STATUS AND DEVELOPMENT OF THE GSI ACCELERATOR FACILITIES

N. Angert, GSI, Darmstadt, Germany

1 ABSTRACT

This paper briefly describes the status of the operation and performance of the GSI accelerator facilities and gives a review on recent developments and modifications at the Unilac, SIS and ESR. In addition, current preparations for an intensity upgrade in the SIS are described and some considerations for a future extension of the GSI accelerator facilities presented.

2 INTRODUCTION

The GSI accelerator facilities comprise the Unilac, the heavy ion synchrotron SIS and the experimental storage ring ESR [1]. The Unilac has two injectors. The Wideröe prestripper injector is equipped with Penning and Chordis/Mevva ion sources, the high charge state injector with an ECR source. These injectors can provide independently two different ion species of all elements from hydrogen to uranium for the main accelerator consisting of four Alvarez structures and 15 single gap cavity resonators, delivering energies between 2 and 15 MeV/u. Beams in this energy range are used in the low energy experimental hall. The energy for the injection into the SIS is usually 11.5 MeV/u. For achieving high energies in the SIS the ions are stripped at this energy (e.g. uranium from 28+ to 73+). The synchrotron (18 Tm) accelerates the ions to energies between 50 to 2000 MeV/u. Beams from the synchrotron are transferred either to the high energy target area or to the ESR (10 Tm), where they can be stored and electron cooled. For the production of radioactive nuclei the beam from the SIS can also be sent through a fragmentation target followed by the magnetic fragment separator FRS for isotope selection for the injection into the ESR, or for the transport to the target area.

3 STATUS OF OPERATION AND PERFORMANCE

The accelerator facilities are in operation for about 6000 hours per year. In 1995 beams of 14 different isotopes have been accelerated for experiments at the Unilac, SIS and ESR. More than 90 % of the scheduled beam time at the Unilac and at the SIS were available for experiments. Since the begin of 1995 the dual beam option from the two Unilac injectors is used also in the synchrotron, offering the possibility to have different ions for the target area and for the ESR. The switching between the two ion species in the Unilac can be done within 15 ms. The operation cycle of the SIS is typically three seconds for fast extraction, depending on the energy. The flat top for slow extraction can be extended up to 8 seconds.

4 RECENT DEVELOPMENTS

4.1 Ion Sources

One of the major achievements on the ion source field was the development of metal ion beams (Ni and Zn) for the production of the superheavy elements Z = 110 (^{62}Ni), 111 (^{64}Ni), and 112 (^{70}Zn) at the ECR source. For the production of Ni-beams a furnace was developed for temperatures up to 1500° C [2]. With that design stable Ni^{9+} beams of 20 µA could be achieved in cw operation from the CAPRICE source over several weeks. This could be also reproduced in several runs. $^{82}Se^{12+}$-beams of up to 40 µA could be produced without any problems over several weeks. For Zn^{10+} beams up to 30 µA could be achieved at the test bench for about one week of operation. The same performance could be reproduced at the Unilac injector, for two weeks. Then the source was „contaminated“ in a way, that a stable operation was no longer possible and beam intensities were steadily decreasing. For Sn the source performance was not very satisfactory. The beam current was only 3 µA in the charge state 16+ and was rather unstable. The sensitivity of the ECR source to the „history“ became relevant in a xenon-run following operation with tantalum. It took about one day with strongly elevated mixing gas (oxygen) pressure before one could get again the standard xenon operation performance.

4.2 Linac Improvements

At the Unilac modifications were accomplished to improve the dual ion and multiple energy performance. In the injection beam line to the Wideröe prestripper-accelerator pulsed quadrupoles have been installed, which allow to change the intensities on a pulse to pulse basis by several orders of magnitude. The same possibility was introduced at the high charge state injector.

The beam switch yard at the end of the Unilac was changed by replacing dc quadrupoles by pulsed ones and by a new configuration of the switching and septum magnets so that switching between two ions or different energies for the three main beam transport systems in the Unilac experimental hall is now possible on a pulse to pulse basis.

4.3 Synchrotron Developments

The possibility for post-acceleration of very heavy ions, which are first accelerated partly stripped in the SIS, extracted, fully stripped and reinjected via the ESR into the SIS for further acceleration, has been used for an experiment for the first time. Dual ion operation on a pulse to pulse basis in the SIS is now available for experiments after some upgrade of the SIS control system.

The main effort in the past two years was spent on SIS modifications for an experimental cancer therapy programme which will take place at GSI for a period of five years. For this application carbon beams, from the high charge state injector, are accelerated to energies between 80 and 430 MeV/u. The extraction time is typically 2 seconds. The beam diameter at the irradiation position should be between 4 and 10 mm. The maximum variation of the beam position during extraction and for the full energy range should be less than 1 mm at the entrance of the new medical cave M. The beam intensities have to be controlled in the range between $1 \cdot 10^6$ and $1 \cdot 10^8$ ions per spill.

To fulfill the therapy requirements a data basis has been generated which contains accelerator parameters for 255 energy steps, 7 beam diameter steps, and 15 intensity steps. The intensity variation is completely performed at the high charge state injector, which is used because of the stable beam parameters from the ECR-source. The beam diameter matching is exclusively done at the entrance of the medical cave. The energy steps are given by according parameters of the SIS. Out of this general data set the parameters for the individual patient are taken during the irradiation without any action by the accelerator operators. During an irradiation up to 64 different energies are foreseen for an individual patient and several intensities and beam diameters. A sophisticated programme has been started for the generation of data with parametrization routines for energies, intensities and beam sizes. Presently these data sets are tested and refined in order to allow a daily reproducible irradiation of a patient over a period of 20 days. The treatment per day of one patient takes only about 5 minutes. About 5 seconds are needed to change from one beam parameter set to the next. It is intended to have up to 20 patients per period and up to 80 per year i.e. four 20-day irradiation periods per year.

In order to get position-stable, reproducible beams it was necessary to introduce after each two second extraction flat top an additional ramping pulse which goes up to about .6 T for the SIS dipoles. Physics experiments seem to be possible between patient irradiations with other beam energies or with another ion provided that the related beam rigidity is not too high. Compatibility test with other ions in the Unilac are being performed. During the preparation of the medical programme an upgrade of the control hardware and modification of the software for hundreds of components was necessary. In addition, care has been taken to fulfill the increased safety requirements needed for that purpose. Details of developments for cancer therapy are given in separate contributions to this conference [3],[4]. A test of the complete system including the raster scan in the irradiation cave M is scheduled for fall 1996. The inclusion of parallel experiments will proceed according to operation experiences. In order to improve the beam stability during extraction, developments for the control of the spill structure of the extracted beam are going on [5].

4.4 ESR Developments and Achievements

At the experimental storage ring ESR [6] new experiments have been performed with electron cooled beams. Methods for mass measurements with the Schottky analysis have been further developed. Presently hardware improvements are underway including the installation of pick-ups and kickers for stochastic cooling.

4.4.1 Heavy Ion Cooling

With low intensity beams of electron cooled ions of C^{6+}, Ne^{10+}, Ar^{18+}, Ni^{28+}, Kr^{36+}, Xe^{54+}, Au^{79+}, and U^{92+} experiments have been performed [7]. The ions have been injected with velocities $\beta \sim 0.6 - 0.7$ and cooled sufficiently long to establish a balance between electron cooling and heating by intrabeam scattering (IBS). Due to radiative electron capture in the cooler the initial number of ions (10^7 to 10^9 in these experiments) in the ring is decreasing with a characteristic decay time for each ion species. The dependance of the ion beam momentum spread and emittance on the ion number N in equilibrium is proportional to $N^{0.3}$ to and $N^{0.6}$ respectively [8].

For e.g. Au^{79+} of 360 MeV/u, cooled with an electron current of 0.25 A, the life time was about 1500 s deduced both from current transformer and from Schottky noise measurements. The momentum spread first decreased proportional to $N^{0.3}$ as expected for the IBS dominated regime. After 2.5 hours of storage time the number of particles was decreased to $\sim 4 \cdot 10^3$ and the momentum spread to $5 \cdot 10^{-6}$. There the momentum spread of Au^{79+} ions exhibits a strong discontinuity with a reduction by a factor of ten. Thereafter it stays constant for particle numbers $N \leq 4 \cdot 10^3$. The constant level of the according frequency spread $\delta f/f \sim 2 \cdot 10^{-7}$ is determined by the stability of the magnet power supplies. The same dependance on the particle number was seen for all other ion species except the light ones C^{6+} and Ne^{10+}. Estimates of the plasma parameter Γ, which describes the ratio of potential energy to thermal energy, show that it is close to unity at this discontinuity. That could be an indication for a transition from a gaseous to a liquid state in the one-dimensional beam-plasma.

The radiative electron capture can be used also to control via the electron current the extraction of charge changed cooled ions [9]. It was used for the first time in a channelling experiment with decelerated 50 MeV/u Au ions providing a beam emittance of $\leq 1\ \pi$ mm mr. The rate of slowly extracted ions can be increased up to 10^5/s at this low energy.

4.4.2 *Precision Schottky Mass Spectroscopy*

Measurement of nuclear masses by means of Schottky noise analysis has been proposed for the ESR 10 years ago [6]. In 1994 experimental tests started. The GSI accelerator facilities offer unique possibilities for the preparation, storage, and cooling of radioactive beams. Projectiles from the SIS pass a thick target in front of the fragment separator (FRS). The FRS selects nuclei within a certain bandwidth of the ratio momentum to charge for the transport to the ESR. In the ESR these different „hot“ fragments are electron cooled all to the same velocity. Therefore, differences in the circulation frequency are caused only by differences in the mass to charge ratio. In the ESR , as mentioned above, low intensity ($N \leq 10^4$) beams can be cooled down to a momentum width of $5 \cdot 10^{-7}$. This leads to an according enhancement of the spectral power density in the Schottky lines. Using heavy, high-Z fragments the signal-to-noise ratio improves proportional to Z^2. With this method a mass resolution of $3 \cdot 10^{-6}$ is achieved. With reference mass lines of stable or known radioactive isotopes a similar relative accuracy is attained [10].

The sensitivity of the Schottky pick-up system is such high that lines from a single circulating heavy nucleus can be seen. Electron capture and stripping at the internal gas jet target could be observed from one circulating W^{74+} ion by the frequency jump deduced from the Schottky signal.

In two runs with ^{179}Au and ^{209}Bi primary beams from the SIS more than 280 nuclides were produced and selected in the FRS and then stored, cooled, and mass analysed in the ESR. The mass of 90 different nuclides could be measured for the first time [11]. That means a considerable fraction of so far known masses of radioactive nuclei.

For heavy ions, around mass 200 an absolut precision of about 100 keV/c^2 could be achieved. The highly sensitive Schottky method allows also to determine life times of radioactive nuclei. The lower limit is presently determined by the time needed to electron cool the „hot“ beams, which takes about 20 to 30 seconds. Life times down to a few seconds may be accessible by a „stochastic precooling“. Pick-ups and kickers are presently being installed and should be commissioned in the second half of 1996. Much shorter nuclear life times between 1 µs and 100 µs may be reached by means of time-of-flight measurements using an isochronous lattice mode in the ESR; i.e. operation at γ_t [12]. Test for operation at γ_t have been performed with a ^{40}Ca beam [13].

5. CURRENT PREPARATIONS FOR THE SIS INTENSITY UPGRADE

5.1 *Present Status of Intensities*

For light ions the Unilac prestripper accelerator is equipped with high current ion sources of the Chordis- and Mevva-type which can provide mA beams. That allows to fill the SIS up to its space charge limit of about 10^{11} particles per pulse (ppp). For heavy ions the presently used Penning ion source can only provide beam intensities of e.g. U^{10+} of several 100 µA. With these currents one can achieve a few times 10^8 ppp in the SIS, what is about two orders of magnitude below the space charge limit. A two stage programme is presently going on to increase the intensities for the heavy ions.

5.2 *Multiple Multiturn Injection into the SIS*

In a first stage an electron cooler will be installed in the SIS [14]. This component will allow multiple multiturn-injection. For that a large fraction of the horizontal acceptance of the SIS of 150 mm mr will be filled first by multiturn-injection. Then the emittance will be electron-cooled down to about 30 mm mr. This procedure, which takes about 100 ms for heavy ions can be repeatedly applied. Thereby, an intensity increase by a factor of 8 to 10 can be expected leading with present ion source currents to a few times 10^9 ppp. The electron cooler energy ranges from 5 to 35 keV. That means that cooling is not only possible at the injection energy of 11.4 MeV/u up to the space charge limit but also after some acceleration in the SIS, up to energies of 65 MeV/u, in order to improve the beam emittance.

The design of the electron cooler was done in the BINP, Novosibirsk. It is presently under construction both in Novosibirsk and at GSI. Gun and collector are ready for tests. The complete set-up is to be installed at the SIS in fall 1997. Cooling measurements of partly stripped ions of the relevant energy have been performed at the TSR in Heidelberg, showing that the desired cooling times can be achieved [15]. That means that the cycling time of the SIS will be increased for a ten-fold injection process by one second.

5.3 *High Current Injector*

In a second stage the Wideröe prestripper injector will be replaced by a high current injector, which is able to accelerate U^{4+} instead of U^{10+}. This concept is based on the following consideration: In the present Penning ion source the electric ion current yield for U^{4+} is at least a factor four higher than for U^{10+}. This means that the particle current is higher by a factor of 10 without specific optimization of the source for that charge state. In addition, there exist low charge state high current devices like the Mevva ion source, which can provide much more current, up to several 10 mA. [16]

For uranium with charge state 4+ or xenon with charge state 2+ one needs about 90 MV to reach the stripper energy of 1.4 MeV/u. As the Wideröe structure can not provide that, it will be necessary to replace it by a novel type RFQ structure and an IH-drifttube linac. The 10 m long RFQ-structure will accelerate the beam from 2.2 to 120 keV/u (8 MV). The two IH-tanks will provide 82 MV. The energy gain per meter in the IH structure is such high, that the new RFQ/IH-combination can be installed at the same space which is now used for the Wideröe-structure and the prebuncher system. A detailed description of the RFQ which consists of an IH-RF structure and four-rod electrodes, designed by Frankfurt University, is given in separate contributions [17], [18]. The RFQ tanks are presently under construction, to be delivered by end of 1996. The particle dynamics calculations and engineering design of the IH-drifttube linac is completed. The RF design was done in collaboration with the Technical University Darmstadt, using the MAFIA code [19]. Inquiries have been sent out expecting offers middle of June and delivery in spring 1997. 36 MHz have been chosen for the RF frequency. That allows to build IH tanks of less than 2 m in diameter. The structures are able to accelerate up to 15 mA electric current for ions with a mass to charge ratio of 65.

5.4 *High Current Related Modifications of the Unilac*

The Unilac was not designed as a high current machine. Therefore, the new task with many mA beams requires modifications of the RF-system to cope with the heavy beam loading in the accelerating structures. Tests are presently performed with a new feedback system for amplitude and phase. The beam diagnostics used in the past like Faraday cups or profile harps are no longer appropriate. Non-intercepting transformers, new pick-up systems, and ionisation profile monitors are being installed now, covering several orders of magnitude in beam intensities, from the µA range for Unilac experiments to many mA for high current SIS injection, on a pulse to pulse basis. For high current tuning and beam loss analysis, intercepting beam stoppers are needed at certain positions along the Unilac. The specific problems related to high power heavy ion beams are described in a separate contribution [20].

The longitudinal matching between the new prestripper- and the poststripper-accelerator needs an additional buncher unit because of the strong space charge forces after stripping at 1.4 MeV/u. The stripper section at 11.5 MeV/u must be completely redesigned. The eliptically shaped beam of 5 mm width and 20 mm hight will be swept horizontally within one macropulse of about 200 µs over the 50 mm stripper foil to distribute the beam energy loss over a large area [21].

6 CONSIDERATIONS FOR AN EXTENSION OF THE GSI ACCELERATOR FACILITIES

6.1 *Introduction*

Considerations for a next generation upgrade of the facilities have been started at GSI last year. There are presently several fields discussed, which should be looked at, involving the users community. To substantiate these discussion working groups were formed dealing with electron-nucleus/nucleon scattering, nuclear collisions at maximum baryon density, physics with secondary beams, nuclear structure physics with radioactive beams, and plasma physics with heavy ion beams. The related accelerator schemes are rather different, including a high luminosity electron-ion collider, a synchrotron for higher energy, a heavy ion collider, and high intensity ion linac scenarios. In the following sections some possible extensions are briefly described.

6.2 *Linac Extension*

An extension of the Unilac to e.g. 100 MeV/u would increase the space charge limit at injection in the SIS. With the new high current injector e.g. 12 mA of U^{28+} could be accelerated and stripped at that higher energy with possibly higher stripping yield. The beam emittance should be lower, what could be exploited to increase the number of turns in the vertical plane. The higher intensity and energy could be both used with respect to radioactive beam production and in the application for plasma physics experiments for inertial confinement fusion. For the latter, one could also install an additional storage ring and compressor linac for a dedicated plasma physics facility. An increase of the average current from the SIS, which would be adventegous for radioactive beam production, could be achieved by upgrading the power system of the SIS to allow a three times higher ramping rate.

6.3 Increase of Ion Energies

The possibility of an energy increase, discussed about 15 years ago is now considered again. A synchrotron for a maximum magnetic rigidity of 100 Tm would offer energies for the heaviest ions up to 10 GeV/u or 30 GeV for protons. With the above sketched Unilac extension and with the SIS as injector synchrotron one could reach heavy ion intensities which are above 10^{11} per synchrotron cycle.

In order tot get to much higher center of mass energies one could add an ion-ion collider for 2 x 10 GeV/u using the forementioned injector chain. In order to compensate intrabeam scattering and beam-beam effects, electron cooling is considered, which seems still feasible at these energies [22], [23]

6.4 Electron-Nucleus Collider

A new idea which is presently considered intensively is an electron-nucleus collider for 3 GeV electron and 10 GeV/u uranium beams. Similar to the ion-ion collider such a facility seems only attractive, with respect to existing experimental possibilities, if high luminosity could be realised. Studies have been started in collaboration with BINP, Novosibirsk. An international working group has been established discussing limiting effects like intrabeam scattering and beam-beam effects, beam cooling schemes and practical aspects like feed back problems etc.

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References

[1] K. Blasche, B. Franzke, Proc. 4th EPAC, London 1994, 133

[2] C. Barué, J. Bossler, S. Schennach, H. Schulte and B. Wolf, Rev. Sci. Instr. 64(3), March 1996, 1368

[3] H. Eickhoff, B. Franczak, U. Krause, C. Riedel and R. Steiner, Accelerator Aspects of the Cancer Therapy Project at the GSI Darmstadt, EPAC-96

[4] B. Franczak, Data Generation for SIS and Beam Lines for the GSI Therapy Project, EPAC-96

[5] U. Blell, A Feedback System to Improve the Spill Structure of a Synchrotron,EPAC-96

[6] B. Franzke, Nucl. Instr. Meth. B24/25 (1987) 18

[7] M. Steck, K. Beckert, H. Eickhoff, B. Franzke, F. Nolden, H. Reich, B. Schlitt, and T. Winkler, Indication for a One-Dimensional Ordering of Electron Cooled Heavy Ion Beams in the Storage Ring ESR, to be published

[8] M. Steck, K. Beckert, F. Bosch, H. Eickhoff, B. Franzke, O. Klepper, R. Moshammer, F. Nolden, P. Spädtke, and Th. Winkler, Proc. 4th EPAC, London 1994, 1197

[9] H. Eickhoff, B. Franzke, GSI-Report 94-1, March 1994, 307

[10] B. Schlitt, K. Beckert, T. Beha, H. Eickhoff, B. Franzke, H. Geissel, H. Irnich, H.C. Jung, T.F. Kerscher, O. Klepper, K.E.G. Löbner, G. Münzenberg, F. Nolden, Y. Novikov, T. Radon, H. Reich, A. Schwinn, M. Steck, K. Sümmerer, T. Winkler, and H. Wollnik, Hyperfine Interactions 99 (1996) 117

[11] T. Radon, GSI-Nachrichten 11-95 (1995) 4

[12] H. Wollnik, Nucl. Instr. Meth. B26 (1987) 267

[13] A. Dolinskii, A. Valkov, H. Eickhoff, B. Franczak, B. Franzke, Operation of the ESR (GSI, Darmstadt), at the Transition Energy, EPAC-96

[14] M. Steck, K. Blasche, W. Bourgeois, B. Franzke, L. Groening, N.S. Dikansky, V.I. Kudelainen, V.V. Parkhomchuk, A.I. Sharapa, A.V. Shemyakin, and B.M. Smirnov, Fast Beam Accumulation by Electron Cooling in the Heavy Ion Synchrotron SIS, EPAC-96

[15] M. Grieser, F. Albrecht, D. Habs, R. v. Hahn. B. Hochadel, C.-M. Kleffner, J. Liebmann, J. Kenntner, H.-J. Miesner, S. Pastuszka, R. Repnow, U. Schramm, D. Schwalm, A. Wolf, and M. Steck, Proc. 4th EPAC, London (1994) 518

[16] E.M. Oks, P. Spädtke, H. Emig, C. Mühle, and I.G. Brown, Development of a Vacuum Arc Metal Ion Source as an Ion Injector for Heavy Ion Accelerators, EPAC-96

[17] U. Ratzinger, K. Kaspar, E. Malwitz, R. Tiede, and S. Minaev, The RFQ Section of the New Unilac Prestripper Accelerator at GSI, EPAC-96

[18] K. Kaspar, U. Ratzinger, Design of the New GSI RFQ Accelerator on the Base of MAFIA Calculations, EPAC-96

[19] B. Krietenstein, T. Weiland, and U. Ratzinger, Simulation of Eigenmodes in IH-Structures with MAFIA, GSI-Report 96-1, May 1996

[20] P. Strehl, Thermal Aspects of Beam Intercepting Diagnostic Devices, EPAC-96

[21] J. Glatz, B. Langenbeck, A High Duty Foil Stripper System in the Injection Line to the Heavy Ion Synchrotron SIS at GSI, EPAC-96

[22] D.J. Larson, D.R. Anderson, J.R. Adney, M.L. Sundquist, and F.E. Mills, Nucl. Instr. Meth. A311 (1992) 30

[23] T.J.P. Ellison, Nucl. Instr. Meth. A364 (1995) 27