POSSIBILITY OF THE HE-COOLED SIC-COMPOSITE DIVERTOR

X.R. Wang[1], S. Malang[2], M. S. Tillack[1]

[1]University of California, San Diego, CA
[2]Fusion Nuclear Technology Consulting, Germany

ARIES-Pathways Project Meeting
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OUTLINE

- **Review of the ARIES SiC-composite divertor designs**
  - ✓ Helium-cooled small SiC-composite tube divertor for ARIES-I (1991)
  - ✓ LiPb-cooled SiC-composite plate divertor for ARIES-AT (2000)

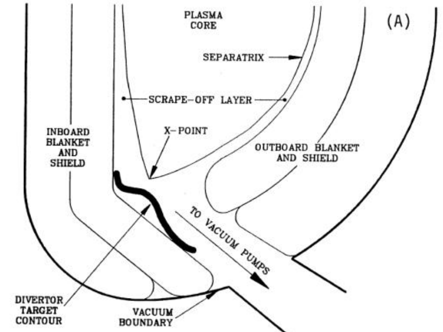
- **Update on the SiC composite properties and design window since ARIES-AT**

- **Possibility of using SiC composite as divertor structural material with an impinging-jet-cooling scheme**
  - ✓ an ARIES-finger with modifications (semi-circular thimble)
  - ✓ an original ARIES-finger (W thimble/channel replaced by SiC-composite)
  - ✓ a larger SiC-composite tube with impinging cooling method

- Summary

He-Cooled SiC/SiC Divertor of ARIES-I Was Designed to Remove a HF up to 4.5 MW/m^2*

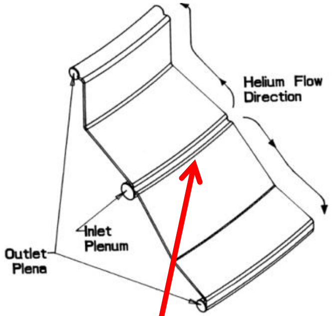
- **Attractiveness of SiC/SiC in fusion application:**
  - ✓ elevated temperature strength,
  - ✓ chemical stability,
  - ✓ low activation / low decay heat
  - ✓ low thermal expansion
- **Issues**
  - ✓ swelling under irradiation,
  - ✓ fabrication and joints,
  - ✓ stress limit



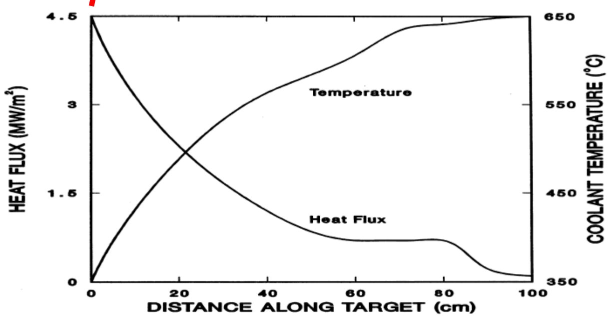
Schematic of the ARIES-I layout

Material Properties Used in Thermostructural Analyses of the ARIES-I Divertor[a]

	SiC Composite	Tungsten
Density (kg/m^3)	3,000	19,000
Young's modulus (GPa)		
E_x	364	370
E_y	360	370
Poisson's ratio, ν	0.16	0.20
Thermal-expansion coefficient (10^{-6}/K)		
α_x	4.4	4.5
α_y	4.3	4.5
Thermal conductivity (W/K-m)		
k_x	15	113
k_y	12	113
Allowable stress (MPa)	190	200
Maximum temperature (°C)	1,100	1,200[b]

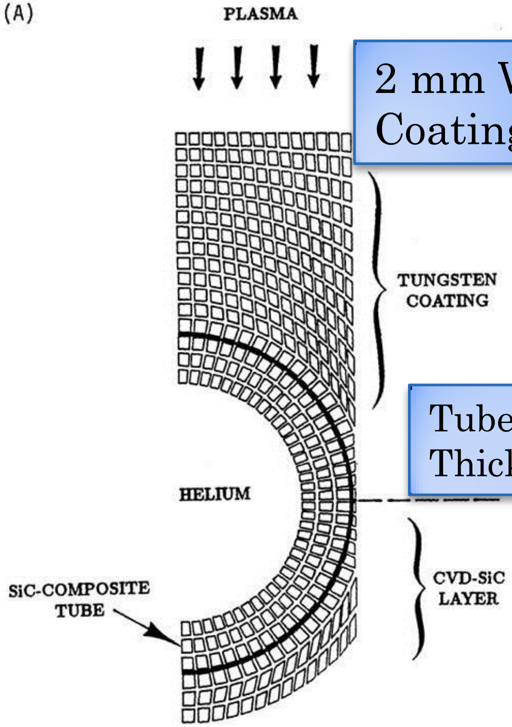


ARIES-Divertor target Configuration



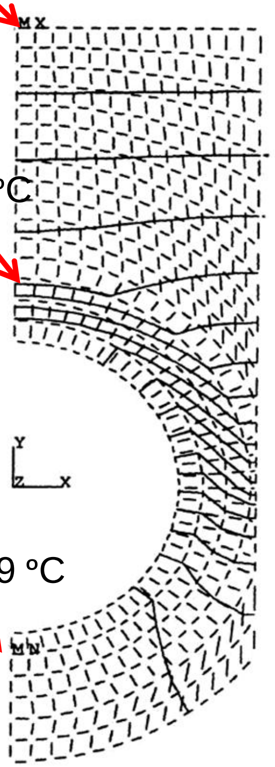
**F. Najmabadi et al., "The ARIES-I Tokamak Reactor Study", Final Report, 1991.*

PUMPING POWER WAS LARGER THAN 10% IN ORDER TO MEET TEMPERATURE AND STRESS LIMITS



2 mm W Coating

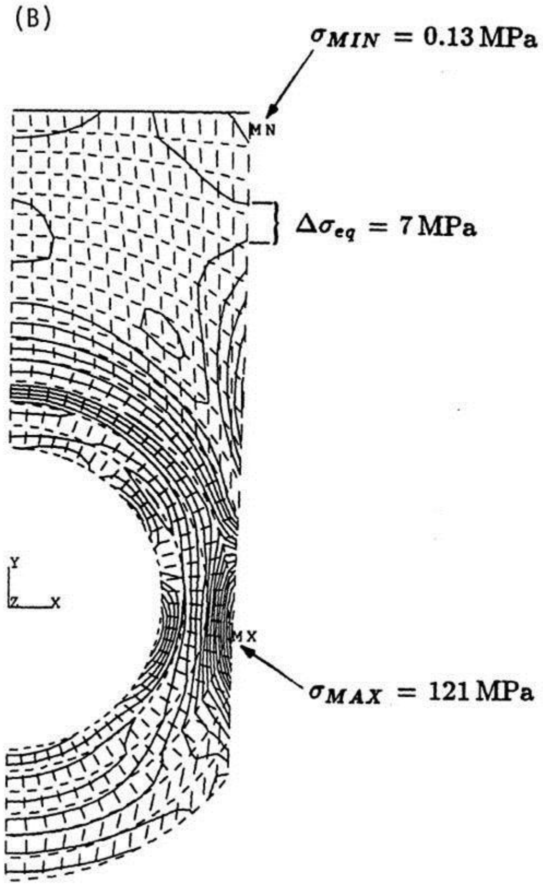
Tube d=2.5 mm
Thickness t=0.5 mm



T_{max}=776 °C

$T_{interface}$=700 °C

T_{min}=399 °C



T_{inlet} =350 °C, T_{exit} =650 °C
P=10 MPa, v=150 m/s
q''_{peak}=4.5 MW/m^2, q_v=23 MW/m^3
HTC=12.9 kW/m^2-K
P_p/P_{th} =12%

σ_p=86 MPa

***CVD**: chemical vapor deposition*
***CVI**: chemical vapor infiltration*

Ts<1000 °C

σ_{p+th} < 190 MPa

STRESS LIMIT OF THE SIC/SIC USED IN ARIES-I &AT IS VERY CONSERVATIVE ASSUMPTION

Properties were Used in ARIES-AT*

Density	**3.2 g/cm³**
Young's modulus	200-300 GPa
Poisson's Ratio	0.16~0.18
Thermal expansion coefficient	4.0×10^{-6} /K
Thermal conductivity, in-plane	20 W/K-m
Thermal conductivity, through thickness	20 W/K-m
Minimum operating Temp (based on degradation of k under irradiation)	600 °C
Maximum operating Temp (based on void swelling)	1000 °C
Maximum allowable combined stresses	**190 MPa**

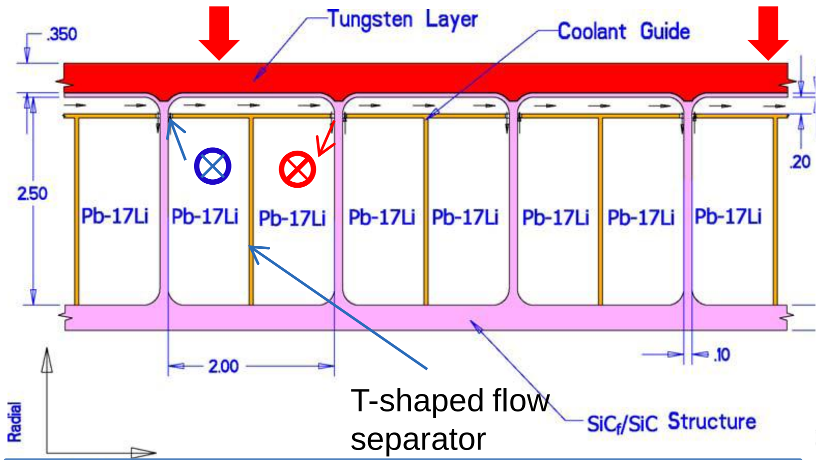
*Summary, *SiC/SiC Town Meeting , ORNL, January 18-19, 2000.*
http://aries.ucsd.edu/Lib/PROPS/sic.html

A.R. Raffray et al., Fusion Engineering and Design 80 (2006)

Stress limits for using in FEM analysis:

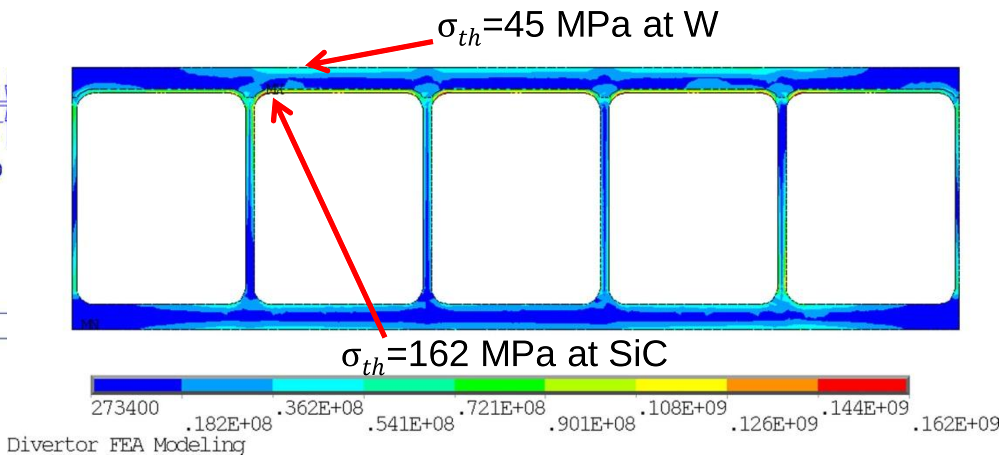
- Conventional stress limits (3 S_m) can not be directly applied to ceramics.
- The SiC/SiC stress limits should take into account for the non-linear elastic behavior associated with **matrix micro-cracking** and **matrix-fiber debonding**.
- Based on the summary of the ARIES Town Meeting, it was recommended to limit the total combined stress to ~190 MPa. **It might be too conservative.**

ARIES-AT LIPB-COOLED SIC-COMPOSITE DIVERTOR COULD ACCOMMODATE A HF UP TO 5 MW/M^2



T-shaped flow separator

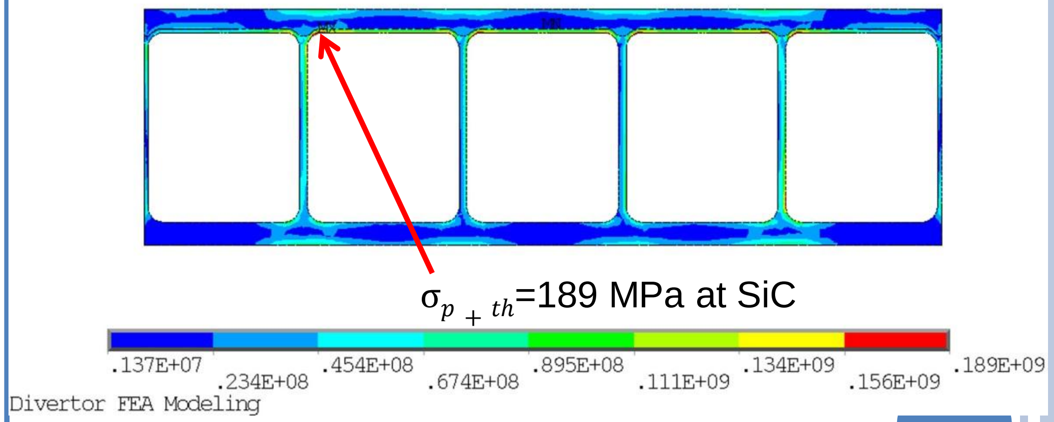
SiC$_f$/SiC Structure



σ_{th}=45 MPa at W

σ_{th}=162 MPa at SiC

Distribution of thermal stress



σ_{p+th}=189 MPa at SiC

Distribution of combined stresses

Thickness of SiC front plate=0.5 mm
Thickness of W armor=3.5 mm
Cross-section of cooling channel=25x20 mm
Operating pressure=1.8 MPa
Peak heat flux=5 MW/m^2
Average heat flux=1.75 MW/m^2
Inlet /outlet temperature=654/764 °C
Max. W temperature=~1150 °C
Max. SiC temperature=~950 °C
Pressure drop=~0.7 MPa
Thermal stress at SiC=~162 MPa
Primary stress at SiC=~25 MPa
Combined stresses= 189 MPa

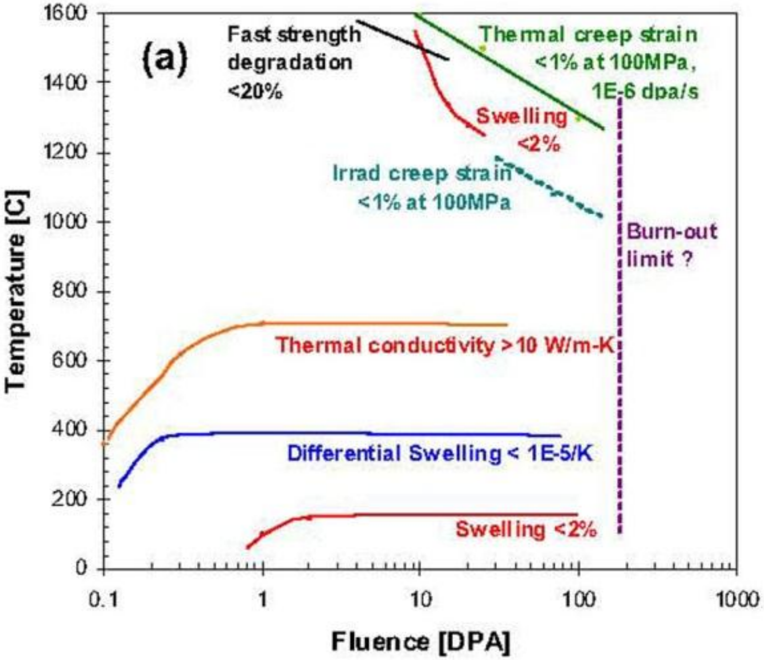
**A.R. Raffray et al., Fusion Engineering and Design 80 (2006)*

UPDATE ON OPERATING TEMPERATURE WINDOW FOR SIC COMPOSITES SINCE ARIES-AT*

- Operating temperature of he-cooled SiC-composites mainly limited by:
  - ✓ High temperature swelling <2%,
  - ✓ Irradiation or thermal creep strain <1% at a uniaxial stress of 100 MPa,
  - ✓ Thermal conductivity through-thickness > 10 W/m-K

- **Yutai Katoh and Lance Snead recommended:**
  - ✓ Lower operating temperature > 700 ^{o}C (ARIES-AT, ~600 ^{o}C)
  - ✓ Upper operating temperature <~1200 ^{o}C (ARIES-AT, 1000 ^{o}C)

- **There is no update on the stress limit in literatures. The same allowable stress (190 MPa) as the ARIES-I and ARIES-AT will be assumed in FEM analysis.**

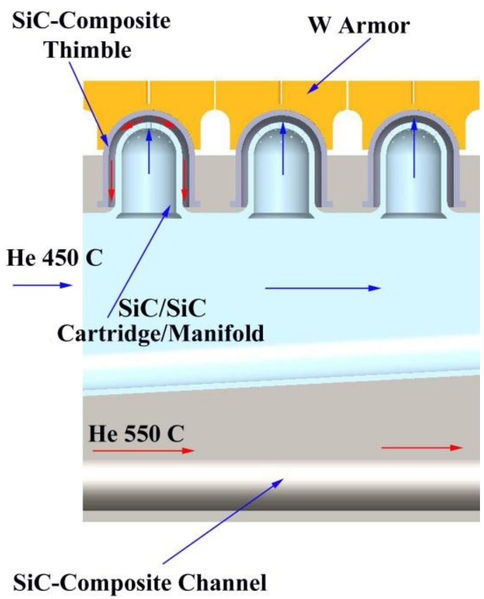


-Preliminary design windows for 3D balanced orthogonal CVI SiC/SiC for thermal structural application

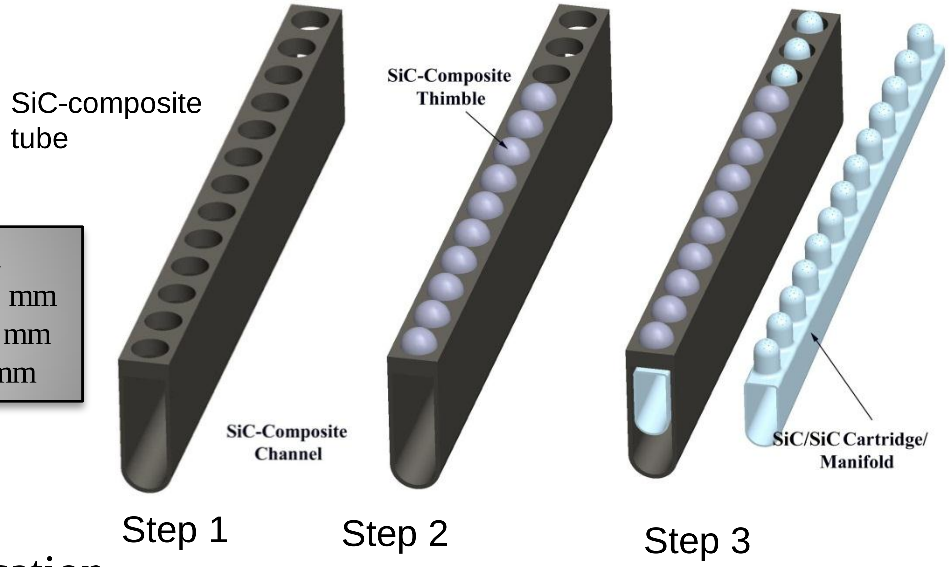
-Dotted lines indicate lack of confidence and/or experimental substantiation.

*_**Yutai Katoh and Lance Snead**, Fusion Science and Technology, 56 (2009)._

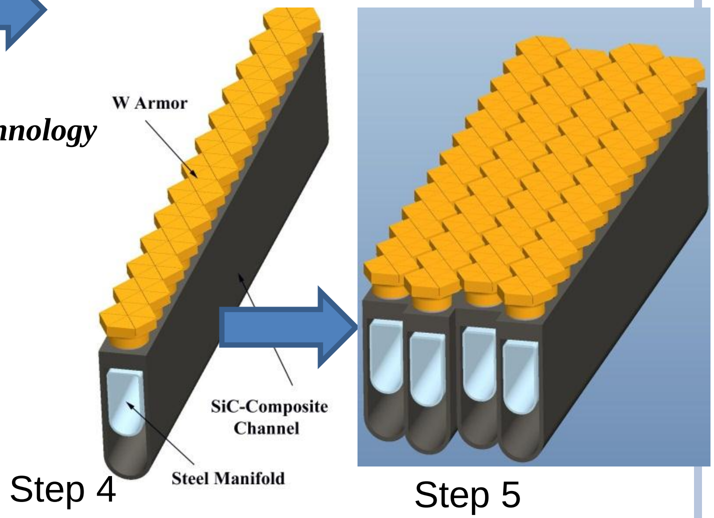
A SiC-Composite Finger Is Designed to Accommodate A HF up to ~5 MW/m^2



Width of Armor=26 mm
Diameter of thimble=20 mm
Thickness of thimble=1 mm
Height of the plate=70 mm



Fabrication Methods:



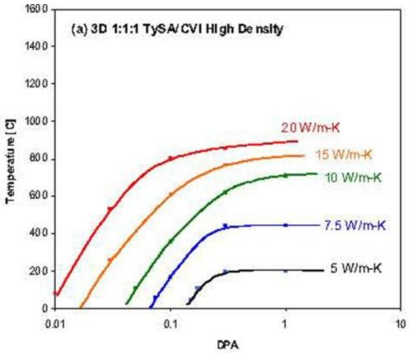
Joints techniques: *H. Kishimoto, A. Kohyama, ***J. of Nuclear Materials***
B. Riccardi et al, ***Int. J. Materials and Product Technology*

- W/SiC composite joints using **hot-pressing** technique*
  - ✓ *Holding temperature of 1500 to 1800 ^{o}C*
  - ✓ *Joint shear strength as high as ~90 MPa*
- SiC/SiC composite joints using **brazing** technique**
  - ✓ *Si-16Ti (melting temperature ~1330 ^{o}C)*
  - ✓ *Si-18Cr (melting temperature ~1305 ^{o}C)*

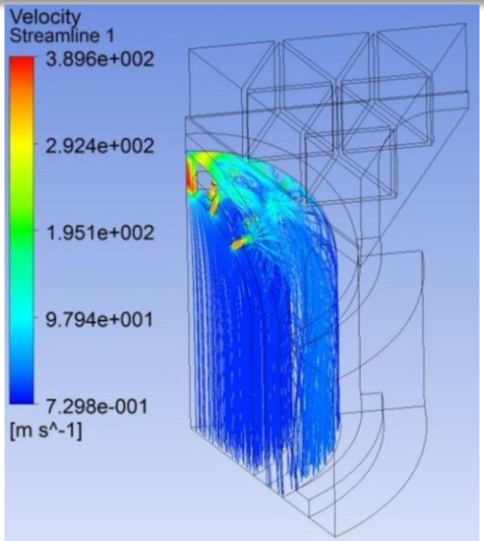
or using silicone resin to joint them together at 1200 ^{o}C.

PUMPING POWER AND STRESS LIMITS ARE NOT SATISFIED FOR A HF OF 5 MW/M^2

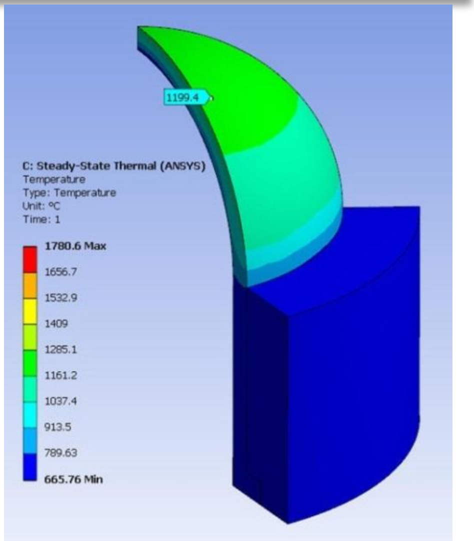
- Temperature-dependent properties of the W are used in the analysis
- Thermal conductivity of the SiC/SiC is dependent on both irradiation temperature and fluence. In analysis, the K(T) is shown in the figure.*



***Yutai Katoh and Lance Snead**, Fusion Sci. and Tech., 56 (2009).*



Velocity



Temperature

- **Operating temperature for SiC/SiC: 700 < T_{SiC} < 1200 ^{o}C**
- **Loads and cooling conditions**

  q"=5 MW/m^2 (uniform), q_v'''=17.5 MW/m^3

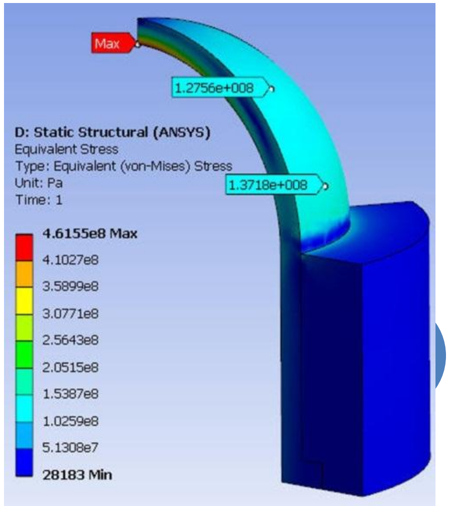
  P=10 MPa, T_{in}/T_{exit}=600/700 ^{o}C **(450/550 ^{o}C for T_{allow}= 1000 ^{o}C)**
- **<u>CFX and FEM results(Not Optimized)</u>**

  V_{jet}=~390 m/s, HTC(Local)=9.78x10^4 W/m^2-K

  P_p=~15% $P_{removed}$ **(P_p~12.5% for T_{allow}= 1000 ^{o}C)**

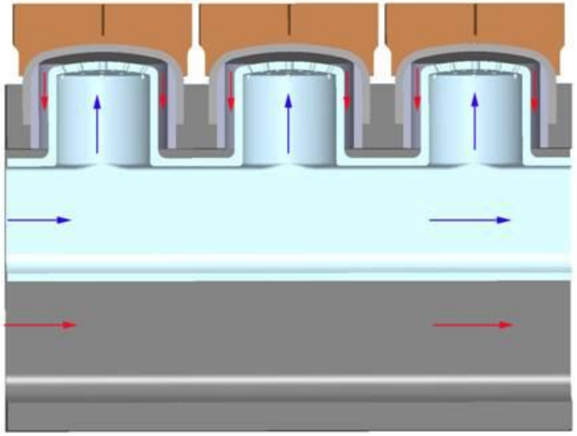
  Max. T_{sic}=1199 ^{o}C(< T_{allow}= 1200 ^{o}C) **(T_{SiC}=999 ^{o}C for T_{allow}= 1000 ^{o}C)**

  Max. σ_{p+th}=~462 MPa (> σ_{allow}=~190 MPa) **(σ_{p+th}=~475 MPa for T_{allow}= 1000 ^{o}C)**
- **Pumping power and stress limits are not satisfied.**

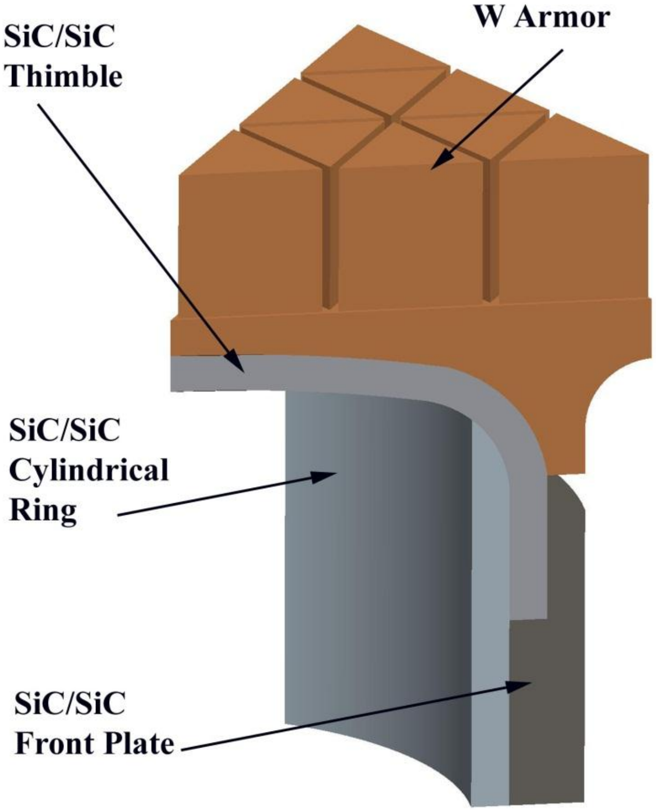


Stress

ORIGINAL ARIES-FINGER CONFIGURATION IS APPLIED IN THE SIC/SIC DIVERTOR

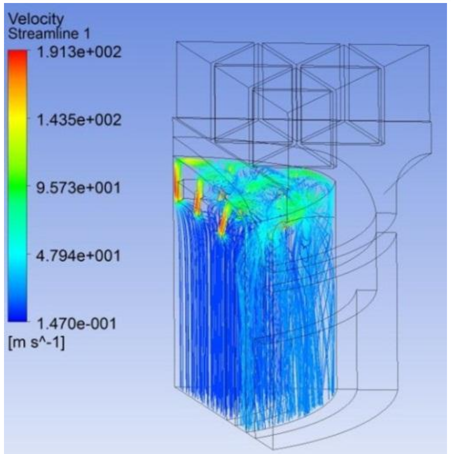


SiC-Composite Finger

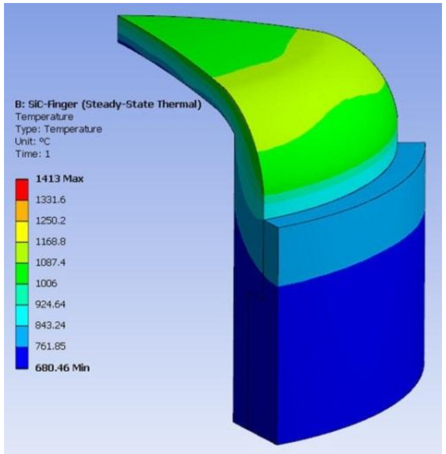


- Using the original ARIES finger configuration
  - ✓ VM-W thimble, cylindrical ring and W channel replaced by SiC/SiC
  - ✓ ODS steel cartridge replaced by SiC/SiC cartridge
  - ✓ 1 mm thick SiC-composite thimble
  - ✓ 1 mm thick SiC-composite cylindrical ring
  - ✓ 2 mm thick SiC-composite front plate
  - ✓ 5 mm W armor
- W armor and SiC composite jointed together by **hot-pressing method**
- SiC-composite thimble, cylindrical ring and front plate jointed together by **brazing method**

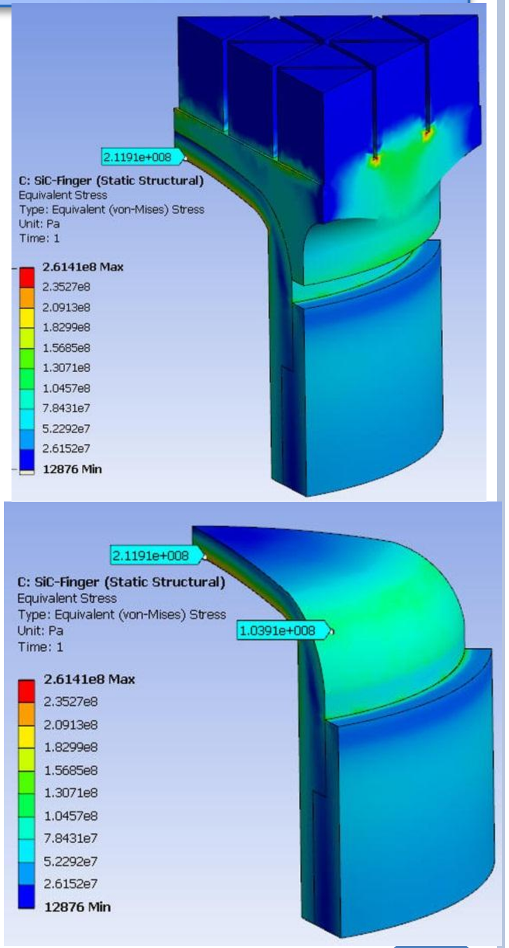
TEMPERATURE AND PUMPING POWER LIMITS ARE SATISFIED



Velocity



Temperature



Stress

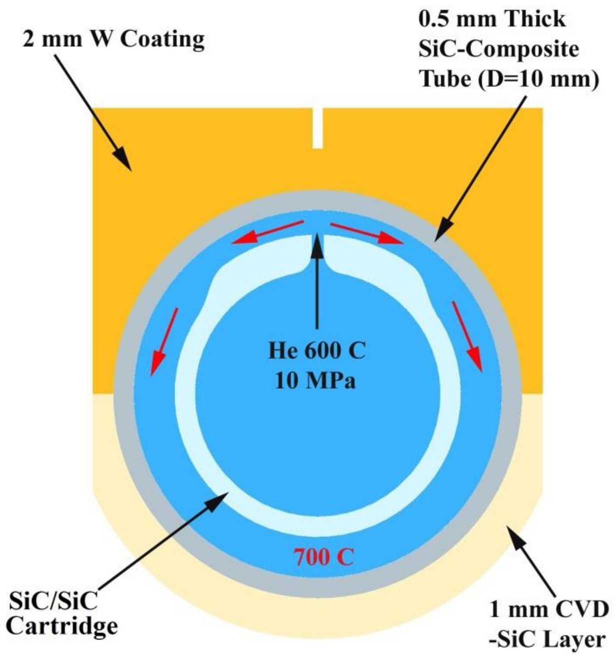
- **Operating temperature for SiC/SiC: $700 < T_{SiC} < 1200$ °C**
- **Loads and cooling conditions**

  $q'' = 5$ MW/m^2(uniform), $q_v''' = 17.5$ MW/m^3

  P=10 MPa, T_{in}/T_{exit}=600/700 °C **(450/550 °C for T_{allow}=1000 °C)**
- **<u>CFX and FEM results</u>**
  - ✓ V_{jet}=~191 m/s, HTC(Local)=6.52x10^4 W/m^2-K
  - ✓ $P_{pumping}$=~6.5% of the $P_{removed\ thermal}$ (<10%) **(P_p~5.7% for T_{allow}=1000 °C)**
  - ✓ Max. T_{sic}=1120 °C(< T_{allow}=~1200 °C) **(T_{SiC}=980 °C for T_{allow}= 1000 °C)**
  - ✓ Max. σ_{p+th}=~212 MPa (> σ_{allow}=~190 MPa) **(σ_{p+th}=~223 MPa for T_{allow}= 1000 °C)**
  - ✓ Max. shear stress at the W/SiC interface σ_{shear} =~58 MPa

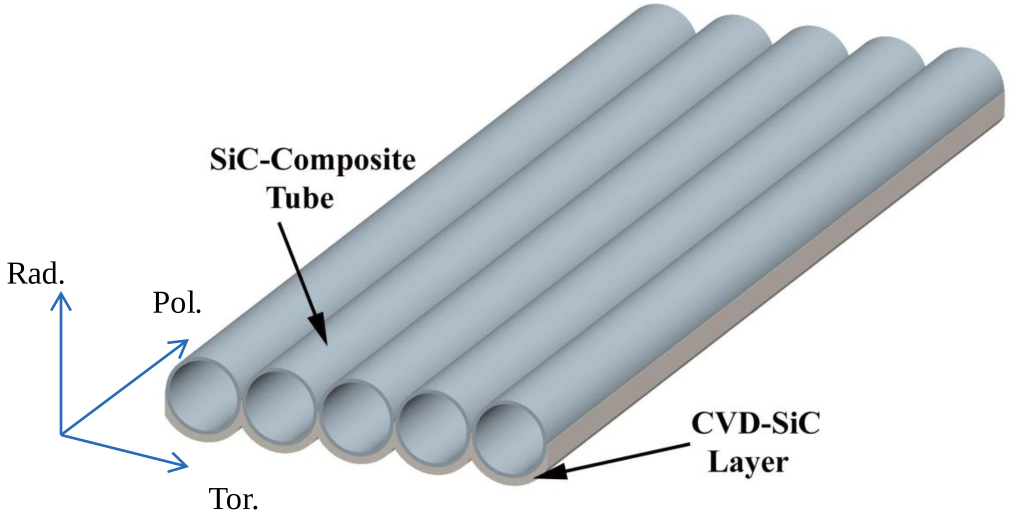
- **The SiC thimble (1 mm thick) could be thinned to ~0.5-08 mm to meet the stress limit. However, there are too many brazing joints required.**

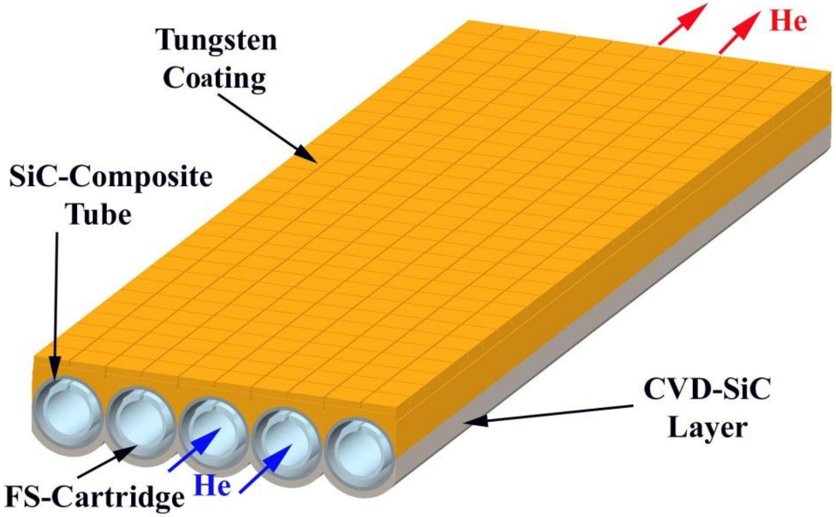
SIC/SIC TUBE TARGET-PLATE COOLED BY JET-IMPINGING SCHEME IS PROPOSED



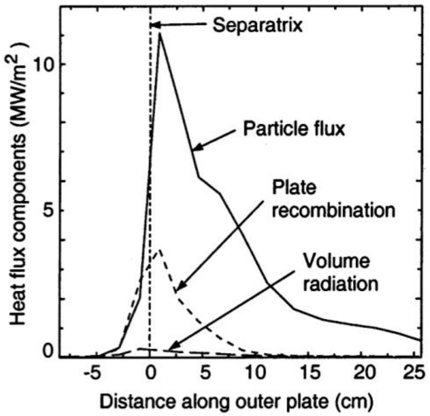
Cross-section of SiC/SiC tube with impinging cooling scheme

- 10 mm diameter tube (~4 times larger than ARIES-I tube)
- ½ mm thick tube
- 1 mm SVD-SiC layer
- SiC/SiC cartridge or ODS-steel cartridge
- Impinging-jet cooling scheme

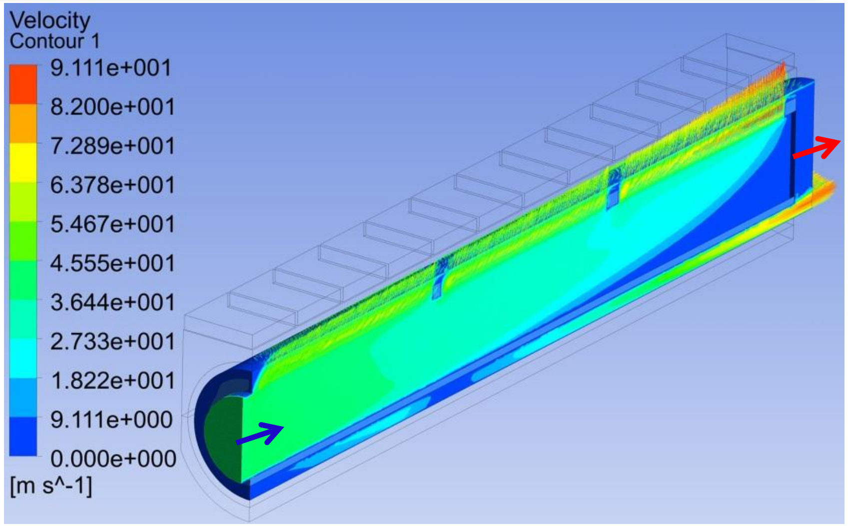




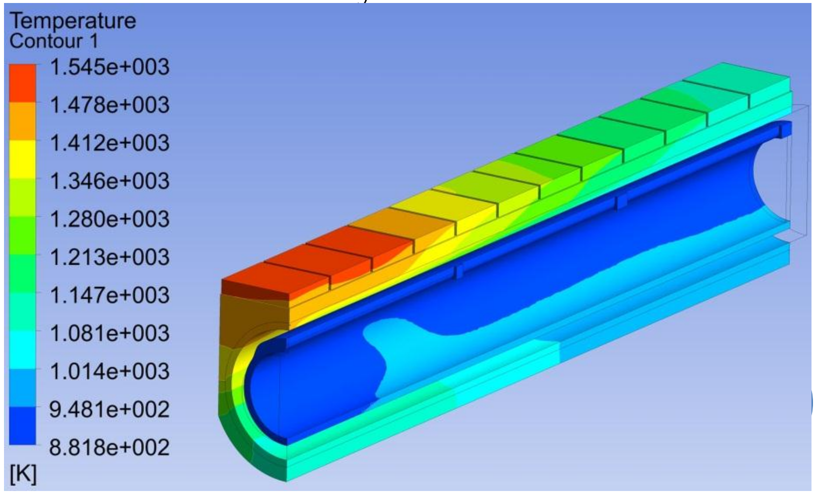
CFX Results Indicate The Temperature and Pumping Power Limits Are Satisfied



- ARIES-AT like heat-flux profile with a max. value of ~5 MW/m^2 and an average of ~ 1.75 MW/m^2 is assumed in the analysis
- q_v= ~17.5 MW/m^3
- T_{inlet}/T_{outlet}= 600/700 ^{o}C based on SiC-composite operating temperature of 700 <T_{SiC}< 1200 ^{o}C
- **<u>CFX results (some optimizations):</u>**
    - ✓ V_{jet}=~91 m/s, $T_{max.\ SiC}$=~1180 ^{o}C, $T_{min.\ SiC}$=~710 ^{o}C, Tmax. W= 1272 ^{o}C
    - ✓ HCT_{local}=~2.623x10^4 W/m^2-K
    - ✓ $P_{pumping}/P_{removed\ thermal}$=~3.5%
- **There is a large room for the pumping power to push to a higher heat flux. The cartridge can be tapered along the poloidal direction to reduce the jet velocity and rise temperature at lower heat flux region.**

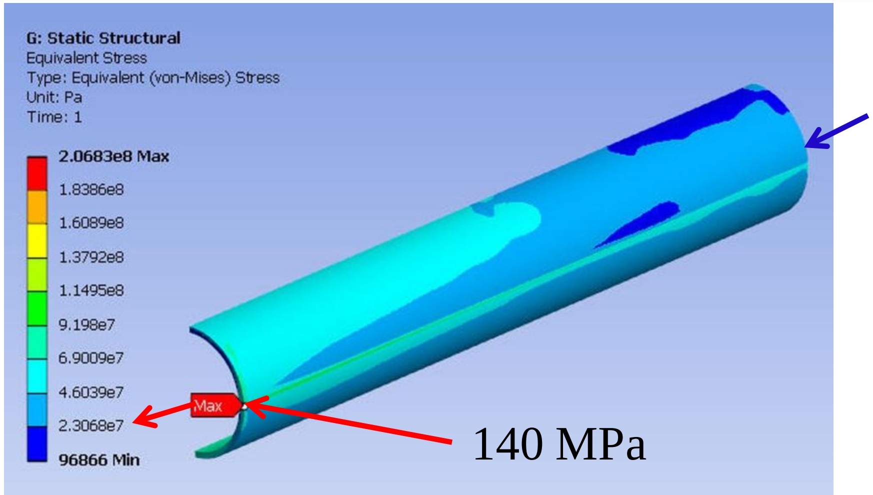


Velocity distribution



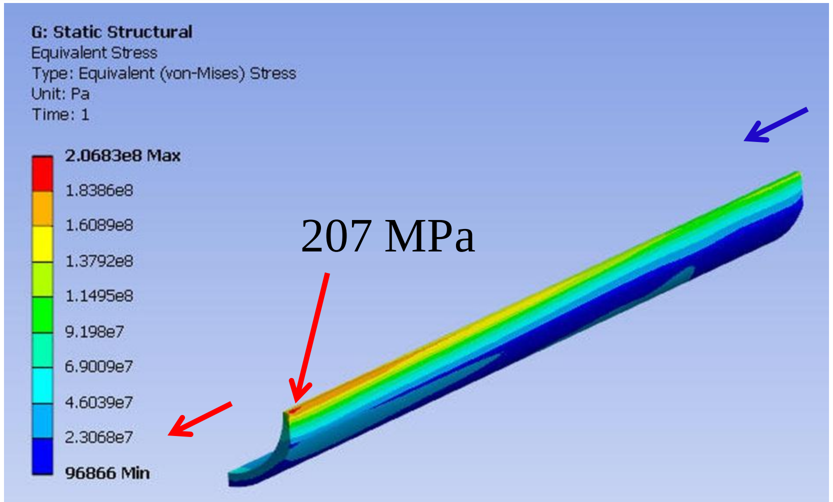
Temperature distribution

STRESS LIMIT IS ALSO SATISFIED ALTHOUGH IT IS VERY CONSERVATIVE



140 MPa

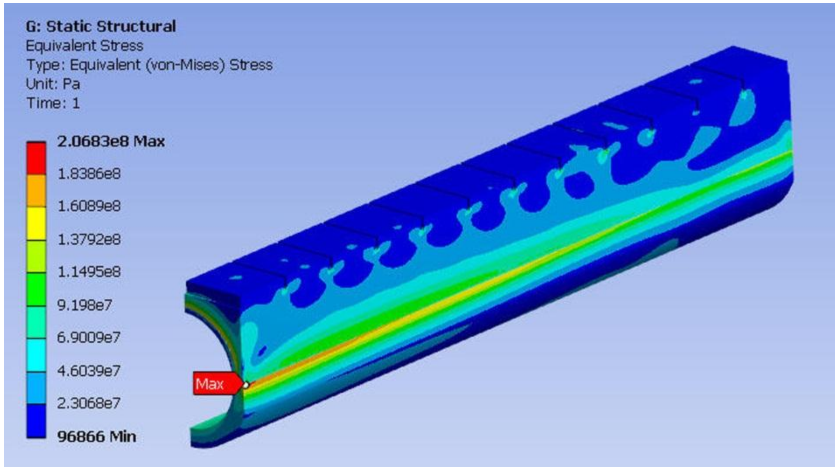
SiC composite tube



207 MPa

CVD-SiC layer

- Max. combined primary and secondary in SiC-composite tube is ~140 MPa (< σ_{allow} =~190 MPa).
- Max. Combined primary and secondary stress in CVD-SiC layer (not a major structure) is ~207 MPa at low heat flux region where the temperature is the lower (~710 ^{o}C).
- Max. shear stress at interface is ~73 MPa
- Further optimization of the cartridge to rise temperature at the lower heat flux region can reduce thermal stress.



SiC composite tube with W coating

SUMMARY AND CONCLUSIONS

- Three configurations of he-cooled SiC-composite divertor concepts have been investigated, including
    1. a modified finger
    2. an original ARIES-finger
    3. a tubular plate with impinging-jet cooling scheme

- CFX and FEM results indicate that both configuration 2 and 3 can possibly accommodate a non-uniform heat flux with a maximum value up to 5 MW/m^2 while satisfying the temperature, pumping power and stress limits.

- The tubular plate design (Configuration 3) has a better thermal performance, and it is easier to be fabricated, much less brazing required, and potentially have higher reliability.