TWO-COMPONENT CHARGE COMPENSATED ION BEAM DYNAMICS

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ABSTRACT

Transversal dynamics of the charge-compensated beam trough ICF driver has been investigated and the main results, obtained by linear theory have been summarized. The nonlinear space charge effects due to intrinsic Coulomb forces have been numerically studied by 2D particle simulation. In addition the final focusing system has been analysed.

1 INTRODUCTION

An efficient way to facilitate high current ion beams transport and focussing in ICF driver is to use two beams with equal current of negative and positive ions, having the same masses and velocities [1]. For sake of brevity we shall call this beam below, as charge compensated beam.

A linear theory of charge compensated beam dynamics was developed in the papers [2, 3] when all considerations were performed in frames of Kapchinskii-Vladimirskii (K-V) model, when both external and space charge forces are assumed to be linear. By means of K-V envelope equations we found out the frequencies of non-coherent oscillations (see for reference [2]). The coherent quadrupole oscillations, as well as small dipole coherent oscillations were explored in [3].

2 LINEAR THEORY RESULTS

The results of the previous studies can be summarized as the following:

- This method allows to increase essentially the ion current through the perodic focusing channel and, therefore, to upgrade the energy deposition into the target.
- To obtain higher currents one should use lower phase advance $\sigma_\circ < 1$ ($\sigma_\circ$ is the phase shift in one period of the focusing structure for zero beam current). To transport conventional one component beam, we have to increase $\sigma_\circ$, that is quite opposite to transport of charge compensated beams.
- The circular frequency of noncoherent oscillations ω (in radians/period) is equal to the phase advance σ and increases rather slow when the current grows up (see Fig.1). For one component ion beam transport this frequency strongly decreases when the current grows up, that is unlike again to charge compensated beams.

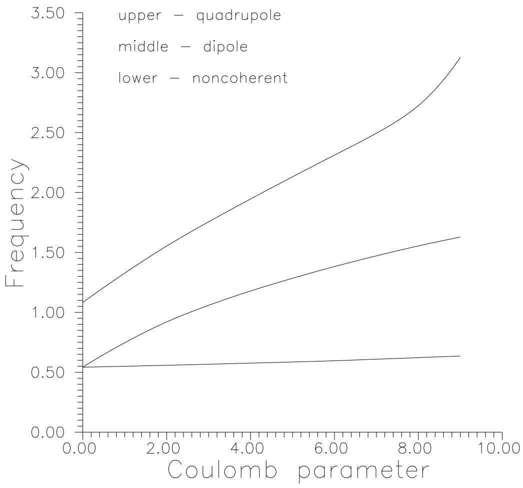

Figure 1: Dependence of $\sigma, \sigma_d, \sigma_q^a$ on λ

- The coherent quadrupole oscillations have two forms: the symmetrical mode and the antisymmetrical one. The circular frequency of coherent quadrupole oscillations for antisymmetrical mode σ_q^a grows rapidly with the beam current, unlike to one for symmetrical mode σ_q^s (equaled practically to double frequency of noncoherent oscillations). Beside that, σ_q^a is always bigger than the circular frequency of small dipole oscillations σ_d and is the biggest of the frequencies inherent in our system (see Fig.1). Thus we conclude that this coherent qudrupole oscillations of antisymmetrical mode can be the most dangerous.
- When σ_q^a approaches to the boundary of quadrupole resonance band (the resonance condition is: $\sigma_q^a = 2\pi$), an instability occurs. This effect limits the beam current in periodic quadrupole focusing channel.

Fig.1 demonstrates the dependence of coherent (σ_d, σ_q^a) and noncoherent (σ) frequencies from Coulomb parameter λ which is determined by the formula: $\lambda = QL/\varepsilon$. Here L is the length of one focusing period of the transport channel, ε is the beam emittance (the calculation was performed for $\varepsilon_x = \varepsilon_y = \varepsilon$) . Q is the beam perveance, determined by the formula:

$$Q = 4\frac{ZI}{(\beta\gamma)^3 AI_p} \qquad (1)$$

Here Z and A are, respectively, the ion charge state and atomic number, I is the beam current of one component

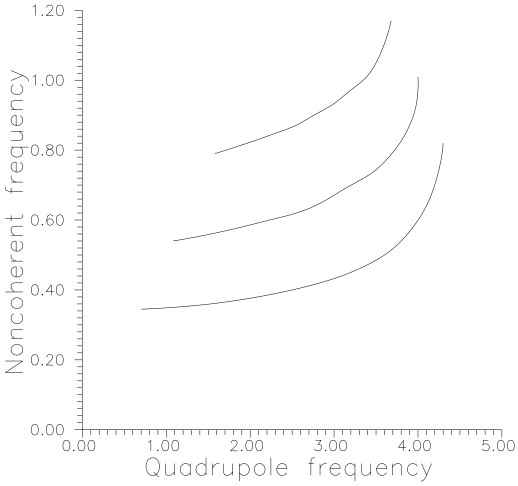

Figure 2: Dependence of σ on σ_q^a

(the total current will be two times higher), I_p is Alfven current for protons ($I_p = 3.1 \cdot 10^7$A), β, γ are usual relativistic factors.

3 INTRINSIC NONLINEAR EFFECTS

In the present paper we have studied nonlinear effects, which couldn't be described in frames of K-V formalism. The tool for these studies is a particle simulation, which now seems to be the only way for quantitative estimate of charge compensated beams dynamics. There are no difficulties to adapt the usual 2D macro-particle algorithm for two-components beam simulation [4].

Thus, the found above envelopes and frequencies should be corrected by the general particle simulation. As a good initial approximation, we take beam parameters for K-V equations (which presents the exact solution for linear model) and test the beam motion during few n periods ($n \approx \pi/\sigma_q^s$) in periodical transport channel. Since the assigned beam envelopes are approximate (for nonlinear case), we observe small oscillations due to mismatching. These oscillations occur nearby the *true* envelopes and mainly are the coherent quadrupole oscillations of symmetrical mode. The small component of the antisymmetrical mode may be neglected far off the resonance of quadrupole oscillations.

The amplitudes of envelope oscillations will be damped soon, due to strong intrinsic nonlinearity of Coulomb forces, and we get the *true* values of the matched envelopes in the periodical channel. The emittance growth during this process is not critical ($\Delta\varepsilon/\varepsilon \approx 10^{-2}$) for our beam parameters: the total current 8kA in two beam component, energy of ions (with charge state Z=1 and atomic number A=209) 10GeV, beam emittance 2cm·mrad.

However, the emittance growth depends on σ_q^a and becomes a critical for $\sigma_q^a \to 2\pi$, but we observe a significant growth of amplitudes earlier, when $\sigma_q^a \approx \pi$, because the resonance band is wide enough. We can conclude, therefore, that the condition $\sigma_q^a \leq \pi$ must be satisfied, that is in accordance to the results of linear theory [3].

Fig.2 demonstrates the frequencies of noncoherent betatron oscillations depending on quadrupole frequency σ_q^a.

4 FINAL FOCUSING SYSTEM

We should remember, that in the final focusing system (FFS) the condition $\sigma_q^a \leq \pi$ will be violated. Thus the FFS-part of the transport line should be considered separately from the periodical transport channels. The input beam parameters at the FFS entrance should be matched to the output beam from the transport channel. A straightforward and time-consumed way to find these FFS-initial-beam parameters is a detailed numerical simulation through the long transport line (about 100–150 periods). However, we can simplify the problem, assuming the initial beam is equal to the found above matched beam.

We have performed the calculation of the FFS for the beam parameters mentioned above (section 3). The maximal emittance growth in FFS for the beam spot size in the focusing point equal to 2mm is less than 5%. The reason of emittance growth is the high modulation of beam envelops in FFS lenses. The maximal beam cross-section radius in these lenses is equal to 20cm, the maximal gradient of magnetic field in lense is equal to 8T/m.

5 CONCLUSION

Study of nonlinear effects in charge compensated ion beam confirms the validity of the formula for the upper limit of the beam current, as it was shown in [3]:

$$I \leq \frac{\pi^2 A\varepsilon I_p}{4|Z|L\sigma_\circ}(\beta\gamma)^3(1 - \frac{4\sigma_\circ^2}{\pi^2}) \qquad (2)$$

In the region $0.1 < \sigma_\circ < 1$ (in radians) this formula gives good numerical results for beam current values. Note, that for $\sigma_\circ \to 0$ the beam current tends to infinity just as the size of the beam cross-section.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] D.G.Koshkarev, Nuovo Cimento, Vol. 106 A, N 11, November 1993, p.1567.

[2] A.V.Barkhudaryan, D.G.Koshkarev and P.R.Zenkevich, ibid. p.1751.

[3] A.V.Barkhudaryan, D.G.Koshkarev and A.N.Talyzin, International Symposium on Heavy Ion Inertial Fusion, Princeton, New Jersey, USA, September 1995.

[4] L.G.Vorobiev, "Two-dimensional particle code for beam simulation in HIF driver", Preprint ITEP 22-94, Moscow, 1994.