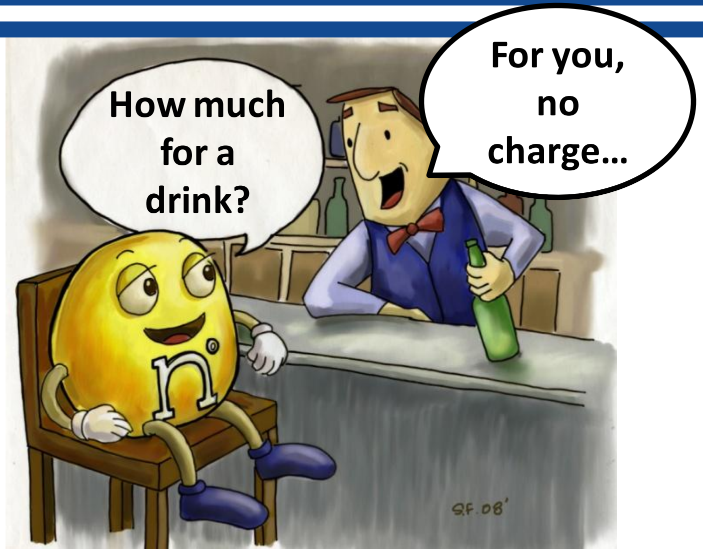
# Fusion Neutron Science for Energy and National Security Applications




UC Berkeley Colloquium, 3/30/09

Presented by Vincent Tang

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**LLNL:** S. Sampayan, J. Morse (UMass), A. Krishnan, G. Meyer, S. Falabella, G. Guethlein, L. Hart, J. Harris, P. Kerr, H. McLean, B. Rusnak, D. Sanders, G. Schmid, C. Spadaccini, L. Wang, G. Caporaso and A. Vazquez (MMech, inc)

Cartoons by S. Tang

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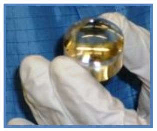
LLNL-PRES-411633

# Fusion Neutron Science

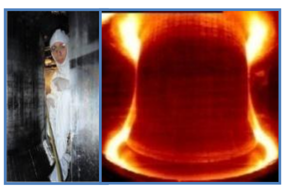
Scale

0.01 m

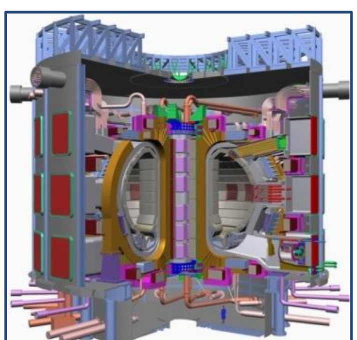


0.1 m

1 m

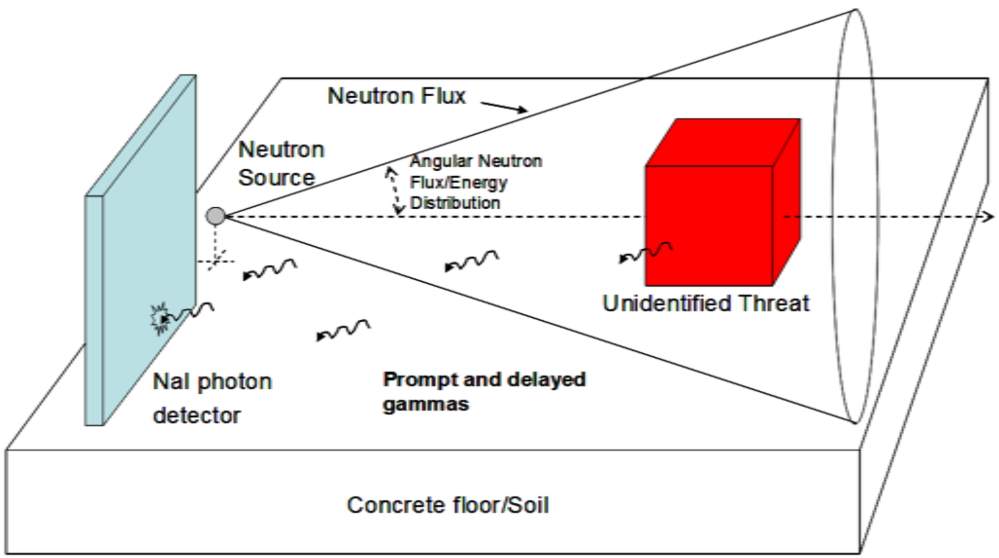


10 m



- Spans multi-disciplinary, multi-scale science and engineering
- Benefits from modern multi-physics simulation and experimental efforts
- Provides unique solutions to significant Energy and National Security problems
- We'll examine two areas that illustrate both the science required and the problems addressed:
- Accelerator neutron sources
  - Near-term: Remote detection of explosives
  - New compact accelerator concepts
- Large plasma neutron sources
  - Driving fusion plasmas with RF waves
  - Near-term: Fusion-fission hybrid reactors

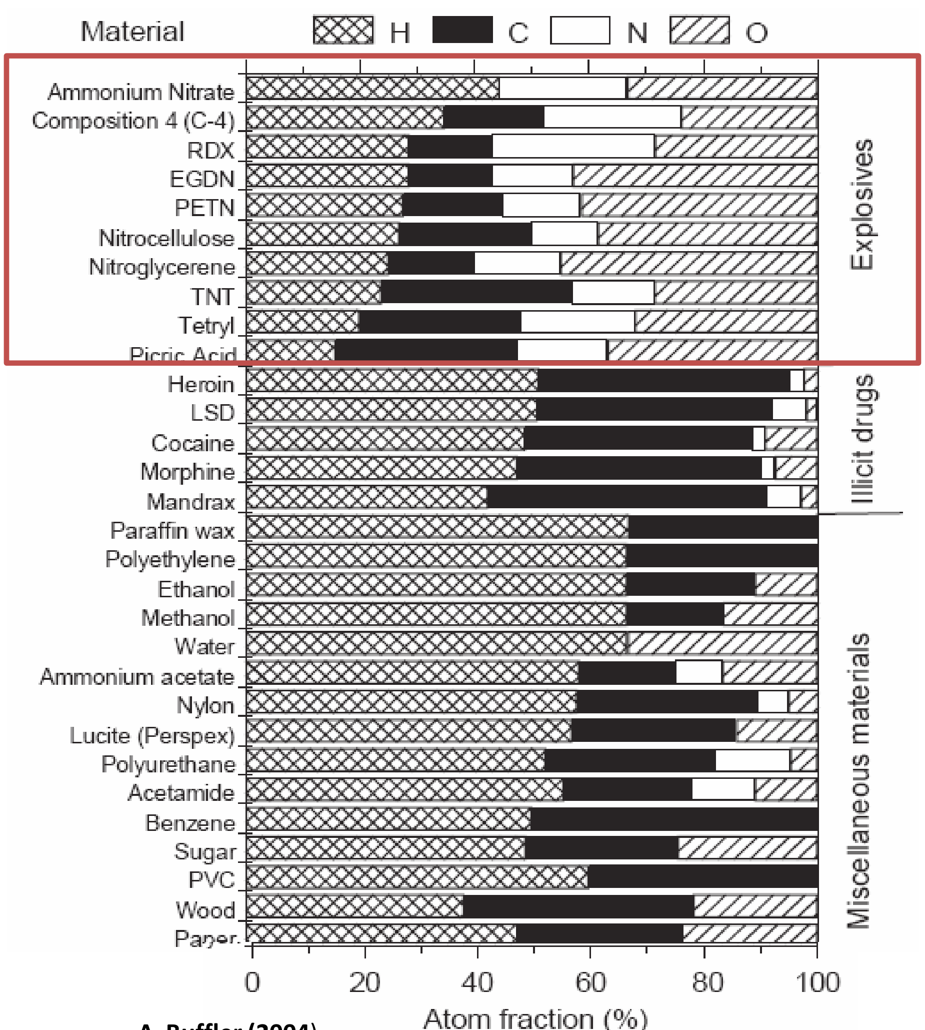
# Remote Detection Using Neutrons



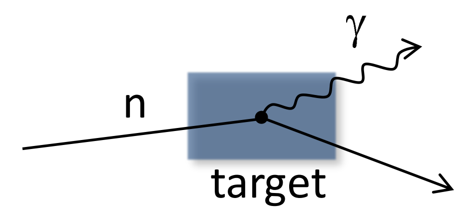

- Neutrons penetrate shielding and activate unique, identifying gamma rays through (n, n’) or (n, $\gamma$) reactions

- Source requirements: $\geq 10^7$ n/s, energies $\geq \gamma$ lines of interest for (n, n’). Pulsing capability can be important

# Neutron Induced Gamma Signatures Enable Identification of Organic Materials




**A. Buffler (2004)**




(n, n′ γ) Prompt Lines:

$^{12}$C: 4.44MeV

$^{16}$O: 6.13MeV

$^{14}$N (1): 2.31 MeV

$^{14}$N (2): 1.64, 2.31MeV

$^{14}$N(3): 4.9 MeV

$^{14}$N(4): 5.11 MeV

$^{14}$N(5): 0.73MeV

$^{14}$N(9): 7.0 MeV

$^{14}$N(12): 3.4 MeV, 5.11 MeV

(n, γ ) Delayed Lines (Thermal Capture):

$^{1}$H: 2.23 MeV

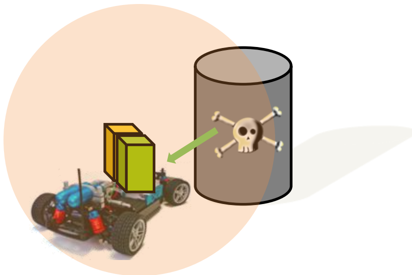
$^{14}$N: 10.83 MeV

Note—for 14 MeV neutrons, potential issue with O→C transmutation*

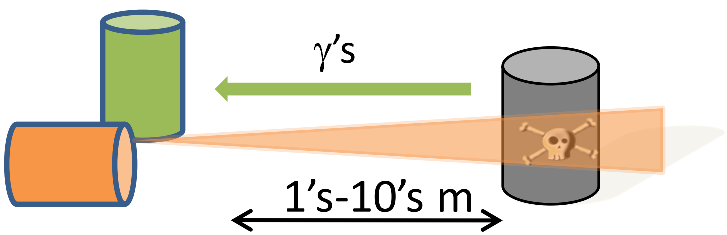
***not too bad, see Seabury and Caffrey, INEEL/EXT-04-02475, 2004**

# Overcoming Signal/Noise: 2 Approaches

- Signal to Noise, $R=S/N$, scales as $1/D^4$, where $D$ is distance to target (i.e. 2 solid angles)
- 2 fundamental ways to increase $R$, along w/ time-gating:
  1) Bring detector and/or source very close to target
  2) Increase directionality of neutron output
- Ultra-miniature, palm-size and lightweight D-T neutron source for 1)—*Such a source could be remote or even thrown to target—a "neutron flare"*
- Portable 4 to 7 MV accelerator utilizing unique properties of D-D reactions for 2)—*Needs to be ~10x smaller and lighter than conventional sources*

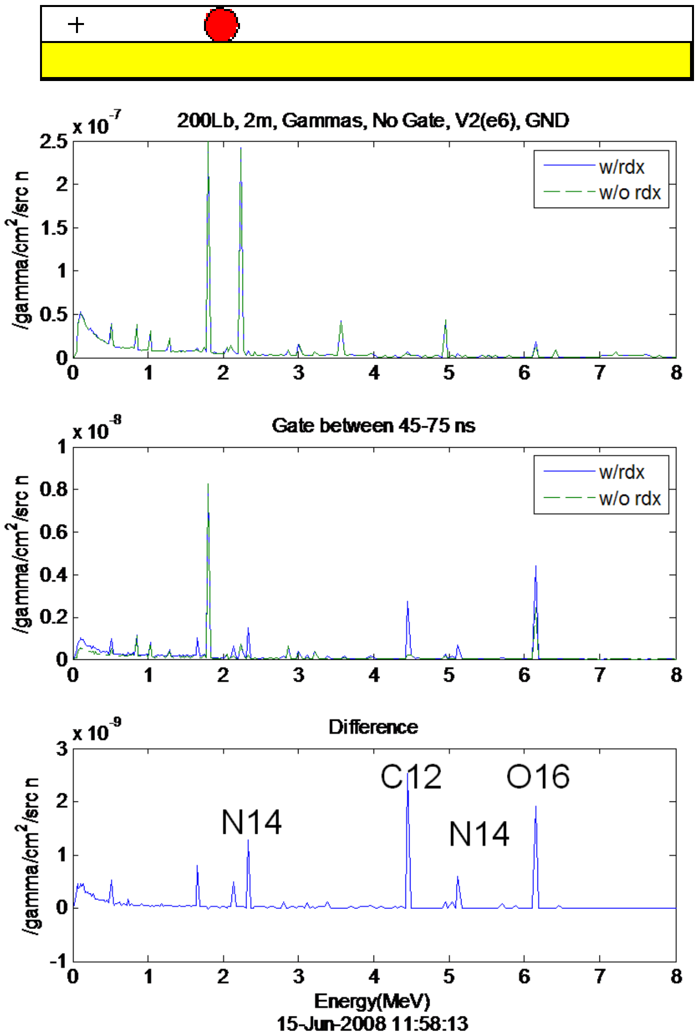


1. Mini, palm-size ~100 kV D-T isotropic neutron source
D + T → $^4$He + n (~14.1 MeV)



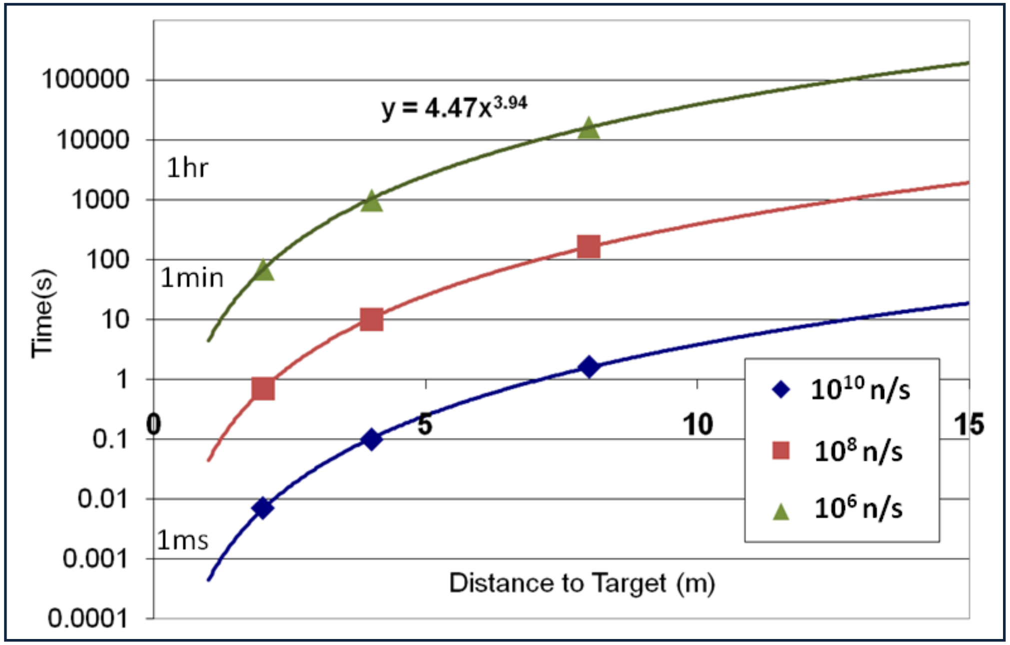

2. Portable D-D, multi-MV accelerator pulsed directional neutron source
D (4 MeV) + D → $^3$He + n(7.2 MeV, forward)

# Basic MCNP Scaling Study



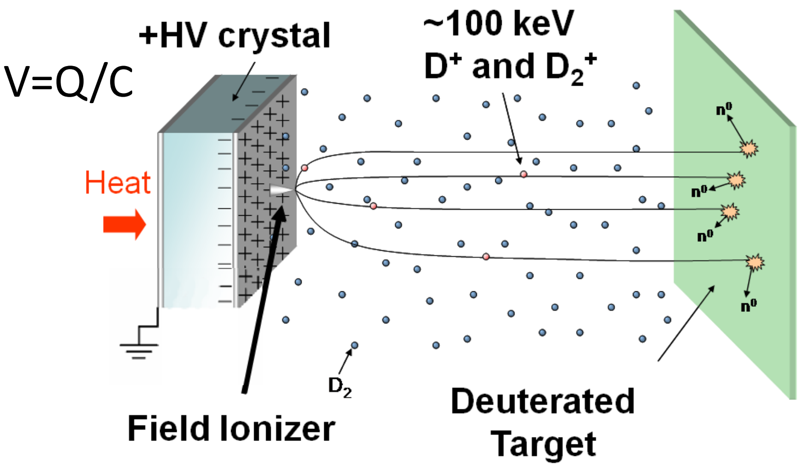

Time to 100 useful counts, 200 lb RDX

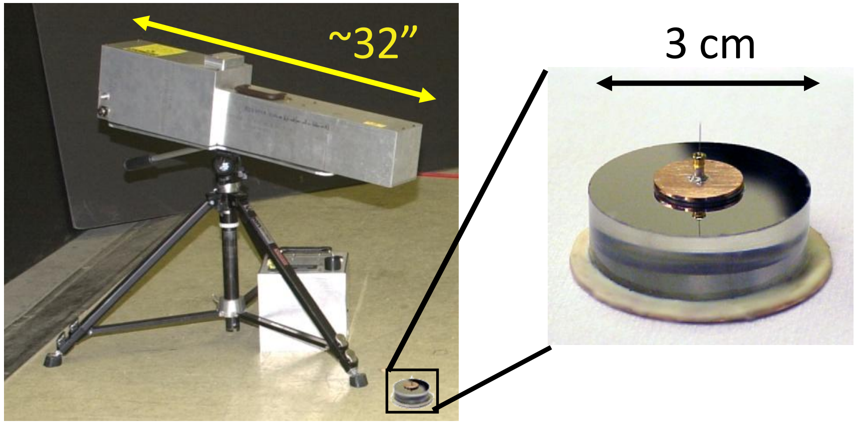
- D-D source, 4 MeV D beam, time-gated
- 50 x 50 cm$^2$ Det., 10% efficient
- Use C (4.4), O(6.13), N (2.31) lines




- <u>Remote detection problem is challenging</u>
- For $10^8$ n/s, side dose is ~0.35 rem/hr

# Pyrofusion: A Palm-size Neutron Flare




Conventional N Tube

V. Tang et al, CAARI (Invited), 2008

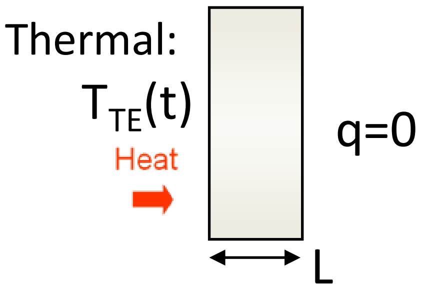
- First results from UCLA (Naranjo et al., 2005)
- Little/no electrical power—thermally powered (10-20 W), could be provided by small external chemical pack (hand warmer)—utilizes >10x higher energy storage compared to batteries
- At LLNL, we significantly extended this work through modeling and experiments by increasing yield and adding pulsing capability, and currently has highest yields and rates

**Patent Pending**

# Coupled Thermal/Electrostatics Model

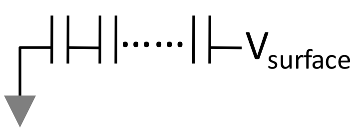
Coupled Model

Thermal:



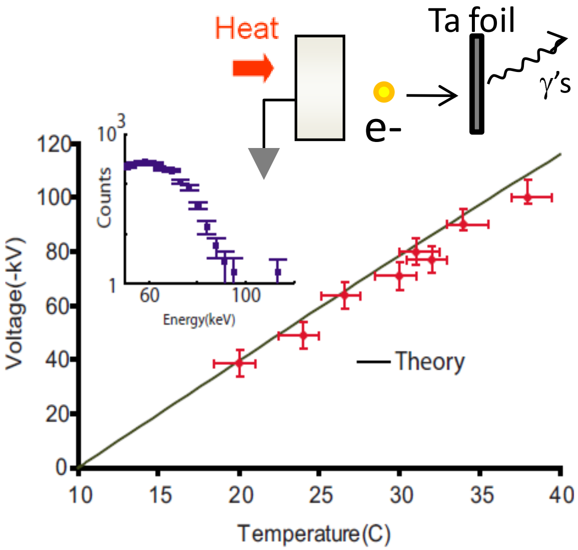

$$\frac{\partial T(x,t)}{\partial t} = \alpha \frac{\partial^2 T(x,t)}{\partial x^2}$$

Potential:




$$\frac{dV_n}{dt} = \frac{1}{C_n}\left[ K_{py}(T(x,t))A\frac{dT(x,t)}{dt} - \frac{V_n}{R(T)} \right]$$

Experiments and comparison with model

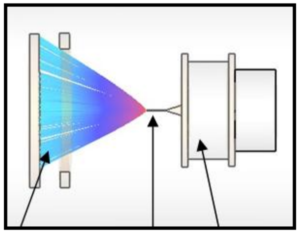


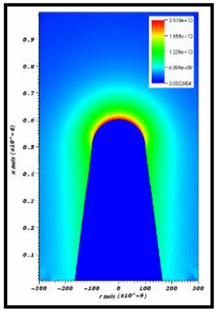

V. Tang et al, J. Appl. Phys., 2009

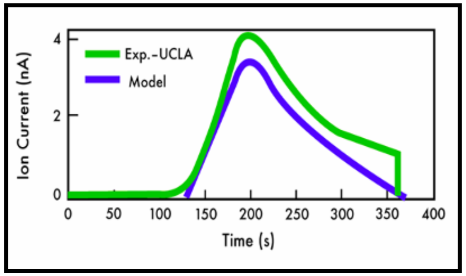
- Limits to rapid heating through rear of crystal due to local field stresses, breakdowns, and field emission losses
- We can understand UCLA's initial results and extend them using this coupled model

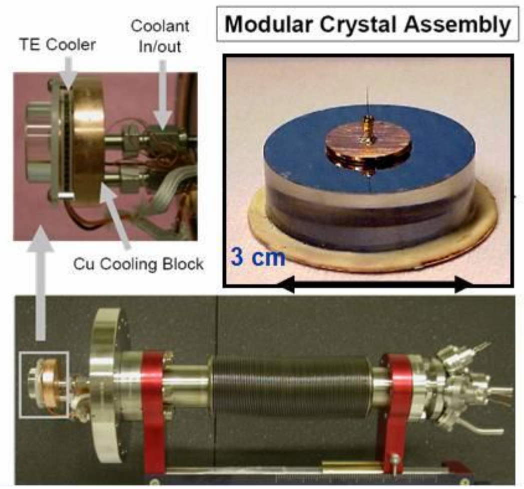
# LLNL Crystal Driven Neutron Source I

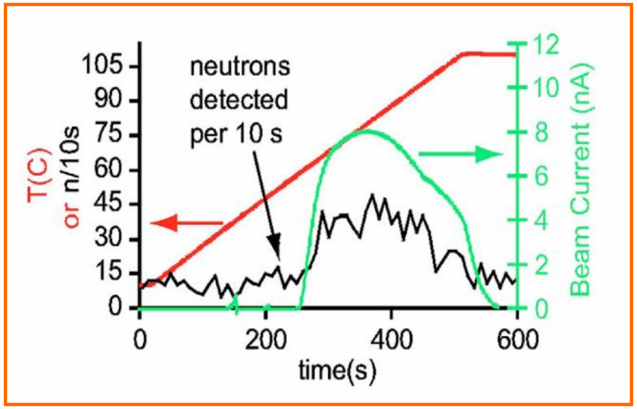
**Pyrofusion Simulation and Models** ⇄ **Modular Pyrofusion Setup** → **Record 190k DD integrated n yield at ~$10^3$ n/s, ~80-90 kV**





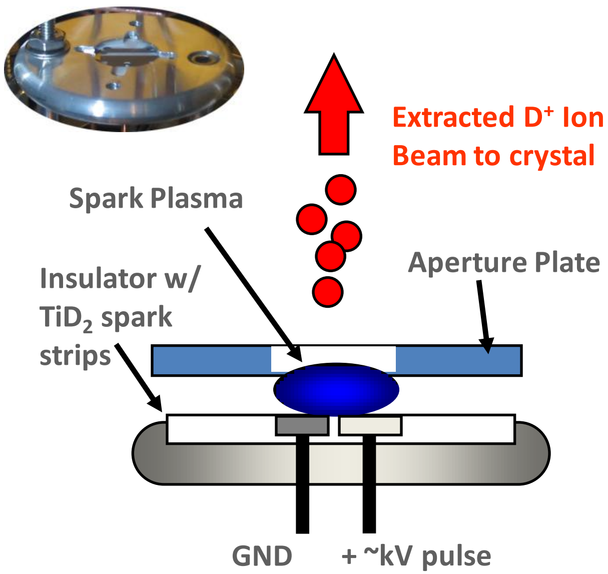




**V. Tang et al, Rev. Sci. Intr., 2007**

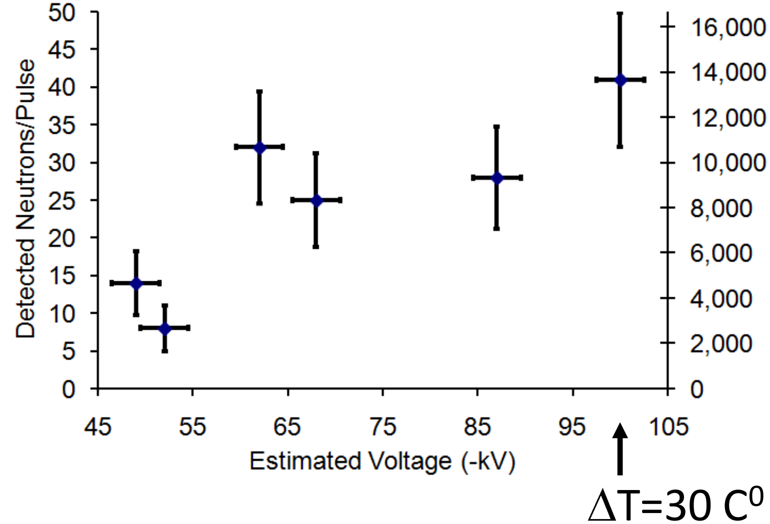
- Model: Multi-physics field ionization model reproduces ion beam measurements
- Experiment: Record ion beam currents (up to 10 nA) and D-D neutron yield (190k) per thermal cycle, extending UCLA work (~2.2x).
- Can we add user-controlled pulsing capability and increase neutron rate?

# LLNL Crystal Driven Neutron Source II

**Proof-of-principle Pulsed Experiment Using Independent Spark Ion Source**



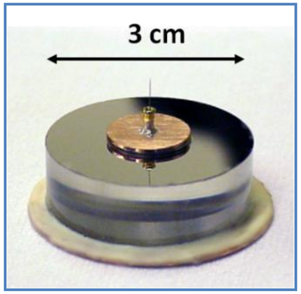

G. Guethlein et al., CAARI, 2008
S. Falabella et al., CAARI, 2008

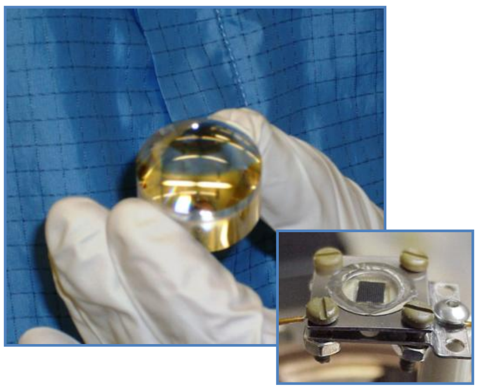



V. Tang et al, J. Appl. Phys., 2009

- LLNL spark D ion source: 25 ns to >100 ns, 2-4 kV input, allows UHV operation--ampere level currents
- Coupled with crystal, permits user-controlled ~100 ns pulse emission giving >10k D-D neutrons per pulse (~3 x $10^6$ DT n), with peak rates >$10^{10}$ D-D n/s

# Next Steps to Higher Yields



- Novel miniature pyroelectric neutron sources can provide new interrogation capabilities for unknown threats and enable new CONOPs
- We demonstrated record ion beam current and neutron yields for both conventional and LLNL pyrofusion configurations
- Next: More yield using domed shaped and larger diameter crystals, and tests with nanotube ion source. Achieve ~$10^7$ DT average n/s, ~10 s operation per cycle
- Further improve Monte Carlo field ionization model

➢ Can we insulate the crystal further to prevent field emission losses/flashover and achieve higher voltages?

➢ Are there materials with higher pyroelectric coefficients and similar high voltage characteristics? (~10 MV/m hold-off)

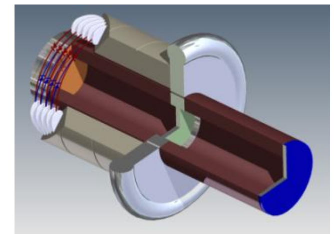
➢ Can we understand and further improve the spark ion source through multi-physics models?

# LLNL Compact Directional Neutron Source

**DARPA Project Goal**: Shrink DC accelerator to make directional neutrons from this (MV/m)

**To This: (>5 MV/m)**

4MV >$10^8$ n/s Directional Neutron Source

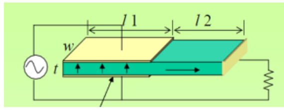


- Phase I Test new piezoelectric HV supply concepts, LLNL high gradient insulator, and ion source in integrated test-bed. Finalize path to compact accelerator (5 months from design to test, utilize off-the-shelf components)
- Phase II Develop identified technologies in Phase I and integrate into final portable prototype accelerator. Test prototype in field scenarios

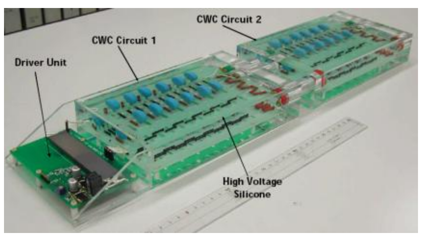
**Patent Pending**

# Developmental Technologies for a Compact Directional Neutron Source

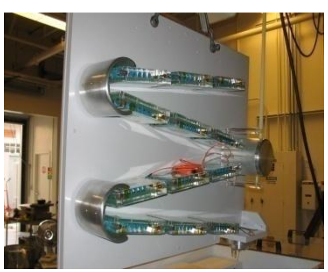
**10 kV Compact Piezoelectric Transformer**



**Sample 100 kV High Voltage Modules (6 stages) Driven by Transformer (6 modules provide 400 kV=1 Set)**




**Phase I Test Supply (2 Sets)**



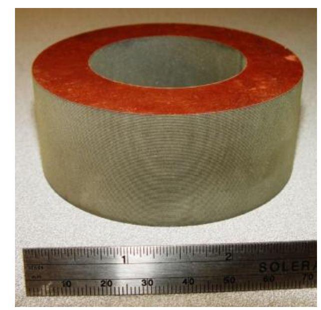
## Accelerator Assembly

**Patent Pending**

**Sampayan, Tang, et al., CAARI, 2008**

**Ampere Class Pulsed Ion Sources**

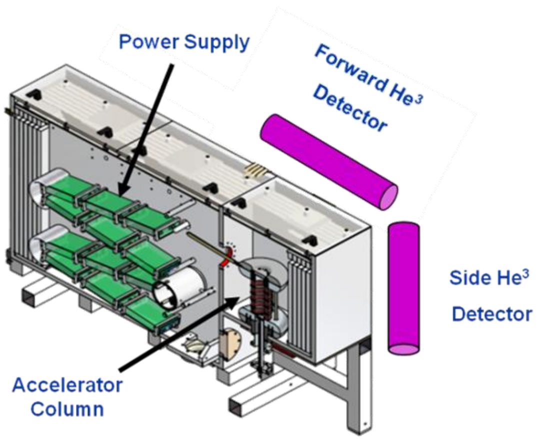
**Multilayer High Gradient Vacuum Insulators (HGI) (Up to ~10 MV/m DC for short sections)**

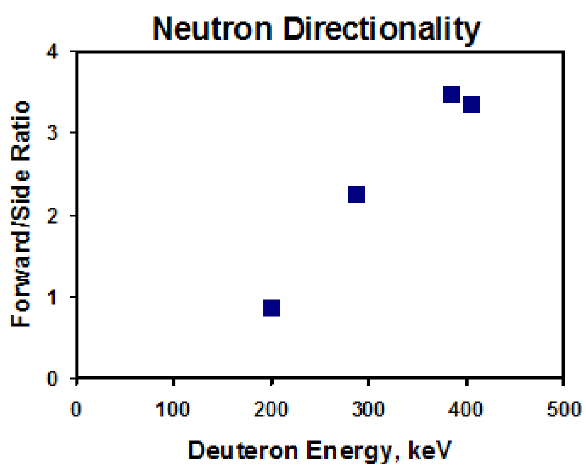


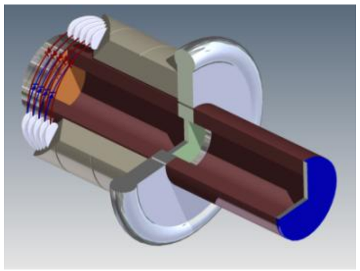
**2 Phase, self-healing dielectric HV insulator, with 10 x higher DC resistivity than conventional Si Oil**

# Accelerator Demonstrated Directionality at Moderate Ion Energies

- 410 keV ions, >3:1 neutron directionality ratio observed, 3.2 MeV neutrons
- ~25 ns pulse neutron rate demonstrated to $>10^7$ n/s (1 kHz equivalent)
- High voltage power supply components and architecture exhibit MV scalability
- Column and supply tested to DC 2 MV/m average field stress
- Numerous science and engineering topics still to be explored

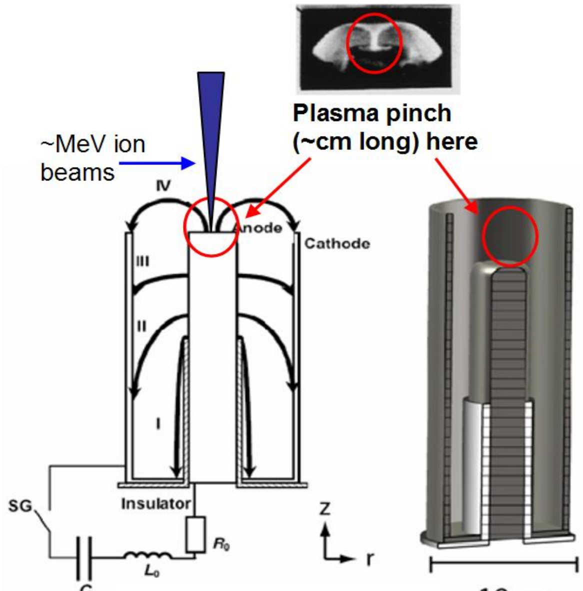


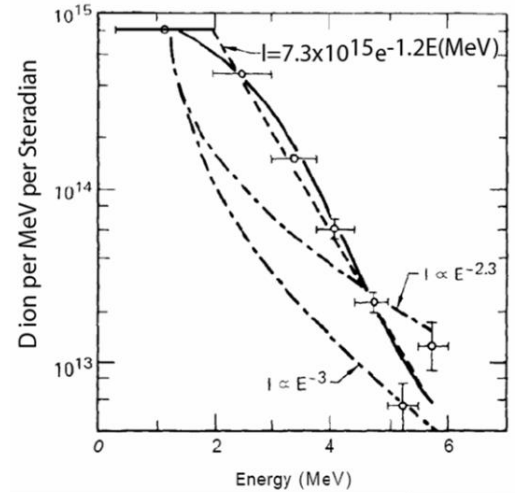



- Continue developing system model for optimum number of multiplier stages and sets for given current, field stress, power, and size constraints
- How does our empirically developed 2-phase self-healing insulator work? What are the fundamental transport phenomena involved?
- What are the optimum detection strategies using a portable and tunable ~4 MV accelerator?

# A Low-Cost, High Gradient Plasma Accelerator?



(Modified from Soto 2004)



LLNL DPF Beam Data (1970-80's)

- The Dense Plasma Focus: simple z-pinch device, with output up to ~$10^{12}$ DD n/pulse, along with MeV beams from ~cm long plasmas (100+ MV/m). Driven by non-linear instabilities
- Not understood; normally optimized for neutron output, not for beam production and acceleration
- ➢ Using modern plasma physics capabilities like advanced PIC codes, can we optimize and exploit the DPF or related z-pinches as a general, low-cost, high-gradient plasma based accelerator?
- ➢ A compact directional neutron source could be an optimal first application—can tolerate high emittance and imperfect beams

V. Tang and B. Rusnak, LLNL-TR-401857, 2008

# Fusion Plasma Neutron Sources

Mass Flow

DT fuel

Ash

Get new tritium from:

$n + {}^{9}Be \rightarrow {}^{7}Be + 2\,n$

${}^{6}Li + n \rightarrow {}^{4}He + T$

Power Flow

Fusion Plasma (~10 keV)

$D+T \rightarrow {}^{4}He+n$

(17.6 MeV)

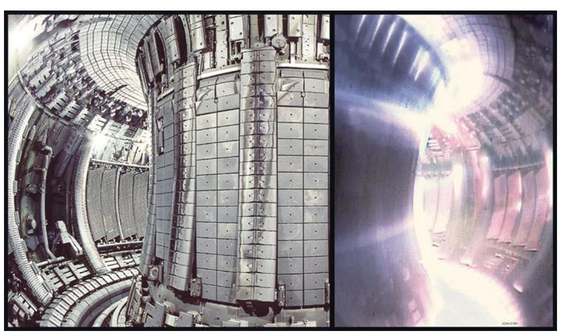
Power in ($P_{in}$):
Applied Heating (RF, neutral beam, lasers, etc).

3.5 MeV ${}^{4}He$

Gain: $Q=P_{in}/P_{out}$

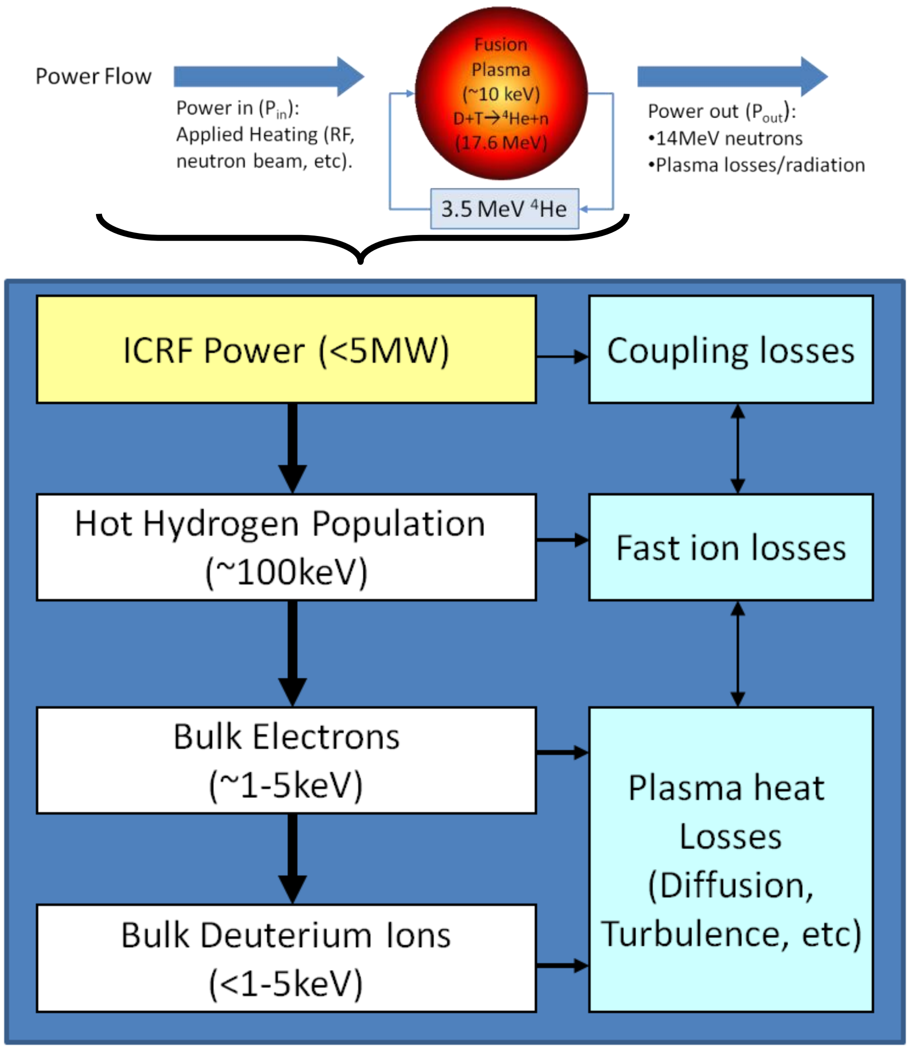
Power out ($P_{out}$):

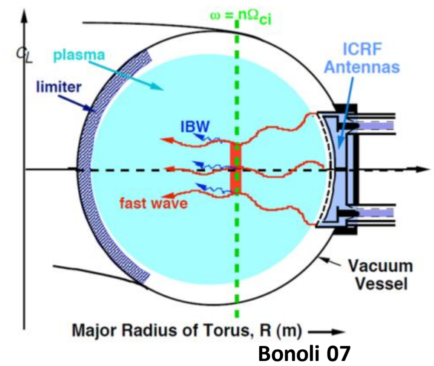
- 14MeV neutrons
- Plasma losses/radiation



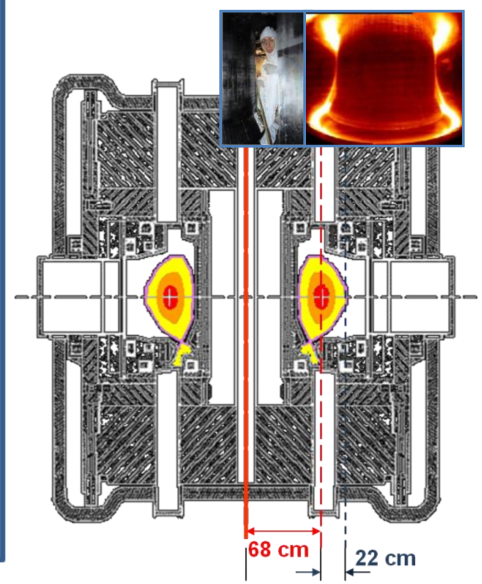
Q~1 to 10 in mid-term (ITER & NIF)
These devices will demonstrate technologies of large plasma neutron sources

# Plasma Heating with Microwaves



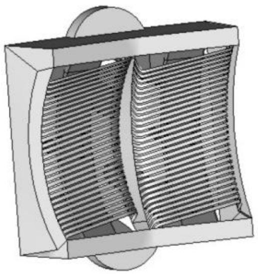




- Ion-cyclotron-range-of-frequency (ICRF) minority heating is one effective method to heat fusion plasmas

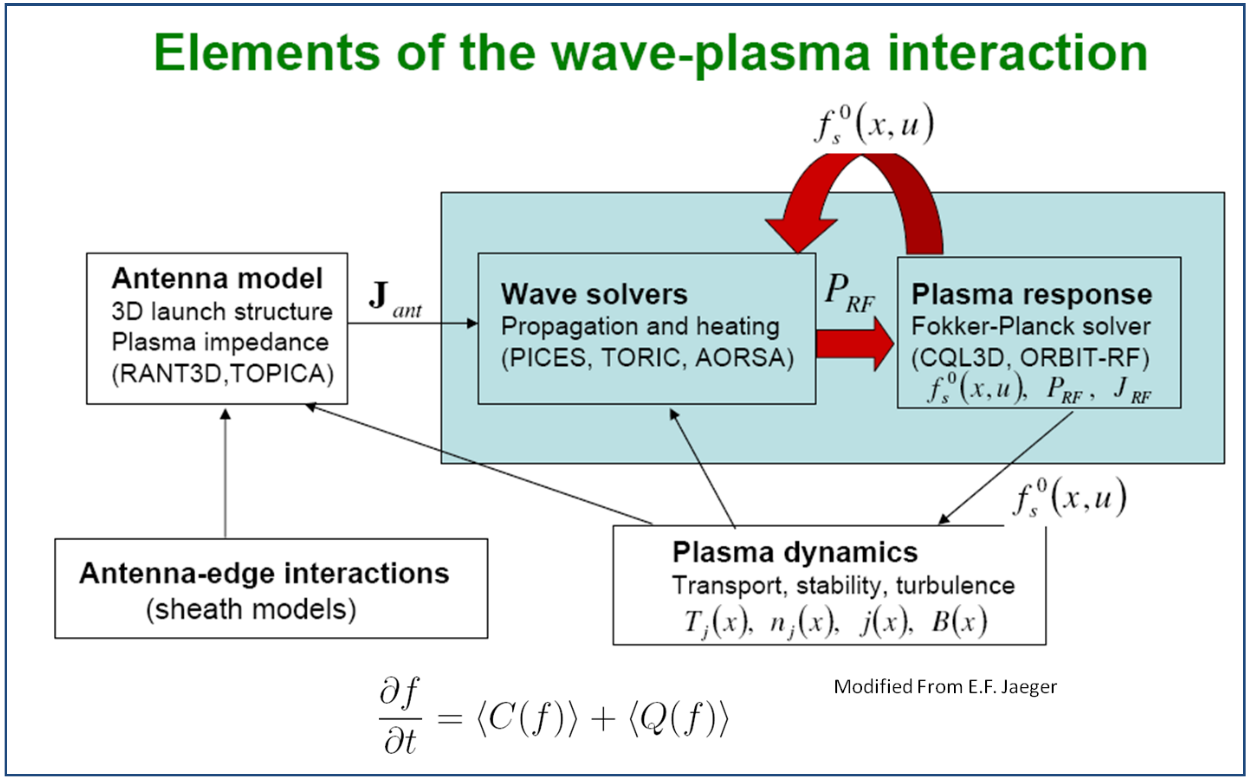


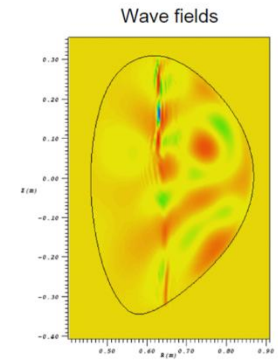

- Alcator C-Mod—RF heated tokamak, only experiment with ITER B field and densities
  - B Field up to 8 T
  - Currents up to ~2 MA
  - Input RF up to ~5 MW
  - Densities up to ~$10^{21}$/m$^3$
  - Temperatures of 1-6 keV

# Simulating RF Heating/Energetic particles



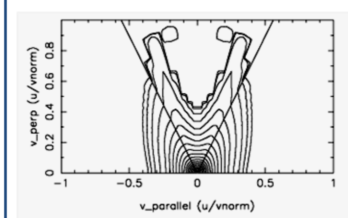
Lancellotti 06




Jaeger 06

Phase space distribution

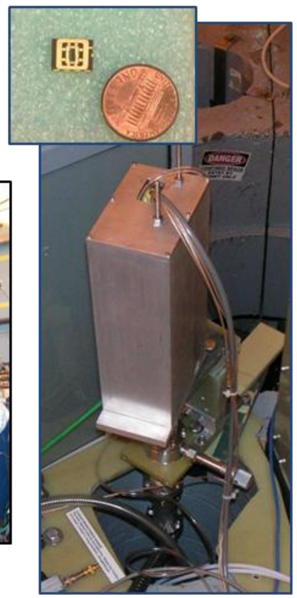


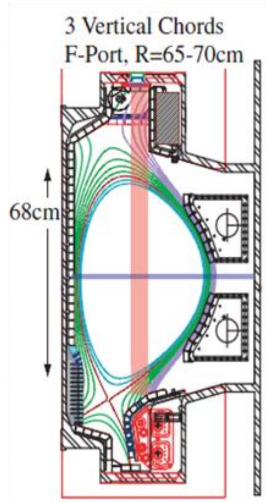

- For good coupling of RF into plasma, need to understand complicated non-linear multi-physics phenomena
- Experimentally, diagnosis of these “minority” energetic species is difficult

# Measurements Illuminate Theory

- New multi-channel Compact Neutral Particle Analyzer—10 x smaller than old NPA via new Si diodes and fast digitization methods. New diagnostic techniques provide spatial, energy, and temporal response

New NPA





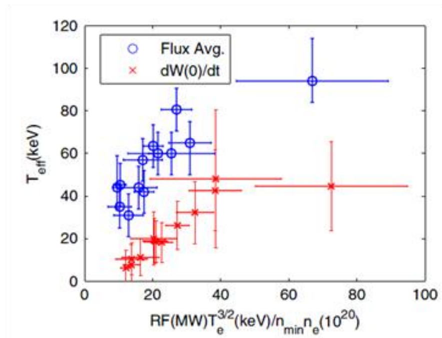

Old NPA

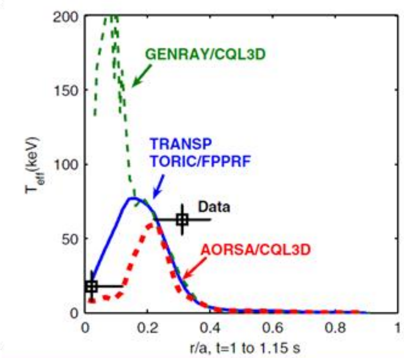
CX basic principle:

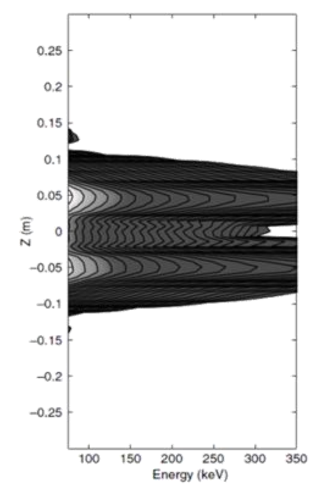
$H^{+}(fast)+H^{0}(slow) \rightarrow H^{0}(fast)+H^{+}(slow)$

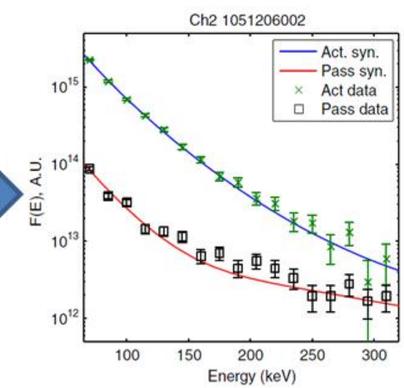
V. Tang et al., Rev. Sci. Instr., 2006

- First direct measurement of core energetic particles at ITER field and plasma densities, and comparison with leading coupled Wave/Fokker-Plank simulations—verified predictive capability and identified key physics




V. Tang et al., Plasma Phys. Cont. Fus., 2007

V. Tang, MIT PhD Thesis

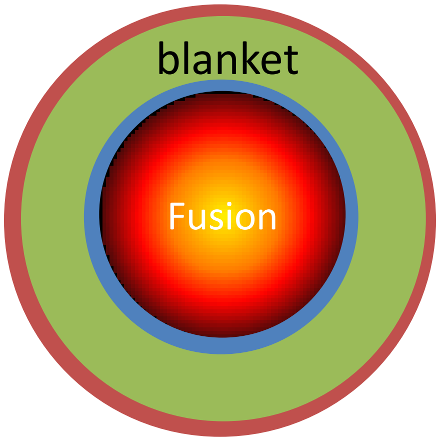
- **Next: Extend comparison to latest coupled wave-solvers and Monte Carlo orbit codes, study energetic particle confinement**
- **Continue development of novel diagnostic options for minority energetic particles (e.g. $\alpha$'s on ITER)**
  - **-Can detectors (Compton cameras, etc) developed for National Security play a role here?**

# Fusion-fission: A Near-term Fusion Application?

Fusion is “neutron rich” while fission is “neutron poor” when normalized by energy output-Can we capitalize on this?

Spare neutrons are valuable

Original concept goes back to the 50’s * and advocated by many (Sakharov, Bethe, Teller. For studies#)




- Waste Burn-up:

  n + (Cm, Am, Np, Pu) → 2 FP + 3 to 4 n (~$10/$10^{20}$ n, for $100B YM?)+

  $^{6}Li + n \rightarrow {}^{4}He + T$

- Fissile fuel breeding:

  n (14 MeV) + $^{9}Be \rightarrow {}^{7}Be + 2\,n$

  n + $^{232}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$ (~$10’s M/kg or ~$1’s/$10^{20}$ n for breeding)

  $^{6}Li + n \rightarrow {}^{4}He + T$

- Deep Burner:

  Not constrained by neutron economy for criticality—can achieve large burn-ups with minimal to no enrichment, no reprocessing.

Surplus Neutrons/Energy produced

Fission (Thermal): ~6 x $10^{-3}$ n/MeV
(500 MWt~2 x$10^{19}$ n/s)

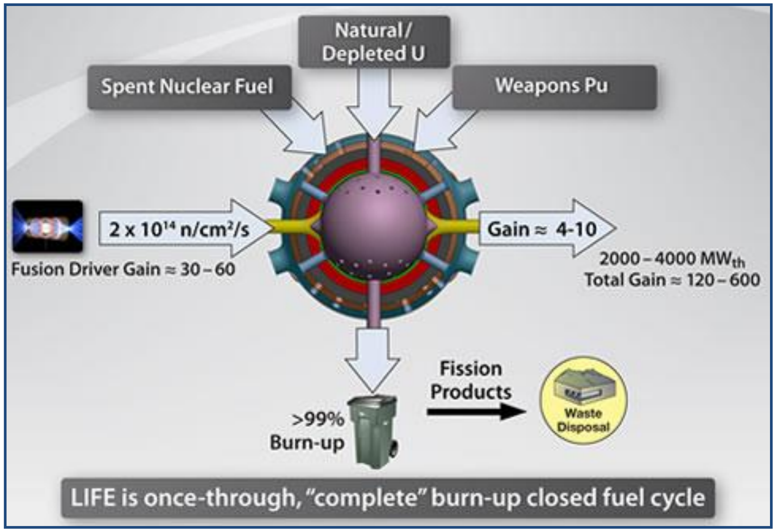
Fusion: ~3.4 x $10^{-2}$ n/MeV
(ITER: 500 MWt ~$10^{20}$ n/s)

*California Research and Development Company, Proposal for a Driven Thermonuclear Reactor, USAEC, Report LWs-24920 (1953)
Imhoff et al, “A Driven Thermonuclear Power Breeder”, Calf. Research Corp., Report CR-6 (1954)

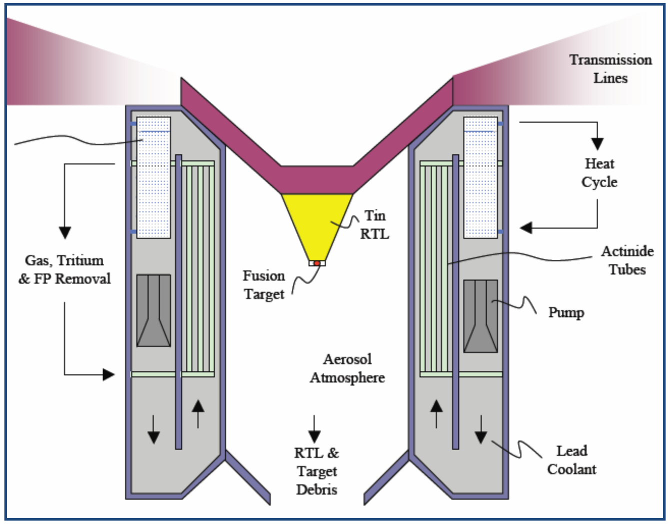
#See Lidsky, Moir, Greenspan, Stacey, Steiner, Cheng, and and Manheimer

+At $0.05 kWh, $10^{20}$ 14.1 MeV n is worth about $2 for power

# Recent Fusion-fission Concepts



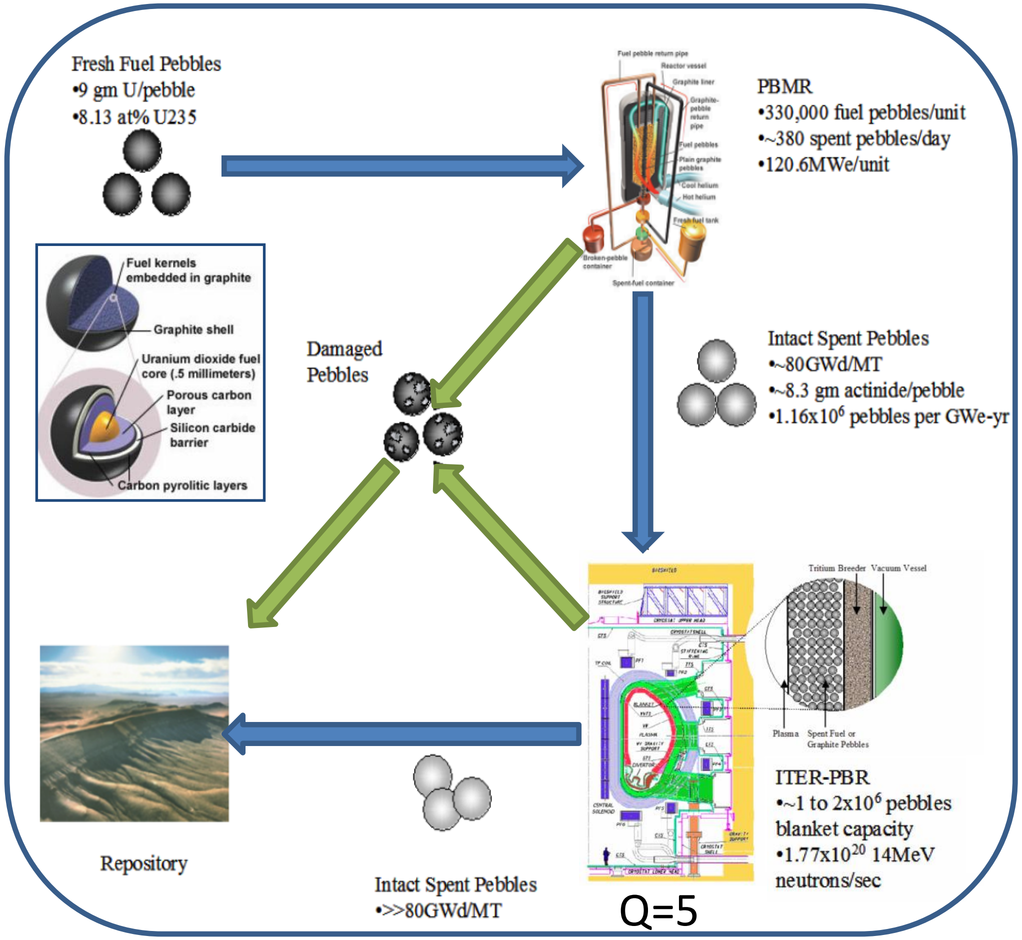

LLNL LIFE Engine (Moses et al.)




SNL In-Zinerator (Cipiti et al.)

- Hybrid type and performance affected by reprocessing constraints and other current nuclear cycle issues
- Typically comes from the fusion side: what can be done with the fusion device I can make now, or in the near-future?
  (More on this later)

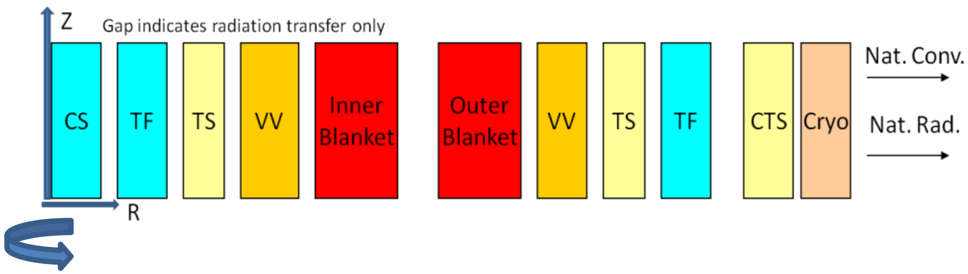
# ITER-Pebble Bed Reactor (PBR) Hybrid

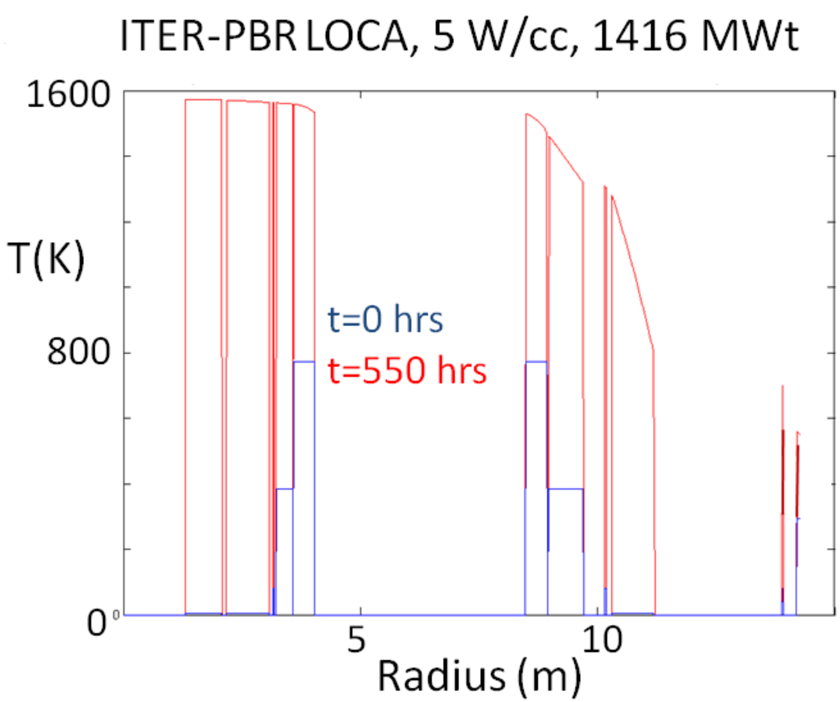



**V. Tang and R. Parker, Fusion Eng. Des. (2003)**
**V. Tang, MS Thesis, MIT**

- Examine extended burn-up of rugged spent Pebble Bed Modular Reactor (PBMR) fuel
- Design constraints:
  (1) Remain passively safe during LOCA
  (2) No reprocessing
  (3) No refueling
  (4) Must maintain tritium breeding
  (5) Use He coolant
  [Combined, these turn out to be very stringent requirements]
- Primary Approach
  - (1) 1-D heat transfer calculation to estimate maximum safe blanket power
  - (2) Use MCNP/Monteburns and Modified “Supercell” pebble model to determine PBMR fuel characteristics, then study BOL characteristics of ITER-PBR designs
  - (3) Select promising BOL designs and study life-cycle and waste-characteristics using Monteburns

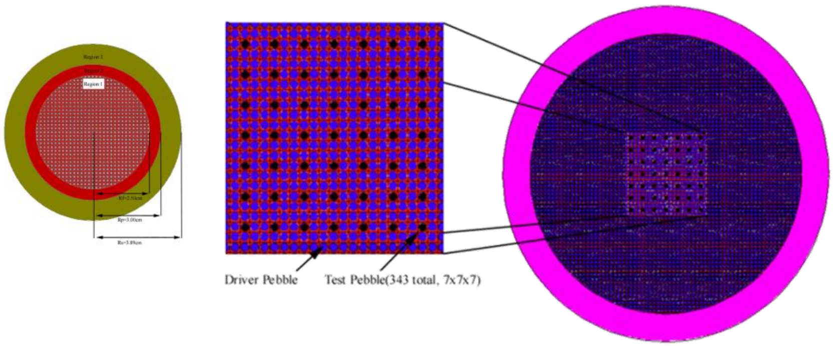
# ITER-PBR LOCA Study

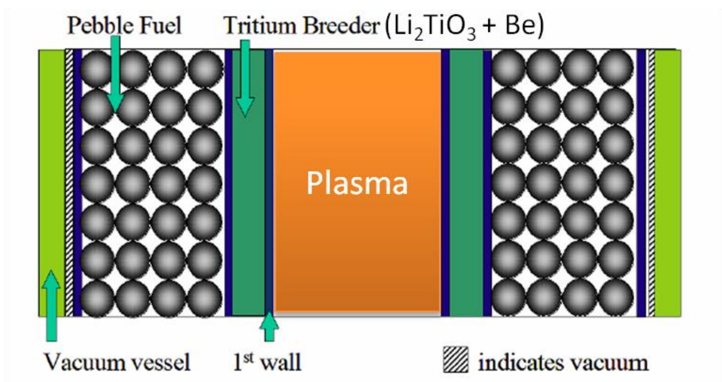



- In-house 1-D cylindrical heat transfer code (Includes conduction, convection, and radiation)
- Use U decay heat vs. time and fission power density estimates for source terms
- Passive safety constraint limits blanket power to ~1400 MWt
  - For ~3000 MWt, Pebbles reach 1600 K after ~11 hours
- Tokamaks have conflicting constraints-need to minimize heat transfer from blanket to superconducting magnets during operation. But during LOCA, need to maximize this

# ITER-PBR Life-Cycle Study




| | PBMR/ITER-PBR | PBMR | PWR |
|---|---|---|---|
| Waste Act. (tons/GWe-yr) | 0.83 | 9.6 | 32 |
| Storage Req. ($m^2$/GWe-yr) | 37.1 | 428 | 1437 |

- Modified Lebenhaft* "supercell" for spent pebble fuel parameters
- Allows us to determine higher actinide inventory
- Benchmark with VSOP code using Pu inventory
- Spent fuel is ~2.2 w% fissile

*Lebenhaft MS MIT Thesis 2001

- 143 BOL blanket designs considered-one chosen for final life-cycle study

- Net power is ~400 MWe for 30 yrs, 417 GWe-yr/MT-HM burn-up, 13.8 GWe-yr produced
- Based on ITER costs, breakeven COE ~$0.132/kW-hr
- TBR of 1.2 to 1.07, Fusion power from 345 to 500 MWt
- LOCA and examined blanket sizes limit power output
  -Molten salts and online reprocessing?
- Waste characteristics are favorable

# Fusion-fission Questions

- We also examined a deep thorium burner*, akin to C. Rubbia's accelerator based concept+, which can produce ~3 GWt with large burn-ups.

- Next: Step back and evaluate subcritical driven concepts fairly in fast 0D to 1D system models that include safety, reprocessing, proliferation, waste storage, fuel costs. This will allow us to study the large parameter space effectively, in consideration of the entire fuel cycle.

- Given near to mid-term energy needs and requirements, can fusion-fission play a competitive role (independent of allowing us to gain experience with fusion)? If so, what are the requirements for the fusion source?

- **Do these requirements differ significantly from the direction of current fusion programs?**
  **(Should we concentrate on low Q, simple, compact machines, for example? Is a larger, high Q source better even if it is more complex?)**

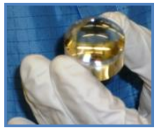
***V. Tang & R. Parker, IAEA Transmutation Workshop, 2001**

**+C Rubbia et al, Report-CERN/AT/95-44 (ET) (1995)**

# Conclusions

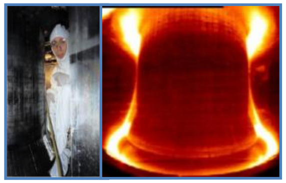
Scale

0.01 m

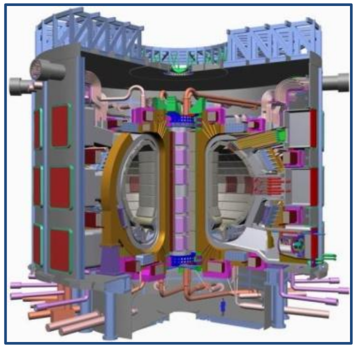


0.1 m

1 m



10 m



- Fusion neutron science have significant Energy and National Security Applications—these neutrons have application in all areas of nuclear engineering
- Unique properties allow fusion neutrons to sustain the fusion fuel cycle, remediate fission waste, breed fissile fuel, and remotely detect explosives and SNM
- Making and using neutrons involve significant and interesting multi-disciplinary, multi-scale experimental, theory, and simulation efforts
  - Spans traditional nuclear, electrical, materials engineering, and atomic and (neutral and non-neutral) plasma physics
- There is a lot of work to do