Electron Cooling R&D

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Beam Cooling in the Fermilab's Recycler

The missions for any cooling system in the Recycler are:

- The multiple Coulomb scattering and other diffusion mechanisms need to be neutralized.
- Transverse and longitudinal emittances of the recycled antiprotons need to be reduced by roughly 1/e in the 8-10 hour store length.
- The momentum spread of stacked antiprotons needs to be reduced between transfers from the Accumulator to the Recycler.

The electron cooling scenario (with an e-cooling system optimized for the longitudinal cooling)

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.

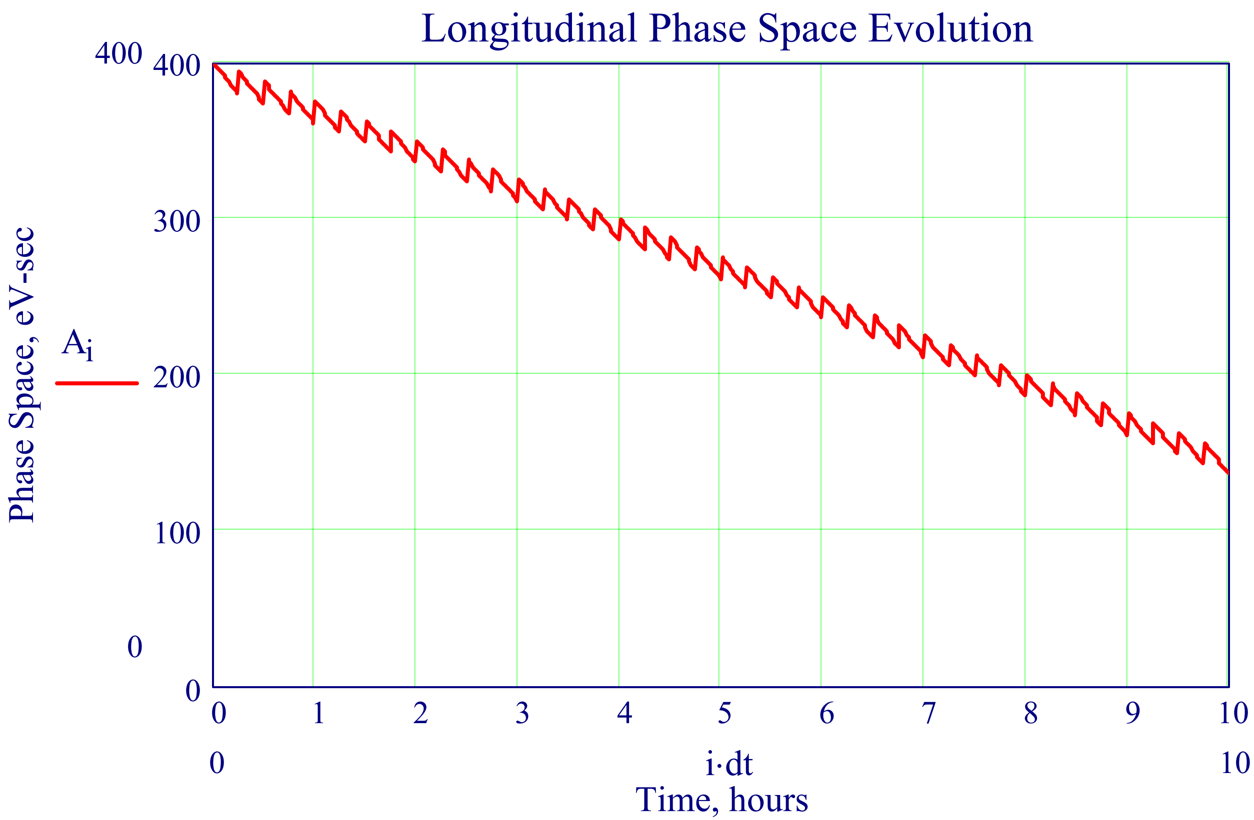
3 After two hours of stochastic cooling the transverse emittance is reduced to 15 π mm-mrad. Electron cooling starts.

4 After 8 to 10 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.

Assume a 50% dilution on each transfer:

4×10 eV-s + dilution = 60 eV-s/hour increase

One needs about 85 eV-s/hour of cooling to cool the stack



No diffusion mechanism is assumed in this graph. The equilibrium long. emittance due to IBS is 30 eV-s for 10^{13} antiprotons.

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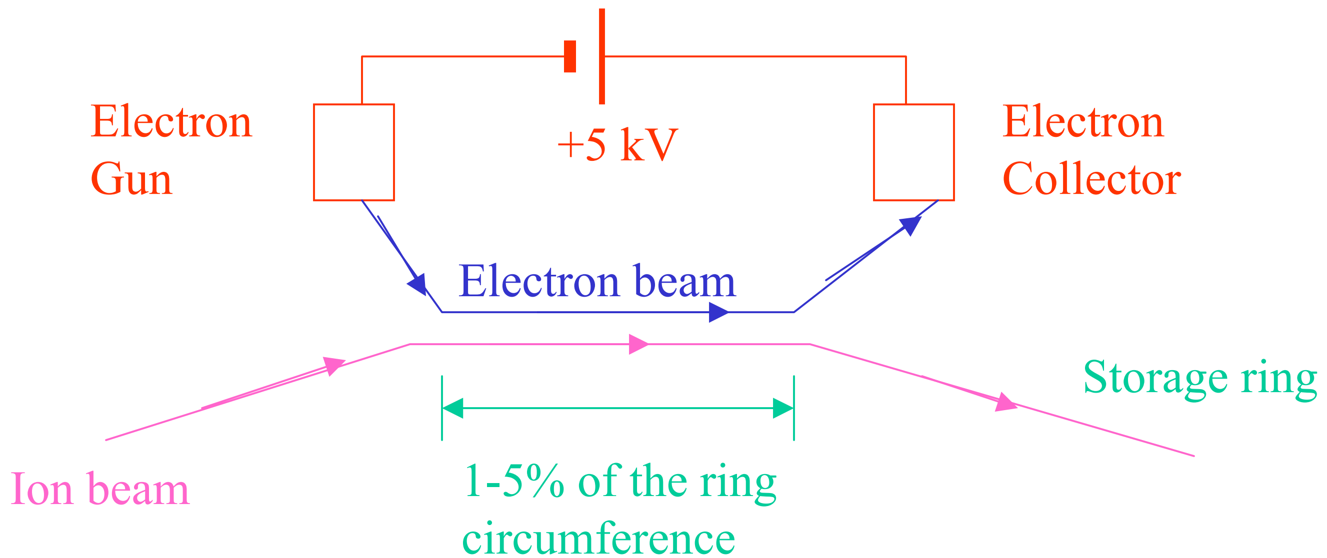
How does electron cooling work?

- A stored ion beam is overlapped with a nearly monochromatic and parallel electron beam in one of the straight sections of a storage ring:



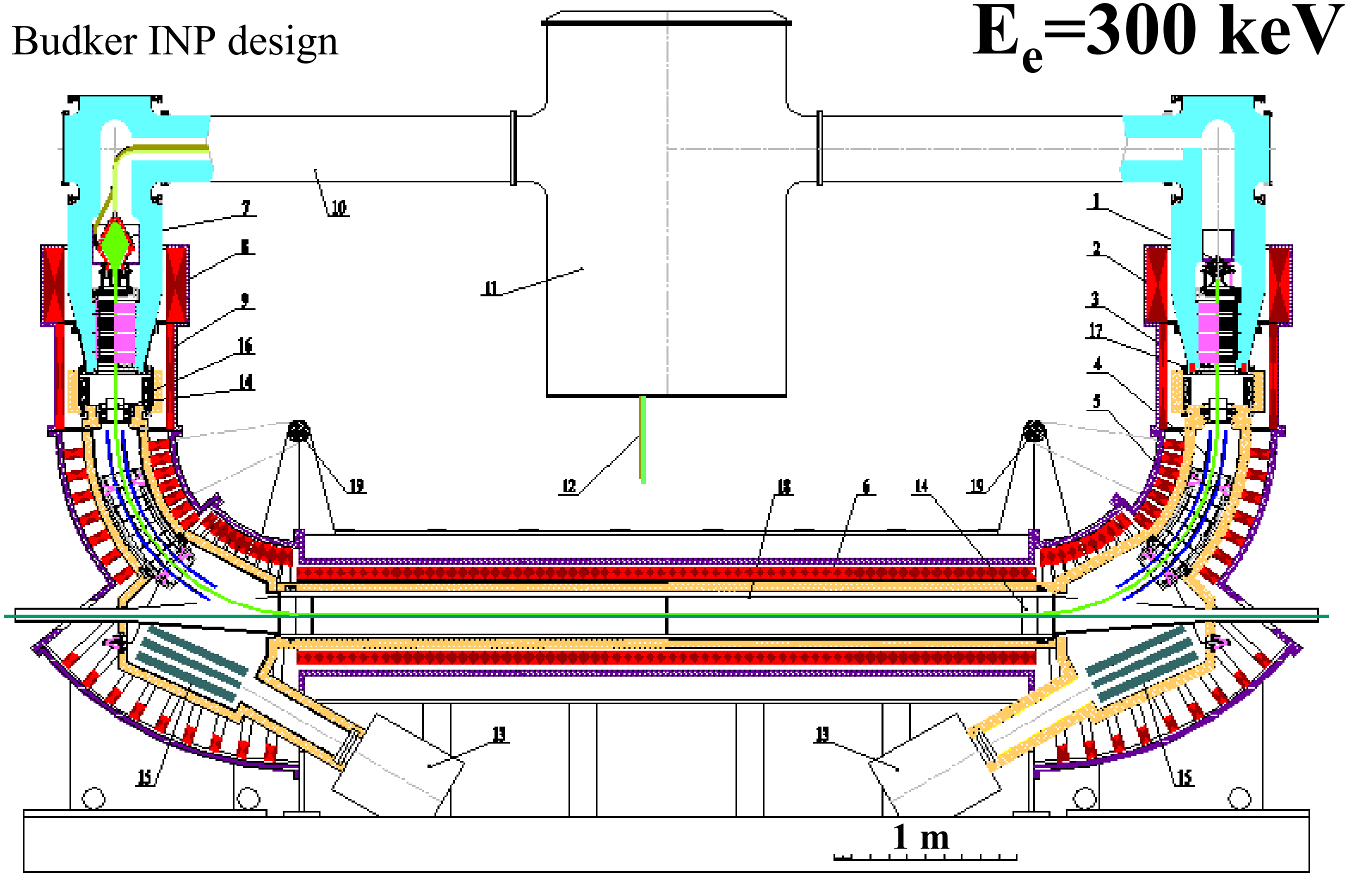
How does electron cooling work? (continued)

- The velocity of the electrons is made equal to the average velocity of the ions.
- The ions undergo Coulomb scattering in the electron "gas" and lose energy, which is transferred from the ions to the co-streaming electrons until some thermal equilibrium is attained.
- Typical parameters of all existing electron coolers:
  - electron kinetic energy: 2-300 keV
  - ion kinetic energy: 4-600 MeV/nucleon
  - electron beam current: up to 5 A

A typical low-energy electron cooler design

Budker INP design

E_e=300 keV



1 - electron gun; 2- main "gun solenoid"; 4 - electrostatic deflectors; 5 - toroidal solenoid; 6 - main solenoid; 7 - collector; 8 - collector solenoid; 11 - main HV rectifier; 12 - collector cooling system.

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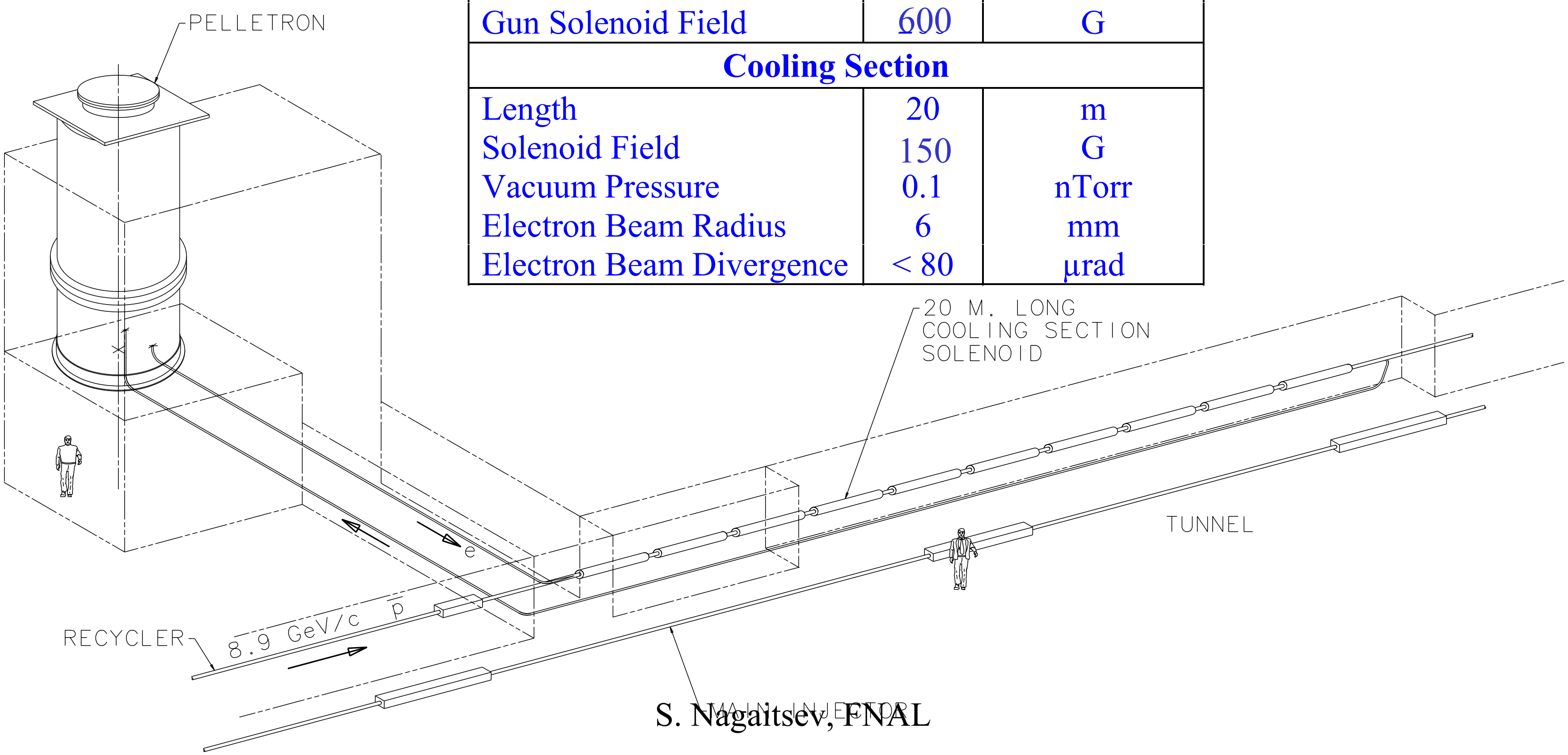
What makes the Fermilab system unique? -- Its high energy (4.3 MeV).

- I define a “high energy” as the energy where the conventional technology to produce and transport electrons becomes inapplicable. These technologies are:
  - A power supply (or energy source);
  - A continuous magnetic field of 1 kG or more;
  - A short cooling section (about 2 m).
- This probably corresponds to $\gamma > 1.5$
- Well understood fundamentals but much R&D is needed.
- At present, only Fermilab has committed funds to do a full-scale R&D for a system to cool 8.9 GeV/c antiprotons.

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



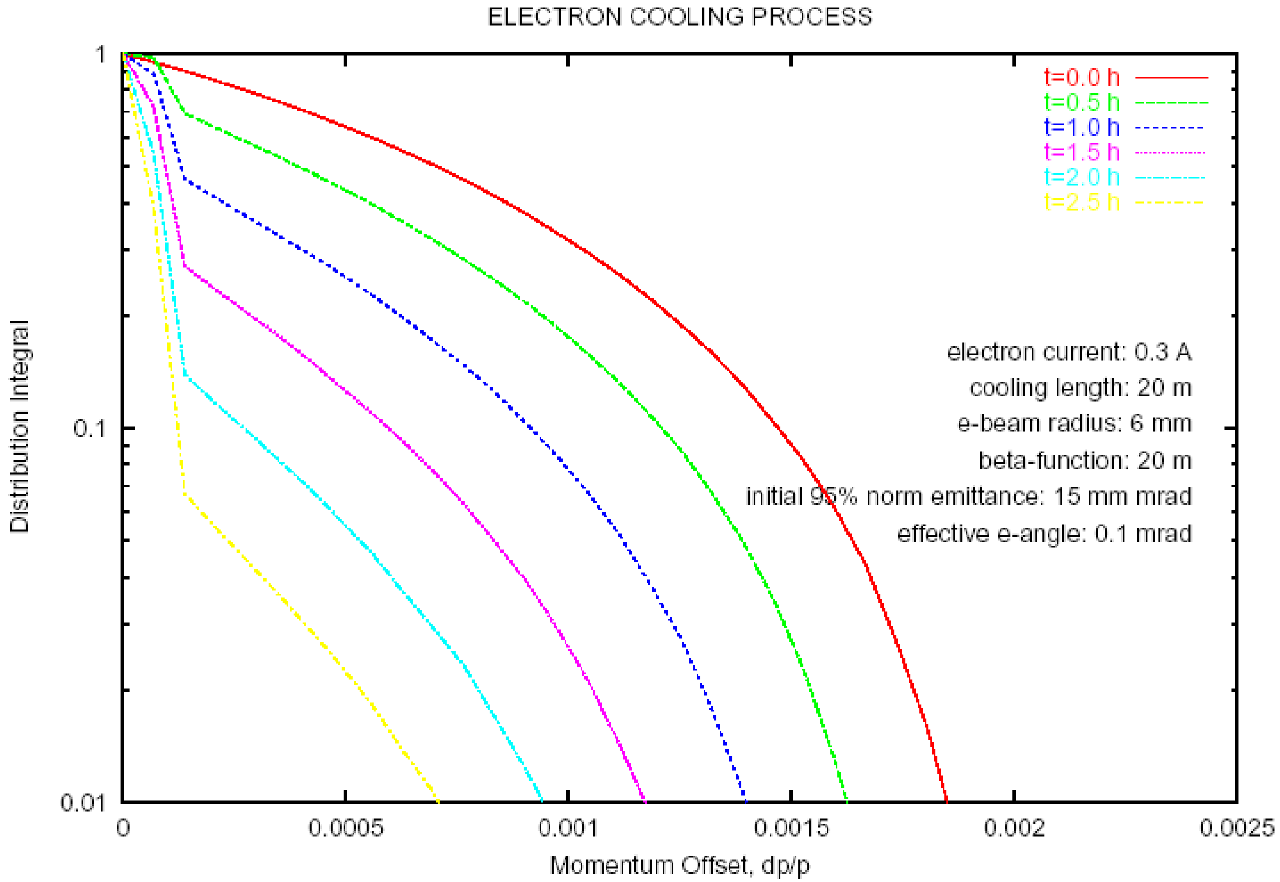
What determines the longitudinal electron cooling rate?

1 **It is proportional to the cooling section length.** Once the length is set, the optimal value of the antiproton beta-function and the electron beam radius are determined.

3 **It is proportional to the electron beam current.**

4 It falls down sharply if the effective electron angular spread in the cooling section is higher than about 0.1 mrad. The specific dependence is greatly affected by the nature of this spread: temperature, misalignment, aberration etc.

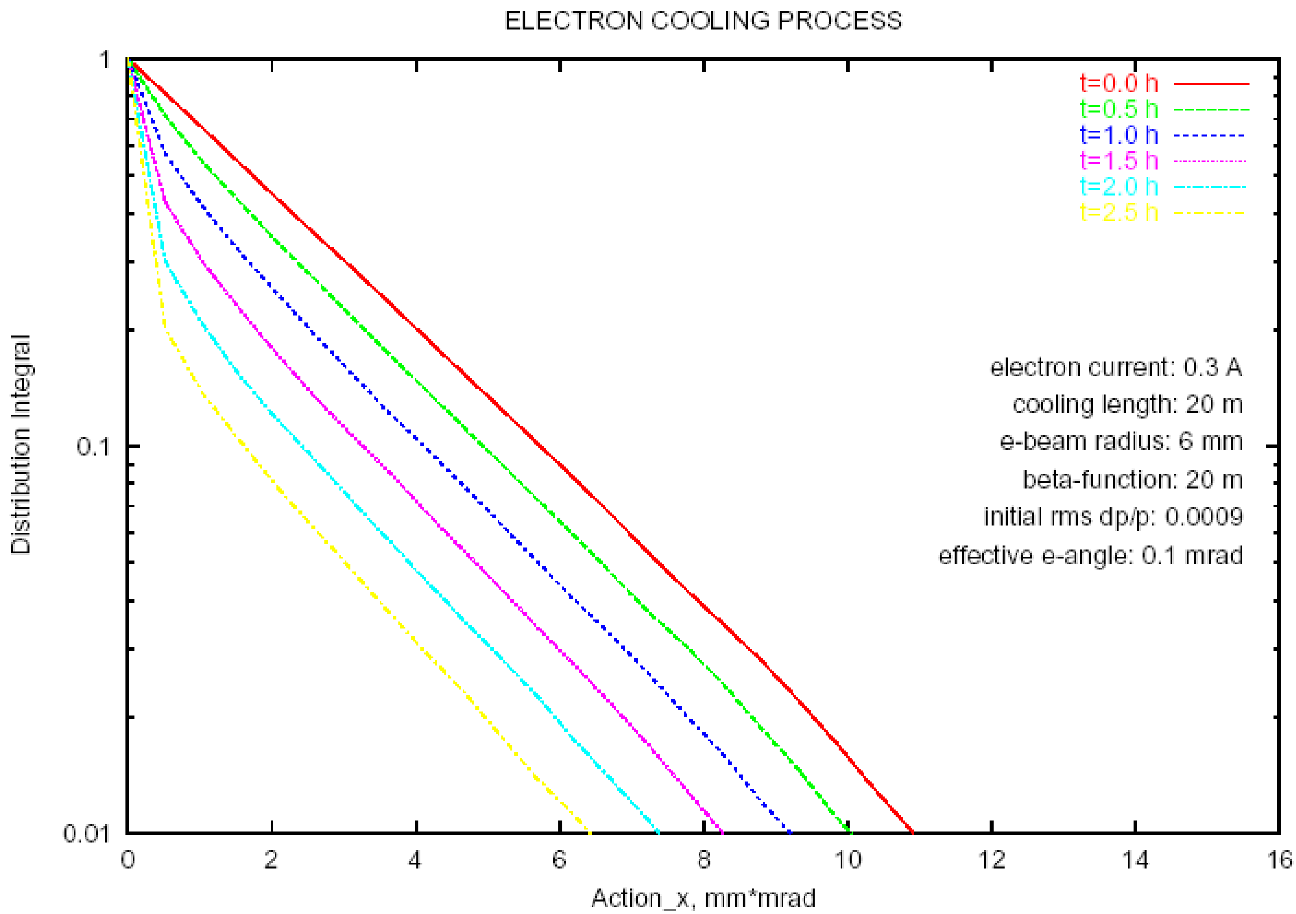
Evolution of the longitudinal emittance



The initial distribution is parabolic with a 400 eV-s (total) emittance

The initial cooling rate: 22 eV-s/hr per 100 mA electron current

Evolution of the transverse emittance



The initial distribution is gaussian with a 15 π mm-mrad (n, 95%) emittance

The initial cooling rate for a 15 π mm-mrad beam: 1.2 π mm mrad/hr per 100 mA

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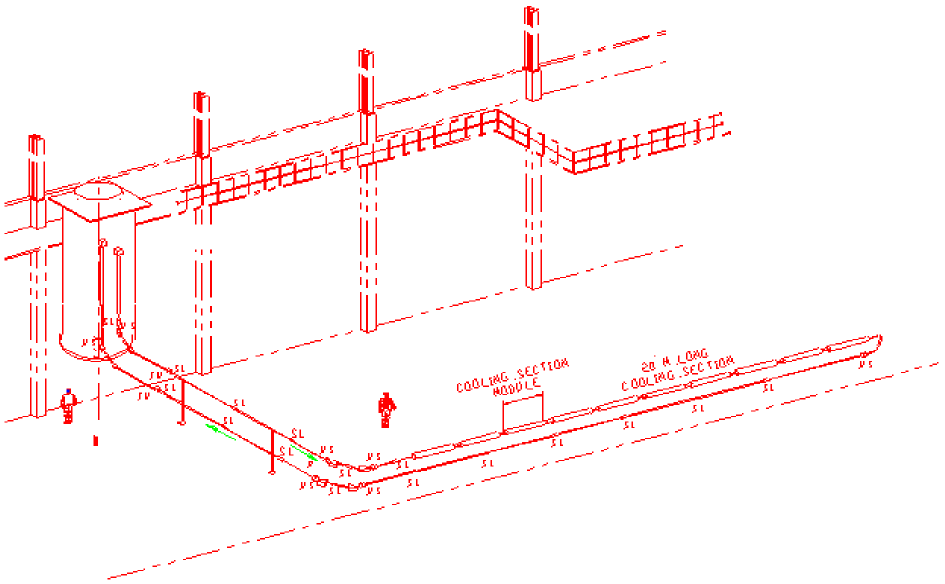
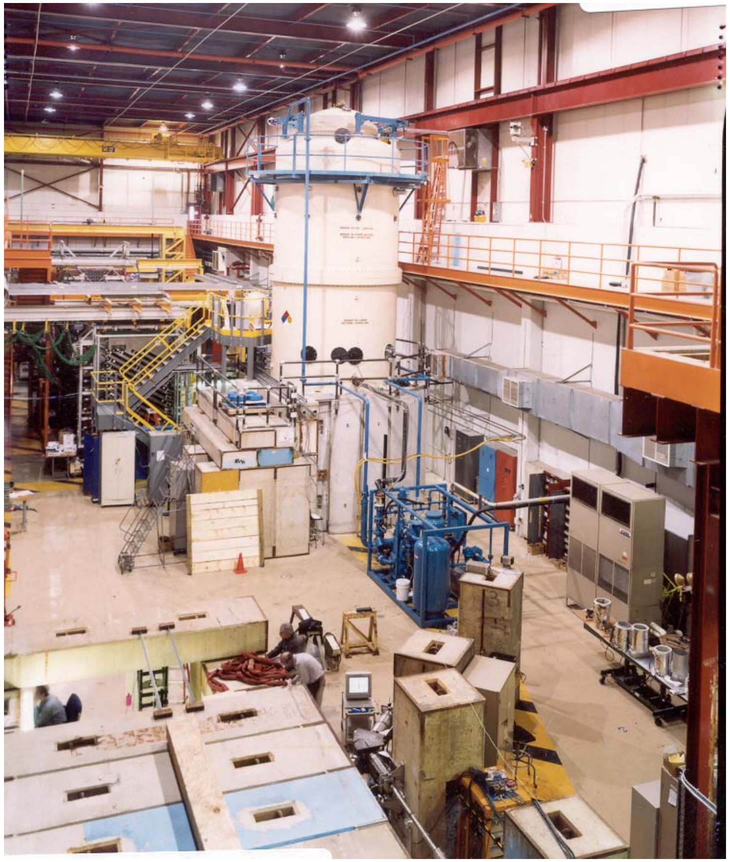
Electron cooling test facility at WideBand building

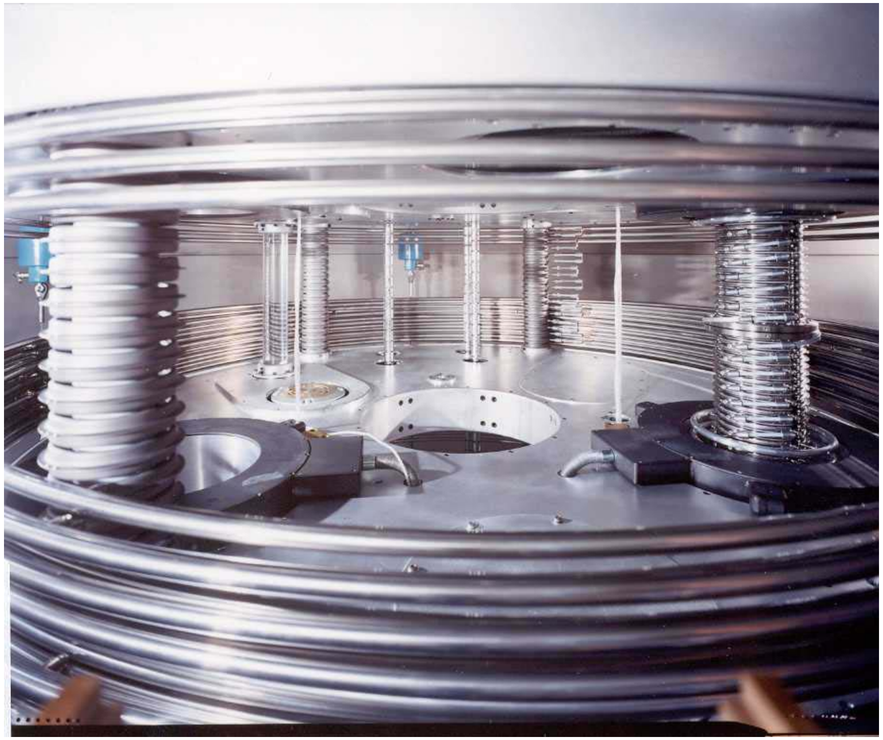
- A 5-MV Van de Graaff accelerator (Pelletron) has been purchased and installed at WideBand building at Fermilab. This accelerator together with an electron beamline form an R&D facility.
- This facility has been constructed to perform the R&D needed for the installation of the Electron Cooler in the MI/RR tunnel.
- A prototype beamline closely resembles the final beamline. Most of it elements will be reused in the MI/RR tunnel.
- All of the Pelletron equipment will be reused.



Fermilab Electron Cooling R&D Facility



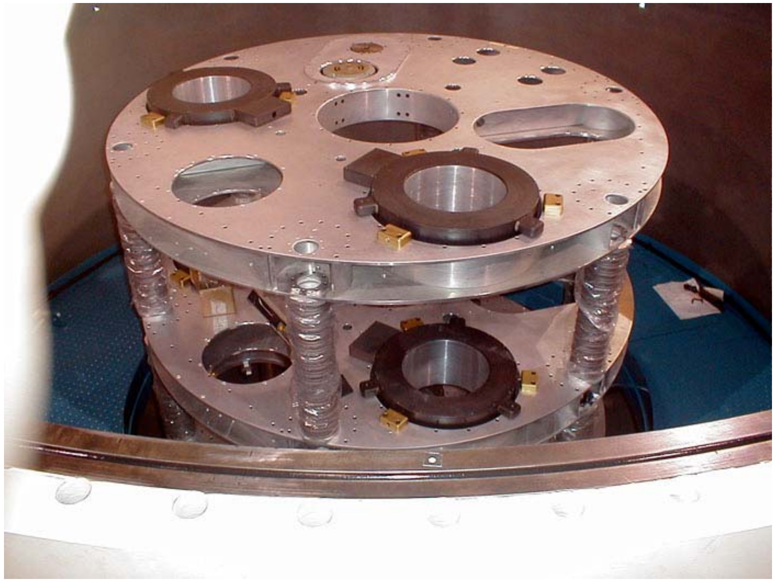
5 MV Pelletron installed



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.

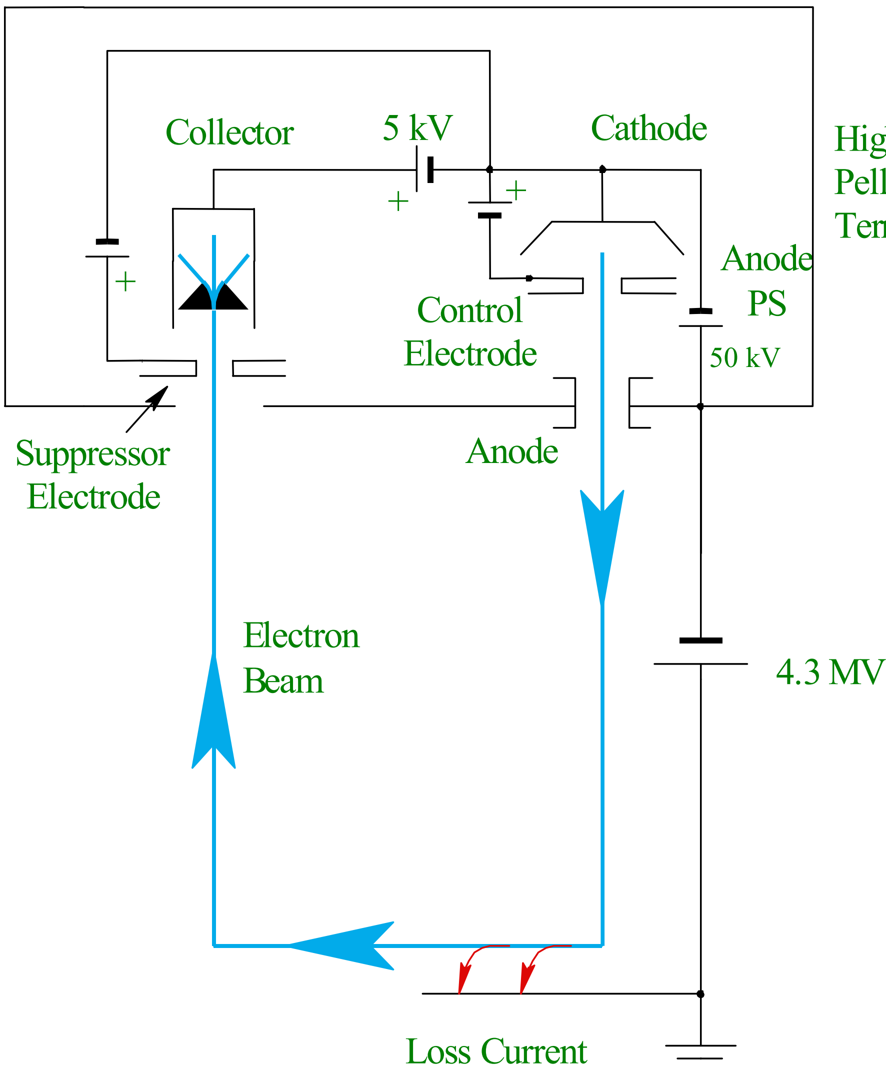


Structure inside the tank -- separator boxes and beam lenses. No beam tubes were installed at the time of this photo.

Electron Cooling R&D
Project Goals

	Goal	Achieved?
• Recirculated electron beam current	0.5 A	YES
• Electron beam kinetic energy	4.3 MeV	YES
• Beam angular spread (cooling section)	80 μrad	Not yet
• Magnetic field at the cathode	600 G	YES
• Beam diam. at the cathode	5 mm	YES
• Energy spread (FWHM)	500 eV	YES
• Pressure (cooling section)	1×10^{-10} Torr	Not yet
• Recirculation stability (ave.)	1 hour	NO (2-20 min) > 1 hour max.
• Beam recovery time	5 min	YES (20 sec)
• Typical time between tank openings	1 month (initial) 6 months (final)	YES

Simplified electrical schematic of the electron beam recirculation system.



For I= 0.5 A, ΔI= 5 μA:

- Beam power 2.15 MW
- Current loss power 21.5 W
- Power dissipated in collector 2.5 kW

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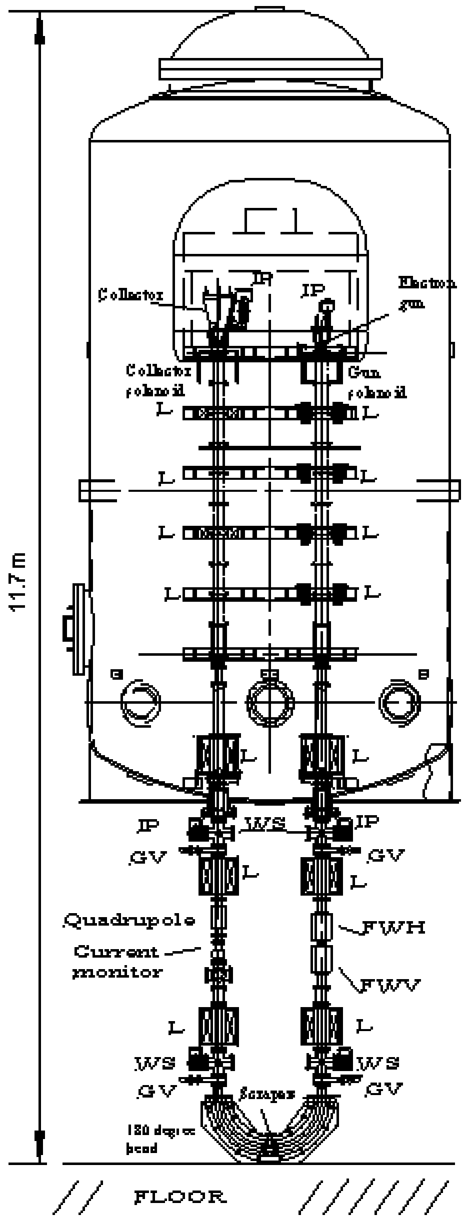
Electron Cooling R&D Facility at WideBand
(Recirculation experiment)



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 lab.

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.

Jan 02: Reached stable 500 - 600 mA beam at 3.5 MeV

Apr 02: NEC replaced acceleration tubes

Oct 02: Reached 500 mA at 4.36 MeV, stability still poor

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Beam recirculation stability

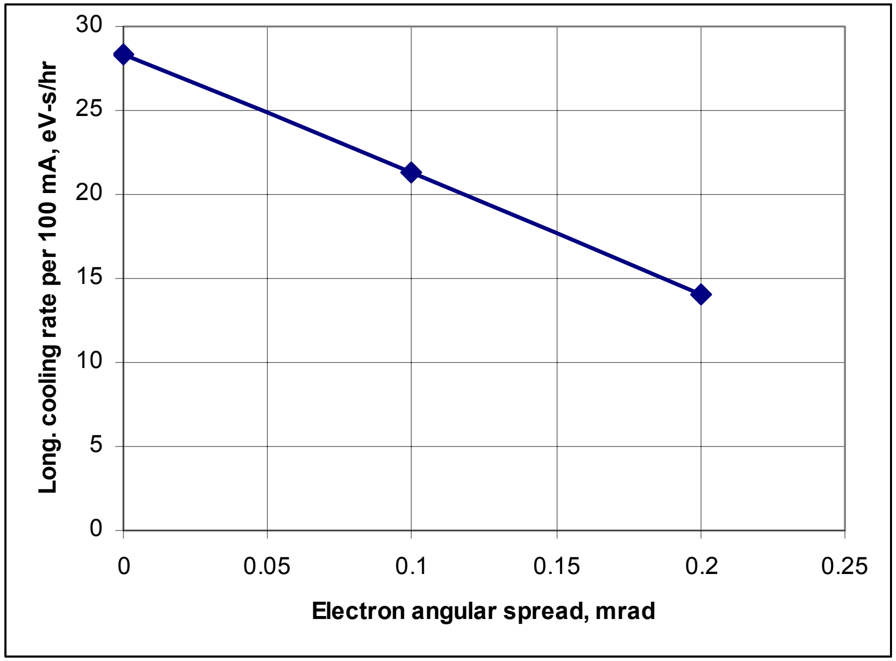
- The recirculation is always intrinsically unstable. All prolonged periods of operation at high beam currents end with a beam abort.
- There are two types of beam abort (recirculation interruption) events:
  - A benign loss of beam while the terminal voltage drops by 50-100 kV;
  - A full spark, when the terminal voltage goes essentially to zero and a large amount of gas (mostly H_2) is released. This can lead to HV deconditioning.
- Our results are:
  - 20 min (aver) between interruptions with a 20 sec recovery at 3.5 MV;
  - 2-4 min between interruptions at 4.34 MV.
- The stability is improved if one has a better vacuum, an effective ion clearing system and a lower electric field in the tubes.
- We have ordered an additional 1-MV acceleration section to reduce the electric field and to improve the stability.

What next?

- We have completed our tests with a short U-bend beam line. We believe that at a reduced electric field and with some additional modifications (under investigation) the stability will be good enough.
- We are currently completing the installation of a full-scale beam line. The switch-over is planned for November, 2002.
- Based on our results with a short beam line, we decided to begin the construction of a building near MI/RR tunnel on Mar. 1, 2003. While the building is being built we will finish the beamline commissioning at the test facility.

Beam quality in the cooling section

- Angular spread of < 0.1 mrad
  - ✓ Cooling section solenoid field quality
  - ✓ Aberrations in the beamline
  - ✓ Stability of the antiproton orbit
  - ✓ Stability of the electron optics
  - ✓ Emittance and space charge
  - ✓ Stray magnetic fields.
- We plan to measure the electron angular spread by measuring beam position and beam envelope in 10 points along the cooling section.



Beam transport line

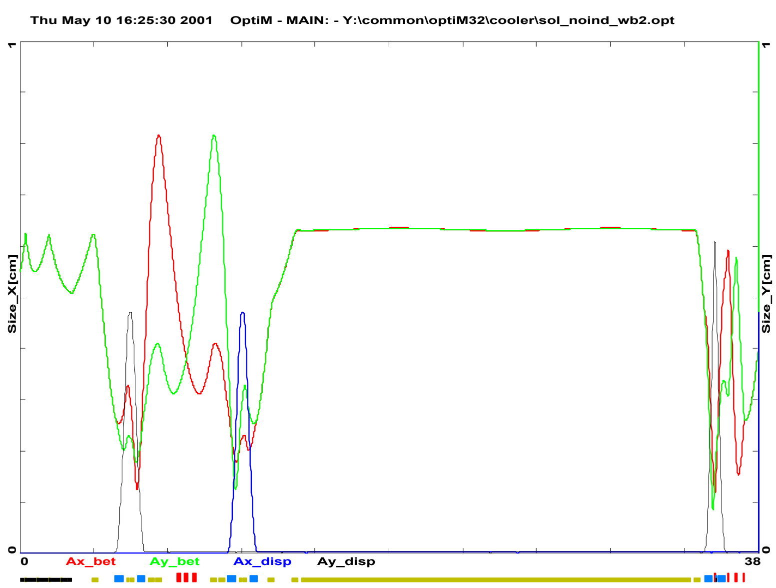
- Angular momentum dominated beam transport
  - Beam transport optics from the exit of the gun solenoid to the entrance of the cooling section is dictated by three beam properties:

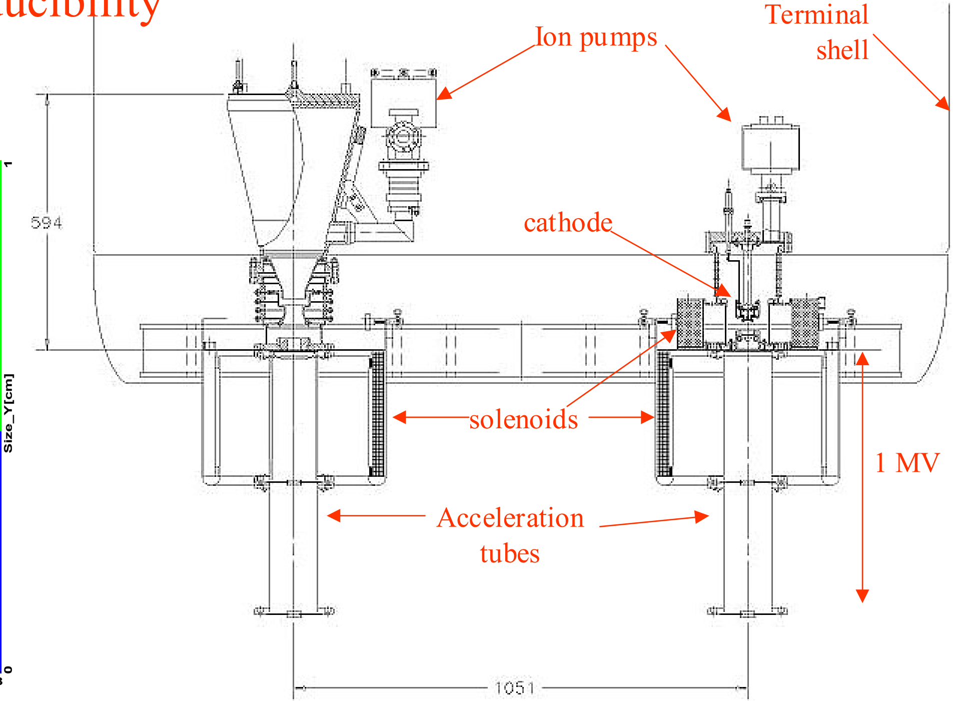
    (1) A large emittance-like contribution from the angular momentum

    $\varepsilon_{N,eff} = eBr_c^2/(2mc^2)$. 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





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Cooling section solenoid

- consists of 10 identical 2-m long solenoids, separated by instrumentation gaps

Total length	20 m
Magnetic field	50 - 150 G

The cooling section solenoids are being currently mapped by a compass-based field sensor and the field quality will be adjusted using corrector coils to meet our design criteria.

An artist's rendering of a proposed building (MI-31) next to the existing service building (MI-30).

The MI-31 building will house the Pelletron and the electron beam line.

The bidding package went out and the "Notice to Proceed" is expected on Mar. 1, 2003

It will take about 330 days to complete the construction. The tie-in portion of the project requires a 6 week MI shut-down and may or may not be executed during the construction project.

An additional installation shut down will be needed to install all the beamline components in the tunnel and to map and correct the cooling section solenoid field in situ.

Conclusions

- The Fermilab high energy electron cooling project has not encountered any "show stoppers" thus far. Many technical hurdles delayed us but the progress was steady.
- Other high energy laboratories will benefit from our R&D program. Additional cooling could be also provided for the Fermilab antiproton Accumulator.