LNS CATANIA PROJECT FOR THERAPY AND RADIOISOTOPE PRODUCTION

L.Calabretta, G. Cuttone, M. Re, D. Rifuggiato, LNS-INFN, Catania, Italy
M.Maggiore, University of Catania, LNS-INFN, Italy

Abstract

A superconducting cyclotron ables to delivering protons and light ions has been designed. It is a four sector compact superconducting cyclotron able to accelerate light ions with charge/mass ratio 0.5. Particles like H_2^+ can be accelerated and extracted by stripping, while other light ions like $^{12}C^{6+}$ will be extracted by electrostatic deflectors. The magnetic circuit, the isochronous field, the extraction trajectories and the beam properties have been studied and are here presented. A description of the new and compact RF cavity design, of the vacuum plant, of the source and injection system will also be given. The maximum energy of the cyclotron is 250 A·MeV. So it could be used for radiotherapy with proton or carbon ions and to produce unconventional medical radioisotopes, too.

The main advantages and the wide application field of this new cyclotron for a radiotherapy centre will be also presented in this paper.

INTRODUCTION

The accelerator study here presented was triggered by the need of LNS-Catania, a medium size laboratory, to build a facility for radioactive ions and for radiotherapy at the same time [1]. Although this proposal was not chosen as development of the laboratory, it was supported as project study for a new radiotherapy centre in Catania.

We want to emphasize that this cyclotron is able to accelerate both protons and Carbon ions to be used for radiotherapy. Although low beam intensities are generally required for therapy, we considered stripper extraction to deliver beam power up to 10 kW allowing the production of new medical radioisotopes. We believe that this kind of cyclotron could be used as a double task machine with real possibilities of operation also in a Hospital. The realization of a therapy centre is a serious investment both economic and of infrastructure and personnel to be trained. For these reasons is very advantageus to use the accelerator for 10-12 hour per day for patients treatment, and use the accelerator during the night to drive a target installation for production of new medical radioisotopes. A real interest towards new radioisotopes has developed and it is documented by the production of radioisotopes performed by TRIUMF and other research laboratories around the world.

Here under the physical characteristics of the cyclotron and its special features are presented. A short presentation of the new Catania centre for therapy and the opportunities offered by this machine will be presented in the last paragraph.

CYCLOTRON MAIN PARAMETERS

The cyclotron here presented is able to accelerate particles having a charge to mass ratio Q/A=0.5, up to 250 A·MeV. So H_2^+ molecules and light ions can be accelerated using the same frequency while the magnetic field need to be changed of $\approx 4\cdot 10^{-3}$. The main characteristics of the cyclotron are summarised in Table 1. This cyclotron does not need any trim coils. The trimming of the magnetic field will be accomplished during the commissioning using trim rods. The moderate value of the mean magnetic field, 3.8 T, due to the large radius, together with the 50 mm hill gap produces a value of flutter quite high to achieve a focusing power K_{FOC} >500 maintaining the maximum spiral of the sectors at a value of 140°, smaller than that of the MSU K1200 cyclotron. Despite its large radius, the cyclotron pole can be opened by lift like the existing superconducting cyclotrons. These solution guarantees a quite fast opening procedure.

The cryostat design is not yet completed but enough room has been allocated to guarantee safe operation and minimum consumption of liquid helium. The distance between the pair of coils is 170 mm which is 50 mm more than in our K800 cyclotron. Penetration channels with useful gap of 70 mm are then feasible. Using the present insulation technology, fiber glass tie rods and high temperature superconducting current leads, the evaluated thermal losses are below 8 W. This moderate value of refrigeration power could be delivered by 4 commercial re-liquefiers. Also a 50 Kelvin shield will be cooled by 2 commercial cryogenerators. The available commercial re-liquefiers and cryogenerators need a maintenance with a frequency of more than one year and allow to avoid the construction and the operation of a Helium liquefier plant. The axial and hoop stresses on the

Table 1: Cyclotron parameters

Sectors n°	4	Hill gap	50 mm
$K_{bending}$	1000	Valley gap	1050 mm
$K_{focusing}$	500	Hill width	34°÷44°
Pole radius	1320 mm	Spiral max	140°
Yoke diameter	4.9 m	Cavities n°	4
B at centre	3.1 T	Frequency	92.3 MHz
Max. <B>	3.86 T	harmonic	4th
Max. Field	4.1 T	Power max.	<45 kW
Coil size: width height	150 x 210 mm^2	Current density	<41 A/mm^2
Total weight	<320 t	LHe Losses	<8 W

superconducting coils have the acceptable values of 9.3 MN and 90 MPa respectively.

Isochronous Field

The optimisation of the magnetic field has been made using the 3D electromagnetic code OPERA. A parametric model of the cyclotron has been built, and an iterative process has been realised in order to optimise several parameters of the machine like sectors width, spiral angle, hill and valley gaps to fulfil the beam requirements, i.e. the isochronous field and radial and vertical focusing frequencies. The beam dynamics properties have been evaluated by the code GENSPE1, which calculates the equilibrium orbits using the magnetic field maps produced by OPERA. Our choice to operate the cyclotron in 4th harmonic needs a very precise isochronous field. This procedure allows to achieve a quite good isochronous field, see curve "without Trim Rod" in Fig. 1, but this is not yet a satisfactory result. The final setting of the magnetic field was achieved by adding the contribution of a set of Trim Rods (T.R.). Twelve trim rods per each hill, placed along the center of the hill and with radial distance of 10 cm among them, were simulated to obtain the individual magnetic field maps. The curve "with T.R." in Fig.1 shows the final phase vs. radius produced by GENSPE1 using the optimized final magnetic field map. The two curves were evaluated assuming an average acceleration voltage of 100 kV to take account of the angular width of the Dees. Fig. 2 shows the working path of the accelerated beam in the plane ν_z vs. ν_r. In figures 1 and 2 the position of the selected orbit to be extracted is shown. It is assumed to extract the beam before the last orbit and after the crossing of the ν_z=1 resonance.

Although the final result is satisfactory a residual oscillation with amplitude of 10° is present in the curve φ vs. R. Perhaps a different distribution and position of the Trim Rods will be investigated to produce a better solution.

Fringing Field

The cyclotron return yoke design was performed looking at two parameters:

- the fringing field in the area around the cyclotron and mainly in the control room;
- the shape of the fringing field around the cyclotron.

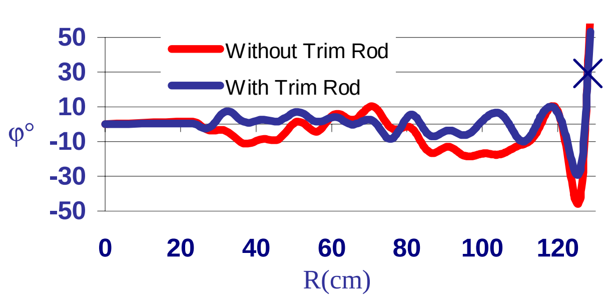

Figure 1: Phase of accelerated ions vs. radius, before and after Trim Rod optimization

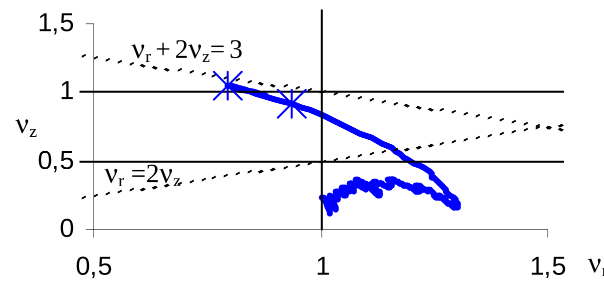

Figure 2: Working path in the (ν_r,ν_z) plane

According to our experience with the k-800 cyclotron, we decided to operate with magnetic stray field below 2 Gauss at a distance of 10 m from the cyclotron center. This value is low enough to allow the permanence of the cyclotron crew in the console area for the standard 8 h/day. The control room is located at a mean distance of about 10 m from the cyclotron. This choice minimizes also the stray field in the areas of RF Amplifier and of other ancillary equipment.

The shape of the fringing field near the cyclotron was designed as smooth as possible and similar to the fringing field shape of the k-800. Moreover was imposed to maintain the magnetic field at 1m from the pole cap below 500 Gauss. This solution allows to install the cryopumps motors at a distance of about 2.5 m from the cold head. Also the turbo molecular pumps could stay at a distance of less than 3 m from the median plane. To achieve the final design of the return yoke the computer code Opera, 2-dimension option , was used. In this case the cyclotron iron shape was simulated assuming a circular symmetry. This was done in the usual way to simulate each section with insertion of different values of iron magnetization corresponding to the different stacking factor values.

RF System

The description of the RF cavity is presented in an other paper at this conference [2]. Here, just for sake of completeness, we recall the main features.

The four spiral accelerating electrodes will be part of four Radio-Frequencies cavities driven at about 92 MHz, fourth harmonic of the particle revolution frequency. The choice to operate in 4th harmonic allows to drive the 4 cavities at the same phase and maximize the energy gain per turn for a given voltage. It means acceleration average voltage of 120 kV at extraction and maximum 70 kV at the central region in order to minimize the probability of accidental sparks. Due to the large capacitance of the accelerating electrodes and to satisfy these requirements a configuration of cavity with three stems is proposed. This solution allows to achieve the required average accelerating voltage of 120 KV at the extraction radius with a RF power lower than 45 kW.

A power amplifier prototype ables to delivering up to 50 kW in the frequency range of 60-110 MHZ was built at LNS to feed our Chopper-500, it has been successfully tested some weeks ago [3]. So the cavities could be driven by four independent RF amplifiers similar to our not expensive prototype. According to our experience the use of four Amplifier instead of one allows to operate with medium size RF transmission lines and feasible and reliable couplers.

Losses and vacuum requirements

Due to the high binding energy of the H_2^+ molecule, ≈16.3 eV vs. 0.7 eV of H^-, it is possible to use magnetic fields as high as 10 T even at energies as high as 1 A GeV without any beam losses due to electromagnetic dissociation. Beam losses, along the acceleration path, are due to the interactions of the H_2^+ ionized molecule with the residual gases. These may produce stripping of the electron of H_2^+. In general for a molecule this probability is higher than for a simple ion. The fraction of lost beam particles was evaluated according to the Betz-Bohr model [4], that takes into account the beam cross section for electron lost versus the beam energy, and it is summarized by the following formula:

$$Losses = 1 - N/No = 1 - e^{-\frac{P}{KT}\int \sigma(E)d\ell} \quad (1)$$

where P is the pressure (Pa) , L is the path length (m), σ(E) is the cross section of electron loss. The formula to evaluate σ(E) is:

$$\sigma(E) \approx 4\pi a_0^2 (v_o/v)^2 (Z_t^2 + Z_t)/Z_i^2 \quad (2)$$

Where a0 and v0 are the radius of orbital and the speed of the electron, Zi and Zt are the number of electron of the incident H2+ and of the residual gases respectively, v is the velocity of the accelerate H_2^+.

Reading historical proceedings of ICCA, we found a nice picture in the paper of H. Steimel [5], which shows the measured current of a H_2^+ beam vs. radius. To check the formula (1) and the value of the parameter a_0 we evaluate the beam losses for the Karlsrhue cyclotron and compared with the experimental results. Although our simulation overestimates the losses at inner radii and underestimates at outer, the agreement was quite satisfactory. Perhaps the differences are due to our assumption of constant accelerating voltage at all radii (240 kV/turn) and of uniform pressure of $2{\cdot}10^{-6}$ Torr as reported by authors. On the contrary if the pressure is better in the central region than in the outer, these could give reasonable explanations of the small differences.

So we used the previous formula to evaluate the beam losses for the present cyclotron design. We assumed an accelerating mean voltage of 800 kV per turn and a pressure value of 10^{-7} mbar. Most of the beam current is lost at small radii along the initial orbits, where the beam has low speed, while large amount of the power is lost at outer radii where the beam is more energetic.

We evaluate both the intensity and power losses, by integrating formula (1) turn by turn, the expected beam lost all along the machine should be of 2.7%, which means a power loss of 100 W for an accelerating beam of 10 kW. These power losses are quite small and acceptable for the proposed cyclotron. Our tests of extraction from the K800 superconducting cyclotron show that also with beam power higher than 100 W dissipated at the extraction radius, very close to the cryostat, there are no detectable effects on the cryogenic parameters of the cryostat.

Although a vacuum of 10^{-7} Torr is nowadays feasible also in a cyclotron, anyway to achieve this goal a careful treatment of all the surfaces inside the vacuum chamber is required. Our evaluation shows that using four split cryogenic pumps, like that installed inside our k800, but with a larger cold head, the required vacuum value should be feasible. Moreover the 50 mm gap between the hill guarantee a vacuum conductance across the new cyclotron better than inside the k800 cyclotron, which has a 24 mm gap.

EXTRACTION

Deflectors Extraction

The extraction of a fully stripped light ion like C6+ needs the use of Electrostatic Deflectors (E.D.). According to our experience E.D. devices are reliable if electric field and voltage applied are lower than 120 kV/cm and 60 kV respectively. Our choice to operate the cyclotron with 4 RF cavities forced us to install E.D. inside two hills. The housing of the E.D. have been designed to stay inside the 50 mm gap of the hill. The length of the two E.D. are 36° and 32° respectively. We remember that the hill width is 44°, so these length are quite conservative and the ends of E.D.1 are at about 8 cm from the boundary of the iron hill. A gap of 5 mm between the electrode and the septum was selected. The simulation studies show that an electric field of 110 kV is

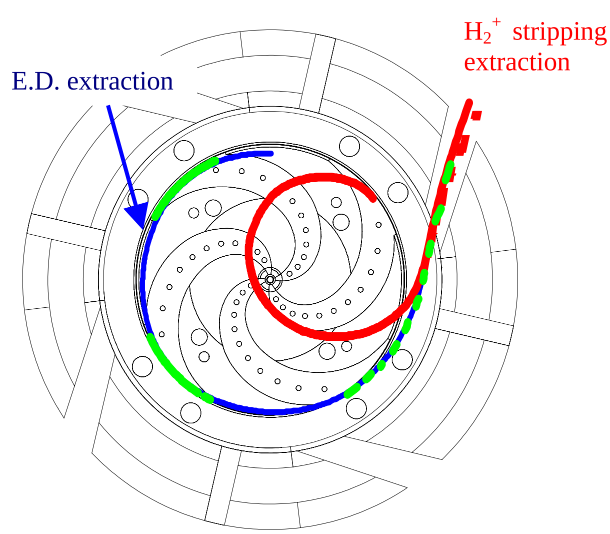

Figure 3: Layout of the cyclotron with overdrawn the extraction trajectories by E.D. and by stripper. The E.D. and the M.C. positions are also shown.

sufficient to extract the beam. To increase the margin of reliability our simulation studies were accomplished not with the last orbit but with a 2 mm inner orbit.

Following the second E.D., placed on the same hill and 4° long, the beam cross the first Magnetic Channel (M.C.), which increases the steering towards the outer radii. The distance between the last accelerated orbit and the extracted trajectory at the position of the first M.C. is 21 mm. A total of 10 M.C. have been used to maintain the beam envelope along all the extraction path at values lower than ±1.5 cm radially. Vertical beam size is ever smaller than ±1 cm. These beam envelopes were evaluated assuming a conservative emittance value of 2·π·mm·mrad at the extraction radius. The stripper angular straggling was left out due to the high energy of the beam and the small thickness of the stripper. The number and the positions of M.C. needs to be optimized.

Stripping Extraction

In Fig. 3 the extraction trajectories of the protons produced by stripping of H_2^+ on a carbon foil, and of C^{6+} ions, extracted by electrostatic deflectors, are shown. As it is quite evident the two trajectories can be delivered to the same direction. This result was achieved quite easily adjusting just the angular position of the stripper. Only the last part of the proton trajectory needs to be steered towards the inner side of cyclotron to compensate the effect of the return yoke field which for proton is stronger than for Carbon beam. The dashed curve, in Fig. 3, is the trajectory without M.C. correction. Just three M. C. were required to focus and to steer in the required direction the proton beam. The radial position of the first M.C. on the proton trajectory is at R=158 cm, quite far from the last accelerated orbit. This first channel is at radius larger than the outer radius of the main coil but inside the cryostat. The gap between the superconducting coils being 150 mm, it allows to design and install the M.C. quite easily.

During last July a test for a “quasi extraction” by stripping was performed in our k800 cyclotron. A Ne^{9+} beam was accelerated up to 45 AMeV and stripped by a 0.1 mm (22 mg/cm^2) carbon foil. After one turn inside the cyclotron the beam strike an alumina screen and a Faraday cup. The sizes measured on the screen show a reduction of the vertical size from 11 mm to 9 mm, while the radial size increase from 9 mm to 15 mm. The radial size increase is partially due to the energy spread introduced by the stripper. Anyway the results agree quite well with the simulation. Also the full current measured before and after the stripping scale according to the ratio of the charge states. No beam losses have been detected.

AXIAL INJECTION LINE

The proposed cyclotron will be equipped with an external ECR source able to deliver both H_2^+ and Carbon ions fully stripped. An injection line with one solenoid lens will transfer the beam from the source to the center of the cyclotron and performs the matching between the source emittance and the cyclotron acceptance. A layout

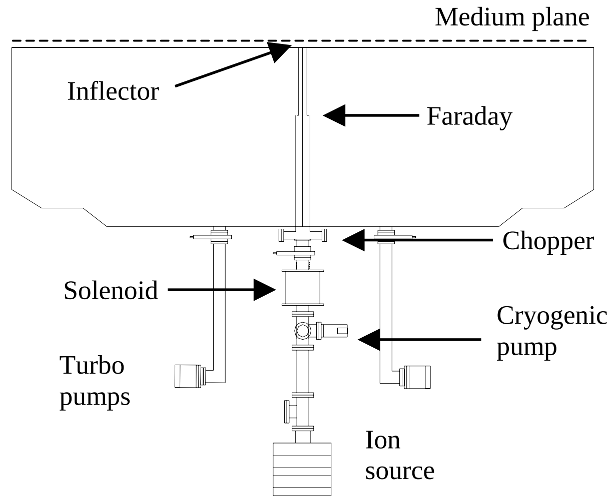

Figure 4: Layout of the axial injection line and part of vacuum plant

of the injection line is shown in Fig. 4. To reduce the cost and simplify the injection line we would like to install the source directly along the axis of cyclotron as shown in Fig. 4, without analyzing magnet.

In this configuration just one solenoid lens is necessary to focus the beam at the entrance of the cyclotron inflector. The ions to be delivered by the source will be only H_2^+ and C^{6+}. A pair of so called baffles will be installed inside the solenoids to remove the contaminants with q/A ≠0.5. Probably the H_2^+ beam will be quite free of contaminants, while the C^{6+} beam could be delivered together with other contaminant like H_2^+, N^{7+}, O^{8+} etc…. which have q/A≈0.5. Fortunately the cyclotron is able to select the required beam. Just one faraday cup will be installed before the entrance of the axial hole of the cyclotron and another inside.

To evaluate the beam dynamic along the axial line the cyclotron’s magnetic field along the vertical axis of the machine was evaluated by the code OPERA 2D. The beam envelope was simulated by the transport code which simulate the cyclotron’s magnetic field by a stack of thin solenoids with lengths equal to the OPERA mesh steps on the axis and the evaluate magnetic field. The position and the characteristics of the solenoid have been optimized to minimize the beam spot at the entrance of the inflector. The Solenoid is placed at 1.1 m after the ion source and at 40 cm from the bottom of the cyclotron. Using the magnetic field along the axis of the cyclotron achieved by the 2D simulation code TOSCA it is possible to focus the beam at the entrance of the inflector with a solenoid magnetic field of 1.64 kGauss. Assuming this geometry and an emittance of 100 π mm.mrad (x=5mm, ϑ=20mrad) a beam spot ϕ=3mm at the inflector entrance is expected.

Low Energy Chopper

A low energy chopper, consisting of a pair of deflecting electrodes driven by a compact pulse generator module producing fast and high voltage pulse up to 1500 V, could be used as variable attenuator of the injected beam [6]. The pulse generator is driven by a remote controlled TTL frequency generator. Through this generator it is very easy to change the length of macro bunch and their repetition rate. This system has been already tested on different continuous particle beams. The accelerated beam follow very well the duty cycle settled by the pulse generator. A lot of tests with attenuation factors from 1 to 99.9 % have been carried out.

CONCLUSIONS AND PERSPECTIVES

The cyclotron here presented is bigger than the usual cyclotron used for proton therapy and of course also its cost will be higher. Anyway the cost of the accelerator is only a 15-20% of the total cost of a medium size radiotherapy facility. So the higher cost of the accelerator could be acceptable looking at the advantages and versatility of the new cyclotron.

The main advantage is the availability of carbon beam. The treatment with carbon allows to reduce the number of treatment session also of a factor two or more. Despite the maximum energy of the cyclotron here presented is only 250 AMeV, a lot of tumors of the head and neck district can be treated. The energy range of a 250 AMeV carbon ion is of 130 mm in water. The distribution of number of patients vs. the deepest treatment made for each patient, extracted by the data base of the patients treated at Chiba center [7], shows that with a 250 AMeV carbon beam it is possible to treat 46% of tumors of the head and neck district. This percentage increases up to 82% and 95% if the beam energy is increased up to 280 and 300 AMeV respectively. This feature is really important now that some center starts to build facility based on synchrotron just to deliver also carbon beam. Moreover the tumor treatments performed with a cyclotron beam are more accurate than treatment with synchrotron beam. The continuous beam of the cyclotron allows to perform more beam sweeping on the tumor increasing the quality of the conform dose deposition [8].

An additional advantage for the proton treatment is the use of an external source, this solution allows to modulate the beam intensity using the chopper described before, and maintaining the source operation in the regime mode.

The really new feature that we like to highlight is the availability of an high energy proton beam with a useful current of 40 μA usable for medical radioisotopes production. Up to now the market for these radioisotopes is limited just because only few research facilities have beams with the right energy and power to perform these task. Moreover the cost of one beam hour produced by TRIUMF and other research centre is quite high and can't allow a commercial production.

The cyclotron here presented offers the possibility to overcome this limitation and to allow to build medical centres for proton therapy and new radioisotopes production at the same time. Radioisotopes like ^{82}Sr/^{82}Rb or ^{67}Cu, ^{32}Si and other more, could be produced and the commercial market could benefit.

The production rate of this cyclotron working on a base of 10 hour per night, 6 days per week, 46 week per year is of 110 mAh per year which is about the half of the integrated current per year delivered by TRIUMF to produce radioisotopes along the last years.

According to the lifetime of stripper used at TRIUMF and by other commercial cyclotron, we extrapolated an expected mean life for a 100 μg/cm^2 stripper of about 20 mAh. Assuming a 40 μA of proton beam, to deliver 10 kW, the stripper has to be replaced each 2 months.

The extra economic benefit due to the production of radioisotopes could compensate the extra cost for the construction of this new kind of cyclotron and produce additional benefit.

The present study has allowed to verify the feasibility of a superconducting cyclotron for light ions and moreover we learn that a cyclotron for carbon ion with energy of 300 AMeV is a straightforward feasible extrapolation of the present design. A simplified design without electrostatic deflector to deliver just proton beam for therapy, low intensity, and for radioisotopes production, high intensity, is feasible too.

The layout of the radiotherapy center for the hospital "A.O. Cannizzaro" is shown in Fig.5. The cyclotron here described has been proposed for this center. Although the proposal has been approved by the Sicilian regional government, we are again waiting for the final founding approval.

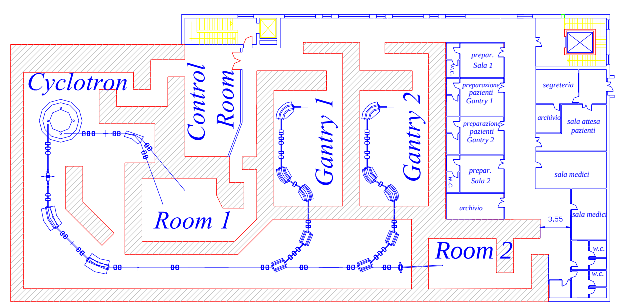

Figure 5: Layout of the proposed therapy centre for Catania Hospital

REFERENCES

[1] L. Calabretta et Al., Nuclear Physics (2004) Nuclear Physics A734 (C) (2004) pp. 378-381
[2] M. Maggiore et Al., "Design of the RF system for a 250 AMeV superconducting cyclotron", XVIIth ICCA 2004, Tokyo
[3] A. Caruso, L. Calabretta et Al., "Status report on Chopper-500", XVIIth ICCA 2004, Tokyo
[4] Betz, Rev. of Mod. Phys. Vol.44, N° 3(1972) 465
[5] H. Steimel, "Int. Conf. On Sect. Foc. Cyc. and Meson Factories", Geneva, CERN, 1963, pag 24
[6] L. Calabretta, A. Caruso et Al., XVIth ICCA, East Lansing, 2001, pag. 297
[7] J.Mizoe, N.I.R.S., private communication
[8] E. Pedroni et Al., Zeitschrift fur Medizinische Physik Vol. 14, Issue 1,03-2004, pag.25