DEVELOPMENT OF THE TECHNOLOGY FOR INTERMEDIATE ENERGY ELECTRON COOLING

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SUMMARY

Low energy (≤300 keV) electron cooling is a well-developed technology. In the past 5 years, 8 systems have been commissioned in the U.S. (1), Europe (6), and Japan (1). We believe that intermediate-energy electron cooling, in the electron energy range of 1–10 MeV for cooling 2–20 GeV/nucleon ion beams, would be exploited on a similar scale if the technology were available. Above electron energies of about 500 keV, the traditional approach of using a Cockcroft-Walton power supply and a magnetically-confined electron beam becomes impractical. Instead, it has been proposed to use non-magnetically confined electron beams generated and collected in the terminal of a Pelletron accelerator for beam energies in the range from 1 to 10 MeV for cooling 2 to 20-GeV proton beams.[1] Although this technology has been partially developed, an order of magnitude improvement in the performance demonstrated to date is needed to exploit electron cooling at higher energies. The COLDER (Collaboration Of Laboratories Developing Electron Recirculation) group is assembling a proof-of-principle system to demonstrate this technology at the National Electrostatics Corporation.

APPLICATIONS

Increasing the luminosity of light ion colliders.

The luminosity, L, of a bunched-beam collider depends upon the ion beam current and rms normalized emittance as I^2/ϵ; the space charge tune shift (ΔQ_{SC}) limit, however, varies as I/ϵ. Consequently, when pushing colliders to higher luminosities after the tune shift limit has been reached at low energies, I and ϵ are usually increased together while keeping the quantity I/ϵ constant resulting in $L \propto I$. An alternate approach is to reduce the beam emittance after partial acceleration. Since ΔQ_{SC} is usually only significant in the lowest energy synchrotron, smaller values of ϵ may be allowed later in the chain of accelerators providing the beam–beam tune shift is not a limitation ($\Delta Q_{SC} \propto C/\gamma^2$ where $C \propto \gamma$ is the ring circumference; thus $\Delta Q_{SC} \propto 1/\gamma$). Stochastic cooling is not able to quickly increase the already high phase-space density of beams in synchrotrons fed by modern sources, but such beams are just "cold" enough for rapid intensity–independent electron cooling. Such an approach could provide increased luminosity by allowing operation with the same beam current with reduced emittance, or provide the same luminosity by allowing operation with a reduction in the beam current and a greater reduction in emittance.[2] The lower beam current reduces radiation damage and synchrotron radiation at very high energies; the lower beam emittance reduces the aperture requirements in all the following machines – a very economical benefit. Since luminosity is a direct measurement of the physics research potential of a machine, the 1–10 M$ electron system cost makes intermediate-energy electron cooling a very economical option in light of the capital and daily operating costs of large colliders such as the SSC and DESY.

Although $\Delta Q_{SC} > 0.3$ for the 0.6-GeV beam injected into the SSC LEB, $\Delta Q_{SC} \approx 0.06$ at injection into the MEB at 12 GeV; thus the beam emittance could be reduced by up to a factor of 4 at this point. An electron cooling system installed in an available straight section of the SSC MEB without lattice modifications could reduce larger-than-design beam emittances by an order of magnitude in $\approx$71 s, and thus not significantly increase the SSC fill time. The cooling rates could be over an order of magnitude higher in the MEB if the lattice were designed to incorporate electron cooling as an integral component! Table 1 gives a summary of some of the relevant parameters for this ideal case (MEB-II) as well as for other rings. A more detailed accounting has been given in Ref. 2.

The emittance of proton beams in HERA is limited by space charge effects in the first synchrotron, DESY III. In the following ring, PETRA II, $\Delta Q_{SC} \approx 0.03$; consequently the emittance could be reduced by approximately a factor of ten. An electron cooling system installed in an available straight section could attain this reduction in about 1/3 of the ring ramp time of 108 s.

Increasing the luminosity of heavy ion colliders

The beam emittance in heavy-ion storage rings and colliders is often limited by intrabeam scattering, IBS, the rate for which scales as Z^4/A^2. In very high-energy colliders electron cooling can reduce the beam emittance before acceleration in the final machine, compensating for IBS at low energies. For colliders operating with beam energies less than 20 GeV per nucleon, the colliding beams can be continuously electron cooled.

The electron cooling time would be as low as 0.1 s for the 4–7 GeV fully-stripped gold beams in the proposed KEK-PS[3] heavy ion collider due to the A/Z^2 scaling of the cooling time and relatively low beam energy. Since the incoherent space charge and beam-beam tune shifts are estimated to be $<10^{-3}$ and 10^{-5}, respectively, the beam emittance could potentially be reduced by over 2 orders of magnitude, resulting in a 10 to 100 fold increase in luminosity.

Improving the performance of light ion storage rings

Performing nuclear physics in a storage ring with internal targets and cooled beams has proven to be a far superior environment for many classes of experiments.[4] At IUCF the possibility of extending this technology from the 500-MeV energy limit of the IUCF Cooler ring to 15-GeV energies (in a conceptual ring called "LISS" – the Light Ion Spin Synchrotron) is currently being explored.[5]

An electron cooling system installed in one of the 4 straight sections reserved for stochastic cooling in the 2.5-GeV CoSy ring in Jülich could provide order of magnitude faster cooling rates than can be achieved with stochastic cooling at a fraction of the cost.

PROJECT OVERVIEW

This project, which began in April 1991, had two principal goals: (1) to determine the feasibility of electron cooling the 12 GeV/c beams in the SSC MEB; and (2) to develop and demonstrate the necessary technology, leading to its commercial availability. In a recently-completed design report[6] we have shown that all the necessary subsystems are technically feasible; potential problems have either been determined to be unimportant, or straightforward solutions have been identified. However, this still leaves unresolved the primary problem, which is to convincingly demonstrate that such a system as a whole can indeed be built and made to operate reliably. The principal technical problem is to demonstrate successful recirculation of a continuous multi-MeV, multi-ampere electron beam.

Collection inefficiencies, $\delta \equiv I_{loss}/I_e$, in the present low-energy electron cooling systems are typically $\approx 10^{-4}$, though values as low as 1×10^{-6} have been demonstrated.[7] We estimate that δ must be in the range from 10^{-5} to 10^{-4} for the higher energy systems. To date the necessary electron collection efficiencies have been obtained in beam tests at the National Electrostatics Corporation (NEC), though with insufficient (0.12 A) current.[8] The required currents have been obtained (>6 A) in a system used as a free electron laser driver at the University of California–Santa Barbara, though only in a pulsed mode with insufficient collection efficiencies.[9] Our goal is to demonstrate the reliable high efficiency DC recirculation of a 2-A electron beam using the 2-MV Pelletron accelerator at NEC.

The system which has been designed incorporates many improvements over previous designs which should ensure its success. Some of these improvements include:

- Improved beam diagnostic systems. The previous system tested at NEC had no working beam diagnostics for beam currents exceeding 10^{-4} A. The present system design includes specially-designed diagnostics to allow measurement of the beam position and beam profile for currents in the range from 10^{-5} to 10^{1} A.
- Improved electron collector. Our collaborators from Novosibirsk have already demonstrated a collector suitable for this application. IUCF is also building a collector which includes a dipole suppressor which may allow δ as small as 10^{-6}.

- Improved electron gun. The present gun design will produce a much smaller beam emittance and has true Pierce geometry in the gun region.
- Ion clearing electrodes. These high-intensity, low-emittance electron beams have space charge, rather than emittance, dominated optics. The system pressure will be improved using nonevaporable getter pumps, and ion clearing electrodes will be employed to prevent space charge neutralization.

All the electron optical elements have been field mapped, and the beam optics have been calculated from the gun through to the collector. A slowly varying solution was found using only two of the beamline solenoids over the full range of electron beam currents. This is a rather elegant solution, considering that the total number of beam waists changes from 5 to 3 as the electron current varies from 0 to 2 A. Further details regarding the electron optics modelling can be found in a previous paper.[10] This preparation, together with a computer control system (lacking in the previous system) and beam diagnostic systems will allow us to understand problems as they inevitably arise during operation.

Nearly all components for the electron recirculation beamline have been procured. The magnets have been machined, assembled, mapped and shimmed. The Pelletron accelerator has been raised to allow more room for the beamline and alignment systems, and concrete radiation shielding has been poured around it. The Pelletron has been refurbished and operated at the design voltage and the radiation monitoring system and magnet power supplies installed.

FUNDING HISTORY AND PLANS

A three-year, 925.4 k$ proposal (not including indirect costs) was submitted to the Texas National Research Laboratory Commission (TNRLC) and funded beginning April 1991 to create a design report assessing the feasibility of electron cooling the 12-GeV proton beams injected into the SSC MEB, and to develop the necessary technology. Although full funding was received the first year, only partial funding was granted during the second year.

In March 1992 an outside technical review committee strongly recommended continued funding for this project and a letter was sent to the TNRLC by the SSC administration stating that this work was highly relevant to the program of the SSCL. Nevertheless, as the TNRLC is reprogramming funds to construction and detector projects, we were told that no further funds would be forthcoming.

This work is not, however, only of interest to IUCF and the SSC; nearly all laboratories having or planning a ring in the 2–20 GeV energy range have expressed interest in this work. As a consequence we have begun to explore the possibility of obtaining a significant portion of the needed remaining funding from a consortium of laboratories having an interest in seeing this technology developed. To date:

- The SSC Laboratory is exploring the possibility of paying the salary of the project's full time engineer/physicist and is also investigating the possibility of funding our collaboration with electron beam experts in Novosibirsk;

- The National Electrostatics Corp. will provide use of their research Pelletron, water and electrical services, and technical expertise at no cost;
- KEK in Japan has tentatively promised 100 k$ worth of equipment over two years;
- The KFA in Jülich is exploring the possibility of providing machine shop services at no cost;
- Indiana University will provide 40 k$/per year in equipment and travel funds; and
- a substantial contribution is also expected from DESY in Hamburg.

Definite commitments from these laboratories will be obtained by early July 1993, at which time we will submit a proposal to the DOE Advanced Energy Projects for the balance of funds needed to successfully complete this project. Electron beam tests will begin 6 months after funding is obtained, and testing is expected to last 1 to 1.5 years.

As a possible extension to this project, we are exploring the possibility of prototyping the transport of this beam through an extended beamline to test the beam optics, alignment, and ion clearing systems which would be needed for systems employed at the SSC or DESY.

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Table I: Proposed Multi-MeV Electron Cooling Systems.

Parameter	Symbol	MEB-I	MEB-II	CoSy	KEK-PS	PETRA II	Unit
Ring Properties							
Circumference	C	3960	3960	184	283	2300	m
Cooling region length	L_c	25	198	4	3.5	50	m
Ion Beam Properties							
Ion species		H^+	H^+	H^+	$^{197}Au^{79+}$	H^+	
Momentum/nucleon	p	13	13	3.2	5; 8	8.4	GeV/c
Norm RMS emittance	ϵ_N	0.60	0.60	2.5	2.0	4.0	π μm
Lasslet tune shift	ΔQ_{SC}	0.07	0.07		8; 3×10^{-4}	0.03	
Electron Cooling System Parameters							
Electron current	I_0	3	3	2	2	2	A
Electron kinetic energy	U	6	6	1.3	2.2; 3.8	4.1	MeV
Time to decrease ϵ_N by factor of 10	$T_{1/10}$	71	6.9	2.9	0.6; 2.4	45	s
Approximate cost		7	14	1	2	5	M$