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Ion-Optical Studies for Improved Ion Transmission in Multistage Isotope-Ratio Mass Spectrometers

J. J. Stoffel(s)
H.-J. Laue

October 1991

**Prepared for the U.S. Department of Energy
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**Pacific Northwest Laboratory
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ION-OPTICAL STUDIES FOR IMPROVED
ION TRANSMISSION IN MULTISTAGE
ISOTOPE-RATIO MASS SPECTROMETERS

J. J. Stoffel(s)
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October 1991

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the U.S. Department of Energy
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SUMMARY

Theoretical and experimental ion-optical studies of multistage isotope-ratio mass spectrometers were conducted to determine what improvement in ion transmission efficiency might be attainable through design changes. The computer program GIOS (General Ion Optical Systems) was used to perform theoretical calculations of focusing properties and ion transmission efficiency. Actual transmission through multiple-sector instruments was determined from measurements of the ion beam vertical profile at the focus of each stage.

For existing mass spectrometers with tandem magnets of normal geometry, our studies determined a feasible design change that significantly increases ion transmission through the analyzer. The use of a cylindrical einzel lens or an electrostatic quadrupole lens near the focal point between the magnets provides vertical focusing of the ion beam to achieve the improved transmission.

We also established a new mass spectrometer design that gives 100% transmission through tandem magnetic analyzers and through a third-stage electrostatic analyzer without the use of an intermediate focusing lens. Non-normal magnetic field boundaries provide ion beam focusing in the vertical plane to achieve this complete transmission.

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1.0 INTRODUCTION

The mass spectrometer with two magnetic analyzers in tandem (White and Collins 1954) provides improved abundance sensitivity (the ability to measure a minor isotope in the presence of an adjacent major isotope) over a single magnetic analyzer by reducing peak tails due to ion scattering. A further major improvement in abundance sensitivity is obtained by the addition of an electrostatic analyzer as a third stage (White et al. 1958).

The geometry of the traditional three-stage isotope-ratio mass spectrometer is shown in Figure 1.1. The first two stages consist of tandem 90°-sector magnets. In the horizontal (x,z) plane^(a) shown, an ion beam diverging from the source slit, S-1, enters the field of the first magnetic sector, MS-1, normally (i.e., perpendicularly), is deflected through 90°, exits the field normally, and is brought to a focus at the mass analyzing slit, S-2. In this normal geometry, the drift lengths, l and l' , preceding and following the sector magnets are equal to the deflection radius, R , of the ion beam in the magnetic field.

Likewise, the ion beam proceeds through the second magnetic sector, MS-2, and is brought to a focus at S-3. The cylindrical electrostatic sector, ES, used as a third stage produces a final focus in the horizontal plane at S-4 preceding the ion detector.

In the vertical (y,z) plane, there is no such focusing of the ion beam. Instead, the beam continually diverges from the ion source throughout its flight path. A slight defocusing occurs each time the ion beam passes through the fringe field of the magnets (Wollnik 1987). Since the cylindrical electrostatic analyzer also provides no focusing in the vertical plane, the ion beam continues diverging to the detector. The vertical divergence of the ion beam results in a loss of ion transmission in the mass analyzer.

(a) We use Wollnik's notation (Wollnik 1987): x is the beam width, y is the beam height, and z is the distance along the ion flight path.

FIGURE 1.1. Schematic Diagram of a Three-Stage Isotope-Ratio Mass Spectrometer with Normal Magnetic Field Boundaries

The existing three-stage mass spectrometers at the Pacific Northwest Laboratory (PNL)^(a) (Lagergren and Stoffels 1970), as well as the two-stage and three-stage instruments at other laboratories, are all of the normal geometry. They are, therefore, subject to the transmission losses described above. To determine what transmission losses are suffered in practice and what improvement in ion transmission efficiency might be obtainable through design changes, we conducted theoretical and experimental ion-optical studies of multistage mass spectrometers.

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

2.0 THEORETICAL CALCULATIONS AND EXPERIMENTAL MEASUREMENTS

The ion transmission efficiency of a mass spectrometer depends on the emittance of the source and the acceptance of the analyzer and detector. One benchmark in the transmission optics of multistage isotope-ratio mass spectrometers is the work of Dietz (1960). Dietz calculated the transmission efficiency of a modified Nier ion lens and of tandem magnetic analyzers to be 97.5% each for a total filament-to-detector transmission of 95%. The minimal transmission loss was attributed to ion beam divergence in the vertical plane produced by the magnetic fringe fields. In an unpublished experimental measurement, Dietz and co-workers determined the cesium ion transmission of their instrument to be >90%. This was an average value for many filaments.

Experience at PNL and other laboratories that use the Nier-Dietz source lens with vertical focusing does not reproduce the high transmission efficiencies quoted above. Todd et al. (1982) modified the lens design to improve ion extraction and focusing in the vertical plane at the source filament. The modification increased transmission through a two-stage spectrometer by a factor of three or four. The increase was attributed to reduction of transmission losses in the source lens rather than in the analyzer, although no data on ion beam divergence from the two lenses were presented to allow such an evaluation.

Ion beam divergence from the source depends on the ratio between ion thermal energy (filament temperature) and kinetic energy (accelerating voltage) as well as the ion-optical properties of the focusing lens. Dietz measured the divergence of Ba^+ ions emitted at ~1600K at accelerating voltages from 1.5 kV to 15 kV. Since the data were presented in terms of the dimensionless parameter $(kT/Ve)^{\frac{1}{2}}$ and since electrostatic lens focusing is independent of ion mass, they can be used to determine beam spreading under other conditions. For U^+ ions emitted at 2100K and accelerated through 14 kV, Dietz's data yield a half-angle of divergence in the vertical plane $\beta = \pm 2.5$ mrad for a V-filament in a source lens without vertical focusing and $\beta = \pm 1.0$ mrad with vertical focusing. These divergence angles are considerably less than others achieved in practice. For example, reduction of U^+

vertical divergence to $<\pm 6.5$ mrad on a commercial isotope ratio mass spectrometer required vertical stops that cut transmission in half (Laue and Wollnik 1988).

At the time of Dietz's work 30 years ago, computer programs were not available for doing ion-optical calculations of mass spectrometers. We used a state-of-the-art computer program called GIOS (General Ion Optical Systems) (Wollnik et al. 1984) to calculate the focusing properties and ion transmission efficiency of mass spectrometers with tandem magnetic analyzers.

GIOS calculates the properties of an ion-optical system by multiplication of transfer matrices. The transfer matrices are comprised of the coefficients of a Taylor series expansion of the transfer function, which describes each of the individual ion-optical elements. The order to which the Taylor series is evaluated defines the order of the calculation. Calculations were done through second order in both the horizontal and vertical planes. Although GIOS has the ability to do calculations through third-order in the horizontal plane, the higher order is not necessary for the low resolution of isotope-ratio mass spectrometers. Test cases showed that the total third-order aberrations are only 1 or 2% of the second-order aberrations.

GIOS models sector fields, both magnetic and electrostatic, by the product of three matrices representing an entrance fringe field, an idealized main field with sharp cutoff at the boundaries, and an exit fringe field. The fringe-field matrices provide an extended fringe-field correction like that developed by Enge (1963). GIOS includes several fringe-field models for magnets with pole clamps as well as provision for specifying fringe-field integrals for other pole structures, such as have been evaluated by Hu et al. (1982). We used the GIOS fringe-field model for a weakly clamped magnet, which is a good approximation to an unclamped magnet.

Parameters that govern ion transmission efficiency include the vertical divergence angle of the ion beam from the thermal ionization source, the total length of the ion path, the clear height of the flight tube in the magnet gap, and the detector vertical aperture. The PNL mass spectrometer parameters

listed in Table 2.1 were used for all calculations. We used a vertical divergence angle of ± 3.6 mrad, which is the maximum angle of acceleration for 14-keV ions with thermal energy of 0.18 eV (Wollnik 1987).

2.1 EXISTING MULTISTAGE MASS SPECTROMETERS

The traditional normal geometry of existing mass spectrometers with tandem magnets was the first case examined theoretically. The two possible arrangements of magnets in tandem were studied: the "C" arrangement, in which the bending direction of both magnets is the same, and the "S" arrangement, in which the bending direction of the second magnet is opposite that of the first magnet. The "C" arrangement is more compact and has traditionally been preferred.

With the "C" arrangement, the focus of the second magnet is a point of zero dispersion; with the "S" arrangement, it is a point of double dispersion. Zero dispersion and double dispersion are not realized in practice since only one separated isotope at a time is allowed to proceed through the analyzing slit at the focus of the first magnet.

TABLE 2.1. PNL Mass Spectrometer Parameters Input to GIOS

Ion source $x = \pm 0.15$ mm, $\alpha = \pm 17.5$ mrad	(1.0°)
$y = \pm 1.6$ mm, $\beta = \pm 3.6$ mrad	(0.2°)
Ion thermal energy/kinetic energy	2×10^{-4}
Magnet deflection angle	90.0°
Magnet deflection radius	30.5 cm
Magnet total airgap	2.0 cm
Clear height in analyzer tube	1.6 cm
ESA deflection angle	90.0°
ESA deflection radius	30.5 cm
Separation between ES plates	2.0 cm
Detector vertical aperture (U^+ ions)	1.9 cm
Detector vertical aperture (I^- ions)	1.8 cm

Calculations with GIOS showed that the image aberrations are somewhat smaller for the "C" arrangement. They also showed that the bending direction of an electrostatic analyzer makes no difference in the ion optics when it follows tandem magnets in the "C" arrangement.

The calculated ion beam envelopes through a normal geometry, three-stage spectrometer are shown in Figure 2.1 for both the (x,z) plane of mass dispersion and the orthogonal (y,z) plane. The figure shows the lack of vertical focusing by the magnetic sectors (MS) and electrostatic sector (ES) and the resultant loss of ion transmission through the slits (AS). Longitudinal and transverse length units (LLU and TLU) for x, y, and z are in meters.

The ion transmission efficiency of the three-stage analyzer was calculated to be 73%. The transmission values given by GIOS are calculated with uniform illumination of the ion source (x,y) phase space. The real-intensity distribution of ions can vary considerably, depending on the source. For instance, ion emission can predominate from two or three hot spots on the ionizing filament. The emission pattern can also change with time as the sample migrates over the surface of the filament (Kelley and Robertson 1985).

We also calculated the maximum value of β from the ion source that would give complete transmission through the spectrometer. This value cannot be determined from geometric parameters alone because of the vertical defocusing of the ion beam in the fringe fields of the magnets. For complete transmission, the maximum value of β allowed from the source is 2.0 ± 0.3 mrad. The lower limit is calculated for a phase space that is parallelogram-like, and the upper limit for one that is elliptical (Wollnik 1987).

We experimentally studied the ion transmission efficiency of the three-stage mass spectrometers at PNL by measuring the vertical divergence of the ion beam. Vertical ion beam profiles were measured by moving a narrow, angled slit (see Figure 2.2) across a stationary beam of ions. Mathematical analysis showed that the finite extent of the scanning slit and its angled shape do not have a significant effect on the measured profile.

```

Z (LLU)  Y =0.200E-01 TLU  X =0.200E-01 TLU
I-----I
I          YYYV-----I
I          BYYY AA-----I
I          BYYYY AAA-----I
I          BYYYY AAAAA-----I
I          BBBBBY AAAAAA-----I
I-----I
I          BBBBBY-AAAAA-----I
MS..... BBBBBY AAAAAA-----I MS
MS..... BBBBBY AAAAAA-----I MS
MS..... BBBBBY AAAAAAAG-----I MS
MS..... BBBBBY AAAAAAAG-----I MS
MS..... BBBBBY AAAAAAAG-----I MS
MS..... BBBBBY AAAAAAAG-----I MS
MS..... BBBBBY AAAAAAAG-----I MS
AS..... BBBBBY-AAAAAAG-----I AS
I          BBBBBY AAAAAAG-----I
I          BBBBBY AAGGG-----I
I          BBBBBY AAGGG-----I
I          BBBBBY AGG-----I
AS..... BBBBBY .....AS
1.09 I          BBBBBY AAGGG-----I
I          BBBBBY AAGGGG-----I
I          BBBBBY AAAAAAGGG-----I
I          BBBBBY AAAAAAGGGG-----I
I-----I
I          BBBBBY-AAAAAAGGGG-----I
MS..... BBBBBY AAAAAAAGGGG-----I MS
MS..... BBBBBY XAAAAAAGGGG-----I MS
MS..... BBBBBY AAAAAAAGGGG-----I MS
MS..... BBBBBY AAAAAAAGGGG-----I MS
MS..... BBBBBY AAAAAAAGGGG-----I MS
MS..... BBBBBY AAAAAAAGGGG-----I MS
MS..... BBBBBY AAAAAAAGGGG-----I MS
AS..... BBBBBY-AAAAAAGGG-----I AS
I          BBBBBY AAAAAAG-----I
I          BBBBBY AAG-----I
I          BBBBBY AAG-----I
I          BBBBBY A-----I
AS..... BBBBBY .....AS
2.18 I          BBBBBY AAG-----I
I-----I
I          BBBBBY-AAAA-----I
ES I          BBBBBY AAAAAAG-----ES
ES I          BBBBBY XAAAAAG-----ES
ES          BBBBBY AAAAAAG-----ES
ES          BBBBBY AAAAAAG-----ES
ES          BBBBBY AAAAAAG-----ES
ES          BBBBBY AAAAAAG-----ES
ES          BBBBBY AAAAAAG-----ES
ES          BBBBBY AAAAAAG-----ES
I-----I
I          BBBBBY AD-----I
AS..... BBBBBY .....AS
2.87

```

FIGURE 2.1. Calculated Vertical and Horizontal Envelopes of the Ion Beam in a Three-Stage Mass Spectrometer with Tandem Magnets of Normal Geometry ($\epsilon = 0^\circ$). The symbols X and Y denote envelopes of an initially parallel beam ($A=B=0$). The symbols A and B denote envelopes of a beam with initial angles of divergence ($A>0, B>0$). The symbols G and D denote envelopes of a beam deviating in mass and energy. Longitudinal and transverse length units (LLU and TLU) for X, Y, and Z are in meters. Parallelogram-like phase space is assumed.

FIGURE 2.2. Slit Arrangement Used to Measure the Ion Beam Vertical Profile in a Mass Spectrometer. Dimensions are in mm.

The vertical profile of 14-kV U^+ ions from a single V-filament source measured by scanning the beam at the focus of the first-stage magnet (S-2 in Figure 1.1) showed a change in slope of the sides (Figure 2.3). This indicated that the height of the beam exceeded the detector aperture, and, consequently, the beam was being cut off. To determine the full vertical profile of the beam, we removed the second-stage flight tube and mounted the ion detector directly after the first stage. The remeasured vertical profile is Gaussian (Figure 2.4), which indicates that the full beam was measured. The difference between the profiles measured with the detector at S-2 and at S-4 indicates that the ion transmission efficiency of our three-stage analyzer for 14-kV U^+ ions was ~75%. This agrees well with the GIOS calculation.

FIGURE 2.3. Vertical Ion Beam Profile in PNL Three-Stage Mass Spectrometer "C" at S-2, the Focus of the First-Stage Magnetic Sector, with the Ion Detector Located at S-4. The beam is 14-kV U^+ ions from a solution sample on a single V-filament.

The above measurements were made with a solution sample. A vertical beam profile was also measured at S-2 with a uranium particle sample. As expected, the profile (Figure 2.5) from the point source of ions is narrower than that from the extended source due to a solution sample.

Filament geometry is critical in determining ion focusing (McHugh 1969). The fact that our V-filament is open at the ends (Stoffels and Lagergren 1983/1984) as opposed to the closed "canoe" of Dietz may account for differences in vertical focusing of the ion beam. We have measured a significant increase in vertical beam spreading with a triple filament assembly on the same Nier-Dietz source lens as compared to the single V-filament (Figure 2.6). This measurement was made on another three-stage mass spectrometer with 9-kV I^- ions

FIGURE 2.4. Vertical Ion Beam Profiles in PNL Three-Stage Mass Spectrometer "C" at S-2, the Focus of the First-Stage Magnetic Sector, with the Ion Detector Located at S-2 and at S-4. The beam is 14-kV U^+ ions from a solution sample on a single V-filament.

emitted from a LaB_6 -coated ionizer at $\sim 1300K$. Since the thermal spreading of 9-kV ions emitted at 1300K is somewhat less than that of 14-kV ions emitted at 2100K, we attribute the difference in vertical spreading to focusing properties of the filament geometries.

We have also been able to reduce the vertical divergence of the ion beam from a single V-filament source by modifying the filament geometry as shown in Figure 2.7. The improvement in vertical beam profile is most apparent at the end of the spectrometer (see Figure 2.8).

FIGURE 2.5. Vertical Ion Beam Profiles at S-2, the Focus of the First-Stage Magnetic Sector, for a Particle Sample and a Solution Sample. The beam is 14-kV U^+ ions from a single V-filament.

2.2 DESIGN IMPROVEMENTS TO EXISTING MASS SPECTROMETERS

Severe limitations were imposed on any possible design changes to improve the ion transmission of the existing instruments. These limitations were necessitated by the constant sample load on the spectrometers, which prevents any extended shutdown for modifications. The limitations imposed were:

- no change to the existing magnets
- no change to the existing flight tubes
- no change to the existing electrostatic analyzer.

Numerous calculations were made with GIOS to determine the effect of adding electrostatic quadrupole lenses to the spectrometers without changing

FIGURE 2.6. Vertical Profile at S-2, the Focus of the First-Stage Magnetic Sector, of the Beam from a Triple-Filament Source of 9-kV I^- Ions Emitted at $\sim 1300K$. The profile from a V-filament source of 14-kV U^+ ions is also shown for comparison.

the existing geometry. The electrostatic quadrupole (EQ) is an astigmatic lens; that is, it focuses in one direction and defocuses in the orthogonal direction. Various combinations of EQ lenses and EQ doublets preceding and following the magnetic sectors were modeled. The effects of lens position and voltage on ion beam height, angle of divergence, and image aberrations were examined. From the results, we judged that the use of multiple EQ lenses was too complex.

However, a single EQ lens located between the magnets was found to give a significant theoretical improvement in ion transmission. By locating the EQ close to the focal point of the first magnetic sector, the lens has a negligible effect on the ion beam in the horizontal (x,z) plane. Yet, the EQ

FIGURE 2.7. Geometry of Single V-Filaments (side view): a) Standard Geometry; b) Geometry for Improved Vertical Focusing

effectively refocuses the beam in the vertical (y,z) plane because the lens action is greater farther from the axis. According to the calculation, all ions that reach the EQ lens are transmitted through the rest of the spectrometer. The only transmission loss occurs in the first stage ahead of the einzel lens, so the transmission efficiency is that of the normal geometry first stage--96%.

According to further calculations, the same improvement in transmission efficiency can be achieved with a cylindrical einzel lens in place of the EQ lens. (Some laboratories already operate with a planar einzel lens for vertical focusing between the magnets.) The calculated vertical and horizontal envelopes of the ion beam in a normal geometry three-stage mass spectrometer with a cylindrical einzel lens near the focus of the first magnet are shown in Figure 2.9. The entire ion beam that reaches the lens is transmitted through the final slit at the end of the spectrometer.

FIGURE 2.8. Vertical Ion Beam Profiles at S-4, the Focus of the Third-Stage Electric Sector, for the Two Filament Geometries of Figure 2.7: o = Profile with Standard Filament Geometry (14-kV U^+ ions); • = Profile with Geometry for Improved Vertical Focusing (9-kV I^- ions)

Although the thin (einzell) lens model in GIOS had not been verified experimentally, the simplicity of design, fabrication and operation of such a lens in comparison with an EQ lens made it an attractive possibility. We built a cylindrical einzel lens with the help of design charts (Shimizu and Kawakatsu 1974). The lens was installed in the inter-stage slit housing of our heavy-element mass spectrometer (see Figure 2.10).

The lens was initially tested with 14-kV U^+ ions from a solution sample on a single V-filament ion source. The mass spectrometer was tuned for maximum ion signal with the einzel lens off. The first application of voltage to the lens produced an increase in ion signal. The ion signal increased with

FIGURE 2.10. Placement of a Cylindrical Einzel Lens in the Slit Housing Between Magnets

lens voltage up to ~ 1000 V, where it reached a plateau (see Figure 2.11). The total increase in ion signal was one-third of the initial value--consistent with an increase in transmission to $\sim 100\%$ from the $\sim 75\%$ indicated by our vertical beam profile measurements. The transmission increase was somewhat less for a particle sample because the narrower vertical beam profile from a particle gives better transmission to begin with and, therefore, less room for improvement.

To verify that the einzel lens does not defocus or shift the beam in the plane of mass dispersion, horizontal ion beam profiles were measured at S-3, the focus of the second magnetic sector, with the lens off and on. The profiles (Figure 2.12) were measured by moving an 0.08-mm-wide slit across the stationary beam.

FIGURE 2.11. Increase of Transmitted Ion Signal with Voltage Applied to a Cylindrical Einzel Lens Located Between Magnets on a Three-Stage Mass Spectrometer. Ions are 14-kV U^+ from a single V-filament ion source. The four curves are for different filaments loaded with either a solution sample or particle sample, as indicated.

The vertical focusing effect of the einzel lens can best be seen at S-4, the final slit preceding the ion detector. Figure 2.13 shows vertical ion beam profiles from a solution sample with the lens off and on. The structure of the "lens on" profile reflects the ion emission pattern along the length of the single V-filament source. Figure 2.14 shows vertical profiles of the ion beam from a single particle sample.

An einzel lens was also installed on our three-stage iodine mass spectrometer, which has a triple-filament source. As stated previously, the ion transmission with the triple filament is considerably less than with the single V-filament, so there is more room for improvement. The increase in ion signal with lens voltage is shown in Figure 2.15. The transmission versus

FIGURE 2.12. Horizontal Ion Beam Profiles at S-3, the Focus of the Second-Stage Magnetic Sector, with a Cylindrical Einzel Lens Located Between Magnets Turned Off and On. The ion detector was located at S-4. The beam is 14-kV U^+ ions from a solution sample on a single V-filament. The profiles were measured by moving an 0.08-mm-wide slit across the stationary beam.

lens voltage curve shows a definite peak instead of a plateau. The voltage for maximum transmission varies from filament to filament depending on the emission pattern and source lens focusing conditions. The maximum increase in transmission was ~80%, which still does not give complete transmission through the analyzer stages following the lens. The range of ion trajectories with the triple-filament source is greater than the einzel lens can successfully focus simultaneously.

Vertical ion beam profiles at the end of the spectrometer from the triple-filament source are shown in Figure 2.16. The profiles are from the filament assembly that showed a peak transmission increase of 47% in Figure 2.15.

FIGURE 2.13. Vertical Ion Beam Profiles at S-4, the Focus of the Third-Stage Electric Sector, with a Cylindrical Einzel Lens Located Between Magnets "Off" and "On." The beam is 14-kV U^+ ions from a solution sample on a single V-filament.

FIGURE 2.14. Vertical Ion Beam Profiles at S-4, the Focus of the Third-Stage Electric Sector, with a Cylindrical Einzel Lens Located Between Magnets "Off" and "On." The beam is 14-kV U^+ ions from a particle sample on a single V-filament.

FIGURE 2.15. Increase of Transmitted Ion Signal with Voltage Applied to a Cylindrical Einzel Lens Located Between Magnets on a Triple-Sector Mass Spectrometer. Ions are 9-kV I^- from a triple-filament ion source. The three curves are for three different filament assemblies.

FIGURE 2.16. Vertical Ion Beam Profiles at S-4, the Focus of the Third-Stage Electric Sector, with a Cylindrical Einzel Lens at S-2 Turned Off and On. The beam is 9-kV I^- from a triple-filament ion source.

3.0 NEW THREE-STAGE MASS SPECTROMETER

3.1 ION-OPTICAL DESIGN

More than 500 calculations were made with GIOS to investigate improved designs for mass spectrometers with tandem magnetic analyzers. To serve as a common basis of comparison, the parameters in Table 3.1 were used for all calculations. We used a vertical divergence angle from the ion source of ± 5.0 mrad, which is the maximum angle of acceleration for 10 keV ions with thermal energy of 0.25 eV (Wollnik 1987).

The design of new multistage mass spectrometers is free of the limitations imposed on the existing instruments. This freedom allowed us to incorporate one of the major ion-optical design features of modern magnetic mass spectrometers, namely, nonnormal entry of the ion beam to and exit from the magnetic field. Nonnormal magnetic field boundaries give focusing in the vertical (y,z) plane as well as the horizontal (x,z) plane. With appropriate entrance and exit angles, the vertical and horizontal focal points can even be made to coincide. Cross (1951) determined that this case of two-direction, or stigmatic, focusing occurs for an angle of the magnet boundaries, $\epsilon = 26.5^\circ$, in the case of a sector angle, $\Phi = 90^\circ$. The drift lengths are extended to twice the radius of deflection, $l = 2.0 R$ (see Figure 3.1), and the mass dispersion is also doubled. Mass resolution, however, increases by only ~20% because the α^2 image aberration is much larger.

The analysis by Cross was based on an ideal magnet boundary with sharp cutoff of the fringe field. The theoretical correction developed by Enge (1963) for real extended fringe fields increases both the boundary angle and focal length. GIOS calculated these corrected parameters to be $\epsilon = 28^\circ$ and $l = 2.1 R$. In practice, nonparallelism of the isoinduction lines with the physical pole edge can require an even greater increase in the angle of the pole boundary (Morris 1967).

The stigmatic focusing, extended geometry, which is used in commercial single-stage mass spectrometers, was our first choice for investigation of a tandem arrangement with improved transmission efficiency. Calculation showed, however, that the stigmatic analyzer is not the optimum choice for a tandem

TABLE 3.1. Mass Spectrometer Parameters Input to GIOS

Ion source $x = \pm 0.15$ mm, $\alpha = \pm 17.5$ mrad	(1.0°)
$y = \pm 3.0$ mm, $\beta = \pm 5.0$ mrad	(0.3°)
Ion thermal energy	0.25 eV
Ion kinetic energy	10^4 eV
Magnet deflection angle	90.0°
Magnet deflection radius	30.5 cm
Magnet total airgap	1.8 cm
Clear height in analyzer tube	1.4 cm
Electric sector deflection angle	90.0°
Electric sector deflection radius	30.5 cm
Separation between ES plates	2.0 cm
Detector aperture	1.5 cm

FIGURE 3.1. Schematic Diagram of a Single-Stage Magnetic Sector Mass Spectrometer with Nonnormal Entry and Exit of the Ion Beam to Give Stigmatic Focusing

arrangement because the ion beam blows up in the second magnet (Figure 3.2). Indeed, although a stigmatic focus is achieved at S-2 and S-3, the beam height at the entrance to the second magnet approaches that of the normal geometry case. Ion transmission is limited by the clear height inside the flight tube

in the gap of the second magnet. The calculated ion transmission efficiency of tandem stigmatic analyzers is 89%. In addition, the vertical divergence angle of the beam becomes twice that of the normal geometry case. As a result, when an electrostatic analyzer is added as a third stage, the final beam height exceeds the detector aperture and further transmission loss occurs.

A number of more exotic arrangements with asymmetric magnetic analyzers were also modeled with GIOS. One example is shown in Figure 3.3. These did not show any advantage over symmetric arrangements for the intended purpose of high abundance-sensitivity isotope ratio measurement. Although some gave increased mass resolution, they generally resulted in reduced ion transmission due to blowup of the beam in the second magnet.

The most favorable geometry found is one in which the fringe-field focusing renders the ion beam parallel in the vertical plane between the magnets. This geometry had been shown to increase the transmission of a single magnetic analyzer (Ezoe 1967), but its effectiveness when used in tandem had not previously been investigated. In the tandem arrangement, there is a stigmatic focus at S-3 because of symmetry. For this case, the field boundary angles and drift lengths were calculated to be 17° and $1.44 R$, respectively

FIGURE 3.3. Example of a Mass Spectrometer with Asymmetric Tandem Magnets

(Figure 3.4). The ion beam envelope (Figure 3.5) stays within the confines of the magnet gap, thereby giving a calculated ion transmission efficiency of 100%.

This parallel, stigmatic, two-stage (or "PS/2") arrangement has a mass resolution approximately 16% greater than the normal geometry because the longer drift lengths increase the mass dispersion.

With 17° of nonnormal entry to and exit from the magnetic field and 90° of ion beam deflection, the sector angle of the magnets is 56° . This is close to 60° , which is a classic sector angle for mass spectrometer magnets (Nier 1940). If 60° magnets would give performance comparable to the ideal 56° geometry, the tandem arrangement could use readily available standard magnets. Furthermore, the design would potentially be valuable to laboratories that have such magnets on hand.

FIGURE 3.4. A Two-Stage Mass Spectrometer Design That Gives a Parallel Ion Beam Between the Magnets in the Vertical Plane and a Stigmatic Focus at the End ("PS/2" geometry)

FIGURE 3.5. Calculated Vertical and Horizontal Ion Beam Envelopes for the Mass Spectrometer with PS/2 Geometry. The symbols and other notations are as in Figure 2.1.

The case of two 60° -sector magnets in tandem with 90° deflection of the ion beam through them (Figure 3.6) was calculated. In this "60/90/2" geometry, the drift lengths, $l = 1.38 R$, are slightly shorter than the PS/2 geometry. The ion beam envelopes (Figure 3.7) are virtually the same as for the ideal 56° geometry. The calculated ion transmission efficiency is still 100%, the same as the ideal case.

We should point out that the ion path through 60° -sector magnets with 90° deflection of the ion beam is different from that with normal 60° deflection of the beam (see Figure 3.8). Hence, if a magnet designed for 60° deflection is used for 90° deflection, the entry and exit points for the ion beam may need to be shifted to use the most homogeneous area of the magnetic field. The deflection radius for 90° deflection is smaller than the radius for 60° deflection by a factor of 0.707. However, because of the extended geometry, the mass dispersion and resolution remain the same.

FIGURE 3.6. A Novel Two-Stage Mass Spectrometer Design Consisting of 60° Magnetic Sectors with 90° Deflection of the Ion Beam Through Them ("60/90/2" geometry)

```

Z (LIU)      Y =0.200E-01 TLU                      X =0.200E-01 TLU
  I                                                    I
  I-----I-----Y---Y-----I-----I-----
  I          BYYYY AA                               I
  I          BBYYY AAAA                             I
  I          BBYYY AAAAAA                           I
  I          BBBYYY AAAAAAAA                         I
  I          BBBYYY AAAAAAAA                         I
  I          BBBYYY AAAAAAAA                         I
  = 15.-----BBBYYY=AAAAA-----I-----
MS..... BBBYYY AAAAAA                               I      MS
MS..... BBBYYY AAAAAA                               I      MS
MS..... BBBYYY AAAAAA                               I      MS
MS..... BBBYYY AAAAAAAGG                           I      MS
MS..... BBBYYY AAAAAAAGG                           I      MS
AS= 15.-----BBBYYY=AAAAAAGG-----I-----AS
  I          BBBBYY AAAAAAAGG                       I
  I          BBBBYY AAAAAAGG                         I
  I          BBBBYY AAAAAAGG                         I
  I          BBBBYY AAGGGG                           I
  I          BBBBY GGGG                               I
AS..... BBBBY .....AS
1.31 I          BBBBB AAGGGG                         I
  I          BBBBB AAAAAAGGGG                       I
  I          BBBBBY AAAAAAGGGGGG                     I
  I          BBBBBBY AAAAAAAGGGGGG                   I
  I          BBBBBBY XAAAAAAGGGGGGG                  I
AS= 15.-----BBBYY XAAAAAAGGGGGGGD-----I-----AS
MS..... BBBBY XAAAAAAGGGGGGGG                       I      MS
MS..... BBBBY XAAAAAAGGGGGGGG                       I      MS
MS..... BBBBY XAAAAAAGGGGGGGG                       I      MS
MS..... BBBBY XAAAAAAGGGGGGGG                       I      MS
MS..... BBBBY AAAAAAAGGGGGG                          I      MS
  = 15.-----BBBYYY=AAAAAAGGGGD-----I-----
  I          BBBYYY AAAAAAAGGGG                     I
  I          BBBYYY AAAAAAGG                         I
  I          BBBYYY AAAAGG                           I
  I          BBYYY AAGG                               I
  I          BBYYY .....AS
2.62 AS..... BBYYY .....AS
  I          BYYYY AAGG                               I
  I-----I-----Y---Y---AAAG-----I-----
ES  I          YYYYY AAAAAAGG .....ES
ES  I          YYYYY AAAAAAGGG .....ES
ES  I          BYYYY AAAAAAGG .....ES
ES  I          BBYYY AAAAAAGGD .....ES
ES  I          BBYYY AAAAG .....ES
  I-----I-----BBBYYY=AAAG-----I-----
  I          BBBYYY A .....I
AS..... BBBYYY .....AS
3.32

```

FIGURE 3.7. Calculated Vertical and Horizontal Ion Beam Envelopes for the Mass Spectrometer with 60/90/2 Geometry. The symbols and other notations are as in Figure 2.1.

FIGURE 3.8. Ion Paths Through a 60°-Sector Magnet with 60° Deflection of the Beam and with 90° Deflection

The improvement in ion transmission efficiency of this new geometry (either PS/2 or 60/90/2) is even greater in a three-stage configuration formed by the addition of an electrostatic analyzer. With normal geometry, there is further loss of transmission in a cylindrical electrostatic analyzer because the beam continues to diverge. With the new geometry, however, there is complete transmission through the third stage. Ion transmission efficiency data, calculated with uniform illumination of the ion source phase space, are summarized in Table 3.2.

The full height of the ion beam as it progresses through the various analyzer arrangements is plotted in Figure 3.9. Upper and lower limits are given for each case. The upper limit is calculated for a parallelogram-like phase space and corresponds to Figures 2.1, 2.9, 3.2, 3.5, and 3.7. The lower limit is calculated for an elliptical phase space, which occurs only after many beam-limiting diaphragms (Wollnik 1987). Reality should lie somewhere in between.

TABLE 3.2. Calculated Ion Transmission (%) of Various Multiple-Sector Mass Spectrometer Designs

Location	Tandem Magnet Geometry			
	Normal $\epsilon = 0^\circ$	Stigmatic $\epsilon = 28^\circ$	PS/2 $\epsilon = 17^\circ$	60/90/2 $\epsilon = 15^\circ$
S-2	96	100	100	100
S-3	56	89	100	100
S-4	41	67	100	100
Resolution	513	619	596	590

FIGURE 3.9. Ion Beam Height Through Three-Stage Mass Spectrometers with Normal ($\epsilon = 0^\circ$), Stigmatic ($\epsilon = 28^\circ$), Parallel-Stigmatic ($\epsilon = 17^\circ$), and 60/90/2 ($\epsilon = 15^\circ$) Magnet Geometries. The upper and lower limits are calculated for parallelogram-like phase space and elliptical phase space, respectively.

An increase in ion transmission efficiency from 41% (normal geometry) to 100% (PS/2 geometry) may be significant when the amount of data obtainable is limited by sample size. Total transmission of ions through the mass analyzer can be even more important than the magnitude of the increase. One case in point is the measurement of large isotope ratios with a Faraday cup following the first magnet and an electron multiplier following the electrostatic analyzer (Stoffels 1982). An uncertain and variable transmission factor between the two detectors, which occurs in a spectrometer with normal geometry magnets, directly affects the ratio measurements. Because the ion beam is cut off at some point(s) between the two detectors, the transmission between them varies with ion source emission and tuneup conditions. Moreover, the transmission factor cannot be determined at the operating conditions used for the ratio measurement because no ion signal is within the range of both detectors. By assuring total analyzer transmission, the PS/2 geometry will eliminate this factor and substantially improve the accuracy and reproducibility of such large isotope ratio measurements.

PNL has designed and is constructing a new three-stage isotope ratio mass spectrometer according to the PS/2 geometry. Figure 3.10 is a plan-view drawing of the spectrometer. One goal being realized in the construction is that the major components are commercially available. The use of standard components from a major mass spectrometer manufacturer is an important step in the direction of making commercially available complete instruments that satisfy our special analytical requirements.

FIGURE 3.10. Plan View of the Three-Stage Mass Spectrometer Being Built by PNL According to the PS/2 Geometry

4.0 CONCLUSIONS

Theoretical and experimental studies of the ion optics of multistage isotope-ratio mass spectrometers were conducted with a view to improving ion transmission efficiency. The design of existing instruments as well as improved designs for new instruments were investigated.

Theoretical calculations of mass spectrometers with tandem magnets of normal geometry show that transmission losses occur due to the lack of analyzer focusing in the vertical plane. The calculations also show that the ion transmission of existing spectrometers of normal geometry can be increased without any basic change in the geometry of the instruments. The addition of either an einzel lens or an electrostatic quadrupole lens at the focus between the tandem magnets gives almost complete transmission of ions.

Our studies also produced a new ion-optical design for multi-stage mass spectrometers with tandem magnetic analyzers. The design uses nonnormal magnetic field boundaries to provide ion beam focusing in the vertical plane. With 17° magnet boundaries, the ion beam is rendered parallel in the vertical plane at the focus of the first magnet and is brought to a stigmatic focus by the second magnet. This geometry gives 100% transmission through a two-stage or three-stage spectrometer without the need for any intermediate focusing lens. It also provides a 16% increase in mass resolution over normal geometry.

A new three-stage isotope-ratio mass spectrometer is being built at PNL according to this improved design. The complete GIOS calculation for the instrument is included as an Appendix.

5.0 ACKNOWLEDGMENTS

We are indebted to Prof. Hermann Wollnik, University of Giessen, Germany, for permission to use GIOS and for helpful discussions. E. Phil Chamberlin, Los Alamos National Laboratory, provided valuable help by getting one of us (J.J.S.) started with GIOS and by doing some initial calculations. Prof. R. Graham Cooks, Purdue University, kindly shared H.J.L.'s time during a post-doctoral appointment to work on this collaboration.

Jack D. Fassett, National Institute of Standards and Technology, originated the idea of using an angled slit to measure vertical ion beam profiles. Lee A. Bond, PNL, assisted in ion beam profile measurements. Delbert L. Lessor determined the effect of the scanning slit on the vertical profile measurements.

Don R. Ells provided technical drawings and assistance in installing the einzel lenses on the existing PNL three-stage mass spectrometers. Richard L. Mays machined the lenses.

We are especially grateful to Leonard A. Dietz, Schenectady, New York, for a critical review of our ion transmission studies on the existing three-stage mass spectrometers.

6.0 REFERENCES

- Cross, W. G. 1951. "Two-Directional Focusing of Charged Particles with a Sector-Shaped, Uniform Magnetic Field." Rev. Sci. Instrum. 22:717-722.
- Dietz, L. A. 1960. "Transmission Optics of Focused Ion Beams Used in Mass Spectrometry." Rev. Sci. Instrum. 31:1229-1233.
- Enge, H. A. 1963. "Effect of Extended Fringing Fields on Ion-Focusing Properties of Deflecting Magnets." Rev. Sci. Instrum. 35:278-287.
- Ezoe, H. 1967. "Two Directional Beam Convergence by Sector Shaped Uniform Magnetic Field." Rev. Sci. Instrum. 38:390-394.
- Hu, Z. H., T. Matsuo, and H. Matsuda. 1982. "Numerical Calculation of Fringing-Field Integrals for Arbitrary Electrode (magnetic pole) Structures." Int. J. Mass Spectrom. Ion Phys. 42:145-155.
- Kelley, J. M., and D. M. Robertson. 1985. "Plutonium Ion Emission from Carburized Rhenium Mass Spectrometer Filaments." Anal. Chem. 57:124-130.
- Lagergren, C. R., and J. J. Stoffels. 1970. "A Computer-Controlled, Three-Stage Mass Spectrometer." Int. J. Mass Spectrom. Ion Phys. 3:429-438.
- Laue, H.-J., and H. Wollnik. 1988. "A New Filter Supplement for Isotope Ratio Measurements." Int. J. Mass Spectrom. Ion Processes 84:231-241.
- McHugh, J. A. 1969. "Surface Ionization--The Rhenium V-Type Single Filament." Int. J. Mass Spectrom. Ion Phys. 3:267-276.
- Morris, W. R. 1967. "An Experimental Analysis of 90° Uniform Field Beam Bending Magnets." In Proceedings of the 2nd International Conference on Magnet Technology, H. Hadley, ed., pp. 727-734. Rutherford Laboratory, Chilton, UK.
- Nier, A. O. 1940. "A Mass Spectrometer for Routine Isotope Abundance Measurements." Rev. Sci. Instrum. 11:212-216.
- Shimizu, K., and H. Kawakatsu. 1974. "Design Charts of Electrostatic Three-Aperture Lenses." J. Phys. E: Scientific Instruments 7:472-476.
- Stoffels, J. J. 1982. "Measurement of Iodine-129 at the Femtogram Level by Negative Surface Ionization Mass Spectrometry." Radiochemical and Radioanalytical Letters 55:99-106.
- Stoffels, J. J., and C. R. Lagergren. 1983/1984. "Fabrication of V-Type Filaments for Surface Ionization Mass Spectrometry." Int. J. Mass Spectrom. Ion Processes 55:217-219.

Todd, P. J., H. S. McKown, and D. H. Smith. 1982. "A New Ion Source for Thermal Emission Mass Spectrometry." Int. J. Mass Spectrom. Ion Phys. 42:183-190.

White, F. A., and T. L. Collins. 1954. "A Two Stage Magnetic Analyzer for Isotopic Ratio Determinations of 10^4 to 1 or Greater." Appl. Spectrosc. 8:169-173.

White, F. A., F. M. Rourke, and J. C. Sheffield. 1958. "A Three Stage Mass Spectrometer." Appl. Spectrosc. 12:46-52.

Wollnik, H., J. Brezina, M. Berz, and W. Wendel. 1984. "GIOS-Beamtrace, a Program for the Design of High Resolution Mass Spectrometers." In Proceedings of the 7th International Conference on Atomic Masses and Fundamental Constants, Report THD-26, Gesellschaft für Schwerionenforschung, Darmstadt, Germany, pp. 679-683.

Wollnik, H. 1987. Optics of Charged Particles. Academic Press, Orlando.

APPENDIX

GIOS CALCULATION FOR THE HIGH-TRANSMISSION THREE-STAGE MASS SPECTROMETER BEING BUILT BY PNL ACCORDING TO THE PS/2 GEOMETRY

*** GIOS VERSION T4M ** GIESSEN 1986 **** DATE 24-MAY-91 TIME 15:53:53 ****
 INPUT DATA INPUT DATA

```

1. PARA-2 (VG) -ES (VG)
C : PNL 3-STAGE MASS SPECTROMETER WITH 17-DEGREE MAGNET FACES FOR
C : PARALLEL (Y,Z) BEAM AT S-2; 18-MM (TOTAL) MAGNET GAP, FF#3;
C : 81.5-DEGREE ELECTRIC SECTOR W/ RADIUS = 31.8 CM, FF#2;
C : ION SOURCE TERM: X = +/- .15 MM, ALPHA = +/- 0.57 DEGREE,
C : Y = +/- 3.0 MM, BETA = +/- 0.30 DEGREE.

2. C O 2 2 ;
3. R P .01 129 1 ;
4. D P .00775 2.E-4 ;
5. P X .00015 .0100 ;
6. P Y .0030 .0050 ;
7. F G 100 ;
8. D L .3900 ;
9. P E ;
10. F F 3 17.0 ;
11. M S .2700 45. .0090 ;
12. P E ;
13. M S .2700 45. .0090 ;
14. A S .1 .007 ;
15. F F 3 17.0 ;
16. P E ;
17. D L .3900 ;
18. P M ;
19. P N ;
20. P E ;
21. P I W P ;
22. P F ;
23. A S .0005 .007 ;
24. P P (X,Y) 10000 .001 .01 ;
25. D L .3900 ;
26. P E ;
27. F F 3 17.0 ;
28. A S .1 .007 ;
29. M S .2700 45. .0090 ;
30. P E ;
31. M S .2700 45. .0090 ;
32. F F 3 17.0 ;
33. P E ;
34. D L .3900 ;
35. P M ;
36. P N ;
37. P E ;
38. P I W P ;
39. A S .0005 .007 ;
40. P P (X,Y) 10000 .001 .01 ;
41. D L .171 ;
42. F F 2 ;
43. E S .3810 40.75 .0100 ;
44. P E ;
45. E S .3810 40.75 .0100 ;
46. F F 2 ;
47. D L .171 ;
48. P M ;
49. P N ;
50. P E ;
51. P I W P ;

```

STATISTICAL INFORMATION

INPUT COMPLETE, GIOS STARTS CALCULATION

.....

..

.. PARA - 2 (VG) -ES (VG)

..

.....

DRIFT LENGTH = 0.39000		LLU	U1 = 0.00000	LLU	V1 = 0.00000	LLU
			U2 = 0.39000	LLU	W = 0.00000	DEG
					V2 = 0.00000	LLU

A.2


```

.....
MAGN FR.FIELD  TABLE 3.  ENTR.ANGLE= 17.00 DEGREES  REL.CURVATURE= 0.0000 |
MAGN FR.FIELD  1.INT= 2.8000  2.INT=-1.0400  3.INT=-2.2400
MAGN
MAGN SECTOR    DEFL.RADIUS = 0.2700 LLU  DEFL.ANGLE = 45.0000 DEGR. |
MAGN SECTOR    PATH LENGTH = 0.21206 LLU  FL.DENSITY = 0.60564 TESLA |
MAGN SECTOR    HALF GAP   = 0.00900 TLU
MAGN SECTOR    N1= 0.0000  N2= 0.0000  N3= 0.0000
MAGN
.....

```

```

.....
                PARALLELOGR.  DISPERSION  ELLIPTICAL  TWISS
                PHASE SPACE                                PARAMETERS
.....
ENVELOPE X      0.0056 TLU  0.0003 TLU  0.0055 TLU  ALPHA=0.612E-01
ENVELOPE A      0.0003 RAD  0.0028 RAD  0.0003 RAD  BETA = 20.2      TLU/RAD
                                           GAMMA=0.497E-01  RAD/TLU
ENVELOPE Y      0.0050 TLU  0.0000 TLU  0.0035 TLU  ALPHA=-.761E-01
ENVELOPE B      0.0060 RAD  0.0000 RAD  0.0043 RAD  BETA =0.831      TLU/RAD
                                           GAMMA= 1.21      RAD/TLU
.....

```

```

.....
MAGN
MAGN SECTOR    DEFL.RADIUS = 0.2700 LLU  DEFL.ANGLE = 45.0000 DEGR. |
MAGN SECTOR    PATH LENGTH = 0.21206 LLU  FL.DENSITY = 0.60564 TESLA |
MAGN SECTOR    HALF GAP   = 0.00900 TLU
MAGN SECTOR    N1= 0.0000  N2= 0.0000  N3= 0.0000
MAGN
.....

```

APERTURE SLIT, RADIAL .10000 TLU, AXIAL .70000E-02 TLU

```

.....
MAGN FR.FIELD  TABLE 3.  EXIT.ANGLE= 17.00 DEGREES  REL.CURVATURE= 0.0000 |
MAGN FR.FIELD  1.INT= 2.8000  2.INT=-1.0400  3.INT=-2.2400
.....

```

```

.....
                PARALLELOGR.  DISPERSION  ELLIPTICAL  TWISS
                PHASE SPACE                                PARAMETERS
.....
ENVELOPE X      0.0039 TLU  0.0011 TLU  0.0039 TLU  ALPHA= 26.0
ENVELOPE A      0.0105 RAD  0.0052 RAD  0.0100 RAD  BETA = 10.1      TLU/RAD
                                           GAMMA= 67.1      RAD/TLU
ENVELOPE Y      0.0050 TLU  0.0000 TLU  0.0037 TLU  ALPHA=0.561
ENVELOPE B      0.0047 RAD  0.0000 RAD  0.0046 RAD  BETA =0.918      TLU/RAD
                                           GAMMA= 1.43      RAD/TLU
.....

```

```

.....
                DRIFT LENGTH = 0.39000 LLU
                U1 = 0.66000 LLU  V1 = -0.26999 LLU
                U2 = 0.66002 LLU  V2 = -0.65999 LLU
                W = -90.00000 DEG
.....

```

TRANSFER MATRIX OF THE SYSTEM AT PATH LENGTH L= 1.2041 LLU

X AND Y IN TLU, A AND B IN RAD, G AND D IN PARTS FROM M0 AND K0

```

(X,X )=-1.0018      (A,X )=-3.3575      (T,X )= 1.0818
(X,A )=-.10815E-02  (A,A )=-1.0018      (T,A )=0.64501
(X,G )=0.38833      (A,G )=0.65132      (T,G )=0.56499

```

(X,D)=0.38833	(A,D)=0.65132	(T,D)=-.43501
(X,XX)=-2.5066	(A,XX)=-1.7232	(T,XX)= 1.8240
(X,XA)=-2.1073	(A,XA)=-2.0541	(T,XA)= 1.4188
(X,XG)= 1.4265	(A,XG)= 2.3467	(T,XG)=-.16412
(X,XD)= 1.4265	(A,XD)= 2.3467	(T,XD)=-1.2485
(X,AA)=-.62812	(A,AA)=-1.0528	(T,AA)=0.56476
(X,AG)=0.67900	(A,AG)=0.85242	(T,AG)=0.22497
(X,AD)=0.67900	(A,AD)=0.85242	(T,AD)=-.42156
(X,GG)=-.27948	(A,GG)=-.55326	(T,GG)=-.40461E-01
(X,GD)=-.17063	(A,GD)=-.45520	(T,GD)=-.80425E-01
(X,DD)=-.27948	(A,DD)=-.55326	(T,DD)=0.39505
(X,YY)=-2.9724	(A,YY)=-7.2092	(T,YY)= 2.5907
(X,YB)=-2.6358	(A,YB)=-4.4619	(T,YB)= 1.4430
(X,BB)=-1.2695	(A,BB)=-1.1956	(T,BB)=0.49815
(Y,Y)=-.14988E-01	(B,Y)=-1.5444	
(Y,B)=0.64733	(B,B)=-.14988E-01	
(Y,YX)=-3.7906	(B,YX)=-7.1902	
(Y,YA)=-4.0912	(B,YA)=-4.2871	
(Y,YG)= 1.0116	(B,YG)= 2.2424	
(Y,YD)= 1.0116	(B,YD)= 2.2424	
(Y,BX)=-3.1469	(B,BX)=-9.9390	
(Y,BA)=-1.8763	(B,BA)=-4.0948	
(Y,BG)=0.97107	(B,BG)= 2.2046	
(Y,BD)=0.97107	(B,BD)= 2.2046	

TRANSFER MATRIX OF THE SYSTEM AT PATH LENGTH L= 1.2041 LLU

X AND Y IN TLU, A AND B IN RAD, G AND D IN PARTS FROM M0 AND K0

MAGNITUDE OF ABBERATIONS M (IJK)		
X(X)=-.15027E-03	A(X)=-.50363E-03	T(X)=0.16227E-03
X(A)=-.10815E-04	A(A)=-.10018E-01	T(A)=0.64501E-02
X(G)=0.30096E-02	A(G)=0.50478E-02	T(G)=0.43787E-02
X(D)=0.77666E-04	A(D)=0.13026E-03	T(D)=-.87002E-04
X(XX)=-.56398E-07	A(XX)=-.38773E-07	T(XX)=0.41040E-07
X(XA)=-.31610E-05	A(XA)=-.30812E-05	T(XA)=0.21282E-05
X(XG)=0.16583E-05	A(XG)=0.27281E-05	T(XG)=-.19079E-06
X(XD)=0.42794E-07	A(XD)=0.70402E-07	T(XD)=-.37455E-07
X(AA)=-.62812E-04	A(AA)=-.10528E-03	T(AA)=0.56476E-04
X(AG)=0.52623E-04	A(AG)=0.66062E-04	T(AG)=0.17435E-04
X(AD)=0.13580E-05	A(AD)=0.17048E-05	T(AD)=-.84312E-06
X(GG)=-.16786E-04	A(GG)=-.33230E-04	T(GG)=-.24302E-05
X(GD)=-.26447E-06	A(GD)=-.70556E-06	T(GD)=-.12466E-06
X(DD)=-.11179E-07	A(DD)=-.22130E-07	T(DD)=0.15802E-07
X(YY)=-.26752E-04	A(YY)=-.64883E-04	T(YY)=0.23317E-04
X(YB)=-.39537E-04	A(YB)=-.66928E-04	T(YB)=0.21645E-04
X(BB)=-.31738E-04	A(BB)=-.29891E-04	T(BB)=0.12454E-04
Y(Y)=-.44965E-04	B(Y)=-.46333E-02	
Y(B)=0.32367E-02	B(B)=-.74941E-04	

Y(YX)=-.17058E-05	B(YX)=-.32356E-05
Y(YA)=-.12273E-03	B(YA)=-.12861E-03
Y(YG)=0.23520E-04	B(YG)=0.52135E-04
Y(YD)=0.60696E-06	B(YD)=0.13454E-05
Y(BX)=-.23602E-05	B(BX)=-.74543E-05
Y(BA)=-.93817E-04	B(BA)=-.20474E-03
Y(BG)=0.37629E-04	B(BG)=0.85428E-04
Y(BD)=0.97107E-06	B(BD)=0.22046E-05

	PARALLELOGR. PHASE SPACE	DISPERSION	ELLIPTICAL PHASE SPACE	TWISS PARAMETERS
ENVELOPE X	0.0002 TLU	0.0031 TLU	0.0002 TLU	ALPHA=-.123
ENVELOPE A	0.0105 RAD	0.0052 RAD	0.0100 RAD	BETA =0.151E-01 TLU/RAD
				GAMMA= 67.1 RAD/TLU
ENVELOPE Y	0.0033 TLU	0.0000 TLU	0.0032 TLU	ALPHA=0.228E-02
ENVELOPE B	0.0047 RAD	0.0000 RAD	0.0046 RAD	BETA =0.699 TLU/RAD
				GAMMA= 1.43 RAD/TLU

NEXT IMAGE IN X-DIR AFTER	-0.1080E-02,	IN Y-DIR AFTER	43.19	LLU
NEXT WAIST IN X-DIR AFTER	-0.1829E-02,	IN Y-DIR AFTER	0.1594E-02	LLU
NEXT PUPIL IN X-DIR AFTER	-0.2984	IN Y-DIR AFTER	-0.9705E-02	LLU

FOCAL CURVE (ANGLE A) OMEGA = 60.18933 DEG
 CURVATURE = 1.95925 LLU
 NO D-PLOT BECAUSE (X.D)= 0.39E+00 NOT SMALL ENOUGH

FOCAL CURVE RANGE OF MAS= DEVIATION FROM -5 TO +5 PERCENT
 RANGE X DIRECTION --+0.358E-01 TLU RANGE Z DIRECTION --+

APERTURE SLIT, RADIAL .50000E-03 TLU, AXIAL .70000E-02 TLU

BEAM CROSS SECTION (X,Y) AT PATH-LENGTH = 1.2041 LLU

X-RANGE = 0.001000 TLU Y-RANGE = 0.010000 TLU
10000 PARTICLES STARTED IN A PARALLELOGRAM LIKE PHASE SPACE (R)
10000 PARTICLES, I.E. 100.0 PER CENT ARRIVED IN THE SHOWN WINDOW

	CENTER OF WINDOW	HALF WIDTH	DISTRIBUTION
--	------------------	------------	--------------

X =	0.0000 +-	0.0002	0.00
-----	-----------	--------	------

A =	0.0000 +-	0.0100	0.00
-----	-----------	--------	------

G =	0.0000 +-	0.0078	0.00
-----	-----------	--------	------

D =	0.0000 +-	0.0002	0.00
-----	-----------	--------	------

Y =	0.0000 +-	0.0030	0.00
-----	-----------	--------	------

B =	0.0000 +-	0.0050	0.00
-----	-----------	--------	------

DIAGRAMM CONTAINS 0 DISCRETE MASSES

MASS DIFFERENCES EQUAL 0.0 PERCENT OF REF. MASS

-
- (.) FROM 1 TO 25 PER CENT OF MAXIMAL BEAM INTENSITY
 - (=) FROM 25 TO 50 PER CENT OF MAXIMAL BEAM INTENSITY
 - (+) FROM 50 TO 75 PER CENT OF MAXIMAL BEAM INTENSITY
 - (*) FROM 75 TO 100 PER CENT OF MAXIMAL BEAM INTENSITY
(100 PER CENT EQUIV. 85 PARTICLES)

BEAM DENSITY VERSUS X

MAXIMAL DENSITY = 974 PARTICLES PER 0.33333E-04 TLU
RMS-ENVELOPE = 0.10786E-03 TLU

BEAM DENSITY VERSUS Y

MAXIMAL DENSITY = 974 PARTICLES PER 0.33333E-03 TLU
RMS-ENVELOPE = 0.18729E-02 TLU

DRIFT LENGTH = 0.39000 LLU
U1 = 0.66002 LLU V1 = -0.65999 LLU
W = -90.00000 DEG
U2 = 0.66004 LLU V2 = -1.04999 LLU

	PARALLELOGR. PHASE SPACE	DISPERSION	ELLIPTICAL PHASE SPACE	TWISS PARAMETERS	
ENVELOPE X	0.0043 TLU	0.0051 TLU	0.0039 TLU	ALPHA=-26.3	
ENVELOPE A	0.0105 RAD	0.0052 RAD	0.0100 RAD	BETA = 10.3	TLU/RAD
				GAMMA= 67.1	RAD/TLU
ENVELOPE Y	0.0051 TLU	0.0000 TLU	0.0037 TLU	ALPHA=-.556	
ENVELOPE B	0.0047 RAD	0.0000 RAD	0.0046 RAD	BETA =0.915	TLU/RAD
				GAMMA= 1.43	RAD/TLU

MAGN FR.FIELD TABLE 3. ENTR.ANGLE= 17.00 DEGREES REL.CURVATURE= 0.0000 I
MAGN FR.FIELD 1.INT= 2.8000 2.INT=-1.0400 3.INT=-2.2400

APERTURE SLIT, RADIAL .10000 TLU, AXIAL .70000E-02 TLU

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.....
MAGN
MAGN SECTOR   DEFL.RADIUS =  0.2700 LLU   DEFL.ANGLE =  45.0000 DEGR. |
MAGN SECTOR   PATH LENGTH =  0.21206 LLU   FL.DENSITY =  0.60564 TESLA |
MAGN SECTOR   HALF GAP    =  0.00900 TLU   |
MAGN SECTOR   N1=  0.0000   N2=  0.0000   N3=  0.0000   |
MAGN
.....

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.....
                PARALLELOGR.  DISPERSION  ELLIPTICAL  TWISS
                PHASE SPACE                                PARAMETERS
.....
ENVELOPE X     0.0059 TLU    0.0060 TLU    0.0055 TLU    ALPHA=0.185
ENVELOPE A     0.0003 RAD    0.0028 RAD    0.0003 RAD    BETA = 20.5      TLU/RAD
                                           GAMMA=0.505E-01  RAD/TLU
ENVELOPE Y     0.0050 TLU    0.0000 TLU    0.0035 TLU    ALPHA=0.760E-01
ENVELOPE B     0.0060 RAD    0.0000 RAD    0.0043 RAD    BETA =0.828      TLU/RAD
                                           GAMMA= 1.22      RAD/TLU
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.....
MAGN
MAGN SECTOR   DEFL.RADIUS =  0.2700 LLU   DEFL.ANGLE =  45.0000 DEGR. |
MAGN SECTOR   PATH LENGTH =  0.21206 LLU   FL.DENSITY =  0.60564 TESLA |
MAGN SECTOR   HALF GAP    =  0.00900 TLU   |
MAGN SECTOR   N1=  0.0000   N2=  0.0000   N3=  0.0000   |
MAGN
.....
MAGN FR.FIELD  TABLE 3.  EXIT.ANGLE= 17.00 DEGREES  REL.CURVATURE= 0.0000 |
MAGN FR.FIELD  1.INT= 2.8000  2.INT=-1.0400  3.INT=-2.2400
.....

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.....
                PARALLELOGR.  DISPERSION  ELLIPTICAL  TWISS
                PHASE SPACE                                PARAMETERS
.....
ENVELOPE X     0.0041 TLU    0.0040 TLU    0.0039 TLU    ALPHA= 26.4
ENVELOPE A     0.0111 RAD    0.0104 RAD    0.0101 RAD    BETA = 10.2      TLU/RAD
                                           GAMMA= 68.3      RAD/TLU
ENVELOPE Y     0.0049 TLU    0.0000 TLU    0.0036 TLU    ALPHA=0.645
ENVELOPE B     0.0051 RAD    0.0000 RAD    0.0050 RAD    BETA =0.850      TLU/RAD
                                           GAMMA= 1.67      RAD/TLU
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                U1 =  0.39006 LLU   V1 = -1.32000 LLU
DRIFT LENGTH = 0.39000   LLU      W  =-180.00000 DEG
                U2 =  0.00006 LLU   V2 = -1.32004 LLU
.....

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TRANSFER MATRIX OF THE SYSTEM AT PATH LENGTH L= 2.4082 LLU

X AND Y IN TLU, A AND B IN RAD, G AND D IN PARTS FROM M0 AND K0

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(X,X )= 1.0073      (A,X )= 6.7272      (T,X )=-1.0838
(X,A )=0.21670E-02  (A,A )= 1.0073      (T,A )=-.11700E-02
(X,G )=-.14089E-02  (A,G )=-1.3050      (T,G )=0.98510
(X,D )=-.14089E-02  (A,D )=-1.3050      (T,D )=-.14902E-01

(X,XX )=-14.172     (A,XX )=-10.365      (T,XX )= 5.4850
(X,XA )=-4.2402     (A,XA )=-.22183E-01  (T,XA )= 1.5232

```

(X,XG)= 3.6797	(A,XG)=-2.3893	(T,XG)=-2.1815
(X,XD)= 3.6797	(A,XD)=-2.3893	(T,XD)=-1.0952
(X,AA)=-.22890E-02	(A,AA)= 2.1048	(T,AA)=-.11275
(X,AG)=0.28019	(A,AG)=-1.8142	(T,AG)=-.36754E-02
(X,AD)=0.28019	(A,AD)=-1.8142	(T,AD)=-.25026E-02
(X,GG)=-.18016	(A,GG)= 1.1798	(T,GG)=0.10808
(X,GD)=-.36173	(A,GD)= 1.0546	(T,GD)=0.21566
(X,DD)=-.18016	(A,DD)= 1.1798	(T,DD)=0.12248
(X,YY)=-.10425	(A,YY)= 14.245	(T,YY)=-2.0263
(X,YB)= 5.2790	(A,YB)= 17.864	(T,YB)=-2.8780
(X,BB)=0.52819E-01	(A,BB)= 2.4823	(T,BB)=-.28735

(Y,Y)=-.99955	(B,Y)=0.46297E-01
(Y,B)=-.19405E-01	(B,B)=-.99955

(Y,YX)=-19.459	(B,YX)=-30.973
(Y,YA)=-5.6838	(B,YA)=-.33914E-01
(Y,YG)= 3.7583	(B,YG)= 5.1293
(Y,YD)= 3.7583	(B,YD)= 5.1293
(Y,BX)= 4.8217	(B,BX)= 18.635
(Y,BA)=0.50058E-02	(B,BA)= 5.6829
(Y,BG)=-.58833	(B,BG)=-3.6315
(Y,BD)=-.58833	(B,BD)=-3.6315

TRANSFER MATRIX OF THE SYSTEM AT PATH LENGTH L= 2.4082 LLU

X AND Y IN TLU, A AND B IN RAD, G AND D IN PARTS FROM M0 AND K0

MAGNITUDE OF ABBERATIONS M (IJK)

X(X)=0.15109E-03	A(X)=0.10091E-02	T(X)=-.16257E-03
X(A)=0.21670E-04	A(A)=0.10073E-01	T(A)=-.11700E-04
X(G)=-.10919E-04	A(G)=-.10114E-01	T(G)=0.76345E-02
X(D)=-.28177E-06	A(D)=-.26100E-03	T(D)=-.29803E-05

X(XX)=-.31886E-06	A(XX)=-.23322E-06	T(XX)=0.12341E-06
X(XA)=-.63603E-05	A(XA)=-.33274E-07	T(XA)=0.22848E-05
X(XG)=0.42776E-05	A(XG)=-.27776E-05	T(XG)=-.25360E-05
X(XD)=0.11039E-06	A(XD)=-.71679E-07	T(XD)=-.32855E-07
X(AA)=-.22890E-06	A(AA)=0.21048E-03	T(AA)=-.11275E-04
X(AG)=0.21715E-04	A(AG)=-.14060E-03	T(AG)=-.28484E-06
X(AD)=0.56039E-06	A(AD)=-.36285E-05	T(AD)=-.50053E-08
X(GG)=-.10821E-04	A(GG)=0.70863E-04	T(GG)=0.64916E-05
X(GD)=-.56068E-06	A(GD)=0.16347E-05	T(GD)=0.33428E-06
X(DD)=-.72064E-08	A(DD)=0.47193E-07	T(DD)=0.48994E-08
X(YY)=-.93825E-06	A(YY)=0.12821E-03	T(YY)=-.18237E-04
X(YB)=0.79185E-04	A(YB)=0.26796E-03	T(YB)=-.43170E-04
X(BB)=0.13205E-05	A(BB)=0.62057E-04	T(BB)=-.71837E-05

Y(Y)=-.29987E-02	B(Y)=0.13889E-03
Y(B)=-.97024E-04	B(B)=-.49978E-02

Y(YX)=-.87567E-05	B(YX)=-.13938E-04
Y(YA)=-.17051E-03	B(YA)=-.10174E-05
Y(YG)=0.87381E-04	B(YG)=0.11926E-03
Y(YD)=0.22550E-05	B(YD)=0.30776E-05

Y(BX)=0.36163E-05	B(BX)=0.13976E-04
Y(BA)=0.25029E-06	B(BA)=0.28414E-03
Y(BG)=-.22798E-04	B(BG)=-.14072E-03
Y(BD)=-.58833E-06	B(BD)=-.36315E-05

.....

	PARALLELOGR. PHASE SPACE	DISPERSION	ELLIPTICAL PHASE SPACE	TWISS PARAMETERS
ENVELOPE X	0.0002 TLU	0.0000 TLU	0.0002 TLU	ALPHA=-.247
ENVELOPE A	0.0111 RAD	0.0104 RAD	0.0101 RAD	BETA =0.155E-01 TLU/RAD
				GAMMA= 68.3 RAD/TLU
ENVELOPE Y	0.0031 TLU	0.0000 TLU	0.0030 TLU	ALPHA=-.456E-02
ENVELOPE B	0.0051 RAD	0.0000 RAD	0.0050 RAD	BETA =0.600 TLU/RAD
				GAMMA= 1.67 RAD/TLU

.....

NEXT IMAGE IN X-DIR AFTER	-0.2151E-02,	IN Y-DIR AFTER	-0.1941E-01	LLU
NEXT WAIST IN X-DIR AFTER	-0.3618E-02,	IN Y-DIR AFTER	-0.2737E-02	LLU
NEXT PUPIL IN X-DIR AFTER	-0.1497	, IN Y-DIR AFTER	21.59	LLU

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APERTURE SLIT, RADIAL	.50000E-03 TLU,	AXIAL	.70000E-02 TLU
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BEAM CROSS SECTION (X,Y) AT PATH-LENGTH = 2.4082 LLU

X-RANGE = 0.001000 TLU Y-RANGE = 0.010000 TLU
10000 PARTICLES STARTED IN A PARALLELOGRAM LIKE PHASE SPACE (R)
10000 PARTICLES, I.E. 100.0 PER CENT ARRIVED IN THE SHOWN WINDOW

	CENTER OF WINDOW	HALF WIDTH	DISTRIBUTION
X =	0.0000 +- 0.0002	0.0002	0.00
A =	0.0000 +- 0.0100	0.0100	0.00
G =	0.0000 +- 0.0078	0.0078	0.00
D =	0.0000 +- 0.0002	0.0002	0.00
Y =	0.0000 +- 0.0030	0.0030	0.00
B =	0.0000 +- 0.0050	0.0050	0.00

DIAGRAMM CONTAINS 0 DISCRETE MASSES
MASS DIFFERENCES EQUAL 0.0 PERCENT OF REF. MASS

-
- (.) FROM 1 TO 25 PER CENT OF MAXIMAL BEAM INTENSITY
 - (=) FROM 25 TO 50 PER CENT OF MAXIMAL BEAM INTENSITY
 - (+) FROM 50 TO 75 PER CENT OF MAXIMAL BEAM INTENSITY
 - (*) FROM 75 TO 100 PER CENT OF MAXIMAL BEAM INTENSITY
- (100 PER CENT EQUIV. 94 PARTICLES)

BEAM DENSITY VERSUS X

MAXIMAL DENSITY = 999 PARTICLES PER 0.33333E-04 TLU
RMS-ENVELOPE = 0.92196E-04 TLU

BEAM DENSITY VERSUS Y

MAXIMAL DENSITY = 999 PARTICLES PER 0.33333E-03 TLU
RMS-ENVELOPE = 0.17312E-02 TLU

DRIFT LENGTH = 0.17100 LLU U1 = 0.00006 LLU V1 = -1.32004 LLU
W = -180.00000 DEG
U2 = -0.17094 LLU V2 = -1.32005 LLU

ELEC FR.FIELD TABLE 2. ENTR.ANGLE= 0.00 DEGREES REL.CURVATURE= 0.0000 |
ELEC FR.FIELD 1.INT= 0.1549 2.INT= 0.1520 3.INT=-0.3027 4.INT=-0.4535 |
ELEC FR.FIELD 5.INT= 0.5657 6.INT=-0.0020 7.INT= 0.0596 |
ELEC

ELEC SECTOR DEFL.RADIUS = 0.3810 LLU DEFL.ANGLE = 40.7500 DEGR. |
ELEC SECTOR PATH LENGTH = 0.27098 LLU VOLTAGE.. = 0.52493 KVOLT |
ELEC SECTOR HALF GAP = 0.01000 TLU |
ELEC SECTOR N1= 0.0000 N2= 0.0000 N3= 0.0000 |
ELEC

	PARALLELOGR. PHASE SPACE	DISPERSION	ELLIPTICAL PHASE SPACE	TWISS PARAMETERS
ENVELOPE X	0.0036 TLU	0.0033 TLU	0.0033 TLU	ALPHA=0.199
ENVELOPE A	0.0005 RAD	0.0001 RAD	0.0005 RAD	BETA = 7.12, TLU/RAD

ENVELOPE Y	0.0052 TLU	0.0000 TLU	0.0037 TLU	GAMMA=0.146	RAD/TLU
ENVELOPE B	0.0051 RAD	0.0000 RAD	0.0050 RAD	ALPHA=-.741	
				BETA =0.930	TLU/RAD
				GAMMA= 1.67	RAD/TLU

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.....
ELEC -----
ELEC SECTOR   DEFL.RADIUS = 0.3810 LLU   DEFL.ANGLE = 40.7500 DEGR. |
ELEC SECTOR   PATH LENGTH = 0.27098 LLU   VOLTAGE.. = 0.52493 KVOLT |
ELEC SECTOR   HALF GAP   = 0.01000 TLU   |
ELEC SECTOR   N1= 0.0000   N2= 0.0000   N3= 0.0000   |
ELEC -----
ELEC FR.FIELD  TABLE 2.  EXIT.ANGLE= 0.00 DEGREES REL.CURVATURE= 0.0000 |
ELEC FR.FIELD  1.INT= 0.1549 2.INT= 0.1520 3.INT=-0.3027 4.INT=-0.4535 |
ELEC FR.FIELD  5.INT= 0.5657 6.INT=-0.0020 7.INT= 0.0596
.....

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.....
DRIFT LENGTH = 0.17100 LLU
U1 = -0.54778 LLU V1 = -0.99542 LLU
W = -261.50000 DEG
U2 = -0.57308 LLU V2 = -0.82630 LLU
.....

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TRANSFER MATRIX OF THE SYSTEM AT PATH LENGTH L= 3.2922 LLU

X AND Y IN TLU, A AND B IN RAD, G AND D IN PARTS FROM M0 AND K0

(X,X)=-.98913	(A,X)=-10.118	(T,X)= 1.1707
(X,A)=0.49045E-05	(A,A)=-1.0109	(T,A)=0.23438
(X,G)=-.14000E-02	(A,G)= 1.3050	(T,G)=0.55063
(X,D)=0.38163	(A,D)= 1.9556	(T,D)=-.35873

(X,XX)=-46.318	(A,XX)=-15.460	(T,XX)= 4.9902
(X,XA)=-9.8437	(A,XA)=-6.0169	(T,XA)= 1.7764
(X,XG)= 14.518	(A,XG)= 16.339	(T,XG)=-2.7480
(X,XD)= 19.627	(A,XD)= 18.357	(T,XD)=-2.3730
(X,AA)=-.83550	(A,AA)=-3.5163	(T,AA)=0.57045
(X,AG)= 1.8955	(A,AG)= 4.5531	(T,AG)=-.62137
(X,AD)= 2.4300	(A,AD)= 4.7981	(T,AD)=-.64650
(X,GG)=-1.2267	(A,GG)=-2.9574	(T,GG)=0.37180
(X,GD)=-3.1451	(A,GD)=-4.9267	(T,GD)=0.51765
(X,DD)=-2.0652	(A,DD)=-3.3074	(T,DD)=0.49426
(X,YY)=0.13365	(A,YY)=-13.841	(T,YY)= 1.7914
(X,YB)=-5.1859	(A,YB)=-35.638	(T,YB)= 4.1339
(X,BB)=-.43006	(A,BB)=-3.3024	(T,BB)=0.43187

(Y,Y)=-.95863	(B,Y)=0.46297E-01
(Y,B)=-.90296	(B,B)=-.99955

(Y,YX)=-46.539	(B,YX)=-30.973
(Y,YA)=-5.6779	(B,YA)=-.33910E-01
(Y,YG)= 8.2460	(B,YG)= 5.1293
(Y,YD)= 8.2598	(B,YD)= 5.1293
(Y,BX)= 14.830	(B,BX)= 18.633
(Y,BA)= 4.2541	(B,BA)= 5.6828
(Y,BG)=-2.7970	(B,BG)=-3.6314
(Y,BD)=-3.0951	(B,BD)=-3.6313

TRANSFER MATRIX OF THE SYSTEM AT PATH LENGTH L= 3.2922 LLU

X AND Y IN TLU, A AND B IN RAD, G AND D IN PARTS FROM M0 AND K0

MAGNITUDE OF ABBERATIONS M (IJK)		
X(X) =-.14837E-03	A(X) =-.15177E-02	T(X) =0.17560E-03
X(A) =0.49045E-07	A(A) =-.10109E-01	T(A) =0.23438E-02
X(G) =-.10850E-04	A(G) =0.10114E-01	T(G) =0.42674E-02
X(D) =0.76326E-04	A(D) =0.39112E-03	T(D) =-.71746E-04
X(XX) =-.10421E-05	A(XX) =-.34784E-06	T(XX) =0.11228E-06
X(XA) =-.14766E-04	A(XA) =-.90254E-05	T(XA) =0.26646E-05
X(XG) =0.16877E-04	A(XG) =0.18994E-04	T(XG) =-.31946E-05
X(XD) =0.58882E-06	A(XD) =0.55072E-06	T(XD) =-.71191E-07
X(AA) =-.83550E-04	A(AA) =-.35163E-03	T(AA) =0.57045E-04
X(AG) =0.14690E-03	A(AG) =0.35287E-03	T(AG) =-.48156E-04
X(AD) =0.48601E-05	A(AD) =0.95963E-05	T(AD) =-.12930E-05
X(GG) =-.73679E-04	A(GG) =-.17763E-03	T(GG) =0.22331E-04
X(GD) =-.48749E-05	A(GD) =-.76363E-05	T(GD) =0.80236E-06
X(DD) =-.82606E-07	A(DD) =-.13230E-06	T(DD) =0.19770E-07
X(YY) =0.12029E-05	A(YY) =-.12457E-03	T(YY) =0.16123E-04
X(YB) =-.77788E-04	A(YB) =-.53458E-03	T(YB) =0.62009E-04
X(BB) =-.10752E-04	A(BB) =-.82560E-04	T(BB) =0.10797E-04

Y(Y) =-.28759E-02	B(Y) =0.13889E-03
Y(B) =-.45148E-02	B(B) =-.49978E-02

Y(YX) =-.20942E-04	B(YX) =-.13938E-04
Y(YA) =-.17034E-03	B(YA) =-.10173E-05
Y(YG) =0.19172E-03	B(YG) =0.11926E-03
Y(YD) =0.49559E-05	B(YD) =0.30776E-05
Y(BX) =0.11123E-04	B(BX) =0.13975E-04
Y(BA) =0.21270E-03	B(BA) =0.28414E-03
Y(BG) =-.10838E-03	B(BG) =-.14072E-03
Y(BD) =-.30951E-05	B(BD) =-.36313E-05

	PARALLELOGR. PHASE SPACE	DISPERSION	ELLIPTICAL PHASE SPACE	TWISS PARAMETERS
ENVELOPE X	0.0001 TLU	0.0001 TLU	0.0001 TLU	ALPHA=-.150
ENVELOPE A	0.0116 RAD	0.0105 RAD	0.0102 RAD	BETA =0.147E-01 TLU/RAD
				GAMMA= 69.7 RAD/TLU
ENVELOPE Y	0.0074 TLU	0.0000 TLU	0.0054 TLU	ALPHA=-1.48
ENVELOPE B	0.0051 RAD	0.0000 RAD	0.0050 RAD	BETA = 1.91 TLU/RAD
				GAMMA= 1.67 RAD/TLU

NEXT IMAGE IN X-DIR AFTER	0.4851E-05,	IN Y-DIR AFTER	-0.9034	LLU
NEXT WAIST IN X-DIR AFTER	-0.2150E-02,	IN Y-DIR AFTER	-0.8867	LLU
NEXT PUPIL IN X-DIR AFTER	-0.9776E-01,	IN Y-DIR AFTER	20.71	LLU

APERTURE SLIT, RADIAL .50000E-03 TLU, AXIAL .90000E-02 TLU

BEAM CROSS SECTION (X,Y) AT PATH-LENGTH = 3.2922 LLU

.....

X-RANGE = 0.001000 TLU Y-RANGE = 0.010000 TLU
10000 PARTICLES STARTED IN A PARALLELOGRAM LIKE PHASE SPACE (R)
10000 PARTICLES, I.E. 100.0 PER CENT ARRIVED IN THE SHOWN WINDOW

	CENTER OF WINDOW	HALF WIDTH	DISTRIBUTION
X =	0.0000 +-	0.0002	0.00
A =	0.0000 +-	0.0100	0.00
G =	0.0000 +-	0.0078	0.00
D =	0.0000 +-	0.0002	0.00
Y =	0.0000 +-	0.0030	0.00
B =	0.0000 +-	0.0050	0.00

DIAGRAMM CONTAINS 0 DISCRETE MASSES
MASS DIFFERENCES EQUAL 0.0 PERCENT OF REF. MASS

-
- (.) FROM 1 TO 25 PER CENT OF MAXIMAL BEAM INTENSITY
 - (=) FROM 25 TO 50 PER CENT OF MAXIMAL BEAM INTENSITY
 - (+) FROM 50 TO 75 PER CENT OF MAXIMAL BEAM INTENSITY
 - (*) FROM 75 TO 100 PER CENT OF MAXIMAL BEAM INTENSITY
(100 PER CENT EQUIV. 62 PARTICLES)

BEAM DENSITY VERSUS X

.....

MAXIMAL DENSITY = 979 PARTICLES PER 0.33333E-04 TLU
RMS-ENVELOPE = 0.10803E-03 TLU

.....

MAXIMAL DENSITY = 979 PARTICLES PER 0.33333E-03 TLU
RMS-ENVELOPE = 0.30623E-02 TLU

BEAM ENVELOPES THROUGHOUT THE SYSTEM
PARALLELOGRAM LIKE PHASE SPACE ASSUMED

THE SYMBOLS X AND Y DENOTE ENVELOPES OF AN INITIALLY PARALLEL BEAM ($A=B=0$)
THE SYMBOLS A AND B DENOTE ENVELOPES OF A BEAM WHICH FILLS A GIVEN PHASE SPACE
THE SYMBOLS G AND D DENOTE ENVELOPES OF A BEAM DEVIATING IN MASS AND ENERGY

Z (LLU)	Y = 0.200E-01 TLU	X = 0.200E-01 TLU
	YYYY	
	BYYYY A	
	BBYYYY AAA	
	BBYYYY AAAA	
	BBYYYY AAAAA	
	BBYYYY AAAAAA	
= 17	BBYYYY AAAAAA	
MS	BBYYYY AAAAAAA	MS
MS	BBYYYY AAAAAAAG	MS
	BBYYYY AAAAAAAG	
MS	BBBBYYYY AAAAAAAG	MS
MS	BBBBYYYY AAAAAAAG	MS
AS= 17	BBBBYYYY AAAAAAGD	AS
	BBBBBY AAAAAGG	
	BBBBBY AAAGGG	
	BBBBBY AAGGGG	
	BBBBB AGGGG	
AS	BBBBB	AS
	BBBBY AAGGGGG	
	BBBBBY AAAGGGGGG	
1.45	BBBBBY AAAAGGGGGGG	
	BBBBBY AAAAAGGGGGGGD	
AS= 17	BBBBBY XAAAAAGGGGGGGG	AS
MS	BBBBBY XAAAAAAGGGGGGGG	MS
MS	BBBBBY XAAAAAAGGGGGGGG	MS
	BBYYYY XAAAAAAGGGGGGGG	
MS	BBYYYY XAAAAAAGGGGGGGG	MS
MS	BBYYYY XAAAAAAGGGGGGGG	MS
= 17	BBYYYY AAAAAGGGGGG	
	BBYYYY AAAAAGGGGG	
	BYYYY AAAGGGG	
	YYYY AAGG	
	YYYY AG	
AS	BYYYY	AS
	BYYYY AAG	
	BBYYYY AAAGGG	
	BBYYYY AAAGGG	
ES	BBYYYY XAAAGGGG	ES
ES	BBYYYY XAAAGGGGG	ES
ES	BBBBYYYY XAAAGGGGG	ES
	BBBBYYYY XAAAGGGGG	
ES	BBBBYYYY XAAAGGGGG	ES
ES	BBBBYYYY AAAAGGGG	ES
ES	BBBBBBYYYY AAAGGG	ES
	BBBBBBYYYY AAAGG	
3.20	BBBBBBYYYY AGG	
	BBBBBBYYYY D	
AS	BBBBBBYYYY	AS
TOTAL LENGTH OF SYSTEM = 3.292		

TRANSFER MATRIX OF THE SYSTEM AT PATH LENGTH L= 3.2922 LLU

X AND Y IN TLU, A AND B IN RAD, G AND D IN PARTS FROM M0 AND K0

(X,X)=-.98913	(A,X)=-10.118	(T,X)= 1.1707
(X,A)=0.49045E-05	(A,A)=-1.0109	(T,A)=0.23438
(X,G)=-.14000E-02	(A,G)= 1.3050	(T,G)=0.55063
(X,D)=0.38163	(A,D)= 1.9556	(T,D)=-.35873
(X,XX)=-46.318	(A,XX)=-15.460	(T,XX)= 4.9902
(X,XA)=-9.8437	(A,XA)=-6.0169	(T,XA)= 1.7764
(X,XG)= 14.518	(A,XG)= 16.339	(T,XG)=-2.7480
(X,XD)= 19.627	(A,XD)= 18.357	(T,XD)=-2.3730
(X,AA)=-.83550	(A,AA)=-3.5163	(T,AA)=0.57045
(X,AG)= 1.8955	(A,AG)= 4.5531	(T,AG)=-.62137
(X,AD)= 2.4300	(A,AD)= 4.7981	(T,AD)=-.64650
(X,GG)=-1.2267	(A,GG)=-2.9574	(T,GG)=0.37180
(X,GD)=-3.1451	(A,GD)=-4.9267	(T,GD)=0.51765
(X,DD)=-2.0652	(A,DD)=-3.3074	(T,DD)=0.49426
(X,YY)=0.13365	(A,YY)=-13.841	(T,YY)= 1.7914
(X,YB)=-5.1859	(A,YB)=-35.638	(T,YB)= 4.1339
(X,BB)=-.43006	(A,BB)=-3.3024	(T,BB)=0.43187
(Y,Y)=-.95863	(B,Y)=0.46297E-01	
(Y,B)=-.90296	(B,B)=-.99955	
(Y,YX)=-46.539	(B,YX)=-30.973	
(Y,YA)=-5.6779	(B,YA)=-.33910E-01	
(Y,YG)= 8.2460	(B,YG)= 5.1293	
(Y,YD)= 8.2598	(B,YD)= 5.1293	
(Y,BX)= 14.830	(B,BX)= 18.633	
(Y,BA)= 4.2541	(B,BA)= 5.6828	
(Y,BG)=-2.7970	(B,BG)=-3.6314	
(Y,BD)=-3.0951	(B,BD)=-3.6313	

--- STATUS = 0 ---

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