# 3.2 Booster Synchrotron

## 3.2.1 Modified FODO Lattice

It is clear, that, with the location of the booster in the ring tunnel, the shape of the booster lattice has to follow closely the shape of the storage ring (in the following just called "ring" for short). In this respect the new dodecagon lattice for the ring is easier to follow than the original hexagon lattice.

After having fixed the circumference of the ring to 288m we have chosen for the booster a value of 270m. This gives an average radial separation of 2.9m between the two machines, which ensures a tolerable magnetic stray field effect from booster to ring.

The chosen circumferences have a ratio of 16:15. The corresponding harmonic numbers are 480 and 450 , both numbers having many common prime factors.

The booster lattice has the same **threefold symmetry** as the ring: It consists of 3 arcs with 3 straight sections of 8.68m length. These are positioned opposite the 3 long straight sections (11.76m each) of the ring, giving a smooth radial separation between ring and booster (see fig. f321_a). The basic lattice parameter are listed in table t321_a.

The basic structure of the arc lattice consists of 13 unit cells, each with two combined function magnets, BD and BF, separated by 1.44m long drifts (socalled FODO structure). At each end of this periodic structure we add a matching cell consisting of a modified FODO cell and a straight section (see fig. f321_b). The free space for the RF-cavity is 2.34m.
The basic focusing properties of the booster lattice are "stamped" into the iron profile of the combined function magnets. But three families of quadrupoles, located in the straight sections, can be used to provide a tuning range of about 1 unit in the horizontal and vertical direction whithout perturbing the betafunctions too much (fig. f321_c). With these quadrupoles one can compensate
possible gradient errors in the combined function magnets up to about $\pm$1%.

In the choice of the bending angles and gradients of the combined function dipoles one had to consider some constraints:

- Simultaneous damping in transversal and longitudinal phase space
- small bending angle in the BF dipole (horizontally focusing, maximum values for dispersion and $\beta_x$), in order to produce a small emittance value.
- the wish to have identical currents in both BD and BF conductors, in order to have a common power supply circuit for all dipoles. This still leaves some flexibility by playing with the number of turns.

The result of this optimizing process is summarized in table t322_a of the chapter on the booster magnets. One can see that the magnet BF is actually a half quad with more focusing than bending, whereas in the BD magnet the bending dominates.
The phase advance in the basic unit cell is about $90^0$ horizontally and $60^0$ vertically. This gives an equilibrium emittance of 9nm at 2.4GeV. One could produce even smaller emittance values with this lattice, but at the expense of stronger gradients and tighter tolerances.

It is advantageous to have the straight sections dispersionless, since both the RF-cavity and the injection elements are located in these straights. To achieve this one installs normally extra quadrupoles or provides special dipoles with reduced lengths at the end of the arc. For the

SLS booster we used the trick of modifying the two drifts in the last FODO cell. This way all the BD and all the BF dipoles are identical.
As mentioned, the lattice functions for the matching section plus two basic FODO cells are shown in fig. f321_b. As one can see, the $b_y$-value is everywhere below 10m except in the BD dipole next to the straight section, where it is 15.5m. It is now interesting to note, that by varying the two quadrupoles in the straight on can obtain a solution, where $\beta_y$ is everywhere below 12m, but has now a periodic beat over 3 basic cells (waltzing solution)! The horizontal behaviour is relatively unaffected by this detuning procedure. The corresponding lattice functions for a $120^0$ arc are displayed in fig. f321_d.

A first order **chromaticity correction** is incorporated into the pole profile of the booster dipoles. However we still plan to install two families of sextupoles (SF and SD) with three pairs of sextupoles in each arc. These magnets will give flexibility in optimizing the chromaticity. In addition they will correct the sextupole component induced by eddy currents in the vacuum chamber, estimated to be less than 0.3 $m^{-3}$ in the BD dipole at injection. The choice of about $90^0$ resp. $60^0$ phase advance in the FODO cells of the three arcs gives a very efficient correction scheme with noninterleaved sextupoles.

This FODO-lattice has surprisingly **relaxed tolerances**. As an example a statistical positioning error of 0.1mm (rms) gives a corresponding closed orbit deviation of 0.6mm horizontally and 0.9mm vertically (see fig. f321_e). The dynamical aperture is about 30mm rad in both planes (see fig. f321_f), comfortably above the geometrical apertures given by the $30*20mm^2$ vacuum chamber.
The energy acceptance of the lattice would be $\pm$7% (see fig. f321_g), but the maximum RF voltage of 0.5MV limits the bucket size to $\pm$0.43% at 2.4GeV.

In a synchrotron the beam values for emittance, energy spread and bunch length vary considerably during acceleration. Fig. f321_h shows a plot of these values during a 3Hz ramping from 100MeV to 2.4GeV. At the maximum energy one needs an RF voltage of about 0.5MV to cover the synchrotron radiation loss. At injection it is advantageous to lower this voltage to about 0.22MV to avoid large energy oscillations. The corresponding energy acceptance is then $\pm$2%, well adapted to the similar acceptance given by the vacuum chamber. Fig. f321_i shows the RF bucket of the booster at injection.

## *Beam aperture requirements:*

The choice of the vacuum chamber dimensions are governed by the transversal and longitudinal beam values at injection. In the transversal direction we assume a normalized emittance at the Linac exit of 50mm rad and an energy spread of 0.4 % rms. In the booster we assume as maximum values for the $\beta$-values 13m in both planes, taking some beating into account . Requiring values of 3 $\sigma_x$ and 3 $\sigma_y$ for the beam amplitude and 4mm for closed orbit distortion we would arrive at a round beam pipe with an inner radius of 10mm. However in the horizontal direction we need about 5mm more amplitude due to the energy dispersion. Adding both the contribution from emittance and energy spread we obtain an energy acceptance of $\pm$2% for a quadratic addition (or $\pm$1.0% for linear addition). With this model we arrive thus at the chosen elliptical chamber with inner dimensions of $30*20mm^2$.

## *Closed Orbit Correction:*

The accuracy for the initial alignment of all booster magnets is estimated to be about 0.15mm rms. This would lead to closed orbit deviations which are about a factor 6 higher in the horizontal direction resp. about a factor 10 higher in the vertical direction. This corresponds to rms deviations of about 0.9mm rms horizontally resp. about 1.5mm vertically. The corresponding maximum deviations can be up to 3 times higher than the rms values. Correction magnets are required to compensate these orbit deviations. One pair of individual correctors for the x- and y- direction will be placed in every FODO cell. The required maximum deflection angle is about 0.4mrad.

## *Residual Fields at Injection:*

The magnetic fields of all magnets have to track very accurately during the ramping process between injection and extraction. We will use powersupplies with programmable cycling profiles. Differences between the magnetic response of the combined function magnets, quadrupoles and sextupoles can thus be handled accordingly. However we plan to put all combined function magnets in series and use the same main powersupply for both the BD and the BF type.

The problem is now, that at the injection energy of 100MeV the magnet fields are quite low with 30mT resp. 6.6mT. The residual fields due to the finite coercivity leads to a perturbation in the accurate tracking between BD and BF. The focusing tunes are perturbed as well, since these magnets have a gradient which is proportional to the deflecting field.

To compensate for this effect we plant to use an extra coil on all BF magnets. A single turn on each pole will do the job, since the required correction is only about 0.2mT.

## *Extraction:*

We want to keep the transferline between booster and storage ring as short as possible. Extraction from the booster occurs thus from a drift in the regular arc section. We adopt the standard solution with a fast kicker followed by a septum magnet. (figure f321_k).

The large circumference of the booster gives a revolution time of 0.9µs and allows a relatively relaxed kicker risetime of about 0.2µs.

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|---|---|
| Circumference | 270 m |
| Symmetry | 3 arcs of 90 m |
| Number of FODO cells/arc | 13 |
| Length of FODO cell | 5.14 m |
| Length of matching cell | 11.59 m |
| Drift between dipoles | 1.44 m |
| straight section | 8.68 m |
| largest drift in straight | 2.34 m |
| vacuum chamber | $30 \cdot 20\ mm^2$ |

**table t321_a:** Booster Lattice Parameter

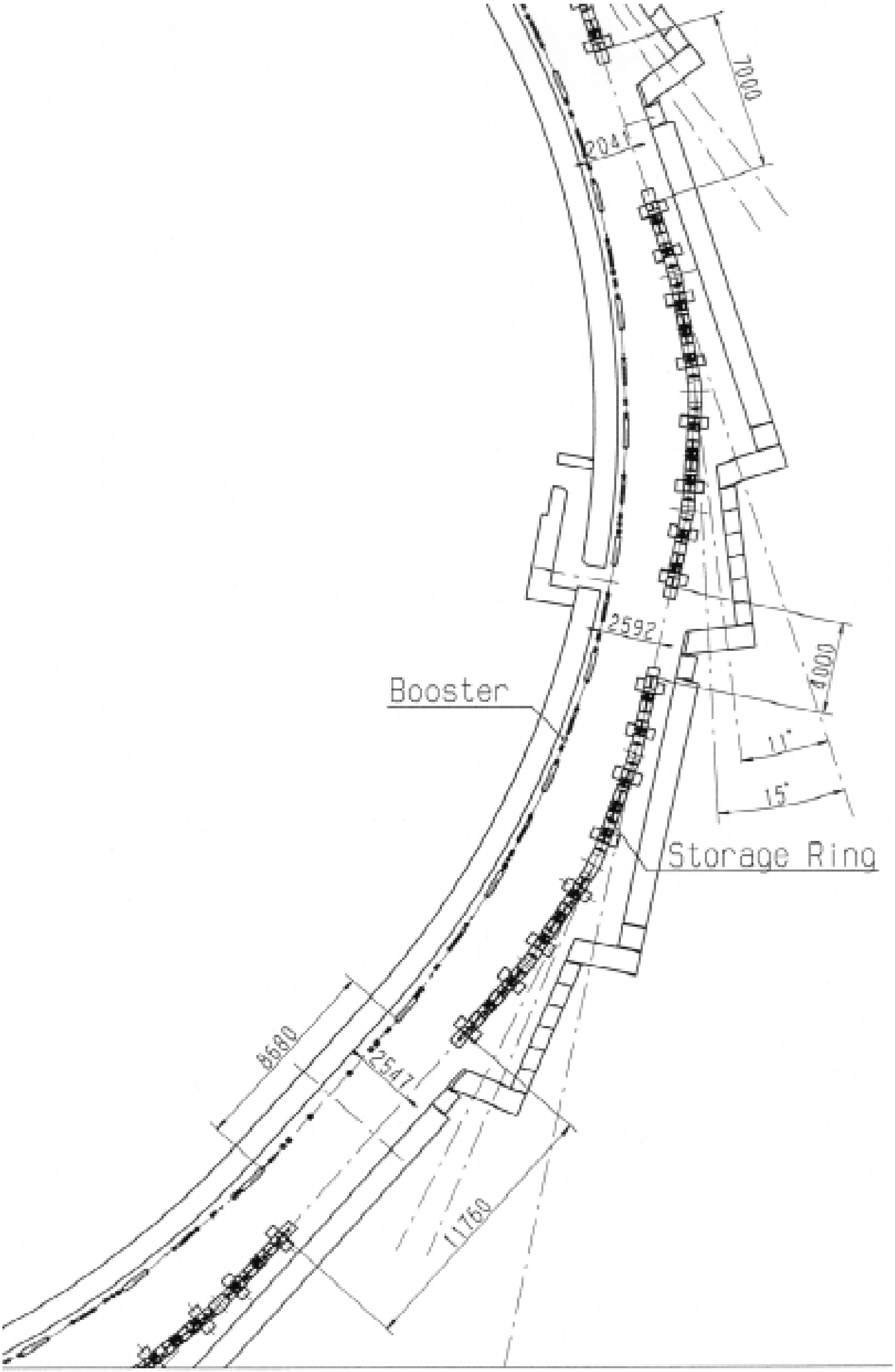



**Figure f321_a:** Top view of one quarter of the booster (inside ring) and the storage ring. The largest separation between the two rings is 3.4m.

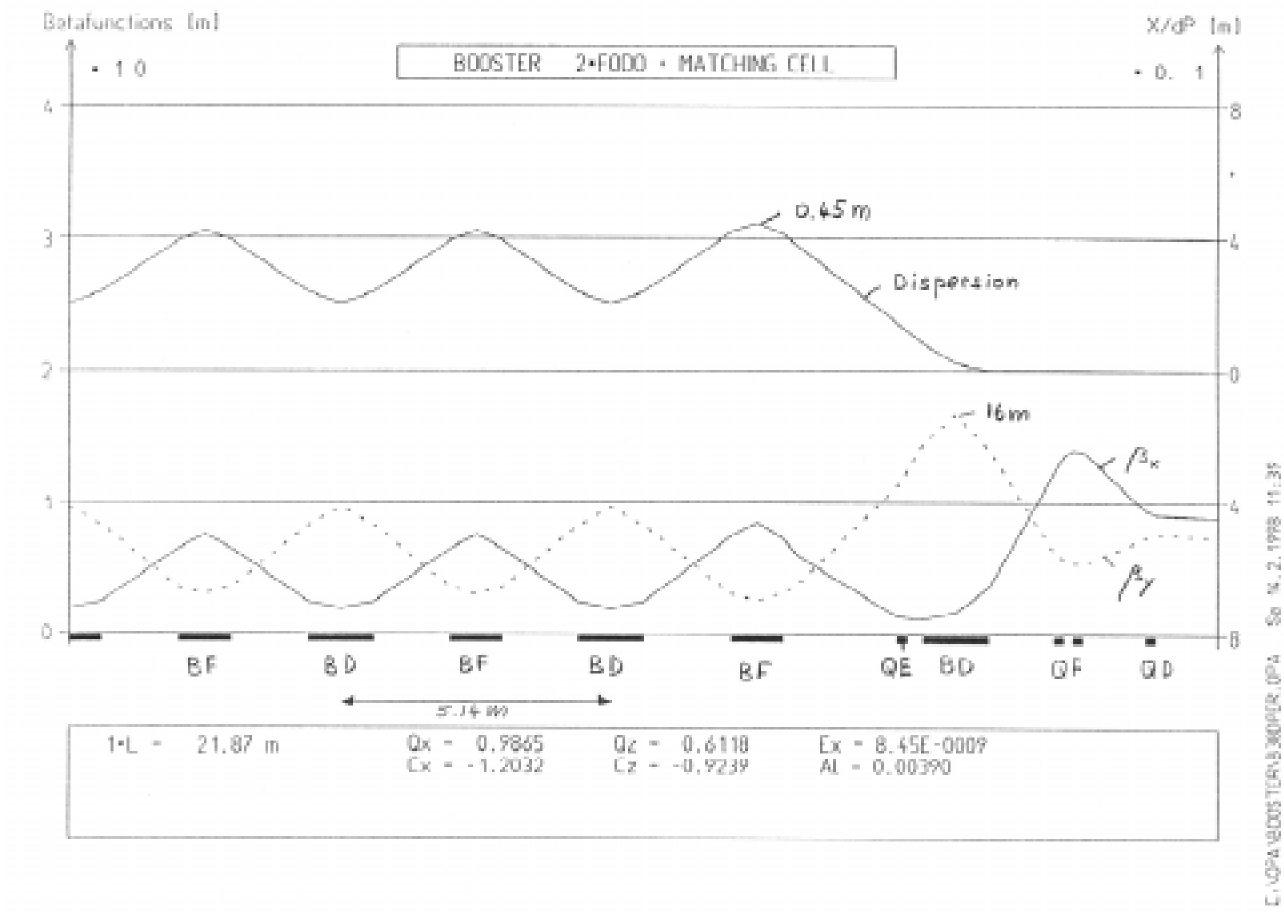



**Figure f321_b:** Lattice functions of two unit FODO-cells plus the matching cell to the 8.68m straight section. The last two drifts between the dipoles BD and BF are adjusted to have zero dispersion in the straight. The quadrupoles QA, QF and QD can be used to provide some tuning range in x and y.

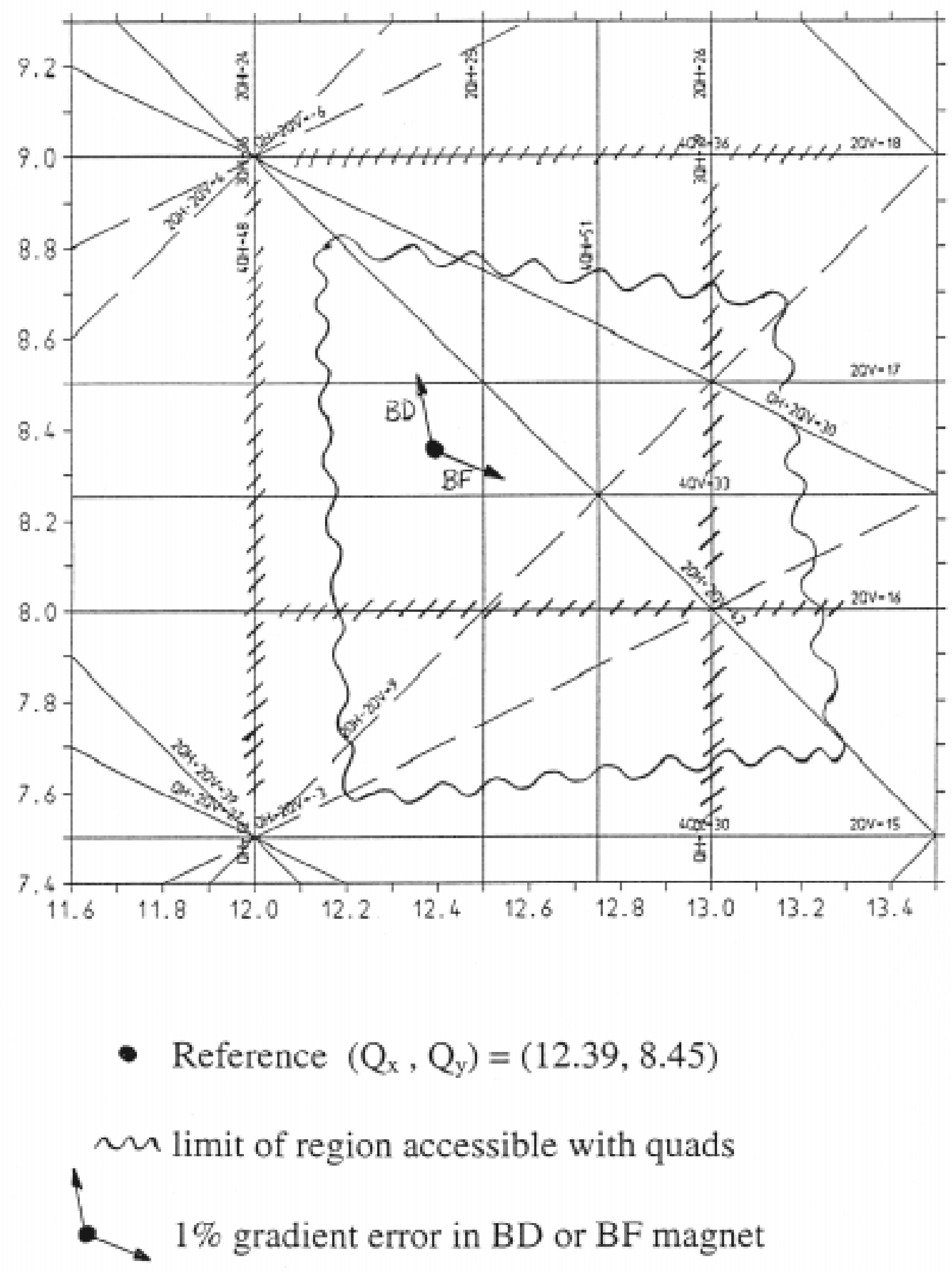



**Figure f321_c:** Tune diagram showing the reference point plus some neighbouring resonances. The region inside the wavy limits is reachable by detuning the 3 families of quadrupoles. An error of 1% in the gradients of BD and BF can be compensated as well with these quadrupoles.

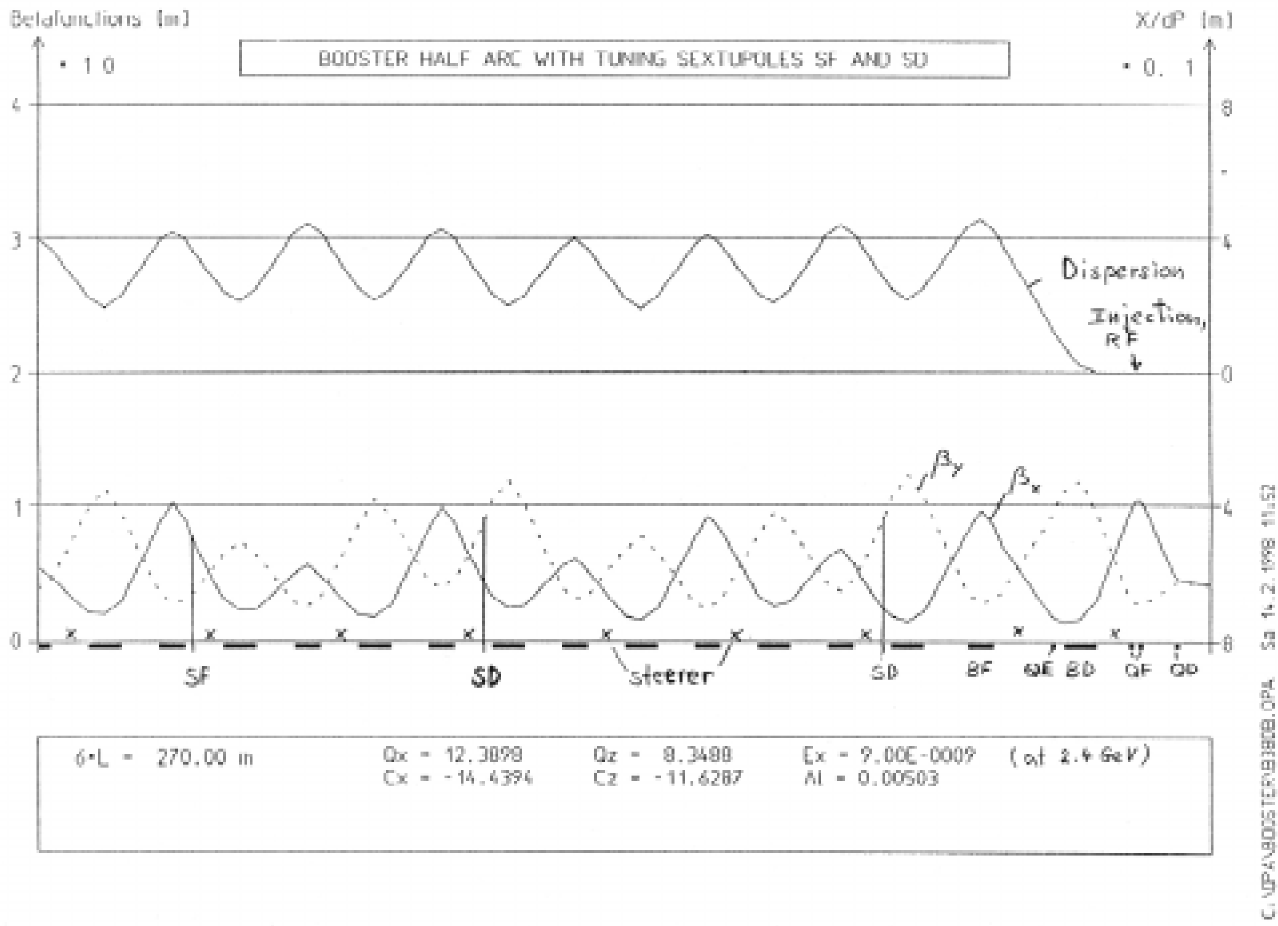
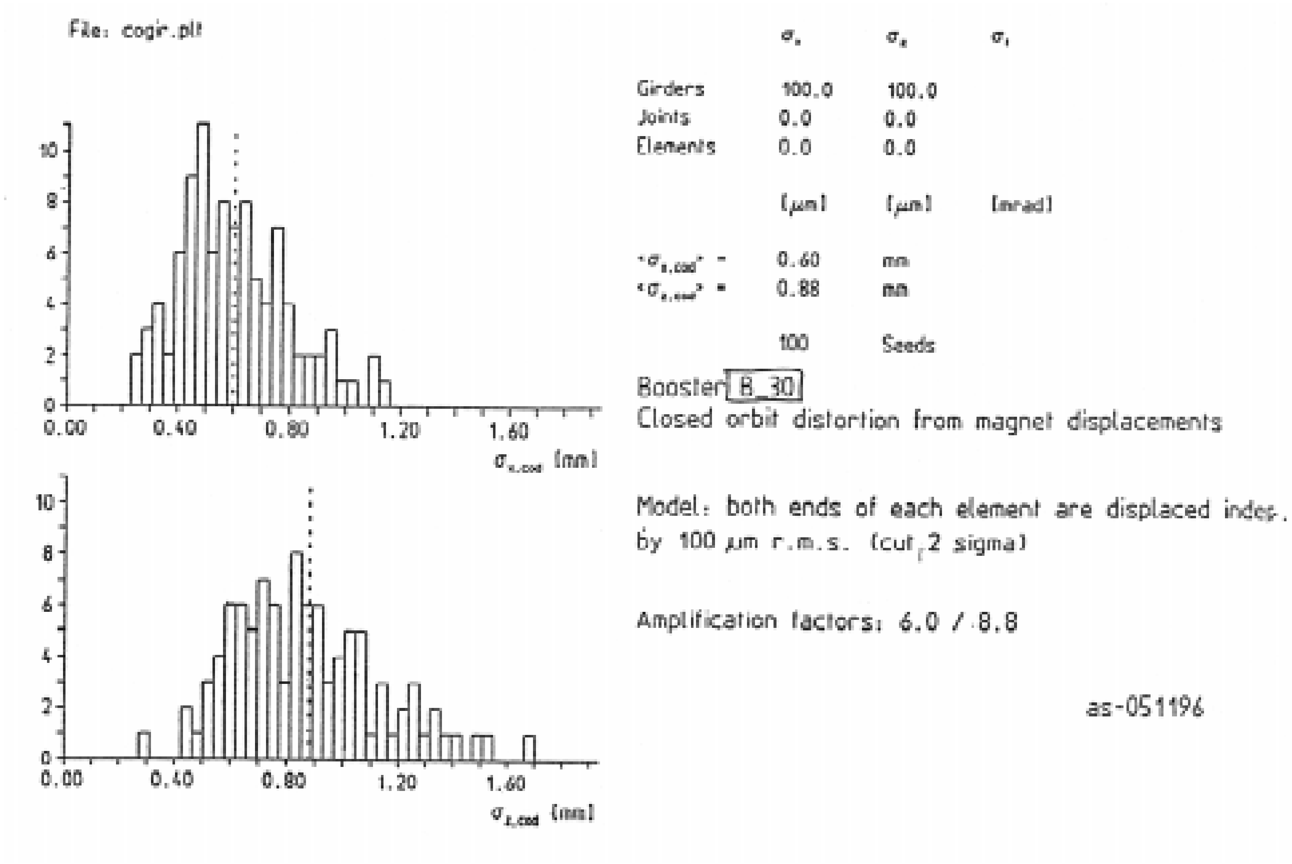
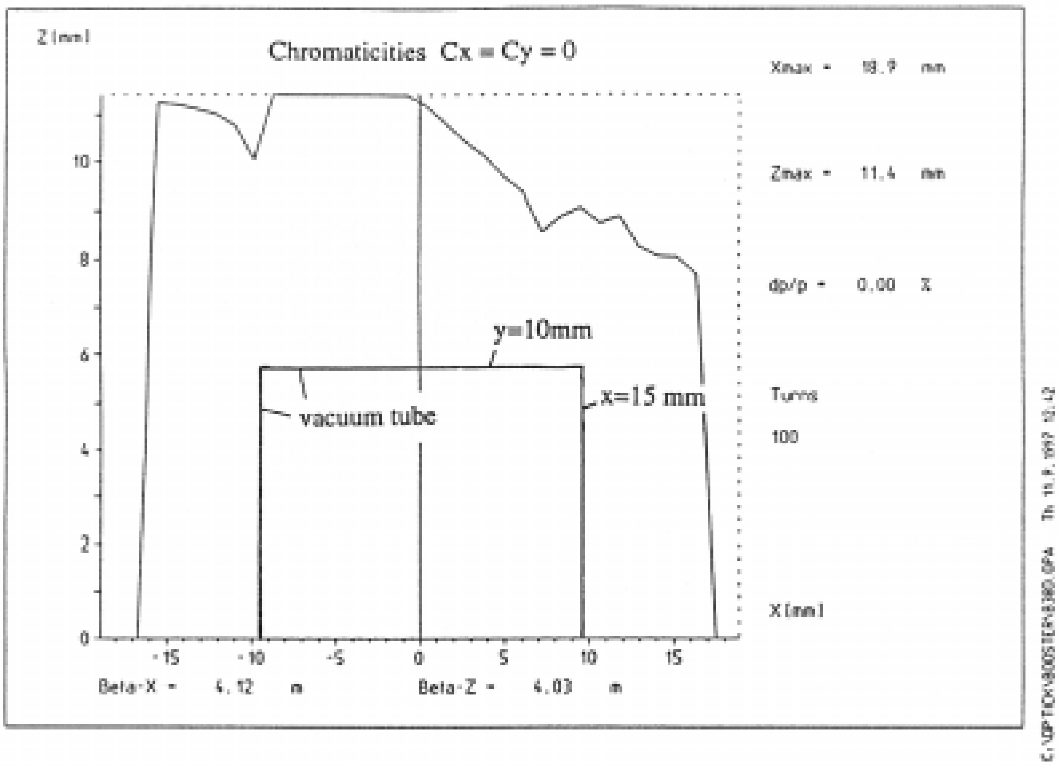



**Figure f321_d:** Lattice functions for half an arc (=1/6 of the booster circumference) with a vertically detuned "waltzing" solution. The maximum value of $\beta_y$ is reduced from 16m for the regular solution to about 12m, with a corresponding increase in the vertical acceptance given by the vacuum chamber.




**<u>Figure f321_e:</u>** Distribution of closed orbit deviations from statistical positioning errors in the booster dipoles by 0.1mm (rms). The amplification factors of 6 and 8.8 for the horizontal and vertical direction indicate a relatively tolerant lattice.



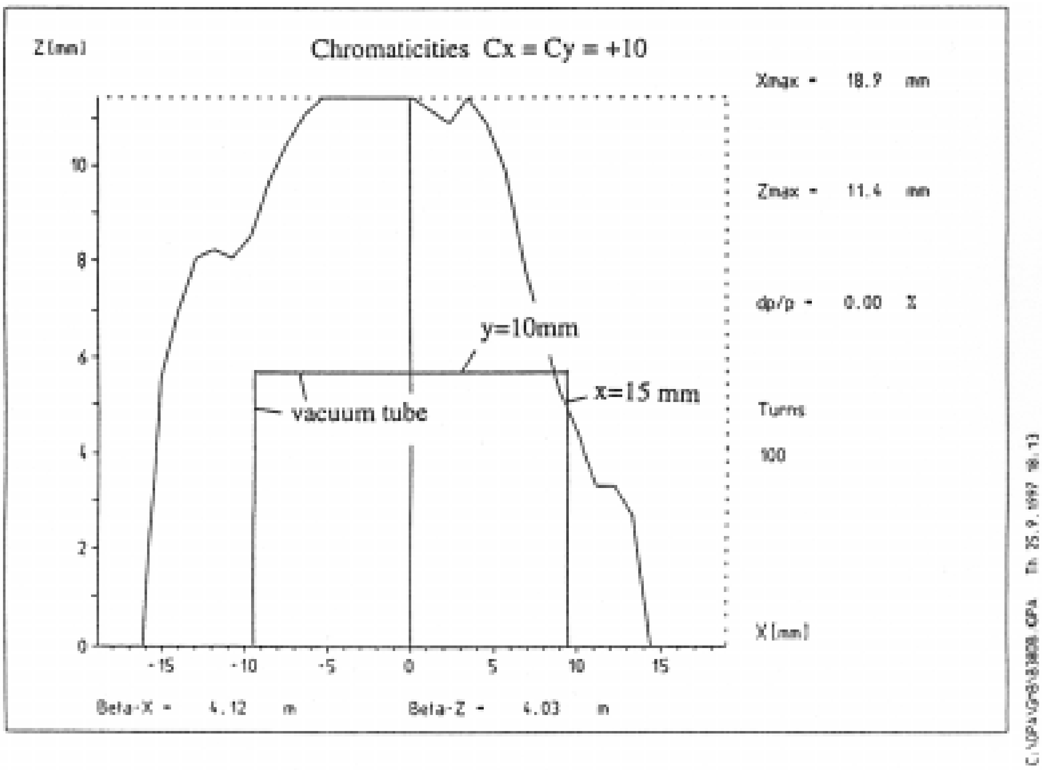




**Figure f321_f:** Dynamical aperture of the booster lattice (without errors) together with the geometrical acceptance given by the vacuum chamber. Shown are two cases with sextupole settings for chromaticity 0 (top) and +10 (bottom).

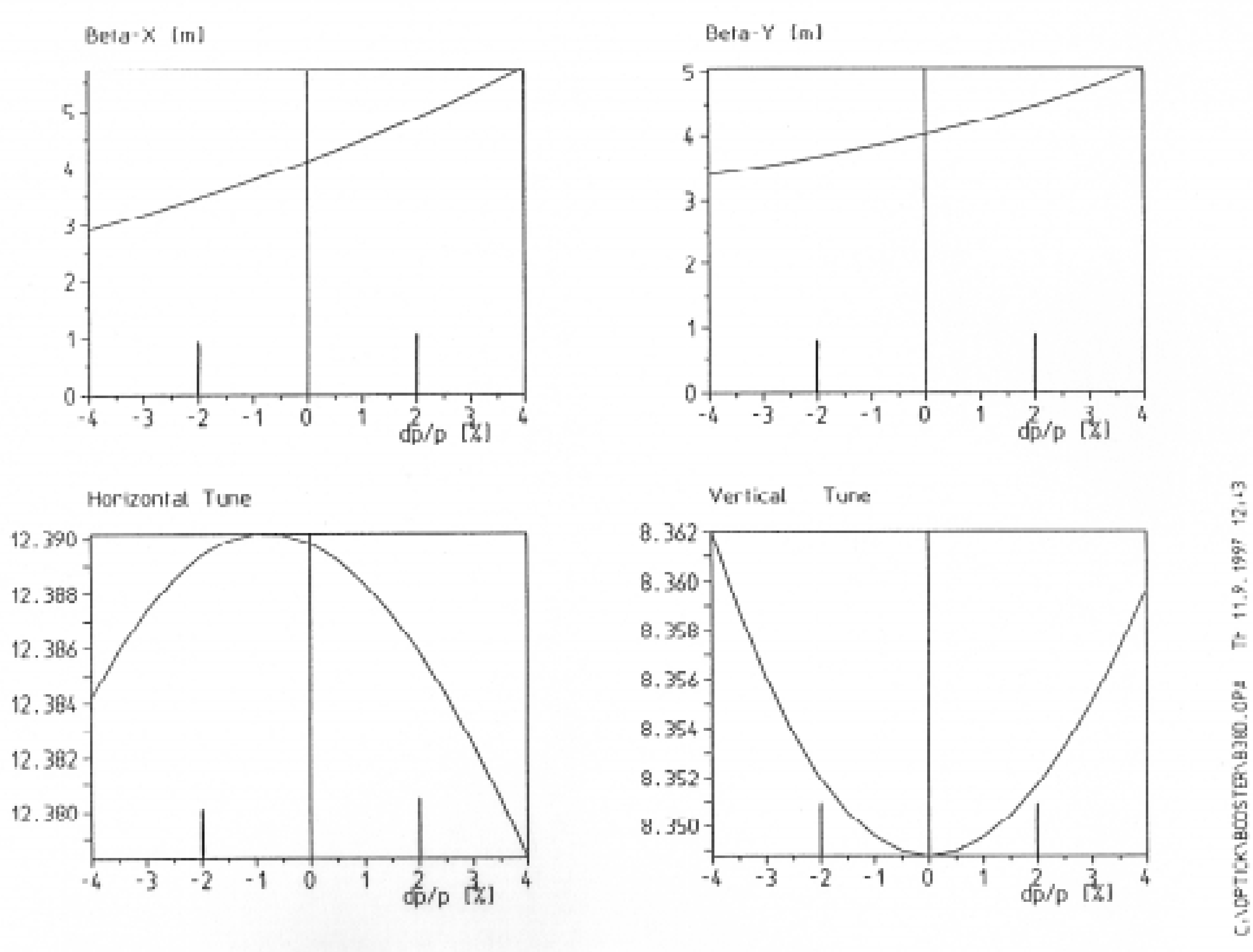



**Figure f321_g:** Momentum acceptance of the booster lattice. The limits of ±2% given by the vacuum chamber are indicated.

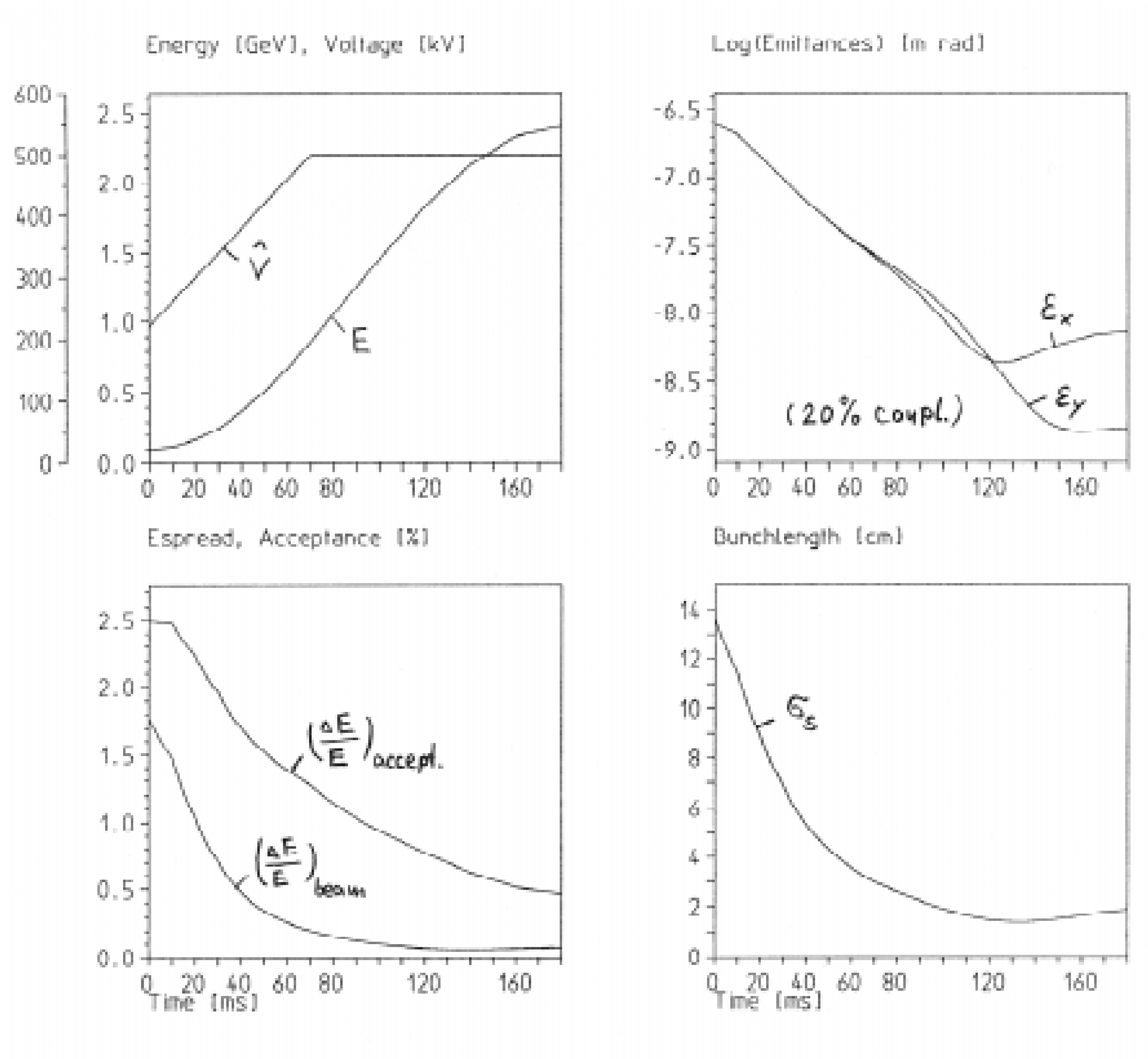



**Figure f321_h:** Variation of beam parameter energy spread, emittances and bunch length during acceleration at 3 Hz from 100MeV to 2.4GeV. The peak cavity voltage is varied during acceleration to optimize the energy acceptance.

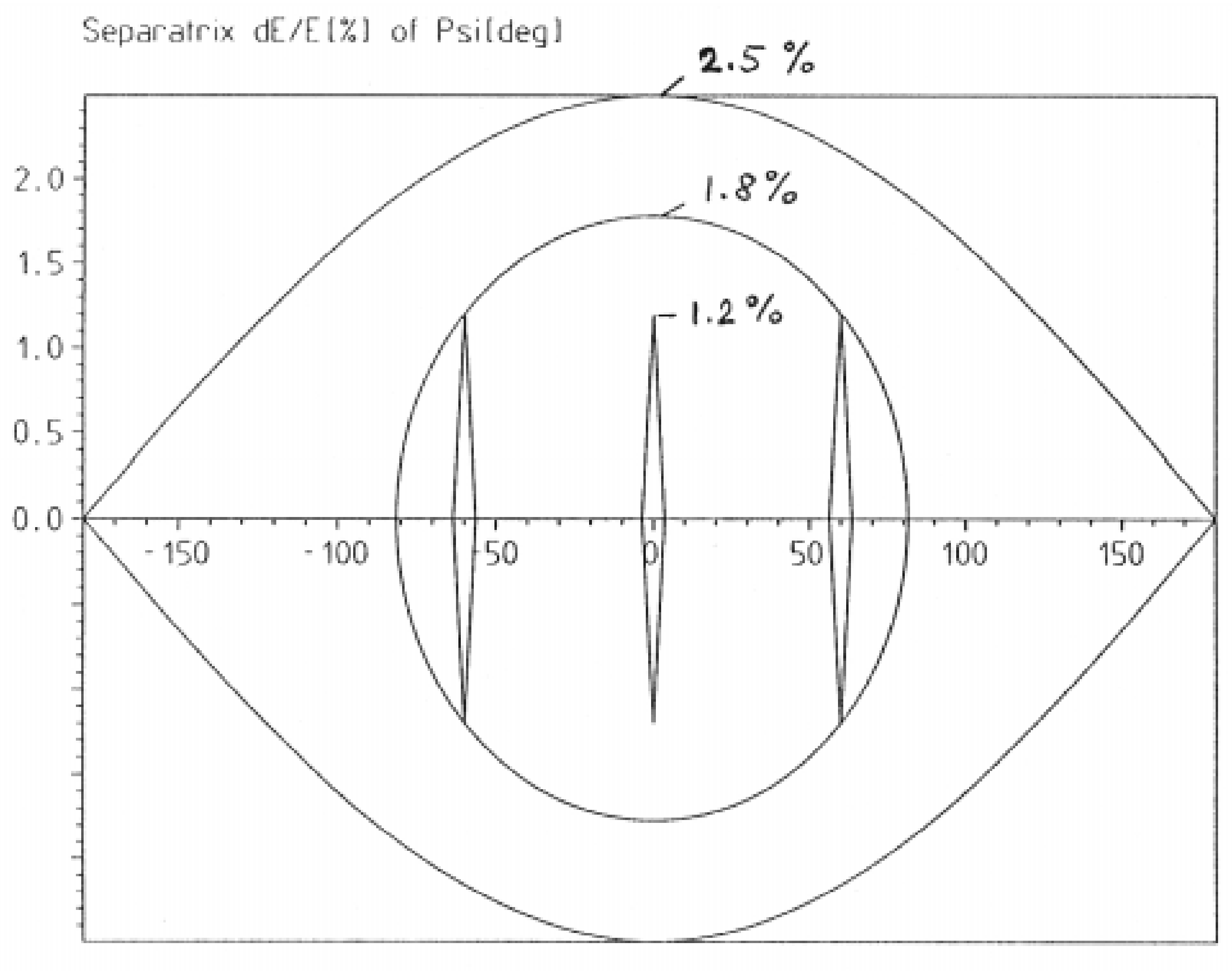



**Figure f321_i:** 500MHz RF bucket at the 100MeV injection energy. With a peak cavity voltage of 220 kV, the energy acceptance is 2.5%. Three successive bunches from the 3GHz Linac will fit into this booster bucket.

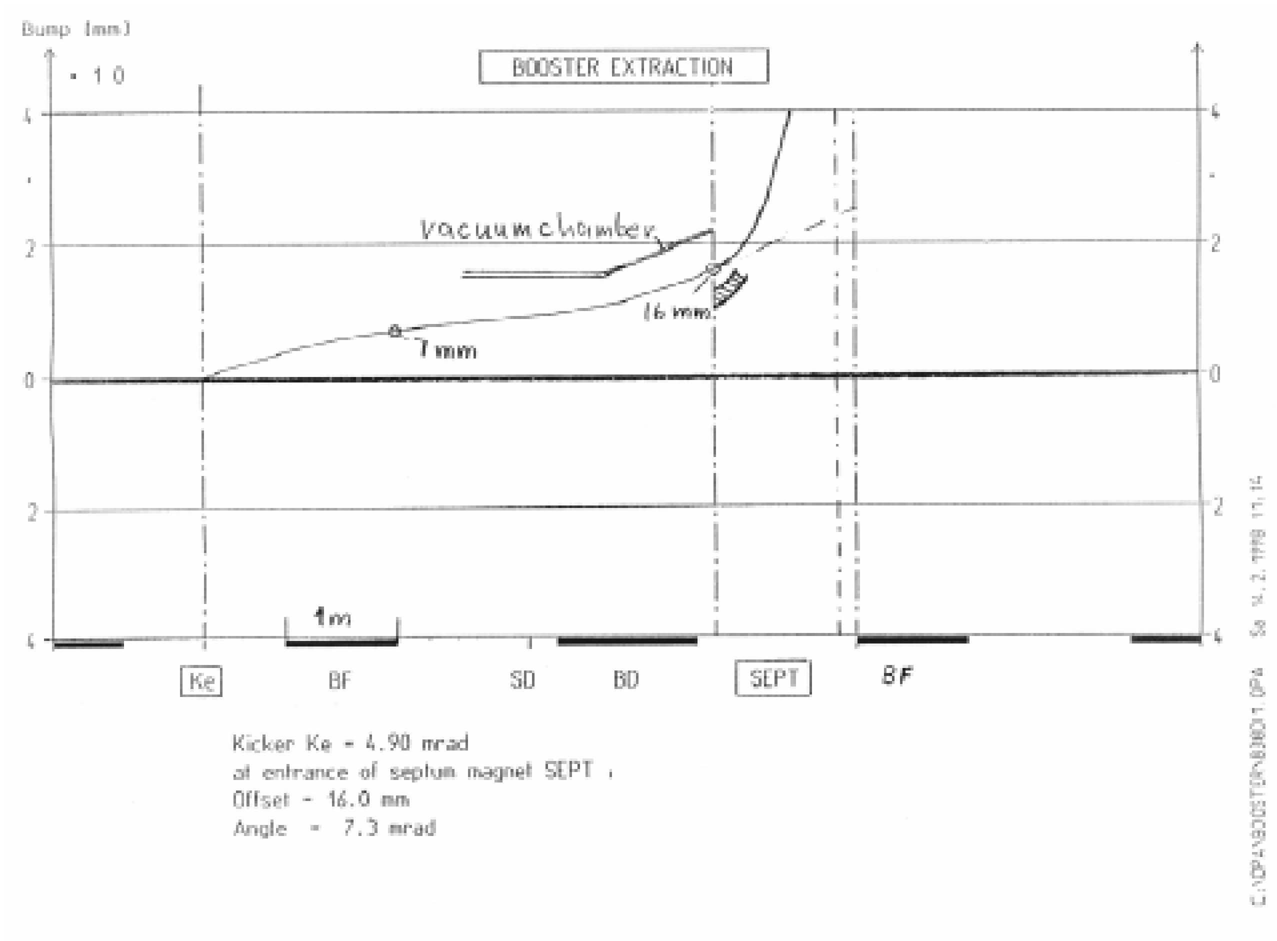



**Figure f321_k:** Extraction from booster with a kicker Ke and a septum Se.