Fermi National Accelerator Laboratory

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**Simulation of Bunches Coalescing in the Main Ring,
in the Presence of a High-Frequency, Wide-Band Resonator**

R. Garoby

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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IN THE PRESENCE OF A HIGH-FREQUENCY, WIDE-BAND RESONATOR

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INTRODUCTION

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Applying the "Keil-Schnell-Boussard" criteria (see Appendix A) for microwave instability inside that bunch gives:

$$|Z/n| \leq 5.6 \Omega \text{ for } N_b = 10^{10} \text{ ppb} .$$

It is very likely that local instabilities develop inside the bunch during the manipulation. The computer program ESME was run under these conditions to give an approximate picture of the bunch distortions. Outputs are presented here.

Since microwave signals had been observed during the second part of coalescing (bunch rotation), some simulations have been done at that part. No catastrophic degradation showed up with the model used, as the computer outputs indicate.

THE MODEL

The high frequency impedance seen by the beam was simulated by a $Q=1$ resonator at 2000 MHz. Two "reasonable" impedance values were tested.

Z (@ 2000 MHz) = 800 k Ω	equivalent to $ Z/n = 19 \Omega$ and
Z (@ 2000 MHz) = 600 k Ω	equivalent to $ Z/n = 9.5 \Omega$.

Care was taken that the program was giving meaningful results. That was checked by comparing the voltage due to the resonator, along the bunch, as computed by ESME, with the one given by approximate formulas (@ CERN 77-10, p. 95). Unfortunately such a formula can only be used when the bunch shape is smooth, so only the initial state has been analyzed. A satisfying set of parameters is: 10,000 macroparticles into 32 FFT bins, for debunching analysis. CPU time is already greater than four hours in the FPS 164 in these conditions.

For bunch rotation analysis, the number of FFT bins was brought up to 256. It was necessary, since bunch length varies drastically. Ten thousand (10,000) macro-particles were also used. Reliability of the results is probably less good than for debunching. But since little bunch distortions are detected up to $N_b = 2 \times 10^{11}$ ppb (2x design value), one can safely consider that an upper limit of the bunch degradation is obtained.

DEBUNCHING SIMULATIONS RESULTS

Figures 1.1, 1.2, and 1.3 show the voltage program used, together with bucket height and ν_s . The table below indicates the parameters used in the simulation together with the relevant output pictures.

$ Z/n $	0.1 Ω	9.5 Ω	19 Ω	19 Ω	19 Ω
N_b		8×10^{10} ppb	5×10^9	10^{10}	2×10^{10}
Figures	2.1 to 2.8	3.1 to 3.8	4	5	6.1 to 6.8

Figure 4 shows the present operational situation (at least if one guesses $|Z/n| = 19 \Omega$!).

The result is already different from the zero intensity one (Fig. 2.6). Bunch distortion is not excessive, but energy spread is obviously greater by 2 or 3 MeV. This could explain the need to go to a higher voltage during bunch rotation (33 kV @ $h = 53$ raised to 44 kV) since bunch rotation basically exchanges energy spread for bunch length.

The situation at $N_b = 10^{10}$ ppb with $|Z/n| = 19 \Omega$ is very bad (Fig. 5), and at $N_b = 2 \times 10^{10}$ ppb (Fig. 6.6) it is hard to describe.

If one guesses $|Z/n| = 9.5 \Omega$, the result (Fig. 3.6) is comparable to $|Z/n| = 1 \Omega$ (Fig. 5) but at two times the intensity.

BUNCH ROTATION RESULTS

Because of program capabilities the simulation was run on a single-bunch with $\epsilon_L = 2$ eV-sec, initially matched to a 200 V $h = 53$ bucket. That was supposed to be an approximation of the chain of 10 adjacent bunches. RF parameters during rotation are the ones previously used by D. Wildman:

$$\hat{V}(h = 53) = 44 \text{ kV}$$

$$\hat{V}(h = 106) = 7.5 \text{ kV.}$$

The low intensity limit is described in Figs. 7.1, 7.2, and 7.3.

Computations have been done for $|Z/n| = 19 \Omega$ and $N_b = 2 \times 10^{11}$ ppb (2x design value). Outputs are shown in Fig. 8.1, 8.2, and 8.3.

The following table summarizes the comparison of some relevant numbers in both cases.

	$N_b = 0$ ppb	$N_b = 2 \times 10^{11}$ ppb
Optimum rotation time	3651 turns	3708 turns
RMS spread in azimuth	7.98×10^{-4} rad	9.64×10^{-4} rad
RMS energy spread	39.7 MeV	34.3 MeV

So the minimum length is observed later (57 turns or more than 1 nsec) and bunch length is increased by $\approx 20\%$. Computation at $N_b = 10^{11}$ ppb indicate only an increase of $\approx 6\%$. No noticeable bunch distortions show up.

This part of the process is much less sensitive to the microwave wide-band resonator than the first one.

CONCLUSIONS

With due regard to the crude models used for the computations, one can nevertheless estimate that:

1. The first part of the coalescing process is very sensitive to the machine impedance. Great difficulties are likely to appear when going to the design intensity, or slightly higher.
2. The bunch rotation is much more tolerant, but some decrease in performance can be suspected, with a threshold around the design intensity ($N_b = 10^{11}$ ppb).

The obvious recommendations that one can make from that basis are:

1. Measure machine impedance and try to reduce it.
2. Modify the first part of the coalescing process to make it less impedance sensitive. One possibility for that is to go to a more adiabatic bunch lengthening technique, which will provide a stretched bunch in a much shorter amount of time.

APPENDIX A

CALCULATION OF THE THRESHOLD FOR MICROWAVE INSTABILITY

Formula:

$$\left| \frac{Z}{n} \right| \leq F \left(\frac{E_o}{e} \right) \left(\frac{n}{\gamma} \right) \left(\frac{[\Delta\beta\gamma]_{1/2 \text{ height}}}{\hat{I}} \right)^2$$

(CERN 77-13, p. 178)

$$F = 0.65$$

$$\frac{E_o}{e} = 938.856 \text{ MeV}$$

$$\gamma = 160 \quad (E_{\text{total}} = 150 \text{ GeV})$$

$$|\eta| = 2.81 \times 10^{-3}$$

If one debunches completely a bunch of emittances ϵ_b , the approximate relation between bunch length ℓ_b (1 rf wavelength) and bunch half-energy spread ΔE_b is:

$$\pi \times \hat{\Delta E}_b \times \frac{\ell_b}{2} = \epsilon .$$

Application

$$\epsilon_b = 0.16 \text{ eVs} \quad \ell_b = 18.8 \text{ ns} \Rightarrow \Delta E_b = 5.42 \text{ MeV}.$$

Assuming a parabolic distribution in the center of the bunch, the full energy spread at half-height is

$$(\Delta E)_{1/2 \text{ height}} = \left(\frac{1}{\sqrt{2}} \right) \times 2 \times \hat{\Delta E}_b = 7.66 \text{ MeV}$$

$$\text{so} \quad (\Delta\beta\gamma)_{1/2 \text{ height}} \approx (\Delta\gamma)_{1/2 \text{ height}} = \frac{(\Delta E)_{1/2 \text{ height}}}{E_o} = 8.17 \times 10^{-3}$$

The mean beam current along the bunch length is:

$$I_o = \frac{Nec}{\ell_b}$$

and the instantaneous current in the center of the bunch is:

$$\hat{I} = \frac{3}{2} I_o$$

Application: $N = 10^{10}$ ppb (CERN Design Report Tevatron 1)

$$\text{So } \hat{I} = 0.128 \text{ A}.$$

Consequently $\left| \frac{Z}{n} \right| \leq 5.6 \Omega$

Editor's Note

This document has been created from a private note written by R. Garoby during his visit to Fermilab. Therefore, the author is not responsible for any errors or omissions since he never intended such a wide audience for this piece of research.

Figure 1.1:

1.1

1.2.

1.2

$$\frac{Z}{n} = 0.2$$

DEBUNCHING INSIDE MAIN RING

TURN # 6000

HBCKT 7.6191+000 [MEV], SBCKT 1.8229-001 [EV-S], ES 1.5894+005 [MEV], MUS 7.9117-005
 DPDT 1.10710-014 [MEV/C/S], PHIS 3.1416+000 [RAD], EVI 1.8947-003 [MeV], EV2 0.0000+000 [MeV]
 IH1= 1113 IH2= 1 PSI1= -7.3464-006 [RAD], PSI2= -6.6005-009 [RAD], ETA= 2.8149-003

2.4

SENCH 1.600-001 [EV-S]

SWITCHES: TTTTTTTTTTTTTTTTTTTTTT

THETA -- RF PHASES 1113. * THETA + -.000 & 1. * THETA + -.000 (*10³)

TURN # 8000

```

HBECKT 6.4121+000 [MEV], SECKT 1.5341-001 [EV-S], ES 1.5094+005 [MEV], MUS 6.6583-005
DFDT 7.84117-015 [MEV/C/S], PHIS 3.1416+000 [RAD], EV1 1.3419-003 [MeV], EV2 0.0000-000 [MeV]
IH1= 1113 IH2= 1 PSI1= -7.3464-006 [RAD], PSI2= -6.6005-009 [RAD], ETA= 2.8149-003

```

TURN # 10000

```

HCKT 5.5352+000 [MEV], SECKT 1.3243-001 [EV-S], ES 1.5094+005 [MEV], MUS 5.7478-005
DPDT 5.84310-015 [MEV/C/S], PHIS 3.1416+000 [RAD], EV1 1.0000-003 [MeV], EV2 0.0000+000 [MeV]
IM1= 1113 IM2= 1 PSI1=-7.3464-006 [RAD], PSI2=-6.6085-009 [RAD], ETA= 2.8149-003

```

Wide band resonator $\left\{ \begin{array}{l} f_R = 2000 \text{ MHz} \\ Z(2f_R) = 400 \text{ k}\Omega \end{array} \right.$

$$\Rightarrow \frac{Z}{n} = 9.5 \Omega$$

$$N_f = 0.10^{40} \text{ ypb.}$$

DEBLANCHING INSIDE MAIN RING

TURN # 2020

BECKT 1.0229+001 (REV), ES 1.5094+005 (REV), NUS 1.1693+004
 PS11 3.1416+000 (RAD), PS12 2.8226+003 (RAD), ETV= 2.8149+003

3.2

SINCH 1.400-001 (REV-01)

SWITCHES: TTTTTTTTTTTTTTTTTT

THETA 1113. * THETA + 3.142 * 1. * THETA + 0.000 (1102)

DEBLANCHING INSIDE MAIN RING

TURN # 4228

ADCT 5.3579-000 (MEV), SECKT 2.2456-001 (EV-5), ES 1.5994+005 (MEV), NUS 5.7463-005
 PRCT 1.3503-014 (MEV/0 5), PHIS 3.1416-000 (RAD), EV1 2.8751-003 (MEV), EV2 2.8000-000 (MEV)
 PHIS 1117 (MC) 1 PHIS 3.1416-000 (RAD), PS12 2.8000-003 (RAD), ETA 2.8149-003

DEBLUNCHING INSIDE MAIN RING

TURN # 6200

PCDNT 7.5191-000 [MEV], SECKT 1.8229-001 [EV-S], ES 1.5894+005 [MEV], NUS 7.9117-005
 IPDT 1.18710-014 [MEV/SC], PHIS 3.1416+000 [RAD], EV1 1.9947-003 [MEV], EV2 2.0000-000 [MEV]
 PHI= 1113 PHD= 1 PS11= 3.1416+000 [RAD], PS12= 2.8226-003 [RAD], ETA= 2.8149-003

FEEDBACKING INSIDE MAIN RING

TURN = 10000

BECKT 5.5050+000 (MEV), BECKT 1.3243-001 (EV-5), ES 1.5094+005 (MEV), NUS 5.7473-025
 EPT 5.84319-215 (MEV/0/5), PHIS 3.1416+000 (RAD), E/1 1.0221-207 (MEV), E/2 3.0032-000 (MEV)
 IN1= 1113 IN2= 1 PSI1= 3.1416+000 (RAD), PSI2= 2.8226-003 (RAD), ETA= 2.8149-003

Wide band Resonator $\begin{cases} f_R = 2500 \text{ MHz} \\ Z(\omega f_R) = 800 \text{ k}\Omega \end{cases}$

$$\Rightarrow \frac{Z}{\mu} = 19 \Omega.$$

$$N_f = 5 \cdot 10^9 \text{ yb.}$$

$$\Rightarrow \frac{|Z|}{n} \approx 19\%$$

$$N_p = 10^{10} \text{ gpb.}$$

Wide band resonator

$$\begin{cases} f_{Rs} = 2000 \text{ MHz} \\ Z(\omega f_{Rs}) = 800 \text{ k}\Omega \end{cases}$$

$$\Rightarrow \frac{Z}{n} = 19.1 \Omega$$

$$N_p = 2.10^{10} \text{ pps}$$

REF ID: A692

-B07 1.2120-001 [NEW], B08T 2.2235-001 [EW-9], ES 1.5894-005 [NEW], NUS 1.2695-004
 C11 2.1-725-014 [NEW/BI], PAIS 3.1416-000 [RAD], EV1 1.8735-003 [NEW], EV2 2.0020-002 [NEW]
 EV3= 1013 EV4= 1 PS11= 3.1416-000 [RAD], PS10= 2.8005-003 [RAD], ETA= 2.3149-003

6.2

00-0- 1,500-001 REV-00

NOTES: ~~XXXXXXXXXXXX~~

[illegible]

DEBLANCHING INSIDE MAIN RING

TURN # 4000

SECT 9.7553-200 (MEV), SECT 2.2456-001 (EV-91), ES 1.5894+005 (MEV), NUS 9.7463-005
 SECT 1.5894-014 (MEV/ES), PHIS 3.1416-000 (RAD), EV1 2.5753-003 (MEV), EV2 2.6302-102 (MEV)
 PSI= 1113 (H) 1 PSI1= 3.1416-000 (RAD), PSI2= 2.9216-003 (RAD), ETA= 2.8149-003

REBUNCHING INSIDE MAIN RING

TURN # 10000

HEAD 5.5352-000 [MEV], SECT 1.3243-001 [EV-S], ES 1.5094+005 [MEV], M03 5.7479-005
 IP17 5.84319-015 [MEV/3], PH15 3.1415-000 [RAD], EV1 1.0000-000 [MEV], EV2 0.0000-000 [MEV]
 IP1= 1.113 IP2= 1 PSI1= 3.1416+000 [RAD], PSI2= 2.8226-003 [RAD], ETH= 2.0149-003

Bunch rotation
 $|Z/n| = 0.2$

Bunch rotation.

$$\left| \frac{Z}{n} \right| = 192$$

$$N_b = 2 \cdot 10^{12} \text{ p/b.}$$

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