REPORT ON THE FIRST YEAR OF SIS OPERATION

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Summary

SIS commissioning took place in 1989 in two periods: From April to June the first phase of running-in with altogether 20 days and four different ion beams, i.e. Ar^{10+}, Xe^{21+}, Kr^{16+} and Ni^{14+}, was used mainly for

- studies of the multi turn injection scheme,
- first tests of rf bunching and beam acceleration,
- first studies of machine optics and
- tests of the extraction kicker modules.

The following five week shut down time in July was scheduled for

- the installation of the extraction line with beam diagnostic equipment,
- a new survey of the SIS alignment and
- replacement of underrated cabling in the main dipole and quadrupole power supplies.

Afterwards new and unexpected technical problems did prevent the regular operation of the main power supplies for several weeks. Therefore the second commissioning period had to be postponed. From September until December altogether 28 days with Ne, Ar, and U beams brought the following results:

- detailed studies of machine optics, especially for the T/D focusing scheme with transition from triplet focusing at injection to doublet focusing at extraction energy,
- acceleration of Ar^{18+} and U^{72+} to the design energies of 1700 MeV/u and 1000 MeV/u with T/D focusing,
- fast and slow extraction of ion beams and running in of the beam line to the machine beam stop and
- first positive experience with SIS supercycle operation using different machine settings from pulse to pulse.

Since January 1990 the SIS has taken up regular operation providing mainly neon and argon beams for commissioning of the beam lines to the experimental area and the ESR, for test runs at the first fragment separator section and the 4π detector array including the magnetic Forward Spectrometer ALADIN and the L.A.N.D. neutron detector, and for ESR commissioning. In addition, a machine improvement program was started with two main goals so far: improvement of slow extraction and improvement of the MCR control tools for routine operation.

Machine Optics

Precise control of all machine functions requires a rather complete understanding of machine optics. Therefore it is necessary to provide a reliable optical model which correctly describes the observed beam behaviour. In order to check the optical model the following machine properties were observed and compared to the theoretical predictions:

- Closed orbit
- Betatron tunes (Q-values)
- Chromaticity

The closed orbit of the stored beam was measured at six out of twelve position monitors around the synchrotron. Fig. 1 shows the result of a measurement at injection energy of 11.4 MeV/u as observed in December 1989. The amplitudes are ± 2 mm in the vertical and ± 6 mm in the horizontal directions. These results may be roughly explained by the displacement of the quadrupole triplets with deviations up to about ± 1 mm in the vertical and ± 3 mm in the horizontal direction. Although the present closed orbit amplitudes did not prevent commissioning, they have to be corrected in order to provide full acceptance and well controlled routine operation.

In the horizontal motion a closed orbit displacement of about 5 mm is superimposed due to inaccurate dipole field setting. These dipole field errors are caused by the remanent field. After ramping the magnets several times from zero to maximum field, a constant remanent field of about 7 G is observed. However, in real machine operation the magnetic history is different. If the preceeding cycle did not reach 1.8 T, the remanent field is smaller. This effect can be seen in fig. 1, where the data for the solid line was taken with all cycles at 11.4 MeV/u while the dashed line shows the displacement due to higher remanent fields with a preceeding 200 MeV/u cycle. The difference in avarage position of 1.9 mm corresponds to a field difference of 0.8 G. Therefore we conclude that it will be necessary to take care of the magnet history when combining different energies in a supercycle.

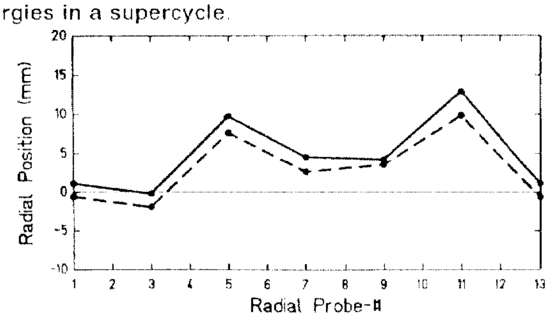

Fig. 1: Closed orbit at 11.4 MeV/u measured at six out of twelve positions. Solid line: preceeding virtual accelerator operated at 11.4 MeV/u; dashed line preceeding virtual accelerator ramped to 200 MeV/u

Another step to understand the machine optics was the comparison of the measured betatron tunes with the values expected from machine setting. First tune measurements had been made using the profile grid after one turn located in SIS period 12. The beam oscillations could be observed over four to ten turns and indicated that the horizontal tune was about 0.3 lower than expected.

Since no information on the vertical tune could be obtained with this method only a crude empirical correction was applied to the optical model in order to make tune measurements with the circulating beam in the next commissioning period in September 1989. The method was to apply a fast transverse kick on the beam and to observe the coherent oscillation with one of the twelve pick-up probes over 20 to 100 revolutions.

These measurements were performed during an acceleration ramp from 11.4 to 150 MeV/u and changing the focusing from triplet to doublet. This way an improved optical model was found which basically consists of a 3.5 % correction in the calibration of the short triplet lens.

The results of tune measurements made in February 1990 based on this model compared with the set values are shown in fig. 2. The agreement is quite satisfactory since the error is well below 0.05. Though the model will need further improvement it can readily be used to control the tune of the machine. Probably the influence of variable remanent fields in the quadrupole lenses has to be studied in more detail. Assuming the same relative variations as in the dipole magnets results in tune variations up to 0.04 which is the order of magnitude observed for the difference between setting and measurement.

Finally, we measured the natural chromaticity of the machine. Using the rf-cavity the beam momentum was changed in the range of $\Delta p/p = \pm 6.1 \times 10^{-3}$ and the tunes were measured at constant settings of the magnets. The results are ξ-h = -1.08 and ξ-v = -1.75 which should be compared with the theoretical values of ξ-h = -0.94 and ξ-v = -1.83 resp. The difference is not very large and probably due to sextupole components of the dipole fields which had not been included in the chromaticity calculation. The chromaticity is independent of momentum indicating that there are no major non-linearities in the machine.

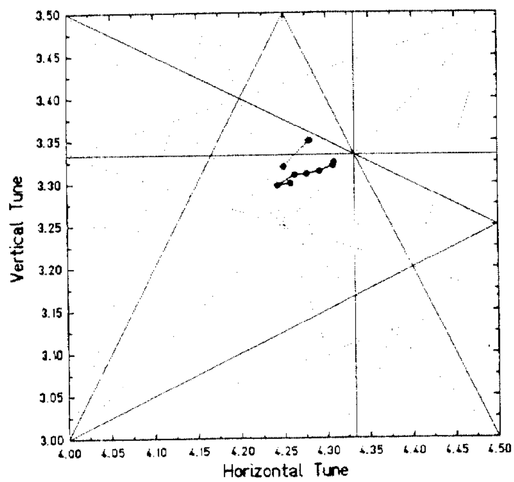

Fig. 2: Measured tune (solid line) and set values (dashed line) during acceleration from 11.4 to 150 MeV/u and changing of the focusing from triplet to doublet.

Acceleration of Ion Beams to High Energy

Already in May a first test had shown that acceleration of Xe^{21+}, up to 100 MeV/u at 0.96 T dipole field is feasible without using beam feedback for the phase and radial position control loops. However, acceleration up to the design energies at a dipole field of 1.8 T did require further improvements:

- In the program for the dipole magnets corrections for the saturation effects were included.
- Adequate control of the tune in the triplet to doublet transition was required. The first tests of rf acceleration had been performed with pure triplet focusing.
- For the acceleration of low intensity beams, e.g. U^{72}, an improvement of the beam diagnostic tools was important.

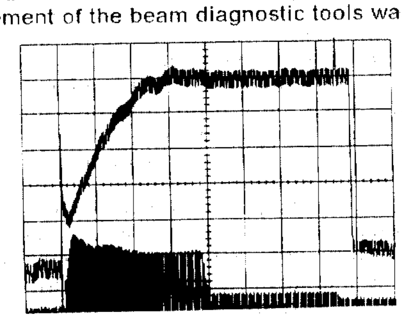

Fig. 3: Accelerating Ar^{18+} up to 1000 MeV/u. upper trace: absolute particle current, not normalized to β. lower trace: RF voltage during acceleration (200ms/div)

The first step on the way to the high design energies was acceleration of Ar^{18+} up to 1000 MeV/u on the 3 rd of October. Fig.3 shows the circulating ion beam current during one cycle that was measured on the dc transformer in the SIS. After multiturn injection of approximately 70 μA more than 50% of the circulating ion current were lost partly at the end of the injection process and partly during rf bunching. During acceleration from 11.4 to 1000 MeV/u the current increased roughly parallel to the change in relative particle velocity from β = 0.15 to β = 0.80 at 1000 MeV/u. The lower trace shows the amplitude of the rf voltage, which goes up adiabatically in the bunching process and finally reaches a maximum value of 7 kV for acceleration. At top energy it is reduced to the small amplitude of 1kV, which is required to keep the four circulating bunches.

On the 31 st of October an U^{72+} beam was available for injection. The rather small electric pulse current of about 1 μA caused at first problems for the optimisation of multi turn injection and acceleration. Fortunately, the experts for beam diagnostic equipment provided just in the right moment a new tool for low intensity beam observation: narrow-band amplification of the pick up signals at injection and flat top field levels. Fig.4 shows the observed 4.847 MHz signal at the 1000 MeV/u flat top level. The signal-to-noise ratio of better than 40 dB should even allow observation of 10^4 circulating uranium ions.

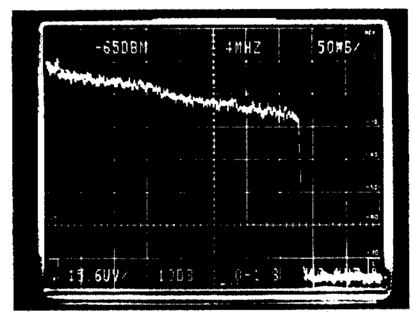

Fig. 4: Narrow-band signal of a 1000 MeV/u U^{72+} bunched beam on the flat top (50 ms/div.)

Two days later, on the 2nd of November, acceleration of Ar^{18+} to 1700 MeV/u could be achieved without difficulties, since the circulating currents were in the range of 100 μA.

Supercycle operation of the SIS was successfully tested in October 1989. Fig. 5 shows an example of supercycle operation with two different final energies: seven cycles at 100 MeV/u and every eigth cycle at 1700 MeV/u. Up to dipole fields of about 1.4 T the high energy cycle did not disturb the following low energy cycles. At 1.8 T, however, an effect as shown due to magnetic field saturation is visible. It will be described later, how these interaction of high energy pulses may be avoided.

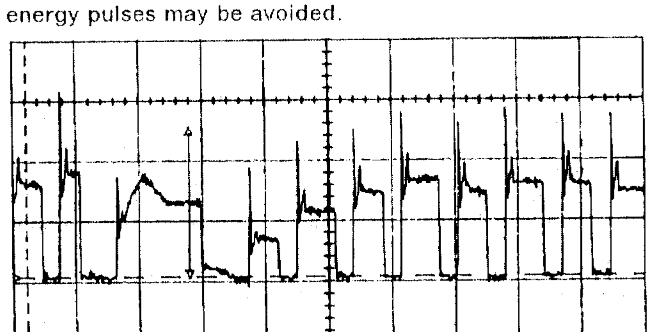

Fig. 5: Supercycle operation in SIS - seven cycles accelerating up to 100 MeV/u, every eighth cycle up to 1700 MeV/u. (2 s/div.)

Fast and Slow Extraction

The operation of SIS requires two different extraction schemes: with fast extraction one or two of the four circulating bunches can be extracted for injection into the ESR, while resonance extraction will provide long pulses of up to several hundred milliseconds for target experiments.

Fast extraction, which is easier to handle, was tested first. Five fast ferrite kicker modules in SIS period 4 are used to deflect any number of the circulating bunches into the extraction channel with three magnetic septa. For energies above 200 or 300 MeV/u it will be necessary to reduce the kick angle and hence to shift the beam close to the magnetic septum before the kick is applied.

The fast extraction with beam displacement using the correction coils on three dipole magnets was successfully tested. The five fast kicker modules, which are now in use, will allow fast extraction up to 10 Tm. Additional four modules will be installed in 1990 extending the energy range for fast extraction up to 18 Tm especially for the production of secondary beams at the FRS. Especially it was proven that the extraction channel with the three septum magnets can be set in a correct way. We should recall here that all three septum magnets are powered in series with the ring dipole magnets. For fine tuning of the deflection channel a small amount of the septum current can be bypassed by means of a transistor bypass current regulator.

Slow or resonance extraction is a more complicated procedure. In the SIS six sextupoles are excited in a suitable pattern at a horizontal tune close to 4 1/3 in order to establish a separatrix for extraction. The main quadrupoles and the sextupoles are set to the required field values at the end of the acceleration ramp within about 30 ms.

So far resonance extraction with a pair of extraction quadrupoles is used as standard procedure. The unstable particles enter the gap of an electrostatic septum, where they are deflected into the extraction channel.

During the developement of resonance extraction two problems have shown up: (1) in the spill a strong intensity modulation with many sharp spikes was observed (fig. 6), and (2) it was difficult to extract slowly at the maximum beam energies.

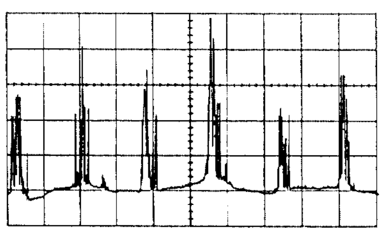

Fig. 6: 300 Hz spill modulation observed during the first tests of resonance extraction (2 ms/div.)

At first, the sextupole and resonance quadrupole power supplies were checked and improved. The result was an obvious improvement of the spill as detected on the secondary electron monitor at the fragment separator. However, a strong 100 Hz modulation of the spill appeared when fast scintillation detectors were used for beam obeservation. It took some time to show that the DC transformers of the main quadrupole power supplies produced a noise signal. Improvement work for the DCCT is now underway.

For extraction of 2 GeV/u neon beams with an electric rigidity of 5300 MV the electrostatic septum has to provide theoretically a deflection of 2.5 mrad at a field strength of 90 kV/cm. It was observed, however, that 3.5 mrad are required for slow extraction. Two ways will be followed in order to achieve slow extraction at the top energy:

- A reduction of the electrostatic septum gap from 16 to 12 mm provides an increase of the field strength from 90 to 110 or 120 kV/cm.
- By correct alignment of the ring magnets to tolerances of about ± 0.2 mm, which is foreseen for September, the closed orbit amplitudes will be reduced from ± 8 mm to ± 0.5 mm. As a consequence the electrostatic septum position will be moved outward in order to increase the divergence of the unstable particles on the separatrix. In addition, an improved control of the closed orbit around the extraction channel is expected.

To improve the spill quality and length it is foreseen to use the existing rf system for stochastic extraction as an alternative to the extraction quadrupole. First tests have been made and since the results are promising, we shall investigate this method in the near future in more detail.

Control and Operation

The control system is characterized by a three level hierarchy: a VAX computer network (Ethernet) for the operator and application software and VME crates, each with a M680xx master and up to 9 M680xx slave computers, which perform real time control of the equipment. All VME crates are also connected to the VAX computer network. About 20 VME crates are used for the control of all the SIS equipment. In each crate all M680xx slave computers, which are called equipment controllers interface to the VME bus via a 64k dual port RAM, where all data sets for up to 16 different synchrotron cycles or virtual machines are stored.

The execution of an arbitrary machine cycle sequence is controlled by the timing system, which distributes 16 bit event codes on a serial synchronisation link to all VME crates, where a parallel event bus is used to transfer the events to all equipment controllers. In this way program modules for real time equipment control can be started with a precision of about 10 μs. The equipment controllers send their information through a Mil-Std 1553-B device bus to the equipment interfaces.

To generate the tables of set values for the various ramped devices one has to ensure that all the data are consistent. Therefore a complete model of the whole accelerator for each of the 16 virtual machines is held in the computer memory. All important numbers such as energy, tune, bump amplitudes, data from calibration measurements, and timing are contained in this model. Thus all tables of magnet currents or voltages can be calculated on-line in a consistent way.

Any necessary modifications are not made in the tables stored in the devices but only in the parameters of the model. Thus it is possible to take care of all consequences that a particular change might have: e.g. increasing the final energy would result in a new calculation of almost all tables, whereas changing the acceleration voltage only affects the amplitude and phase program for the cavity.

Since the model parameters are normalized to mass, charge, and energy as far as possible, most numbers to be entered by an operator do no change for different kinds of ions. So it becomes clear that the imperfect ion optical model for the focusing is not a problem for the operation of the machine, since these errors can be compensated very easily just by entering a slightly different set value for the tune. All implications due to the various ions and energies are treated by the program.

The calibration data for one device are held separately for each virtual machine. Therefore it is possible to calculate currents based on different remanent fields depending on the context in the super cycle. This feature, however, has not yet been used extensively.

During the commissioning and for the next future of standard operation the user surface to this program is an alphanumeric terminal connected to the VAX computer network. To turn devices on and off or to check the status for the various virtual machines a control program is used which gives quick and useful information if e.g. the beam is lost due a failure in a power supply.

In addition NODAL programs provide access to all properties of all devices that can be controlled by the computer. They were developed by the software and hardware designers and are not to be used for standard operating, but have proved as very useful tools during commissioning.