COMMISSIONING OF THE 7 MEV/U, 217 MHZ INJECTOR LINAC FOR THE HEAVY ION CANCER THERAPY FACILITY AT THE UNIVERSITY CLINICS IN HEIDELBERG

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Abstract

A clinical synchrotron facility for cancer therapy using energetic proton and ion beams (C, He and O) is presently installed and under commissioning at the Radiologische Universitätsklinik in Heidelberg, Germany. The current status of the linac commissioning is reported. The installation and commissioning of the linac is performed gradually in three steps for the ion sources and the LEBT, for the RFQ, and for the IH-type drift tube linac. In April 2006 first ion beams have been produced. Various beam measurements with different ion species have been performed using a special test bench with versatile beam diagnostics elements. The status of the 20 MV IH-DTL cavity and the linac RF system is also briefly reported.

INTRODUCTION

The Heidelberg ion beam therapy (HIT) facility at the Radiologische Universitätsklinik in Heidelberg, Germany [1] consists of two 14.5 GHz permanent magnet ECR ion sources from PANTECHNIK, a 7 MeV/u injector linac [2] and a 6.5 Tm synchrotron to accelerate the ions to final energies of 50 – 430 MeV/u. The 216.8 MHz injector linac (Figure 1) comprises the low energy beam transport lines (LEBT), a 400 keV/u radio frequency quadrupole accelerator (RFQ) [3][4], and a 20 MV IH-type drift tube linac (IH-DTL) [2][5][6].

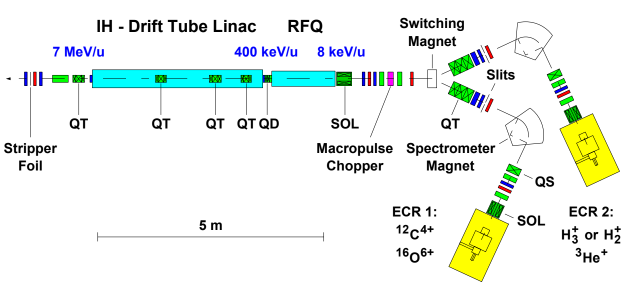

Figure 1: Layout of the Injector Linac [2]. SOL = solenoid magnet, QS = quadrupole singulet, QT = quadrupole triplet. Green: focusing and steering magnets, red: profile grids and tantalum screen, blue: beam current monitors (Faraday cups and beam transformers).

The installation and commissioning of the injector linac is performed in three consecutive steps for the ion sources and the LEBT, for the RFQ, and for the IH-DTL. In October 2005 the building was finished preliminarily, accelerator installation started in November 2005. Until end of March 2006, the LEBT and the ion sources have been assembled in the LINAC hall including the complete technical infrastructure as well as functional tests of all components. First ion beams have been produced at the beginning of April 2006 [7].

ION SOURCES AND LEBT

Commissioning of both ion sources and a part of the ion source acceptance tests planned on site have been performed in April and May 2006. The requested beam intensities as listed in Table 1 could be exceeded for $^3He^{1+}$, $^{12}C^{4+}$ and $^{16}O^{6+}$. Commissioning with hydrogen beams is scheduled for September / October 2006.

Table 1: Specified ion species and intensities behind the 90° analysing magnet.

Ion	I / µA	U_{source} / kV
$3H^+$	700	24
$^3He^{1+}$	500	24
$^{12}C^{4+}$	200	24
$^{16}O^{6+}$	150	21.3

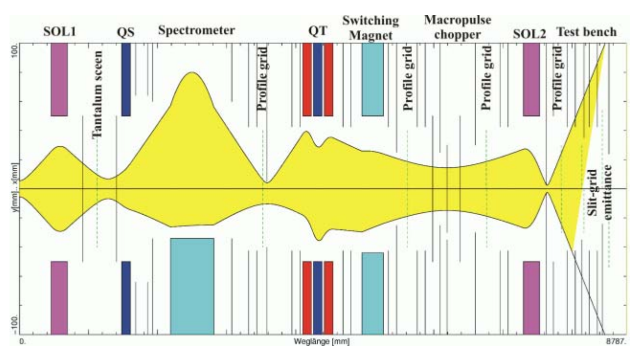

Figure 2: Beam envelopes along the LEBT and the beam diagnostics test bench as calculated with MIRKO [8]. The final solenoid magnet is adjusted to the RFQ acceptance.

A major goal of the LEBT commissionig was to achieve settings for different ion beams matched to the RFQ acceptance. For this purpose, a versatile beam diagnostics test bench has been designed and installed behind of the LEBT at the position of the RFQ. It consists of an AC beam transformer, a profile grid, a slit-grid emittance measurement device, and a Faraday cup. Figure 2 shows the calculated beam envelopes along the

LEBT for a $^{12}C^{4+}$ beam matched to the RFQ injection. Additionally to the standard beam diagnostics elements [9] the test bench at the RFQ matching-in is shown. Various systematic measurements of beam parameters at RFQ injection have been performed until mid of July 2006 using both ion sources and different ion species ($^{4}He^{2+}$, $^{16}O^{6+}$, $^{12}C^{4+}$).

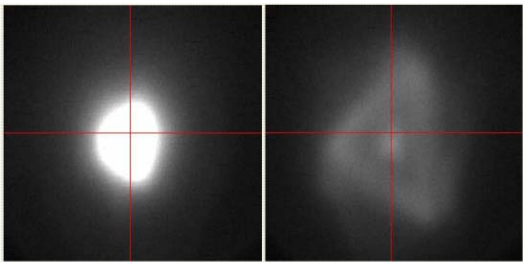

Figure 3: Images of ^{4}He ion beams measured with the tantalum screen behind SOL1 for two different settings of the solenoid.

Behind SOL1 following each ECR ion source a tantalum screen is used to monitor the beam (Figure 3). Behind this screen a quadrupole singulet is located to match to the following spectrometer magnet and to achieve an optimised resolution. A typical spectrum of an ECR ion beam for carbon operation is shown in Figure 4.

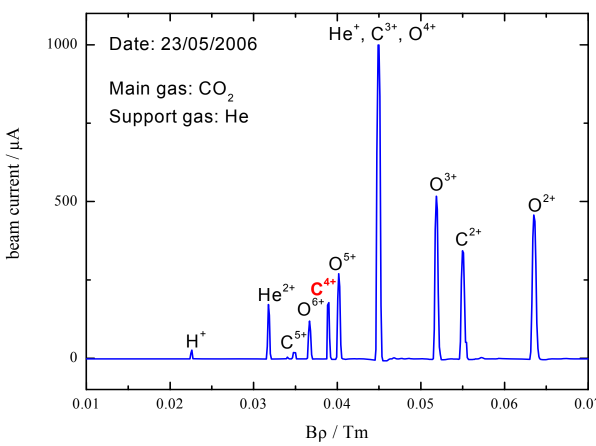

Figure 4: Spectrum of one of the ECR ion sources. The peak at Bρ = 0.0386 Tm corresponds to the desired $^{12}C^{4+}$.

After selecting the desired ion species with the slits following the analysing magnet a cylindrical beam shape along the straight section downstream of the switching magnet is produced by a quadrupole triplet. After adjusting the beam centre along the whole LEBT with the steerer magnets, a transmission of typically 80 – 90 % is achieved up to the RFQ entrance. Figure 5 shows top to bottom the measured beam profiles along the LEBT for a $^{12}C^{4+}$ beam (compare to Fig. 2). The first line shows the profiles in front of the analysing slit, the second and third lines show the profiles along the straight section in front of the RFQ. The profiles at the bottom are from the additional grid behind of the solenoid magnet SOL2 which will be used for focusing the beam into the RFQ later. In case of Figure 5 the solenoid field is about 80 % of the field required for RFQ injection.

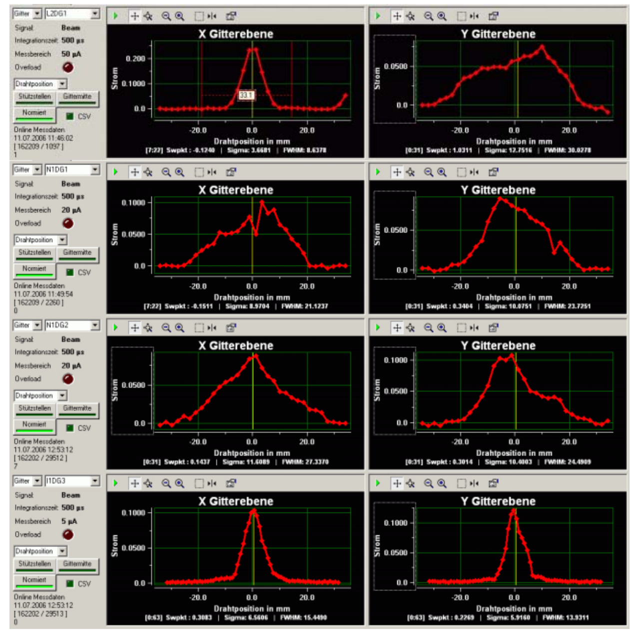

Figure 5: Measured profiles of a $^{12}C^{4+}$ beam along the LEBT (left: horizontal profiles, right: vertical profiles). The transmission achieved in this case is about 80 %, the beam current on the first grid about 190 µA.

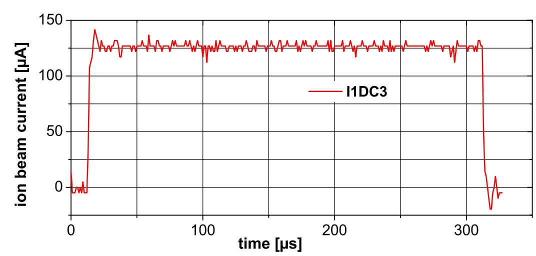

Figure 6: A triggered Faraday cup signal behind the macropulse chopper.

As the beam behind the macropulse chopper is pulsed, all beam diagnostics behind the chopper have to be triggered. In Figure 5 this applies to the last two profile grids. Figure 6 shows the beam current mesured at the final Faraday cup at the end of the beam diagnostics test bench. The data aquisition time is chosen a bit longer than the actual beam puls (300 µs) to see the switching of the chopper.

For the LEBT settings of Figure 5 an example of an emittance measurement for $^{12}C^{4+}$ at RFQ injection is displayed in Figure 7 (left part). Typical values for 90 % ellipses are 200 – 300 π mm mrad and depend strongly on the ion source settings. These values are very close to the expected RFQ acceptance and are somewhat larger than the emittances measured directly behind of the analysing slits during the factory acceptance tests of the ion sources at PANTECHNIK (about 180 π mm mrad). This may be caused by aberrations of the LEBT magnets and by slightly different ion source settings. For $^{16}O^{6+}$ the measured emittances are much smaller (typically 50 – 80 π mm mrad, see right part in Figure 7).

Various emittance measurements have been performed for different settings of SOL2. The measured Twiss parameters agree very well with the ion-optical simulations and the beams could be matched to the expected RFQ acceptance successfully. Emittance measurements at different times along the macropulse did not show any significant differences.

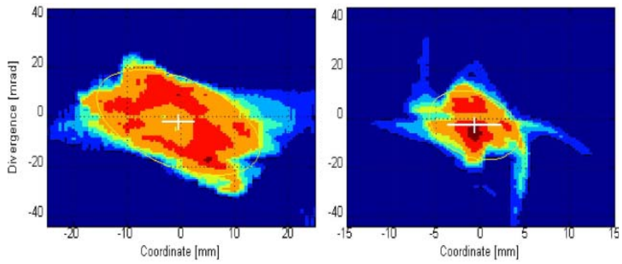

Figure 7: Examples for beam emittances measured in the horizontal phase plane about 0.7 m behind of the RFQ matching point (left: $^{12}C^{4+}$, right: $^{16}O^{6+}$). The ellipses correspond to about $4 \times$rms emittances of roughly $280\,\pi$ mm mrad and $70\,\pi$ mm mrad, respectively. The measurements have been performed at different settings of the solenoid magnet SOL2.

RFQ

In advance to the commissioning of the RFQ in Heidelberg an RFQ beam test bench has been set up at GSI in order to investigate and to adjust the rebuncher drift tube setup integrated into the RFQ tank. Precise measurements of the output energy with the time of flight (ToF) method have been performed for various rebuncher geometries and voltages using proton beams [4].

In July 2006 the RFQ has been installed in the HIT facility in Heidelberg and RF commissioning is in progress. Commissioning with ion beams is scheduled for September 2006. For this purpose the beam diagnostics test bench has been installed behind of the RFQ and has been additionally equipped with capacitive pick-ups providing for ToF energy measurements.

IH-DTL

The 3.8 m long mild steel tank of the 20 MV IH-DTL cavity [2][5][6] as well as the 52 small copper drift tubes have been produced at PINK GmbH Vakuumtechnik in Wertheim, Germany. First RF tuning steps have been performed already in the factory. The height and the special shape of the inner surface of the upper and lower half shells as well as the final size of the undercuts of the girders have been fixed and finally machined during these activities. Afterwards, the IH tank has been delivered to GSI in June 2005 and was copper plated at GSI. After vacuum tests and mechanical refinishing operations, all drift tubes have been assembled within the final tank (Figure 8). The small drift tubes could be aligned within a tolerance of ±0.2 mm regarding to the tank axis without additional mechanical machining of the drift tube stems. The large drift tubes from DANFYSIK containing the magnetic quadrupole triplet lenses have been aligned by milling of the seperate distance plates in between of the lower tank half shell and the stems of the drift tubes.

Final RF tuning has been performed at GSI by mounting small tuning blocks on the girders in between of the stems of the small drift tubes and by additional tuning plates installed on the inner surface of the half shells. Furthermore, four drift tubes of the first section have been replaced by longer ones to enhance the electric field along this section. To control the resonant frequency of the cavity during operation, two moveable tuning plungers have been installed. After installation of the final components, a quality factor of about 14'000 has been achieved. Final tuning is still in progress. Installation and commissioning of the IH-DTL in Heidelberg is planned for September – December 2006.

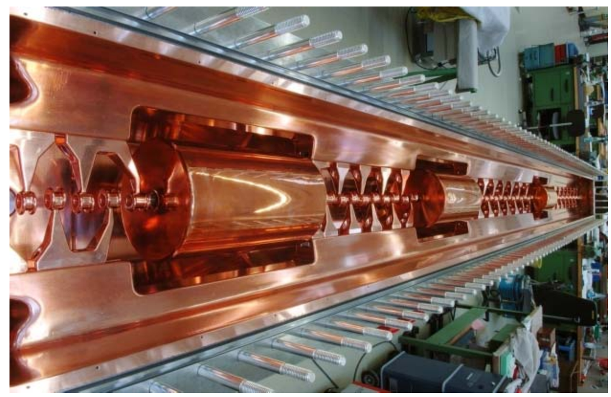

Figure 8: Open IH cavity after copper plating and assembly of the drift tubes. Each of the three large drift tubes contains a magnetic quadrupole triplet lens.

RF SYSTEM

The cavity amplifier from BERTRONIX for the IH tank has been successfully commissioned at a special test setup at GSI [2] during 2005. An RF pulse power of more than 1.5 MW could be delivered to a water dummy load using a THALES tetrode TH 526 B. The 200 kW amplifier from THOMSON for the RFQ has been operated already at the RFQ test bench at GSI at power levels up to 30 kW [4]. The complete RF system has been installed in Heidelberg in April 2005. Commissioning in Heidelberg is done on a water dummy load in advance to the commissioning on the resonant cavities.

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