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Feasibility of Traveling Wave Direct Energy Conversion of Fission Reaction Fragments

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Abstract. Fission fragment direct energy conversion has been considered in the past for the purpose of increasing nuclear power plant efficiency and for advanced space propulsion. Since the fragments carry electric charge (typically in the order of 20 *e*) and have100 MeV-range kinetic energy, techniques utilizing very high-voltage DC electrodes have been considered. This study is focused on a different approach: the kinetic energy of the charged fission fragments is converted into alternating current by means of a traveling wave coupling scheme (Traveling Wave Direct Energy Converter, TWDEC), thereby not requiring the utilization of high voltage technology. A preliminary feasibility analysis of the concept is introduced based on a conceptual level study and on a particle simulation model of the beam dynamics.

Keywords: Fission Fragments, Direct Energy Conversion.

INTRODUCTION

The possibility of producing electric energy from a fission reaction via a direct conversion process, thus avoiding the heat-engine conversion, has a strong appeal because potential improvements in efficiency and complexity, and because of reduced overall vulnerability of the reactor and to lower waste material activation due to the reduced energy of the fragments after the conversion process.

This study is focused on the analysis of a particular approach to the direct conversion process, assuming that a proper fission core design is available in which the fission fragments can escape the fissile core without significant loss of energy (a natural candidate for this process would be the gas core reactor). Studies on the feasibility of a fission core with escaping fragments have been done previously in relation to electrostatic concepts for direct energy conversion [Miley, 1970 and references therein], [Tsvetkov, 2004], [King, 2005], [Clark, 2005]. Unlike previous approaches based on a DC, high-voltage conversion, this study considers the possibility of a converting the particle kinetic energy into alternating current via a traveling wave coupling process.

This scheme was conceived in the early 90's for potential fusion reactors applications and resulted in the development of the Traveling Wave Direct Energy Converter (TWDEC) [Momota, 1992], [Momota, 1999]. In the TWDEC, the energy of a particle beam is collected on a series of electrodes, with the advantage of producing a smaller alternating potential instead of a DC high-voltage. The energy extraction process occurs as the electrodes are capacitively coupled to a density-modulated (bunched) beam of charged particles: as bunches approach and then leave the electrodes behind, an alternating potential is induced.

RESEARCH FOCUS

The present study is focused on the exploration of a direct energy converter configuration that utilizes a collimated a beam of charged reaction fragments from a nuclear fission core. In general terms, positively charged fission fragments are magnetically collected and focused into a beam. Relatively low particle density is assumed, to avoid significant space charge effects. A density modulation is then introduced resulting in a beam “bunched” pattern. The bunched beam then passes through a series of hollow electrodes where, in turn, an alternating potential is induced. Some level of controlling the electron flow for maintaining the proper charge neutralization needs also to be considered, although it is not in the particular scope of this study.

There are several issues that need to be addressed to turn a fission fragment –based TWDEC concept into a design suitable to for a proof-of-principle experiment; however the focus of in this paper is limited to the specific study of the applicability of the TWDEC concept itself.

The first issue is, of course, the availability of an effective scheme that allows the extraction of fission fragments from a fission critical core without significant loss of energy. This problem has been considered in the past, as mentioned above, for the original concept of a high-voltage, electrostatic technique of energy extraction. This study is not focused on the fragment extraction issue, as it is not peculiar to the TWDEC concept but is rather common to any approach to fission direct conversion. Without considering the issue resolved, a properly designed source of fragments is assumed available; while for any near term experimental test purposes a neutron source bombardment of a thin layer of fissile material could be utilized [Krieve, 1966].

The second important issue is the collimation of the fragments into a beam from a presumably quasi-isotropic source. For the same aforementioned reasons this is also not a focus of this study. This aspect should be addressed along with the problem of managing the free electrons that make up the charge neutralizing balance.

It will be here simply assumed that fragments are collected and available in a beam-like directed flow of positive ions, with the proper statistical distribution of masses and charges determined by the type of fission reaction and by the parameters that control the process of the neutron multiplication.

Within this outlined framework, the two problems that are being analyzed in detail in this study, as they are critical for an efficient implementation of the TWDEC concept, are the beam modulation and the means for reducing the beam velocity spread in the direction of propagation (that is the longitudinal direction, along the axis of the TWDEC).

TECHNICAL DEVELOPMENTS

Particle Simulation Model for the Beam Modulation

The TWDEC requires a bunched beam pattern to achieve the proper synchronization between the electric potential produced on the electrodes of the decelerator section and the position of the beam along the axis of the device. A preliminary study is being developed by utilizing a particle-in-cell (PIC) model. The model is in cylindrical geometry, in two dimensions (*r*-*z*), assuming azimuthal symmetry. The XOOPIC code [Verboncoeur, 1995] is used for this purpose, run in the electrostatic mode.

The model can provide a quantitative description of the beam dynamics as a basis for more a complex exploration of the parameter space. A reference test calculation has been developed by considering a 100 MeV particle beam of ions with atomic number Z=20 and atomic mass A=100 *amu*. The model consists of set of five ring-shaped electrodes that are biased alternatively at positive and negative DC potential with a superimposed a sinusoidal AC component. The time varying potential can be imposed with a phase difference on each electrode, for a more effective the field-particle coupling.

A parametric study is being conducted to optimize the choice of the bias potentials and the electrode dimensions. In the present model a beam of 2 cm radius is simulated for a 1 m length; the electrodes have a finite longitudinal extension (5 cm) and the total electrode structure is about 60 cm long. While a continuous (low density) beam is injected, the simulation shows a beam collimation along with a density modulation (Figure 1). A regime condition is rapidly obtained, as shown by the total density fluctuation vs. time (Figure 2) resulting from the imposed AC potential.

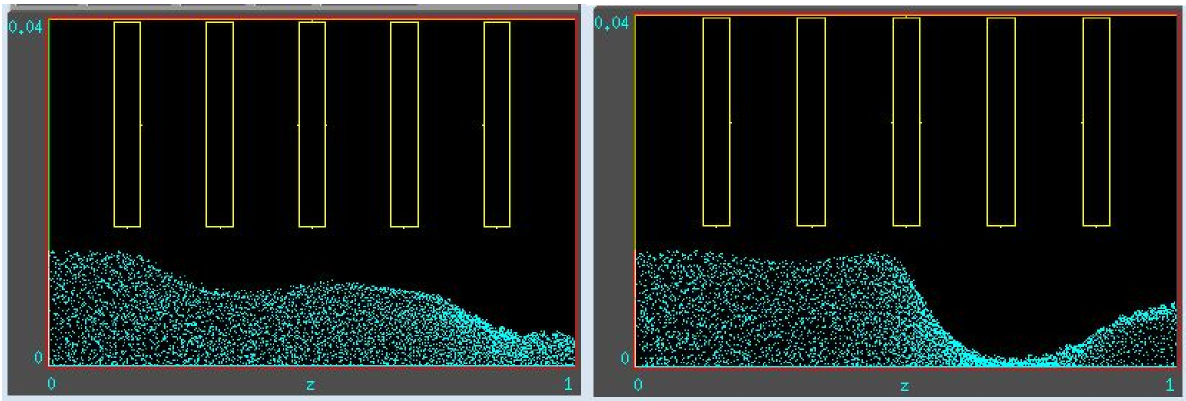

Figure 1. PIC simulation example: 2D *r-z* (4 cm radial, 1 m longitudinal) plot of particle positions. The aspect ratio is distorted for plotting purposes. The beam is injected from the left side and leaves the right side (open end boundary). The rectangular structures are biased electrodes. The plots show two different time instances of the regime condition as particles are injected and leave the system.

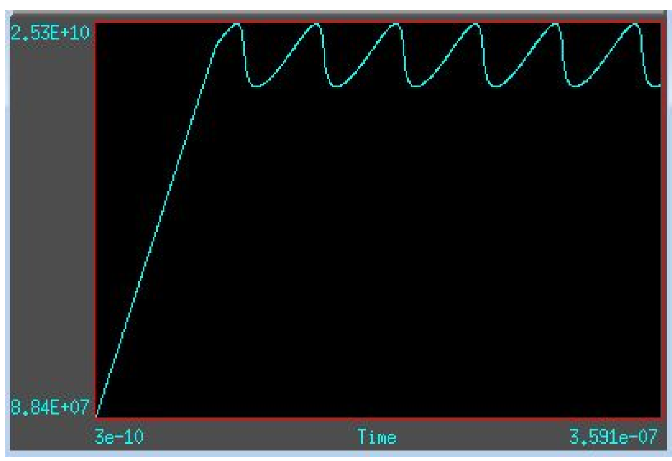

Figure 2. PIC simulation example: imposed fluctuations of total beam density vs. time as the particles are injected at a constant rate. The simulation is reaching rapidly a regime condition after the beam reaches the open end of the simulation domain, as the injected particles are on average compensating the ones leaving the simulation region.

Conceptual Scheme for the Utilization of a Multiple-Species Beam with Velocity Spread

An important issue for maintaining efficiency in the TWDEC operation is to ensure that the particle injection process provides a mono-energetic beam, or at least a beam with particles with a uniform velocity along the axis.

Nuclear reaction fragments, however, are characterized by a considerable velocity distribution spread and can be made of different species. For example, the U-235 fission reaction has the typical double-hump mass fragment distribution with A=95 amu and A=137 amu as most probable yield [ENS, 2003]. The total fragment energy release from U-235 fission is always about 169 MeV, and therefore the different fragments will acquire different velocities.

A scheme is devised below to equalize the speed of the injected particles along the axis of the converter. As an initial assumption, a unidirectional beam of fragments at different speeds is assumed. Figure 3 depicts the described arrangement for illustration purposes (it should be noted that the simulations examples in Figure 1 and 2 are related to a later stage of the process, after the beam has been injected).The beam is injected into a bending magnetic dipole acting as a velocity filter. Particles with larger speed will be deflected less, leading to a spreading of the deflected beam. The beam is then injected into a solenoidal magnetic field, with the trajectory of faster particles entering at a larger angle to the field lines.

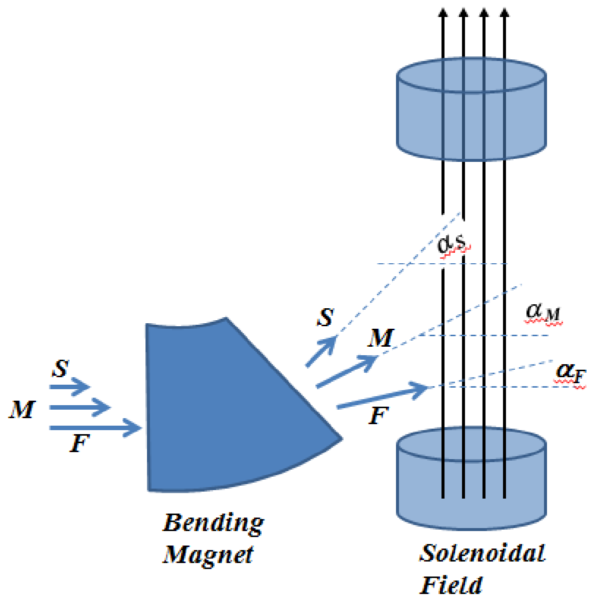

Figure 3. Conditioning of a particle beam with a velocity spread for TWDEC injection. The beam is injected into a bending magnetic field (velocity filter). Particles with higher speed will be deflected less. Three cases are shown. Fast (F), medium (M) and slow (S) particles are co-injected. After the deflection the incident angles with respect to the solenoidal magnetic field are different: $\alpha_S > \alpha_M > \alpha_F$.

As a result, the faster particles will have a smaller fraction of their original speed directed along the solenoidal magnetic field lines. The beam will be then still made of particles at different total energies, spiraling with different radii around the field lines, but characterized by longitudinal drift speed.

A simple analysis of this scenario can be considered. A collection of particles with different collimated velocities v_{0i} is entering the velocity filter region where a uniform magnetic field B_{vf} perpendicular to the particle velocity direction is imposed. Each particle orbit will follow a circular arc path of radius

$$r_i = \frac{m_i v_{0i}}{q_i B_{vf}} \tag{1}$$

Assuming that the velocity filter field is a square region of side L_{vf}, each particle will be deflected by an angle α_{vf} where

$$\sin(\alpha_{vf}) = \frac{L_{vf}}{r_i} \tag{2}$$

After the deflection the particles enter the solenoidal field B_s (Figure 3), now at angle α_s··/2-α_{vf} with the direction of the field. The particles will follow a typical spiraling trajectory with a drift velocity along the field lines given by

$$v_{di} = v_{0i}\cos(\alpha_s) = \sin(\alpha_{vf}) = v_{0i}\,\frac{L_{vf}}{\frac{m_i v_{0i}}{q_i B_{vf}}} = \frac{q_i B_{vf}}{m_i} L_{vf} \tag{3}$$

Following this scheme the particles will have acquired a drift velocity along the guiding solenoidal magnetic field that depends only on their charge-to-mass ratio and on the magnetic field of the deflector B_{vf}. The original particle velocity spread only affects the motion in the perpendicular plane (along with the solenoidal field B_S) and not the longitudinal drift along the field.

Such a beam has now only a discrete set of different drift velocity components (mostly corresponding to fission fragments with the highest likelihood of being generated). Without any further refinement, in principle, for the purpose of utilization in a TWDEC-like structure, the discrete velocity components can be then separated and re-directed through separate DEC channels.

For the most effective design, since the particles with different charge-to-mass ratio will follow different paths, the structure of the velocity filter can be tapered to provide different effective path lengths, such that particles with smaller deflection radius r_i will also encounter a shorter length L_{vf} , therefore effectively compensating for any factor that would affect the drift velocity along the solenoidal field (that would guide the particles towards the TWDEC modulator).

A more accurate understanding of the parameters of this process can be developed by taking into account the actual fission fragment distribution in a properly defined computational model that includes a realistic magnetic field pattern, including the effect of fringe fields at the edges of the velocity filter.

CONCLUSION

A preliminary study has been conducted on a novel fission direct energy conversion approach that utilizes a traveling wave conversion scheme, previously conceived and developed up to an experimental stage for fusion energy applications. One of the main issues related to the utilization of a beam made of fission fragments has been addressed through a conceptual scheme based on magnetic velocity filtering. A computer model is in the early development phase and has been tested for applications to beam modulation. Further numerical investigations are in progress for an accurate feasibility assessment and for the determination of parameters suitable for the design of a proof of principle experiment.

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