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AN ECR-TYPE LIGHT ION SOURCE FOR THE KARLSRUHE ISOCHRONOUS CYCLOTRON

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Abstract

An ion source for fully stripped light ions ($^{12}C^{6+}$ up to $^{20}Ne^{10+}$) is under development. In the first stage of the source a plasma is created and in the second stage ionisation to high charge states takes place. The required high electron energy and density is achieved by microwave heating at electron cyclotron resonance (ECR) frequency in the magnetic field of two superconducting solenoids and an additional permanent hexapolar magnet. Currents up to several 100 nA at 26 MeV/N will be obtainable in the scattering chamber.

A general description of the set-up with details of the magnetic field configuration and vacuum system will be given.

Introduction

The Karlsruhe isochronous cyclotron is a fixed frequency machine designed to accelerate ions with Z/A = 1/2 to an energy of 26 MeV/nucleon. At present this energy range is only covered by a few operating accelerator facilities. So it was of interest to look for a suitable ion source particularly because an axial injection system is already used since several years to inject $^{6}Li^{3+}$-ions and polarized deuterons into the cyclotron [1,2].

The design aim of the axial injection system was to accept an ion beam with a normalized emittance ($\varepsilon \cdot \beta$) of $0.5 \cdot \pi \cdot$mm$\cdot$mrad. Practical experience with the existing external sources showed that 10-20 % of the dc beam current could be accelerated and extracted from the cyclotron. This rate was achieved using a bunching system giving a gain of 3 to 4. A suitable heavy ion source for the Karlsruhe cyclotron has to deliver a fully stripped continous ion beam of more than 1 μA within a normalized emittance of $0.5 \cdot \pi \cdot$mm$\cdot$mrad, to perform nuclear physics experiments efficiently [3]. To achieve a good bunching factor a small energy spread would be favourable. From practical experience with the Lambshift source C-LASKA an energy spread of less than 30 eV/A must be required.

Principle of a source for fully stripped ions

The fundamentals of a fully stripped ion source have been discussed in detail by several authors [4,5]. The stripped ions are produced by electron collisions in a multistep process. Here the electron temperature T_e and the product of electron density n_e and the transit time of the ion τ_i in the electron cloud have to fulfil certain conditions. For example if 10 % of the ions in a neon plasma are in the charge state 10 (^{20}Ne fully stripped) then [5]

$$n_e \cdot \tau_i = 2 \cdot 10^{10}\ \mathrm{s \cdot cm^{-3}},\ T_e = 12\ \mathrm{keV}$$

This conditions can be fulfilled in a magnetically confined plasma in which the electrons are accelerated by electron cyclotron resonance. An ECR plasma stripper, whose magnetic field consists of a mirror device and a superimposed hexapolar field, is the second stage of the 'Supermafios' source in Grenoble [6,7]. From this device a beam of highly charged ions could be extracted. The measured beam quality fits whithin the acceptance of the Karlsruhe cyclotron.

The maximum obtainable charge state increases with the transit time τ_i of the ions but only if a fairly low vacuum pressure is provided. Otherwise the highly charged states will be lost by charge exchange with the neutral gas. Only with a neutral background of about 10^{-8} mbar the collision time for charge exchange of fully stripped ions with neutrals is longer than τ_i = 0.05 s, obtained typically in plasma confinement systems. This vacuum condition can only be fulfilled in a two stage source. A dense plasma with low charge states is produced at 10^{-2} mbar in the first stage. The plasma diffuses along the field lines of a guiding magnetic field into the second stage (ECR plasma) stripper. Here the neutral background is drastically reduced by differential pumping.

Design considerations

The production of highly stripped ions with a two stage ECR source was first demonstrated by Geller [7]. Because of the extremely high power consumption of 3 MW such a source is however not suited for operation with accelerators unless the power consumption can be drastically reduced. This power consumption for the magnetic field is a direct consequence of the big dimensions of the source which are necessary for a vacuum pressure of < 10^{-7} mbar in the second stage assuming an ion drift length of about 1 m.

To produce a high intensity of fully stripped ions the vacuum was not satisfying in the 'Supermafios' source. Assuming an electron density of $n_e = 8 \cdot 10^{11}/\mathrm{cm}^3$, a transit time for the ions of τ_i = 0.025 s is necessary to get Ne^{10+}. If the ion temperature is 1 eV, then the drift length will be L ≃ 9 cm calculated from

$$L^2 = 4\ \tau_i\ D_{ii}$$

where D_{ii} is taken from Spitzer formula [8].
From this result it becomes evident that a shorter source with much less power consumption (e.g. 'Micro Mafios' [7]) could be as efficient as the big 'Supermafios' if the vacuum in the second stage could be improved considerably.

On the other hand, if the 'Supermafios' geometry is maintained, a higher output of fully stripped ions can be expected, if it is possible to improve the vacuum in such a design, too. This second approach will be tried in Karlsruhe.

Vacuum

To allow ion production at a pressure of 10^{-2} mbar a differential pumping system is necessary. Using two throttles of 6 l/s conductance and two pumping stages the neutral gas flow into the second stage (10^{-8} mbar vacuum pressure required) is negligible compared to the injected plasma (500 μA ≙ 10^{-4} mbar$\cdot$l/s). Supposing this second stage consists of a vacuum tube of 120 cm in length which is pumped on the opposite side of the entrance tube only, it turned out that at least a tube diameter of about 0.5 m and a pumping speed of 10^4 l/s are necessary to get the required pressure of 10^{-8} mbar. Assuming a more realistic gas flow of 10^{-3} mbar$\cdot$l/s a minimum diameter of 0.8 m is inevitable or additional lateral pumping has to be used. This lateral pumping can be easily realized if the hexapolar magnetic field in the 2nd stage can be achieved by using a permanent magnet [4,7,9] which is inserted into the vacuum chamber.

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The hexapolar magnetic field in the 2^{nd} stage

In order to study the usefullness of $SmCo_5$ permanent magnets a small hexapolar magnet was built up. The magnetic field strength B_M at the pole face is 3.5 kG. The small hexapolar magnet was inserted into a magnetic mirror field to measure the superposition of the two fields. A cross-section of the whole experimental set-up is shown in fig. 1. As expected, the two fields affected each other by less than 1.5 %. Therefore it is possible to use a permanent hexapole in the second stage by means of $smCo_5$ magnets.

The radial dependence of the absolute field strength can be described by

$$B = B_m \left(\frac{r}{r_m}\right)^2$$

With r_m = 14 cm this field is comparable to the hexapolar field of 'Supermafios'.

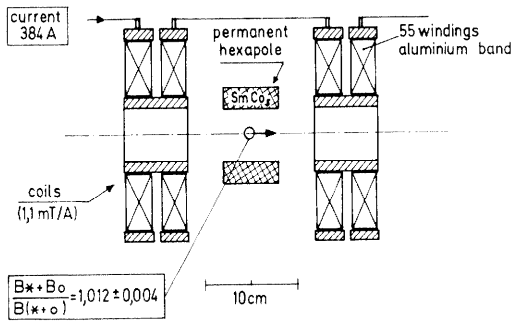

Fig. 1: Experimental set-up for measuring the superposition of a permanent hexapolar field with a mirror field of two coils. The maximum longitudinal field strength of the coils on the axis is 4.2 kG. The permanent hexapolar magnet was made out of $SmCo_5$ and was 6 cm in length. The maximum field on the pole face is 3.5 kG.

The magnetic mirror field

Since length and diameter of the vacuum chamber in the second stage were fixed by the vacuum requirements, an arrangement of the coils had to be found to give a similar mirror field as in 'Supermafios'. In addition it should be possible to increase the field strength by a factor of two (higher ECR frequency should result in a higher electron density). The calculation of the appropriate coil configuration was done with the computer code 'Soleno' [10]. This led to an arrangement with two coils of 0.8 m inner diameter at both ends of the second stage. Since the power consumption even for the lower field is at least 700 kW it was decided to use two superconducting coils in separate cryostats.

An additional coil between the two superconducting ones can be used to adjust the field gradient in the ECR zone. Another small coil is necessary to obtain the high magnetic field in the 14.5 GHz ECR zone for the plasma generation in the first stage. The arrangement of the coils and the shape of the magnetic field on the axis are shown in fig. 2.

Present state of the design

The schematic drawing in fig. 2 gives an overlook of the present design state of HISKA (Heavy Ion Source KArlsruhe). The vacuum apparatus will be made of stainless steel and consists of three parts.

Part one consists of a differential pumping system which makes it feasible to produce the plasma at a pressure of 10^{-2} mbar. The second part of the source is a cylindrical vacuum tank in which the permanent hexapole is inserted. The permanent magnet slabs are fixed on three rings (11) centered in the tank. The cross section of this vacuum chamber is given in fig. 3.

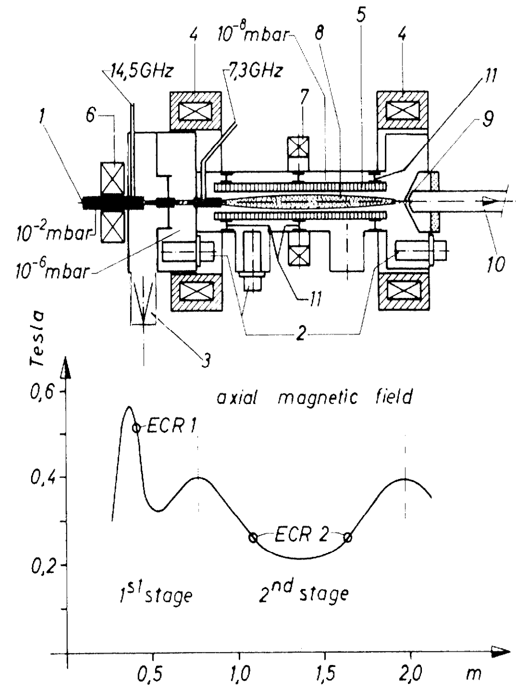

Fig. 2: Cross-section of the heavy ion source HISKA in the present state. The magnetic field strength along the axis is drawn to scale below. (1) gas inlet; (2) cryo pumps; (3) turbo-pumps; (4) superconduction coils; (5) permanent hexapolar magnet; (6)(7) additional coils; (9) extraction system; (10) beam line to the cyclotron; (11) rings for fixing and centering the magnet slabs

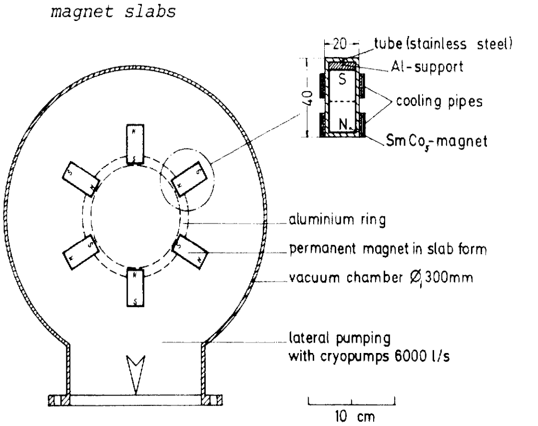

Fig. 3: Cross-section of the permanent hexapolar magnet inserted into the vacuum tube of the second stage. The $SmCo_5$ magnets are inside a rectangular tube. They are cooled since otherwise the magnets will be destroyed at a temperature above 100°C

The permanent magnets are fitted into rectangular tubes made of stainless steel which are sealed vacuum tight. The magnets are indirectly cooled because at temperatures in excess of 100°C an irreversible reduction in the magnetic flux density will occur. The arrangement of the magnetic strips in the vacuum chamber gives the space required for lateral pumping. This lateral pumping which is done by commercially available cryopumps (2) (> 12000 l/s) giving a pressure of about 10^{-8} mbar. The third part contains the extraction system (9) which is not yet designed in detail. The whole source has to be operated at a high voltage potential of 10-20 kV.

The longitudinal mirror field of the ECR-plasma stripper is obtained by two superconducting coils (4) at a distance of 120 cm. For further adjustment of the field gradient in the ECR-zone an additional coil (7) is provided. The field of the first superconducting coil and the field of an additional coil (6) are superimposed giving the ECR-zone (14.5 GHz) in the first stage of the source.

Alternative plasma injection

The plasma generation by means of an ECR ion source as it was done in 'Supermafios' requires a second transmitter and at least one additional coil, which leads to complications in the mechanical construction. Therefore the injection of a plasma generated in a magnetic field region where the strength is considerably lower than the maximum field of the mirror device was studied. A simple set-up with a rf-source and a mirror field shown in fig. 4 was used. This rf-source produces for different gases (He, Ne, Xe), a plasma with an electron density of $n_e = 10^{11}/cm^3$ and an electron temperature of 30 eV [11]. The electrical rf-field of 150 V/cm and 80 MHz is oriented transversely to the magnetic field lines on the mirror device. The N_2 plasma effusing out of the 7 mm hole of the discharge bottle spred out in the direction of the magnetic field lines. The diameter of the plasma column was 12 mm between the two coils (point A) and about 15 mm behind the second coil (B) and was independent of the magnetic field strength.

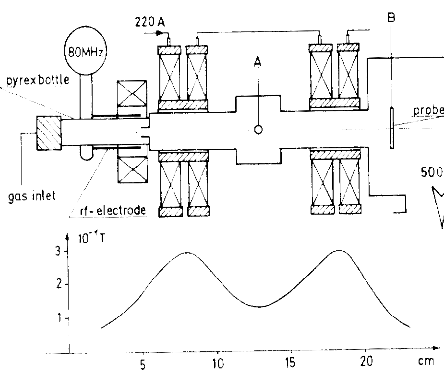

Fig. 4: Cross section of the experimental arrangement to investigate the plasma injection. A simple rf discharge delivers a plasma which is transported through the magnetic mirror to point B. With a single-probe measurement the electron temperatur and the plasma density were determined. Plasma diameters are measured at points A and B. The magnetic field distribution along the axis is shown below

To measure the electron density behind the mirror field a disk probe was used at point B. The measured current as a function of the probe voltage is given in fig. 5. From these measurements an electron temperature of about 50 eV was evaluated. Assuming thermal velocity of the nitrogene ions, an ion density of $n_i = 2 \cdot 10^{10}/cm^3$ can be deduced.

Hence, the plasma produced in a magnetic field much lower than the peak field of the magnetic mirror can be injected with tolerable losses of plasma density. This enables a simpler arrangement of the magnetic coils.

To get higher plasma densities it might be better to have a duoplasmatron or an ECR source. The latter can then be operated at the same frequency as in the second stage using the same transmitter.

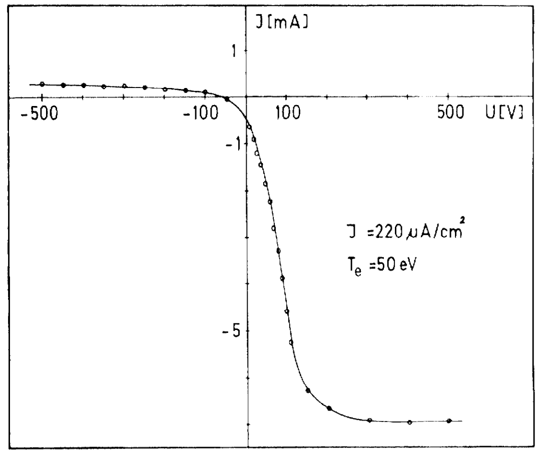

Fig. 5: Measurement of the disk probe current at point B as a function of the probe voltage

Outlook

This year we will start to build up the vacuum apparatus included the differential pumping system with turbopumps in the first stage and cryo-pumps in the second stage. The transmitter for 14.5 GHz will be delivered in early summer so that the assemblage of the microwave equipment can be started. The whole set-up will be ready for the test bench early next year.

Operation of the source HISKA at the cyclotron is planned to start in 1981. Currents up to several μA's of fully stripped light ions are expected.

Acknowledgements

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