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DATE: *August 11, 2006*

Memo

TO: RHIC E-Coolers

FROM: *Ady Hershcovitch*

SUBJECT: **Minutes of the August 11, 2006 Meeting**

Present: Ilan Ben-Zvi, Peter Cameron, Alexei Fedotov, Harald Hahn, Ady Hershcovitch, Dmitry Kayran, Jorg Kewisch, Vladimir Litvinenko, Derek Lowenstein, Eduard Pozdeyev, Thomas Roser, Alessandro Ruggiero, Gang Wang.

Topic discussed: Calculations and Simulations

Calculations and Simulations: during this meeting three presentations were made. First presentation was by Jorge on optimization of electron bunch emittance. The following two were given by Alexei on cooling at AGS injection energy and on enhanced recombination.

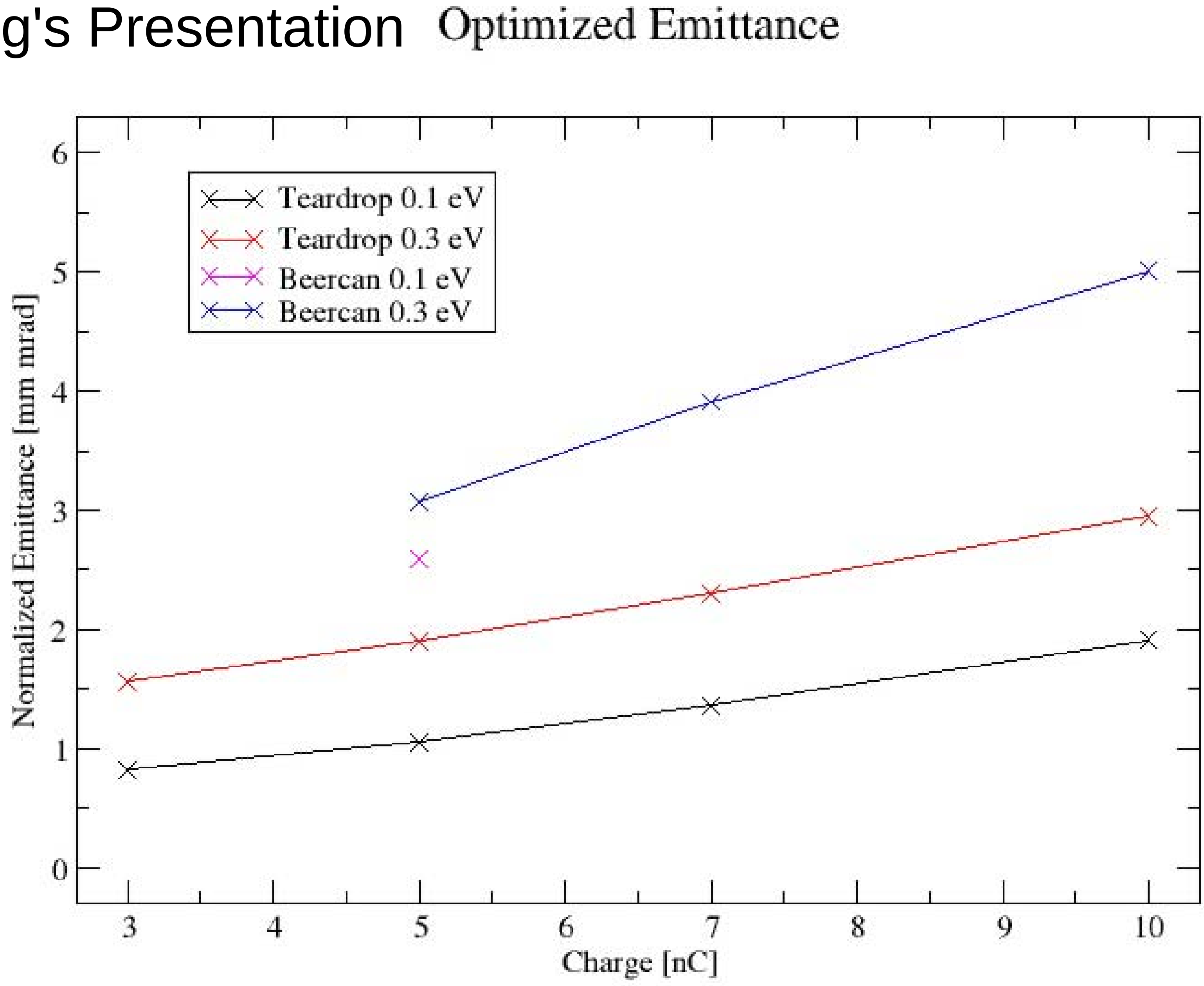
Optimization of Electron Bunch Emittance: the meeting started with a report by Jorg on his continuing work on optimization of electron bunch emittance. In his simulation bunches are followed, and parameters (especially distances among various elements) were optimized (to minimize emittance at LINAC exit), from the gun cathode to the end of the first accelerating cavity. The RHIC II goal is to reach emittance of 4 mm-mR for 5 nC bunches. Comparison was made for bunches with "beer-can" and "tear-drop" distributions with initial energy spreads of 0.1 eV and 0.3 eV. Ilan pointed out that the 0.1 eV case corresponds to what's expected from a diamond cathode, while the latter is for a photo-cathode.

As it can be seen from the first slide in Jorg's presentation, bunches with "tear-drop" distribution yield better results. However, generating bunches with "beer-can" distribution is a proven technology. Next Jorg examined detailed phase space distribution of "beer-can" bunches and realized that 10% of their electrons contribute to a large portion of the emittance (2^{nd} and 3^{rd} slides). But, these electrons have negligible contributions to either heating or cooling of ions, and therefore can be ignored. As it can be seen from the 4^{th} slide, very significant reduction in emittance is attained with 90% of the electron beam is utilized. Further reduction in portion of utilized beam seems to yield worthwhile results for 80% beam utilization. Basically, 10 nC bunches will meet RHIC II emittance requirement if we take into account this property of beer-can bunches.

Cooling at AGS injection energy: the meeting continued with Alexei's first presentation of cooling gold ions at AGS injection energy (motivated by low-energy QCD task). The idea is to cool gold ion with a kinetic energy of 97 MeV per nucleon (gold beam coasting in AGS after injection). Cooling by a factor of 3 in 10 seconds is achievable with a cooler having the following parameters: electron energy of about 50 keV, electron current of about 0.5 A, solenoid magnetic field in the range of 0.02-0.15 T, solenoid length of 1 m. Full length of the cooler of 2.5-3 meter. Basically, as the last slide in Alexei's first presentation indicates, the CELSIUS electron beam cooler can be used (with a modified solenoid).

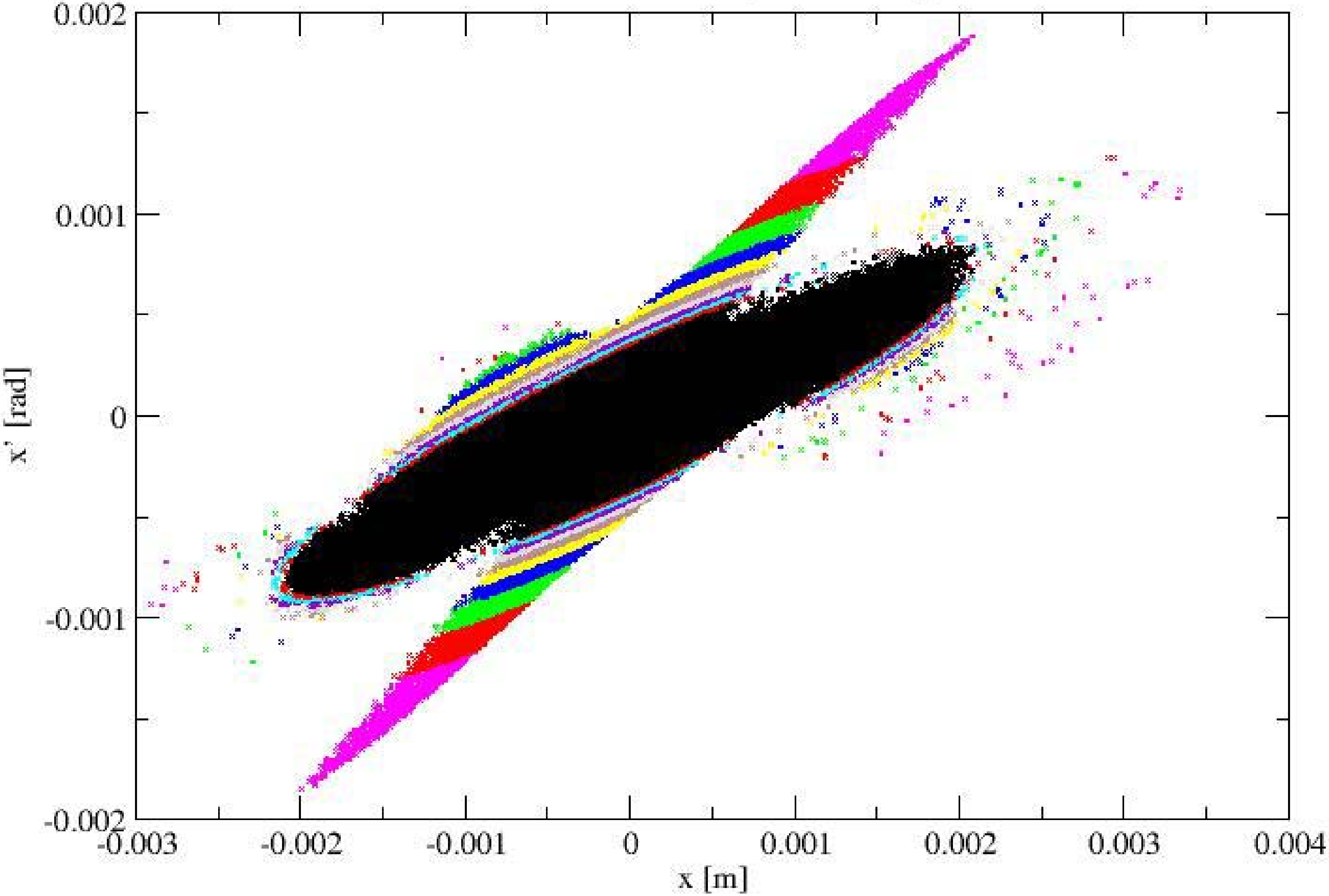
Enhanced Recombination: the meeting concluded with Alexei's second presentation on the issue of "enhanced recombinations" Standard radiative recombination theory predicts that RHIC II will loose about 20% of luminosity due to recombination. Present parameters of undulator are chosen to avoid this 20% loss. Experimentally measured recombination coefficient at small relative energies (E_{rel}) was found to be much higher than expected from theory (as can be seen in the 4^{th} slide of Alexei's second presentation), hence termed "enhanced recombination". The RHIC electron beam cooler will operate with E_{rel} very close to zero. Therefore, there is a need to understand and be prepared to compensate for enhanced radiative recombinations. The latest and most believable theory [published in PRL **95**, 243201 (2005)] has been successful in explaining enhanced radiative recombination in all existing systems. According to this theory, the enhanced radiative recombination requires the solenoid magnetic field. A discussion ensued on whether the short focusing solenoids will result in enhanced radiative recombinations. It is probably not the case. Then, although undulators reduce the friction force by 10%, they will prevent radiative recombination, enhanced or otherwise.

Jorg's Presentation



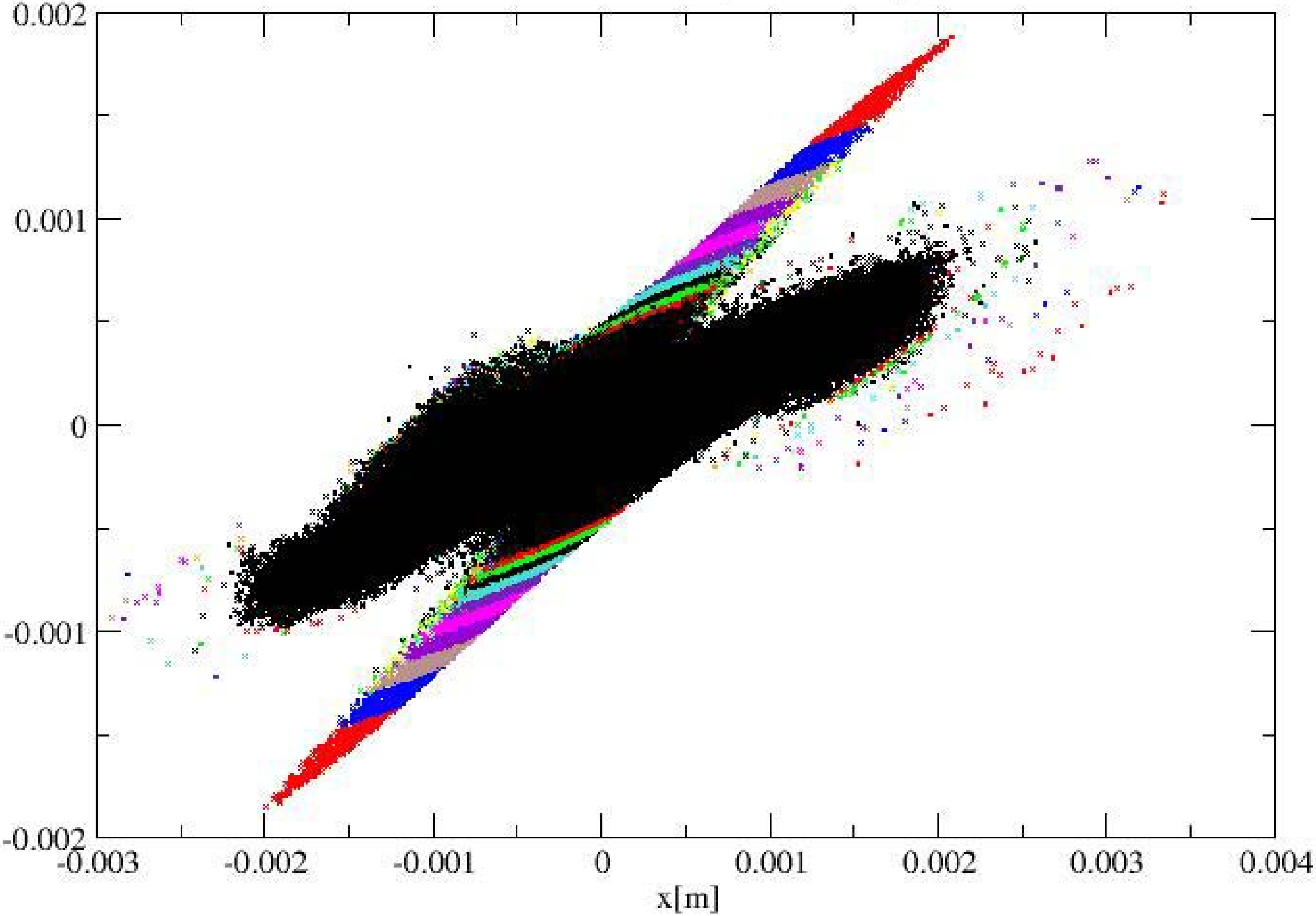
Discarding 10% of the particles (in x only)

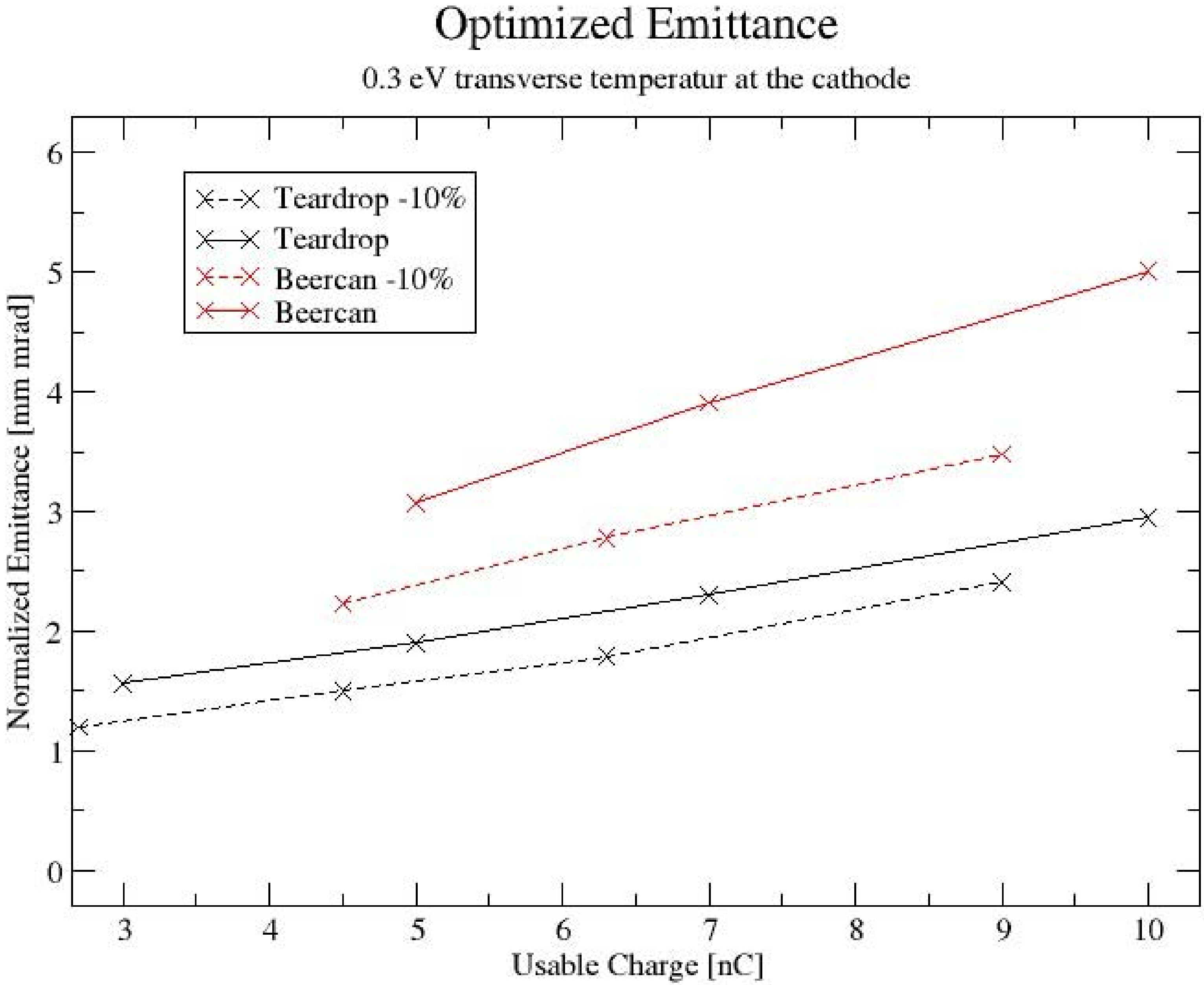
10 nC Beer can, black=kept, colored=ignored



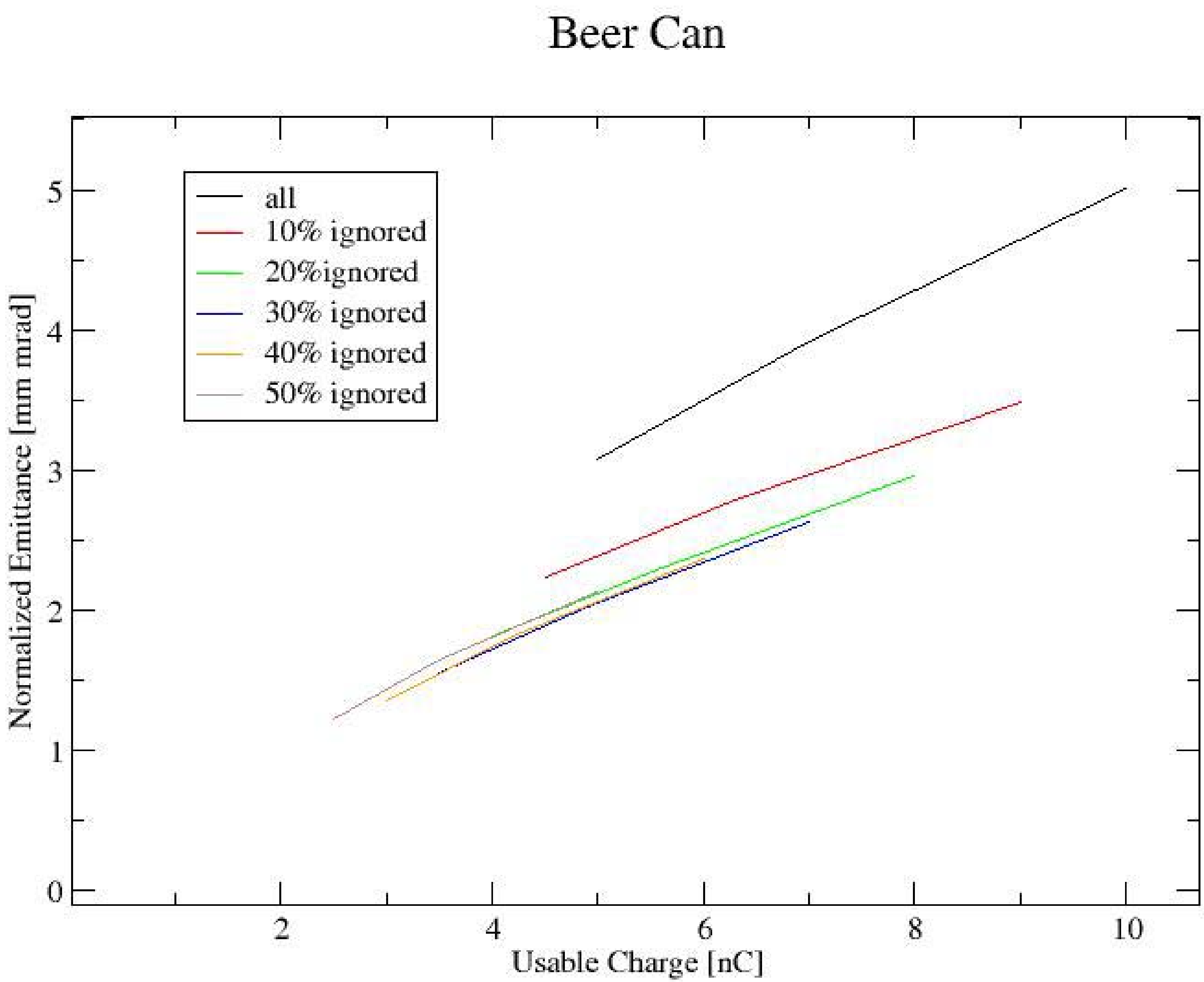
Discarding 10% of the particles (in x and y alternating)

10 nC Beer can, black=kept, colored=ignored





Optimized Emittance
0.3 eV transverse temperatur at the cathode
Teardrop -10%
Teardrop
Beercan -10%
Beercan
Normalized Emittance [mm mrad]
Usable Charge [nC]
0
1
2
3
4
5
6
3
4
5
6
7
8
9
10



Beer Can
all
10% ignored
20%ignored
30% ignored
40% ignored
50% ignored
Normalized Emittance [mm mrad]
Usable Charge [nC]
0
1
2
3
4
5
2
4
6
8
10


HowStrange.com

Alexei's First Presentation

Cooling Au ions at injection

energy of AGS

(motivated by Low-Energy QCD task)

(July, 2006)

Parameters of ion beam

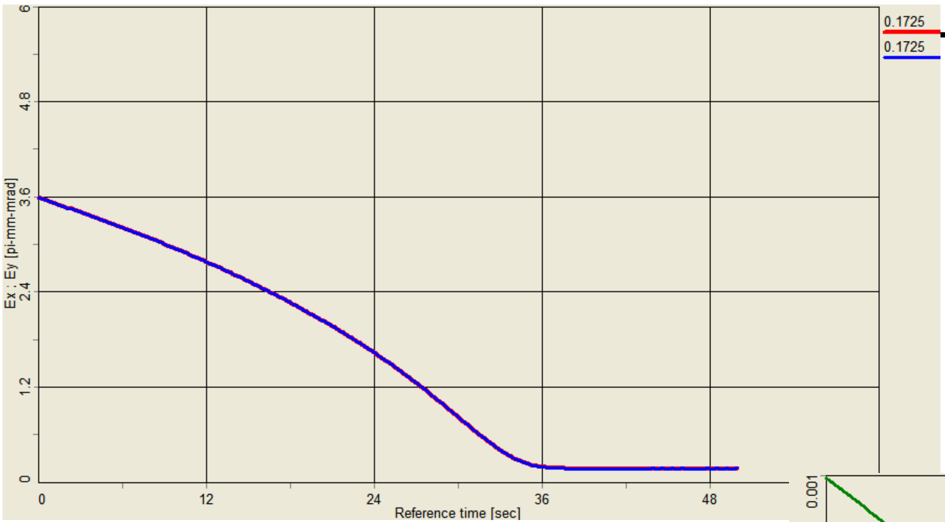
- Au, Kinetic energy 97 Mev/n
- Cooling coasting beam at AGS injection:

Ion beam:

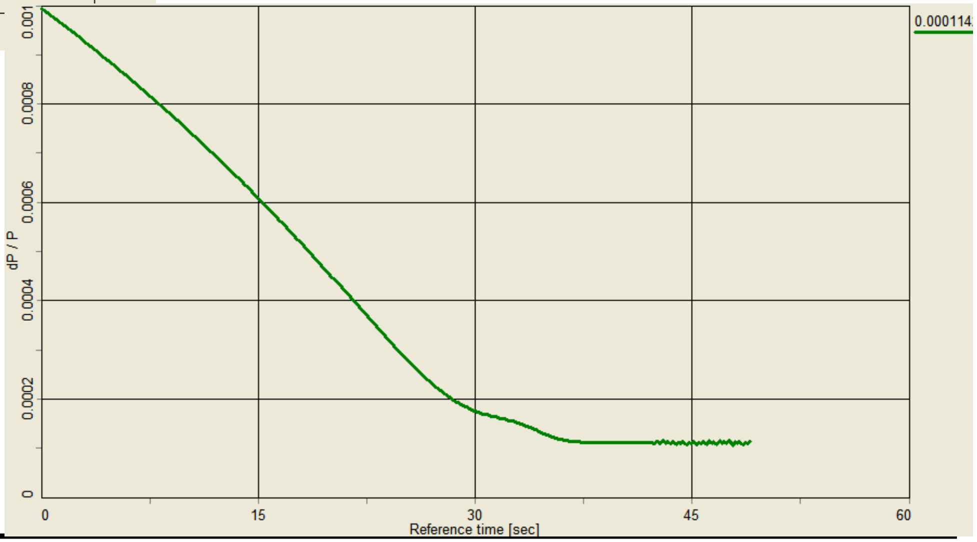
1. Normalized 95% emittance: 10 pi
2. Rms momentum spread: 1e-3
3. Solenoid cooling length = 1m,
4. full needed space is about 2.5m (we have maximum available space in AGS 3 m)

Using BETACOOL and AGS lattice at injection; Martini model of IBS.

B=0.1T, Ie=0.1A

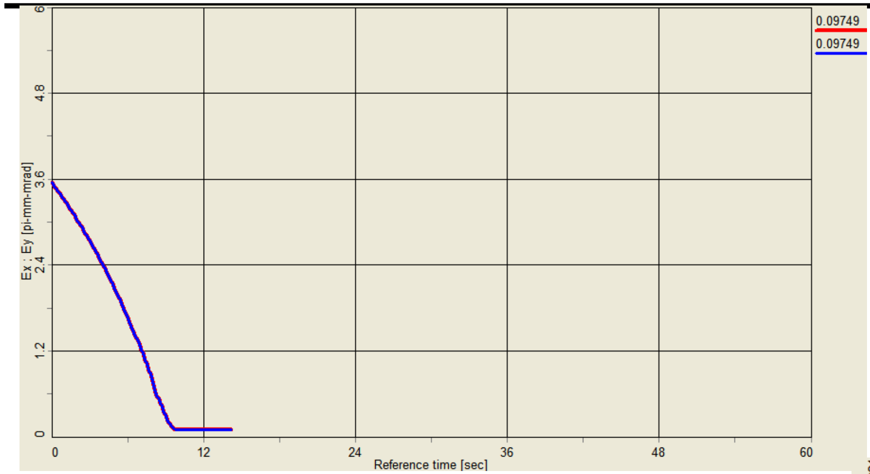


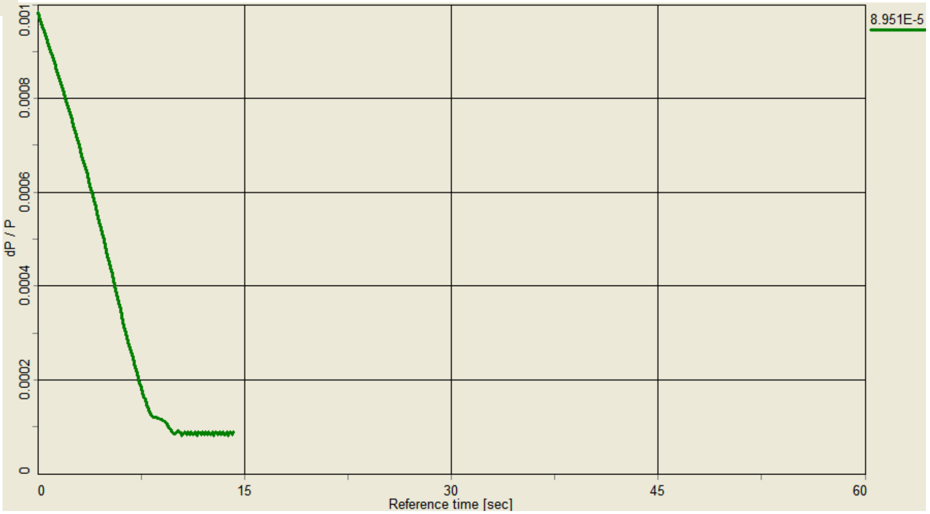
0.1725
0.1725
Ex ; Ey [pi-mm-mrad]
Reference time [sec]



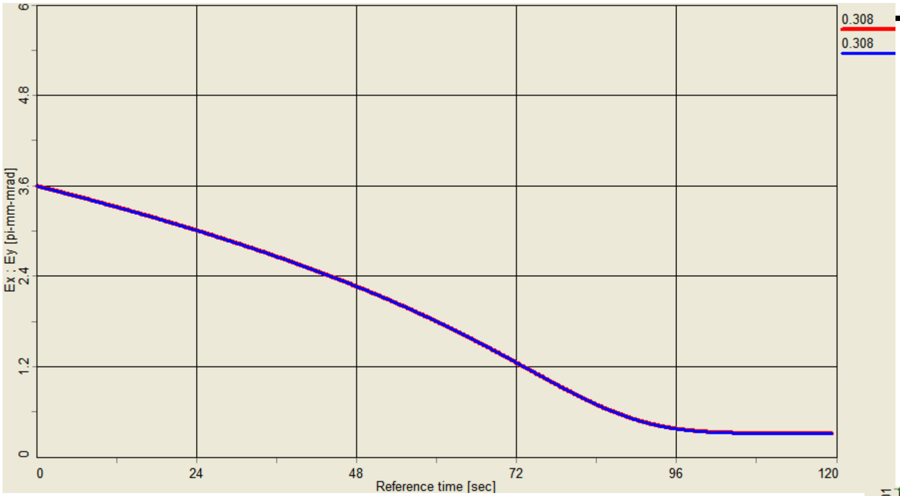
0.000114
dP / P
Reference time [sec]

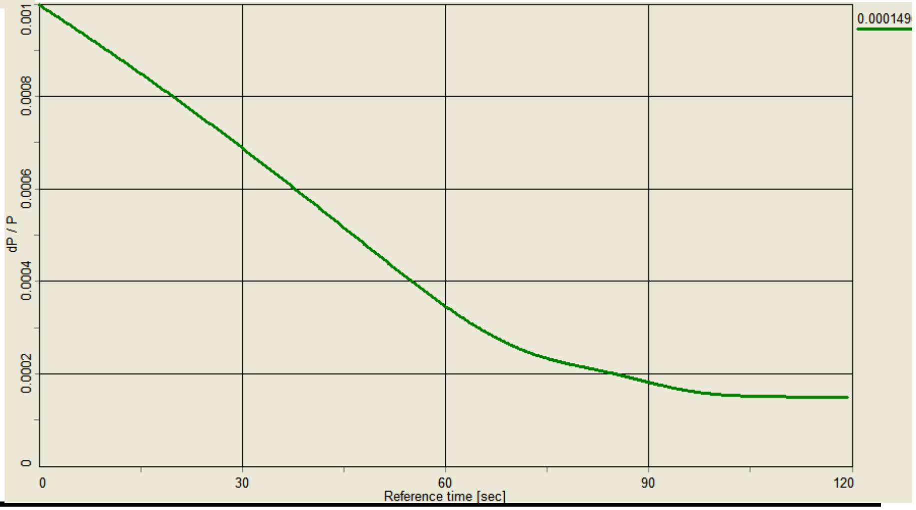
B=0.1T, Ie=0.5A


0.09749
0.09749
Ex ; Ey [pi-mm-mrad]
6
4.8
3.6
2.4
1.2
0
0
12
24
36
48
60
Reference time [sec]

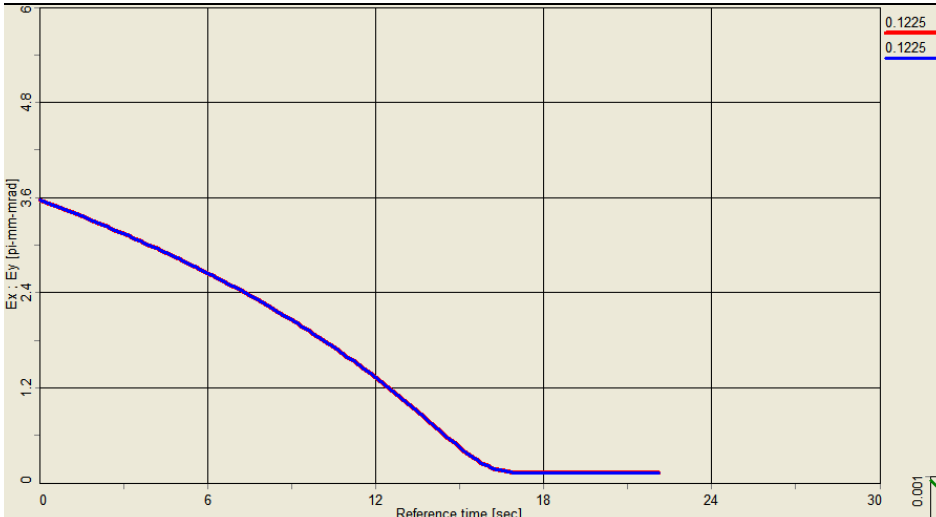

8.951E-5
dP / P
0.001
0.0008
0.0006
0.0004
0.0002
0
0
15
30
45
60
Reference time [sec]

B=0.02T, Ie=0.1A – low-end parameters

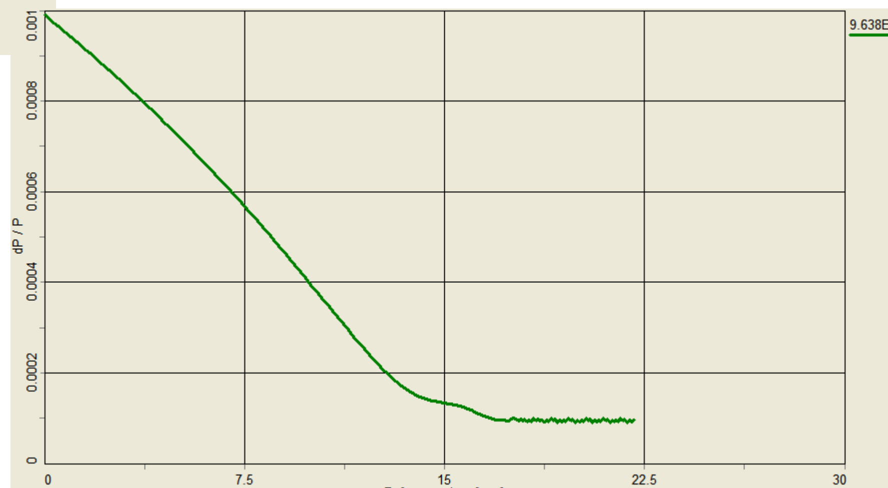




Typical operational parameters: B=0.1T, Ie=0.25A



Cooling by an order of magnitude in 15 sec.



Cooling of longitudinal rms momentum spread by a factor of 3 in 10 sec. Can be faster or slower depending on the Ie being used.

AGS cooler design parameters

- Electron energy: 20-80keV (nominal energy 50keV)
- Electron current: 0-1A
- Solenoid magnetic field: 0.02-0.15 T
- Solenoid length: 1 m
- Full length of the cooler: 2.5-3m

CELSIUS cooler

- Electron energy: 10-300keV
- Electron current: 0-2.8A, but starting 0.5A reduction in cooling force due to space charge, also gun losses, etc. Typical operation with currents 0.1-0.5A.
- Magnetic field: 0.02-0.2T
- Solenoid length: 2.5m
- Full length: about 4.5 m

Replacing solenoid with L=1m – fits in 3m space in AGS.

Alexei's Second Presentation

Enhanced recombination

(August 8, 2006)

Questions

The topic is related to the question whether we need undulator to suppress recombination or not.

1. Standard Radiative Recombination theory predicts that we will loose about 20% of Luminosity due to recombination. Present parameters of undulator are chosen to avoid this 20% loss.

2. Experimentally, measured recombination coefficient at small relative energies (Erel) was found much higher than expected from theory - “enhanced recombination”:

Q1) Is this region of Erel applicable to our case?

Q2) What is the mechanism for this enhancement? Is it applicable to RHIC case?

Q3) Will undulator help to compensate such enhancement, if it is applicable to RHIC case?

Theoretical coefficient for radiative recombination

recombination coefficient

$$\alpha_r = \int (V_i - v_e)\sigma(V_i - v_e) f(v_e) d^3 v_e$$

cross section

$$\sigma = A \left(\frac{h\nu_0}{E}\right)^2 \sum_1^\infty \frac{1}{n(n^2 + h\nu_0/E)}$$

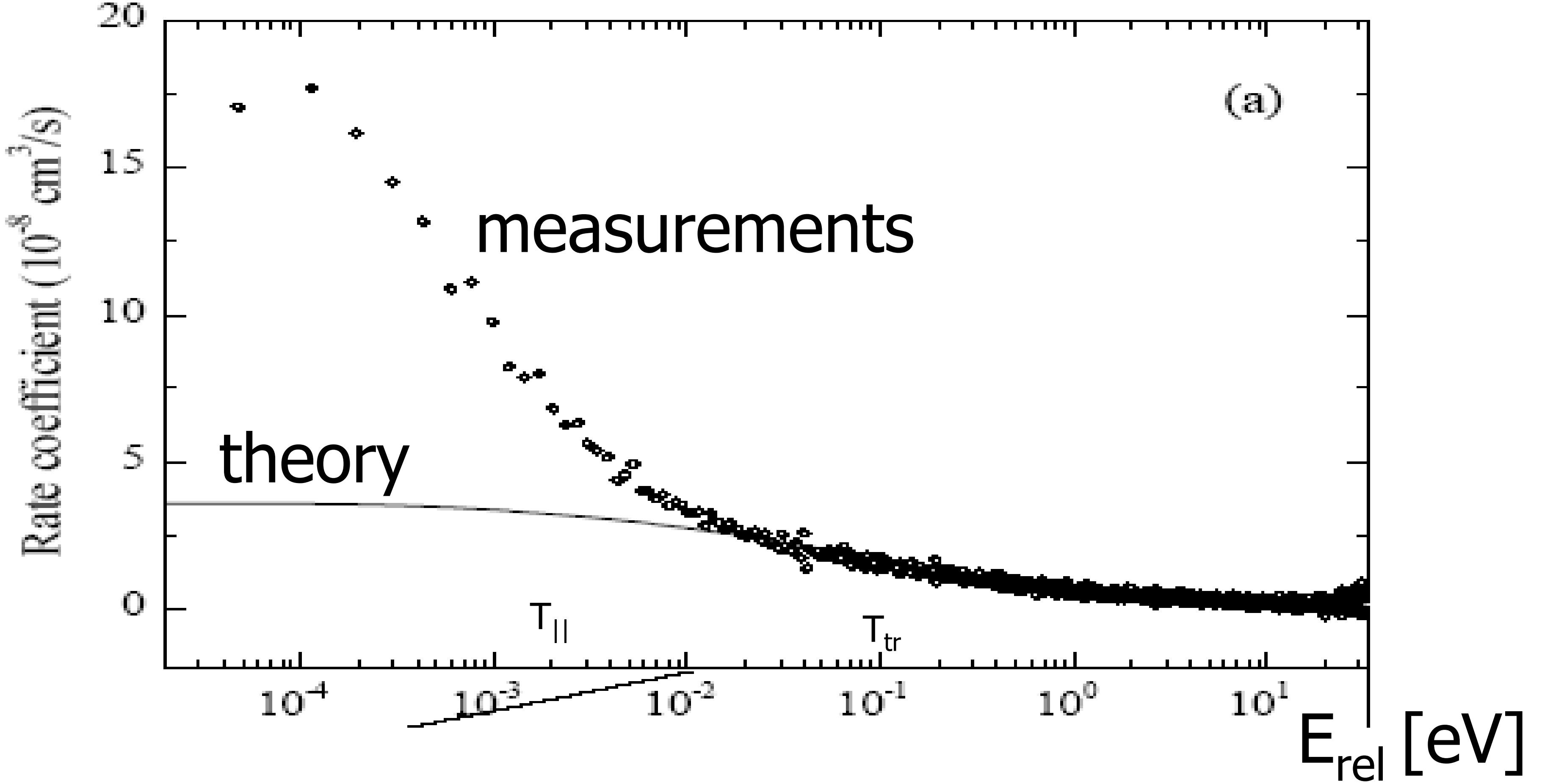
cross section expression used in simulations

$$\sigma = A\left(\frac{h\nu_0}{E}\right)\left(\ln\sqrt{\frac{h\nu_0}{E}} + 0.1402 + 0.525\left(\frac{E}{h\nu_0}\right)^{1/3}\right)$$

Valid for

E<< $h\nu_0$(13*Z^2 eV)

Recombination coefficient for fully stripped U92+ (GSI, 2001) – similar for fully stripped Bi83+



Situation during e-cooling (example of low-energy cooler: ions at 100MeV)

Electron cooling:

Ion and electron beam are matched in Energy:

$E_e := 54.466\,10^3\,V$ $\quad E_e = 5.447\times 10^4\,V$ $\quad \gamma_e := \frac{\left(E_e + \frac{mc2}{q}\right)}{\frac{mc2}{q}}$ $\quad \gamma_e = 1.107$

$E_i := 100\cdot 10^6\,V$ $\quad E_i = 1\times 10^8\,V$ $\quad \gamma_i := \frac{\left(E_i + \frac{Mc2}{q}\right)}{\frac{Mc2}{q}}$ $\quad \gamma_i = 1.107$

$E_{rel}=0$

Energy detuning for recombination measurements

$E_e := 55.466 \cdot 10^3 V$ $\quad E_e = 5.547\times 10^4 V$ $\quad \gamma_e := \frac{\left(E_e + \frac{mc2}{q}\right)}{\frac{mc2}{q}}$ $\quad \gamma_e = 1.109$

$E_i := 100 \cdot 10^6 V$ $\quad E_i = 1\times 10^8 V$ $\quad \gamma_i := \frac{\left(E_i + \frac{Mc2}{q}\right)}{\frac{Mc2}{q}}$ $\quad \gamma_i = 1.107$

$$v_{rel} := \frac{\left(v_{ez} - v_{iz}\right)}{1 + \left(v_{ez} \cdot \frac{v_{iz}}{c^2}\right)}$$

$$v_{rel} = 8.509\times 10^5 \frac{m}{s}$$

$$\gamma_{rel} := \left[1 - \left(\frac{v_{rel}}{c}\right)^2\right]^{\frac{-1}{2}}$$

$$\gamma_{rel} - 1 = 4.028\times 10^{-6}$$

$$E_{rel} := \left(\gamma_{rel} - 1\right) \cdot \frac{mc2}{q}$$

$$E_{rel} = 2.058V$$

E_{rel} for cooling using RHIC parameters

$E_e := 55.466 \cdot 10^6 V$ $\quad E_e = 5.547 \times 10^7 V$ $\quad \gamma_e := \frac{\left(E_e + \frac{mc2}{q}\right)}{\frac{mc2}{q}}$ $\quad \gamma_e = 109.546$

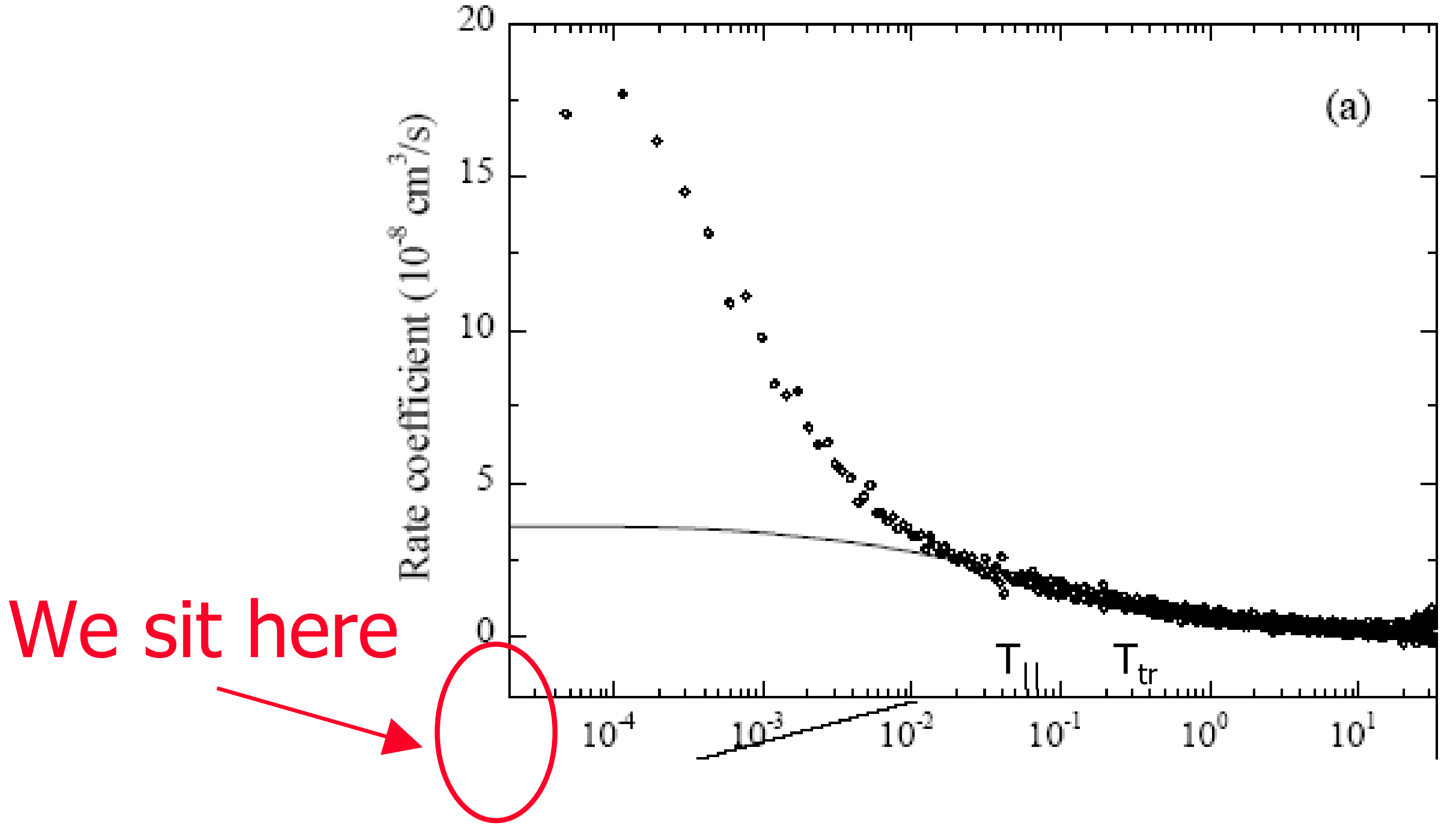
$E_i := 100 \cdot 10^9 V$ $\quad E_i = 1 \times 10^{11} V$ $\quad \gamma_i := \frac{\left(E_i + \frac{Mc2}{q}\right)}{\frac{Mc2}{q}}$ $\quad \gamma_i = 107.582$

$$v_{rel} := \frac{(v_{ez} - v_{iz})}{1 + \left(v_{ez} \cdot \frac{v_{iz}}{c^2}\right)}$$

$$v_{rel} = 230.138 \frac{m}{s}$$

$$E_{rel} := (\gamma_{rel} - 1) \cdot \frac{mc2}{q} \qquad E_{rel} = 1.506 \times 10^{-7} V$$

Without undulators our Erel=0



Answer to question Q1

Region of relative energies Erel close to zero is exactly where we sit for cooling.

Thus the question of "enhanced recombination" observed at very small Erel is very relevant.

Q2 (A. Wolf):

There were many attempts to explain recombination enhancement at low relative energies but they did not reproduce observed scaling and measurements. The model which is in good agreement with experiments and simulations was recently presented:

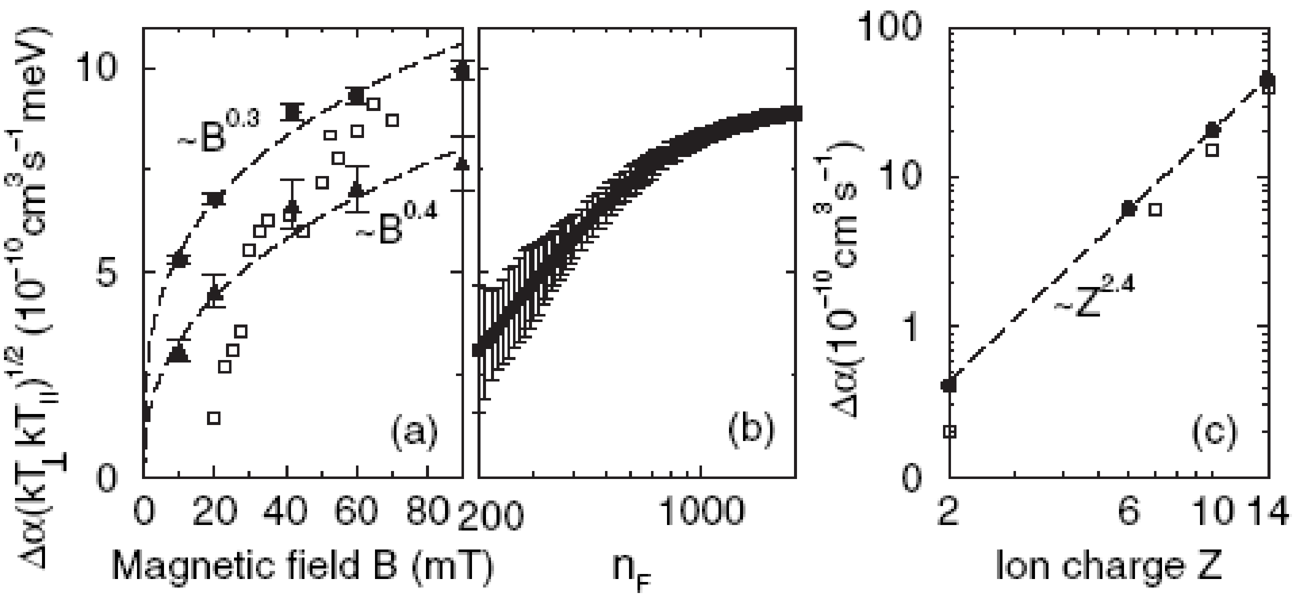
PRL **95**, 243201 (2005) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2005

Enhancement of Low Energy Electron-Ion Recombination in a Magnetic Field: Influence of Transient Field Effects

Maria Hörndl,[1,*] Shuhei Yoshida,[1] Andreas Wolf,[2] Gerald Gwinner,[3] and Joachim Burgdörfer[1]

Mechanism of "enhancement"

1. **Formation of bound states due to merging system**
2. **Radiative decay of these transiently formed states inside the solenoid stabilize a fraction of these bound electrons:**



Answer to Q2 and Q3:

1. For RHIC case with non-magnetized cooling - no stabilization of such bound state produced by merger without strong solenoidal magnetic field is expected – no enhancement is expected.
2. The use of undulator has extra advantage. If we use undulator with present parameters we produce Erel=28eV which suppresses recombination loss (with only 20% reduction in the friction force). In addition this put us in the region of Erel where there is perfect agreement between recombination theory and measurements.
3. Even if one would have such "enhancement" for the RHIC case, using undulator with such large Erel would solve the problem – will not require to compensate "enhanced" measured rate – standard theoretical description is sufficient.

Recombination coefficient used in simulations with undulator

$$E = \frac{m}{2}\left(\left(v_{\perp} + v_{und}\right)^2 + v_{\parallel}^2\right)$$

$$\alpha_r = \frac{1}{Int}\int_0^{3\Delta_\perp}\int_{-3\Delta_\parallel}^{3\Delta_\parallel} \sigma(E)\sqrt{\left(v_\perp + v_{und}\right)^2 + v_\parallel^2}\,\exp\left(-\frac{\left(v_\perp + v_{und}\right)^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right) v_\perp dv_\parallel dv_\perp$$