ECR-SOURCES AND MULTIHARMONIC MODE OPERATION AT JULIC

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Summary

The demand for particle beams with A≥20 at low energies of 4-5 MeV/A for high spin nuclear spectroscopy matches with the energy range of 2.5-5 MeV/A of the JULIC cyclotron operating in the 9ω-mode. In this mode the cyclotron should accept ions with Q/A>1/5. Then the usable mass range of the ISIS project[1,2] (Injektion schwerer Ionen nach ECR-Stripping) can be extended to A>20. The small prototype ECR-source pre-ISIS 2* which was set into operation to study the performance of ECR plasmas delivers the required ions with significant intensities. For the normal 3ω-mode operation (22-45 MeV/A) this latter ion source provides beam currents larger than 300 μA especially for light ion beams up to ^{4}He. Heavier ions will be produced by the large ISIS ECR-source. First results concerning 9ω-mode operation with the internal source are presented.

Introduction

The cyclotron JULIC is almost entirely used for fundamental nuclear physics research work. It was originally designed for the acceleration of deuterons and α-particles from an internal ion source in the energy range of 22-45 MeV/A operating in the for this machine fundamental harmonic mode h=3. Additionally protons and $^3He^{++}$ can be accelerated in the same energy range. After completion of the project ISIS, which is presently under construction, a number of light heavy ions will be additionally available.

However, in the spectroscopy of discrete γ-rays emitted after nuclear reactions a large improvement of the experimental technology has been achieved during the last years. The use of multi-detector arrangements and anti-Compton spectrometers has been introduced. Presently a Compton suppression array for high resolution in beam spectroscopy (project OSIRIS[3]) is realized in cooperation with the Institut für Kernphysik of KFA. For compound reactions with heavy ions, which is the most effective method to reach very high spin states, energies of 4-5 MeV/A are favourable. This would well match with the energy range 2.5-5 MeV/A of the cyclotron if operated in harmonic mode h=9.

ECR sources at JULIC

Fig. 1 gives a schematic view of the ISIS arrangement. After extraction from an ECR ion source the beam passes a 180° bending system the first part of which is used for charge state selection. In the basement a sequence of solenoids transports the beam underneath the cyclotron where it is bent upward into the center of the machine and then inflected by a hyperbolic inflector. There will be an additional light ion source in the horizontal injection beam line. This allows the independent operation of the large ECR source for development or atomic physics work, when the cyclotron operates with light ions.

In order to accelerate heavy ions in the fundamental harmonic mode h=3 charge states of Q/A>1/3 are needed, which require a powerful ion source. Beside the design work for the superconducting ISIS ECR ion source two small single stage ECR sources pre-ISIS 1[4] and pre-ISIS 2[5] have been built by our ion source group since 1981. Presently an upgraded two stage version pre-ISIS 2*[6] is in operation. The intention was to have some flexible test device for getting experience with problems of ECR plasma sources rather than to set up a source for highly charged heavy ions.

Fig. 2 shows a schematic drawing of the two stage test source pre-ISIS 2* together with the axial and radial magnetic field distribution. The magnetic resonance field for the injector stage was achieved by adding another watercooled solenoid and an iron end plate to the original pre-ISIS 2 arrangement. The microwave power for the injector stage as well as for the hot plasma stage is delivered by one 5 GHz klystron. By means of microwave power splitting a defined part of the incident power is guided through a quartz window into the first stage. Total microwave power consumption for the production of carbon, nitrogen and oxigen ions is in the order of 300 W, in case of argon ions less than 600 W.

The ions produced in the first stage with mainly charge state 1 enter the second stage through a 8 mm diameter bore. No separate pumping is applied to the injector stage. The performance of the source was tested for a number of ions with special emphasis given to nitrogen. A remarkable intensity increase of the higher nitrogen charge states is observed with the first stage switched on. Simultaneously the neutral gas pressure in the main stage drops indicating, that mainly ions are injected. This results in a reduced probability for charge exchange with neutral gas atoms.

In Fig. 3 nitrogen spectra from the pre-ISIS 2* source are displayed with and without the injector stage

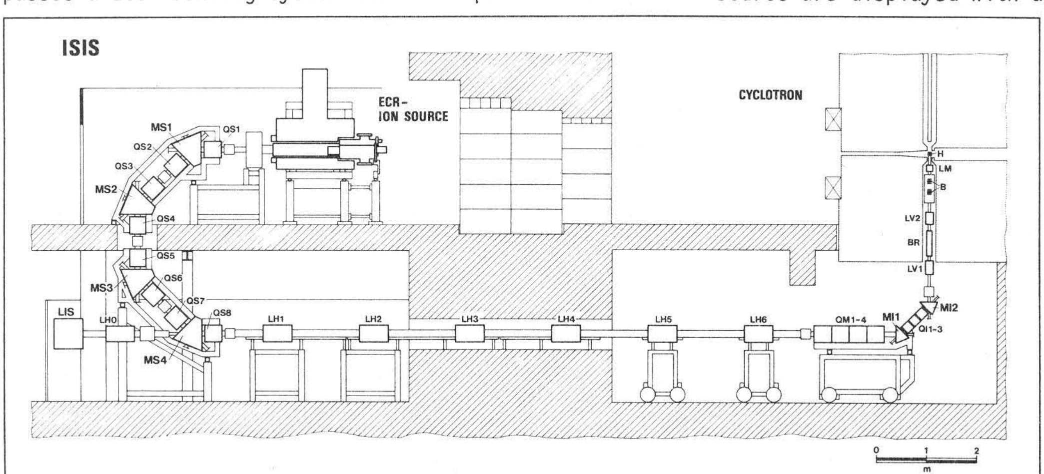

Figure 1:
Layout of ISIS at JULIC:

LIS	light ion source
QS,QM,QI	quadrupole lenses
MS, MI	dipole magnets
LH, LV	solenoid lenses
BR	beam rotator solenoid
LM	magnetic lens
B	bunching system
H	hyperbolic inflector

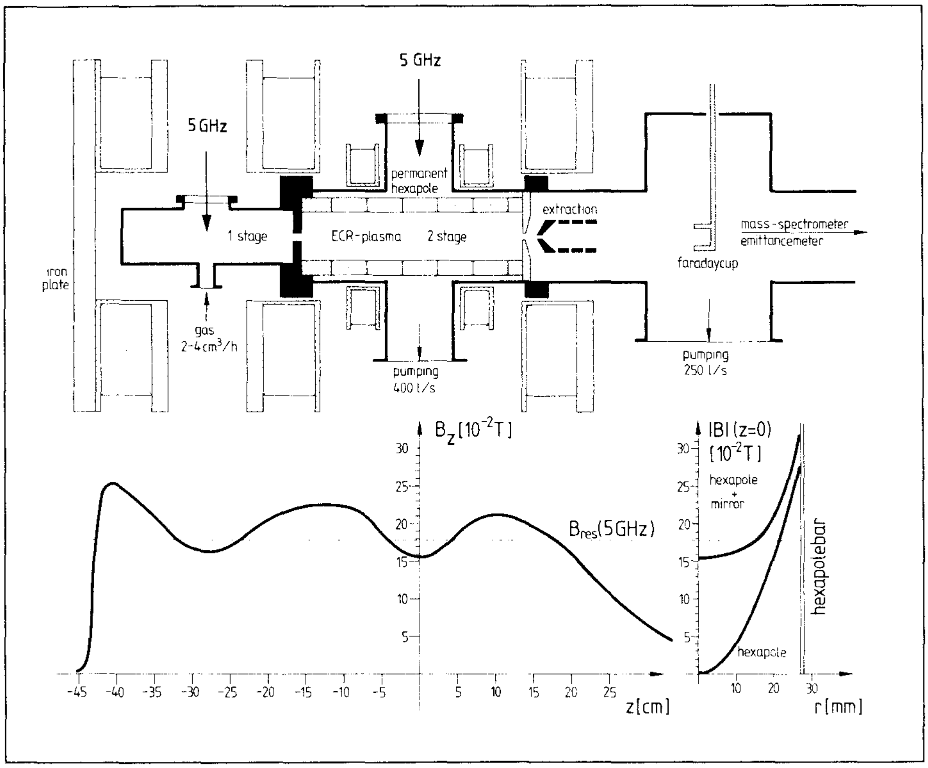

Figure 2: Schematic drawing of pre-ISIS 2* ECR source including the axial and radial magnetic field distribution.

electrons in the plasma. With both stages in operation the energy spread in the extracted beam was determined to be about $\Delta E/E \approx 5$ eV. Because of the sheeth potential between the confined plasma and the wall of the second stage vacuum chamber the total energy of the extracted ions is about 20 to 30 eV per charge state beyond the source potential defined by the power supply. Table 1 comprises the intensities of a number of light heavy ions obtained from pre-ISIS 2*. For light ions up to α-particles the source works best as a single stage device with the injector stage switched off. The ion intensities obtained in this mode of operation are presented in Table 2.

From these data it is obvious that this type of source is well suited to serve as a powerful light ion source LIS (Fig. 1) in the ISIS project. It has to be pointed out that the pre-ISIS 2* source, is exceptionally reliable, stable and easy to operate. With a power consumption of about 60 kW and a demand for only 5 cm^3 gas per hour it is one of the less expensive sources.

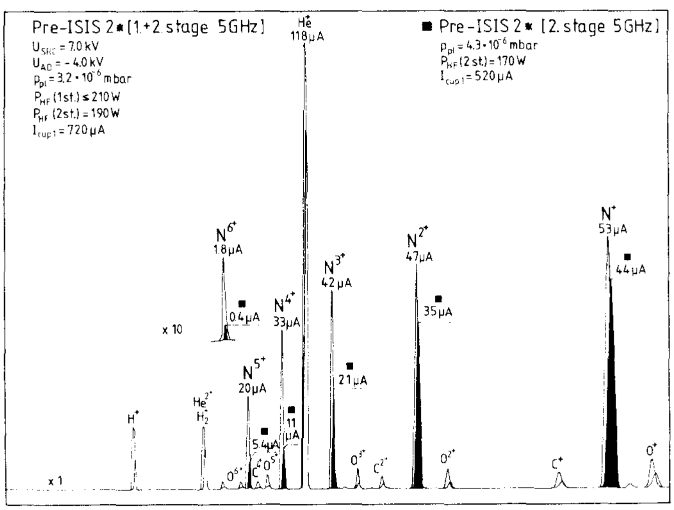

Figure 3: Spectra of nitrogen ions from pre-ISIS 2* with and without injector stage in operation.

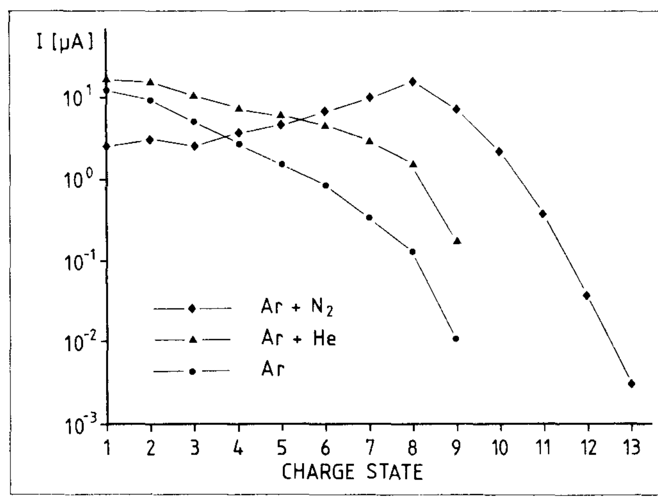

Figure 4: Argon charge states from pre-ISIS 2* for different gas compositons.

in operation. The numbers attached to the nitrogen peaks are measured currents obtained at 1.3 m from the source exit.

The addition of a lighter gas to the working gas has two advantageous effects: The operation of the source is more stable and, even more important, leads to an improved efficiency in the production of higher charge states. Fig. 4 demonstrates, that the addition of nitrogen strongly shifts the charge state distribution of the extracted argon beam to higher states. This leads to the assumption, that the confinement for heavier ions is increased at the cost of the lighter, more mobile ones. As another result it could be observed, that the accepted microwave power rises with the effectiveness of the compound gas (Ar: 160 W, Ar + He: 250 W, Ar + N_2 = 580 W), probably resulting in a higher average energy of the

Multiharmonic mode operation of JULIC

The new center region for external injection of ions from the ECR-source is designed for the mode h=3. Beside the fundamental h=3 mode some priority is given to h=9-mode; the h=6-operation requires a severe modification of the center region and is presently treated with less emphasis.

The internal ion source as well as the future inflector are not sufficiently movable and the puller geometry is fixed. Thus the transit time problem in the h=9 mode for the first acceleration gap can not be solved by using approximately scaled parameters from the h=3-operation. But it turned out that the present center region for internal ion source operation works in h=9-mode using a Dee voltage four times higher than according to scaled orbits.

GAS \ e·Q	1-3	4	5	6	7	8	9	10	11	12	13
C-13	>30µA	17µA	1.6µA	30nA							
N-15	>40µA	36µA	18µA	1µA	16nA						
O-16	>40µA	37µA	36µA	11µA	170nA						
Ne-20	>40µA	36µA	12µA	2.1µA	340nA	15nA					
S-32	>15µA	10µA	8µA	5µA	3µA	1.8µA	1µA				
Ar-40	>20µA	8µA	6µA	7µA	10µA	15µA	7µA	2.2µA	370nA	35nA	3nA

Table 1: Intensities of light heavy ion species obtained from pre-ISIS 2* source at 6 kV after momentum separation.

ION	INTENSITY
p	500µA
d	400µA
$^4He^+$	600µA
$^4He^{++}$	400µA
$^3He^+$	450µA
$^3He^{++}$	340µA

Table 2: Light ion beam currents from pre-ISIS 2* in light ion source mode.

Fig. 5 shows the resonance chart of JULIC for multiharmonic mode operation. It demonstrates that JULIC was designed for Q/A = 1/2. The energy of protons and $^3He^{2+}$ is limited by the maximum frequency of the resonators. The frequency range is a factor $\sqrt{2}$, i.e. the energy of the light particles can be changed by a factor of two. For heavier particles the upper limit probably is determined because of low beam currents. For h=3-mode the Q/A value has to be larger than 1/3 but for h=9 lower charge states with higher intensities of the ions can be applied.

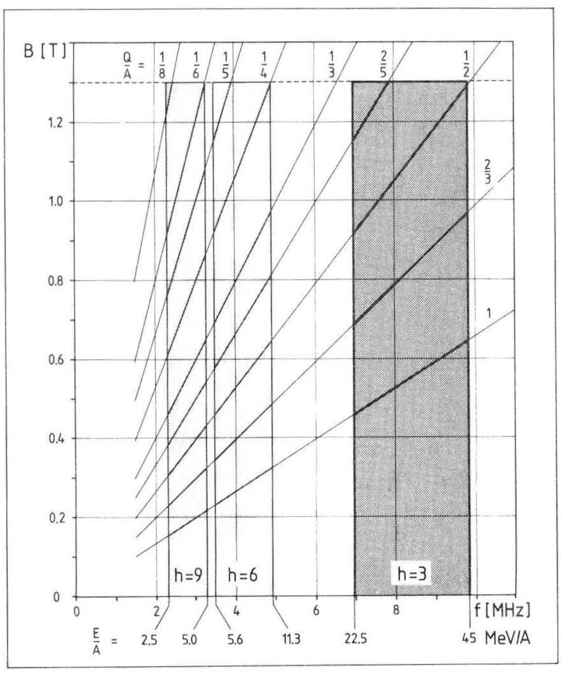

Figure 5: Operating diagram of JULIC, f orbit frequency of particles, B center magnetic field, h harmonic mode.

Total turn number and beam phase

The calculation of rf-phase behaviour and beam losses due to stripping reactions etc. requires that the path length of ions in the cyclotron is known. In order to calculate the number of turns n in multiharmonic mode operation the geometry of JULIC has to be taken into account. 3 Dees in 3-fold symmetry are driven in phase by one generator. The geometrical azimuthal width of each Dee is 40^0 and that of the accelerating gaps 5.6^0. The factor by which the energy gain per turn is reduced due to a not optimal Dee angle α equals

$$\Delta E(\alpha)/\Delta E_{max} = |\sin \frac{h}{2}\alpha| \ . \qquad (1)$$

Beside the geometrical dimensions two additional contributions influence the effective angle α: 1. A correction has to be applied due to the strongly assymmetrical configuration of the gap. In a rough approximation this correction becomes -1.8^0. 2. Due to the fact, that the transit time of particles is shorter in the valley than in the hill sector, a second negative correction results: The orbit radius in the hill is three times smaller than in the valley giving a correction of -2.1^0. From this the effective angle is estimated as 41.7^0.

Assuming an ideal isochronous field and neglecting relativistic effects, the minimum turn number is $n = E/\Delta E$. It is obvious from equation (1) that n is strongly dependant from the effective Dee width α in high harmonic modes. Experimentally it has turned out, that the effective Dee angle α fortunately exceeds the estimated figure. - For $^4He^+$-ions of 16 MeV and a Dee voltage of 40 kV the turn number becomes (6 accelerating gaps) $n = E/\Delta E(\alpha) = 16\cdot 10^3/1\cdot 6\cdot 40\cdot 0.13 = 500$.

The phase shift of a particle being accelerated from radius r_1 to r_2 is

$$\sin \phi_{RF,1} - \sin \phi_{RF,2} = \frac{2\pi\cdot h\cdot n}{r_{max}^2} \int_{r_1}^{r_2} \frac{\Delta B}{B}\, d(r^2) \qquad (2)$$

Since n is about the same for h=3 and h=9 phase deviations caused by $\Delta B/B$ or $\Delta f/f$ should be enlarged by the factor of 3. While in normal mode operation the field can be easily adjusted so that phase errors are less than $\pm 5^0$, the situation in h=9-mode operations is still tolerable. Concerning beam losses due to charge exchange during acceleration the total path length is about the same but the stripping cross sections ($\sim$ 1/velocity) should be approximately three times larger.

First experimental results in h=9 mode

A few experiments in h=9 mode have been performed with the internal ion source and the original center region geometry installed[7]. The intention was to get some information about difficulties related to this mode of operation well before the external injection system comes to operation. Basic problems involved with the h=9 mode are:

1. Extraction of ions of $A \geq 20$ and a value $Q/A \approx 1/4$ from the source with intensities > 100 nA. Transportation of extremely low energy beams to the center of the cyclotron. (A compact machine like JULIC requires injection energies of $E \approx 0.5$ keV/A in this mode.)
2. Optimization of one center region for h=3 and h=9. The idea to install an individual center region for each mode is believed to be unpracticable. Preferably a puller change should be sufficient.
3. Beam dynamics problems caused by non ideal Dee angle, trim coil configuration and setting procedure, stability of magnetic field and RF.
4. Gas stripping of the non totally ionised particles.

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While the first two problems are not investigated in detail up to now, early experiments can provide an approach to questions concerning 3. and 4. Although by no means optimized for h=9 mode acceleration the original center region really works.

The very first experiments have been done with deuterons to get rid of the stripping problem. By iterative tuning RF and trim coil currents the beam was guided to the extraction radius. The phase optimization procedure (12 phase probes, matrix method) could be successfully applied in this mode without modification. Beam currents of about 100 nA have been extracted with an extraction efficiency of 30 % but it has to be mentioned that the beam loss on the first 4 orbits is about a factor of 10 and strongly dependent on RF amplitude, ion source position and trim coil setting. Fig. 6 shows the phase deviation vs. radius. The phase error is significant only on the first two probes. - Up to now we have not made detailed investigations with regard to beam dynamics in the original 3ω-mode center region of JULIC operating in 9ω-mode.

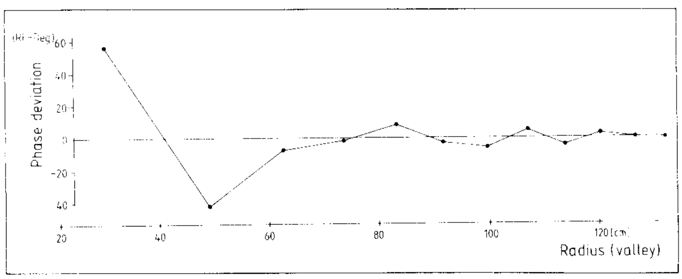

Figure 6: Phase history for deuterons accelerated in h=9 mode operation (E/A = 3.7 MeV/A, f_{RF} = 26.3 MHz, V_{DEE} = 22 kV).

As the shape of the average magnetic field by pole face geometry is adapted to a relativistic mass increase of 4.1 % (i.e. 77 MeV deuterons), high negative trim coil currents had to be applied for the low mass increase of ≈ 0.4 % in the h=9 mode. Practically this means, that there is a lower limit Q/A respectively a higher limit for the energy of ions to be accelerated in this mode. So far it can be stated that for E/A = 4-5 MeV/A the charge state must be Q/A > 1/4 to achieve the appropriate isochronous field with the available trim coil currents.

The gas stripping problem was investigated with $^4He^+$-particles. Beam current vs. radius drops according to $I = I_0 \cdot \exp(-a \cdot p \cdot t)$ with I beam current, t = acceleration time, a = constant proportional to σ_{loss}/v. σ_{loss} is the stripping cross section and v the velocity of particles. After careful tuning the acceleration conditions for $^4He^+$ (e.g. phase history) resembled those for d as given in Fig. 6. Again up to 100 nA could be extracted with an extraction efficiency of 44 %. Some results are given in Fig. 7 where $\lg I/I_0$ is displayed vs. R^2 ($R^2 \sim t$) for different pressures and gas compounds. The deviation from a straight line is probably due to a non homogeneous pressure distribution or gas composition along radius.

It is planned to proceed on the way to achieve multiharmonic mode operation of JULIC but presently first priority is given to the realization of the ISIS project.

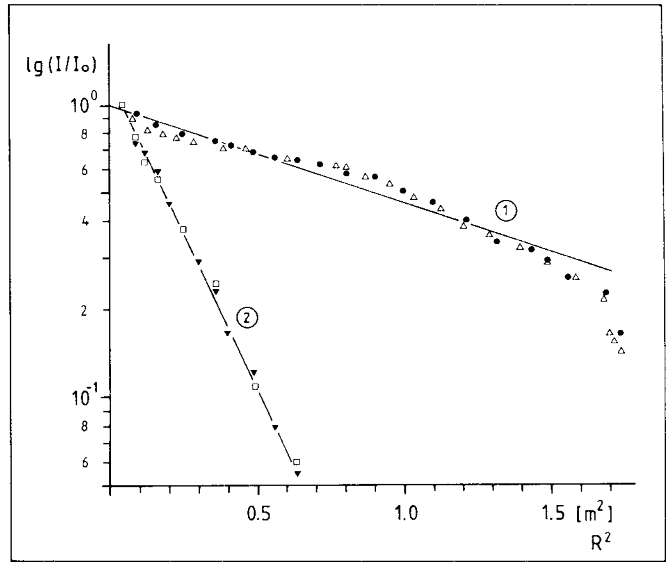

Figure 7: The beam current vs. R (R = radius of the valley probes) is displayed on a log scale for different gas pressures and compositions:
Curve 1: mixed composition at p ≈ $8 \cdot 10^{-6}$ Torr
Curve 2: 12 % He-gas, ≈ 80 % N_2-gas at p ≈ $2.9 \cdot 10^{-5}$ Torr
△,● and ▼,□ resp. mark different measurements for the identical conditions (f = 23 MH_z, V_{Dee} = 27 kV).

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