Recycler Electron Cooling

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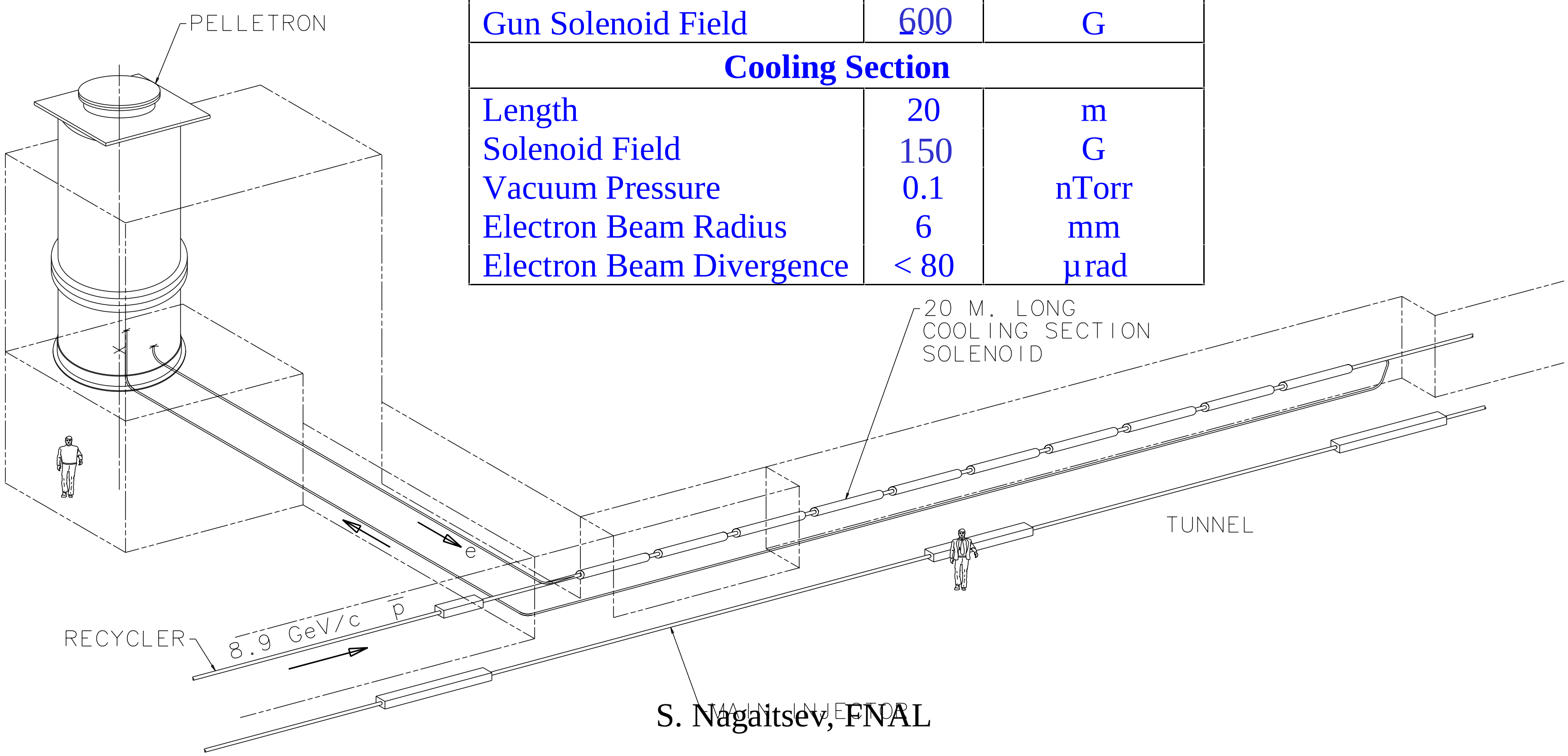
Schematic Layout of the Fermilab's Recycler Electron Cooling

Electron Cooling System Parameters

Parameter	Value	Units
Electrostatic Accelerator		
Terminal Voltage	4.3	MV
Electron Beam Current	0.5	A
Terminal Voltage Ripple	500	V (FWHM)
Cathode Radius	2.5	mm
Gun Solenoid Field	600	G
Cooling Section		
Length	20	m
Solenoid Field	150	G
Vacuum Pressure	0.1	nTorr
Electron Beam Radius	6	mm
Electron Beam Divergence	< 80	μrad



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The electron cooling scenario

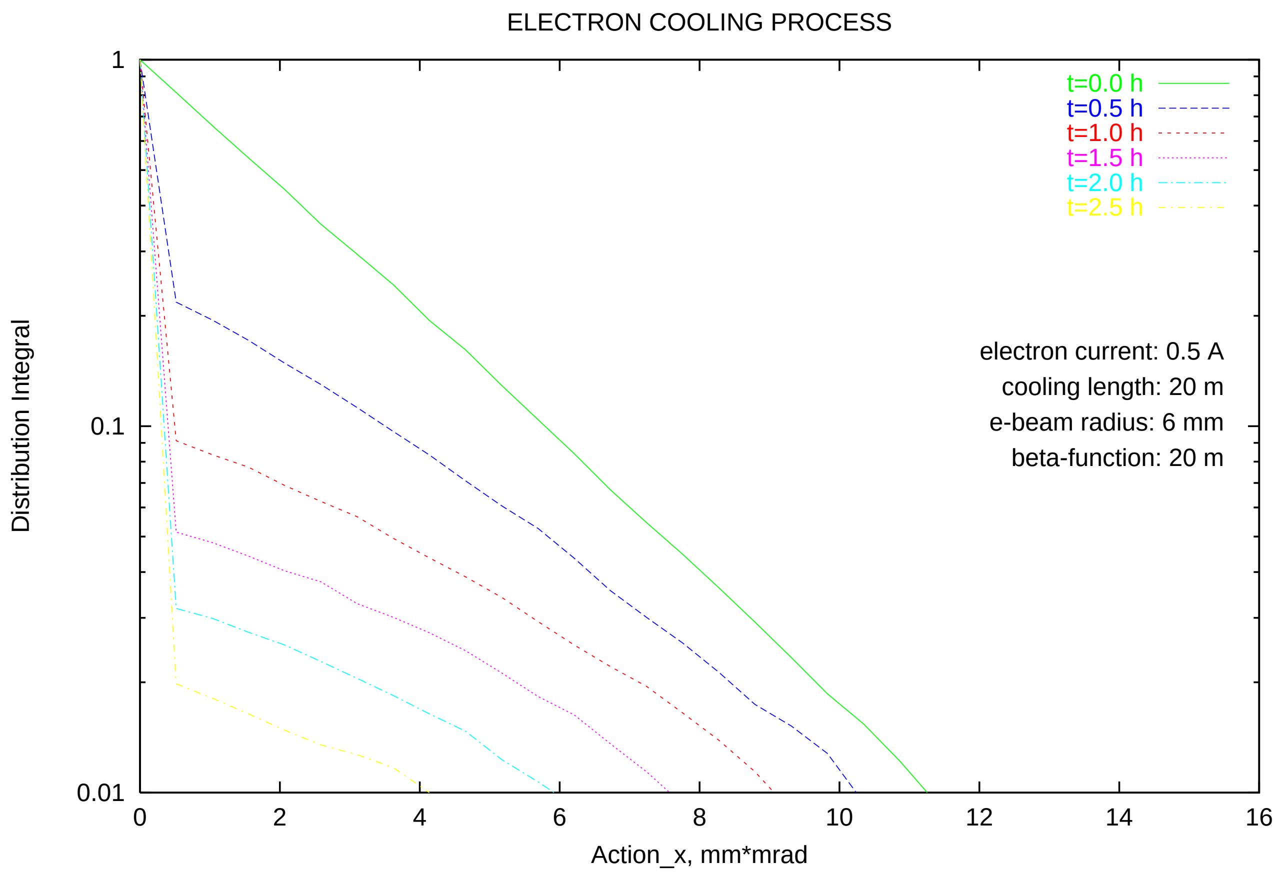
1 "Hot" antiprotons arrive at the Recycler: 2.5-10x10^{12} pbars, 400 eVs, 30 π mm-mrad (n, 95%). Transverse stochastic cooling starts and cools pbars to 15 π mm-mrad in two hours.

2 Every 15 minutes a new portion of pbars arrive from the Accumulator: 10^{11} pbars, 10 eVs, 15 π mm-mrad.

3 After two hours of stochastic cooling the transverse emittance is reduced to 15 π mm-mrad. Electron cooling starts.

4 After 3 to 8 more hours of continuous transfers from the Accumulator we end up with a stack of: 150 eVs or less, 10 π mm-mrad or less.

Evolution of the transverse emittance



Initial distribution: gaussian with a 15 π mm-mrad (n, 95%) emittance

Initial cooling rate for a 15 π mm-mrad beam: 6 π mm mrad/hr

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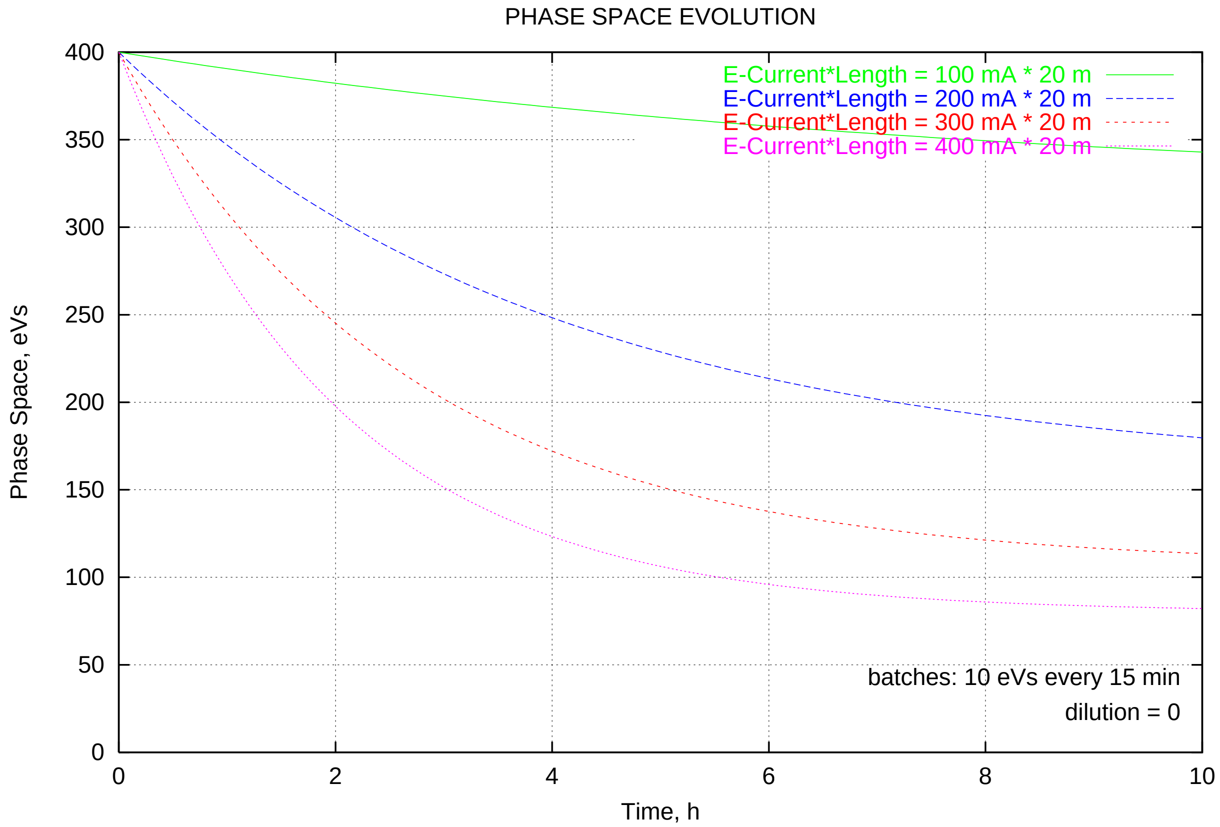
Evolution of the longitudinal phase-space area



Current electron cooling system design is optimized for the longitudinal cooling. The efficiency of the long. cooling depends primarily on the frequency of transfers from the Accumulator and the effect of these transfers on the stack emittance (should be <1% increase).

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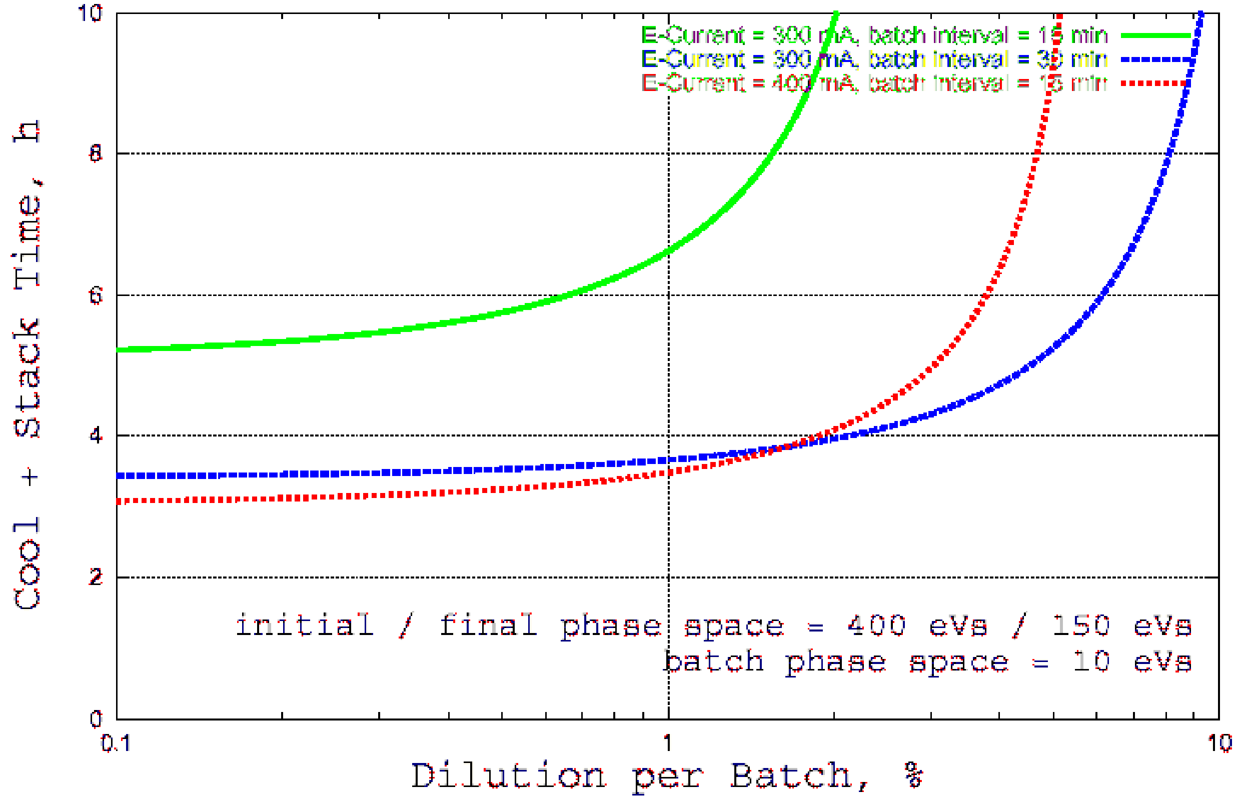
Importance of longitudinal emittance dilution



Time required to reduce the longitudinal phase-space area from the initial 400 eVs to the final 150 eVs as a function of the stack emittance dilution per one transfer.

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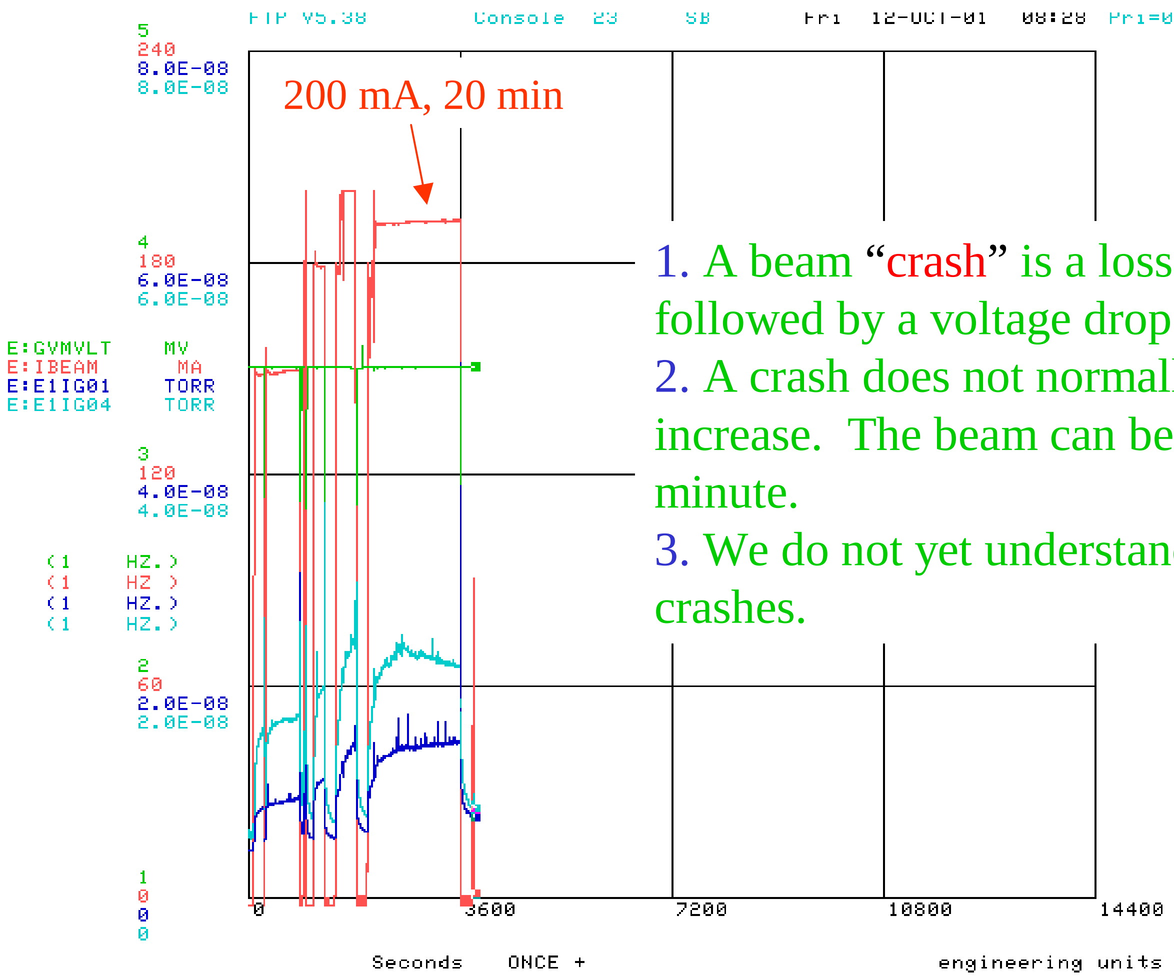
Electron Cooling R&D
Project Goals

• Electron beam current	0.5 A
• Electron beam kinetic energy	4.3 MeV
• Beam angular spread (cooling section)	80 μrad
• Energy spread (FWHM)	500 eV
• Pressure (cooling section)	$1\text{x}10^{-10}$ Torr
• Typical time between beam “crashes”	1 hour
• Crash recovery time	5 min
• Typical time between tank openings	1 month (initial)
	6 months (final)

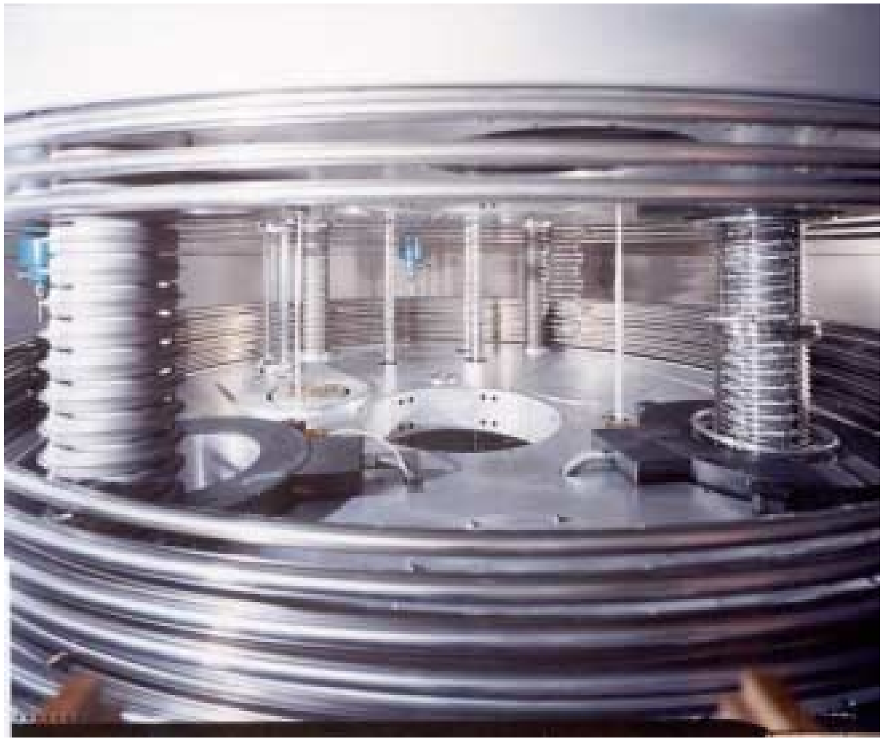
Notes on stability



1. A beam "crash" is a loss of beam recirculation, followed by a voltage drop.
2. A crash does not normally result in a pressure increase. The beam can be restored within one minute.
3. We do not yet understand the reason for such crashes.

Fermilab Electron Cooling R&D Facility

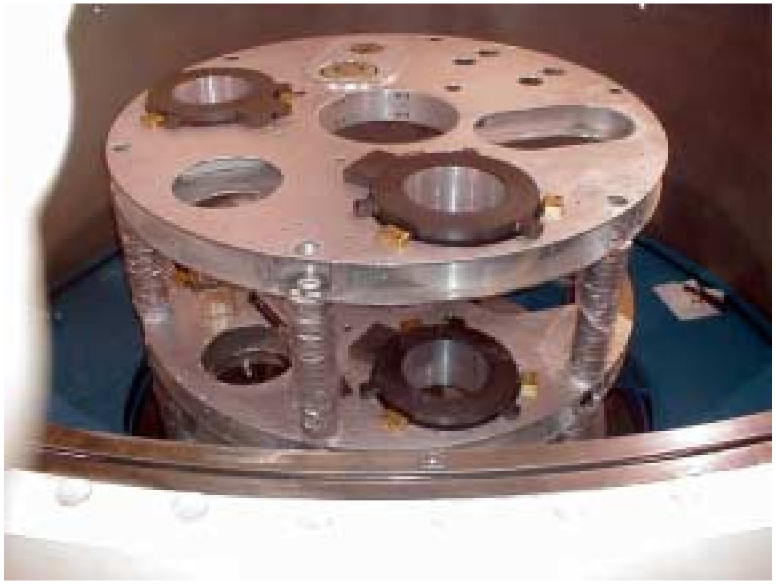
5 MV Pelletron installed



High-voltage column with grading hoops partially removed to show the accelerating tube (right) and the charging chains (far center).

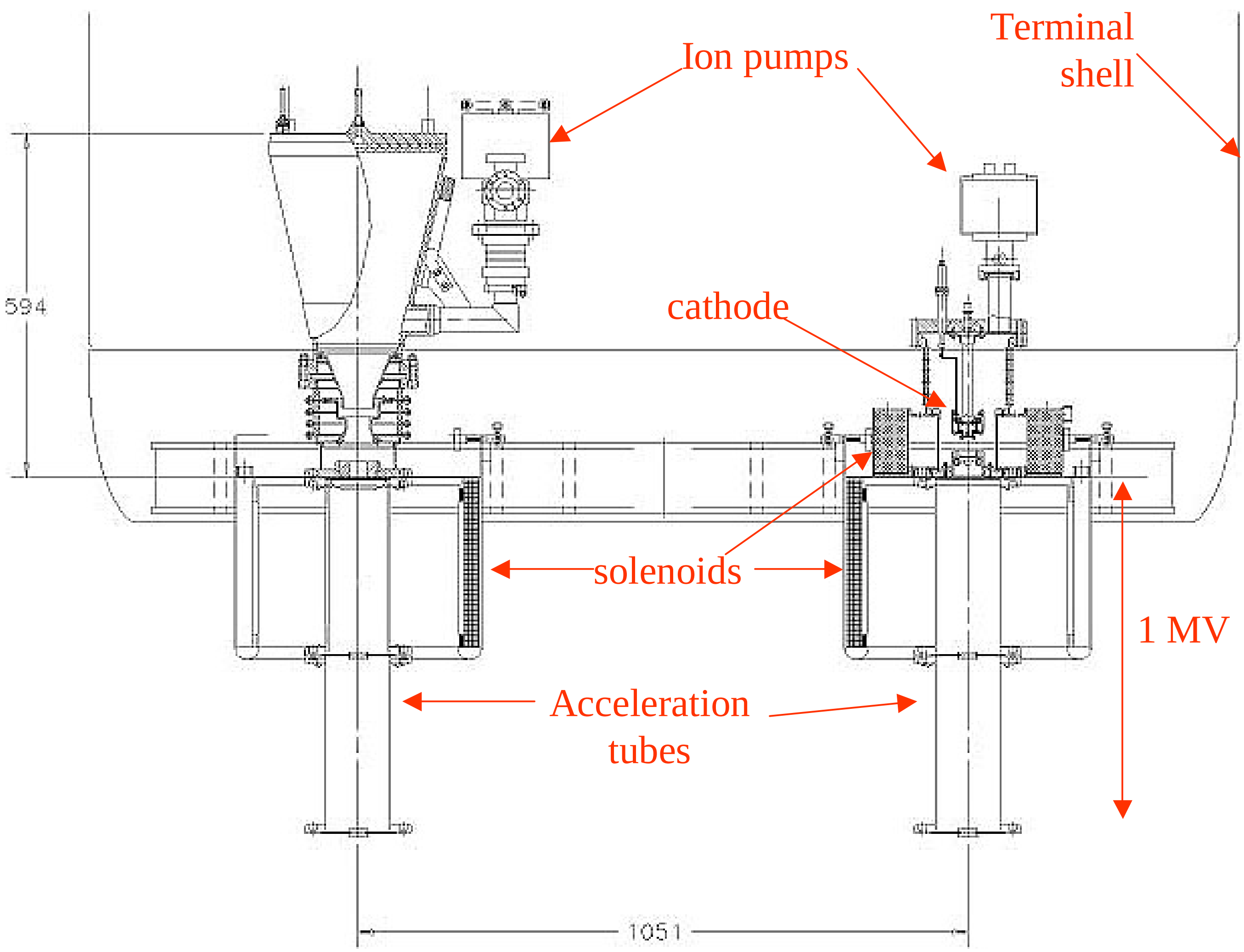
Fermilab Electron Cooling R&D Facility

The Pelletron tank is accessed through a manway.



Structure inside the tank -- separator boxes and beam lenses. No beam tubes were installed at the time of this photo.

Electron gun and collector assembly



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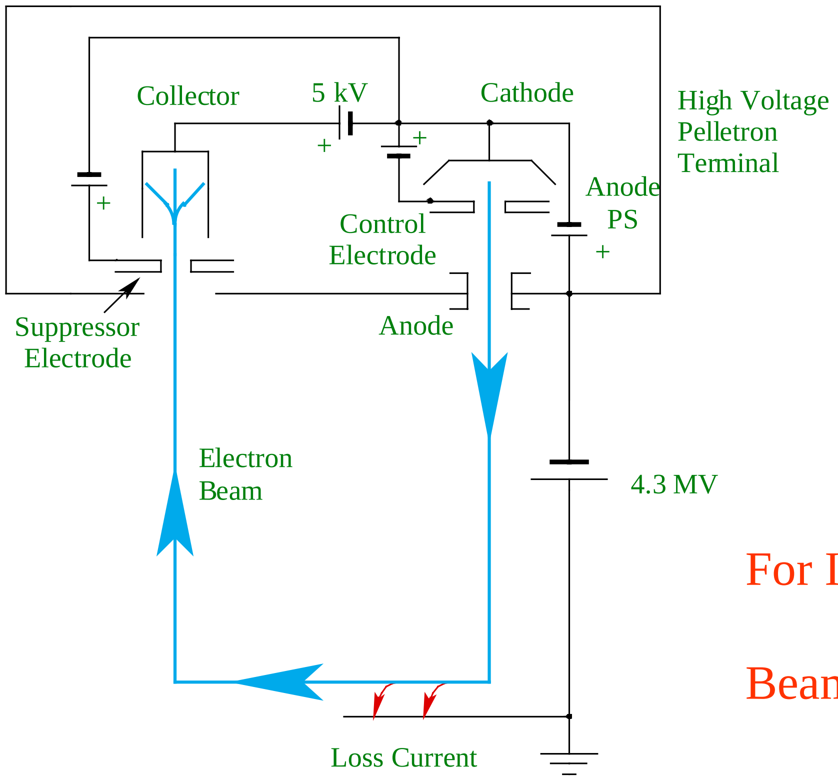
Simplified schematic of beam recirculation



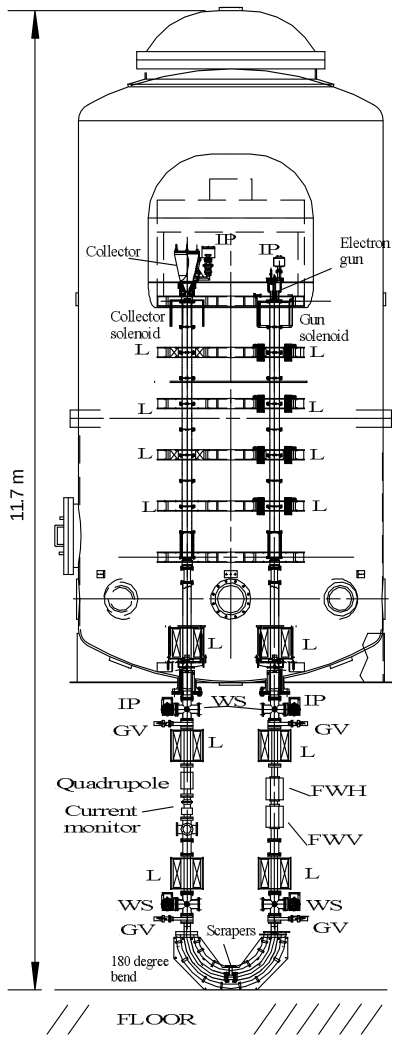
For I= 0.5 A, ΔI_{loss}= 5 µA:

Beam power 2.15 MW

Current loss power 21.5 W

Power dissipated in collector 2.5 kW

Electron Cooling R&D Facility at WideBand
(Recirculation experiment)



GOAL

- To demonstrate a 0.5 A recirculation for 1 hr. at 4.3 MV

HISTORY

Feb 99:	5 MV Pelletron ordered.
Jun 00:	Pressure tank installed at WideBand.
Dec 00:	Tank at 80 psig, 5 MV tests without vacuum tubes.
Feb 01:	Gun-side vacuum tubes installed and tested.
Mar 01:	Collector-side tubes installed. Operations began.
Apr 01:	Beam permit issued. All components in place.
May 01:	First beam of 30 μA in the collector at 4.3 MV.
July 01:	Reached 10 mA, HV conditioning is very unstable, tubes do not behave properly.
Aug 01:	Switched to operations with 3.5 MV. Routine conditioning to 4.3 MV.
Oct 01:	Reached stable 100 - 150 mA beam.

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Remarks about the current recirculation setup at Fermilab

- Our plan is to reach a stable 500 mA at 3.5 MV by the end of this calendar year. Also, we would like to demonstrate a high duty-cycle operation (90% or better) in a 24-hour period with currents above 300 mA.
- Tubes will have to be replaced sometime next year. The tubes will have to be baked and it will take several months to recover vacuum.
- We are planning to test every type of diagnostics on a short U-bend setup.
- We are also planning to perform tests on a slow beam position feed-back system. In the future full-scale beam line this will work together with the NMR-based magnet stabilization and the dispersionless beam transport line.

Summary of what has been accomplished in our recirculation test thus far

- Successfully bridged the NEC control system, supplied with the Pelletron, with Acnet. The machine is now 100% Acnet compatible and transparent.
- Electronics has been protected against sparks (Apr-July, 2001)
- Replaced mechanical hardware, damaged by sparks, with more robust components:
  - replaced: two damaged vacuum HV feedthrus; one beam-punctured bellows with a thick tube; one poisoned cathode; one damaged gun control (grid) electrode.
- Installed several levels of protection against beam-related full-tube breakdowns, which normally resulted in a tube de-conditioning (Aug, 2001):
  - A scraper in a high-dispersion position to absorb the beam during a crash.
  - A protection "box" that disables the beam if some parameter (i.e. HV) goes out of tolerance.
  - A software (slow) beam disable if the some Acnet parameters are out of tolerance
- Established a procedure for HV conditioning. Established a procedure for steering the beam into collector. Any crew member can now reach 100 mA in about one hour from scratch.
- Realized the significant role that ions play in beam stability (Oct 2001).

Beam transport line

- Angular momentum dominated beam transport
  - Beam transport optics from the exit of the gun solenoid to the entrance of the cooling section is dictated by three beam properties:

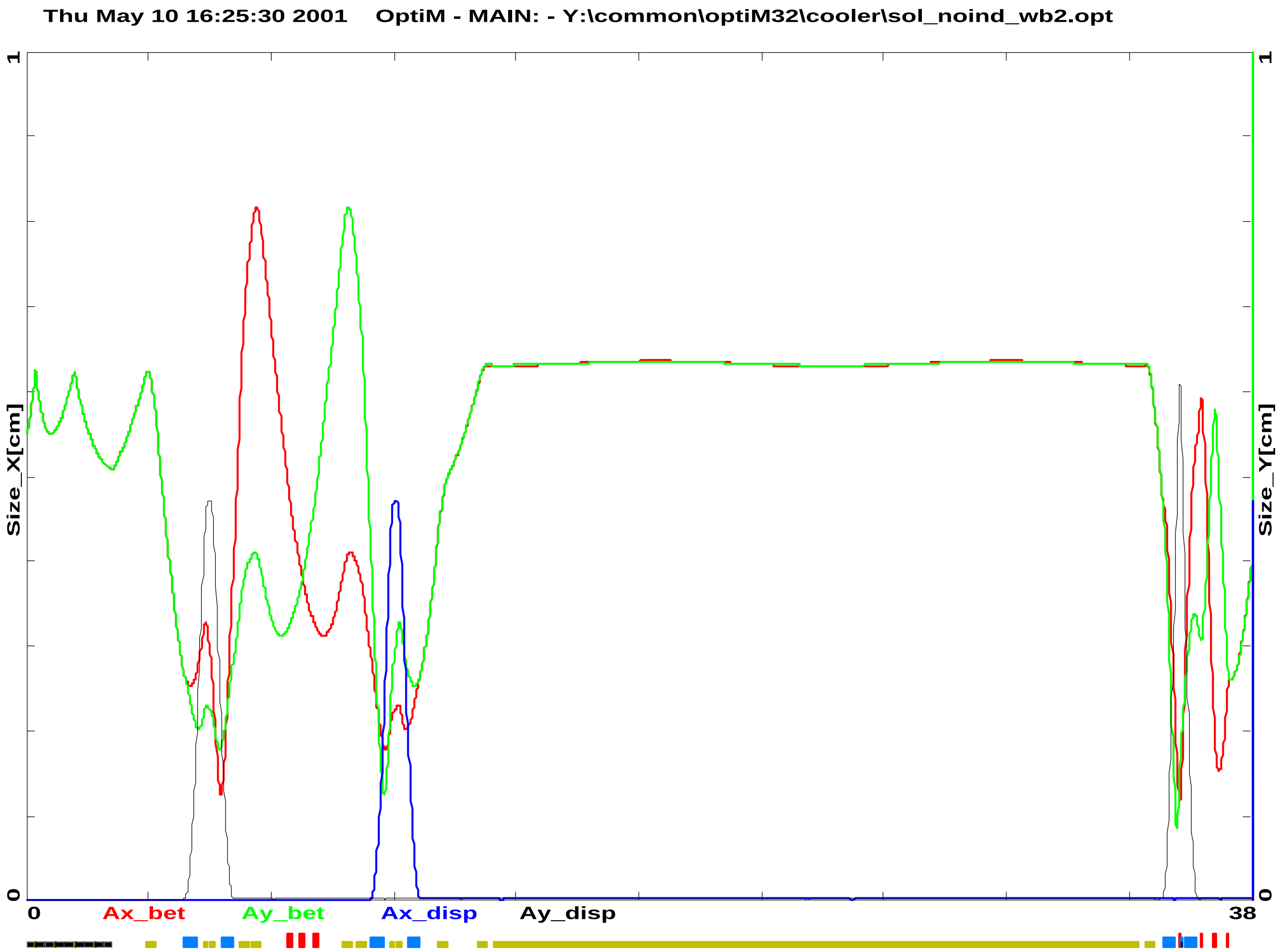
    (1) A large emittance-like contribution from the angular momentum

    $\varepsilon_{N,eff} = eBr_c^2 /(2mc^2)$. For B = 600 G, r_c = 0.25 cm, $\varepsilon_{N,eff} \approx$ 100 mm-mrad

    (2) Low beam aberrations

    (3) High optics stability and reproducibility
- Bends are made of two NMR-regulated dipole magnets and two opposing-field solenoids. All mounted on an adjustable frame and shielded by a mu-metal shield. Aluminum vacuum chamber will be used.
- All elements are ordered and are due in Jan.-Mar., 2002
- We will start switching over to a longer beam-line in Mar., 2002

Beam envelope in a full-scale beamline



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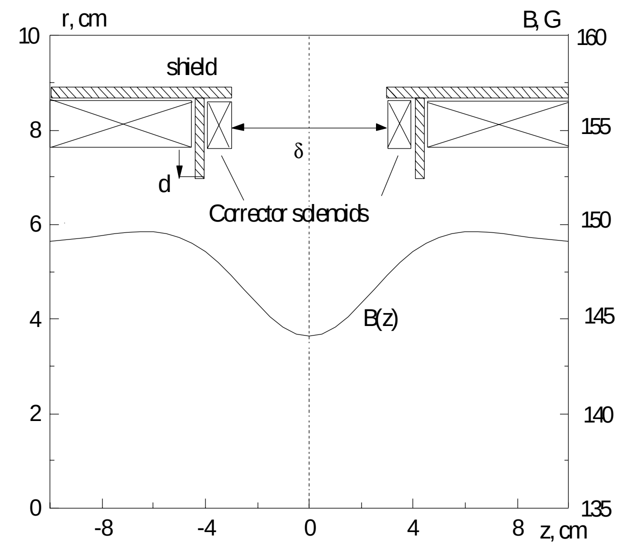
Cooling section solenoid

- consists of 10 identical solenoids, separated by instrumentation gaps

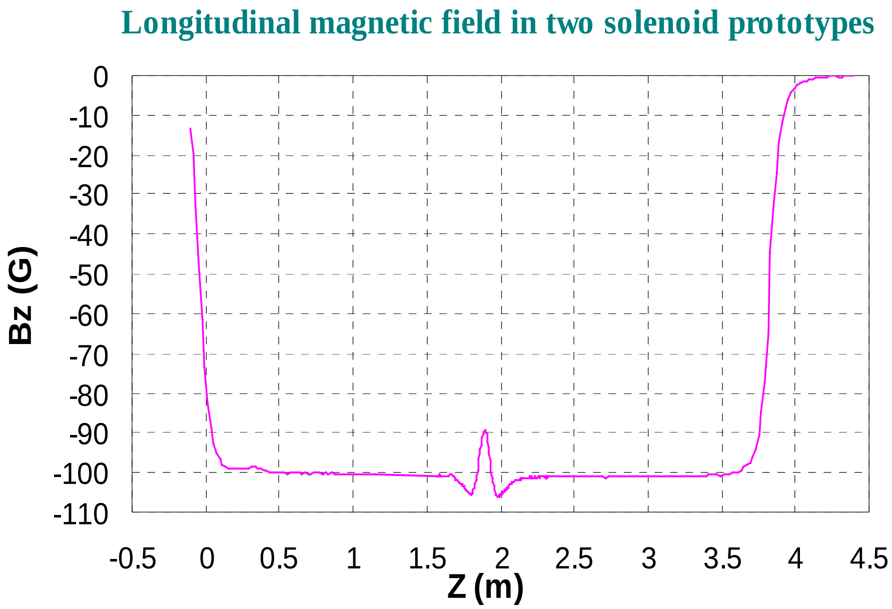
Total length	20 m
Magnetic field	50 - 150 G
Electron angles in the section	< 0.1 mrad
Integral of transverse magnetic field	≤ 0.3 G·cm

Solenoid Overview

- Ten 2-m long modules, each with its own PS
- Each module:
  - a solenoid (188 cm long), 4 A, 80 V, 150 G
  - two corrector solenoids to correct gap effects
  - 20 transverse correctors (may be eventually connected in series with the solenoid PS)
  - 8-cm long gap for instrumentation
  - shielding with a coefficient of at least 1000 to shield stray fields of about 5 G.
- Two prototype modules were produced, installed and measured. Their properties were found satisfactory. The production of 12 more improved modules is now complete.

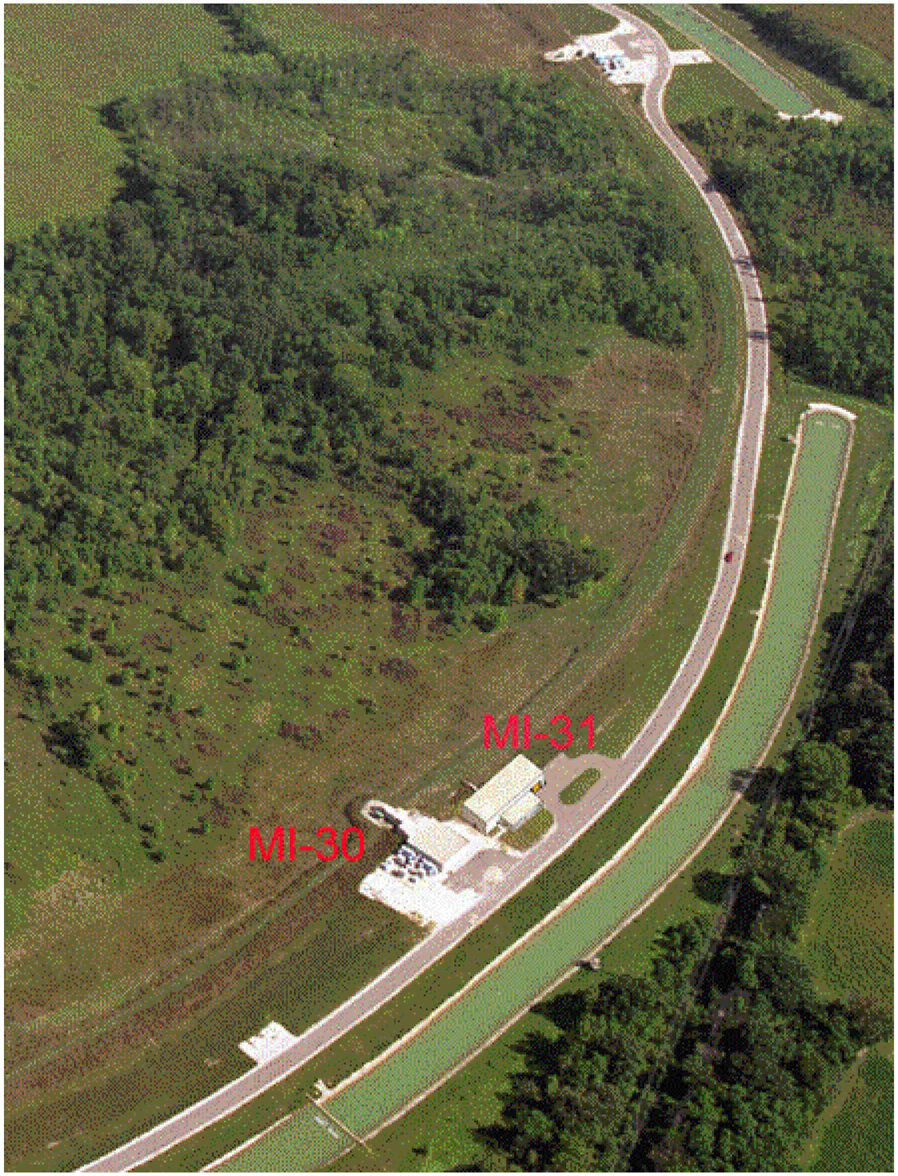


Two prototype cooling section solenoid modules installed



Summary on the solenoid section

- 90% of all work has been done to understand the sensor performance and to make it stable and reproducible. This has now been achieved.
- The compass-based sensor can measure the solenoid transverse field with a relative accuracy of several mG. Absolute precision, determined by an angle between the magnetic axis of the compass and the mirror, is about 20 mG in a 100 G longitudinal field.
- Quality of measured solenoid prototypes is satisfactory for our purpose. Integrals of transverse fields can be made below 1 G·cm at the solenoid field of 150 G, if corrector currents are in optimum.
- Twelve new solenoids have been wound and epoxied by the TD. Two will be ready for installation in December, 2001.
- We are planing to have a shielding coefficient of 5000. Only two prototypes of this 3-layer design are being manufactured. The remaining shields will be ordered after the shields are tested.
- We are investigating a possibility to use a Type-I SC solenoid to eliminate all transverse correctors.



An artist's rendering of a proposed building (MI-31)

next to the existing service building (MI-30).