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EURISOL DS/TASK12/TN-06-02

Preliminary design of a Rapid Cycling Synchrotron for the EURISOL Beta-Beam Facility

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1. Introduction.

General considerations concerning the optical design of the Rapid Cycling Synchrotron (RCS) for the Beta Beam facility have been presented on the occasion of the two Beta Beam task meetings held at CERN in April 2005 and at Saclay in last October [1].
Following the trends identified during these meetings and taking into account the updated baseline scenario described in [2], we present here the main characteristics of a RCS pulsed at 10 Hz and capable of accelerating ion beams to energies corresponding to 3.2 GeV protons (magnetic rigidity of 13.4 T.m). A parameter list for the main magnets and for the accelerating system is proposed and first simulation results of the multiturn injection and the fast extraction schemes are given.

2. RCS specifications and lattice design.

In the initial scenario, the RCS repetition rate had been fixed to 16 Hz and $^{6}He^{2+}$ or $^{18}Ne^{10+}$ beams were supposed to be injected at 100 MeV/u and accelerated to 300 MeV/u ($B\rho_{max}$=8.1 T.m for He and 4.86 for Ne). Later, the maximum rigidity was fixed to 8 T.m for both ion species [3] but because of a too large space charge tune shift in the PS, the RCS top magnetic rigidity has been reconsidered and increased to 11 T.m (equivalent to 2.5GeV protons). In the same time, the repetition rate was reduced to 10 Hz in order to increase the accumulation time at the ECR source and therefore to increase the number of ions per pulse.
Taking into account the recommendations made during the meeting held at Saclay in October, we propose now a RCS accelerating He and Ne ions to an even higher maximum rigidity of 13.44 T.m (equivalent to 3.2 GeV protons) at a repetition rate of 10 Hz.
This RCS has a 3-fold symmetry and a circumference of 208 m. Its optical structure is based on a missing magnet FODO lattice providing 3 arcs and 3 dispersion free long straight sections for housing the injection system, the extraction fast kickers and the accelerating cavities.
It is mainly composed of 24 bending dipoles and 42 focusing quadrupoles. The betatron phase advance per FODO cell has been chosen to have a working point located far from low order systematic resonances and to cancel the dispersion function in straight sections with only 2 quadrupole families.
Sextupoles and correction dipoles are inserted between main magnets to compensate for the natural chromaticity and to correct the closed orbit distorsions due to unavoidable misalignments and dipole field errors.

Major parameters of the RCS are summarized in Table 2.1. The dipole bending radius has been fixed to 12 m in order to obtain a peak magnetic field value of 1.12 T at the extraction energy and therefore to reduce the field ramping rate for the 10 Hz operation.
Figure 2.1 shows the optical functions of one super period calculated with the well-known code BETA [4]. The location of the working point in the tune diagram is shown in Figure 2.2. One can see that it is in a region where there are no systematic resonance lines up to the fourth order.

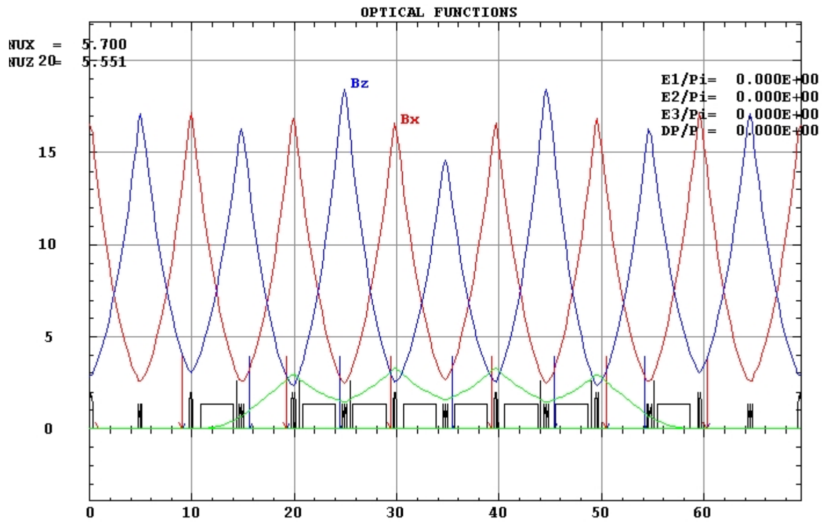

Figure 2.1 RCS optical functions

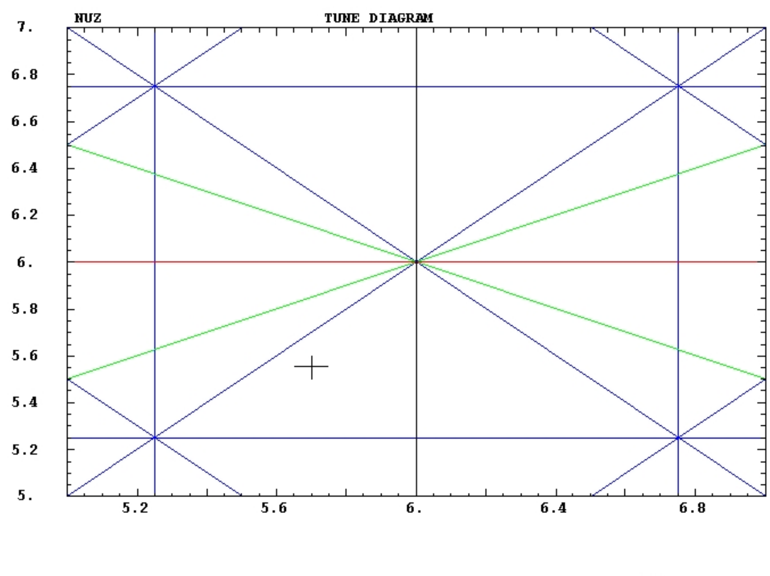

Figure 2.2 Working point in the tune diagram with resonance lines up to the fourth order

Injection energy	100 MeV/u
Extraction energy	3.2 GeV eq. Proton
Maximum rigidity	13.4 T.m
Periodicity	3 fold symmetry
Number of FODO cells	21
Circumference	208.14 m
Horiz/vert. Tunes	5.7 5.55
Repetition rate	10 Hz
RMS horizontal emittance at injection	20 π.mm.mrad
RMS vertical emittance at injection	10.72 π.mm.mrad
Natural normalized chromaticities	-1.55 , -1.22
Transition energy γ	4.48
Number of bending magnets	24
Dipole bending radius	12 m
Dipole length	3,1416 m
Maximum bending field	1,1203 T
Number of quadrupole magnets	42
Quadrupole length	0,4 m
Maximum gradient	<11 T/m

Table 2.1 Lattice parameters

In Figure 2.3, beam sizes at injection (assuming dp/p = 0) are calculated for a total emittance ε_T equal to $5\varepsilon_{RMS}$, that is, 100 π mm.mrad in the horizontal plane and 54 π mm.mrad in the vertical plane.

RMS emittance values at injection in the RCS are deduced from those given at injection in the PS neglecting a possible blow-up.

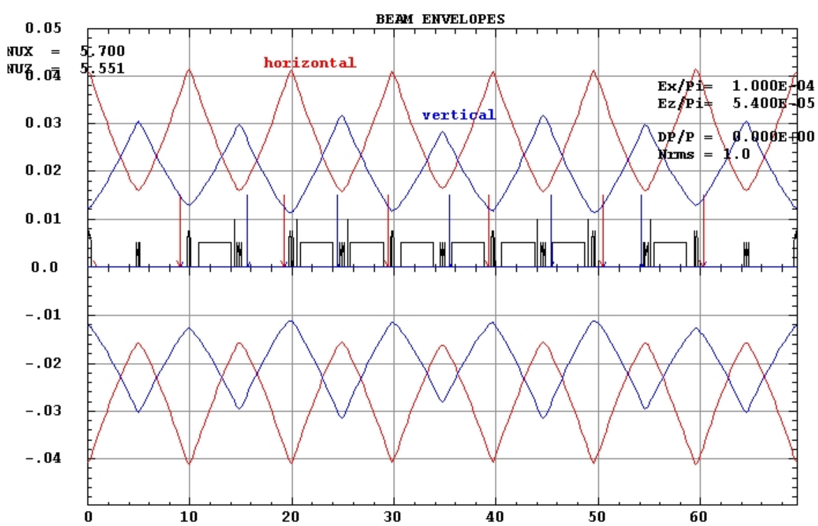

Figure 2.3 Beam envelopes at injection

3. Magnetic field cycle and accelerating voltage.

Bending and focusing magnets are supposed to be excited with resonant circuits.
With a biased sinusoidal ramp, the time variation of the dipole magnetic field is given by :

$$B(t) = \frac{\Delta B}{2}[r - \cos(2\pi f t)]$$

where $\Delta B = B_{max} - B_{min}$ and $r = \frac{B_{max} + B_{min}}{B_{max} - B_{min}}$

At 100 MeV/u, we have:

$$(B\rho) = 4.44 \text{ T.m for } {}^{6}He^{2+} \quad \text{and} \quad B_{min} = 0.37 \text{ T}$$

$$(B\rho) = 2.66 \text{ T.m for } {}^{18}Ne^{10+} \quad \text{and} \quad B_{min} = 0.222 \text{ T}$$

With f = 10 Hz, it follows that :

$$B(t) = 0.745\text{-}0.375 \cos 20\pi t \quad \text{and } (dB/dt)_{max} = 23.57 \text{ T/s for } {}^{6}He^{2+}$$

$$B(t) = 0.671\text{-}0.449 \cos 20\pi t \quad \text{and } (dB/dt)_{max} = 28.22 \text{ T/s for } {}^{18}Ne^{10+}$$

This results in a reasonable peak ramp rate dB/dt of 28 T/s for ${}^{18}Ne^{10+}$ which will determine the required peak accelerating voltage V according to the equation:

$$V\sin\varphi_s = 2\pi R\rho(dB/dt)$$

φ_s being the RF synchronous phase, R the ring physical radius and ρ the dipole bending radius.

Assuming $\sin\varphi_s = 0.5$, in the absence of detailed longitudinal motion calculation, an estimated peak value of V is 140kV in the frequency range of 0.6 to 1.33 MHz for the harmonic number h=1.
This means that five cavities (four + one spare) similar to those built for the J-PARC RCS [5] will be required to provide the necessary voltage. Their length being of about 2 m, there will be no problem to install them in the drifts separating quadrupoles in long straight sections.

4. Closed Orbit and chromaticity correction

4.1 Closed Orbit correction

Closed orbit distortions have been statistically evaluated using a procedure implemented in the code BETA. Main sources of errors are quadrupole and bending magnet misalignments, and bending magnet field errors. In order to correct the resultant distortions, 6 horizontal and 5 vertical correctors coupled with 9 horizontal and 7 vertical beam position monitors (BPM) per period are used as shown in figure 4.1. Table 4.1 gives the RMS error values for dipoles and quadrupoles. The closed orbit distortion before correction is shown in Figure 4.2 and the residual distortion after correction is shown in Figure 4.3. We can see that the maximum distortion is approximately 1 mm in straight sections. RMS deflection angles of horizontal and vertical correctors are given in Table 4.2. The maximal strength is less than 0.3 mrad that is about 13 Gauss.m in terms of integrated magnetic field at 100 MeV/A

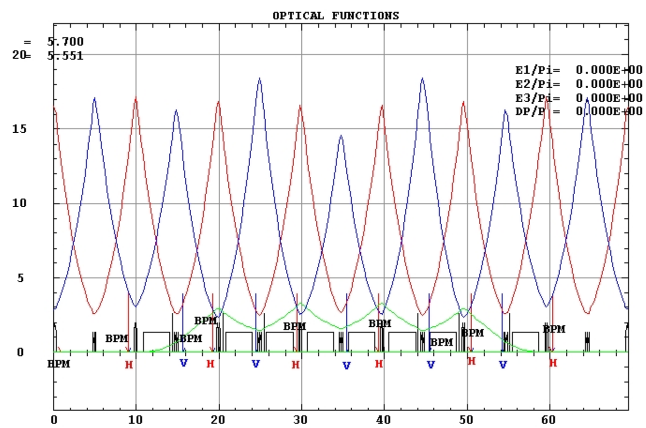

Figure 4.1 Corrector and BPM location in the machine

r.m.s. dB/B DI ( )	.10000E-02
r.m.s. dL DI (m)	.50000E-03
r.m.s. dx DI (m)	.10000E-02
r.m.s. dz DI (m)	.50000E-03
r.m.s. ds DI (m)	.10000E-02
r.m.s. dPhix DI (rad)	.10000E-02
r.m.s. dPhiz DI (rad)	.10000E-02
r.m.s. dPhis DI (rad)	.50000E-03
r.m.s. dAlpha CO (rad)	.10000E-02
r.m.s. dn DI ( )	.10000E-01

r.m.s. dKL/KL QP ( )	.10000E-02
r.m.s. dx QP (m)	.20000E-03
r.m.s. dz QP (m)	.20000E-03
r.m.s. ds QP (m)	.50000E-03
r.m.s. dPhix QP (rad)	.10000E-02
r.m.s. dPhiz QP (rad)	.10000E-02
r.m.s. dPhis QP (rad)	.50000E-03

Table 4.1 Dipole and quadrupole errors at 1 RMS

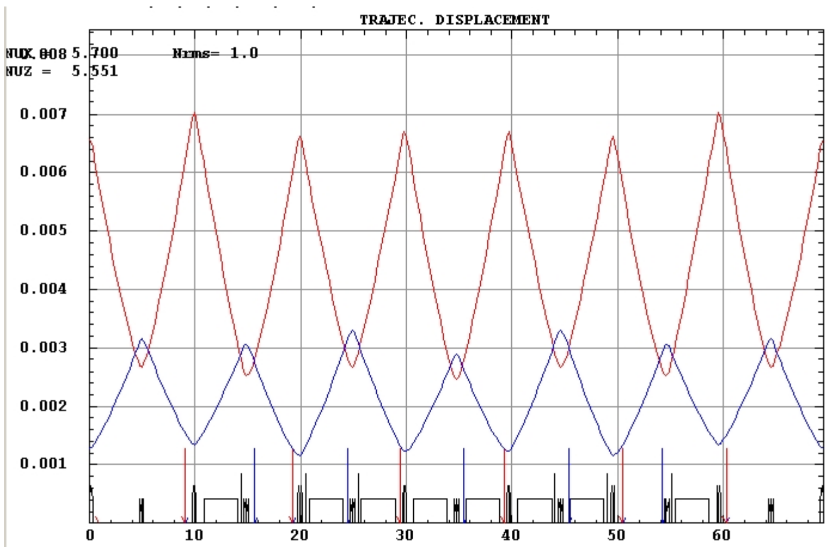

Figure 4.3 RMS closed orbit distortion before correction

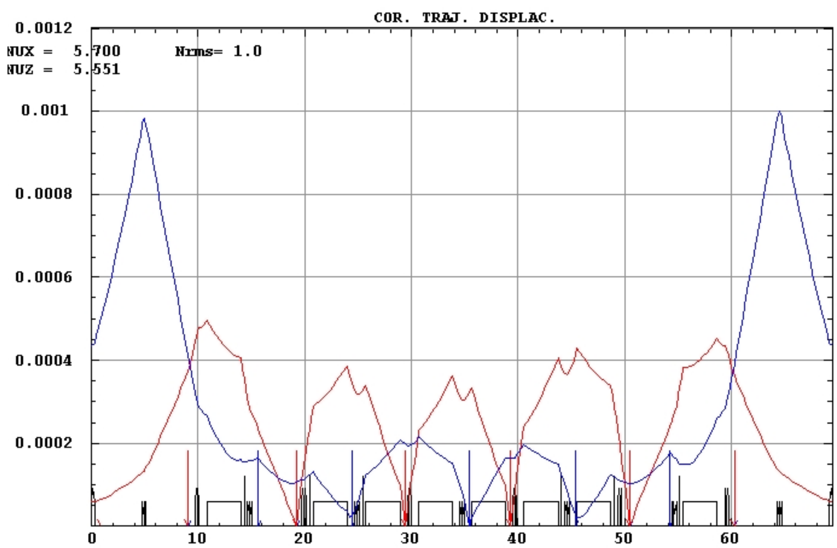

Figure 4.3 RMS closed orbit after correction

CORHOR 1	.21701E-03
CORHOR 2	.22310E-03
CORHOR 3	.28188E-03
CORHOR 4	.28569E-03
CORHOR 5	.23466E-03
CORHOR 6	.20875E-03

CORVER 1	.13366E-03
CORVER 2	.14783E-03
CORVER 3	.15858E-03
CORVER 4	.15257E-03
CORVER 5	.12794E-03

Table 4.2   Corrector strength (rad)

4. 2 Natural chromaticity correction

Correction of the RCS natural chromaticity is performed with sextupoles inserted in the arcs. Figures 4.4 and 4.5 show the chromaticity variation in one period before and after compensation. The maximum integrated sextupole strength ½ B”L/Bρ is 0.27 m^{-2} ignoring the chromaticity induced by eddy currents in dipole vacuum chambers.

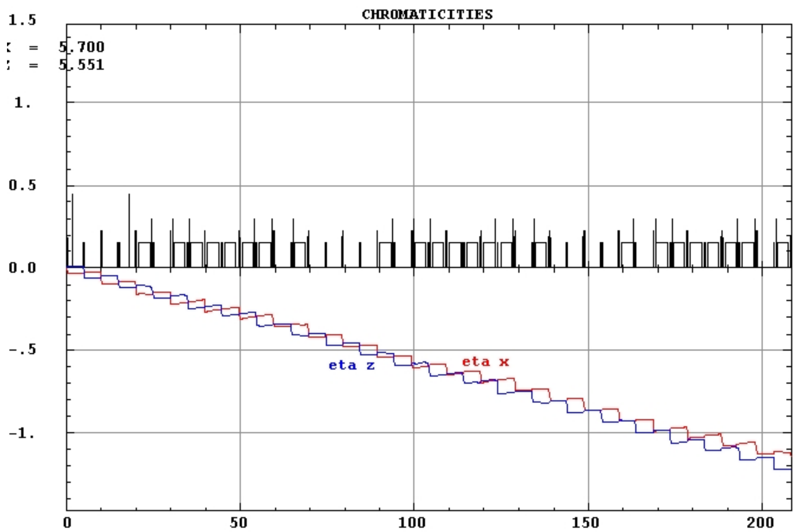

Figure 4.4 Natural chromaticity before correction

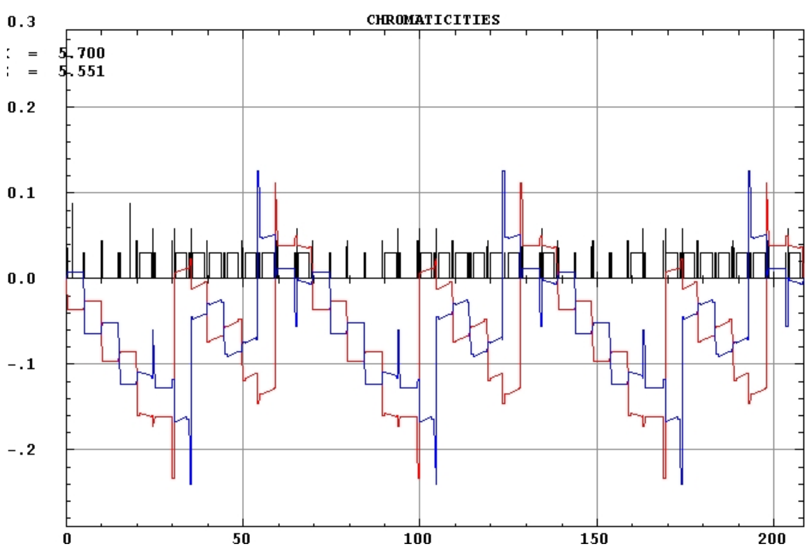

Figure 4.4 Natural chromaticity after correction

5. First studies of multiturn injection.

Preliminary simulations of the multiturn injection process have been carried out with the code WinAGILE [6] neglecting space charge effects and small variations of the pulsed magnetic field. The revolution period of ions at injection being about 1.6 μs, the number of turns that has to be injected for a source pulse of 50 μs is equal to 31.
The total emittance being 50 π mm.mrad at 50 kV [3], emittance values of the incident beam at 100 MeV/u have been taken equal to 1 π.mm.mrad and 1.5 π.mm.mrad. For each case, the filling of 100 π.mm.mrad (5 RMS values) and 80 π.mm.mrad (4 RMS values) has been simulated. Optimum filling of phase space has been achieved with a closed orbit bump produced by two or three pulsed dipoles of 4.5 mrad maximum strength.
The end of the injection septum wall is approximately set 40mm from the central orbit of the ring so that the number of turns for the bump to collapse is 41. The horizontal β function is 9 m at the exit of the septum.

Phase space distributions of the injected beam at the end of the process are shown in the Figures 5.1 to 5.4 and the injection efficiency are given in the Table 5.1.

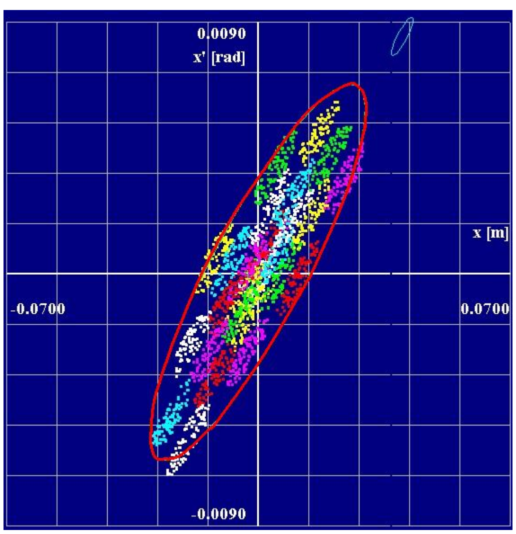

Figure 5.1 Injected total emittance of 100 π.mm.mrad after 41 turns with an incident beam emittance of 1 π.mm.mrad.

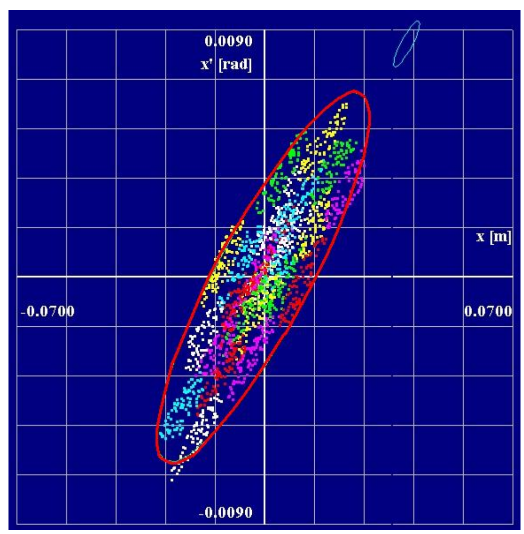

Figure 5.2 Injected total emittance of 100 π.mm.mrad after 41 turns with an incident beam emittance of 1.5 π.mm.mrad.

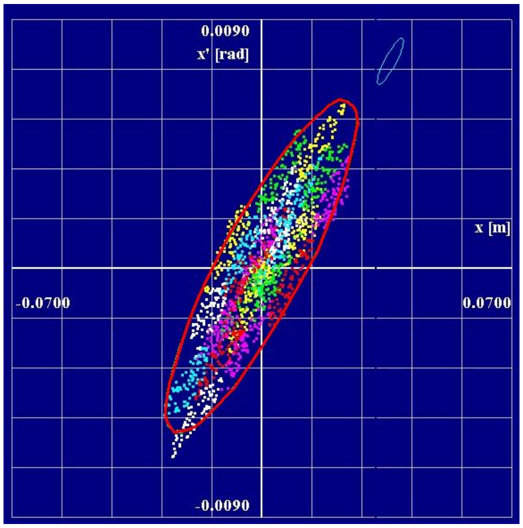

Figure 5.3 Injected total emittance of 80 π.mm.mrad after 41 turns with an incident beam emittance of 1 π.mm.mrad.

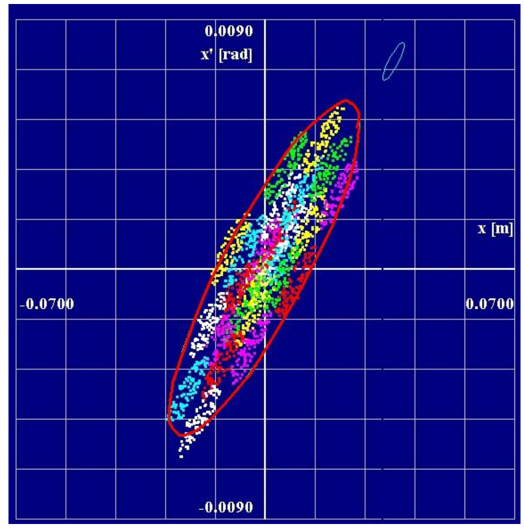

Figure 5.4 Injected total emittance of 80 π.mm.mrad after 41 turns with an incident beam emittance of 1.5 π.mm.mrad.

	100 π.mm.mrad	80 π.mm.mrad
1 π.mm.mrad	79%	63%
1.5 π.mm.mrad	79%	60%

Table 5.1 Multiturn injection efficiency

6. Fast extraction system

The extraction system consists of 7 fast kickers (numbers 1 to 7 in Figure 6.1) and 3 septum magnets (symbolized by kicks 8, 9, 10). The kicker layout located upstream of a defocusing quadrupole is designed to produce a sufficient separation between the circulating and the extracted beams at the entrance of the first septum magnet. Then, septum magnets produce the needed deflection angles to eject the beam from the ring and to avoid the yoke of the next quadrupole. Figure 6.1 shows the beam envelope at injection in red (emittance of 100 π.mm.mrad) and the beam at extraction in blue (emittance of 33 π.mm.mrad).
Kicker and septum magnets are assumed to have characteristics and performances similar to those that have been designed for the 3 GeV proton beam extraction of the J-PARC RCS [7]. The deflecting angles required in our case are listed in Table 6.1.

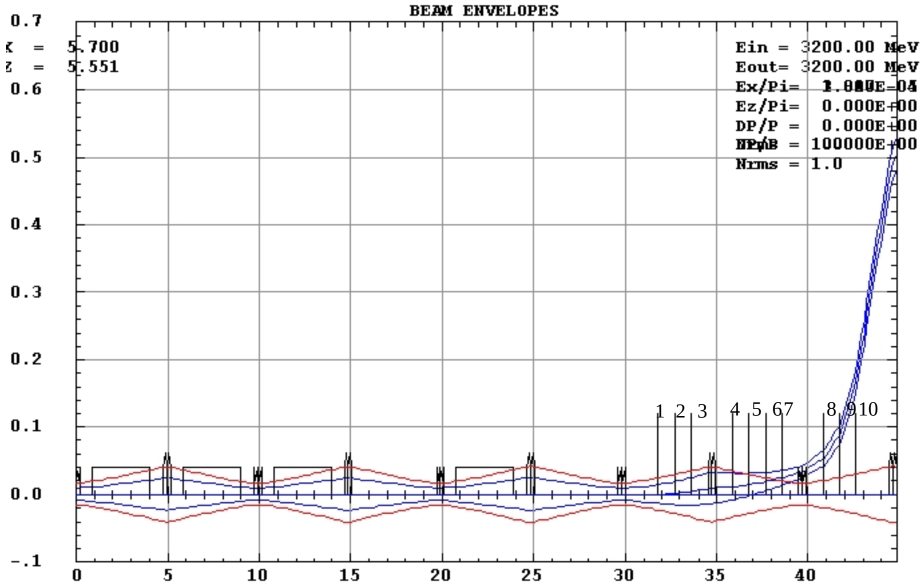

Figure 6.1 Extracted beam(blue line) and injected beam (red line)

1	1,50
2	1,50
3	1,50
4	1,50
5	1,50
6	1,50
7	1,50
8	20,00
9	50,00
10	80,00

Table 6.1 Kicker and septum magnet deflecting angles (mrad)

References.

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Appendix.

RCS structure input for the code BETA.

*** LIST OF ELEMENTS ***

```
QP1     QP  .2000000E+00  -.735966E+00   .0000000E+00
QP2     QP  .2000000E+00  .777186E+00    .0000000E+00
SX2     SX  .1000000E-06  -2.72064E6     .0000000E+00  .0000000E+00
SX1     SX  .1000000E-06  2.168E6        .0000000E+00  .0000000E+00
COIE    CO  .1308990E+00  0.120000E+02  .0000000E+00  .0000000E+00 .0000000E+00
DIP     DI  .2617990E+00  0.120000E+02  .0000000E+00  .0000000E+00
COIS    CO  .1308990E+00  0.120000E+02  .0000000E+00  .0000000E+00  .0000000E+00
SD1     SD  .7000000E+00
SD2     SD  .7000000E+00
SD3     SD  .314159E+01
SD4     SD  .324159E+01
SD5     SD  .350000E+00
SD6     SD  .350000E+0
SD10    SD  0.50
SD11    SD  0.2
SD12    SD  0.2
```

*** STRUCTURE ***

```
QP2   SD2   SD3   SD1   QP1   QP1   SD1   SD3   SD2   QP2
QP2   SD11  SD10  COIE  DIP   COIS  SD6   SX2   SD6   QP1
QP1   SD10  SD11  SD4   SD12  SD10  QP2   QP2   SD5   SX1
SD5   COIE  DIP   COIS  SD10  SD12  QP1   QP1   SD5   SX2
SD5   COIE  DIP   COIS  SD10  SD12  QP2   QP2   SD10  SD12
COIE  DIP   COIS  SD1   QP1   QP1   SD10  SD11  COIE  DIP
COIS  SD10  SD12  QP2   QP2   SD2   COIE  DIP   COIS  SD5
SX2   SD5   QP1   QP1   SD10  SD12  COIE  DIP   COIS  SD5
SX1   SD5   QP2   QP2   SD2   SD4   SD10  SD11  QP1   QP1
SD6   SX2   SD6   COIE  DIP   COIS  SD1   QP2   QP2   SD10
SD12  SD3   SD1   QP1   QP1   SD1   SD3   SD2   QP2
```