Fermi National Accelerator Laboratory

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Application of a New Scheme for Passing Through Transition Energy to the Fermilab Main Ring and Main Injector

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Introduction

In the vicinity of the transition energy of an ion synchrotron the longitudinal oscillation frequency drops and the motion becomes non-adiabatic; the result is emittance dilution. Furthermore, because the synchrotron oscillation is too slow to average particle energy gain, particles off the synchronous phase get too much or too little acceleration depending whether they lead or lag; therefore, momentum spread is increased. In this regime rf focusing degrades beam quality. To confront these effects directly J. Griffin has proposed eliminating the rf focusing near transition by flattening the rf waveform with a second or third harmonic component.[1] The rf is phased so that all particles in the bunch are accelerated by the flattened portion, receiving just the acceleration required by the magnet cycle as illustrated in fig. 1(b). We will show by concrete examples related to the Fermilab Main Ring (MR) and Main Injector[2] (MI) that one can eliminate rf focusing sufficiently long before and after transition to reduce the maximum momentum spread and emmitance growth significantly. Additionally, the bunch has its maximum phase spread at transition so that the peak current and resulting microwave instability is mitigated, and the bunch above transition becomes a satisfactory match to an accelerating bucket. We call this procedure the "slide-under" technique to distinguish it from the single-frequency "duck-under" technique and simultaneously to recognize that there are ideas in common.

The process is illustrated schematically in fig. 1. A bunch is accelerated in a standard bucket to $\eta = \gamma_T^{-2} - \gamma^{-2} \approx -10^{-4}$ with a voltage program chosen to optimize the momentum spread for the next steps. The fundamental phase is moved to 90° and the harmonic system is turned on at about 28% of the fundamental for second harmonic or 13% for third harmonic. The width of the flattened region is about 70° for second harmonic or 54° for third. While the bunch is below transition it shears as shown in fig. 1(c) with lower momentum particles lagging those of higher momentum, reaching its greatest phase spread at transition. When $|\eta|$ returns to its initial value, the bunch is again upright, and a conventional accelerating bucket can be restored. The linearity of the shearing motion is affected by the "Johnsen parameter" α_2, the second order term in the dependence of orbit length on relative momentum offset.[3] The maximum phase drift is given by[1]

$$\Delta\varphi|_{\max} = \frac{\omega_{\rm rf} t_o}{\gamma_T^2}\left[\frac{\dot\gamma t_o}{\gamma_T} - \alpha_2\frac{\Delta p}{p}\right]\frac{\Delta p}{p} ,$$

where t_o is the starting time relative to transition time for the synchronous particle. We infer from this equation and parameters for the MR and MI that for both it is possible to pass through the non-adiabatic time for all particle momenta with no rf focusing. The result should be brighter beams or higher intensity limits than possible with conventional technique. We present below results of modeling carried out with the ESME code[4] including space charge and nonlinearity in the equations of motion to order $(\Delta p/p)^2$. We also comment on hardware requirements.

A Main Ring Test

The Fermilab Main Ring has been converted from its original service as a high intensity source for a 400 GeV fixed target program to a 150 GeV injector for the Tevatron. Losses at transition have become a serious problem because non-planar bypasses and other modifications for collider operation have reduced the momentum aperture to $\sim 0.4\%$ and because the acceptable losses are governed by the close proximity of the superconducting Tevatron magnets. It is now difficult to exceed 0.2 eVs or $2.5 \cdot 10^{10}$ protons/bunch at transition. The slide-under technique is a direct attack on this limitation. The relevant MR parameters are

mean radius	1000.00	m
γ_T	18.75	
$\dot\gamma$ at t_T	88.7	s^{-1}
Johnsen parameter α_2	0.816	
harmonic number h	1113	
maximum rf volts	4.0	MV
accelerating volt. at trans.	1.75	MV
longitudinal emittance (95%)	0.2	eVs
protons per bunch	3	$\times 10^{10}$
coupling impedance $Z_{\parallel}/n$	9.0	Ω

The third harmonic scheme is favored because substantially less new hardware is needed; therefore an earlier test

*Operated by the Universities Research Association under contract with the U. S. Department of Energy

of the concept is possible. The $\sim 54°$ flat on the rf waveform is narrower than desirable. It limits the emittance that can be handled and may shorten the time available for slide-under to somewhat less than the non-adiabatic time for the full momentum spread. Figure 2 shows the phasespace distribution for a MR bunch which has been carried through transition to $\gamma = 25$ with an optimized voltage-phase program (duck-under). Figure 3 is a comparable result from a 6.7 ms third harmonic slide-under starting at $\eta = -9 \cdot 10^{-5}$. Emittance growth of 45% vs. 8% clearly favors the new approach; more favorable comparison may be obtained by lengthening the slide-under slightly and optimizing other parameters.

A single 159 MHz cavity can provide the 250 kV required. The plan is to borrow a bare cavity, install a large enough Fe Yt garnet ferrite tuner to tune ~ 20 kHz, and excite it with a standard Fermilab PA running as a class C tripler. If the ferrite is unbiased during the greater part of the accelerating cycle when the cavity is not used, it may be lossy enough to make the unexcited cavity harmless.[5] If beam loading proves a problem it might be necessary to develop a PA with fast feedback to keep the fields under control. Because the amount of acceleration can not be controlled by adjusting the phase, both fundamental and third harmonic amplitudes must be controlled by radial position information.

The Main Injector

The Main Injector project is to replace the original 400 GeV ring with a 150 GeV ring in a new tunnel, optimized as an injector for the Tevatron. It will also have a high intensity fixed target mode at 120 GeV. The following parameters reflect the latter mode:

mean radius	538.302	m
γ_T	20.4	
$\dot{\gamma}$ at t_T	161.9	s^{-1}
Johnsen parameter α_2	0.0	
harmonic number h	588	
maximum rf volts	4.0	MV
accelerating volt. at trans.	1.68	MV
longitudinal emittance (95%)	0.5	eVs
protons per bunch	6	$\times 10^{10}$
coupling impedance $Z_{\|\|}/n$	5.0	Ω

At least four improvements over the MR make the MI a far better machine at transition, *viz.*, larger good field aperture, lower dispersion, faster ramp, and $\alpha_2 = 0$. The result shown in fig. 4 for emittance growth in a second harmonic slide-under is practically the same as for an optimum duck-under. If brighter beam is obtained from the Booster, however, the advantage of the slide-under in preserving that brightness would be apparent. At this time the utilization of the second harmonic scheme in the MI is provisional.[6] The choice to pursue the option will rest on further modelling and, it is hoped, observations in the MR or elsewhere.

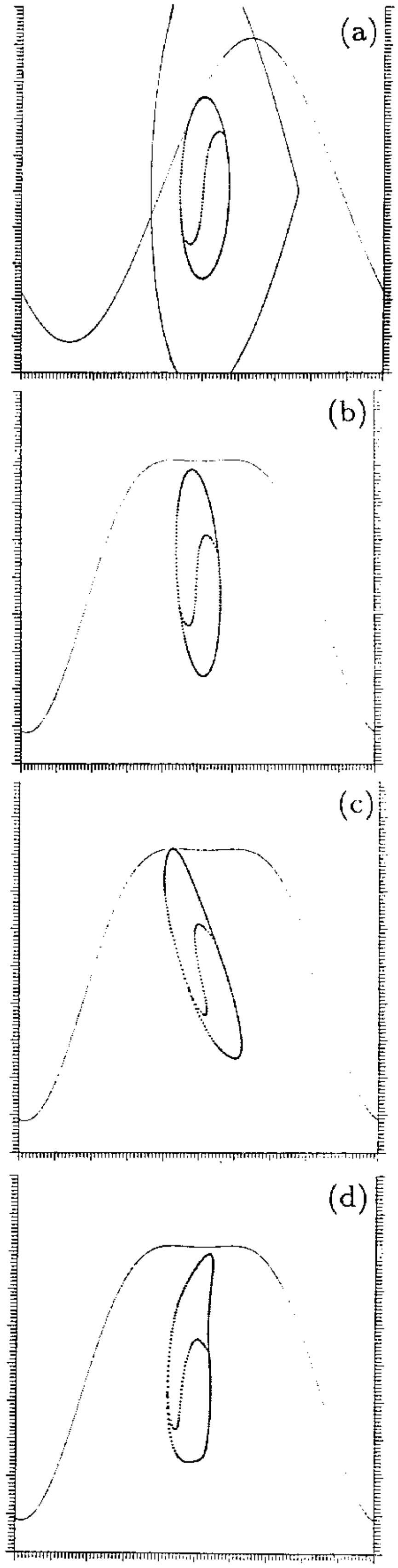

Figure 1: Steps in slide-under — see Introduction

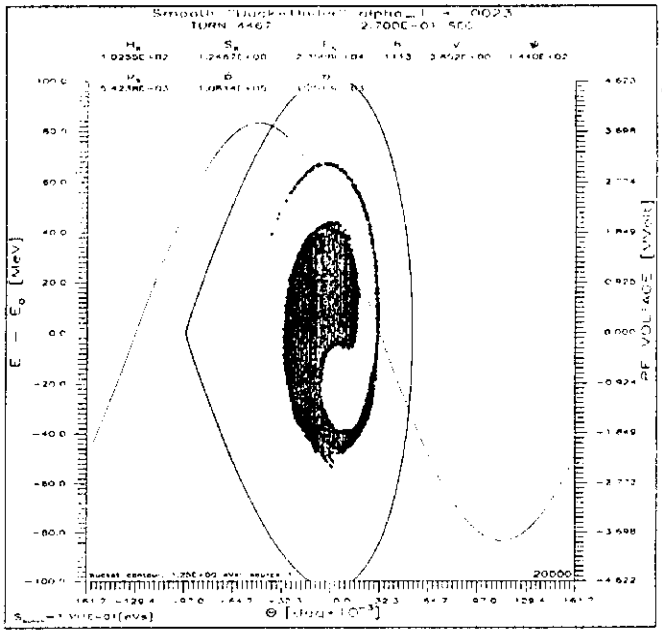

Figure 2: Main Ring bunch after duck-under transition crossing; note both mismatch and μ-wave instability.

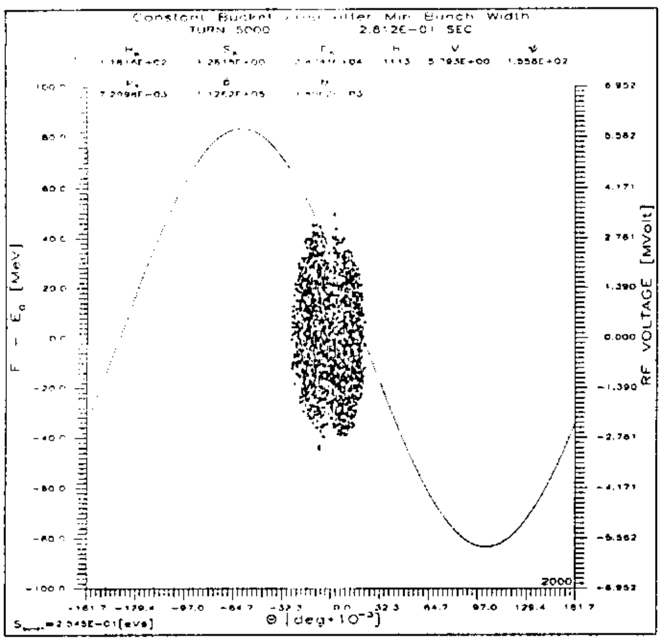

Figure 3: Main Ring bunch after slide-under transition crossing

Conclusions

The application of a novel technique for transition crossing to the Fermilab Main Ring and Main Injector project has been described on the basis of numerical modelling. The demonstrated reduction of momentum spread and peak beam current at transition contribute in several ways to reduced emittance blowup and beam loss during transition crossing. The fundamental idea of eliminating the detrimental effects of rf focusing during the few milliseconds of non-adiabatic particle motion is pleasingly direct. The details of optimizing the phase to account for higher order asymmetry in the bunch shearing, the choice of starting time and momentum spread, and the best bucket to match the distribution produced are the objects of an active modelling effort.

The tolerance of the Main Injector to conventional transition crossing results primarily from its fast ramp. An alternative scenario for antiproton acceleration uses a very slow ramp and depends critically on the slide-under technique, which was originally conceived in that context. The usefulness of the technique for the project depends on options now open. The utility and desirability of a timely experimental test is apparent.

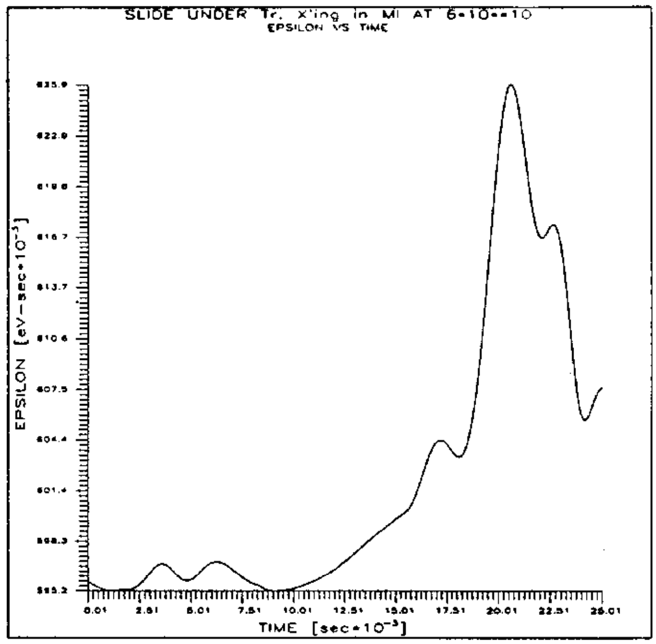

Figure 4: Longitudinal emittance ($6\epsilon_{rms}$) vs. time for slide-under in MI

References

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[5] W. Funk, priv. comm. on HERA 53 MHz cavities built by AECL Chalk River Laboratory

[6] Conceptual Design Report Fermilab Main Injector Rev. 2.3 Addendum", Fermilab (March 91)