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A Bunch Transfer Scheme for the Beauty Factory in the ISR Tunnel

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1. Introduction

The *B*eauty *F*actory in the ISR tunnel (BFI) requires in one of the modes e^+ and e^- beams at 5.3 GeV [1,2]. The PS can provide these beams, if the present 114 MHz rf system is extended [3]. It would operate with 8 equidistant bunches as for LEP [4].

Other modes of BFI will require a 3.5 GeV beam from the PS and an 8 GeV beam from the SPS [1,2] which would operate with 8 bunches as foreseen for LEP [4]. The PS would provide for the SPS a 3.5 GeV beam as for LEP [4].

This note shows that the BFI circumference is determined by the range of possible circumferences in the ISR tunnel and, in detail, by the requirements of beam transfer from the two existing synchrotrons, which have a given circumference.

The maximum number of bunches in BFI is 160. This number and the choice in which range the radiofrequency should lie constrain the harmonic numbers and the precise values of the possible frequencies.

The bunch transfer schemes PS − BFI and PS − SPS/SPS − BFI are discussed in detail. The 8 GeV beam passes in the latter case through less than 3/4 of the PS used as a beam transfer line [6]. The energy loss by synchrotron radiation (5×10^{-4}) is negligible during the transfer in the PS. EPA delivers 8 bunches to the PS as for LEP as explained elsewhere [4,5]. The risetime and falltime of the BFI injection kickers are also defined in this note.

In order to increase the injection rate of electrons from the SPS it might be desirable to operate with 16 bunches in the SPS. Circumferences and harmonic numbers are compatible with this mode. It would need installation of electron bunch cutting equipment either in EPA or PS and modification of the kickers concerned but these details are left for a later examination. Here we comment only on the effect on the risetime of the BFI injection kickers.

Throughout this note we assume that the number of bunches in BFI always contains 16 as factor, a condition that is fulfilled at present with 32, 80 and 160 bunches [2].

2. BFI Circumference

Consider first the PS – BFI transfer. Since rephasing is complicated and time-consuming, we transfer the beam with the PS rf locked to BFI rf or vice versa. The 8 equidistant PS bunches are transferred into 8 equidistant collecting buckets of BFI. The cogwheeling requires for the circumferences C_i

$$p \frac{C_{PS}}{8} = m \frac{C_{BFI}}{8} \quad (1)$$

To access all bunches in the PS and the 8 collecting buckets in BFI, p and m must be odd. If (1) holds, the transfer from PS or from PS to BFI even operating with 16 collecting buckets is also guaranteed as shown later. Table 1 gives the set of possible combinations of the lowest p, m and the resulting circumferences taking into account that the PS circumference is 628, 324 m [4]. It can be seen that the set

$$p = 23 \quad m = 15 \qquad (2)$$

gets close to $C_{BFI} = 964\, m$ being at present the working hypothesis [1]. Hence, we need to decrease the average BFI radius by 9 cm which is easily possible.

Table 1, Possible circumferences of BFI

p	m	C_{BFI} (m)
5	3	1047.2
7	5	897.7
11	7	987.4
13	9	907.6
17	11	971.1
23	15	963.430
29	19	959.0
33	21	987.4
35	23	956.2
39	25	980.2
41	27	954.1
45	29	975.0
47	31	952.6
51	33	971.1

Higher values of p, m complicate the transfer and the time the PS has to operate at 5.3 GeV gets longer, which would substantially increase the synchrotron radiation dose to be sustained by the PS machine components.

3. BFI Radio-Frequency

The revolution frequency is f_0 = 311.172 kHz in BFI. Since the number of bunches could eventually become k_b = 160, the harmonic number must contain 160 as factor. The precise value of the frequency f in some interesting ranges is given in table 2 in the second column.

Table 2, Possible choice of f

h	f (MHz)	f_i (MHz)	f_i used in	$(f - f_i)/f_i$
160	46.788	–	–	
320 = 2 x 160	99.575	100.111	SPS 7)	$-5.4.10^{-3}$
640 = 4 x 160	199.150	200.395	SPS 4)	$-6.2.10^{-3}$
1120 = 7 x 160	348.513	352.209	LEP 8)	$-1.1.10^{-2}$
1280 = 8 x 160	398.300	400.790	LHC 9)	$-6,2.10^{-3}$
1600 = 10x 160	497.875	499.667	HERA 10)	$-3.6.10^{-3}$
4880 = 30 x 160	1518.52	–	–	–

The first line gives the lowest possible f. The last three columns compare with existing rf systems. It remains to be seen to what extent standard components of these existing rf systems can be used despite of the frequency deviation. The frequency deviation to LEP certainly precludes the use of LEP klystrons according to W. Schnell.

4. Transfer Schemes

4.1 Transfer at 5.3 GeV or 3.5 GeV from PS to BFI

At the end of each PS cycle, a bunch is transferred every

$$\frac{23}{8}\, C_{PS} = \frac{15}{8}\, C_{BFI} \quad (3)$$

according to (1) and (2). Since the revolution time in *BFI* T_0 = 3.21366 μs, (3) corresponds to Δt = 6.03 μs. All bunches could in principle be transferred in 42 μs. However, at 5.3 GeV, 2 modules of the fast PS kicker (FAK) out of the existing 12 have to be fired per bunch transfer. Hence, one has to recharge at least 4 modules after the first 4 bunches have been transferred and, then, transfer of the remaining 4 bunches takes place as has been foreseen for LEP [4]. This recharging lasts only about 30 ms and does therefore not really disrupt the BFI filling. The study of the injection kickers in progress might show that they also require about 100 μs for recharging between bunch transfers. In order to simplify the pulsing of the BFI septum, one could also envisage to study a faster charging of the PS kicker modules to make their recharging equal to the charging time of the BFI kickers.

We consider as example that BFI operates with 32 bunches. The detailed scheme is sketched in Fig. 1 for the first 2 PS cycles. The waiting time for the PS and BFI kicker reloading has been disregarded as irrelevant for the explication of the process. BFI and PS make just the proper integer number of turns in these 30 ms. Fig. 1 shows how the bunches coming from the PS are placed in the first 16 of the 32 collecting BFI buckets as a function of time.

The accumulation will be done through stacking in horizontal betatron phase space in the usual way by moving the equilibrium orbit close to the septum with a fast bump. Radiation damping will reduce the large betatron amplitudes of the injected particles to their equilibrium values so that the bunch can pass close by the septum when the next bunch to be added is injected. The damping times τ_x, shown in table 3, are very long compared to the revolution time T_0 but are very short compared to the duration of one PS acceleration cycle ($\geq$ 0.6 s). Hence, the kicker rise time and fall time must be chosen such that collecting buckets containing already PS bunches injected in the same PS cycle are not bumped to the septum.

Table 3, BFI horizontal damping times

E (GeV)	**3.5**	**5.3**	**8.0**
τ_x ms	**79**	**23**	**6.6**

However, collecting buckets containing particles injected in previous PS cycles can be bumped to the septum without risk of particle loss if the distance between bumped instantaneous orbit and septum is a couple of σ_x because the beam is sufficiently damped. As example, consider the last bunch having PS label 2, injected at the end of the 2nd PS cycle. Inspection of Fig. 1 shows that we require for the BFI injection kickers a rise and falltime t_k.

$$t_k < \frac{T_o(BFI)}{8} = 0.4 \mu s$$

The time elapsed between injection into collecting bucket 6 and bucket 2 (containing bunch 1 of PS) is

$$7 \frac{15}{8} T_0 = 42 \, \mu s << \tau_x$$

and bucket 6 and bucket 10 (containing bunch 3 of PS) is

$$1 \frac{15}{8} T_0 = 6.0 \, \mu s << \tau_x$$

Hence, the buckets 2 and 10 will still contain particles with large amplitudes stemming from the betatron stacking and, therefore, cannot be moved to the septum.

All other collecting buckets falling into the rise and falltime contain PS bunches which had more than a PS cycle time ($\geq$ 0.6 s) to damp. They will be moved towards the septum from time to time but never earlier than 0.6 s after an injection.

It is obvious that a BFI operating with 160 bunches can be filled in the same way. One would simply advance the whole pattern by C_{BFI} / 160 once the first 32 buckets are filled. After having advanced 4 times in total all 160 collecting buckets are filled, and the whole procedure is repeated until the required intensity is reached. The procedure for 80 bunches in BFI is similar.

4.2 Transfer from PS to SPS and from SPS to BFI

We assume first that PS and SPS operate with 8 bunches. The condition for correct transfer from the PS to SPS is

$$m \frac{C_{SPS}}{8} = p \frac{C_{PS}}{8} \quad n, p \; integer \neq even \qquad (5)$$

For $C_{SPS} = 11 \cdot C_{PS}$ the obvious choice is $m = 1, p = 11$
resulting in a bunch transfer every

$$\frac{C_{SPS}}{8} = 11 \frac{C_{PS}}{8} \qquad (6)$$

or every $\Delta t = 2.88 \; \mu s$. The transfer is completed in 20.2 μs.

Since the transfer energy is 3.5 GeV, only one module of FAK in the PS is required per bunch, because there is a new development since the LEP Design Report [4], which foresaw 2 modules per bunch. This is called "Kick enhancement" and is a scheme using pulsed quadrupoles to change the β's in the appropriate positions [12]. Thus, the kicker recharging as at 5.3 GeV is not needed.

The beam for LEP is accelerated in the SPS with the 200 MHz rf system operating with the nominal harmonic number h = 4620 which does not contain 8 as a factor. Hence, 8 equidistant bunches are precluded in the SPS. The bunches are grouped in two families containing 4 equidistant bunches each. The families are spaced $n \; C_{SPS}$ / 28 relative to each other. Since two-turn injection into LEP is used to combine the two families into one in LEP, this splitting in two families is no constraint [4,5].

In principle, transfer to BFI is possible with this bunch configuration in the SPS. After the ejection of the first family, the second family is brought into the correct position prior to ejection by rephasing the SPS relative to BFI. However, since a change to h = 4616 or 4624 is possible when operating with the 200 MHz SW system according to D. Boussard, we prefer to use the equidistant configuration of the 8 bunches, becoming possible with one of the new harmonic numbers that contain 8 as a factor. The transfer becomes more straight-forward. By the way, also the 350 MHz superconducting cavity [11] could be used as its harmonic number 8120 contains 8 as pointed out by D. Boussard.

Now we consider the transfer scheme SPS $-$ BFI in detail. Remember, the PS is used only as transfer line. Since (1) holds, a bunch transfer occurs every

$$23\ \frac{C_{SPS}}{8} = 11\times 15\ \frac{C_{BFI}}{8} = 165\ \frac{C_{BFI}}{8} \qquad (7)$$

or every $\Delta t = 66.3\ \mu s$. The 8 bunches are transferred within 464 μs, if possible recharging of the BFI kickers is ignored.

Since there are again 8 equidistant collecting buckets in BFI, the injection pattern is similar and a kicker risetime and falltime less than 0.4 μs is sufficient.

As pointed out in the introduction, operation with 16 bunches in the SPS could be one of the possible solutions to double the total number of 8GeV electrons provided by the SPS. This would imply either electron bunch cutting in EPA as already tested with the positrons [13] or bunch cutting in the PS. Each of the schemes has important consequences for the kickers. Examination of these questions is left for later. Here we only point out that

1. the PS harmonic hnumber $h = 240$ and one of the new SPS harmonic numbers $h = 4624$ are divisible by 16;

2. bunch transfer of 16 bunches is possible as (7) holds;

3. the BFI kicker would need an upgrading so that their risetime and falltime is halved and becomes less than 0.2 μs.

The transfer through the PS is always performed without using the PS kickers. An injection bump and an ejection bump make the closed orbit pass through the septum gaps. If the septa are powered, the orbit is no longer closed but becomes the appropriate trajectory linking to the injection and ejection transfer line.

5. Conclusions

It has been shown that the circumference of BFI, already approximately defined around 964 m by lattice considerations, has to be 963.430 m to allow for correct transfer. This choice and the maximum number of bunches $k_b = 160$ determine uniquely the possible set of rf frequencies. A subset close to frequencies used in other machines has been given.

Transfer schemes covering the bunch transfer from PS to BFI at 5.3 GeV for the symmetric BFI mode; from PS to BFI at 3.5 GeV and from PS via SPS to BFI at 8 GeV for the asymmetric mode have been outlined for 32, 80 and 160 bunches in BFI. If the risetime and falltime of the BFI injection kickers is chosen to be less than 0.4 μs the kickers cope with the symmetric and asymmetric mode of BFI operating with up to 160 bunches. provided PS and SPS operate with 8 bunches. The existing kickers in PS and SPS do not need any modification.

It might be interesting, possible at a lager stage, to double the 8 GeV electron injection rate by filling 16 buckets in the SPS. We checked that circumferences and harmonic numbers are compatible with this mode of operation. Risetime and falltime of the BFI kickers would have to be halved.

6. References

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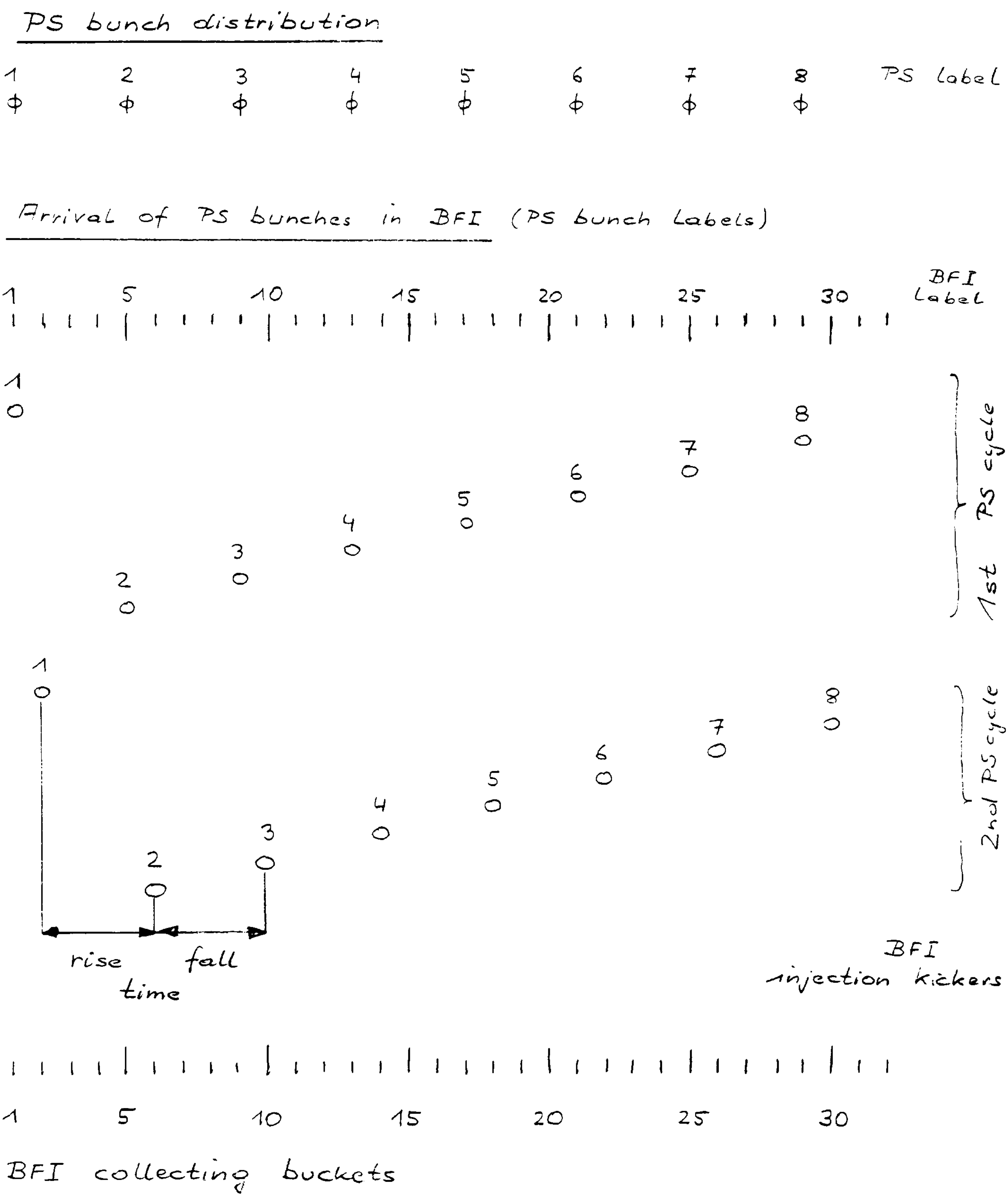

Fig. 1 Transfer of PS bunches to BFI

Example covers 2 PS cycles ;

32 collecting buckets in BFI.

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