MORE ABOUT A UNIVERSAL COMPACT ISOCHRONOUS SUPERCONDUCTING CYCLOTRON ARCHETYPE

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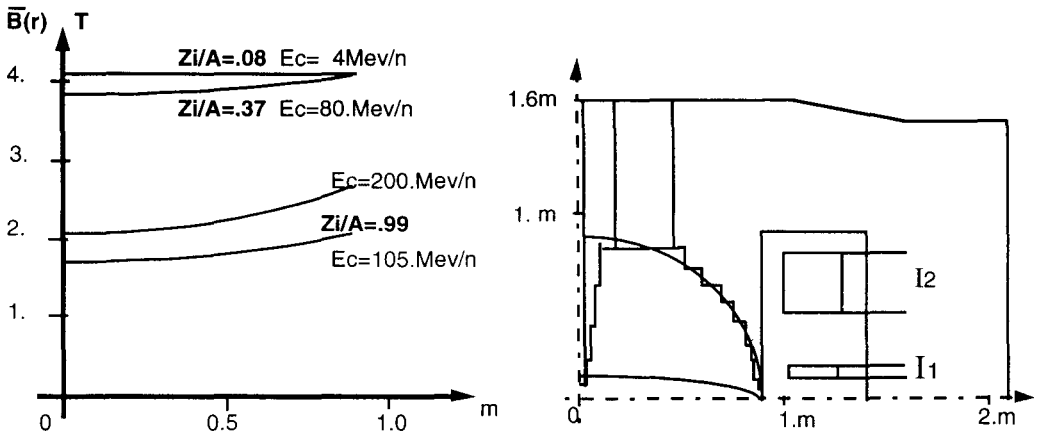
ABSTRACT : Except the fact that they can accelerate protons at comparable energies, AGOR and CYCLONE 235 stand at two extremities as far as the complexity of the conceptual design is concerned. The widest range of ions species associated with a very large energy and RF frequency ranges for AGOR, a fixed energy and a constant RF frequency for only protons in CYCLONE 235. In fact, the two designs have in common the same theoretical "model" that I described in a referred paper (1). Now, I suggest we look again at this model and try to show how it could be regarded as the "Universal Compact Isochronous Superconducting Cyclotron Archetype". Based on the behavior of CYCLONE 235, and on some more recent calculations, I will explain why the name of "Archetype" can be used, and show how attractive is the simplicity of the ejection scheme ensued in terms of reliability and cost.

1) THE CONCEPTUAL DESIGN OF THE ARCHETYPE :

The magnet of the universal compact isochronous superconducting cyclotron model I suggested in the Ref (1) and represented below is composed of a) : 2 pairs of main coils, one pair close to the median plane is able to create for I1 max the exact radial gradient needed for the acceleration of the more energetic lightest ion : protons 200MeV, the second pair in Helmoltz position is able to create a field constant with the radius for any value of I2.

b) : one pair of saturated poles delivering a magnetic contribution constant with the radius. I suggested to give to the constant opening hills a pure elliptic and complete gap profile, and to the valleys a modified elliptic profile for taking into account the RF holes all together able to deliver also a constant contribution.



Isochronous average fields for various Zi/A and kinetic energies

Sectional view of the magnet

Fig 1 : Figures presented in the previous paper Ref 1

2) WHAT DOES THE DESIGN OF SUCH MAIN COILS PROVIDE:

The design of the main coils is theoretically able to deliver the complete range of magnetic fields associated with a coherent universal cyclotron with a minimum minimorum of local correction.(coherent : meaning an energy continuity achievable through an overlap of the minimum energy proton(Zi/A = .99) and He3 (Zi/A = 0.66) less-equal to the maximum energy of the Zi/A = 0.5 and Zi/A = .33 ions respectively)

One can be easily convinced by the optimized character of these two pairs of main coils separate and thus cumbersome when one will know that the two extreme required fields can be reached without local correction and simultaneously by a zero value of one current only by adding a constant as a function of the radius, example :
for the heaviest ions Zi/A = 0.08 B(o)max = 4.05T, dB/dr ≈ 0.0, Ec = 4MeV/n => I1 = 0.0 and I2 = I2max and for the lightest ion at maximum energy Zi/A = 0.9928 B(o)p = 2.00T, dB/dr = max, Ec = 200MeV/n
=> I1 = I1 max I2 ≈ 0.0 .
As a result, all the intermediate fields are reachable for intermediate unidirectional currents with a minimum minimorum of local corrections.

The only constraint imposed by this main coil geometry is to require a flat magnetic pole pieces contribution thus unvarying with the functioning point.

The invariability is assured by the choice of the minimum field B(o) >1.7 T . This value lets saturated the iron (particularly the iron of the hills)

One can be easily convinced by the optimized character of the constancy with the radius when it is associated with the achievement of the maximum field without local corrections because it means that there is no

lack in the contribution of the big main coil and thus no need of compensation.The widest range of isochronism for a given ion is thus achievable.

3) WHY THE DESIGN OF THE COMPLETE MAGNET CAN BE CALLED ARCHETYPE :

When the radial constancy of the pole pieces contribution to the magnetic field is created by complete elliptical hill and valley gap profiles, we extend the list of the optima already delivered by the coil design. The achievement of CYCLONE235 has confirmed the theory of the magnetic behavior of the elliptic hill gaps, and some more recent studies have been undertaken for comparing the virtues of two protontherapy machines having one an Elliptic Hill Gap =>EHG and the other a Constant Hill Gap =>CHG machine.

Making use of a complete EHG :

a) we optimize the achievement of the mean isochronous field on the complete pole diameter; the saturated hills of constant azimuthal opening deliver a rigorously constant with r contribution. See Fig 2. It is well known that in a CHG machine the hill azimuthal opening must be incresead beyond the radius Rp-g to compensate for the decreasing pole edge contribution. See Fig 3

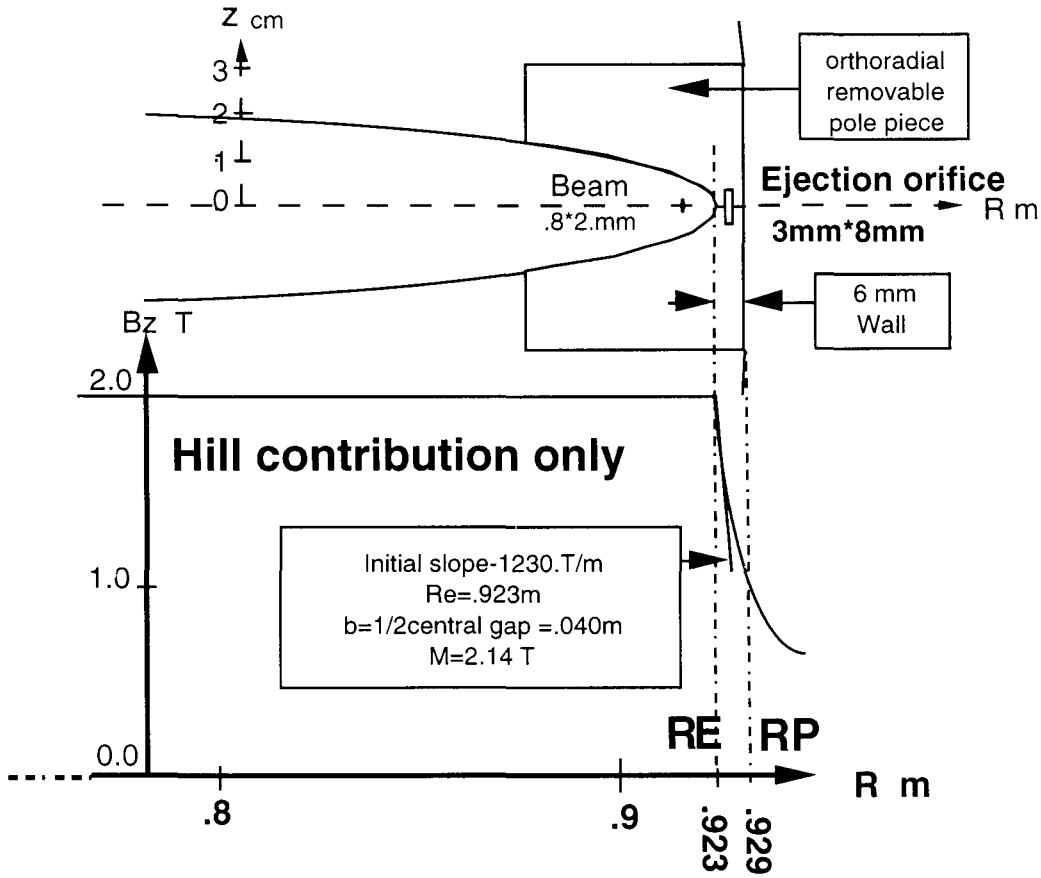


Fig 2 : Vertical Hill cut aroud the pole radius showing the ideal beam which insures an ejection yield greater than 95% below the proper magnetic Hill contribution internal and external.

b) We optimize the vertical focussing with the modulation amplitude more or less the same until the generating ellipse radius RE. See Fig3, and thus

c) We permit the reduction of the spiralling, which is important for the RF cavity behavior.It is well known that it is the contrary that happens in a CHG machine for b) and c).

d) We optimize the electrotechnical aspect by reducing the Ampere-turns figure through 2 contributions :

d-1) the mean equivalent hill gap is exactly equal to half the central elliptic gap

d-2) the hill fringing field is decreasing abruptly with a starting slope of -1230. T/m, see Fig2 reducing the fringing magnetic flux to a minimum.

In an EHG machine, the electromotive force is mostly used for creating the useful flux, saving more than 30% in Ampere-turns compared with the CHG machine.(Ref 2)

d) Saving more than 30% of Ampere turns means important savings in the superconducting coils budget through the holding strips and the volume of superconductors.

We can appreciate that all these optimizations allow us to call "Archetype" the model presented in ref 1

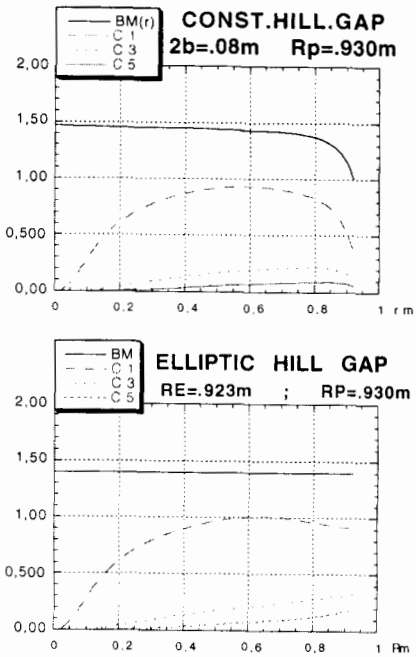


Fig 3 : Compared mean iron contributions BM(r) and modulation harmonic amplitudes C1,C3,C5.

4) THE SIMPLIFIED EJECTION :

In this previous paper, the simplified ejection was just a mentioned probable hypothesis.The first studies on this subject have been undertaken at IBA in 1991 for ejecting the 235 Mev proton beam of the future CYCLONE 235.

Explanations : it is well known that in a conventional CHG machine the ejection system has the goal to guide the beam through an annulus the radial extension of which has around the hill gap dimension. The internal radius of this annulus is the extreme internal radius the beam reaches, where it receives from an electrostatic deflector a first radial kick, the external radius of the annulus being the one of the completely radially unstable closed orbit at same energy. Unfortunately, the annulus is also the place where the magnetic hill field reaches its maximum and : the seat of a completely unusefull magnetic fringing flux. As a consequence, we are obliged to put in that annulus one or two electromagnetic channels that counteract these magnetic field peaks to help the beam reach the external radius.

The two electromagnetic channels CEM1 and CEM2 in AGOR illustrate this assertion.

It was clear that this kind of complicated and very expensive ejection system was unthinkable in a protontherapy machine working in an hospital and that is the reason Y.Jongen and I went to a complete Elliptic Hill Gap machine which makes this annulus to disappear. Obviously, if we cannot accelerate until RE the radius of the generating ellipse where the local hill gap vanishes to zero, we can accept the beam pass at RE-3.mm before entering the electrostatic deflector in the downstream valley. An electric field of 140.kV/m in an horizontal aperture of 4 or 5mm seen all along the 400.mm in length creates a deflection angle which is 14.5 mrd with 210.Mev p and goes to a minimum of 12.9 mrd for Zi/A = .335 ions. This small deflection figure will be converted in a radial displacement of a tens of a millimeter in the downstream hill where a small, Fig 2,

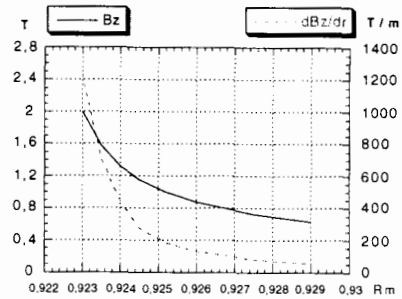


Fig 4 : Hill fringing field and its radial derivative

rectangular orifice can be managed in the remaining wall. The beam when inside the wall experiences the hill fringing field which radially drops down with a slope. of -1230.T/m. This means that a radial displacement of only 3.mm is sufficient for experiencing a magnetic field which has the exact value of the mean field seen in the last turn. From this point, the local radius of curvature becomes greater than the machine radius.

The key parameter at the wall entrance is the ejected "Pr "value which is dependant upon N the azimuthal periodicity of the machine and upon the central field B(o) choice. Recent calculations[2] have shown that N = 4 is much more favorable than N = 3, and obviously 'Pr' increases with a B(o) decrease. Considering that a reasonable "Pr" value (that determines the orifice length) must not be lower than Pr = 100.mrd (5.8°), leads to central fields lower than B(o) = 1.95 T.

The strength of the equivalent lens around $\int G \cdot dl = 16 \cdot T$ may be compensated as soon as possible by a iron bars magnetostatic channel which provides radial gradients of 30 to 40 T/m. on 0.4 to 0.6 meter.The total azimuthal extension of such a simple ejection system lies in 140.°, to be compared to the 362.° at AGOR !!.

It must be emphasized that this simplified ejection is non resonant, and thus insensitive to the first harmonic defects. In particular those induced by the iron bar channel.

When realized with an iron bars channel followed by common lenses it is very cheap and well adapted to recurrent production as it has been proved by IBA.

5) CONCLUSION

If the need of a new Universal Superconducting Compact Isochronous machine arises everywhere in the world I would recommend to go resolutely on the way exposed here and in ref 1. Recent calculations using PE2D have shown an unexpected good behavior of the internal field in the range 3 to 5 T of a complete EHG machine. The local corrections with N = 4 were half the AGOR one.!! and unnecessary near the pole radius.

Ref [1]: A. Laisne "IPN-ORSAY Project First Machine Design Studies".9th Conference on Cyclotrons and their Applications,Caen,Sep.1981, p. 203

[2]: Internal Technical Note on compared ejection from 3 and 4 sectors isochronous machines Pantechnik 1996

Acknowledgments : I gratefully acknowledge Y.JONGEN who accepted the risks to be the first in the world to build a complete elliptic hill gap machine ... and faithfully managed the IBA protontherapy team he created in 90.