The Heavy Ion Synchrotron SIS

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Abstract

A description is given of the heavy ion synchrotron SIS, which is part of the new SIS/ESR facility at GSI. The important design features related to the acceleration of heavy ions are described. The lattice design provides flexible operation with dynamic change-over from triplet to doublet focusing and between different modes of dispersion setting. The precise control of focusing is supported by a novel type of power supplies. Operation of the SIS in a time-shared mode with slow extraction for target experiments and with fast extraction for ESR injection is used routinely. The concepts are reported, which allow a precise control of all machine parameters. The beam diagnostic equipment for beams of 10^3 to 10^{10} ions per pulse is shortly discussed. Typical beam parameters for the external beams are presented. Finally, near future developments are summarized.

1 THE GSI ACCELERATOR FACILITY

The heavy ion synchrotron SIS is part of the new GSI accelerator facility [1]. As shown in the plan view of Fig.1 the Unilac, which is in operation since 1975, provides low energy beams up to $20MeV/u$. The new SIS/ESR facility was conceived for acceleration, storage and cooling of high energy heavy ion beams. Construction of the new facility had begun in December 1986. The inauguration in April 1990 indicated the start-up for experiments and ESR commissioning.

The SIS is designed for the acceleration of all kinds of heavy ions to maximum energies between 1 and $2GeV/u$. The high energy beams can be delivered either directly to several experiments in the target area or to the ESR through a beam line with stripper and charge separator. A third way for the SIS high energy beams leads to the production target in front of the fragment separator, where secondary beams can be produced by projectile fragmentation. The FRS separator prepares pure beams of any interesting nuclear fragment, e.g. neutron rich or proton rich isotopes, which can be either studied directly at the final focal plane or can be injected into the ESR for ring experiments.

The Unilac was up-graded for its role as SIS injector. A new injector with an ECR ion source, a short RFQ section, and an IH linac was installed midway in order to provide two ion beams of different species: one for a low energy experimental program and another one for SIS injection.

In Fig.2 the status of SIS operation is summarized for the interval from December 1990 until March 1992. It can be seen that slow resonance extraction was used in a broad energy range, while fast extraction mostly for the ESR storage ring took place between 150 and $300MeV/u$. Usually the SIS has been used in a time-shared mode with slow extraction of ion beams for target station experiments at the same time as fast extraction to feed the ESR. These modes could be combined on a pulse-to-pulse basis, so that with ESR filling usually needing only a few hundred pulses every hour, most of the SIS capacity was available for target station experiments.

As shown in Fig.3 maximum intensities after slow extraction range from 10^7 ions per spill for heavy ions up to $5 \cdot 10^9$ for neon. These intensities, which are at least for heavy ions about a factor of 1000 below the space charge limit, are restricted by the available Unilac currents, typically about $100\mu A$ for neon (10+) or $1\mu A$ for uranium (70+). Particle currents are even lower, e.g. in case of uranium seven orders of magnitude below the usual proton injection currents of $100mA$.

In order to improve the available beam intensities, new developments are necessary. It is planned to improve the ECR ion sources at the new injector for short pulse operation. At CERN laser ion sources for milliampere currents of heavy ions are being developed. The most expensive way would be the construction of a new RFQ injector for the acceleration of low charge ion beams like uranium (2+).

Several of the basic SIS design features were determined by the low Unilac injection currents: (1) A lattice with a large acceptance and with an efficient multi turn injection scheme was required. (2) Operation at low intensities without the use of beam feedback loops had to be foreseen. (3) Time-shared operation for target experiments and for ESR feeding was important in order to make economic use of the available ion beam intensities.

2 LATTICE DESIGN

A strictly periodic lattice with 12 identical cells was chosen [2]. Fig.4 shows one of the 12 lattice periods. The focusing changes during acceleration from triplet to doublet structure. The triplet focusing at injection leads to fairly large machine acceptances of $A_{h,v} = 200/50\pi mm \cdot mrad$, while doublet focusing would yield only half this value for the horizontal acceptance. At high energies doublet focusing reduces quadrupole strength and makes beam extraction and chromaticity control easier. In addition, with four instead of two power supplies for the F and D doublet

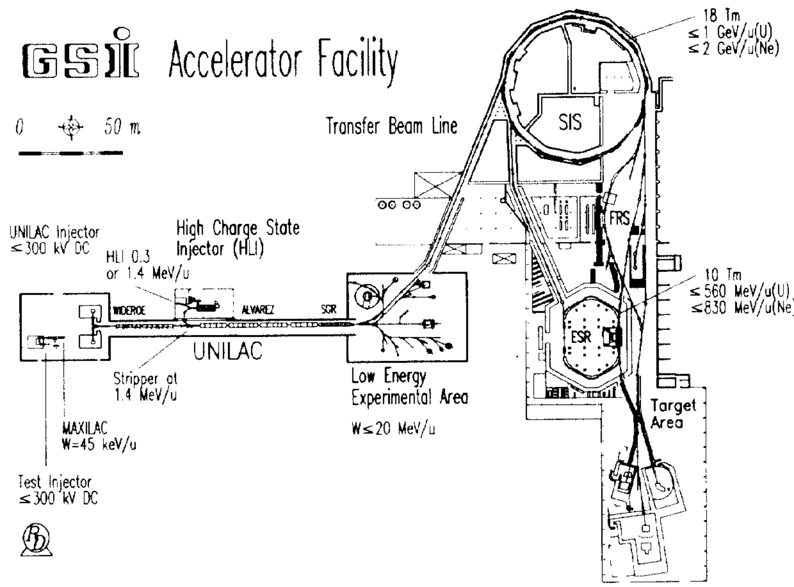

Figure 1: Plan view of the GSI accelerator facility

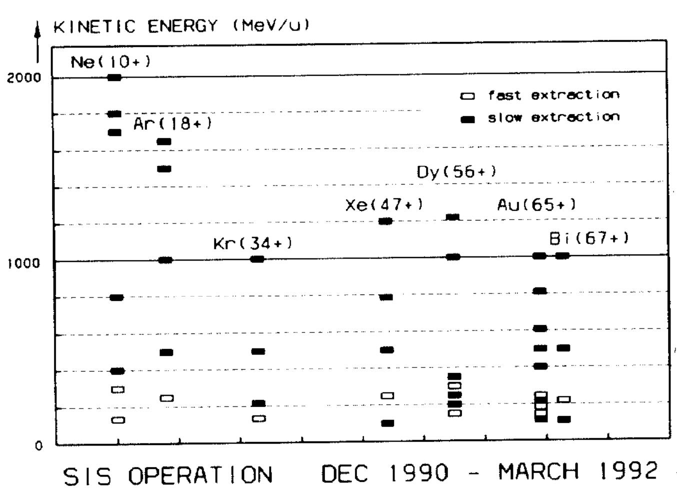

Figure 2: SIS operation from Dec. 1990 until March 1992

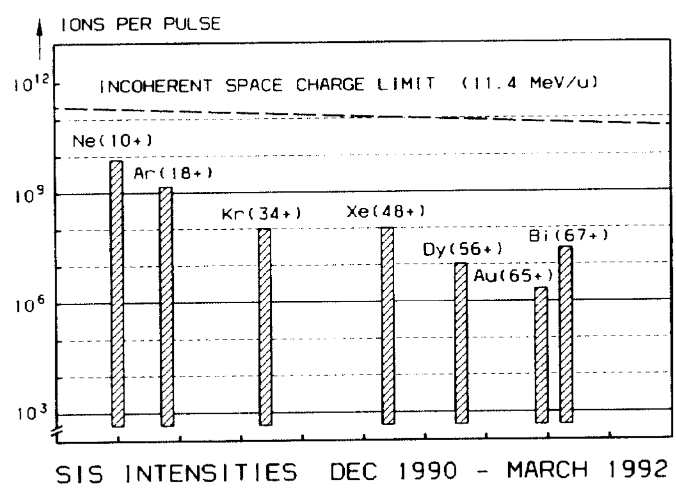

Figure 3: SIS beam intensities for target experiments

lenses a variable grouping from twelve to six focusing periods was prepared. Originally it was conceived to shift the transition point beyond the maximum proton energy of $4.5GeV/u$ (Fig.5). Meanwhile it shall be mainly used to tune zero dispersion in every second lattice period for the extraction of short bunches with about 1 % momentum spread in order to reduce the beam diameter in the extraction channel.

3 MACHINE COMPONENTS

Fig. 6 shows a photograph of one of the twelve machine periods, which all contain two bending magnets and the triplet group with two long doublet lenses and one additional triplet lens. Since the design and operation of the main magnet power supplies were essential for SIS operation, these supplies shall be shortly discussed.

For the dipoles altogether four converter/rectifier sets are used, which can be grouped either for a fast $10T/s$ field ramp up to $1.2T$ dipole field at $2300A$ magnet current or with two pairs of power sets in parallel operation for a reduced ramp rate of $4T/s$ up to the maximum field of $1.8T$ at $3500A$. The high ramping rate should allow repetion rates up to three pulses per second in order to achieve high average intensities with low injection currents. Actually, the magnets are usually run with a rather low ramping rate of $1.5T/s$, which is only 40% of the original design value for high energy operation. The restriction was imposed by the electricity company, since the direct connection of the full $30MW$ pulsed load to the $110kV$ main line was not tolerable for other customers, who operate small generators feeding power into the public line. In future a direct connection to the nearby $220kV$ main line may provide full use of the installed power supply capability.

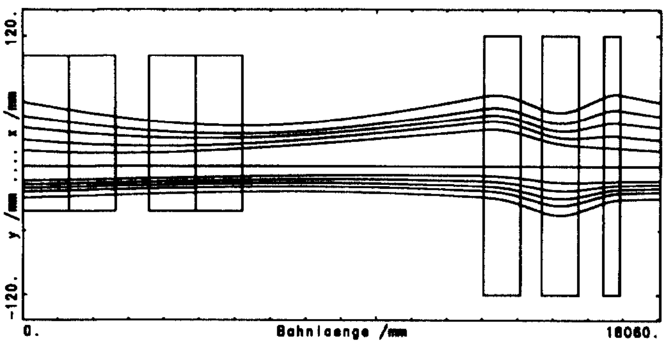

Figure 4: Beam envelopes for change-over from triplet to doublet focusing during acceleration.

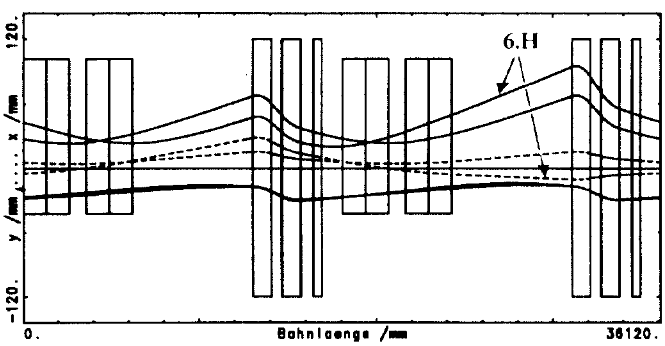

Figure 5: Beam envelopes and dispersion functions for standard (γ_t=5.4) and for sixfold symmetry (γ_t =∞).

For the quadrupoles five power supplies are in use: four supplies for the 24 long quadrupoles in order to provide separate F- and D-focusing and moreover quadrupole focusing with six periods and a fifth power supply to feed the twelve short triplet lenses.

In all dipole and quadrupole power supplies the usual active and passive filters are replaced by a current injection supply parallel to the load (PE), which superimposes a correction of up to 3% on the main power converter current. With this novel scheme the actual magnet current immediately follows the reference value with a precision of about $1\mu s$, while the conventional design with passive and active filters would lead to a variable delay in the order of $10ms$ [3]. Although the PE-scheme requires a precise presetting of the load voltage to an accuracy of a few volts, all necessary corrections for the effects of iron saturation and eddy currents could be included once for all during commissioning. Afterwards all kinds of supercycles with a combination of different low and high energy machine settings could be used with perfect tracking of dipoles and quadrupoles.

Supercycle operation is efficiently supported by the SIS control system, which is characterized by a three level hierarchy: (1) The operation layer, which provides the operators with tools to define and adjust accelerator parameters, (2) the front end layer made of VME crates with MC 68020 based controllers, and (3) the equipment interface layer [4]. The communications within the operation and front end layers are based on an Ethernet network. The

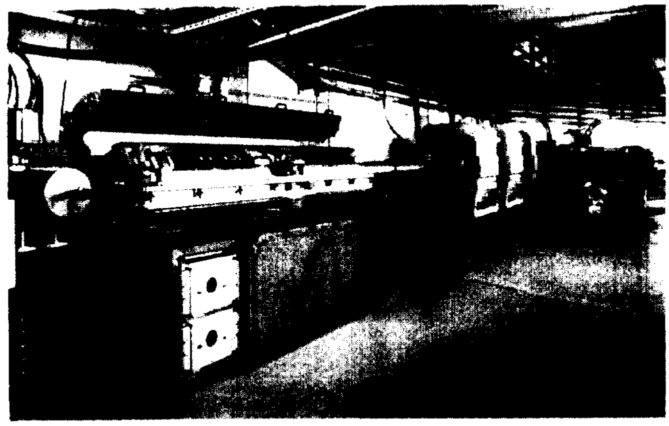

Figure 6: SIS machine period

VME equipment controllers exchange information with the interface modules via a field bus.

Machine timing is organized by a special VME crate, operating as control unit for the distribution of 16 bit event codes to all front end crates. Eight bits are used to define up to 256 event codes for each machine cycle, while four bits define up to 16 different machine settings, and four bits are reserved.

In the front end layer altogether about 30 VME crates - each with up to nine equipment computers - perform the real time control of the SIS equipment. Each equipment computer holds the respective machine parameters for up to 16 machine settings in a dual port RAM. Program modules, which can be started by relevant events within a few microseconds, provide the necessary data for the equipment interfaces. Function generator interfaces produce any ramped control function by linear interpolation between control data.

4 OPERATION AND PERFORMANCE

SIS supercycle operation for a time-shared use of up to 16 machine settings is controlled in the following way: (1) At first the machine cycle is prepared by defining injector pulse, ion mass and charge, energies, ramp rate, optics, type of extraction, and destination. (2) In a second step, the supercycle with a sequence of machine cycles is defined and then activated. (3) Finally, active machine cycles undergo fine tuning, especially for injection and extraction.

In Fig. 7 it is shown, how multi turn injection can be tuned using beam transformer signals for the injector line and for the circulating beam. For an injected pulse current of 15μA accumulation in transverse phase space yields a circulating current of 430μA. The effective enhancement factor of 28 for $160\mu s$ or 36 turn injection is in good agreement with the ratio of the SIS horizontal acceptance to the Unilac beam emittance of about 5π mm ·mrad.

The standard focusing scheme for acceleration is pure triplet focusing at injection with a change-over to doublet focusing at high energy keeping the Q-values almost constant. Fig. 8 shows the quadrupole currents and Fig. 9 the precision of quadrupole focusing for any focusing scheme

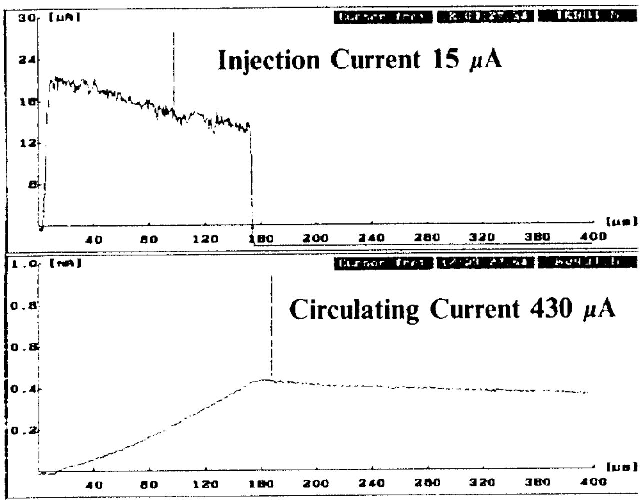

Figure 7: Multi turn injection

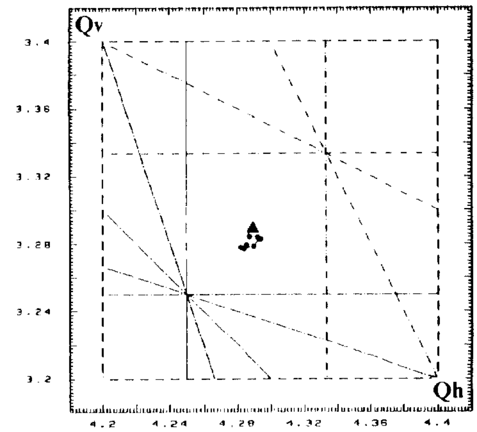

Figure 9: Tune measurements for several focusing modes from triplet (T) to doublet (D) focusing at a dipole field of 1.1 T. The triangle indicates the set tunes.

from triplet to doublet structure, which is better than 0.02 at a medium dipole field. Only at very low and at very high energies there is still a discrepancy of up to 0.03, which has to be eliminated by better correction of the quadrupole remanent fields and of saturation effects.

RF acceleration is usually run without beam feedback loops. Therefore, acceleration of low intensity beams with a few hundred ions or less can be used, e.g. for the setting up of experiments.

The beam diagnostic equipment was designed for the observation of very low beam intensities [5]. Fig. 10 shows the scheme for the detection of low voltage signals from the capacitive probes. The usual broad band amplification of the probe signals was replaced by signal processing at a fixed intermediate frequency of 50 MHz. In this way it was possible to observe circulating ion currents as low as 1nA or about 1000 heavy ions.

5 EXTRACTION AND EXTERNAL BEAMS

In the SIS both fast and slow resonance extraction are installed. The fast extraction is mainly used to feed the ESR by bunch-to-bucket transfer. The nine kicker modules can be used for the extraction of one, two, three, or all four bunches up to the maximum SIS energy. At present, the standard procedure is the transfer of two bunches to the ESR. The transfer of all four bunches by two consecutive shots with a delay of about 20 ms will be used soon.

The target station for 'high energy density' experiments makes also use of fast extraction. Studies of beam-target interaction physics, which are important for the development of inertial confinement fusion, require a high specific energy deposition. It can be achieved with short 10 to 50 ns bunches of small beam spot diameter. Fig. 11 shows that a 300 MeV/u neon beam could be focused to a diameter below 1 mm using conventional quadrupole lenses [6].

All other target station experiments need long beam pulses, which are provided by slow resonance extraction. For that purpose six of the twelve chromaticity sextupoles are set to shape the separatrix, which defines the onset of unstable non-linear particle motion. Two extra quadrupoles are used to shift the machine tune into resonance at Q_H=4 1/3. The unstable particles are deflected by an electrostatic wire septum into the extraction channel with three septum magnets. These magnets are connected

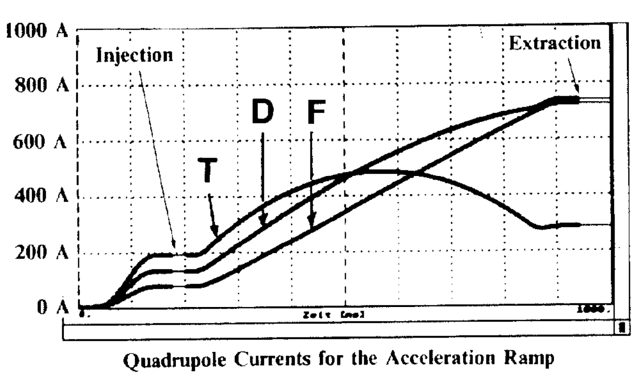

Figure 8: Quadrupole currents for the acceleration ramp

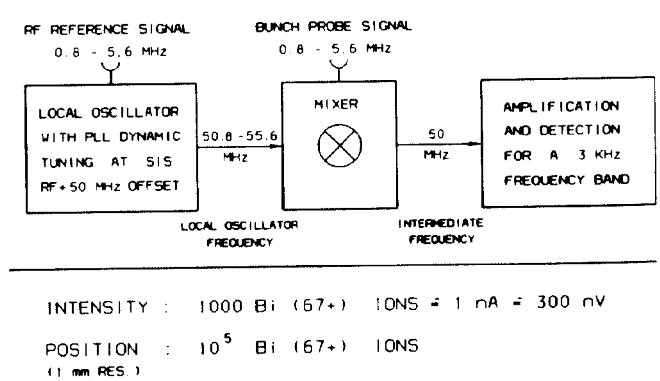

Figure 10: Narrow band bunch signal processing

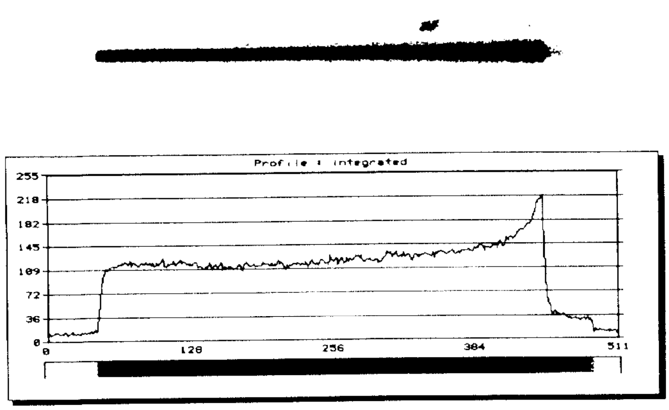

Figure 11: Fine focusing of a 300 MeV/u neon beam to a diameter below 1 mm. The range in the glas target is 50 mm. The light intensity profile reflects the Bragg curve.

in series to the main bending magnets and therefore do not require an expensive pulsed power supply.

Fig. 12 shows an example for the performance of slow resonance extraction. For the pulse length intervals between 10 ms and 5 s have been used. Even for quite long spills, intensity fluctuations were below 10 %. A spill plateau is tuned using a third order parabola for the extraction quadrupole current. It is foreseen to install an extraction current regulation loop for rectangular pulse shaping in the future.

The beam emittances after resonance extraction obviously depend on beam injection, end energy, and extraction setting. Typical values are 1 to 5π mm·mrad. The resulting beam spot size is 3 to 5 mm. Momentum spread is below $1 \cdot 10^{-3}$. A well-known disadvantage of standard resonance extraction is the observed shift of mean momentum in the spill. In order to avoid a corresponding shift of beam position at the target stations, so far achromatic settings were used for all beam transport lines.

Stochastic extraction is a complementary technique, which avoids the unwelcome momentum shift. The development of this extration procedure is underway.

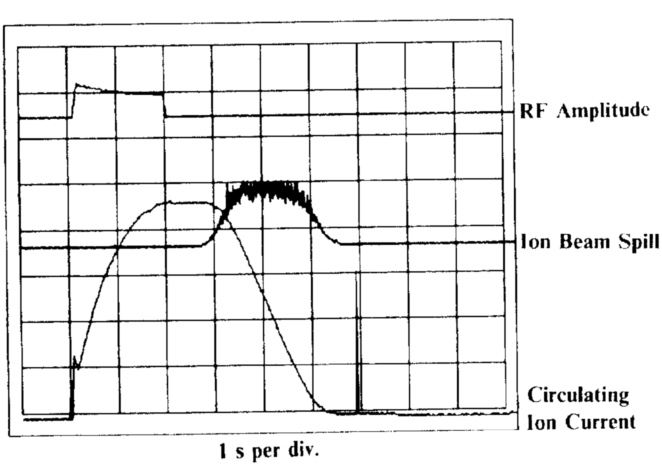

Figure 12: Resonance extraction

6 NEAR FUTURE DEVELOPMENTS

Heavy ion beams were proposed for radio therapy since several years. About 300 patients have been treated in Berkeley. At GSI a new strategy for an optimal dose delivery system is being developed. A magnetic raster scan technique was proposed in order to achieve a homogenious dose distribution for any three dimensional target volume. The volume is divided into slices corresponding to the range of the particle beam. Starting at the distal end, each slice will be painted with a pencil beam [7]. SIS machine operation and extraction techniques have already performed three prior conditions for this novel technique: (1) small stable beam spots, (2) beam current cut off within 400 μs and (3) delivery of 200, 250, 300, 350 MeV/u ion beams in a periodic sequence or on request. Stable beam position could be achieved for energy stepping with the four energies and ranges.

Another development is the commissioning of the reinjection line ESR/SIS at the end of 1992. The following uses are planned: (1) Acceleration of fully stripped heavy ions to maximum energies above 1425 MeV/u. (2) Slow standard and stochastic extraction of cold ion beams e.g. for channeling experiments. It is still an open question, how far a low beam emittance can be maintained for slow extraction. (3) Transfer of intense short and cold ESR ion bunches through the SIS to the target station for 'high energy density' experiments. The SIS may be used for rebunching in order to achieve extremely short bunches. For that purpose the optical mode with zero dispersion in the SIS extraction period may be necessary.

It is well known that intense ion beams are disturbed by transverse and longitudinal instabilities. These effects, which were already observed in the ESR for a cooled beam of 10^9 circulating ions, can be also studied in the SIS, when reinjection is available.

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