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ION-OPTICAL MEASUREMENTS AT CRYRING@ESR DURING COMMISSIONING

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Abstract

During the commissioning phase of CRYRING@ESR, several ion-optical measurements such as momentum spread, dispersion function, effective acceleration voltage and orbit response matrix were performed at the ring. The measurements help the commissioning process to reveal possible gauge errors and will be used to improve the theoretical model and to control the closed orbit.

INTRODUCTION

CRYRING@ESR is a heavy ion storage ring, which can cool and decelerate highly charged ions down to a few 100keV/u. It has been relocated from Sweden to GSI, downstream of the Experimental Storage Ring (ESR), within the FAIR project. The ring will be used as a test facility for FAIR technologies and for physics experiments with slow exotic ion beams for several FAIR collaborations: SPARC, BioMat, FLAIR and NUSTAR [1]. The general layout of CRYRING@ESR with its local injector and ion source is presented in Fig. 1.

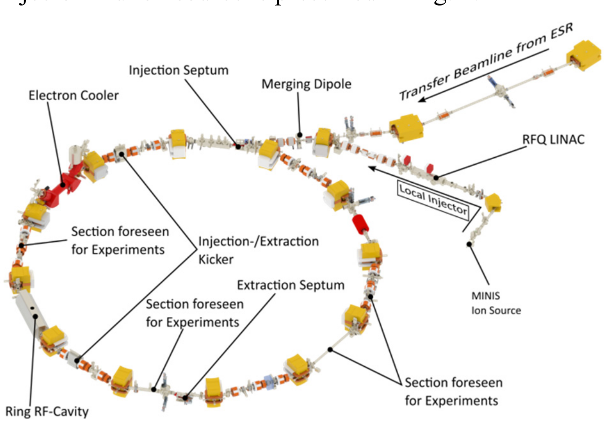

Figure 1: Overview of the CRYRING@ESR facility with main installations indicated.

The installation started in 2014 and finished in early 2016. Integration testing and commissioning with beam started in 2016 [2]. Stored beam was established in mid-2017 [3]. Until Q1 2018, the following commissioning goals were reached: acceleration of H_2^+ to maximum rigidity, production, storage and acceleration of H_2^+, Ar^+, Mg^+ ions. The CRYRING electron cooler was tested with stored H_2^+ ion beams at 300keV/u. The reduction of the phase space volume of the ion beam under electron cooling has been observed in all 3 phase space planes with the appropriate beam diagnostics devices (i.e. Schottky noise spectrum longitudinally, ionization profile monitor horizontal/vertical). Apart from commissioning, several ion-optical measurements were performed at the ring, which are presented here.

DISPERSION

The horizontal dispersion D_x describes the transverse displacement $\Delta x(s)$ of the beam orbit as a function of the relative momentum spread $\frac{\Delta p}{p}$ as:

$$\Delta x(s) = D_x(s) \cdot \frac{\Delta p}{p}, \tag{1}$$

where s is the location in the observation. The dispersion function is inferred from the orbit change (measured with beam position monitors (BMPs)) induced by a shift in the beam energy by changing the ring rf-frequency. A frequency shift Δf changes the relative momentum spread of the beam as follows:

$$\frac{\Delta p}{p} = -\frac{1}{\eta} \cdot \frac{\Delta f}{f_0}, \tag{2}$$

where η is the slip factor of the lattice and f_0 is the nominal, injection-energy matched frequency of the ring-rf. The measurement of the dispersion function at CRYRING was performed by changing the rf frequency and getting the relative orbit shift at the BPM positions. The measurements were done with H_2^+ ions at 300keV/u, which corresponds to a nominal frequency of 139.46kHz and a slip factor of 0.8 (transition-gamma is 2.269). The following detuned rf frequencies were applied: 139.32kHz, 139.36kHz, 139.51kHz and 139.56kHz. During the analysis of the $\Delta x(s)$, it became clear that the data show strong non-statistical fluctuation (up to 6mm from peak to peak) in the horizontal plane. The fluctuations in vertical plane were much less pronounced (0.3 – 1 mm from peak to peak). One can see an example from BPM8 in Fig. 2. In order to get rid of the injection oscillations, the measurements with BPMs were triggered 480ms after the injection (revolution time is 7µs). The FFT analysis has shown that the low frequencies dominate the signal (see Fig.3).

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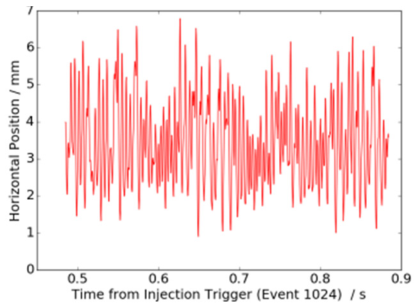

Figure 2: Turn-by-turn orbit data of BPM8, triggered at 480ms after injection.

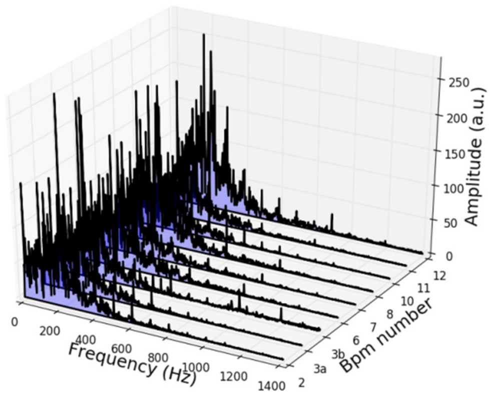

Figure 3: FFT analysis of the orbit position data for the different horizontal BPMs.

A root cause analysis has revealed that the orbit of the low energy particles is distorted by the ripple of the power converters of the ring magnets (dipoles and quadrupoles). This effect, seen by BPMs, will be reduced in the future for higher particle energies and longer BPM data acquisition time, as the present acquisition time is only 20ms. For the analysis, a simple statistical mean was calculated from the data sets for each ring-rf frequency. For comparison of the measurements with the theory, MAD-X calculations of the dispersion function along CRYRING were performed [4]. Figure 4 shows a comparison of the simulations and measurements. A difference up to 30% in sections 3, 10 and 11 is observed, which is likely due to simplifications in the model and have to be investigated.

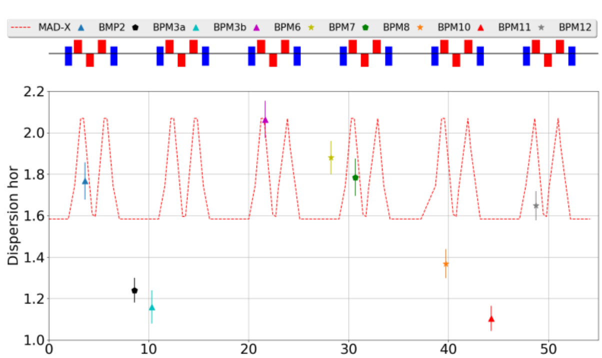

Figure 4: Comparison of a MAD-X calculation (red dashed line) of dispersion function along CRYRING with measurements.

ORBIT RESPONSE MATRIX

The Orbit-Response Matrix (ORM) is essential information for both orbit control and optics analysis. It can be either calculated using a theoretical model of the ring or measured directly on the machine. The ORM formalism associates the closed orbit offsets at the BPMs with the applied correctors' kicks as following:

$$\begin{pmatrix}\Delta x\\ \Delta y\end{pmatrix} = M \cdot \begin{pmatrix}\Delta\Theta x\\ \Delta\Theta y\end{pmatrix}, \tag{3}$$

where M is the orbit response matrix, Δx and Δy are the horizontal and vertical closed orbit offsets at the BPM positions, $\Delta\Theta_x$ and $\Delta\Theta_y$ are the horizontal and vertical corrector kicks. CRYRING has 18 BPMs (9 per plane) and 12 correctors (6 per plane), which yields a non-quadratic response matrix M (18, 12). For the orbit correction purposes it needs the matrix pseudo-inversion M^{-1} (for the non-quadratic matrices) to calculate the required kicks:

$$\begin{pmatrix}\Delta\Theta x\\ \Delta\Theta y\end{pmatrix} = M^{-1} \cdot \begin{pmatrix}\Delta x\\ \Delta y\end{pmatrix}. \tag{4}$$

The widely used method to do so is the Singular Value Decomposition (SVD), which is applied at CRYRING ORM. The orbit responses Δx and Δy were calculated the same way it was done for the dispersion measurements. As an automated orbit correction procedure is not established yet, the measured ORM was compared quantitatively with the theoretical one to reveal the gauge errors in the correction coils and in the BPMs.

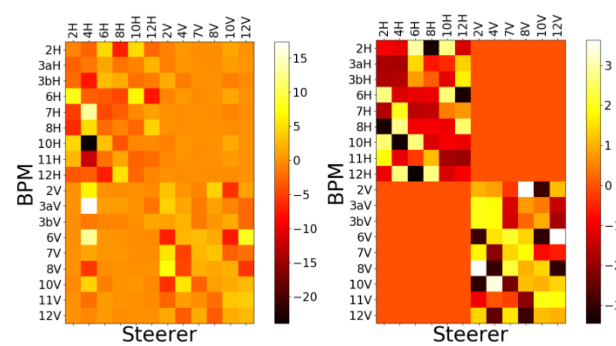

Figure 5: CRYRING ORM measured (left) and theoretical (right).

An ideal machine is not coupled and has only a diagonal ORM contribution as can be seen from the theoretical model in Fig. 5. Measured coupled response from kicks in horizontal (Steerer 4H) and vertical (Steerer 10V) planes suggests a misalignment of those corrector coils. Measured overall response on the kicks is approximately 3 times higher than in theory (an "out of range" measured response of BPM 10H on kick 4H (<-20) is not taken here into account as the corrector is misaligned), which indicates a systematic overestimation of the correctors' calibration curves. Further ORM

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measurements are planned for the next commissioning phase.

LONGITUDINAL DYNAMICS

CRYRING can get the beam from two different sources: either from ESR or from the local injector (multi-turn injection scheme). All commissioning work was performed with the beam from the local injector so far. During the adiabatic rf-capture and acceleration process the largest part of the particles were lost (50-90%), which triggered the following investigations. A ratio between gap voltage V_{gap} and effective acceleration voltage V_{eff} was measured by changing the gap voltage and measuring synchronous frequencies f_{s0} of the bunch (see [5] and Fig. 6). The effective voltage then was calculated as:

$$V_{eff} = \frac{{f_{s0}}^2}{f_0^2} \cdot \frac{2\pi\beta^2 E}{h\eta cos\varphi} \quad (5)$$

where β is relativistic β, E is the total beam energy and φ is synchronous phase. The following ratio was experimentally defined: $V_{gap} \approx 3.7 \cdot V_{eff}$. This compares well with the theoretical factor of 3.2.

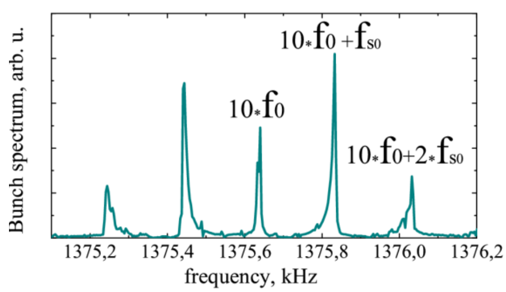

Figure 6: BPM signal spectrum at 10th harmonic of revolution frequency. Bunch revolution frequency was 137.565kHz.

The present rf cavity provides a maximum gap voltage of 370V (V_{eff}=100V). Further simulations to check the longitudinal dynamics were initiated. BLOND code was used to model the machine [6]. The momentum spread of the injected DC beam was measured and turned out to be equal to the longitudinal ring acceptance ($\Delta p/p = \pm 1\%$).

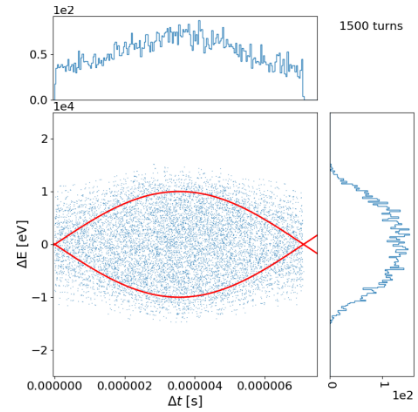

Figure 7: Longitudinal phase space of CRYRING during the rf capture process with the maximum effective voltage of 105V. Simulations were performed with BLOND code.

As can be seen in Fig. 7, the maximum effective acceleration voltage of 100V, applied on the H_2^+ beam, is not sufficient to capture it completely. The estimated beam losses during the acceleration are 50%. Based on the findings above, an upgrade program of the rf station was initialized and the maximum required V_{eff} had to be specified. For this purpose a study with BLOND code was performed with different projectiles and harmonic number 1. The most demanding momentum spread (±1%) and ramping rate (7T/s) were used in the simulations.

Table 1: Calculation of the Required Effective Acceleration Voltage for the Different Ions and Charge States.

Projectile	Atomic Mass	Charge State	Veff for stationary bucket	Veff for running bucket
p	1	1	2kV	3.4kV
H_2^+	2.015	1	250V	1.2kV
Ca_1^+	40.078	1	150V	470V
Kr_{36}^+	83.798	36	350V	1kV
C^+	12.011	1	150V	470V

A maximum required effective voltage of 3.4kV was determined (see Table 1).

CONCLUSION AND OUTLOOK

Ion-optical measurements and calculations presented here support the commissioning process of the machine. Despite the restricted quality, ORM and dispersion measurements help to find gauge errors in the ring. The measurements of the ORM will be repeated regularly until the ring is completely commissioned and closed orbit is controlled. The chromaticity and tune diagram will be measured as well. The quadrupoles and sextupoles cannot be controlled separately, which excludes beam based alignment and beta beating measurements. Further simulations with BLOND code are planned for the higher harmonic number h = 18 as it reduces the effective voltage by the factor of $h^{-1/2}$.

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REFERENCES

[1] M. Lestinsky, V. Andrianov, B. Aurand, *et al.,* "Physics book: CRYRING@ESR" *Eur. Phys. J. Spec. Top*. (2016) 225: 797. https://doi.org/10.1140/epjst/e2016-02643-6

[2] W. Geithner *et al.*, "Status and outlook of the CRYRING@ESR project", Hyperfine Interact (2017) 238: 13. https://doi.org/10.1007/s10751-016-1383-5

[3] F. Herfurth, et al., "Commissioning of the Low Energy Storage Ring Facility CRYRING@ESR", *in Proc International Workshop on Beam Cooling and Related Topics (COOL'17)*, Bonn, Germany, September 18-22, 2017, THM13. http://inspirehep.net/record/1655669/files/thm13.pdf

[4] MAD-X Code. http://madx.web.cern.ch/madx/

[5] T. Linnecar, Schottky beam instrumentation, in: Beam Instrumentation, J. Bosser (ed.) (CERN, Geneva, 1992) [CERN-PE-ED 001–92]. p169

[6] BLOND Code. https://blond.web.cern.ch/