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HEAVY ION SPACE CHARGE LIMITS

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ABSTRACT

Modern ultra-high vacuum technology makes it possible to accelerate and store heavy ions in low charge states. Such quasi-neutralized beams give rise to very high space charge limits in conventional charged particle storage rings and transport systems. In addition, the z^2 dependence of dE/dx gives rise to very short ranges for very high energies. Space charge limits are evaluated for a linear transport system, and it is shown that realistically achievable powers and energies are of interest for the ignition of thermonuclear pellets.

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Three rather general conditions must be met in order to ignite a thermonuclear pellet. A certain power P must be deposited in the pellet. This pellet diameter sets a requirement on the beam emittance ϵ . The absorption length for the energy comes in also, or else the beam power P_b must be increased proportionately. Typical requirements are $P \sim 10^{15}$ watts,^{1,2} with a pellet radius of ~ 1 mm, and an absorption length $\sim 100 - 300$ microns. In addition, a total integrated beam power of $\sim 10^5 - 10^6$ Joules is necessary. We will first demonstrate that these conditions are obtainable using existing conventional technology and without any extrapolation of physical theory or understanding.

The transport of unneutralized charged particle beams in conventional strong focusing channels is limited in flux by the electrostatic defocusing within the beam and the finite strength of quadrupoles along the channel. Since virtually arbitrary gradients can be obtained, the "in fact" limiting condition is the pole tip field B , where we have the condition that the gradient $G = B/r$; r being the beam radius. Defining $\epsilon = rr'$ as the emittance/ π , we obtain a relation for the power which can be transmitted by a strong focusing channel of pole tip field B , and acceptance ϵ .

$$P_{\max} = 1.687 \times 10^{15} (\beta\gamma)^{7/3} (\gamma-1) \left(\frac{A}{z}\right)^{4/3} \epsilon^{2/3} B^{2/3} \text{ watts} \quad (1)$$

A is the mass in units of proton mass, and z is the charge of the particle; β, γ have their usual relativistic significance.

The pellet radius a is related to the emittance through the f number of the focusing system. We have the relation $\epsilon = aa' = a/2f$. Since $f \geq 1$ for most realizable lens systems, and $a \approx 1$ mm, ϵ is fixed at 5×10^{-4} meter-radians or less. Realizable pole tip fields give $B \approx 2 - 10T$. The only real handle we have on the power is β and $(\frac{A}{z})$. A large A/z value is obtainable by using singly charged U ions. β is limited by the range of the charged particles. If we use a beam of U ions, a β value of $\sim .4 - .5$ will result in a range of a few hundred microns in gold. Note that at their high velocities, the energy loss is not significantly temperature dependant.³

There is no need for recourse here to an appeal for anomalous energy loss mechanisms. The loss mechanism is simple, well understood, and verifiable experimentally for many ions.

Taking $\beta\gamma = .5$, and singly charged U ions on a 1 mm radius pellet, we obtain the following expression for the power deposited in the outer shell:

$$P = .367 \times 10^{15} \left(\frac{B}{T}\right)^{2/3} \text{ watts}$$

It should be emphasized that these relations are generally conservative. Applying this to electrons with $B\gamma \sim 1$ would give a power of only $\sim 10^9$ watts. Clearly, space charge neutralization might significantly improve the high power transport.

Now we have shown that a high energy beam can be transported and put onto a small pellet, and deposit 100% of its energy in the pellet. It remains to make plausible the generation of such a pulse. The method proposed is to accelerate U^+ in a conventional circular accelerator up to the required energy (~ 25 GeV), and then store them in a storage ring. The space charge limit⁴ of a storage ring can be written in terms of the beam stored energy, and we obtain:

$$E_s = 1.4 \times 10^8 \left(\frac{A}{Z}\right)^2 \epsilon \beta^2 \gamma^3 (\gamma-1) \text{ Joules}$$

For an example, with $\beta\gamma = .5$, $A/z = 238$, $\epsilon = 5 \times 10^{-4}$

$$E_s = 1.4 \times 10^8 \text{ Joules.}$$

The size of such a storage ring could be estimated by observing that $\beta\rho = 3.13 \beta\gamma A/z$. For our example, $B\rho = 372$ T-m, corresponding to a 100 GeV proton storage ring. Extrapolating from existing designs⁵ and cost estimates we expect such a device to cost less than 50 million dollars; well within the scope of a large power station. In addition, an accelerator

system capable of 10MW average beam power⁶ might cost between 100 - 200 million dollars, and consume ~ 30 MW of electricity. Based on these estimates, we would expect to produce competitive power with pellet gains of ~ 100.

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