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Status and perspectives of the cyclotron JULIC as COSY injector

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Abstract Since January 1996, the cyclotron JULIC operates more than 7500 hours per year as injector of H^- or D^- beams for the cooler synchrotron COSY at the IKP of the Forschungszentrum Jülich. Usually about 8 μA of unpolarized or 1 μA of polarized H^- ions are delivered at 45 MeV for charge-exchange injection into COSY; higher beam intensities would be required especially for polarized beams to fill COSY to its space-charge limit. Also unpolarized D^- ions at 75 MeV were delivered with good results, although the septum-deflector insulators give problems at higher voltage. The demand for deuterons at COSY is growing, however, and the first polarized D^- beam is already scheduled for tests. This report sums up the characteristics of the cyclotron in its present mode of operation and describes the quest for higher beam intensities as well as for providing D^- beams reliably. The results are presented and discussed in terms of JULIC's future suitability as COSY injector.

Key words cyclotron JULIC • H^-/D^- operation • injector for the cooler synchrotron COSY • limitation of beam intensity • polarized beams • unpolarized beams

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Introduction

From its commissioning in 1968, the cyclotron JULIC has accumulated almost 190,000 working hours in different modes of operation. At first an internal and later, after the introduction of axial injection in 1986, external ion sources have been used to provide positive light and heavy ions at a kinetic energy of up to 45 MeV/nucleon. During 1990/91 JULIC was converted for its present use as COSY injector [3] and received a hardware upgrade, including an external microwave source (MWS) for H_2^+, a new remotely driven RF amplifier and Pyrotenax® field-correction (trim) coils, as well as the incorporation of its control system into that of COSY. In this configuration, H_2^+ beams of 10 μA at 76 MeV were routinely extracted from the cyclotron, out of ~60 μA just before axial injection, and also the control software was extended. H^- operation started in 1996 after the installation of the external multicusp source for H^-/D^- ions, because this allows to make use of nuclear-polarized H^- beams from a colliding-beam source (CBS). For polarized H^- (H^-_{pol}), the delivered beam current is an order of magnitude too low to fill COSY to its space-charge limit [2]. The first D^- beam at 75 MeV was extracted in October 2000 with ~8.4 μA delivered to COSY for a test run [1].

Operational characteristics

Operation of JULIC as COSY injector implies that the beam is accelerated in pulses lasting 10 to 20 ms at a maximum repetition rate of 0.5 Hz, while almost all cyclotron systems operate continuously. The beam pulses are generated by a chopper in the beamline (QBL) between the ion

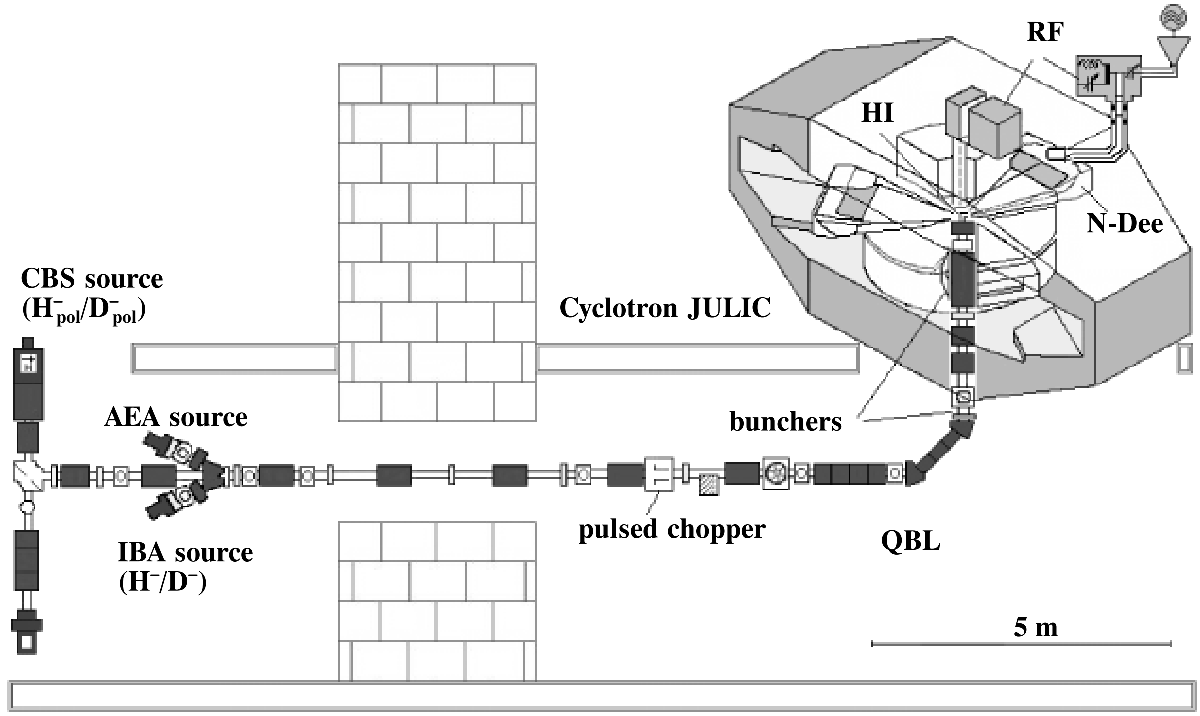

Fig. 1. Schematic layout of the cyclotron JULIC as injector of negative ions for the cooler synchrotron COSY, showing the arrangement of the ion sources, source beamline (QBL) and axial injection (compare the text).

sources and axial injection (see Fig. 1), but the CBS is pulsed as well. The chopper can also be operated with micro-pulsing to reduce the beam intensity in COSY, if required. H^- ions are injected at 4.5 keV and D^- ions at 7.6 keV. The unbunched beam from any of the ion sources is matched to the RF-phase acceptance of the cyclotron using a double-gap buncher with sinusoidal voltage, which can be combined with a special sawtooth buncher [2] located below the cyclotron. A hyperbolic inflector (HI) near the cyclotron centre is used for final injection via a puller onto a constant orbit. The isochronous magnetic field is produced with a pair of main coils around the poles and three sets of 9 trim-coil pairs located on the pole faces of the 3 spiral sectors (hills). The main excitation is regulated to stabilize the magnetic field to $\sim 10^{-6}$, compensating slow temperature drifts and thus allowing operation of JULIC without permanent attendance. The beam phase and current are measured real time by capacitive probes located in a hill.

Three Dees are used to provide the required acceleration. They are located between the hills and operate on the 3rd harmonic of the orbit frequency as $\lambda/4$ resonators in the frequency range from 20 to 30 MHz with a peak voltage of up to 40 kV. For the acceleration of $H^-(D^-)$ to 45(75) MeV, frequencies of ~29.6(27.3) MHz and amplitudes of ~20(33) kV are necessary. The Dees are connected in the central region to a capacitively terminated $3\lambda/4$ resonance line at the top of the magnet yoke, which is used to automatically keep the resonance frequency in tune. The RF power from the amplifier is inductively coupled into the north Dee at its outer edge. The beam is extracted by means of a septum deflector in the pole gap of a hill, and finally guided and focused by 3 subsequent magnetic channels through the fringe field of the magnet into the beamline to COSY. Only multi-turn extraction is possible and the septum deflector is a critical device at reversed polarity. During routine operation, the amplitude or frequency of the RF system sometimes must be slightly corrected to maintain optimum beam conditions for COSY. In this H^-/D^- mode, JULIC has already accumulated more than 53,000 hours of operation since early 1996. Table 1 lists beam properties achieved with the cyclotron as COSY injector. Due to operational demands there is usually very little time available for more detailed measurements or experiments.

The septum deflector presents one of the main difficulties to reliably operate JULIC over long periods with negative ions, especially at the higher reverse deflector voltage necessary for D^-. Not only a reduced septum transmission (from ~70% for H_2^+ to ~40%) was observed but also a varying and with time deteriorating electrical strength of the deflector insulators. Many modifications were tried and tested externally, leading to a new septum deflector with higher transmission of >60% [1, 2], but its durable electrical strength is still not satisfactory, even under good vacuum in the low 10^{-7} mbar range. Operation at 44 kV for D^- ions in January 2002 was only possible in pulsed mode, and meanwhile the deflector electrode had to be replaced again due to a complete breakdown of its insulators. To alleviate this problem, the gap between deflector and septum was reduced, allowing ~20% lower deflector voltages, and at the same time pulsing is being maintained. As additional measure to improve the reliability, even decreasing the D^- energy to 56 MeV is considered, thus further reducing the deflector voltage to less than the 28 kV previously used for H^-. Such a change would also reduce the acceptance of COSY, however, and requires operating the RF system at ~23.7 MHz.

Quest for higher beam intensities

The beam current delivered to COSY can be increased either by a better performance (intensity and emittance) of the ion sources or by a higher transmission (acceptance) of the different sections along the beam path. Almost all aspects affecting the beam intensity received attention over the past 6 years. The performance of the ion sources was improved by tedious development, especially for polarized beams [2], and now is approaching its limits. This also applies to the D^-_{pol} beams scheduled for tests with JULIC. As is shown in Table 1, the multicusp sources deliver beam currents in the range of 200 to 400 μA with a geometric emittance of more than 60π mm·mrad. In contrast, the CBS can provide up to 11 μA of H^-_{pol} (~10 μA of D^-_{pol} until now), but with a better emittance of ~25π mm·mrad (similar to H_2^+). Beam losses in the QBL are usually between 40% and 50%, compared to ~65% for H_2^+, indicating that its acceptance was improved. One therefore gets two (D^-) to three (H^-) times as much beam current from the multicusp sources before axial injection than for H_2^+, but only up to ~7 μA of H^-_{pol} (i.e. about 30 times less than for H^-). The beam currents extracted from the cyclotron are close to 10(15) μA for H^-(D^-) and in the order of 1 μA for H^-_{pol} (~80% polarization). Hence the cyclotron JULIC transmits about 5% (H^-) to 12% (D^-) of the beam from the multicusp sources, while ~16% is typical for H^-_{pol} beams (like for H_2^+).

Functionally, the beam path through the cyclotron can be subdivided into axial injection (up to the puller), internal acceleration region and extraction. The transmission values for injection in Table 1 include beam losses on the first 12 to 14 turns, however, because during operation the beam current is first measured in the cyclotron with the phase probes at 0.3 m radius. The transmission for injection is then typically between 20% (H^-) and 30% (D^-) when only the buncher with the sinusoidal voltage is used, also at the much lower beam currents for H^-_{pol} indicating that space-charge effects are not significant. These values are considerably smaller than the 34% for H_2^+ and reflected by reduced bunching factors. After introducing the additional sawtooth buncher and reducing the energy spread of the CBS from 35 eV to ~10 eV, the bunching factor for H^-_{pol} beams and thus their transmission for injection could be almost doubled, leading to a current of 1.2 μA extracted from JULIC. No gain in intensity was observed for beams from the multicusp sources using the sawtooth buncher.

The beam losses for injection may seem high, but in reality about half of these appear to occur after the puller on the first turns up to 0.3 m radius. Unfortunately, this can only be measured with special equipment and not very accurately. Knowing that the axially injected beam in JULIC picks up a strong vertical oscillation in the central region (see Fig. 2), which usually also shows up as two vertically separated peaks in the extracted beam [1, 2], numerous attempts were made to eliminate any possible cause for such an oscillation but so far without success. The issue became even more important due to the fact that only one of the two beam peaks after extraction is accepted by COSY.

Measures that have been tried to eliminate this effect or at least to reduce its impact on the transmission of JULIC included: (a) shifting the magnetic median plane for better vertical beam alignment in the machine; (b) increasing the aperture wherever possible; (c) computing and analysing the magnetic field in the central region to check the effect of existing asymmetries and shims; (d) replacing slightly magnetic parts in the central region; (e) improving the vertical beam alignment and focusing in the central region with tilted and wire-corrected pullers; (f) correcting the vertical beam alignment with 3 electrostatic

Table 1. Beam properties and transmissions measured for JULIC as H^- and D^- injector for COSY. The results for H_2^+ serve as reference.

Particle	H_2^+	H^-	H^-_{pol}	H^-	D^-	H^-_{pol}	D^-
Year	1995	1997	1999	2000	2000	2001	2002
Ion-source type	**MWS**	**IBA**	**CBS**	**AEA**	**IBA**	**CBS**	**IBA**
Beam current (μA)	180	~300	5.2	~400	225	11	210
Source emittance (π mm·mrad)	<30	>60	~25	>60	>60	~25	>60
Kinetic energy before injection (keV)	7.8	4.5	4.5	4.5	7.6	4.5	7.6
Beam current before injection (μA)	**62**	**180**	**2.2**	**215**	**130**	**7.4**	**125**
Transmission for injection (%)	34	23	59*	19	26	38*	29
Beam current at radius 0.3 m (μA)	21	41	1.3	40	34	2.8	36
Transmission inside JULIC (%)	71	63	75	55	59	71	72
Beam current at radius 1.31 m (μA)	15	26	0.97	22	20	2.0	26
Transmission for extraction (%)	67	38	37	45**	41**	60**	58**
Beam current after extraction (μA)	**10**	**10**	**0.36**	**10**	**8.2**	**1.2**	**15**
Kinetic energy after extraction (MeV)	76	45	45	45	75	45	75
Total transmission for JULIC (%)	**16**	**5.6**	**16**	**4.7**	**6.3**	**16**	**12**
Bunching factor	2.8	1.8	3.5*	1.8	2.0	4.9*	2.2

* Two double-gap bunchers (parabolic "sawtooth" and sinusoidal voltage).
** New septum deflector (0.2 mm wire fence, FC-77® cooling of deflector and with increased radial aperture).
MWS = microwave source; AEA, IBA = multicusp sources; CBS = colliding-beam source.

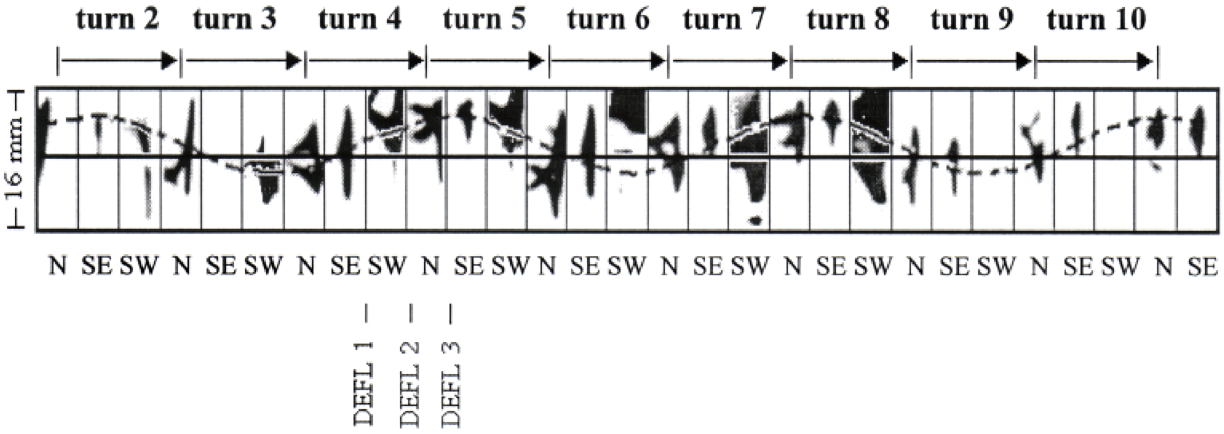

Fig. 2. The beam images measured at different occasions on the first turns of JULIC for 45 MeV H^- ions at extraction. The results indicate a vertical oscillation with an amplitude of close to 4 mm and an unusual pattern of beam-spot shapes. The position of the 3 electrostatic vertical deflectors installed later is also marked.

deflectors on the 4th and 5th turns. Some of these measures brought marginal improvements, but the oscillation stayed. The results indicate that it takes up about as much of the vertical aperture as the beam itself, and that it is phase dependent leading to the unusual beam-spot shapes shown in Fig. 2. This view is supported by the fact that the oscillation cannot be cured by static measures and implies that it is generated in the puller region where the beam bunches experience a very large phase shift (design: from –100° to +40°) when they cross the gap. Hence such effects could be caused by a phase dependent vertical steering action of the RF field due to the existing asymmetries in the central region, which will be further investigated.

Conclusions

Operation of the cyclotron JULIC as injector of H^- and D^- ions for COSY has been successful over the past years, especially in terms of beam availability. Only the septum deflector caused persistent problems, in particular for D^- operation, but recent precautions should improve its reliability. The RF system and other hardware of the cyclotron like its vacuum pumps and drive mechanisms, however, show increasing signs of age and need progressively more attention. Preparations for the first test with D^-_{pol} beams are well advanced, but otherwise the development of the ion sources has matured. With its present limitations by the vertical beam oscillation, JULIC delivers beam currents up to 10, 15 and 1.2 μA for H^-, D^- and H^-_{pol} ions, respectively, although in routine operation the values are typically ~25% lower. Even if the oscillation could be eliminated against all expectations, only an intensity gain by up to a factor ~2 seems possible, while beam currents in the order of 20 μA would be needed to fill COSY to its space-charge limit, which is an order of magnitude out of range for polarized ions with the present configuration of the injector.

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