Overview of ARIES-CS In-vessel Components: Integration of Nuclear, Economics, and Safety Constraints in Compact Stellarator Design

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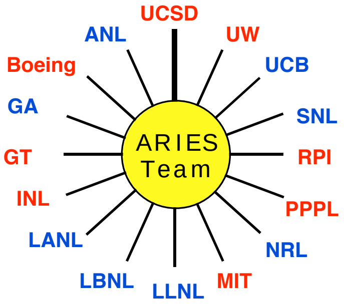
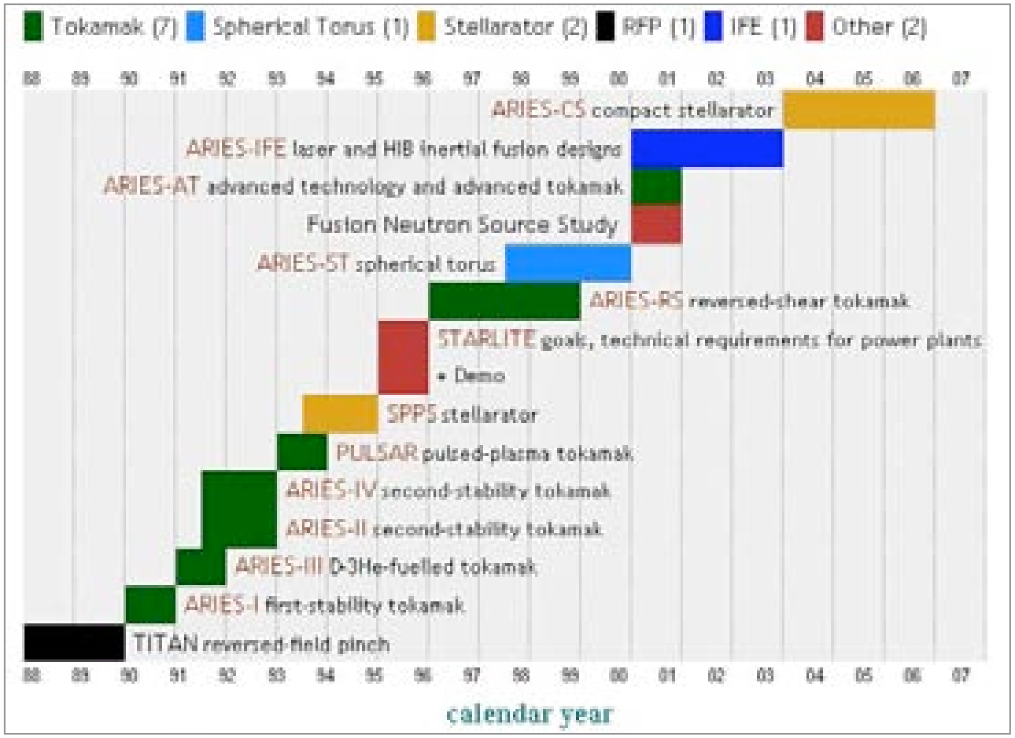
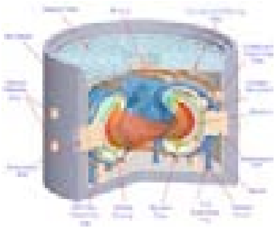
2nd IAEA TM on
First Generation of Fusion Power Plants: Design & Technology
June 20 - 22, 2007
Vienna, Austria

PPCA.I-2

Multi-Institution ARIES Project



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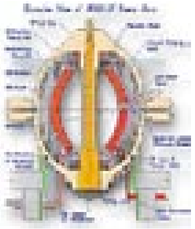
ARIES-CS


ARIES-AT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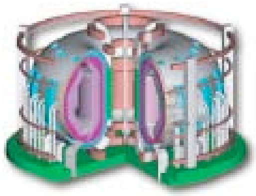
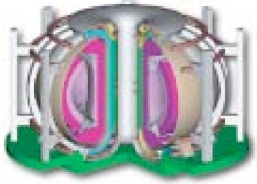

ARIES-I


ARIES-III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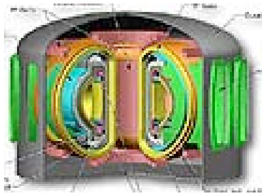
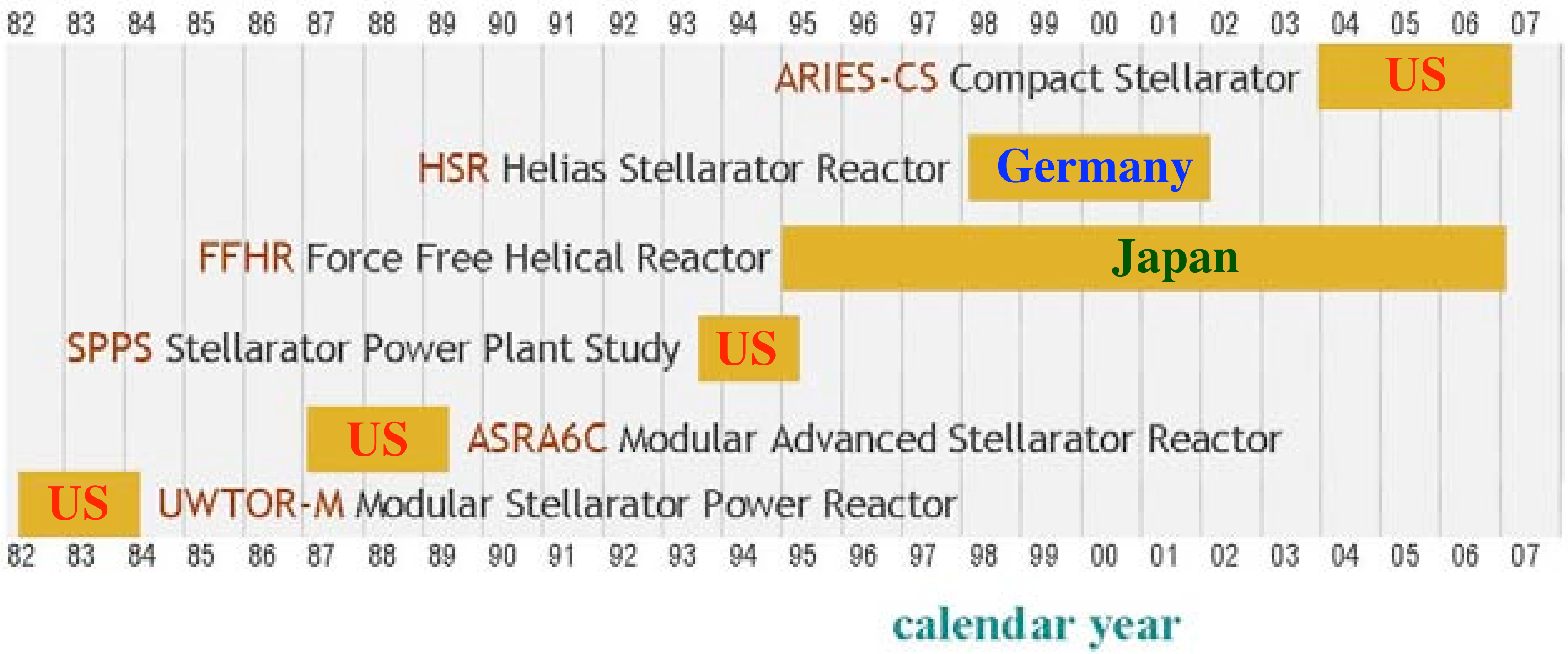
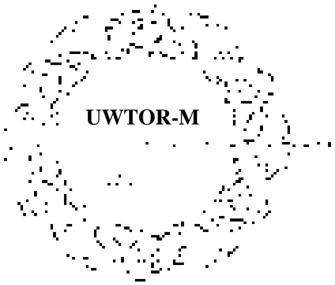
SPPS

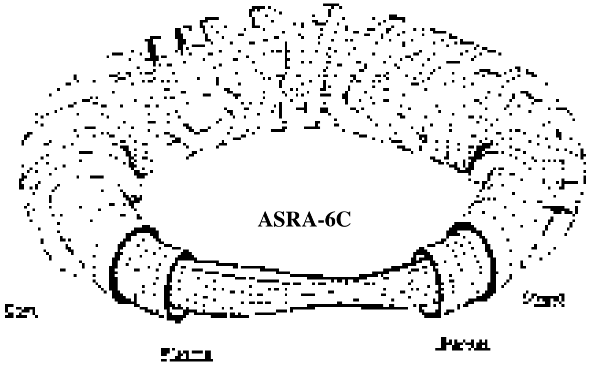

ARIES-RS

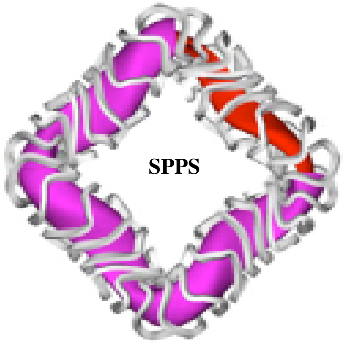
Six Stellarator Power Plants Developed Worldwide Over Past 25 y

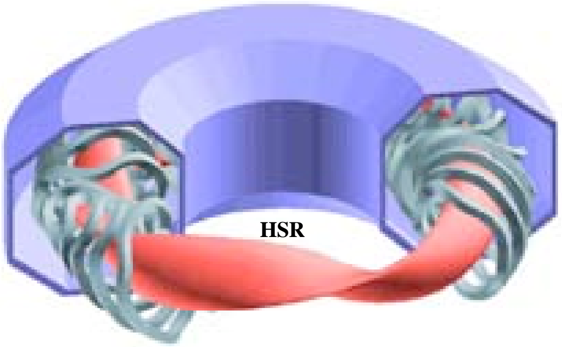


Six Stellarator Power Plants Developed Worldwide Over Past 25 y (Cont.)









Stellarators Offer Unique Features and Engineering Challenges

Advantages:

- Inherently steady-state devices
- No need for large plasma current
- No external current drive
- No risk of plasma disruptions
- Low recirculating power due to absence of current-drive requirements
- No instability and positional control systems.

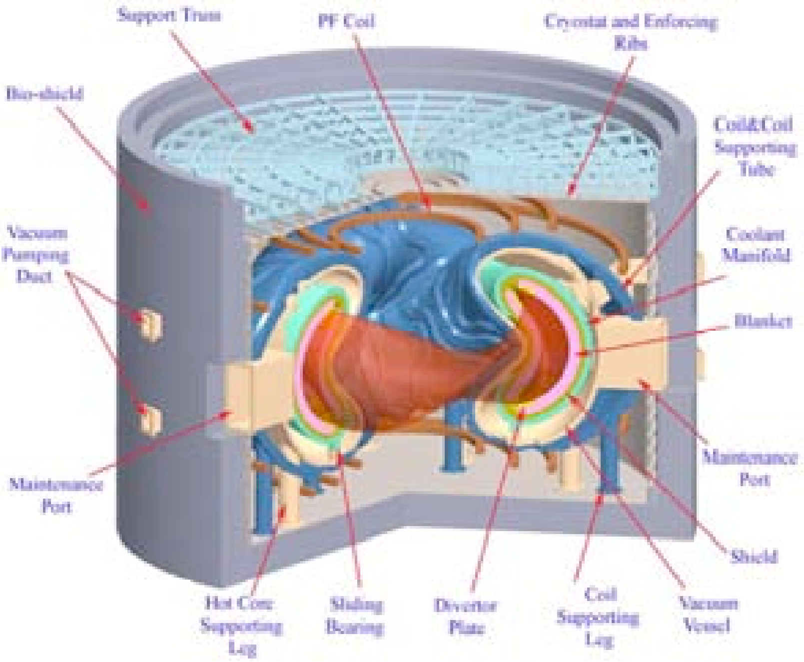
Challenges:

- Complex geometry
- Maintainability and component replacement
- Highly constrained local shielding areas
- 3-D modeling
- Managing large volume of active materials.

ARIES Compact Stellarator

Study aimed at reducing stellarators' size by:

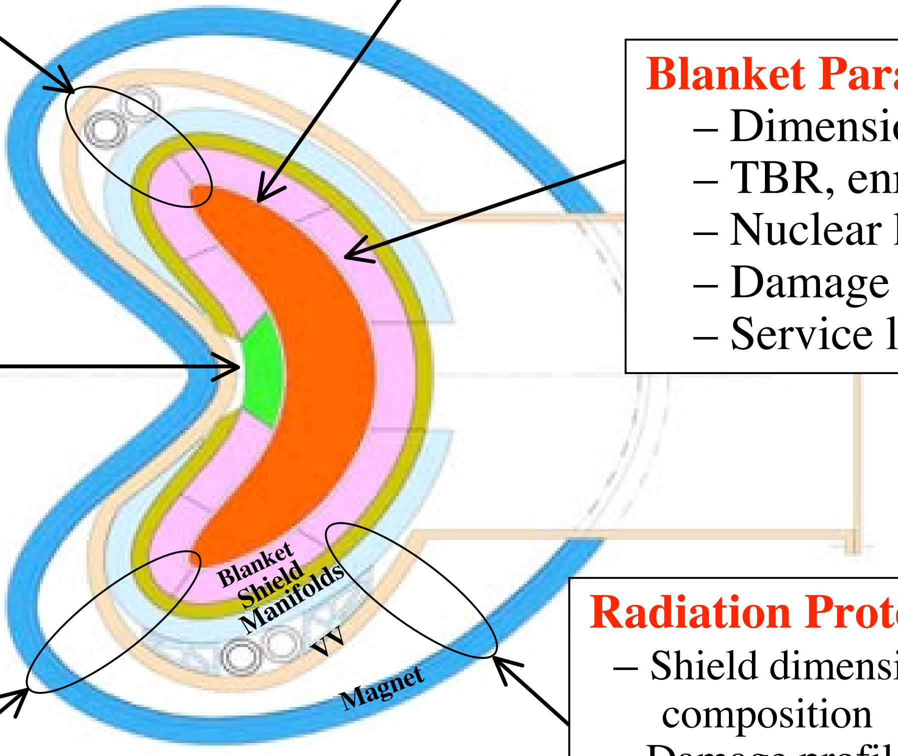
- Developing compact configuration with advanced physics & technology
- **Optimizing minimum plasma-coil distance (Δ_{min}) through rigorous nuclear assessment.**



3 Field Periods Configuration

Average Major Radius	**7.75 m**
Average Minor Radius	**1.7 m**
Aspect Ratio	**4.5**
Fusion Power	**2400 MW**
Average NWL	**2.6 MW/m^2**
Net Electric Power	**1000 MW$_e$**
COE ($2004)	**78 mills/kWh**

ARIES-CS Nuclear Areas of Research



Radial Build Definition:
- Dimension of all components
- Optimal composition

Neutron Wall Loading Profile:
- Toroidal & poloidal distribution
- Peak & average values

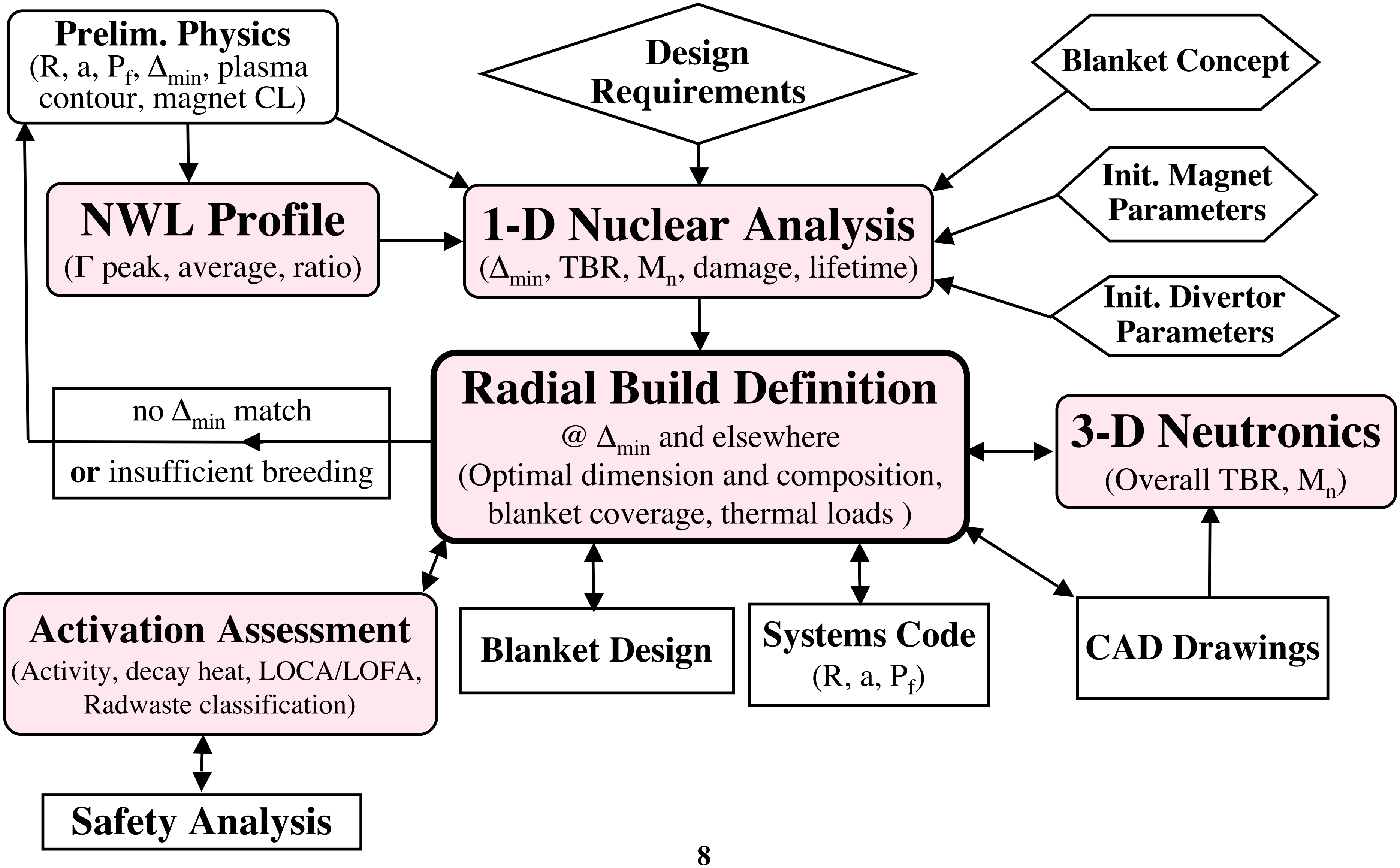
Blanket Parameters:
- Dimension
- TBR, enrichment, M_n
- Nuclear heat load
- Damage to FW
- Service lifetime

High-Performance Shielding Module at Δ_{min}

Activation Issues:
- Activity and decay heat
- Thermal response during LOCA/LOFA events
- Radwaste classification & management

Radiation Protection:
- Shield dimension & optimal composition
- Damage profile at shield, manifolds, VV, and magnets
- Streaming issues
- Workers and public protection

Nuclear Task Involves Active Interaction with many Disciplines



Prelim. Physics
(R, a, P_f, Δ_{min}, plasma contour, magnet CL)

Design Requirements

Blanket Concept

NWL Profile
(Γ peak, average, ratio)

1-D Nuclear Analysis
(Δ_{min}, TBR, M_n, damage, lifetime)

Init. Magnet Parameters

Init. Divertor Parameters

no Δ_{min} match
or insufficient breeding

Radial Build Definition
@ Δ_{min} and elsewhere
(Optimal dimension and composition, blanket coverage, thermal loads)

3-D Neutronics
(Overall TBR, M_n)

Activation Assessment
(Activity, decay heat, LOCA/LOFA, Radwaste classification)

Blanket Design

Systems Code
(R, a, P_f)

CAD Drawings

Safety Analysis

Reference Dual-cooled LiPb/FS Blanket Selected with Advanced LiPb/SiC as Backup

Breeder	Multiplier	Structure	FW/Blanket Coolant	Shield Coolant	VV Coolant
Internal VV[*]:					
Flibe	Be	FS	Flibe	Flibe	H_2O
LiPb (backup)	**–**	**SiC**	**LiPb**	**LiPb**	$\mathbf{H_2O}$
LiPb (reference)	**–**	**FS**	**He/LiPb**	**He**	$\mathbf{H_2O}$
Li_4SiO_4	Be	FS	He	He	H_2O
External VV[#]:					
LiPb	–	FS	He/LiPb	He or H_2O	He
Li	–	FS	He/Li	He	He

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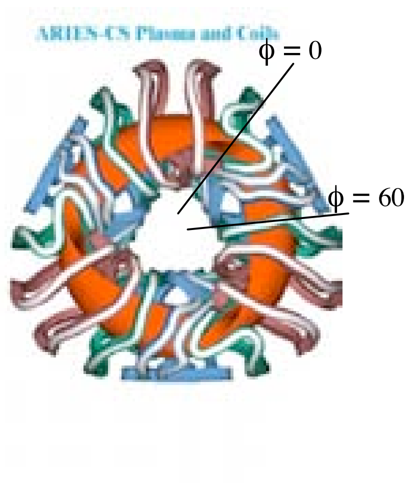
[*] VV inside magnets.

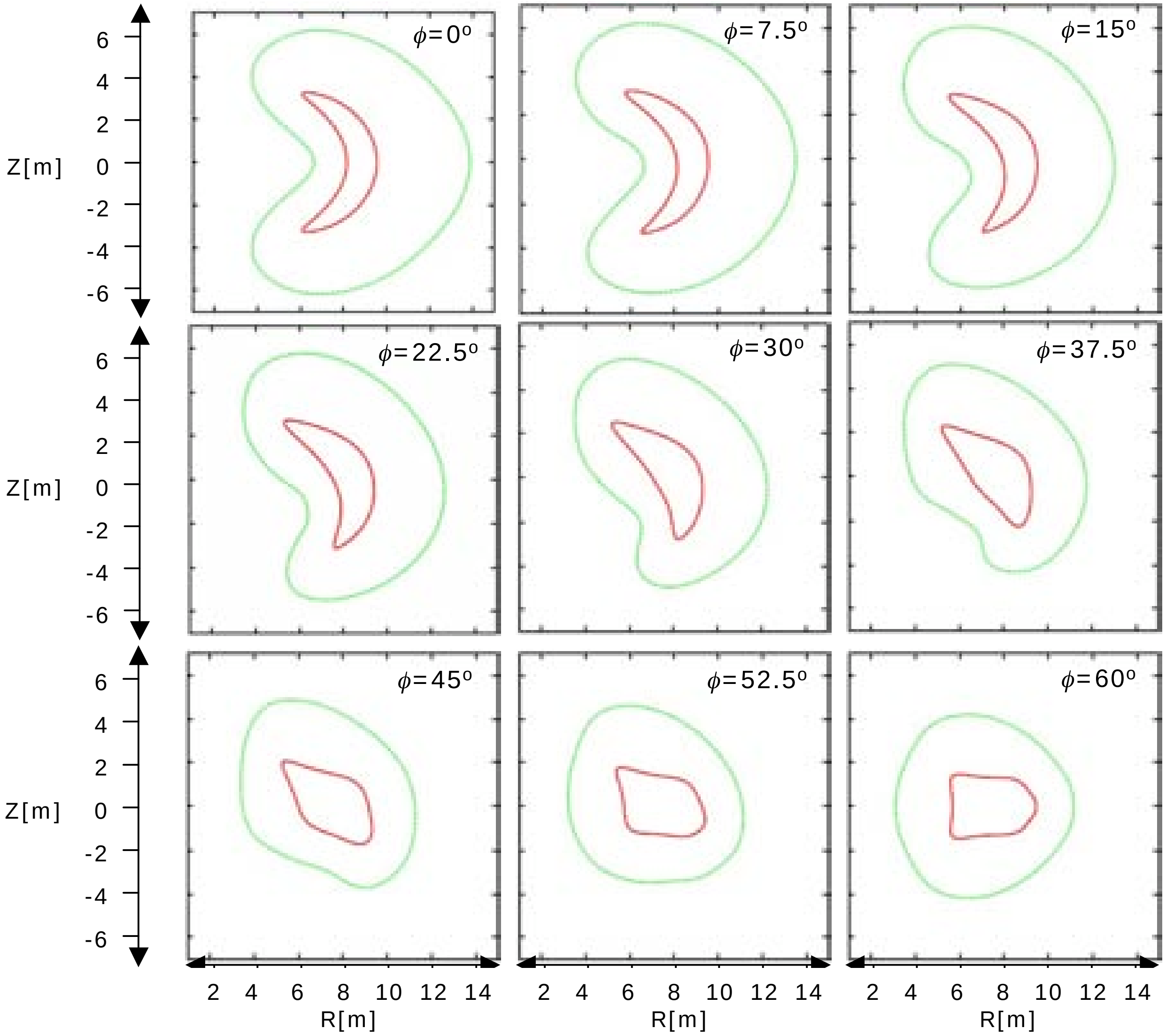
[#] VV outside magnets.

ARIES-CS Requirements Guide
In-vessel Component Design

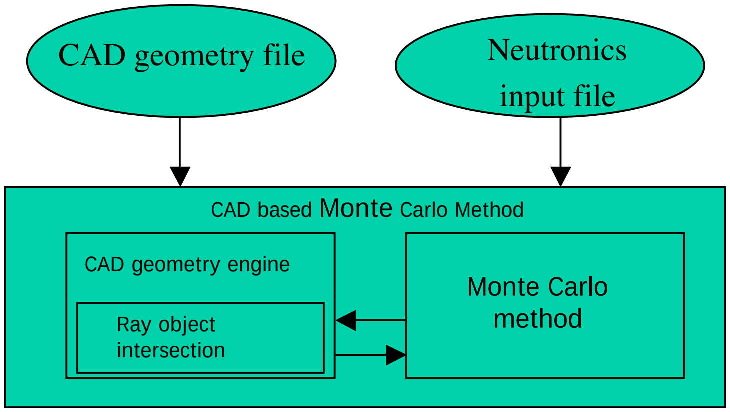
Calculated Overall TBR	1.1	
Net TBR (for T self-sufficiency)	~1.01	
Damage to Structure (for structural integrity)	200	dpa - advanced FS
Helium Production @ Manifolds and VV (for reweldability of FS)	1	He appm
S/C Magnet (@ 4 K):		
Peak Fast n **fluence** to Nb_3Sn ($E_n > 0.1$ MeV)	10^{19}	n/cm^2
Peak Nuclear **heating**	2	mW/cm^3
Peak **dpa** to Cu stabilizer	6×10^{-3}	dpa
Peak **Dose** to electric insulator	$< 10^{11}$	rads
Plant Lifetime	40	FPY
Availability	85%	
Operational dose to workers and public	< 2.5	mrem/h

FW Shape Varies Toroidally and Poloidally: Challenging 3-D Modeling Problem





UW Developed CAD/MCNP Coupling Approach to Model ARIES-CS for Nuclear Assessment


CAD geometry file

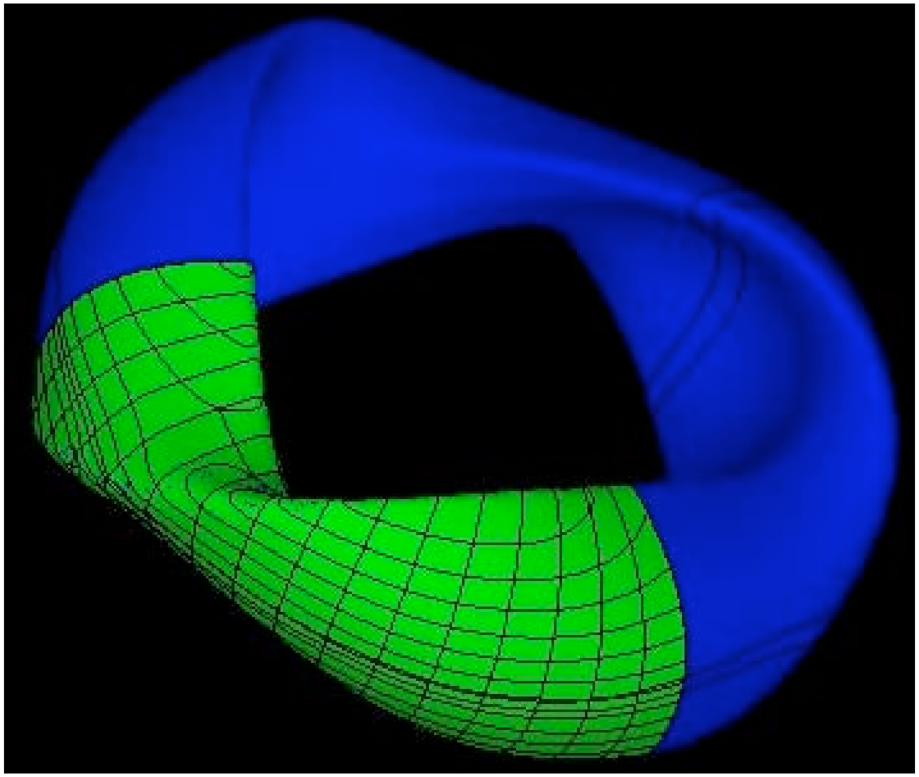
Neutronics input file

CAD based Monte Carlo Method

CAD geometry engine

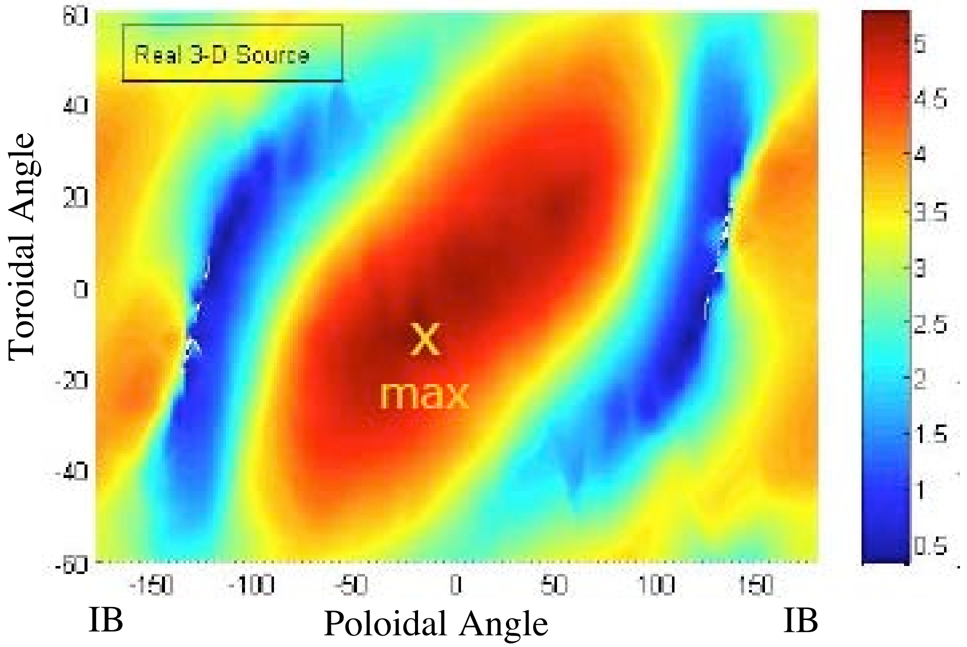
Ray object intersection

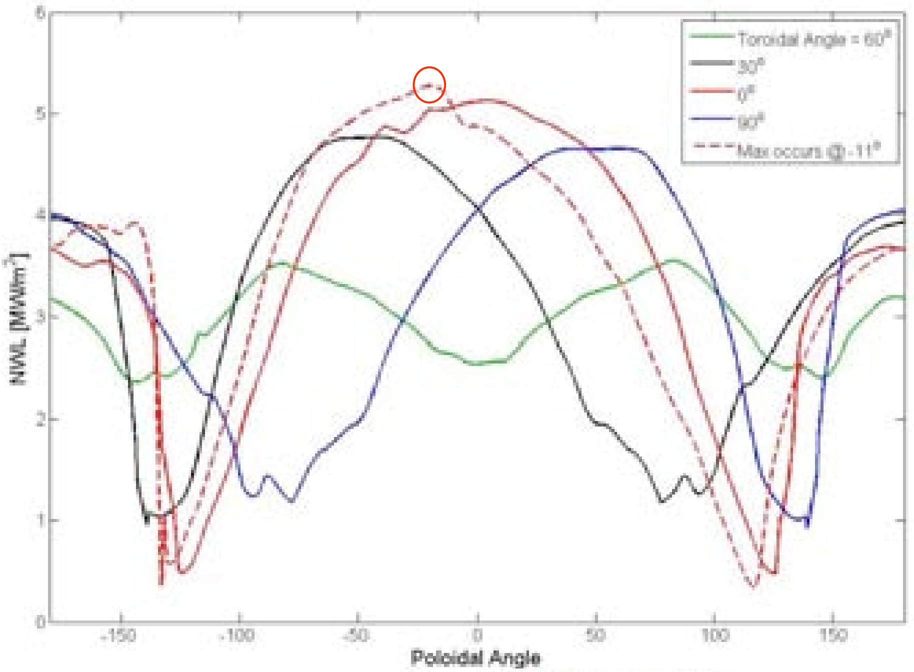
Monte Carlo method



- Only viable approach for ARIES-CS 3-D neutronics modeling.
- Geometry and ray tracing in CAD
- Radiation transport physics in MCNPX.

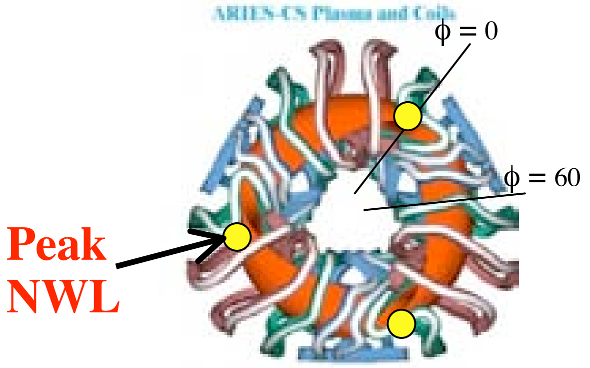
Neutron Wall Loading Distribution





	Peak (Min) [MW/m²]	Toroidal Angle (degrees)	Poloidal Angle (degrees)
	5.26 (0.32)	-11 (-4)	-18 (-116)

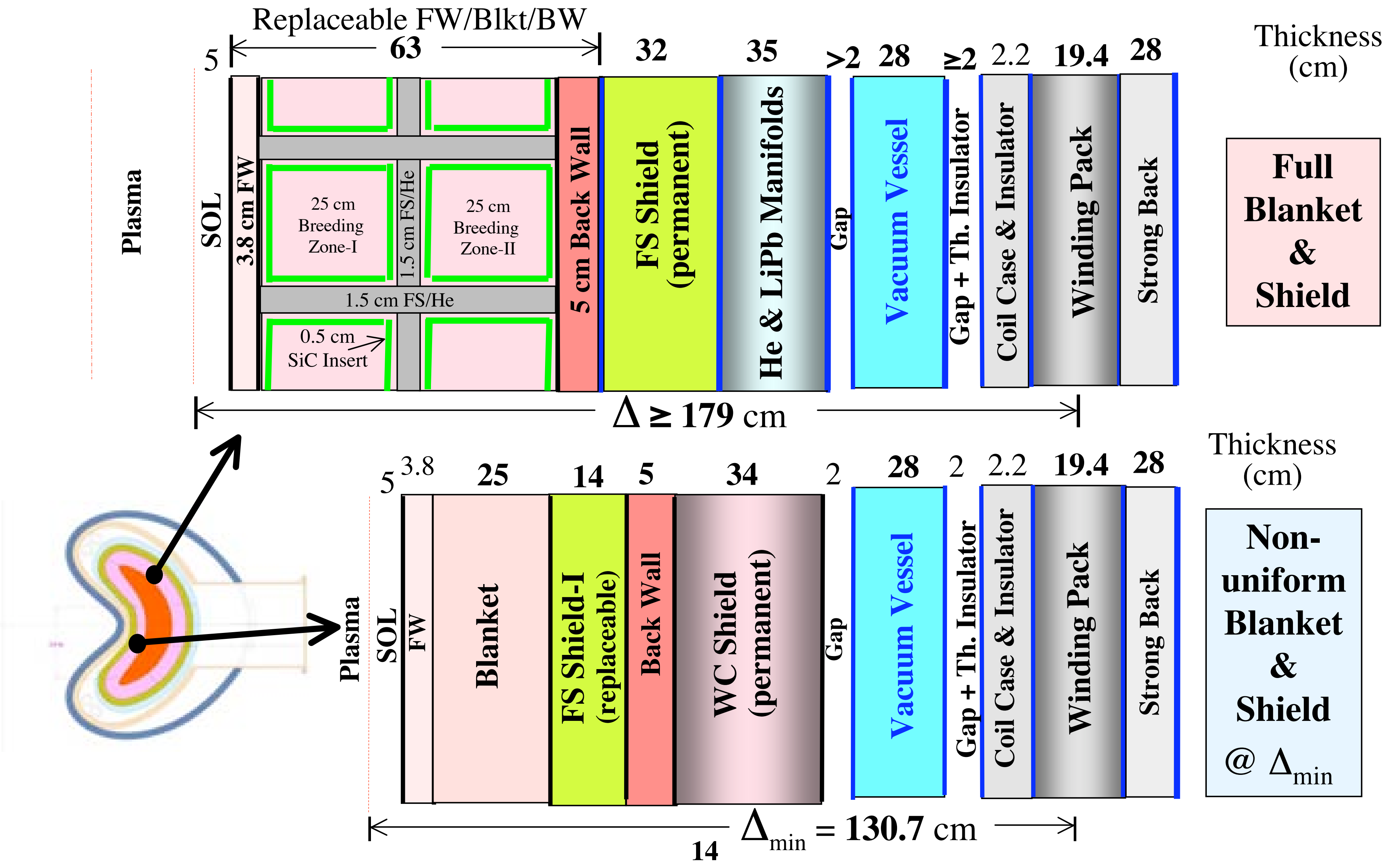
Peak/Ave. NWL = 2



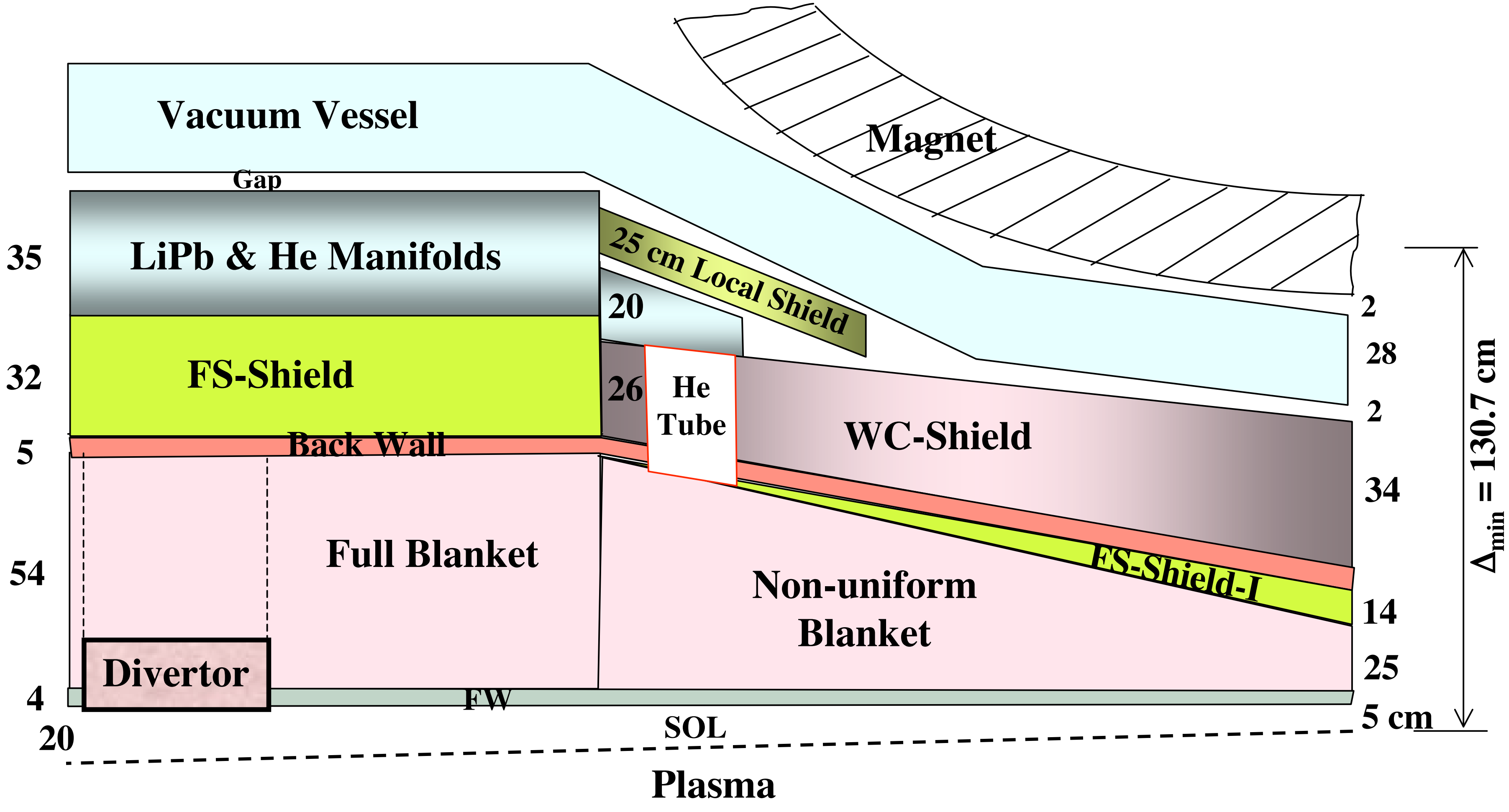
Peak NWL

Well-Optimized Blanket & Shield Protect Vital Components

(5.3 MW/m^2 Peak Γ)



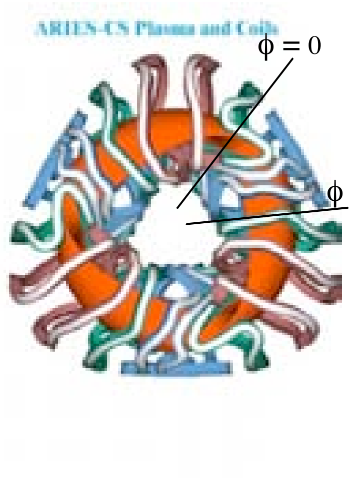
High Performance Components at Δ_{min} Help Achieve Compactness, Minimize Major Radius, and Enhance Economics

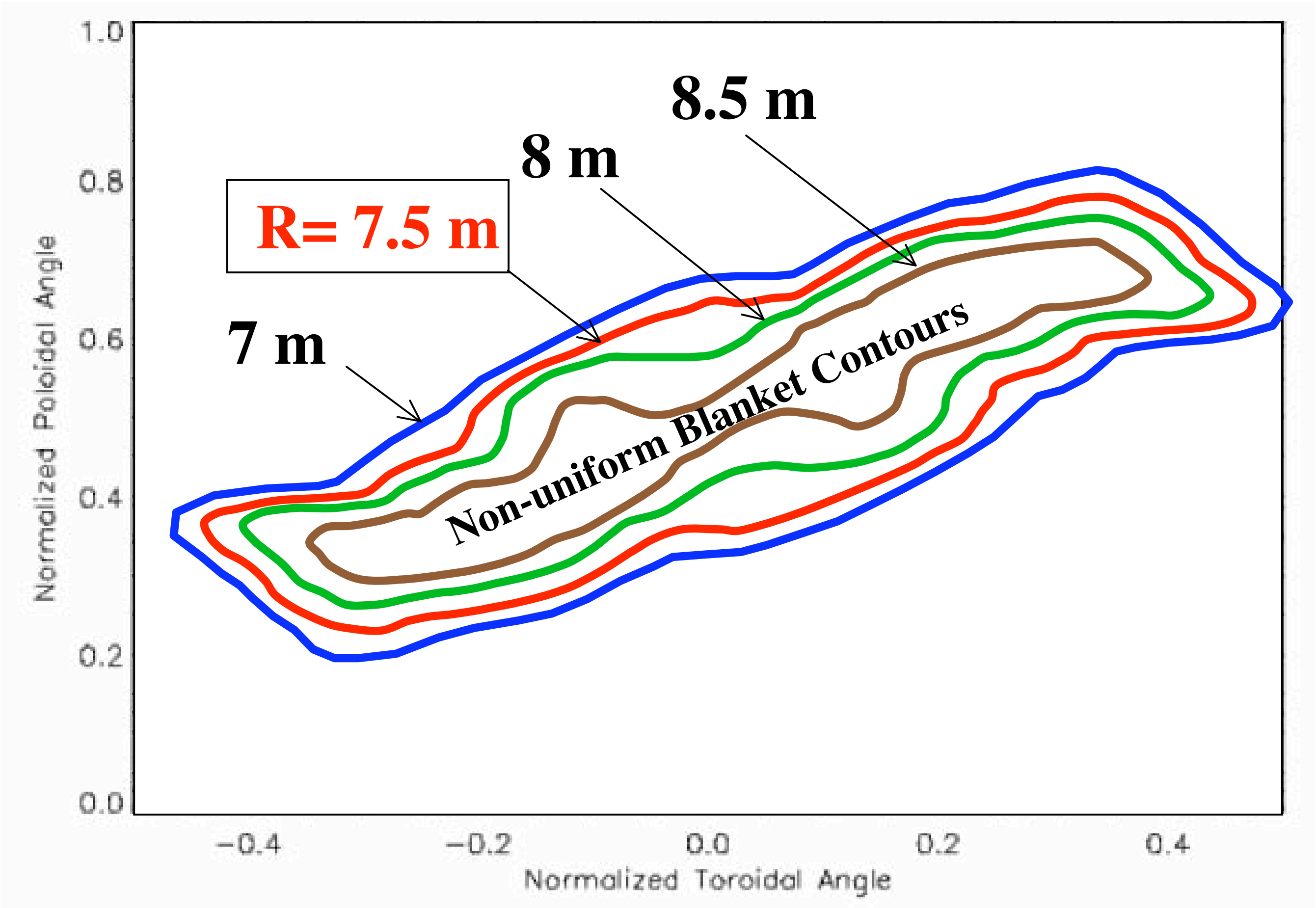


Full Blanket/Shield **and** Divertor
(61%+15%= 76% of FW area)

Non-uniform, Tapered Blanket/Shield
(24% of FW area)

Tritium Breeding Requirement Determined Minimum Major Radius





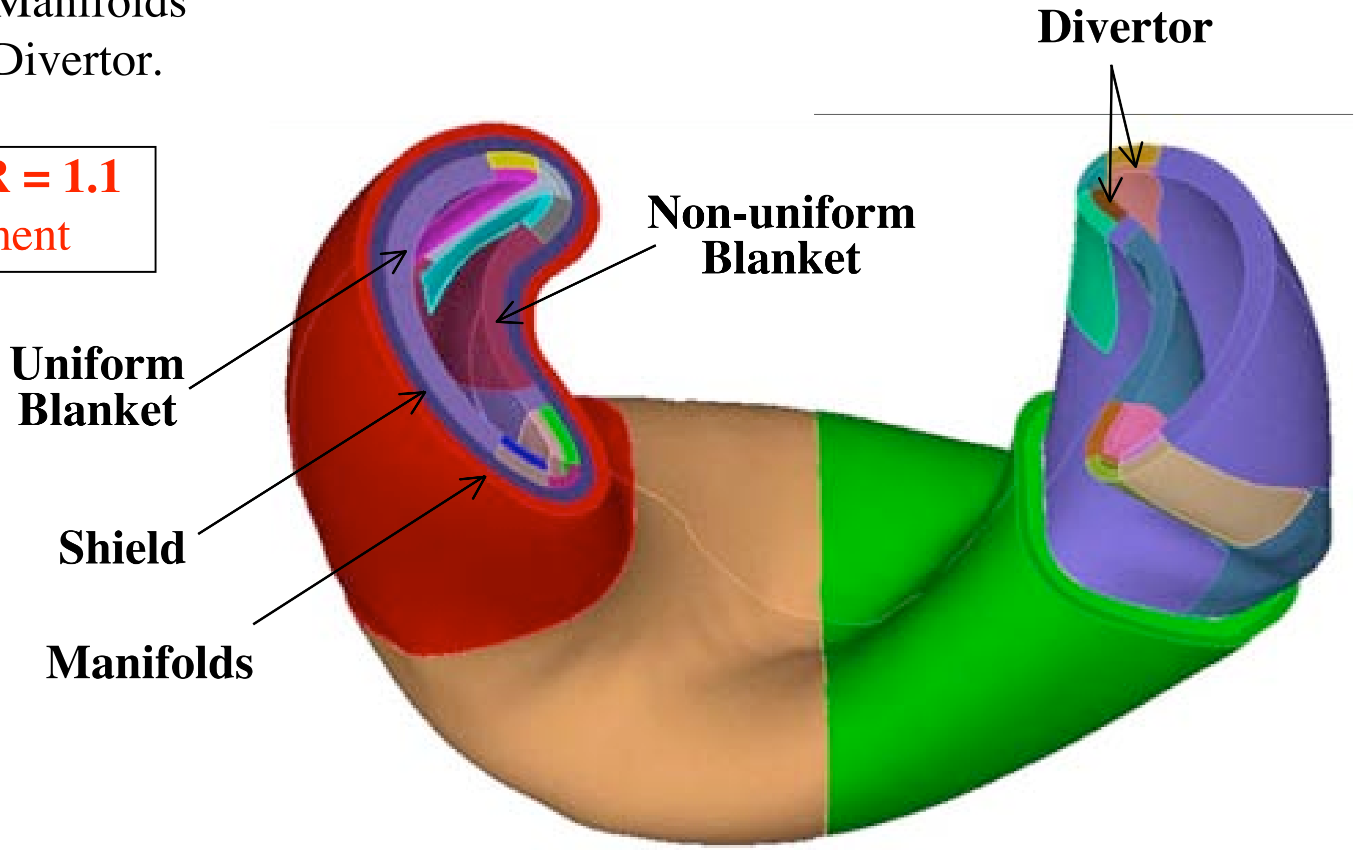
- Large machines breed more T as non-uniform blanket coverage decreases with R.
- Designs with R < 7.5 m will not provide T self-sufficiency.

R=7.75 m Reference Design Provides Tritium Self-Sufficiency

3-D model includes essential components for TBR:

- Non-uniform and full blanket/shield
- Homogenized: FW/Blanket/BW
  - Shield
  - Manifolds
  - Divertor.

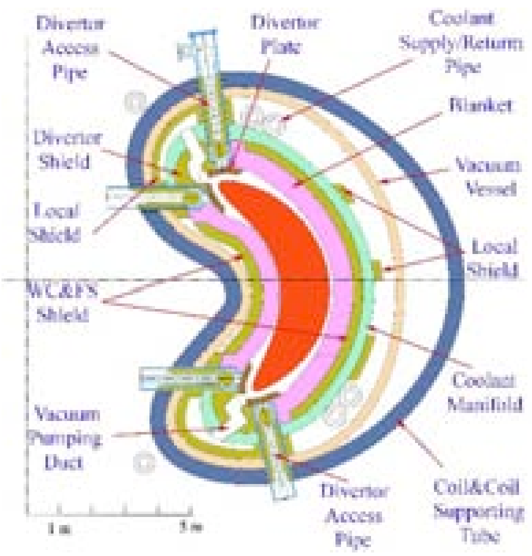
Calculated Overall **TBR = 1.1** with 70% Li enrichment

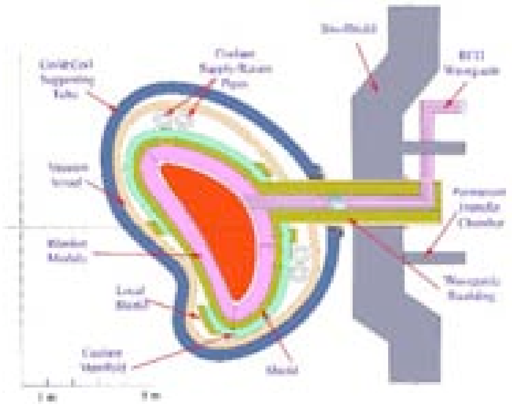


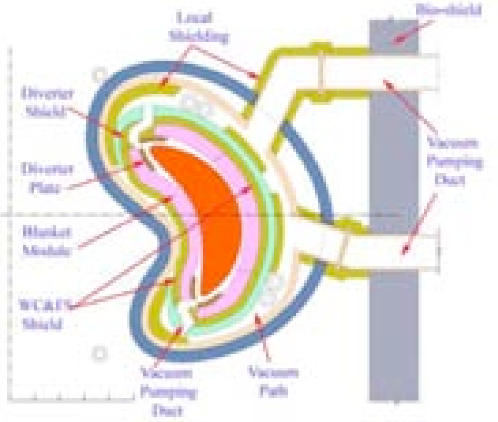
Neutron Streaming Through Penetrations Compromises Shielding Performance

- **7 types of penetrations**:
  - 198 He tubes for blanket (32 cm 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 - HX to/from blanket (72 cm ID each)
  - 6 main He pipes - HX to/from divertor (70 cm ID each)

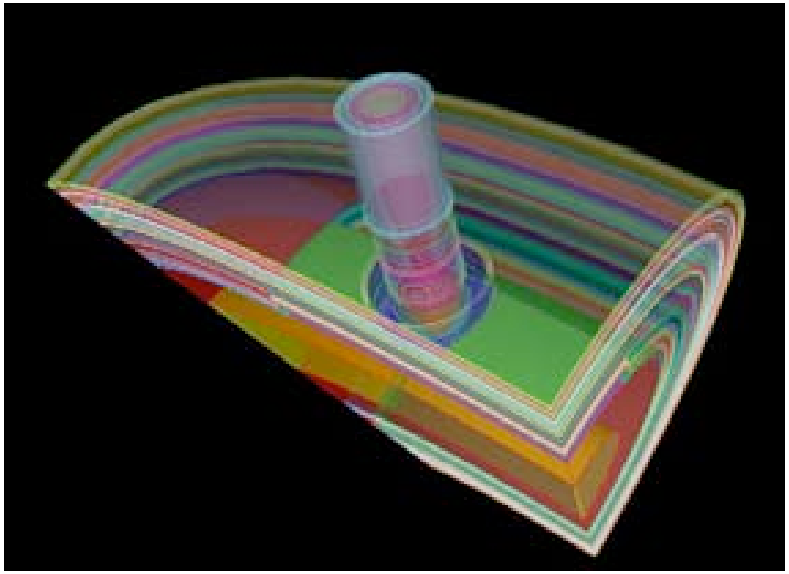
- **Potential solutions**:
  - Local shield behind penetrations
  - He tube axis oriented toward lower neutron source
  - Penetration shield surrounding ducts
  - Replaceable shield close to penetrations
  - Avoid rewelding VV and manifolds close to penetrations
  - Bends included in some penetrations.



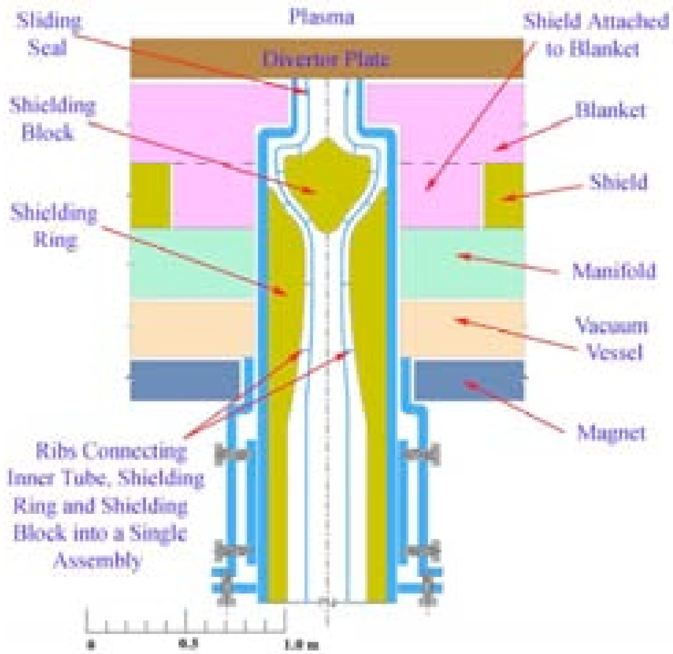


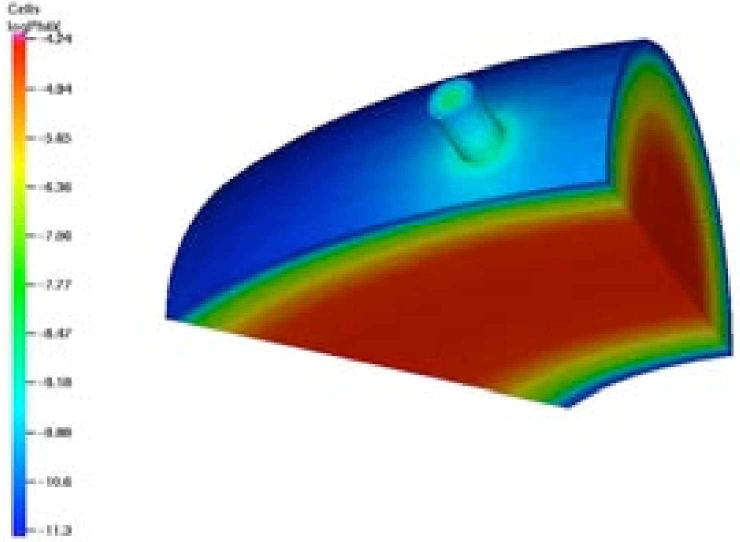


3-D Assessment of Streaming Through Divertor He Access Pipe



Attila 3-D Model



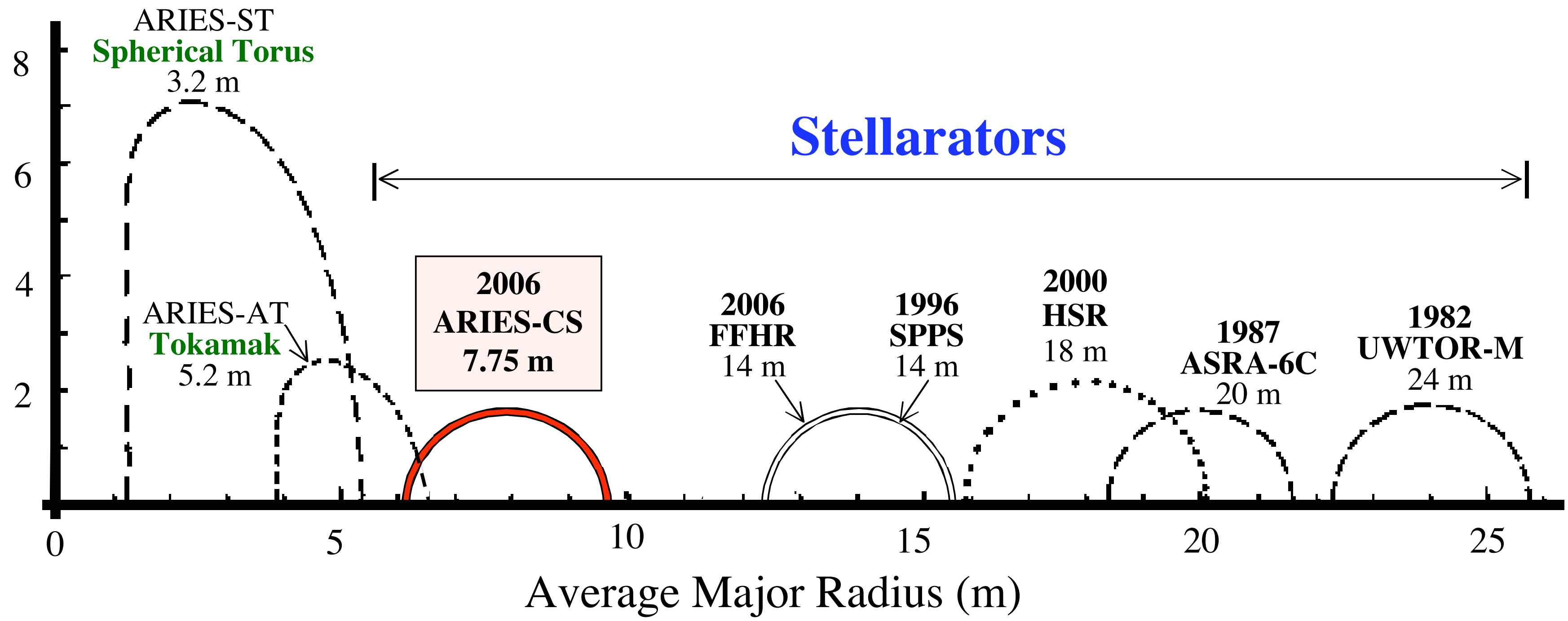


Shield inserts help protect surrounding components

Key Nuclear Parameters

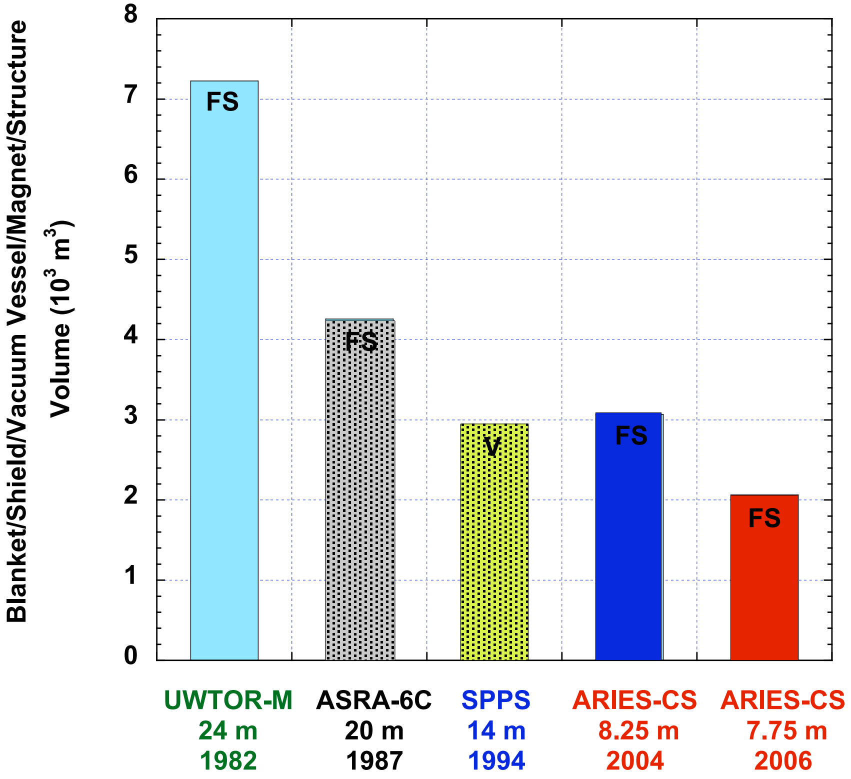
Peak NWL	**5.3 MW/m^2**
Average NWL	**2.6 MW/m^2**
Peak to Average NWL	**2**
Calculated Overall TBR	**1.1** with 70% Li enrichment
Net TBR	**~1.01**
FW/blanket Lifetime	**3 FPY**
Shield/manifold/VV/magnet Lifetime	**40 FPY**
Overall Energy Multiplication	**1.16**
Δ_{min}	**1.3 m**
Δ_{max}	**1.8 m**

ARIES-CS Major Radius Approaches R of Advanced Tokamaks



Well optimized radial build along with advanced physics and technologies helped reduce ARIES-CS size

ARIES Project Committed to Radwaste Minimization



Stellarator waste volume dropped by 3-fold over 25 y study period

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* Actual volumes (not compacted, no replacements).

Highlights of ARIES-CS Safety Features

Environmental impact:

- **Low activation materials** with strict impurity control
  ⇒ minimal long-term environmental impact.
- **No high-level waste**.
- **Minimal radioactive releases**# during normal and abnormal operations.

No energy and pressurization threats to confinement barriers (VV and cryostat):

- Decay heat problem solved by design
- Chemical reaction avoided
- No combustible gas generated
- Chemical energy controlled by design
- Overpressure protection system
- Rapid, benign plasma shutdown.

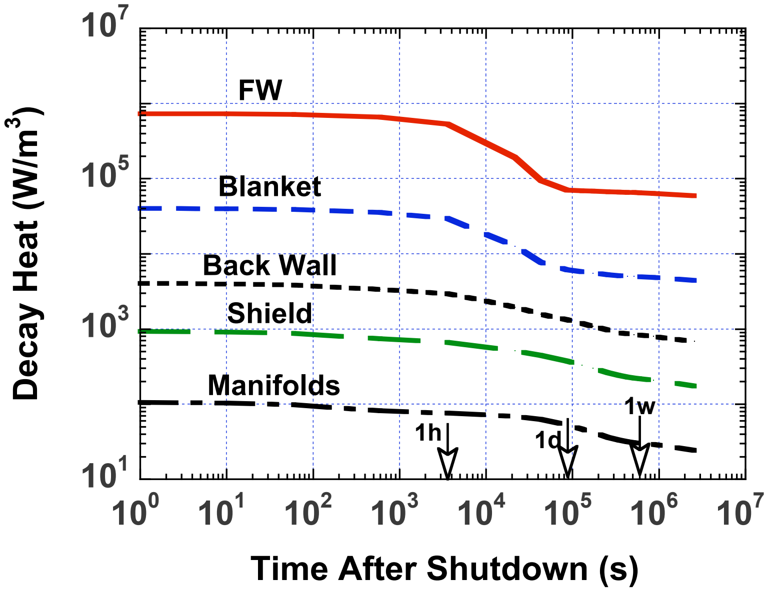
Occupational and public safety:

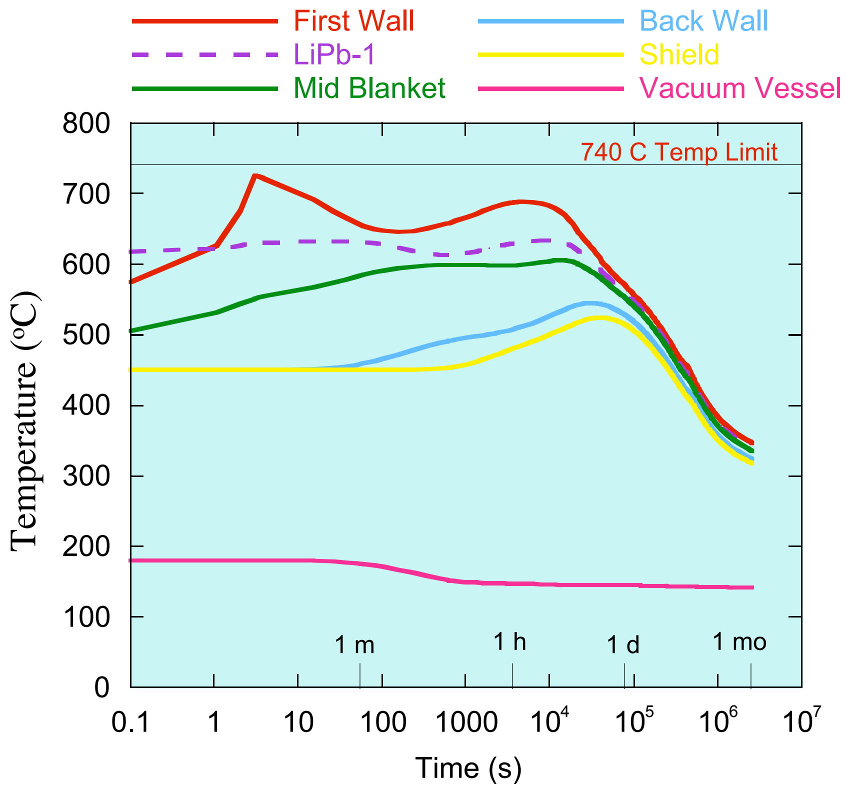
- **No evacuation plan** following abnormal events (early dose at site boundary < 1 rem*) to avoid disturbing public daily life.
- **Low dose** to workers and personnel during operation and maintenance activity (< 2.5 mrem/h*).
- **Public safety** during normal operation (bio-dose << 2.5 mrem/h*) and following credible accidents:
  - External events (seismic, hurricanes, tornadoes, etc.).
  - LOCA, LOFA, LOVA, and by-pass events.

Such as T, volatile activated structure, corrosion products, and erosion dust. Or, from liquid and gas leaks.

* 1 rem (= 10 m Sv) accident dose stated in Fusion Safety Standards, DOE report, DOE-STD-6002-96 (1996).

In-vessel Components Exhibit Structural Integrity during LOCA/LOFA Event





- **Design Base Accident scenario**: He LOCA and LiPb LOFA in **all** modules and water LOFA in VV.
- Plasma stays on for 3 seconds after onset of LOCA/LOFA.
- Peak FW temperature remains below 740^{o}C – reusability limit for ferritic steel.

Radwaste Management Approach

- **Three options examined**:
  - **Disposal** in repositories: LLW (WDR < 1)
  - **Recycling** – reuse within nuclear facilities (dose < 10,000 Sv/h)
  - **Clearance** – release slightly-radioactive materials to commercial market if CI < 1.

- Lack of geological repositories and tighter environmental controls will force fusion designers to promote recycling and clearance, avoiding disposal*

  ⇒ **minimize radwaste burden for future generations**.

- There's **growing international effort** in support of this new trend.

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* L. El-Guebaly, "Environmental Aspects of Recent Trend in Managing Fusion Radwaste: Recycling and Clearance, Avoiding Disposal," This IAEA TM, Wednesday @ 9 AM.

Comparison Between Reference and Backup Systems

	LiPb/He/FS	**LiPb/SiC**
Calculated Overall **TBR**	1.1	1.1
FW/blanket **lifetime**	3 FPY	3.4 FPY
Overall **energy multiplication**	1.16	1.1
η_{th}	42%	56%
Structure **unit cost***	103 $/kg	510 $/kg
Blanket/divertor/shield/manifolds **cost***	$288M	$282M
Cost* of **heat transfer/transport system**	$475M	$175M
Pumping power	183 MW_e	---
LSA factor	2	1
Cost of Electricity*:		
Reference design (R=7.75 m)	**78** mills/kWh	**60** mills/kWh
Full blanket/shield everywhere (R=10.1 m)	**87** mills/kWh	

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* in 2004 $.

Conclusions

- Nuclear assessment received considerable attention during ARIES-CS design process.
- First time ever complex stellarator geometry modeled for nuclear assessment using UW newly developed CAD/MCNP coupling approach.
- Radial build satisfies design requirements in terms of breeding sufficient tritium and shielding vital components.
- Novel shielding approach developed for ARIES-CS helped reduce radial standoff by 40%, major radius by 30%, and overall cost by 10%.
- ARIES-CS demonstrates adequate performance in several safety and environmental areas.
- Successful integration of well-optimized radial build into final design, along with carefully selected engineering parameters and overarching safety and environmental constraints, delivered attractive and truly compact stellarator power plant.