

**SERSE, A SUPERCONDUCTING ELECTRON CYCLOTRON
RESONANCE ION SOURCE**

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ABSTRACT

At the "Laboratorio Nazionale del Sud" (L.N.S.) the K-800 Superconducting Cyclotron (C.S.) is under construction and by 1993 it will be coupled to the 15 MV Tandem.

In order to increase both energies and intensities of the beams extracted from the C.S., a project for a superconducting ECR ion source has been developed and it will be carried out as a joint venture between the L.N.S. and the C.E.N. of Grenoble. This source will be the first superconducting ECR source to be coupled to a Superconducting Cyclotron in Europe, and it is particularly suited to exploit the K-800 Superconducting Cyclotron capabilities.

The source will be working at 14.5 GHz and the confinement will be performed by superconducting magnets able to give more than 1.3 Tesla on the plasma chamber wall, allowing to operate the source in the so-called "High Magnetic Field" mode. High charge states as $35-40^+$ for the heaviest ions are expected.

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1 - INTRODUCTION

In the "Laboratorio Nazionale del Sud" (L.N.S.) are presently available the beams accelerated by the 15 MV MP-Tandem, whose energies are ranging between 1 and 10 MeV/amu.

By the spring of 1993 the booster for this Tandem, the K-800 Superconducting Cyclotron (C.S), will be completed, allowing to reach energies well beyond the Coulombian barrier for every ion species (fully stripped light ions will reach 100 MeV/amu while the heaviest ions are foreseen to get 20 MeV/amu).

The acceleration scheme (fig. 1) is the following: the Tandem beam ($I=100-200$ pA after the analysis, $q=1-10$) will be injected radially in the cyclotron; here it will be stripped again by a foil stripper and it will decrease its magnetic rigidity in order to enter in a stable orbit and to be accelerated. Final energies are given by the charge states of the beams, according to the formulas (1):

$$\frac{E}{A} \leq K_b \frac{Z^2}{A^2} \qquad \frac{E}{A} \leq K_{foc} \frac{Z}{A}$$

where $K_b = 800$ MeV and $K_{foc} = 200$ MeV.

There is an important constraint on the injection process (2):

$$\frac{Z_f}{Z_i} > \frac{1}{2} \cdot (1 + \sqrt{\frac{T_f}{T_i}})$$

where Z_f, T_f are charge states and energy at the exit of the cyclotron while Z_i, T_i are charge states and energy at the exit of the Tandem [1].

This condition is very strict for the lightest ions, because it imposes to select $Z_i = 1, 2^+$ whereas the probability for these charge states at the exit of the Tandem gas stripper is low (the charge states distribution CSD at equilibrium is peaked on 3-5+).

The intensities for the lightest ions would then be smaller than 1 pA working with the Tandem gas stripper in "equilibrium regime", but some recent test in the so called "non-equilibrium regime" have given interesting results (in a short test we have obtained about 100 pA for C^{1+} with a very low gas pressure, but longer tests have to be performed in order to prove long time stability of this regime): if those results will be confirmed, it will be possible to provide 5-10 pA of light ions beams at the exit of the Cyclotron.

Moreover for the heaviest ions we cannot have very high charge states because the formula (2) also limits the Tandem beams energy and so we cannot choose too high charge states to be accelerated (the probability to obtain these charge states at the exit of the cyclotron stripper is very poor, e.g. for Uranium we need 38+ but the CSD has a maximum peaked on 34+).

In fig. 2 the energies for the different ions are shown.

We can conclude that this acceleration scheme has three drawbacks:

- 1) we will work with two different accelerators and this fact will lengthen the unscheduled maintainance times;
- 2) the negative ion sources of the Tandem are not able to provide noble gas and are not very efficient for some elements as Na, K, etc.;
- 3) for the heaviest ions the intensities are low, the trasmission in the Tandem is bad and the tubes lifetime decrease.

For these reasons the possibility of an axial injection in the C.S.

has been provided. A simple and highly reliable positive ion source is needed, able to give high intensity beams ($0.1-10 \text{ p}\mu\text{A}$) with charge states ranging from $\frac{Z}{A}=0.5$ for light ions down to $\frac{Z}{A}=0.15-0.2$ for the heaviest ions (then for the most part of elements comparable or better with respect to the charge states obtainable by the Tandem).

There are some different possibilities for positive ion sources [2]:

1) **PIG** : this kind of source cannot give us very high charge states.

2) **LASER** : is not presently able to give us the intensities we require (if we want high charge states we need pulsed UV lasers, and then the duty cycles are low) and moreover it is not very reliable and stable.

3) **EBIS** : is able to give the highest charge states and it has had a large success for atomic physics facilities or synchrotron injection; however the low intensities of the beam extracted do not make this source suited for a cyclotron (the EBIS is pulsed while the cyclotrons need CW beams).

4) **Room temperature ECRIS** working with 14.5 GHz transmitter are now competitive with a Tandem because the best charge states are almost the same as the one produced by Tandem + stripper (e.g. U^{32+}) and the intensities are higher. Their cost can be high, but it is very cheap in comparison to the cost of a Tandem or of another accelerator (both the construction and the running costs are one order of magnitude lower). The ECRIS fulfills our request of stability and reliability (it can work for weeks or months without maintenance).

The goal of charge states higher than the ones provided by the system Tandem + stripper cannot be however obtained because it needs very high confinement time of the ion in the plasma and so it requires magnetic fields which cannot be obtained with room temperature magnets.

5) **Superconducting ECRIS** can easily overcome the levels of field required to get a very good confinement. The drawbacks of this kind of source are:

- a) long time for design and construction of the superconducting magnets;
- b) higher initial costs;
- c) liquid He supply.

Nevertheless we believe that a superconducting ECRIS working at 14.5 GHz can permit us to exploit the C.S. in the best way because it has been proved (with the source SC-ECRIS at MSU, tested at 6.4 GHz) that the increase of the magnetic confining field gives an increase of the charge states [3].

If the increase measured at 6.4 GHz will be confirmed by the next experiments with SC-ECRIS at 14.5 GHz, it could be possible to obtain fully stripped ions until Si and heavy ions with charge states higher than $\frac{Z}{A}=0.15$ (e.g. U^{36+} or U^{38+}) with intensities higher than 10 pA at the exit of the cyclotron (probably 20-200 pA).

The drawback c) is not a problem at L.N.S. because the liquifier of C.S. can supply the required quantity of He, while the other drawbacks are real, but they are oversized by the benefits:

- a) easier acceleration process and reduced maintenance times;
- b) slightly higher energies;
- c) higher intensities;
- d) this source can provide all species of ions, included noble gases.

2 - ION PRODUCTION IN THE ECRIS

In a ECRIS [2,4,5,6] the stripping of the ions is carried out inside a plasma where the electrons are confined in a magnetic bottle and are accelerated until they reach an equilibrium energy T_e , by means of a resonance between the cyclotron motion of the electrons ($\omega = \frac{eB}{m}$) and an external microwave field. When the electrons are in the magnetic trap, they drift back and forth, spiraling around the magnetic field lines.

During this motion they are accelerated or decelerated (depending on the phase they have during the crossing of the resonance surface). The averaged effect of these interactions is a heating of the plasma, until the energy lost from the plasma (via the electrons which escape) is equal to the energy absorbed from the microwave field.

The typical T_e in a ECRIS can be as high as 5-20 KeV, so the electrons are able to strip the K-shell of the lightest ions. This process is possible in a ECRIS because the electron confinement times are increased of a factor 1000-10000 (with respect to the transit times) in the magnetic well given by the superposition of a mirror field (for the axial confinement) and a hexapole field (for the radial confinement).

2.1 - Description of the source

In a ECRIS a gas is injected in a small cylinder (I stage) where the pressure is $\sim 10^{-3}$ torr so that is possible to create an ECR plasma of electrons and ions with charge states very low (because the charge exchange process is dominating at high pressure, causing short lifetimes for the multiply charged ions). This plasma diffuses in the second stage where the pressure is very low (10^{-7} torr) and the microwave field is very strong, so the electrons are accelerated until $T_e \approx 5-20$ KeV and the ions are stripped by the interactions with these electrons.

It has to be noted that the magnetic field is useful to confine the electrons and not the ions which are confined because of the quasineutrality of the plasma: this also means that the plasma have to be quiet for a good ion confinement.

The stripping process continues as a step-by-step process (multiple ionization has much lower cross sections) until there is equilibrium between the processes which lower the CSD (as charge exchanges and ions losses) and the ionization process.

Then the beam is extracted from the plasma by an accel-decel extraction system. The plasma forming electrode is on H.V. positive potential ($\sim 10-15$ KV) while a second electrode is at negative potential, accelerating the ions escaping from the plasma. Then the beam sees a retarding potential going towards the third electrode, at ground potential.

This system permits to decrease the beam emittance with respect to a two-electrode system. However the emittance of a ECRIS beam can be high because of the interaction of the beam with the stray magnetic field and because of the space charge effects. After the extraction it is convenient to have the analysis magnet, in order to decrease the intensities of the beam to transport in the beamline and thus the space charge effects. Typical emittance values for such a source are in the range of 50-100 mm. mrad. for $V_{extr}=10-12$ KV.

2.2 - Semiempirical approach

Unfortunately there is not a complete model of the heating and stripping process in the ECRIS, so up to now only two valuable tools have been available for the design of an ECRIS:

a) the quality factor $n_e \tau_i$, i.e. the product of the electron density and the ion confinement times, which gives a figure of the probability of the stripping interaction undergone by the ions.

With a 14.5 GHz source we expect to have $n_e \sim 2.5 \cdot 10^{12} \text{ cm}^{-3}$, $\tau_i \sim 20 \text{ msec.}$ so

$$n_e \tau_i \sim 5 \cdot 10^{10} \text{ cm}^{-3} \cdot \text{sec.}$$

As it is shown in fig. 3 it seems to be possible to reach $\bar{q} \sim 38+$ for Uranium ions [7,8].

b) the semiphenomenological "scaling laws" which have not been so far fully demonstrated, but are in good agreement with the experimental results concerning the ECRIS [9].

$$1) n_e \propto \omega^2$$

$$2) \tau_i \propto B^{3/2}$$

$$3) T_e \propto P_{RF}$$

$$4) \bar{q} \propto \log(B_{max})$$

$$5) P_{RF} \propto \sqrt{\omega} \cdot \bar{q}^3 \cdot V$$

where \bar{q} is the mean charge state of the ion species in the plasma, P_{RF} is the microwave power, ω is equal to $2 \pi f_{RF}$ and V is the volume of the plasma chamber.

So there are two direction for the increase of the mean charge state: one can increase the frequency of RF supply (and then n_e , but

also B_{ECR} [10], so this solution imply both higher frequencies and higher fields, see fig. 4) or one can only increase B_{max} (and then the interaction time τ_i , see fig. 5).

In each case the microwave power P_{RF} has to be increased to reach higher T_e .

In the past ten years people had tried the first solution, going from the first generation 6.4-10 GHz ECRIS towards the second generation ECRIS working at 14-18 GHz.

Recently [11] the results of the superconducting SC-ECRIS of the MSU-NSCL have confirmed the scaling laws and have reinforced the idea that the increase of the \bar{q} with the logarithm of B_{max} is effective.

For ECR frequency of 14.5 GHz (where the corresponding B_{ECR} is 0.51 T) superconducting magnets are needed, because the permanent magnet hexapoles can give fields as high as 0.8-0.9 T on the walls of the plasma chamber, and then the plasma stability is not good (a rule of thumb for the plasma stability is $\frac{B_{max}}{B_{ECR}} > 2$).

The use of superconducting magnets will permit also the tuning of the radial confining field, whereas the lack of control on the hexapole is the main drawback of the room temperature ECRIS, which use permanent magnets hexapole.

Also the problems concerning the high electrical consumption in the coils can be avoided with the superconducting ECRIS.

The explanation of the so-called "high B" operation mode can be given in a simple way: a plasma is stable if

$$p_{particle} < p_{magnetic}$$

where
$$p_{particle} = n_e kT_e + n_i kT_i + n_0 kT_0$$

and
$$p_{magnetic} = \frac{B_{max}^2}{2\mu_0}.$$

In the ECRIS plasma

$$n_0, n_i \ll n_e \text{ and } T_0, T_i \ll T_e.$$

Then the condition for plasma stability is

$$n_e k T_e < \frac{B_{max}^2}{2\mu_0}.$$

i.e. an high B_{max} is beneficial both for plasma confinement and for the electron temperature and density (plasma energy content is higher).

3 - THE SUPERCONDUCTING ECRIS PROJECT

In the following we are going to discuss our proposal for a superconducting ECRIS operating in "High B mode" with a microwave field of 14.5 GHz.

This source will exploit the experiences done at MSU-NSCL by T. Antaya and coworkers for SC-ECRIS [12,13], which is a ECRIS prototype built for laboratory studies and working at frequencies ranging from 6.4 to 30 GHz. It seems realistic to operate with a more simplified design at a frequency of 14.5 GHz, minimizing the risks of this new project, and obtaining, from that prototype design, a highly reliable source.

For the construction of this source we have signed a joint-venture with the ECRIS group of the DRFMC at the Centre d' Etudes Nucleaires de Grenoble (CENG), because they have the best know-how about the ECRIS (the first ECRIS was built in Grenoble more than 20 years ago and since then twenty ECRIS have been built for different laboratories) and they have a good know-how about the cryogenics (the Cryogenics Dpt. of the CENG have a large experience in the design of superconducting magnets for tokamaks and accelerators). The feasibility studies have been completed and the industrial designs will be drawn in a few months.

In order to work at 14.5 GHz (where the resonance field B_{ECR} is 0.518 T) with "High B" fields (i.e. mirror ratio $\frac{B_{max}}{B_{ECR}} > 2$) we need to be able to reach a field of 1.3 T on the walls of the plasma chambers.

This is a very ambitious request, because it's easily obtainable for the mirror solenoids but it's hard to fulfill for the hexapole (it means $B_{hexapole} > 4.0$ T). The magnetic field we want to obtain has a so-called "B-min geometry", i.e. the field increases in every direction going from the center of the trap towards the periphery.

In the radial direction this is carried out by the hexapole, whose field increase as $B_{hex} \propto r^2$, while in the axial direction the field geometry has the shape drawn in fig. 6 (originated by 5 solenoidal coils) so that in the first stage we have an ECR crossing, where the plasma is created, and in the second stage we have an ECR surface

some cm. long.

With solenoids and hexapole both superconducting we could be able to vary the mirror ratio up to 2.5 in a continuous way, finding the best configuration for the different ion species.

The geometry of the iron yoke, of the mirror coils and of the hexapole will be very similar to the one of the SC-ECRIS at MSU, but it will be simplified in order to allow:

- a) easy mounting and dismounting of the source; also the cryostat have to be, if possible, dismountable;
- b) dimension as small as possible;
- c) very robust magnet, able to tolerate relatively frequent changes of field;
- d) easy tuning of the magnet.

For this reason we intend to minimize the forces existing between the magnets. Any movement can be dangerous with forces of $1.5 \cdot 10^5$ N: a $10 \mu m$ displacement could dissipate 1.5 Joule, starting a quench.

4 - THE MAGNETIC FIELD CONFIGURATION

The preliminary project [14] foresees a cryostat of coaxial shape, 79 cm. long, 23 cm. external radius and 9.5 cm. internal radius.

If the forces and the mechanical constraints will allow it, we intend to reduce the dimensions of the magnet and of the cryostat.

Further calculations have to be done before the industrial design, but the first feasibility studies and the experiments of SC-ECRIS at MSU show that a 14.5 GHz superconducting source working with very high magnetic fields is within the possibilities of present technology.

The fig. 7 shows the project of the magnetic system. The cryostat contains one hexapole and 5 solenoids, divided in a group of three, generating a maximum field of 2.1 T and a group of two, giving a maximum field of 1.6 T.

If all the solenoids work at maximum current, the minimum in between is 0.7 T; at 14.5 GHz it will be necessary to work at lower currents, but this configuration permits to maintain the possibility for a future upgrading at higher frequencies.

The solenoids are coaxials with the hexapole and surround it. The induction created by the hexapole is 1.44 T on the walls of the plasma chamber. Then our goal of a magnetic field equal or higher than 1.3 T (i.e. mirror ratio > 2.5) is within the design specifications of this magnet.

In fig. 8 a cross section of the source is shown.

All the cryostat will be enclosed in an iron yoke, 4 cm. thick (with one bore on the extraction side and two small bores for the injection of gas and RF). All the feedthroughs for gas and RF will be done along the axis, avoiding any radial opening.

On the inner side the cryostat will be electrically insulated from the plasma chamber.

The magnets are surrounded on the external side by a liquid nitrogen shield, which has been avoided on the inner side, to reduce the space between the plasma chamber and the hexapole. This is acceptable because the liquid He consumption will be lower than 5 l/h (1 ÷ 2 l/h for the cryostat and 2 l/h for the current leads).

4.1 - The hexapole

It consists of six long coils located inside a circle (28 cm diameter). Each coil has the following characteristics:

length : 575 mm.

width : 140 mm.

section of the coil : 41 mm. (height) · 26 mm. (width)

bending radius at the end : 48 mm.

distance chamber-hexapole : 29 mm.

conductor : multifilamentary NbTi

diameter of the conductor : 1.0 mm.

Cu/superconductor ratio : 3.3

wire diameter : less than 0.11 mm.

critical current at 5 T : 360 A

number of turns : 700

working current : 260 A

maximum current density : $171 \frac{A}{mm^2}$

maximum field in the conductor : 4.2 T

This level is reached at the extremity, where the contributions of the solenoids are added.

All the conductors will be impregnated by epoxy resin.

4.2 - The solenoids

The 5 solenoids are completely identical. They have the following characteristics:

internal diameter : 292 mm.
external diameter : 368 mm.
width : 50 mm.
conductor : multifilamentary NbTi
diameter of the conductor : 0.5 mm.
Cu/superconductor ratio : 4.0
wire diameter : less than 0.065 mm.
critical current at 5 T : 85 A
number of turns : 6000
working current : 40 A
maximum current density : $126 \frac{A}{mm^2}$
maximum field in the conductor : 2.5 T

All the conductors will be impregnated by epoxy resin.

4.3 - Forces and stresses

The level of electromagnetic forces in the coils can be very high and a very careful design have to block all the component assuring the tight positioning of each one and avoiding the small movements that could damage the system.

In the straight parts of the hexapole are present the highest forces ($\sim 150,000$ N) which try to open the structure of a single coils. So if no space is allowed between each coil of the hexapole, all the forces are exactly equilibrated. At the ends the interactions with the solenoids make necessary a strong blocking structure, as it is necessary to fix the solenoids who are attracted each other.

This is carried out by a stainless steel and aluminium framework which supports the 5 solenoids and permits to fix radially the hexapole coils. The cool-down shrinkage is taken in account by letting free one end of the hexapole.

The stresses given by the transmission of this forces are calculated to be in the range of $0.5-1 \frac{kg}{mm^2}$, and so they will be well tolerated by the wires (the elastic limit for the NbTi is $18 \frac{kg}{mm^2}$) and by the resin ($1.8-3.2 \frac{kg}{mm^2}$).

4.4 - Feeding and protection

The magnetic system is fed by 6 pairs of current leads. One pair (260 A) feeds the hexapole, whose coils are connected in series. The 5 solenoids have independent current leads (40 A) in order to have the possibility to adjust the axial profile during the tests.

The magnets are self-protected against the quench, i.e. can tolerate the discharge process, so the quench detection system (done by voltage comparators) have only to switch off the current.

A pair of days will be necessary for warm-up and cool-down process and 6 months for the tests of the magnetic system after the construction.

The experience of ISIS at Julich (the only superconducting magnets ECRIS which has been working for a long time) tells that, after the test period, the reliability of the superconducting magnets is very high.

5 - THE MECHANICAL STRUCTURE

The source designed in fig. 9 is a 2-stage source: first stage is a small cylinder (8 cm. long, 2.5 cm. radius) on one side of the main plasma chamber (50 cm. long, 7 cm. radius). The total length of the source is 93 cm. and the diameter is 56 cm.

The plasma chambers will be mounted in the cryostat bore, at room temperature. Between the cryostat and the plasma chambers a water flow tube takes away the power dissipated in the chambers.

In the area of the first plasma chamber there are the gas inputs and the RF waveguides for both the stage. These inputs have been designed along the axis of the source, so that the radial ports are avoided and the source is easy to be dismantled, maintaining in a fixed position the magnets and the extraction system.

At the end of the main plasma chamber a three electrode extraction system will be mounted, with the first electrode connected to the chamber, the second well insulated either from the chamber and from the third electrode, connected to ground.

The extractor's second electrode has to be moveable by remote control, where the positions of the other two electrodes will be fixed after the tests.

The RF waveguides will be insulated electrically by means of a small teflon foil (0.5 mm. thick) and their vacuum insulation will be done by an alumina window 5 mm. thick.

5.1 - The pumping system

The vacuum of 10^{-3} torr in the first stage will be realized by a TMP of 520 l/s, whilst in the second stage a 1500 l/s one is needed for reaching in a few hours the required 10^{-7} torr. Because of our constraints on the cryostat the pumping of the second stage will be carried out through the extractor. A third 520 l/s pump will be located just after the analysis magnet in order to minimize the charge exchange process (pressure have to be better than 10^{-7} torr in the beamline).

All the TMP pumps will be screened by the stray magnetic field with an iron "dress" thick enough to reduce the magnetic field in the TMP down to the levels admitted by the company.

High vacuum gauges will be located in the first stage and in the extraction region. No gauges can be accepted in the second stage, because we have not clearance. Another gauge will be located just before the analysis magnet.

6 - THE RF SYSTEM

We have chosen the frequency of 14.5 GHz as a compromise between the request of higher frequency and the availability of commercial transmitters: in fact at this frequency there are two different commercial transmitters with a power of 2-2.5 KW, where at 18 GHz only much more expensive 15 KW transmitters exist; at higher frequencies gyrotrons could be used, but the costs are prohibitive and the reliability is low.

However if in next future higher frequency amplifiers would become commercial, our source will be able to support it.

The two 14.5 GHz transmitter made by Varian (USA) and Thomson (France) have almost the same specifications, except for the fact that the Varian transmitter is cheaper (but it is not stabilized as we require, so a feedback circuit will be necessary).

The final decision will be taken only after the consultations.

We will need a RF power of 2-3 KW, according to the scaling law n. 5), because the plasma chamber volume of the superconducting ECRIS is about ten times bigger than for the normal conducting ECRIS, so the RF power have to be bigger. One transmitter could be perhaps sufficient, but we judge more convenient to buy two 2.5 KW transmitters for the following reasons :

- a) it is convenient to have one generator for each stage;
- b) it is convenient to have more power than estimated (our calculation is an extrapolation from the data of SC-ECRIS done with the scaling laws, so it could be perhaps optimistic);
- c) the delivery times for the transmitter are ~ 10 months, so if one transmitter breaks, the source can run with one transmitter.

A scheme for the RF coupling to the cavities is shown in fig. 10.

The alumina window and the 20 KV insulation will be located behind a bending of the waveguide in order to avoid interactions with the plasma.

The two cavities are both multimode ($\lambda=20.8$ mm., so $\frac{d}{\lambda} \sim 2$ for the first stage and $\frac{d}{\lambda} \sim 7$ for the second stage) then the reflected power can be minimized.

Whenever it would be necessary to work with ion species which can pollute the main cavity, a 0.5 mm. thick copper liner could be put on it during the run, and could be removed at the end.

7 - THE EXTRACTION SYSTEM

The extraction is not very important for the source itself but it is very important for the transport and for the injection into the cyclotron. Then we need to minimize the emittance and our goal is an emittance of 50π mm. mrad. or better (i.e. $\epsilon_N = 0.1-0.2 \pi$ mm. mrad $MeV^{-1/2}$) for both light ions with $\frac{Z}{A}=0.5$ and for heavy ions with $\frac{Z}{A}=0.2$.

Preliminary studies have been done with the code CHEOPS [15], which is a modified version of the Hermannsfeldt's code. Those results will be verified when the map of the magnetic field will be available. With this simulations all the emittances are of the order of $50-100 \pi$ mm. mrad, but the experiments done in other sources have shown that the emittance are lower if the plasma is stable (the ion temperature is $\sim 1 \div 10$ eV, and the beam divergence is low for such T_i). Even if the magnetic field can cause an emittance growth, the reduced extraction hole could easily compensate the growth (we recall that in a ECRIS the emittance is

$$\epsilon \propto \frac{B_{extr} \cdot r_{extr}^2}{B\rho}$$

for small extraction holes [16]).

In fig. 11 the extraction geometry is drawn.

The extraction electrode has a Pierce design, with a slope of 67.5° with respect to the axis; in its center a 4 mm. hole is drilled, because $\phi \leq \frac{\lambda}{4}$ in order to avoid RF fields escaping from the plasma chamber.

This electrode has the same potential of the plasma chamber (up to +20 KV) and there the beam is created by the electric field existing between the plasma and the second electrode ("puller", which has a 12 mm. wide hole and a potential between 0 and -5 KV), whose shape is almost parallel to the Pierce one.

It seems that puller slopes in the $60-90^\circ$ range have almost the same effect on the beam emittance, and the results of simulations are almost the same for any plasma border shape, while this result is not valid for slopes of 45° (the electric field is less uniform and

the plasma border conditions are very important for the emittance). The third electrode shape is not important, so a cylindrical tube of 30 mm. internal diameter will be sufficient.

The most important item in the extractor seems to be the distance between the extraction electrode and the puller, which can be in the order of 20-100 mm., depending on the charge states of the ion. For the lowest ones this distance have to be lower (as required by the Child-Langmuir law) while for the highest states it has to be bigger (this can be explained by the smoother gradient of the electric field: the focusing force is $F = q \cdot E$, so if q is higher then E have to be smaller, i.e. d have to be bigger, otherwise the beam is overfocused and it blows out).

The distance between the puller and the ground has a poor effect on the emittance, so the ground electrode can be fixed to the puller (10 mm. distant).

8 - GAS FEEDING

The way to put the gas into the ion source is now well established. Two gas bottles are located on the source and they are controlled by needle valves, so the gas is injected in a small, well-known quantity. The two bottles contain the gas to ionize and another support gas, useful to obtain the so called "gas mixing effect" [17].

Since the middle of the Eighties it is known that when two gases are mixed in the ECRIS the CSD of the heaviest ions is improved. Now all the ECRIS use this method even if for every source and every species the percentages of the support gas are different (some people have used up to 95 % of support gas).

We plan to use a more complicated method, allowing gas input in both the stages. In this way (fig. 12) if we have to run with polluting or expensive gases we can create a support plasma in the first stage with gases as Helium or Oxygen; this dense plasma diffuses in the second stage where it can ionize the polluting gas, sent directly to the second stage in a very small quantity.

8.1 - Metallic ion feeding

In this case some tricks have to be used. The simplest is carried out using a compound which is gaseous at room temperature, but typically these compounds are fluoride or chloride, corrosive or polluting elements.

The most common system are the 'piston' method and the deposit.

If a rod of the metal is injected in the plasma chamber and is gradually heated by the electrons, the movement of the rod permits to increase or decrease the quantity of evaporated metal.

The deposit in the plasma chamber also exploits the electrons of the plasma but it is not so easily controllable, because it requires the exact knowledge of the flux lines in the chamber.

A more complicated method, but a very effective one, is the use of an oven which vaporizes the metal and give different quantities of vapour by changing the current in the heating circuit. This method permits an evaporation process which is not depending on the RF fields and on the magnetic fields, and it is easier to tune for the operator. Otherwise it needs long efforts for the design and the construction.

For the first tests with metallic ions we plan to use the piston method or the deposit. Nevertheless we have room enough in the first stage position, and we can put an oven in a next time.

9 - THE ANALYSIS SYSTEM

The beam extracted from the source will be focused by a solenoid on the focal point of the analyzing magnet [18]. The magnet will be a double focusing dipole, with a transfer matrix, from A to B (fig. 13)

$$R = \begin{pmatrix} -1.00316 & -0.00025 & 0. & 0. \\ -25.02932 & -1.00316 & 0. & 0. \\ 0. & 0. & -0.60023 & 0.03714 \\ 0. & 0. & -17.22517 & -0.60023 \end{pmatrix}$$

We have no requirement on the time structure of the beam, so we can write only the $(xx')(yy')$ submatrix.

There are three different requests to be fulfilled:

a) **magnetic rigidity** $B\rho$: is ranging from 20 Kgauss · cm. for the fully stripped ions at $V_{extr}=10$ KV up to 70 Kgauss · cm. for $\frac{Z}{A}=0.1$ and $V_{extr}=20$ KV.

b) **mass resolution** $\frac{M}{\Delta M}$: have to be higher than possible in order to distinguish different isotopes.

c) the **acceptance** have to be, if possible, higher than 50π mm. mrad. in both (xx') and (yy') subspaces.

We think to use a 90° magnet with $\rho=100$ cm. either to obtain a very good mass resolution (up to $\frac{M}{\Delta M}=200$) or to limit the aberrations (which are proportional to $\frac{r_{beam}}{\rho}$).

The magnet acceptance will be $\geq 50 \pi$ mm. mrad. in both the subspaces for a 80 mm gap.

9.1 - The diagnostics

We foresee only beam diagnostics because the plasma diagnosis create more complications (CSD will be the only plasma diagnosis tool).

After the source (before the solenoid) we will put a Beam Profile Monitor (BPM) so we will "see" the beam coming out from the source and we will optimize the extraction process.

An emittance meter capable to measure the emittance of each beam in a few minutes will be located after the analysis magnet. In this way it will be possible to make on-line diagnosis of the beam.

Two Faraday Cups (FC) will be put in front of and behind the analysis magnet, to optimize the transmission of the magnet (the best positions are near the two focal point of the magnet, fig. 13).

10 - THE BEAM TRANSPORT LINE

The beam line from the focal point B (fig. 13 and fig. 14) until the cyclotron median plane has been designed [18] in order to maintain the characteristics of the system designed in Milano, and to include the existing beam line elements. The transport up to the matching sections (fig. 14) will be accomplished by means of 6 solenoids (realizing a -I transfer) and a point-to-point unitary 70° bending section (5 quadrupole + 1 dipole). Then the global matrix from A to D is almost an I matrix for the (xx') subspace and a (-I) matrix for the (yy') subspace:

$$R = \begin{pmatrix} 0.99997 & 0.00034 & 0. & 0. \\ 0.00164 & 1.00003 & 0. & 0. \\ 0. & 0. & -1.00004 & 0.00019 \\ 0. & 0. & 0.00123 & -0.99996 \end{pmatrix}$$

Starting from D the design is the same of the Milano beam line, except for a couple of solenoids in the vertical line (necessary because of the C.S. room constraints), and this will allow to match the beam emittance to the acceptance of the mirror.

The envelope of the beam is shown in fig. 15.

The 4 matching quadrupoles, the two 45° bending unit with the triplet and 4 vertical solenoids are now at L.N.S. and they will be installed in the next future.

The remaining elements, i.e. 1 focusing solenoid, 1 analysis dipole, 6 transfer solenoids, 1 bending dipole, 5 quadrupoles and 2 vertical solenoids will be purchased in 1993.

As soon as possible (after the magnetic field in the C.S. will be measured) the study of the inflector will begin. Because of the high magnetic field at the center of the cyclotron, it will be a spiral inflector, which needs less space.

11 - THE CONTROL SYSTEM

In the beginning only the quench detection will be computer controlled, because until the source will be well known, it will not be an easy task to operate it with the intermediation of the computer.

After the preliminary tests, a project will be done to permit the remote control (exploiting the existing network of the negative ion sources which will permit to operate the ECRIS from the control room) and, if it is possible, the fully automatization of the source (we intend to minimize, however, the degrees of freedom of the operator).

12 - CONCLUSION

In tab. 1 the time schedule is shown.

The time necessary for the construction, due to the innovative aspects of this source, fits very well with the program of the C.S. In the beginning the cyclotron is scheduled to work with radial injection of the Tandem beams and by the 1995 beams for the Cyclotron will be available from the superconducting ECR source.

The acquisition of this source will be made by means of a joint-venture contract signed by the INFN-LNS and the Centre d' Etudes Nucleaires de Grenoble.

The collaboration between the LNS and the CENG is well established and this feasibility study has been supported by the scientists of the ECRIS group at CENG. The capability to develop a reliable high-performance ECR source has been demonstrated and the basis for an effective upgrading of the Superconducting Cyclotron performances has been put.

With this project the LNS will be able to get one of the most performant source in the world essential to maximize the capability of the existing facilities and for the future development plans of the Laboratory.

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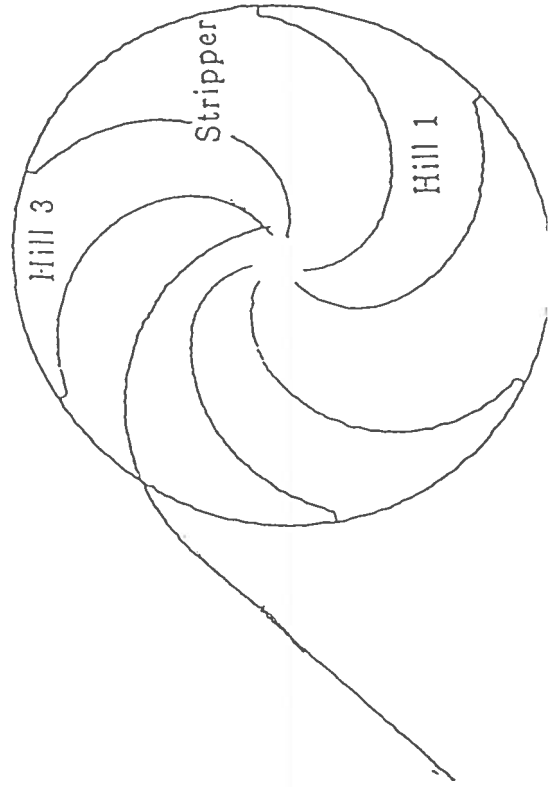
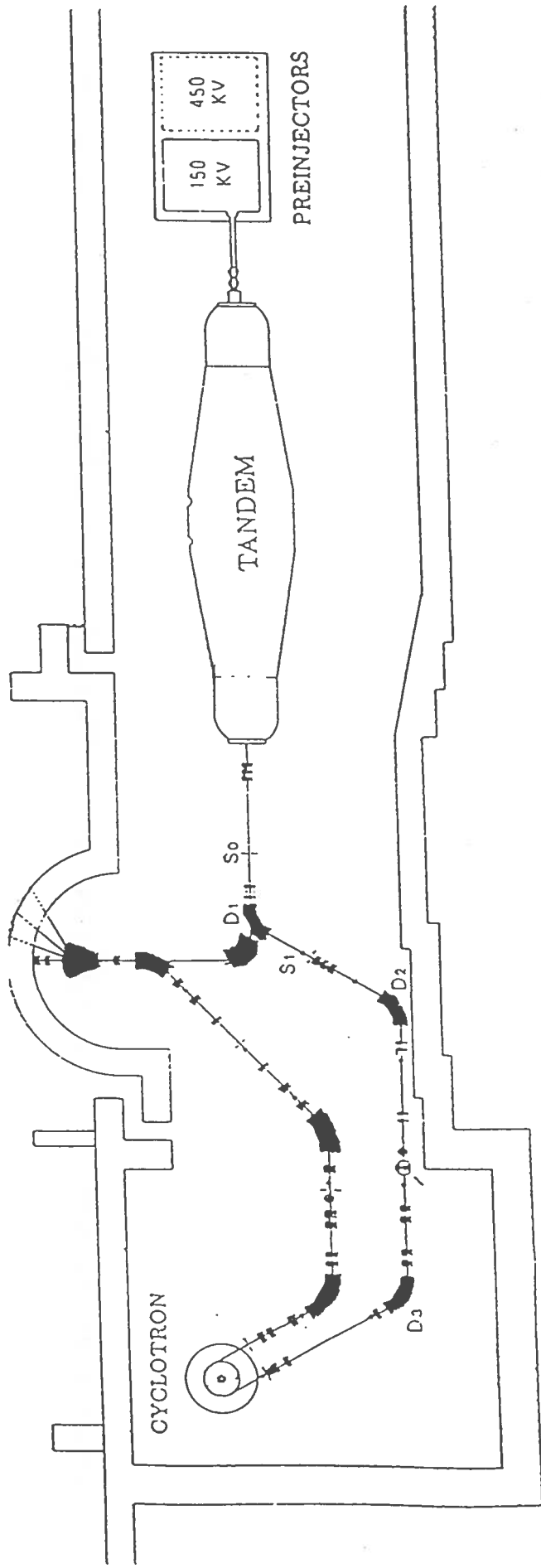


FIG. 1 - The L.N.S. facility

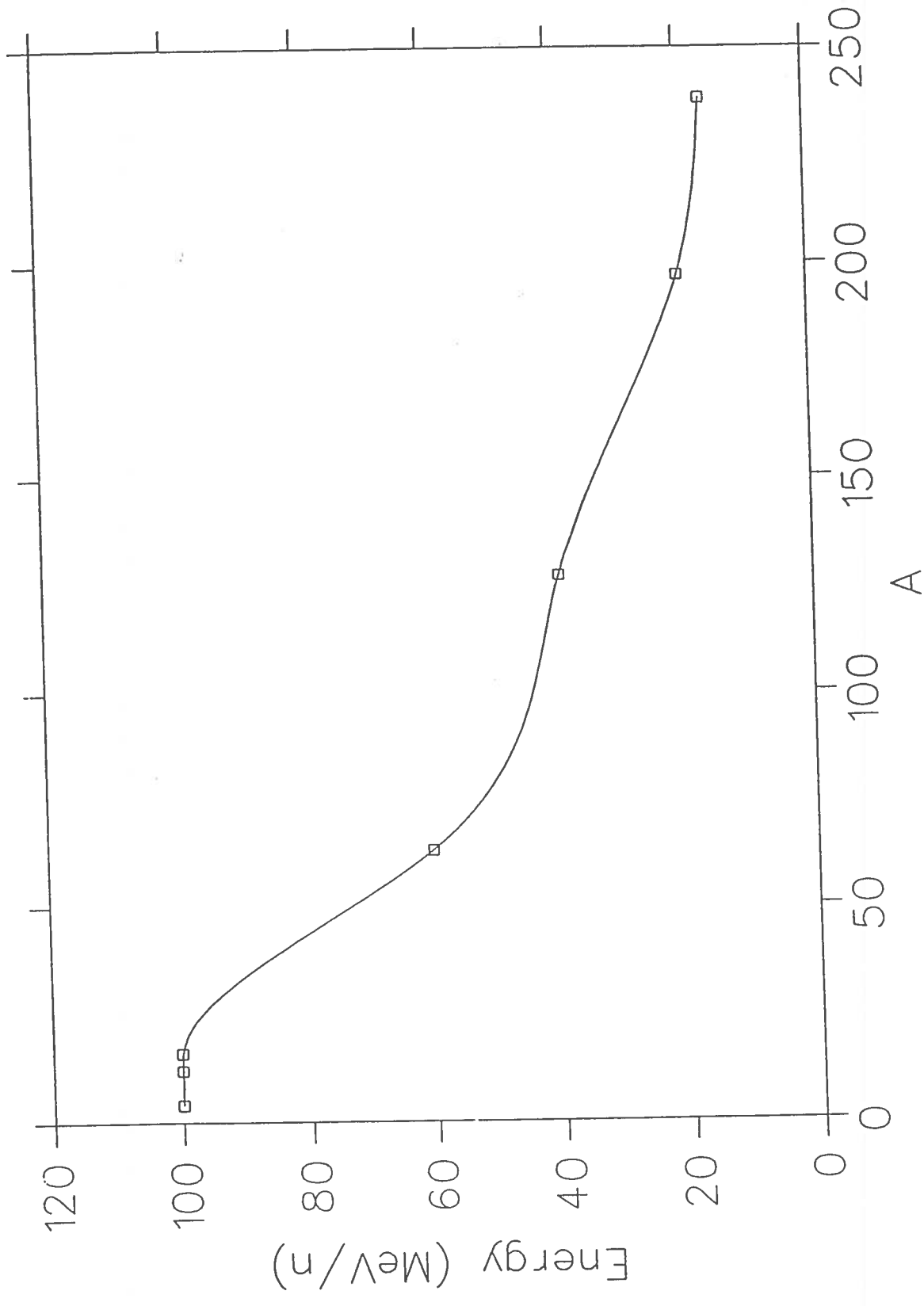


Fig. 2 - Energy of the beams extracted from the C.S.

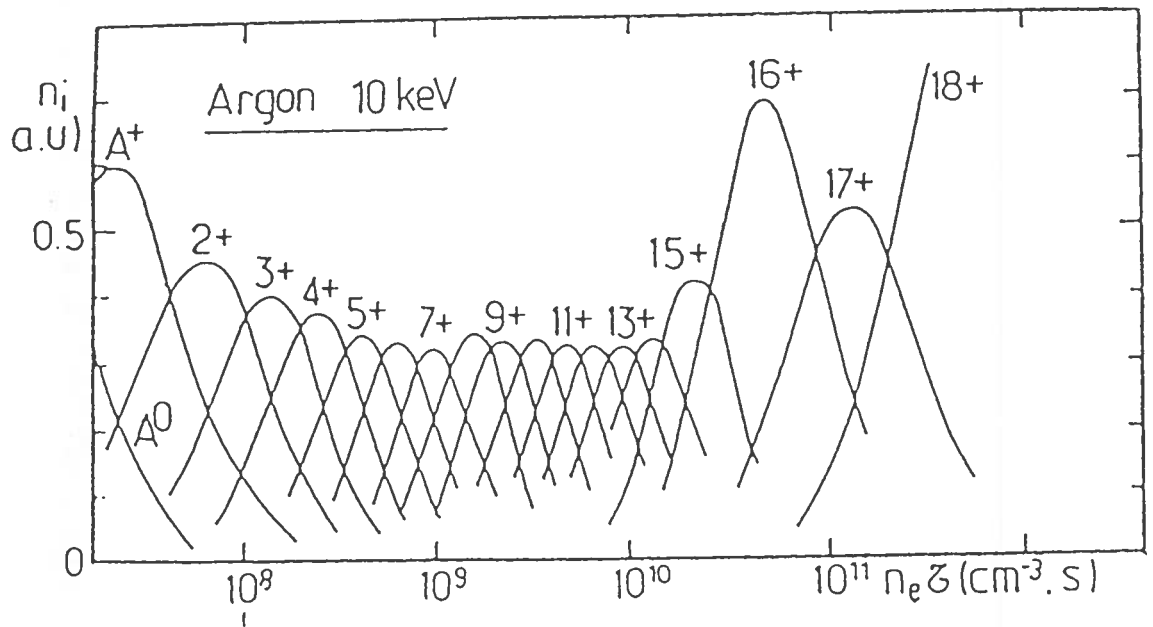
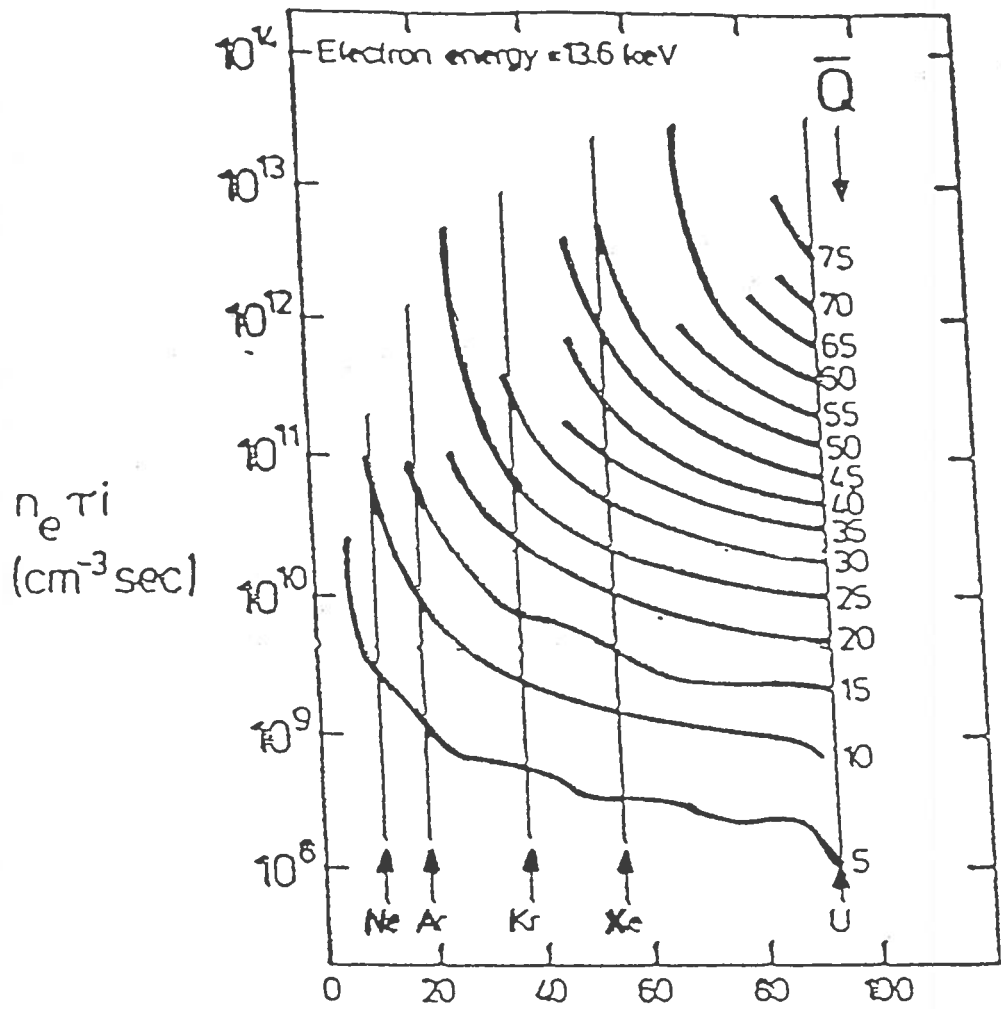


FIG. 3 - Optimum charge state evolution with the quality factor (from ref. 7,8)

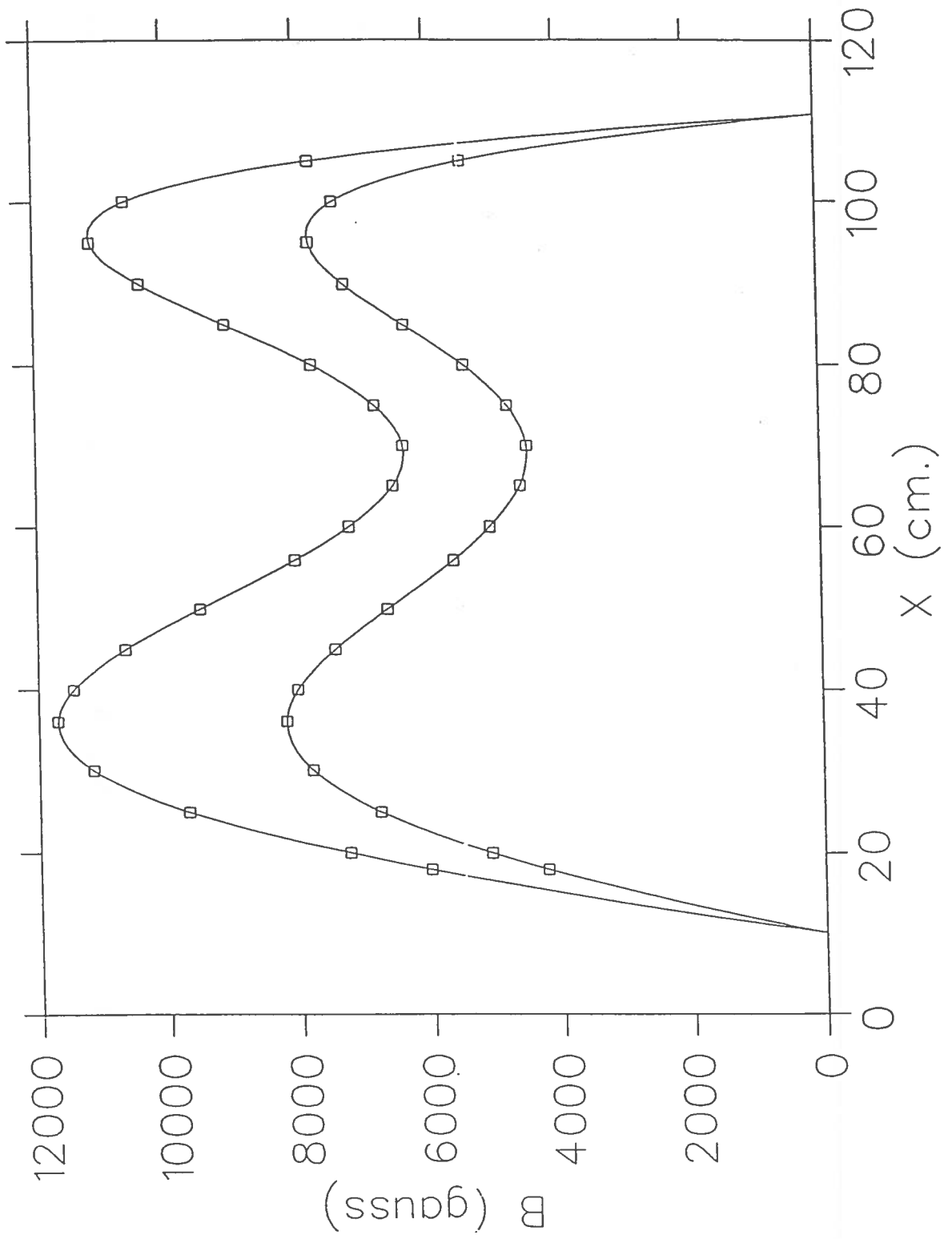


FIG. 4 - Magnetic field scaling for upgraded frequency

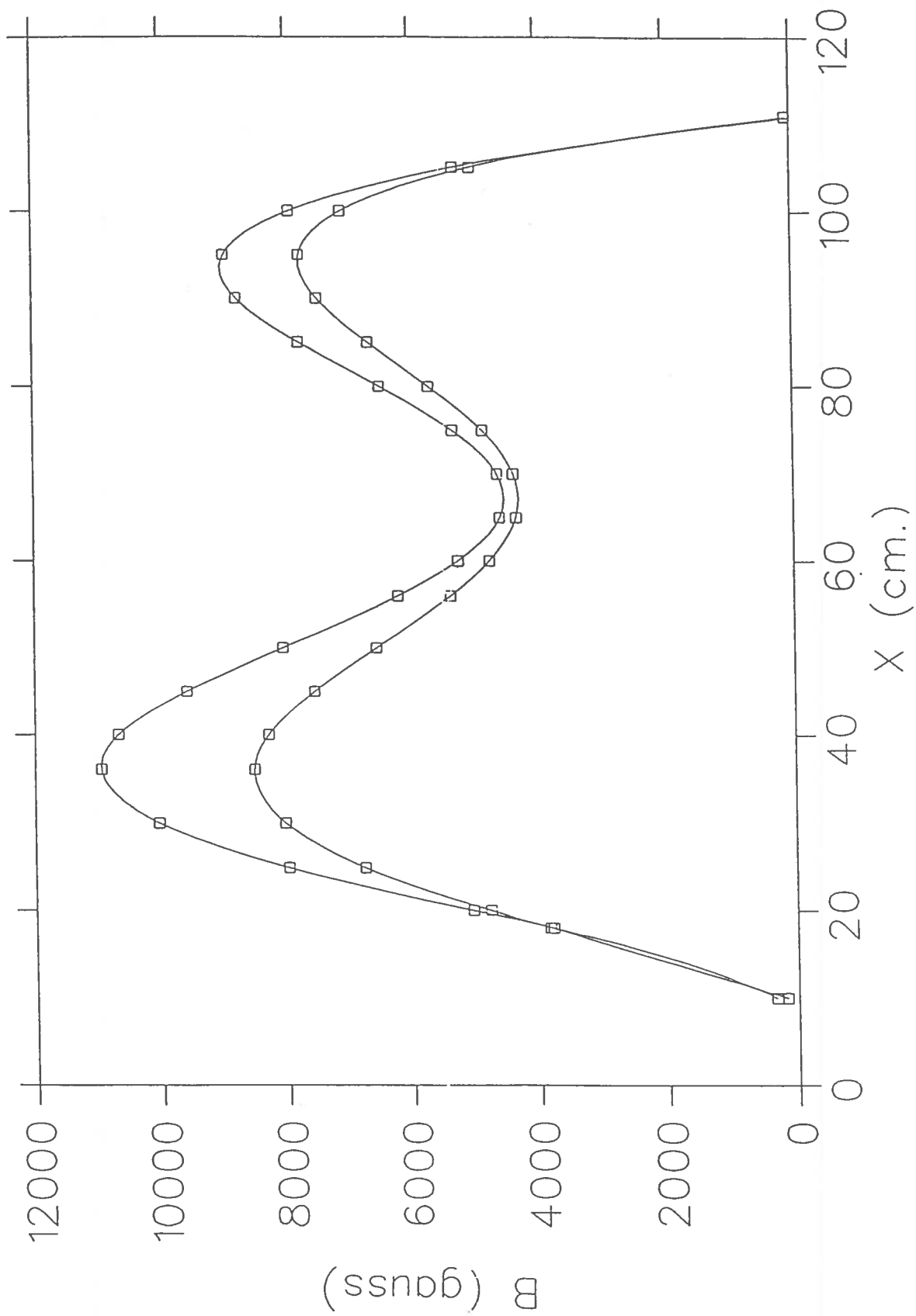


FIG 5 - Magnetic field increase in "High B" mode

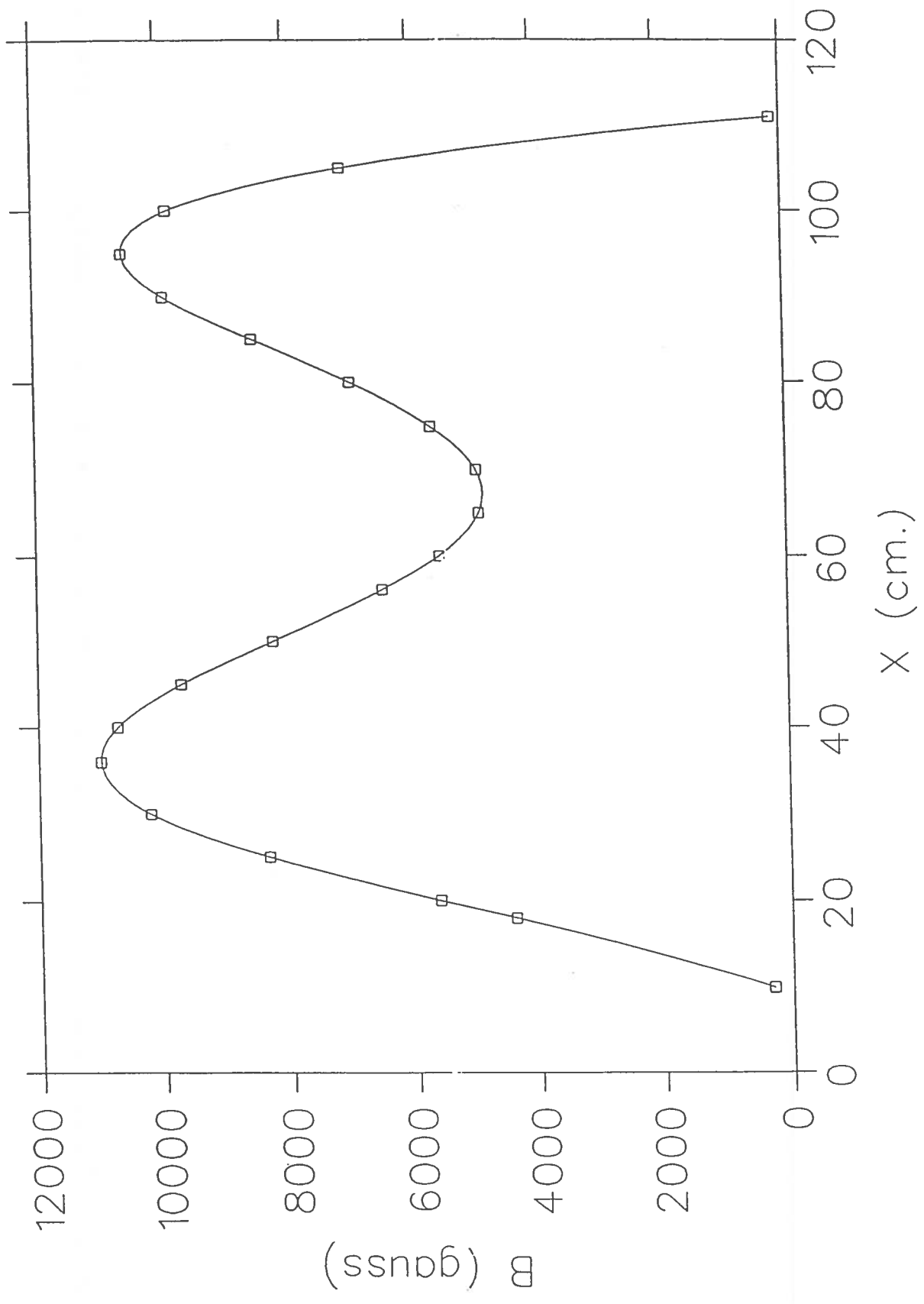


FIG. 6 - Axial field generated by the solenoids (40 A)

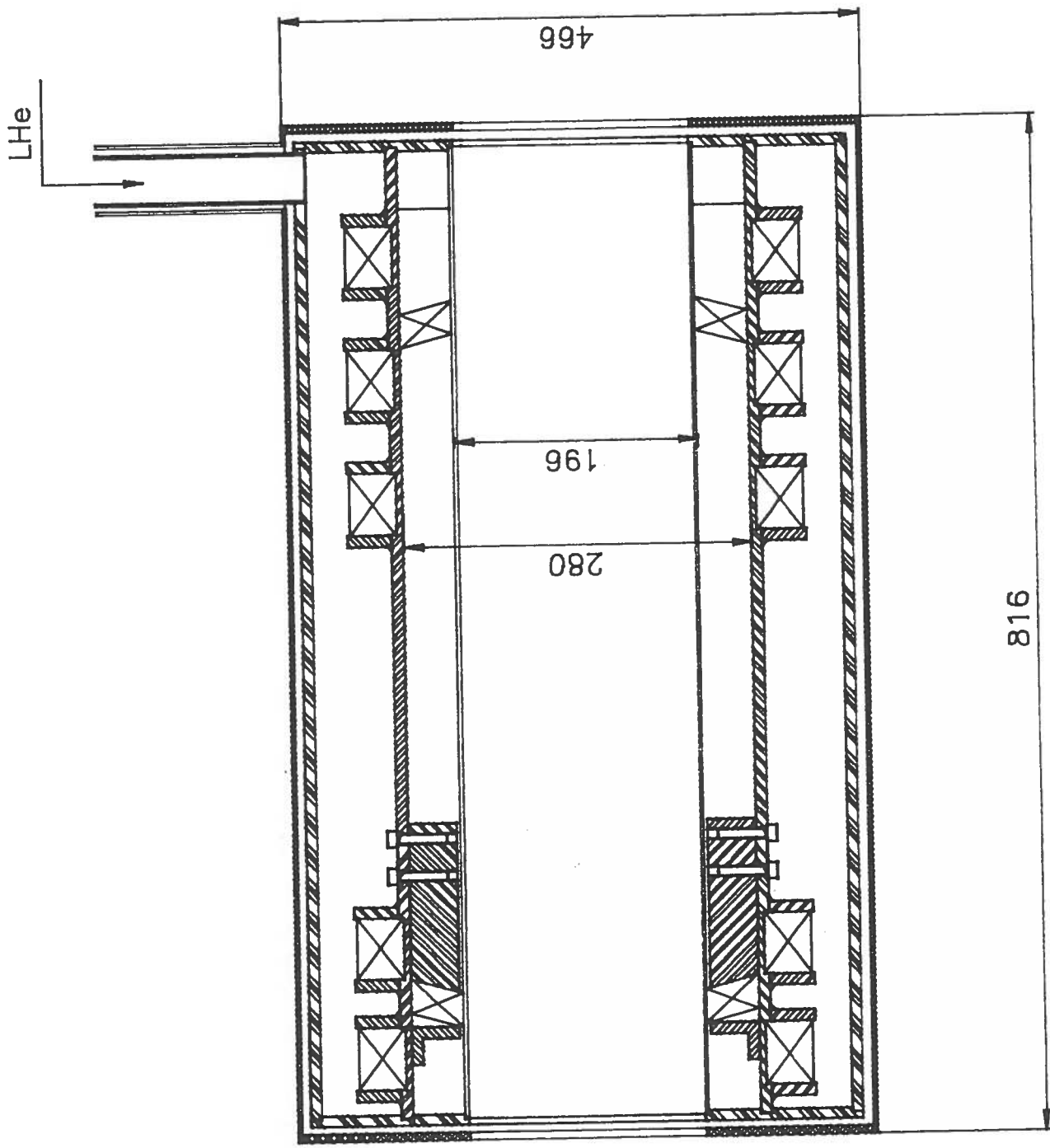


Fig. 7 - The magnets and the cryostat

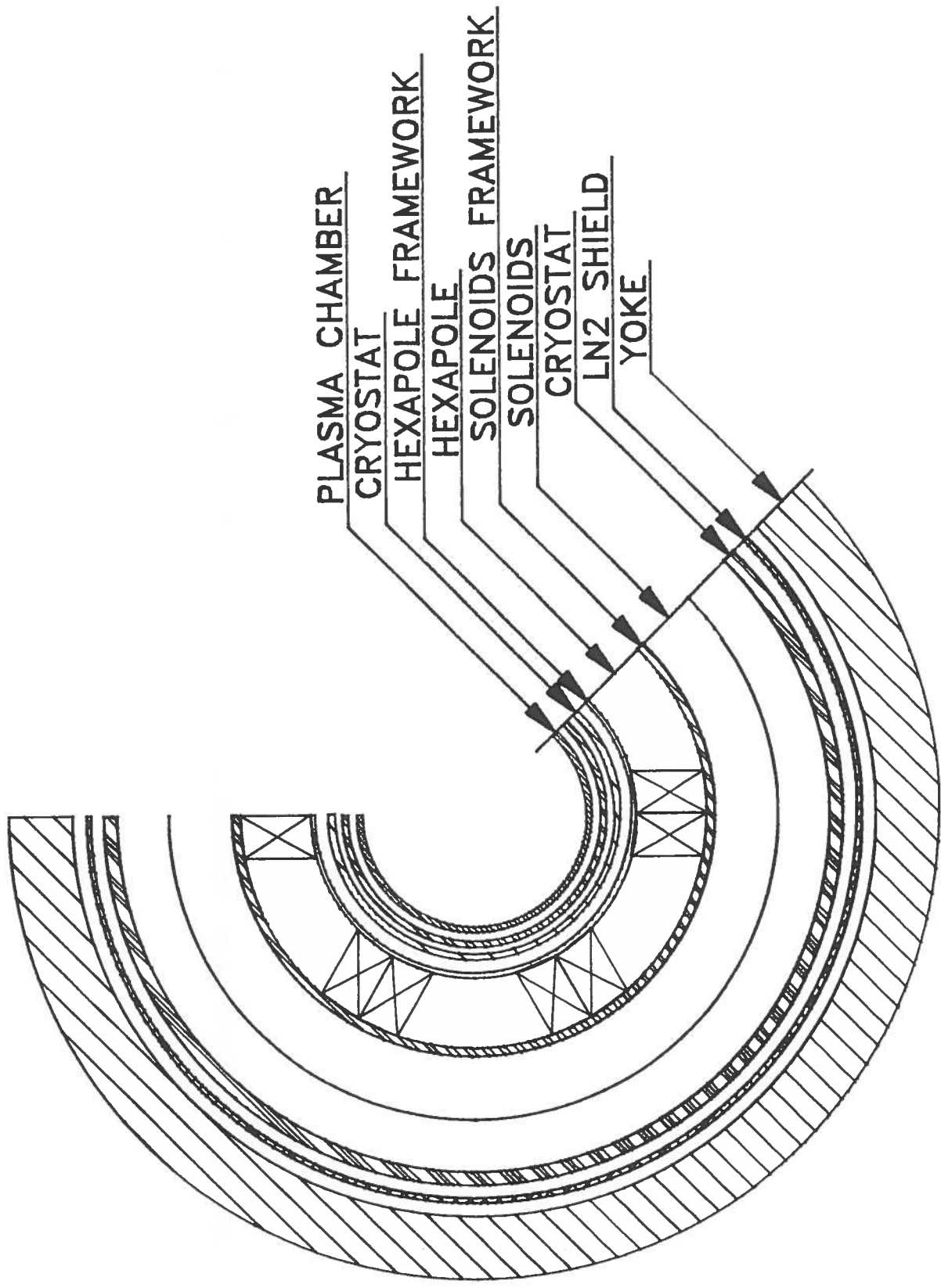


Fig. 8 - Cross section of the source

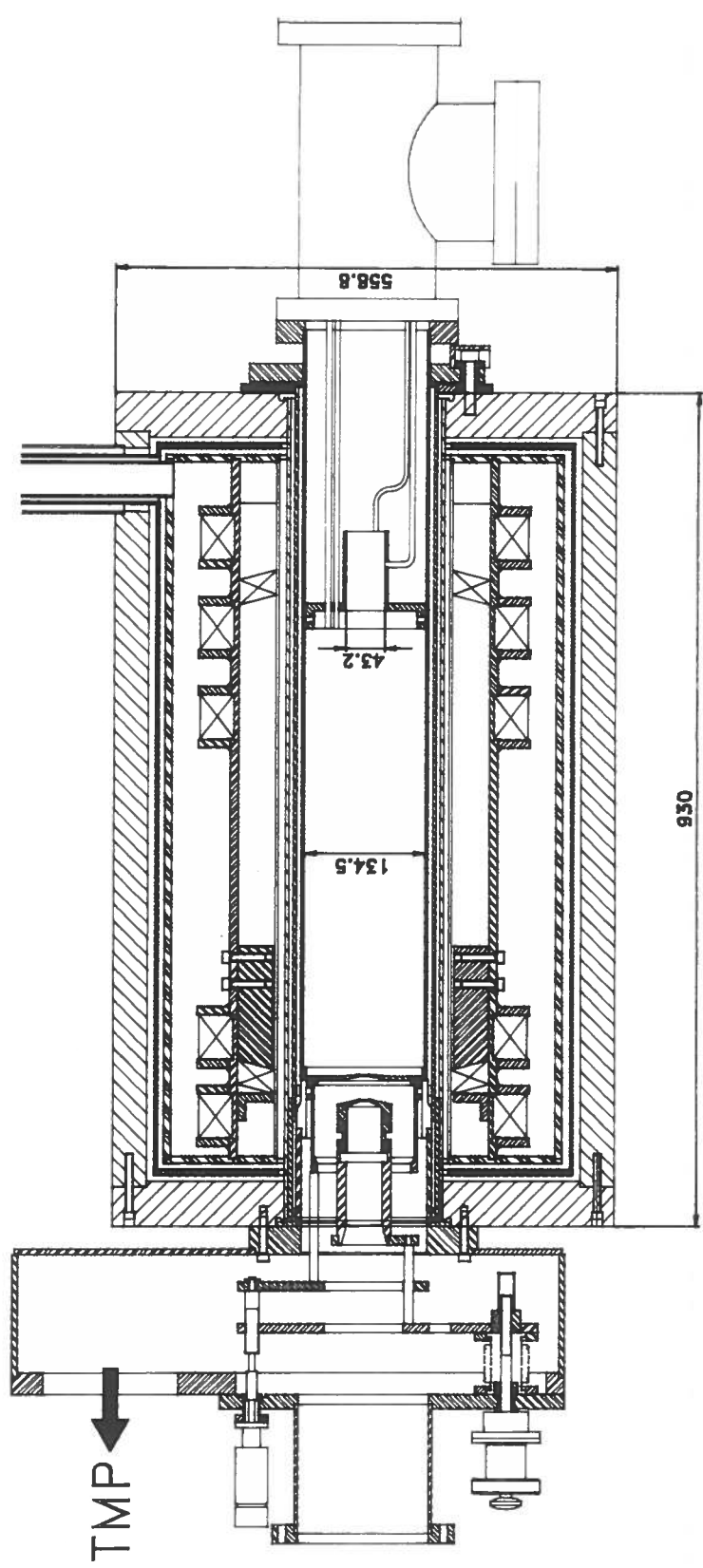


Fig. 9 -- Axial view of the source

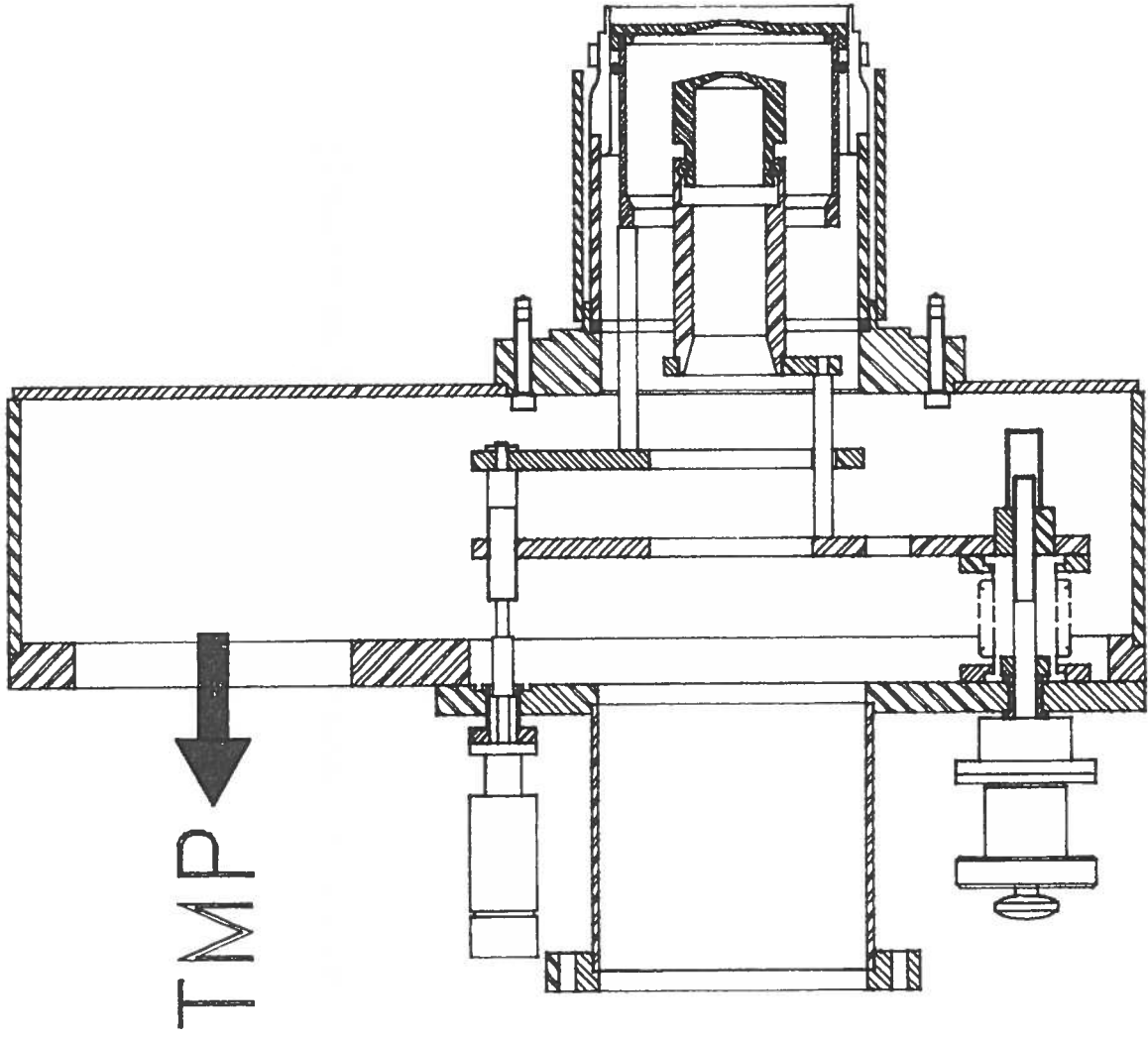


Fig. 11 - The extraction region

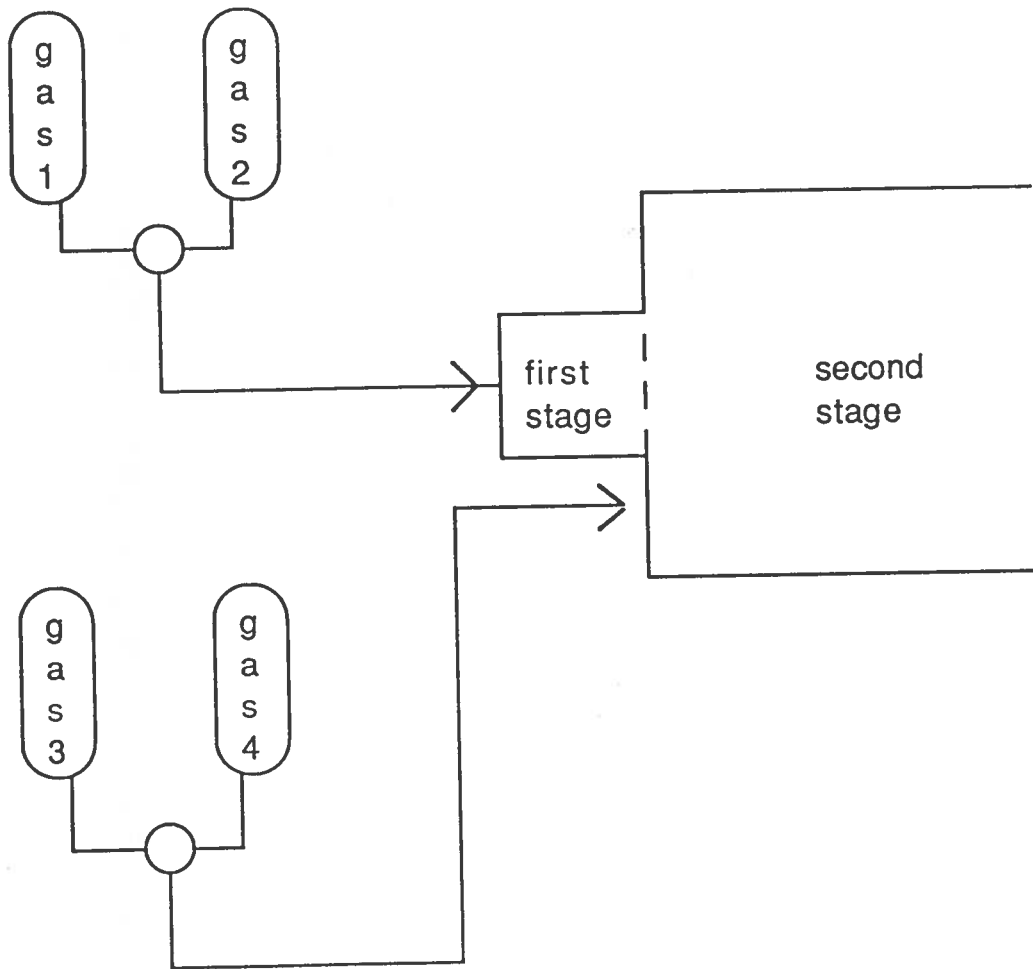


FIG. 12 - The gas input system

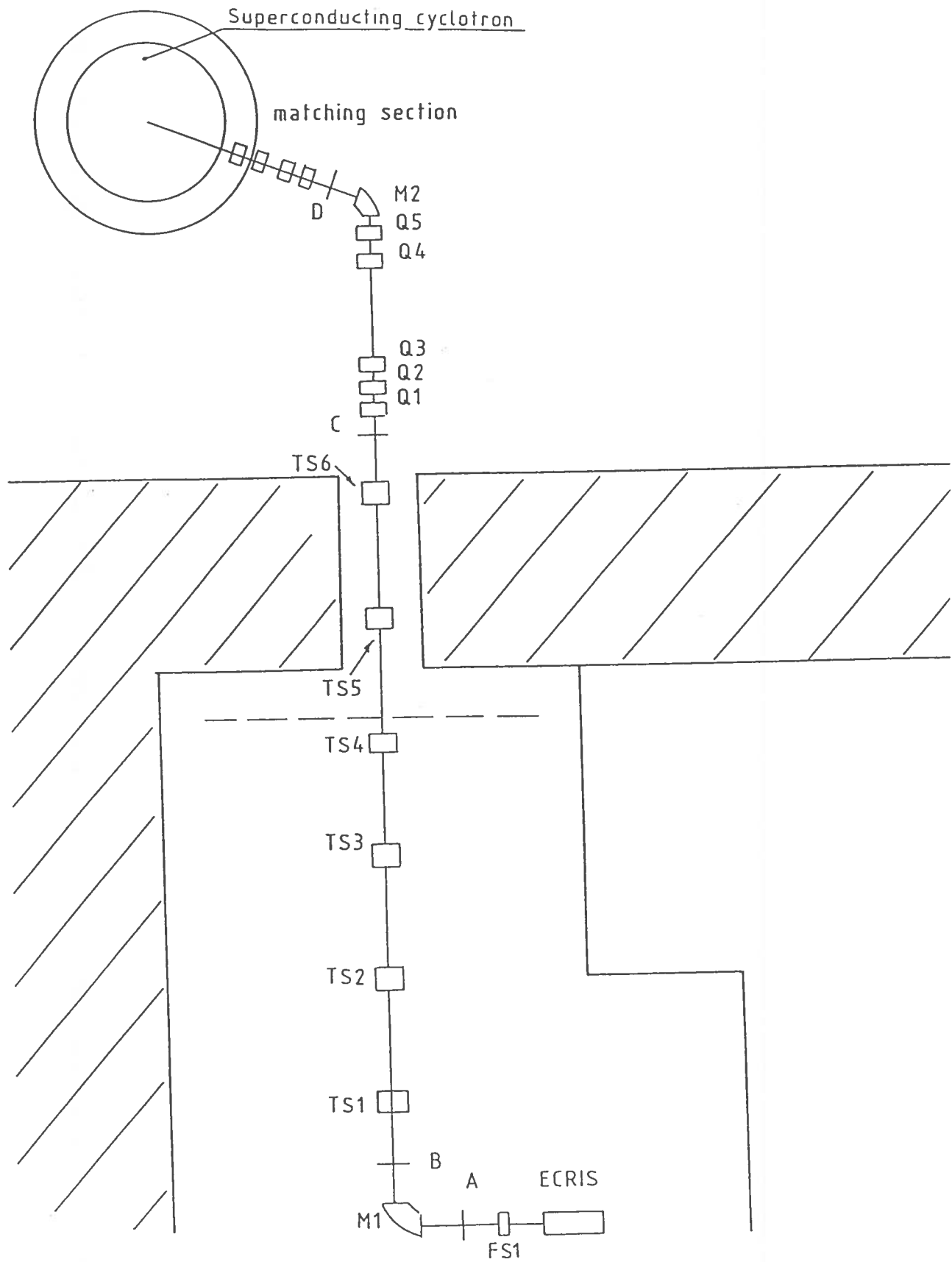


FIG. 13 - Transfer beam line

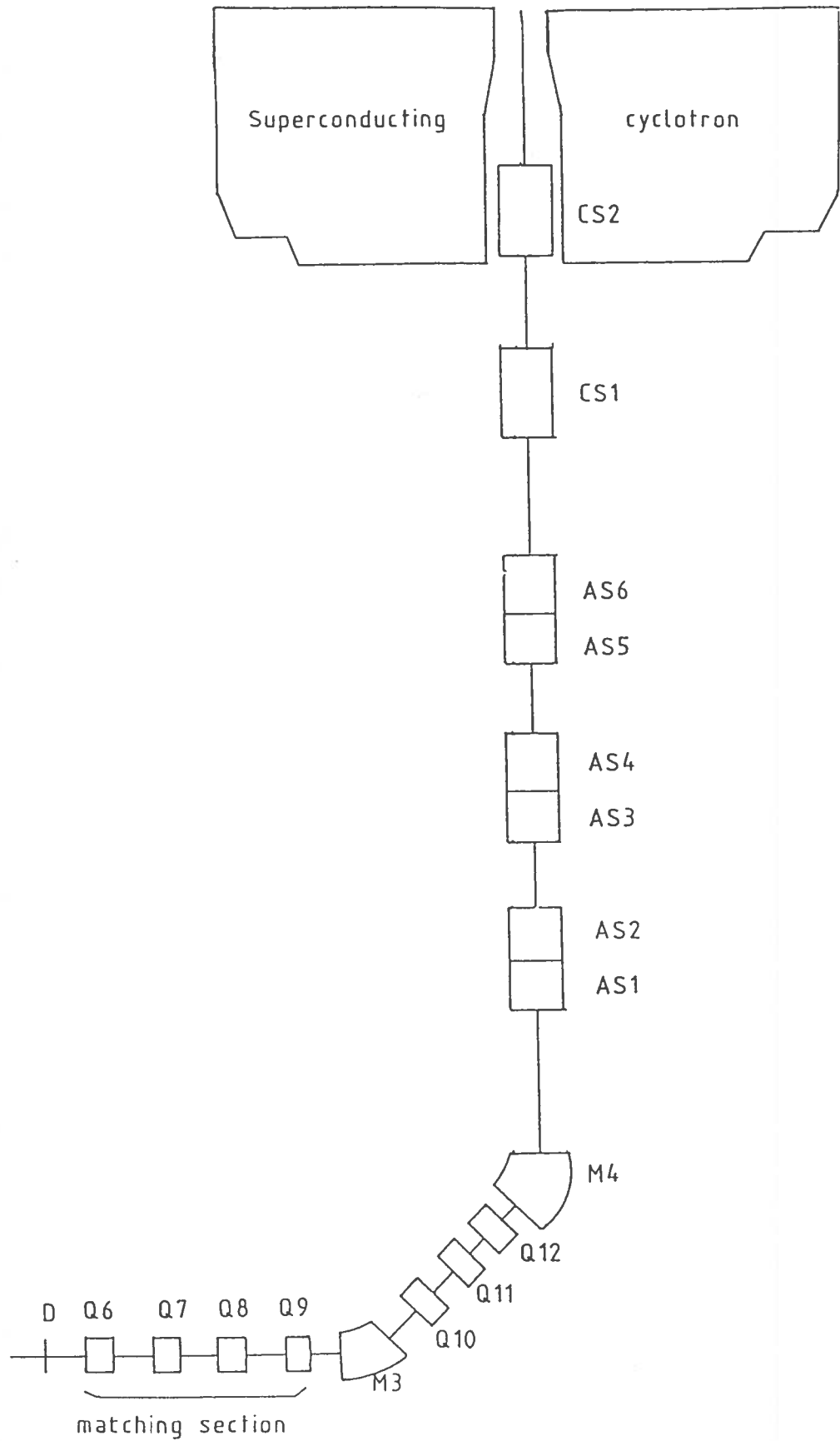


FIG. 14 - Axial beam line

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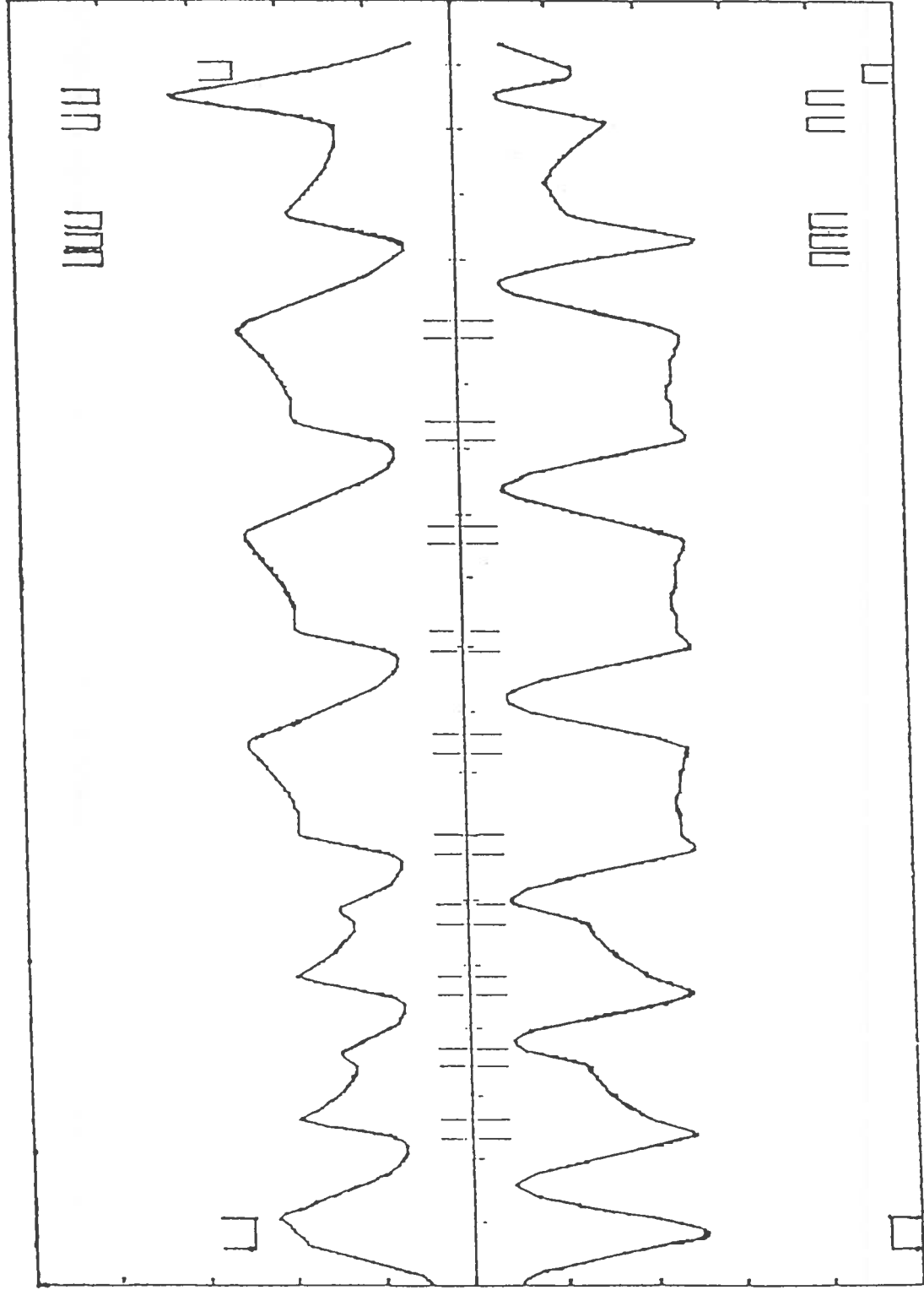


FIG. 15 - Beam envelope calculated by TRANSPORT

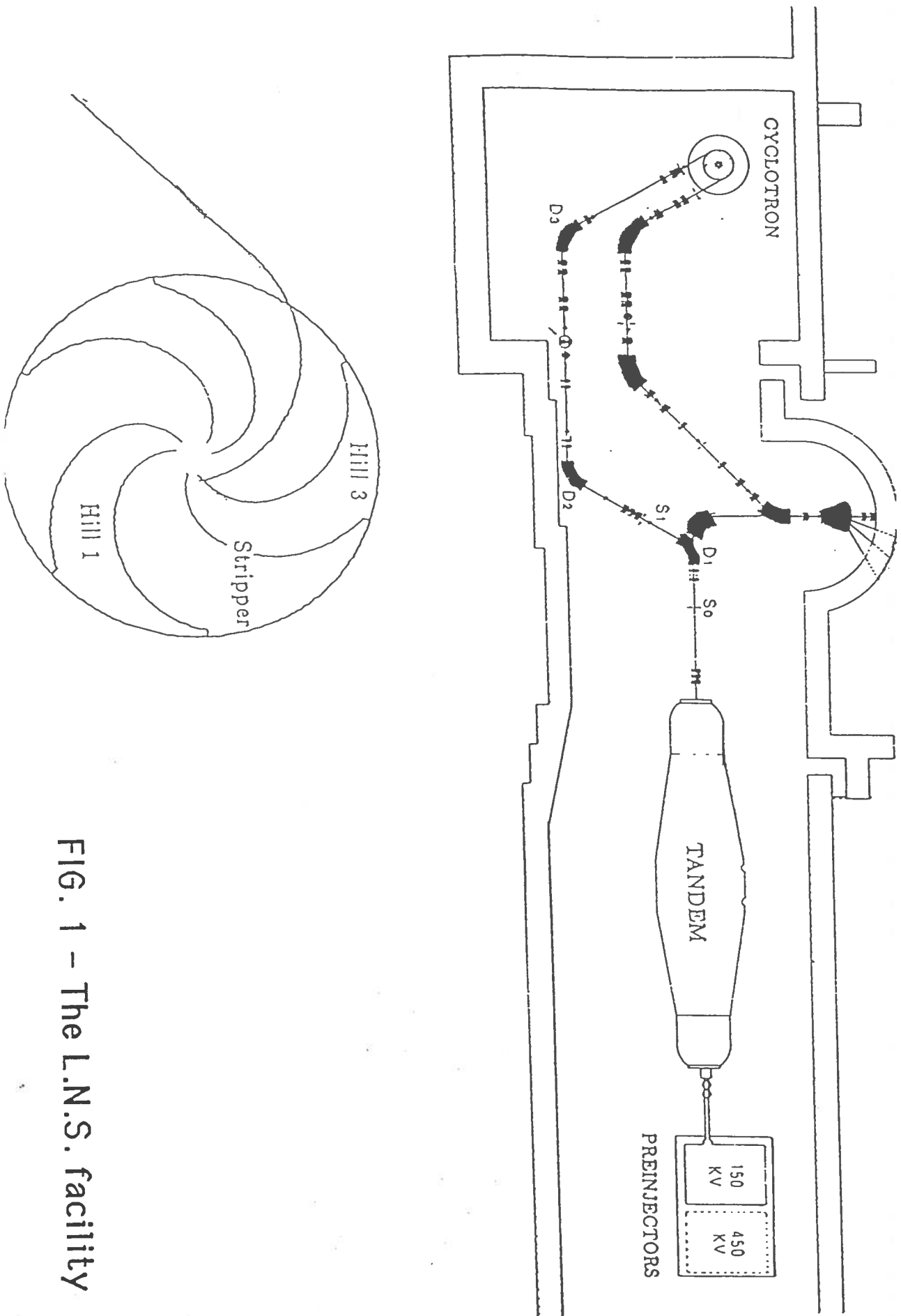


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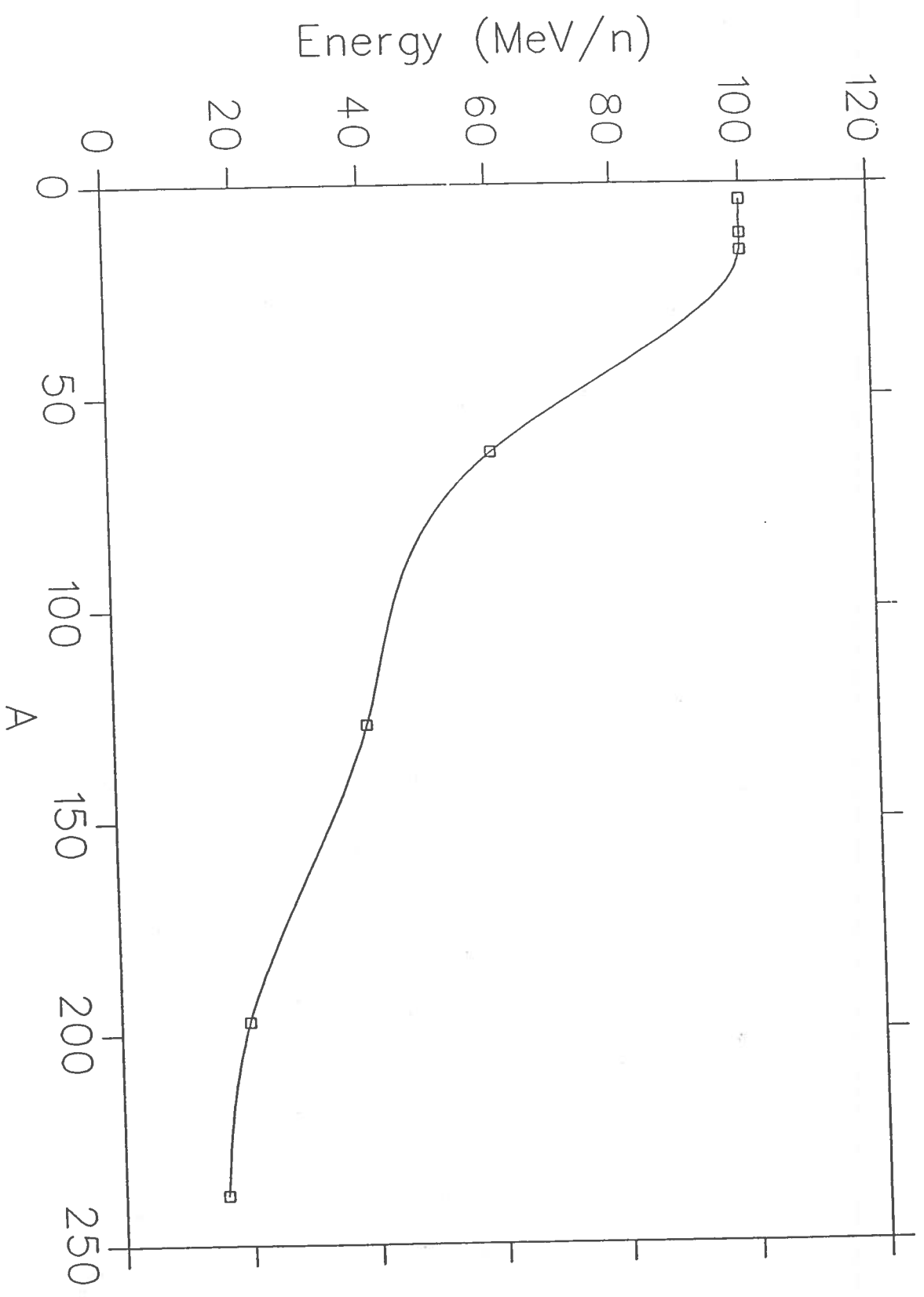


Fig. 2 - Energy of the beams extracted from the C.S.

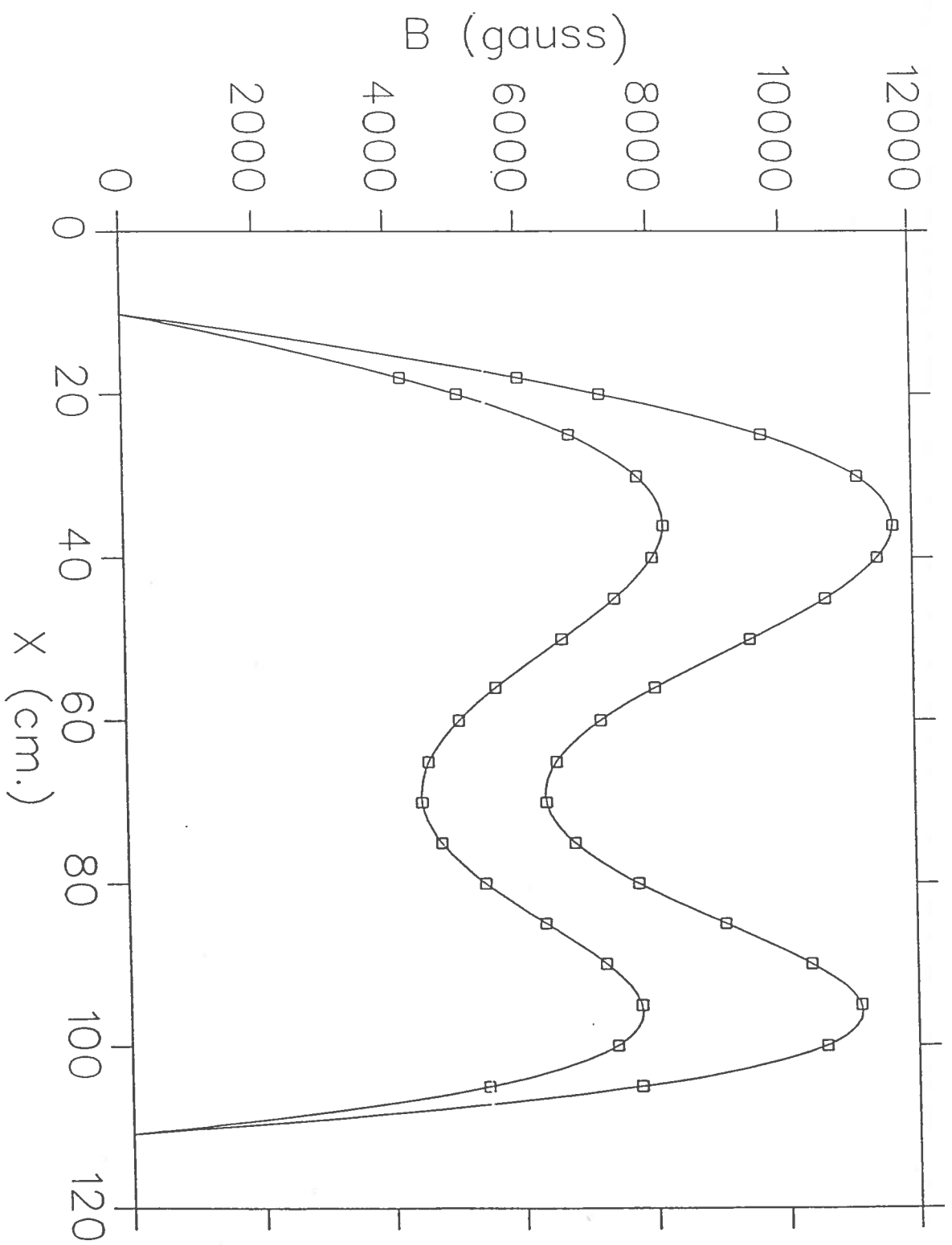


FIG. 4 - Magnetic field scaling for upgraded frequency

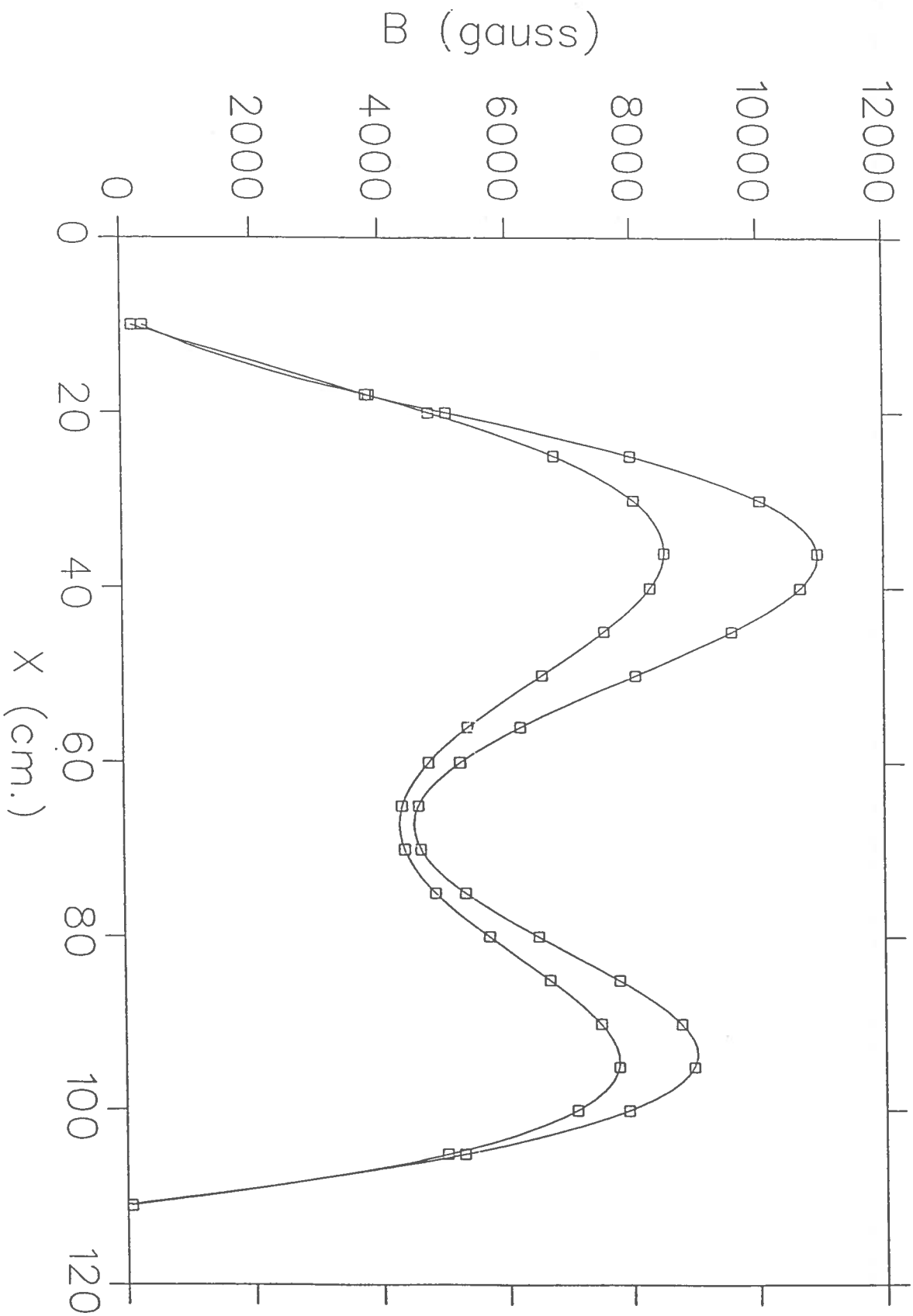


FIG 5 - Magnetic field increase in "High B" mode

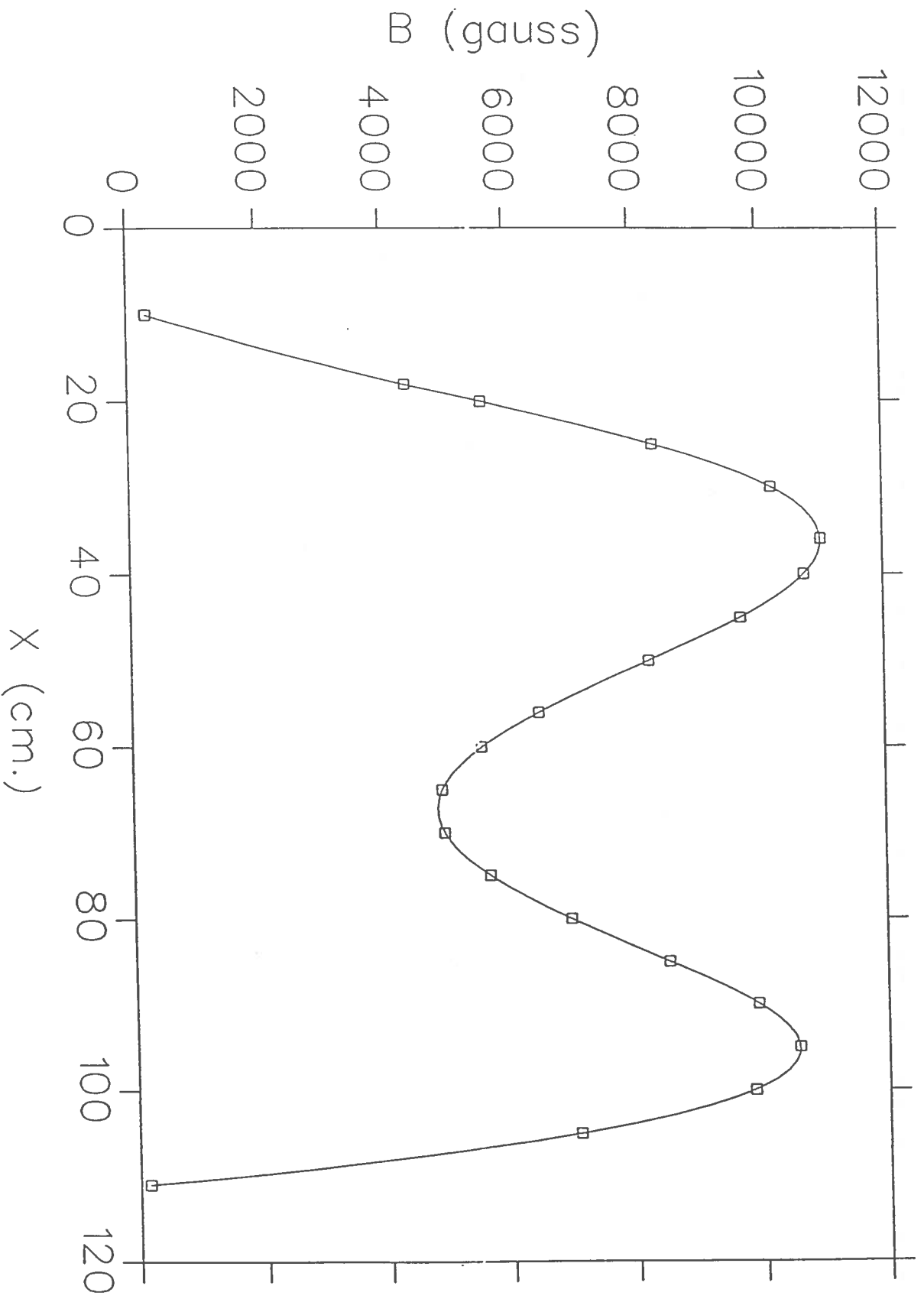


FIG. 6 - Axial field generated by the solenoids (40 A)

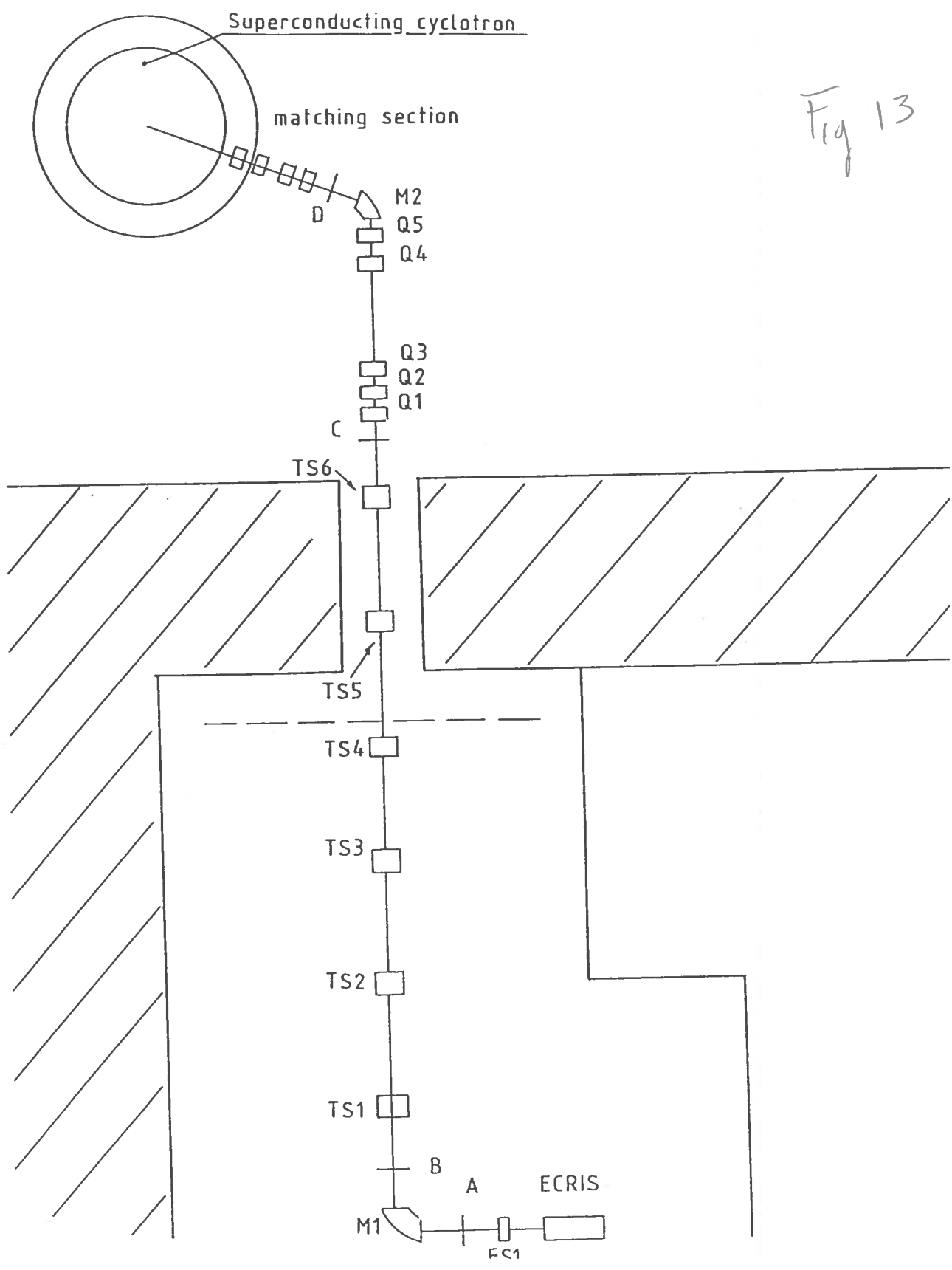


Fig 13

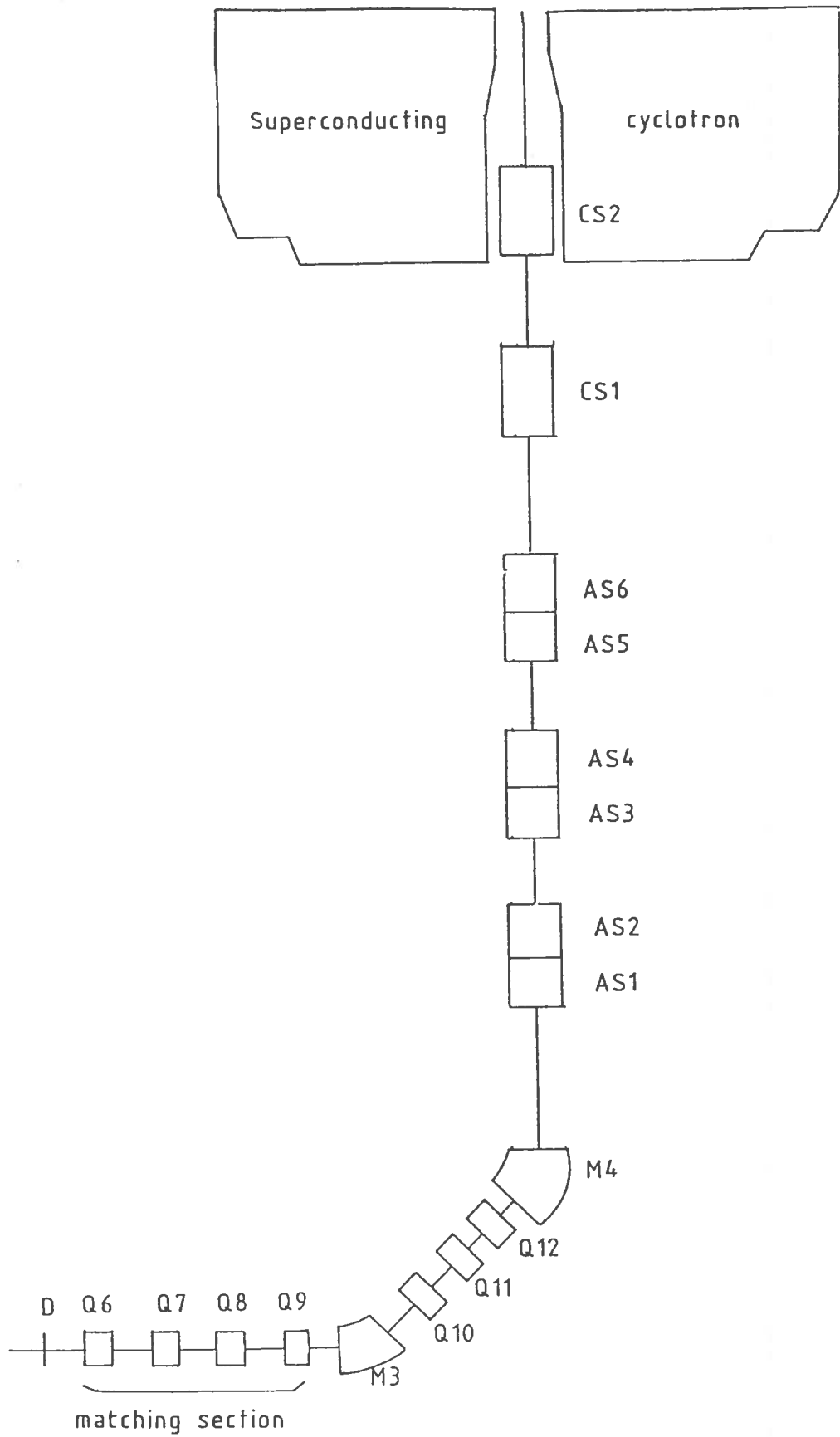


FIG. 14 - Axial beam line

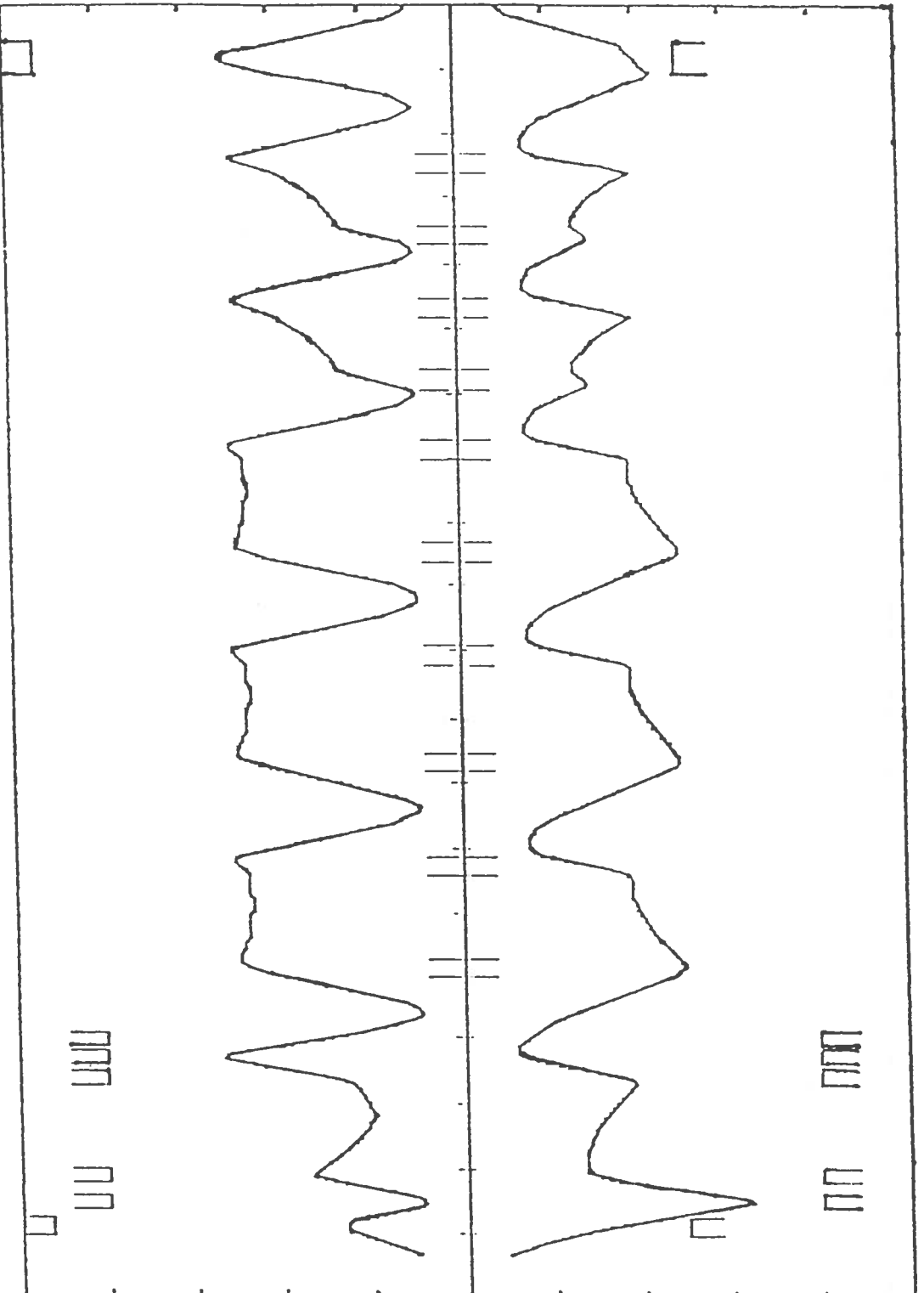


FIG. 15 - Beam envelope calculated by TRANSPORT