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Memo

DATE: *March 17, 2006*

TO: RHIC E-Coolers

FROM: *Ady Hershcovitch*

SUBJECT: **Minutes of the March 17, 2006 Meeting**

Present: Ilan Ben-Zvi, Andrew Burrill, Alexei Fedotov, Wolfram Fischer, Harald Hahn, Ady Hershcovitch, Dmitry Kayran, Jorg Kewisch, Derek Lowenstein, Thomas Roser, Triveni Srinivasan-Rao, Dejan Trbojevic, Gang Wang.

Topics discussed: Low Energy Cooling

Low Energy Cooling: according to some QCD theoretical predictions, there is a sharp transition point between phase 1 (hadronic matter) and phase 2 (quark-gluon plasma) in heavy ion collision. This point is referred as the critical point, which is supposed to occur at center of mass (CM) collisions of about 9 GeV/u. AGS heavy ion experiments occurred in the phase 1 energy range, while present RHIC experiments are in the phase 2 energy range (100 GeV/u) well above the critical point. To study collisions at the critical point (or even verify its existence), experiments have been proposed to use RHIC to collide 9 GeV/u heavy ions.

Alexei and Dmitry gave presentations (please see below) showing feasibility of performing electron beam cooling at these low energies at RHIC. Alexei opened the meeting by showing that electron beam cooling at these ion energies is feasible and that cooling time are expected to be in the range of seconds (or 10's of seconds). Cooling time at low energies in RHIC depends strongly on electron beam emittance. And, in general cooling time is faster for larger electron charge per bunch. But, the higher the bunch charge, the larger the electron beam emittance. Nevertheless, Alexei showed with BETACOOL calculations that indicate that the lower electron beam emittance is the overwhelming factor. Thus, electron beam cooling with a 1.5 nC charge per bunch for this application is as effective as cooling with 5 nC per bunch electron beam. In the presentation Alexei showed that both magnetized electron beam cooling at COSY and non-magnetized cooling at FNL were shown to work at energies of 4 GeV pbar and 8 GeV p respectively. Furthermore, exit electron beam energy at the ERL and RHIC II electron guns can cool ions with energies of 4.6 and 8.3 GeV/u respectively.

Dmitry showed with PARMELA simulations of the ERL setup that solenoidal coils before and after LINAC can prevent emittance growth as the electron beam crosses the gun – LINAC gap. The effect is very noticeable for large bunch charges where factor 3 in increase bunch charge raises emittance by only 30%.

Alexei's Presentation

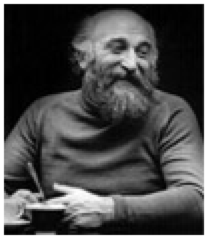
1

Electron Cooling in RHIC at Low Energies

Alexei Fedotov

Collider-Accelerator Department, BNL

(March 17, 2006)



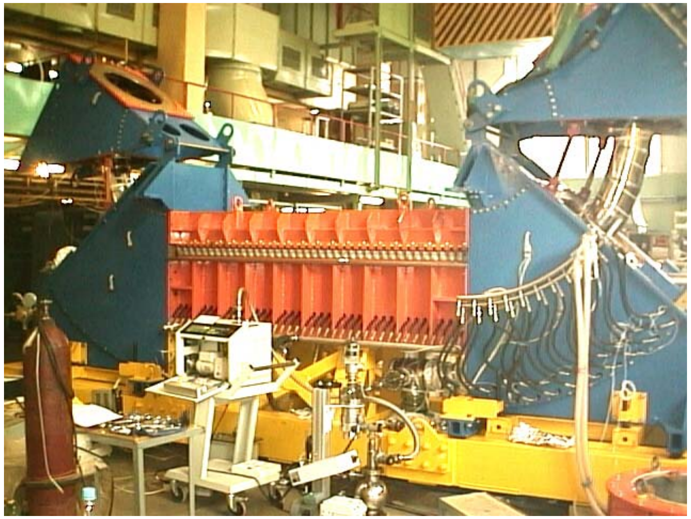
Electron cooling was invented by G.I. Budker (INP, Novosibirsk, 1966)

First experimental cooling. NAP-M storage ring (Novosibirsk, 1974)

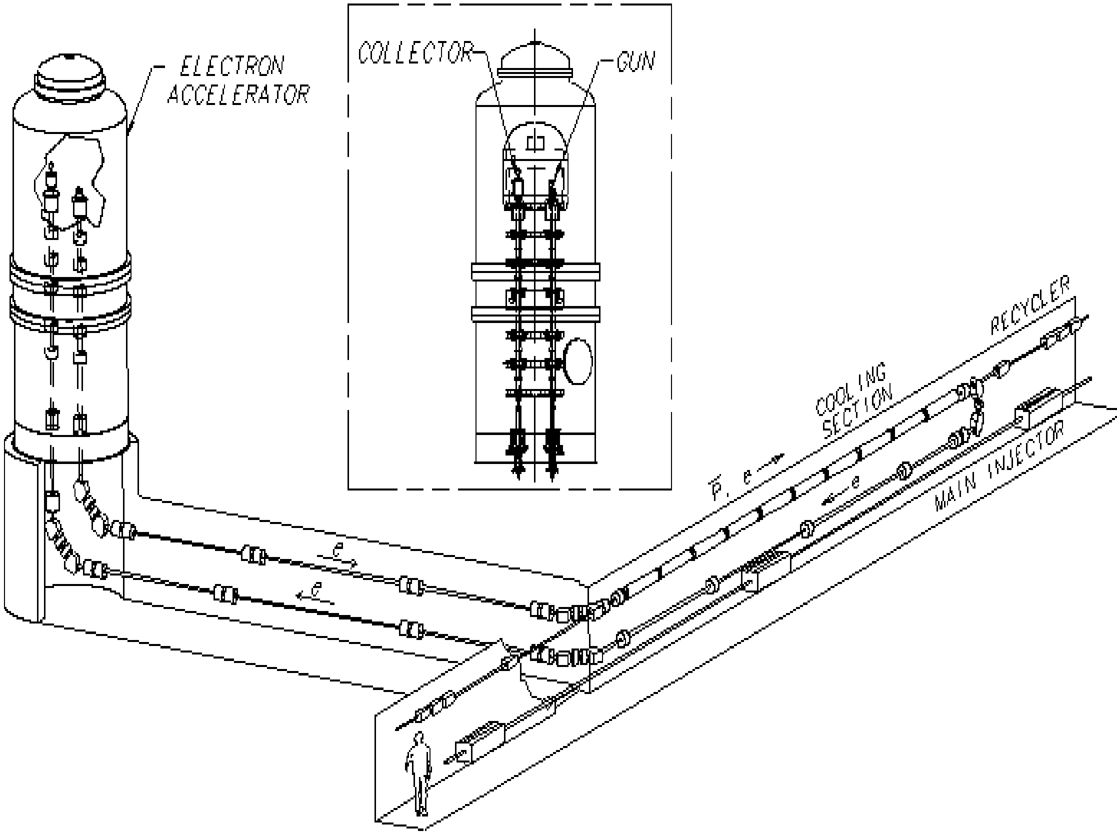
Principles of electron cooling:

- **Produce a beam of cold (low emittance) electrons.**
- **Move these electrons with a velocity of the heavy particles to be cooled.**
- **Heavy particles scatter off the electrons and energy is transferred to electrons. This energy transfer appears as a friction force acting on the ions. The ions are "cooled".**
- **The electrons are renewed.**

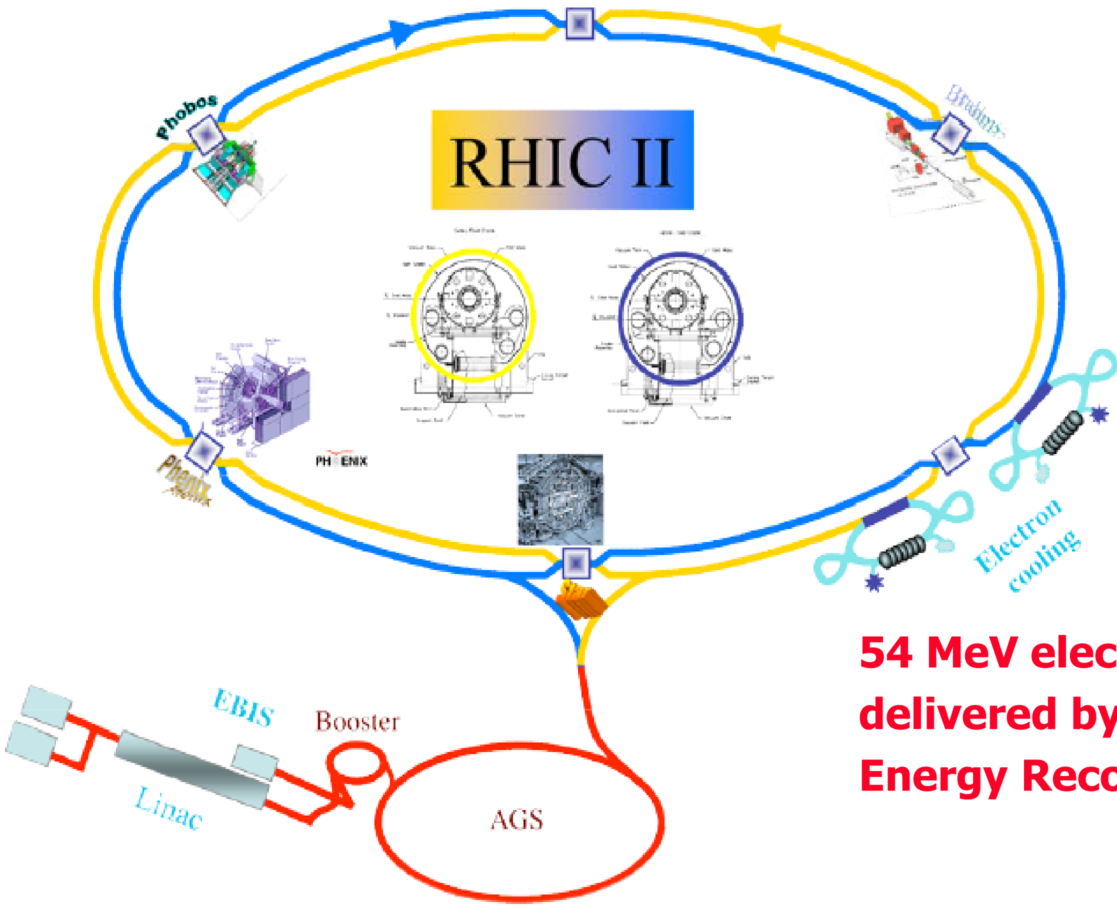
Low-energy (3-400 KeV electrons) cooling (< 1 GeV/u ions): 10’s of coolers were constructed: 1975-2005



Medium-energy (4 MeV electrons) cooling at FNAL – to cool 8 GeV pbars – successfully operating since July 2005



High-energy (54 MeV electrons) cooling - to cool Au ions at 100 GeV/u energies – RHIC-II upgrade



54 MeV electrons delivered by Energy Recovery Linac (ERL)

Magnetized and Non-magnetized cooling

1. All low-energy (3-400KeV electrons) coolers 1975-2005 are based on "magnetized cooling" – electron beam transport and alignment of electron and ion beam is done with continuous magnetic field. Strong magnetic field completely suppresses transverse temperature of electron beam, so that effectiveness of cooling is determined by a very low longitudinal temperature of electrons.

2. "Non-magnetized cooling" – relies on the fact that rms velocity spread of electrons is comparable or smaller than the one of ions which need to be cooled.

Practical implementation of e-cooling for low energy in RHIC

1. Magnetized cooling: 2 MeV electrons is considered as COSY upgrade. 4.3 (8) MeV electrons 8 (15) GeV pbars is planned for HESR GSI (FAIR project) – both are technically challenging projects.
2. Non-magnetized cooler at FNAL 4.3 MeV electron energy - can cover ion energies up to (E_k=8 GeV).
3. RHIC-II cooler 54 MeV electrons (100 GeV/u ions) is based on RF SC gun.

Two guns are presently being designed:

3.1 Prototype ERL gun (1/2 cell): designed energy of electrons at gun exit 2.5 MeV – (E_k= 4.6 GeV ions)

3.2 RHIC-II cooler gun (1.5 cell): designed energy of electrons at gun exit 4.5 MeV – (E_k= 8.3 GeV ions)

Cooling at different energies

Cooling times for relativistic energies are much longer than for typical low-energy coolers (γ=1).

In approximation of cold electron beam one gets cooling time:

$$\tau = \frac{A}{Z^2} \frac{\gamma^2}{4\pi r_p r_e n_e c \eta \Lambda_c} \left(\frac{\gamma \varepsilon_{in}}{\beta_{ic}} \right)^{3/2}$$

When rms velocity spread of electron beam is significant compared to the ion beam, dependence of cooling time on relativistic factor γ is less pronounced.

- Very fast for low energies
- Very fast for heavy ions

Present design of high-energy electron cooler for RHIC-II is based on the non-magnetized approach.

For non-magnetized cooling – the challenging requirement is to get small electron emittance for high charge of electron beam.

For 100 GeV/u, γ=108 cooling, we need

electron beam with Q=5nC and rms normalized emittance $\varepsilon_{e,n} < 4\ \mu m$

Present simulations (Chang, Kayran) for 1.5 cell gun give $\varepsilon_{e,n}$=3-5 μm

For ½ cell gun (ERL prototype under construction at BNL):

expected rms normalized emittance for Q=5nC: $\varepsilon_{e,n} < 10\ \mu m$

Cooling times at low energies in RHIC will slightly depend on:

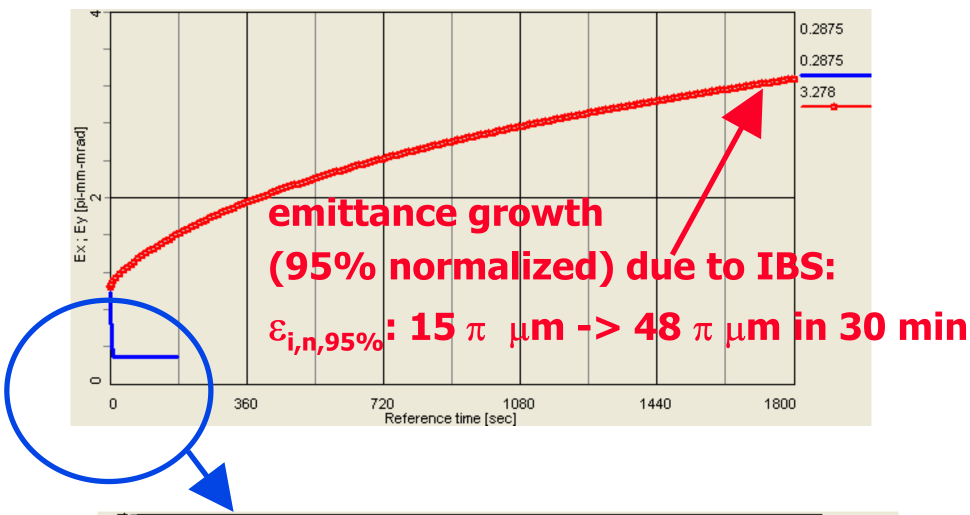
- Emittance of ion beam at such low energy
- Emittance of electron beam

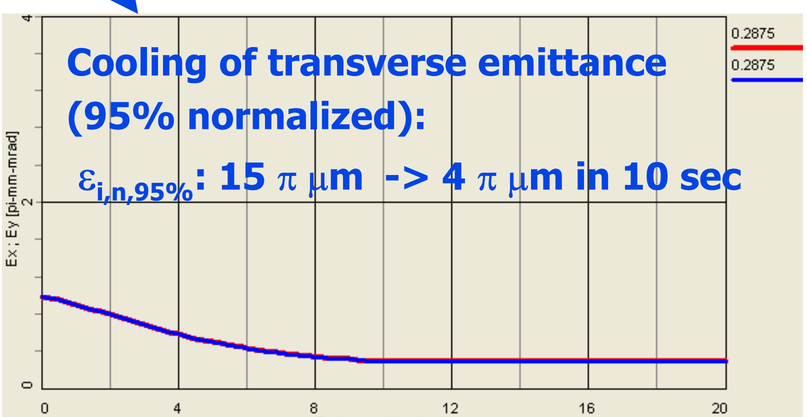
Simulations results (using BETACOOL) are shown for the followings emittances of electron beam (electron charge Q=5nC):

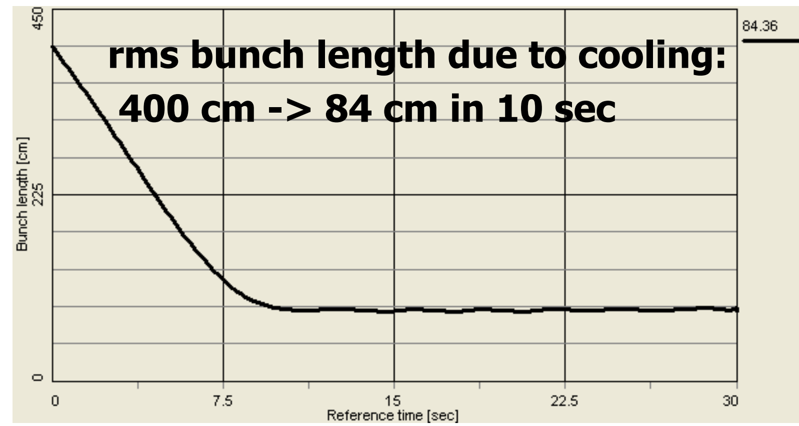
- E_k=1.5 GeV/u (c.m. 5 GeV) – electron rms normalized emittance 15 μm.
- E_k=5.0 GeV/u (c.m. 12 GeV) – electron rms normalized emittance 10 μm
- E_k=9.0 GeV/u (c.m. 20 GeV) – electron rms normalized emittance 10 μm.

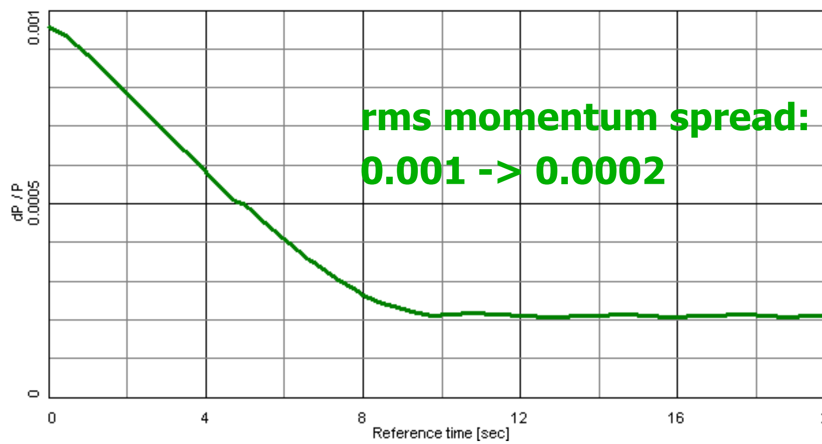
Technical aspects such as electron beam transport at low energy, emittance preservation for such a beam, alignment of electron and ion beams require careful consideration and are not discussed here.

Cooling Au ions at E_k=1.5 GeV/u (γ=2.61)
Electron beam: q=5nC, rms $\varepsilon_{e,n}$=15μm, σ_p=1e-3, L=80m 11
(Figs: plotted emittance is rms unnormalized)



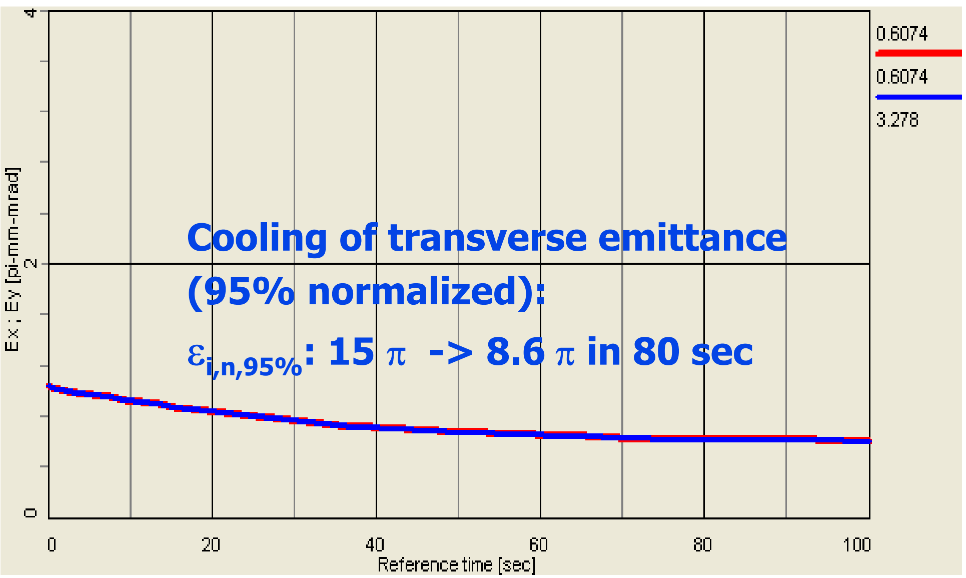


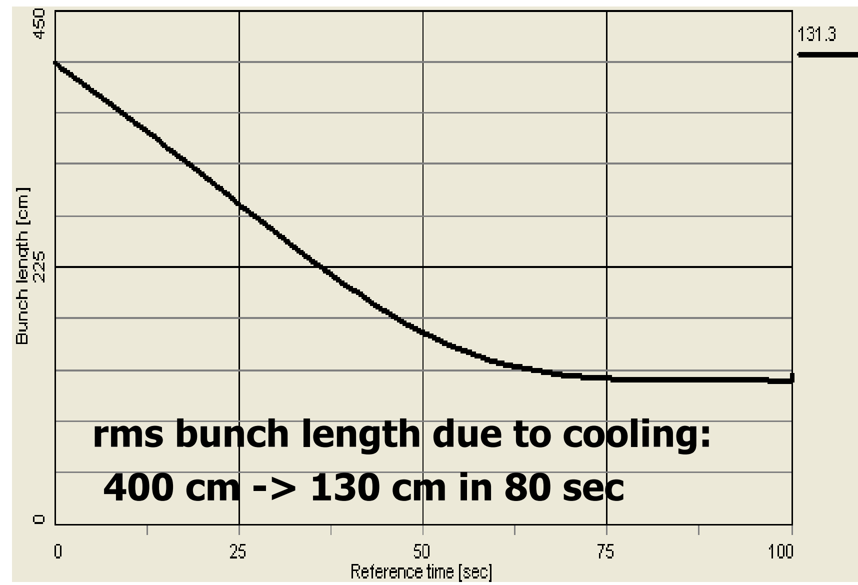




Cooling section length: L=80m

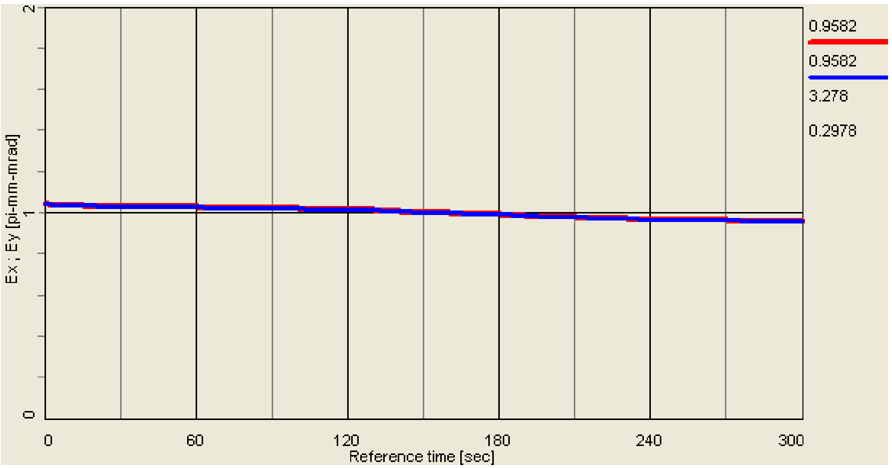
Cooling Au ions at E_k=1.5 GeV/u (γ=2.61)
Electron beam: q=5nC, rms $\varepsilon_{e,n}$=15μm, σ_p=1e-3, L=10m 12
(Figs: plotted emittance is rms unnormalized)

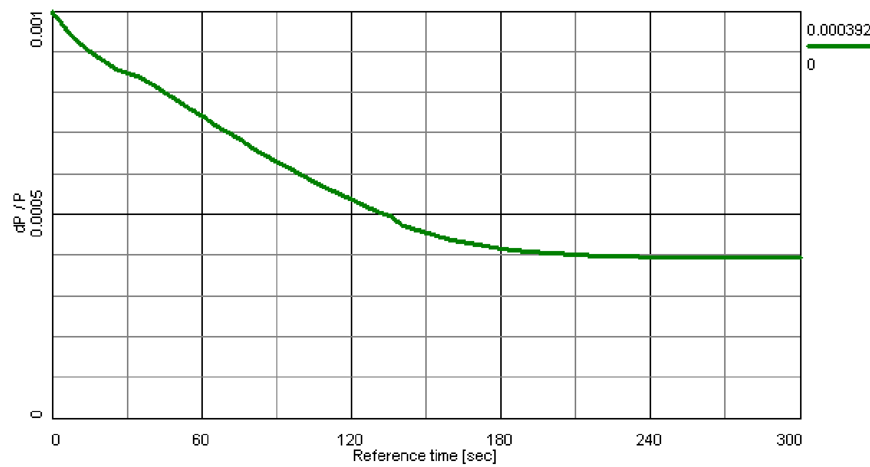


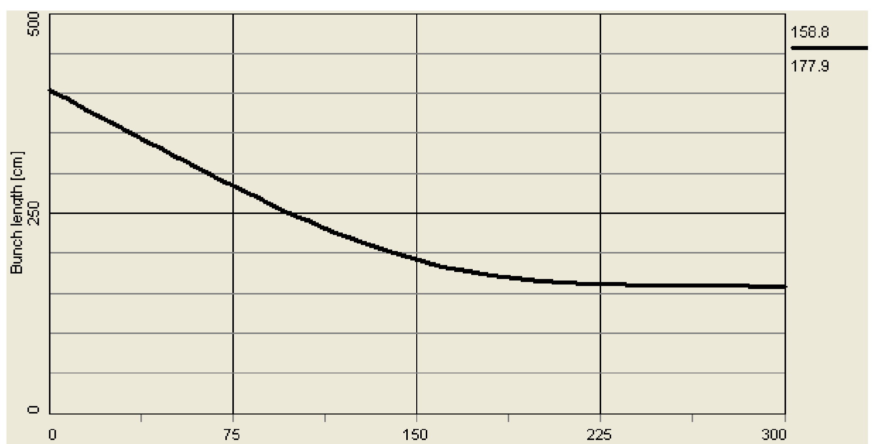


Cooling section length: L=10m

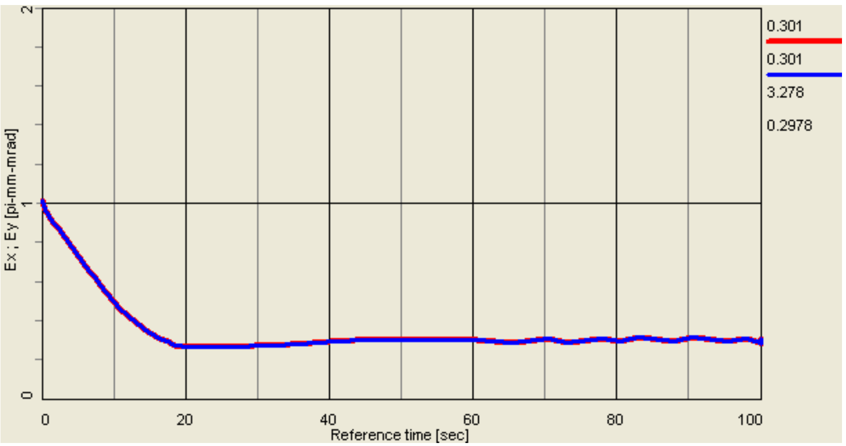
Cooling Au ions at E_k=1.5 GeV/u (γ=2.61)
Electron beam: q=1.5nC, rms $\varepsilon_{e,n}$=15μm, σ_p=1e-3, L=10m

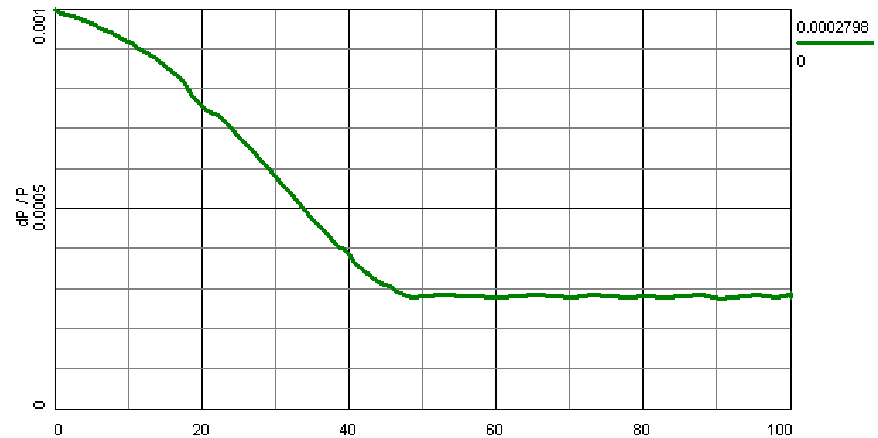


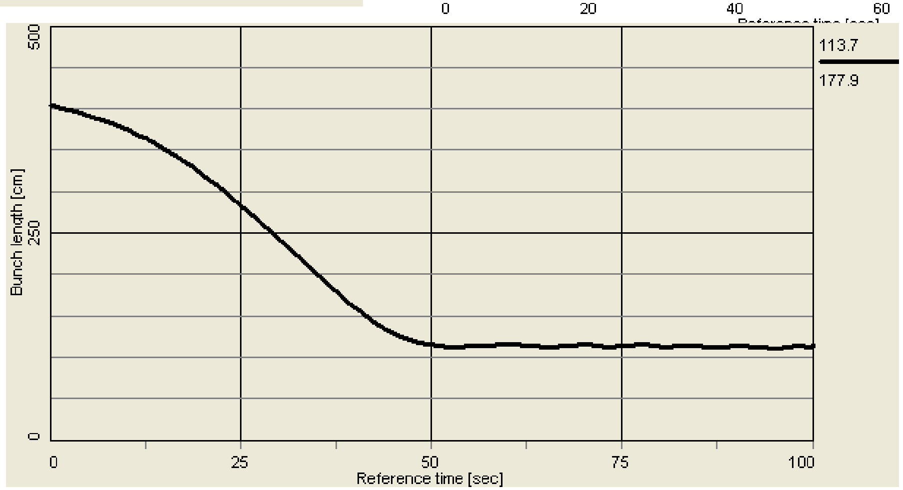




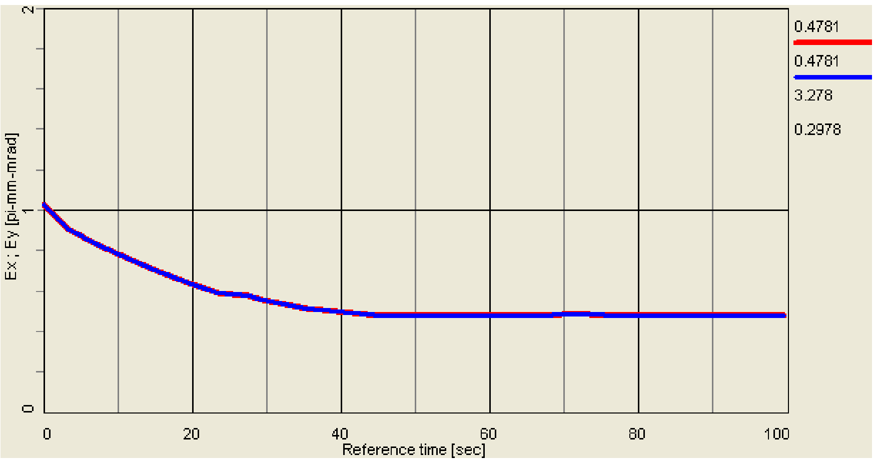
Cooling Au ions at E_k=1.5 GeV/u (γ=2.61)
Electron beam: q=1.5nC, rms $\varepsilon_{e,n}$=3 μm, σ_p=1e-3, L=10m

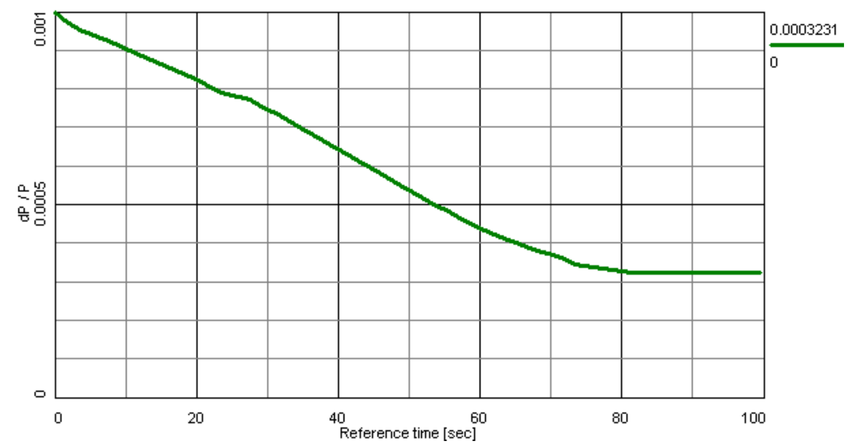


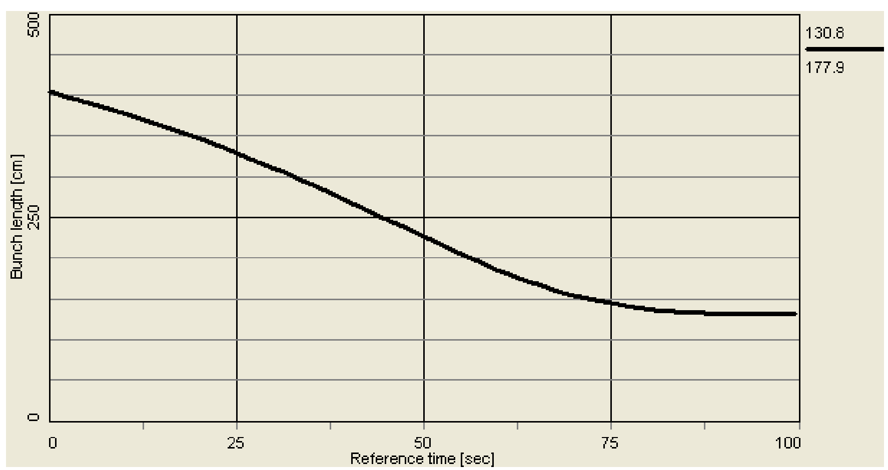




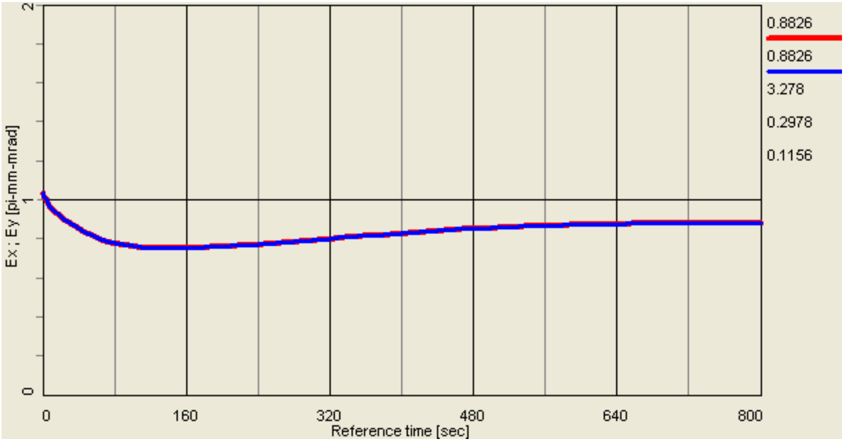
Cooling Au ions at E_k=1.5 GeV/u (γ=2.61)
Electron beam: q=1.5nC, rms $\varepsilon_{e,n}$=6 μm, σ_p=1e-3, L=10m

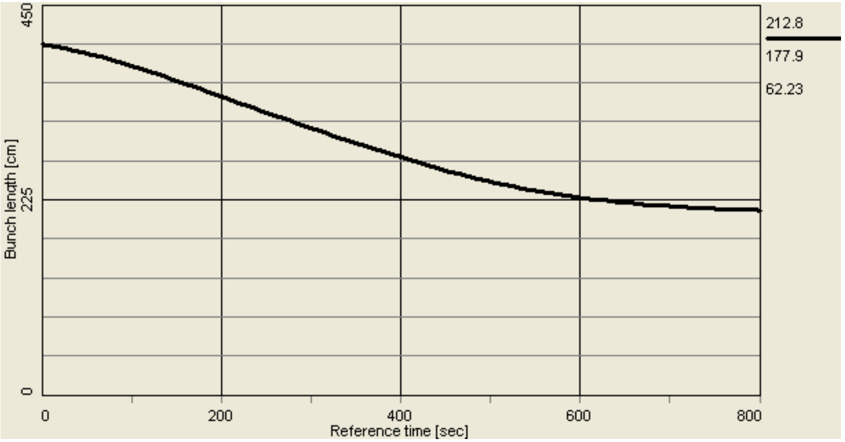




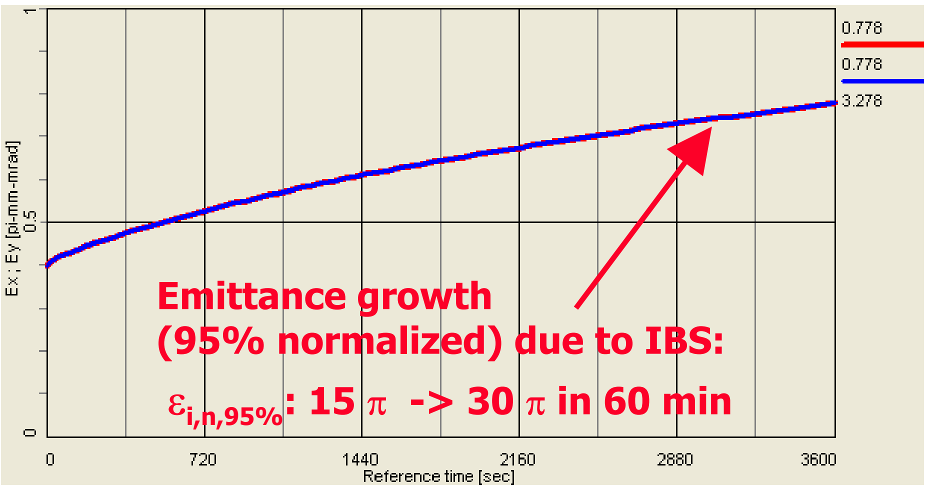


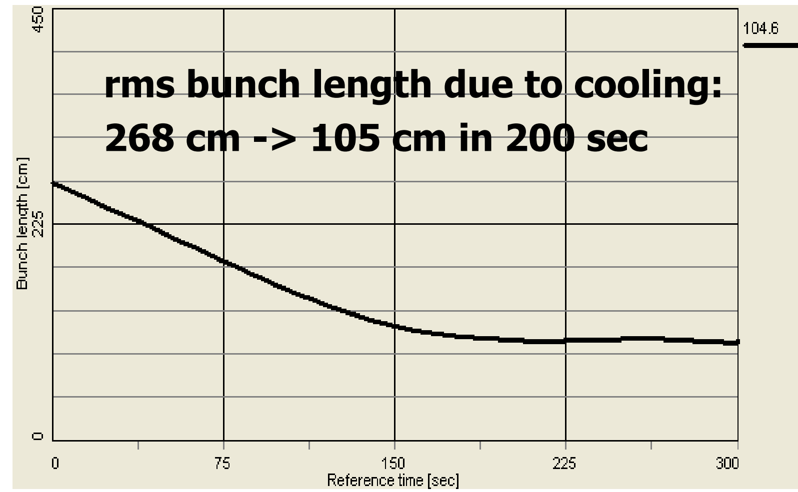
Electron beam: q=1.5nC, rms $\varepsilon_{e,n}$=6 μm, σ_p=1e-2, L=10m

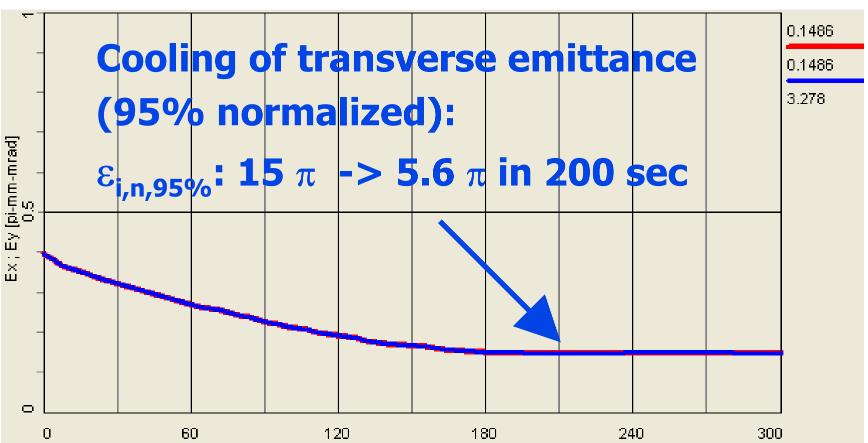




Cooling Au ions at E_k=5 GeV/u (γ=6.37)
Electron beam: q=5nC, rms $\varepsilon_{e,n}$=10μm, σ_p=1e-3, L=10m 17
(Figs: plotted emittance is rms unnormalized)

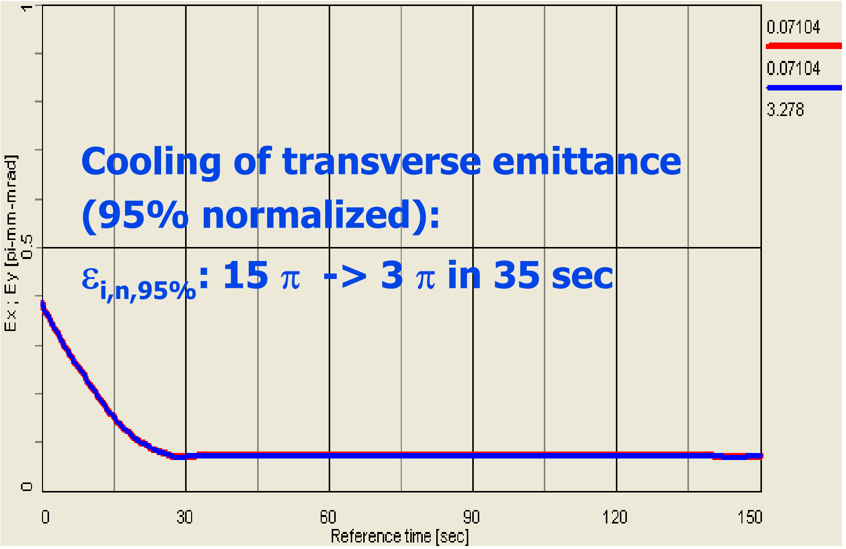


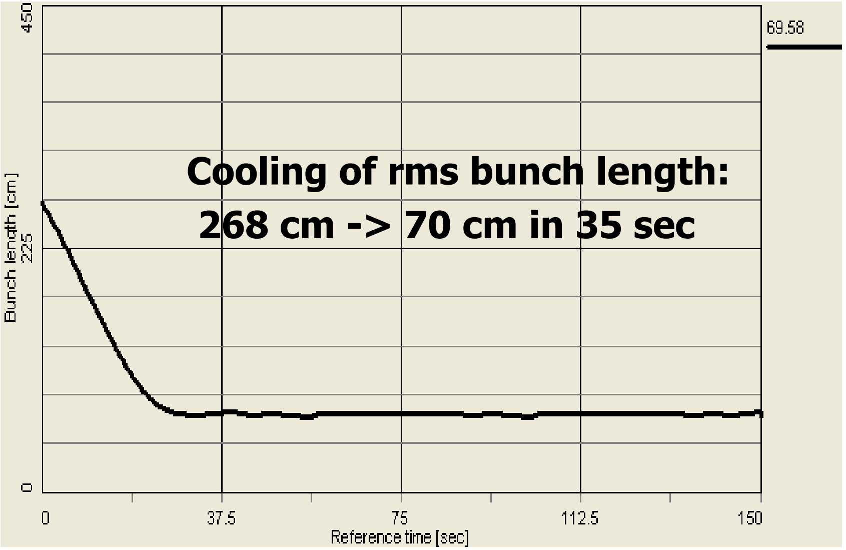




Cooling section length: L=10m

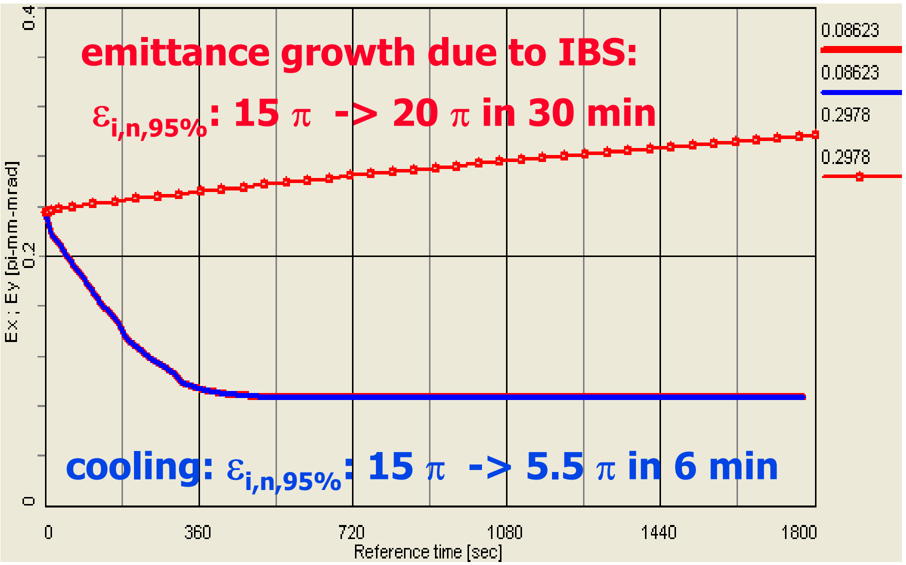
Cooling Au ions at E_k=5 GeV/u (γ=6.37)
Electron beam: q=5nC, rms $\varepsilon_{e,n}$=10μm, σ_p=1e-3, L=80m
(Figs: plotted emittance is rms unnormalized)

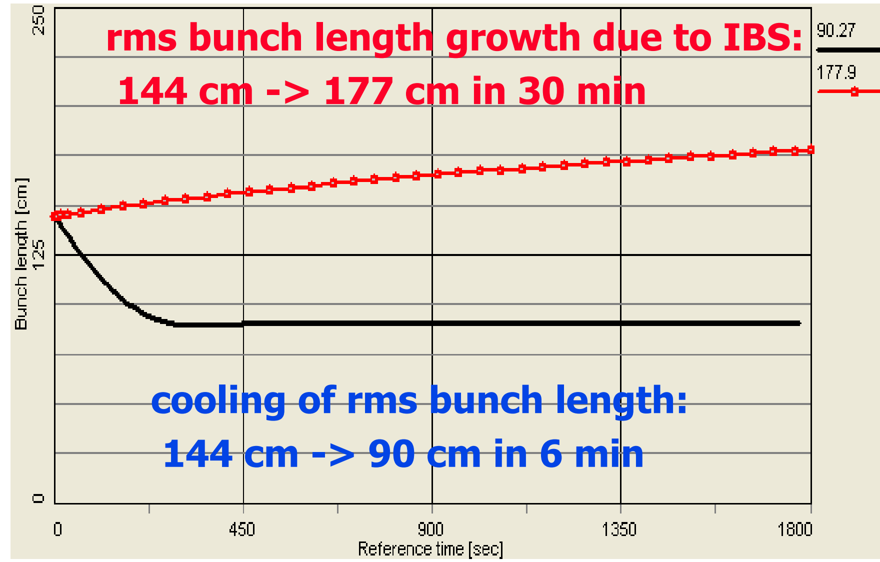




Cooling section length: L=80m

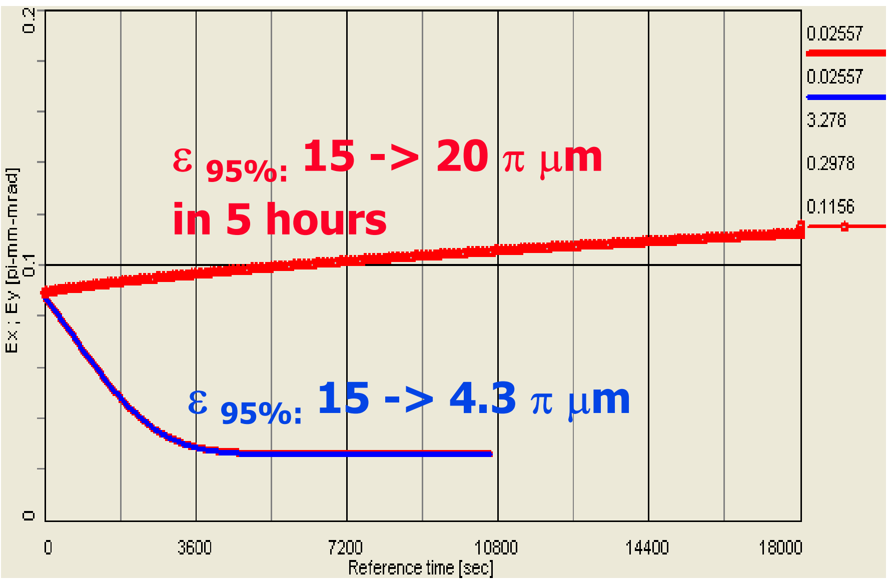
Cooling of Au ions at E_k=9 GeV/u (γ=10.66) Electron beam: q=5nC, rms $\varepsilon_{e,n}$=10μm, σ_p=1e-3, L=10m (Figs: plotted emittance is rms unnormalized)

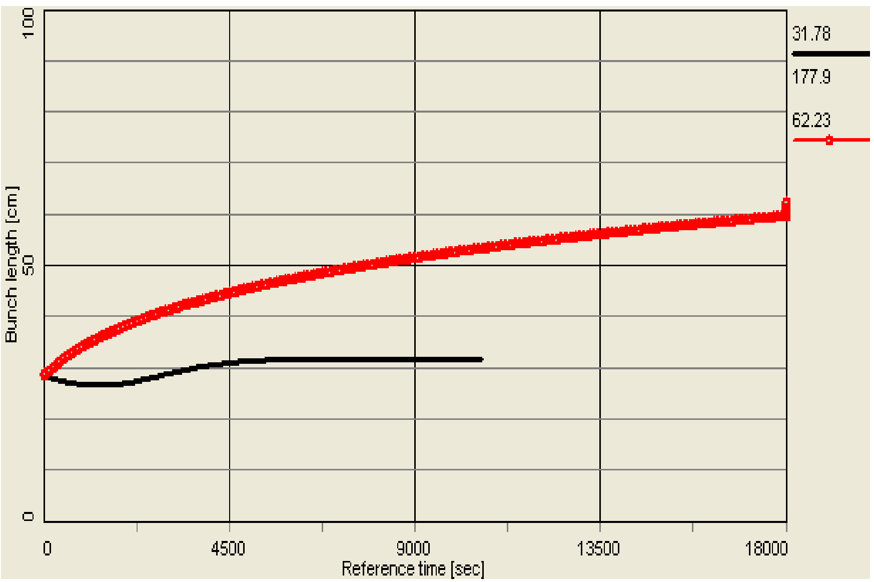




cooling at present RHIC injection energy just with L=10 m cooling section

Cooling of protons at injection E_k=25 GeV (γ=28)
Protons: N=1.5e11, rms $\varepsilon_{p,n}$=15µm, $\sigma_{p,p}$=5e-4
Electron beam: q=5nC, rms $\varepsilon_{e,n}$=4µm, $\sigma_{p,e}$=3e-4, L=80m

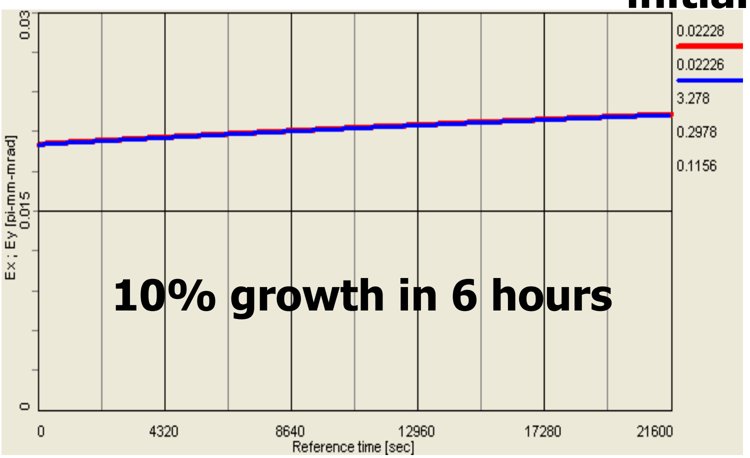


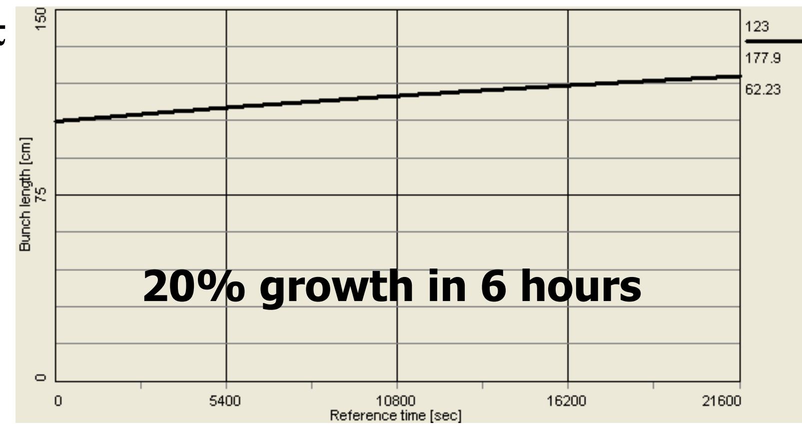


Present Run-6
protons at store (γ=120), N=1.4e11

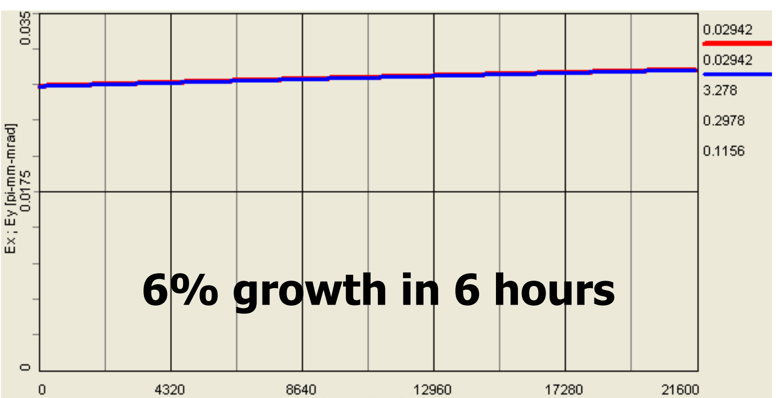
initial emittance

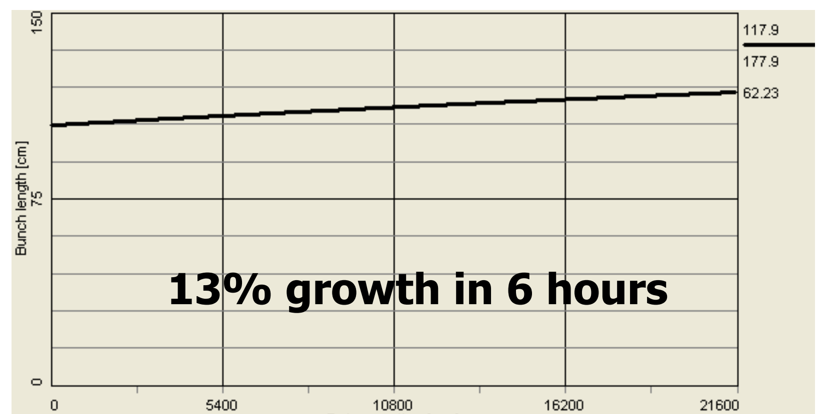
15 π





20 π



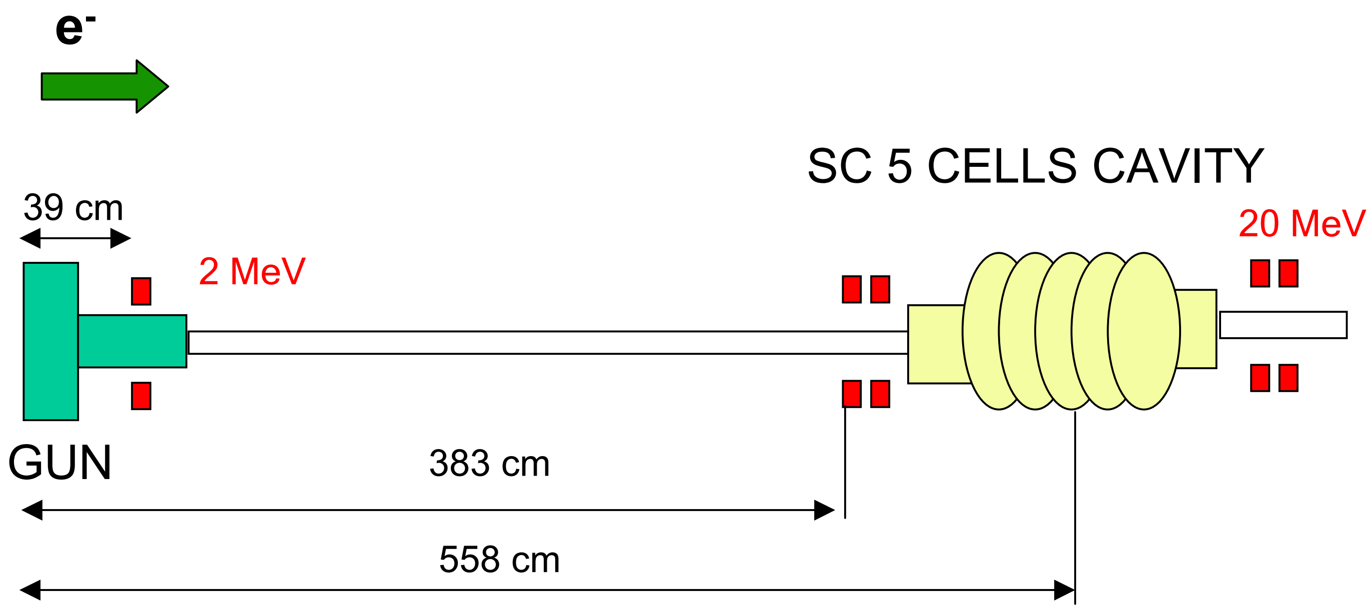


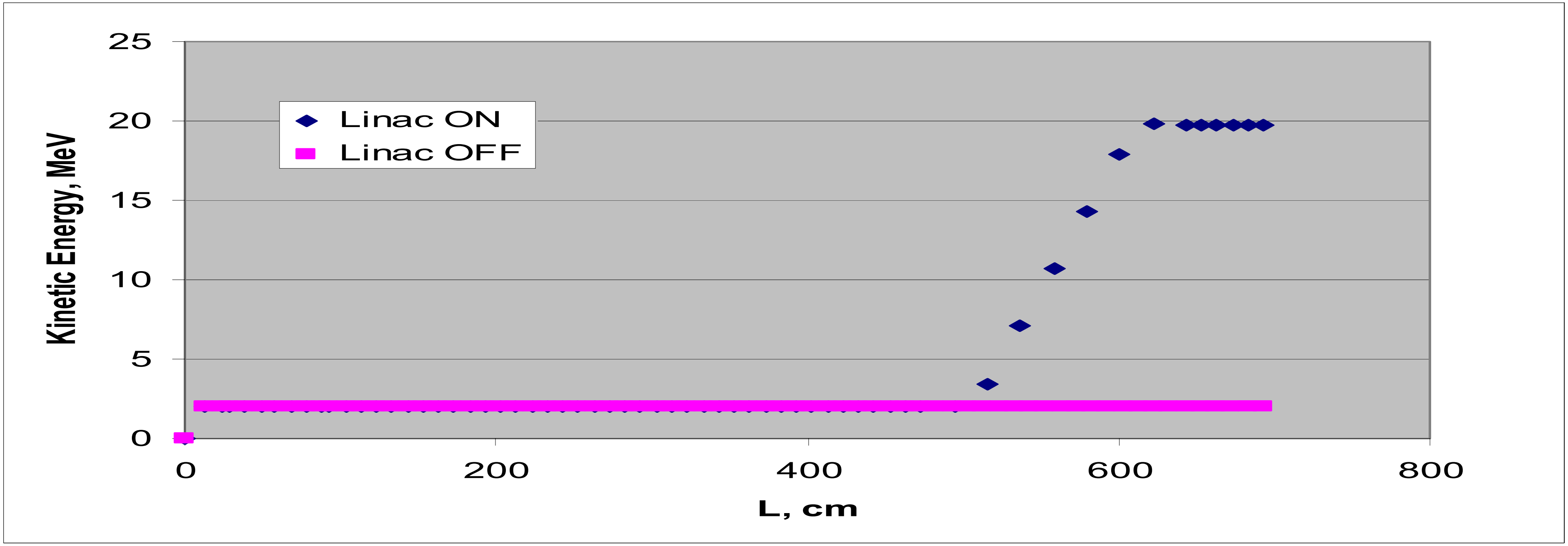
Summary

- Cooling times at low-energies in RHIC are very short.
- It seems feasible to employ RF gun which is developed for ERL project at BNL (presently under construction at Collider-Accelerator Department) to provide such a low-energy cooling.
- Actual technical aspects of electron beam transport will need to be addressed when the energy of interest or a range of energies will be defined.

Dmitry's Talk

Simple tested magnetic system





Result of PARMELA simulation: linac ON and linac OFF

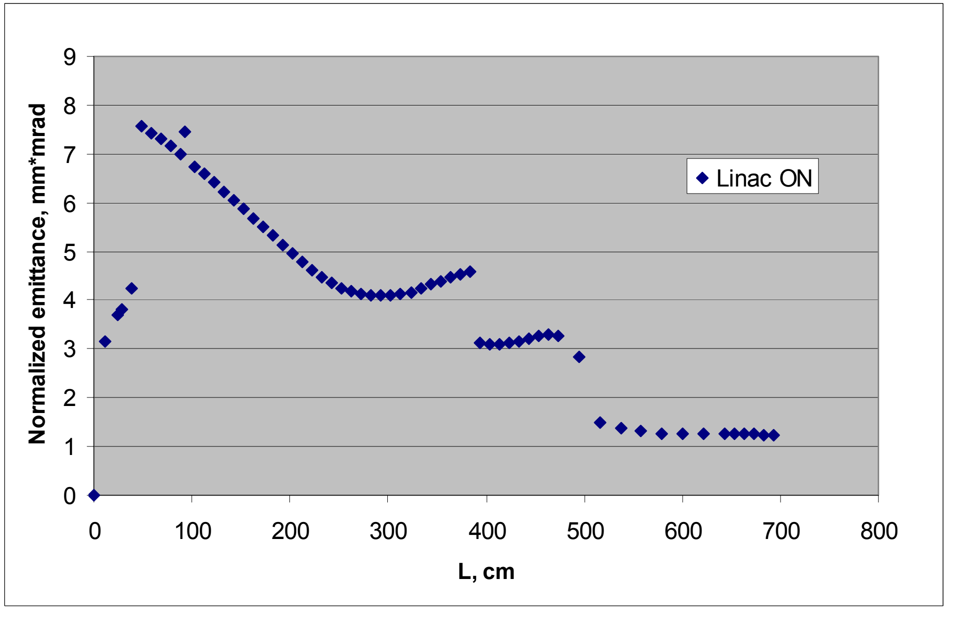
Launched Beam:

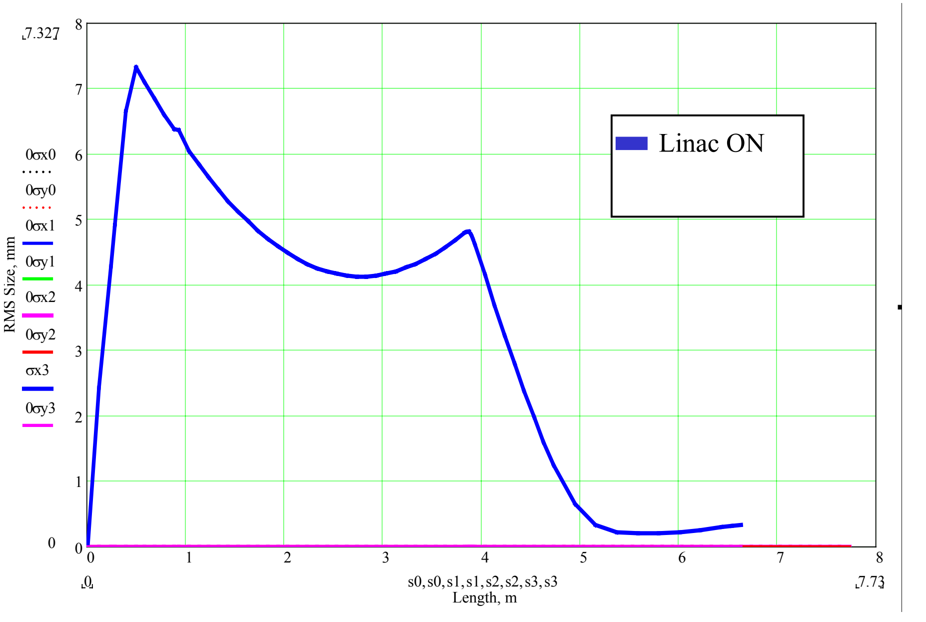
phase 40°, Q=1.4 nC,

R=2 mm, L=51 psec, flat-top,
no thermo emittance

max kE=20 Mev — Solenoid2 B=600 G

max kE=2.0 Mev — Solenoid2 B=400 G





Normalized RMS Emittance

RMS Beam size

Result of PARMELA simulation: linac ON and linac OFF

Launched Beam:

phase 40°, Q=1.4 nC,

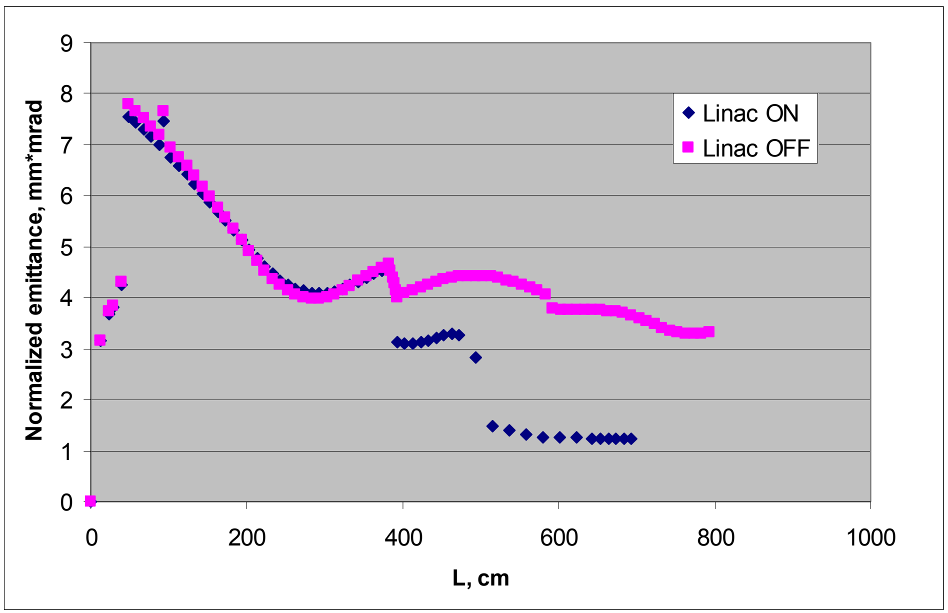
R=2 mm, L=51 psec, flat-top,
no thermo emittance

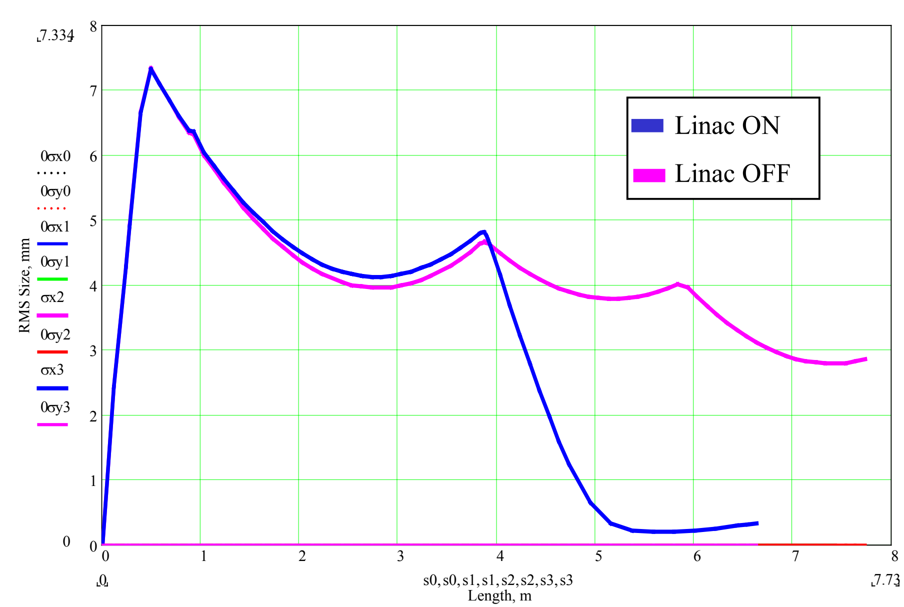
max kE=20 Mev

Solenoid2 B=600 G

max kE=2.0 Mev

Solenoid2 B=400 G





Normalized RMS Emittance

RMS Beam size

Result of PARMELA simulation: linac ON and linac OFF

Launched Beam:

phase 40°, Q=5 nC,

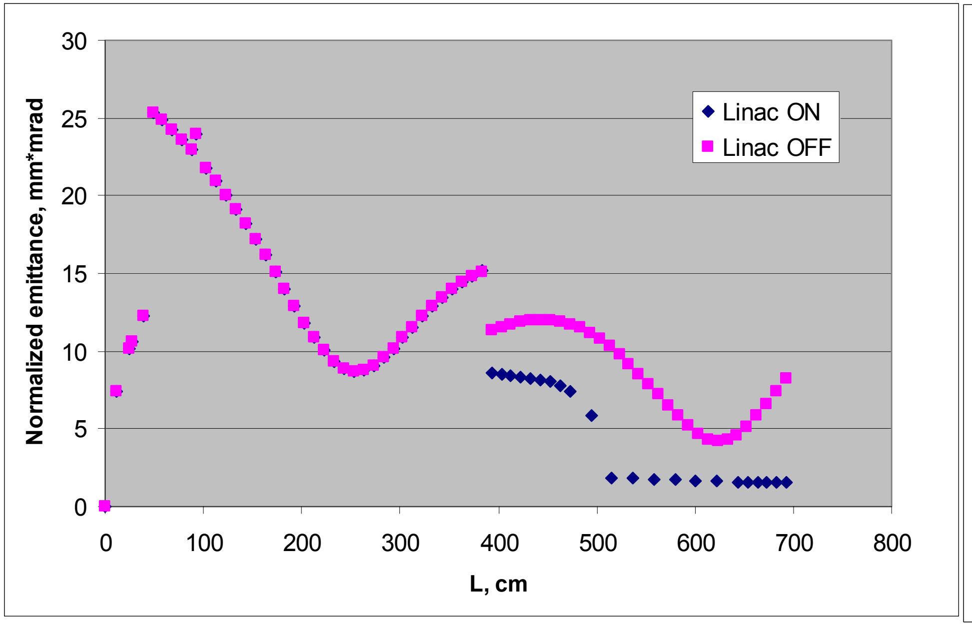
R=3 mm, L=83 psec, flat-top,
no thermo emittance

max kE=20 Mev

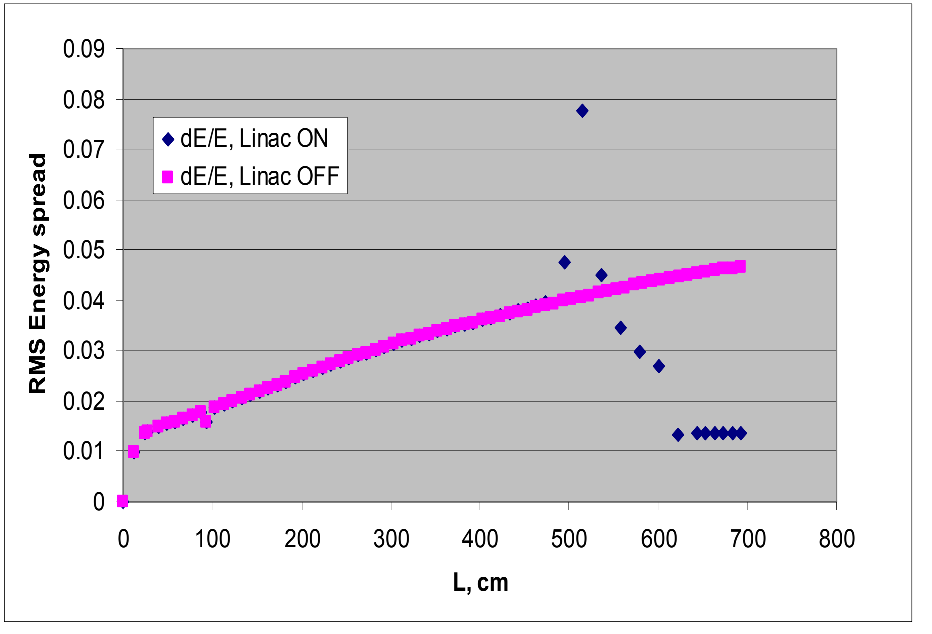
Solenoid2 B=600 G

max kE=2.0 Mev

Solenoid2 B=450 G

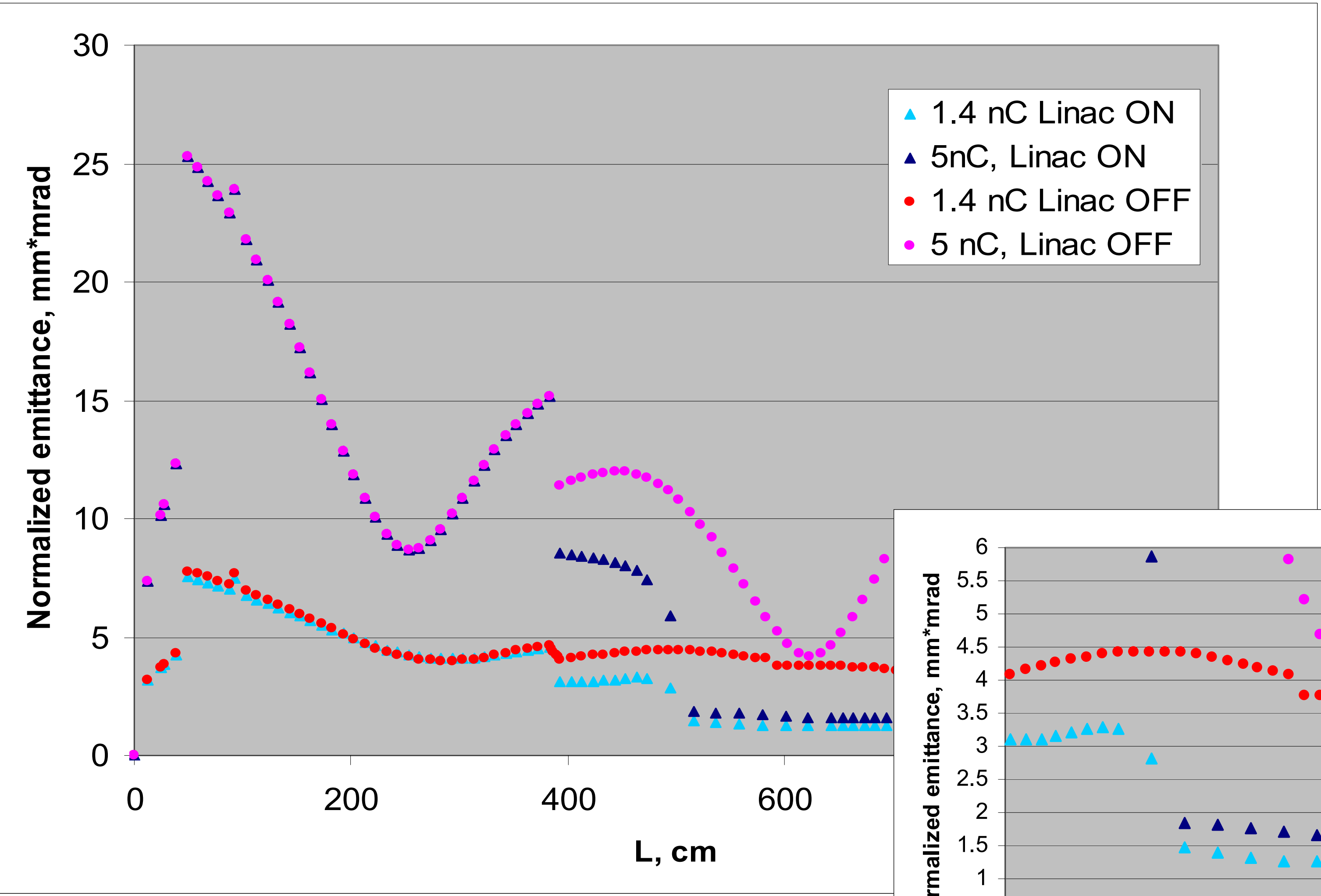


Normalized RMS Emittance

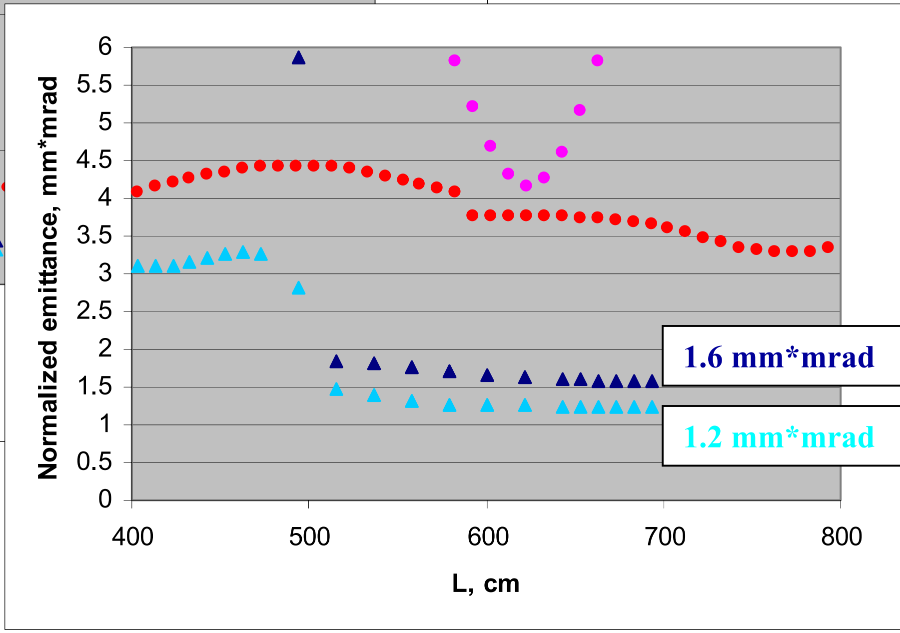


RMS Energy spread

Summary



30
25
20
15
10
5
0
0
200
400
600
Normalized emittance, mm*mrad
L, cm
1.4 nC Linac ON
5nC, Linac ON
1.4 nC Linac OFF
5 nC, Linac OFF



6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
400
500
600
700
800
Normalized emittance, mm*mrad
L, cm
1.6 mm*mrad
1.2 mm*mrad