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# GENERATION OF RELATIVISTIC ELECTRON BUNCHES IN PLASMA SYNCHROTRON GYRAC-X FOR HARD X-RAY PRODUCTION

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– Experiment performed on plasma synchrotron Gyrac-X operating on synchrotron gyromagnetic autoresonance (SGA) is described. Gyrac-X is a compact plasma x-ray source in which kinetic energy of relativistic electrons obtained under SGA converts into x-ray by falling e-bunches on to a heavy metal target. The plasma synchrotron acts in a regime of a magnetic field pulse packet under constant level of microwave power. Experiments and numerical modeling of the process showed that such a regime allowed obtaining dense short lived relativistic electron bunches with average electron energy of 500 keV – 4.5 MeV. Parameters of the relativistic electron bunch (energy, density and volume) and dynamics of the electron bunches can be controlled by varying the parameters of the SGA process. Possibilities of x-ray intensity increase are also discussed.

## 1. Introduction

Synchrotron gyromagnetic autoresonance (SGA) is electron cyclotron resonance (ECR) in plasma confined in a simple mirror trap in a magnetic field smoothly growing in time. Unlike ECR in case of SGA the relativistic change of the electron mass is compensated with the change of the magnetic field in time $B(t)=B_0[1+b(t)]$ ($B_0=m_0c\omega/e$, $m_0$ and $e$ are the rest mass and the charge of the electron, $\omega$ - angular frequency of HF field, $b(t)$ - monotonically growing function of time. As a consequence the resonant condition $\omega \cong \omega_{ce}$ ($\omega_{ce} = eB(t)/m_0\gamma c$, $\gamma = (1-v^2/c^2)^{-1/2}$, $v$ – velocity of the electron) is maintained automatically. Under SGA the electron phase $\varphi$ (phase is the angle between the vector of electric field strength **E** and the vector of the impulse of the electron **p**) is being trapped into such an interval that average time energy of the electron grows in accordance with the law of the magnetic field growth: $W(t) \cong b(t)$, where $W = \gamma - 1$ – kinetic energy of the electron in $m_0c^2$ units. The maximum value of energy of electrons gained during SGA is limited only by radiation loss. The average electron energy is determined by the value of the magnetic field and doesn't depend on the microwave field strength: $\widetilde{W}(keV) \cong 511 \cdot [B(t)/B_0 - 1]$.

The possibility of such a process was shown theoretically [1] and experimentally [2, 3, 7]. Experiments performed on plasma synchrotrons Gyrac-0, Gyrac-D and Gyrac-X as well as simulation of SGA show that variation of SGA parameters (initial plasma density and its dimension, electric field strength, velocity of magnetic field growth) gives a possibility of obtaining of different plasma objects. In case of comparatively small initial radial plasma size and plasma density one can obtain an accelerated bunch of electrons. In cases of greater plasma dimension and density relativistic plasma formation is generated. The work is aimed to experimental and numerical study of relativistic electron bunches generation and their transportation to a heavy metal target for x-ray production.

## 2. Experimental device

Gyrac-X is a plasma x-ray source in which kinetic energy of relativistic electrons obtained under SGA converts into x-ray by falling of electron bunches on to a heavy metal target.

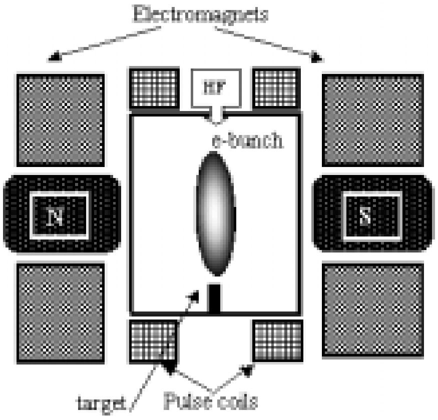

*Fig. 1. Sketch of the Gyrac-X plasma synchrotron*

A sketch of Gyrac-X is represented in Fig. 1. The $TE_{111}$ cavity is exited by microwave at the frequency 2.4 GHz, 350 W. The static magnetic mirror field produced by coils (L=15 cm, $R \cong 1.05$) satisfies the ECR condition in the midplane of the cavity. Pulse coils produce the pulse magnetic field: $t_{incr} \cong (100-500)\,\mu s$, $B_{\max} \cong 500\,G$. The stainless wall of the cavity allows penetration of pulse magnetic field with a small decrease of its strength.

Electromagnets used in Gyrac-X experiments give it possible to form static magnetic field profiles for different experimental scenarios: 1) increasing pulse magnetic field [2, 3], 2) reverse pulse magnetic field [6]. The obtained experimental data showed that in the first case SGA-trapping is greater by factor of 2 in comparison with the case of reverse magnetic field. The installation allows running the heating process in the regime of a pack of SGA-pulses [6] but under constant level of microwave power.

Diagnostic of the relativistic plasma produced were performed by undertaking analysis of the bremsstrahlung radiation from gas as well as from a W-target (1.5x1.5mm$^2$) placed into relativistic plasma area. X-ray measurement were made by a NAI(Tl) scintillator spectrometer (crystal 25x25 mm$^2$, the detection efficiency of photons with energy 100-300 KeV is no less than 50%) in the regimes of amplitude analysis and registration of x-ray total photon flux intensity. The x-ray detector system was calibrated against a primary standard - $\gamma$-source Cs$^{137}$, Na$^{22}$ of known intensities. The collimated x-ray telescope collects photons from a volume of hot-electron location. The electron bunch radial dimension was defined by bremsstrahlung photon flux from the target moving along the radius.

Diagnostics of produced relativistic plasma were performed making analysis of the bremsstruhlung radiation from gas as well as from a W-target placed into the relativistic plasma location. Figure 2 presents oscilloscope traces of such a flux at fixed radius and shows that at the peak of the SGA regime a copious amount of emission is detected, which is obviously radiated by hot electrons colliding with the target. Determined by this means the value of the radius corresponds to the expected relativistic Larmor radius, which only depends on the maximal value of electron energy at a given value of the pulse magnetic field strength. Moreover, the energy of most of the energetic individual bremsstrahlung photons from gas measured during amplitude analysis equals the expected value of electron energy at a given value of the pulse magnetic field strength.

Values of density and average energy of trapped electrons are obtained by integral measurement and amplitude analysis from gas. Experiments and numerical modeling of the process showed that such a regime allowed to obtain dense short lived electron bunches. Lifetime and densities of the electron bunches were determined by initial plasma parameters, microwave electric field strength, velocity of magnetic field growth and repetition rate of SGA-pulses. The measurement of intensity of radiation from gas showed that its maximum power is equal $6 \cdot 10^4\,\text{MeV/s}$ at rise time of magnetic field 100 μs, relativistic plasma density - $4 \cdot 10^8\,\text{cm}^{-3}$). The radiation power depends on the rise time of pulse magnetic field – a shorter rise time of magnetic field affects the SGA process by better trapping condition for the electrons of initial plasma.

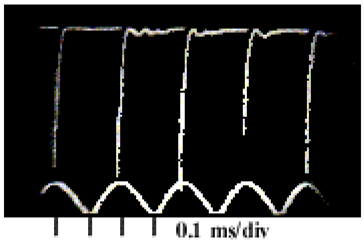

*Fig. 2. Oscillogramms of x-ray flashes from the target (upper) and pulse magnetic field (lower)*

Obtained experimental and numerical simulation data showed that time interval during which relativistic bunches fell on a target strongly depends on the rate of magnetic field decrease. Variation of the repetition rate of SGA-pulses resulted in a maximum value of bremsstruhlung intensity at $f \cong 10\,\text{kHz}$.

W-target insertion in relativistic plasma location showed an increase of radiation intensity but only small part of trapped particles falls on it. The intensity strongly depends on location of the target and its size. Insertion of the target inside the cavity deeper than 2.4 cm detunes the resonance.

## 3. Simulation of electron bunches generation and their transportation on to a target

Simulation of SGA was carried out to investigate the main problem of SGA – the problem of trapping of plasma electrons in a regime of autoresonance acceleration and to define the influence of SGA parameters and parameters of initial plasma on trapping conditions. Considering the conditions of experiments 3D-electrostatic model using particles has been applied [4]. Equations for motion of plasma particles were solved by means of leap-frog scheme [5]. The numerical calculations provide information on 3D plasma evolution, trap losses of particles, energy spectra of electrons and ions, and plasma density that are beyond the reach of both analytical methods and 2D simulation. The aims of the simulation: a) to analyze space particles distributions and electron energy spectra dependence on initial conditions (initial plasma density and volume occupied by plasma); b) to determine trapping efficiency of electrons and losses particles from the trap.

To solve this problem a 3D electrostatic model with the use of a CIC scheme is explored. Plasma heating and confinement is simulated for a typical 2.4 GHz plasma synchrotron.

Initially monoenergetic electrons (5 – 50 eV) and ions (1eV) homogeneously distributed in space have random directions of velocities. We simulated a hydrogen plasma beam of densities of $10^{10}\,\text{cm}^{-3}$ axially injected into the cavity and confined in a mirror trap (mirror ratio R=1.02). Microwave electric field strength is taken 3 kV/cm. The velocity of magnetic field growth in time provides average electron energy increase 100 keV/μs. To satisfy requirements of a particle in cell method 10 – 20 particles in a cell are taken. Because of complexity of the problem under investigation, schemes using Cartesian coordinates to solve equations for particles motion as well as Poisson equation have been used as the most cheapest and developed. Equation of motion for each charged particle in the form of Newton-Lorentz

$$\frac{d\mathbf{p}}{dt} = e\left(\mathbf{E}_{hf} + \mathbf{E}_s + \mathbf{E}_{ind} + \frac{\mathbf{v}\times\mathbf{B}}{c}\right), \qquad (1)$$

where **p** and **v** are respectively the impulse and the velocity of a charged particle, *e* is the electron charge, $\mathbf{E}_{hf}$ is the microwave electric field strength, $\mathbf{E}_s$ is the self-consistent plasma electric field, $\mathbf{E}_{ind}$ is the inductive electric field, **B** is the superposition of magnetic fields created by static magnetic coils and pulse magnetic coils. Then a dimensionless centered finite difference approximation of equation (1) after normalization to $m_o c\omega$ takes a form

$$\frac{\mathbf{u}^{n+1/2} - \mathbf{u}^{n-1/2}}{\Delta\tau} = \mathbf{g}^n + \frac{\mathbf{u}^{n+1/2} + \mathbf{u}^{n-1/2}}{2\gamma} \times \mathbf{b}^n, \qquad (2)$$

where **u** is an impulse of the electron in $m_o c$ units, $\mathbf{g}^n$ is the total dimensionless electric field strength at time moment *n*, $\mathbf{b}^n$ is the normalized magnetic field value, $\gamma$ – relativistic factor, $\tau = \omega t$ is dimensionless time, $\Delta\tau$ is a time step. The equation (1) solved by a second-order leap-frog Boris scheme [5]. For ions a nonrelativistic equation is used. This is justified, as the ions are not resonant particles.

The Poisson equation for periodic conditions (influence of the cavity walls is supposed to be neglected) is solved at each time step by using the Boisvert code. Spatial limitation of plasma is accounted for by assuming the particles reached the cavity walls to be lost. Self-consistent electric field values are derived from the obtained potential distribution on the mesh with the use of finite difference derivatives. Electric field values at points of particle locations are obtained through inverse bilinear interpolation. Magnetic field formed by static magnetic coils and pulse magnetic coils is calculated at grid points. The use of particle in cell method provides such an overwhelming spectrum of time depended plasma parameters and characteristics that one has to limit oneself just several of them. In the proposed model the following diagnostics have been applied:

1. Time dependence of losses for both sorts of particles: electrons and ions.
2. Evolution of space distributions of electrons and ions.
3. Time dependence of electron and ion energy spectra.

Obtaining this data is enough to analyze collisionless processes taking place in the phenomena of interest.

Cross-sections of space distribution of plasma electrons after reaching average electron energy W=500 keV are presented in Fig. 3. Ions are not shown in the figure. Calculation was made for initial plasma beam of radius $r_0$=4 mm, density $n_0 = 4\cdot10^{10}\,\mathrm{cm}^{-3}$, electric field strength E=3 kV/cm. It is seen from Fig.3 that as a result of SGA a relativistic electron bunch is produced. Total number of trapped electrons $N_{tr} = 3\cdot10^{10}$.

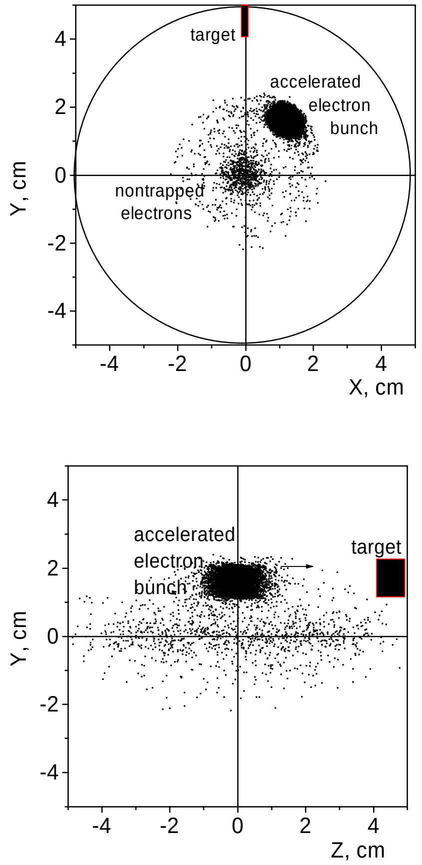

*Fig. 3. Cross-sections of spatial distribution of electrons after SGA pulse.*

Dynamics of such a bunch can be controlled by variation of magnetic field in time. A routine practice to transport plasma electrons to a target is a magnetic field decrease due to short-circuiting both pairs of magnetic coils. Usually time of a magnetic field decrease is equal to one of an increase. In this case the electron bunch transforms to the electron ring. Interaction of the electrons with the target lasts long enough but x – ray power is rather low. To increase x – ray power a number of approaches can be proposed. One of them – proposed in the work – throwing a bunch on a target placed by the side wall cavity or directly on to the cavity's side wall. This is achieved after the short-circuiting one of pulse magnetic coils when total magnetic field reaches its maximum value. Another way is to add one more coil producing reverse magnetic field. The removal of the magnetic mirror results in appearance of the axial magnetic gradient in the place where the electron bunch is located. As a result a diamagnetic force $F_z = -\mu\cdot\mathrm{grad}B_z$ (where $\mu$ is the magnetic moment of the bunch which is proportional to the kinetic energy of the electrons) acts on the bunch. Under action of the diamagnetic force the bunch is pushed towards the cavity's side wall. Simple estimate of an optimal value of axial gradient showed that for the above mentioned parameters grad$B_z$ should not exceed 8 G/cm. However this estimate is valid just for static magnetic field in case of a single particle approximation. That is why optimal condition for the bunch transportation was obtained from the analysis of simulation results. Time of interaction of the bunch with the target and consequently the power of x-ray depends on the velocity of magnetic field decrease.

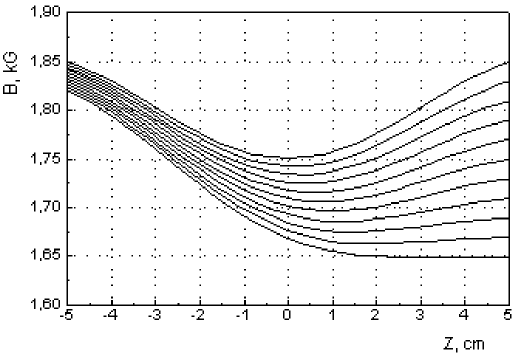

*Fig.4. Time dependence of magnetic field B(z,r) profile, r = 2 cm*

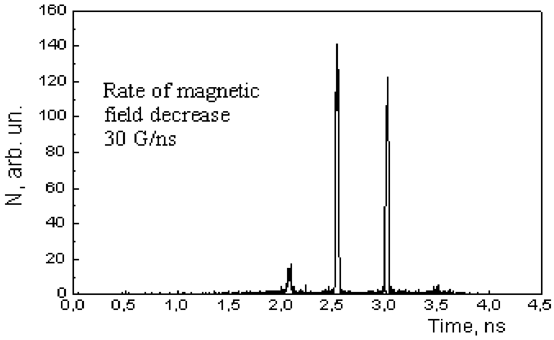

*Fig.5. Number of electrons has fallen on the target at optimal transportation condition*

Figure 4 illustrates time dependence of a magnetic field profile for $r_0$=2 cm corresponding to the center of the bunch for different time moments. Upper curve corresponds to the end of SGA stage.

For different values of the velocity of the magnetic field decrease one can obtain different times of interaction of the bunch with the target At optimal transportation condition bunch-target interaction time can be less than 2 ns (Fig. 5).

Figure 5 presents a number of electrons falling on a target at optimal transportation condition. It is seen from this figure that interaction of the bunch with the target lasts during just a few electron revolutions (several nanoseconds). Taking into account that the bunch contains $1 \cdot 10^{10}$ electrons at the energy of 0.5 MeV one can obtain that at conversion rate 10% instantaneous power of x-ray burst is about 16 kW. Such an installation can acts with repetition rate up to 400 Hz.

One more way to rise x-ray power is the use of the scheme with $TE_{112}$ cavity (see Fig. 6). In this case two electron bunches are produced as a result of SGA. These bunches are confined in local internal magnetic mirrors. After short-circuiting of two internal coils internal magnetic mirrors are removed. Then as a result of appearance of the magnetic gradients in the places when electron bunches are located both bunches are pushed to the central plane of the system where they simultaneously face the target and produce x-ray burst (see Fig. 6). X-ray intensity increase by a factor of two takes place in this case.

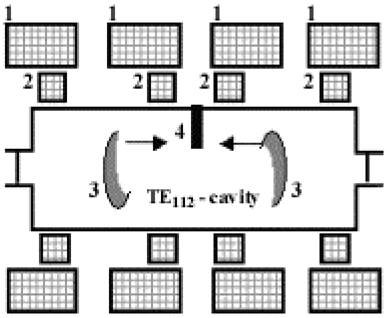

*Fig. 6. Scheme of x-ray source with two electron bunches. 1 – static magnetic field coils; 2 – pulse magnetic field coils; 3 – electron bunches: 4 – target*

Taking into consideration that the achievable electron energy under SGA is determined by the terminal value of the magnetic field and doesn't depend on the microwave field strength one can obtain electron bunches with energy of tens MeV (such a regime can be possibly used for synchrotron radiation production). However the density of trapped electrons does depend on microwave field strength [3]. One more parameter influencing both the density of electron bunches and repetition rate of SGA cycles is the velocity of magnetic field growth [6].

All things considered, one can estimate feasible parameters of the electron bunch produced by SGA: average energy of electrons 200 keV – 4.5 MeV, volume 0.25 – 2.0 $cm^3$, density $1 \cdot 10^9$ -$1 \cdot 10^{10}$ $cm^{-3}$. As for the typical x-ray burst it can range between 10 and 500 kilowatt during 2.0 – 50 ns. The repetition rate can be as high as 400 Hz.

## 5. Conclusion

Obtained experimental and numerical modeling data show that the most salient feature of SGA is the possibility of obtaining Gyrac produced plasma or electron bunches with parameters (average electron energy, density and volume) which can be varied in wide intervals. The SGA-regime can be used to obtain a controlled bunch of relativistic electrons due to variation of magnetic field in time. So the sphere of its applications may be very wide. Interest to sources of radiation on the basis of synchrotron gyromagnetic autoresonance may be enhanced by the prospect of designing a synchrotron radiation source as well as a compact x-ray source for industrial application. Such a source of intense hard x-ray can be used in atomic and nuclear physics, defectoscopy, material processing, medicine and biology.

## 6. References

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