Neutron Streaming Through Divertor He-Access Pipes:
3-D Assessment and Recommendations

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Background

- Radial builds and radiation levels are normally defined for perfect geometry without penetrations.
- Penetrations are necessary for vacuum pumping, coolant supply lines, plasma control, and maintenance ports.
- Such penetrations compromise shielding performance as streaming neutrons:
  - Enhance damage at surrounding components (shield, manifolds, VV, and magnet)
  - Increase flux and dose levels behind magnet.
- Unlike liquid-cooled system, He coolant tubes/pipes raise streaming concerns.
- Designing penetration shields for He system represents challenging task.
- **Example**: ARIES-CS dual-cooled LiPb/He/FS design.
- Results applicable to ARIES-AT with DCLL system.

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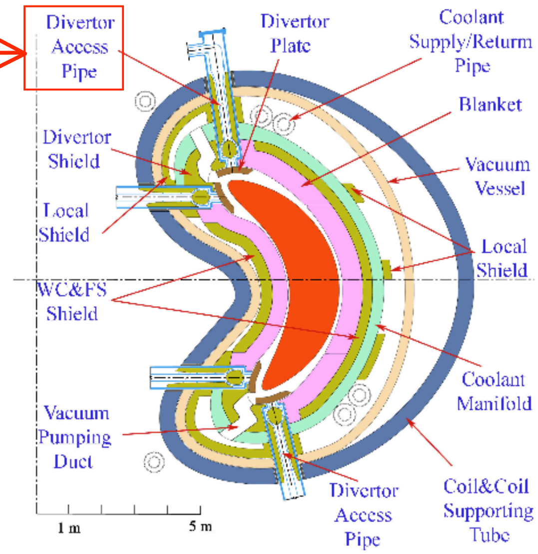
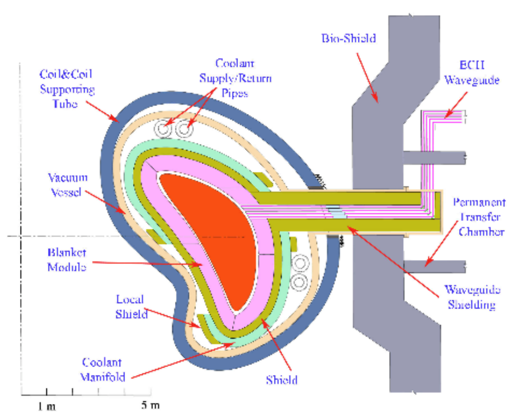
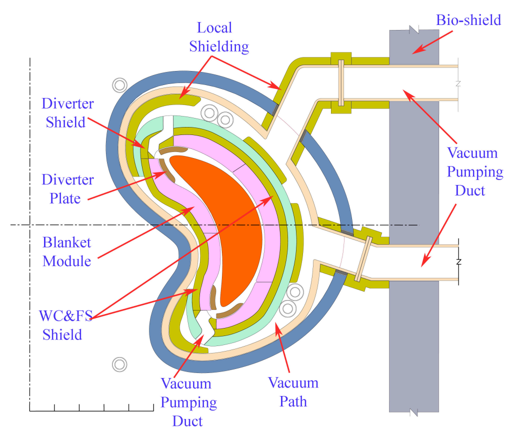
ARIES-CS Penetrations

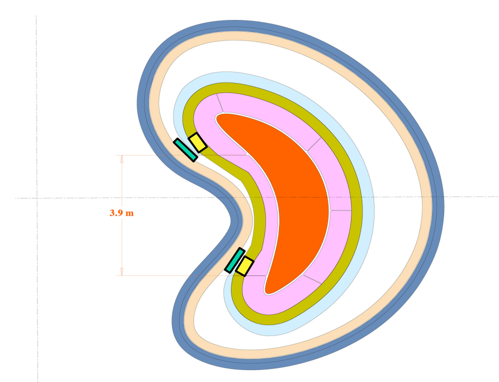
- **Eight types of penetrations**:
  - 198 He tubes for blanket (32 cm inner diameter (ID))
  - **24 Divertor He access pipes (30-60 cm ID)**
  - 30 Divertor pumping ducts (42 x 120 cm each)
  - 12 Large pumping ducts (1 x 1.25 m each)
  - 3 ECH ducts (24 x 54 cm each).
  - 6 main He pipes connecting HX to blanket and shield (72 cm ID each)
  - 6 main He pipes connecting HX to divertor (70 cm ID each)
  - 4 access holes (3 cm diameter) for each blanket module.



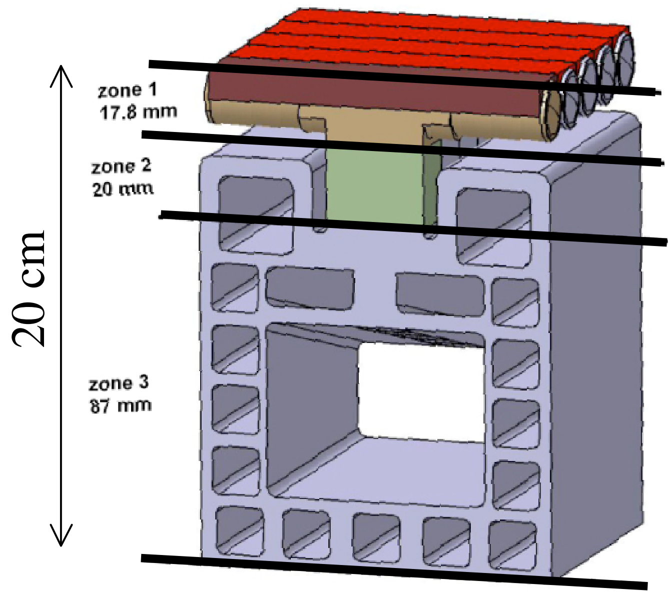
- **Potential solutions**:
  - Local shield behind penetrations
  - He tube axis oriented toward lower neutron source
  - Penetration shield surrounding ducts
  - Replaceable shield close to penetrations
  - Avoid rewelding of manifolds and VV close to penetrations
  - Several bends along penetration lines.



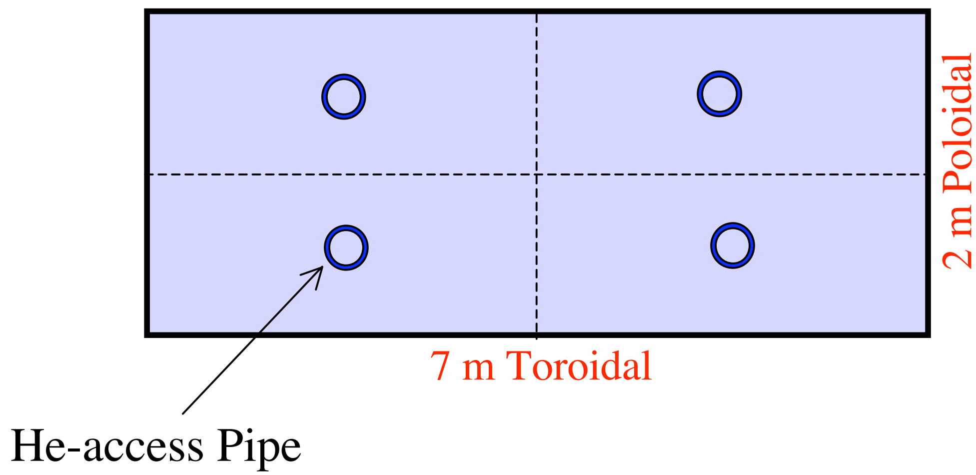




ARIES-CS Divertor System



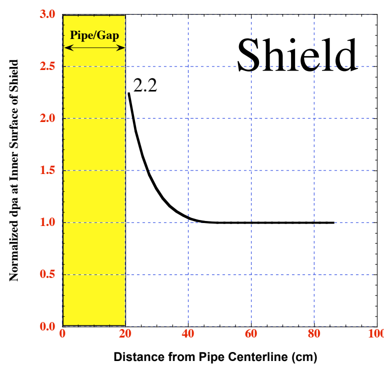
Layout of Divertor System

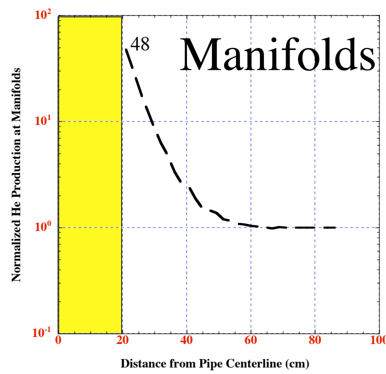


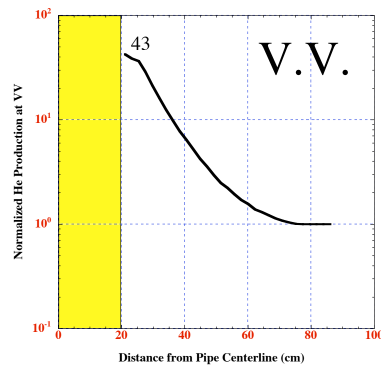
- 2 divertor systems per field period
- 4 He-access pipes for each divertor system
- 24 He-access pipes in 3 FP of ARIES-CS

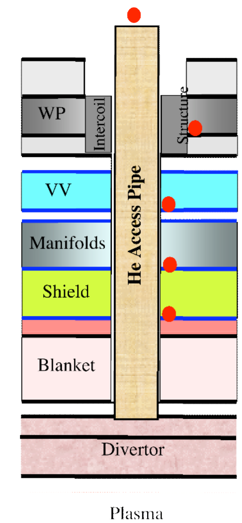
Preliminary 2-D Analysis Indicated Streaming Problems for He-Access Pipes

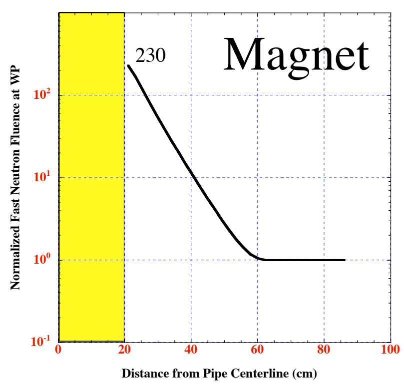
(Simple Pipe with 30 cm ID)

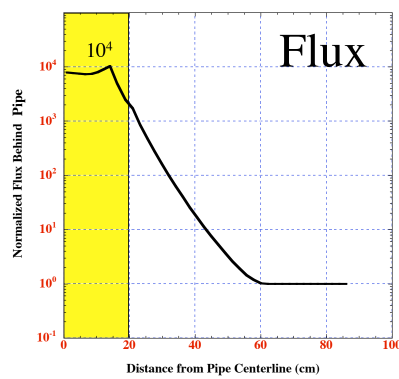


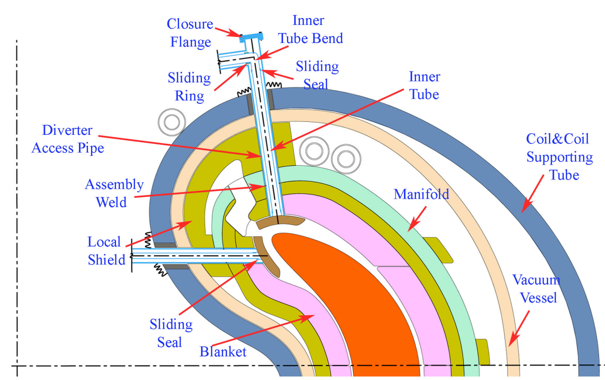






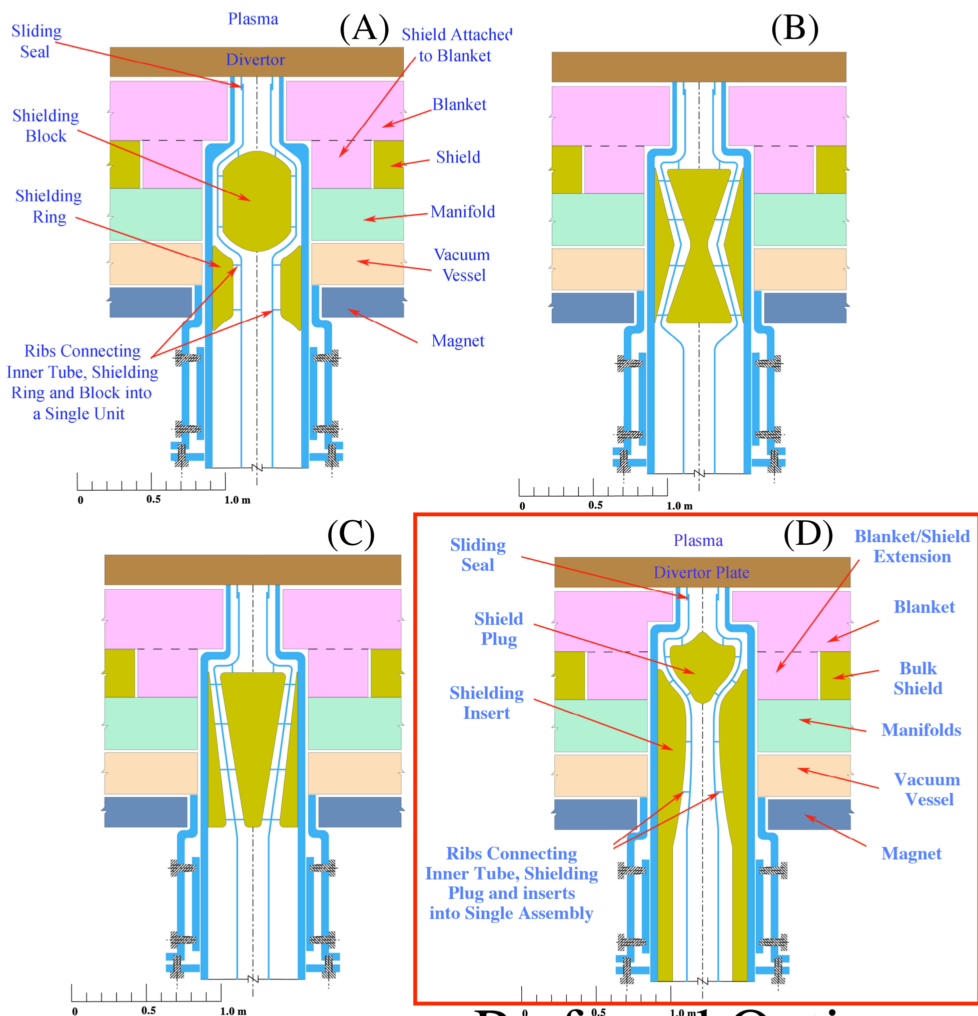




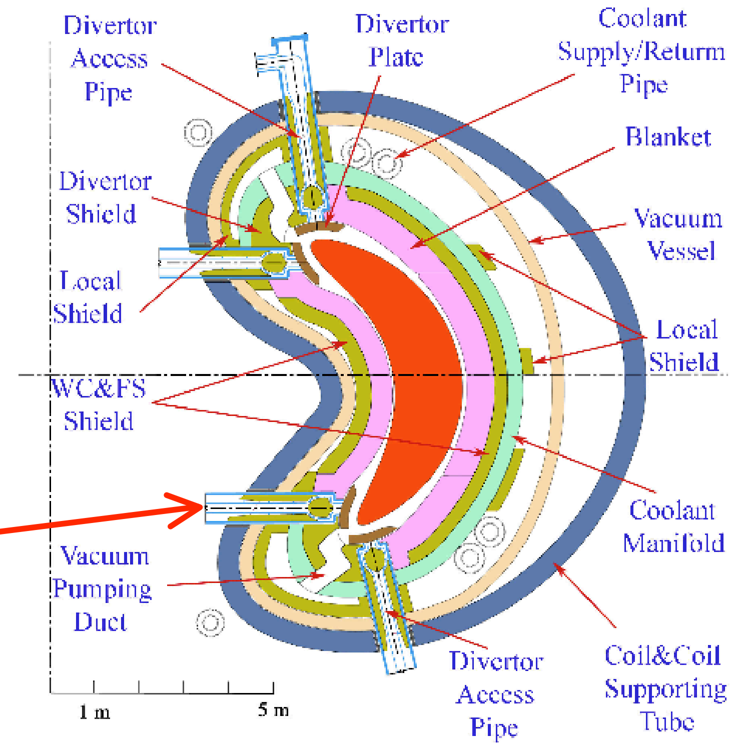


- **Streaming problems**:
  - – Shield surrounding pipe is not life-of-plant component
  - – Manifolds and VV close to pipe are not reweldable
  - – Winding pack should be 30-40 cm from pipe
  - – Inner part of pipe wall should be replaceable
  - – Pipe wall not reweldable
  - – Flux at end of pipe is excessive ⇒ protect externals with local shields.

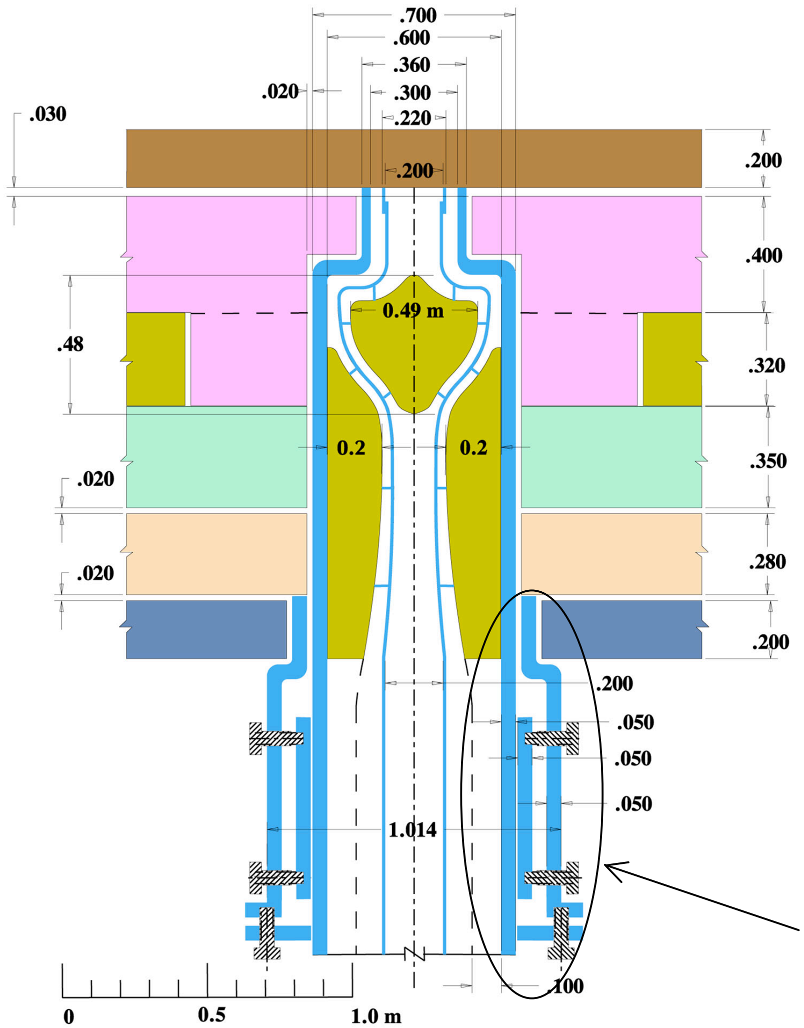
S. Malang Proposed 4 Options for He Access Pipes with Shield Plug and Inserts (30-60 cm ID)



Preferred Option



Selected Design for Streaming Analysis



WC Shielding Plug and Inserts

	1 Pipe	24 Pipes
Volume (m^3)	0.05+0.4	11
Mass (tons)	7	170*

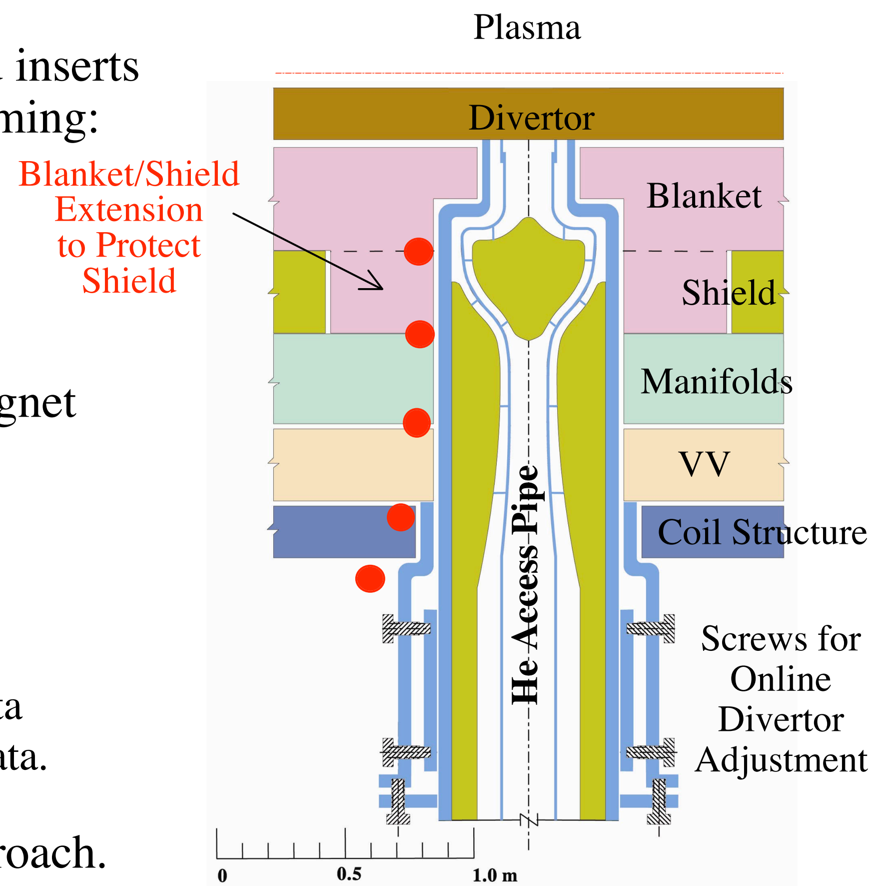
* 3 times total divertor mass (54 Tons).

Could this structure support 9-10 tons?
How to attach to VV?

3-D Neutronics Model

Purpose:

- Examine effectiveness of shield plug and inserts
- Estimate peaking in damage due to streaming:
  - dpa at shield
  - He production at manifolds
  - He production at VV
  - Fast neutron fluence at winding pack
  - dpa & He production along pipe wall
- Assess radiation environment behind magnet due to streaming.



Peak **NWL** @ divertor ~2.7 MW/m^2.

3-D codes: Attila: discrete ordinates; 46 n + 21 γ group structure, FENDL-2.1 data
MCNPX: Monte Carlo; FENDL-2.1 data.

Direct **CAD/Attila and MCNPX** coupling approach.

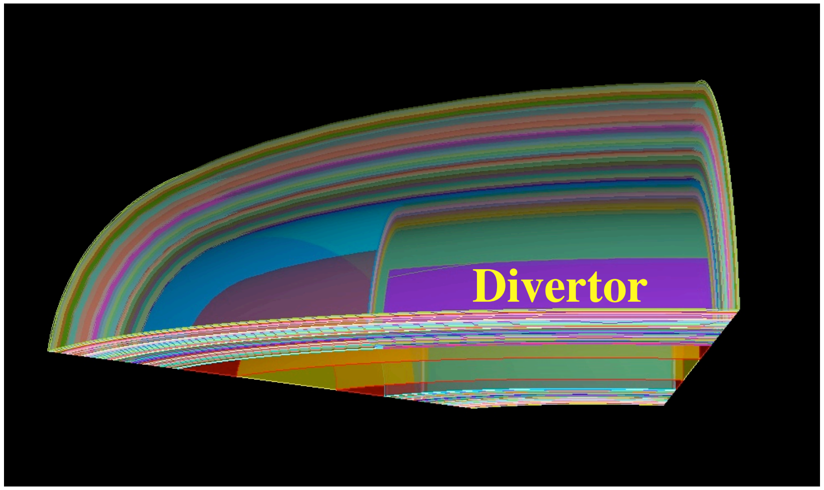
Dimensions and compositions based on reference radial build: http://fti.neep.wisc.edu/aries-cs/builds/build.html

3-D Neutronics Model (Cont.)

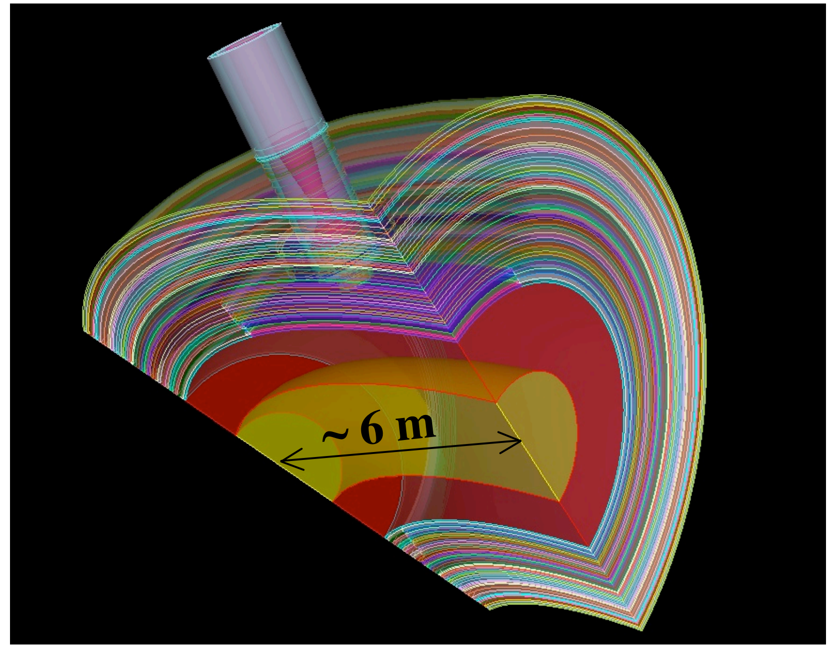
Peaking Factor due to streaming calculated by Attila/MCNPX codes relative to nominal values (away from pipe).

	Nominal Values	Design Limits	Allowable Peaking Factor
dpa at shield (dpa @ 40 FPY)	135	200	1.5
He production at manifolds (He appm @ 40 FPY)	**1**	1	1
He production at VV (He appm @ 40 FPY)	0.2	1	5
Fast neutron **fluence** @ magnet (n/cm^2 @ 40 FPY)	0.2×10^{19}	1×10^{19}	5

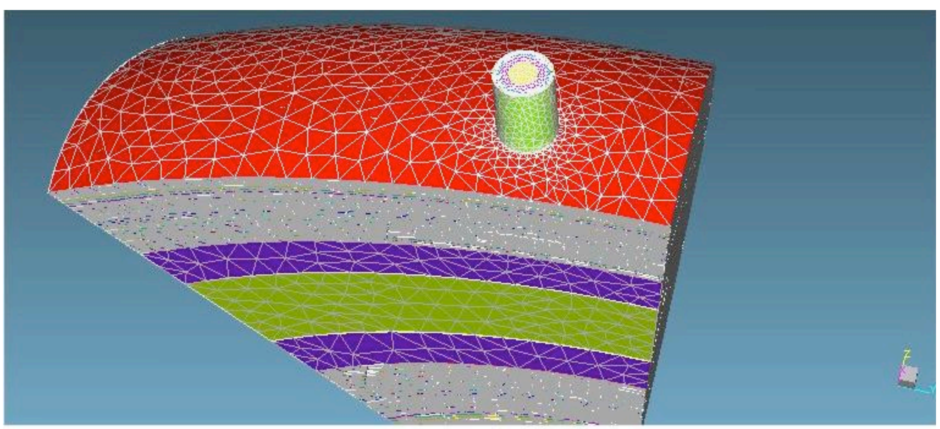
3-D Attila Model



1/4 Model of Divertor System w/o Pipe in 45° Torus

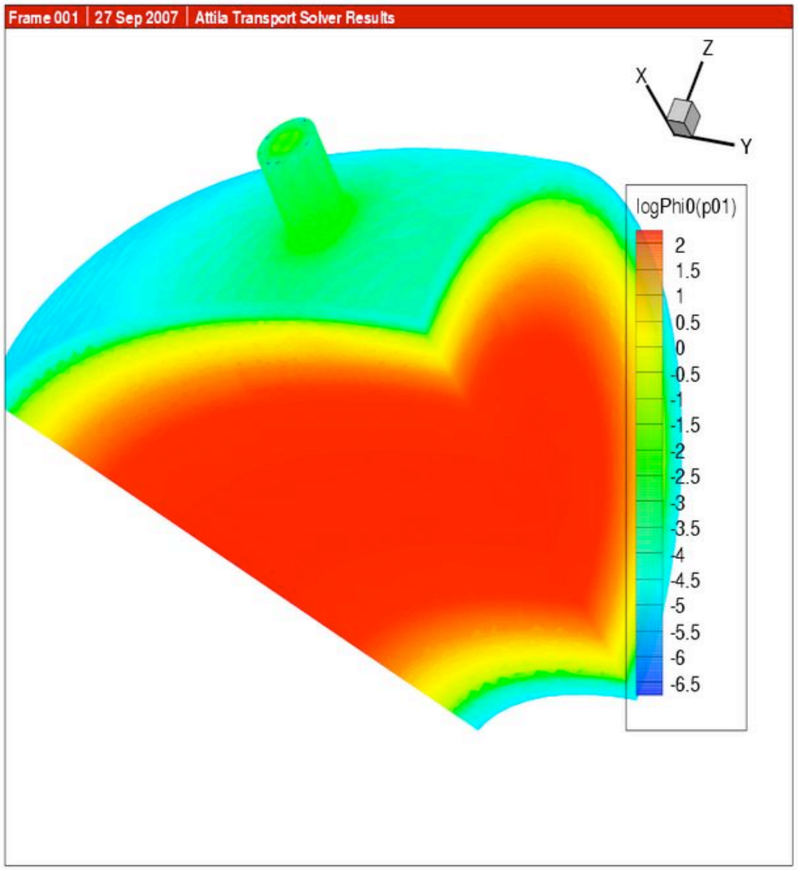


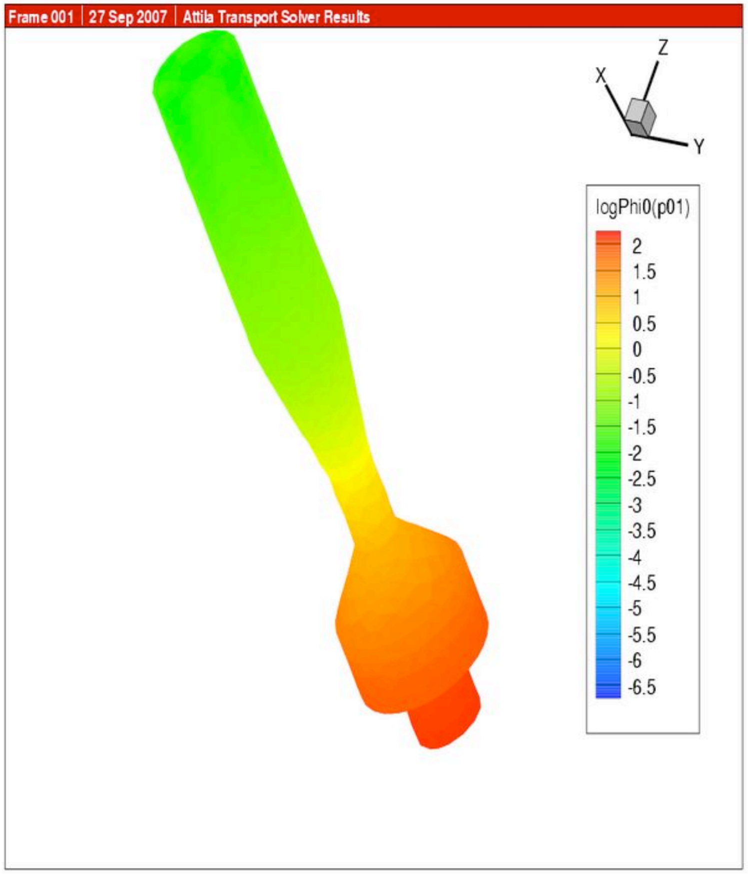
1/4 model of Divertor System w/ Pipe in 45° Torus



Tetrahedral mesh representation

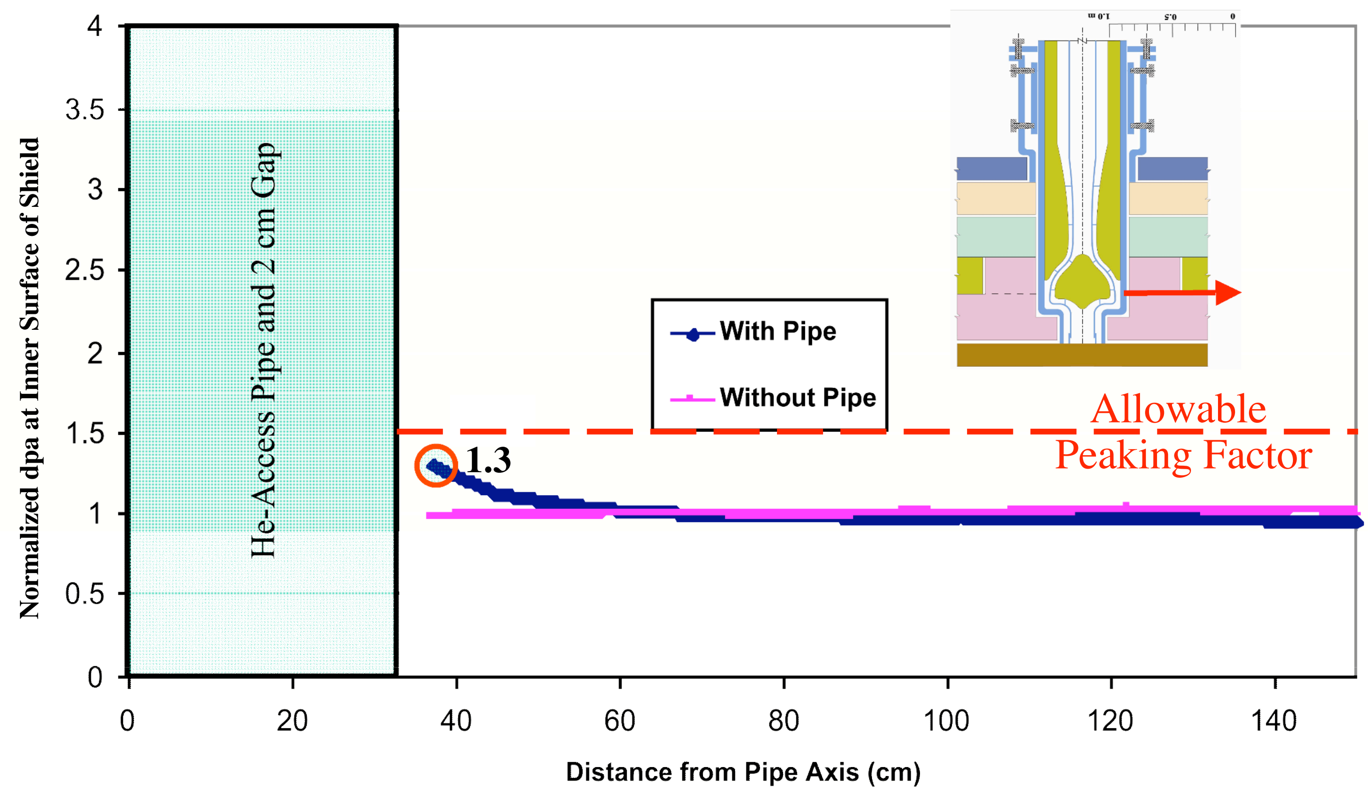
Attila Results: Neutron Flux Map
(Relative values; Log scale)





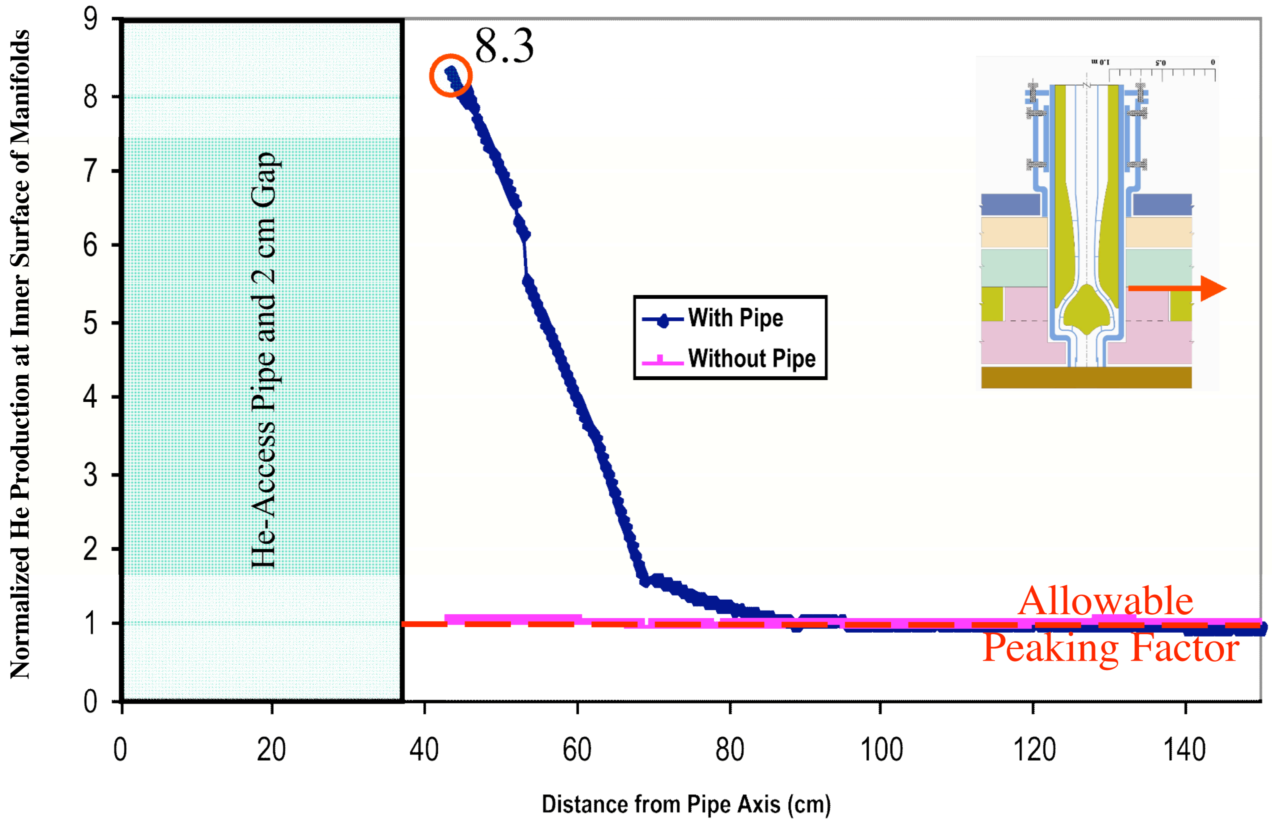
- Streaming causes 3-4 orders of magnitude increase in flux behind magnet.
- Shielding plug attenuates flux by 20 fold.

Shield Plug Helps Protect Bulk Shield



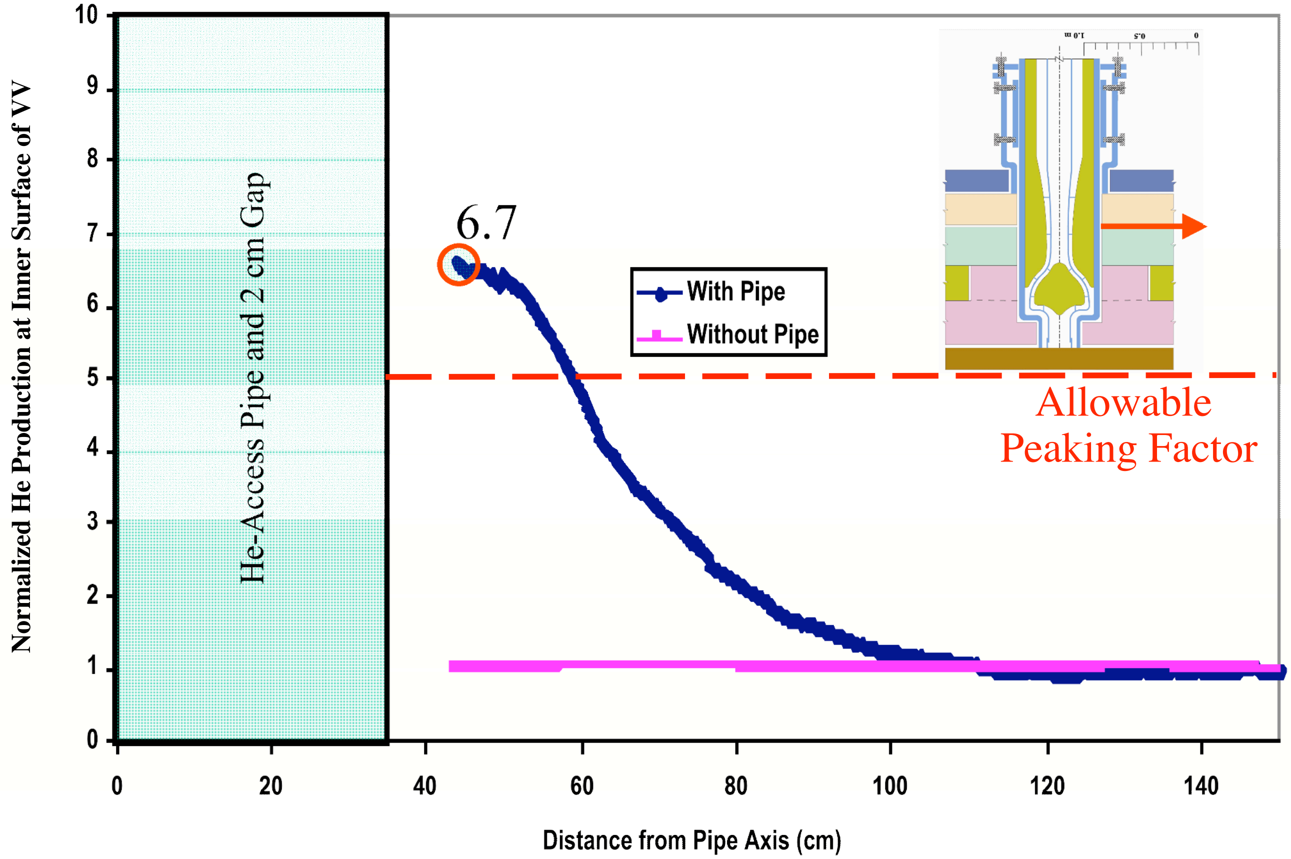
Peaking Factor = 1.3 ⇒ ~ 175 dpa @ 40 FPY (< 200 dpa limit)
⇒ Bulk shield is permanent component
⇒ No need for blanket/shield extension.

Part of Manifolds Surrounding Pipe Cannot be Rewelded after 0.5 FPY



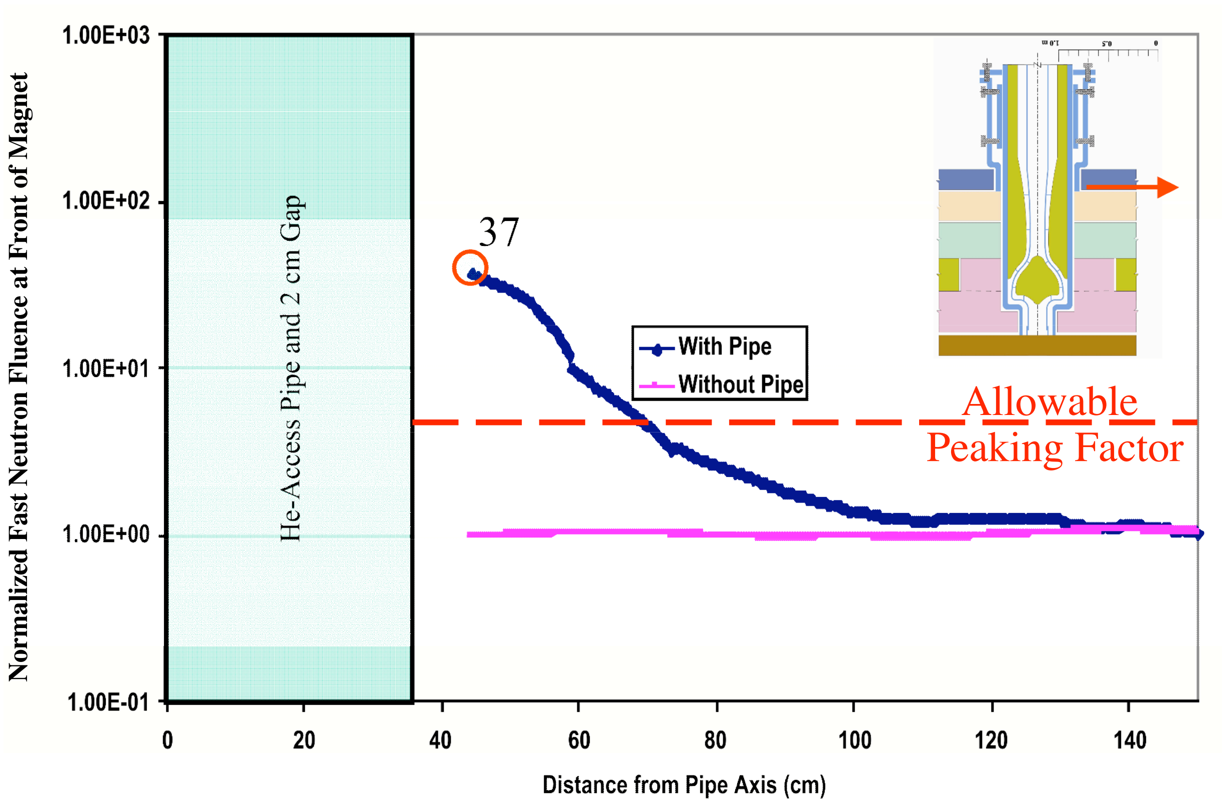
Peaking Factor = 8.3 ⇒ ~ 8 He appm @ 40 FPY (> 1 appm limit)
⇒ Avoid rewelding 40 cm thick manifolds surrounding pipe

Part of VV Surrounding Pipe Cannot be Rewelded after 30 FPY



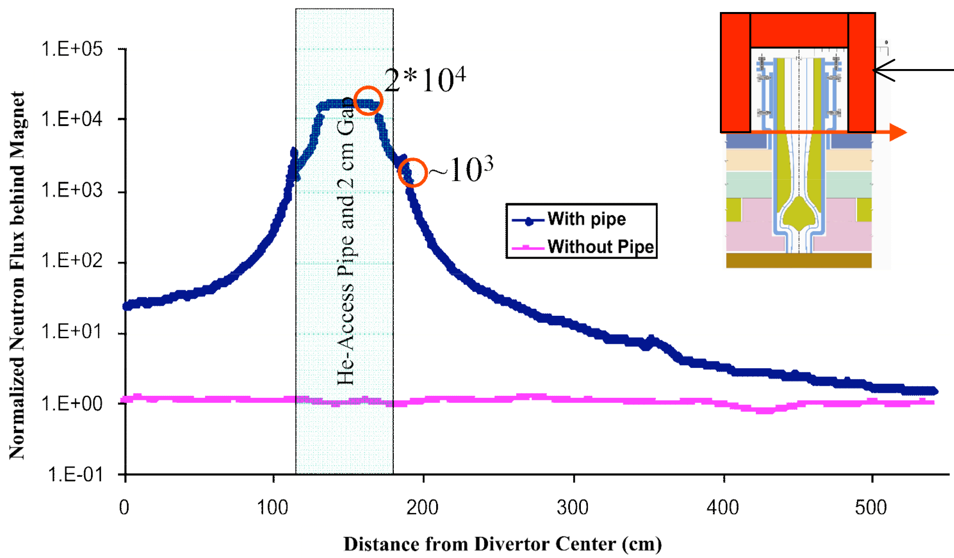
Peaking Factor = 6.7 ⇒ ~ 1.3 He appm @ 40 FPY (> 1 appm limit)
⇒ Avoid rewelding 20 cm thick VV surrounding pipe

40 cm Inter-coil Structure around Pipe Helps Protect Winding Pack



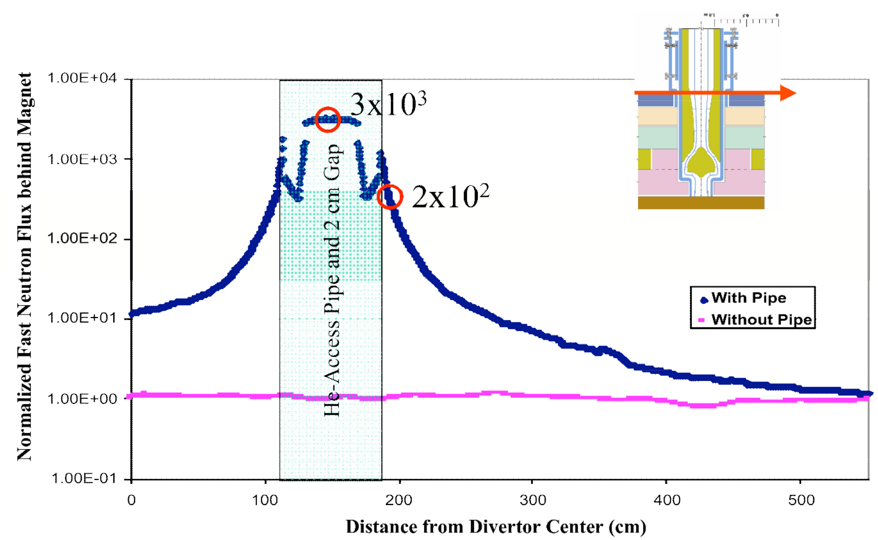
Peaking Factor = 37	⇒ ~ 9 x 10^{19} n/cm^2 @ 40 FPY (> 10^{19} n/cm^2 limit)
	⇒ Winding pack should be placed 40 cm away from pipe

Excessive Neutron Flux Behind Pipe Calls for Local Shield to Protect Externals

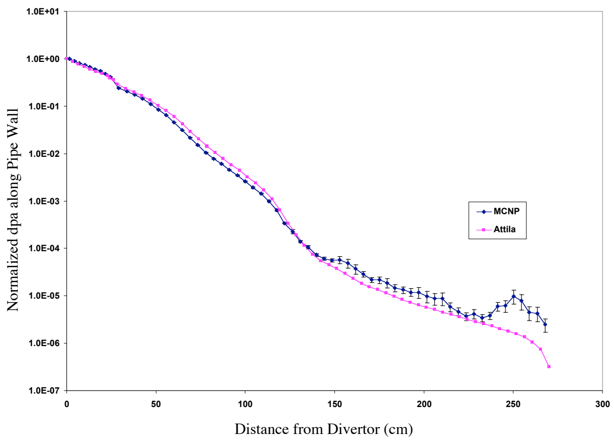


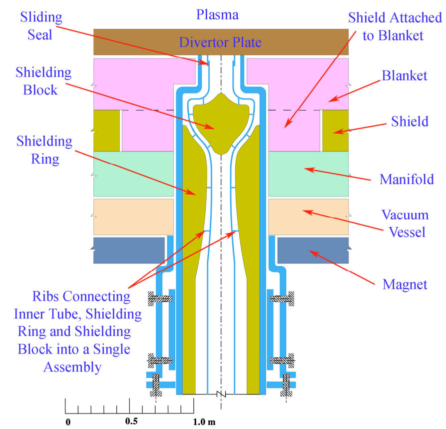
Behind magnet:

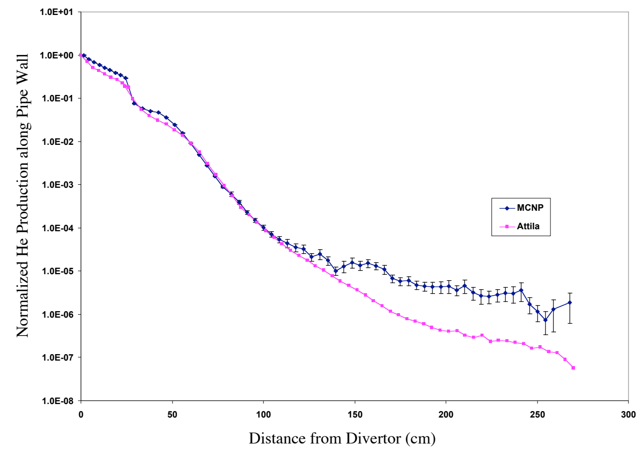
- High flux covers large area
- Around pipe, fast flux (E_n> 0.1 MeV) comprises 20% of total flux.



Damage to Pipe Wall and Screws







Pipe wall lifetime ~ 4.5 FPY, exceeding divertor lifetime (3 FPY)

Damage to screws (at ~2 m) will not exceed 10 dpa @ 40 FPY
⇒ < 0.05% n-induced swelling at screws, causing no problem, per Malang.

- Front 60 cm of pipe wall is not reweldable after 3 FPY and should be replaced with divertor
- End of pipe (> 120 cm) can be reused repeatedly during 40 FPY
- Middle of pipe (60-120 cm) reaches 1 appm limit gradually at various times, ranging between 3 and 40 FPY.

Concluding Remarks and Recommendations

- **3-D results indicate**:
  - Bulk shield is well protected ⇒ no need for blanket/shield extension
  - Peaking in damage is more pronounced at magnet than at shield
  - Helium production at manifolds and VV exceeds reweldability limit by 2-8 fold
    ⇒ avoid rewelding within 20-40 cm from pipe
  - Winding pack should be placed at least 40 cm from pipe
  - Neutron-induced swelling in screws (that adjust divertor plates during operation) is negligible (< 0.05%)
  - Front 60-120 cm of pipe wall is not reweldable and should be replaced along with divertor system every 3 FPY.

- Final ARIES-CS design accords with these recommendations.

- Neutron flux behind pipe is excessive, calling for 60-80 cm thick local shield to protect externals.

- Neutron attenuation through shielding plug and inserts is not sufficient to eliminate streaming problems entirely.

- Future studies could develop more effective scheme(s) to attenuate streaming neutrons and reduce flux outside pipes. For example, simple pipe with smaller diameter (< 60 cm) and several right-angle bends represents a better approach, eliminating the need for massive shielding plug and inserts (170 tons for 24 pipes of ARIES-CS).

Publications

- D. Henderson presented preliminary results at **SOFE** meeting - June 07, Albuquerque, NM.

- **UWFDM-1331** report published:

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

  "Analysis of Radiation Streaming Through ARIES-CS He-Access Pipes using Attila and DAG-MCNPX 3-D Neutronics Codes,"

  University of Wisconsin Fusion Technology Institute Report,

  UWFDM-1331 (Dec. 2007).

  Available at: http://fti.neep.wisc.edu/pdf/fdm1331.pdf.

- Presentation will be given by A. Ibrahim at **2008 ANS Student Conference**, Feb 28 - March 1, 2008, College Station, TX.

- Abstract and full paper will be submitted to **18th TOFE**, October 08, San Francisco.