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ALPHAS AND DEUTERONS VIA PSB: FACTS AND FIGURES

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1. INTRODUCTION

During an ISR physics run in 1980, the PS was fed with an 8 mA α-beam from the old linac and transferred 4×10^{11} charges per pulse to the ISR, eventually yielding $\sim 3.5\times3.5$ A α-stacks and a luminosity of $\sim 4\times10^{28}$ cm^{-2} sec^{-1} at 62 GeV[1]. Later it was suggested that including the PS Booster in a CPS ion acceleration scheme should increase the intensity (and longitudinal density) by a factor of 3, at the expense of somewhat increased transverse emittances[2]. With another ISR ion physics run scheduled for August 1983, it was decided to have a try at the PSB right now rather than waiting for the O^{8+} programme in 1986[3].

Indeed, as it was worded in the Weekly Bulletin, this "alpha bet paid off": the detour via the PSB resulted in a PS intensity for d's and α's more than three times that available in 1980, and moreover substantially eased the task of the PS itself. Obviously, this did not come true without considerable effort at the Booster (= BR+CO+OP+PO groups) which is reported in this note. The α-exercise has shed new light on the Booster part of the future O^{8+} programme and items to be reviewed in this context are discussed as well.

2. BASIC SCHEME AND PARAMETERS

Just to remind the reader of the basic scheme: Operated in the 2 $\beta\lambda$-mode, the old linac delivers d,α with half the speed of protons. Thus, with the usual RF frequency of about 3 MHz, 10 bunches per PSB ring are captured instead of 5 and accelerated up to 6 MHz RF frequency. At this point the beam is adiabatically de-bunched, the cavity tune moved back to 3 MHz, and the coasting beam re-bunched with $h = 5$, enabling the same RF capture equipment to be re-used for this purpose. To match the usual $B\rho = 4.881$ Tm for PSB-PS transfer, the ions are accelerated to and synchronized at ∿ 5.9 MHz (revolution time 850 ns) instead of ∿ 8.0 MHz (625 ns) for p: the ejection, recombination, PS injection kicker pulses are too short to cope with all 5 bunches, thus only 4 bunches per ring are available.

Machine parameters as they were with best performance are given in the Table 1 below (for general PSB parameters see Ref. 4; performance figures are summarized in Table 2).

Note that at injection the ion speed (β) is not exactly ½ β of protons as one would expect for the "2 $\beta\lambda$" acceleration: the value is slightly smaller because the old linac has a smaller nominal output energy than the new linac.

At PSB-PS transfer, $B\rho$ is strictly identical to p transfer so as to minimize modifications (in fact, only kicker timings have to be changed). For identical B and ρ (that is to say $\Delta\bar{R} = 0$), it is the RF frequency at ejection which has to cope with the tiny difference of mass/charge ratio between d and α: it is adjusted 20 kHz higher for α (lighter) than for d, in agreement with calculations.

3. HARDWARE MODIFICATIONS

3.1 Injection line supplies

The momentum of d,α is 5.7 % lower than of p from the new linac, thus the larger guiding elements have to be adjusted accordingly: septum magnets BI.SMV, BI.SMH, vertical bending magnet BI.BVT, quadrupoles BI.QNO. This is a straightforward operation for dedicated ion runs but impossible with the present hardware in a PPM environment.

TABLE 1

PSB machine parameters for d,α acceleration

(performance figures in Table 2)

Parameter	p (new linac)	d (α if different) (old linac)
PSB INJECTION		
B(G)	1255	1183
β,γ	0.314,1.0533	0.1542,1.01210
$B\rho$ (Tm)	1.0340	0.9747
T (MeV)	50.0	22.68(45.08)
f_{rev}(kHz), τ_{rev}(μsec)	599.3,1.67	294.5,3.396
Injected turns per ring	$\leq$ 15	7.5
Injection slow kicker collapse time (μs)	45	
Harmonic number	5	10
f_{RF} (MHz)	2.996	2.949
Longitudinal acceptance (mrad) ($\phi_s = 5^o$, V = 13 kV)	9.8	4.6
Bucket half-height (keV/charge)	390	190
CHANGE OF HARMONIC NUMBER		
B(G)	2464	
$B\rho$ (Tm)	2.030	
β,γ	0.544,1.192	0.3097,1.0517
T (MeV)	180.1	96.92(192.6)
Harmonic number	5	10 → 5
f_{RF}(MHz)	5.191	5.911 → 2.955
Longitudinal acceptance (V = 13 kV) (mrad)	14.5	5.93 → 8.39
TRANSFER TO PS		
B(G), $B\rho$ (Tm)	5924,4.881	
β,γ	0.842,1.853	0.6157,1.2690(0.6177,1.2716)
T (MeV)	800.0	504.3(1012.0)
f_{rev}(MHz), τ_{rev}(ns)	1.607,622	1.174(1.178),852
f_{RF}(MHz)	8.033	5.870(5.890)
Longitudinal acceptance (V = 13 kV) (mrad)	30.2	11.3

3.2 Main magnet power supply[5]

The harmonic change (h = 10 → 5) requires an intermediate flat top around 2500 G. The cycle used in normal p operation (rise time 392 msec) starts from a flat bottom ("I_{11}", computer-controlled) and follows a function generator prescribing the voltage L dI/dt ("BR.GMSS" function generator) so as to reach an ejection flat top current "I_{22}" (computer-controlled). For the ion cycle, a further computer-adjusted parameter was introduced: "I_{21}", the intermediate flat-top current (see Fig. 1). An extra timing "Ready Intermediate Flat Top" is generated in this case; 50 msec later - this flat-top length is adjustable - the cycle starts rising again (RBI2). The total rise time (RBI1-RFT) is 483 msec, which is compatible with 0.83 msec repetition time. As the main magnet current on the flat bottom (I_{11}) is lower by 5.7 %, the B-train starting value has to be changed (via computer).

The possibility of interleaving ion-type cycles (with intermediate flat top) between p cycles in PPM at this stage proved invaluable for debugging the beam control for the de-bunching, re-bunching process which was carried out on parasite cycles with protons. The PPM is done via the Booster magnet cycle line of the PLS, "CION", by which the intermediate flat-top pulses "Warning Flat Top 1" and "RBI2" are generated; PLS-line CION also modulates flat bottom current I_{11} and the B-train initial value.

3.3 Beam Control

What follows is a short summary of a more detailed note covering the subject[6] (see also Fig. 2).

The first RF trapping can be coped with by existing equipment, the frequency for ions (h = 10) being only slightly lower (2.95 MHz) than for p (3 MHz, h = 5). The particular features of the beam control system for ion acceleration and the sequence of events is as follows:

(i) A switch changes the phases of the phase PU electrodes with respect to the cavity so as to be compatible with h = 10.

(ii) RF capture and acceleration on h = 10; about 20 msec prior to RIFT, the RF voltage is lowered (via function generator) from 13 to ∿ 6 kV to fill the bucket and to prepare for de-bunching.

(iii) At RIFT, sudden decrease of RF voltage to 600 V; the 10 bunches start to de-bunch.

(iv) Change of cavity tunes 6 MHz → 3 MHz; the tuning frequency is kept ∿ 50 kHz above the re-capture frequency thus avoiding perturbations of the (non-negligible) bucket on the coasting beam.

(v) Phase change of phase PU electrodes for h = 5.

(vi) Cavities tuned to h = 5 of the coasting beam frequency, immediately followed by

(vii) the adiabatic re-trapping on h = 5, essentially identical to the first capture: fine adjustment of re-trapping frequency per ring possible.

(viii) Acceleration to the ejection flat top, synchronisation of the 4 PSB rings, and the PS, to 5.87 MHz for d (5.89 MHz for α).

This system was implemented - including a few new hardware modules - in a rather "bricolage" style (and non-PPM) as there was only one dedicated ion period on the programme.

3.4 Kicker timing

The revolution period for ions (852 nsec) on the ejection flat top is much longer than the 800 MeV kickers' flat top lengths ($\sim$ 630 nsec; 1250 nsec for BT.KFA20, active for rings 2+1). Some tricky gymnastics enables 3 RF periods (= 511 nsec) plus one bunch length (95 nsec) to be housed within the kicker pulse and thus 4 bunches per ring to be ejected. The 16th bunch is lost due to the limits imposed by BT.KFA20 (and by the way also by PI.KFA45).

The firing of the 7 ejection/recombination kickers is adjusted

(i) with a delay, in multiples of RF periods, after Warning TRansfer, by computer (timing "Start" and "End" kickers, in PPM), and

(ii) in fractions of an RF period (down to 1 nsec) by local manipulations on the drift stabilizers (no PPM possible at present). Satisfactory settings for recombination of 15 consecutive bunches were indeed found7) and used during the ion operation period.

3.5 Instrumentation

In the injection line, the beam transformers BI.TRA show strong perturbation due to the noise of fast distributor BI.DIST, but the digital indications for BI.TRA20 appeared correct (BI.TRA10 wrong). The magnetic position monitors BI.UMA became virtually useless below 8 mA beam current, but worked fairly well for deuterons (10 mA).

As to the normalized ring beam transformers, the circuit normalizing the intensity is based on the RF frequency; it was modified6) in order to cope with h = 10 acceleration as well as the intermediate flat top where the RF is changing.

Adjustment of the recombination beam trajectories was based on fairly useful analogue signals on the electrostatic PU's BT.UES and BTP.UES; their digitization would have implied major modifications to timing and gating circuits and was thought not worth the effort; however, the gates of the 800 MeV line beam transformers BTP.TRA, BTM.TRA were adjusted to cope with the ions.

4. PERFORMANCE AND OPERATIONAL ASPECTS

After having overcome the more basic difficulties of ion acceleration in previous dedicated (d,α) and parasite (p) ME sessions[8], the setting-up sessions proper were mainly used for further refinements improving the performance. As a complement to the list of basic parameters presented in Table 1, best performance figures, achieved for deuterons (26.8.83) and alphas (23.8.83),are given in Table 2.

In 1983, the 1980 ion acceleration performance figures[9] were exceeded by more than a factor of 3. The ISR reported an initial luminosity of 5×10^{29} cm^{-2} sec^{-1} for the α-stack, more than 10 times the 1980 figure.

With $n_d = 1.6\times10^{12}$ d per ring the PSB starts to "feel" the space-charge force: the Laslett Q-shift at injection, for equal ε_H, ε_V, is equivalent to the one experienced by n_p protons, where

$$n_p/n_d = \tfrac{1}{2}\,\frac{(\beta^2\gamma^3)p}{(\beta^2\gamma^3)d} \; .$$

At Booster injection, this factor amounts to 2.34 (equivalent to 3.75E12 p/ring), and at PS injection it is 2.91 (equivalent to 7.0E12 p). Nevertheless, this intensity is still comparatively low by PSB standards, enabling the beam to survive without most of the beam stabilizing systems:

TABLE 2

PS Booster performance for d and α (best achieved)

Parameter		d		α	Comments
Current from linac (mA) BI.TRA10		10-11		8-9	see Fig. 3
Pulse length (μs) (FWHH)		110		90	
Charges per pulse prior to injection (10^{10} charges, all rings)		740		500	BI.TRA20
$\Delta p/p$ ("wires")		± 6		± 5	
ΔT (keV)		± 140		± 225	(α: ± 110 keV/charge)
ε_o (63 % of beam) $\pi\mu$radm		∿ 6		∿ 6	
Transverse linear mismatch		30-60 %		30-60 %	ok as long as < 60 %
(Q_H, Q_V) at injection		(4.19,5.30)		(4.19,5.27)	see Fig. 4
Charges injected, all rings (10^{10})		610		390	Inj. efficiency ∿ 80 % !
Charges RF trapped, all rings		480		320	ΔT_{LINAC} excessive
Charges accelerated PSB, all rings		340		230	Main loss at recapture, see Fig. 5
Transverse emittances at PSB-ejection (Beamscope) $\pi\mu$radm	ε_H	22	phys.	36	Average of 4 rings. Difference in ε_H between d and α not understood
	ε_H*	17	norm.	28	
	ε_V	16	phys.	15	
	ε_V*	12.5	norm.	12	
Longitudinal emittance at PSB ejection	(mrad)	5.6		5.3	see Fig. 6
	(eVs)	.179		.169	
Bunch length (nsec)		97		92	
Charges recombined (BTP.TRA) (10^{10})		240		170	15-16 bunches only
Charges accelerated in PS[9] (10^{10}) to 3000 G		220(65)		130(40)	1980 figures in brackets
Efficiency PS(3000 G)/Linac exit		30 % (∿ 10%)		26 % (∿ 10%)	

(i) the Hereward damping loop;

(ii) the coupled-bunch mode longitudinal feedback systems;

(iii) the transverse feedback loop;

their adaptation to the ion cycle would have required considerable effort.

Operational Aspects: The elementary lines chosen for the PLS were

user (ISR or PHY25) = cycle CION * Q-value QION * intensity IME *
* ejection mode UPS20.

Quite some effort went into the construction of the main power supply L dI/dt function BR.GMSS (see Fig. 1) tailored to this special cycle (but not to the longitudinal acceptance as it turned out).

Most of the elements to be changed in the injection line are "PPM-ized" anyway and had their values set on the PLS-line QION; a few are not PPM-ized and were set one by one at every change-over.

To go from p to ions, the purely "mechanical" part of the switch-over took about 1 hour (interventions in MCR, CCR, BOR, BCER), followed by typically 1-3 hours of setting-up. The alphas proved more difficult than d due to their lower intensity and the ensuing shortcomings on the instrumentation (Chapter 3.5); also the d-beams from the linac were more stable and reproducible. Obviously, the total operational effort would have been about halved in a period without storms. - Returning to p took typically 1 hour and proved fairly straightforward.

5. OUTLOOK

The possibility of further d,α runs within a year or so cannot be completely excluded. Substantial intensity (or efficiency) increases are not likely to be achievable for these runs.

For the O^{8+} programme looming on the horizon, the recent d,α exercise was very useful for checking the modifications proposed in Ref. 2 and pinning down several items to be reviewed (see below). Note that the validity of extrapolation is somewhat hampered by an oxygen intensity a factor $\sim$ 1000 lower than with d or α.

(i) With the linac beam energy spread exceeding the longitudinal PSB acceptance (taking into account the adiabatic trapping factor $\pi/2$), only $\sim$ 75 % trapping efficiency was achieved. For O^{8+}, feeding the debuncher cavity DB13 with the RF from the old linac may potentially render $\Delta p/p$ small enough to ensure an efficiency of 90-95 %.

(ii) Parasite observations[10] on the pulsed 50 MeV septa BI.SMV, BI.SMH revealed the necessity of better matching of the 3rd harmonic pulse component to keep a good quality flat top on some of them; this will require some development work for PPM-operation with oxygen.

(iii) How to develop an injection line beam transformer for 10 μA beam if already at 10 mA the distributor noise exceeds the signal (Fig. 3) ?

(iv) The rather disappointing efficiency of the 2nd trapping ($\sim$ 75 %) can be improved by

- decreasing $\Delta p/p$ from linac via DB13;
- performing the harmonic change at 8 MHz (down to 4 MHz) rather than at 6 MHz (to 3 MHz); this provides a larger stationary bucket area at recapture (9.0 mrad instead of 8.4).
- more careful programming of $\dot{B}(t)$ after the intermediate flat top, matched to constant longitudinal acceptance for ions (rather than for p); this may eliminate the slow loss after re-capture (Fig. 5).

These findings, important as such, barely alter the money/manpower estimates quoted earlier[2] for adapting the PS Booster to oxygen operation in PPM mode: $\sim$ 1 MSF and 15 man-years, to be shared between BR, CO, PO, MU groups.

REFERENCES

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2) K. Schindl, Light ions via the PS Booster, PS/BR Note 81-10.

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4) K.H. Reich and K. Schindl, PSB parameter list, PS/BR Note 82-11.

5) R. Gailloud, PS/PO/Memo 83-34.

6) J. Fopma, L. Magnani, PS/BR Note 83-3 (to be published)

7) J.D. Schnell, Settings sur les compteurs CAMAC et les drift stabilizers ..., handwritten note, 11/8/83.

8) PS/BR/ME 83-1,3,5,7, issued by B. Frammery and K. Schindl.

9) PS/MD/83-5, issued by J.P. Potier.

10) J.P. Royer, private communication.

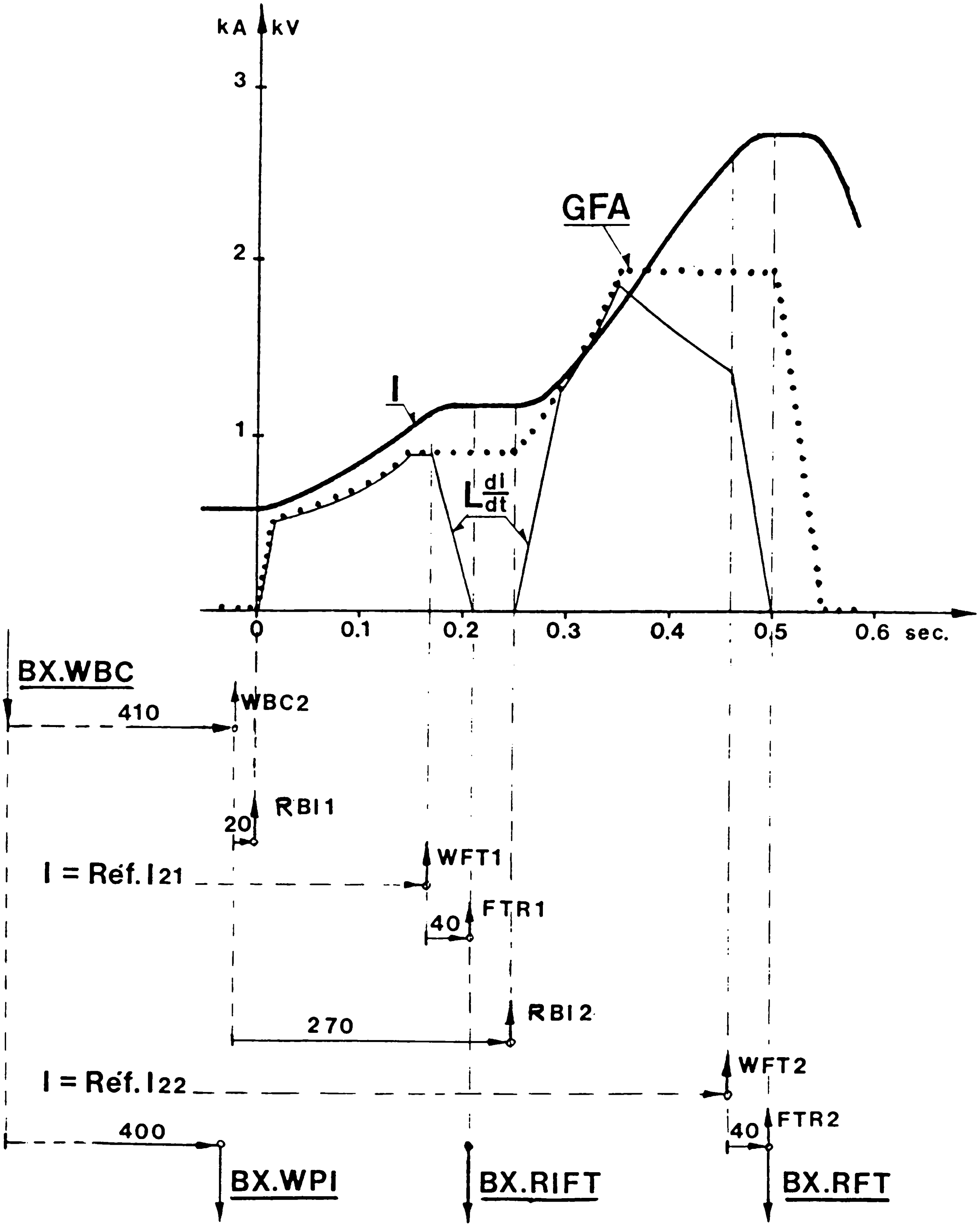


Fig. 1: Main magnet power supply, ion cycle with intermediate flat top. Underlined timings are general Booster timings, the others are internal system's pulses.

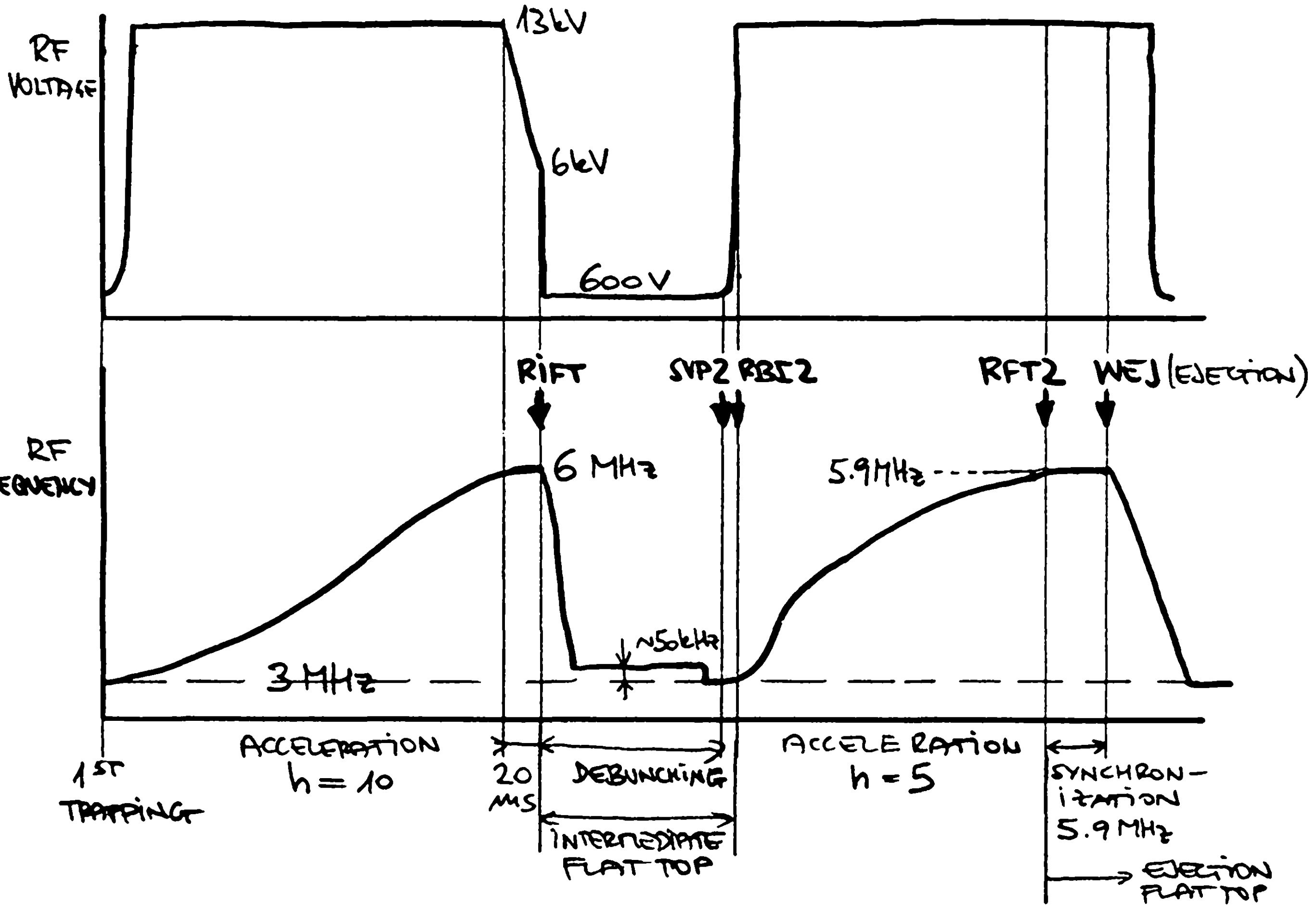


Fig. 2: RF + Beam Control: sequence of events (schematic)

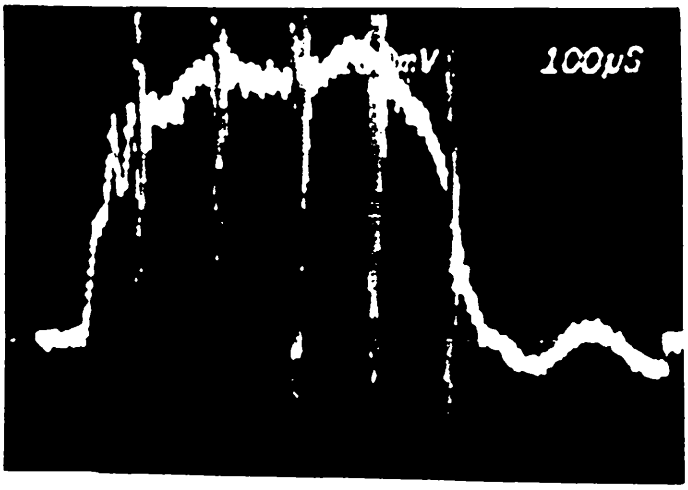


Fig. 3: Injection line beam

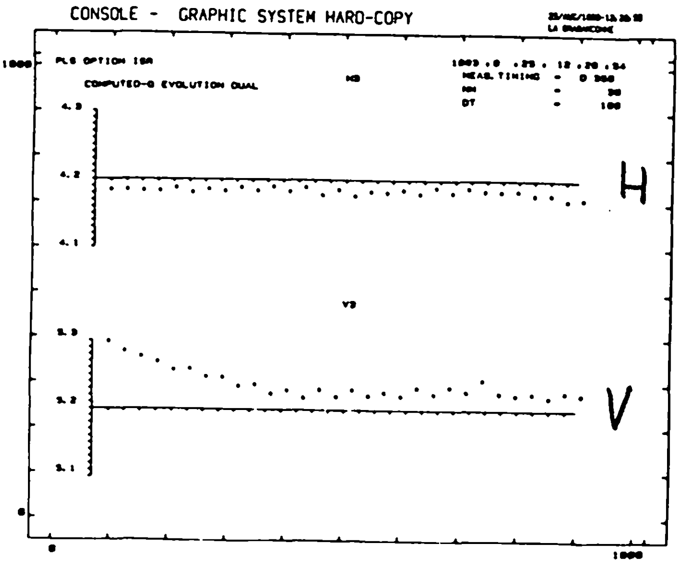
Transformer BI.TRA10

2 mA/DIV

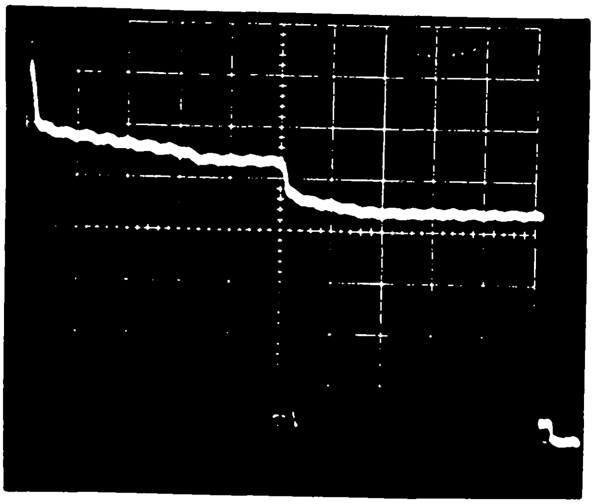
20 µs/DIV

Deuterons

The spikes coincide with level switching of BI.DIST



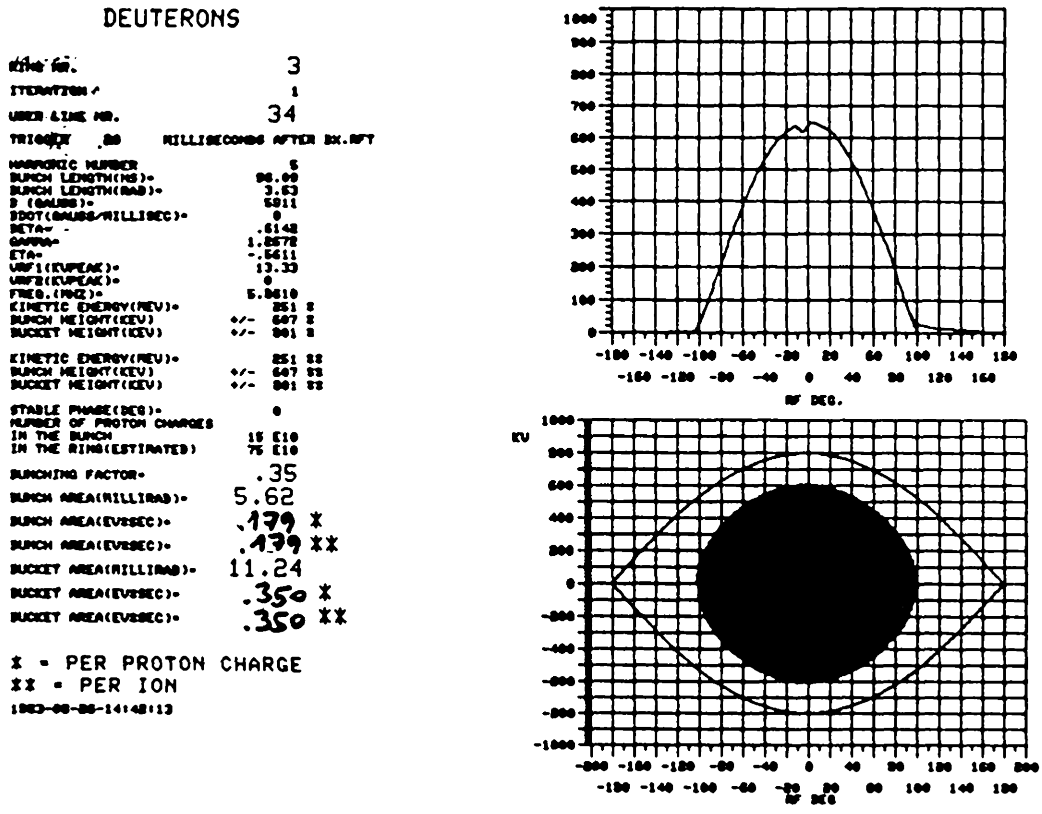
<u>Fig. 4</u>: Zero-intensity tunes, ring 3, during first 300 ms of cycle, for deuterons: Q_V had to be increased because of moderate space-charge detuning as would be generated by ∿ 3.7E12 p/ring.



<u>Fig. 5</u>: Acceleration of d in ring 2 on normalized beam transformer

2×10^{11} charges/DIV.

50 ms/DIV



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DEUTERONS

RING NO.                              3
ITERATION #                           1
USER LINE NO.                        34
TRIGGER   .80    MILLISECONDS AFTER IN.RFT

HARMONIC NUMBER                       5
BUNCH LENGTH(NS)=                 96.00
BUNCH LENGTH(RAD)=                 3.03
B (GAUSS)=                         5811
BDOT(GAUSS/MILLISEC)=                 0
BETA=  -                          .6142
GAMMA=                           1.2672
ETA=                             -.5611
VRF1(KVPEAK)=                     13.30
VRF2(KVPEAK)=                         0
FREQ.(MHZ)=                      5.0610
KINETIC ENERGY(MEV)=              251 *
BUNCH HEIGHT(KEV)          +/-    607 *
BUCKET HEIGHT(KEV)         +/-    801 *

KINETIC ENERGY(MEV)=              251 **
BUNCH HEIGHT(KEV)          +/-    607 **
BUCKET HEIGHT(KEV)         +/-    801 **

STABLE PHASE(DEG)=                    0
NUMBER OF PROTON CHARGES
IN THE BUNCH                     15 E10
IN THE RING(ESTIMATED)           75 E10

BUNCHING FACTOR=                    .35
BUNCH AREA(MILLIRAD)=              5.62
BUNCH AREA(EVxSEC)=                .179 *
BUNCH AREA(EVxSEC)=                .179 **
BUCKET AREA(MILLIRAD)=            11.24
BUCKET AREA(EVxSEC)=               .350 *
BUCKET AREA(EVxSEC)=               .350 **

* = PER PROTON CHARGE
** = PER ION
1983-08-26-14:48:13
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Fig. 6: Deuteron bucket and bunch prior to ejection (vertical scale 200 keV/DIV instead of 100 kV/DIV).

Distribution

Y. Baconnier - PS
J.M. Baillod - PS
R. Billinge - PS
M. Bouthéon - PS
E. Brouzet - PS
C. Carter - PS
G. Daems - PS
J. Fopma - PS
H. Fiebiger - PS
B. Frammery - PS
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H. Haseroth - PS
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K. Schindl (3) - PS
H. Schönauer - PS
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D.J. Williams - PS

Opérateur BR

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G. Jubin
K. Priestnall
I. Robinson
M. Ruette

LEP

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D. Neet