EHF - 87 - 43

PS/BR-HS/fp
2 octobre 1987

INJECTION AND ACCELERATION IN AN ISR-TYPE MAIN RING FROM THE EHF 9 GeV/25 Hz BOOSTER

H. Schönauer

1. Introduction

A possible intermediate stage to a full-sized Hadron Facility proposed by F. Bradamante may consist in a slow-cycling Main Ring/Stretcher of 960 m circumference using ISR magnets.

In order to assess RF and power supply requirements, one has to look at possible injection schemes first.

The situation is similar to the one of injection from the TRIUMF Kaon Stretcher (E-ring) into the superconducting 100 GeV-extender TR-100 proposed by J.R. Richardson : A number of batches has to be stacked somehow in a machine of about the same circumference. The beam has to be bunched in view of subsequent acceleration. This immediately excludes the stacking scheme of the ISR leading to an unbunched beam which incidently was accompanied by non-negligible losses.

The two principal stacking options, namely in betatron or in longitudinal phase space have been described by Schönauer [1] and Pedersen [2], respectively.

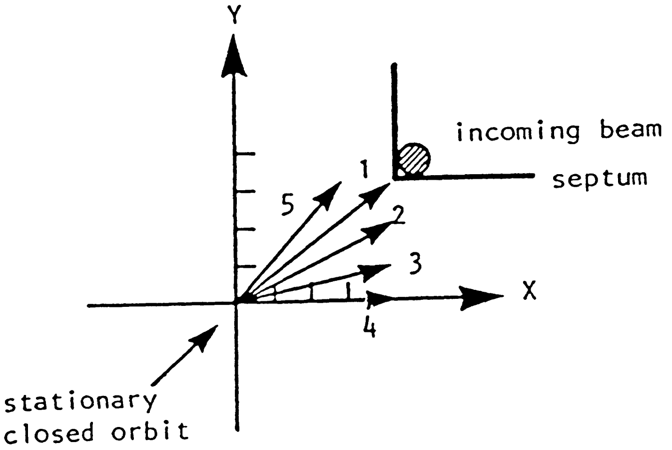
Let us apply their findings to the EHF BOOSTER/ISR combination.

2. Stacking in transverse phase space

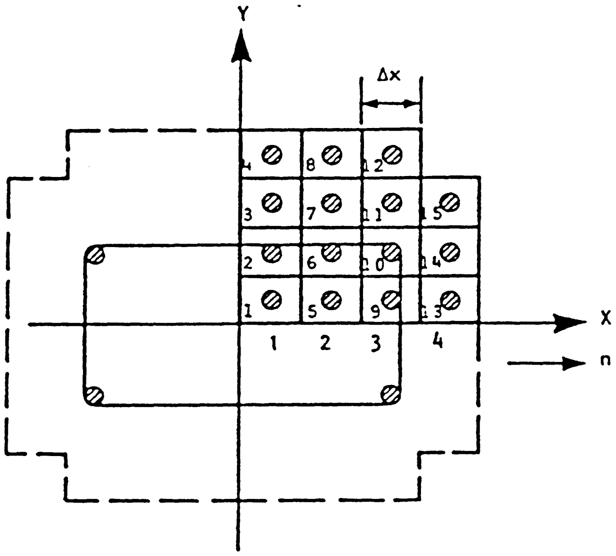
In this case, injection is related to classical multiturn injection, with the difference that injected turns arrive with 40 ms interval. This means replacing the ramping injection bump by a series of programmd kicks (?) which must collapse within the void in the beam. This has the beneficial consequence that the injected beam never hits the septum again and the drawback, that the freshly injected beam has now time to smear out to an annular domain in phase space, entailing a dilution of the phase space area. In other words, the final transverse emittance will be much larger than the injected one times the number of batches injected.

The following description of the scheme is extracted from Ref.[1] and assumes 15 batches to be stacked.

In order to obtain the least possible transverse emittances of the final circulating beam, both H and V planes are involved. This requires an unusual septum, L-shaped in physical space. Injection is best depicted in physical x-y space.



The vectors numbered 1, 2, 3 ... etc. represent the amplitudes of the programmed orbit bumps for the 1st, 2nd, 3rd turn injected. These bumps are programmed such that the final circulating beam is built up by a "grid" of the 15 individual turns:



Each turn fills a square like the one depicted for the 10th turn, wherein it undergoes Lissajous' figures. One ends up with a quasi-elliptic beam cross section whose half axes, X, Y are given by

$$X = n\Delta x$$
$$\Delta x = x + s, \text{ where}$$

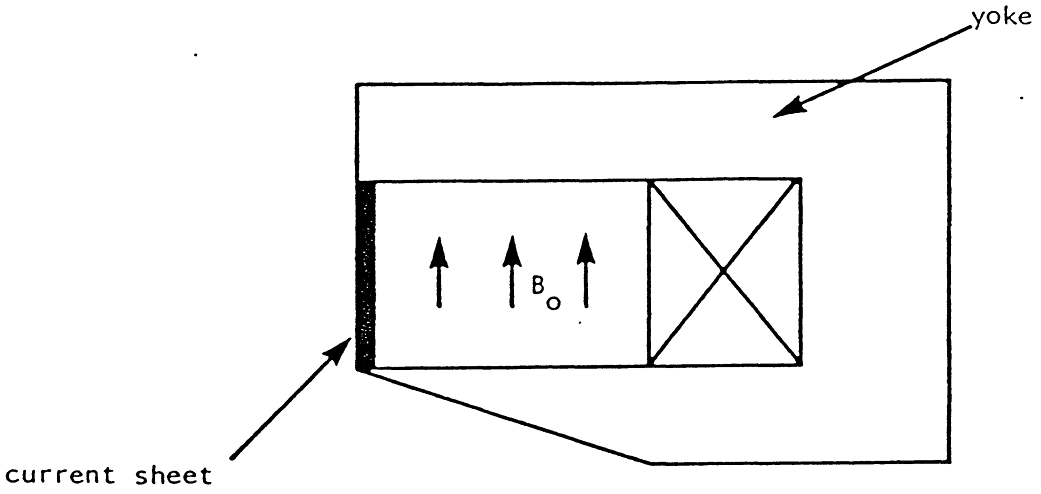
n ... $\sqrt{N_{turns}}$ rounded up to next integer, in our case $\sqrt{15} \rightarrow n = 4$

x ... half width of incoming beam

s ... effective septum thickness, including sagitta, stay-clear area, etc.

The same expressions hold for the Y plane.

The use of an L-shaped septum was already contemplated before the CERN PS Booster was built. A possible realisation might be a Half-Lambertson Septum, introducing a current sheet as reflection plane:



TR#83

If the field inside is limited to conservative figures, the tapered part of the yoke can be kept reasonably thin. At 30 GeV 0.25 T × 2 m give 5 mrad and the special septum could be complemented by a stronger conventional septum downstream.

In any case the tapering angle can be made very small for the low field considered.

For $i = 800$ A/mm^2 and $B_o = 0.25$ T, the current sheet thickness is

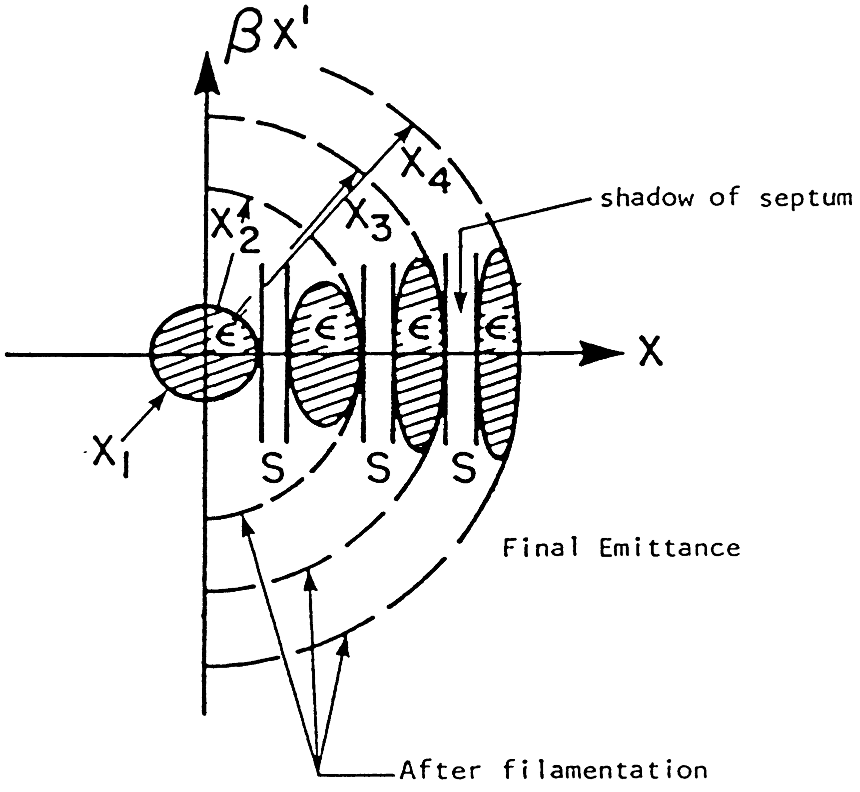
$$d = \frac{B_o}{\mu_o i} = 0.25 \text{ mm}$$

Note that the halo of the circulating D-beam ought to be scraped before extraction: the small percentage lost over the circumference of the Driver appears less harmful than if it were lost on the septum. This also allows the stay-clear zone to be reduced.

However, the scheme of equidistantly distributed turns as described above is too simple as it applies to multiturn-injection where individual turns are injected in a short interval, not allowing the circulating turns to smear out.

This filamentation represents a strong handicap for transverse stacking, as it dilutes the occupied phase-space and leaves little hope of restricting the final emittance to be of the order $E \simeq 2n\epsilon$ (ϵ = emittance of injected turns).

If one tries to optimise the final emittance by varying the matching between injected and circulating beam, one may proceed as suggested in the figure:



(Note that each of the 4 turns shown represents 4 turns distinguished by different amplitudes in the other plane).

Assuming the first turn to be matched (thus depicted on a circle in x, βx' space), the matching condition for the following turns is that the ellipse of the injected turn just osculates the circumscribing circle. Obviously a slimmer (upright) ellipse would increase the final radius after smear-out whereas a rounder one wastes even more phase space.

Emittances

This matching condition leads to another 4th-order algebraïc equ., which was solved numerically for 1 to 4 turns and several equivalent septum thickness S/X_1. Resulting final beam radii, normalized in the radius of the injected beam X1, were given.

Table 1

Normalized Beam Radii Rn/X1 for
n = 1...4 turns injected into x plane

First Beam Radius		n ... # of turns stretched in x			
	S/X_1	1	2	3	4
$\frac{Rn}{x_1}$	0.1	1	2.56	3.93	5.18
	0.2	1	2.65	4.10	5.43
	0.4	1	2.82	4.43	5.94
	0.8	1	3.16	5.12	6.97

The final emittance is then given by

$$\varepsilon_{x,n} = \varepsilon \left(\frac{R_n}{x_1} \right)^2$$

Assuming injection of 2 or 3 turns in the radial and 2 turns in the vertical plane (i.e. a total of 8 or 12 booster batches (480 m in long) into the ISR-main ring C = 960 m and with a typical β -value β ≈ 25 m and a Linac emittance ε = 2.5 π μmrad (26).

	4 turns	6 turns injected
Ex final (2 σ)	17.5 π	40 π
X (2σ)	21 mm	32 mm
Ez final (2 σ)	20 π	
z (26)	22 mm	

To ensure a nearby lossless injection, 2σ values should be replaced by 100% emittances, which have to be guessed. For a parabolic density distribution, this should be a factor 1.5 in emittance.

Let us assume a factor 2 for safety, then the corresponding beam radii would be x (100%) = 45 mm (for 6 turns), z (100%) = 32 mm which leaves a safe margin to the pipe wall, w x h = 80 X 45 mm. A possible halo of the booster beam has to be scraped off in the booster to ensure a clean transfer.

Note that one is free to blow-up the longitudinal emittance simultaneously to a value that stays below microwave threshold.

3. Stacking in the longitudinal phase plane.

An RF stacking scheme for TR-100 was derived by F. Pedersen, which applies equally to our scenario. Again the description is copied from the original work and only frequencies and harmonic number have been corrected for th EHF configuration.

It utilizes a dual harmonic RF system (h = 180 and h = 360), and an injection kicker consisting of a conventional full aperture kicker combined with an RF dipole.

The scheme is less sensitive to longitudinal microwave instabilities than the RF stacking scheme used in the ISR (and proposed for ISABELLE), since both injected and circulating beams are kept bunched at all times. In addition, less momentum aperture is required since the injected beam has the same energy as the circulating beam and no injection kicker shutter is required.

Some problems may arise in the required fast fall time of the RF dipole, and to cope with the relatively heavy beam loading appearing when one of the two RF systems is turned down to low voltage.

<u>Description of Stacking Process</u>

The circulating bunches will initially occupy every second bucket in a h = 360, f = 114 MHz RF system, each bunch occupying a phase space area A_c (fig. 4a).

An additional Booster pulse of area A_i is injected into the empty buckets by an f = 57 MHz RF dipole plus a conventional kicker, (fig. 4b) which cancels the negative half period of the RF dipole leaving the circulating bunches undisturbed by the injection kick. The kicker and the RF dipole will have to have a fall time less than the kicker gaps, which are 5 57 MHz RF periods.

A h = 180 f = 57 MHz RF system is then adiabatically turned on, phase-locked with an appropriate relative phase to the 114 MHz RF, while the latter is adiabatically turned off. The circulating and injected bunches will slowly move towards each other, eventually touching each other (fig. 4d). If the phase relationship between the two RF systems is chosen properly, the circulating bunches will just fill a separatrix with area A_c while the injected bunches will fill an adjacent separatrix with area A_b. Later the two bunches will occupy a common area $A_c + A_i$ enclosed by a common phase space trajectory, and finally be contained in the 57 MHz buckets (fig. 4e).

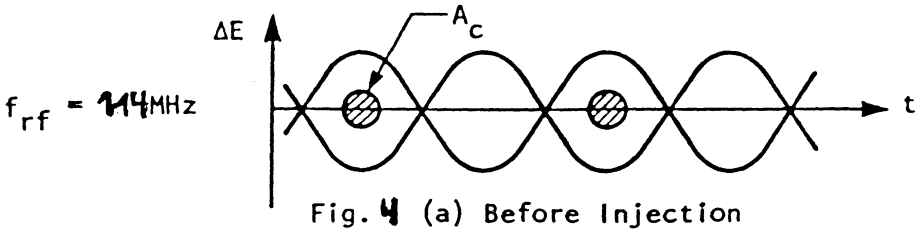
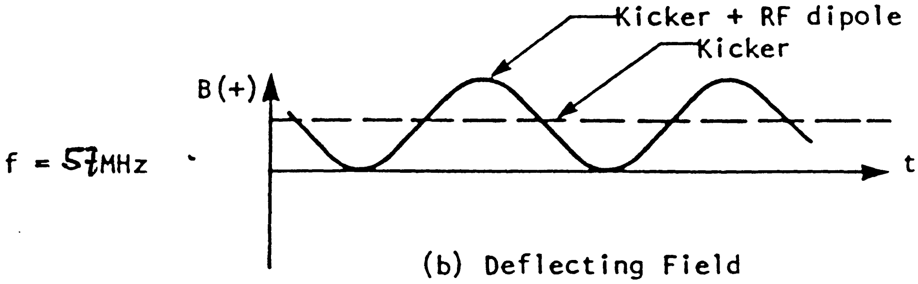
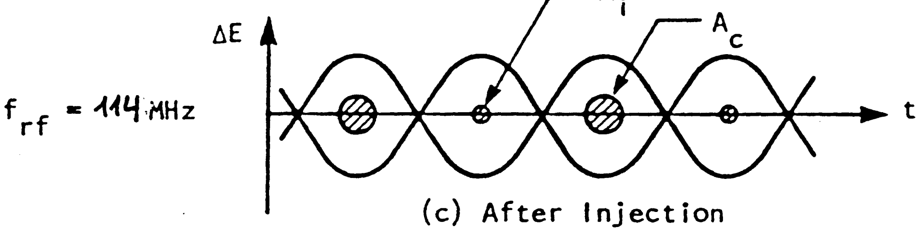


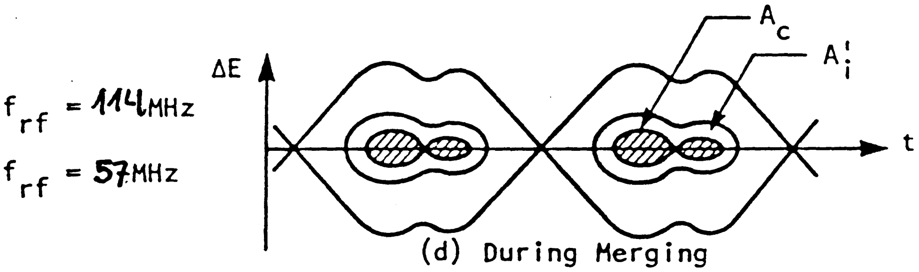
Fig. 4 (a) Before Injection



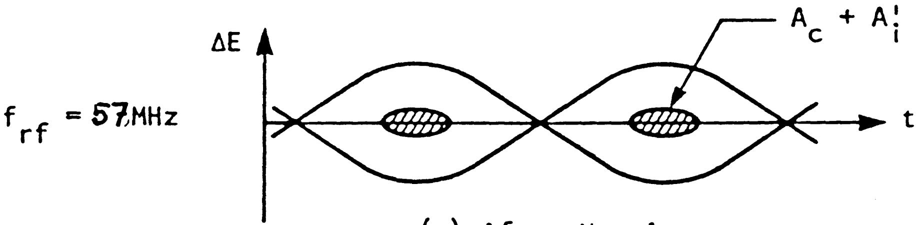
(b) Deflecting Field



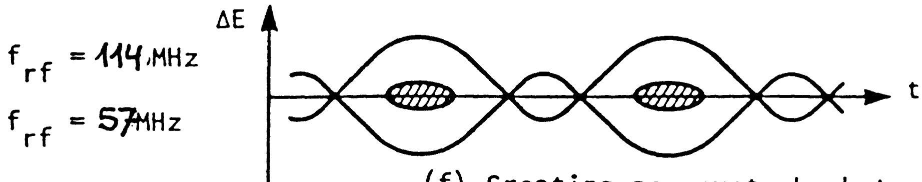
(c) After Injection



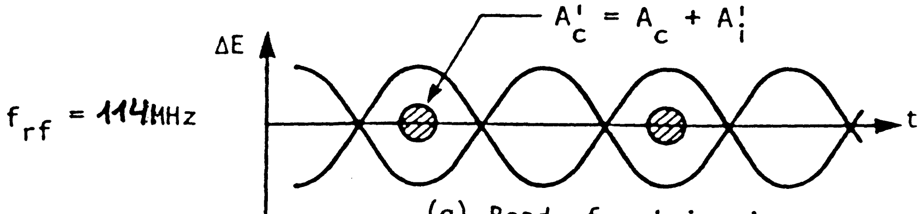
(d) During Merging



(e) After Merging



(f) Creating new empty buckets



(g) Ready for Injection

The 114 MHz RF system is then adiabatically turned on again while the 57 MHz is turned down but this time with a different phase. As soon as the 114 MHz voltage exceeds half the 57 MHz voltage, new empty buckets will form in between the old ones (fig. 4f), and when the 57 MHz RF is off, the circulating bunches will again occupy every second bucket of the 114 MHz RF system, this time with an area $A_c' = A_c + A_i$ per bunch, and the ring is ready for addition of another Driver pulse.

4. Variants of the scenario

Within the frame of a 30 GeV stretcher built with ISR magnets, I try to give a very rough estimate for the extra costs of slowly cycling this stretcher between 30 GeV and 9 GeV, the energy at which it can be "fed" by the EHF injector, i.e. a 1.2 Linac and a 9 GeV, half-size, 25 Hz, 3.1×10^{13} p/p Booster.

As the idea of using ISR magnets was contemplated at an early stage of the TRIUMF KAON project, we can profit from their feasibility study.

One major cost item being the magnet power supply, it could determine the repetition rate. From a study made at TRIUMF [3] in 1984 we learn that its cost varies only little between 0.5 and 2 Hz repetition frequency (cf. the table below).

The other expensive component is the RF system required. Inspection of the possible combinations of repetition frequency and number of booster batches injected, mainly by the RAMA code shows that a minimum bunch area of 0.25 eVs is required for stability regardless of the stacking metthod. This implies a minimum of 6 booster batches, On the other hand, 12 batches is the maximum feasible number for betatron stacking. In practice, it is also a limit to RF stacking as the voltages needed to hold bunches of > 0.5 eVs (6 x 0.075 eVs + 10% dilution during merging) become forbiddingly high.

To estimate the cost of the RF system, we assume that it is essentially determined by the power to be delivered to the beam. From the feasibility study EHF-86-33 we extract (for the Main Ring) a figure of 10 DM/W beam power. Based on this factor, the options and the cost are compiled in the following table. TRIUMF costs quoted in 1983 Can $ are converted into DM by a multiplication with a factor 1.65

References:

1. H. Schönauer : TRI-100: Aperture Requremennts and Injection
   TRI-DN-86-28 , TRIUMF Design Note 1986

2. F. Pedersen : A Dual Harmonic RF System for RF stacking in
   Longitudinal Phase Space for a 100 GeV Extender
   TRI-DN-86-31 , TRIUMF Design Note 1986

3. K. LAcey : Cost Esstimates of Resonant Power Supply Systems
   for ISR Magnets
   TRI-DN-84-24 , TRIUMF Design REport 1984

Table 2

Intensity limits and RF + Power Supply cost for various repetition rates of the slow-cycling Stretcher-Accelerator

frep (Hz)	0.5	1		2		4
# Booster turns stacked	12	6	12	6	12	6
$I_{average}$ (μA)	20		33		50	
V_{RF} (kV)	480	360	650	560	890	920
P_{beam} (MW)	1		1		4	
I_{beam} (A)	25.6	13.4	26.5	13.8	26.3	14.2
V_{RF} (kV) 2nd harmonic	1300	360	1300	360	1300	360
Power supply Cost (MOM)	24	25		26		30
RF Cost + (MDM)	10		20		40	
Costs RF + Power Supply (MOM)	35		46		66	70

N.B. The average intensities given do not take into account the reduction of the duty factor due to the length of the flat top for slow extraction. This length is 80 ms for the nominal 100 μA in the EHF scenario.

5. Conclusions

The table clearly shows that for a chosen intensity, the rep. rate should be as high as possible. Nevertheless frep = 4 Hz may entail some eddy current problems. Thus I believe that the 2 Hz/6 batches/33 μA combination is the winner.