BEAM DYNAMICS OF AN INTEGRATED RFQ-DRIFTTUBE-COMBINATION*

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Abstract

In a collaboration with the GSI in Darmstadt an RFQ-Drifttube-Combination for the Heidelberg cancer therapy center HICAT has been designed, built and successfully tested with beam at the IAP Frankfurt. The integration and combination of both an RFQ and a rebunching drifttube unit inside a common cavity forming one single resonant RF-structure has been realized for the first time with this machine. The results of the beam measurements and questions about the beam dynamics simulations of such a combination have been investigated in detail with the code RFQsim.

INTRODUCTION

A buncher is used for matching the longitudinal beam properties of an RFQ to the acceptance of a following drift tube structure. A common solution is a separate cavity with a short sequence of drift tubes forming one or two gaps working at -90° ideal phase for beam bunching, like for example at the HLI [1] at GSI. The design studies for HICAT lead to a very compact overall concept [2], well suited for a daily operation in a clinical environment. On the basis of that we tried to do a combination of a 4-rod-RFQ [3] and drift tubes inside a common tank, driven by only one RF-amplifier. The advantages of an integrated solution are a very compact and easy to use machine, which saves building and operating costs. The basic parameters of the structure are summarized in table 1.

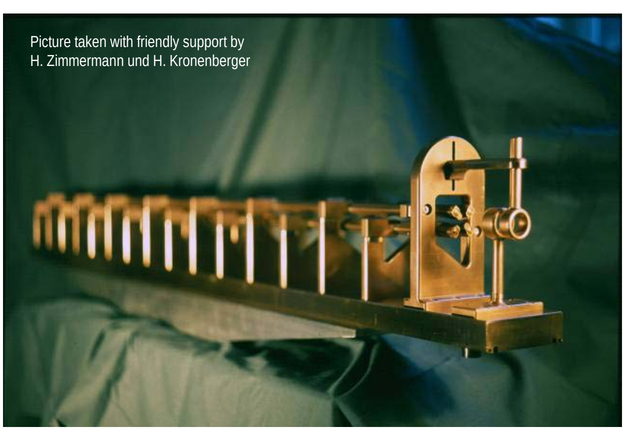

Figure 1: The RFQ-Drifttube-Combination.

Operating frequency	216.816 MHz
Ion species	$^{12}C^{4+}$, protons
Length of tank	1.40 m
Tank diameter	250 mm
# of RFQ cells	219
# of matching in cells	8
Min. aperture	2.63 mm
Max. modulation	1.867
Max. focusing strength *B*	4.84
Input energy	8 keV/u
Input emittance	$\varepsilon_{x,y}$=150 π mm mrad
Electrode voltage	70 kV
Exp. Power consumption	165 kW
Current	max. 2 mA H^+
Output energy	403 keV/u
max. beam angle at the exit	±20 mrad (in both planes)
Phase width at IH entrance	$\Delta\varphi \leq \pm 15°$

Table 1: Basic RFQ parameters.

The 217 MHz RFQ will be a part of the HICAT accelerator complex, which is generally divided into two parts: a linac-section for pre-acceleration of $^{12}C^{4+}$ up to 7 MeV/u and the following synchrotron ring-structure for acceleration of completely stripped $^{12}C^{6+}$ to final energies between 50 and 430 MeV/u. The linac consists of an IH-type drift tube structure [4] following the RFQ. The Ions are generated in two separate ECR sources, to switch between two different ion species very fast.

BEAM TESTS

The design and the building of the combination have been done at the IAP in Frankfurt. It was ready for beam testing in the fall of 2003. In 2004 we have then performed several beam tests with H^+ in Frankfurt. A duoplasmatron and an Einzellens system for injection had been chosen for ion production resp. injection into the RFQ [5]. For diagnostics we had a slit grid emittance measuring system for both planes, a Faraday cup and two bending magnets for energy analysis. The RFQ was driven by a 24 kW rf-amplifier.

The ion source and the Einzellens system had been mounted directly to the end flange of the RFQ tank (fig. 2). For impulse separation we had a 90° dipole

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magnet (fig. 3) with a radius of r = 165 mm and a faraday cup for beam detection.

In a first step we have measured the spectrum of the ion source. The RFQ was driven only in transport modus at 10 kW (design value: 18.5 kW) and 4% duty cycle, where no acceleration occurs and the ions are just passing with extraction energy. The spectrum is shown in fig. 4 and shows a huge amount of H_2^+ and H_3^+ and only 5.5% H^+, which means 5.5 μA at a total beam current of 0.1 mA [5].

Figure 2: Ion source, einzel-lense system and RFQ.

Figure 3: 90° bending magnet for impulse diagnostics.

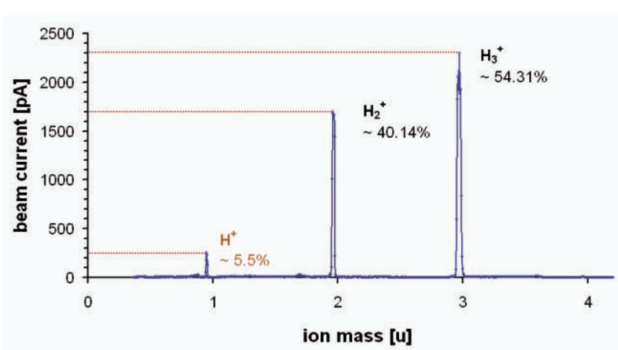

Figure 4: Measured ion spectrum with the RFQ in transport modus at 10 kW.

For calibration of the bending magnet we decided to use argon (fig. 5). At extraction energies around 8 keV, the impulse and consequently the position of the argon peak is almost at the same position as for accelerated protons with 403 MeV protons. Fig. 6 shows the "proton-peak", measured at 22 kW rf-power. The second drifttube was mounted at the design height of 29 mm above the lowest possible position (Abb. 1). (The height in which the drift tube is mounted to the last RFQ stem determines its voltage.)

The measured energy was 430.8 keV/u, which is about 7% above the design value. To find the reason for that we decided to execute energy measurement without the drift tube section. These results are shown in fig. 7 where the energy behind the RFQ without drifttubes is plotted against the rf-power of the cavity. This diagram gives impressive information about the power consumption of the structure: 18.5 kW for proton operation (corresponding to 166.5 kW for an q/A = 1/3, 165 kW were predicted). The second information we gained from that diagram is that there seems to be an energy gain of 28 keV/u by the drifttubes, as the RFQ energy stops very close to the design value of 403 keV/u, independently to the rf-power resp. to the electrode voltage, which is typical for RFQs.

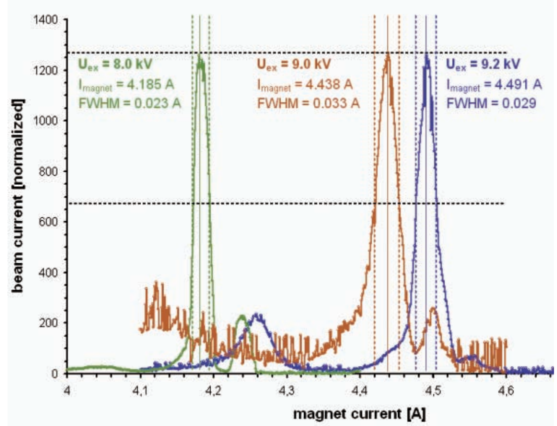

Figure 5: Argon peaks of different extraction energies for calibration of the bending magnet.

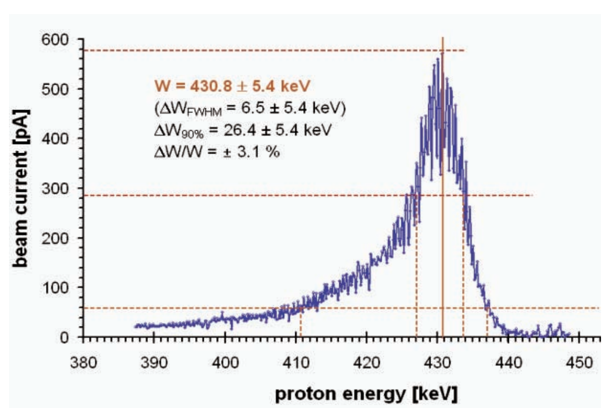

Figure 6: Measured proton energy of the RFQ-drifttube combination.

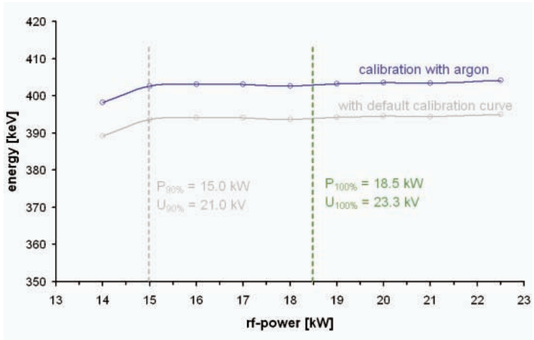

Figure 7: Energy as a function of rf-power (measurement without drifttubes).

THE INFLUENCE OF THE DRIFTTUBES ON BEAM ENERGY

To raise the measuring precision and to do a detailed investigation of the beam properties it was decided to do further measurements by means of the time of flight (TOF) method at GSI with more powerful amplifiers and a more suitable and reliable ion source. These measurements were very successful; results are reported in [6]. Within the context of these measurements we have executed several preceding simulations of both, beam dynamics and rf-properties with CST-MWS.

The only explanation for a change in energy within the drifttubes is a phase other than the desired 0° for bunching. One reason might have been a phase deviation between RFQ and drifttube which could be excluded by means of MWS simulations. Then we executed RFQsim calculations with the aim to calculate the energy dependence on the electrode voltage respectively the rf-power. The results of these simulations is a clear dependence of the beam energy on the electrode voltage in a way that there is a energy gain with voltages slightly below and an energy loss with voltages above the design value (fig. 8). This issue becomes clear if one envisions the phase shifting of the bunch with voltage variation. If the voltage is to low, the bunch comes closer to the crest of the rf-voltage to keep the ideal energy gain. This means a delay in time, the bunch comes too late into the bunching gap and experiences an accelerating force and vice versa in the case of higher voltages.

Simulations of fig. 8 are done under the assumption of an ideally homogenous voltage distribution along the RFQ-electrodes. In reality there are always deviations from that idealized case. To do investigations on the influence of the so called unflatness we have executed further simulations. Two scenarios have been calculated exemplarily, voltage distributions with an unflatness of dU = 4% and dU = 15%. For comparison the results are shown in fig. 9 together with a third curve for the ideal case. They prove the insensitivity of this RFQ to an unflatness of a few per cent. Due to self-regulating mechanisms (phase-focusing, AG-focusing) this RFQ is able to cope with it in the case of 4% unflatness with only marginal changes in beam parameters. They become more evident with e.g. 15% unflatness.

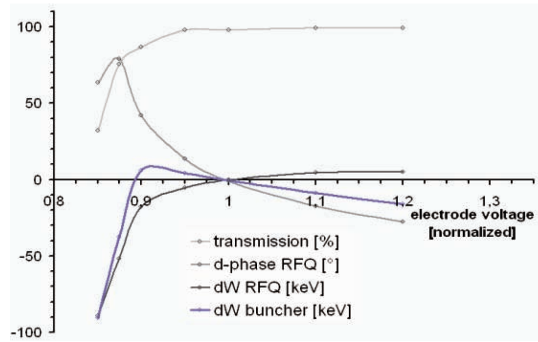

Figure 8: Some simulated beam parameters as a function of the electrode voltage at the end of the RFQ (black and grey curves) and behind the buncher (blue curve).

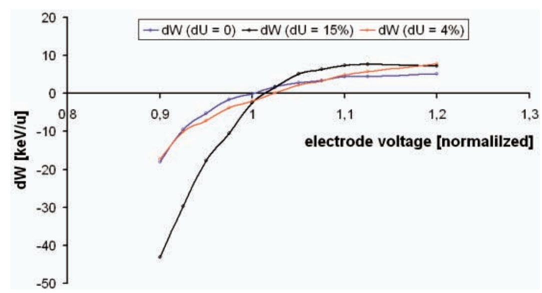

Figure 9: Simulations with unflatness. The blue curve corresponds to the black one in fig. 8 (ideal case).

CONCLUSIONS

An RFQ-Drifttube-Combination has been set into operation at the IAP in Frankfurt in 2004 for the first time. However limitations of the ion source and the rf-amplifier made it difficult to do high resolution energy measurements for the final voltage and phase tuning of the bunching unit, which had been done afterwards at GSI by means of more precise TOF measurements.

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