ASPEN Laser and A New IFE Power Plant Concept

IFE Workshop Category: General

Conner Galloway[a], Cliff Thomas[b], Mike Tobin[c], Manuel Perlado[d], Javier Sanz Gonzalo[e], Raquel Gonzalez Arrabal[d], Pedro Velarde[d], Christophe Debonnel[f], Frank Sage[g], Wayne Meier[h], J. Gary Eden[i], Mike Campbell[b], Robert O. Hunter Jr.[j]

Author Affiliations:
a – Xcimer Energy
b – Laboratory for Laser Energetics
c – Johns Hopkins University Applied Physics Laboratory
d – Instituto Fusión Nuclear "Guillermo Velarde" (IFN-GV) Universidad Politécnica Madrid (UPM)
e – Universidad Nacional De Eduación a Distancia (UNED)
f – Commissariat à l'Énergie Atomique et aux Énergies Alternatives
g – US Army ATEC, White Sands Missile Range
h – Woodruff Scientific, Inc
i – University of Illinois Urbana-Champaign
j – Innoven Energy

EXECUTIVE SUMMARY

Significant research and development of high energy excimer lasers was undertaken by the US for national security missions several decades ago. Although much of this research was not documented in open literature, details of this design support a modern adaptation, which we call ASPEN, that might be particularly well-suited to IFE. The ASPEN architecture naturally supports a target that can be illuminated by two beams, where each can deliver up to 12 MJ of high-quality light at relatively low cost ($\lesssim$ \$20 per joule).

An inexpensive yet high-energy driver opens the door to an IFE design space that needs to be explored. We anticipate commercial operation would employ high yields ($\gtrsim$ 1GJ) at low rep rate ($\lesssim$ 1Hz), and have tens of meters standoff to final optics that occupy a small solid angle ($\lesssim 10^{-4}$ of 4π sr). Here, we describe a direct drive hybrid target that can be driven by ASPEN (and potentially other drivers as well) that builds on current understanding, and is readily adapted to the legacy and much-studied chamber concept HYLIFE and HYLIFE-II. The combination of ASPEN, hybrid target, and HYLIFE addresses many of the outstanding challenges in IFE, and could provide a compelling path forward.

LASER SUMMARY

The ASPEN laser architecture consists of two primary components: KrF laser amplifiers and a novel spatial and temporal pulse compression system. The KrF units are large single-pass amplifiers, capable of generating several megajoules each over a few microseconds. At this relatively long pulse length and resulting low pump power, no electrical pulse compression is necessary, and based on extensive prior DoD work it is anticipated that light can be made at a hardware cost of \$5 to \$10 per joule. Of course, a pulse of a few microseconds is not directly useful for ICF, and the fundamental ASPEN innovation is a method to temporally compress this high-energy and low-cost light to nanosecond scale with the efficiency and quality required for ICF.

The pulse compression system in ASPEN would use three main stages:

1) **Beam Combination - Spatial Compression:** Output from multiple KrF amplifiers (shown upper right of Fig. 1 outputting salmon-colored beams) is transferred to several co-linear beams occupying a total area of less than 1 square meter, still at 3 us pulse length. This is done using a seeded forward stimulated rotational Raman scattering amplifier (located in the middle of Fig. 1 below where the salmon-color beams converge). The co-linear beams that are output from the Raman amplifier (shown in orange in Fig 1) are high fluence, but have an intensity < 1 Gigawatt/cm^2. A key feature of ASPEN is that this high-fluence light will not touch a solid optic or window.

2) **Temporal Compression 1:** The high-fluence beams output from the Raman amplifier are compressed via seeded backward stimulated Brillouin scattering to 30 ns pulse length. A separate front-end laser system provides the 30 ns input seed **(**indicated by the purple beam in the bottom left corner of Fig. 1). This first compressor is the long tube extending from bottom left that contains the orange-colored beam.

3) **Temporal Compression 2 - Imaging Amplifier:** The high-fluence, 30 ns output from the first Brillouin compressor is used to pump a second and final Brillouin compressor, which is seeded by a pulse (shown in blue in Fig. 1) from a nanosecond-scale, near-diffraction-limited, front-end laser system. For a full beamline, this front-end laser system produces ~2 kJ of narrowband (~GHz) light, which is imaged onto target by a near-diffraction-limited imaging system at *low fluence* – a few tenths of a J/cm^2. After light leaves the final focusing optics (under 1 square meter total area) of the imagining system, it is then amplified in the Brillouin compressor ~10^4, resulting in ~12 MJ taken to target through a windowless vacuum transition section that is actuated on each shot. Thus, once the light is amplified to high fluence, it does not touch a solid material surface until it hits the fusion target. The vacuum transition section can be located half to three quarters of the way from target to final optic, well over 10 meters from chamber center, and remain isolated from the chamber and out of line of sight of target.

Pulse compression of KrF via stimulated scattering processes has been considered before, but was determined to be too inefficient and not scalable to many MJ [Obenschain 2015, Murray 1979]. Innoven Energy has discovered an operating regime, overlooked by previous efforts, that could enable high efficiencies with temporal compression ratios of several thousand, extending work of [Averbakh 1975]. Phenomena that might affect the operation of the ASPEN laser have been modeled in detail, and include gas breakdown, multiphoton absorption, kinetic theory, transient effects, distribution function hole boring thresholds, amplified spontaneous emission, non-linear index effects, and scintillation. None of these issues is predicted to inhibit operation. A 'demonstration laser' has also been designed that implements a scaled-down version of the ASPEN compression system, that could be used to validate the concepts described above.

ASPEN has several attributes that make it a good candidate for an IFE driver in addition to economics. With a final optic standoff as high as 50 m and a final optic area of under 1 square meter per beamline, ASPEN affords significant flexibility on IFE chamber design. ASPEN is anticipated to operate at a repetition rate of 0.25 Hz using existing pulsed power switching technology, but might be raised to 1 to 2 Hz with advances in solid state switching, or by adding additional sets of KrF amplifiers that would alternatively fire and pump the Raman amplifier. The compression system is expected to handle ~1 Hz rep rate due to the very small relative frequency shifts of the Raman and Brillouin processes employed, with minimal energy losses to scattering and ASE. Low rep rate also helps to simplify chamber clearing, target injection, and gas flow handling, as needed for the KrF amplifiers. Finally, ASPEN can readily generate multiple pulses of different energies and pulse lengths for targets that require pulse shaping, with very minimal adjustment to the architecture.

A mature ASPEN laser wall plug efficiency of 7% suggests the need for a target gain of more than 140, which is expected to be achievable with such a high-energy driver. However, the actual operating point would only be identified at the end of a deliberate cost and optimization analysis.

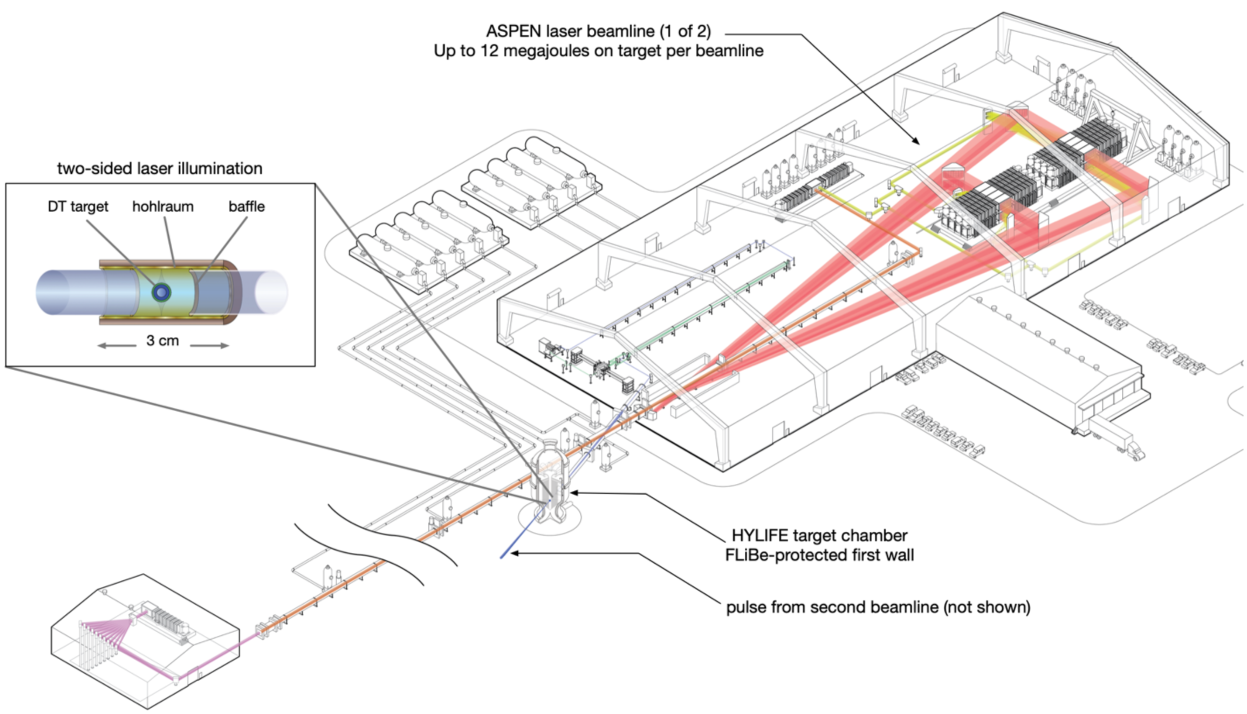
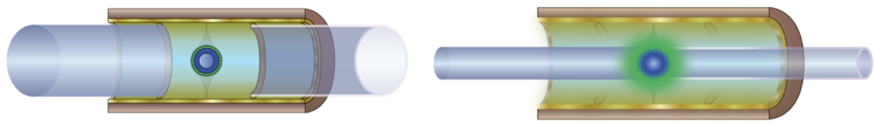


Fig. 1 ASPEN + hybrid target + HYLIFE Concept Illustration

TARGET SUMMARY

The two beamlines described above are used to irradiate a hybrid target that relies on a combination of indirect and direct drive to set the adiabat of the fuel and drive the subsequent implosion (~380 km/s). To be conservative, our design uses the same parameter space as successful experiments at OMEGA and NIF, though we would expect to exploit any future advances. X-ray drive is known to mitigate laser imprint, and large targets should reduce the important of flaws and imperfections (which are relatively smaller).



Of the total energy, at most ¼ is needed for the initial pulse (or less). Thin baffles at the zeros of Legendre mode P2 convert this energy to x-rays, and are sized to drive a near-symmetric first shock in the fusion fuel. By choice, we use a configuration that has proven to be predictable at NIF (i.e., a low-gas-fill hohlraum, with a case-to-capsule radius or CCR ~ 3). The primary drive/pulse is then delivered directly, with laser spots that match the radius of the capsule ***after*** the first shock has traversed the DT.

This geometry mitigates 1) any interactions between the high-Z wall and main drive (a complication for indirect drive) and 2) the beam overlaps that cause cross-beam transfer (a loss mechanism for direct drive). The case is simple, provides a shield against IR, and has the strength and thermal inertia to survive injection. (Essentially, it is an integral sabot.) More energy is coupled to the target than is possible with indirect drive alone, which should enable more mass to be imploded to a higher product of pressure and time. In net, the goal is to enable targets at 2-3x the scale of NIF (and 8-27x more mass) with a similar advantage in areal density. For implosions that are strongly adiabat-shaped, and robust, we estimate the gain could exceed 240 when extrapolating from recent data.

Clearly, we want to fully-utilize the energy available to ASPEN and potentially reduce the size of the driver in time. This approach is not without risk however, as the implosion needs to be symmetric, and is surrounded by an extended plasma. Large targets increase the likelihood of laser-plasma interactions (LPIs). To verify the mechanisms used to control symmetry, we are making plans to test the same concepts within independent calculations. The properties of KrF should help to limit backscatter (i.e., short wavelength, and high-quality spots) but might be insufficient by themselves. To be conservative (again), the peak intensity is ~ 10^{15} W/cm^2, and comparable to existing data. If Stimulated Raman (SRS) or Brillouin (SBS) are problematic, then the design would be updated to include a higher-Z ablator like SiC or Alumina. Either would reduce hydro efficiency and gain, but would help to mitigate any hot electron preheat, and increase absorption. It is important to note that recent experiments with Silicon have generated record levels of performance at OMEGA. Existing facilities could be used to explore this design, and simple variants thereof. Experiments would need to use light at 351 nm, and simulations studies would interpolate to 248 nm.

Finally, recent progress in developing low density foams to wick DT as a liquid into target appear advantageous for this approach to ensure capsule stability subsequent to injection into the chamber. Further, exploring the use of FLiBe with a thin layer of high Z material on its interior as the hohlraum/sabot would provide much increased compatibility with the in-chamber coolant and reduce the quantity of high Z material to remove from the FLiBe and reduce the associated activation concerns.

CHAMBER SUMMARY

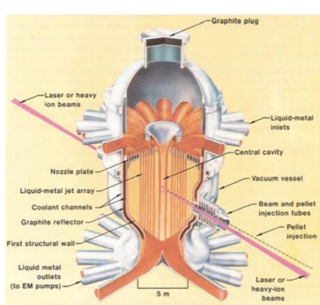
The chamber leverages substantial prior studies of the High Yield Lithium Injection Fusion Energy (HYLIFE-II) concept. Very importantly, thick flowing jets of either FLiBe or FLiNaBe shield the first wall from target emissions, moderate the neutron flux to a fission-like spectrum, breed tritium, and exchange heat with helium to drive a gas turbine that extracts 45% of the fusion energy as electricity. The thick liquid first wall protective jets may also sweep out the debris from each target shot providing an efficient means for recovery and recycling of the target materials. If this chamber concept is feasible, then the need for a special fusion neutron irradiation facility to qualify specially-developed materials to operate in the 14 MeV environment is eliminated – a multi-billion dollar avoided investment and greater than a decade delay in bringing IFE to market.

Other advantages of HYLIFE-II concept include the complete capture of the debris and x-ray energy released from the fusion target, increasing the net efficiency and facilitating the recovery of target material. The reduction of the fusion neutron energy spectrum to fission-like causes fewer displacements per atom in the structural first wall (SFW) leading to the possibility of a single first wall made of conventional steel lasting the entire design life of the plant. It also broadens the natural very short neutron pulse duration. The neutron activation induced in the first wall is much reduced, potentially allowing disposal of the chamber by burial disposal upon decommissioning. The vapor pressure over these liquids at the operating temperature supports transport of the laser power without breakdown in the vacuum. The final optics are placed 50 m from the chamber center such that all target debris and x-rays that pass up the two beam lines are stopped by the final conversion gases that provide the final pulse compression. The final optic mirror would appear to last the life of the plant as would the phase plate materials which may need periodic annealing (every few months) depending on their specific operating temperature.

The main risks that need retiring related to this chamber concept is the time for chamber clearing and the ability to keep droplets or aerosols out of the two laser beam paths during shots. Research at the University of California Berkeley (UCB) has produced various models including a series of codes called TSUNAMI that model the behavior of eutectic salts under fusion chamber conditions and helped support various chamber designs at repetition rates higher than those considered here with two-beam illumination schemes. Small scale experiments such as done at UCB in the early 2000s will be very cost-effective steps to continue to retire risks related to chamber operation with thick liquid protective walls. Further issues such as chemical compatibility of the eutectic salt with the first structural wall material in limiting corrosion and maintaining the salt's constituent purity with respect to lithium are seen as key material and chemical engineering issues to resolve rather than potential showstoppers. Small scale experiments such as done at UCB in the early 2000's will be very cost-effective steps to continue to retire risks related to chamber operation with thick liquid protective walls. Both Kairos and Commonwealth Fusion Systems are also planning to employ FLiBe and discussions have already begun to join in pursuing common research goals.

IFE POWER PLANT OPERATIONS SUMMARY

The IFE Power Plant Target Fabrication Facility will need to generate of order 100,000 or less high precision IFE targets per day at an affordable cost. While studies by General Atomics have shown excellent promise in meeting target fabrication tolerances at the needed rate and cost, further development is required for the novel target considered. Target injection, tracking, and irradiation studies including hardware and software have also shown promise, but need further development. Over the 50 years of IFE Power Plant studies, many codes have been developed by the government to model different aspects of operation. We are assessing which existing models could be mated to identify the optimum configuration of target design, liquid eutectic salt jet configuration, chamber size, repetition rate, operating temperature, and total eutectic salt quantity. Further, extensive use of artificial intelligence algorithms may be beneficial to the precise and optimal IFE plant operations including target injection and laser irradiation.



Original High Yield Lithium Injection Fusion Energy Concept (Circa 1982)

ECONOMICS

Not enough is known today to estimate the COE and Capital Costs of ASPEN, or any other concept for IFE. However, due to the extensive efforts in the 1980's with this laser technology, we believe the driver can constructed at $10 to $20 per joule optical on target. This is so substantially less than any other driver candidate – at least as this time – that the implications for IFE can only be positive. Analyses by Meier et al[2] show that when the driver is only 5 to 10% of the total cost, then the COE is reduced by 25% and perhaps more. ASPEN might produce low-cost electricity at the GW scale, then walk toward small-scale generation with improvements and updates. Trends indicate that 10's of GW electric power will be needed as old fission plants come off-line. Locating large power stations close to population centers will also be a need. The reduced safety, waste, and proliferation concerns and lack of carbon emission that IFE would bring may also be better factored into the overall cost of this versus other options to provide fusion-based electricity. The concept described here would seem to have the components needed to succeed – large driver energy, a clever target concept, a modest repetition rate, straightforward tritium breeding, heat removal, and a scheme for protecting a first wall built with existing steel. A KrF laser of this energy class would also have other attractive uses in high energy density physics and other fields of research.

Table of Range of Parameters for Future System Optimization

Laser Energy	2 - 24 MJ
Illumination	2-sided
Target Yield	0.5 - 8 GJ
Gain	240 - 360
Chamber	HYLIFE-II (thick liquid wall protection)
Final Optic Standoff Distance	25 - 50 m
Final Optics Total Area	0.375 m^2 per 6 MJ on target
Repetition Rate	0.25 to 2 Hz
Electric Power Output	0.2 - 4 GWe

FUTURE RESEARCH NEEDS

- SBS compression has been demonstrated previously but not in the same regime. Small-scale tests could be used to validate understanding and retire risk. Results should apply broadly, and could be of use in other contexts including ArF or fast ignition.
- As described here, the hybrid target uses features that have been demonstrated in direct and indirect drive, but not at the same energy or scale. Simulations in 1 and 2-D could be used to validate expectations, and the mechanisms needed to obtain good implosion symmetry. Preliminary work at UPM and LLE shows promise. Simulations studies could be followed by experiments at OMEGA or NIF.
- Thick liquid layers as employed by HYLIFE-II are known to provide an effective means of protecting the first wall, and allow for structures to be made from conventional materials. This could reduce cost and the need for further materials development. This solution should be revisited and adapted.
- The potential for wall damage may depend on the time history of the neutron emission – whether pulsed or continuous. Experiments are planned at the pulsed U-Mo10 reactor at WSMR to assess.
- Target fabrication and injection techniques are critical, and will need continued development at GA. Exploration of a FLiBe hohlraum with a thin high-Z liner is another near-term need.
- U of Madrid (UNED) today performs all neutronics calculations supporting ITER. UNED should refine all relevant ASPEN values related to tritium breeding, waste categorization, first wall damage, and impurity levels needed to support economics analyses.

REFERENCES

1) Allen M. Hunter and Robert O. Hunter Jr., “Bidirection Amplification with Nonsaturable Absorption and Amplified Spontaneous Emission”, IEEE Journal of Quantum Electronics, Vol. QE-17, No. 9, May 1981.
2) Allen M. Hunter, Robert O. Hunter Jr., and Thomas H. Johnson, “Scaling of KrF Lasers for Inertial Confinement Fusion”, IEEE Journal of Quantum Electronics, Vol. QE-22, No. 3, May 1986.
3) J. J. Ewing et. al., “Optical Pulse Compressor Systems for Laser Fusion”, IEEE Journal of Quantum Electronics, Vol. QE-15, No. 5, May 1979.
4) Murray et. al., “Raman Pulse Compression of Excimer Lasers for Application to Laser Fusion”, IEEE Journal of Quantum Electronics, Vol. QE-15, No. 5, May 1979.
5) S. Obenschain, “High-energy krypton fluoride lasers for inertial fusion”, Applied Optics, Vol. 54, No. 31, 2015
6) V. S. Averbakh et. al., “Stimulated molecular scattering of light in gasses at different pressures”, Soviet Journal of Quantum Electronics, Vol. 5, No. 10, 1975.
7) Conner Galloway et. al, “Radiation and electron thermal conduction damping of acoustic perturbations in igniting deuterium-tritium gas”, Journal of Plasma Physics, Vol. 85, Issue 6, 2019.
8) Abbott, R. et al., Cylindrical Liquid Jet Grids for Beam-Port Protection of Thick-Liquid Heavy-Ion Fusion Target Chambers, Fusion Technology, 39, 732-738, (2001).
9) Moir, R. et al., HYLIFE-II: Inertial Confinement Fusion Power Plant Design – Particle Accelerators 1992, Vols 37-38 p.467-480.
10) Moir, R.W., R.L. Bieri, X.M. Chen, T.J. Dolan, M.A. Hoffman, et al., HYLIFE-II: A Molten salt inertial fusion energy power plant design-final report, Fusion Technol. 25 (1994) 5-25.
11) Reyes, S. J. F. Latkowski, J. Sanz, J. Gomez Del Rio, “Safety Assessment for Inertial Fusion Energy Power Plants: Methodology and Application to the Analysis of the HYLIFE-II and SOMBRERO Conceptual Designs,” Journal of Fusion Energy Vol. 20 (1): (2001) 23-44.
12) Pitts, J.H., J. Hovingh, W. R. Meier, M.J. Monsler, E.G. Powell, and P. E. Walker, “Potential Design Modifications for the High Yield Lithium Injection Fusion Energy (HYLIFE) Reaction Chamber, LLNL, UCRL-82895, November 1, 1979.
13) Pitts, J. H. and I. U. Ojalvo, “Fluid and Structural Dynamic Design Considerations of the HYLIFE Nozzle Plate”, LLNL, UCRL-84874, February 1, 1981.
14) Nuckolls, J. H. “Feasibility of Inertial Confinement Fusion”, LLNL, Energy and Technology Review, December 1982.
15) Meier, W.R. “Displacement Damage in the First Structural Wall of An Inertial Confinement Fusion Reactor: Dependence on Blanket Design”, LLNL, UCID-20121, July 13, 1984.
16) Liu, J. C. “Experimental and Numerical Investigation of Shock Wave Propagation Through Complex Geometry, Gas Continuous, Two-Phase Media”, University of California at Berkeley, PhD Dissertation, September 7, 1993.
17) Chen, X.M., V. E. Schrock, P. F. Peterson, P. Colella “Gas Dynamics in the Central Cavity of the HYLIFE-II Reactor”, 10th Topical Meeting of Fusion Technology, Boston, MA, June 7-11, 1993.
18) Moir, R.W., R.L. Bieri, X.M. Chen, T.J. Dolan, M.A. Hoffman, P.A. House, R.L. Leber, J.D. Lee, Y.T. Lee, J.C. Liu, G. R. Longhurst, W.R. Meier, P.F. Peterson, R.W. Petzoldt, V.E. Schrock, M.T. Tobin, W. H. Williams, “HYLIFE-II A Molten Salt Inertial Fusion Energy Power Plant Design – Final Report, Fusion Technology, Vol. 25, January 1994.
19) Jantzen, C. “Gas Dynamics Modeling of the HYLIFE-II Reactor”, Proceedings of the International Symposium on Heavy Ion Inertial Fusion, Princeton, NJ, November 14, 1995.
20) Debonnel, C.S., G.T. Fukuda, P.M. Bardet, and P.F. Peterson “Control of the Heavy-Ion Beam Line Gas Pressure and Density in the HYLIFE Thick-Liquid Chamber” Fusion Engineering and Design, 63-64 (2002) 647-652.
21) Velarde, G., J.M. Perlado, J.M. Martinez-Val, E. Minguez, M. Piera, J. Sanz, P. Velarde, E. Alonso, M. Alonso, E. Dominguez, J.G. Rubiano, J.M. Gil, J.G. Del Rio, D. Lodi, J. Marian, P. Martel, F. Ogando, J. Prieto, R. Rodriguez, S. Reyes, M. Salvador, P. Sauvan, M. Velarde, “Implosion Physics, Alternative Target Designs and Neutron Effects on Inertial Fusion Systems, Nuclear Instruments & Methods in Physics Research Section A. 464 (2001) 61-71.
22) C.S. Debonnel, T.X. Wang, M. Suzuki, E. Garcia, and P.F. Peterson. Visual Tsunami: A versatile, user-friendly, multidimensional ablation and hydrodynamics design code. Fusion Science and Technology, 47(4):1165–1169, May 2005.
23) C.S. Debonnel, D.R. Welch, D.V. Rose, S.S. Yu, and P.F. Peterson. Gas transport and density control in the HYLIFE heavy-ion beam lines. Fusion Science and Technology, 43(3):408–413, May 2003.
24) C.S. Debonnel, S.S. Yu, and P.F. Peterson. X-ray ablation and debris venting for the heavy-ion point design. Fusion Science and Technology, 44(2):274–278, 2003.
25) C.S. Debonnel, S.S. Yu, and P.F. Peterson. Progress towards thick liquid fusion chambers for assisted-pinch and solenoid focusings. Nuclear Instruments and Methods in Physics Research A, 544:342–346, 2005.