BEAM STABILIZATION BY FEEDBACK CONTROL OF THE ACCELERATING PARAMETERS IN A CYCLOTRON

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If a cyclotron is operated as an injection machine for a second accelerator i. e. a synchrotron, the beam has to be matched precisely with respect to emittance, momentum and dispersion. A well-defined beam must be provided over long periods of time. Long term investigations of the important accelerating parameters of the cyclotron JULIC, which is presently used as pre-accelerator for the cooler synchrotron COSY-Jülich, showed that far beyond stability of main coil current, accelerating voltage and frequency the conditions of the environment like room temperature, characteristics of cooling systems and others have to be taken into account. - A feedback control of the main accelerating parameters was implemented, which significantly improves the long term stability of the beam.

1 Introduction

The cyclotron JULIC was upgraded in 1990/91 in order to serve as injector[1] for the Cooler Synchrotron COSY-Jülich[2,3], which is in operation since 1993. An extensively modified RF system provides more power and better stability of frequency/phase and amplitude. New power supplies for the main coils as well as for the additional trim coils should provide the stability for the magnetic field. The cyclotron up to now operated as injection machine for more than 20 000h. Even if the very close figures for the stability of the RF parameters as well as for the currents generating the magnetic field meet the specifications, it appeared from experience that additional measures are necessary to provide time invariant external beams necessary for the stripping injection into the synchrotron.

2 Definition of Stability Figures

The external beam of the cyclotron JULIC is characterized by multi-turn extraction. The total number of turns n is about 400 and the phase width of the beam close to 15°. A more detailed analysis shows, that in optimized case more than 70% of the external beam is extracted from 2 turns and that extraction takes places from not more than 4 turns. It is well known that the characteristics of the beams extracted from a machine with multi-turn but close to single-turn extraction are especially sensitive to parameter stability. At JULIC the axial oscillation number ν_z at extraction radius varies in the range 0.4...0.47. Due to ν_z close to 0.5 the axial oscillation can cause a situation, that particles enter the extraction system with a significantly different angular distribution, which can result in a „splitted" external beam (see Fig. 3). The influence of parameter stability on emittance and momentum spread of the external beam was experimentally investigated before modification. Inspite of large errors due to the old situation when RF parameter stability was bad, the results imposed a demand for $\Delta f/f < 2\cdot 10^{-6}$ and $\Delta u/u < 1\cdot 10^{-4}$ to keep changes of the horizontal emittance $\Delta\varepsilon_x/\varepsilon_x < 5\%$ and of momentum spread $\Delta p/p < 2\%$. A second definition for the required stability of amplitude u_{RF}, frequency f_{RF} and magnetic field B can be deduced from the influence on the total turn number n. The relations are given by the equations 1, 2, 3 (with h = harmonic number, Δn = variation in turn number):

$$\Delta n = n \cdot \frac{\Delta u_{RF}}{u_{RF}} \tag{1}$$

$$\Delta n = 2\pi \cdot h^3 \cdot n^3 \cdot \left(\frac{\Delta f_{RF}}{f_{RF}}\right) \tag{2}$$

$$\Delta n = 2\pi \cdot h^3 \cdot n^3 \cdot \left(\frac{\Delta B}{B}\right) \tag{3}$$

Phase stability of the external beam for injection into COSY should be better than $\Delta\varphi = \pm 1°$. So the relation is given in equation 4

$$\Delta\varphi = 2\pi \cdot h \cdot n \cdot \left(\frac{\Delta B}{B} + \frac{\Delta f_{RF}}{f_{RF}}\right) \tag{4}$$

When fixing the specs for the upgrading program we demanded, that the turn pattern influenced by the sum of instabilities should vary not more than about 0.1 ... 0.2 turn. This defines the stability requirements as given below (total turn number $n \approx 450$, harmonic number h=3)

$$\frac{\Delta B}{B} \le 2 \cdot 10^{-6} \quad \Rightarrow \quad \Delta n \approx 0.05$$

$$\frac{\Delta f_{RF}}{f_{RF}} \le 2 \cdot 10^{-6} \quad \Rightarrow \quad \Delta n \approx 0.05$$

$$\frac{\Delta u_{RF}}{u_{RF}} \le 1 \cdot 10^{-4} \quad \Rightarrow \quad \Delta n \approx 0.05$$

$$\Delta\varphi \le \pm 1° \quad \Rightarrow \quad \left(\frac{\Delta B}{B} + \frac{\Delta f_{RF}}{f_{RF}}\right) \le 2 \cdot 10^{-6}$$

3 Experimental Verification of Stability

Since 1993 the cyclotron is operated to provide H_2^+-beam of about 76 MeV and 10 µA for the stripping injection into COSY. Operating the cyclotron over a long period of time at a fixed energy with the same beam gives the chance, to investigate extensively the influence of accelerating-parameter stability on the beam. In the external beam line we tested

- beam intensity as a function of frequency (equivalent: magnetic field) and amplitude
- distribution of beam intensity in the horizontal and vertical plane with beam profile monitors (wire grids)

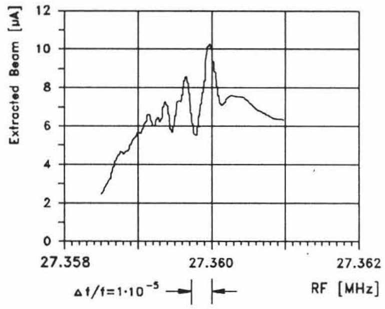

Figure 1: External beam current as a function of frequency f_{RF}

The dependence of $I_{Beam} = f(f_{RF})$ is shown in Figure 1. $I_{Beam} = f(B)$ was also tested; as expected it is fully equivalent to the variation of frequency. Frequency was altered in increments of 25 Hz, which corresponds to $\Delta f/f < 1 \cdot 10^{-6}$. As can be seen from the plot, one increment can change the intensity of the external beam by up to 15%.

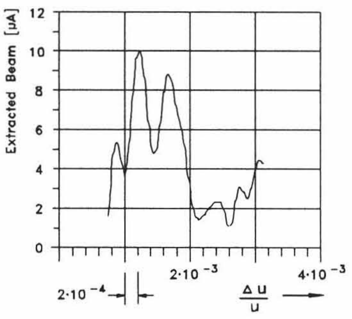

Figure 2: External beam current as a function of amplitude u_{RF}

The dependence of beam current from amplitude is displayed in Fig. 2. A change of $\Delta u/u < 1 \cdot 10^{-4}$ can reduce beam intensity by about 30%. The new RF system provides a frequency stability that far exceeds the requirements (phase stability of RF: $\Delta\alpha < \pm 0.3°$). Amplitude stability referred to the point, where it is measured in the system, is better than $\Delta u/u < 1 \cdot 10^{-4}$ (short and long term), but the beam integrates over the radial shape of the voltage distribution, which depends on additional parameters, i.e. the combined function of frequency tuning elements at the accelerating system and the thermal elongation of the dees. There are indications, that the resulting amplitude stability does not fully meet the specified value under all conditions. We have no final solution for this problem so far and try to minimize the effect by keeping the RF system in continuous operation in order to preserve a steady state situation.

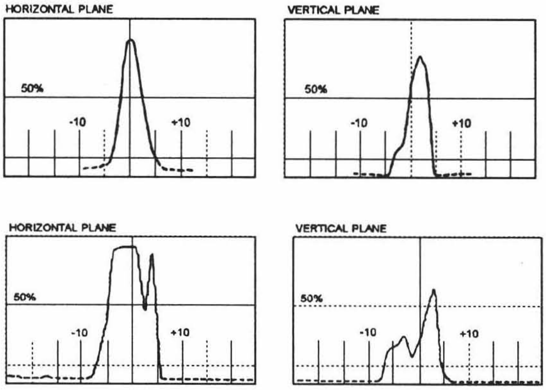

Figure 3: Beam profile of the external beam in horizontal and vertical plane, horizontal scale in mm
upper diagrams: all parameters optimized (see text)
lower diagrams: frequency detuned by $\Delta f/f \approx 1 \cdot 10^{-5}$

The beam profile at the exit of the cyclotron in horizontal and vertical plane detected by wire grids is shown in Fig. 3 as a function of the main accelerating parameters. It displays in the upper part an optimized situation: All sensitive parameters are tuned for best possible profile i.e. frequency and amplitude. It appears that in the vertical plane an ideal symmetric distribution can not be achieved. The lower diagrams display the situation when the frequency is detuned by $\Delta f/f \approx 1 \cdot 10^{-5}$. The beam profile splits in both planes. Former measurements showed that also the momentum distribution in the external beam is severely influenced by changes of magnetic field, frequency and amplitude.

Additional parameters like buncher phase, the ion-optical tuning of the source beam line and the characteristics of the external ion source severely influence the profile of the external beam. So it is advisable to keep this settings as stable as possible too.

4 Stabilization of the Magnetic Field

In order to achieve a stability of the magnetic field close to $\Delta B/B \approx 1...2 \cdot 10^{-6}$ it is not sufficient to provide currents for main and trim coils with an effective stability of the same order. A number of additional (even more important) influences have to be taken into account, some of which were investigated in detail. The magnetic field of JULIC was monitored by a NMR-probe mounted in one valley sector of the magnet; the main coil current was simultaneously measured to see the correlation. The permanent operation of the cyclotron as injector for COSY with invariant settings allowed data taking over long periods of time. Fig. 4 displays the results of a run of 500 hours.

The current of the main coil power supply was tested to be stable within $\Delta I/I \leq 2\cdot10^{-6}$ over 8 hours but it drops over long times due to an aging of the internal ZERANIN® shunt used for regulation. (This effect is observed over 3 years now. It still continues with slightly reducing rates). Obviously the observed field drift (Fig. 4) is not correlated with current. An explanation for the periodical changes can be deduced from the scale displaying the days of the week at the top of the graph. The central heating system for the buildings in the Forschungszentrum Jülich reduces the temperature over the weekends. Inspite of separate regulation, the temperature in the cyclotron vault dropped during the test run by 1...1.5 °C. Due to this change the magnetic field immediately starts to raise with a rate of $\Delta B/B \approx 0.5\cdot10^{-6}$/h. Without further change in temperature the field is drifting over two days due to the thermal capacity of the magnet (800 tons of iron). At the end of the period the field tends to return toward the previous situation.

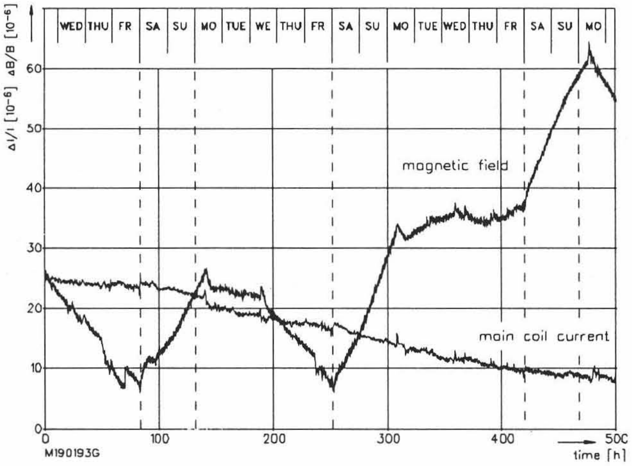

Figure 4: Long term plot of magnetic field and main coil current

In order to correlate changes of temperature with field drift, temperature probes are installed on the surface and in bore-holes of the iron. It is complicated to develop a model because of the complex structure of the magnet and the fact, that the field reacts very fast (in the order of minutes) on extremely small changes in temperature of $\Delta\vartheta < 0.1$°C.

Since about two years the magnetic field is stabilized by a PC-based system. A separate winding of 6 turns on the pole is driven by a small power supply to cover a drift range of $\Delta B/B \approx \pm2\cdot10^{-4}$. For improved accuracy 10 readings from the NMR-probe are averaged first and then compared with the preset value by a window comparator. For error correction the small power supply is programmed to center the field level precisely in the window. - The system is able to stabilize the field referred to the point of detection reliably within $\Delta B/B \leq \pm1\cdot10^{-6}$ over any period of time.

The described scheme is preferred instead of regulating the main coil power supply to ensure, that in case of failure no excessive change in magnetic field can occur, which would take a long time to recover. A computer based system can easily skip unwanted field regulations in case that magnetic elements, which are additionally relevant for the magnetic field, fail or are intentionally tuned or switched. This are in first order trim coils, compensated screening channels (part of the extraction system) and steering magnets in the fringe field of the magnet

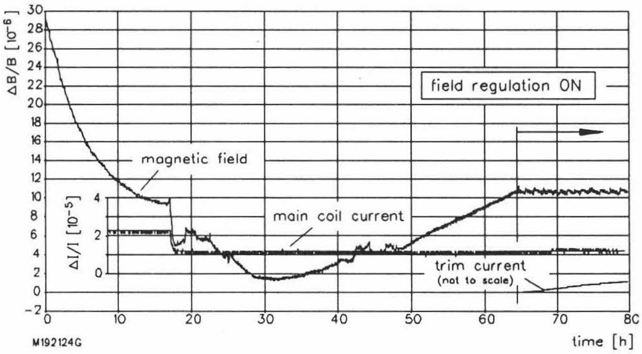

Figure 5: Effect of field regulation

The plots in Fig. 5 display a typical situation when the magnetic field is switched on for operation at the maximum proton (or with reverse polarity for H^-) energy of 45 MeV. Inspite of using cycling procedures the initial field drift as displayed in the plot lasts about 30 hours. Then temperature effects dominate the drift. Field regulation was switched on after 64 hours and keeps the level within a window here adjusted for $\Delta B/B = \pm2\cdot10^{-6}$. Generally field regulation is switched on after 3 to 5 hours from start and helps to abbreviate the initial drift, but it takes some more hours until the field shape and hence the average field is sufficiently stable for the accelerator operation with beam.

5 Beam Phase Stabilization

The NMR-based stabilization of the magnetic field operates reliably since July 1993. It proves to be an important precaution to leave the cyclotron unattended over periods of several days producing stable beams for the injection into COSY. Long term monitoring showed, that inspite of stabilization small variations of the extracted beam could not be excluded. Obviously it is not sufficient, to stabilize the field with respect to the single test point where the NMR detects the field level. Long term drift effects and small changes of iron temperature influence the shape and hence the average value of the magnetic guiding field.

Since modification of the cyclotron a new non beam disturbing detection system[4] is available to monitor continuously phase and intensity of the internal beam at 12 locations. Based on principles described in ref.[5] the layout of the new system is widely defined by the demands of COSY. Stripping injection requires a pulse structure of the cyclotron beam. A pulsing system, installed in the low energy beam line between external ion sources and cyclotron, provides beams from continuous mode down to pulses of 2...1µs. (Pulsed beams from 10ms to 2µs are used for accelerator diagnostics only.) An often used operating mode of COSY for experiments and for machine development is characterized by a pulse width of 10ms and a repetition rate of 10s. - The phase probe unit is able to take full information (phase and amplitude) in 12 parallel channels from beam pulses down to 5ms and currents in the range of 50µA down to 20nA with a phase accuracy of 1°. The original configuration was modified in one respect: One internal phase probe is replaced by a capacitive probe in the transfer beamline to COSY. This allows detection of the external beam current as well and (referred to the internal currents) the continuous monitoring not only of extraction efficiency but the full transmission of the cyclotron.

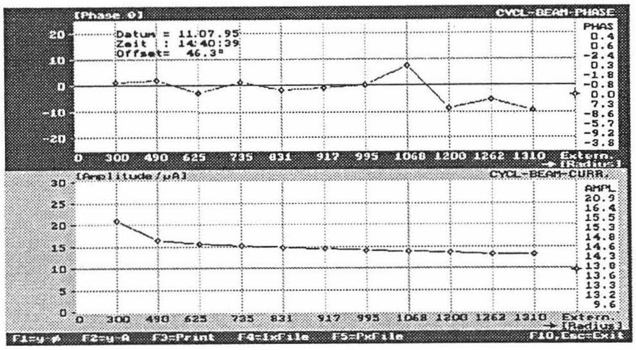
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Figure 6: Screen capture of the phase probe monitor

The upper trace in Fig. 6 displays the phase, the lower one the intensity of the internal beam over the valley radius from 300 to 1310 mm. Additionally the signals from the external probe are displayed and marked with EXTERN. Computed values for phase and current are numerically displayed on the right hand side of the screen for a more precise information .

Especially the phase at extraction radius is a very sensitive indicator for the integral influence of magnetic field and the frequency of the accelerating voltage. As frequency instabilities can be neglected, phase deviations directly indicate changes in the average magnetic field. Deviations in phase at extraction radius from the preset value are used to calculate changes in the level of the magnetic field required for correction. This new established value is referred to the point where the NMR probe detects the field. (1° phase shift at extraction radius requires a change in field level of 15mT). The field control system then adjusts the current in the auxiliary main coil winding to achieve the required field again. - Extensive validity checking had to be added to prevent the system from malfunction in case a true phase reading is not possible (no beam, beam chopped in µs-pulses etc.). In such cases the field is stabilized according to the last valid reading.

When cyclotron parameters, elements of the ion source beamline and external injection system, or steering magnets in the fringe field of the magnet, have to be tuned, phase and field controls must be switched off to avoid interaction. The idea behind the systems realized so far is, to preserve the experimentally optimized situation over a reasonable period of time (minimum 1 week according to the beam time schedule of COSY). Experience reveals, that stabilization of field and phase contributes remarkably to the long term stability of the external beam.

6 Additional Diagnostic Tools

The pulse structure of the beam with a typical duty cycle of 1:1000 (net beam time of less than 90s per day) allows the partial use of the beam for other purposes, i.e. radioisotope production. An irradiation unit is installed at the exit of the cyclotron to expose a target periodically to the beam at times, when it is not used for injection into COSY. Mechanical positioning was preferred, which has the advantage of simplicity and garantees, that the characteristics of the beam are not influenced.

Beyond irradiation of targets this unit is also used to push a viewer into the beam.. Synchronized with beam pulsing, the system allows quasi-continuous monitoring of the beam profile with much higher information than grids can provide. The intention is, to evaluate with the aid of image-analyzing software possible correlation between beam profile and cyclotron parameters i.e. the amplitude of the effective acceleration voltage. - The system was just taken into operation but results can not be reported so far.

References

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