OPTICAL DIAGNOSTICS FOR FRANKFURT NEUTRON SOURCE

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Abstract

A non-interceptive optical diagnostic system on the basis of beam tomography, was developed for the planned Frankfurt Neutron Source (FRANZ). The proton driver linac of FRANZ will provide energies up to 2.0 MeV. The measurement device will non-interceptively derive required beam parameters at the end of the LEBT at beam energies of 120 keV and a current of 200 mA. On a narrow space of 351.2 mm length a rotatable tomography tank will perform a multi-turn tomography with a high and stable vacuum pressure. The tank allows to plug different measurement equipment additionally to the CCD Camera installed, to perform optical beam tomography. A collection of developed algorithms provides information about the density distribution, shape, size, location and emittance on the basis of CCD images. Simulated, as well as measured data have been applied to the evaluation algorithms to test the reliability of the beam. The actual contribution gives an overview on the current diagnostic possibilities of this diagnostic system.

OPTICAL DIAGNOSTICS IN THE LEBT

Alternative methods to extract information from tomography data out of the beam in more characteristic detail are developed [1]. In this contribution beam position,shape and emittance will be regarded. Beam position and beam shape fascilitate the analysis of the effects of the chopper in the LEBT on the beam and the proper alignment of the source. Shape and emittance of the beam will evaluate the quality of the beam before entering the acceleration section after the last solenoid.

METHODS

Different methods were developed and implemented to support a different, more detailed information about the characteristic of the beam.

Beam Position

The beam position is a two-part information, consisting of the center of gravity and the main axis of gravity that determines the direction of the beam through this center. This direction can be defined by the aberration angle of the main axis of gravity from the z-direction. The center of gravity for the volume data V is given by P_x, P_y and P_z, where x and y are the transversal directions and z is the longitudinal direction of the volume. The back projected volume is a three-variant dataset of intensity values. The axis of gravity of V only depend on the actual intensity distribution. The determination of these axes is known as eigenvalue problem. Therefore, the eigenvectors of the inertia tensor of the distribution are the demanded directions. The inertia tensor is given by:

$$T = \sum_i m_i \begin{pmatrix} \tilde{y_i}^2 + \tilde{z_i}^2 & -\tilde{x}_i\tilde{y}_i & -\tilde{x}_i\tilde{z}_i \\ -\tilde{y}_i\tilde{x}_i & \tilde{x_i}^2 + \tilde{z_i}^2 & -\tilde{y}_i\tilde{z}_i \\ -\tilde{z}_i\tilde{x}_i & -\tilde{z}_i\tilde{y}_i & \tilde{x_i}^2 + \tilde{y_i}^2 \end{pmatrix} \quad (1)$$

Where m_i is the intensity of a point in the volume and the $\tilde{x}, \tilde{y}$ and $\tilde{z}$ are the whitened point coordinates, which means that the center of gravity is subtracted from the original coordinates. T is a bilinear representation of the torsional moment of the correlated volume. Note that the torsional moment in z-direction is nearly zero, since the impulses of longitudinal direction are much stronger than in the transversal directions. Because of this circumstances, the eigenvector with the smallest eigenvalue is the main axis of gravity in z-direction. Given the longitudinal direction by a vector $\vec{z} = (0, 0, P_z)$, the aberration angle of the main axis of gravity from the z-direction is given by the scalar product of the smallest eigenvector $\vec{e_1} = (e_{1,1}, e_{1,2}, e_{1,3})$ and $\vec{z}$:

$$\cos\phi = \frac{\vec{z} \cdot \vec{e_1}}{P_z \cdot \sqrt{e_{1,1}^2 + e_{1,2}^2 + e_{1,3}^2}} \quad (2)$$

Beam Shape

The beam shape is directly given by the back projected intensity distribution in the transversal (x, y)-plane of every longitudinal z position of the volume. It is not in every case straightaway obvious in which degree the beam is rotational symmetric. In [2] a symmetry factor was introduced to compare the degree of symmetry of different beams on the basis of a transversal projection of the beam. Given a projection of the beam in the (x, y)-plane and the center of gravity at a given longitudinal position z, compute the integrals over all intensity values from the center of gravity to the edge of the plane in radial angles from 0° to 180° around the center of gravity. The symmetry factor then is defined by :

$$\xi = \frac{\sigma^2_{\eta_\alpha}}{\overline{\eta_\alpha}} \quad (3)$$

where $\sigma^2_{\eta_\alpha}$ is the variance and $\overline{\eta_\alpha}$ is the mean of all intensity integrals. If the variance is 0, the beam is ideal rotational symmetric. Values greater than 0 indicate a growing asymmetry of the beam projection. $\overline{\eta_\alpha}$ is a normalization factor that allows to compare symmetry factors across different beam distributions and independent of the size of the

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(x, y)-plane. A fractional determination of the beam size also belongs to the determination of the beam shape, but is not discussed in this place.

Emittance

For the determination of emittance the tomography algorithm was used to backproject the phasespace of the transversal directions (x, x') and (y, y') instead of the position space (x, y). This was performed according to [3]. On the phasespace planes the emittance can be computed by determining the centered second moments of the phasespace image, where m is the position of the phasespace image in x direction and n is the position in x' direction. i_{nm} is the intensity value of the position (n, m):

$$\overline{x^2} = \frac{1}{M} \sum_{m=1}^{m_{max}} \sum_{n=1}^{n_{max}} m^2 \cdot i_{nm} \tag{4}$$

$$\overline{x'^2} = \frac{1}{N} \sum_{m=1}^{m_{max}} \sum_{n=1}^{n_{max}} n^2 \cdot i_{nm} \tag{5}$$

$$\overline{xx'} = \frac{1}{NM} \sum_{m=1}^{m_{max}} \sum_{n=1}^{n_{max}} nm \cdot i_{nm} \tag{6}$$

Note, that the data here again has to be whitend by substracting the center of gravity before to obtain the centered moments. By the centered second moments the emittance is given as rms-emittance:

$$\epsilon_{rms} = \sqrt{\overline{x^2} \cdot \overline{x'^2} - \overline{xx'}^2} \tag{7}$$

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EXPERIMENTAL DATA

The raw data consits of projections along one transversal direction and the longitudinal direction around the beam from 0° to 180° in steps of one degree. The raw data, simulated as well as measured, is backprojected by the filtered backprojection algorithm into 3-dimensional volume data, containing the information of the density distribution of the particles given by the intensity of the residualgas radiation (measurement) or cumulated particle density(simulation) (Fig.1).

Simulated Data

The simulated data consists of a combination of two particle ensembles, each with 10.000 particles, that are placed congruently on the transversal plane in the first data set. 10 data sets were created, where the two particle ensembles are moved apart (which can be seen in Fig.2. The dimension of a projection is 510x510 pixel (43x43 mm). The dimension in the (x, y)-plane is 360x360 pixel covering 917mm^2 (30.29 x30.29 mm). For the simulation a starting distribution was created and then drifted by the simulation tool Lintra.

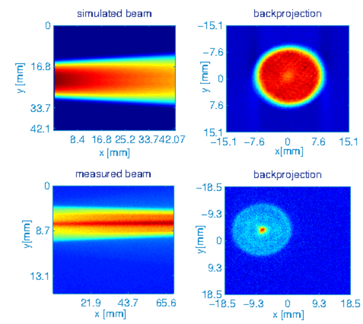

Figure 1: Example of experimental data.(right)

Measured Data

The measured data is taken of an 10 keV He^+ beam with a nitric indicated residualgas radiation. It is focussed by a 0.21 T magnetic field. The projections are taken by a CCD camera with a resolution of 1200x1600 pixel (52.47 x 69.9 mm) and an exposure time of 5000 ms. The backprojected position space is 854 x 854 pixel covering 1391.3 mm^2 (37.3 x 37.3 mm)

RESULTS

The 10 simulated data sets were created to test the methods introduced before in different situations. In particular, the two beams of the 10 data sets were not only moved apart, but also the center of gravity was shifted and there is an effect, that with increasing distance the total ensemble of 20.000 particles should show an abberation from the lognitudinal direction. The emittance, here computed as a $4\pi\epsilon$ emittance, is increasing.The last beams of the dataset exceed the image border.

Beam Position

In figure 2 the result for the 10 data sets are shown in form of cummulated slices with their center of gravity in x and y direction. On the right, the determined angle of

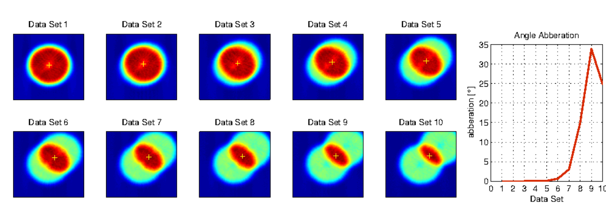

Figure 2: Result of the beam position method.

abberation is ploted. For the first 5 data sets it was not existing up to minimal. Then it rapidly increases. This is a point where the weight of the one ensemble moving apart takes a not neglible influence of the torsional moment of the tensor. The reason, why this effect seems to decrease with data set 10 is, that for the algorithm there seemingly is a loss of particles (these ones crossing the edge of the image). This is, as if the beam losses weight at this position, such that the torsional moment is slewing back. The angle abberation of the measured beam has been 0.006°. In Fig.1 it can be seen, that the beam is not at all in the middle of the image. The angle abberation is not an indicator of this (this could be determined just by the center of gravity), but it indicates in which direction the main beam axes is runnung through this center of gravity.

Beam Shape

The beam shape directly could be seen by the backprojected slices of a volume. In most cases, it would not be too hard to decide whether the density distribution is gaussian-like, hollow or something else. Nevertheless it might be not obvious in which extend a beam is radial symmetric. The symmetry factor could be used in two ways. The first is to compute the symmetry factor on the cummulated slice to have a measure of symmetry for the whole beam that gives the posibility to compare different beams or to evaluate the correctness of the source extraction and the transport from it to the measurement point. The beam of data set 1 nearly

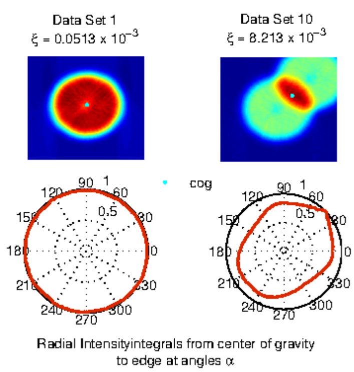

Figure 3: Comparison of the symmetry characteristics of the cummulated slice of data set 1 and data set 10.

is radial symmetric, but also the beam of data set 10 is not completely asymmetric. One can find an axes symmetry (if one imagines an axes from 50° to 220° across the polar plot). The symmety factors are increasing from data set 1 to 10, where $0.0513\text{x}10^{-3}$ is the smallest and $8.213\text{x}10^{-3}$ is the highest. Having a look on the symmetry characteristics of the measured beam in Fig. 4 one can see that this beam is asymmetric. Its overall characteristics may be described as gaussian, but there are not neglible outgrowths, that become visible in the symmetry characteristics. An other possibility to use the symmetry factor is, to apply it to every slice of the volume and to observe the evolution of symmetry within the beam along time (z-direction). It could be observed that symmetry is increasing over time, if there only is a drift.

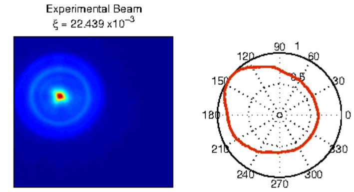

Figure 4: The measured beam as cummulated slice with its symmetry characteristics. Note, that the middle of the polarplot is the center of gravity, not the middle of the image.

Emittance

The backprojection of the phasespace by the tomography algorithm and the determination of the emittance is currently in progress. It has to be dealt with some non-linear space charge effects and couplings of the solenoids within the LEBT. For the 10 data sets the approximated emittance in form of a not normalized $4\pi\epsilon$- emittance derived from still very *noisy* phasespace reconstructions is given in Fig.5. The decreasing emittance of data set 9 and 10 also is an effect of the apparent particle loss.

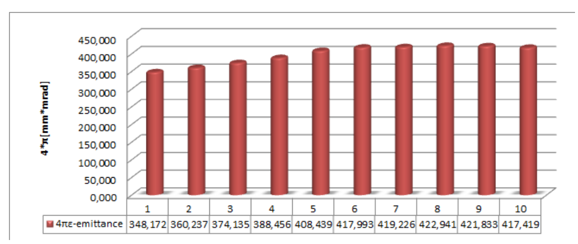

Figure 5: The approximated $4\pi\epsilon$ emittances of the 10 data sets.

CONCLUSION

Three methods to analyze and evaluate the beam in the LEBT section of FRANZ were introduced and tested. Exemplarily, it was shown that these methods could describe the constitution of the beam on different aspects, that allow to evaluate the quality of the beam in more detail. The evaluation of the backprojected phasespace on the one hand, and the comparison of the symmetry evolution with the entropy evolution of a beam on the other hand, is in progress.

REFERENCES

[1] H. Reichau, O. Meusel, U. Ratzinger, C. Wagner, "Estimation of Profile Length in Hybrid Ion Beam Tomography", Proceedings of BIW 2010, TUPSM059, p.292

[2] K. Schulte, "Untersuchung von Messmethoden zur Parameterbestimmung eines Nichtneutralen Plasmas", Diplomathesis, Goethe-University Frankfurt Main, 2008

[3] D. Stratakis, "Tomography as a diagnostic tool for phase space mapping of intense particle beams", Phys.Rev.Sp.T. - Acc. and Beams, 2006