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THE CONSIDERATIONS OF IMPROVING TMCI THRESHOLD IN HEPS BOOSTER*

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Abstract

The High Energy Photon Source (HEPS) is proposed in Beijing, China. The on-axis swap-out injection scheme will be used in the storage ring mainly because of the small dynamic aperture. Therefore, the booster needs to store more than 2.5 nC bunch charge. Under this requirement, the transverse mode coupling instability (TMCI) at the injection energy becomes the bunch charge restriction in the booster. Several changes in booster and linac for improving bunch charge threshold limited by TMCI are considered. The details will be expressed in this paper.

INTRODUCTION

HEPS is a high-energy, ultralow-emittance storage ring based light source, which is to be built in China. The lattice of the HEPS storage ring is based on the hybrid 7BA with longitudinal gradient bends and anti-bends [1-5]. The natural emittance of the HEPS storage ring is about 34 pm at 6GeV. Due to the strong nonlinear effect, the dynamic aperture (DA) is not large enough to accommodate the off-axis local-bump injection scheme which is commonly used in the third generation light sources. The on-axis swap-out injection [6-8] is chosen as the baseline injection scheme. Two operation modes are considered in the storage ring: the high-brightness mode (680 identical bunches with total beam current of 200 mA) and the high-bunch-charge mode (63 bunches uniformly filled in the ring).

The on-axis swap-out injection scheme needs to inject the full-charge bunch into the storage ring to replace the stored bunch. For the high-bunch-charge mode, the injector needs to provide 14.4 nC per bunch to the storage ring.

In the early design, a 300 MeV linac, which can provide a 5 ps full-charge single bunch to the booster, was proposed. The combined-function dipoles were used in the booster lattice design. However, we found the Transverse Mode Coupling Instability (In the early design, a 300 MeV linac, which can pro-vide a 5 ps full-charge single bunch to the booster, was proposed. The combined-function dipoles were used in the booster lattice design.

TMCI occurs when the frequencies of two neighbouring head-tail modes approach each other due to the detuning with increasing beam current. For a Gaussian bunch, the threshold of the instability can be expressed with the transverse loss factor [9], shown in Eq. (1)

$$I_0^{th} = \frac{2\nu_s \omega_0 E/e}{\sum_j \beta_{\perp,j}\, \kappa_{y,j}} \Theta. \tag{1}$$

where I_0^{th} is the threshold of the beam current, ν_s is the synchrotron tune, $\beta_{\perp,j}$ is the average beta function in the j^{th} element, $\kappa_{y,j}$ is its loss factor, E is the beam energy and Θ is about 0.7.

The Eq.(1) indicates that the TMCI threshold current can be increased by increasing the beam energy, increasing the synchrotron tune, decreasing vertical beta function, and so on.

In the rest of the paper, we will reports the TMCI analysis and the improvements for increasing TMCI threshold, including the development of the linac physical design, evolutional of booster lattice structure, 'high-energy accumulation' scheme, and so on.

ANALYSIS OF TMCI

Since the TMCI threshold increases as the bunch energy becomes higher, the bunch threshold current due to TMCI should be determined by the values at the injection energy of the booster. We therefore carry out the TMCI threshold calculation mainly at the injection energy of the booster, which should be the extremely conservative estimation of the threshold.

Both analytic formulae and the simulations can be used to predict the TMCI threshold. We get very good agreement when comparing the results generated by the two methods at zero chromaticity. However, it's nontrivial to get the proper estimation of the threshold at nonzero chromaticity using the analytic formulae. We therefore choose to use the particle tracking method to calculate the TMCI threshold.

As mentioned above, the initial proposal was to inject a 300 MeV, 5 ps single bunch to the booster. The threshold when chromaticity is 0 and +5 are roughly 3 nC/bunch and 1.2 nC/bunch, respectively. These results are much lower than the required 14.4 nC/bunch.

We first considered to increase the initial bunch length to reduce the peak density. The remarkable increase of the threshold current can be observed if the initial bunch length goes up to 1 ns. However, it's not possible to get reasonable bunch quality from the linac if we need a 1 ns bunch because the RF frequency of the linac is about 3 GHz. We therefore move to the requirement of multi-bunches from linac and inject them into the same RF bucket of the booster.

To increase the threshold further, the momentum compaction factor is necessary to be increased. In the first version of the booster lattice, the momentum compaction factor is about 9×10^{-4}, which is much lower than that of the existing boosters for the third generation synchrotron light sources. We then scan the momentum compaction factor to check how the TMCI threshold varies accordingly. The study shows remarkable increase of the threshold current if the momentum compaction factor can be one order of magnitude higher. Considering to some other constraints in the

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lattice design, the new lattice can achieve roughly 4 times higher momentum compaction factor than the original lattice.

EVOLUTION OF LINAC

The HEPS linac has had several iterations of design to meet the requirement that can increase the TMCI threshold of the booster. At first, the linac, namely V1 in this paper, is a 300 MeV S-band (2998.8 MHz) normal conducting linac with sub-harmonic bunching cavities, one single bunch per pulse and bunch length in 5 ps.

After testing the different initial bunch in the simulations, we found that using multi-micro-bunches in one bucket and stretching the bunch length can get higher single bunch instabilities thresholds, and the requirements for linac is changing. The pulse mode chose multi-micro-bunch per pulse using 2998.8 MHz pre-buncher instead of sub-harmonic cavities. The rms bunch length was changed from 5 ps to 20 ps by introducing bunch lengthening system. So the second version design of the linac, namely V2 in this paper, is a 300 MeV linac with multi-micro-bunches per pulse and rms bunch length in 20 ps. One bunch lengthening system was included in the design [10].After testing the different initial bunch in the simulations, we found that using multi-micro-bunches in one bucket can get higher single bunch instabilities thresholds.

With in-depth study and exports' suggestion the 500 MeV linac is more beneficial for physics design. After comprehensive consideration the HEPS linac is adopted at last, namely V3 in this paper, which of energy is 500 MeV, pulse mode is multi-micro-bunch per pulse and rms bunch length is 5 ps [11] without bunch lengthening system. The evolution of HEPS linac layout is shown in Fig.1.

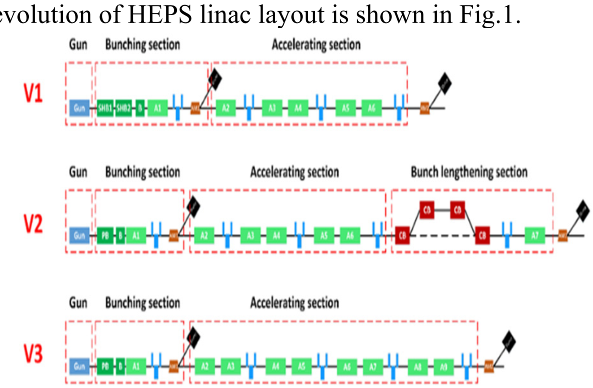

Figure 1: The evolution of HEPS linac layout.

EVOLUTION OF BOOSTER LATTICE STRUCTURE

In the past two years, the main optimisation goal of HEPS booster was to reduce the emittance down to several nanometres. Several candidate lattices were proposed [12-14], and a 15BA lattice with combined function dipoles was chosen. The emittance can be reached as low as 4 nm·rad under this lattice. Meanwhile, the momentum compaction factor of this lattice is about 9×10^{-4}, which is much lower than most of the existing boosters.

With scan the momentum compaction factor, we found to augment the momentum compaction factor of booster lattice is an effective way to increase TMCI threshold. There is a remarkable increase of the threshold current if the momentum compaction factor can be one order of magnitude higher.

Through scan the unit cell of this lattice, we found the quantum lifetime decreased sharply with the momentum compact factor increase. When we constraint the RF voltage less than 7.2MV and quantum lifetime longer than half-hour. The momentum compact factor cannot larger than 3×10^{-3}.

A new lattice with traditional FODO structure is adopted [15]. This lattice has four super-periods. Each super-period has 14 standard FODO cells in the middle and 2 matching cells in the two ends. Each super-period has 32 dipoles, 37 quadrupoles and 17 sextupoles. The main parameters are listed in Table1.

Table1：Main Parameters of the FODO Structure Lattice

Parameter	Unit	Value
Circumference	m	453.5
Emittance @ 6 GeV	nm.rad	37
Tunes(x/y)		16.83/10.73
Energy spread @ 6 GeV		9.6×10^{-4}
Natural chromaticity(x/y)		-18.5/-14.9
Momentum compaction factor		3.8×10^{-3}
Energy loss per turn @ 6 GeV	MeV	4.0
Damping time @ 6 GeV	ms	4.5/4.5/2.3

This lattice allows a larger momentum compaction factor and a smaller average vertical beta function. This arrangement significantly increases the bunch charge threshold at 500MeV. As a price, the natural emittance of this lattice at 6 GeV is increased to about 40 nm·rad, which still satisfies the demand of the storage ring injection.

Based this lattice and the V3 linac, the simulation results show the TMCI threshold at +1 chromaticity at 500 MeV is about 5 nC/bunch, which should fulfil the single bunch charge requirement by the injection of the storage ring [16].

'HIGH-ENERGY ACCUMULATION' SCHEME

The on-axis swap-out injection scheme is also chosen in other ultra-low emittance light sources, such as APS-U and ALS-II. As a weakness of this injection scheme, it needs to inject the full-charge bunch into the storage ring to replace the stored bunch.

For some special filling patterns, like 48-bunch mode in APS-U, the injector should support about 20 nC single – bunch-charge to storage ring. This will be a big challenge to injector.

To fitful the high-bunch-charge requirement, APS-U carried out several improvements to its injector, and ALS-II planned to use a dedicated full energy accumulator ring.

HEPS injector should to reliably produce 14.4 nC single-bunch charge to storage ring for the high-bunch-charge

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mode filling pattern. Storage 14.4 nC in booster at 500MeV is very difficult to achieve because of two reasons. One reason is accumulated injection could not work at 500MeV due to the damping time is much longer than the revolution time. The other is TMCI threshold restriction.

To inject high-charge bunch to the storage ring, while avoiding the strong TMCI effects at the lower energy of the booster ramping loop, the booster is used as an accumulator ring at 6 GeV， we call it 'high-energy accumulation' scheme

The Eq. (1) shows the threshold of TMCI is proportional to beam energy. The single-bunch-charge TMCI threshold at 6 GeV is 12 times to it at 500MeV.

The booster damping time at 6 GeV is about 4.5 ms, which is much shorter than the 1.5 µs repetition time, the off-axis local-bump injection scheme can be used for beam accumulation.

For detailed describe the 'high-energy accumulation' scheme, we will take the high-bunch-charge mode as an example, when the bunch charge of storage ring reduces by a certain factor (e.g., from 14.4 nC to 13 nC), this bunch will be extracted and injected to the booster after passing through a high energy transport line. The bunch will merge with an existing bunch in the booster (e.g., 2 nC) which has been injected from the linac and accelerated to 6 GeV. And then the merged bunch is extracted from the booster and re-injected to the storage ring passing through other high energy transport line (here is a 96% transport efficiency). The process is shown in Figure 2 [17].

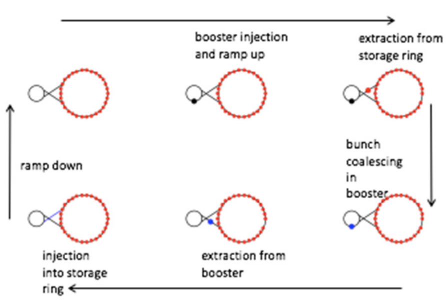

Figure 2: The diagram of a whole injection process with 'high-energy accumulation' scheme.

CONCLUSION

In the early design, a 300 MeV linac with a 5 ps full-charge single bunch and a 15BA lattice booster with combined-function dipoles were proposed. However, TMCI limits the single-bunch charge .For increasing the TMCI threshold in the HEPS booster , many improvements have been made in the linac and the booster . With these updates, the TMCI can fulfil the single bunch charge requirement by the injection of the storage ring.

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