ESTIMATION OF PROFILE WIDTH IN HYBRID ION BEAM TOMOGRAPHY

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Abstract

In beam diagnostics, optical techniques had become increasingly important as they provide information with the advantage of minimal effect on the beam. The planned Frankfurt Neutron Source will consist of a proton driver linac providing beam energies up to 2.0 MeV. The rotatable diagnosis tank hybrid ion beam tomography tank HIBTT will be placed at the end of the low energy beam transport section (LEBT) to provide beam tomography based on the visible radiation of the ion beam in front of the RFQ. The beam energy in this section will be 120 keV and the current 200 mA. Additional to the CCD camera that takes optical data for the tomography, other non-interceptive devices could be used to gain additional information. The question behind this hybrid approach to non invasive beam diagnostics is: what and how much information can be extracted from an ion beam without disturbing or destroying it? The actual contribution deals with the information of profile width in beam profile measurements. The presentation introduces a definition and an information sensitive method for profile width determination and verifies them using experimental and numerical data.

INTRODUCTION

Beam diagnosis systems that provide knowledge about beam properties and behavior of an ion beam serve as a source of potential controllability through attained information. What one could actually learn about an ion beam, or rather, which and how much information can be extracted from it without disturbing or destroying it, essentially influences the extent of possible control over the beam. Based on a theory of information, an extended diagnosis pipeline was derived that forms the basis for a beam diagnostic system for HIBT (hybrid ion beam tomography), consisting of a flexible measurement device and an associated, modular software agent. The hardware device is the hybrid ion beam tomography tank (HIBTT) that was developed to serve as a multi-measurement device (Figure 1). It consists of a rotatable vacuum chamber with four 100 mm adapter flanges sthat everal non-invasive measuring equipment could be plugged into. HIBTT rotates within a maximum angle of 270 degrees in >5000 steps of angle encoding driven by a pecking motor and drive belts. The seal was constructed to resist vacuum pressures up to 10^{-7}mbar. Accordingly the software agent for data analysis has to be built in a modular manner. This permits analysis of data from several measurement devices without adjusting the basic structure. To analyze the measured data, an interface module for the software agent might be implemented if not contained in the default assembly. Furthermore, collective phenomena that arise from intense beams or non neutral plasma can be identified. In the first section of this contribution a suitable theory of information for beam diagnostics will be introduced. The second section deals with an information sensitive approach to profile width in optical beam measurements by giving a general definition of profile width, an error estimation and a first algorithm that will be implemented and proved in relation to the introduced error estimation.

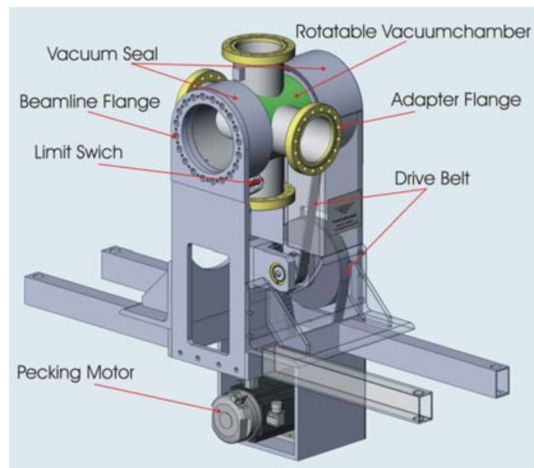

Figure 1: HIBTT is designed to serve as a multi measurement device for non- invasive beam diagnostics.

INFORMATION AND BEAM DIAGNOSTICS

Unfortunately no consistent theory of information in general exists, so one has to specify what has to be understood by the term *information* as the case arises. Consider a definition for beam diagnosis:

Let the term beam diagnosis be considered as ascertainment of distinctive properties called information for the evaluation of beam quality.

Then one has to point out the meaning of *information* in this context. In [1] three dimensions of information are introduced. The syntactical dimension of information, where the information theory of Shannon [2] resides, deals with relations between individual symbols, e.g., single particles or a beam in this case. Around this dimension lies the semantical dimension of information, which assigns a

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meaning to the relations taken from the first dimension. In this dimension information always arises between two reference layers, e.g. the information of emittance arises between the micro layer of n particles and the macro layer of a 6n-dimensional phase space. The syntactical dimension provides the necessary syntax in the form of Liouville's Theorem. The third dimension containing the previous two is the pragmatical dimension, which is the point of origin of the diagnosis, since it permits one to distinguish relevant data from non-relevant data in matters of a predefined aim or question. Based on this dimension a concept of data is needed, since the data basis is the source of information retrieval. A general definition of information (GDI) that comprises a proper definition of data and its correlation to information defines an instance of information σ as a semantic content, iff it consists of n data for $n \geq 1$, the data is well-formed in terms of a syntax in form of constraints that cluster data correctly, and the well-formed data is meaningful[3],[4]. That means the data must comply with the semantics of the system at hand.
The implementation of beam diagnosis in order to explore what information could be gained demands a careful acquisition and analysis of a large amount of data, out of which the distinctive properties could be mined. A multi-functional measurement device and information-sensitive algorithms are needed. Additionally a preferably precise definition of the information that has to be extracted. Otherwise one will meet with the dt-problem: achieving an answer that could not explicitly interpreted, since the underlying question is not unambiguously determined.

SENSITIVE INFORMATION MINING IN BEAM DIAGNOSTICS

With HIBT, established methods as well as new ideas of information mining shall be analyzed with regard to information acquisition. In a first approach data will be provided by a CCD camera, that was tested before on exposure behavior, noise, exposure time in relation to intensity, intensity in relation to residual gas composition and other inquiries to ensure a nearly all-over view on the data provided by this measurement device. Several optical methods for the determination of emittance use the parameter of profile width, e.g., [5],[6],[7]. The error propagation of this methods is seriously influenced by the exactness with that the profile width could be specified. For instance, the determination of emittance from beam profile measurements [7] evidences that an abberation of 1% from the exact profile width results in a maximal error in the range of 12 % - 14% for a determination of emittace out of three profile widths. An abberation of 5% even causes a maximal error of about 25% [6]. Therefore an exact determination of profile width is essencial for the accuracy of methods using optical beam profile measurements to determine the emittance.

Theoretical derivation

Initially a definition of profile width will be presented, that enables to define an error estimation for the exactness of a profile width.

Definition 1 (Isolumen)
Two lines $g_1^{I_l}, g_2^{I_l}$ with:

$$g_{1,2}^{I_l}(x) = m_{1,2}^{I_l} \cdot x + b_{1,2}^{I_l} \tag{1}$$

are called *isolumen* for intensity I_l, iff
$\forall p_x^{(0,0)}(x) \in g_1^{I_l}, g_2^{I_l}$:

$$min_P\{\overline{\overline{I_p^{(i,j)}}(x) - I_l}\} \tag{2}$$

where P is an optical beam measurement, e.g. a CCD camera picture, $p_x^{(0,0)}(x)$ a pixel at position (x,$g_{1,2}^{I_l}(x)$) of P, $I_p^{(0,0)}(x)$ is the intensity of pixel $p_x^{(0,0)}(x)$, N_r is the neighborhood of $p_x^{(0,0)}(x)$ of size r, such that:
$N_r =$

$$\begin{pmatrix} p_x^{(-r,-r)} & \dots & p_x^{(-r,-0)} & \dots & p_x^{(-r,r)} \\ \vdots & & \vdots & & \vdots \\ p_x^{(0,-r)} & \dots & p_x^{(0,0)} & \dots & p_x^{(0,-r)} \\ \vdots & & \vdots & & \vdots \\ p_x^{(r,-r)} & \dots & p_x^{(r,0)} & \dots & p_x^{(r,r)} \end{pmatrix} \tag{3}$$

$I_p^{(i,j)}(x)$ then is the intensity of $p_x^{(i,j)}(x)$ at position $(x + j, g_{1,2}^{I_l}(x) + i)$ for i,j = -r,...,0,...+r

Two lines thus are called isolumens for an intensity I_l, iff they fit in the area along an optical beam measurement P, where the mean overall distances between the mean intensity of the defined neighborhood and intensity I_l is minimal. Out of Definition 1 one could specify:

Definition 2 (profile width)
The profile width at position x $x_{prof}(x)$ for intensity I_l in an optical beam measurement P is defined as:

$$x_{prof}(x) := |g_1^{I_l}(x) - g_2^{I_l}(x)| \cdot \frac{l}{N} \tag{4}$$

where l is the width of P in [mm] N the width of P in pixel, and $g_{1,2}^{I_l}(x)$ are the vertical coordinate of the isolumen $g_{1,2}^{I_l}$ for I_l

Next, an error quantity will be introduced, that helps to compare isolumens found by different algorithms, to get a quality criterion relating to the exactness of profile width. For all algorithms that take a given optical measurement, size and quantification have to be the same in order to compare them. W.l.o.g the optical measurement is a picture from a CCD camera taken along the drift. Therefore only the distance between two isolumens could be consulted to implement an error quantity for profile width viz. the error depends on the correctness with which the isolumens are determined. To proof how exactly an isolumen is determined, the deviation of the proximity of the line from the exact intensity value I_l has to be computed. The mean x_k over all $p_x^{(i,j)}$ and its aberration from I_l has to be considered:

$$x_k = \frac{1}{(2 \cdot r + 1)^2} \sum_{j=-r}^{r} \sum_{i=-r}^{r} I_p^{(i,j)}(x) \quad (5)$$

The error could then be determined by the root mean square error between all x_k and I_l as follows:

$$\chi = \sqrt{\frac{1}{N^2} \sum_{k=1}^{N} (x_k - I_l)^2} \quad (6)$$

IRF-Method for isolumen determination

In the following an information sensitive algorithm based on the previous considerations will be presented. By a simple smoothing of the whole data by filtering, e.g., with a Gaussian filter, inclosed information will be erased or blurred. Therefore an information sensitive filter will be introduced. The intensity range filter takes an intensity I_l and a confidence interval $\pm\Delta\kappa$ to separate relevant information. An overview of the IRF-Method is given in Figure 2.

The algorithm works as follows:
The input for the algorithm is a picture taken from a CCD camera, the desired intensity level I_l and $\Delta\kappa$

1. *Normalization:* The original picture P is normalized colum by colum to value 1. Therewith intensity levels I_l could be implemented as percentage values. Result of this step is P^1

2. *IRF:* all values that are not in the defined confidence interval will be set to zero:

   $$\{\forall p_x \in P^1 | I_l - \Delta\kappa > p_x \vee I_l + \Delta\kappa < p_x\} = 0 \quad (7)$$

   The result of this step is P^1_{IRF}.

3. *Divide:* The centroid line of P^1_{IRF} is computed. Along this line the picture is divided in two pictures $P^{1,T}_{IRF}$ and $P^{1,B}_{IRF}$, where in $P^{1,T}_{IRF}(P^{1,B}_{IRF})$ are all values under(over) the centroid line will be set to zero. With $P^{1,T}_{IRF}(P^{1,B}_{IRF})$ the top(bottom) isolumen is computed.

4. *Balance:* The intensity distribution within the intensity range will be balanced around I_l by their distance. As a consequence of this the distribution will be approximated to a Gaussian distribution. This balancing is done by:

   $$\forall I_p(x) \in P^{1,T/B}_{IRF} : I_p(x) = I_l - |I_p(x) - I_l| \quad (8)$$

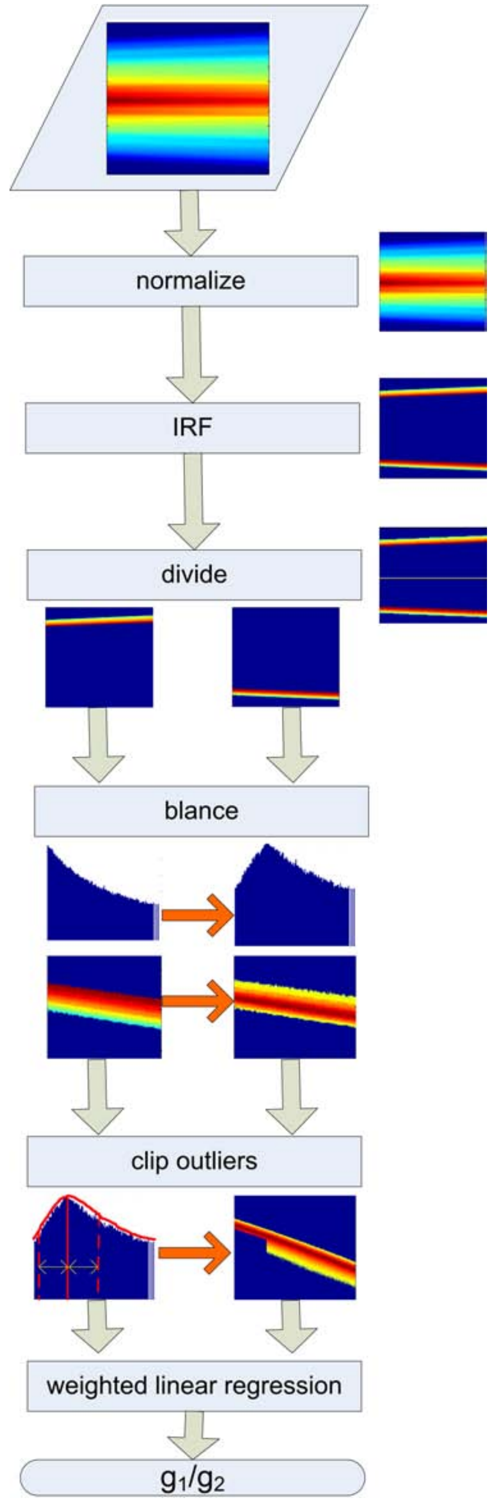

Figure 2: The IRF-method determines isolumens sensitive to information.

   The result of this step are the two pictures $P^{1,T}_{bal}$ and $P^{1,B}_{bal}$

5. *Clip outliers:* All relevant data for a proper determination of the desired information viz. all values

that are part of the chosen confidence interval are untouched up to now. If desired, one can skip to the next step. In case of a beam where single intensity points are widespread within the picture, outliers could adversely influence the determination of the isolumen. This might be the case within data with a bad signal to noise ratio. The accuracy of the isolumen also in this cases could be increased by clipping outliers. Therefore, in a defined window the expectancy μ of the position of intensities in the confidence interval and the standard deviation σ is computed. The vertical distribution then is clipped (Figure 3) with $n \cdot \sigma$ to both sides(top and bottom). The results of this step are $P^{1,T}_{cut}$ and $P^{1,B}_{cut}$

6. *weighted linear regression:* A weighted linear regression is performed on $P^{1,T}_{cut}$ and $P^{1,B}_{cut}$ to gain the isolumen $g_1^{I_l}$ and $g_2^{I_l}$.

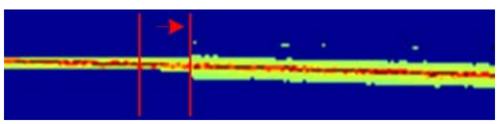

Figure 3: Clipping outliers in step 5 of the IRF-Method. Outliers are pixels with an intensity value that fits the chosen confidence interval but do not lie in the expected position for this intensity

Results and discussion of IRF-Method

The IRF-Method was performed on numerical computed pictures of different shapes as well as on a measured picture without noise reduction, to imitate a kind of worst case scenario. The measured picture is taken by a CCD camera in a test assembly, which was constructed to have the possibility of prior analysis, since HIBTT is under construction. Picture 10 shows a H^{1+} beam at a current of 20 keV, 1.3 mA and a residual gas pressure of about 10^{-5}mbar Intensities from 0.0 to 1.0 were tested in steps of 0.1 (Figure 4).

For picture 1 (Figure 5) and 2 the error constantly rises from 0% up to a maximum of 2%.

Concerning that with higher intensities the fluctuations within the beam are declining one might expect an oppositional behaviour, but the beam becomes more dense in direction to the beam axis; therefore single intensity levels close ranks, such that the neighbourhood around an isolumen has to be chosen to be very small. This effect is amplified in the next pictures, where the overall beam is densely focussed (Figure 6).

Additionaly numerical effects cause an irregular ascent in the direction of the beam-axis, which also disturbs neighborhood estimation. Pictures 8 (figure 7) and 9 show the same effects. Additionally, for intensity one an error peak of about 4 % was computed, which is not remarkable, since intensity level 1.0 is ambigious because of the already mentioned numerical effects, seen as dark lines (figure 8). .

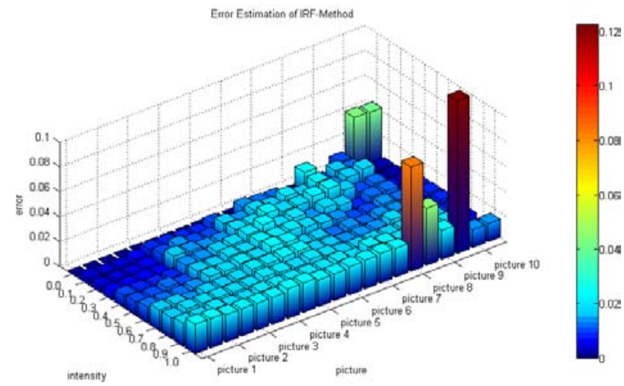

Figure 4: Error Estimation of the IRF-Method on nine numerical and one measured picture. For every picture the upper and the lower isolumens were computed and estimated with χ.

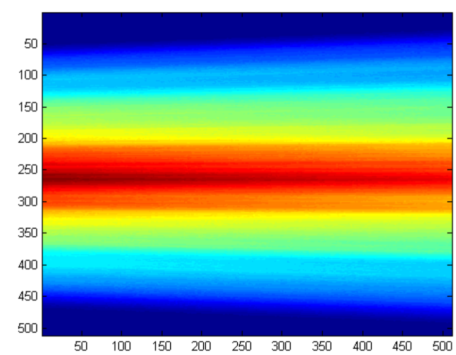

Figure 5: Picture 1 shows a slightly defocused beam that was computed numerically.

Picture 10 (CCD) first shows a significant difference within intensity level 0.0. This is caused by noise effects. The isolumen for 0.0 lies at the borders of the picture. Within the numerical pictures in this range all intensities are 0, so that the error at this level also is 0.0 for all pictures from 1 to 9. In picture 10 noise is spread to the edges of the whole picture and influences the error in this area. For intensity level 1.0 the error also rises but only to a maximum of about 1%. As one could see for intensities in the range of 0.1-0.9 the error is $>1\%$. The beam in picture 10 is free of numerical artifacts and shows a continously ascending intensity level. That is why intensities in the neighbourhood of an isolumen do not differ too much for reliable isolumens to be found.

EVALUATION

The IRF-Method determines isolumens with a good approximation as far as numerical effects as well as noise effects could be suppressed. To determine the profile width on the basis of isolumen one has to make sure, that always only two isolumen are determined for one intensity level.

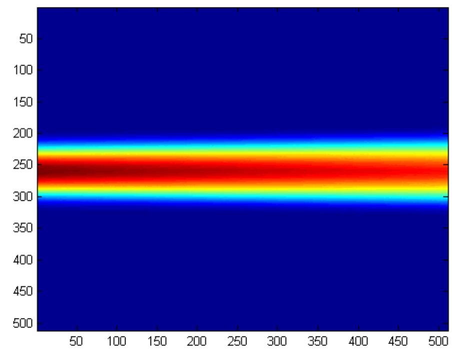

Figure 6: Picture 3 shows a highly focused beam that was computed numerically. Higher intensity levels are very dense.

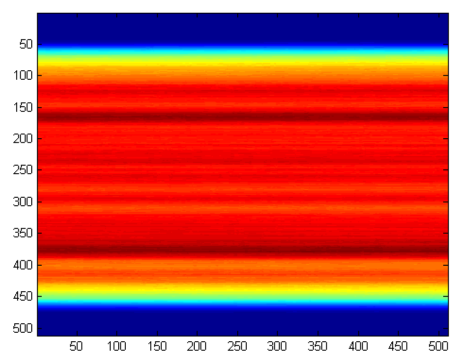

Figure 7: Picture 8 shows a strongly defocused beam that was computed numerically. Dark lines in the middle are numerical artifacts, which significantly could disturb the proper determination of isolumens, because unambiguousness gets lost.

Some other differences analysis have to be made, e.g., influence of unequal picture size, difference with noisy and filtered pictures. The error estimation provides a possibility of comparison for isolumens computed by different algorithms, but does not prove if the two isolumen are minimal for a picture, as is claimed in the definition for an isolumen. This constraint has to be ensured by the algorithms themselves.

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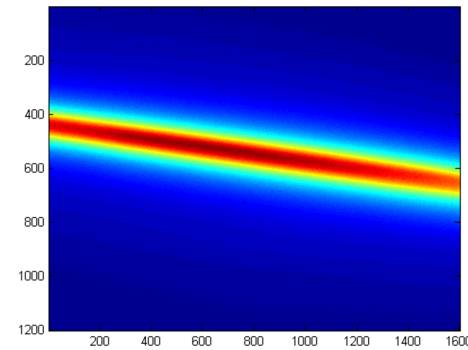

Figure 8: Picture 10 shows a H^{1+} beam, taken by a CCD camera.

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