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Fermilab R and D Program in Medium Energy Electron Cooling

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Abstract

Fermilab began an R & D program in medium energy electron cooling in April 1995 with the object of cooling 8 GeV antiprotons in a new 3.3 km permanent magnet storage ring (Recycler) to be built in the same tunnel as the Main Injector (MI). The MI is to be completed in 1998, and it is planned to install the Recycler by the end of 1997 to reduce interference during the final rush of MI installation. Although the Recycler will employ stochastic cooling initially, its potential for contributing an order of magnitude to Tevatron collider luminosity is tied to electron cooling. The short time scale and Fermilab's limited familiarity with low energy electron beams has given rise to a two-phase development plan. The first phase is to build a cooling system based on an electron beam of $\geq$ 200 mA before year 2000. The second phase of about three years is planned to reach electron current of 2 A or more. This report describes the general scheme for high luminosity collider operation as well as the R & D plan and progress to date.

Antecedents

As I understand, Budker wanted to develop a high energy $\bar{p}$-p collider from the early days of INP; the invention of electron cooling was a response to the challenge of collecting a useful beam from the large, thinly populated, production phase space. The invention has proved very valuable for experiments in nuclear and atomic physics and has been exploited in routine operation at several laboratories with apparatus differing little from the original at Novosibirsk. However, thirty years later the original promise is yet to be fulfilled. Despite their early interest and contributions to the understanding of electron cooling, both CERN and Fermilab concluded that the stochastic cooling technique was more effective in cooling from the sparse $\bar{p}$ population. In fact it worked so well that Fermilab has been able to push its Tevatron collider luminosity from 10^{30} toward 10^{32} $cm^{-2}s^{-1}$ primarily by refining the stochastic cooling systems. However, the possibility of detailed determination of the properties of the top quark and hopes for hints of higgs or supersymmetry rest on yet another order

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of magnitude in luminosity. Gains on the stochastic cooling front are increasingly difficult and costly; it may be impracticable to stochastically cool enough $\bar{p}$'s for 10^{33} luminosity. However, it is clearly possible to stochastically pre-cool enough $\bar{p}$'s into the phase space region where electron cooling will be highly effective. This idea was clear to the designers of the Fermilab Antiproton Source who suggested electron cooling as a promising upgrade for the Accumulator.[1] An attempt in the early 1980's by a U. Wisconsin/Fermilab/National Electrostatics Corp. collaboration to demonstrate the production of a suitable electron beam was not entirely successful.[2] Plans from INP for a $\bar{p}$ source at IHEP using electron cooling were never realized;[3] however, high efficiency charge recovery was demonstrated with a one ampere, 1 MeV electron beam.[4] Similarly, a project by the Indiana University Cyclotron Facility to provide the SSC with an alternate way to meet its stringent emittance goal by cooling 12 GeV/c protons in the Medium Energy Booster[5] was cut short by the end of SSC funds.

Now it seems the time has come at last to realize the electron cooling technique in a new energy domain. Although the Fermilab Main Injector (MI) project[6] was initiated several years before the demise of the SSC, there has been intense activity at the lab in the last three years to understand how to exploit it to fill the big hole in the high energy program for the next ten years or more (see, for example ref. [7]). One of the ideas that has taken firm root is to augment the MI with an 8 GeV storage ring in the same tunnel. It is planned to make this ring, called the Recycler, economical and minimally interfering by using permanent magnets.[8] The Recycler with electron cooling should multiply the effectiveness of the MI project by a factor of ten. However, such an electron cooling system has not been built before, and the time to get the Recycler installed along with the MI before 1999 is limited to say the least. It is fortunate, therefore, that initial operation with a stochastic cooling system can satisfy the requirements set for the next collider run. This leaves a little time for creativity in the electron cooling R & D program. Sergei Nagaitsev is covering the present concept for the system in a talk devoted to that subject, so I will concentrate on the role of Recycler in collider operation and how we expect to get there from here.

Collider Scenarios — Recycler, TeV*, TeV33, *etc.*

The MI construction project was started in 1992 with a principal goal of attaining $5 \cdot 10^{31}$ cm^{-2}s^{-1} luminosity in the Tevatron collider. While an inadequate funding profile added a year to the project, the accelerator systems, particularly the Booster fed by a newly augmented linac, continued to improve the luminosity above 10^{31} and to surpass the MI assumptions on injection parameters. The SSC project was canceled in the summer of 1993, and by the next year the official luminosity goal associated with the MI project had risen to $8 \cdot 10^{31}$.[9] There was also by this time a flurry of brainstorming with different initiatives for luminosity and Tevatron energy surfacing every few weeks; part of this creativity was directed toward the creation of catchy identifiers for the competing ideas. In another year a more or less coherent plan had evolved. The MI plus the Recycler should lead to a luminosity of $2 \cdot 10^{32}$ cm^{-2}s^{-1} during the 1999 collider run; this package was awarded the label TeV*. By adding electron cooling to the Recycler it should be possible to work up from there to

$\gtrsim 10^{33}$, a goal with the label TeV33. These labels have applied to somewhat different ideas at different times.

At luminosity of 10^{33} cm^{-2}s^{-1} a considerable fraction of the loss in luminosity during a store comes from the desired $\bar{\text{p}}$-p collisions; the beam is simply being used up. To run in a steady state, at least these losses must be compensated by new production during the store. As the name Recycler is intended to imply, one of its functions is to recover antiprotons remaining at the end of a store; estimates and simulation indicate that it should be possible to return half of the initial $\bar{\text{p}}$ intensity back to the 8 GeV ring. The prime function is to act as a second stage accumulator to receive pre-cooled beam and build up the stack needed for one high luminosity store. For this function the electron cooling serves most importantly as a means of longitudinal phase space stacking; that is, the momentum spread of each Accumulator batch must be reduced to make room for the next. The permanent magnets substantially eliminate problems with power supply failures, one of the principal causes of accidental loss of the stack. With pre-cooled $\bar{\text{p}}$'s headed one way and re-heated $\bar{\text{p}}$'s coming the other during each Tevatron loading, there are some interesting details to the scenario.

A rather detailed computer model for collider operations has been developed which includes emittance growth, beam loss, filling time, stacking rate, reliability experience, *etc.*;[10] it can be used, for example, to calculate the length of store which will optimize integrated luminosity for a particular set of conditions. For TeV33 operation with 50 % $\bar{\text{p}}$ recovery and a setup time from experiment off to experiment resumed of one half hour, the model indicates an optimum store of only three hours; however, the optimum is broad and little is lost with a six hour cycle. This longer cycle, a little more forgiving of the upstream systems, is adopted as the nominal case. A plot of Recycler $\bar{\text{p}}$ current *vs.* time (Fig. 1) indicates the fundamental structure of a store cycle. The regular staircase increase reflects the injection of $3.85 \cdot 10^{11}$ antiprotons every half hour from the Accumulator. This represents half or less of the stack selected from the densest part of the core. The normalized 95 % transverse emittance of each batch is roughly $10^{-5}\ \pi$ m and the rms energy spread is 1 MeV.[1]

The Accumulator circumference is one seventh of the Recycler circumference. Each fresh Accumulator batch is injected into a gap in the beam on the central orbit of the Recycler. A short gap is maintained in the recycler beam throughout the cycle to facilitate ion clearing. In a few seconds before the injection the gap is adiabatically broadened to accommodate the new beam. After injection a new ion-clearing gap is introduced and the azimuth devoted to the new batch is adiabatically expanded further until the momentum spread for new beam and previous stack are the same. At this point the rf barrier between the new beam and the stack is removed.

This seemingly involved bit of RF gymnastics depends crucially on what are called barrier buckets.[12] They provide a means for manipulating the beam in independent azimuthal partitions. If one has a gap shunted by an impedance which is real over the range of the fundamental beam circulation frequency $f_\circ$ and twenty or so harmonics, one can introduce

[1]These numbers do not come directly from calculation. John Marriner has described a pre-cooling system capable of handling a $\bar{\text{p}}$ flux of $9 \cdot 10^{11}$ h^{-1} which gives similar emittance and energy spread values.[11] His design for the Accumulator is quite different from the system now in use and is intended for transfers to the Recycler every twenty seconds or so, but it shows that the required pre-cooling is realistic. There is no fundamental obstacle to more frequent transfers if the pre-cooling requires it.

almost arbitrary h=1 rf waveforms. For example, a single period of an h=6 sinusoid with positive slope at the zero crossing[2] will produce stable synchrotron oscillations for one sixth of the azimuth without capturing beam from the rest of the ring. Those particles will slip above and below the isolated bucket with no net gain or loss of energy (see Fig. 2a). If one reverses the phase so that the slope is negative, the center is an unstable fixed point, and the separatrix opens away from the center. When a particle with energy differing from the synchronous energy by ΔE_s less than the bucket height drifts into the region of non-zero rf voltage, it is accelerated or decelerated to reverse the direction of its drift and returns whence it came with the opposite sign for ΔE_s as illustrated in Fig. 2b. Thus by introducing such a waveform slowly, *i.e.* adiabatically, it is possible to remove beam from a portion of the azimuth without changing the longitudinal emittance. The waveform can consist of square wave segments rather than sinusoids, and by making the segment repetition rate not quite an integer multiple of f_o one can produce moving buckets or barriers for moving beam around the ring. The recycling process depends on such manipulations.

At the end of the store the Recycler should contain enough beam for a complete refill. The cooled stack is compressed into about one quarter of the circumference. The protons are removed from the Tevatron and the $\bar{p}$ bunches are returned to the MI in several separate batches. Each batch is decelerated in the MI, manipulated for maximum debunching and injected into a portion of the unoccupied circumference. A barrier is established to hold each batch in its partition. This step of recycling the $\bar{p}$'s produces the sudden 50 % increase of Recycler beam current just before the extraction of cooled $\bar{p}$'s for the next store as seen in Fig. 1. Now cooled beam can be captured and injected into the MI in several successive batches for acceleration to the 150 GeV Tevatron injection energy. Then the hot recycled beam can be spread out over the entire circumference while the Accumulator is collecting its next batch. In this way the hot beam will cool over an entire store period. One operationally attractive element of this scheme is that, in the event of a failure that prevents or curtails a store, it is possible to resume operation rather promptly at lower luminosity using the recycled $\bar{p}$'s from the previous store.

Development Program

The development program got its formal start in April 1995. The initial charter was to develop cooling for the Recycler for the beginning of the 1999 collider run to achieve luminosity of $2 \cdot 10^{32}$. An electron current of 200 mA was selected as the criterion for moving from system development to cooling tests in the Recycler. However, it was later concluded that even with stochastic cooling only, the Recycler can make a cost effective contribution to the benefits from the Main Injector. Therefore, although the programmatic pressures are still severe, the decision on proceeding with the Recycler no longer requires detailed assumptions about the outcome of the development effort. Consequently, rather than looking for the fastest possible route to a minimal system for 200 mA, which might need to be discarded entirely before reaching TeV33 goals, the strategy has shifted to attempting to assure that the chosen design has the potential for incremental development to work with multi-ampere

[2]The recycler operates below its transition energy.

electron beam. We are actively pursuing an adaptation of a design dating to the Fermilab ideas of the 1980's wherein a beam is circulated from a gun in the terminal of a 5 MV electrostatic accelerator through a cooling section with periodic focusing for the electrons and then decelerated in another column to a collector also in the HV terminal. A schematic of this approach applied to the Recycler appears as Fig. 3, and the general beam and system parameters are given in Table I for the initial goal of 200 mA electron beam current. The entries labeled "stacking" and "recycling" indicate respectively the parameters applying to stochastically cooled $\bar{p}$'s received from the Accumulator and those applying to $\bar{p}$'s returned from the Tevatron at the end of a store. The characteristic cooling time $t_{\rm stop}$ is given by

$$t_{\rm stop} = \frac{\gamma^2 a^2 \beta e \varepsilon_{\perp \rm n}^3}{120\pi^3 r_{\rm p} r_{\rm e} \eta I_{\rm e} x^3} \ ,$$

where a is electron beam radius, x is the antiproton beam radius, r's are classical particle radii, $I_{\rm e}$ is electron beam current, η is the cooling straight fraction of circumference, γ and β are the Lorentz parameters for mean electron and synchronous antiproton, and $\varepsilon_{\perp \rm n}$ is the normalized antiproton emittance to be cooled. The significance of $t_{\rm stop}$ is the time that the $\bar{p}$ velocity spread would be zero by extrapolation of the drag formula that applies to large velocity spread; although the formula does not apply over the entire velocity range, $t_{\rm stop}$ is an easily calculated figure of merit with the correct scaling properties and is representative of the actual time for useful cooling. The formula holds provided

$$a > x, \ \ \varepsilon_{\perp \rm pn} > \varepsilon_{\perp \rm en} \ \ ;$$

Note in Table I that the radius condition is initially violated. Both the beam physics and many aspects of the implementation of this approach are treated extensively in a thesis resulting from the University of Wisconsin/Fermilab studies.[13] The details of our baseline design, the status of our studies, and our reservations about this concept are being covered in the paper of Sergei Nagaitsev.[14]

All of the experimental and hardware design work to date is directed toward the baseline design, but there have been several different approaches discussed which could eventually prove more effective. There are some months now that we can afford to keep some options under consideration; much of what is underway in creating a beam optics test capability will be useful regardless of the particular implementation. Let it suffice to say that there is not yet an irrevocable commitment to the scheme indicated; the experimental activities are intended to provide some empirical justification for major design choices.

Test of recirculation to Pelletron accelerator

A U. California Santa Barbara group was developing a recirculated electron beam from a Pelletron[3] electrostatic accelerator in the early 1980's at National Electrostatics Corporation (NEC).[15] Noting that the beam properties sought were similar to that needed for cooling

[3] Pelletron is the trade name for an electrostatic generator of the Van de Graaff type manufactured by National Electrostatics Corp., Middleton WI. It is distinguished particularly by the use of charging chains consisting of cylindrical metal pellets articulated with insulating couplings.

Table I: Beam and system parameters for electron cooling in the Recycler

electron energy	4.87	MeV
antiproton energy	8.94	GeV
Lorentz beta	0.994	
Lorentz gamma	9.53	
antiproton $\varepsilon_\perp$ (6σ, normalized)		
stacking	9.5	π mm mrad
recycling	20	π mm mrad
antiproton energy spread ($\pm 2\sigma$)		
stacking	± 2	MeV
recycling	± 9	MeV
antiproton beam radius		
stacking	0.014	m
recycling	0.02	m
electron beam radius	0.01	m
electron $\varepsilon_\perp$ (rms)	0.8	mm mrad
cathode radius	0.0035	m
cathode temperature	1200	K
electron beam current	200	mA
electron energy stability	± 60	eV
charge recovery efficiency	99.9	%
length of cooling section	66	m
ring circumference	3319	m
$\bar{\text{p}}$ Courant-Snyder β_x and β_y	200	m
characteristic cooling time (t_{stop})		
stacking	3.7	min
recycling	11.6	min
Recycler injection frequency		
stacking	2	h^{-1}
recycling	0.017	h^{-1}
ring vacuum	~ 1	nTorr
stray magnetic field	~ 2	mG

at GeV energies, a U. Wisconsin/Fermilab/NEC group measured the beam properties[16] and put together an experiment to test whether they could return the beam to the terminal with adequate efficiency to support an ampere level dc electron beam with about 200 μA of charging current.[2] Fermilab is commissioning a very similar test at NEC using the same Pelletron but making a number of improvements in the beamline, shielding, instrumentation, *etc.* A number of the beamline components have been borrowed from Indiana University which was working toward the same end when they lost funding.[17] After a few months working with the gun and collector from the original experiment, a new gun and collector being built at Budker Institute will be tried. The beamline schematic is shown in Fig. 5. The principal object of this exercise is to attain a stable beam of 200 mA or more. The criterion for stability is simply uninterrupted operation for at least one half hour. Needless to say there are more subtle objectives than these demonstration items. We wish to examine regulation and control, verify optics calculations, develop instrumentation, *etc.* It will be useful to determine what factors control the maximum current and whether a higher limit can be reached by changes which retain the overall approach. If the simple recirculation can be obtained within about a one year period, it will then be attractive to make at least some of the experiments on optics for longer beamlines at the NEC site. As of 1 June, the Pelletron has been conditioned to 2.3 MV without beam. An operational test with a low current beam passing directly to a faraday cup is a matter of a few days past or future. Tests of recirculation efficiency at 2 MeV will take place in the last half of 1996.

Optics development with a proton analog beam

A Pelletron or other HV dc machine is a large and expensive item. It is possible to learn about much of the beam dynamics and many of the basic beam handling techniques by using a proton beam of the same emittance, momentum, and beam perveance. The energy of a proton beam to model the 4.3 MeV electron beam required for Recycler cooling is 12.5 keV; thus, experiments can be done at tabletop scale without radiation protection measures. The current which corresponds to the initial 200 mA goal is only 60 nA. Therefore, one of the original duoplasmatron proton sources from the earliest operation at Fermilab has been modified for low emittance, low current, dc operation. The proton analog layout is shown in Fig. 5. It consists of the duoplasmatron, a mass selection magnet to obtain a pure proton beam, a solenoid to render the beam more or less parallel and an instrumented pinhole iris assembly to achieve the desired emittance and current. The adjustable parameters for obtaining simultaneously the desired current and emittance are source arc current, source solenoid field, focus on the iris, and iris aperture. Where space charge neutralization arising from background gas is not an issue, the beam should provide an excellent model for the electrons. Certainly we do not expect absolute fidelity of the model because the phase space distributions are unlikely to be the same, but by the time we are addressing subtleties at this level we will have already learned much. Early experience with this system showed the need for good mass separation and for careful design of the profile grids to minimize errors from insulator charging and differential recapture of secondary electrons from the signal strips. Duoplasmatron modifications are complete and the initial test setup is being replaced by a more thoroughly engineered version which should be helpful throughout the development effort. The primary device for observing the analog beam will be multi-strip beam profile monitors mounted on a carriage which can place any of three devices into the beam; the longitudinal position of the carriage is adjusted by a precision screw nearly 4 m long. The entire assembly can easily be moved from place to place in the beam line. One of the first areas of interest will be to look at the effects of the achromatic bends on the beam. Prototype dipoles and quads are being built for mechanical development and optics tests. The scheme shown in Fig. 1 has bends in both planes, and the 180° horizontal bends in the tunnel require a bend radius of less than 1 m. At some current these are bound to become interesting.

5 MeV rf electron accelerator

Because there may be instances in which the difference between an electron beam and its proton analog is of central importance, a 5 MeV rf accelerator and debuncher are also being installed in the development area. Medical electron accelerators of this energy are available as surplus; it is possible, therefore, to get an inexpensive electron source with adequate duty factor and current capability to model even high current cooling beams.[4] Naturally the beam quality is markedly inferior, but for instrumentation development and study of beam-gas interactions the electron beam will be an important complement to the proton analog.

Prospectus

Fermilab is in the early stages of a serious effort to apply electron cooling in a new energy domain; it appears essential for realizing the research program for the next ten years. Therefore, even in the current climate of retrenchment and diminishing expectations, one can expect that the resources will be available to make major contributions in technique and understanding and realize many of the hopes of the early proponents. The technical challenges are considerable and the time short. However, the Laboratory has done well at learning and applying new techniques in pursuing its fundamental mission in particle physics. Having both the motivation and the resources, Fermilab is poised to return after a lapse of a decade as a significant contributor to electron cooling research.

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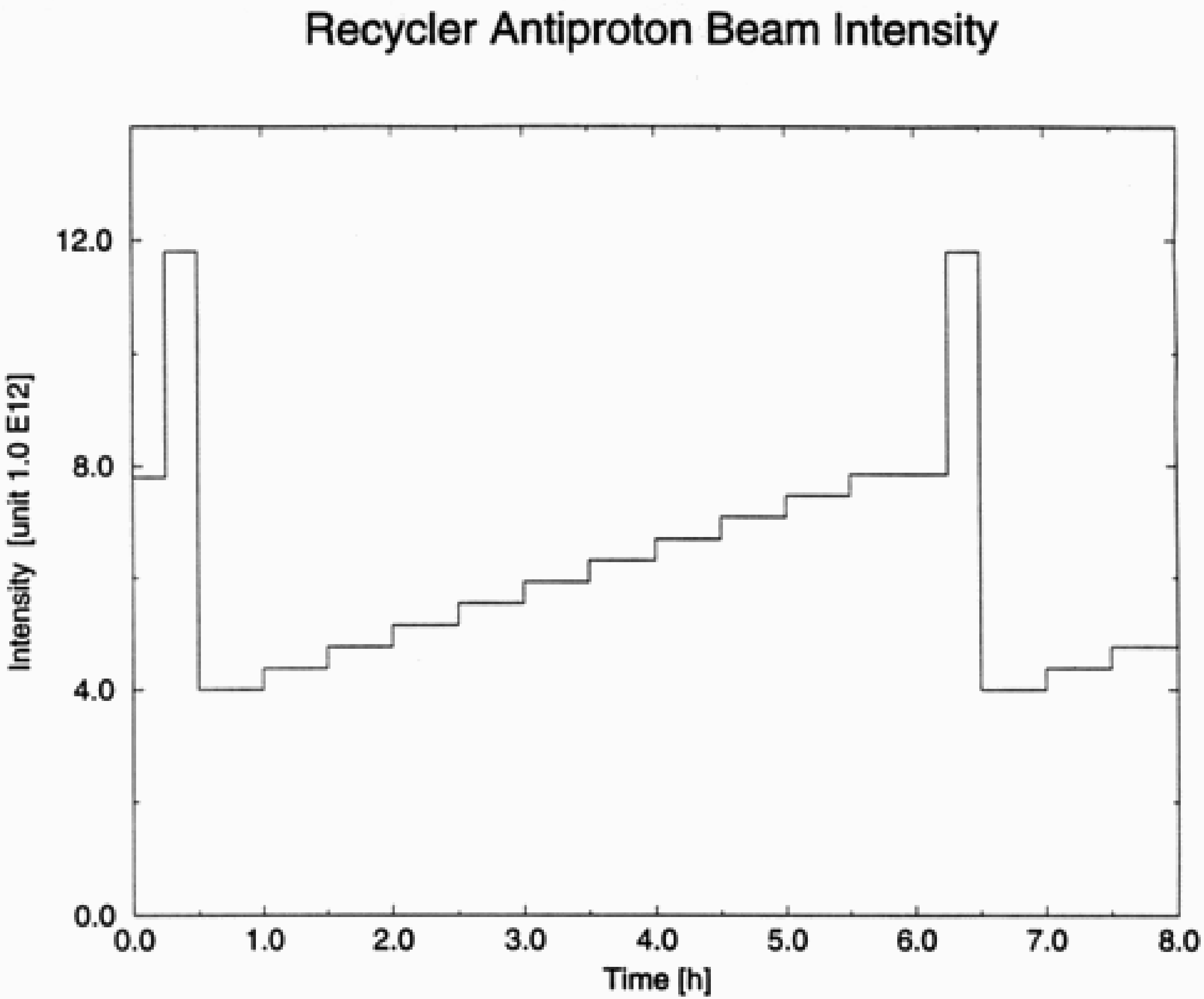
Figure 1: The beam intensity in Recycler during steady running with a six-hour cycle including one half hour of experiment off-time in the collider.

Figure 2: Harmonic 1 rf waveforms for manipulating beam in a fraction of the Recycler azimuth (a) An isolated bucket (b) An RF barrier

Figure 3: Schematic layout of an electron cooling system for the 8 GeV Recycler storage ring.

Figure 4: A short beamline to establish the feasibility of high efficiency acceleration and charge recuperation with a 2 MeV electron beam from a Pelletron accelerator

Figure 5: A 12.5 keV proton source to model the 4.3 MeV electron beam to be used for cooling in the Recycler



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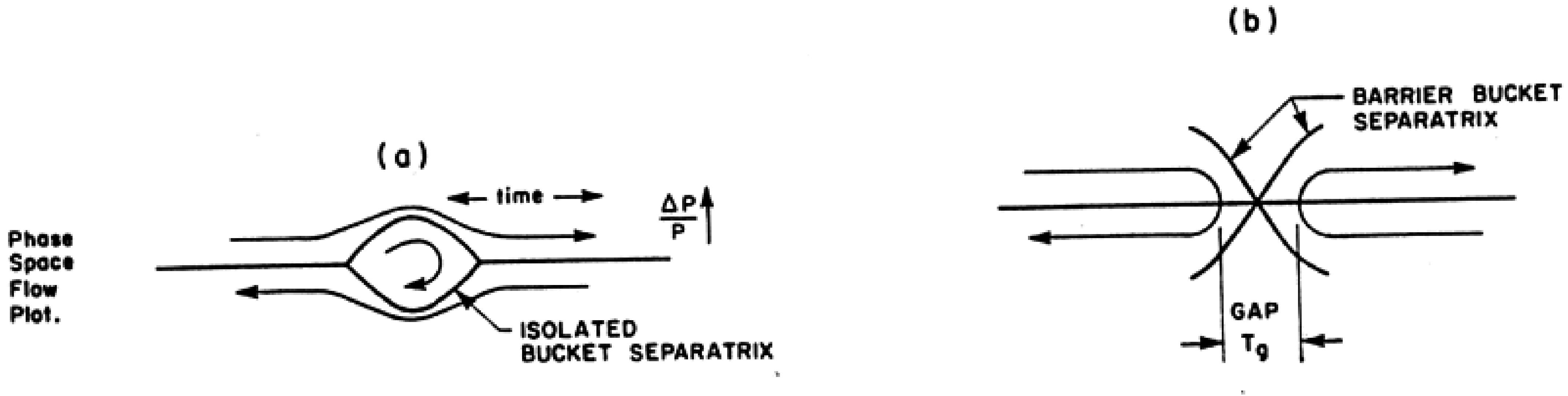

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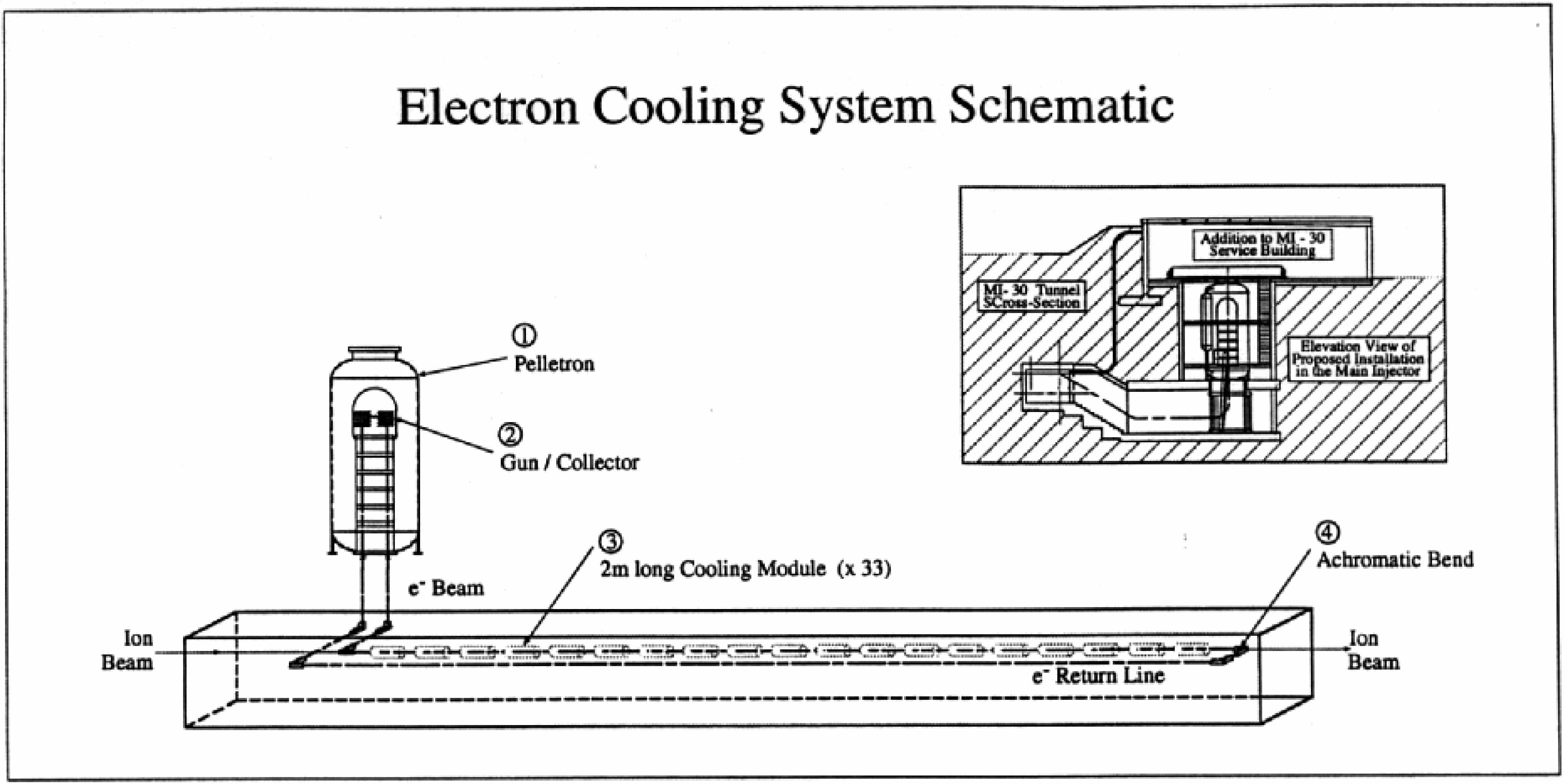

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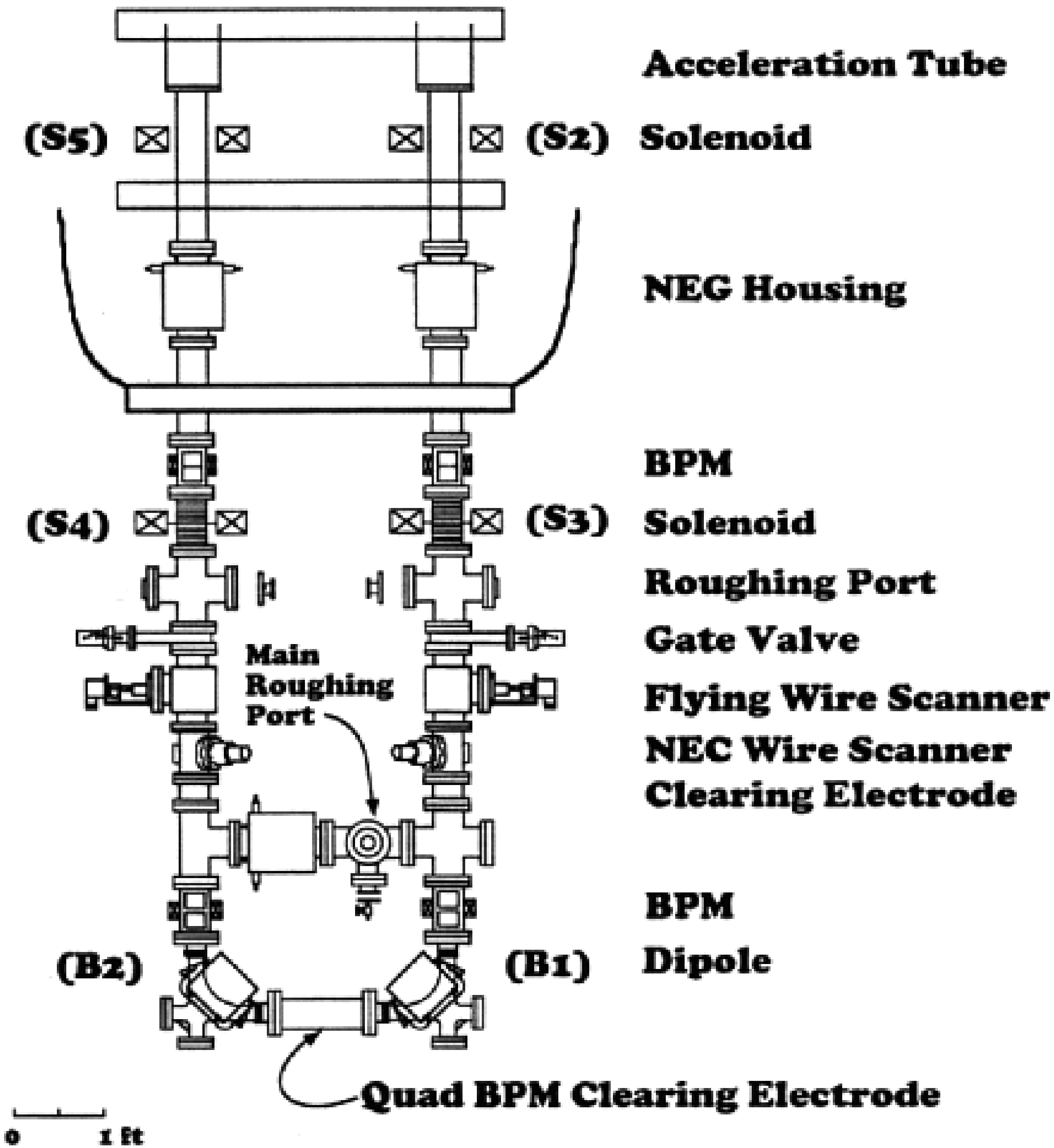

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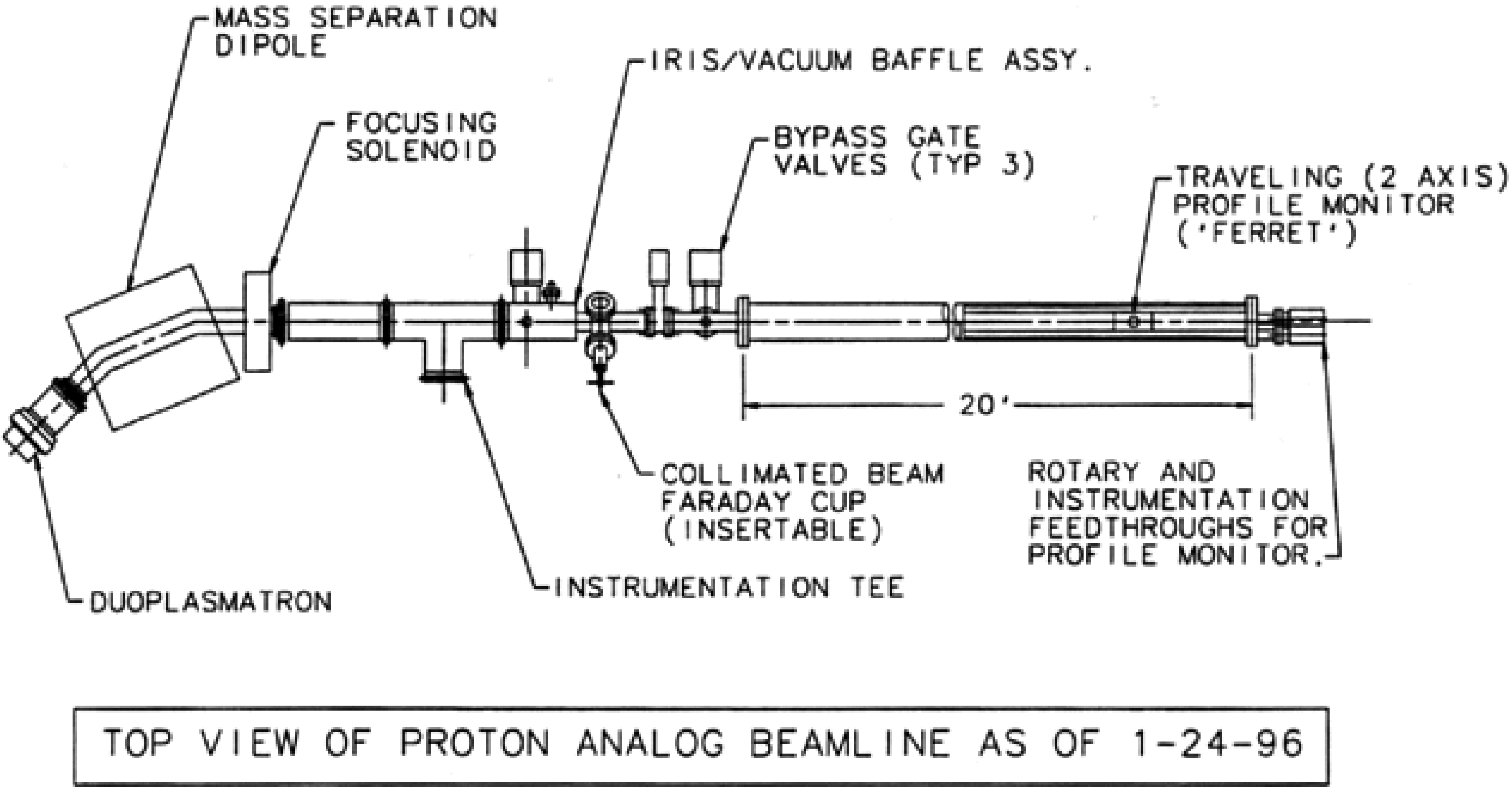

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