A VERY COMPACT PROTONTHERAPY FACILITY BASED ON AN EXTENSIVE USE OF HIGH TEMPERATURE SUPERCONDUCTORS (HTS)

C BIETH, A LAISNE

PANTECHNIK 4 rue Alfred Kastler 14000 CAEN

ABSTRACT : The present worldwide protontherapy development is slowed down by the volume and the general costs of the existing proton generators and delivery dose equipments. The use of High Temperature Superconducting cables recently available on the market (HTS) (1), working around 30K modify completely the design of protontherapy equipment. At this temperature, independant cryocoolers able to work in any position can be extensively used. Added to a significant simplification of the associated cryothechnics, it becomes possible to gain what was promised by the use of superconductivity concerning the volume, the weight, the general dimensions, the consumpted power. The complete facility presented is composed of a very compact isochronous cyclotron 210.Mev of only 88 tons 3.2m in diameter equipped with an internal ECR ion source of infinite lifetime, followed by a superconducting voxel scanned isocentric gantry of 35 tons only, 5.2 meters in diameter.

1. General overview

For deep-seated tumors, the clinical specifications call for a penetration in the patient of 25 g/cm^2 , corresponding for the water to an energy of 200 MeV for a proton beam[1]. But the energy needed at the exit of the accelerator is dependent on the beam delivery technique: passive by scatterers or active by scanning. As, for the moment, no predominant choice can be defined, we have selected an energy of 210 MeV. The current required, for a dose rate of 30 - 40 Gy/min (on volumes smaller than 50.cm3) and 2-10 Gy/min (for volumes between 50 and 1000 cm^3), varies from 1 nA to 300 nA, and is also depending on the beam spreading technique. The beam can be in a continuous mode or pulsed if required.

In order to use the full quality of the protons we suggest to use the voxel scanning technique[2]. The deposition of the dose is performed by scanning the target volume in three dimensions with the proton beam sharply focused on a small spot. This technics may have also a definitive advantage on the other technics concerning the transport system : it may be at fixed energy (the energy degrader may be put just in front of the patient) thus no need of fast beam tuning. The number of analysing dipole and diagnostics, the local radiation protection are also reduced.

The simplest generator and the best adapted to this kind of deposition mode is a compact isochronous cyclotron, as far as low operation, maintenance, costs, long life reliability, and well known technology are concerned[3]. Using the newest technologies, like HTS for the coils[4], an internal Electron Cyclotron Resonance (ECR) source for the beam production[4], a simplified ejection, cryogenic panels for the pumping system integrated in the vacuum chamber, fully computerized control system, this second generation facility is a real compact one with a minimum running cost, tuning time and maximum safety.

2). PK 210 a fixed energy superconducting compact isochronous cyclotron

A compact isochronous cyclotron delivering a proton beam of around 210 MeV and using room temperature coils, is a heavy machine (about 230 tons), a big consumer of electrical power (close to 220 kW for the magnet coils and power supply plus 100 kW for the RF system), has a large diameter (external diameter around 4.3 meters) with a large vacuum volume, and needs additional requirements like : demineralized high resistivity water with a heat exchanger (around 100 m^3 /h), evacuation of the power dissipated in the air for the cyclotron vault and power supplies (about 50 kW) and, of course, rooms with adequate surfaces to place all these equipments.

The PK210 project is based on the new high temperature superconducting wires, produced by American Superconductor Corp, with a working temperature of 29°K, just surrounded by a multi-layer super insulation. Frigories needed are produced by new one-stage cryocoolers directly connected to the coils. Figure 1 shows the basic principles of this new system compared to the standard helium liquefier. The use of this technique is possible because we have designed the cyclotron with a relatively low magnetic field (2.01T in the central region) in order to simplify the ejection problems. With such a field we are below the critical current of the HTS for temperatures in the range of 25 to 35K. The cryostat around the coils, and all the peripheric equipment (quench security valves, helium gas tank and so on), are extremely simplified.

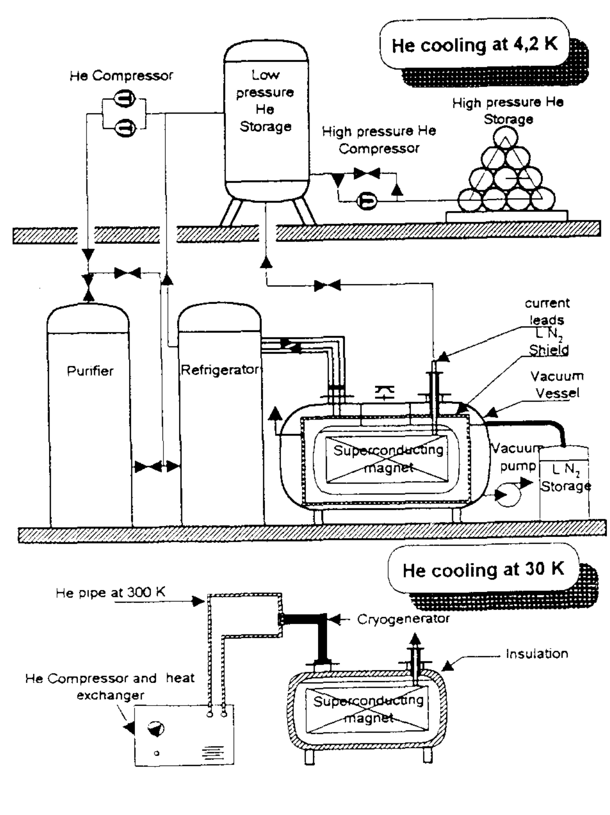

Figure 1 : Cooling circuit

In the classical cyclotron we generally use a hot filament P.I.G. source introduced axially through the magnet yoke. Pantechnik has patented the concept of an internal ECR source using the main magnetic field of the cyclotron. This source has an infinite life time and is very easy to operate with a very low power, high frequency, solid state generator connected to the source through a wave guide ended by a vacuum window.

So, by using the up to date technologies, we have eliminated the disadvantages of superconducting cyclotron, reduced the volume and complexity of the conventional cyclotron, increased the reliability, operability and running cost, while the total cost of the cyclotron is still competitive with the existing one.

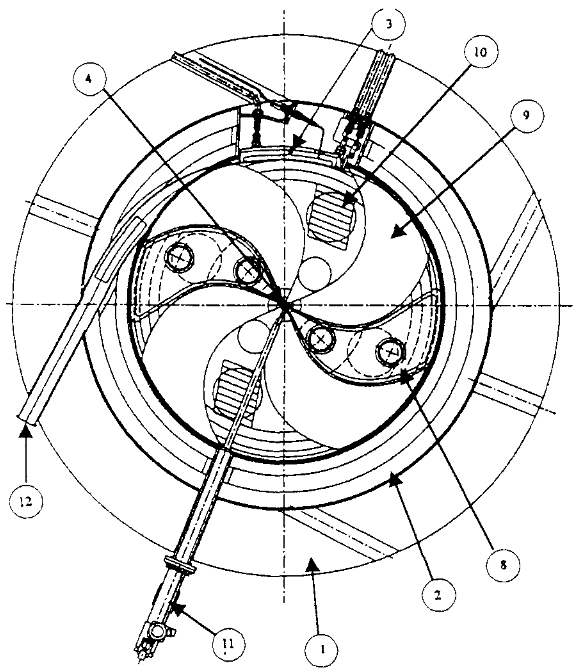

Figure 2 : View of the cyclotron in the median plan

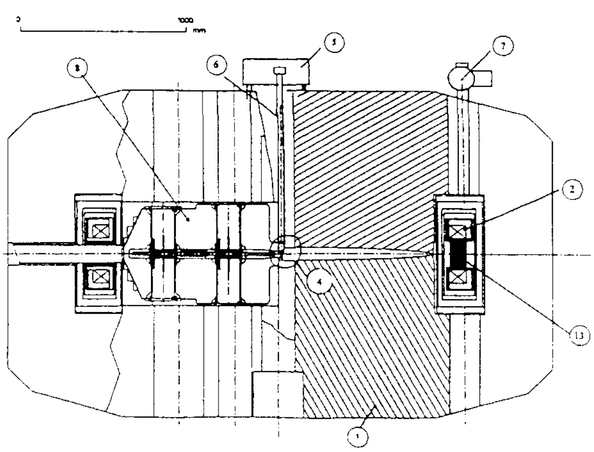

Figure 3 : Cross section of the cyclotron through a hill and a RF valley

The main parameters of the PK 210 cyclotron are summarized in the following table.

Table 1

PK210 MAIN PARAMETERS		
Proton energy (fixed		210 MeV
Ejected beam current	maximum	300 nA
	minimum	1 nA
Expected beam emittance		< 1 π.mm.mrad
Turn on/off time from ion source generator		30 µs
External magnet diameter		330 cm
Total magnet height		172 cm
Total weight		90 t
Electrical power total consumption		< 160 kW

2.1 Magnet design

The machine parameters results of a compromise between two opposite trends. The higher the central field, the smaller the radial dimension and weight, but the more difficult to eject. Due to the important impact on the price of an increase of the ejection element number located in the cryogenic environment, and the use of HTS, we chose a central field value of 2 Tesla only. The iron volume is nevertheless half that of a machine with room temperature coils.

The Hill gap has a complete elliptic radial profile, closed on the median plane by a 7mm thick pole edge wall. The ejected beam must get out through it using a small rectangular hole 3.*16.mm.

The consequences of these choices are : a machine diameter limited to 3.3 meters 1.72m height, 88t weigh ; a simplified design of the magnet divided into two monobloc halves with two central plugs (foundry cost reduction) ; a limited (by 30%) magnetomotive force and radial strength in the main coils, compared with constant hill gap machines ; a very low attractive force between the coils (31t) and consequently a minimization of the heat losses at low temperature ; a non resonant simplified ejection insensitive to first harmonic defects spanning only 140° in azimuth. (See figure 3).

The fine isochronization of the magnetic field is obtained by adjustment of the azimuthal length of the hills, whose edges are designed removable.

The table 2 gives the parameters of the magnet system.

2.2 RF system

In two opposite valleys are placed the RF accelerating electrodes, and the free valleys are used for the electrostatic deflector, the cryogenic pumping panels and the radial beam probe.

The accelerating resonators have to resonate on the 4 th. harmonic of the ion orbital frequency, i.e. 123.4 MHz. In order to improve the turn separation at the extraction radius a peak voltage of 140 kV has been selected. In the central region, to avoid sparks, a maximum voltage of 60 ~ 70 kV peak has been chosen[5], [6].

Table 2

ELECTROMAGNET CHARACTERISTICS	
2 monobloc half magnet with 2 central plugs	
Yoke external diameter	3.26 m
Yoke internal diameter	2.40 m
Yoke total height	1.72 m
Yoke total weight	88.t
Pole Radius RP	0.93 m
Number of spiraled sectors	4
Min spiralization for	45.2° at RP
Complete Elliptical hill-gap profile	
Generative Ellipse half axes	0.04*0.923 m
Valleys heigth	0.32 m
Central field	2.01 T
maximum Hill field	3.50 T
minimum Valley field	1.50 T
Electromotive force	670 000.At
Super-conducting cryocooled coils	
Coil temperature	25 to 35°K
Coil internal and external radii	1.02 and 1.12m
Coil height	0.08 m at z = 0.1 m
Radial force	+ 38.3 t/rd
Vertical force	- 4.88 t/rd

The stems are symmetrical with respect to the median plane, and to obtain a resonant structure with a radialy increasing voltage four pillars are necessary.
The RF power needed to produce the required voltage distribution has been minimized by searching the right positionning of the pillars, their optimum diameters and by reducing the total electrode capacity. The horizontal electrode spanning varies from 45° in the central region to 35° at the ejection radius, thus increasing the RF gap from 1.5 cm to 7 cm, this also gives space for the removable hill edges. Figure 4 shows the calculated radial RF voltage distribution on the two accelerating gaps (inter-exter). Parasitic modes have been investigated, mainly the mode 3*F, and it has been seen that, with a fixed frequency machine this mode presents no difficulty.
The fine tuning system will use variable cylindrical plungers, situated in the vicinity of the stems.
The coupling system and a magnetic coupling loop, giving an impedance of 50Ω, connected to the amplifier through a coaxial line.

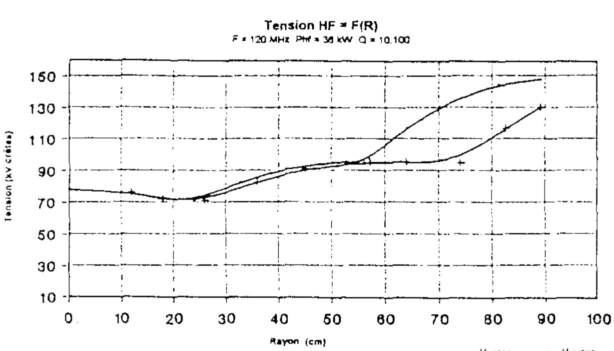

Figure 4 : RF voltage distribution

The main characteristics of the accelerating system are summarized in the following table.

Table 3

ACCELERATING SYSTEM	
Number of cavities	2
Electrodes azimuthal openings (middle of the gap)	45° (inj) to 35 (eject)
Harmonic mode	h = 4
Frequency	123.4 MHz
Central voltage	60-70
Ejection voltages	130 and 150 kV peak
Total CW cavities RF power	2.36 kW
RF Amplifier output	80 kW

We think that two independent electrodes (not connected in the center), could give some additional flexibility in the final adjustment of the extracted beam, and reduce the total RF power.
With this solution we need two independent amplifiers, but with half the total RF power. It is easier to find such tubes or amplifiers than an unique one.

2.3 The internal ECR source

This ECR source is designed to produce more than 100 μA of continuous beam. The source makes use of the magnetic field shape in the central region to produce an electron cyclotron resonance at 56 GHz. The solid state amplifier, with a maximum power of 20 W, is placed on the top of the cyclotron and is connected to a wave guide ended by a pressurized ceramic window attached to the source[7].
Like in existing machines, the beam can be precisely centered, with a phase acceptance limited to ±7.2° The phase compression leads to a final phase extension of ± 3.7 So the energy spread of the extracted beam will be in the range of $1.1*10^{-3}$.

2.4 The simplified ejection

The simplified ejection is a consequence of the choice of a magnet gap evoluting with an elliptic law as a function of the radius, as indicated before because it creates a very steep hill fringing field > 1000 T/m.

The choice of four sectors allows to locate a conventional electrostatic deflector in a valley, where the vertical space is important. The electrostatic deflector uses a conservative electric field of 140.kV/cm, with a thin septum of 0.1 mm and a length of 40cm.
Beyond the electrostatic deflector, the deflected beam gets out of the machine through a small rectangular hole (3mm wide*16 mm height), managed in the 7mm thick wall which obstructs the median plane. Beyond this hole the beam enters a very simple iron bars magnetostatic channel which corrects the radial defocusing effect due to the radial gradient seen upstream.
The beam leaves the machine 140° only after entering the electrostatic deflector, (to be compared to the 360° of all the other superconducting projects and AGOR).
The following table summarizes the main characteristics of the extraction system and predicted beam parameters.

Table 4 :

EXTRACTION and BEAM CHARACTERISTICS	
Electrostatic deflector	
Electric field	140 kV/cm
Voltage on the electrode	70 kV
Septum thickness (tungsten)	0.1 mm
Electrode length	40 cm
Remote positionning adjustment	
Magnetostatic channel	
Gradient	30-50 T/m
Length	60-40 cm
positionning adjustment	manual
Beam characteristics	
Output energy	210 MeV
Maximum extracted current (DC)	300 n.A
Beam emittance (both planes)	< 1π.mm.mrad
Beam turn-off by interlocks	10 ms

2.5 The vacuum system

As far as the proton acceleration is concerned, the vacuum requirements are not very severe: a vacuum of 1.10^{-4} mbar is sufficient. But the RF accelerating system is dependent on particular parameters.
For this reasons we use a cryogenic pumping system including cold panels inside the free valleys (at 20K) protected with a thermal screen (at 80K). The frigories for these panels are produced by (external) cryocoolers similar to those of the main magnetic superconducting coils. With this technique, we have the maximum pumping speed directly in the median plane, without contamination. From the atmospheric pressure, and after a dry nitrogen venting, the pumping time to obtain 1.10^{-4} mbar is less than 15 minutes.

2.6 Command and control system

Today there is no doubt that the command and control system of such an accelerator must be done using programmable logic controllers (PLC). Many industrial PLC are available and give a perfect reliability

3) The beam transport

As the cyclotron works at fixed energy, the energy variation needed during the treatment must be obtained through degraders, and the characteristics of the beam transport system will be relevant of the position of the degrader.
When the degrader is inserted just after the cyclotron, the transport is affected by the emittance growth, the energy spread, the energy variation. So the beam transport system must include analyzing dipole magnet, definition slits and must restore the achromatism and rotational symmetry at the gantry coupling point. For low energy, the beam intensity is reduced at least by a factor of 10.
When the degrader is placed after the last bending magnet of the gantry, the beam transport is simplified, and the magnets (Q poles and dipoles) can be much smaller, reducing also the total weight and electrical power.
We suggest to use the solution where the degrader is placed after the last bending magnet of the gantry, in the nozzle, so the full beam transport system is at fixed energy and can be tuned very simply, without beam losses. All the bending magnets will use the same HTS high temperature superconducting material as the cyclotron coils. This reduces tremendously the total electrical power consumption of the equipment.

4) The proposed gantry

We have selected the voxel scanning technique developed at PSI to provide the highest precise dose distribution, but associated with an isocentric gantry[8].
Following the design of the cyclotron magnet, we will use high temperature superconducting coils for the main gantry magnets. Thanks to the cryocooler, the magnet can rotate over 360°. Even with an isocentric gantry the total diameter of the system can be reduced because: the emittance of the beam is small (compared to the PSI emittance) less than 1.π.mm.mrad. So quadrupoles and dipoles can be smaller.
The total weight of the rotating equipment, including the counterweight, is very light: less than 35 tons. So the reduced mechanical structure is supported by two boggie rollers and the angular orientation is given by an encoder with a total precision and repeatability better than ±0.2°.
The total rotation angle can be ± 180°, from the vertical axis, with a variable rotating speed and emergency stopping.

Table 5 :

GANTRY SYSTEM	
External diameter	5.2 m
Total length	5.5 m
Total weight (with counterweight)	25 tons
Rotation angle	± 181°
Beam extension with scanning	± 10 cm
Positioning angular precision	± 0.2°
Positioning angular repeatability	± 0.2°
Isocenter movement over	< 1 mm

References:

[1] J.C. Rosenwald (Institut Curie - Paris), On Hadrontherapy Archamps (20-24 Nov. 95)

[2] E. Pedroni : the 200 MeV protontherapy project at PSI (Med. Phys. 22 (1) , (janvier 95)

[3] With the collaboration of P. Mandrillon. Centre A. Lacassagne, Nice

[4] American superconductors Corporation. Westboroughs MA01581

[5] N. Fietier, Centre A. Lacassagne, Nice, « RF calculation for a superconducting cyclotron »

[6] C. Bieth, Pantechnik, Caen, « Optimisation of the RF resonators for the PK210 project »

[7] P. Sortais, C. Bieth, An internal ECR source for a protontherapy cyclotron, Pantechnik internal report (1997)

[8] Pré-étude d'une tête isoscentrique pour la Protonthérapie, PANTECHNIK, nov 1996