ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB189

BEAM COMMISSIONING OF XiPAF SYNCHROTRON

H. J. Yao[1,2,3], S. X. Zheng[1,2,3†], Y. Yang[1,2,3,4], W. B. Ye[1,2,3], X. Y. Liu[1,2,3], Y. Li[1,2,3], H. J. Zeng[1,2,3], M. W. Wang[4], W. L. Liu[4], D. Wang[4], X. L. Guan[1,2,3], X. W. Wang[1,2,3], Z. M. Wang[4]
[1]Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, Beijing, China
[2]Laboratory for Advanced Radiation Sources and Application, Tsinghua University, Beijing, China
[3]Department of Engineering Physics, Tsinghua University, Beijing, China
[4]State Key Laboratory of Intense Pulsed Radiation Simulation and Effect (Northwest Institute of Nuclear Technology), Xi'an, China

Abstract

XiPAF (Xi'an 200 MeV Proton Application Facility) is a project to fulfil the need of the experimental simulation of the space radiation environment. It comprises a 7 MeV H^- linac, a 60~230 MeV proton synchrotron and experimental stations. The Installation of the synchrotron, beam line and one experimental station were completed at the end of December 2019, and commissioning has just begun. Circulating beam around the synchrotron was observed on the first day of operation, and now 10~200 MeV proton beam directly extracted from the synchrotron had been transported to the experimental station for user experiments. The results of the commissioning and data analysis are presented in this paper.

INTRODUCTION

XiPAF [1] was started in 2014 with a cooperation between Tsinghua University and Northwest Institute of Nuclear Technology in Xi' an, China. The XiPAF synchrotron [2] is a proton ring of 30.9 m circumference, in which the beam is injected at 7 MeV and accelerated to the maximum energy of 230 MeV. The lattice structure is based on a DBFO cell. A stripping injection section is designed to inject 7 MeV H^- beam to the ring and to accumulate more particles. A 3rd-order resonance and RF-Knockout (RF-KO) technology is adopted to realize slow extraction.

Due to the construction delays of the XiPAF formal plant, a temporary plant was opened for installation and commissioning in 2018. Due to the space limitation the layout of XiPAF was modified, which is shown in Fig. 1. The results of this paper are based on this modified layout in the temporary plant. Compared with XiPAF design, the main changes are as following:

- MEBT has been modified and shortened.
- HEBT has been modified shortened, and only one beam line was installed.
- The Alvarez-type DTL is replaced by the IH-DTL [3].

The installation of XiPAF accelerators started on June 2018 in the temporary plant and the first beam from the linac was observed in January 2019 [3]. After that, the transport beam lines, and the synchrotron were starting to install and completed at the end of December 2019. The beam commissioning of XiPAF linac, together with the MEBT and the synchrotron began on 3rd January 2020, and at that night the first turn circulating beam after stripping injection was seen on the scintillating screen in the ring. On 15th January, 60 MeV slow extraction beam from the synchrotron was measured using the ionization chamber (IC) on HEBT. Then beam commissioning was interrupted by COVID-19 until August 2020. At the end of 2020, the initial beam commissioning was finished, and several user experiments have been carried out to validate the beam environment provided by the facility.

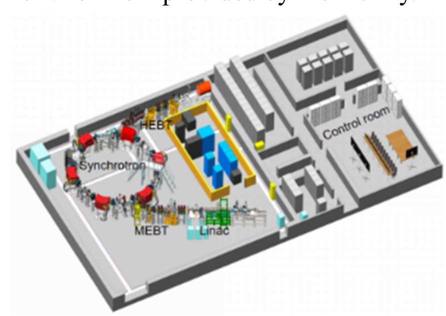

Figure 1: XiPAF layout in the temporary plant.

INJECTION AND CAPTURE TEST

The changes of XiPAF in the temporary have a certain influence on beam parameters. In addition, the emittance and beam intensity of H^- ECR source did not meet the design requirements, so the beam parameters at the injection point is different from the designed value, as shown in Table1. From this, the measurement beam intensity is far less than the designed value, while the emittance is far greater. All these changes will bring difficulties to beam commissioning of the synchrotron.

Table 1: Beam Parameters at the Injection Point

Parameters	Designed value	Measured value
Energy (MeV)	7	7.11
Intensity (mA)	5	1.1
Norm. rms emittance (x/y) (π mm-mrad)	0.2 / 0.2	0.8 / 0.6
Momentum dispersion	±0.45%	±0.55%

The beam diagnostics layout of XiPAF synchrotron is sketched in Fig. 2. There are twelve shoebox BPMs [4] (six

† zhengsx@tsinghua.edu.cn

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB189

for horizontal and six for vertical), one DCCT, one FCT, and two scintillating screens one is on the injection section and near the stripping foil, and the other locates the straight segment adjacent to the injection section.

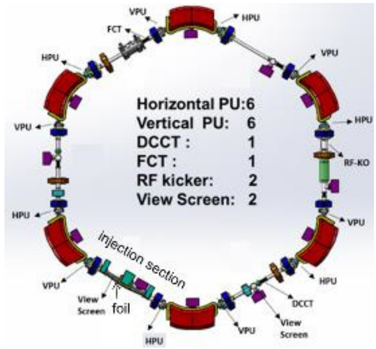

Figure 2: Beam diagnostics layout of XiPAF synchrotron.

The injection system of XiPAF synchrotron consists of a septum magnet, a carbon foil, two bumper magnets, and three Chicane dipoles [5]. Two scintillating screens are used to observe the circulating beam on the first turn. As the injected beam is accumulated in the ring, the beam signal can be measured on DCCT and FCT (Fast Current Transformer). Due to the slow response of DCCT, it is unable to accurately measure the evolution of beam intensity during the injection phase. So, the variation of beam intensity with time can be obtained by integrating the FCT signal [6].

The beam intensity curve during the injection phase is shown in Fig. 3, the blue line is the beam signal measured by FCT, the red one represents the beam intensity by integrating the FCT signal. In this case, the injected beam is 1.1 mA measured by ACCT at exit of MEBT. After 60 µs injection, the beam intensity accumulated in the ring is 47 mA, corresponding to $2.5{\times}10^{11}$ ppp.

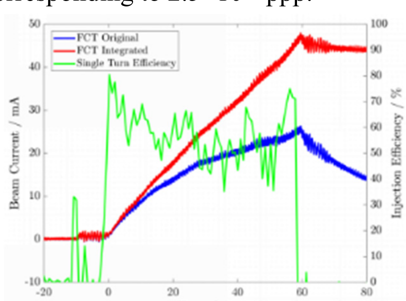

Figure 3: Beam intensity curve during the injection.

After the injection, in order to achieve the adiabatic capture, the RF voltage increases linearly from 0 to 600 V over 10 ms. When the beam is captured, its central energy oscillates with the synchronous energy as the center, and its transverse motion oscillates with the closed orbit. For a selected closed orbit, the synchronous energy under this closed orbit can be changed by adjusting RF frequency and the field strength of dipoles synchronously to keep the closed orbit as a constant. If the synchronous energy matches with the injected beam energy, the maximum capture efficiency can be obtained. The result of capture efficiency is 65% calculated by the data measured by FCT.

BEAM ACCELERATION TEST

The schematic diagram of the magnets and RF cycle is shown in Fig. 4. During the acceleration, the working point is changed gradually from the injection tune (1.744,1.706) to the extraction one (1.678, 1.725) by setting the ramping curve of quadrupoles.

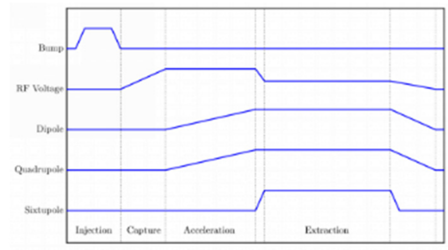

Figure 4: The diagram of the magnets and RF cycle.

The mismatch of the beam energy, the magnetic field of dipoles and RF frequency and phase, will cause the beam to oscillate laterally and beam loss. The matching between the field of dipoles and RF frequency can be achieved by modifying the frequency curve based on the closed orbit curve measured by BPMs during acceleration.

The dual-harmonic acceleration was used in XiPAF synchrotron, the ratio (denoted by the symbol r) of RF voltage of the second harmonic to the first harmonic determines the shape and size of the Bucket. The beam intensity curves under three acceleration conditions (r = 0, r = 0.5, r = -0.5) were measured using DCCT, as shown in Fig. 5(a). The dual-harmonic acceleration (r = -0.5) can significantly improve the acceleration efficiency and beam intensity. After acceleration to 60 MeV, the beam intensity is 53 mA, as shown in Fig. 5(b), corresponding to $1{\times}10^{11}$ ppp.

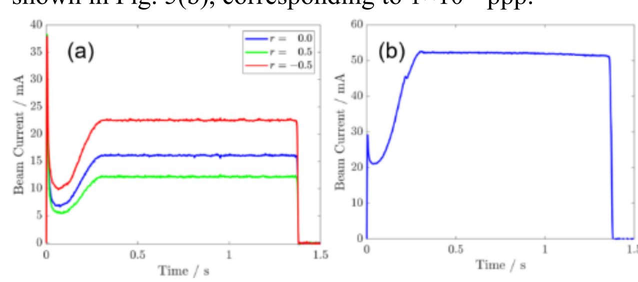

Figure 5: The results of dual-harmonic acceleration, (a) is beam intensity for three r values, (b) is the beam intensity after optimization.

SLOW EXTRACTION TEST

Before the extraction, the optics measurement and correction have been carried out at 7.1 MeV and 60 MeV, the measurement has a good agreement with the corrected optical model, refer to [7] for details.

The extraction system of XiPAF synchrotron is described in Ref. [8]. An ionization chamber (IC) on the HEBT is employed to measure the extracted beam. Limited by the thickness of shielding walls of the temporary plant, the beam extraction commission in this stage is focused on 60 MeV and 10 MeV. The beam extraction of 200 MeV was briefly tested, without the optimization the extracted beam intensity on IC is about $2{\times}10^{10}$ ppp.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB189

60 MeV Slow Extraction

For 60 MeV beam extraction, two key points of beam commission are extraction efficiency and the spill ripple. For XiPAF synchrotron, the main sources of beam loss during the extraction are as following:

- The beam envelope exceeds the vacuum pipe size near the first extraction septum magnet MS1 (the pipe size near MS1 side is smaller than the requirement, can be alleviated by a local bumper orbit [6]) during the process of RF-KO excitation before extraction.
- Beam loss on the anode wires of the electrostatic septum (ES) because of the improper position and angle of particles at the entrance of ES.

Figure 6 shows the variation of extraction efficiency with the area of the triangle when the ES anode wire array is located at 19 and 22 mm. The black line is the simulation results, and the red line is the measurement results. In the experiment, the maximum extraction efficiency by RF-KO is 85%, refer to [9] for detailed analysis.

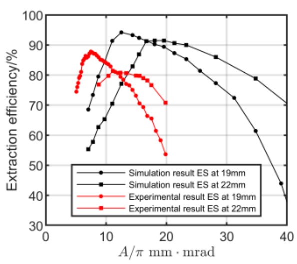

Figure 6: Extraction efficiency of simulation and experiment.

The spill ripple magnitude is written as R = σ/μ, using the definition in Ref. [10]. In our experiments, the dual FM method was adopted, and the feedback system was used to modify the amplitude of the RF-KO over the extraction duration. Finally, a smooth spill structure was obtained (shown in Fig. 7), and R value is 0.179.

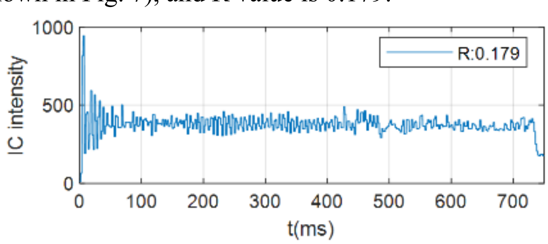

Figure 7: Spill structure with dual FM method and the feedback.

10 MeV Slow Extraction

XiPAF is built for Single-Event Effect (SEE) test, which requires slow extraction beam from 10 ~ 200 MeV. Traditionally, the low energy beam (10 ~ 60 MeV) is achieved by the degrader, which may cause beam loss and energy spread increase. Compared with using degrader, the direct low energy extraction can obtain higher beam intensity within the energy spread requirements [11].

In this commission phase, 10 MeV beam extraction from the synchrotron was carried out, and the results are given here briefly, and more details will be reported soon elsewhere. The space charge effect is a priority in the slow extraction of 10 MeV beam. When the extraction working point is above the $\nu_x = 5/3$ resonance line, limited by the Laslett tune shift, after acceleration to 10 MeV, the beam intensity is 6.4 mA, the maximum extraction intensity is 1.1×10^{10} ppp.

In order to improve the beam intensity of 10 MeV direct extraction, the working point was selected to the value of below $\nu_x = 5/3$ resonance line. After parameters optimization, including working point (ν_x =1.663), RF voltage during the extraction (60 V), the central frequency of RF-KO, etc. the beam intensity of 10 MeV direct extraction measured by IC is 4.7×10^{10} ppp, as show in Fig.8.

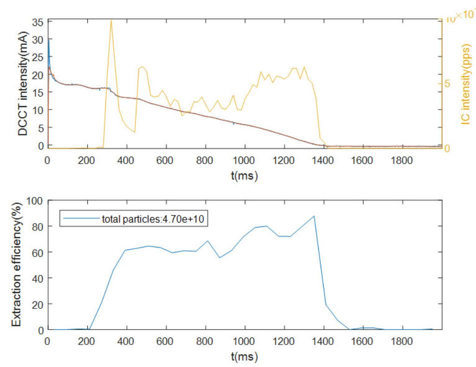

Figure 8: Beam intensity and extraction efficiency for 10MeV slow extraction.

CONCLUSION

The beam commissioning of XiPAF synchrotron in the temporary plant is finished, 10 ~ 200 MeV proton beam has been extracted directly from the ring. The extraction beam intensity for 10 ~ 60 MeV is about 5×10^{10} ppp.

So far, some user experiments from five organizations have been carried out on XiPAF, including single particle effect and displacement damage effect experiments of more than 50 core electronic devices. In the temporary plant, the extraction efficiency optimization and spill ripple research will be continued, and the multi-energy extraction will be further developed. Now the formal plant of XiPAF is under construction. Once it is completed, all the equipment will be moved to new plant, where it will be installed and commissioned according to the design scheme.

REFERENCES

[1] S. X. Zheng *et al.*, "Overall design and progress of XiPAF project", in *Proc. 13th Symposium on Accelerator Physics (SAP'17)*, Jishou, China, Aug. 2017, pp. 183-185. doi:10.18429/JACoW-SAP2017-WECH2

[2] G. R. Li *et al.*, "Design of a compact ring for proton radiation applications", *Chinese Physics C*, vol. 41, no. 1, p. 017001, 2017. doi:10.1088/1674-1137/41/1/017001

[3] P.F. Ma *et al.*, "Development of a compact 325 MHz proton interdigital H-mode drift tube linac with high shunt impedance", *Phys. Rev. Accel. Beams*, vol. 24, no. 2, p. 020101, Feb. 2021. doi:10.1103/physrevaccelbeams.24.020101

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB189

[4] W. Wang *et al.*, "Development of shoebox BPM for Xi'an Proton Application Facility", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May. 2016, pp. 175-177. doi:10.18429/JACoW-IPAC2016-MOPMB038

[5] H. J. Yao *et al.*, "H- charge exchange injection for XiPAF synchrotron", in *Proc. 57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'16)*, Malmö, Sweden, Jul. 2016, pp. 49-51. doi:10.18429/JACoW-HB2016-MOPR004

[6] X. Y. Liu *et al.*, "Injection optimization and study of XiPAF synchrotron", presented at IPAC'21, Campinas, SP, Brazil, May 2021, paper TUPAB326.

[7] X. Y. Liu *et al.,* "Injection Optimization and Study of XiPAF Synchrotron", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper TUPAB326.

[8] H. J. Yao *et al.*, "RF-Knockout Slow Extraction Design for XiPAF Synchrotron", *in Proc. 57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'16)*, Malmö, Sweden, Jul. 2016, pp. 52-54. doi:10.18429/JACoW-HB2016-MOPR005

[9] W. B. Ye *et al.*, "XiPAF Synchrotron Slow Extraction Commissioning", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper WEPAB205.

[10] K. Noda *et al.*, "Aadvanced RF-KO slow-extraction method for the reduction of spill ripple", *Nucl. Instrum. Methods*, vol. 492, no. 1-2, p. 253-263, Oct. 2002. doi: 10.1016/S0168-9002(02)01319-0

[11] G. R. Li *et al.*, "Study of Achieving Low Energy Beam by Energy Degradation and Direct Resonance Extraction in a Compact Ring", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 850-852. doi:10.18429/JACoW-IPAC2016-MOPOY003