Attainment of a High-quality Electron Beam for Fermilab's 4.3 MeV cooler

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COOL '05

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Outline

- Introduction
- Project history
- Setup description
- Recirculation stability
- Electron angles in the cooling section
- Operational status
- Plans

Introduction

- Mission of the Recycler Electron cooling: to provide an effective cooling tool for longitudinal cooling and storing of 8 GeV antiprotons in the Recycler ring
- The first cooling has been demonstrated in July 2005 (see report of S. Nagaitsev et al.). Now electron cooling is routinely used.

Beam parameters

- Initial specifications for the electron beam parameters in the cooling section:

- Electron energy	4.34	MeV
- Beam current, DC	0.5	A
- Beam radius	5	mm
- Electron angles, rms	0.2	mrad
- Length of the cooling section	20	m

History: proof of principle

Pre-history:

- Novosibirsk BINP 1 MeV, 1A (1985);
- Fermilab & NEC 1 MeV, 0.1 A (F.Mills et al., 1989)
- Progress in e-gun and collector (A. Sharapa et al.)

Fall 1995-	beginning of the ECool project
June 1997-	first current in the collector of a test machine at 1.2 MV
June 1999-	end of the 1 MV test; Imax = 0.9 A; 0.5 A is stable

History: R&D toward necessary parameters

March 2001-	Fist time HV on both tubes in the 5 MV machine
Nov. 2002 -	Imax=1.7 A at 3.5 MeV in a short line; 0.5 A is stable
July 2003 -	first DC beam in the full-scale line
May 2004-	end of WB test; Imax =0.8 A; 0.1 A beam with a cylindrical envelope in the cooling section

History: commissioning

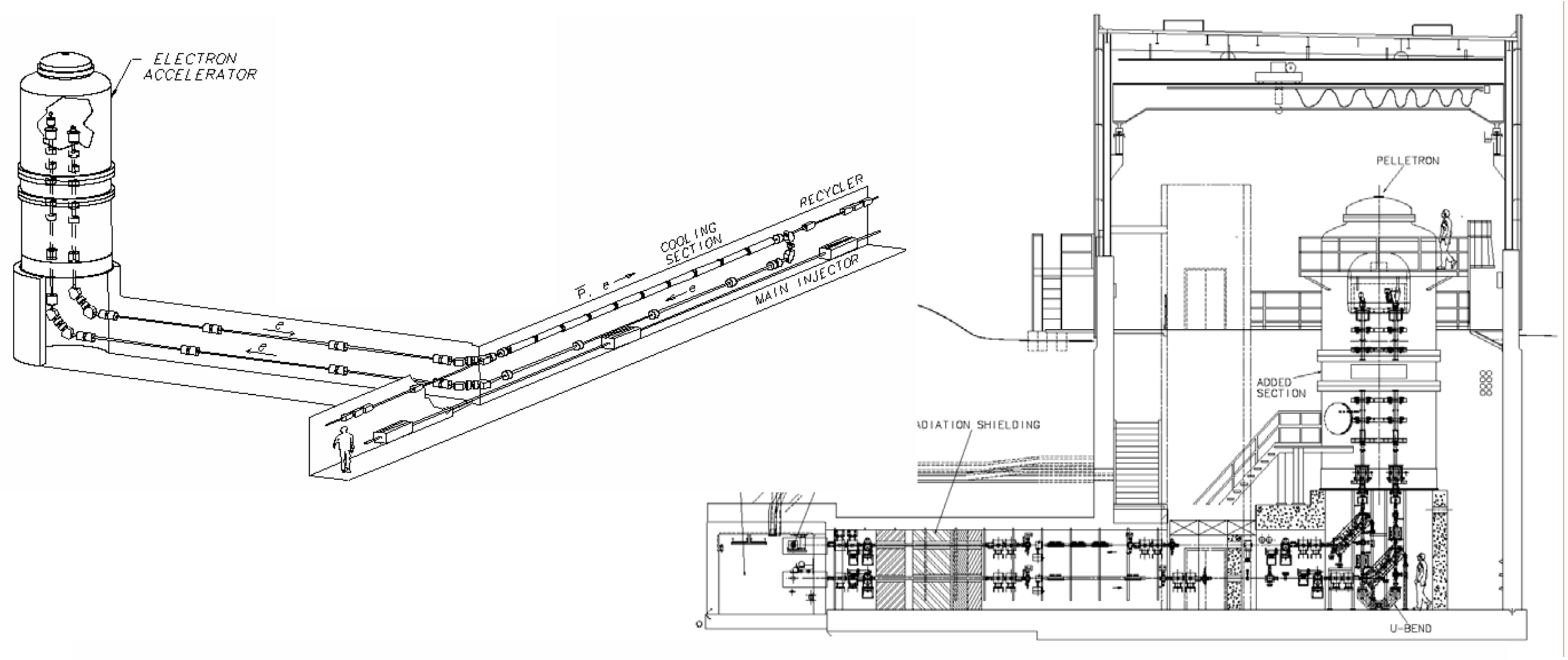
- March 2005- for the first time, 5 MV in the Pelletron at MI-31
- July 2005- Imax = 0.4 A; I = 0.2 A is stable enough;

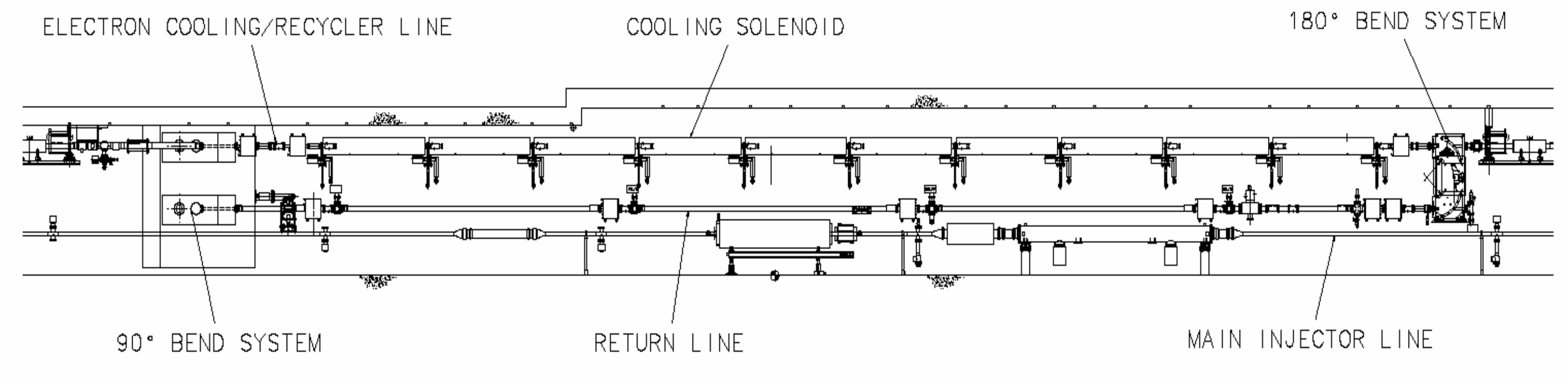
  first cooling of 8 GeV pbars

September 2005- all shots are e-cooled;

electron beam is used at 50 – 100 mA and is stable

Setup


ELECTRON ACCELERATOR
RECYCLER
COOLING SECTION
MAIN INJECTOR
P, e
e
e
e
PELLETRON
ADDED SECTION
ADIATION SHIELDING
U-BEND


ELECTRON COOLING/RECYCLER LINE
COOLING SOLENOID
180° BEND SYSTEM
90° BEND SYSTEM
RETURN LINE
MAIN INJECTOR LINE

Setup parameters

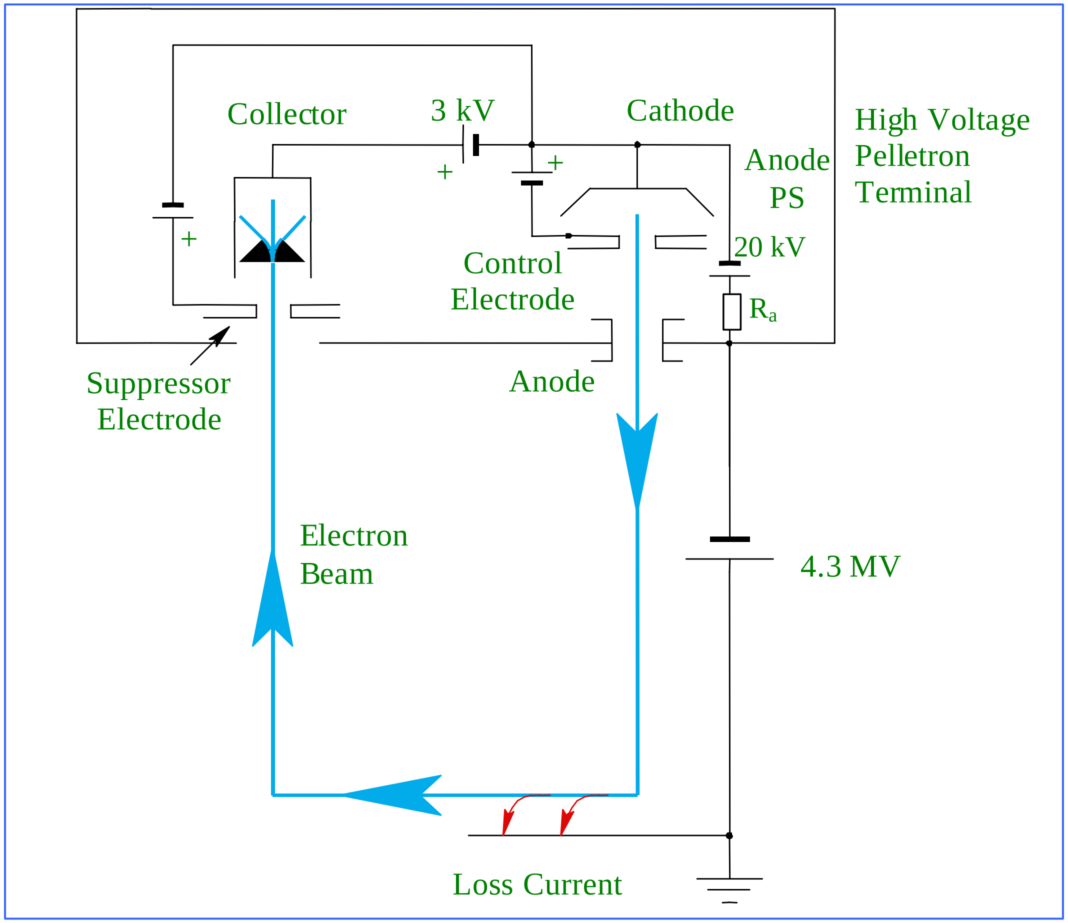
Parameter	Unit	Value (for cooling)	Value (maximum)
Electron energy	MeV	4.338	5
Beam current used for cooling	A	0.05 - 0.2	0.6
Magnetic field in the cooling section	G	105	190
Beam radius in the cooling section	mm	3 - 5	
Pressure	nTorr	0.2 - 1	
Total length of the beam line	m	80	

Specific features

- An electrostatic accelerator working in the energy recovery mode
- Transport of the beam with a large effective emittance
- Low magnetic field in the cooling section
- Sharing the tunnel with the Main Injector

Recirculation

The beam power of 2 MW requires the energy recovery (recirculation) scheme.



Current losses

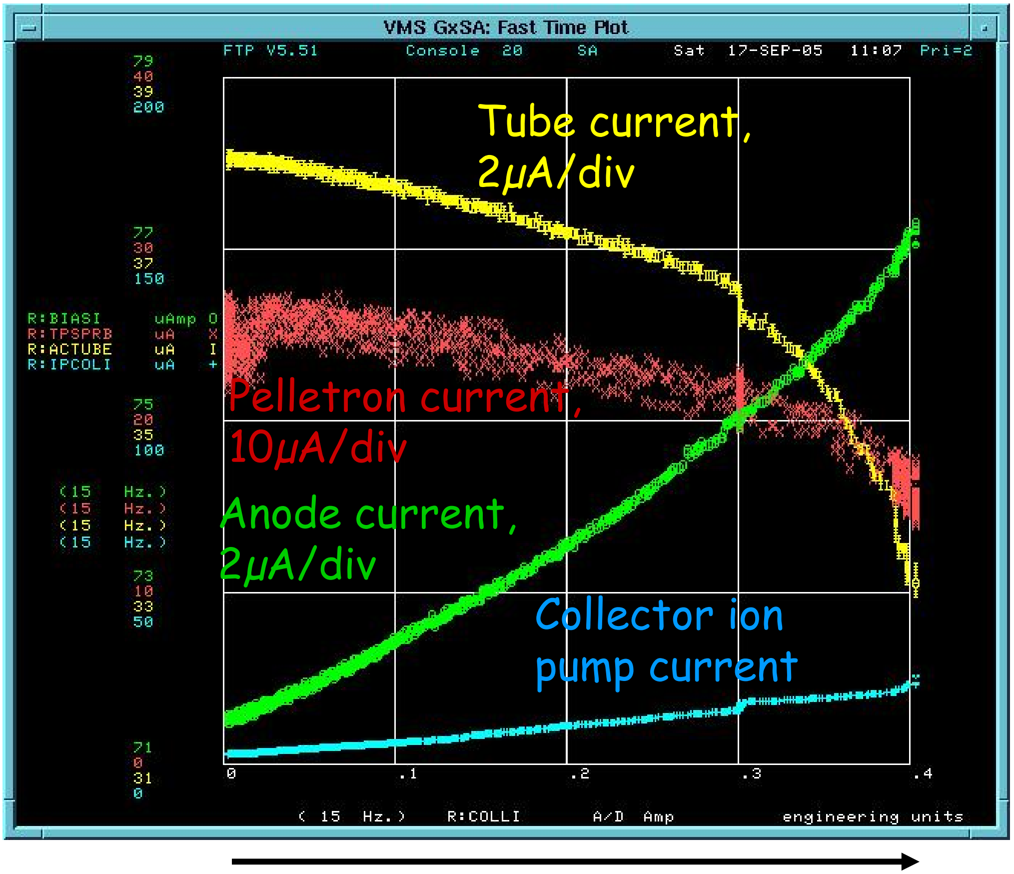
Current losses have to be low.

(1) Losses to the tube electrodes should not exceed few μA to avoid overvoltage

(2) Losses at the ground should not exceed few tens of μA to avoid damaging the vacuum chamber

IBS in the electron beam seems to significantly affect the current losses.

See report of A. Burov et al.

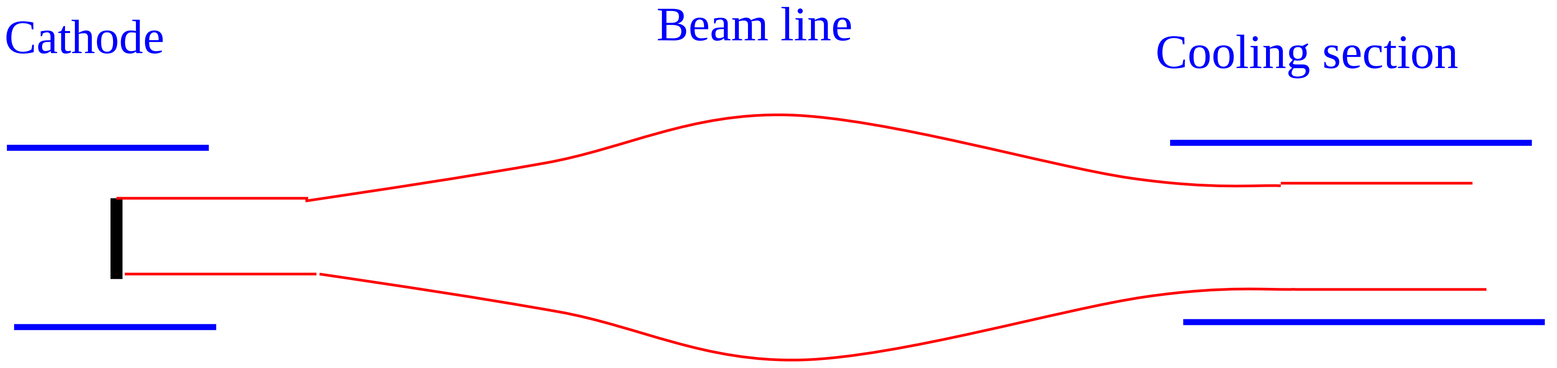


Beam current, 0.1A/div

Typical plot of losses as functions of the beam current. $dI/I = (1.2\text{-}1.5)\cdot 10^{-5}$.

Effective emittance

Figure of merit: magnetic flux inside the beam in the cooling section = effective emittance outside the longitudinal magnetic field



Cathode

Beam line

Cooling section

$B_{cz} = 90\ G$

$R_{cath} = 3.8\ mm$

$\varepsilon_t = R_{cath}\sqrt{\frac{T}{mc^2}}$

$= 2\ \mu m$ (normalized)

$B_z = 0$

$R = 2\ \text{-}10\ mm$

$\varepsilon_{eff} = B_{c_z} R_{cath}^2 \frac{e}{2mc^2}$

$= 38\mu m$ (normalized)

$B_{cz} = 105\ G$

$R_{beam} = 3.5\ mm$

$\varepsilon_{cs} < 7\mu m$

(normalized)

Low energy portions of the acceleration and deceleration tubes have to be immersed into a longitudinal magnetic field.

A 3D beam line has to provide an axially symmetrical beam transformation.

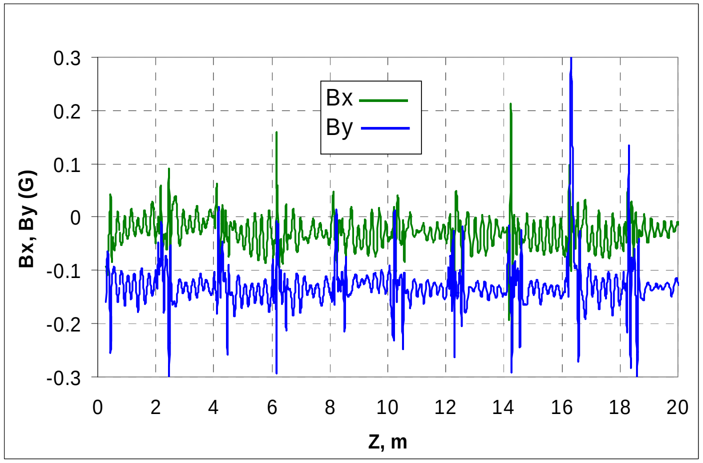
See report of A. Burov et al.

Low magnetic field in the cooling section

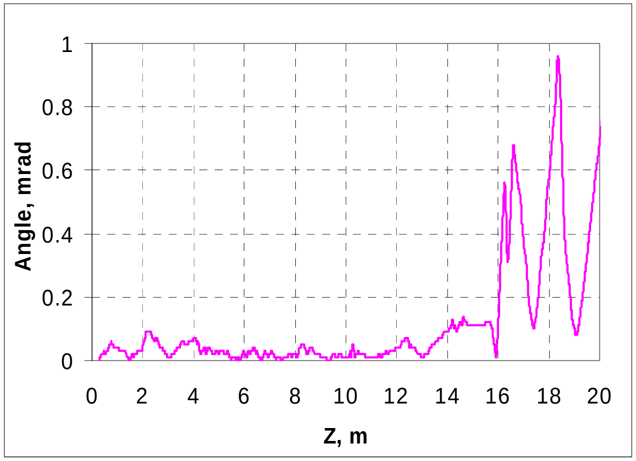
- Cooling is not magnetized
- The role of the magnetic field in the cooling section is to preserve low electron angles,

$$\frac{2I}{\gamma^2\beta^2 cR}\cdot\frac{1}{B_z} << 0.2mrad$$

- A typical length of $B_\perp$ perturbation, ~20 cm, is much shorter than the electron Larmor length, 10 m. Electron angles are sensitive to $\int B_\perp dz$, not to $B_\perp$.



Transverse magnetic field map after compensation. Bz = 105 G.

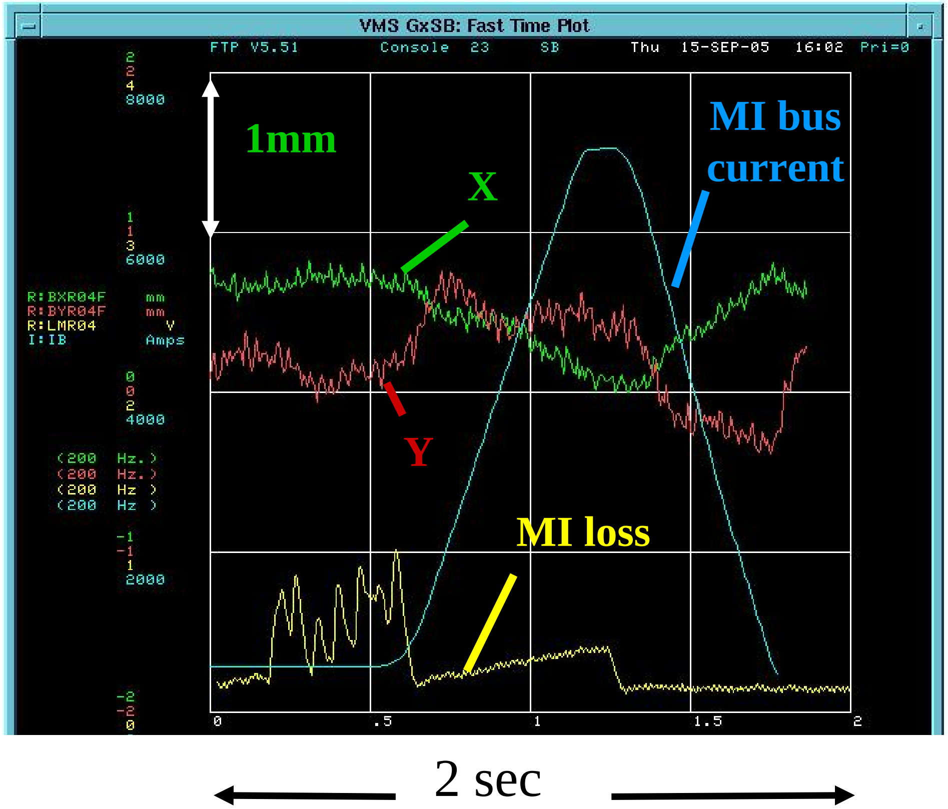


Simulated angle of an 4.34 MeV electron in this field. R.m.s angle in the first 8 sections is 50 μrad.

See report of V. Tupikov et al.

Neighborhood with the Main Injector

- Magnetic fields of busses and MI magnets in the time of ramping causes an extensive motion of the electron beam (up to 0.2 mm in the cooling section and up to 2 mm in the return line)
- MI radiation losses sometimes result in false trips of the ECool protection system



Electron beam motion and MI losses at R04 location in the time of MI ramping. 0.55 Hz oscillation is due to 250 V (rms) energy ripple.

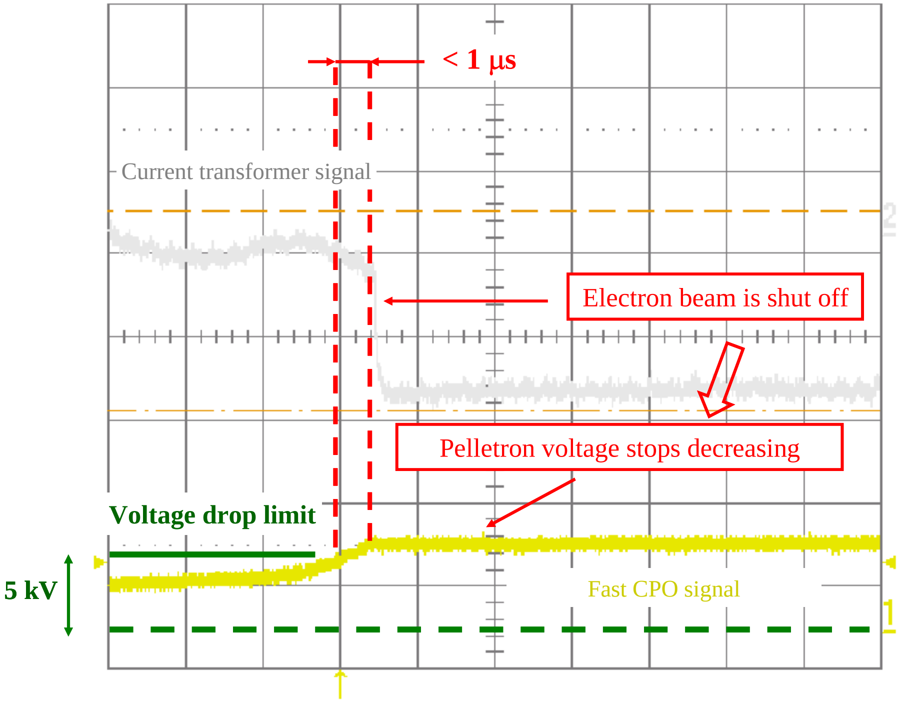
Recirculation stability: protection system

The ECool protection system closes the gun if the Pelletron voltage decreases by more than 5 kV or the signal of a radiation loss monitor exceeds a threshold.

Mission of the protection system is to prevent damages to the vacuum chamber and acceleration tubes

Oscillograms of a recirculation interruption at I=0.2 A.

The gray trace is the cathode current (~0.1 A/div), and the yellow trace is the decrease of the (negative) terminal voltage. The protection system is activated at the 5 kV drop. Time scale is 10 µs/div.

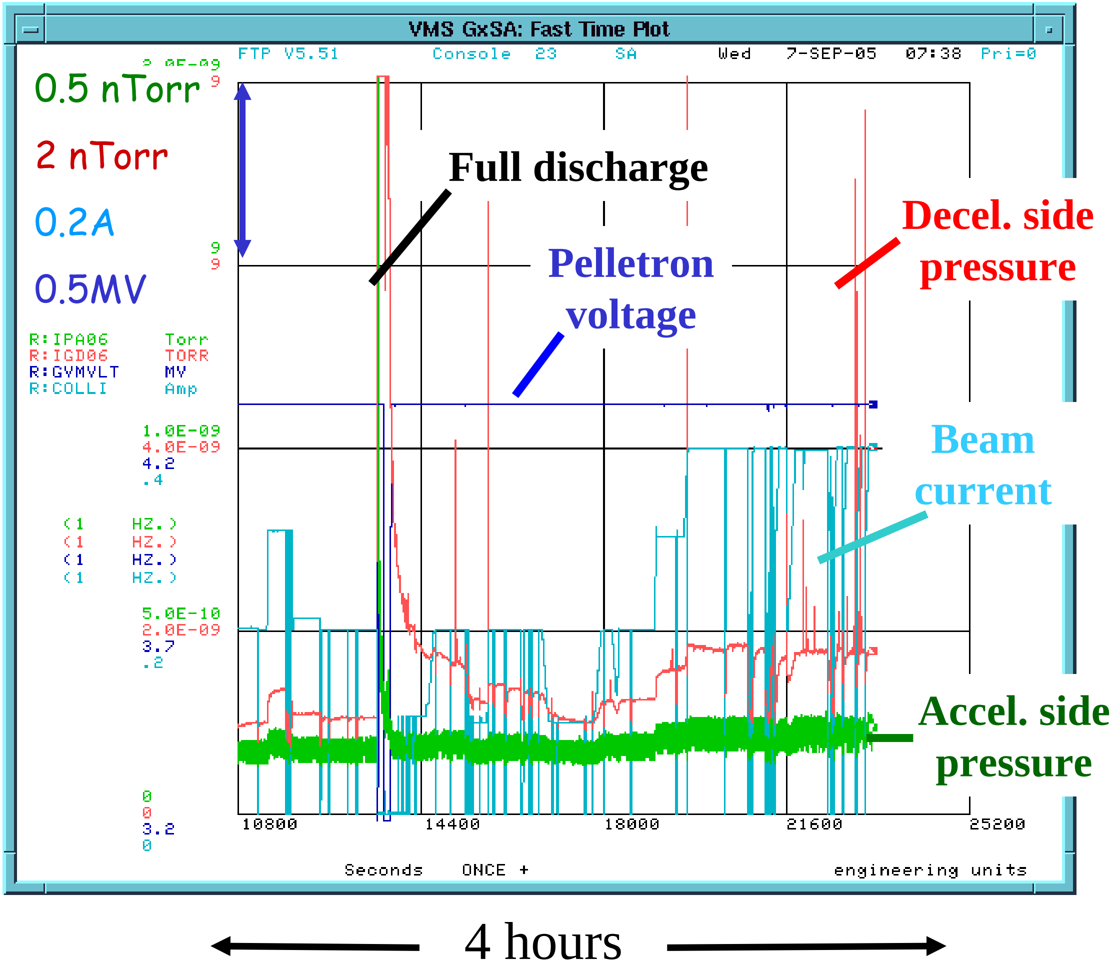


Recirculation stability (cont.)

Two types of events when the protection system is activated:

(1) recicrulation interruption without large terminal voltage drops

(2) full discharges.



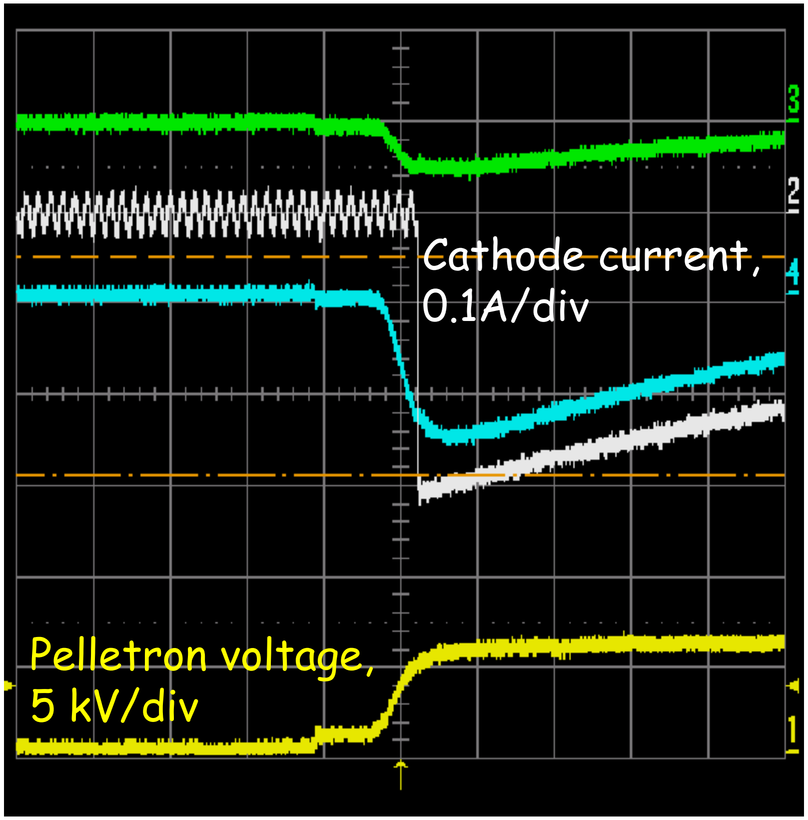
A “history plot” of a shift of beam tuning

Recirculation stability: interruptions

Short interruptions of the beam affect the cooling time only as a decrease of an average current. The beam recovery time is 20 sec.

Reasons for the interruptions:

- beam studies
- beam motion caused by MI ramps
- MI losses
- "natural" interruptions. Most likely, result from partial discharges or slow redistribution of potential in acceleration tubes



0.2 ms/div

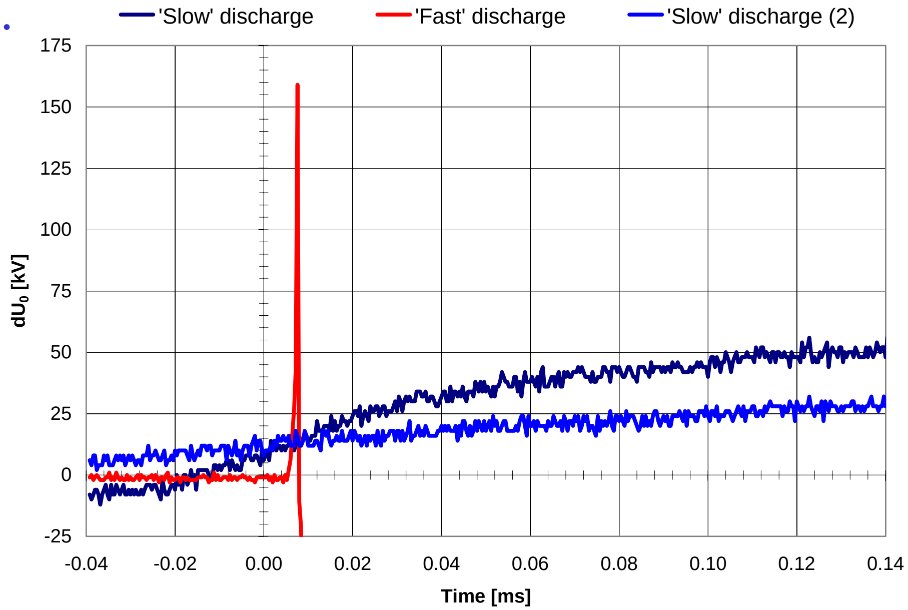
Oscillograms of a "natural" interruption at 0.4 A. Green and blue traces indicate a redistribution of the potential along the acceleration and deceleration tubes.

Recirculation stability –Full discharges

The terminal voltage drops by MVs; the discharge begins in vacuum and ends by sparking the protection gaps in SF6.

Typically it requires 5-30 min to recover; may damage electronics; deteriorates the tube strength.

- Random events; the frequency depends on how close the applied electric field to a limit, which depends on tube history.
- The frequency depends on the beam current and the beam line settings. The present model explains the dependence by a redistribution of the potential along tubes resulted from beam losses (see the report of L. Prost et al.)



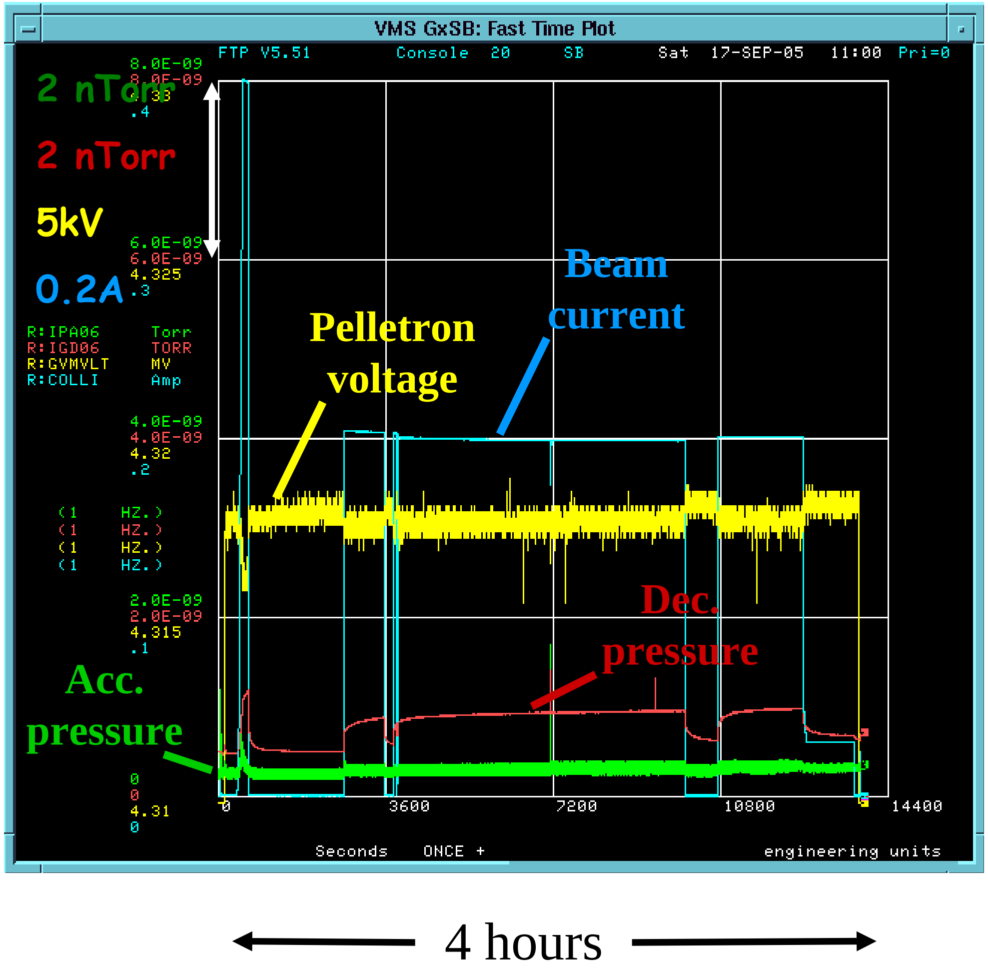
Oscillograms of 'fast' (red) and 'slow' (blue) discharges recorded by the fast capacitive pickup (Fast CPO) that measures the terminal voltage 'drop' (the terminal voltage actually becomes more positive)

Recirculation stability (cont.)

At currents of 0.2 A and below, the beam stays for hours without "natural" interruptions.

Above I = 0.4 A, the recirculation stability dramatically drops. The recirculation is interrupted every 5-20 min; eventually, a full discharge occurs.

After ~ 10 full discharges, the tubes strength drops from 5.2 MV almost down to the working point of 4.32 MV. At this point, the tube conditioning should be repeated (~ 6 hours).



A "history plot" of a cooling shift

Electron angles in the cooling section

Initial plan assumed that the rms electron angle averaged over the beam cross section, cooling section length, and time is 0.2 mrad.

Component	**Upper limit, μrad**	**Present estimation, μrad**	**Diagnostics**	**Comments**
Temperature	90	60	Calculated	Plan to estimate with OTR
Aberrations	90	50	Simulated	Plan to estimate with OTRs and BPMs
Envelope scalloping	100	200	Movable orifices (scrapers)	For the 0.2 A beam boundary at 10^{-5} level of losses
Dipole motion caused by magnetic field imperfections	100	50	Magnetic measurements + BPMs	In the first 8 modules (i.e. over 16 m)
Beam motion	50	40	BPMs	With a slow feedback
Drift velocity	20	10 < 30	Calculated Movable orifices	For I =0.2 A
Total	**200***			The angles are summed in quadratures.

See report of A.Burov

Diagnostics

Main diagnostics:

- BPMs for the dipole motion
  - 39 pairs of capacitive pickups;
  - modes: DC +32 kHz modulation, 2 μsec pulsing, pbars;
  - resolution up to 5 μm
- Movable orifices for the beam envelope in the cooling section (see report of T.Kroc et al.)
- Optical Transition Radiation monitors (OTRs) to analyze the beam current density distribution (see report of A. Warner et al.)
- In addition: a multiwire harp, a pepper pot, an analyzing hole

Electron angles in the cooling section

The main contribution seems to be coming from the envelope angles

Component	Upper limit, µrad	Present estimation, µrad	Diagnostics	Comments
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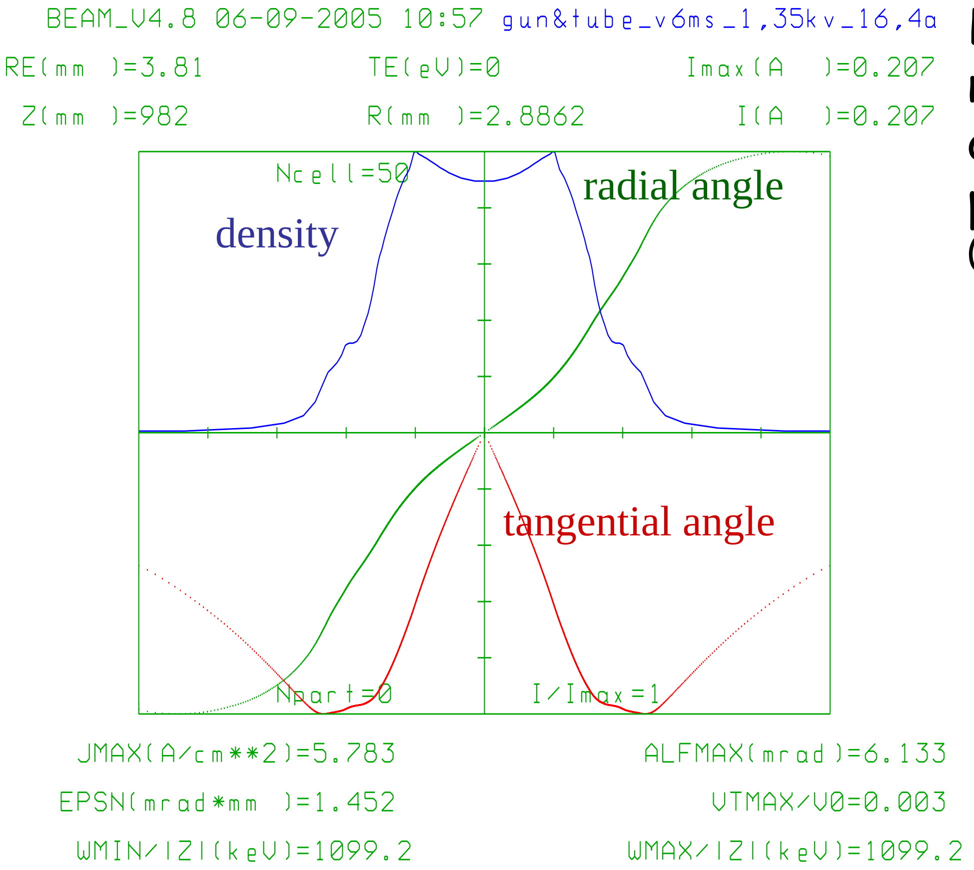
See report of A.Burov

Envelope angles

A cylindrical boundary doesn't guarantee low angles in the middle of the beam because of aberrations



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BEAM_V4.8 06-09-2005 10:57 gun&tube_v6ms_1,35kv_16,4a
RE(mm )=3.81            TE(eV)=0            Imax(A )=0.207
Z(mm )=982              R(mm )=2.8862       I(A )=0.207
JMAX(A/cm**2)=5.783               ALFMAX(mrad)=6.133
EPSN(mrad*mm )=1.452               VTMAX/V0=0.003
WMIN/IZI(keV)=1099.2              WMAX/IZI(keV)=1099.2
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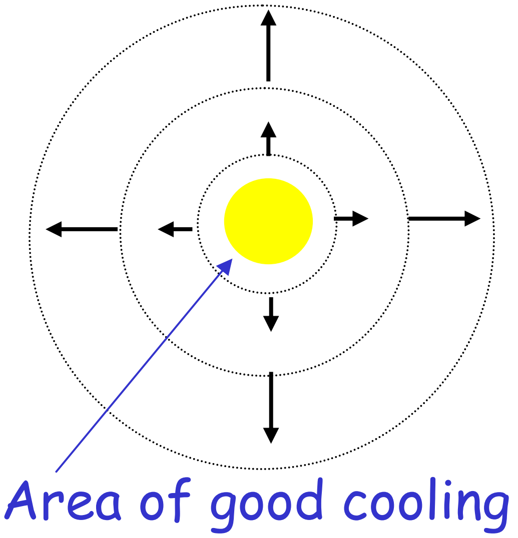
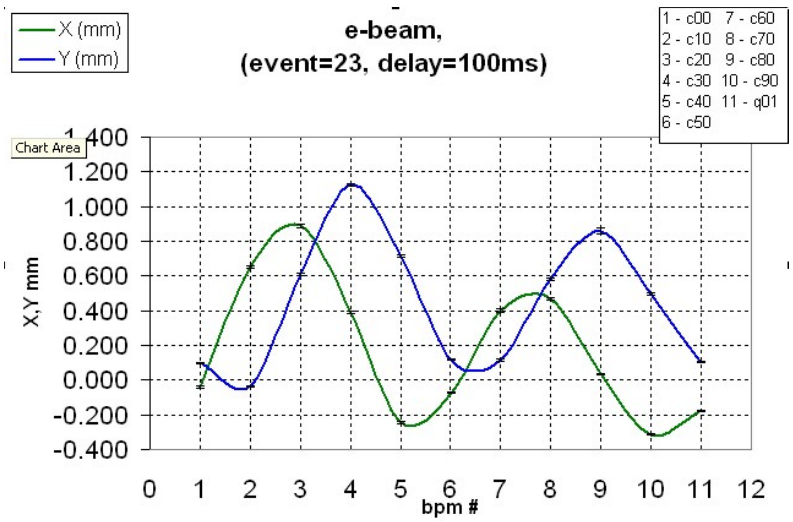
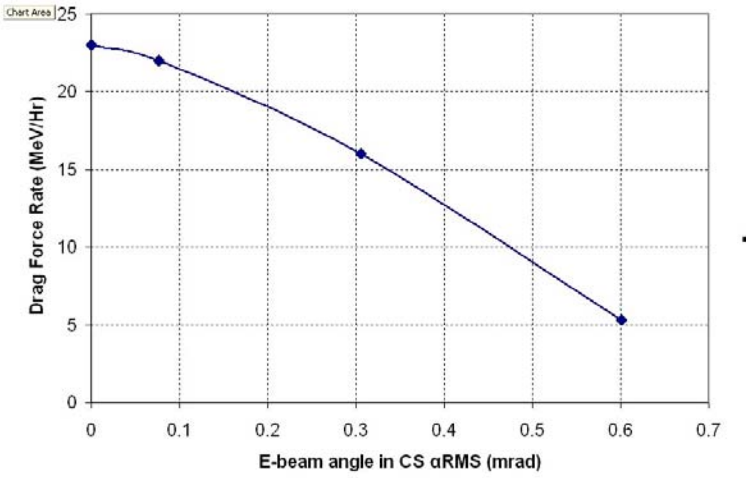
Beam profile for 200 mA. This non-linearity leads to ~ 400 μrad of the core envelope angle for a perfectly cylindrical halo.
(UltraSAM +BEAM, M.Tiunov)

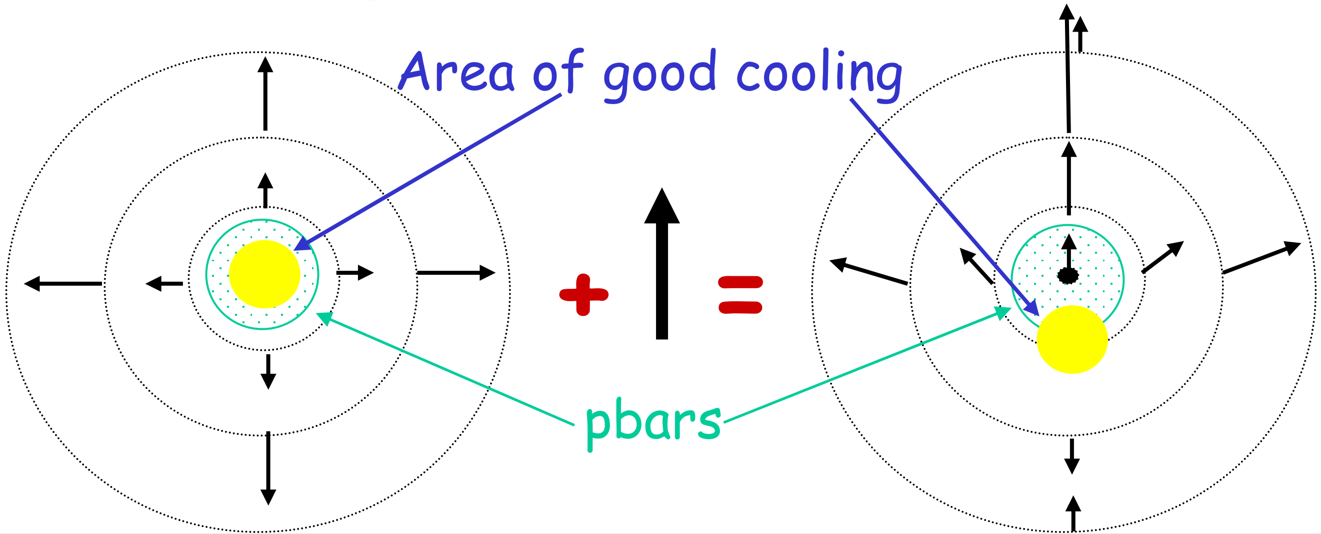


Envelope angles + dipole kick

Large envelope angle may be the reason for a weak dependence of the cooling force on a dipole kick (with 1E10 pbars)







Area of good cooling

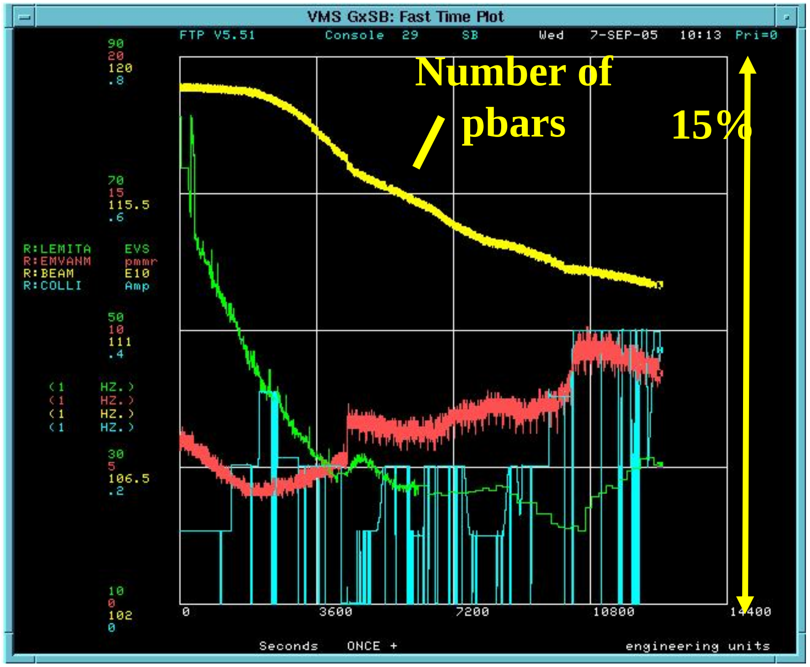
pbars

Operational status

- Every Tevatron shot is prepared with the electron cooling
- Cooling system works reliably (with minor exceptions) and predictably
- Beam centroid position is stabilized with a feedback (~ 0.2 Hz) in the cooling section and at the entrance of the deceleration tube
- Typically cooling is done at I = 50-100 mA
- Cooling at higher currents results in a decrease of the pbar life time

Operation: pbar lifetime decrease

4 hours of pbar cooling.

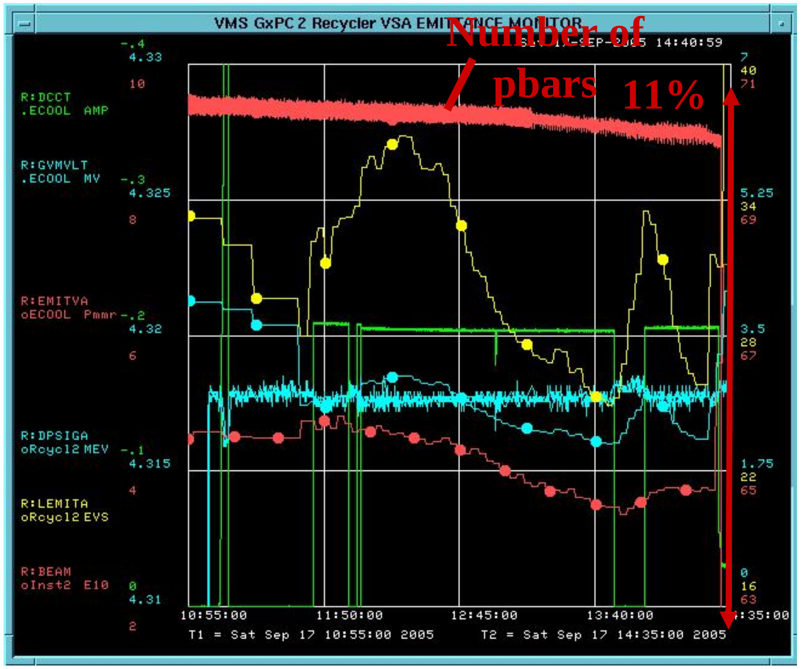


Blue- e-beam current (0.2A/div).

Yellow- pbar number (from 102 to 120 E10)

Red- vertical emittance (n95%, from 2 to 10 π μm)

Green- longitudinal emittance (95%,, from 10 to 90 eV·s)



Cooling with dipole e-beam oscillations.

Blue- Pelletron V. (from 4.31 to 4.33 MV)

Yellow- longitudinal emittance (95%, from 16 to 40 eV·s)

Red with dots- vertical emittance (n95%, from 2 to 10 π μm)

Green- e-beam current (0.1A/div).

Red- pbar number (from 63 to 71 E10)

Plans- “large scale”

- Make electron cooling fully operational.
- Cool effectively the Recycler Stack at > 200×10^{10} pbars.

Some of "small scale" plans

- Try cooling with a shifted electron beam to avoid overcooling of the central part at high e-beam currents
- Try to optimize the envelope angles looking the equilibrium emittance
- Measure the optics of the beam line accurately enough to be able to extend simulations from the gun to the cooling section. It should allow adjusting the envelope angles in a predictable way.