SOME REMARKS ON FUTURE ERA COMPRESSORS

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Abstract

The present ERA compressors which produce relativistic electron rings, consist of a set of Helmholtz coil pairs. For future accelerators a high repetition rate is desirable, which can be obtained with a single coil connected with a capacitor and operated with the resonance frequency of the capacitor-inductance loop. In order to fulfill the requirements for the proper focussing of the ring and to minimize the stored energy of the system it is necessary that the coil has a special geometry (flat cylinder) and winding distribution which is similar to that of a watch spring. A comparison between a conventional compressor and a spring coil compressor shows, that this new concept needs an energy per ring which is about one order of magnitude smaller than that of a conventional one.

I. Introduction

The electron ring compressors which are built up to now consist of multi stage Helmholtz coil systems, in which an electron ring is compressed by time adjusted switching of nested Helmholtz coil pairs. If there are no additional field shaping coils, the field index $n=-\delta B_z/\delta r\cdot r/B_z$ is a rapidly varying function of time and radius, because the focussing property of a Helmholtz coil depends on the radius (fig. 2). This variation of the field index during the compression may lead to resonance losses of the ring. Another disadvantage of a multi stage compressor is the complex circuitry. Several capacitor banks must be charged, switched to the coils and crowbarred. For an operation with a high repetition rate this is a rather difficult and costly way, because of the many high current switches and because of all of the energy that is dissipated after each compression cycle. A spring coil compressor can be driven periodically by an oscillator which is operated at the resonance frequency of the coil-capacitor loop. Such a system does not need sophisticated switching elements. The losses are reduced to 4 times the ohmic losses during the compression stage only.

II. Compression dynamics

The magnetic field of a single coil which is driven by the same current I in all of the windings may be written in the following form:

$$B(r,t) = \hat{B}(r)\cdot\hat{I}_n(t) \qquad (1)$$

$\hat{I}_n(t)$: normalized dimensionless current factor

$\hat{B}(r)$: magnetic fields for a current of 1 Ampere.

Because the current factor I cancels in the expression for the field index, the field index depends only on the radius r and not on the current I. In a single coil compressor the field index is already sufficient to define the magnetic field and the vector potential in the midplane:

$$\hat{B}(r) = B_i \exp\left(-\int_{r_i}^{r} n(r)/r\, dr\right) \qquad (2)$$

$$\hat{A}_\phi(r) = B_i\int_0^r r\cdot\exp\left(\int_{r_i}^{r} -n(r)/r\, dr\right)dr \qquad (3)$$

r_i: injection radius

B_i: injection field

If an electron ring with momentum p_i is brought into a magnetic field its canonical momentum is a constant of the motion:

$$\begin{aligned} pr - A_\phi r &= B_z r^2 - A_\phi r \\ &= (\hat{B}r^2 - \hat{A}_\phi r)I_n = \text{const} \end{aligned} \qquad (4)$$

The current I_i which is necessary for the injection is defined by

$$I_i = \frac{p_i c}{e_o\cdot r_i\cdot \hat{B}(r_i)}\cdot\text{Ampere} \qquad (5)$$

e_o: electron charge

The current I(r) which is necessary to drive the ring from the radius r_i to r can be expressed by r and n(r) only:

$$I/I_i = \frac{\hat{B}_i r_i^2 - \hat{A}_{\phi i} r_i}{\hat{B}r^2 - \hat{A}_\phi r} \qquad (6)$$

$$= \frac{r_i^2 - \int_0^r r\exp\left(\int_r^{r_i} n(r)/r\, dr\right)dr}{r^2 \exp\left(-\int_{r_i}^{r}\frac{n(r)}{r}dr\right) - \int_0^r r\exp\left(\int_r^{r_i}\frac{n(r)}{r}dr\right)dr}$$

The momentum p depends on r only and the momentum ratio may be expressed by:

$$p(r)/p_i = \frac{r \cdot B(r) \cdot I(r)}{r_i B_i I_i} \tag{7}$$

$$= r/r_i \cdot I/I_i \cdot \exp\left(\int_r^{r_i} n(r)/r \, dr\right)$$

During the compression the field index pattern is of great importance (betatron resonances). Therefore in the following three types of field index curves and their consequences are discussed.

III. Influence of field index

1) $n = n_i$

Such a field index is possible only in the outer region of the coil. Because of the need of extracting the ring after compression the field index must go to zero during extraction. However for a rough estimate this fact may be neglected.

The current ratio for this scaling field is just $I/I_i = (r_i/r)^{2-n_i}$ and its compression ratio $p/p_i = r_i/r$. If the current ratio is expressed by the compression ratio

$$I/I_i = (p/p_i)^{2-n_i} \tag{8}$$

it is evident that compression with a low field index is more power consuming than with a high.

2) $n = n_i(r/r_i)^2$

This field index is approximately the same as for the single Helmholtz coil pair in fig. 2. The current ratio is

$$I/I_i = \frac{1 + (n_i - 1)\, e^{-\frac{n_i}{2}}}{1 + (n_i (r/r_i)^2 - 1)\, e^{-\frac{n_i}{2}\left(\frac{r}{r_i}\right)^2}} \tag{9}$$

If $n_i = 1$ one gets the following current and compression ratios:

$$I/I_i = 0.67(r_i/r_{comp.})^2; \tag{10}$$

$$p/p_i = 1.1\, r_i/r_{comp.}$$

In this case only half of the current is necessary to get the same momentum compared with the case of field index zero.

3) $n = \begin{Bmatrix} n_i : r_i > r > r_1 \\ 0 : r_1 > r \end{Bmatrix}$

This field index pattern is a rough approximation of a spring coil field with a field index that is constant in the outer coil region and decreases to zero in the inner coil region. The resulting current and momentum ratios may be expressed analytically:

$$I/I_i = \frac{1 + \frac{n_i}{2(1-n_i)}\left(\frac{r_1}{r_i}\right)^{2-n_i}}{\begin{Bmatrix} 1 \\ \frac{2-n_i}{2-2n_i} \end{Bmatrix}\left(\frac{r}{r_i}\right)^{2-n_i} + \begin{Bmatrix} 1 \\ 0 \end{Bmatrix} \frac{n_i}{2(1-n_i)}\left(\frac{r_1}{r_i}\right)^{2-n_i}} \tag{11}$$

$$p/p_i = \frac{r \cdot I \cdot r_i^{\,n}}{r_i \cdot I_i \cdot \max\{r, r_1\}} \tag{12}$$

Fig. 1 shows the two functions for $n_i = 0.8$ and $r_1 = 0.067$ m. The current ratio curve is not as steep as in the constant field index case. The same is valid for the momentum ratio. That implies that a ring is compressed without being accelerated azimuthally very much.

IV. Comparison between Helmholtz and spring coil compressor

Based on these considerations a spring coil was computed. This coil has a nearly constant field index between the radii 0.22 m and 0.1 m. The geometry and the main parameters of such a cylinder coil compressor are given in fig. 1. As one would expect the current ratio in the constant field index region is flatter than in the Helmholtz coil (fig. 2). Because normally the current rises linearly the constant field index region is passed very fast such that the advantage of the constant field index is weakened. At the same time the momentum ratio is also very flat, which means that the electron ring gains less momentum than in a Helmholtz coil compressor. This is an advantage for a subsequent hf acceleration because the transverse energy of the electron ring is lower which gives a better mass ratio between electrons and ions. For expansion acceleration on the other hand a high compression Ratio is necessary because the azimuthal momentum is the source for the axial acceleration. It is therefore necessary to compress to smaller radii in order to get the same momentum as in a Helmholtz coil compressor. A comparison for both types must consider these two aspects.

The comparison is made between a continuously driven (1 kHz) spring coil and a Helmholtz coil system in the normal operation mode (quarter wave and crowbar). Because nearly all the energy of a Helmholtz system is wasted in the crowbar time it needs much more energy than a spring coil where no crowbar is necessary. For this reason the spring coil needs only a tenth or less of the energy per compression cycle compared with the Helmholtz coil system while its physical parameters like momentum ratio, compression time and radius are similar or even better. Furthermore it is clear that a Helmholtz coil system would meet with many difficulties if it would be operated with 1 kHz:

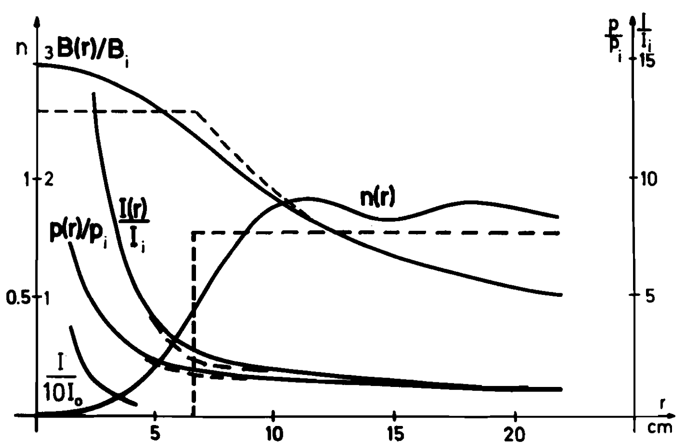
1) The switching spark gaps would burn away very quickly and their recovery time must be reduced.
2) The recharging of three big 30 kV capacitor banks within milliseconds would be extremely difficult.

Table 1: Comparison between Helmholtz and cylinder coil compressor

	Helmholtz coil	spring coil	
Energy in	30 kJ	17 kJ	100 kJ
Compression radius	3 cm	3 cm	1.7 cm
Momentum ratio	6	3.5	6
Compression time	170 μsec	175 μsec	435 μsec
Charging voltage	30 kV	30 kV	
Energy/ Compression cycle	30 kJ	0.26 kJ*	4 kJ*
Field index	oscillating	constant and	decreasing
Coil circuitry and switching problems	complicated	simple	

*computed for a fullwave and with the assumption of 10 mm² thick copper windings with a total ohmic resistance of 7.5 m Ω.

Fig. 1 - 2: Magnetic field ratio $B(r)/B_i$ field index $n(r)$, current ratio $I(r)/I_i$ and momentum ratio $p(r)/p_i$ for different compressors.



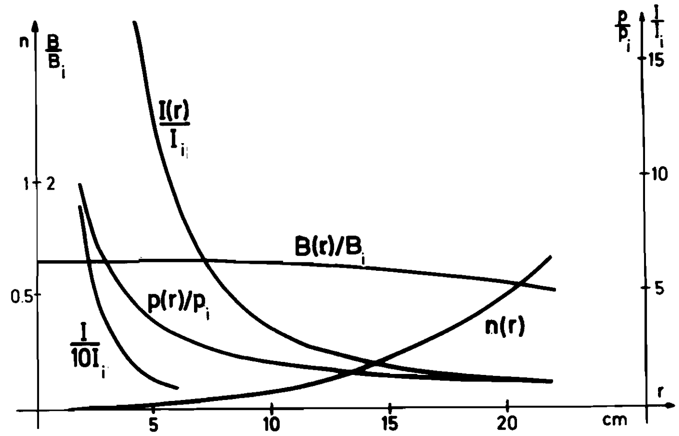


Fig. 1: A hypothetical coil (--) with n_i=0.8 down to r_1=6.7 cm and a spring coil (——) with R = 5×28.5, 28, 27.5, 23, 20,18, 16, 14, 11, 10, 9, 8, 7, 6.5, 6, 6 cm; Z = ± 4, ± 4.5, ± 5, ± 5.5, 15×±6, ± 6.5 cm; L = 330 μH

Fig. 2: Single Helmholtz coil with R = 6 × 36, 6 × 33.4 cm; Z = 4×±32.5, 4×±31, 4×±29.5 cm; L = 100 μH