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INVESTIGATION OF A MONOCHROMATOR SCHEME FOR SPEAR*

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1. Introduction

Because of the energy spread of the particles in an electron beam due to quantum fluctuations the hadronic event rate at narrow resonances is significantly reduced. This effect may to some extent be reduced by use of a "monochromator scheme" as suggested by Renieri.[1] This scheme requires a vertical dispersion in the interaction point but with different signs for the two beams. If for instance positrons have a positive dispersion the electron have to have a negative one. Under these condition positrons with the energy $E_0 + \Delta E$ hit electrons with $E_0 - \Delta E$ and vice versa as shown in Fig. 1. Such a scheme makes it more likely that particle with the correct total energy $2E_0$ collide in the interaction point.

The required particle dependent dispersion at the interaction point may be generated by use of a skew electrostatic quadrupole mounted in a position with a horizontal dispersion. The skew quad couples the horizontal dispersion into the vertical plane with different signs depending on the particle charge. This scheme requires two skew quadrupoles, one on each side of the interaction point. With a properly matched phase advance between these quads one can avoid a dispersion coupling in the rest of the storage ring.

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Unfortunately, as demonstrated by H. Wiedemann,[2] this simple monochromator scheme does not improve the hadronic event rate. The reason is that with the skew quadrupoles not only the dispersion but also the betatron oscillations are coupled into the vertical plane, increasing the betatron beam size σ_y^* at the interaction point significantly. Since the enhancement factor of the monochromator scheme is mainly determined by the ratio $\frac{\Delta p}{p} \cdot \eta_y^* / \sigma_y^*$, where η_y^* is the dispersion in the interaction point and $\Delta p/p$ is the beam energy spread, the hadronic event rate will approximately stay constant.

The way out is the more sophisticated monochromator scheme suggested at Novosibirsk,[3] which uses four electrostatic quadrupoles at proper locations (Fig. 2). The first quad $ESQ1$ has in the vertical plane 90° betatron phase advance to the interaction point and is mounted at a position with zero horizontal dispersion. The second quad ($ESQ2$) has a position with a sufficiently large horizontal dispersion. The betatron phase between the two electrostatic skew quads should be 180 degrees in both planes.

The skew quadrupole $ESQ2$ is used to couple the horizontal dispersion into the vertical plane generating the required vertical dispersion η_y^* in the interaction point. Because of optical reasons the vertical dispersion passes through $ESQ1$ on the axis and is therefore not affected by $ESQ1$. The coupled betatron oscillation, however, can be compensated by setting $ESQ1$ to a proper value which is given by

$$ESQ1 = -ESQ2 \sqrt{\frac{\beta_{x1} \cdot \beta_{y1}}{\beta_{x2} \cdot \beta_{y2}}} \tag{1}$$

where β's refer to the β-functions at $ESQ1$ and $ESQ2$. When the betatron coupling is compensated, the resulting betatron beam size σ_y^* becomes very small, thus overcoming the difficulty encountered in the scheme using only one pair of skew quads.

Generally with such a monochromator scheme one gets an increase of the hadronic event rate for a ***given luminosity*** of

$$\lambda = \sqrt{1 + \left(\frac{\eta_y^*}{\sigma_y^*} \cdot \frac{\Delta p}{p}\right)^2} \tag{2}$$

The aim of the study presented in this paper is to investigate the possibility of inserting a monochromator scheme with compensation of the betatron coupling in SPEAR.

2. Monochromator Scheme With The Mini-β^* SPEAR Lattice

We have first looked at the possibility to insert the monochromator scheme into the recently implemented SPEAR mini beta lattice.[4] Actually there are locations for the electrostatic skew quads satisfying approximately the monochromator constraints mentioned above (Fig. 3). $ESQ1$ is mounted close to the horizontal focusing quadrupole $Q2$ and $ESQ2$ between $QF2$ and QF. Both places have enough space for an electrostatic quadrupole of $2m$ length.[*] There is no horizontal dispersion in the $ESQ1$ region whereas between $QF2$ and QF the dispersion has a relatively large value of $\eta_x = 2.61\ m$. The betatron phase advance between the two electrostatic skew quads is $\Delta\psi_x = 202$ degree and $\Delta\psi_y = 158$ degree in the horizontal and vertical planes respectively. This doesn't fulfill exactly the 180 degree constraint but may be sufficient to get a small vertical beam size σ_y^* at the interaction point. The phase between $ESQ1$ and the interaction point is $\Delta\psi_y = 96$ degree which is close to the correct value. In fact an attempt was made to produce a lattice strictly satisfying these phase conditions by varying the quadrupole strengths. This has not produced any surprises and the results described below essentially stay unchanged.

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[*] We will show later that the $2m$ space is not absolutely critical. The electrostatic skew quads can have a shorter length, perhaps $1m$ would suffice.

In order to calculate the dispersion η_y^* at the interaction point one has to estimate the maximum available strength of an electrostatic quadrupole which is given by the following relation

$$k = 2 \times 10^{-9} \, \frac{U}{E \cdot R^2} \tag{3}$$

If U is the voltage between one pole and ground in volts, E the beam energy in GeV and R the pole radius in m, the quadrupole strength k is given in m^{-2}. Since electrostatic devices are generally very weak compared to normal iron magnets, the pole radius R should be chosen to be small. On the other hand the skew quads must not reduce the beam aperture which is supposed to be at least $\pm 12 \cdot \sigma$. Under these conditions the minimum pole radius of $ESQ2$ is $R = 0.049\ m$. The upper limit of the voltage is of the order of $V_{\max} = 100\ kV$. With these values the resulting quadrupole strength at the ψ'-resonance ($E = 1.89$ GeV) becomes $k = 0.044\ m^{-2}$.

The skew quad $ESQ2$ generates a vertical dispersion which starts at this point with an angle

$$\eta_y' \;=\; k\,\ell\,\eta_x \tag{4}$$

where η_x is the horizontal dispersion at $ESQ2$ and $k \cdot \ell$ is the integrated quadrupole strength. The vertical dispersion in the interaction point is provided by the following transformation

$$\eta_y^* \;=\; \eta_y' \sqrt{\beta_y^* \, \beta_y} \; \sin\, \psi_y \tag{5}$$

In this equation β_y^* and β_y are the vertical beta function at the interaction point and at the location of $ESQ2$ respectively. With the values

$$
\begin{aligned}
k &= 0.044\ m^{-2} \\
\ell &= 2.0\ m \\
\eta_x &= 2.61\ m \\
\beta_y &= 4.79\ m \\
\beta_y^* &= 0.03\ m \\
\psi_y &= 4.43\ \text{rad}
\end{aligned}
$$

one can calculate the vertical dispersion to be

$$\eta_y^* = -0.084\ m$$

which seems resonably large. The strength of $ESQ1$ given by Eq. (1) is $k = -0.013\ m^{-2}$ assuming again $\ell = 2m$. The betatron beam size which is given by the relation

$$\sigma_y^* = \sqrt{\epsilon_y\, \beta_y^*} \tag{6}$$

requires the knowledge of the vertical beam emittance ϵ_y. This emittance results from quantum excitation due to synchrotron radiation in the bending magnets where $\eta_y \neq 0$. In a machine like SPEAR with a constant bending radius ρ for all magnets the emittance may be expressed as

$$\epsilon_y = \frac{a \cdot E^2}{\rho \cdot \ell_b} \int\limits_{\text{bends}} H_y(s)\, ds \tag{7}$$

with

$$H_y(s) = \gamma_y\, \eta_y^2 \; + \; 2\,\alpha_y \eta_y \eta_y' \; + \; \beta_y\, \eta_y'^2 \tag{8}$$

The constant a has the value $a = 1.4675 \times 10^{-6}\ m/\text{GeV}^2$ and ℓ_b is the total orbit length inside all bending magnets around the ring. Since the vertical dispersion is nonzero only in the interaction region between the two skew quads $ESQ2$ the integral in (7) has only to be calculated over all bending magnets in this region.

Since there is no vertical bending in SPEAR, the coupled vertical dispersion behaves like a normal particle trajectory. In particular the function $H_y(s)$ representing the surface of the phase ellipse is a constant in the interaction region. Therefore one can express $H_y(s)$ by taking the optical values in the interaction point which reduces (8) to

$$H_y(s) = \frac{\eta_y^{*^2}}{\beta_y^*} = \text{const.} \tag{9}$$

With this expression the vertical emittance becomes

$$\epsilon_y = \frac{a\ E^2\ \eta_y^{*^2}}{\rho\ \beta_y^*} \cdot \frac{\ell_\eta}{\ell_b} \tag{10}$$

where ℓ_η is the sum of the orbit length in all bending magnets with nonzero vertical dispersion.

In the SPEAR mini beta lattice there are three normal and one half bending magnets on either side of the interaction point between the two $ESQ2$'s. Providing that the monochromator scheme is installed only in one interaction region we get $\ell_\eta = 7 \cdot \ell_0$ where $\ell_0 = 2.36825\ m$ is the total length of one normal bending magnet. The total length of all SPEAR bends is $\ell_b = 34 \cdot \ell_0$. The resulting vertical emittance at $E = 1.89$ GeV is

$$\epsilon_y = \frac{a\ E^2\ \eta_y^{*^2}}{\rho\ \beta_y^*}\ \frac{7}{34} = 1.98 \times 10^{-8}\pi \text{ m-rad} \tag{11}$$

with the bending radius $\rho = 12.815\ m$. The horizontal emittance of the SPEAR mini beta optics at the same energy is $\epsilon_x = 1.786 \times 10^{-7}\pi$ m-rad which gives the emittance ratio of $\epsilon_y/\epsilon_x = 0.11$.

Taking the expressions (2), (6) and (10) the enhancement factor due to the monochromatization finally becomes

$$\lambda = \sqrt{1 + \frac{\rho \cdot \ell_b}{a \cdot E^2 \, \ell_\eta} \left(\frac{\Delta p}{p}\right)^2} \tag{12}$$

which gives the value for the unchanged SPEAR mini beta lattice of

$$\lambda = 1.85 \tag{13}$$

with the energy spread $\Delta p/p = 4.52 \times 10^{-4}$ at $E = 1.89$ GeV.

In this calculation the vertical emittance is only determined by quantum fluctuations, all other effects as residual betatron coupling etc. have been neglected. This would slightly reduce the λ - value. It is interesting to mention that under this condition the enhancement factor doesn't depend on the optical data η_y^* and β_y^* at the interaction point. Therefore they are not the suitable parameters to vary in order to optimize the relatively low enchancement factor of $\lambda = 1.85$. Note that λ in this case is also independent of the beam energy since $\Delta p/p \sim E$. Note also that since λ is independent of η_y^*, the skew quads only have to be strong enough that the resulting $\frac{\Delta p}{p} \cdot \eta_y^*$ is much larger than the vertical beam size coming from residual betatron coupling. This means the skew quad strength can be reduced or their length shortened somewhat to accomodate practical considerations. One such consideration is that the space suggested for $ESQ2$ presently also contains the injection kicker. By shortening $ESQ2$, it might be possible to have both $ESQ2$ and the kicker in the available free space.

3. Investigation of a Particular Monochromator Lattice for SPEAR

Since for the given mini beta optics the increase of the hadronic event rate on a narrow resonance due to monochromatization is only a factor of two, we further investigated the possibility of removing the restrictions of keeping the magnet configuration unchanged. We have thus studied those configurations in which the first vertically focusing quadrupole $Q3$ has been left in its position so that no modification of the particle detector MARK III is necessary.

A particular monochromator optics has to satisfy the following constraints:

1. The number and strength of bending magnets in the region with vertical dispersion should be as small as possible. On the other hand at least one magnet is required to get a zero horizontal dispersion at the first skew quad $ESQ1$.
2. The development of beam waists in both planes between $ESQ1$ and $ESQ2$ provides the required 180 degree phase advance.
3. In order to get a sufficiently large vertical dispersion η_y^* in the interaction point the horizontal dispersion at the skew quad $ESQ2$ should be also sufficiently large.

Based on these three constraints a monochromator optics for SPEAR has been designed which is shown in Fig. 4. Only one weak bending magnet with the standard length ℓ_0 but only half of the field strength of the normal bends is installed between $ESQ1$ and $ESQ2$. This provides because of a relatively long drift space a horizontal dispersion of $\eta_x = 1.2\ m$ at $ESQ2$. The geometry of the storage ring is changed from the existing one but the circumference has been kept fixed.

Since the weak bending magnet has a radius $\rho_w = 2 \cdot \rho$ the emittance formula has to be modified. In this case is

$$\epsilon_y = a \cdot E^2 \cdot H_y(s) \frac{\ell_\eta / \rho_w^3}{(2\ell_\eta / \rho_w^2) + (\ell_b / \rho^2)} \tag{14}$$

where $\ell_\eta = 2\,\ell_0$ is the length of the two weak bending magnets and $\ell_b = 30\ell_0$ the total length of all other magnets around the ring. Actually there are four weak bending magnets installed in the ring namely one per quadrant but only two of them contribute to the vertical emittance. After some manipulations considering the relation (9) the emittance becomes

$$\epsilon_y = \frac{a \cdot E^2 \cdot \eta_y^{*^2}}{124 \cdot \rho \cdot \beta_y^*} \tag{15}$$

The resulting enhancement factor for this particular monochromator optics is

$$\lambda = \sqrt{1 + \frac{124\,\rho}{a \cdot E^2} \cdot \left(\frac{\Delta p}{p}\right)^2} \tag{16}$$

The bending radius for this lattice is $\rho = 12.061\ m$ and the energy spread is $\Delta p/p = 4.65 \times 10^{-4}$ at $E = 1.89$ GeV. With these values we finally obtain an enhancement factor

$$\lambda = 7.85 \tag{17}$$

which is a significant improvement of the hadronic event rate.

Unfortunately we found that it was not possible to match this monochromator section properly to the rest of the ring. Even significant modifications in the arcs and the addition of more independent quadrupole families couldn't provide a satisfactory solution. In particular the chromaticity rose to values of more than $\xi = -30$ in both planes which is too large to be compensated in a small machine like SPEAR without reduction of the dynamic aperture. Both the high chromaticity and the extremely critical optics as found in computer calculations makes it unlikely that this optics will properly work in a real machine. Reduced maximum beam currents and a much more unreliable operation may easily cancel the enhancement factor. Therefore for this small machine SPEAR this particular mononchromator insertion doesn't seem to be a resonable solution. For a larger machine, however, with longer straight sections which allow better matching to the arcs, the scheme described in this section may improve the hadronic event rate at a resonance considerably.

4. Summary

We investigated the possibility of mono-chromatizing SPEAR for the purpose of increasing the hadronic event rate at the narrow resonances. By using two pairs of electrostatic skew quads in the monochromator scheme it is found that the event rate can be increase by a factor of 2 for the mini beta optics assuming the luminosity is kept unchanged. An attempt to increase this enhancement factor by major rearrangements of the ring magnets has encountered serious optical difficulties; although enhancement factor of 8 seems possible in principle, this alternative is not recommended.

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References

1. A. Renieri, Frascati, Preprint / INF-75 / 6 (R), 1975.
2. H. Wiedemann, "Is it Possible to Improve the Event Rate for Narrow Resonances in SPEAR and PEP?," SLAC/PEP Note-320, October 1979.
3. A. A. Avdienko et al., "The Project of Modernization of the VEPP-4 Storage Ring for Monochromatic Experiments in the Energy Range of ψ and Υ Mesons," Proceedings 12th Intern. Conf. on High Energy Accelerators, Fermilab, 1983, p. 186.
4. K. Wille, "A Proposed Mini Beta Insertion for SPEAR," SLAC/AP-9, March 1984.

Figure Captions

1. Basic concept of the monochromator.
2. Monochromator scheme with compensation of the betatron coupling.
3. Insertion of the monochromator scheme into the unchanged SPEAR mini beta lattice.
4. Design of a particular monochromator optics for SPEAR.

Monochromator scheme:

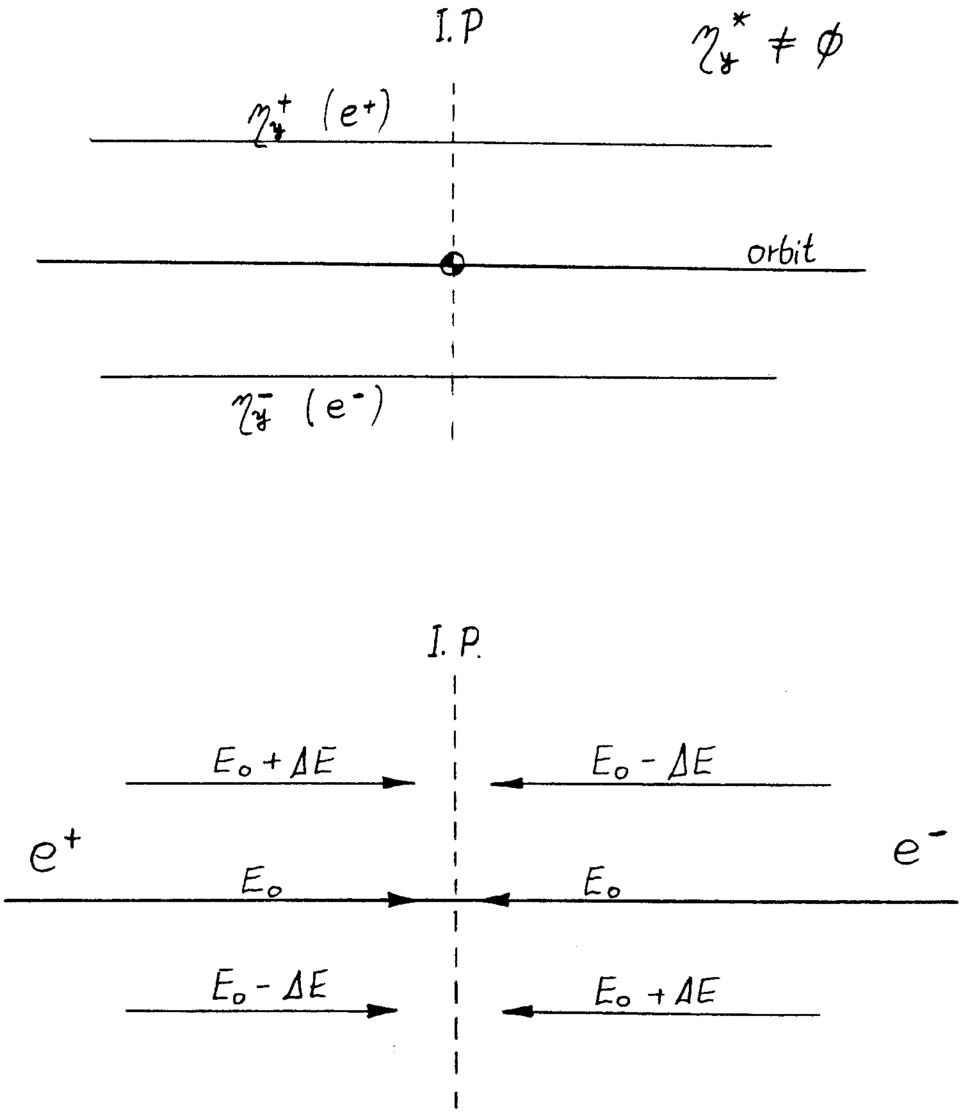

Fig. 1

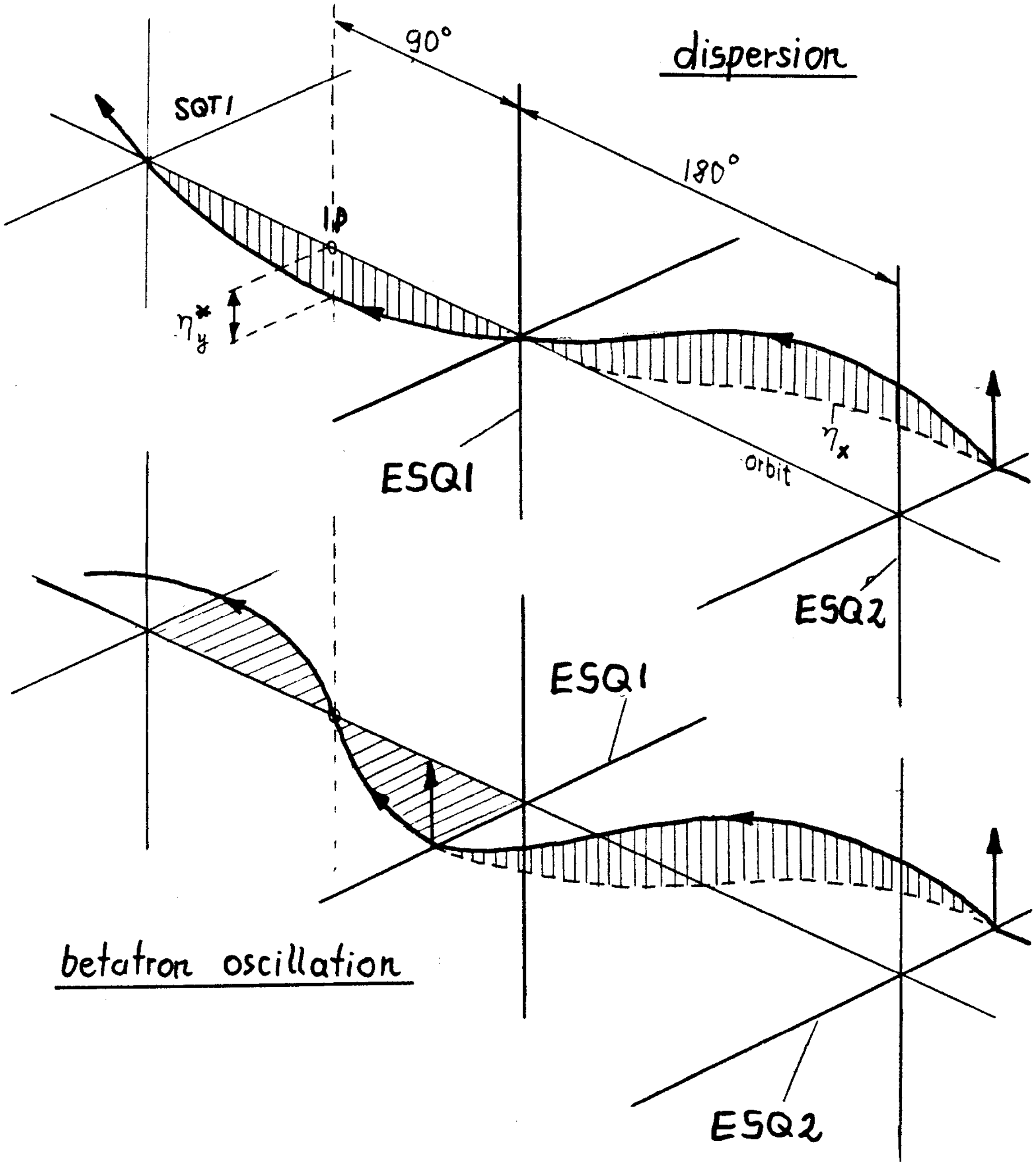
90°
dispersion
SQT1
180°
IP
η_y^*
ESQ1
orbit
η_x
ESQ2
ESQ1
ESQ2
betatron oscillation

Fig. 2

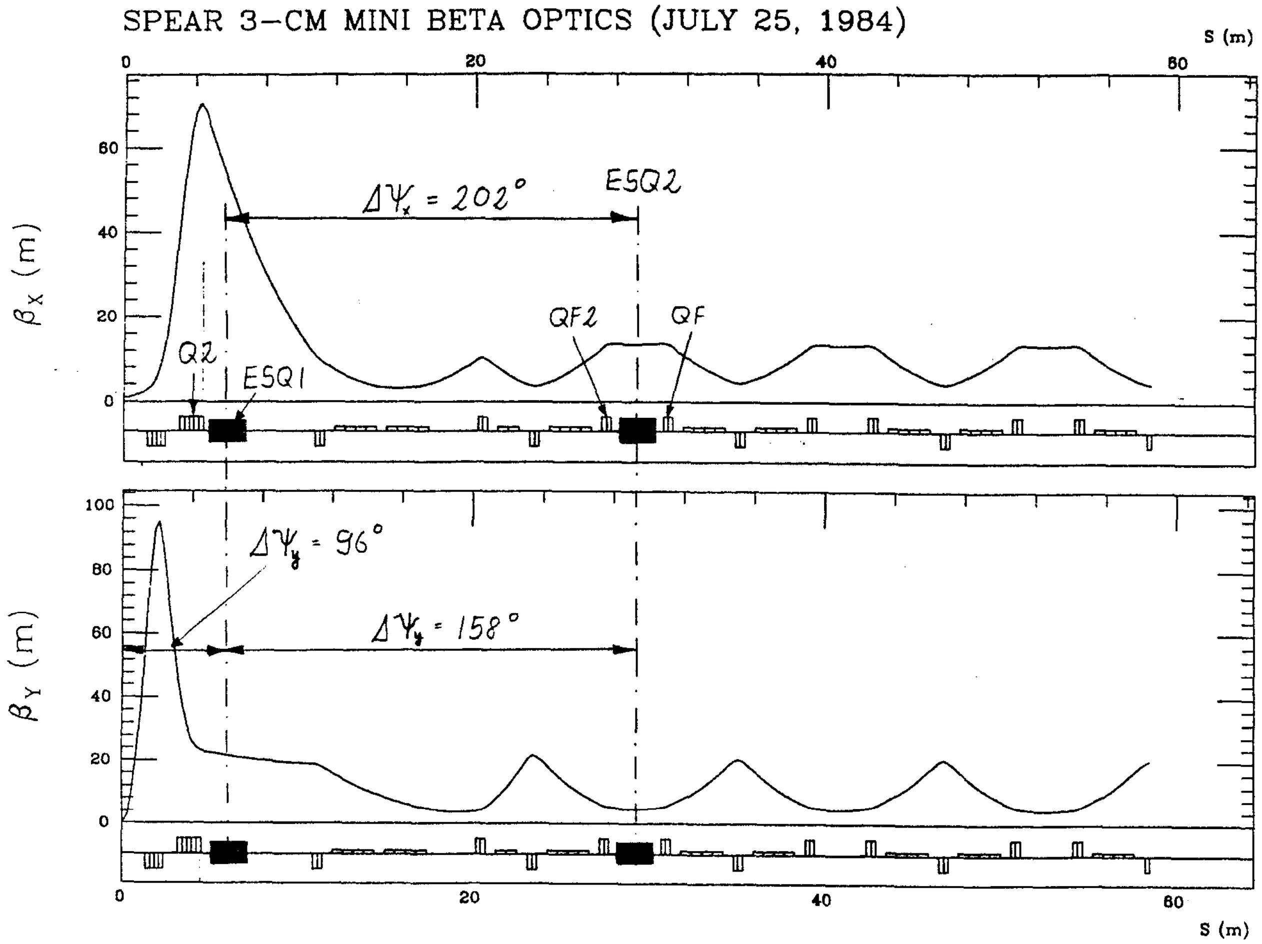
SPEAR 3–CM MINI BETA OPTICS (JULY 25, 1984)
S (m)
0
20
40
60
β_X (m)
60
40
20
0
$\Delta\Psi_x = 202°$
ESQ2
QF2
QF
Q2
ESQ1
β_Y (m)
100
80
60
40
20
0
$\Delta\Psi_y = 96°$
$\Delta\Psi_y = 158°$
0
20
40
60
S (m)

Fig. 3

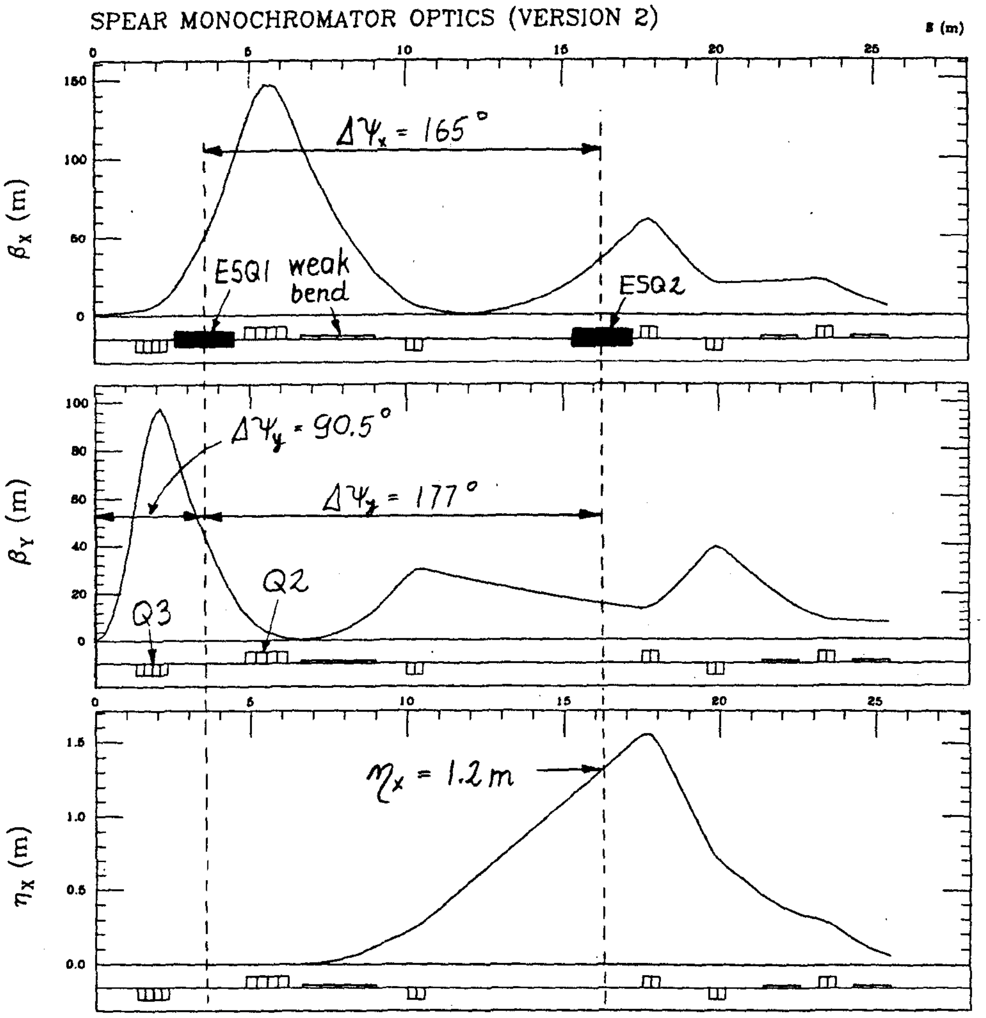
SPEAR MONOCHROMATOR OPTICS (VERSION 2)
s (m)
0
5
10
15
20
25
150
100
50
0
β_X (m)
$\Delta\Psi_x = 165°$
ESQ1
weak bend
ESQ2
100
80
60
40
20
0
β_Y (m)
$\Delta\Psi_y = 90.5°$
$\Delta\Psi_y = 177°$
Q3
Q2
1.5
1.0
0.5
0.0
η_X (m)
$\eta_x = 1.2 m$

Fig. 4