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Operation of the RFQ-injector at the ISL cyclotron

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Abstract Since 1999, a new injector for the k132 cyclotron at ISL-Berlin has been operated successfully. The new machine consists of an ECR-source on a high voltage platform and an RFQ accelerator of novel 2-stage-design. Beams are injected radially into the cyclotron at an energy level of 90 to 360 keV per nucleon, at a charge to mass ratio of 1/8 to 1/5. We report on operation experience and hardware improvements.

Key words accelerator • cyclotron • injector • ISL-Berlin • RFQ-injector

Introduction

For several years, RFQs (**R**adio **F**requency **Q**uadrupoles) have been considered to be a good choice as an injector for linacs but not for a cyclotron. The latter is suitable for acceleration of a large variety of beams by variation of the magnetic and the RF fields, whereas the RFQ accelerator usually is a fixed frequency machine, with precisely calculated and manufactured beam channel profile to provide focussing and accelerating forces by the same RF fields, for just one beam. Ten years ago, first RFQs have been developed for variable frequency operation, which allows variable output energy of the RFQ-beams. This prompted ideas to use the RFQ-type of accelerator as a cyclotron injector (another application has been reported from RIKEN in Japan with a 90 keV/n VE-RFQ as injector for their frequency variable linac). At ISL (**I**onen-**S**trahl-**L**abor-Berlin – Ion Beam Laboratory) [3, 4, 9], these ideas have been successfully applied for the first time, and operation experience can be reported.

Accelerator description

A general view of the different accelerators of the facility is shown in Fig. 1. The main accelerator is the k132 cyclotron [5], with radial injection of beams from either a 5.5 MV Van de Graaff or from the new variable frequency RFQ, installed in the former tandem-tower of the ISL predecessor VICKSI.

The cyclotron has been built in the late 1970's by SCANDITRONIX. Each of the four normal conducting sector magnets has a weight of about 90 t. The maximum mean field is 1 T with a maximum current of 2000 A. The maximum dimension is about 13 m if measured over the two RF-resonators placed in opposite magnetic valleys. The RF-system can be operated in the frequency range of 10 to 20 MHz with a maximum voltage of 140 KV on the dee-tips. The operation of the 2 resonators is either push/push

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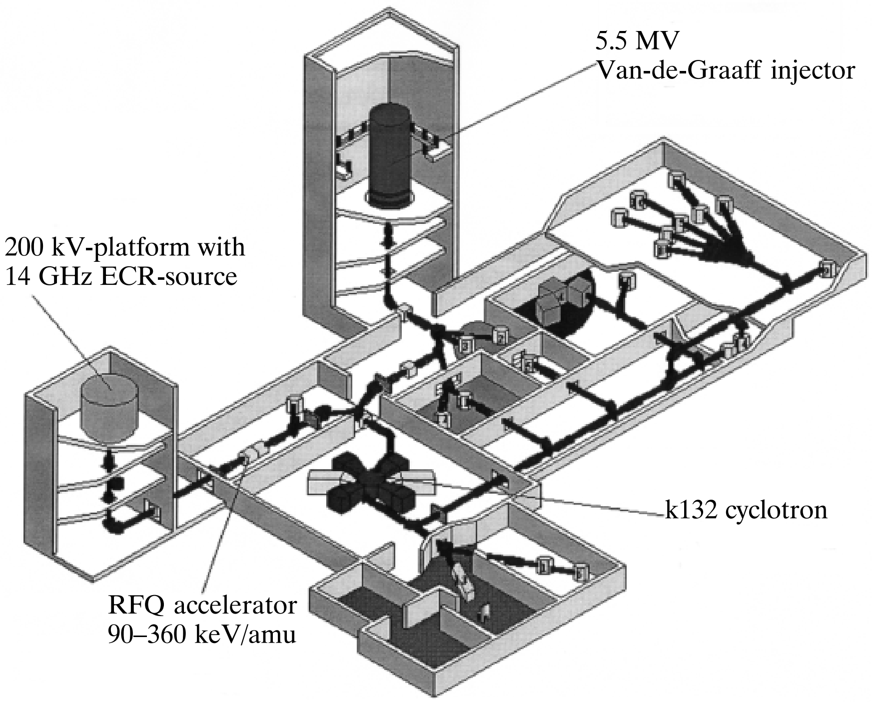

Fig. 1. ISL layout.

or push/pull, at harmonics 2 to 7 of the particle revolution frequency. The machine has no internal ion source, but a radial injection path for externally produced beams. Three injection elements bring the beam to a fixed injection orbit with a radius of 40 cm. The fixed injection-orbit and extraction at 180 cm result in a fixed relation between injected and extracted beam energy, if the necessary field corrections for relativistic effects are neglected. Then, the cyclotron can be considered as a beam energy multiplier. The extracted beam energy in the ISL-case is about a factor of 17 higher than the injected one. Beams within a very large range of energies from 1.5 to 72 MeV/nucleon may be extracted.

The injection beam line merges the two injectors at about 10 m upstream of the cyclotron. Another 10 m upstream to the left (Fig. 1), the accelerator of the new RFQ-injector is shown: it consists of the 2 stages RFQ1 and RFQ2. Both stages are operated in the frequency range of 85 to 120 MHz with RF-fields in continuous wave mode at the 8th harmonic of the cyclotron. Two RF amplifiers provide an independent drive for each stage with a maximum power of 20 KW. Injection into the RFQ is done with heavy ion beams at high charge state from an ECR-source of SUPERNANOGAN-type [8]; in contrast to the Van-de-Graaf injection there is no stripper. The beams are pre-accelerated to an energy of 15 to 30 keV/nucleon and bunched at the cyclotron frequency with more than 50% of the dc-beam within a pulse width of less than 1 ns. The first RFQ-stage accelerates the beam bunches to 6 times the input energy. By change of RF-phase and -amplitude, the second RFQ-stage either accelerates the beam by an additional factor of 2, or the beam is just transported. This RFQ-design allows for beams from the new injector with an energy range of 90 to 360 keV/nucleon, which means 1.5 to 6 MeV/nucleon on target. For the lowest energy, a minimum ratio of charge q to mass A of 1/8 is required, and the cyclotron RF has to be operated at harmonic number 7 with respect to the particle revolution frequency. At maximum energy, the ECR-source must deliver beams with q/A of at least 1/5, and the cyclotron runs at harmonic number 5. More detailed descriptions with respect to the accelerator design can be found in [1, 2, 7] and references therein. To stress the considerable improvement of ISL obtained with the new RFQ the energy-mass-characteristics of the accelerator-facility (Fig. 2), beam energy on target *vs.* mass number of accelerated ions, is shown for the present ISL, Berlin. The area in black covers available beams with the Van-de-Graaff injector, the large area of heavy ion beams, shown as lined, is opened up by our new RFQ-injector.

RFQ accelerator improvement

Early operation experience indicated the necessity of further RFQ accelerator improvement to overcome several deficiencies [6], which can be largely ascribed to the prototype character of the machine.

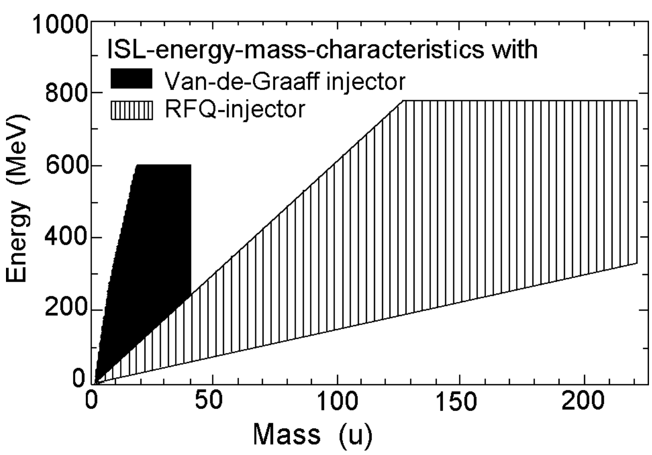

Fig. 2. ISL: ions and energies.

The parasitic oscillations of the RFQ in the middle part of the frequency range got more severe at higher operating power and were obviously cohered with amplifier mismatch. By change of the coupling loop design, the power transfer into the RFQ-cavities has been modified: each amplifier provides up to 25 KW of RF-power, fed via 10 m of coaxial cable onto a coaxial switch. This switch either connects onto a broadband load during amplifier tuning, or to the resonator for RFQ-operation. The impedance matching of the high Q resonator to the 50 Ohm transfer cable is done with the coupling loop. Usually the loop position is mechanically tuned for optimum matching at each change of operating frequency. We tried to avoid this tuning by searching for one fixed loop position good for every frequency within our range of operation. Our early solution to this problem was imperfect, since self oscillation was induced within a part of the RFQ-frequency-band. The new loop is optimized so as to enhance the capacitive part of coupling. After this modification, no more self oscillation was observed, and the reflected power is less than 1% over the complete operating band.

Several breakdowns were caused by the electronics. The system is designed in NIM-technique with several different modules. Therefore, many internal and external connections must be provided, resulting in shaky contacts to be a main cause for unscheduled breakdowns. Another cause are defect components of the power amplifiers. Since there have been almost no spare parts delivered by the manufacturer, one additional driver has been bought and a complete set of spare electronics is in production. The DOS-based operating system of the PCs used for RFQ-setup and surveillance is going to be changed into a WINDOWS-system in order to be able to run several tasks in parallel. First tests of this new control on the running system have been successful.

If operated with very heavy ions, beam loss in the RFQ-structure seems to be increased. In addition, at power levels above 10 KW the RFQ tends to develop heavy sparking. Partly, this is attributed to poor vacuum conditions. The vacuum system of the RFQ-tank uses two turbopumps only and does not allow for the specified low pressure of below 1×10^{-7} mbar due to insufficient pumping speed. We tested additional cryo panels, cooled to liquid nitrogen temperature, and achieved the required pressure within the 10^{-8} mbar-range. However, we want to avoid the necessary installation for a permanent liquid nitrogen supply and, therefore, decided to test a Sterling pump, instead. At present, a pump of this type is going to be installed.

Another case of concern with respect to beam losses is the damage to the RFQ beam channel. Several openings of the RFQ-tank revealed changes of the surfaces of the RFQ-electrodes. At areas exposed to accelerated beam particles strong sputtering is apparent. Therefore, a complete spare set of electrodes has been manufactured at NTG. This set is still waiting for its final galvanic treatment at GSI.

In order to further reduce beam loss in the acceleration channel, an additional chopper has been taken into operation in front of the RFQ. Due to the limitations of bunching, about half of the beam from the ion source does arrive at wrong times at the RFQ-entrance, and was lost in the acceleration channel. With the new chopper, about two-third of these potentially harmful particles are deflected onto a plate in front of the RFQ. The clearance for the beam at this position was decreased from 8 mm to 4 mm without cutting into the RFQ beam admittance.

Injector operation experience

"Operation" of our machine is excellent as far as running a beam on target is concerned. There are occasional failures of components, and sometimes the computer control is impaired, but in the long run unscheduled downtimes have been kept well below a few percent of operating time. Also, feeding the beam through the RFQ itself is a minor detail done in seconds. However, speeding up beam tuning of the whole accelerator system is of great concern. Usually, one shift of 8 h is sufficient for beam setup with the old CN-injector. With the new RFQ-injector, setup-times of more than a day were necessary in the beginning. As of today, we are still planning with two shifts of beam tuning. There are several reasons for this:

- The ECR-source needs "tender loving care" for a high state of charge and/or metallic ions.
- The RFQ acts as a very strong coupling element in every dimension of phase space.
- The settings of 7 RF-phases for the different accelerator components must be found.
- The RFQ output energy changes strongly on several parameters, without clear dependancy.

Once a beam has been developed, the complete set of parameters can be stored and reloaded for the next scheduled setup. This gives a fine starting point for tuning, but the reproducibility especially for the RF phase values, is not good enough for the beam to show up at the right spot, directly. To further speed up beam tuning, hard- and software have been changed:

- The stability of the ECR-ion-source was drastically improved (new source, new regulated high voltage supply, new gas supply scheme).
- A new "injector phase" is available, which allows a "one parameter" – shift of the injected beam in the cyclotron by 360 degrees of RF-phase.
- The energy calibration of the RFQ-analyzing magnet and a new software tool in the control room provides a fast and sensitive tuning procedure for the RFQ-parameters.

The efforts on ion source development have been largely payed off. The new high voltage supply is stabilized to the 10^{-5}-range, and the gas for the plasma got a fast and precise flow control. These changes led to a stability of better than 2% of the beam intensity on target, short and long term. Stable beams like these enable beam tuning to the tip.

Phase control of the different RF-systems is the most difficult task during beam tuning, if beam diagnostics is insufficient. The bunchers in front of the RFQ can be tuned to a pickup signal, which asks for about 1 eμA of beam to be able to deliver a response with sufficient sensitivity. The settings of 4 parameters, phase and amplitude of the double drift buncher system, must be found by observing just this one beam signal. Another pickup signal, directly downstream of the RFQ, is used to find phases for the 2 RFQ-stages. Good pickup signals are produced by an extracted beam over a very large range of energy. The proper energy

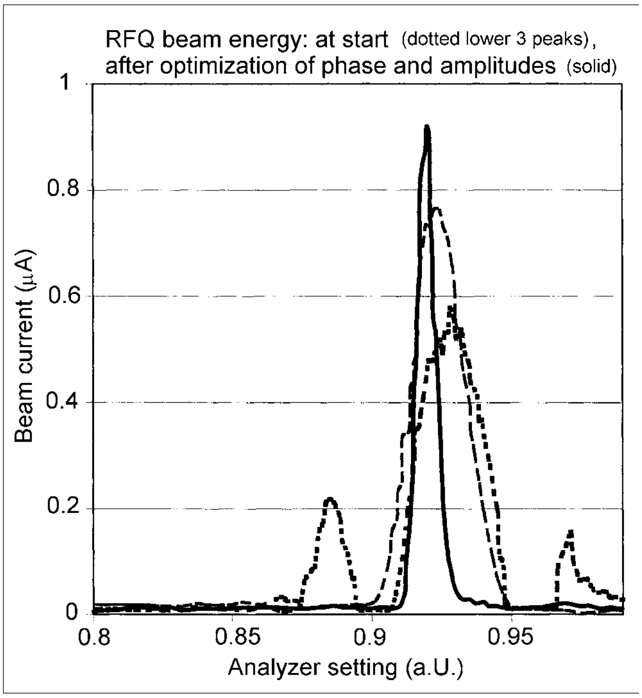

Fig. 3. Analyzing RFQ beam energy.

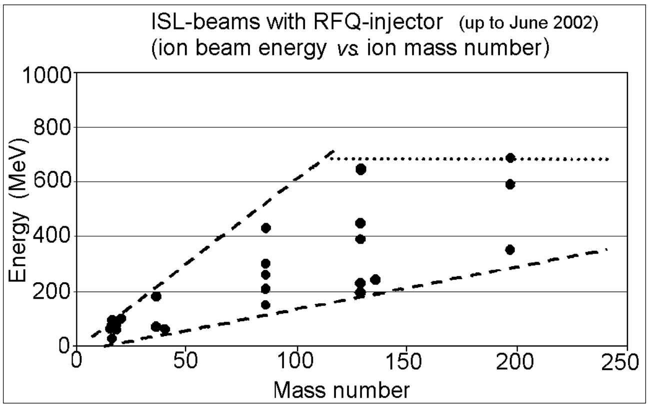

Fig. 4. ISL-beams with RFQ-injector.

only shows up several meters further downstream, if another dipole and 4 quadrupole settings have been found. Finally, the beam is to be injected into the cyclotron. With a new "injector phase", the reference signal for all injector systems can be shifted within the range of 360 degrees of RF-phase with respect to the cyclotron. The radial probe signal of the first beam turns in the cyclotron is used to determine the proper injection phase. This method is insensitive and time consuming, but a pickup in front of the cyclotron would give insufficient signals due to the initially large time spread of the beam bunches there. Afterwards, the rebuncher, located 7 m upstream of the cyclotron, is taken into operation and is tuned. Again the signal of the radial probe defines the proper setting. The tuning of this buncher-phase is very sensitive, because of the combined shift in beam energy, which transforms immediately into a change of beam position at cyclotron injection. A change of only one degree of this phase may mean a complete loss of beam in the cyclotron.

At RFQ-commissioning, beam energy selection has been very time consuming. Depending on input conditions and RF-phase of the second stage, the RFQ can deliver output beams within a broad range of energy. This behaviour has been predicted. Actual data are presented in Fig. 3, made at machine setup: After first extraction of beam from the RFQ and optimization of beam intensity, the analyzing magnet after the RFQ often shows a broad energy distribution as given with the lowest dotted curve. Three different beam energies, each with large energy spread, are measured. Tuning of the amplitude of both RFQ-stages and the phase changing of the second stage by just a few percent may improve the measured energy spread drastically, as shown with the other curves, best with the solid line.

Several beams (Fig. 4) have been newly developed with the RFQ-injector. The most important are three beams of gold particles at 351, 592 and 688 MeV cyclotron extraction energy for research on ion tracks. The higher energies require high charge states of the ion; in case of the 688 MeV-beam (3.5 MeV/nucleon) the 32+ is needed. Here the source output is rather limited, and good beam transmission is difficult to achieve due to fading beam diagnostics. With an analyzed source output of 200 enA, just 20 enA were left for injection into the cyclotron, and no more than 5 enA could be extracted at full energy. Therefore, further optimization is necessary. The overall transmission for the 351 MeV-beam is better than 10%, and a beam intensity of 400 enA could be delivered on target. The Figure shows all beams which have been developed up to June 2002 with the RFQ-cyclotron combination.

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