

# Compact, Energy Efficient Neutron Source: Enabling Technology for Thorium Breeder and Accelerator Waste Transmutation

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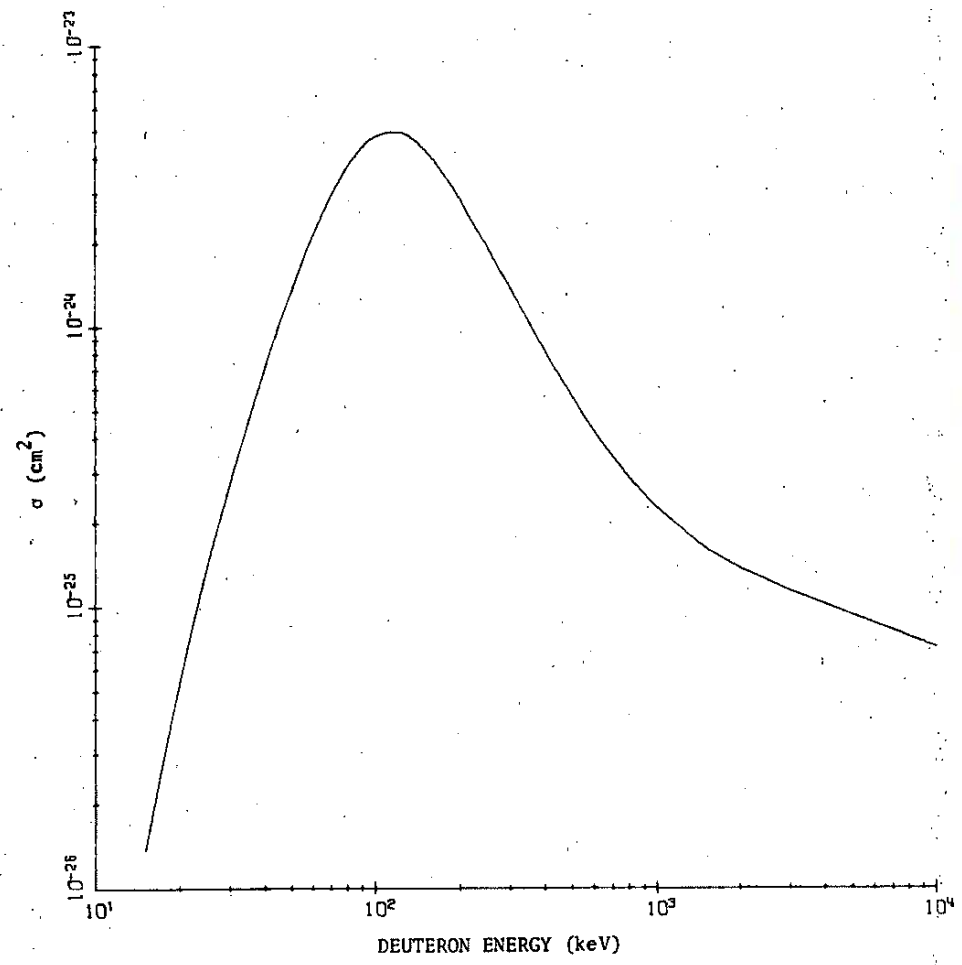


# Compact, Versatile, Energy Efficient Neutron Source: Enabling Technology for Accelerator Transmutation of Waste and Uranium Free Thorium Breeder Reactor

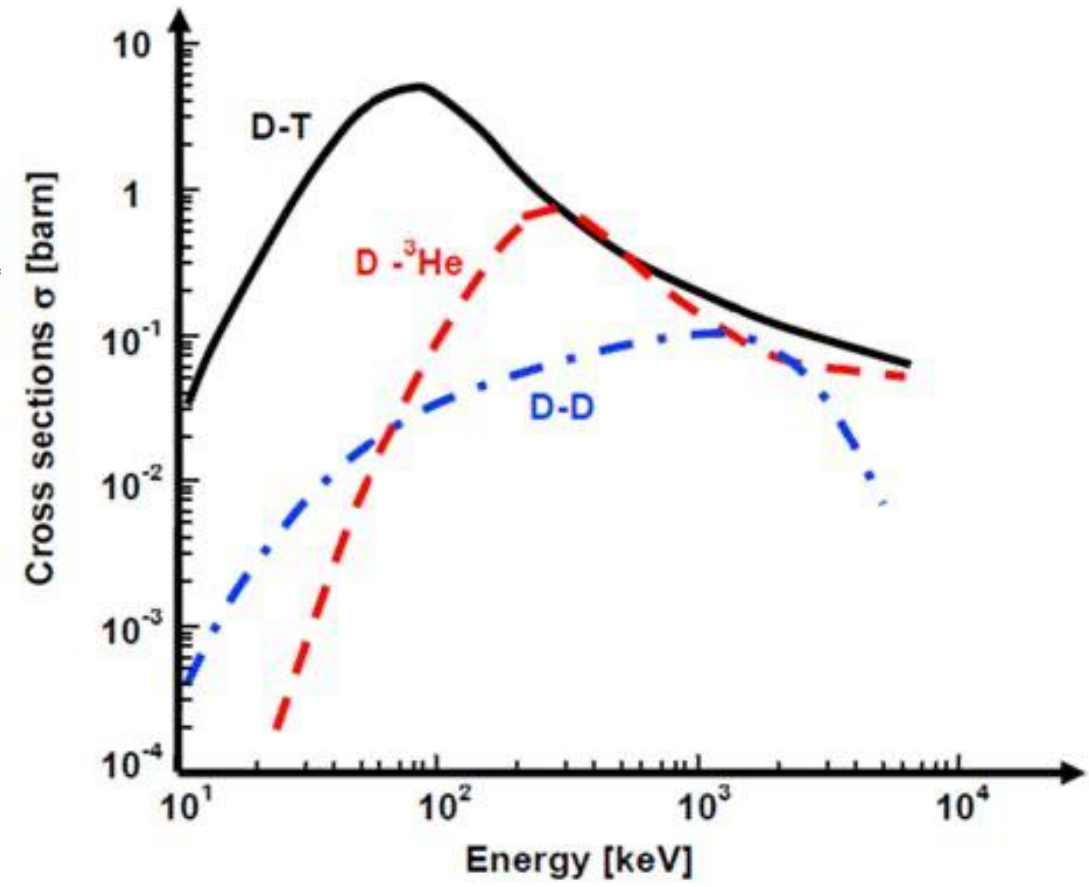
In this novel neutron source, a deuterium beam (energy of about 100 keV) is to be injected through a Plasma Window into a tube filled with tritium gas or tritium plasma to generate D-T fusion reactions whose products are 14.06 MeV neutrons and 3.52 MeV alpha particles. At the opposite end of the tube, the energy of deuterium ions that did not interact is recovered. Energy recovery can be close to 100%. Beryllium walls of proper thickness will absorb 14 MeV neutrons and release 2 – 3 low energy neutrons. Each ion source and tube forms a module. Larger systems can be formed from multiple units. Beam propagation can be further enhanced with vortex stabilized discharges, electron beams in opposite direction (with energy recovery) or magnetic fields where possible. Beam attenuation by electrons results in their heating, which in turn reduces ion beam attenuation. Equilibrium electron temperature exceeding 200 eV can be achieved, resulting in energy efficient neutron generation. Concept description and basic calculation will be presented. Among possible applications for this neutron source concept are sub-critical nuclear breeder reactors and accelerator transmutation of radioactive waste. **Advantage over spallation sources DC versus RF acceleration. Possibility of energy recovery! Very inexpensive proof of principle test.**



Basic idea is to have 125 keV deuterium slowing down to 75 keV, before energy recovery since the fusion cross section  $\sigma$ , which is well known, has a broad peak of 6 barns in the energy range of about 75-125 keV.



Cross section for  $T(d,n)^4\text{He}$



# Advantages

1. **Energy Efficient** (much more than spallation neutron sources)
2. **Compact**
3. **Modular; multi-embodiments possible**
4. **Neutron injected isotropically**
5. **Flexible: works horizontal & Vertical**
6. **Inexpensive and easy to test**
7. **Low cost to implement**
8. **Wide neutron energy spectrum possible**

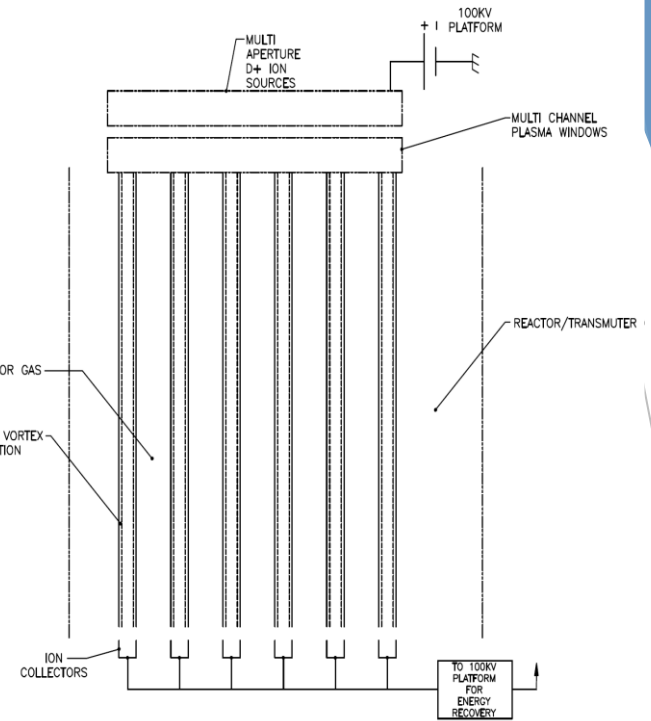
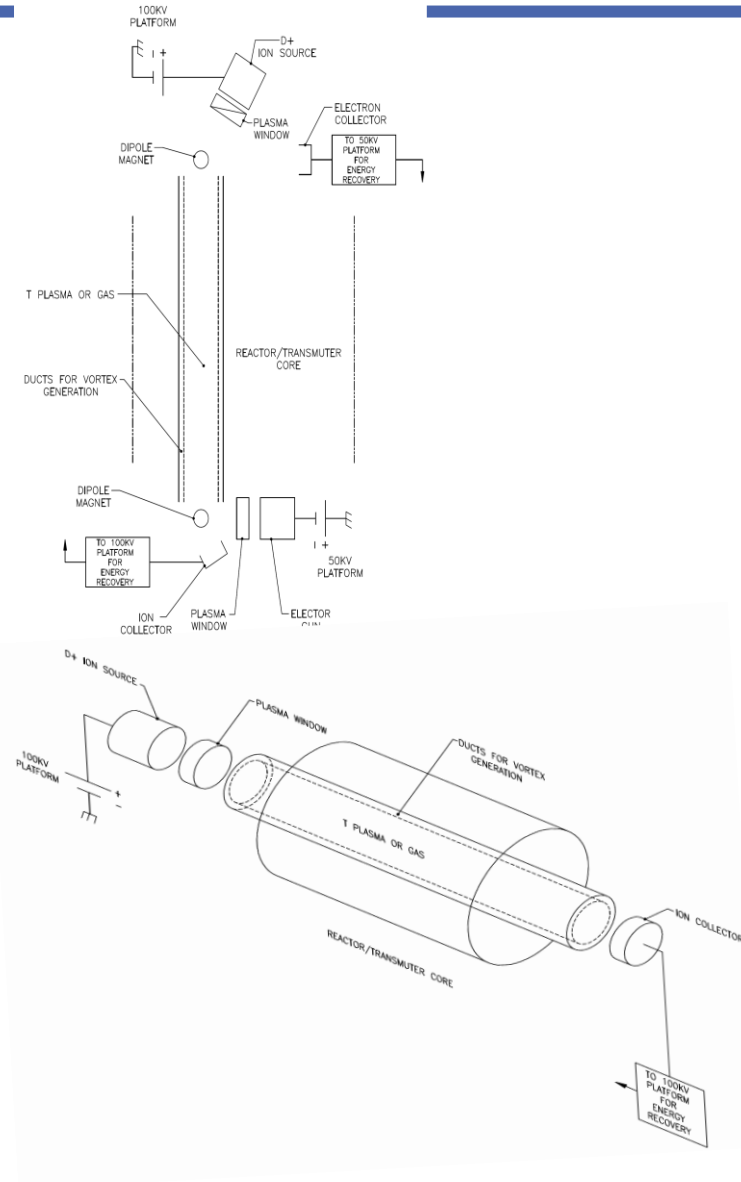
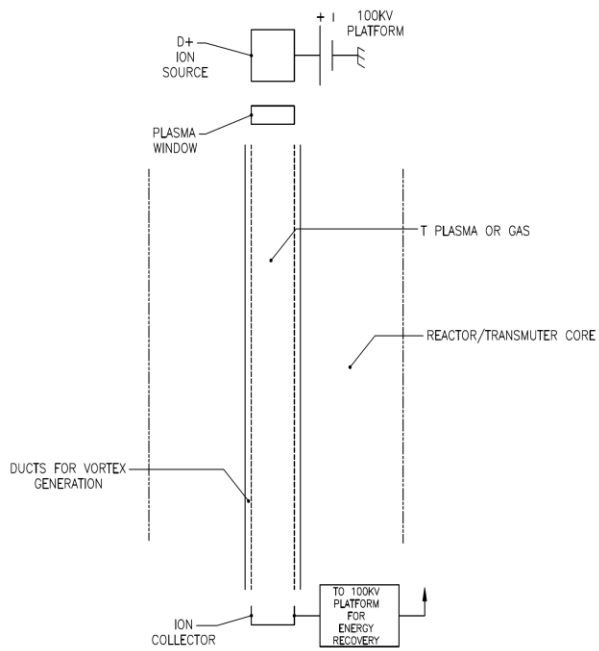


# Novel Features

- 1. Energy Recovery**
- 2. Vortex Stabilized Discharges (or HCA) for ion beam propagation.**
- 3. Self-heating warm electrons for reducing ion energy loss.**
4. Possible use of e-beams with energy recovery for enhanced ion beam propagation.
5. Possible use of e-beams with energy recovery for pure tritium plasma.
- 6. Neutron multiplication walls** (spallation by 3.52 MeV alphas)
- 7. Dense internal targets to enhance neutron yield.**

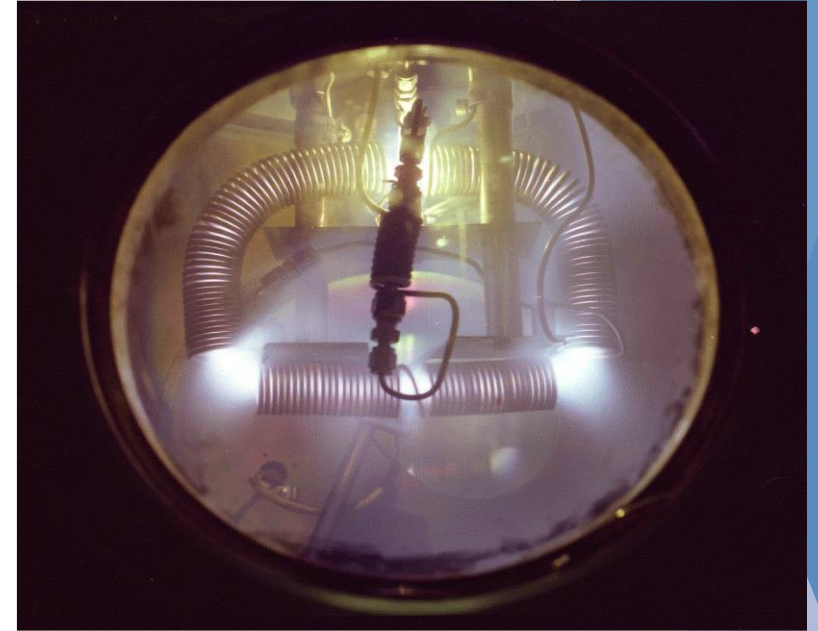
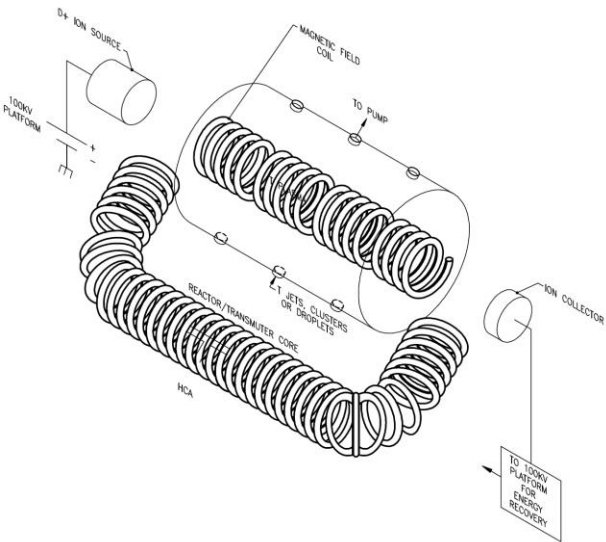


# Embodiments

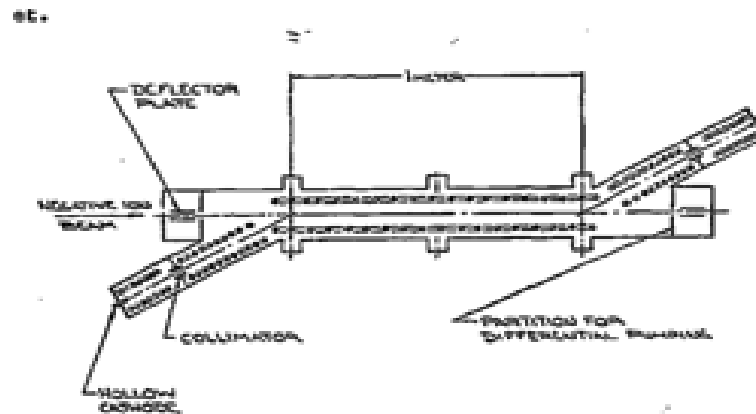
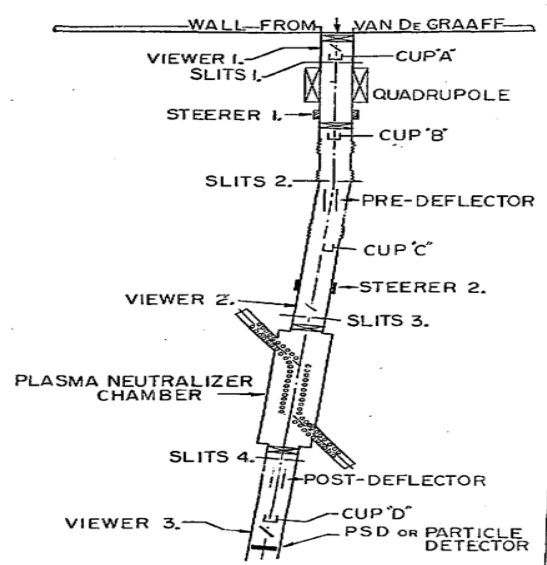


# Experimentally Achieved Plasma Targets

25 cm long target



1-meter long steady state [many hours 3 shifts] hydrogen target generated: plasma density  $10^{14} \text{ cm}^{-3}$  with background density of  $10^{-6}$  Torr (set on MP6 BNL Van de Graaff beamline)



# Preliminary computations of 3 scenarios

Basic concept comprises of a DC deuterium beam (energy of about 100 keV) injected through a Plasma Window into a tritium gas or tritium plasma filled tube to generate D-T reactions: 14.06 MeV neutrons and 3.52 MeV alpha particles.

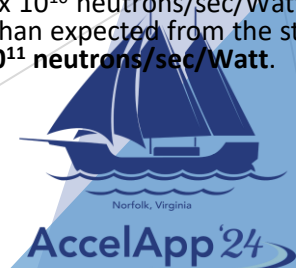
D-T fusion power  $P_f = I_d (1 - \exp \{-[n_t \sigma x]\}) Q$ , where  $\sigma$  is the D-T fusion cross section,  $I_d = I_d / 1.6 \times 10^{-19}$  (i.e. particle current),  $x$  is the interaction length and  $Q$  is the energy generated per reaction  $Q = 17.58$  MeV/fusion reaction. Without  $Q$  this equation yields neutrons/sec. Next formalism for computing number of neutrons generated per deuterium beam power is shown for various target scenarios. Computations are the ratio of the above equation and beam power loss (un-recovered power). The unrecovered power is computed from ion slowing down. For all cases consider 1 A of 125 keV deuterium slowing down to 75 keV, before energy recovery. The fusion cross section  $\sigma$ , which is well known, has a broad peak of 6 barns in the energy range of about 75-125 keV. For energy loss estimation, ion energy of about 100 keV, which is the average, is considered.

## Deuterium Beam in Tritium Gas

Energy loss can be computed from CSDA (continuous-slowng-down approximation). The NIST website <http://physics.nist.gov/PhysRefData/Star/Text/> But, this CSDA range is small for the fusion interaction length for the following reasons: first, the CSDA is a penetration length. At energies below 6 GeV, particle attenuation process is dominated by multiple small angle scattering. Thus, a particle travels a path, which is larger than the range (and hence the fusion interaction length) due to this random walk process. Second, intense particle beam travels substantially longer ranges than single particles of the same energy due to various collective effects. For example, 100 keV electrons have a CSDA range in dry air of  $1.6 \times 10^{-2}$  g/cm<sup>2</sup> and air density near sea level is  $1.2 \times 10^{-3}$  g/cm<sup>3</sup>, therefore, the CSDA range for a single electron is 13 cm. Nevertheless, electrons from 100 keV electron beam of only a few mA, which is used in the atmosphere, can be observed well over a meter down stream.

**In T gas target reducing 1 A D<sup>+</sup> beam from 125 to 75 keV (recovering 75 kW; generating 11.5 kW in fusion), yields 4 neutrons/sec @  $1 \times 10^{11}$  neutrons/sec/Watt**

Using basic principles the gas scenario computation results can be duplicated. The total power lost due to the interaction of the deuterons with the electrons of the tritium gas, either by ionization or scattering, is given by the stopping power  $dE/dx$  of deuteron in hydrogen times the number of electrons per cm<sup>3</sup>:  $P_{loss} = I_d (1 - \exp \{-[dE/dx n_e x]\}) Q \approx I_d dE/dx n_e x$ . The ratio of fusion power to the lost power is then:  $P_f/P_{loss} = (Q n_t \sigma) / (dE/dx n_e)$  for a neutral tritium gas where  $n_t = n_e$   $P_f/P_{loss} = (Q \sigma) / (dE/dx)$ . For an average deuteron energy of 100 keV we have:  $Q \approx 17.6$  MeV,  $\sigma \approx 6 \times 10^{-24}$  cm<sup>2</sup>, and  $dE/dx \approx 4.5 \times 10^{-21}$  MeV cm<sup>2</sup> and then  $P_f/P_{loss} = 0.023$ . A single particle calculation gives a rather low efficiency of 2.3 %. Similarly the neutron flux per lost beam power is:  $dn/dt/P_{loss} = n/\Delta E = \sigma / (dE/dx) = 0.0013$  MeV<sup>-1</sup> =  $0.8 \times 10^{10}$  neutrons/sec/Watt. Note that the neutron flux with the electrons can be substantially suppressed as discussed below. For example, the propagation of 100 keV electrons in air was shown to be about 10 times more than expected from the stopping power. A reduced effective stopping power for 100 keV deuteron in tritium gas would increase the efficiency to 23% and the neutron flux would increase to  $0.013$  MeV<sup>-1</sup> or  **$0.8 \times 10^{11}$  neutrons/sec/Watt**.



# Other Possible Scenarios

## Deuterium Beam in Cold Electron Tritium Plasma

Computing deuterium ion slowing down in plasma can be performed using the test particle model, which was originated by Norman Rostoker. Next a case of deuterium ions in 100 keV ionized plasma like from a hollow cathode arc with a temperature of about 10 – 15 eV, and densities exceeding  $1 \times 10^{14} \text{ cm}^{-3}$ . Electron thermal velocity and ion beam velocity given by  $V_{Te} = 4.19 \times 10^7 T_e^{1/2} \text{ cm/sec}$  &  $V_i = 1.38 \times 10^6 \mu^{-1/2} E_i^{1/2} \text{ cm/sec}$  respectively, where  $\mu$  is ion mass expressed in units of proton mass  $T$  and  $E$  are in eV. Ion slowing down by electrons rate  $v^{i/e}$  is defined as

$$\frac{dE_i}{dt} = -v^{i/e} E_i \quad \text{Hence} \quad \frac{\Delta E_i}{\Delta t} \approx -v^{i/e} E_i \quad \Delta E_i \approx -v^{i/e} E_i \Delta t$$

When parallel and perpendicular diffusion in velocity space can be neglected, which is the correct assumption for all the cases to be considered, the resultant energy loss is solely due to beam velocity reduction. At this level of computations, we can approximate that  $E_i$  is roughly constant at 100 keV. For ions faster than thermal electrons  $v^{i/e}$  (in  $\text{sec}^{-1}$ ) is given by

$$v^{i/e} = n_e Z^2 \lambda_{ie} 1.7 \times 10^{-4} \mu^{1/2} E_i^{-3/2}$$

where  $n$  is density in  $\text{cm}^{-3}$ ,  $\lambda$  is Coulomb logarithm, which in this case is about 10 (from the NRL formulary), and  $Z$  is ion charge state. Unless otherwise noted all other units are cgs and  $T$  are in eV.

Without considering plasma heating (by the  $D^+$  beam) the **yield is  $1.5 \times 10^9$  neutrons/second/Watt** of beam power loss. Even with anomalous propagation, it is still worse than the case for plasma density of  $3 \times 10^{14} \text{ cm}^{-3}$   $v^{i/e}$  is  $2.28 \times 10^4 \text{ sec}^{-1}$ . But  $v^{e/i}$  is  $5.5 \times 10^4 \text{ sec}^{-1}$  for 15 eV electrons, and it decreases as  $T_e$  increases. Basically elaborate calculations must be done to determine equilibrium electron temperature. Significant plasma heating (especially electron heating) occurs, if energy loss is due to bremsstrahlung and classical/empirical energy loss 31 eV/meter (but not Bohm 42kW/m!), since energy deposition from deuterium is 752.4 eV/meter.

## Deuterium Beam in Hot Electron Tritium Plasma

Finally the case where the deuterium ions have velocity lower than the electron thermal velocity is explored. Ion velocity of  $3 \times 10^8 \text{ cm/sec}$  is matched by electrons whose thermal energy is 54 eV, thus requiring an electron temperature larger than 55 eV. A possible scenario is to start with low density HCA, heat electrons with ECRH, and build up density (at constant temperature). Under these conditions, significant plasma heating (especially electron heating) occurs, if energy loss is indeed due to bremsstrahlung and classical/empirical energy loss (but not Bohm!), since energy deposition from deuterium will be higher. When ions are slower than thermal electrons,  $v^{i/e}$  (in  $\text{sec}^{-1}$ ) is given by  $v^{i/e} = 1.7 \times 10^{-4} n_e Z^2 \lambda_{ie} \mu^{1/2} E_i^{-3/2}$ . Equilibrium temperature computation that involves transition from  $V_D > V_{the}$  to  $V_D < V_{the}$  is extremely difficult to compute analytically, since the analytical formulas are for asymptotic cases, and since hot electrons also heat tritium ions rapidly. So it is assumed that electron temperature is above 60 eV. Consider plasma density of  $3 \times 10^{14} \text{ cm}^{-3}$  (1-inch diameter) and 1 A ion beam. Bremsstrahlung power loss is  $P_{Br} = 1.69 \times 10^{-32} n^2 T_e^{-1/2} = 1.52 \times 10^{-3} T_e^{-1/2} \text{ Watt/cm}^{-3}$  or  $P_{Br} = 0.77 T_e^{-1/2} \text{ Watt/meter}$  of tritium target length

semi-empirical expression for power loss of plasma neutralizer target confined in D-shaped solenoid due to diffusion is  $3.355 \times 10^5 \times T_e^{1/2} / B^2 \text{ Watt/meter}$  ( $T$  in eV,  $B$  in G). Expressions should include a factor of  $(1 + \pi/2)$  to account for plasma around a core. Thus equilibrium temperature can be computed from  $3.355 \times 10^5 \frac{T_e^{1/2}}{B^2} + 0.77 T_e^{-1/2} = v^{i/e} E_i \Delta t = 7.92 \times 10^4 T_e^{-3/2}$

Which for 1 kG,  $T_e = 268 \text{ eV}$ , no chance to reach “breakeven” conditions even if the magnetic field is raised to 3.5 kG (electron temperature will reach only 315 eV).



# Summary of Computations

## Deuterium Beam in Tritium Gas

Without anomalous propagation, can obtain up to  $1.1 \times 10^{10}$  neutrons/sec/Watt of beam power lost. With enhanced propagation, can obtain  $1.0 \times 10^{11}$  neutrons/sec/Watt of beam power lost.

## Deuterium Beam in “Cold” Electron Tritium Plasma

Here D ions are slower than thermal electrons of 10 – 15 eV, in this case one can obtain  $1.5 \times 10^{11}$  neutrons/sec/Watt of beam power lost.

In the above computations, relatively high tritium plasma and/or gas densities are possible. Density is to be determined by tube (interaction) length (until D beam is slowed down to 75 keV. In this case up to  $10^{11}$  neutrons/sec/tube is possible.

## Deuterium Beam in Warm Electron Tritium Plasma

Condition is met by 55 eV electrons. Assume electron temperature of 60 eV, plasma electron will heat. Electron temperatures can exceed 200 eV, with efficiency of neutron generation of  **$6.2 \times 10^{10}$  neutrons/sec/Watt!**

If a stainless steel interaction tube is to be surrounded by beryllium (or other metal like Nb) for neutron multiplication (works with 14 MeV neutrons, but not with spallation neutrons); factor **2 multiplication** can be achieved (though it could be even higher).



# Comparison

GA concept (Rodriguez and Baxter ICONE 9, 2001) is based on a spallation neutron source for transmutation based on a 1 GeV 15 mA proton beam, which generates **40 neutrons/proton**. And it's 15 MW of incident proton beam power!

GA concept could generate  $3.75 \times 10^{18}$  neutrons/sec. Hence it could generate  $2.5 \times 10^{11}$  neutrons/sec/Watt of proton beam power.

Given that maximum efficiency of RF acceleration is no more than 30%. Usually RF acceleration is only 10 – 20%. Superconducting cavities can reach 80% but require large refrigeration power overall 30% efficiency. This factor alone reduces power cost of neutron generation to  **$7.5 \times 10^{10}$  neutrons/sec/Watt**

Since **DC acceleration** and **DC power supplies** are **extremely efficient 80%!** (e.g. over 80% of electric wall power required to generate welding electron beams is deposited in weld! Some electrons are reflected),  $D^+$  ion beam power cost for generating neutrons (considering 80% acceleration efficiency with neutron multiplication of 2.5) can reach  **$1.24 \times 10^{11}$  neutrons/sec/Watt** (or even close to  $2 \times 10^{11}$  neutrons/sec/Watt with higher magnetic fields).

Comparison does not even address the difference in complexities and cost

Based on SNS experience, a spallation neutron source is a major project, costing billions of dollars has yet to reach performance goals

Nevertheless, SNS gets 25 neutrons/1 GeV proton (in liquid Hg target; depletion). European (ADS) is based on a 350 MeV proton beam and a liquid Pb-Bi target yielding 6 neutrons per proton, which is equivalent to 17 neutrons per 1 GeV proton, i.e., a factor of about 3 lower yield than that of the GA concept. Only **W or U targets**, which cannot be effectively cooled, **yield 40 neutrons per 1 GeV proton**.



# Additional Comments; Conclusion

1. D-T fusion with energy recovery can exceed neutrons/sec/Watt compared GA concept especially when whole systems are considered.
2. Needed power supplies, ion sources and energy recovery systems are practically table top
3. Although the GA concept was the system to “beat”, it is based on a 40 neutrons per 1 GeV proton yield. But, only solid tungsten or uranium targets, which cannot be effectively cooled can yield 40 neutrons per 1 GeV proton. More realistic is the European accelerator driven system based on a Pb-Bi target yielding equivalent to 17 neutrons per 1 GeV proton, which is a factor of 3 lower than in the GA concept.
4. Further studies of deuterium beam propagation in various internal targets and with contrastreaming electron beam are needed.
5. Though intuitively seems favorable, the benefits of large spectrum of neutron energy (fast burner) and uniformity of injected neutrons need to be studied.

Overall the concept is worthy of further consideration, especially since proof-of-principle experiment with 62 MeV protons & hydrogen plasma is inexpensive.

Table top experiment can determine electron temperature & ion propagation.

