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## THE KARLSRUHE ECR ION SOURCES

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### Resumé:

Le cyclotron à fréquence unique de Karlsruhe marche avec deux sources d'ion extérieures, une source de  $\text{Li}^{+++}$  du type ECRIS et une source de rayon atomique équipée d'un ionisateur du type electron beam (EB). L'intensité de la source  $\text{Li}^{+++}$  est augmentée considérablement après qu'elle est exploitée avec deux étages (de quoi le premier est opéré dans le mode  $2\omega_{\text{CE}}$ ) et après l'échauffement de la chambre de plasma a été amélioré. Pour augmenter l'intensité de la source polarisée l'ionisateur EB sera remplacé par un du type ECRIS. Les premiers tests sont accomplis avec succès en coopération de PSI.

### Abstract:

Two external ion sources are used for nuclear physics experiments at the Karlsruhe fixed frequency cyclotron, an ECRIS for  $\text{Li}^{+++}$  ions and a polarized atomic beam source. The output of the  $\text{Li}^{+++}$  ion source have been increased considerably since it is operated with two stages and the heating of the discharge tube has been improved. In the first stage the  $2\omega_{\text{CE}}$  mode is used. In order to increase the intensity and to improve the beam quality of the polarized atomic beam source the electron beam (EB) ionizer of this source will be replaced by an ECR ionizer. First tests of such a new ionizer have been performed successfully in cooperation with the PSI.

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<sup>(1)</sup>The experiments concerning the ECR ionizer for an atomic beam source have been performed in cooperation with the PSI (SIN).

### Introduction:

The Karlsruhe ECRIS developments are part of the program to improve the external ion source equipment of the Karlsruhe cyclotron. The cyclotron is a fixed frequency machine built in 1959 - 1964 and designed to accelerate ionized particles with a charge to mass ratio of 1/2 to an energy of 26 MeV/nucleon. An axial injection system was installed and used since 1973 for polarized deuterons from a Lambshift source and for  $\text{Li}^{++}$  ions produced by a Penning source. Beams of about 40 nA at maximum could be extracted from the cyclotron for both ions.

With the appearance of the ECR sources much effort was put into the development of those sources with the aim to offer an 364 MeV  $\text{N}^{7+}$  beam.

Following the test source p-HISKA from which  $\text{N}^{7+}$  ions could be produced and accelerated in the cyclotron first time, the source HISKA was installed. This was a large volume source with a 60 cm long permanent hexapole magnet and superconducting coils of 0.8 m inner diameter. A new building for the external ion sources was built and connected by a 16 m long beamline with 11 electrostatic einzel lenses to the cyclotron. There was also enough space for the installation of a new atomic beam source for polarized deuterons (PASKA) (constructed by Glavish and delivered by SENTEC) and the ECRIS LISKA for the production of Li ions developed in Karlsruhe. The arrangement of this ion sources is shown schematically in Fig. 1.

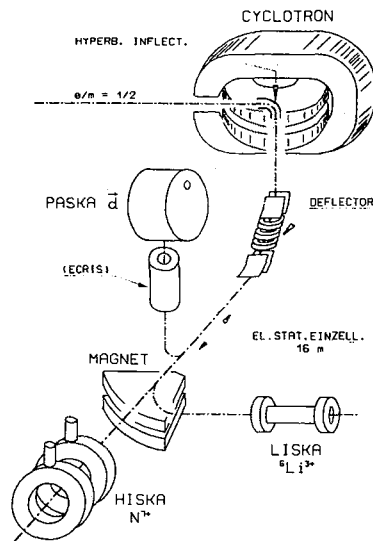


Fig. 1: The external ion sources of the Karlsruhe cyclotron

The development of HISKA suffered very much from the low reliability and the high LHe consumption of the superconducting coils. Finally when the coils could be operated reasonably in 1986, there was no longer a demand for nitrogen ions. Therefore it was decided to dismount HISKA and to concentrate the activities in  $\text{Li}^{++}$  ions and polarized deuterons, in which the nuclear physicists are more interested.

### LISKA the Karlsruhe ECRIS for Li ions

$\text{Li}^{+++}$  ions had been delivered by the Karlsruhe cyclotron using an external Penning source Fig. 2 for about ten years.

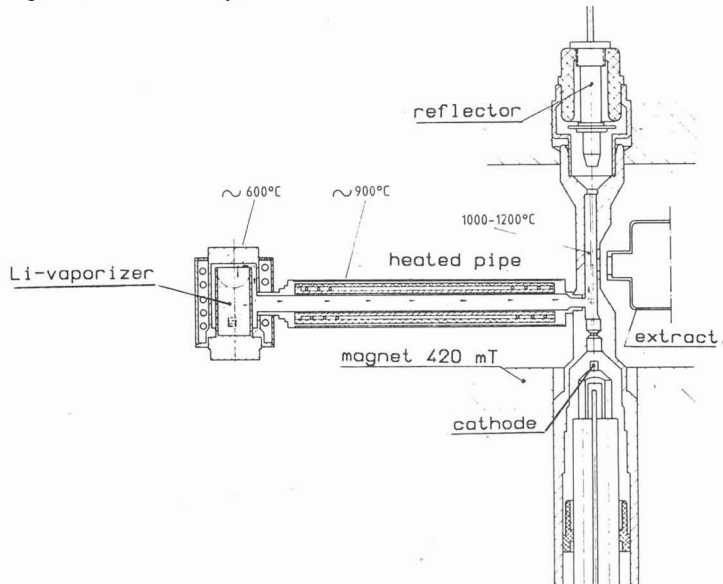


Fig. 2: The external Penning source of the Karlsruhe cyclotron for  $\text{Li}^{+++}$  ions

As shown in Fig. 3 no modification of this source lead to any durable increase of the intensity extracted from the cyclotron. But a remarkable progress resulted from replacing the Penning source by the new developed ECR ion source LISKA I.

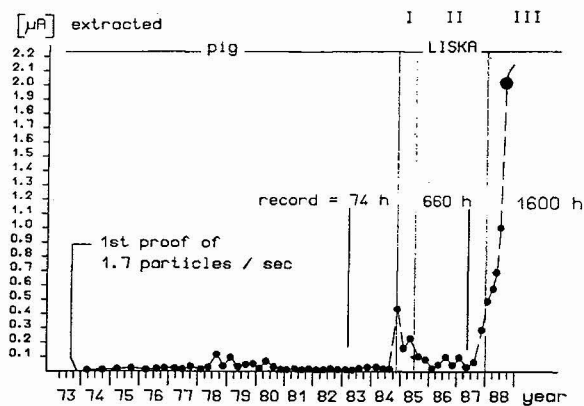


Fig. 3: The intensity of the extracted 156 MeV  $\text{Li}^{+++}$  ion beam as a function of time achieved with different external ion sources.

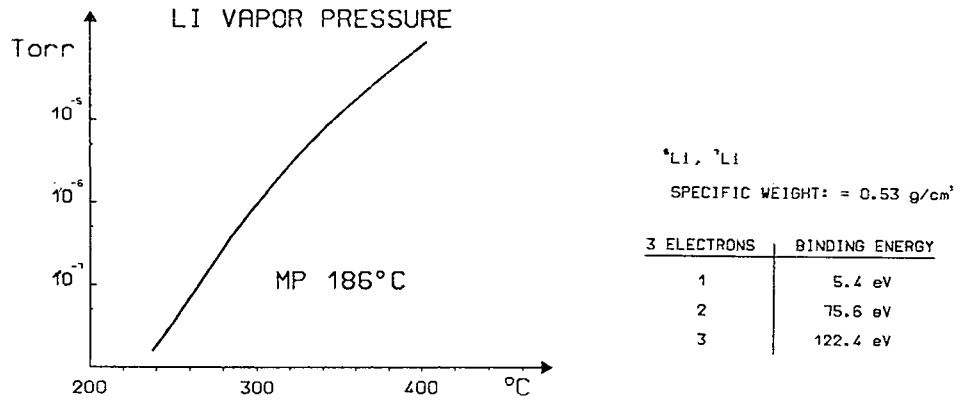


Fig. 4: Li vapor pressure as a function of temperature

Lithium with only three electrons should be a candidate for high yield of fully ionized ions in an ECRIS. The special difficulties arise from its physical and chemical properties. Lithium is a metal, which tends to condense at any cool place in a vacuum system and is therefore an enemy of all insulators. The vapor pressure is shown in Fig. 4 as a function of the temperature. It can be seen that at moderate temperature around  $350^{\circ}$  one should be able to operate an ECR discharge. Otherwise at room temperature the Li vapor pressure is so low, that every cold surface will introduce a large pumping speed. So as a construction principle the Li plasma must not be allowed to see any cold surface.

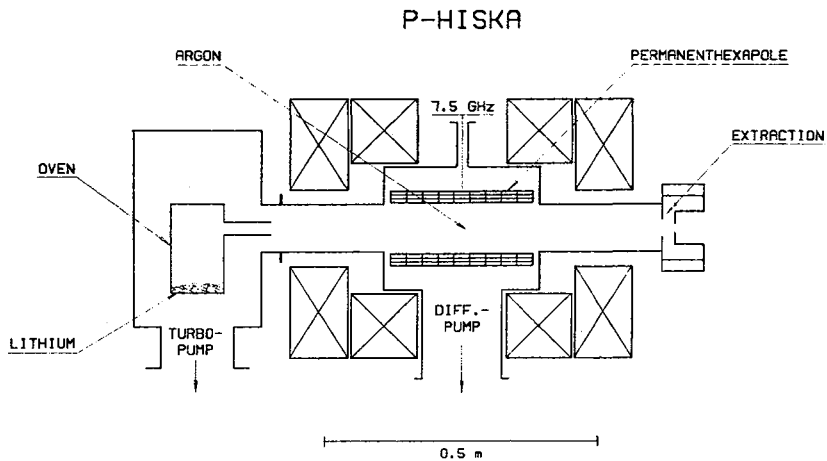


Fig. 5: The first experiment to produce  $\text{Li}^{+++}$  ions with an ECRIS

The first attempt to produce  $\text{Li}^{++}$  ions with an ECRIS was undertaken using the Li oven from the Penning source and p-HISKA the testsource for highly charged ions from gases. Fig. 5. About  $3 \mu\text{A}$  of  $\text{Li}^{++}$  could be produced, but the operating time was short, since there was no recycling of Li from the walls of the discharge tube. The oven filled with 5g of Li had to be operated at very high temperature to get sufficient Li vapor in the discharge. Argon buffer gas was used to maintain a stable discharge. The escaping Li lead to steadily growing problems, finishing the operation time after 24 h.

In consequence the development of a special Li ECRIS was started. LISKA I (Fig. 6) was a one stage source with completely heatable discharge chamber (65 mm diameter and 300 mm length). The plasma was confined longitudinally by the field of two pancake type coils. For the radial confinement a permanent hexapole was mounted outside the vacuum chamber. In Fig. 7 both field distributions are shown.

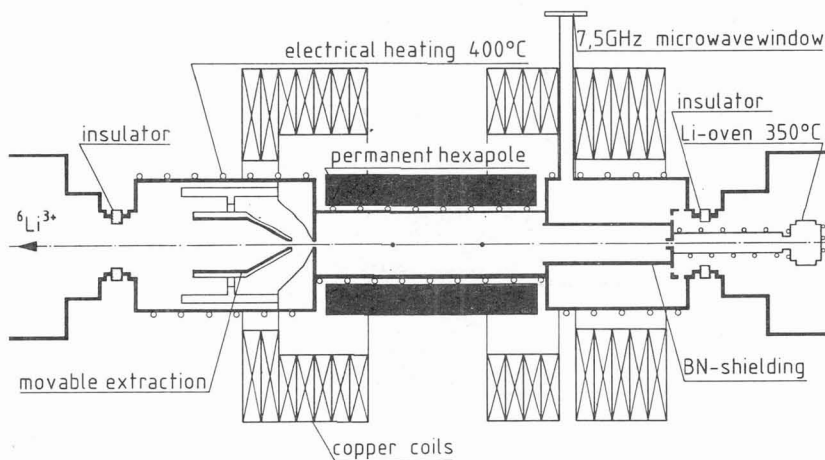


Fig. 6: LISKA I

Already this first version of an Li-ECRIS was a great progress concerning operation time and intensity. Under typical operation conditions LISKA I delivered a total beam of  $500 \mu\text{A}$  were in the  $\text{Li}^{++}$  state,  $0.5 \mu\text{A}$  at maximum could be accelerated to 156 MeV. The first nuclear physics experiment with this source lasted for 600 h. Only an interrupt of 24 h was needed to recharge the Li-oven. The charge distribution was less satisfying at least for an ECRIS. Typically 75 % of the current were  $\text{Li}^+$ , 20 %  $\text{Li}^{++}$ , 2 %  $\text{H}_2^+$ , 1 %  $\text{H}^+$  and only 2 % in the  $\text{Li}^{+++}$  state wanted.

After one year of operation the plasma chamber of LISKA I broke. The succeeding LISKA II had a larger diameter of the plasma chamber. Also a first stage ECR had been tested, producing a sharp minimum B-field configuration by inserting an ion ring inbetween the first coil packages. Fig. 8. Mainly since the heating of the discharge chamber was not optimum no better results could be achieved than with LISKA I.

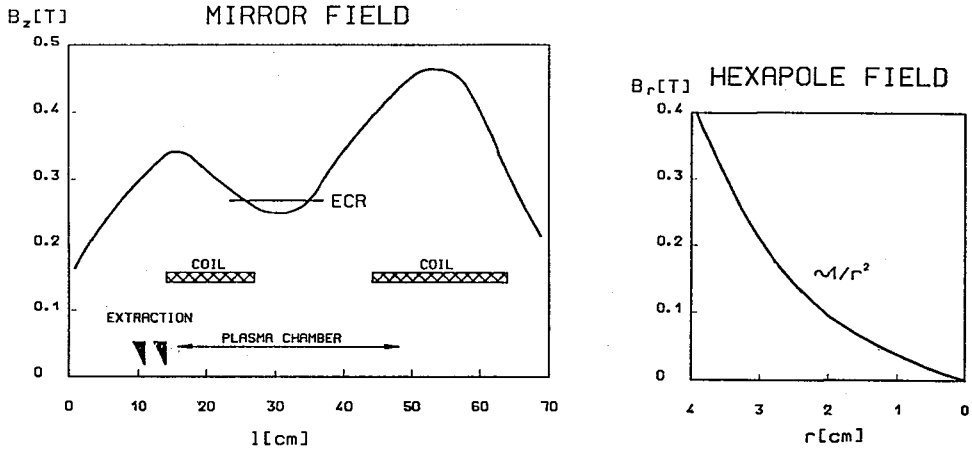


Fig. 7: The magnetic field distributions of LISKA I

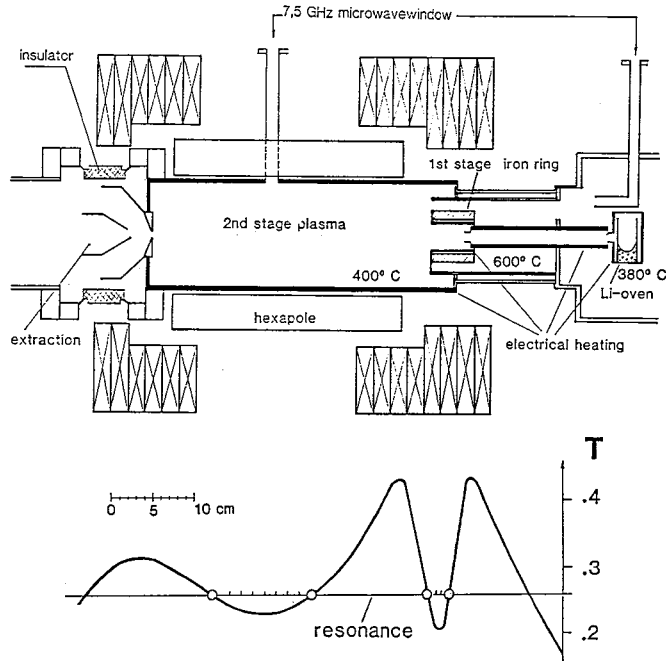


Fig. 8: LISKA II with a first stage ECR

LISKA III used at present is a two stage source and delivers so far the best results concerning stability, operating time and intensity. The essential characteristics of this source (Fig. 9) are described below. Lithium vapor from the oven is guided into a small cylindrical (28 mm diameter) vacuum chamber, where it is ionized by 7.5 GHz microwaves in the  $2 \omega_{ce}$  mode [1]. One resonance zone is inside the first stage plasma chamber, the

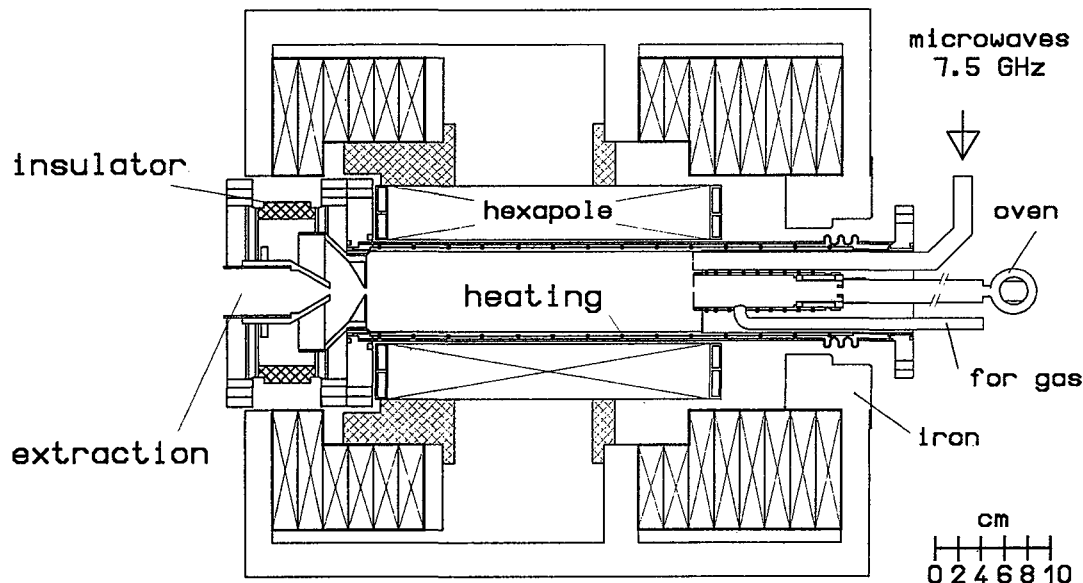


Fig. 9: LISKA III

other follows immediately after the 3 mm diameter hole from which ions and neutrals escape into the second stage. A plot of the axial magnetic field is given in Fig. 10. This field is achieved with only one power supply. The microwave power is guided off axial into the vacuum chamber of the second stage. To couple sufficient microwave power from the second stage into the first stage the 3 mm diameter hole inbetween is extended to a 0.2 mm wide slot, so only one microwave power has to be adjusted.

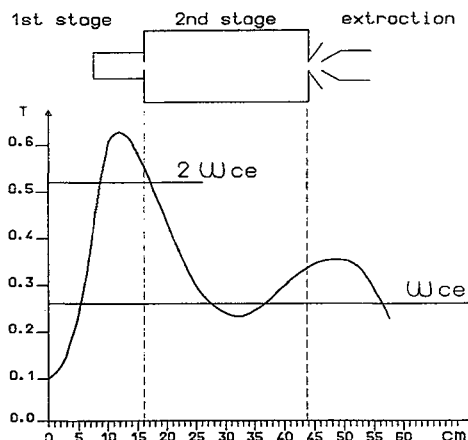


Fig. 10: Axial magnetic field of LISKA III

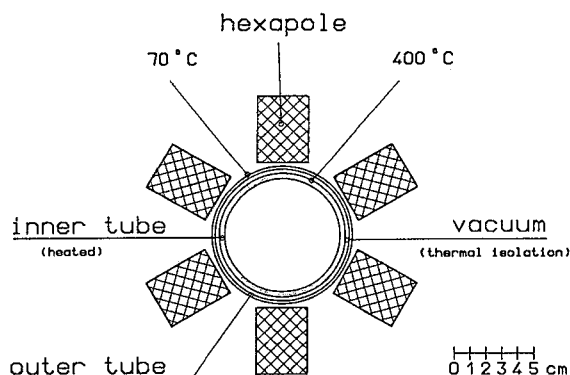


Fig. 11: Cross section of the discharge chamber of LISKA III



One very important experience gained with all preceding versions of the source was, that an efficient and homogeneous heating is of fundamental importance. Hence the plasmachamber of LISKA III is a double wall construction. The cross section of the plasma chamber is shown by Fig. 11. The inner tube of 6.5 cm diameter is heated electrically up to about 400 °C. For thermal insulation it is surrounded by vacuum, which is maintained in an outer tube. In this way the CoSm<sub>5</sub> magnets can be arranged to the plasma as close as possible. To get optimum temperature distribution five heating currents have to be adjusted carefully. Separately heated are the oven, the vapor pipe, plasma chamber one, plasma chamber two and the plasma electrode. The diameter of the extraction hole is 0.8 cm, the gap between the electrodes is 3 cm.

Without any further focusing element the source is connected to a 90° double focusing magnet, which analyses the extracted beam and focuses it into a four sector diaphragm of 1.5 cm diameter (Fig. 12). By the help of the four sector diaphragm the beam is centered. Up and down can be corrected by exciting the two magnet coils asymmetric.

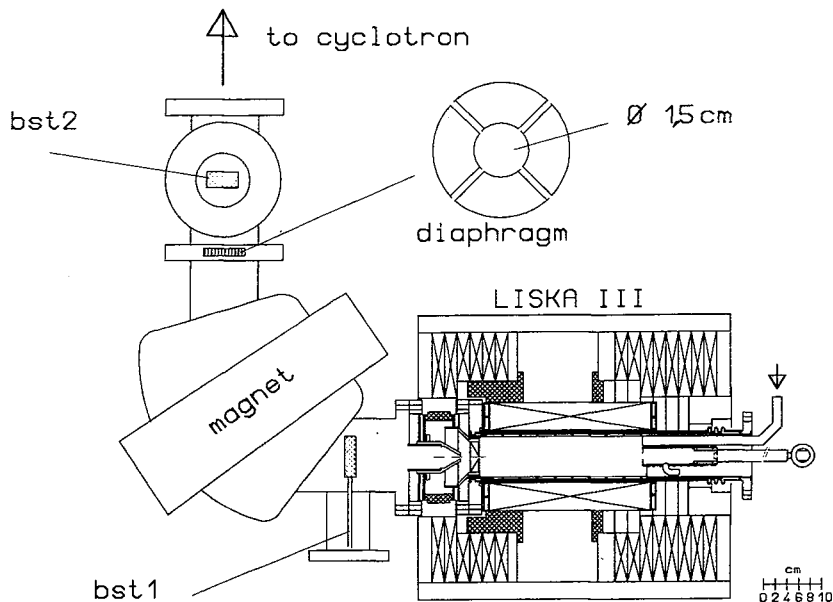


Fig. 12: The charge state analysis of the Li ion beam

The charge state distribution obtained with Li is shown in Fig. 13. The small admixing of <sup>7</sup>Li enables to discriminate between the <sup>6</sup>Li<sup>+++</sup> ions and the hydrogen molecular ions, if one assumes that there is no difference between the relative charge state distribution of both Li isotopes. So it is concluded that 60 μA <sup>6</sup>Li<sup>+++</sup> are delivered by the source, an improvement of a factor of ten compared with LISKA I. The emittance should be less than 600 mm mrad, which had been measured for a He<sup>+</sup> beam from LISKA I (Fig. 14).

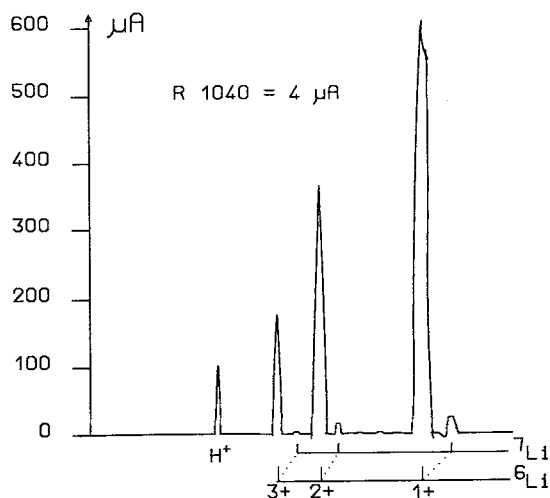


Fig. 13: Charge state distribution of the Li beam from LISKA III

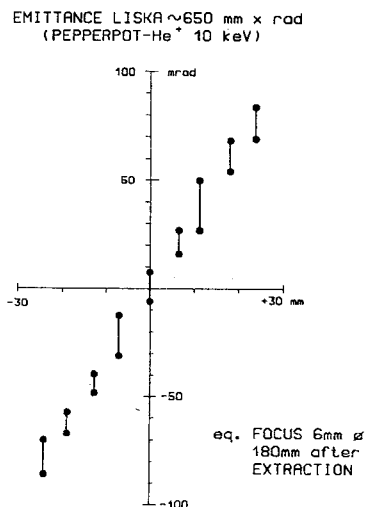


Fig. 14: Emittance measurement of LISKA I

LISKA III has now been operated for more than 1600 h without refilling the Li oven. The extracted 156 MeV  $\text{Li}^{3+}$  beam is typically 1.0  $\mu\text{A}$  (2.5 have been extracted at maximum). About 100 W microwave power are needed and the total power consumption is 70 kW.

#### An ECR-ionizer for the polarized atomic beam ion source

The principle of a polarized atomic beam ion source is illustrated in the schematic diagram of Fig. 15. In an rf-discharge hydrogen atoms are produced from the molecules. This atom expand put of a copper nozzle, which is cooled by an He-refrigerator. The suitable part of this diverging beam is peeled out by a skimmer and the one half of this beam with electron polarization up is focused by the inhomogeneous field of two hexapole magnets. The other part with electron polarization down is defocused. The electron polarized beam obtained in this way is running through rf-transition units where the occupation number of certain hyperfine structure levels are interchanged in order to transfer the electron polarization to the nucleus. The atoms then enter an electron bombardment ionizer in which they are ionized by electron impact.

The schematic view of Fig. 16 gives an impression of such a source which was designed in Karlsruhe, built by NTG and is under test at present at KFK. As at some other running sources this is equipped with an electron beam (EB) superionizer of the ANAC/CERN design. A 180 mT longitudinal magnetic field confines an oscillating electron beam,

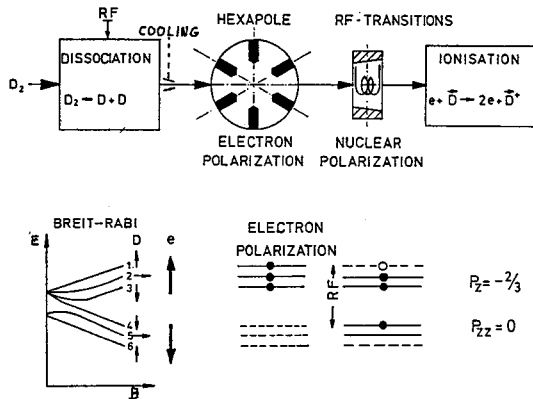


Fig. 15: The principle of the polarized atomic beam ion source

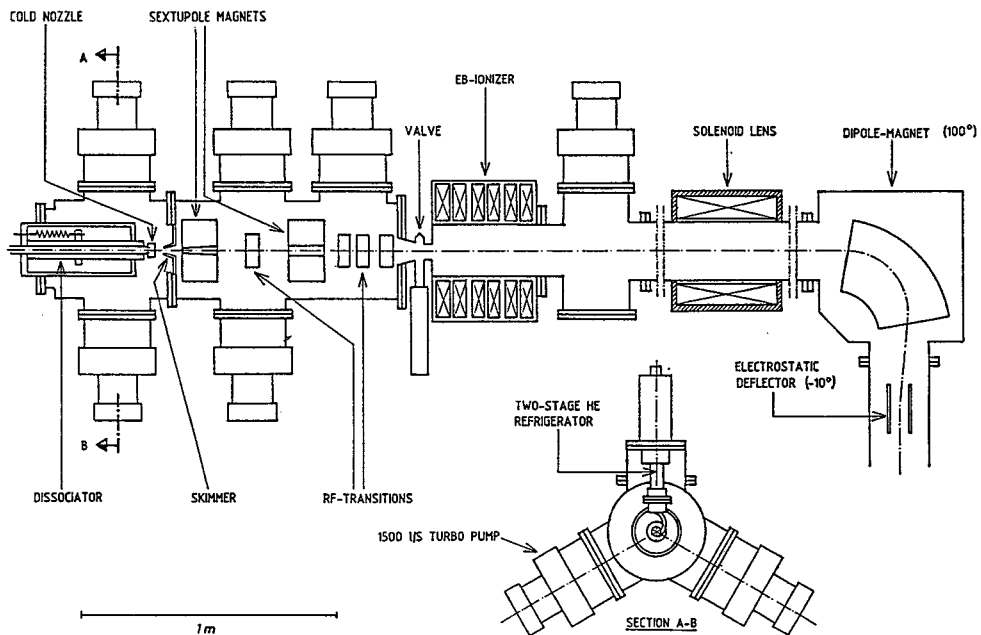


Fig. 16: Schematic view of the KfK designed atomic beam source

drawn from a heated filament. The distribution of the magnetic an electric fields and the electrode system of this ionizer are given in Fig. 17.

This ionizer is well established and optimized to the most possible.

The ionization efficiency of an EB-ionizer is increased with higher electron current but the space charge potention connected to this current increases too. This results in an increasing energy spread of the extracted ion beam. From our experience the efficiency of this ionizer for a cold atomic beam is in the order of 10 % estimating an electron

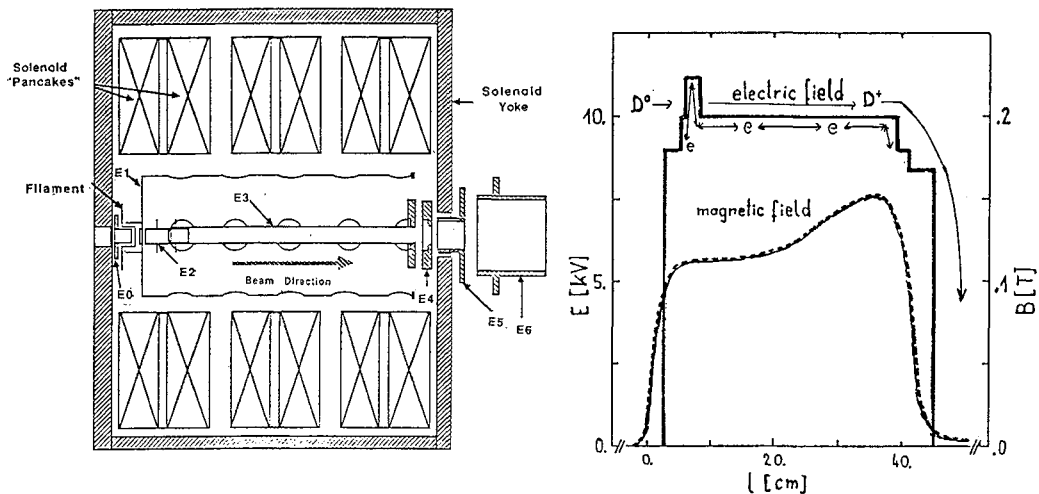


Fig. 17: The ANAC/CERN electron beam ionizer and the distribution of its magnetic and electric fields

density of  $1 \text{ A/cm}^2$ . The resulting energy spread is  $\pm 400 \text{ eV}$  and the measured emittance  $100 \text{ mm mrad } \sqrt{\text{MeV}}$  for 90 % of the beam.

The common opinion is, that further improvement of efficiency, brightness and energy spread requires another ionization method. An ECR-ionizer has been proposed by Jaccard [2] and its characteristic features have been discussed by Clegg et al. [3] [4]. Due to the high electron density in an ECR-plasma a higher ionization efficiency is expected. In addition the space charge neutralized ECR-plasma should enable to extract a beam of small energy spread. The last point is of fundamental importance if one has to use long (low energy) beamlines and a bunching system for injection as in Karlsruhe e.g. The basic question was, whether such an ECR-ionizer would conserve the polarization.

Fig. 18 shows a schematic views of the first ECR-ionizer for an atomic beam source built in Karlsruhe.

The plasma is confined longitudinally by the field of a pair of ironshielded solenoid magnets and radially by the field of a permanent sextupole magnet. Fig. 19 shows the field in z and in r direction.

The plasma chamber consists of a 300 mm long Pyrex tube of 60 mm diameter. Pyrex has a low recombination coefficient for atomic hydrogen. If atoms recombine to molecules, their polarization is lost, ionized again this would led to an unpolarized background. Microwaves of 2.45 GHz frequency are transmitted through the pyrex tube into the plasma chamber by means of a copper cavity surrounding the pyrex tube. Cooling is done blowing air through the space between cavity and pyrex tube. The atomic beam enters

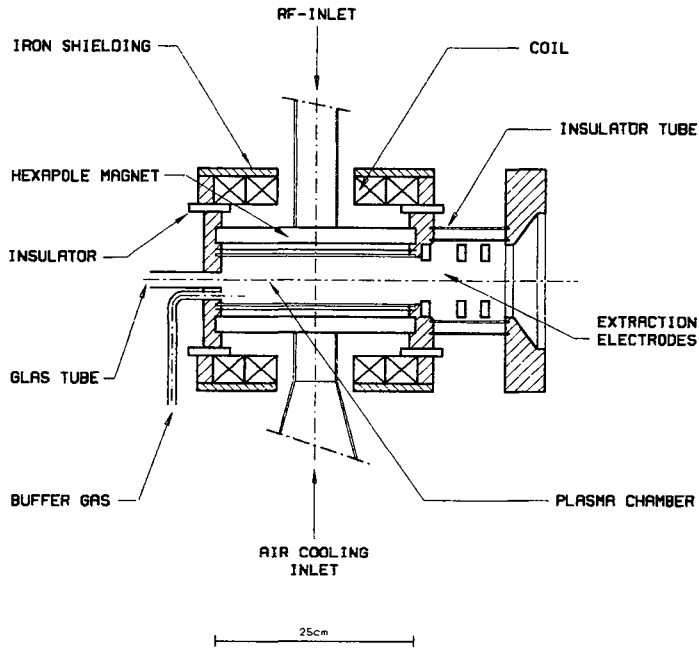


Fig. 18: The first ECR-ionizer for a polarized atomic beam source

the plasma chamber chamber through a 20 mm diameter glass tube. In order to stabilize the discharge an inlet for buffer gas is foreseen.

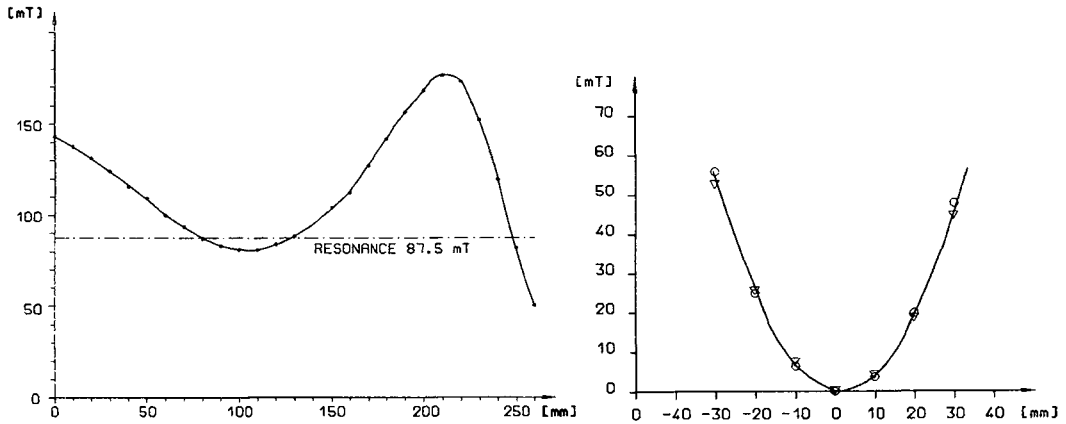


Fig. 19: a) Longitudinal magnetic field (zero corresponds to the position of the extraction system)

b) Magnetic hexapolar field inside the plasma chamber Δ max. rad., O max tang. component

After some basic tests at KFK the ionizer was incorporated into a testbench at PSI. Fig. 20 shows the complete experimental set up. An atomic beam source similar to the one now operating at the PSI injector cyclotron delivers a 30 K cold atomic beam of about  $5 \times 10^{16}$  atoms/sec. [5] By means of a strong field transition (3-5) a deuteron beam is

produced with a tensor polarization of -1. The atoms enter the ECR ionizer through the Pyrex tube of 20 mm diameter. The extracted ions are focused by two electrostatic lenses into a 90° deflection magnet. After the deflection the tensor polarization can be measured by a polarimeter using the  $T(d,n)\alpha$  reaction at about 40 keV.

In the first experiments a polarization of about 20 % was observed, instead of 90 %, which can be achieved by an atomic beam source equipped with an EB-“superionizer”. This polarization did not depend on the magnetic field strength and the microwave power, indicating that no depolarizing hyperfine structure mixing occurs in the ECR-zone. Usually the ionizer can be operated with less than 50 W microwave power. The tests covered magnetic field  $\pm 10$  % around the values of maximum intensity and 15 to 100 W microwave power.

Concerning the polarization the geometry and material of the source are much more important.

The polarization of 20 % at the beginning was observed with a classical stainless steel extraction system with 10 mm holes. Paving the plasma electrode and any other metal part, which could be seen by the atomic beam and the plasma electrode with Pyrex resulted in 40 % polarization. With a large diameter extraction system, allowing an almost undisturbed passage of the atomic beam through the ionizer 85 % were finally achieved. With such an open geometry the addition of a small amount of buffer gas ( $N_2$ ) was helpful to stabilize the discharge and to optimize the efficiency.

To get an information about the beam quality the emittance of the polarized beam after the 90° deflection was measured. The measurement device Fig. 21 was the same which had been used earlier to measure the emittance of the Karlsruhe polarized source PASKA. The results of both measurements are compared in Fig. 21.

With a three electrode system, giving a beam with good transmission to the polarimeter 150  $\mu A$  of polarized deuterons with an emittance area of 60 mm mrad  $\sqrt{MeV}$  were observed after the 90° analyzing magnet. Corresponding values for present sources equipped with an EB-superionizer are 75  $\mu A$  within an estimated emittance of 80 mm mrad  $\sqrt{MeV}$  at PSI and 30  $\mu A$  within a measured emittance of 100 mm mrad  $\sqrt{MeV}$  at Karlsruhe. The smaller intensity of the Karlsruhe source is due to a different performance of the atomic beam apparatus.

This first results are very promising for the improvement of polarized ion sources based on the atomic beam method. It is intended to equip both the sources at PSI and at KFK with an ECR-ionizer in the near future. An advanced model is assembled at present in Karlsruhe and will be tested soon.

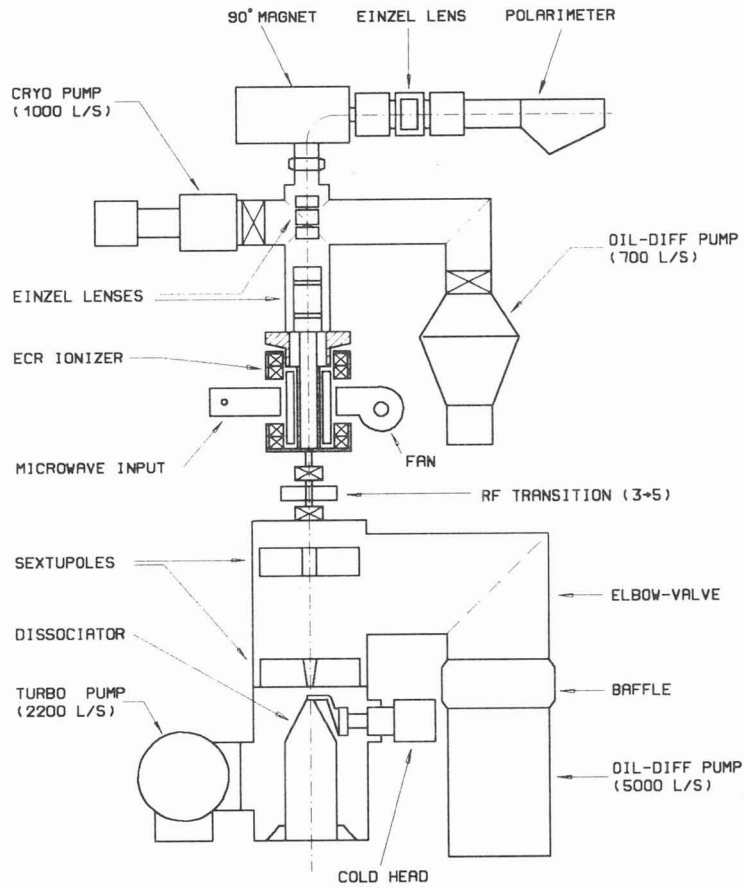


Fig. 20: Schematic diagram of the ECR test bench at PSI

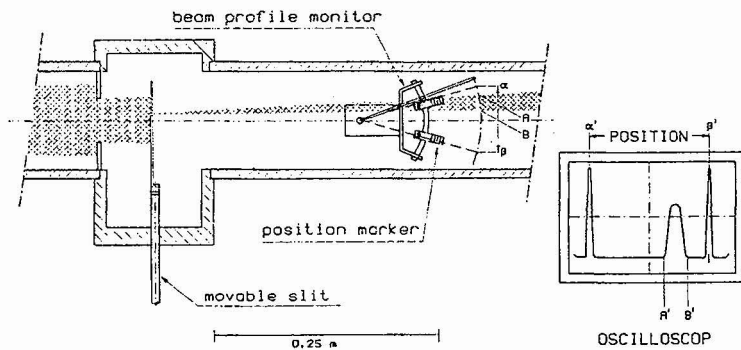


Fig. 21: The emittance measurement device

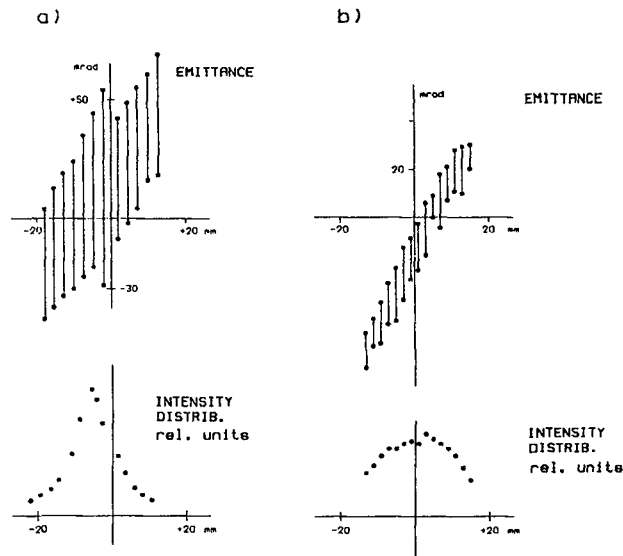


Fig. 22: Measured emittance and intensity distribution of a polarized deuteron beam obtained with  
 a) an EB ionizer (total current  $30 \mu\text{A}$ )  
 b) the ECR ionizer (total current  $150 \mu\text{A}$ )

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