Progress in Inertial Fusion Energy Technology: September 2002 – January 2003

Compiled by S. Reyes
Please direct comments and/or contributions to reyessuarez1@llnl.gov

Progress in IFE Technology: September 2002 – January 2003

Integration, Systems Studies, Safety & Environment and Driver-Chamber Interface — Lawrence Livermore National Laboratory

W. R. Meier, J. F. Latkowski, R. W. Moir, R. Abbott and S. Reyes

- Completed updated concept for an integrated point design for heavy ion fusion power plant working with members of IFE VLT and HIF VNL.

- Completed CAD model of HYLIFE chamber to be used to guide design improvements and define maintenance procedures for critical components such as nozzles (Figure 1).

- Began investigation into possible use of braided steel as a first wall in HYLIFE style thick-liquid protected target chambers. Braided steel structures would likely be more failure resistant and easier to replace than a first wall constructed of continuous solid structures.

- Recent calculations indicate that use of smaller focusing angle and vortex tube result in better shielding of final focusing magnets. The HIF Robust Point Design 2002 would have acceptable nuclear heating (recirculating power for cooling magnets is only ~3 MWe), magnet lifetimes (range from 100 to 1600 full-power-years), and improved superconductor activation (only the NbTi in last magnet fails to meet WDR<1). There is enough margin in the lifetime results that the shielding could be redesigned to provide better neutron shielding (at a cost of reduced gamma-ray shielding), thereby reducing activation of the last magnet and meeting requirements for Class C disposal.

- Completed safety assessment for Hg and Pb and hohlraum materials, analysis included radiological and chemical toxicity hazards.

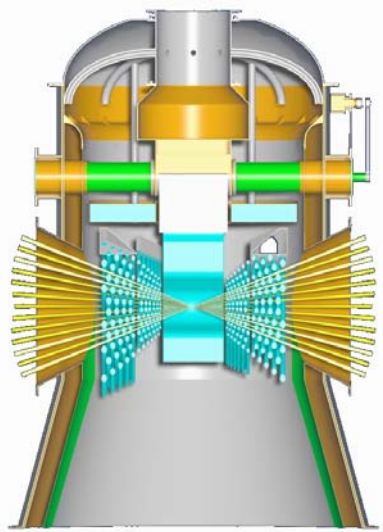


Fig. 1. Cross-section of CAD model for HYLIFE-II chamber

Publications and Presentations

15th TOFE, November 2002, Washington DC:

[1] J. F. Latkowski and W. R. Meier, "Shielding of the Final Focusing System in the HIF Point Design." **[2]** J. F. Latkowski et al., "Status of Safety and Environmental Activities for Inertial Fusion Energy." **[3]** W.R. Meier et al., "IFE Chamber Technology - Status and Future Challenges." **[4]** S. Yu et al., "An Updated Point Design for Heavy Ion Fusion." **[5]** S. Reyes et al., "Safety Issues of Hg and Pb as IFE Target Materials: Radiological Versus Chemical Toxicity."

Others:

[6] J. F. Latkowski and W. R. Meier, "Final Focus Magnet Shielding Update," presented at the September 2002 ARIES meeting. **[7]** W. Meier at al., "Updated Point Design for Heavy Ion Fusion" presented at the January 2003 ARIES meeting. **[8]** W.R. Meier, "IFE Chamber Development - To ETF and Beyond", presentation to FESAC Development Path Panel, Oct 28, 2002. **[9]** W.R. Meier et al., "Addressing Key Science and Technology Issues for IFE Chambers, Target Fabrication and Target Injection," presented at the IAEA Fusion Energy Conference, Lyon France, Oct 14-20, 2002. **[10]** J. Latkowski et al., "LLNL Chambers Progress," presented at the HAPL meeting, December 2002. **[11]** J. Latkowski et al., "XAPPER, it is here," presented at the HAPL meeting, December 2002. **[12]** S. Reyes et al., "Overview of Recent Developments on Fast Ignition Laser IFE," presented at the HAPL meeting, December 2002.

Progress in IFE Technology: September 2002 - January 2003 (Cont'd.)

IFE Chamber Dynamics Modeling and Experiments— University of California, San Diego
M. S. Tillack, F. Najmabadi, S. S. Harilal, C. V. Bindhu, D. Blair, B. Christensen, J. O'Shay (**http://aries.ucsd.edu/IFE**)

- We have completed our initial studies of homogeneous nucleation and growth of clusters in ablation plumes. The studies helped to clarify the role of ionization in the birth and growth of clusters. Figure 1 is an example result showing the size distribution of Si clusters using $5x10^9$ W/cm^2 laser intensity, obtained using an atomic force microscope on atomic flatness witness plates. The ionization fraction at this intensity is ~1%. Documentation of this work is underway.
- We are continuing our assessment of mechanisms for droplet ejection from liquid surfaces, with a particular emphasis on spinoidal decomposition. We completed a UCSD report and are now developing an experimental plan.
- We fabricated a permanent magnet with peak field of 0.8 T (see Figure 2). Initial data have been acquired with an Al plasma expanding into vacuum. Figure 3 shows images of visible emission from 50 to 200 ns following the energy pulse. Clear evidence of confinement and enhanced emission is seen.
- We have completed studies of the effect of background gas on laser propagation at high intensity. Measure-ments were made on the temporal profile, spatial profile and wavefront. Publications are in preparation.

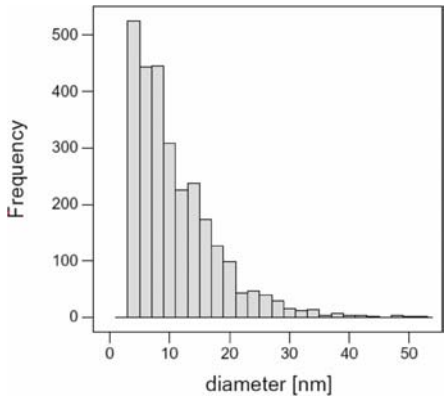


Fig. 1. Si nanoparticle size distribution obtained using $5x10^9$ W/cm^2 laser intensity

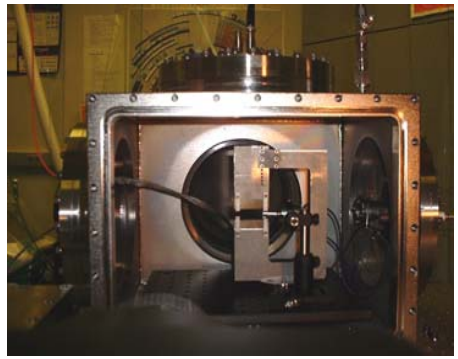


Fig. 2. Photograph of permanent magnet inside vacuum chamber

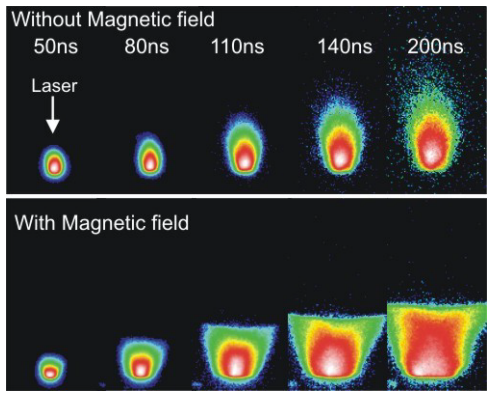


Fig. 3. Visible emission from an Al plasma expanding into vacuum, with and without magnetic field

Publications and Presentations:

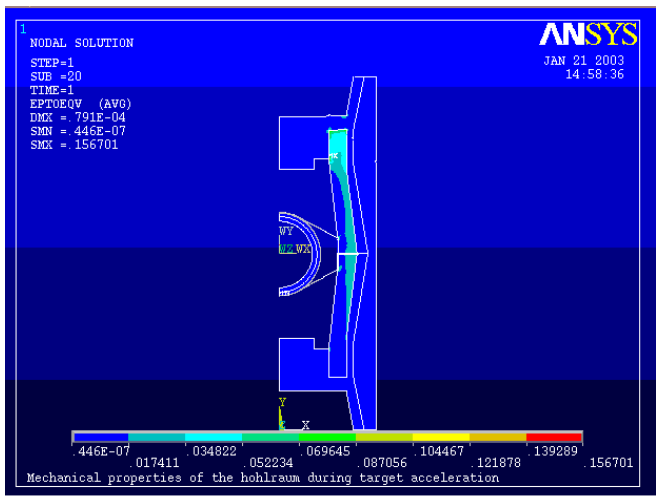
[1] S. S. Harilal, C. V. Bindhu, M. S. Tillack, F. Najmabadi and A. C. Gaeris, "Plume Splitting and Sharpening in Laser-produced Aluminum Plasma," Journal of Physics D: Applied Physics **35** (2002) 2935-2938. **[2]** S. S. Harilal, C. V. Bindhu, M. S. Tillack, F. Najmabadi and A. C. Gaeris, "Internal Structure and Expansion Dynamics of Laser Ablation Plumes into Ambient Gases," Journal of Applied Physics, March 15, 2003. **[3]** B. Christensen and M. S. Tillack, "Survey of mechanisms for liquid droplet ejection from surfaces exposed to rapid pulsed heating," UCSD-ENG-100, January, 2003. **[4]** M. S. Tillack, "Progress and Future Challenges for Inertial Fusion Energy Technology Research at UC San Diego," UCSD seminar, October 17, 2002. **[5]** S. S. Harilal, "Internal Structure and Expansion Dynamics of Laser Ablation Plumes," Mechanical and Aerospace Engineering departmental seminar, UCSD, November 26, 2002. **[6]** M. S. Tillack, "Particulate Formation in Laser Plasma," VIII Symposio en Fisica de Materiales, Centro de Ciencias de la Materia Condensada, Universidad Nacional Autonoma de Mexico (Ensenada, BC), January 24, 2003.

Progress in IFE Technology: September 2002 - January 2003 (Cont'd.)

Target Fabrication, Injection, and Tracking – GA/LANL

D. Goodin, R. Petzoldt, N. Alexander, L. Brown, G. Besenbruch, A. Nobile, James Maxwell, and Jim Hoffer

- Initial cost estimates for indirect drive target production were prepared. Baseline estimate was $0.41 per injected target for a 1000 MWe plant.
- Stress and strain calculations were conducted for accelerated HIF targets. Information may be used to set acceleration limits and guide minor target design changes.
- We performed guest editor duties for a special issue of Fusion Science and Technology for the "IAEA Technical Meeting on Physics and Technology of Inertial Fusion Energy Targets and Chambers" on 17-19 June 2002.
- Laser Chemical Vapor Deposition (LCVD) is being developed for low density metal foam production in hohlraums. A new LCVD system has been commissioned and carbon fibers are being grown. Growth of metal fibers will begin this summer.
- Concepts that define the steps for fabrication of the target by LCVD have been developed and are being evaluated.



Strain von Mises, Memb=1e-6m, a=10000m/sq.s

Fig. 1. Calculated target strain for simplified accelerated target

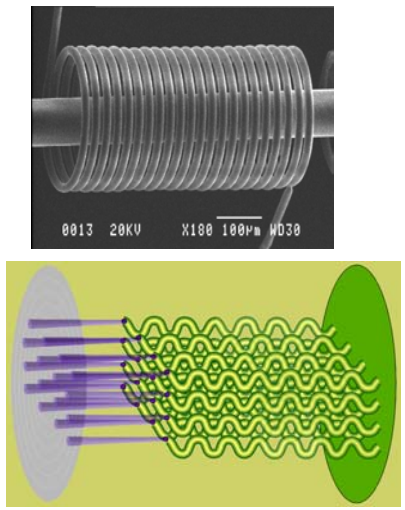


Fig. 2. Laser Chemical Vapor Deposition provides free form fabrication capability

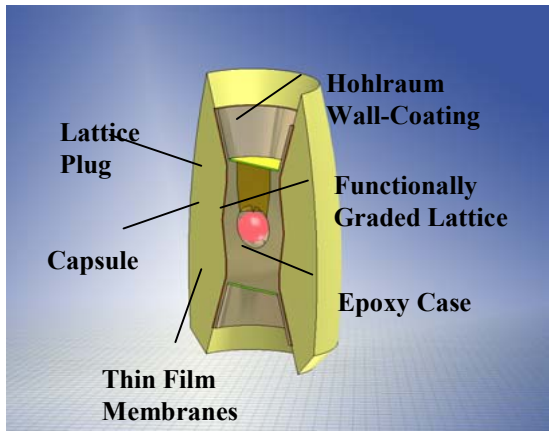


Fig. 3. Concept for target fabrication from inside out using LCVD with molded epoxy case

Publications and Presentations

[1] Symposium on Fusion Technology, Dan Goodin, "Addressing the Issues of Target Fabrication and Injection for Inertial Fusion Energy" (Poster and Paper).

[2] ARIES, Ron Petzoldt, "Indirect-drive Target Aerosol Limits, Foam Mechanical Properties, and Target Injection Accuracy" and "Indirect Drive Materials Selection and Costing Studies."

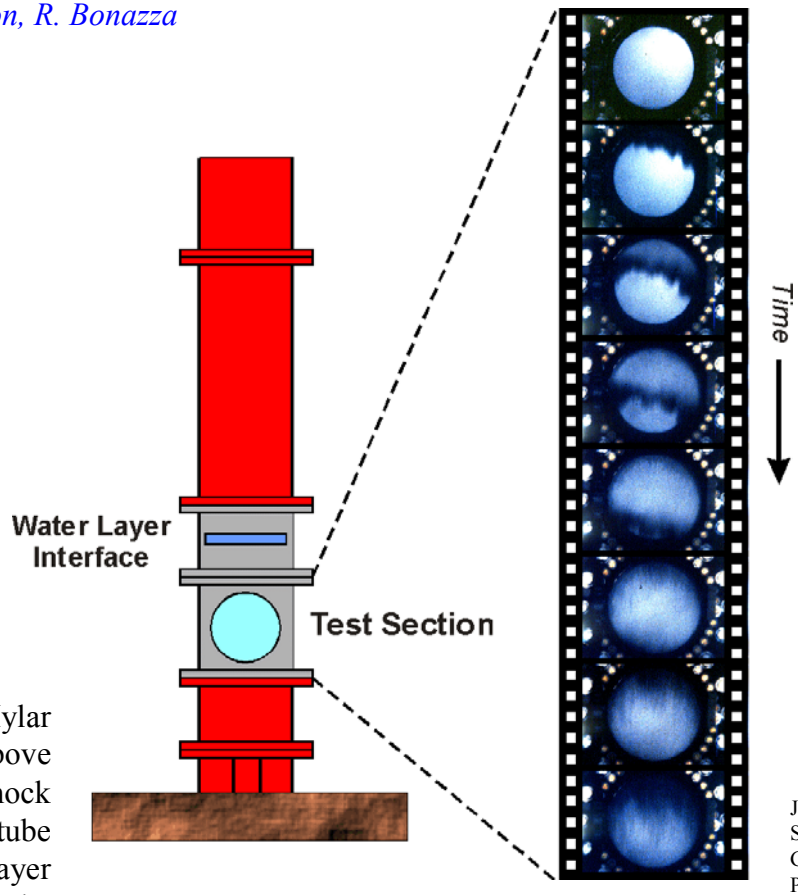
Progress in IFE Technology: September 2002 - January 2003 (Cont'd.)

Liquid Layer Protection – University of Wisconsin, Madison

P. Meekunnasombat, J. Oakley, M. Anderson, R. Bonazza

- The inertial fusion energy reaction results in a blast wave that emanates from the center of the reaction chamber to the first wall of cooling tubes. One proposed idea is to use liquid sheets of molten salt to protect the first wall from fusion debris and to assist in the removal of thermal energy.
- A shock tube is used to experimentally study a flat liquid layer subjected to a shock wave. The shock wave accelerates the liquid layer down the shock tube where it is imaged in the test section. The pressure history is digitally recorded as well as the pictures of the breakup of the water layer.

A water layer is placed on a 0.94 μm Mylar membrane at the interface section 0.46 m above the test section. A Mach 2.12 planar shock wave from the driver at the top of the shock tube accelerates a 12.8 mm thick water layer downwards into the test section where the shocked liquid layer is imaged.



The shocked water layer starts to break upon shock impact due to several hydrodynamic instabilities. This results in a thickening of the liquid layer and significant droplet and aerosol production. The remaining intact shocked liquid layer contacts the end wall generating high peak pressures (about 7-10 times higher than experiments without the liquid layer). These results agree qualitatively with the few shock tube experiments conducted at UC-Berkeley by J.C. Liu et al 1993 to study liquid wall protection. After contacting the end wall, the shocked liquid layer breaks further resulting in further aerosol and liquid droplet concentrations which remain in the shock tube for long times (several 10's of seconds

J. C. Liu, "Experimental and Numerical Investigation of Shock Wave Propagation Through Complex Geometry, Gas Continuous, Two-Phase Media" UC-Berkeley Ph.D. Thesis Dept of Nuclear Engineering 1993.

A motion picture of the water layer breakup is taken at the test section with a high-speed analog camera at 10,000 frames per second. The figures above show a schematic of the shock tube along with a movie frame sequence of the shocked water layer. In the movie frames, the shocked water layer appears as the black object moving downwards toward the bottom of the shock tube.

Publications and Presentations

[1] Experimental Investigation of a Shock-accelerated Liquid Layer with Imaging and Pressure Measurement; P. Meekunnasombat, J. Oakley, M. Anderson and R. Bonazza, November 2002 [presented at the 15th Topical Meeting on the Technology of Fusion Energy, Washington DC].

[2] Experimental Hydrodynamics Model for First Wall Protection in IFE Reactors; R. Bonazza, J. Oakley, M. Anderson, P. Meekunnasombat, S. Wang, P. Brooks, April 2002 [presented at the High Average Power Lasers Meeting, General Atomics, La Jolla CA].

Progress in IFE Technology: September 2002 - January 2003 (Cont'd.)

ARIES-IFE Nuclear Analysis - University of Wisconsin-Madison

L. El-Guebaly, P. Wilson, D. Henderson, and A. Varuttamaseni

- Completed recycling study for candidate hohlraum wall materials: Au/Gd, Au, W, Pb, Hg, Ta, Pb/Ta/Cs/, Hg/W/Cs, Pb/Hf, Hf, solid Kr, and solid Xe. Main conclusions are:
  - Hohlraum walls represent small waste stream for IFE-HIB (< 1% of total nuclear island waste) ⇒ recycling is not a "must" requirement for ARIES-IFE-HIB unless materials have cost/resource problems (e.g., Au and Gd).
  - With or without recycling, Au and Au/Gd hohlraums result in highest COE.
  - Without cooling period, recycling generates high-level waste (HLW) except W, Ta, Xe.
  - Cooling periods < 250 days allow all recycled materials except Au/Gd to satisfy both Class C low-level waste and recycling dose requirements, as shown in Figures 1 and 2.
  - On-line removal of transmutation products could shorten cooling periods and may allow recycling of Gd. Removed transmutation products will be high-level waste (HLW).
  - Recycling introduces additional design issues and problems:
    - HLW that violates ARIES requirements
    - Design complexity
    - Remote handling in hohlraum fab
    - High cost
  - One-shot use scenario is the preferred option for all hohlraum wall materials except Au and Gd.
- **Recommendation**: Use low cost materials once-through and dispose as Class A LLW instead of recycling expensive materials (such as Au and Gd). This scenario offers:
  - Attractive safety features
  - Less complex design
  - Radiation-free hohlraum fab
  - Lower COE
- **Suggestion**: If target physics permits both high-Z and low-Z materials, make hohlraum walls out of breeding or liquid wall materials (Pb, LiPb, Li, Sn, LiSn, Flibe, or Flinabe) to eliminate the need for hohlraum separation and disposal processes.

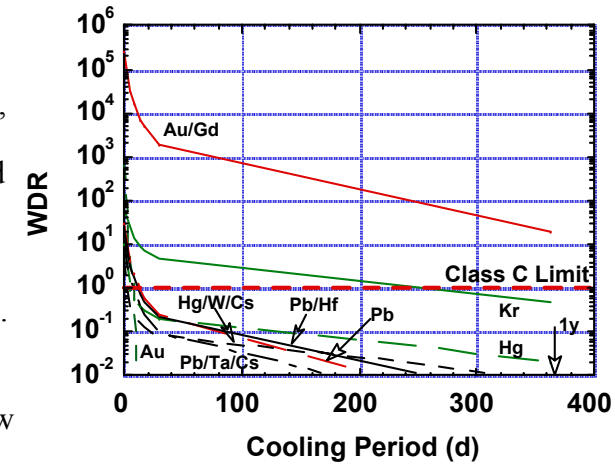


Fig. 1 Variation of waste disposal rating with cooling period.

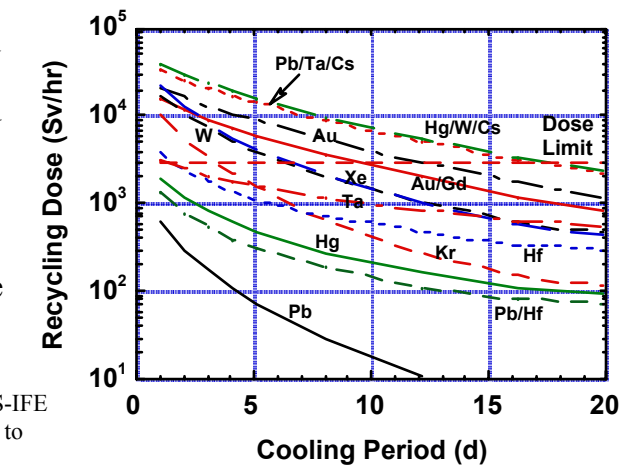


Fig. 2 Reduction of dose with cooling period.

Publications and Presentations:

[1] L. El-Guebaly, D. Henderson, P. Wilson,L Waganer, and R. Raffray, "Radiological Issues for Thin Liquid Walls of ARIES-IFE Study", Presented at 15th ANS Topical on Technology of Fusion Energy, Washington, D.C., November 2002, and submitted to Fusion Science and Technology.

[2] L. El-Guebaly, P. Wilson, D. Henderson, and A. Varuttamaseni, "Feasibility of Target Materials Recycling as Waste Management Alternative", Presented at 15th ANS Topical on Technology of Fusion Energy, Washington, D.C., November 2002, and submitted to Fusion Science and Technology.

[3] I. Sviatoslavsky and L. El-Guebaly, "Coolant Cleanup and Process Requirements", ARIES project meeting, October 2002.

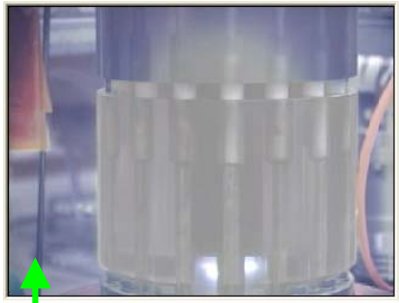
[4] L. El-Guebaly, "Ferritic Steel Lifetime Assessment and Self-Consistent Nuclear Parameters for ARIES-IFE-HIB", ARIES E-meeting, October 2002.

[5] L. El-Guebaly, P. Wilson, D. Henderson, L. Waganer, and R. Raffray, "Activation Assessment of IFE Thin Liquid Wall Materials and Proposed Variations for Liquid Waste Minimization," University of Wisconsin Fusion Technology Institute Report, UWFDM-1182 (November 2002).

[6] L. El-Guebaly, P. Wilson, D. Henderson, A. Varuttamaseni, and the ARIES Team, "Recycling of IFE Target Materials versus One-Shot Use Scenario: Key Issues and Preferred Option," University of Wisconsin Fusion Technology Institute Report, UWFDM-1183 (November 2002).

[7] M.C. Billone, A.R. Raffray, D.K. Sze, L. El-Guebaly, and the ARIES team, "ARIES Assessment of IFE Structural Material," University of California San Diego Report UCSD-ENG-101 (2002).

Progress in IFE Technology: September 2002 - January 2003 (Cont'd.)

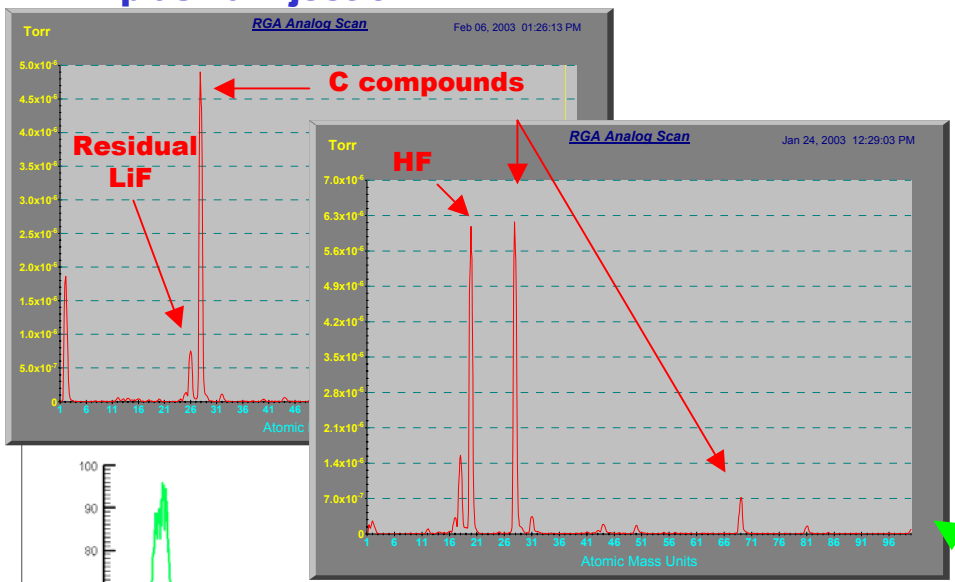


LiF plasma injection

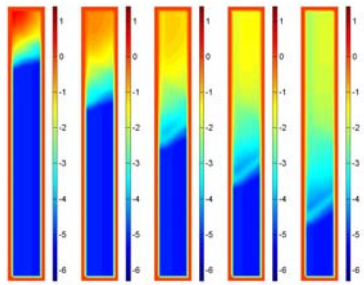
Vapor Dynamics and Condensation and Free Surface Flow Studies - University of California, Los Angeles

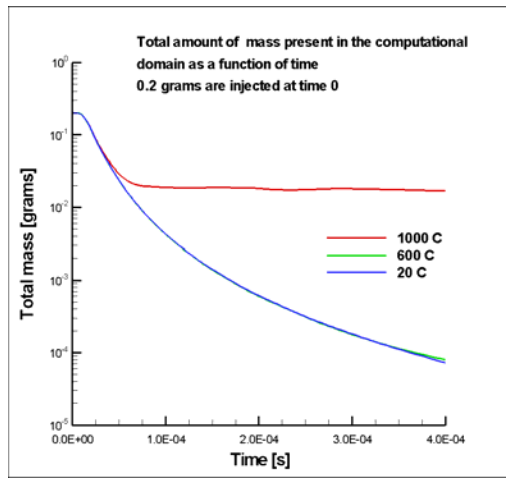
M. Abdou, A. Ying, N. Morley, P. Calderoni, A. Konkachbaev, W. Guo, M. Ni, T. Sketchley

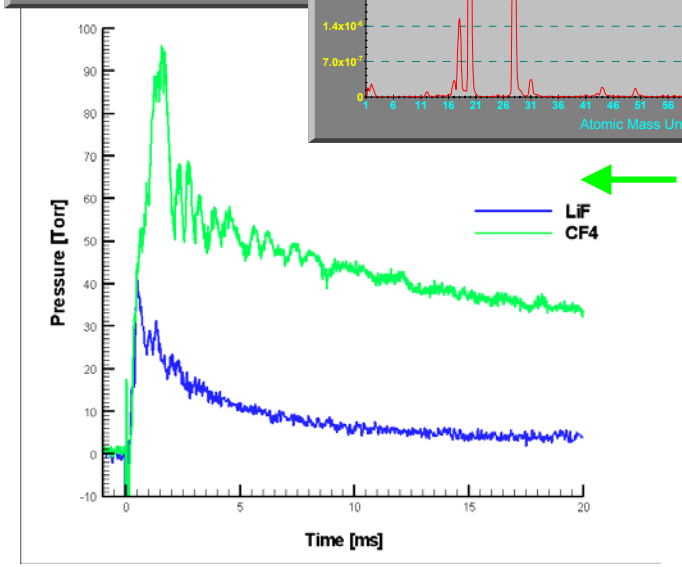
- Pure lithium fluoride experiments performed to characterize material behavior and finalize diagnostic design for flibe use
- Diagnostics identified and tested: total pressure data, mass spectroscopy, ionized gas emission spectroscopy, time of flight jet velocity measurement
- 1-D condensation boundary conditions implemented in Tsunami and results obtained for simplified constant wall temperature case



Numerical results from Tsunami runs for UCLA experiment (simplified) conditions



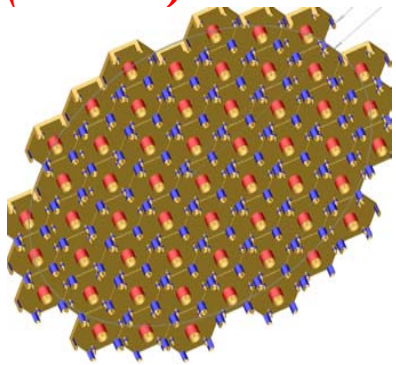




Pressure history and residual gases composition

Technical issues with pressure sensors have been effectively resolved. Time history of total pressure in the condensation chamber is recorded for testing material Teflon $(CF_4)_x$ and prototypical flibe component LiF. Data show how the recombination products of Teflon are mainly non condensable, as residual pressure is about 50 % of the initial peak. The condensation of LiF is completed in less then 10 ms. Present conditions are not IFE prototypical yet, as the chamber is at ambient temperature and there are still about 2 Torr of residual gases produced in the chamber after LiF shots from carbon impurity sources.

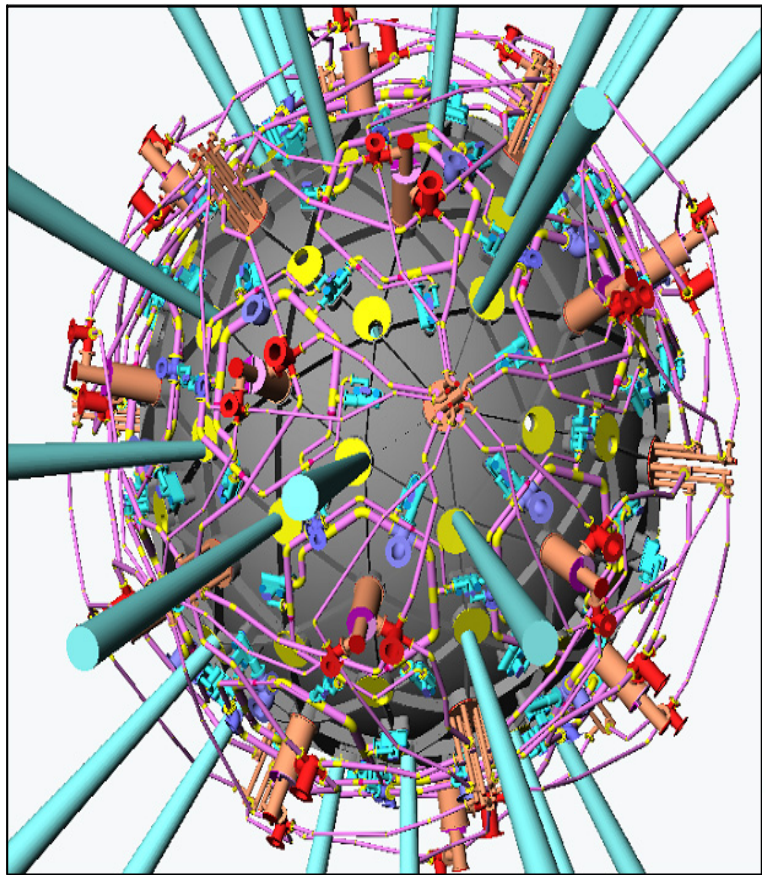
Progress in IFE Technology: September 2002 - January 2003 (Cont'd.)

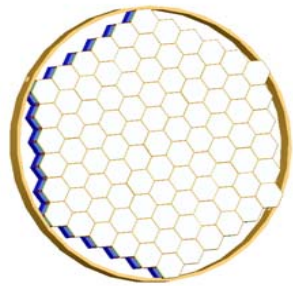


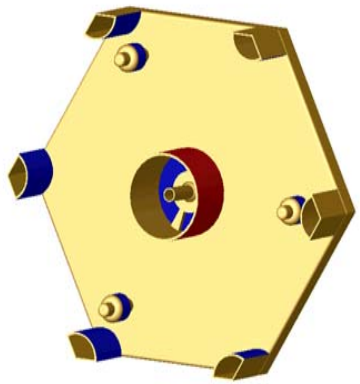
Laser Damage to Optics —University of California, Los Angeles (UCLA)

N.M. Ghoniem, Q. Hu, and Razvan Ungareanu

- Completed preliminary design of a modular IFE chamber;
- Laser beam positioning and focusing have been developed and identified;
- Laser beam shutters have been designed;
- Continued development of modular, segmented reflective optics;
- Laser mirror module cooling and stress analysis are being iterated for more uniform surface temperature distributions;
- A piezo-electric control system for beam steering is developed, and is under further evaluation;
- Ray-tracing studies are continued to determine optimum location for mirrors, mirror geometry, and surface contours for manufacturing;
- The optics design is now being implemented by a small business, MER, with iterations through the collaboration with UCSD.
- A multi-layer shell model for in-elastic deformation due to radiation effects has been completed, and is now being coded by Ungareanu.







Progress in IFE Technology: September 2002 - January 2003 (Cont'd.)

Thick-Liquid Protection—University of California at Berkeley

P. F. Peterson, S. Pemberton, C. Debonnel, G. Fukuda, D. Olander

- UCB completed design and analysis of the liquid protection and beam-line configuration for RPD-2002. Shown to scale in the figure, the work included liquid jet geometries that have been verified in scaled water experiments, and evaluation of the performance of a magnetic shutter system to prevent debris from entering the final-focus magnet region.

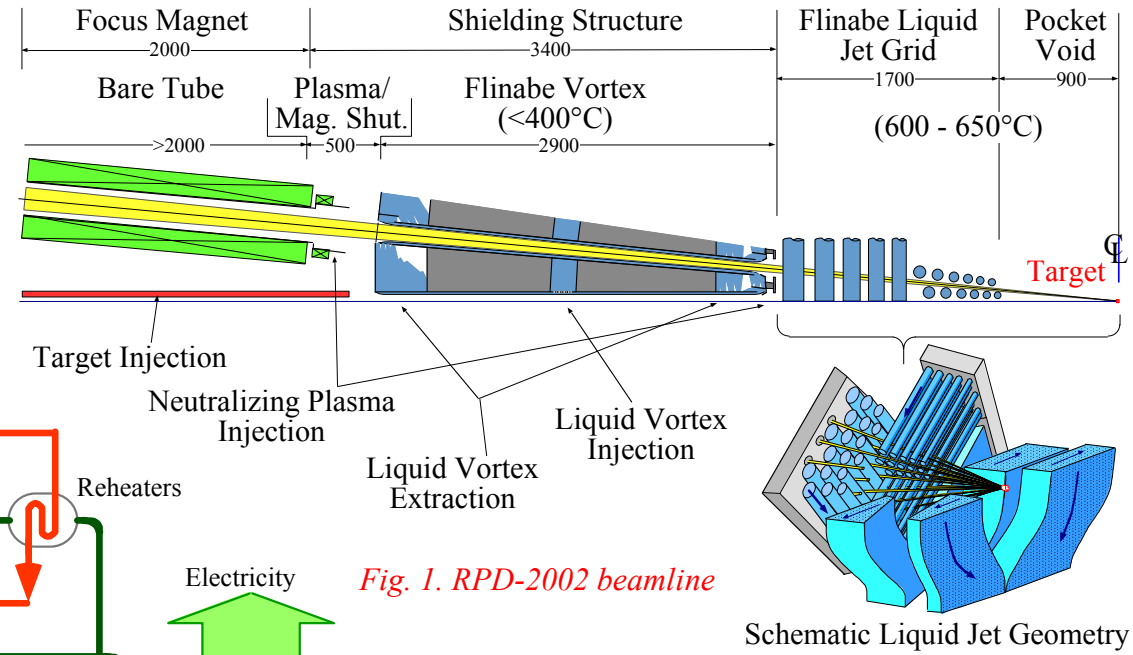


Fig. 1. RPD-2002 beamline

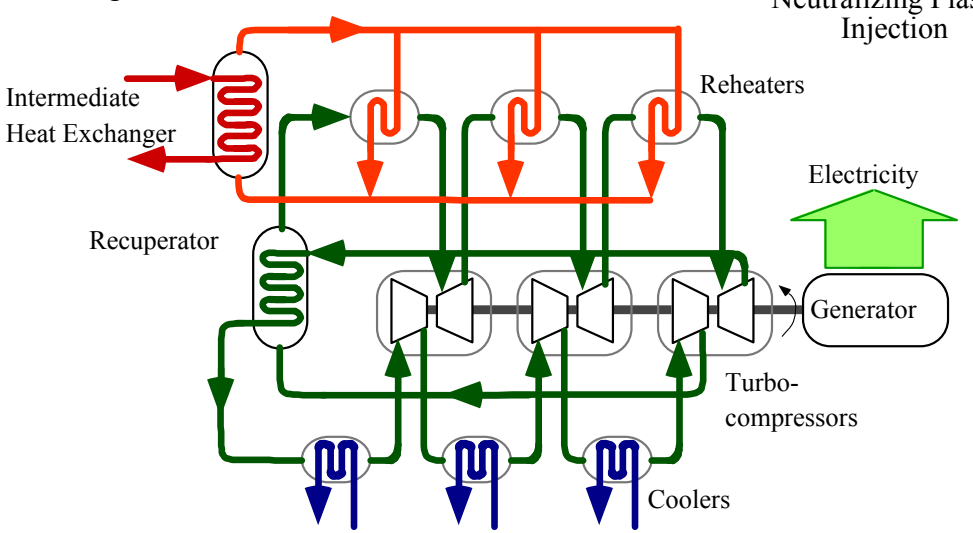


Fig. 2. Multiple-reheat Brayton cycle for flibe-cooled fusion systems

- UCB has identified a multiple-reheat helium Brayton cycle that has significant advantages over steam Rankine cycles for power conversion for fusion energy systems cooled by flibe or flinabe. The use of multiple reheat stages, as shown in the figure, increases the thermodynamic efficiency of the cycle, so that gross plant efficiencies of 43% are possible with 620°C flibe temperatures, using component efficiencies for current gas-reactor system designs. Besides having higher power density and lower capital cost, the helium coolant simplifies tritium management and recovery.

Publications and Presentations

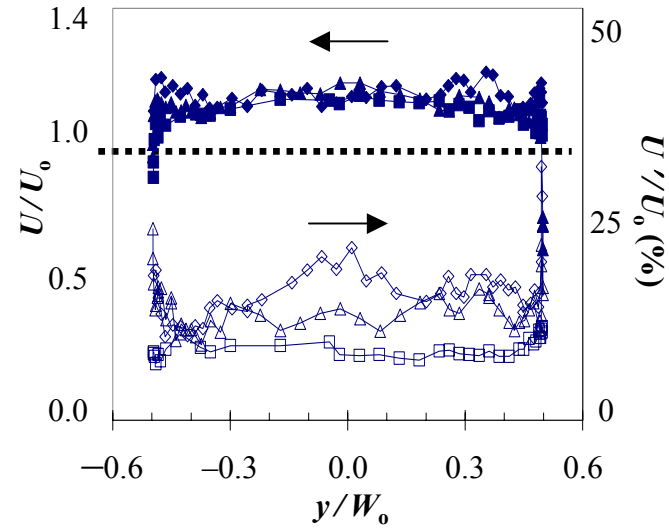
[1] S. Pemberton, R. Abbott, P. Peterson, "Thick-Liquid Blanket Configuration and Response for Heavy-Ion Point Design," presented at the 15th Topical Meeting on the Technology of Fusion Energy, Washington DC.

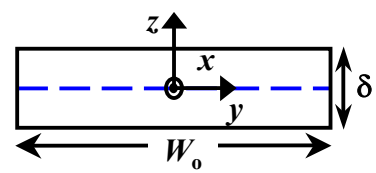
Progress in IFE Technology: September 2002 - January 2003 (Cont'd.)

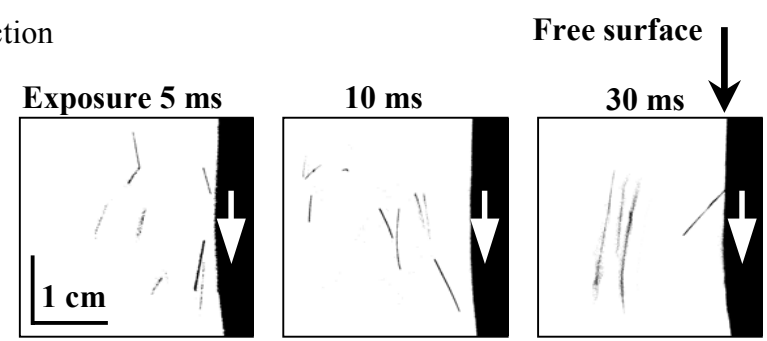
Thick-Liquid Protection — Georgia Institute of Technology

S.G. Durbin, M. Yoda, S.I. Abdel-Khalik

- **Turbulent liquid sheets:**
  - Quantified initial conditions with mean velocity and rms velocity fluctuation profiles at nozzle exit for 3 nozzles using laser-Doppler velocimetry (LDV)
  - Started investigating drop formation and ejection
    - Drops of $O(10\ \mu m)$ diameter detectable using current flow visualization setup
- **Initial conditions:**
  - 3 nozzle geometries
    - Re based on $(U_o, \delta) = 97{,}000$
    - U_o = avg. speed at nozzle exit
  - y-profiles at $x = -2$ mm (just inside nozzle)
  - Avg. streamwise speed U nearly uniform for all nozzles
  - RMS fluctuations $U'/U_o \sim 10$–20%
- **Drop formation/ejection:**
  - Important issue for liquid protection
  - Directly visualizing drops ejected from turbulent liquid sheet
    - Min. observable dia. ~10 µm
  - Investigating onset of drop formation: min. x location for drop formation = $f(We)$ (We = Weber number) [Sallam *et al.* 2002]
  - Developing techniques to measure ejected drop mass flux
  - Evaluate nozzle and flow conditioning based upon drop formation and ejection
- **Drop visualizations:**
  - Edge view of turbulent liquid sheet at $Re = 97{,}000$
    - $x/\delta \approx 23$
    - Min. resolution (based on imaging resolution) = 50 µm
  - Note streaks due to ejected drops
    - Drop ejection speeds / trajectories







Publications and Presentations

[1] S.G. Durbin, M. Yoda, S.I. Abdel-Khalik, and D.L. Sadowski (2002) "Turbulent liquid sheets for protecting IFE reactor chamber first walls". Submitted to *Fusion Science and Technology* (**Best Student Paper Award** at 15th Technology of Fusion Energy Meeting, Washington, DC)

[2] S.G. Durbin, M. Yoda and S.I. Abdel-Khalik (2002) "Impact of initial conditions on turbulent liquid sheets," 55th Annual Meeting of the American Physical Society Division of Fluid Dynamics, Dallas, TX

[3] M. Yoda and S.I. Abdel-Khalik (2002) "Experimental results for thin and thick liquid walls", ARIES Fall Quarter Project Meeting, Princeton, NJ