ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR07

# DEVELOPMENT OF A SPILL-STRUCTURE MANIPULATION CAVITY AND FIRST EXPERIMENT WITH BEAM IN SIS18

K. Groß*, R. Balß, H. Klingbeil[1], U. Laier, D.E.M. Lens, J.S. Schmidt, P. Spiller, T. Winnefeld, B. Zipfel, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
P. Hülsmann, Deutsches Elektronen-Synchrotron, Hamburg, Germany
[1]also at Technische Universität Darmstadt, Darmstadt, Germany

## *Abstract*

For several years, significant effort has been spent at GSI to improve the time structure of the spill during slow extraction in SIS18. This led to the requirement to extend the possibilities to experimentally improve the micro-spill structure by partially or fully capturing the beam with an RF of more than 40 MHz. Therefore, a so-called spill-structure manipulation cavity was designed, realized and optimized which allows the mentioned experiments. In this contribution, the design of the cavity and the challenges of its realization are described, and measurement results concerning the first experimental operation in the SIS18 synchrotron are presented.

## BACKGROUND

The spill structure has a high impact on the data rate of physics experiments. A bad spill quality leads to low data rates, as well as problems like saturation, failures in the readout electronics or traces, that can no longer be separated for evaluation. Requirements on the time structure of the extracted particle beam strongly depend on the application. Fluctuations in the rate of extracted particles arise naturally from the remaining particle distribution in the accelerator as well as from ripples in the power supplies of the magnets. In the past beam time two developments designed to improve the spill quality were tested with beam in SIS18, from where the beam was extracted over several seconds and guided to the experiments. The macro-spill feedback [1] uses the measured particle rate at the experiment, which is fed into a controller acting on the RF knock out system to control this rate over the entire spill. In addition, new excitation signals reduce the time during which the particles are exposed to fluctuations of the magnets' power supplies [2, 3]. The micro-spill cavity forces the beam into an rf time structure, which is with > 40 MHz [4] fast enough not to harm the experiments while overwriting the unwanted fluctuations in the millisecond-range [5]. This cavity was installed in the SIS18 synchrotron in July 2023 and is described in the following.

## CAVITY CONCEPT

### *Design and Parameters*

To minimize effort and costs for the pilot cavity a stocked single-gap resonator from UNILAC [6] was modified. The original cavity with an inner diameter of 1477.4 mm and an inner length of 728.2 mm was designed for 108 MHz, which is sufficiently high for our purposes. The resonator had to be adapted to include a beam pipe in order to comply with the vacuum requirements in the synchrotron. The cavity weighs more than 5 t.

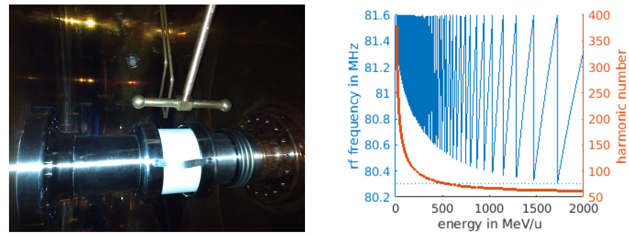

Figure 1: Coupling loop, tuning plunger and beam pipe with gap and shortcut (left) and rf frequency with corresponding harmonic number over beam energy (right).

As shown in Fig. 1 the gap can be short-circuited by a connection manually screwed into the field forming electrodes. To disable the impedance seen by the beam in case the spill manipulation is not needed, access to the accelerator tunnel is required.

The spill-structure manipulation system is equipped with amplitude and tuning loops including several modules from the LINAC LLRF. The prototype was designed to be locally operated during dedicated proof-of-principle experiments. The operational parameters of the cavity system are given in Table 1.

Table 1: Operational Properties

| | |
|---|---|
| Frequency range (low voltages | 80.3 to 81.6 MHz down to 79 MHz) |
| Gap voltage amplitude $\hat{U}$ (in test environment | 1.5 kV up to 25 kV) |
| Impedance $R_s$ (without short-circuit) | ≈ 500 k$\Omega$ |
| Quality factor $Q_0$ | 4000 to 5000 |

### *Field Simulations and Measurements*

Simulations in CST MICROWAVE STUDIO® were performed to predict and understand the properties of the cavity. In the current configuration the calculated unloaded quality factor of about 4106 shown in Fig. 2 is in good agreement

* k.gross@gsi.de

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR07

with the measured loaded quality factor of 2460 with critical coupling (cf. Fig. 3).

| Material/Solid | Conductivity | Mu | Loss/% | Q |
|---|---|---|---|---|
| **Cond. Enclosure** | 5.8000e+07 | 1 | 5.36 | 7.6663e+04 |
| Vacon (Kovar) | 2.0408e+06 | 1000 | 13.9 | 2.9538e+04 |
| Stainless Steel | 1.3333e+06 | 1 | 39.7 | 1.0352e+04 |
| Copper | 5.8000e+07 | 1 | 1.27 | 3.2411e+05 |
| **Sum of Surface Losses** | | | 60.2 | 6.8219e+03 |
| **Volume Losses** | | | 39.8 | 1.0314e+04 |
| **Sum** | | | | 4.1061e+03 |

Figure 2: Loss calculation from CST with the conductivity in $\mathrm{S\,m^{-1}}$.

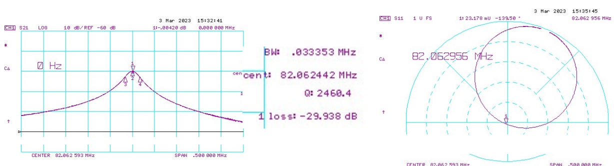


Figure 3: Measurement of the Q factor of the cavity.

Losses found from the field simulations are discussed in the following. The decision for a beam pipe made of stainless steel instead of copper was a consequence of the high losses in the gap ceramic, limiting the applicable power and reachable gap voltage.

### *Impedance and Gap Voltage Amplitude*

The gap voltage is not measured directly. The impedance was derived from the field simulations and the field measurement was calibrated by gamma spectroscopy. The spectrum of bremsstrahlung radiation is shown in Fig. 4. For this measurement the cavity was operated in cw for several hours with 200 W and 400 W respectively. In the following, an ex-

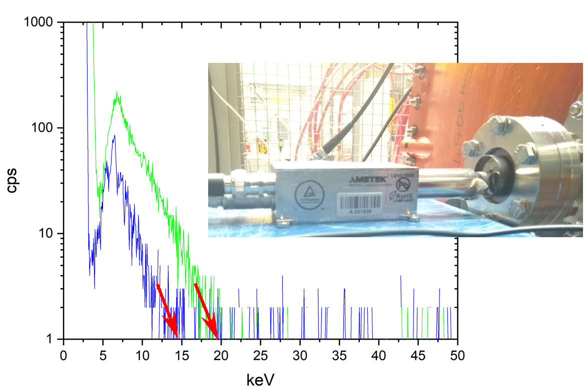


Figure 4: Measurement (left) performed by E. Kozlova, A. Sokolov, using a diamond window (right) from A. Gumberidze.

emplary power $P_c$ of 36 W coupled into the resonator is used, to restrict the heating discussed in the next section. From the impedance the gap voltage peak amplitude is calculated to

$$\hat{U}(P_c) = \sqrt{2}\sqrt{R_s P_c} = \sqrt{1000\,\mathrm{k}\Omega \cdot 36\,\mathrm{W}} = 6\,\mathrm{kV} \qquad (1)$$

## CHALLENGES AND OPTIMIZATION

### *Gap Ceramic*

A closer look at Fig. 2 reveals considerable dielectric volume losses $P_{loss} \approx 40\% P_c$ in the gap ceramic. This leads to a significant initial temperature gradient $\dot{T}$ when switching on or raising the power $P_c$. The relevant dimensions and material properties of the ceramic gap are summarized in Table 2. From an equilibrium temperature in the environment

Table 2: Properties of Ceramic / Frialit 99.7 hf @ 70 MHz

| | | |
|---|---|---|
| Length | $l$ | 146 mm |
| Inner / outer Diameter | $2r_i$ / $2r_o$ | 170 / 190 mm |
| Mass | $m_c$ | 3.22 kg |
| Relative permittivity | $\varepsilon_r$ | 9.8 |
| Dielectric loss tangent | $\tan(\delta)$ | $3.8 \cdot 10^{-4}$ |
| Specific heat capacity | $c_c$ | $900\,\mathrm{J\,kg^{-1}\,K^{-1}}$ |

the resulting initial gradient is found:

$$\dot{T} = \frac{P_{loss}}{m_c\, c_c} = \frac{40\% \cdot 36\,\mathrm{W}}{3.22\,\mathrm{kg} \cdot 900\,\frac{\mathrm{J}}{\mathrm{kg\,K}}} \approx 0.3\,\frac{\mathrm{K}}{\mathrm{min}}$$

With Eq. (1) the losses in the ceramic can as well be estimated from the volume $V$, length $l$ and the dielectric properties of the material at 80 MHz

$$P_{loss} = \frac{1}{2} V \omega \varepsilon_0 \varepsilon_r \tan(\delta) \left(\frac{\hat{U}}{l}\right)^2 = 11.6\,\mathrm{W}$$

which is 32% of the input power. The reason for the deviation from the expected value of 14.4 W is due to the field distribution in the partly shielded ceramic.

### *Tuning Range*

Due to the installed beam pipe the fields are concentrated at the beam axis. Therefore, tuning plunger and coupling loop had to be modified in order to reach the closer gap area as shown in Fig. 1 on the left.

The tuning range is limited by spark over from the beam pipe. On the right of Fig. 1 the coverage of all revolution frequencies from the injection level to highest rigidity by the tuning range and harmonic numbers between 62 and 380 is presented. With the gap voltage limitation due to the temperature gradient the frequency drift is small and therefore not relevant for operation.

## EXPERIMENTAL BEAM OPERATION

### *Setup*

On November 29th, 2023 the first proof-of-principle experiment was performed with $^{14}N^{7+}$ at 300 MeV $u^{-1}$. It was divided into three parts with no beam, high and low beam

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR07

current respectively. We started with the conditioning of the gap ceramic which took 100 minutes. The second part of the experiment was dedicated to beam current measurements. At flattop the beam was debunched and adiabatically rebunched before being slowly extracted. From the revolution frequency of 904.851 kHz the operating frequency of 81.436 59 MHz (12.28 ns) was derived. The last part was used for spill measurements performed by the beam diagnostics department.

To get feedback from physics experiments the system was further operated in the HADES beam time for gold ions at 200 MeV u$^{-1}$ and 800 MeV u$^{-1}$ as well as used by mCBM at 1.2 GeV u$^{-1}$, where the system was operated at harmonic numbers $h = 104$, $h = 70$ and $h = 65$.

### *Measurements and Results*

Conditioning is dominated by a glow discharge in the beam pipe going along with a disturbance of the vacuum. The power going into the cold plasma leads to a mismatch visible as reflected power. During that time the system was operated cw without beam. The power coupled into the resonator was gradually increased to keep the vacuum pressure and the temperature gradient constant as shown in Fig. 5 together with a photo of the luminous effect inside the beam pipe. Conditioning is required to reach gap voltages higher than 1.5 kV. The reason still has to be analyzed, as the effect was limited to the times, when the gap was aired in test environment, but before each operation with the cavity being installed in the accelerator. It was shown that the

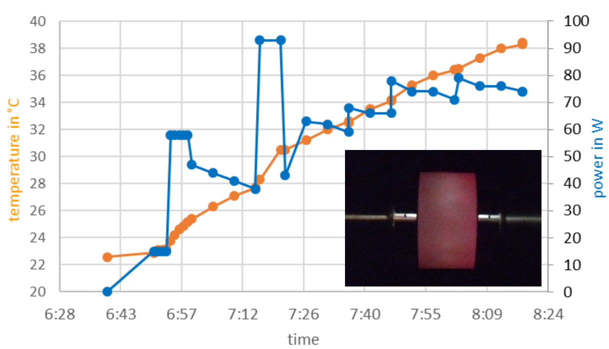


Figure 5: Input power with temperature of the ceramic and photo of the gap (bottom right) during conditioning.

beam was successfully bunched at the high harmonic in the synchrotron. No closed-loop phase synchronization with respect to the revolution frequency was necessary to keep the beam bunched during extraction. Figure 6 shows a record of the measured beam currents using a fast current transformer and about 0.43 mA DC current.

The influence of the gap voltage amplitude, i.e. the bunching factor, and the rf frequency were analyzed. Another measurement on March 6$^{th}$ showed that the time structure remains preserved during extraction (cf. Fig. 6). Thus the extracted beam is pushed towards the pearl chain structure aimed for.

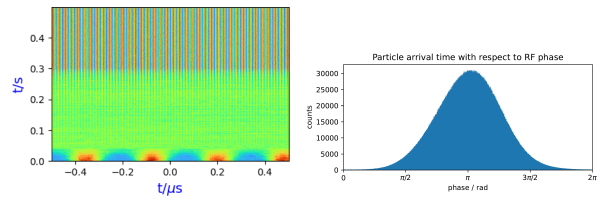


Figure 6: Waterfall plot of beam current (FCT) with debunching at harmonic number h=4 (bottom left) and rebunching at h=90 (top left) and distribution of the extracted particles over one rf period performed by T. Milosic (right).

### *Outlook*

In the close future the prototype micro-spill system has to be integrated into the control system and prepared for routine operation to allow a wider range of usage. This includes the development of an automatic short-circuit mechanism. Furthermore, dedicated machine experiments are planned, using the cavity for tune wobbling or empty bucket channeling. Based on particle tracking simulations for different energies and ion species as well as the mentioned measurements a decision on the required gap voltage is needed for further developments. Up to now, the gap voltage is limited to 1.5 kV without conditioning and to maximum 6 kV with conditioning due to thermal issues.

## CONCLUSION

The spill manipulation cavity is a pillbox cavity equipped with beam pipe and ceramic gap to meet the vacuum requirements. It was installed in SIS18, tested and used for experiments in the beam time. The micro-spill structure of the extracted beam was successfully improved by bunching the beam at a high harmonic not interfering with physics experiments at GSI and FAIR.

## ACKNOWLEDGEMENTS

Special thanks to the following (partly former) colleagues and departments (alphabetical order) making this project possible

**Development and Commissioning:** Accelerator Radiation Protection, Atomic, Quantum & Fundamental Physics, Construction (B. Benz, J. Kalenda), Linac RF (B. Schlitt, G. Schreiber, W. Vinzenz, J. Zappai et al.), Ring RF (B. Breitkreutz, C. Christoph, O. Disser, M. Hardieck, H.G. König, S. Lux, S. Schäfer, C. Thielmann et al.), SIS100/SIS18 (J. Stadlmann), Transport and Installation (D. Acker, K. Lück, M. Grenz-Gustafson, M. Diebel, K. Kalaitzidis et al.), Vacuum Systems (M.C. Bellachioma, E. Renz, G. Savino)

**Spill Measurements:** Accelerator Physics (S. Sorge), Beam Instrumentation (P. Boutachkov, O. Chorniy, P. Forck, T. Milosic, J. Yang), SIS100/SIS18

**Machine Operating and Discussions:** (Accelerator) Operation(s) (R. Aßmann, A. Bloch-Späth, C. Böhm, V. Kamerdzhiev, H. Kummerfeldt, F. Lorenz, S. Reimann, Y. Valdau)

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR07

## REFERENCES

[1] P.J. Niedermayer, R.N. Geißler, and R. Singh, "Software Defined Radio Based Feedback System for Transverse Beam Excitation", in *Proc. IBIC'23*, Saskatoon, Canada, Sep. 2023, pp. 306–307. doi:10.18429/JACoW-IBIC2023-WE2C02

[2] P.J. Niedermayer *et al.*, "Investigation of micro spill in RF KO extraction using tailored excitation signals", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 2427–2430. doi:10.18429/JACoW-IPAC2023-TUPM094

[3] P. Niedermayer, R. Singh, "Excitation Signal Optimization for Minimizing Fluctuations in Knock Out Slow Extraction", *Research Square preprint*, Feb. 2024. doi:10.21203/rs.3.rs-3933161/v1

[4] J. Pietrazko, "The Hades/CBM physics case requirements", oral presentation at *Slow Extraction Workshop*, Darmstadt, Germany, June 2016.

[5] S. Sorge, P. Forck, and R. Singh, "Spill ripple mitigation by bunched beam extraction with high frequency synchrotron motion", Phys. Rev. Accel. Beams 26, 014402, Jan. 2023. doi:10.1103/PhysRevAccelBeams.26.014402

[6] D. Böhne, "The Unilac, Development and Present Status", in *Proc. LINAC'76*, Chalk River, Canada, Sep. 1976, paper A01, pp. 2–11.