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FINAL PREPARATION OF ACCELERATED AND POLARISED PROTONS AT COSY JÜLICH

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Abstract

To prepare for the extraction of polarised protons at a momentum of 1950 MeV/c to an external target, full advantage of the most recent developments of the COSY control system was taken along with the established hardware of the Cooler Synchrotron (COSY) in Jülich, Germany. Challenges in beam development included the operation close to transition energy as well as seven depolarising resonances (4 intrinsic and 3 imperfection resonances) which have to be crossed during the acceleration. To overcome the intrinsic resonances, tune jumps were carried out with the Q-jump quadrupole system of COSY. To identify the correct time window for the jump, the precise measurement of the tune during the acceleration ramp was used. We present how the recent developments in the control system, along with the established techniques, enabled us to successfully accelerate and extract the polarised beam. 2023 was the last year of operation for COSY.

INTRODUCTION

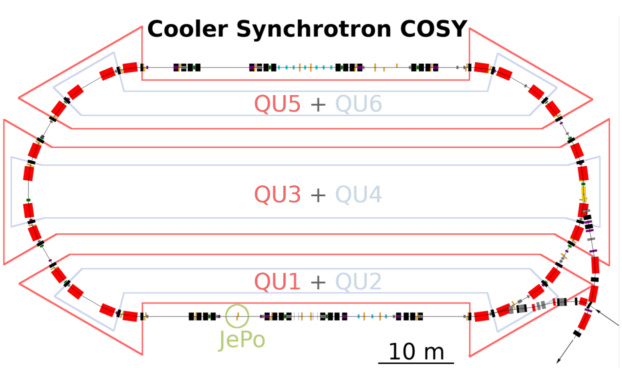

Figure 1: Schematic of COSY. The interconnecting lines demonstrate the families of quadrupoles in the arc sections, which are used to set and control the betatron tune of COSY. The arrows indicate the connections to the injection beam line and the extraction beam lines. The JEDI polarimeter JePo is highlighted in green.

Since the initial demonstration in 1996 [1], polarised protons have been stored and accelerated repeatedly in COSY [2]. The main challenge in accelerating and extracting polarised protons is to cross several depolarising resonances. As a horizontal betatron tune close to the resonance at $Q_x = 3.\bar{6}$ is necessary to extract the beam, and as higher order depolarising resonances are energy dependent, the tune space is confined even further. These challenges are addressed by precise measurement of the betatron tune, and the implementation of suitable countermeasures to adjust the tune accordingly.

PREPARATION OF THE ACCELERATION RAMP

A conventional acceleration ramp is set up as a basis for the subsequent acceleration of polarised protons. The protons are injected at a momentum of 294 MeV/c. The quadrupoles in the straight sections are set up such that a telescopic setting, defined as a phase advance of $\Delta\phi_{x,y} = 2\pi$, is achieved in each of the two sections. Consequently, the betatron tune is controlled by the quadrupoles in the arc sections only, which are grouped into six families (see Fig. 1). The quadrupole families in the straight section are referred to as telescope quadrupoles (QT), while the quadrupole families in the arc sections are referred to as unit cell quadrupoles (QU). The unit cell families with odd numbers (red connection lines in Fig. 1) have a major effect on the vertical tune ν_x, whereas the families with even numbers (blue lines) influence the horizontal tune ν_y. At energies below the transition energy all even (odd) families are operated at the same current and the COSY lattice shows a six-fold peridicity [3]. During acceleration above the original transition energy, the field of the inner families QU3 and QU4 is increased in order to shift the transition energy. The periodicity of COSY is then only two-fold [3]. At the topical beam time the ramp is set up in accordance with the aforementioned procedure. Subsequently the families QU3 and QU4 are modified. The objectives of these modifications are:

- no resonances are to be crossed to prevent from beam losses,
- in preparation for the crossing of intrinsic resonances, the betatron tune has to remain comparably constant after the initial acceleration phase of ~ 500 ms,
- maintain a distance to the betatron tune resonances to provide sufficient room for the tune-jumps (cf. section on polarisation),
- at the end of the ramp (flat top), the vertical tune should be above 3.57 (cf. next section).

The precise measurement of the betatron tune in the ramp is enabled by the continuous measurement mode of the fast

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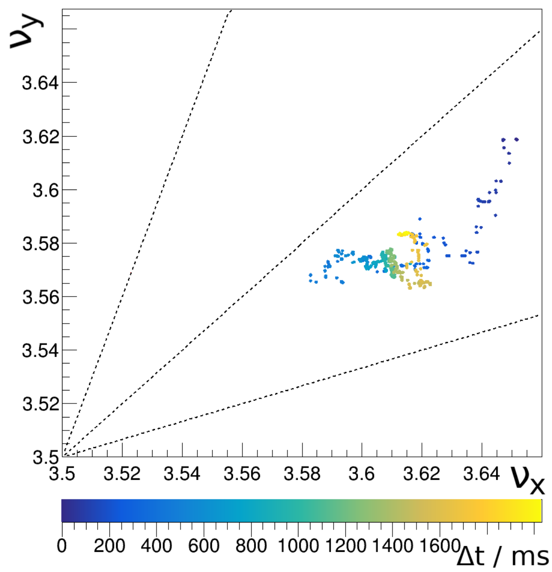

Figure 2: Betatron tune measurement during accelerating ramp from 294 MeV/c to 1950 MeV/c without application of tune jumps, the evolution is color-coded, the dashed lines represent resonances.

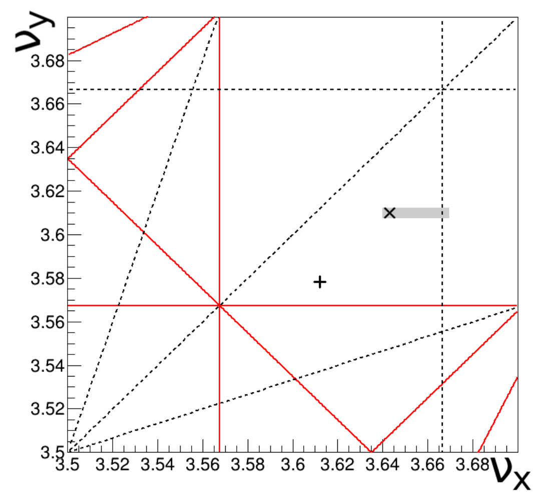

Figure 3: Resonances and measured betatron tune at 1950 MeV/c. The dashed lines represent betatron tune resonances, while the solid lines represent higher order depolarising resonances. + denotes the tune prior to rebunching, x is the tune after rebunching. The grey area represents the bandwidth of the extraction noise.

betatron tune measurement system [4]. The system is set up such that a spectrum is measured every 4096 turns, which corresponds to a tune measurement every ~ 2.8 ms at flat top momentum. By recursively adjusting the ramps and measuring the tunes, the result depicted in Fig. 2 is achieved.

PREPARATION FOR EXTRACTION

Once the ramp has been set up, the beam is prepared for extraction. At the end of the ramp, the accelerating radio frequency RF is switched off, and the transition energy which has been shifted towards higher values in the previous step, is lowered below the particles' energy. In parallel, the dispersion in the straight sections is set to zero. Both are achieved by tweaking the inner and outer unit cell families separately. Then the betatron tune is shifted towards the horizontal resonance, which is used for extraction. Subsequently the beam is re-bunched by switching on the RF.

For this beam time, a momentum of 1950 MeV/c is chosen as the flat-top momentum, as it allows for the necessary adjustments to be made without operating COSY at either a betatron tune resonance or a depolarising resonance, as illustrated in Fig. 3. This momentum corresponds to a Lorentz factor of $\gamma = 2.31$ which is close to the transition energy of $\gamma_{tr} = 2.11$. In order to achieve successful rebunching at $\gamma \approx \gamma_{tr}$, it is necessary to ensure that the frequency of the RF precisely matches the frequency of the coasting beam. This is achieved by carrying out Schottky measurements of the beam with and without RF. To extract the beam to the extraction beam line the radio-frequency knockout method is employed. Details regarding this method, which has been established at COSY some month in advance to the topical beam time can be found in [5]: To extract the beam it is transversely excited. The selected betatron tune for extraction, along with an indication of the width and position of the excitation noise in tune space, is depicted in Fig. 3.

MAINTAINING THE POLARISATION DURING ACCELERATION

During the acceleration several resonances, causing depolarisation, have to be crossed. These occur when the product of the Lorentz factor γ and the gyromagnetic anomaly G meets one of the following resonance conditions:

$$\gamma G = \text{integer}$$

or

$$\gamma G = \text{integer} \cdot P \pm \nu_y,$$

with the superperiodicity P of the accelerator [3]. The former resonances are referred to as imperfection resonances, the latter are referred to as intrinsic resonances. Assuming that the two-fold superperiodicity can not be maintained during the ramp, COSY has a superperiodicity of $P = 1$. Thus three imperfection resonances and four intrinsic resonances must be crossed. To cross the imperfection resonances, the orbit is distorted at the corresponding energies resulting in an adiabatic spin flip [6]. In order to cross the intrinsic resonances, the tune jump system of COSY [7] is employed. As soon as the resonance is reached, a fast quadrupole is used to detune COSY and hence cross the resonance within the rise time of 10 μs. As the exact time to trigger this jump is tune-dependent, this time and the amplitude of the tune jump are adjusted using the fast betatron measurement system. Figure 4 illustrates the tune measurement, along with the intrinsic resonances that are crossed. As the betatron tune is measured during acceleration, we can allow for minor tune changes during the acceleration ramp and are still able to trigger the jump at the optimal time.

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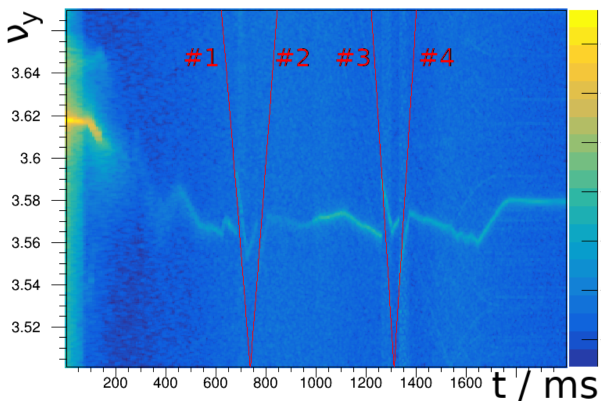

Figure 4: Measured vertical tune during acceleration including tune jumps to overcome intrinsic resonances (red lines, #1: $\gamma G = 6 - \nu_y$, #2: $\gamma G = 1 + \nu_y$, #3: $\gamma G = 7 - \nu_y$, #4: $\gamma G = 0 + \nu_y$).

MEASUREMENT OF THE ASYMMETRY

To demonstrate the successful acceleration of polarised beams the polarimeter of the JEDI collaboration (JePo) [8] is employed. The JePo is located within COSY as illustrated in Fig. 1. Beams with three distinct polarisation states are accelerated: One state with positive polarisation, one state with negative polarisation and one state where the beam remains unpolarised. These beams are injected and accelerated in COSY in subsequent cycles. In each of these cycles a target is then moved vertically into the COSY beam and the number of particles scattered to the right N_r and left N_l is recorded. Subsequently, an asymmetry A is calculated:

$$A = \frac{N_r - N_l}{N_r + N_l}.$$

The resulting asymmetries are shown in Fig. 5. As expected for vertically polarised beams the three states show clearly separated asymmetries, with the unpolarised state in between the two polarised states. Hence we conclude

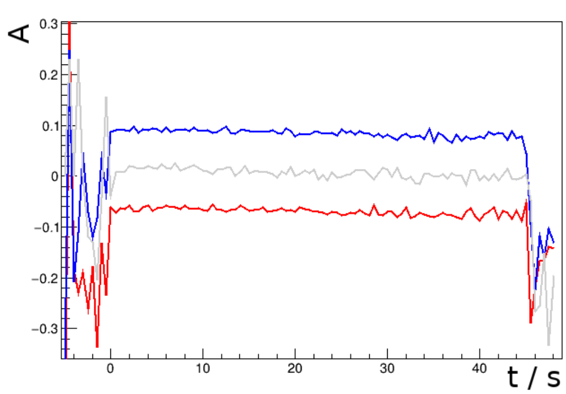

Figure 5: Measured asymmetry A of different polarisation states (top blue line, bottom red line) and an unpolarised beam (central grey line). The measurement is conducted between $t = 0$ s and $t = 45$ s.

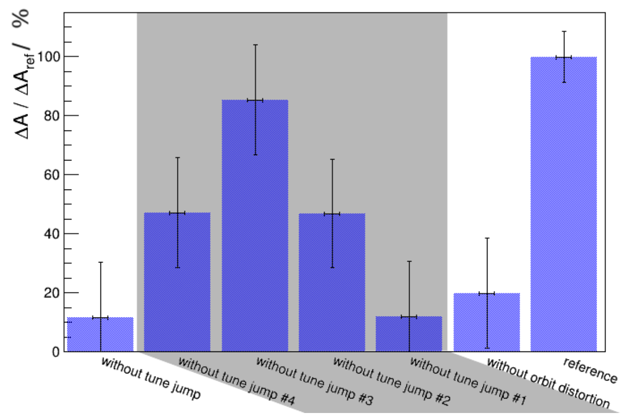

Figure 6: The influence of different steps during preparation of the beam as measured by the difference in asymmetry of the positively polarised beam to the negatively polarised beam, normalised to the difference in asymmetry of the beam with full preparation. For the descripition of individual jumps see caption of Fig. 4.

that the polarisation of the beam is successfully maintained during acceleration.

To test the influences of the different measures to overcome the depolarising resonances, the asymmetry measurement is repeated while omitting single measures and recording the change in asymmetry for both polarisation states. The difference between positive and negative polarisation is calculated and normalised to the reference case, where all jumps and spin flips are applied. The results are presented in Fig. 6. It is observed that omitting either the orbit distortions for the spin flips or all tune jumps results in a nearly complete loss of the polarization. Especially the first jump to overcome the $\gamma G = 6 - \nu_y$ resonance is crucial in order not to lose the polarisation. When omitting any of the other tune jumps some polarisation can be preserved.

CONCLUSION

The ability to accelerate polarised protons at COSY could be maintained until the conclusion of the operation. Novel developments at COSY, like the continuous betatron tune measurement, served as valuable tools to prepare the polarised beam.

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