Draft 20 yr HIFS Research Plan

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Response to PAC Q8: Develop a new HIFS plan that reflects new thinking both in accelerators and targets

Presented to the 8th HIFS-VNL PAC

Lawrence Berkeley National Laboratory

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Recent events motivate initiating a new 20 year plan towards fusion:

1. **At APS, Ray Fonck said FESAC (OFES) should consider 20 year research plans for the domestic fusion program (both magnetic as well as inertial fusion science) to take advantage of ITER construction roll off as well as NIF ignition. Ray complimented us on our current HEDP science program and suggested that our long range plan define scientific goals that build upon and extend ion driven HEDP towards heavy ion fusion.**

2. **Last month, LLNL announced plans for a National IFE workshop to be sponsored in April. The HIFS-VNL needs to revisit long range fusion planning that was put on hold since DOE asked us to focus on near term warm dense matter physics in 2003.**

3. **Public and Congressional concern for global warming and energy security is accelerating.**

The draft you were sent represents the beginning conceptual phase of a new plan adding exploration of ion direct drive beyond WDM studies- much more assessment work remains.

The new draft plan begins with a *roll-forward* approach, extending WDM experiments towards direct drive target physics. *But, how much early effort should we also put into integrated reactor studies for roll-back?*

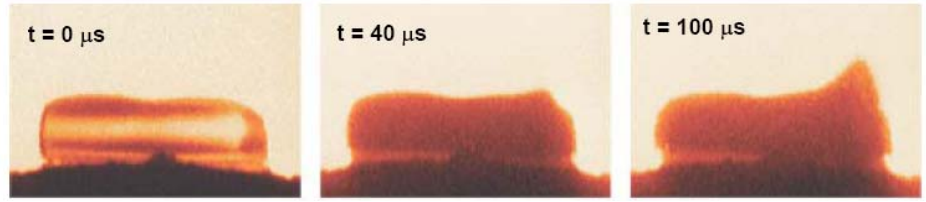
- **The last long-range HIF plan we presented at Snowmass 2002 was a *roll-back* approach: each development step IBX→IRE→ETF→RPD was derived to demonstrate requirements for the next higher step:**

> ***40 page Heavy Ion Fusion White Paper July 2002***
>
> **Strategic Plan and Research Needs for Heavy-Ion Fusion Energy Development: An Integrated Research Program**
>
> Grant Logan, John Lindl, Jill Dahlburg, Ron Davidson, Ed Lee, (Editors), with contributions by Debra Callahan, Max Tabak, Wayne Meier, Per Peterson, Jeff Latkowski, Dan Goodin, Peter Seidl, Alex Friedman, Simon Yu, Joe Kwan, John Barnard, Christine Celata, Matthaeus Leitner, Gian-Lucca Sabbi, Will Waldron, George Caporaso, Glen Westenskow, Patrick O'Shea
>
> U.S. HIF Virtual National Laboratory, and U.S. Virtual Laboratory for Technology

Given Fonck's guidance, we accept that this roll-forward plan may not provide answers to many reactor questions for some time, and so we cannot be sure direct drive will be better for HIF. We cannot support the 5 man-years of effort we put into the RPD study with present staff, but we have started a small "skunkworks" effort.

Hydra-code calculations (Barnard) suggest we could begin ion-driven hydrodynamics/RT studies on cryo-D2 targets with NDCX-II

- ***GSI first practiced ion-driven target hydrodynamics with cryogenic Xenon targets at beam intensities well below those required for full target ionization:***

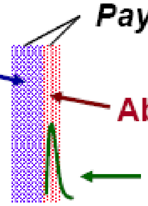


- **Direct drive hydrodynamics/RT physics can benefit from "pump-probe" <u>double pulses</u>:**

Solid D_2 "payload"

Payload and ablator D_2 layers are doped with different impurities to diagnose optical depth modulations

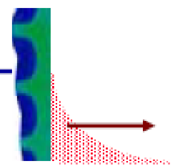
Time just before first pulse



Ablator D_2 layer ~ > than initial ion range

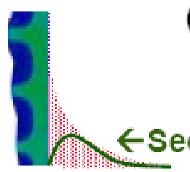
First ns ion beam pulse dE/dx (beam enters from the right)

Time ~ 10 ns later before second pulse arrives



RT "bubbles & spikes" grow measurable amplitudes.
(1) Can upstream beam GHz RF modulation reduce RT?
(2) Do RT non-uniformities in ablation plasma smooth out with time and distance (any "ablative stabilization")?

Second ion pulse arrives, and stops *<u>mostly within ablation blow-off</u>* (in 1-D approx.)!

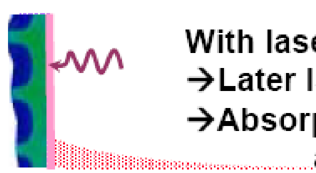


(1) "Rocket science": what ion range/ablator thickness maximizes hydro implosion efficiency with later ion pulses re-pressurizing same ablation layer mass?

← Second ns ion beam pulse dE/dx

(2) How is RT growth affected (any "cloudy day" effect?)

With laser direct drive, later pulse ablates at fresh critical density layer further left



With laser direct drive, ablation plasma << critical density,
→Later laser light transmits through ablation plasma.
→Absorption in inverse bremsstrahlung layer moves left as ablator layer erodes

← Unique physics with ion drive using NDCX-II. →Requires very small prepulses!

Seeking HIF research plans with more "science sex appeal"

From the 7th VNL-PAC report: "There is also support for HEDP within the Congress (the Senate Energy and Water Bill included the establishment of an HEDP office within DOE's Office of Science) but the HIFS program suffers from low visibility in both the House and Senate. While other HEDP initiatives were mentioned in the report language from both Houses, HIFS was not mentioned."

"Science sex appeal" (such as fast ignition has), needs

1. **Clear relevance to improve fusion, in addition to interesting HEDP science.**
2. **A target concept with understandable potential (from basic energetic arguments) to get higher gain, assuming detailed issues can be resolved favorably.**
3. **Opportunity to leverage existing assets to do affordable experiments in the near term.**

Slides sent to PAC
January 30
in response to Q8

Ignition in NIF should motivate plans for expanded research towards inertial fusion energy (IFE)

How can we go from heavy-ion-driven warm dense matter research to *accessible fusion research* ?

There are many pathways to HIF depending on the type of heavy ion driven target, but one can consider the following two *direct drive* pathways that exploit European (GSI-ITEP) and US (VNL) accelerator WDM capabilities in different ways:

- *Direct-drive* heavy-ion-driven fast ignition targets in cylindrical geometry→ use ~ 5 MJ of <u>*long range (~ 10 g/cm^2) 100 GeV*</u> heavy ion beams (Sharkov, Basko concept), which can build upon the GSI/ITEP WDM program.
- *Direct-drive* heavy-ion-driven spherical implosions using conventional central ignition, late-shock ignition (R. Betti -Rochester), or fast impact ignition (Murakami-Osaka)→ use ~1 MJ of <u>*short range (~ 0.003 g/cm^2 200 MeV*</u> heavy ion beams with neutralized compression and focusing→ can build upon US WDM program.

Indirect-drive heavy ion hohlraum "distributed radiator" targets have been most extensively studied previously but require ~7 MJ of <u>medium range (~0.03 g/cm2), e.g. 4 GeV</u> heavy ions→ space charge with vacuum compression and final focus leads to multi-GeV beam energy requirements for both RF storage ring and multiple-beam linac drivers.

(Refer to GSI 1997 HIDIF study, and US Robust Point Design linac study 2003)

Rationale for an extended HIFS-VNL plan based on direct drive

1. **Near-term HEDP opportunities shape present heavy ion research. NIF ignition may motivate heavy ion fusion, but indirect drive experiments may be out of reach for heavy ion accelerators. Pursuit of heavy ion direct drive physics offers *new basic heavy ion HEDP research opportunities not previously explored.***

2. **Recent innovations to enable ion-driven HEDP *also enable direct drive ion-target physics unique to inertial fusion science*, that point to higher gains, and to more affordable future accelerator-driven target hydrodynamic experiments.**

3. **NIF is presently configured to test ignition in polar direct drive with lasers as well as indirect drive. Direct drive experiments with ion beams might supplement NIF laser target data with relevantly-scaled heavy-ion-driven implosion physics (*a new heavy ion fusion science mission beyond warm dense matter physics*).**

Indirect drive remains an option for HIF, while we plan to explore heavy ion driven direct drive.

▪ NIF first ignition will be based on laser indirect drive.

▪ X-ray drive of capsules within Hohlraums are not sensitive to the source of x-rays.

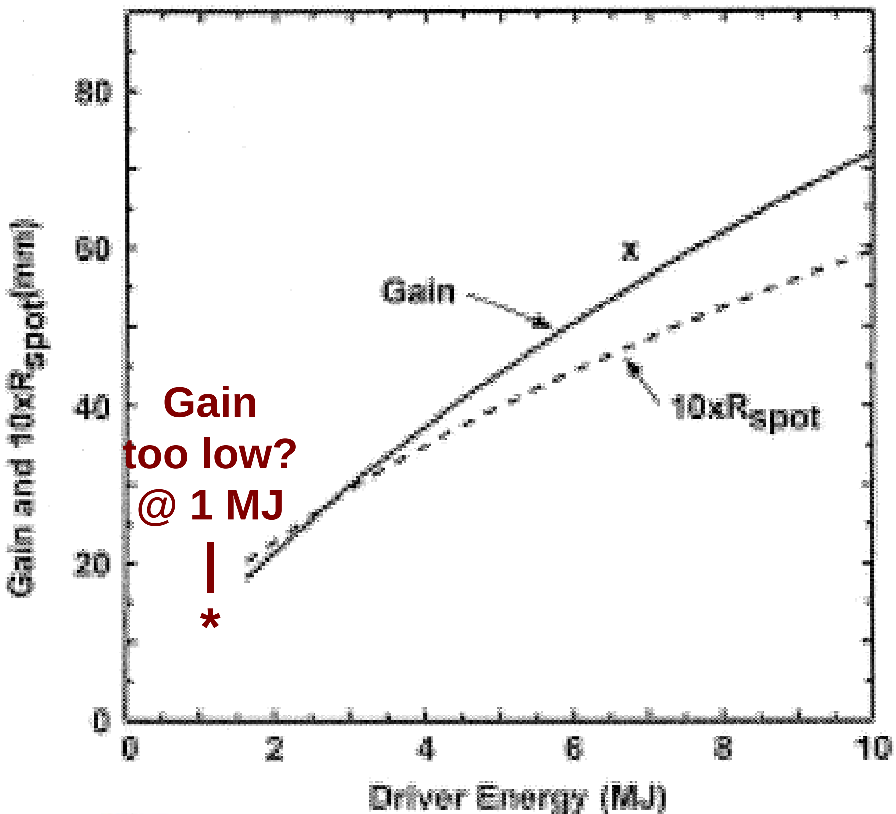
▪NIF ignition will validate much of the x-ray transport and capsule physics of published HIF indirect drive target designs [Callahan/Tabak]

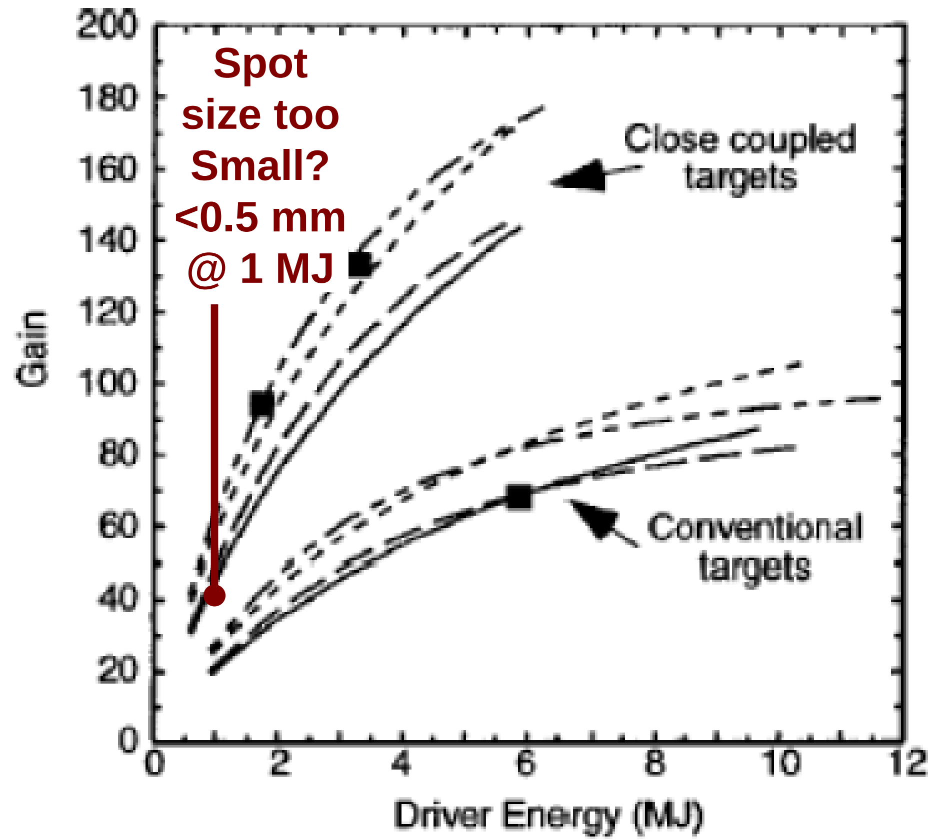
▪The Robust Point Design study [S.S. Yu, W.R. Meier, R.P. Abbott, J.J. Barnard, T. Brown, D.A. Callahan, P. Heitzenroeder, J.F. Latkowski, B.G. Logan, S.J. Pemberton, P.F. Peterson, D.V. Rose, G-L. Sabbi, W.M. Sharp, D.R. Welch, Fusion Science and Technology 44 (2003) 266] describes a self-consistent heavy ion accelerator and final focus/chamber that meets detailed 2-D heavy ion fusion target design requirements [D.A. Callahan-Miller and M. Tabak, Phys. Of Plasmas, 7, 2083 (2000)]

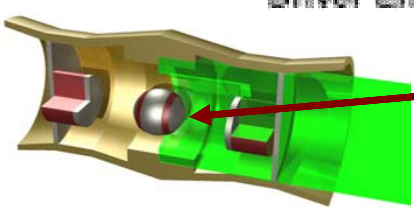
Previous heavy ion fusion target designs present challenges for experiments at low gain thresholds.

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

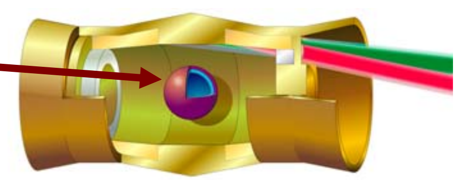
Callahan's HIF04 NIMA paper for HYBRID



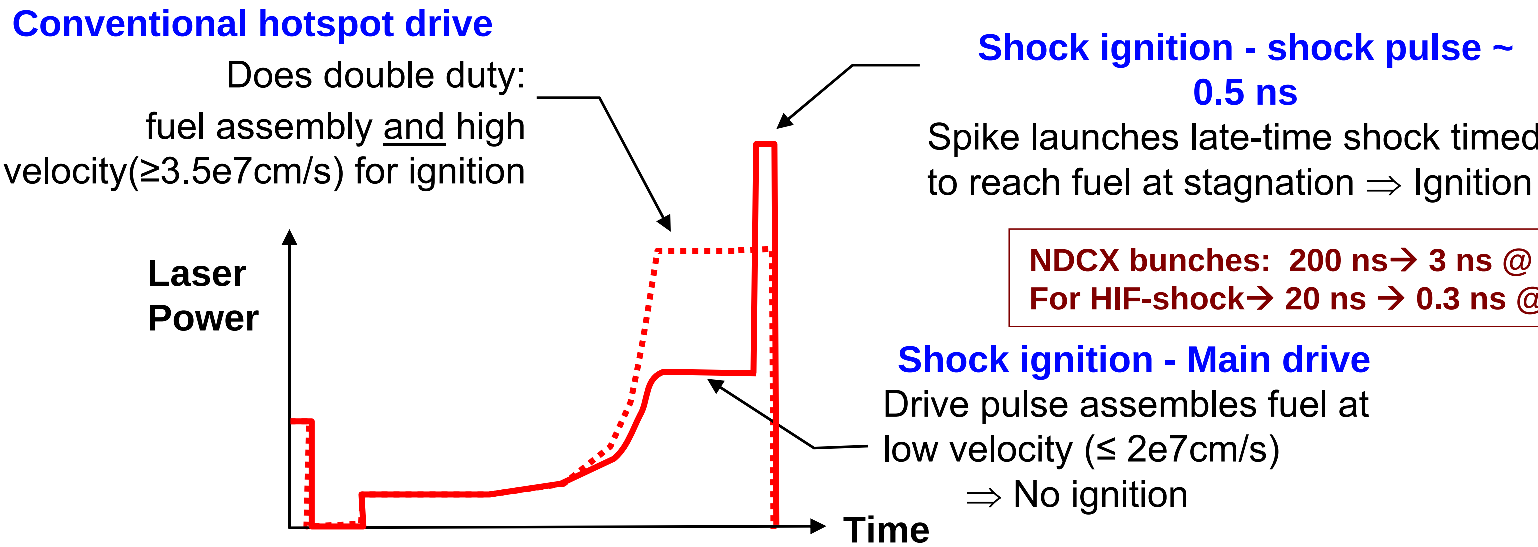




2 mm radius capsules absorb 1 MJ out of 7 at full driver size.



Essence of Shock-Ignition (R. Betti, U Rochester): obtain similar benefits as fast ignition with *lower peak power* and *larger beam spots*: implode at low velocity and ignite separately with a late convergent shock. (J. Perkins-LLNL: *"NIF can test this ignition. Particle beams may work best"*.



NDCX bunches: 200 ns→ 3 ns @ β = 0.01 now.
For HIF-shock→ 20 ns → 0.3 ns @ β = 0.1.

Shock-Ignition Decouples Target Compression from Ignition

- Higher target gains for the same drive energy (and vice-versa)
- Benefits similar to "fast-ignition", but time/spatial requirements less stringent and uses same laser (no PetaWatt compressor lasers req'd)
- Target burns like a regular hot-spot target
- Major issue is late-time LPI; may be more benign as occurs only at late time

Revisiting Heavy Ion Fusion direct versus indirect drive

The US HIF program has adopted indirect drive for the past 25 years, *despite higher drive energy requirements*, for several reasons:

(1) Indirect drive was necessary for early *non-uniform* laser beams, while the HIF program relied on defense laser facilities for much of its target physics validation.

(2) Thick-liquid protected chambers required *two-sided illumination*.

(3) Hohlraums might allow HI-beam spot sizes of order the hohlraum size, i.e., *bigger than the fuel capsule.*

(4) Indirect drive demands *lower drive pulse contrast ratios* (easier for heavy-ion accelerators) compared to direct drive.

(5) Laser ablative RT growth reduction *might not apply to ion drive.*

(6) Hohlraums could *protect cryo-capsules* from hot fusion chamber environments.

→In light of recent scientific advances, lets re-examine these issues!

Reasons to re-consider direct drive for heavy ion fusion

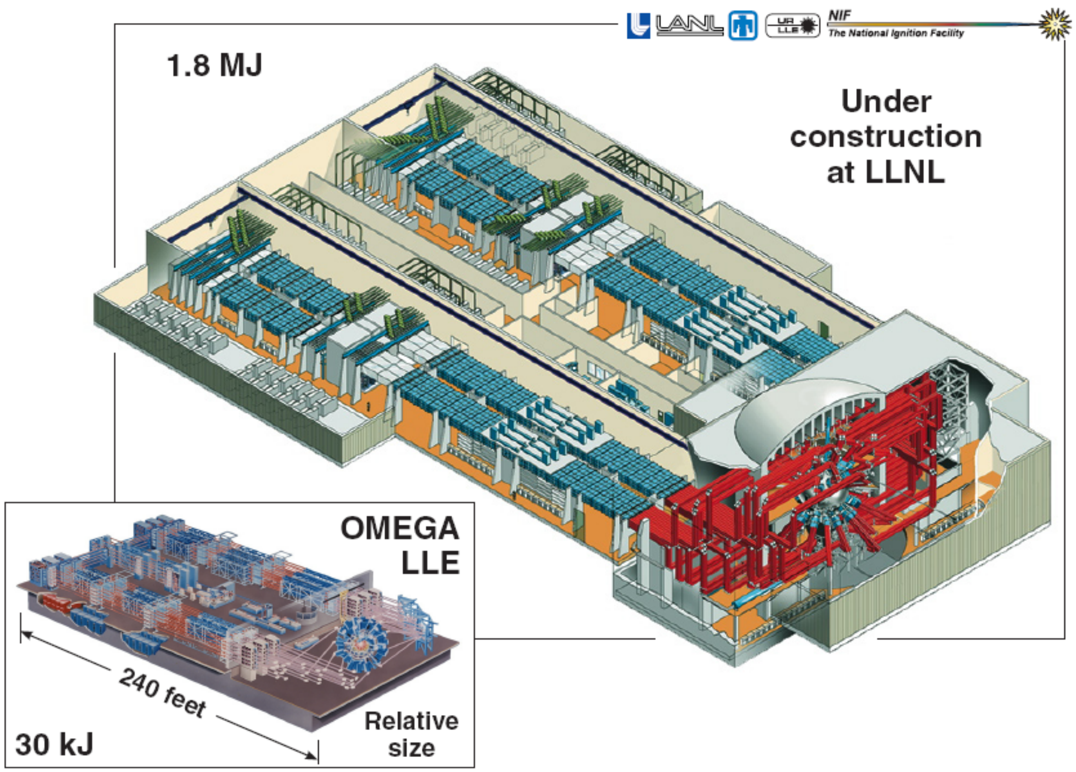
With modern (mostly DT) direct drive capsules *and* super-efficient heavy ion beam coupling, <1 MJ drive may suffice for ηG >20!

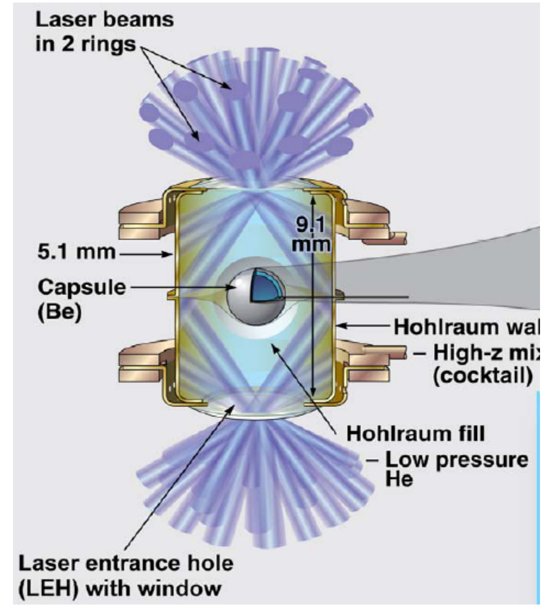
1. **Laser beam smoothness now makes direct drive viable for NIF→ enables early direct drive ignition tests *in polar geometry, suitable for liquid protected chambers.***
2. **Direct drive fuel capsule radii (~ 2mm) allow *ion beam spots comparable to indirect drive needs*. (The larger hybrid HI target exception unduly restricted beam illumination solid angle <10^{o} → difficult for many beams).**
3. **Neutralized beam drift compression now allows multiple pulses of lower range ions *→ion picket fences→ more pulse shape contrast possible.***
4. **Upstream ion beam RF modulation→ *new dynamic RT stabilization!***
5. **Thin *metal enclosures might still be used* with ion direct drive, even if only as a thin sabot to protect the cryo-capsules.**

→ ***Pursuit of direct drive allows HIF to take advantage of ongoing progress in modern laser facilities as much as it has for indirect drive.***

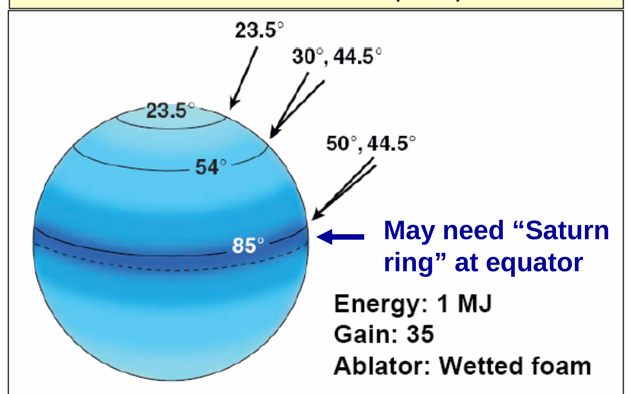
First ignition tests in NIF will be indirect drive, *but polar direct drive tests will soon follow.*

Meyerhofer (8-29-06) : "We expect ignition in polar direct drive on NIF soon after first ignition with indirect drive."
Marshall, Craxton (11-06-APS) -showed new Rochester results on their 2-sided, polar direct drive experiments measuring 80-90% of the yield with full 4Pi drive.



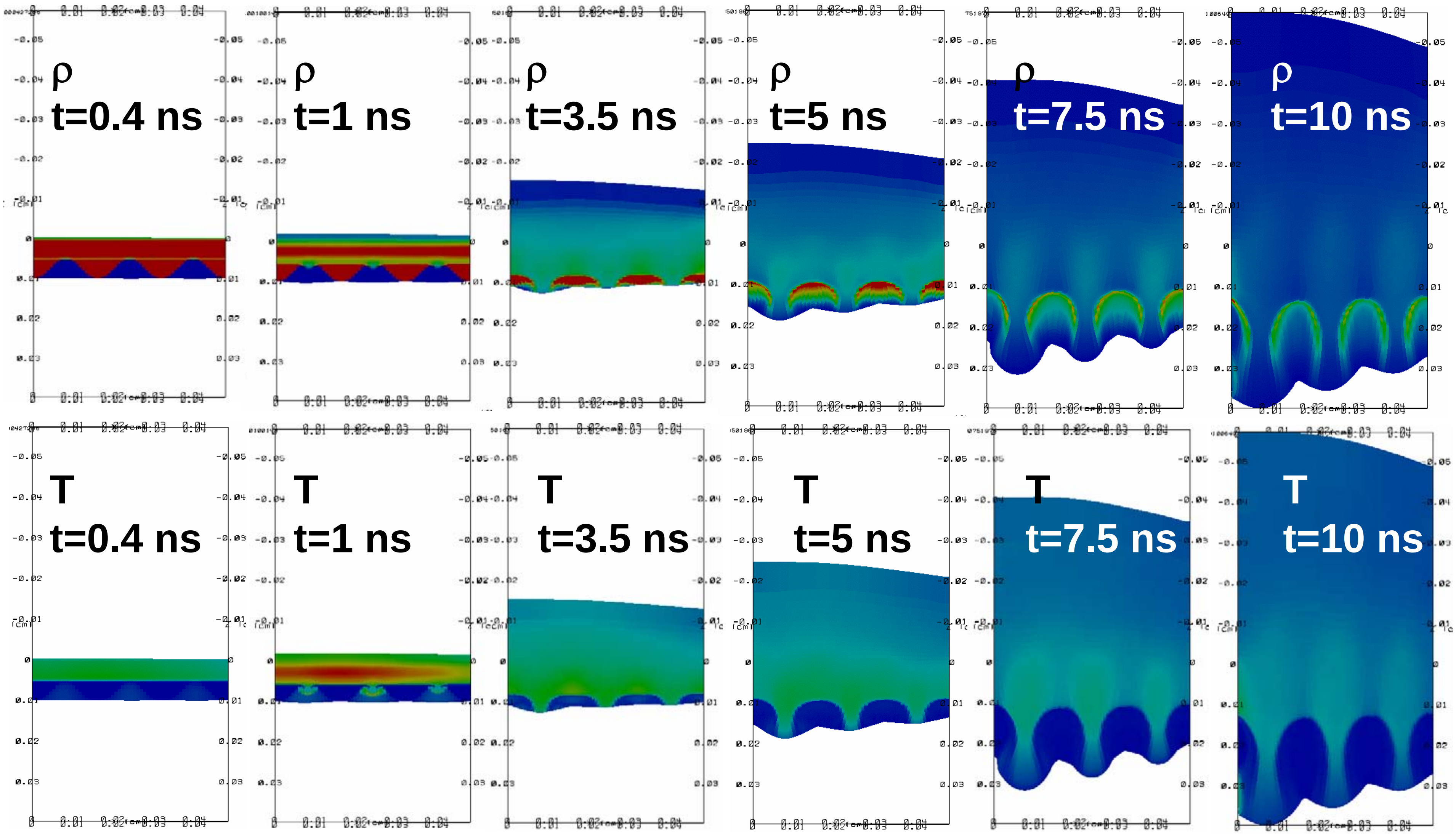


Polar Direct Drive (PDD)



The required intensity variations on the target can be achieved through a combination of spot shape, pulse shape and beam pointing

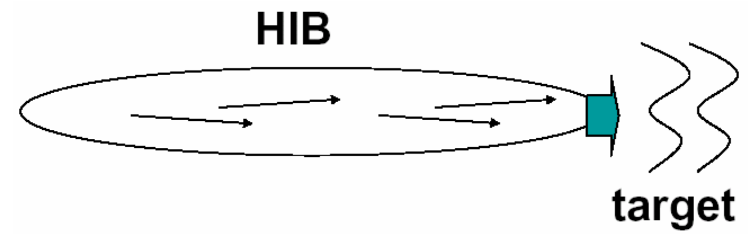
Planar heavy ion direct drive experiments can begin with NDCX-II-scale beams (calculations by Barnard/ Samthanam using LLNL HYDRA code)



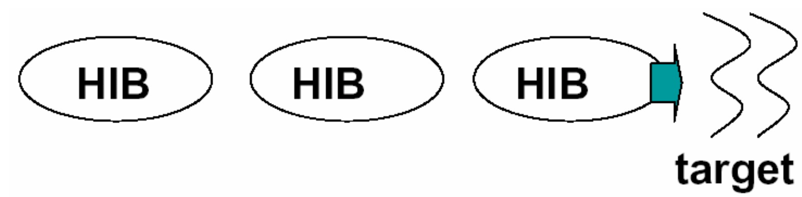
→Can modulated beams stabilize ion R-T modes (S. Kawata) ?

S. Kawata has proposed several techniques to reduce RT growth in ion-beam-driven direct drive

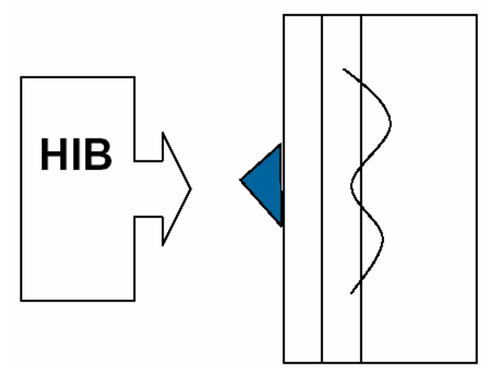
HIB axis rotation or swing
-> reduce the R-T growth!



Successive HIBs induce a dynamically
Oscillating *g*!
-> reduce the R-T growth!



Large-scale HIB-energy deposition profile
-> Large-scale density gradient
-> Reduce the R-T growth!



$\delta g(x)$, induced by an shaped Ablator, controls R-T phase & growth

L&PB, 11(1993)757

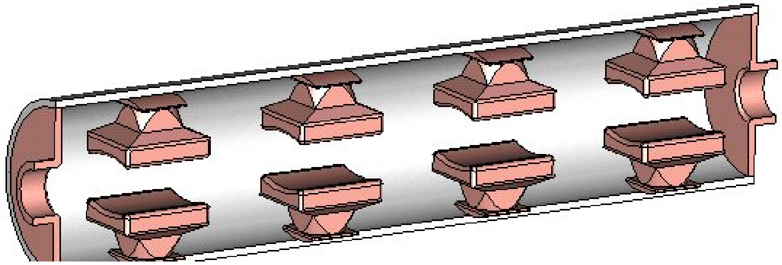
Shaped target with an Ablator
for R-T phase control

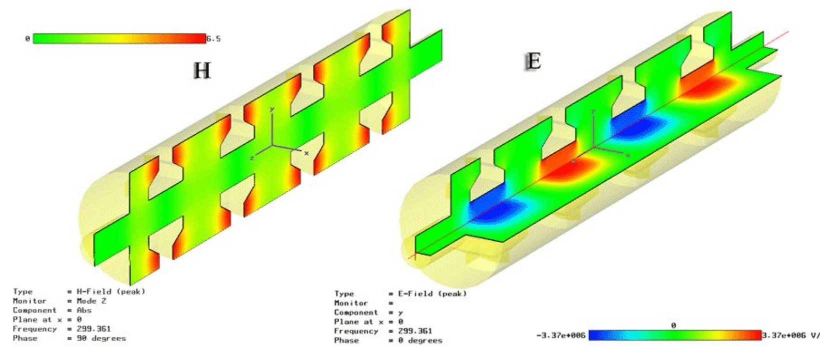
→These techniques can be explored on NDCX-II

Our GSI/ITEP collaborators are developing the tools we would need to test dynamic stabilization of ion direct drive RT instability

ITEP design of RF HIB GHz Wobbler for GSI

(Much lower RF fields are required to modulate 100 MeV Ar beams compared to 200 GeV Uranium beams!)

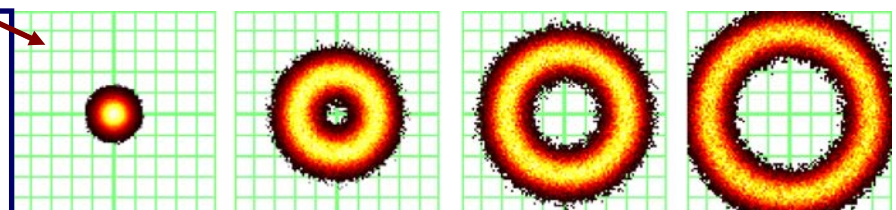




Beam spot rotation improves symmetry for direct drive: fewer beams needed for azimuthal symmetry

Transverse beam intensity distributions @ the focal plane with a single rotating beam!

→Two sided (polar) direct drive implosion studies may be possible with two twirled ion beams from two linacs, each with 10-pulse picket fences



The minimum heavy ion beam energy needed to explore two-sided direct-drive implosion symmetry and pulse shaping is ~ 10 kJ

Initial shell volume & mass assuming 1 mm outer radius, 300 μm-thick

$$V_{D2} := \left(\frac{4}{3}\right)\cdot\pi\cdot\left[\left(10^{-3}\right)^3 - \left(0.7\cdot10^{-3}\right)^3\right] \qquad V_{D2} = 2.8\times10^{-9} \quad \text{kg}$$

$$M_{D2} := V_{D2}\cdot\rho_{D2} \qquad M_{D2} = 5.5\times10^{-7} \quad \text{kg} \qquad M_{D2}\cdot10^{6} = 0.6 \quad \text{mg}$$

Minimum velocity to diagnose implosion symmetry $v_{imp} := 10^{5}$ m/s

Required implosion drive pressure (D2 energy density)

$$p_{D2} := 0.5\cdot\rho_{D2}\cdot v_{imp}^{\ 2} \qquad p_{D2} = 1\times10^{12} \quad \text{Pa} \qquad p_{D2}\cdot10^{-11} = 10 \quad \text{Mb}$$

Energy imparted to D2 shell "payload"=1/2 of initial shell mass

$$E_{D2} := 0.5\cdot V_{D2}\cdot p_{D2} \qquad E_{D2} = 1.4\times10^{3} \quad \text{J}$$

Beam energy coupled assuming pessimistic 20% hydro efficiency

$$E_B := 0.2^{-1}E_{D2} \qquad E_B = 6.9\times10^{3} \quad \text{J}$$

Required incident beam energy assuming
70% ion coupling efficiency (30% beam "spill"):

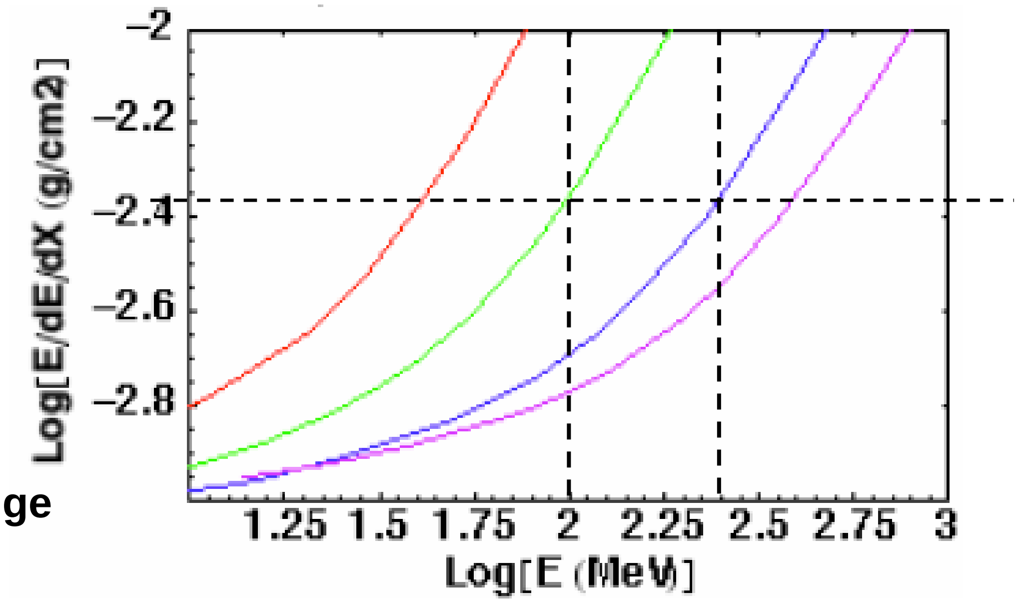
$$E_{Bin} := 0.7^{-1}\cdot E_B \qquad E_{Bin} = 9.8\times10^{3} \quad \text{J}$$

→10 kJ is similar in energy scale to Gekko 12, and early Omega direct drive facilities

Serendipity: neutralized drift compression/focus using background plasma enables lower ion ranges needed to drive modern DT capsules!

From Hydra (John Barnard) **Ne** **Ar** **Kr** **Xe**

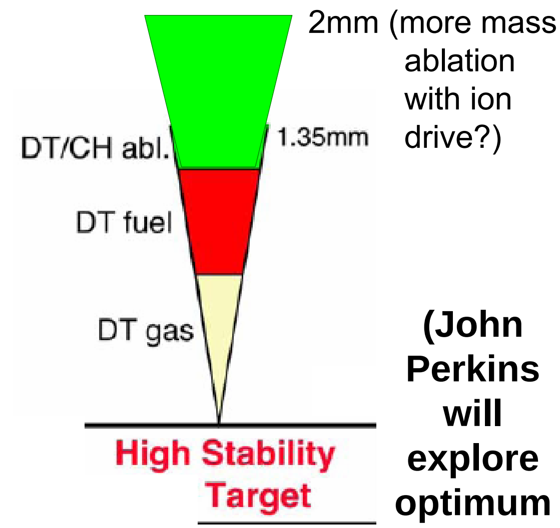
Ion range



Ion energy

100 MeV Ar or 250 MeV Kr→

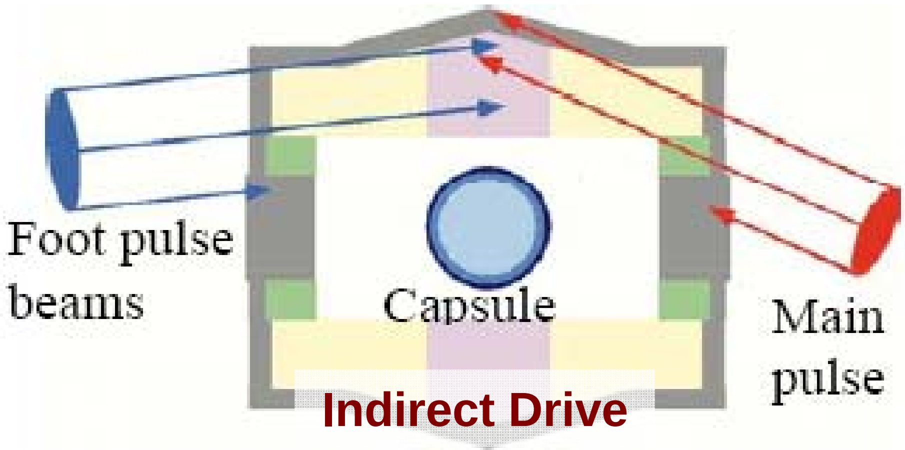
<u>4 x 10^{-3} g/cm^2</u> **~160 microns in**
0.25 g/cm^3 DT **solid DT @ 500 eV**

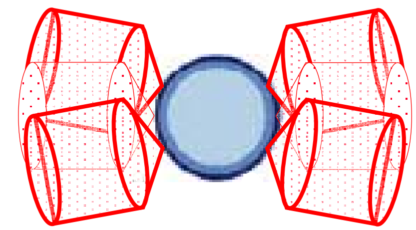


(John Perkins will explore optimum ion ranges)

The 1980's HIBALL target used heavy lead "tamper shells" to improve direct drive symmetry as well as to stop 10 GeV heavy ions @ 0.1 g/cm^2→ required >5 MJ beam energy in direct drive! Modern light DT targets require much lower ion range and higher beam perveances, which now can be focused with neutralized beam focusing.

Indirect drive versus polar direct drive for heavy ion fusion

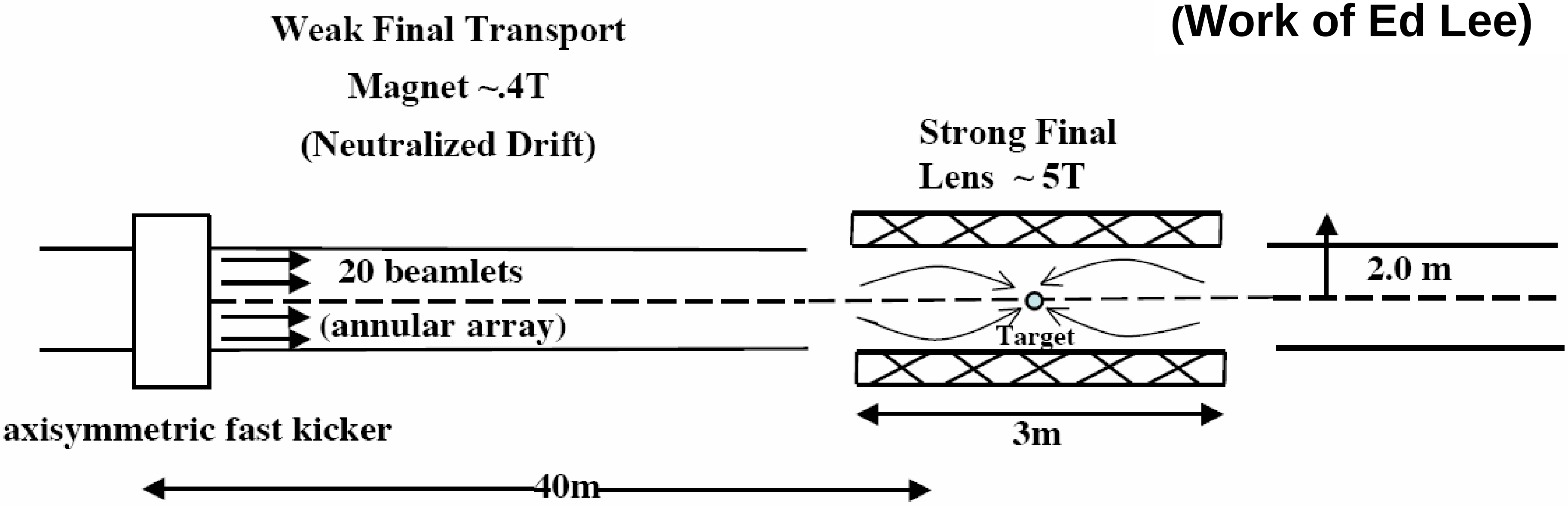




Beam smoothness: (insensitive)	< 1 % (*only* low l-mode issues)
Minimum # pulses: ~12 azimuth x 5 picket fence pulse shaping x 2 ends ~120	~ 20 azimuth x 10 picket fence pulse shaping x 2 ends ~ 400
Ion beam spot radius ~2 mm	~2 mm (1 mm for shock ign.)
Capsule absorbed energy ~ 1 MJ	~ 1 MJ
In flight aspect ratio ~ 36	~ 30 (or 10 for shock ignition)
Ion beam drive energy ~ 7 MJ	~ 1 MJ
Peak beam power ~ 500 TW	~ 200 - 500 TW (final shock)
Yield (Gain) ~ 400 MJ (57)	Yield (Gain) ~ 100 MJ (100)

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

A new 20-year heavy ion science campaign plan will be consistent with the National HEDP Task Force Plan, but extend beyond NIF ignition

For the next 5 years, we will continue to address the top-level scientific question in Thrust Area #4 in the National HEDP Task Force Report:

"How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?"

→Beam compression physics and 1 eV warm dense matter targets using 0.1 to 1 J beams with existing equipment (NDCX +upgrades).

→Any path to heavy ion fusion has to address the above question.

The same top level question still applies following NIF ignition, but with additional heavy-ion-fusion-specific target physics: ion-cryo-target coupling, pulse shaping, symmetry, and RT-stabilized ion-driven implosions. These HEDP topics also address Thrust Area #10 in the National HEDP Task Force Report: "*Can inertial fusion ignition be achieved in the laboratory and developed as a research tool?*"

→ For this extended beam driven HEDP area, a new 10 kJ-scale accelerator tool is necessary to explore these new fusion science opportunities.

→In parallel with construction of this new accelerator, NDCX-II should be further upgraded to an HEDP user facility (IB-HEDPX) for a range of experiments including initial studies of planar ion-driven-direct-drive coupling.

Twenty-year science campaign for heavy-ion-beam-driven HEDP and fusion research

Science Area	FY06 FY07	FY08 FY09	FY10 FY11	FY1 FY13 FY14 FY15 FY16 FY17	FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25
Beam-Target Interaction	Target design + fast beam /target diagnostics	Beam dE/dx WDM experiments	Initial beam-cryo D2 target interaction	Operate IB-HEDPX WDM user facility: EOS, critical points, metal-insulator transitions for many materials	Operate IB-HEDPX WDM user facility: Physics of WDM phenomena relevant to NIF high yield and future FTF fusion chambers
Focusing onto Targets	Larger plasma source	High B focus with time dependent corrections	Double pulse target interaction	Ion planar direct drive hydro experiments with shaped double pulses	Optimize targets with pulse shaping in ion beam direct drive using ten-pulse bunch trains
Longitudinal Beam Compression	60x compression	Compression with 20x transverse focusing	Compress and focus pulse-shaped ion bunches	Optimize compression and focusing using double-pulse beams	Optimize compression and focusing using ten-pulse bunch trains
High Brightness Beam Transport	E-cloud in: 4 quadrupoles 4 solenoids	Beam steering and brightness	Perpendicular and parallel brightness in double pulses	Optimize perpendicular and parallel beam brightness with double-pulse beams	Optimize perpendicular and parallel beam brightness with ten-pulse bunch beams
Advanced Theory and Simulations	Advanced source to target models	Advanced source through target models	Begin direct drive/ multi pulse models	Further develop and apply multi-pulse beam acceleration/ focusing models for both direct and indirect drive	Integrated accelerator beam dynamics with target hydro modeling
Facility & resource needs (Constant $ estimate)	1. Operate NDCX 2. Assemble NDCX-II **$8M/yr tot.**	1. Operate NDCX I 2. Operate NDCX-II **$10M/yr tot**	1. Operate NDCX-I 2. Upgrade II to IB-HEDPX **$16 M/yr tot**	1. Operate IB-HEDPX and support users ($20M/yr) 2. Construct heavy ion target implosion HEDP physics facility ($20M/yr) **= $40M/yr tot.**	1. Operate IB-HEDPX and support users ($20M/yr) 2. Operate heavy ion implosion physics facility (20M/yr) 3. Target & chamber R&D needed for FTF ($20M/yr) **= $60 M/yr tot.**

First heavy ion WDM experiment @ < 1 eV

1 eV in WDM targets; basis for IB-HEDPX

NIF National Ignition Campaign

Begin implosion symmetry tests in NIF of four successive no-yield capsules on the fly to understand precision requirements for IFE (TBD, not included in this budget)

20yr Objective: Develop the beam and HEDP target physics knowledge base for a heavy-ion fusion test facility (FTF)

The new twenty year plan builds upon a large knowledge base developed in heavy ion fusion research over the last thirty years

1. Theory and simulations of intense, space-charge dominated beams: transport, beam brightness evolution, collective effects, instabilities, e-clouds, neutralization, compression and focusing.
2. High brightness beam transport: development of experimental control and understanding of intense beam centroid motion, 4-D distribution evolution, emittance growth, transport limits, and multi-species gas and e-cloud effects.
3. Longitudinal beam compression: experimental control of longitudinal velocity distributions allows up to 60 X longitudinal compression factors, enabling few-ns pulses needed for near-term target experiments.
4. Focusing onto targets: Near emittance-limited beam spots (over 20 X in radial compression to 1 mm spots) using plasma neutralization of otherwise highly space-charge dominated beams.
5. Beam-target interactions: GSI collaborators have measured and calculated heavy ion beam dE/dx within a few percent, focused to < 300 micron spots, compressed to < 130 ns pulses, and heated metal targets to 1 eV.

The long-range HEDP/HIF science campaign envisions three levels

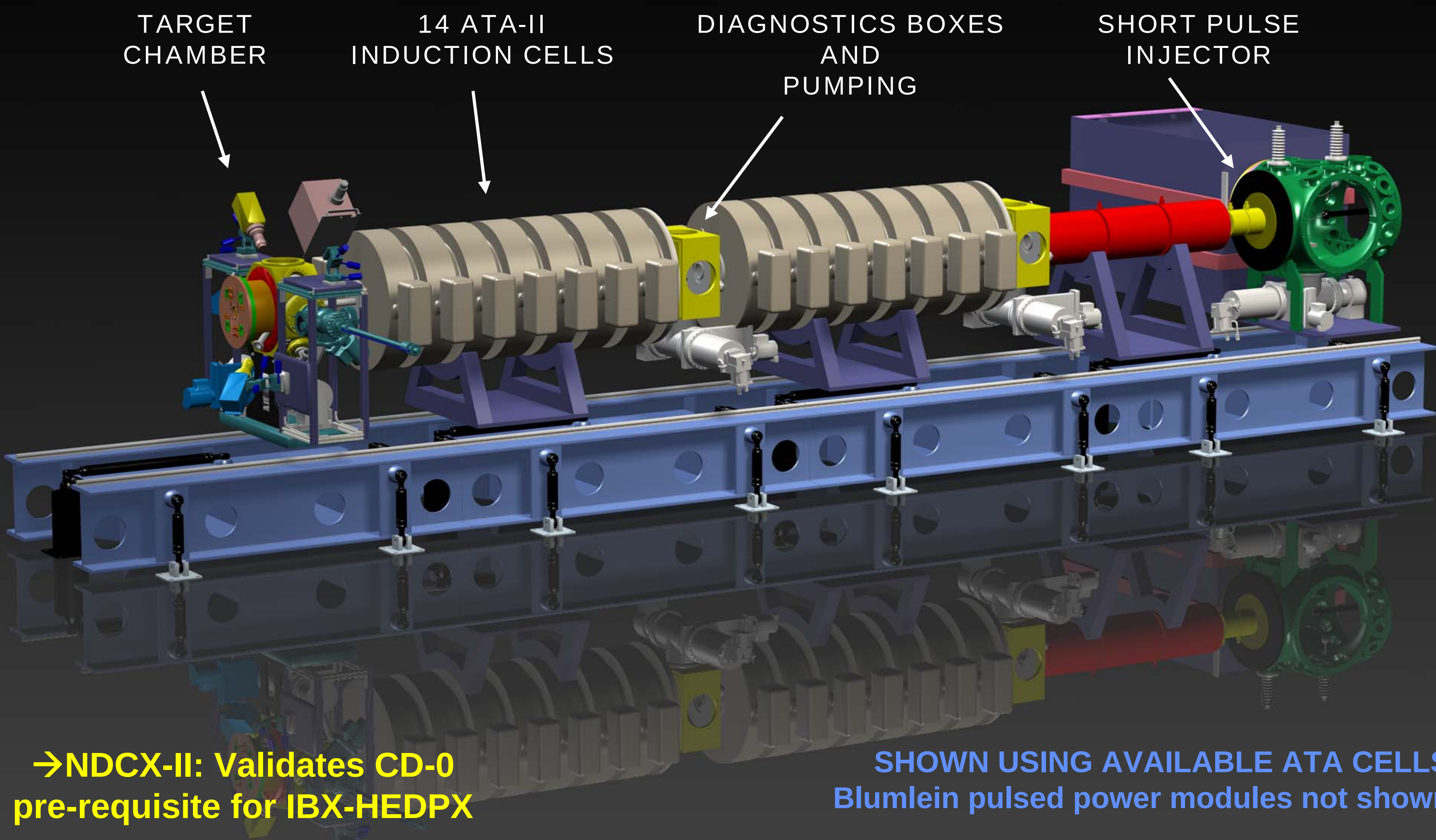
Level I (before NIF ignition ~ 2011) **<u>Integrated beam-target physics:</u>** **The beam intensity and profile heating the target depend on the accumulated beam phase-space changes through each region along the accelerator system. Source-through-target physics models need to be validated by experiments to predict target temperature profiles for WDM physics @ 1 eV. *Best opportunity*: Upgrade NDCX with existing ATA cells for 3 MeV lithium beam acceleration with NDC and solenoid focus (single and double pulses), ~ 0.1- 1 J, ~ $2M hardware over next 3yr VNL program.**

Level II (In parallel with NIF operation ~2012-2025) **<u>Ion direct drive implosion physics:</u>** **E.g., 2-beam/20 pulse, 2-sided cryo-shell implosion experiments to explore heavy ion direct drive physics: two-sided ion-shell coupling, pulse-shaping, hydro, shock timing, and ion-RT stabilization. *Best opportunities*: Upgrade NDCX-II to IB-HEDPX. Build a new tool for fusion physics: 2 induction linacs @100 MeV, opposite a target chamber, ~500J/pulse, ~10 kJ total beam, ~ < $100M.**

Level III (Post NIF ~ 2025-2050) **<u>Heavy ion fusion physics:</u>** **Burning plasma physics with high pulse rate targets, fusion chamber materials and gas dynamics). *Best opportunity*: Fusion test Facility (FTF) with HIF direct drive with gain 40 @ 1 MJ, 6 Hz, for < $ 0.5 B. Liquid vortex chamber hydro validation.**

Campaign Level I can use existing equipment for both 3 MeV Li Bragg peak WDM and new double-pulse direct-drive experiments

Thanks to LLNL Beam Research Program, we have enough parts for 6 MeV of acceleration.
Our main cost item would be to replace solenoids to 1.5 to 2 T (6 m x 100K/m ~ $600K)



→NDCX-II: Validates CD-0 pre-requisite for IBX-HEDPX

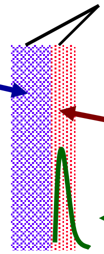
SHOWN USING AVAILABLE ATA CELLS.
Blumlein pulsed power modules not shown.

Double-pulse planar target interaction experiments should reveal *unique* heavy-ion direct-drive coupling physics

Solid D_2 "payload"

Payload and ablator D_2 layers are doped with different impurities to diagnose optical depth modulations

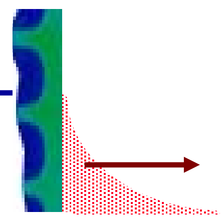
Time just before first pulse



Ablator D_2 layer ~ > than initial ion range

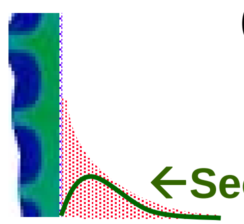
First ns ion beam pulse dE/dx (beam enters from the right)

Time ~ 10 ns later before second pulse arrives



RT "bubbles & spikes" grow measurable amplitudes.
(1) Can upstream beam GHz RF modulation reduce RT?
(2) Do RT non-uniformities in ablation plasma smooth out with time and distance (any "ablative stabilization")?

Second ion pulse arrives, and stops ***<u>mostly within ablation blow-off</u>*** (in 1-D approx.)!



(1) "Rocket science": what ion range/ablator thickness maximizes hydro implosion efficiency with later ion pulses re-pressurizing same ablation layer mass?

←Second ns ion beam pulse dE/dx

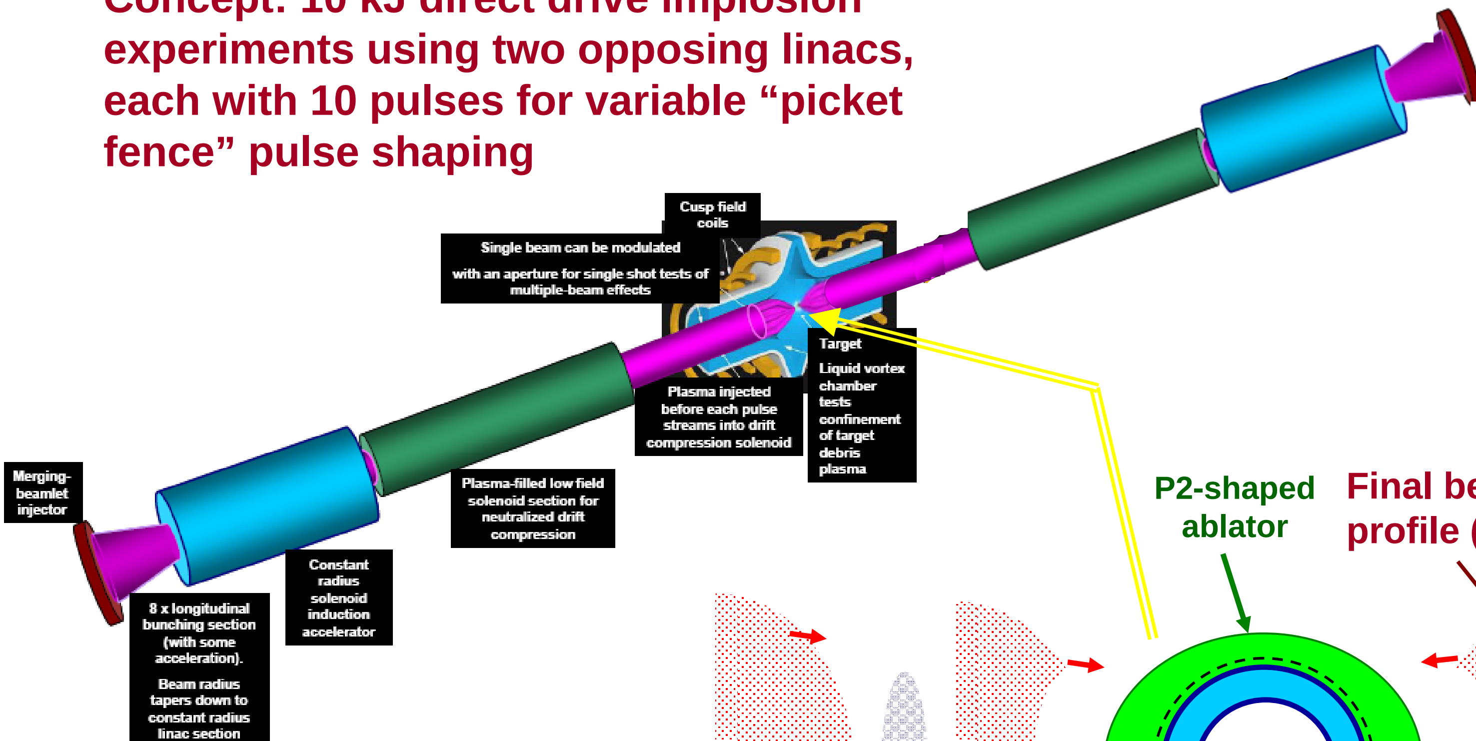
(2) How is RT growth affected (any "cloudy day" effect?)

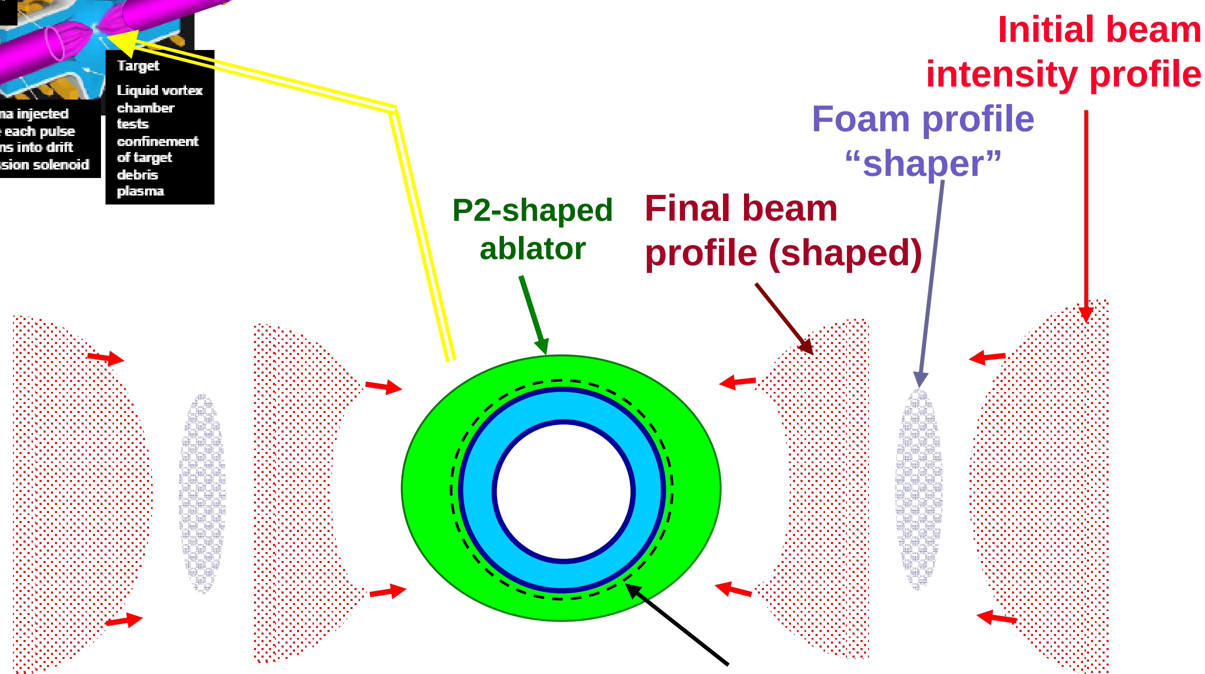
With laser direct drive, later pulse ablates at fresh critical density layer further left

With laser direct drive, ablation plasma << critical density,
→Later laser light transmits through ablation plasma.
→Absorption in inverse bremsstrahlung layer moves left as ablator layer erodes

Campaign Level II: In addition to IB-HEDPX, a new accelerator tool is needed to explore heavy-ion-specific fusion target physics in parallel with NIF operation

Concept: 10 kJ direct drive implosion experiments using two opposing linacs, each with 10 pulses for variable “picket fence” pulse shaping





Three “knobs” to control P2 asymmetry with two beams:
1. **Upstream GHz wobblers**
2. **Foam profile shapers**
3. **Ablator shaping**

Goal is implosion drive pressure on the Cryo D_2 payload with < 1 % non-uniformity

What is the present status?

▪ NDCX experiments demonstrate short pulse feasibility: 150 ns compressed to 3 ns FWHM @ β =0.01 → these same bunches would be 15 ns compressing to 300 ps (150 ps rise) @ β = 0.1. Limit of 200X compression ratios is expected. No limit on final beam perveance in background plasma. Solenoid focus tests next year. Available ATA equipment + 60 ns bunch injector allows major upgrade in 3 years. IBEAM systems studies show high modular induction linac system efficiency 25 to 50% @ 1 MJ.

▪Fast solid state switching (20 ns rise) and beam kickers now demonstrated successfully on DARHT→ supports new multi-pulsing concepts and smaller focal spots with chromatic corrections (Ed Lee).

▪Basic principles of vortex control (tangential injection and ejection) demonstrated at UCB→ allows flexible free liquid surface geometry control→ compatibility with axisymmetric focus magnets. Turbulence supports high surface heat fluxes. Many opportunities to optimize (Peterson/Philippe).

→ Biggest current missing element: we have not yet developed a heavy ion target design that meets our goals: Minimum gains > 40 @ < 1 MJ total beam energy, spot size requirement > 0.7 to 2 mm radius (for beam emittances of 1 to 2 mm-mr, respectively). John Perkins suggests using polar direct drive, possible also with shock ignition. We have conceptual ways to provide the shorter pulses and higher peak power levels needed. (much easier than 200 kJ in <100 ps and < 50 micron spots for fast ignition!)

To fulfill this vision, we must be…

innovative and creative…

"Ah, but a man's reach
Should exceed his grasp,
Or what's a heaven for?"
- *Robert Browning*

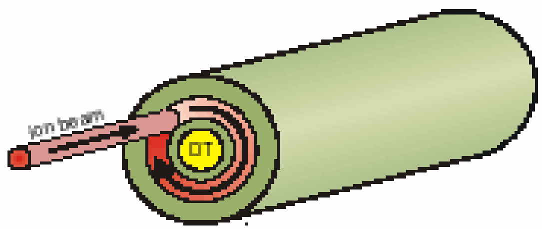
..but also careful and wise…

"Mental things which have not passed through understanding are vain and give birth to no truth other than what is harmful. Those who wish to grow rich in a day shall live a long time in great poverty, as happens and will in all eternity happen to the alchemists, the would-be creators of gold and silver."
- *Leonardo Da Vinci*

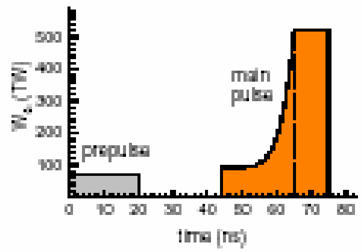
(IAEA-2004) M. Basko summary of Russian studies of fast ignition using 100 GeV heavy-ion synchrotrons:

Fast ignition with heavy ions: target performance

Direct drive cylindrical target: compression stage

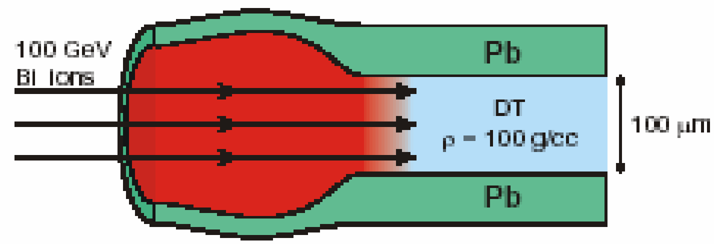


Compression pulse:



- Target compression is accomplished by a separate beam of ions with the same energy of E_i = 0.5 GeV/u.
- Azimuthal symmetry is ensured by fast beam rotation around the target axis (~10 revolutions per main pulse).
- Relative inefficiency of cylindrical implosion is partly compensated for by direct drive.

Ignition and burn propagation



Ignition pulse:

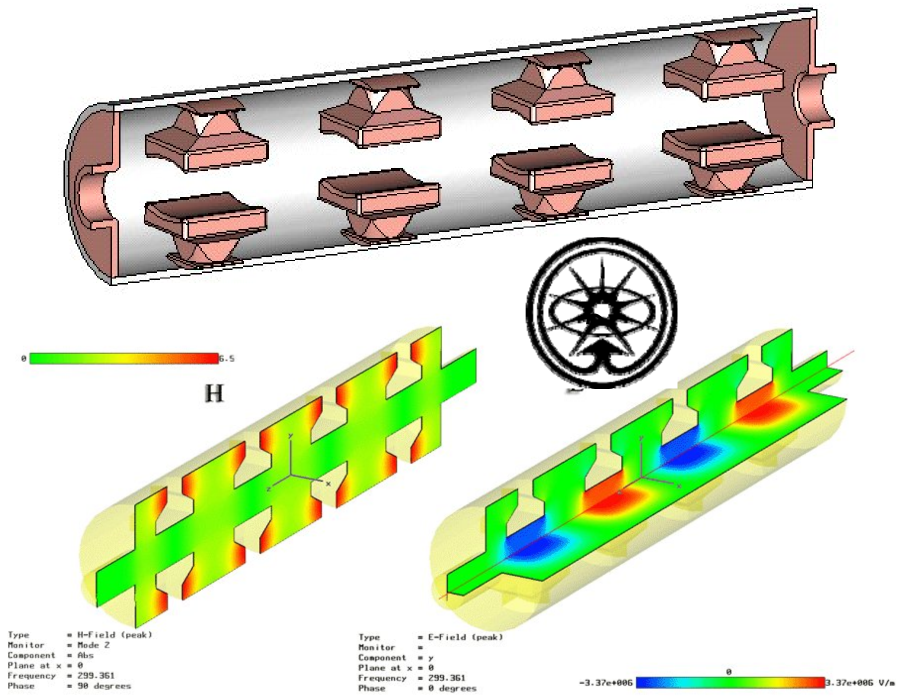
beam energy:	E_{igb} = 400 kJ
pulse duration:	t_{igp} = 200 ps
beam power:	W_{igb} = 2 PW
focal radius:	r_{foc} = 50 μm
irradiation intensity:	$I_{igb} = 2.5\times10^{19}$ W/cm^2

2-D hydro simulations (ITEP + VNIIEF) have demonstrated that the above fuel configuration is ignited by the proposed ion pulse, and the burn wave does propagate along the DT cylinder.

An energy gain of $G \approx 100$ can be expected.

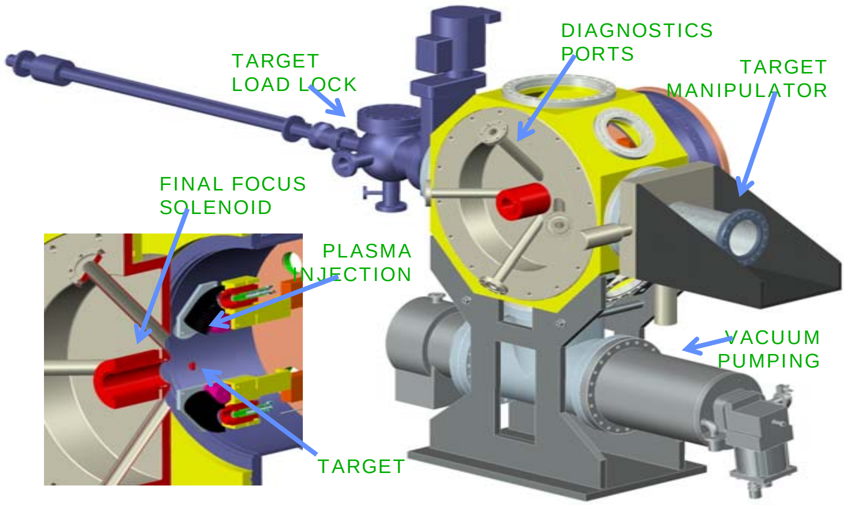
The LAPLAS technology could provide the means for driving the ITEP heavy ion target design.

Design of rf beam deflector (wobbler)

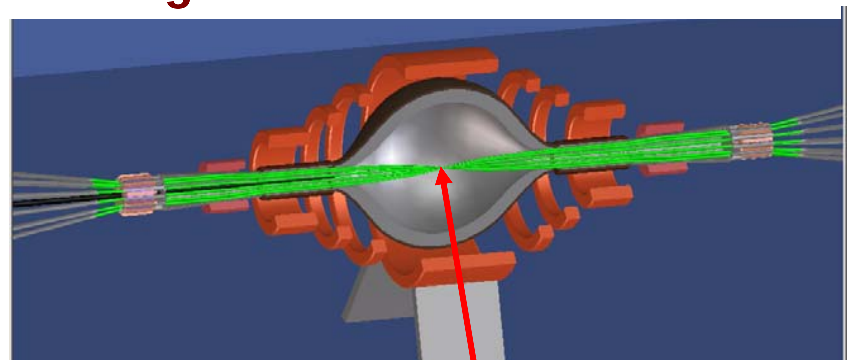


Can a new approach to heavy ion fusion reduce the time between near-term research and fusion energy?

WDM target and chamber



HIF target and fusion chamber



NDCX (2008)	*LLF (2011 potential?)*
400 keV	*60 MeV (Ar^{+8}@7.5MV)*
1 MW peak	*3 GW peak*
3 ns	*1 ns*
3 mJ	*3 J*
1 mm rspot	*0.5 mm r_{spot}*
3 μm range	*100 μm in solid H_2*

↑Focus for our WDM group next two years

Validated science can give confidence in scaling
←--------→

New heavy ion fusion?
200 MeV (Ki^{+8}@ 25 MV)
300 TW peak
14 ns effective, shaped
1 MJ
0.5 to 1 mm r_{spot}
100 μm in DT

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 (Small Modular HIF Driver) describes one possible solution for improving HIF driver development path; this meeting focuses on target/chamber aspects:

Low yield targets + high pulse rate vortex chambers might satisfy “Demo-small,-then grow large” desired development path objective for low unit cost electricity & hydrogen fuel production.

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.

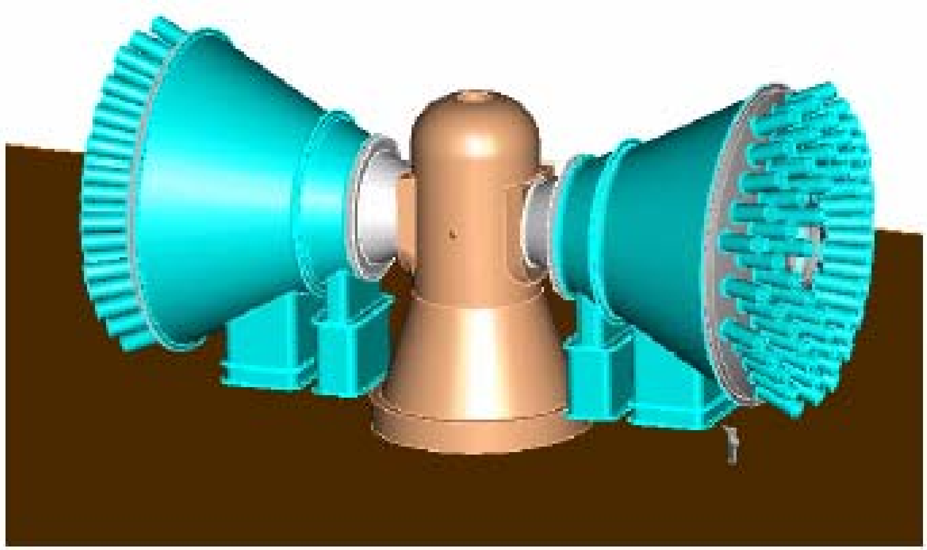
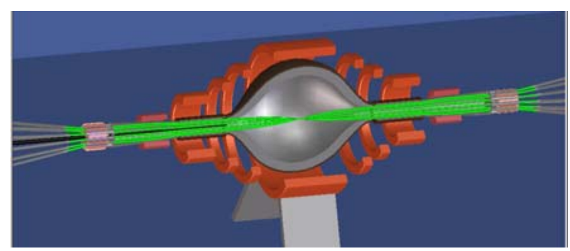
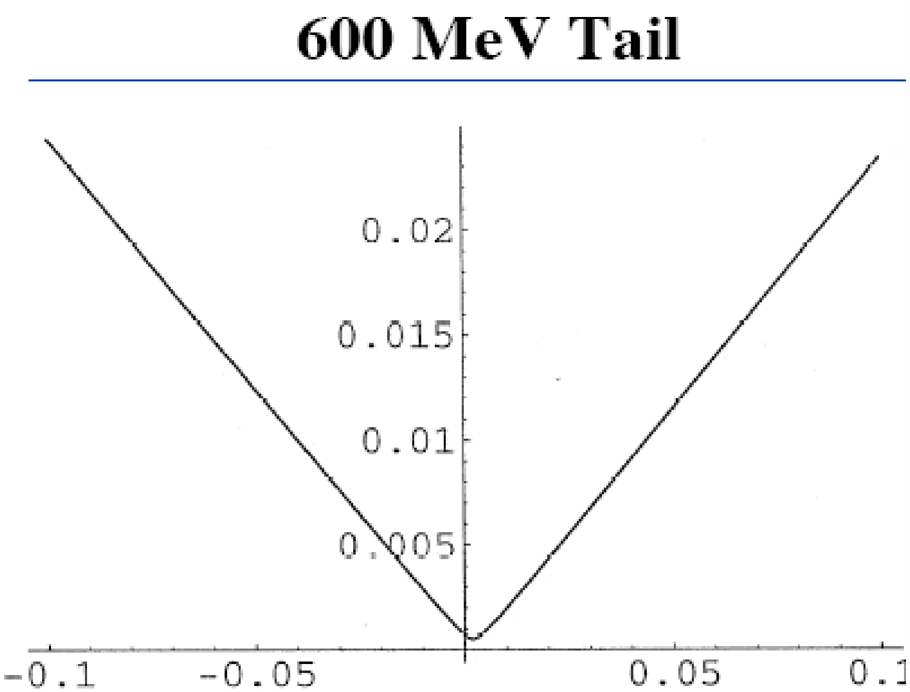


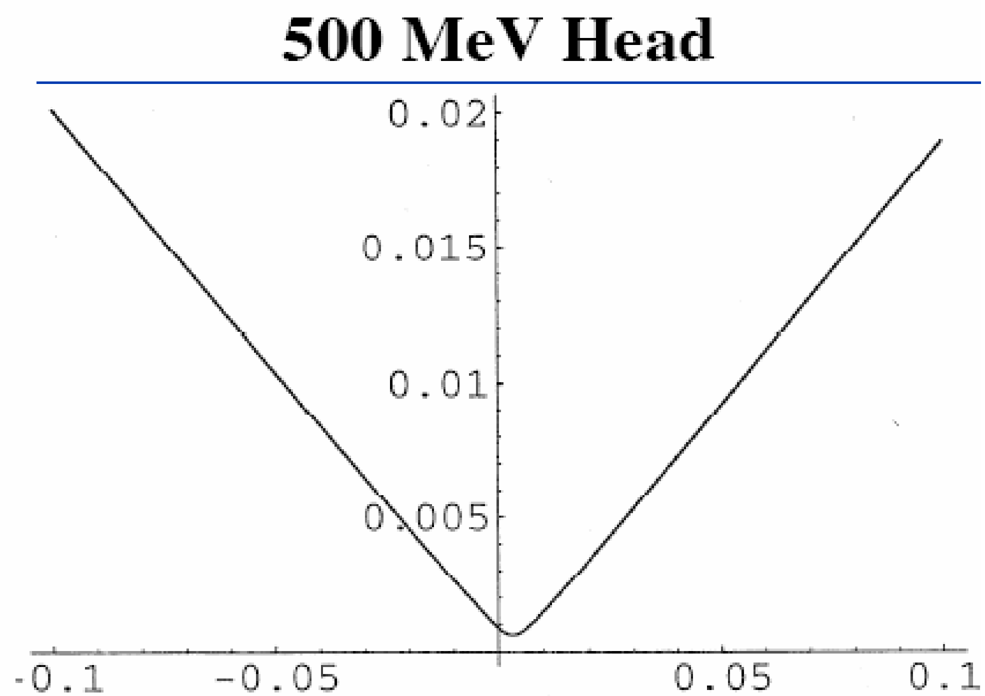
Fig. 3. An isometric view illustrating the coupling of final focus magnet array with the chamber.

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?



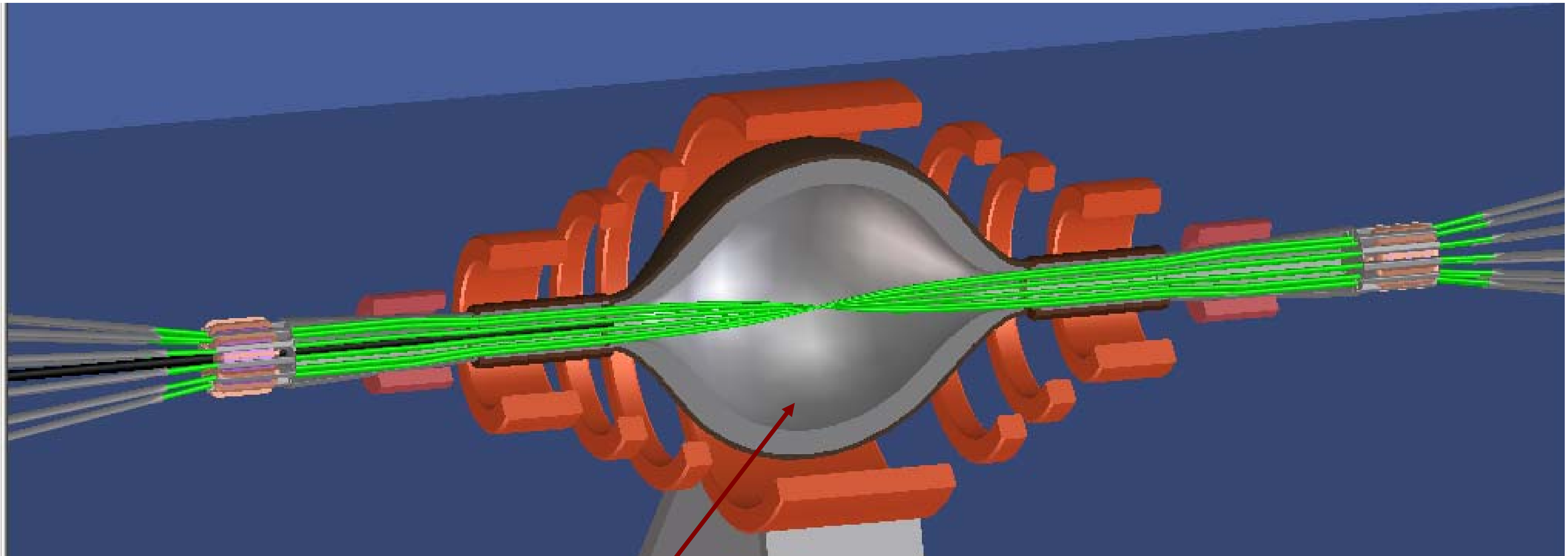
In the absence of space charge within background plasma, Ed Lee's Mathematica model for axisymmetric vortex chamber magnetic fields including aberrations shows sub-millimeter spots for Ar^{+8}





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)



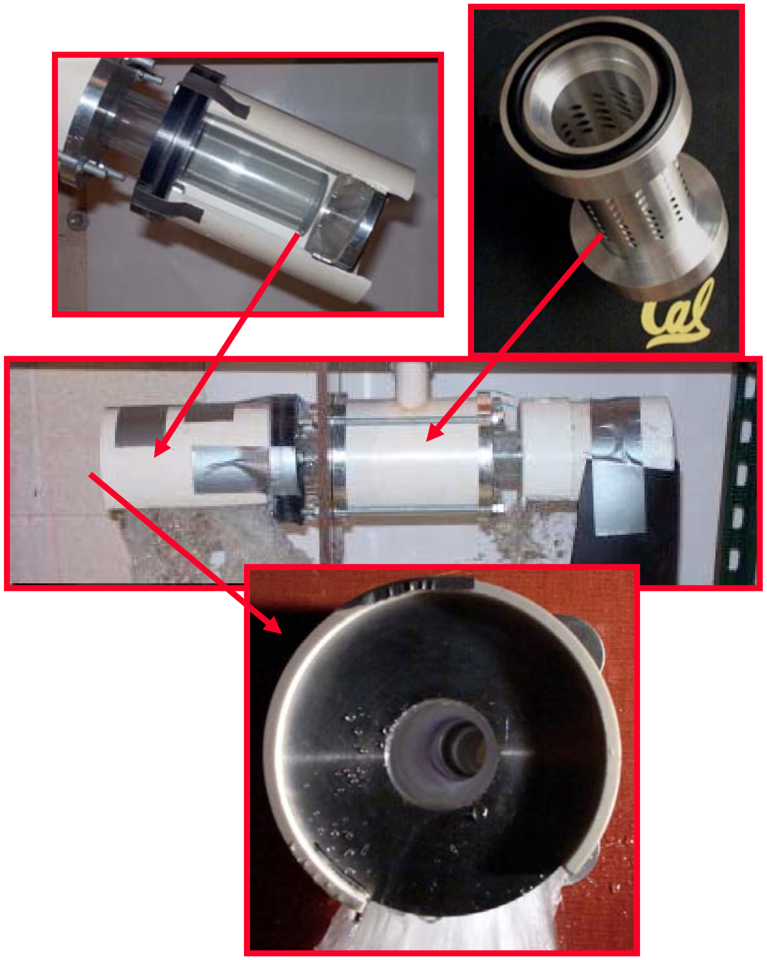
Assume ~1 m^3 cavity volume, 2 m^2 liquid cavity surface, ~ 40 MJ magnetic field energy damps turbulence from 30-40% of fusion yield captured into a special target coated with a thick Flibe layer

Liquid Flibe | **Dense vapor** | **Magnetized resistive plasma**

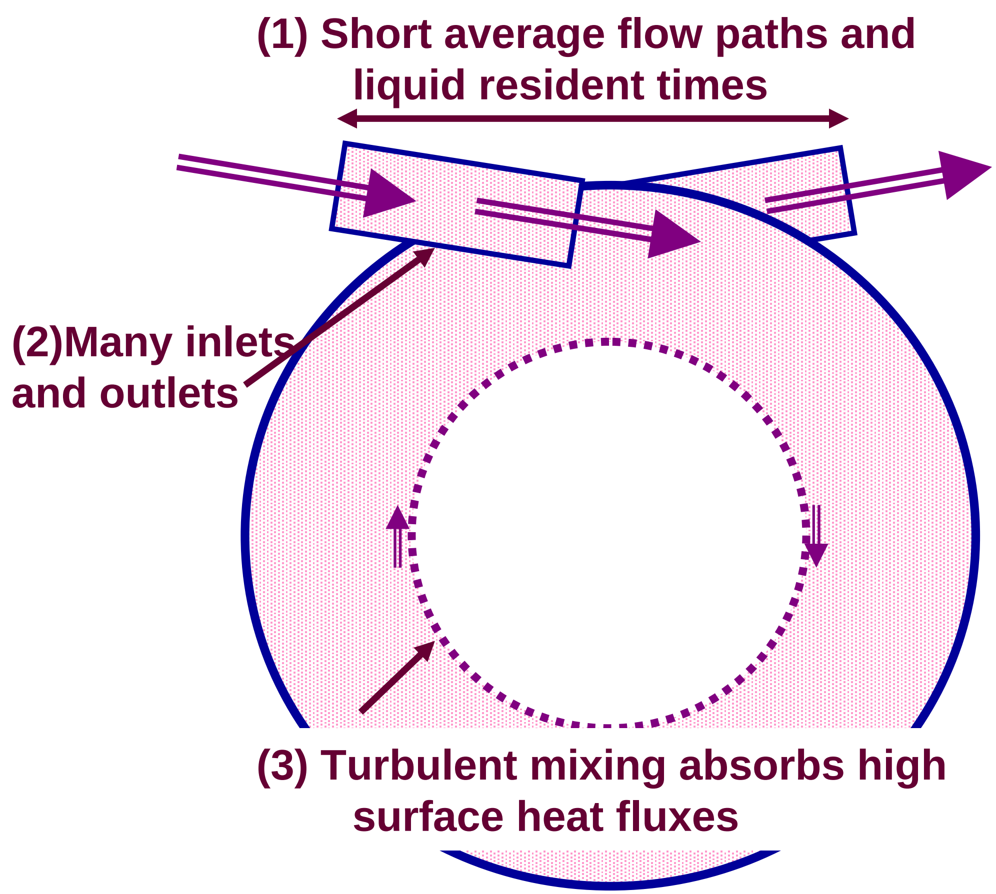
Constant pressure (r) to liquid (after a few bounces)

← Density gradient   Temperature gradient →

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*