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PS/RF Note 2002-198

GHOST BUNCHES AND BLOW-UP LOSSES WITH HIGH-INTENSITY BEAMS

S. Hancock and E. Métral

Abstract

High-intensity beams are blown up longitudinally in both the PS Booster and PS machines for two reasons. The first is to reduce the large incoherent space-charge tune shift at PS injection and the second is to provide enough longitudinal emittance to prevent a fast single-bunch vertical instability from developing near transition. However, depending on how the additional blow-up is made in the PS, empty buckets can become populated by ghost bunches and these can perturb the neutron Time-of-Flight facility. The simplest way to avoid this is to adjust the ejection kicker length to extract only the desired bunch, but this means that the ghost bunches are then lost in the PS machine. The number of ghost particles can easily amount to ~5×10^{11} protons per cycle, with much of this lost near transition. Of course, the cleanest solution is not to create these ghosts in the first place. The purpose of this note is to report the results of a detailed study made on the influence of the blow-up parameters on the particle distribution and how this affects the above two mechanisms.

Geneva, Switzerland
November 2002

1 INTRODUCTION

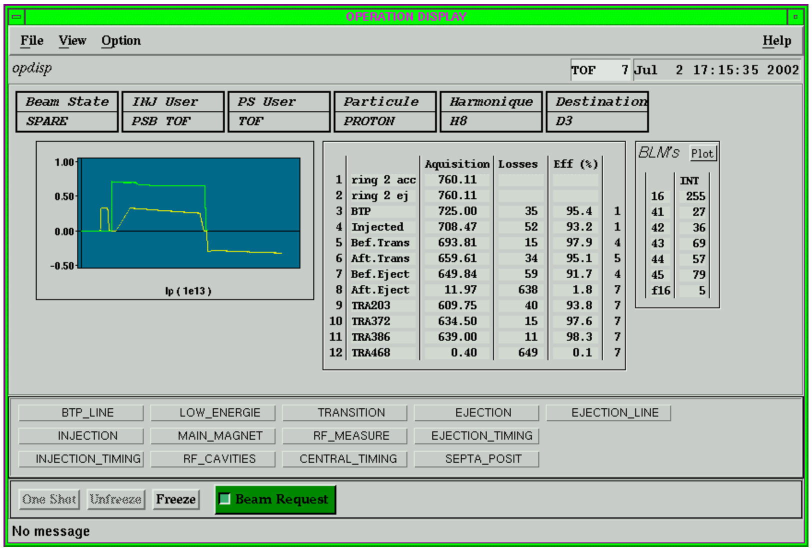
High-intensity beams are blown up longitudinally in both the PS Booster (PSB) and PS machines. One reason is to reduce the large incoherent space-charge tune shift that can convey the beam onto resonances and cause transverse emittance blow-up. For a reason which was not (until a few months ago) completely understood, the horizontal tune at PS injection has had to be reduced below the bare machine value of ~6.25 as the bunch intensity increases above $\sim 3\times 10^{12}$ protons per bunch (ppb). A possible explanation was thought to be provided by the Montague fourth-order coupling resonance $2Q_x - 2Q_y = 0$ excited by the space-charge potential [1,2], which shares emittance between the two transverse planes. However, since these measurements were made, a single-bunch beam of $\sim 6.5\times 10^{12}$ protons has been injected into the PS with transverse tunes of $Q_x \approx 6.20$ and $Q_y \approx 6.27$. Therefore, the Montague stopband is not responsible for the fast (during the first ms) losses observed in the past. The main explanation has to do with the trajectory at injection, which still has to be studied in detail. In the case of the single-bunch beam of $\sim 7\times 10^{12}$ protons for the neutron Time-of-Flight (nToF) facility, the horizontal tune had been decreased to ~6.1. Consequently, a controlled longitudinal blow-up is made to prevent too much transverse blow-up due to crossing the integer resonance $Q_x = 6.0$. Cf., the transverse blow-up observed last year on the AD beam has been largely eradicated with a clean longitudinal blow-up in the PSB. This is in agreement with the calculated horizontal space-charge tune shift which implies that the integer resonance is no longer crossed.

A second reason for needing large longitudinal emittance at high intensity in the PS is to avoid a vertical coherent single-bunch instability of high frequency, which has been observed near transition. The beam can be stabilized by controlled longitudinal blow-up [3,4]. For the nTOF case of $\sim 7\times 10^{12}$ ppp, a longitudinal emittance of >2.1 eVs is required. However, that of the bunch arriving from the PSB is only ~1.5 eVs and, depending on how the additional blow-up is made in the PS, empty buckets can become populated by ghost particles. This perturbs nToF. The simplest way to avoid this is to adjust the ejection kicker length to extract only the desired bunch, but this means that the ghost bunches are then lost in the PS machine. The number of ghost particles can easily amount to $\sim 5\times 10^{11}$ protons per cycle, with much of this lost near transition. Of course, the cleanest solution is not to create these ghosts in the first place.

A detailed study has been undertaken on this subject during several machine development sessions between 27 June and 8 July 2002. The purpose of this note is to report the influence of the blow-up parameters on the distribution of particles in longitudinal phasespace and how this affects both how many leak out of a single bunch and the fast losses near transition.

2 OBSERVATION AND CURE OF GHOST BUNCHES

The initial conditions of this study are those of the operational nToF beam as shown in Figs. 1 to 3. A lone bunch of $\sim 7\times 10^{12}$ ppb is transferred from the PSB with a longitudinal emittance of ~1.5 eVs. Just after the start of acceleration in the PS it is 2.2 eVs and the beam is stable at transition. However, ghost bunches are observed.



opdisp

TOF 7 Jul 2 17:15:35 2002

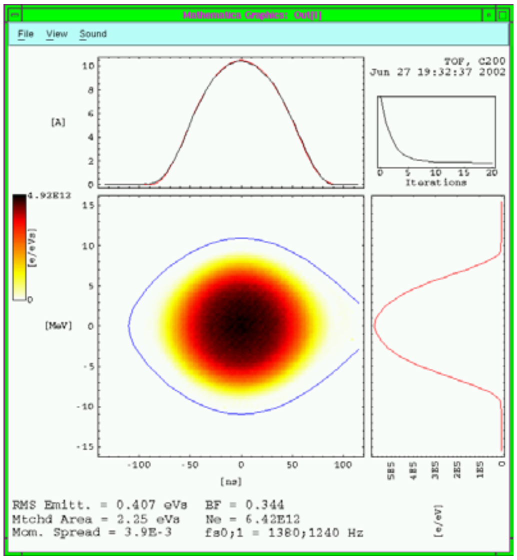
Beam State	INJ User	PS User	Particule	Harmonique	Destination
SPARE	PSB TOF	TOF	PROTON	H8	D3

		Aquisition	Losses	Eff (%)	
1	ring 2 acc	760.11			
2	ring 2 ej	760.11			
3	BTP	725.00	35	95.4	1
4	Injected	708.47	52	93.2	1
5	Bef.Trans	693.81	15	97.9	4
6	Aft.Trans	659.61	34	95.1	5
7	Bef.Eject	649.84	59	91.7	4
8	Aft.Eject	11.97	638	1.8	7
9	TRA203	609.75	40	93.8	7
10	TRA372	634.50	15	97.6	7
11	TRA386	639.00	11	98.3	7
12	TRA468	0.40	649	0.1	7

	INT
16	255
41	27
42	36
43	69
44	57
45	79
f16	5

No message

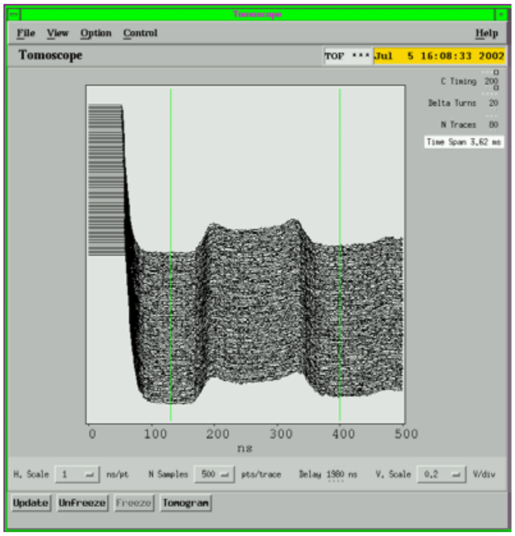
FIGURE 1. *Operation display with the initial blow-up conditions: 3×3 kV, 14 kHz.*



TOF, C200
Jun 27 19:32:37 2002

RMS Emitt. = 0.407 eVs   BF = 0.344
Mtchd Area = 2.25 eVs   Ne = 6.42E12
Mom. Spread = 3.9E-3   fs0;1 = 1380;1240 Hz

FIGURE 2. *Tomogram of the main bunch with the initial blow-up conditions: 3×3 kV, 14 kHz.*



Tomoscope

TOF *** Jul 5 16:08:33 2002

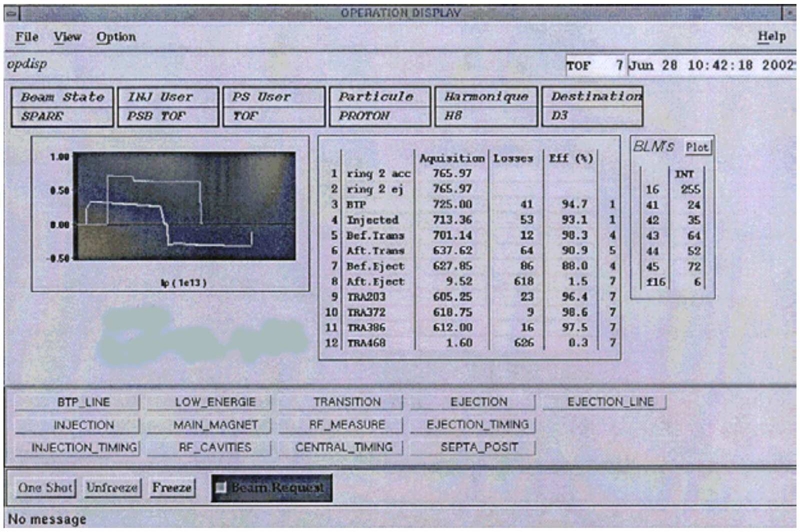
C Timing 200
Delta Turns 20
N Traces 80
Time Span 3.62 ms

H. Scale 1 ns/pt   N Samples 500 pts/trace   Delay 1980 ns   V. Scale 0.2 V/div

FIGURE 3. *Tomoscope display of the first ghost bunch after the main one with the initial blow-up conditions: 3×3 kV, 14 kHz.*

As can be seen from Fig. 1 (8th acquisition value), the ghost bunches represent ~12×10^{10} protons remaining in the PS machine after ejection of the main bunch. Three 200 MHz rf cavities are used to blow up the beam during 20 ms on the PS injection plateau. The rf voltage per 200 MHz cavity is 3 kV and the phase modulation frequency is 14 kHz. Note that the phase modulation depth was kept constant at 180° throughout this study.

One immediate question is whether it is the value of the longitudinal emittance which matters at transition or the form of the particle distribution. To address this, the voltage per 200 MHz cavity was reduced from 3 to 2 kV to put the beam at the limit of stability. The longitudinal emittance is now 2.1 eVs (see Fig. 5).



TOF 7 Jun 28 10:42:18 2002

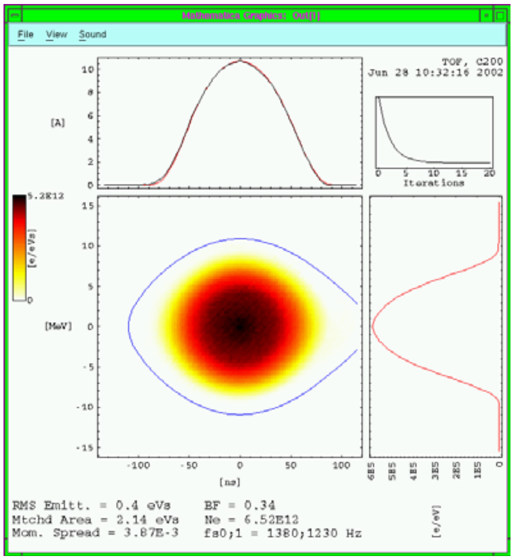
Beam State	INJ User	PS User	Particule	Harmonique	Destination
SPARE	PSB TOF	TOF	PROTON	H8	D3

		Aquisition	Losses	Eff (%)	
1	ring 2 acc	765.97			
2	ring 2 ej	765.97			
3	BTP	725.00	41	94.7	1
4	Injected	713.36	53	93.1	1
5	Bef.Trans	701.14	12	98.3	4
6	Aft.Trans	637.62	64	90.9	5
7	Bef.Eject	627.85	86	88.0	4
8	Aft.Eject	9.52	618	1.5	7
9	TRA203	605.25	23	96.4	7
10	TRA372	618.75	9	98.6	7
11	TRA386	612.00	16	97.5	7
12	TRA468	1.60	626	0.3	7

	INT
16	255
41	24
42	35
43	64
44	52
45	72
f16	6

No message

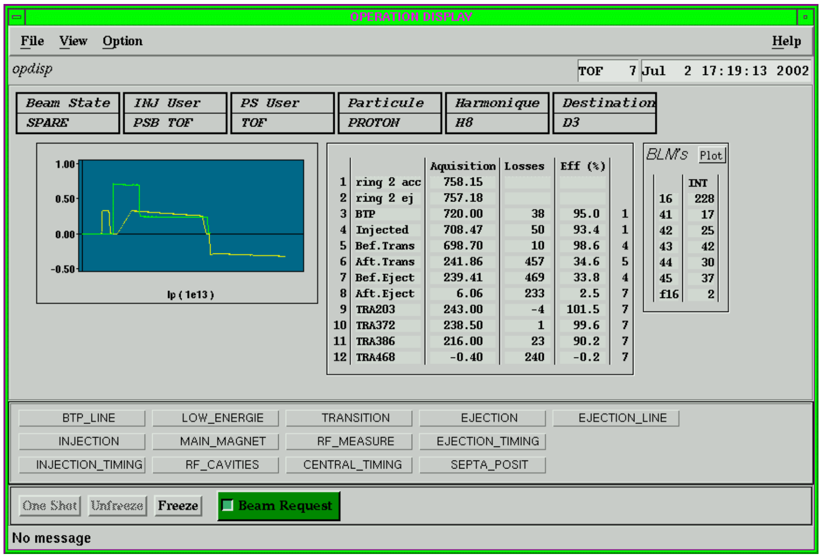
FIGURE 4. *Operation display with the following blow-up conditions: 3×2 kV, 14 kHz.*



```
RMS Emitt. = 0.4 eVs       BF = 0.34
Mtchd Area = 2.14 eVs      Ne = 6.52E12
Mom. Spread = 3.87E-3      fs0;1 = 1380;1230 Hz
```

FIGURE 5. *Tomogram with the following blow-up conditions: 3×2 kV, 14 kHz.*

If the blow-up modulation frequency is then set to 8 kHz, the beam is dramatically unstable at transition (see Fig. 6). The longitudinal emittance is now too small at 1.9 eVs (see Fig. 7), albeit by only 10% with respect to the previous conditions.



TOF 7 Jul 2 17:19:13 2002

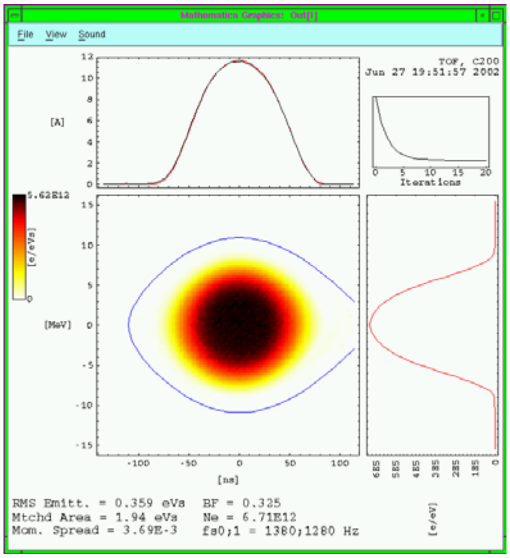
Beam State	INJ User	PS User	Particule	Harmonique	Destination
SPARE	PSB TOF	TOF	PROTON	H8	D3

		Aquisition	Losses	Eff (%)	
1	ring 2 acc	758.15			
2	ring 2 ej	757.18			
3	BTP	720.00	38	95.0	1
4	Injected	708.47	50	93.4	1
5	Bef.Trans	698.70	10	98.6	4
6	Aft.Trans	241.86	457	34.6	5
7	Bef.Eject	239.41	469	33.8	4
8	Aft.Eject	6.06	233	2.5	7
9	TRA203	243.00	-4	101.5	7
10	TRA372	238.50	1	99.6	7
11	TRA386	216.00	23	90.2	7
12	TRA468	-0.40	240	-0.2	7

	INT
16	228
41	17
42	25
43	42
44	30
45	37
f16	2

No message

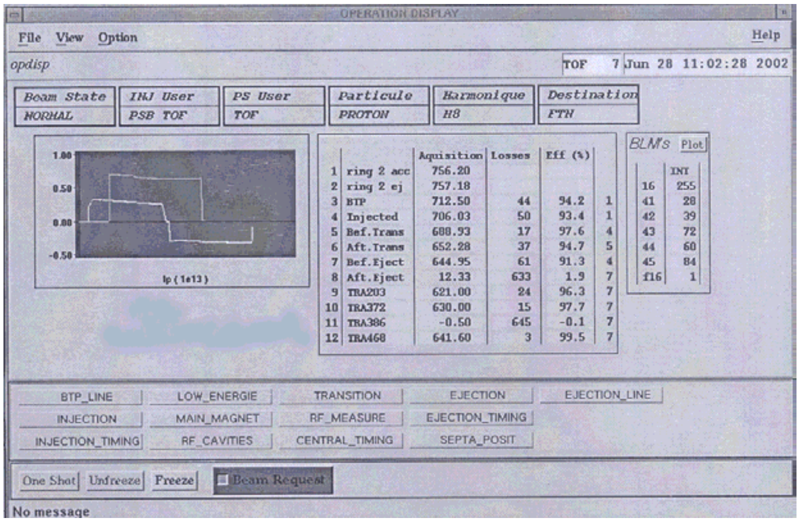
FIGURE 6. *Operation display with the following blow-up conditions: 3×2 kV, 8 kHz.*



RMS Emitt. = 0.359 eVs   BF = 0.325
Mtchd Area = 1.94 eVs   Ne = 6.71E12
Mom. Spread = 3.69E-3   fs0;1 = 1380;1280 Hz

FIGURE 7. *Tomogram with the following blow-up conditions: 3×2 kV, 8 kHz.*

The voltage per 200 MHz cavity had to be increased to 12 kV to re-establish (see Fig. 8) the previous transition losses. The longitudinal emittance (see Fig. 9) is now back at precisely the same critical value of 2.1 eVs seen before (in Fig. 5).



TOF 7 Jun 28 11:02:28 2002

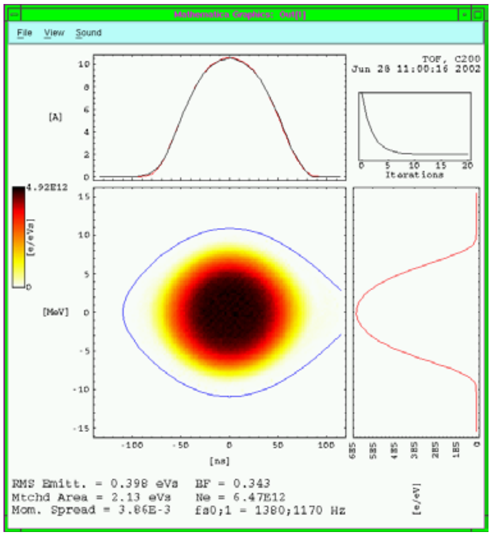
Beam State	INJ User	PS User	Particule	Harmonique	Destination
NORMAL	PSB TOF	TOF	PROTON	H8	FTH

		Aquisition	Losses	Eff (%)	
1	ring 2 acc	756.20			
2	ring 2 ej	757.18			
3	BTP	712.50	44	94.2	1
4	Injected	706.03	50	93.4	1
5	Bef.Trans	688.93	17	97.6	4
6	Aft.Trans	652.28	37	94.7	5
7	Bef.Eject	644.95	61	91.3	4
8	Aft.Eject	12.33	633	1.9	7
9	TRA203	621.00	24	96.3	7
10	TRA372	630.00	15	97.7	7
11	TRA386	-0.50	645	-0.1	7
12	TRA468	641.60	3	99.5	7

	INT
16	255
41	28
42	39
43	72
44	60
45	84
f16	1

No message

FIGURE 8. *Operation display with the following blow-up conditions: 3×12 kV, 8 kHz.*



```
RMS Emitt. = 0.398 eVs   BF = 0.343
Mtchd Area = 2.13 eVs    Ne = 6.47E12
Mom. Spread = 3.86E-3    fs0;1 = 1380;1170 Hz
```

FIGURE 9. *Tomogram with the following blow-up conditions: 3×12 kV, 8 kHz.*

It would seem, therefore, that what matters at transition is simply the size of the beam in longitudinal phasespace. This result is very reproducible and sensitive.

One has to find the best way to provide the required longitudinal emittance by adjusting the principal free parameters [5], namely the phase modulation frequency of the blow-up and the ratio of the rf voltage of the 200 MHz cavities to that of the main 10 MHz ones. Keeping the voltage of the 10 MHz cavities at its initial value of 36 kV, the results of Fig. 10 are obtained. Many particles leave the main bunch and are either lost at the start of acceleration or contribute to ghost bunches.

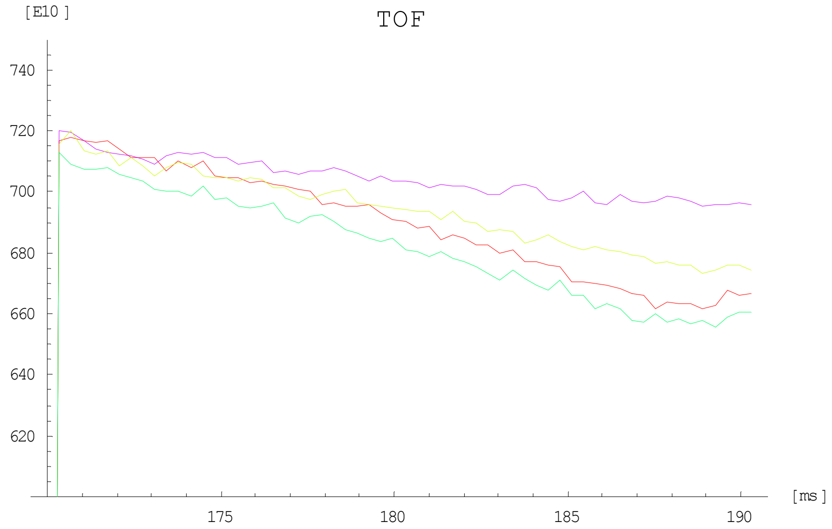
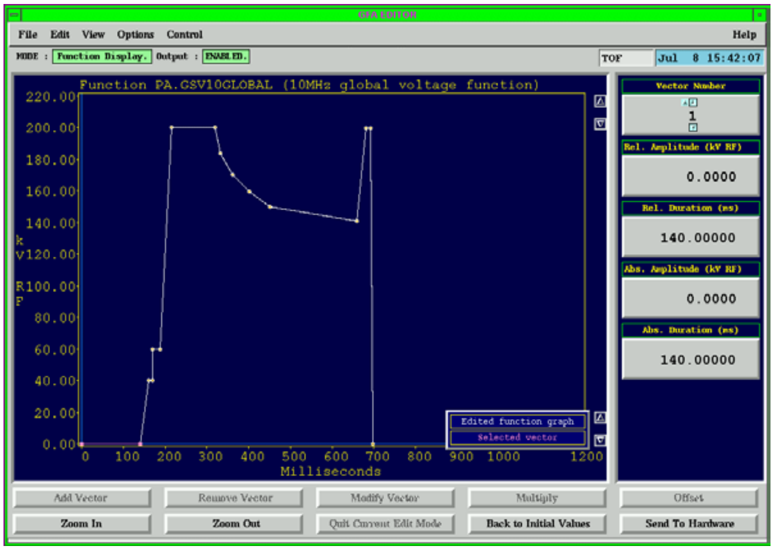


FIGURE 10. *Intensity of the main bunch seen by the Tomoscope during the first 20 ms in the PS for different blow-up parameters. From top to bottom (on the right where the curves are clearly separated): (i) 3×3 kV, 8 kHz; (ii) 3×2 kV, 14 kHz; (iii) 3×3 kV, 14 kHz; (iv) 3×12 kV, 8 kHz.*

The voltage of the 10 MHz cavities was then set to 40 kV (CCV) for injection and a step to 60 kV (CCV) introduced to prevent quadrupolar oscillations and to provide plenty of acceptance (see Figs. 11 and 12). The improved acceptance means that there are almost no ghost bunches in the scan over modulation frequency which followed. The results obtained are summarized in Figs. 13 to 15, where the density profiles, the associated losses at transition and the longitudinal emittances are compared for the different settings. An optimum value of the modulation frequency is seen at 16 kHz, while the differing density profiles on either side of this shallow optimum confirm that it is merely the overall size of the particle distribution which really counts.



MODE : Function Display. Output : ENABLED.

Function PA.GSV10GLOBAL (10MHz global voltage function)

Vector Number: 1

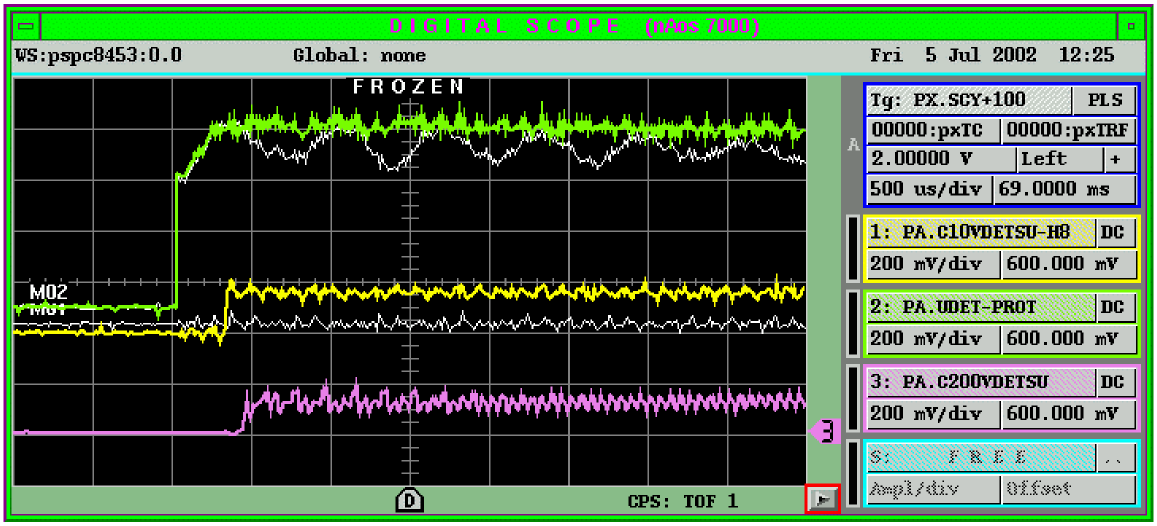
Rel. Amplitude (kV RF): 0.0000

Rel. Duration (ms): 140.00000

Abs. Amplitude (kV RF): 0.0000

Abs. Duration (ms): 140.00000

FIGURE 11. *10 MHz rf voltage function with a step shortly after injection to prevent quadrupolar oscillations and provide plenty of acceptance during the blow-up.*



WS:pspc8453:0.0 Global: none Fri 5 Jul 2002 12:25

Tg: PX.SCY+100 PLS

00000:pxTC 00000:pxTRF

2.00000 V Left +

500 us/div 69.0000 ms

1: PA.C10VDETSU-H8 DC

200 mV/div 600.000 mV

2: PA.UDET-PROT DC

200 mV/div 600.000 mV

3: PA.C200VDETSU DC

200 mV/div 600.000 mV

S: FREE ..

Ampl/div Offset

CPS: TOF 1

FIGURE 12. *Suppression of longitudinal quadrupolar oscillations (stored top trace) observed on nAos with the 10 MHz rf voltage function of Fig. 11.*

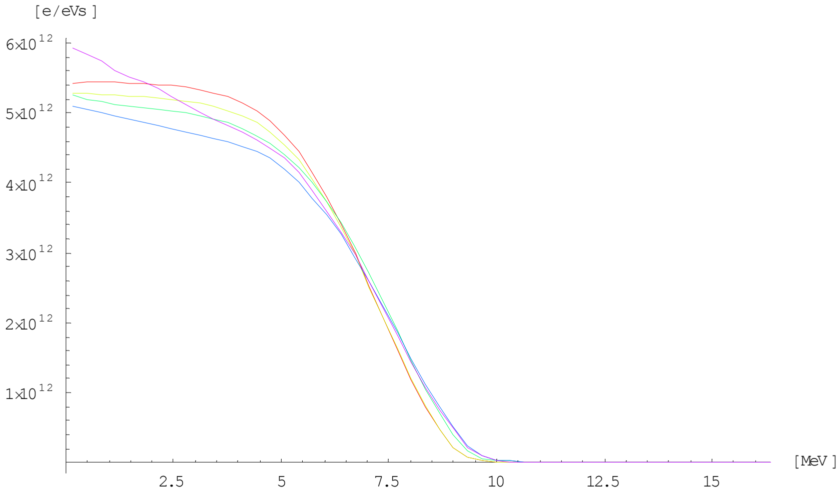


FIGURE 13. *Charge density versus synchrotron amplitude (expressed as the energy excursion at the synchronous phase) derived from tomogram data for different phase modulation frequencies. From top to bottom (on the left) all at 3×3kV: (i) 18 kHz; (ii) 10 kHz; (iii) 12 kHz; (iv) 14 kHz; (v) 16 kHz.*

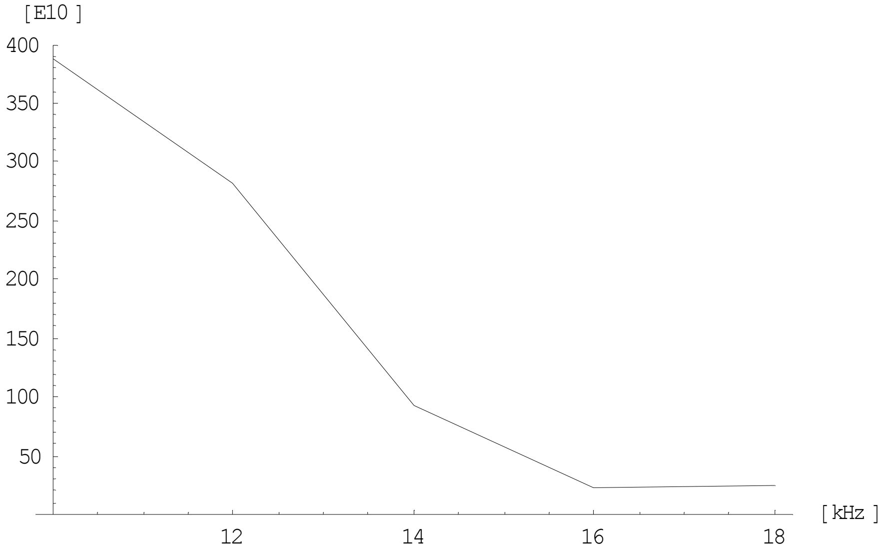


FIGURE 14. *Transition losses versus phase modulation frequency.*

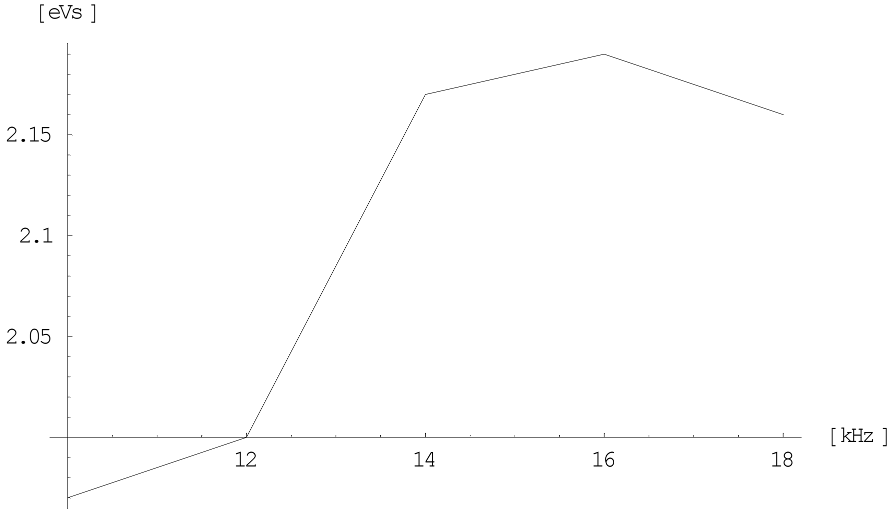
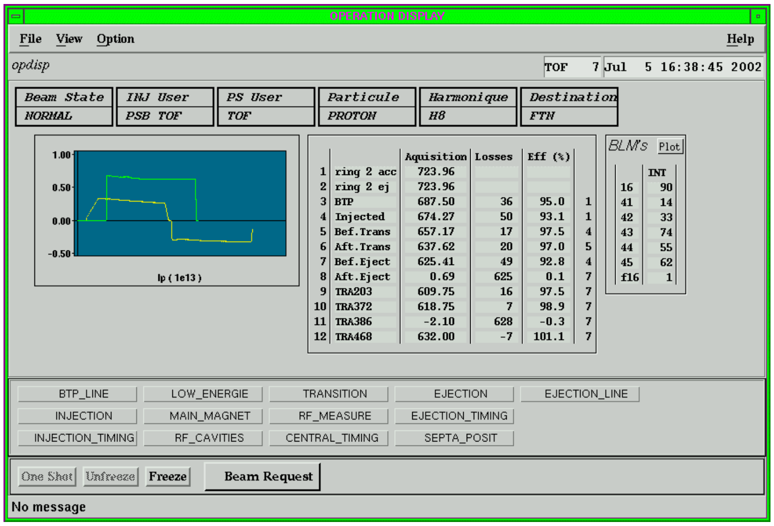


FIGURE 15. *Longitudinal emittance versus phase modulation frequency.*

3 CONCLUSIONS

Ghost bunches and their associated losses on the nToF single-bunch beam have been studied in detail. The main conclusion is that the beam is stabilized near transition for a certain value of the longitudinal emittance independently of the shape of the density profile of the bunch. This result is in agreement with predictions [4] and is very reproducible and sensitive. If the longitudinal emittance is just 10% lower, then the beam is profoundly unstable. The required emittance can be obtained by several sets of blow-up parameters and an optimal set has been found which practically eliminates the ghost bunches.

The new settings were obtained as follows. A step function in the main 10 MHz rf voltage is made to prevent quadrupolar oscillations and to provide plenty of acceptance. Three 200 MHz cavities each provide 3 kV of blow-up voltage. Their phase modulation depth is 180º at a modulation frequency of 16 kHz. The number of particles remaining after PS extraction, which was ~12×10^{10} at the beginning of the study, is reduced to <1×10^{10} (see Fig. 16), i.e., to ~0.1% of the main bunch.



TOF 7 Jul 5 16:38:45 2002

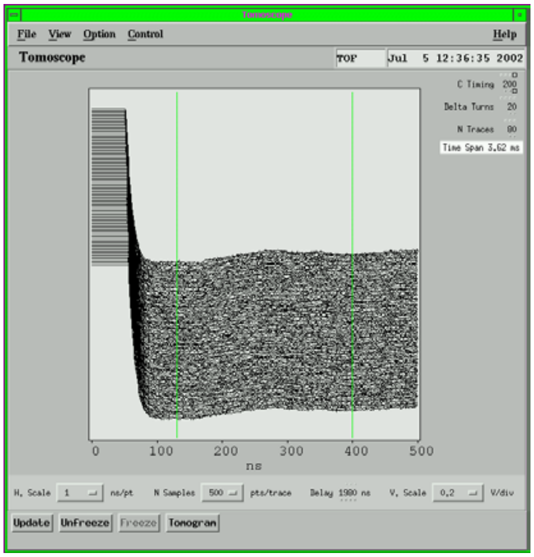
Beam State	INJ User	PS User	Particule	Harmonique	Destination
NORMAL	PSB TOF	TOF	PROTON	H8	FTN

		Aquisition	Losses	Eff (%)	
1	ring 2 acc	723.96			
2	ring 2 ej	723.96			
3	BTP	687.50	36	95.0	1
4	Injected	674.27	50	93.1	1
5	Bef.Trans	657.17	17	97.5	4
6	Aft.Trans	637.62	20	97.0	5
7	Bef.Eject	625.41	49	92.8	4
8	Aft.Eject	0.69	625	0.1	7
9	TRA203	609.75	16	97.5	7
10	TRA372	618.75	7	98.9	7
11	TRA386	-2.10	628	-0.3	7
12	TRA468	632.00	-7	101.1	7

	INT
16	90
41	14
42	33
43	74
44	55
45	62
f16	1

No message

Figure 16. *Operation display with optimal blow-up conditions: 3×3 kV, 16 kHz.*



TOF Jul 5 12:36:35 2002

C Timing 200

Delta Turns 20

N Traces 80

Time Span 3.62 ms

H. Scale 1 ns/pt

N Samples 500 pts/trace

Delay 1980 ns

V. Scale 0.2 V/div

FIGURE 17. *Tomoscope display of the first ghost bunch after the main one with optimal blow-up conditions: 3×3 kV, 16 kHz. The scale is the same as in Fig. 3.*

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[5] R. Cappi, R. Garoby, E. Shaposhnikova, "Experimental Study of Controlled Longitudinal Blow-up", CERN/PS 92-40 (RF), 1992.