Overview of IEC Research at the University of Illinois

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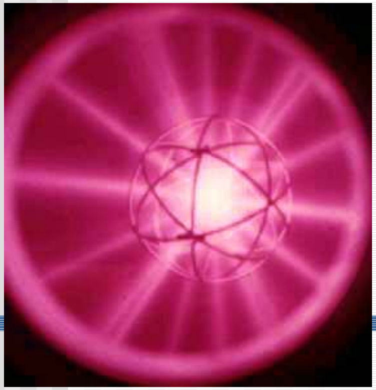
US-Japan IEC Workshop, University of Wisconsin., Madison, WI 10/9/02

Key IEC Activities at UIUC

- Study of ion-injected IEC to reduce bkg. Pressure
- Study of IEC fusion space propulsion and power
  - Simulation of proton collimator using electrons
  - Design study of IEC rocket for Jupiter mission*
- Study of other IEC applications
  - NDA luggage – carton inspections*
  - IEC driven subcritical reactor
  - Student lab research reactor
- Study of advanced IEC concepts
  - NBI CB type unit*
- Modeling studies
  - Cylindrical IEC discharge physics*

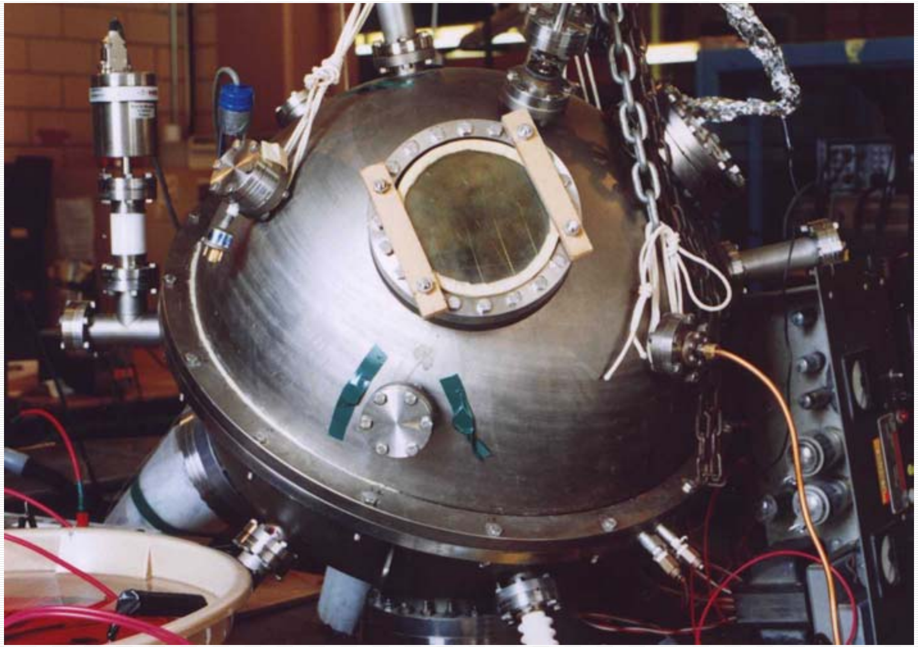
* Topics covered in more detail in other UIUC talks at this workshop

- Study of ion-injected IEC to reduce background pressure



IEC-N Device at the University of Illinois

- Vacuum Vessel 61 cm in diameter.
- Small, compact fusion device.



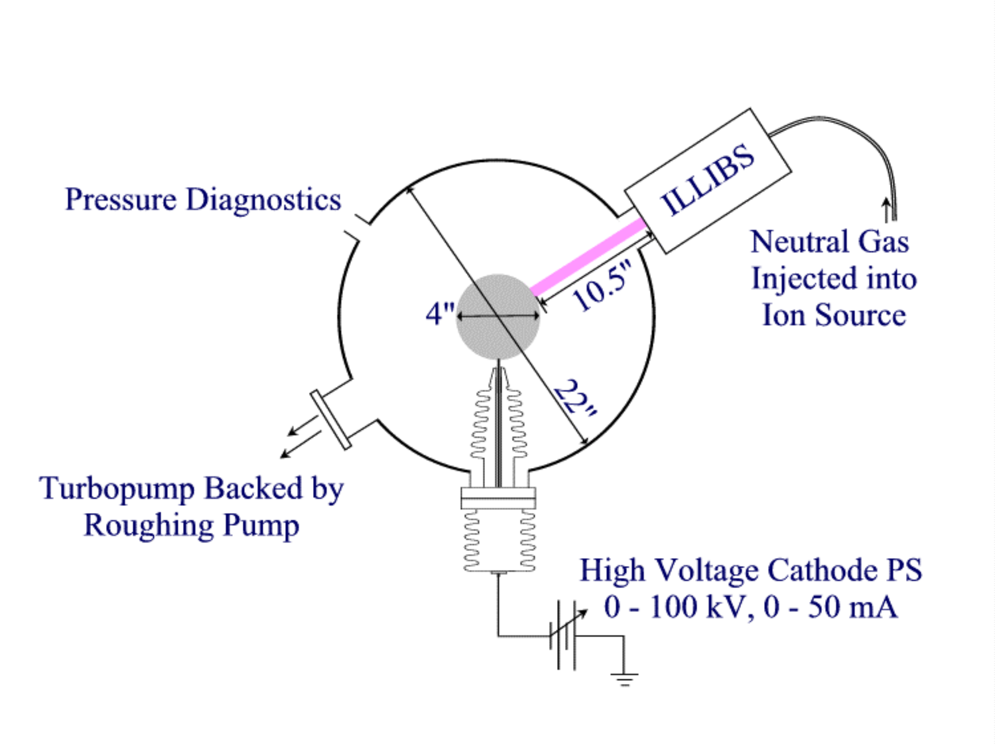
ILLIBS Ion Gun Injection Experiments

- **ILLIBS, Illinois Ion Beam Source, experiments were conducted with IEC N-Device (55-cm in diameter) with an inner cathode grid diameter of 10-cm.**

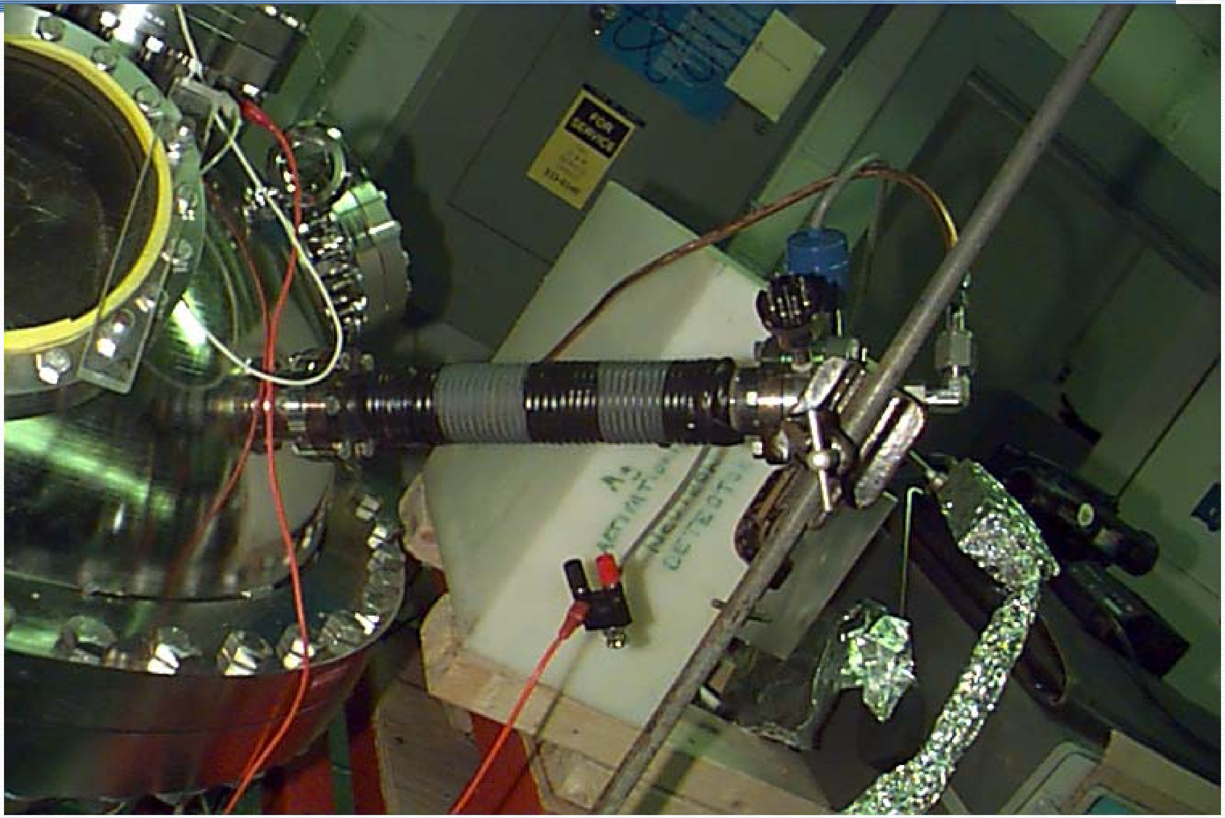
- **The RF (13.5 MHz) input power was fixed at power of ~ 100 W.**

- **A series of experimental data of neutron counts was obtained at different pressures and cathode voltages.**

Typical Experimental Setup for Illinois Ion Beam Source and Current Measurements Results

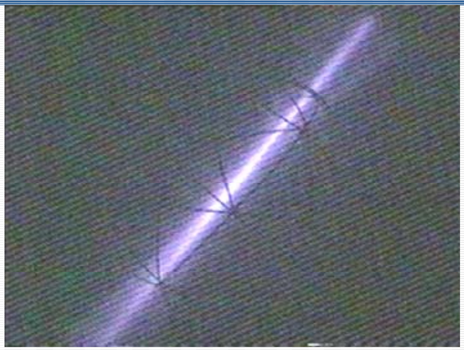


ICRF Ion Source Experimental Setup

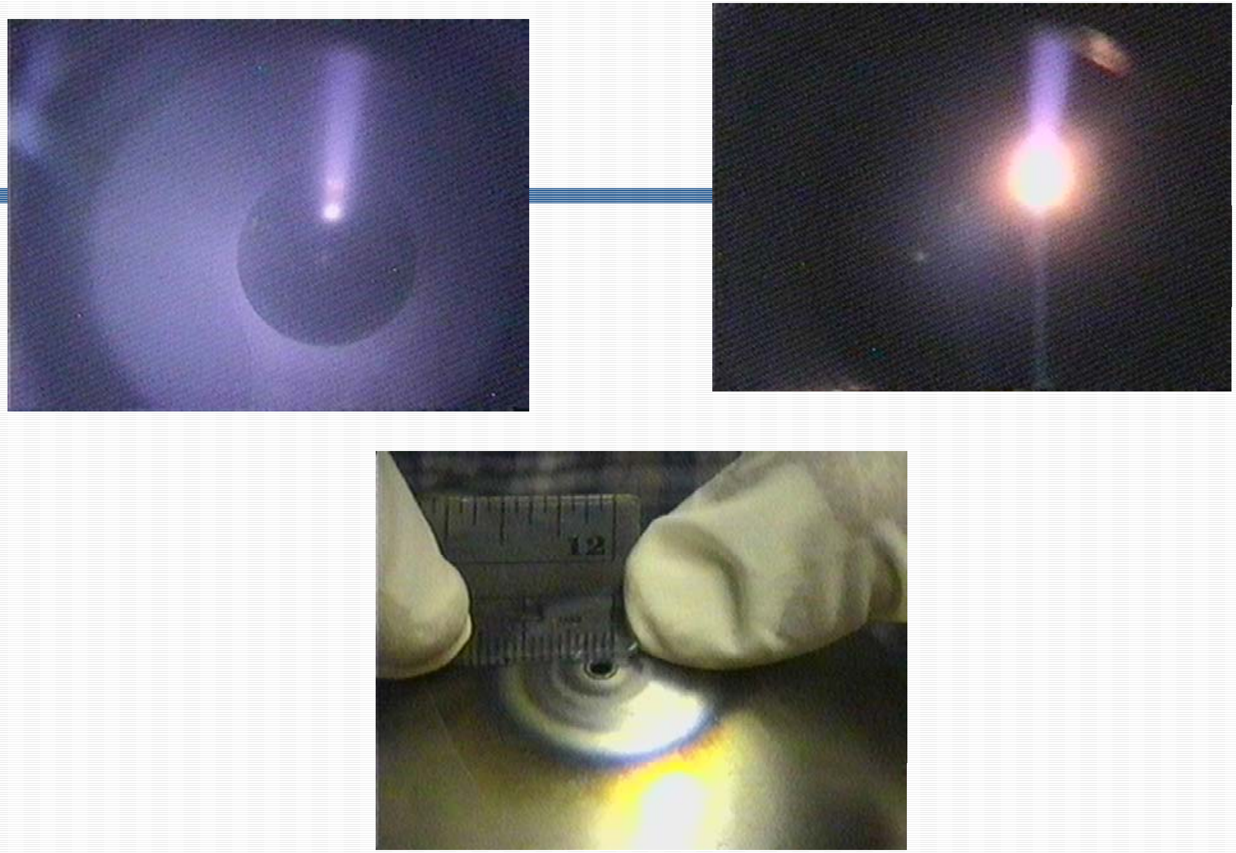


Details of ILLIBS ion source is not shown here.

Single and Multi Ion Beams Generated in IEC Below Break Down Pressure

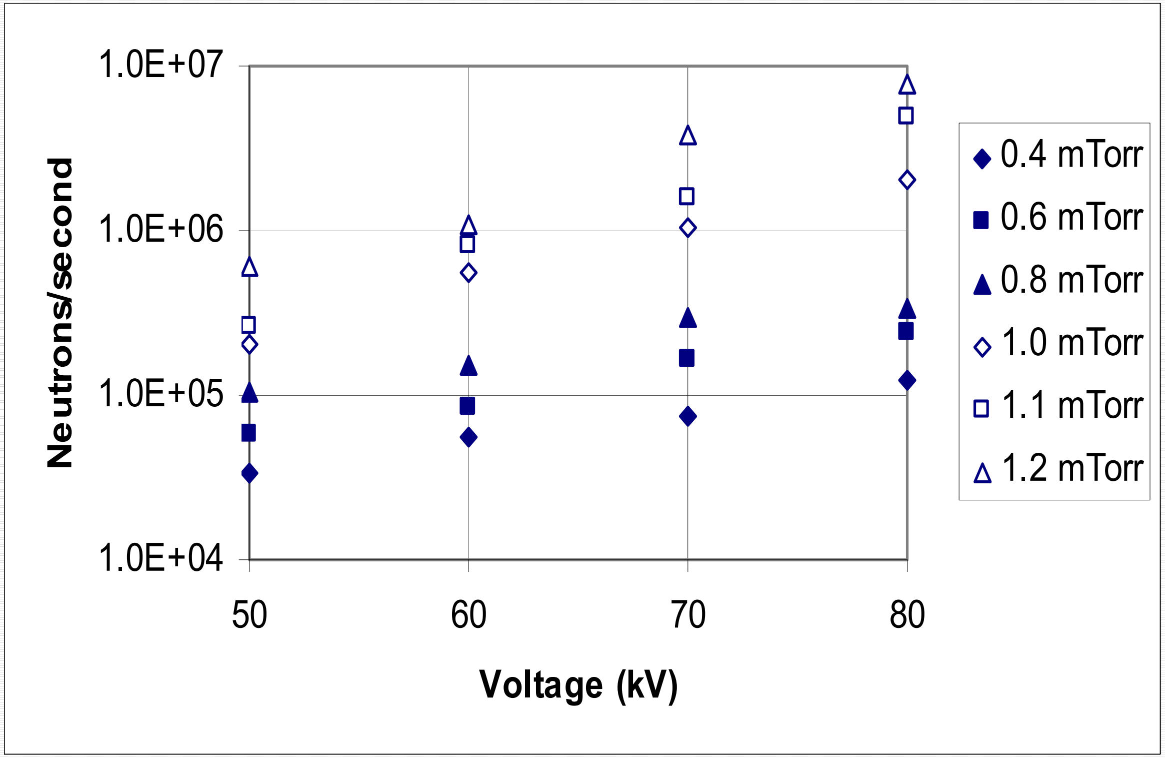


Photos of ion beam tracing inside IEC chamber, single ion beam (left) at 1.2 mTorr, 50 kV, and 0.015 Tesla, and multi-ion beam components (right) at 1.2 mtorr, 60 kV, and 0.03 Tesla. The multi-ion beam is generated above 50 kV, at pressure greater than 1 mTorr, and with magnetic field equal to or greater than 0.015 Tesla. The ion beam is generated from the upper part of these photos. However the orientation of the video camera was changed during the experiments and therefore the ion beam exit is either shown upper-left or upper-right.



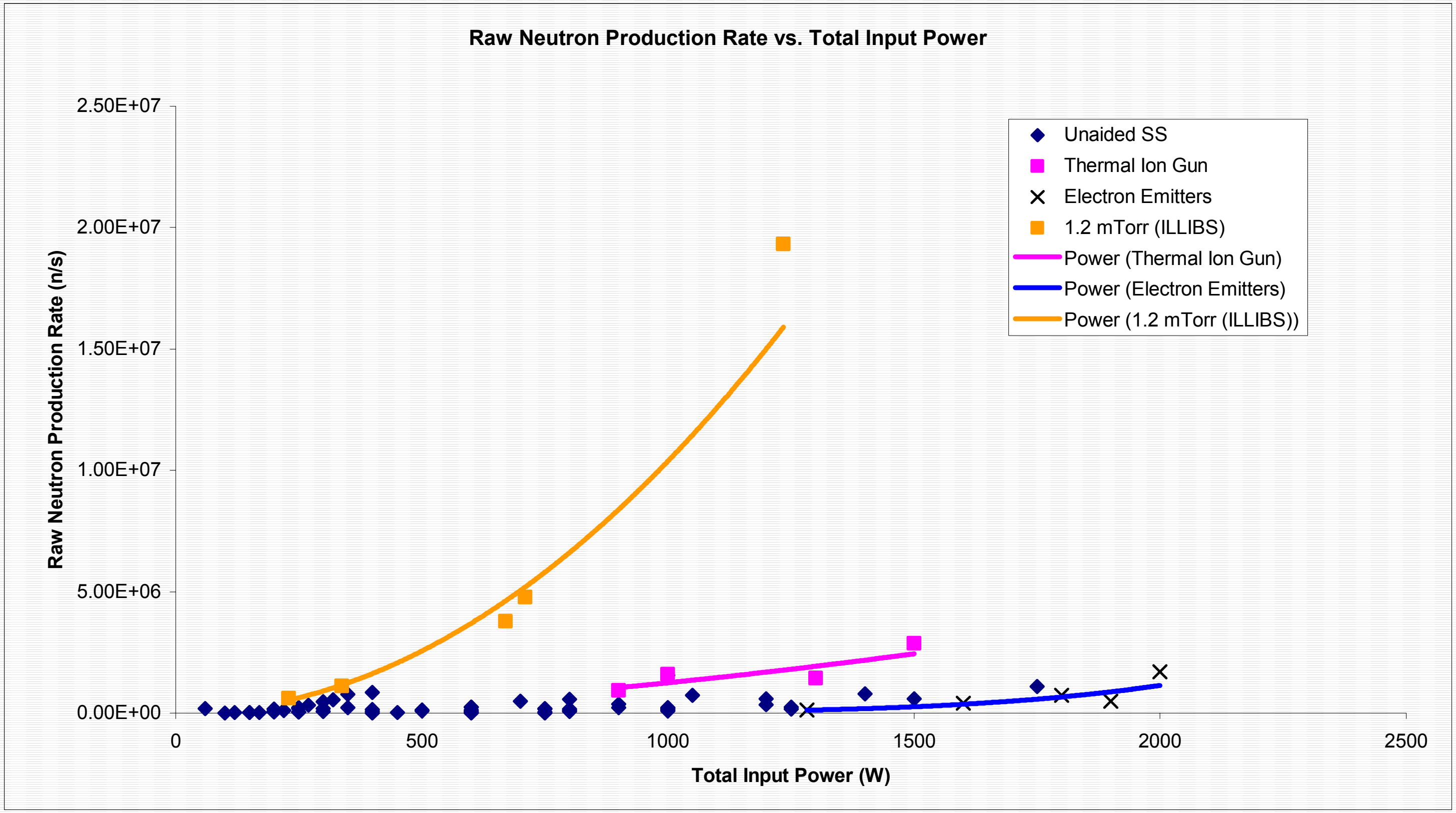
Ion beam tracing at 2 mTorr 10 kV (top-left) and 13 kV (top-right).
The ions were extracted at a distance of 26.6 cm. Effective ion beam diameter (bottom), the diameter of the hole, was measured to be 2.89 ± 0.01 mm (actually measured by digital caliper).
The extracted voltage at this pressure is 13 kV, with corresponding current of 65 mA.
It is shown in the figure the elliptical diameter of the Gaussian beam, shown dark grayish with semimajor axis 21 mm and semiminor axis 17 mm.
No peak current was obtained in this experiment (due to limitation of used equipment).

Neutron rate vs. the cathode voltage at different pressure. The magnetic field was at 0.015 Tesla.



Comparison of ILLIBS Ion Gun With Different Ion Sources

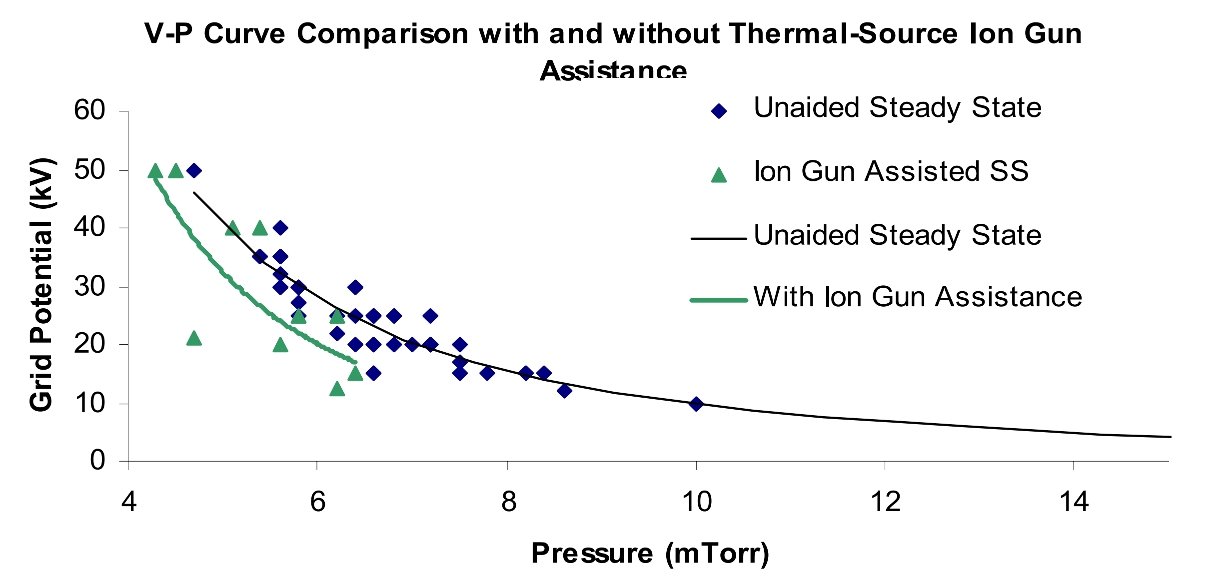
[Power Consumption]



This graphic shows one of the reasons for eliminating internal electron emitters as a primary ion source. Electron emitters have both the lowest outputs and the highest power consumption. Inefficient use of power and high rate of failure are two other reasons. Notice the positive prospect of using the RF-ILLIBS as an IEC ion source.

Comparison With Different Ion Sources

[Pressure Effect]



Pressure and voltage relationship for IEC operation with and without the Thermal-Source Ion Gun in operation. The curves represent least squares fit. Notice the reduction of the pressure achievable with the ion gun in operation . The use of ILLIBS ion gun in IEC has produced a significant shift in Paschen curve. The pressure drop was 0.4 mTorr with variable voltage above 50 kV.

Due to safety hazard, the maximum allowable voltage was 80 kV.

Summary, ILLIBS Injected IEC Performance

- Using the RF ion source:(Illinois Ion Beam Source: ILLIBS) for injection into N-device
  - Extraction beam power efficiency: 22 (mA/cm^2)/W).
  - Ion beam flux 6 x 10^{18} ions/(cm^2-sec).
  - Ion beam divergence 10.8 x 10^{-3} radian.
  - Steady State D-D neutron rate 2 x 10^7 n/sec
  - neutron production efficiency: 1.5 x 10^4 n/J

Scaling Estimates

- A D-D neutron rate of **2×10^9 n/sec** at 1-kW RF power and 0.06 Tesla should be achievable at production efficiency of **1.6×10^5 n/J** evaluated at 75 kV and 1.5 A.

- For D-T fuel, the neutron rate of **6×10^{11} n/sec** should be available at 75 kV and at 1.5 A. This leads to neutron production efficiency of **4.8×10^7 n/J**.

IEC-based Neutron Generator for Security Inspection System

SIEC (left) & CR-IEC (right)

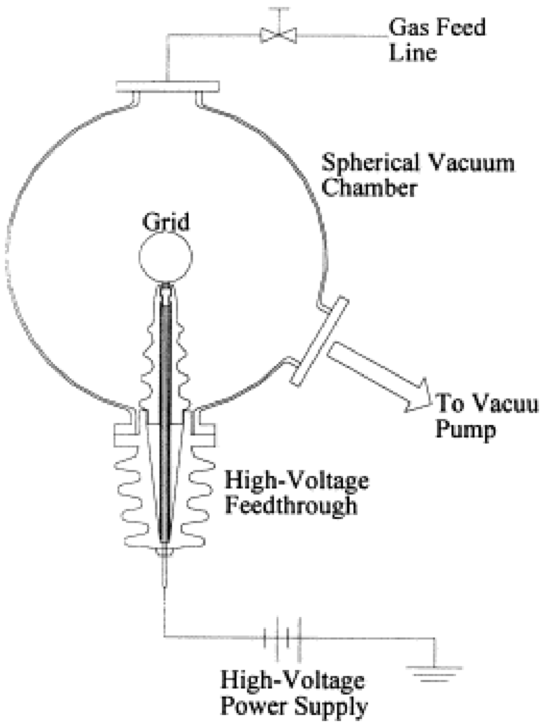


Fig. 1 Spherical IEC Device

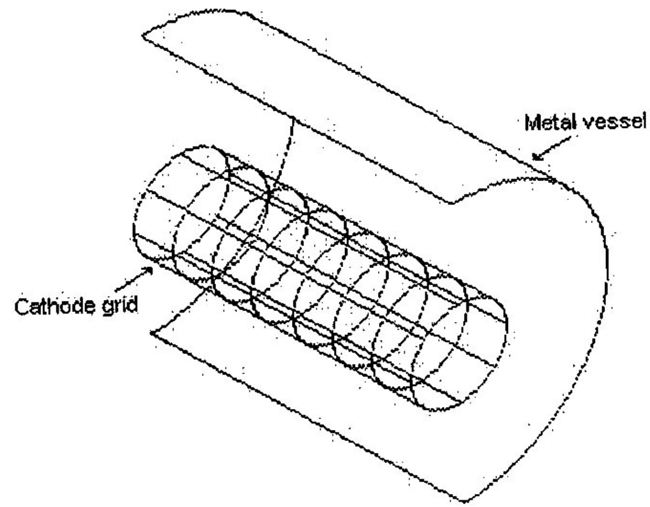


Fig. 2 Cylindrical IEC Device

IEC device as a neutron generator:

- Offers unique multiple source operation (2.5, 14.7 MeV neutrons and x-rays);
- Simple configuration;
- Easily switched on/off, and;
- Reliably produces neutrons with minimum maintenance;
- Data from prior studies:
  - spherical IEC: ~10^8n/s (DD) and ~10^{10}n/s (DT)
  - cylindrical IEC: ~10^9n/s (DD)
  - spherical IECGD neutron generator: 2x10^6n/s (DD);
- X-ray production from Bremsstrahlung by electron injection with reversed bias IEC.

Schematic Layout – uses multiple IEC sources to provide 2.5-, 14.7-Mev neutrons and x-rays to reduce false signals

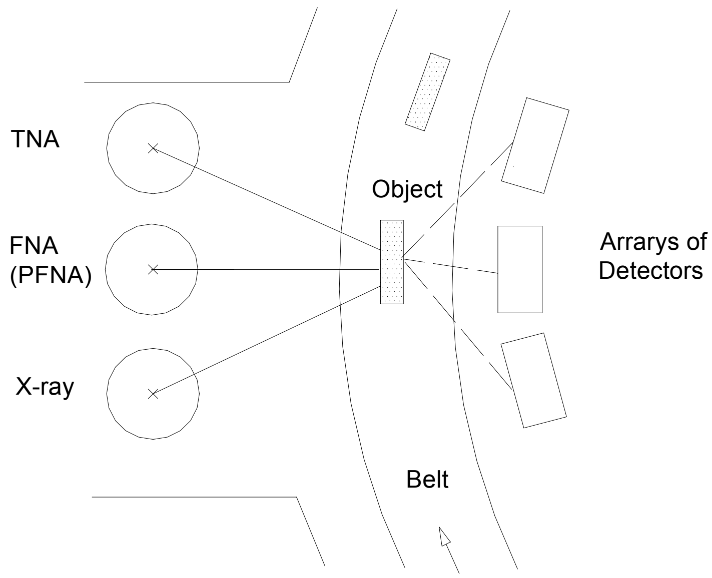
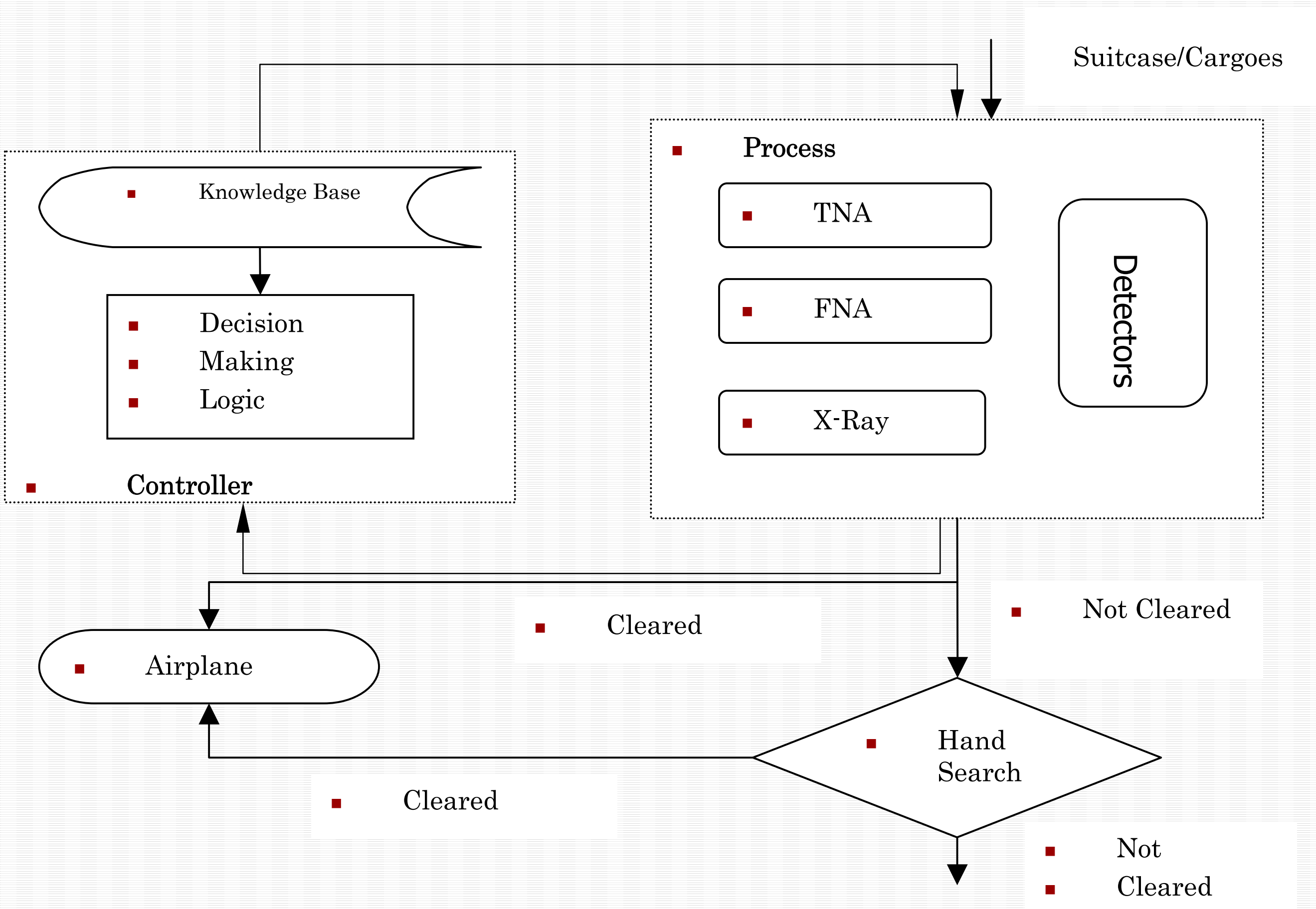


Fig.4 Schematic layout of Inspection System

Fuzzy logic control for multiple measurements reduces error and improves process speed



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Conclusion – IEC for Security Inspection System

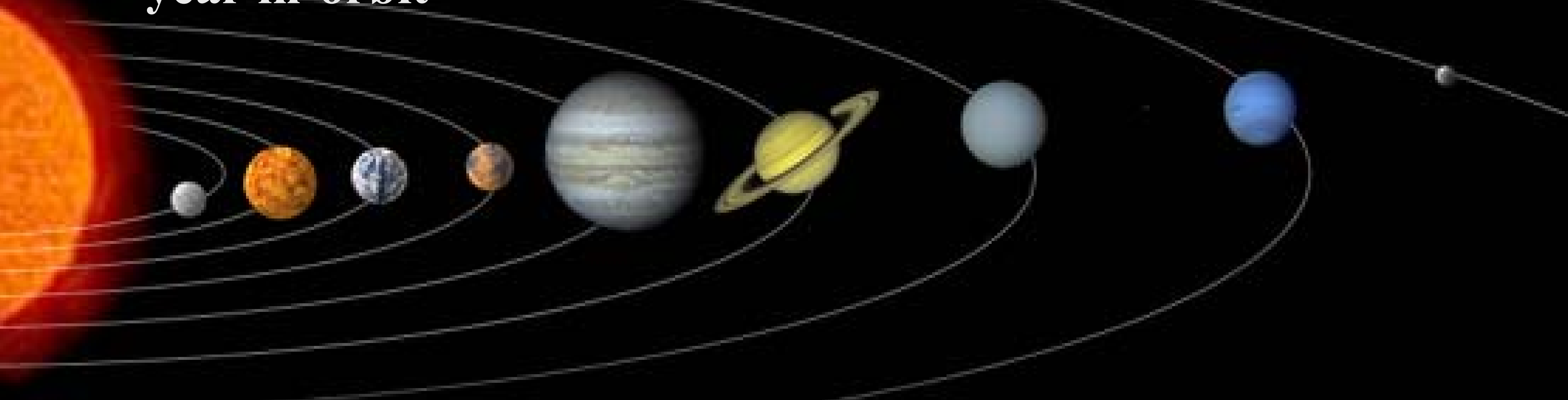
- Simple configuration, easy multiple source operation and reliable neutron production of IEC devices potentially offer a very attractive NAA-based security inspection system.
- A unique fuzzy logic system is recommended for combination of TNA/FNA and X-ray techniques to allow fast inspection while minimizing “false” alarms.

- Study of IEC fusion space propulsion and power
  - Design study of IEC rocket for Jupiter mission
  - Simulation of proton collimator using electrons

The Challenges of Human Interplanetary Travel

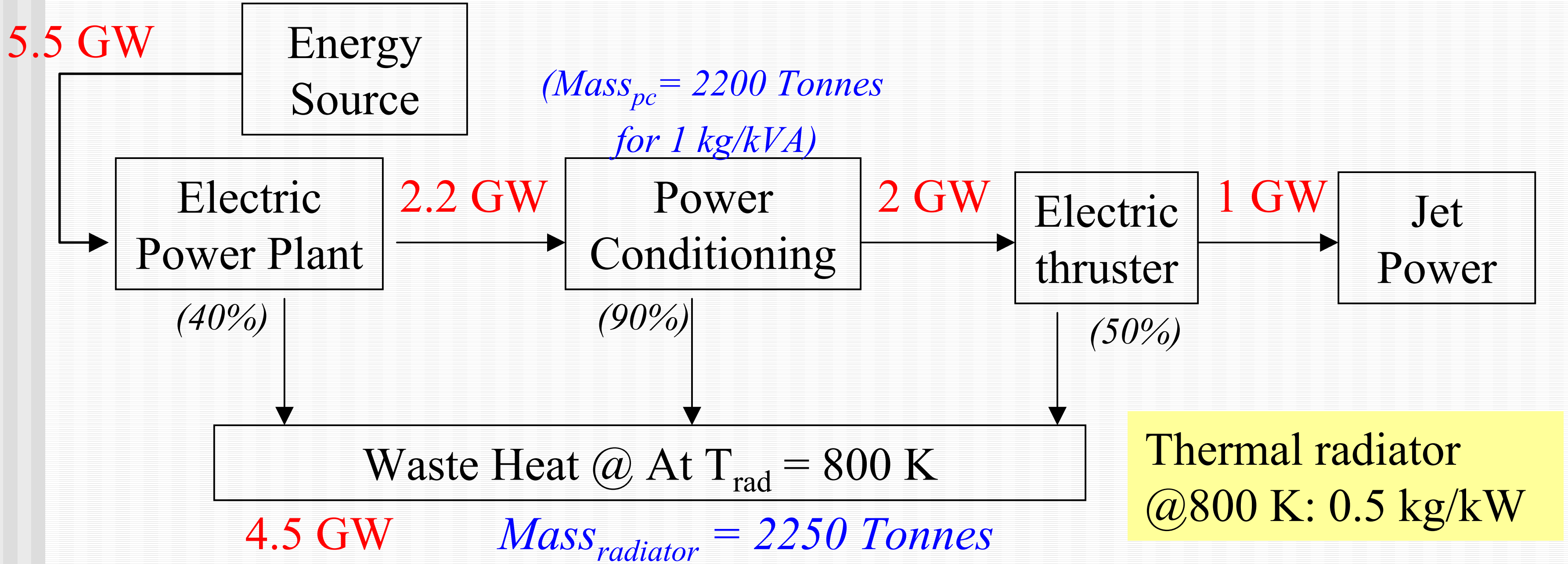
- **Enormous distances**
- **Physiological hazards**
- **Costs**
  - **Zero-g**
    - **Muscle and skeleton deterioration set in after about 100 days**
  - **Cosmic Radiation**
    - **Leukemia and other cancer risk become significant after about one year in-orbit**

Nearest approach to Earth **(in 10^6 km)**	
Mercury	92
Venus	41
Mars	77
Jupiter	629
Saturn	1279
Uranus	2725
Neptune	4,354
Pluto	5,750



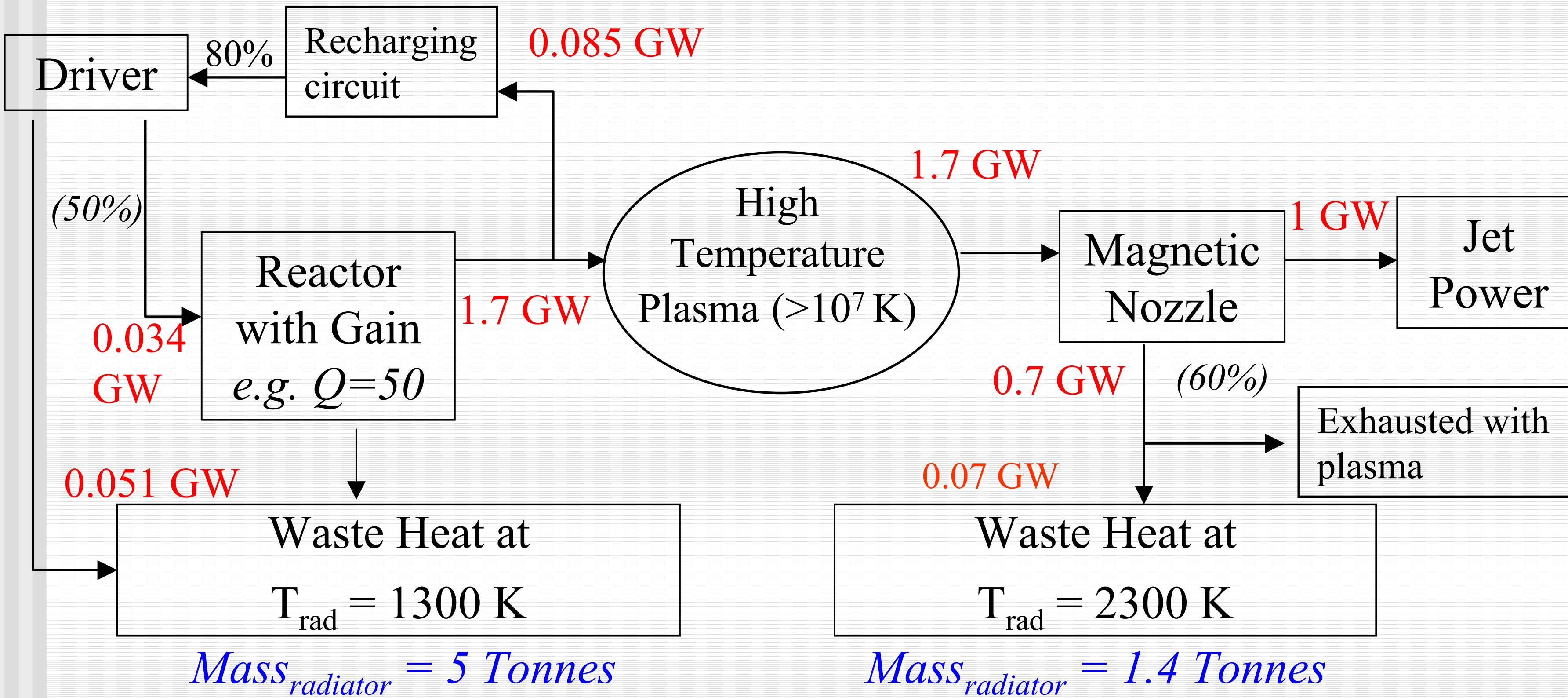
The Need to Look Beyond Existing Propulsion Technologies

- **Chemical and fission thermal propulsion :** ***Propellant exhaust velocity is too low***
- **Fission electric propulsion:** ***Specific power too low***



Fusion is the Ideal Energy Source for Propulsion

- **Direct-Drive Fusion Propulsion:**



Radiator @1300 K:
0.15 kg/kW

Radiator @2300 K:
0.02 kg/kW

Future IEC Jupiter Mission – Fusion Ship I, STAIF 2002

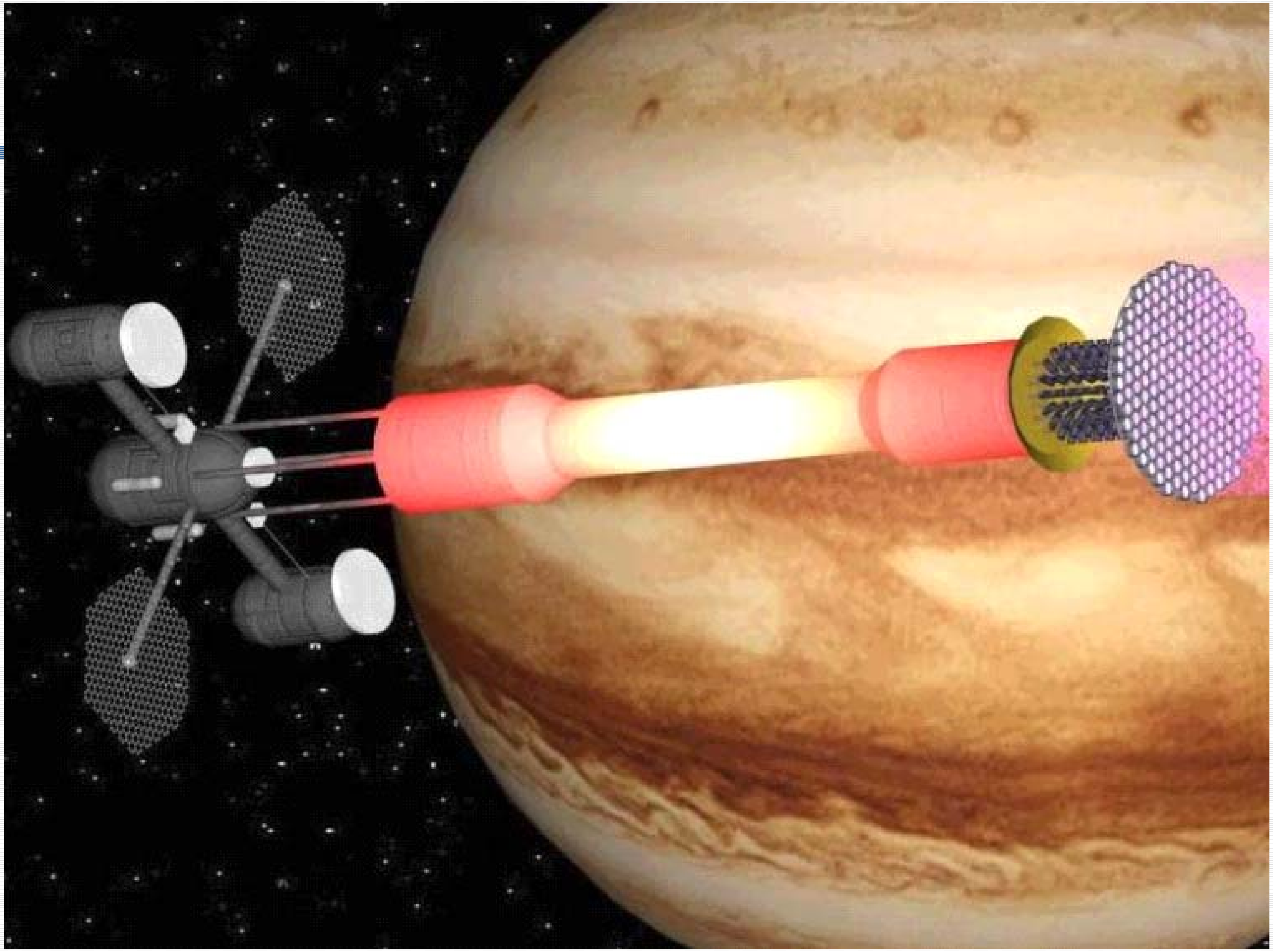


Image of 100 MWe IEC fusion powered spacecraft with ion thruster propulsion.

New Fusion Ship II Design (STAIF 2003) Decreases Trip Time to Jupiter to 1 Year

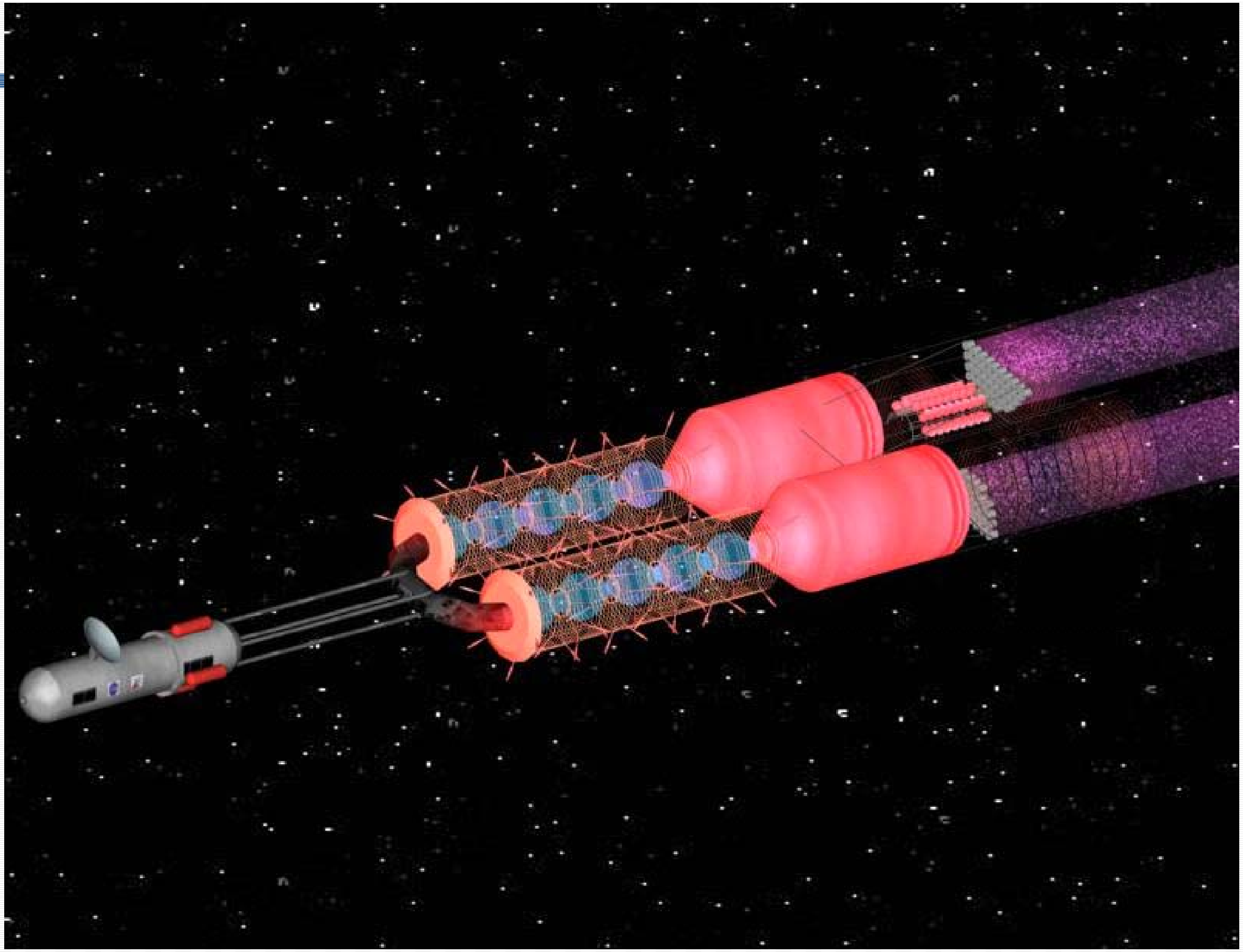


FIGURE 1. Image of Fusion Ship II, a 750 MWe IEC fusion powered manned spacecraft with ion thruster propulsion.

Fusion Ship II Schematic – uses 10 IECs connected via magnetic collimator, "U" configuration.

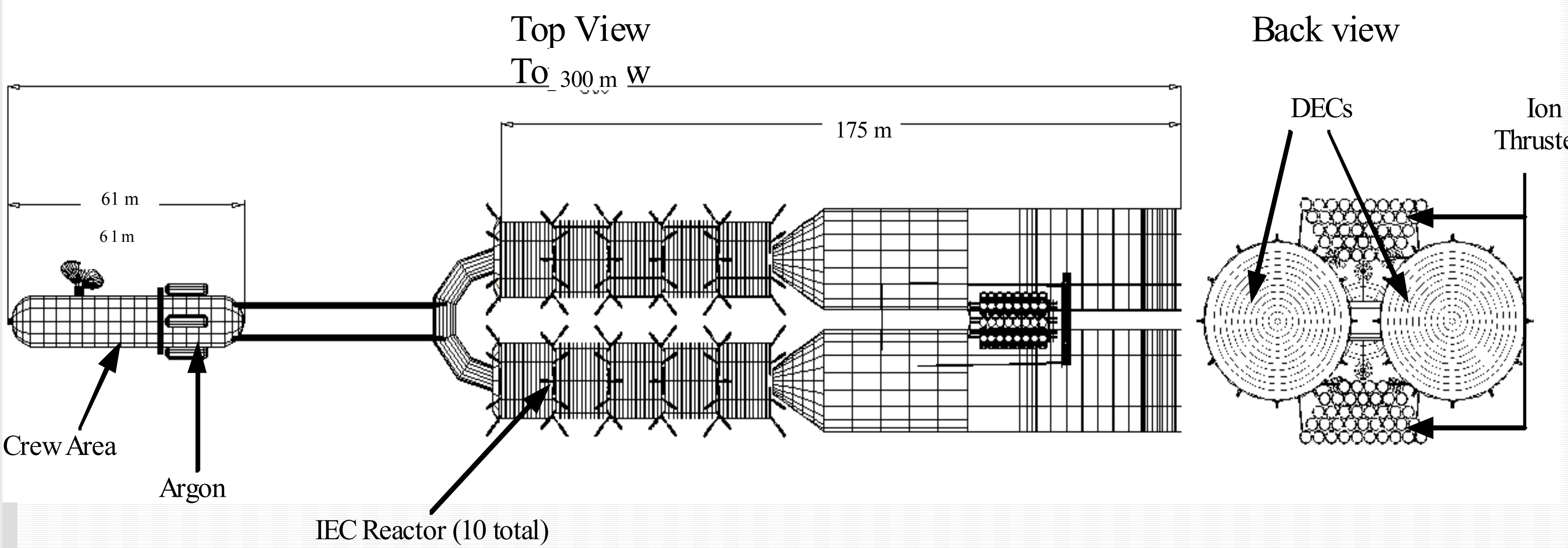


FIGURE 2. Scale schematic of Fusion Ship II, a 750 MWe IEC fusion powered spacecraft.

Fusion Ship II has faster trip time while maintaining 500MT Mass

TABLE 7. Comparison of IEC design and magnetic fusion design.

	Fusion Ship I	Fusion Ship II	Magnetic Fusion Design
Overall Mass, MT	500	500	1690
Overall Length, m	174	300	240
Number of crew	10	10	6 – 12
Thrust Power, MW	86	750	4830
Reactor gain	4	9	73
Reactor power, MW	296	2178	7895
Thrust system	Krypton ion	Argon ion	H_2 – magnetic nozzle
Specific impulse	16,000	35,000	35,435
Jupiter one way trip time, days	400	210	118

R&D Elements and Metrics

- **Physics of the fusion approach**
  - Confinement and fusion burn: macroscopic stability, transport, energetic particles
  - Heating, refueling, impurity control, etc.
- **The enabling technologies**
  - Drivers, radiators, Materials, thermal management, magnetic nozzles, etc.
- **The desirability of the concept as a space propulsion system**
  - Specific power, total mass, reliability, environmental considerations, etc.
- **The steps that are needed to research and develop the fusion approach**

Fusion power gain (Q)

System and Mission cost

R&D cost and schedule

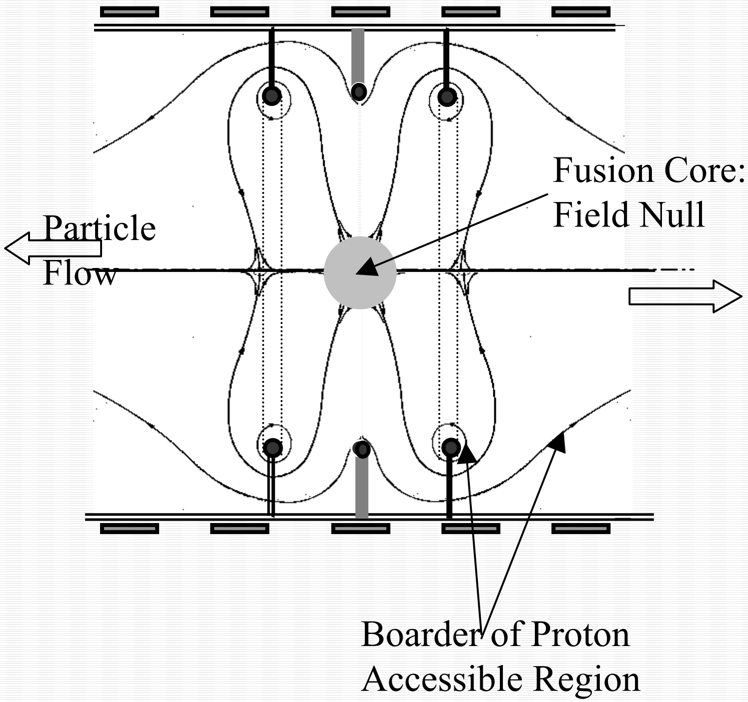
- Study of advanced IEC concepts
  - NBI CB type unit

Collimator

A collimator converts the isotropic velocity distribution of fusion particles to a direct flow so as to make the traveling wave direct energy converter effective.

The collimator consists of a pair of floating coils (Helmholtz Coil) that eliminates the external magnetic field (~ 0.96 T) at the center and a stabilization coil fixed to the vacuum wall.

No magnetic field appears at the wide area around the center, an essential feature for IEC operation.



A high current density of ~140 AT/mm^2 on Helium II cooled floating coils isolates 14.7-MeV protons and other charged particles from the coils and the vacuum wall. Floating coils are supported by three thin pipes for feeding current and recycling coolant.

Collimator Concept

- The accessible domain of *14.7MeV* protons originate at the center of the collimator is separated from Helmholtz coils, by applying enough current density on the coils (Fig.2). No bombardment loss allows series operation of multi-SIEC connected along the magnetic channel (Fig.3). The Series operation increases the total output and improves confinement by the number of SIECs.

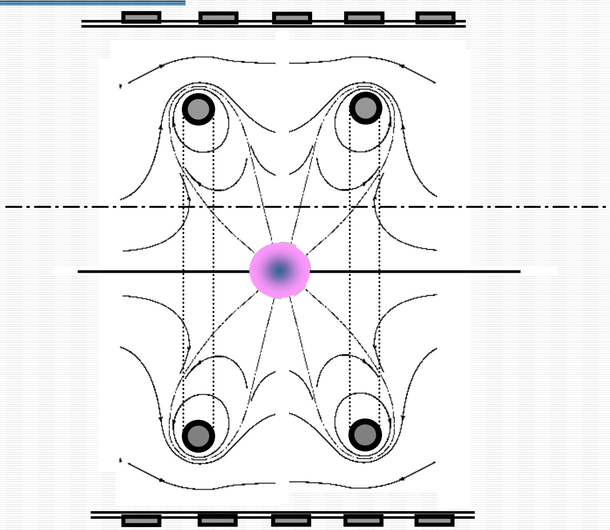


Fig.2: 14.7MeV Proton in a Collimator

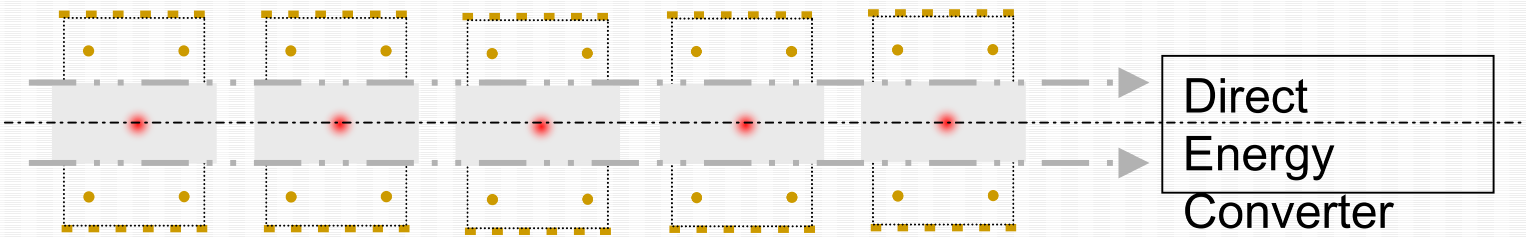


Fig.3: Series Operation of SIEC Fusion Cores

Magnetic Trapping and Leakage of Fuel Ions

- While only small fraction of low energy fuel particles can be confined inertially, a body of the fuel particles will be magnetically trapped within a certain region inside the collimator. Indeed, the representative magnetic field of $\gtrsim 1T$ outside the core region is strong enough to trap bulk plasma ($n_{3He} = n_d \gtrsim 5 \times 10^{18} m^{-3}$, $100keV$).

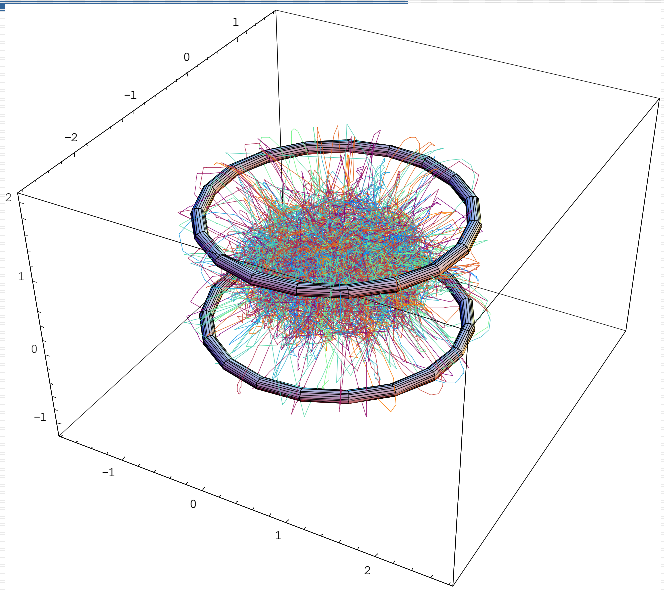


Fig.6: Magnetic Trapping of 100keV Fuel Deuterium in a Collimator: (by Alan L. Miller).

- An example of magnetic trapping in a collimator is presented in Fig.6 . *100keV* deuteriums start at the center in random directions.Trajectories form a sphere in which particle motion is Ergodic (KAM).

Conclusions, NBI IEC

- From a view point of *D-^{3}He* power plant, operation of SIEC fusion is expected to be maintained by neutral atom beam injection.
- A pure SIEC supported by NBI requires an extremely sharp focusing of injected beam. Magnetic trapping by a collimator magnetic field seems practical.
- Series operation of fusion units improves confinement. For a purpose of evaluation of the concept, detailed analyses including steady state, energy confinement, and stability are in progress.

- Study of other IEC applications
  - IEC driven subcritical reactor
  - Student lab research reactor

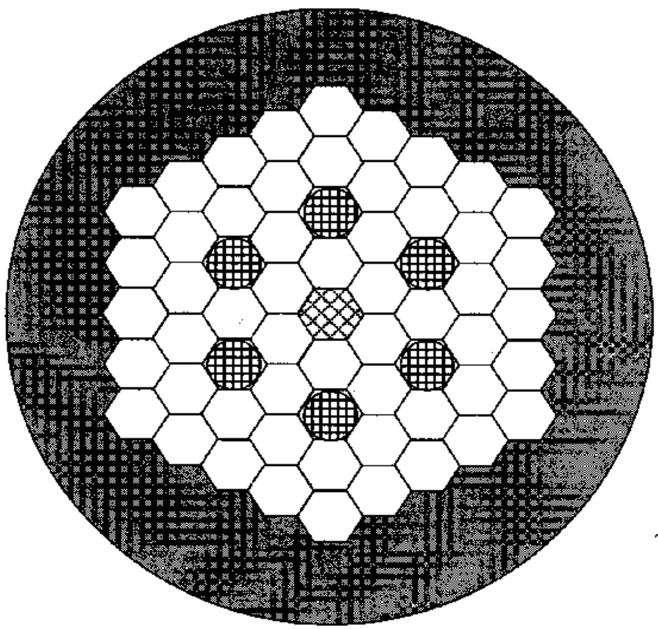
Accelerator Driven Sub-critical Reactor Approaches

- Main approach: accelerator, spallation-target system.
  - Issues large size and cost.
  - In-core target engineering complications.
- We propose a Cylindrical IEC source.
  - Fit within fuel element channels.
  - Replaces accelerator-target by multiple modular neutron sources.
  - Provides design flexibility and flux profile control.
  - Modest cost module.
  - Develop a single module and replicate.
- Overall costs attractive.

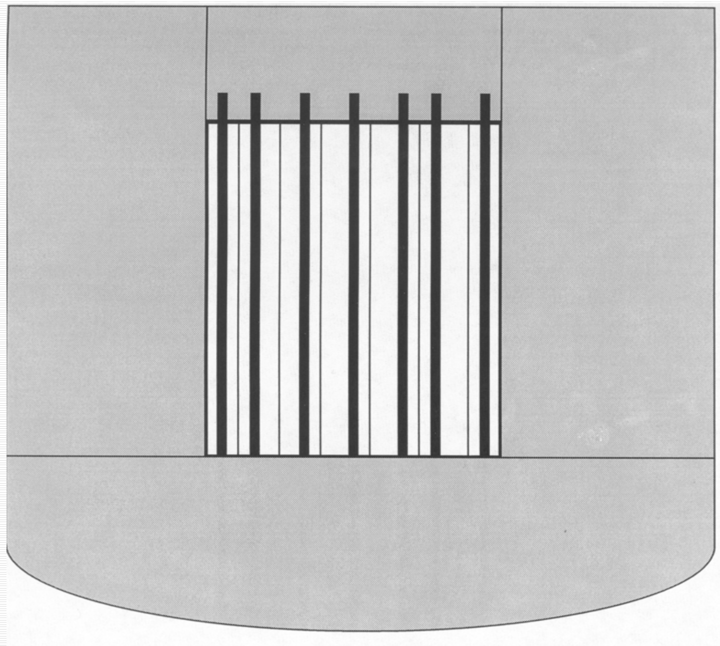
Conceptual Illustration

- 1000-MWe plant illustration.
- IEC units occupy seven fuel channels.
- Stacked with 15 units/channel.
  - Selected to optimize neutron profiles.
  - "Distributed source" design vs. centered targeted accelerator-driven plant.
  - Central target poses severe heat removal problems.
  - Waste heat from the IEC deposited on the channel wall, removed by normal coolant flow.

Vertical Cross-Section Showing IEC Modules



Top Cross-Section View Shows IEC Modules in Channel Locations



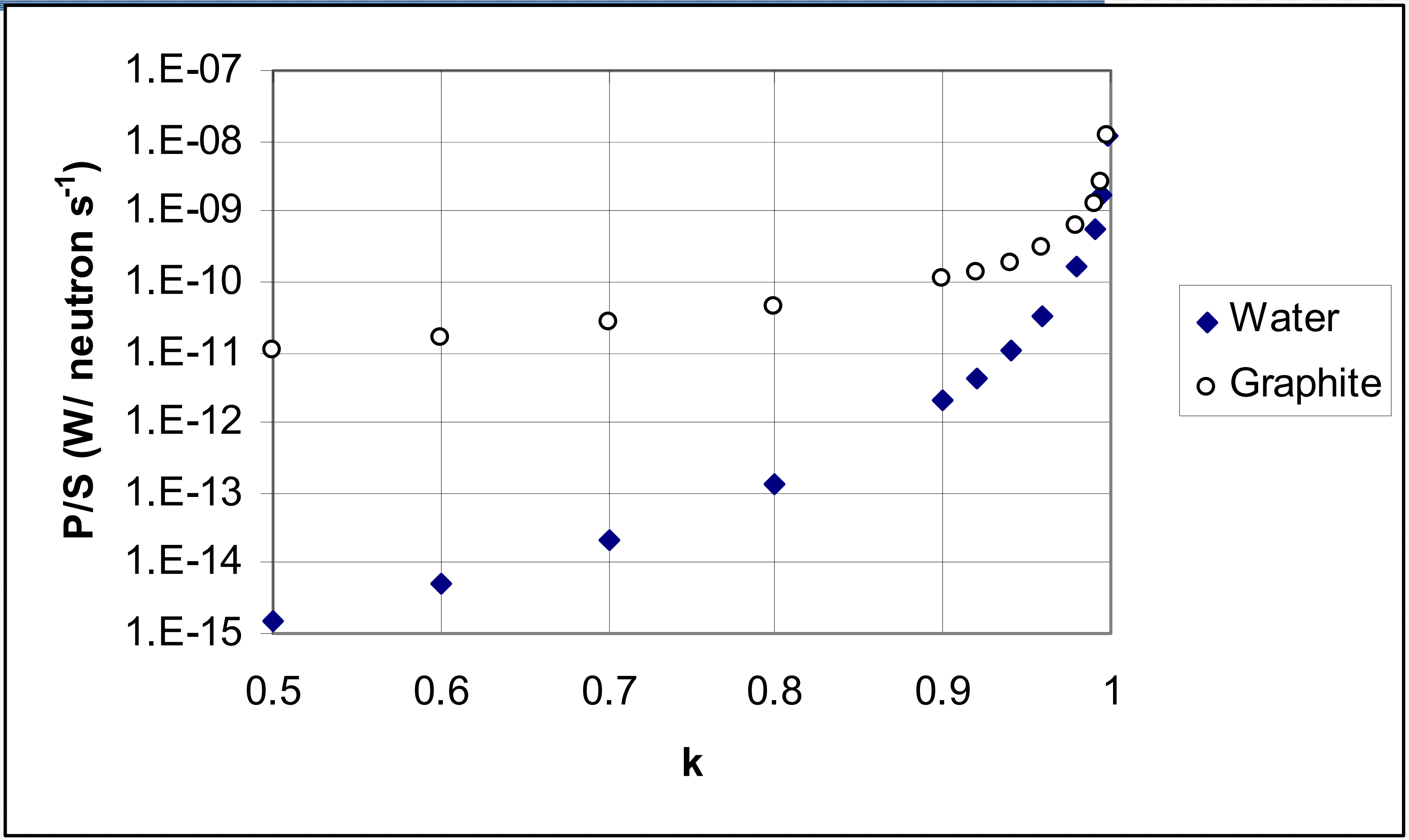
Near Term Application to Low Power Research Reactors

- IEC neutron requirement close to present
- Added safety would allow students to modify subcritical core arrangement for experiments with reduced license review requirements.
- Rebirth of nuclear industry will require added training/research facilities in universities follow drastic shut-down of higher power research reactors at many campuses.

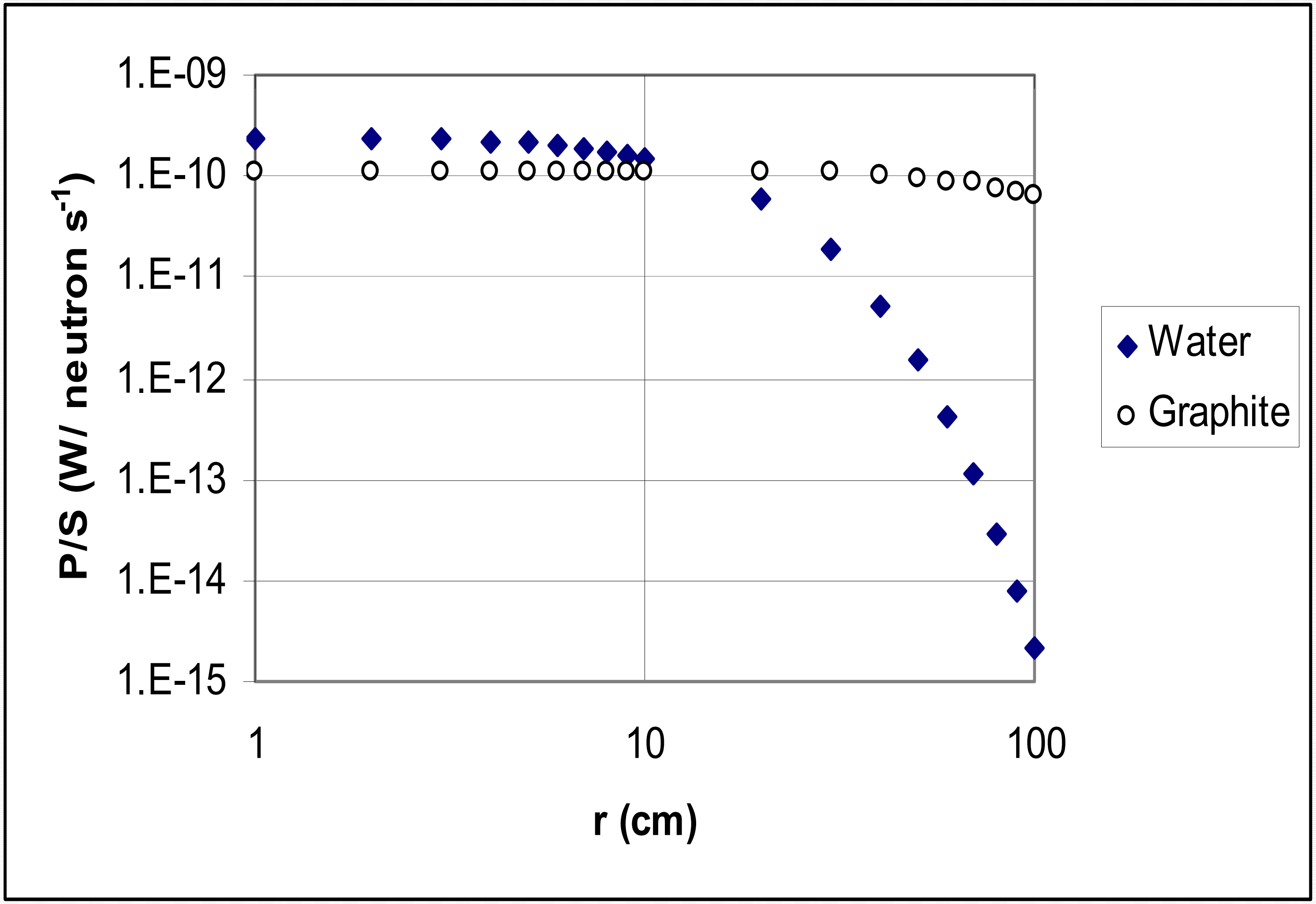
Example: 1-kW Graphite-moderated Sub-critical System

Fuel	UO_2
$^{235}U/^{238}U$ ratio on fuel	0.005
Fuel density (g/cm^3)	10
Moderator material	Graphite
Moderator density (g/cm^3)	1.6
Moderator volume fraction	95%
Multiplication factor	0.99
Diffusion coefficient (cm)	0.9744
Absorption cross section (cm^{-1})	0.00265
Radius (cm)	30
Source strength (neutrons/s)	$1x10^{12}$
Power (kW)	1.2

A k=0.95 assembly would require a 5x10^12 DT IEC which is achievable with present devices.



Power level per unit source (P/S) vs radius for k=0.95. In the graphite case, P/S is fairly constant for assemblies up to 50-cm radius.

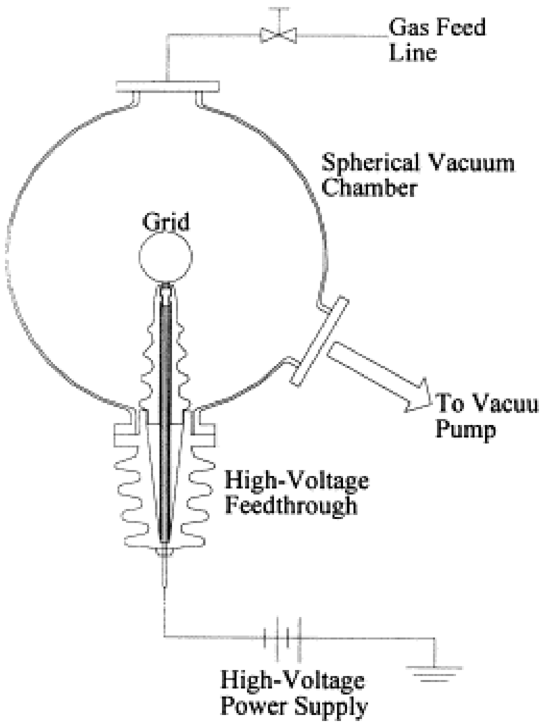


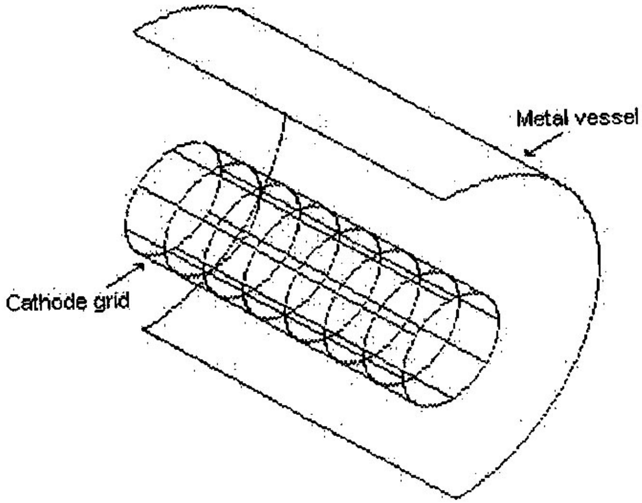
Summary, IEC Driven Sub-critical Research Reactors

- High power reactors for central stations would require IEC yield improvements of many orders of magnitude, but if achieved, appear competitive with other neutron sources such as accelerator-target devices.
- Low power (about 1 kW) sub-critical research assemblies could use versions of present devices, providing near term use and experience

- Modeling Studies
  - Cylindrical IEC discharge physics

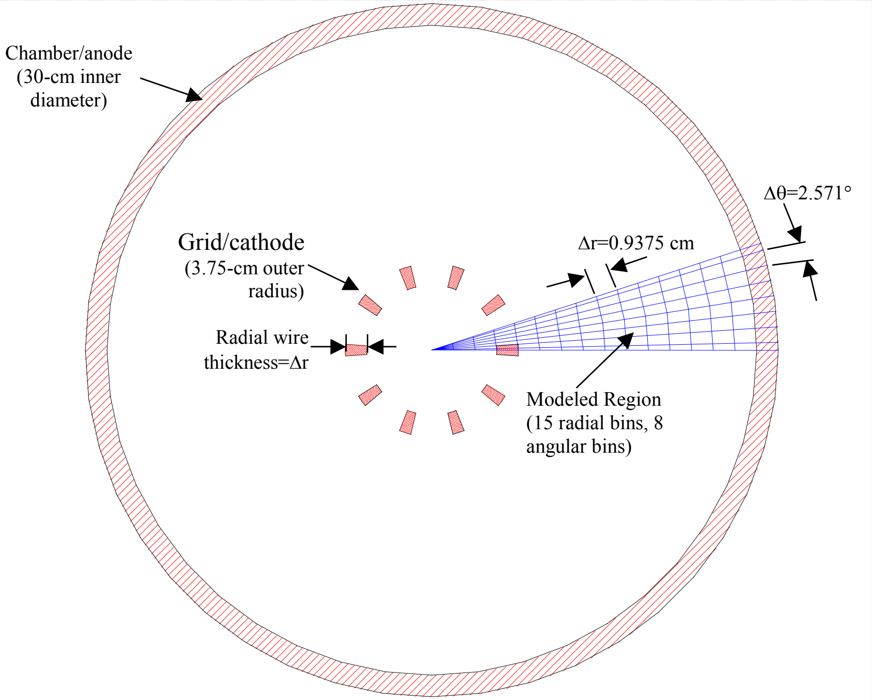
SIEC (left) & CR-IEC (right)





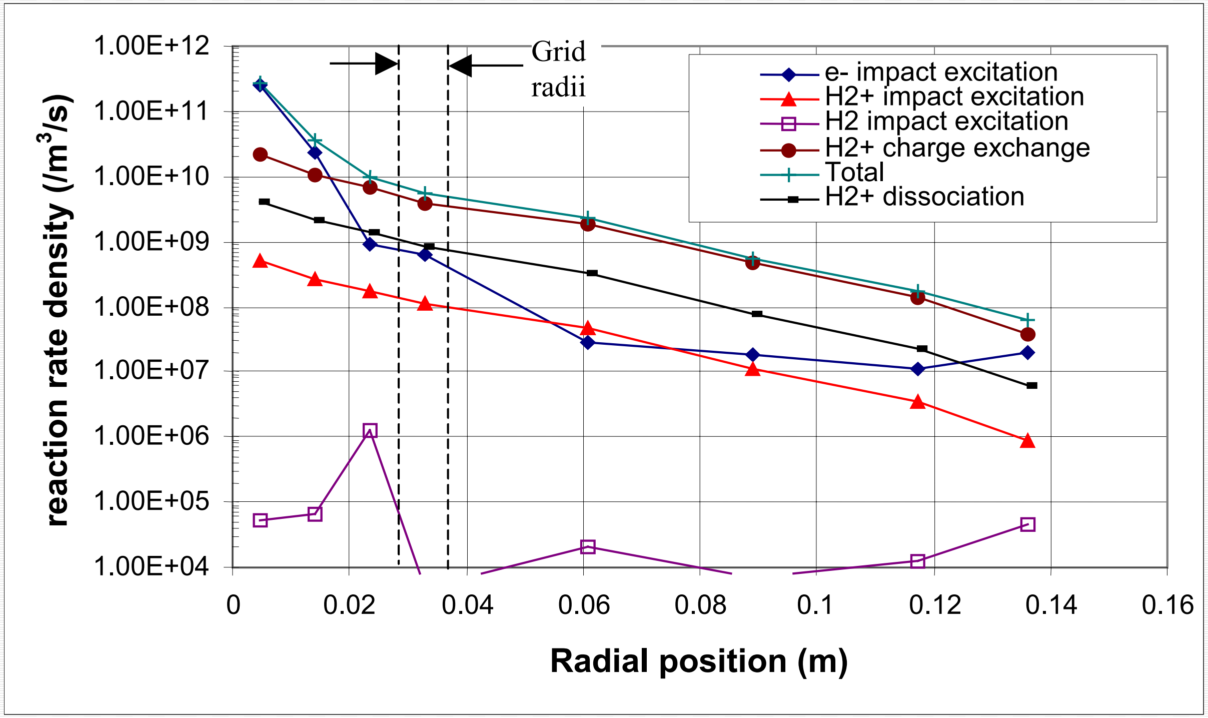
RC-IEC Modeled Geometry Using the MCP Simulation Code

- Single cathode grid and cylindrical anode
- Modeled in r-θ coordinates
- Symmetry allows modeling of only a portion of device if discharge is symmetric
- Physics of RC discharge is similar to spherical
- Convenient for modeling because actual physical geometry is well approximated in two dimensions (r,θ)
- Ideal for measurements, but no experimental data available for discharge RC-IEC



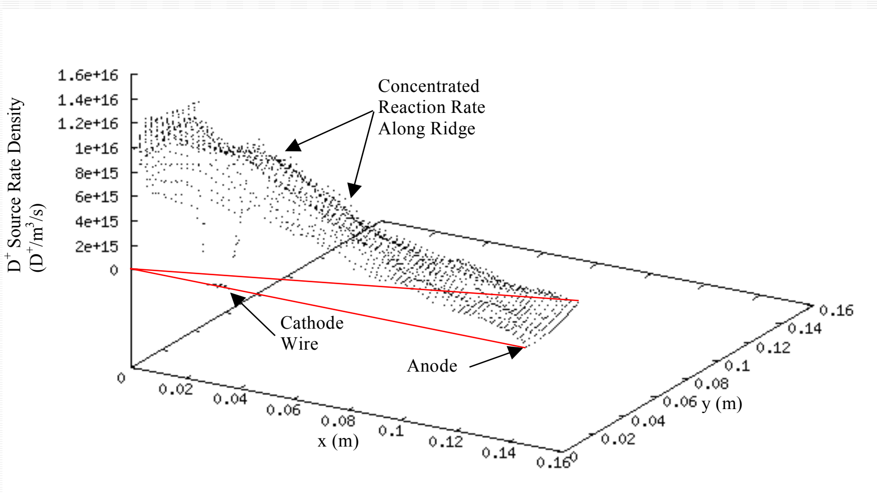
Reaction Rate Profiles

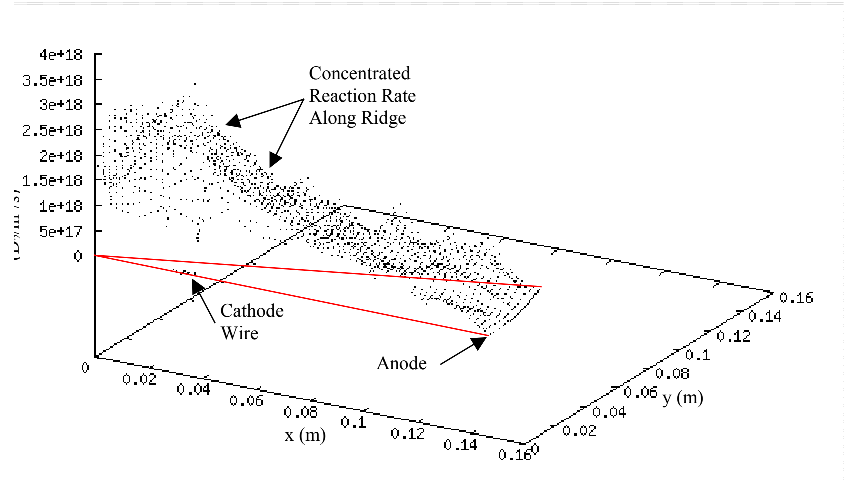
- Calculated reaction rate density for light-producing reactions along symmetry line
- Molecular-ion charge exchange and dissociation produce most light in spokes
- Electron impact excitation produces light in core



Rate Density Distributions

- Molecular-ion charge exchange produces fast D_2
- Molecular-ion dissociation produces D^+ and D
- Source rate density distributions are peaked along symmetry line





Summary – MCP Modeling Studies

- Star-mode light emission
  - Light emission in spokes is dominantly from charge-exchange molecular fast neutrals
  - Light emission in core region is from electron-impact excitation of background gas
  - Concentration of charge exchange collisions and dissociation collisions along grid-hole symmetry line coincides with spoke-like appearance of Star-mode light
- Potential distributions
  - Central virtual anode causes a hollow-cathode discharge with high ionization rate density in center
  - Virtual anode height increases with increasing current
  - Linear relation between virtual anode height and perveance seems to exist, but must be verified

Summary – good progress has been obtained in key topics.

- Study of ion-injected IEC to reduce bkg. Pressure -- ILLIBS RF source appears very attractive for efficient ion injection.
- Study of IEC fusion space propulsion and power
  - Simulation of proton collimator using electrons – experiment under construction
  - Design study of IEC rocket for Jupiter mission* - 1 yr Jupiter mission obtained with 500MT class vessel.
- Study of other IEC applications
  - NDA luggage – carton inspections*-- multiple IEC sources with fuzzy logic system potentially reduces false signals and decreases processing time
  - IEC driven subcritical reactor – attractive if ultra high neutron rates possible with IEC
  - Student lab research reactor – first step using present IEC device
- Study of advanced IEC concepts
  - NBI CB type unit* -- NBI and magnetic trapping appears attractive and is under study.
- Modeling studies
  - Cylindrical IEC discharge physics* -MCP provides new insight

* Topics covered in more detail in other UIUC talks at this workshop

Thanks for your attention

Questions, please contact:

- George H. Miley at g-miley@uiuc.edu