DESIGN OF A PHOTO–DETACHMENT EMITTANCE INSTRUMENT FOR FETS

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Abstract

Photo detachment is a possibility to diagnose non-destructively H^- ion beams. For emittance measurements, the produced neutrals are more suitable then the photo-detached electrons. Such a Photo-Detachment Emittance Measurement Instrument (PD–EMI) is planned for the Front End Test Stand (FETS) at Rutherford Appleton Laboratory (RAL/ UK). FETS comprises a Penning ion source of 60 mA beam current with up to 2 ms pulse length at 50 pps, a Low Energy Beam Transport (LEBT), a four-vane RFQ with 3 MeV and a Medium Energy Beam Transport (MEBT) with a chopper system. The PD-EMI will be integrated at the end of the MEBT to commission the RFQ which is currently under construction. The introduction gives an overview some results reached so far and explains the conceptual design. Beam simulations show how to implement this to the MEBT being under construction. The remaining paper concentrates then on the hardware which is the dipole magnet, the laser and optics. The design and and engineering of the magnet chamber needs special attention to both satisfy beam transportation and diagnostics purpose. First measurements about the laser and its parameters will be presented.

INTRODUCTION

The papers focus is on the beam instrumentation, its design and engineering to build a non-destructive instrument to measure the beam emittance (PD–EMI). The main components of such a device are a suitable laser (pulse energy, beam quality), the dipole magnet to separate the neutralized particles from the rest of the H^- beam and the detached electrons and a detector system consisting of a scintillator and an image intensified CCD camera. The particle detector is of no further consideration here but after summarizing the general idea of non-destructively measured emittances utilizing photo-detachment, the magnet, the laser and in particular the vacuum vessel are presented in more detail.

The FETS project aims to demonstrate a fast chopped H^- beam at 3 MeV beam energy with up to 50 pps and 2 ms pulse duration and 60 mA current. For beam diagnostics, that means non-invasive techniques to avoid heat load and activation of mechanical parts such as a slit or wire are most preferred. More information about the test stand itself and its current status can be found in [1].

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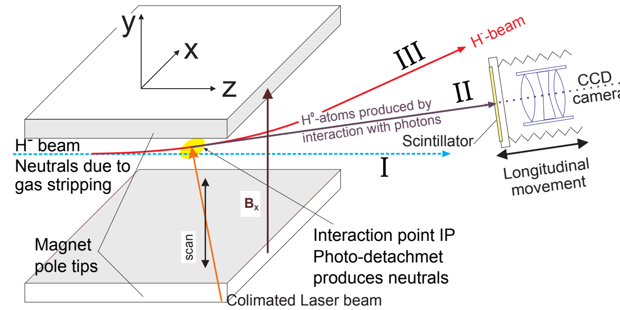

Figure 1: Sketch of the basic idea of the Photo-Detachment Emittance Instrument (PD-EMI). The laser neutralises a small portion of the beam, these particles hit a detector which measures the distribution. Three beamlets can be distinguished; neutrals due to gas stripping, neutrals due to photo-detachment and ions on the reference beam path of the dipole.

General Layout

The basic principle to use photo-detachment for diagnostics is shown in Fig. 1 and described elsewhere in depth [2, 3].

A small portion of the beam gets neutralised with a collimated, i.e. focused laser beam and the produced atoms are detected with a scintillator. If the scintillator is movable and/ or a quadrupole doublet upstream of the magnet varies the focal length, emittance measurements can be done under different for different phase space projections i.e. the transport changes and the beam gets imaged from different angles. This variation of the transport matrix used together with the beam profile and techniques like tomographic image reconstruction (more about Maximum Entropy in [4, 5]) allows to calculate any phase space projections than just yy' [6], only depending how the coordinate system was chosen to extract the profile. If there was no change in the focal length (no change of the sign of β_{twiss}) the beam would always be imaged from a similar angle not providing sufficient information for image reconstruction.

This concept of varying the focus for different emittance measurements was developed into a kind of "diagnostics beamline" [7]. The MEBT layout used for these studies was very similar to the 'baseline' design published in [8]. Very recently, a new MEBT layout was proposed with the aim of reduced costs, mainly by sparing quadrupols and a buncher cavity [9]. This design is longer (see Fig. 2) than

ISBN 978-3-95450-118-2

Table 1: Overview of the Main Data for the Dipole Magnet. A C–typed magnet will be chosen to provide the space for the laser optics.

B–field	
Bending radius	477 mm
H^- energy	3 MeV
Reference path length	≈ 500 mm
Bending angle	65°
IP angle	25°
Gap height	75 mm
Gap width	160 mm
Gap between coils	160 mm

the 'baseline' and does not include a doublet at the end. Both PD-EMI and the beam dumps should be carefully matched to the actual layout. This work is of very immediate interest but is on hold as long as the MEBT output parameters are agreed. However, limitations to these alterations are given through a feasible dipole with a reasonable ratio of yoke width and gap height.

For reasons described above but also for general flexibility (e.g. variable focal length) is was necessary to work out a robust design of dipole and vessel that has the option to be changed within reasonable margins if necessary. It is still under discussion where more compromises are reasonable, either more on the transport side or limiting the emittance measurement. However, the component requires the most care to design is the vacuum chamber because all important parameters for beam transportation and diagnostics are given by the geometry. Compared with the vessel, the magnet is more simple.

It is worth to mention that also the width of the vessel/ magnet yokes should not be excessive because of difficulties to maintain over a long drift length a collimated laser beam. Aim should be a Rayleigh-length z_R of the same order as the H^- beam diameter lies. This has mainly an impact on the magnet design in terms of gap-to-width ratio.

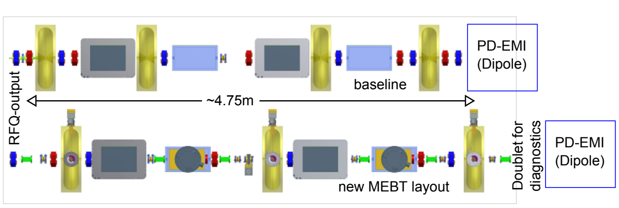

Figure 2: Above, the standard MEBT layout with 4 bunchers and 11 quadrupoles is shown (baseline-design). Below, a very new proposal is which is longer yet less elements. More drift space can be used for e.g. diagnostics or vacuum. There is the possibility of reduced costs for the new proposal. But at least one more doublet is required to focus the beam into the diagnostics.

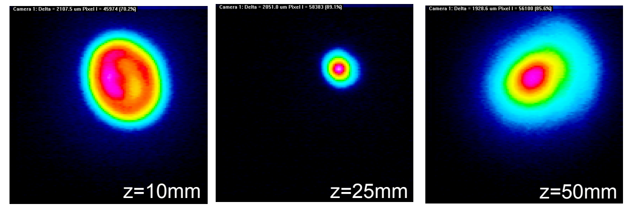

Figure 3: Laser modes measured along a beam path before and after a focusing lens. These were used to extract profiles in x- and y for the M^2 calculation.

MAGNET DESIGN AND ASSEMBLY PROCEDURE

The main parameters of the magnet are summarized in Table 1. It is not intended to build the magnet in-house but simulations with POISSON [10] have shown that a field homogeneity of $\leq 10^{-3}$ can be reached without to many difficulties. Due to a C–magnet the shims are slightly dif-

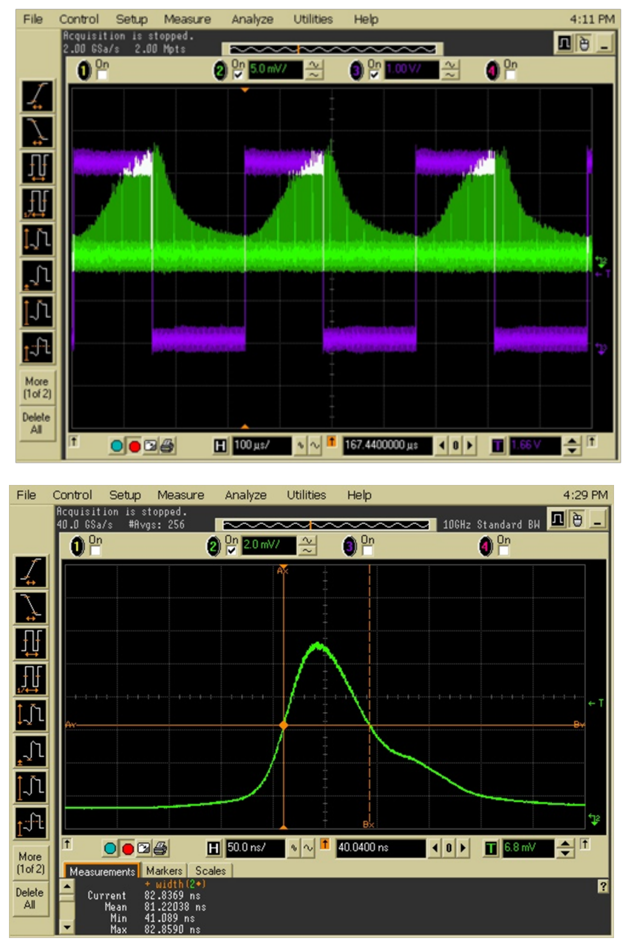

Figure 4: Temporal behaviour of the laser pulse, measured with a 50 ps photo diode and a 50 Gs/s, 10 GHz oscilloscope. Top, the PA is triggered with a 3 KHz signal, shown green is the 30 kHz pulse of the MO. Below, such a single pulse is resolved in time, τ=83 ns at FWHM.

ISBN 978-3-95450-118-2

ferent to compensate the antisymmetry of the return yoke. It is aimed for a good field region of about ≈ 40–45 mm. Another important factor are the costs, the power supply should be within the "15 kW class" and the magnet should not cost more than ≤ 30 k£. First offers from companies like Danfysik and Elyt confirm that this is reasonable.

Yet one speciality is required for the magnet. The present assembly plan assumes to split the magnet horizontally in two halfs whenever changes on the laser beam path or similar are planed. This is due to the fact of designing a prototype for test purpose and access is needed from the top, if changes on the laser beam path are wanted. The procedure for assembly and alignment of PD-EMI would as be as follows:

- Mount bottom half of the dipole on support frame of the beam line and adjust to the beam reference path
- Place the lower part of the vessel on the lower part of the C–magnet and secure both
- Install and adjust all necessary mirrors and movable stages for the laser beam path
- Place the top lid onto the vacuum vessel and secure
- Lower the upper part of the C–magnet, align the yokes and secure everything

LASER BEAM PARAMETERS

A pulsed/ CW laser has been purchased from a French company called Manlight (`www.manlight-alcen.com`). The system is a compact MOPA CW fibre amplifier delivering (according to specification) up to 30 W at 30. . . 100 kHz Master Oscillator (MO) and is optimised for the amplification (Power Amplifier PA, hence MOPA) of a Single Longitudinal Mode (SLM) laser source The PA

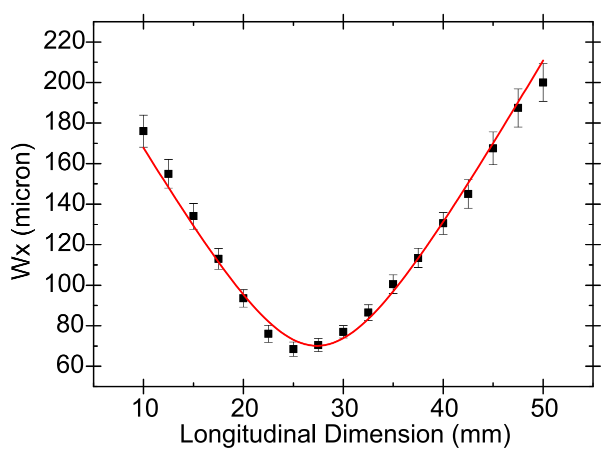

Figure 5: Fitted envelope to beam radii in near and far field at clip points of 13.5%. Each radius was averaged over 64 measurements. For the x-plane M^2=1.61 and for the y-plane it is M^2=1.81

amplifies than with a maximum modulation frequency of 5 kHz this bunch train and allows external triggering.. The power is delivered through a polarized beam source; the actual output is at 1080 nm (measured) and a compact housing comprises an optical system for focusing.

Since the laser has strong influence onto the performance of the PD–EMI it is worth to verify the company's specifications. The interest is mainly on the beam quality described through M^2 and pulse duration and power, i.e. pulse energy if the system is pulsed. The latter drives the rate of neutralized particles while the former determines the spatial resolution of the emittance measurement, hence a low M^2 is eligible, i.e. a Rayleigh length z_R of the order of the ion beam diameter or better. A procedure to measure M^2 without special equipment was described first by E.A. Siegman [11] fitting the following envelope to a number of beam radii $\sigma(z)_{x,y}$,

$$\sigma^2(z) = \sigma_0^2 + M^4 \left(\frac{\lambda}{\pi\sigma_0}\right)^2 (z - z_0)^2 \qquad (1)$$

measured in front of and after a focal point.

First measurements of the laser have been carried out to verify the laser power. To do this, a CW power meter was used. The CW power can then be transformed with the known rep. frequency and means that the pulse energy must be highest at the lowest frequency and vice versa. At nominal power of 30 W a pulse energy of 1 mJ or 8 kW pulse power. But we were only able to measure 10.1 W; hence the energy drops to 340 µJ.

First results of commissioning the laser can be found in Figs. 3 and 4, the fit of the envelope is shown in 5. Compared to the discrepancy in output power, the mode quality in Fig. 3 looks rather good. This is also an indication that the coupling fibre is not misaligned. But the measurements with a fast photo diode in Fig. 4 show again a difference to the laser factory's specification. Instead of 150 ns the pulse is only 80 long. The modulation of 3 kHz of the PA has an oscillation build-up of ≈ 100 µs and no plateau. More measurements are required to investigate the behaviour of the flat-top if the modulation frequency is reduced to its minimum of 1 kHz.

M^2 is smaller than 2 in both planes (see Fig. 5) and provides good enough beam quality to focus the beam with sufficient long Rayleigh length z_R.

LAYOUT AND ENGINEERING OF THE MAGNET VESSEL

A first "working–version" of the vessel is shown in the Fig. 6 and Fig 7. As shown, the vessel is only narrow in between the yoke of the dipole and overlaps at bigger radius to allow mounting of CF100 flanges directly using tapped holes. The bottom is fixed, the top is a removable lid, sealed with an O–ring and secured with M4 screws.

The horizontal view in Fig 7 shows the tight space for the three different beamlets on the exit side. transport requirements for the emittance measurement and the radial space

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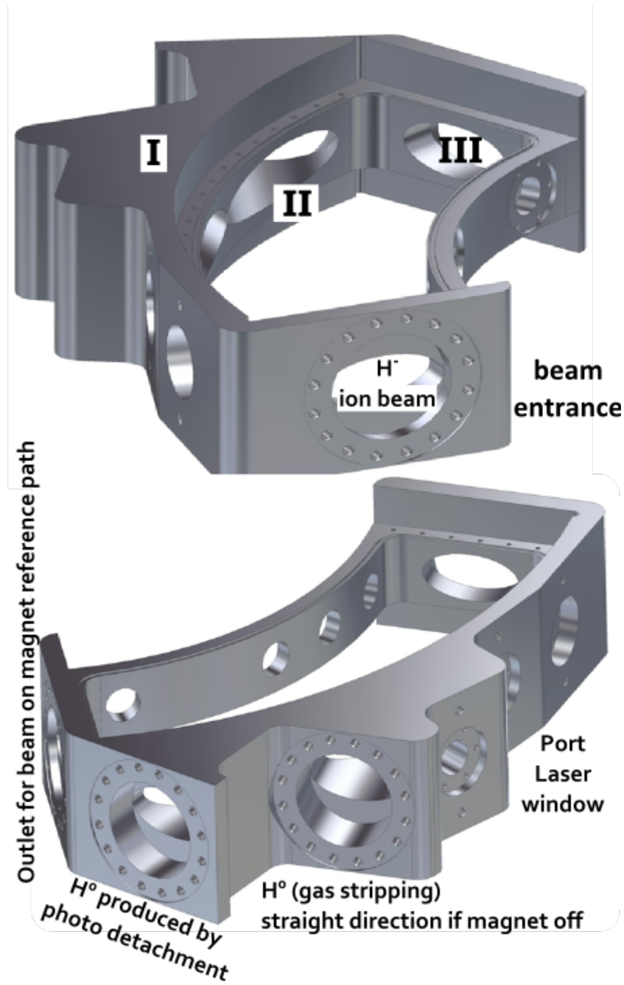

Figure 6: Two different views of the vessel design. The narrower part fits in between the magnet yokes. The side walls are higher to provide space for flanges mounted without adapters to save space. The coils need to be provide vertical clearance that the side wall fits in between.

needed for the beam dumps. This is best seen in In between the beamlets I and III which both require a beam dump with an outer diameter of CF250, the scintillator, a CF100 vacuum window and the CCD camera will be installed on a rail system.

In discussion with the mechanics company N.A.B. Precision Tooling Ltd., also the manufacturer of the FETS RFQ, (`www.nabprecisiontooling.com/`) the idea arose to machine the vessel from solid on a multiple axis milling machine, mainly to avoid welding. Fillets are wide for Aluminium and the relatively complicated shape of the bend with the beam pipes for the 3 beamlets would require a lot of welding which is labour-intensive and failure–prone. Therefore it looks more promising to use more material and more (milling) machining time but less manual work.

It is also desirable to use an Aluminium alloy instead of stainless steel because of lower activation if the beam looses particles and produces possibly neutrons. Theoretically, pure Al should be used because it does not produce

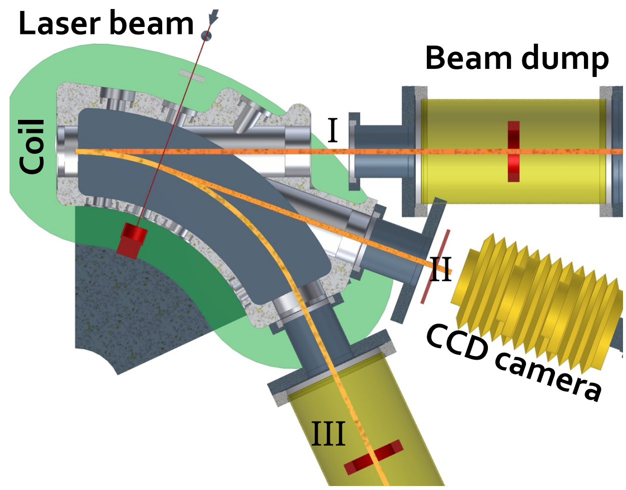

Figure 7: Impression of the whole assembly with all three beam lines. Despite all the effort to provide enough space for the neutrals (2nd beamlet) the space for scintillator and camera is tight due to the radial dimensions of the beam dump (at least CF250).

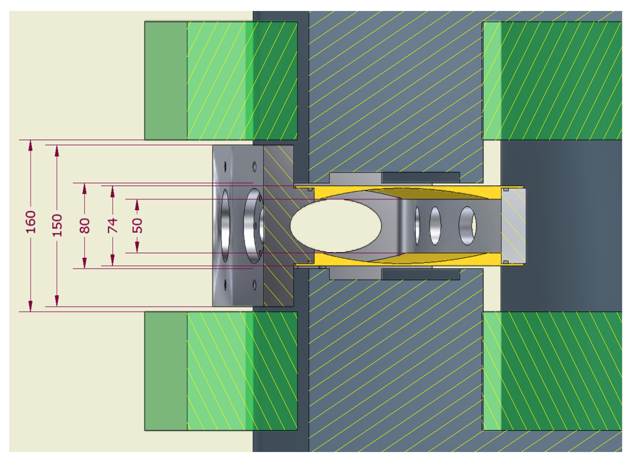

Figure 8: Both vessel and magnet shown. The coils provide the space for the flanges of the three beam lets and the movables stage to scan the laser. Due to tapering towards the centre a minimal clearance of at least 40–45 mm is sustained everywhere.

neutrons due to a (p,n) reaction. But this is from an engineering point of view not acceptable because of the low Yields strength (tensile). A compromise is an Al–alloy with a low percentage of heavier elements, especially copper is essential to avoid. This would also allow to temper the vessel and gain additional strength.

Another important design aspect is the internal vessel height to provide maximum clearance for the beam. Realistically it is possible to achieve about 50–55 mm clearance if the gap height of the magnet is 65–70 mm. Therefore it is essential to know the minimum lid thickness, i.e. minimum thickness along the middle axis of the magnet. For better results, the top and bottom were assumed to ta-

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Table 2: Overview of the Main Data for the Dipole Magnet. A C–typed magnet will be chosen to provide the space for the laser optics.

Case	Property	[MPa]
Simply supported	Max. stress	103 MPa
	Max. deflection	0.8 mm
Fixed	Max. stress	62 MPa
	Max. deflection	0.47 mm

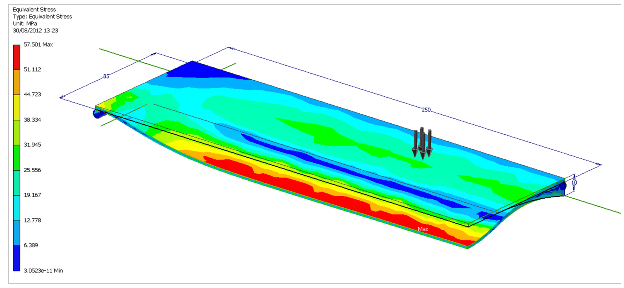

Figure 9: Example of static pressure simulation to check the stability of bottom and lid. The shown example tapers from just 2 mm around the central path up to 10 mm near the side walls.

pers out from just 2 mm in the middle up to 10 mm at the edges, please see Fig. 8. At the presence, simulations have been performed assuming the Al–alloy 6061 with a yield strength (tensile) of 275 MPa and an ultimate strength (tensile) of 310 MPa. The size is 500 × 170 mm and of rectangular shape (Fig 9. The results are summarized in Tab. 2.

The expected deflection is acceptable because neither bottom nor lid will support anything critical regarding alignment or precise positioning but mounted either outside of the vacuum or if necessary, attached to the side walls.

SUMMARY AND OUTLOOK

The paper gives an overview of the status of the design of the various components of PD-EMI. It is planed to order a magnet within the next year, first contacts with companies like Danfysik have confirmed that the dipole is a fairly standard magnet and stays within our budget. The laser does not deliver the full beam power to specifications but both pulse energy and quality should be adequate for basic measurements.

Most sophisticated is the vessel to provide space for all three beamlets and enough vertical height to allow sufficient flexibility in matching the beam into the dipole. Ideally, the focal length should vary around the interaction point, i.e. the sign of β_{twiss} of the beam distribution must change. The presented 'working-version' was not only developed with the aim to serve all the criteria of beam transportation, magnet design, laser guidance and resolution of PD–EMI but also with a scalable layout in case some parameters change and this needs to be considered. This could be in particular an issue for the new MEBT layout which has changed very recently. This design work needs to be finished in order to be acknowledged in the simulations for the diagnostics and beam dump.

Another issue is the fringe field of the dipole magnet. As a starting point, the fringe field simulated with POISSON will be implemented in General Particle Tracker (GPT, `www.pulsar.nl/gpt`).

The static simulations need also some refinement. So far, only the reference beam path was considered but the 1$^{\text{st}}$ and 2$^{\text{nd}}$ beam path require the same clearance and should be considered, i.e. the tapered edge needs to thinned down.

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ISBN 978-3-95450-118-2