HIF preparation strategy for the NAS-IFE review

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Program Advisory Committee meeting December 8, 2010 at LLNL

The following NAS-IFE charges…

- Assess the prospects for generating power using inertial confinement fusion;
- Identify scientific and engineering challenges, cost targets, and R&D objectives associated with developing an IFE demonstration plant; and
- Advise the U.S. Department of Energy on its development of an R&D roadmap aimed at creating a conceptual design for an inertial fusion energy demonstration plant.

A subpanel on Fusion Target Physics will assess the current performance of fusion targets associated with various ICF concepts in order to understand the spectrum output, the illumination geometry, the high-gain geometry, and the robustness of the target design.

…lead to PAC Charge # 2: Heavy Ion Fusion Plans for NAS. The NAS charges for inertial fusion energy roadmap plans for each IFE candidate are quite broad in science and technology scope for drivers, chambers, and targets. Please review and provide advice on the balance and emphasis for R&D on heavy ion fusion options that could be proposed in response to the two NAS review charges. Could the proposed heavy ion fusion R&D effort be more selective and focus on fewer options, (to be spread less thinly), while still avoiding making premature down selections? Please comment on where our proposed strategy might be improved.

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We are very pleased to have the opportunity to describe a research agenda specifically aimed at heavy ion fusion energy.

Our strategy is to:

1. **Update the Snowmass roadmap of three steps to an IFE Demo for induction linac driver and low cost liquid chamber technology R&D, as incorporated in 2003 and 2004 FESAC reports, including recent advances;**
2. **Exploit HEDP advances: next five years use NDCX-I, NDCX-II and its extension to IB-HEDPX to test HIF-relevant beam manipulations (Alex Friedman);**
3. **Plan modifications of existing facilities (e.g., HCX, NDCX-I) as test beds for dynamic vacuum/e-cloud accelerator R&D @ 5 Hz (Peter Seidl);**
4. **Optimize a variety of HIF targets that exploit high efficiency HIF drive; (John Perkins);**
5. **Seek ways to simplify the driver-chamber-target for an HIF Demo with single-side drive [E.g., the X-target concept (Enrique Henestroza)];**
6. **Host 2011 workshop on Accelerators for Heavy Ion Fusion to assess advances in accelerator driver technology (Peter Seidl);**
7. **Evolve a flexible HIF develop plan that exploits collaborations and avoids premature downselections. The last talk of this session will elaborate (Logan).**

Heavy ion fusion has been considered for a variety of driver, focusing, chamber, and target options:

Accelerator
- Induction Linac
- RF Linac
- RF Linac + Storage Ring/ Synchrotron
- Induction Recirculator
- Dielectric Wall Accelerator

→

Focusing
- Ballistic, Neutralized
- Ballistic, Vacuum
- Self Pinch, 2-stage

→

Chamber
- Thick-Liquid-Protected Wall
- Thin-Liquid-Protected Wall
- Solid Dry Wall + Gas Fill
- Granular-Solid Flow Wall

→

Target
- Indirect Drive, Central Hot Spot Ignition
- Indirect Drive, Fast ignition
- Direct Drive, Central Hot Spot Ignition
- Polar Direct Drive + Shock Ignition
- Hydro Drive +Fast or Shock Ignition

The US has focused on induction linacs, but advances in RF technology warrant re-assessment in the spring 2011 workshop. Any driver with ~ 100 beams, and with liquid chambers, could apply to most target options.

All heavy ion fusion R&D plan options can exploit long-recognized HIF advantages:

(a) **High energy particle accelerators of MJ-beam energy scale have separately exhibited intrinsic efficiencies, pulse-rates, average power levels, and durability required for IFE.** ***Advantage of being able to build upon a credible high energy particle accelerator experience base.***

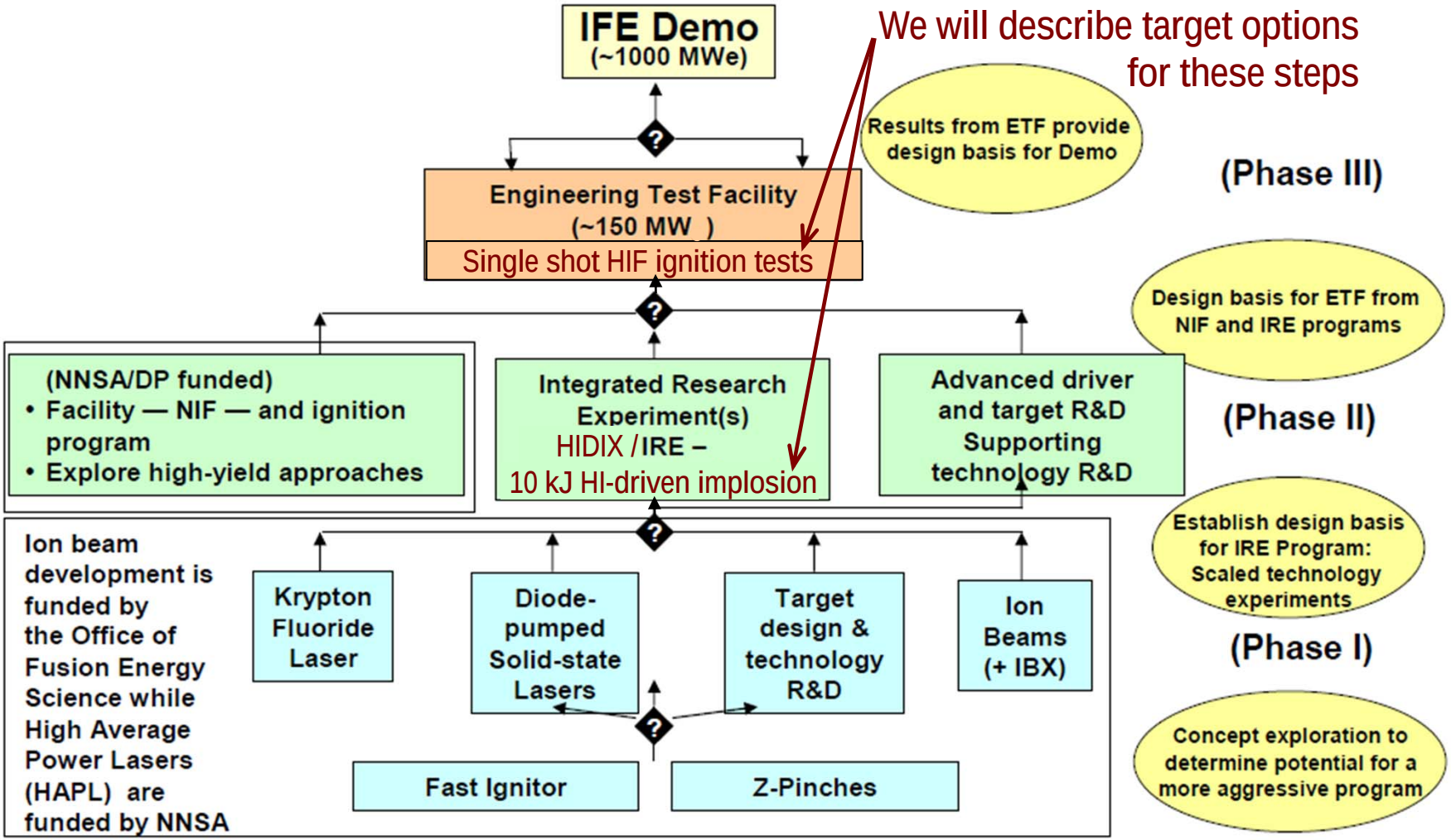
(b) **Thick-liquid protected target chambers with 30 year plant lifetimes, compatible with heavy ion beam propagation in the chamber.** ***Minimizes risk from a long fusion materials development program outcome.***

(c) **Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron and gamma radiation.** ***Detailed studies show shielded final focus magnets can last for many full power plant years of operation.***

(d) **Because heavy ions can penetrate metal cases surrounding cryogenic-DT fuel, heavy ions can drive targets efficiently, and injected HIF targets can be protected against hot IFE chamber gas.** ***Facilitates target injection.***

(e) **Studies find competitive economics and attractive environmental characteristics (no high level waste; only class-C low level waste).** ***Molten salt (HYLIFE-II type) chambers designed to last for 30 year plant life.***

The HIF roadmap, like Snowmass and 2003/2004 FESAC plans, has three steps to an HIF Demo: a ~10-kJ-scale IRE→ single shot ignition tests @ ~1-2 MJ→ ~100 MW-average-fusion-power ETF



(from 2002 Snowmass Executive Summary for IFE - John Lindl)

Figure 3. The Inertial Fusion Energy Roadmap

Our strategy remains consistent with HEDP in the near term and HIF in the longer term (slide from the August 2008 HIFS-VNL PAC):

Science Area	FY07 through FY09	Five-Yr-Plan FY10 through FY14	FY15 through FY 18	FY19 through FY26
Beam-Target Interaction	Target design, initial WDM experiments, fast beam diagnostics, beam dE/dx	Explore a variety of new WDM and Initial beam-cryo D2 target interaction at 1 eV.	-Construct IB-HEDPX. -Develop beam target physics basis for HIDDIX on NDCX-II.	-Operate IB-HEDPX user facility 1-10 eV HEDP, critical point properties -Physics of beam-driven heavy ion fusion targets
Focusing onto Targets	Optimize high-B final focus together with near target plasma sources	Beam target interaction with ramped ion ranges. Time dependent focusing corrections.	NDCX-II planar direct drive experiments with ramped range and rotating beam spots	Optimize techniques for two sided direct drive-tailor beam ion range on target in time and in radius.
Longitudinal Beam Compression	Optimize longitudinal and transverse focusing with new induction buncher	Compress ramped range beams with beam spot rotation to high rotation frequencies.	Optimize compression and focusing using ramped and rotating beams	Optimize techniques for ramping up the beam power on target for low adiabat compressions.
High Brightness Transport	E-cloud in quads and solenoids, beam steering and brightness optimization	Perpendicular and parallel brightness of beams in neutralized drift and for beam stripping on plasma jets.	Develop high brightness injectors for HIDDIX with beam stripping and ramped energy beams	Identify sources of beam emittance growth and ways to mitigate those mechanisms to minimize target spot sizes
Advanced Theory and Simulations	Advanced source-to-target models, and source-through-target modeling	Develop models for beam compression, rotation and zooming. Develop beam-driven target hydro and Rayleigh Taylor stability model	Integrated accelerator-to-target models for IB-HEDPX exps. Physics design support for HIDDIX linac and targets.	Integrated accelerator beam dynamics and brightness evolution together with target hydro-response modeling to guide IB-HEDPX and HIDDIX experiments
Facility & resource needs (estimated in constant dollars)	1. Optimize NDCX-I with new tilt core, plasma sources, and higher-B final focus magnet. 2. Test ATA equipment for NDCX-II. 3. Develop diagnostics. **$7.8 M/yr total**	1. Operate NDCX-I for 0.5 eV WDM - -two phase and ion-ion plasmas. 2. Assemble NDCX-II using existing ATA accelerator modules. 3. Operate NDCX-II for 1eV HEDP and planar direct drive experiments. **$10M/yr increasing to $16 M/yr tot.**	1. Construct IB-HEDPX and develop users ($20M/yr) 2. Design and R&D for HIDDIX (Use NDCX-II with mods + component R&D ($20M/yr) **~ $40M/yr total**	1. Operate IB-HEDPX and support users ($20M/yr) 2. Construct heavy ion direct drive implosion physics facility HIDDIX (30M/yr) 3. Target & chamber R&D needed for IFE and for HIFTF ($10M/yr) **~ $60 M/yr tot.**

First heavy ion WDM experiment @ < 1 eV

NDCX-II assembly starts

NIF National Ignition Campaign

NDCX-II validates IB-HEDPX design. Begin IB-HEDPX construction. Begin Design and R&D for HIDDIX.

Begin HIDDIX construction

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

* Updated and extended from Fig. 3.1 of National HEDP Task Force Report

A balanced HIF R&D portfolio to support the HIF roadmap requires :

Target physics & design

Direct and indirect drive targets for power plant and for an intermediate target and accelerator physics facility

Symmetry, Stability, beam pointing, distribution

Accelerator physics & driver design:

Multi-beam ion sources, injection, matching

Controlling beam-plasma interactions

Focusing elements: magnetic, electric quads, solenoids

Halo formation and control

Acceleration

Neutralized & un-neutralized drift compression

Achromatic focusing systems

Time dependent chromatic correction

Final focusing, reactor interface, design

•Reactor and driver interface

•Tritium breeding

•Radiation shielding

•Liquid protection

•Enabling technology

•Advanced plasma source development

•Pulsed power

•Insulators (eg: glassy ceramics, embedded rings)

•Superconducting materials (Nb3Sn)

•Quadrupole, solenoid design

•Focusing arrays

•Reactor materials and components

->We seek NAS support for a balanced near-term HIF program.

The Snowmass 2002 white paper was used during the 2003 and 2004 FESAC reviews, and gives more specific detail on tasks, costs and schedule needed for accelerator, target and chamber R&D.

Heavy Ion Fusion White Paper 9-20, 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, and Patrick O'Shea
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Estimated overall HIF R&D cost and schedule is similar to the 2002-2003 plans, except dates moved forward ~8 years. Projected budget needs higher than in our 20-year science plan to enable more robust technology R&D on accelerator, liquid chamber, target fabrication, and injection.

*Heavy Ion Fusion White Paper -- Strategic Plan and Research Needs for Heavy-Ion Fusion Energy Development: An Integrated Research Program, G. Logan et al.,(2002)

Fiscal year	04	05	06	07	08	09	10	11	12	13	14	15	16
1. Accelerator R&D	24	31	34	34	34	37	37	37	80	80	80	80	80
Integrated modeling	3	4	4	4	4	4	4	4	5	5	5	5	5
Supporting science	10	7	7	7	7	7	7	7	7	7	7	7	7
IBX construction		10	14	14	12								
IBX operating						14	14	14	7	7	7	7	7
IRE construction									55	55	55	55	55
Enabling accelerator	8	7	6	6	6	6	6	6	6	6	6	6	6
Advanced accelerator	3	3	3	3	5	6	6	6					
2. HIF target physics	3	3	3	3	3	3.5	3.5	3.5	6	6	6	10	10
HIF target design	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5	2.5	2.5	2.5	5	5
HIF target exps.	1.6	1.6	1.6	1.6	1.6	2.0	2.0	2.0	3.5	3.5	3.5	5	5
3. HIF target/chamber	8	8	8	8	8	9.5	9.5	9.5	14	14	14	20	20
HIF target fab/ inj	4	4	4	4	4	5	5	5	9	9	9	12	12
HIF chamber	4	4	4	4	4	4.5	4.5	4.5	5	5	5	8	8
Total HIF R&D budget	35	42	45	45	45	50	50	50	100	100	100	110	110

To be updated to reflect accelerator, target physics progress.

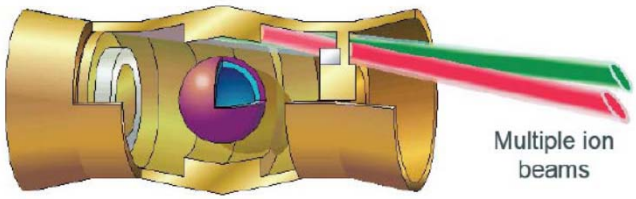
R&D for driver, chamber, and target fabrication are governed by target design requirements.

HIF should not be limited solely to central hot spot ignition, as new targets using shock ignition or fast ignition may best exploit deeply penetrating heavy ion beam energy deposition.

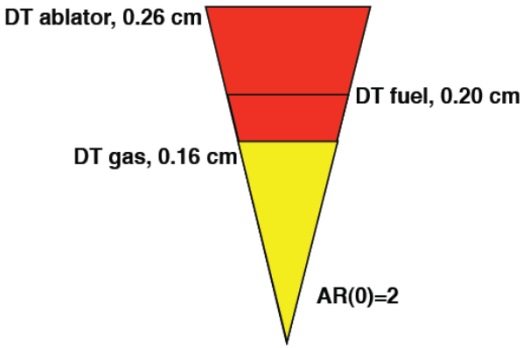
There are several classes of HIF targets to consider with different risks and R&D paths.

There are three classes of options for heavy-ion-fusion targets (Perkins/Henestroza). Each has several variations. Examples shown have 2-D target designs done or "in the hopper".

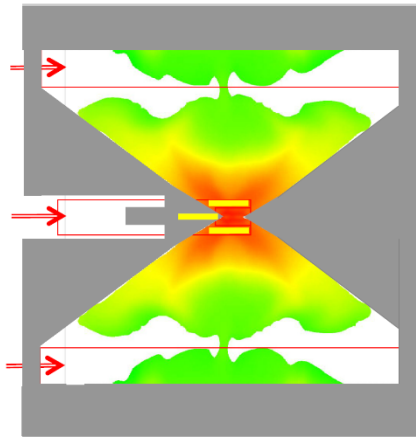
1. **<u>Indirect drive (2-sided hohlraum)</u>** ***2-D Lasnex design (2002):*** **7 MJ, 3→ 4 GeV Bi^{+1} , gain 68.**
   Two-sided illumination, like NIF.



2. **<u>Heavy-ion direct drive</u>** ***1-D Hydra design (2010):***
   3.6 MJ, 0.22 → 2.2 GeV, Hg^{+1} ion beams, gain 150.
   Future 2-D design planned for polar drive illumination, tamped, with shock ignition.

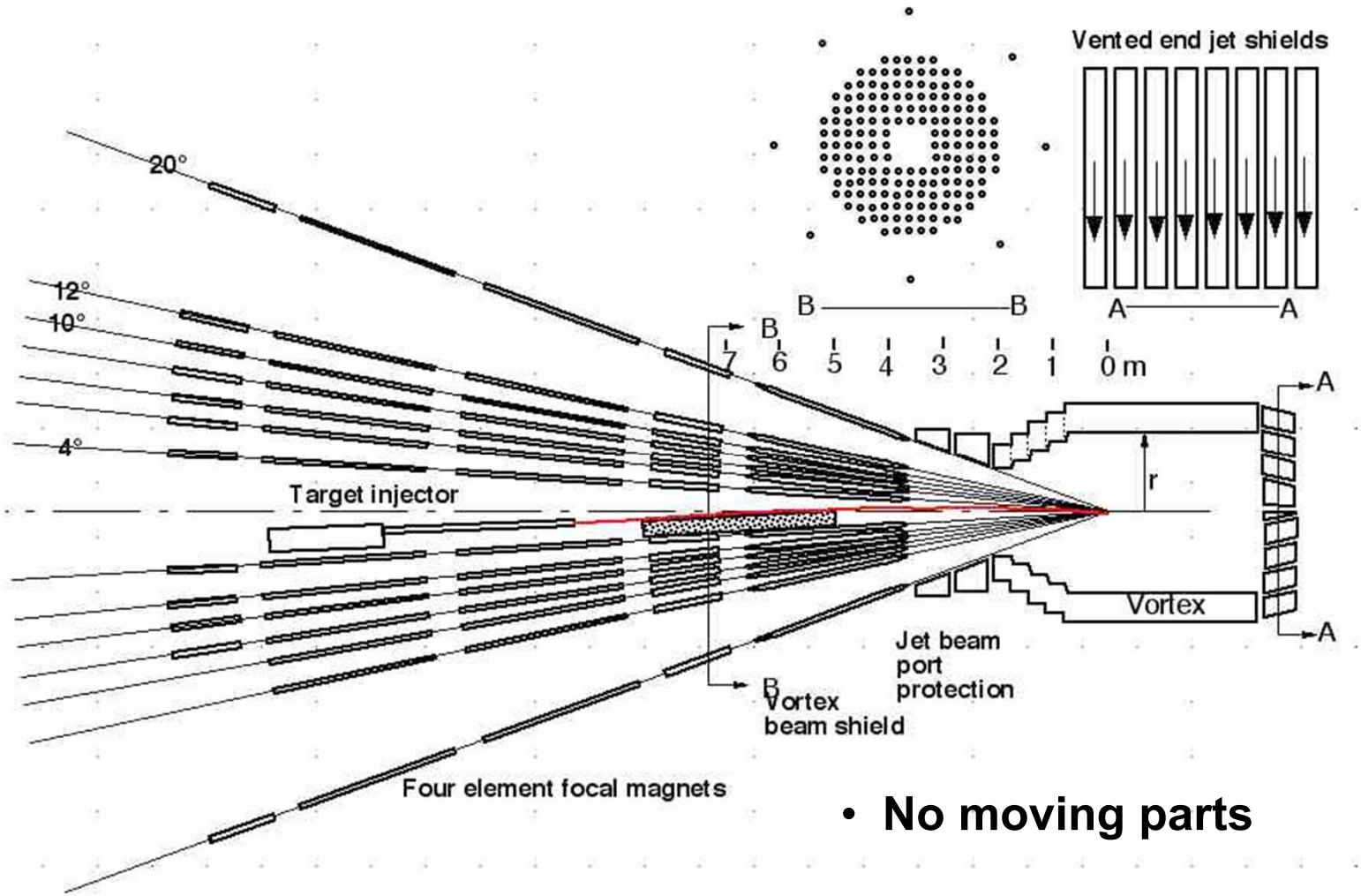


3. **<u>X-target hydro-drive</u>** ***2-D Hydra design (2010):***
   3 MJ compression+3 MJ ignition, all 60 GeV U beams, gain 50. One-sided illumination (publication submitted)



→All three options are intended to use multiple-beam linac drivers with thick-liquid-protected chambers to mitigate material neutron damage risks.

Liquid jets and a vortex chamber protect solid structures for the life of the plant (R. Moir Dec. 6, 2010)

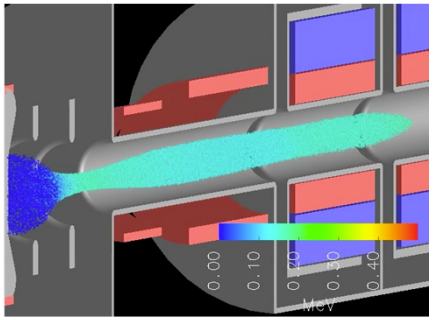


- **No moving parts**

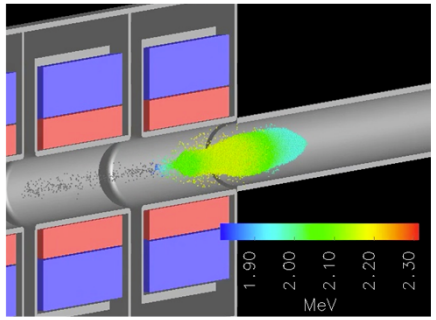
NDCX-II now under construction will provide a test bed for HIF beam manipulations over the next five years (Alex Friedman)

- 11 M$ construction began July 2009, to be completed in March of 2012
- Rapid initial bunch compression allows re-use of 70-ns pulsed power sources from the ATA accelerator, and compressed to sub-ns.
- Detailed 3-D simulations using the Warp code confirmed the physics design & set engineering requirements
- rapid initial bunch compression could reduce front end length and cost for HIF drivers

During injection



Entering final compression

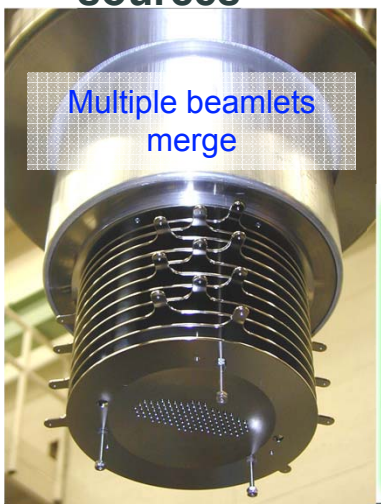


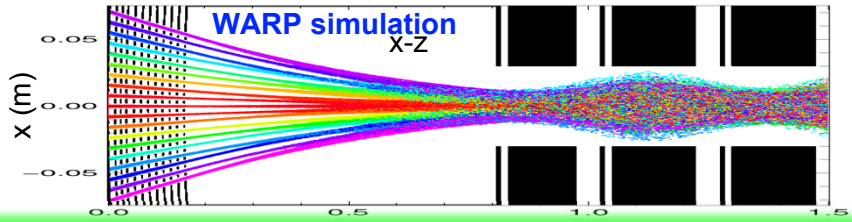
Ref: A. Friedman, et al., *Phys Plasmas*, 2010)

	NDCX-I	NDCX-II (baseline)
Ion species	K^+ (A=39)	Li^+ (A=7)
Ion energy	300-400 keV	(1.2 MeV) → > 4 MeV
Focal radius	1.5 - 3 mm	(0.5 mm)
Pulse duration	2 - 4 ns	~(1 ns) → < 200ps
Peak current	~ 2 A	~ (10 A) → > 100 A

Need for driver-scale beam experiments: Sources, injection, matching, transport. Must preserve brightness in the presence of high space charge <u>at ≈ 5 Hz.</u> The beam is susceptible to beam-gas, e-cloud effects.

(a) High current, low emittance, surface ionization sources and **<u>multi-aperture gas</u>** **sources**

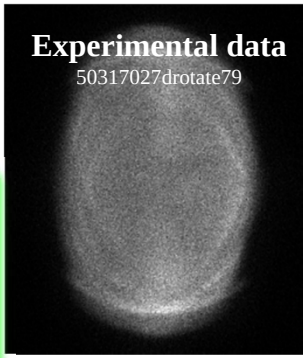




Remaining issues: Compact **arrays & gas load, matching, reliability, lifetime.**

Neg. ions? Higher charge states?

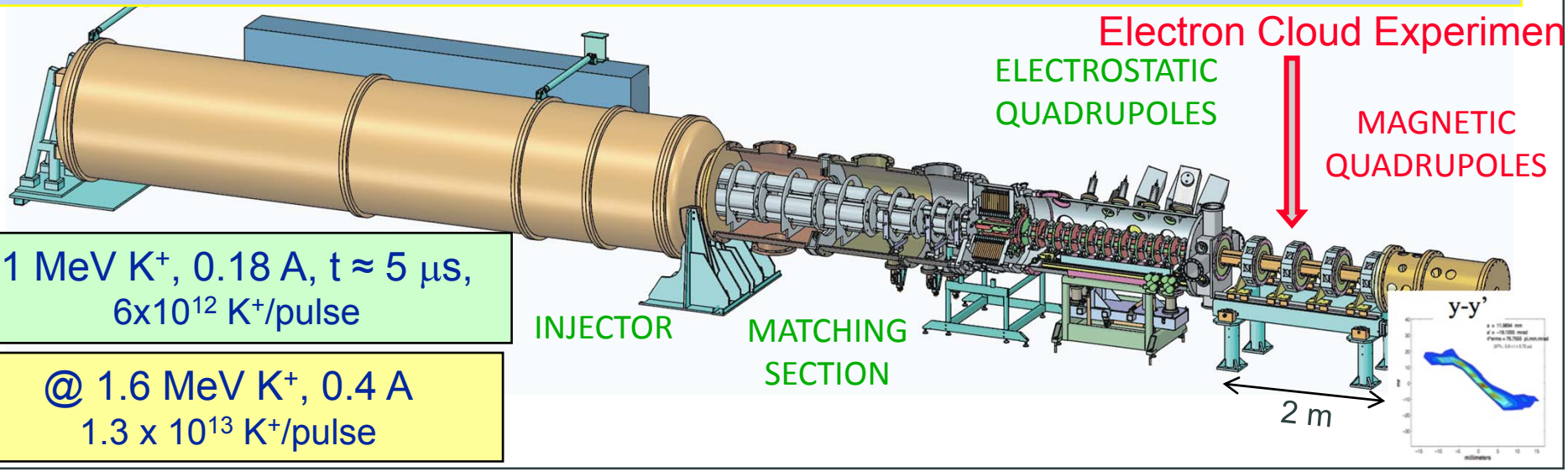
<u>Study at 5 Hz (driver repetition rate)</u>



<u>Energy</u>	<u>Current</u>
0.4 MeV	71 mA
1.6 MeV	568 mA

ε_n < 1 mm•mrad

(b) **Injection, matching, transport** (HCX): explore & control e-cloud, halo-induced gas build-up



1 MeV K^+, 0.18 A, t ≈ 5 μs,
6×10^{12} K^+/pulse

@ 1.6 MeV K^+, 0.4 A
1.3×10^{13} K^+/pulse

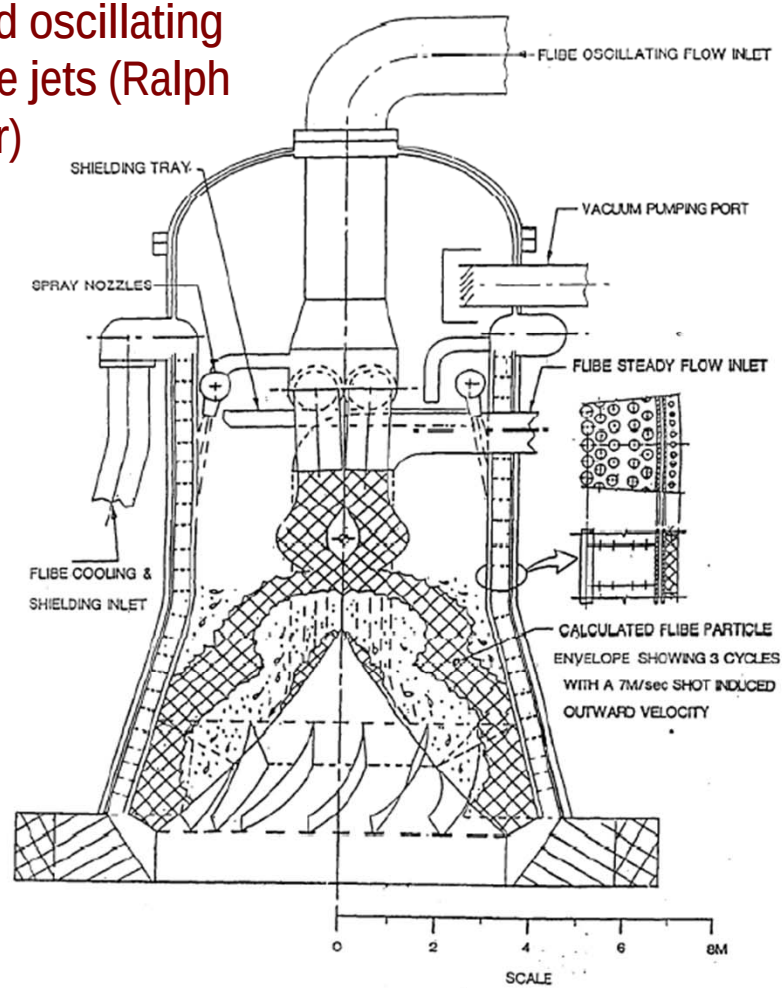
Conclusion

- Heavy ion fusion has a variety of driver, focusing, chamber, and target options: downselection is not required before NIF ignition;
- All heavy ion fusion R&D plan options can exploit long-recognized HIF advantages;
- Our strategy remains consistent with HEDP in the near term and HIF in the longer term;
- Advances in accelerator technology and target design need to re-assessed.

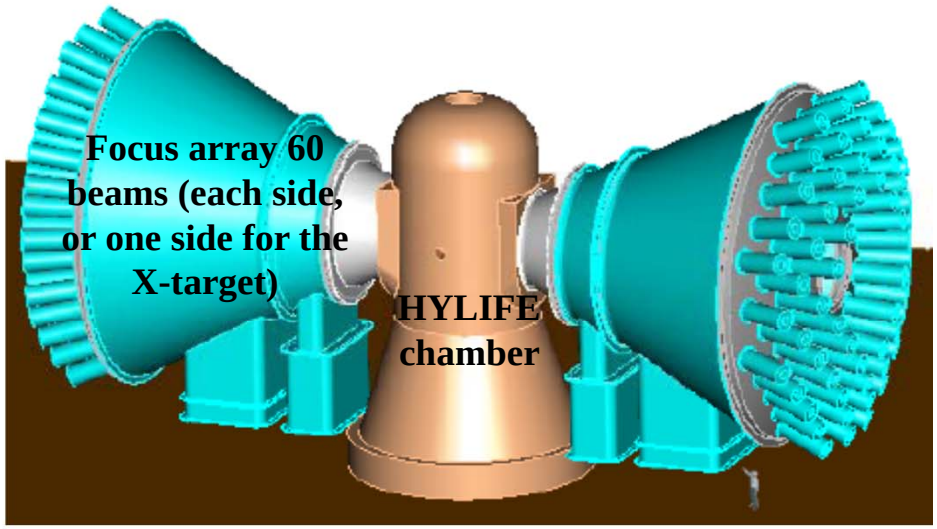
Backup slides

Thick liquid protected chambers lower R&D cost compared to solid first wall materials R&D. Ion beam propagation and final focusing magnets are compatible with high temperature Flibe vapor.

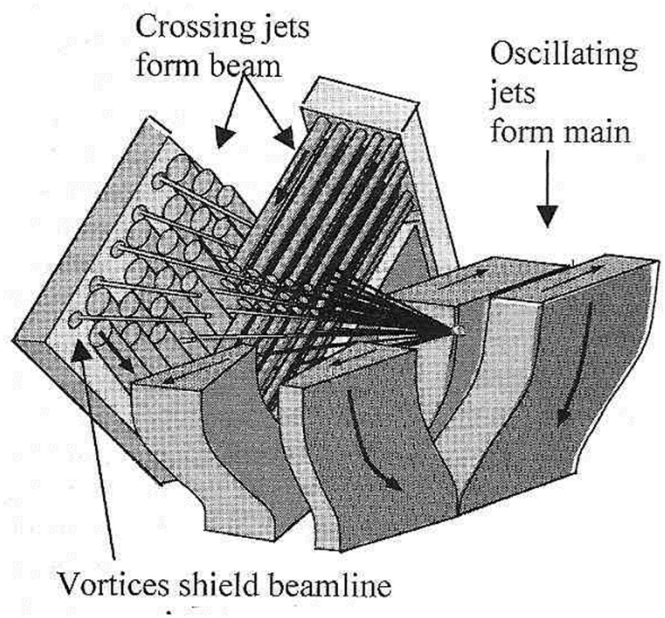
HYLIFE-II chamber used oscillating Flibe jets (Ralph Moir)



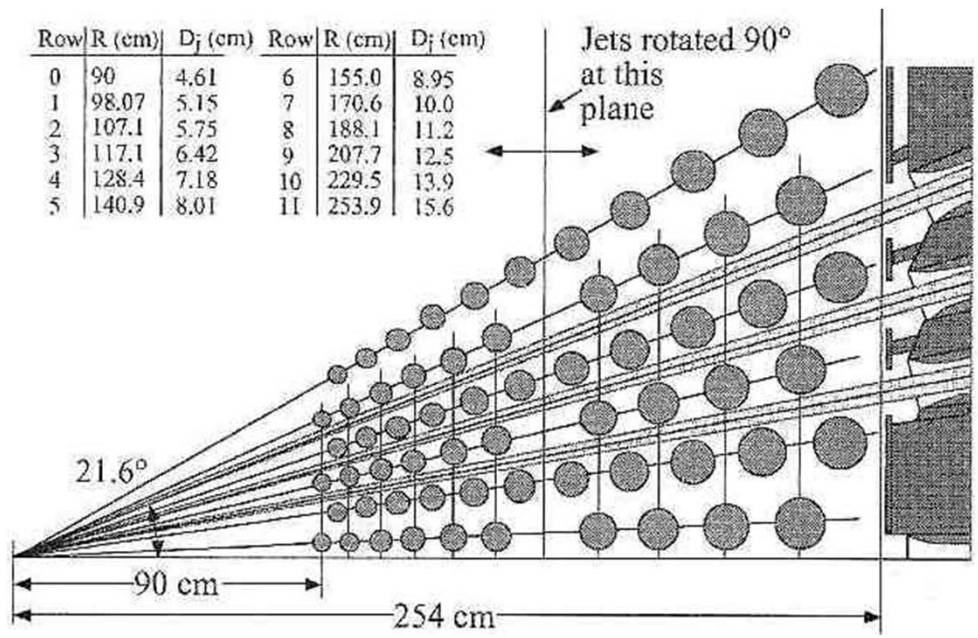
Indirect drive, polar direct drive, and X-targets could all be adapted to use liquid chambers and compatible focusing optics.



Liquid jets protect beam ports from neutron damage



Row	R (cm)	D_j (cm)	Row	R (cm)	D_j (cm)
0	90	4.61	6	155.0	8.95
1	98.07	5.15	7	170.6	10.0
2	107.1	5.75	8	188.1	11.2
3	117.1	6.42	9	207.7	12.5
4	128.4	7.18	10	229.5	13.9
5	140.9	8.01	11	253.9	15.6



- **Alternative chamber uses oscillating jets for wall protection but has moving parts**