EXTERNAL ION SOURCES AND INJECTION LINES AT THE BONN ISOCHRONOUS CYCLOTRON

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Abstract

The complex of external ion source facilities at the Bonn Isochronous Cyclotron is described. A universal ion source of the Penning type was developed for the production of intense beams of multiply charged ions. Details of this ion source and performance figures are presented. An atomic beam polarized ion source is used for the production of polarized protons and deuterons. A modified atomic-beam polarized ion source using a superconducting solenoid ionizer is under construction. For the combined installation of the universal ion source and the polarized ion source a compact beam transport system has been developed which allows the optimum matching with the cyclotron. A buncher with triangular shaped pulses is used in order to increase the beam intensities. Ionoptical and technical details of the external beam lines and the axial injection are presented.

Introduction

The Bonn Isochronous Cyclotron is an energy variable multiparticle 3-Dee machine[1-3] designed for the acceleration of protons, deuterons, ^{3}He- and ^{4}He-particles. In the normal 3rd harmonic mode of operation the energy range is 7-14 MeV/nucleon for charge-to-mass ratios $Q/A \geq 1/2$. Ions heavier than α-particles can be accelerated to an energy of $E=60Q^2/A$ MeV for $Q/A \geq 1/3$. The main characteristics of the accelerator are a high beam quality, a great flexibility in beam preparation and a versatile experimental equipment.

In 1975, an axial ion injection system was installed in connection with a polarized-ion source[4,5]. Meanwhile, a universal external ion source of the PIG type has been designed and constructed for the production of intense proton-, deuteron-, ^{3}He- and ^{4}He-beams as well as multicharged heavy ion beams like lithium, carbon and nitrogen. This development conforms to the increasing interest in heavy ion experiments in the 50-100 MeV range for studies of nuclear structure and reaction mechanisms. The existing atomic beam polarization source has been modified and equipped with a new type of ionizer which makes use of the Penning discharge in a superconducting solenoid . As a result, an order of magnitude greater polarized beam intensities of 2-6 μA are expected at the target stations.

In the course of these changes the existing axial injection system has also been modified and a compact beam handling system for the installation of the universal ion source as well as the polarized-ion source has been designed and constructed. The universal ion source is now routinely in operation and the modified polarized ion source will be installed at the beginning of 1979.

The PIG Ion Source

The universal ion source is a Dubna[6] type hot cathode PIG (Penning Ionization Gauge) source with radial extraction. It is designed and constructed according to an existing source at CEN/Saday [7,8]. The source has a water-cooled copper anode with a circular sectional anode chamber and a replaceable Ta slit. The cathodes are tantalum plates and boron nitride is used as insulator. Both cathodes are connected together electrically. One cathode is indirectly heated with electrons from a hot filament using a 2kV/2A pulsed power supply.

The ion source is in the center of an H shaped type magnet with circular poles of 300 mm diameter and a 200 mm gap (see fig. 1). The operational magnetic field is 0.2-0.4 T. The anode A and the associated power supplies of the discharge are all at the injection potential which is + 7.7 kV for the highest possible particle energies. The extraction slit has an axial aperture of 10 mm and a radial aperture of 1-2 mm depending on the required beam quality and beam intensity. The entrance slit of the extraction electrode (the "puller") is 2·12 mm^2 wide. Its distance from the anode and its lateral position can be adjusted by remote control. The extraction electrode E is at a high negative preacceleration voltage (-20 to -25kV). The magnet is provided with soft-iron shim plates S in order to extract the ion beam perpendicularly to the magnetic field boundary. The resulting magnetic field distribution exhibits a characteristic depression at the boundary between the central pole and the shim plates yielding an appropriate axial focusing of the extracted beam. The shim plates are electrically isolated and at the same high negative preacceleration voltage as the extraction electrode E.

The block diagram of the power supplies is shown in fig. 2. In order to obtain a higher instantaneous arc power and to increase the fractions of multiply-charged ions[8] a pulsing device for the discharge has been provided. The repetition frequency (50-1000 c/s) and the pulse length can be adjusted in order to optimize the output. Besides pulsing continuous operation is also possible. The arc power supply enables arc currents up to 6 A and arc voltages up to 3 kV.

The vacuum at the ion source is maintained at 10^{-5} mbar with a 350 mm diameter oil diffusion pump which is equipped with a -40° cold baffle. A rather stable operation is obtained with a gas flow rate of 1-2 cm^3/min. As usual it is observed that a smaller gas flow yields higher output of multiply-charged heavy ions. The complete ion source can easily be exchanged within 10 min by disconnecting the main flange on top of the vacuum chamber (see fig. 1). The lifetime of the source is mainly limited by the erosion of the tantalum cathodes. With hydrogen and helium ions the lifetime is more than a week, with nitrogen ions the lifetime is 8-12 hours.

The Polarized Ion Source

An atomic beam polarized-ion source for the production of polarized protons and deuterons was installed[5] at the Bonn Isochronous Cyclotron in 1975. The source was designed and constructed by the Institut für Angewandte Physik der Universität Bonn under the direction

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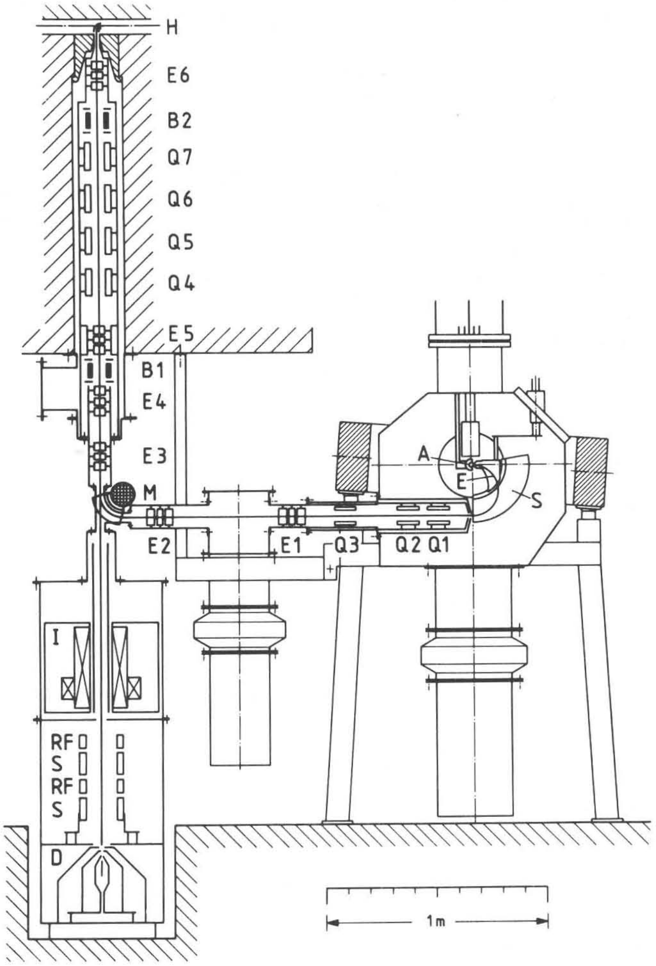

Fig. 1. Layout of the external ion sources and injection lines. A-anode of the PIG ion source, E-extraction electrode, S-shim plates, Q1-Q7-electrical quadrupole lenses, E1-E6-einzel lenses, M-deflecting magnet, B1-B2-buncher, H-hyperboloid inflector, D-dissociator, S-sextupole, RF-RF transition, I-ionizer

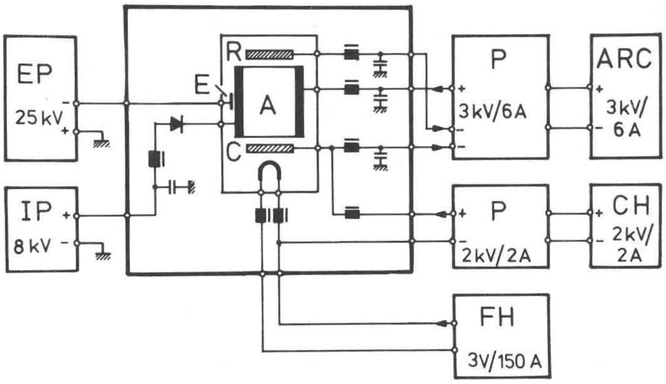

Fig. 2. Block diagram of the PIG power supplies. A-anode, C-cathode, R-reflector, EP-extraction potential, IP-injection potential, P-pulser, ARC-arc power supply, CH-cathode heater, FH-filament heater

of Prof. S. Penselin. Details of the ion source are described elsewhere[4]. Meanwhile a source improvement program led to several modifications of the existing polarized-ion source facility. A cross section through the modified ion source is shown in fig. 1.

First of all, the efficiency of the ionization of the polarized atomic beam was considerably increased by replacing the conventional strong field electron impact ionizer with a Penning discharge in the strong field of a superconducting solenoid[9]. A polarized deuteron beam intensity of 60 μA and a tensor polarization of (0.75±0.03) was achieved. The measured emittance was about 1200 mm·mrad at the mean injection energy of 5.7 keV. Since the emittance is determined by the product $B \cdot R^2$, i.e. the magnetic field B and the radius R where the ionization takes place a smaller emittance is readily obtained with an appropriate circular collimator at the exit of the ionizer. With a 7 mm diam. aperture the emittance corresponds to the cyclotron acceptance of 500 mm·mrad at 5.7 keV injection energy and the polarized beam current is 20 μA. The corresponding ionization volume is confined to a very narrow tube of 3 mm diameter. Thus, a further improvement of the polarized ion source output seems to be possible with an improved focusing of the atomic beam. Investigations in this direction are going on during the present assembling and testing phase of the modified polarized ion source.

Besides the replacement of the ionizer the vacuum system has been changed in order to obtain a very compact design and to conform to the available space under the lower yoke

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of the cyclotron (see fig. 1). The main gas flow of the dissociator is removed by a turbomolecular pump. Cryogenic vacuum pumps are used for the second vacuum stage of the dissociator and the sextupole chamber. The ionizer vacuum is simply maintained by the cryogenic pumping effect of the cryostat of the superconducting solenoid. The following pressures are obtained: less than 10^{-3} mbar in the first pumping stage and 10^{-5} mbar in the second cryogenic pumping stage of the dissociator and less than 10^{-6} Torr in the following elements of the polarized ion source.

Beam Transport

The beam guiding system between the PIG ion source and the median plane of the cyclotron starts at the point where the beam leaves the shim plates S of the source magnet and enters a field free magnetic channel, i.e. an iron tube which acts as a magnetic shunt. At the entrance of the iron tube the beam is decelerated from the preacceleration energy to the injection energy. The phase space distribution is characterized by a sharp radial waist and a divergent axial beam envelope. Due to the strong dispersion of the ion source magnet the actual charge state of the ion beam is readily selected.

The complete beam handling system consists of six einzel lenses E1-E6, seven electrical quadrupole lenses Q1-Q7, two bunchers B1 and B2, a double focusing 90° bending magnet M and a hyperboloid inflector H. The electrical quadrupole lenses Q1, Q2 and Q3 are used to focus the divergent beam into a nearly parallel beam and to reduce the astigmatism which is present at the starting point. The resulting envelopes are shown in fig. 3. The einzel lenses E2 and E3 are used in order to achieve narrow radial and axial envelopes in the compact 90° bending magnet. The einzel lens E3 is also used to match the beam of the polarized ion source onto the optics of the axial injection system. From emittance measurements very similar envelopes are expected from lens E3 on.

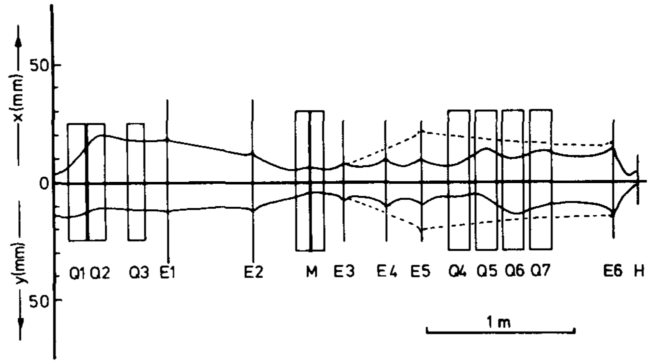

Fig. 3. The envelopes from the PIG ion source to the hyperboloid inflector H. (see also fig. 1)

The ionoptics in the axial part of the beam line is very similar to the previous design[10] and to that of the Karlsruhe isochronous cyclotron as described by Lütter et al.[11]. Orbit calculations in the central region show that an appropriate beam matching is achieved assuming a radial focusing frequency $\nu_r=1$ and an axial focusing frequency $\nu_z=1/6-2/3$. The electrical quadrupole lenses Q4-Q7 are used in order to match the x- and y-envelopes to the periodic solution inside the cyclotron (solid curves in fig. 3). The dashed curves in fig. 3 represent an approximate solution without making use of the electrical quadrupole lenses Q4-Q7. This indicates the flexibility in the adjustment. The optimum matching is done by trial and error.

The transverse geometrical acceptance of the beam transport system and the hyperboloid inflector is at least 500 mm·mrad in both planes (including space charge effects of a 500 µA beam current). Beam diagnostics along the line is done by several Faraday cups and by using the outer electrode of the hyperboloid inflector as cup. The beam centering is monitored with several 4-quadrant collimators. Several x-y steering plates are mounted to provide fine adjustment of the beam axis.

Beam Bunching and Pulsing

Bunching of the DC beam is achieved with two two-gap buncher units B1 and B2. The drift length between the gaps is 3/2 of a cyclotron period. The aperture diameter is 25 mm and the gap width is 1 mm. A frequency variable modulating voltage of symmetrical sawtooth shape is produced by adding appropriately higher harmonic Fourier-components (3rd and 5th harmonic) to the basic sinusoidal signal of the cyclotron RF. The sawtooth generator is synchronized with the cyclotron RF voltage via an adjustable phase shifter. The signal of the sawtooth generator is amplified using commercial wide-band power amplifiers. The coupling with the buncher is achieved with a wide band transformer yielding an impedance transformation 50 → 200 Ω and a voltage transformation of 1 → 2.

The buncher B2 is located near the inflector H in order to minimize debunching from the ion source energy spread and space charge effects. A relatively high energy modulation of ±2% is needed in order to obtain proper bunching at the first acceleration gap of the cyclotron. The dispersion of the hyperboloid inflector transforms an energy spread of ±2% into a vertical (=axial) betatron oscillation with an amplitude of ±0.35 mm. However, regarding the amplitude of the incoherent axial betatron oscillation the increase of the axial phase ellipse is small under normal operation conditions.

With buncher B1 the required energy modulation is only ±0.5%. This buncher is especially suited for low beam currents where

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space charge effects are negligibly small. Its main use is prebunching in combination with buncher B2 in order to optimize the effective buncher position with respect to various debunching effects.

There are very different pulsing modes required from the experiments. For very long pulses a square wave voltage is applied on one of the steering plates. Microscopic beam pulse suppression is achieved by applying a deflection voltage to the hyperboloid inflector. The normal micropulse intervals lie between 34 and 50 nsec according to the RF frequency range 20-29 MHz. The deflection voltage is generated in an oscillator which oscillates on a subharmonic of the cyclotron frequency. Thus, arbitrary pulse intervals between two, ten and more than ten normal micropulse intervals are achievable. It should be noted that a single turn extraction mode[2] is the essential pre-requisite for this kind of pulse suppression. The advantages of the external beam pulsing are low deflection voltages and simple accessibility.

Operation and Performances

The universal ion source operation and performance depends on the ion type which is reqired. For the light ions up to ^4He it is possible to extract DC currents up to 300 μA with an emittance of 500 mm mrad. Higher beam currents are possible at greater emittances. Concerning multiply-charged heavy ions the following DC -ion currents have been extracted in the testing period: 12 μA of $^{12}C^{4+}$ ions and 10 μA of $^{14}N^{5+}$. After the installation at the cyclotron light ions are produced at sufficient intensities required from the experiments. The achievable output is comparable to that of the internal ion source with the exception of helium ions where higher beam currents are possible with the external PIG source. There are also indications of an improved beam quality due to the phase matching facility of the buncher system though a detailed investigation of these phenomena has not yet been performed. Recently, first experiments with 80 MeV $^{12}C^{4+}$ ions and 100 MeV $^{14}N^{5+}$ ions have been performed with 50-250 nA external beam currents at the target.

The following transmission data are obtained: Without bunching, 10% of the primary DC intensity is accepted by the cyclotron and accelerated up to the extraction. Using the buncher facility 25%-35% of the primary DC is accepted. Transmission losses in the axial injection line are very small.

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