Update on Progress and Current Research in the Development of Heavy Ion Fusion

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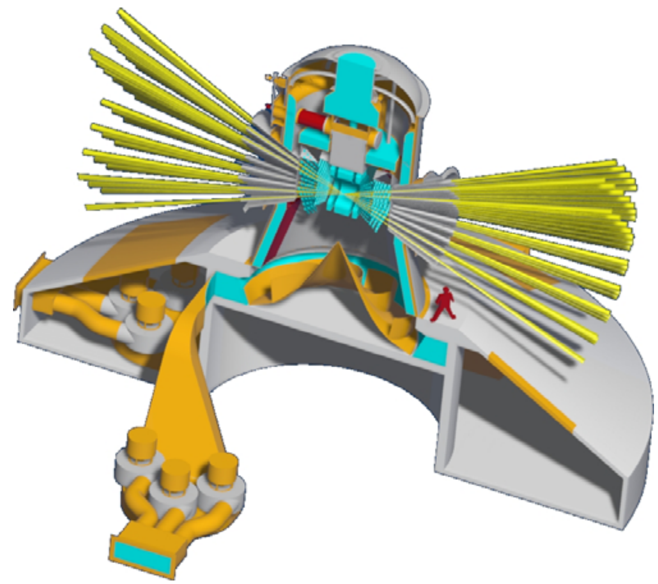
14-16 September 2004



Cut-away of chamber design for Robust Point Design (TOFE 2002)

* This work performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Heavy ion research is pursuing beam science common to both High Energy Density Physics (HEDP) and IFE

Progress:

- **We have made good progress at higher currents (25-180 mA) in the STS, HCX, and NTX experiments, and supporting theory and simulations**

Plans:

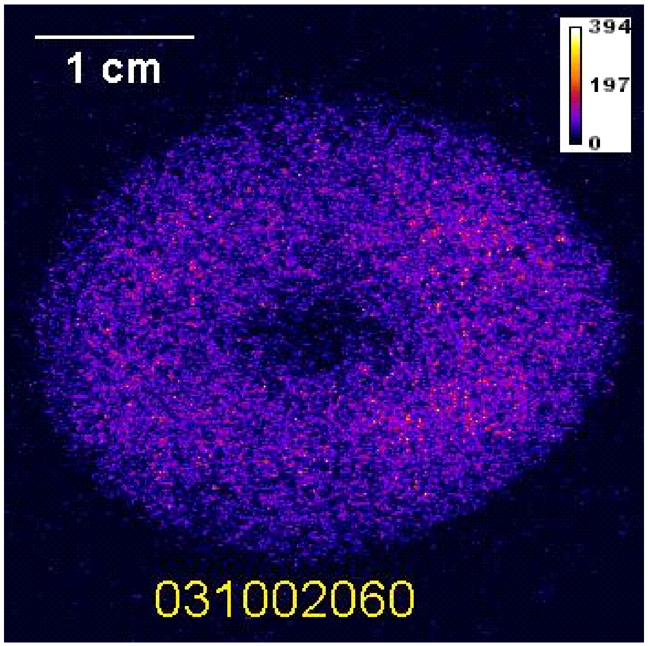
- **Over the next 5-10 years, we plan to continue high brightness beam transport, and a new area in neutralized drift compression and focusing. Both address a scientific question central to both HEDP and IFE:**

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

Understanding how beams can be compressed to drive targets to 1eV for HEDP would be an important intermediate step towards 250 eV targets for IFE

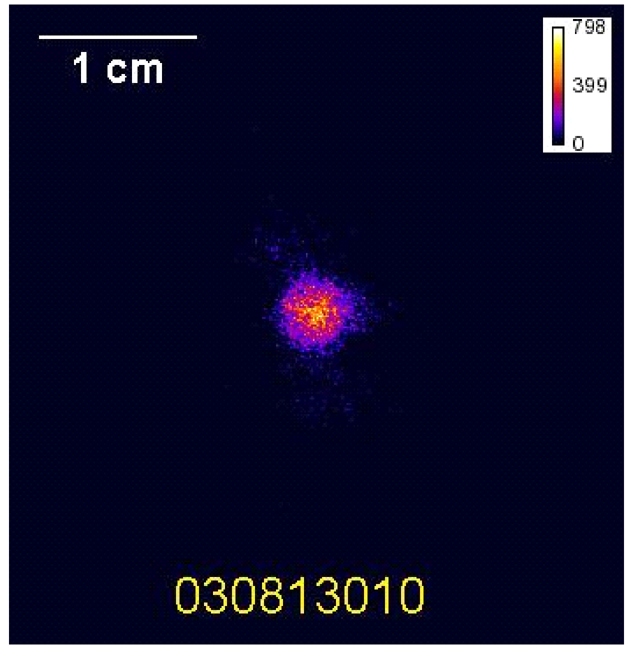
Plasma neutralization of space charge reduces beam focal spot size by 10x, consistent with particle simulations

Non-neutralized transport



FWHM: 27 mm

Effect of plasma plug and volume plasma on spot size

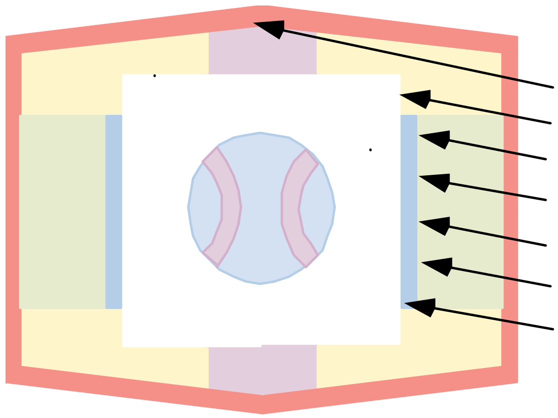


FWHM: 2.14 mm

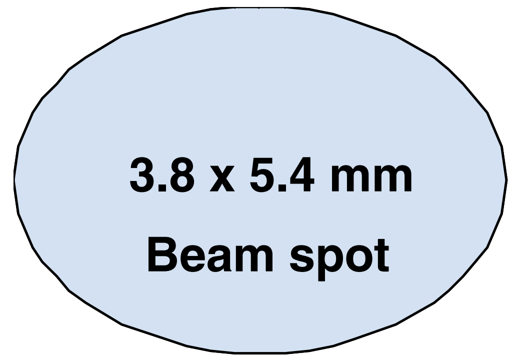
Ref. P. Roy (LBNL)

The “hybrid” target has become the target of choice because it allows a large beam spot

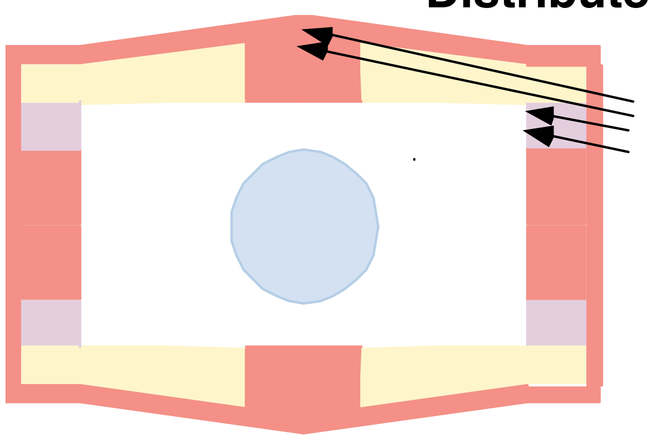
Hybrid Target



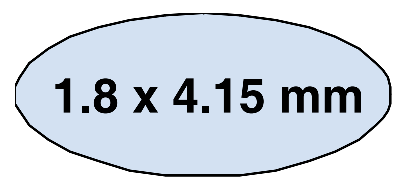
6.7 MJ -- Gain ~ 60



Distributed Radiator Target



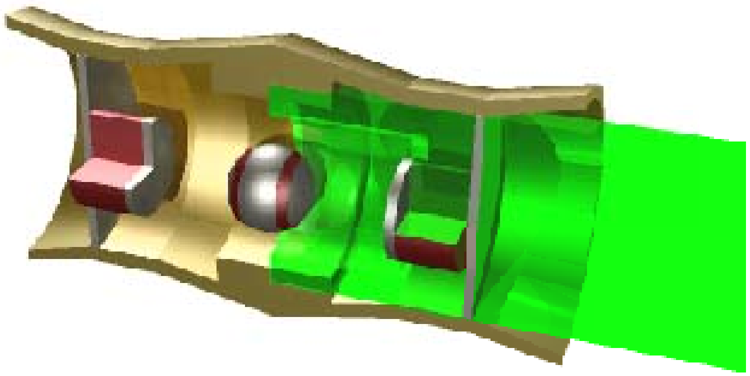
5.9 MJ -- Gain ~ 70



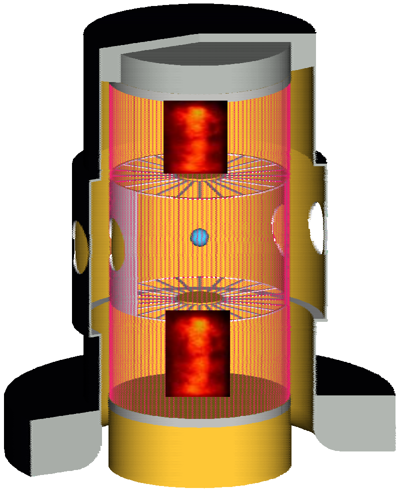
The hybrid target uses shine shields and shims to control symmetry

- The distributed radiator target and the NIF point design use beam placement to control symmetry
- The hybrid target uses internal shields to control symmetry
  - Shine shields controls P_2
  - Shims corrects the P_4
- The hybrid target and the Z double-pinch target use similar methods for controlling symmetry
  - Collaborations have begun

HI hybrid target

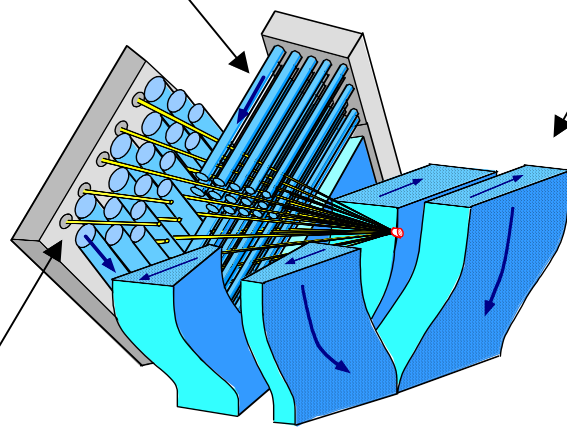


Z double-pinch target



Prototypical flow configurations have been demonstrated for thick liquid wall chambers

Crossing jets form beam ports



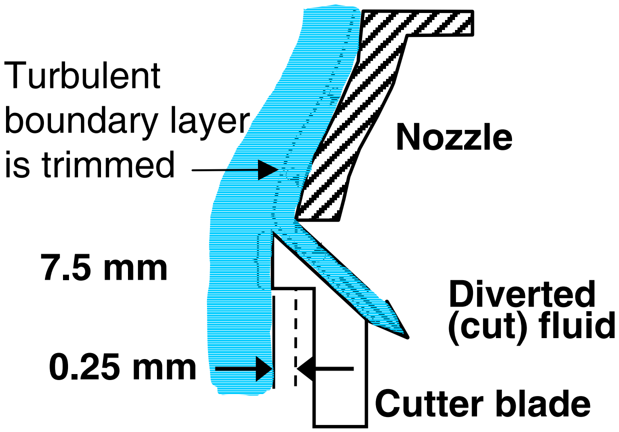
Oscillating jets form main pocket

Vortices shield beam-line penetrations

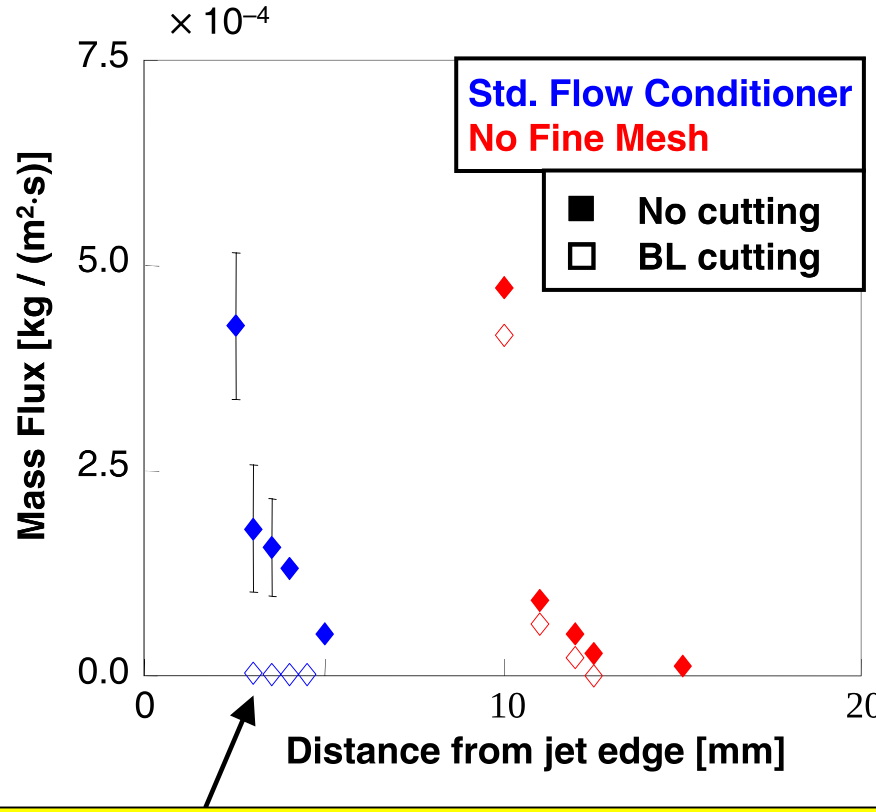
UCB

Drop ejection from jets can be controlled – important in beam and target injection paths

Expt'l Setup:



Results:

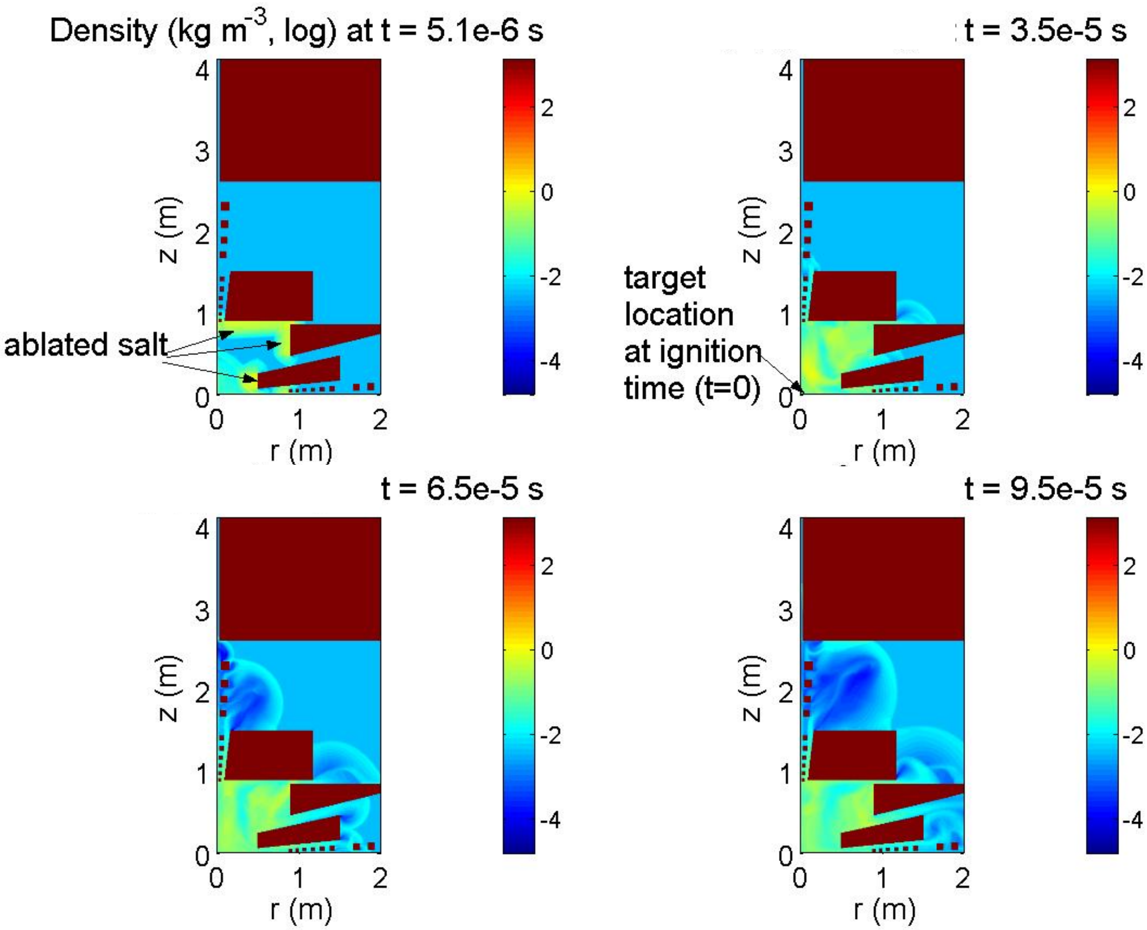


Flow conditioning and boundary layer trimming are needed to suppress drop ejection

Georgia Tech

Gas dynamics studies address key design issues for beam lines and thick-liquid-wall chambers

Typical TSUNAMI results showing ablation and vapor flow in chamber



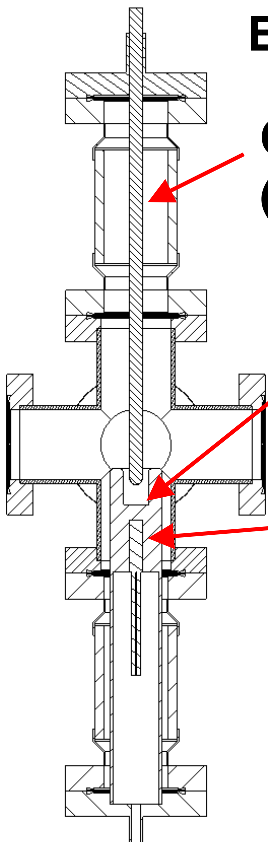
- **Beam and target propagation set stringent requirements for the background gas density and the cleanliness of the beam tubes**
- **Thick-liquid structure response mostly determined by gas dynamics**

UCB / LBNL

Rapid condensation needed for high rep-rate has been shown experimentally

Expt'l Setup:

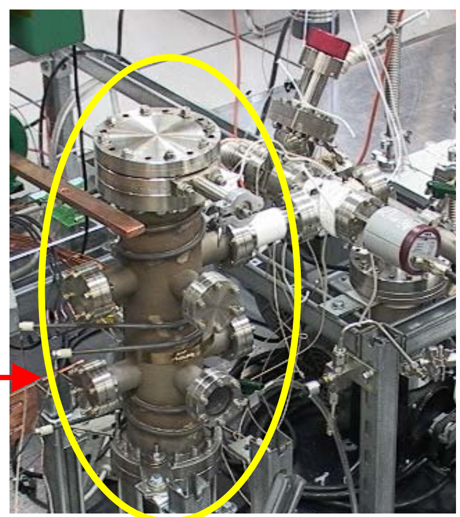
UCLA



Cathode (10" W rod)

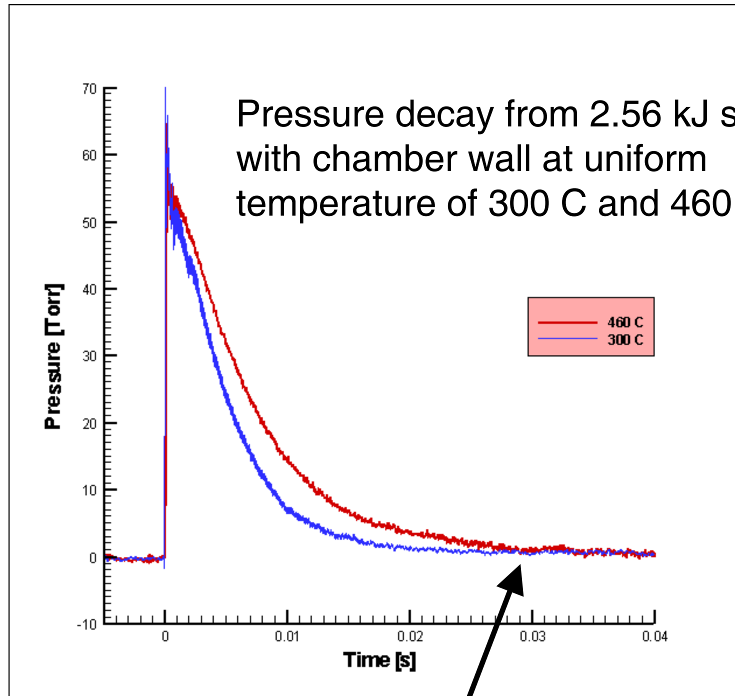
Flibe pool

Anode: Nickel crucible



Test chamber

Results:



Transient condensation of super-heated LiF vapor is completed in about 30 ms. This scales to <100 ms in IFE chamber, compatible with allowed clearing period.

ARIES assessment of HIF was completed in 2003

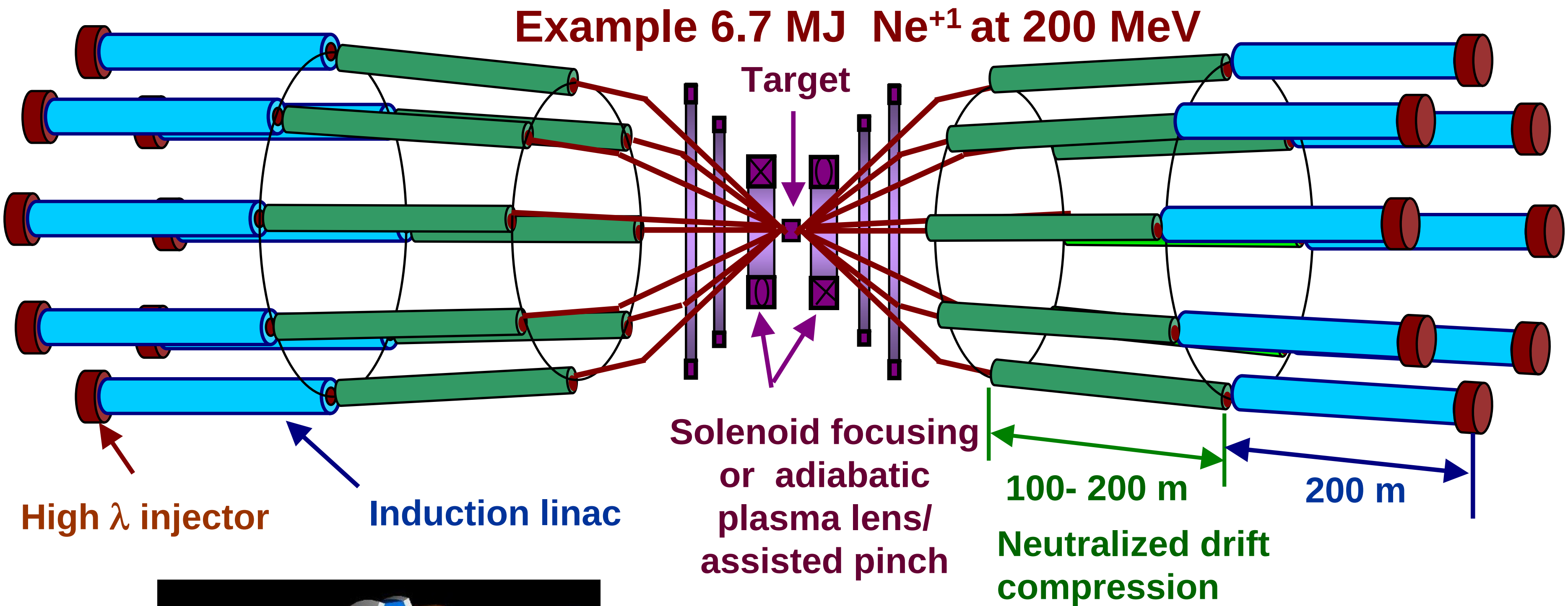
ARIES-IFE Study of HIF

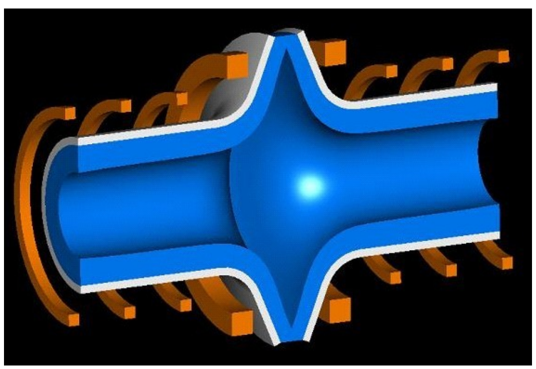
Transport Mode / Chamber Concept	Ballistic Transport *chamber holes ~ 5 cm radius* *most studied*		Pinch Transport *chamber holes ~ 0.5 cm radius* *higher risk, higher payoff*	
	Vacuum-ballistic *vacuum*	**Neutralized-ballistic** *plasma generators*	**Preformed channel** ("assisted pinch") *laser + z-discharge*	**Self-pinched** *only gas*
Dry-wall *~6 meters to wall*	Not considered now: Requires ~500 or more beams	Not considered: insufficient neutral-ization for 6 meters	ARIES-IFE (2001) Option: uses 1-10 Torr *2 beams*	ARIES-IFE (20 Option: uses 1-100 mTorr ~2-100 beams
Wetted-wall *~ 4-5 meters to wall*	HIBALL (1981) Not considered: exceeds 0.1 mTorr, so in neutralized-ballistic category	OSIRIS-HIB (1992) Possible option: but tighter constraints on vacuum and beam emittance	ARIES-IFE (2001) Option: uses 1-10 Torr *2 beams*	PROMETHEUS-H (1992) ARIES-IFE (20 Option: uses 1-100 mTorr ~2-100 beams
Thick-liquid wall *~ 3 meters to wall*	Not considered: exceeds 0.1 mTorr, so in neutralized-ballistic category	HYLIFE II (1992-now) Main-line approach: uses pre-formed plasma and 1 mTorr for 3 meters *~50-200 beams*	Option: uses 1-10 Torr *2 beams*	Option: uses 1-100 mTorr ~2-100 beams

Potential operating space was defined for various chamber and beam transport options

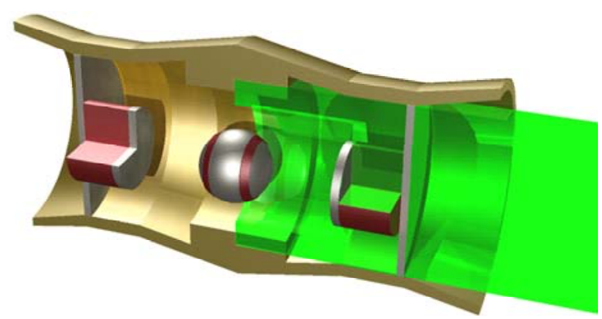
Ref. Najmabadi (UCSD)

Neutralized compression might lead to an improved IFE driver with a modular development path



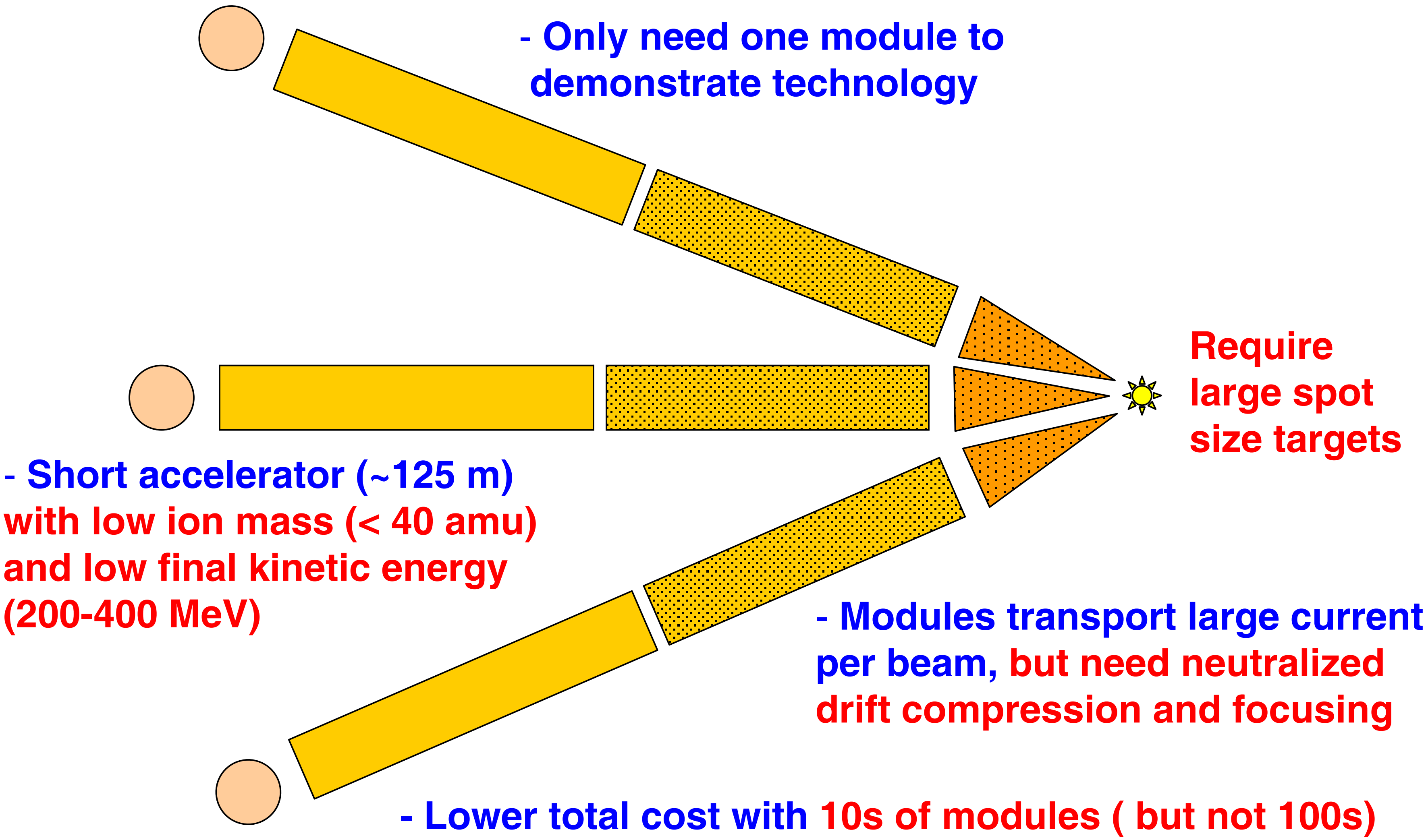


Liquid vortex chamber

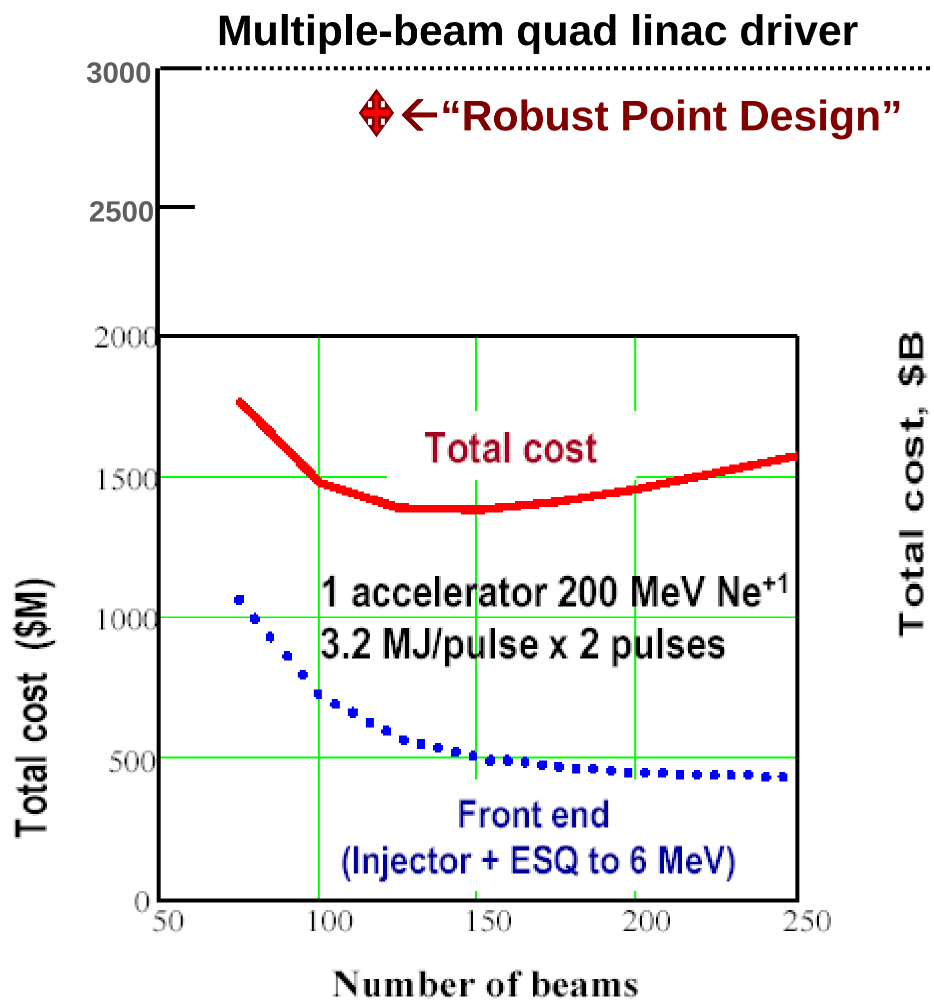


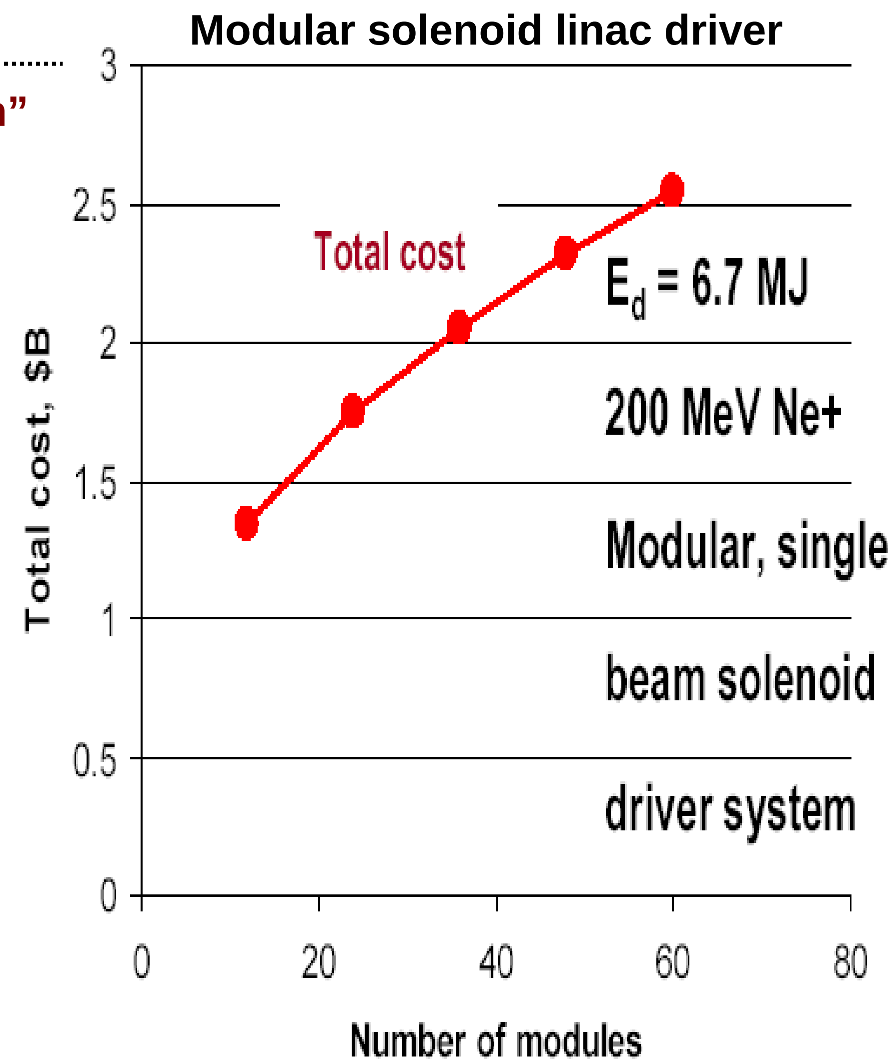
Large spot “hybrid target”

Modular solenoid drivers have potential advantages in some parameter regimes



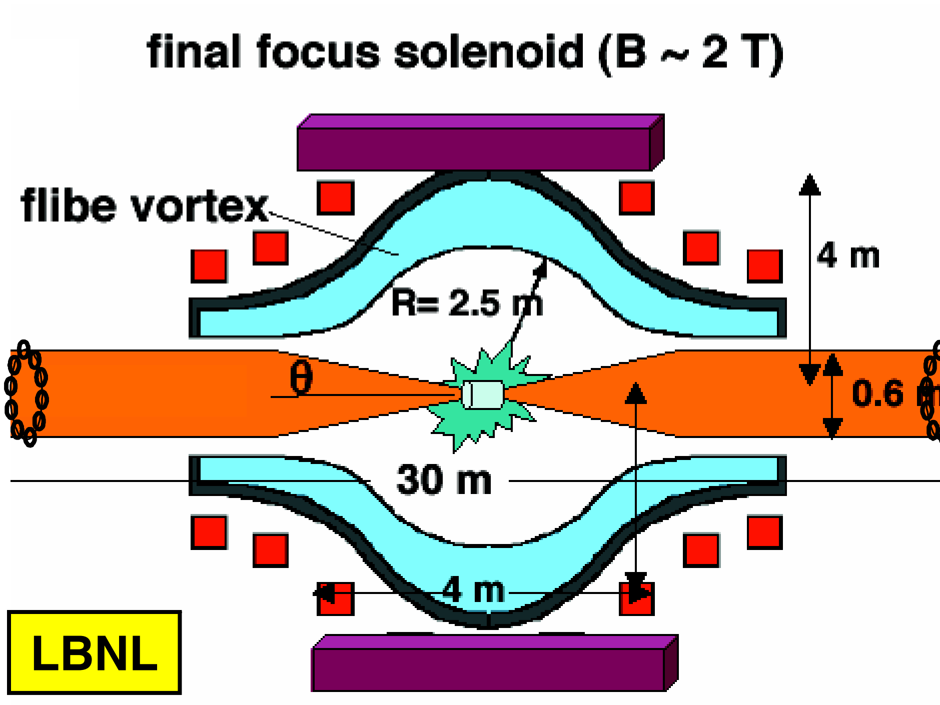
Neutralized drift compression/focusing + hybrid targets may reduce costs by ~50% for both conventional multiple-beam quadrupole and modular solenoid driver options for IFE

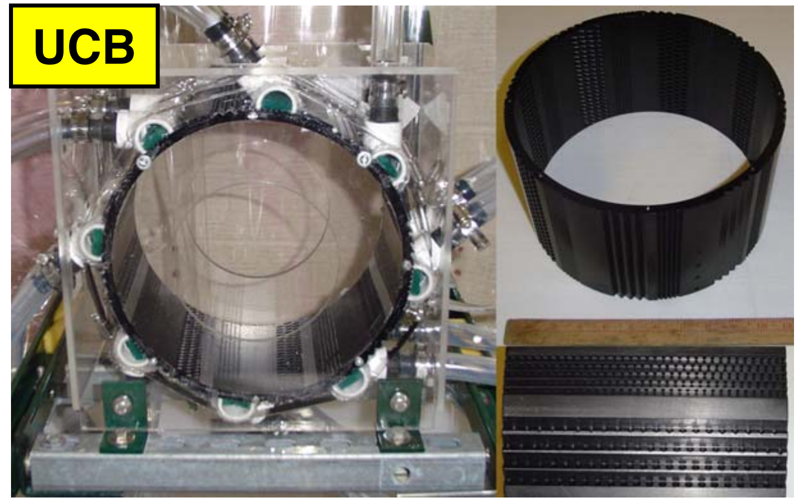




Work has begun on vortex chamber concept

- Vortex chamber concept matches well with neutralized drift compression
- Shock due to x-ray/ion induced ablation is a key issue

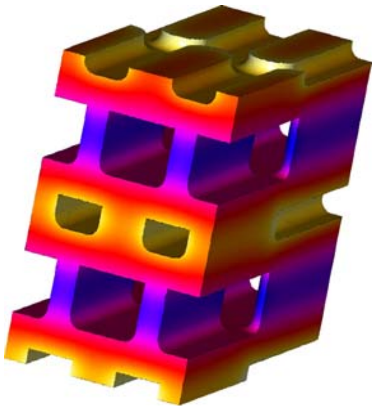




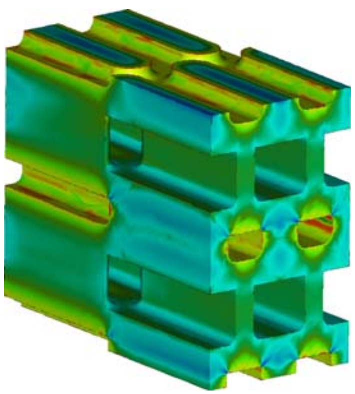
- UCB vortex experiment has injection and extraction at many points around cylindrical test section.
- Objective is to validate feasibility of establishing thick liquid layer.

Innovative work on power conversion systems is aimed at improved efficiency

Ceramic heat exchanger design



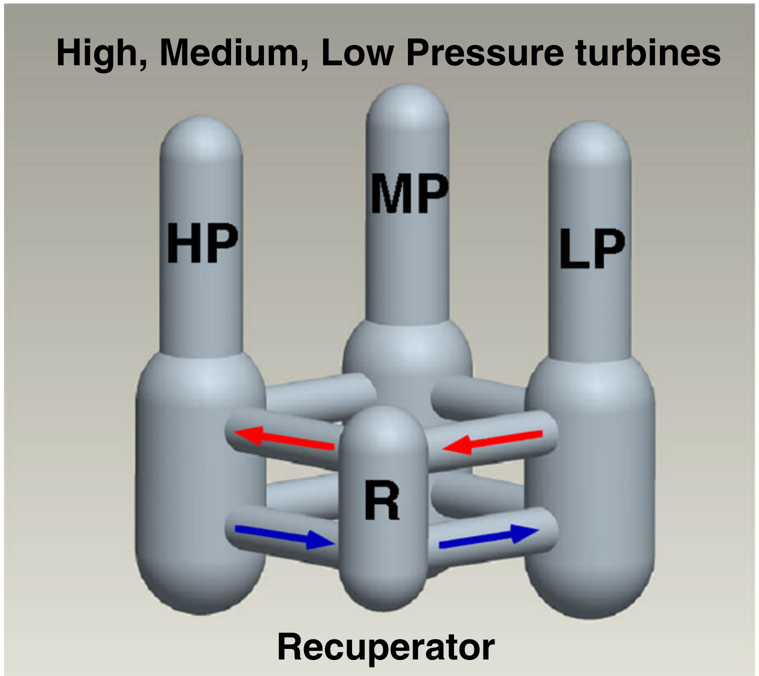
Temperature distribution in heat exchanger element



Maximum principal stress distribution

LLNL

Compact power conversion system

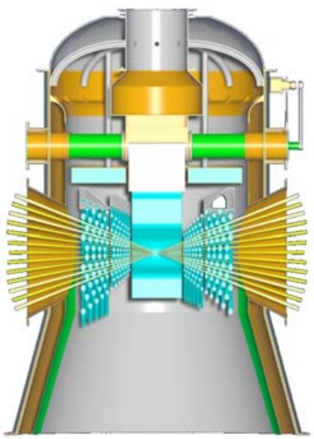


Adapting GA's Gas Turbine-Modular Helium Reactor (GT-MHR) Power Conversion Unit to fusion (vessels are ~ 30 m high)

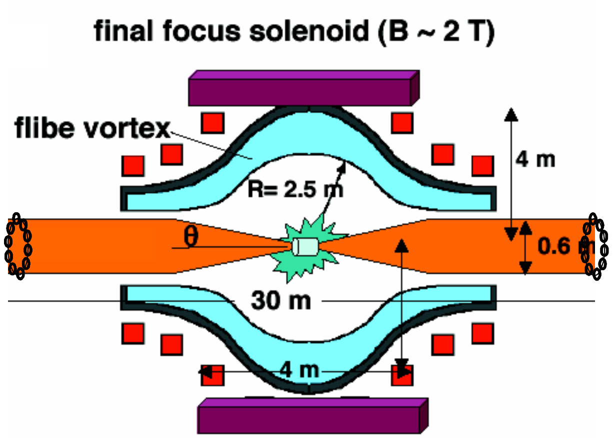
UCB

Path forward in chamber R&D must seek synergy with Z-IFE

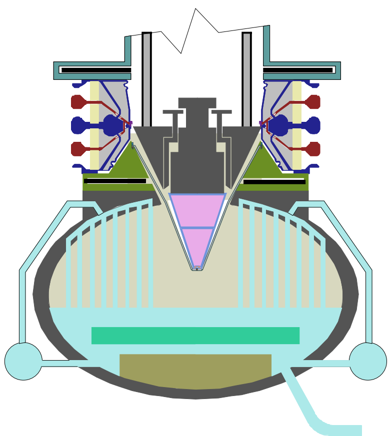
- There is considerable synergy in the R&D required to address key issues for HIF and Z-IFE
  - Thick-liquid-wall chambers
  - Shock mitigation
  - Molten salt technology
  - Target debris and tritium recovery



HIF RPD chamber



HIF vortex chamber



Z-IFE chamber

New efforts on HEDP with ions could benefit from IFE chamber and target expertise

- Modeling experimental HEDP targets for both laser-proton drive as well as for Neutralized Drift Compression Experiment (NDCX)

- NDCX-HEDP experimental chamber design to support high shot rate HEDP

- Experimental HEDP target fabrication for both laser-proton driven HEDP as well as for candidate NDCX targets to be tested at GSI and then NDCX

Summary: Significant progress has been made on all aspects of HIF, but program focus is changing

- HIF Program is now focusing on beam science for HEDP with applications to IFE
- Target work is concentrating on hybrid target with modeling and experiment to address symmetry issues
- Demonstration of prototypical flows gives confidence that thick liquid protection can be established
- Keys issues related to rep-rated chamber dynamics (post-shot gas flow, drop generation and control, condensation) have been addressed with modeling and experiments
- New ideas on modular drivers, vortex chambers, and advanced power conversion systems are being explored
- Chamber work is being terminated by OFES – seeking synergistic opportunities with Z-IFE project