The Recycler Electron Cooler at Fermilab

Learning Experience of a High Voltage Electron Cooler Construction and Operation

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Outline

- Choice of the scheme
- Challenges
  - Beam recirculation
  - Beam quality
- Operation

COOLER DESIGN SCHEME

Choice of the scheme (I)

- Based on SSC MEB proposal for relativistic cooling
  - No longitudinal magnetic field at the gun
  - Lumped focusing in the cooling section

- Pros
  - Use of industrially-manufactured electrostatic accelerator
  - Cooling section simpler than for strong continuous focusing
    - Significantly cheaper too
- Cons
  - Low transverse velocities in cooling section ⇒ large value of the β-function ⇒ susceptible to perturbations
    - Drift instability from wall image charges
    - Ion instability
  - Ineffective cooling inside the lenses
    - Large azimuthal velocity

Choice of the scheme (II)

- Combine advantages from longitudinal magnetic field in the cooling section and lumped focusing in the transport lines

- 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

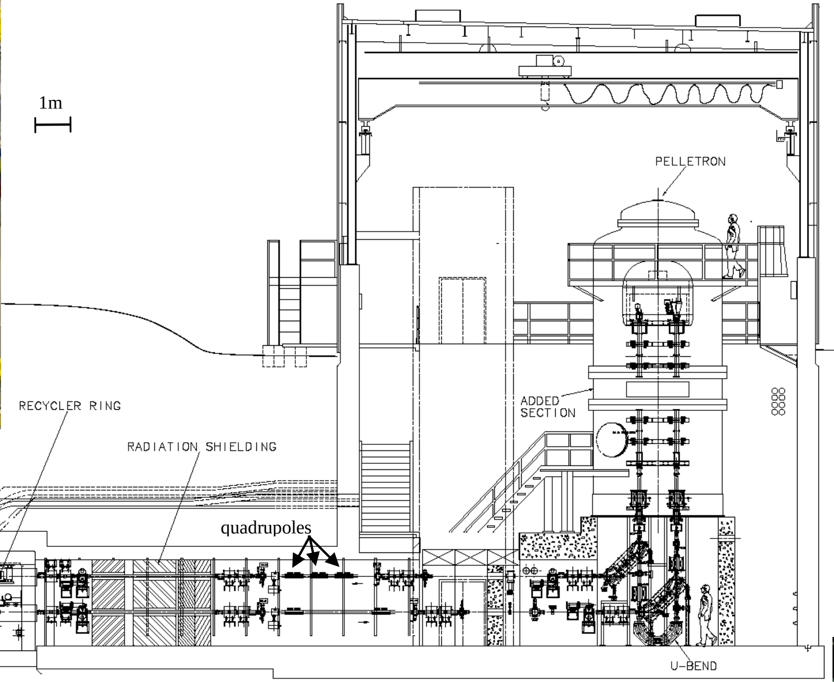
Applicability

- 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
- Outside of the magnetic field, the (*non-normalized*) effective emittance is tolerable, ~4μm

Cooler in the Recycler Ring

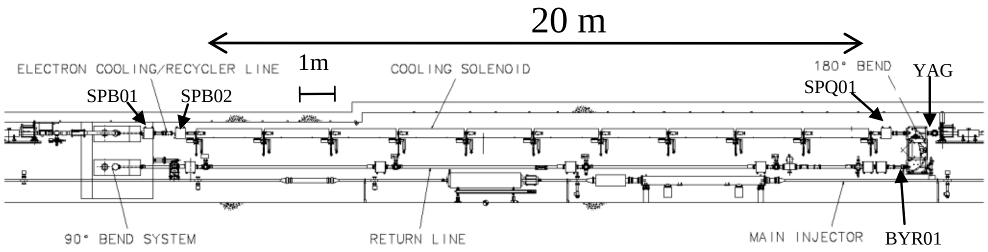


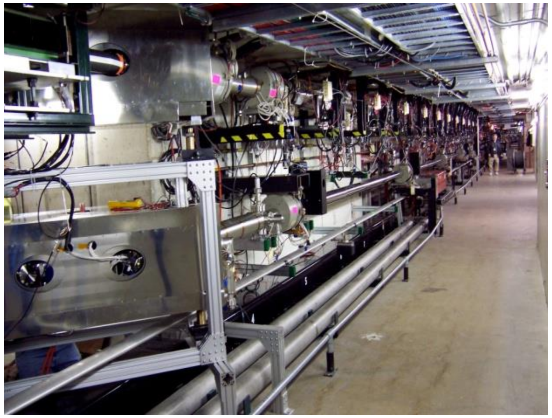
MAIN INJECTOR TUNNEL

February, 2005

beginning of commissioning

The Pelletron and beam “supply” and “transfer” lines





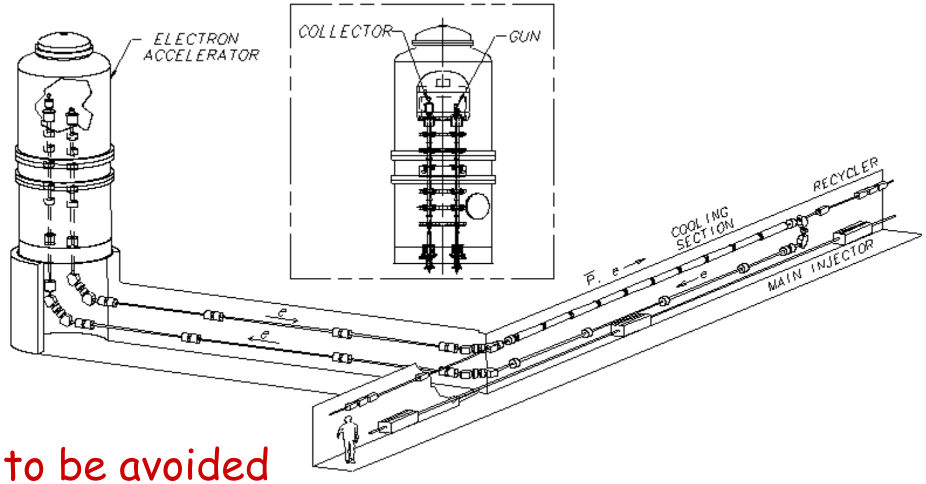
Portion of the Main Injector tunnel containing the cooling section and the “return” line.

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



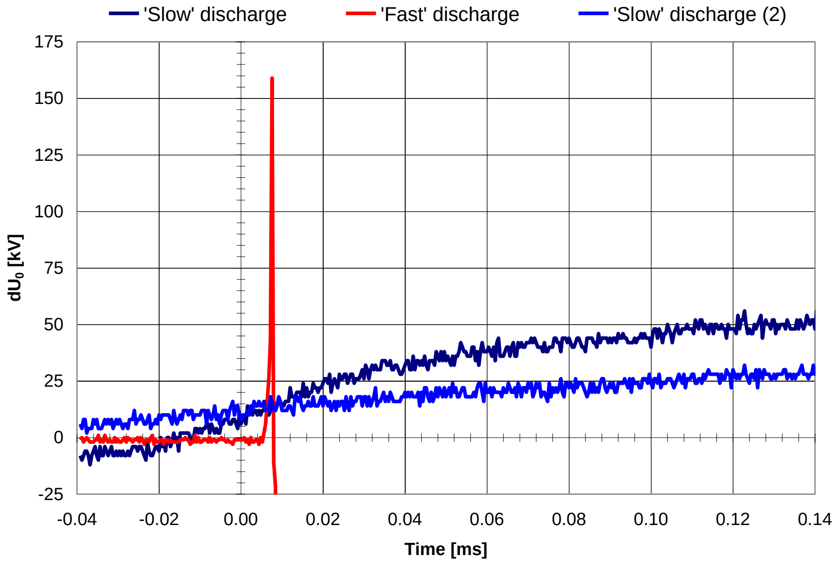
- High electron beam power:
  - ➢ 4 MeV × 0.5 A = 2 MW DC
    - Energy recovery scheme is a must
    - Very low beam losses are required
    - High voltage discharges need to be avoided

- 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

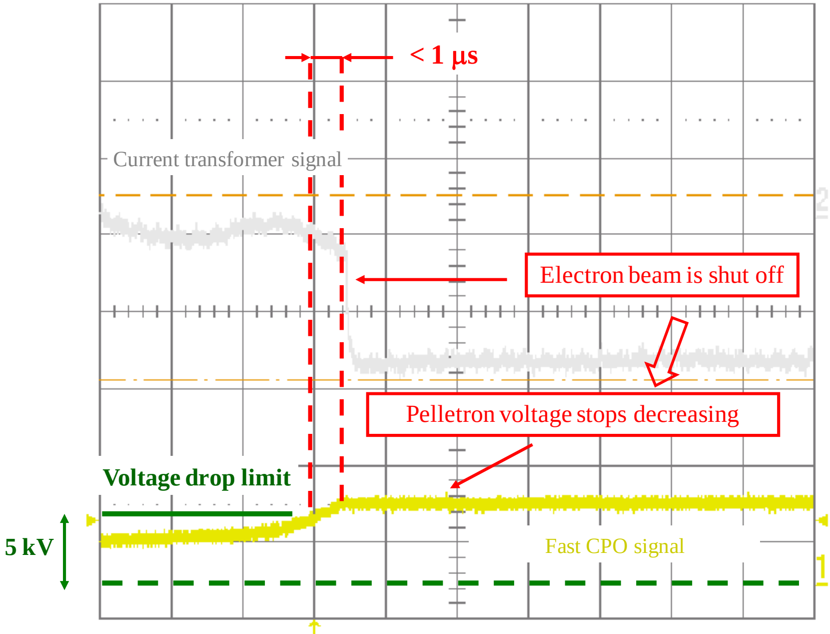
HV & BEAM STABILITY

Beam recirculation

- Initially, insufficient stability ⇒ main obstacle during R&D and commissioning
- Remedies:
  - Increase total length of acceleration tubes
    - 5 MV nominal → 6 MV nominal
  - Fast protection circuitry



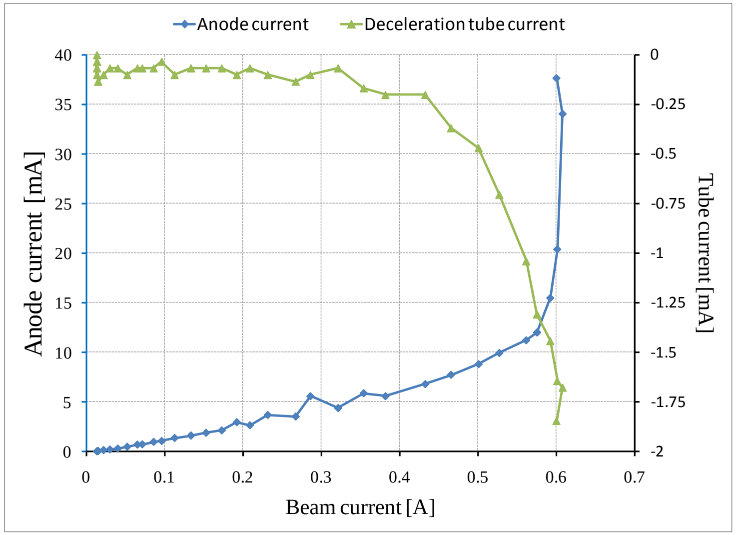
Oscillograms of 'fast' (red) and 'slow' (blue) discharges recorded by the fast capacitive pickup (Fast CPO) that measures the terminal voltage 'drop' (the terminal voltage actually becomes more positive)



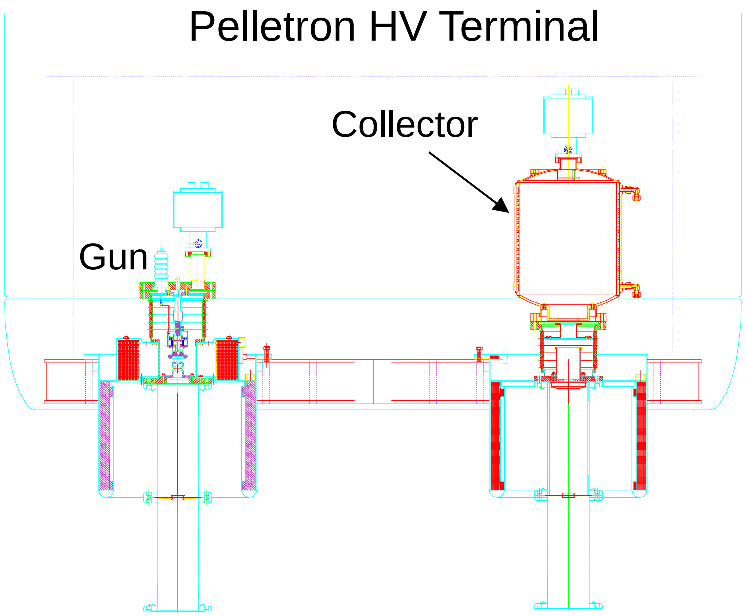
Oscillograms of a recirculation interruption, showing the effectiveness of the fast gun shut off

Beam recirculation 'remedies': Gun and collector

- Developed gun and collector allowed a high beam current with low loss. The best results:
  - At a low-energy test bench: 2.6 A, relative beam loss $2{\cdot}10^{-6}$
  - 4.3 MeV beam, short beam line: 1.8 A, relative beam loss $1.2{\cdot}10^{-5}$
  - 4.3 MeV beam, full beam line: 0.6 A, relative beam loss $1.6{\cdot}10^{-5}$
    - The likely reasons for the higher beam loss with the longer beam lines are interaction with the residual gas and the energy spread increase due to IBS

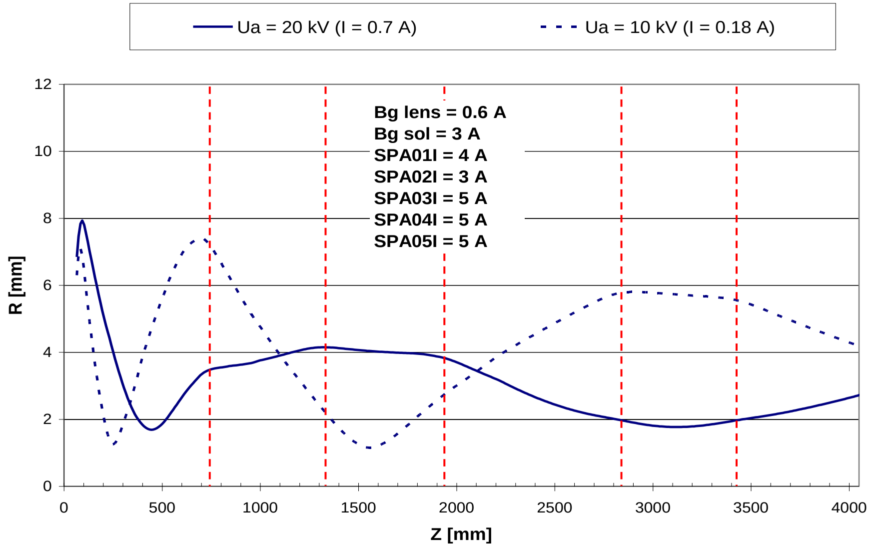


Anode current and changes in the deceleration tube current as functions of the beam current. Full line; ion clearing mode (December 31, 2011.).



Beam recirculation 'remedies': Beam optics

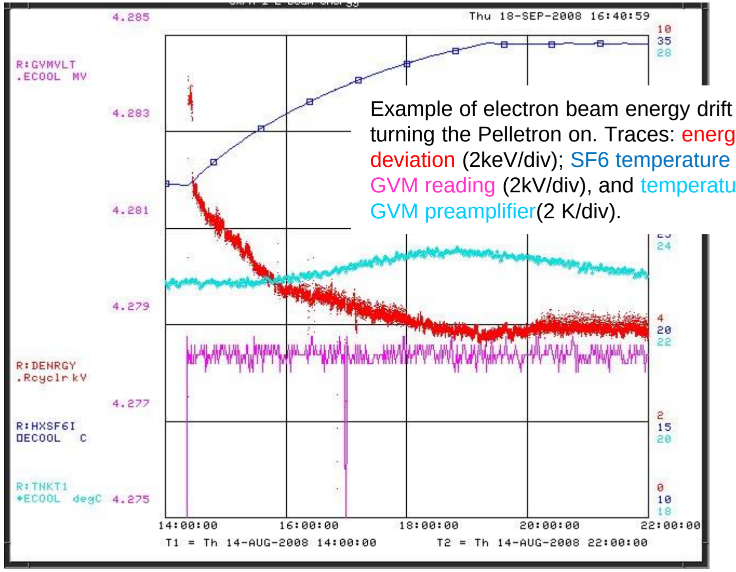
- Adjust beam envelope in *deceleration tube* to transport out electrons coming out of the collector
- Adjust beam envelope in *acceleration tube* so that beam core remains far from the tube electrodes when the beam trips
    - Big difference in the occurrence of full discharges originating in the acceleration tube.



Simulations of the beam envelope (edge) in the accelerating column for nominal settings (solid curve) and settings representing a partial discharge (dotted curve). The limiting aperture is 12 mm. Vertical dotted lines represent the locations of the magnetic lenses.

- Protection of deceleration tube from irradation when the beam trips by using optics with high dispersion in the return line

Energy drift



Example of electron beam energy drift after turning the Pelletron on. Traces: energy deviation (2keV/div); SF6 temperature (5 K/div); GVM reading (2kV/div), and temperature of the GVM preamplifier(2 K/div).

- Temperature – related
  - Pelletron temperature
  - GVM preamplifier temperature
- Caused by changing balance of currents
  - Chain current variation
    - Was a problem in the time of charging efficiency degradation
  - Variation of the beam loss or corona current
- Changes in GVM reading associated with SF_6 permittivity
  - At ~6 atmospheres (abs) $\varepsilon_{SF_6} = 1.012$
  - The charge generated on GVM at a given voltage increases correspondingly
  - 1% SF_6 pressure increase results at the same terminal voltage in the GVM reading increase by about 0.01%
    - Results in 0.5 keV/psi energy drop
    - Was noticed in the time of an SF_6 leak

BEAM QUALITY (i.e. angles)

Non-magnetized cooling force

- 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

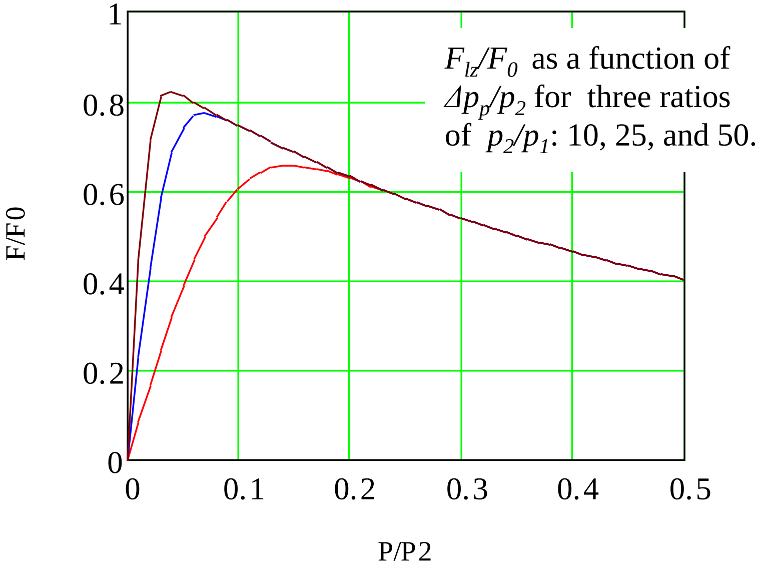
$$F_{lz}(\Delta p_p) = F_0\int_0^{\frac{\Delta p_p}{p_1}} \frac{e^{-u^2}u^2}{u^2 + \left(\frac{\Delta p_p}{p_2}\right)^2}du$$

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

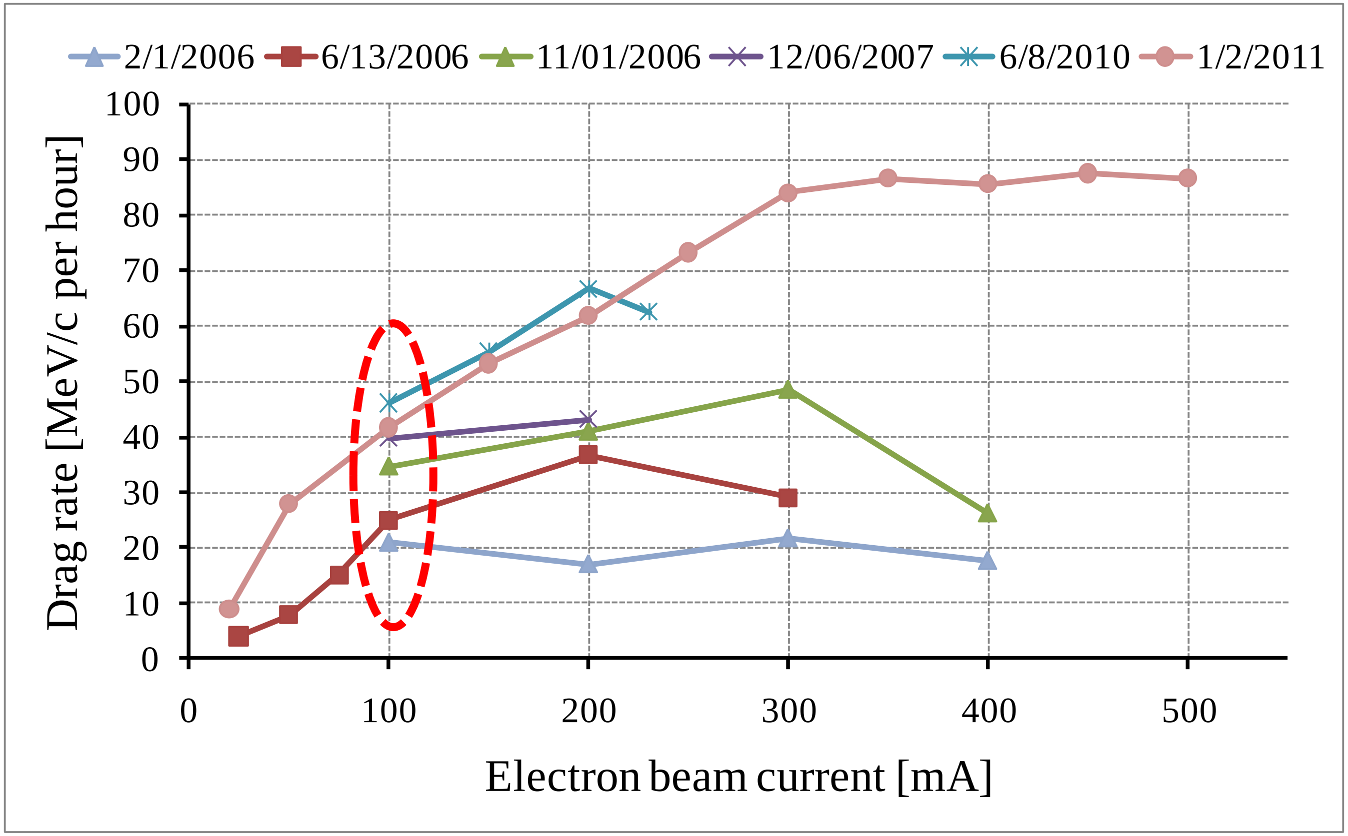
$$p_2 = \vartheta_t \cdot \sqrt{2}\gamma^2 \beta c M_p$$

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

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.

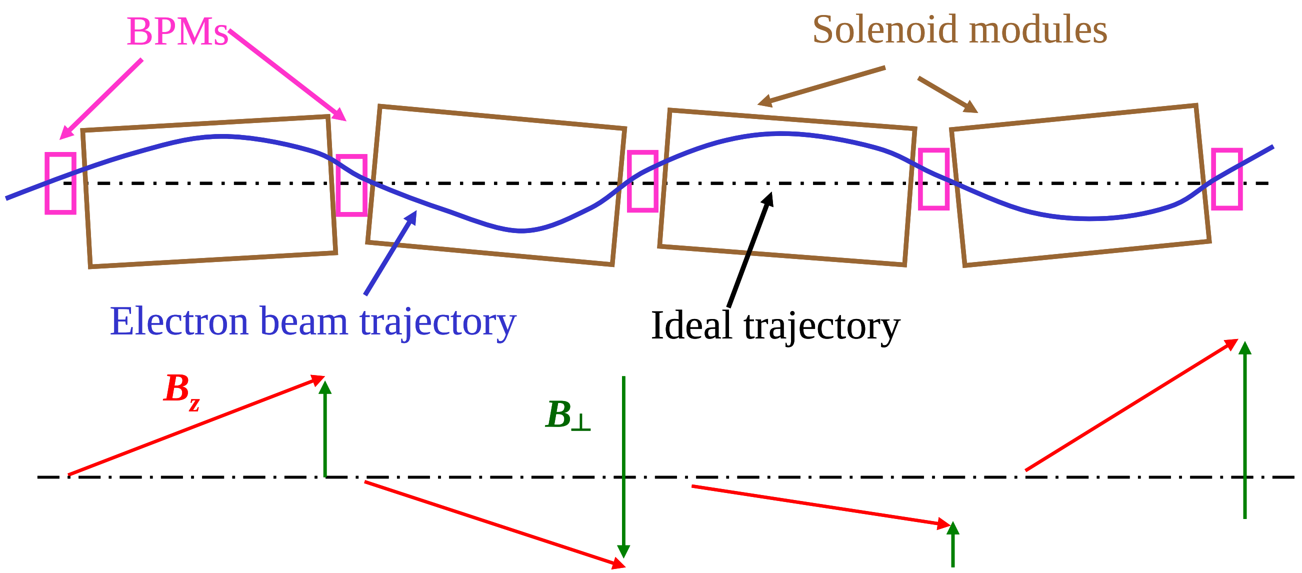
Improvements at low beam currents



- 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 (mis)alignment

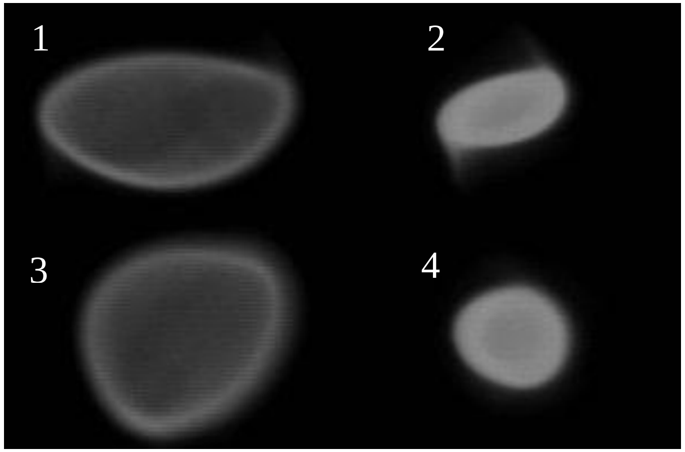
- The cooling section consists of 10 identical modules, which are rigid but can move with respect to one another, hence creating field errors
  - Periodic re-alignment
  - Special procedure based on measuring beam cooling properties



Mechanical tilt of a solenoidal module results in an additional transverse field in the cooling section, which excites dipole beam oscillations.

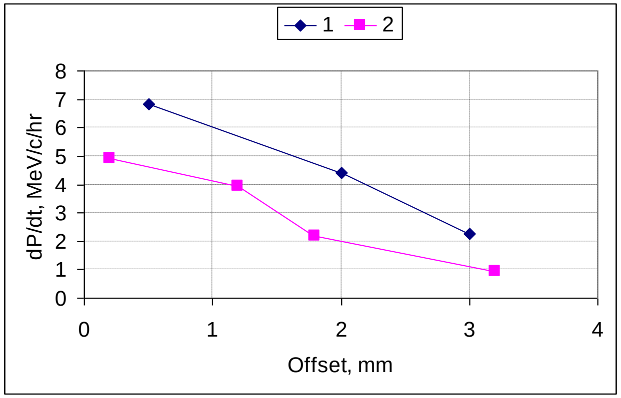
Adjustments of focusing

- Beam imaging at a YAG scintillator showed a large ellipticity
  - Could correct it with quadrupoles
    - But pulse beam ≠ DC beam



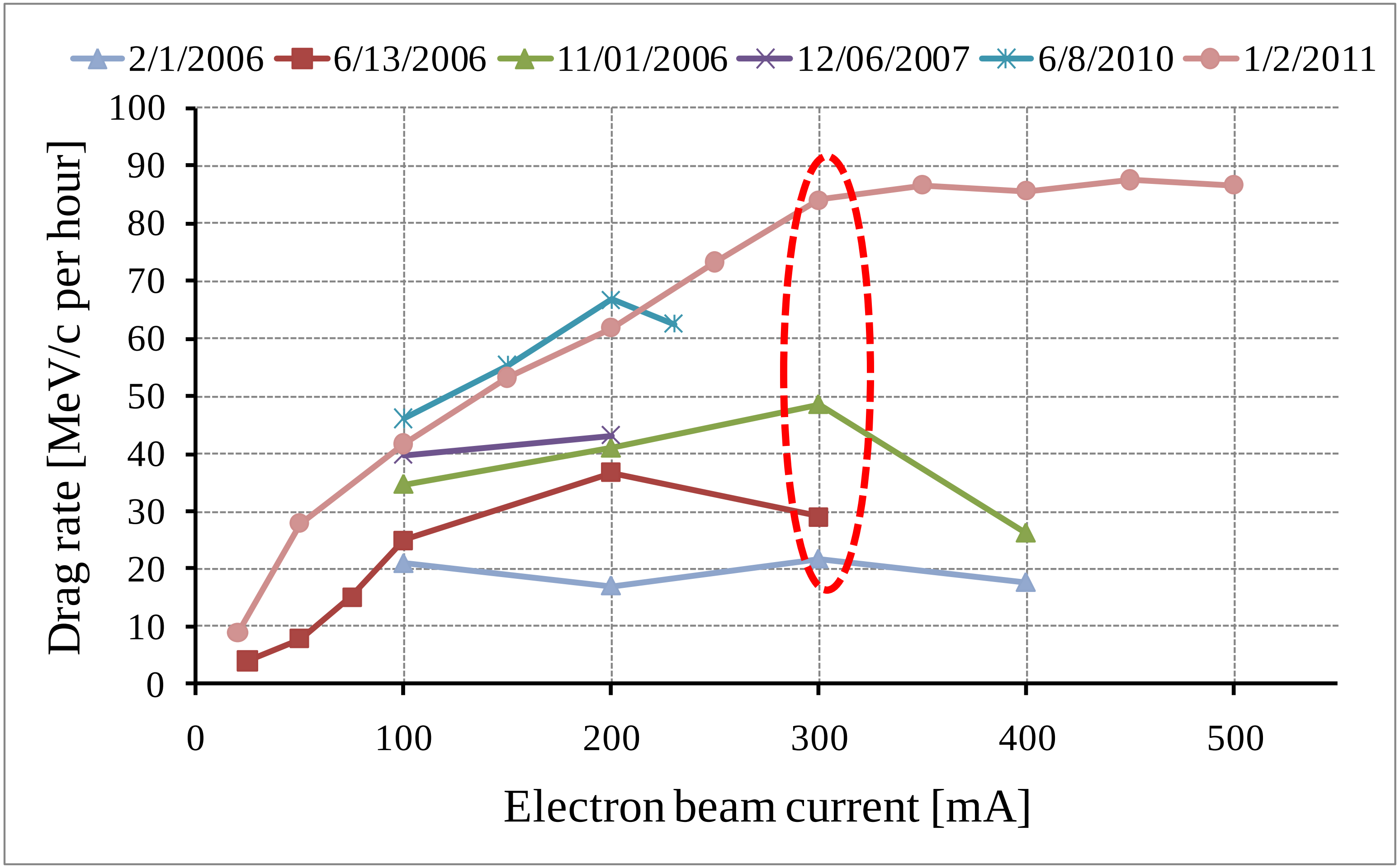
Images of the beam with zero (1 and 2) and optimized (3 and 4) quadrupole currents. I_e ~ 0.1A, 2μs pulse.

- 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)



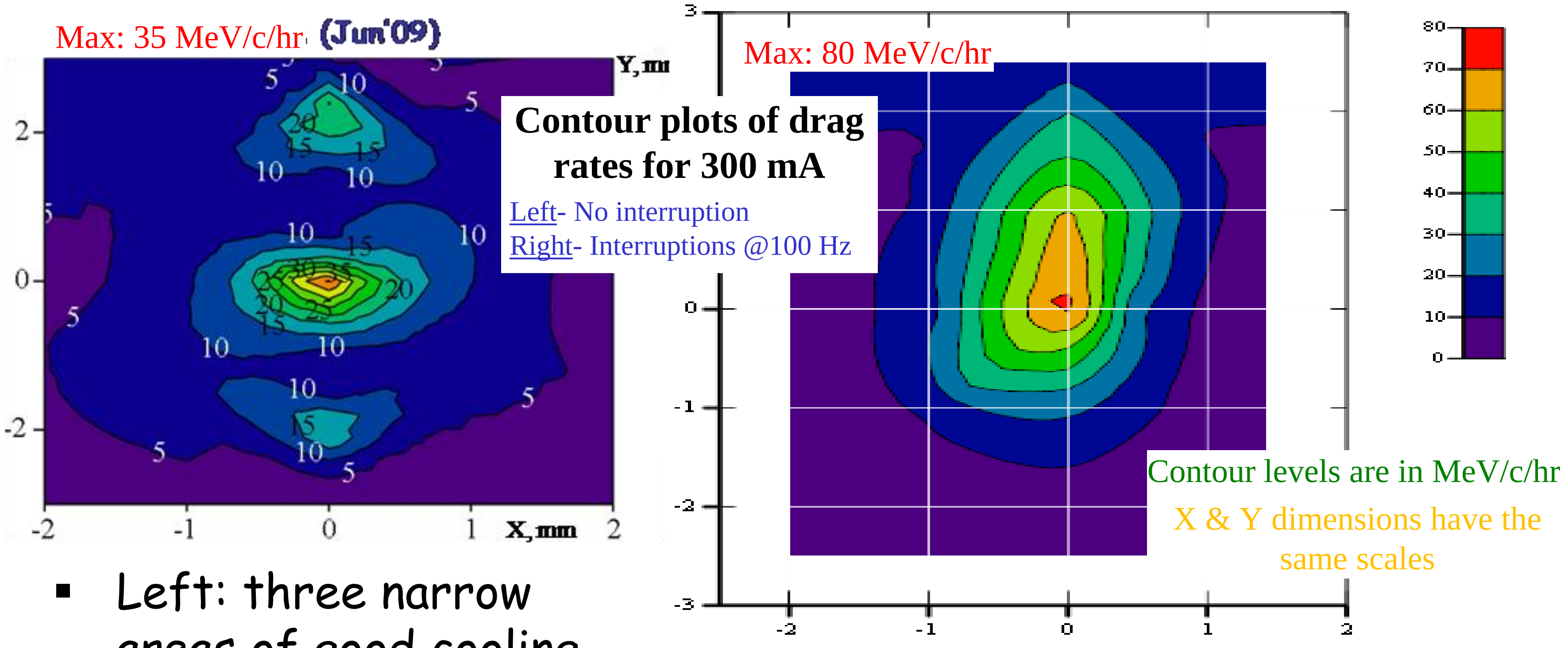
Longitudinal cooling rates at various vertical offsets of the electron beam before (set 2) and after (set 1) adjustments of quadrupoles. I_e ~ 0.1A.

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 effect & Cooling with ion clearing



Contour plots of drag rates for 300 mA

Left- No interruption

Right- Interruptions @100 Hz

Contour levels are in MeV/c/hr

X & Y dimensions have the same scales

- Left: three narrow areas of good cooling
  - Hypothesis: highly non-linear focusing effect from trapped ions
- Remedy: clear ions by interrupting the electron current for a microsecond (at tens of Hz)
  - 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

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

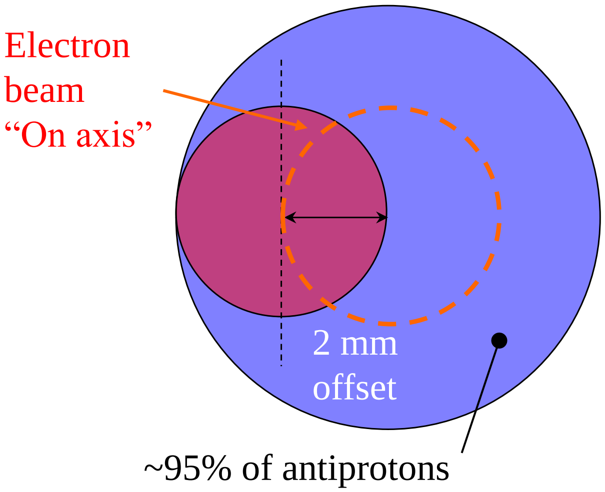
OPERATION

Cooling

- July 9, 2005 – First indication of the cooling force

- The cooler's performance was significantly improved and optimized
  - Procedures for tuning, feedback loops, automation…
  - 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

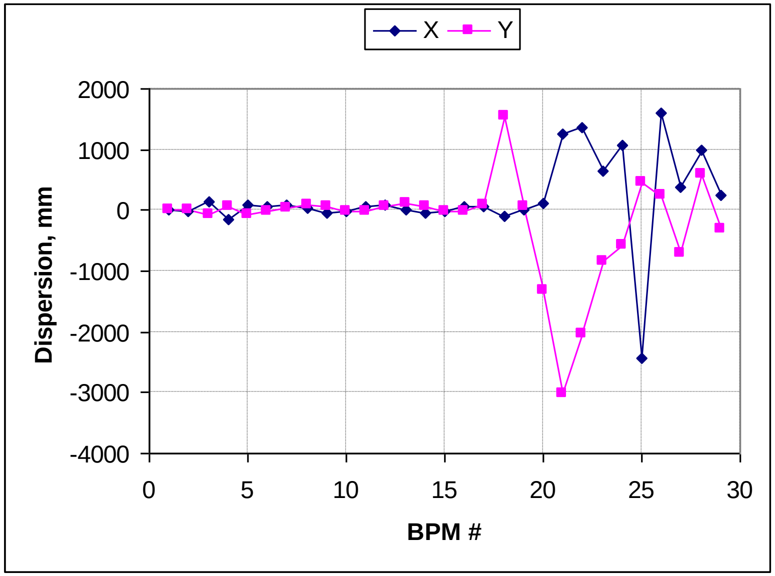


Availability/Reliability

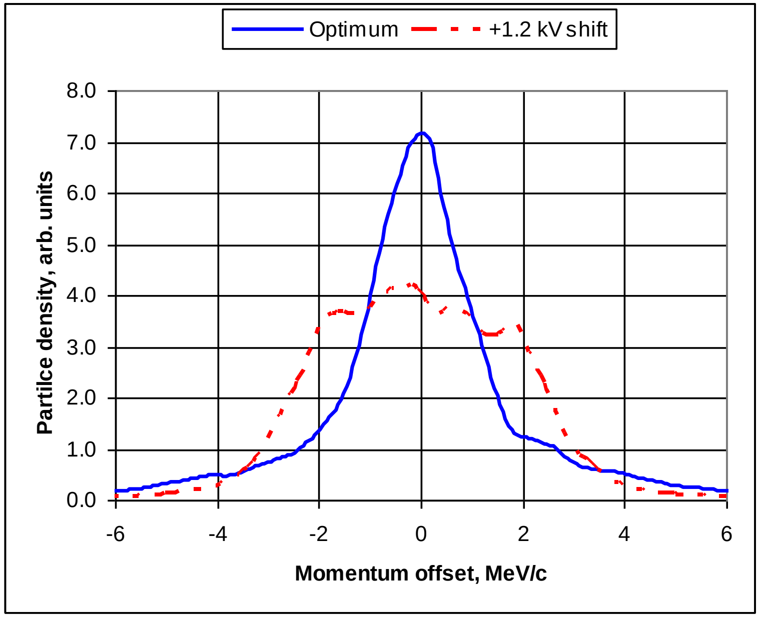
- Pelletron ran 24/7 and was turned off only when either a component had failed or during planned shutdowns (~once a year)
  - Beam 'interruptions' (*short*)
    - Beam trips:
      - Protection system turns off the beam if a drop of HV by >5 kV or other problem is detected
      - < 1 trip per day
      - ~20 s to recover
    - Full discharges:
      - Unprovoked: ~once a year
      - 1-3 hours to fully recover
  - Failures (*long down time*)
    - The worst situation is to have to go 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

Electron beam energy drift

- Electron energy drift
  - Corrected with a feedback loop based on BPM reading in a high-dispersion area
  - Adjustments to an 'energy parameter' based on the Schottky longitudinal distribution profile



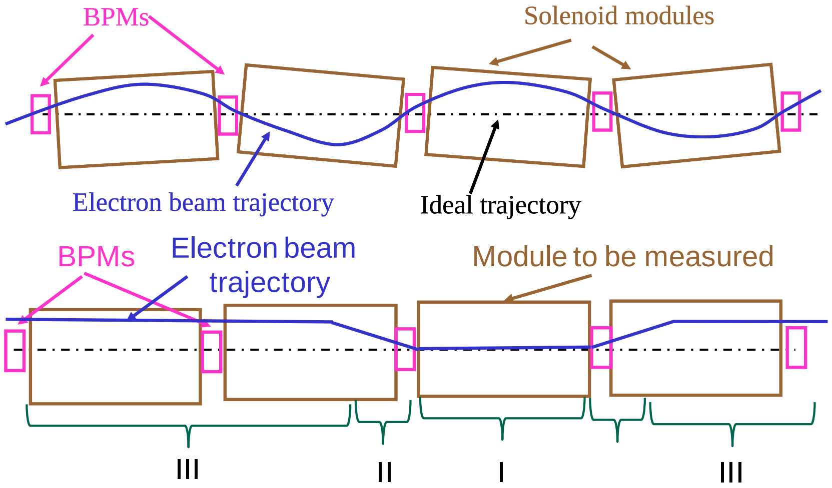
Measured dispersion in the electron beam line. The horizontal axis shows the BPM number counted along the beam line. Reading of the vertical channel of the first BPM after the 180 deg bend deviates with the energy change as 0.33 mm/keV.



Equilibrium momentum distribution of antiproton beam for cooling at two electron energies. Blue- optimum energy tuning, red - the electron energy is shifted by 1.2 keV; electron beam is on axis.

Correction of the magnetic field drift in the cooling section

- <u>Procedure</u>: optimize 10 pairs of correctors in each module measuring the cooling force produced by the module
  - Time consuming
  - Re-alignment of the magnetic field ~once a year
    - Typically after a long shutdown (of the whole accelerator complex)
  - Effectiveness of the procedure questionable at times


BPMs

Solenoid modules

Electron beam trajectory

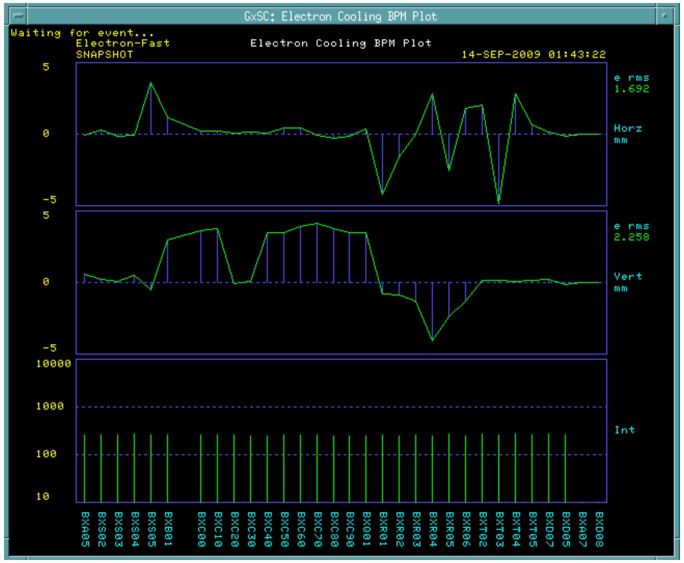
Ideal trajectory

BPMs

Electron beam trajectory

Module to be measured

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

Impedance-driven instability (transverse)

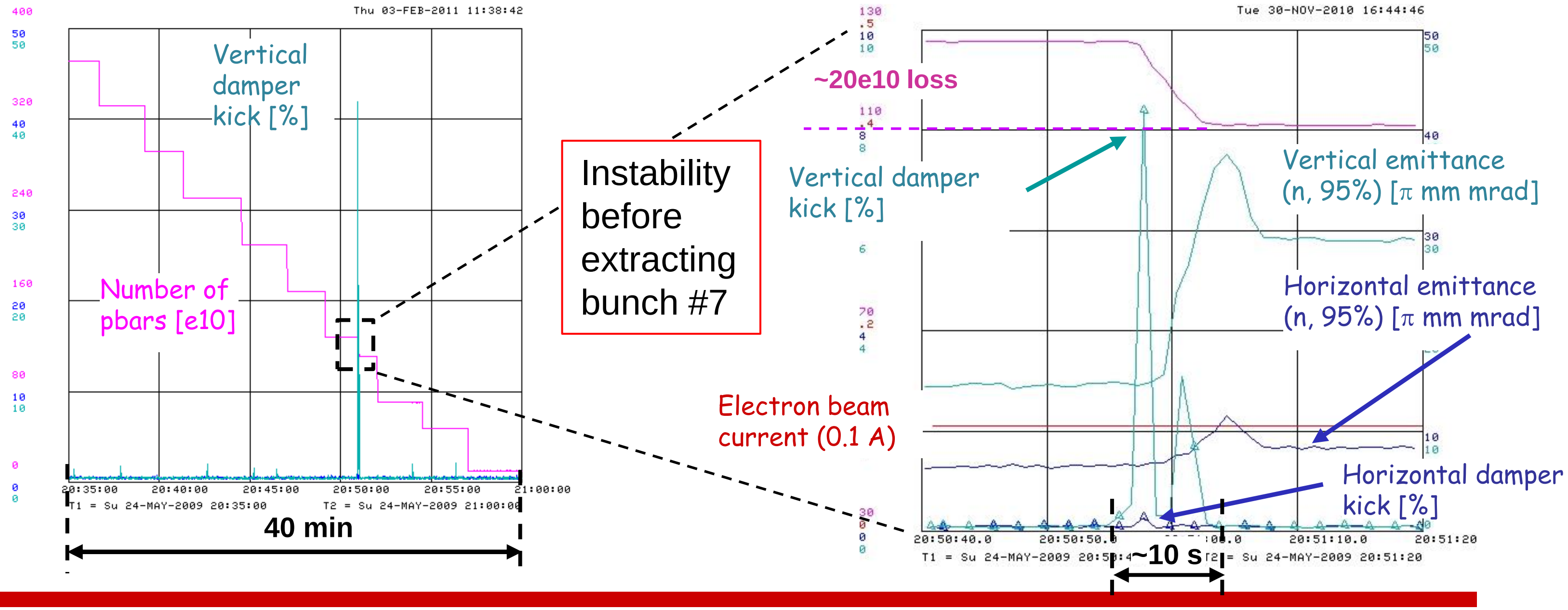
- Due to own space charge of pbars when *deeply* cooled
  - Dampers suppressed them very efficiently
  - A few were observed during extraction process
    - Complicated RF gymnastics
- Defined a ‘phase density’ parameter
  - Monitored on-line
  - Kept far from the calculated (and experimentally determined) instability threshold

antiproton ≡ $\overline{p}$ ≡ pbar

$$D_{95} = \frac{N_{\overline{P}}}{\varepsilon_{L\,95} \cdot \varepsilon_{T\,n95}}$$

# of pbar ×10^{10}

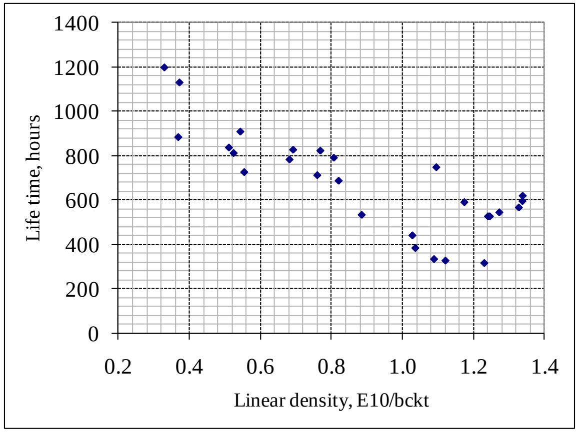
Emittances in eV·s & μrad

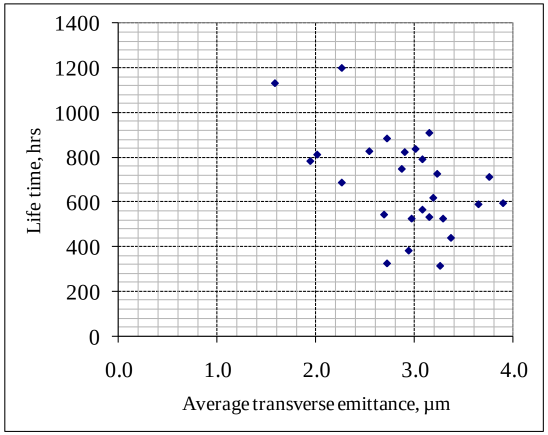


Lifetime

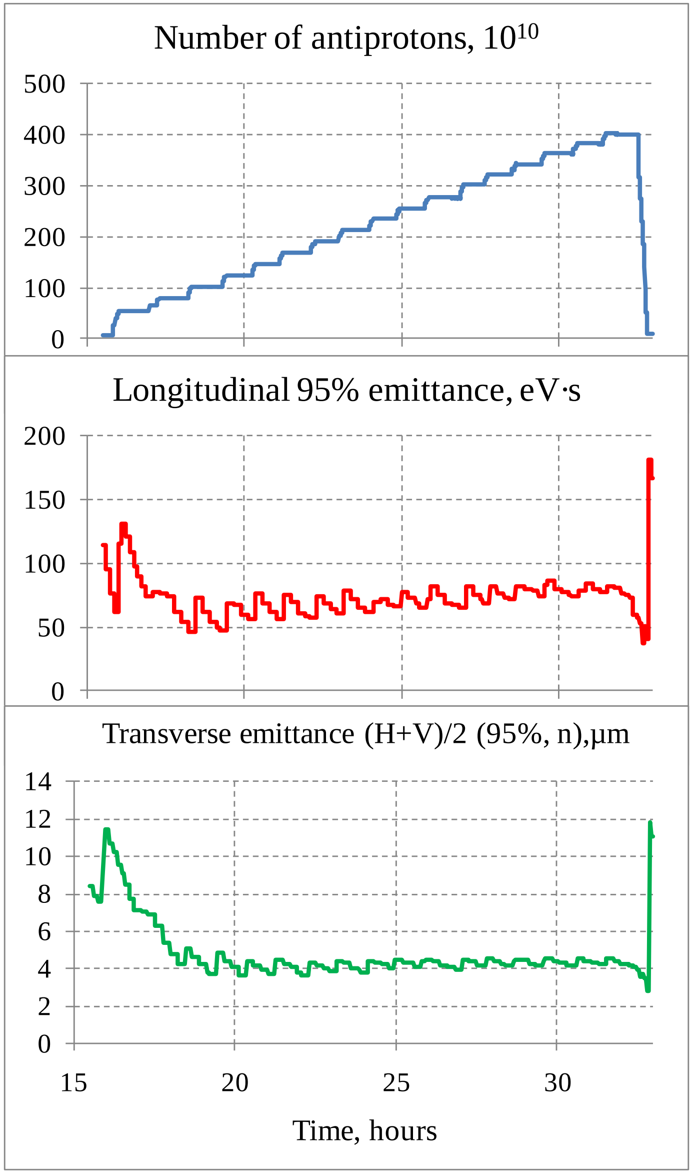
- Antiprotons are typically accumulated for ~15 hours
  - Preserving the antiproton beam lifetime is crucial
  - No single parameter (or a combination) would ***uniquely*** determine the lifetime
- Some observations:
  - The lifetime value correlates best with the linear density
    - But not with the transverse emittance for instance
  - Strong cooling deteriorates the lifetime – Stochastic cooling improves it
    - Keep stochastic cooling well tuned even if its effect on the measured emittance of large stacks was insignificant

The linear density is calculated as a ratio of the total number of antiprotons, $\times 10^{10}$, to the length of the RF barriers gap, in units of 53-MHz buckets - the Recycler perimeter in this unit is 588 buckets.





Recycler cooling cycle



- 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.

Summary

- Unique electron cooler
  - High energy (4 MV), huge beam power (2 MW)
  - Low magnetic field in the cooling section with lumped focusing outside
    - 'Non-magnetized' cooling
    - Transport of a beam with large effective emittance
- Reliable machine running 24/7
- The Recycler Electron Cooler significantly contributed to the success of Run-II
  - i.e. property of cooling and overall operation of the cooler satisfied the needs (and maybe beyond expectations)