ECRIPAC: A NEW CONCEPT FOR THE PRODUCTION AND ACCELERATION TO VERY HIGH ENERGIES OF MULTIPLY CHARGED IONS USING AN ECR PLASMA

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ABSTRACT A concept of a new ECR device aimed to produce pulsed beams of ions accelerated up to 0.5 GeV/nucleon without the help of any conventional accelerator is exposed.
The main idea is the conjuction of two fundamental physical principles experienced formerly in the PLEIADE and GYRAC devices.

1. PURPOSE OF THE PROPOSAL Up to recently, for heavy ion acceleration, one used sources with low charged ions, coupled to simple or cascading accelerators with strippers. The basic scheme is seen on fig. 1a.
The invention of the ECR ion sources for highly charged ions simplified in many cases the accelerator scheme (fig. 1b).
The purpose of the present proposal is to obtain the same kind of performance without any ion accelerator using only a dedicated ECR plasma device (fig. 1c). However, as the energy of the ions is adjustable, the device, which we have named ECRIPAC (Electron Cyclotron Resonance Ion Plasma ACcelerator), could satisfy not only high energy physicists but also atomic and surface physicists, as well as practical users of energetic ion beams for medical and technological applications.
Its main idea is to superpose two well known ECR principles which both already worked experimentally but separately.
We call them for simplicity and according to their original names :

a) the PLEIADE principle, [1,2,3,4,5]
b) the GYRAC principle [6,7,8,9,10].

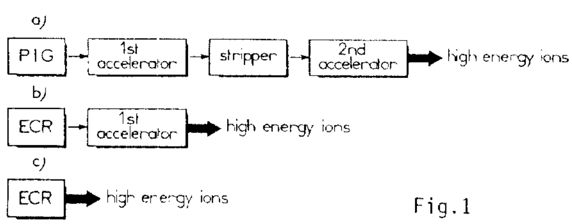

Fig.1

2. CONJUNCTION OF THE TWO PRINCIPLES Let us imagine a PLEIADE magnetic structure with a very high magnetic field so that the ECR condition is nowhere fulfilled (see fig. 2).
Let us apply in a small area around some point X_0, near the top of the mirror, an auxiliary *reverse* magnetic field which is time dependent. The peak intensity of the reverse magnetic field is chosen by such a way that the compound field in the point X_0 is slightly lower than the value B_0 which is being equal to the non-relativistic resonant value $B_0 = \omega_{hf} \cdot c[m_0/e]$.
If one fill in this small magnetic mirror trap around X_0 with an multiply charged ions ECR plasma from an ECRIS such as, say, MINIMAFIOS, then that plasma will be trapped there.
Now let us continuously *decrease the reverse field* : the compound field increases (fig. 3, dashed lines) and GYRAC begins to work. The result is that the perpendicular kinetic energy of the whole electron component increases together with the compound magnetic field. The increase of the electron magnetic moment (which is proportional to the perpendicular kinetic energy of electrons) results in the axial compression of the plasma which is more and more concentrated near the plane X_0. This, in its turn, yields an increase of the density of the plasma which takes a shape of a thin disk fixed on the plane X_0.
When the reverse field is completely cancelled, all the plasma electrons have aquired a perpendicular energy $W_{\perp e}^{(s)} = 0.51\ [\ (B_s/B_0) - 1]$ MeV (1). This energy, in contrast to the PLEIADE alone, *is as high as we want* depending only on B_s/B_0.
At that moment the static magnetic gradient is completely restaured and the electrons are subjected to a very strong diamagnetic force $-\mu\nabla B$ along the magnetic lines. Due to the inertia of ions, the plasma is *disrupted* and a small fraction of multiply charged ions is accelerated together with the diamagnetically accelerated electrons (see fig. 4).

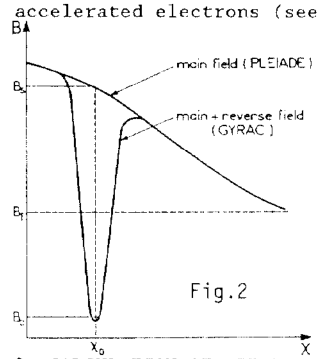

Fig.2

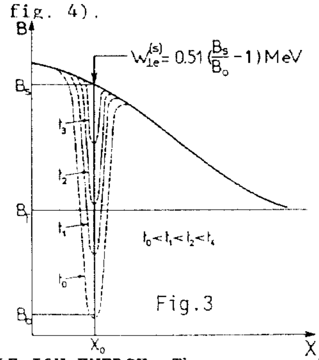

Fig.3

3. CALCULATION OF ATTAINABLE ION ENERGY The source of parallel energy for ions and electrons is the perpenducular energy of electrons :
$n_e W_{/\!/e}^{(f)} + n_i W_{/\!/i}^{(f)} = n_e \Delta W_{\perp e}^{(f)}$ (2) where $\Delta W_{\perp e}^{(f)}$ is the fraction of the initial energy $W_{\perp e}^{(s)}$ given by
$\Delta W_{\perp e}^{(f)} = W_{\perp e}^{(s)} [1 - (B_f/B_s)]$ (3) "f" and "s" meaning "final" and "starting" respectively.
In the accelerated bunch the velocities of electrons and ions along the magnetic field are equal, $v_{/\!/i} = v_{/\!/e}$, which means that $W_{/\!/e}^{(f)} = (\gamma_f\ m_0/M_i)\ W_{/\!/i}^{(f)}$ (4) where γ_f is the final relativistic factor for electrons.
Inserting (4) and (2) into (2), one obtains the ion energy per nucleon
$W_{/\!/i}^{(f)}/A = W_{\perp e}^{(s)} [1 - (B_f/B_s)] / [\gamma_f (m_0/m_p) + A(n_i/n_e)]$ (5)
Here m_p is the proton rest mass, A is the mass number of ions. Remember that
$W_{\perp e}^{(s)} = m_0 c^2 [(B_s/B_0) - 1] = m_0 c^2 (\gamma_s - 1)$ (6) and then

$$\boxed{W_{/\!/i}^{(f)}/A = m_0 c^2 \frac{(\gamma_s - 1)[1 - (B_f/B_s)]}{\gamma_f (m_0/m_p) + A(n_i/n_e)}}$$ (7) . This is the final formula for the ion energy per nucleon in a ECRIPAC device.

Let's now analyze two extreme cases.
Case 1 : $n_i \lll n_e$ The accelerated ion density is so small that the second term in the denominator (7) can be neglected. In this case (7) turns to $W_{/\!/i}^{(f)}/A = m_p c^2 [(\gamma_s - 1)/\gamma_f][1 - (B_f/B_s)]$ (8). In practice, for instance, if $[(\gamma_s - 1)/\gamma_f] \simeq 1$ and $B_f/B_s \sim 0.5$ we have
$W_{/\!/i}^{(f)}/A = m_p c^2 .\ 0.5 = 470$ MeV/nucleon. Thus one would obtain 5.6 GeV for Carbon ions, 18.8 GeV for Argon ions and 112 GeV for Uranium ions.
Note, that in this extreme case the ion energy is

independant of the initial electron energy $W_{\perp e}^{(s)}$. The only condition is that $\gamma_s \gg 1$, i.e. $W_{\perp e}^{(s)} \gg 0.51$ MeV which is easy to satisfy.
Case 2 : $n_i = n_e$ In this case the 1st term of the denominator in (7) can be neglected and then we have $W_{/\!/ i}^{(f)} = m_0c^2(\gamma_s - 1)[1 - (B_f/B_s)]$ (9) or

$W_{/\!/ i}^{(f)} = W_{\perp e}^{(s)}[1 - (B_f/B_s)]$ (10) which corresponds exactly to the PLEIADE case. For example with $\gamma_s = 100$, $W_{\perp e}^{(s)} = 50$ MeV, $B_f = 0.5\ B_s$ we obtain $W_{/\!/ i}^{(f)} = 25$ MeV which is still interesting for many purposes.

4. MAXIMAL RATE OF ACCELERATION Ions are accelerated by the ambipolar electrical field div E = 4 π ρ (11) where ρ is the electrical charge density. Since at the end of the GYRAC stage the plasma is expected to have the shape of a disk, we can apply div E = E/d (d is the depth of the plasma disk) and then we can re-write (11) under the form : $E/d = 4\pi e n_e$ (12) so that the accelerating field is simply $E = 4\pi e n_e d$ (13), E being determined by the product $n_e d$, the accelerating effect is the same for a dense but thin plasma as for a dilute but thick plasma. The depth of a plasma produced during the GYRAC stage is much smaller than its diameter Φ (which roughly equals to $4c/\omega_{hf}$). In practice, with $f_{hf} = \omega_{hf}/2\pi = 2.45$ GHz for example, Φ is about 8 cm and the depth of 1 cm. Such a disk gives a rate of acceleration

$R = 1.8\ 10^{-10}\ Zn_e d$ (MeV/meter) (14) where Z is the charge state of accelerated ions.
Typical values of R at different n_e and Z with d = 1 cm are given in the table :

n_e cm^{-3}	$3\ 10^{10}$	$1\ 10^{11}$	3.10^{11}	$1\ 10^{12}$	$3\ 10^{12}$	$1\ 10^{13}$
R MeV/m	5.4 Z	18 Z	54 Z	180 Z	540 Z	1800 Z

5. PLASMA DENSITY AND MAGNETIC COMPRESSION We have seen that as high is the plasma density as high is the acceleration rate and as short is the ECRIPAC device.

Whereas, in an ECR plasma, to increase n_e one has to increase ω_{hf} $\left(n_e \sim \omega_{hf}^2\right)$. For instance, to reach $n_e = 3.10^{11}$ cm^{-3} a frequency in the range of 10 GHz is needed. Such a high frequency requires a high ECR magnetic field and, consequently, a very high B_s to reach a good γ_s.
However, one can reach a high density with a considerably lower frequency, when a magnetic compression of an initial low density GYRAC plasma can be applied.
The physical mechanism of the magnetic compression is very well known and was successfully reproduced for an ECR plasma [11]. During the magnetic compression in a magnetic bottle n_e increases proportionnally to B, while $W_{\perp e}$ increases proportionnaly to $\sqrt{B}$.

6. OPTIMAL MAGNETIC FIELD GRADIENT AT START Let's now consider the starting period of ion acceleration. Ions feel the action of two opposite forces : electrostatic Z.e.E and inertia $M\ddot{x}$, where $\ddot{x}$ is the value of *electron* acceleration by the diamagnetic force - μ∇B.
To keep ions inside the electron swarm, one has to satisfy the inequality $M\ddot{x} \leqslant ZeE$ (15) where :

$\ddot{x} = \mu\nabla B/\gamma_s m_0 = \left(W_{\perp e}^{(s)}/\gamma_s m_0\right)(\nabla B/B)$ (16)
Ions which do not satisfy this inequality are *shaked out* and therefore are not accelerated (fig. 4). Combining the two last expressions we get

$\left(Mv_{\perp e}^{(s)2}/2\right)(\nabla B/B) \leqslant ZeE$ (17). Since $v_{\perp e}^{(s)} \simeq c$, we have

$(\nabla B/B) \leqslant \left(2ZeE/A\ m_p c^2\right) = (Z/A)\left(2eE/m_p c^2\right)$ (18) or

$\nabla B/B \leqslant 1.9\ 10^{-4}(Z/A)E$ (19) where E is in V/cm, $\dfrac{\nabla B}{B}$ is in cm^{-1}. Using $E = 4\pi e n_e d$, we get finally

$\boxed{\nabla B/B \leqslant 7.2\ 10^{-13}\ (Z/A)\ n_e d}$ (20). Here n_e is in cm^{-3}, d is in cm.
The obtained conditions (20) is quite mild. For example, to accelerate Argon ions with $Z \geqslant 10$ by a plasma with $n_e = 3.10^{11}$ cm^{-3}, d = 1 cm, the magnetic field gradient should not exceed the value $\nabla B \leqslant 5.4\ 10^{-2}$ B, where B is in Gauss, ∇B is in Gauss/cm, which is quite easy to satisfy. In this case all low charge ions ($Z \leqslant 10$) are shaked out and are not accelerated in contrast to highly charged ions Ar^{10+}, Ar^{11+}, ... which are accelerated up to GeV range energies.

7. NUMBER OF ACCELERATED IONS PER PULSE As it has been shown in section 3 the highest ion energy is achieved at so small n_i that the following condition is satisfied : $\gamma_f(m_0/m_p) \gg A(n_i/n_e)$ (21). This relationship allows to estimate the value A n_i, i.e. *the number of nucleons per cm^3* which can be accelerated to the highest energy :

$\boxed{An_i \ll \gamma_f n_e(m_0/m_p)}$ (22). To have a numerical value we rewrite it as $An_i = 0.1\ \gamma_f n_e(m_0/m_p)$ (23) or

$\boxed{An_i = 5.4\ 10^{-5}\gamma_f n_e}$ (24).

8. PLASMA STABILITY In the most interesting case ($n_i \lll n_e$) the plasma is strongly charged and looks to be unstable because of repulsion of the electrons. However, this difficulty is possibly easy to overcome due to two effects :
- magnetic attraction of relativistic electrons,
- short time of ion acceleration.

The first effect *reduces* the Coulomb repulsion force *by the factor* γ^2. So, it relaxes the repulsion efficiently but is unable to cancel totally these forces. The *weak* remaining repulsion results in a *slow* axial spread of the electron swarm. But, if the accelerating force - μ∇B is larger than the spreading force $4\pi e^2 n_e d/\gamma^2$, then the acceleration cycle is finished before the electron swarm is spreaded.
Thus, the condition of stability is $\mu\nabla B > 4\pi e^2 n_e d/\gamma^2$ (25). Since $\mu = W_{\perp e}/B = m_0c^2(\gamma - 1)$, then we have $m_0c^2(\gamma-1)(\nabla B/B) > 4\pi e^2 n_e d/\gamma^2$ (26) or

$$\frac{\nabla B}{B} > \frac{4\pi e^2}{m_0 c^2}\frac{n_e d}{\gamma^2(\gamma-1)} = 3.6\ 10^{-12}\frac{n_e d}{\gamma^2(\gamma-1)} \quad (27)$$

where (∇B/B) is in cm^{-1}, n_e is in cm^{-3}, d is in cm.
On the other hand, as we have shown in Section 6, the magnetic gradient is limited by the *shake out* condition $\nabla B/B < 7.2\ 10^{-13}(Z/A)\ n_e d$ (28).
Combining (27) and (28) we have a stability condition

$\boxed{\gamma^2(\gamma-1) > 5\ (A/Z)}$ (29). So, to ensure the stability of the electron swarm, the initial electron energy should be high enough.
It is easy to see that the condition (29) is in fact *very soft*. For instance, to accelerate even so heavy ions as, say, U^{30+} up to 100 GeV range energy, the stability requires only $\gamma_s > 3.4$ which corresponds to $W_{\perp e}^{(s)} > 1.2$ MeV.

9. CONCEPTUAL DESIGN OF ECRIPAC DEVICE An ECRIPAC device conceptually consists in a plasma injector, a GYRAC section and a PLEIADE section (see fig. 5).
The injector, of ECR type, produces a cold highly ionised plasma which diffuses to the GYRAC section under differential pumping.

Both GYRAC and PLEIADE sections represent ECRIPAC itself and are a cylindrical metallic tube serving as a resonant multimode or monomode cavity subjected to a solenoidal magnetic field. The main magnetic field is created by a serie of magnetic coils and is either stationary or pulsed dependingly on the mode of operation. A small reverse field pulsed coil is located in the GYRAC section just between first and second coils. The cavity is limited in both sides by diaphragms aimed to increase the quality factor of the resonator. The left (see fig. 5a) diaphragm determines the diameter of the injected high ion charge ECRIS plasma while the right one have a large enough orifice to allow accelerated ions and electrons pass through to the target. The fig. 5b shows the axial distribution of the magnetic field during the reverse coil action and before (or after) this coil is energized.

Fig. 6 shows the scenario for the single-pulse-mode operation of an ECRIPAC. In this case, the main field is monitored in long pulse regime (some milliseconds) in contrast to the case of periodic-pulse-mode when the steady-state magnetic field is apparently more advantageous.

As it is seen from Fig. 6, the reverse field pulse is much shorter (10 - 100 μs) and is applied on the top of the main field pulse when the magnetic field is nearly time independent.

The ECRIS injector works during a short time between the moment t_1 when the reverse field is maximum and the moment t_2 when it reaches an ECR value.

At this moment, the microwave pulse is applied and the GYRAC process starts. The microwave pulse is stopped in the moment t_3 when the electron energy is high enough (~ 1 MeV). During the time interval between t_3 and t_4 the adiabatic compression of the GYRAC produced plasma takes place. At t_4 the PLEIADE mechanism produces a diamagnetic shock resulting in a *skake out* of low charge ions and acceleration of high charge ions.

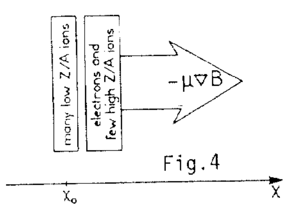

Fig.4

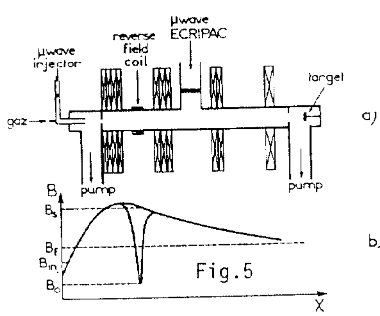

Fig.5

10. TWO EXAMPLES OF ECRIPAC DEVICES

10.a. ECRIPAC with extreme theoretical energy :

1.	Frequency $\omega_{hf}/2\pi$, GHz	2.45
2.	Microwave pulse duration, ms	0.1
3.	Pulsed microwave power needed, kW	20
4.	ECR magnetic field B_0, kGs	0.87
5.	Magn. field after GYRAC stage B_G, kGs	1.74
6.	Magn. field after compression B_s, kGs	26.1
7.	B_f/B_s	0.5
8.	Electron energy after GYRAC stage $W_{\perp e}$, MeV	0.5
9.	Electron energy after compression $W_{\perp e}^{(s)}$, MeV	2
10.	Injected plasma density, cm^{-3}	$2\ 10^{10}$
11.	Plasma density after compression, cm^{-3}	3.10^{11}
12.	Starting magnetic field gradient for Z/A ⩾ 0.25, kGs/cm	1.4
13.	Number of accelerated nucleons per pulse	$2.6\ 10^8$
14.	Energy per nucleon, GeV/nucl.	0.5
15.	Optimal length of acceleration, meter	35

10.b. ECRIPAC as a medium energy nuclei provider : A device of such a kind could be an ECRIPAC for 10 MeV/nucleon ended or not by a foil or gaseous stripper with a total number of nucleons as high as 10^{11} per pulse. Here the first 11 quantities are the same while some others are to be changed. They are in particular :

12.	Starting grad B for Z/A ⩾ 0.05, kGs/cm	0.26
13.	Optimal length of acceleration, meter	4
14.	Number of accelerated Argon ions per pulse (after stripper Z = 18)	$2.5\ 10^9$
15.	Number of accelerated Xenon ions per pulse (after stripper, Z = 54)	$0.8\ 10^9$

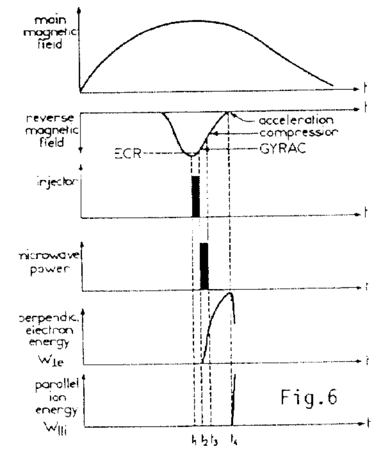

Fig.6

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