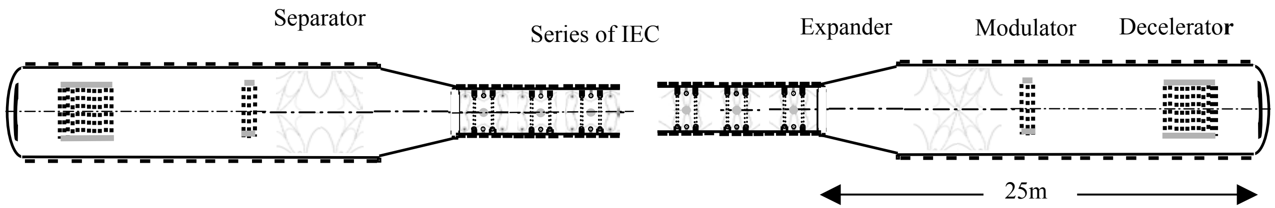
NBI SUPPORTED SIEC



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Integration of NBI into IEC Reactor Concept

- Future D-^{3}He fueled Spherical IEC (SIEC) power reactor should employ direct conversion to achieve high efficiency
- Then it becomes necessary to collimate the 14.7MeV protons to lead them to the direct converter
- A traveling wave type direct converter is selected to avoid excessive voltage requirements characteristic of plate type converters
- Neutral beam injection fits naturally into the above configuration.
- A series of IEC fusion units connected by the collimator is selected to increase output power and the confinement time.

D-^{3}He Fueled SIEC Fusion Reactor - Need for Collimator

- Since the energy of fusion protons from D-^{3}He reaction is as high as 14.7MeV, it requires much higher voltage than the applicable electrostatic potential limit (such as *1.5MV*) to convert fusion power to electricity.
- A use of "Traveling Wave Direct Energy Converter (TWDEC)" resolves the problem and gives conversion efficiency as high as 65%.
- Since velocity distribution of fusion products is isotropic, one has to align these charged particles in a directed flow before guiding them to TWDEC. This can be performed automatically by operating a SIEC near the center of a "Collimator".

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- A Collimator consists of a pair Helmholtz coils anti-parallel to a magnetic channel (Fig.1). Currents on the coils are chosen so as to eliminate magnetic field at the center.

- End of the magnetic channel is connected to TWDEC. A SIEC suffers no magnetic field, while fusion protons as well as unburned leaking fuel ions are aligned to the line of force towards TWDEC.

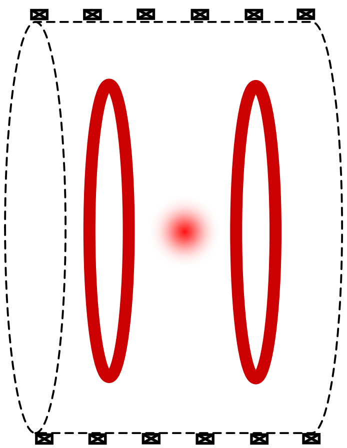

Fig.1: Pair Helmholtz Coils anti-parallel to a Magnetic Channel

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- The accessible domain of *14.7MeV* protons is separated from Helmholtz coils. This fact allows series operation of multi-SIEC connected along the magnetic channel (Fig.2).

- The Series operation increases the total output and improves confinement by increasing the number of SIEC fusion units (Fig.3).

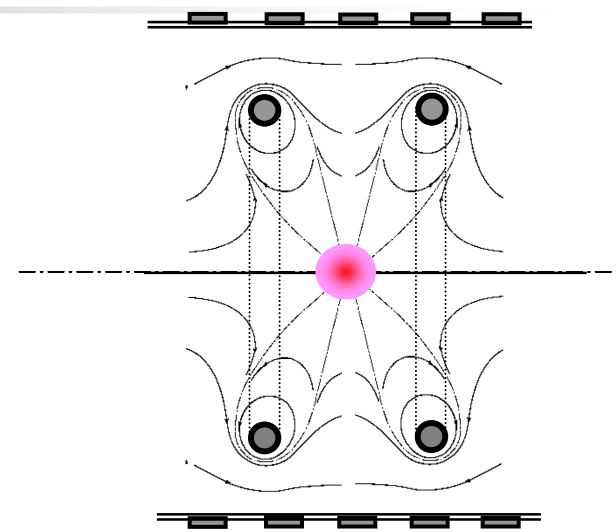

Fig.2: 14.7MeV Proton in a Collimator

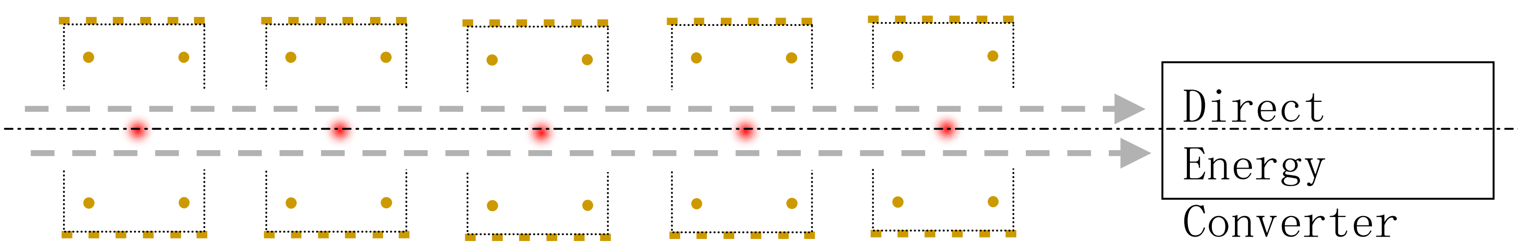

Fig.3: Series of SIEC Fusion Units

Ion Beam Source separated from Fusion Core – Logic for NBI

- In a conventional SIEC, ions are born between a spherical anode and a concentric meshed spherical cathode. Ions are accelerated by and path through the cathode towards the center.
- The fuel gas pressure of >1 *mTorr* is required to breakdown with an applied voltage of $\sim 100kV$.
- Inside a fusion unit, however, a high vacuum of $< 10^{-5}$ *mTorr* is required to avoid energy loss of ions due to charge exchange with neutrals,
- The pressure difference will be supported by orifices between the SIEC fusion unit and energetic particle beam sources outside the unit.
- Ions and electrons are hard to penetrate into a fusion core through peripheral collimator magnetic field. Energetic neutral atom beam is, therefore, required to operate SIEC fusion system.

Magnetic Trapping and Leakage of Fuel Ions

- An inertial force due to injected particle beam confines, practically, a low pressure plasma.

- Fortunately, collimator magnetic field appears to be capable to confine a high power fusion plasma within a certain region in the collimator. (The representative magnetic field: $2T$ is strong enough to trap plasma: $n_{3He} = n_d \gtrsim 2 \times 10^{19} m^{-3}$, $100keV$).

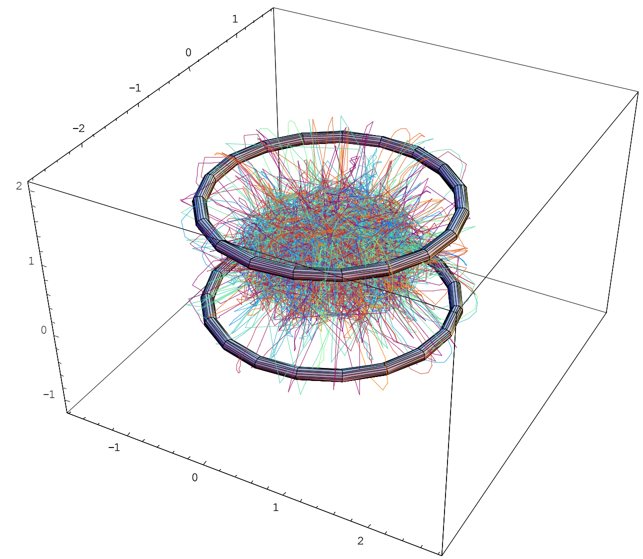

Fig.3: Magnetic Trapping of 100keV Fuel Deuterium in a Collimator: (by Alan L. Miller).

- An example of magnetic trapping in a collimator is presented in Fig.3 . *100keV* deuteriums start at the center in random directions.Trajectories form a sphere in which particle motion is Ergodic (KAM).

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- Plasma particles are magnetically trapped by a collimator magnetic field. Particles that satisfy the mirror loss criteria:

$$v_z^2 > (B_m / B^{(j)} - 1)v_\perp^2 - (2q_i / M_i)\phi$$

will be lost along the magnetic channel towards direct energy converters. B_m is the maximum of magnetic field along z-axis and $B^{(j)}$ is the minimum magnetic field where *j*-th particles conserve their magnetic moments.

- Representative values $B_m/B^{(j)}$ of *100keV* deuterium and electrons are respectively as large as ~*30* and *2000*. A negative plasma potential ϕ appears at the plasma region, due to the extremely small loss angle of electrons.

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- The loss flax $\Gamma^{(j)}$ of the j-th species of particles is represented by the equation:

$$\Gamma^{(j)} = 2\varepsilon \int_0^{\theta_m} 2\pi r^2 \sin\theta d\theta \int_{v_z^2 > \left(B_m/B^{(j)} - 1\right) v_\perp^2 - (2q_i/M_i)\phi} |v_z| \cos\theta \, f^{(j)}(r, v_\parallel, v_\perp) \, d\vec{v}$$

- Since the loss-cone is small, the distribution function can be approximated by maxwellian. Thus we have an expression for the particle loss of j-th species:

$$\Gamma^{(j)} = \varepsilon \sqrt{\pi} R^2 n^{(j)} \frac{B^{(j)}}{B_m} \sqrt{\frac{2kT}{M_j}} \times \left[e^{q_j \phi / kT} \text{ for } q_j \phi \le 0, \;\; 1 \text{ for } q_j \phi > 0 \right]$$

The geometrical factor ε corresponds the upper limit of the integral with respect to θ and takes a value $\sim 4 \times 10^{-3}$ in normal case.

The Plasma Potential and Particle Confinement

- The steady state condition: $e\Gamma^{(D)} + 2e\Gamma^{(3He)} = e\Gamma^{(e)}$ cooperated with the expression of loss fluxes gives the equation for the plasma potential:

$$e^{e\phi/kT} = \frac{1}{3\sqrt{2}} \frac{B^{(D)}}{B^{(e)}} \sqrt{\frac{m}{M_p}} \left(1 + 2\frac{B^{(3He)}}{B^{(D)}} \right)$$

Therefore, the plasma potential is given by:

$$e^{e\phi/kT} \approx 0.777 \qquad \therefore \phi \approx -0.25 \times kT/e$$

- According to the expression for the loss flux, the particle loss time of electrons, deuterium, and helium-3 can be estimated; giving respectively *17.4 ms*, *10.8 ms*, and *25 ms*. Plasma radius is assumed to be *1m*.

- As is mentioned previously, the overall confinement time can be elongated by the number of series of SIEC fusion units.

Conclusions

- An SIEC fusion energy production needs NBI.
- A magnetic trapping of plasma particles by collimator magnetic field allows *D-He3* fueled high power SIEC fusion unit. A representative confinement time of plasma particle confined in $r=1m$ sphere is ~*16.4ms*.
- Series of fusion units improves confinement as well as output power by the number of fusion units.
- For a purpose of evaluating the concept, detailed analyses including steady state plasma equilibrium, energy confinement, and stability are needed.

Acknowledgment

This Research was partially supported by NASA SBIR Program under NASA Contract #: *NAS8-02012*

Thank You

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