TRANSITION CROSSING FOR THE BNL SUPER NEUTRINO BEAM *

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Abstract

The super neutrino beam facility proposed at the Brookhaven National Laboratory requires proton beams to cross the transition energy in the AGS to reach 1 MW beam power at top energy [1]. High-intensity beams are accelerated at a fast repetition rate. Upon transition crossing, such high-intensity bunches of large momentum spreads suffer from strong nonlinear chromatic effects and self-field effects. Using theoretical and experimental methods, we determine the impact of these effects, and the effectiveness and complications of transition-jump compensation schemes, thus to determine the optimum crossing scenario for the super neutrino beam facility.

INTRODUCTION

During the past four decades, the intensity of the proton beam has been continuously raised to the record above 7×10^{13} protons per pulse at a repetition rate of 0.5 Hz during high-intensity operations (Table 1). At a beam power of 0.14 MW, one of the primary concerns is the radio-activation caused by the beam loss. Beam loss incurred during the time of transition-energy crossing is one of the most important factors.

Table 1 lists parameters pertaining to the present high-intensity operation. As discussed in the following section, a transition-energy jump (γ_T-jump) [2, 3, 4] is necessary to reduce the momentum spread, and to minimize the effects of chromatic nonlinearity and self-field mismatch [5, 6]. However, the existing second-order γ_T-jump also disrupts the machine lattice, significantly reducing the momentum aperture. This momentum aperture reduction, combined with the intentional blow-up of the longitudinal bunch area

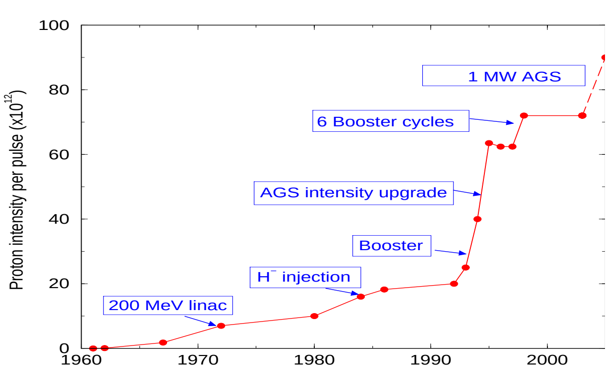

Figure 1: Evolution of the AGS proton-beam intensity.

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Table 1: Main parameters for routine high-intensity proton operations in the AGS.

Average output beam power	0.14	MW
Injection energy	1.5	GeV
Extraction energy	24	GeV
Repetition rate	0.5	Hz
Nominal transition energy, γ_T	8.5	
Revolution frequency at γ_T, $\omega_s/2\pi$	0.369	MHz
Acceleration rate, $\dot\gamma$	60	s^{-1}
Ramp rate, $\dot B$	2.2	T/s
RF voltage, V_{rf}	300	kV
RF harmonic number, h	6	
RF synchronous phase, ϕ_s	0.54	rad.
Beam intensity (proton per pulse)	70	10^{12}
Bunch area (95%)	5	eV·s
Typical fractional beam loss	~ 2	%

to damp instability at the injection flat-bottom, results in a typical beam loss of 2 - 3% at transition. The corresponding average loss of beam power of 1.2 W per tunnel meter is marginally adequate for hands-on maintenances [8].

With the super-neutrino upgrade (Table 2), the repetition rate is increased from 0.5 to 2.5 Hz. The ramp rate $\dot\gamma$ is increased by more than a factor of three. This rate increase tends to improve the transition crossing efficiency. However, the corresponding increase in RF voltage enhances the momentum spread and the chromatic nonlinear effect. A γ_T jump of similar amount is still necessary. This pa-

Table 2: AGS parameters for the super neutrino facility.

Average output beam power	1	MW
Injection energy	1.2	GeV
Extraction energy	28	GeV
Repetition rate	2.5	Hz
Nominal transition energy, γ_T	8.5	
Acceleration rate, $\dot\gamma$	196.6	s^{-1}
Ramp rate, $\dot B$	7.2	T/s
RF voltage, V_{rf}	1	MV
RF harmonic number, h	24	
RF synchronous phase, ϕ_s	0.52	rad.
Beam intensity (proton per pulse)	89	10^{12}
Number of proton per bunch	3.9	10^{12}
Bunch area (95%), $6\langle S\rangle$	0.8-1.2	eV·s
First-order non-linear compaction, α_1	2.0	
Transition energy with γ_T-jump, γ_T	9.5	
Transition jump amount, $\Delta\gamma_T$	1	
Transition jump time	< 1	ms
Momentum aperture (without γ_T-jump)	2.4	%
Momentum aperture (With γ_T-jump)	1.6	%
Typical fractional beam loss	0.2 - 3	%

per studies the condition to reduce the transition beam loss below about 0.2% so that hands-on maintenance (average radio-activation below 1 mSv/hour after 4-hour shutdown at 30 cm distance from the beam line, and average uncontrolled beam loss below 1 W/m) can be practically realized.

BEAM-LOSS MECHANISMS

Near transition, the longitudinal particle motion becomes non-adiabatic during a characteristic time $2T_c$ [7],

$$T_c = \left(\frac{\pi E_s \beta_s^2 \gamma_T^3}{ZeV_{rf}|\cos\phi_s|\dot{\gamma} h \omega_s^2}\right)^{1/3}$$

where Z is the charge, E_s is the particle total energy, V_{rf} is the RF voltage, and ϕ_s is the synchronous phase. At transition, the rms momentum spread $\sigma_{\Delta p/p}$ reaches the maximum value,

$$\hat{\sigma}_{\Delta p/p} = 0.71 \frac{h\omega_s}{E_s \beta_s^2}\sqrt{kT_c\langle S\rangle}$$

where $k = ZeV_{rf}|\cos\phi_s|$. The leading source of beam loss at the AGS is the momentum spread exceeding the momentum aperture at locations of maximum dispersion.

The chromatic non-linear effect results from particles of different momenta crossing transition at different time. The non-linear time $2T_{nl}$ is given by [7]

$$T_{nl} = \left|\alpha_1 + \frac{3\beta_s^2}{2}\right| \frac{\sqrt{6}\hat{\sigma}_{\Delta p/p}\gamma_T}{\dot{\gamma}}$$

where α_1 is the first-order non-linear momentum compaction. The amount of longitudinal emittance growth is proportional to the ratio T_{nl}/T_c [7]

$$\frac{\Delta S}{S} \approx \begin{cases} 0.76\dfrac{T_{nl}}{T_c} & \text{for } T_{nl} \ll T_c \\ \exp\left[\dfrac{4}{3}\left(\dfrac{T_{nl}}{T_c}\right)^{3/2}\right] - 1 & \text{for } T_{nl} \geq T_c \end{cases}$$

The longitudinal space-charge force defocuses the beam below transition and focus the beam above transition. At transition, the self-field mismatch is proportional to the ratio of the self field and the RF field [7],

$$\frac{\Delta S}{S} \approx \frac{h\hat{I}|Z_{\parallel}/n|}{3V_{rf}|\cos\phi_s|\hat{\sigma}_\phi}$$

where $\hat{\sigma}_\phi = 0.52\sqrt{\langle S\rangle/kT_c}$ is the bunch length at transition, and $\hat{I}$ is the peak current. The capacitive space-charge impedance is $Z_{\parallel sc}(n\omega_s)/n = -j\frac{g_0 Z_0}{2\beta_s\gamma^2}$, where $Z_0 = (\epsilon_0 c)^{-1} = 377\ \Omega$, and $g_0 \approx 4$ is the geometric factor. Near transition, $Z_{\parallel sc}/n \approx -j10\ \Omega$. On the other hand, the inductive machine impedance $Z_{\parallel ind}/n$ is estimated to be between $j15\Omega$ and $j30\Omega$. The effect of space-charge at transition is expected to be greatly compensated by the inductive coupling of the machine.

In the absence of a γ_T-jump, the beam fills the entire momentum acceptance of about 2.4% upon transition crossing according to the measurement performed at AGS in 2004. Without jump, the expected beam loss is above 20%.

γ_T-JUMP COMPLICATIONS

The γ_T-jump is necessary to reduce the beam loss by effectively increasing the rate of transition crossing. The required jump is $\Delta\gamma_T \sim 1$ within 1 ms, effectively increasing the crossing rate by more than a factor of 5 (Fig. 2). The jump is realized by exciting a dispersion wave at harmonic 9 (near horizontal tune of 8.8) using 6 pulsed quadrupoles of alternating polarity, located at about 1.5 betatron period apart [4].

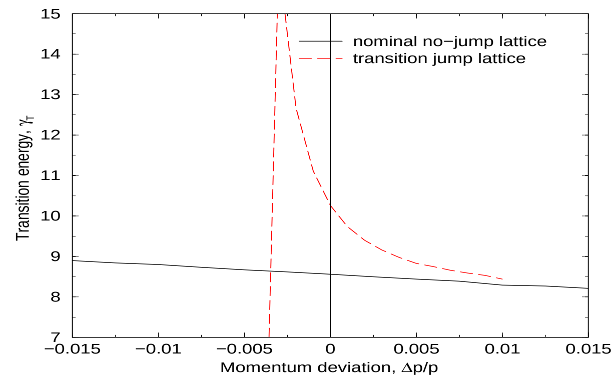

Figure 2: Dependence of transition energy on the momentum deviation in the AGS.

During the γ_T-jump, the perturbation in the betatron tunes is small ($|\Delta\nu_{x,y}| < 0.03$). However, the maximum dispersion is increased by nearly a factor of 5 from 2.3 to 9.5 m (Fig. 3). The maximum β-function is increased by 20-30% (Fig. 4). Consequently, the momentum acceptance is reduced from 2.4% to 1.6%.

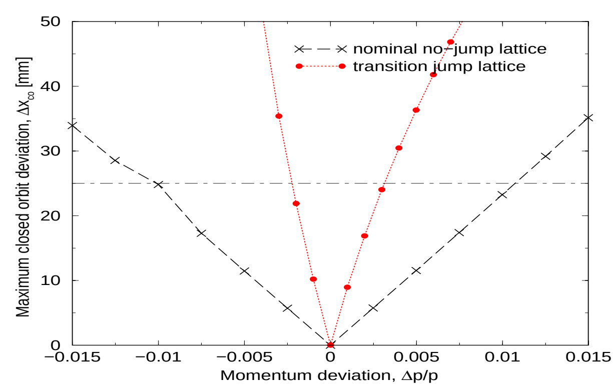

Figure 3: Dependence of the closed orbit on the momentum deviation in the AGS.

Longitudinally, the lattice disruption caused by the γ_T-jump enhances the non-linear momentum compaction by more than a factor of 10. This enhancement effectively reduces the amount of transition jump at different momenta, as shown in Fig. 2.

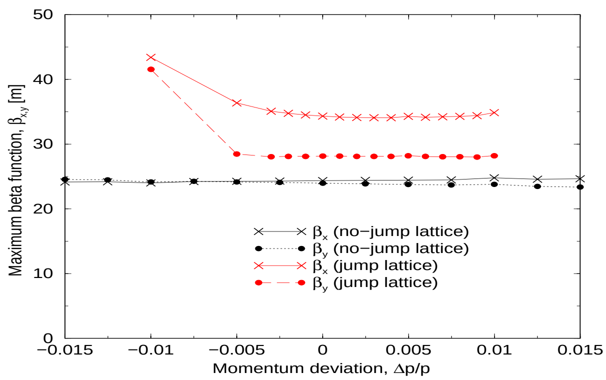

Figure 4: Dependence of β-function on the momentum deviation in the AGS.

COMPUTATIONAL AND EXPERIMENTAL VERIFICATIONS

Computationally, the MAD codes [9] (Figs. 2, 3, and 4) are recently used to confirm the γ_T-jump lattice design with SYNCH [10]. Longitudinal dynamics is studied with the simulation codes TIBETAN [7]. Fig. 5 shows the longitudinal phase space of the beam before, at, and after transition with initial 95% bunch area of $6\langle S\rangle = 0.8$eV·s.

Several machine experiments have been performed since the commissioning of the γ_T-jump system in the AGS. The dispersion function during the jump is measured by radially displacing the closed orbit and analyzing the dependence on revolution frequency [4]. The non-linear momentum compaction α_1 and its enhancement during the jump are obtained by measuring the change of transition crossing timing as a function of the radial orbit displacement [11]. The results agree with the design values within measurement accuracy. The momentum aperture and its reduction during the γ_T-jump are measured and used to benchmark the beam loss as a function of momentum spread when the chromatic effect is dominant [12, 13].

DISCUSSIONS AND SUMMARY

With the high-intensity, high-repetition super neutrino operation, transition crossing is one of the bottleneck where excessive beam loss may occur. Although the higher acceleration rate helps, the high RF voltage enhances the chromatic effects. A γ_T-jump is needed.

With the existing γ_T-jump scheme, the increase in the dispersion function reduces the momentum aperture at transition. In order to keep the uncontrolled beam loss below about 0.3% (beam power of $\sim$ 1 W/m), the 95% bunch area needs to be below about 0.8 eV·s. It would be a challenge to paint the linac beam into this relatively small area, and to keep the beam stable from injection to transition. Further analysis is needed to evaluate the coupling impedance and stability criteria.

The phase II of the super neutrino proposal calls for a beam power of 2 MW. Dramatic improvements are needed to control the beam loss at transition. One possibility is to re-design the γ_T-jump lattice with reduced dispersion disruption. The other is to introduce beam collimation to reduce the uncontrolled beam loss. An efficient beam collimation in the AGS is non-trivial since neither transverse aperture nor longitudinal space is readily available.

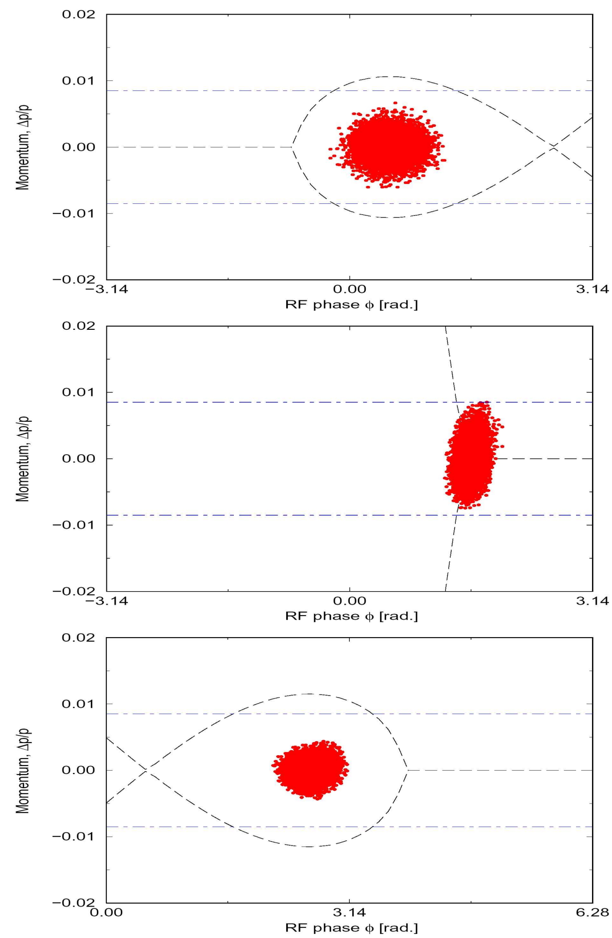

Figure 5: Longitudinal phase space of the proton beam before, at, and after crossing the transition energy in the AGS.

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