Preliminary Design of a Very Compact Protosynchrotron for Proton Therapy

L. Picardi, C. Ronsivalle, A. Vignati, ENEA-INN-FIS P.O.Box 65, 00044 Frascati (ITALY)
G. Silvestrov, T. Vsevolozskhaya, BINP, Academ. Lavrentyev 11, Novosibirsk 630090 (RUSSIA)
R. Bartolini, Fondazione Adroterapia, Via Puccini 11, 28100 Novara (ITALY)

Abstract

In the framework of the Italian "Progetto Adroterapia", which aims to promote the cancer therapy with protons a compact 80 - 200 MeV proton synchrotron has been designed. The work started from the 200 MeV protosynchrotron [1] under development at the Budker Institute for Nuclear Physics of Novosibirsk (BINP), but the design has been revised in a more conservative way. The use of 4 Tesla warm 3.5 msec pulsed dipole magnets allows a synchrotron with only 6.4 m of circumference. Magnet design, dynamic aperture, injection and extraction systems are described.

1. INTRODUCTION

The "Progetto Adroterapia" [2] leaded by Ugo Amaldi foresees the construction of a big protons and ions therapy center using a conventional 250 MeV protonsynchrotron, connected to 3-4 smaller proton therapy centers equipped with compact accelerators. To this end a comparative study between different types of machines (synchrotron, linac and cyclotron) has been setup in order to choose, by the spring of 1995, the one that is best suited to be built by the italian industry. The 200 MeV compact protosynchrotron designed by BINP [1] is the first accelerator that has been considered. A collaboration between the ENEA INN-FIS Dept. at Frascati and BINP started to study the main problems and the possible improvements in design and technology of the high-field short pulse synchrotron suggested by BINP [3].

The main differences respect to the original BINP design resulting from this study are listed in the following points.

- A reduction of the maximum field from 5 to 4 Tesla and a new design of the magnet section in order to reduce the multipolar components of the magnetic field (expecially the sextupole one) below acceptable values. The larger size of the machine allows more space to include RF cavities, injection and extraction magnets, and corrections.
- A choice of a stable working point by the computation of the dynamic apertures in various conditions.
- An injection system composed by a 12 MeV H^- cyclotron (also suitable for Positron Emission Tomography) and a charge exchange injection scheme. The injection energy is larger than in the original BINP scheme (1 MeV). This allows a reduction of the RF frequency sweep.
- The RF system has also been redesigned.

Fig.1 shows the layout of the protosynchrotron that has been named STAC (Sincrotrone Tecnologicamente Avanzato e Compatto).

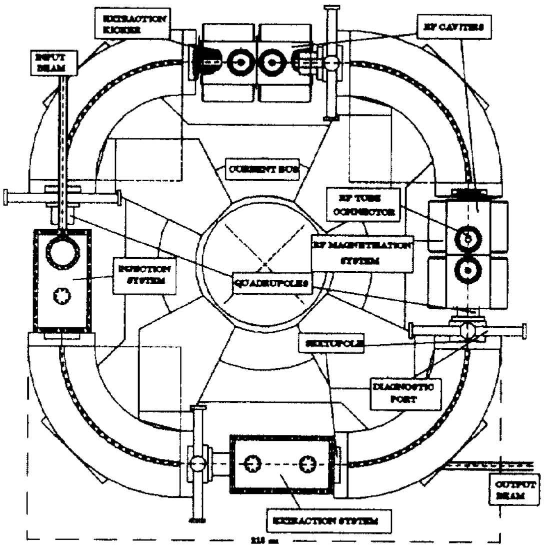

Fig. 1 - Schematic design of the proton synchrotron

2. MAIN PARAMETERS OF THE STAC

The general parameters and the lattice parameters of the STAC are listed in tables 1 and 2.

Table 1
STAC general parameters

Maximum Energy	200	MeV
Protons per pulse	10^{10}	
Pulse repetition rate	1	Hz
Pulse length	300	nsec
Injection type	Charge-Exchange	
Injection Energy	12	MeV
Maximum dipole field	4	Tesla
Total surface of the accelerator and therapy complex	300	m^2
Rough cost estimation	10	M$

The STAC lattice has been chosen similar to the BINP one. The BODO lattice is particularly simple and suitable for a compact synchrotron. The horizontal focusing is obtained by the dipole bending, and the vertical focusing by four quadrupoles placed very close to the dipole ends.

Fig 2 shows the behaviour of the optical functions in one period.

Table 2
STAC Lattice parameters

Period	BODO
Dipole magnet: Radius Bending angle Field index	 54 cm π/2 0
Q-pole Length Gradient	 8.4 cm 11 T/m
Long drift	54.2 cm
Number of periods	4
Total length	6.393 m
Q_x	1.422
Q_y	0.54
$\beta_{x,max}$	1.38 m
$\beta_{y,max}$	2.1 m
$D_{x,max}$	0.63 m

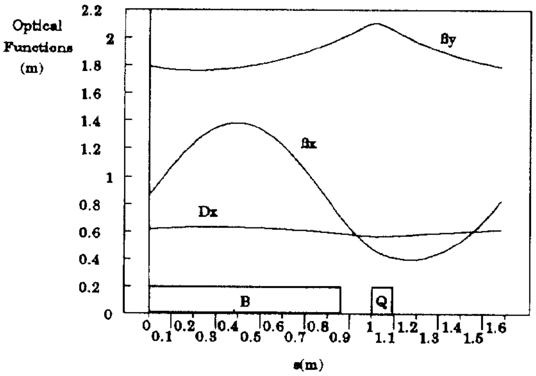

Fig. 2 - STAC optical functions in one period

3. DYNAMIC APERTURE

The high field (4 T) dipole magnets [1] are excited by a single turn coil, in which a 3.5 msec 180 kA half sine shaped current pulse flows.

The calculation of the dynamic aperture has been performed by the RACETRACK code [4] in which the non-linear elements have been included dividing the bending magnet in six parts and introducing in between five multipoles. The multipolar coefficients were obtained by MERMAID [5] a russian bidimensional code for magnets operating both in static and pulsed mode. The multipolar coefficients of the dipole vary during the pulse because of the combined action of the iron saturation and the different diffusion of field in the copper conductor (skin layer) and orbit calculations have shown that the adimensional sextupole coefficient for the STAC must remain below 2 10^{-3} to get a good dynamic aperture.

In the BINP original magnet the sextupolar coefficient reached, at the end of the pulse, 16 10^{-3}. This produced a strong shrink of the dynamic aperture above 80 MeV.

For the STAC magnet an optimization study of the cross-section of the magnet was performed by evaluating the multipolar coefficients and the corresponding dynamic aperture. Several magnet geometries have been compared. In the best one the sextupolar coefficient is below 2 10^{-3} and produced the dynamic aperture sketched in Fig 3.

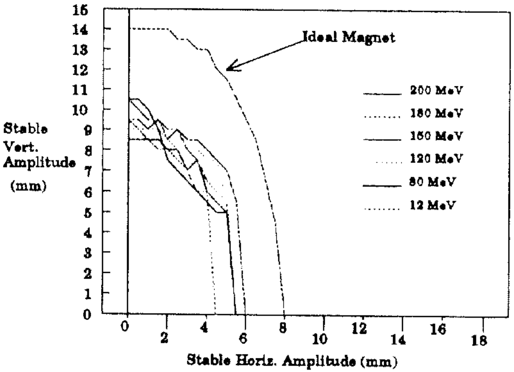

Fig.3 - Dynamic aperture of the STAC design

In Fig. 4 the cross sections of the BINP original magnet and the STAC version are compared.

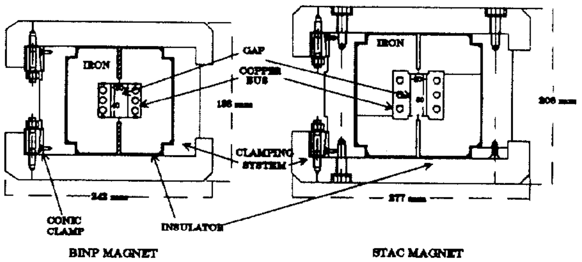

Fig. 4 - Cross section of the BINP and STAC dipole magnets

4. INJECTION AND EXTRACTION

Charge-exchange injection is performed by means of a shift of the ring equilibrium orbit to the center of a stripping target placed 1 cm apart (fig.5). The injection conditions have been optimized by computing the beam dynamics with a code which takes into account the multiple scattering and energy losses in the target. The best injection conditions are summarized in table 3.

Table 3.
Injection parameters

Injection Energy	12 MeV
Target thickness	0.5 μm
Target area	3x3 mm²
Number of turns	300
Injection time	40 μs
Number of captured particles for I_{inj}= 500 μA	9 10^{10}

This number of stored particles is obtained if the emittance of the cyclotron beam is less than 3 π mm mrad and the kinetic energy spread is not larger than ±0.5%. Beam extraction is obtained by means of a time dependent shift of the ring equilibrium orbit towards the septum magnet.

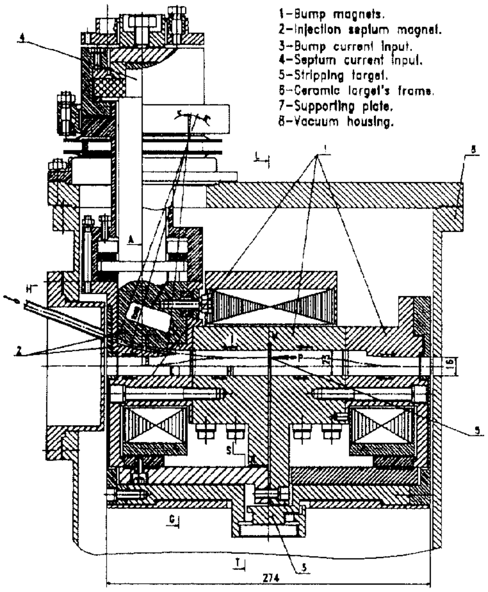

Fig. 5. Charge exchange injection system

The shift is made by a special magnet placed half a revolution upstream of the septum. The magnet is supplied by half-sine current pulse with a duration equivalent to 20 beam revolutions. The linearly rising part of the pulse is used for the extraction. During this time the beam is displaced towards the septum. The real extraction takes place during the last 8 revolutions only, because of the rather small size of the accelerated beam compared to the ring aperture. The parameters for extraction has been optimized (table 4).

Table 4.
Extraction Parameters

Septum thickness	0.5 mm
Septum position	10 mm above the median plane
Shifting field integral	2.9 kOe cm/turn
Efficiency	70 %
Extracted beam emittance	1.6 π mm mrad
Extraction duration	0.3 μs

5. RF SYSTEM

The cavity design is based on the RF system of the B-5 synchrotron operating since 1976 in St. Petersburg [6]. It is a quarter-wave coaxial line heavily capacitively loaded, and with the inductive part entirely filled with ferrites. The cavity is tuned by means of an external magnet. The magnetization field penetrates into the ferrites through windows, which are cut longitudinally in the cavity body. The windows are shut with a thin foil transparent to external magnetic flux (thickness « skin depth). The removal of the power dissipated in the ferrites is obtained by a good thermal contact with the body.

The accelerating voltage is produced by means of two cavities mirror-faced and oppositely phased (push-pull), each one driven by its own tube. The main parameters are listed below.

Table 5
RF System Parameters

Number of gaps	4
Gap voltage	3.1 kV
Initial Frequency	7.42 MHz
Final Frequency	26.5 MHz
Sweep Time	3.5 msec
Tube	EIMAC 4CW100
Number of ferrite rings	10
Ferrite inner diameter	11 cm
Ferrite outer diameter	18 cm
Length of one cavity	24.3 cm

6. DOSE FIELD FORMATION

A rotating gantry and the possibility of a large field (20x20 cm^2) irradiation are often useful in therapy. These items are in course of definition. At the moment we refer to the design proposed by BINP and extensively described in [7]. Briefly, the compact gantry uses a 5 Tesla pused magnet and is designed to be only 3.5 m in diameter and the dose field formation is achieved by means a system composed by a cylindrical aluminum lens and an energy degrader.

7. CONCLUSIONS

The STAC is a modification of the compact protosynchrotron designed at BINP some years ago and in course of development. It corrects some aspects of the original BINP design and nowadays is the most compact and economic proton accelerator project for radiotherapy. However, we stress that it has to be considered first from the point of view of accelerator R&D, checking experimentally the correct working and reliability of the machine.

The complete investigation on the possibilty of the STAC in the framework of the comparative suty of the "Progetto Adroterapia", will include a series of tests at Novosibirsk on the existing components, and a check of the design with the italian industry.

8. REFERENCES

[1] Averbukh, et al. "Project of small dimensional 200 MeV proton synchrotron", Proceedings of EPAC, Rome, 1988, p. 413.

[2] U. Amaldi, G. Tosi "The Hadrontherapy project two Years later", TERA 93/2 GEN 5, Fondazione Adroterapia

[3] L.Picardi, "Status of the study of the compact proton synchrotron for hadrontherapy", TERA 93/4 ACC3, Fondazione Adroterapia

[4] A. Wrulich, "RACETRACK, a computer code for the simulation of non-linear particle motion in accelerators", ISSN 0418-9833 DESY 84-026, 1984

[5] MERMAID, gently offered by the author, A. Dubrovin, BINP, Novosibirsk

[6] J.A. Averbukh, "Accelerating RF cavities for ion synchrotrons" PTE, 1978, N4 p. 19

[7] L. Picardi et al. "Preliminary design of a Synchrotron Technologically Advanced and Compact (STAC) for Proton Therapy", Proceedings of the International Symposium on Hadrontherapy, Como, Italy, Oct. 18-21 1993, to be published in NIM.