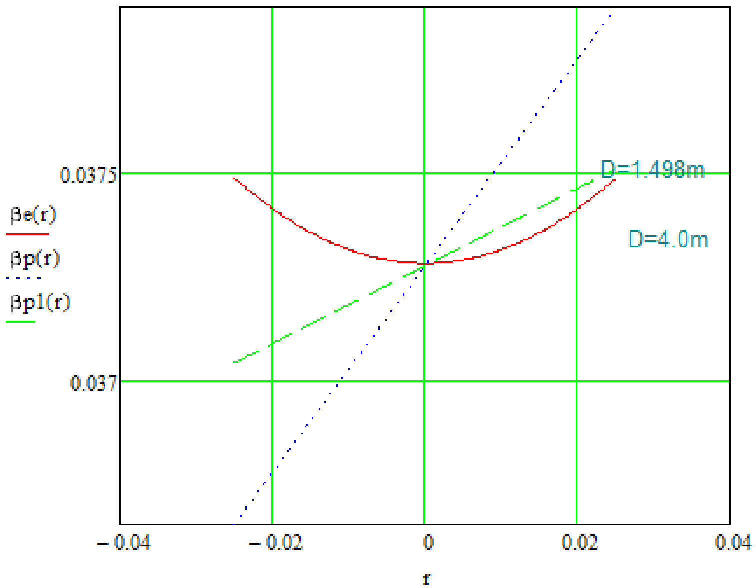
Cooling down time for Pb54+ ions at 4.2 MeV/u as a function of horizontal beta function in the cooler.

machine	*1*	*4*	*6*	*7*	*97*
β_h (m)	1.9	9.5	0.65	4.8	5.0
β_v (m)	6.4	10.5	5.5	5.0	5.0
D (m)	3.6	9.9	0.0	5.0	0.0



Cooling down times for 50 MeV protons as a function of the horizontal offset between proton and electron beam for machine 1 and machines 97-0, 97-1 and 97-2.

$$D \approx \sqrt{\frac{1}{30\Omega}\frac{\gamma+1}{\gamma}\frac{\beta U a_e^2}{I_e(\Delta p/p)}}$$



Many different models/theories on how to evaluate the cooling time.
All give different results BUT all agree that :

$$\tau \propto \frac{\theta^3}{\eta I_e} \frac{A}{Z^2} \gamma^5 \beta^4$$

- Where $\theta = \theta_i - \theta_e$ is the relative difference in angle between the electrons and ions. $\theta_i = \sqrt{(\varepsilon/\beta)}$, $\theta_e = v_t/v_{//}$
- The parameter $\eta = l_{cooler}/l_{machine}$.
- I_e is the electron current.
- A is the atomic mass and Z the charge state of the ion.
- Relativistic factors β, γ.

Cooling Performance Check (A. Burov)

$$\theta_{eS} := \frac{1}{\beta} \cdot \sqrt{r_e \cdot n_e^{\frac{1}{3}}}$$

$\theta_{eS} = 3.838 \times 10^{-4}$ Schottky contribution

$$\theta_{ekin} := \frac{1}{\beta^2} \cdot \sqrt{\frac{T_c^2}{2 \cdot m_e^2}}$$

$\theta_{ekin} = 6.447 \times 10^{-4}$ kinematic transformation contribution

$$\theta_{eSC} := \frac{\pi\, n_e \cdot r_e \cdot a_{fin}^2}{\beta^2}$$

$\theta_{eSC} = 1.159 \times 10^{-4}$ e space charge contribution

$$\frac{\theta_{eSC}}{\theta_{fin}} = 0.232$$

$$\theta_{ed} := \frac{2 \cdot \pi\, n_e \cdot e_G \cdot a_{fin}}{B_c \cdot \beta}$$

$\theta_{ed} = 4.165 \times 10^{-4}$ e-drift contribution

$$\frac{\theta_{ed}}{\theta_{fin}} = 0.833$$

Electron IBS contribution:

$\omega_e := c\cdot\sqrt{4\cdot\pi\cdot n_e\cdot r_e}$ $d_e := \frac{v}{\omega_e}$ $d_e = 6.499$ cm plasma length

$r_{eL} := \frac{v\cdot\theta_{eT}}{\omega_{eL}}$ $r_{eL} = 7.591\times 10^{-3}$ Larmor radius $\frac{r_{eL}}{\theta_{fin}} = 15.177$

$r_{emin} := \frac{r_e}{\beta^2\cdot\theta_{eT}^2}$ $r_{emin} = 1.428\times 10^{-6}$

$Logee := \ln\left(\frac{r_{eL}}{r_{emin}}\right)$ $Logee = 8.578$

$\theta_{ei} := \sqrt{\theta_{ekin}^2 + \theta_{eS}^2 + \theta_{eSC}^2}$

$$\tau_{ee} := \left(\frac{2\cdot\pi^{\frac{3}{2}}\cdot n_e\cdot r_e^2\cdot c\cdot Logee\cdot KT\left(\frac{\theta_{ei}^2}{\theta_{eT}^2}\right)}{\beta^3\cdot\theta_{eT}^3}\right)^{-1}$$

$\tau_{ee} = 2.845\times 10^{-4}$ ee transverse to longitudinal IBS time, M. Reiser's book, Eq. 6.150

$l_{cc} := 110$ distance from the cathode to the cooler's entrance

$\tau_{flight} := \frac{0.5\cdot l_c + l_{cc}}{v}$ $\tau_{flight} = 3.637\times 10^{-7}$

$\theta_{elt} := \frac{1}{\beta}\cdot\sqrt{\frac{T_c}{m_e}\cdot\left(\frac{\tau_{ee}}{\tau_{flight}}\right)^{-1}}$ $\theta_{elt} = 1.08\times 10^{-3}$ ee IBS contribution

$$\theta_{ecool\_ini} := \sqrt{\theta_{elt}^2 + \theta_{ekin}^2 + \theta_{eS}^2 + \theta_{eSC}^2 + \theta_{ed}^2 + \theta_{ini}^2}$$

$\theta_{ecool\_ini} = 1.676 \times 10^{-3}$

effective ecool angle, initial

$$\theta_{ecool\_fin} := \sqrt{\theta_{elt}^2 + \theta_{ekin}^2 + \theta_{eS}^2 + \theta_{eSC}^2 + \theta_{ed}^2 + \theta_{fin}^2}$$

$\theta_{ecool\_fin} = 1.472 \times 10^{-3}$

same. final

$$\tau_{ec\_fin} := \left(\frac{2 \cdot \sqrt{2 \cdot \pi} n_e \cdot r_p \cdot r_e \cdot c \cdot \eta_c \cdot LogCool}{\beta^3 \cdot \theta_{ecool\_fin}^3} \right)^{-1}$$

$\tau_{ec\_fin} = 0.011$

e-fold dp/p cooling time,
Derbenev & Skrinsky,
Part Acc, 1978

$$\tau_{ec\_ini} := \left(\frac{2 \cdot \sqrt{2 \cdot \pi} n_e \cdot r_p \cdot r_e \cdot c \cdot \eta_c \cdot LogCool}{\beta^3 \cdot \theta_{ecool\_ini}^3} \right)^{-1}$$

$\tau_{ec\_ini} = 0.017$

$$\frac{\tau_{ec\_fin}}{\tau_{IBS\_dpp\_fin}} = 0.057$$

$$\frac{\tau_{ec\_ini}}{\tau_{IBS\_dpp\_ini}} = 2.989 \times 10^{-3}$$

relative to dp/p IBS. If $\frac{\tau_{ec}}{\tau_{IBS\_dpp}} << 1$, the beam could be cooled better.
Other limit means impossiblility to cool so deeply.

Betacool Simulations

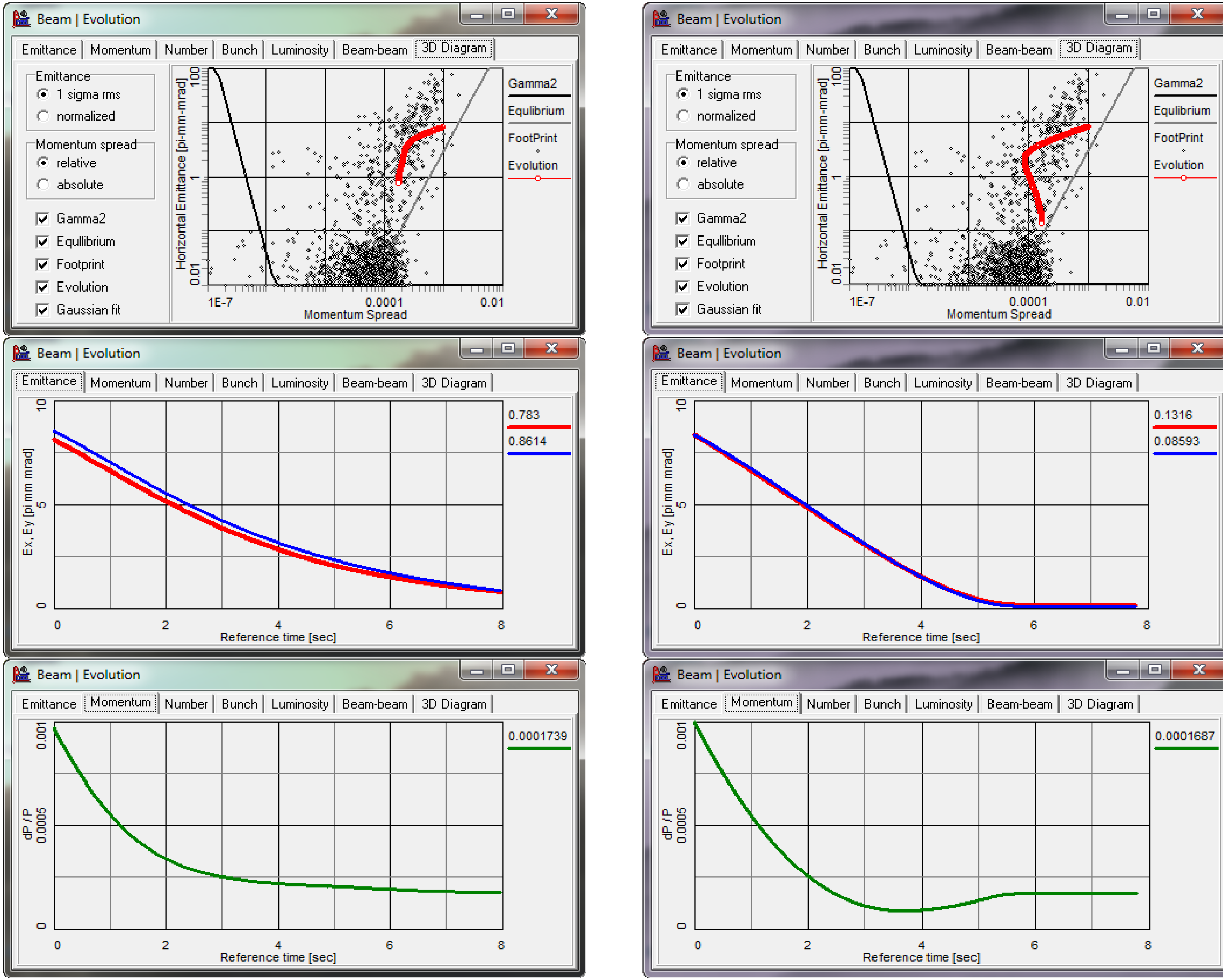
Compared “Model Beam” & “RMS Dynamics” algorithms for 35 MeV/c

Initial transverse emittances = 75 π mm mrad to 15 π mm mrad
$\Delta P/P = \pm 2‰$
Ee = 355 eV, Ie = 5 mA, tranverse temperature: 0.1eV & 0.01eV

“Model Beam” for 13.75 MeV/c

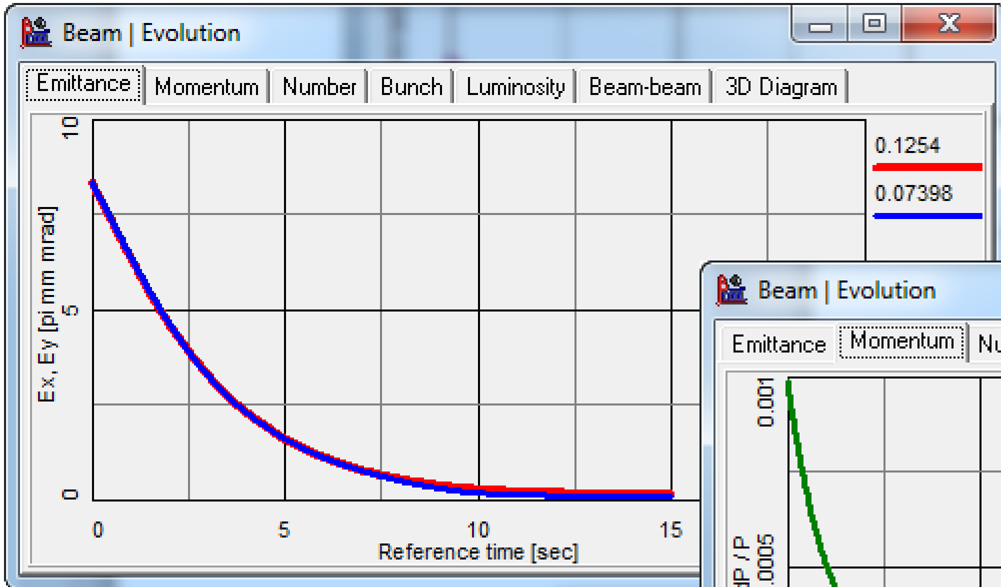
Initial transverse emittances = 15 π mm mrad
$\Delta P/P = \pm 1‰$
Ee = 55 eV, Ie = 1/2 mA, tranverse temperature: 0.03eV & 0.01eV

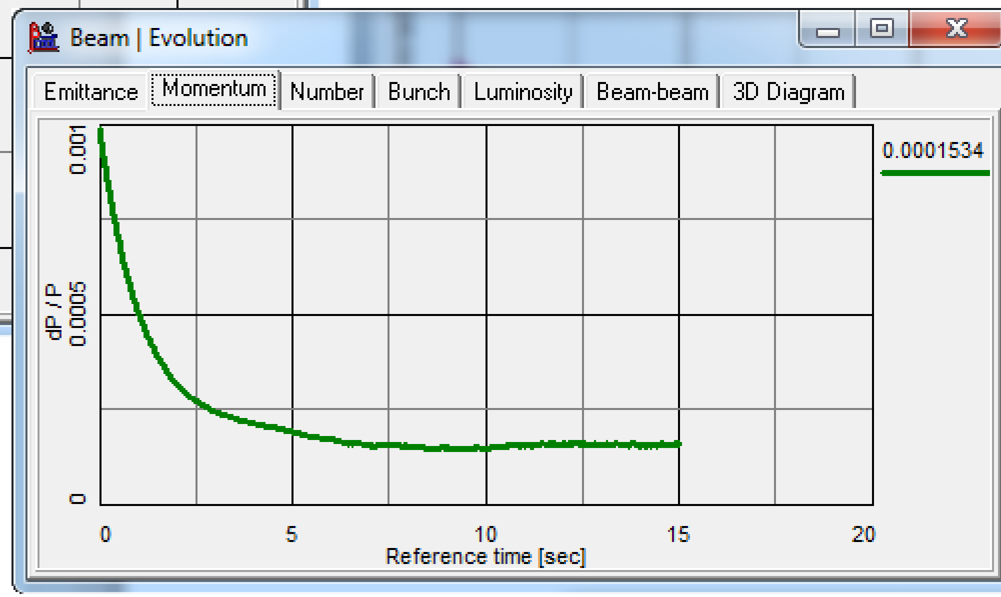
- Betacool (A. Smirnov & co.)
  - Code for long term beam dynamics simulation.
    - http://betacool.jinr.ru
  - RMS Dynamics
    Evolution of RMS parameters (emittances, particle number) are simulated
  - Model Beam
    Ion beam is represented by an array of model particles and each effect calculates a kick of the ion momentum components and changes the particle number
  - Tracking
    Ion beam is presented by array of real particles and Coulomb scattering is calculated by the Molecular Dynamics technique
  - 3D Phase Diagram
    A few of 3D projection of 6D phase space volume of ion beam.
    Results of beam dynamics simulation for different algorithms on the same diagram

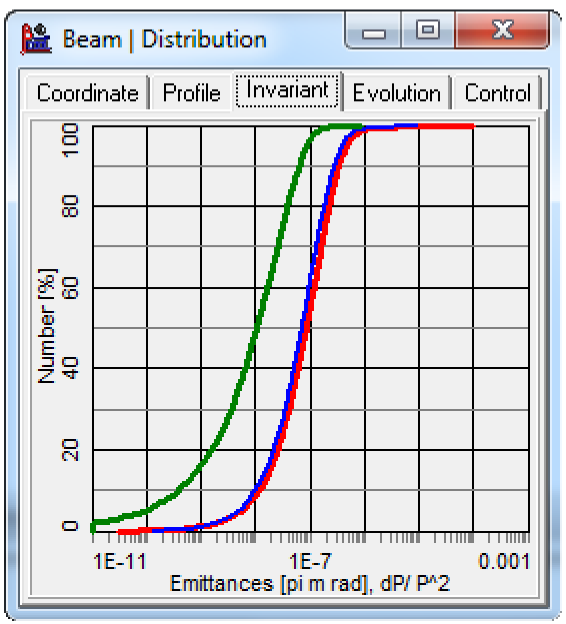


$50\,\pi$ mm mrad, ±2‰

INITIAL PARAMETERS			MODEL BEAM			RMS DYNAMICS		
$\varepsilon_{h,v}$	ΔP/P	kT	$\varepsilon_{h,v}$	$\varepsilon_{h,v}$	ΔP/P	$\varepsilon_{h,v}$	$\varepsilon_{h,v}$	ΔP/P
$\pi\ 10^{-6}$	$\pm 10^{-3}$	eV			$\pm 10^{-4}$			$\pm 10^{-4}$
75	2	0.1	17.4	19.3	5.6	0.78	0.54	1.69
50	2		4.7	5.2	3.5	0.78	0.54	3.4
25	2		1.0	0.6	3.5	0.78	0.54	3.4
15	2		0.95	0.54	3.5	0.78	0.54	3.4
50	2	0.01	3.18	2.52	3	0.54	0.36	2.88
50*	2		1.0	0.4	3.1			
15	2		0.65	0.4	3.1	0.54	0.36	2.88

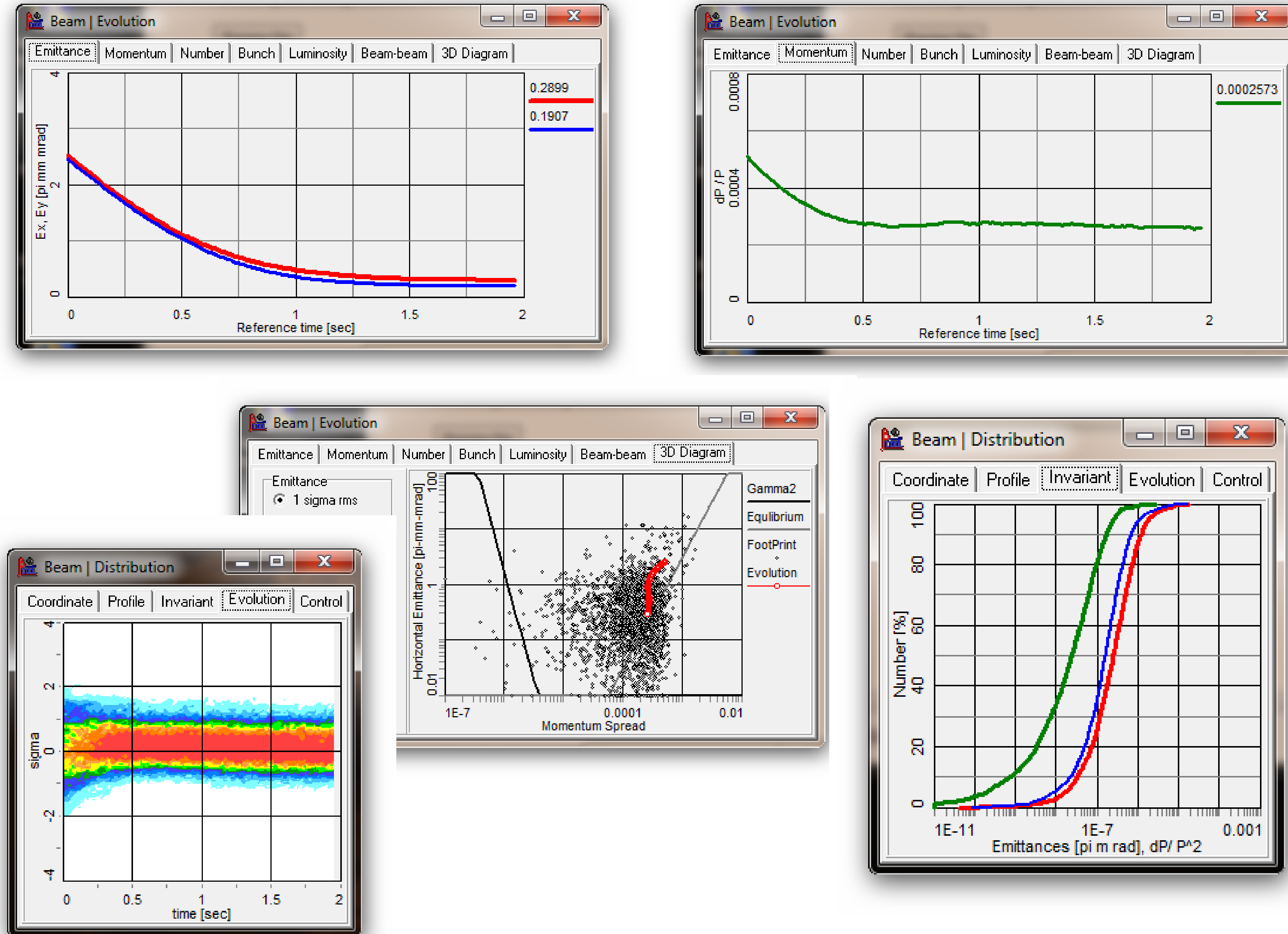






“Model Beam”, simulation time extended to 15 s.

Ie (mA)	kT (eV)	ε_h (μm)	ε_v (μm)	$\Delta P/P$ (10^{-3})
1	0.03	2.4	1.5	±0.6
1	0.01	2.1	1.3	±0.5
2	0.01	1.9	1.1	±0.5

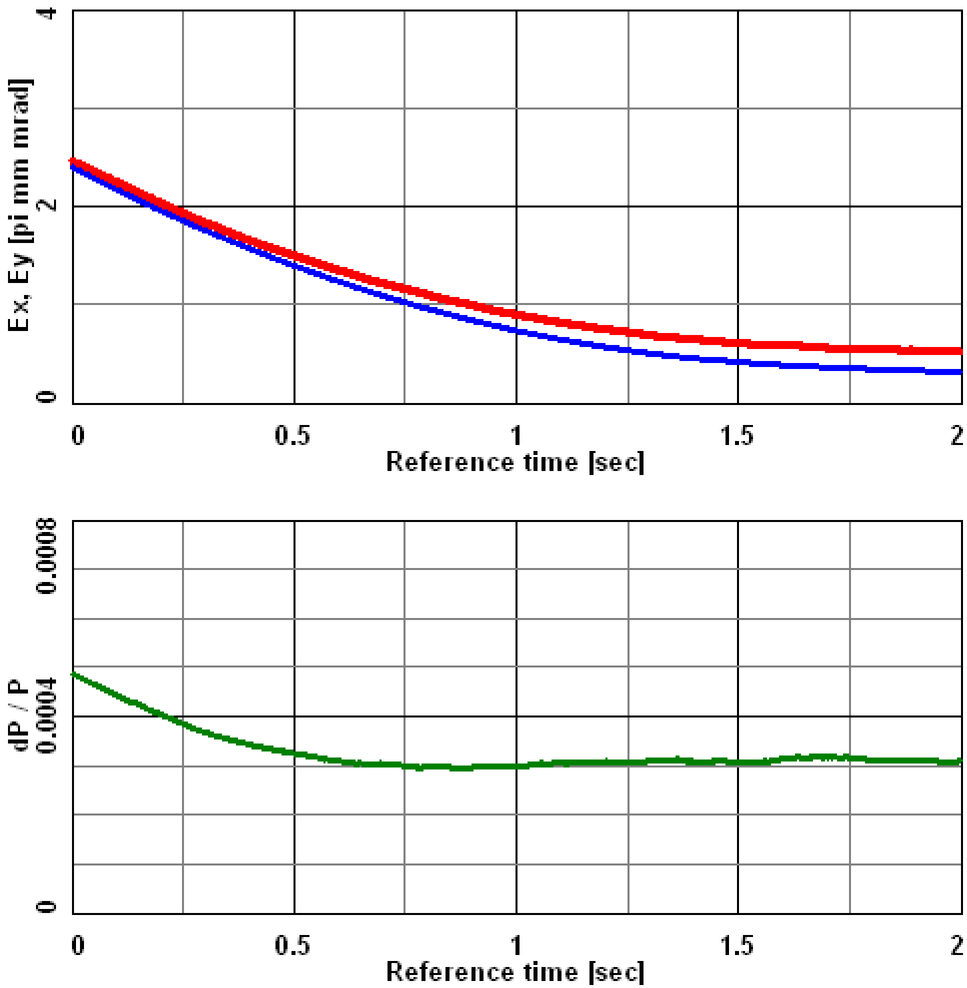


Beam | Evolution
Emittance
Momentum
Number
Bunch
Luminosity
Beam-beam
3D Diagram
Ex, Ey [pi mm mrad]
0.2899
0.1907
Reference time [sec]
dP / P
0.0002573
Emittance
1 sigma rms
Horizontal Emittance [pi-mm-mrad]
Momentum Spread
Gamma2
Equlibrium
FootPrint
Evolution
Beam | Distribution
Coordinate
Profile
Invariant
Evolution
Control
sigma
time [sec]
Number [%]
Emittances [pi m rad], dP/ P^2

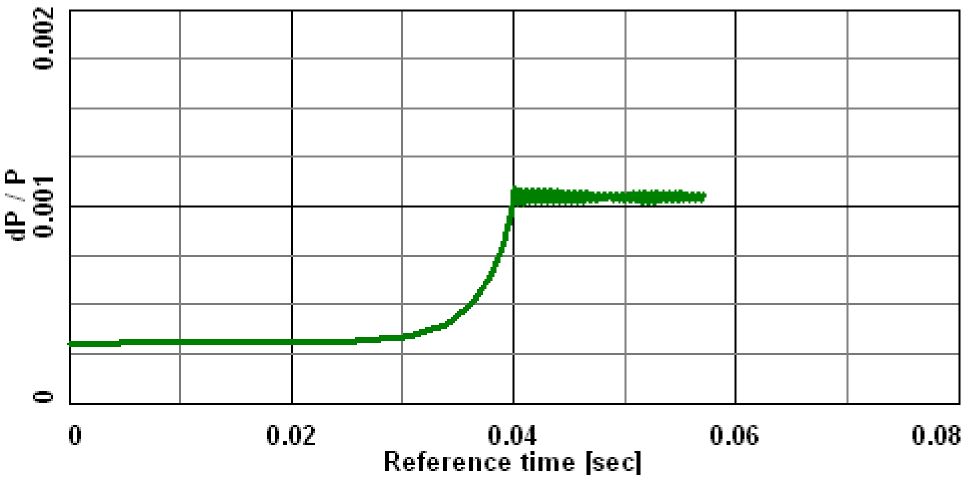
Extension of cooling on beam bunching process: motivation

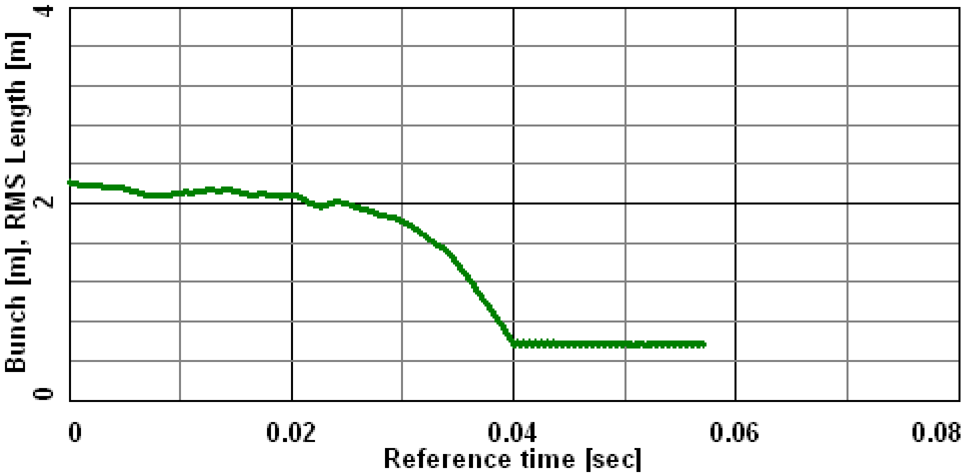
- Useful for efficient beam transfer via those section of electrostatic beam lines to experiments which have big dispersion (matching sections)
- Critical for experiments with request of small momentum spread in beam (GBAR, ASACUSA?)
- Useful in case of increased number of particles in a bunch (bigger IBS rates)
- Allows to reduce maximal voltage in cavity which is needed for getting short bunch, now bunch length is reduced by cooling

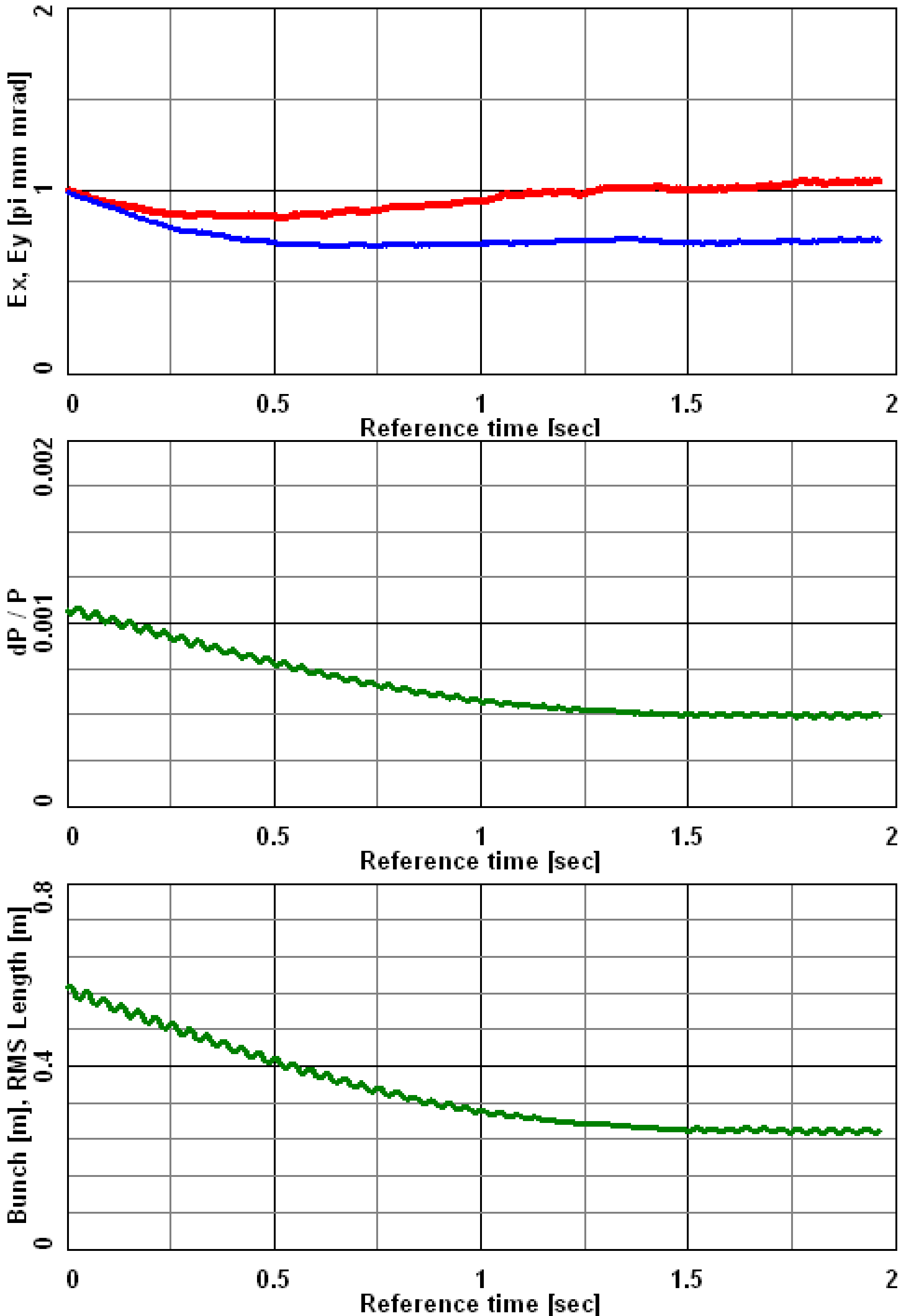
Electron cooling of coasting beam with I_e = 1 mA



Capture and bunching with RF=20 V







Electron cooling of bunched eam with I_e = 1 mA

Beam parameters during cooling and bunching processes

with RF = 20 V and I_e = 1 mA

	ε_x, π mm mrad	$\Delta p/p_{rms}$, 10^{-3}	σ_{rms}, m	t, s
initial coasting	**2,5**	**0,5**	**-**	**0**
cooling of coasting	**1**	**0,3**	**-**	**0,8**
capture and bunching	**1**	**1,06**	**0,55**	**0,84**
cooling of bunched	**1,05**	**0,5**	**0,26**	**2,3**

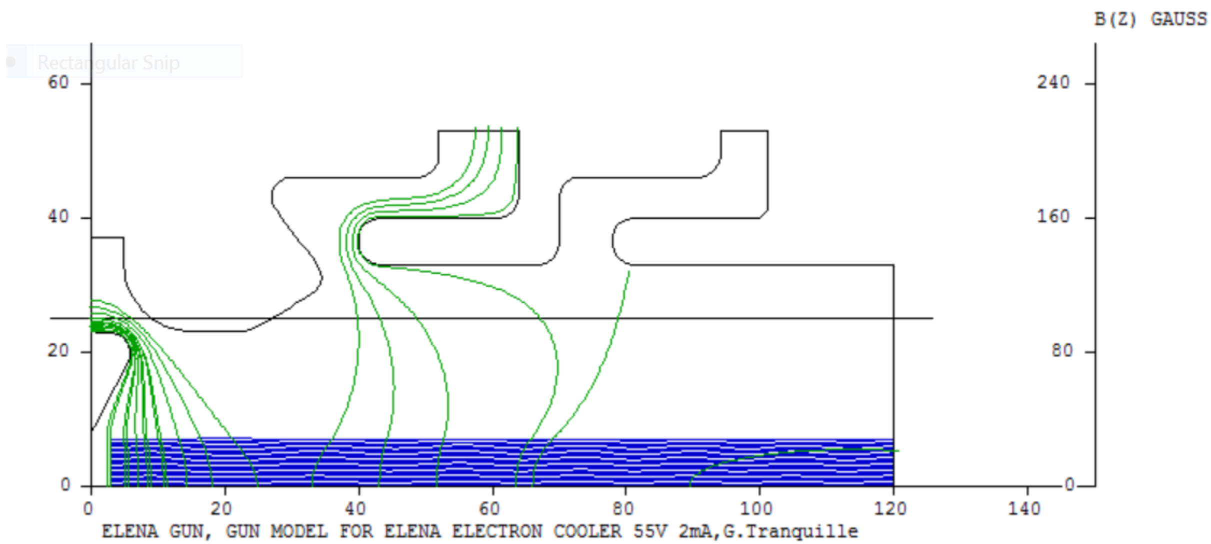
Electron Gun & Collector Design

Simulations using EGUN and COMSOL multiphysics package

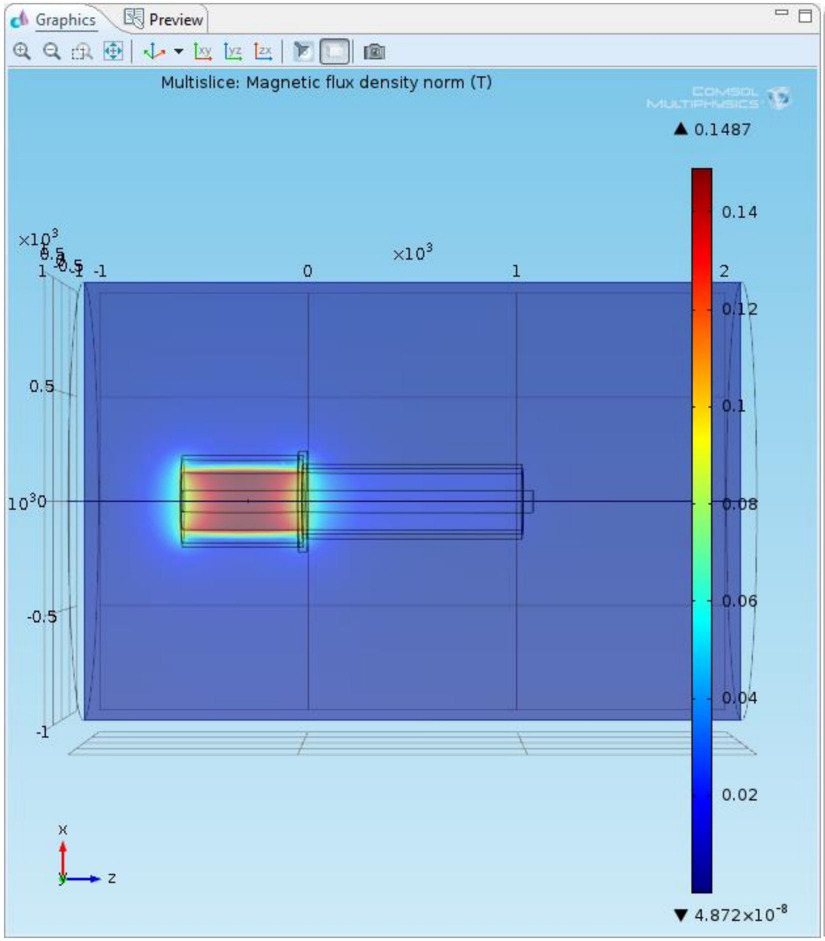
- S-LSR gun design checked
- S-LSR gun at 55 eV and 2 mA, without expansion
- Modified gun with 16 mm cathode, new electrode:

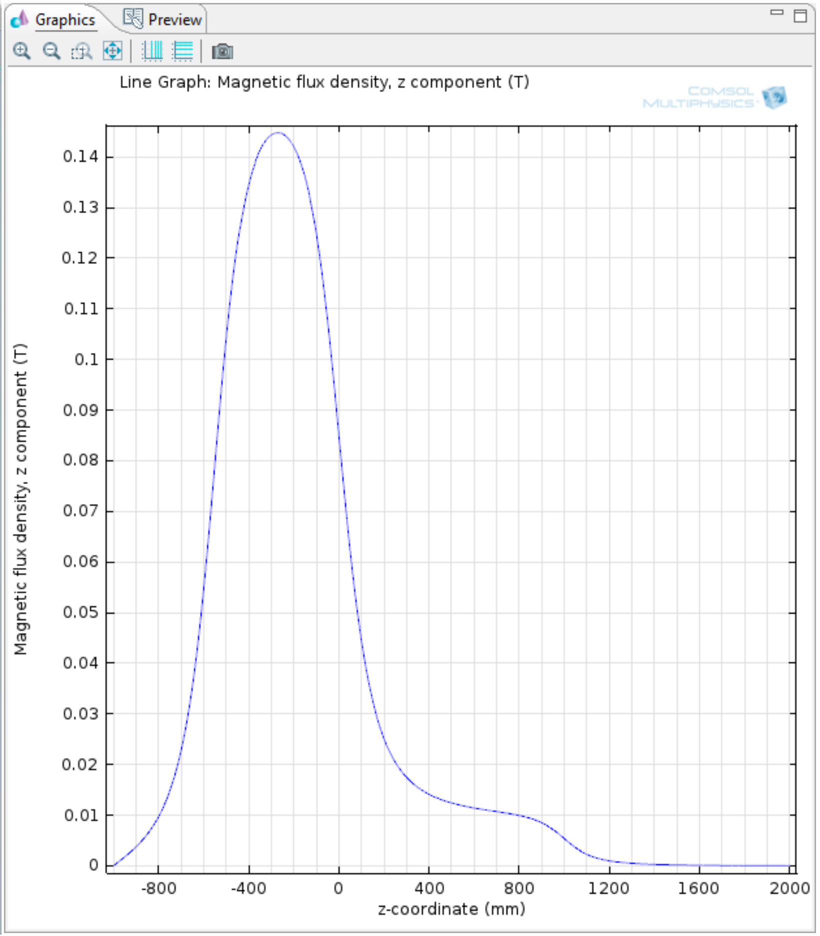
  355 eV, 10 mA, no expansion

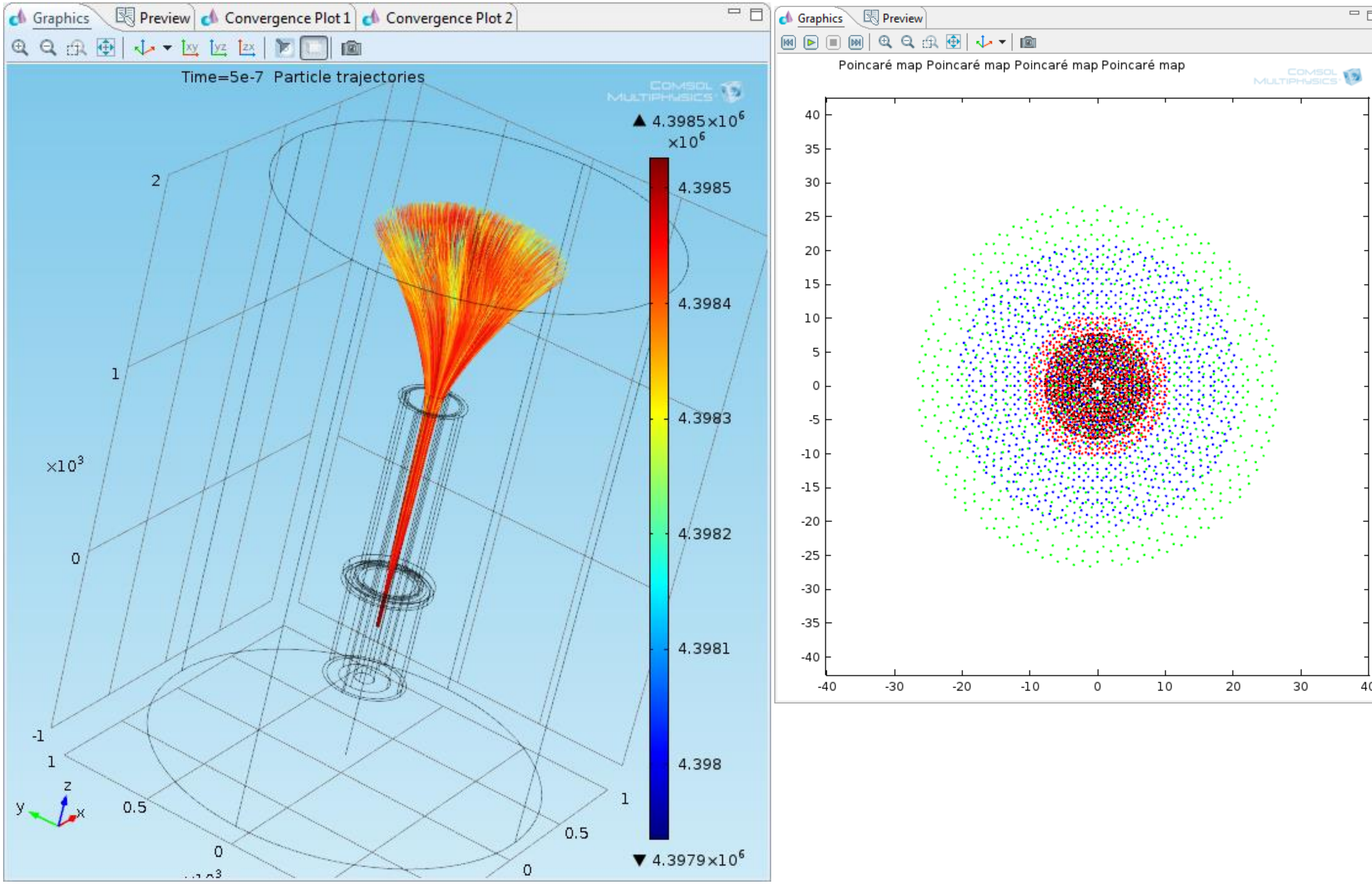
  55 eV, 2 mA, no expansion



Modelling the cooler in COMSOL



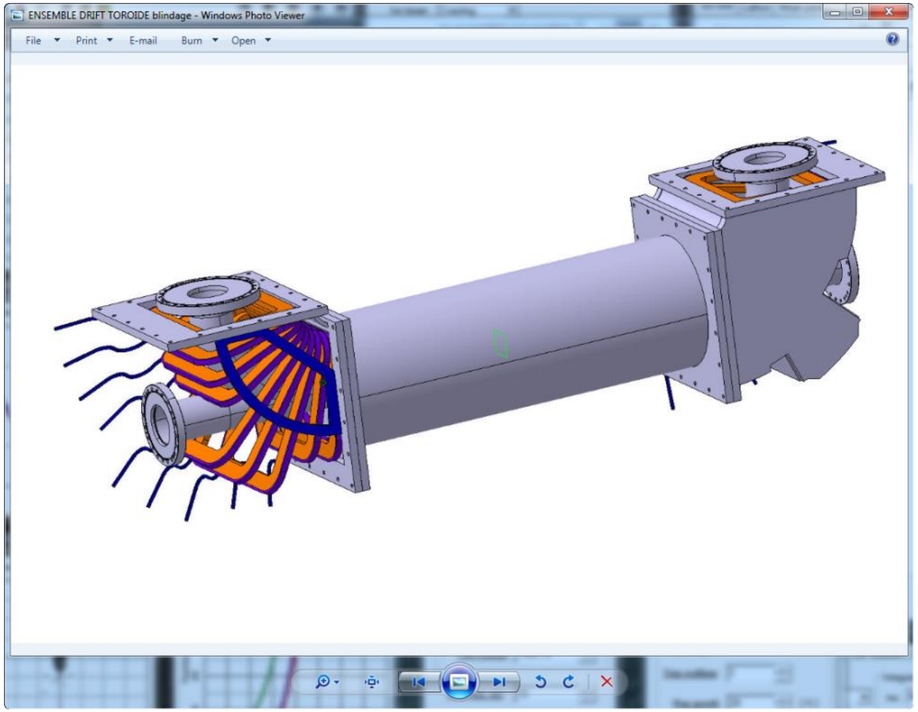




Expansion and transport of a 55 eV electron beam in COMSOL

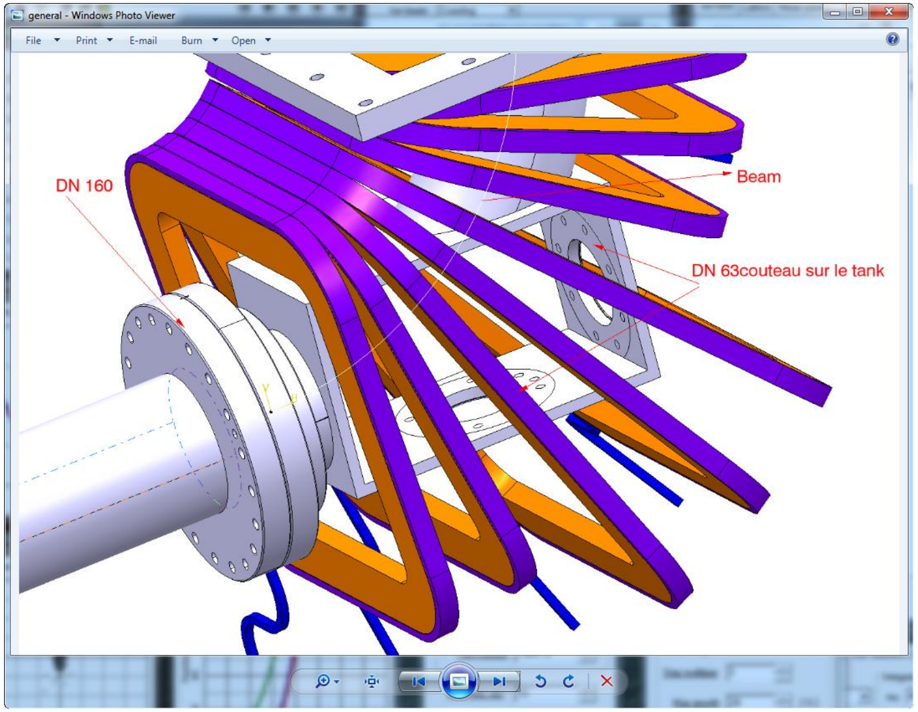
Vacuum System

- Vacuum system must be XHV compatible
  - 316 LN NEG coated vacuum chambers
  - ST101 NEG cartridges at gun exit and collector entrance
  - DN 100
  - CF flanges, sliver coated seals
  - Hydroformed bellows
  - NEXTorr pumps (collector and toroid chambers)
  - Whole system bakeable at 300°C for 24 hours
  - Bakeout jackets
- Whole mechanical structure to be tilted by 90°
  - Support with rails to slide out gun/collector solenoids



Ecool toroids and drift solenoid

Design of toroid vacuum chamber



- Mechanical design well under way.
- All drawings made with CATIA.
- Optimisation of the toroid vacuum chamber.

Roadmap

Abandon construction of cooler by Toshiba.
Magnetic system to be made by external company.
Vacuum chambers, supports etc. designed and made at CERN

Gun and collector designs to be finalised by the end of the year.

3 firms contacted and interested in building the magnetic system
- Specifications sent
- Quotation received from Danfysik – visit on 22nd October

Tender process can take up to 3 months. Can we circumvent this process?
1 year for construction of magnet system (design, construction, measurements and delivery)

1st draft of vacuum system ready in 1 month. Work with EN-MME and TS-VSC to produce production drawings. In parallel order raw materials.
Start building the vacuum system as soon as the main workshop has time.

Conclusions & Outlook

Electron cooling performance has been investigated:

- Performance limited by electron IBS contribution but not a showstopper
- The maximum electron current is determined by the e-beam space charge

Cooler design inspired by the S-LSR cooler at Kyoto University

Much time has been wasted negotiating with Toshiba Co. for the construction of the cooler

- Need to move quickly to our “plan B”

Design is well advanced – could have construction drawings ready in 4-5 months

Construction of vacuum system etc. depends on main workshop and availability of raw materials – 1 year for manufacturing (problem for the ELENA project in general)

Magnetic system to be made in industry – 1 year for design, manufacture, measurements and delivery - Tender process needs to be reduced or avoided

Cooler should be ready by the end of 2015