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DESIGN AND TEST RESULTS OF A DOUBLE-SLIT EMITTANCE METER AT XiPAF

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Abstract

Xi'an 200 MeV Proton Application Facility (XiPAF) is composed of a linac injector, a 200-MeV synchrotron and a high energy transport line. To study the beam dynamics along the beam line, a double-slit emittance meter is used to measure the beam phase space in the linac. To have knowledge of the phase space upstream of the emittance meter, an inverse transport method is proposed in the presence of space charge. The design and preliminary test results of the emittance meter are presented in this paper.

INTRODUCTION

XiPAF (Xi'an 200 MeV Proton Application Facility), a proton radiation facility, consists of a linac injector, a medium energy transport line (MEBT), a synchrotron ring, a high energy transport line (HEBT) and a target [1]. The linac is composed of a low energy beam transport line (LEBT), a four-vane type RFQ and an alvarez-type DTL. During commissioning, knowledge of beam phase spaces at the LEBT output, RFQ output and DTL output are critical for beam matching. Especially at XiPAF, there is no matching section between RFQ and DTL [2]. The beam parameters of the linac are shown in Table 1. Due to the large energy range, the conventional electric scanner is not appliable. A double-slit type emittance meter is used to measure beam transverse phase spaces. Due to the small beam size and large divergence, it's usually hard to measure the beam phase spaces at the exit of the RFQ and DTL directly. Therefore, it's essential to deduce the beam phase spaces at the exits from the measured beam phase space downstream. The transportation is commonly achieved by transport matrix with assumption of linear particle motion. Whereas, the method is ineffective when the space charge effect is significant. A method, using the PIC code rather than transport matrix to simulate the particle motion, is proposed to transport the beam phase space from downstream to upstream with space charge effects. With this method, the knowledge of beam phase space distribution along the beam line can be obtained from the measured phase space at the position of the emittance meter. This paper shows the design and test results of the emittance meter.

Table 1: Main Beam Parameters of XiPAF Linac

Parameter	Value	Unit
Species	H^-	\
Beam energy	0.05~7	MeV
Peak current	3~10	mA
Pulse length	10~1000	μs
Repetition rate	0.5	Hz

DESIGN

Figure 1 shows the operation principle of the double-slit emittance meter. The emittance meter contains two slits: the position slit and angle slit. The width of the position slit determines the position resolution. The width of the angle slit and drift distance determine the angle resolution. The smaller the slits, the higher the resolution, but lower signal amplitude.

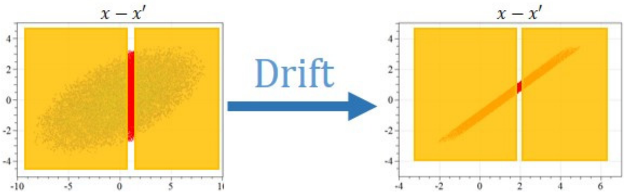

Figure 1: Operation principle of the double-slit emittance meter.

Due to the space limitation, the maximum drift distance is 247 mm. Figure 2 shows the signal amplitude as a function of slit widths. The widths of the two slits at XiPAF are 0.2 mm and 0.1 mm, respectively. Then the maximum current signal is 31.6 μA, and position and angle measurement resolution are 0.2 mm and 0.4 mrad, respectively. The current signal is measured by a Faraday cup mounted behind the angle slit.

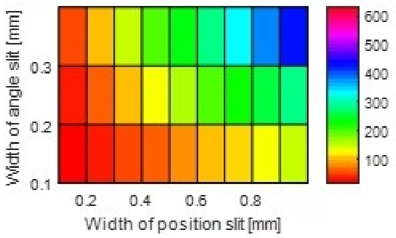

Figure 2: Signal amplitude as a function of slit widths.

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MECHANICS

The majority of the beam will be blocked by the position slit, bringing heat loading. Taking copper as the material of the slit, the maximum temperature is only 410 K, therefore water cooling is unnecessary. The range of 7 MeV H$^-$ in copper is 133.6 μm. Thus, the minimal thickness of the slits should be large than the value. The parameters of the emittance meter are shown in Table 2. Each slit is formed by two copper sheets. Since the thickness of the slit decreases the acceptance of angle [3], the trapezoidal shape of slit is adopted, as shown in Fig. 3.

Table 2: Parameters of the Emittance Meter

Parameter	Value	Unit
Material	Copper	-
Width of slit	0.2/0.1	mm
Thickness of slit	3/1	mm
Distance between slits	247	mm

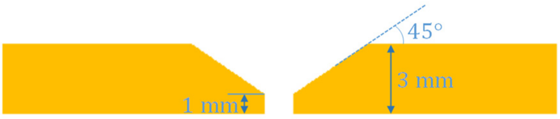
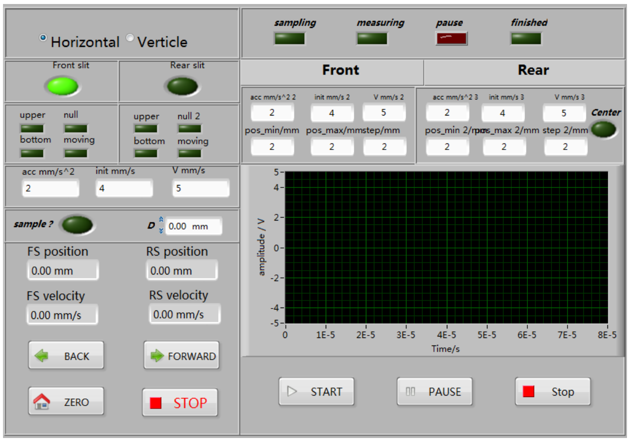


Figure 3: Position slit geometry.

CONTROL AND ACQUISITION

Linear motion of each slit is achieved by server motors, which have a moving repeatability of 5 μm. The beam current acquired by the Faraday cup is transformed to a moderate voltage signal by an I-V converter at the front end. The NI-PXIe system is used to control the motors and acquire signals. The PXIe 6356 card samples the voltage signal at a rate of 1 MHz, and the motors are controlled by calling the dynamic link library (DLL). A GUI, which achieves automatic emittance measurement, is shown in Fig. 4.


● Horizontal ○ Verticle

Front
acc mm/s^2 2: 2
init mm/s 2: 4
V mm/s 2: 5
pos_min/mm: 2
pos_max/mm: 2
step/mm: 2

Rear
acc mm/s^2 3: 2
init mm/s 3: 4
V mm/s 3: 5
pos_min 2/mm: 2
pos_max 2/mm: 2
step 2/mm: 2

acc mm/s^2: 2
init mm/s: 4
V mm/s: 5
D: 0.00 mm
FS position: 0.00 mm
RS position: 0.00 mm
FS velocity: 0.00 mm/s
RS velocity: 0.00 mm/s

Figure 4: Control interface of the emittance meter.

EXPERIMENTAL RESULTS

The emittance meter was installed downstream of the RFQ at Tsinghua University to measure the beam phase space and test its performance. The experimental setup is shown in Fig. 5. To eliminate the effect of secondary emission electrons on the current measurement, a minus biasing voltage is added. The measurement results are shown in Fig. 6. The measurement speed is about 1 step per second, and the total time for one plane is about 30 minutes.

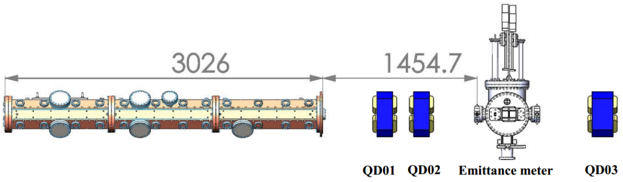


Figure 5: Layout of the experiment.

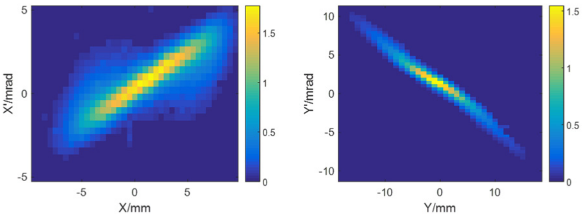


Figure 6: Measured beam phase space in horizontal plane (left）and vertical plane (right).

PHASE SPACE INVERSE TRANSPORT

As shown in Fig. 5, the emittance meter is not installed at the RFQ exit directly, inverse transportation is needed to deduce the beam phase space at the RFQ exit. A method similar to reconstruct beam phase space from multiple profiles in presence of space charge [4] is proposed. The detailed procedures are as following:

1. Generate a large uniform-distributed multi-particle beam in both transverse planes as the initial solution. As for the longitudinal distribution, the physically designed distribution is used.
2. Beam motion from the RFQ exit to the location of the emittance meter is simulated with a PIC code, Tracewin [5].
3. Simulation results are compared with the measured phase spaces pixel by pixel. A weight is given to each particle according to the measured signal at this pixel and the number of particles falling into it. The particles falling outside the measured phase space are weighted as zero.
4. Normalize the weights defined in step 3 to keep a constant particle number. Then redistribute the initial distribution with the weights.
5. Restart the iteration until the simulation result converges to the measurement result.

The reconstructed beam phase spaces at the RFQ exit are shown in Fig. 7, and Fig. 8 shows the simulated phase space at the location of the emittance meter with the reconstructed phase space at the RFQ output as input. Comparison of twiss parameters are shown in Table 3. The reconstructed results are well coincident with the measured results.

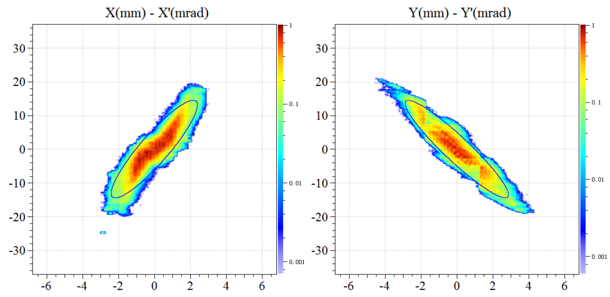


Figure 7: Reconstructed beam phases at the RFQ exit.

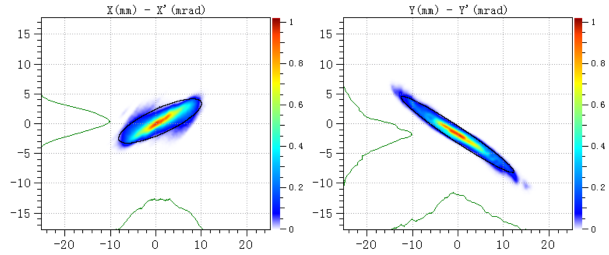


Figure 8: Simulated beam phase spaces at the position of the emittance meter using the reconstructed phase space as input.

Table 3: Comparison of Twiss Parameters of Measured and Simulated Phase Space

	α_x	β_x [m]	$\epsilon_{xn} rms$ [μm]	α_y	β_y [m]	$\epsilon_{yn} rms$ [μm]
Measured	-1.2	3.9	0.34	4.6	9.1	0.30
Simulated	-1.3	4.0	0.33	4.3	8.6	0.29

To verify the reconstructed result further, phase spaces are measured again with adjusting the current of the quadrupole QD02 from 67.7A to 77.7A. The beam space at emittance meter is also simulated with the new currents setting, still using the reconstructed phase space at the RFQ exit as input. The results by the simulation and measurement are shown in Fig. 9 and Fig. 10. They are also well agreed, verifying the effectiveness of the reconstruction method.

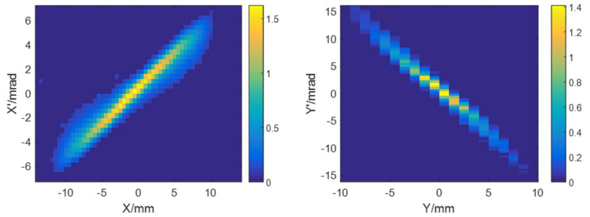


Figure 9: Measured phase space with QD02=77.7 A.

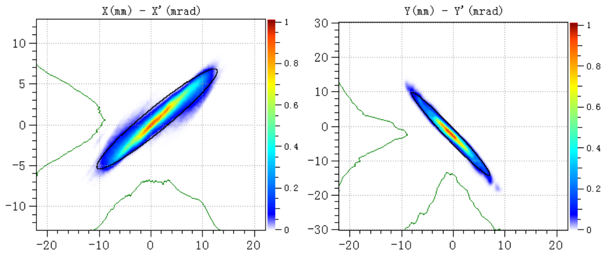


Figure 10: Simulated phase space with QD02=77.7 A.

CONCLUSION

In this paper, a double-slit emittance meter used for beam emittance measurement at XiPAF linac is introduced. The instrument has a position resolution of 0.2 mm and an angle resolution of 0.4 mrad. About 30 minutes is needed for the measurement of one transverse plane for a moderate measurement range. An emittance reconstruction method has been proposed to transport beam phase space from downstream to upstream in the presence of space charge. The method has been successfully applied at Tsinghua University, and it will be adopted in the coming commissioning of XiPAF.

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