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ON-LINE RETUNING OF ISAC LINAC BEAM WITH QUADRUPOLE SCAN TOMOGRAPHY*

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Abstract

The method of tomographic reconstruction has been in use at TRIUMF and elsewhere for several years, allowing for the diagnostic extraction of elements of the beam matrix on-line. One of the more recent applications of the technique at TRIUMF-ISAC consists of using the measured density distribution as the input for a real-time tune re-computation. This technique is advantageous since it does not require installation of dedicated emittance meters, but can instead be carried out with existing position monitors. Instead of requiring an operator to manually re-tune quadrupoles in a matching section, which can be time consuming, the method allows for a fast and reproducible means to precisely control the beam and can be proceduralized for use by operators tuning the machine.

BACKGROUND

The effect of a quadrupole field (electric or magnetic) on an ellipsoidal particle distribution in its position-momentum space is an excitation which causes a specific transformation. Upon leaving the field's influence, it then drifts apart over time, with an example shown in Fig. 1. Knowing that the initial beam parameters are unchanged upon entry into the quadrupole, which is set to three different settings, produces three different point-to-point transformations, represented by transfer matrices $\mathscr{M}_i$. A downstream position-intensity monitor is used to measure the transverse beam distribution at each quadrupole setting. This is in fact recording the different projections of the same initial beam distribution in (x,x') configuration space, which has been altered by the sequential effects of the quadrupole and drift to diagnostic.

By using the inverted transfer matrix from the diagnostic back to the start of the quadrupole field, one has the means to connect the beam distribution at both points in space. It is assumed that the initial beam distribution possesses no couplings beyond (x,x') dimensions, so as to ensure the x-emittance is conserved during the measurement. This allows for the use of the 1D position-intensity distributions to be used together with a tomographic reconstruction algorithm, using each projection as a reconstruction constraint of the 2D phase space beam distribution at the entrance of the quadrupole.

MAXIMUM ENTROPY TOMOGRAPHY

The Maximum Entropy Tomography (MENT) algorithm implementation used at TRIUMF [1] expects the 4 elements

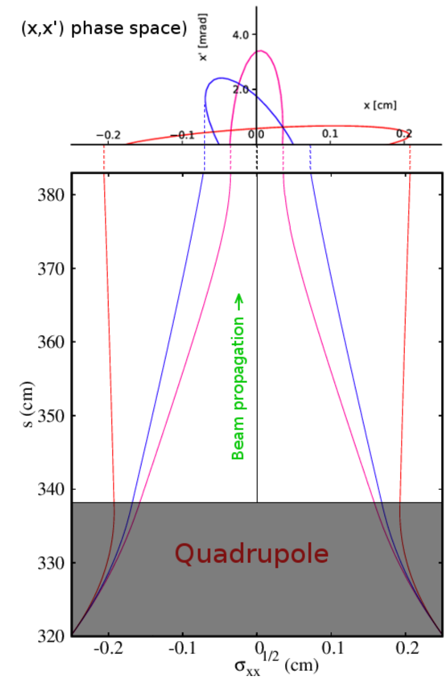

Figure 1: (Bottom:) Transverse 2 rms beam containment envelope undergoing different quadrupole excitations and drifting a short distance to a beam monitor at the top of the plot. The quantity $\sqrt{\sigma_{xx}}$ is the 2 rms size of the beam. (Top:) Measured position-intensity distributions at this monitor correspond to the projection of the distribution on the physical length axis of its phase space.

of the (x,x') transfer matrix from quadrupole entrance to diagnostic. Tomographic reconstruction refers to the process of recreating an N-dimensional distribution or shape from a collection of (N-1) dimensional projections or images. The distribution satisfies the dual criteria:

$$f(x,y) \geq 0 \tag{1}$$

and

$$\int\int_{\mathscr{D}} f(x,y)dxdy = 1, \tag{2}$$

where $f(x,y)$ is defined on a domain $\mathscr{D}$. Projections G_{jm} which image the function $f(x,y)$ in (N-1) dimensions and viewed from different projection angles θ_j are supplied to the algorithm as constraints of $f(x,y)$:

$$G_{jm} = \int_{s_0}^{s_1}\int_{t_0}^{t_1} f(s,t)\,ds\,dt, \tag{3}$$

where the variables (s,t) are related to (x,y) by:

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$$x(s,t) = s\cos\theta_j - t\sin\theta_j \quad (4)$$

$$y(s,t) = s\sin\theta_j + t\cos\theta_j. \quad (5)$$

In other words, the frame (s, t) is rotated about the origin of (x, y) by an angle θ_j, for j distinct projections. The entropy η of the distribution $f(x, y)$ is:

$$\eta(f) = -\int\int_{\mathscr{D}} f(x,y)\ln[f(x,y)A]\,dx\,dy, \quad (6)$$

A is the area of the domain $\mathscr{D}$ over which the function $f(x, y)$ is defined. MENT iteratively works to find the distribution $f(x, y)$ subject to the constraints imposed by the images of Eq. (3) which maximizes the entropy η of Eq. (6). Doing so *"yields the image with the lowest information content consistent with the available data,"* further adding that the method *"avoids introducing extraneous information or artificial structure."* [2].

The algorithm accepts the set of transfer matrices $\mathscr{M}_i$ associated with each quadrupole setting; this matrix contains both the focal effect of the quadrupole and the drift from device to diagnostic. An added benefit of this method is that the transfer matrix does not necessarily need to relate the profile monitor to the entrance of the scanned quadrupole. Instead, a global transfer matrix, which for example can contain several devices including multiple quadrupoles, can be provided, so long as the scanned quadrupole is included. This means that MENT can be used to reconstruct the distribution at any location connected to the diagnostic with a known transfer matrix.

Quadrupole scans should include a minimum in the 2 rms size of the transverse intensity profiles, which imposes a strong constraint for ellipse or cigar-like distributions (Fig. 1, pink distribution). Moreover, MENT is particularly well versed at handling cases where the number of provided input datasets does not exceed 10. On-line, anywhere from 4 to 8 intensity profiles per quadrupole scan is found to be a working optimum. The envelope code TRANSOPTR is used for the transfer matrix computation associated with each quadrupole setting. A model of the ISAC transport beamlines and accelerators has been built from system blueprints and original commissioning documents, enabling its use at multiple locations in the ISAC network. For each quadrupole setting, TRANSOPTR is executed in parallel. The transfer matrix returned by the code is bundled together with the intensity trace in a standard format for processing by the MENT algorithm. The initial beam distribution values used for the on-line TRANSOPTR computation can be ignored altogether; the transfer matrix computation is independent form the evolution of the beam distribution.

DATA ACQUISITION

Beam intensity profiles are acquired using Rotary Position Monitors (RPMs) which provide a reading of the vertical and the horizontal beam intensity distribution. Figure 2 depicts an RPM and the $\pm 11^\circ$ swing of the device. During the measurement the RPM bissects the beam twice, capturing both the horizontal and vertical beam intensity profiles.

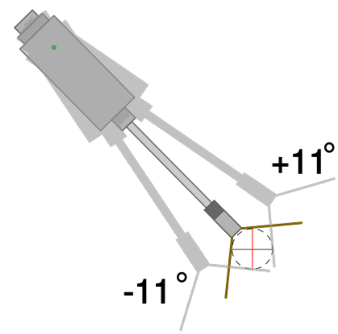

Figure 2: Sketch representation of an ISAC rotary position monitor (RPM), which is used for quadrupole scan tomography at ISAC. Beam position shown as red cross.

An example RPM profile is shown in Fig. 3, which shows two example ISAC beam intensity distributions measured on-line, showing different types and levels of noise associated with the measurements. This highlights a reality of RPM based tomographic reconstruction: The method is sensitive to noise and in certain cases discriminating between signal and noise can be difficult. The blue trace in Fig. 3, as an example, contains nonzero noise contamination which may arise due to the effect of a nearby RF cavity. On the other hand, the green trace is much easier to define, with a high signal to noise ratio and relatively constant background noise level between peaks. In practice, the green trace would be suitable for use in MENT, while the blue trace would not, excluding that particular RPM for this method.

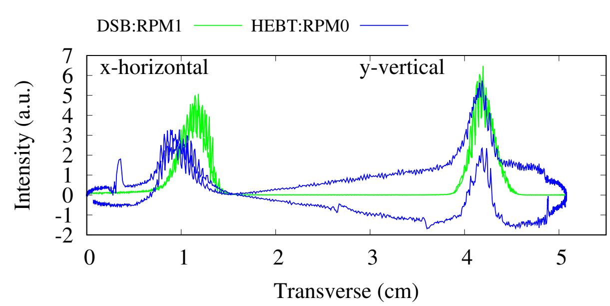

Figure 3: Example RPM beam intensity profiles measured at ISAC, showcasing two different levels of noise contamination. There are two overlapping intensity profiles due to the cyclical $\pm 11^\circ$ sweep (Fig. 2).

ISAC-RFQ OUTPUT BEAM TOMOGRAPHY

The TRANSOPTR model of the ISAC medium energy beam transport (MEBT) section [3] was used to perform a series of quadrupole scans. A more elaborate description on the method is provided at [4]. For this particular demonstration, the composite transfer matrix of the entire sequence going back to the exit of the ISAC-RFQ was used, including

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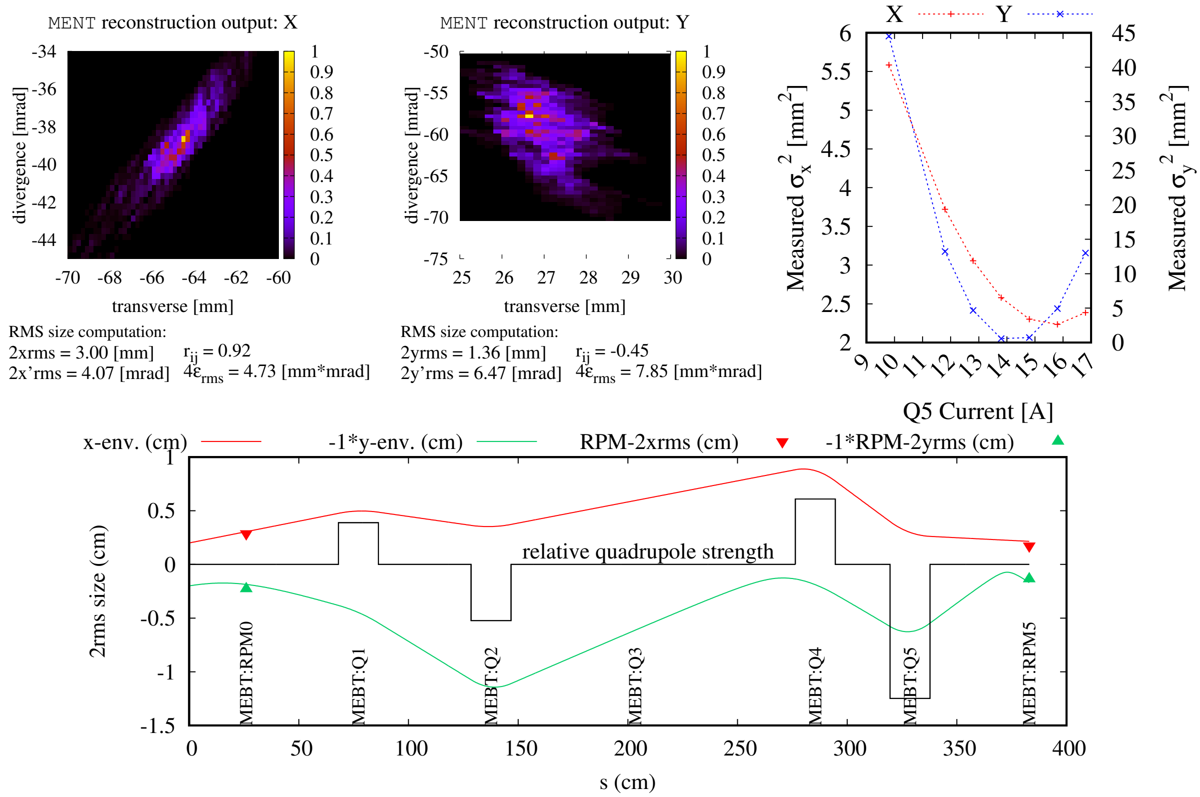

Figure 4: Top left and middle: A single quadrupole scan at MEBT:RPM5 was able to capture both the (x,y) output RFQ beam distributions. Normalized MENT reconstructed density distributions shown. Top right: The measured, squared 2 rms beamsize (σ^2) at MEBT:RPM5 vs. quadrupole MEBT:Q5 current is displayed. Bottom: The measured beam distribution was used in TRANSOPTR to re-tune the RFQ output beam on-line. Measured 2 rms beamsizes are superimposed on the plot.

quadrupoles Q1 to Q5. This allowed, using only Q5 and a downstream RPM, a measurement of the output transverse vertical and horizontal phase space distributions for RFQ accelerated beam. The out-of-RFQ distribution was then used as the starting parameter for a TRANSOPTR envelope optimization of quadrupoles Q1 to Q5, producing a round (x,y) focus at the location of MEBT:RPM5, shown at the bottom of Fig. 4. This in effect allows for the dynamic re-computation of the linac's output based solely on a series of intensity profile measurements. This operation demonstrates the ability to quickly measure the beam distribution on-line, without resorting to dedicated emittance meters, and re-tune tune the RFQ's transverse output in short order.

CONCLUSION

The methods associated with quadrupole scan tomography provide the means to measure phase space distributions in the ISAC accelerator. This is not only an important tool for machine study, but also for beam investigations related to operation and beam delivery to experiments. Future developments include the capability to couple the procedural steps of accelerator tuning together with a real-time TRANSOPTR optimization, for which quadrupole scan tomography can be utilized. This scheme, which we refer to as model coupled accelerator tuning (MCAT), is intended to allow the operators to control the machine through software, instead of resorting to manual tuning.

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