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The upgrading of the SERSE project

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Abstract

At Laboratorio Nazionale del Sud (LNS) a project for a high performance electron cyclotron resonance (ECR) ion source has been carried out and the superconducting source SERSE is now under construction.
Recently the developments in the field of ECR sources have suggested to improve the original design of the magnetic trap of this superconducting source.
Particularly a very high mirror ratio on the injection side will be the relevant feature of this source, which may work with very asymmetric loss cone on the different directions.
This magnetic trap may provide a very large confinement time and then high charge states ion beams can be provided.
The new design of the magnetic confining system will be briefly described with the reasons which led to this upgrading. The possibilities opened by a future application of 30 GHz gyrotron to this source will be discussed too.

1 - Introduction

The choice of an ECR ion source as injector for the K-800 superconducting cyclotron now under completion at Laboratorio Nazionale del Sud [1] was mainly due to the need of high charge states ion beams with intensities in the order of 1 eμA, but also to the ion beam stability and reproducibility along with the easy tuning and the low maintainance of ECR sources which are largely appreciated by the accelerators' community.

A project of a superconducting source has been carried out at LNS [2,3] and now the source SERSE [4,5] is under construction.

The choice of the superconducting magnets for the B minimum trap of SERSE was done supposing that the performance of the ECR sources improve with the increase of the confining field and because superconducting magnets are needed when the field exceeds 1 T. The availability at LNS of a LHe liquifier which is used to feed the superconducting cyclotron and the possibility to have a cryogenic plant with moderate costs also pushed in the direction of very high confining field.

The superconducting magnets will make possible to operate routinely the ECR source at 14.5 GHz with a very high level of confinement, maintaining also the capability to upgrade the frequency in the gyrotron domain (28-35 GHz) when CW gyrotrons will be commercially available.

The idea that increasing the field the ECR source works better found its formulation in the so-called "High B mode" concept [3,6] which provided the main ideas for the design of high confinement ECR ion sources.

This concept has been proved recently by a series of experiments performed at Michigan State University (MSU) on the SC-ECR ion source [7,8].

Even if the frequency of that source (f_{MSU}=6.4 GHz) is more than two times lower than the operating frequency of SERSE (f_{SERSE}=14.5 GHz), an extrapolation to higher frequency and magnetic field of these results seems to be reasonable (because the resonance condition of an ECR ion source requires B_{ECR} to be proportional to the frequency).

The increase of the performance with the increase of the "mirror ratio" B_{max}/B_{ECR} has shown no saturation in the experiment at MSU, especially for the axial confining field on the injection side, proving the statement that "the higher the field, the better the performance".

2 - The "High B mode" and the SC-ECRIS results

From plasma physics it is well known that higher the "mirror ratio" of a magnetic trap, smaller the loss cone and then the number of lost particles from a confined plasma.

In an ECR source the confining trap is given by the superposition of the mirror field and the hexapolar field, then we will have different loss cones from the plasma in the different directions, depending on the B_{max}.

It is well known that the most performant ECRIS are those ones which have both radial and axial mirror ratios high, but in order to have a significant amount of extracted current, the field on the extraction side has to be smaller than on the injection side, whereas for the radial direction the rule is that the field must be as high as possible.

The original design of SERSE [2,5] was based on the assumption that the maximum axial field should be of the same order of the radial confining field. Then the radial field was pushed up to the maximum level achievable with the present technology for the required size of the plasma chamber, well above the level of other existing sources, and the field maxima of the axial profile were kept close to that level.

The results obtained in the experiment performed on the SC-ECRIS at MSU have shown that the symmetric profile is not the best one, leading to modify the SERSE axial confining field, with respect to the original design [9]. Different loss cones from the ECR plasma for different directions may be envisioned. This new concept, based on the experimental evidence, links the capability to vary widely the magnetic field to the source performance. The magnetic topology of the original SERSE design works in the correct range, but the absolute level of the two axial field maxima must be raised.

The best solution for the optimization of the source towards the high charge states production is then the increase of the magnetic field maxima, both on axial and radial direction. This comes from the "High B mode" concept which is founded on the consideration that the increase of the magnetic field affects not only the mean electron temperature and the ion confinement time, but also the electron density.

A well-known rule of plasma physics [10] states that the condition for having a quiet plasma in a magnetic trap is:

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

where $p_{particle}$ is the pressure related to the momentum of charged particles in the plasma and $p_{magnetic}$ is the magnetic pressure.

But $p_{particle} = \Sigma\, n\, k\, T = n_e\, k\, T_e + n_i\, k\, T_i$ and $p_{magnetic}$ is defined as $B^2/2\mu_0$, for the above formula may be rewritten:

$$n_e\, k\, T_e + n_i\, k\, T_i \; << \; B^2/2\mu_0$$

Otherwise in a ECRIS plasma $T_e >> T_i$, $n_e \approx <q>\, n_i$ because of the plasma quasineutrality, hence the electron component overcomes the ion component and the formula may be simplified:

$$n_e\, k\, T_e << B^2/2\mu_0 \,.$$

It may be concluded that the magnetic field increase is effective both on electron density and temperature and then it is very beneficial for the ionization of the highest charge states.

The consequence of this theory is the so-called “ECRIS catechism” [11]: for increasing values of the mirror ratio B_{max}/B_{ECR} the plasma turbulences tend to disappear until, when $B_{max}/B_{ECR} >> 2$, the “Paradise” is reached and a quiescent plasma with only few turbulences is obtained, resulting in a source very easy to be tuned, a very stable ion output and a broad curve of I^{q+} vs. P_{RF}.

This way of operation (the so-called “High B mode” [3,6]) is allowed to 14.5 GHz ECRIS only working with superconducting magnets, because the resonance field B_{ECR} is about 0.5 T, therefore B_{max} must be higher than 1 T.

A consequence of this concept is that the increase of frequency is not useful if the magnetic field is not sufficient to support the higher cutoff electron density.

The "High B mode" concept has been successfully applied to SC-ECRIS at MSU [7,8], operating before in “normal B mode” with results at the top of the 6.4 GHz ECRIS population. When increasing the field produced by the superconducting magnets well above the 2 B_{ECR} value, the results have became comparable to the ones of the best 14.5 or 18 GHz sources. Another encouraging result has been that the charge state distribution (CSD) was continuously improving and a very stable plasma appeared.

This mode of operations seems to give T_e and t_i higher than for any room temperature ECRIS and $n_e \approx n_{cutoff}$ at 6.4 GHz without any electron feeding by e-guns, biased disks or wall coating. In fact the electron escape rate is so reduced that the use of a biased disk does not give a consistent increase of performance.

3 - The new magnetic system

The magnetic field topology of SERSE was originally determined by the capability to work at 14.5 GHz in the "High B mode" and at 30 GHz in “normal B mode”, i.e. to reach at least 1.4 T on the plasma chamber wall, with a maximum for the mirror in the order of 2.2 T for the axial field to be reached when working at 30 GHz.

For the frequency of 14.5 GHz the axial field maximum was in the same order of the radial (1.35 T).

In fig. 1 the field profiles obtainable with the original design are outlined.

In tab. 1 the main features of the old design are shown.

The criterion used to maintain safe and reliable operation of the magnets was to operate each coil at current values well below the critical value [9].

All coils were designed with a temperature safety margin not lower than 1°K in the worst case, i.e. in the windings position where the magnetic field is the highest [4,5,9].

Following the design of the magnetic system, the cryostat was designed [12] interfacing that magnetic system with the requirements coming from ECRIS designers.

The sketch of the whole source was carried out, taking into account the requirement of an easy dismounting and handling of some components like extraction system or plasma chamber (fig. 2)

After the results obtained by SC-ECRIS at MSU the upgrading of the magnetic system was studied to get the same magnetic field profile realized on the MSU device but scaled with the ratio f_{SERSE}/f_{MSU}.

A series of calculations have been made on the basis that $B_{ECR} \propto \omega$ and $n_e \propto \omega^2$, then it is possible to get the same shape of the electron distribution with a n_e five times higher than in SC-ECRIS (obviously this assumption neglects the recombination effects inside the plasma).

In fig. 3 the field profile with the expected best confinement time is shown.

The role of the second coil, which works with reverse field, in the achievement of the best "High B mode" configuration, is fundamental and it is the main difference with respect to the old configuration.

Fig. 3 shows that the magnet system should get a mirror ratio higher than 5 on the injection side and higher than 3 on the extraction side, maintaining the ECR surface position more or less unchanged.

In tab. 2 the main features of the new design are shown.

If compared with the ones in tab. 1 it comes out that the coil n. 2 is a factor four bigger and the coil n. 1 is upgraded by 35% whereas coil n. 3 is less than 10% bigger.

In fig. 4 the comparison between the old axial profile and the new one is shown.

The sextupole field already designed fulfills our requirements and it represents the maximum field allowed by this source geometry with a reasonable safety.

This new configuration proposed has the big advantage of keeping the same number of solenoids, modifying their position only slightly. The operating currents of all three solenoids remain below 120 A. However two solenoids will get larger in size which lead to an increase in volume of superconducting wire for these coils of about 60%.

The temperature safety margin for the superconducting wires is 1°K in the worst case, which is in agreement with the adopted safety criterion, but the external discharge across the biggest solenoid reaches a value of 600 V, thereby nearly doubling the value of the initial design. This value comes closer to the limiting dielectric strength of the cryostat current leads which is about 1000 V, but it is within the specifications.

In conclusion, there is no need to change the specifications of magnet power supplies and cryostat current leads with respect to the old design [9]. The most of the old design does not need any change and no further delay may be expected.

The choice of a new configuration, as for calculation and larger winding time, have postponed the time schedule by about half year with respect to the old design. The new schedule is shown in tab. 3.

4 - The expected performance

The very asymmetric mirror trap shown in fig. 3 should allow a perfect confinement on each side, except for the extraction side, where the mirror ratio is relatively low, but however higher than 3.0.

This configuration represents the exact scaling at 14.5 GHz of the axial field profile used for 6.4 GHz SC-ECRIS at MSU, and the hexapole field will get also a higher mirror ratio than two (for SERSE $B_{max}/B_{ECR}=2.8$).

This small volume high maxima configuration should give the best charge state distribution because of the high magnetic pressure which can be reached.

In fact $n_{cutoff} \propto \omega^2$ and $n_e kT_e << B^2 / 2\mu_0$, then increasing B and ω in the same way, the electron cutoff density is expected to increase. On the other hand the field increase should rise T_e, and the charge states obtainable with SERSE 14.5 GHz should be well high not only because of a higher n_e but also because of a higher T_e. Realistically 2-3 times higher n_e and T_e are expected with respect to the ones reached in the SC-ECRIS at MSU.

Otherwise a low total current should result because of the small plasma volume (proportional to the length of the plasma volume, which is in this case L_{plasma}=71 mm.). The highest charge states transport would take benefit of this fact, taking rid of the most of the space charge effects, at least at the extraction and in the preanalysis section.

The extraction of low current high charge states ion beams is a convenient operating condition for the injection of slow heavy ions into the cyclotron.

To understand how the upgrading of SERSE should affect the source performance, we refer to a graph [13] which shows the charge states obtainable by an ECR ion source for different values of the quality factor $n_e\tau_i$ (electron density times ion confinement time) and of the electron temperature T_e (fig. 5).

SC-ECRIS is able to produce about 1 eμA of Ne^{10+}, Ar^{16+}, Kr^{26+}, Xe^{35+}, then increasing $n_e\tau_i$ and T_e by a factor two or three (because of the highest magnetic pressure), SERSE 14.5 GHz should be able to produce 1 eμA of Si^{14+}, Ar^{17+}, Kr^{29+},

Xe^{40+}, etc.

For a cyclotron this gain, in the order of 10% on the q/m ratio with respect to the other ECR sources, means a 20% gain on the extracted ions energy.

In fig. 6 the energies obtainable after the acceleration in the K-800 superconducting cyclotron [1] are compared with the ones obtainable by using the 15 MV Tandem as injector [14] or a standard room temperature ECR source.

Other configurations useful for the comprehension of the physics of ECR sources may be obtained with this magnetic system. Lower mirror ratios but larger plasma volumes are obtainable with the profile in fig. 7, which is interesting for the production of medium charge states high intensity beams. The ECR zone is extended on a length of 200 mm. with mirror ratios of 3.3 for the injection side and 1.9 for the extraction side. Therefore the magnetic pressure is the limiting condition for the increase of electron temperature in the plasma and finally for the buildup of high charge states.

However the increase of extracted beam currents should be provided by the increase of plasma volume as recently discussed [15] and demonstrated [16].

By getting lower volumes but higher gradients and mirror ratios, the charge state distribution may improve (fig. 8,9) and the total extracted current should decrease.

The tests to be carried out with the different axial and radial field which can be obtained by SERSE in a continuous way may give relevant results not only in terms of high charge states and currents, but also in terms of knowledge of the phaenomena which arise during the ECR ionization process.

5 - The 30 GHz upgrading

More improvements may be probably expected from the frequency upgrading of SERSE.

The performance of ECR ion sources are linked to the plasma density and to the electron energy. In line of principle, the frequency increase should permit the increase of the plasma density, provided that the magnetic field is sufficient to adequately confine the plasma.

In an ECRIS with high confining field as SERSE, the magnetic system should be able to support a 30 GHz microwave generator; this generator should allow the source to achieve a cutoff density four times higher than working with a 14.5 GHz klystron, obtaining a consistent increase in the production of very highly charged ions.

Otherwise by changing the frequency and maintaining the field unchanged, the magnetic pressure does not change and then the electron temperature should decrease as the density increases and the highly charged ions production could be decreased with respect to the 14.5 GHz operation.

Nevertheless higher currents of highly charged ion should be delivered by the source.

In tab. 4 the characteristics of the generators are summarized. These characteristics fit very well with the requirements of this source in terms of microwave power and stability which must be in the order of 10^{-3} so that ripples of the generator output which reflects on the plasma quiescence, and finally the ion output, can be avoided.

On the other way a high level of power may permit a significant increase of the electron energy, to ionize up to the K-shell, which counteracts the decrease due to the limited magnetic pressure.

The coupling of high power high frequency microwave to the plasma needs a careful study about the effects of high levels of power deposition per unit volume and different ideas needs to be verified [17]:

1) investigations of quasi-gasdynamics regime of the plasma confinement in mirror magnetic traps;

2) arising of microinstabilities and their influence on plasma confinement;

3) input of UHF energy into the plasma by means of quasioptical beams of electromagnetic waves, etc.

The suggested axial profile for the 30 GHz operations is shown in fig. 10. The gradient is about the same as for 14.5 GHz operations, but the mirror ratios are less than 3 for the injection side and less than 2 for the extraction.

The plasma volume is relatively high with respect to the 14.5 GHz operations and then reasonable amount of current should be provided.

In 1996, after the end of tests at 14.5 GHz in "High B mode", SERSE may be coupled to the gyrotron, opening new possibilities in the field of ECRIS.

The comparison between 14.5 GHz SERSE working in "High B mode" and 30 GHz SERSE working in normal B mode will give more informations about the effectiveness of ECR frequency increase.

However the availability of CW gyrotrons is expected to give an increase of electron density and temperature in ECR sources, provided that in future a source with magnetic fields in the order of 3÷4 T could be built.

In this direction the tests to be performed with SERSE will be fundamental in order to correctly address the future projects.

6 - Conclusions

The extrapolation from recent experimental results have suggested to carry out an enhancement of the SERSE magnetic trap.

The feasibility study has shown that a reasonable compromise can be reached between the improvement of the axial mirrors and the requirement of a safely operating magnet system.

The upgrading of the magnet system entails a six months shift of the whole schedule of the SERSE project; the source will be mounted and tested at CEA/DRFMC, Grenoble on next summer 1995 and the delivery of the source to LNS is now expected in June 1996. Nevertheless the estimated increase of performance is so huge to justify the delay and the costs connected with this enhancement.

The chance of pushing the frequency up to 30 GHz will be also envisioned, but at the moment it is limited by the technical difficulties related to the purchase of adequate generators.

Acknowledgements

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The cryostat has been designed by Dr. P. Seyfert and Dr. R. Lagnier and it is under construction at CEA/DRFMC/SBT, Grenoble.

The contribution of Ing. F. Alessandria and Mr. M. Cafici in the supervision of the cryogenic design and in the interfacing with the LNS cryogenic plant is acknowledged.

The source design has been performed in collaboration with Dr. P. Briand and Dr. G. Melin (CEA/DRFMC/PSI, Grenoble).

The discussion with Prof. V. Kutner (JINR, Dubna) about the 30 GHz upgrading has been very fruitful.

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Figure captions

Fig. 1 - The axial field profile of the original SERSE design (L_{plasma}=78 mm.).

Fig. 2 - Sketch of the source SERSE.

Fig. 3 - Best axial field profile given by the new magnetic system (L_{plasma}=71 mm.).

Fig. 4 - Comparison between the profiles of fig. 1 and fig. 3.

Fig. 5 - The charge states obtainable by an ECR source plotted vs. $n_e\tau_i$ and T_e.

Fig. 6 - The energies obtainable with the superconducting cyclotron of the LNS (solid line), as follows from data in fig. 5 for the charge states given by SERSE, compared with the energies obtainable with the superconducting cyclotron when using the 15 MV Tandem as injector (dotted line) or coupling a standard room temperature ECR source to the cyclotron (dashed line).

Fig. 7 - Axial field profile for high intensity beams (L_{plasma}=200 mm.) obtained with $(NI)_1$=600000 At, $(NI)_2$=-200000At, $(NI)_3$=300000 At.

Fig. 8 - High gradient axial field profile (L_{plasma}=133 mm.), obtained with $(NI)_1$=730000 At, $(NI)_2$=-200000At, $(NI)_3$=380000 At.

Fig. 9 - High gradient axial field profile (L_{plasma}=96 mm.), obtained with $(NI)_1$=750000 At, $(NI)_2$=-200000At, $(NI)_3$=400000 At.

Fig. 10 - Axial field profile for SERSE working at 30 GHz (L_{plasma}=78 mm.).

Table 1 - Main features of the old design

	#1	#2	#3	hexapole	
-Operating current (nominal)	106	-16	72	121	A
- (intermediate)	70	-132	52	121	A
-B_{max}	5.5	3.6	4.8	6.4	T
-Number turns	6076	360	5952	3040	
-Energy stored	89.7	0.6	42.3	100	KJ

Table 2 - Main features of the new design

	#1	#2	#3	hexapole	
-Operating current (maximum)	117	-49	87	121	A
-B_{max}	6.1	3.1	4.7	6.4	T
-Number turns	7360	4284	5394	3040	

Table 3 - The new time schedule

Date	Work description
Sep 93	order of the superconducting magnets and call for tender for cryostat; start of the drawings for source, support and installation;
Oct 93	effective start of manufacturing period of superconducting magnets; start of construction or order for 14.5 GHz rf generators;
May 94	manufacturing design and start of construction of the source;
Jan 95	factory tests of the superconducting coils;
Feb 95	delivery of the superconducting coils at DRFMC, Grenoble;
Jun 95	commissioning of the superconducting coils;
Jul 95	assembly of the source with cryostat; commissioning of rf generators;
Aug 95	beginning of the SERSE source tests at DRFMC/SBT;
May 96	final acceptance tests at DRFMC;
Jun 96	delivery of SERSE to INFN/LNS;
Jul 96	beginning of SERSE source tests at INFN/LNS.
Sep 96	end of SERSE source tests at INFN/LNS;

Table 4 - The main features of the gyrotron to be coupled to SERSE.

Frequency	30 GHz
Power	10 KW
Efficiency	30%
Electron beam voltage	20 KV
Electron beam current	1.5 A
Water consumption	70 l/min
Gyrotron length	1 m
Magnetic field	0.6 T
Total power supply	50 KW
Mains	3*380 V/50-60 Hz
Weight	70 kg

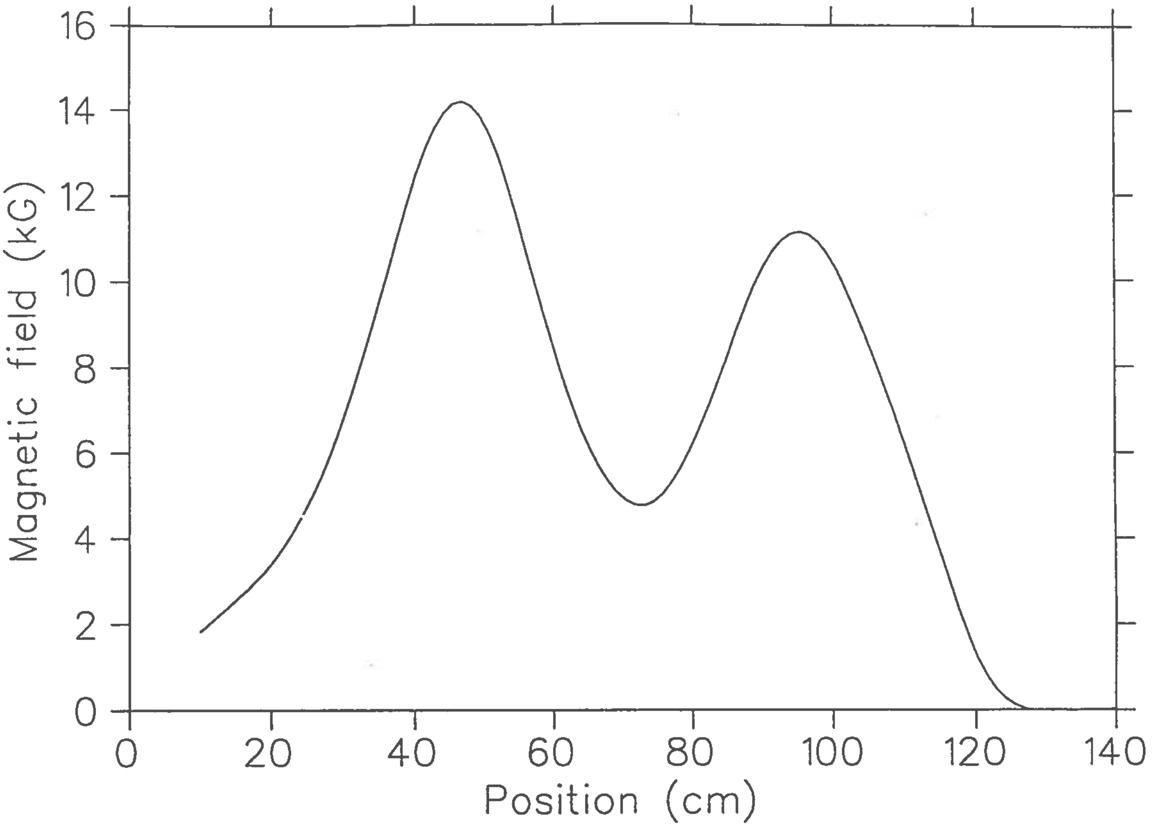
Magnetic field (kG)
Position (cm)
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
120
140

Fig. 1

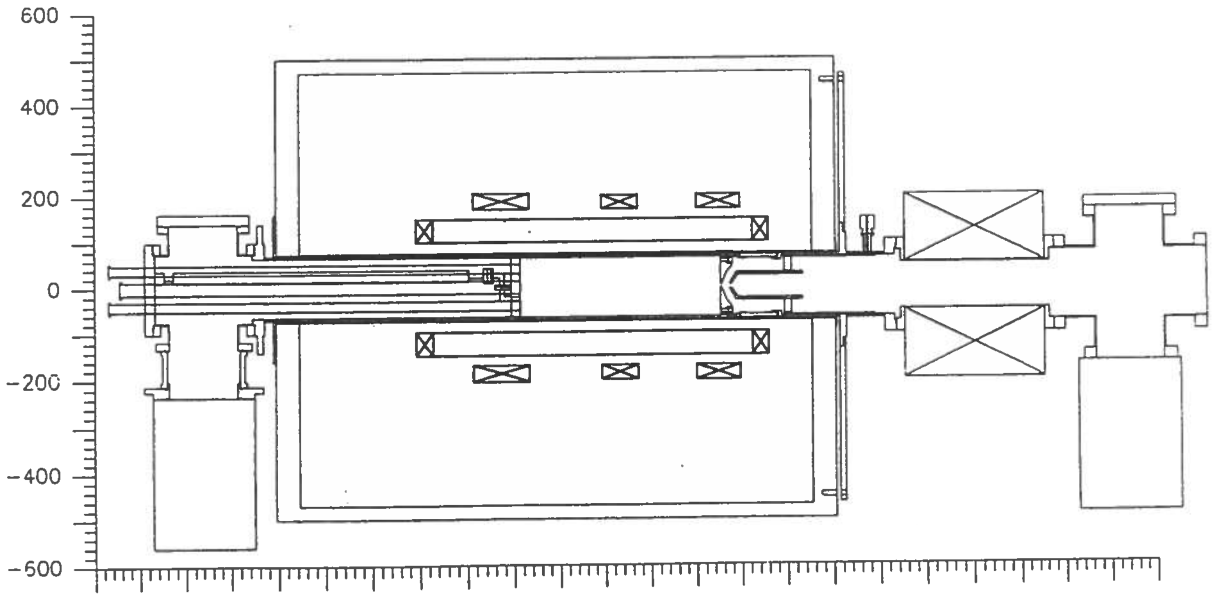
600
400
200
0
-200
-400
-600
-1000
-800
-600
-400
-200
0
200
400
600
800
1000
1200

Fig. 2

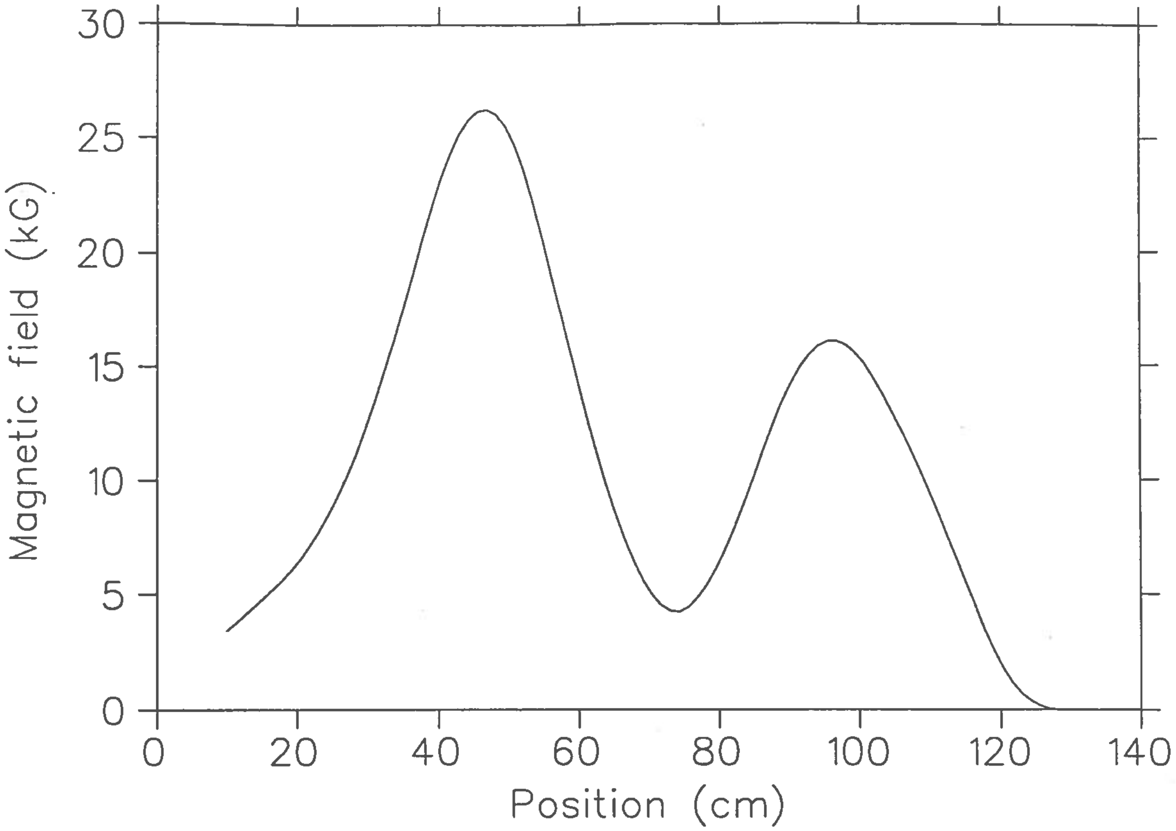
30
25
20
15
10
5
0
Magnetic field (kG)
0
20
40
60
80
100
120
140
Position (cm)

Fig. 3

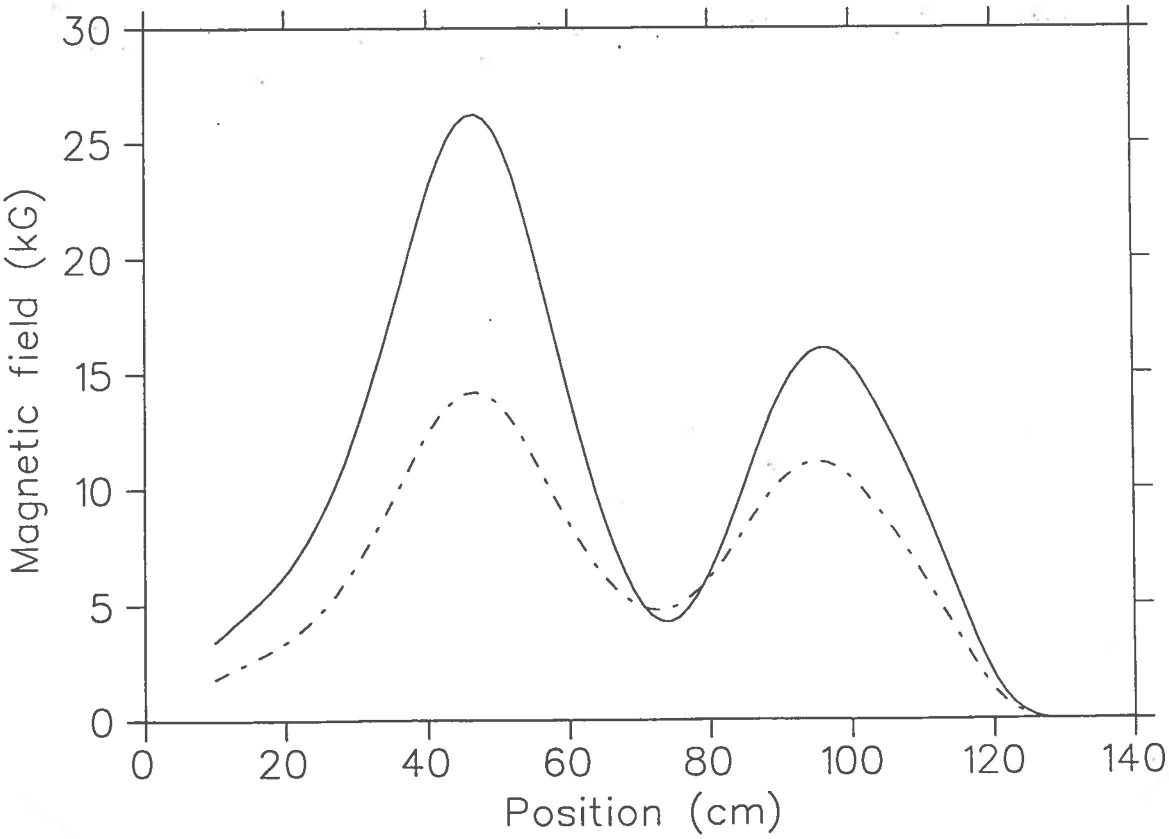
30
25
20
15
10
5
0
Magnetic field (kG)
0
20
40
60
80
100
120
140
Position (cm)

Fig. 4

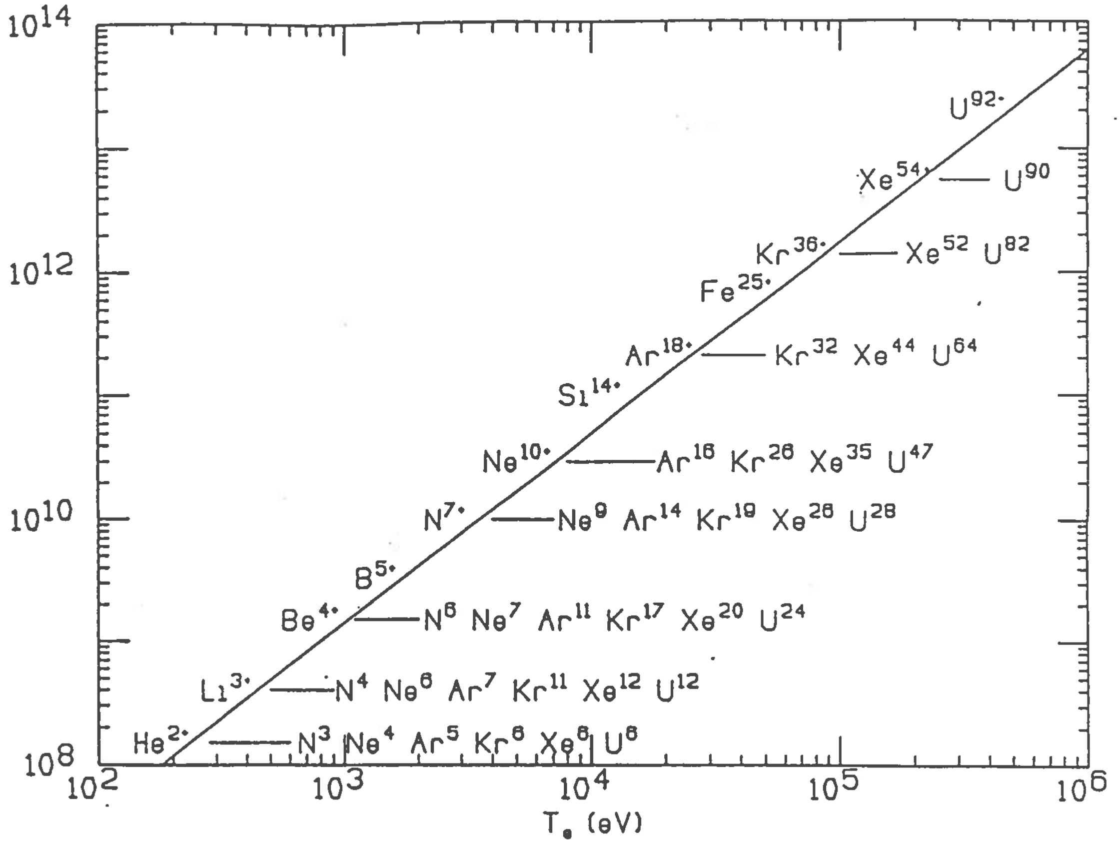
10^{14}
10^{12}
10^{10}
10^{8}
$n_e \tau_i$ (cm^{-3}·sec)
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
T_e (eV)
U^{92+}
Xe^{54+} U^{90}
Kr^{36+} Xe^{52} U^{82}
Fe^{25+}
Ar^{18+} Kr^{32} Xe^{44} U^{64}
Si^{14+}
Ne^{10+} Ar^{16} Kr^{26} Xe^{35} U^{47}
N^{7+} Ne^{9} Ar^{14} Kr^{19} Xe^{26} U^{28}
B^{5+}
Be^{4+} N^{6} Ne^{7} Ar^{11} Kr^{17} Xe^{20} U^{24}
Li^{3+} N^{4} Ne^{6} Ar^{7} Kr^{11} Xe^{12} U^{12}
He^{2+} N^{3} Ne^{4} Ar^{5} Kr^{6} Xe^{6} U^{6}

Fig. 5

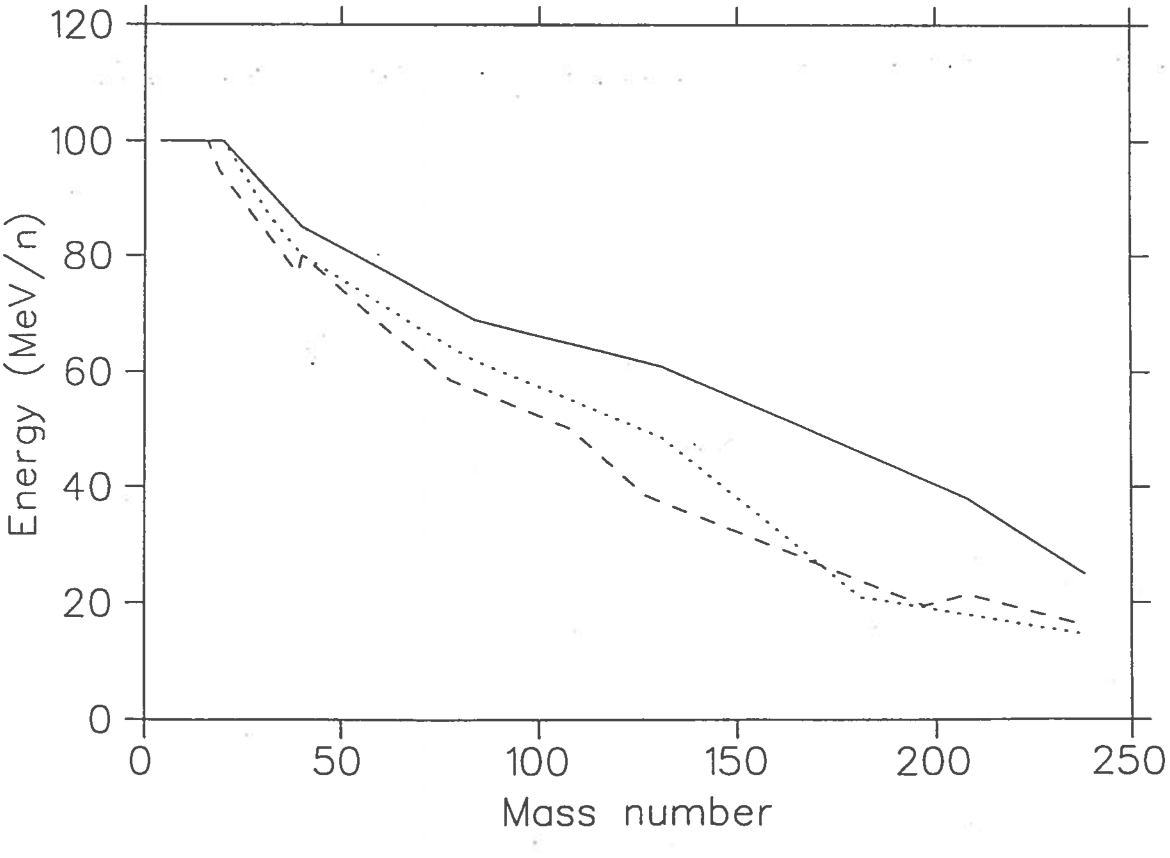
120
100
80
60
40
20
0
Energy (MeV/n)
0
50
100
150
200
250
Mass number

Fig. 6

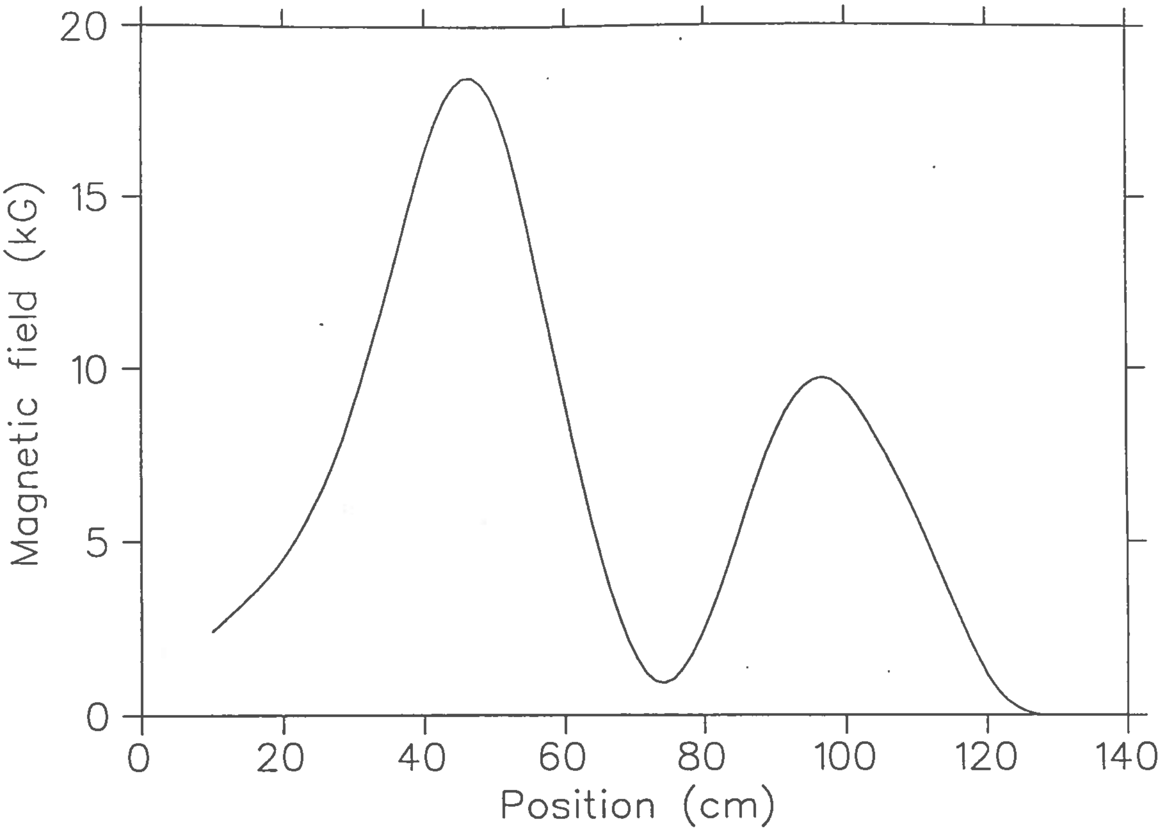
Magnetic field (kG)
0
5
10
15
20
0
20
40
60
80
100
120
140
Position (cm)

Fig. 7

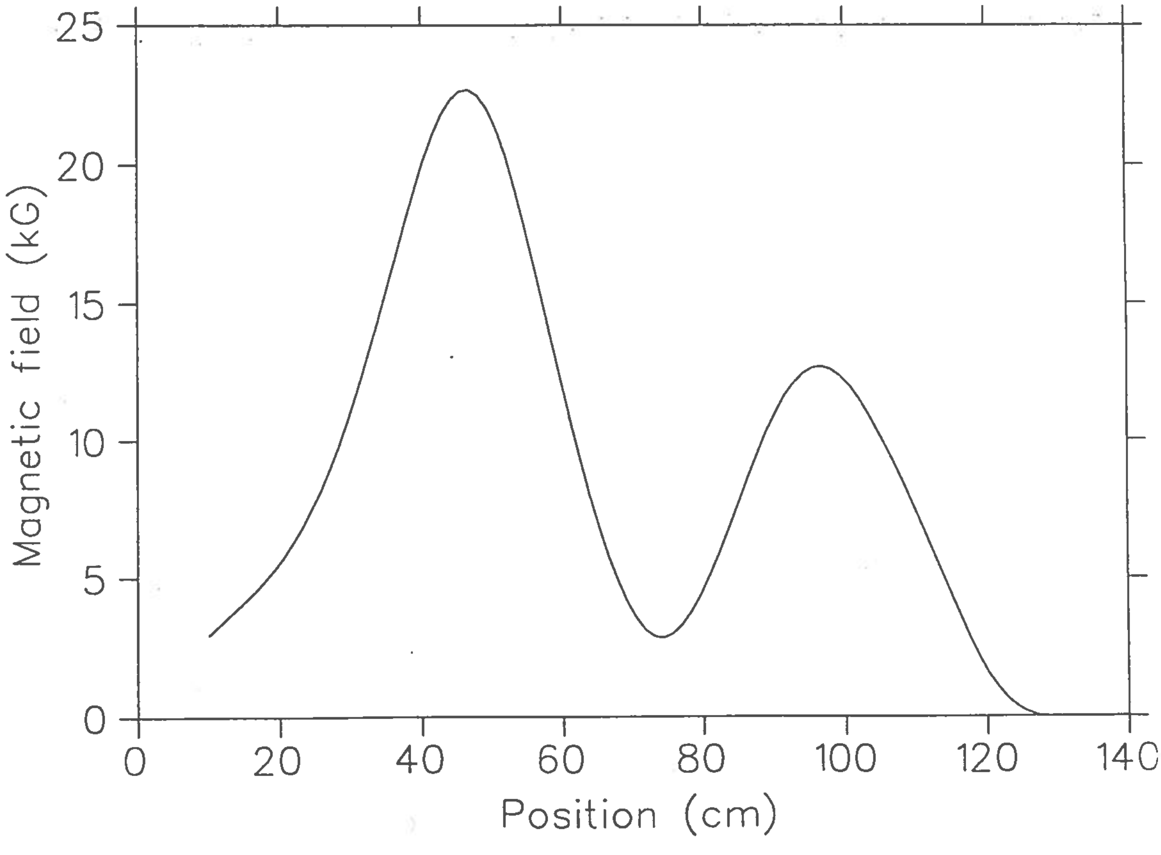
Magnetic field (kG)
0
5
10
15
20
25
0
20
40
60
80
100
120
140
Position (cm)

Fig. 8

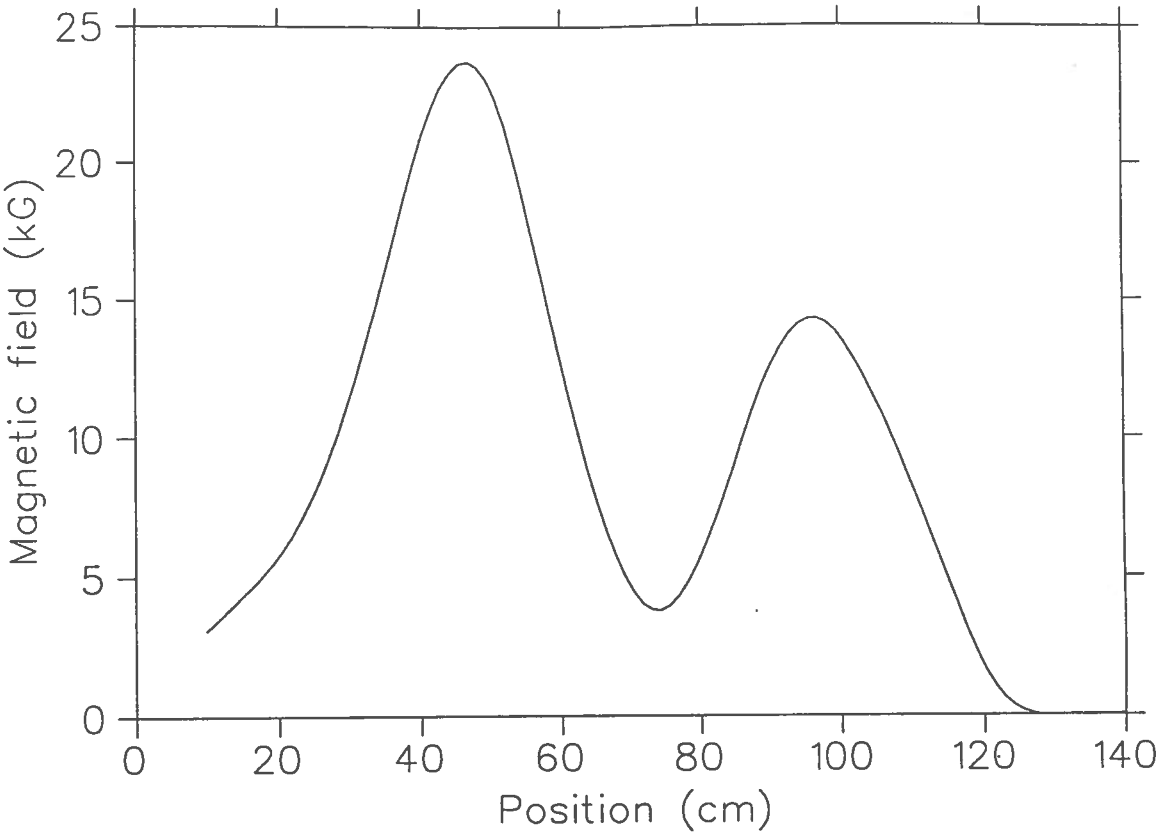
Magnetic field (kG)
0
5
10
15
20
25
Position (cm)
0
20
40
60
80
100
120
140

Fig. 9

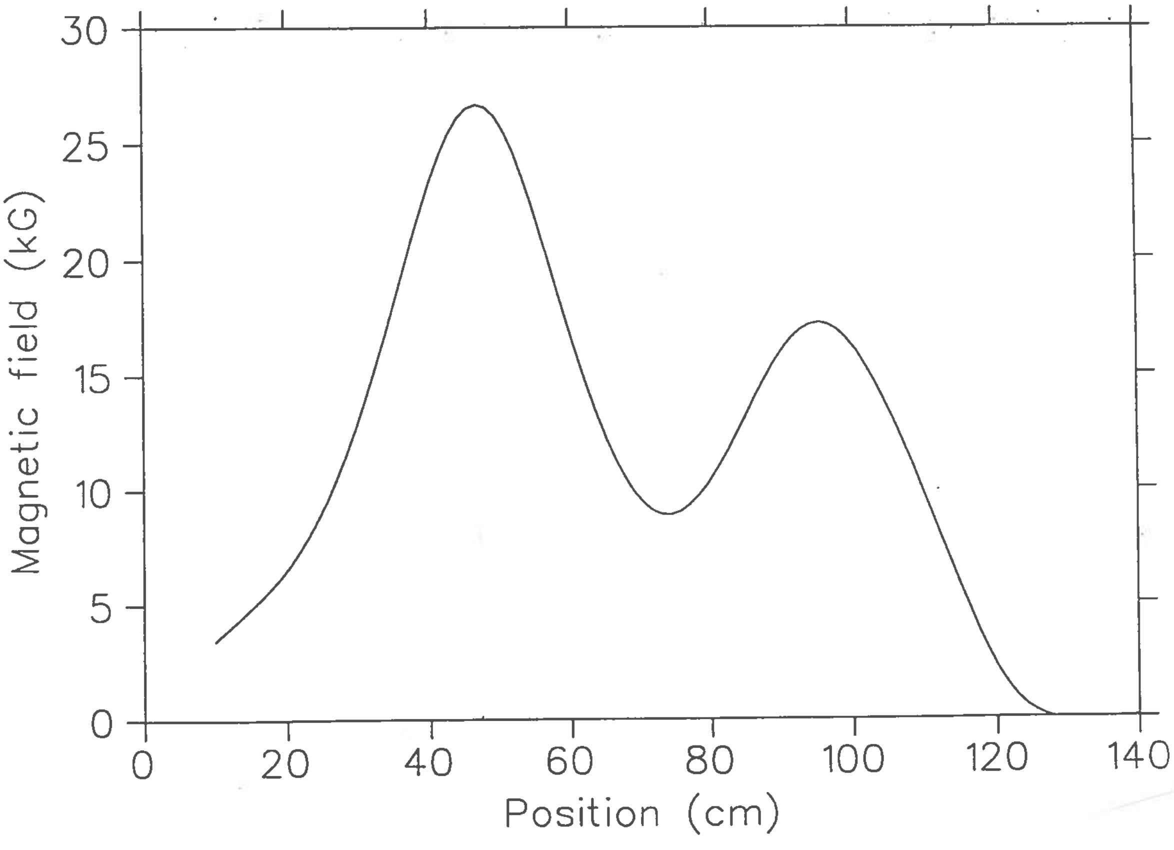
Magnetic field (kG)
0
5
10
15
20
25
30
Position (cm)
0
20
40
60
80
100
120
140

Fig. 10