TRANSVERSE BEAM BREAK-UP STUDY OF SNS SC LINAC*

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Abstract

Numerical simulation indicates that cumulative beam breakup (BBU) instability is not a concern to SNS SC linac. First, simulation is carried out for CW operation mode where the driving harmonics are those with frequency multiples of bunch frequency 402.5 MHz. Even when the median HOM frequency is exactly on resonance with multiples of bunch frequency of 402.5 MHz, the cavity-to-cavity HOM frequency spread can ensure operation of linac. Second, in the case of pulsed operation mode, additional driving harmonics of 1 MHz and 60 Hz are added on top of those of CW mode. The shunt impedance of these additional modes is relatively small. BBU is not a concern also for pulsed mode operation, as is verified for a few most dangerous modes. More systematic analysis of BBU of pulsed mode operation is done by Sundelin *et al* [1] and presented at this conference.

1 INTRODUCTION

SNS H⁻ linac is different from highly relativistic electron linacs in that the beam particle velocity is significantly less than the velocity of light c. Effects of wake field and bunch energy loss of a beam with $\beta < 1$ is relatively unknown. Recently Kurennoy did some calculation on bunch energy loss for particle beams with $\beta < 1$ [2]. It is shown that

$$\frac{k_s(\beta,\sigma)}{k_s(1,\sigma)} = \exp\left[-\left(\frac{\omega_s\sigma}{c}\right)^2 \frac{1}{\beta^2\gamma^2}\right]\frac{(R/Q)(\beta)}{(R/Q)(1)} \qquad \textbf{(1)}$$

where $k_s(\beta,\sigma)$ is the loss factor of mode s and σ is half of rms bunch length of a Gaussian beam. Here β and γ are relativistic factors, and *R/Q* is the shunt impedance. For very short bunches, exp[…]≈1. And it is a reasonable approximation to use

$$(R/Q)(\beta) = \frac{2c^2}{\varepsilon_o\omega^3}\frac{\left|\int_0^l e^{-i\omega z/\beta c}\frac{\partial E_z(0,0,z)}{\partial x}dz\right|^2}{\int_V E^2 dV} \qquad \textbf{(2)}$$

for H⁻ (or proton) replacing *R/Q*(1) of highly relativistic electron linacs.

A study is performed to investigate the effects of HOM (Higher Order Mode) of SNS superconducting (SC) linac on cumulative beam breakup. This is to provide tolerable Q value of HOM and to provide a systematic view of the dependence on parameters involved such as frequency, Q value, R/Q, frequency spread of HOM. For simulation, TDBBU code [3] developed at JLab is used with the relevant input of SNS SC linac.

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Fundamental mode frequency of SNS SC linac is 805 MHz while bunch frequency is 402.5 MHz because beam bunch is in every other bucket. The linac bunch train is 645 ns long and the gap is 300 ns. And the macro bunch train is 1 ms long. For example, when $Q=10^5$, $\omega=2\pi\times$ 2400MHz and g=302.4 ns, only 2.3% of HOM field is damped during this 302.4 ns gap because the remaining field is proportional to exp(-ωg/2Q). This is a pessimistic condition from the beam breakup viewpoint.

2 BENCHMARKING

Benchmarking of TDBBU code is done by repeating the simulation in Gluckstern's paper [4] and by comparison with the analytical theory. The TDBBU simulation has also reproduced the Gluckstern simulation results exactly as is shown in Fig. 1.

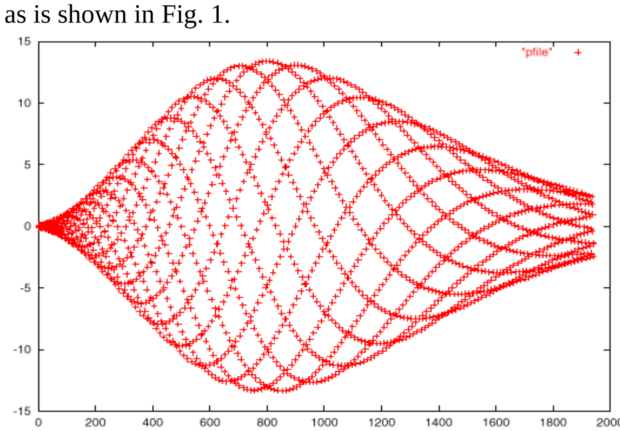

Figure 1: Plot of transverse beam centroid displacement at the end of the linac.

3 THRESHOLD CURRENT VERSUS Q VALUE OF HOM

The dependency of threshold current on Q of HOM is studied under pessimistic conditions. In the simulation, all the cavities both in the medium beta section and high beta section are assumed to have the same f_{HOM} of 2012.6 MHz. This is only 0.1MHz away from the resonance frequency 2012.5 MHz. Threshold beam current is defined as the beam current that produces deflecting factor of 2 at the end of SC linac during 1ms beam bunch train. When the deflection factor is larger than 2, beam loss due to the foil miss becomes a concern. The deflection factor *D* scales as

$$D \propto \exp[\sqrt{IQ_{HOM}R/Q}], \qquad \textbf{(3)}$$

where *I* is the beam current, Q_{HOM} the quality factor of a HOM and *R/Q* the shunt impedance. Figure 2 shows curves of threshold current for five different values of shunt impedance R/Q.

One interesting fact is that threshold beam current starts to saturate around Q=1.0x10^7 for all five values of shunt impedance. Because the "rise time" of the HOM is 1.0x10^7/(π*2.0126 x10^9)~1.58 ms for a 2012.6 MHz mode when Q is around 1.0x10^7. In other words, the instability cannot grow without a long enough pulse for the HOMs to be appreciably excited. When R/Q=100 Ω, threshold current of 36mA corresponds to Q=2.5x10^7. It should be noted that threshold current is inversely proportional to shunt impedance R/Q.

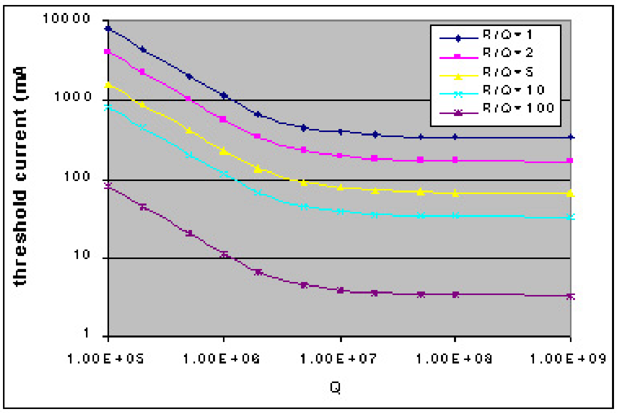

Figure 2: Plots of threshold beam current (mA) versus Q for different values of shunt impedance R/Q in Ohm.

4 EFFECT OF HOM FREQUENCY SPREAD

Due to tolerances on manufacturing process of cavities, the frequency of a HOM varies from cavity to cavity. In the case of JLab FEL cavities, cavity to cavity f_{HOM} ranges from 5MHz to 30MHz. Cornell data shows that 0.38% maximum fractional f_{HOM} is measured. This HOM frequency spread effectively reduces the Q of the mode [5] and increases threshold beam current. In the simulation, Q=1.0x10^7 is assumed and shunt impedance R/Q is set to 100 Ω for all the cavities and the beam current I to 500 mA, more than ten times of the design current. Q=1.0x10^7 is chosen because threshold current starts to saturate from this value. 100-Ω shunt impedance is chosen because MAFIA study [6] indicates that biggest shunt impedance is less than or equal to about 100 Ω. Beam current is set to 500 mA to allow enough safety factors. One of resonant HOM frequencies is chosen. Median frequency of HOM is set to 2012.5 MHz.

Effect of HOM frequency spread is studied for the Lorentzian HOM frequency distribution and uniform HOM frequency distribution. The Lorentzian HOM frequency spread is given by

$$g(f) = \frac{1}{\pi}\frac{\Delta f}{(f - f_o)^2 + \Delta f^2} \qquad \textbf{(4)}$$

where f_o is the median HOM frequency and Δf is frequency spread (half-width-half-maximum).

The average deflecting factor versus frequency spread (half-width-half-maximum) in MHz is displayed in Fig. 3. HOM frequency spread dramatically reduces average deflecting factor. Average is taken over 1000 Monte Carlo linacs. 3.0MHz Half-Width-Half-Maximum Lorentzian HOM frequency spread makes linac operation possible even for 500-mA beam current under most severe resonant condition.

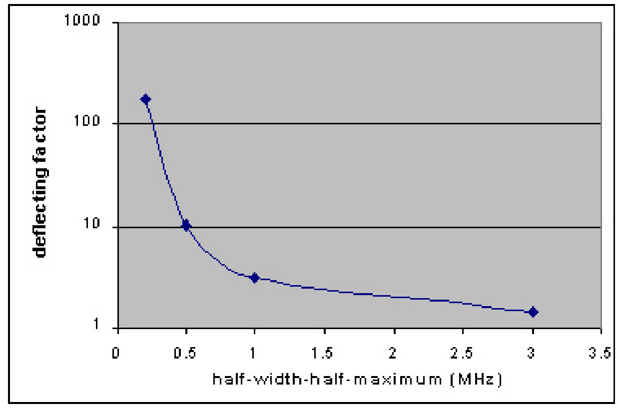

Figure 3: Plot of deflecting factor vs. HWHM (half-width-half-maximum) spread of Lorentzian HOM frequency distribution.

5 EFFECT OF PULSED MODE OPERATION

There is a 300 ns gap in every 945 ns midipulse, which corresponds to 1.058 MHz spectral line. The duration of each macropulse is about 1 ms. The frequency of macropulse is 60 Hz. Preliminary transverse and longitudinal beam breakup simulation is done to estimate the effects of these time structure for a few seemingly dangerous modes. In the simulation presented in Fig. 4, modes listed in Table 1 are taken into consideration. These modes are obtained from MAFIA run. These modes have f_{HOM} quite close to multiples of bunch frequency 402.5 MHz and Q values are assumed to be 10^8. One monopole mode other than the five-passband modes is taken into consideration. Maximum R/Q value is used for all the cavities instead of energy dependent R/Q values.

Table 1: HOM data used for simulation

Cavity	HOM	f_{HOM} [MHz]	R/Q [Ω]	Q
β_{med}	Monopole	2817.5	0.500	10^8
β_{med}	Dipole	1623.9	1.680	10^8
β_{med}	Dipole	2021.5	3.900	10^8
β_{med}	Dipole	2410.5	1.710	10^8
β_{med}	Dipole	2429.9	0.195	10^8
β_{high}	Monopole	2817.5	0.500	10^8
β_{high}	Dipole	2380.5	0.174	10^8
β_{high}	Dipole	2416.7	0.361	10^8
β_{high}	Dipole	2818.8	0.408	10^8
β_{high}	Dipole	2837.2	1.060	10^8

All bunches are transversely offset by 1 mm at injection. Figure 4 shows plots of x (mm), E_f (MeV) and ϕ (deg) at the end of SC linac vs. 945-ns long midipulse number over 10 macropulses. Simulation is done with ±0.01MHz and ±0.1MHz f_{HOM} spread (monopole and dipole modes, uniform distribution). There is no sign of instability transversely and longitudinally, even though there is some fluctuation. With ±0.1MHz uniform f_{HOM} spread (in blue), the fluctuation is already negligible. Even with $Q=10^8$, ±0.1MHz uniform f_{HOM} spread is sufficient. In reality, f_{HOM} spread of other SC cavities is much larger than this. So this BBU issue is not a concern for SNS SC linac.

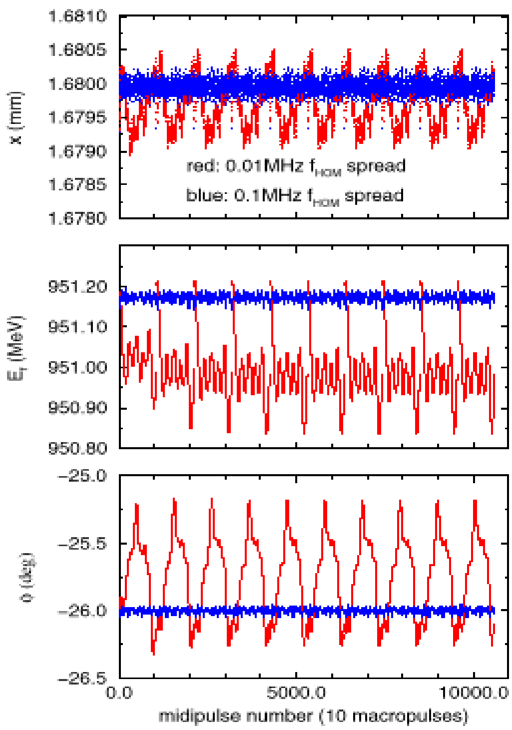

Figure 4: Plots of x (mm), E_f (MeV) and ϕ (deg) at the end of SC linac for 10 macropulses. 10 macropulses are clearly shown. The gap is depicted here. With ±0.1MHz f_{HOM} spread (uniform distribution), there is no beam breakup instability in both transverse and longitudinal motion.

Now comes the issue of HOM power dissipation in the cavities. Figure 5 shows plots of cavity heat load in W for the monopole mode in Table 1 for three different values of uniform f_{HOM} spread. This is for one Monte-Carlo machine. Cavity heat load stays below 0.01W for most cavities with ±1.0MHz uniform f_{HOM} spread. It should be noted that usual f_{HOM} spread is much larger than the ±1.0MHz uniform f_{HOM} spread. Again HOM power dissipation is not dangerous with a sufficient f_{HOM} spread. More systematic analysis of cavity heat load is done by Sundelin [1] and Kim [6]. The cavities with high heat load have f_{HOM} quite close to resonances.

Figure 6 shows plots of beam energy jitter for three different f_{HOM} spread vs. pulse number. The beam energy jitter is already less than 0.05MeV for 0.1MHz f_{HOM} spread. Slight spread of HOM frequency dramatically stabilizes the beam.

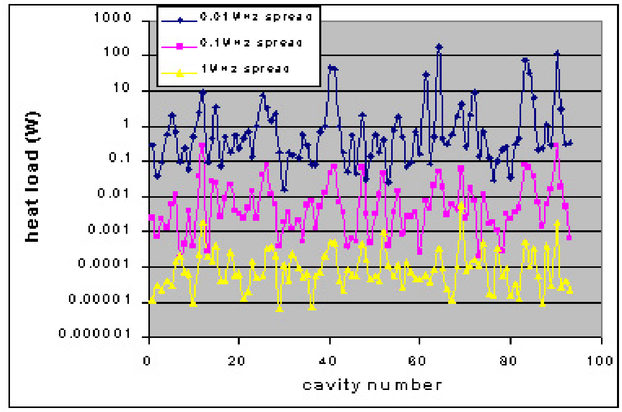

Figure 5: Plots of cavity heat load in W for the monopole mode in Table 1 for three different uniform f_{HOM} spread.

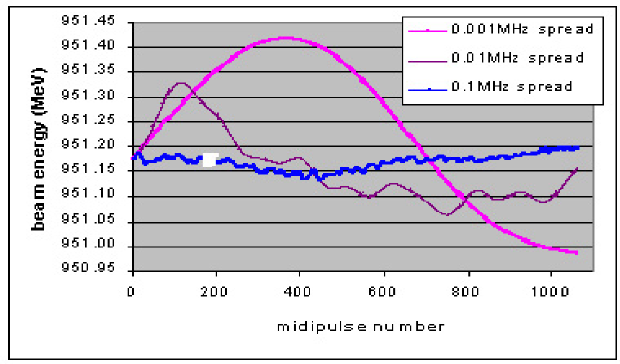

Figure 6: Plots of final beam energy jitter for three different f_{HOM} spread vs. pulse number.

6 CONCLUSION

Study indicates that HOM beam break-up is not a concern even for a pulsed mode operation of SNS superconducting linac. This is mainly due to the HOM frequency spread of cavities due to manufacturing tolerances. Heat load does not seem to be a concern up to $Q=10^8$ with ±1.0MHz uniform f_{HOM} spread.

7 REFERENCES

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