ISBN: 978-3-95450-230-1 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2021-TUPP12

DEVELOPMENT OF A PEPPER POT EMITTANCE MEASUREMENT DEVICE FOR THE HIT-LEBT

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Abstract

The Heidelberg Ion Beam Therapy Centre (HIT) is a synchrotron based medical accelerator facility for the treatment of cancer patients with ions. Since the first treatment in November 2009 about 7000 patients have been irradiated with protons or carbon ions and, since July 2021, also with helium ions. In 2010 HIT started the operation of a test bench with a setup comparable to the LEBT at the accelerator. Since 2013 the test bench serves as a common low energy beamline of Siemens Healthcare and HIT with components from both partners. In parallel to ion source and RFQ research and development we have experimented with our proprietary pepper pot device. We plan to install the final version of the pepper pot into the LEBT section and use the measured beam distributions for the design of a new RFQ. With the recent redesign of the mask-target assembly we have increased the active area of the device and generated a possibility for an accurate pixel calibration by a specialised calibration mask. Our tool PePE (Pepper Pot Emittance Evaluation) offers different approaches for the reconstruction of the 4D emittance parameters from the raw image. The evaluation process was validated by a pepper pot image generated from a simulated beam with known properties.

INTRODUCTION

For reliable beam dynamics simulation and accelerator design the knowledge of the phase space occupied by the beam is of major importance. The pepper pot device is particularly suitable for characterizing the output beam of the ion source. Its vital component is the mask, a metal sheet with a regular grid of holes, reminding of the lid of a pepper pot thus giving the instrument its name. When inserted into the beam the mask cuts out a set of beamlets which are made, after a drift, visible on a scintillating screen. A digital camera records the light spots in a raw image which has to be processed with respect to the location and intensity of the beamlets. The beamlets have to be related to the holes giving not only the position but also the angle coordinate, the latter from the small difference between the beamlet position on the screen and the hole position on the mask. The hole spacing has to be chosen *small* enough to fulfil the demands on spatial resolution but *big* enough to avoid overlapping of the beamlets, leading to unfeasible images.

The resolution will in most cases be lower compared to e.g. a slit-grid-assembly but the major benefits of the pepper pot are the fast data acquisition (single shot) and the 4D information including not only the real space (x-y) and the pure phase spaces (x-x' and y-y') but also the momentum space (x'-y') and the mixed phase spaces (x-y' and y-x').

TEST BENCH

The HIT test bench has its origin in 2010 when it was set up as a test facility for the third ion source branch for our low energy beam transport system (LEBT) [1]. After installation of the source and most of the beam line components into the productive accelerator, we continued to operate the test bench with alternating components. The exploratory focus is now on ion source optimisation, emittance measurement and RFQ characterisation.

The HIT test bench in its current state represents a LEBT with a subsequent RFQ accelerator (see Fig. 1). The ECR ion source for the production of $^{12}C^{4+}$, H_3^+ and $^4He^{2+}$ ions is directly coupled to a spectrometer dipole and followed by a dual stroke round aperture (⌀10 mm, ⌀20 mm or out) for charge separation. The beam line behind the dipole comprises a triplet, a chopper for pulsed beam operation and a solenoid for the final matching of the beam into the RFQ. For beam alignment three steerer pairs are installed. The beam line is well equipped with beam diagnostic devices such as Faraday cups, beam transformers and profile grids. The pepper pot emittance meter with a mask, a quartz target, a mirror and a camera is located in a diagnostics chamber between chopper and solenoid. The diagnostic line downstream the RFQ contains three capacitive phase probes for time-of-flight resp. energy measurements.

The last subject of investigation has been the pepper pot device, which was, in its original form, developed in 2010 [2]. After having collected a number of measurement data for all available ions, we could draw our conclusions of how to improve the device. A couple of optimisations, described in the following section, have already been put into effect and measurements are in progress.

PEPPER POT HARDWARE

The pepper pot equipment is attached to two distinct actuators both mounted to the same diagnostics chamber: one holding the mask and the screen, the other one the mirror directing the light through a glass window to the camera installed on the flange. The distance between mask and screen is adjustable, realised by a fixed screen and a displaceable mask. The most important properties of mask and screen are summarised in Table 1.

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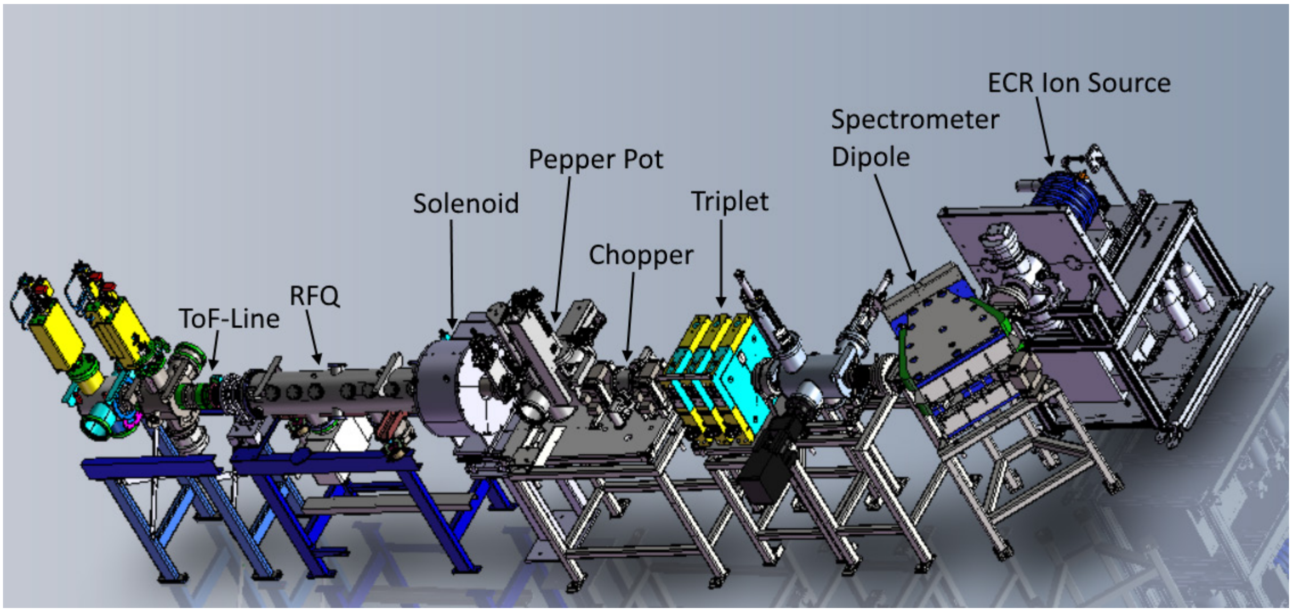

Figure 1: Test bench setup with an overall length of approx. 8 m.

Table 1: Main Pepper Pot Characteristics

Mask	
material	tungsten
thickness	100 µm
hole spacing	1.5 mm
hole diameter	100 µm

Screen	
material	quartz glass
supplier	QGH [3]
product	Herasil 3
thickness	200 µm

The camera in use is a Prosilica GT from Allied Vision [4] with 16 bit colour depth (monochrome) and a maximum image size of 2464 × 2056 (5.1 megapixel). During our first sets of measurements at the test bench we recognized that the beams do not fit on the 45 mm × 45 mm mask, when no aperture was inserted upstream. We further estimated from profile measurements in the LEBT that the mask will also be too small in its final place in the medical accelerator. We consequently designed a new pepper pot layout with a larger, round mask with an active area of now 72 mm in diameter. The formerly 60 mm (effectively 55 mm) diameter quartz glass disk was increased to a 80 mm (effectively 74 mm) keeping material and thickness. The mask-screen distance is now realised in steps of 5 mm instead of being floating improving the accuracy. The new setup with round mask and round screen is shown in Fig. 2.

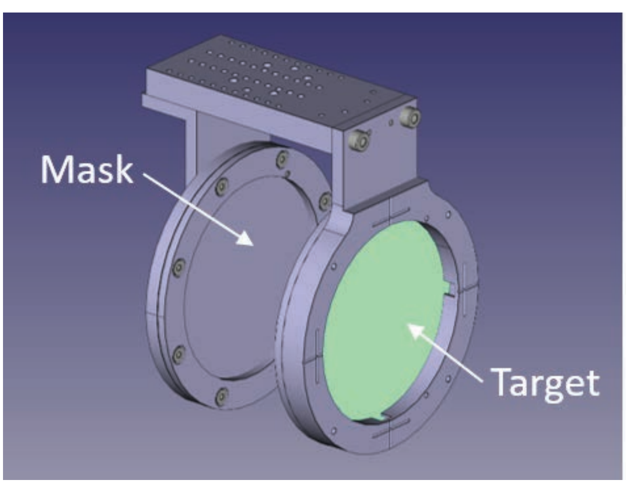

Figure 2: New pepper pot assembly with round mask and target (screen).

PIXEL CALIBRATION

Pixel calibration. i.e. the translation of pixels into millimetres, is an important detail of the pepper pot measurement. It depends on the optics and has to be performed for the plane of the screen (not the mask!). We formerly used the support ring of the screen to do the pixel calibration. For the enhanced design we came up with a new method using a calibration mask. This mask has nine holes arranged as a cross and can be placed at the location of the screen.

MEASUREMENT SEQUENCE

A pepper pot measurement essentially means to take an image of the viewing screen, showing a number of light spots. This raw image (in our case tif-format) has then to be evaluated with respect to its local brightness maxima. To ensure a robust functioning of the search algorithm the image is first processed applying the following steps:

- **subtraction of the dark image** (if available)**:** this eliminates defective pixels and effects from interfering light
- **selection of the relevant area:** this cuts off artefacts at the edge of the image, e.g. caused by (intentionally) larger edge holes and reduces calculation time

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- **smoothing with a Gaussian filter:** this suppresses the presence of local maxima connected to noise
- **subtraction of the background:** a user defined value can be subtracted from the entire image
- **noise reduction:** by zeroing pixels below a certain brightness threshold, the beamlets can be clearly confined from each other; the threshold can be changed by the user during the evaluation and allows for the iteratively optimisation on the basis of the visual result

The found beamlets are assigned to the closest hole in the mask, with the hole coordinates defining the x- and y-position of the beamlet. The angle in both directions is determined by the beamlet-to-hole difference and the distance between mask and screen. The final emittance calculation can then be made by using all non-zero pixels (PIX-method, most accurate, but slow), the maxima-pixel only (MAX-method, fast, but less accurate) or by a centre-of-mass algorithm based on Voronoi-cells. The latter has been discarded as it has, in the current realisation, not passed the validation process.

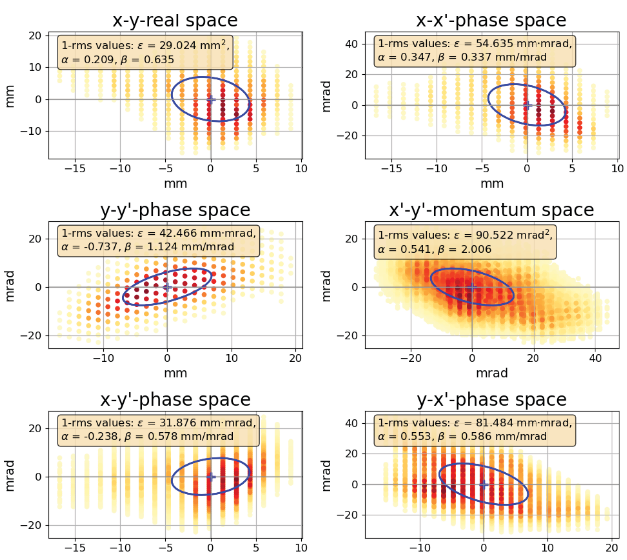

Figure 3: Pepper pot result of a 126 μA carbon beam (dual stroke at ⌀20 mm) at the HIT test bench using the PIX-method.

All described steps are implemented in a Python code we call PePE (**Pe**pper **P**ot Emittance **E**valuation). The result of a data evaluation with this tool is displayed in Fig. 3. It shows the six 2D-subspaces of a 126 μA carbon beam (dual stroke at ⌀20 mm) at the HIT test bench based on the PIX-method. These data have been recorded with the original quadratic mask.

VALIDATION BEAM

A validation of the evaluation algorithm can be performed by comparison with other emittance meters known for giving well established results. Another possibility is to generate a particle distribution of predefined properties (Twiss parameters) as validation beam [5].

The procedure consists of the following steps:

- **Particle generation:** in the presented case 2.5 millions uniformly distributed particles correlated in the horizontal (convergent) and vertical phase space (divergent), uncorrelated in the mixed phase spaces
- **Masking:** particles not passing the mask holes are filtered out; the remaining ~11 000 particles are plotted in Fig. 4
- **Drift:** particle drift from the mask to the screen (here 15 mm)
- **Image generation:** from a 2D histogram of the particles a tif-image is generated, which is evaluated as it was a real measurement

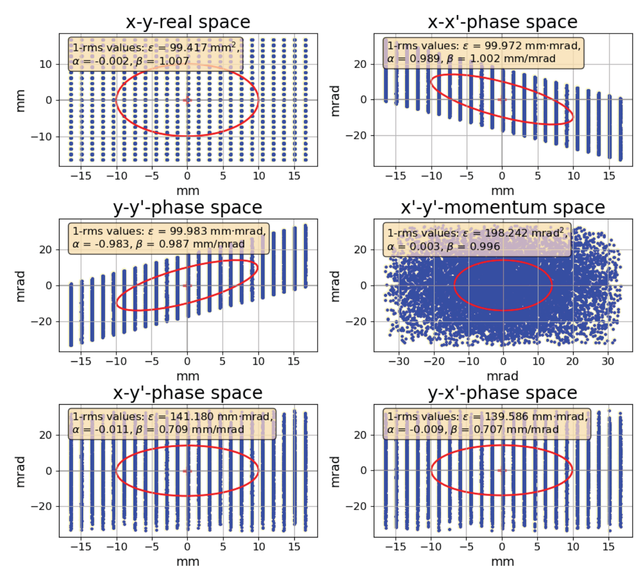

Figure 4: Validation beam after masking (~11 000 particles).

The image generated as described was analysed with the two evaluation methods PIX (all pixels are taken into account) and MAX (only pixels with local intensity maxima are taken into account). The results are summarised in Table 2 (1-rms-values). For the pixelwise evaluation all Twiss parameters are confirmed within an accuracy of ~3 %, the emittance remaining within a limit of 1.5 %. Regarding the evaluation of the intensity maxima only, the deviation of the ellipse parameters reaches up to 16 %, whereas the values for the emittance reveal a systematic underestimation of max. -8.5 %.

This investigation validates the PIX-method, whereas the result of the MAX-method stills remains within tolerable errors considering the fact that a substantial part of the data is discarded. Of course the explicit numbers in Table. 2 depend on statistics and my vary with the number of simulated particles but this does not affect the conclusion.

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Table 2: Evaluation and Comparison of the Validation Beam

Parameter [Unit]	Input	Result (two methods)	
		PIX	MAX
α_x [1]	0.989	0.981 (-0.8 %)	1.030 (+4.1 %)
β_x [mm/mrad]	1.002	0.971 (-3.1 %)	1.025 (+2.3 %)
ϵ_x [mm mrad]	99.97	101.5 (+1.5 %)	95.3 (-4.7 %)
α_y [1]	-0.983	-0.979 (-0.4 %)	-1.140 (+16 %)
β_y[mm/mrad]	0.987	0.964 (-2.3 %)	1.056 (+7.0 %)
ϵ_y[mm mrad]	99.98	100.2 (+0.2 %)	91.5 (-8.5 %)

LEBT INTEGRATION

Emittance measurements at the end of our LEBT have been performed in the frame of the initial commissioning with a mobile slit-grid arrangement [6]. For daily operation emittance measurements were not foreseen in the design.

Provided tests of the new pepper pot layout are successful, we will integrate the device in our LEBT to give us the possibility to measure the emittance of the production beam at any time. As space is limited we plan to free two sockets in a diagnostics chamber right behind the switching magnet (red magnet in Fig. 5). The upper socket will house the actuator with mask and screen, whereas the horizontal socket will hold the mirror and the camera.

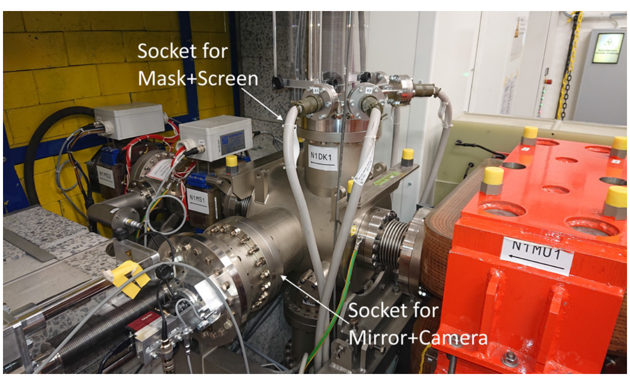

Figure 5: Designated place of installation of the pepper pot in the LEBT behind the switching magnet (red magnet).

CONCLUSION AND OUTLOOK

At HIT, a pepper pot emittance meter was constructed which recently got a new design with a larger active area. In parallel, an evaluation tool was developed giving us the correlations of all 2D subspaces. We found a way to validate the algorithm by the generation and evaluation of an artificial pepper pot image.

In a next step we are going to repeat earlier measurements with the new mask-screen layout. The resulting particle distributions are an important ingredient for our ongoing project of designing a new RFQ with the goal of transmission optimisation.

ACKNOWLEDGEMENTS

This work wouldn't have been possible without the contribution of Siemens Healthcare GmbH, Erlangen, Germany, represented by A. Robin, to the test bench. They have provided the ECR source and most of the magnets. Specials thanks goes to Eckelmann AG, Wiesbaden, Germany, for the integration of the test control system.

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