

Radiation shielding of spacecraft's in manned interplanetary flights

Piero Spillantini ^a

^aUniversity and INFN - Firenze, Italy

The high energy protons of the Solar Cosmic Rays (SCR) are by far the most dangerous for the health of the astronauts in manned flights outside the protection of the Earth magnetic field. However, since the astronauts are in any case protected by the walls of the spaceship, only protons with kinetic energy exceeding 20 MeV must be taken into consideration. They have a small dispersion around the direction of the solar wind, what makes easier the protection against their action because absorber's of adequate thickness can be located in the side of their arrival direction. The mass of the required absorber rapidly increases with the energy of the proton, and is already 1,400 kg/m² for stopping protons of 500 MeV. It is therefore necessary to have recourse to the use of magnetic superconducting lenses for defocussing the beam of the arriving protons and protect the astronauts behind them. It is presented and discussed a scheme of toroidal lens protecting a volume of 10 m² cross section at all energies of interest and weighing a few hundred kg. It is presented the program for developing a prototype of such a lens to be validated on board of the International Space Station and for sending an interplanetary probe for mapping the characteristics of the high energy SCR from Earth to Mars and correlating them with the solar activity phenomena.

1. Introduction

The strong terrestrial magnetic field prevents most of the cosmic ray radiation approach the Earth. This fact protects the health of the humans on the terrestrial surface, as well also of those flying on board of orbiting space stations.

Instead, far away from the Earth, the crew members of a spaceship travelling in the interplanetary space will be exposed for quite a long time to the whole flux of the cosmic ray radiation. The risk for their health is so high that it is considered the most serious impediment to the human exploration of the solar system.

The first point to be made clear is that this fright of the deadly danger of the cosmic ray radiation is mainly due to the wrong prejudice that it is isotropic, i.e. it arrives with the same intensity from all the directions.

This is not true [1]. The isotropic part is constituted only by its very low energy portion (up to a few MeV), that cannot penetrate the body of a spaceship, not even the space-suit of an astronaut, and by its portion of galactic origin, that has very high energy per particle and crosses also thick layers of materials, but whose flux amounts to no more than a few percent of the total.

In the most dangerous energy range for the astronauts travelling inside a spaceship, between about 30 MeV and a few hundred MeV, the cosmic ray radiation is mainly constituted by protons of solar origin, accelerated in powerful solar flares, and travelling driven by the magnetic field lines drawn by the intense outflow of the low energy particles from the Sun, the solar wind.

Since the solar wind flows with a speed that can vary in a relatively narrow interval (between 200 and 600 km/s), the direction of the magnetic field lines frozen in the flow is relatively stable, with a maximum variation of a few ten degrees on the ecliptic plane and a negligible component perpendicular to it. Its direction changes very slowly with the time, in the time-scale of hours or days, and can be forecast, and also real-time measured by magnetometer's.

2. The energetic solar cosmic rays

The energetic solar cosmic rays (SEPs: Solar Energetic Particles) travel winding themselves around the lines of the magnetic field, with a maximum pitch angle of a few degrees, that rapidly shrinks with the energy (fig.1).

The SEP flux is anything but constant: in cor-

respondence of the most violent solar flares it can increase in a fraction of hour by huge factors, up to 10^6 over the flux of the GCR in the same energy interval, and last a few days (fig.2). Often the time interval between powerful solar flares is one or a few days, so that a new burst overlaps the previous one, resulting in a high flux lasting up to a few weeks (fig.3). In fig.4 the flux of the energetic solar protons between 20 and 80 MeV, registered by the IMP4 and IMP5 satellites, has been integrated per year, and compared with the flux of GCR in the same energy interval. In the same figure it is also indicated what it would be the ratio to the whole spectrum of the GCR radiation in the interplanetary space.

The directionality of the SEPs allows to conceive the possibility of stopping them by range in an absorber: only the GCR radiation remains unshielded (fig.5), but it amounts to no more than a few percent of the total. The intensity of this unshielded radiation varies by a factor of 2 during the 11 year solar cycle, anticorrelated with the intensity of the solar activity. A direct consequence of this fact is that, in the case that the astronauts could be fully protected from the SEPs, manned interplanetary flights should be afforded during the periods of maximum solar activity, and NOT DURING ITS MINIMUM!

Many of the solar flares give SCR radiation fluxes exceeding those of the GCR radiation up to energy of 500 MeV, and some of them also at energies more than 1 GeV. For the full protection of a few m^2 area by an absorber, its mass should be several tons (table I). This is an unpractical solution in space flights, and we must have resort to less massive systems.

3. Use of a magnetic lens for deviating the energetic solar cosmic rays

A promising solution seems to be the use of a magnetic lens for defocusing the quasi-beam of the SEPs (fig.6), taking advantage of the fact that they are all positive (the electrons have a much smaller energy and are stopped in the materials of the lens itself).

Obviously the lens must supply a very intense magnetic field, what implies that it must be re-

alised by superconducting coils. Under reasonable assumptions, a NbTi coil system cooled by liquid helium favourably compares with a passive absorber at all the energy of interest (see table II and fig. 7 for a magnetic lens of 2 m radius). In fig. 8 are reported the trajectories of 500 MeV protons as deviated by a toroidal lens of transversal circular section. The main parameters for such a lens, allowing the full protection up to 500 MeV in a volume of several hundred m^3 , are reported in the table annexed to the figure.

It is important to underline that the toroidal shape of the coil could be realised in such a way that it could fully contain the produced magnetic field, avoiding the difficulties due to the external residual field.

It is also worthwhile to note that the electron burst arrives at least 10 minutes ahead of the proton burst, allowing to alarm the spaceship and give therefore the possibility of 'last minute' manoeuvring, such as aligning of the lens axis with the direction of the arriving particles, increasing the current circulating in the coils, moving devices and materials for adding passive absorber on the particle trajectories, switching electric power to the lens systems for extra cooling of for supplying extra-current, etc..

4. A program for developing the technologies for realising a s.c. magnetic lens

There are two important problems to be investigated and solved before designing a shielding based on the use of a superconducting magnetic lens.

4.1. A probe to Mars

The first problem concerns a better knowledge of the angular dispersion of the energetic SCR's, and of its variations.

Also if there are plenty of data of fluxes, and some data of their angular asymmetries in the interplanetary space, collected by dedicated devices on board of many probes sent to space exploration, most of the devices could only measure anisotropy in coarse angular sections. At our knowledge, no efforts were made for obtaining from the data the distributions of the arrival

Table 1
Protons in an Aluminium absorber

Kinetic energy MeV	Range in aluminium		Mass
	gr/cm ²	cm	Kg/m ²
20	0.58	0.2	6
50	2.93	1.1	29
100	10.0	3.7	100
200	33.3	12.3	333
500	149.	55.	1490
1000	412.	153.	4120

Table 2
Comparison between the magnetic lens and an equivalent Al absorber

		magnetic lens						Absorber		
E _k MeV	p MeV/c	B _{max} T	Itot MA	I A mm ⁻²	mag. kg	sys. kg	tot kg	ρ×L gm/cm ²	L cm	tot kg
40	277	0.70	0.87	1020	18	50	68	2	0.74	250
100	441	1.13	1.41	980	30	50	80	10	3.7	1250
150	551	1.40	1.74	950	38	50	88	16	5.9	2000
300	808	2.07	2.57	840	63	63	126	52	19.3	6500
500	1090	2.80	3.48	700	103	103	206	141	52.2	17625
1000	1696	4.36	5.41	560	200	200	400	376	139.3	47000

angles of the energetic SCR's as a function of the time and of their energy, and correlated with the solar activity. It is therefore necessary a systematic work for extracting this kind of information from all the data registered by the already launched probe's, in particular those collected at distances from the Sun between 1 and 1.5 AU. This will give an important input for the optimisation of the parameters for a device dedicated to the mapping of the CR characteristics in the interplanetary space between the Earth and Mars, and on the long observation time of the flight of a probe to Mars [2].

The next occasion to be caught could be the MARS 2005 mission, that presently is in the design definition phase. The variations of the solar wind direction and the dispersion around it of the energetic SCR's should be measured as a function of the time and in correspondence of different solar phenomena, and for all the compo-

nents: the protons, that are the most abundant, the electrons, that arrives several minutes in advance and can alarm the spaceship crew, and the ions, whose content in SCR's is small but must be known since they are individually more dangerous than the protons.

4.2. A prototype s.c. magnetic coil on board of the ISS

The second problem to be overcome is a technical one. It concerns the cooling of the superconducting coils. It is the most serious to be solved for operating superconducting devices in space. The cooling cannot be based on the concept of the liquid helium 'bath' used in other space enterprises, because of the length of the mission without any refilling possibility.

It must be developed a cooling system based on cryorefrigerators that could have a mass and an electric consumption much better than presently achievable.

A long technical R&D will be necessary in this direction, whose first step will be that of implementing a prototype coil system for equipping a physics experiment.

The most suitable experimental item is a high statistics isotope composition experiment up to energies of several GeV/nucleon [3]. In fact this research requires a very high magnetic field (more than 1 tesla) on a not enormous volume (several ten litres). The field could be produced by a 'quasi-lens' configuration consisting of only 2 coils of limited dimensions (less than 0.2 m² in area) and mass (<40 kg in mass). In this magnetic a precise microstrip silicon tracker will measure the momentum of the incoming particle. The particle velocity will be measured in one (perhaps two) Ring Imaging Cherenkov counter. The sketch of a possible experimental apparatus is reported in fig. 9. The range of the energy it can cover for each nuclear charge in the isotopic composition measurement is reported in fig. 10.

The 'quasi-lens' coil system should be 'cooler free', equipped by appropriate cryorefrigerators for avoiding the use of liquid helium to cool the coils. A solution that should be studied and prototyped is that of a superconducting coil system based on High Temperature Superconducting (HTS) cable cooled at a moderately low temperature, in the range 20-30 K [4]. The current density in the cable would be less for a factor of 2 than in the NbTi cable at 4 K, but the much lower heat dissipation should bring the electric consumption and the mass of the needed cryorefrigerators inside affordable limits.

REFERENCES

1. Spillantini P. et al., "Radiation shielding of spacecrafts in manned interplanetary flights", preprint INFN/AE-99/002, January 1999, to be published in Nucl. Instr. & Methods.
2. Spillantini P., "Cosmic Ray Surveyor in the Earth-Mars travel and on Mars (CREAM Surveyor)", ASI International Workshop "The Italian role and perspectives for the Exploration of Mars", Rome, 1999.
3. Spillantini P., "Misura della composizione isotopica dei raggi cosmici fino a 10

GeV/nucleone e $Z > 20$ e validazione del prototipo di 'Cryogen Free Superconducting Magnet' sulla ISS", Workshop nazionale ASI "Utilizzo scientifico della Stazione Spaziale Internazionale", L'Aquila, 1999; Spillantini P. et al., "Misura degli isotopi rari e degli isotopi radioattivi a bordo della ISS", proposal of experiment in answer to the AO of the ASI, 1999.

4. Alenia-Aerospazio, Space Division, "CFSM (Cryogen Free Superconducting Magnet)", proposal of feasibility study in answer to the AO of the ASI for technological experiments on board of the ISS, 1998.

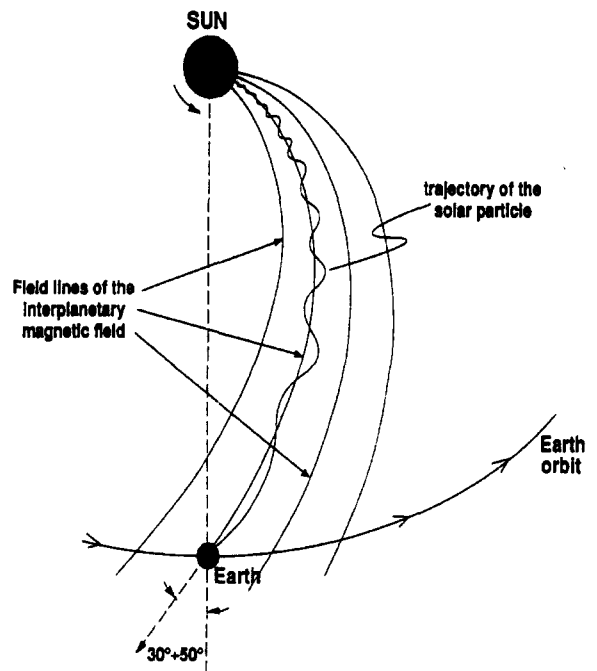


Figure 1. The energetic solar cosmic rays travel, winding themselves around the lines of the magnetic field with a pitch angle that rapidly shrinks with the energy.

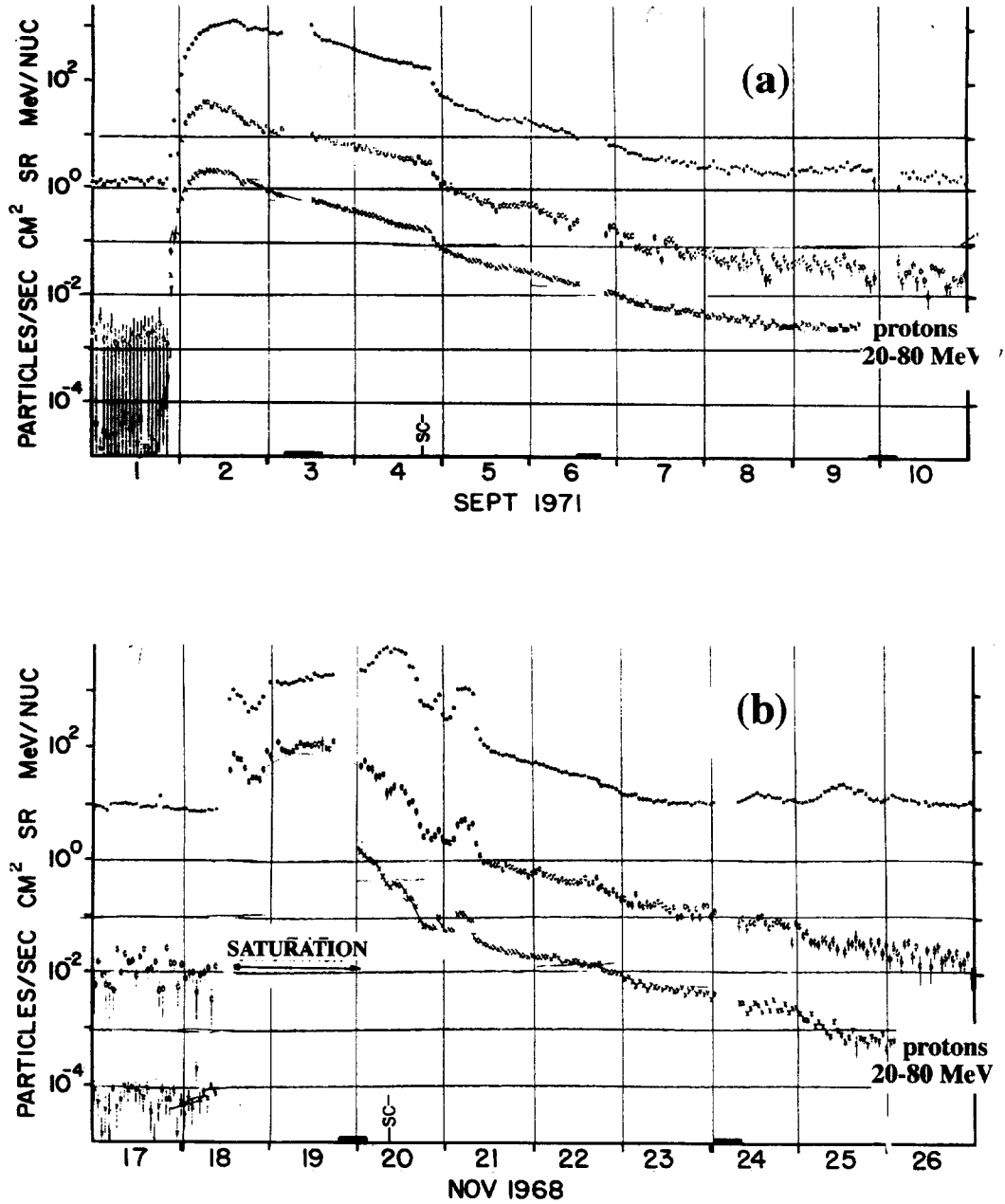


Figure 2 :Rate of high energy protons at about 1 AU (from the IMP4 satellite) in correspondence of two typical solar flares. In (b) the detector saturates during 1.5 days at a level by $>10^4$ higher than the galactic cosmic rays in the same energy range.

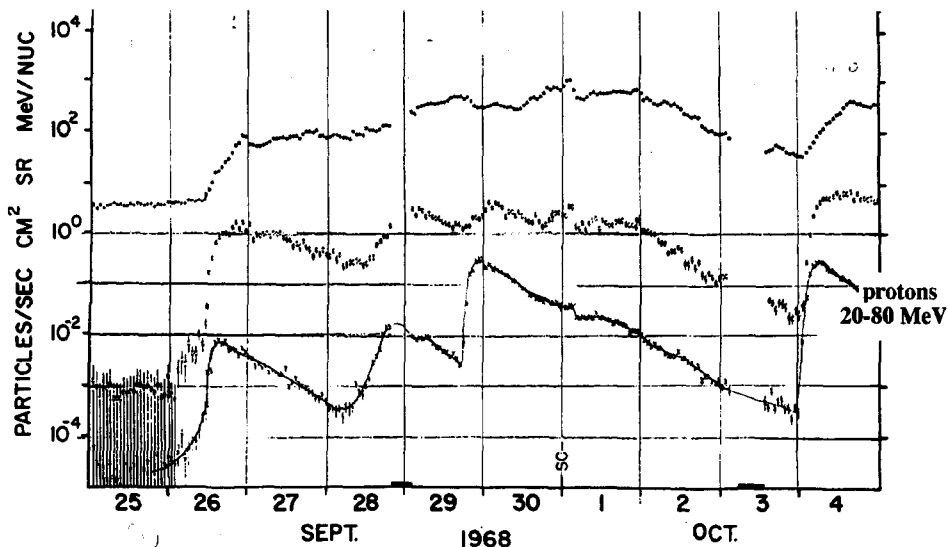


Figure 3 :Rate of high energy protons at about 1 AU (from the IMP4 satellite) in correspondence of five overlapping solar flares (August 26, 28, 29 (two flares) and September 4, 1968).

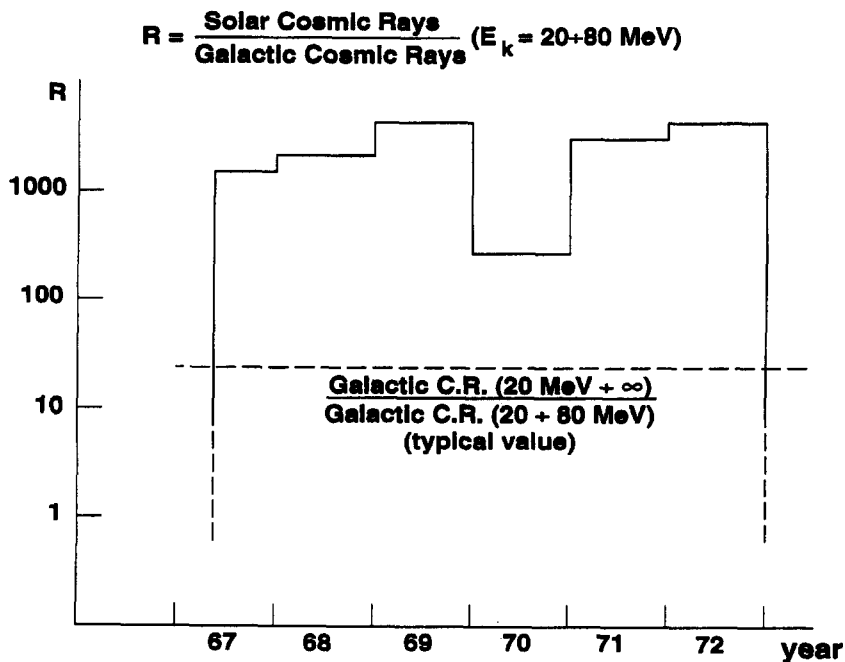


Figure 4 :Ratio between the flux of the energetic solar protons (20-80 MeV) integrated per year and the flux of the galactic cosmic rays in the same energy interval. The ratio with the whole spectrum of the galactic cosmic rays (GCR) is only indicative, given the poor knowledge of the interstellar GCR spectrum and its dependence from the solar activity.

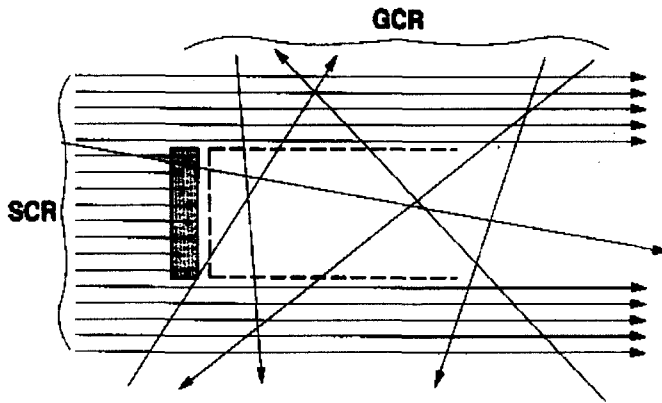


Figure 5 :The directionality of solar energetic particles allows to stop them in an absorber: only the GCR radiation (a few % of the total) remains unshielded

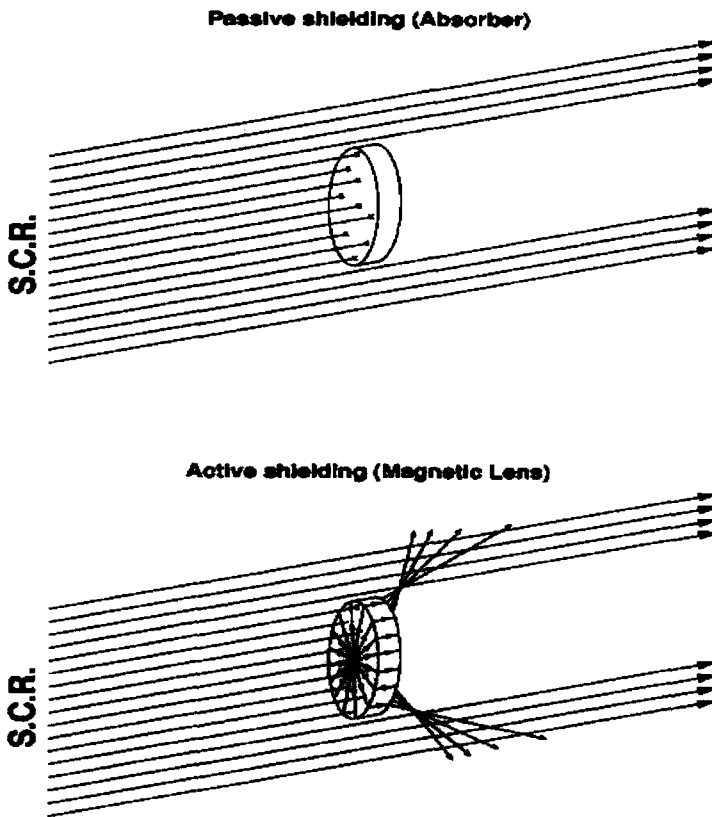


Figure 6 :A defocusing magnetic lens can play the same role of an absorber in protecting a volume from the solar energetic particles.

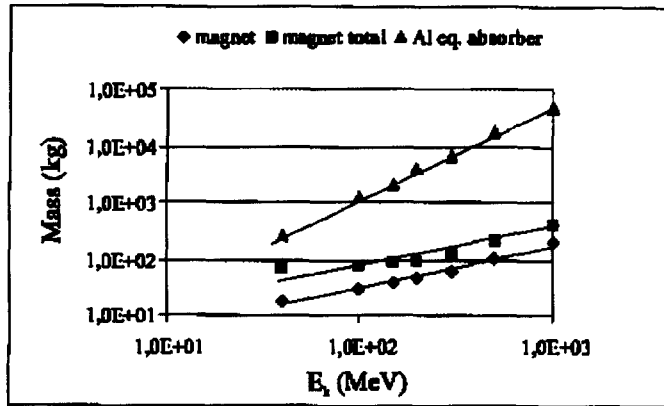
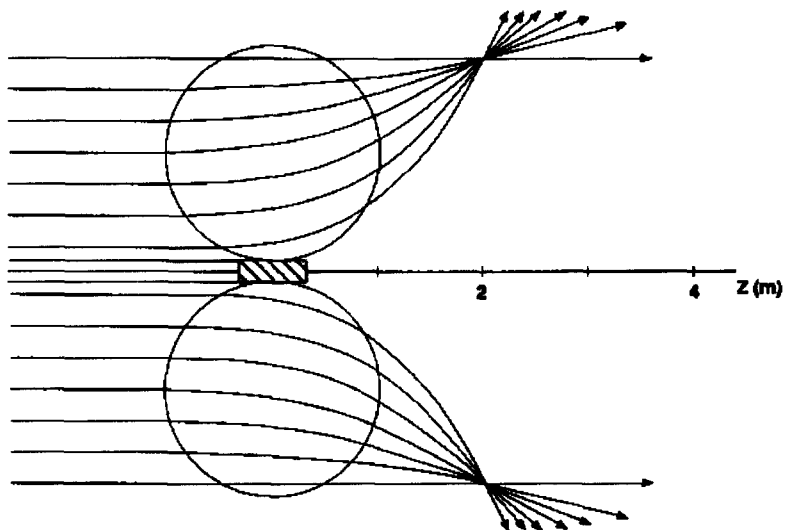


Figure 7 :A magnetic lens of 2m radius based on a NbTi coil system cooled by liquid helium favourably compares with a passive absorber at all the energy of interest.

**Circular shaped coils with NbTi s.c. at 4 °K and
 $\delta = 700 \text{ A/mm}^2, I = 2.5 \text{ MA}$**



full protection: up to $E_k = 500 \text{ MeV}$ (protons)

protected volume: ($\varnothing = 4 \text{ m}$) x ($L > 10 \text{ m}$)

$B (R = .25 \text{ m}) = 2.8 \text{ T}, B (R = 2.0 \text{ m}) = .36 \text{ T}, B(\text{outside}) = 0$

**'cold' mass ~ 100 kg
 mech + services + ... ~ 100 kg } total ~ 200 kg**

mass of the "equivalent absorbing power" Al absorber $\approx 17.6 \text{ t}$

pre-alarm time (electrons) $> 10 \text{ min}$

Figure 8 :Trajectories of 500 MeV protons as deviated by a toroidal lens of circular transversal section.

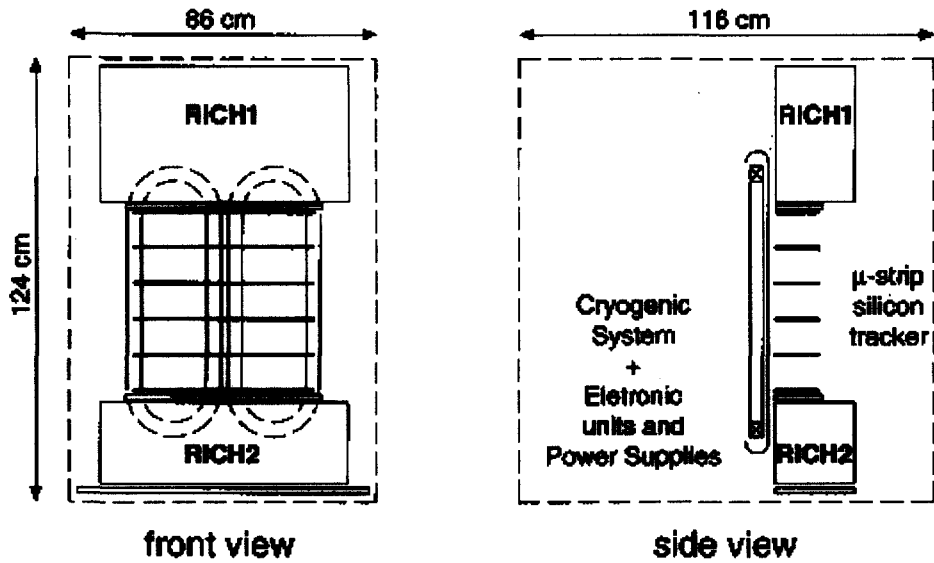


Figure 9 :Sketch of an experimental apparatus for measuring the isotopic composition at high energies and the validation of the test coils.

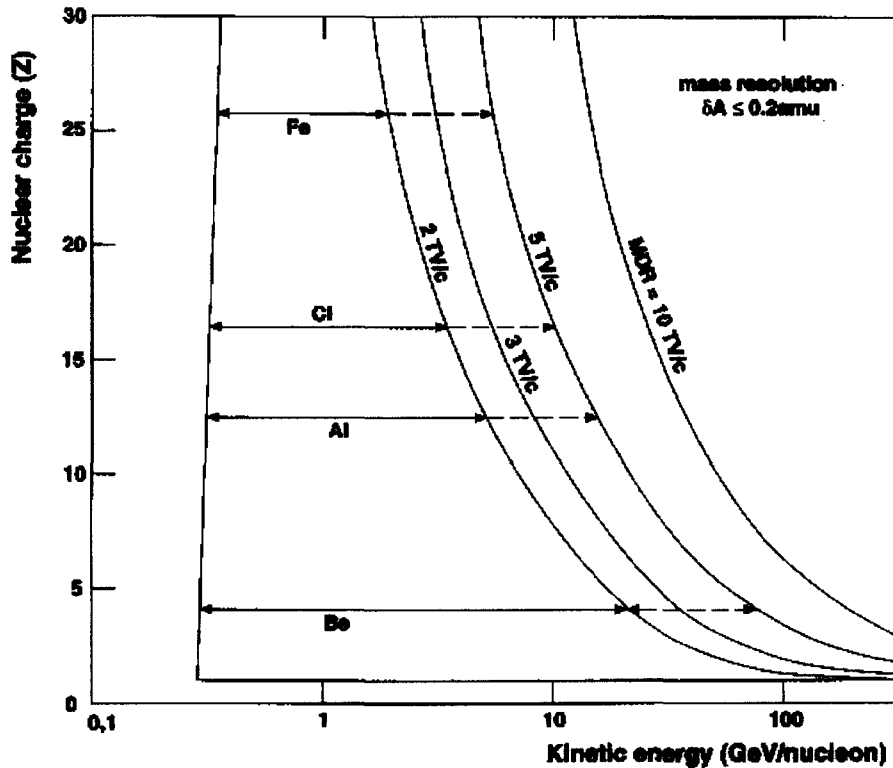


Figure 10 :Energy range covered for each element in the isotopic composition measurement for some values of the maximum detectable rigidity of the magnetic spectrometer.