

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. 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 of transition-jump compensation schemes, and determine the optimum crossing scenario for the super neutrino beam facility.

1 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 radioactivation 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 the major parameters pertaining to the present high-intensity operation. As discussed in the following section, a transition-energy jump (γ_T -jump) is nec-

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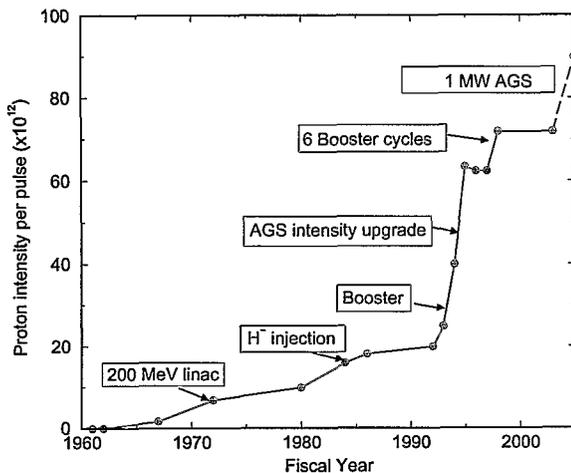


Figure 1: Evolution of the AGS proton-beam intensity.

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

Nominal transition energy, γ_T	8.5	
Injection energy	1.5	GeV
Extraction energy	24	GeV
Repetition rate	0.5	Hz
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
Number of proton per bunch	12	10 ¹²
Bunch area (95%)	5	eV·s
First-order non-linear compaction, α_1	2.0	
Transition energy with γ_T -jump, γ_T	9.5	
Transition jump amount, $\Delta\gamma_T$	± 0.5	
Transition jump time	± 0.5	ms
Momentum aperture (without γ_T -jump)	2.4	%
Momentum aperture (With γ_T -jump)	1.6	%
Typical fractional beam loss	2 - 3	%

essary to reduce the momentum spread, and to minimize the effects of chromatic nonlinearity and self-field mismatch. 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 to damp the 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 - 1.9 W per tunnel meter has made hands-on maintenance difficult.

With the super-neutrino upgrade, the repetition rate is increased from 0.5 to 2.5 Hz.

2 MAIN MECHANISMS

The proton beam crosses the transition energy at $\gamma_T = 8.5$. During a non-adiabatic time $\pm T_c$, the beam may experience emittance growth and beam loss caused by chromatic non-linear mismatch, beam self-field mismatch, and beam instabilities. Table 2 shows the main parameters pertaining to transition crossing in the AGS.

Table 2: Main parameters of the AGS for the super neutrino facility.

Nominal transition energy, γ_T	8.5	
Injection energy	1.2	GeV
Extraction energy	28	GeV
Repetition rate	2.5	Hz
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%)	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, $\Delta\gamma_T$	± 0.5	
Transition jump time	± 0.5	ms
Momentum aperture (without γ_T -jump)	2.4	%
Momentum aperture (With γ_T -jump)	1.6	%
Typical fractional beam loss	0.2 - 3	%

2.1 Momentum Aperture Limitation

In the absence of the transition jump, the characteristic non-adiabatic time

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

is about ± 0.87 ms, where E_s is the particle total energy, and ω_s is the angular revolution frequency. The non-linear time T_{nl}

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

is about ± 1.9 ms, where the rms momentum spread reaches its design peak value of $\hat{\sigma}_{\Delta p/p} \approx 0.52\%$ at transition. The amount of beam longitudinal emittance growth due to the chromatic mismatch is proportional to the ratio T_{nl}/T_c . Upon transition crossing, the beam fills the entire momentum acceptance of about 2.4% (according to the measurement performed at AGS in 2004). The expected beam loss is about 20% in the absence of the transition jump.

2.2 Chromatic Nonlinear Effect

2.3 Self-field Mismatch

The longitudinal space-charge coupling impedance is given by

$$Z_{||,sc}(n\omega_s)/n = -j \frac{g_0 Z_0}{2\beta_s \gamma^2}$$

, where $Z_0 = (\epsilon_0 c)^{-1} = 377 \Omega$, and $g_0 \approx 4$ is the geometric factor. Near transition, $\gamma \approx \gamma_T$, $Z_{||,sc}/n \approx 10 \Omega$. The effect of space-charge self force at transition is expected to be greatly compensated by the inductive coupling

impedance of the machine that is independent of the beam energy.

2.4 Microwave Instabilities

3 γ_T -JUMP COMPLICATIONS

It is necessary to use the transition jump method to effectively increase the rate of transition crossing. The required amount of transition jump is $\Delta\gamma_T = \pm 0.5$ during a time of ± 0.5 ms. Such a jump effectively increases the crossing rate by a factor of 5. The transition jump is realized by pulsing a single family of 6 quadrupole magnets for 1 ms at a current of 2.2 kA. A disadvantage of such a transition jump scheme is the temporal disruption of the lattice optics. During the jump, the maximum horizontal dispersion is increased from xxx to xxx m. The maximum beta function is increased from xxx to xxx m. Consequently, the total momentum acceptance is reduced from 2.4% to 1.6%. At this momentum acceptance, the expected beam loss is about 2%. Figure 5 shows the longitudinal phase space of the beam before and after transition.

4 SUPER-NEUTRINO SCENARIO

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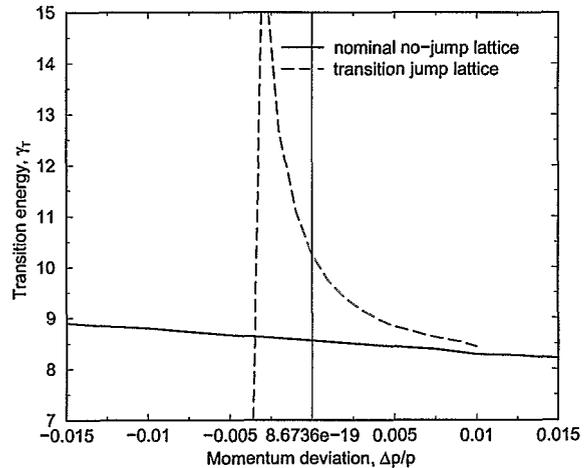


Figure 2: Longitudinal phase space of the proton beam after crossing the transition energy in the AGS.

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5 DISCUSSIONS

Transverse instability

6 SUMMARY

We thank L. Ahrens, M. Blaskiewicz, D. Raparia, T. Roser, W.T. Weng, and S.Y. Zhang for many discussions.

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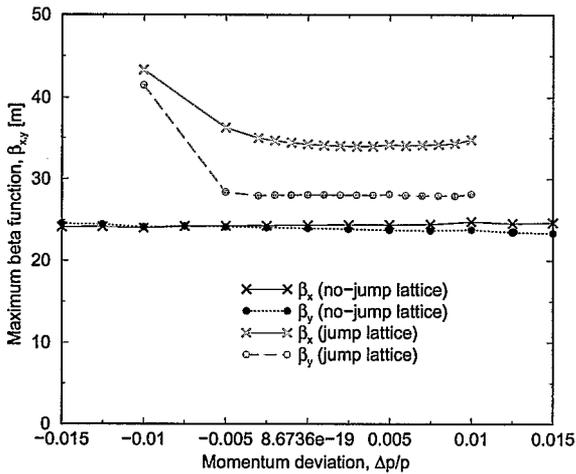


Figure 3: Longitudinal phase space of the proton beam after crossing the transition energy in the AGS.

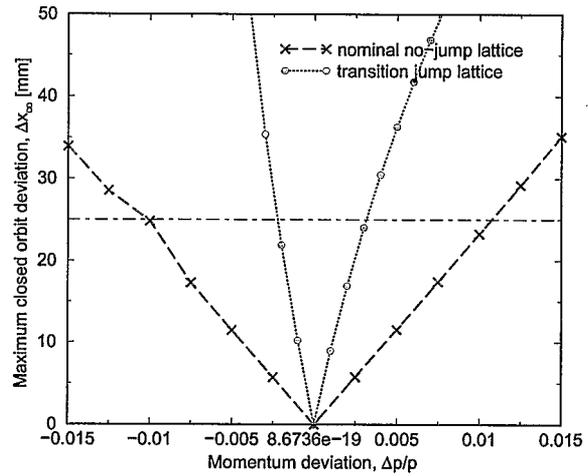


Figure 4: Longitudinal phase space of the proton beam after crossing the transition energy in the AGS.

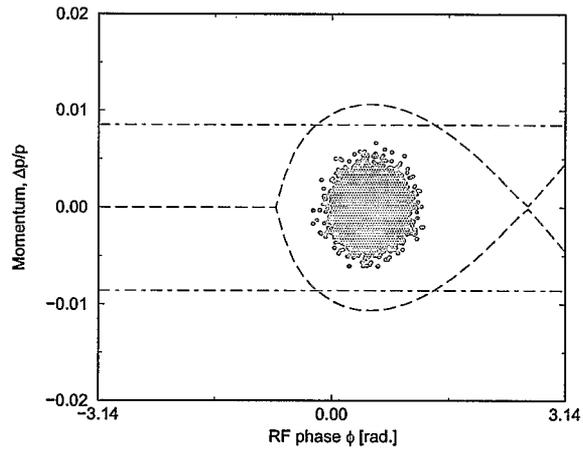


Figure 5: Longitudinal phase space of the proton beam before crossing the transition energy in the AGS.

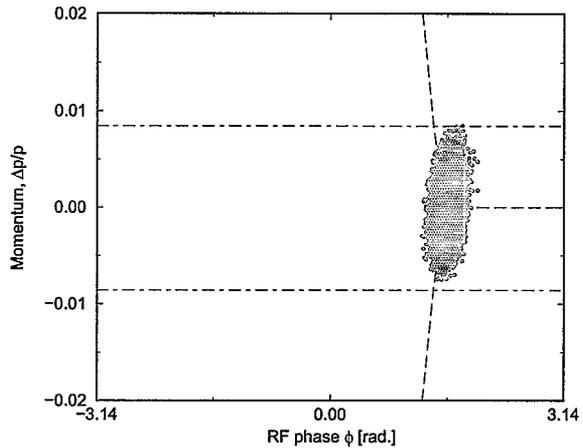


Figure 6: Longitudinal phase space of the proton beam before crossing the transition energy in the AGS.

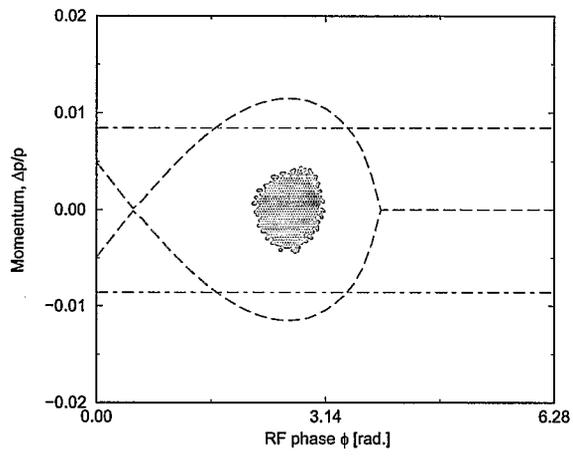


Figure 7: Longitudinal phase space of the proton beam before crossing the transition energy in the AGS.

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