Ultimate performance of relativistic electron cooling at Fermilab

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September 15, 2011

COOL'11

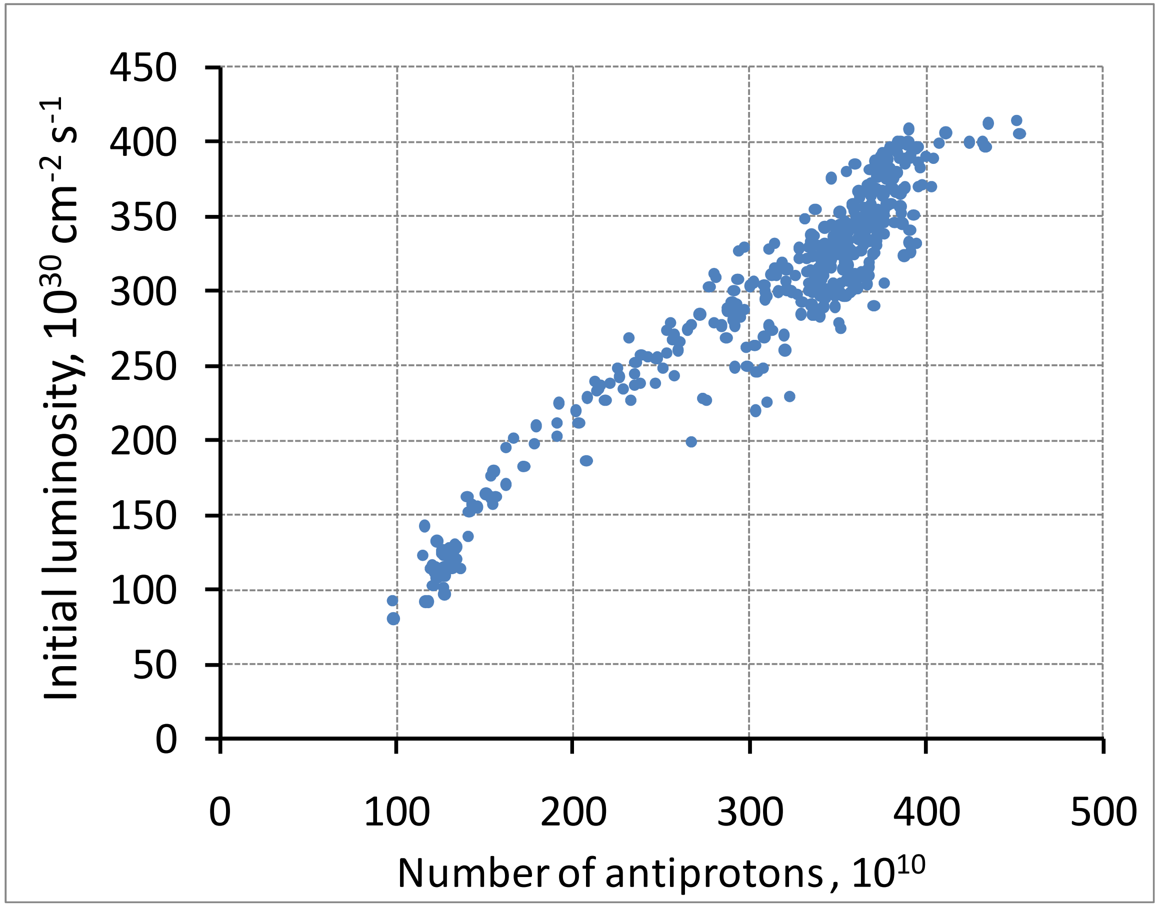
A **eulogy** (from *εὐλογία*, eulogia, Classical Greek for "good words") is a speech or writing in praise of a person or thing, especially one recently deceased or retired. - *Wkipedia*

Outline

- Why Fermilab needed it
- Challenges and the choice of the scheme
- Operation
- Cooling measurements

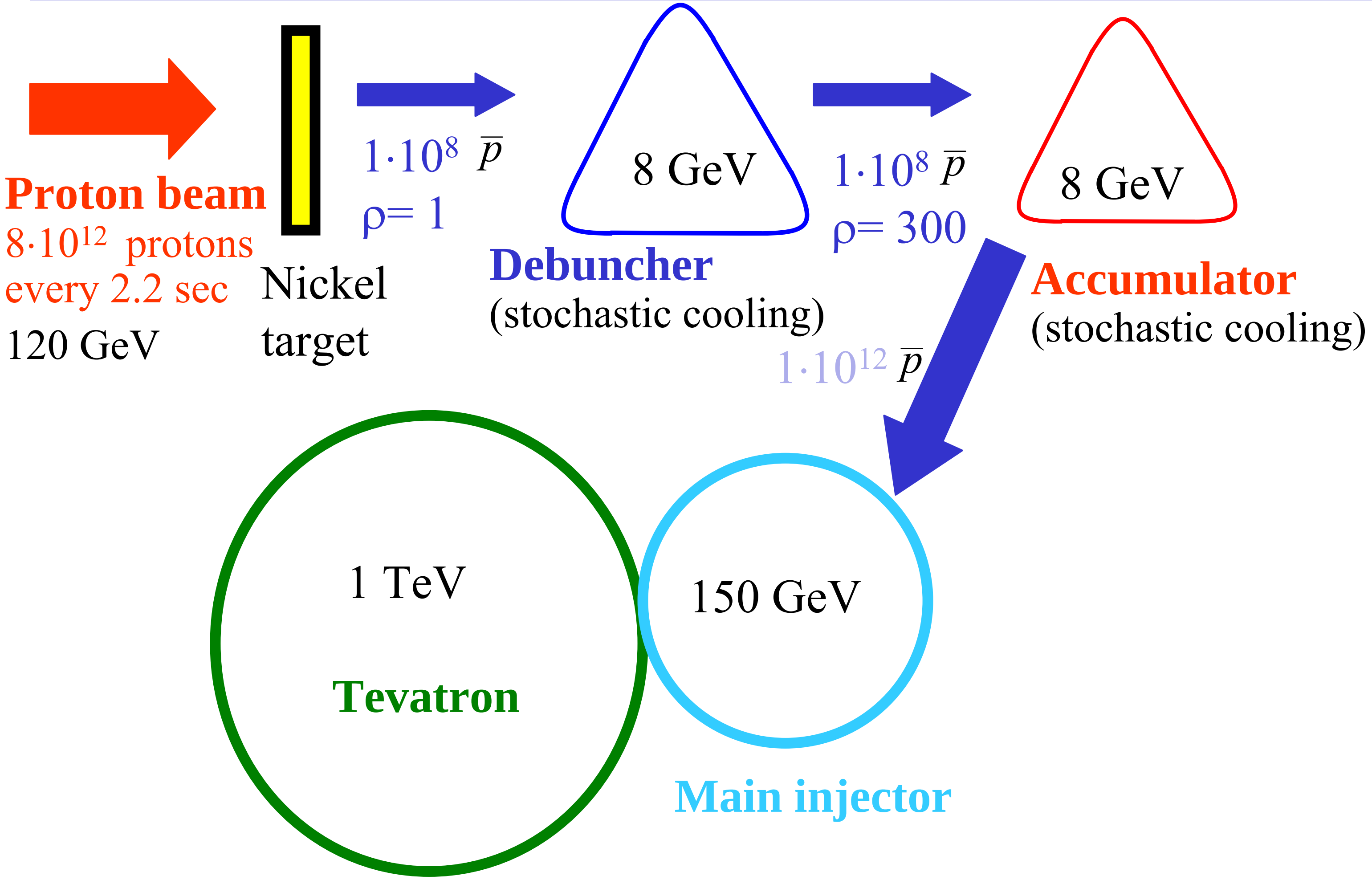
Tevatron luminosity and antiprotons

The Tevatron luminosity is almost linear with respect to the total number of antiprotons available for Tevatron stores. Increase of antiproton production and improvement of the beam quality was the central component of the Tevatron Run II.



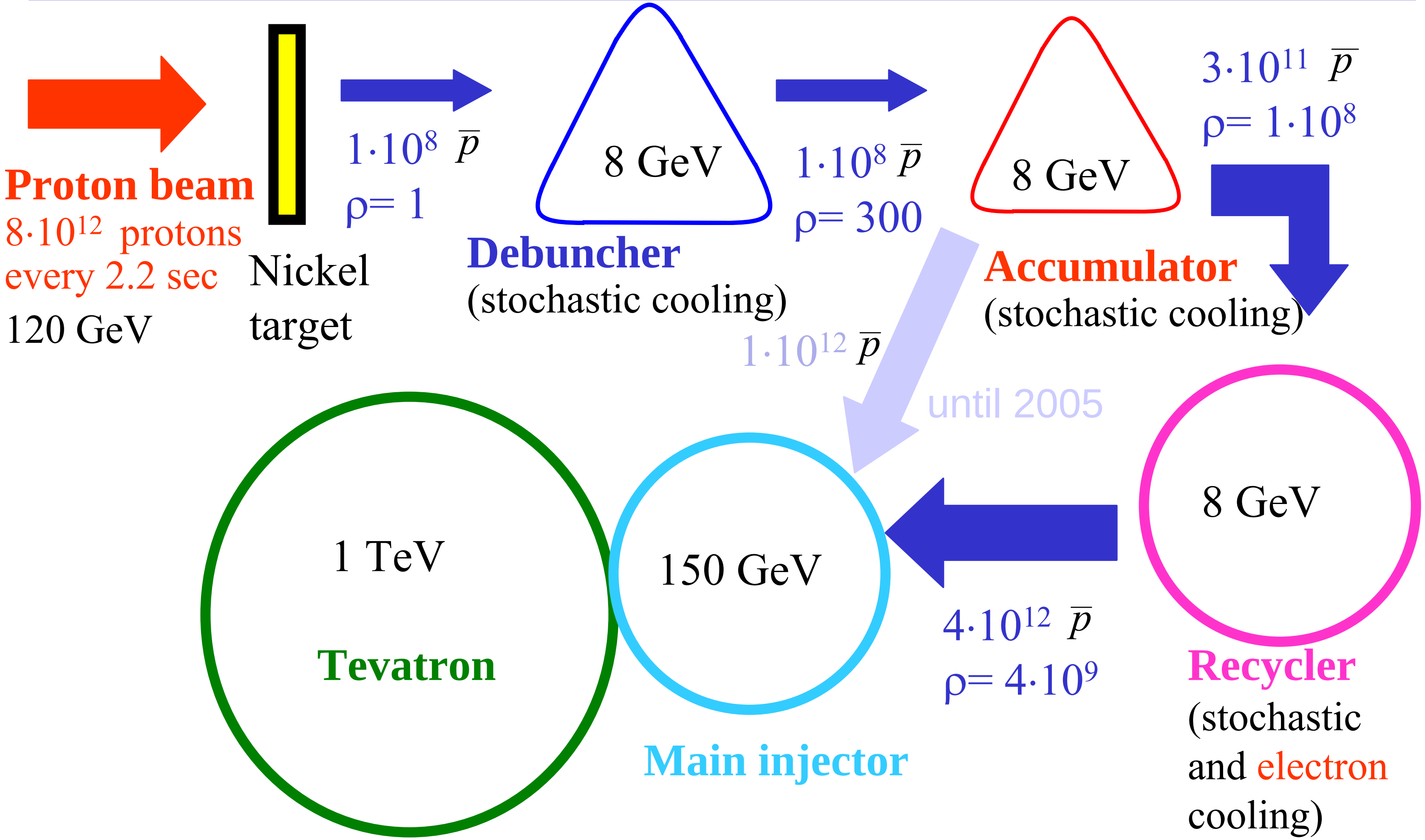
Average initial luminosity as a function of the number of antiprotons injected into the Main Injector. Shown are the stores in 2011.

Fermilab's antiproton production chain



Until 2005

Fermilab's antiproton production chain

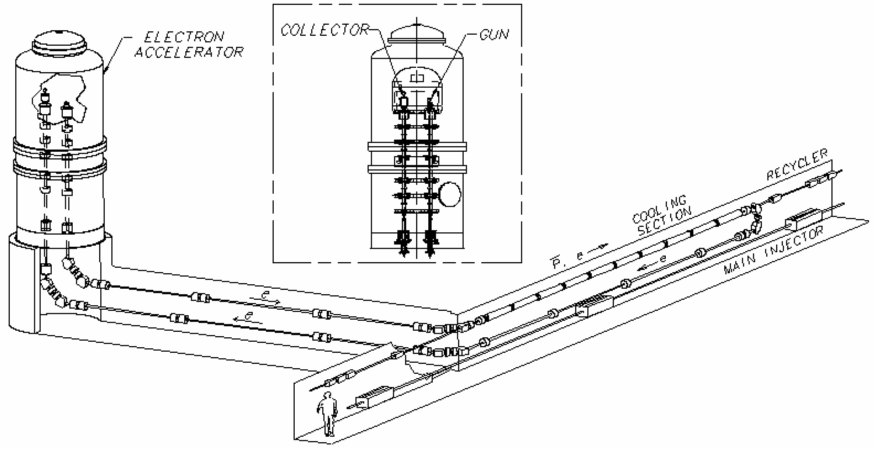


Electron cooling in the Recycler Ring eliminated a bottleneck in the antiproton production chain.

Difficulties of implementing relativistic electron cooling

Design parameters of the RR ECool	
Energy	4.3 MeV
Beam current (DC)	0.5 Amps
Angular spread	0.2 mrad
Effective energy spread	300 eV

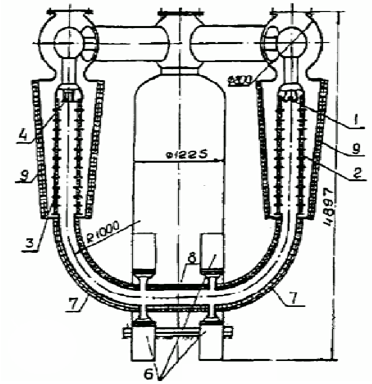
RR = Recycler Ring



- High electron beam power:
  - 4 MeV × 0.5 A = 2 MW DC
    - Energy recovery scheme is a must
    - Very low beam losses are required
    - High voltage discharges need to be avoided
- Beam quality:
  - Transverse electron beam temperature (in the rest frame) should be comparable to the cathode temperature ~1400K
    - Only a factor of ~10 increase is allowed

Pre- history of relativistic electron cooling

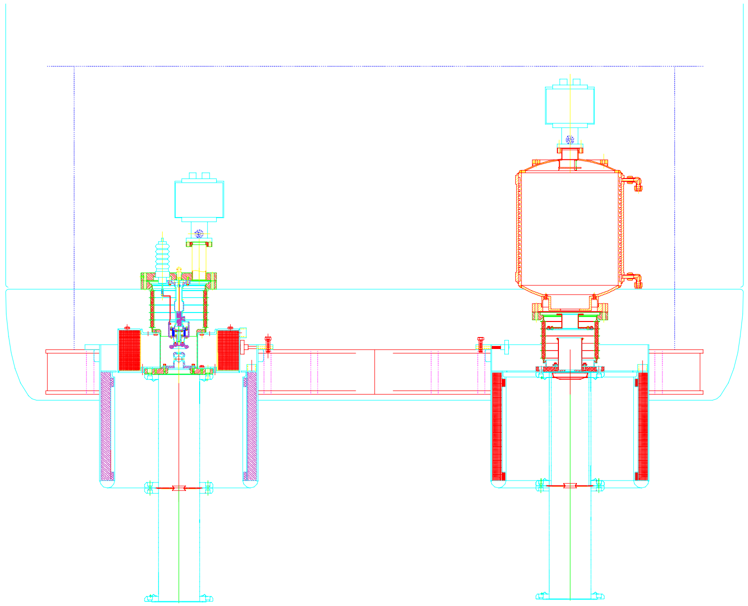
- Fermilab, 1983: "Intermediate energy electron cooling for antiproton sources using a Pelletron accelerator"
  - ➢ A pulsed electron beam from a Pelletron
- Fermilab, UCLA, NEC, 1989: tested a 2-MV, 0.1-A DC recirculation system with a Pelletron.
  - ➢ Poor stability
- Novosibirsk, 1987: successfully tested a prototype 1-MV, 1-A electron beam system.
  - ➢ Continuous magnetic field
  - ➢ Stable
  - ➢ Acceleration tubes are not sensitive to vacuum UV



- Fermilab, IUCF, NEC, 1995: started to work with a 2-MV Pelletron again- beginning of the RR ECool project
- Why the Pelletron?

Choice of the scheme

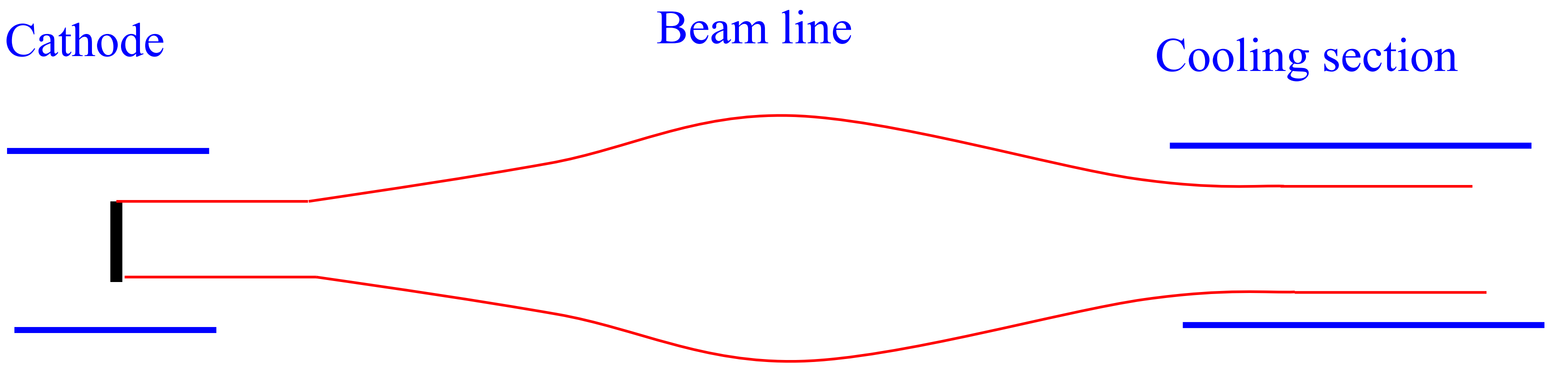
- The main reason: the scheme without continuous longitudinal magnetic field looked doable in the time frame useful for the Tevatron Run II. Also,
  - Pelletrons have had the terminal potential up to 25 MV
    - Known for being reliable machines
  - Cheaper
  - Easier to incorporate into the existing MI/RR tunnel
- Problems
  - Gun and collector used in the previous attempts did not allow reliable beam recirculation
    - Ideas for a low–halo gun and a low-loss collector were developed at BINP
  - Lumped focusing in the cooling is not adequate for effective cooling
    - Space charge, residual ions, image charges…



Full line, ion clearing mode (December 31, 2011.).

Transport with an interrupted longitudinal magnetic field

- Longitudinal magnetic field in the cooling section and in the gun with lumped focusing in between



$B_{cz} = 90\ G$
$R_{cath} = 3.8\ mm$

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

$= 2\ \mu m$ (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)

- The transverse velocities in the cooling section can be low only if the fluxes through the emitter and the beam in the cooling section are equal.
- Outside of the field, the beam behavior is dominated by an effective emittance proportional to the magnetic flux through the emitter

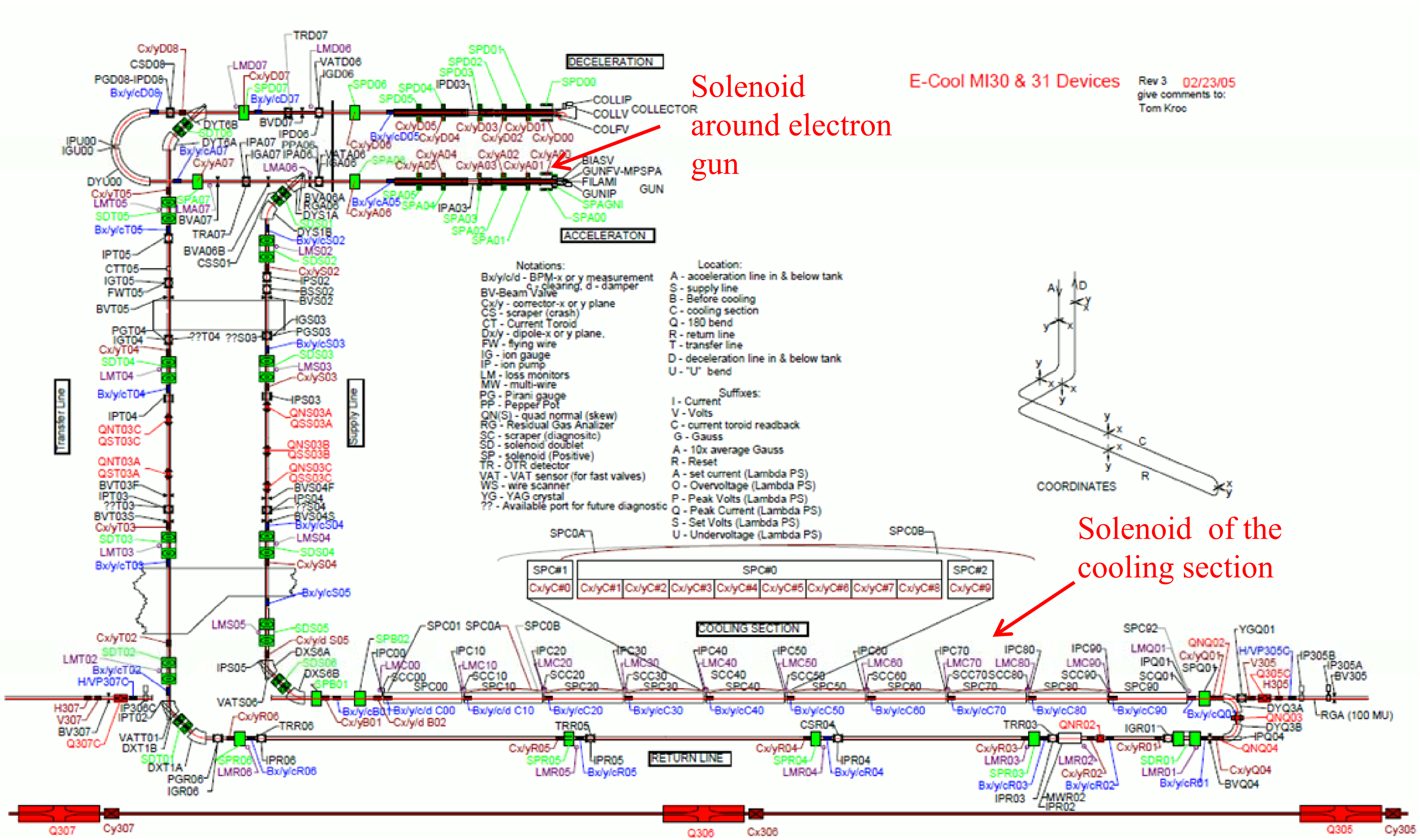
Applicability

- When is the scheme with interrupted magnetic field applicable?
  - The figures of merit is the magnetic flux through the beam in the cooling section and the energy

$$\varepsilon_{B,eff} = \frac{e\Phi}{2\pi\gamma\beta m_e c^2} \approx \frac{eB_{CS} R_{CS}^2}{2\gamma\beta m_e c^2}$$

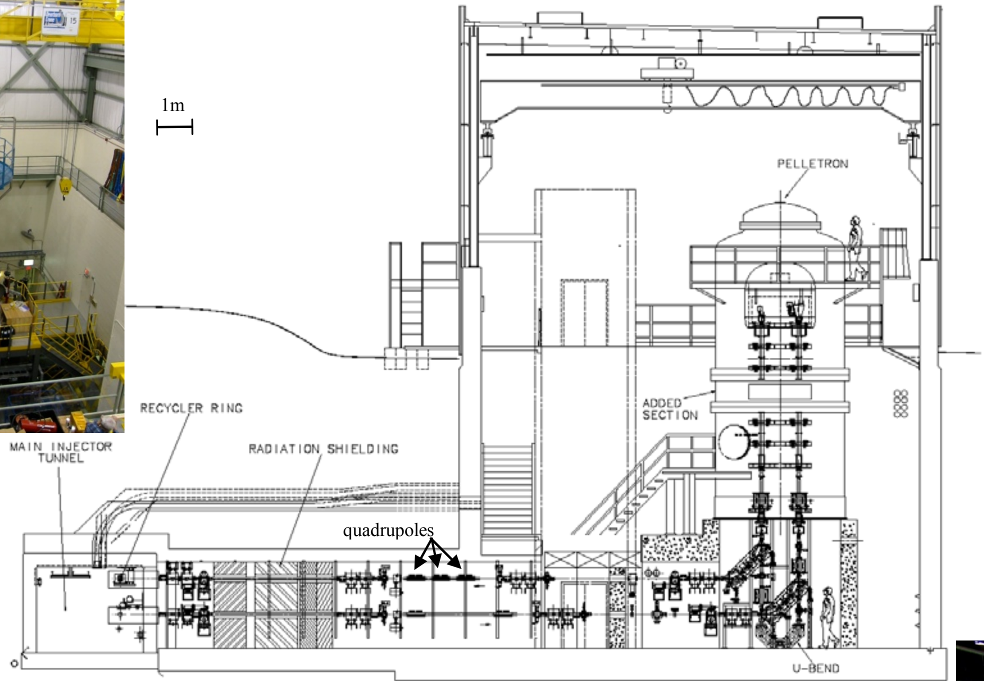
  - The scheme can work when the required beam radius and the magnetic field in the cooling section are low and the energy is high.
- Cooling time required from RR Ecool is many minutes
  - Cooling is adequate without effects of strong magnetization
- Typical rms radius of the antiproton beam is 1-2 mm
  - Electron beam size can be similar
- $\gamma\beta = 9.4$
- Outside of the magnetic field, the (non-normalized) effective emittance is tolerable, ~4μm

Realization



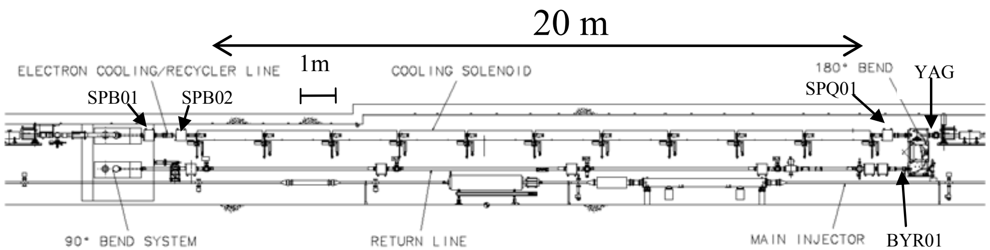
Schematic of the Recycler Electron cooler

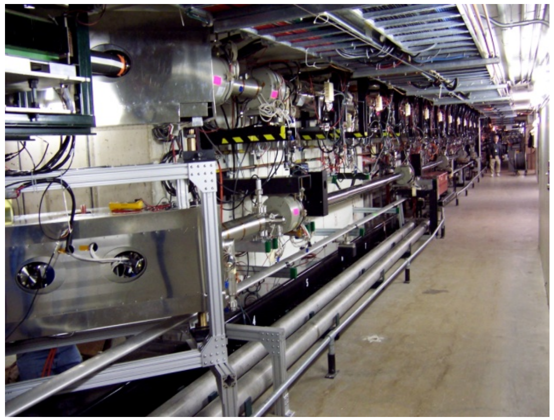
Cooler in the Recycler Ring



February, 2005- beginning of commissioning

The Pelletron and beam "supply" and "transfer" lines





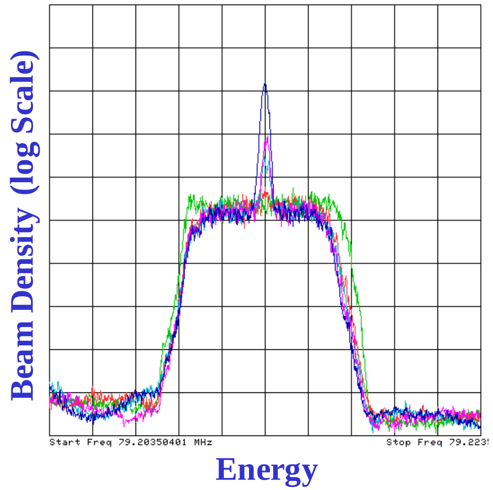
Portion of the Main Injector tunnel containing the cooling section and the "return" line.

Some of difficulties and solutions

- Full discharges
  - Decreasing the acceleration gradient (increased the tube length)
  - Improvements to the protection system (closing the gun in 1 μs)
  - Minimizing current losses to acceleration tubes < 1μA
  - High dispersion in the return line
  - Optimum trajectory in the acceleration tube

- Magnetic fields from the Main Injector
  - Compensation of bus currents, additional magnetic shielding
  - Changes in optics that made the system more tolerable to the beam motion

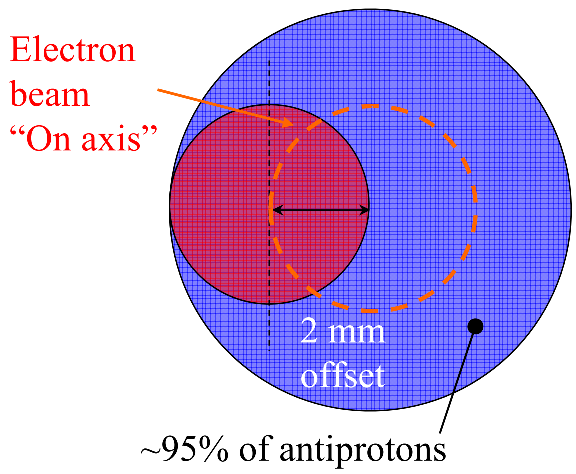
- Energy matching
  - Absolute energy calibration of the electron beam by measuring the electron Larmor wave length in the magnetic field of the cooling section
  - A special wide energy distribution of antiprotons to observe the first interaction between beams



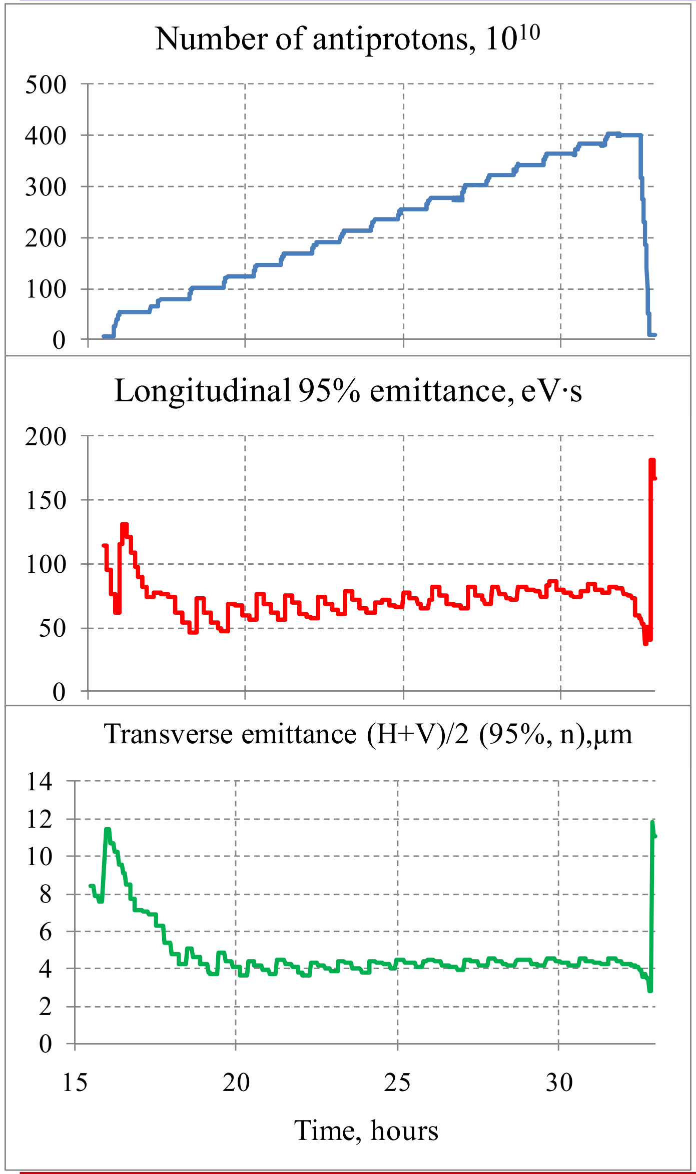
One of the first indications of interaction between antiprotons and electrons.

In operation

- July 9, 2005 – first indication of the cooling force
- Since then, Electron Cooling became an important part of the Tevatron complex
  - When the cooler is ‘broken’, the rate of integrating luminosity drops by ~3
- The cooler’s performance was significantly improved and optimized
  - Procedures for tuning, feedback loops, automation…
  - Increasing of cooling rates
    - Allowed increasing the rate of unloading antiprotons from the Accumulator and improve emittances of the beam in the Tevatron
  - Optimization of the cooling scenario
    - Cooling off – axis
    - Cooling with a helical trajectory
    - Increasing the electron beam current for final cooling before extraction
- Significant efforts for maintenance
- The most interesting – studies!



Recycler cooling cycle



- The main result is an efficient storage of antiprotons and cooling them to the parameters required for the Tevatron
  - Typical beam loss due to the finite life time in the Recycler is ~5%
  - Number of stored antiprotons is up to $6 \cdot 10^{12}$ with a life time > 300 hrs
  - Phase density at extraction is limited by an instability

Typical cycle of accumulation of antiprotons in the Recycler ring and following extraction.

June 17-18, 2011. Electron beam was kept at 0.1A , shifted by 2 mm from the axis except right before extraction, when it was switched to 0.2A in ion clearing mode and moved on axis. Average life time was 256 hours.

Average initial luminosity in the Tevatron was $408 \cdot 10^{30}$ cm^{-2} s^{-1}.

Operational issues

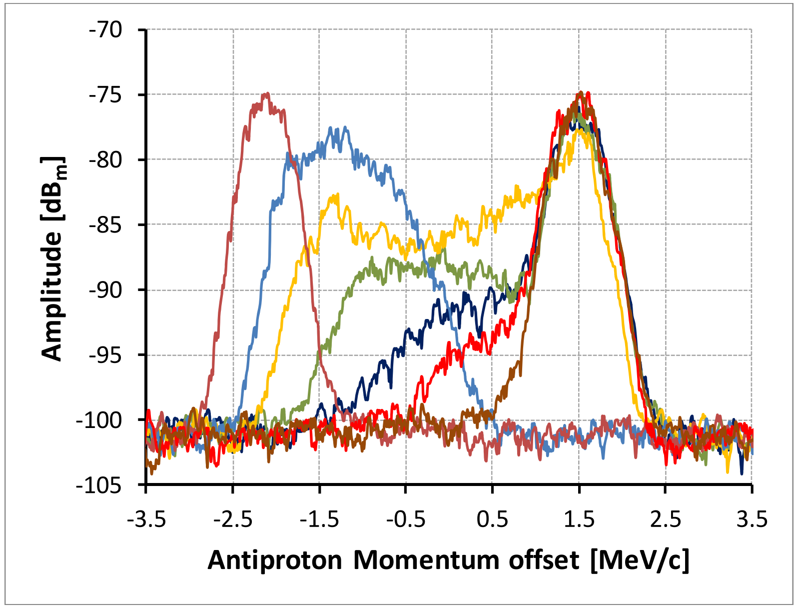
- The cooler normally works 24/7 and turned off only when either a component has failed or during planned shutdowns (~once a year)
  - High requirements to reliability of operation
- The worst case is an access into the Pelletron tank
  - 8-10 hrs to open, 6-8 hrs to close
    - Typical turn-around time ~ 36 hrs
  - Normally, several accesses per year
    - Mostly, to repair electronics
    - Often something breaks right after closing the tank
  - The only exception is August 2011
    - 7 accesses over 26 days! (After working with no problems for half of year)

Operational issues (cont.)

- Unprovoked full discharges became rare (~1 per year)
  - 1 – 3 hrs to fully recover
- Beam trips
  - Protection system turns off the beam if a drop of HV by >5 kV or other problem is detected
  - 0.3 – 3 trips per day
  - ~20 sec to recover
- Electron energy drift
  - Caused by electronics drifts and mechanical shifts of the terminal
  - Corrected with a feedback loop based on BPM reading in a high-dispersion area
- Drift of the magnetic field in the cooling section
  - Will be described in more details

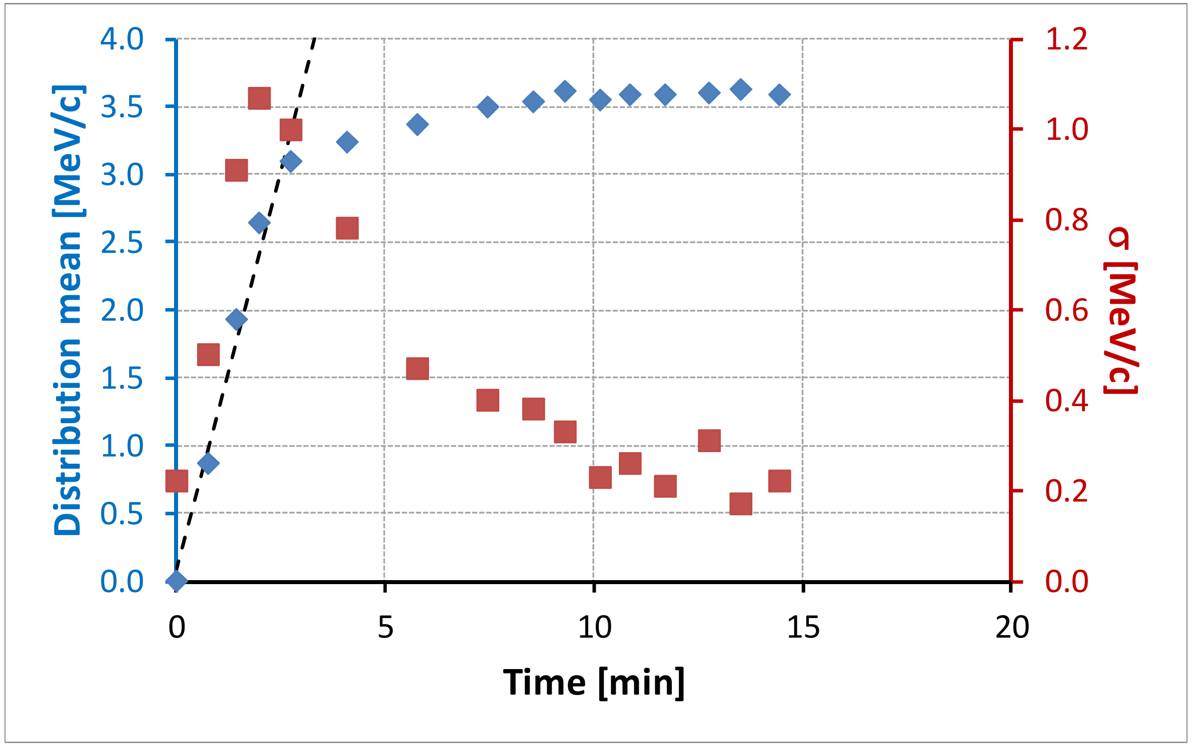
Studies: Drag rate measurements

- The electron beam quality is assessed with the drag rate measurements
  - The longitudinal cooling force is highly sensitive to electron angles, $F \prec 1/\theta_e^2$
  - Procedure
    - A coasting antiproton beam (N_p~1×10^{10}) is cooled to an equilibrium The electron energy is changed by 0.5–10kV.
    - While the antiprotons are dragged to the new equilibrium, their longitudinal distribution is recorded every ~15 sec.
    - The drag rate is calculated as the time derivative of the mean momentum recorded over 2 min after the jump.



Evolution of the antiproton momentum distribution recorded by a Schottky monitor after a 1.9 keV jump of the electron energy. I_e=0.5A with ion clearing at 100 Hz. The time between the first and the last traces is 7 min. January 2, 2011.

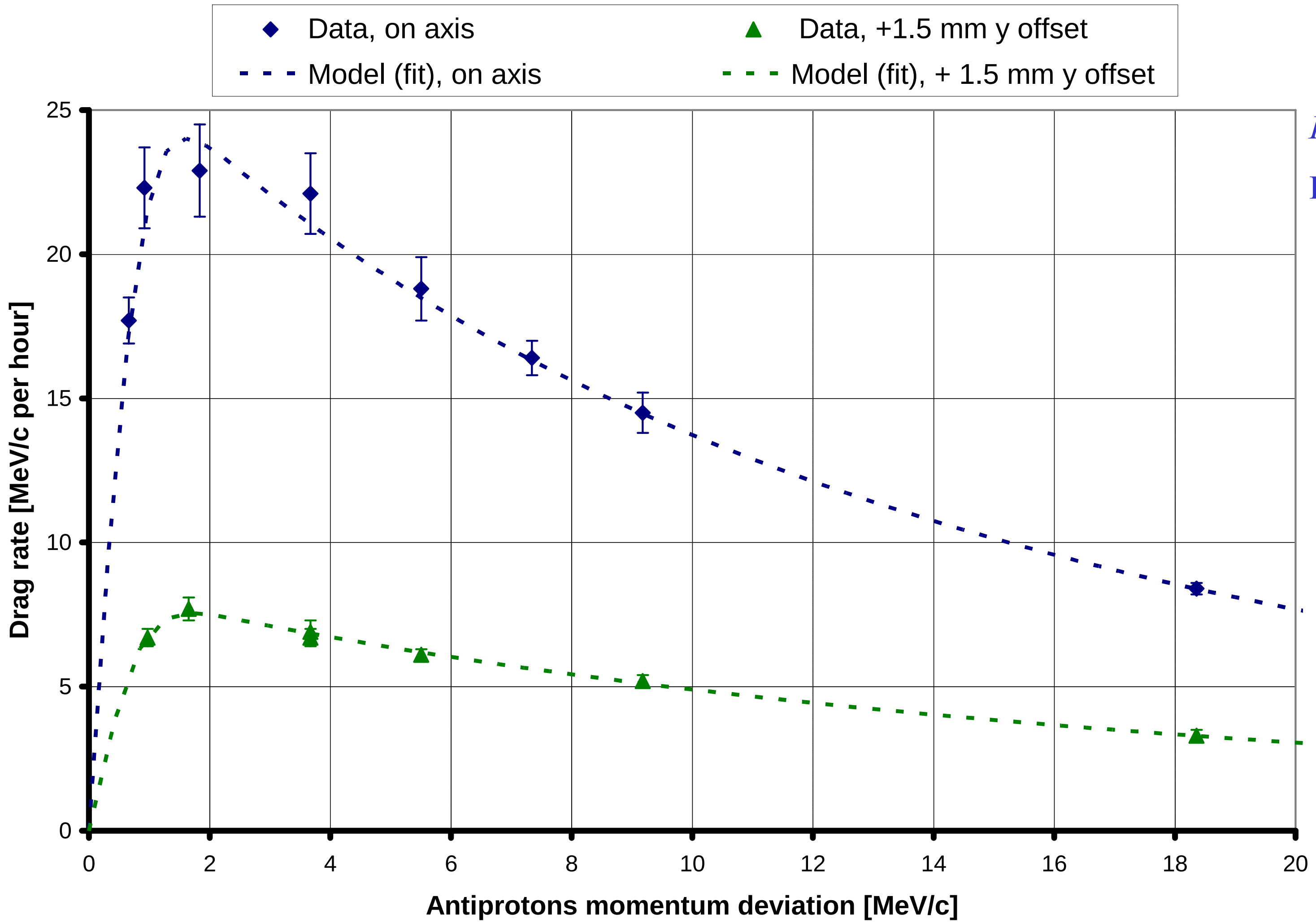
Studies: Drag rate measurements



Corresponding evolution of the mean and rms values of the momentum distribution. The drag rate is 71 (MeV/c)/hr. I_e= 0.5 A. (Not a standard measurement)

- Drag rate ≈ Cooling force
  - Note that equilibrium $\Delta p/p \approx 2 \cdot 10^{-5}$
- Works only for not-too-high cooling force
- The "pencil" antiproton beam can probe the electron beam at various offsets
  - In equilibrium, rms antiproton beam radius ~0.4 mm

Cooling force as a function of the antiproton momentum deviation



I_e= 0.1 A

Feb 2006

Fitted parameters (i.e. beam radius, beam transverse angle, energy spread) agree to within ~20% with direct measurements of the electron beam properties.

Non-magnetized cooling force

- The data were fitted to the classical formula neglecting magnetic field and assuming constant characteristics across the beam

$$\vec{F}_b\left(\vec{V}_p\right) = -\frac{4\pi e^4 n_{be}}{m_e}\eta\int L_C \frac{f_e(\vec{v}_e)}{(\vec{V}_p-\vec{v}_e)^2}\frac{\vec{V}_p-\vec{v}_e}{\left|\vec{V}_p-\vec{v}_e\right|}d^3v_e$$

n_e - electron density in the beam rest frame
m_e - electron mass
V_e - the velocity of the particle
η=(cooling section length)/(ring circumference)
L_c - Coulomb logarithm

  - If the dependence of the Coulomb logarithm on velocities is neglected and the electron beam distribution is Gaussian, the formula for the longitudinal cooling force in the lab frame for a particle without transverse velocity is much simpler

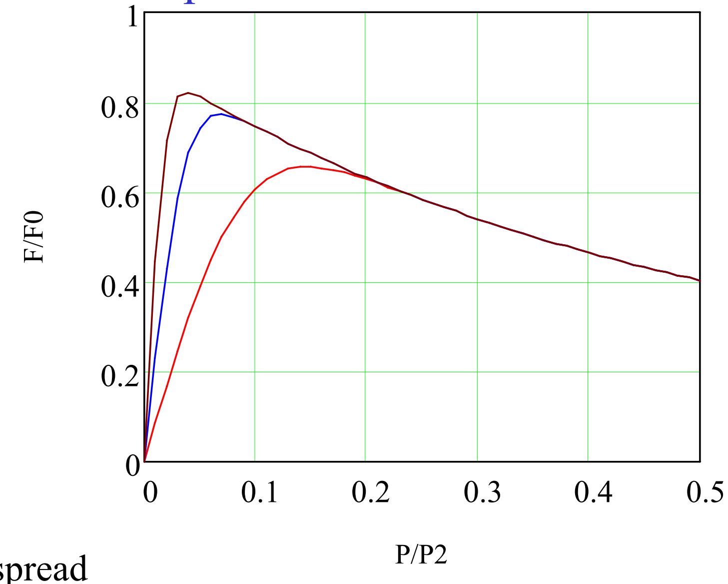
$$F_{lz}(\Delta p_p) = F_0 \int_0^{\frac{\Delta p_p}{p_1}} \frac{e^{-u^2}u^2}{u^2+\left(\frac{\Delta p_p}{p_2}\right)^2}du$$

$$p_1 = \delta W_e \cdot \sqrt{2}\frac{M_p}{\beta m_e c}$$

$$p_2 = \vartheta_t \cdot \sqrt{2}\gamma^2\beta c M_p$$

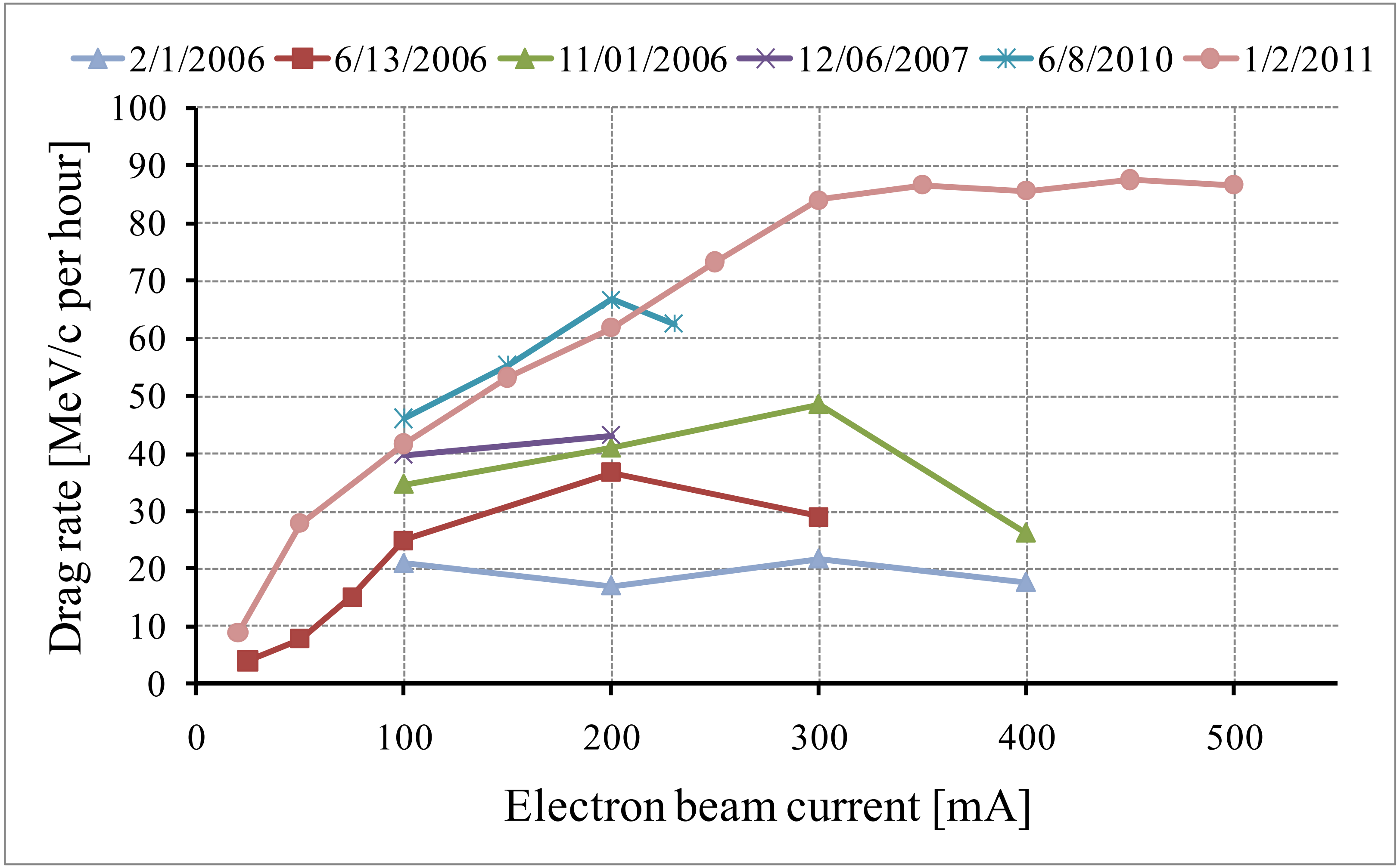
$$F_0 = -\frac{n_{el}}{\vartheta_t^2}\cdot\frac{2}{\sqrt{\pi}}\cdot\frac{4\pi\cdot e^4\eta\cdot L_c}{m_e c^2\gamma^3\beta^2}$$

θ_t - electron angle, δW_e – energy spread



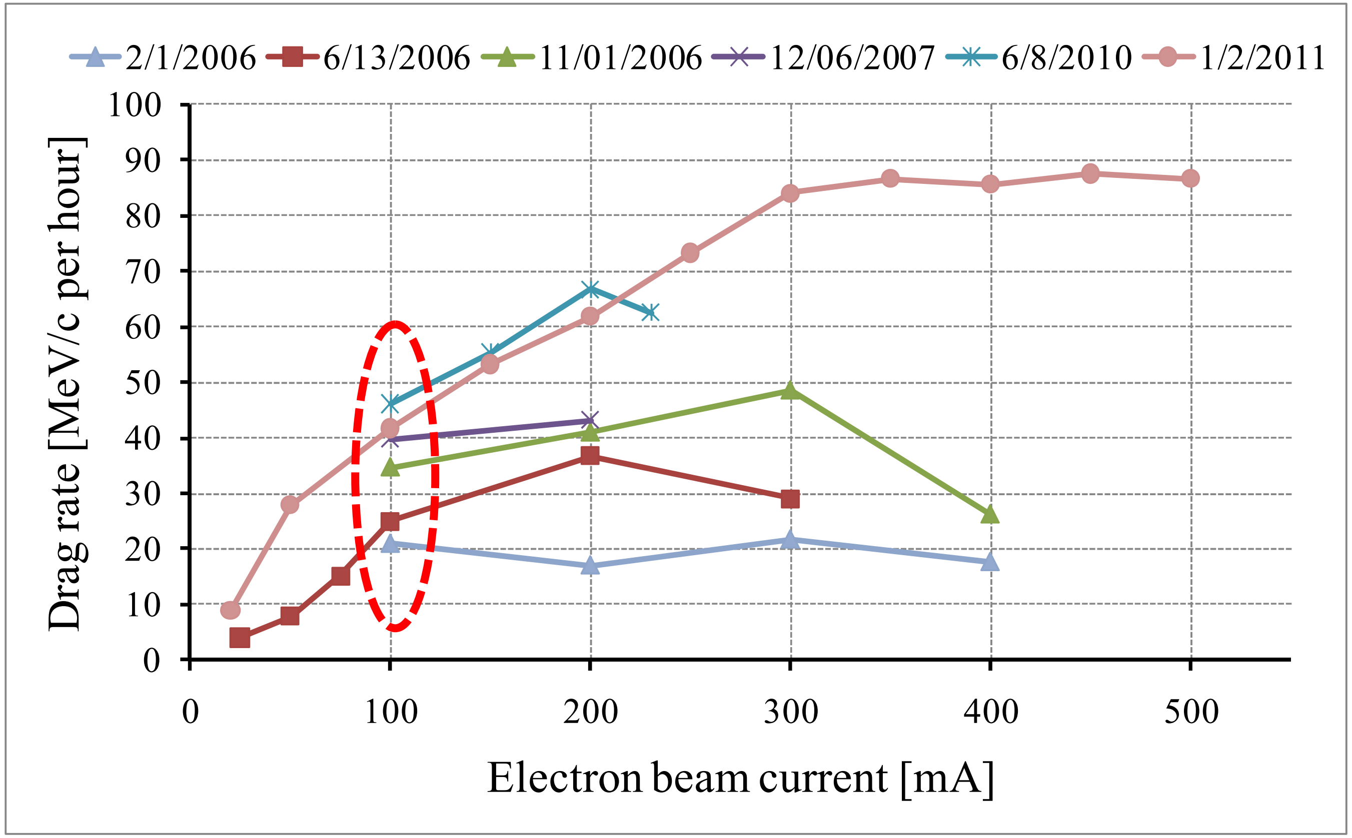
F_{lz}/F_0 as a function of $\Delta p_p/p_2$ for three ratios of p_2/p_1: 10, 25, and 50.

Cooling force as a function of the beam current



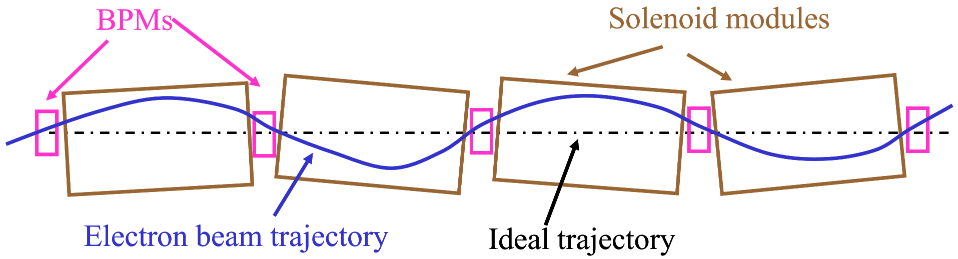
In all measurements, the voltage jump was 2 kV and the electron beam was "on axis". All points in each curve are taken at constant focusing settings.

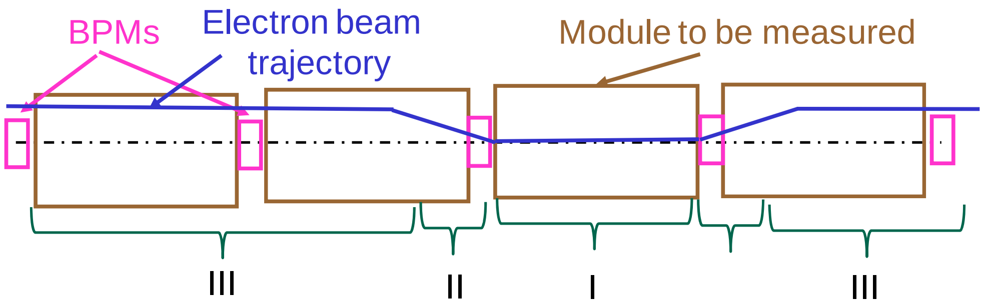
Improvements at low beam currents



- At low beam currents, main improvements came from
  - Alignments of the field in the cooling section
  - Adjustment of quadrupole focusing
- All adjustments were made at I_e= 0.1A

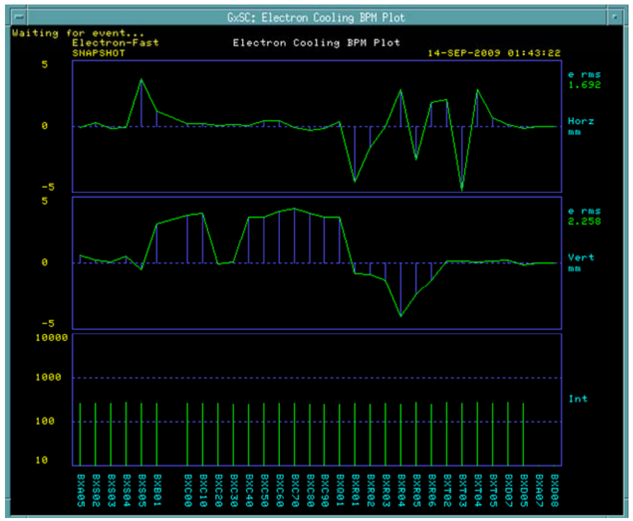
Cooling section field alignment





The cooling section consists of 10 identical modules, which are rigid but can move with respect to one another, hence creating field errors.

I. area being measured
II. transition area (large angle)
III. large offset (4 mm with the electron beam radius ~2.3 mm)

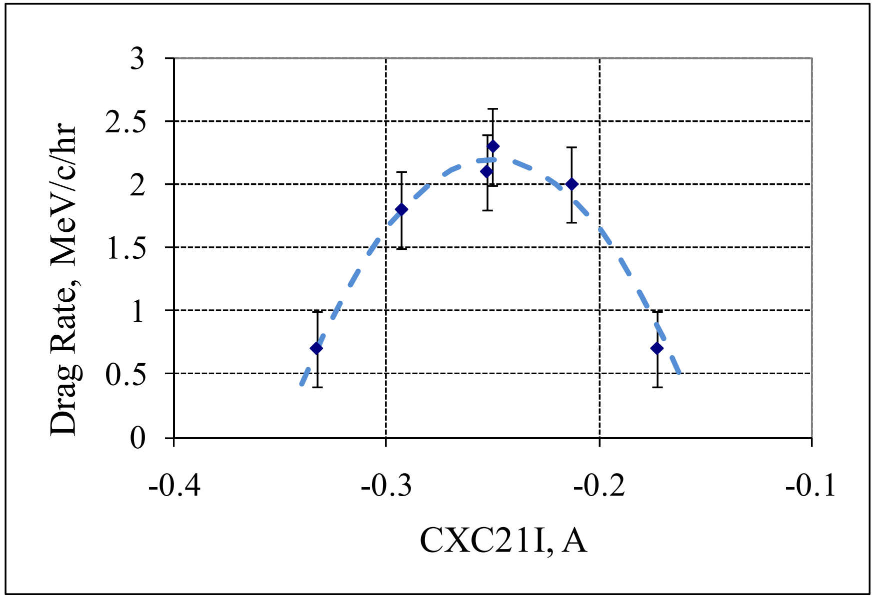


Trajectory during adjustment of the 3rd module.

- Procedure: optimize 10 pairs of correctors in each module measuring the cooling force produced by the module.
  - Tilt or shift of the solenoid results in dipole fields similar to fields generated with either 8 pairs of central correctors or 2 pairs of end correctors
  - The assumption is that cooling in the transition area doesn't contribute significantly

Cooling section field alignment (cont.)

- The data are noisy and not always easy to interpret
  - Uncertainty is always high but the procedure still works
- Alignment of the entire cooling section takes 2-3 eight-hour shifts
- Needs to be repeated roughly twice a year for optimum performance
  - Alignment is affected by the tunnel drifts and by changes of the temperature
  - Needs to be done after long shutdowns

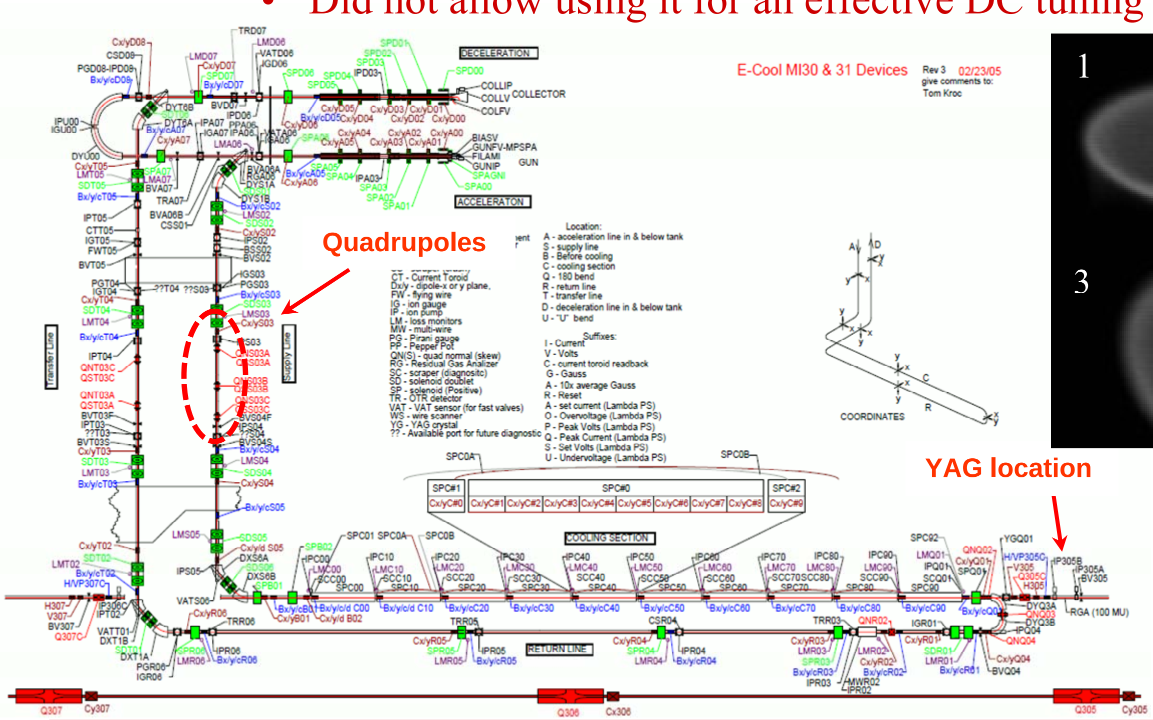


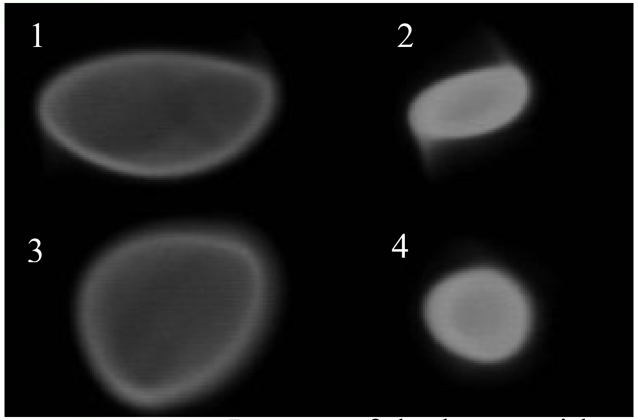
Drag rate as a function of a change in currents of all 8 central X correctors by the same amount in module #3.

Example of a "good" measurement. The dipole field of the central correctors is ~0.8 G/A. A typical change of the currents resulting from alignment is ~0.02A. The same field is produced by a shift of one end of a module by ~0.3 mm. I_e = 0.1A, 2kV jumps.

Adjustments of focusing

- There were several indications of large focusing errors
  - In part, drag rates measured across the beam were dropping with the offset much faster than the calculated electron beam density
- Beam imaging at a YAG scintillator showed a large ellipticity
  - Could correct it with quadrupoles
  - Corrections made in pulse mode, where focusing is different from DC
    - Did not allow using it for an effective DC tuning

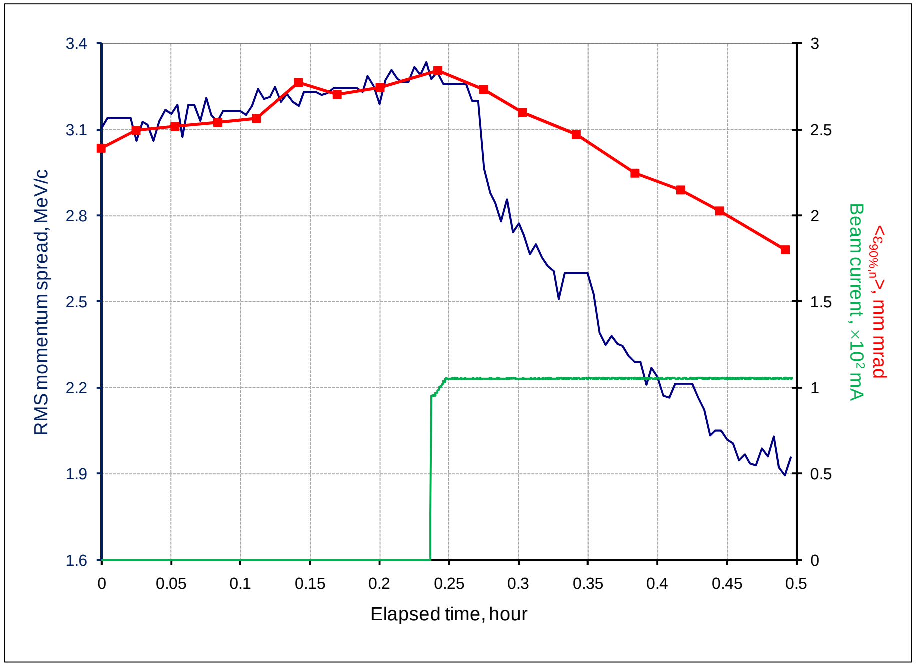




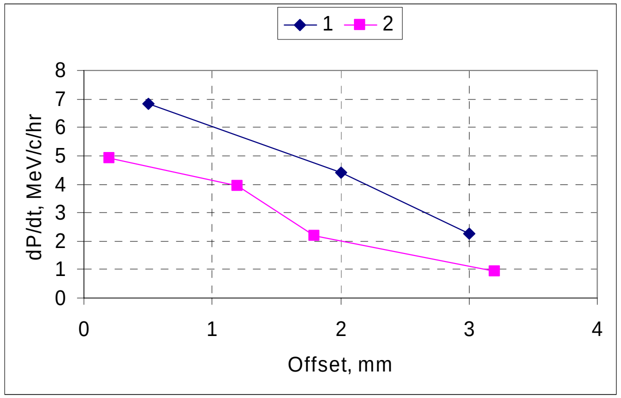
Images of the beam with zero (1 and 2) and optimized (3 and 4) quadrupole currents. $I_e \sim 0.1$A, 2μs pulse.

Adjustments of focusing (cont.)

- Tuned quadrupoles based on the drag rate measurements (off-axis)
  - Maximizing the drag rate for each of 6 quadrupoles
- Cooling rates increased by ~1.5 times longitudinally and by ~2 times transversely (at I_e= 0.1A)

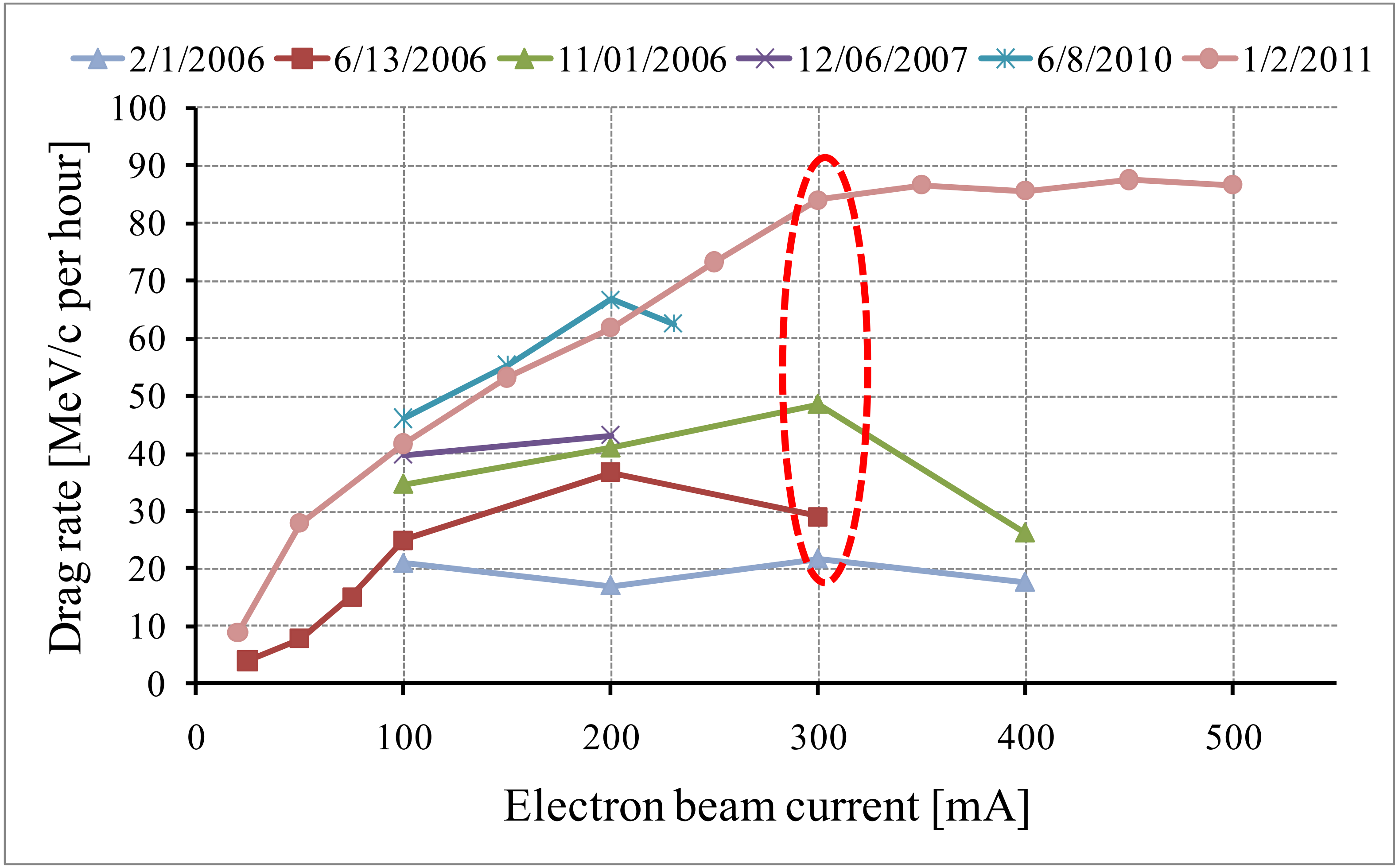


Typical cooling rate measurement (October 26, 2007) .
I_e~ 0.1A, beam on axis, focusing settings include quadrupoles.
Transverse emittances measured with flying wires.



Longitudinal cooling rates at various vertical offsets of the electron beam before (set 2) and after (set 1) adjustments of quadrupoles. I_e~ 0.1A.

Improvements at higher beam currents

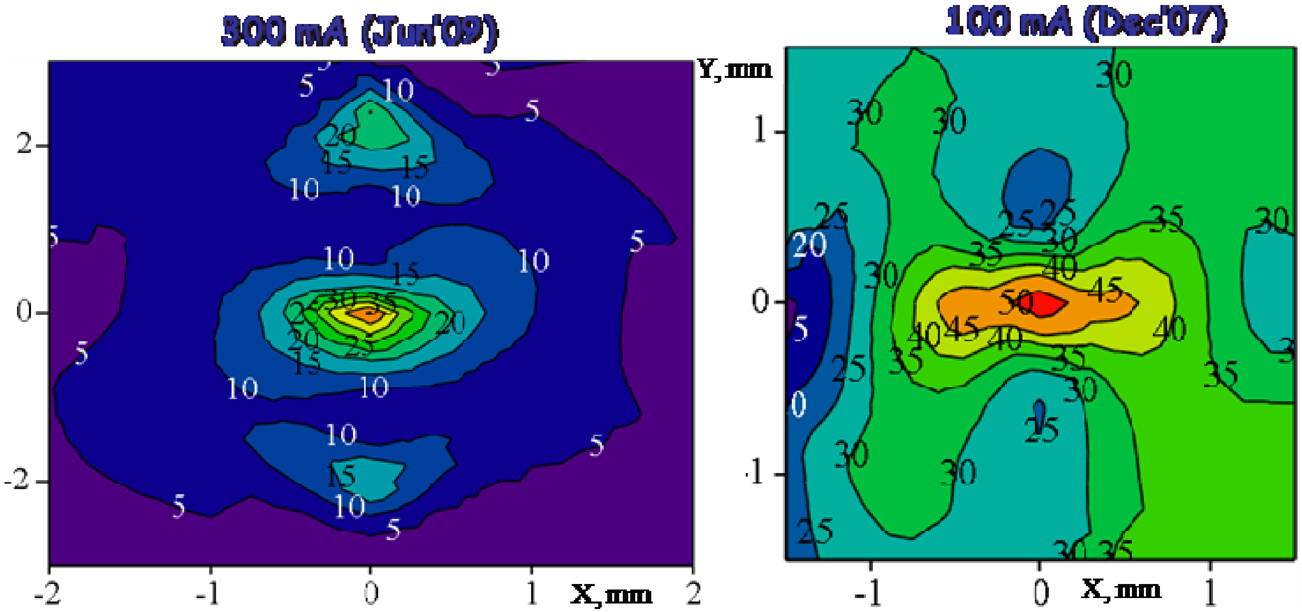


- At higher beam currents, the main improvement came from ion clearing
- Tuning was made mainly at $I_e = 0.3A$

Ions - estimations

- At I_e= 0.1A, the potential difference between the beam center and the vacuum pipe is ~ 15 V. It is a deep well for thermal-energy ions (W_i ~ 0.03 eV) created by the primary electrons.
- Focusing effect from the ions is $\sim\eta_c I_e \gamma^2$, and with $\gamma^2 \approx 100$ can be much higher than the defocusing effect from the beam space charge.
  - Simulations predict that the space charge is important at I_e= 0.1A.
    - Change of the current increases angles in the cooling section by $\kappa \sim 1$ rad/A/m
  - Therefore, neutralization η_c needs to be kept <1% at all relevant currents
  - Calculated time to reach η_c ~1% is ~0.2s.
    - H_2 at 0.3 nTorr
- Each BPM is used for ion clearing
  - One of the plates is biased at -300V while the other is grounded
  - Should be enough to effectively remove ions
    - Thermal ions fly ~5m distance between BPMs in the supply line in ~ 3ms
- However, there are barriers for ions created by
  - Size variations of both the electron beam and the vacuum pipe
  - Solenoidal lenses

Ions - effect



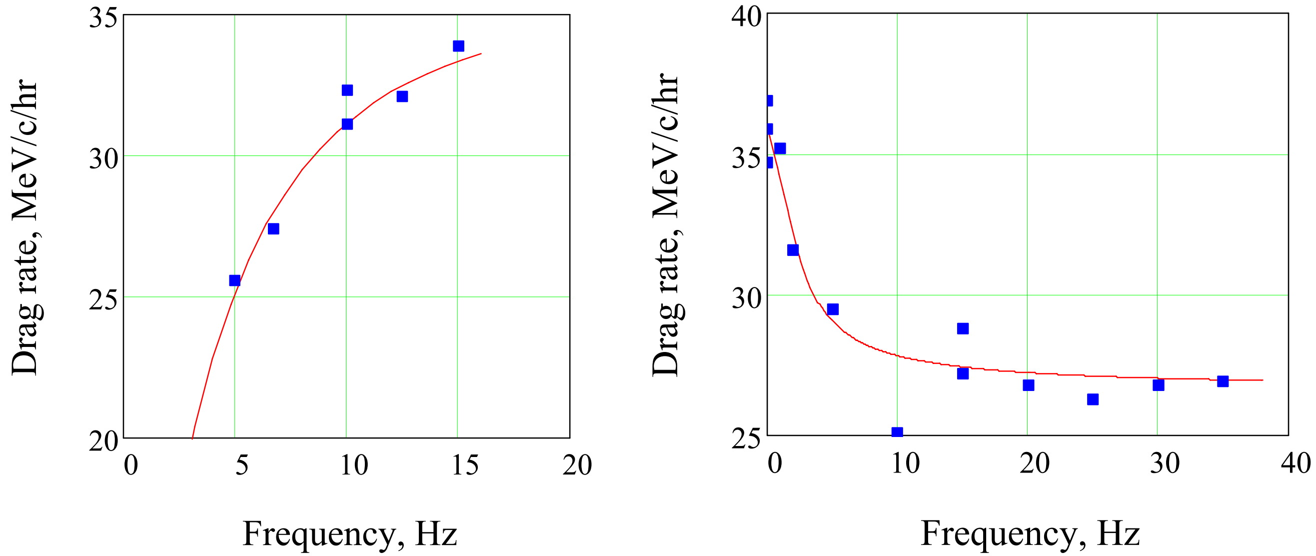
Contour plots of drag rates.

Left- I_e=0.3A, right – 0.1A. Contour levels are in MeV/c/hr.

- While at I_e= 0.1A the drag rates drops with offset smoothly, at I_e= 0.3A there are three narrow areas of good cooling
- Hypothesis: the reason is a highly non-linear focusing effect of ions
- Proposed remedy: clear ions by interrupting the electron current for a microsecond
  - In the beam electric field, the ions gain a high transverse velocity (W_i~10 eV) to reach the wall in ~1 μs after turning the beam off.

Ions - removal

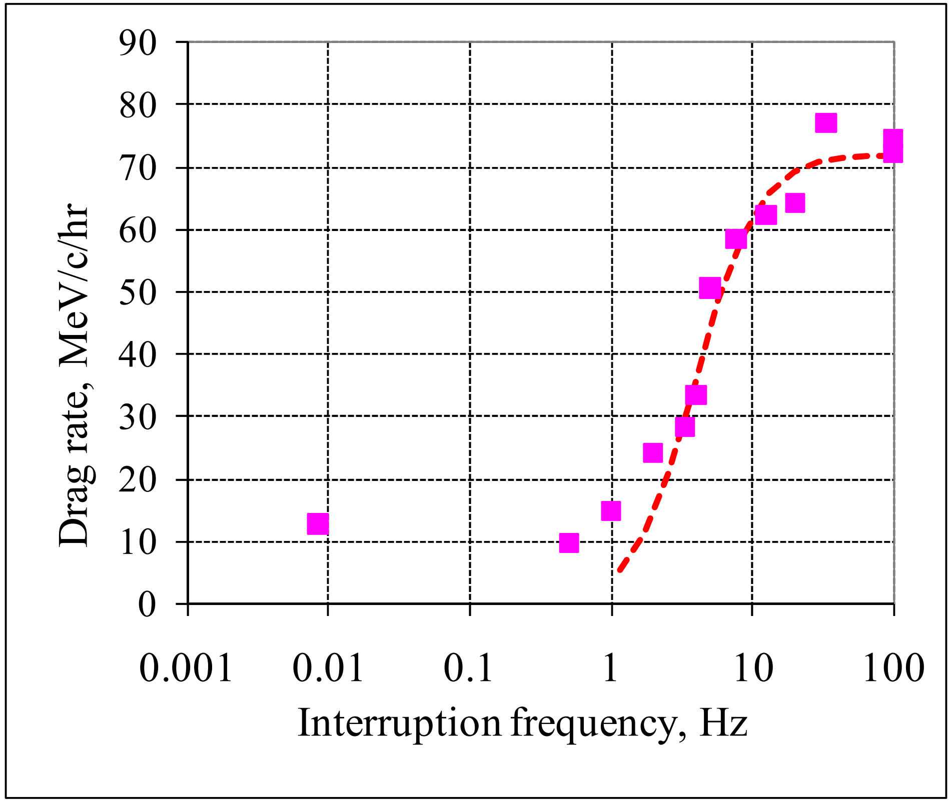
- The capability to interrupt the beam for 2 – 20 μs at frequencies up to 100 Hz was implemented
  - Negligible effect on the duty factor
- Strong dependence of drag rates on the interruption frequency
  - Naturally, the rate is maximum where it had been optimized
  - Duration of the interruptions doesn't have any measurable effect



Drag rate as a function of the interruption frequency for I_e = 0.3 A (left) and 0.1 A (right).
The interruption length was 2 μs; beams were on axis. The squares represent the data, and the solid lines are fits. Focusing was optimized at 15 Hz for 0.3 A and with no interruptions for 0.1A (January 26, 2010).

Ions – removal (cont.)

- The data are in a reasonable agreement with the ion hypothesis



Drag rate as a function of the interruption frequency for I_e = 0.3A and separation between beams of 1 mm. The interruption time was 2 µs; Focusing was optimized on axis at 20 Hz (January 2, 2011). The squares represent the data, and the line is a fit to $F(f) = F_0 / [1 + (f_0 / f)^2]$ with f_0= 4 Hz.

Model parameters:

RMS angle at best focusing α_0= 0.1 mrad.

Compensation time τ_{comp} = 17 s is calculated for 0.3 nTorr H_2.

$$F = \frac{F_0}{1 + (\Delta\alpha / \alpha_0)^2}; \quad \Delta\alpha = \kappa I_e \gamma^2 \eta_c \delta;$$

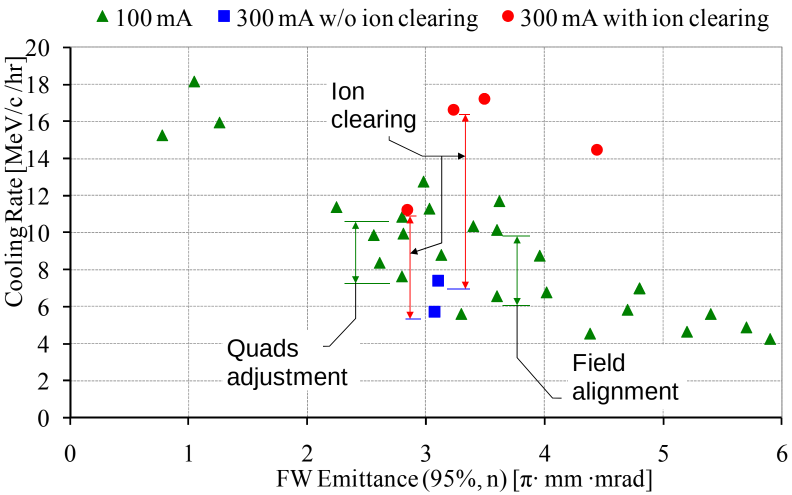
$$\langle \eta_c \rangle = \frac{1}{2 f \tau_{comp}}$$

$$F(f) = \frac{F_0}{1 + (f_0 / f)^2}; \quad f_0 = \frac{\kappa I_e \gamma^2 \delta}{2\alpha_0 \tau_{comp}}$$

To fit the data, one mayassume that ions are accumulated only in a portion of the beam line so that their contribution is decreased by δ~0.4, the only free parameter in this model.

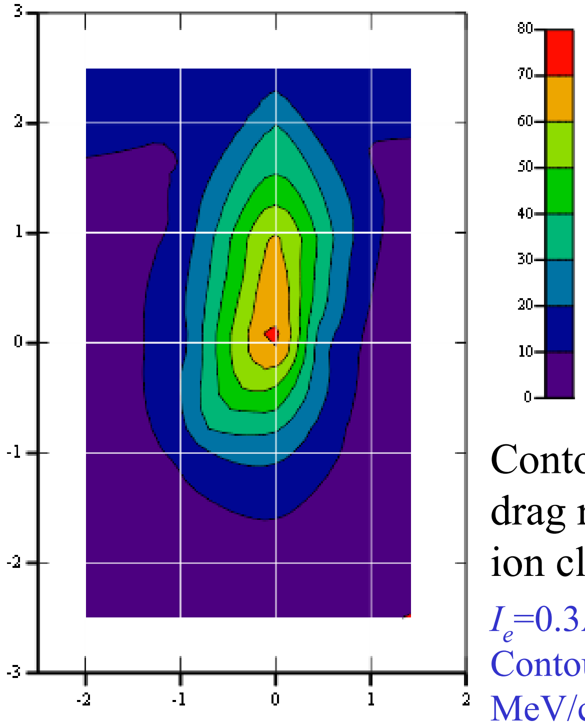
After that, the steady state neutralization factor comes at ~2%.

Cooling with ion clearing



Longitudinal cooling rate measured in 2006-2010.

The arrows connect points measured on the same day to show the range of several improvements. All measurements are "on axis".

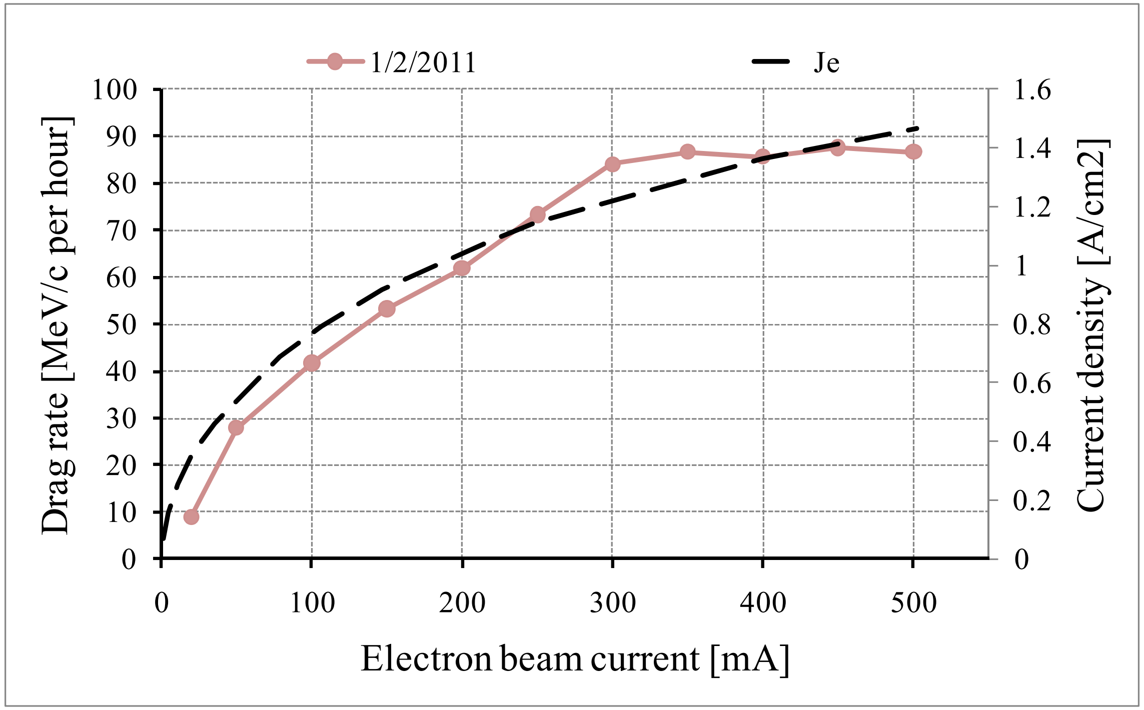


Contour plot of drag rates with ion clearing.

I_e=0.3A, 100 Hz. Contour levels are in MeV/c/hr.

- While cooling improved significantly, we couldn't use it to its full strength in operation because of an antiproton instability.
  - Also, the beam trips are more frequent at higher electron currents
  - In 2011, used I_e= 0.2 A and ion clearing in the time of beam preparation for Tevatron shots

Cooling force at higher currents



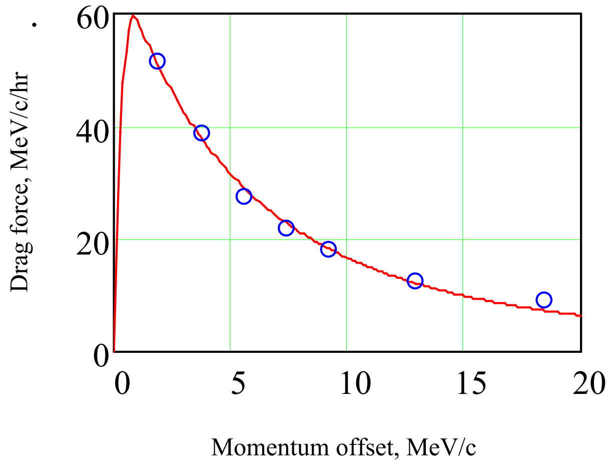
The black curve is the simulated current density at the beam center in the cooling section.

- One may expect that with ion clearing the cooling force will increase proportionally to the current density. The measured drag rate stalls after I_e= 0.3 A.
  - One of explanations is that the measurement procedure is too slow. The distribution comes close to the new equilibrium during the 2 min interval.
  - Focusing might need to be adjusted at higher currents.

Summary of cooling improvements

- Tuning of focusing with quadrupoles
- Alignment of the magnetic field in the cooling section
- Ion clearing

- All improvements of cooling properties were made through decreasing the transverse electron velocities (angles) in the cooling section
  - The main study tool was the drag rate measurements
  - The total rms angle is decreased probably by 1.5 – 2 times
    - Very difficult to come up with a defendable procedure of summation



Drag rate as a function of momentum offset. I_e=0.1A, focusing is optimized for ion clearing, 100 Hz. The circle is data, and the solid line is a calculation with θ_e= 80µrad, δW_e= 200eV, L_c= 9. January 4, 2011.

The angles in the cooling section

Effect	Angle, μrad	Method of evaluation
Thermal velocities	57	Calculated from the cathode temperature
Envelope mismatch	~50	Resolution of tuning and simulations
Dipole motion (above 0.1 Hz)	~35	Spectra of BPMs in the cooling section
Cool. Sec. field imperfections	~50	Magnetic field measurements and tracking
Non-linearity in lenses	~20	Trajectory response measurements
Ion background	< 10	Cooling measurements
Total	**~100**	Summed in quadratures

- Estimations of angles in the cooling section for the best case.
  - I_e=0.1 A. 1D values are shown.
- Agrees with cooling force measurements

The End

- The Recycler Electron cooler is an interesting machine, which significantly contributed to the success of Run-II.
  - It was fun to work!
- Its operation comes to the end on September 30, 2011 together with the Tevatron.
  - So far, no plans for further use
  - Proposals are very welcome