LEBT SIMULATIONS AND ION SOURCE BEAM MEASUREMENTS FOR THE FRONT END TEST STAND (FETS) *

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Abstract

The Front End Test Stand (FETS) at the Rutherford Appleton Laboratory (RAL) is intended to demonstrate the early stages of acceleration (0-3 MeV) and beam chopping required for high power proton accelerators, including proton drivers for pulsed neutron spallation sources and neutrino factories. Optimisation of the beam focusing within the Low Energy Beam Transport (LEBT) is necessary to minimise beam losses upon acceleration within the FETS RadioFrequency Quadrupole (RFQ). Simulations of the LEBT are currently under way using the General Particle Tracer package (GPT). Previous envelope calculations suggest weak and strong focusing solutions for the LEBT solenoids. Definitive beam dynamics simulations in GPT require further measurements of the transverse emittances and beam profile of the ion source beam, due to the sensitivity of the simulations on the initial beam profile and level of space charge compensation. A pepperpot emittance/profile measurement system has been designed for use on the ISIS ion source development rig. Results from this pepperpot system are used to constrain the initial conditions for the GPT simulations.

INTRODUCTION

High power (MW range) proton accelerators (HPPAs) have many applications, including drivers for spallation neutron sources, neutrino factories, nuclear waste transmutation, energy amplifiers and tritium production facilities. For the short pulse operation necessary for neutron spallation sources and neutrino factory drivers, only much lower beam powers have been used so far (0.08 MW for PSR and 0.16 MW for ISIS) [1]. Both machines use H^- injection to accumulate intense short bunches and need an increase of at least a factor of 30 to reach the goal of 5 MW for future HPPAs. In order to contribute to the development of HPPAs, to prepare the way for ISIS upgrades and to contribute to the UK design effort on neutrino factories [2], a front end test stand is being constructed at the Rutherford Appleton Laboratory (RAL) in the UK. The aim of the FETS project is to demonstrate the production of a 60 mA, 2 ms, 50 pps chopped beam (see [3] for a detailed description and the current status of the project).

ION SOURCE

The ion source development program, based on the highly successful ISIS H^- ion source at RAL [4], has already shown encouraging results. The aim is to increase the extracted H^- ion current from 35 mA to 70 mA and to increase the pulse length from 250 μs to 2 ms. After re-engineering the source on the basis of results from detailed electromagnetic [5] and thermal [6] modelling and upgrading the discharge power supply, the required ion current has already been extracted from the source (see Fig. 1).

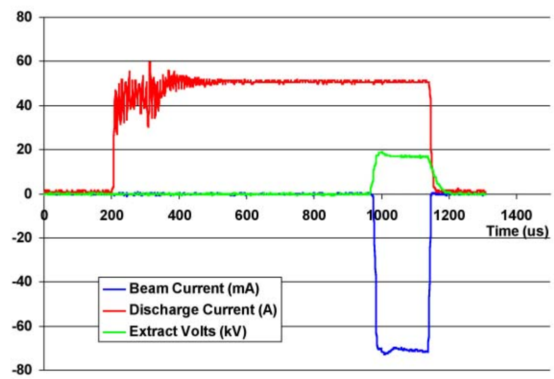

Figure 1: Output pulses for the Penning H^- ion source, showing a peak beam current of 70 mA.

The pulse length of the discharge has been increased by a factor of four. Further improvements including an upgrade of the extraction voltage and improvement of the beam extraction will follow. First simulations of the ion beam extraction have been performed using MAFIA [5].

Additionally the phase space distribution of the ion beam has been measured using an Allison type emittance scanner apparatus 70 cm downstream of the extraction slit, and is shown in Fig. 2.

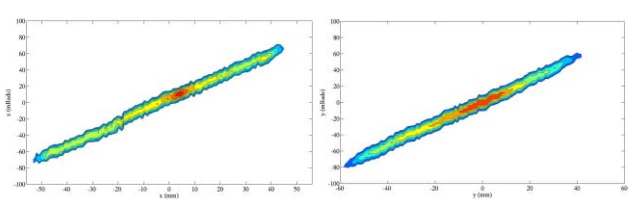

Figure 2: Horizontal and vertical phase space distributions for the ion source beam; the measured emittances are: $\epsilon_{x,rms} = 0.88\pi$ mm mrad; $\epsilon_{y,rms} = 0.94\pi$ mm mrad.

Further experiments to determine the two-dimensional transversal phase space distribution and the degree of space charge the using newly developed diagnostics devices are under preparation and will be described later on in this article.

* Work supported by CCLRC, PPARC and HPRI-CT-2001-50021 (EU)

LEBT

The goal of the LEBT is to transport the H^- beam from the ion source into the entrance of the RFQ, where the converging beam needs to fit into the acceptance of the RFQ. The LEBT will be based on the three-solenoid design of the test stand previously built and operated at RAL to test the RFQ [4]. The solenoids will incorporate built-in Lambertson dipoles for beam steering. The LEBT will be designed to produce a good vacuum which is essential to minimise stripping losses of the H^- beam.

The particle dynamic design of the LEBT requires the measured ion source output emittance as the initial particle distribution. First simulations using linearised K-V envelope equations and GPT [7] show a strong influence between the initial conditions, the degree of space charge compensation in the the beam transport section and beam injection into the RFQ. Two classes of solutions are found – "hard" and "soft" focusing. The former gives a converging beam at the entrance of the second solenoid which then becomes highly divergent before being focused at the end of the LEBT by the last solenoid. This behaviour will lead to large emittance growth and so these solutions are not considered further.

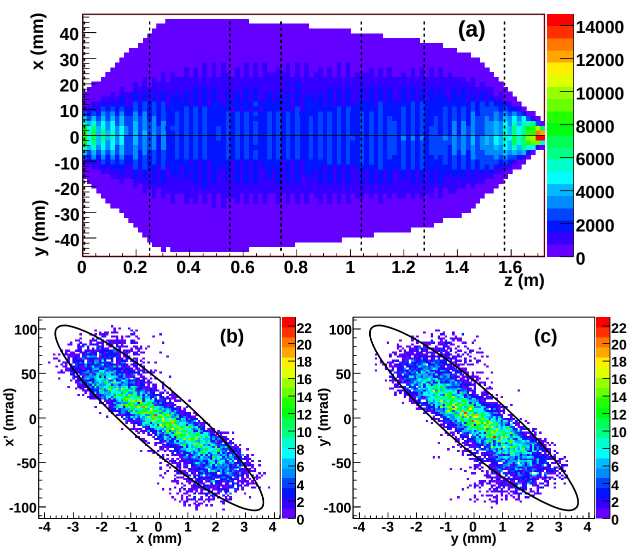

Figure 3: Results of GPT simulations: (a) beam envelope along the length z of the LEBT (dotted vertical lines show the drift and solenoid sections); (b) x-x' and (c) y-y' at the end of the LEBT with typical RFQ acceptance ellipses.

Fig. 3 shows an example "soft" focusing solution using GPT for a 65 keV H^- beam with zero space charge travelling along the LEBT, with three 30 cm long solenoids with magnetic fields 0.21 T, 0.05 T and 0.25 T in between four drift sections of length 25 cm, 19 cm, 24 cm and 15 cm. The magnetic fields have distributions like those shown in Fig. 4. The assumed initial emittance is $\epsilon = 0.25\pi$ mm mrad with unequal Twiss parameters $(\alpha, \beta)_x = (-8.93, 1.53)$ and $(\alpha, \beta)_y = (-6.60, 1.04)$ in both transversal planes due to the slit extraction at the ion source. It can be seen that the beam is rather well behaved and can be focused into the RFQ acceptance of $\epsilon = 0.3\pi$ mm mrad. Note that there is some beam aberration at the end of the LEBT, which first appears after the first solenoid. The total beam loss is estimated to be 10% with a beam loss of 6% at the entrance of the RFQ, no transversal beam loss observed in the LEBT and 4% beam loss due to stripping losses.

In parallel to the beam transport calculations several designs of the distribution of the magnetic fields in the solenoids have been investigated using MAFIA [8]. Currently the optimum design has coils of equal length along z but different inner radii in a so-called "2-5-2" arrangement: two coils of inner radius r_1 at the start, another five coils of larger inner radius r_2 in the middle, and two coils of inner radius r_1 at the end. Fig. 4 shows an example magnetic field distribution for a "2-5-2" solenoid using MAFIA.

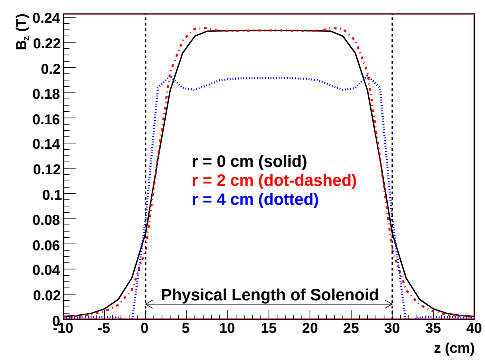

Figure 4: Example magnetic field along z for different x-y radii for a "2-5-2" solenoid (r_1=45 mm,r_2=55 mm).

Preliminary work on the LEBT design is nearly finished and experiments to measure the degree of space charge compensation as a function of time as well as the two-dimensional determination of the transversal phase space density distribution are in preparation.

PEPPERPOT EMITTANCE MEASUREMENTS

Due to the high sensitivity of the LEBT output on the initial beam conditions shown by the beam transport simulations, optimisation requires an accurate model of the beam at the ion source exit. The built-in beam models within GPT represent an oversimplification and a suitable match could not be found with the emittance measurements using the Allison type scanner [9]. While a number of attempts were made to "reverse-engineer" the ion beam x-y profile, using the measured emittance profiles, none of these resulted in a beam that was considered realistic. In addition, there are no measurements of the level of space charge compensation within the ion beam, which also has a significant effect on the beam transport and focusing in the LEBT.

Time-reversed simulations in GPT that attempted to match the measured emittance profiles with ion source extraction simulations in MWS [5], through variation of the level of space charge compensation, were only partially successful.

It was therefore decided that a Pepperpot emittance scanner should be constructed. The pepperpot consists of an intercepting screen, a phosphor imaging screen, a high-speed CCD camera and associated support structures: the assembled system is shown in Fig. 5. The intercepting screen is a 25 x 25 array of 100 μm diameter holes, on a 3 mm pitch, laser-drilled into a 0.3 mm-thick tungsten sheet. This is mounted to a 10 mm-thick copper block, through which 2 mm diameter holes are drilled at an identical pitch to allow the ion beamlets to pass. The phosphor screen consists of P46 phosphor sputtered onto a glass plate, mounted 3 mm from the copper block; an additional 45 nm aluminium layer coated over the phosphor reflects backscattered photons and improves surface conductivity.

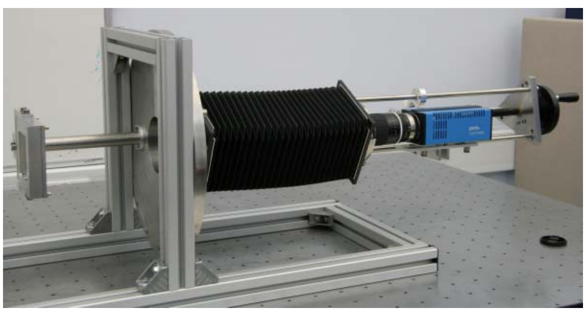

Figure 5: The Pepperpot emittance scanner, prior to installation onto the ion source (shown mounted into aluminium test frame).

The light spots produced by the beamlets impacting on the phosphor are imaged using a PCO 2000 high speed camera with a 2048 x 2048 monochrome sensor and a Nikon 105 mm f/2.8 macro-lens: mounted 700 mm from the phosphor screen, this provides a resolution of 45 μm per pixel and an angular resolution of 3.5 mrad. The camera is mounted to an aluminium support plate and is tilted with respect to the phosphor by an angle of 60 mrad to minimise smear on the image. The entire camera and screen assemblies are mounted to a central rod that passes through the vacuum flange on the rear of the ion source, allowing the screen and camera to move longitudinally while keeping the distance between the two fixed; a vacuum window is mounted in the centre of this flange. Three support rods attached to the outer face of the flange provide extra stability, and to which the camera is fixed with a three-arm spider. Two rulers mounted to the screen support structure allow calibration measurements on the relative size and rotation of the pepperpot images. A light-tight bellows encloses the light path between the vacuum window and the camera lens to ensure the optical path is light tight. With the described set up it is possible to measure the 4D transversal emittance at various points along the beam axis and therefore allows evaluation of the emittance growth and an estimate of the degree of space charge compensation.

Prior to data taking, a uniform white light source was used to calibrate the pepperpot, with measurements made of the relative sizes of the holes in the tungsten intercepting screen, the precise hole spacing and geometry and the amount of smear on the image. The vacuum flange, with complete pepperpot assembly, was then installed at the ion source test lab at RAL. The tungsten screen is currently situated some 10 cm upstream of the current Allison emittance scanners. Data taking is currently at the preliminary stage: an example data image is shown in Fig. 6. Further analysis of the image data is required to extract emittance information comparable to that shown in Fig. 2. In addition, further investigations on the subject of space charge compensation using two Hughes-Rojanski type residual gas ion energy analysers will be performed.

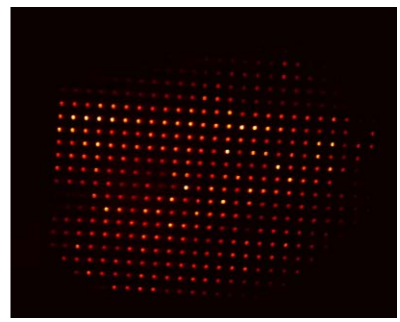

Figure 6: A false-colour intensity image taken with the pepperpot emittance scanner of the ion source beam, at a beam energy of 16.5 keV. The imaged area is 90 x 73 mm ^{2}.

SUMMARY

The progress on the front end test stand work at RAL to contribute to the development of high power proton accelerators has been described. Design and development work is well under way, with first beam through the LEBT planned at the end of 2007.

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