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LONGITUDINAL TOMOGRAPHY FOR ANALYSING THE LONGITUDINAL PHASE SPACE DISTRIBUTION IN RCS OF CSNS*

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Abstract

It is proved that in the beam commissioning of the RCS of CSNS, the longitudinal optimization is vital for the promotion of the beam power. The WCM is the only beam instrument for the measurement of the longitudinal parameters. It is important for us to deduce the longitudinal phase space distribution, using the WCM data. The longitudinal tomography is applied, and some satisfying results have been obtained.

INTRODUCTION

The RCS of China Spallation Neutron Source (CSNS) the layout of which is shown in Fig.1 boosts the kinetic energy of one proton from 80 MeV to 1.6GeV in 20ms [1], and in this process the proton beam transfers over the RCS about 19600 rings. At the injection time, the cycling period the beam is about 1.95 μs, while at the extraction time, the cycling period decreases to 0.818 μs. The designed beam power of CSNS is 100 kW, with a mean current 62.5μA and a repetition rate 25 Hz. The RCS is running with a harmonic number 2.

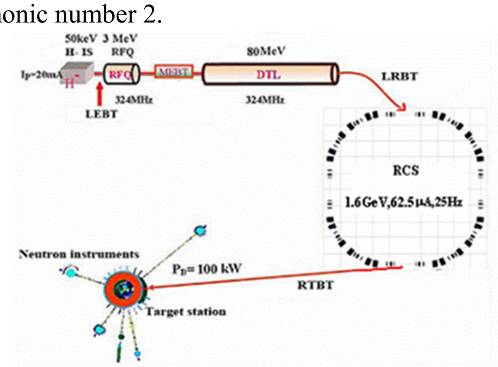

Figure 1: Layout of China Spallation of neutron Source.

During the beam commissioning of increasing the beam power from 50 kW to 80 kW, it is discovered that modifying of the ring RF frequency curve and the Amplitude curve is one of the key point for beam optimization. The effect of the longitudinal optimization is observed by the beam transformation efficiency, the beam loss, and by wall current. There is a DCCT, a SCT, a wall current monitor (WCM), and 72 beam loss monitor installed in the RCS. The WCM is used to measure the bunch length, the bunching factor, the longitudinal tune, and so in. The WCM installed in the RCS is running with a sampling rate of 100 MHz over the 20 ms boosting time.

To more elaborately analysing the longitudinal parameters, it is hoped that the longitudinal phase space distribution should be studied. It is a pity that the phase space distribution couldn't be directly measured by the beam instruments. The WCM could measure the longitudinal phase distribution of the bunch after sophisticated data processing, as introduced in our work [2]. Based on these result, it is promising that the longitudinal phase space distribution would be derived, using the so-called tomography method.

LONGITUDINAL TOMOGRAPHY

Tomography

Tomography is a powerful mathematical tool to reconstruct the initial distribution from a set of projection from different angles. It has been widely used in medical instrument, industrial inspections, x-ray astronomy, and so on. Applying the tomography to the accelerator beam commission study has a history of more than 20 years. Generally speaking, there are three main kinds of reconstruction algorithm in the application of tomography: filtered back projection (FBP) or convolved back projection (CBP), algebraic reconstruction technique (ART), Maximum entropy. In this work, the algebraic reconstruction method is adopted to reconstruct the longitudinal phase space distribution of RCS of CSNS. ART algorithm is one of the most typical iteration algorithm [3-8].

WCM data

In another work, the method to derive the longitudinal phase distribution based on WCM data has been introduced [2]. Based on such kind of data analysing, an example of the result of the longitudinal phase distribution of the bunch measured by WCM is shown in Fig.2. The x axis indicates the boosting time. The y axis indicates the longitudinal phase. Notice that the harmonic number of the RCS of CSNS is 2, so the phase in Fig. 2 has a range of 0~720 degree. The colour indicates the distribution density of the bunch. There is a systematic error between the phase distribution and the synchrotron phase of the ideal particle. Before next step of analysis, this systematic error must be deducted.

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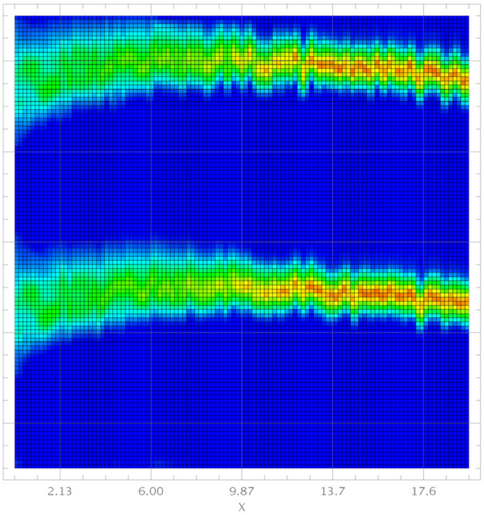

Figure 2: Longitudinal phase distribution of the bunch over the boosting time.

Longitudinal Mapping

The most important step of phase space reconstruction is the longitudinal mapping.

$$\Delta E_{n+1} = \Delta E_n + eV(\sin\phi_n - \sin\phi_s)$$

$$\phi_{n+1} = \phi_n + \frac{2\pi h\eta}{\beta^2 E_s}\Delta E_n$$

The mapping process is executed according to the above equations. h is the harmonic number; β is the relativistic factor; E_s is the synchrotron energy; $\phi_s$is the synchrotron phase. In the $\Delta E - \phi$ phase space, single particle tracking is executed under every possibilities. In real program implementation, the phase space is divided equally into 1000*1000 grids. Every grid is treated as a single particle, then the tracking is executed. The mapping process is shown in Fig.3, with 2 single particles as example.

Our software is developed based on the open-XAL framework. To maintaining the processing efficiency, the tracking data is stored in a multidimensional array. If N turn tracking is executed, then a 1000*1000*N array is generated and stored in the RAM. If the N is selected too large, then a java heap space error is triggered. Our experience shows that to avoid this error, the tracking turn N must be selected as no larger than 300. On the one hand, the longitudinal oscillation period is about 150 turn after injection. On the other hand, in the principle of ART algorithm, projection data from more than 10 different angles could guarantee the effectiveness of the reconstruction. As a conclusion, even if the tracking turn N can't exceed 300, using the N turn WCM longitudinal phase distribution data is more than enough for the longitudinal phase space reconstruction.

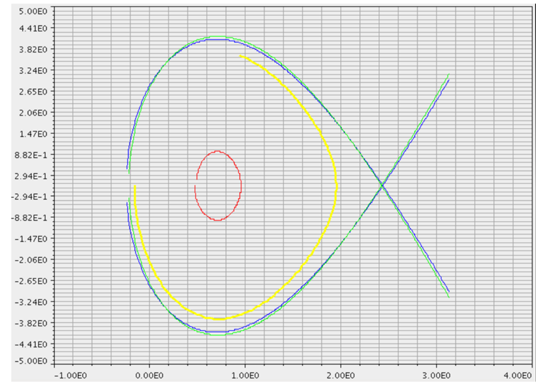

Figure 3: Longitudinal mapping process. Take two single particles as example. The green curves indicate the separatrices.

Reconstruction Process

Now everything is ready for the reconstruction of the longitudinal phase space.

First, an initial longitudinal phase space distribution is arbitrarily guessed or is generated by some kind of rules at m-th turn. This distribution is also a 1000*1000 two-dimensional array. Every point indicates the probability that the particles in the bunch are located in the neighbourhood of that grid.

Second, following the mapping regulation, every element of the 1000*1000 two-dimensional array is tracked over the next N turn. Now based on the initial guessed distribution, the guessed distribution in the next N turn are obtained.

Third, execute the iteration algorithm. It must be pointed out that the wall current measured by WCM is treated just as the projection of the longitudinal phase space distribution on the ϕ axis of the ΔE-ϕ phase space. The guessed phase space distribution in the previous step is also projected on the ϕ axis. The projected 1-dimensional distribution is now compared with the longitudinal phase space distribution shown in Fig.2 deduced from WCM data at every turn of the N turn. The error between the projected distribution and the measured distribution obtained from WCM is the iteration parameter playing the key role in the iteration process. This error is the indicator of the iteration convergence. Generally, experience shows that after 30~40 iterations, the error could converge to a relatively small value, and then the iteration is stopped.

Take a sample of the longitudinal phase distribution data between 1000^{th} ~1200^{th} turn (1.89~2.25 ms) as example. These data are plotted as 3D surface plot in Fig.4.During this range, the longitudinal oscillation period is more than 100 turns. The 200 turn range is selected, to make sure that the longitudinal phase space distribution of the bunch roughly rotates more than one cycle in theory. If the range is selected too small, the accuracy of the future result would be questionable, while if it is selected too large, computation efficiency would become very uneconomical.

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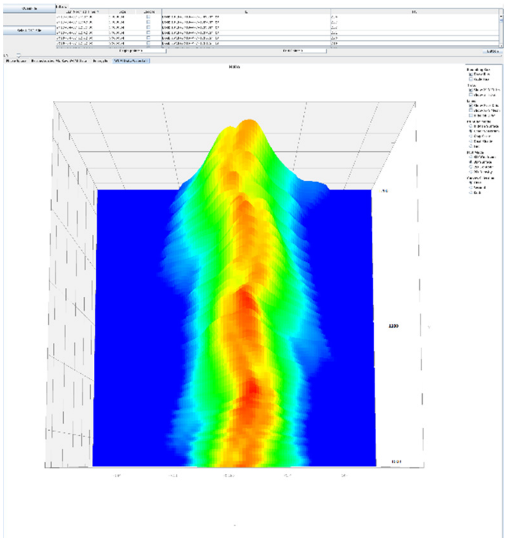

Figure 4: Longitudinal phase distribution of the bunch between 1000th turn and 1200th turn.

Applying the ART algorithm to analyse this group of data, the longitudinal phase space could be reconstructed, and the distribution are plotted in Fig. 5.

Because compared to the situation in the previous turn, the rotation of the longitudinal phase space distribution is small, so the different projection angles or the longitudinal phase distributions are not selected turn by turn continuously. On the contrary, during such range of turns, 25 samples with equal intervals are selected. As mentioned before, projection data from 25 different angles are enough to ensure the accuracy of the result of the reconstruction algorithm.

Another reason why the data of all turns are not selected is to reduce the calculation time. To increase the accuracy of the result, the computation efficiency decreases obviously as the samples of turn increasing.

PROBLEM

Although applying the ART algorithm to reconstruct the longitudinal phase space has manifested some promising result, there are still some problems.

In theoretical simulation, there is a trend that a small error would appear near the unstable fixed point in the sepatrix.

During the iteration process, different feedback algorithm would result in difference in the final result.it also results in different final error.

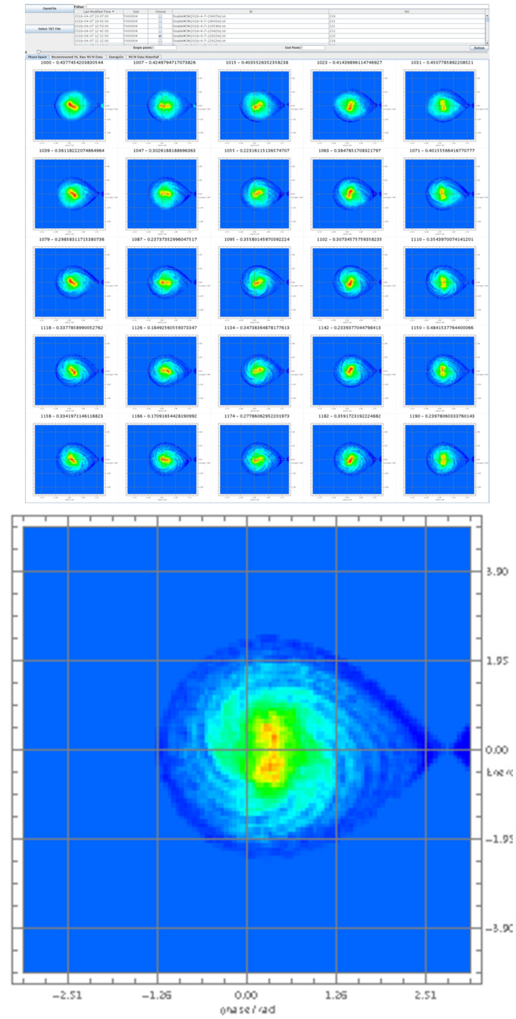

Figure 5: The reconstructed longitudinal phase space distribution of the 25 samples between 1000th turn and 1200th turn(above). The result at 1190th turn is zoomed in to show more details.

CONCLUSION

WCM is a powerful longitudinal beam instrument in beam commissioning. Tomography is a widely used tool to reconstruct initial distribution from a set of projection data from different angles. We have successfully applied the ART algorithm to reconstruct the longitudinal phase space during the beam commissioning of RCS of CSNS.

There are still some problems existing in the current algorithm. We would continue to improve the algorithm in the future, and try our method to realize longitudinal tomography.

In the future, an IPM would be installed in the RCS, so we would also use tomography to analysis the transverse phase space.

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