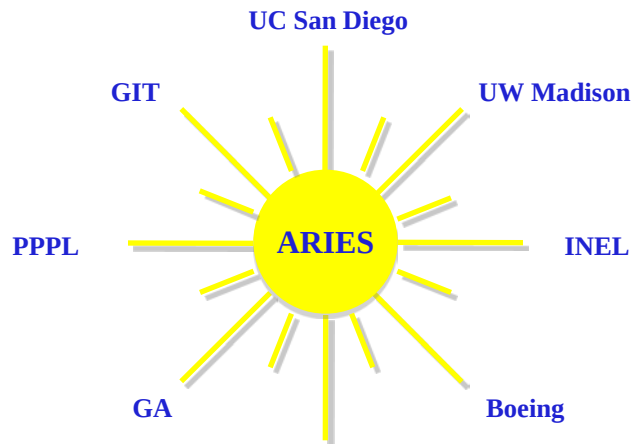


ARIES ACT1 Power Core Engineering



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and the ARIES Team

ANS 20th Topical Meeting on the
Technology of Fusion Energy

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The ACT1 power core evolved from ARIES-AT (advanced physics and advanced technology)

Similarities

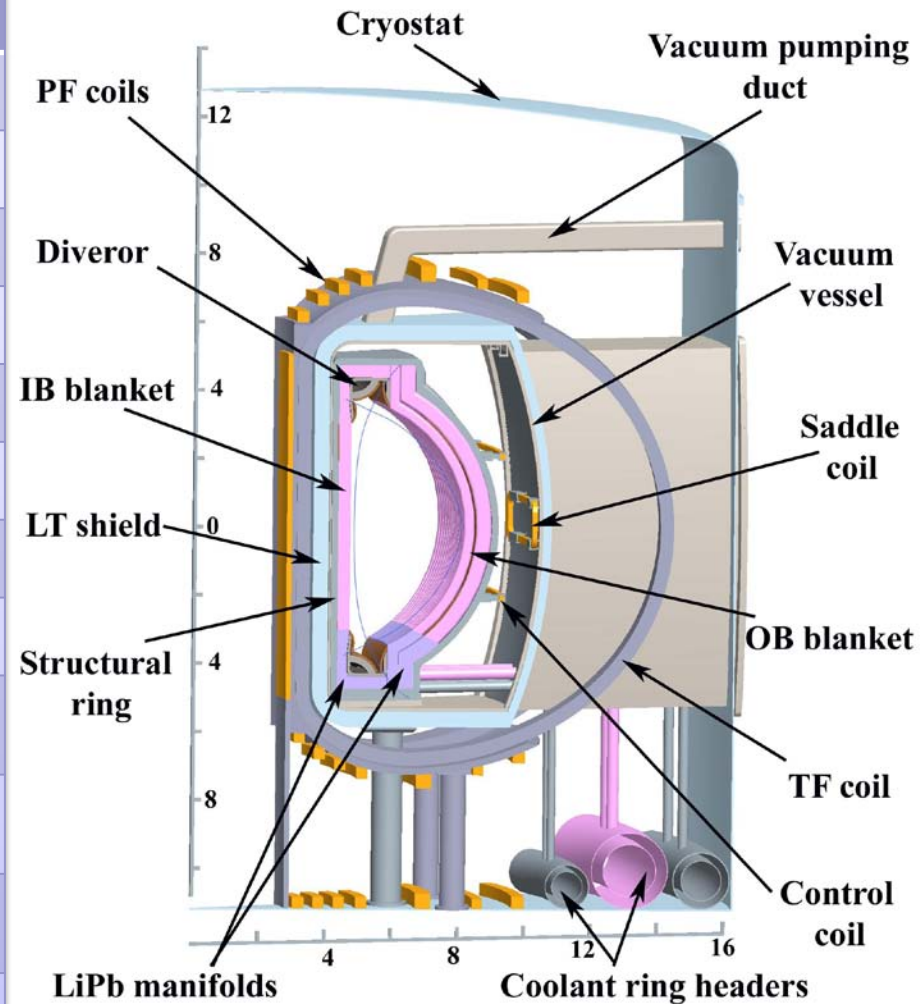
1. High performance plasma ($\beta_N=6\%$)
2. SiC composite breeding blanket with PbLi at $T_o \sim 1000$ C
3. Brayton power cycle with $\eta \sim 58\%$

Differences

1. Machine parameters, *e.g.* $R=6.25$ vs. 5.5 m, smaller SOL
2. Power core design choices
 1. He-cooled W divertor
 2. Steel structural ring
 3. Separate vacuum vessel and LT shield

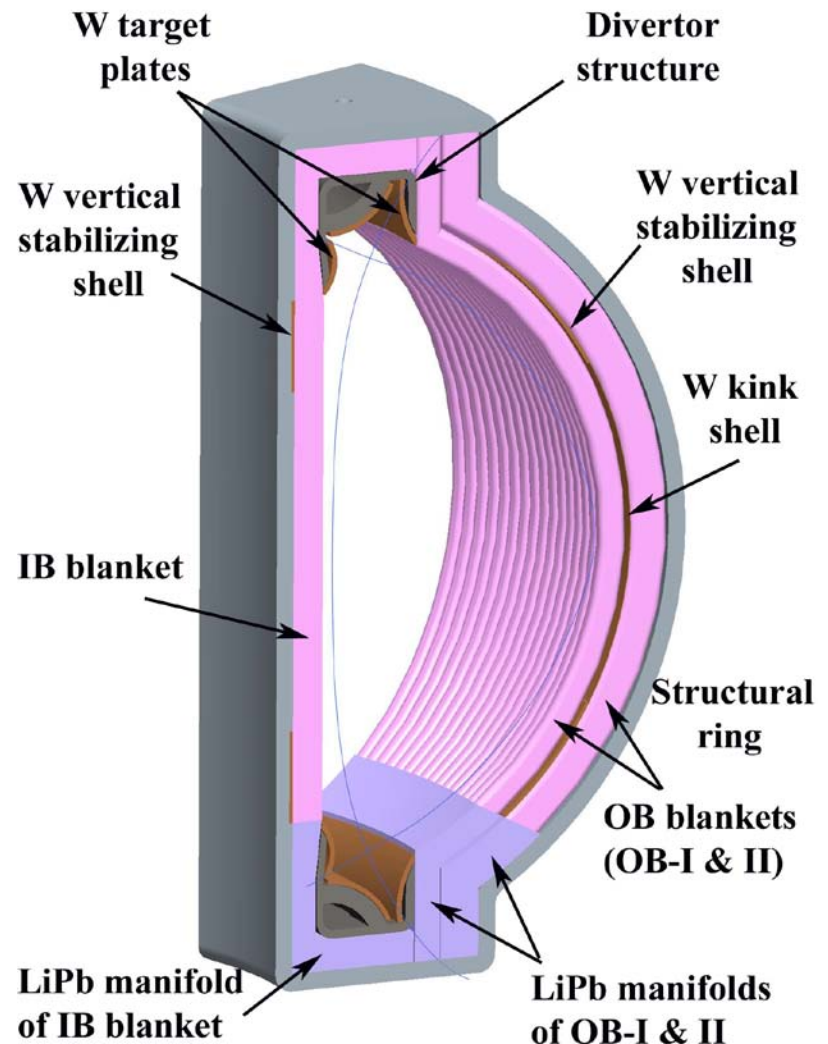
Plasma and material choices are aggressive, but the power density is modest (for a power plant)

	ACT1	ITER	
Major radius	6.25	6.21	m
Aspect ratio	4	3.1	
Toroidal field on axis	6	5.3	T
Normalized beta	5.75	1.8-2.8	%
Plasma current	10.9	15	MA
Fusion power	1813	500	MW
Thermal power	2016	651	MW
Auxiliary power	154	110	MW
Average n wall load	2.3	0.5	MW/m ²
Peak n wall load	3.6	0.7	MW/m ²
Peak FW heat flux	0.3	4.0	MW/m ²
Peak divertor heat flux	10.6	10	MW/m ²
Thermal conversion	57.0	0	%



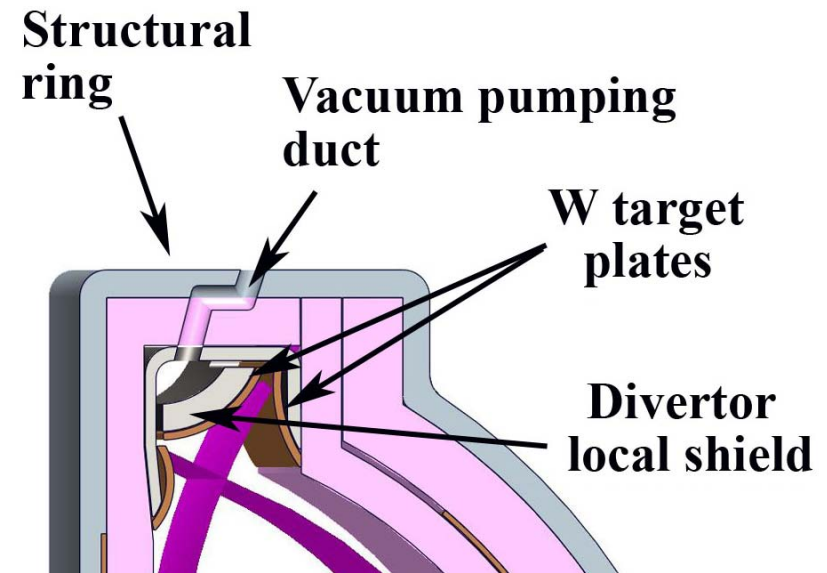
The power core replacement unit is self-supporting and maintained as a single unit

1. Internal parts are attached to a continuous steel ring.
2. All coolant access pipes are located at the bottom.
3. Sectors are moved on rails through large maintenance ports and transported in casks.
4. Immediate replacement with fresh sectors minimizes down time.
5. Main penalty is larger coils.



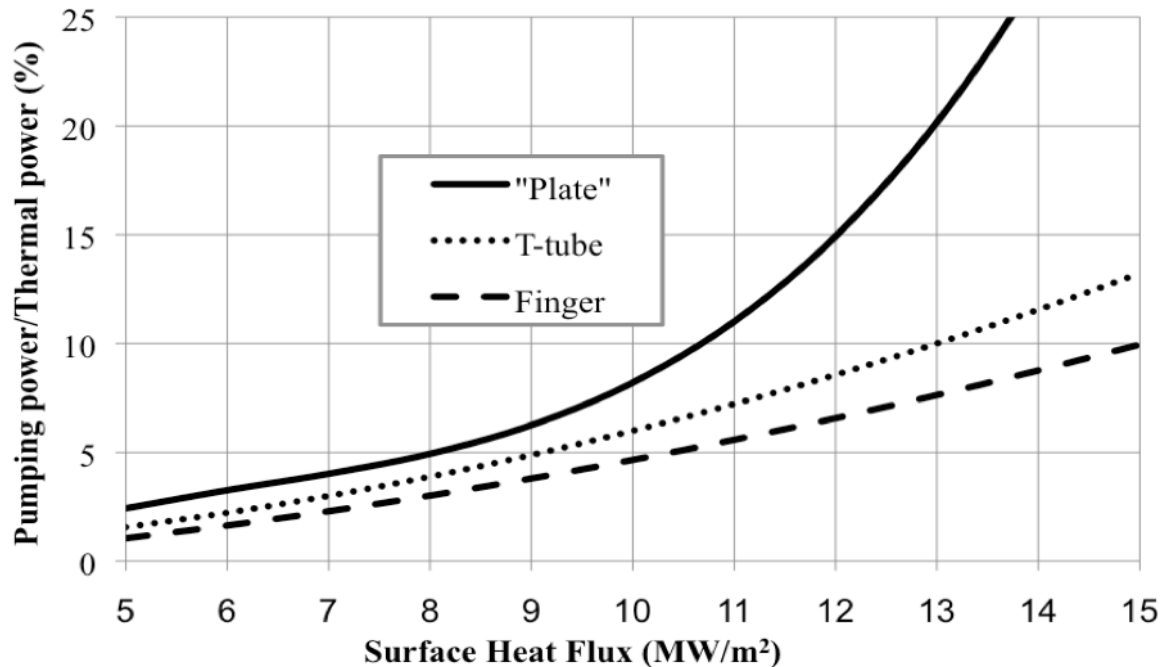
A He-cooled W-alloy divertor was chosen to allow high temperature and heat flux capability

Coolant	He	
Coolant pressure	10	MPa
Surface power	277	MW
Volumetric power	26	MW
Peak surface heat flux	10-14	MW/m ²
Inlet temperature	700	C
Outlet temperature	800	C
<i>Allowables:</i>		
W-alloy minimum	800	C
W-alloy maximum	1300	C
W armor maximum	2190	C
Steel maximum	700	C



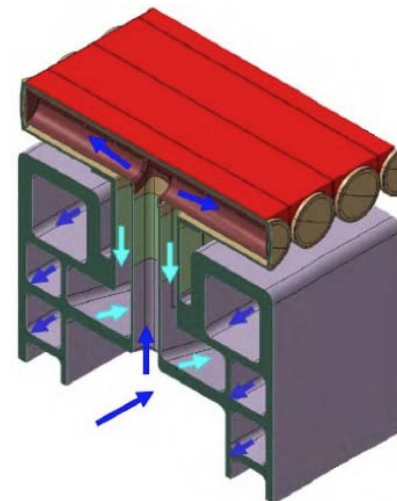
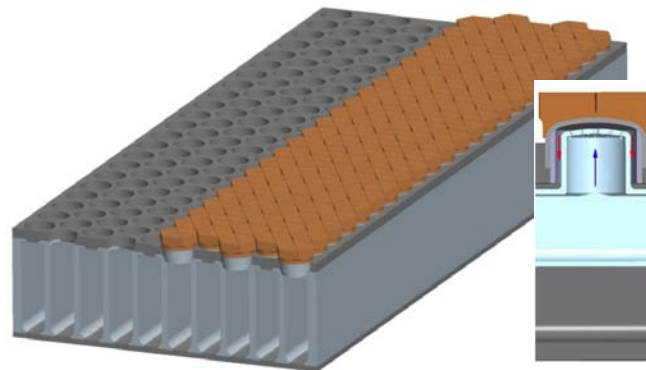
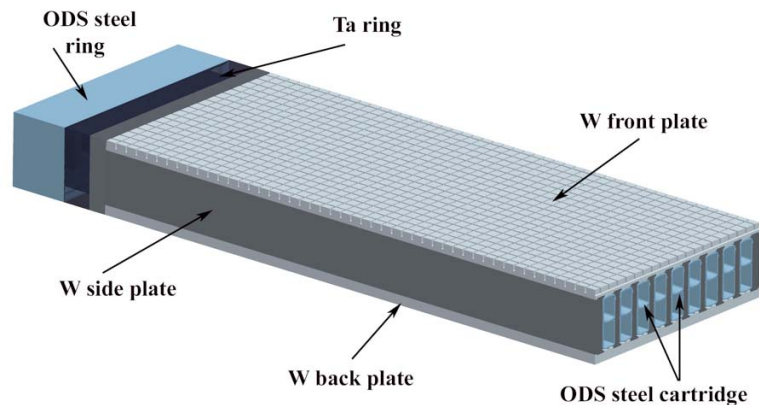
1. Jet cooling has been shown to accommodate up to 14 MW/m².
2. W-alloy development is needed.
3. Better edge physics needed to predict heat flux accurately.

The choice of divertor plate configuration is a tradeoff between performance and complexity

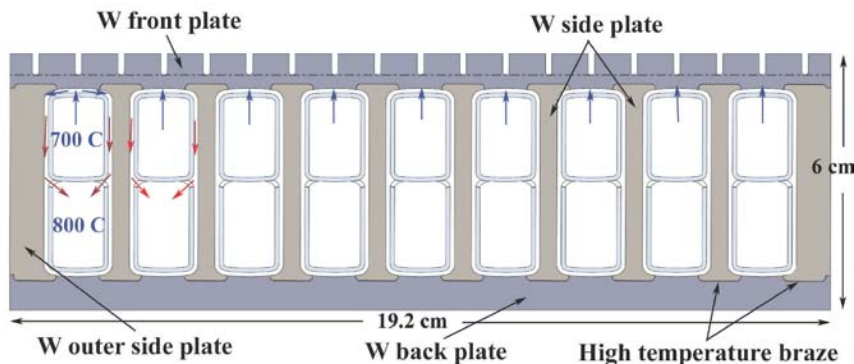
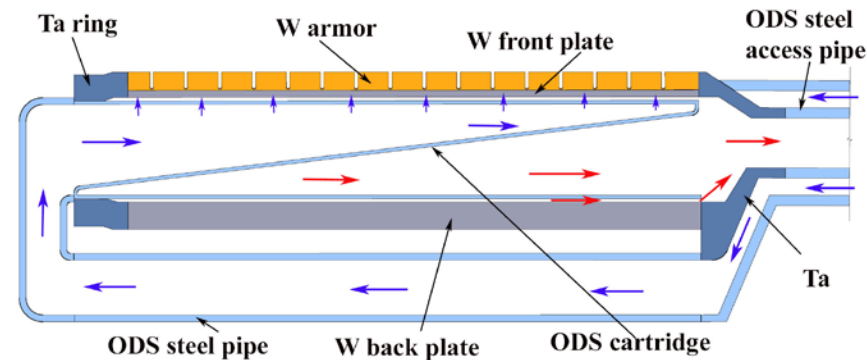
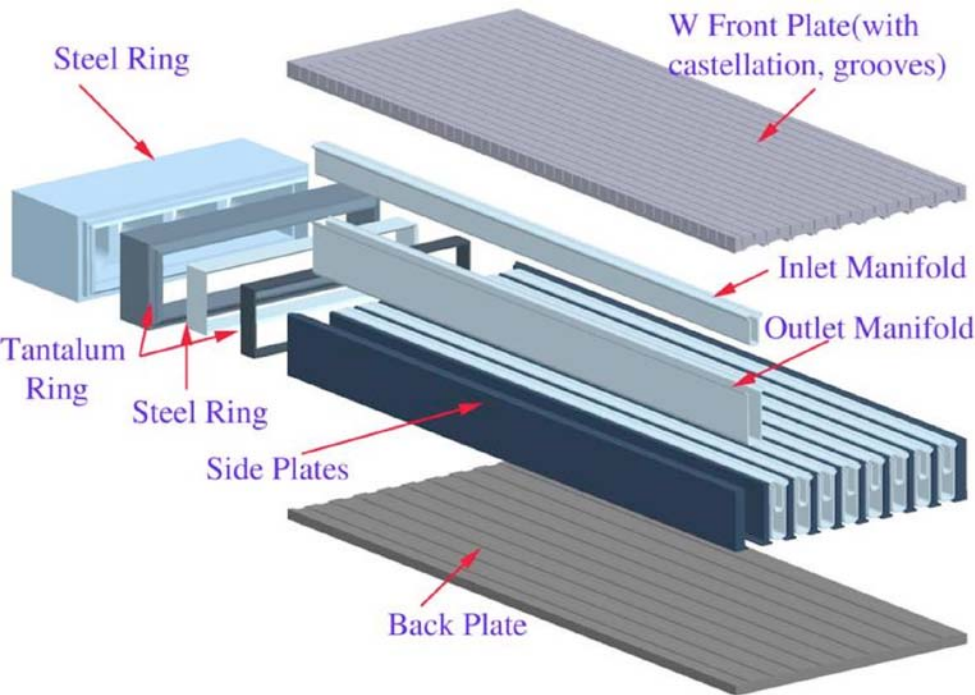


Concept	Size	#
Plate	~1 m	10^4
T-tube	~10 cm	10^5
Finger	~1.5 cm	10^6

(results for 600/700°C He inlet/outlet temperature)

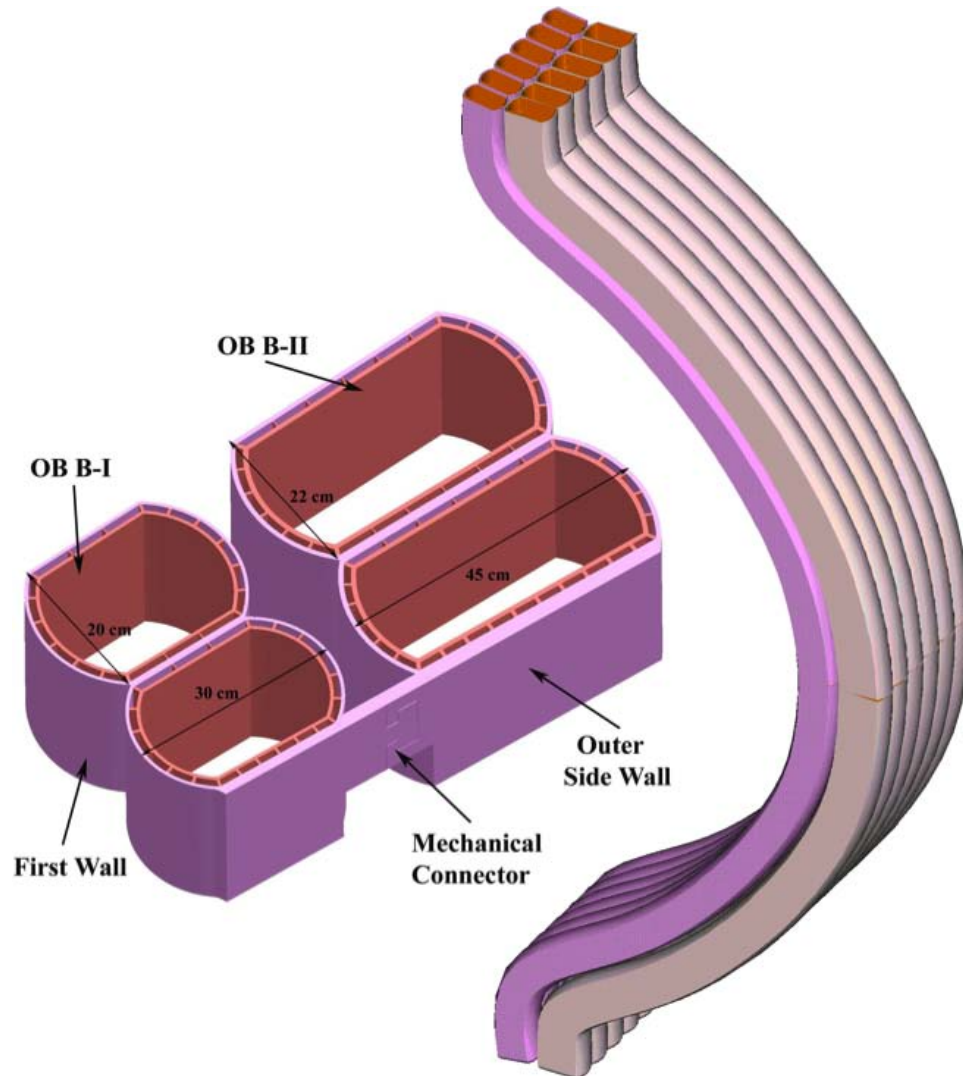


The plate divertor provides acceptable performance for peak heat flux $\sim 10 \text{ MW/m}^2$



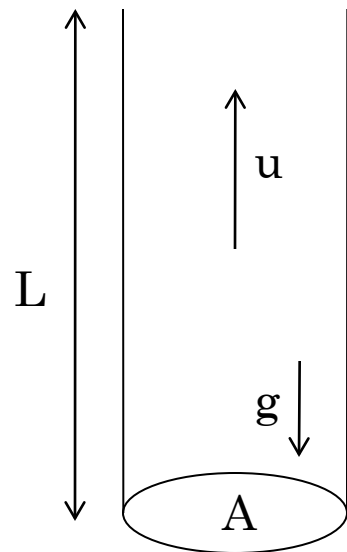
- Extensive jet flow modeling performed using both ANSYS and Fluent with various turbulence models
- Experimental verification performed at Georgia Tech (3 papers at this conference).

The breeding blanket uses annular pipes to maximize coolant outlet temperature

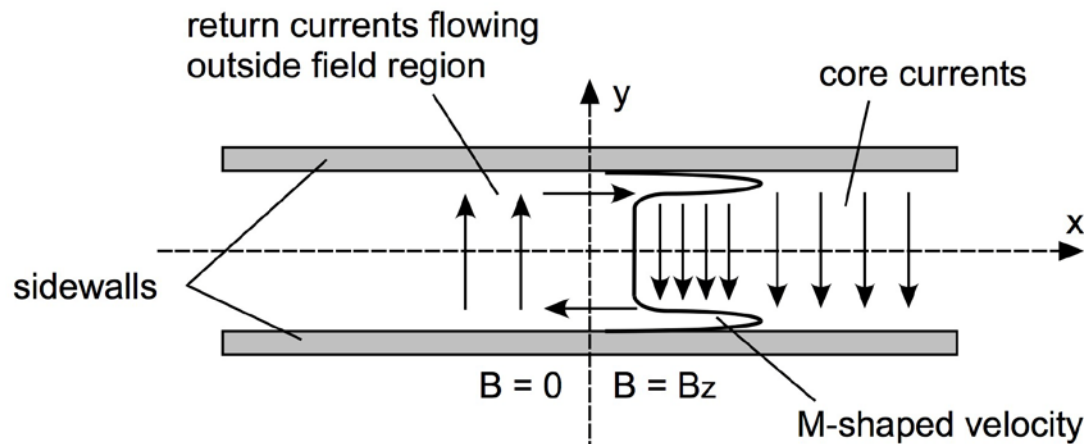


Surface power	128	MW
Volumetric power	1560	MW
Peak surface heat flux	0.3	MW/m ²
Peak wall load	3.6	MW/m ²
Coolant	PbLi	
Inlet temperature	740	C
Outlet temperature	1030	C
SiC/SiC temp limit	1000	C
Peak pressure in blanket outer duct	2.0	MPa
Peak pressure across inner duct	0.3	MPa
SiC/SiC stress allowable	190	MPa

3D MHD is a dominant force acting upon the coolant in insulated channel blankets

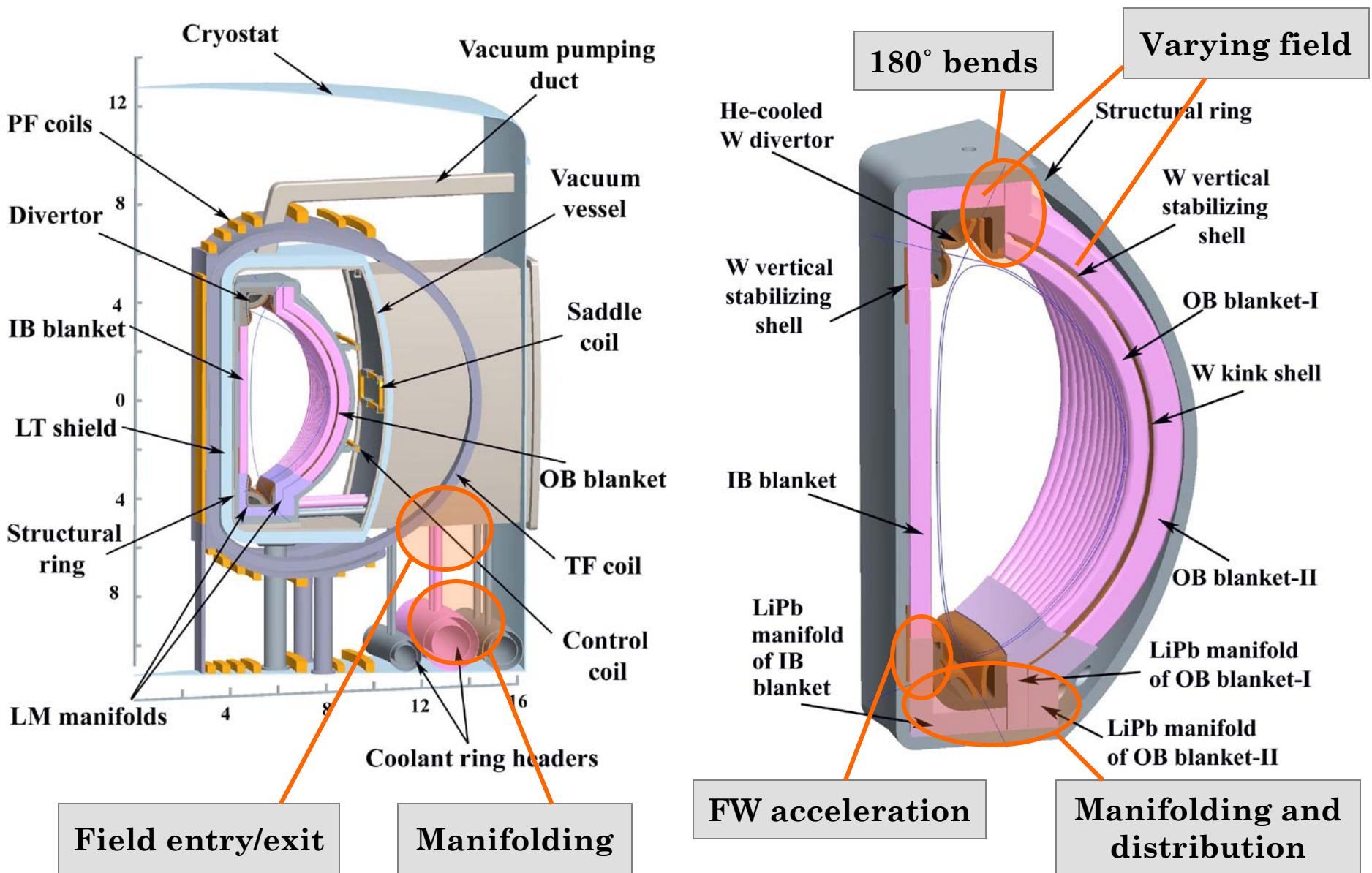


		FW	core	
inertia	ρu^2	160,000	100	<i>conservative</i>
gravity	$\rho g L$	8×10^5	8×10^5	
wall shear	$\sigma u B^2 L / Ha$	190,000	475	<i>dissipative</i>
3D MHD	$k N (\rho u^2) / 2$	3×10^6	7×10^5	



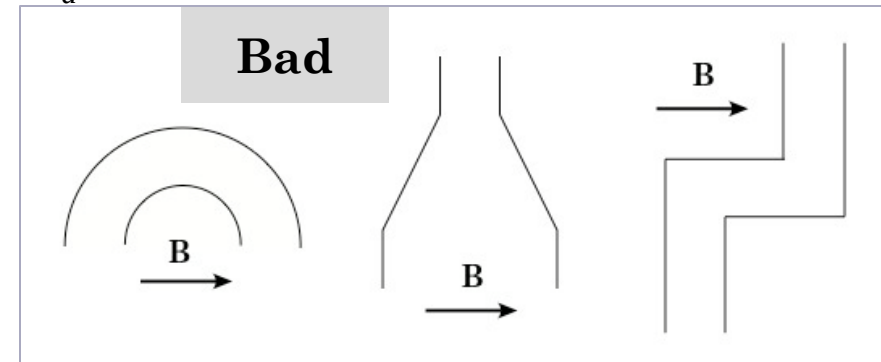
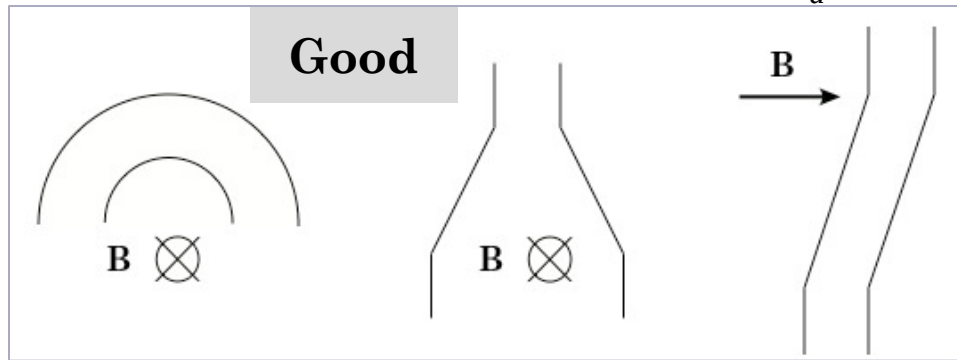
	FW	core	
ρ	10250		kg/m ³
σ	$7.6e5$		$\Omega \cdot m$
μ	$6.5e-4$		kg/(m s)
L	8		m
B	8		T
u	4	0.1	m/s
a	0.03	0.3	m
Ha	8200	82,000	$a B (\sigma / \mu)^{1/2}$
$Re_{ }$	$2e6$	$5e5$	$\rho u a / \mu$
N	35	14,000	$\sigma a B^2 / \rho u$
k		1	

Areas of concern for 3D effects



Flow paths were designed to minimize 3D MHD effects by maintaining constant voltage

$$V_{ab} = \int_a^b E \cdot dl = \int_a^b u \times B \cdot dl$$

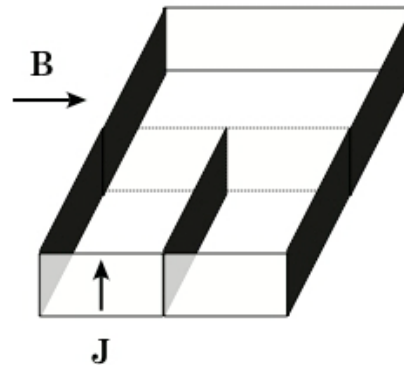
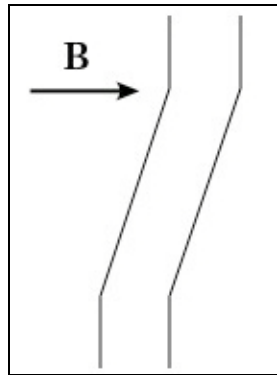
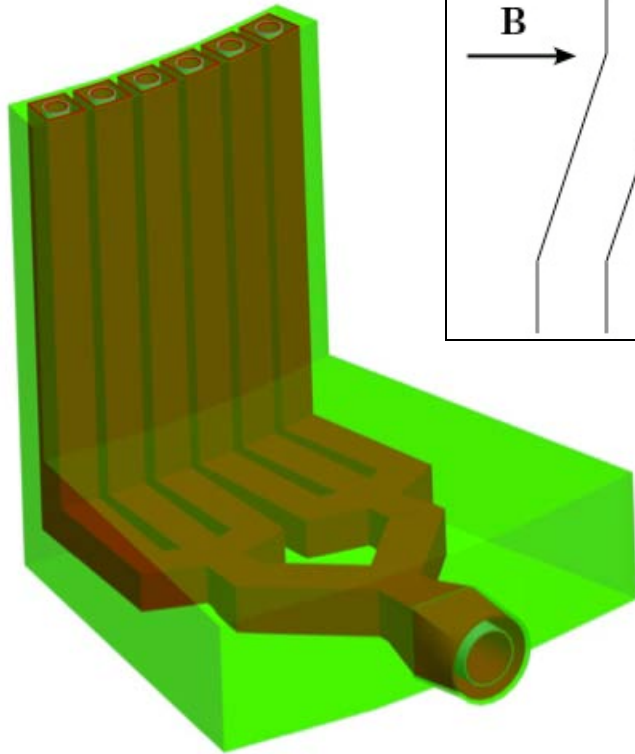


$$\Delta p_{3D} = kN(\rho u^2 / 2)$$

where k depends on wall conductance, pipe shape (e.g. circular or rectangular) and other details.

Flow condition	k
Geometrical change in a uniform magnetic field	0.25 - 2
Transverse field strength change(depending on abruptness)	0.1 – 0.2
Inlet or outlet manifold (Smolentsev <i>et al</i>)	1.5

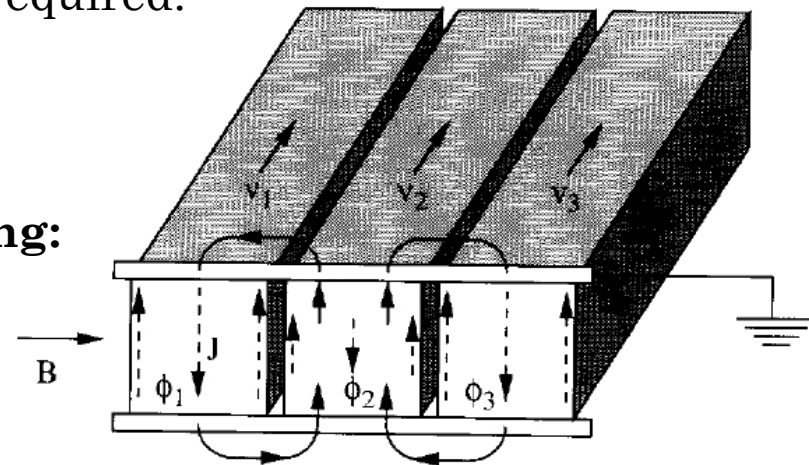
3D MHD is difficult to avoid in the manifolds



Outlet central ducts can be combined using relatively benign design elements

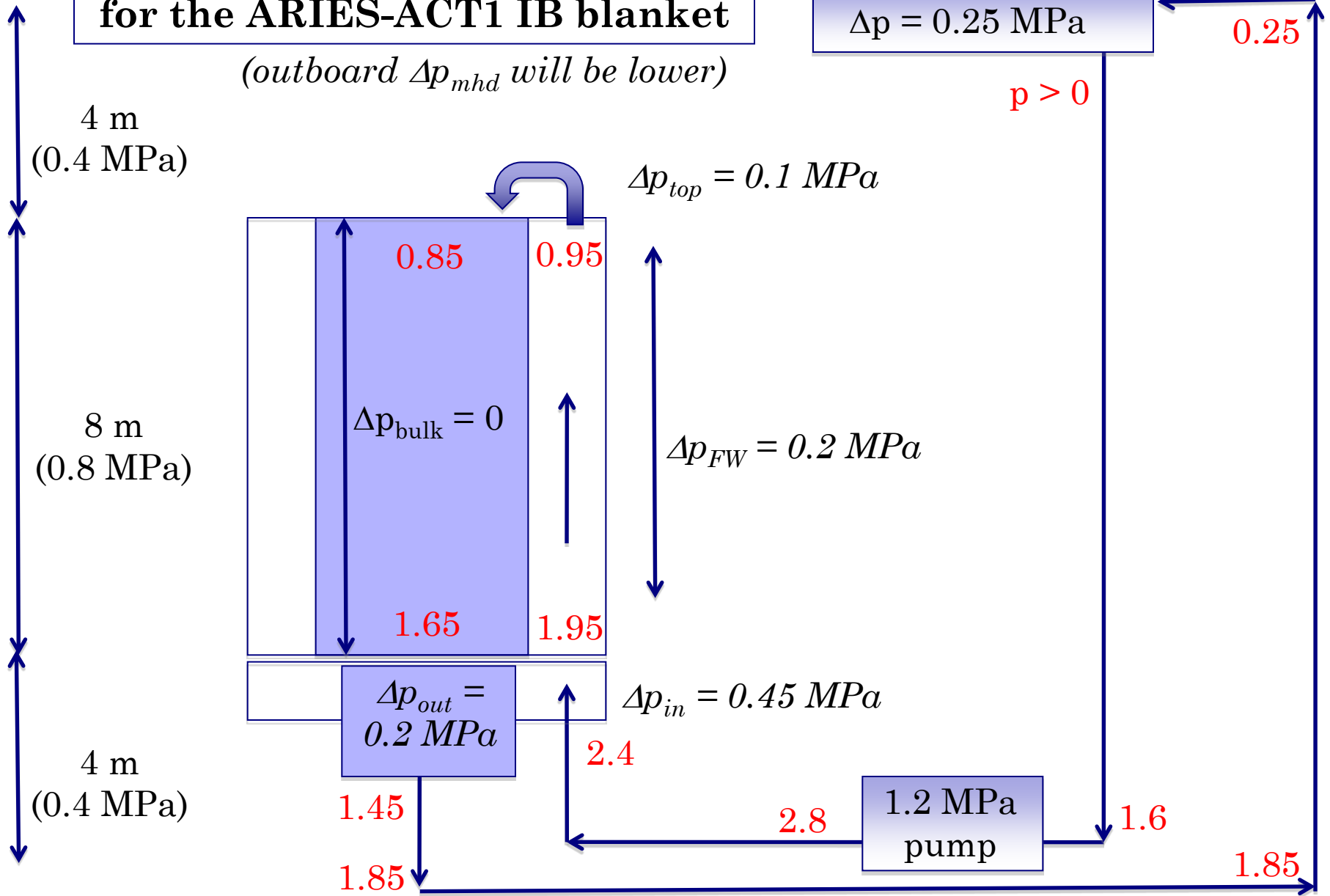
Inlet to parallel FW channels is far more complex. Some form of orifice control is probably required.

e.g. MHD flow balancing:



Pressures and pressure drops for the ARIES-ACT1 IB blanket

(outboard Δp_{mhd} will be lower)

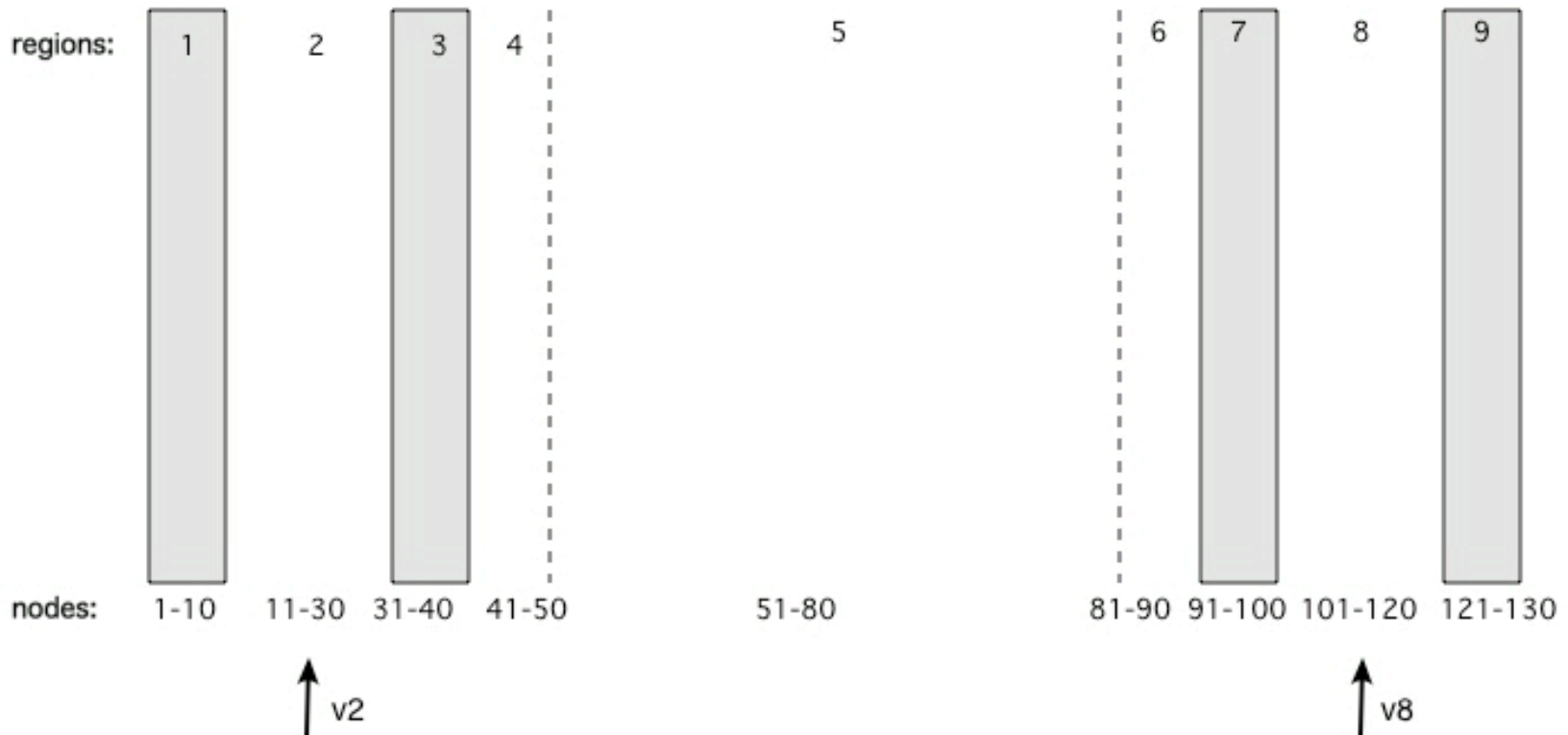


Computational approach for laminar heat transfer with variable flow

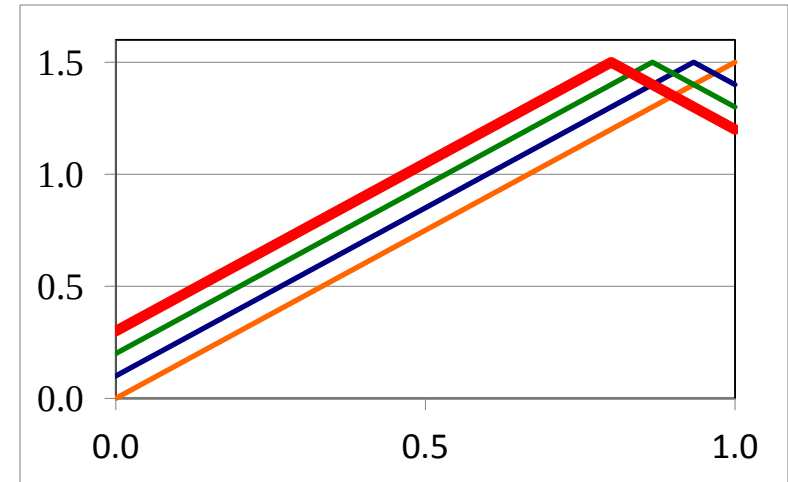
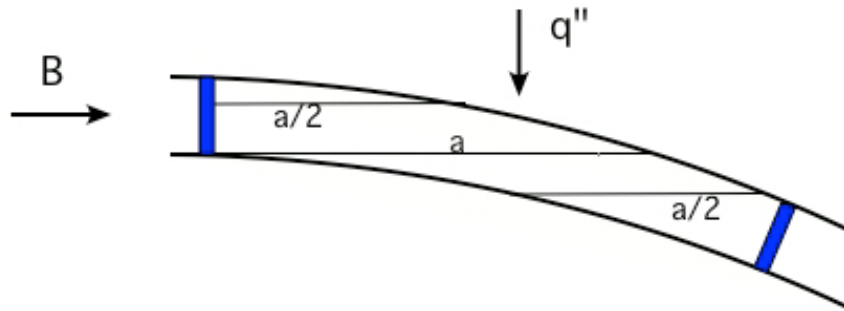
$$u(x) \frac{\partial e(x,z)}{\partial z} = k \frac{\partial^2 T(x,z)}{\partial x^2} + Q(x) \longrightarrow \frac{de}{dt} = k \frac{\partial^2 T}{\partial x^2} + Q - u \frac{\partial e}{\partial z} = 0$$

FW and SW flows are mixed to create uniform central duct inlet temperature

↓ v4,v5,v6



Stagnation can occur in curved FW channels

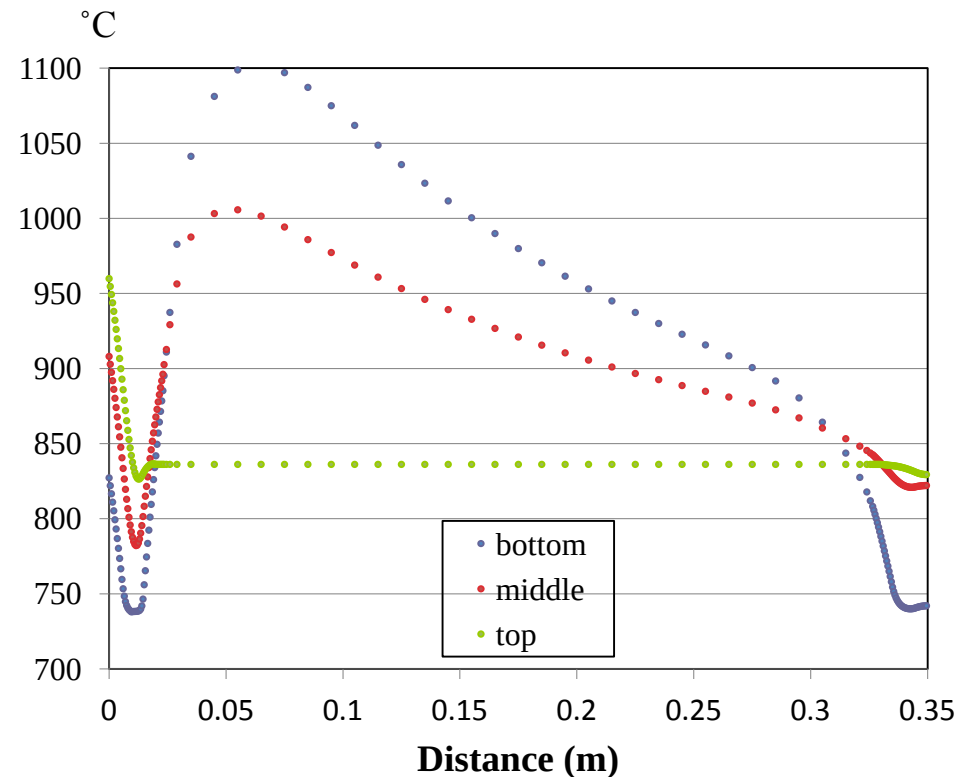
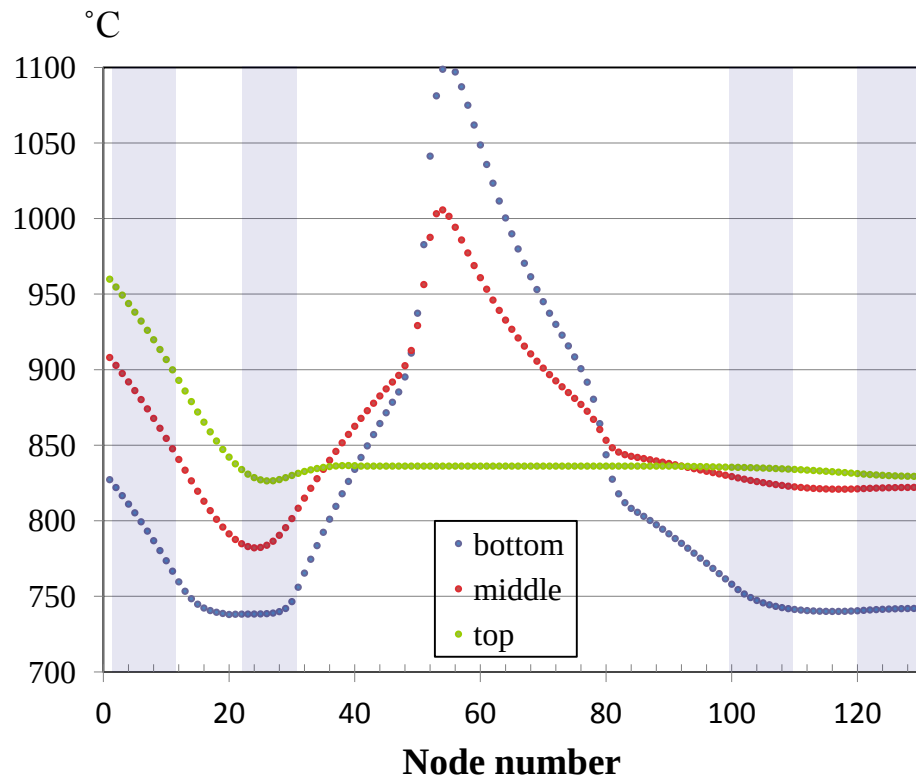


- First order approximation to pressure gradient in an insulated duct.

$$\nabla p = \frac{\sigma_f u B^2}{Ha} \quad Ha = aB\sqrt{\sigma/\mu}$$

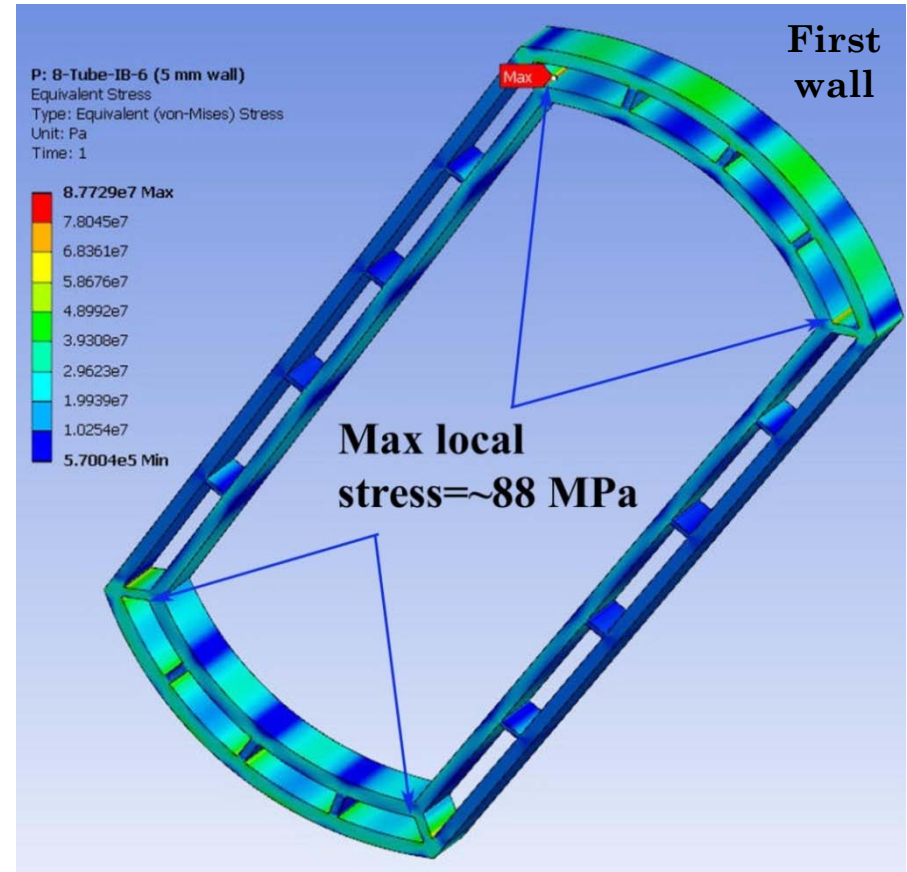
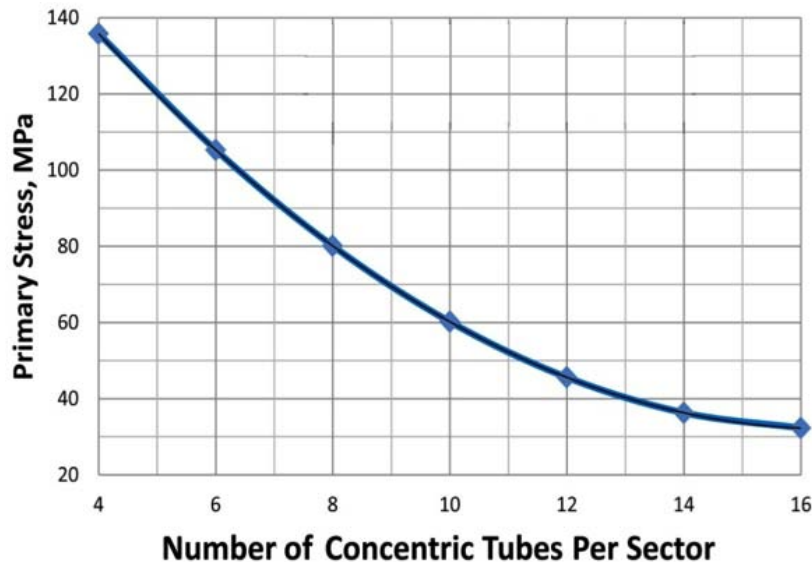
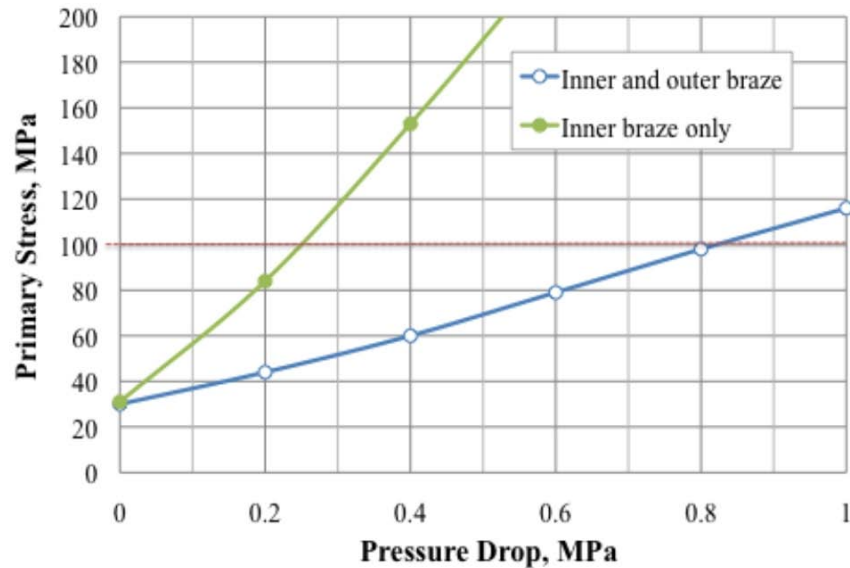
- In a curved duct, Ha varies from front to back. So u also varies.
- The effect can be approximated by $u \sim a$ (*L. Buehler and L. Giancarli, "Magnetohydrodynamic flow in the European SCLL blanket concept," FZKA 6778, 2002*).
- At a fixed volume flow rate, the pressure gradient increases by 50%.

Structures remain within their limits, with a modest variation from front to back

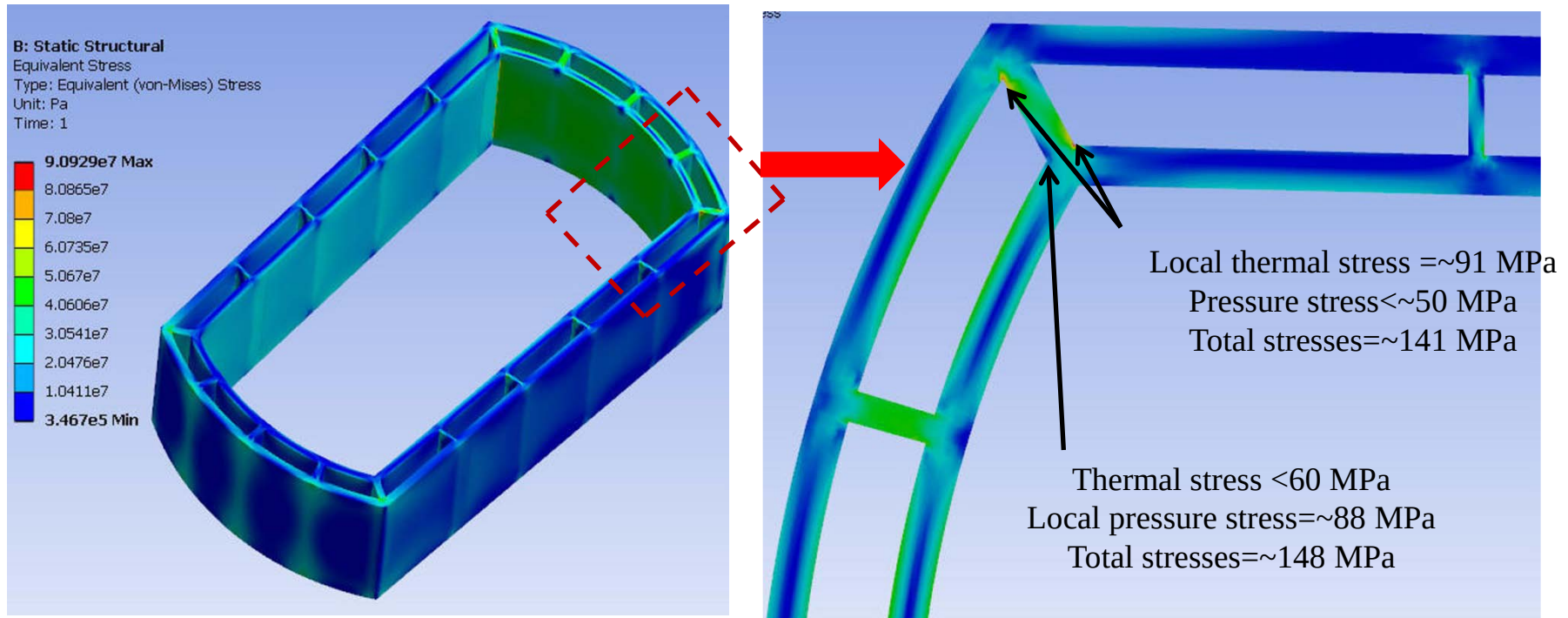


- Outboard blanket-I
- 10 m length from bottom to top
- Radial and axial variations in volumetric heating
- Constant surface heat flux, constant properties

Primary stress analysis determines module dimensions and fabrication requirements



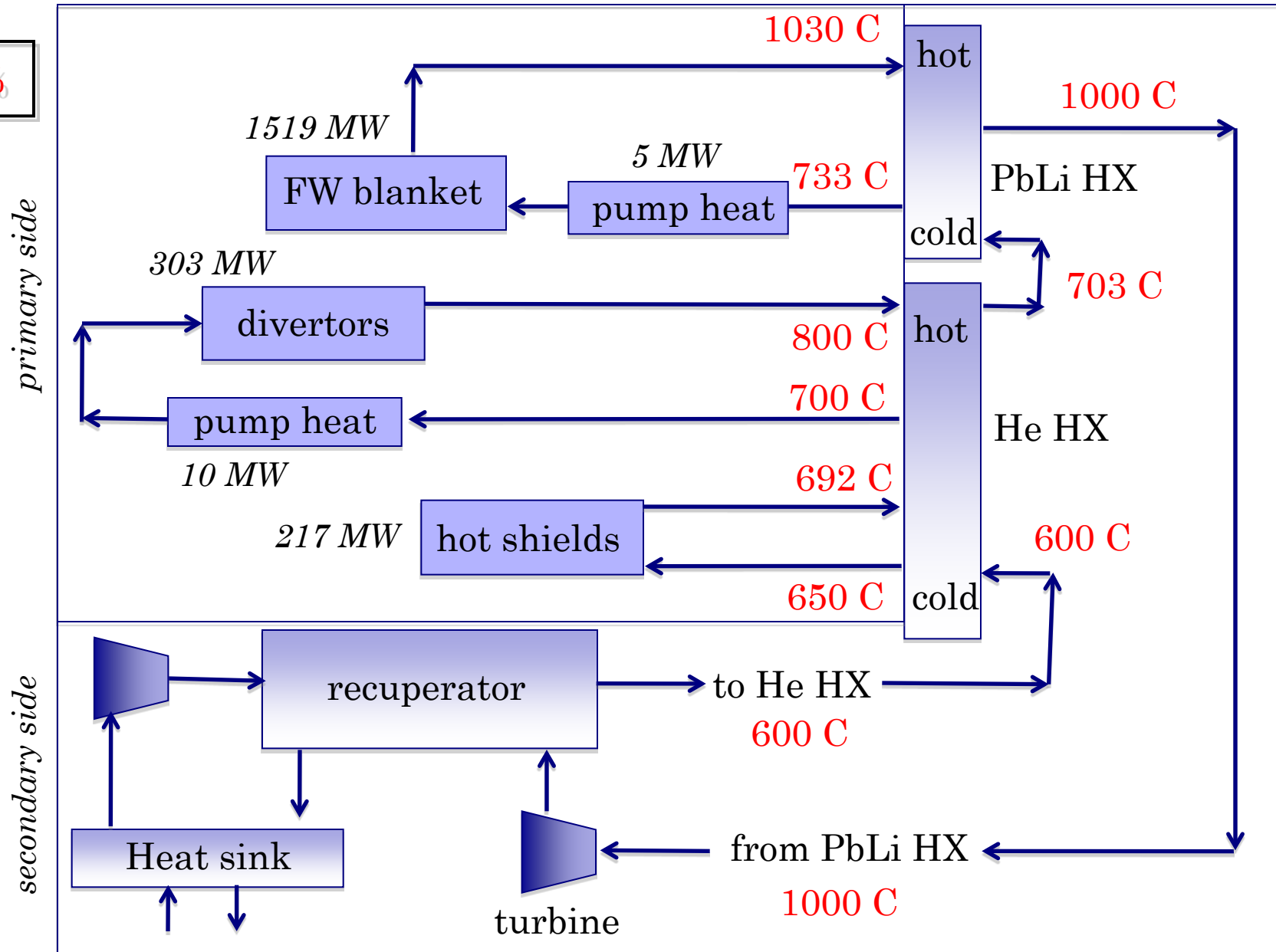
Thermal stresses satisfy requirements



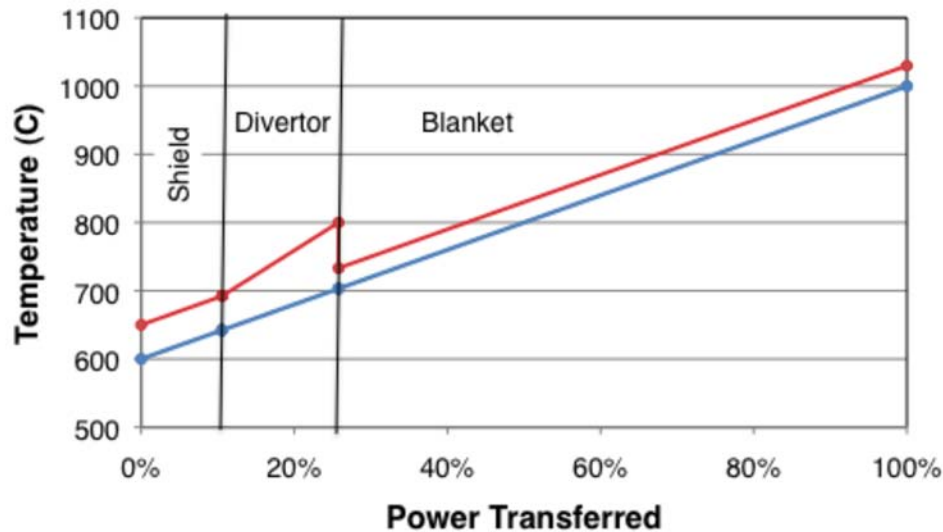
- Location is near the IB blanket bottom
- $3S_m$ rules for metal pressure vessels do not apply:
- Limit of **190 MPa** combined primary and secondary stress (Raffray *et al*, “Design and material issues for SiCf/SiC-based fusion power cores,” *Fusion Eng. Design* **55** (2001) 55-95.)
- We allocated 100 MPa for primary and 90 MPa thermal stress.

Power flows and bulk coolant temperatures in ARIES ACT1

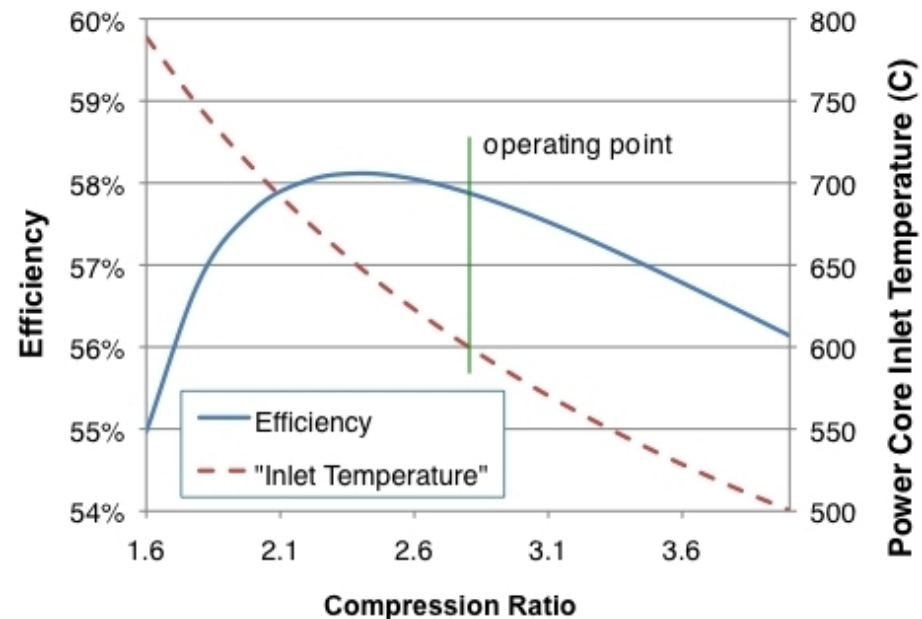
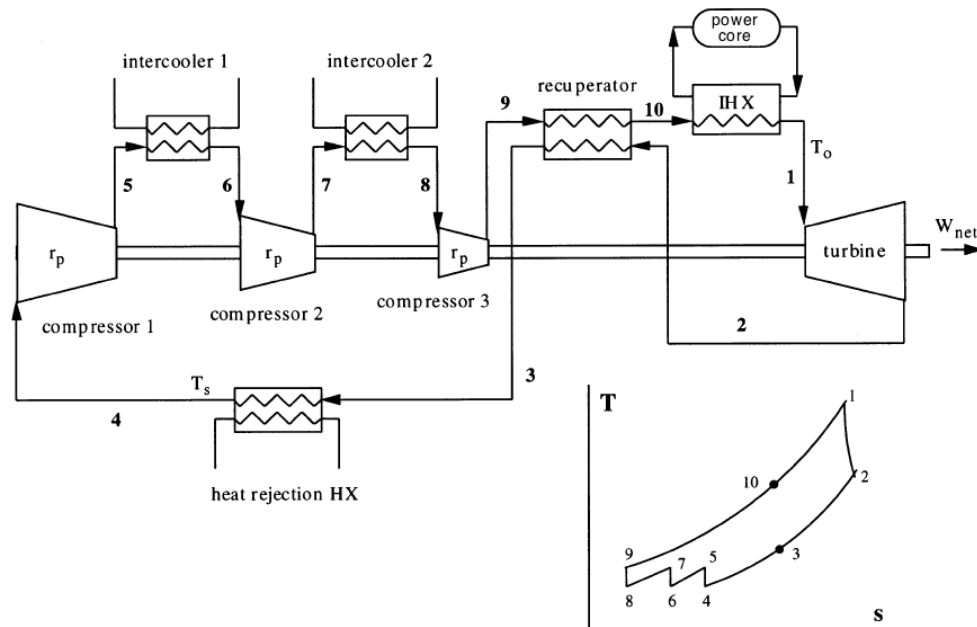
$\eta = 58\%$



Our Brayton cycle achieves ~58% efficiency



- Matching all of the coolant temperatures is needed.
- $\eta_{\text{recuperator}} = 96\%$, $\eta_{\text{turbine}} = 92\%$
- Result depends on inlet temperature as well as outlet; >57% could be achieved with 550°C inlet.





R&D Needs

- Characterization of steady and transient surface heat loads.
- MHD effects on flow and heat transfer, especially the inlet manifold.
- Fabrication, assembly and joining of complex structures made of SiC composites, tungsten alloys, and low activation ferritic steels.
- Mechanical behavior of steel, W and SiC structures, including fracture mechanics, creep/fatigue, and irradiation effects.
Failure modes and rates.
- Determination of upper and lower temperature limits of W alloys and advanced ferritic steels.
- Fluence lifetime of components under anticipated loading conditions.
- Tritium containment and control.