Neutronics and Shielding Issues for IFE Designs

Mohamed Sawan
Laila El-Guebaly

Fusion Technology Institute
The University of Wisconsin

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General Observations

- Several neutronics and shielding issues are generic to all IFE blanket concepts (dry walls, wetted walls, and liquid walls)
- 10^5-10^8 higher instantaneous radiation effects (damage, gas production, heating, ...) in IFE compared to MFE
- Geometrical, spectral, and temporal differences between IFE and MFE impact neutronics features
- Scaling neutronics parameters with neutron wall loading between MFE and IFE systems is misleading
- It is easier to achieve tritium self-sufficiency in IFE systems
- Despite the simpler IFE chamber geometry, multi-dimensional analysis is still needed
- Innovative penetration shielding design could prolong lifetime of final optics and final focusing magnets

Topics

- Target Neutronics
- Chamber Neutronics
- Shielding

Target Neutronics

- Initial split of energy from DT fusion energy is 14.1 MeV n and a 3.5 MeV α
- In IFE target, DT fuel is heated and compressed to extremely high densities before ignition and neutron fuel interactions cannot be neglected
- Softening of neutron spectrum, neutron multiplication, and gamma production occur
- Energy deposited by neutrons and gamma heats target and ultimately takes the form of radiated x-rays from the hot plasma and expanding ionic debris
- Spectra of neutron and gamma photons emitted from the target represent the source term for subsequent chamber neutronics, shielding, and activation calculations

Coupled Target Neutronics and Hydrodynamics

- In the past, target neutronics were performed using single target configuration at start of burn with uniform densities and source profile
- Densities, configuration, and source distribution are continuously varying during burn
- Target neutronics calculations need to be coupled with target hydrodynamics calculations to account for varying configuration during burn as well as distributed material densities and fusion neutron source
- Detailed partitioning of energy produced from target can then be accurately determined

Example of Target Neutronics Calculations

- High gain target developed for LIBRA-SP light ion reactor study
- Indirect-drive target with outer Au radiation case, a low density CH foam which absorbs Li beam ion energy and converts it to x-rays, a CH ablator with CF_2 x-ray pulse-shaping layer, and an inner DT fuel region
- Spherical geometry neutronics calculations coupled to BUCKY-1 calculations
- Calculations for time intervals during the burn
- Results combined weighted by yield fraction in each interval

Target Energy Partitioning in LIBRA-SP

Target

Endoergic Losses
2.11%

Ion Debris
6%

Gamma Photons
0.07%

x-rays
22%

Neutrons
69.82%

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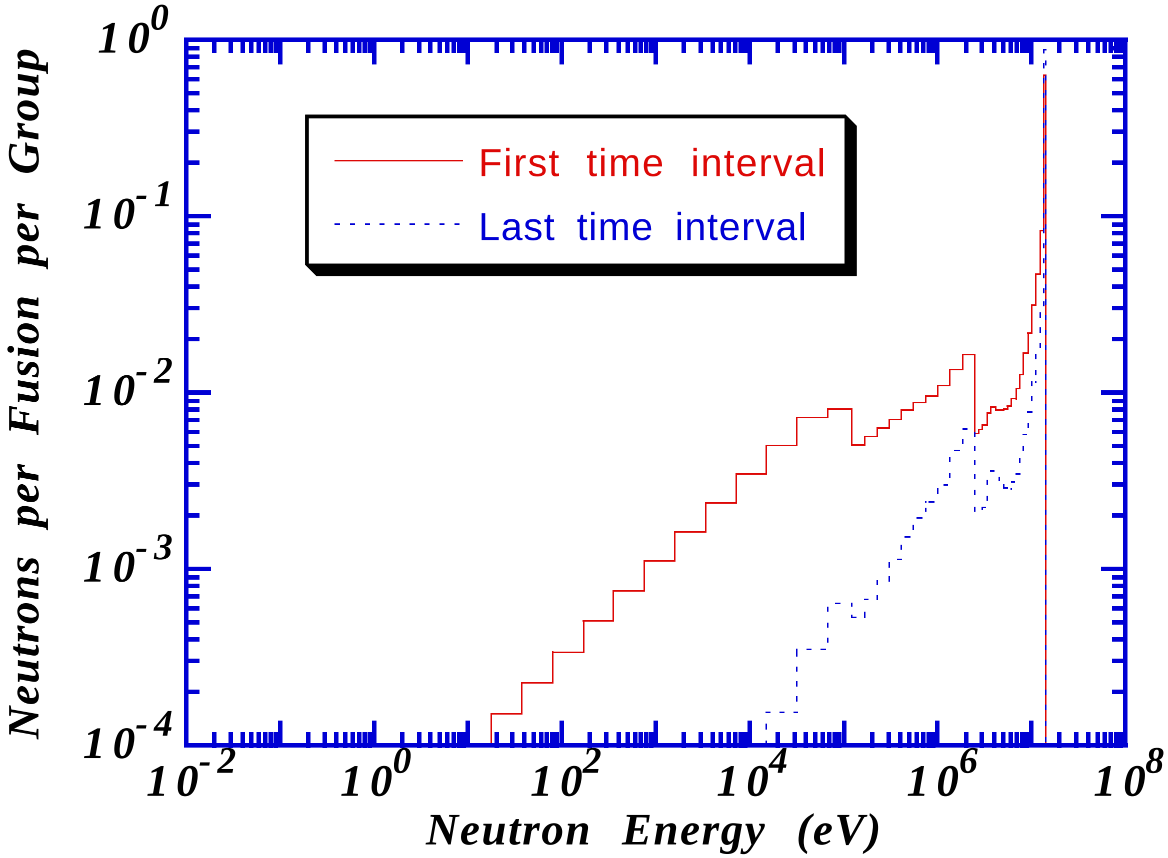
Neutron Spectrum Gets Harder at End of Burn



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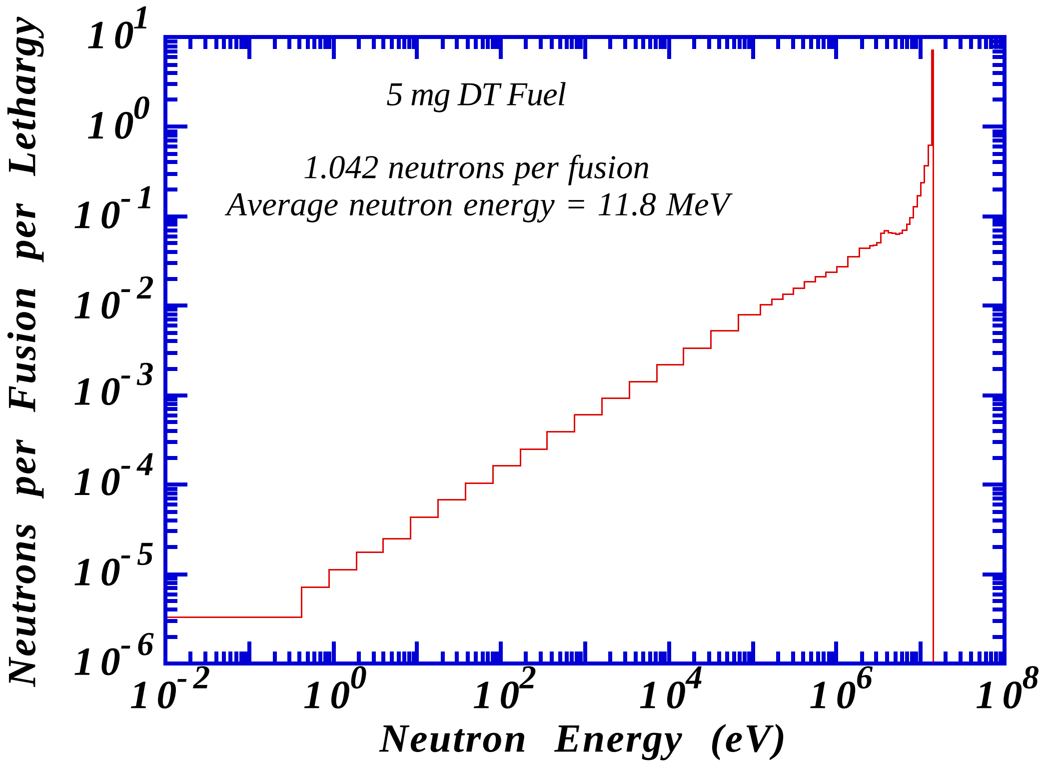
1.042 Neutrons Emitted from Target per Fusion



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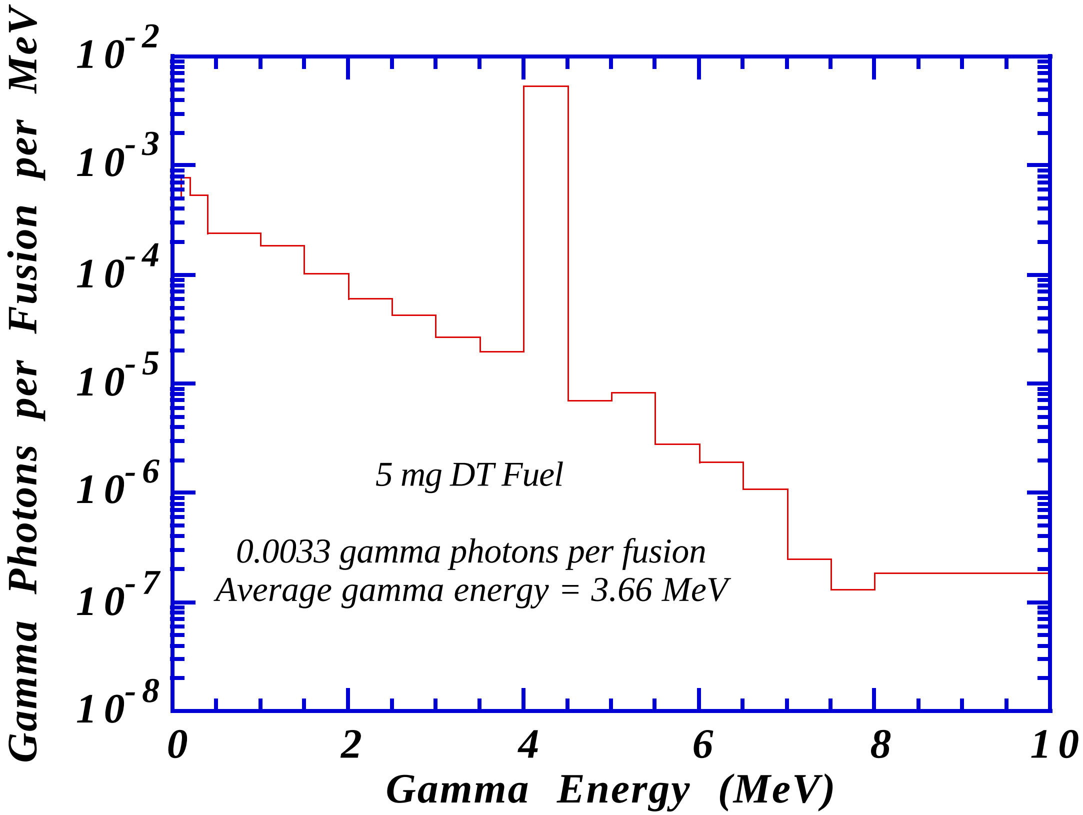
0.0033 Gamma Photons Emitted from Target per Fusion



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Impact of Coupled Target Hydrodynamics/Neutronics Calculations

	Uncoupled Calculations	Coupled Calculations
Neutron multiplication	1.060	1.042
Energy carried by neutrons (MeV/fusion)	11.75	12.29
Average energy of neutrons (MeV)	11.08	11.80
% of neutrons @ 14 MeV	61.4%	69.6%
Emitted gamma per fusion	6.21×10^{-4}	0.0033
Energy carried by gamma (MeV/fusion)	0.002	0.012
Average gamma energy (MeV)	3.17	3.66
Absorbed n energy (MeV/fusion)	1.960	1.429
Absorbed gamma energy (MeV/fusion)	1.88×10^{-6}	1.34×10^{-4}
Endoergic losses (MeV/fusion)	0.388	0.371

Chamber Neutronics

- Similar blanket function in IFE and MFE plants
- Basic requirements are:
  - Achieve adequate TBR (≥1.1) to insure tritium self-sufficiency
  - Maximize overall energy multiplication (M_o)
  - Provide adequate shielding for permanent chamber wall
- Basically, blankets developed for MFE systems can be utilized in IFE systems

Neutronics Features of MFE and IFE Chambers are Different

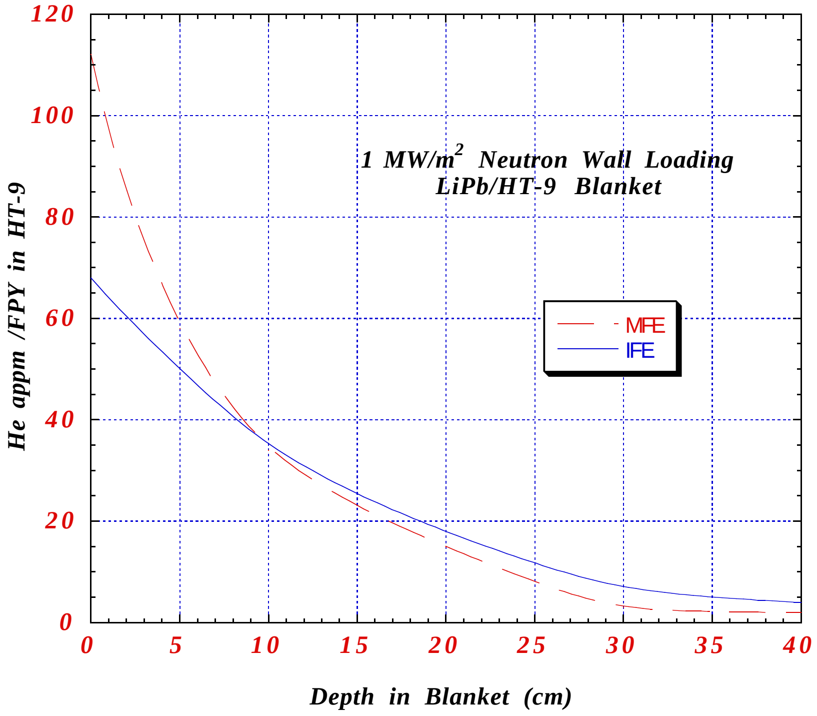
I. Geometrical differences:

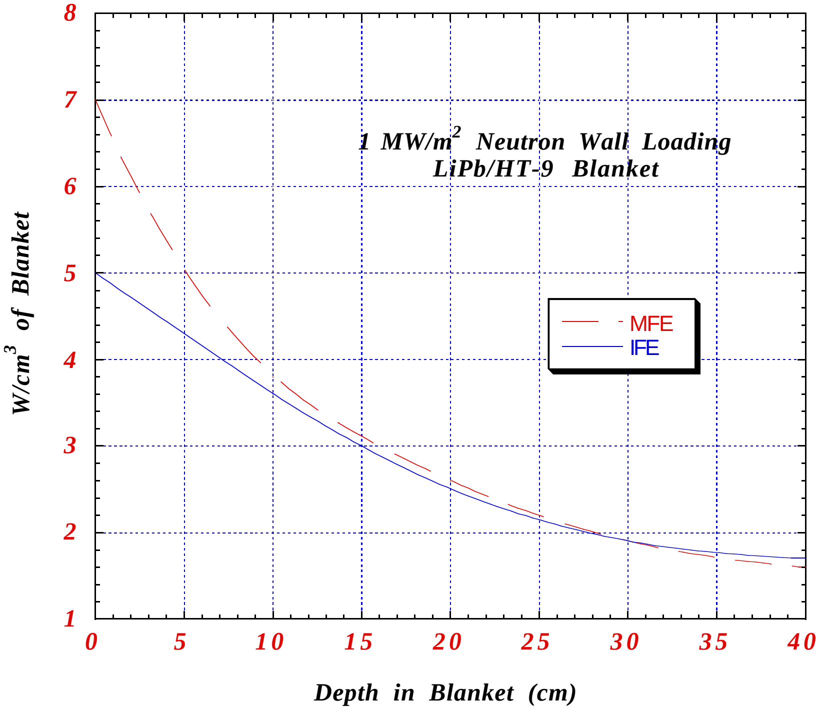
IFE	Point source in nearly spherical chamber
MFE	Volumetric source in toroidal or cylindrical chamber

Implications:

- Significantly different angular distributions of source neutrons incident on FW (more perpendicular to FW in IFE)
- For same neutron wall loading, lower radiation effects (dpa, He, T, heating) at FW and front of blanket in IFE ⇒ Longer FW lifetime
- Less radial gradient of radiation effects in IFE blankets
- Effect more pronounced for radiation effects produced by high energy neutrons
- Scaling with neutron wall loading can not be used freely between MFE and IFE systems

Impact of Geometrical Differences on Nuclear Parameters





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II. Spectral differences:

IFE	Softened source neutron spectrum (10-12 MeV average)
MFE	14.1 MeV neutron source

Implications:

- For same fusion power, IFE blankets have lower radiation effects
- Effect more pronounced for radiation effects produced by high energy neutrons
- ~20% higher neutron source strength is required in IFE to achieve same neutron wall loading as in MFE with net effect on blanket radiation effects depending on type of nuclear reactions
- Slightly larger radial gradient of radiation effects results from softer IFE spectrum
- Scaling with neutron wall loading can not be used freely between MFE and IFE systems

III. Temporal differences:

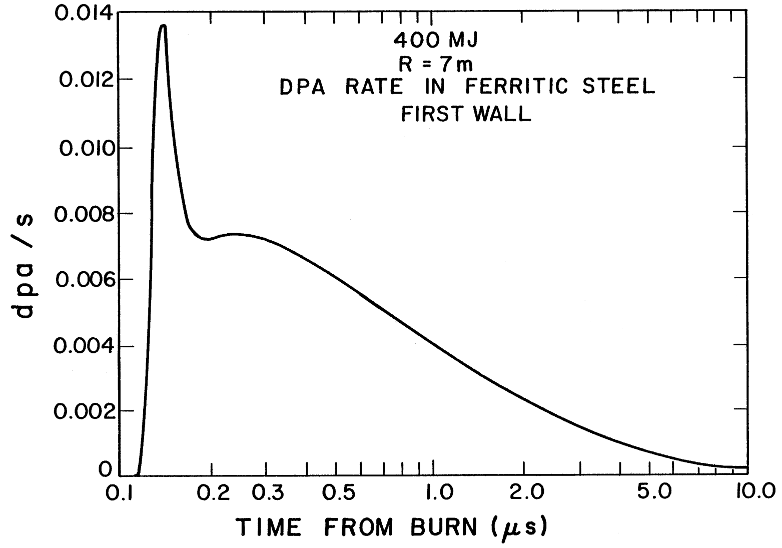
IFE Pulsed operation (1-10 Hz)

MFE Steady state operation

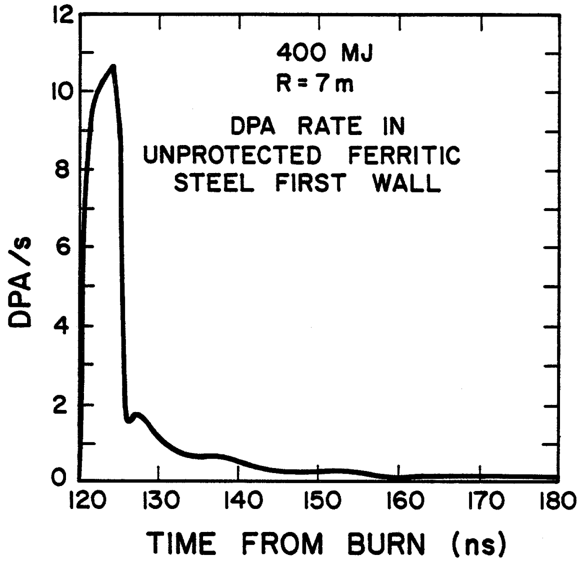
Implications:

- Neutrons emitted from IFE target over extremely short burn time (10-100 ps)
- Uncollided neutrons from target travel at ~50,000 km/s reaching the FW in 30-100 ns
- Neutrons slowed down in target travel at lower velocities resulting in time of flight spread
- Period over which a particular radiation effect occurs is larger for reactions produced by lower energy neutrons or secondary gamma and at locations deeper in blanket
- In HIBALL, dpa in the ferritic steel chamber wall occurs over ~ 1 μs but He production occurs over only 26 ns
- About 5 to 8 orders of magnitude higher instantaneous reaction rates occur in pulsed IFE chambers compared to the equivalent MFE steady state rates at same wall loading

Pulsed Radiation Damage in HIBALL



Chamber wall protected by 2 m INPORT tubes
8.6x10^{-8} dpa/s average



Unprotected chamber wall
8.1x10^{-7} dpa/s average

- It is essential to determine instantaneous damage rates for accurate prediction of structure lifetime by materials experts

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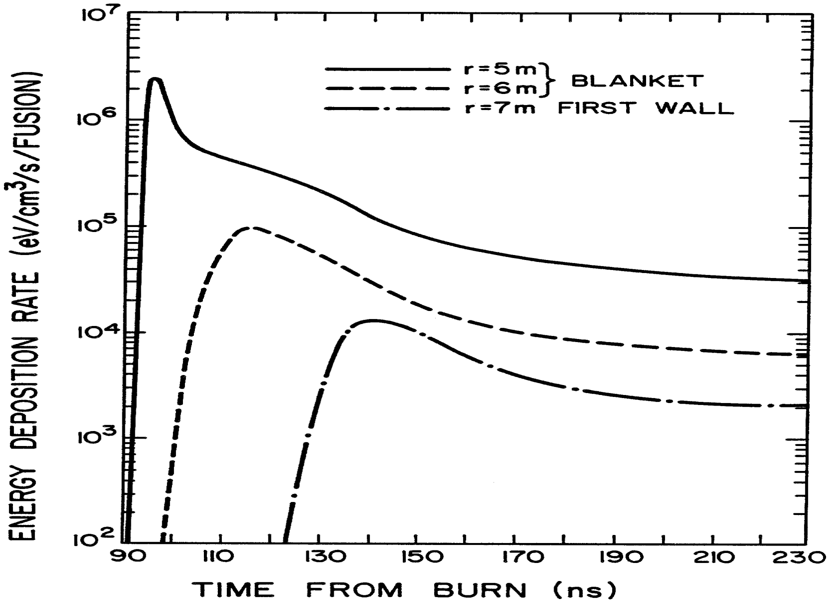
Pulsed Nuclear Heating Rates in HIBALL



- Large instantaneous energy deposition rates occur in IFE FW/blanket
- This can lead to isochoric heating problems with significant coolant pressure waves
- It is essential to accurately determine instantaneous energy deposition rate to ensure the structural integrity of the chamber components

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Impact of Wall Protection Scheme on Neutronics Features

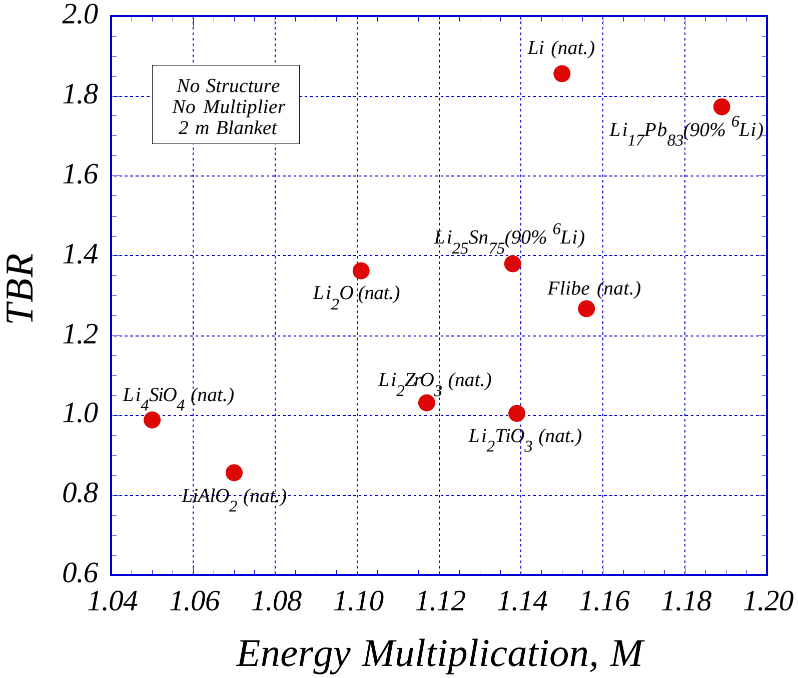
- Various IFE wall protection methods influence the FW/blanket design and neutronics features
  - Dry wall (e.g., SOMBRERO, SIRIUS-P)
  - Wetted wall (e.g., HIBALL, PROMETHEUS-L)
  - Liquid wall (e.g., HYLIFE)

- Blanket neutronics features of dry wall and wetted wall designs are identical since thin liquid sheet in wetted wall provides negligible neutron attenuation

- Thick liquid wall concepts have different neutronics features due to protection of blanket structure by thick liquid layer and elimination of structure in thick breeding liquid layer

Tritium Breeding Potential in IFE System

- Breeding potential varies substantially with FW/blanket concepts



Breeders fall into three groups regarding their breeding potential

- Liquid Li and LiPb have largest breeding potential
- Li_2O, Flibe, and LiSn have medium breeding potential. To achieve tritium self-sufficiency with these breeders, the structure content needs to be minimized and/or moderate amount of neutron multiplier should be added
- Ceramic solid breeders (Li_2ZrO_3, Li_2TiO_3, Li_4SiO_4, and $LiAlO_2$) have poor breeding potential. They need substantial amount of neutron multiplier to achieve adequate breeding

IFE Blankets Have High Potential for Achieving Tritium Self-Sufficiency

- Blankets can be made as thick as needed in IFE chambers without impacting the high cost driver
- No divertor or RF/CD systems in IFE power plants

  ⇒ High blanket coverage
- Driver beam penetrations in IFE represent less than 0.5% of FW area for direct drive KrF concepts with up to ~100 beam ports. For indirect drive concepts, this fraction is much lower. Higher fractions up to 5% might be required with DPSSL driver
- Blanket concepts that have problem achieving adequate overall TBR in MFE systems might be applicable to IFE systems
- Pulsed nature of IFE does not affect time integrated overall TBR

TBR Values in Previous IFE Designs

Study	Driver	First Wall	Blanket Materials	TBR
SOLASE (77)	Laser	DW	Li_2O/C	1.25
HYLIFE (79)	Laser	LW	Li/FS	1.75
HIBALL (81)	HIB	WW	LiPb/SiC	1.25
CASCADE (83)	Laser	DW	$LiAlO_2$/BeO/SiC	1.05
SOMBRERO (92)	Laser	DW	Li_2O/C	1.25
OSIRIS (92)	HIB	WW	Flibe/C	1.34
PROMETHEUS-L (92)	Laser	WW	Li_2O/Pb/SiC	1.2
PROMETHEUS-H (92)	HIB	WW	Li_2O/Pb/SiC	1.2
SIRIUS-P (93)	Laser	DW	Li_2O/C	1.1
HYLIFE-II (94)	HIB	LW	Flibe/SS-304	1.17
LIBRA-SP (95)	LIB	WW	LiPb/FS	1.4

Energy Multiplication in IFE Systems

- Because of neutron target interactions, energy multiplication is defined differently
- Breakdown of energy emitted from target is required to determine overall chamber energy multiplication

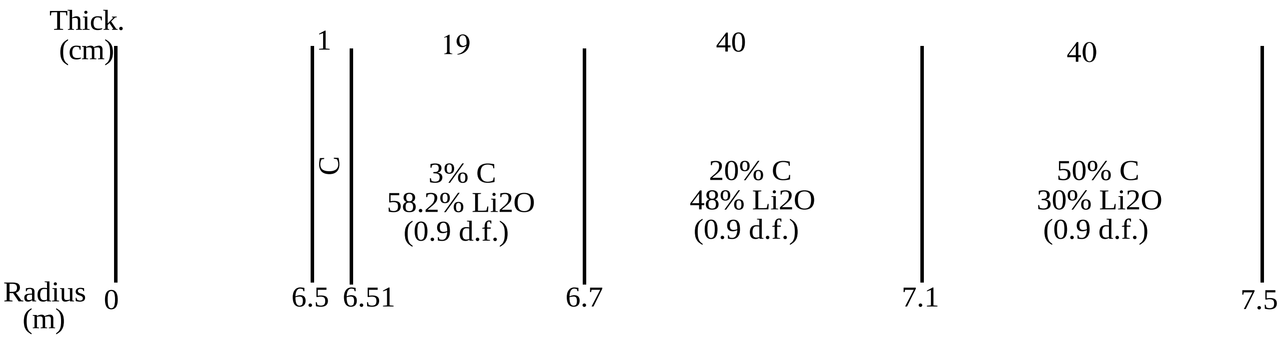
17.6 MeV from 1 DT fusion

⇓

E_n (neutrons)
E_g (gamma)
E_x (x-rays)
E_d (debris)
E_{lo} (lost in endoregic reactions)

- Nuclear energy multiplication defined as total blanket nuclear heating divided by the neutron and gamma energy incident of FW
  $M_n = E_{nucl} / (E_n+E_g)$
- Overall energy multiplication defined as the ratio of total thermal power (volumetric and surface) to the DT fusion power
  $M_o= (E_{nucl}+E_x+E_d)/17.6$
- For LIBRA-SP, $M_o = 0.6989\ M_n + 0.28$

Neutronics Performance Parameters of SOMBRERO Blanket Design


Thick. (cm)

1

19

40

40

C

3% C
58.2% Li2O
(0.9 d.f.)

20% C
48% Li2O
(0.9 d.f.)

50% C
30% Li2O
(0.9 d.f.)

Radius (m)

0

6.5

6.51

6.7

7.1

7.5

RADIAL BUILD OF REFERENCE SOMBRERO BLANKET DESIGN

- Neutron wall loading = 3.43 MW/m^2
- Li_2O with natural lithium
- 1 m thick blanket with increasing C/C content towards back
- Local TBR= 1.25
- Overall chamber energy multiplication M_o = 1.08
- Peak power density in FW = 10.87 W/cm^3
- Peak power density in blanket= 12.57 W/cm^3
- Peak dpa rate in FW = 15.33 dpa/FPY
- Peak He production rate in FW = 3769 appm/FPY
- Peak burn-up rate in FW = 0.19% per FPY
- Need to define lifetime criterion for C/C composite

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3-D Calculations Needed for IFE Chambers

- 1-D spherical neutronics calculations can be performed for regions surrounding target

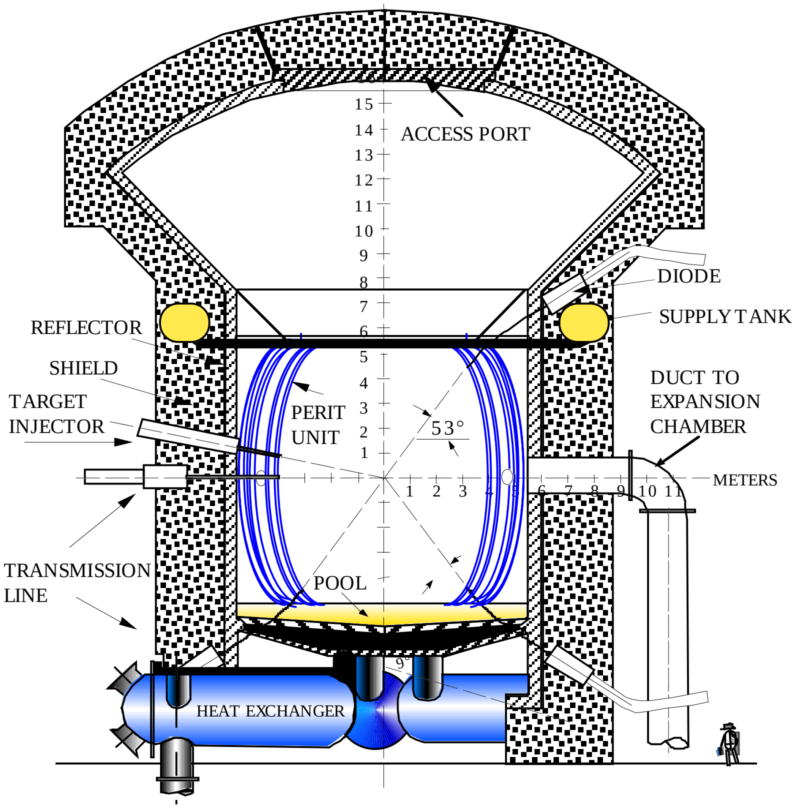
- 1-D local nuclear parameters combined with coverage fractions to determine overall TBR and energy multiplication

- This approach yields reasonable estimates for overall parameters (TBR and M_o)

- Larger differences expected for local damage and heating due to
  - ➢ Deviation of chamber configuration from spherical geometry
  - ➢ Impact of different materials in chamber regions on secondary n and γ
  - ➢ Different angular distribution of incident neutrons

- 3-D neutronics analysis is needed for accurate prediction of local nuclear parameters

3-D Calculations for LIBRA-SP



Model:

- 1.2 m thick PERIT region
  - 0.5 packing fraction
  - 8% HT-9, 92% LiPb in tubes
  - 90% ^{6}Li enrichment

- 0.6 m deep LiPb pool
- 0.25 m thick perforated splash plate
  - 80% HT-9, 20% LiPb
- 0.5 m deep sump tank of LiPb

- 0.5 m thick chamber wall
  - 90% HT-9, 10% LiPb

- Chamber surrounded by concrete biological shield

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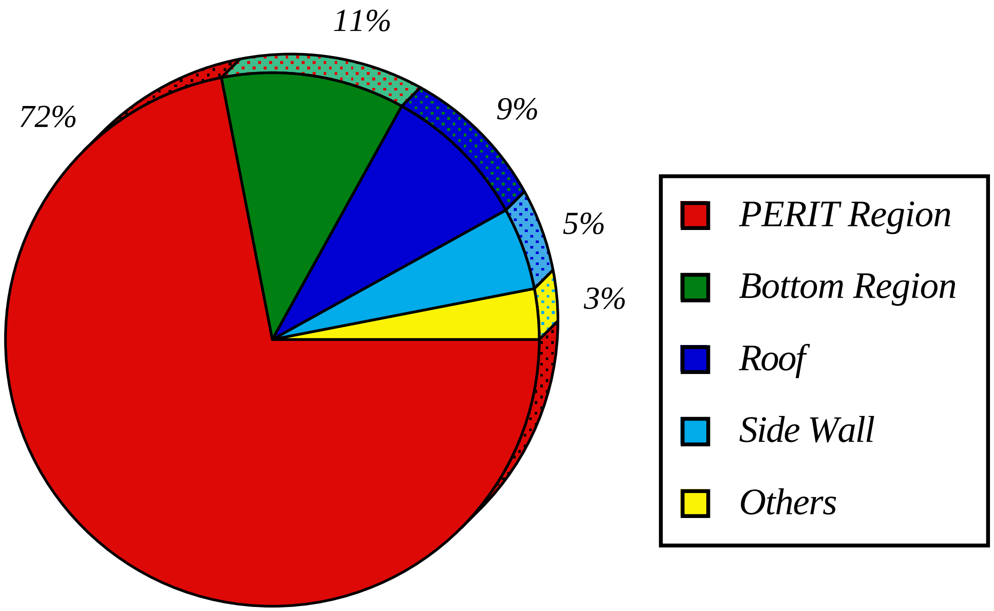
Tritium Breeding in LIBRA-SP

- The overall TBR from 3-D calculation is 1.4

- This is only 3% lower than the 1.44 value predicted from coupling the 1-D results with coverage fractions



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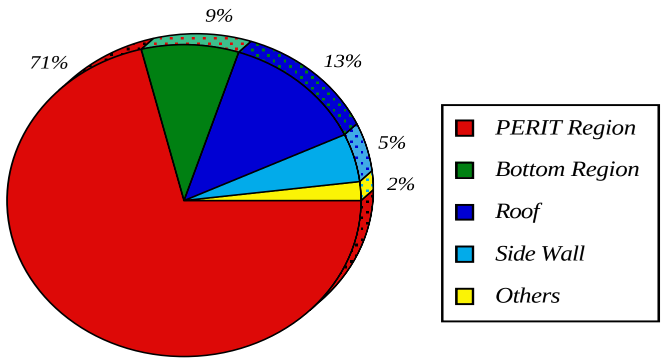
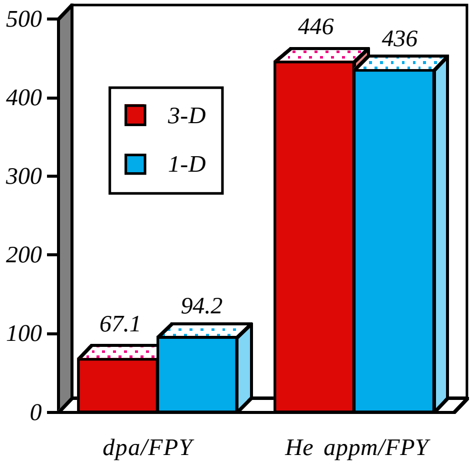
Energy Multiplication in LIBRA-SP

- Nuclear energy multiplication, M_n, is 1.255
- This is only 2% lower than the 1.288 value from 1-D calculations
- Overall reactor energy multiplication, M_o is 1.157



Time-Integrated Peak Radiation Damage in PERIT Tubes



- dpa from 3-D is 30% lower than from 1-D
- Less secondary neutrons due to
  - – mushroom shaped configuration
  - – lower neutron multiplication in steel roof
- He production is slightly larger (2%) than 1-D estimate because of harder spectrum of secondary neutrons scattered from roof

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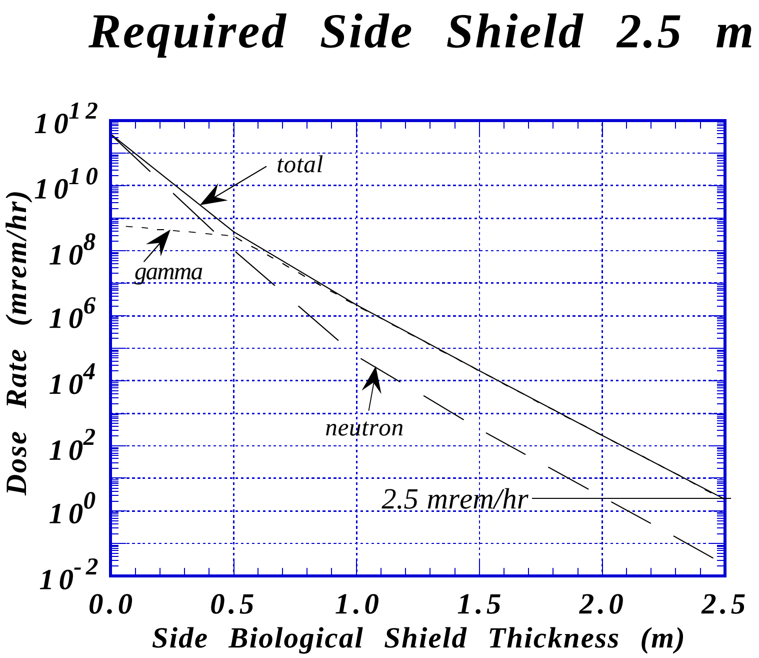
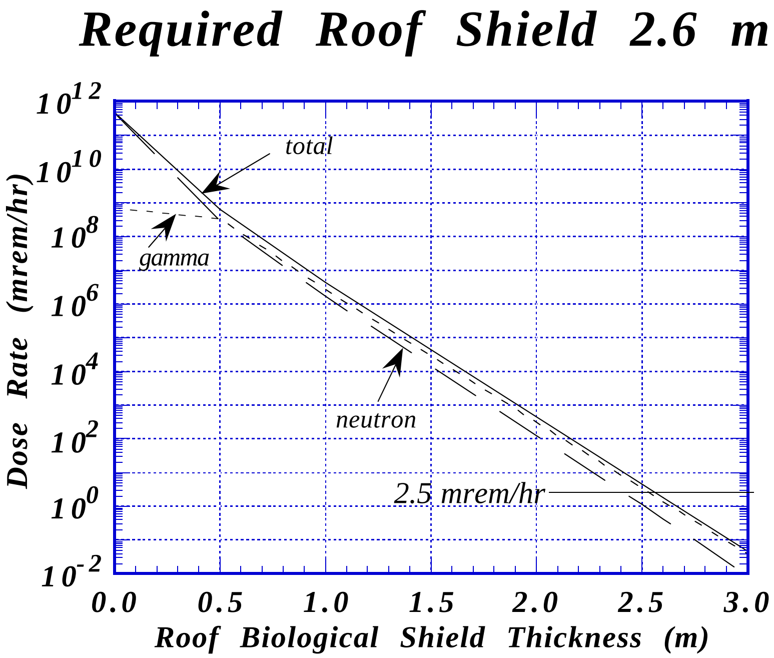
Biological Shield Design

- Biological shield is needed outside the chamber to maintain occupational biological dose rate <2.5 mrem/hr outside building during operation
- Required shield thickness depends on location of shield and material used in components between target and shield
- 2.5-3.5 m thick steel reinforced concrete shield is needed
- If allowed by maintenance approach, significant reduction in shield volume and cost is realized by placing the biological shield as close as possible to the chamber

Biological Shielding Required in LIBRA-SP





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Beam Line Penetration Shielding

- ➢ Penetrations in IFE chamber required for ions or laser transport from driver to target

- ➢ Measures must be taken to protect the vital components from streaming radiation

- ➢ Shielding issues are different for the two drivers considered
  - Laser
  - HIB

Shielding of Final Optics in Laser Driven IFE

- Final laser optics located in direct line-of-sight of source neutrons experience largest radiation damage
- Damage level in these components can be reduced only by moving them farther from target
- Damage contributed mostly by direct source neutrons

Dielectric coated mirrors

- Sensitive to neutron radiation that degrades optical transmission of dielectric material, decomposes dielectric materials, and destroys interfaces between dielectric layers
- Removing them from line-of-sight of target neutrons prolongs their lifetime

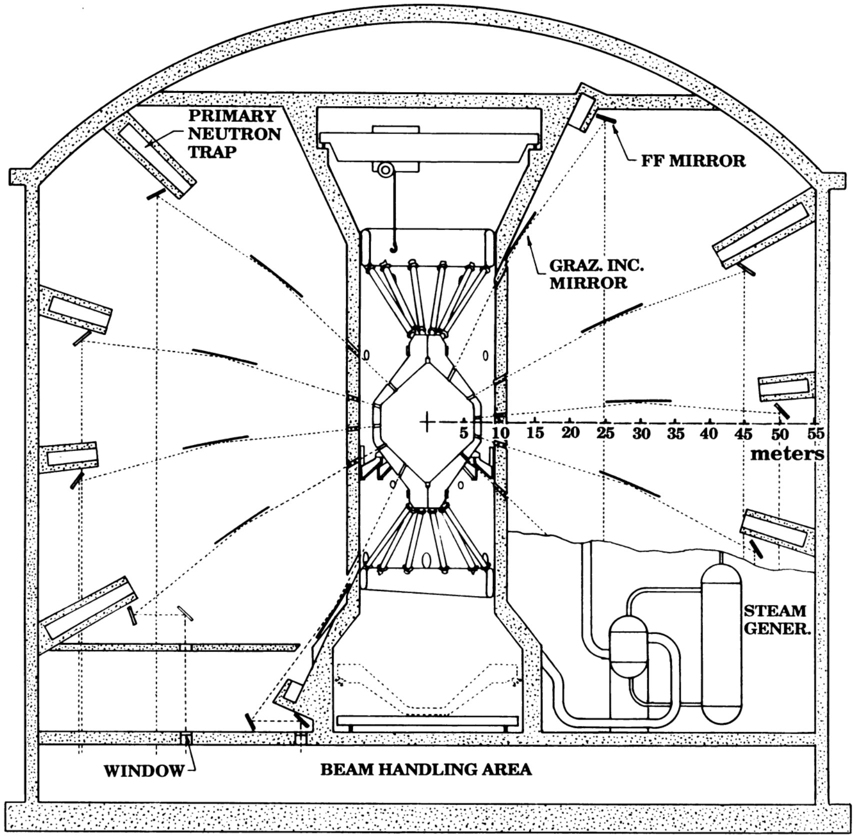
Grazing incidence metallic mirrors (GIMM)

- More radiation resistant and can be used in direct line-of-sight
- Lifetime of GIMM is limited by mirror deformation from swelling and creep that leads to defocusing of laser beam
- GILMM is another option with more radiation tolerance

Shielding of Final Optics in Laser Driven IFE

- Althought dielectric coated mirrors are placed out of direct line-of-sight of source neutrons, secondary neutrons resulting from interaction of streaming neutrons with GIMM and containment building produce damage in coating
- Neutron traps can be attached to outer containment building to reduce secondary neutrons
- Effectiveness of neutron trap is reduced by neutron interactions with GIMM
- Direct source neutron interactions with GIMM increase neutron flux at dielectric coated mirrors by a factor of ~2
- Multi-dimensional calculations required for accurate evaluation of nuclear environment at final optics
- Experimental data needed for accurate prediction of final optics lifetime

Cross Section of SOMBRERO Building



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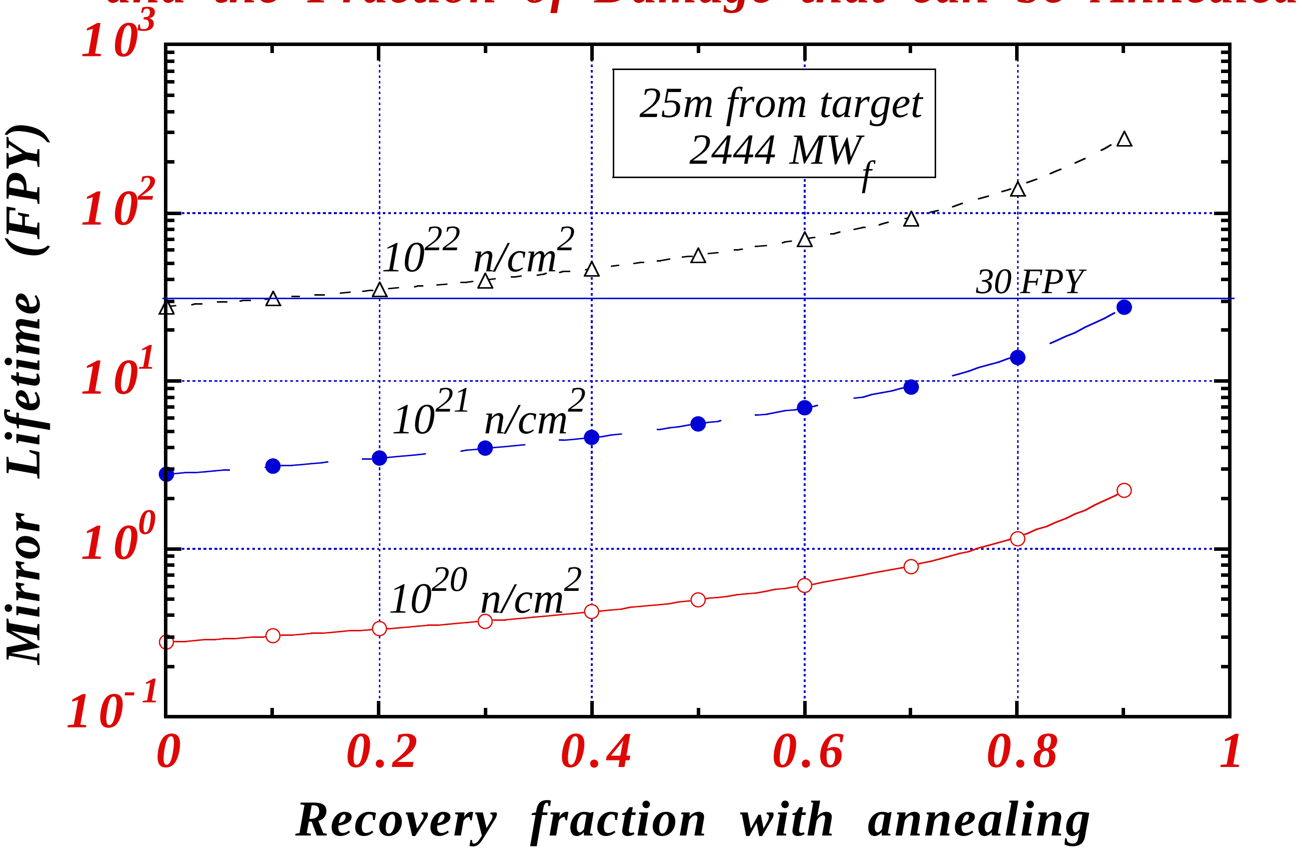
The Useful Life of a Grazing Incidence Mirror Depends on Both the Neutron Fluence and the Fraction of Damage that can be Annealed



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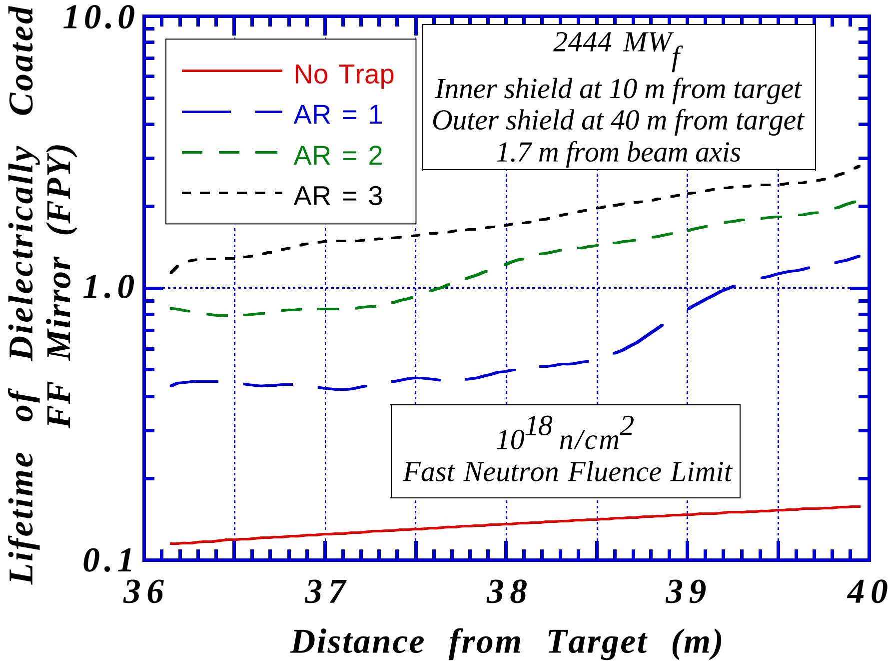
Lifetime of the Dielectric Coated FF Mirrors Increases with Trap Aspect Ratio, Distance from Target, and Neutron Fluence Limit



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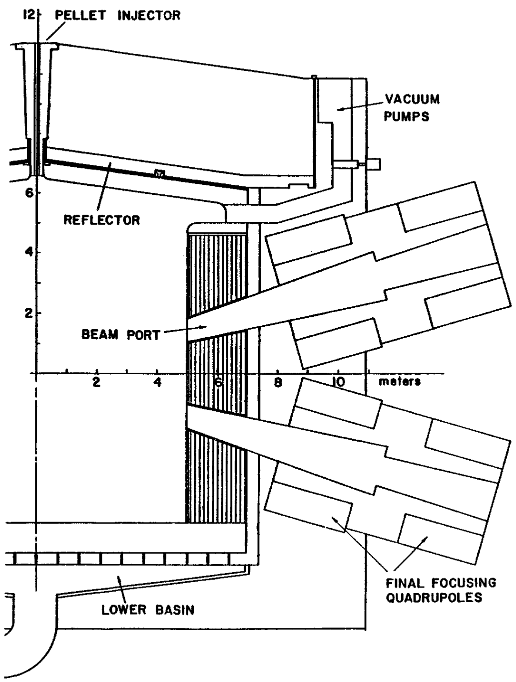
Shielding for Final Focusing Magnets in HIB Driven IFE

- Final focusing system consists of set of quadrupole magnets (usually superconducting)
- Shielding provided between the ion beam and the final focusing magnets
- Shield configuration should not interfere with the ion beam envelope



- Effective shield configuration developed for HIBALL and utilized in OSIRIS
- Radiation effects in magnets can be reduced by about three orders of magnitude by tapering inner surface of shield along direct line-of-sight of source neutrons
- All direct source neutrons impinge on neutron dumps at optimized location that minimizes magnet damage
- Magnets are lifetime components

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Critical Issues to Be Addressed

- Integration of target hydrodynamics with target neutronics and impact on source spectra and strength
- Lifetime criteria for structural materials under pulsed irradiation
- Pulsed radiation damage and heating with impact on structure lifetime
- Lifetime criteria for final optics
- Impact of shielding design on lifetime of final optics and final focussing magnets