STATUS REPORT OF THE AXIAL INJECTION SYSTEM AT THE KARLSRUHE ISOCHRONOUS CYCLOTRON

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Abstract

A $^6Li^{3+}$-ion source and a Lambshift source for polarized deuterons are now in operation at the Karlsruhe Isochronous Cyclotron. Both sources are mounted horizontally outside the cyclotron. A 16 m long injection transport system whose elements are electrostatic quadrupoles and einzel lenses, brings the beam up to the cyclotron median plane. The efficiency is drastically improved using a bunching system with a simulated sawtooth voltage. Maximum external beam currents are at present 40 nA of polarized deuterons (52 MeV) and 5 nA of $^6Li^{3+}$ ions (156 MeV).

1. Introduction

The Karlsruhe isochronous cyclotron is a fixed energy machine to accelerate ions of e/m=1/2 to a final energy of 26 MeV/nucleon. The demand for high energy polarized deuterons and for high energy $^6Li^{3+}$ ions required the installation of an axial injection system. This is evident in the case of the polarized deuterons produced in a Lambshift source. As for the $^6Li^{3+}$ ions it is also very advantageous because of the restricted space in the center, vacuum problems and the deposition of Li on the surrounding dees.

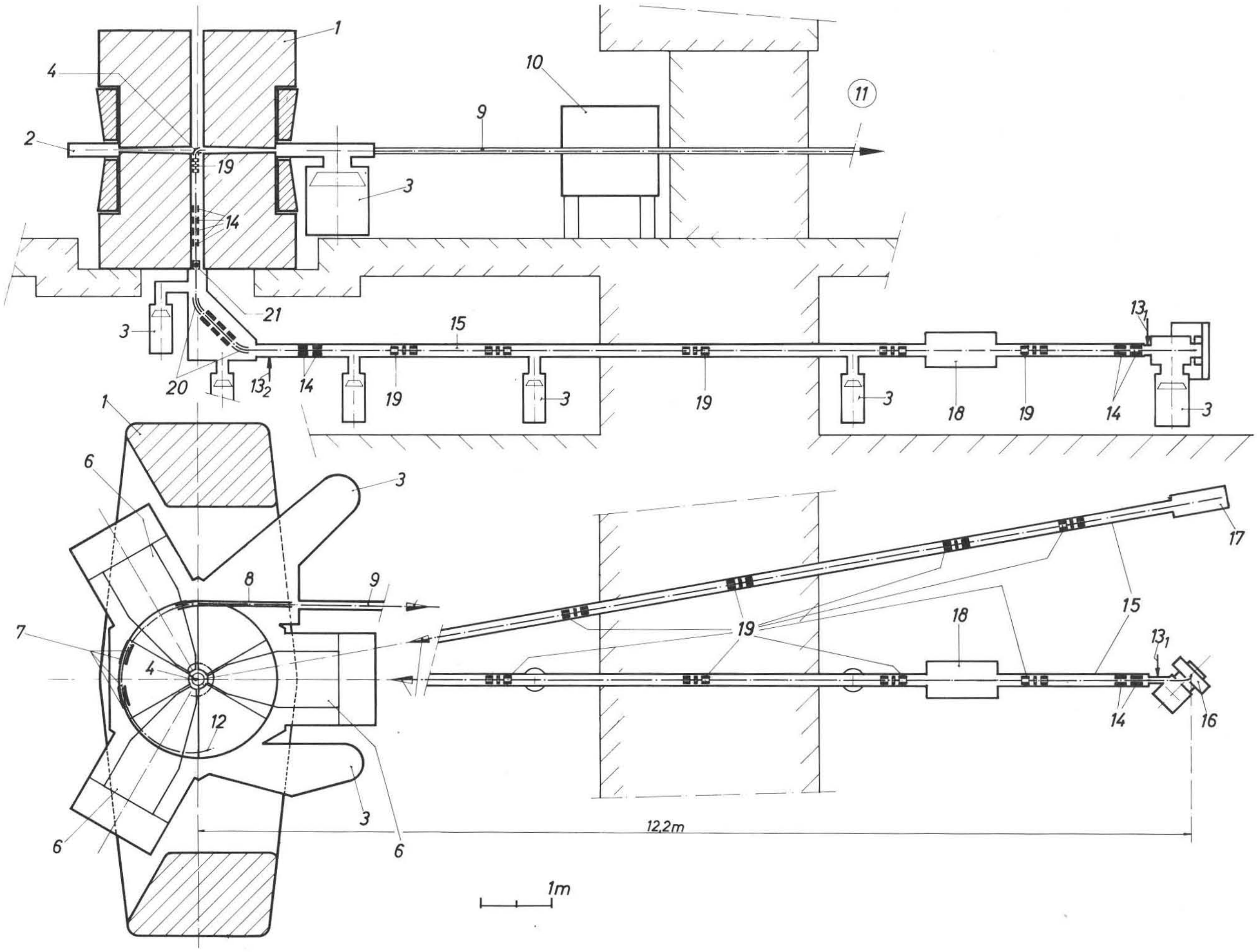

Fig. 1: Schematic cross-sections of the Karlsruhe axial injection system. 1: cyclotron magnet; 2: vacuum chamber; 3: diffusion pumps; 4: hyperboloid inflector; 6: accellerating system; 7: electric extraction elements; 8: magnetic channel; 9: high energy beam line; 10: switching magnet; 11: experimental hall; 13: beam stop; 14: electrostatic quadrupoles; 15: horizontal line; 16: $^6Li^{3+}$ ion source; 17: Lambshift ion source; 18: emittance measurement set up; 19: einzel lenses; 20: 90° bending element; 21: buncher

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For both sources currents above several 100 nA are not to be expected, so the most important point is to inject the beam with high efficiency and low distortion into a centered orbit. In the following sections the various components of the injection system will be briefly described and illustrated.

2. Injection Transport Line

The sources are situated in a new ion source room below the experimental area. The beam lines between source and cyclotron center are shown schematically in fig. 1. A horizontal line of 12 m length guides the beam from the source to an achromatic electrostatic 90° bending element below the cyclotron. This bending element can be rotated under vacuum between the two beam lines. The vertical part of the beam line is inserted into a 16 cm diameter hole in the magnet. This part was developed and built by AEG[1-3]. By this arrangement the ion sources are accessible during internal irradiations, whereas the enormous length of the transport line has not brought any serious difficulties. It was necessary to shield the whole injection line against the stray field of the cyclotron using 10 mm iron shielding. A careful analysis of the vertical injection optics together with the philosophy of the hyperboloid inflector was given previously[1-3]. The whole line is designed to transport beams of 500 mm mrad at 10 kV.

The main problem with the transport system was the proper matching of the ion source emittance onto the axis of the guiding system. In the case of the Penning ion source we found that different operating conditions may shift the center of emittance ellipse by up to 8 mm and 12 mrad in both planes at the input of the horizontal line. To support the matching procedure an emittance measuring system was built up between the Penning source and the beam line, consisting of a multiple-slit diaphragm (16 slits, 0.2 mm wide, 4 mm distance) and an analysing slit (0.2 mm wide) after a field free drift space of 30 cm. Fig. 2 shows a representative result. Beam matching is achieved by small variations of the ion source position and the magnetic field of the Penning source.

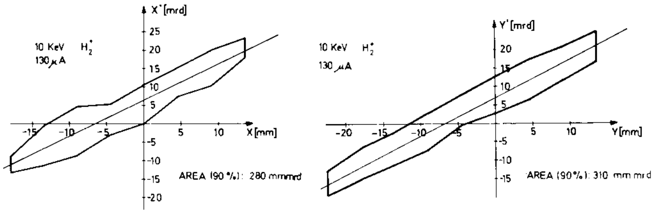

Fig. 2: Representative results of an emittance measurement for a 10 keV H_2^+ beam. X-axis means horizontal.

According to our experience the values for the 20 high voltage parameters for an optimum transmission from source to accelerated beam are reproducible within a few percent. In order to detect instabilities of the power supplies and to avoid incorrect settings the high voltage power supplies are now controlled via CAMAC by a NOVA 2 computer.

The vacuum system consists of 6 diffusion pumps with a total pumping speed of 3500 l/s. It produces a vacuum of about 10^{-6} Torr in the transport line. There have been many pessimistic suggestions about losses of the slow high charge state $^6Li^{3+}$ ions due to interaction with the residual gas. We measured the accelerated beam intensity as a function of the pressure in the injection line for various ions. From the results shown in fig. 3 no dramatic differences for H_2^+, d^+, α and $^6Li^{3+}$ can be observed. Some of the losses in the injection line from source to hyperboloid inflector (see section 5), however, must be attributed to residual gas interactions.

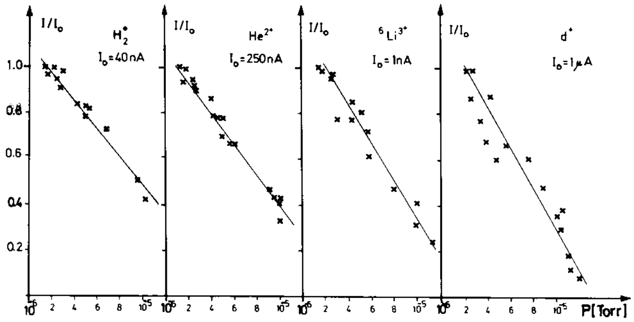

Fig. 3: Measurements of the beam losses due to residual gas interaction in the injection line. I_O: accelerated beam current at best vacuum

3. Bunching

In order to get reasonable intensities the phase acceptance of the cyclotron, only ∿ 10 % for d.c.-currents, must be improved. This has been done by the installation of a two gap bunching element. It consists of an accelerating tube placed near a waist of the beam 1760 mm upstream of the hyperboloid inflector. This rather long distance allows the use of low bunching voltage (U_B ∿ 150 V). The diameter of the bunching tube (12 mm) is a compromise between the acceptance of the system and the distortion in energy produced by aperture effects. It is well known that in order to obtain perfectly narrow bunches one has to apply a sawtooth modulating voltage. The generation of such a sawtooth at 33 MHz is difficult even for the low peak-to-peak amplitude of about 150 V. We therefore calculated the bunching effect for different simulated sawtooth voltages composed of a superposition of different harmonics following the work of Blasche et al.[4]). We found better results for

$$U_B = U_O \{\sin \omega t + \frac{1}{3} \sin 2 \omega t + \frac{1}{9} \sin 3 \omega t\}$$

than for the Fourier series of a sawtooth

$$U_B = U_O \sum_{i=1}^{5} \frac{1}{i} \sin i \omega t$$

truncated after the fifth harmonics. The generation of the simulated sawtooth voltage together with the resulting wave form at the bunching electrode is shown in fig. 4.

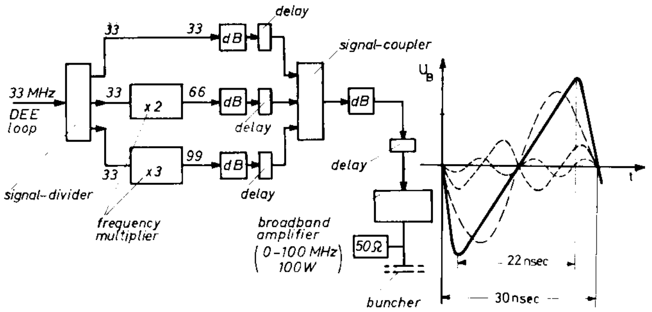

Fig. 4: Generating of a 33 MHz - sawtooth using three harmonics.

4. Ion sources

Three different ion sources have been in use at the injection system

- a commercially available Duoplasmatron, type ORTEC 350 for the commissioning tests of the vertical line
- a Lambshift source
- a Penning source for $^6Li^{3+}$ 5)

An extensive paper on the Lambshift source is given on this conference^6) so we will concentrate on the $^6Li^{3+}$ source.

4.1 $^6Li^{3+}$ Penning source

Since our last publication 5) the Li^{3+} source was improved by replacing one of the two directly heated cathodes by a tantalum reflector on cathode potential. As for the standard internal sources the use of directly heated HfC-cathodes (instead of tungsten)^7) improves the mean lifetime by a factor of 4. The geometrical layout of our present source is given in fig. 5. Ideal operating conditions for high currents of Li^{3+} ions are in principle:

- low density pure Li-vapour
- high arc voltage ($U_a \geq 200$ V) at low arc currents I_a.

For example we get 0.1 µA of Li^{3+} for U_a = 250 V; I_a = 1.2 A. Increasing the arc power to U_a=250 V; I_a = 1.5-2 A increases only the Li^+, not the Li^{3+} current. A maximum of 1 µA Li^{3+} could be achieved at U_a = 350 V; I_a = 1.2 A. The main difficulty operating such a Li source is to adjust and to stabilize the appropriate Li-vapour pressure, because the Li vapour density in the discharge tube is not only defined by the Li-oven temperatur but also by the discharge power. The ^6Li consumption is about 0.02 g/cm^3 h. At present the mean life time of this source is about 30 h.

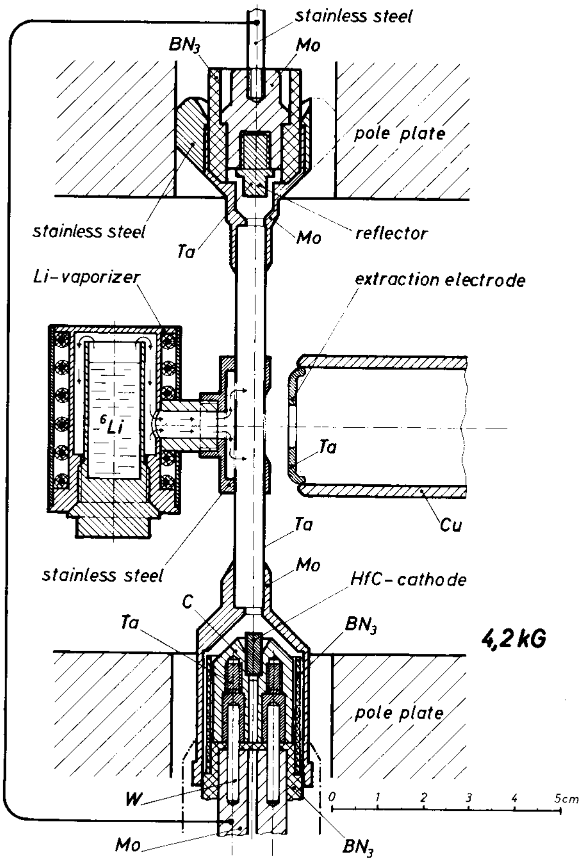

Fig. 5: Section through the $^6Li^{3+}$ Penning source

5. Performance

The quality of an injection system is given by the transmission from source to external beam. In different periods of operation we obtained total efficiencies scattering by a factor of 4. The reasons for this are not completely understood. In the following we list the results for the different ion sources used. Some of the differences in efficiency may due to source properties.

5.1 Duoplasmatron

Beam intensities for d^+ and H_2^+ in the vertical line up to 40 µA were produced with 90 % transparency up to the inflector electrode. The acceptance of the cyclotron was in the range of 6-10 % so that the total efficiency (source to accelerated beam) was 5-8 %. The stripping loss of the H_2^+ beam, with the internal source normally 90 %, was reduced by a factor of 2. The effect of the buncher was not investigated for this source.

5.2 $^6Li^{3+}$ Penning Source

As the $^6Li^{3+}$ currents are very low, and always contaminated with H_2^+ and $^4He^{2+}$, we use α-particles produced in the same source for setting up the beam. The transparency from the horizontal line up to the inflector was 40-70 % and the acceptance of the cyclotron was 7-10 %. With these α-particles we measured the phase widths and bunching factors given in fig. 6. Simulated sawtooth bunching increases the beam intensity by 40 % compared to sinusoidal bunching and yields shorter pulses of 1 nsec fwhm. This small phase width results in an improvement of the extraction rate from 40 % (unbunched beam) to 65 %. The observed bunching gain in the external beam was therefore approximately 7, and the overall efficiency (source to extracted beam) 0.4-2.5 % without and 2.8-22 % with the buncher. In table I the best values obtained so far for a low intensity α beam are listed.

The maximum produced $^6Li^{3+}$ beam intensities before August 75 are 15 nA in the internal beam and 5 nA in the external beam.

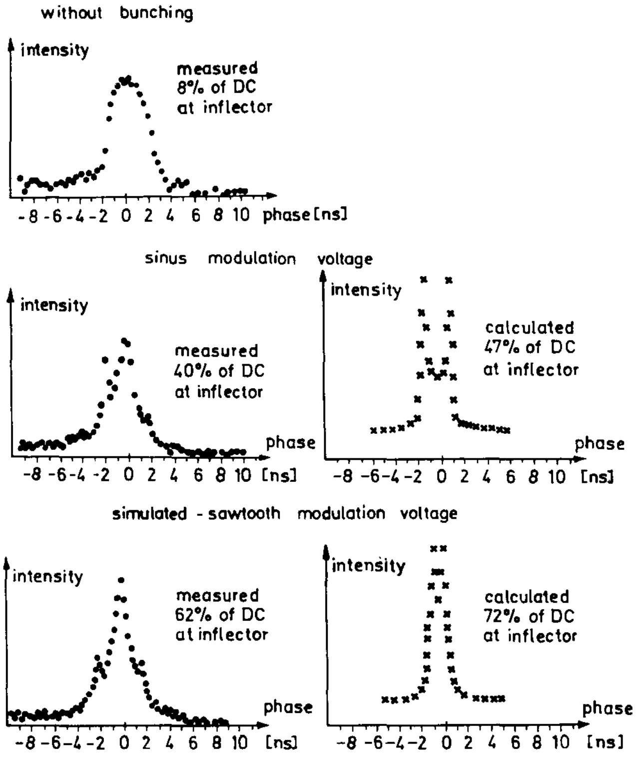

Fig. 6: Comparison of calculated and measured bunching effects. The data were taken with 1 μA $^4He^{2+}$ current in the horizontal line. The phase distribution of the internal beam was measured by γ-ray time of flight. At 33 MHz accelerating frequency 1 nsec corresponds to 12° rf.

Table I: Injection of $^4He^{2+}$ ions from the Li^{3+} source

Current behind source	1000 nA	100 %
at vertical beam line	790 nA	79 %
on inflector	700 nA	70 %
r=800 mm without buncher	53 nA	5.3 %
with buncher	318 nA	31.8 %
extracted without buncher	23 nA	2.3 %
with buncher	160 nA	16 %

5.3 Lambshift Source

As there is an extensive paper on this conference we only give here the results of relevance to the injection system in table II.

Table II Injection of deuterons from the Lambshift source

Current behind source	880 nA	100 %
at vertical beam line	620 nA	70 %
on inflector	480 nA	55 %
r=800 mm without buncher	33 nA	3.8 %
with buncher	114 nA	13 %
extracted without buncher	10 nA	1.1 %
with buncher	35 nA	4 %

6. Concluding Remarks

The Karlsruhe axial injection system is now used for nuclear experiments with polarized deuterons and high energy $^6Li^{3+}$ ions. Several publications [8,9]) within the last year demonstrate a reliable operation of the set up. In the first half year of 1975 the axial injection was used for about 14 % of the whole beam time.

Many people made important contributions to the work described in this paper. Of these we should like to mention J. Biber, H. Kuhn and L. Wiss for their assistence in source construction and operation, E. Röhrl and K. Heidenreich for building up the buncher electronic, and the cyclotron crew.

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DISCUSSION

J. ZICKY: Why do you use such a long horizontal beam path for the axial injection system?

H. SCHWEICKERT: Indeed, we first thought to install the sources right below the cyclotron but the available room there was very confined. With our arrangement it is possible to work at the sources during internal beam irradiations. The length has not caused any serious difficulties.

G. DUTTO: Have you measured the phase width of the external beam and of the internal beam?

H. SCHWEICKERT: We have only done internal measurements of the phase width so far. But we know from rountine measurements with our internal source that there is no significant difference.

G. DUTTO: Do you think that the bunching efficiency depends on the phase width?

H. SCHWEICKERT: The bunching efficiency depends only on the phase width, if you look at it in the external beam because the extraction rate in our machine is dependent on the phase width.

W. VAN KAMPEN: You mentioned for the transmittance of the beam line a figure of 500 mm × mrad at 10 keV. Is the inflector at the central region included in this figure?

H. SCHWEICKERT: Yes, the transmittance includes the hyperboloid inflector.

R.C. ROGERS: What is the mechanical shape of the buncher?

H. SCHWEICKERT: The buncher has no special shape; it is a simple tube, 25 mm long and 12 mm diameter.

E.G. MICHAELIS: What is the vacuum in your transfer line and how do you pump it?

H. SCHWEICKERT: As far as we can measure it -- and we cannot measure it in the region of the hyperboloid inflector -- it is about 1-2 × 10^{-6} in the whole line. There have been many pessimistic suggestions, especially about losses of the high-charge state $^{6}Li^{3+}$ ions due to residual gas interactions. We have measured beam losses due to residual gas interaction in the transport line. No dramatic difference for H_2^+, d^+, α, and $^{6}Li^{3+}$ could be observed.

M. REISER: Your figures seem to indicate that the extraction efficiency for the externally injected beams is about 40 to 50%. How does this compare with internal source operation and could the efficiency be improved?

H. SCHWEICKERT: The extraction efficiency is at present about 10-20% lower for the externally injected beams compared with the internal source. This may be due to two facts: first, we have not yet got much time to centre the injected beam and secondly we have for the standard internal particles a narrower phase width.