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J.A. MacLachlan

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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THE FERMILAB RECYCLER — AN 8 GeV PERMANENT MAGNET STORAGE RING WITH ELECTRON COOLING

J. A. MacLachlan
Fermi National Accelerator Laboratory
Batavia IL 60510, USA

The Fermilab Recycler is an 8 GeV storage ring of 3.3 km circumference being installed in the same tunnel as the Main Injector (MI) 150 GeV synchrotron. The MI will be completed in 1998 and the Recycler will be completed and commissioned during 1999. The Recycler will increase the supply of $\bar{p}$'s for the Tevatron collider by stacking multiple batches from the existing Accumulator ring and by recovering and cooling the $\bar{p}$'s remaining at the end of a collider store. Besides its interest for contribution to improved Tevatron luminosity, it has novel technical features which may warrant other application. Almost all of the magnets are strontium-ferrite-excited, iron-dominated, permanent magnets of very economical design. The stacking, recovery, and cooling scenarios involve rather intricate manipulation of the longitudinal phasespace distributions with a broadband rf system. Initially, all of the cooling will be provided by stochastic systems. Constraints imposed by the MI tunnel result in a lattice with undesirably large dependance of circulation period on momentum; the longitudinal cooling in particular is limited by this difficulty. An electron cooler is being developed to replace the longitudinal stochastic cooling. At the higher fluxes foreseen within the next six years, electron cooling will likely replace the stochastic systems for the transverse motion also. The electron beam required is approximately 0.5 A at 4.3 MeV in a 20 m cooling region, favoring a system which departs from conventional practice in several respects. However, many system parameters are similar to those for existing low energy coolers.

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1 Overview

Construction of the Fermilab Main Injector (MI) started in 1992 and is to be completed in 1998. In 1997 the project was augmented by the approval of the Recycler ring as an engineering change. The Recycler[1] is an 8 GeV storage ring hung from the ceiling of the MI tunnel. It has a dual role as a second stage accumulator for antiprotons from the existing Antiproton Source and as a cooler for the antiprotons that remain at the end of a colliding beam store in the Tevatron. The stored protons are scraped away at store energy and the remaining $\bar{p}$'s decelerated in the Tevatron and MI to 8 GeV. Half or more of the original $\bar{p}$'s can be recovered, effectively doubling the available $\bar{p}$ flux.

There are some unusual aspects to the origins of the Recycler. Although additional-ring proposals for recovering antiprotons had been discussed for years, the MI project was well underway in 1994 with no active plans for this capability. At this time Fermilab and the whole US high energy physics community was reassessing future options in the wake of the cancellation of the SSC project. In an atmosphere where new initiatives were clearly needed but new funding was not in evidence, two or three energetic physicists conceived and promoted the idea of an inexpensive storage ring in the MI tunnel. It seemed clear already that the MI project had an unnecessarily large contingency allocation, and the hope of directing those funds toward enhanced capability drove the design for a ring that could

Figure 1: This aerial view of part of the Fermilab site shows the ring road and cooling ponds of the Main Injector at the lower left, the Antiproton source just above center, and part of the Tevatron berm, road, and cooling ponds to the right.

be built within the overall project budget and realized within the project schedule. Both the cost and the tight schedule led to the development of the simple permanent magnets used in the ring. It is something of an anomaly to go from concept to comissioning of a 3.3 km storage ring with new technology in less than five years. That the Laboratory could and should build this ring was readily accepted within the Laboratory; that the Department of Energy supported this grass-roots initiative is a credit to that organization, occasionally disparaged for unresponsive bureaucracy.

The Recycler concept included electron cooling from the beginning, but scepticism about meeting the schedule and a lack of manpower favored use of stochastic cooling, a familiar and proven technique. The development of an electron cooler has continued as a small-scale special project. The combination of some success in producing suitable beam current at lower energy in a test at National Electrostatics Corp. in Middleton WI [2] and modelling efforts has dispelled most of the doubt about the practicability of an electron cooler with substantially greater cooling power and stack current capability. The idea to proceed with building a cooler has established credibility, but schedule and funding are not established. The physics research program has need for collider luminosity higher than that planned for the coming run by a factor of four or more in a few years. Electron cooling can make a big contribution to luminosity improvement, but to make the maximum contribution to the physics program, a prompt commitment is required. The technical case is strong, although there are of course risks inherent in new approaches. The physics opportunities offer a major return on an effort of moderate scale and moderate risk. The cooler could be comparable in cost to the Recycler itself and give a similar performance multiplier; decision time is nigh.

There is more than one reason to describe the Recycler to a seminar honoring Budker and the Budker Institute. An obvious one is the intent to exploit electron cooling for $\bar{p}$-p collisions, the inspiration for Budker's invention over thirty years ago.[3] Another point, one that there will not be adequate time to develop in detail, is some striking similarity between the institutional cultures at Fermilab and BINP that made the undertaking feasible. Note in what follows the exploitation of new technology to make economical accelerator systems. Note that the technology, while new, is no more high-tech than absolutely necessary; much of the component fabrication is done within the Laboratory. It is reported that Budker was one of the accelerator builders and laboratory leaders most admired by Fermilab's founding director Bob Wilson. That admiration was reportedly reciprocal. It is a legacy of Wilson's emphasis on fresh approaches and minimal elaboration that has made it possible to build an entire storage ring from savings on a synchrotron of similar scale. It was the openness of the Laboratory culture that allowed the progression from bright idea to realization in a very short time. There are many contrasts between Fermilab and Budker institute, but there are also similarities in inovativeness and intellectual openness which underlie much of the accomplishment at both. The view of the Main Injector tunnel in Figure 2 shows two of the Recycler gradient magnets in place and a number of empty hangers. They even look a little like VEPP4. All of the magnets should be in place by the end of 1998.

Figure 2: Main Injector tunnel during Recycler installation. Two Recyler gradient magnets and a number of hangers can be seen attached to the ceiling. The magnet installation will be completed in 1998.

2 $\overline{\mathrm{p}}$ Flux and Tevatron Luminosity

Figure 3 shows typical Tevatron luminosity in $\mathrm{pb}^{-1}\ \mathrm{wk}^{-1}$ at three times past and three points for projected need over the next eight years. The plot is a semi-log plot reminiscent of the so-called Livingston plot of accelerator energy *vs*. time. For Fermilab it is Tevatron luminosity that is in the youthful phase of exponential growth, with a doubling time of about 2.3 years. The first projected point is for operation with the MI and the Recycler using stochastic cooling only, the second reflects the initial goal for electron cooling, and the third represents another doubling to a level labeled TeV33 because it corresponds to peak luminosity about $10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. Electron cooling is the principal technical means to the second and third projected points. Because the antiproton supply is limited, the collider is run with the maximum number of protons per bunch allowed by the $\overline{\mathrm{p}}$ tune shift. With the beams already focused transversely to about the practical limit, the only way to significantly increase the luminosity is to use more $\overline{\mathrm{p}}$'s per bunch or to raise the number of bunches of both species. Therefore, practically, luminosity increases in proportion to the $\overline{\mathrm{p}}$ supply. Electron cooling does nothing, of course, to increase $\overline{\mathrm{p}}$ production, but it improves a critical link in the supply chain between the target and the collider. Already at the fluxes of about $7 \cdot 10^{10}$ $\overline{\mathrm{p}}$/hr that have been obtained to date, the accumulation becomes less efficient as the stack in the Accumulator grows toward 10^{12} $\overline{\mathrm{p}}$. The Recycler provides a larger ring for building up bigger stacks, and it is also capable of receiving $\overline{\mathrm{p}}$'s returned after a store.

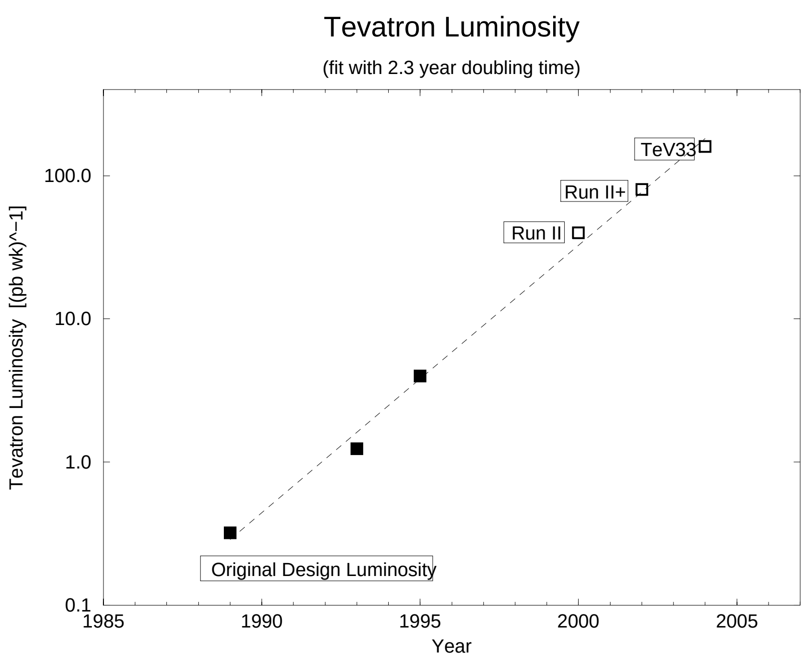

Figure 3: Tevatron collider luminosity past and projected on a semi-log scale in the manner of the Livingston plot for accelerator energy. The doubling time is apparently just over two years.

The new Main Injector is the source of protons for $\overline{\text{p}}$ production (at 120 GeV) and for the colliding bunches in the Tevatron (at 150 GeV). The 8 GeV $\overline{\text{p}}$ from the target are received at approximately 1.5 s intervals into the Debuncher where the momentum spread is reduced from about 4 % to about 0.3 % by a phasespace rotation and both transverse and longitudinal stochastic pre-cooling are applied. The antiproton beam is stacked in the Accumulator ring. The transverse emittance is reduced by about a factor of ~ 20, but the longitudinal phasespace brightness is raised by a factor of about 10^5 during the stacking period of one half hour. At the end of the stacking, the cooled core of about $2 \cdot 10^{11}$ is injected into the Recycler. These figures correspond to the $\overline{\text{p}}$ flux goal for the Recycler with electron cooling.

Figure 4 indicates the $\overline{\text{p}}$ intensity in the Recycler over the period of a collider cycle. It shows an intensity of $5 \cdot 10^{12}$ cooled $\overline{\text{p}}$ at the beginning when the experimental use of the preceeding store is complete. After a few minutes to scrape away the remaining protons, the stored beam is decelerated to 150 GeV and injected into the the MI in nine separate batches for deceleration to 8 GeV and injection into the Recycler. Each on of those injections corresponds to the steps in the increase to $7.5 \cdot 10^{12}$, and each injection is separated from the cold stack and compressed into less than ten percent of the azimuth by the rf system to make room for the batch to follow. The resetting of injection conditions for the Tevatron takes a little less than an hour; then the stack is delivered to the Main Injector in nine separate batches for injection into the Tevatron. Each batch is bunched in the Recycler with the interval needed in the Tevatron. For about an hour, while physics running has started in the Tevatron and $\overline{\text{p}}$'s are being stacked in the Accumulator, the stochastic cooling in the Recycler brings the transverse spread of the recycled beam into a range where the electron cooling will work efficiently. Then over the next six hours or so the Accumulator delivers batches of $2 \cdot 10^{11}$ $\overline{\text{p}}$ every half hour.

There are several technical challenges in the scenario outlined above, including high flux targeting and high gradient lithium lenses, on which BINP is a current or past collaborator. This talk, however, singles out the Recyler storage ring itself and the electron cooling planned for it.

3 Features of the Storage Ring

Because the Recycler is built in the Main Injector tunnel, which is in general only 3 m wide, the lattice is constrained to a layout similar to the MI, and the transition energy is likewise nearly 20 GeV. To reduce the cost, the ring magnets are low-field gradient permanent magnets described just below. Even with bend field of about 0.14 T, the 3.3 km circumference remains sparsely filled. The view of the Main Injector tunnel in Figure 2 indicates the limited impact of the second ring. There are 54 normal arc and 18 dispersionless cells of 34 m and 32 dispersion supresser cells of 26 m. The standard arc cells consist of four 4.4 m gradient magnets of 29 cm (w) $\times$ 23 cm (h) cross section hung about 19 cm below the ceiling of the 2.4 m high tunnel. The standard cell lengths are manipulated in part of the ring to avoid interference with the MI rf by creating a 46 cm radial offset. At this special region electromagnetic quadrupoles are installed in a so-called phase trombone to adjust the betatron tunes over a range ± 0.5. Table 1 is the conventional parameter list for the Recycler.

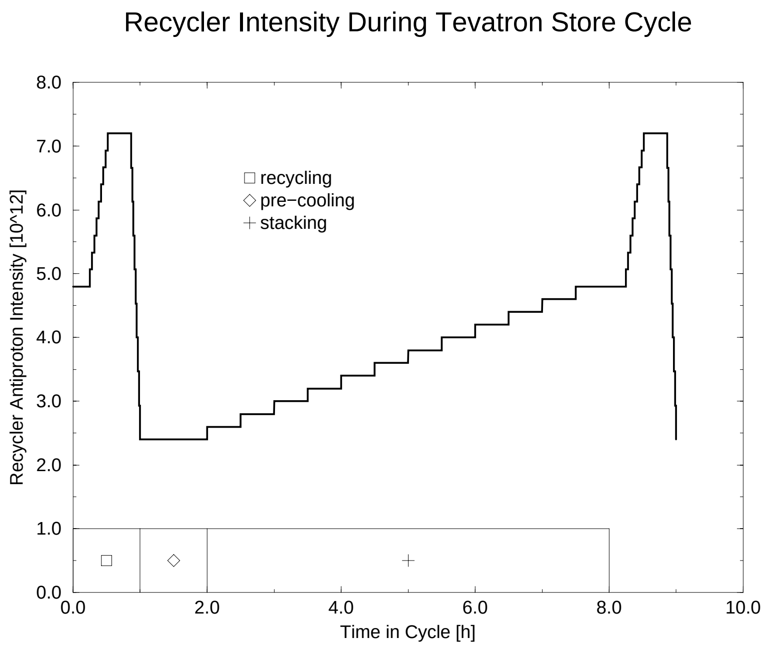

Figure 4: Recycler beam current over a full store cycle starting at the setup for a new store

3.1 Permanent magnets

A key to both fast schedule and low cost for the Recycler is the adoption of permanent magnets. A schematic exploded view of the gradient magnet components appears in Fig. 6. The 10 cm wide strontium ferrite bricks are separated by Ni-Fe alloy strips which practically eliminate the temperature dependence of the magnetic field by acting as a temperature sensitive flux shunt. The flux return is standard structural plate; the only precision machining required is for the pole tips which include a chromaticity correcting sextupole component in addition to the gradient. The ferrite bricks are an industrial commodity similar to that used for ion pump magnets. The bricks are magnetized and sorted into approximately matched sets providing $3-5$ % excess field integral. A final strength trim is made by adjusting the ferrite at the magnet ends. The integrals of the field harmonics are also adjusted by pole end-packs to achieve 10^{-4} precision in the field integral across an aperture 8.9 cm $\times$ 4.4 cm whereas random longitudinal field variation of ± 5 % is accepted.

Despite the individual adjustments, the magnets are not labor-intensive. They are economical in material and, of course, do not require low-conductivity water, power connection, or controls. The elimination of these distributed systems for much of the Recyler not only substantially reduces the capital cost, but it will greatly enhance reliability by eliminating common sources of accelerator failure. The Recycler should rarely lose its stack; should it do so, operation could be quickly restored at reduced intensity with the $\overline{\mathrm{p}}$'s from the Accumulator the Tevatron.

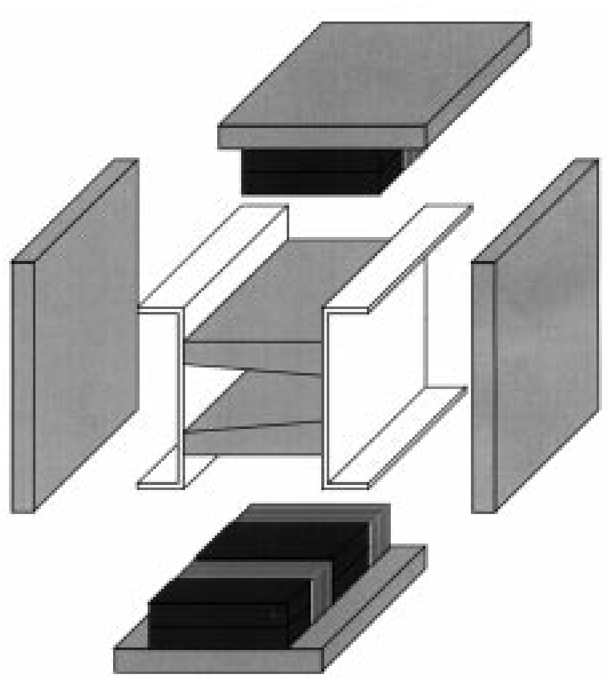

Figure 5: The Recycler gradient magnet in exploded view. For every four inch wide strontium ferrite brick there is a one-half inch interval of temperature compensating material consiting of iron-nickle alloy with a low Curie temperature.

3.2 Broadband rf system

The Recycler must segregate new Accumulator batches from the stack, the stack from recycled beam, recycled batches from one another, *etc*. These different populations must be integrated in a controlled, adiabatic fashion to avoid dilution of the longitudinal phasespace density. This requires a linear broadband rf system to provide multiple excluded regions, hereafter called barriers. The rf waveforms to control the longitudinal distributions are applied across four ferrite loaded 50 ohm gaps. With a passband from 10 kHz to 100 MHz and a peak voltage capability of 2kV, it is possible to isolate several sectors of the azimuthal distribution with energy spread up to about ± 20 MeV. The wide passband allows nearly rectilinear waveforms which maximize the barrier height for a given peak voltage. All of the many different waveforms are synthesized at low level by a direct digital synthesizer which can change from one practically arbitrary waveform to another with phase continuity.

The process of adding a batch from the Accumulator to an existing stack is a typical example of the required beam manipulations. The stack with a height of roughly ± 3 MeV fills the circumference of the Recycler except for a short gap for ion clearing maintained by a single period square wave. The gap is enlarged to one seventh of the circumference to make room for the new batch by replacing the single barrier by a pair which are moved apart adiabatically. One barrier is lowered to just maintain the separation of stack and new batch. Then the other barrier is moved toward it to spill the batch uniformly along the top and bottom of the stack. When the spill is complete the remaining barrier is adjusted to reestablish the correct clearing gap. Done sufficiently slowly, the process is the inverse of adiabatic capture and provides merging without dilution, unlike conventional rf stacking onto a coasting beam.

3.3 Stochastic cooling systems

The Recycler has basically the lattice of the Main Injector and approximately the same transition energy. Consequently the time dispersion, $\eta = \gamma_T^{-2} - \gamma^{-2} = -8.7 \cdot 10^{-3}$, is large. Both transverse and longitudinal systems would have better performance at lower η. However, because electron cooling was the initial choice, there was no reason to attempt a special low-γ_T lattice.

The longitudinal cooling system will be of the notch filter type; the top frequency that can be used is set by the condition that the Schottky bands should not overlap. For the Recycler this puts the top frequency at 2 GHz and therefore places a severe limit on the bandwidth. One longitudinal system will operate in the frequency band 0.5 – 1.0 GHz and a second in the range 1.0 – 2.0 GHz. Because the $\overline{\text{p}}$ transverse temperature is 30 – 50 times the longitudinal temperature, only the longitudinal intrabeam scattering (IBS) is significant. The IBS diffusion and the demands of longitudinal phase space stacking make the performance of the longitudinal system especially important. It is the performance of this system which appears to limit the Recycler to flux of about $2 \cdot 10^{11}$ $\overline{\text{p}}$ per hour and argue for the importance of following through with the original plan for electron cooling.

The horizontal and vertical betatron cooling systems operate in the band from 2.0 – 4.0 GHz with some overlap of the Schottky bands at the upper end of the range. The upper frequency limit is set, however, by mixing between pickup and kicker. This so-called bad mixing is minimized by separating the pickup and kicker by only about one sixth of the circumference and using optical transmission along the cord between them. The transverse cooling has margin to accommodate higher flux than the longitudinal system. The electron cooling will be easier to build if it does not need to provide the principal transverse cooling for the recycled $\overline{\text{p}}$'s.

3.4 Status

The Recycler is under construction with major installation to be completed in 1998. Minor installation and commissioning will take place during the commissioning of the Main Injector in 1999. The first run with the MI will be a fixed target run starting in the Spring of 1999 for which the Recycler is not used. The earliest need for a fully functional Recycler is late 1999.

4 Electron Cooling

Fermilab stopped active development in low energy electron cooling about fifteen years ago and dropped work on medium energy cooling nearly ten years ago. However, the designers of the Antiproton Source were aware that electron cooling could be used to improve the stack intensity in the Accumulator.[4, 5] It was with the birth of the Recycler idea and the push to secure a hadron collider program in the aftermath of the termination of the SSC project that the old proposal received an attentive hearing. The technique could have been developed twenty years ago, but it is the more recent experience with the power and limits of stochastic cooling that makes a strong case for developing it now.

4.1 Cooling at medium energy

To those who worked so hard to get good cooling at low energy, the dependance of the rate on energy made medium energy cooling seem very challenging. A scaling formula for the approximate cooling time is

$$t_{\rm cool} = \frac{\gamma^2 a^2 \beta e \varepsilon_{\perp \rm n}^3 C}{120\pi^3 r_{\rm p} r_{\rm e} x^3 I_{\rm e} \ell_{\rm c}} \quad ,$$

where a and x are the electron and proton beam radii, r's are classical particle radii, $I_{\rm e}$ is electron beam current, ℓ_c is the length of the cooling section, C is the circumference, γ and β are Lorentz parameters for the velocity of the beam frame. However, it turns out not so bad as the first impression. True, at 8 GeV one pays a factor of about 100 penalty in the rate, but, for example, the space charge force is reduced by a factor of 1000, making a solenoid to control the space charge divergence of the beam an almost trivial object. An easy, low-field solenoid has a couple of important advantages, *viz.*, it's not so hard to make it long and it can be introduced just at the cooling region without nonlinear correction for the end field. Finally, low rate is not the issue it would be in a cooler with target; the stacking interval is many minutes, and the required energy spread reduction between batches is less than twenty percent. There are problems, perhaps some unforeseen, but so far, the more the concept is examined, the better it looks.

4.2 System concept

Fermilab has no history in MV level electrostatic accelerators, but a general feature of the advice received is that an extension or modification of current practice normally requires a long and tedious empirical development process. Therefore, a guiding principle in selecting the approach to develop a working cooler in four years or so has been to select a highly developed high voltage generator with a good service record and change as little as possible in it. The Pelletron manufactured by National Electrostatics Corporation appears to be well suited on the bases of robust charging system, high gradient acceleration tubes with excellent vacuum characteristics, and acceptable cost. The plan for the Fermilab cooler is to locate a 5 MV vertical Pelletron beside the MI tunnel and run a conventional beam transport to and from the cooling interaction region. The terminal at -4.3 MV would contain an electron gun immersed in a 200 G solenoid, which would also enclose about the first 500 kV of the accelerating tube. Two more short solenoids along the accelerating tubes are used to maintain nearly constant beam envelope radius. Parallel to the accelerating column runs an identical column for decelerating the return beam to a collector in the terminal. The collector is a conical Faraday cup with an entrance solenoid of about 100 G and transverse field over the volume of about 100 G to eliminate loss of secondaries; it is biased at about 5 kV positive from the gun cathode. In Figure 6 is a schematic drawing of a 5 MeV Pelletron configured for recirculating electron beam which would be suitable for this design.

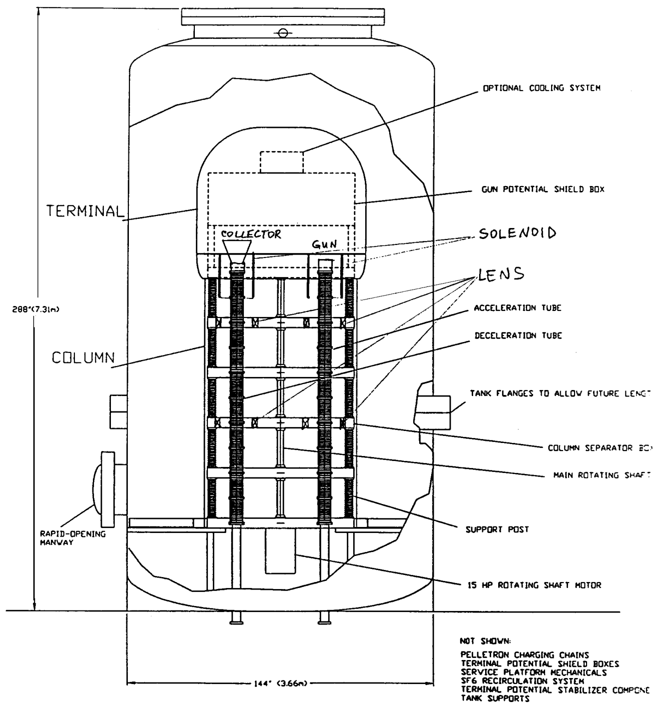

Figure 6: Schematic of a 5 MeV electrostatic accelerator of the Pelletron type configured for recirculating electron beam

The 20 m interaction region is located in a 100 m long straight section of the Recycler. An insertion will be installed to match the $\overline{\rm p}$ beta functions to the cooling section length. The cooling section will be enclosed in nearly continuous 50 G solenoids. At this field the electron beam matched to the $\overline{\rm p}$ beam will enclose the same flux it enclosed at the gun cathode. The solenoid is far too weak to produce magnetized cooling, but sufficiently strong to stabilize the beam against coherent transverse motion and to counter space charge defocusing. Having such a low field leads to two important simplifications in the design. The pitch of the Larmour spiral is about the same as the 20 m length of the interaction region, so small discontinuities between segments for current leads, instrumentation, *etc.* will not affect the beam. Secondly, the end fields are so weak that no nonlinear correction is required to preserve emittance. Therefore, the solenoid will consist of 1 – 2 m segments of two layer coils. Alignment is required to $< 100\mu$rad, but the simple structure may make the necessary precision possible by construction, without adjustment. Time-dependant stray field from the MI is an important concern, but, so long as beam centroid positions can be measured accurately enough for the needs of electron cooling alignment, the effect of stray fields can be controlled, dynamically if necessary. The general system parameters are collected in Table 2 and the beam characteristics in Table 3.

4.3 Progress in modelling and laboratory development

What has been described is a concept for which a full design does not yet exist. Nonetheless, the focus of the development studies which began in 1995 has narrowed to a single basic scheme and both laboratory studies and design calculations are recognizably converging on a clear development path.

The principal challenge of medium energy cooling has always appeared to be the necessity to recover a large fraction of the electron beam energy to make the high voltage power supply feasible. In 1996 Fermilab started to work on electron beam recirculation using an old Pelletron at National Electrostatics in Middleton WI. Budker Institute entered into this activity, initially to provide a gun and collector, eventually taking active part in the studies. These experiments have provided some important practical lessons, but it will only be possible to report the quantitative results here and refer to conference papers for precedents and details.[2, 6] Electron current up to 225 mA has been achieved for intervals of a few seconds, and 100 mA current can be maintained for hours. The available Pelletron limits the beam energy in these tests to 1.2 – 1.5 MeV. Substantial improvement on this performance is expected with a new machine and the benefit of experience gained.

Numerical and analytical studies have been devoted to verifying cooling rate projections and optimizing system parameters. They have contributed substantially to the overall confidence in the consistency and practicability of the scheme. Some useful development of the familiar binary collision model (sometimes called Novosibirsk model) has been made in the course of focusing on the special requirements of the Fermilab project; it will be discussed in a forthcoming publication.[7] Looked at in the beam frame, there is not a whole lot of difference between medium energy cooling and the low energy precedents. Primarily what differentiates the regimes is the hardware to get a good electron beam at 4.3 MeV and the γ^2 penalty in the rate going from beam frame to lab frame.

5 Prospectus

For the Recycler itself the decisions have been made, the magnets are being installed, and its effectiveness as a stochastically cooled $\overline{\mathrm{p}}$ accumulator should be clear in one to two years. For the electron cooling upgrade, the concept has achieved credibility, but considerable work is needed to support a final project proposal. For example, little work has been done on the detailed optics design in the transport and interaction regions. Some numerical modeling of the acceleration section has been done but must be extended to deal with the planned magnetic field at the cathode. There is no engineering concept for the interaction region, and the thinking on instrumentation has scarcely moved beyond pious acknowledgement. The desired time scale for the development means the Laboratory faces an imminent (or possibly overdue) decision to raise the scale of commitment. The current development group is promoting the purchase of a 5 MV electrostatic accelerator this year. The claim is that only with prototype development effort at full beam energy will it be possible to work out an operational design on an attractive time scale. If the purchase and the addition of some manpower is delayed into 1999, the programmatic motivation will start to wane. This is a brief but strategic opportunity to realize Budker's vision of thirty years ago to use electron cooling of $\overline{\mathrm{p}}$'s to open new horizons in high energy physics. The flexibility and imagination reflected in the launching of the Recycler effort is an encouraging demonstration that Fermilab can move decisively from concept to new technology when there is clear contribution to the mission of high energy physics research; medium energy electron cooling is such a target of opportunity.

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Epilog

Between the presentation of this paper and its eventual transmogrification to the written word, events have caught up with some of the speculation. In mid October the decision was made to purchase a Pelletron and enlarge (somewhat) the development team. Some analysis of longitudinal intrabeam scattering in the Recycler has disclosed that it had been over-estimated by its designers. Thus, the stochastic cooling in the Recycler should work better than previously expected, and the boundary conditions for the optimization of the electron cooling and the probable date for its routine use have changed. The maximum current obtained in the electron beam recirculation tests has reached 680 mA, the limit of the gun currently installed; 200 mA can be circulated indefinitely.

Table 1: Technical parameters for the Recycler

Circumference	3319.4			m
Momentum	8.889			GeV/c
Max. C-S β	55			m
Max. dispersion	2.0			m
Horiz. phase advance per cell	86.8			degree
Vert. phase advance per cell	79.3			cm
Horiz. tune	25.425			
Vert. tune	24.415			
Horiz. chromaticity	-2			
Vert. chromaticity	-2			
Transition γ	20.7			
Transverse admittance	40			π mm-mrad
Momentum aperture	1			%
Superperiodicity	2			
Number of major straight sections	8			
Number of standard cells in straight sections	18			
Number of standard cells in arcs	54			
Number of dispersion supresser cells	32			
Length of standard cells	34.576			m
Length of dispersion suppresser cells	25.933			m
Number of gradient magnets	108	108	128	
Magnetic length of gradient magnets	4.267	4.267	2.845	m
Bend field of gradient magnets	1.45	1.45	1.45	kG
Quadrupole field of gradient magnets	3.6	-3.6	7.1	kG/m
Sextupole field of gradient magnets	3.3	-5.9	0	kG/m^2
Number of lattice quadrupoles	72			
Magnetic length of quadrupoles	0.5			m
Strength of quadrupoles	30			kG/m

Table 2: Technical parameters of the cooler

Electrostatic Accelerator		
terminal voltage	4.3	MV
terminal regulation	± 200	V
charging capacity	400	μA
terminal capacitance (est.)	350	pF
circulated current	0.5	A
gun solenoid field	200	G
gun cathode diameter	0.5	cm
gun-terminal bias	-50	kV
collector efficiency	99.995	%
collector-cathode bias	5	kV
beam diameter (typical)	0.8	cm
height of HV tank	7.3	m
outside diameter of HV tank	3.7	m
HV insulation - SF_6	6.4	atm. abs.
column vacuum	10	nT
time for tank access, in & out	4	hr
Cooling Section		
length	20	m
solenoid field	≤ 50	G
vacuum	0.1	nT
beam radius	0.6	cm
antiproton beam C-S β	20	m

Table 3: Antiproton beam parameters for the Recycler

Stack intensity (max)	5	$\cdot 10^{12}$
normalized rms emittance (h & v)	1.6	$\cdot 10^{-6}$ m
total longitudinal emittance	54	eVs
Accumulator Batches intensity (typical)	20	$\cdot 10^{10}$
normalized rms emittance (h & v)	1.6	$\cdot 10^{-6}$ m
total longitudinal emittance	10	eVs
number of batches in stack (typical)	14	
batch injection interval (typical)	30	min.
Recycled Beam intensity (typical)	2.2	$\cdot 10^{12}$
(before stoch. cooling) normalized rms emittance (h & v)	5	$\cdot 10^{-6}$ m
total longitudinal emittance	240	eVs
(after stoch. cooling) normalized rms emittance (h & v)	2.5	$\cdot 10^{-6}$ m
total longitudinal emittance	240	eVs