Status Report on SIS-ESR

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Abstract

The main line of SIS-ESR development is the intensity upgrade program. High intensities for heavy ions at the space charge limit will support above all the development of the experimental program with beams of relativistic exotic nuclei and the plasma physics program. Another focal point of machine development is the improvement of SIS operation for the radio therapy program with patient treatment starting in 1997. At the ESR the intensity limits are studied for coasting and bunched beams. The development of ESR operation for a second generation of experiments with exotic isotope beams from the FRS and with energy variation in the ESR is discussed.

1 INTRODUCTION

The heavy ion synchrotron SIS, which provides a large variety of ion beams from deuterium to uranium in the energy range from 50 to 2000 MeV/u, and the experimental storage ring ESR have been in operation since 1990. Since then the first generation of experiments was performed for a broad range of measurements mainly in nuclear and atomic physics.

However, the maximum intensities foreseen in the 1985 proposal have not yet been achieved, especially for heavy ion beams. This is primarily because Unilac ion beam currents are still of the order of 10 μA for the injection of gold, lead or uranium into the SIS. The high current prestripper linac designed in 1985 for heavy ion currents above 1 mA had to be postponed due to the need for further optimization of the design concept. Instead a new RFQ/IH injector linac HLI has been built. With an ECR ion source it is well suited for operation with rare isotopes required for heavy element synthesis at the Unilac, with carbon ions in a radiotherapy program, or with even lead ions for SIS injection comparable to the CERN lead injector. Nevertheless, the highest intensities for SIS operation are still provided by the 20 year old Wideröe prestripper with Penning, MEVVA or Chordis ion sources. Both the Wideröe and the HLI linac enable two ion beam operation for the Unilac poststripper and also for the SIS which is especially important for the radiotherapy program.

Now two new developments have to be launched for the accelerators: (a) Development of high intensity SIS operation up to the space charge limit of $2\cdot10^{11}$ neon and $4\cdot10^{10}$ uranium ions per cycle and (b) improvement of accelerator operation for the radiotherapy program with patient treatment starting in 1997.

High intensities are important for experiments with secondary beams and require a careful optimization of machine operation. They will also open up new prospects for the plasma physics program which may contribute to the studies of inertial confinement fusion. The radiotherapy program requires further development of versatile machine operation, since the acceleration of carbon ions for patient treatment shall be interleaved for a few minutes every hour with normal SIS operation, which will provide heavy ion beams for basic research most of the time. Moreover, the active raster scan technique combined with energy variation from pulse to pulse for radiation dose delivery also needs precise machine and beam transport control.

The experimental storage ring ESR also benefited from the higher SIS intensities. For light ions the intensity limits were reached for both coasting and bunched beams, while the available intensities for heavy ions of the order of 10^8 stored ions helped to support a viable research program in atomic physics. The main lines of machine development are now deceleration of cooled ion beams, extraction, and control of coherent beam instabilities for coasting beams. In addition, it is planned to proceed with the storage of secondary beams from the fragment separator FRS, to develop the capability for precise mass measurement, and to install stochastic cooling in 1995.

2 INTENSITY UPGRADE

During the past year a remarkable increase in SIS intensities mainly for heavy ions was achieved (Fig. 1). The progress was mainly the result of Penning ion source tuning for synchrotron operation. It is planned to further increase the present $1\cdot10^8$ heavy ions per pulse by a factor of five by means of further ion source development.

It includes both higher ion source discharge power and extraction voltage and, possibly, a separation of the magnetic fields for the Penning discharge and for charge state selection. Moreover, the Wideröe prestripper could be operated with U^{9+} instead of U^{10+}. The goal of these measures is to reach about 50 μA of U^{73+} for SIS injection and $5\cdot10^8$ ions per pulse by the end of 1995.

An additional increase of beam intensities shall be achieved by electron cooling of the injected beam. With a repetitive combination of multi turn injection and successive electron cooling, e.g. 10 to 15 cycles within 1 s, it should be possible to reach at least $4\cdot10^9$ ions per pulse. This scheme is in operation at the TSR (Heidelberg) since 1990 and it is also under consideration for lead ions at LEAR (CERN). The cooling time calculated with a semi-

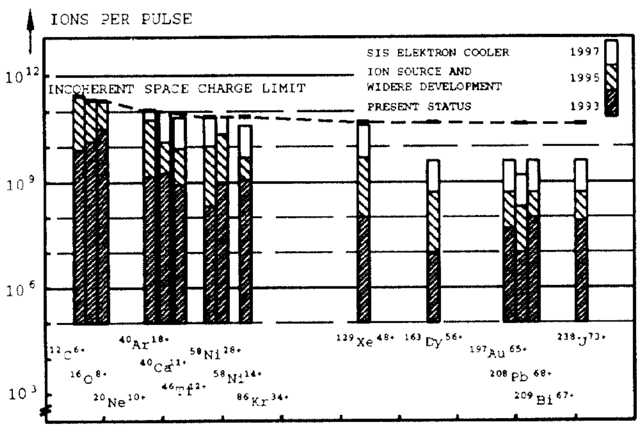

Figure 1: SIS beam intensities by the end of 1993 and preview of expected intensities. Ion source development and a new SIS electron cooler will yield up to $4 \cdot 10^9$ heavy ion per pulse. A new high current linac will boost the intensities to the space charge limit.

empirical formula is about 100 ms for U^{73+} at 11.4 MeV/u. In a recent experiment with carbon and sulfur ions at the TSR the validity of the formula was confirmed [1].

Assuming 100 ms for effective cooling of the full 150π mm·mrad beam emittance down to 30π mm·mrad, a series of 10 repetitive multi turn injections is planned within 1 s and with an expected intensity gain factor of about 8 providing $4 \cdot 10^9$ ions per pulse. The ultimate limit of this procedure - the incoherent space charge limit for 30π mm·mrad - is about $1 \cdot 10^{10}$ ions. Since the shortest SIS cycle time for full energy operation is increased from 3 to 4 s, the available ion intensities per 1 s will be increased at least by a factor of 6. It was also checked that beam losses during 1 s injection time at 11.4 MeV/s are negligible. Charge exchange processes at residual gas molecules were measured for Bi^{69+} ions (Fig. 2). With an extrapolated beam life time of 16 s for U^{73+} the expected losses are 3 %. The beam losses due to capture of cooler electrons are far below 1 %. An eventual deterioration of beam emittance from intra-beam scattering was investigated theoretically [2]. It could be shown that with intensities at the space charge limit the emittances tend to decrease slightly while momentum spread grows slowly.

Electron cooling in the SIS also yields better beam quality: about 3π mm·mrad and $\delta p/p = 2 \cdot 10^{-4}$ at full intensity and maximum energy. It is even better for low intensities, e.g. 0.01π mm·mrad and $\delta p/p = 1 \cdot 10^{-5}$ at 10^6 ions per pulse [3].

The SIS electron cooler will be designed for electron energies from 5 to 35 keV corresponding to ion energies from 10 to 70 MeV/u. Adiabatic expansion of the electron beam diameter from 25 mm to about 70 mm delivers both adequate beam cross section and low electron temperature of 20 meV. It is planned to start commissioning of the electron cooler in 1997.

As a third step in the intensity development program a high current injector will replace the Wideröe linac by the end of 1998. The Penning ion sources in use for heavy ions like U^{10+} do not provide the required ion current. Therefore MEVVA ion sources will be used for metal ions like U^{4+} in order to achieve ion currents of 10 mA at the source, and of about 4 mA of U^{73+} for SIS injection with stripping at 1.4 and 11.4 MeV/u.

For U^{4+} the total prestripper accelerating voltage has to be increased from 33 MV to 85 MV. A short RFQ injector combined with an IH-linac can provide 85 MV in the space of the existing Wideröe [4].

An important technical problem still under study is the high specific energy deposition for intense heavy ion beams. Therefore high safety standards are required both for the Unilac and the SIS injection scheme. In particular the stripper at 11.4 MeV/u needs new developments. It has been proposed to move the target from pulse to pulse or to use plasma stripper targets.

3 SIS MACHINE DEVELOPMENT

For light ions the Unilac almost provides the injection currents required to approach the incoherent space charge limit. However, further Unilac development is needed with respect to beam quality and beam loss control, which are not yet optimized for high intensity operation. So far $5 \cdot 10^{10}$ Ne^{5+} ions were stored in the SIS, the corresponding Q-shift of 0.02 was still far below the expected limit of 0.25 for $2 \cdot 10^{11}$ Ne^{10+} ions.

SIS operation at the space charge limit has to be supported by careful control of machine parameters: (a) An error of 0.05 in Q_V at injection will be removed next time [5], (b) The linear interpolation of control data has been corrected where necessary.

The progress with light ions should advance the plasma physics program. Fig. 3 summarizes, which specific energy deposition and which plasma temperatures could be attained with uranium ions in the course of the intensity upgrade program.

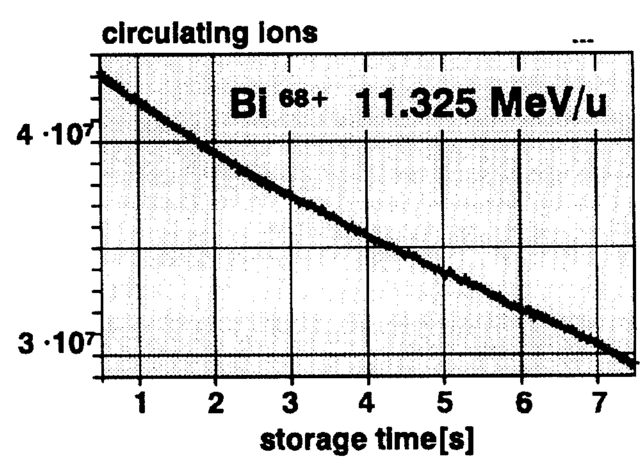

Figure 2: Beam life time for Bi^{68+} ions at 11.4 MeV/u injection energy and $4 \cdot 10^{-11}$ mbar average SIS pressure.

In order to achieve a high specific energy deposition bright heavy ion beams must be focused to a small spot diameter like 200 μm assumed in the diagram. Recently a stable spot of 300 μm diameter was achieved for a 5π mm·mrad emittance of the SIS beam using a conventional fine focusing lens system. In addition, plasma lenses are being tested for even better focusing [6].

The ultimate goal is the deposition of $2 \cdot 10^{11}$ U^{28+} ions at an energy of 150 MeV/u with the range of 0.6 mm in a gold target. It is expected that electron cooling in the SIS can provide the small transverse beam emittance required for beam focusing. An adequate scheme for the formation of one short 20 ns bunch by merging of four SIS bunches still has to be developed. If this machine development program should be successful, a specific energy deposition of 2 MJ/g and a corresponding plasma temperature of about 100 eV or 10^6K are within reach, quite close to the parameter field of implosion studies for an inertial confinement reactor.

The combined ESR-SIS operation with injection of cooled ESR ion beams into the SIS was tested in July 1993 [7]. Two cooled ESR bunches with about $3 \cdot 10^8$ Ne^{10+} ions were transferred at 250 MeV/u for further acceleration up to 500 MeV/u (Fig. 4). As soon as the overall transmission of presently 20 to 30 % is optimized the new ESR-SIS transfer scheme will be used for: (a) two-stage acceleration of very heavy ions to maximum energies, e.g. 1430 MeV/u for U^{92+}, (b) the transfer of low emittance beams, e.g. for channeling experiments at the FRS, and (c) storage and bunch rotation of cooled ESR bunches for plasma physics experiments.

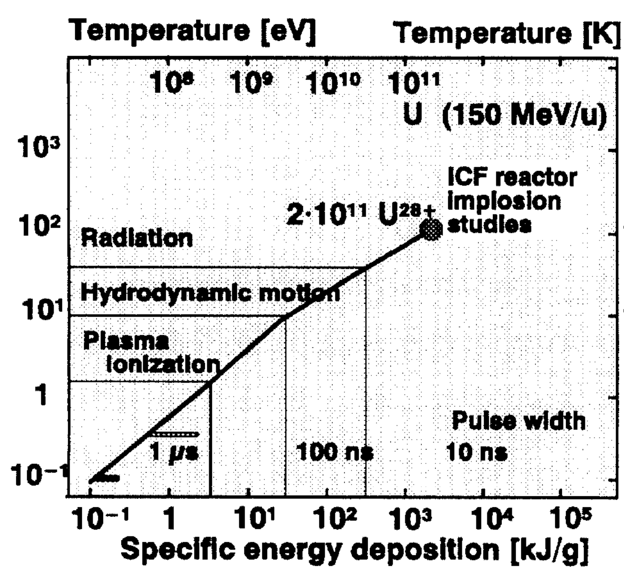

Figure 3: Bright ion beams for plasma physics. At the space charge limit of $2 \cdot 10^{11}$ U^{28+} ions the specific energy deposition of 2 MJ/g will yield plasma temperatures of about 100 MeV.

4 SECONDARY BEAMS

The intensity upgrade program, however, will mostly further the studies of exotic nuclei. The SIS provides a large variety of ions with energies above 1000 MeV/u. Therefore all secondary beams are produced as bare nuclei, thus supporting the detection techniques at the fragment separator (FRS).

Projectile fragmentation at a thick target yields neutron rich light nuclei like ^{11}Li (about 5000 for 10^{10} carbon ions per cycle), which can be transported through a new beam line from the FRS directly to the target hall for nuclear reaction studies. The same technique also delivers proton rich nuclei. In contrast to ISOL techniques planned or applied at other laboratories, the FRS approach has the following advantages: (a) clean separation of isobars due to the Z-dependent energy loss at a degrader target midway in the FRS, (b) identification of short-lived isotopes ($\tau \geq 100ns$), (c) highly efficient detection techniques using the kinematic forward focusing, and (d) storage of secondary beams in the ESR, e.g. for precise mass measurements or nuclear reaction studies at a gas target.

One example is the recent production of the double magic tin isotope ^{100} Sn^{50} [8]. By fragmentation of ^{124} Xe^{54} about 7 of these exotic nuclei could be produced in a ten day run at an average intensity of 1-$2 \cdot 10^8$ xenon ions per spill. The intensity upgrade would provide about 300 to 400 $^{100}Sn^{50}$ per day, which may be sufficient for nuclear spectroscopy, Coulomb excitation, and direct mass measurements in the ESR.

A complementary technique is projectile fission in the strong Coulomb field of heavy target nuclei. The fragments resulting from peripheral collisions are forward emitted and efficiently separated in the FRS. This is a very efficient source of neutron-rich isotopes. Their properties such as binding energy, half-life, decay schemes are of special interest for stellar processes of element formation.

In this way fission of ^{238}U was studied, showing the well known double humped isotope distribution (Fig.5). During a short 10 hour run about forty new isotopes were

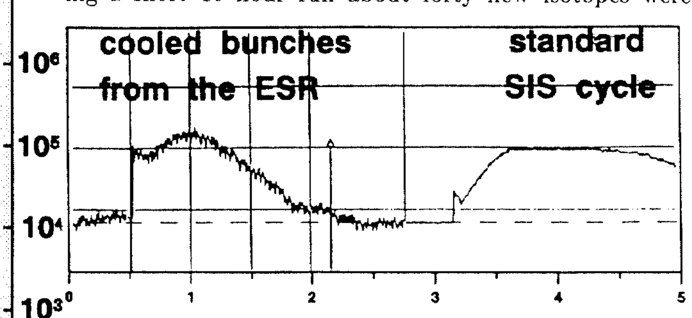

Figure 4: Transfer of a 200 MeV/u cooled ESR beam to the SIS. On the left side the beam transformer signal shows acceleration of the cooled ESR beam to 500 MeV/u and slow resonance extraction, on the right a standard SIS cycle follows with acceleration of a 11.4 MeV/u Unilac beam to 400 MeV/u.

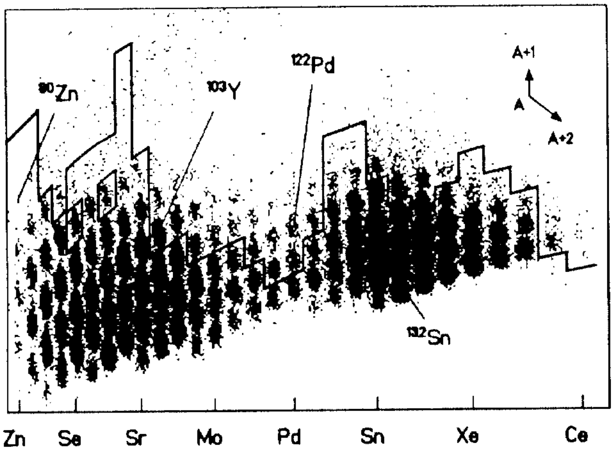

Figure 5: Coulomb fission of ^{238}U in a lead target. The full line indicates the present limit of known isotopes. Beyond many of the newly discovered isotopes are visible.

discovered [9].

5 RADIOTHERAPY AT GSI

In 1993 a proposal for the installation of an experimental radiotherapy was submitted to the German government [10]. In a joint program the Radiological University Hospital Heidelberg, the GSI Darmstadt, and the German Cancer Research Center proposed to make use of the superior dose distribution and of the enhanced radiobiological efficiency of ion beams such as ^{12}C or ^{16}O for the treatment of deep seated tumors. It is expected to provide little damage to the healthy tissue in the entrance channel and to the radiosensitive organs adjacent to the target volume by a combination of the favourable characteristics of ion beams with an active beam delivery system.

The proposal includes a construction phase of three years for a medical cave with its beam line and an annex building, followed by a five year clinical phase with approximately 70 patients per year (Fig. 6).

The central point of the beam delivery system is the raster scan technique which combines the energy variation of the synchrotron from pulse to pulse with magnetic beam scanning [11]. Using this technique it was possible for the first time to produce a target conform irradiation of a convex volume like a sphere.

It is planned to use up to 127 well defined energy settings for the SIS and the beam transport system in the energy range from about 80 to 300 MeV/u, which can be combined to realize any required dose distribution. Probably it will be necessary to add to each energy setting a few additional parameters like beam intensity or adjustment of the last quadrupole doublet in front of the raster scan device.

6 STATUS OF ESR OPERATION

The maximum intensities for storage and cooling of ion beams are summarized in Fig. 7. For light ions a few SIS cycles suffice to fill the ESR up to the limit, where transverse microwave instabilities (MWI) set in at currents of about 5 mA. The present feedback damping system provides stability up to about 10 mA.

For heavy ions the SIS intensities are lower. With 15 % stripper efficiency for U^{92+} at 300 MeV/u about 100 SIS cycles are required to reach 10^8 ions in the ESR. A longer filling time does not improve the ESR beam current, since losses due to REC processes in the cooler counteract any further intensity increase. With higher intensities in the SIS and improved transfer efficiency the number of injection cycles will be reduced and the 10 mA level will be reached.

Equilibrium temperatures for cooled ion beams are determined by the balance of electron cooling and heating due to intra-beam scattering. The equilibrium momentum spread scales roughly with $N^{1/3}$ and is $2 \cdot 10^{-4}$ for 10^9 stored ions, while the beam emittances are proportional to $N^{2/3}$ with about 2π mm·mrad at the same intensity [12].

The formation of short and bright bunches is a key issue for the investigation of high energy density in matter. One way is the accumulation and cooling of bright beams in the ESR, which have to be bunched for transfer to the SIS. It could be shown that bunched beams become unstable at rather low intensities of 1-3 mA due to electron cooling. One possible explanation are velocity differences between the ion and the electron beams due to varying ion space charge forces [13].

Therefore an alternate scheme for the formation of bright bunches is being studied. After adiabatic bunching of the cooled coasting beam within about 50 ms, a process that has to be optimized, a fast bunch rotation will produce the short bunches required for plasma physics experiments. First experiments have shown the validity of the concept [14].

So far all ESR experiments were performed at the stacking energies between 200 and 320 MeV/u. Several experiments, however, demand energies in the range of 50 MeV/u

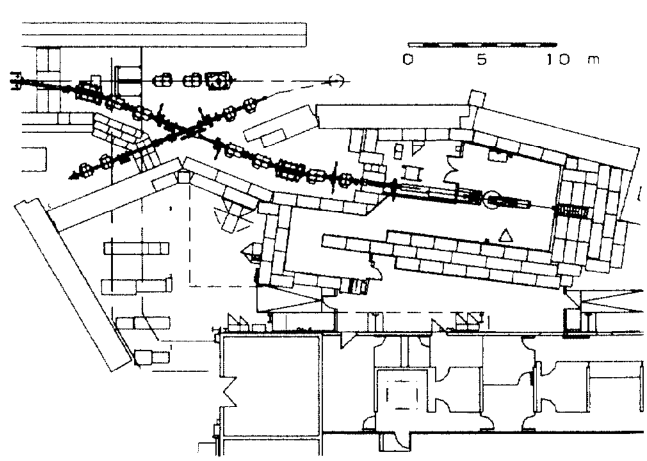

Figure 6: Radiotherapy cave

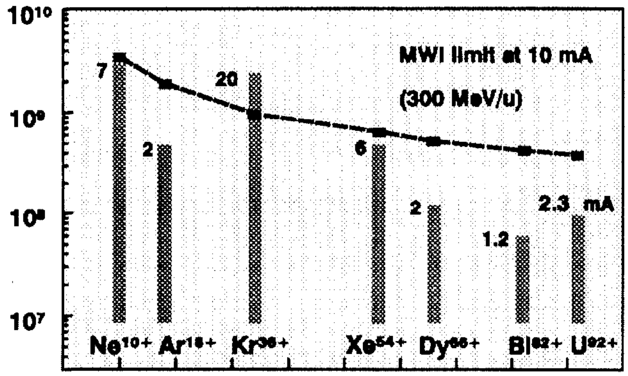

Figure 7: ESR coasting beam intensities by the end of 1993. The present intensity limit caused by transverse microwave instabilities at 10 mA is indicated

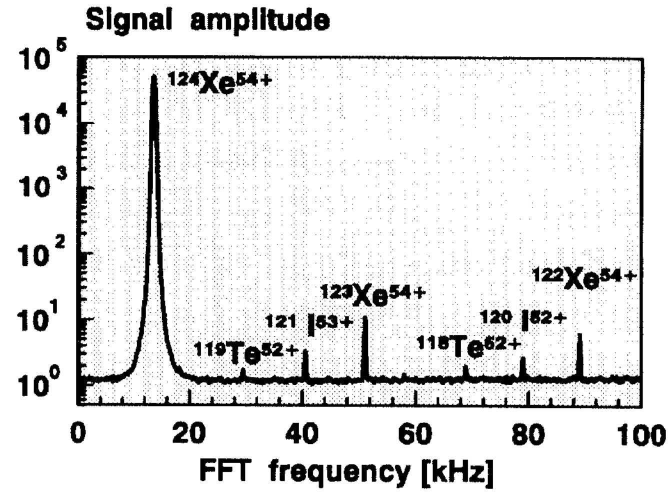

Figure 8: Mass spectrum of electron cooled secondary nuclei produced by interaction of the primary $^{124}Xe^{54+}$ beam with a nitrogen gasjet target. The low intensity secondary beams are cooled to an extremely small momentum spread below $1 \cdot 10^{-6}$.

or even below. Therefore acceleration and deceleration of stored beams are now being developed. So far acceleration from 250 to 500 MeV/u and deceleration to 50 MeV/u were successfully demonstrated. In the near future ramping of the electron cooler energy and beam controlled rf phase regulation will further improve the ESR operation at low energies.

In addition, it is planned to develop the extraction of stored beams. So far fast extraction was used for bunch to bucket transfer to the SIS. Slow resonance extraction still has to be developed. It was shown, however, that charge exchange extraction is an alternate extraction scheme especially for cooled heavy ion beams. In a first test run U^{91+} ions were fully stripped at the ESR gasjet target and U^{92+} ions could be extracted at a rate of several hundred ions per second with the high quality of the cooled ion beam.

Storage of secondary beams was already tested in 1991. Meanwhile new beam diagnostic equipment for beams of exotic nuclei from the FRS has been installed in front of the ESR. It is planned to use the improved injection scheme for an experiment with double magic ^{56}Ni beam in August 1994. The installation of the stochastic cooling system is now planned in 1995.

Mass measurements for nuclei at the stability limits will also start in 1994 In a first test run, interaction of a primary $^{124}Xe^{54+}$ with a nitrogen gasjet target in the ESR was studied. Fig. 8 shows the primary beam and beams of secondary nuclei. The low intensity secondary beams are cooled to an extremely small momentum spread, typically below $1 \cdot 10^{-6}$. The relative mass differences are measured with comparable accuracy. The test spectrum showed that this accuracy is feasible.

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