What HIF has to do to compete in coming IFE competition

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4th HIF Skunkworks meeting

LBNL

April 5, 2007

What we said would be required at the June 22 2006 HIF Skunkworks meeting (tall order!):

- **Nuclear fission revival *now in progress* sets a new, tougher standard for economic competitiveness of *any* future fusion development program.**

- **Our HIF development strategy *must* improve from 2002 in order to become competitive; we need an affordable development path to:**

→modular linac drivers with NDC to enable 2-module IRE < $100M

→smaller 100MWe ETF/DEMO @ < 1 MJ @ < $0.5B total cost driver

→demo small, grow large: pathways to ultimate CoE < CoE *fission.*

In just the last 9 months we learn:

- **Our most serious IFE competition may be solid-state DPSSL laser-driven fast ignition: 1 MJ indirect drive for compression + 100 kJ Petawatt igniter with cone→ Gain 200. Liquid vortex FLiBe blanket, target prototype able to be validated on NIF. Early application plan for fusion-fission hybrids. *Major LLNL initiative already underway!***

Cores @ 5 $/kg = $ 12 M (see pg 22 -This would triple for ferrite, but then η_a > 40%)

Switching @ 10^{-6} $/W = $ 21 M
Solenoid coils @ 220 $/kg: $ 33 M
Cost of these three components = $66 M direct -three major components.
Doubling this amount to account for other detailed components left out:
-->total cost ~ $132 M all direct hardware
Multiplying by an RPD- 2.8 factor for assembly and indirect costs,
this small 1 MJ driver would have ~ $ 370 M total driver capital cost< Demo goal
(Fig. 21 compares the RPD, the 2003 modular driver, and this small modular driver)

DEMO: Power output and CoE would depend on rep rate
(see Fig. 3 chamber concept for fast clearing)
Assuming advanced thermal conversion η_{th} ~ 0.5 , gain G= 40 (40 MJ yield/target)
@ 6 Hz : 240 MW fusion, 120 MWe gross, 100 MWe net -->CoE ~ 6 - 8 cts/kWehr
@ 60 Hz: 2400 MW fusion, 1200 MWe gross, 1000 MWe net-->CoE~ 4 - 6 cts/kWehr
(depending on costs per target and Balance of Plant costs). Steam cycle balance of plant costs set asymptotic CoE > 2.7 cts/kWehr. Chambers designed for CFAR MHD plasma conversion could reduce BoP costs 5 X in $/kW for thermal conversion.
(Plasma MHD conversion is another future innovation worthy to work on.)

IRE: One of the 40 driver modules
Assume one-of-a-kind units costs 4 X more than 30-yr n^{th}-of-a-kind RPD unit costs.
One module total capital cost = 4 X 370 / 40 = $37 M IRE, not counting development.
One could add > $60 M additional for IRE supporting development (but not the prior HIF research program) and still meet the IRE goal < $100M.
(Fig. 22 illustrates a one module IRE).

Hyrdogen Plant: Increase number of linac modules to 120--> $ 1.1 B total driver cost
Fig. 3: Gain 130 @ 3 MJ for close-coupled targets--> 400 MJ yield targets.
Increase vortex chamber (like in Fig. 4) 4X in inner radius, 3 X in outer radius to handle 12 GW of average fusion power @ 30 Hz pulse rate -->6 GWe net for electrolysis for hydrogen fuel, and/or air conditioning to cope with global warming.

A May-1-06 systems analysis described three major thrusts for improving HIF:
(1) High gain 1 MJ targets
(2Modular HIF driver development path
(3) Liquid vortex chambers
→might satisfy "Demo-small,-then grow large" desired development path objective for low unit cost electricity & hydrogen fuel production. (See target, chamber and driver updates this mtg.)

Vision: Two additional thrusts to win the competition

- Heavy ion direct drive for potential 4 X increase in coupling efficiency and target gain without fast ignition
- → reduces minimum investment for 100 MWe DEMO
- → also enables the next thrust for efficient plasma MHD direct conversion for low Balance of Plant cost.

- T-lean targets with reasonable size (< 3 MJ) drivers for

(a) 30 times more available neutrons per fusion watt compared to DT for fissile fuel production, and or

(b) more efficient capture > 90% of fusion yield for plasma direct conversion for low cost electricity and hydrogen production.

Interfacing with the nuclear fission renaissance underway: beat them (CoE) or join them (hybrids) is not a choice.

- Sequence of fission → affordable fusion is compelled if fraction of GDP for energy is to be constrained for economic development.
- Global warming impacts (on water and food) are now inevitable. Consequent misery to Earth's coming 10 billion population is not inevitable but can be mitigated with large growth in fission energy over the time it will necessarily take to develop reliable fusion.
- Uranium ore / fission breeder cost may become a fission fuel cost issue for the last decades of final transition from fission to fusion.

→The fusion strategy has to be (*after* fusion reliability DEMO):

first join them: be prepared to provide extra neutrons for fissile breeding ASAP if fission fuel cost becomes an economic burden on society;

then beat them: ultimate Cost-of-Electricity lower than fission due to (a) lower fuel cost, plus (b) low cost direct conversion.

We are re-visiting T-lean targets from 10 years ago: this time in the context for heavy-ion direct drive

(Clips from a recent MathCAD document sent around)

T-lean fuel assemblies for MHD direct conversion

Develop and benchmark MCAD model based on Tabak's Case C run[1] for isobaric hot spot ignition (see Fig. 1) with his f = 0.1 tritium parameter (to maximize non-neutron yield for direct conversion with ηG_f>100 for low recirculating power)

TABAK

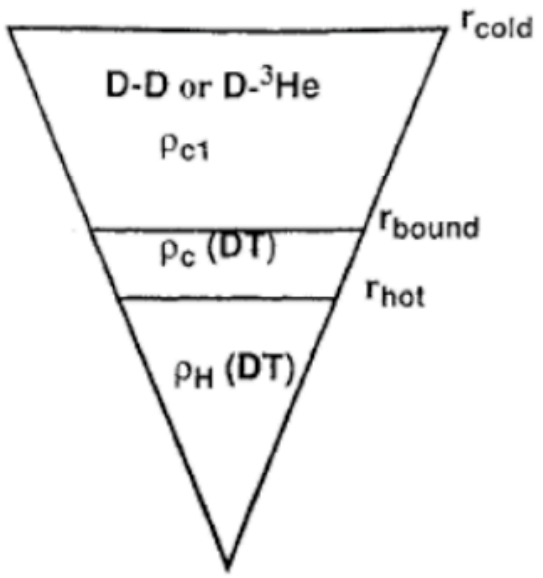


FIG. 1. Pie diagram of compressed core.

[1] Max Tabak, Nuc. Fusion 36, No2 (1996). Calculates DD burn assuming 10 keV initial DT hot spot. (If needed, a late shock (Betti- Perkins) could be applied to insure ignition at lower implosion velocities and at lower adiabats, say α=1.5 instead of at α=2 as Max assumed). We assume DD main fuel instead of D-^{3}He for reasons Max stated.

Fuel assembly energy (variable) (MJ)

Min tritium loading parameter for ηG>100

$ORIGIN := 1$

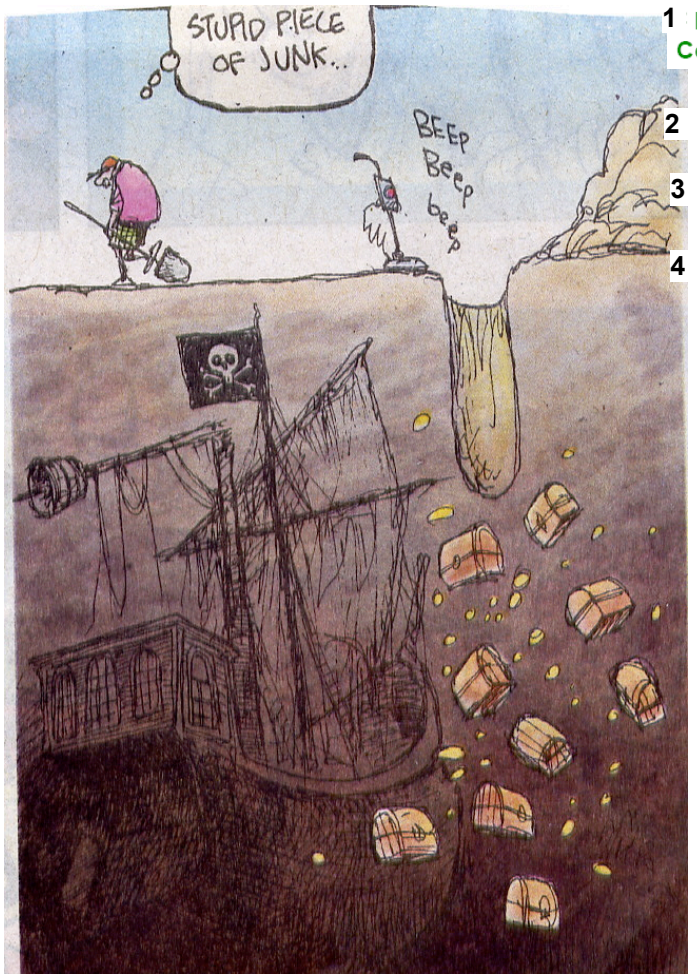
For $i := 1 .. 7$ $Ef_i := 0.05 + 0.05 \cdot i^2$ fuel energy cases

$f := 0.1$ $r_{bound}(r_{hot}) := r_{hot} \cdot (1 + 2 \cdot f)$ DT radius

$\zeta := 1 - (1 + 2 \cdot f)^{-3}$ DT load parameter

Use Max's formulary[1] for fuel assemblies optimizing gain for given fuel energies:

Grant Logan, Max Tabak, Stefano Atzeni and John Perkins have been searching a decade for a self-T breeding target with direct conversion potential* to make fusion truly unique…



1 B. Grant Logan "Inertial fusion reactors using Compact Fusion Advanced Rankine (CFARII) MHD Conversion" Fusion Engineering and Design 22, 151 (1993)

2 Max Tabak, Nuc. Fusion 36, No2 (1996).

3 Atzeni and Ciampi Nuc. Fusion 37, 1665 (1997)

4 L. John Perkins "Advanced LASNEX model Advanced fuel IFE" LLNL (1998) unpublished?

* Mission-Impossible Quest? Yes, but very good company!

We all got discouraged when we estimated that large energy drivers > 10 MJ might be required, and associated large fusion yields > 1 GJ….

…so we mostly stopped working on this the last several years…..

…until Max and I vowed to go back and dig deeper on this quest in this new series of Skunkworks meetings!

T-lean fuel assembly parameters with MCAD model of Tabak's Case C isobaric ignition calculations (adiabat =2)

Fuel energy	Deuterium density	Hot spot DT radius	Outer-D radius	D-Mass load	T-Mass load	Rho-r total	D-burn fraction	T-burn fraction	Fusion yield
$Ef_i =$	$\rho_{cdd}(2, Ef_i)$	$\frac{r_{hdt}(Ef_i)}{10^{-4}} =$	$\frac{r_{cdd}(Ef_i)}{10^{-4}}$	$\frac{M_d(2, Ef_i)}{10^{-3}}$	$\frac{M_t(2, Ef_i)}{10^{-3}}$	$= \rho r(2, Ef_i)$	$f_{bd}(2, Ef_i)$	$f_{bt}(2, Ef_i)$	$Y_f(2, Ef_i)$
0.1	1106	20	64	1.2	0.02	5.4	0.025	0.412	11
0.25	840	32	102	3.6	0.07	6.4	0.036	0.42	40
0.5	682	45	144	8.3	0.16	7.3	0.048	0.427	111
0.85	582	58	188	15.6	0.29	8.1	0.059	0.432	245
1.3	512	72	232	26	0.49	8.8	0.069	0.436	466
1.85	461	86	277	39.7	0.74	9.4	0.08	0.439	798
2.5	421	100	322	56.9	1.05	10	0.089	0.442	1268
(MJ)	(g/cm^3)	(μm)	(μm)	(mg)	(mg)	(g/cm^2)			(MJ)

All these cases contain a minimum Tritium atom fraction of 1.3 % needed for self sufficient T-breeding with D(d,p)T reactions

Internal (fuel) energy gains G_f versus energy of assembled fuel at igntion time (overall gain= $\eta_c G_f$)

M.Tabak results[1] for fuel gain G_{mt} for his Case C:

$Gmt_1 := 105$ $Gmt_2 := 160$ $Gmt_3 := 230$ $Gmt_4 := 295$

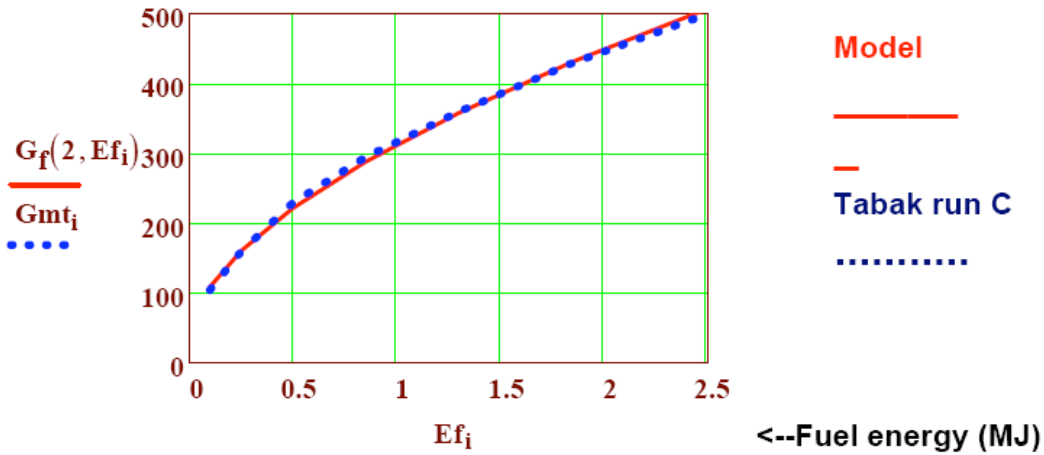
$Gmt_5 := 360$ $Gmt_6 := 430$ $Gmt_7 := 500$

$G_f(\alpha, E_f) := Y_f(\alpha, E_f) \cdot E_f^{-1}$ Eq 12

i =	Ef_i =	$G_f(2, Ef_i)$ =
1	0.1	109
2	0.25	161
3	0.5	222
4	0.85	288
5	1.3	358
6	1.85	431
7	2.5	507

Fig 2 shows the model and the Case C runs agree well. (good enuf for government work).

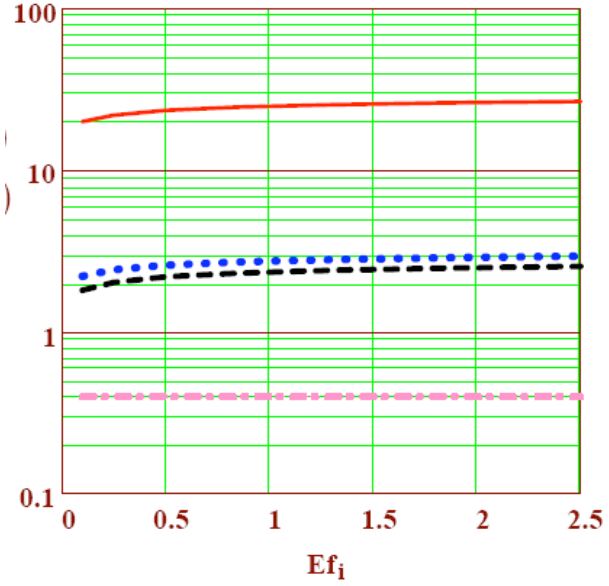
Fig. 2: Fuel gain G_f (model) and in Tabak's Case C vs. fuel energy E_f



Next lets consider T-breeding:

Predictions of the model for neutron production

Fuel energy	Initial T mass	T-mass bred	T-mass consumed	Net T--Mass produnced	Neutrons per T burned
$Ef_i =$	$\frac{M_t(2, Ef_i)}{10^{-3}} =$	$\frac{M_{tb}(2, Ef_i)}{10^{-3}} =$	$\frac{M_{tc}(2, Ef_i)}{10^{-3}} =$	$\frac{M_{tn}(2, Ef_i)}{10^{-3}} =$	$N_{ndd}(2, Ef_i) =$
0.1	0.02	0.01	0.01	-0.0035	1.8
0.25	0.07	0.05	0.05	-0.0022	2
0.5	0.16	0.14	0.13	0.014	2.2
0.85	0.29	0.33	0.27	0.0606	2.3
1.3	0.49	0.65	0.49	0.1547	2.4
1.85	0.74	1.14	0.82	0.314	2.5
2.5	1.05	1.83	1.27	0.5572	2.6
(MJ)	(mg)	(mg)	(mg)	(mg)	



Ratio of available neutrons per MeV yield (ratio of T-lean case over the pure DT case)

neutons produced per T burned

in-situ neutrons per T burned (T-lean cases)

neutrons available per T burned (DT case)

<--Fuel energy (MJ)

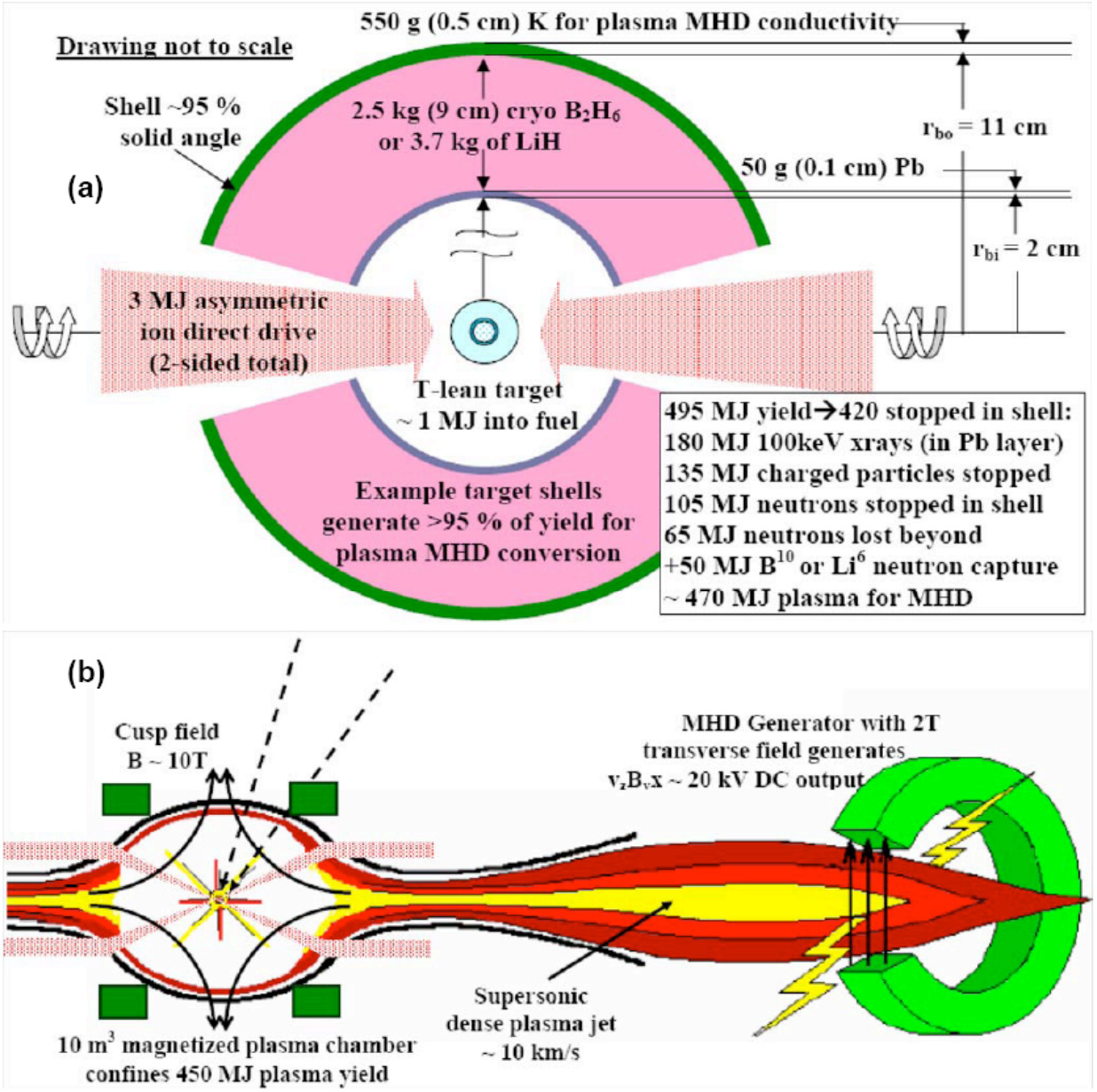


Figure 4: (a) Example target shell for efficient conversion of T-lean target output into 1 to 2 eV dense plasma for direct MHD conversion. All shell materials condense and recycle (Rankine cycle).
(b) Schematic of the CFAR MHD scheme (adapting the old 1992 CFAR Logo!)--no detailed design yet.

Power plant example with 1 MJ T-lean fuel assembly (3 MJ driver).

Note some key facts about the marriage of T-lean targets to CFAR energy conversion:
(1) A 10 T cusp field on a 2-m vessel/coil radius with a protective 0.6 m-thick Flibe vortex layer inside aids final focusing of ion beams and prevents large shocks to the vessel wall with large yields. The plasma created from the T-lean target shell is conductive enough for the field to confine the 470 MJ plasma until drained out through the MHD generators in ~50 ms. Unlike CFAR ref, we assume here < 50 % duty factor for MHD generation to allow the chamber pressure to drop to low values for target insertion. 65 MJ of neutrons+ 15 MJ of x-rays not stopped in the target shell act like a small 80 MJ yield in the 10 m3 Flibe vortex pocket.
(2) Because plasma conductivity is 105 times greater at 25,000 K than at 2500 K, the extractable MHD conversion power density ~σu2, where u~10km/s is the plasma jet velocity, is >30 times the power density of steam turbine generators. As a consequence, the CFAR BoP cost can be much lower, < $ 80 M/ GWe.

Large T-lean column densities (ρr ~ 10 g/cm^2) stop a significant fraction of the neutrons, and a small target shell can capture most of the rest for plasma production useful for MHD direct conversion

Table 5 blanket radius & loss -yield ration vs fuel energy

Ef_i =	$\rho r(2, Ef_i)$	$Y_f(2, Ef_i)$	$r_{bo}(2, Ef_i)$	$FY_{nb}(2, Ef_i)$ =
0.1	5.4	11	3.6	0.37
0.25	6.4	40	5.6	0.28
0.5	7.3	111	7.8	0.21
0.85	8.1	245	10.1	0.17
1.3	8.8	466	12.6	0.13
1.85	9.4	798	15	0.1
2.5	10	1268	17.5	0.08
MJ	g/cm^2	MJ	cm	

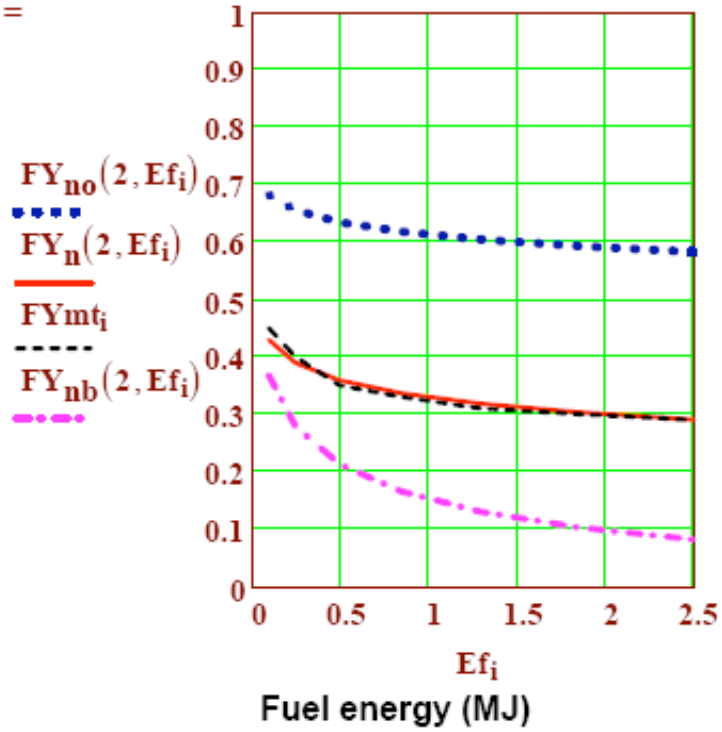


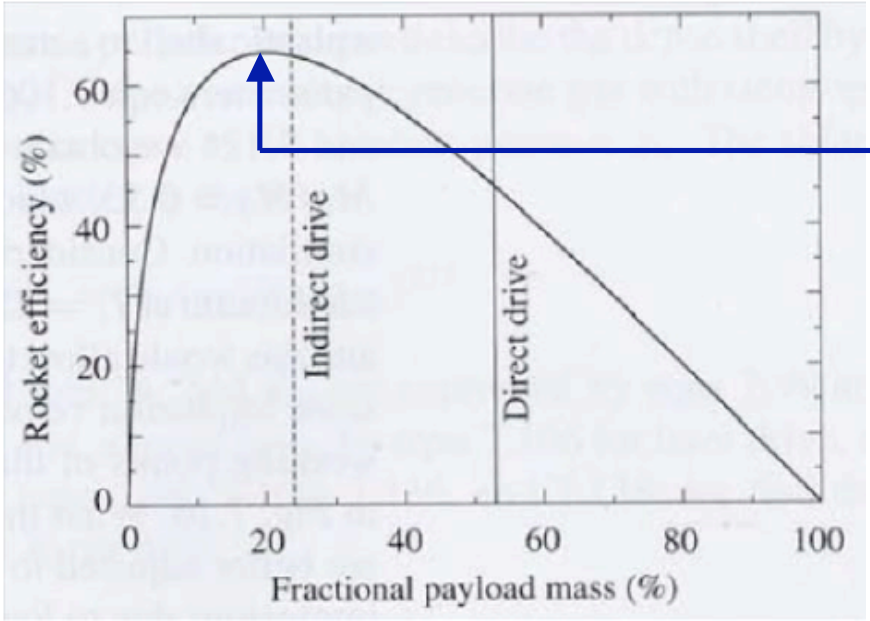
Figure 6. Fraction of total T-lean target yield escaping target and shell as neutrons as a function of fuel energy E_f (adiabat α=2). The model (solid red curve), and Max Tabak's case C runs agree well and show signficant reduction of lost neutron energy below the un-attenuated neutron yield (blue dotted line) within the large ρr of T-lean targets. The shell captures ~ 50% of remaining neutron energy escaping the target (depending on the fuel ρr- see dashed magenta curve for FY_{nb}).

Page 8

Pure hydrogen ablators can be ideal for heavy-ion direct drive enabling high coupling efficiencies for T-lean targets

Rocket efficiency and implosion efficiency with pure H2 ablators. We assume a pure hydrogen ablator for ion beam direct drive because hydrogen provides the highest exhaust velocity for ablative drive for a given specific energy deposition by short range ions. Working backwards, we will estimate specific ion beam requirements at the end. We assume thin coatings between the DT, DD, and H ablator layers such that the hot spot decay heat gives equilbrium temperatures of 19-->14-->10 deg K for these layers respectively. The DT layer would be filled through the hydrogen layer by a thin fill tube.

Figure 7: the classic spherical rocket efficiency η_r as a function of the fractional payload mass



Initial hydrogen ablator mass $M_{ho} = 4\ M_{do} + M_{to}$

An issue is managing space charge in accelerators delivering the energy with short enough range ions to avoid too much ablation. Another factor can be ionization energy losses which reduce the capsule hydro efficiency η_c below the rocket efficiency η_c. However, since pure hydrogen has a small ionization energy of 13.6 eV per atom, we don't worry about the latter so much. So, from Fig. 7, we choose to drive at the peak rocket efficiency

$\eta_r := 0.65$

“Best possible” coupling efficiencies for ion direct drive could be 4 x laser direct drive, enough to make large T-lean targets with reasonable driver energies < 3 MJ.

The ion direct drive capsule implosion efficiency and target gain vs fuel energy. Results are summarized in Table 6.

$$\eta_c(\alpha, E_f) := E_f \cdot E_d(\alpha, E_f)^{-1} \qquad \text{Eq. 44}$$

$$G_t(\alpha, E_f) := \eta_c(\alpha, E_f) \cdot G_f(\alpha, E_f)$$

Table 6: T-lean implosion efficiency and gain vs fuel energy.

$Ef_i =$	$E_d(1.5, Ef_i)$	$\eta_c(1.5, Ef_i) =$	$G_t(1.5, Ef_i) =$	$u_{imp}(1.5, Ef_i)$	$u_{ex}(1.5, Ef_i)$	$T_{ex}(1.5, Ef_i)$	$r_a(1.5, Ef_i) =$	
0.1	0.24	0.41	65	$3.7 \cdot 10^7$	$2.3 \cdot 10^7$	41	0.28	
0.25	0.62	0.404	98	$3.4 \cdot 10^7$	$2.1 \cdot 10^7$	35	0.41	
0.5	1.26	0.398	136	$3.2 \cdot 10^7$	$2 \cdot 10^7$	30	0.54	<--DEMO
0.85	2.16	0.393	178	$3 \cdot 10^7$	$1.9 \cdot 10^7$	27	0.66	
1.3	3.34	0.389	222	$2.9 \cdot 10^7$	$1.8 \cdot 10^7$	25	0.78	<--Power Plant
1.85	4.79	0.386	267	$2.8 \cdot 10^7$	$1.7 \cdot 10^7$	23	0.9	
2.5	6.53	0.383	314	$2.7 \cdot 10^7$	$1.7 \cdot 10^7$	22	1.02	
MJ	MJ			cm/s	cm/s	eV	cm!	

Current work is focusing on ion energy/range vs time for shaped pulses such that (a) low adiabat α<1.5 can be achieved while (b) keeping the specific beam energy deposition and ablator exhaust velocity close to the above idea values. We know that strongly rising ion energy and range during the shaped pulse will be required. Ed Lee has a concept allowing for an order of magnitude variation of ion range during the pulse.

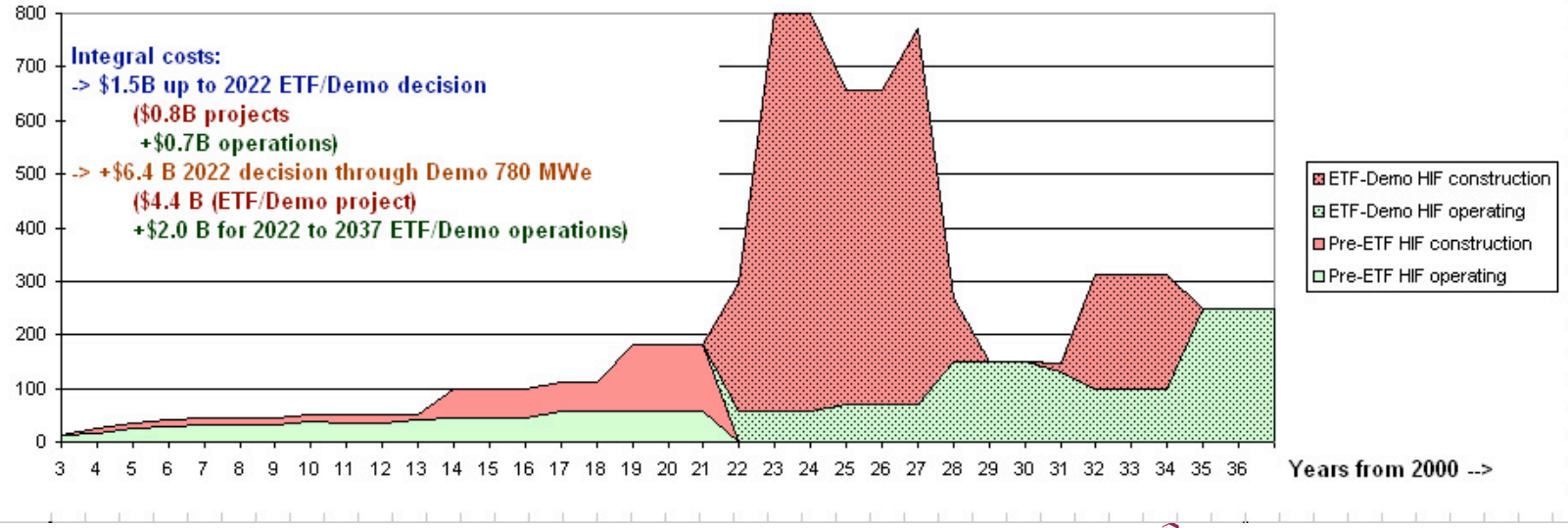
Backup slides

Competition forces us to improve our 2002 HIF development path

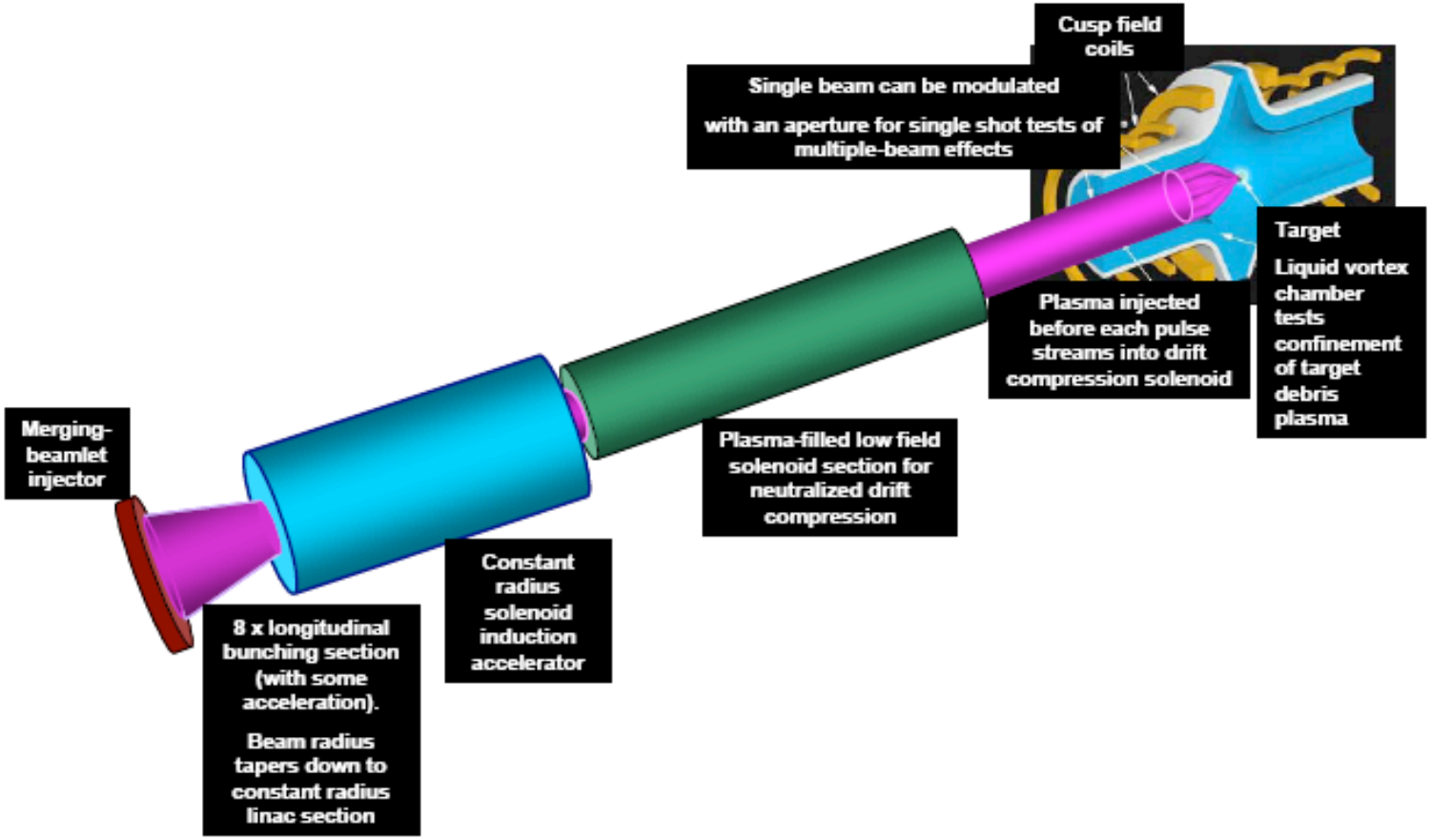
Years - 2000	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
National ignition facility																																														
HIF (Pre-ETF)																																														
Integrated beam experiment																																													
Z ablation/target exps																																													
HIF-IRE accelerator / focus																																													
Hydraulics integ. test facility																																													
Flibe integ. loop test facility																																													
Flibe chamber test facility																																													
IFE target test facility																																													
ETF / Demo (if HIF selected)																																													
HIF-ETF driver / target tests																																													
Integrated chamber expts.																																													
Fusion power technology																																													
Demo commerical potential																																													
Supporting HIF Program																																													
Key																																													

- National ignition facility: HIF-relevant indirect-drive target physics
- HIF (Pre-ETF): ^Indirect-drive ignition
- Integrated beam experiment: 5 MeV; Integrated compression and focusing; [$70 M]
- Z ablation/target exps: ^Source-to-target beam physics
- HIF-IRE accelerator / focus: 450 MeV; Focusing + 1/4 scale target exps; [$300 M, including 30 M R&D + 30 M chamber/target system]
- Hydraulics integ. test facility: HIF-specific; 1/4 scale hydraulics/clearing rate tests; [$10 M]
- Flibe integ. loop test facility: Generic, 1/2 HIF; Flow/chemistry; ^ Accelerator validation; [$6 M / 2]
- Flibe chamber test facility: Generic, 1/2HIF; Vapor/plasma condensation; [$6 M / 2]
- IFE target test facility: Generic, 1/4 HIF; target sys R&D; Indirect drive target fab/injection tests; [$40 M / 4]
- ETF / Demo (if HIF selected): ^Liquid chamber and HIF target validation
- HIF-ETF driver / target tests: 5.5 MJ induction linac driver and target testing; 4 GeV; Target gain (0 to 280 MJ); [$2.64 driver+.35 bldgs+.26 target = $3.25 B)
- Integrated chamber expts.: "Cold" (no-yield) Flibe chamber and injection testing; No-yield chamber exps; [$ 0.53 B]
- Fusion power technology: Low fusion power (450MWf) accelerated chamber testing; | Low power testing @ 50 MJ; [$ 0.26 B]
- Demo commerical potential: Demonstrate economic and environmental potential; ^ETF/Demo decision; add BoP; 450 MWf-->1.8 GWf power demo; [$ 0.71 B]
- ^HIF-high-gain; ^DEMO power >780 MWe
- Supporting HIF Program: Target design/fab/injection,HIF target physics on Z&NIF, small beam experiments, theory/simulation, chamber dynamics, enabling lower cost/innovative technology
- Key: Design and R&D; Construction; Operation; Program; ^Key decision points; [Facility costs-TPC, in 02$]

Total annual HIF program cost including facility constructions- based on RPD multi-beam MQ linac, q/A =1/200



This IRE example with NDC could be one of the 40 driver linac modules, delivering 5 programmable pulses delivering a total of 25 kJ of 500 to 600 MeV Argon ions, with up to 12 TW of peak beam power for beam-target radiator tests and vortex chamber dynamics experiments.



Not shown in this IRE drawing is a fast ramping kicker needed for time-dependent focusing corrections for < 1 mm spot target experiments. Ed Lee has an NDCX-II kicker concept that could apply here.

Ed Lee is working on NDC focusing schemes offering dramatically smaller driver/chamber interfaces with 20 beams/end @ 3-5 pulses = 120 to 200 bunches for target pulse shaping. *5X higher peak beam power enabled.*

RPD multi-beam vacuum quadrupole final focus arrays dwarf HYLIFE chamber. Demo version needed 5.5 MJ ETF/DEMO chamber for 280 MJ yield =88% of RPD.

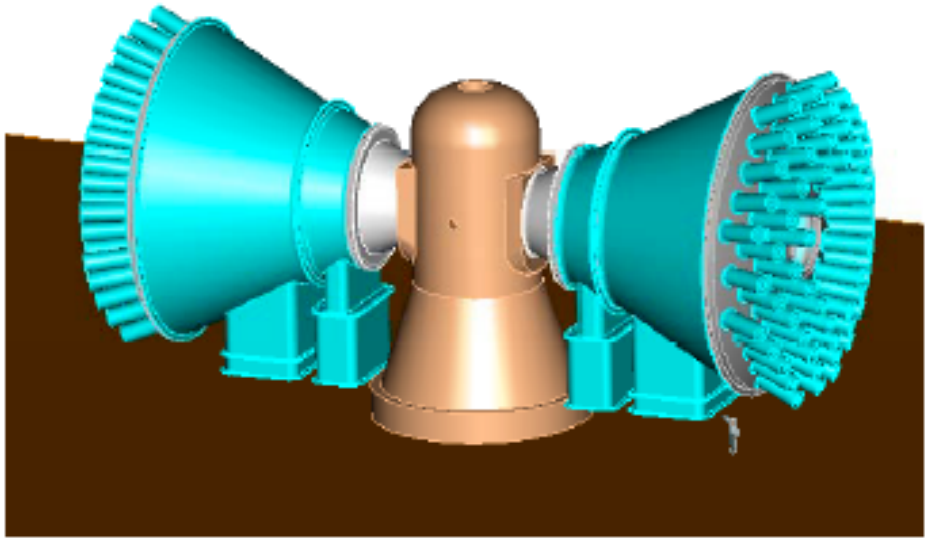
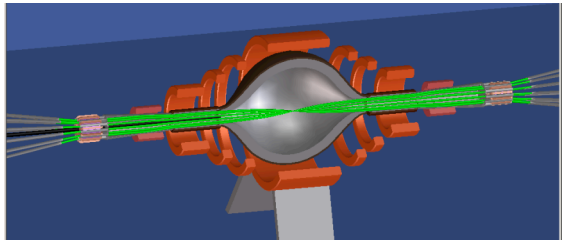


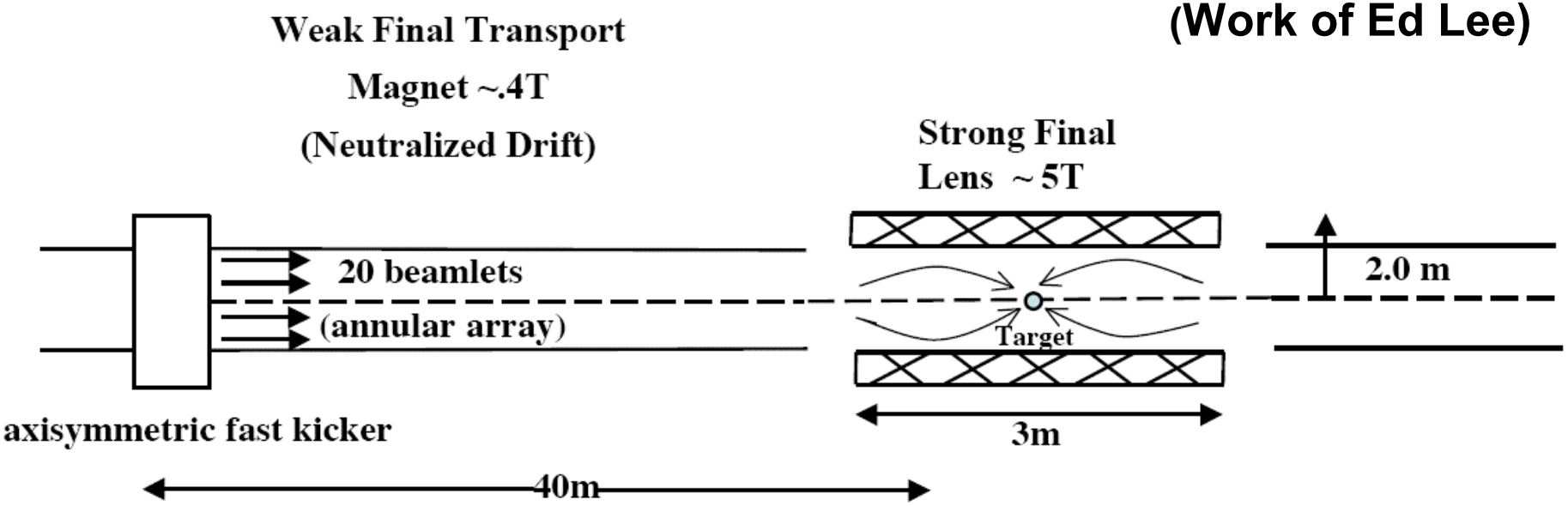
Fig. 3. An isometric view illustrating the coupling of final focus magnet array with the chamber.

Can we find target solutions for 1 to 2 MJ driver energy with 40 MJ yields for HIF DEMO exploiting new pulse shaping capability with NDC, and can we develop 10 to 20 Hz pulse rate vortex chambers with < 10 cent targets for economical DEMO net electricity?



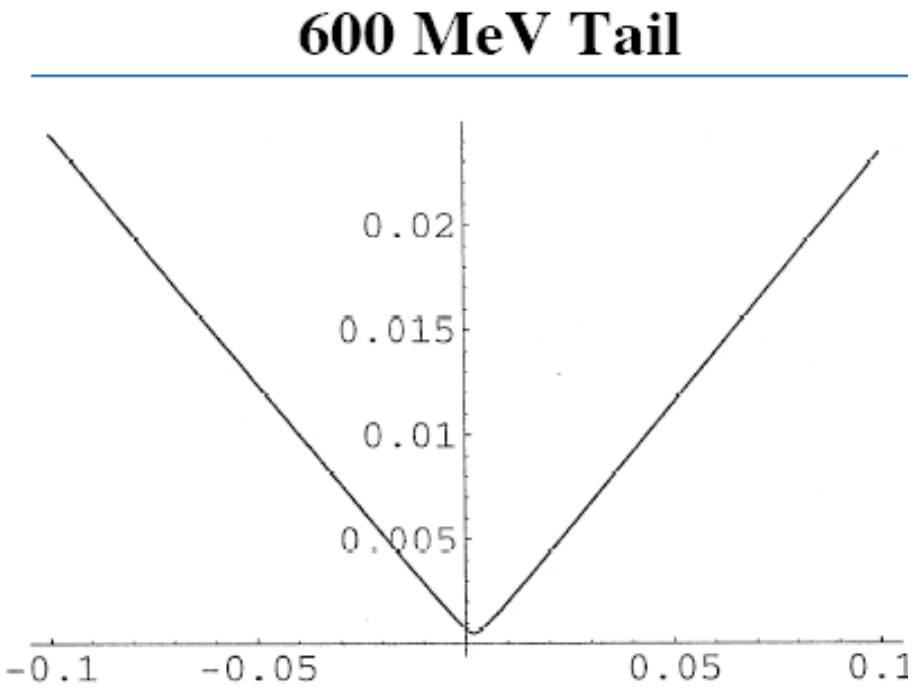
A Solenoid Final Focus System Can Accommodate A Broad Range of Kinetic Energies

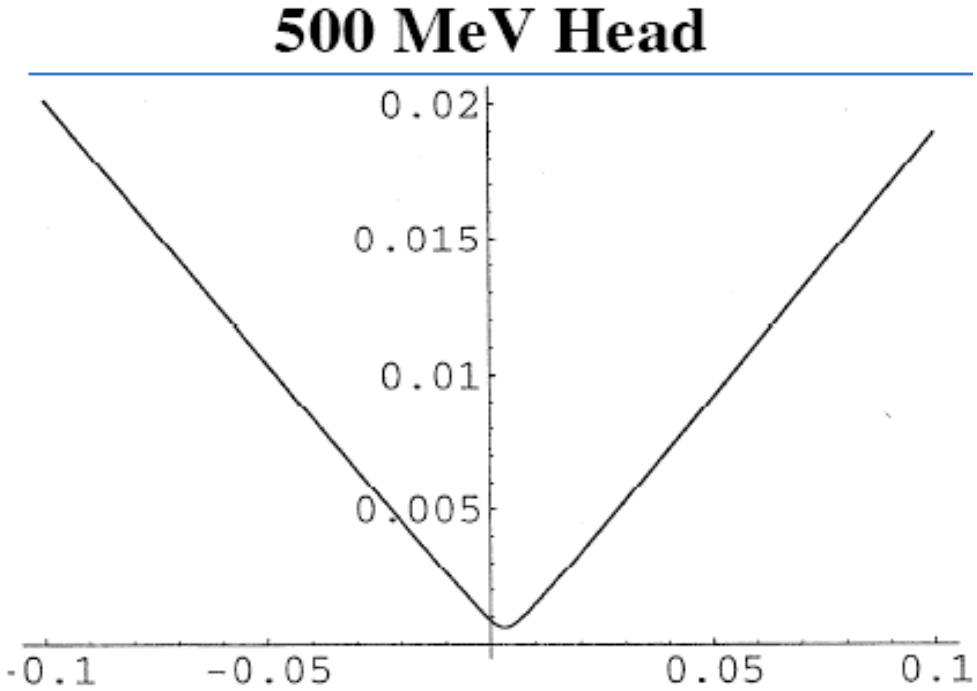
(Work of Ed Lee)



- Beam Head (500MeV) is given a parallel "to" point focus to the target
- Beam Tail (600MeV) is given an inwards kick of 27mr to compensate increased focal length
- Spot radii ≈.75mm are achieved with $\varepsilon_n = 1.0x10^{-6}\mathrm{m-r}$ and initial beamlet radii of 2.0cm

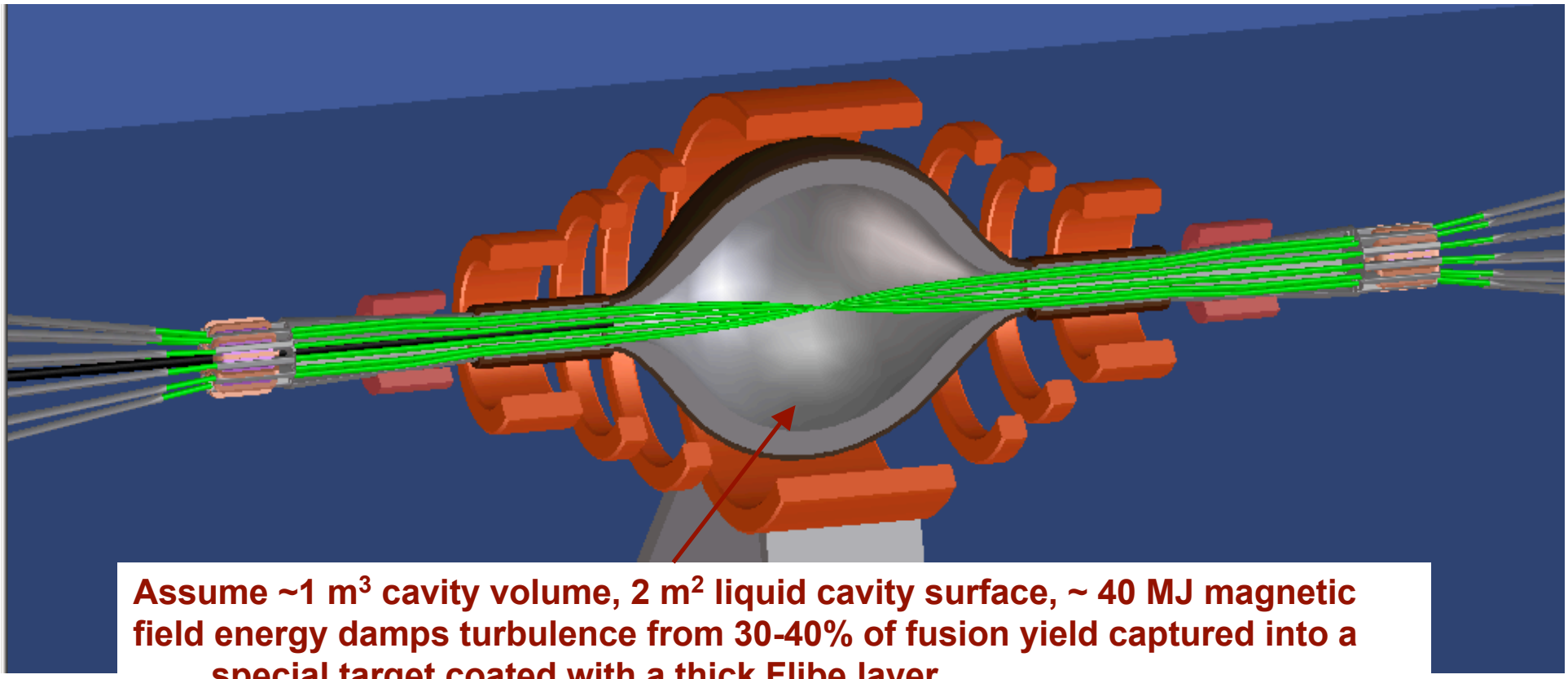
Absent space charge within background plasma, Ed Lee's Mathematica model for axisymmetric vortex chamber magnetic fields including aberrations shows sub-millimeter spots for Ar^{+8}



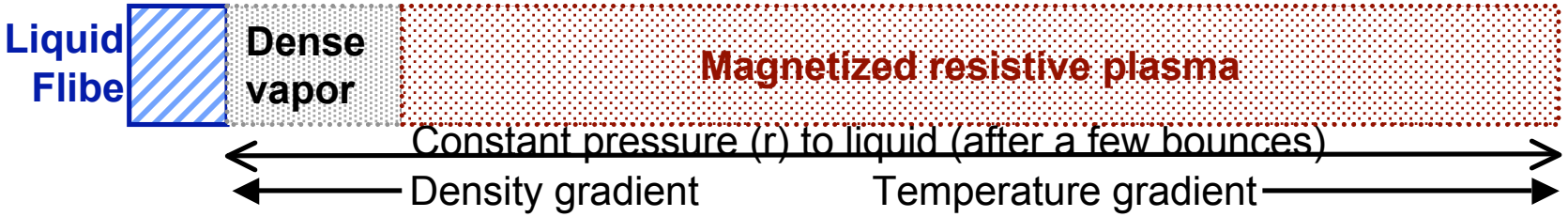


Assumes 10% upstream coherent velocity ramps for compression, and a transverse normalized emittance of 1 mm-mr.

Serendipity: with special overcoated hohlraum targets, the new magnetized vortex chamber is ideal to confine target plasma well enough to neutralize the beam on subsequent shots (even after 20x decay)



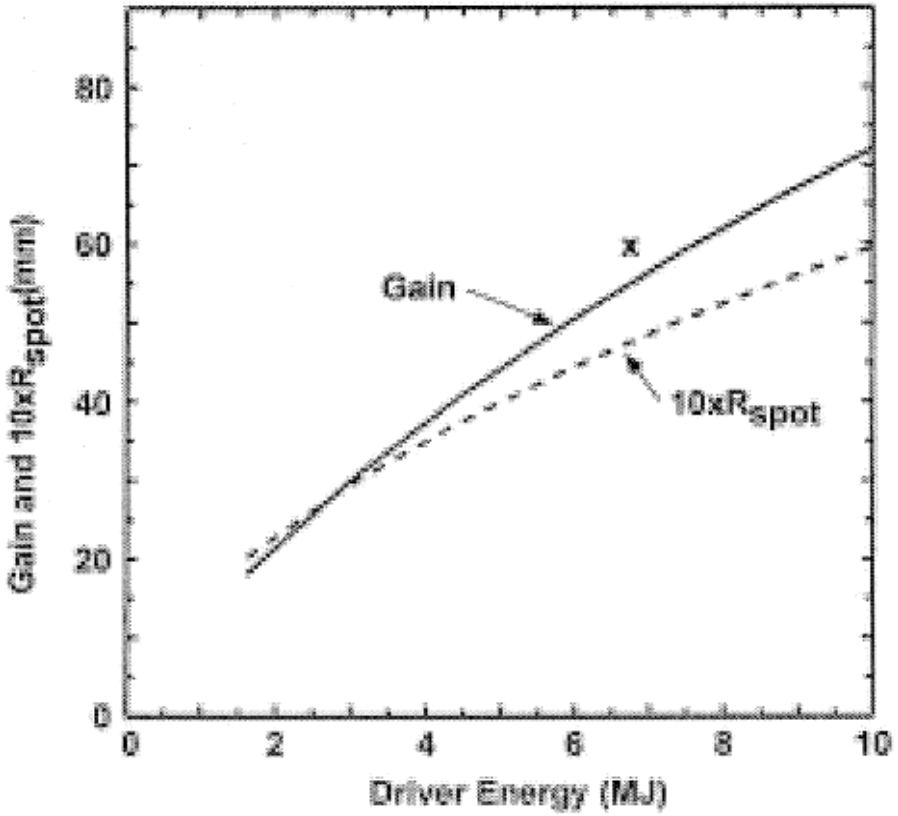
Assume ~1 m^3 cavity volume, 2 m^2 liquid cavity surface, ~ 40 MJ magnetic field energy damps turbulence from 30-40% of fusion yield captured into a special target coated with a thick Flibe layer

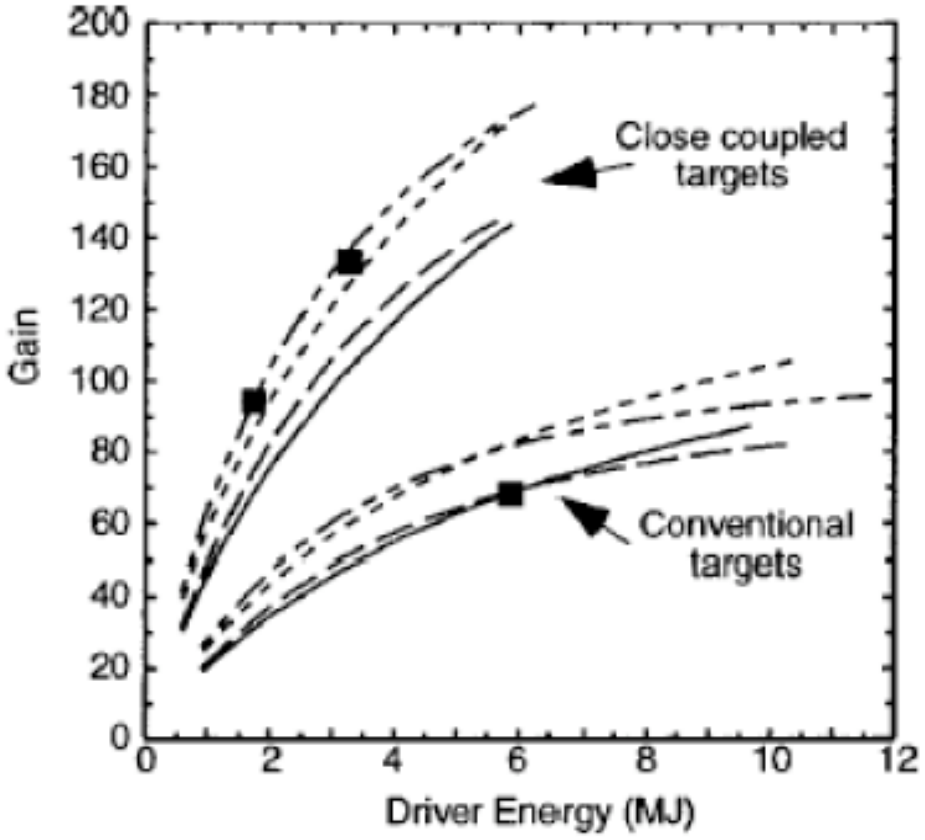


Can we find a better compromise for small DEMO target spot size and gain at 1.5 MJ between scaled down close-coupled and hybrid?

Phys. Plasmas, Vol. 7, No. 5, May 2000

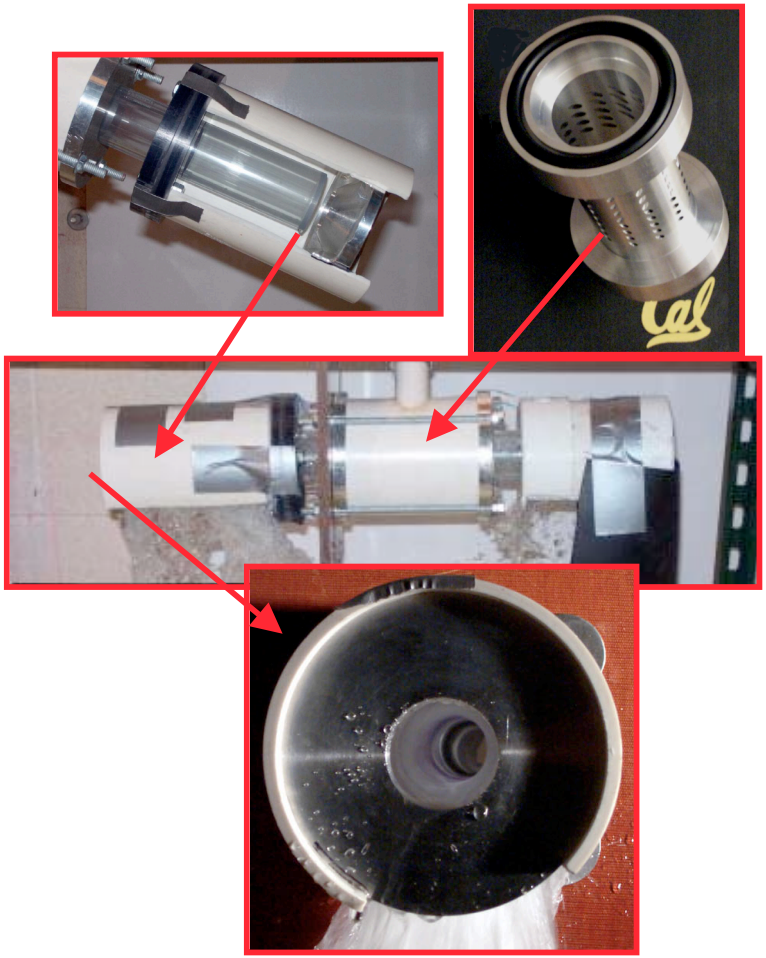
Callahan's HIF04 NIMA paper for HYBRID



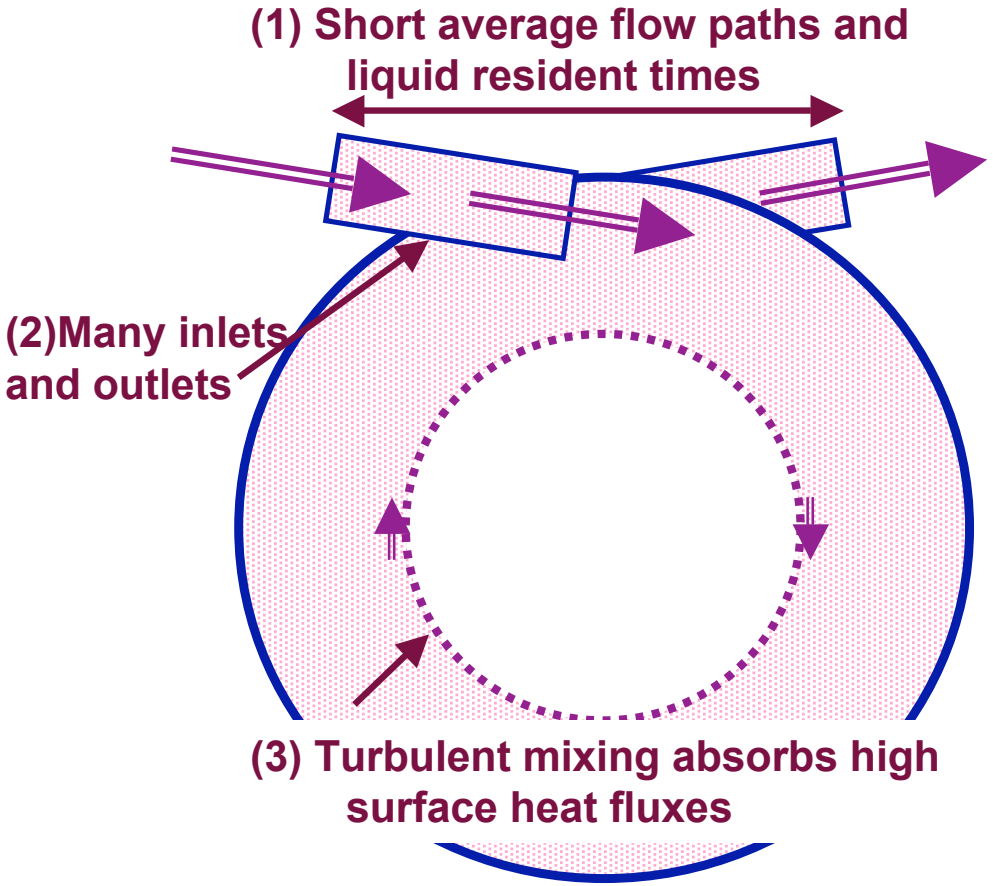


Can we morph a target between the above two types at 1.5 MJ, To obtain a gain 40 @ 1 mm spot size?

Development of liquid protected chambers can be done with modest budgets using scaled, hydrodynamically-equivalent water flows. Vortex=potential high pulse rates?



UCB experiments



Given fast (<1 to 10 ms) plasma clearing of cavity: (1)+(2)+(3) = ***very high potential chamber thermal power densities***

Quest for ultimate low CoE

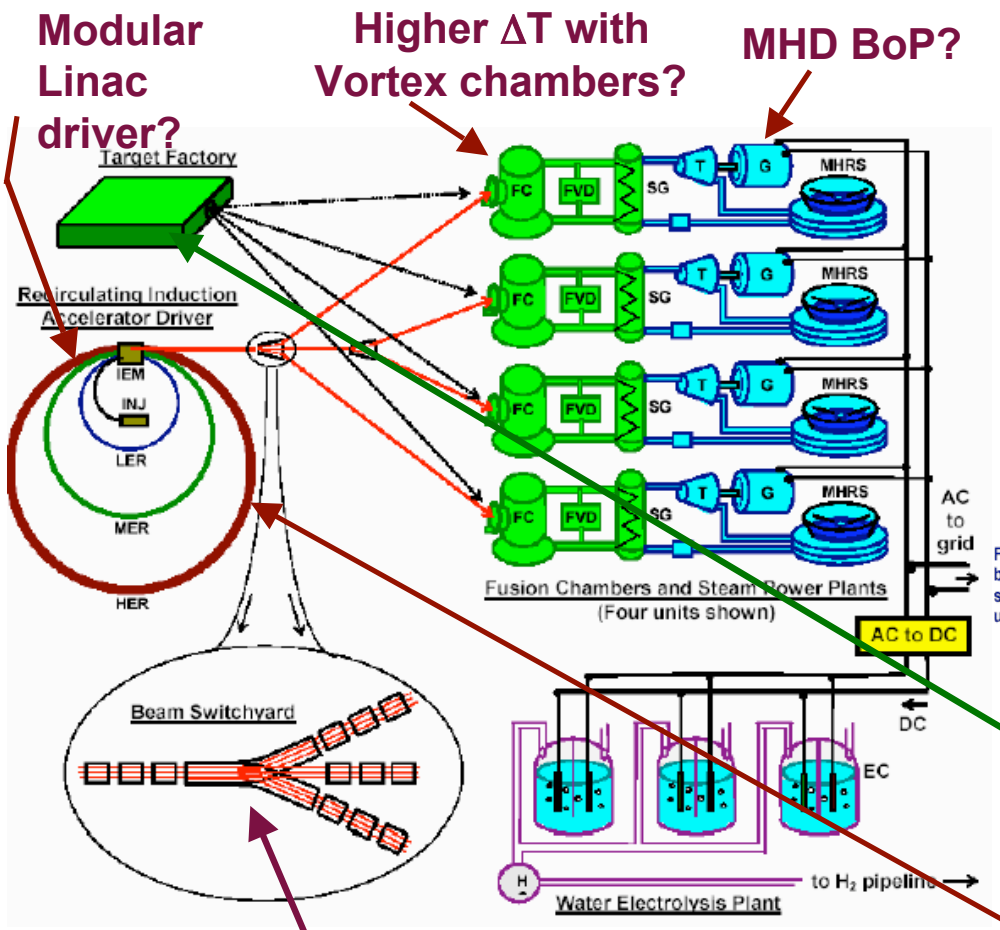
We have three hopes for ultimate HIF CoE < CoE fission

- **Beam switching into many cheap, thick-liquid chambers**
  (Logan, Moir, Hoffman " Fusion Tech. 1995 "Requirements for low cost electricity and hydrogen fuel production from multi-unit inertial fusion plants withed a shared driver and target factory" shows this approach beating multi-unit fission CoE above ~4 GWe total plant outputs, for drivers < $1.2B total capital cost (~<$500M direct)

- **Fast clearing vortex chambers supporting > 20 Hz pulse rates for > 5 GWe outputs, with < $0.5B total capital cost driver and < 10ct targets**

- **Exploit unique, low cost direct conversion, e.g., CFAR-II MHD**

At large enough plant outputs, cheap enough (drivers, liquid chambers and targets), ultimate fusion CoE can beat future fission CoE *because of lower fuel costs*.



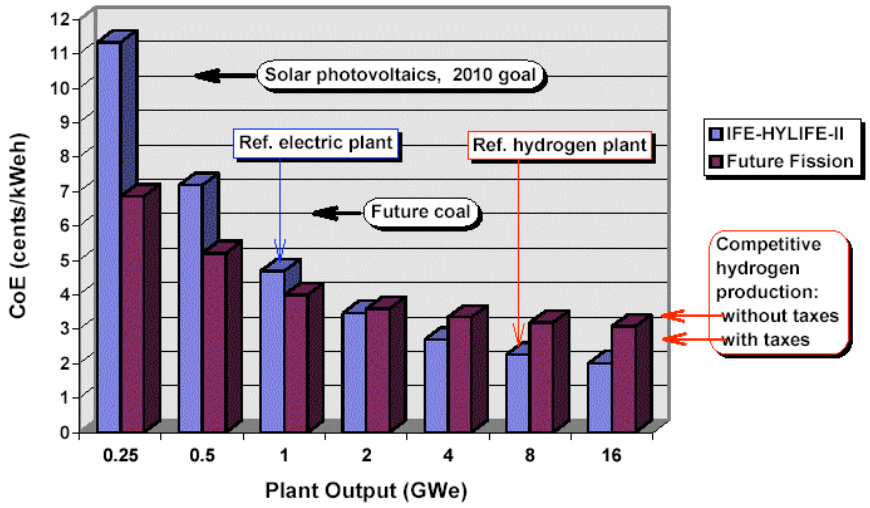


Fig. 12: The economy-of-scale variation of cost of electricity as a function of plant output, comparing inertial fusion energy based on HYLIFE-II (IFE-HYLIFE-II) and future fission plants (based on model in Eqs. 21 and 22). The fission cases assume single units up to 1 GW_e, then multiple- 1 GW_e units for outputs above 1 GW_e. The IFE-HYLIFE-II cases assume multiple 2 GW, units for outputs above 2 GW_e. Typical oil refinery outputs are equivalent to hydrogen electrolysis plants of 8 to 16 GW_e output.

John Woodworth's target factory model shows cost/target continuing to drop with very high production rates

Latest modular solenoid drivers with NDC might cost less than $500M direct @ 3 MJ

→requires solution to "1000-spaghetti-beamines" switchyard problem!

(2) HIF chambers for small fusion yields, >50 Hz, and <1 meter final focus lengths.

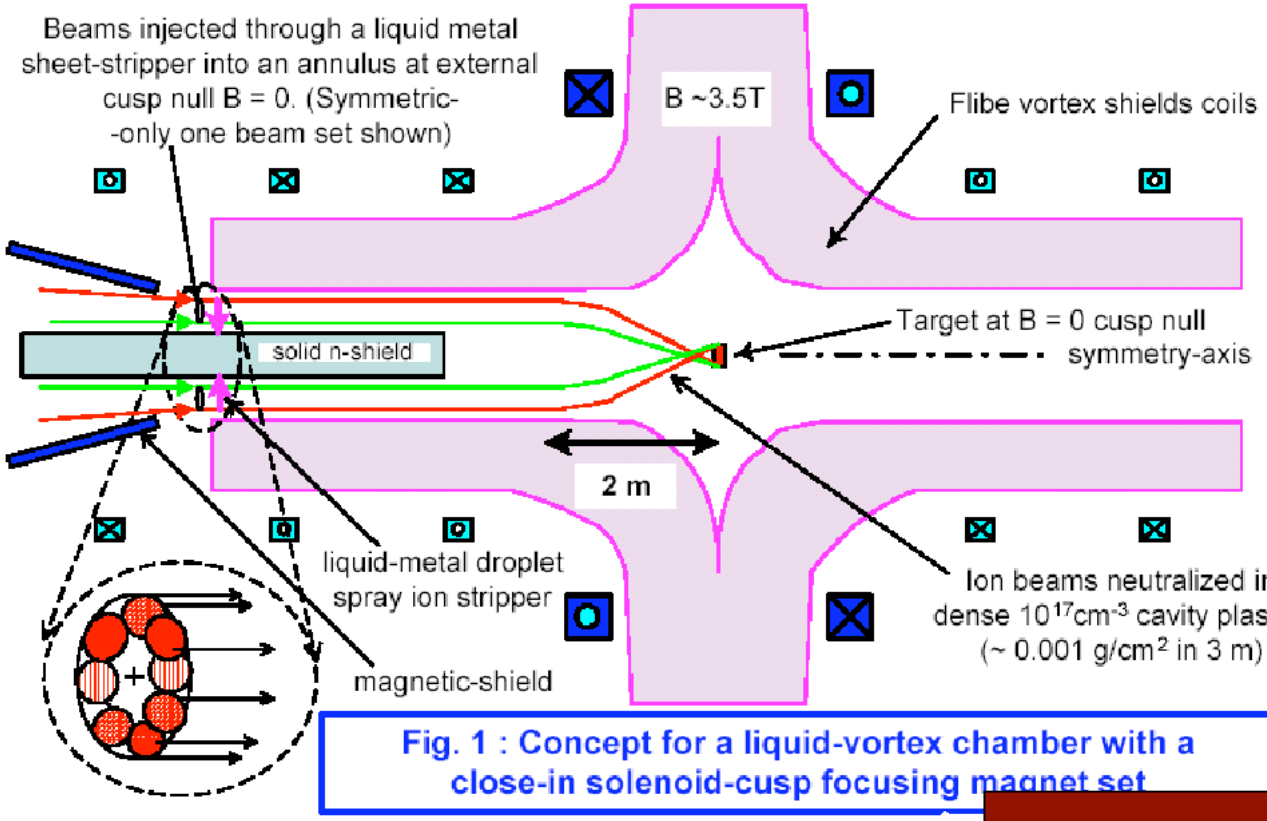


Fig. 1 : Concept for a liquid-vortex chamber with a close-in solenoid-cusp focusing magnet set

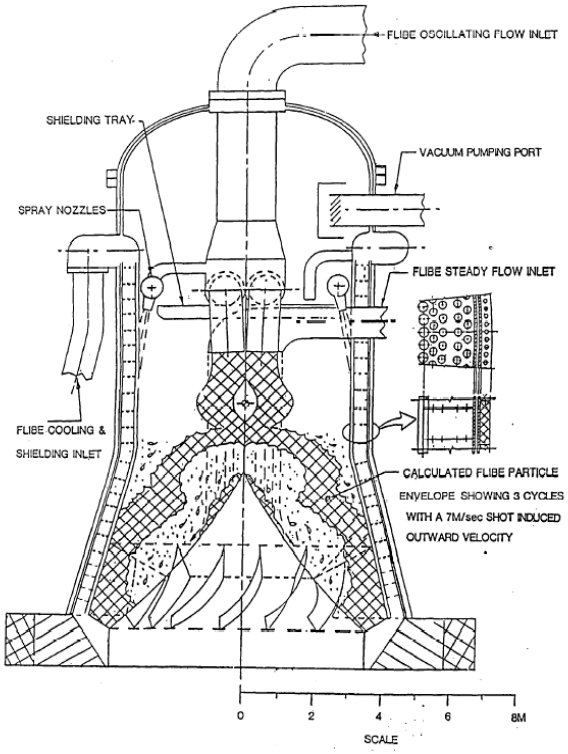
Figure 4: Example of a full size liquid Flibe vortex chamber reproduced from an unpublished June 17 2002 study by Logan for a 350 MJ fusion yield Distributed Radiator Target design. (Double-ended, only one end shown) For a 35 MJ yield (10 x smaller), roughly all dimensions would shrink by a factor of $10^{1/3}$ ~ 2.2, except the Flibe layer thickness can shrink only ~20%. The net result would be an effective final focal length of only 1 m.

High leverage innovation: the cheapest way to reduce CoE is through higher chamber pulse rates (if we can do it!) 1 eV plasma flows out at 8 km/s!

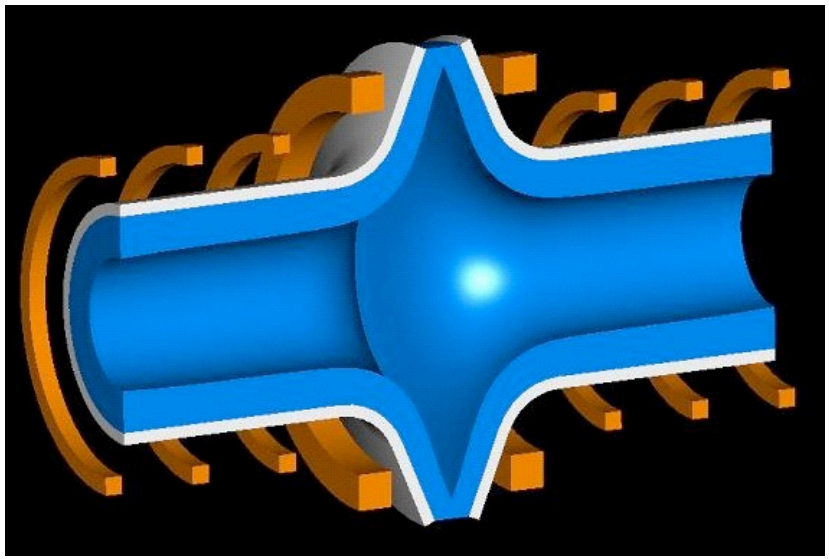
Add 2-4 cm material around hohlraum OD to make lower temperature confined plasma, →reduced liquid surface ablation!

Wayne Meier finds "free-driver-and-target" CoE > fission @ 1 GW_e: can we increase ΔT (inlet to outlet) to decrease Flibe primary loop flow/kW_{th} and pumping power? Materials?

HYLIFE-II concept with oscillating jets of molten salt. (~ \$40M/2.5 GW_{th})

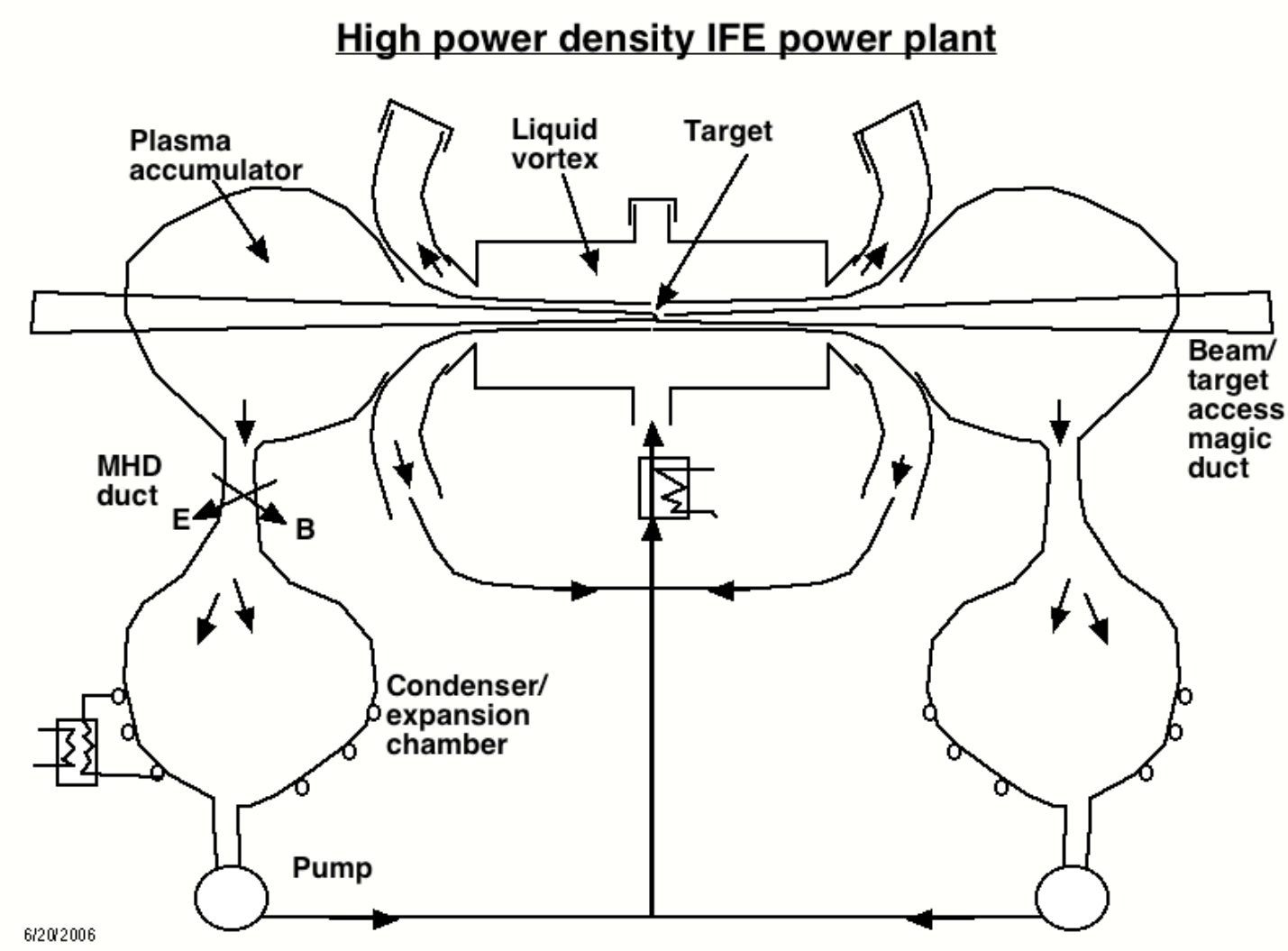


Large liquid vortex chamber concept shields focusing magnets with neutronically-thick liquid layers in steady state



→These liquid chambers should cost less than fission reactors for the same thermal power!

Ralph Moir's thoughts for the June 22, 2006 meeting at UCB



Issues/miracles:
1 How to get target and beam into place in hot, high-density plasma environment
2 Target design illuminated from two small angle cones
3. Liquid vortex that defies gravity
4. MHD system that does not radiate too much energy away yet stays sufficiently ionized
5. Electrode design that works

Fusion Engineering and Design 22 (1993) 151–192
North-Holland

1992 CFAR study: dense 1 eV target plasmas containing lithium can persist for seconds in 7m magnetized chambers (> 100ms in 1 meter chambers).

Inertial fusion reactors using Compact Fusion Advanced Rankine (CFARII) MHD conversion

B. Grant Logan

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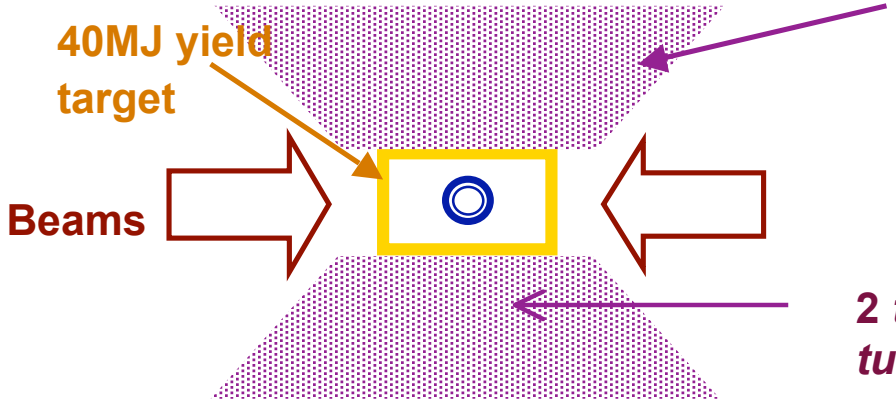
Submitted 24 March 1992; accepted 7 August 1992
Handling Editor: R.W. Conn

This study evaluates the potential performance (efficiency and cost) of inertial fusion reactors assumed capable of vaporizing blankets of various working materials to a temperature (10,000–20,000 K) suitable for economical MHD conversion in a Compact Fusion Advanced Rankine II (CFARII) power cycle. Using a conservative model, 1-D neutronics calculations of the fraction of fusion yield captured as a function of the blanket thickness of Flibe, lithium and lead–lithium blankets are used to determine the optimum blanket thicknesses for each material to minimize CoE for various assumed fusion yields, "generic" driver costs, and target gains. Lithium-hydride blankets are also evaluated using an extended neutronics model. Generally optimistic ("advanced") combinations of lower driver cost/joule and higher target gain are assumed to allow high enough fusion yields to vaporize and ionize target blankets thick enough to stop most 14 MeV neutrons, and to breed tritium. A novel magnetized, prestressed reactor chamber concept is modeled together with previously developed models for the CFARII Balance-of-Plant (BoP), consisting of a supersonic plasma jet, MHD generator, and "raindrop" condensor. High fusion yields (20 to 80 GJ) are found necessary to heat and ionize the Flibe, lithium, and lead–lithium blankets for MHD conversion, with initial solid thicknesses sufficient to capture most of the fusion yield. Much smaller fusion yields (1 to 20 GJ) are required for lithium-hydride blankets. For Flibe, lithium, and lead–lithium blankets, improvements in target gain and/or driver cost/joule, characterized by a "Bang per Buck" figure-of-merit of $\gtrsim 20$ joules yield per driver \$, would be required for competitive CoE, while a figure-of-merit of $\gtrsim 1$ joule yield per driver \$ would suffice for lithium-hydride blankets. Advances in targets/driver costs would benefit any IFE reactor, but the very low CFARII BoP costs (contributing only 3 mills/kWh to CoE) allows this type of reactor, given sufficient advances that non-driver costs dominate, to ultimately produce electricity at a much *lower* cost than any current nuclear plant.

We can engineer chambers to get either low or high cavity pressures at target injection time:

- If we *want* l*owest* pressure→ minimize the target hohlraum mass, keep liquid Flibe walls far away to minimize Flibe ablation, put in many openings for rapid venting, oscillate liquid and inject Flibe spray to force rapid chamber clearing and condensation.
- However, if we *want high* cavity pressures→ put Flibe layers around the hohlraum to increase plasma mass production, minimize vents in the cavity, and add a magnetic field to contain the target plasma and stop turbulent plasma eddies (like the current vortex, and similar to the CFAR chamber scheme considered in 1992).



ARIES (GA-2002) studied using a *thick Flibe overcoat* to protect cryo targets during injection into hot chambers (CFAR studied even thicker layers-1992 paper)

2 to 3 cm thick frozen Flibe (0.3 to 5 kg) turns into ~ 1 eV Flibe 1m^3 plasma

A small Demo with 40 MJ yield can capture 33% of the yield into 1 eV plasma, sufficient for a DEMO.

Table 2

1-D neutronics data used for energy capture fraction $F_c = ($ lithium, and lead–lithium blankets (from calculations by Sa shells, starting at $r_{inner} = 5$ cm

Δr (cm)	Flibe { florine 57%, lithium 29%, berylium 14% (atom %)	
	F_c	TBR
0	0.2	0
10	0.476	0.108
20	0.673	0.289
40	0.933	0.839
60	1.038	1.154
80	1.066	1.246
100	1.072	1.265
150	1.073	1.269
200	1.073	1.269

Δr~3 cm

0.33

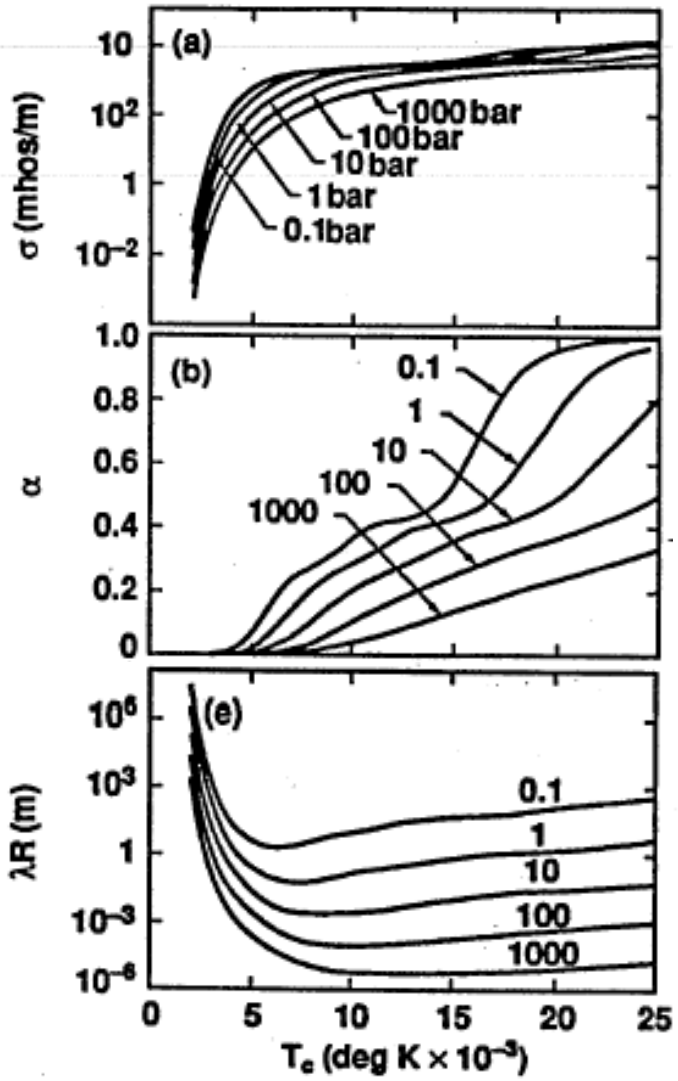
← The rest of the breeding comes out of the vortex

Plasma energy confinement improves around 1 eV due to radiation trapping in large dense plasmas where $\lambda_R << r_c$

Plasma conductivity

Ionization fraction (Saha)

Optical (Rosseland) Mean-free-path



Heat transport The 1992 paper
Solved the 1-D radiation transport equation.

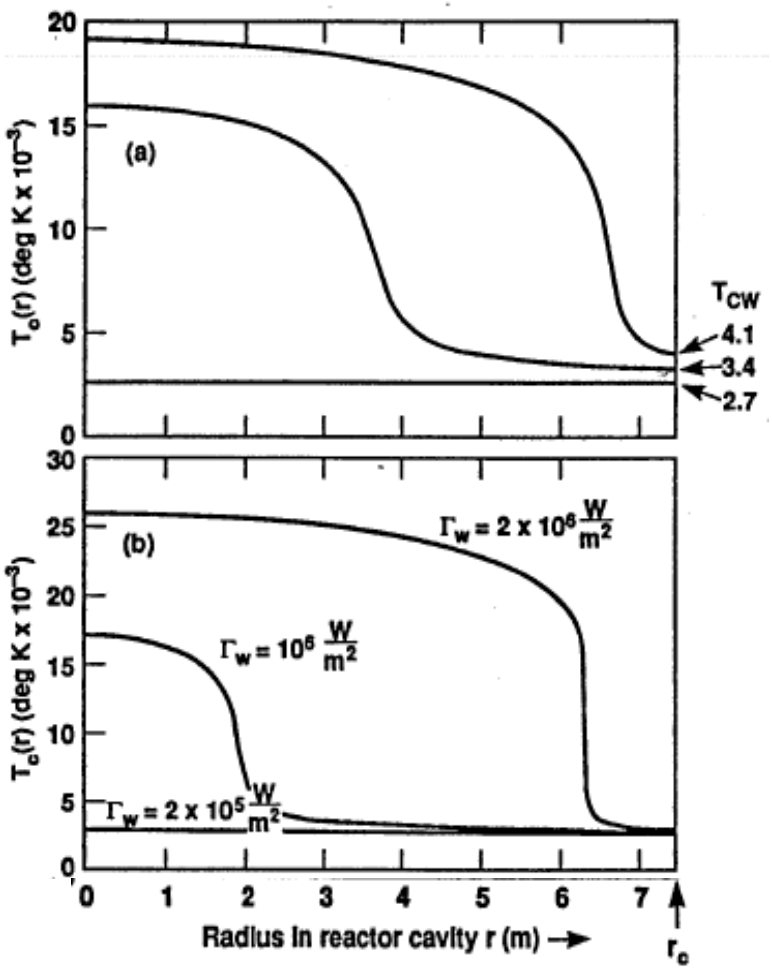
$$\lambda R(T, p) = 6.7 \times 10^{-15} T^{5.5} \left[1 + \alpha(T, p)^{-1}\right]^2 p^{-2} \quad \text{(m)},$$

$$\Gamma_r = -\frac{4}{3} \lambda R \frac{\partial}{\partial r} (\sigma_{SB} T^4) \quad (\text{W/m}^2),$$

During heat decay under pressure equilibrium

$$\Gamma_r(r) = \Gamma_w r / r_c,$$

When cavity plasma is large enough and dense enough to be optically thick, radiation transport determines the energy loss time



"Snapshot" radial temperature profiles for various edge temperatures and radiation heat fluxes

$$\tau_{cool}(T_c, p_c, r_c) = \frac{h_c \rho(T_c, p_c) V_c}{S_c \Gamma_w} \quad (s)$$

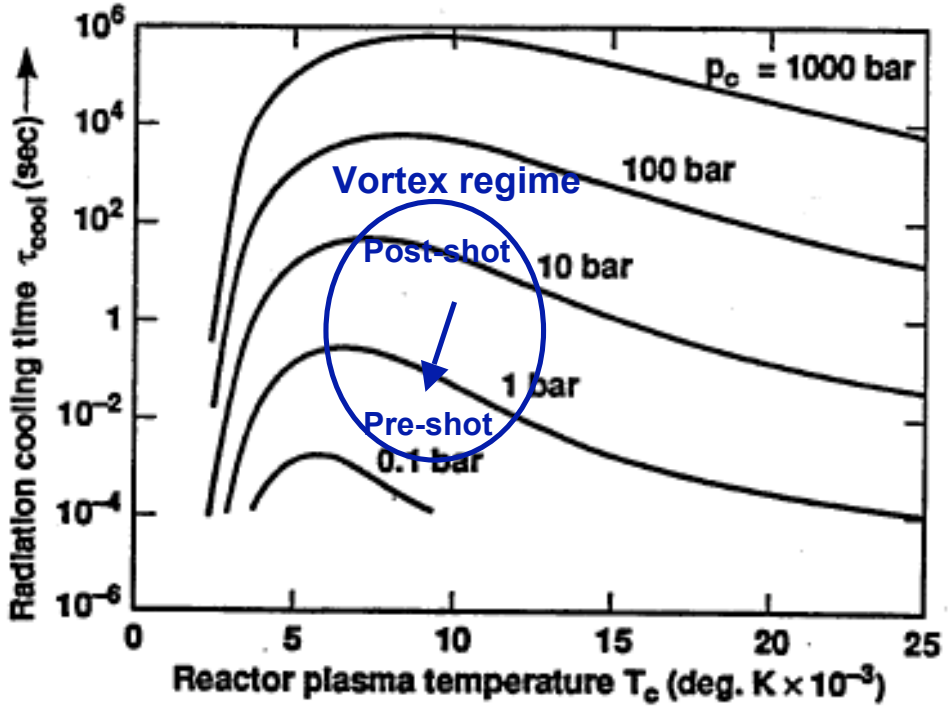


Fig. 7. Reactor plasma radiation cooling time τ_{cool} (s) as a function of reactor plasma temperature T_c, for various reactor plasma pressures p_c (flibe plasma, 2:1 ellipsoidal reactor vessel with minor radius $r_c = 7.4$ m).

The magnetized vortex plasma is conductive and resistive enough to provide ideal shock dissipation

Magnetic Reynolds # > 1 for fast initial radial shocks where expanding target plasma compresses magnetic flux outward….

$$R_m = \mu_0 \sigma u r_c > 1,$$

But the resistive magnetic diffusion time for compressed field layers to relax is short compared to time between shots-converts shock energy into ohmic heating of plasma

$$\tau_B \simeq \mu_0 \sigma r_c^2 = 0.58 \text{ s}$$

=0.1 s for r_c =3m @ 1.6 eV

0.01 s @ 1 eV

0.001 s @ 0.6 eV

→"Goldilocks theorem"-choose the target shell thickness and resulting cavity plasma temperature that is not too hot or too cold, but "just right"