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**C&D - 96**

**The 11th International Advanced ICFA Beam Dynamics**

**Workshop on Beam Cooling & Instability Damping  
dedicated to the 30th Anniversary  
of the Electron Cooling**

**18-26 June 1996**

**CONFERENCE HANDBOOK**

**Dubna  
1996**

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**on board a ship "A.Suvorov"  
Moscow – Nizhny Novgorod – Moscow  
18–26 June 1996**

**CONFERENCE HANDBOOK**

**Dubna  
1996**

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## **Section I. Damping of coherent oscillations**

### **1.1. Damping of Coherent Oscillations**

**L. Vos**

*CERN, Geneva, Switzerland*

Damping of coherent oscillations by feedback is straightforward in principle. It has been a vital ingredient for the safe operation of accelerators since a long time. The increasing dimensions and beam intensities of the generation of hadron colliders impose unprecedented demands on the performance of future systems. The arguments leading to the specification of a transverse feedback system for the CERN SPS in its role as LHC injector and the LHC collider itself are developed to illustrate this. The preservation of the transverse emittance is the guiding principle during this exercise keeping in mind the hostile environment which comprises: transverse impedance bent on developing coupled bunch instabilities, injection errors, unwanted transverse excitation, unavoidable tune spreads and noise in the damping loop.

### **1.2. Nonlinear damping of coherent transverse oscillations of a beam in hadron cyclic accelerators and colliders.**

**I.N.Ivanov, V.A.Melnikov**

*JINR, Dubna 141980 Russia*

The correlation between the requirements to the quality of a beam and parameters of systems of damping of transverse coherent oscillations for modern hadron accelerators and colliders is considered. The special attention directed to the systems, in which the signal in a kicker is not proportional to a signal of a pickup. It is shown, that the nonlinear mode of suppression can provide the greater rate of damping. The possibility of a limitation of a beam's blow-up at injection and accumulation is reached by an appropriate choice of a level of discrimination of a pickup's signal.

### 1.3. Coherent Signals from Proton Bunches beyond the Stationary Bunch Spectrum

L. Vos

*CERN, Geneva, Switzerland*

The beams in the LHC will be permanently excited by ground motion. Special feedback will reduce the emittance blow-up due to this excitation to acceptable levels. However, coherent excitation will remain at a level much higher than the incoherent Schottky noise. This phenomenon may be exploited advantageously for continuous tune measurement, but real Schottky observations at frequencies within the bunch spectrum are not possible.

Observation of real Schottky signals in the LHC is an issue of some importance for the following reason. Schottky signals carry a wealth of beam information: tune and also transverse emittance if the intensity is known. This information is constantly available and not in the least during beam collisions. The emittance aspect may be an interesting and cheap complement of the more complex synchrotron light profile measurement. Real Schottky signals can be observed at frequencies beyond the bunch spectrum on the proviso that the bunches are rigid. Nevertheless, care should be taken that the working frequency of such a monitor is chosen below the cut off frequency of the vacuum chamber in order to be isolated from all kinds of possible signal pollution. A monitor based on this principle has been installed in the Tevatron [1]. It behaves exactly as expected but it came as a bad surprise that the bunches are not rigid! This causes very large signals at the revolution harmonics reducing the dynamic range to the extent that the system becomes unusable. It also destroys the hopes of bunched beam cooling in the Tevatron [2] as it did in the SPS [3]. This paper is an attempt to make some progress in our understanding of this phenomenon in view of possible Schottky observations in the LHC and eventually beam cooling in the Tevatron and also in HERA [4].

## **1.4. Damping Systems for the CERN Large Hadron Collider**

**T.P.R.Linnecar**  
*CERN, Geneva, Switzerland*

In the Large Hadron Collider (LHC) it is essential to control both longitudinal and transverse emittance. Longitudinally it is imperative to restrict particle loss which may quench the magnets, and transversely conservation of emittance is necessary to attain the maximum luminosity. Damping systems in all three planes will be installed in the LHC to control the injection oscillations and help maintain stability against coupled bunch modes of oscillation that may be driven by parasitic impedances in the ring after injection and through the acceleration cycle. The power bandwidth of these systems is given by the batch structure and kicker ripple while the small signal bandwidth is determined by the highest coupled bunch mode, which depends on the bunch spacing. The maximum power itself depends on the injection errors. We consider the longitudinal damper for which the main characteristics will be given together with the present status of the design. Reference will also be made to the transverse damping systems, whose specifications are known but for which a detailed design has to be made. A further phenomenon which may be the ultimate limit to the LHC performance is the PACMAN effect. This effect arises from the different beam-beam forces felt by different bunches in the collision region due to the batch structure around the ring. It manifests itself as a localised closed orbit bump which cannot be compensated for all bunches. In the worst case it can lead to complete beam loss. The effect is described briefly together with a first estimation of a possible fast feedback system to compensate it.

## **1.5. Longitudinal Coupling Impedance Imposed by a Beam Feedback in a Synchrotron**

**S.Ivanov**  
*IHEP, Protvino, Russia*

Commonly, a longitudinal beam feedback processes a slowly varying signal at zero intermediate frequency (a phase offset, an amplitude departure). Often, only a portion of data confined in a pickup'd band-pass beam signal is retained (like, say, in a purely

phase feedback). Sometimes, a beam feedback employs different RF-bands to pick-up beam data and return correction back to the beam. All the manipulations thus involved with signal spectra result in a cross-talk between various beam-current and electric-field waves propagating along the orbit, which is shown to be described by an impedance matrix with, at most, three non-trivial elements per row. Of os this matrix which puts on a firm quantitative basis an intuitive notion that a linear feedback is seen by a beam as an artificial coupling impedance controlled from the outside. This (impedance) approach has at least two plain advantages .

(i) It allows one to mount the feedback's effect into the well-established theory of longitudinal coherent instabilities to use most of its inventory: beam transfer functions, threshold maps, handling of coupled-bunch motion, etc.

(ii) Destabilizing effect of beam environment, being available in standart terms of coupling impedances, is naturally taken into account since early stages of the feedback's R&D.

### **1.6. The reactive feedback system against transverse mode coupling**

**V.Danilov, E.Perevedentsev**  
*BINP, Novosibirsk, 630090, Russia*

### **1.7. F.Pedersen.Damping of instabilities in e+e-factories**

**F.Pedersen**  
*CERN, Geneva, Switzerland*

### **1.8. On the Emittance Growth due to Noise in Hadron Colliders and Methods of Its Suppression**

**Yuri Alexahin**  
*JINR, Dubna 141980 Russia*

Emittance growth in colliding hadron beams due to fluctuating mutual off-centering at the interaction points is considered. The approximate analytical approach used permits to take into account motion of the both colliding beams and to reveal dependencies on the

noise source and the feed-back system major characteristics. Requirements on the LHC transverse oscillation damping system are discussed.

### **1.9. Transverse Damping System with a Digital Filter**

**V.Zhabitsky**

*JINR, Dubna 141980, Russia*

Theory of resistive wall instability damping using a feedback system with a digital filter and delay is developed. A system of equations is obtained for description of beam motion including the wake fields for beam. To solve equations the Z-transform method is used. The analytical solution for the damping time and for the eigen frequencies are obtained and the system stability analyzed.

### **1.10. The System for Suppression Initial Transverse Oscillations of a Beam for the I Stage UNK.**

**E.M.Gleibman et al.**

*JINR, Dubna 141980, Russia*

The offered paper contains the description of the system for suppression initial transverse oscillations of a beam for the I stage UNK. The system consists of a complex of pickups and head electronics engineering for a measuring of parameters of oscillations of a beam, high-voltage precision generator of impulses for a correcting magnet and system of automatic control by the generator. The outcomes of bench trials of a power part of the system are described.

### **1.11. The pulse devices for nonlinear damping of coherent transverse oscillations of a beam.**

**V.A.Melnikov**

*JINR, Dubna 141980 Russia*

Some ideas of implementation of nonlinear modes of a damping of transverse oscillations of beam are explained. Possibility and advantages of pulse engineering to development of such a systems is

considered. Outcomes of numerical simulation of operation of impulse devices in injected and collision modes for LHC are presented.

## ***Section II. Synchrotron Radiation***

### **2.1. Synchrotron Radiation as a Cooling Method**

**G.Kulipanov**

*BINP, Novosibirsk, 630090, Russia*

### **2.2. First Results Obtaining of KSRS Design Parameters**

**V.Ushkov**

*Kurchatov Institute, Moscow, 123182 Russia*

Stages of KSRS design parameters obtaining are described. The main points of them are outlined: obtaining design parameters of standwave electron linac at energy about 80 MeV, ejection from storage ring SIBERIA-1 at energy 450 MeV, injection closed orbit optimization in SIBERIA-2 storage ring and general features of energy ramping process in SIBERIA-2 up to energy 2.5 GeV. First experience of storage in single bunch and multibunch modes are described too.

## ***Section III. Stochasting cooling***

### **3.1. Status of stochasting cooling**

**D.Moehl**

*CERN, Geneva, Switzerland*

### **3.2. The Stochasting Cooling Use in AAC Complex at CERN**

**F.Pedersen**

*CERN, Geneva, Switzerland*

### **3.3. Recent Developments in Stochastic Cooling at Fermilab**

**M. Church**

*Fermi National Accelerator Laboratory, Batavia IL 60510, USA*

Fermilab now has over 10 years of operational experience with stochastic cooling systems. New techniques and refinements of old techniques continue to push the state of the art. I will discuss recent developments which include strategies for new pickup and kicker arrays, laser signal processing, recent measurements on system performance, bunched beam cooling, new calculational/modeling techniques, and requirements for future Accelerator upgrades.

#### **Section IV. Laser cooling in storage ring**

##### **4.1. Laser Cooling : Status & Perspectives**

**J. Hangst**

*Aarhus University, DK-8000, Aarhus C., Denmark*

##### **4.2. Anomalous behavior of the Beam Thermal Noise in a Storage Ring**

**V.A. Lebedev**

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The properties of the thermal noise in a beam subjected to cooling in a storage ring are considered. It is shown that a non-Gaussian tail in the beam distribution function can create anomalous behavior of the noise. The effect is important for both laser and electron coolings but it is much more powerful for laser cooling where the noise of a cooled beam is significantly amplified. Comparison of analytical estimate, numerical calculations and experimental results obtained on ASTRID storage ring are considered.

**Section V. Physics of electron beam in the electron cooling****5.1. The Experimental Study of the Electron Beam Neutralization**

**J. Bosser, R. Ley, R. Maccaferri, D. Mohl, G. Molinary,  
G. Tranquille, V. Varenne**  
*CERN, Geneva, Switzerland*

**Y. Korotaev, I. Meshkov, E. Syresin, A. Smirnov**  
*Laboratory for Nuclear Problems  
JINR, Dubna, 141980, Russia*

The neutralization of space-charge can under certain allow an increase of the cooling force. In this paper the physics of neutralization, technique and diagnostic of neutralized state are discussed. The results of the experiments performed at CERN - LEAR and JINR Test -Bench are presented. The experiments were carried out in the following parameters range: electron energy 2,5-27 keV, beam current 0,1-2,5 A, magnetic field 400-600 G.

**5.2. Ion Accumulation and Space Charge Neutralization in the Intensive Electron Beams for Ion Sources and Electron Cooling**

**G.D. Shirkov, E.M. Syresin**  
*JINR, Dubna, 141980 Russia*

The Electron Beam Ion Sources (EBIS), Electron Beam Ion Traps (EBIT) and electron beams for electron cooling applications have the beam parameters in the same ranges of magnitudes. EBIS and EBIT produce and accumulate ions in the beam in the result of electron impact ionization. The cooling electron beam accumulate positive ions from the residual gas in accelerator chamber during the cooling cycle. The space charge neutralization of cooling beam is used also with the purpose to reduce electron energy spread and enhance cooling ability.

The report presents the analysis of the most important processes connected with ion production, accumulation and losses in the intensive electron beams of ion sources and electron cooling systems for proton and ion colliders. The elastic and inelastic collision processes of charged particles in the electron beams are considered. The inelastic processes such as the ionization, charge exchange, recombination

charge states of ions and neutral atoms in the beam. The elastic Coulomb collisions charge the energy of particles and result the energy redistribution among components in the electron-ion beams. The characteristic times and specific of processes of ionization, beam neutralization, ion heating and loss in the ion sources and electron cooling beams are determined. The dependence of negative potential in the beam cross section on neutralization factor is studied. The problem of beam stability and limits of electrical current are considered.

### **5.3. The Active Methods of Instability Suppression in a Neutralized Electron Beam**

**J. Bosser, R. Ley, R. Maccaferri, D. Mohl, G. Molinary,  
G. Tranquille, V. Varenne**

*CERN; Geneva, Switzerland*

**Y. Korotaev, I. Meshkov, E. Syresin, A. Smirnov**

*Laboratory for Nuclear Problems  
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A large space-charge of a dense beam is detrimental to the cooling process. The generation of an neutralized electron beam is restricted by beam-drift instability. For instability suppression active methods are used: a kicker with transversal electric field (shaker), longitudinal modulation of electron beam, clearing electrodes, placed in the vacuum chamber and the region expell secondary electrons. The results of experiments dedicated to the development of beam stabilization at JINR Test -Bench and in the electron cooling system at LEAR are discussed

### **5.4. Stationary Parameters of Neutralised Electron Cooling System**

**I.Meshkov, E. Syresin**

*Laboratory for Nuclear Problems  
JINR, Dubna, 141980 Russia*

**E.Mustafin, P.Zenkevitch**

*ITEP, Moscow, Russia*

Stationary parameters of neutralised electron cooling system (the electron current, the neutralization degree and so on) are defined

by an energy balance equation for the ions. We discuss main sources of the ion heating: incoherent heating (natural and artificial) as well as coherent heating due to the dipole oscillations excited by an interaction between the primary electrons and the neutralised ions. Analysis of the energy balance equation with account of these terms permits to estimate the stationary parameters. Results of the estimation are compared with experimental data obtained at JINR test bench and LEAR e-cooling system.

### **5.5. The secondary electrons in the electron cooling system**

**E Syresin**

*Laboratory for Nuclear Problems  
JINR, Dubna, 141980, Russia*

Secondary electrons in the electron cooling system determine the current losses. Their parameters depend on the collector efficiency.

The second problem, which takes place with the secondary electrons, is related to of neutralised electron beam. The formation of dense neutralised electron beams restricts by beam-drift instability. It is a stream instability which appears in stationary conditions due to a feed back, created by secondary electrons.

In this report the behaviour of the secondary electrons in LEAR electron cooling system with S-shape toroid magnets is examined. The parameters of secondary electrons for primary electrons beams with a current 0,1-3 A and electron energy 3-30 keV are discussed.

### **5.6. Influence of Fast Secondary Electrons on the Dipole Oscillations in Neutralised Electron Beam**

**E.Mustafin, P.Zenkevitch**

*IITEP, Moscow, Russia*

It is well known that a maximal electron current in neutralised electron beam (NEB) is constrained by the dipole instability due to an interaction between the primary electrons and the neutralised ions. Influence of the fast secondary on this instability has been considered. We have examined two cases: 1) secondary electrons with "full memory" (these electrons "remember" amplitude and phase of the

dipole oscillations during reflections from the ends of the cooling system; 2) secondary electrons with "loss of memory". For both cases dependence of NEB parameters from a concentration of the secondary electrons has been investigated. At the last, we analysed a possibility to suppress the dipole oscillations by use of feedback system

### **5.6. Backward from Cool E-beams to Disturbed Ones: Transportation of Intense E-beams in Gas and Plasma**

**M. Zavialov**  
*ARETI, Moscow, Russia*

## **Section VI. ELECTRON COOLING PHYSICS**

### **6.1. Electron Cooling, the First 30 Years and Thereafter**

**N. Dikansky**  
*BINP, Novosibirsk, 630090, Russia*

### **6.2. Electron Cooling of Highly Charged Ions in the ESR**

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F. Nolden, H. Reich, B. Schlitt and M. Steck**  
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In the ESR storage ring fully stripped ions up to Uranium can be stored and cooled at beam energies between 50 and 370 MeV/u. Longitudinal cooling forces for heavy ions from  $C^{6+}$  to  $U^{92+}$  at various energies have been measured with the ESR electron cooler.

Two experimental methods have been established which allow the determination of the cooling force for relative ion velocities from zero to  $10^7$  m/s. At low velocities the equilibrium between cooling and longitudinal heating with rf noise is used in combination with timegated BTF measurements for obtaining the momentum distribution of the beam. For high relative velocities the cooling force is deduced from the momentum drift of the ion beam after a rapid change of the electron energy.

Measurements for several ion species are presented which show a pronounced deviation from the expected  $q^2$  scaling in the regime of the magnetic cooling force. Further investigations have been performed to study the influence of magnetic field strength and beam energy on the longitudinal cooling force.

### 6.3. Electron Cooling at CRYRING

H. Danared

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Frescativagen 24, S-104 05 Stockholm, Sweden*

Electron cooling is studied at CRURING using both coasting and bunched beams. Cooled beams of many different ion species, from singly charged atomic or molecular ions to highly charged heavy ions as  $\text{Si}^{14+}$  or  $\text{Pb}^{54+}$  have been used for investigation of ion-electron recombination and other phenomena. The work with adiabatic electron-beam expansion is continued through the installation of a superconducting gun solenoid with a 5 T field.

Using coasting beams, the influence of adiabatic beam expansion on drag forces and energy resolution in recombination experiments has been studied. Spectra of, e.g., dielectronic recombination show, that transverse electron energy spread is close to the 10 meV one expects with the ten times beam expansion (at high electron densities the energy spread increases somewhat). The longitudinal energy spread is around 0.1 meV, in rough agreement with what the longitudinal relaxation of the electron beam should give. The longitudinal drag force that the electrons exert on the ion beam also agrees with these values of the energy spread, provided that no effects of the magnetic field in the cooler are taken into account. Why the magnetic field does not seem to influence the drag force is still not understood.

The behavior of cooled bunched beams can also be used to study the properties of the electron beam. As shown at IUCF<sup>1</sup>, the phase motion of the bunch with respect to the rf signal that occurs when the rf frequency is shifted from the revolution frequency of the cooled beam without rf can give information about several aspects of the drag force. Using small rf amplitudes and frequency shifts, we have studied beams where the phase of the bunch with respect to the rf signal is stable. Then one can have an equilibrium situation where the energy gained by a particle passing through the rf drift tube is equal to the energy lost when it passes through the cooler or vice versa. The

resulting change of the phase of the bunch has been used to measure drag forces at relative velocities below the drag force maximum. A preliminary measurements on  $C^{3+}$  ions showed a drag force which is consistent with earlier measurements on singly charged ions<sup>2</sup>, and with a scaling of the drag force with a lower power of  $\eta$  than 2, as determined at GSI<sup>3</sup>.

<sup>1</sup> D.D.Caussyn et al., Phys.Rev.Lett., **73** 2696 (1994)

<sup>2</sup> H.Danared et al., Phys.Rev.Lett., **72** 3775 (1994)

<sup>3</sup> M.Steck et al., Proc. 4th EPAC, p.1997

#### **6.4. Simulation of Electron Cooling and Intrabeam Scattering Processes of Heavy Ion Beam in HIRFL-CSF**

**Y.N.Rao**

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**T.Katayama**

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Tanashi, Tokyo 188, Japan*

This paper is devoted to the simulation of electron cooling and intrabeam scattering processes of heavy ion beam in the proposed HIREL-CSR, according to the analytical cooling force formulae and the intrabeam scattering growth rate expressions. Some important effects like the betatron and synchrotron oscillations and space charge effect of the electron beam have been considered. Evolution of beam emittance and momentum spread under joint action of the electron cooling and intrabeam scattering are shown. The dependence of ion beam properties in equilibrium on the number of particles and the electron current are presented.

#### **6.5. Electron Cooling and Bunched Beams in the IUCF Cooler: Intensity Related Effects.**

**S.Nagaitsev<sup>1</sup>**

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Electron cooled bunched proton beams in the IUCF cooler are nearly completely space dominated longitudinally, meaning that the

longitudinal charge density of the bunch is, to first order, determined by the balance between the internal force of electrostatic repulsion between particles and the external force of the applied radio frequency focusing field. This leads to a number of phenomena, such as coherent synchrotron frequency shift and intensity dependent electron cooling effects, which have not been observed before. In addition, the installation of transverse beam profile monitor in the IUCF cooler allowed us to investigate various proton beam properties, such as space-charge tune shift, correlation between transverse and longitudinal beam profiles and transverse cooling rates as a function of proton beam current and energy. Measurements of transverse electron cooling rate, performed at the IUCF cooler ring with 300 MeV bunched proton beam, showed unexpectedly low ( $\sim 25$  ms) cooling time. This effect might be similar to the "superfast" cooling observed by Novosibirsk group in the NAP-M ring<sup>2</sup>. This paper elaborates on these and other experimental studies in the IUCF cooler.

<sup>1</sup> Current address: Fermi National Accelerator Laboratory, Batavia IL 60510 USA.

<sup>2</sup> Y. Derbenev, I. Meshkov, Studies on Electron Cooling of Heavy Particle Beams Made by VAPP-NAP Group at the INP at Novosibirsk, CERN 77-08, PS-div., 1977.

## **6.6. Strongly Enhanced Electron Cooling Performances Using Inserted Devices Acting on the Ion Beam**

**S. Gustafsson**

*INFN, LNL, Legnaro, Italy*

Experience has shown that the Electron Cooler can give transverse beam temperatures of around 1000 K but the E.C. should theoretically be able to cool down to much lower temperatures than has been demonstrated. A lack of understanding in the complex cooling procedure could be the reason but also optical effects in the Toroids, used to guide the electrons into the trajectory of the ion beam, have a strong influence.

In this contribution is demonstrated the problem of the Toroids and a cure is proposed and examined. The study demonstrates that the E.C. can produce much lower beam temperature than what is the case to day, especially for heavy ions with high charge state. To do so a

compensation element has to be installed inside, or close too, each toroid in a way to cancel the inherent gradient of the Toro d.

Another interesting device is a selective heating instrument that allows a separate cooling of the transverse beam directions. This can decouple the horizontal and vertical phase spaces allowing a better and faster cooling of the non heated phase space. Disconnecting the device gives then a cooling down of the heated phase space with only small influence from the already cooled phase space.

### **6.7. Measurements of Transverse Cooling Time and Beam Profiles in CELSIUS**

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*Institute for Radiation Sciences, Uppsala University, Sweden*

**L.Hermansson, D.Reistad**

*The Svedberg Laboratory, Uppsala, Sweden*

CELSIUS is equipped with a magnesium jet profile monitor constructed and built at INP, Novosibirsk. The monitor has been used to measure transverse cooling times of oxygen ions at different energies, electron currents and beam alignments. Also, the shape of the beam profiles was studied as a function of the angle between the electron and ion beams. Results of these measurements are compared with some theoretical estimates and will be reported.

### **6.8. Recent Results on Ion Accumulation in LEAR for LHC**

**J.Bosser, D.Moehl et al**

*CERN, Geneva, Switzerland*

## **Section VII. Advanced electron cooling technique**

### **7.1. Fermilab R&D Program in Medium energy Electron Cooling**

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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 a electron beam of  $> 200$  mA in four years. 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

<sup>1</sup> Operated by the Universities Research Association under contract with the U.S. Department of Energy.

### **7.2. High Voltage Electron Cooling - Status and Trends**

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### **7.3. Electron Cooling for the Fermilab Recycler**

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In all scenarios of the possible Tevatron upgrades, luminosity is essentially proportional to the number of antiprotons. Thus, a tenfold increase in luminosity could be achieved by putting five times more protons on the antiproton production target and gaining an additional

factor of two from recycling antiprotons left over from the previous store. Stacking and storing ten times more antiprotons puts an unbearable burden on the stochastic cooling system of the existing Accumulator ring. Thus, one is led to consider an additional stage of anyoproton storage - the so called Recycler ring. Electron cooling of the 8 GeV antiprotons in the Recycler could provide an attractive way around the problema of large stacks. Such a system would look much like the IUCF proposal to cool 12 GeV protons in the SSC Medium Energy Booster<sup>2</sup>. Although electron cooling has now become a routine tool in many laboratories, its use has been restricted to lower energy accelerators (<500 MeV/nucleon)/ An R&D program is currently underway at Fermilab to extend electron cooling technology into the GeV range. This paper describes the electron cooling system design as well as the Recycler ring parameters required to accommodate this system.

<sup>1</sup>Operated by the Universities Research Association under contract with the U.S. Department of Energy.

<sup>2</sup>MEB E-Cool Design Report 1992, Indiana University Cyclotron Facility, Bloomington IN 47405 (October 1992)

### ***Section VIII. Crystalline beams***

#### **8.1. Status of the Crystalline Beam Idea Realisation**

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#### **8.2. Project of a Storage Ring for Crystalline Beam Studies**

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The Conceptual Design of a low-energy heavy-ion storage ring, called CRYSTAL, proposed for the experimental demonstration of Crystalline Beams is presented.

The design of the project has been optimized for the study of crystalline beams; but provisions have also been made for carrying out experiments of different nature in nuclear, atomic and molecular physics. The Tandem-ALPI heavy-ion facilities of the Laboratori Nazionali di Legnaro is assumed as the injector for the storage ring. For the Crystalline mode the possibility to inject particles from an independent low energy source is also considered.

The storage ring has a circumference of 70 meters, large enough to allow a maximum magnetic rigidity of 3.8 Tm. It has a periodicity of eight, made of eight dipole magnets surrounded by doublet quadrupoles, sextupoles and a drift space free of magnets 3.4 meters long.

The demonstration of Crystalline Beams is feasible with very effective electron and laser cooling and requires dedicated diagnostics.

The existence of stable ground states for Crystalline Beams has been demonstrated by computer simulations. The basic structures are the helices and twisted multiplets. The ground state configurations depend on the focusing parameters of the storage ring. The transition thresholds from one ground state to another depend on the focusing parameters and particles density.

### **8.3. Radiation Excitation of Quantum Oscillator**

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## **Section IX. Exotic beam generation**

### **9.1. Production of Antihydrogen in Relativistic Collisions**

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Experimental observation of antihydrogen atoms will be presented. Once available, antihydrogen will be well suited to investigations of fundamental CPT violation studies under different forces. The investigations of the PS210 collaboration at LEAR,

however, concentrated on the production and detection of this simplest atomic bound state of antimatter only. The production of antihydrogen is predominantly based on the  $e(+)$   $e(-)$  pair creation via the two-photon mechanism in an antiproton - nucleus interaction, as suggested by C.T. Munger et al.(2). (See also Ref. (3)). A Xe cluster target was used for the production of neutral antihydrogen atoms which were identified by a unique sequence of annihilation characteristics. The antihydrogen signature was observed for eleven atoms, including possibly two background events. The measured yield has the right order of magnitude compared to the theoretical production predictions (2, 3). Thoughts about future possible directions of antimatter research will be sketched.

References:

- (1) G. Baur et al.; Phys. Lett. B 368 (1996) 251
- (2) C.T. Munger, S.J. Brodsky, and I. Schmidt;  
Phys. Rev. D49 (1994) 3228
- (3) G. Baur; Phys. Lett. B311 (1993) 343

## 9.2. Antihydrogen beam generation using storage rings

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The scheme of antihydrogen generation using two storage rings – one for antiprotons and another one for positrons is discussed. The peculiarity of the proposed scheme is relatively low particle energy – in the range 50–0.5 MeV of antiprotons (27–0.27 keV positrons) and application of positron ring focusing system with longitudinal magnetic field and entirely immersed in it (magnetised) positron beam. The expected generation rate of antihydrogen atoms is of order of  $3 \cdot 10^4$   $s^{-1}$  at 50 MeV antiproton energy and  $30 s^{-1}$  at 0.5 MeV.

The beam injection scheme, particle storing and dynamics of the circulating positron beam is considered.

### 9.3. Conceptual Design of Low Energy Positron Storage Ring

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The conceptual design of low energy positron storage ring for studies of electron cooling of positrons and positronium generation is presented.

Using of a longitudinal magnetic field for focusing of positrons is essential feature of the storage ring. The electron and positron beams superposition and separation is produced by centrifugal drift of electrons. The long term stability of the positron beam is provided with additional spiral coils, which form a quadruple magnetic field, similar to "stellarator" one. The storing of positrons is carried out in longitudinal phase space.

The two versions of the storage ring parameters are presented: the storage ring for generation of positronium and one as a part of the complex for antihydrogen atoms generation.

The scheme of the storage ring using an electron linac for low energy positron production is proposed. The positronium generation rate is limited by single scattering of positrons in residual gas, and is equal about  $10^4$  "atoms"/sec, when vacuum pressure is  $10^{-10}$  Torr. When positron energy is of 25 keV storing time is equal about 10 sec.

### 9.4. Production of Exotic Systems in-Flight in the Charge-Exchange Reactions

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It is proposed to produce a number of exotic systems in the charge-exchange reactions, using overlapping storage rings as sources of initial particles. High efficiency of this method is provided by using in collisions the appropriate ions and the absence of losses in medium due to in-flight production. The yield of the positronium, protonium, antihydrogen and ions of antiprotonic helium isoelectronic sequence is estimated and some possibilities of measurements on the beam of the produced particles are discussed.

## 9.5. U400M Cyclotron and RIB Accumulation and Cooling in the K4 Storage Ring.

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Accumulation and cooling of beams of radioactive ions of He<sup>6</sup>, B<sup>8</sup>, C<sup>16</sup>, N<sup>17</sup>, O<sup>14</sup>, O<sup>20</sup>, P<sup>35</sup> and K<sup>47</sup> with the energy of order of 30-50 MeV/amu on the orbit of a storage ring such as K4<sup>1</sup> is considered. The High Resolution Beam Line ACCULINNA<sup>2</sup> recently put into operation in the Flerov Laboratory of Nuclear Reactions of JINR (Dubna) can produce these beams with the emittance of  $\varepsilon_{\perp} \approx 15\pi$  mm-mrad and the momentum spread  $\Delta p/p \approx 2\%$ . Beam intensities will range from  $1 \cdot 10^7$  to  $2 \cdot 10^9$  pps/p  $\mu$ A. We show that from  $5 \cdot 10^2$  to  $1 \cdot 10^6$  of such radioactive ions can be stored and cooled on the ring orbit by making use of multiple single turn injection events<sup>1</sup>.

To cool the beams two methods are considered. Due to the low intensity and high momentum spread of injected beams the stochastic cooling with the band width of about 1 GHz seems to be more appropriate. In this case it is possible to accumulate on the orbit of the ring all radioactive ions mentioned above, even those which have the life-time of 1 s (He<sup>6</sup>, B<sup>8</sup> and C<sup>16</sup>).

Another method, electron cooling, will be suitable only for storing radioactive ions not lighter than N<sup>17</sup>. Moreover, the ion momentum spread should be decreased in this case down to 0.2%. This is possible for our beam line only at the expense of intensity reduction. But due to the  $(\Delta p/p)^3$  dependence of the longitudinal electron cooling time one gains in the rate of single turn injection events. For electron cooling, typical longitudinal cooling time will take 30-100 ms after each injection event, whereas the transverse cooling time will be 20-50 ms. These cooling methods allow one to have quasi steady cooled beams on the ring orbit accumulated from  $\approx 100$ -2000 injection events. Luminosities of  $5 \cdot 10^{23}$  through  $1 \cdot 10^{27}$  cm<sup>-2</sup> s<sup>-1</sup> will be reachable with an internal target of the thickness of  $1 \cdot 10^{15}$  cm<sup>-2</sup>.

1. Yu.Ts.Oganessian et al., Z.Phys.A, v.341, 1992, p.217.

2. R.Kalpakchieva et al., In: Workshop on Experimental Perspectives with Radioactive Nuclear Beams, Padova, Italy, 1994. Ed. C.Signorini and A.R.Spalla, LNL-INFN (REP) 96/95.

**Section X. Muon cooling****10.1. Ionisation cooling and muon colliders****A.Skrinsky.***BINP, Novosibirsk, 630090, Russia***Section XI. Seminar "Concepts and Problems of Electron-ion colliders"****11.1 The Investigation of Nuclear Structure by the Use of Storage Rings – Presence and Future****Gottfried Muenzenberg***Gesellschaft für Schwerionenforschung (GSI) Darmstadt, Germany*

The use of storage rings offers a rich field of new and unique possibilities to study nuclear structure. Beam storage permits to keep exotic nuclei in exotic ionic charge states, cooling creates beams of high phase space density for high resolution experiments.

Already in the first direct measurements ground- and isomeric states could be resolved. More than hundred new masses of nuclides in the neutron deficient region ranging from lutetium to bismuth were measured. Studies of bare, hydrogen- or helium like nuclei undergoing electron capture allow to study the influence of the electron density at the nuclear surface on the decay.

Next generation experiments will be nuclear structure studies in direct reactions as  $(d, p)$ ,  $(p, p')$  or Coulomb break-up with high precision by using an internal low-density target.

The new physics with a combination of a heavy-ion storage ring and a 100 MeV electron collider to measure nuclear charge distributions and to study nuclear structure will be discussed. Filling the ring with low energetic exotic nuclei as target for nuclear reactions between exotic nuclei would lead to a new generation of experiments to study nuclear matter under extreme conditions and to proceed to the very limits of nuclear stability.

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