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Laser photodetachment neutraliser for negative ion beams

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ABSTRACT

We outline a speculative design for a photodetachment neutraliser for a negative ion neutral beam system, with neutralisation efficiency of 95% or more. The practical difficulties are enormous. The ion beam must pass through an optical cavity capable of reflecting the light many times. For 500 reflections, the laser optical power output ~800 kW, giving circulating power ~400 MW. All sources of light loss combined need to be kept to 0.2% or less per pass. The losses due to photodetachment itself, and due to Thomson scattering in the beam plasma are negligible. A key task is to maintain the reflectance of the mirrors above 99.97% for long periods of operation, protecting all the components from thermal and neutron damage, and from caesium, sputtered atoms and other contamination. A diode-pumped Nd-doped YAG laser can have overall electrical-to-light ("wall-plug") efficiency up to 25%. A DEMO concept reactor such as the EU Power Plant Conceptual Study (PPCS) Model B requires 270 MW heating power. If this is all provided by neutral beams, then a laser neutraliser might reduce the electrical power consumption for this from 900 MW to 520 MW.

1. Introduction: neutralisation of negative ion beams

A major consideration for ITER, DEMO and beyond is the energy efficiency of the heating and current drive systems. Present-day and planned systems have overall wall-plug efficiency in the range 20–30% [1]. In contrast, conceptual studies for power plants assume 60–70%.

The biggest source of energy loss in the ITER neutral beam system is the low neutralisation efficiency. The only method currently used to neutralise high power negative ion beams is the simple gas cell. This gives a neutralisation efficiency of 58% for 1 MeV ions [2], and even less for the higher energies that may be required for DEMO. A gas neutraliser also releases a copious flow of gas from each end, requiring enormous cryopumps and imposing high stripping losses in the accelerator. Even for ITER it has not been proven that stripping losses will be acceptable.

If a plasma neutraliser is used instead, neutralisation efficiency can reach 80% for 30% ionisation, and the gas required is much less [3,4]. A multi-cusp magnetic trap with microwave ECR heating at the plasma periphery has been proposed as an effective system for production of cold plasma with high ionisation in a large volume. Experimental results suggest that the plasma parameters necessary for ITER can be obtained with a superconducting magnetic system providing the maximum field ~1 T. The required microwave power input into the plasma is about 0.5 MW. It is claimed that the problems of beam deflection and divergence can be successfully eliminated. The microwave sources would be gyrotrons, which have demonstrated wall-plug efficiencies ~45–50%, including waveguide losses [5].

Grisham [2] has proposed a supersonic lithium vapour jet perpendicular to the direction of beam propagation. The maximum neutralisation efficiency in lithium vapour has been measured as 65% for 400 keV H^- (equivalent to 800 keV D^-).

A photodetachment neutraliser would consist of a laser and an optical cavity through which the negative ion beam would pass. The following reaction takes place, for the example of deuterium, $h\nu + D^- \rightarrow D + e$.

The cross-section for hydrogen is given in [6,7]. We assume that the cross-section is the same for deuterium.

2. Photodetachment neutralisers—review

Fink first proposed photodetachment in 1975 [8], and derived the basic parameters of such a neutraliser [9]. He concluded that the damage limit of the mirrors would control the minimum length of the neutraliser. In [10] Fink considered photodetachment in the presence of a background gas. He found that a gas target can improve the net neutral fraction, but only if the photodetachment fraction (the neutral fraction with no gas) is below about 80%. For example, for 60% photodetachment, gas can improve the neutral fraction to at most 75% for 1 MeV D^-. This combined system requires only half the power of a pure photoneutraliser, but about

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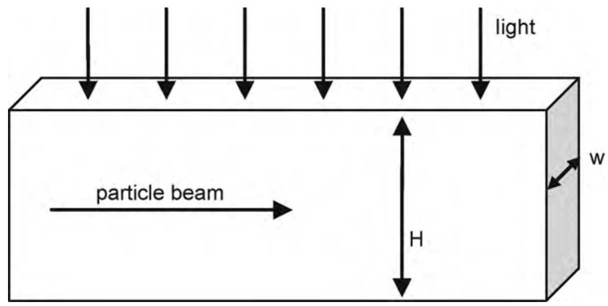

Fig. 1. The geometry considered.

70% as much gas as a gas neutraliser. The benefits of a combined gas and optical neutraliser are therefore modest.

In 1983, Fink proposed the supersonic chemical oxygen–iodine laser (COIL) [11], but by 1987 had moved on to the more conventional Nd:YAG (neodymium-doped yttrium aluminium garnet). The laser power required is proportional to the width of the beam, which could be very small if a slit ion source is used. Sources with an array of circular apertures fit the laser profile less efficiently. The LBL self-extracting surface conversion source provided 4 A/m of accelerated ions from a single slit 3 cm wide [12].

Vanek [13] described cavity and laser technology. They proposed a mirror with three layers of cooling channels built-in. They listed mirror materials in order of suitability: (1) (most suitable) silicon (which they rejected because of failures in the development of single crystal heat exchangers); (2) silicon carbide; (3 and 4) tungsten and tungsten carbide; (5) molybdenum; (6) (least suitable) copper. Since a window was required, they proposed one made from two plates of sapphire with organic coolant in between. As well as absorption, scattering and surface reflection, there would be thermal lensing in the coolant. To minimise this they suggested a folded optical path in the vacuum space, reducing the number of times the light passes through the window. Even so it is unlikely that any window can be built with >99% transmission as they proposed.

3. Wavelength, power and efficiency

Fig. 1 shows the geometry considered.

The laser power required is:

$$\text{Power} = \frac{hc}{\lambda}\frac{\ln(1-f)}{\sigma}\sqrt{\frac{2eV_B}{Mm_p}}\frac{w}{G}. \qquad (1)$$

The symbols have the meanings given in Table 1, together with the values used in this paper except where stated.

Table 1
Symbols and their values.

λ	Wavelength	1064 nm
f	Degree of neutralisation (fraction of ions neutralised)	0.95
σ	Cross-section for photodetachment	3.375×10^{-21} m^2 at 1064 nm
V_B	Acceleration voltage	1 MV
M	Relative atomic mass	2 (deuterium)
G	Number of times the light passes through the cavity (loosely called "gain")	500
w	Width of neutraliser	0.25 m
h	Planck's constant	
c	Speed of light	
m_p	Mass of proton	
e	Charge of the electron	

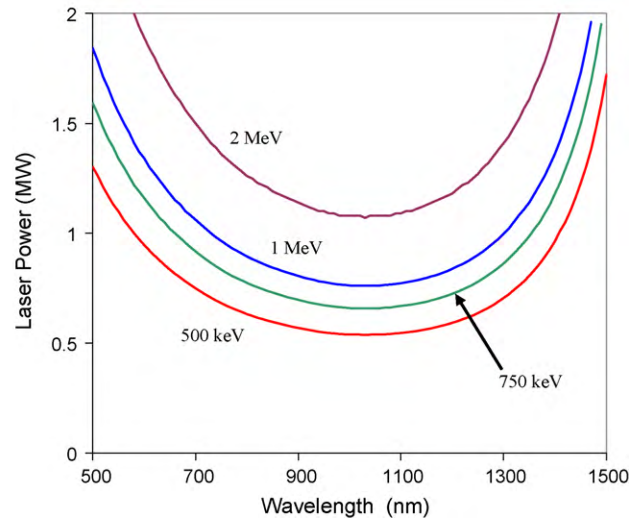

Fig. 2. Laser power required as a function of wavelength, for different beam energies.

Eq. (1) can be derived by noting that

$$\text{rate of neutralisations per unit volume} = n_i n_p c\sigma = -\frac{dn_i}{dt},$$

where n_i and n_p are the ion and photon densities, respectively, the relative velocity is c, and the derivative is taken along the path of an ion. The photon density is assumed to be constant, so attenuation along the photon path is neglected. The neutralised fraction f is

$$f = 1 - \frac{n_i(\text{final})}{n_i(\text{initial})},$$

and the time taken by the ion to traverse a neutraliser of length L is

$$\frac{L}{\sqrt{2eV_B/Mm_p}}.$$

The gain G is given by $G = 1/\varepsilon$, where ε = fraction of energy lost per pass.

Fig. 2 shows the laser power required as a function of wavelength, for different beam energies.

Fig. 3 shows the overall efficiency of a neutral beam system (power injected into plasma/electrical power required). The system is based on the ITER beamline with MAMuG (Multi-Aperture–Multi-Grid) accelerator, but with some anticipated improvements, with parameters in Table 2 [14,15].

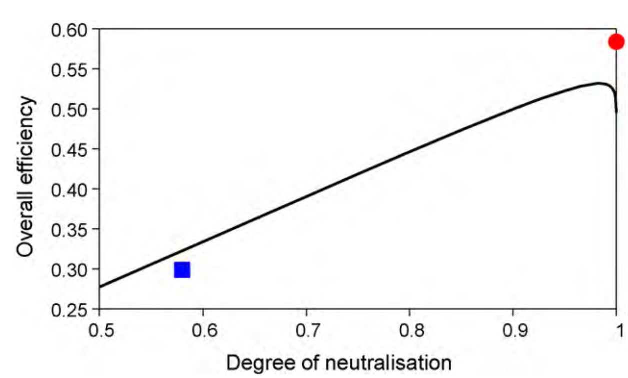

Fig. 3. Energy efficiency of the neutral beam system. — laser neutraliser; ■ efficiency of beamline with gas neutraliser; ● max theoretical efficiency given perfect neutralisation with no power consumption by the laser.