

## PHASE SPACE TOMOGRAPHY

### INTRODUCTION AND OBJECTIVE:

A common challenge for accelerator systems is to maintain beam quality and brightness over the usually long distance from the source to the target. In order to do so, knowledge of the beam distribution in both configuration and velocity space along the beam line is needed. However, measurement of the velocity distribution can be difficult, especially for beams with space charge.

In this experiment we demonstrate a simple and portable tomographic method to map the beam phase space and measure the beam emittance, which can be used in the majority of accelerators. Special emphasis is given to intense, space-charge dominated beams.

### BACKGROUND:

Read carefully the Tomography Lecture handout that was given to you. The following papers can be also useful: D. Stratakis, et al. Phys. Plasmas **14**, 120703 (2007) and D. Stratakis, et al., Phys. Rev. ST Accel. Beams **9**, 112801 (2006).

If time allows you can also read Sections 3.4.1 - 3.4.5, 4.1, 4.2, 4.3, 5.3.4 in M. Reiser's Theory and Design of Charged Particle Beams.

### EQUIPMENT:

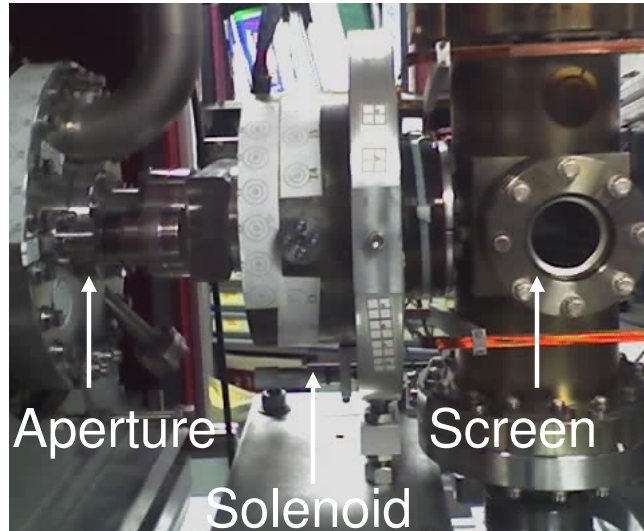
Our present experiment will be carried out along the injector line of UMER and is illustrated in Fig. 1. Our transport line consists of a thermionic gun, one short solenoid and a phosphor screen (IC1) that displays the transverse current density (integrated over many pulses). The solenoid and the screen are located at 17.7 cm and 28.4 cm from the aperture, respectively. A Bergoz fast current transformer between them is used to measure the beam current.

An advanced, high resolution progressive scan, fully programmable digital charged coupled device (CCD) camera from IMPERX (model IPX-1M48-L) will be used in our experiments. Furthermore, we will use a macro lens (AF Micro-NIKKOR 60mm f/2.8D). A macro lens is a lens with the ability to focus from infinity to extremely close distances (up to 0.22 m), allowing it to capture images of tiny objects in frame-filling, larger-than-life sizes. The camera specifications (such as frame rate, triggering, electronic shutter etc) as well image acquisition are fully controlled by using XCAP-STD, from EPIX (model EPX-XCAPSTD-L).

In your experiments a total of 41 solenoid scans will be performed. The beam intensity pictures are captured by the CCD camera and stored. Then by using appropriate MATLAB codes each scanned beam distribution is projected into x and y axes in order to Tomographically reconstruct the  $xx'$  and  $yy'$  phase spaces, respectively. The

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reconstruction is performed at the screen location (IC1) so that distributions in both spatial and phase space can be compared at the same plane. Specifically, the program is set to reconstruct the phase space at IC1 for solenoid current  $I=6.4$  A but you can modify this if you wish.



**Figure 1:** Experimental configuration

**MATLAB CODES:**

The codes are mainly described in the Tomography Lecture handout. Specifically look at Sec. 2.4.3 and Sec. 2.4.4.

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**PROCEDURE:**

1. Familiarize with the equipment: camera, mirror, lens, XCAP software, etc.
2. Turn on the beam at 10 keV. Set the solenoid current at 6 A. Check the XCAP acquisition window. Do you see the beam on the computer monitor? Check if the beam is well focused.
3. Turn the beam off. Now make sure that the whole fluorescent screen is within the area of interest in XCAP acquisition window. In order to do so, you might have to increase the camera gain. Save the photo as 8 bit bmp with the filename: GroupID\_Callibration.bmp, where ID is your group number.
4. Determine the coordinates of Screen Center and the Screen Size in pixels. Record those numbers. You will need them in the data analysis later.
5. Turn on the beam and set the energy at 10 keV. Set the solenoid current at  $I=7.8$  A.
6. Check XCAP if you see the beam. Is the image saturated? If yes, reduce the amount of light that reaches the camera sensor. If no, cover the camera with the black cloth and proceed to step 7.
7. Open the text file Curents.txt and make sure it matches the values shown within Table 1. Those are the currents that you will use to scan the solenoid.
8. Scan the solenoid. Start from Run1 as shown in Table 1. Save the photos in the Folder USPAS/Tomography/Tomo UNIFORM. When saving, use the filename UNIFORM\_Run##\_GroupID, where ## is the run number (use a zero in front of runs 1 to 9). **Some photos are not very intense so you have to integrate over many frames.** The number of frames to be added for each run is illustrated on Table1.
9. Now turn the beam off and set the FiveBeamlet aperture. Repeat step 8. Save the photos in the Folder USPAS/Tomography/Tomo FIVEBEAMLET. When saving use the filename FIVEBEAMLET\_Run##\_GroupID.
10. Use the Bergoz coil to measure the beam current for the two apertures used in the experiment. Record those numbers.

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Table 1: Desired currents for solenoidal scan

Run ##	Frames	Current (A)
01	16	4
02	16	4.4
03	16	4.8
04	16	5.2
05	16	5.5
06	8	5.8
07	4	6.1
08	4	6.4
09	2	6.7
10	1	7
11	1	7.2
12	1	7.4
13	1	7.6
14	1	7.8
15	1	8
16	1	8.1
17	1	8.2
18	1	8.3
19	1	8.4
20	1	8.5
21	2	8.6
22	2	8.7
23	2	8.8
24	2	8.9
25	4	9
26	4	9.1
27	4	9.2
28	4	9.3
29	4	9.4
30	4	9.5
31	8	9.6
32	8	9.7
33	8	9.8
34	8	10
35	8	10.2
36	8	10.4
37	16	10.6
38	16	10.8
39	16	11.1
40	16	11.4
41	16	11.8

**ANALYSIS / QUESTIONS:**

1. Now you have to calculate the transport matrix, rotation angles and scaling factors for each current. To do so open MATLAB and go to the folder USPAS\Tomography\ Tomo\_Codes to activate the code ScalF\_RotA\_Calc.m.
2. First you will do the analysis for “Uniform Aperture” experiment. In the code, go to Step 4 and enter the current that you measured in the experiment (make sure that the beam parameters for the Fivebeamlet aperture are commented). Go to Step 7 and set the correct path for the txt file that contains the beam currents. Once you will run the code, the program will create a new txt file that beside the currents will contain the corresponding scaling factors and angles also. The name of this file is given in Step 10. Make sure it is set as ScalF\_RotA\_IC1\_UNIFORM.txt.
3. Open the file you just created and check if for all currents there is a corresponding scaling factor and rotation angle.
4. Now you will process the photos from the experiment. Following the discussion given in the lecture you have to center the beam photos. To do so activate the code PhotoProcessing.m.
5. In the code, go to Step 1 and set the correct path for the photos you got in experiment.
6. In Step 2 enter the screen size (SCREEN\_Pixel) and origin coordinates (Origin\_H and Origin\_V) that you measured in the experiment.
7. In Step 3 set the correct Prefix for your photos (UNIFORM\_).
8. Run the code. Notice that the new photos are all centered and have more pixels (i.e. 2000x2000). Now you will use those to do tomography.
9. Open MATLAB and activate the code Tomography.m.
10. In the code, go to Step1 and set the correct path for the centered photos you got previously. Set the correct Prefix for your photos (centered\_UNIFORM\_)
11. In Step 2 set the correct path for the txt file you just created in 2 (the file with the scaling factors and angles). Run the Tomography code.
12. Observe the reconstructed phase-space distribution. Is the beam converging or diverging?
13. There is some background noise. What could be the source of such artifact?

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14. Now you have to calculate the beam emittance. Using the information discussed in the lecture and the handout, write a MATLAB that calculates the 4xrms beam emittance from the reconstructed phase space distribution.
15. Repeat Steps 1-14 for the FiveBeamlet aperture experiment. In your analysis, to avoid confusion, when you name the files replace “UNIFORM” with “FIVEBEAMLET”. When running the code ScalF RotA Calc.m make sure that the beam parameters for the Uniform aperture are commented).
16. How does the phase space look now? How does it differ from the uniform case? Briefly provide reasoning for this result. What is the 4xrms emittance now?