EMITTANCE MEASUREMENT INSTRUMENT FOR A HIGH BRILLIANCE H^- ION BEAM[*]

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Abstract

Among present challenges for beam diagnostics and instrumentation are issues presented by high beam intensity, brightness, resolution and the need to avoid inserting mechanical parts into the beam. This very often means applying non–destructive methods, which avoid interaction between ions and mechanical parts and, furthermore, allow on–line measurements during normal beam operation. The preferred technique for H^- beams is the photo–detachment process where (laser) light within the range of $400 \ldots 1000\,\mathrm{nm}$ has a sufficient continuous cross section σ_{PD} to neutralize negative ions. The actual diagnostics are then applied to either the neutrals produced or the electrons. The latter are typically used for beam profiles whereas neutrals are more suitable for emittances, and form the subject of the present paper. This provides an overview of the basic features of the diagnostic technique, followed by discussion about computing the missing second transverse projection view using a method called Maximum Entropy Method (MaxEnt, MEM).

INTRODUCTION

The Front End Test Stand (FETS) project [1] at RAL, UK, makes high demands on the diagnostics because of its beam power ($60\,\mathrm{mA}$ H^-, $\leq 3\,\mathrm{MeV}$ beam energy, $\leq 10\,\%$ duty cycle). Using a non–destructive method, i.e. no mechanical parts inside the ion beam, minimizes the influence on the ion beam with the advantage of an on–line diagnostic tool. The experimental set–up uses a Penning source with slit extraction, a solenoid LEBT, a four–vane RFQ who brings the beam from 70 keV up to 3 MeV and a MEBT consisting of quads, rebuncher and a fast/ slow chopper. Particularly the latter and the slit extraction results in a lack of symmetry which makes a 4D emittance measurement highly desirable.

The basic principle of the implemented Photo Detachment Emittance Instrument (PD–EMI) is illustrated in Fig. 1 and widely discussed in [2, 3]. Compared to more common devices like slit–grid/ harp ("slit–slit") and pepperpot ("point–point") instruments the laser acts like a slit whereas the particle detector takes the place of a pepperpot device, therefore the PD–EMI can be described as an instrument with a slit–point transfer function. The yy' emittance in Fig. 1 can be measured in a direct way by gathering angle profiles for each laser position.

In principle it would be possible to measure in x–direction similarly to yy' with a second set of mirrors. But it is technically a challenging problem to place the necessary movable stages inside a dipole. It is also not very attractive in price. A more physical drawback is the separation of the 4D emittance measurement into two projections. But a detector movable longitudinally along the drift length of the neutralized ions could help to overcome the problems: The laser will be moved several times through the ion beam and at each time the z positions of the detector is moved along the drift of the neutrals. It is then possible to add up all detector signals for a given z which results in a $\rho(x, y)_{z(n)}$ density distribution. Each extracted 1D profile is then mapped to the laser position by a drift matrix to calculate the xx' emittance.

The Maximum Entropy Method MEM

The best candidate to do the xx' emittance reconstruction utilises a principle called maximum entropy method (MEM). This is a powerful and a extensively used technique for the deconvolution of data and the reconstruction of images (astronomy, tomography, neutron scattering). First applications in accelerator science are published in [5, 4] and a very good but general introduction is given in Sivia's textbook [6].

The strengths of MEM are its generality and ability to deal with *noisy* and *incomplete* positive data. It is based on Bayes' theorem and uses an entropy as described in information theory. The linear transformation between the

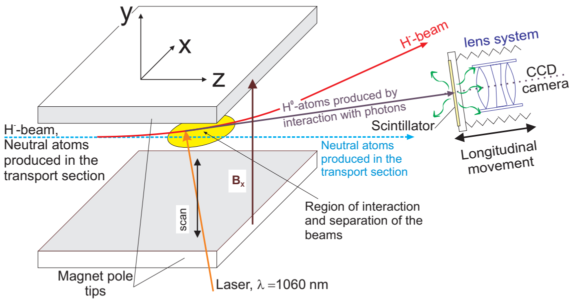

Figure 1: The negative ions penetrate the dipole and after some displacement a laser scans through the beam and neutralize a small amount of ions. The neutrals produced by photo detachment are guided to a detector system (yy' emittance). The other transverse emittance can then be reconstructed by moving the scintillator and collecting $\rho(x, y)$ profiles along the drift.

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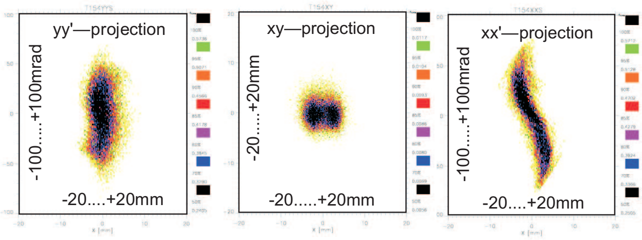

Figure 2: The three projected views of the chosen particle distribution from an ion source measurements. The distribution is scaled down in radius and angle to a level more likely downstream the RFQ.

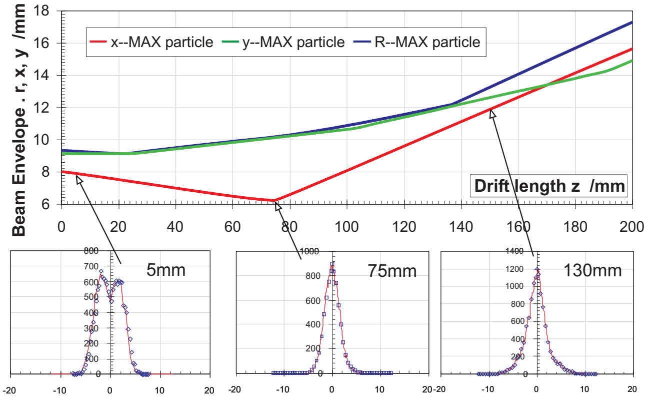

Figure 3: On the top the envelope of $x_{\max}$, $y_{\max}$ and $r_{\max}$ of the given entrance distribution. Below are three profiles $I(x_{z(n)})$ representing examples of the used projection data for the Maximum Entropy Method.

existing data and the reconstructed test object is important. Then the entropy S can be seen as a regularization function which helps to stabilize the chosen procedure, like least–squares for a free–form solution, resulting in the "most probable" distribution which also satisfy all the observed constraints. For the phase space reconstruction a software called MemSys5 is chosen [8] originally written by J.Skilling and S.Gull.

Rotation Matrix

If not other mentioned the whole paper uses a coordinate system as given in Fig. 1. But with rotating the orthogonal system it is possible to get emittances others than in x–or y–plane and does not affect the described MEM. The algorithm is applied to another projected view Θ_m of the 2D $\rho(x,y)_{z(n)}$ for all $n = 0 \ldots N$. Additionally to index n which indicates the longitudinal position, index m represents the rotation angle. For that purpose new coordinates s, t can be introduced with $x = x_m(s,t)$ and $y = y_m(s,t)$. The m$^{\text{th}}$ pair of transformed coordinates for $\rho_m(x,y)_{z(n)}$ are specified by a rotation matrix like

$$\begin{pmatrix} s \\ t \end{pmatrix} = \begin{bmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{bmatrix} \times \begin{pmatrix} x \\ y \end{pmatrix} .$$

EMITTANCE RECONSTRUCTION

The ability of the described MaxEnt method has been investigated on an ion beam distribution measured downstream of the ion source with our pepperpot device. The three different views of projection xx', yy' and xy are shown in Fig. 2. A Cartesian coordinate without any rotational offset was used to reconstruct the xx' emittance. Furthermore the measured emittance was scaled down keeping the shape of each profile in the different subspaces constant to an expected value downstream the RFQ at a beam energy of 3 MeV.

In the next step the drift of the neutrals was simulated as illustrated in Fig. 3. The different development of the $x_{\max}$, $y_{\max}$, $r_{\max}$–envelopes represents the non–symmetric emittance. The deconvolution has been performed with maximal 8 profiles at $z = 10, 25, 50, 60, 75, 90, 100\ 150\,mm$ whereas Fig. 3 presents only three of them.

For the deconvolution a default model was used where starting with a homogeneous distribution for the test object and in accordance with the available data either the intensity will be increased or reduced after every iteration. Apart from the small influence of the chosen model any further assumptions not represented by known data are avoided. The emittances shown in Fig. 4 are reconstructed with 17 iterations which takes on a typical desktop less then 30 sec. Figure 4 compares three different reconstructions with the entrance emittance where number and position of the profiles vary. The results imply that not the number but the phase advance is critical. As long as the changes in between the profiles are small, increasing the number of profiles improve the emittance only very little. This is also visible in the difference of the blue covered areas at the edges of Fig. 4(A) and Fig. 4(B). These parts are not covered by any information of the profiles and therefore such low intensity levels represent the starting point of the default model. Example (A) covers the phase space more efficiently than (B) even with less profiles. Furthermore it is in better agreement with the original distribution and the reconstruction (C) with 8 profiles.

It should also be mentioned that the fractional rms emittance of (A) and (B) does not diverge more than $\approx 20\%$ from the deconvolution with eight profiles if you consider only intensity levels $\leq 80\,\%$. For a more detailed study about the rms values of Fig. 4 (C) and Fig. 4 (D) in Fig. 5 graphs of both are shown. It was necessary to adopt the internal "phase space resolution" for each particle distribution on which then the rms formalism can be applied. To quantify this variation an intermediate step was introduced to test the smoothness of the graphs for each phase space resolution. The rms resolution is chosen to avoid erratic curves at high values and stepwise behaviour at low values. The deviation of each single emittance in between the described margins is of the same order $\Delta \approx 20\%$ as in the reconstruction with different number of profiles. The pos-

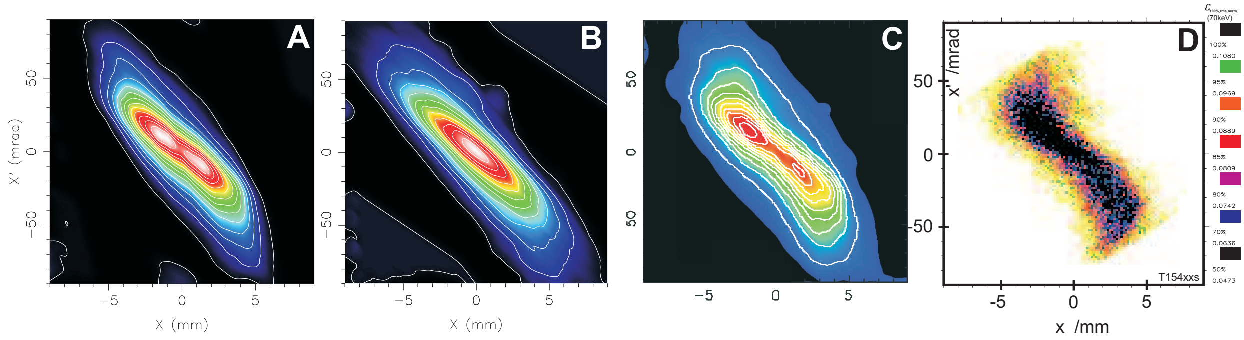

Figure 4: Different reconstructed emittances (A,B,C) in comparision with the original distribution **(D)**, all in same scale. The following profiles were used: **(A)**: $z = 25, 90, 150\,\mathrm{mm}$; **(B)**: $z = 75, 90, 100, 150\,\mathrm{mm}$; **(C)** $z = 10, 25, 50, 60, 75, 90, 100, 150\,\mathrm{mm}$.

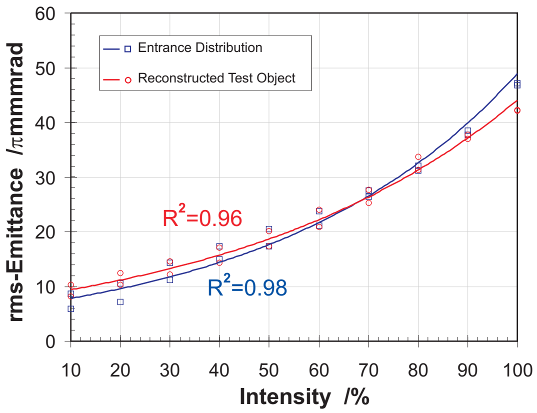

Figure 5: Comparison of the fractional emittance of both the entrance distribution and the reconstructed distribution (C). The phase space resolution for the applied rms–formalism is varied in a similar way for both distributions.

sible precision of a reconstruction with profiles with sufficient phase advance is in that context good enough.

In real measurements it would be reasonable to use the yy' emitttance to compare this result with a reconstruction in the same plane. This might be helpful to specify the discussed problems like phase advance and correct phase space resolution for the rms formalism.

SUMMARY & OUTLOOK

A method called Maximum Entropy (MaxEnt, MEM) is presented to reconstruct the xx' emittance using a movable particle detector, the other transverse plane is measured according to a standard slit–slit principle. To generalize that concept a rotational matrix can be applied to be independent of the orthogonal coordinate system. The whole phase space information would then consist of a set of 2D projection views at different angles.

Further investigations about the MEM–limitations are necessary, e.g. beam noise and especially an estimation about the phase advance (i.e. alteration of profiles).

The paper does also not include a discussion about more technical aspects which are issues in the near future like magnet design, beam transport simulations through the dipole and experimental test of laser beam guiding and mirror movement concerning laser positioning.

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REFERENCES

[1] A.P. Letchford et al., "Status of the RAL Front End Test Stand", LINAC 2008, MOP009

[2] C. Gabor, "Untersuchungen zur zerstörungsfreien Emittanzmessung an einem Testaufbau für negative Ionen", Goethe–Universität Frankfurt, IAP, PhD–thesis, 2007

[3] C. Gabor, D.A. Lee, J.K. Pozimski, A.P. Letchford, "Laser–Based Beam Diagnostics for the RAL Front End Test Stand FETS", 11th Int. Conf. on PNNIB, AIP Conf. Proc. 925, p.183, 2006

[4] U. Rohrer, "Introduction of 2–Dimensional Beam Tomography for Monitoring Transverse Beam Emittance at SIN", PSI Ann. Rep 1982, NL 5–6

[5] G.N. Minerbo, "MENT: A Maximum Entropy Algorithm for Reconstructing a source from Projection Data", Computer Graphics and Image Processing, 10 (1979), pp. 48. . . 68

[6] D.S. Sivia, J. Skilling, "Data Analysis — A Bayesian Tutorial", 2nd edition, Oxford University Press, 2006

[7] R.C. Conolly, K.F. Johnson, D.P. Sandoval, V. Yuan, "A transverse phase-space measurement technique for high-brightness H^- beams", Nucl. Instr. and Meth., A313, 1992, pages 414–419

[8] Maximum Entropy Data Consultants Ltd., J. Skilling, S. Gull, "MemSys 5" `http://www.maxent.co.uk`