Progress in Alternate Chambers Activities

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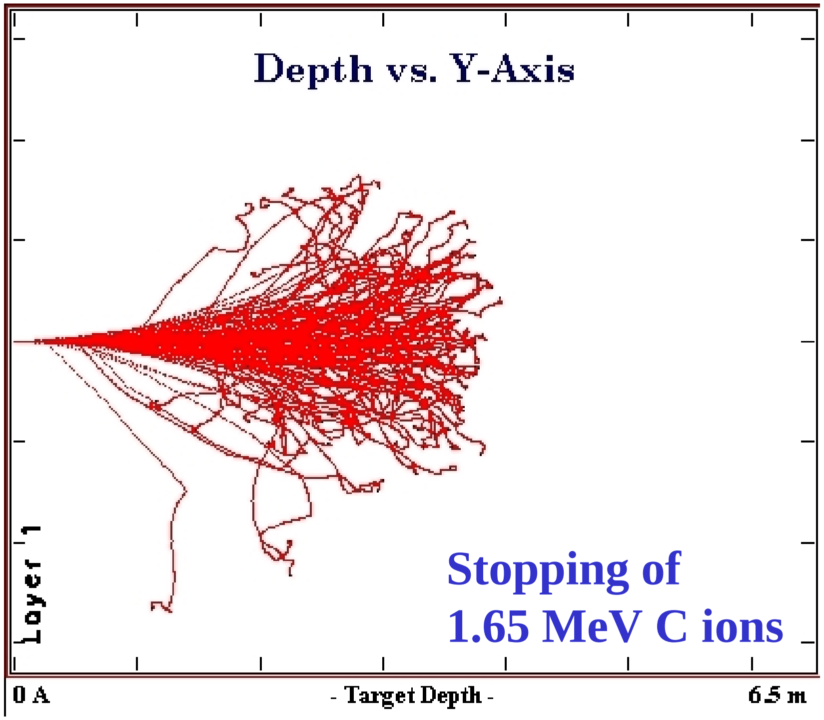
Outline

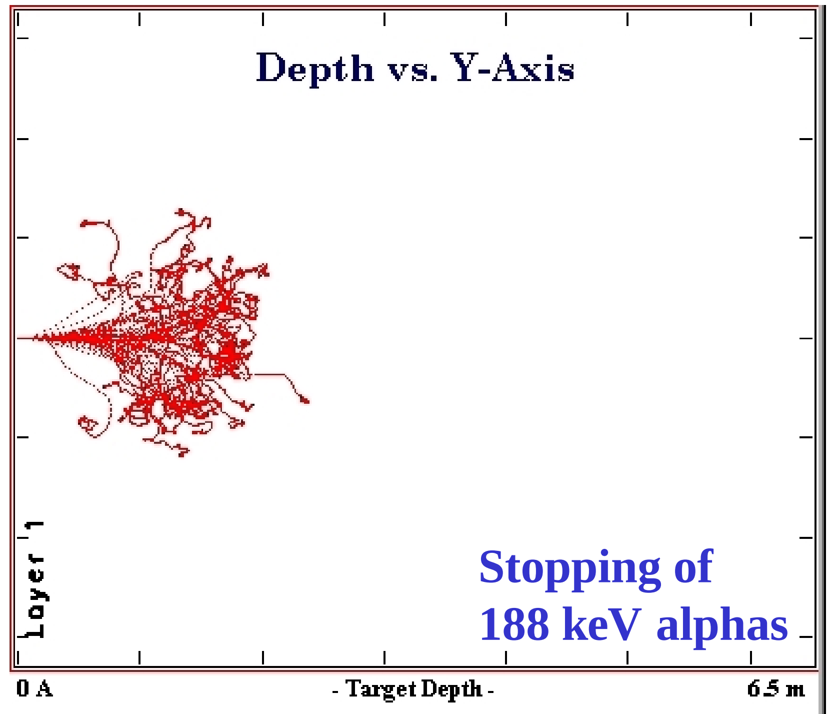
- Ion threat to first wall and optics
- Magnetic deflection progress and plans
- Fast ignition progress
- Safety & environmental support
- Neutron damage modeling for graphite

The reduction in chamber gas pressure to reduce target heating increases ion damage to chamber wall and optics

- Ion radiation damage issues need attention
- Focus on avoidance of melting/vaporization misses bigger picture of radiation damage from ions
- Several damage mechanisms need to be considered:
  - Sputtering
  - Blistering/spalling/bubble formation
  - Modification of macroscopic properties resulting from the above:
    - Chambers: thermal conductivity, strength, etc.
    - Optics: reflectivity, absorption
- **These issues are not new, but they need to be revisited in light of the reduced gas pressure and significantly harder ion spectra**

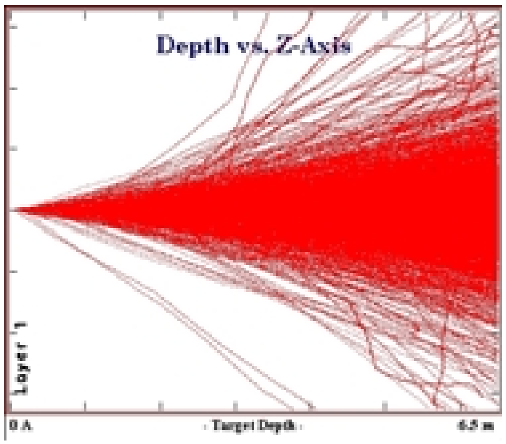
Sombrero used 0.5 Torr of Xe gas to effectively stop charged particles



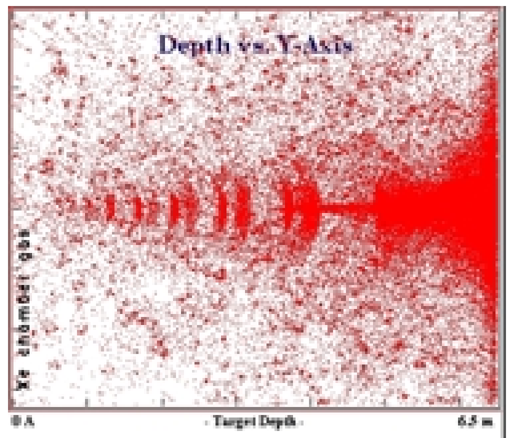


- ❑ The 1.6 MeV carbon ions were stopped by 3.25 Torr-m of Xe
- ❑ Calculations completed with SRIM 2000.

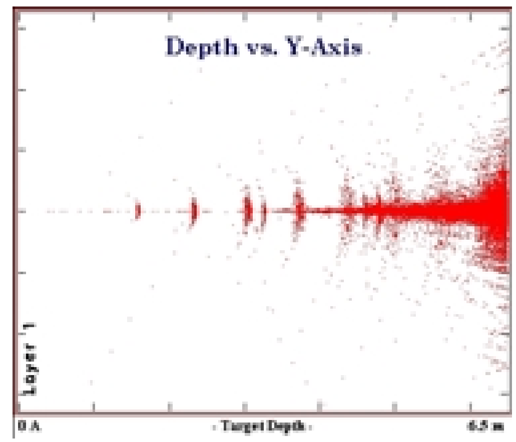
With less Xe gas, most charged particles make it to the wall and/or optics



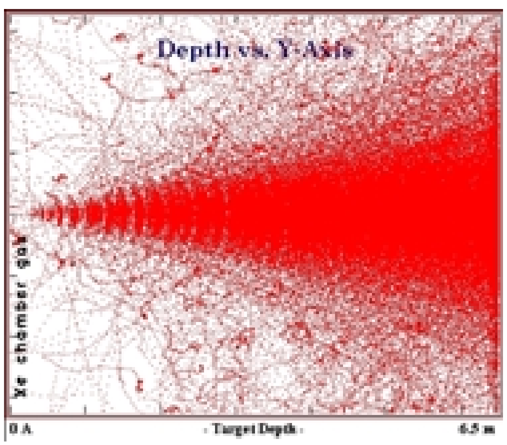
Debris Au ions



Debris D ions



Burn α ions

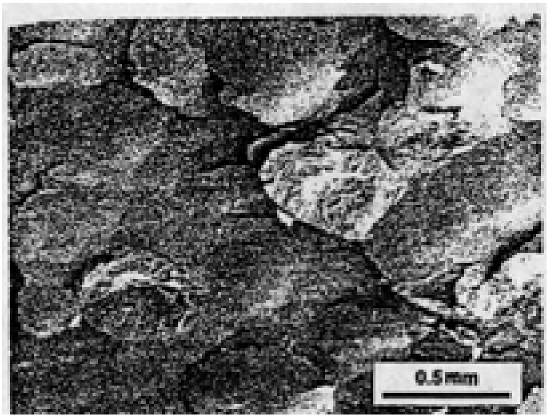


Debris C ions

- Plots show charged particle interactions with only 50 mTorr* (0.325 Torr-m) of Xe gas:
  - Ion output increased from ~20% in SOMBRERO study to 28% in NRL target
  - Harder ion spectra from the NRL target (Perkins' LASNEX results)

*Note: The target injection folks say that even 50 mTorr is too much gas.

The expected charged particle fluences would have significant effects upon graphite



SEM of blisters on surface of pyrolytic graphite implanted with 3.5 MeV He ions at 770 K to ~6 dpa (7×10^{17} cm^{-2})

V. N. Chernikov et al., J. Nucl. Mater. 227 (1996) 157.

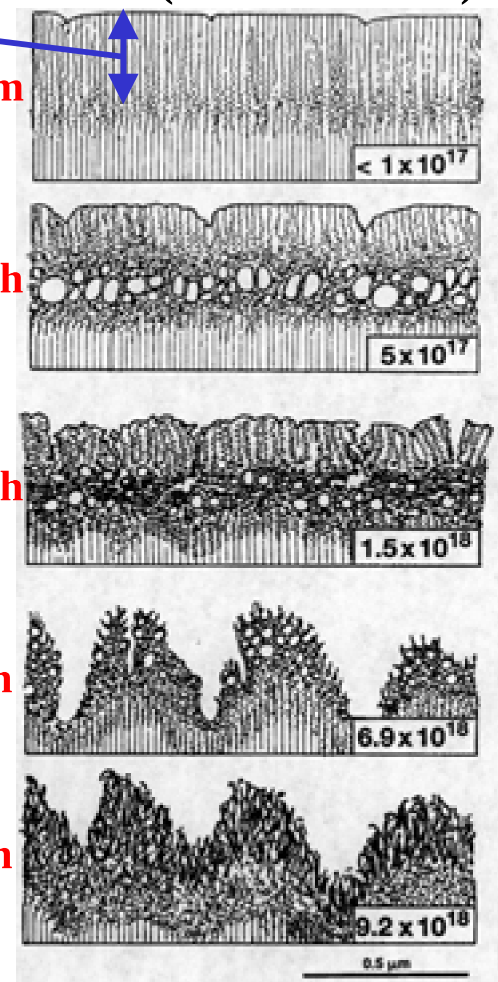
0.3 µm for 40 keV alphas/
1.2 µm for 230 keV alphas/
5 µm for 1.8 MeV alphas

- Burn alpha annual fluence is 2.4×10^{21} α/cm^2 with average energy of 1.8 MeV
- Debris alpha annual fluence is 2.2×10^{21} α/cm^2 with average energy of 230 keV
- Sputtering would remove 26 kg/y (29 µm/y) of material

Times required for burn alphas to reach indicated fluences

Dose (40 keV He$^+$/cm^2)

22 m
1.8 h
5.4 h
25 h
33 h

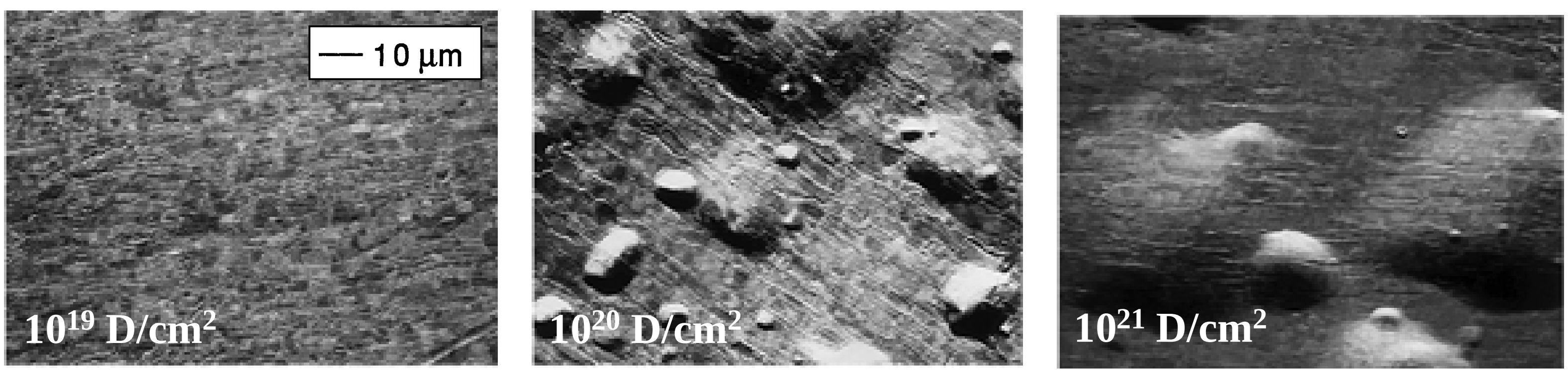


Sketches based upon detailed analysis of TEM data

V. Kh. Alimov et al., J. Appl. Phys. 78(1) (1995) 137.

Tungsten also has ion radiation damage issues

- Deuteron implantation damage is severe even with sub-keV ions
- Expected annual fluences:
  - Burn D^+: 5×10^{20} cm^{-2} with E_{avg} = 3.7 MeV, R = 26 µm
  - Debris D^+: 3×10^{22} cm^{-2} with E_{avg} = 140 keV, R = 0.55 µm
- Sputtering would remove ~200 kg/y (20 µm/y)



A. A. Haasz et al., J. Nucl. Mater. 266-269 (1999) 520.

Optics may be strongly affected by large charged particle fluences

Fused Silica

- Sputtering: removal of 1.9 μm/y (**5.5 × λ_{DPSSL}**) for lens at 30 m

- Ion irradiation on SiO_2 optics may cause significant changes in optical properties:
  - 3% absorption at 546 nm induced by 20 keV He^+ irradiation to fluence of 5×10^{15} cm^{-2}
  - 0.04% absorption at 200-600 nm from 1.2×10^{17} Au/cm^2 at 3 MeV (we expect 55× this per year)
  - Literature shows changes in refractive index as well

Aluminum

- Sputtering: removal of ~15 μm/y (**59 × λ_{KrF}**) for Al GIMM (85º) at 30 m

- H_2^+ and He^+ irradiation produces dislocation loops and gas bubbles:
  - He bubbles keep spherical shape even after annealing at 893 K (see figure)
  - Bubbles near surface may affect reflectivity and/or beam quality

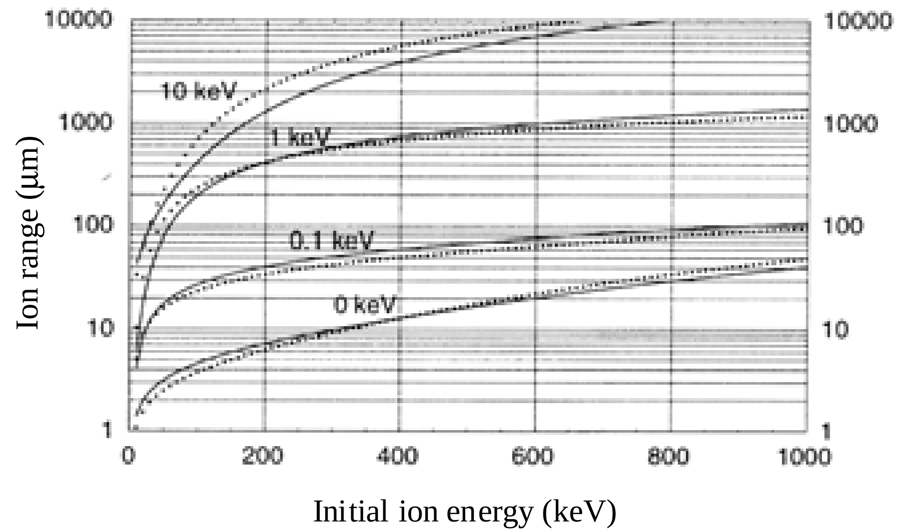
893 K

He bubbles in aluminum after irradiation with 17 keV He^+ ions with a fluence of 1.2×10^{14} $ions/cm^2$ at 573 K.

K. Ono et al., J. Nucl. Mater. 183 (1991) 154.

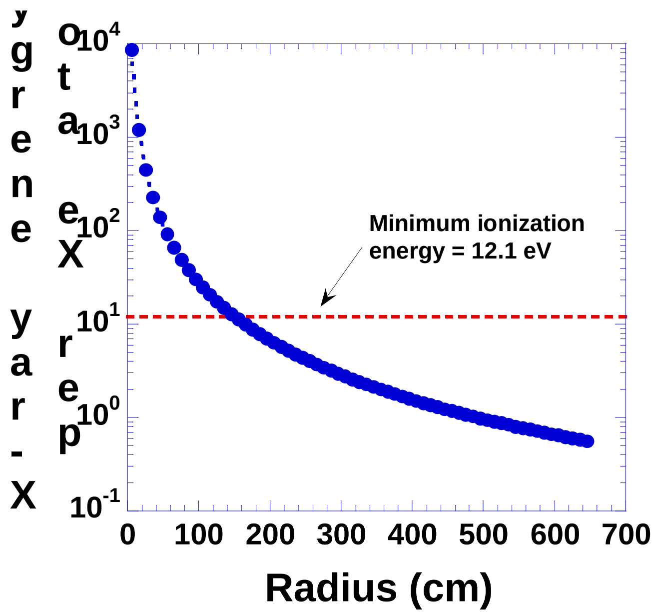
The x-ray pulse, which arrives prior to the charged particles, will affect stopping

- X-rays will pre-ionize the Xe gas → need detailed calculations to ensure that stopping is modeled correctly



Ion ranges for tritons stopping in solid density deuterium (dashed lines indicate the converse) as a function of the electron temperature of the substrate.

L. J. Perkins et al., Nucl. Fusion **40** (Jan. 2000) 1-19.

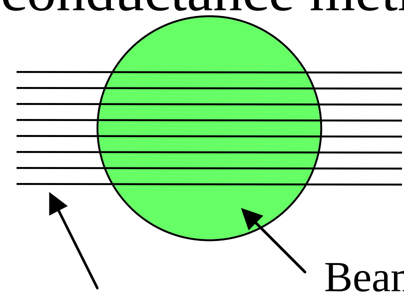


The first meter of Xe gas is likely to be ionized when the charged particles pass through it.

Currently available facilities can provide high fluences of high-energy charged particles

- We propose to irradiate some carbon fibers using the Ion Beam Lab at LLNL:
  - Alphas up to 4 MeV
  - Beam current of ~1 μA focused down to ~0.1 cm^2 → 6×10^{13} He/cm^2-s
  - Get to 10^{18} He/cm^2 with 4-5 h irradiation
  - We expect an annual fluence of 2.4×10^{21} cm^{-2} with E_{avg} = 1.8 MeV (burn α's), but we expect to see effects at <10^{18} cm^{-2}

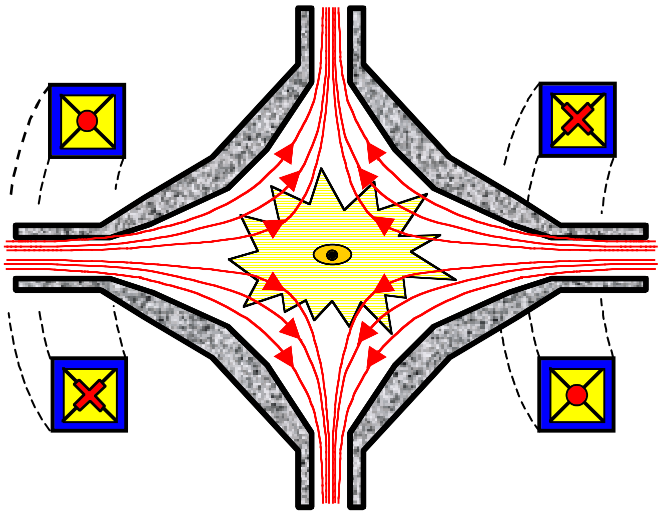
- Measure thermal conductivity via parallel thermal conductance method?



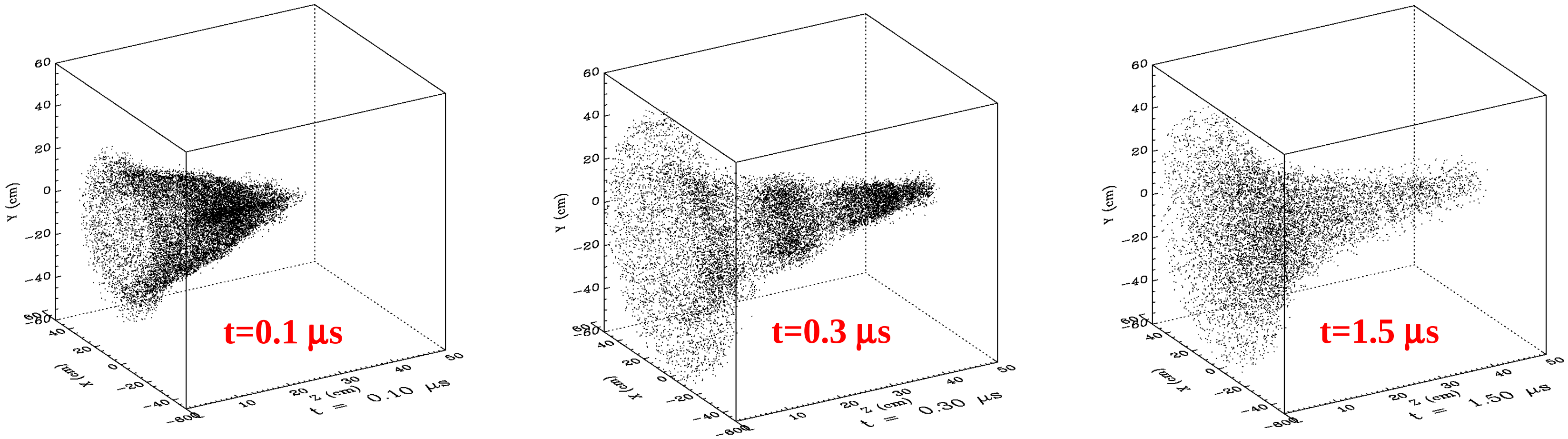
Ion Beam Laboratory at LLNL

Magnetic deflection of ions may offer a solution/improvement

- Perkins has collaborated with GA to perform a magnetic deflection calculation for a cusp field (mirror is interchange unstable) and target with high charged particle output:
  - Field was 5 T at coils; Modeled 20 keV protons w/ 2 keV thermal spread
  - Found confinement time, τ, of 1.5 μs
  - Confinement time scales as m/E; NRL target has E~280 keV and m~2.6 → τ ~ 0.3 μs
  - Mirror would have longer confinement time



From L. J. Perkins et al., "Inertial Fusion Energy with Advanced Fuels," Presented at the Second International Conference on Inertial Fusion Sciences and Applications, Kyoto, Japan (Sep. 2001).



We are proceeding with a magnetic deflection variation to SOMBRERO

- LASNEX – Results provided by L. John Perkins: obtain ion species densities and energy spectra 100 ns after target implosion

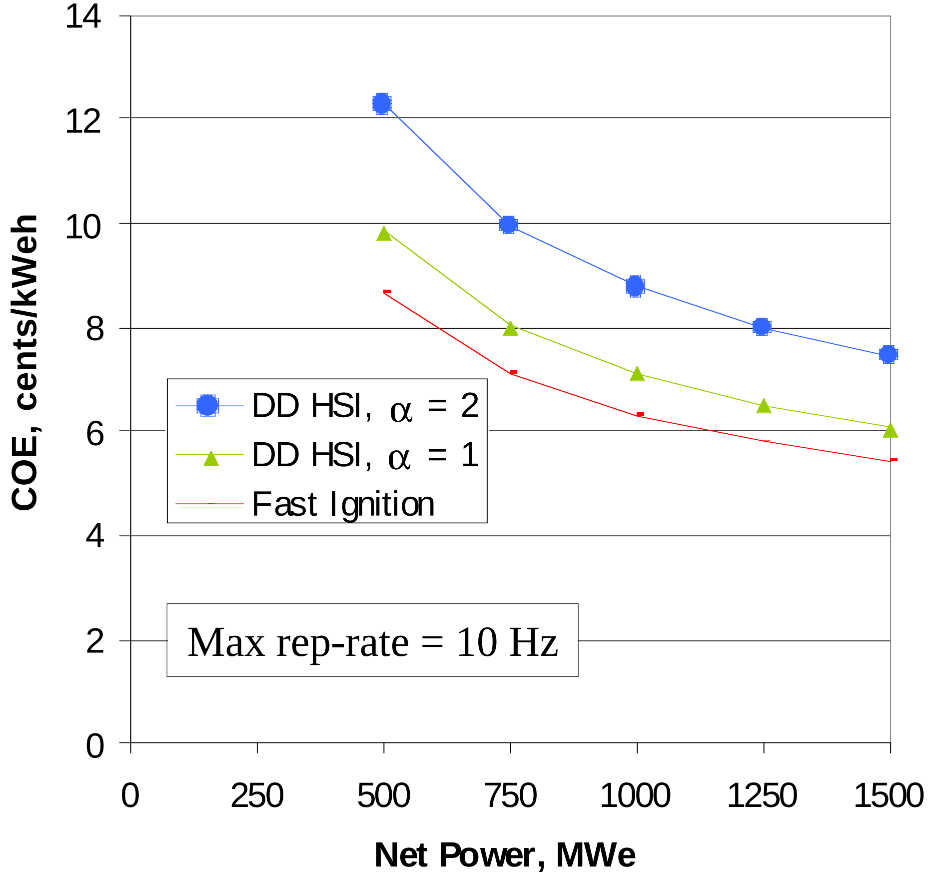
- Lsp – Mission Research: 3-D time-dependent PIC code to follow ions to the first wall, thru beam ports and to the optics

- TOSCA3D – Vector Fields: 3-D finite element code to model external magnetic fields; will allow consideration of fields from finite magnets and iteration to include induced fields from expanding plasma ball

- SRIM/TRIM – Biersack and Eckstein: Monte Carlo code to simulate atomic collision processes in solids (may eventually move to SUSPRE to make calculations truly coupled)

- TART – X-ray transport and deposition

With fast ignition, a given COE can be met at lower net power

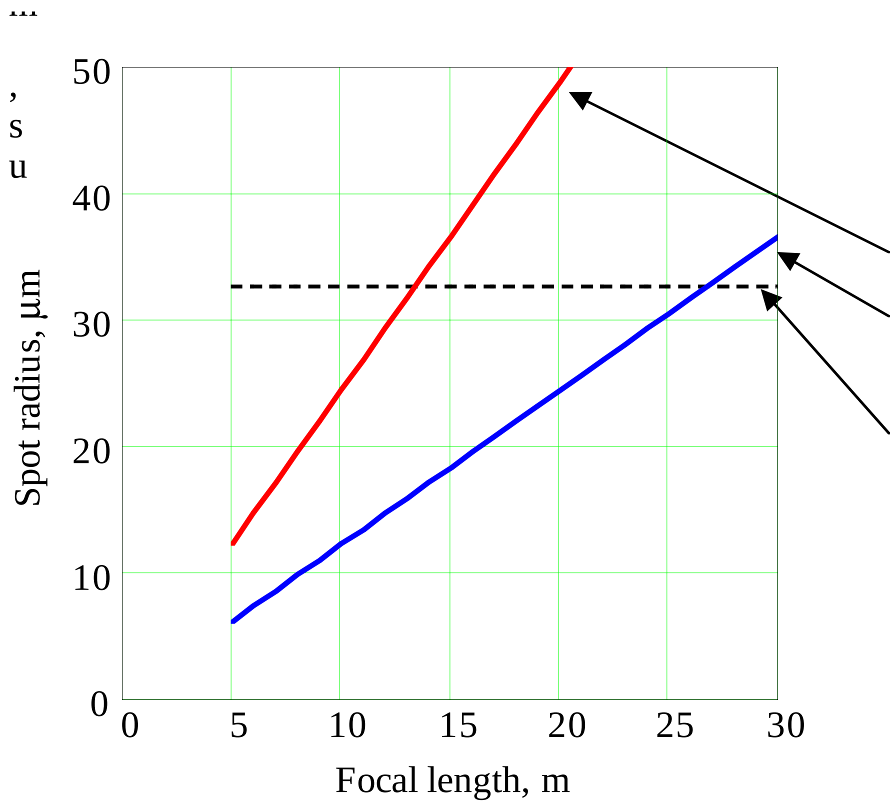


<u>Example:</u>

For COE = 8¢/kW_e-hr
FI needs < 600 MW_e
vs. 750-1250 MW_e
for hot spot ignition

- ❑ Small plant components (e.g., HTS) could have lower development cost
- ❑ Multi-unit plants could take advantage of small unit sizes

Allowable stand-off for ignitor beams increases with optics diameter



Diffraction limited spot radius with final optic diameter of:

D_o = 50 cm

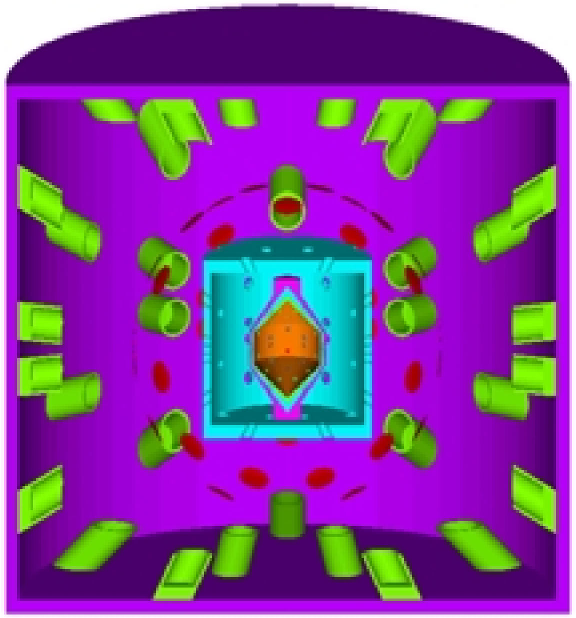
D_o = 100 cm

Typical required spot size ~ 33 µm

Optics must be protected from (or be able to survive) x-ray, debris and neutron threats from targets → protection becomes easier with a larger stand-off distance

LLNL helps address key safety & environmental issues for laser IFE

- Contributions to the Laser IFE Materials Plan:
  - Summary of chamber wall and optics "threat spectra"
  - Guidance in the selection of materials with consideration of waste disposal, recycling, afterheat, and accident dose issues
- Completed LOCA and LOFA analyses for SOMBRERO; emphasized importance of C/C oxidation
- Investigated clearance issues for SOMBRERO components
- We will continue to use a portion of our chambers funding to address S&E issues as programmatic needs require



SOMBRERO 3-D model for neutronics analysis

We are modeling radiation damage, tritium diffusion, and tritium retention in graphite

Simulation model

Molecular dynamics simulations to study the defects produced during irradiation in graphite

We have implemented a bond-order potential for carbon-hydrogen systems in our parallel molecular dynamics code. This is the most accurate empirical potential for graphite to this date.

Goal of the simulations

Understand defect formation in graphite at the atomistic level and quantify number of defects with energy of recoils

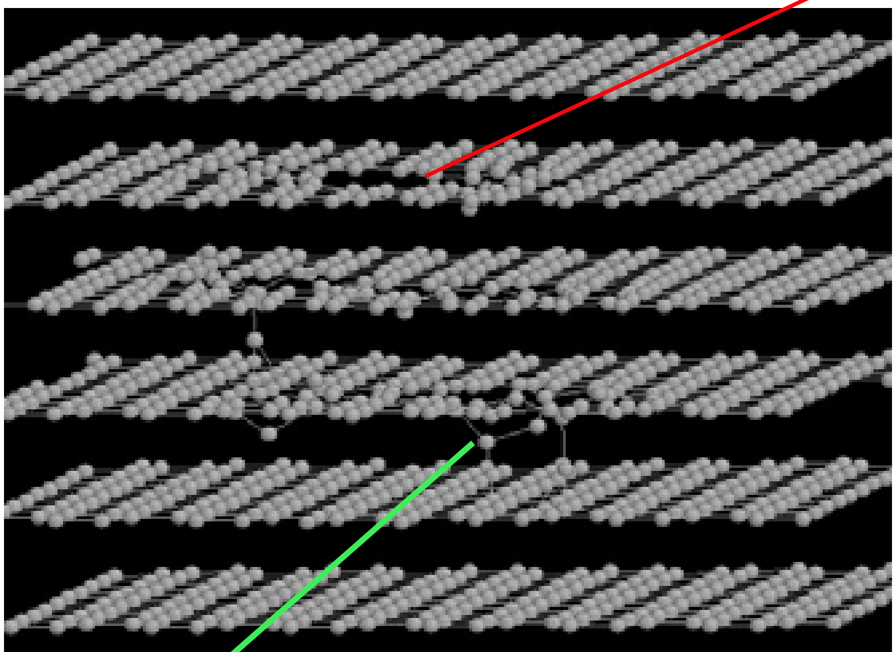
Understand tritium diffusion in the presence of defects generated during irradiation

Combine results of defect production with detailed neutron flux calculations at the first wall and understand the effects of pulsed irradiation in final microstructure

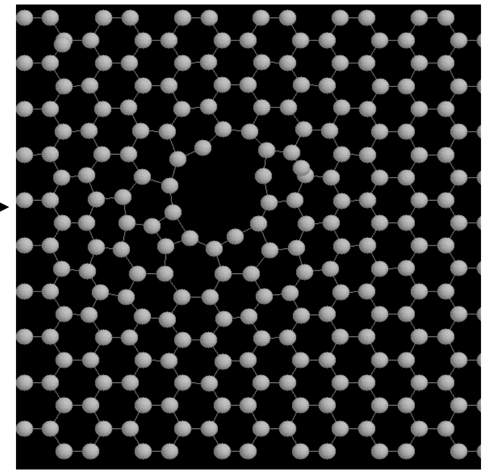
Atomistic modeling provides details into formation/ behavior of defects produced during n^0 irradiation

Damage produced by a 200 eV C recoil along the c-direction in graphite

Vacant sites



Interstitials



Radiation produces vacant sites in the lattice that could act as trapping sites for tritium

Our calculations show a strong binding between a single vacancy and H ~ 3.8 eV

Calculations of defect structures and energetics will have to be validated with first principles calculations and compared to previous models

Summary

- Ion radiation damage issues may be quite severe for chamber wall and final optics materials:
  - Root cause is reduced chamber gas pressures (10 vs. 500 mTorr Xe)
  - Sputtering and property changes may occur
  - Effects of Xe pre-ionization upon ion stopping need to be investigated
  - Ion irradiation experiment to be conducted

- Magnetic deflection may offer at least a partial solution:
  - Work is beginning with Lsp and TOSCA3D
  - Simple calculations suggest that moderate fields (several Tesla at the coils) should be adequate
  - "Real" fields, including those induced by the expanding plasma ball, will be considered

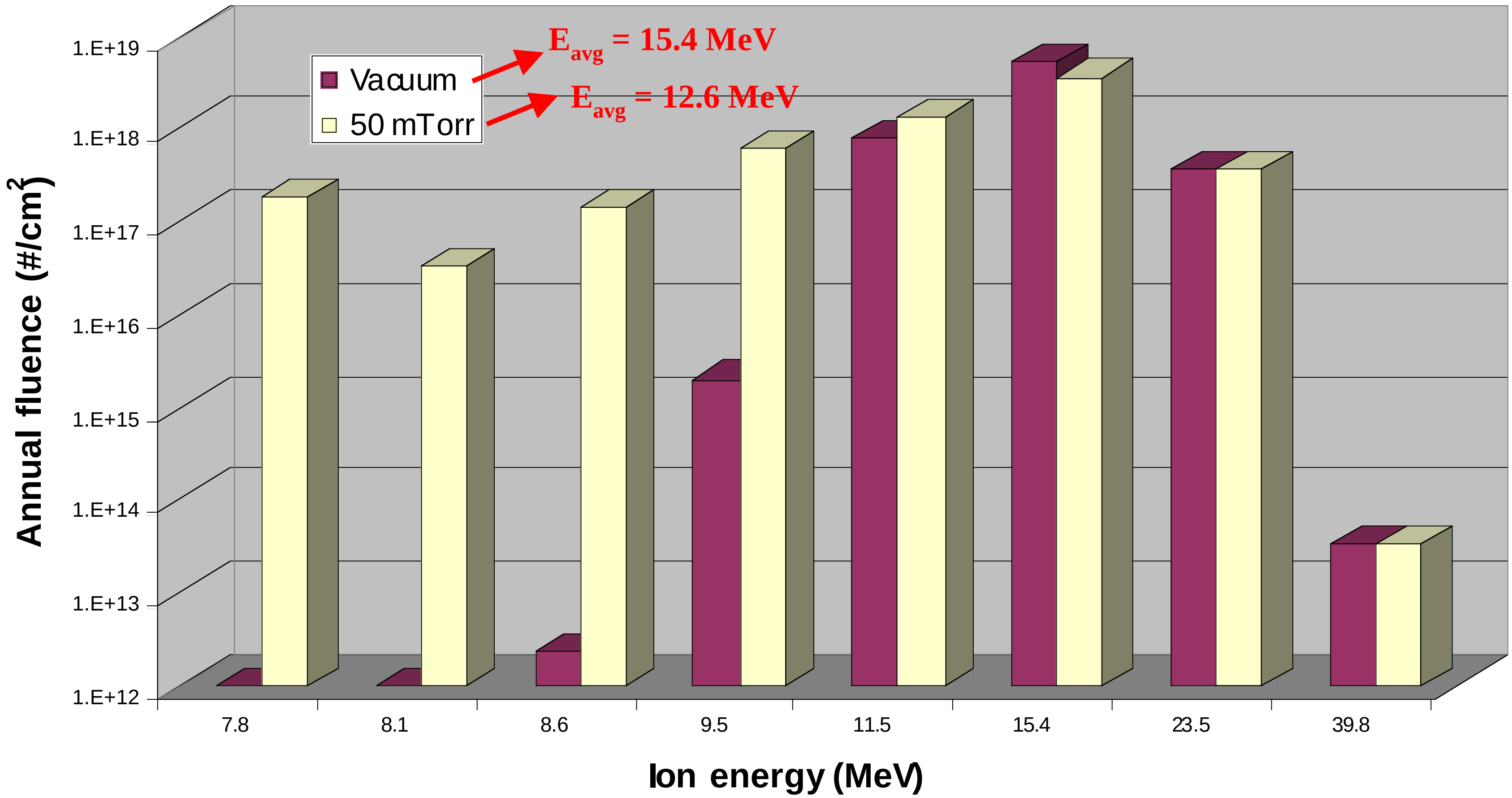
Summary, (Cont'd.)

- Our fast ignition work is centered on systems and integration issues; We plan to direct our focus towards optics and layout issues
- Safety & environmental support will continue to be provided as needed by program
- A bond-order potential for graphite has been implemented in the MDS code; calculations are underway to study defect behavior and influence upon tritium migration & trapping

BACKUP SLIDES

Ion threat, (Cont'd.)

The high-energy Au flux is largely unimpeded by 50 mTorr of Xe



A gas puff near the optics probably will not work

Ion	Peak energy (MeV)	Range (m) in 10 mTorr Xe	Range (Torr-m)
Au	39.8	400	4
C	2.45	200	2
α	12.3	5300	53
He3	12.7	6500	65
T	12.7	27000	270
D	13.3	36000	360
P	14.8	67000	670

- Ranges provided by SRIM 2000 package
- Protons with a 670 Torr-m range could be stopped with a 1-m-thick gas puff at a pressure of 670 Torr (0.9 atm)