ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOPA09

DESIGN OF A 4D EMITTANCE DIAGNOSTIC FOR LOW-ENERGY ION BEAMS

Thomas Roger Curtin, Mark Curtin, Ion Linac Systems, Inc., Albuquerque, NM, USA

Abstract

Characterization of ion beams from an ion injector consisting of an electron-cyclotron-resonance (ECR) source in combination with a low-energy-beam-transport (LEBT) typically exhibits a complex four-dimensional transverse phase-space distribution. The importance of measuring the ion beam correlations following extraction and transport of the low-energy beam is critical to enabling optimization of beam transmission through downstream accelerating structures. A design for a transverse, four-dimensional emittance meter for low-energy protons from the Ion Linac Systems (ILS) ECR-LEBT ion injector is provided.

INTRODUCTION

Detailed knowledge of the transverse beam parameters is essential to enable proper optimization of beam transmission in downstream accelerating structures. Procedures to measure the two-dimensional (2D) transverse beam parameters, where horizontal and vertical motions are separate, have been well established. However, various beamline elements such as skew quadrupole magnets, solenoids, and beamline element field asymmetries generate a correlation between the horizontal and vertical components. The purpose of this diagnostic is to characterize the four-dimensional (4D) beam phase space distribution by capturing multiple downstream transverse (xy) images allowing potential correction of transverse coupling from the source. There are two strategies to properly characterize the 4D emitted beam: the *single-optics/multiple-locations* strategy proposed by Woodley and Emma [1] and the *multiple-optics/single-location* strategy given by Prat and Aiba [2]. The first strategy proposes a long beam line of roughly 150 m consisting of six profile monitors and ~15 quadrupole magnets. The second involves having the 2D beam parameters measured at a single location and having quadrupole strengths change to generate the required optics for the 4D reconstruction. Due to the lack of 150 m of space required to perform the first method, the second method is used for this diagnostic.

4D TRANSVERSE BEAM CHARACTERIZATION

The 4D beam matrix describes the transverse properties of the beam:

$$\sigma^{4D} = \begin{pmatrix} <x^2> & <xx'> & <xy> & <xy'> \\ <xx'> & <x'^2> & <x'y> & <x'y'> \\ <xy> & <x'y> & <y^2> & <yy'> \\ <xy'> & <x'y'> & <yy'> & <y'^2> \end{pmatrix} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy}^T & \sigma_{yy} \end{pmatrix} \quad (1)$$

The matrices σ_{xx} and σ_{yy} describe the 2D horizontal and vertical motions, and σxy describes the cross-plane coupling. The transport of the 4D beam matrix from s_0 to s can be calculated as follows:

$$\sigma_s^{4D} = R \cdot \sigma_{s_0}^{4D} \cdot R^T \quad (2)$$

Where R between s_0 and s is:

$$\sigma^{4D} = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} \\ R_{21} & R_{22} & R_{23} & R_{24} \\ R_{31} & R_{32} & R_{33} & R_{34} \\ R_{41} & R_{42} & R_{43} & R_{44} \end{pmatrix} = \begin{pmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{pmatrix} \quad (3)$$

According to Eqs. (1), (2), and (3), when the lattice between s_0 and s, the elements R_{yx} and R_{xy} are zero allowing the beam sizes and x-y correlation to be expressed in terms of the matrix elements of σ^{4D} as follows:

Assuming the transport matrix elements are known, the 10 independent elements of σ^{4D} at s_0 can be computed by measuring beam sizes and x-y correlations at the point s. The initial simulation considered 8 captured images. Future simulations will map out the emittance sensitivity as a function of the number and quality of capture images.

SIMULATION OF DIAGNOSTIC

Presently we plan to validate the 4D emittance diagnostic using the Ion Linac Systems (ILS) Electron Cyclotron Resonance (ECR) 30 keV ion source. The initial layout of the 4D emittance diagnostic is depicted in Fig. 1 below including a pepper-pot 4D emittance diagnostic for cross-checking.

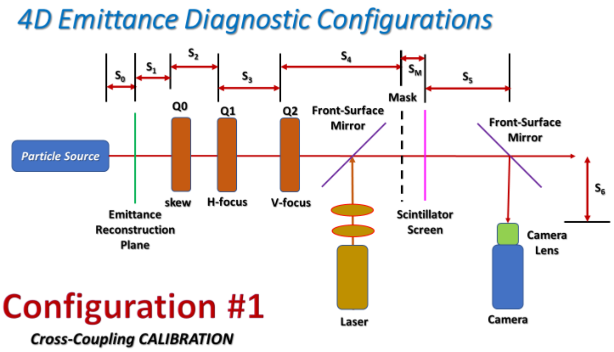


Figure 1: Diagnostic design for manufacture.

The system length is 1 m long in total and follows the ProLAB build below (Fig. 2). The quadrupoles themselves are 0.1 m in length separated by 0.1 m with an aperture radius

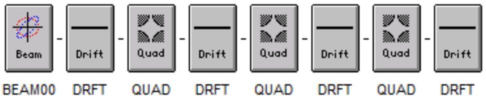
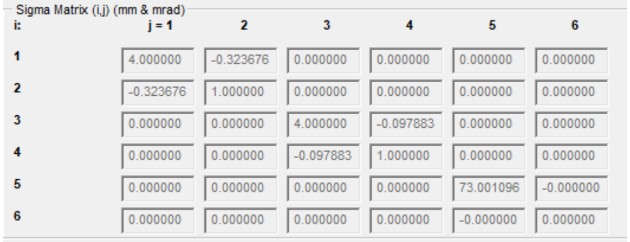


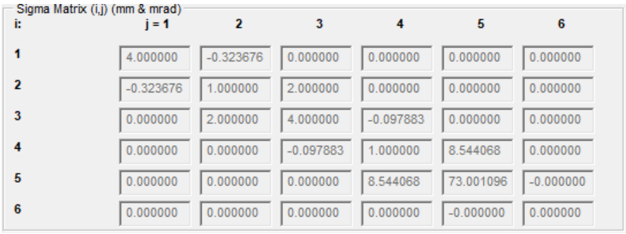
Figure 2: ProLAB Design of Diagnostic.



Sigma Matrix (i,j) (mm & mrad)

i:	j = 1	2	3	4	5	6
1	4.000000	-0.323676	0.000000	0.000000	0.000000	0.000000
2	-0.323676	1.000000	0.000000	0.000000	0.000000	0.000000
3	0.000000	0.000000	4.000000	-0.097883	0.000000	0.000000
4	0.000000	0.000000	-0.097883	1.000000	0.000000	0.000000
5	0.000000	0.000000	0.000000	0.000000	73.001096	-0.000000
6	0.000000	0.000000	0.000000	0.000000	-0.000000	0.000000

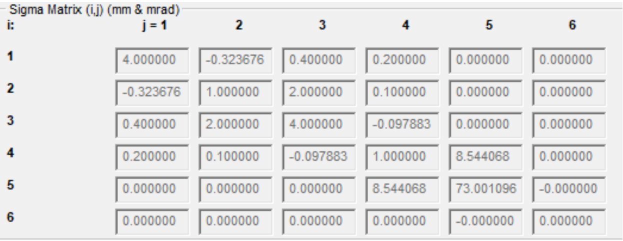
Figure 3: ProLAB initial Sigma Matrix 1.



Sigma Matrix (i,j) (mm & mrad)

i:	j = 1	2	3	4	5	6
1	4.000000	-0.323676	0.000000	0.000000	0.000000	0.000000
2	-0.323676	1.000000	2.000000	0.000000	0.000000	0.000000
3	0.000000	2.000000	4.000000	-0.097883	0.000000	0.000000
4	0.000000	0.000000	-0.097883	1.000000	8.544068	0.000000
5	0.000000	0.000000	0.000000	8.544068	73.001096	-0.000000
6	0.000000	0.000000	0.000000	0.000000	-0.000000	0.000000

Figure 4: ProLAB initial Sigma Matrix 2.



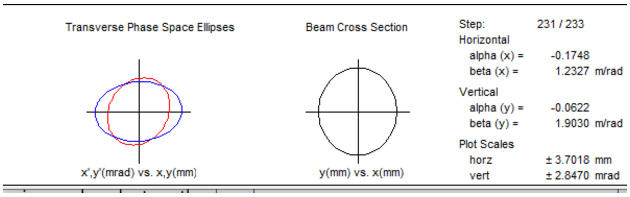
Sigma Matrix (i,j) (mm & mrad)

i:	j = 1	2	3	4	5	6
1	4.000000	-0.323676	0.400000	0.200000	0.000000	0.000000
2	-0.323676	1.000000	2.000000	0.100000	0.000000	0.000000
3	0.400000	2.000000	4.000000	-0.097883	0.000000	0.000000
4	0.200000	0.100000	-0.097883	1.000000	8.544068	0.000000
5	0.000000	0.000000	0.000000	8.544068	73.001096	-0.000000
6	0.000000	0.000000	0.000000	0.000000	-0.000000	0.000000

Figure 5: ProLAB initial Sigma Matrix 3.

of 0.1 m. For the initial emittance, 3 main values were used in order of complexity (Figs. 3, 4, and 5).

Using PRO Lab, simulations at 8 different quadrupole strengths ranging from 0 to 20 kG/m for the H-focusing quadrupole, and 0 to −20 kG/m for the V-focusing quadrupole in steps of 2.5 kG/m (example shown in Fig. 6) for a total of 8 unique emittances.



Step: 231 / 233
Horizontal
alpha (x) = -0.1748
beta (x) = 1.2327 m/rad
Vertical
alpha (y) = -0.0622
beta (y) = 1.9030 m/rad
Plot Scales
horz ± 3.7018 mm
vert ± 2.8470 mrad

Figure 6: Beam Ellipse at end of Cavity.

Using the alpha and beta values given at the profile monitor allows for the reconstruction of the 4D matrix using the math described previously.

NEXT STEPS

Four-dimensional measurements are needed to understand the emittance increase due to cross-plane coupling. The simulations run in ProLAB show that the use of this diagnostic will allow for the reconstruction of the 4D beam matrix. The next steps are first to do a comprehensive sensitivity analysis to quantify the emittance uncertainty as a function of the number of captured images and reconstruction analysis . Next steps also include developing the hardware components needed for the diagnostic (Bill of Materials (BOM)), detailed layout, procurement packages, image capture and analysis software. Although the diagnostic is specifically planned for factory acceptance testing (FAT) of the proton ion source for the ILS Hungary project we also wish to quantify how modifications to the design would enable characterization of electron beams.

REFERENCES

[1] M. D. Woodley and P. J. Emma, “Measurement and Correction of Cross-Plane Coupling in Transport Lines”, in *Proc. Int. Linear Accel. Conf. (LINAC’00)*, Monterey, CA, USA, Aug. 2000, paper MOC19, pp. 196–198. `https://jacow.org/l00/papers/MOC19.pdf`

[2] E. Prat and M. Aiba, “Four-dimensional transverse beam matrix measurement using the multiple-quadrupole scan technique”, *Phys. Rev. ST Accel. Beams*, vol. 17, p. 052801, May 2014. `doi:10.1103/PhysRevSTAB.17.052801`