

**OVERVIEW OF THE BEAM DIAGNOSTICS IN THE
MEDAUSTRON
ACCELERATOR: DESIGN CHOICES AND TEST BEAM
COMMISSIONING**

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Abstract

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BEAM DIAGNOSTICS OVERVIEW

The work package beam diagnostics at MedAustron is responsible for the design and procurement of all beam diagnostic devices from the ECR-sources, via the Low Energy Beam Transfer (LEBT) line, the Linac, the Medium Energy Transfer (MEBT) line, Synchrotron and the High Energy beam Transfer (HEBT) line to the scanning magnet entrance.

Low Energy Beam Transfer Line

The LEBT transports the DC beam of H_3^+ or C^{4+} particles from the ECR ion-source up to the entrance of the RFQ. Due to the low energy of the particles coming from the source (~ 8 keV/nucleon) and the high beam intensity (up to 1 mA) the beam size is chosen relatively large (up to 7 cm transversal). Another critical aspect is the beam power of up to 400 W immediately after the ECR-source, which is absorbed by beam destructive monitors. To guarantee normal operation of these monitors, cooling with demineralised water is foreseen.

As the beam in the LEBT is DC, Wire Scanners were chosen for the beam profile and position measurements. A wire with 0.1 mm diameter can be moved through the beam with up to 300 mm/s. Wire Scanners are always deployed in pairs, one horizontal and one vertical unit.

Faraday Cups (FC) were chosen as beam intensity monitors and are used all along the line and will also provide a calibration for the Current Transformer.

Synchronous acquisition of the Slit Plate positions, Wire Scanner profiles and FC intensity measurements will allow an accurate emittance measurement at several points in the LEBT.

During the commissioning of the LEBT line, a temporary beam diagnostics tank will be placed at the position of the RFQ. Its purpose is to measure the beam emittance and properties at the RFQ matching plane. This temporary tank will be equipped with the spare monitors of the LEBT line (Faraday Cups, Wire Scanners and Slits).

A Cylindrical Faraday Cup and a Current Transformer placed at the end of the line will allow online beam intensity measurements in this line.

Medium Energy Beam Transfer Line

The MEBT line starts after the Linac with a stripping foil, which brings the hadron beams to the required charge state, i.e. H_3^+ to protons and C^{4+} to C^{6+} . It shapes and transports the beam for injection into the synchrotron. The beam in this line has a pulse structure (nominal 30 μ s) at an energy of 7 MeV/nucleon. The beam current amounts up to 1.5 mA.

Due to the pulsed beam in the MEBT, the beam profile will be measured with Profile Grid Monitors made of 128 wires with 0.1 mm diameter (64 per plane) measuring both transverse planes simultaneously.

Faraday Cups will measure the beam intensity, check the stripping foil efficiency and calibrate the AC Current Transformers.

Two sets of Slit Plates spaced by 90 deg phase advance will allow forming a "pencil beam" to optimize the injection process during the multi-turn injection. Slit Plates will also shape the beam and contribute to the emittance measurements.

A Degradar will attenuate the beam intensity according to treatment needs using filters (sieves) with three different transparency factors: 10%, 20% and 50%.

At the end of the MEBT line, an AC Current Transformer and a dual plane electrostatic Pick-up allow for an online, non-destructive measurement during normal operation to check the beam transition into the synchrotron.

Synchrotron

A classical multi-turn injection scheme in the horizontal plane is used for injection into the synchrotron. The beam is then bunched, accelerated to the desired energy and debunched before slow resonant extraction into the HEBT.

The whole process can last up to several seconds, depending on the chosen extraction time.

The synchrotron delivers protons for medical treatment from 60 MeV to 250 MeV and carbon ions from 120 MeV/nucleon to 400 MeV/nucleon. For research purposes protons will be accelerated up to 800 MeV. The revolution period thus ranges from 2 μ s to 0.2 μ s.

The intensity of the injected beam can be varied by up to a factor of 10 with the help of the MEBT degrader for both particle types.

Electrostatic Pick-ups (11 horizontal and 9 vertical) measure the beam centre-of-charge transverse position in a non-interceptive way. In normal operation mode, the Pick-up signals are averaged with 1 kHz for orbit corrections. Alternatively a subset of the monitors can be read out turn-by-turn, synchronized to the bunch passage (RF-train) for bunch shape measurement, RF-loops, tune measurements, etc.

An AC Current Transformer provides the total beam charge injected into the synchrotron, allowing tuning of the multi-turn injection process. For the same purpose, two luminescent screen monitors are installed in the injection/extraction area, up- and downstream of the electrostatic injection septum. One of the screens observes the beam directly after injection and the other one the beam after the first turn in the machine.

A DC Current Transformer taking the relativistic β into account provides the total number of ions circulating in the synchrotron. During extraction it measures the total number of particles sent towards the patient. Both AC and DC Current Transformers will have calibration coils implemented.

Two Schottky Pick-ups measure the relative momentum spread $\Delta p/p$, the non-integer part of the betatron tune Q , the tune spread and the transverse velocity spread. These monitors are of special interest as MedAustron will have a coasting beam during the slow extraction process. [1]

An amorphous Si-Diode detector and the Septum Shadow Monitor placed in front of the magnetic thick extraction septum measure the beam loss on the septum wall and provide a way to position the extracted beam with respect to the septum.

High Energy Beam Transfer Line

The HEBT consists of the main beam line, from which different beam lines divert towards the treatment rooms and the experimental room. The beam is extracted at different energies on a cycle to cycle basis. The extraction time may vary from 0.1 s to 10 s and, taking into account that the synchrotron injected intensity can be adjusted by a factor 10, the intensity range varies up to a factor 1000. The maximum number of particles per spill in the irradiation room is 2×10^{10} protons or $1 \times 10^9 C^{6+}$.

Scintillating Fibre Hodoscopes (SFX) will thus measure the position and profile of the beam in the HEBT. An SFX detector simultaneously provides vertical and horizontal profiles. After having calibrated the fibres using the synchrotron DC Current Transformer one can deduce the beam transverse dimension, mean position and

intensity from the profiles. Each SFX plane is made out of 128 fibres grouped together in pairs of two. The fibres are 0.5 mm thick and placed without intermediate gap.

During the first 80 ms of extraction, the beam is directed onto a tungsten block, in front of which a Qualification Monitor (QM) is installed. It consists of a horizontal/vertical profile monitor based on scintillating fibres followed by a scintillator plate coupled to a photomultiplier acting as a fast intensity monitor (10 kHz).

Beam emittance in the HEBT will be measured with quadruple magnets in combination with one of the downstream SFX.

Table 1: Overview of the MedAustron Beam Monitors

Beam Monitor	Beam Line	Amount
Wire Scanners	LEBT	28
Slit Plates	LEBT, MEBT	40
Faraday Cups	LEBT, MEBT	11
Cylindrical Faraday Cup	LEBT	1
Current Transformers	LEBT, MEBT, MR	5
Profile Grid Monitors	LEBT, MEBT	7
Position Pick-ups	MEBT, MR	21
Stripping Foils	MEBT	1
Degraders	MEBT	3
Schottky Pick-ups	MR	2
Scintillating Plates	MR	2
Septum Shadow Monitor	MR	1
Diode	MR	1
Scintillating Fibre Hodoscopes	HEBT	29
Qualification Monitor	HEBT	1
In total		153

MEASUREMENTS AT THE MEDAUSTRON INJECTOR TEST STAND

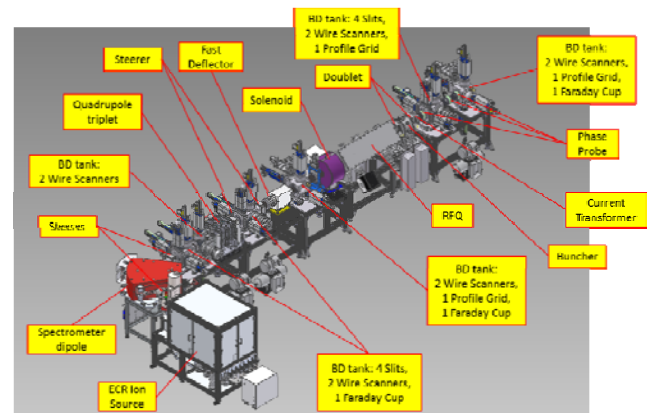


Figure 1: Layout of the final ITS

The Injector Test Stand (ITS) at CERN was set up to test the ECR ion source, the newly developed RFQ and to set up the beam in the LEBT. It is also very beneficial for a wider range of equipment, hardware and software tests.

The LEBT beam monitors were tested in a standalone mode and are now in use for the source performance tests. The layout of the ITS is depicted in Figure 1.

Beam intensity

With 7 different gain settings, the FC has a dynamic range of 100 nA to 100 mA (full scale) with an achievable resolution of 1 nA (with a confidence of 99.73% over 5000 samples) in the highest gain (10^8 V/A) and a bandwidth of 10 kHz. The FC placed immediately after the spectrometer magnet is used for beam intensity stability measurements as well as for measuring the beam spectrum when coupled to the dipole ramp. Figure 2 displays the proton source spectrum, the three peaks, H^+ , H_2^+ and H_3^+ are clearly visible. In Figure 3 the stable operation of the source over 2 hours measured with an FC is shown. The source is stable to within $5 \mu A$ at the nominal level of $500 \mu A$ of H_3^+ . The visible drift is due to the warming up of the source which is as expected. In total, 4 FCs are deployed at the ITS.

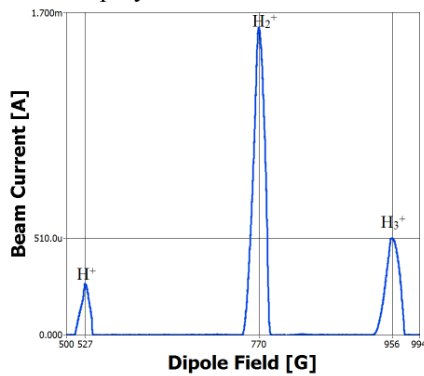


Figure 2: Proton source spectrum measured with an FC during the dipole ramp with a slit opening of 29 mm.

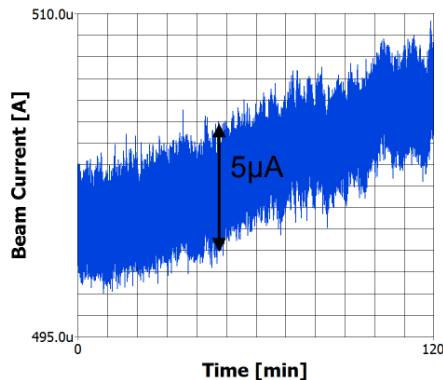


Figure 3: H_3^+ beam intensity measured over 2 hours with the Faraday Cup. The beam current amounts to $\sim 500 \mu A$ H_3^+ .

Beam profile and position

All along the ITS line, 12 Wire Scanners are measuring the beam profile and position in both planes. The positioning resolution achieved amounts to $\sim 100 \mu m$. The smallest wire current which can be measured in the highest gain (10^8 V/A) is ~ 130 pA. In order to increase the statistics, the beam profile is measured twice, once when moving in and once moving out. The two overlapping profile scans of the same measurement can

be seen in Figure 4. The backlash of the potentiometer can be corrected for.

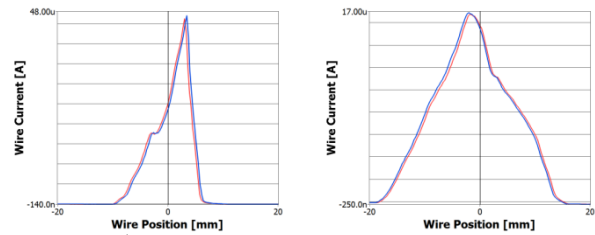


Figure 4: H_3^+ horizontal and vertical beam profile measured with the Wire Scanner immediately after the spectrometer.

Beam emittance

The transverse emittance was obtained by consecutive profile measurements ~ 0.5 m downstream of the 1 mm wide slit, which was moved through the beam in steps of 1 mm. Particle distribution in the phase space determines the rms TWISS parameters and the rms emittance from which the rms emittance ellipse is retrieved. This ellipse can be adapted by the user, to fit the analysis needs.

Figure 5 displays the emittance measured directly after the spectrometer. The $180 \pi \cdot mm \cdot mrad$ ellipse computed from the particle distribution in the phase space after offset correction (-6.5 nA) and noise cut (~ 15 nA) is drawn. The corresponding beam currents within the rms and the $180 \pi \cdot mm \cdot mrad$ ellipse are calculated with a total beam current of $530 \mu A$.

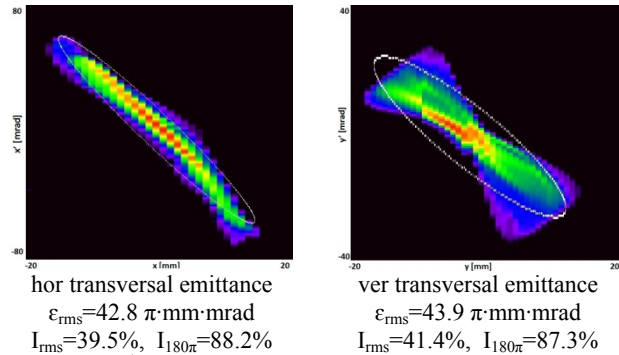


Figure 5: H_3^+ transverse emittance in both planes. The ellipse defining the $180 \pi \cdot mm \cdot mrad$ is visualized.

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