Operational Experience with Third Harmonic RF Cavity for Improved Beam Acceleration Through Transition in the Fermilab Main Ring

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Abstract

An RF cavity operating at three times the frequency of the present Main Ring rf system at Fermilab has been installed to minimize the beam loss and longitudinal emittance (ϵ_l) growth related to the transition crossing. Tests have been carried out with beam intensities ranging from $3x10^9$ to $2.3x10^{10}$ ppb and $\epsilon_l \simeq .07$ eVs . No beam loss conditions have been attained. Attempts have been made to reduce emittance growth after the transition.

I. An Overview of the Transition Crossing RF System at FNAL

One of the major problems encountered in many medium energy proton synchrotrons is the beam loss due to longitudinal emittance dilution during transition crossing. A number of remedies have been discussed by A.Sorenssen[1]. Very recently a focus-free transition crossing (FFTC) scheme has been proposed[2] as an alternative to the previously suggested methods. The basic principle of this scheme has been explained elsewhere[3]. Implementation of the FFTC requires addition of a second or third harmonic rf system (or combination of these) to the fundamental rf system. The feasibility and limitations of this technique in the Fermilab Main Ring (MR) has been examined using the computer program ESME[4].

The MR at FNAL did not have any specific scheme to reduce beam loss or emittance growth during transition crossing other than normal transition phase jump (NTPJ) scheme. In the NTPJ scheme one accelerates the beam up to the transition energy with a positive phase angle on rising side of rf wave. At the transition the phase is suddenly changed to the falling side of the rf wave form to maintain the rf focusing. Earlier studies made[5] with NTPJ scheme for initial ϵ_l in the range of .09 to .22 eVs showed that the beam loss at transition increases with initial beam intensity and initial ϵ_l. The emittance growth was about 60% at higher intensities. Hence, the MR is one place to test the new scheme for transition crossing.

At Fermilab a third harmonic rf system was developed and installed in the MR during the June 1992 shut down period to test the FFTC scheme. We report our operational experience with this rf system and plans for improvements.

The implementation of the FFTC scheme in MR included development of a 1) 159 MHz rf cavity, 2) perpendicularly biased tuner, 3) power amplifier, (PA) and 4) low level rf system and necessary software programs. Ref. 6-9 explain the details of various hardware and software developments of the third harmonic rf system.

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II. Measurements and Discussion

With the third harmonic rf cavity in the MR, measurements have been made with the beam to understand the beam dynamics for the FFTC scheme and compare with the NTPJ. Initial studies were done with a 4 s long MR ramp having a 1.0 s front porch at 8.9 GeV and a 0.5 s front porch at 40 GeV . The beam was aborted after about 2.1 s. The front porches were mainly to facilitate measurements of ϵ_l before and after the transition crossing. For later studies we switched to the regular pbar production ramp, 2.56s long with final energy 120 GeV . All the studies were carried out using a short batch of 13 bunches of protons. There were a number of parameters that needed to be optimized to get the best performance for FFTC scheme viz; the duration of the third harmonic rf, the initial and final rf phase angles, the ratio of 159 MHz to 53 MHz rf voltages, choice of rf curve to keep the growth of ϵ_l minimum, etc. The tests have been carried out for different initial ϵ_l and beam intensities.

Table I gives results of measurements for different intensities at low longitudinal emittances. The RF-curves I, II and III represent three different rf accelerating voltage curves. RF-curve I had bucket area S_A of 0.42 eVs at 8.9 GeV and increasing up to 1.7 eVs at 40 GeV in the acceleration cycle. This had a minimum $S_A = 0.25$ eVs at about 14.7 GeV . The RF-curve II had a an approximately

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increasing S_A from 0.18 eVs to 1.0 eVs . The third one, RF-curve III had almost constant S_A of about .3 eVs .

Table I. Comparison of NTPJ and FFTC measurements.

I_{Beam} (ppb) and ϵ_{Init} (eVs)	Mode of Tran. Crossing	Beam Loss	$\%\epsilon_l$ Growth*
2.7×10^9 .064(±7%)	NTPJ	No loss	67%
RF-curve I	FFTC (sym.)	no loss	77%
2.3×10^{10} .08(±12%)	NTPJ	5-6%	132%
RF-curve II	FFTC (non-sym. 6.5ms)	No loss	72%
1.93×10^{10} .085(±12%)	NTPJ	No loss	60%
RF-curve III	FFTC (non-sym. 6.5ms)	No loss	40%

* Error on emittance growth measurement ≃ 15% of the value.

To start with, the ratio of 159 MHz to 53 MHz rf voltage amplitudes was 0.129 and the FFTC time was selected in the range of 13 ms to 15 ms symmetric around the transition time in the MR. In this case, one expects to see a distinct bunch shearing in $(\Delta p, \Delta\phi)$-space during transition crossing with the third harmonic cavity on. This arises from the partial de-bunching and then re-bunching of the beam during the focus-free time. For similar operational conditions in the NTPJ scheme, bunches narrow in $\Delta\phi$ direction as the transition energy is approached and reach a minimum value at transition. $\Delta\phi$ grows slowly after the transition. The bunch length monitor and mountain range pictures taken during transition crossing for FFTC clearly showed bunch shearing. Fig 1a and 1b display a typical mountain range pictures for NTPJ and symmetric FFTC schemes respectively. However, the emittance growth observed was essentially the same for both cases as shown in first row of Table I.

Similar measurements done with higher beam intensities and low emittances showed a beam loss up to 6% and a larger emittance growth. In this case the space charge force and wall impedances play important role in beam loss and emittance growth. For example the space charge forces counteract rf forces before the transition and help rf force after the transition. This causes the bunch to oscillate about the equilibrium bunch length resulting emittance growth as well as beam loss (when beam hits the momentum appertuire of the accelerator). Hence in case of symmetric and long FFTC, the bunch matching after the transition becomes difficult. This can be encountered by keeping the third harmonic rf cavity on for a shorter time after the transition. To avoid the unnecessary additional de-bunching of the beam before the transition the third harmonic rf cavity on time was made shorter. This non-symmetric and shorter FFTC improved the performance of the beam during transition crossing. The total FFTC time was varied in the range of 6 ms to 10 ms. As shown in second row of Table I we find an FFTC time of 6.5 ms (with third harmonic rf cavity on at 4 ms before transition and off at 2.5 ms after the transition) gave no beam-loss and smaller emittance growth as compared with NTPJ. Considerable emittance growth after the transition for this case was perhaps due to very large bucket area offered by RF-curve II. An rf curve with parabolically increasing bucket area (S_A = .35-.72 eVs) gave no beam-loss for FFTC but about similar emittance growths.

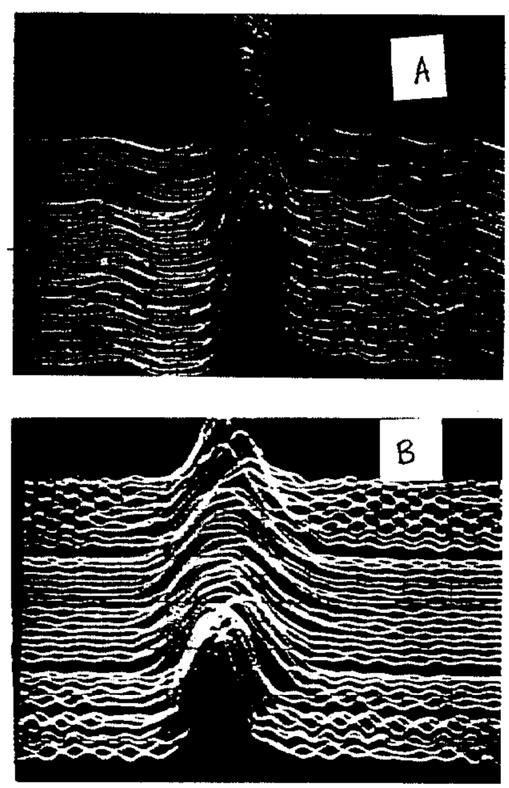

Fig. 1 Comparison of mountain range pictures for NTPJ(A) and FFTC(B) schemes. The third harmonic rf cavity was on for 13ms.

Studies in the MR showed that one of the causes for large beam emittance growth after the transition was the rf-bucket mis-match. For $(\epsilon_l)_{Init} \simeq 0.08$ eVs an rf curve with constant bucket area in the range of 0.35 eVs to 0.45 eVs (which has S_A about a factor of two smaller than previously used) gives a better bucket match. With this type of rf curve (RF-curve III in Table I) we found only about 40% emittance growth which is better than the NTPJ scheme.

III. Summary and Future Plans

A third harmonic rf system has been added to the fundamental 53 MHz rf system of the MR at Fermilab to reduce beam loss and emittance growth arising due to transition crossing. No beam-loss conditions have been reached. By properly selecting an rf accelerating voltage curve the emittance growth was reduced.

Detailed ESME simulations are being carried out for higher beam intensities in the MR. Preliminary results show that an rf waveform with a tilt obtained by increasing or decreasing the phase difference between the 53 MHz and 159 MHz rf can be used to ameliorate bunch shape distortion arising from space charge and image current forces. This would require only a small modification in our LLRF system.

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