BALLISTIC BUNCHING OF FAST IONS IN A MIRROR TRAP

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Abstract. The fast ions produced inside a mirror trap by neutral beam injection could form periodic short-lived density peaks near a turning point if the injection energy is properly modulated in time. Achievable parameters of thus formed fast ion bunches are analyzed in this paper. The theory is illustrated by estimates for the neutron source based on a gas-dynamic trap. The bunching of deuterium and tritium ions can produce periodic short bursts of neutron radiation with the intensity 1.5 times higher than the average level. The modulation of the neutron flux could extend the field of application for the neutron source. Also, the bunching could serve as a precise plasma diagnostics in mirror traps.

Since the mid-80s, in Budker Institute of Nuclear Physics and in other research centers the work is underway toward the concept of 14 MeV neutron source based on a gas-dynamic trap (GDT) [1, 2]. Intense neutron fluxes in the source are to be produced by continuous oblique injection of energetic deuterium-tritium beams into the relatively cold target plasma confined in an axisymmetric mirror trap. Generation of neutrons occurs in narrow regions of increased fast ion density near the mirrors at the turning points (where the longitudinal velocity of fast ions turns to zero).

Parameter	Value
Plasma electron temperature, T_e:	0.65 keV
Mirror-to-mirror distance, L:	11.4 m
Injection angle, θ_0:	30°
Injection energy, ε_0:	65 keV
Energy modulation amplitude, $\Delta\varepsilon$:	20 %
Initial energy spread of the beam, $\delta\varepsilon_0$:	0.1 %
Initial angular spread of the beam, $\delta\theta_0$:	0.01
Background plasma density, n_0:	$2\cdot 10^{14}$ cm^{-3}
Bounce-period of fast deuteruim ions, T:	10 μsec
Length of the enhanced neutron yield region, l_h:	2 m

Table 1. Parameters of the neutron source and input data for calculations.

In this paper we consider the possibility of neutron flux modulation using ballistic bunching of fast ions, as applied to the GDT-based neutron source. By the ballistic bunching is meant a temporal modulation of the neutral beam energy so that the particles injected at later times overtake the earlier injected particles thus forming a dense fast ion bunch somewhere inside the trap. Previously, the possibility of the ballistic bunching was pointed out by D. D. Ryutov (1995). Here we estimate the effect of bunching on the neutron flux for the version [3] of the neutron source. The parameters and limitations used in calculations are listed in Table 1.

Unfortunately, even in the most optimistic case, the bunching gives no substantial increase in the average neutron yield. However, availability of intensity-modulated neutron fluxes could offer new opportunities in materials testing and in other applications of thermonuclear neutrons. The experimental investigation of the ballistic bunching could also give a useful information on the stability of the plasma with a fast ion population, on the noise level in the plasma, etc.

The peak density of bunched fast ions is determined by the energy modulation law, energy and angular spreads of the injector, scattering on the background plasma, and some other, less important, factors.

In derivation of the required energy modulation law, we neglect the angular spread of the fast ions, so that turning points of all particles trapped at the considered field line coincide. The velocity of a fast particle, both before and after the ionization, is proportional to the square root of its energy ε. Consequently, two particles emitted with energies ε_{opt} and ε_0 at times t_1 and t_0, correspondingly, will meet at a time $t_b = t_0 + \tau$, if the energy ε_{opt} changes according to the law

$$\varepsilon_{opt}(t_1) = \varepsilon_0 \frac{\tau^2}{(t_b - t_1)^2}. \tag{1}$$

Here τ is the time a "marked" particle takes to travel to the bunching point. The period (Δt) and the amplitude ($\Delta\varepsilon$) of the energy modulation are in one-to-one correspondence:

$$\Delta t \approx \tau\, \Delta\varepsilon/(2\varepsilon_0). \tag{2}$$

Note that each particle can participate in bunch formation only once. It is straightforward to take into account an ion energy variation caused by Coulomn scattering or electrostatic potential.

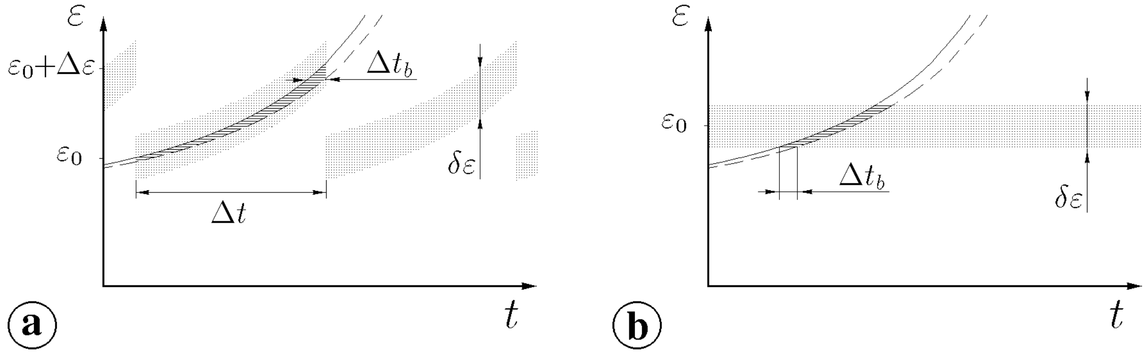

Fig. 1. Calculation of the ion density: (a) optimum modulation, (b) no modulation.

Let us find the limitation on the ion bunch density which is imposed by the energy spread $\delta\varepsilon$ of bunched particles. This can be easily done geometrically. First, we plot a "portrait" of the injected beam on (t, ε) plane (Fig. 1; dependences $\varepsilon(t)$ are shown by dots to reflect finiteness of $\delta\varepsilon$). Solid curves in Fig. 1 show the energy that the particle (emitted at a time t) should have to reach the bunching point at the time t_b. Shown dashed are the analogous curves for the bunching moment $t_b + \Delta t_b$. All the particles falling between these two curves (hatched areas in Fig. 1) pass the bunching point during the time interval Δt_b. To find their total number, it is necessary to specify how many particles of a given energy are emitted per unit time, that is, the particle density on the (t, ε) plane. In estimates we assume this quantity (W) to be constant within dotted areas. Then the number of particles is just a dashed area times W. For the optimum modulation (Fig. 1a), the number of "dashed" particles participating in bunching is $\Delta\varepsilon\, \Delta t_b\, W$. With no energy modulation (Fig. 1b), $N\, \delta\varepsilon\, \Delta t_b\, W$ particles pass the same point during the same time, where the factor $N \gg 1$ appears because any fast ion passes the bunching point many times during its lifetime. Thus, at the moment of bunching, the peak ion density at the bunching point is

$$M_{opt} = 1 + \frac{\Delta\varepsilon}{N\,\delta\varepsilon} \tag{3}$$

times greater than the background fast ion density at the same point.

A severe limitation on the peak bunch density is imposed by the angular spread of bunched particles. Since the bounce-period T depends on the pitch-angle θ, any angular spread $\delta\theta$ (initial or acquired) is equivalent to the energy spread

$$\delta\varepsilon_\theta = \frac{2\varepsilon_0}{T}\left|\frac{\partial T}{\partial\theta}\right|\delta\theta. \tag{4}$$

Unless special care is taken, the derivative $\partial T/\partial\theta$ is of the order of T, and the "fictitious" energy spread (4) turns out to be much greater than the actual energy spread $\delta\varepsilon$ of the bunched particles. For the considered injector parameters, no bunching is possible without a magnetic field profile designed to diminish $\partial T/\partial\theta$.

For the plasma parameters from Table 1 and deuterium ions, the deflection time $\tau_d \approx 50\,$msec, the slowing down time $\tau_\varepsilon \approx 5\,$msec, and the parallel diffusion time $\tau_{\Delta\varepsilon} \approx 250\,$msec [4]. Although τ_ε is the shortest time from the three, it is typically much greater than τ, so that slowing down of fast ions can be disregarded in estimating the bunch density. Deflection and parallel diffusion, however, should be taken into account, since angular and energy spreads acquired due to scattering can be much larger than the initial angular and energy spreads of the injector. In plasma, these spreads grow in time according to the formulae

$$\delta\theta = \sqrt{\frac{t+t_\theta}{\tau_d}}, \quad t_\theta = \tau_d\,\delta\theta_0^2 \sim 5\,\mu\text{sec}, \qquad \delta\varepsilon = \varepsilon\sqrt{\frac{t+t_\varepsilon}{\tau_{\Delta\varepsilon}}}, \quad t_\varepsilon = \tau_{\Delta\varepsilon}\left(\frac{\delta\varepsilon_0}{\varepsilon}\right)^2 \sim 0.25\,\mu\text{sec}. \tag{5}$$

The angular spread cause the fast ions to reflect at different points. Denote by B_0 the magnetic field at the point of particle capture, and by s the longitudinal coordinate of the turning point. Then the spread $\delta\theta$ results in the difference

$$l_\theta(\tau) = \frac{2B_0\cos\theta_0}{\sin^3\theta_0}\left|\frac{dB}{ds}\right|^{-1}_{s=s_0}\delta\theta \;\sim\; L\,\delta\theta \sim L\sqrt{\frac{\tau+t_\theta}{\tau_d}} \tag{6}$$

in longitudinal position of the turning points. It can be shown that the energy spread much less contribute to widening of the bunch, so (6) gives the length of the bunch.

Let us estimate N, the number of times a fast ion passes the bunching point as a "background" fast ion. Once a fast ion is injected, it appears at the bunching point every bounce period untill it is widely scattered (to have a turning point too far from the bunching point) or decelerated (to make a little contribution to the neutron flux). Out of all ions injected at the time $t = 0$, the number of ions having the reflection point within the bunch region decreases roughly as $l_\theta(t)/l_\theta(\tau)$. The decrease of effective ion density due to ion deceleration is some complicated function of the ion energy; in doing estimates we approximate it by the linear function $G(t) = 1 - t/\tau_\varepsilon$. Thus,

$$N \sim \int_\tau^{\tau_\varepsilon}\sqrt{\frac{\tau+t_\theta}{t+t_\theta}}\left(1-\frac{t}{\tau_\varepsilon}\right)\frac{dt}{T} + \frac{\tau}{T} \approx \frac{\tau}{T} + \frac{4\sqrt{\tau+t_\theta}\,\sqrt{\tau_\varepsilon}}{3T}, \tag{7}$$

where we assume $\tau \gg T$ to perform integration instead of summation, neglect τ and t_θ as compared to τ_ε, and, by the last term, take into account that for $t < \tau$ all the particles reflect within the bunch region. The dependence $M_{opt}(\tau)$ obtained by the substitution of (7) and (5) into (3) is shown in Fig. 2. The behavior of the function $M_{opt}(\tau)$ weakly depends on the model adopted for the decrease of effective ion density.

We see that, for a noticable increase of the peak ion density, the injection-to-bunching time τ should be short (several bounce oscillations). If the injection energies of deuterium and tritium are equal, the time τ can have only certain discrete values. Otherwise ions of the two kind will not be bunched at the same point. The minimum possible value corresponds to the case when deuterium ions make one bounce oscillation more than tritium ions:

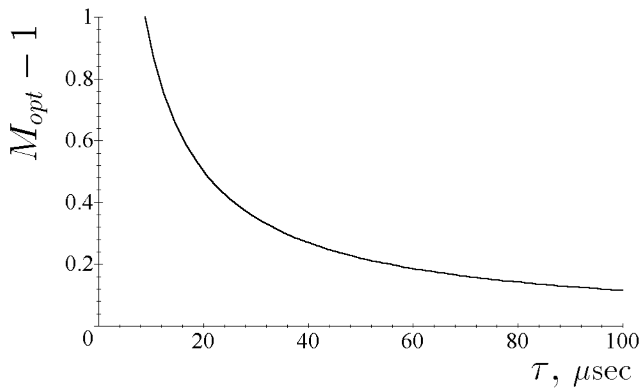

Fig. 2. Increase of fast ion density as a function of τ.

$$\tau_{min} = \frac{\sqrt{3}T}{\sqrt{3} - \sqrt{2}} \approx 5.5T \approx 55\,\mu\text{sec}. \quad (8)$$

For this τ, the increase of the fast ion density is rather small: $M_{opt} - 1 \sim 0.2$. Thus, for the listed above parameters of the neutron source, the ballistic bunching can not substantially increase the peak ion density. Also note that the region of the modulated neutron flux is rather narrow:

$$l_\tau = l_\theta(\tau_{min}) \sim 0.03\,L \sim 30\,\text{cm} \ll l_h. \quad (9)$$

For practical applications of the ballistic bunching, the bunch should appear at all field lines simultaneously and at the same cross-section of the trap. It can be shown that the criterion of identical behaviour of particles on different field lines is easy to meet only if the plasma pressure inside the trap is much less than the magnetic field pressure.

In conclusion, with the ballistic bunching, it is possible to produce controllable short bursts of neutron flux in GDT-based neutron source. However, the bunching has no effect on the average neutron yield because of the short duration of neutron bursts.

References

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