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The PSB as an e-, e+ Accumulator ?

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1. Introduction

In the comparison of the various options for the electron-positron accumulator (EPA), the PSB has been looked at by J.-P. Delahaye and not considered to be a serious candidate for this role. Indeed there are strong arguments of both operational and technical character virtually excluding any further detailed investigation :

(a)When deciding for the PS + SPS as LEP injector, it was conditio sine qua non that proton physics can continue during LEP filling periods. As it stands, the Booster is indispensible for SPS fixed target physics, for 25 GeV/c proton physics and for $\bar{p}$ production for LEAR.

(b)Owing to its design,the PSB is not well suited to store low energy electrons : at 600 MeV/c its bending field is 0.24 T and the ensuing transverse damping times of the order of 450 ms are very long compared with the envisaged linac repetition period of 10 ms .

In view of these obvious drawbacks it was only logical to stop thinking about the Booster and pass on the design of a dedicated storage ring. Nevertheless, in a situation dominated by a penury of financial (and labour) resources, on might ask whether an adaption of the PSB such to allow simultaneous e+,e- storage and p acceleration could result in interesting cost savings. Moreover,the concept of the LEP injector system has evolved such that the adaption of the PSB seems easier to the present than to the initially proposed configuration [1,2,3] .

Mainly for this reason, and applying the novel idea of magnetic separation of rings outlined below, the author reconsidered the question some time ago. First results were encouraging: adaption of rings is feasible and rather inexpensive. But a more global look including beam transport problems renders this solution less attractive.

Since the question about the feasibility of the Booster as an e+,e- preinjector may always arise, and in fact has recently been asked by R.Billinge, this note has been written up although the dedicated EPA ring has been adopted officially. The cost estimates given in Section 8 confirm this choice.

2. Basic concept of the adaption of the PSB :

Separation of the main magnet circuit of rings (1 + 4) and rings (2 + 3).

As it is well known, the PSB is a stack of four superposed rings. The bendings and quadrupoles of these rings are linked by their connection in series and to a common main power supply. For the rest they are equipped and controlled individually. The magnetic field being far below saturation (B = 0.24 T at 0.6 GeV/c and Bmax = 0.59 T at proton ejection energy), magnetic separation, without substantial interference, appears perfectly feasible. Residual coupling effects should easily be compensated with the existing correction elements.

A natural and advantageous division would be the one into rings (1 + 4) and rings (2 + 3) for the reasons

- magnetic symmetry around the median plane with the consequence :
- each ring of one group experiences the same residual interference effects
- bending magnet coils are already electrically separated this way.

This separation means that (during LEP filling periods)

- two rings may continue to accelerate protons
- two rings are available for e+, e- storage

During LEP collision periods all four rings are available for p acceleration.

The modification implies :

- modification of quadrupole connections (at present the four of one stack are in series)
- reconnecting them to their bus and to
- two new busbars going round the ring to permit their independent excitation
- reconnecting the main power supply with 2 + 2 groups (at present 4 groups, of which 3 are powered in normal operation)
- add and connect two addtional supplies for the now four quadrupole families.

The block diagram of the present and the proposed magnet circuit is shown in Figs. 1a, 1b .

The proposal of separation of Booster rings might be of interest in its own, leaving e+- aside : a good part of CPS operations requires only two rings ore one : $\bar{p}$ production in 2-Ring mode, AA and other test beams, 25 GeV/c physics, MD beams etc.

Powering only two rings during these cycles may save up to 1 GWh/year or about 100 kF at present energy cost. A separate study will find out whether the payback time of this modification justifies its implementation.

3. Schemes to adapt damping times to linac repetition rate.

Constraint : all schemes have to allow for dispersion-free sections and have to preserve stability against turbulence. Input data for all schemes looked at are taken from the appendix to the Pink Book [1] and from K. Huebner [2] and J.P.Delahaye [3], if they have changed since then.

Principal new parameters are :
- 8 bunches in the accumulator
- Nb = 2.4 10^{10} e+/b, 1.2 10^{10} e-/b maximum
- the 8 e+ bunches are split ("sliced") into 2 x 8 bunches going into two consecutive PS cycles.

The fact that incoming linac pulses are distributed into 8 respectively 2 x 8 bunches considerably reduces the damping rate required for the injection process. Nevertheless some artificial damping has to be provided by one or two wigglers, or the linac pulse frequency has to be reduced.

From the many possible solutions, five different options have been chosen and compared. Three of them (I - III) take the existing rings and just add wigglers etc., whereas the other two (IV, V) use individual bendings rather than wigglers to form a bypass where all elements particular to e+,e- operation are concentrated.

This facilitates (a) adaption of the lattice to provide a dispersion-free section to house injection elements, and (b) reduces length and bending angle of the injection channels; (c) if sufficiently long (option V), the main RF cavity can be bypassed too. (d) the strong bendings in the bypass replacing the wiggler(s) of the in-ring solutions II, III are fairly simple zero gradient magnets. In the ring, wigglers of very strong field *and* strong gradient would be required, which are certainly not easy to design. The bypasses preserve $J_\varepsilon = 2$, $J_x = 1$ and consequently a sane longitudinal damping rate.

Table 1 allows comparison of the five options considered. The table mainly deals with damping times,dispersion suppression and with stability with respect to turbulence.

4. More constraints to be met

(a) Cog-wheeling Booster -PS is not straightforward. In order to transfer 8 bunches to the PS one has to change the unusable circumference ratio of 4/1. For the in-ring solutions I - III this can only be done by changing the radial position prior to ejection. In any case the ratios are such that RF frequencies have to be "synchronized" by PLL techniques, and the whole transfer takes some time :

Option	C(PS)/C(PSB)	ΔR (mm)	T bunch-to-bunch
I - III	799/200	31 mm	52 us
IV	113/28	<30 mm	7.4 us
V	19/5	- mm	1.3 us

(b) Existing normal sextupoles are not sufficient to produce zero chromaticity in both planes. Four normal sextupoles of the same strength as the existing ones (2.25 T/m) have to be added in L1 sections.

(c) Zero chromaticity should help to tame high frequency head-tail modes. Lower frequencies <100 MHz are covered by the existing wide band feedback system, which needs some minor modifications.

5. Linac sites and injection lines

Obviously the potential linac sites are others than those compared for a dedicated ring [4]. Two linacs sites have been considered and the corresponding injection lines evaluated in Table 2 :

A) Linac in TT1 tunnel (straight part), making use of the existing TT1 line to transport the beam to the PSB.

B) Linac on the carpark South of the computer building 513. The level of this site being about 10m above the PSB level, the injection line has to be bent down , after crossing TT2 .

Other sites of potential interest would be the (not even finished) tunnel of the neutrino oscillation experiments or the area East of the PSB.

Figs. 2,3 and 4 show some combinations of injection and transfer lines with the three ring adaption schemes considered : options I-III,IV,V of Table 1 .

6. Transfer schemes; kickers and septa

There is a considerable variety of transfer routes by combining the e+,e- schemes given in Table 3.

For all bending foreseen in transport lines and bypasses, strong field (1.6 T) bending modules of 22.5 deg bending are assumed everywhere.

Generally speaking, the transfers from and to the PSB are the most expensive part of the project, for several reasons :

(a) transport lines are all underground

(b) natural ejection region of PSB blocked by 800 MeV proton ejection equipment.

(c) A major constraint is that for options I-III the Booster lattice has to be taken as it is ($\beta_H \cong 6$ m in L1 section) and no optimization to reduce kicker strength is possible. Kicker deflections to produce bumps of 20 mm amplitude is 3 - 4 mrad, corresponding to 60- 80 Gm for options II,III . Option I, implying postacceleration to p > 1.05 GeV/c requires about twice this strength.This more than compensates what has been gained saving the wigglers.

These facts are reflected in the following section where the cost of the individual components is estimated. The cost of the machine gun type ejection kickers suggests e+, e- transfer combinations of Table 3 where one single kicker can serve both e+, e- ejection.

7. Cost estimate of components

7.1. Adaption of the ring.

Element (group)	relevant for option		unit price	group price	
1 Modif.of quad. connections	all			500 kF	[6]
Cabling				350 kF	[7]
2 Modification of main power supply	all		370 kF		[8]
3 Strong Robinson wiggler	II,III		350 kF		
4 Short bypass	IV				
5 quadrupoles			50 kF	250 kF	
5 power supplies			15 kF	75 kF	
10 bendings 22.5 deg			40 k	400 kF	
10 power supplies for bendg.			25 kF	250 kF	
20 m tunnel			15 kF	300 kF	
vacuum equpt.				100 kF	
		Total		1755 kF	
5 Long bypass	V				
12 quadrupoles				600 kF	
12 power supplies for qu.				180 kF	
14 bendings 22.5 deg				560 kF	
14 power suppl. for bendg.				350 kF	
50 m tunnel				750 kF	
vacuum equipmt.				250 kF	
		Total		2690 kF	

6 RF cavity + electronics	Total		1000 kF
7 Sextupoles for chromat. contr. all			
4 normal sextupoles		30 kF	120 kF
4 power suppl.		15 kF	60 kF
	Total		180 kF

7.2. Modification of linac design to meet PSB constraints.

1 Energy Compression System	I,(II)	600 kF
2 Linac rep.rate 50 Hz	I	-

7.3. Injection and transfer lines

1 quadrupole per 5m length	25 kF	
1 power supply for quad.	15 kF	
1 bending 22.5 deg	40 kF	
1 power supply for bending	25 kF	
tunnel per m length	15 kF	
vacuum per m length	4 kF	
instrumentation per m	3 kF	
Total beam transport per m length	30 kF	
Total bendings per 22.5 deg	65 kF	
Modifications of existing hardware : existing 800 MeV line : septa + bendings in ppm		500 kF
BR.SMH in ppm		200 kF
whole injection line in ppm		500 kF

7.4. Kickers and septa

1 Kickers + power supplies :

∫Bdl required	for option	injection	ejection (8 modules)
160 Gm	I	400 kF	8 x 200 kF
80 Gm	II,III,IV	200 kF	8 x 120 kF
40 Gm	V	100 kF	8 x 80 kF

2 Septa + power supplies

I-IV	200 kF	200 kF
V	200 kF	250 kF (symmetric septum)

8. Overall cost estimate.

Table 4 displays the estimated costs following the estimates of sect 7 . The outcoming total includes adaption of the machine itself plus beam transport from the linac to the PSB and from the PSB to the PS. Excluded is the injection into the PS, controls, and specific e+,e- instrumentaion in the ring.

9. Conclusions

Assuming that the electrical (and magnetical) separation of the PSB main magnet is feasible, independent operation of two pairs of rings - (1 + 4) and (2 + 3) - allows proton acceleration to continue in two rings during e+,e- filling periods.

Comparing a few possible adaption schemes, a coarse but rather conservative estimation of costs for the complex machine + transport lines shows that

- two of the"poor man's solutions" I - III promise some savings, with respect to the dedicated ring, at the expense of somewhat limited performances and a Booster ring stuffed to its limit with hardware.

- the long-bypass solution V keeps e+- and p equipment properly separated, and offers all the flexibility needed to make it perform as well as a dedicated ring (there is even some spare capacity for future demands in form of an unused Booster ring). However it turns out that this (preferable) solution apparently also costs as much as a dedicated ring. This is not obvious as one would expect to realize at least some savings on building, cabling and vacuum equipment (some more savings should be possible on the control system not considered here,which practically exists for the PSB and needs to be built for FPA).

In all cases, possible savings have to be balanced against the increased operational complexity of an already complex machine, and, of course, reduced p output.

The latter may however be acceptable if one keeps in mind, that the PSB will increase its intesity towards $3\ 10^{13}$, or $1.5\ 10^{13}$in two rings, and multibatch filling could catch up for the rest *]. AA produces $\bar{p}$ only for LEAR in this case, and a reduced accumulation rate might be sufficient then. 25 GeV/c physics does not need the high intensity anyway.

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*] The circumferential structure due to transfer of two rings only to be expected in the SPS can be avoided for an even number of batches by a suitable alternation in the ejection timing in the PSB.

10. Acknowledgements

I am indebted to the persons who provided cost estimates (R. Gailloud, J.Pasquali and M.Perrin), to J.P.Delahaye and D.Warner for information on preinjector problems, W.Hardt for information on Robinson Wigglers, M. Chanel and H. Umstaetter for introduction into MAGNET and POISSON programs, and K. Huebner and K.H.Reich for their comments on the manuscript.

11. References

1. LEP Injection System - CERN/ISR-LEP/79-33/Add.
2. K. Huebner, ISR Seminar 22/3/1982.
3. J.P.Delahaye, pers. comm.
4. P.H. Standley : On the siting of the LEP preinjector, PS/LR/Note 81-6
5. K. Huebner commented that doubling the length of the linac pulse would probably affect the intensity of the later part of the pulse.
6. M. Perrin, pers. commun.
7. J. Pasquali, pers. commun.
8. R. Gailloud, pers. commun.

Figure Captions :

Fig.1a :Block diagramm of the present magnet circuit.

Fig.1b : Block diagram of the proposed separated magnet circuits.

Fig.2 :Ring configurations I - III, combined with linac site A and transfer schemes 4(e+) and 7(e-).

Fig.3 : Short bypass (IV) shown with both linac sites A and B and transfer schemes 2(e+) and 5(e-). <<- indicates position of the common ejection kicker.

Fig.4 :Long bypass (V) with linac site B and dedicated transfer lines 2(e+) and 8(e-).

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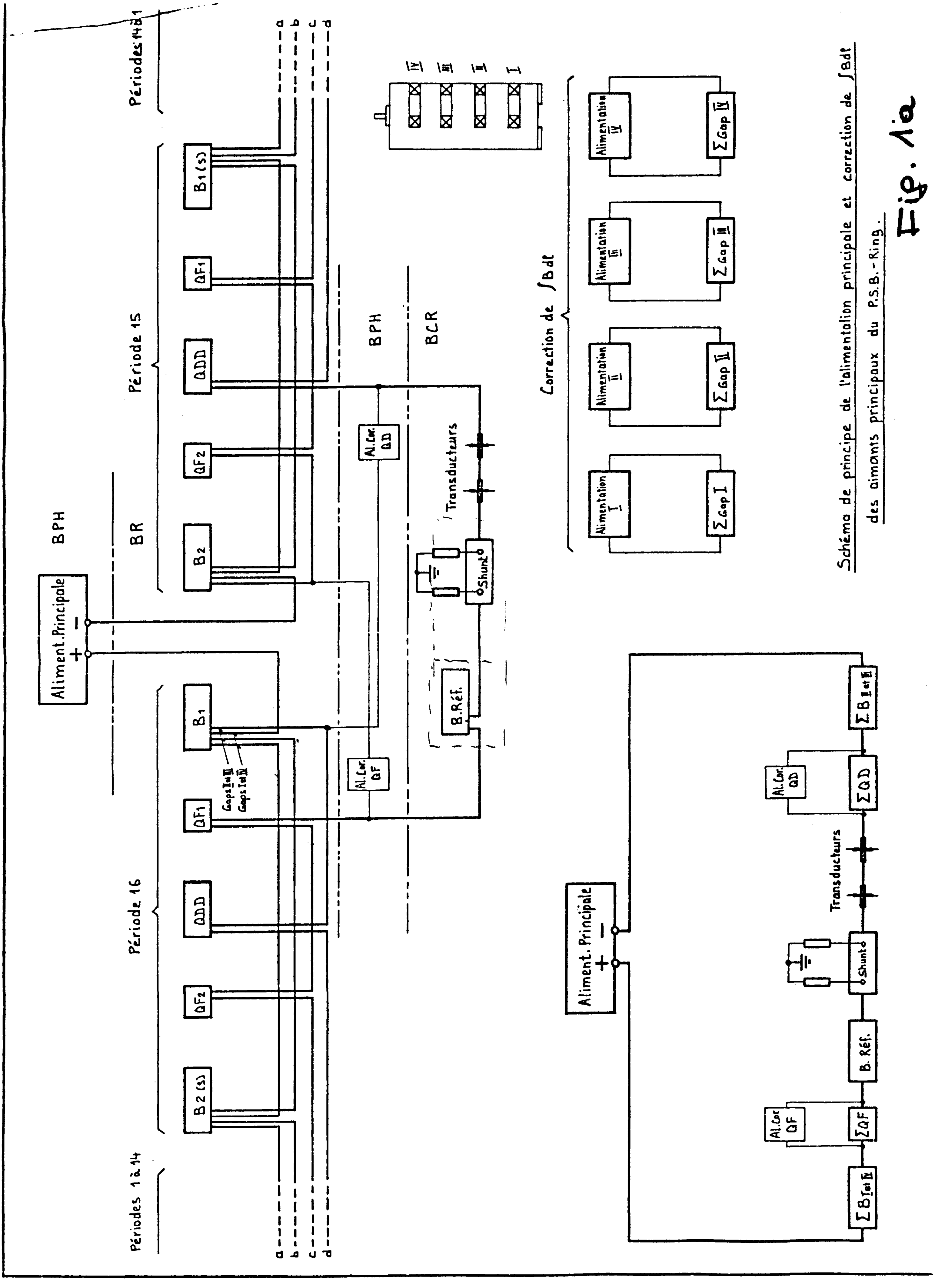

Fig.1a :Block diagramm of the present magnet circuit.

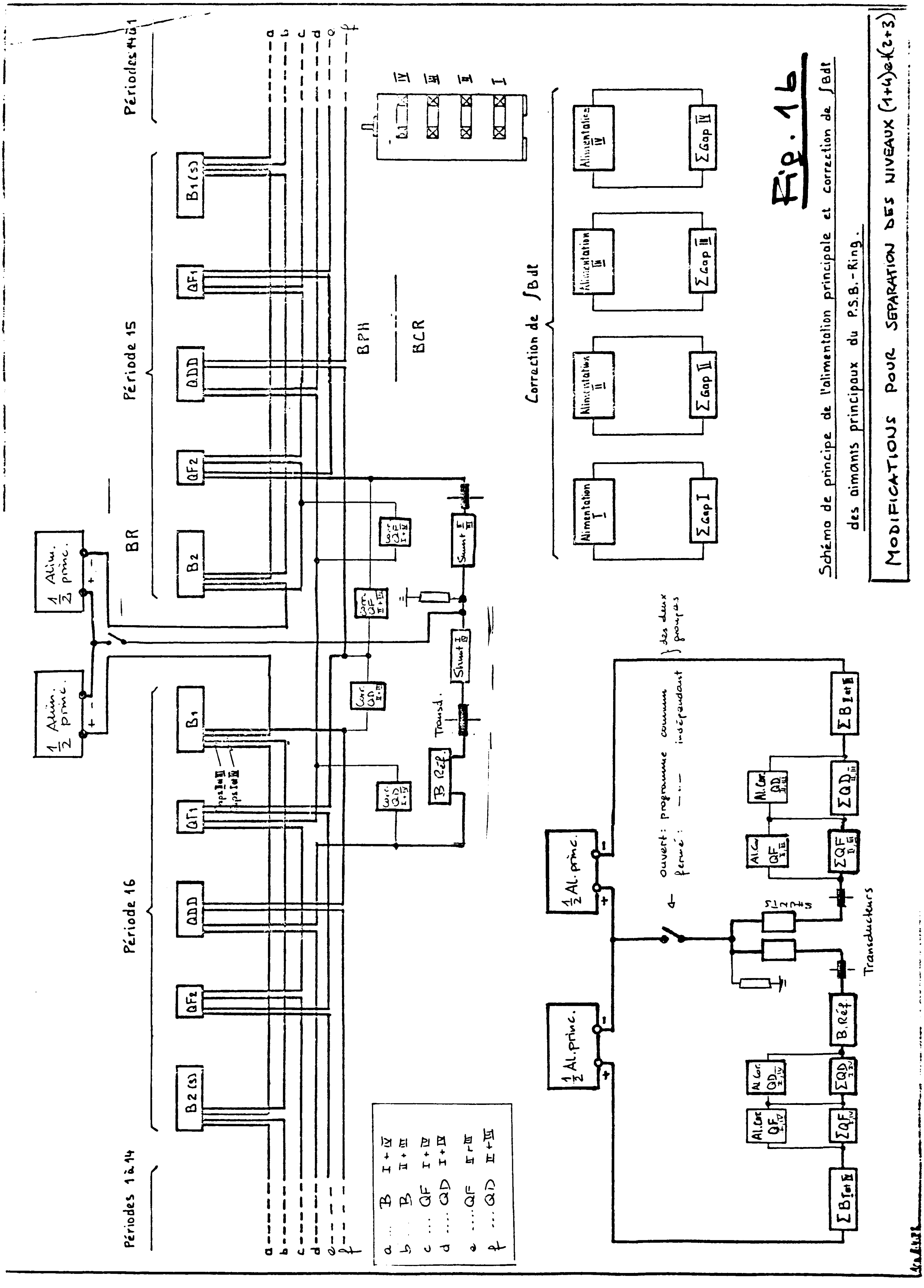

Fig.1b : Block diagram of the proposed separated magnet circuits.

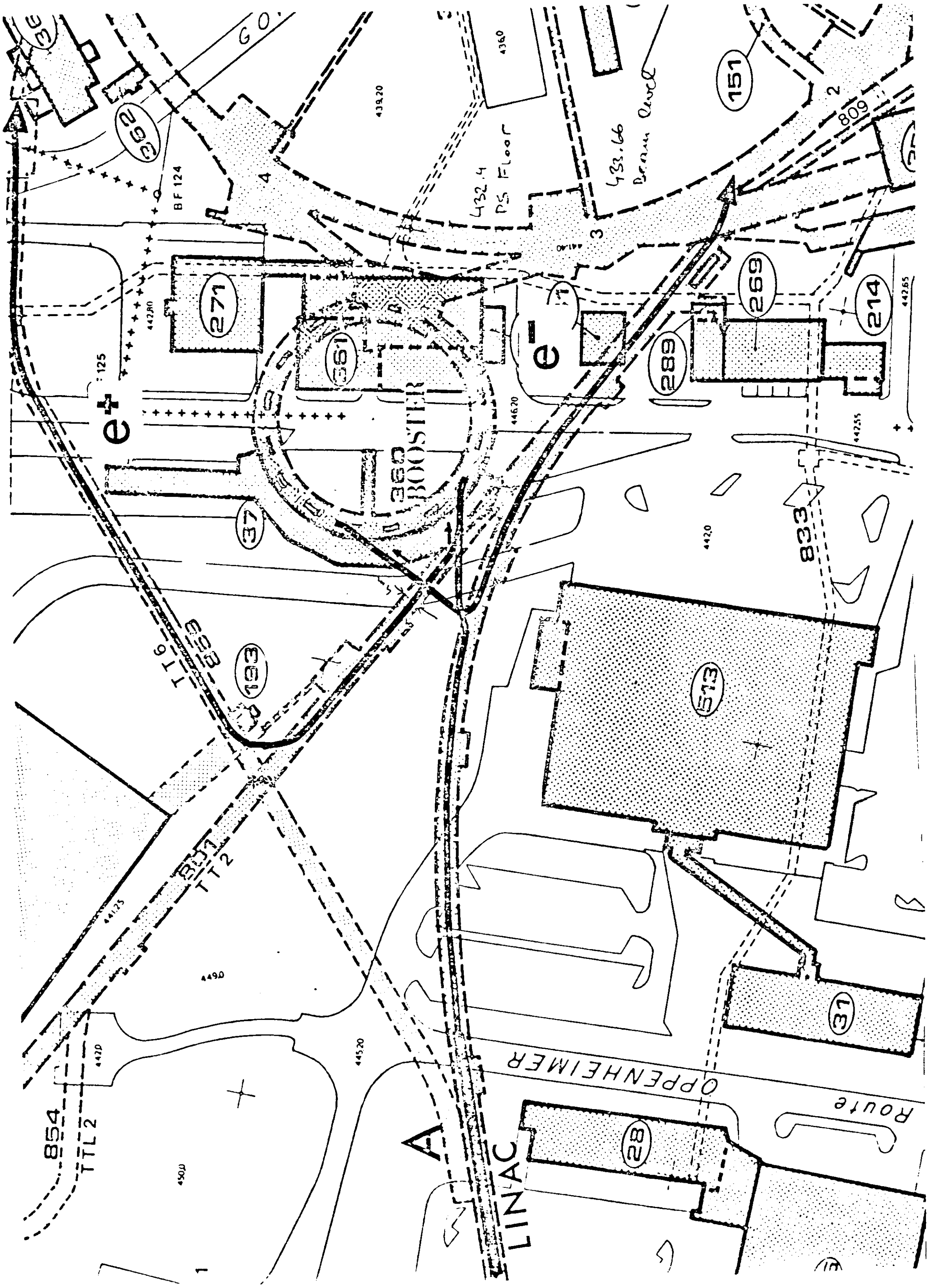

Fig.2 :Ring configurations I - III, combined with linac site A and transfer schemes 4(e+) and 7(e-).

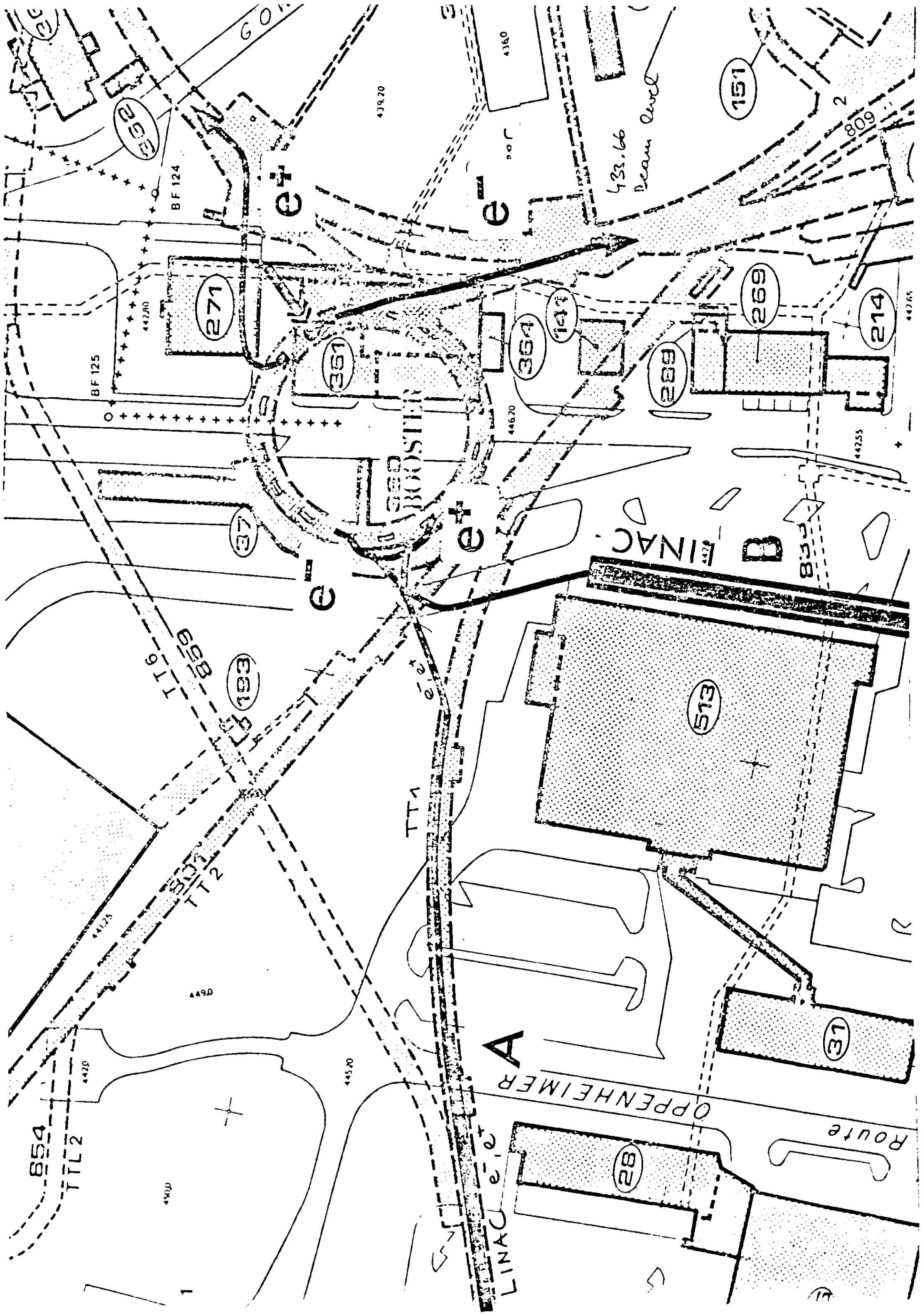

Fig.3 : Short bypass (IV) shown with both linac sites A and B and transfer schemes 2(e+) and 5(e−). <<- indicates position of the common ejection kicker.

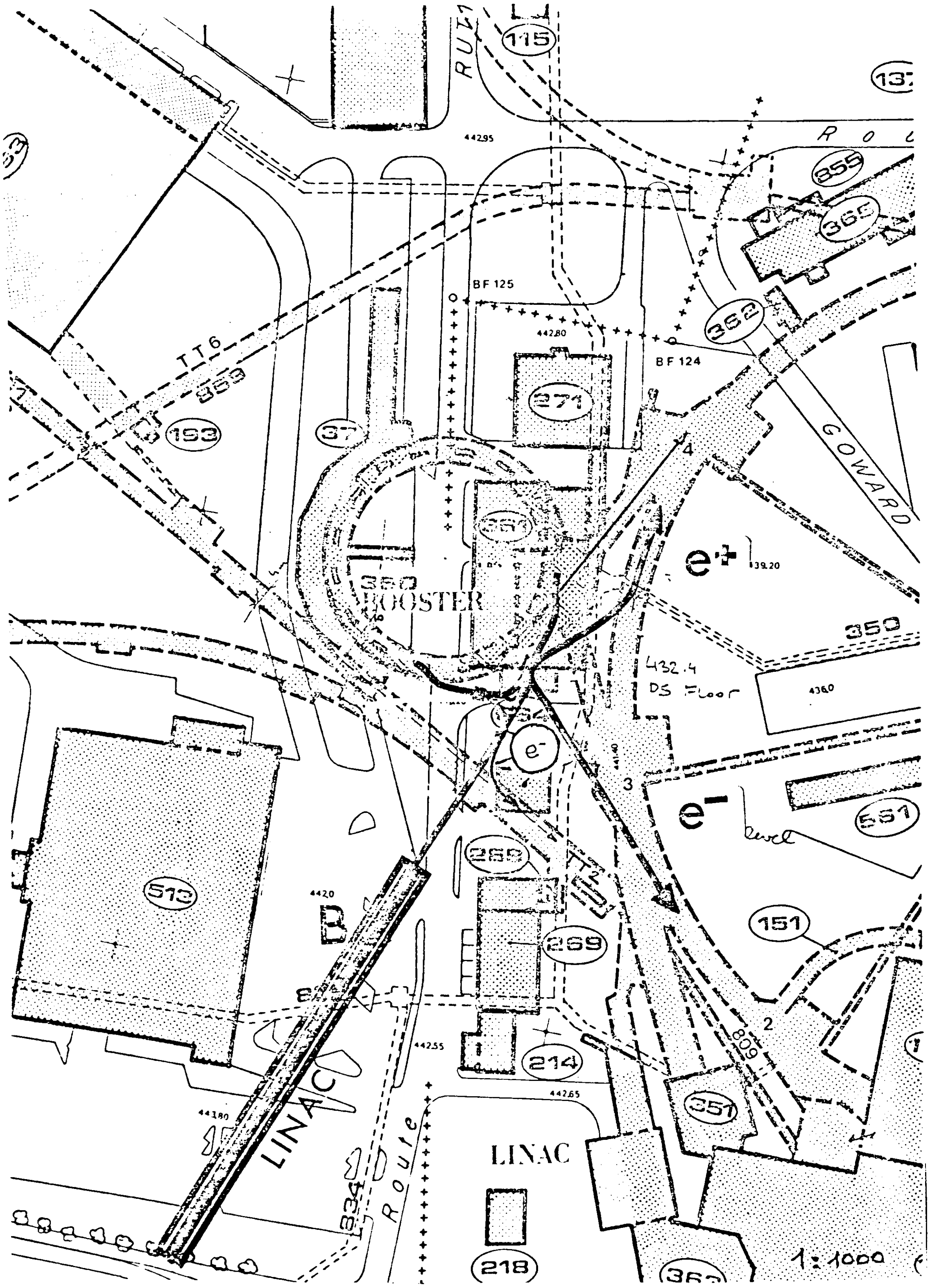

Fig.4 :Long bypass (V) with linac site B and dedicated transfer lines 2(e+) and 3(e−).

TABLE 1: RING CONFIGURATION

Schemes to adapt damping time and dispersion suppression to Linac parameters

a Ref	b Configuration	c Rings/RF	d Radiation damping parameters	e	f Bunch width/length	g Dispersion suppression	h observations
I	Bare machine [1] Linac Rep. rate 50 Hz	2 Rings 8 bunches/ring $h = 8$ (15.3 MHz)	$U_0 = 1.4$ keV $J_\varepsilon = 2$ $J_x = 1$	$\hat{V}_{RF} = 48$ kV $\tau_\varepsilon = 225$ ms $\tau_x = 450$ ms	$\sigma_{\varepsilon 0} = 1.8\ 10^{-4}$ $\sigma_0 = 0.11$ m $\sigma = 0.2$ m turbulent	hardly possible, relies on ECS [2]	- ECS [2] obligatory, with compression better than 4 - 72 S-band pulses (instead of 36) every 20 ms [8] - post-acceleration [3] required
II	One strong Robinson-Wiggler; existing RF-system	2 RINGS 4 bunches/ring $h = 4$	$U_0 = 5.3$ keV $J_\varepsilon = 1.4$ $J_x = 1.6$	$\hat{V}_{RF} = 20$ kV $\tau_\varepsilon = 82$ ms $\tau_x = 75$ ms	$\sigma_{\varepsilon 0} = 5.2\ 10^{-4}$ $\sigma_0 = 0.68$ m $\sigma = 0.76$ m stable	Wiggler designed to create wiggle in η, $0 \leq \eta < 3$ m around the machine	- ECS [2] nearly essential $\hat{V}_{RF} \approx 32$ kV required to capture $\frac{\Delta p}{p} = \pm 0.01$ 20 kV imposed by existing RF system - wiggler perhaps not realisable [4] - bunches too long to be captured by PS 200 MHz system [5]
III	Two Robinson-wigglers	1 RING 8 bunches $h = 8$	$U_0 = 4.0$ keV $J_\varepsilon = 1$ $J_x = 2$	$\hat{V}_{RF} = 50$ kV $\tau_\varepsilon = 160$ ms $\tau_x = 80$ ms	$\sigma_{\varepsilon 0} = 4.3\ 10^{-4}$ $\sigma_0 = 0.3$ m $\sigma = 0.38$ m stable	possible with suitably designed wiggler	- wiggler design may be tricky
IV	Short Bypass (2 PSB periods)	1 RING 8 bunches $h = 8$	$U_0 = 6.8$ keV $J_\varepsilon = 2$ $J_x = 1$	$\hat{V}_{RF} = 50$ kV $\tau_\varepsilon = 47$ ms $\tau_x = 93$ ms	$\sigma_{\varepsilon 0} = 4.2\ 10^{-4}$ $\sigma_0 = 0.3$ m $\sigma = 0.38$ m stable	no problem (bypass designed for $\eta = 0$)	- homogeneous bendings in the bypass
V	Long Bypass (4 PSB periods)	1 RING 8 bunches $h = 8$	$U_0 = 10$ keV $J_\varepsilon = 2$ $J_x = 1$	$\hat{V}_{RF} = 50$ kV $\tau_\varepsilon = 33$ ms $\tau_x = 66$ ms	$\sigma_{\varepsilon 0} = 4.2\ 10^{-4}$ $\sigma_0 = 0.3$ m $\sigma = 0.38$ m	no problem	- homogeneous bendings in the bypass - main RF cavity (3-8 MHz) may be circumvented by the bypass

COLUMNS:

a) Reference to text and other tables

b) Configuration : wigglers / bendings

c) Nr. of PSB rings used for accumulation/ /nr. of bunches / harmonic nr.

d) U_0.. radiation loss/turn ; partition numbers

e) $\hat{V}_{RF}$.. RF voltage to provide an acceptance of $\pm \Delta p/p = 0.01$;
$\tau_{\varepsilon,x}$: longitud., radial damping time constant

f) $\sigma_{\varepsilon 0} = \sigma_\varepsilon/E$, σ_0 = bunch length, for vanishing intensity ; σ = —— —— for $N_b = 2.5\ 10^{10}$

g) method to suppress dispersion to permit $(\Delta p/p)_{Linac} \simeq \pm 0.01$

FOOTNOTES :

1) Owing to long transverse damping time (450 ms) of the bare machine, the usual method of injection can only be maintained if the repetition rate of the Linac is halved to 50 Hz, whereas the number of S-band pulses is doubled to 72 to preserve intensity.

2) Energy Compression System as used at Mainz, DESY, Bonn, Tokyo Linacs. The possible compression is however limited to about 4, due to the length of $\approx 10°$ (7.5° for e^-) of the Linac bunches in RF phase

3) Postacceleration of the full stack to reach a non-turbulent regime,
to a) $E = 1.05$ GeV (threshold); at this E $\tau_\varepsilon = 42$ ms, $\tau_x = 84$ ms, $U_0 = 13.1$ keV
b) $E = 1.463$ GeV (momentum of 800 MeV protons), $\tau_\varepsilon = 15.5$ ms, $\tau_x = 31$ ms, $U_0 = 50$ keV
(this means an additional RF voltage)

4) Limited by the length of PSB straight sections, the maximum field would be ~ 2.2 T. If this is not possible, two weaker wiggler have to be inserted (per ring).

5) The length of a 200 MHz bucket is 1.5 m. The bunches could however be be transferred into the buckets of the 9 MHz RF system ($h = 16$)

TABLE 2: INJECTION SCHEMES FOR THE TWO LINAC SITES CONSIDERED

Ref.	Positions of injection septa	compatible with Ring configuration # (Table 1)	A: Linac in TT1 tunnel		B: Linac on carpark south camp. bldg	
			Length	Σ bendings	Length	Σ bending angles
a	e^+, e^- septa 4 machine periods distance (because of η variation)	I – III	60 m	45°	–	
b	injection septa in short bypass	IV	45 m, excl. TT1, excl. bypass	45°	55 m excl. bypass	90°
c	injection (ejection) septa in long bypass	V	50 m, excl. TT1, byp.	22.5°	60 m excl. bypass	135° (incl. vertical)

TABLE 3: TRANSFER SCHEMES

Ref.	$e^\pm$	Transfer route	compatible with Ring configuration #	Length of beam transport to be built	Σ of bending angles	observations
1	e^+	existing 800 MeV transfer line	I – V	0	0	whole transfer line in ppm; kicker power supplies to be rebuilt for "machine ppm" operation
2		dedicated e^+ transfer line	I – III V	50 m 30 m	135° 45°	Common kicker for e^+ and e^- ejection if e^+ septum in 3L1, combining 2 (e^-) and 5 (e^+)
3		transfer via TT6	I – IV	45 m + TT6	135°	
4		transfer via TT2-junction-TT6	I – IV	TT2+15 m (junction)+TT6	210°	
5	e^-	via exist. injection septum, branching off at position of DHz 60	I – V	50 m	45°	BR. SMH to be ppm
6		via existing injection channel, branching of in the PS	I – V	0	45°	whole injection line to be ppm
7		via TT2	I – IV V	5 m + TT2 15 m + TT2	135° 90°	
8		dedicated e^- transfer line	V	60 m	22.5°	one septum for: e^+ injection e^- ejection (combined with 2) e^+ —"—

TABLE 4: COST ESTIMATE (Material)

All figures in MF

Ring configuration as defined in Table 1	I	II	III	IV	V
1. Adaption of machine					
1 - Modification quadrupole connections, cables	0.88	0.88	0.88	0.88	0.88
2 - 〃 of Main Power Supply	0.37	0.37	0.37	0.37	0.37
3 - Robinson wiggler(s) + power supplies		0.7 (1.4)[1]	0.7		
4 - Short bypass				1.38	
5 - Long bypass					2.69
6 - RF cavity 15.3 MHz + electronics	1.0		1.0	1.0	1.0
7 - sextupoles for chromaticity control	0.18	0.18	0.18	0.18	0.18
2. Modification of linac design - ECS Rep. rate 50 Hz	0.6				
Subtotal 1+2	3.03	2.13 (2.83)[1]	3.13	3.81	5.12
3. Injection line					
A - Linac in TT1 tunnel	1.63	1.63	1.63	[2] ● 1.48	2.15
B - Linac on carpark South Rte. 513				1.91	[2] ● 2.19
Vertical switching	0.2	0.2			
4. Transfer line					
e^+ 1 - Existing 800 MeV line	● –	● 0.5	● 0.5	0.5	0.5
e^+ 2 - dedicated e^+	1.89	1.89	1.89	● 1.89	● 1.03
e^+ 3 - via TT6	1.74	1.74	1.74	1.74	
e^+ 4 - via TT2-junction-TT6	1.04	1.04	1.04	1.04	
e^- 5 - via existing inj. septum	1.83	1.83	1.83	1.83	1.83
e^- 6 - via 〃 inj. line	● 0.63	● 0.63	● 0.63	● 0.63	0.63
e^- 7 - via TT2	0.54	0.54	0.54	0.54	0.71
e^- 8 - dedicated e^-					● 1.86
Subtotal 3+4	2.46	2.6	2.76	4.0	5.08
5. Injection/ejection: Kickers + septa + power suppl.					
● For the combination e^+, e^- of pt. 4 marked with a dot - injection kicker(s)	0.8	0.4	0.4	0.4	0.2
〃 septa	0.4	0.4	0.4	0.4	0.2
ejection kicker(s)	3.2	1.92	1.92	0.96	1.28
〃 septa	0.2	0.2	0.2	0.2	0.25
Subtotal 5	4.6	2.92	2.92	1.96	1.93
Grand total (without instrumentation + controls):	10.09	8.01 (8.33)[1]	8.81	9.77	12.18

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1) ( ).. if two wigglers per ring are to be built (one wiggler beyond today's technology)

2) ● .. option chosen for computing totals