# Appendix D. Intensity Upgrade of the Main Injector

W. Chou, J. Griffin, I. Kourbanis

## D.1. Main Injector Modes of Operation

The Main Injector needs to provide beam for Collider operations, neutrino experiments (NuMI) and slow spill to the 120 GeV switchyard. In Stage 1, the Proton Driver will provide a total of $3 \times 10^{13}$ p/cycle in 119 rf buckets at 53 MHz. The MI is filled with 4 Proton Driver batches (588/126 = 4.66) resulting in a total intensity of $12 \times 10^{13}$. The first 84 bunches with a total intensity $2.1 \times 10^{13}$ will be used for stacking, resulting in a 4.2x intensity increase. The rest of the 360 bunches can be used for NuMI, or for NuMI and the 120 GeV switchyard. The total beam intensity available for NuMI will then vary from $6.5 \times 10^{13}$ (NuMI + KAMI + Meson slow spill) to $10 \times 10^{13}$ (NuMI + stacking).

For collider operations we need to produce 99 proton bunches with $2.7 \times 10^{11}$ p/bunch and transverse emittance of $20\pi$ mm-mrad spaced 132 ns apart (7 buckets at 53 MHz). Due to the smaller transverse emittance required, the total Proton Driver intensity will be around $1 \times 10^{13}$ p/cycle or $8.5 \times 10^{10}$ p/bunch. Three bunches at a time will be injected from the Proton Driver to the MI for a total of 4 - 9 batches at the required 132 ns spacing. Then the batches will be accelerated to 150 GeV and coalesced before they are injected into the Tevatron. Since the antiprotons required for the collider come from the Accumulator and Recycler Rings at a fixed 8 GeV energy, protons in the MI will have to be decelerated from 12 to 8 GeV for tuning the antiproton transfer lines.

In Stage 2 the Proton Driver will provide $3 \times 10^{13}$ p/cycle in 18 rf buckets at 7.5 MHz. In this case we plan to fill the MI with four Proton Driver batches resulting in 72 bunches at 53 MHz with $1.7 \times 10^{12}$ p/bunch. Out of the 72 bunches 12 will be used for stacking and 60 for NuMI and switchyard. The total intensity available for each user will be the same as in Stage 1.

The bunch intensity in Stage 2 will be too high for collider operations while the bunch spacing is ideal (we assume 99 on 99 with 132 ns spacing). The Proton Driver intensity will have to be reduced by a factor of 6. Then 9 of the 18 Proton Driver bunches will be injected into the MI and accelerated to 150 GeV. In this case no coalescing will be required.

## D.2. Crossing Transition in the MI with High Intensity Bunches

### D.2.1. ESME Simulations

In all the MI operation scenarios outlined above, bunches with intensities 4 - 28 times larger than the MI design intensities are accelerated through transition. For this reason we performed a series of ESME [1] simulations of MI transition crossing. Below we outline the general parameters of the ESME simulations:

1. We considered parabolic bunches with 20,000 macroparticles.
2. Each 53 MHz bucket was divided into 64 bins.
3. Only space charge was considered.
4. We considered a magnetic field ramp closely representing the current MI PS ramps.
5. Transition was crossed with a *dp/dt* of 150 GeV/sec.
6. The effect of a $\gamma_t$ jump was simulated. The $\gamma_t$ jump considered was a first order bipolar jump that maintained a clearance of

$$|\gamma - \gamma_t| \geq 0.8 \cong 2\,(d\gamma/dt)\,T_{nonlinear} \qquad \text{(D.1)}$$

   except for 0.5 ms. Transition is crossed at $d(\gamma - \gamma_t)/dt = 4000\ s^{-1}$, twenty times faster than without a jump. A plot of the $\gamma_t$ jump is shown in Figure D.1.

7. The effect of an inductive insert [2] was simulated. The insert considered was a pure inductor with $|Z/n| = 2.6\ \Omega$ up to 1.06 GHz. The value of the inductance was chosen so that the space charge force is cancelled at transition. A plot of the inductor impedance vs. frequency is shown in Figure D.2.

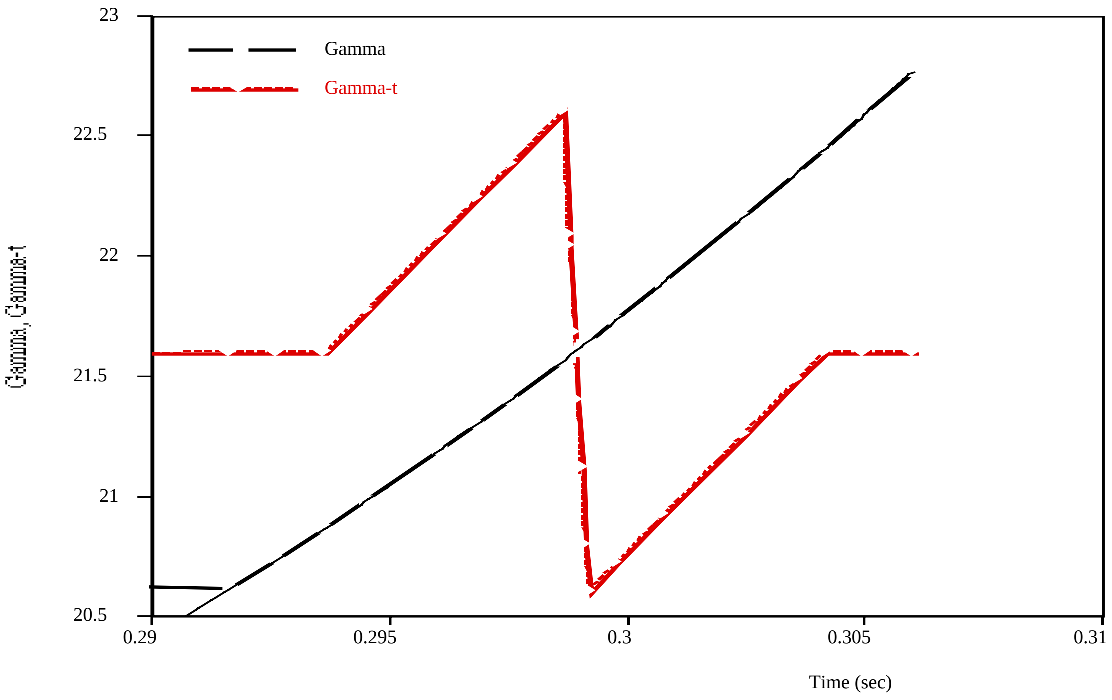

**Figure D.1.** Main Injector $\gamma_t$ jump used in the ESME simulations

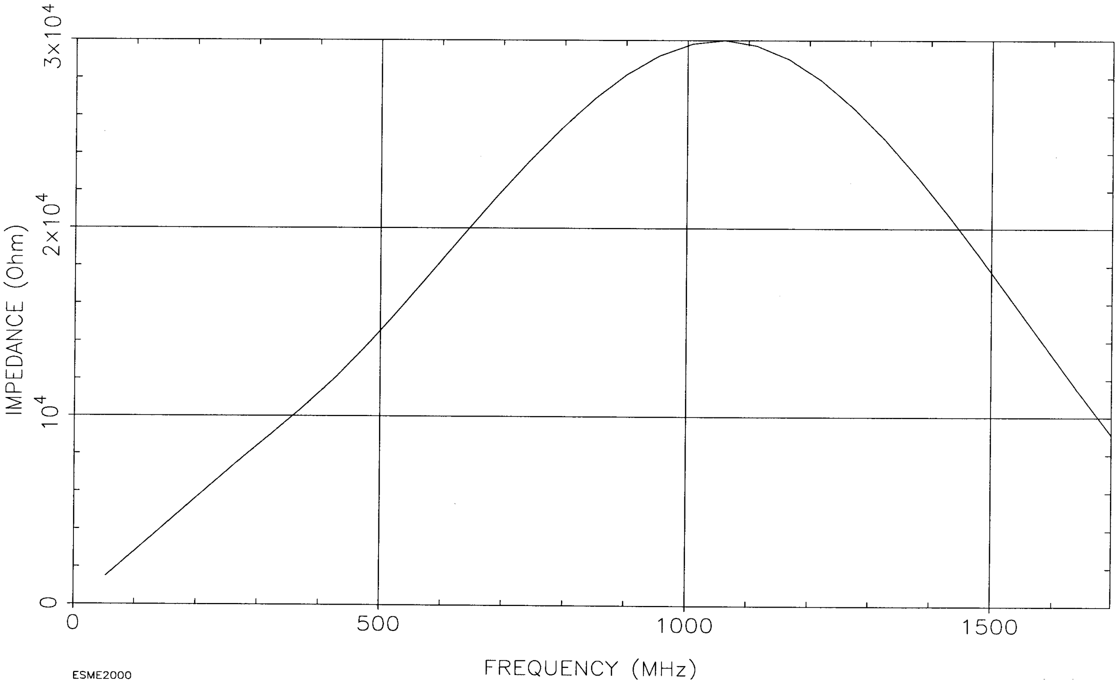

**Figure D.2.** Impedance vs. frequency for the inductor used in the ESME simulations

### D.2.2. Simulation results for Stage 1

In this case a single parabolic bunch with longitudinal emittance of 0.2 eV-s (95%) and charge of $2.5 \times 10^{11}$ p was accelerated through transition in the MI. Only normal transition crossing and crossing transition with a $\gamma_t$ jump were studied. No particle loss was observed in either case, but the longitudinal emittance blowup was reduced from 300% to 5% with use of the $\gamma_t$ jump.

### D.2.3. Simulation results for Stage 2

In this case we used as input the actual bunch distribution from the ESME simulations of the Proton Driver. The bunch longitudinal emittance was 0.4 eV-s and the charge $1.7 \times 10^{12}$ ppb. Normal transition crossing, transition crossing with a $\gamma_t$ jump and transition crossing with an inductive insert were studied. The simulation results are outlined below.

1. With normal transition crossing beam breakup and 20% beam loss was observed (Figure D.3).
2. In the case of transition crossing with a $\gamma_t$ jump there was no particle loss but an emittance blowup of 70% was observed (Figure D.4).
3. In the case of transition crossing with an inductive insert, 1% particle loss was observed (Figure D.5).
4. In the case where both the $\gamma_t$ jump and the inductive insert were used during transition crossing, only 12% emittance blowup was observed (Figure D.6).

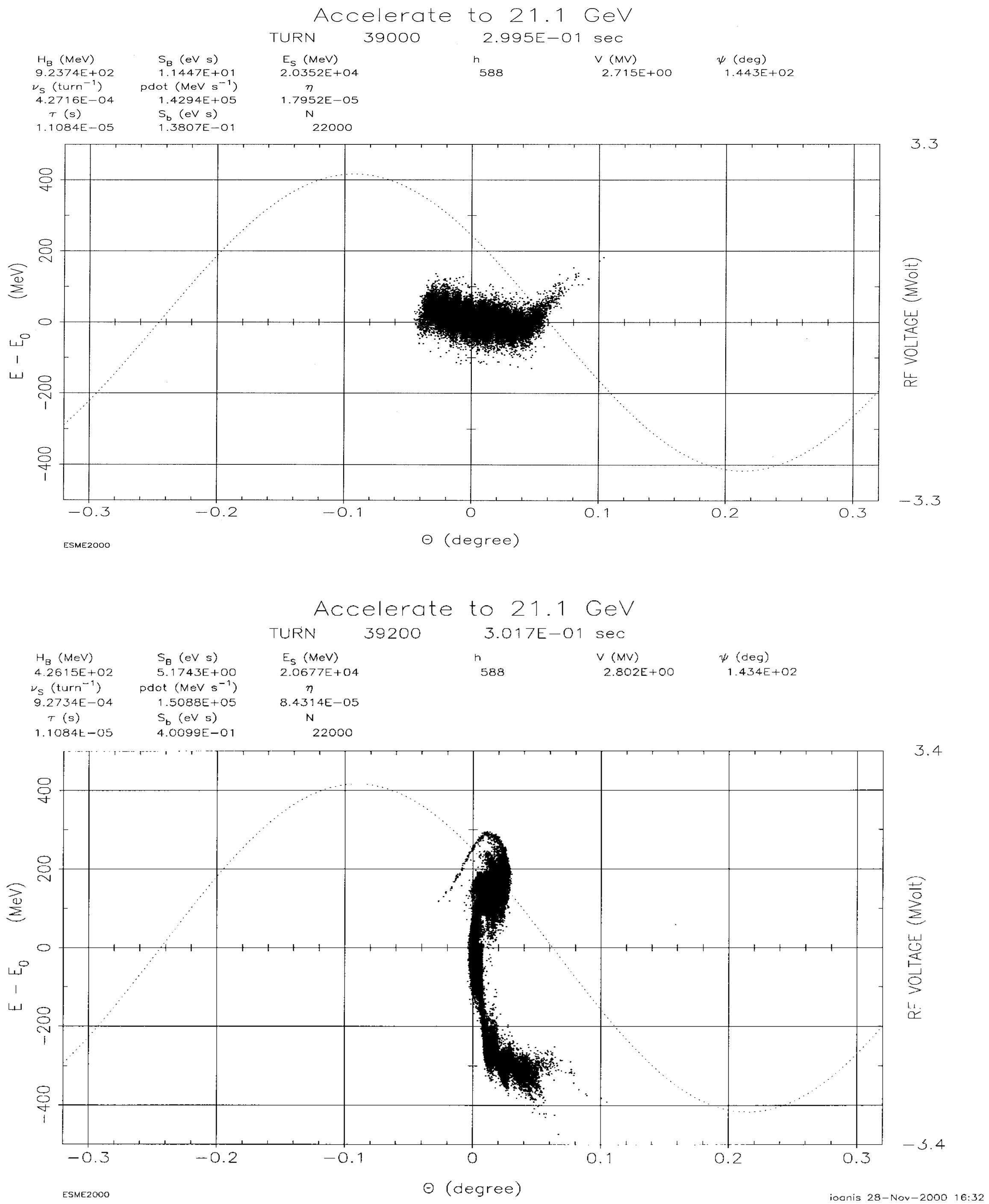

**Figure D.3.** Beam distributions at transition and 200 Turns after transition for normal transition crossing

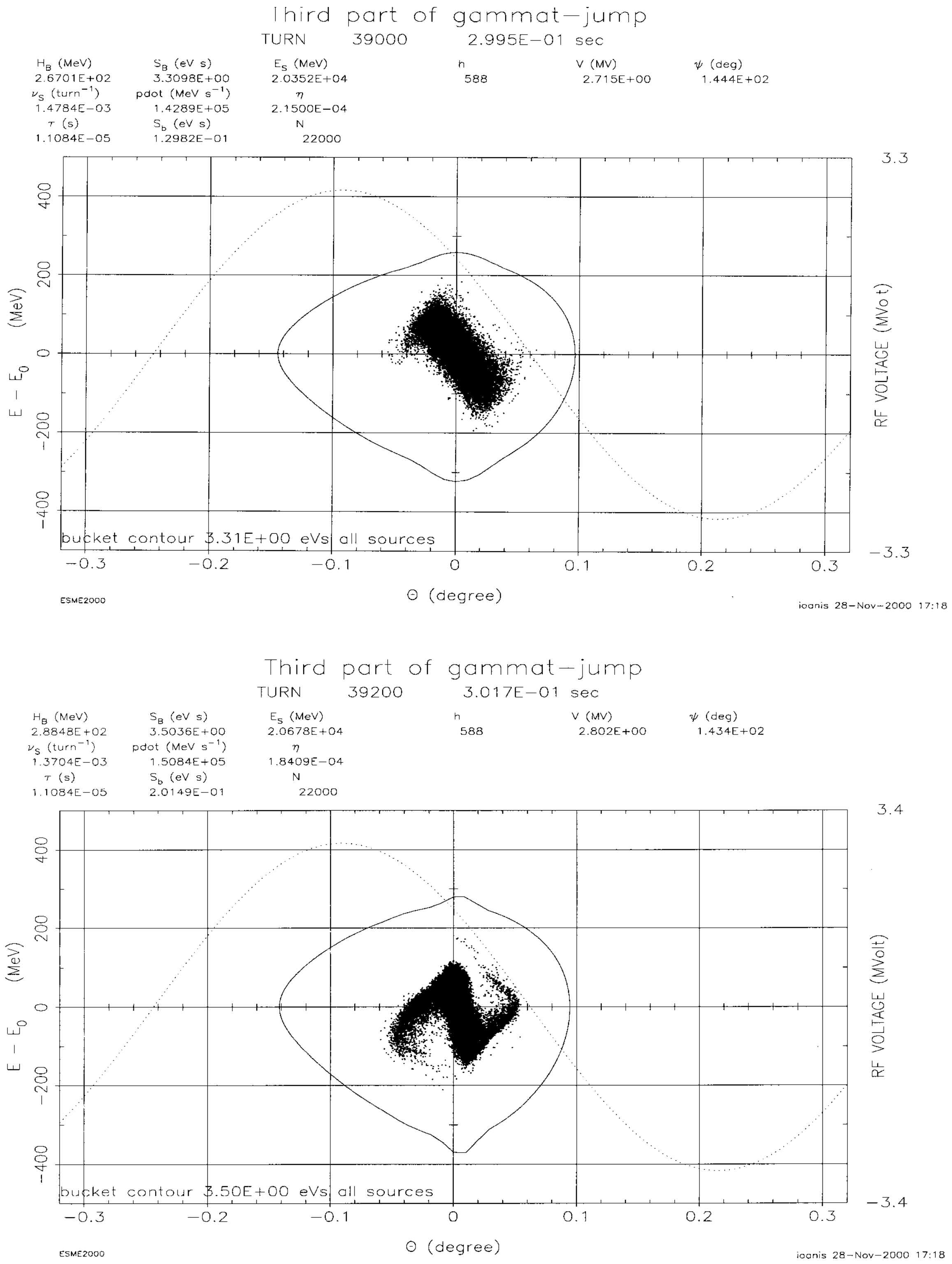

**Figure D.4.** Beam distributions at transition and 200 Turns after transition in the case of transition crossing with a $\gamma_t$ jump

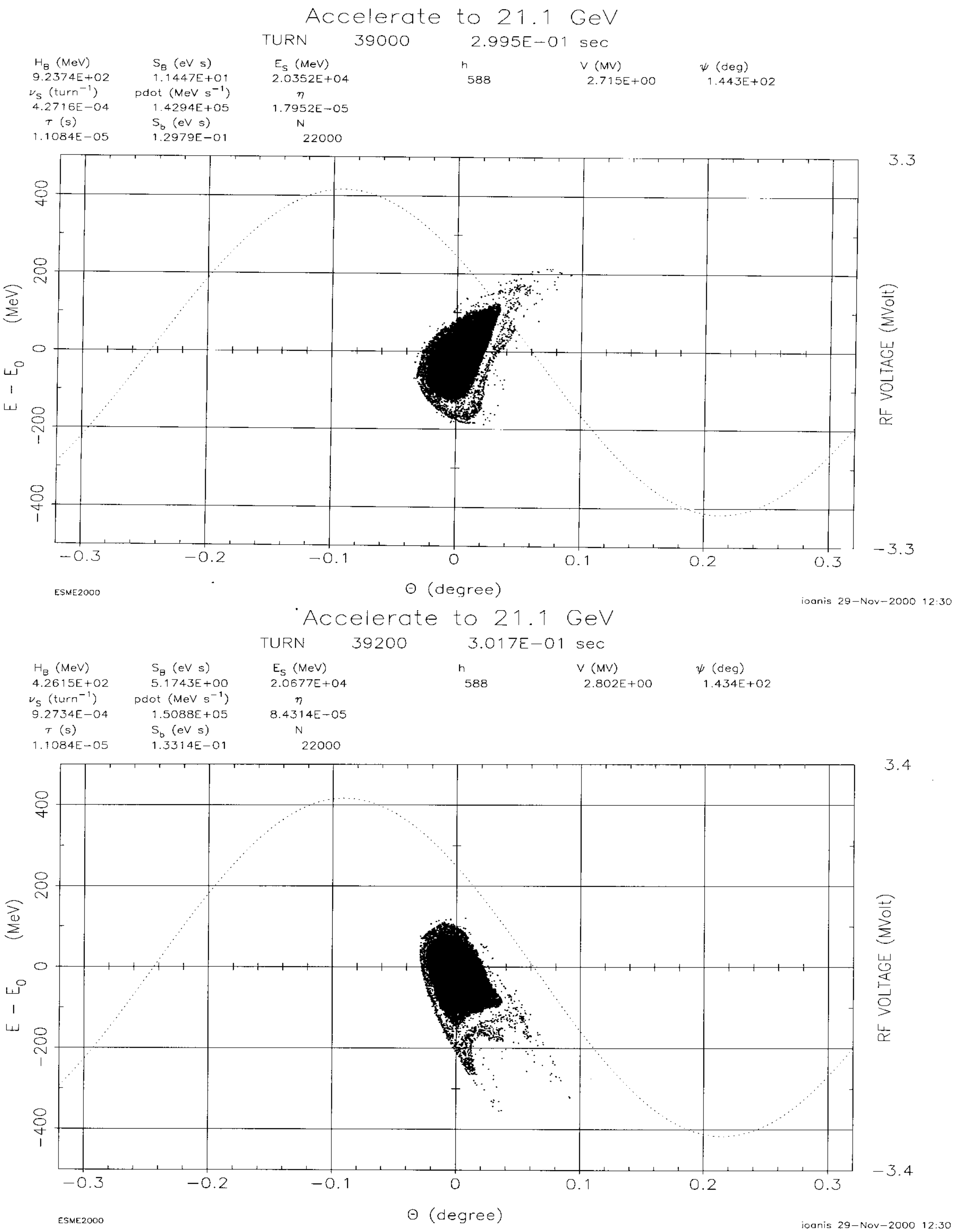

**Figure D.5.** Beam distributions at transition and 200 Turns after transition in the case of transition crossing with an inductive insert

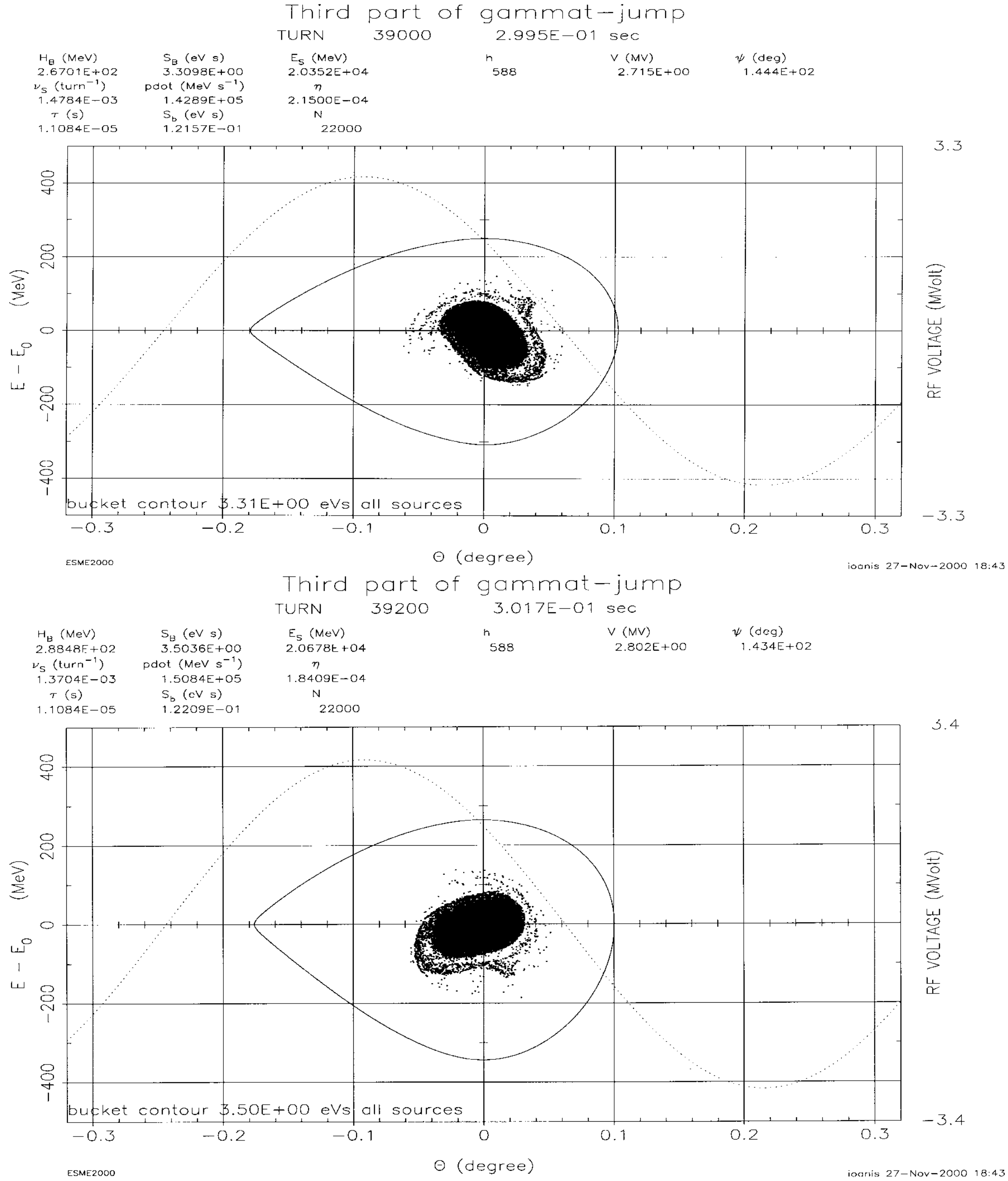

**Figure D.6.** Beam distribution at transition and 200 Turns after transition in the case of transition crossing with both a $\gamma_t$ jump and an inductive insert

## D.3. Necessary Upgrades in the Main Injector

### D.3.1. RF Voltage and Power Requirements

For MI acceleration at 240 GeV/s (current maximum *dp/dt*) the required accelerating voltage V × sin($\phi_s$) is:

$$V\sin\phi_s = F_\infty^{-1}\frac{d(pc)}{dt} = \frac{240\times10^9}{90.314\times10^3}\frac{GeV/s}{s^{-1}} = 2.66\times10^6 Volts \qquad \text{(D.2)}$$

The rf power required by the beam is:

$$P = eV\sin\phi_s\frac{\beta c}{2\pi R} = 3.84\times10^{-8} W/proton \qquad \text{(D.3)}$$

The total rf power required to accelerate the maximum intensity of 12 $\times10^{13}$ protons in the MI is then 4.61 MW. The total rf power available is 3.6 MW. If however, we reduce the maximum acceleration to 180 GeV/s the existing rf power is enough to accelerate the full intensity. In all the transition crossing simulations that follow, a maximum acceleration rate of 180 GeV/s has been assumed.

Since the MI cavities can develop 4.3 MV per turn, $\Gamma$ = sin($\phi_s$) = 0.62 and the corresponding moving bucket factor $\alpha(\Gamma)$ = 0.231. At $\gamma = \sqrt{3}\ \gamma_t$, where bucket area is minimum with constant ramp rate, the corresponding bucket area is 1.87 eV-s.

### D.3.2. $\gamma_t$ -jump System

As was shown from the MI transition crossing simulations, a $\gamma_t$-jump is required for higher intensity bunches. A conceptual design of a first order $\gamma_t$-jump system has been published [3]. The system consists of 8 sets (triplets) of pulsed quadrupoles that provide a jump of $\Delta\gamma_t$ from –1 to +1 within 0.5 ms. Each triplet has two quadrupoles in the arc and one of twice integrated strength in the straight section, with a phase advance of $\pi$ between each quad. This design was chosen to keep the perturbation to the original lattice localized.

In order to find space to install the eight triplets, four (out of a total of 54) horizontal sextupoles and four (out of a total of 62) octupoles will have to be removed.

### D.3.3. Inductive Insert

An inductive insert has been shown to reduce the effect of space charge at transition and prevent beam breakup and instabilities. The inductive insert used in the simulations was a perfect inductor (no real part) so more simulations are needed using a realistic inductor.

Since the inductive insert is going to be used to compensate the space charge around transition, a microwave ferrite needs to be used. It is estimated that about 1 - 2 meters of ferrite will be needed.

### D.3.4. Dynamic and physical aperture

The normalized transverse emittance of the beam out of the Proton Driver is going to be 60π. Since the MI acceptance is 40π at 8 GeV there is no problem in accepting the larger beam at 12 or 16 GeV.

However, there are certain areas in the MI where the physical aperture is noticeably small, in particular, in the MI-52 region. It is conceivable that this area would be a radiation hot spot due to large particle losses. Possible solutions include the use of large quadrupoles, local shielding and careful beam shielding.

### D.3.5. Beam acceptance of MI Beamlines

Both NUMI and Switchyard lines have enough vertical aperture to accommodate the larger emittance beam from the Proton Driver. However there are expected to be horizontal aperture limitations for emittances larger that 40π. In the case of NuMI some (up to six) small aperture dipoles will need to be replaced.

### D.3.6. Passive and active dampers for beam instabilities

The impedance budget and the thresholds for microwave and mode coupling instability in the MI have been calculated [4,5]. It is expected that in Stage 2, where the bunch intensity will be increased by a factor of 28 compared to the MI design intensity, we will exceed the microwave and mode coupling instability thresholds at 120 and 150 GeV. A possible solution will be a controlled blowup of the longitudinal emittance after transition.

Since the total intensity in the MI will increase by a factor of 4, coupled bunch instabilities driven by the higher order modes of the rf cavities will become an issue. In particular the two narrow-band passive dampers for the modes at 128 and 225 MHz may have to be supplemented by active dampers.

### D.3.7. Stopband correction

In Stage 1 the total intensity in the MI will be increased by a factor of four while the injection energy will increase from 8 to 12 GeV and the transverse normalized emittance from 40π to 60π. Because of this the space charge Laslett tune shift will remain the same.

In Stage 2 the average current remains the same while the peak current is increased by a factor of seven. In this case the Laslett tune shift can become as large as –0.4 and some sort of stopband correction will be required.

# References

[1] J. MacLachlan and J.F. Ostiguy, "User's Guide to ESME 2000."

[2] A.M. Sessler and V.G. Vaccaro, CERN Report CERN 68-1, 1968.

[3] W. Chou et al., "Design of a $\gamma_t$-Jump System for Fermilab Main Injector," Proc. of the 1997 PAC, p.994 (1997).

[4] M.A. Martens and K.Y. Ng, "Impedance and Instability Threshold Estimates in the Main Injector," FERMILAB –TM-1880, March 1994.

[5] W. Chou, "Intensity Limitations in Fermilab Main Injector," Proc. of the 1997 PAC p. 991 (1997).