INTEGRATED PLAN FOR MATERIALS R&D IN LASER INERTIAL FUSION ENERGY (IFE)

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- Statement of Objectives;
- Key Science and Technology Challenges;
- Framework and Integration Logic;
  - Approach;
  - On-going Activities;

➢ Development of Material Systems and Components for High Average Power Density Laser Optics;

- Develop both reflective and transmissive optics;
- Investigate effects of laser, X-ray, neutron and ion/debris;
- Critical issue for transmissive optics : degradation of transmissivity as a result of color center formation;
- Considered materials : SiO_2, CaF_2, MgF_2 and Al_2O_3;

- **Critical issue for reflective optics: degradation of the Laser-Induced Damage Threshold (LIDT) by surface deformation mechanisms;**

- **Considered material systems: FCC metals (e.g. Cu & Al), BCC metals (e.g. Mo & W), SiC, Layered structures and innovative design concepts ;**

- **Design objective:**
  - **Minimize (or compensate for) gross structural deformation by gravity, thermal and mechanical loads;**
  - **Control microscopic surface deformation caused by material defects.**

Development of Reliable Chamber Structures and Components for the IFE Dry-wall Concept;

- **Key Issues:**
  - **Pulsed neutron damage;**
  - **Intense X-ray effects;**
  - **Effects of repetitive thermomechanical shock Loading.**

- **Material Systems : engineered high-temperature composites, with variants of C/C, C/SiC, SiC/SiC; (2) Refractory alloys (W & Mo); ODS Ferritics; Layered structures.**

(1) Pulsed Neutron Effects on Material Degradation:

- Key Issue: Effects of damage rate (6-7 orders of magnitude larger than MFE) and inter-pulse transients on microstructure & properties.
- Common Issues with MFE:
  - High rates of gas generation in C/ SiC;
  - Burnup and stoichiometric changes;
  - SiC: Degradation of K_{th}, micro-cracking, differential swelling, hermiticity.
  - C: Dimensional stability (i.e. shrinkage/ swelling);
- Questions: (1) property extrapolation; (2) materials engineering; (3) effects of pulsed irradiation & excessive gas generation.

(2) Pulsed X-Ray Effects on Surface Ablation:

- Mechanisms of Radiation Enhanced Sublimation (RES) in intense non-equilibrium conditions;
- Surface modification technologies for materials engineering;
- Photon-surface interaction processes:
  - Threshold events;
  - Effects of surface defects, segregation & contamination;
- Cumulative X-ray pulsing effects on sub-threshold events;
- Effects on degradation of optics.

(3) Synergistic Neutron & Thermomechanical Damage to Structural Components;

- Transient pressure and surface loading effects:
  - Stress waves, vibrations;
  - Gradual destruction of fiber/ matrix/ interphase properties.
- Degradation of strength by neutrons/ thermo-mechanical loads;
- Realistic lifetime and reliability limits, which account for damage evolution mechanisms;
- Integration of component design is necessary.

(4) Control of Macroscopic and Microscopic Surface Deformation of Reflective Optics:

- Multiple length-scale deformation by: differential swelling, thermal expansion, gravitational & mechanical loads, sub-surface defects & fatigue-induced dislocation motion;
- Macroscopic deformation: >> control via deformable mirrors and active control loops;
- Microscopic deformation: >> control via materials design, layered structures and coatings.
- Issues:
  - Length-scale limit for active deformation control ?
  - Function separation into optics & mechanical?

(5) Mechanisms of Laser-Induced Damage in Reflective Optics:

- LIDT is caused by surface and near-surface defect generation. For a single-shot ~ 1-10 J/cm^2.
- Amorphous & engineered coatings can improve LIDT for single shot (amorphous Ni >> 40 J/cm^2).
- Data and models on multiple-shot LIDT are lacking. Limited data shows a factor-of-ten reduction after 10000 shots.
- Role of microstructure engineering (e.g. coatings, surface modification techniques & nano-structured multi-layers)?
- Effects of dust, debris and neutrons?

(6) Mechanisms of Optical Absorption in Transmissive Optics:

- Mechanisms of oxygen-deficient centers (F-centers), strained Si-O bond centers, E+ centers and non-bridging hole centers have been determined.
- Fluence limits for concentration buildup of color centers?
- Annealing kinetics, agglomeration & interaction with H, T, and He?
- Transmutation effects? Latkowski calculates 27.5 appm/FPY H, 69.1 He, 54 C, 2 N, 15 Mg, and 4 Al.
- Transient effects: in-situe versus ex-reactor behavior?

(7) Safety and Environmental Impact of Materials:

- The interaction of tritium with ceramic fiber composites (graphite and SiC) and refractories ?
- The attachment, release and diffusion of hydrogen isotopes in graphite and SiC?
- Safety and environmental limits on alloy compositions can be leveraged from MFE studies.

- <u>“Cradle-to-Grave” approach</u>;
- <u>Balanced Mix between</u>:
  - Fundamental understanding of mechanisms;
  - Integration of material and design concepts;
  - Data-base generation for IRE and ETF.
- <u>Experiments:</u>
  - Collection of a database;
  - Motivated by theoretical ideas and concepts;
- <u>Theory & Modeling:</u>
  - Validated by experiments within the program;
  - Advanced models of structural performance and reliability.

X-Ray Ablation Experiments and Analysis of Optics (LLNL):

- IFE-relevant x-ray fluences may be as low as 10 mJ/cm^2 (below the single-shot ablation threshold)
- The repetitive nature of the insult experienced by the final optic (>10^8 shots) is to be investigated;
- Falcon Laser & Z-pinches (5-100 mJ/cm^2 x-ray pulses in a few nsec) will be used for 10^4-10^5 shots;
- A physical model of rapid surface heating and electronic excitation of surface states, followed by ejection of ions will be developed.

Final Optics Material Development (LLNL):

- Annular Core Research Reactor (ACRR) at SNL will be used;
- Extremely pure materials (CaF_2) will be used to study the effects of impurities;
- Existing SiO_2 samples with ~5 year IFE-equivalent doses (irradiated at LANSCE in 1995) will also be tested ;
- Additional materials (e.g. MgF_2 and Al_2O_3 & reflective optics?) will also be tested.
- Thermal annealing studies to determine kinetics.

MD Damage Simulations in Optical Materials (LLNL):

- Large-scale MD simulations of fused silica will be used to characterize the recoil-induced damage in terms of density, coordination, ring statistics and correlation.
- Model will be related to the extensive experimental data available for fused silica ?
- Research will be useful in the future to predict the response of candidate materials for the final optic.

- **MD Damage Simulations in Chamber Materials (LLNL):**
  - **Study defect production and migration in C & SiC (?)**
  - **Construct a global model of defect production and accumulation.**
  - **Compare results (?) with those for continuous irradiation and experimental measurements.**

- **Pulsed Fusion Neutron Source Development (U. Texas):**
  - **Measure the fusion yield from exploding clusters with 10 J laser pulses using the JanUSP laser at LLNL;**
  - **Explore the yield per shot as function of laser pulse width, and the yield increase as the clusters are made larger;**
  - **How will these experiments be correlated with MD studies?**

IFE Final Optics Neutron Irradiation (LANL):

- Using LANSE and WNR, radiation effects on SiO_2, CaF_2 transmissive optics will be investigated.
- Pre- and post-irradiation examination of irradiated samples will be carried out.
- Point defect models, to determine the concentration of color centers in irradiated samples will be correlated to measurements.

❑ Laser Induced Damage Threshold (LDIT) of GIMM (UCSD):

- ❑ The goal is to experimentally determine LIDT at grazing incidence with clean surfaces;
- ❑ The reflectivity and wave front changes of clean surfaces will also be modeled;
- ❑ The effects of surface contaminants on reflectivity, LIDT and wave front will be measured and modeled.

Conclusions

- **Very challenging scientific and technical issues for IFE materials require a dedicated, self-consistent and integrated R&D approach.**
- **Augmentation and focusing of on-going activities are recommended;**
- **A detailed R&D plan has been worked-out, with ample opportunity for modifications and improvements.**