The First RFQ-Injector for a Cyclotron*

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Abstract

Based on the development of the variable energy 4-rod-RFQ a new injector for the ISL heavy ion cyclotron at the HMI Berlin (the former VICKSI machine) will be built. The ECR source together with two VE-RFQs will replace the 8UD-Tandem injector in order to meet the demands of solid state physics users. The design of the new RFQ injector and the status of the project will be discussed.

1. Introduction

The ISL [1] is an isochronous cyclotron with four separated sectors. It has an external injection of beams with variable energy from either a CN-Van-de-Graaff or an 8UD-Tandem. Figure 1 shows the layout of the accelerator complex and its major facilities.

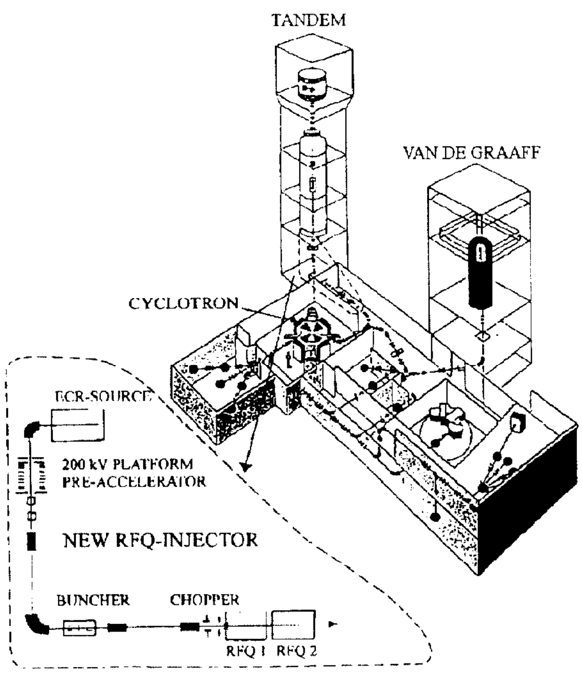

Fig. 1 Scheme of the heavy ion accelerator complex with the planned changings in the encircled area

The full energy range of the cyclotron extends from 1.4 to 32 MeV/u for heavy ions. The limitation for this machine is the injected ion beam, which must have a charge-to-mass-ratio between 1/8 and 1/2 with an energy between 0.08 and 1.9 MeV/u. To reach the necessary charge-to-mass-ratios a gas or foil stripper must be used. This is one of the main reasons for the beam current limitations, in particular for heavier ions.

The scientific program at the ISL is changing from nuclear physics to solid state physics. To meet demands from solid state physics users, which use already 50% of the available beam time [2] it is necessary to get higher intensities in the energy range between 2 to 6 MeV/u, which is impossible with the machine described above.

For this reason, the tandem injector will be replaced by a combination of an ECR ion source on a 200 kV platform and a VE-RFQ, which will produce highly charged ions with charge-to-mass-ratios between 1/8 and 1/4. This combination will accelerate the ions to energies between 0.09 and 0.36 MeV/u to cover the range of final energies out of the cyclotron between 1.5 and 6 MeV/u.

2. The VE-RFQ-Structure

In a Radio Frequency Quadrupole (RFQ) structure [3,4] acceleration is achieved by a geometrical modulation of quadrupole electrodes leading to axial components of the field. The mechanical modulation of the RFQ-quadrupole electrodes, as indicated in figure 2, creates an electrical field which has a longitudinal component to accelerate and a radial component to focus. The shape of the electrodes is characterized by the parameters aperture radius a, modulation m and the modulation period L.

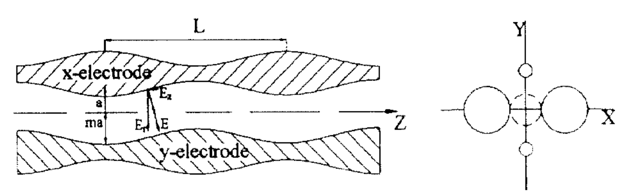

Fig. 2 Scheme of the modulated RFQ electrodes

Electrical focusing forces are independent of the ion velocity v_p and, if rf-fields are applied, higher voltages than in a dc quadrupole system can be reached, giving a very strong focusing with a large radial acceptance.

Typical for RFQs is the fixed velocity profile which can only be changed by varying the cell length L or, for an unchangeable structure, by varying the frequency f. The second possibility of changing the Wideröe [5] resonance condition: $L = \beta_p \lambda_0/2 = v_p/2f$, is the way which has been used for RFQs with variable energy (VE-RFQ) [6]. For this reason it's possible to change the output energy using the same electrode system by varying the resonance frequency of the cavity: $v_p \sim f$, $T \sim v_p^2$.

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To change the frequency of the 4-Rod-RFQ, a type of RFQ resonator developed in Frankfurt [7], the resonator can be tuned capacitively or inductively. Figure 3 shows the latter way of tuning by a movable tuningplate, which varies the effective length of the stems.

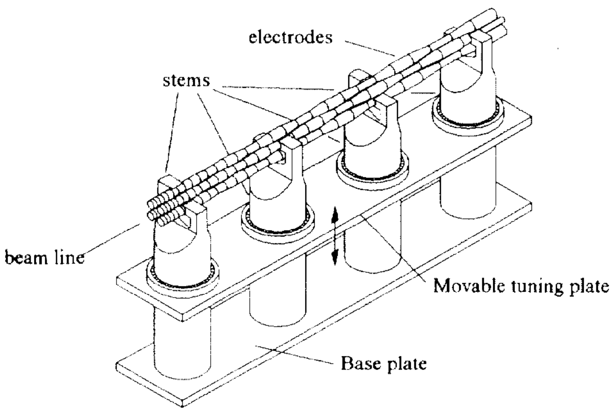


Fig. 3 Scheme of the VE-RFQ

In Frankfurt the VE-RFQ was developed at first for the application as a cluster postaccelerator at the 0.5 MV Cockroft-Walton facility at the IPNL in Lyon (France) [8,9]. It is designed for E_{in}=10 keV/u and an output energy between E_{out}=50 and E_{out}=100 keV/u for m=50u.

Based on the experiences of this project, a first combination of an ECR ion source with an VE-RFQ has been built for the IKF Frankfurt. The VE-RFQ structure is designed for a minimum specific charge of 0.15, an output ion energy of E_{out}=100-200 keV/u, a maximum electrode voltage of 70 kV and has a structure length of 1.5 m.

3. RFQ as Cyclotron-Injector

A first proposal to use an RFQ to improve the axial injection system of a compact cyclotron was made by Hamm [10]. To inject in a Separated Sector Cyclotron, the RFQ has to provide a bunched beam at a well defined injection energy given by the inner radius of the SSC. The operating frequency of the RFQ must be synchronized with the cyclotron frequency, which for RFQs normally means a fixed output energy per nucleon. This would be a possible solution for fixed energy cyclotrons.

To keep the energy variability of the cyclotron it's necessary to have an injector which has also a variable energy and frequency. VE-RFQs have a fixed ratio of output to input energy given by the length of the first and last modulation cell. This is similar to the energy gain factor of a SS-Cyclotron which makes them well suited as injectors [11].

To cover the energy range of 1.5-6 MeV/u the injection energy of the ISL must be between E_{in}=90 and E_{in}=360 keV/u, at cyclotron frequencies of 10 to 20 MHz.

The new injector consists of an ECR-source and a VE-RFQ. The RFQ-parameters are shown in table 1.

Table 1
RFQ parameters

min./max. E_{in}	15.16/29.72 [keV]
min./max. E_{out} RFQ 1	90.98/178.35 [keV]
min./max. E_{out} RFQ 2	178.35/355.09 keV
Energy gain factor RFQ 1	6
Energy gain factor RFQ 2	1.96
charge-to-mass-ratio	1/8-1/4
Frequency	85-120 [MHz]
Electrode voltage (max.)	50 [kV]
Length/diameter	3/0.5 [m]

The new injector has to fit into the existing tandem beam line. To stretch the energy range the RFQ will be split into two RFQ stages. Each stage with a length of 1.5 m consists of a ten stems 4-Rod-RFQ-structure. With a rf-power of 20 kW per stage an electrode voltage of 50 kV is possible. In the first mode of operation both RFQs accelerate, the output energy of the cyclotron is between E_{out}=3-6 MeV/u with a harmonic number of 5 for the cyclotron. For the low energy beam only RFQ 1 accelerates while RFQ 2 is detuned to transport the beam. In this mode the energy range of the cyclotron is between E_{out}=1.5-3 MeV/u. The cyclotron works on the harmonic number 7. In both modes the RFQs are tuned to the eigth harmonic of the cyclotron. The cyclotron parameters are shown in table 2.

Table 2
Cyclotron parameters

K-factor	134 [MeV]
Injection radius	0.43 [m]
Extraction radius	1.8 [m]
Number of trimcoils	12
Rf-frequency	10 to 20 [M]Hz
max. dee-voltage	140 [kV] (peak)
energy gain factor	16.8-18.6
Harmonic number H	2 to 7

The RFQ-output emittance depends largely on the input conditions. For input beams with $\Delta E/E < 1\%$, normalized emittance $\varepsilon_n < 0.5\ \pi$ mm mrad and a bunch length $\Delta t < 1$ ns a transmission of 100% is expected. To reach this beam quality it's necessary to have a buncher-chopper system between the ECR and the RFQ [12].

The ECR-source is mounted on the 200 kV platform, formerly used for the tandem. The vertical beam is bent 90 °, passes through the buncher-chopper-system and will be injected into the RFQs. The final matching into the RFQ will be done by a triplet lens approximately one meter before the RFQ to allow for diagnostics and a Faraday cup. The beam from the RFQ is transported into the injection beamline of the cyclotron, to which a rebuncher has been added to make a proper time focus for the cyclotron. A planview of the ECR-RFQ-Cyclotron complex is shown in figure 4.

Figure 5 shows results of PARMTEQ-simulations for the first RFQ.

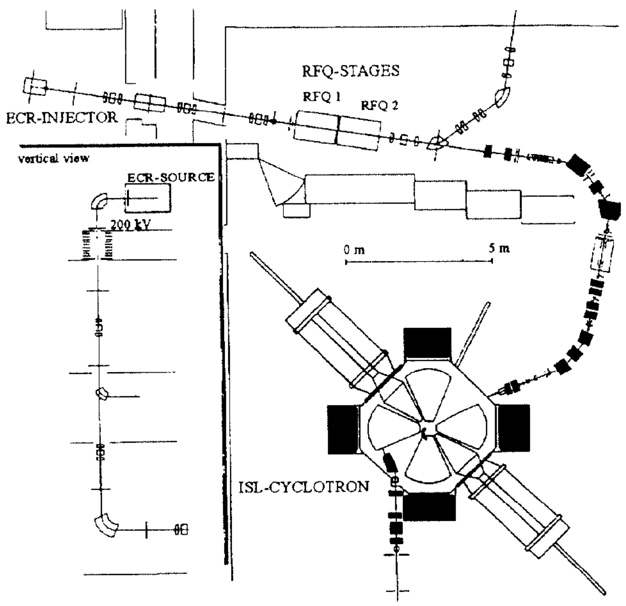
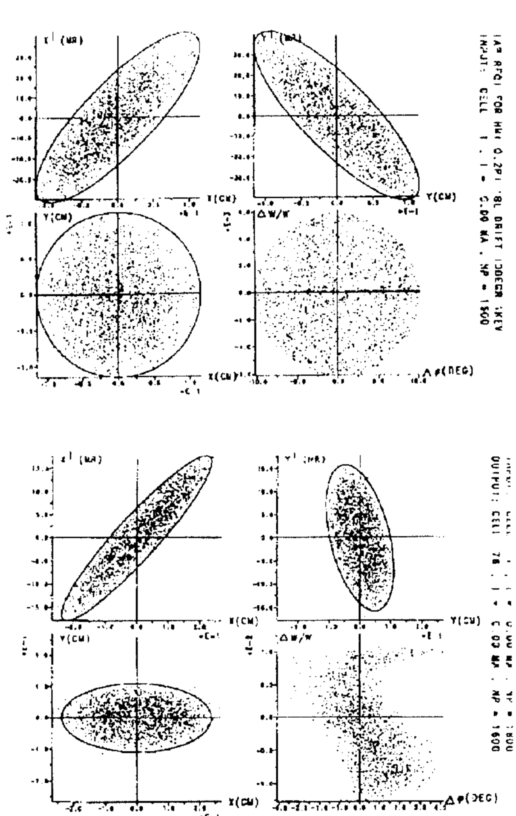


Fig. 4 View of the Cyclotron with the new Injector



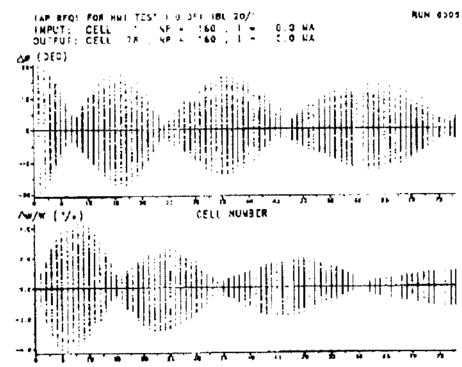


Fig. 5 PARMTEQ-simulations of RFQ 1

4. Status and Schedule

At present the injection system and the RFQ-design is being optimized. To reach a proper matching with the existing quadrupole triplet, the space between the lens and the RFQ-entrance, planned to be used for emittance measurements, steering, beam transformers, and chopper slits, must be optimized.

The mechanical design of the RFQ-tank is done, the details of structure support stems and electrode cooling not yet fixed. Beam dynamic simulations for the electrode design and especially for the region between the RFQs is in progress.

The RFQ-system will be manufactured by NTG [13]. First tests are scheduled for October 1995.

5. References

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