ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST032

A NEW APPROACH TO CYCLOTRON DESIGN

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Abstract

Cyclotrons are the oldest type of circular accelerators, with many applications, design of the majority of cyclotrons nowadays follow has become a standard for most of developers, and there is a clear trend for switching towards superconducting magnets to increase the magnet field level and decrease the size and weight. A new approach, described in this paper allowed the author to design a line-up of cyclotrons from 15 to 230 MeV as compact and power efficient as superconducting cyclotrons, but using resistive copper coil.

INTRODUCTION

Every day more and more cyclotrons for medical and industrial applications are being produced. Especially in the energy range between 10-70 MeV proton (mostly) beams for medical isotopes production such as PET, SPECT isotopes. Also recently discovered FLASH [1] proton therapy created a demand for 230 MeV proton accelerator which can produce beams with higher current then existing accelerators. Cyclotrons seems to be a good choice for such task. The modern trend in cyclotrons is to apply superconducting coils to increase magnetic field strength of the cyclotron in order to make the accelerator more compact, and thus reduce the overall cost of the cyclotron complex.

Why is it important to make cyclotron compact:

- Compact mean less materials (steel and copper) used for production
- Compact means that the bunker is smaller, and for medical equipment it is very important, as usually space around medical facilities is restricted.

How can we make cyclotron more compact?

- Higher magnetic field makes poles smaller
- Higher frequency of RF system
- Smaller coil

Increase of magnetic field leads to problems with flutter, it becomes more difficult to manage shimming of the magnet, and injection and extraction becomes way more challenging. That is why author has decided to follow other 2 options to make cyclotrons more compact and cheaper.

If we look at frequency allocation chart [2] we will find out that the highest frequency in medical cyclotrons is 106.8 MHz, used by IBA C235 [3] is also the end of the lane dedicated for FM Radio, but between 108 and 136 MHz there are frequencies dedicated for aeronautical navigation, therefore it is not suitable for cyclotron. Author believes that the optimal frequency is 145 MHz, which is dedicated for amateur use. If we use 145 MHz as harmonic 6 the central field would be 1.55 Tesla.

Harmonic 6 means that about 30 degrees of azimuthal width is required for each cavity. But what if we don't use all 6 cavities, but instead have 3 sectors of 90 degrees and 3 valleys of 30 degrees for RF system. In this case more steel means less amper-turns in coil needed, meaning smaller coil. As the result we get a much more compact cyclotron. The 15 MeV cyclotron (see Fig. 1, Table 1) in more details presented in [4]. For the 230 MeV [5] cyclotron 3 sectors is not a suitable option due to resonances induced by 3rd harmonic of magnetic field. Instead, 4 sectors were used and same 6th harmonic 4x145 MHz RF cavities were used operating in push-pull mode. The goal is to create maximal level of unification between all cyclotrons in the line-up between 15 MeV and 230 MeV covering all the range, used in medical applications.

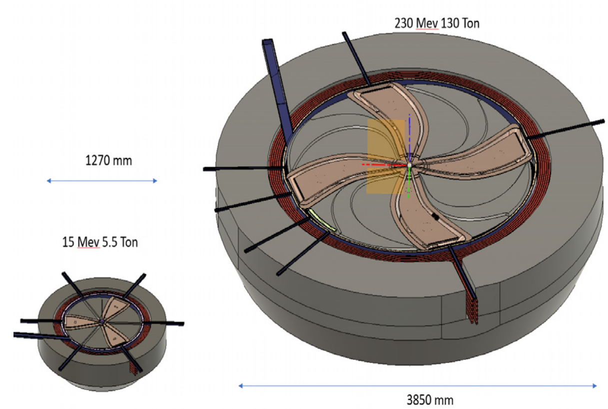

Figure 1: Overview of 15 MeV and 230 MeV cyclotrons.

Table 1: Parameters of 15 MeV Cyclotron

Parameter	
Magnet type	Compact, copper coils
Number of sectors	3
Ion source	Internal/External
Final energy MeV	15
Final radius, mm	360
Mean magn. field, T	1.55
Dimensions (height×diameter), mm	750 × 1290
Weight, kg	5500
Hill/Valley field, T	2.1/0.3
Hill/Valley gap,mm	25/210
A*Turn number	27 000
Magnet power consumption, kW	25
RF freq., MHz	145
Harmonic number	6
Voltage, kV	30-50
Turn number	120
RF power, kW	8
Beam intensity, μA	Up to 1000
Extraction type	Stripping foil

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All of the cyclotrons for proton therapy, that were recently developed use superconducting coil: Varian [6], SC200 [7], MSC230 [8]. However, is it necessary? There are many disadvantages of SC coils is expensive cryogenics equipment that requires servicing and consumes power.

In comparison copper coil only requires water cooling, and because water cooling is also required for RF system, it is convenient to copper coil instead of superconducting. It is a common misconception that superconducting coil can save power, cryogenics equipment still requires a lot of power and with RF system and all the auxiliary systems power consumption of the cyclotron is not defined by just magnet. In fact, usually it is only 20-30% of total power consumption.

The proposed design of the 230 MeV resistive cyclotron (see Table 2) is almost as compact as superconducting MSC230, but much cheaper due to rather small copper coil instead of a SC coil.

Table 2: Parameters of 230 MeV Cyclotron

Parameter	
Magnet type	Compact, copper coils
Number of sectors	4
Ion source	Internal, PIG
Final energy MeV	230
Final radius, mm	1200
Mean magnetic field, T (center/extraction)	1./2
Dimensions (height×diameter), mm	2000 x 3850
Weight, tonne	130
Hill, Valley gap, mm	20/50 mm, 460 mm
A*Turn number	80 000
Magnet power consumption, kW	95
RF freq., MHz	145
Harmonic number	6
Voltage, kV	30-110
Turn number	600
RF Power, kW	80
Beam intensity, μA	Up to 100
Extraction type	1ESD, 2 correctors

Both cyclotrons were simulated in CST studio (see Figs. 2, 3 and 4) and full beam dynamics studies performed.

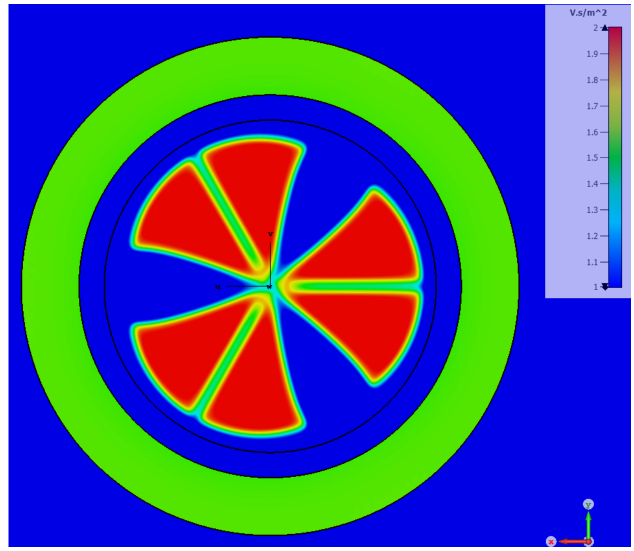

Figure 2: Magnet flux distribution of RC3/6.

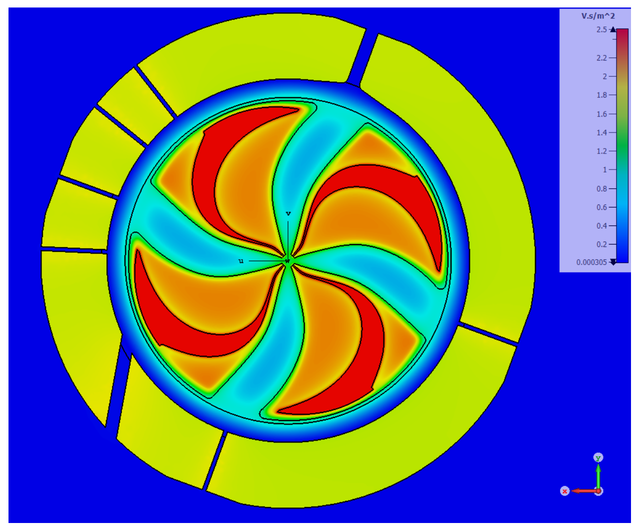

Figure 3: Magnet flux distribution of 230 MeV cyclotron.

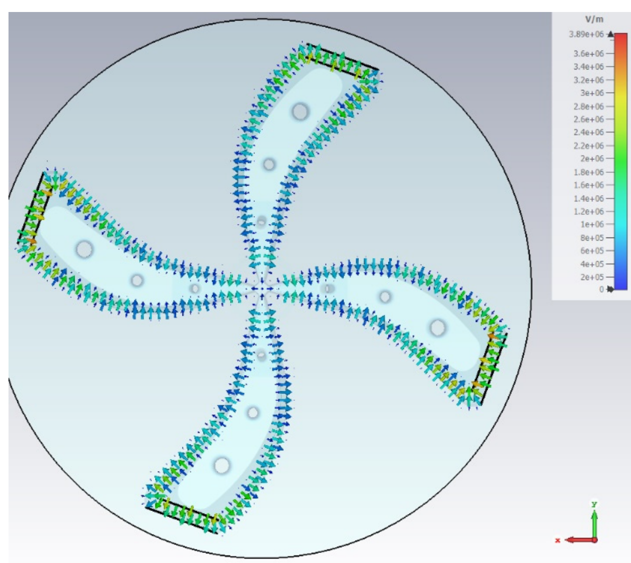

Figure 4: RF system of 230 MeV cyclotron in Push-Pull mode.

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CONCLUSION

The conceptual design of a line of cyclotron, covering the full range of energies used for medical application has been performed for 15 MeV and 230 MeV accelerators. The design is cheap and simple to produce and operate. Author will continue to develop other cyclotron using this scheme for the energies between the currently developed model.

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