

Testing the fast pulse operation of SIS12

B. Franczak, C. Omet, A. Redelbach, P. Schütt, P. Spiller

June 2005

1. Course of the experiment

During this experiment the magnet power supplies have been operated in SIS12 mode, so that a maximal current of 2.3 kA for the main SIS dipole magnets at a magnetic rigidity of 12 Tm was feasible. It had been clarified that a continuous operation would be possible up to an electric power of 5 MW, while for higher power an asynchronous single shot mode had been foreseen. Both SIS RF-cavities were in operation, each of them offering up to 14 kV.

As a start, tests of the precision of SIS dipoles and quadrupoles were performed without beam at an extraction energy of 600 MeV/u and a ramping rate of 8 T/s. The measurements of the dipole field by a Hall probe and the fast ramping of the SIS magnets did not show an increase of deviations.

1.a Fast acceleration of $^{181}\text{Ta}^{61+}$

For the fast acceleration of $^{181}\text{Ta}^{61+}$ up to 250 MeV/u, the tune values were set to (4.29, 3.25) at injection and to (4.30483, 3.25) for slow extraction, respectively. At a ramping rate of $\dot{B}=2.0$ T/s, no losses on the acceleration ramp of S11MU2 dipoles could be seen in the trafo measurements. The losses before acceleration, i. e. during RF-capture have been quantified to be roughly 15 percent for medium intensities of $9 \cdot 10^8$ particles.

Increasing the ramping rate to $\dot{B}=3.0$ T/s, led to similar results concerning particle losses. Using position measurements ('POSI' program), a beam shift in radial direction at the end of acceleration could be detected and also reduced using the RPOSI parameter in SISMODI. Moreover, it was noted that the bucket height was rather large, i. e. $dp/p=0.2\%$ directly after acceleration for maximal RF voltages of 9 kV of the cavities.

Raising the ramping rate to $\dot{B}=4.0$ T/s, corresponding to an electric power of 5.5 MW in SIS dipoles, the RF capture losses were increased significantly to 50 percent for particle intensities of $9 \cdot 10^8$, see also figure 1. This result was in accordance with position measurements showing larger beam shifts than before. It was however possible to gradually reduce RF capture losses by means of the 'RPOSI' parameter, adjustment of the parameters for slow extraction ('QDEL=0') and doubling the rounding times to 64 ms. The outcome of these optimization can be seen in figure 2, where RF capture losses can be quantified to be 25 percent. At the same time, the radial beam position was very close to the central orbit. However, it was necessary to readjust RPOSI due to radial beam shifts some minutes later. In order to illustrate the reduction of losses during this optimization procedure, the corresponding measurement of vacuum pressure is displayed in figure 3. More specifically, the average SIS vacuum pressure decreased from $7.6 \cdot 10^{-11}$ mbar to $5.8 \cdot 10^{-11}$ mbar within the displayed interval of optimization.

Some efforts were made to reduce losses by variation of the 'WIRKOP' parameter being defined as an additive correction to the dipole field proportional to \dot{B} . Since a setting of 'WIRKOP' in the range of -0.0001 ms to 0.0001 ms did not lead to an improvement of RF capture losses, this parameter was set to zero in the following. It was also tested to directly inject into a bucket by

magnifying the corresponding RF voltage ('UINJ') to 18 kV. However this had to be undone, to reduce particle losses directly after injection.

At an increased ramping rate of $\dot{B} = 5$ T/s, the RF capture losses were raised to a level of 50 percent again. However, the radial position turned out to be close to the central orbit.

The following measurements were done at maximal $\dot{B} = (5.8-6.25)$ T/s corresponding to electrical power of (6-7)MW. The consequence was an increase of RF capture losses to approximately 75% for particle intensities in the range of $1 \cdot 10^8$. It was however noted that virtually no losses occurred during the acceleration ramp. Doubling the time for RF capture to 16 ms did not lead to any significant reduction of RF capture losses. Increasing the maximal RF voltage from 18 kV to 24 kV and finally to 28 kV had a substantial effect on RF losses: The corresponding amplification of the bucket area reduced RF capture losses to 35 percent for a voltage of 24 kV and to 30 percent for 28 kV. Since the RF bucket area A_B scales with the RF amplitude V_{RF} and the synchronous phase ϕ_S according to [1]

$$A_B \propto \sqrt{\frac{V_{RF}}{\cos \phi_S} \frac{1 - \sin \phi_S}{1 + \sin \phi_S}},$$

the loss reduction mentioned is rational.

In the following the RF capture time was set to 8 ms and the maximal RF voltage was kept, resulting in a minimization of RF capture losses to approximately 25 percent, see figure 4. In order to obtain even greater ramping rates, the rounding time was reduced to 48 ms with virtually no effect on the losses. Inspection of the position measurement revealed that the medium radial position was shifted by about 3 cm outwards.

For a maximal ramping rate of 8.15 T/s, the parameters defining the triplet focussing had to be readjusted to TRIN=0.9, TRZW=0.4, TREX=0.4. This was necessary to avoid large voltages for the triplet quadrupole as discussed in section 2.

In order to reach maximal extraction energy at maximal ramping rate, the extraction energy was set to 650 MeV/u. As a pre-stage a ramping rate of 6 T/s was chosen, leading to virtually no losses during ramping in conjunction with 45 percent RF capture losses.

Then the ramping rate was raised to maximal 9.6 T/s corresponding to 20 MW. For this setting, the ramping rate was 4.5 T/s at the beginning of the acceleration ramp and up to 9.6 T/s subsequently. As a consequence of this high ramping rate, particle losses at the end of the acceleration ramp could be noted. In combination with initial RF capture losses, the total losses were roughly 40 percent at the end of the acceleration period. The form of the acceleration ramp led to a bucket height of $dp/p = 0.07\%$ for maximal \dot{B} and a RF phase of 51 degrees. In a following measurement the total losses during acceleration could be reduced to approximately 25 percent, see also figure 5.

1.b Fast acceleration of $^{181}\text{Ta}^{24+}$

During the second part of this experiment, a fast acceleration of unstripped $^{181}\text{Ta}^{24+}$ was tested. To this end the fast extraction mode at 50 MeV/u corresponding to a magnetic rigidity of 8 Tm was set. Due to the reduced injection energy of 8.735 MeV/u, the RF system was operated at harmonic number 6. Although the intensity reached up to $6 \cdot 10^9$ particles, it suffered from a moderate multiturn efficiency. The tunes were set to constant values of (4.29, 3.26). Starting with the normal ramping rate of 1.3 T/s, the RF capture losses were at a level of 20 percent. Doubling the particle intensity to $6 \cdot 10^9$ after injection led to a significant increase of total losses to more than 80 percent.

At an extraction energy of 126 MeV/u and electric power of 7 MW the total losses could be reduced to roughly 50 percent after readjusting injection energy and radial position at injection. It should be noted that the form of asymptotic losses for $^{181}\text{Ta}^{24+}$ is a consequence of charge changing processes and ionization leading to an increase of vacuum pressure.

It was also possible to accelerate $^{181}\text{Ta}^{24+}$ to 100 MeV/u at a maximal ramping rate of 5.3 T/s with only marginal losses of approximately 10 percent for $1 \cdot 10^9$ particles, see also figure 6. This remarkable result was also reproducible for a measurement 5 minutes later. A position measurement showed a central beam position, however it is difficult to use this measurement in high current operation due to overmodulation effects.

Then the working point was changed to (4.29, 3.29) and extraction energy was set to 20 MeV/u at a ramping rate of 2.4 T/s, so that a continuous operation was possible. This led to total losses of roughly 60 percent.

The increase of energy to 100 MeV/u at $\dot{B} = 5.3$ T/s resulted in losses of 55 percent for intensities of $3 \cdot 10^9$ particles.

The measurements were completed with three slightly increased ramping rates at an extraction energy of 100 MeV/u:

For a maximal $\dot{B} = 5.6$ T/s the radial position at injection and also the bumper amplitude was readjusted, leading to losses at the level of 30 percent.

Ramping the main dipole magnets up to $\dot{B} = 5.8$ T/s, losses at the aforementioned level were confirmed.

The final trafo measurements at maximal $\dot{B} = 5.9$ T/s and 12.6 MW have also shown losses of 30 to 35 percent, see e. g. figure 7.

2. Towards a booster operation of SIS12

2.a Reduction of machine cycle periods

Several plots are intended to illustrate the effect of a fast ramping of SIS magnets over a machine cycle.

In figure 8 we display various machine parameters corresponding to actual settings at the end of the $^{181}\text{Ta}^{61+}$ experiment. It should be noted that injection started at approximately 300 ms in this case. As previously stated, one can see the increase up to maximal $\dot{B} = 9.6$ T/s with the intermediate value of 4.5 T/s. It is also obvious that the dipole ramp at the end of the extraction flattop could be significantly increased. In order to illustrate the effects of fast ramping for a future cycle, we contrast ramping rates of 6 T/s and the normal 1.3 T/s in figures 9 and 10 for fast extraction cycles. Note also the double cavity operation for 6 T/s at maximum RF voltage as opposed to the standard operation mode. In analogy we also show the corresponding results for $^{181}\text{Ta}^{24+}$ in figures 11 to 13, respectively.

It is also useful to display some parameters being of particular interest for fast ramping, e. g. bucket area, RF phase or also the triplet focussing setting of S12QS3T and the required voltage, see also figure 14. These parameters correspond to the experimental values set for fast acceleration of $^{181}\text{Ta}^{61+}$. It should be noted that the voltage set for S12QS3T is very close to its maximum near 500V, implying a constraint during fast ramping operation.

2.b Special settings and parameters

Here we will comment on some parameters particularly important for this experiment:

The maximal RF voltage was set to 28 kV, corresponding to 14 kV for each cavity. This voltage was also used at flattop.

Throughout the course of the experiment, the radial position at injection ('RPOS1') had to be readjusted several times to optimize RF capture and injection.

Setting the parameters for the tune for slow extraction to zero had a positive effect on beam losses. Obviously the working point plays an important role for beam losses, however its effect was not systematically studied in this experiment.

It was also necessary to readjust the parameters for triplet focussing ('TRIN, TRZW, TREX') to minimize the required voltage of S12QS3T, see also figure 14.

For maximal ramp rates the ramping ('BPUU') at the beginning of the acceleration was chosen smaller than the subsequent maximal \dot{B} ('BPUP'), as is also illustrated in figure 8.

The additive correction to the dipole field proportional to \dot{B} ('WIRKOP') did not lead to further reduction of losses, however its effect was best for a value of -0.00005 ms.

Prolongation of RF capture time ('TEINF') to 16 ms also did not lead to any obvious improvement. An increase of the rounding time from normal 32 ms to 64 ms and finally to 48 ms reduced the RF capture losses.

Summary of main results and problems

This experiment has demonstrated that ramping rates of 6 T/s can be attained with the existing SIS12 operation mode with a level of 30 percent losses or even below. It could be demonstrated that for fast ramping operation the RF voltage is a crucial parameter for losses during RF capture due to the accessible bucket area.

Another important implication is that the accuracy of magnet fields and magnet power supplies is at least sufficient to accelerate with $\dot{B}=6\text{T/s}$. As for the minor losses at maximal ramping rate of 9.6 T/s, a further investigation is required. It is also worth noting that an optimization based on position measurements could be done as far as possible.

In summary, an optimized acceleration of $^{181}\text{Ta}^{61+}$ at intensities of 10^8 particles led to losses at the level of 25 percent both at maximal ramping rates of $\dot{B}=9.6\text{T/s}$ and $\dot{B}=6\text{T/s}$. The tests of acceleration of $^{181}\text{Ta}^{24+}$ at intensities of 10^9 particles could be achieved with even lower losses. However, it has to be noted that due to moderate multiturn efficiency, only up to 3 turns have been injected, so that a loss analysis for better multiturn efficiency is still required.

Some of the position measurements were dubious due to overmodulation for high current beams. It has to be clarified if the power supplies required for the triplet quadrupole are flexible enough to fulfill the needs for future fast pulse operation. It might be also an option to modify the quadrupole optics focussing to this end.

A definite reason for the interlocks of the main dipole power supplies during continuous operation remains to be found.

Finally, in future experiments it is of primary interest to study fast ramping for increased particle intensities as a basis for the booster operation of SIS.

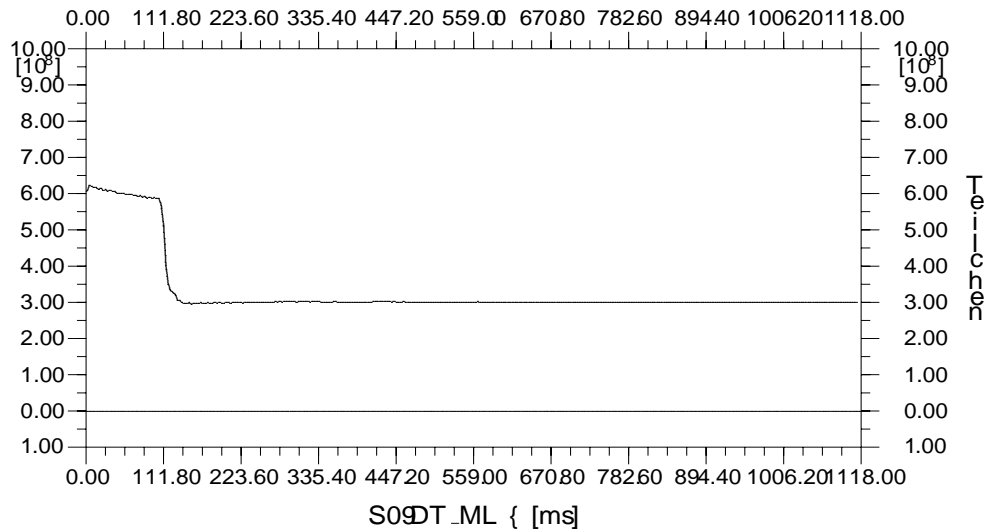
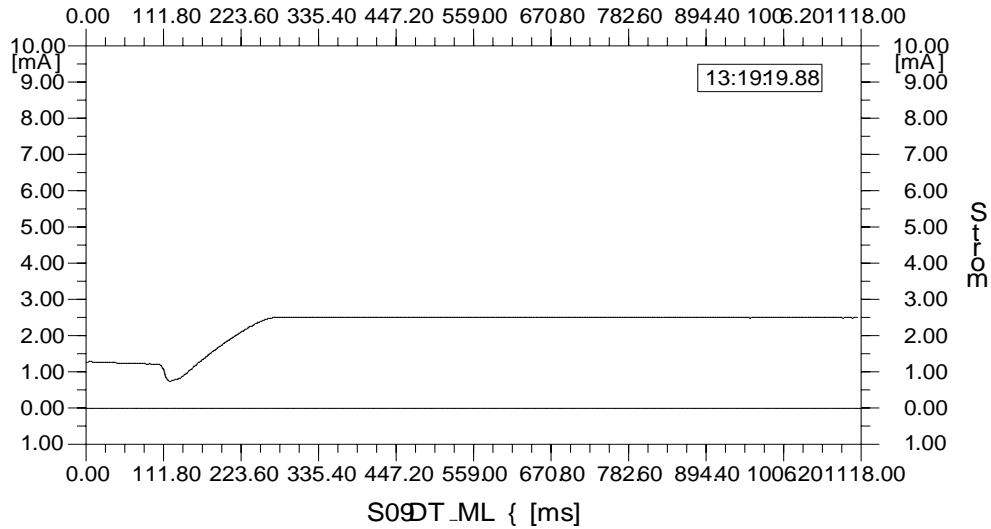
References

[1] S. Y. Lee, Accelerator Physics, World Scientific, 1999.

DT_ML-T RAFO-PROTOKOLL

HTP | S09 | $^{181}\text{TA}^{61+}$ | 250.000 MeV/u

8. Jun 05 13:19:06



Gain	5	Average	1
Delay	2.00ms		
StromWert	2.51mA		2932ms nach Meßstart
TeilchenZahl	$3.02 \cdot 10^8$		

8. Jun 05 13:19:06

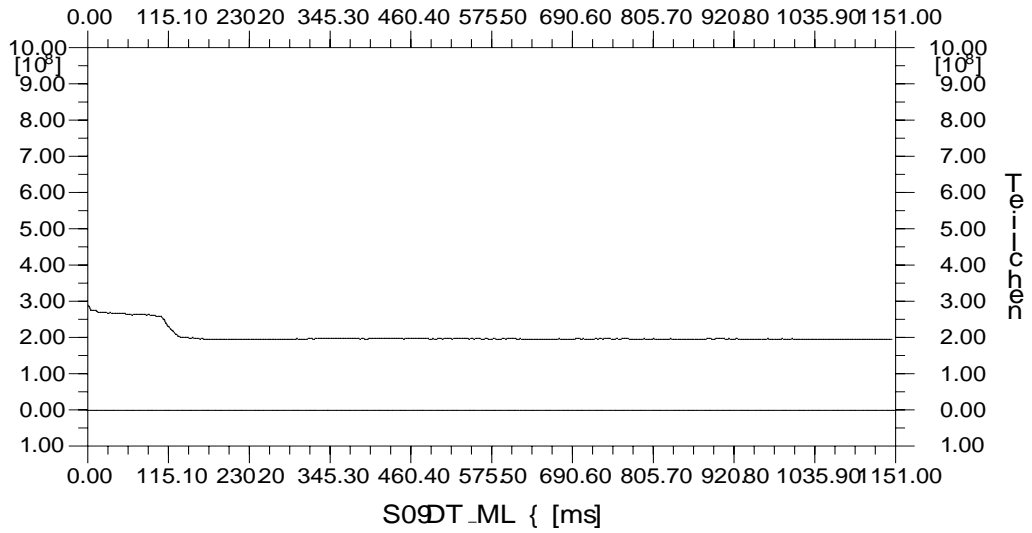
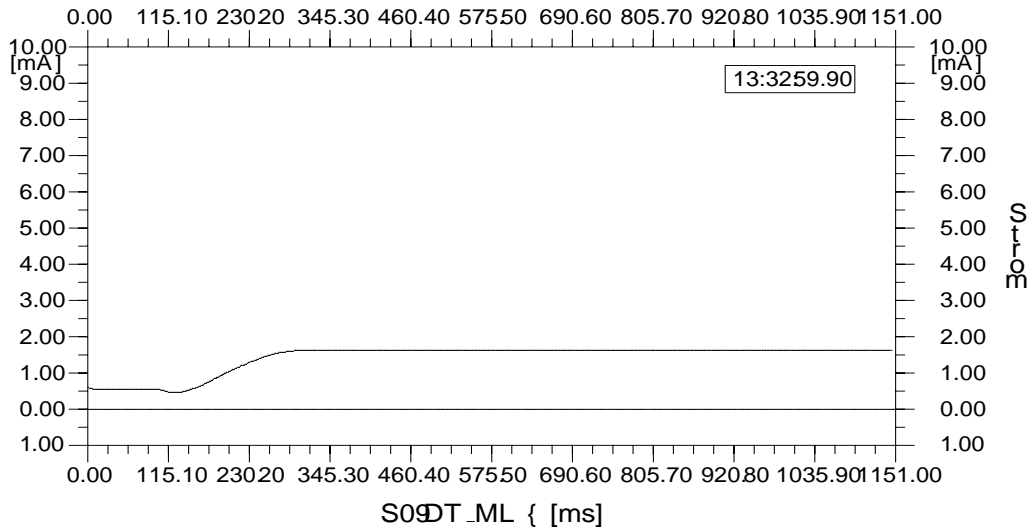
HTP | S09 | $^{181}\text{TA}^{61+}$ | 250.000 MeV/u

Figure 1: Particle currents and intensities in SIS for a ramping rate $\dot{B} = 4.0$ T/s.

DT_ML-T RAFO-PROTOKOLL

HTP | S09 | $^{181}\text{TA}^{61+}$ | 250.000 MeV/u

8. Jun 05 13:33:06



Gain	5
Delay	2.00ms Average 1

8. Jun 05 13:33:06

HTP | S09 | $^{181}\text{TA}^{61+}$ | 250.000 MeV/u

Figure 2: Particle currents and intensities in SIS for a ramping rate $\dot{B} = 4.0$ T/s.

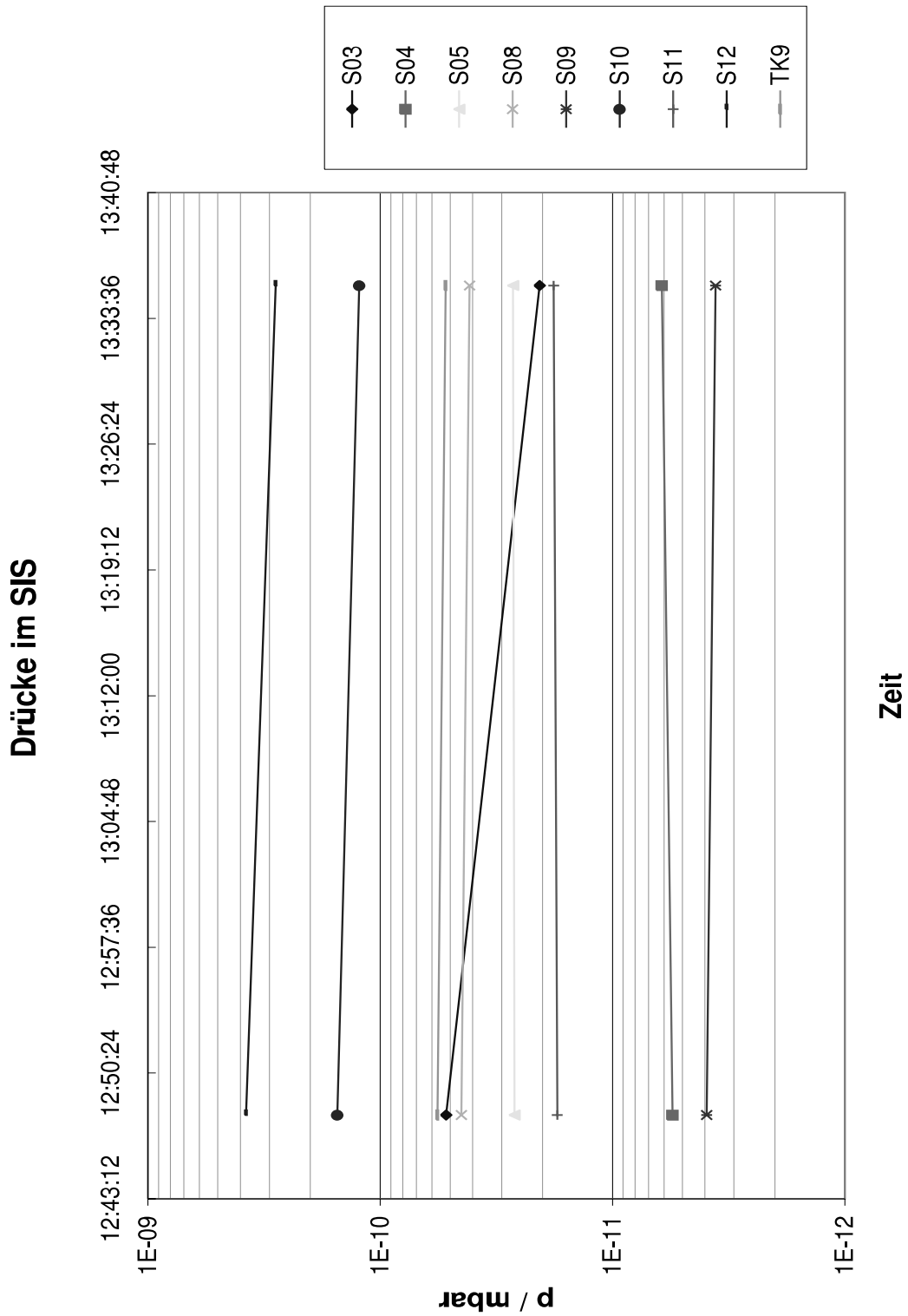
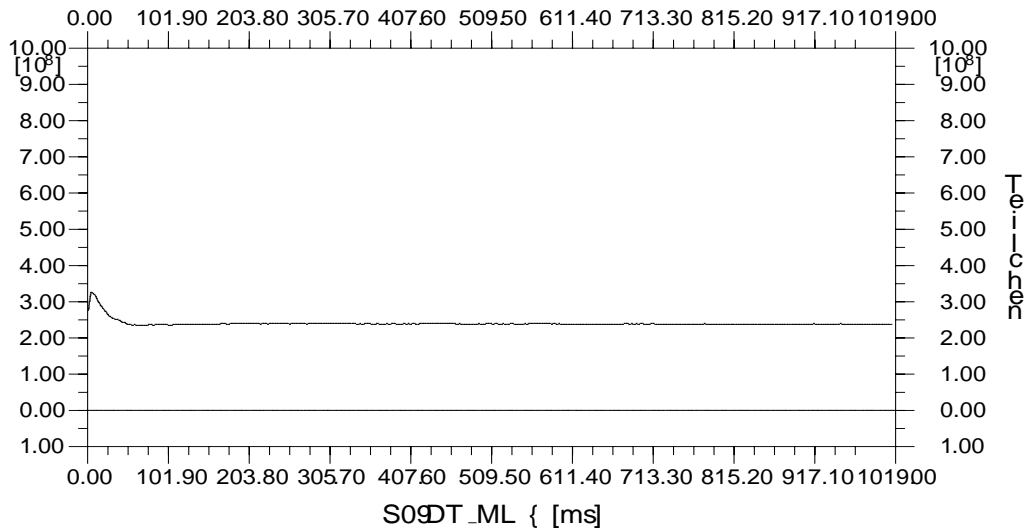
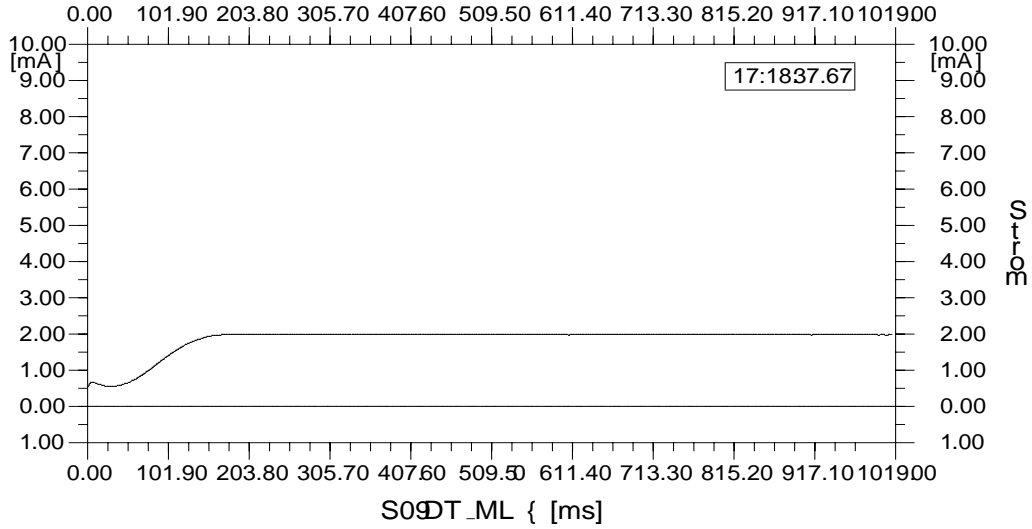


Figure 3: Vakuum pressure in SIS measured during optimization of setting as a function of time.

DT_ML-T RAFO-PROTOKOLL

HTP | S09 | $^{181}\text{TA}^{61+}$ | 250.000 MeV/u

8. Jun 05 17:18:43



Gain	5	Average	1
Delay	2.00ms	StromWert	1.35mA
StromWert	1.35mA	TeilchenZahl	2.36 10 ⁸
TeilchenZahl	2.36 10 ⁸		99.7ms nach Meßstart

8. Jun 05 17:18:43

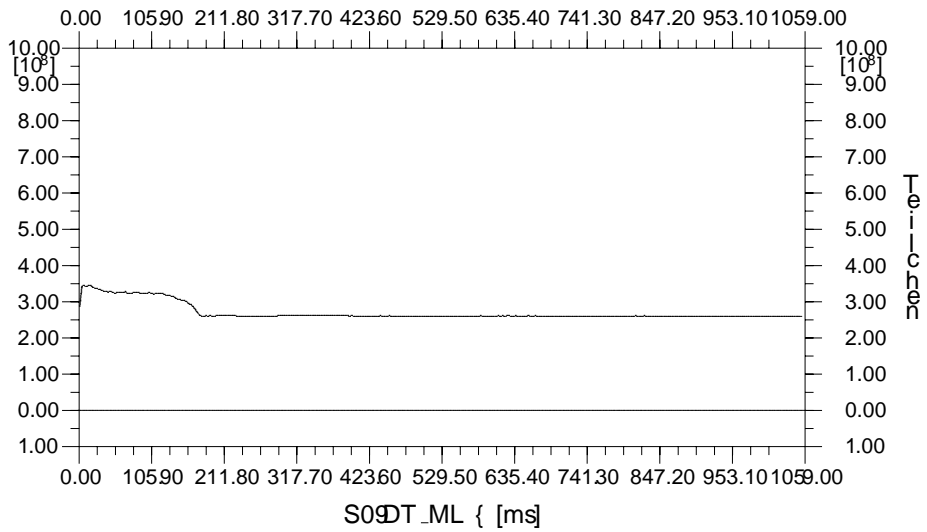
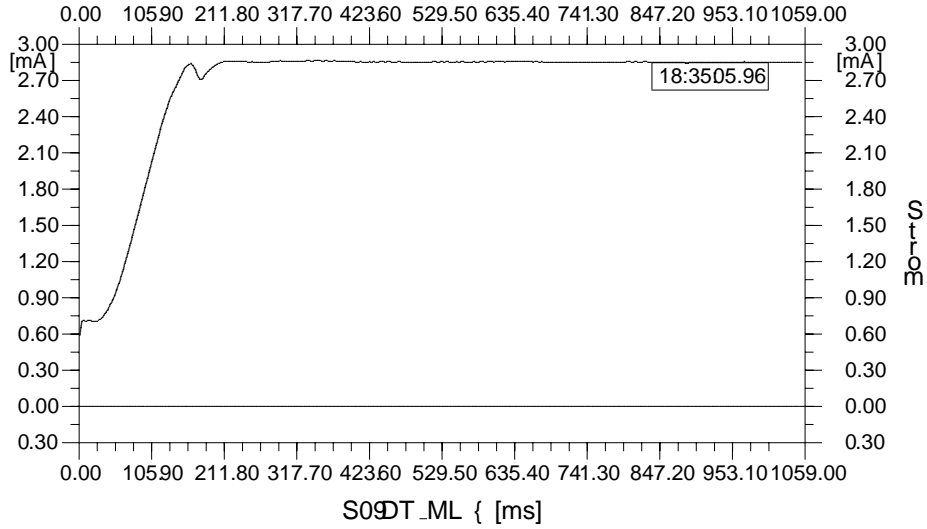
HTP | S09 | $^{181}\text{TA}^{61+}$ | 250.000 MeV/u

Figure 4: Particle currents and intensities in SIS for a ramping rate $\dot{B} = 6.0$ T/s.

DT_ML-T RAFO-PROTOKOLL

HTP | S09 | $^{181}\text{TA}^{61+}$ | 650.000 MeV/u

8. Jun 05 18:3513



Gain	6	Average	1
Delay	2.00ms		
StromWert	2.85mA		206.8ms nach Meßstart
TeilchenZahl	2.62 10 ⁸		

8. Jun 05 18:35:13

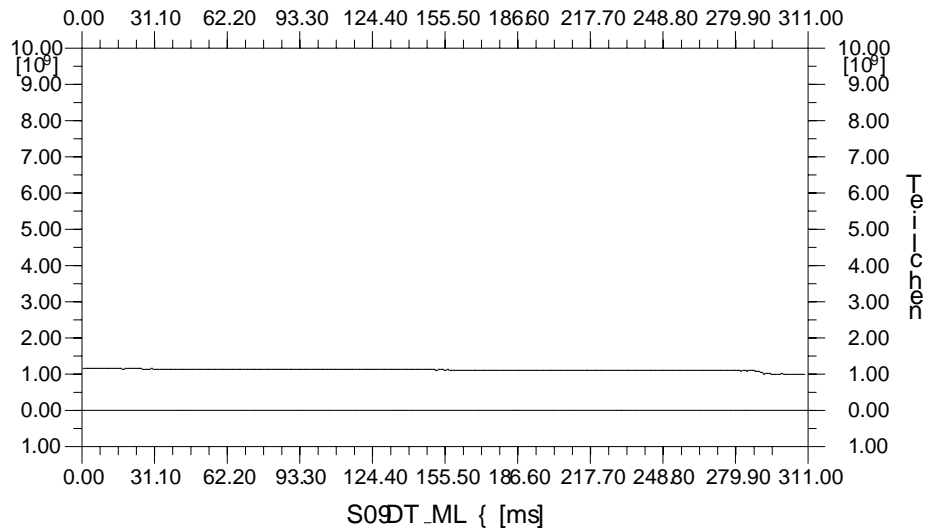
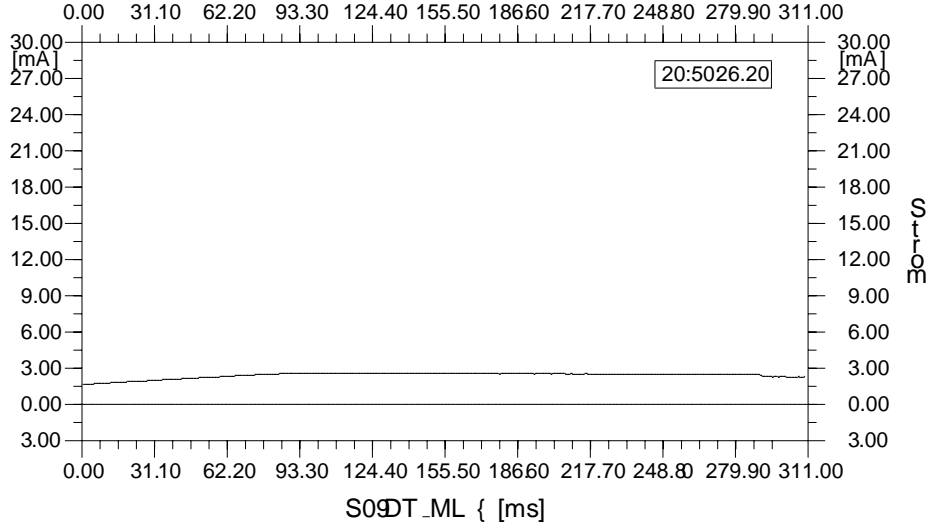
HTP | S09 | $^{181}\text{TA}^{61+}$ | 650.00 MeV/u

Figure 5: Particle currents and intensities in SIS for a ramping rate $\dot{B} = 9.6$ T/s.

DT_ML-T RAFO-PROTOKOLL

HTP | S11 | $^{181}\text{TA}^{24+}$ | 100.000 MeV/u

8. Jun 05 20:5046



Gain	4		
Delay	ms	Average	1
StromWert	2.51mA		2631ms nach Meßstart
TeilchenZahl	1.10 10 ⁹		

8. Jun 05 20:50:46

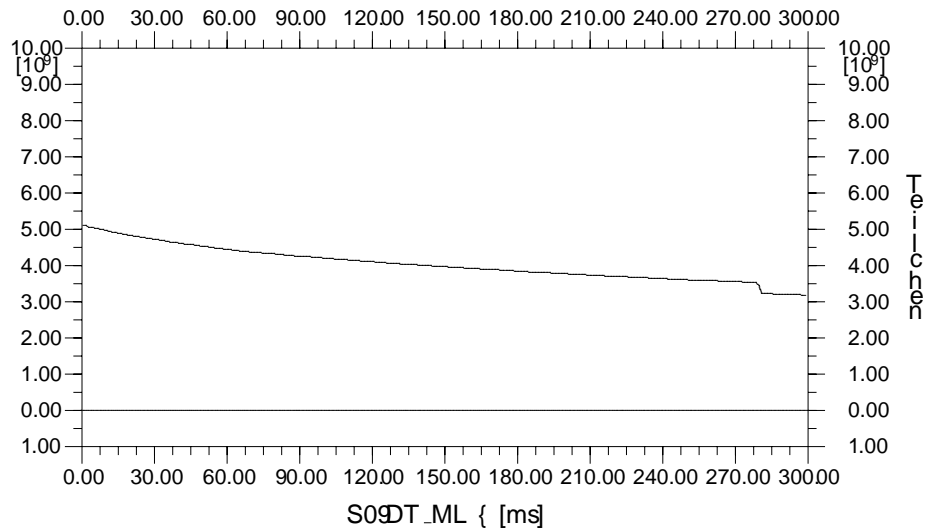
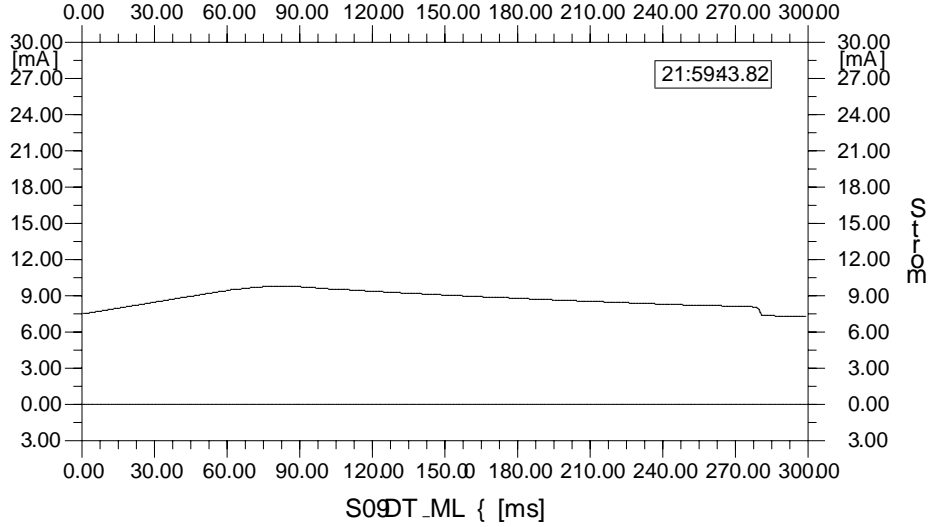
HTP | S11 | $^{181}\text{TA}^{24+}$ | 100.00 MeV/u

Figure 6: Particle currents and intensities in SIS for a ramping rate $\dot{B} = 5.3$ T/s.

DT_ML-T RAFO-PROTOKOLL

HTP | S11 | $^{181}\text{TA}^{24+}$ | 100.000 MeV/u

8. Jun 05 21:59:32



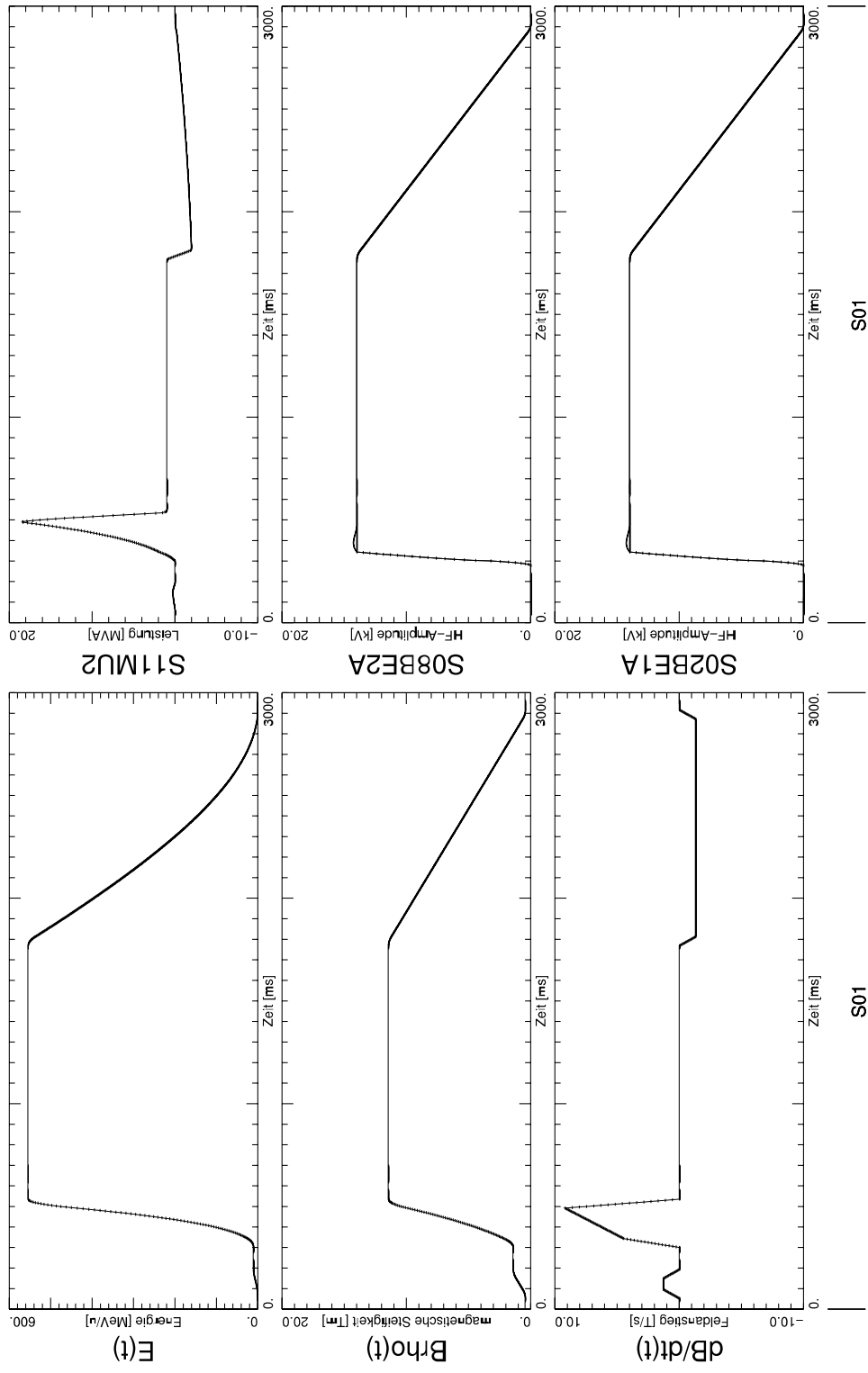
Gain	4		
Delay	ms	Average	1
StromWert	8.15mA		2667ms nach Meßstart
TeilchenZahl	3.57 10 ⁹		

8. Jun 05 21:59:32

HTP | S11 | $^{181}\text{TA}^{24+}$ | 100.00 MeV/u

Figure 7: Particle currents and intensities in SIS for a ramping rate $\dot{B} = 5.9$ T/s.

SIS – Ta61+, E(final)=650MeV/u (9.6 T/s), SIS12, Exp.–Setting 10.06.2005



F:\ZyklusRun\ExperimenteFlamps\um05SIS12-Ta61-Exp-10Ts.PS

Figure 8: SIS machine cycle based on the experimental settings for the acceleration of $^{181}\text{Ta}^{61+}$ at maximal $\dot{B} = 9.6 \text{ T/s}$.

SIS – Ta61+, E(final)=250MeV/u (6 T/s), SIS12, fast cycle 10.06.2005

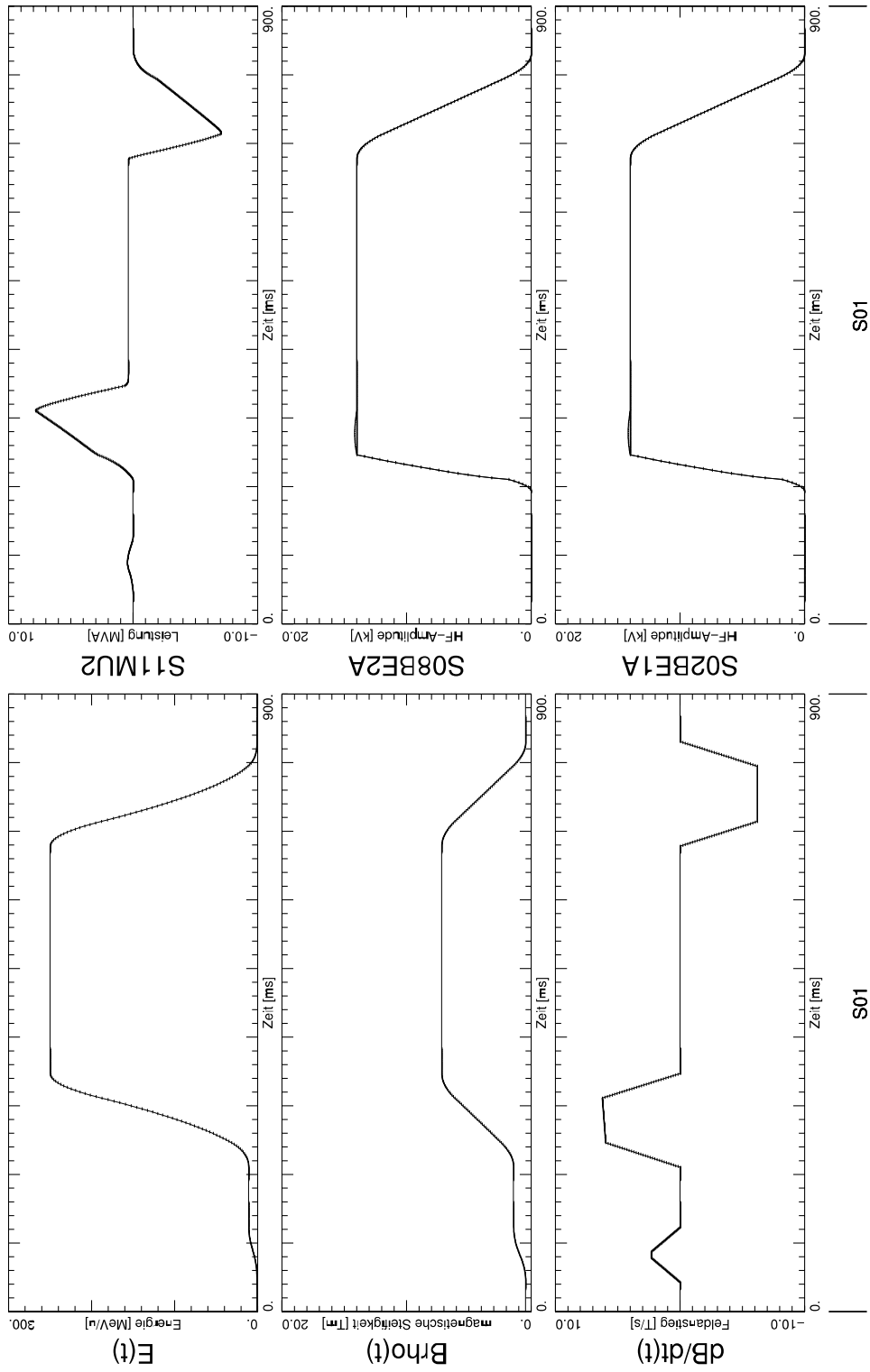


Figure 9: Fast SIS machine cycle for the acceleration of $^{181}Ta^{61+}$ at maximal $\dot{B} = 6.0$ T/s.

SIS – Ta61+, E(final)=250MeV/u (1.3 T/s), SIS12, normal mode 10.06.2005

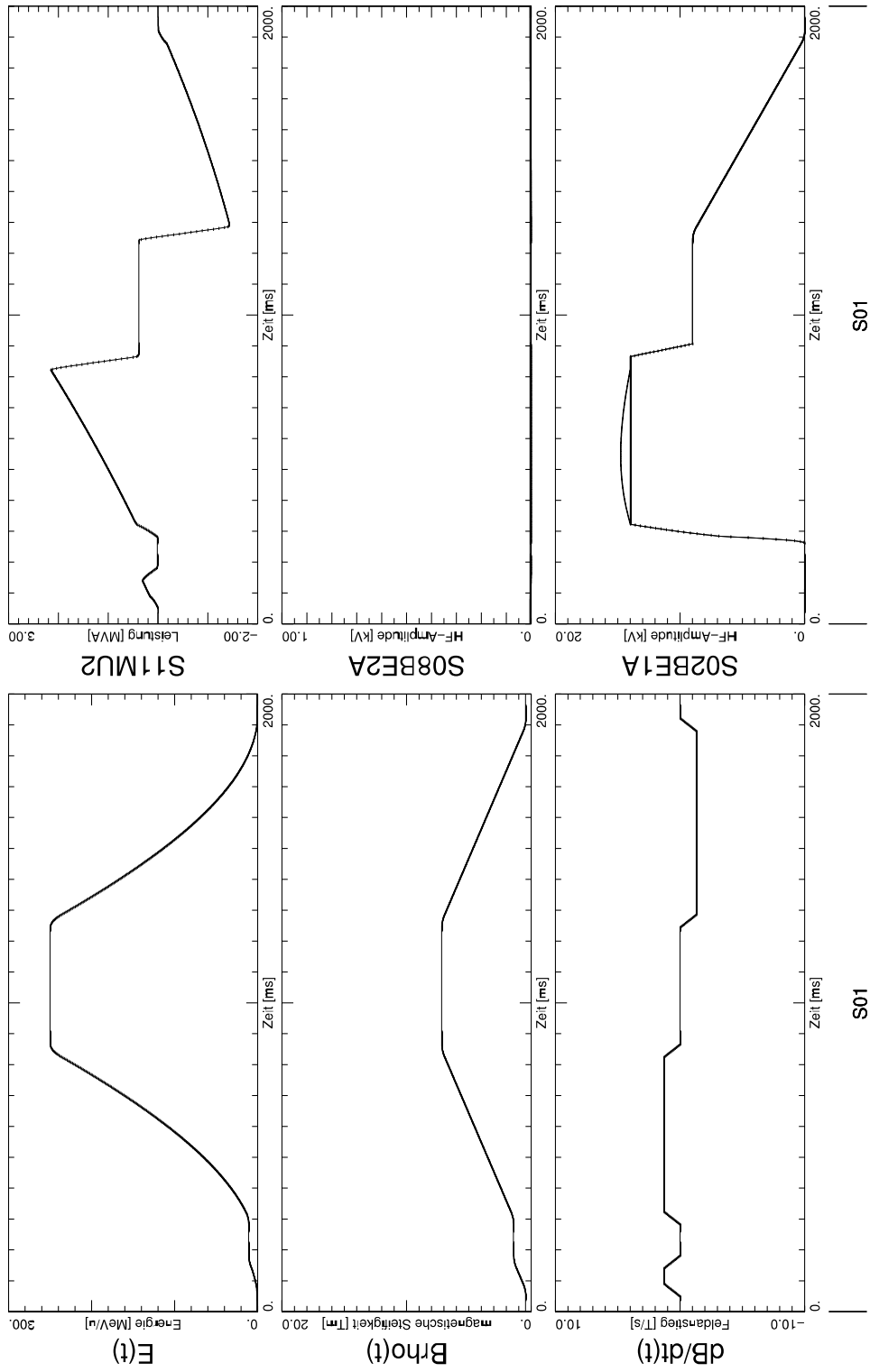
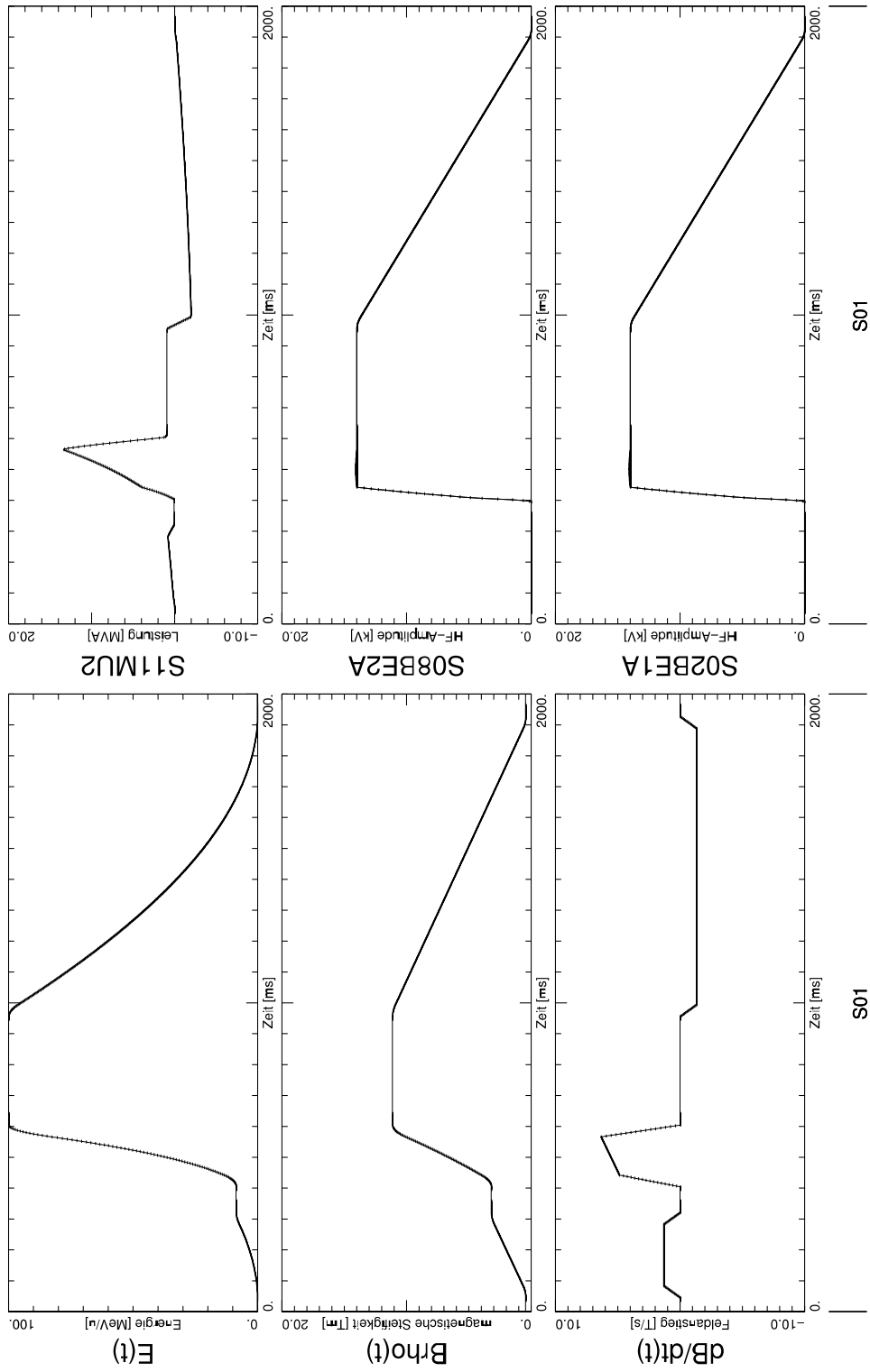


Figure 10: Standard SIS machine cycle for the acceleration of $^{181}\text{Ta}^{61+}$ at maximal $\dot{B}=1.3$ T/s.

SIS – Ta24+, E(final)=100MeV/u (5.9 T/s), SIS12, Exp.–Setting 10.06.2005



F:\Zyklus\Run\Experimente\Rampus\un05SIS12-Ta24-Exp-6Ts.PS

Figure 11: SIS machine cycle based on the experimental settings for the acceleration of $^{181}Ta^{24+}$ at maximal $\dot{B}=5.9$ T/s.

SIS – Ta24+, E(final)=100MeV/u (6 T/s), SIS12, fast cycle 10.06.2005

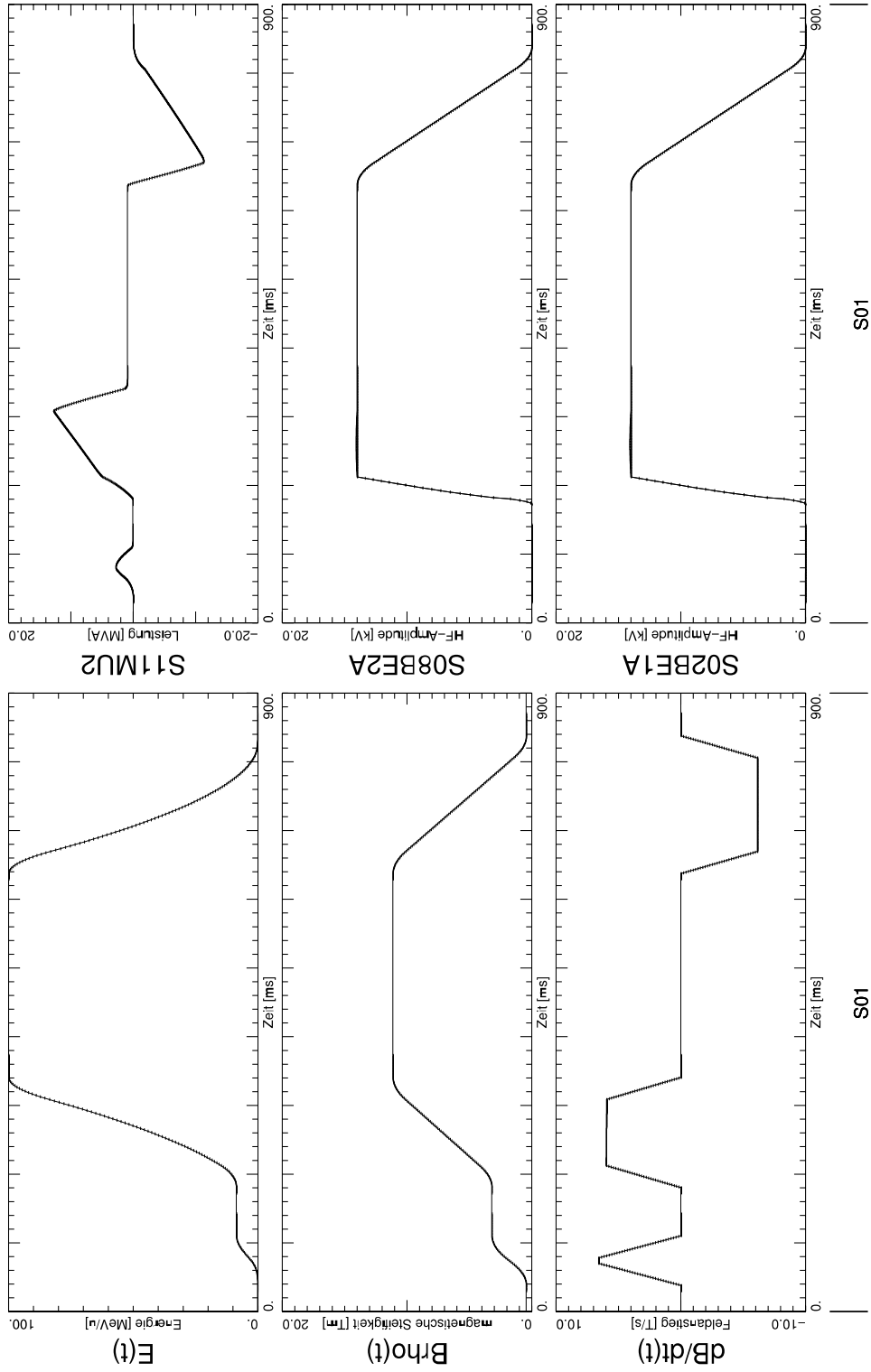


Figure 12: Fast SIS machine cycle for the acceleration of $^{181}\text{Ta}^{24+}$ at maximal $\dot{B} = 6.0$ T/s.

SIS – Ta24+, E(final)=100MeV/u (1.3 T/s), SIS12, normal cycle 10.06.2005

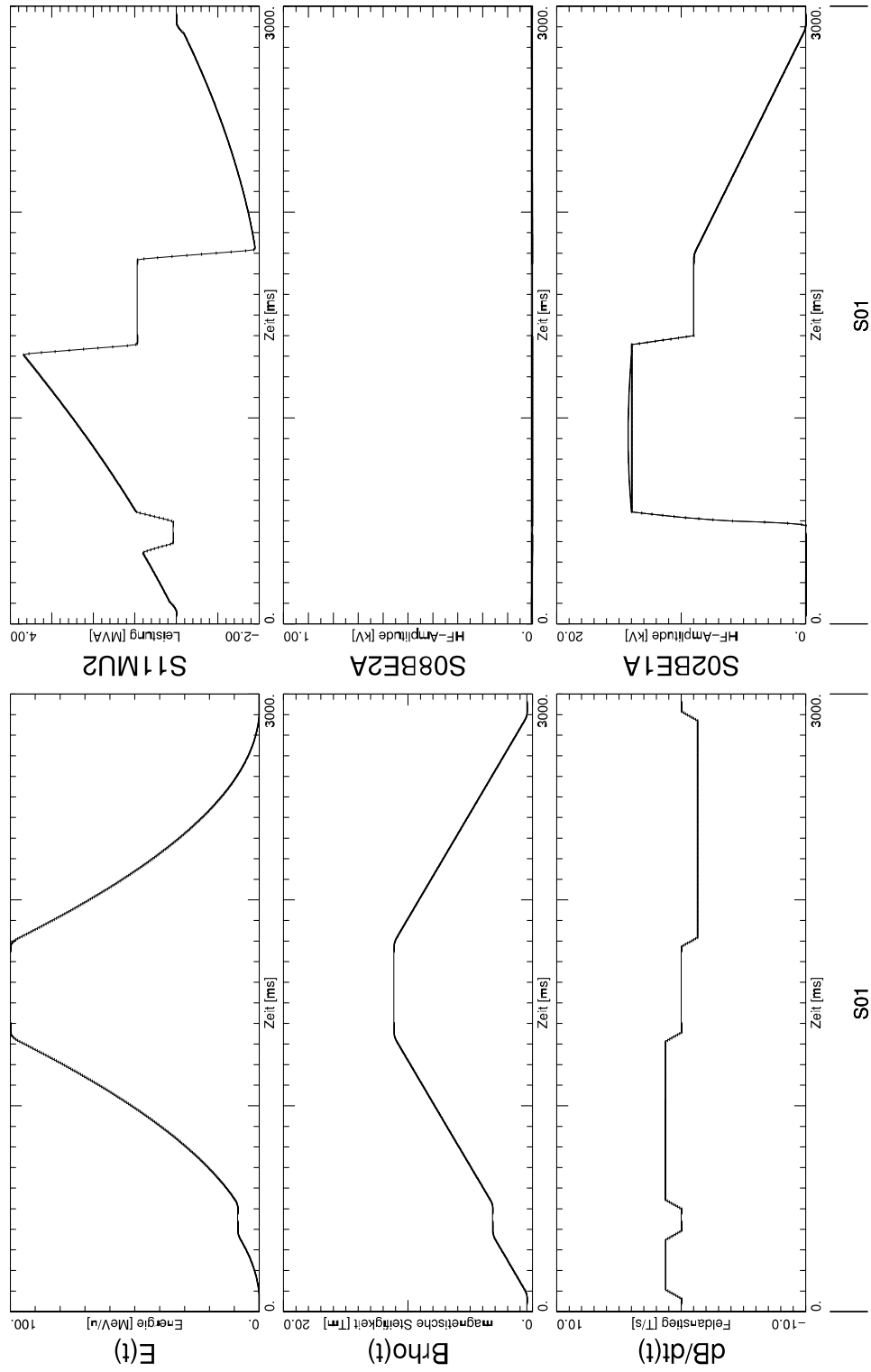


Figure 13: Standard SIS machine cycle for the acceleration of $^{181}\text{Ta}^{24+}$ at maximal $\dot{B}=1.3$ T/s.

SIS – Ta61+, E(final)=650MeV/u (9.6 T/s), SIS12, Exp.–Setting 15.06.2005

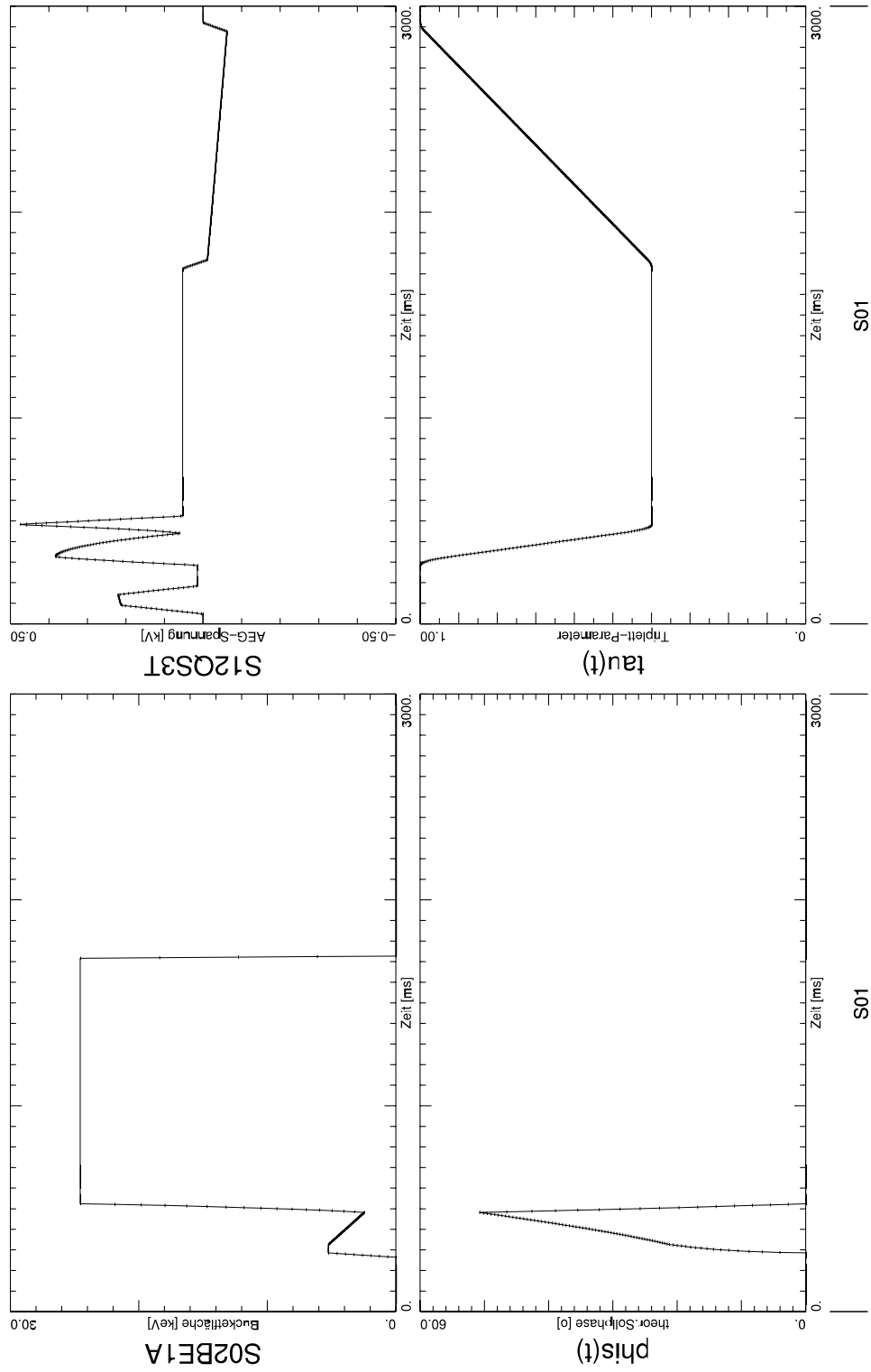


Figure 14: Bucket area, RF phase, voltage at S12QS3T and triplet focussing parameter based on the experimental settings for the acceleration of $^{181}\text{Ta}^{61+}$ at maximal $\dot{B} = 9.6 \text{ T/s}$.