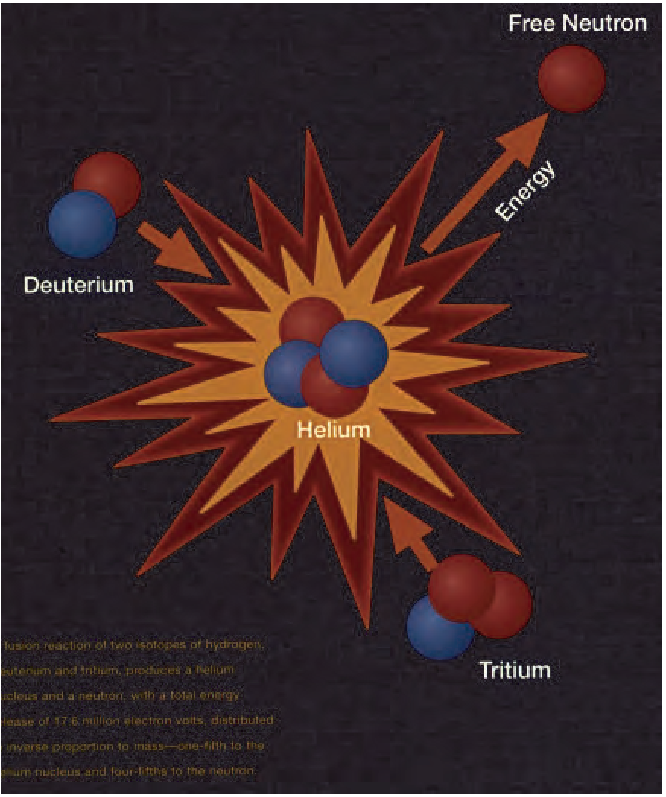
Fusion 101
The fusion parameter space from first principiles



fusion reaction of two isotopes of hydrogen,
euterium and tritium, produces a helium
ucleus and a neutron, with a total energy
lease of 17.6 million electron volts, distributed
inverse proportion to mass—one-fifth to the
lium nucleus and four-fifths to the neutron.

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Abstract

Under what conditions (fuel density, temperature, magnetic field, etc.) can useful fusion energy release occur? This and other related questions can be answered by a rather simple analyis that is summarized in this presentation. By comparing loss rates with fusion rates, we can identify the density-temperature space where fusion gain can be achieved. This simple analysis offers a general understanding of the extreme differences between ICF and MCF. The analysis shows that the constraint of steady-state operation forces MCF to operate at the low end of the density spectrum and the constraint of unmagnetized fuel forces ICF to operate at the high end. Most importantly, the analysis shows the implications of relaxing these constraints, mainly, that operation at an intermediate density with magnetized fuel has many attractive features and potentially overcomes some of fusion’s obstacles, particularly cost. One approach to accessing the intermediate density regime is magnetized targets driven by various candidate drivers. Pretty much lost in history is the fact that the first neutrons produced in the U.S. electron beam fusion program came from a magnetized target at SNL. Unfortunately, SNL prematurely abandoned magnetized targets, a decision that may have contributed to the ultimate demise of the electron beam and light ion beam fusion programs. Recently, there has been renewed interest in magnetized targets at SNL, LANL, AFRL, U. of Rochester, and elsewhere.

FUSION 101--the questions

- Under what conditions (fuel density, temperature, magnetic field, etc.) can useful fusion energy release occur? What are the practical limits on these conditions?
- Why are there so many orders of magnitude difference in density, volume, power, etc., between NIF (very high density) and ITER (very low density)?
- Are three common perceptions correct?
  There are only two viable approaches to fusion--ICF and MCF.
  Fusion is very high cost. Fusion is 30 years away.
- Have there been any promising fusion stones left unturned?
- Is there anything in between ICF (NIF) and MCF (ITER)?
- What would be the cost of a facility to access an intermediate region?

"Ballpark" answers--American Journal of Physics Vol. 77, pp. 407-416, May 2009.

- $\dot{Q}_{loss} = \phi \dot{Q}_{FUS}$; find n_i, T, B so that $\phi < 1$; $\dot{Q}_{loss} = \dot{Q}_{TC} + \dot{Q}_{RAD}$

  $\dot{Q}_{RAD} = C_{RAD} n_i^2 T^{1/2}$ (Bremsstrahlung) $\dot{Q}_{TC} = -\nabla \bullet (K \nabla T)$ (K = thermal conductivity)

- **Radiation losses determine a minimum temperature:**

$$\frac{\dot{Q}_{FUS}}{\dot{Q}_{RAD}} = \frac{\varepsilon_{FUS} n_i^2 \frac{\overline{\sigma v}}{4}}{C_{RAD} n_i^2 T^{1/2}} = \frac{\varepsilon_{FUS} \frac{\overline{\sigma v}}{4}}{C_{RAD} T^{1/2}}, \quad \text{independent of } n_i \qquad \frac{\dot{Q}_{FUS}}{\dot{Q}_{RAD}} \geq 1 \quad \text{when } T > 3\ keV$$

- $\dot{Q}_{TC}, \nabla T$ **must be approximated:**

$$\dot{Q}_{TC} \approx -\frac{1}{V}\int \nabla \bullet (K \nabla T) dV = -\frac{1}{V}\oint_S K \nabla T \bullet d\vec{S} \approx -\frac{S}{V} K \nabla T \approx \frac{KT}{\gamma \alpha a^2}$$

$$a = \text{characteristic dimension}, \quad V = \varepsilon a^3, \quad \frac{V}{S} = \gamma a, \quad \nabla T \approx -\frac{T}{\alpha a}$$

- **ε, γ are geometric quantities, i.e., for spheres $\varepsilon = 4\pi/3$, $\gamma = 1/3$.**

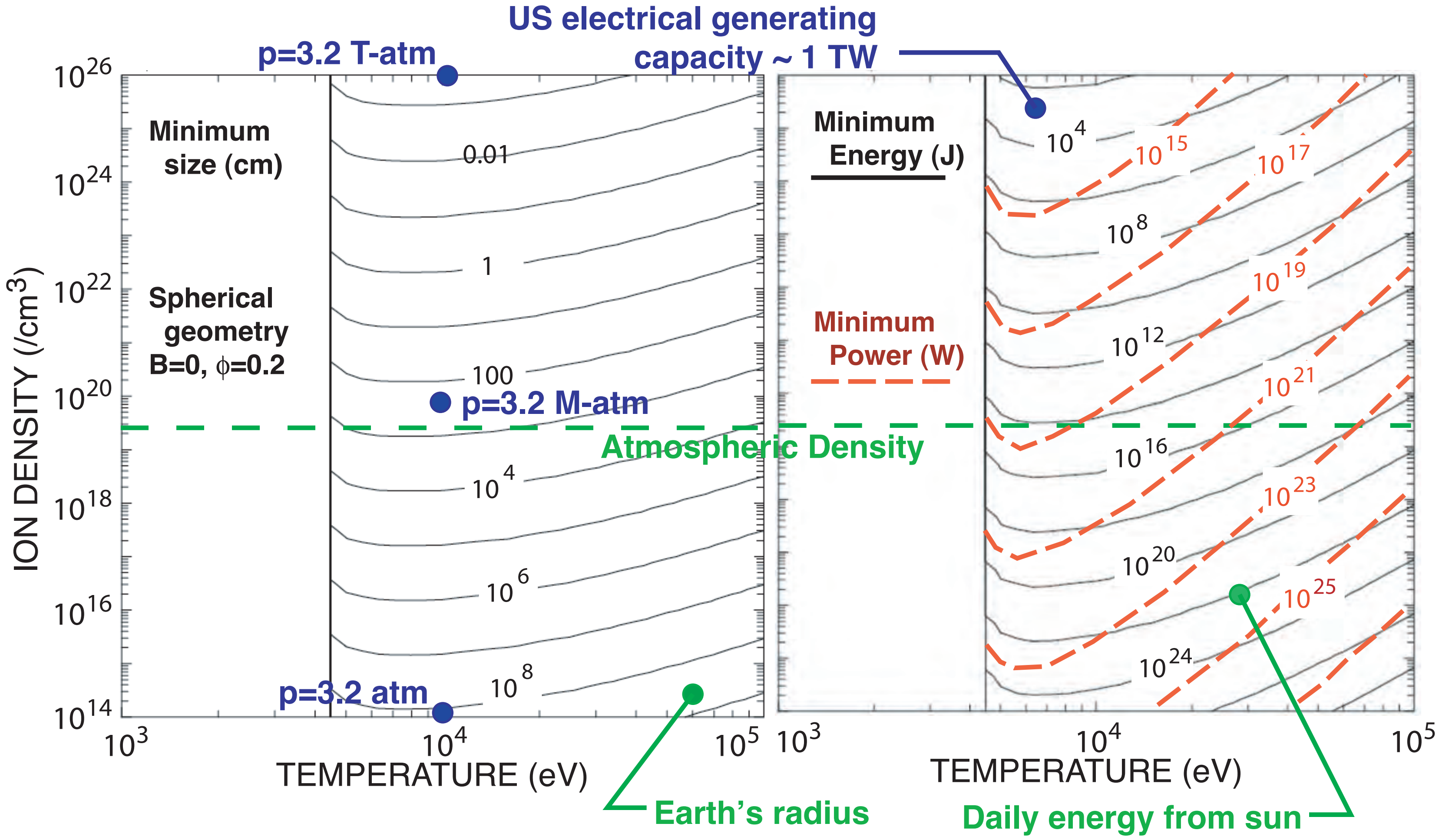
- **Loss rates depend upon *n_i, T, a*, model for *$K = K_i + K_e$*, geometry (ε, γ), profile details (α), and, possibly, magnetic field *B* (through *K*).**

The conduction rate can be used to determine the minimum system size and other relevant parameters for a desired loss ratio ϕ.

- **Minimum size** $a_{\min}^2 = \frac{KT}{\gamma\alpha}\frac{1}{\phi\dot{Q}_{FUS} - \dot{Q}_{RAD}}, \quad a_{\min} = a_{\min}(n_i, T, B)$
- **Fuel Mass** $M = n_i(m_i + m_e)\varepsilon a_{\min}^3$
- **Fuel thermal energy** $E_{PLAS} = 3n_i T\varepsilon a_{\min}^3$
- **Required heating power** $P_{HEAT} = (\dot{Q}_{TC} + \dot{Q}_{RAD})\varepsilon a_{\min}^3$
- **Required surface heating (intensity)** $I_{HEAT} = \frac{P_{HEAT}}{S}$
- **In the simplest, “classical,” form, the thermal conductivity for an unmagnetized plasma depends only on temperature: $K_o=C_oT^{5/2}$. With magnetization, the conductivity is reduced by a factor of $1+(\omega\tau)^2$.**

Unmagnetized fuel must operate at very small size, very high density & pressure

$$p_{atm} = 3.2 \times 10^{-15} n_i T_{keV}$$



p=3.2 T-atm

US electrical generating capacity ~ 1 TW

p=3.2 M-atm

Atmospheric Density

p=3.2 atm

Earth's radius

Daily energy from sun

Unmagnetized fuel must operate at very small size, very high density & pressure

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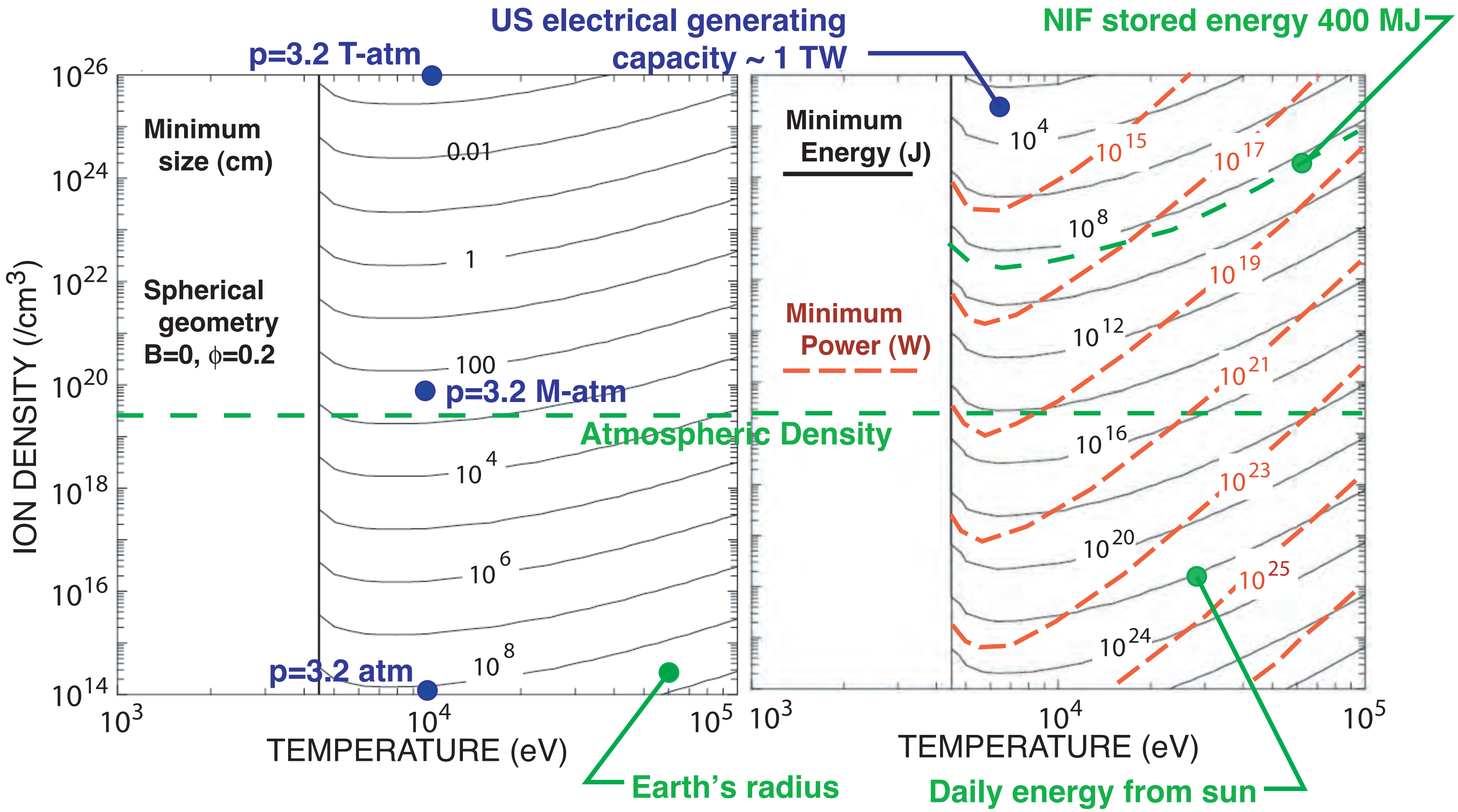

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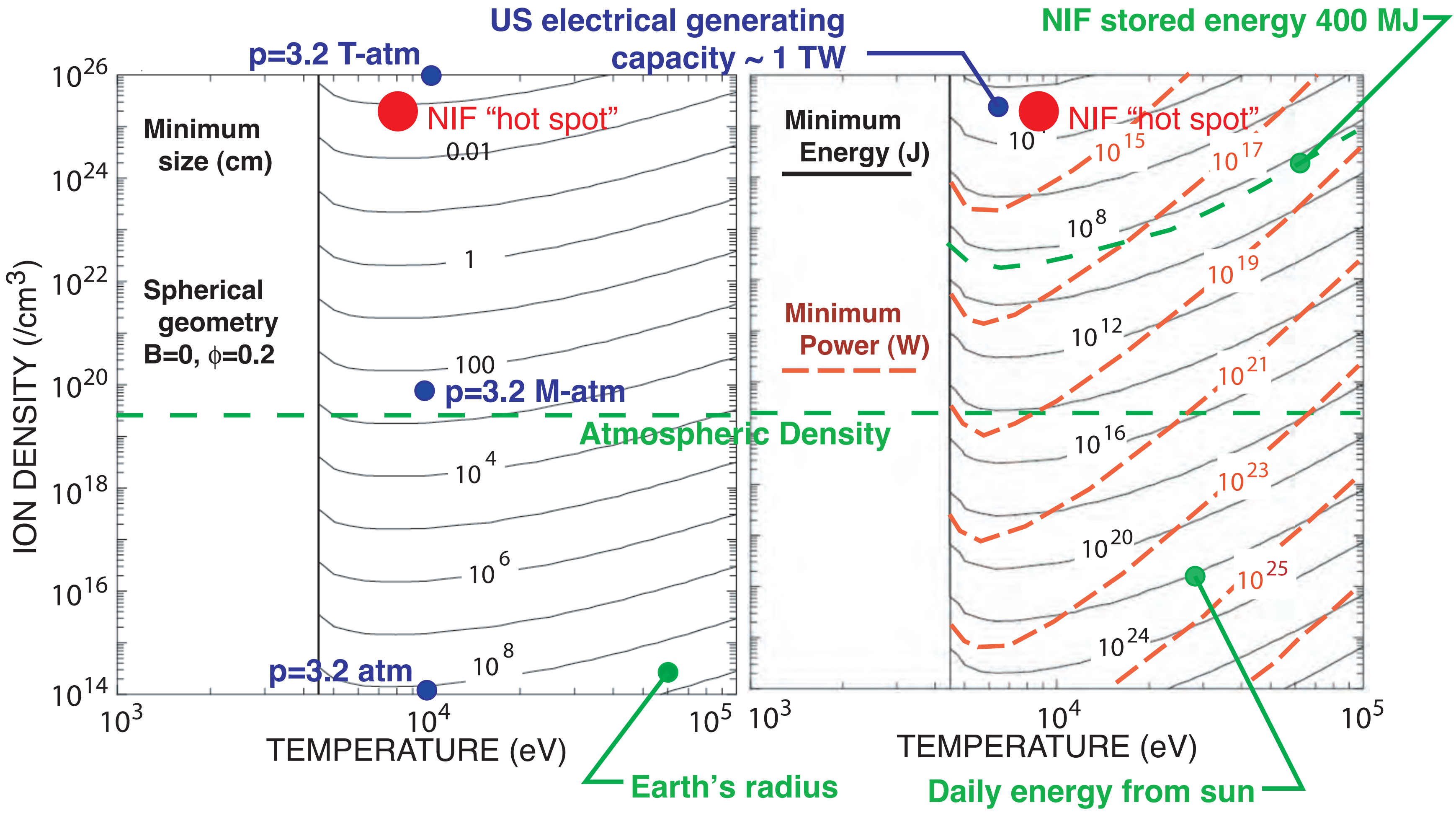

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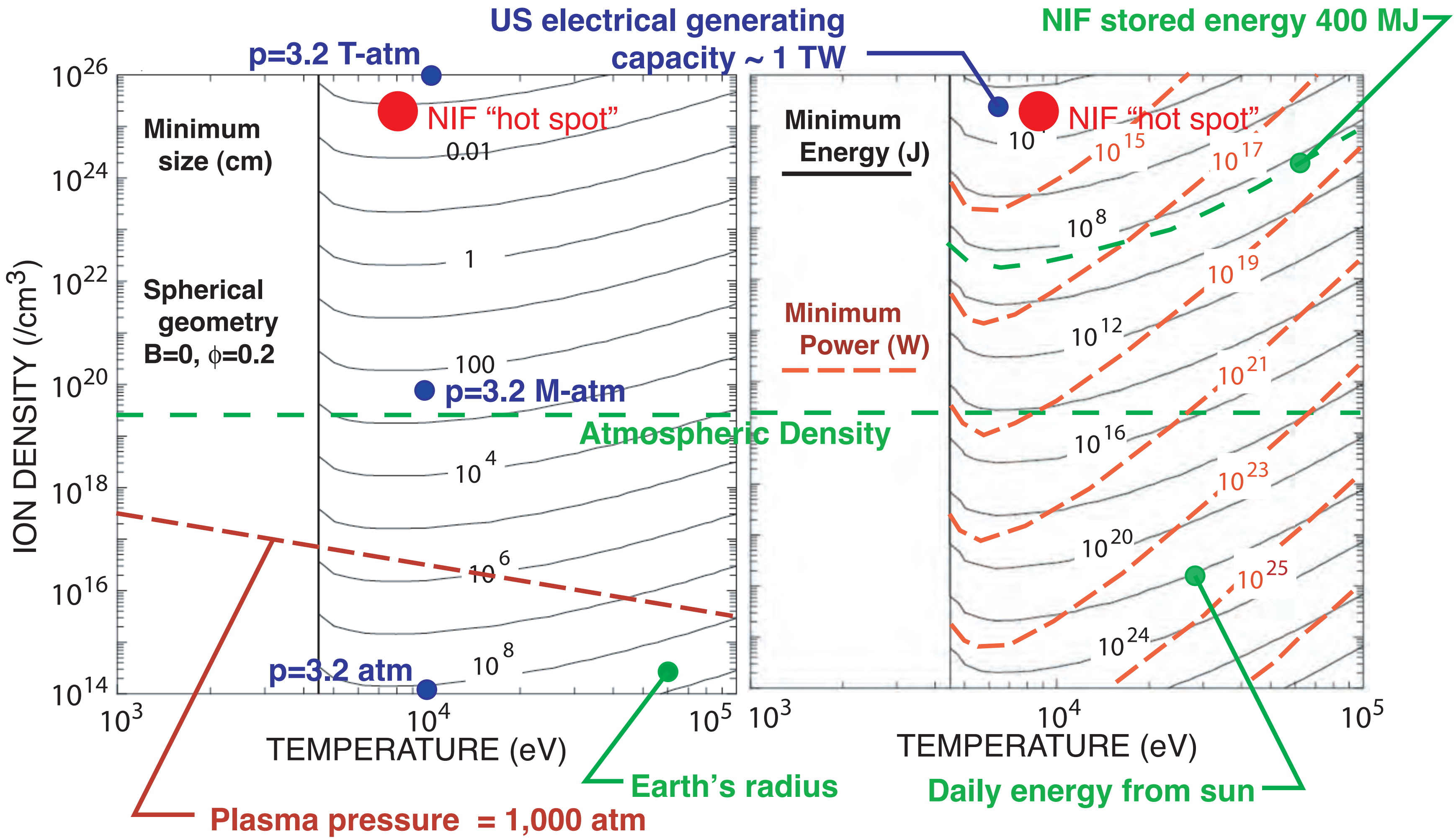


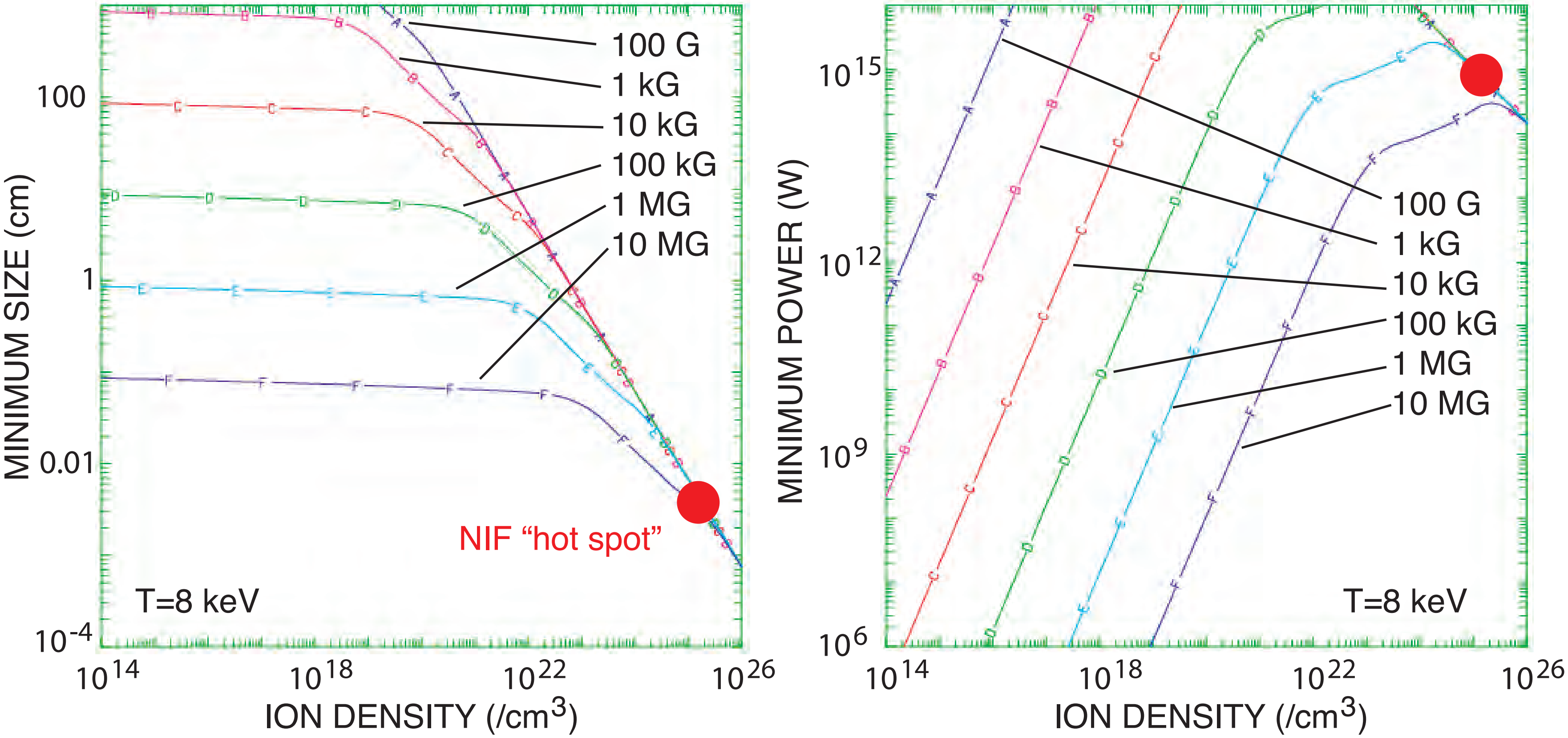
- "Steady state" operation requires pressure < 1000 atm., is not possible, so unmagnetized fuel must be "pulsed," i.e., a small nuclear explosion.

Electron thermal conductivity establishes the density lower limit; the dominant role of thermal conductivity was recognized early.

- **Reference: Enrico Fermi, "Super Lecture No. 5--Thermal Conduction as Affected by a Magnetic Field," Los Alamos Report 344, Sept. 17, 1945.**

  "A posible method of cutting down the conduction to the walls would be the application of a strong magnetic field, H. This tends to make the electrons go in circles between collisions, so impedes their mobility. Actually, it makes them go in spirals, and does not reduce the conductivity parallel to H but only to the other two dimensions, so one would probably want to design the container elongated in the direction of H, or even toroidal...with the lines of force never leaving the deuterium...rather large fields will be required...thus a field in excess of 20,000 gausses would help reduce conduction loss. While it would not be possible to produce such fields in a large volume in a steady state, the technical problem of making the field is much aided by the fact that the time during which the field is needed is much shorter than the usual relaxation time of magnetic fields, so it need be applied only instantaneously."

At densities lower than the NIF hot spot, a magnetic field can significantly reduce the size and the heating power required.



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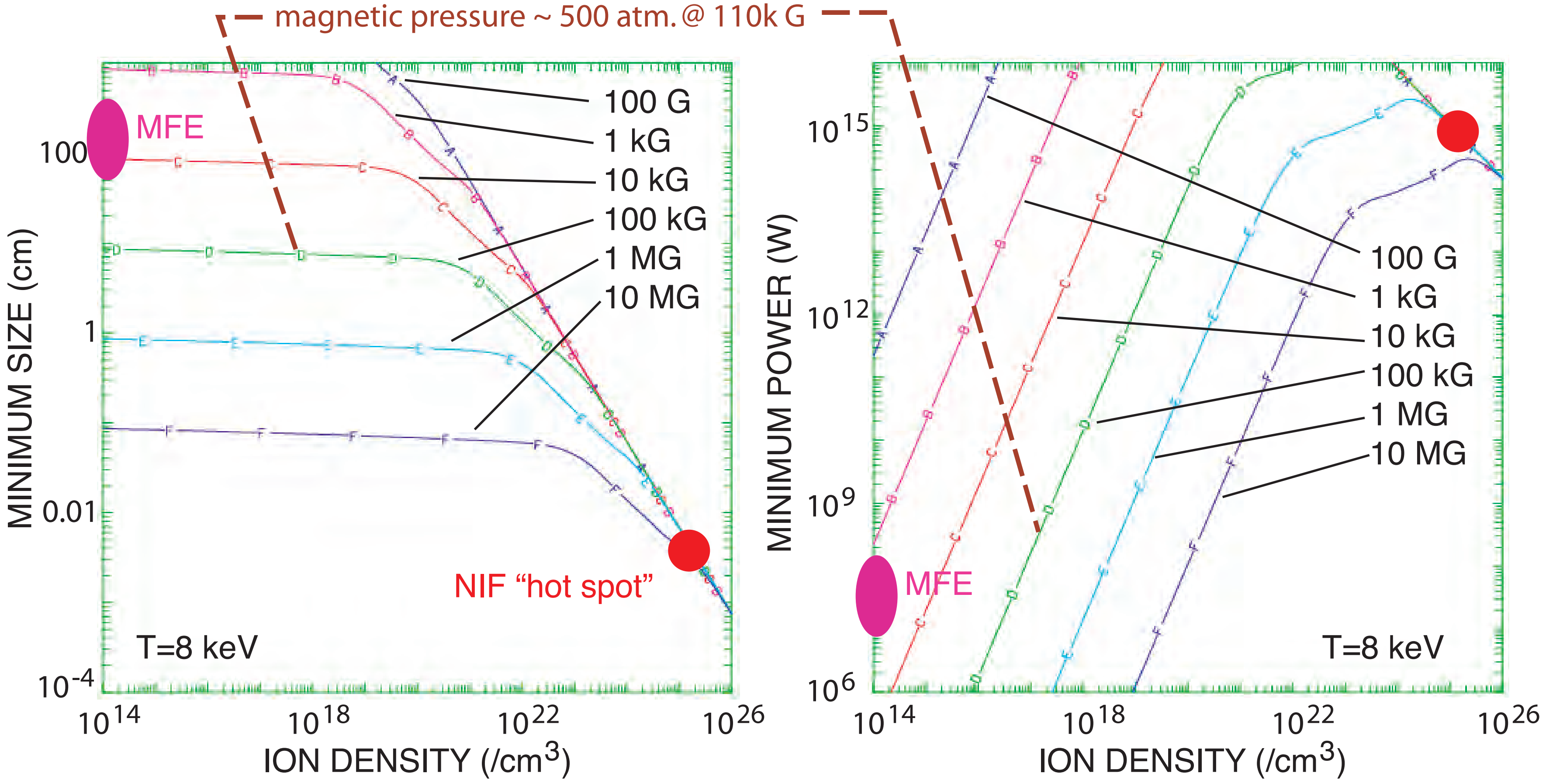


- **Reduced size, power make "steady-state" fusion @ n ~ 1e14, B ~ 10 kG, i.e., MFE, feasible; the low power can be met with RF and neutral beams.**

- **Non-"classical" transport, enhanced radiation increase size, power required.**

NIF and ITER differ by factors of 1e4-1e16 in basic physical quantities.

	ITER	Ratio NIF/ITER	NIF
Geometry	Toroidal		Spherical
Cost ($M)	10,000		3,000
n_i (/cm^3)	10^{14}	1.4×10^{11}	1.4×10^{25}
ρ (g/cm^3)	4.2×10^{-10}	1.4×10^{11}	57
T (keV)	8		8
p (atm)	2.6	1.4×10^{11}	3.6×10^{11}
B (kG)	50		0
τ_L (s)	0.9	$1/1.4 \times 10^{11}$	6.6×10^{-12}
M (mg)	350	$1/3.5 \times 10^{11}$	0.01
a (cm)	240	$1/6.9 \times 10^{4}$	3.5×10^{-3}
V (m^3)	8.3×10^{2}	$1/4.6 \times 10^{15}$	1.8×10^{-13}
E_{plas} (J)	3.2×10^{8}	$1/3.4 \times 10^{4}$	9.3×10^{3}
P_{heat} (W)	1.3×10^{8}	8.5×10^{5}	1.1×10^{14}
I_{heat} (W/cm^2)	18	4.2×10^{16}	7.5×10^{17}

- **Stacks of $1: 1e4=3.3 ft, 1e12 (bailout)=encircle earth 2.5 times**
  1e16=3 round trips to sun

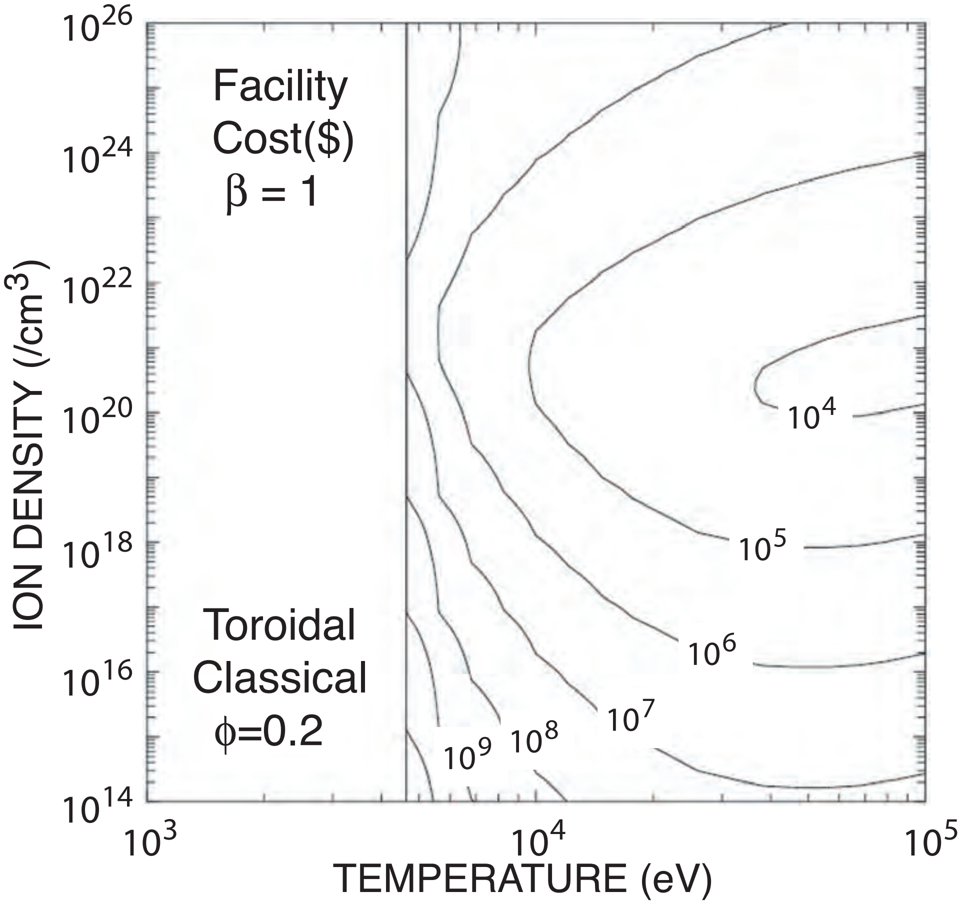
- **The constraint of unmagnetized fuel forces ICF to operate at high-density, the constraint of "steady-state" forces MCF to operate at low density.**
  What if these constraints were relaxed???

Knowing the cost of ITER and NIF, the cost of fusion facilities in any region of parameter space can be estimated.

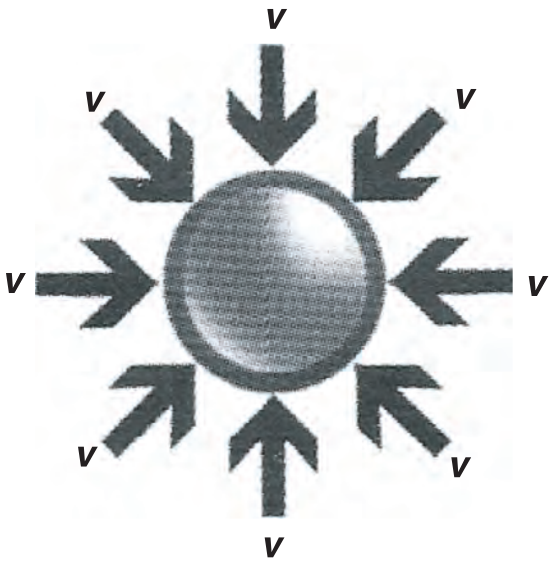
- $$Cost = c_1 E_{PLAS} + c_2 P_{HEAT} \approx \frac{\$10B}{E_{ITER}} E_{PLAS} + \frac{\$3B}{P_{NIF}} P_{HEAT}$$

- **The reduced size/energy (when compared to ITER) and reduced power (when compared to NIF) lead to a very much lower cost at an intermediate density using magnetized fuel.**

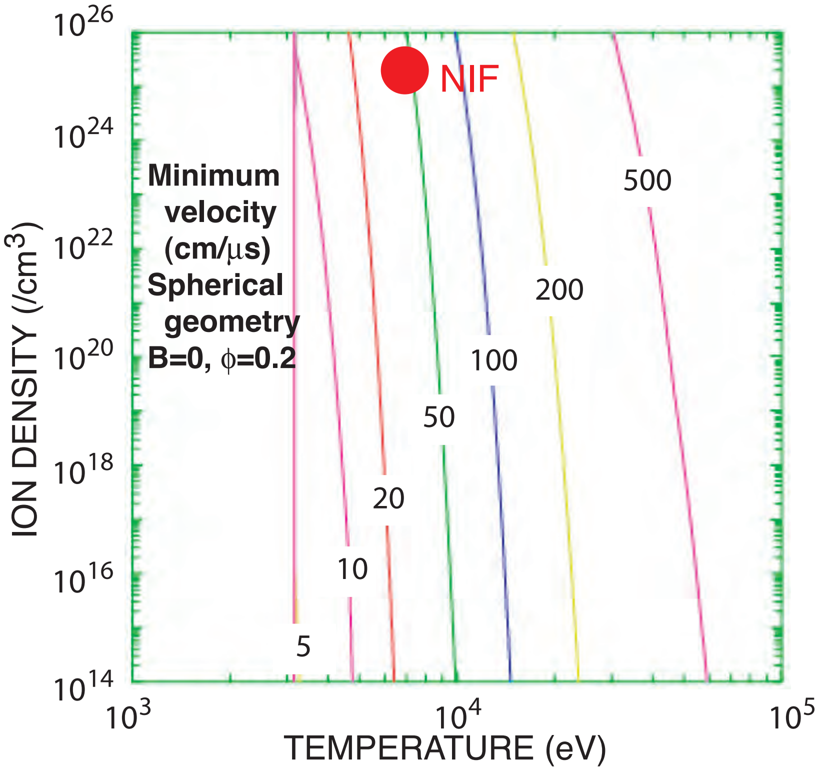
- **Can the intermediate space be accessed? At all? At low cost?**



In ICF, the fuel is heated by compressional (hydrodynamic) work of the pusher



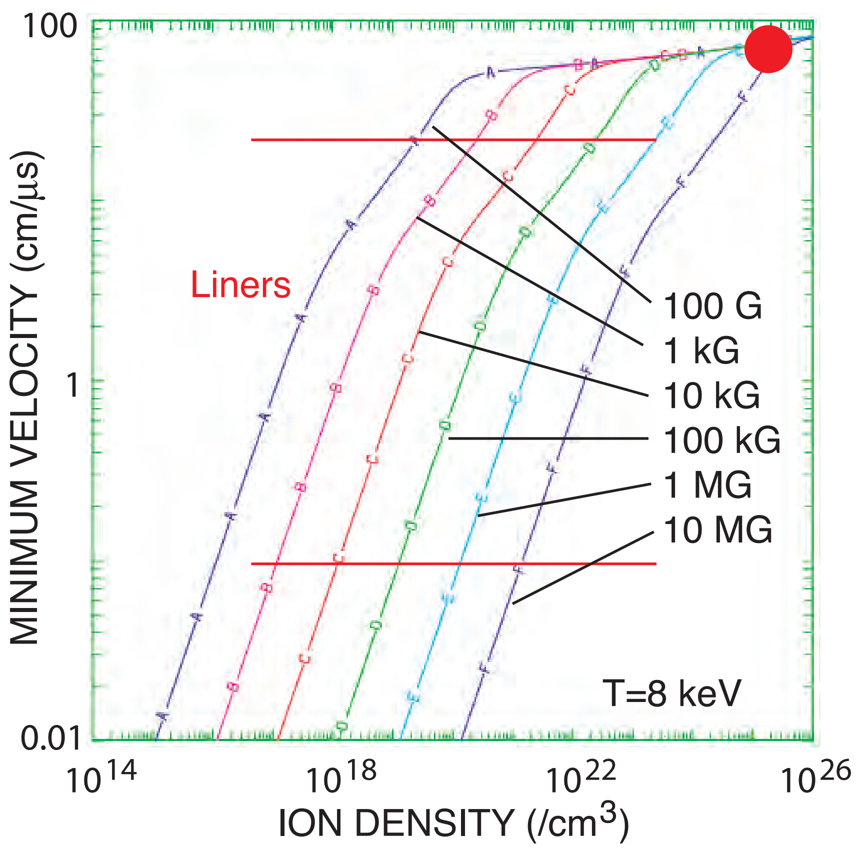
$$v_{\mathrm{IMP}} = \frac{I_{HEAT}}{p} = \frac{I_{HEAT}}{2n_iT}$$

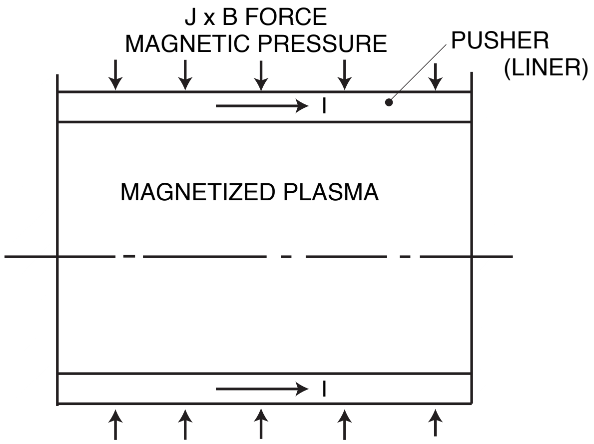


- **NIF requires an implosion velocity of 40 cm/μs (900,000 mi/hr) and a radial convergence (initial-radius/final-radius) of 30.**

- **For conventional targets, "the optimal velocity...is the primary determinant of the minimum size driver for ignition..."(J. D. Lindl, UCRL-119015, 11/95), i.e., reduced velocity means reduced cost.**

A magnetic field can reduce the required target energy and implosion velocity to the range demonstrated by modern high-current pulsed power machines (Atlas, Shiva-Star, Z, DEMG)

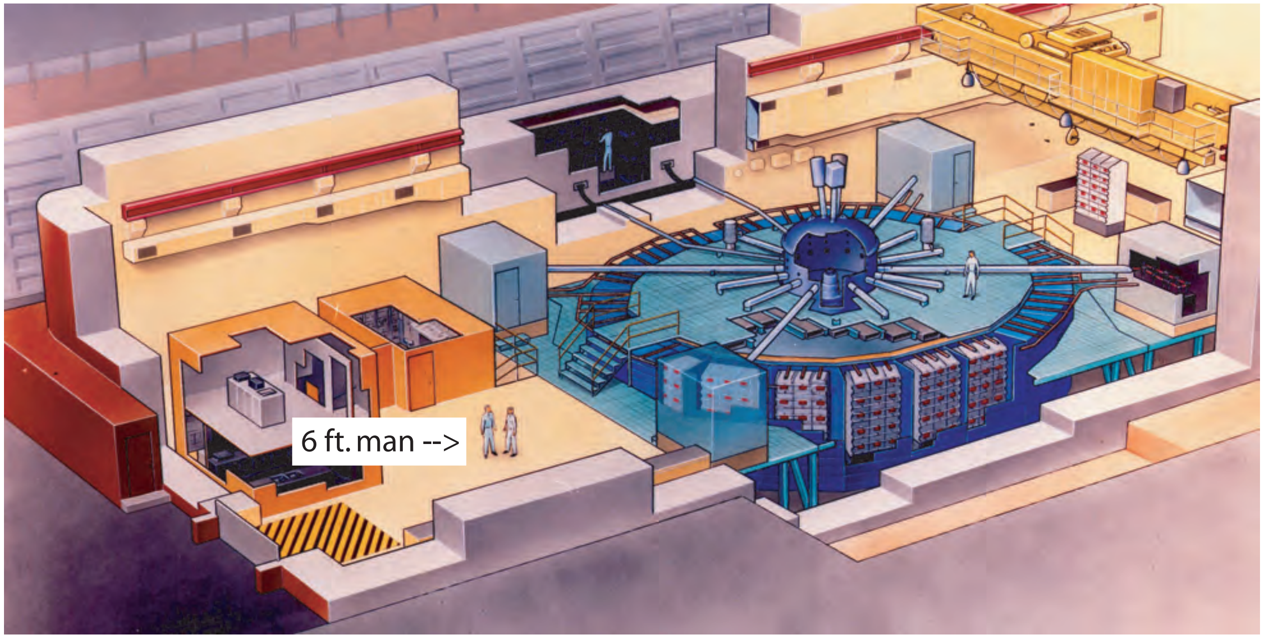




- **Accessing the intermediate density region by compressing a preformed, magnetized plasma with an imploding pusher/liner is known as Magnetized Target Fusion (MTF), a.k.a. Magneto-Inertial Fusion (MIF).**

The Atlas capacitor bank (23 MJ, 30 MA, 6 μs) at NTS was designed to drive imploding liners in the range of 1-10 MJ, 0.1-1 cm/μs to create high energy density environments.

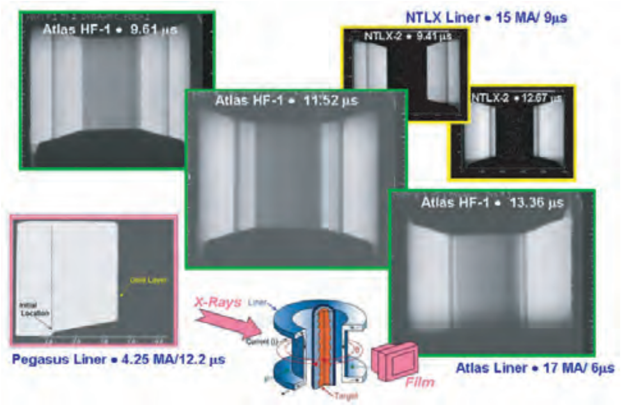
- Atlas is, serendipitously, an ideal machine for accessing the intermediate density regime by compressing magnetized fuel with a magnetically driven liner.

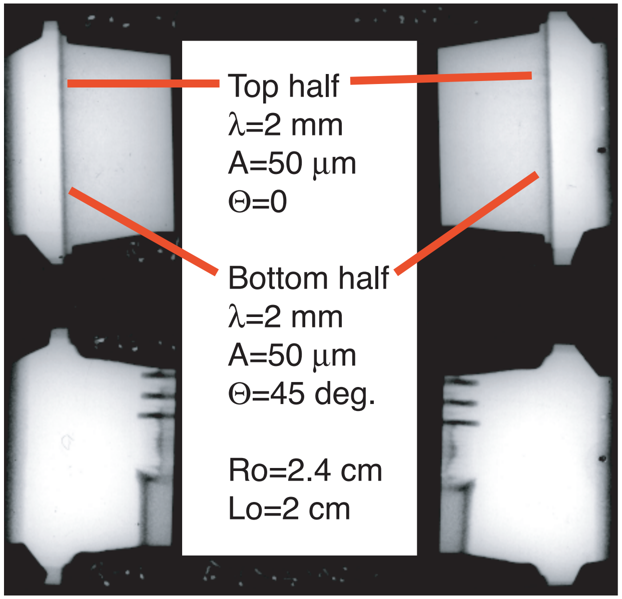


- Atlas' cost of $50M confirms the simple cost estimates for fusion facilities.

Magnetically driven liner technology is relatively mature, offers highest efficiency coupling from “wall” to target plasma; the magnetically driven Rayleigh-Taylor instability is a concern.

- **LANL has demonstrated high-precision implosions on a variety of facilities; two-dimensional MHD computations agree well with observations and offer insight into design considerations for stability (Reinovsky et al., IEEE Trans. Plas. Sci. 36, p. 112, 2008).**



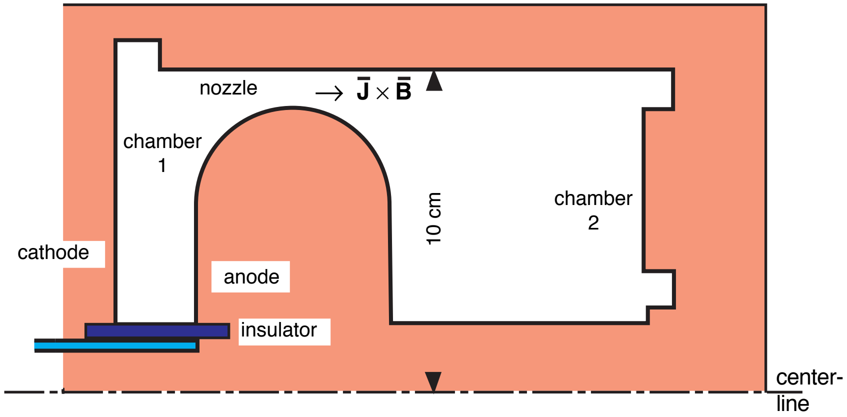


LANL/VNIIEF

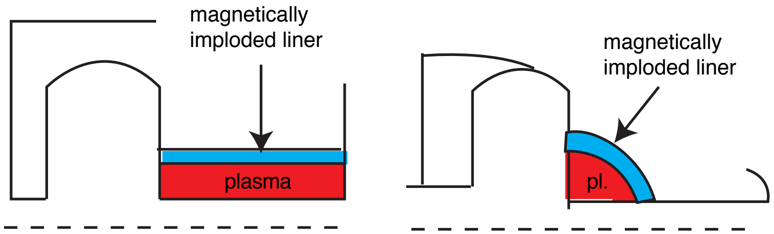
- **A joint AFRL/LANL liner experiment showed good stability at a radial convergence of ~ 17 (Degnan et al., IEEE TPS 36, p. 80, 2008).**

- **A joint LANL/VNIIEF experiment (left) showed that imposed screw perturbations lead to a stable implosion (Anderson et al., 2001 IEEE Pulsed Power Conf. Digest of Papers, p. 354); the generality of this technique has yet to be explored.**

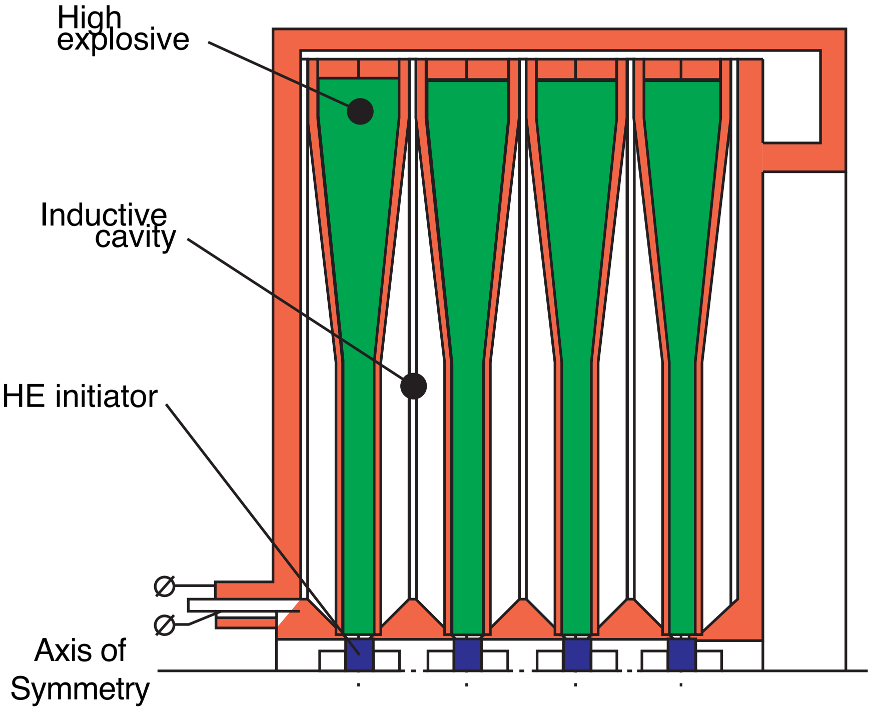
The Russian “MAGO” plasma has near-ideal density and temperature (1e18/cm3, 300 eV) for MTF; 1e13 D-T neutrons are produced in the formation stage.



MAGO (Magnitnoye Obzhatiye)



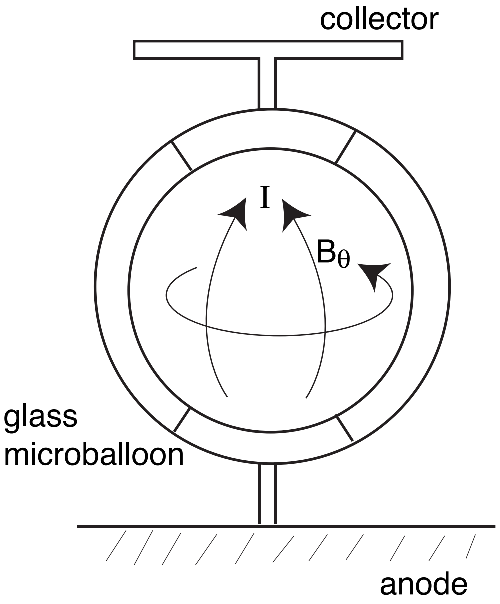
Implosion scenarios



Disk Explosive Magnetic Generator (DEMG)

- The All-Russian Institute of Experimental Physics (VNIIEF--the “Russian Los Alamos”), building on the work of Nobel Laureate Andre D. Sakharov (”father of Russian H-bomb”), has developed explosively powered generators that develop more electrical current (300 MA) and energy (200 MJ) than any US facility.

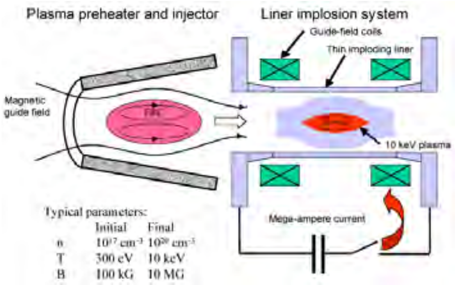
The first neutrons ever produced by the US particle beam fusion program came from a magnetized target driven by an electron beam (REHYD, 1 MeV, 250 kA, 100 ns, 0.04 TW); see Phys. Today 8/77



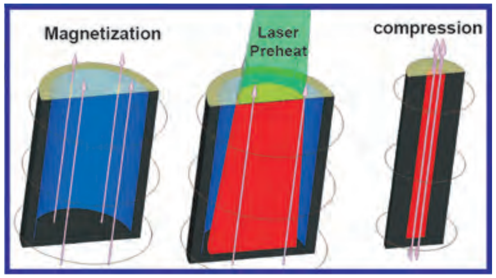
The Sandia "Φ" Target

- **A non-relativistic precursor (5-15 kA, 1 μs) was stopped by the collector, creating a voltage which induced an electrical discharge in the fuel.**
- **The 3-mm-diameter targets imploded at 4 cm/μs.**
- **10^6-10^7 neutrons were observed in CD_2 wire and D-T gas fillled ($6 \times 10^{18}/cm^2$) targets.**
- **No neutrons were observed without the precursor or in a variety of "null" targets.**
- **Two-dimensional MHD computations indicated a 5-20 eV preheat, 300-500 ev final temperature, consistent with the observed neutron yield (Lindemuth and Widner, Phys. Flu. 24, 1981, p. 746).**
- **Sandia computations predicted high gain for ion and electron magnetized targets at low intensity (Sweeney and Farnsworth, Nuc. Fus., 1981, p. 41).**

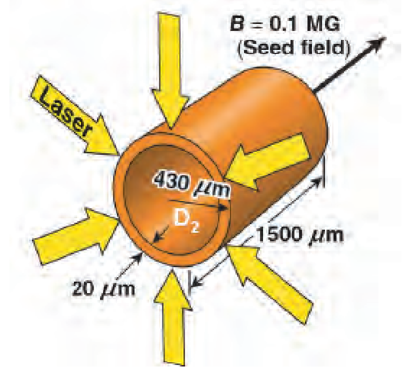
The > 1e4 density, > 1e2 velocity range of MTF admits many plasma/driver combinations; plasma may be magnetically or wall confined with simple magnetic topology; pulse-shaping is not needed



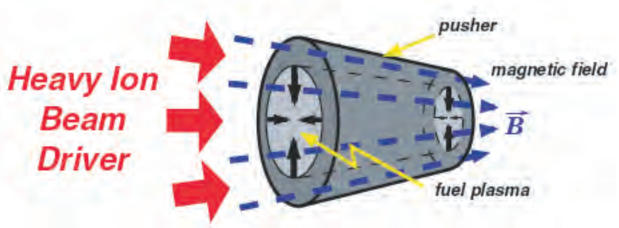
AFRL/LANL/UNR FRC/Shiva-Star
(J. Degnan, G. Wurden et al.)



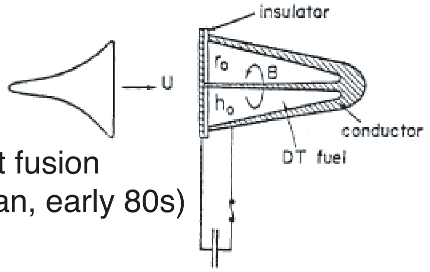
SNL "Z" MAGLIF (S. Slutz et al.)



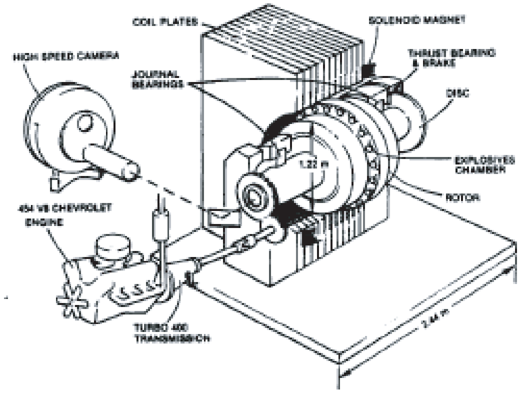
LLE Omega (Fiksel,Hohenberger et al._



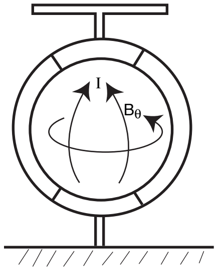
HIF (Kemp et al.)



impact fusion
(Tidman, early 80s)

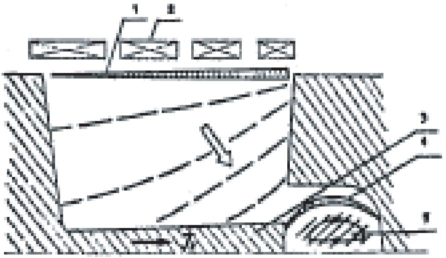


NRL LINUS (Turchi et al., 70s-80s)
Reciprocating 0.1 mm/μs liquid liner



SNL e-beam Φ-target (late 70s)

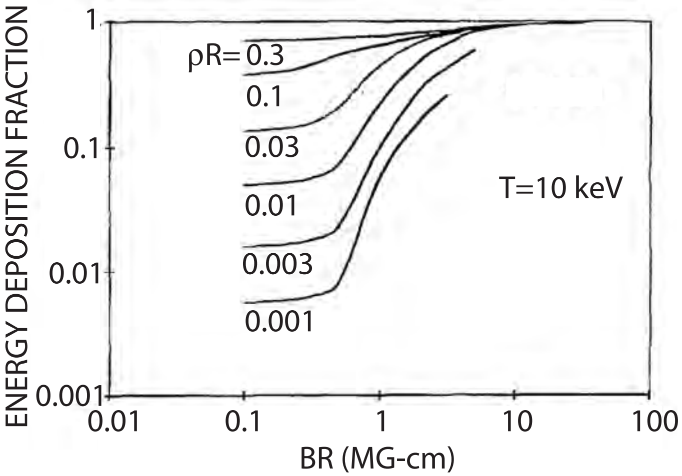
Plasma-jet liner (Witherspoon et al.)

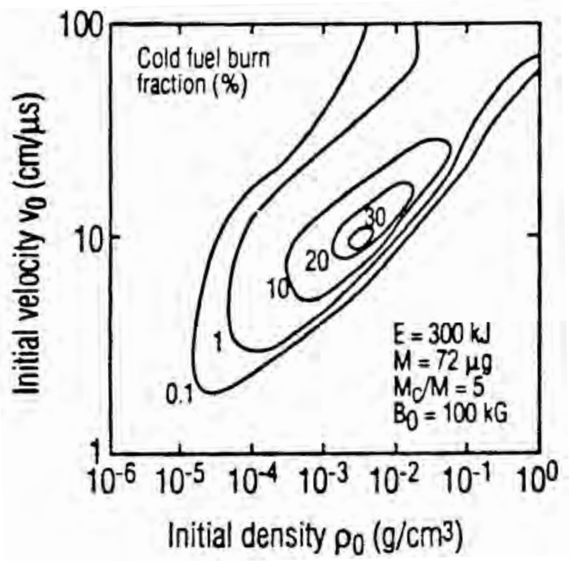


Russian (Kurtmullaev et al, 70s-80s)

A magnetic field can trap alpha particles and enhance self-heating (ignition); a magnetized “hot spot” can ignite “cold fuel” to achieve high gain

- **The parameter BR, rather than ρR, determines the depostion fraction; ignition is possible for very low ρR (Kirkpatrick & Lindemuth, in Current Trends in International Fusion Research, NRC Canada, p. 261, 1999).**

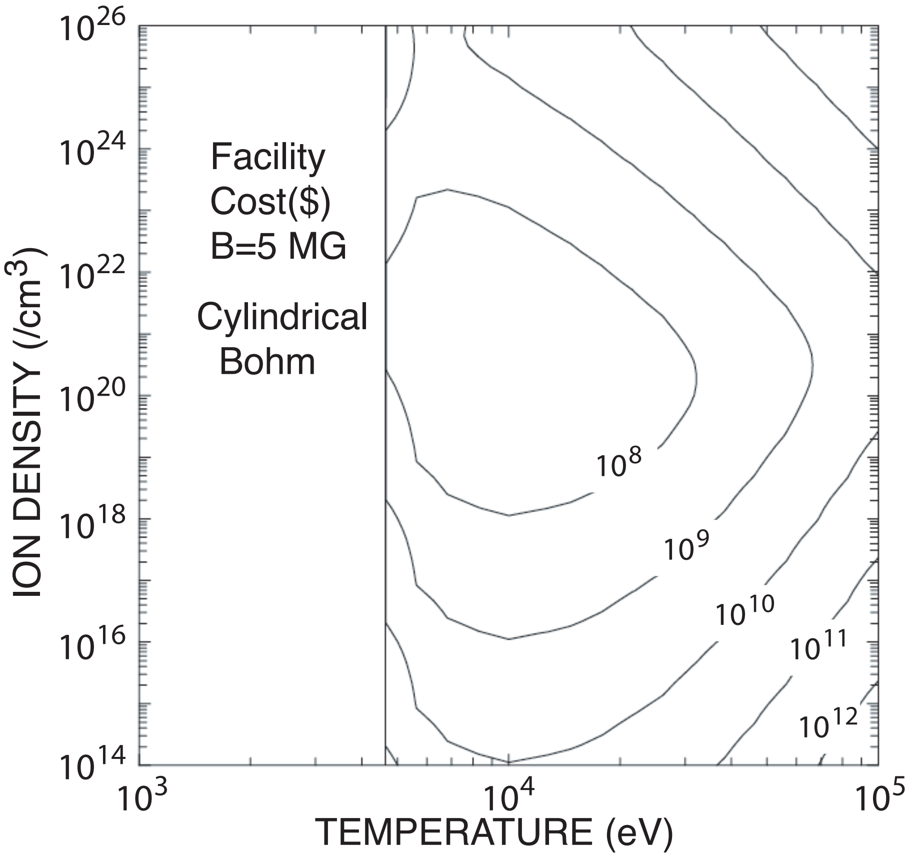




- **An extension of the L-K model showed high gain at low velocity (Lindemuth and Kirkpatrick, Fus. Tech. 20, p. 829, 1991); LASNEX calculations give similar results.**

- **But, the high efficiency of MTF drivers may mean that high gain is not as criticial for magnetized targets.**

But, what if the thermal losses are Bohm-like rather than classical?



- **Computations by Dawson and experiments at Columbia U. suggest that the losses should be classical, but even if the losses are Bohm, there is a large intermediate space where MTF should be lower cost than ICF, MCF**

EDEMO /Pilot plant (20 years)

Electricity generation with reduced mission

Electricity generation

No need real steady state

Burning plasma control

Sufficient T Breeding

As a CTF

H_2 production

Testing tokamak system availability (reliability, buildability, operability and maintainability)

P_{fusion}~200MW, t = a few hours to weeks

16:20 SO2B-3 T. P. Intrator,Tuesday

Based on existing technologies:

Option 1: Pure Fusion

- A FDF-class with SC coils
- A ST-type compact device

Option 2: Fusion –Fission hybrid

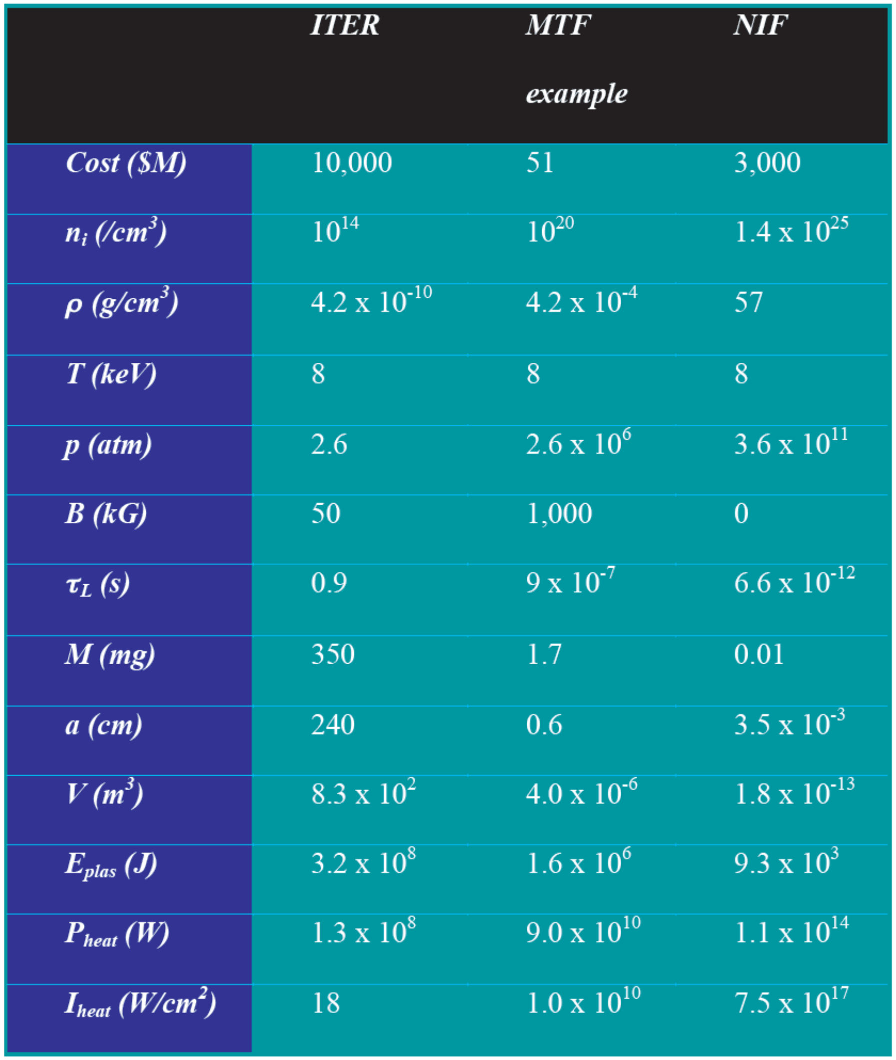
- Fusion: Q=1-3, Pth=50-100MW
- Fission: M= 20-30, Pt = 0.3-1.5GW

Or:

ITER-type machine with different blanket: Pt =5GW, Pe=1.5GW

15:30 SO2B-1 A. Sykes Tuesday

Controlled Fusion is a long-term, expensive proposition--or is it????



	ITER	*MTF* *example*	*NIF*
Cost ($M)	10,000	51	3,000
n_i *(/cm^3)*	10^{14}	10^{20}	1.4×10^{25}
ρ *(g/cm^3)*	4.2×10^{-10}	4.2×10^{-4}	57
T (keV)	8	8	8
p (atm)	2.6	2.6×10^{6}	3.6×10^{11}
B (kG)	50	1,000	0
τ_L *(s)*	0.9	9×10^{-7}	6.6×10^{-12}
M (mg)	350	1.7	0.01
a (cm)	240	0.6	3.5×10^{-3}
V (m^3)	8.3×10^{2}	4.0×10^{-6}	1.8×10^{-13}
E_{plas} *(J)*	3.2×10^{8}	1.6×10^{6}	9.3×10^{3}
P_{heat} *(W)*	1.3×10^{8}	9.0×10^{10}	1.1×10^{14}
I_{heat} *(W/cm^2)*	18	1.0×10^{10}	7.5×10^{17}

- **ICF and MCF differ by 10^{10}--10^{12} in fuel density and time scale and by more than 10^{15} in burning fuel volume. The vast parameter space between these two extremes is unexplored.**
- **MTF can be investigated using machines that already exist (e.g., Atlas $50M).**
- **The low cost and size of experimental facilities should significantly reduce fusion's development time.**
- **Unfortunately, unless the US program adopts a "balanced portfolio" approach, MTF (and other alternate concepts) will never have a chance to reach technical maturity.**