Comparison of Hollow Electron Beam Devices and Electron Heating

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Basis of hollow electron cooling technique

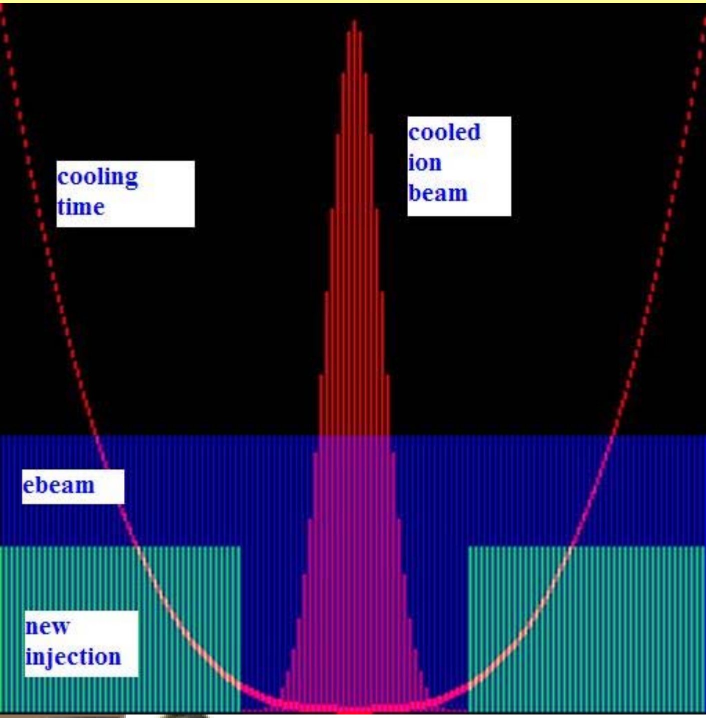
- Theoretical model hollow electron beam cooling advantages :

a- for low intensity ion beams (suppression recombination),

b- for high ion intensity ion beam (suppression “heating”)

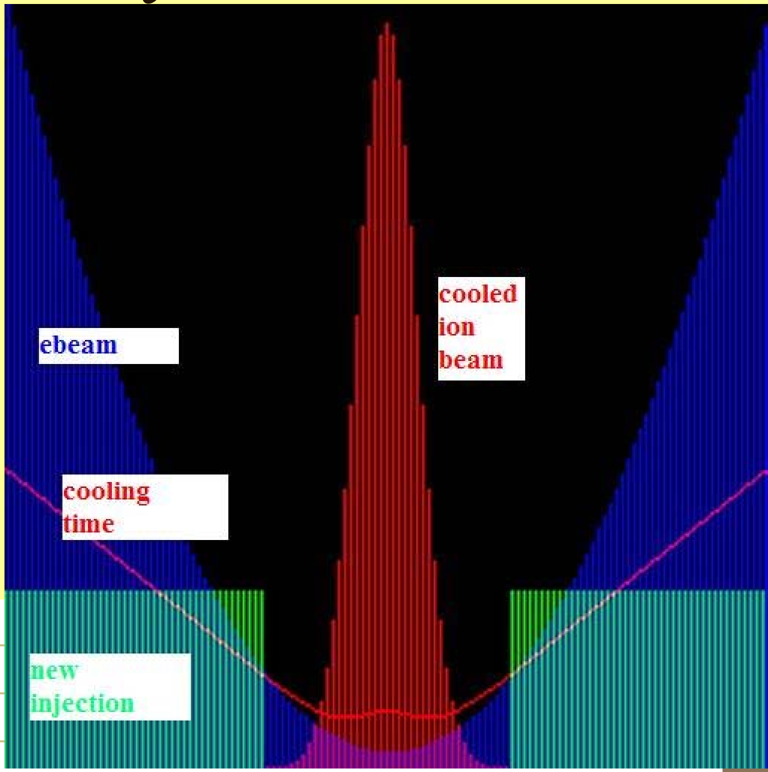
- Vertical shift electron beam cooling of antiproton beam at **RECYCLER (FNAL)**
- **LEIR** cooling experiments with Pb^{+54}
- **CSRm** cooling and accumulation C^{+6}

Advantages for low intensity beams



Red-storage ion beam, green-new injected ion beam ←blue- flat electron beam,

Right fig.-parabolic shape electron beam cooling→



Too fast cooling↑ too slow cooling↑
←amplitude→

- Low recombination for storage ion beam core where electron beam density low.
- Cooling at center not so fast for hollow electron beam and density of ion beam lower (unwanted instability not so intensive) but cooling time at few time faster for ion beam tail (the ions with high amplitude of oscillations).

Number of accumulate cycles $l_{cool}*t_{life}$

Cooling time: $1/l_{cool}\sim 1/<n_e(x)>$ -average at transverse direction electron beam density

Recombination time: $t_{rec}\sim 1/ne(0)$ – density at center of electron beam. Decreasing density at centre increased life time.

$$N_{acc} = \tau_{life} \times \lambda_{cool} \propto \frac{< n_e(r) >}{n_e(0)} = 1/g_e$$

Plasma oscillations at cooling section

$$\frac{d^2 x_i}{dt^2} = \frac{eZ_i}{M_i} E$$

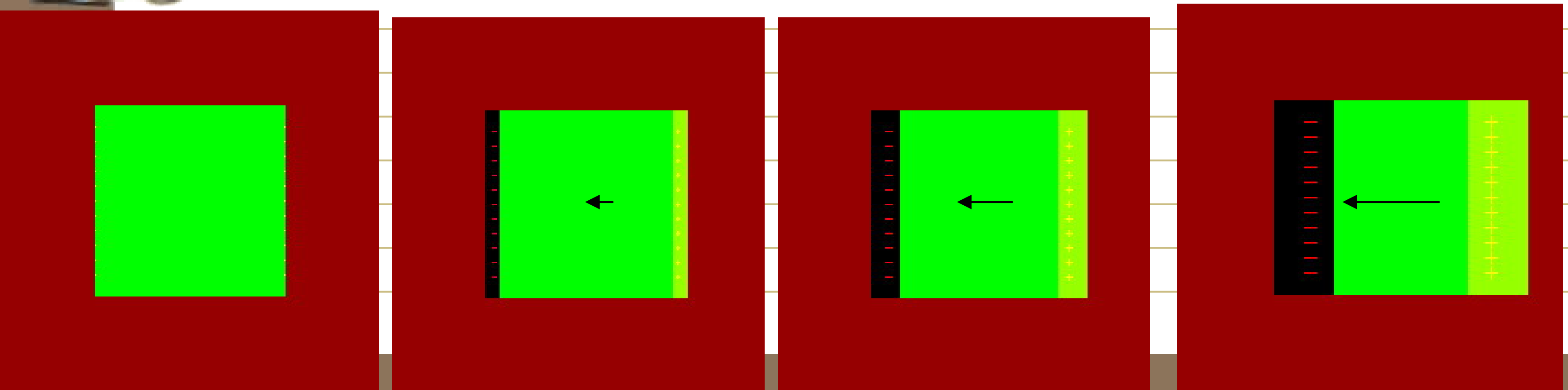
Ion beam oscillations

$$\frac{d^2 x_e}{dt^2} = -\frac{e}{m_e} E$$

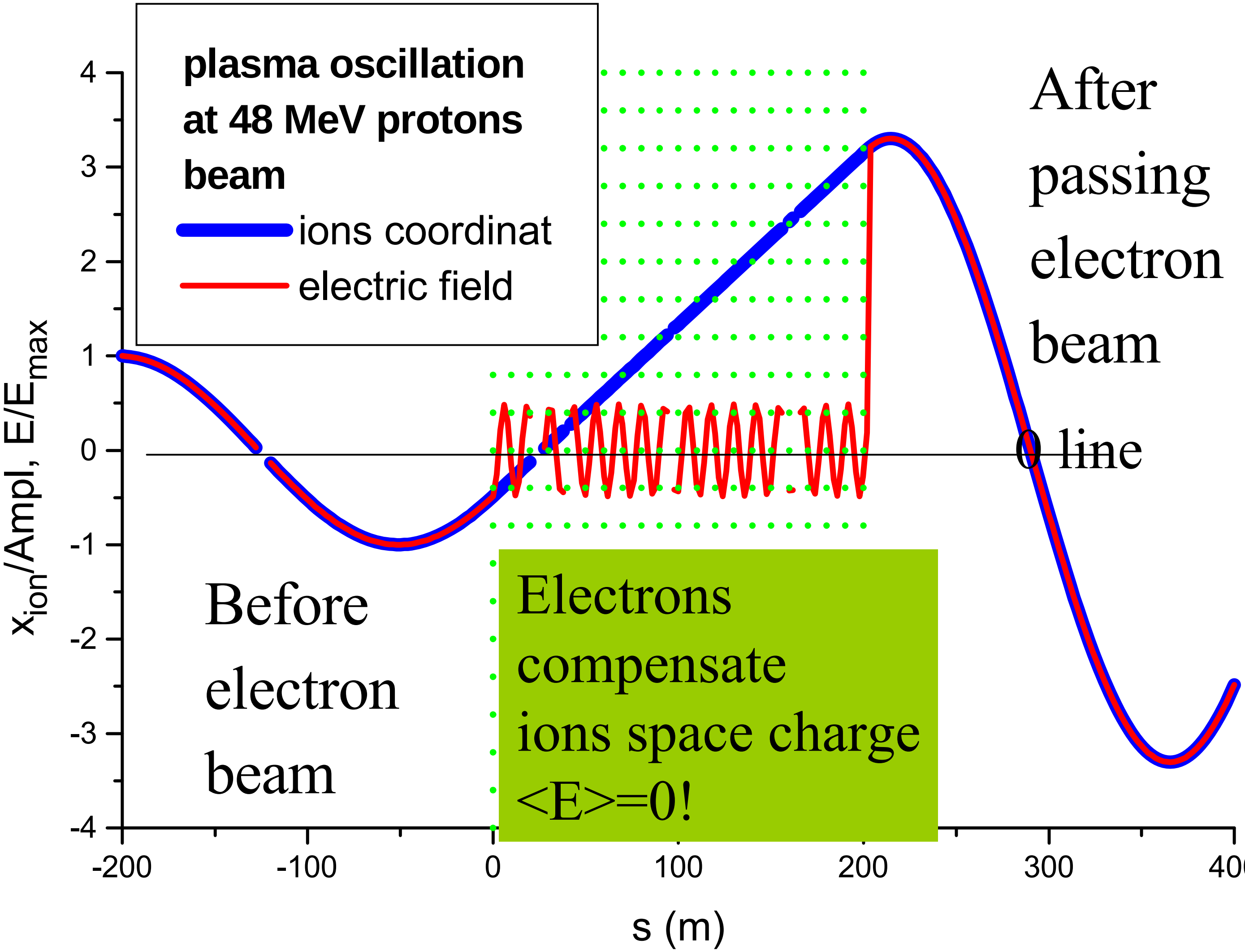
electron beam oscillations

$$E = 4\pi e n_e x_e - 4\pi e Z_i n_i x_i$$

Electric field at plasma oscillations



Plasma Oscillations At high Intensive beams



The figure demonstrated that after come in electron beam the light electrons have high frequency of plasma oscillations and practically compensated the ion space charge. The ions continue moved as free and after come out from electron beam have amplitude of oscillation at 2 times more! Of course 200 m cooling section still not exists and so long cooling section taking for made effect more clear visible on figure. At this case increment too fast 1 turn. At practica there is 1000-10000 turns at storage ring.

Problems of cooling intensive electron and ion beams

$$\delta p = -\int F dt \approx -F * \tau$$

Momentum loss at single pass cooling section

How large exited zone at the electron beam by action single ion?

$$\rho_{\max} = \tau\sqrt{V^2 + V_{eff}^2}$$

$$N_i^* = n_i \rho_{\max}^3 4\pi / 3$$

ρmax=0.2 cm   N=8000 ions

For $n_{ion}=10^6$ $1/cm^3$

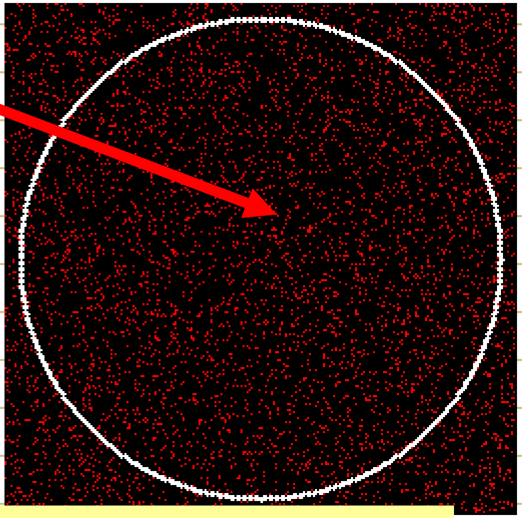
How large kick from neighboring ions N^* that generate the same kick field but for itself do not worry about others ions?

$$\Delta p^2 = -2\delta p p + \delta p^2 n_i \frac{4\pi}{3} \rho_{\max}^3$$

cooling↑

↑Heating from neighbor ions

$$\frac{\delta p}{p} < \frac{2}{N^*}$$



Red points ions at $0.2*0.2*0.2$ cm^3

$$\left(\frac{\Delta p}{p}\right)^2 = -2\frac{F\tau}{p}(1-\omega_e^2\omega_i^2\tau^4 g)$$

Single turn cooling decrement
and
heating term

$$\omega_e = \sqrt{\frac{4\pi e^2 n_e}{m_e}} = c\sqrt{4\pi r_e n_e},$$

$$\omega_i = \sqrt{\frac{4\pi e^2 Z^2 n_i}{M_i}} = c\sqrt{4\pi r_i n_i}$$

Electron and ion beams plasma frequency
τ is time of flight cooling section at beam system of reference

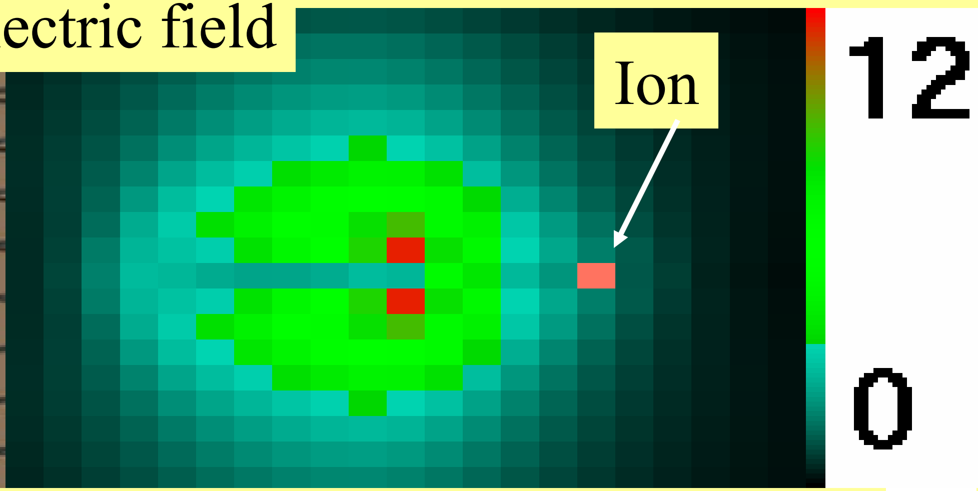
$$g = \int E^2 dV/(4\pi\rho_{\max}^3/3)/(F/qZ)^2 \approx 1.4$$

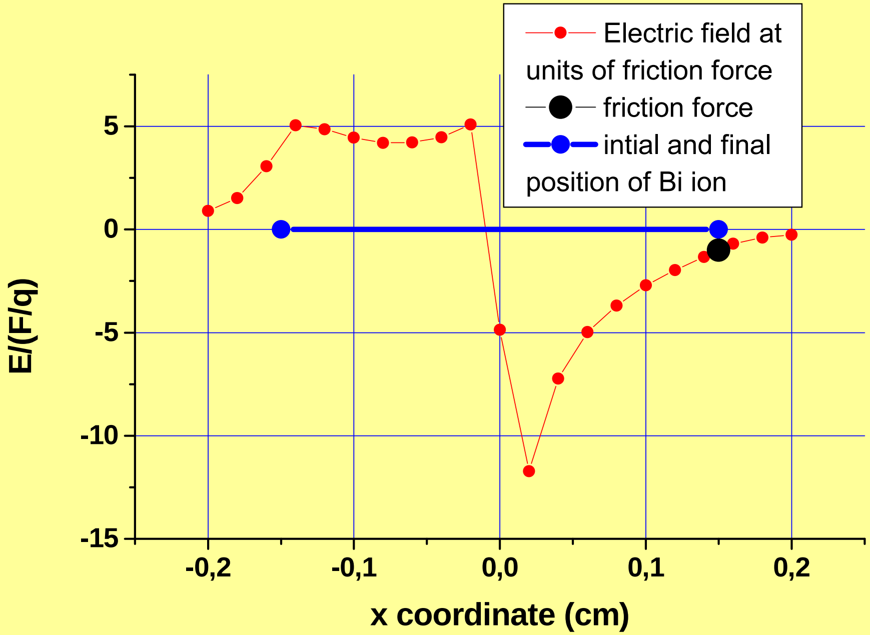
g is numerical factor that can calculated by computer simulation.

Example of calculation was made for Bi^{+67} ion moves with velocity 4.6E6 cm/s at an electron beam with density 1E6 1/cm^3, time of interaction 6.5E-8s, length of path is $\rho_{\max} = V\tau$ 0.3 cm

Wave at electron beam by moving Bi ion

Electric field





Electric field around moving ion Bi at plane (color map) and Electric field along ion trajectory (down figure) at units cooling force Fcooling E/(Fcooling/(Z*q))

Heating parameter

$$\delta = \omega_e^2 \omega_i^2 \tau^4 = (4\pi)^2 n_e n_i r_e r_i (c\tau)^4$$

$$n_e = \frac{j_e}{\gamma\beta c * q}$$

Electron beam density at beam Reference system

$$n_i = \frac{N_i}{l_{bunch} 2\pi\sigma_\perp^2 \gamma}$$

Ion beam density

$$\tau = \frac{l_{cooler}}{\gamma\beta c}$$

Time of flight cooling section

Electron heating limit

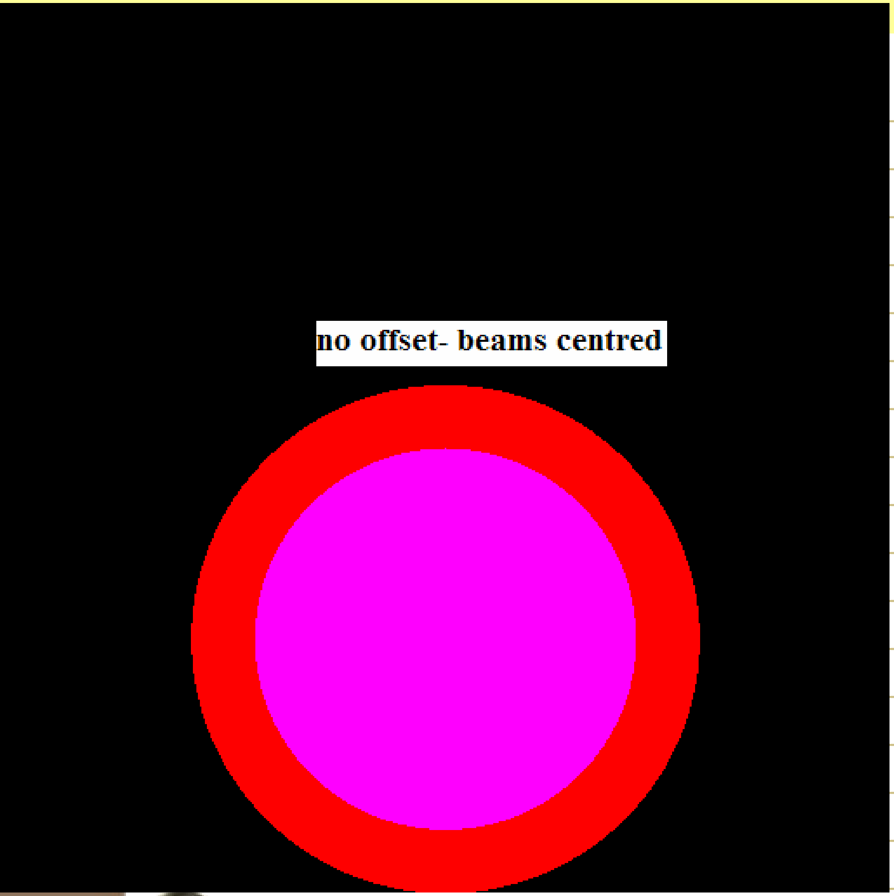
$$n_i \times n_e \le \frac{6}{r_e r_i (c\tau)^4 * g(4\pi)^2 \ln(\rho_{\max} / \rho_{\min})}$$

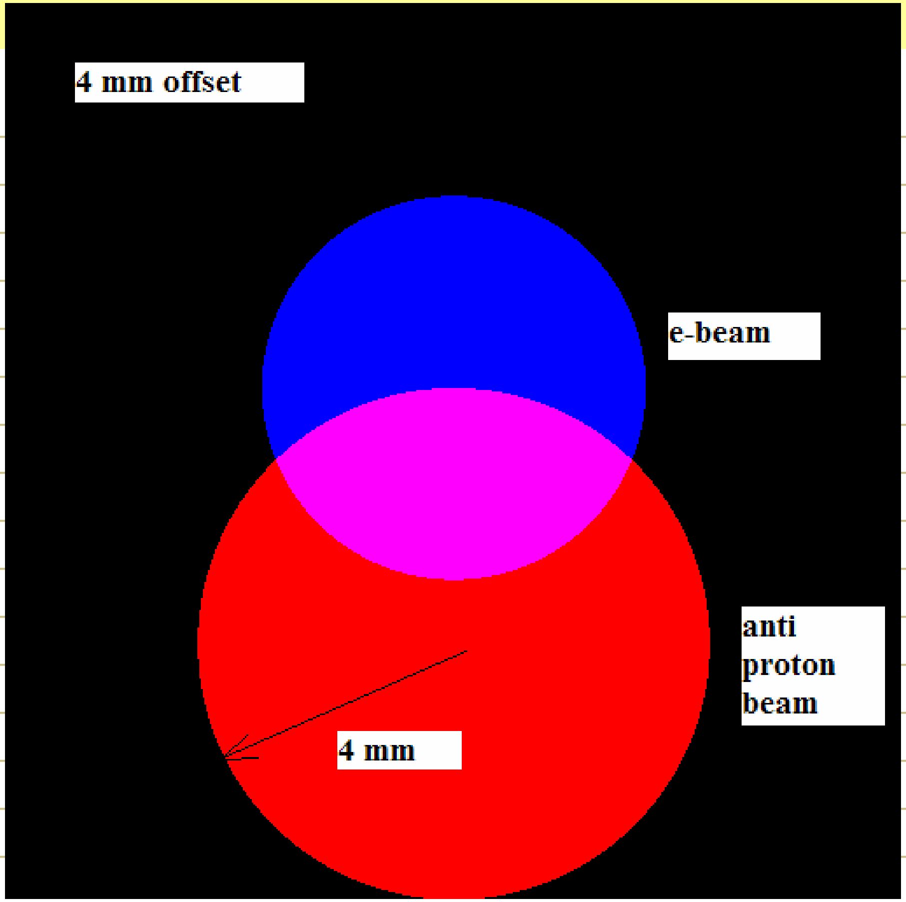
Decreasing electron beam density at center $n_e(0)$ opens space for increasing ion beam density n_i

Project: Electron cooling for RHIC

Fast painting of an electron beam over 6 dimensional coordinates can produce any distribution of the average friction force and as result to control the 6-dimensional density distribution of the ion beam.
BNL, C-A/AP 47 Aprill 2001.
http://www.agsrhichome.bnl.gov/AP/ap_notes/ap_note_47.pdf)

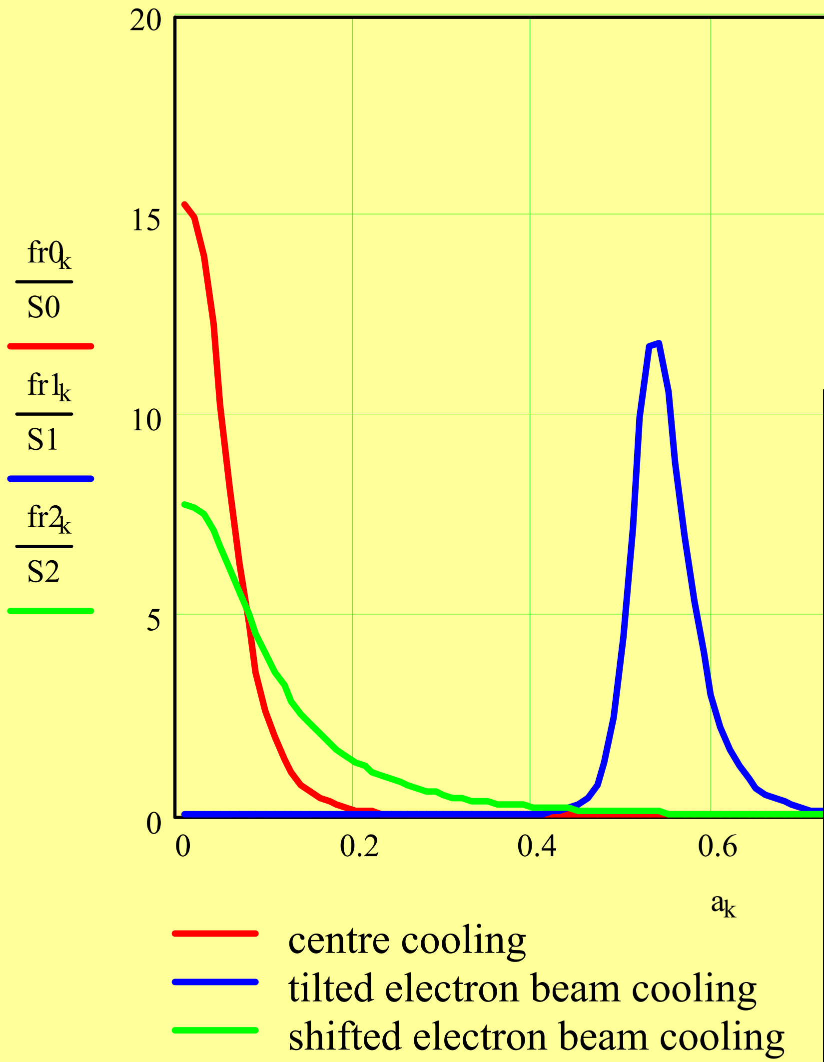
FNAL cooler experiments (2005) with vertical offset cooling



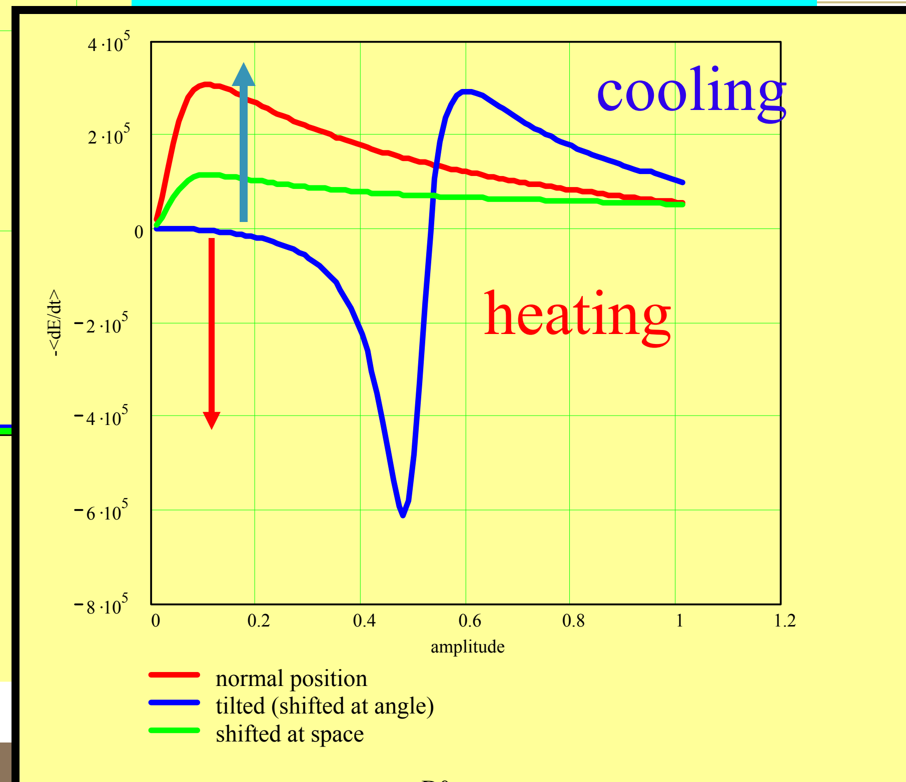


- Aim was limited overcooling and stop degradation life time of the storage antiproton beam at recycler

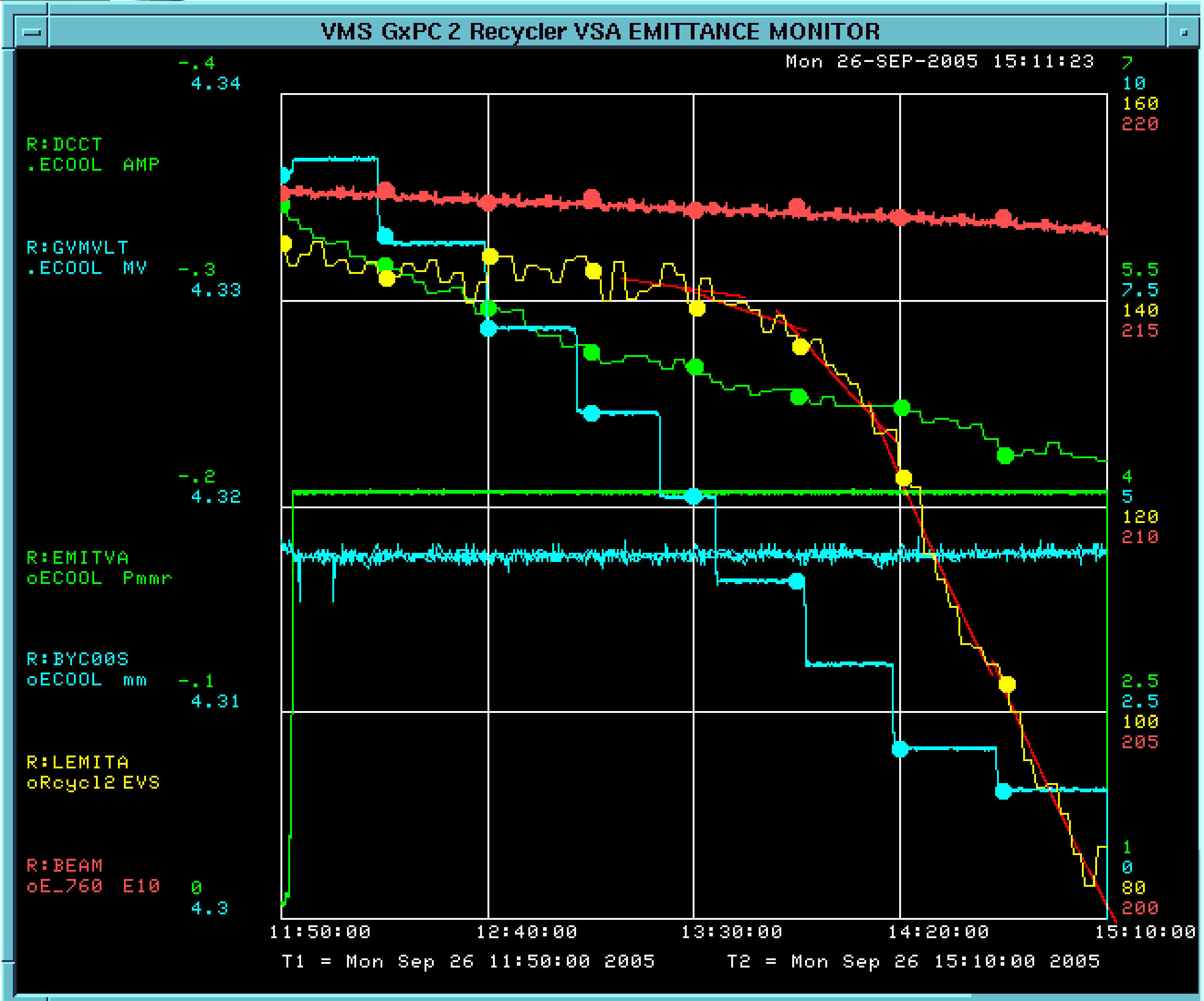
Why shifted but not tilted?



For tilted cooling
all ions concentrated
around tilted angle
and have high amplitude
and low life time!!

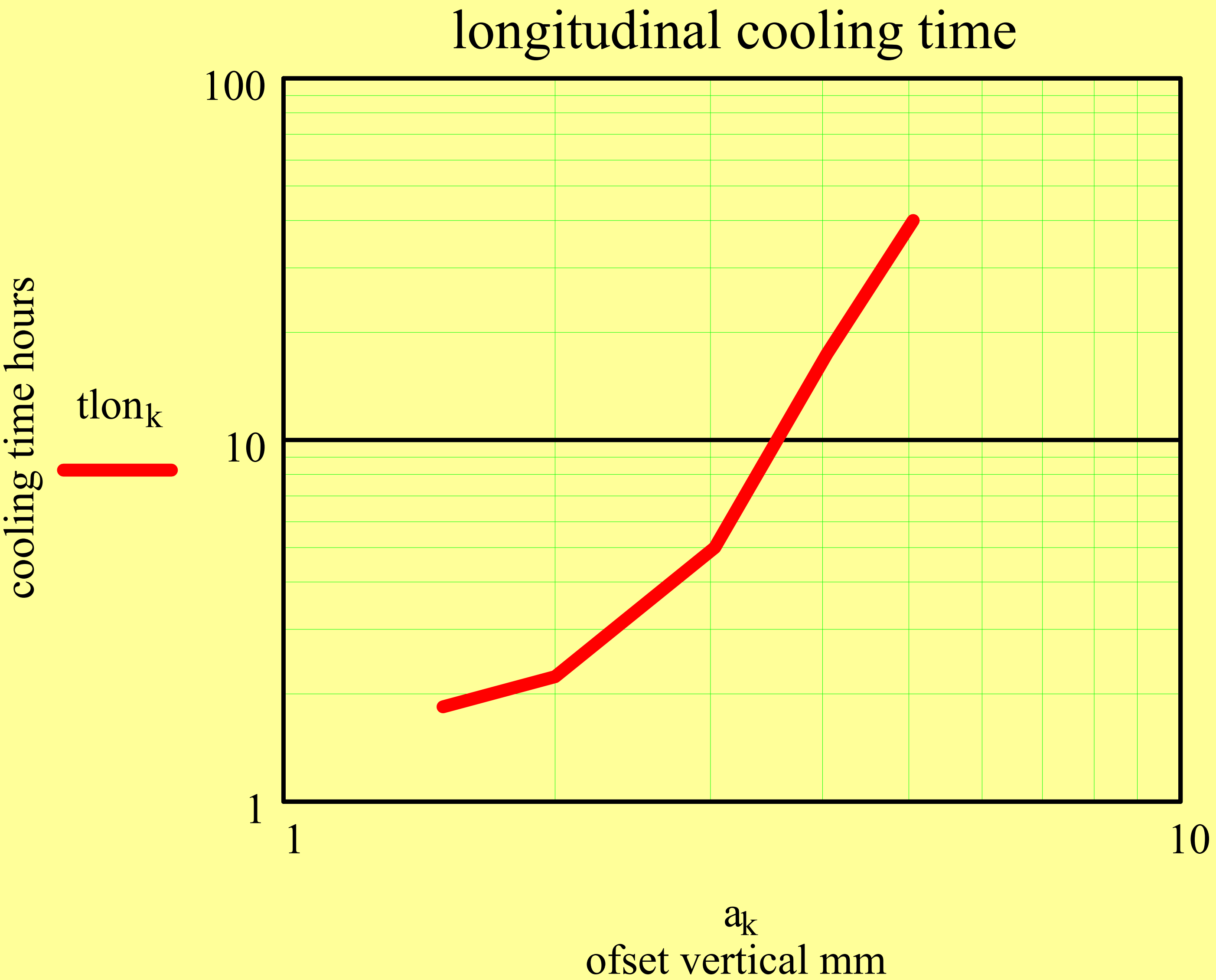


First experiments with vertical electron beam offset cooling. September 26 2005 (15:10:00)



Testing cooling with shift vertically electron beam:
9,8,7,6,5,4,3,2,1.5 мм (blue line)
clear see that longitudinal emittance cooled faster for close position electron beam
red line show fitting of cooling time:
Initially 5 mm-40 hours
Final 1.5 mm-2 hours

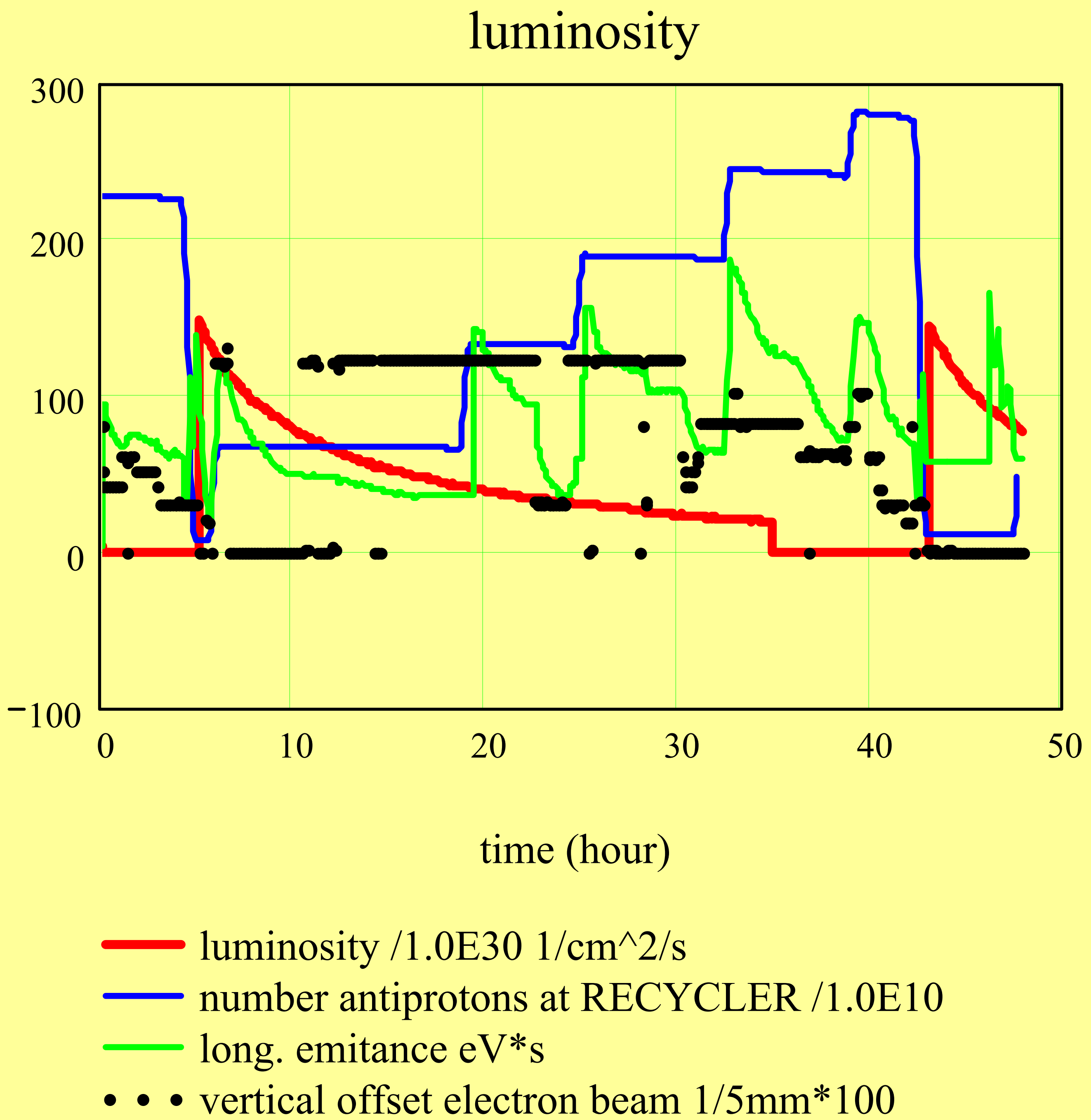
Longitudinal cooling time versus offset vertical position



Fermi National Accelerator Laboratory
ACCELERATOR DIVISION

World Records
*Initial Luminosity: 1.413 E32 [1/cm**2 sec], 4 Oct 2005. This was a Recycler-only shot and a new worlds record*

Experiments show high potential of offset cooling for control Ion beam instability for intensive antiproton beam.



High art of operator for “painting” the vertical offset electron beam to find optimum (balance) between cooling and and life time for save maximum antiprotons at TEVATRON

New low energy coolers

For high energy cooler cooling time measured at hours and we have time for “painting” e
but for low energy cooler time scale is 0.1-1 s.
No time for painting!

BASIC FEATURES OF THE COOLERs

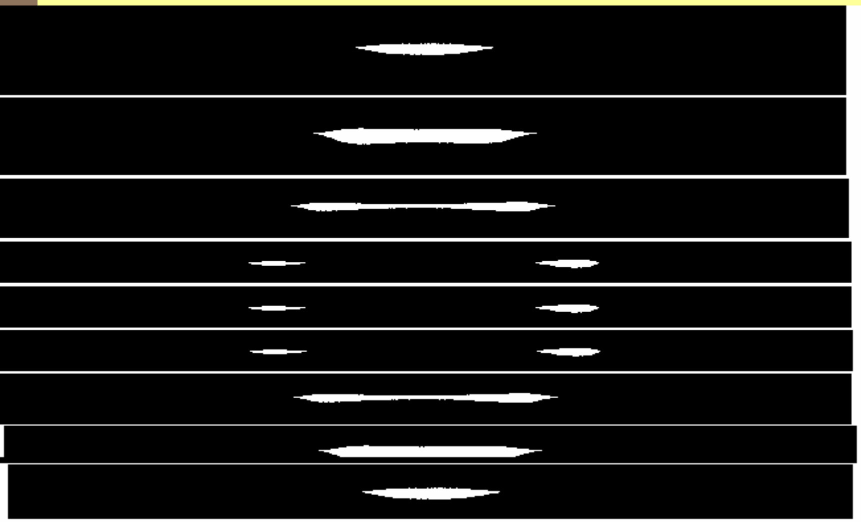
Variable Profile of Electron Beam

Electrostatic Bending

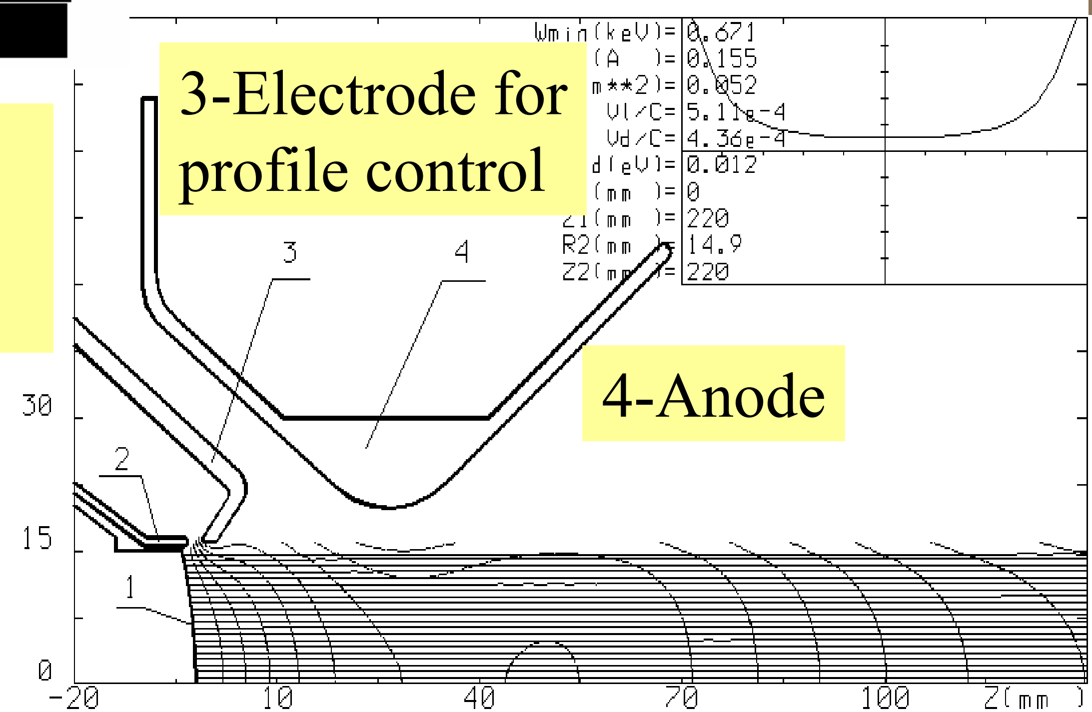
Magnet System Design

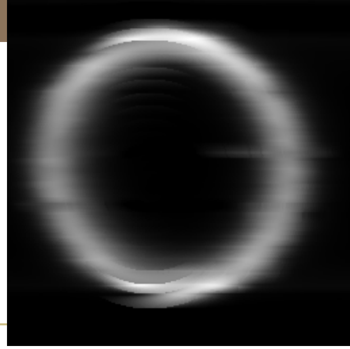
1999 Idea of variable profile electron gun:

EPAC02, THE ELECTRON GUN WITH VARIABLE BEAM PROFILE FOR OPTIMIZATION OF ELECTRON COOLING, http://accelconf.web.cern.ch/AccelConf/e02/PAPERS/WEPRI049.pdf

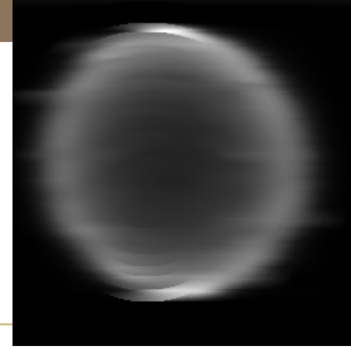


Photos of tungsten wire at different position inside electron beam

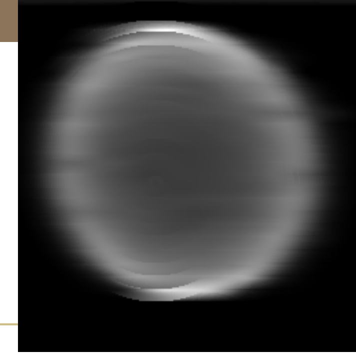




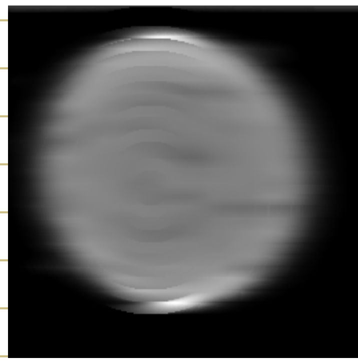
$U_{contrrol}/U_{anode}$= 0.6/0.9 kV



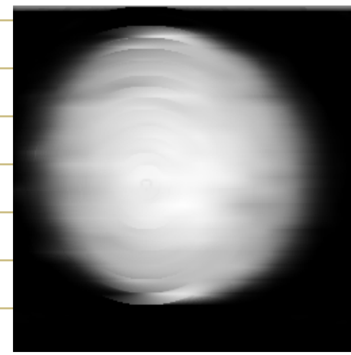
$U_{contrrol}/U_{anode}$= 0.3/0.9 kV



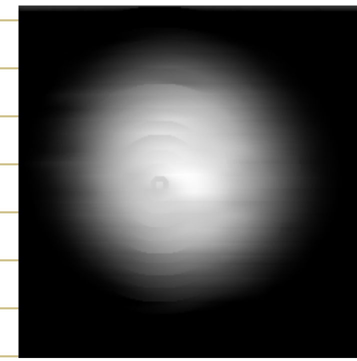
$U_{contrrol}/U_{anode}$=0.2/0.9 kV



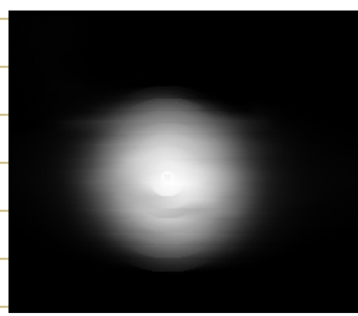
$U_{contrrol}/U_{anode}$=0.1/0.9 kV



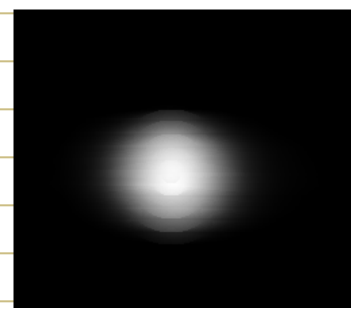
$U_{contrrol}/U_{anode}$= 0.05/0.9 kV



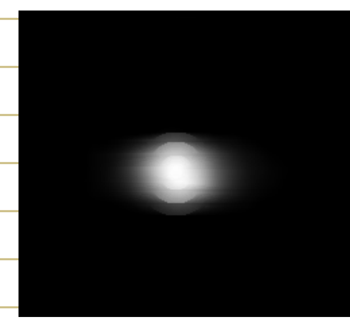
$U_{contrrol}/U_{anode}$= 0/1.4 kV



$U_{contrrol}/U_{anode}$= –0.2/2.8 kV



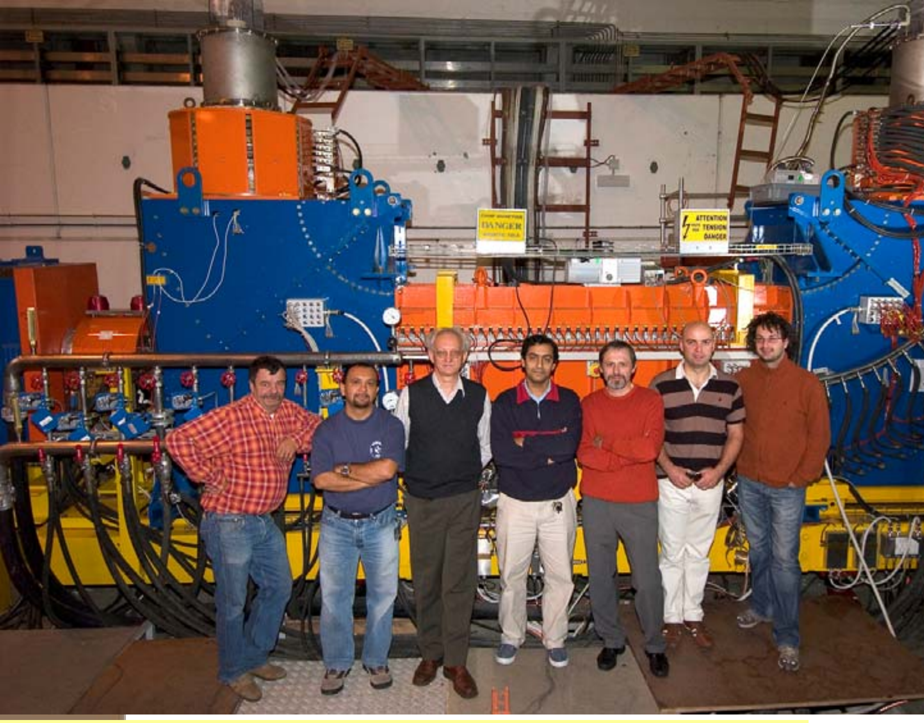
$U_{contrrol}/U_{anode}$= -0.4/2.8 kV



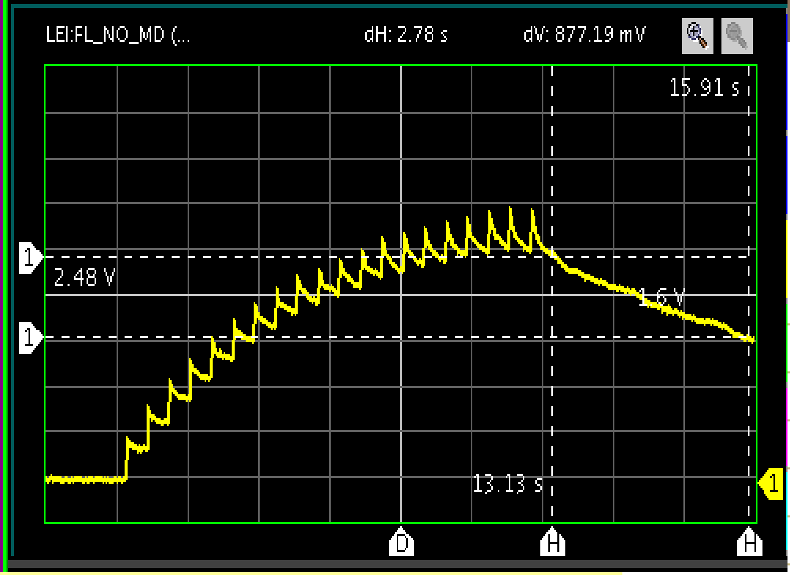
$U_{contrrol}/U_{anode}$= –0.6/2.8 kV

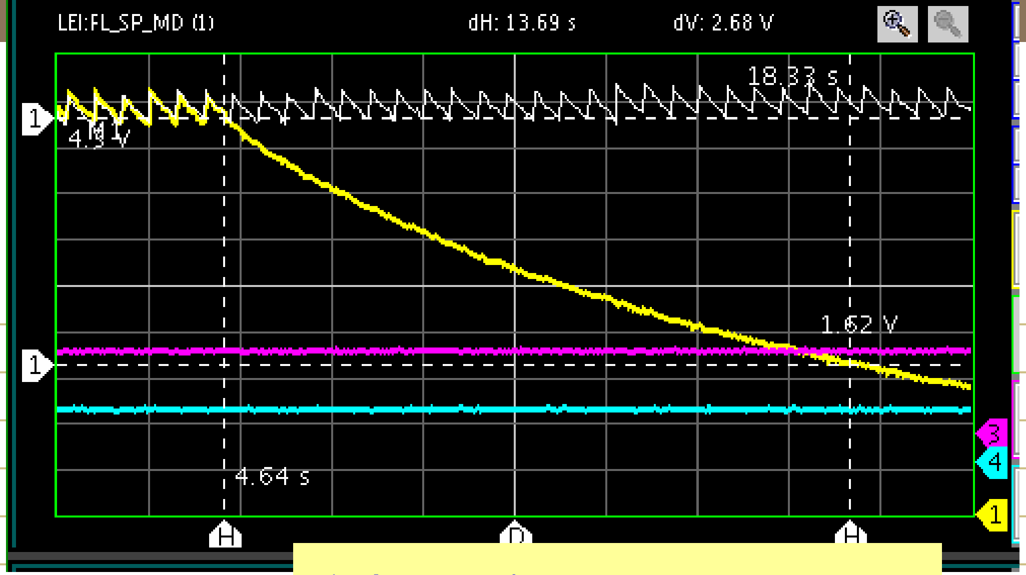
Electron beam distribution for different voltage on the control electrode and the anode.

Cooler with tuneable coils sections



LEIR cooler experiments 2006





0.3 sec Ni>0.7×10^9

7 sec Ni<0.7×10^9

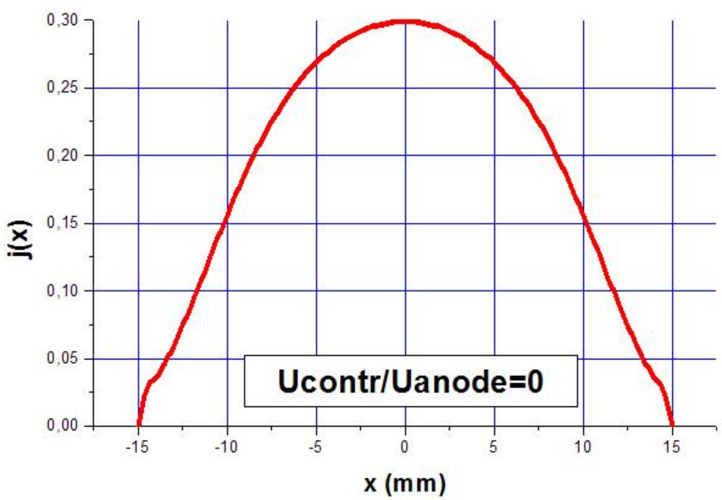
Ucontr=0 V,Ugrid=1800 V

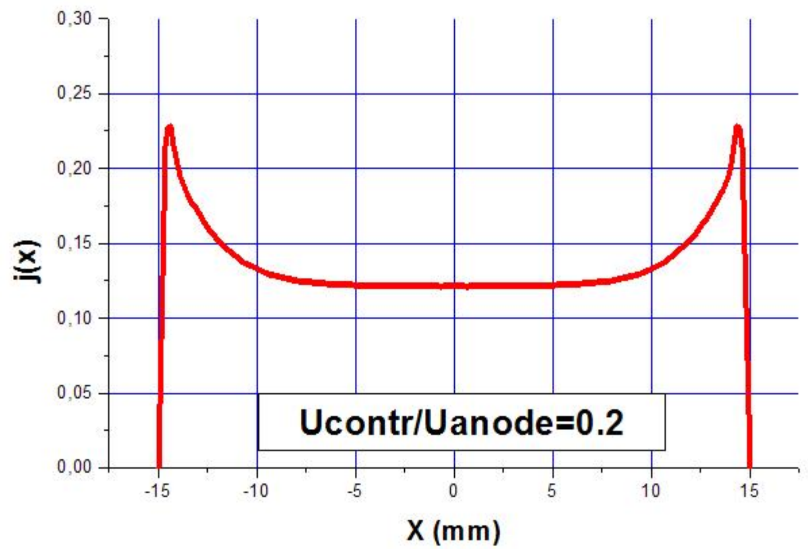
Je(0)=30 mA/cm^2

14 sec! Ni=1.7×10^9

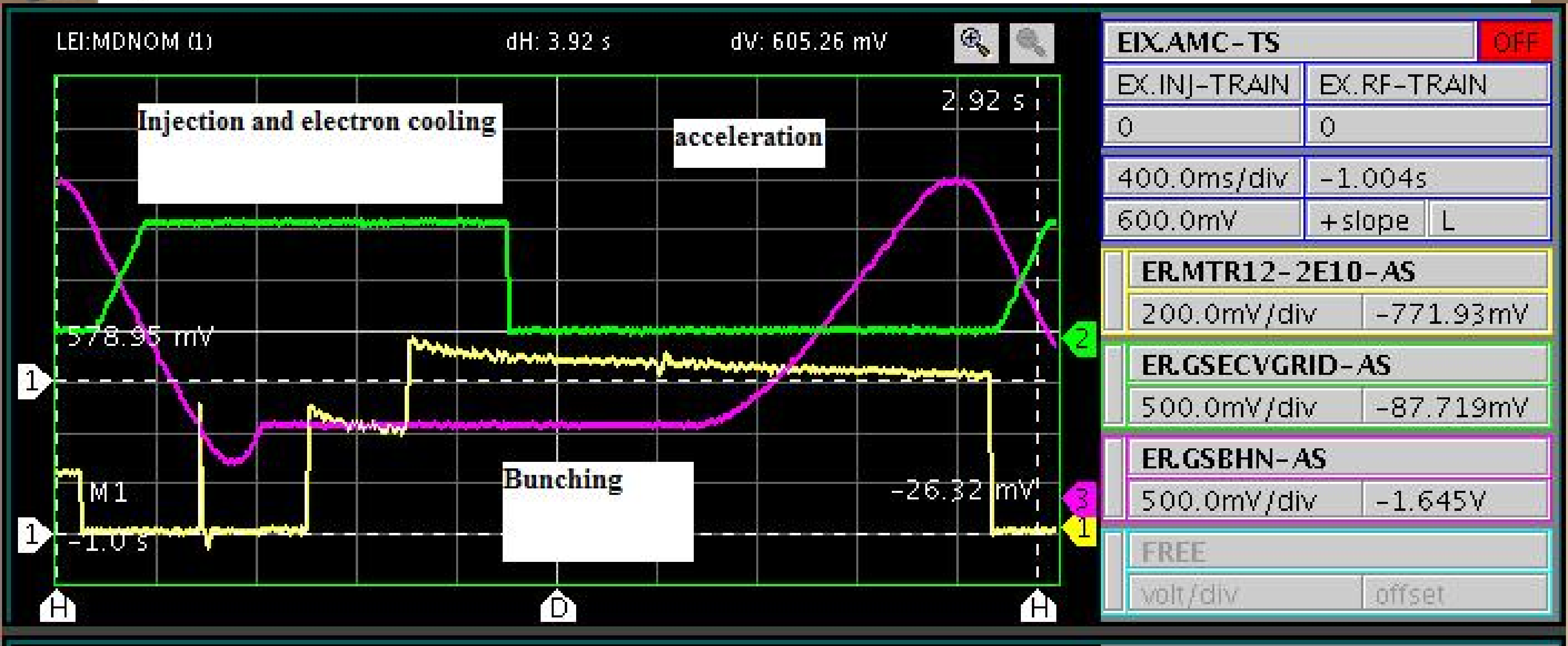
Ucontr=200 V,Ugrid=900 V

Je(0)=12. mA/cm^2





Typical magnet cycle of LEIR with period 3.6 s

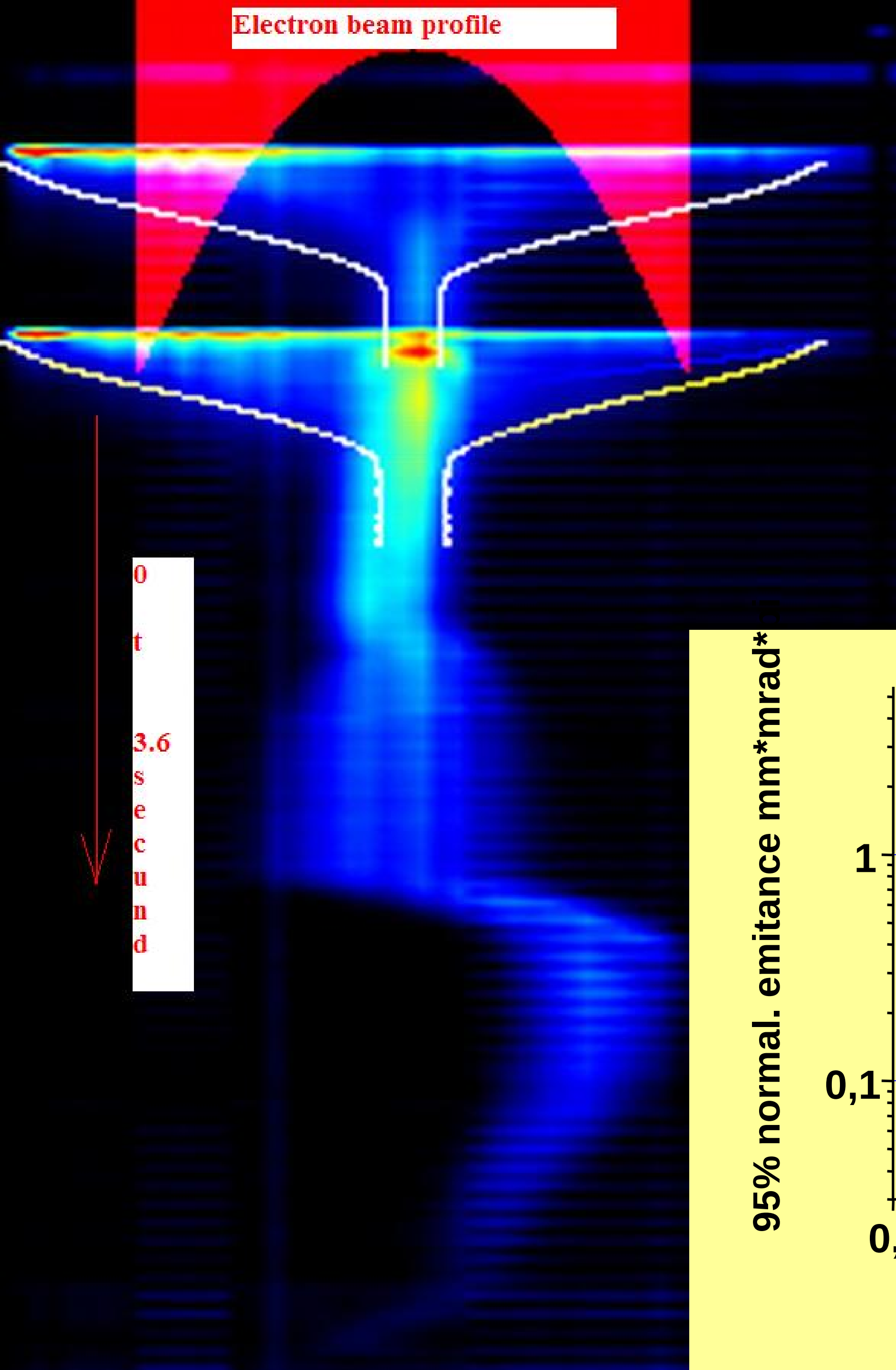


Yellow line is intensity ion beam (number ions)

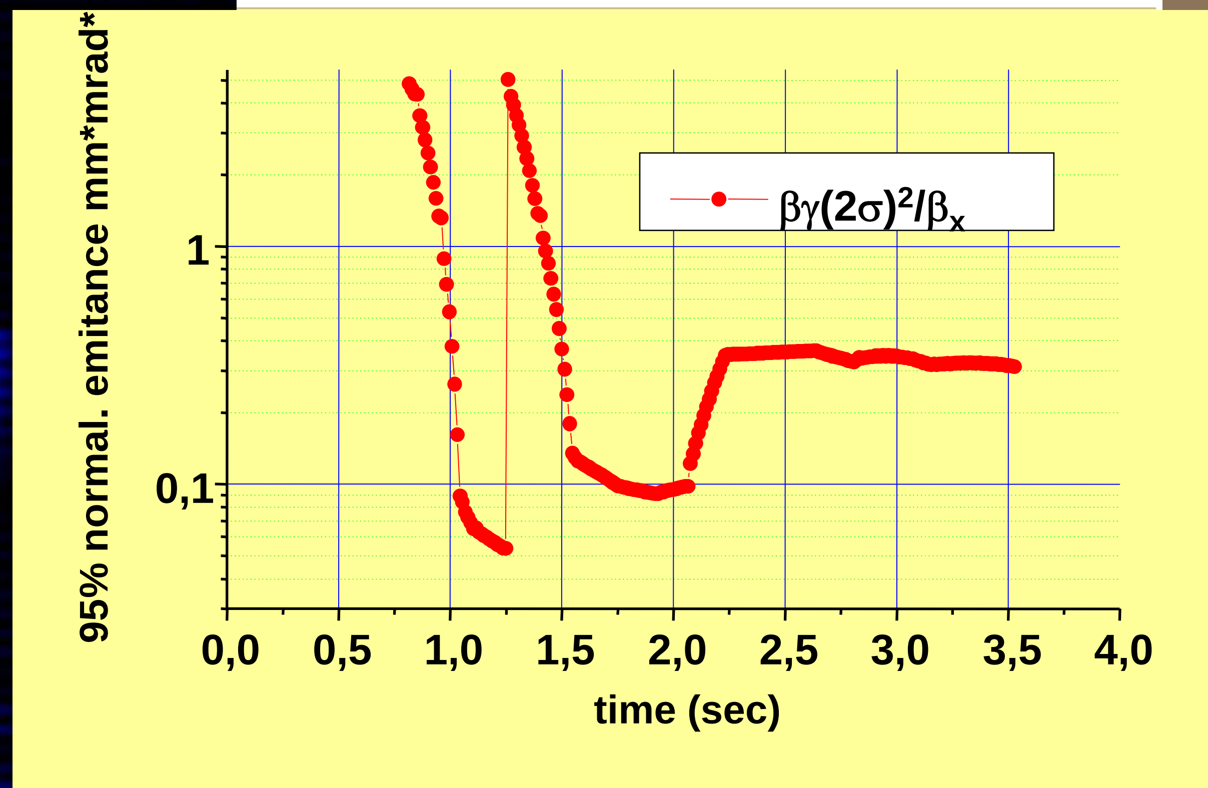
Pink line is magnet field value

Green line is anode voltage (the electron beam current control for cooling: on for injection, off acceleration)

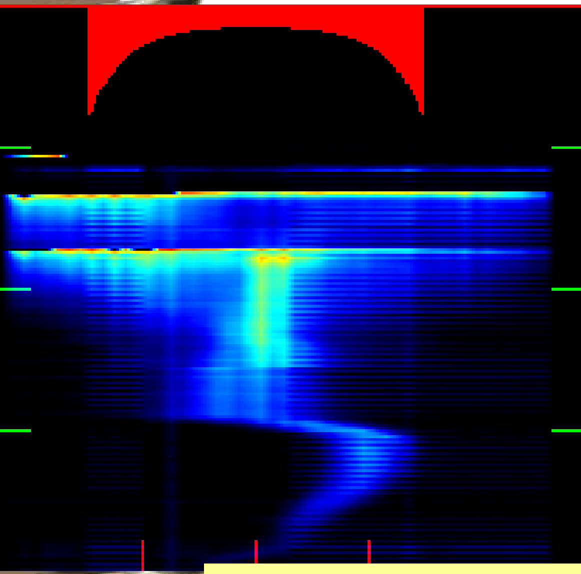
Profile monitor signal for Typical cycle of LEIR

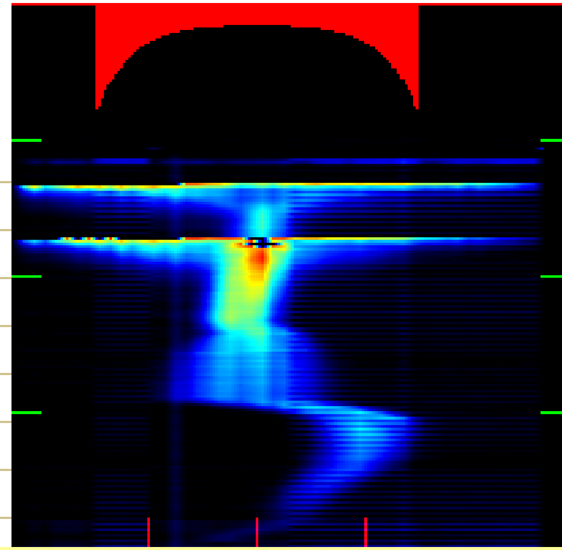


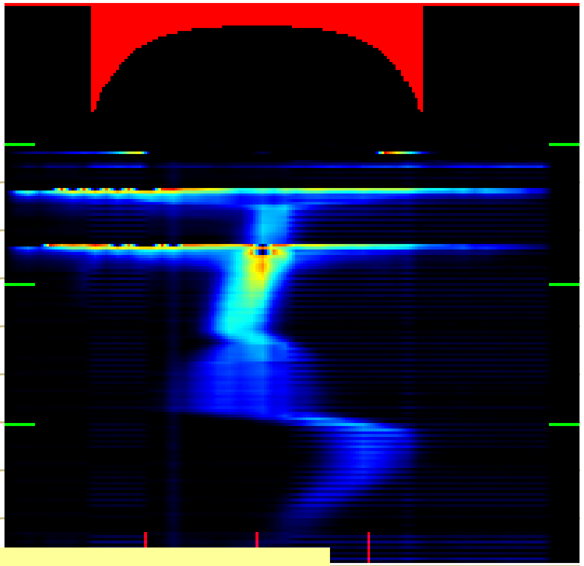
Normalized emittance versus time



Increasing electron current with the same profile Ucontr/Ugrid=0.5

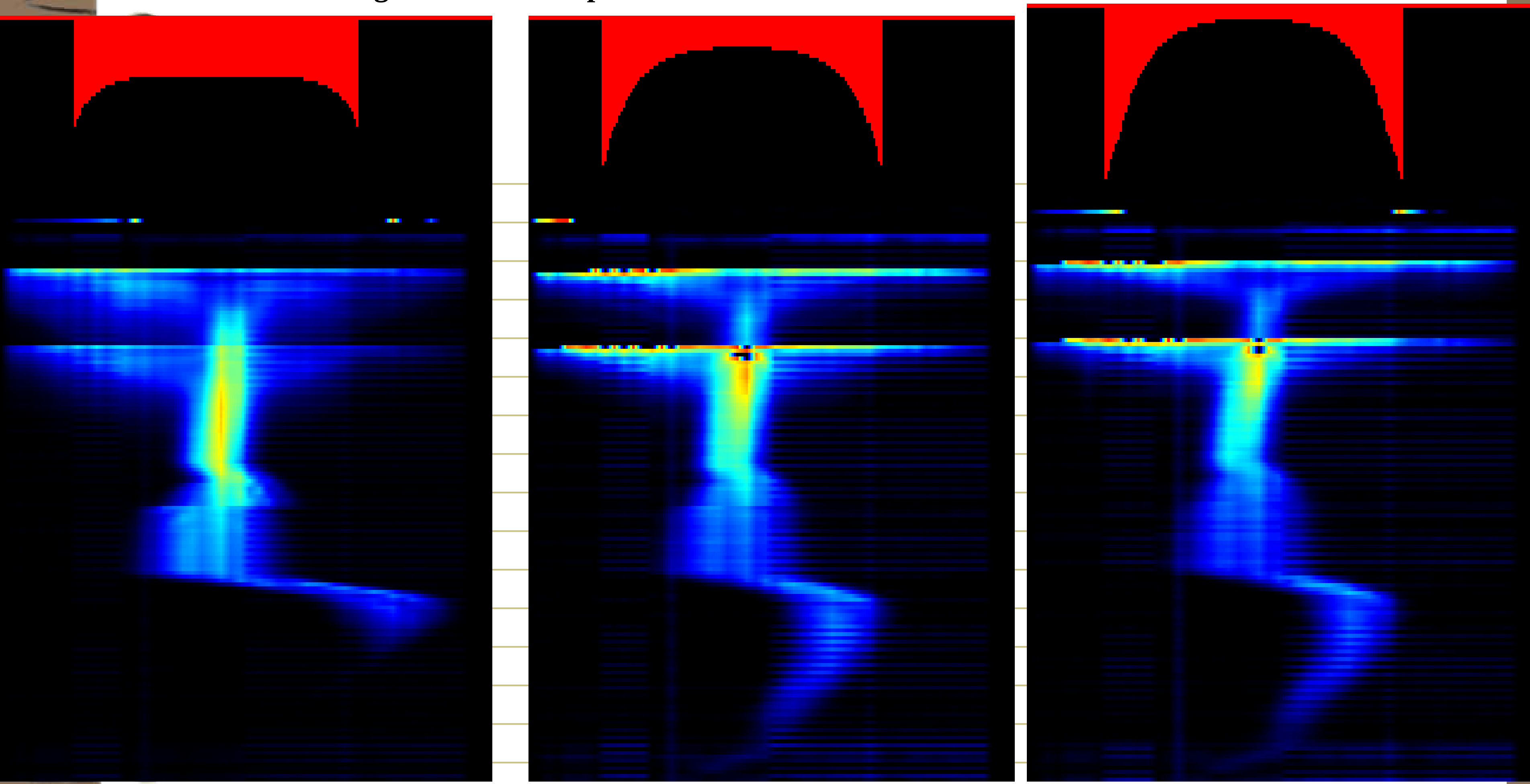






Ugrid (V)=	300	600	900
Ucontr (V)=	150	300	450
Ugun (V)=			
Je (mA)=	60	110	260
J0 (mA/cm^2)=	3.6	6.7	17.7
Norm. Emittance (mm*mrad)=	0.15	0.05	0.03
Cooling time (sec)=	0.5	0.08	0.05

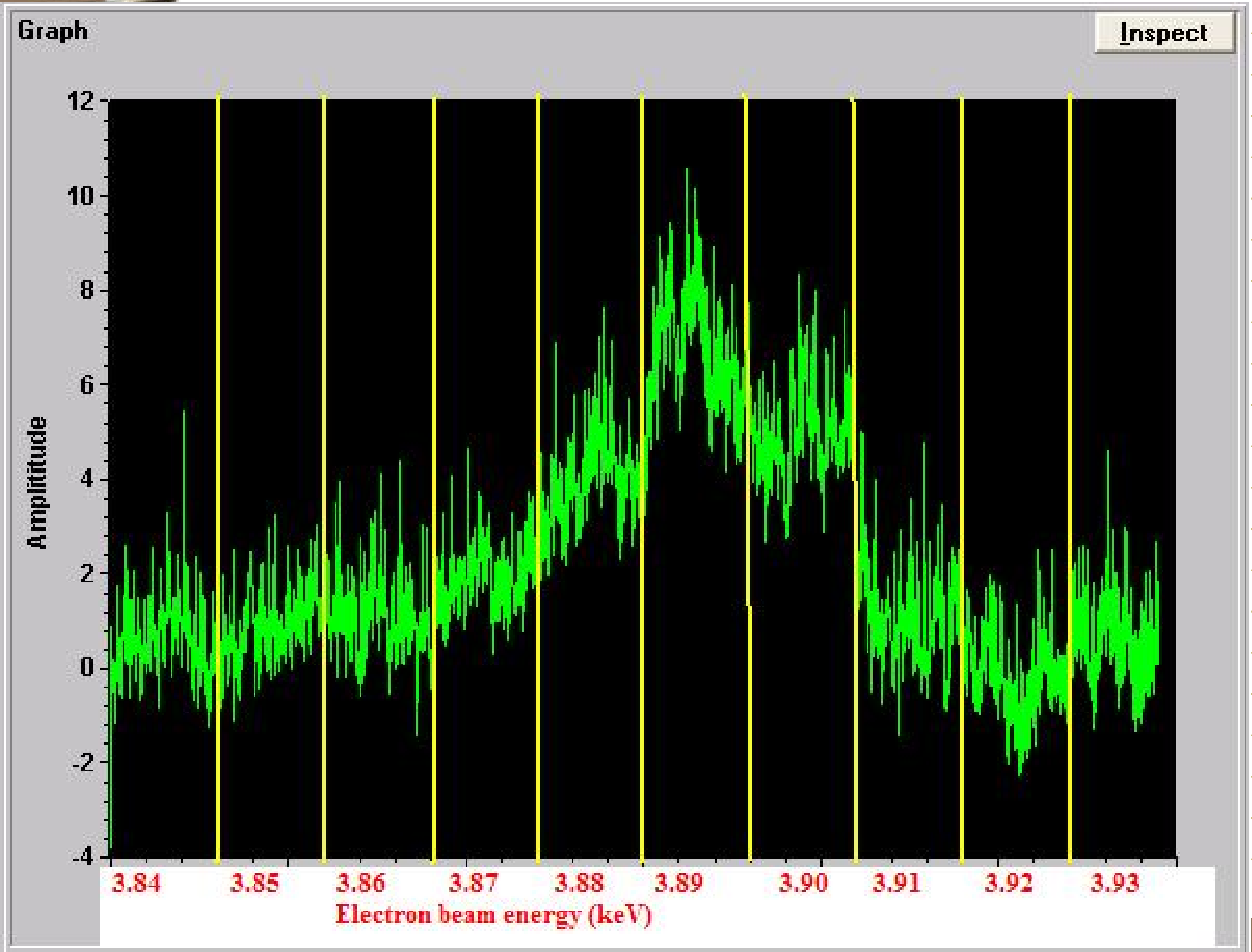
Cooling with different profile electron beam



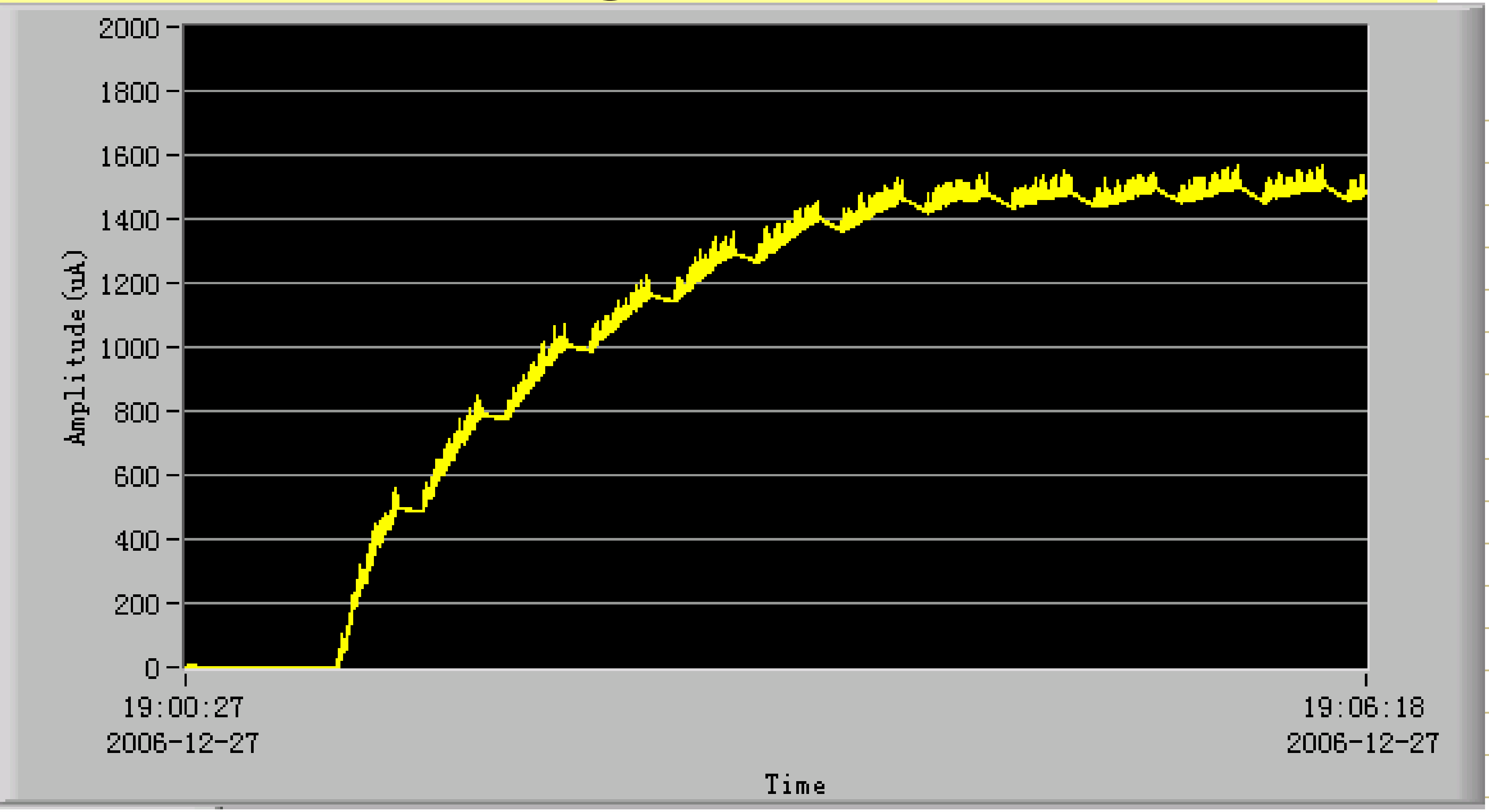
Uanode (V)=	1000	600	500
Ucontr (V)=	200	300	600
Ucontr/Uanode	0.2	0.5	1.2
Je (mA)=	140	160	280
je(0) (mA/mm^2)=	18	9.7	7.3
Cooling time (sec)=	0.3	0.1	0.07

P.R. China, Lanzhou Institute of Modern Physics
CSRm electron cooler

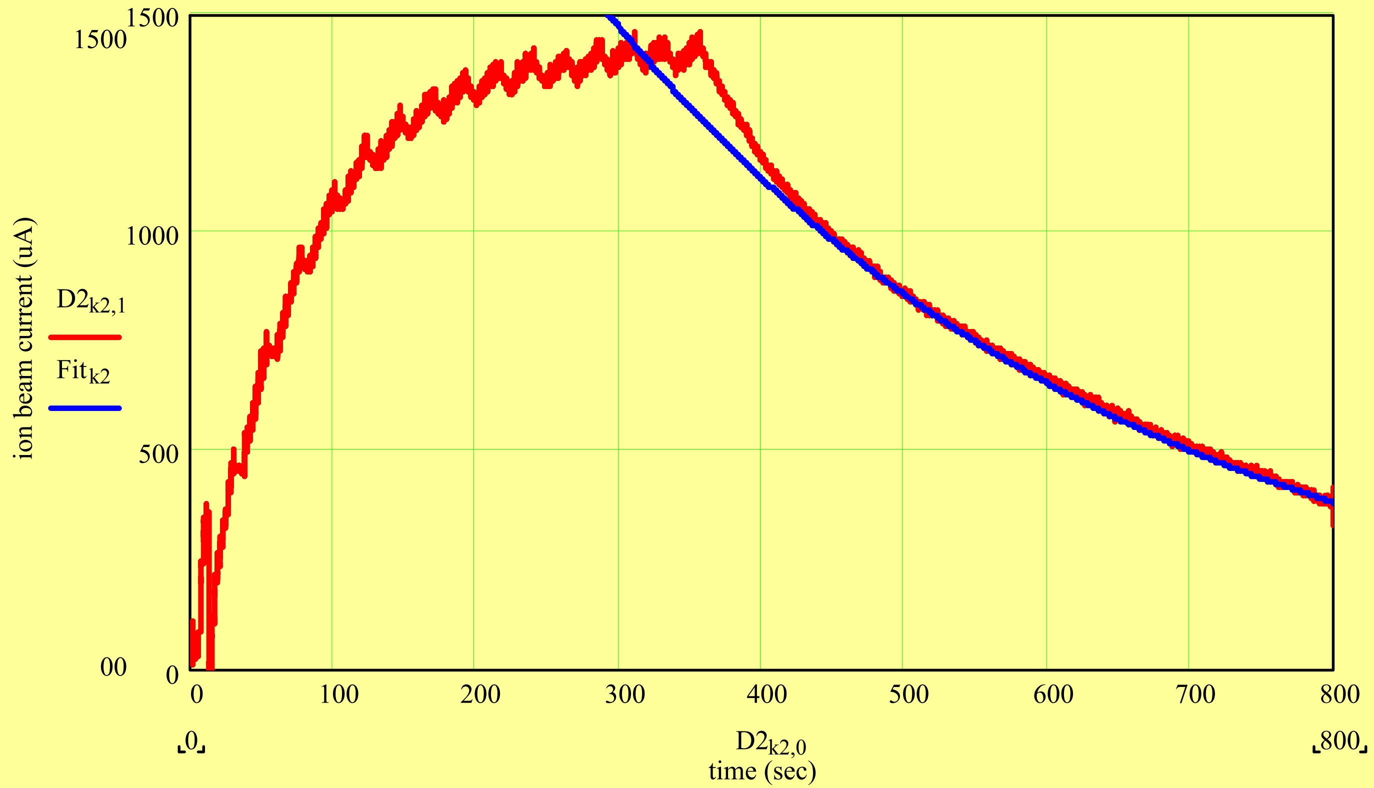
The first evidence of the electron cooling- July 2006



CSRm cooling at the end of 2006



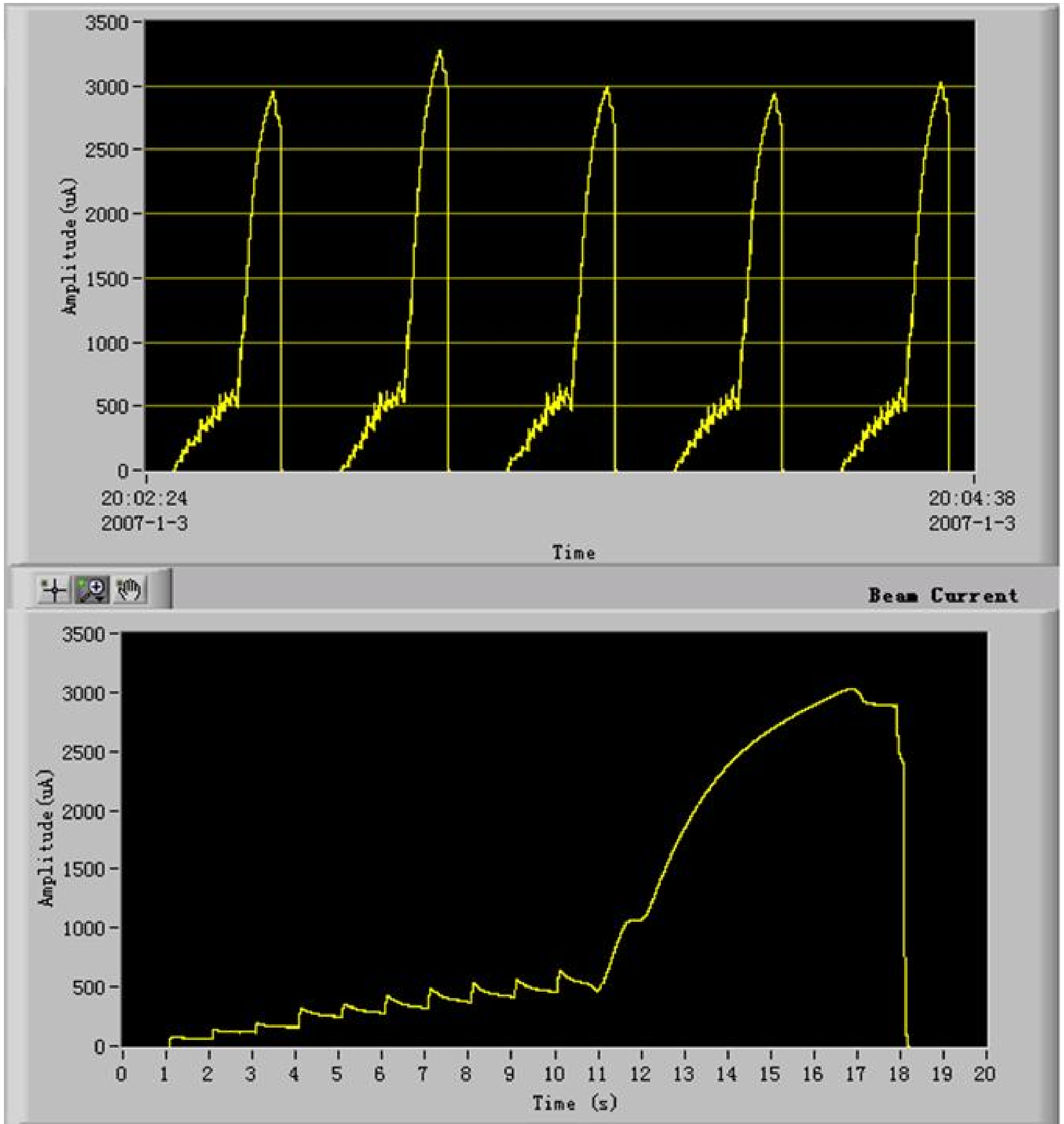
- Accumulation C^{+6} ions up to 1500 μA



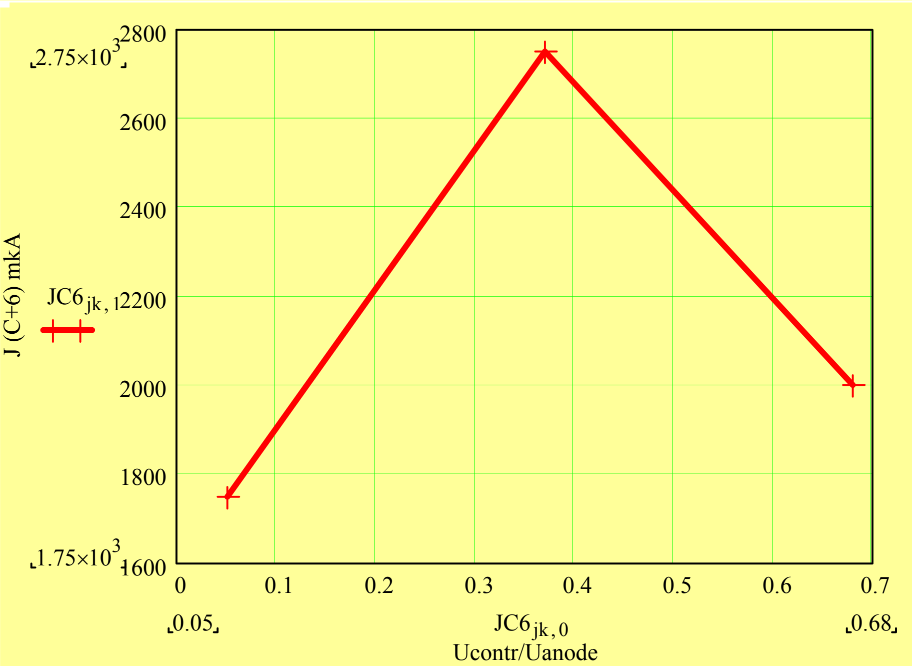
Decay became exponentially only for low current

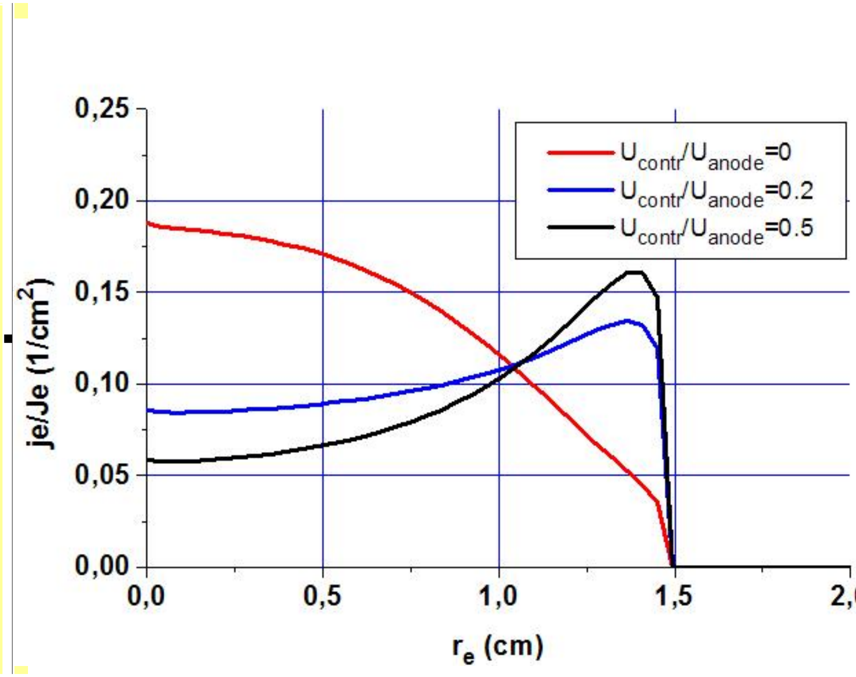
Decay time 400 sec! vacuum about $3\text{-}4\times10^{-11}$ Torr

CSRm accumulation and acceleration C^{+6}



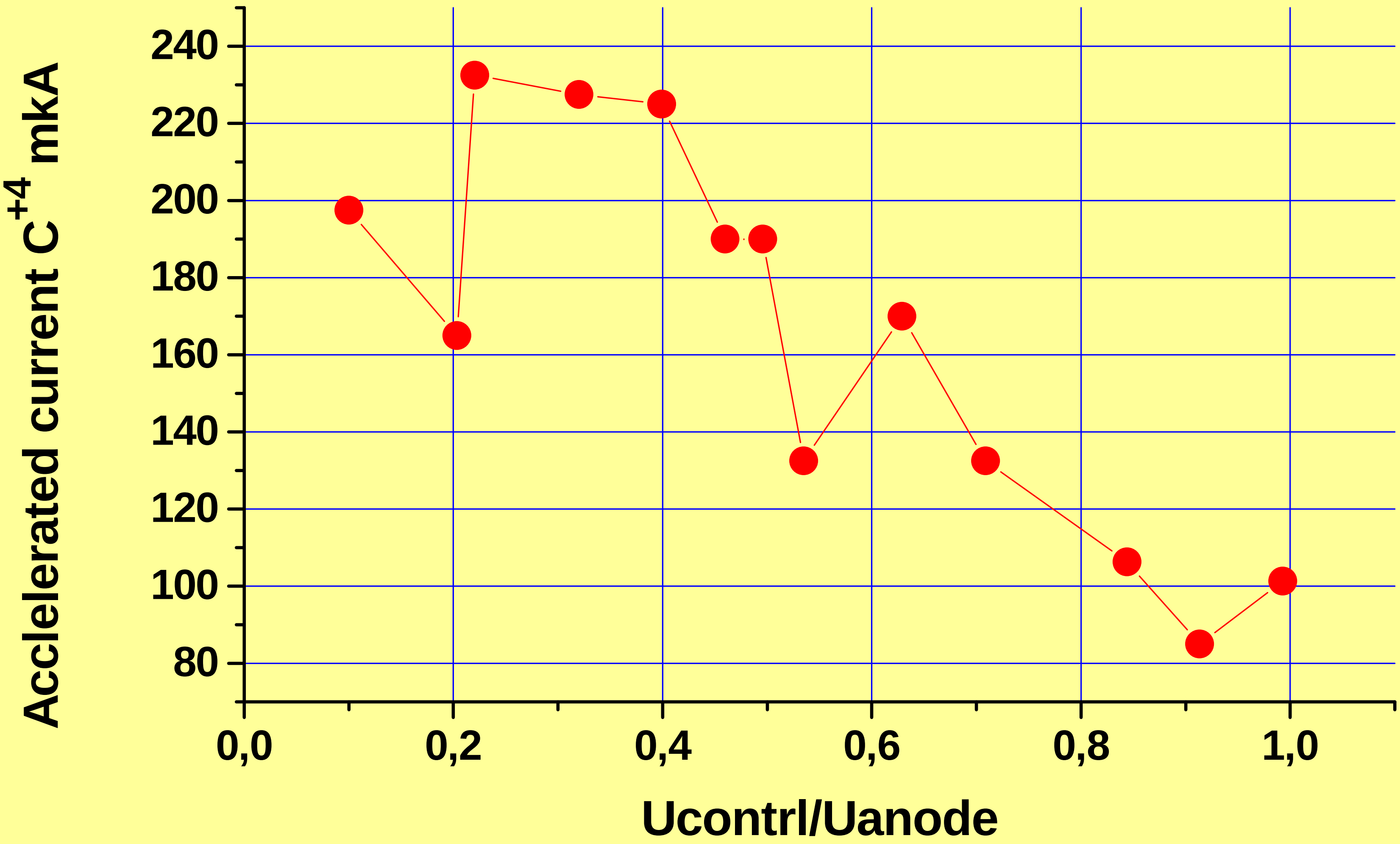
Experiment with different shape of electron beam





Maximum accumulated and accelerated ion beam current C+6 versus ratio voltages Ucontr/Uanod, optimum for =0.3-0.4.

C^{+4} accelerated current



Accumulation C^{+6} at CSRm

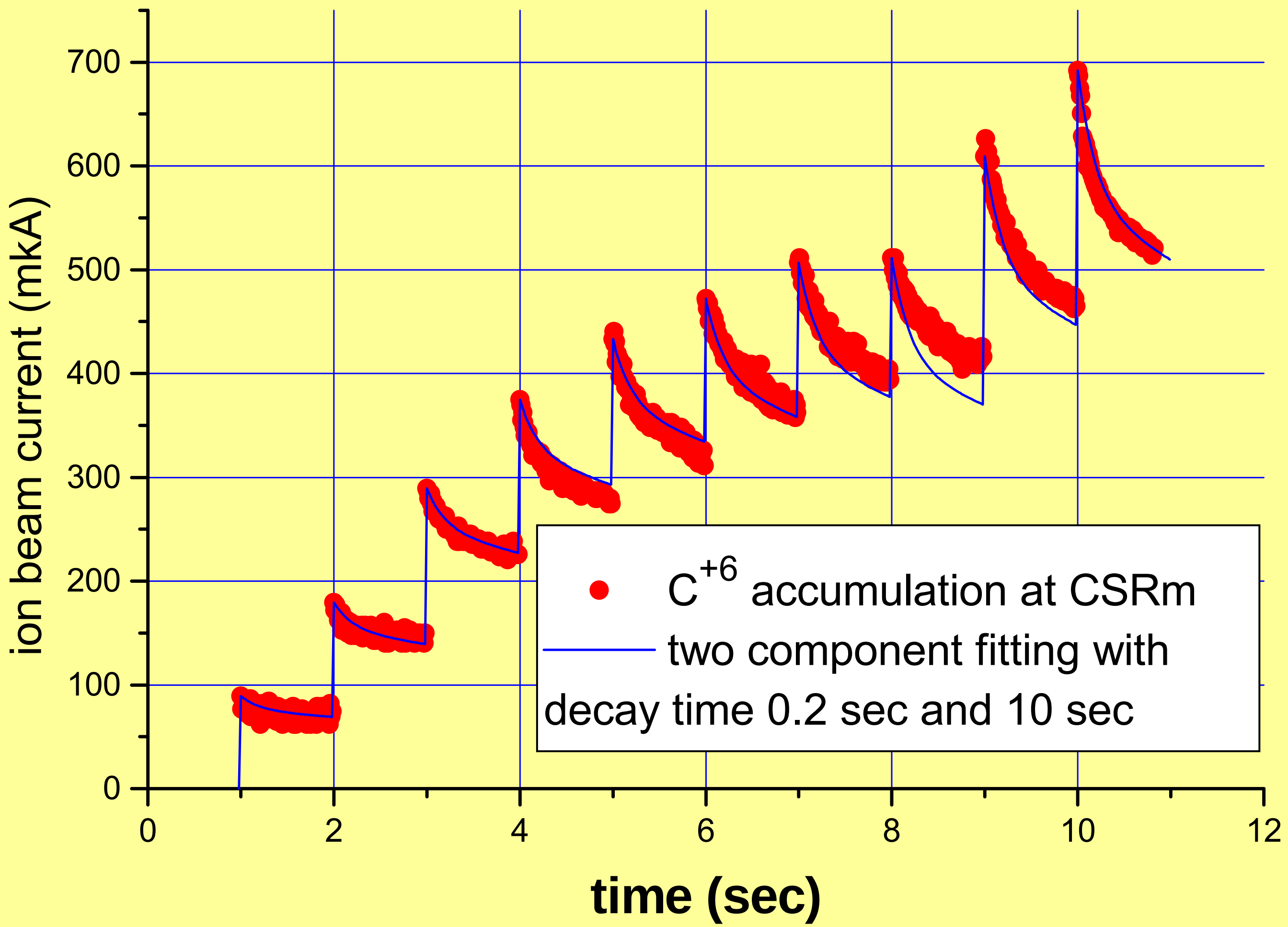
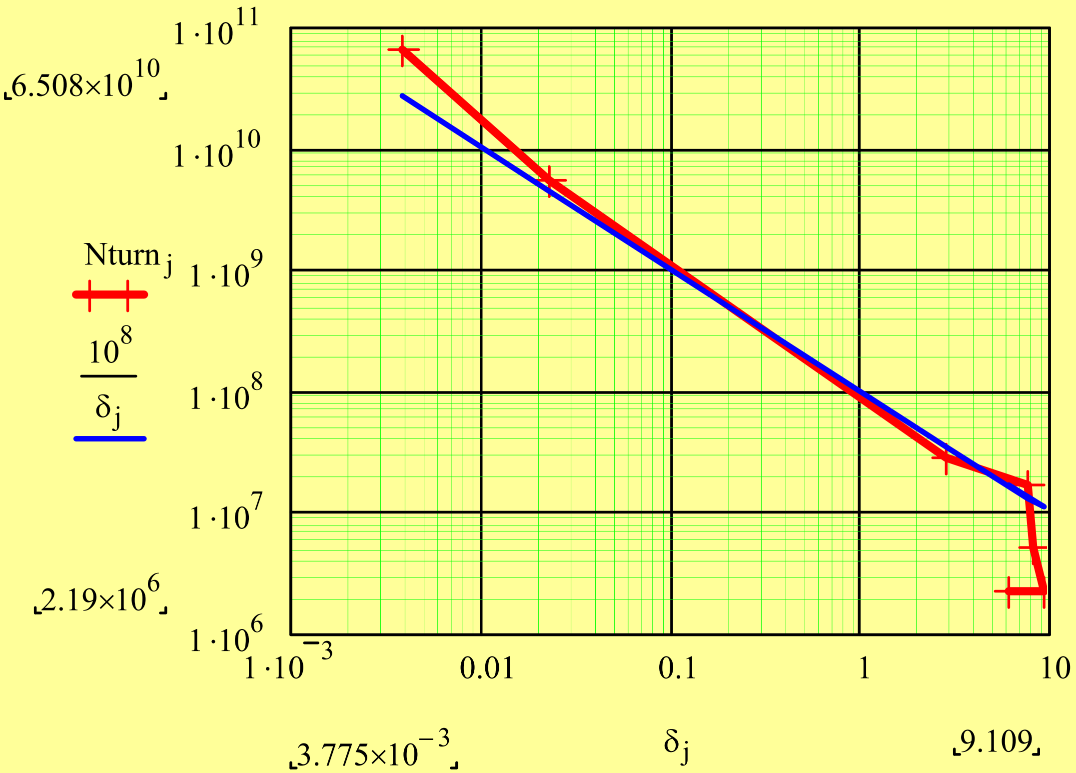


Table 1. Parameters of high intensive ion beam electron coolers

ring	Ee(keV)	Je (mA)	ae(cm)(g)	ion	Ji (mA)	ai (mm)	ΔQ_L	t(ns)	δ
SIS	6.5	400	2.2(1)	Kr+34	5	4.5	0.12	62	6
LEIR	2.5	100	2.12(2)	Pb+54	2.5	2	0.12	67	9
LEIR	2.5	100	2.12(0.5)	Pb+54	5	3	0.11	67	8
CSRm	3.8	100	2.12(0.4)	C+6	1.5	5	0.05	109	7.6
CELSIUS	6	60	2.12(1)	He+2	0.52	1	0.06	43	2.8
CELSIUS	217	600	2.12(1)	p+1	6	0.7	0.01	6	0.023
RECYCLER	4300	200	0.3(1?)	Pbar-1	32	2.5	0.008	7	0.003

Life time and interaction



$$\delta = \omega_e^2 \omega_i^2 \tau^4 = (4\pi)^2 n_e n_i r_e r_i (c\tau)^4$$

Life time (number of turns at ring) versus interaction parameter: Nturn~$10^8/\delta$!! Is it reality? or just random?

CONCLUSION

- Decreasing the electron beam density at the accumulating zone practically give improvement at life time and maximal number storage ions.
- Life time under electron cooling is function of the space charge parameter.
- At LEIR and CSRm coolers the accumulating beams corresponded requirements of projects.
- Optimization of the hollow electron beam cooling will continue.