# Operation Report of UNILAC and SIS

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The statistics of the accelerator operation in 2000 were collected with the help of the program **PROST** [1]. The topics of accelerator development and experiments are described in separate contributions [2], [3] and [4] to this annual report.

## 1. General overview

In 2000 the new operation capabilities of the High Current Injector (HSI) determined the accelerator operation. After its start of operation in November 1999 a lot of experiences have been made concerning the pulse to pulse operation with up to three ion sources (see Figure 1 for the multiplicity of accelerated isotopes). The new operation possibilities allow to satisfy better the growing demands of the experiments concerning time sharing operation and beam intensity, but to satisfy them a careful scheduling of the beam time becomes more and more essential.
There was three longer beam periods in this year of over 2 month length and a shorter one (the second) of one and half month length. A four week shut down in September were used for maintenance of the Alvarez I cavity and the vacuum system behind the SIS.

Table 1: Overall beam time of the accelerator facility

| | Total beam time ´00 (h) | Target time ´00 (h) | Target time ´99 (h) |
|---|---|---|---|
| UNILAC experiments | 6013 | 4854 | 3806 |
| SIS experiments | 8166 | 5118 | 4255 |
| ESR experiments | | 1031 | 1081 |

The total beam time in comparison with the achieved target time is given in table 1 for the different experimental areas. The operation time of the accelerator facility (number of working hours), 6088 h in 2000, were two shifts shorter than in the last year. The main reason for the higher values of target time at the UNILAC and the SIS experimental area is due to the more extensive use of the time sharing operation. The value for the ESR accelerator remains nearly constant.
As shown in Figure 1 beams of 25 different isotopes (twice as much as in the last year) were accelerated. They were delivered to 20 low energy experiments at the UNILAC and to 29 high energy experiments behind the SIS. Ion beams from the Penning terminal with a mass to charge ratio below 20 (high duty cycle) were due to the low terminal voltage difficult to handle. This led sometimes to unstable beam parameters at the experiments. The planed installation of a new power supply for the preacceleration gap should solve this problem in 2001.

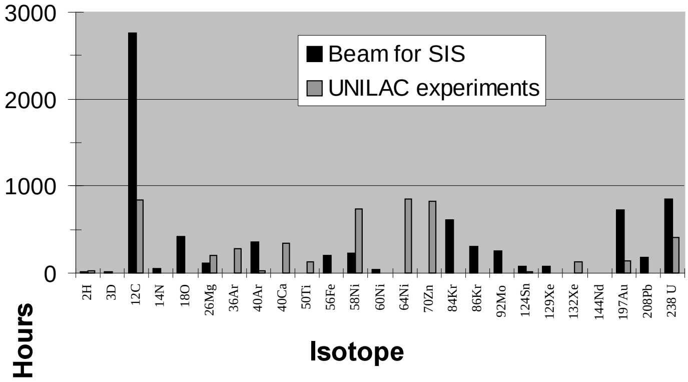


Figure 1: Accelerated isotopes in 2000

## 2. UNILAC Operation

The beam time for the UNILAC experiments is summarized in table 2. The column „performance“ indicates the efficiency of the accelerator operation. It contains the ratio (in percent) between the corresponding number of hours and the total beam time. The difference between operation time and total beam time is due to the time sharing operation of the accelerator.

Table 2: Beam delivered to UNILAC experiments in 2000

| | (h) | Performance |
|---|---|---|
| Target time for experiment runs | 4854 | 80,8% |
| Beam for experiment tests | 33 | 0,5% |
| Accelerator development | 108 | 1,8% |
| Accelerator tune-up | 496 | 8,2% |
| Ion source replacement | 103 | 1,7% |
| Unscheduled down time | 311 | 5,2% |
| Retuning | 52 | 0,9% |
| Stand-by | 56 | 0,9% |
| Total beam time | 6013 | |

The sum of beam time for experiment (including tests) is higher as in 1999. The 108 hours for accelerator development result to a large fraction from the commissioning of the new High Current Injector.
The unscheduled down time was due to failures of injectors (36h), rf-amplifiers (78h), magnet power supplies (48h), beam diagnostics (3h), vacuum system (38h), computer control (12h) and others (96h).

Table 3 displays the provided beam time of the UNILAC for SIS injection. The operation of the new stripper section in the

Table 3: UNILAC beam delivered to SIS in 2000

| | (h) | Performance |
|---|---|---|
| Beam available for SIS injection | 7261 | 88,9% |
| Accelerator development | 79 | 1,0% |
| Ion source replacement | 106 | 1,3% |
| Accelerator tune-up | 238 | 2,9% |
| Unscheduled down time | 439 | 5,4% |
| Retuning | 43 | 0,5% |
| Total beam time | 8166 | |

beam transfer line to SIS allows the injection of stripped and unstripped ions into the SIS in the time sharing mode. Technical problems due to different field values of the dipole magnets in this operation mode made a permanent correction of the settings necessary. By installation of Hall probes in the corresponding magnets (scheduled in 2001) this problem should be solved.

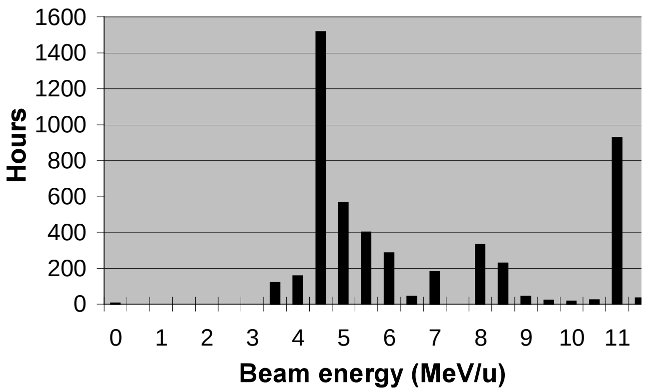


Figure 2: Beam energies of the UNILAC experiments

In Figure 2 the target time of the UNILAC experiments (without beam injected into SIS) is displayed versus energy. The upgrading of the phase control unit reduced the number of the available single gap resonators, so the energy range was restricted. The beam energies in the range from 4 to 6 MeV/u mainly result from the experiments for superheavy element synthesis and nuclear physics. Energies around 8 MeV/u were used for nuclear chemistry experiments and above 10 MeV/u for material science and for the plasmaphysics experiments.

## 3. SIS Operation

In table 4 the operating statistics for the SIS is given. The total target time is about 400 h higher compared to last year.

The loss in beam time due to technical failures distributes to power supplies (43h), rf-amplifiers (20h), beam diagnostics (5h), computer control (23h), vacuum system (149h) and others

Table 4: SIS operation time in 2000

| | (h) | Performance |
|---|---|---|
| Beam for target area | 3681 | 54,8% |
| Therapy | 1437 | 21,4% |
| Beam delivered to ESR | 1031 | 15,3% |
| Beam for experiment tests | 6 | 0,1% |
| Total target time | 6155 | 91,6% |
| Accelerator development | 141 | 2,1% |
| Accelerator tune-up | 70 | 1,0% |
| Unscheduled down time | 354 | 5,3% |
| Total beam time | 6720 | |

(114h). A leak caused by a broken vacuum window in an experimental setup is mainly responsible for the high number of vacuum loss hours.

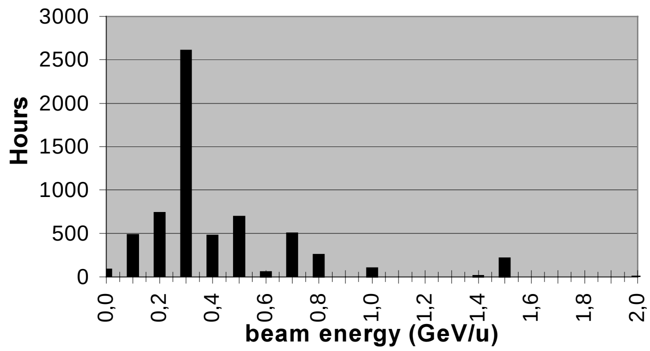


Figure 3: Beam energies delivered to the SIS experiments

Figure 3 shows the beam time versus energy for the SIS experiments. The high fraction of target time at about 400 MeV/u results as well as in the last year from the acceleration of $^{12}C$ beam for the cancer therapy. The lower range of energy was also used (Figure 3) to provide beam for the ESR and for plasma physics experiments.

## References

[1] **PR**ogramm für **O**perating und **ST**atistik

[2] J. Klabunde et. al. UNILAC Status and Developments

[3] K. Blasche et. al. SIS Status Report

[4] M. Steck et. al. ESR Operation and Development

# Ion Source Development and Operation

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The past year was characterized by a a reliable ion source operation serving the accelerator and the beam time schedule. Ion source development took place mainly to produce the desired beams, in addition, collaborations have been established and continued to improve the different ion source types.

## Operation

### ECR Ion Source

The ECR ion source (ECRIS) at the High Charge State Injector (HLI) delivered ion beam to the accelerator facilities without interruption during all beam time blocks in 2000. Most of the time was dedicated to the cancer therapy. The production of $C^{2+}$ beams for this purpose has become routine operation and worked without any problems. Besides therapy the HLI predominantly had to provide beams for the production of Super Heavy Elements (SHE) and for nuclear chemistry experiments.

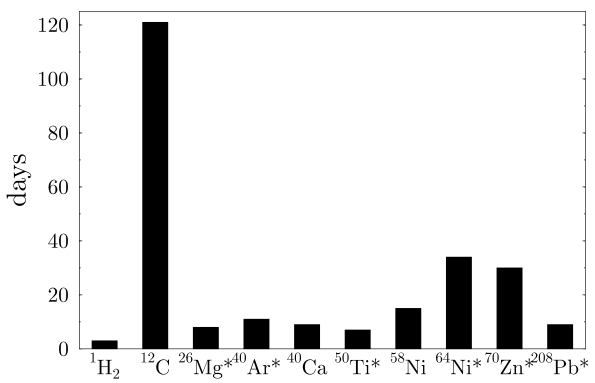


Figure 1: Element statistics of the ECRIS in 2000. An asterisk indicates the use of enriched isotope material.

Long periods were covered by $^{58}Ni^{9+}$ (natural) and $^{64}Ni^{9+}$ (enriched material) beams which could be performed with high reliability getting intensities of several tens of e$\mu$A. The usual material consumption of typically 5...6 mg/h for Ni could be considerably reduced for $^{64}$Ni to $\leq 3$ mg/h by carefully recycling condensated sample material from the orifice of the oven.

Another long time run for the production of SHE was $^{70}Zn^{10+}$. It was routinely produced from $^{70}$ZnO pellets. A very constant beam of 70 e$\mu$A was obtained.

$^{50}$Ti was also requested for the production of SHE. Following the experience obtained from former experiments isotopic material of very high purity was used. However, the need for a high operating temperature of 1700 °C again showed that this is almost beyond the limit of the standard oven.

A solution of this problem appears to be a new type of high temperature oven which is being developed [1]. Its main features are an operating temperature of up to 2000 °C and a heating process by thermal radiation from a heater spiral of 10 mm diameter without any mechanical support. Thus any ceramics in the hot parts of the oven is avoided.

Tests was performed which proved the principal function of this oven. Nevertheless further modifications are necessary to improve its technical reliability in order to achieve satisfying long time operation. A 70 hours run could be performed at the test bench using natural Ti contained in a tungsten crucible. The achieved stability and intensity were comparable to the operation of Ni.

$^{208}Pb^{27+}$ was delivered to the SIS operating the ECRIS in afterglow mode. It was possible to reproduce the intensity and beam quality of a long beam time in the preceding year. However, the long time for preparation and optimization until sufficient stability is obtained demonstrates that it is not useful to schedule short beam time periods for the afterglow mode.

Two experiments at the UNILAC requested the alkaline earth ions $^{40}$Ca and $^{26}$Mg, respectively. The $^{40}Ca^{7+}$ ion beam could be reproduced under the same good conditions as it was done once before in 1999. A $^{26}Mg^{4+}$ ion beam was produced for the first time. Previous tests with natural Mg sample material had been encouraging. As for Ca the hot screen inset inside the plasma chamber is used for Mg, too. 60 e$\mu$A of $^{26}Mg^{4+}$ were achieved, but an increase of the intensity upon request by the experiment led to instable operating conditions caused by uncontrollable passive heating of the oven by the ECR plasma. This behaviour showed that further development work is necessary to improve the reliability of operation.

For $^{40}$Ca as well as for $^{26}$Mg the efficiency of ion beam production turned out to be very good compared to other metal ion operation. For $^{40}$Ca 18 % of the sample material is transformed into ion beam distributed in the charge states 1+ ... 12+. 1.8 % of the material can be analyzed in the requested charge state 7+. For $^{26}$Mg the corresponding values are 11.8 % in all charge states including 1+ ... 9+ and 2.5 % in the requested charge state 4+.

As further experiments are planned for the future which require beams of alkaline earth metals investigations were continued at the test bench. A common problem of these elements is the low operating temperature causing big difficulties to control the evaporation. Therefore, several modifications of the standard oven were applied in order to decrease the influence of passive external heating of the oven.

Experiments at the test bench (EIS) had shown that $H_2^+$ ions can be extracted from the ECRIS with 5 kV. This low extraction voltage is suitable for injection into the RFQ. An accelerator experiment at the HLI proved that a $H_2^+$ ion beam of good stability can be accepted and transported by the accelerator.

## Penning Ion Source

The PIG source was used for standard beams as shown in Fig. 2. The particle current for several elements could be increased by the lower charge state required by the new prestripper accelerator. For the heaviest elements we are able to use charge state 6+ instead of 10+, nearly doubling the particle current in front of the accelerator.

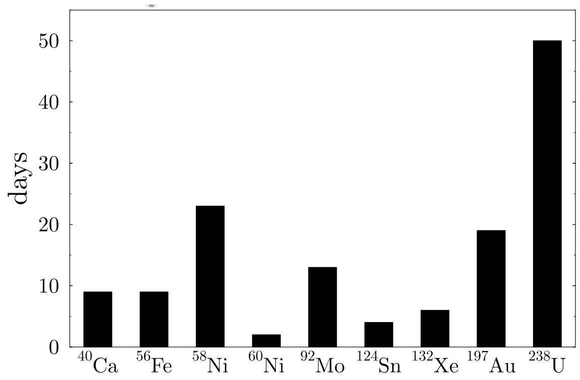


Figure 2: Element statistics of the PIG ion source in 2000.

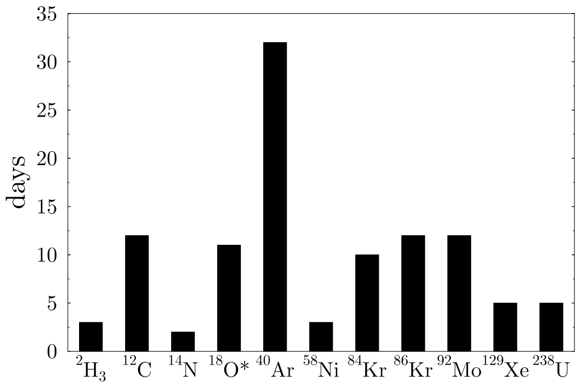


Figure 3: Element statistics of the high current ion sources. All gases have been provided by the MUCIS, whereas for all metals the MEVVA was used. For $^{18}$O enriched material has been used.

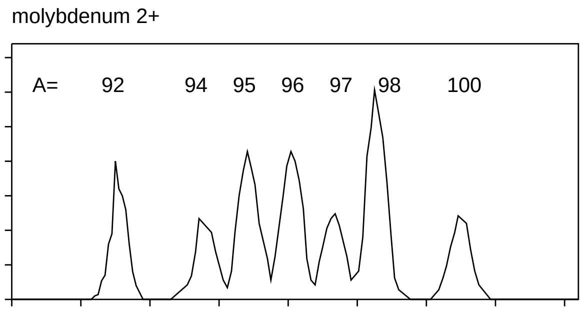


Figure 4: Isotope separation for $Mo^{2+}$. Note, that not a single pulse was missing during the measurement and the detected pulse currents reflect the natural isotope distribution, showing the good shot-to-shot reproduceability.

## High Current Ion Sources

For the commissioning of the high current injector up to 18 mA $^{40}Ar^{1+}$ have been produced by the MUCIS and transported to the RFQ. This beam is very reproducible and stable. For an experiment a $^{92}Mo^{2+}$ (15% isotope) was required. We checked three different ion sources for that purpose. It turned out, that the MEVVA delivered the highest ion currents in front of the RFQ (see table 1 and fig. 4.). Note, that all sources were operated with natural Mo. For a $^{197}Au^{4+}$-beam we found a different classification, showing that each source might have different capabilities for different elements.

Tab. 1: Comparison of different ion sources (regular PIG source, Half PIG type [2], MEVVA) for different elements. The current in front of the RFQ are given in emA.

| | PIG | H-PIG | MEVVA |
|---|---|---|---|
| $^{92}Mo^{2+}$ | 0.1 | 0.2 | 1.0 |
| $^{197}Au^{4+}$ | 0.3 | $\leq$0.1 | $\leq$0.1 |

The motorized remote cathode changer was taken into operation to prolong the operating time of the MEVVA ion source.

## Ion Source Development

Several collaborations to improve our ion sources and to investigate the applicability of new types of ion sources are in progress:

- A new development for ECR sources with 28 GHz micro wave heating promises higher particle currents and is investigated in a European collaboration[3].
- A laser ion source [4] was investigated to demonstrate high particle currents with a charge state distribution suitable at the high current injector. In this experiment with a 100 J laser up to 20 emA $Pb^{4+}$ with a pulse duration of 80 $\mu$s was a remarkable result.
- The subject of further improvement of the MEVVA ion source was a better noise reduction even for the high B field operation necessary for the production of $U^{4+}$[5]. This item is still to be improved.

## References

[1] R. Lang, J. Bossler, H. Schulte, and K. Tinschert, RSI **71**, 651 (2000).

[2] M. Müller, Dual HCD Ion Source, this report.

[3] Research collaboration agreement K598/PS, CERN, CEA, ISN, GSI.

[4] K.N. Makarov, et. al., Feasibility study of $U^{4+}$ pulsed ion beam generation in Laser Ion source. Internal report, ITEP, TRINITI.

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# Dual HCD Ion Source

for high current metal ion beams

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From the plasma of a **H**ollow **C**athode **D**ischarge high current beams of positively charged metal ions have been extracted . Up to mass 100 ion beams with currents beyond 10 mA have been delivered in long time operation ( 50 to 100 hours). Ion source economy with respect to sputter material consumption is at least one order of magnitude better compared to conventional sputter PIG ion sources [1].

Ion sources for low charged Ions (Z/A) = 0.017 became interesting for the GSI Intensity Enhancement Project since the UNILAC Prestripper accepts now for example 4+ Uranium ions from the injector. This gave reason to think about ion generators covering well this (Z/A) range. The suitably modified hollow cathode discharge was found as a device fulfilling some of the demands at least for metal ions below Mass 100. The mechanical set up was derived from existing GSI PIG Ion Source structures [2] to fit advantageously the necessary infrastructure as were magnets, vacuum chambers and manifolds. Ions from PIG discharge are usually extracted out of the hollow anode. This ion source geometry is modified by introducing an additional coaxial electrode. The electrode sequence: “heated Cathode - Anode – SE – Anode – cold Cathode” can be seen as a symmetrical or **D**ual **H**ollow **C**athode **D**ischarge geometry. Ions are extracted in the same manner as formerly from the PIG Source but now out of the hollow cathode sputter electrode SE.

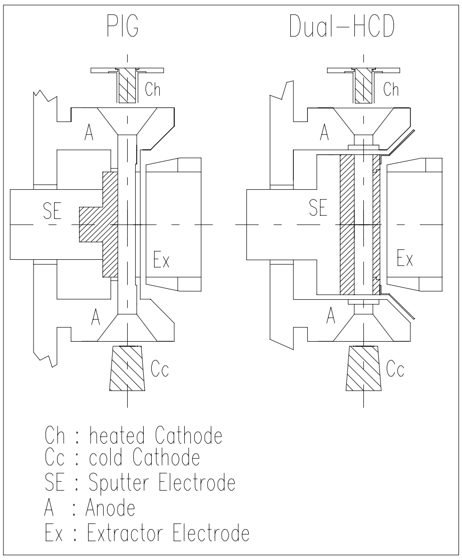


Fig.1: **Dual HCD and PIG Ion Source**

Sputtered particles from the inner wall of the hollow cathode, mostly of atomic nature, travel through the plasma column to become ionised in collision processes or to leave the plasma again hitting the cathode-wall . Ionised particles may contribute to the Sputtering by Self-Sputtering and / or being re-implanted into the surface, anyway staying available for further ion beam production.

Ions in the vicinity of the slit window going to leave the plasma are accelerated in the cathode fall before entering the strong electric extraction field of the outer ion beam forming area. The acceleration of the positive ions in the steep cathode fall prior to extraction is perhaps the reason for the surprisingly good beam quality.

Up to now most work was directed on the production of high current ion beams from lighter ions up to mass 100 . The **D**ual **HCD** was operated in the non-homogenous ”magnetic bottle” field of the Compact - PIG - Ion Source [3] as well as in the homogenous magnetic field of the GSI PIG Ion source magnet . Results for selected ion species are shown in Table 1. Enhanced ion beam yields from the Compact Ion Source Set up are due to the higher extraction Voltages available in this arrangement.

| **Element** | | | **Discharge** | | | | **Ion Beam** | |
|---|---|---|---|---|---|---|---|---|
| Ion | | Mass | U | I | B-Field | | Curr | Extr |
| | | **amu** | **V** | **A** | **Tesla** | **Form** | **mA** | **kV** |
| **Mg1+** | | 24 | 500 | 16 | 0.54 | H | **20** | 14 |
| **Al 1+** | | 27 | 500 | 12 | 0.5 | B | **20** | 16 |
| **Al 1+** | | 27 | 750 | 16 | 0.15 | B | **45** | 23 |
| **Ti 1+** | | 48 | 500 | 6 | 0.77 | H | **6** | 13 |
| **Ti 1+** | | 48 | 1000 | 22 | 0.15 | B | **24** | 25 |
| **Ti 2+** | | 48 | 2400 | 6 | 0.53 | H | **8** | 13 |
| **Ti 2+** | | 48 | 600 | 23 | 0.15 | B | **15** | 24 |
| **V 2+** | | 51 | 750 | 8 | 0.55 | H | **4** | 14 |
| **V 1+** | | 51 | 1100 | 13 | 0.15 | B | **13** | 21 |
| **Fe 1+** | | 56 | 1650 | 18 | 0.8 | H | **5** | 12 |
| **Ni 1+** | | 58 | 2000 | 15 | 0.84 | H | **11** | 13 |
| **Cu 1+** | | 63 | 1000 | 4 | 0.14 | B | **16** | 18 |
| **Mo 2+** | | 98 | 500 | 15 | 0.15 | B | **10** | 22 |
| **Zr 2+** | | 90 | 400 | 18 | 0.75 | H | **3** | 13 |
| **Ta 3+** | | 181 | 500 | 7 | 0.86 | H | **1.5** | 13 |
| **Ta 4+** | | 181 | 500 | 6 | 0.86 | H | **2** | 17 |
| **Pb 1+** | | 208 | 200 | 4 | 0.14 | B | **1** | 6 |
| **Pb 2+** | | 208 | 200 | 4 | 0.15 | B | **2** | 12 |
| **U 1+** | | 238 | 550 | 16 | 0.84 | H | **0.4** | 3.2 |
| **U 2+** | | | | | | H | **1.2** | 6.4 |
| **U 3+** | | | | | | H | **2.5** | 9.6 |
| **U 4+** | | | | | | H | **1.6** | 12.8 |

Table 1:**Ion Yields from Dual HCD Ion source**
Values for 1% duty cycle operation (10/s;1 ms)
H : homogenous magnetic. Field (PIG)
B : magnetic bottle field (CPIG)

Ref :

[1] P.M. Morozow , B.N. Makov and M. S. Joffe, Atomnaya Energiya 3, 272, (1957)

[2] ”Handbook of Ion Sources” by B. Wolf, GSI Darmstadt, Germany, Crc Press Boca Raton New York London Tokyo, 1995, P 69).

[3] M. Müller, IEEE Trans. Nucl. Sci. NS-30 (1983) 1499

# UNILAC Status and Developments

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### Status of Operation

In 2000 both injectors – the new high current injector HSI and the high charge state injector HLI – were used for routine operation. The UNILAC was mainly operated in the time – sharing mode, for some fractions of beam time the three-beam operation was practiced. The scheduling of beam time and operation statistics in 2000 are reported in ref.[1].
As in the last year, long periods of beam time were used for the acceleration of carbon for the cancer therapy from the HLI with very high efficiency. For UNILAC experiments rare isotopes were accelerated by the HLI to take advantage of the low consumption rate of the ECR source ($^{26}$Mg, $^{60}$Ni, $^{64}$Ni, $^{36}$Ar, $^{58}$Fe, $^{70}$Zn). $^{70}$Zn and $^{64}$Ni ions were used successfully for the search for super heavy elements. Over 60 days for each ion the availability was above 90%, interruptions occurred only for refilling of the ECR source with material every 5-6 days. For SIS injection the beam was mainly accelerated by the new injector linac HSI. PIG, MUCIS and MEVVA sources were in operation. The highest particle intensities were reached for argon from the MUCIS. More details on the status of high current acceleration are given in the following paragraph.

### High Current Operation and Developments

Besides the routine operation of the linac, the commissioning of the HSI was continued. The scheme of the HSI is shown in Fig. 1.

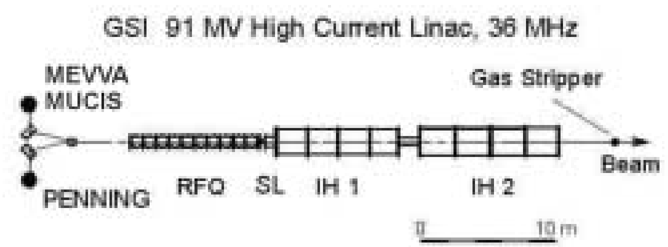


Fig. 1 Scheme of the new high current injector (HSI)

The aspects and status of the high current operation are reported in several contributions to the international linear accelerator conference 2000 (refs. 2-8). In table 1 the achieved beam intensities are listed. The design intensities at the end of the LEBT could be attained only for gaseous light ions up to argon from the MUCIS. Beam experiments indicated limitations of the beam transport of high current from the ion source through the dc pre-acceleration gap. Furthermore, the stability of the MEVVA ion source has to be improved at high intensities. As shown in table 1 the transmission of the whole HSI decreases to about 50% at high intensities. The RFQ is the bottleneck as emerged from many measurements. The transmission of the IH drift tube linac is better than 90% over a wide range of beam intensities and ion species. The beam loss within the RFQ can not be explained completely by large transversal input emittances; measurements of the emittances resulted in normalized 90%-values from 0.25 up to 0.45 $\pi$·mm·mrad without any significant influence to the RFQ transmission. Mismatch problems due to space charge effects or misalignment inside the RFQ are not excluded. Computer simulations and beam measurements are underway for better understanding of the RFQ behavior.

Table 1 Achieved beam intensities and comparison with design

| | | LEBT (Achieved) | LEBT (Design) | HSI-Transmission |
|---|---|---|---|---|
| MUCIS | $H_3^+$ | 3.5 mA | 0.8 mA | - |
| | $D_3^+$ | 3.5 mA | 1.6 mA | - |
| | $N^+$ | 4 mA | 3.8 mA | - |
| | $^{18}O^+$ | 5 mA | 4.8 mA | 45 % |
| | $CO^+$ | 6 mA | 7.5 mA | 45 % |
| | $^{40}Ar^{1+}$ | 18 mA | 10 mA | 45 % |
| | $^{86}Kr^{2+}$ | 3 mA | 11.5 mA | 50 % |
| | $^{129}Xe^{2+}$ | 0.75 mA | 17.5 mA | - |
| MEVVA | $C^+$ | 5.5 mA | 3.2 mA | - |
| | $^{92}Mo^{2+}$ | 0.65 mA | 12.4 mA | 67 % |
| | $^{52}Cr^{1+}$ | 5.5 mA | 14 mA | 40 % |
| | $^{58}Ni^{1+}$ | 10 mA | 15.5 mA | 50 % |
| | $^{238}U^{4+}$ | 4-6 mA | 16 mA | 50 % |

The argon intensity at the RFQ entrance could be increased above the design level (see table 1). By that the theoretical current limit of 10 emA $Ar^{1+}$ was reached. In Fig. 2 the transmission of a high intensity argon beam from the LEBT to the end of the UNILAC is shown. The measurements are compared with the design values of current and transmission.

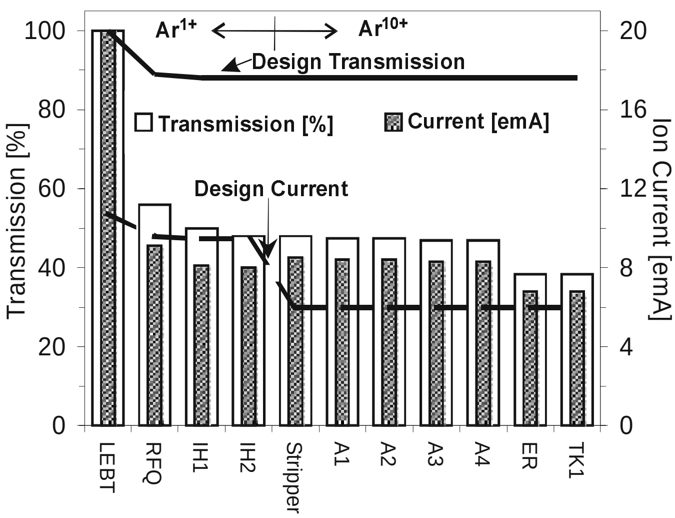


Fig. 2 Measured argon beam intensities along the UNILAC

In February 2000, a $U^{4+}$ beam from the MEVVA source was accelerated for the first time. As listed in table 1, the design goals for the intensity of uranium could not be attained. A maximum intensity of 10 emA was measured at the end of the LEBT, but the fluctuations of ion source current - up to 25% - prevented a successful tuning and stable operation of the accelerator facility. At the lower level of 4 emA a better reproducibility of the beam pulses could be achieved by optimization of source parameters. If the reduced transmission of the HSI by a factor of two is taken into account, the gap between present performance and design goal is a factor 6 to 8. Subject of improvements of the MEVVA source is the reduction of noise at the required intensity level [9]. Higher intensity and brilliance of the beam are expected by optimizing the transport from the ion source through the gap with solenoid focusing.

Fig. 3 summarizes the emittance measurement data at several energy stages of the HSI (120 keV/u, 750 keV/u and 1.4 MeV/u) and after the Alvarez linac at 11.4 MeV/u. The measurements were taken at 6.5 emA of $Ar^{1+}$ at the HSI exit. The $Ar^{10+}$ current came up to 7 emA after stripping and charge state analysis. The emittance growth agreed to the computer simulations.

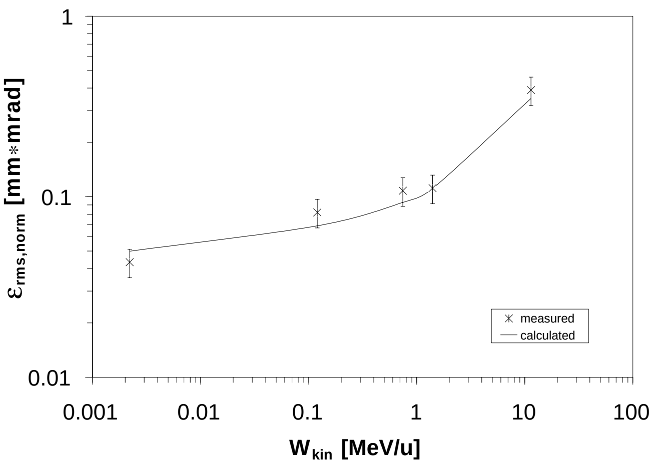


Fig. 3 Transversal emittance for several energy stages of the HSI and at 11.4 MeV/u; beam intensities: 6.5 emA $Ar^{1+}$ at the HSI exit, 7 emA $Ar^{10+}$ after the Alvarez

The RFQ and the superlens SL of the HSI (see fig. 1) still show pronounced dark current contributions at voltage amplitudes above 75% of the design level. There was no essential improvement after a long operation time at the $U^{4+}$ rf voltage level (91% of the maximum design level). Further conditioning tests are planned in the year 2001. Both IH tanks, IH1 and IH2, show modest dark current contributions. In 2000 all rf structures of the HSI were conditioned up to the voltage level for $^{238}U^{4+}$.

### Proton and Deuteron Acceleration at the UNILAC

After the replacement of the Wideröe prestripper accelerator by the HSI, the performance for light ions has been changed. With the Wideröe injector maximum intensities of protons and deuterons were attained by injection of $H_3^+$ and $D_3^+$ molecules resp. It was shown that the molecules – without gas stripping at 1.4 MeV/u – could be accelerated without loss up to 11.4 MeV/u. When the molecules pass the carbon foil stripper before injection into the synchrotron SIS, they break up into protons or deuterons. 280 μA deuterium $D_3^+$ were measured before the carbon foil and then transferred to 840 μA deuterons. $2\cdot10^{11}$ particles per pulse were accelerated in the synchrotron.

The new injector linac is optimized for maximum particle intensities of heavy ions ( Kr to U ). The maximum mass to charge ratio A/q is 65, the intensity limit is calculated by 0.25·A/q emA (electrical current). For singly charged ions the intensity limit is even lower (60%) compared to the Wideröe linac, but with better ion source performance and with the new LEBT, the previous maximum intensity should be surpassed.

The adjustment of the low rf power level is not a trivial task. The rf power needed for $D_3^+$ is by a factor 98 lower compared to the power of $^{238}U^{4+}$, for $H_3^+$ it is a factor 393. After an elaborate tuning of the rf transmitters and the control electronics, stable conditions for the rf phase and amplitude control could be adjusted only for $D_3^+$. At this low power level multipactoring did not occur.

Therefore, beam tests were performed with $D_3^+$ from the HSI, protons were injected from the ECR source into the high charge state injector HLI. During the first run an intensity of 600 μA deuterons were attained at SIS injection starting with an intensity of 1 mA $D_3^+$ at the RFQ entrance. By further improvement of ion source performance, HSI and poststripper transmission, an intensity of 3 mA $D^+$ should be feasible to fill the synchrotron to the space charge limit of $10^{12}$ particles per pulse.

From the ECR source $H_2^+$ molecules were extracted with an intensity of 100 μA. Due to the overall transmission of 50%, at least 100 μA protons can be expected at SIS injection at present, up to $5\cdot10^{10}$ protons per pulse can be accumulated in the SIS.

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# SIS Status Report

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### 1. Status of Operation

In 2000 sixteen different ion species – $^{1}$H, $^{2}$D, $^{12}$C, $^{14}$N, $^{18}$O, $^{26}$Mg, $^{40}$Ar, $^{56}$Fe, $^{58,60}$Ni, $^{84,86}$Kr, $^{92}$Mo, $^{124}$Sn, $^{129,132}$Xe, $^{197}$Au, $^{208}$Pb, and $^{238}$U – were accelerated in the SIS. Altogether 6155 h of beam time were provided for experiments, often with one or more high-energy target experiments and the ESR running in a pulse-to-pulse timesharing operation mode. Another 211 h were used for accelerator tune-up and development. The total downtime of 354 h (5,3 % of the total operation time) was to a large part caused by a vacuum break-down in one of the experiment set-ups.

The total user time of 6155 h was distributed to radiotherapy with carbon ions (1437 h or 23 %), to production runs for target experiments (3681 h or 66%), and to the ESR (1031 h or 17 %).

SIS intensities for very heavy ions like $U^{73+}$-ions were still restricted, since the new high current injector HSI at the front-end of the Unilac has not yet reached the design injection current of 2 to 4 mA. With the available current of 150 µA the SIS provided about $2\cdot10^{9}$ $U^{73+}$-ions per machine cycle instead of $2\cdot10^{10}$. A comparable beam intensity has been achieved with much lower injection currents using beam accumulation with a series of multiturn-injections based on electron cooling. In this scheme the intensity was limited to about $2\cdot10^{9}$ $U^{73+}$-ions due to the onset of coherent transverse beam instabilities, which are typical for cooled low-emittance beams.

A new record beam intensity of $1.2\cdot10^{11}$ $Ar^{11+}$-ions was delivered for a FRS experiment. In this machine run the Unilac provided an injection current of about 3 mA, since no additional stripping of $Ar^{11+}$ was necessary for the low energy of 500 MeV/u used in the experiment. The available beam intensity was close to the space-charge limit of $1.6\cdot10^{11}$ $Ar^{11+}$-ions.

The new HSI has been designed for low-charge-state heavy ions with A/q = 65. However, it could be shown that the Unilac can still provide light ions like $^{2}$D-beams of about 1 mA for injection into the SIS, which will give about 2 to $3\cdot10^{11}$ $^{2}$D-ions per machine cycle.

SIS operation with high intensity ion beams demands a careful control of beam losses. The efficiency of the multiturn injection will be controlled by a new interlock system, which was ordered in 2000. Beam losses during resonance extraction and along the beam transport system especially from the SIS to the FRS will be studied carefully using additional beam loss monitors in the extraction channel (diamond detectors) and along the beam-line (plastic scintillators).

The usual slow-extraction scheme is third-order resonance extraction with two fast extraction quadrupoles, which gradually shift $Q_h$ towards 4 1/3 driving the coasting ions into a betatron resonance. Meanwhile an alternate scheme with operation at a constant $Q_h$ close to the resonance was tested. A transverse rf noise voltage is used to knock out ions by excitation of large radial oscillations, which lead into resonance [1]. The new scheme provides excellent position stability for the extracted beam and an easy way to interrupt the spill and to proceed with slow extraction after a short pause. Both features are useful for the radiotherapy program. Further studies will show if the efficiency of the slow extraction process and the spill-structure can be improved, too. The complete device with an rf-noise-synthesizer locking onto the revolution frequency, newly developed power amplifiers and integration in the SIS control system is almost ready for routine operation.

### 2. SIS Machine Development

In 2000, a new device for precise dynamic tune measurement has been tested. Fig. 1 shows the measured horizontal and vertical tunes recorded in one machine cycle. It can be seen that the variation of both tunes is about 0.02 during acceleration, whereas on the flat top the vertical tune is constant and the horizontal tune increases slightly. The new Q-meter will be used for further precise tuning of the Q-values along the acceleration ramp, where the focusing scheme is shifted from triplet focusing at injection to almost duplet focusing at high energy.

Acceleration of protons to the maximum energy of 4.7 GeV requires a dynamic shift of the transition energy on the ramp, which is realised by a gradual change-over from 12 to 6 superperiod focusing. This scheme was successfully tested. Protons could be accelerated to 4.7 GeV without any beam losses on the acceleration ramp, since passing of the transition energy was avoided. On the flat-top the focusing scheme was reversed tuning 6 superperiod focusing back to the standard scheme with 12 superperiods, which is required for slow extraction. It could be shown that the coasting beam passes the transition energy without losses and phase-space degradation.

In 1999, it has been shown that transverse phase-space is kept constant during acceleration. However, in the longitudinal phase-space a blow-up by a factor of 3 is observed mainly during the rf-capture process (Fig. 2). Therefore the capture process has to be improved during the next time. At present the reduction of momentum spread due to the new debuncher system (36 MHz) in the SIS injector line does not yield the expected small momentum spread of the accelerated beam.

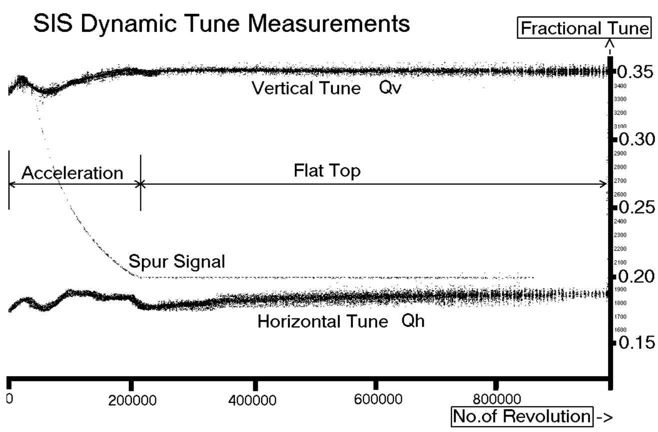


Fig. 1: Dynamic tune measurement for a SIS machine cycle.

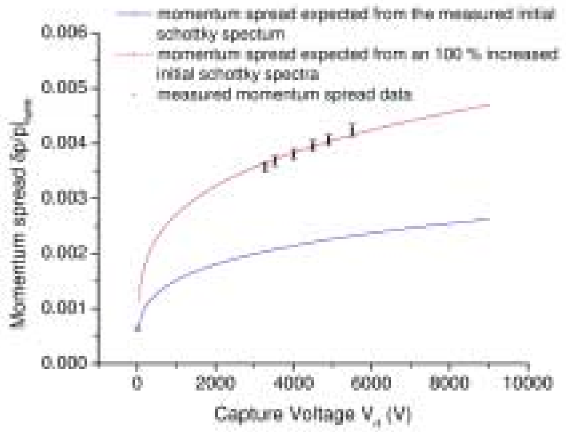


Fig. 2: Longitudinal phase space during RF-capture in the SIS. The measured momentum spread exceeds the calculated values by a factor of 2.

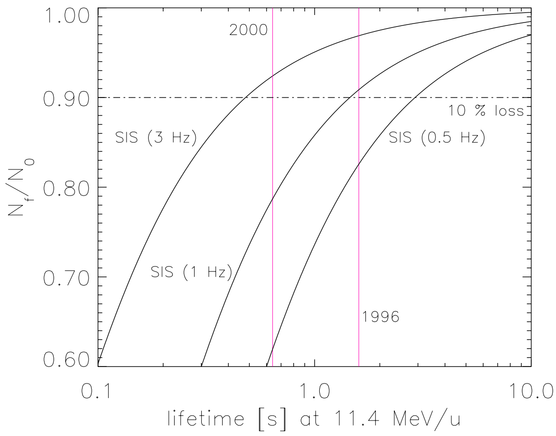


Fig. 3: Fraction of injected ions after acceleration versus beam life time at injection energy for three SIS operating modes.

It is very important to maintain the small phase space volume of the injected ion beam during RF-capture, acceleration, and debunching in the SIS, since a very low momentum spread is necessary for an effective use of the new bunch compressor system.
The acceleration of low charge-state ions e.g. $Ar^{11+}$-ions and especially $U^{28+}$-ions is used to provide very high beam intensities. Table 1 shows the 1/e beam life time for $U^{28+}$-ions at low energies and at 150 MeV/u as measured in 1996 and 2000. In 1996 the life-time was considerably larger than in 2000, although the measured average pressures $<p_{tot}>$ did not differ very much. It is assumed that the content of heavy molecules in the rest gas mass spectrum has increased since 1996.

Table 1: Beam life time (1/e) for $U^{28+}$ ions at low energy and at 150 MeV/u as measured in 1996 and 2000.

| Energy (MeV/u | τ (sec) | $<p_{tot}>$ (mbar) | $N_0$ | Date (year) |
|---|---|---|---|---|
| 6 | 1.2 | $5\cdot10^{-11}$ | ? | 1996 |
| 8.7 | 0.56 | $5.6\cdot10^{-11}$ | $3\cdot10^{8}$ | 2000 |
| 150 | 1.6 | $5.6\cdot10^{-11}$ | $1.5\cdot10^{8}$ | 2000 |

Fig. 3 shows the resulting beam losses during acceleration, which amount to about 40 % with the present rather slow ramp rate of dB/dt = 1,5 T/s. However, with the vacuum of 1996 these losses can be reduced to 3 to 10 % for the SIS12 and SIS18 operation mode, if the design ramp rates of 10 and 4 T/s would be used. In any case, further improvements of the SIS vacuum system are planned for the future.

### 3. SIS Component Replacement and Development Program

In 2000 a complete set of new vacuum-chambers for the 24 dipole-magnets has been ordered. The 14 years old original chambers made from 0.3 mm thick stainless steel sheet reinforced with stiffening ribs have approached the fatigue limit. As a consequence of 5-10 bake out procedures they are all compressed by 5 to 10 mm and the vertical aperture is reduced from 70 to 60 mm.

In addition, three or four vacuum-chambers developed leaks during the bake out. The design of the new vacuum chamber removes the deficiencies of the original chambers, e.g. a long tube is used instead of three short welded sections and the stiffening ribs are strengthened. The installation of the new dipole chambers will be part of an extensive program that shall lead to a lower average vacuum pressure of about $1\cdot10^{-11}$mbar and to a reduction of heavy molecules in the residual gas.
In addition to the vacuum improvement program the following projects are under way:

1. a transverse feedback system,
2. a feedback system around the power amplifiers of the accelerating cavities,
3. a set of new correction coils, and
4. four bunch-compressor cavities.

The transverse feedback system shall be used to damp coherent transverse instabilities observed during operation with cooled ion beams e.g. with $2\cdot10^{9}$ $U^{73+}$-ions. It is planned to extend the range for stable operation with cooled beams to about $5\cdot10^{9}$ ions. The feedback-system includes two of the existing position monitor probes as pickup-system, a new feedback kicker, a new DSP processing stage (100 MHz, 12 bit), new power amplifiers, and a closed orbit suppressor system (CERN). All components are ready for tests of the complete system in March/April 2001.
The feedback systems around the power amplifier are developed to reduce the impedance of the two installed cavities from $R_p \simeq 3$ kΩ to below 1 kΩ. A complete SIS accelerating station has been built up for this development. Many components of the power amplifier stage were redesigned and adapted to the new requirements.
The set of new correction coils was designed to compensate and control the resonances $Q_V = 3\ 1/3$, $Q_V = 3\ 1/2$ and $Q_h$-$Q_V = 1$ to prepare SIS operation at a new high current working point ($Q_V = 4.2$, $Q_h = 3.6$), which allows operation with $2\cdot10^{11}$ $Ne^{10+}$-ions and $4\cdot10^{10}$ $U^{73+}$. The control of the difference resonance $Q_h$-$Q_V = 1$ will be used to optimise multiturn-injection and rf-capture and to manipulate the horizontal and vertical beam emittances. The correction coils are in production and the necessary power supplies will be ordered soon. It is planned to commission the complete system in the first quarter of 2002.
The four bunch compressor cavities will be installed to produce a short high intensity bunch before fast extraction e.g. a bunch

with $2\cdot10^{11}$ $U^{28+}$-ions of 50 ns or 10 m pulse width [2,3]. Fig. 4 shows the design of the new bunch-compressor cavities.
Each compressor cavity has an inductive load of twelve cores made of amorphous metallic alloy (MA core). VITROVAC 6030F from Vakuumschmelze (Hanau) is an appropriate material and two prototype cores will be delivered soon. The submission for the complete set of 48 cores is underway. The cavities are inductively coupled to the power amplifier stage by the anode cable led around the MA cores. For the low duty cycle operation the Thomson RS2054 is an adequate RF-tube. The components of the power amplifier stage were ordered and a prototype stage will be built soon.

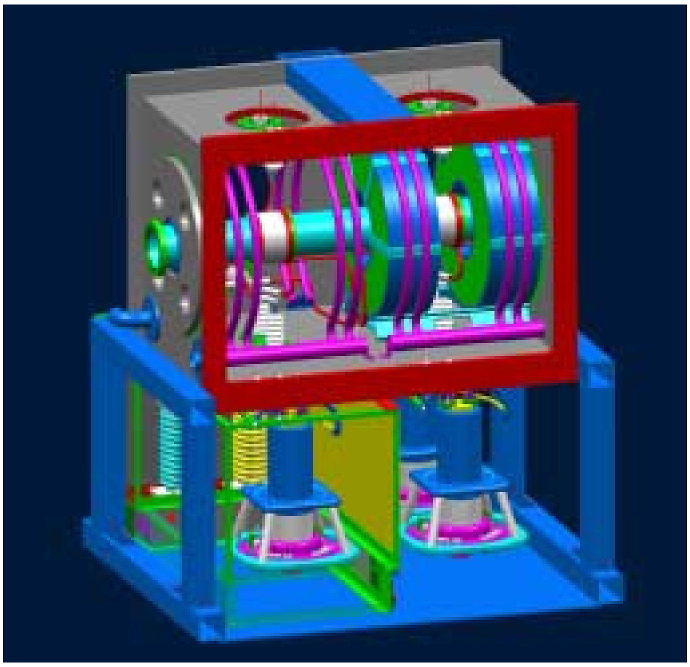

Fig. 4: Design of the SIS bunch compressor cavity based on magnetic alloy cores. Two out of four cavities are shown. Each cavity (top) is driven by a final amplifier stage in push-pull operation (bottom).

#### 4. High Energy Beam Transport System

In 1998 a pion production target with a new beam line to the target area and the new HADES set-up have become part of the high energy facilities. At that time power supplies of the existing beam lines had to be used for sixteen additional beam line magnets to keep investment costs low. Meanwhile first experiments with the new pion beam line and with HADES have shown that power supply switching and the resulting strong restrictions for time sharing operation are a strong disadvantage for an efficient use of the high energy facility. Therefore it was decided to order all necessary power supplies. Installation was realised during the winter shut down 2000/2001. Now time sharing operation is available and with polarity switching different secondary beams like $\pi^+$, $\pi^-$ or $\bar{p}$ can be provided easily.
In the beam line from the ESR to Cave A five new scintillator screens were installed.
In the SIS extraction beam line two prototype diamond detectors were installed. The first one is a square (30 × 30 mm) carrying nine parallel strips to show the horizontal beam profile and the second one is a smaller square (20 × 20 mm) with 16 pixels in a 4 × 4 array arrangement to monitor the (x,y) distribution of the beam intensity. At present both detectors are only 30 mm apart. Fig. 5. shows the pulse signals from a single uranium ion at an energy of 200 MeV/u passing the two CVD-diamond detectors [4]. The signal in the second detector is delayed by 200 ps according to the 30 mm distance showing the excellent time resolution of diamond detectors. As soon as both detectors will be fully equipped with 2 GHz broadband amplifiers, pulse shaping and pulse frequency dividers, the new diamond detectors will be used to monitor the beam intensity with high precision, and at the same time transverse beam-profiles as well as the time resolution of the spill-structure.

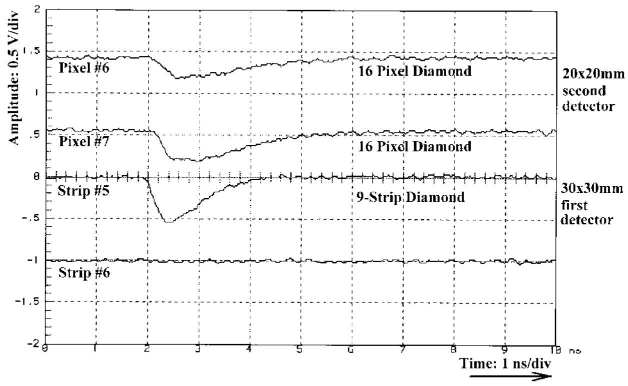


Fig. 5: Diamond counter signals from a single uranium ion at 200 MeV/u (v = 0.57 c) passing through two detectors. The first detector (lower two traces) is passed first at one strip, the second detector (upper two traces) is passed last. The ion trajectory in the second detector lay between two pixels and the signal was recorded coincidentally on two pixels of the same detector.

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# Simulation of Multibunch Instability

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Longitudinal multibunch instability is a potential source of longitudinal beam quality reduction and beam loss in high intensity synchrotrons [1]. For the SIS high current design parameters of $2 \times 10^{11} U_{238}^{28+}$ ions at injection energy of 11.4Mev/u, with momentum spread $\Delta p/p_0 = \pm 3.5 \times 10^{-4}$ (coasting beam), a coupled bunch instability can be driven by the ring impedances after rf capture.

We use a self-consistent particle-in-cell (PIC) code to simulate the longitudinal motion of the beam under the presence of the rf field and the induced field. All electromagnetic characteristics of the beam environment and space charge are modeled as impedance. For each time step we fast Fourier transform the beam signal and couple it with impedance in order to get the induced field. Each particle is pushed using the local field quantities. Up to 500K macro-particles are usually used in the simulation to reduce the space charge induced simulation noise.

We set rf voltage $V_{rf} = 10kV$, and make the capture slow enough (140ms, due to low initial momentum spread) to be adiabatic. There is an initial rise due to coasting beam instability. In our case space charge impedance $Z_{SC}(p\omega_0)/p$ is $-3.36k\Omega$. Resistive impedance is assumed at h=1(around 215 kHz), and $\frac{Z_R(p\omega_0)}{p}|_{p=1} = 1.5k\Omega$, which is a possible value for SIS whole ring resistive impedance because of some special structures and resistivity between welded chambers in SIS. The simulation results are shown in Fig.1 and Fig.2. A cavity offset can also generate resistive impedance. The shunt impedance (10kΩ) of the bunch compressor cavity [3] operating around 1 MHz is another possible source of coupled bunch instability in the SIS.

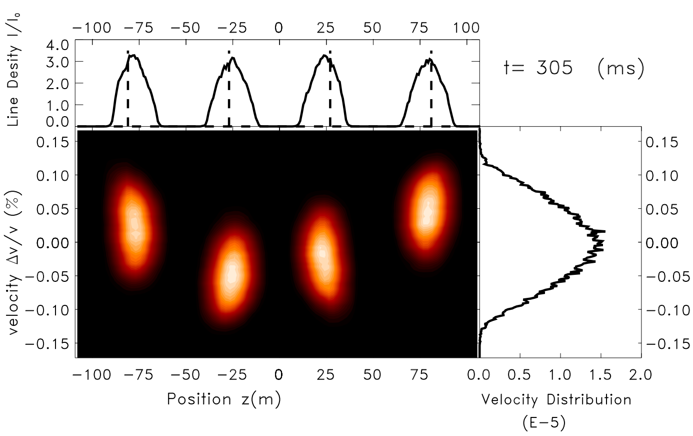


Figure 1: Evolution of the coupled bunch instability for the captured four bunches (total $2 \times 10^{11} U_{238}^{28+}$ ions) at injection energy of 11.4Mev/u in SIS, with momentum spread $\delta p/p|_{FWHM}$ increasing from $1.4 \times 10^{-3}$ to $2.3 \times 10^{-3}$.

Multibunch instability can be damped by the synchrotron frequency spread created by nonlinearity of rf bucket. There is a boundary in the impedance plane, inside which bunches are stable. Fig.3 shows the result

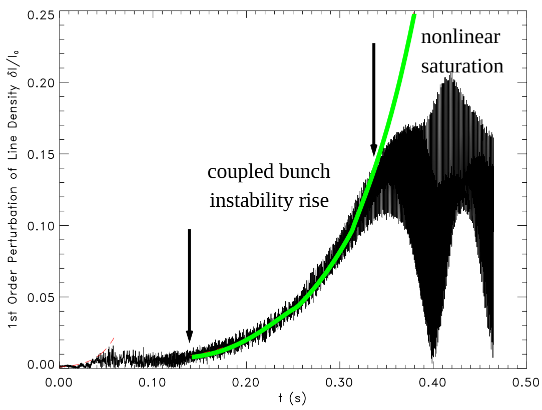


Figure 2: Evaluation of the instability rise time. Time evolution of first order Fourier component of line density.

from simulation and analysis. The stable boundary is obtained from a series of simulation runs. The rise curve is calculated by solving Sacherer's integral problem for the linearized problem.

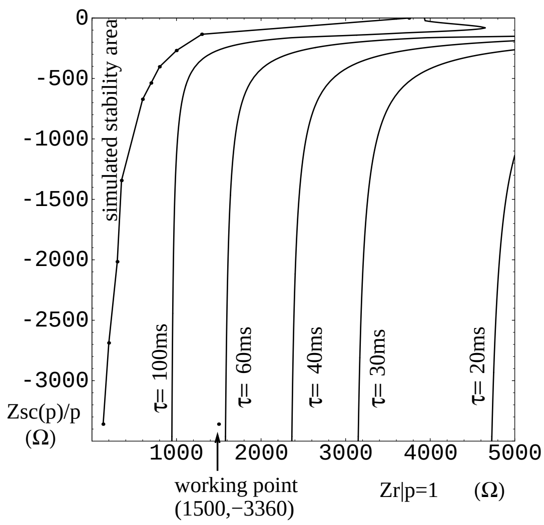


Figure 3: Stability graph in $Z_{SC}(p)/p, Z_r|_{p=1}$ plane.

We plan an experiment in SIS for the coming beam time using one cavity working at h=4 for capturing, and a second cavity with RF off and frequency tuned at h=5 or 7 to create a resistive impedance The coupled bunch mode can be measured and compared with calculations.

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# ESR Operation and Development

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## 1 Operation for Physics Experiments

The storage ring ESR was operated until August with beam, during the rest of the year 2000 several technical modifications were performed. Experiments in the ESR were devoted to atomic physics, mainly with very highly charged ions, mass measurements with the time-of-flight method, and the observation of the bound beta decay of thallium [1]. Atomic physics experiments mainly used decelerated bare heavy ions in combination with the internal gas jet target. The heavy ions for atomic physics (gold and uranium) were injected after stripping at around 300 MeV/u and decelerated to various energies between 120 and 30 MeV/u. The typical intensities for the decelerated beam were a few times $10^7$ ions. The efficiency for deceleration to these energies was 30 - 50 %, typically.

## 2 Machine Development

A new set of stripper foils was installed in front of the ESR. Additional carbon foils with thicknesses between 10 and 30 mg/cm$^2$ allow to inject for heavy ions ($A \geq 200$) charge states with 2-6 bound electrons in sufficient abundance at energies above 200 MeV/u, e.g lithium-like systems will be available at higher energies this way.

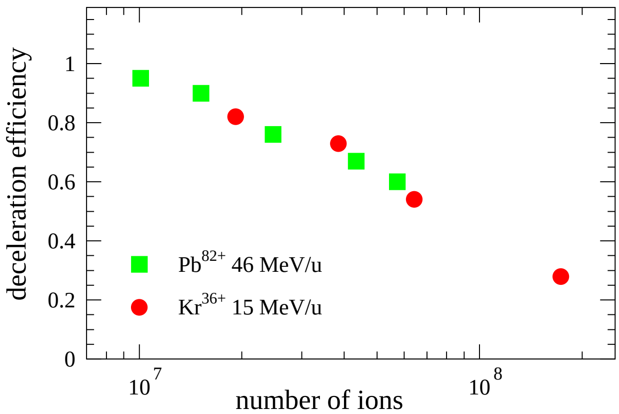


Figure 1: Efficiency for deceleration from 300 MeV/u injection energy to the energy indicated in the legend.

Experiments to decelerate heavy ion beams to even lower energies were continued. For energies below 12 MeV/u the rf frequency has to be changed from harmonic h=2 to h=4. The debunching and rebunching has been successfully tested at energies between 12 and 30 MeV/u. Supported by continuous electron cooling the de- and rebunching process proved to be free of significant loss. With the beam bunched at harmonic h=4 the lowest energy achieved was 9 MeV/u, but still large losses were observed. The intensity of the beam at 9 MeV/u was on the order of a few times $10^5$ ions. The ramping speed at the low energy part of the deceleration procedure (below 15 MeV/u) had to be reduced to 0.01 T/s in order to minimize adverse hysteresis effects. Measurements of tune and of beam position during ramping showed moderate variations, which cannot account for the large losses. The main reason for the losses has not been spotted, but it is likely a combination of the unavoidable adiabatic emittance growth and closed orbit distortions. This is in agreement with measurements of the efficiency for deceleration (Fig. 1). The relative losses increase with beam intensity. It is well known that the emittance of the cooled ion beam, which is always the starting point for deceleration, increases with intensity due to intrabeam scattering [2]. Therefore for higher beam intensity the larger emittance beam is subject to larger losses at aperture limitations.

A first attempt to use the drag force of the electron cooler for deceleration was successful. The rf amplitude was set to zero during deceleration, whereas the accelerating voltage of the electron beam and the magnetic field of the ring magnets were ramped synchronously with a constant electron beam of 0.25 A [3]. The energy of the ion beam was reduced from 15 to 11 MeV/u within 6.7 s, corresponding to a ramp rate of 0.005 T/s, which is only a factor of two slower than what has been achieved with the rf system. However, further studies have to show whether this deceleration mode can provide favorable conditions for routine deceleration to lowest energies.

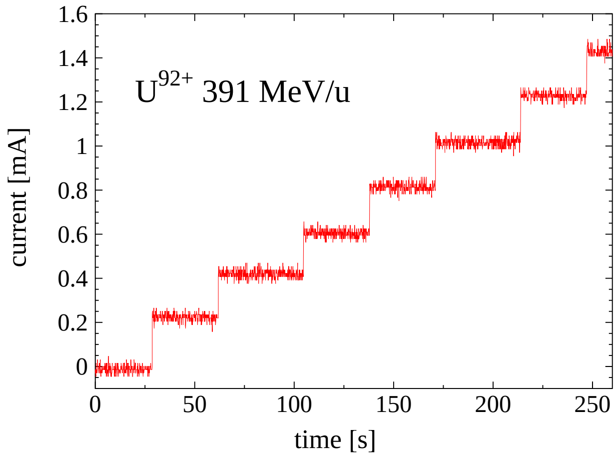


Figure 2: Accumulation of a 391 MeV/u uranium beam by a combination of stochastic precooling, rf stacking and electron cooling of the beam stack.

Stochastic cooling of heavy ions was demonstrated for the first time with a beam of bare uranium ions at an energy of 391 MeV/u [4]. The stochastic cooling system is presently tuned to the corresponding beam velocity ($\beta = 0.71$). Cooling times of about 0.5 s were measured for the longitudinal and vertical cooling. Horizontal cooling was a factor of five slower. The stochastically precooled beam was subsequently stacked by a momentum reduction of 1.8 % with the rf system and continuous electron cooling of the stacked beam at the lower momentum. Figure 2 shows the circulating ion current increase with time. The low and irregular repetition rate of the injections is caused by the availability of the synchrotron SIS for injection into the ESR, as this machine development was performed parasitically to physics experiments served by the synchrotron. The first experience promises that this mode will also be available after some further improvements for fast accumulation of radioactive beams.

The observation of the strong reduction of the momentum spread for electron cooled heavy ion beams of a few thousand ions or less has been explained by an ordered structure of the ions which are confined by their nearest neighbors to their longitudinal position [5]. New experiments have shown that the existence of such an ordered structure can also be indicated by the temporal evolution of the momentum spread after an interruption of cooling. By a fast high voltage switch which stops or starts the extraction of electrons from the cathode within less than 1 ms the cooling was switched on and off alternatingly for time intervals of 6.8 s. The evolution of the momentum spread was monitored by fast Fourier analysis of the longitudinal Schottky noise (Fig. 3).

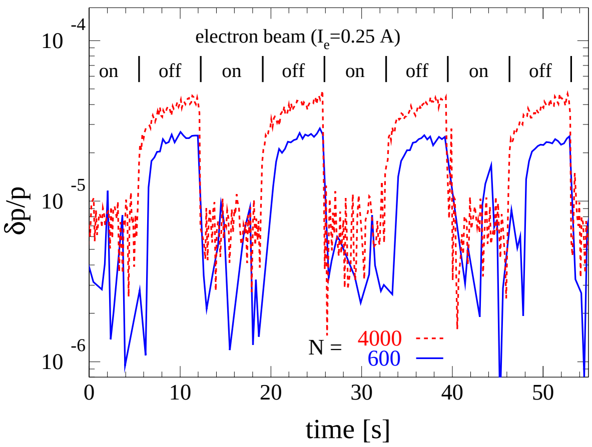


Figure 3: Momentum spread of a $U^{92+}$beam at 390 MeV/u above (dashed) and below (full line) the transition point to small momentum spread as a function of time. The electron beam is switched on and off for time intervals of 6.8 s. The low intensity cold beam heats up with a delay of about 1 s.

The high intensity beam (particle number $N \simeq 4000$) shows an instantaneous longitudinal heating due to intrabeam scattering. The beam with an intensity below the transition point to small momentum spread ($N \simeq 600$), which is supposed to be in an ordered state, remains in the cold state for nearly 1 s (more than $10^6$ revolutions in the storage ring) before the momentum spread starts growing in a manner similar to the higher intensity beam. The ordered structure is obviously not immediately destroyed by intrabeam scattering.

## 3 Technical Developments

The long shutdown starting in September 2000 was used for several new installations in the ESR. The ramping range of the dipole magnets was hitherto limited by the power supplies for the correction coils sitting in the main dipoles to improve the flatness of the radial field distribution. Replacement by more powerful and bipolar power supplies will allow ramped operation over the full magnetic rigidity range of the ESR. This will be particularly valuable for bare decelerated heavy ions. They can be injected at higher energy with a higher stripping efficiency and then be decelerated to the required energy. It will also ease ESR operation in general.

The internal gas jet target section was completely disassembled. The reconstruction of this area will make room for the installation of new experimental equipment, such as a zero degree electron spectrometer downstream the target, Helmholtz coils to guide electrons produced in the interaction of the beam with target atoms, or a cryogenic bolometer for X-ray detection. The modification of the target section is a prerequisite for a large variety of new experiments which are planned with the internal gas target.

The stepping motors driving the detector pockets for the installation of particle detectors behind the gas target and the electron cooler were replaced by pressurized air actuators. The new actuators can be positioned within 1 s with an accuracy of 0.1 mm for particle detection, compared to times of the order of minutes which were needed to position the detectors with stepping motors. The thickness of the stainless steel entrance windows to the detector volume has been reduced from 50 to 25 $\mu$m in order to detect decelerated heavy ions with energies down to 7 MeV/u.

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# Multiple Coulomb Ordered Strings of Ions in the ESR

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In a recent paper, Radon *et al.* [1] reported on high precision mass measurements with Schottky mass spectrometry of about 100 new isotopes with a high resolving power. In that experiment fully stripped isotopes were produced by fragmentation of a $^{209}Bi^{67+}$ beam at 930 MeV/u, separated in the fragment separator, and stored and cooled in the ESR. For fixed magnetic rigidity each species of the beam has its own frequency $f_i = v/C_i$, where $C_i$ is the length of its trajectory close to the circumference of the ESR, $C$=108.4 m. Neighboring masses $\Delta m$ run on slightly different trajectories due to their different rigidities and, thus, have different frequencies. Typical deviations were found from the measured frequencies of known isotopes as compared to the known calibration curve. If there are at least two masses so close to each other that their difference in frequencies is smaller than about 80...90 Hz on the average, the lower (higher) one is shifted characteristically to a higher (lower) value. This anomalous effect limits the mass resolution to about 20 $\mu$u and such masses then have to be discarded from the results.

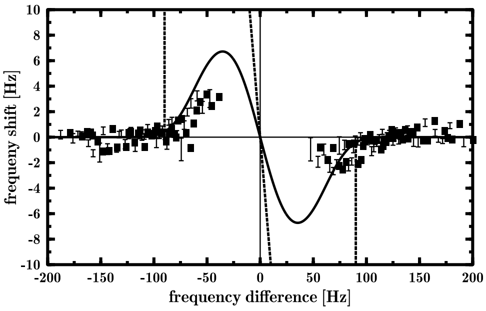


Figure 1: Average anomalous frequency shifts of neighboring isotopes *vs.* difference between their measured frequencies. (after Ref.[1]) with the result of the model calculation included (full line). The dashed sawtooth curve would result without folding over their thermal overlap volume.

In the present work we explain and make a model for the origin of these anomalous frequency shifts on the basis of the anticipation that the ions run on strongly correlated trajectories. The parameters here are of the same order of magnitude as the ones of the machine experiments on the anomalous jump to very low momentum spreads in the ESR [2] and in the SIS [3]. There it has been shown [4] that under the experimental conditions intra-beam scattering is strongly suppressed and that the ions cannot pass each other any more and, thus, run on strings.

Nuclides with different masses but with the same velocity run on different trajectories which are horizontally displaced so that, apart fom thermal fluctuations, $v = Cf$ remains constant, thus $\Delta C/C = -\Delta f/f$. This difference in length of trajectory transforms into the horizontal displacement $-\Delta x = (C/2\pi)\Delta f/f = 17\,\mathrm{m}\times\Delta f/f$. This fact leads to the model that if the displacement is larger than the thermal diameter, the two (or more) strings run on well separated trajectories yielding two (or more) distinct peaks in the Schottky spectrum which lie at the correct positions. The result of Fig. 1 is obtained assuming that this locking is not instantaneous if the clouds start to overlap, but that there is a smooth transition with a probability proportional to the overlap region of the clouds due to the averaging procedure over the experimental data, and folding this probability together with the experimental resolution of 15 Hz into the sawtooth curve of shifts (the dashed lines in Fig. 1). The dashed sawtooth line would result if the strings were always captured if their thermal radii start to overlap. Note that apart from the uncertainty coming from the assumed capture probability this model has no free parameters and that the result agrees nicely with the experiment.

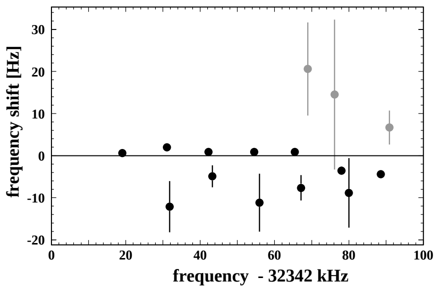


Figure 2: Measured anomalous frequency shifts in a relatively warm beam. The dots with nearly zero shifts belong to isotopes of the primary beam, others are nearby fragment nuclides. The gray dots are questionable by the lack of intensity (after Ref.[5]).

There is indication that the effect of locking or capture is not restricted to the existence of ultra-cold chains. During the preparation of the precision mass experiments similar anomalous frequency shifts have been observed in Ref. [5] in an experiment with a bare gold beam at 295 MeV/u. Its isotopes and other strongly populated fragments had velocity spreads of about $10^{-5}$ and thermal widths of about 4 mm. By cooling and scraping the beam radius the velocity spread decreased by one order of magnitude. Nearby fragment nuclides with slightly larger masses then acquired anomalous negative frequency shifts of the order of a few Hz, see Fig. 2.

Evidently, the low intensity fragment isotopes (with negative shifts and error bars) and masses slightly larger than the mass of the primary beam (with nearly zero shifts and no error bars) have been absorbed into the cloud of the primary beam itself, thereby reducing their frequencies slightly. The observed positive frequency shifts are statistically irrelevant.

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# Design of a 7 MeV/u, 217 MHz Injector Linac for Therapy Facilities

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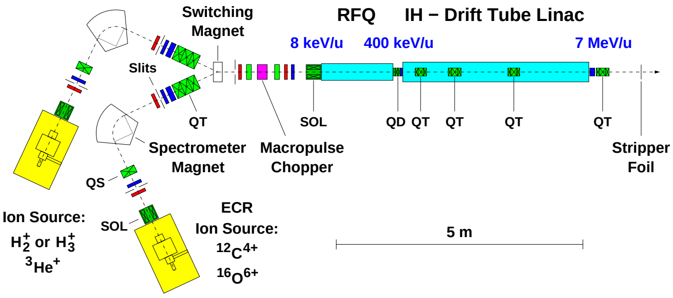


Figure 1: Schematic drawing of the injector linac. SOL ≡ solenoid magnet, QS, QD, QT ≡ magnetic quadrupole singlet, doublet, triplet.

Table 1: Major parameters of the injector linac.

| | | |
|---|---|---|
| Design ion | $^{12}C^{4+}$ | $(A/q = 3)$ |
| Operating frequency | 216.816 | MHz |
| Final beam energy | 7 | MeV/u |
| Pulse currents after stripper | $\approx 100$ | e$\mu$A $C^{6+}$ |
| | $\approx 0.7$ | mA protons |
| Beam pulse length | $\leq 200$ | $\mu$s @ $\leq 5$ Hz |
| Duty cycle | $\leq 0.1$ | % |
| Norm. transverse exit beam emittances (95 %) [1] | $\approx 0.8$ | $\pi$ mm mrad |
| Exit momentum spread [1] | $\pm 0.15$ | % |
| Total injector length [2] | $\approx 13$ | m |

[1] Not including emittance growth effects in the stripper foil.
[2] Including the ion sources and up to the foil stripper.

A dedicated clinical synchrotron facility for cancer therapy using energetic proton and ion beams (carbon, helium and oxygen) has been designed at GSI for the Radiologische Universitätsklinik in Heidelberg [1]. A compact injector design is proposed (Fig. 1 and Table 1) [2, 3]. The LEBT allows for switching between two ion sources as well as for beam chopping and for controlled beam current variation. A 4-rod type RFQ of about 1.5 m in length accelerates the ions from 8 keV/u to 400 keV/u. A very compact intertank section has been proposed for matching the beam parameters at the exit of the RFQ to the ones required at the entrance of the subsequent IH-type drift tube linac (Fig. 2). It consists of a two-gap rebuncher integrated into the RFQ tank [3], a pair of steerer magnets, a magnetic quadrupole doublet and a diagnostic box comprising a beam transformer and a phase probe. The total length between the RFQ and IH tanks is about 20 cm only. The IH-DTL for the acceleration to 7 MeV/u has a length of roughly 3.8 m and an expected rf power consumption around 1 MW. It consists of three integrated magnetic quadrupole triplets and 56 accelerating gaps grouped in four KONUS sections. Finally, the beam is focused by another quadrupole triplet following the DTL onto a stripper foil located about 1 m behind of the linac.

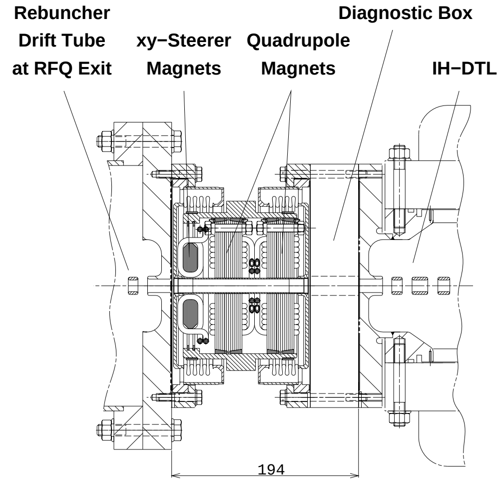


Figure 2: Design of the intertank matching section.

In the last year we focused on the optimization of several details and proceeded in the design of the most challenging critical parts. The integration of two drift tubes into the RFQ tank has been further investigated at the IAP by detailed measurements using rf models and by MAFIA simulations [3, 4]. Realistic field configurations of the transition from the RFQ electrodes to the drift tube geometry have been calculated by 3D simulations and have been integrated into the particle dynamics simulations using a modified PARMTEQ version.

The DTL design has been optimized and a 1:2 scaled rf model is under construction. Due to the comparatively high frequency of 217 MHz the diameter of the IH tank amounts to roughly 30 cm only, requiring very small triplet lenses of around 25 cm in length and about 16 cm in diameter. First 3D design studies of these small quadrupole magnets using the TOSCA code have been performed by B. Langenbeck and C. Mühle, GSI.

To enhance the efficiency of synchrotron injection the momentum spread of the ion beam can be reduced to $\Delta p/p \leq \pm 0.1\,\%$ by an additional debunching cavity installed in the synchrotron injection line. Detailed particle dynamics simulations and a first cavity design study have been performed [5].

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# An RF Chopped Electron Beam Driver for H-Type Cavities

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During the last three years a high power rf generator design capable of providing several MW rf power at frequencies between 200 and 300 MHz has been investigated. Instead of using conventional techniques for bunch formation in electron beam based generators like grids or longitudinal velocity modulation it is based on an innovative scheme which was first proposed in 1986 [1]. It allows to directly drive the resonant mode of an H-type cavity by the electron beam resulting in a much simplified rf driver system. The basic concept is to use a continuous electron beam produced by a thermionic gun. The time structure of the electron beam is achieved by a rf driven chopping system using the E×B drift which deflects about 80% of the beam to a suppressed collector where the main part of the beam energy is recovered. The remaining bunched electron beam is injected into the IH tank where the beam energy will drive the $IH_{110}$ mode. To increase the efficiency of the beam deflection a second deflector stage working on dc potential may be added [2]. The setup of the total system is shown in Fig. 1. To prove the feasibility of the proposed rf generator the individual components were simulated with the three dimensional particle in cell code TS3 which is part of the simulation package MAFIA. It is capable of solving Maxwell´s equations including the self fields of charged particles in motion. Starting with the high perveance electron gun the simulations resulted in a reasonable geometry which delivers a 100 A, 100 keV beam with a radius of 5 mm which is injected into a confining magnetic field with a flux density of 100 mT.

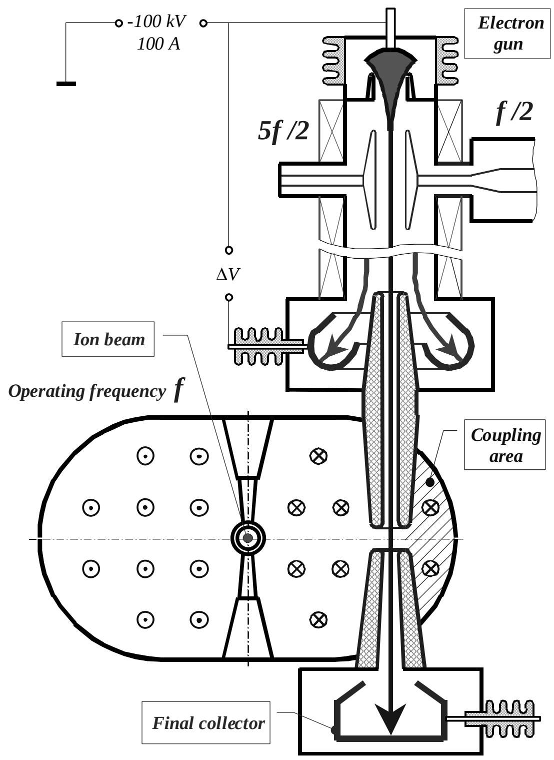


Figure 1: Setup of the total rf system

The chopper stage is directly connected to the gun exit and driven by an rf of about 50 kV while the dc stage needs a potential of about 60 kV. The appropriate rf voltage results from superposing two sinusoidal signals with the frequencies f/2 and 5f/2 at an amplitude ratio of 5:1. Figure 2 shows the resulting electron density distribution right behind the two deflecting stages predicted by the simulations.

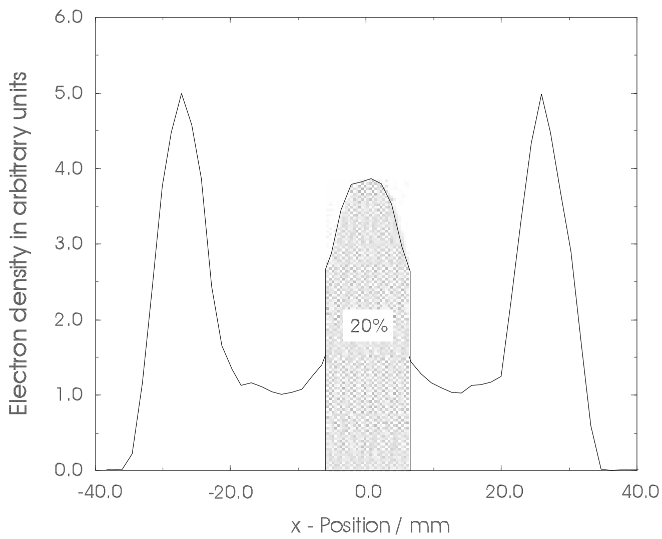


Figure 2: Electron density distribution behind the deflector

The hatched area corresponds to a transverse beam width of ±6.3 mm. Longitudinally the beam has a rectangular profile with a length of about 96 degree in units of the operating frequency of 200 MHz [3].

A 200 MHz prototype of the deflector is under construction at the IAP, University of Frankfurt. Its purpose is to demonstrate the chopper principle and to compare the results with the predictions of the simulations.

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