H$^-$ - OPERATION OF THE CYCLOTRON JULIC AS INJECTOR FOR THE COOLER SYNCHROTRON COSY-JÜLICH

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Since more than two years the cyclotron JULIC is operated as H$^-$-Injector for COSY. Unpolarized beams from two external sources as well as polarized beams from a colliding beams type source can be provided by the cyclotron at a maximum energy of 45 MeV. For the requirements of COSY it becomes particularly important to deliver polarized beams with the highest possible intensity. Attempts to increase the intensity from the polarized ion source are described. The transmission through the cyclotron is improved by means of an additional double gap buncher in the source beam-line which can be driven by a parabolic waveform voltage. Other measures include vertical centering of the beam by shifting the magnetic median plane and a modification of the extraction system with a new septum deflector which is adapted to higher positive voltages at the electrode.

1 Introduction

The cyclotron JULIC serves as injector for the Cooler Synchrotron COSY-Jülich which is in operation since 1993 [1], [2], [3]. In the first 3 years only H_2^+ - beams were used for the stripping injection into the ring. But for the planned acceleration of polarized particles in COSY an ion source of the colliding beam type was realized providing negative H$^-$ and D$^-$ ions. Additionally unpolarized H$^-$ sources were ordered from the industry and connected to the external injection system of the cyclotron.

In previous short test beam times it could be confirmed, that the acceleration of H$^-$-beams in the cyclotron is possible without significant modifications. So at the beginning of 1996 the operation of the COSY-injector (and consequently the injection into the COSY-ring) were completely changed to negative ions. In case of H$^-$-ions the cyclotron is operated at 45 MeV which is the maximum energy for particles with Q/A=1. The beam transmission through the cyclotron was originally optimized for ions with Q/A=1/2 (i.e. d, α, H_2^+) at the high end of the energy tuning range taking into account saturation effects in the magnet. A typical transmission of 16...17% could be achieved for H_2^+-ions previously used for the injection into the ring. For H$^-$-ions the transmission figure in the present situation does not exceed 6... 7% mainly due to a not well adapted geometry of the septum deflector and hence a bad transmission efficiency for these particles. Nevertheless unpolarized H$^-$ beam intensities of 10 μA can be extracted from the cyclotron during routine operation, but the external beam current of polarized protons of 0.5 ... 0.7 μA achieved so far has to be increased.

A program is on the way to improve the beam current from the polarized source. Simultaneously, we work for a better transmission through the cyclotron by improving beam bunching and injection efficiency but also by optimizing the extraction system within the existing tight geometrical boundaries. - The improvement program is constrained by the fact, that the cyclotron as injector for COSY has to be in continuous operation for about 7500 h/year.

2 Ion sources

Two independent sources for unpolarized H$^-$ beams have been installed to minimize losses of beamtime caused by the unavoidable exchange of the source filaments after about three weeks of operation. Both sources are of the multi cusp type and commercially available. One has been delivered by IBA company in Louvain-La-Neuve (Belgium), the other one by AEA company in Culham (England). The beam quality from both sources is similar at the requested low beam energy of 4.5 keV. H$^-$ currents for both sources range between 200 and 350 μA. The specified beam current at the exit of the cyclotron of 10 μA can be achieved with about 150 μA at the injection. Experience showed that with the existing injection system the extracted current cannot be increased beyond this figure. Any increase in current at injection causes a decrease in the transmission efficiency of the cyclotron. This dependence could not be investigated in detail so far, but it seems that space charge effects mainly in the hyperboloid inflector have a dominant influence [4].

The polarized ion source for COSY (Fig. 1) has been built and set into operation by a collaboration of groups from the universities of Bonn, Erlangen and Köln. The source is designed to deliver polarized H$^-$ or D$^-$ ions within the acceptance of the cyclotron (0.5π·mm·mrad, $\beta \cdot \gamma$-normalized) during the 10...20 ms injection period of COSY. Since the source has to deliver beams with high polarization and brilliance, a colliding beams type source (CBS) was chosen. Polarized negative ions are produced in a charge exchange reaction between a ground state nuclear polarized hydrogen or deuterium beam and a fast neutral cesium beam. As the H$^-$ ionizing process is very selective with respect to atoms a high degree of polarization can be expected. The emittance and therefore the brilliance of the polarized H$^-$ beam can be adjusted but the interdependence between emittance and degree of polarization has to be observed. - A more detailed description of the functional scheme of the CBS source is given in [5]

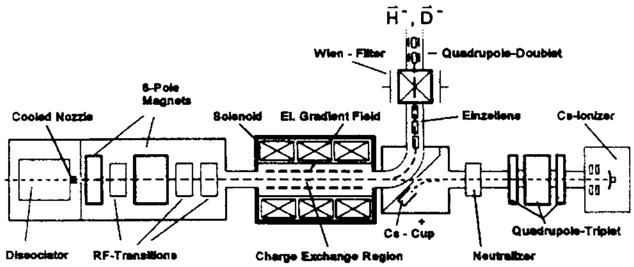

Fig. 1: The COSY Colliding Beam Polarized Source (CBS)

The H⁻ beam intensity is approximately proportional to the densities of the atomic beams. To provide sufficient beam current for the injection into COSY continuously over several weeks the source has to be operated at high power level with good reliability. Extended operational tests of the source showed limitations in the design of cesium loaded components. Some parts of the source had a high probability to failure with increased cesium intensities and required modification [6]. The first component to be replaced was the cesium ionizer prototype. The essential fourth degree of freedom for adjusting the tungsten cathode in the electrode and a new positioning system were integrated in the new construction. The former very critical resistive heating of the ionizer was replaced by a new electron beam heating system which proved reliable and effective [7].

The new ionizer went in operation in September 1997 and shows excellent results. A charged cesium beam of 10 mA could be achieved without difficulty. This beam was transported by a quadrupole triplet with negligible losses and analyzed in the deflector chamber by current measurements and residual gas luminescence.

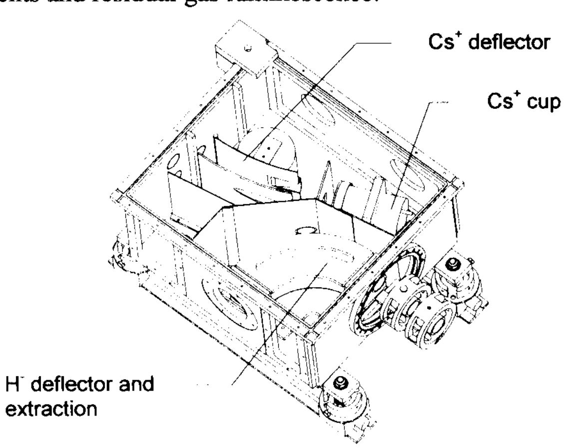

Fig. 2: Vacuum chamber for the Cs-deflector, Cs-cup and H⁻extraction with the 90°-deflector.

Additionally, the cesium deflector and beam dump were modified for high current operation. After testing several designs for the deflector high voltage and large aperture models were rejected in favor of a construction with minimized distances and the lowest possible voltage. High voltage operation showed at increased currents and long dc periods a nonlinear increase in the secondary electrons load of the components. Fig. 2 gives an impression of the new design. The cup was replaced in order to decrease the deflection angle and the deflection voltage. The deflector itself was equipped with double shielded isolators and minimum aperture. Water-cooled radiation shields for the cup chamber are in operation. The pumping speed in the cesium cup region was increased, necessary for short recovery times after a break in vacuum. The graphite cup must be conditioned with increasing cesium beam intensity.

The extraction elements of the ion source were modified to improve the extraction efficiency and the undisturbed transport of the ion beam

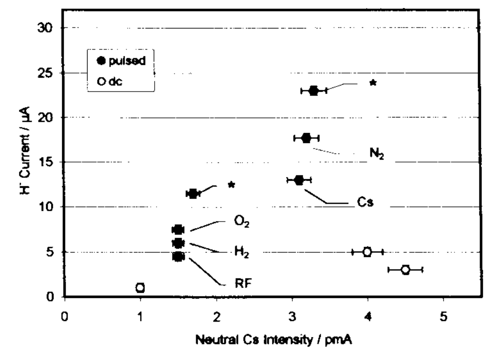

Fig. 3: Increasing beam intensity by pulsing (see text)

For the injection into COSY a beam pulse of 10 to 20 ms is required with a repetition rate ranging between 5 s and > 20 min. Therefore, it is expedient to provide pulsed beams by the injector cyclotron. The H⁻ beam intensity was increased by a consequent pulsing of the atomic Cs^0 and H^0 beams. The improvement of the intensities is shown in Fig. 3. In continuous operation of the source (open dots) a H⁻ output of 5 µA was reached. The filled dots marked with labels show the development of the pulsed beam. Several steps mark the development achieved by pulsed operation: pulsing the dissociator (RF), the pulsed injection of hydrogen (H_2) and oxygen (O_2), the higher intensity of the cesium beam (Cs) and the pulsed admixture of nitrogen (N_2). The timing (pulse width and sequence) is critical and had to be experimentally optimized. The asterisk (*) finally indicates the situation after optimization of the dissociator, the skimmer geometry and an integral tuning of the source.

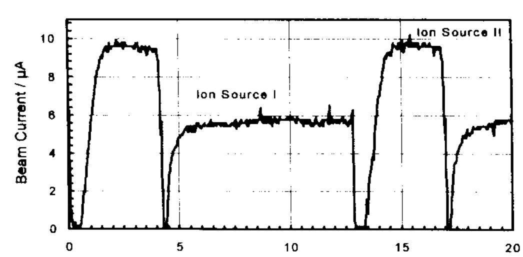

Fig. 4: Extracted current from the cyclotron as a function of time in case of source switching

All three ion sources are equipped with a full set of power supplies to provide parallel operation. For each of the sources a separate setup of the power supply settings for the source beam line elements was stored by the computer control system. This feature was used to switch from one source to an other and to change simultaneously the corresponding settings of source beam line components in less than 1 s. Fig. 4 displays the beam current at the exit of the cyclotron in case of switching between the two unpolarized sources. The time constant is dominated by magnetic elements in the source beamline but the beam is stable after less than 2 s.

The idea is to switch between unpolarized and polarized beam during normal COSY operation in order to open the possibility for further improvement and optimization of the polarized ion source. Development is still necessary to achieve the specified beam current of 30 μA at the exit of the source, to improve reliability, to extend the intervals between scheduled maintenance and to optimize the handling. - The next step will be the implementation of pulsed operation of the charged cesium beam section of the source.

3 Sawtooth buncher

The unbunched H^- beams from the ion sources have to be matched to the rf-phase acceptance of the cyclotron. At present time this is done with a double gap buncher operating with sinusoidal voltages. The $3\cdot\beta\cdot\lambda/2$ structure is mounted about 80 cm in front of the hyperbolic inflector in the centre of the cyclotron. Only the quasi-linear part of the sine voltage leads to the desired effect. It would be preferable to use a sawtooth-like effective bunching voltage instead which has a much longer linear region (up to 90% of the period). This can be achieved by applying a parabolic voltage to a $\beta\cdot\lambda$-structure with two gaps, so that each particle experiences the difference between the buncher voltages at a slightly shifted phase (Fig. 5).

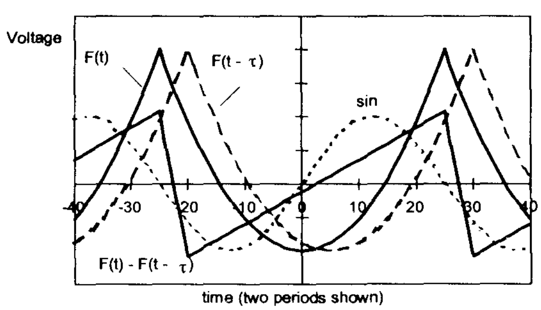

Fig. 5: A particle crossing two gaps with a parabolic

An additional buncher was designed and for testing mounted about 240 cm in front of the injection point [8]. Access to a preferable position closer to the center would in our case require a very time consuming dismounting of the external injection system. Fig. 6 gives an idea of the basic buncher configuration which is dominated by the attempt to keep the capacitance of the centre electrode to ground at a minimum (·5 pF). The distance d between the gaps is $\beta\cdot\lambda$. (d = 30 mm for E = 4.5 keV, f = 30MHz).

Grids (optimized with SUPERFISH/POISSON calculations) are necessary to homogenize the electric field in the gap regions for achieving a good transit time factor.

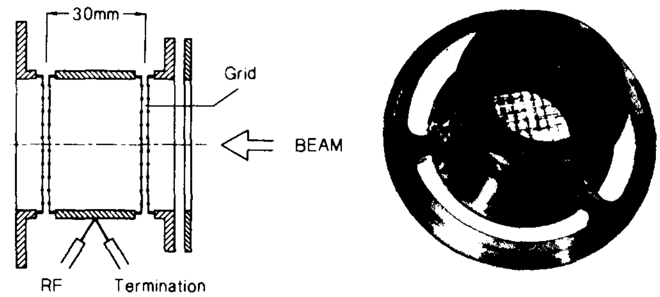

Fig. 6: Double gap buncher

The bunching voltage has to be phase locked to the rf-system of the cyclotron (Fig. 7). An arbitrary waveform generator (AWG) sends the parabolic signal to a broadband amplifier which drives the buncher structure. The generator is synchronized with the cyclotron-rf and triggered by selecting a suitable level of the fundamental, thus providing phase adjustment between the two systems.

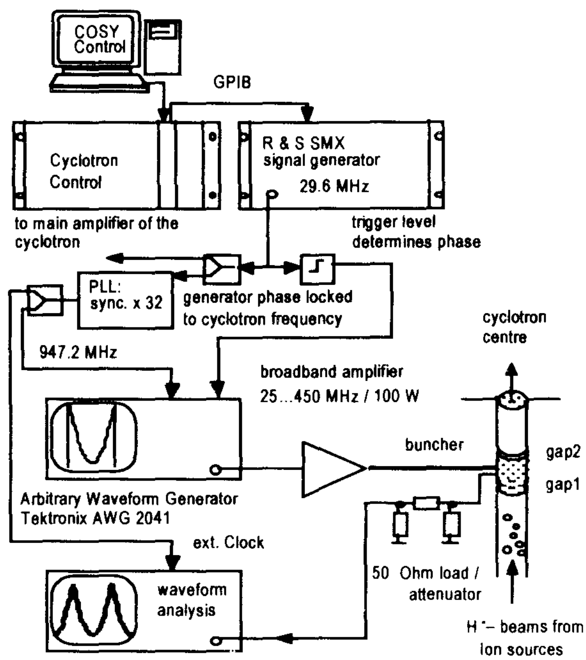

Fig. 7: Rf- layout of the non-sinusoidal buncher system.

The ideal parabolic waveform is distorted by the transfer functions of cables and amplifier, as well as the structure itself. If the final transfer function is known (measured with a network analyzer) then a predistorted signal can be programmed in the Tektronix AWG 2041 which is able to produce arbitrary waveforms with a clock rate of up to 1 GHz and an amplitude resolution of 8 bit.

A broadband amplifier (AR100W1000A, 100 W, 1 GHz) is used to drive the 50 Ω load. It turned out, that the power of this device is not sufficient to achieve the necessary voltage at the buncher. So it is paralleled with a 300 W, 30 MHz broadband type (ENI A-300) which provides the power for the fundamental harmonic content. Special filter/matching networks for input and output had to be developed.

The sawtooth bunching system was installed and electrically tested in May 1998 but results, i. e. the bunching efficiency can not be reported so far.

4 Septum deflector

The total transmission through the cyclotron is strongly dependent on the transmission of the septum deflector. While a figure of up to 70% is normal for H_2^+-ions, not more than 40...45% have been achieved in case of H^-. This is due to the fact, that the curvature of the element was optimized for particles with Q/A = ½ at the high end of the energy range, where saturation effects in the magnet have to be considered which is not the case for H^--beams of 45 MeV. A new septum deflector with a larger aperture should overcome this problem preserving the possibility to accelerate particles like D^- with high transmission.

Many iterative steps were necessary, to develop a new septum deflector which meets our requirements. It is a well known fact, that problems occur, when a complex configuration like a septum deflector is operated with a positive voltage at the electrode. Tests had to be done under realistic conditions, i. e. in magnetic field at a vacuum pressure of $2...3 \cdot 10^{-7}$ mbar. For this purpose we made use of a test magnet equipped with a vacuum chamber. Tests of different electrode materials revealed, that titanium was the best choice. Furthermore, the geometry of electrode and septum support had to be optimized carefully. The entrance edge of the septum is formed by 0.02 mm thick stripes of tantalum while the subsequent part (where the extracted beam is already separated from the internal beam) consists of a wedge of solid titanium. The electrode is cooled by a highly insulating liquid (Fluorinert® FC-77).

In the configuration for negative ions a field strength of about 120 kV/cm could be obtained allowing to increase the radial aperture from 4 to 5 mm. After installation in the cyclotron, first tests with H^- beam revealed an improvement of septum transmission from originally 45% to > 65%. Unfortunately the tantalum stripes were destroyed after a few days of operation. Probably excessive mechanical tension was the reason, that the stripes ruptured while they were heated up by the beam.

Presently a modified version of the septum deflector is under development and will be available at the end of the year. We plan to return to a septum formed by a tungsten wire fence (0.2 mm ∅, 0.3 mm dist.) which is an improved version of the septum installed in JULIC since 1975 [9].

5 Centering of the median plane

A beam diagnostic unit is installed at the exit of the cyclotron where a viewer screen can be moved into the beam periodically, when the beam is not needed for injection into COSY. Synchronized with beam pulsing, the system allows quasi-continuous monitoring of the beam profile with much higher information content than grids can provide. The beam image is captured by a frame grabber and analyzed in a PC. Fig. 8 shows a typical plot of the local beam distribution at the exit of the cyclotron. The left part is the viewer image while the right part shows a 3D luminance plot. It is obvious that there are two distinct spots in vertical direction indicating a coherent axial oscillation of the beam.

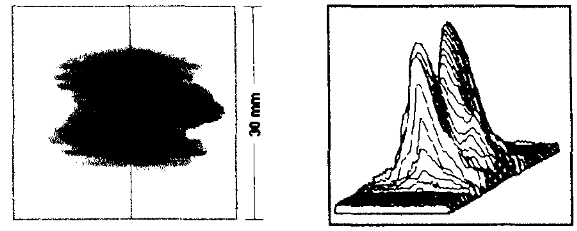

Fig. 8: Local beam distribution at the exit of the cyclotron

Multiturn extraction is typical for the cyclotron, but more than 80% of the intensity is extracted from two turns. With an oscillation number of ν_z = 0.4 at extraction radius the effect can be easily explained, but it still indicates an unfavorable situation for extraction efficiency as well as for the injection into the ring. Attempts were made to correct or at least reduce the coherent axial amplitude.

We know that there is an unsymmetry in the z-plane of the accelerating field in the center, mainly due to the shape of the interconnection of the dee tips. This requires a slight displacement of the hyperboloid inflector from the median plane. To correct this, the puller electrode was modified in several iterative steps. Instead of using a parallel configuration, the gap between inflector and puller was given a wedge form. There was a significant effect on the coherent axial oscillation but a total cancellation could not be achieved.

Additionally there are indications for a small mismatch between the median plane of the magnetic field in the center (up to a radius of ~ 10 cm) and the main field, but under the constraint of continuous operation there is no chance to modify the central region.

After the start of cyclotron operation with H^- ions a non symmetrical distribution of halo beam on (precisely aligned) vertical scrapers at the entrance of the extraction system was observed. The main coils at JULIC are located as usual above and below the median plane. So we took the opportunity to add a small amount of additional current to one coil and to reduce correspondingly the current in the other coil with separate power supplies to correct the shift of the magnetic median plane.

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