Need for Inboard Shield to Protect Center Post of ST Power Plants

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Abstract

The center post (CP) is the most critical in-vessel component in spherical tokamaks (ST). Advanced ST power plant designs normally call for high neutron wall loads (>5 MW/m^2) forcing the CP to operate in a high radiation environment. Radiation degrades the physical properties of the current carrying conductor and severely affects the overall performance of the CP. An unshielded CP does not appear to offer an attractive design. This paper presents the rationale for shielding the CP of ARIES-ST, the reasons for the design choices, and the consequences of the choices on the power plant design.

http://fti.neep.wisc.edu/FTI/pdf/fdm1080.pdf

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Objectives

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- Identify key shielding issues and concerns for ARIES-ST

- Present rational for CP shielding, reasons for choices, and consequences of choices on ARIES-ST design

- Develop subsystem requirements for inboard shield

- Assess radiation damage to center post:
  - dpa to Cu
  - change in Cu resistivity
  - activation of CP
  - nuclear heat load to CP

ARIES-ST Key Parameters

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Net Electric Power	1000 MWe
Aspect ratio	1.6
Elongation	3.4
Beta	35%
Major radius	3.3 m
Minor radius	2.1 m
Neutron wall loading (MW/m^2):	
Peak outboard	8
Peak inboard	5
Machine average	6
LiPb outboard blanket	1 m thick FS Structure He coolant
Water cooled center post	80 cm radius 20 m high 85% Cu, 15% H_2O 300 tonnes
Plant lifetime	40 FPY
Cost of Electricity	110 mills/kWh

ARIES-ST General Guidelines

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- Minimize COE, nominal Figure-of-Merit

- Optimize overall design, not only single component

- Factor in safety and economic requirements from beginning

- All components must meet both 10CFR61 and Fetter's limits for Class C waste until NRC develops official guidelines for fusion power plants

Main Issues/Concerns for Inboard Side

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- Unshielded CP does not offer attractive ARIES-ST design

- Inboard shield competes with CP for valuable inboard space

- Main issues/concerns:
  - Compatibility of inboard shield with in-vessel components (mainly CP and blanket)
  - Impact of inboard materials on outboard breeding
  - Influence of inboard side on overall power balance:
    - Joule losses in CP
    - Overall energy multiplication (M_n)
    - Heat load to CP
  - Radiation effects at CP:
    - Radiolysis of water coolant
    - Change in Cu resistivity (due to transmutations)
    - Embrittlement of Cu
    - Radwaste level
    - CP lifetime:
      - Change out frequency
      - Replacement cost
      - Availability
      - Radwaste stream

Subsystem Requirements for Inboard Shield

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- Design requirements for inboard shield:
  - must be compatible with CP and blanket
  - enhance outboard breeding
  - maximize neutron energy multiplication (M_n)
  - protect CP against radiation
  - reduce heat load to CP
  - meet stress and temperature limits
  - must be replaceable, reliable, and maintainable

- Safety Requirements:
  - Class C low level waste for shield and CP (with impurity control)
  - No degradation during LOCA/LOFA
  - Low afterheat

- Economic Requirements:
  - Prolond CP lifetime
  - recover inboard heating
  - reduce Joule losses

Several contradicting requirements means inboard shield design is a compromise between several design constrains

Shielding parameters should be chosen to optimize overall design, not only to minimize Joule losses in CP

Economic impact of design choices can only be assessed self-consistently using integrated systems analysis

Options for Inboard Shield

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I- Helium-cooled FW/shield (reference)
II- Water-cooled FW/shield
III- LiPb/FS/SiC He-cooled FW/blanket
IV- High performance shield [currently being persued]

Features:

I- Helium cooled FW/shield:

+ 21 cm thick FS/He FW/shield
+ ~450 MW deposited in i/b FW/shield will be recovered
+ highest nuclear energy multiplication (1.1)
+ low impact on outboard breeding
+ simple inboard design
– 10 cm He manifold behind shield
– Joule losses in CP** ~400 MW
– He pumping power ~60 MW

II- Water cooled FW/shield:

+ ~16 cm thick FS/H_2O FW/shield
+ no need for water manifold behind shield
+ relatively lower Joule losses in CP (~300 MW)
+ simple inboard design
– degrades outboard breeding TBR<1.1 (unacceptable)
– ~450 MW deposited in i/b FW/shield is dumped as low grade heat
– low nuclear energy multiplication (1.0)
– Large and costly TF coils
– high CP replacement cost

III- LiPb/FS/SiC He cooled FW/blanket* :

+ ~25 cm thick LiPb/FS/SiC FW/blanket
+ ~450 MW deposited in i/b FW/blanket will be recovered
+ highest overall breeding (TBR > 1.1)
+ allow for thinner o/b blanket (75 cm instead of 1 m)
+ lower inboard afterheat
– need 5-10 cm i/b He manifold behind blanket
– complex i/b design
– Joule losses in CP 400-500 MW
– high He and LiPb i/b pumping power

** Flared
* Needed if o/b breeding is below 1.1

Heat Load to In-Vessel Components

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Nuclear Heating (MW)	Inboard	Outboard	Divertor
Blanket System	--	3060	--
Shield	330	10	350
CP	200	--	--

- Inboard FW/shield contains ~ 450 MW of surface and volumetric heating

Inboard heating must be recovered as high grade heat to improve power balance

Overall Energy Multiplication:

All components	1.17
All components except CP	1.1 (reference)
All components except inboard	1.0

Impact of Inboard Materials on Outboard Breeding

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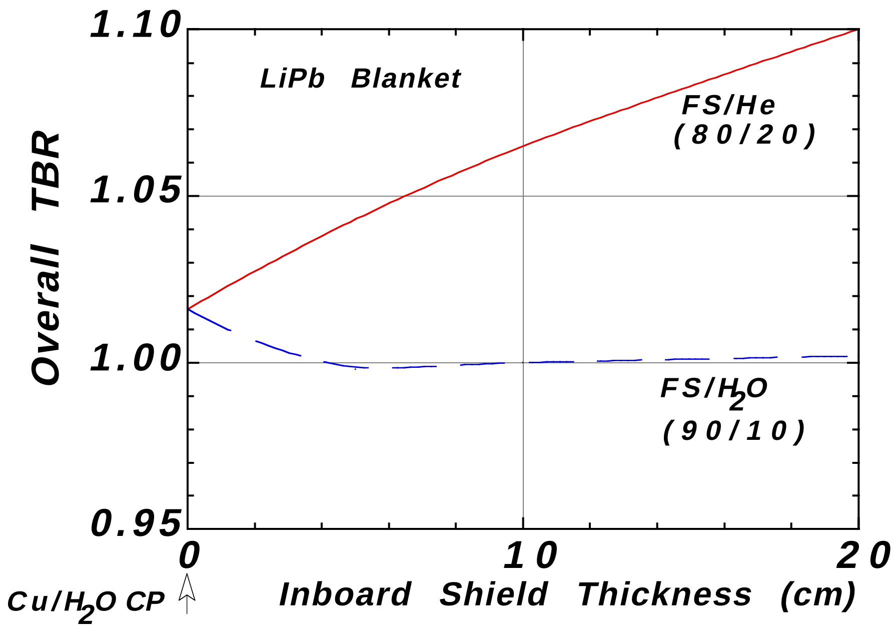

- Helium cooled i/b shield helps meet breeding requirements (1.1 TBR)

- Water cooled i/b shield degrades both breeding and power balance (cost of added water circuit will offset benefit of recovered heat at 35% efficiency)

LiPb blanket will not breed with water cooled inboard shield or bare CP

Radiation Damage to CP: Atomic Displacement in Cu

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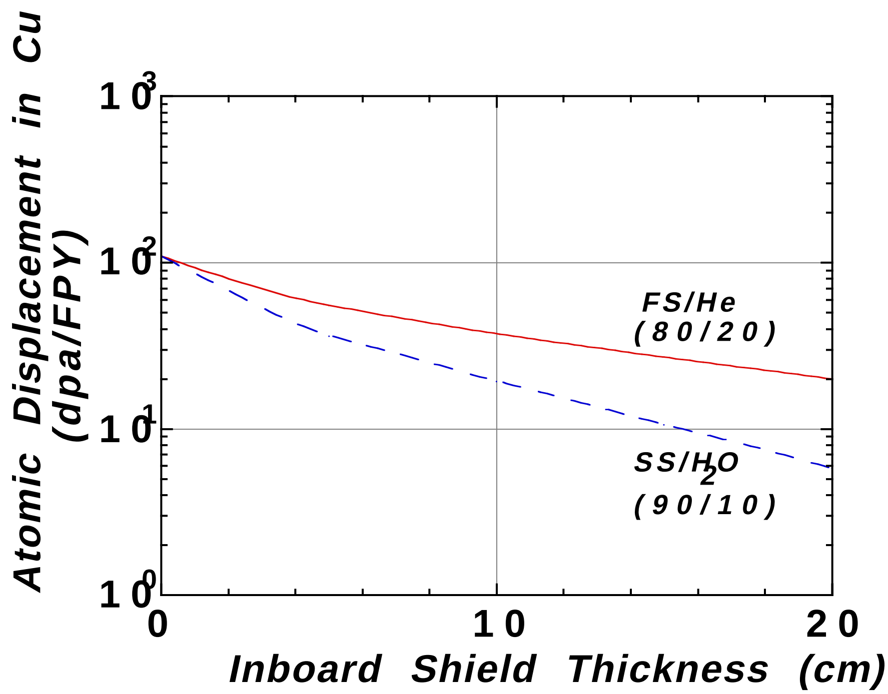

- Water is efficient shielding material, but degrades outboard breeding
- Irradiation tests @ T < 150ºC indicates dramatic embrittlement of all Cu alloys at 0.1 dpa

Shielded CP becomes brittle shortly after operation

Structural design criteria for embrittled Cu need to be applied to CP design

More radiation resistant Cu alloys should be developed to meet ST-specific needs

Radiation Damage to CP: Change in Cu Resistivity

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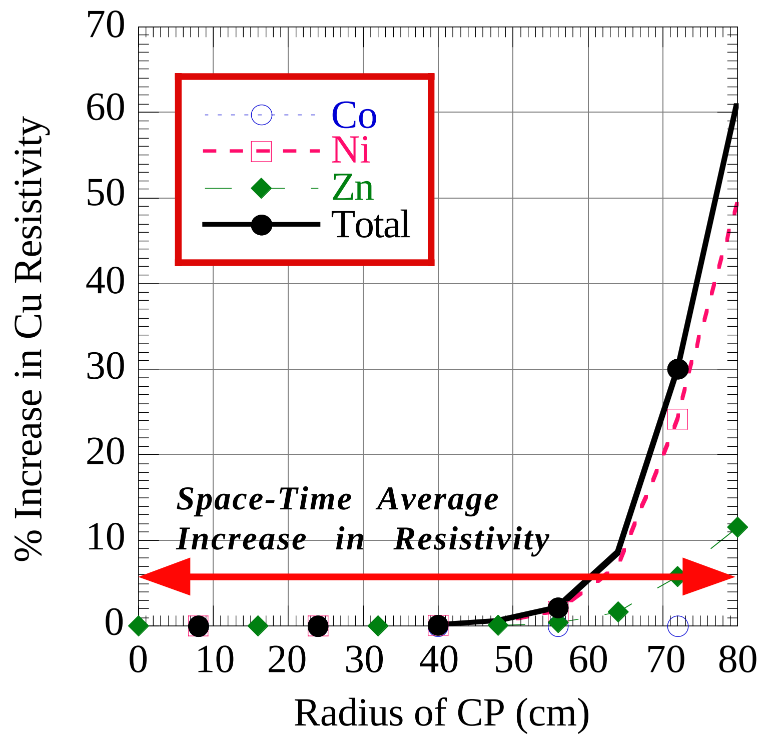

- For 20 cm inboard FS/He shield, space-time average change in Cu resistivity over 3 FPY is 6% (~20 MW Joule losses)
- Outermost 20 cm thick layer exihibits large transmutations, forcing current to flow in less resistive central region
- More resistive outermost layers of unshielded CP is ineffective for current flow

Radiation Effect at CP: Activation of Cu

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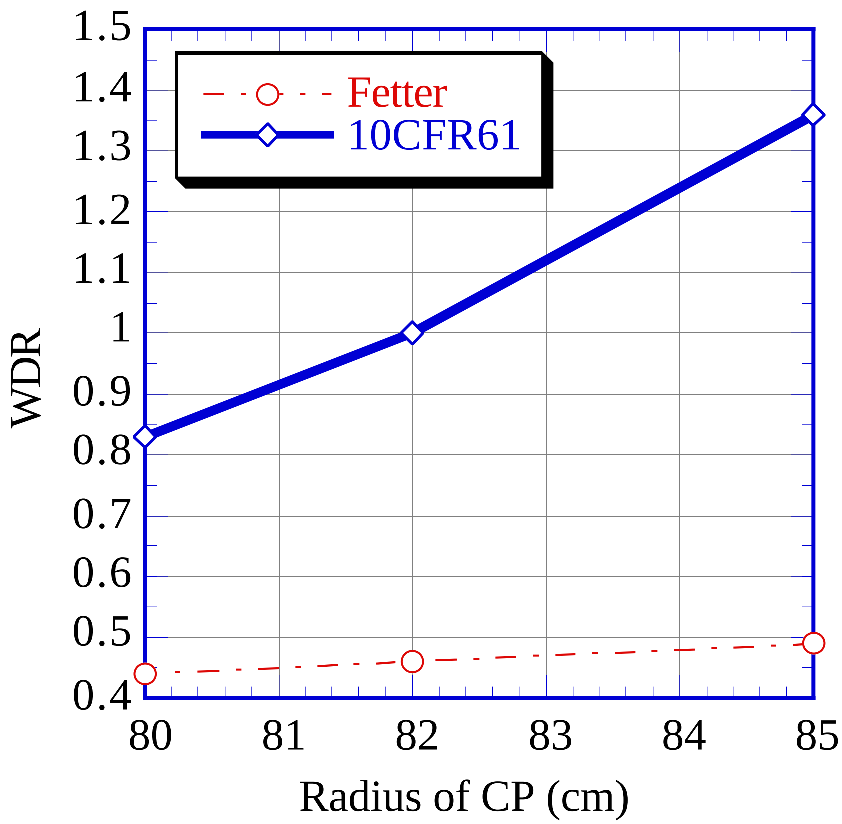

- 18 cm thick inboard shield allows CP to be disposed of as Class C waste (WDR=1) after 3 FPY of operation

- Unshielded CP does not meet Class C low level waste requirement

20 cm FS/He shield fulfills both waste disposal and breeding requirements

Radiological Limits and Implications

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- For 20 cm inboard shield:

CP Lifetime	3 FPY (same as for FW/B)
CP Replacement Cost	2 mills/kWh
Change in Cu Resist.	6%

- Different radwaste limits may prolong CP Lifetime, meaning:

CP Lifetime	> 3 FPY
CP Replacement Cost	< 2 mills/kWh
Change in Cu Resist.	> 6%

$\Rightarrow$ Net change in COE is very small (< 1%)

Adopting less restrictive radiological limits
has no significant impact on COE

Inboard Radial Build

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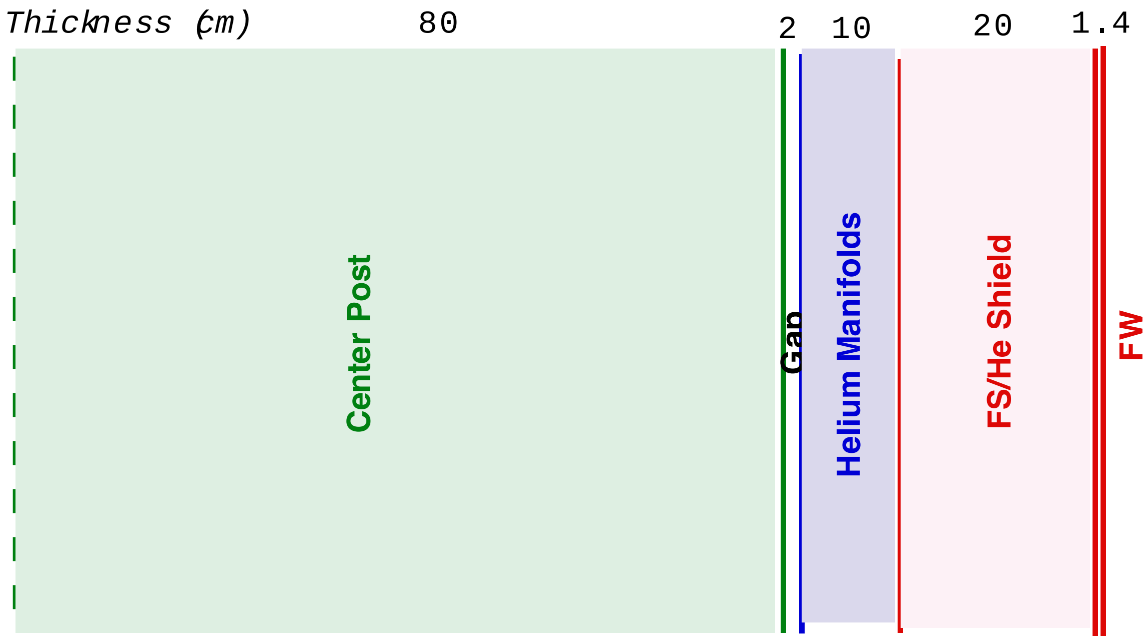

FW	30% FS , 70% He
Shield	80% FS , 20% He
He Manifolds	10% FS , 90% He
Center Post	85% Cu , 15% H_2O

- Study is underway to reduce size of He manifold

Conclusions

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- Unshielded CP does not offer attractive ARIES-ST design
- Inboard shield design proceeded iteratively with guidance from neutronics, safety, and economics analyses
- Because of several contradicting design requirements, inboard shield was a compromise between many constraints
- Inboard shielding parameters were chosen to optimize overall design, not only to reduce Joule losses in CP
- Size of inboard shield was determined by breeding, power balance, and lifetime considerations
- 20 cm inboard FS/He shield helps meet safety, economic, and design requirements. It offers:
  - Simple design
  - Acceptable breeding (1.1)
  - Useful inboard thermal power and high Mn (1.1)
  - 3 FPY CP lifetime (same as for FW/B)
  - < 200 MW heat load to CP
  - 6% space-time av. increase in Cu resistivity
  - Class C CP waste
  - ~2 mills/kWh CP replacement cost
  - ~400 MW Joule losses in flared CP
- Less restrictive safety requirements and blanket with higher breeding margin could allow the use of high performance shield to reduce Joule losses below 400 MW
- Designing inboard shield in absence of breeding, safety, and economic assessments could be misleading