Status of ARIES-AT Blanket and First Wall Design

Presented by A. René Raffray

University of California
San Diego

ARIES Meeting
December 1-3, 1999
UCSD, San Diego, CA

Blanket Presentation Outline

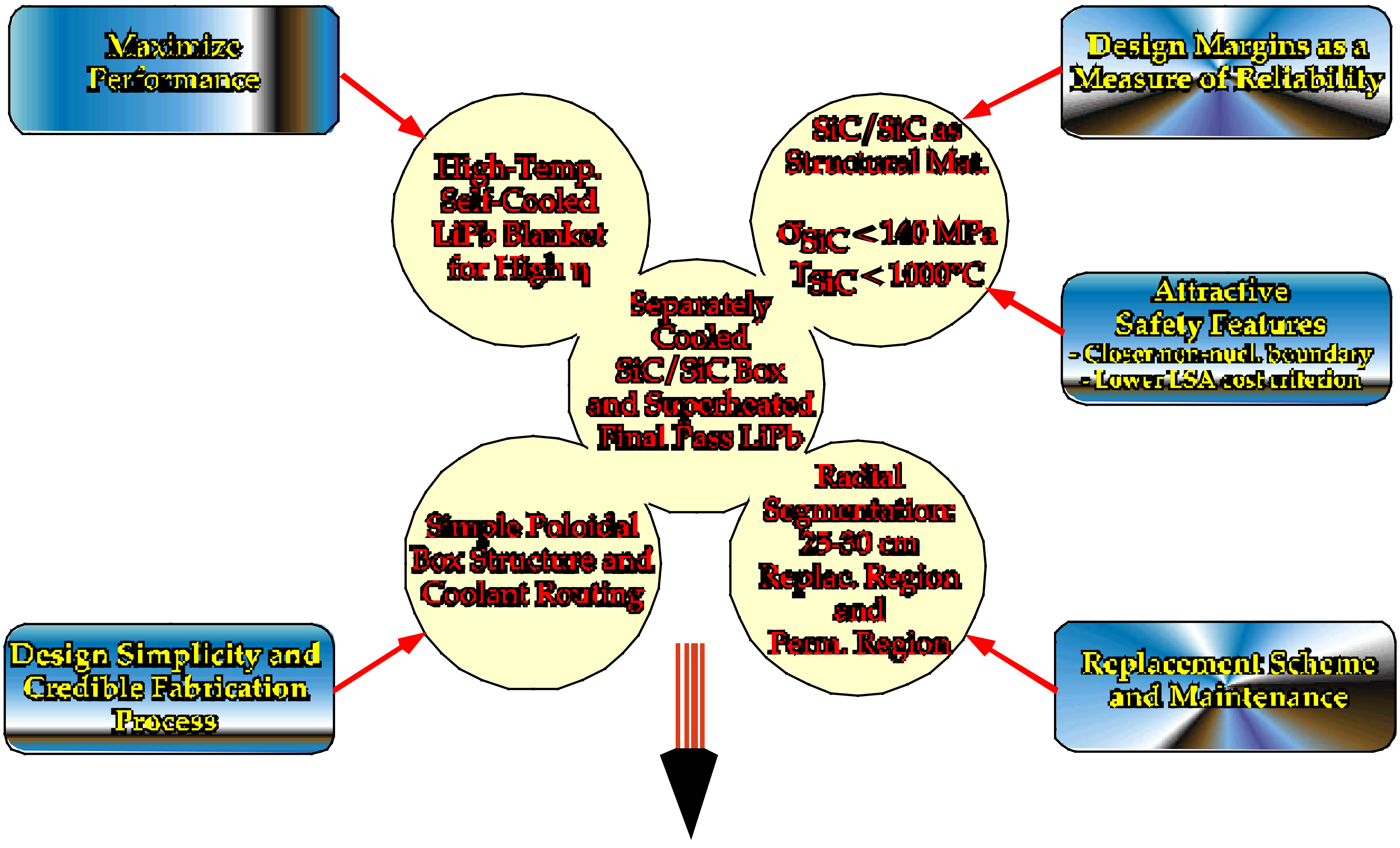
- **Status (RR)**
  - Design philosophy and guidelines emerging from initial design effort
  - MHD flow considerations
    - FW flow channel configuration and routing
  - Example design point

- **Overall Coolant Routing and Assembly Considerations (IS)**

- **Alternative Blanket Configuration Based on Same Design Guidelines (SM)**

- **Discussion Session (All)**
  - Help converge on final configuration
  - Identify key issues on which to focus future efforts

Minimize COE while maintaining reasonable margins, credible fabrication and maintenance processes, and attractive safety features



Maximize Performance

High-Temp. Self-Cooled LiPb Blanket for High η

Design Margins as a Measure of Reliability

SiC/SiC as Structural Mat.

$\sigma_{SiC} < 140$ MPa

$T_{SiC} < 1000°C$

Attractive Safety Features
- Closer non-nucl. boundary
- Lower LSA cost criterion

Separately Cooled SiC/SiC Box and Superheated Final Pass LiPb

Design Simplicity and Credible Fabrication Process

Simple Poloidal Box Structure and Coolant Routing

Replacement Scheme and Maintenance

Radial Segmentation: 25-30 cm Replac. Region and Perm. Region

ARIES-AT BLANKET DESIGN

SiC/SiC Properties Used for ARIES-AT Blanket Analysis

Density (kg/m^3)	3200
Density Factor	0.95
Young's Modulus (GPa)	360
Poisson's ratio	0.16
Thermal Expansion Coef. (ppm/°C)	4.4
Thermal Conduct. in Plane (W/m-K)	25
Therm. Conduct. through Thickness (W/m-K)	20
Maximum Allowable Primary Stress (MPa)	~140
Maximum Allowable Secondary Stress (MPa)	~190
Maximum Allowable Operating Temp. (°C)	1000
Max. Allow. SiC/LiPb Interface Temp. (°C) (TBD)	~ 1000°C assumed
Maximum Allowable SiC Burnup (%)	3

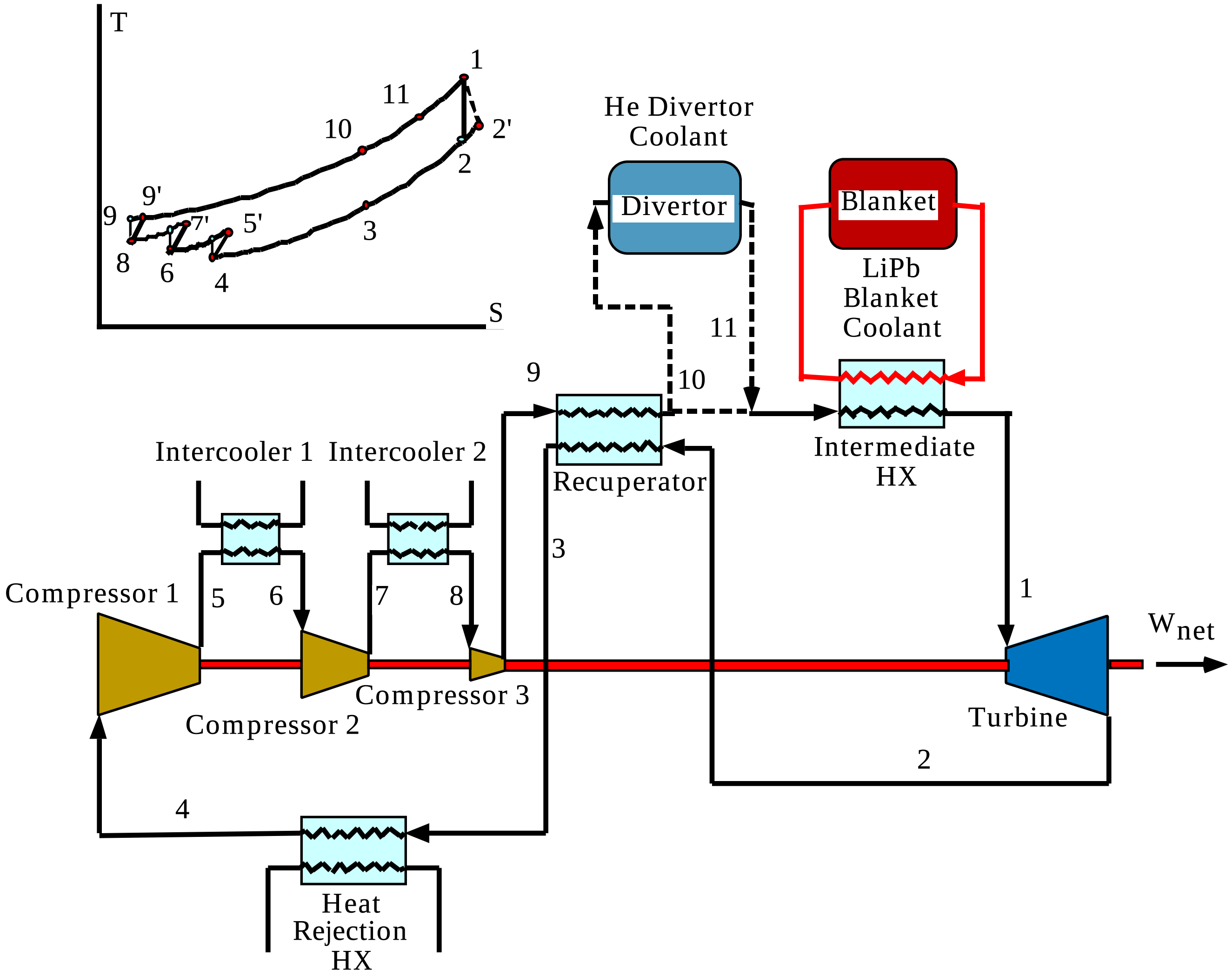
ARIES-AT Machine and Power Parameters Used for Blanket Analysis

(OB=Outboard, IB=Inboard, FW= First Wall)

Power Parameters	
Fusion Power (MW)	1737
Neutron Power (MW)	1390
Alpha Power (MW)	347
Current Drive Power (MW)	41
Maximum Surface Heat Flux (MW/m^2)	0.71
Average Surface Heat Flux (MW/m^2)	0.51
Transport Power to the Divertor (MW)	280
From Neutronics Analysis	
Overall Energy Multiplication	1.1
Maximum Thermal Power (MW)	1927
OB Max. Neutron Wall Load (MW/m^2)	6.1
OB Avg. Neutron Wall Load (MW/m^2)	5.2
IB Max. Neutron Wall Load (MW/m^2)	4.0
IB Avg. Neutron Wall Load (MW/m^2)	3.0
OB Max. Heat Generation in FW SiC (MW/m^3)	31
OB Avg. Heat Generation in FW SiC (MW/m^3)	26
OB Max. Heat Generation in FW LiPb (MW/m^3)	23
OB Avg. Heat Generation in FW LiPb (MW/m^3)	19
Machine Geometry	
Major Radius (m)	4.8
Minor Radius (m)	1.2
Outboard FW Location at Midplane (m)	6
Outboard FW Location at Lower/Upper End (m)	4.8
Inboard FW Location (m)	3.6

Brayton Power Cycle

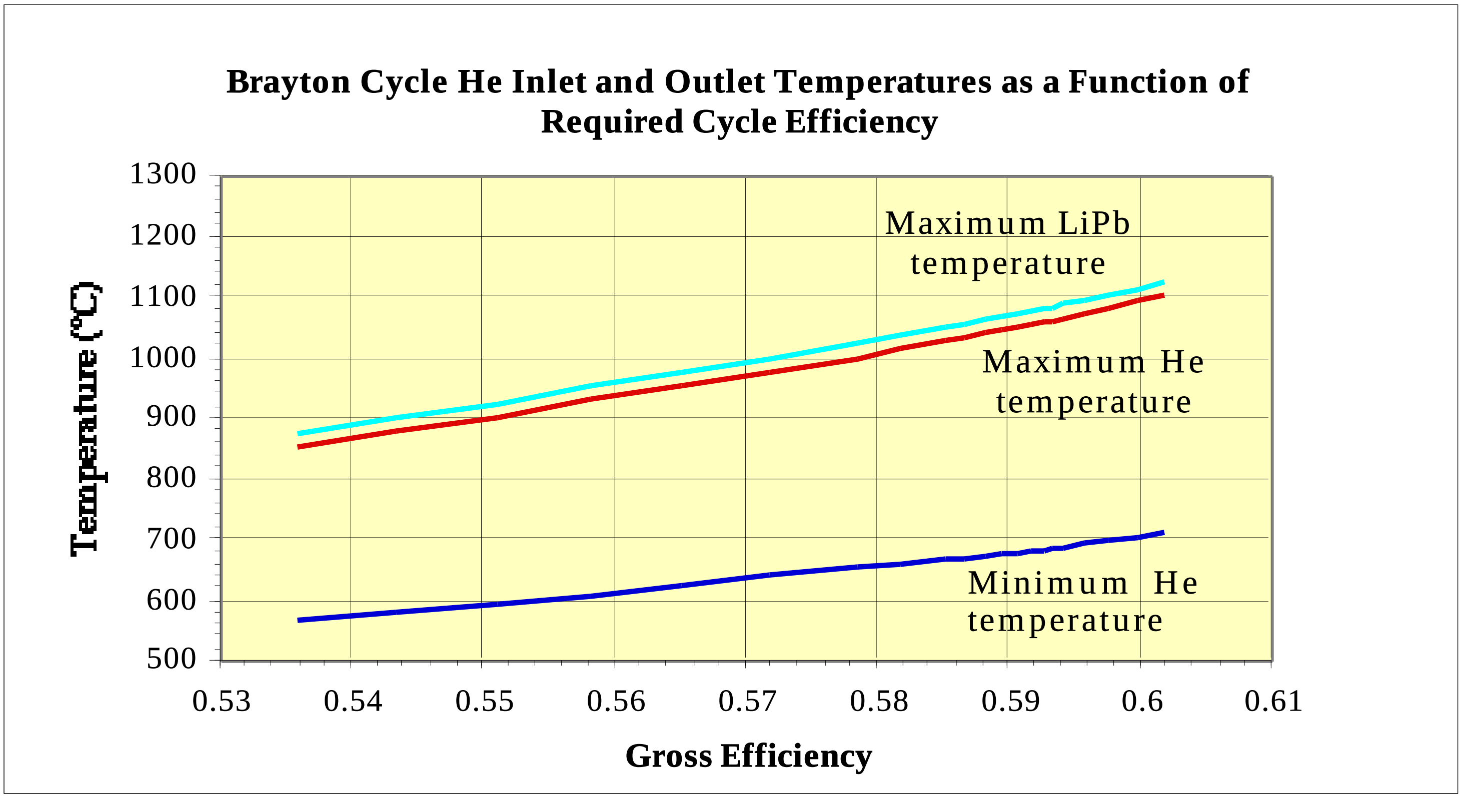
- Best near-term possibility of power conversion with high efficiency
  - *Maximize potential gain from high temperature operation with SiC/SiC*
  -
- Compatible with a liquid metal blanket through use of intermediate HX



Power Cycle Parameters

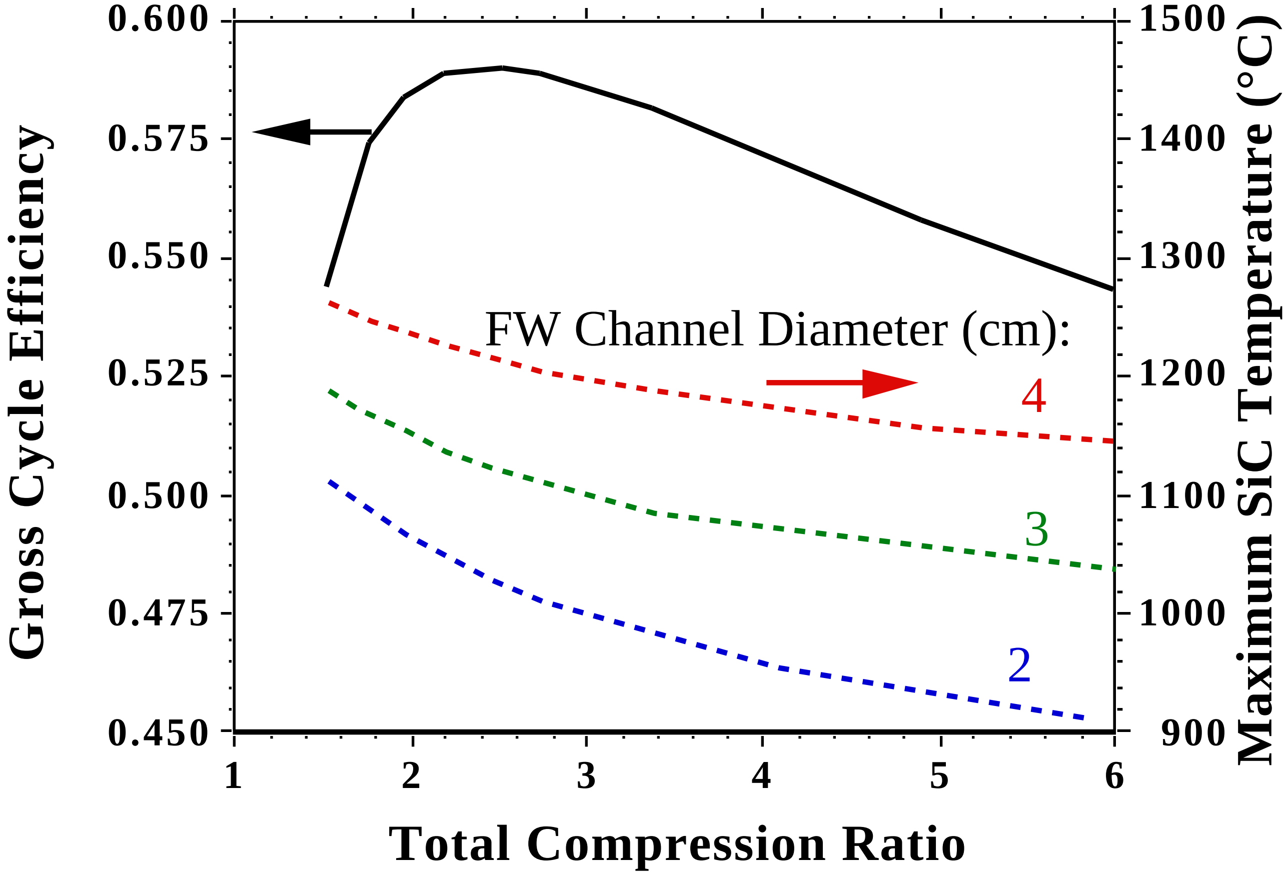
- Brayton Cycle Parameters:
  - Min. He temp. in cycle (heat sink) = 35 °C
  - 3-stage compression with 2 inter-coolers
  - Turbine efficiency = 0.93
  - Compressor efficiency = 0.9
  - Recuperator effectiveness = 0.96
  - He fraction. ΔP in out-of-vessel cycle = 0.025

- Intermediate Heat Exchanger:
  - Effectiveness = 0.9
  - $\dfrac{(m' C_p)_{He}}{(m' C_p)_{LiPb}} = 1$



Cycle Efficiency and Maximum SiC Temperature as a Function of Total Compression Ratio for Different Poloidal LiPb FW Channel Diameters

- **MHD flow laminarization effect included in heat transfer and pressure drop analysis**
- **Max. Brayton cycle He temp. = 1050°C**
- **Example design point:**
  - **Total compression ratio = 3**
  - **FW channel diameter = 2 cm**
  - **SiC max. temp. < 1000°C**
  - **Cycle efficiency ~ 59%**
  - **LiPb pressure drop ~ 1.3 MPa**



LiPb-Cooled First Wall Poloidal Configuration with Tapering Channels

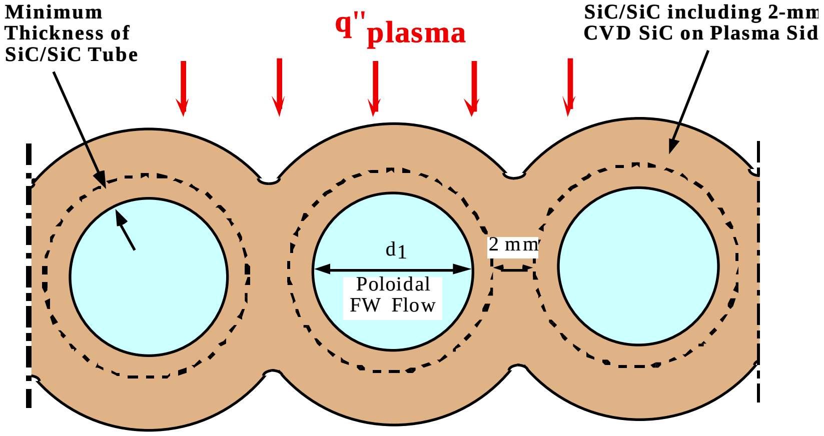
- **Minimum channel wall thickness was set as one tenth of the diameter**

- **MHD flow laminarization effects considered in heat transfer and pressure drop calculations**

- **Circular channels initially considered but rectangular channels preferable based on heat transfer performance**
  - **Slug flow velocity profile in rectangular channels compared to near-parabolic velocity profile in circular channels under perpendicular magnetic field**

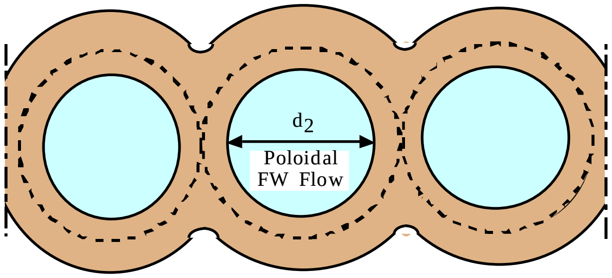
Outboard Midplane

Plasma-side

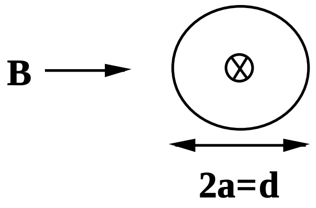


Upper/Lower Outboard

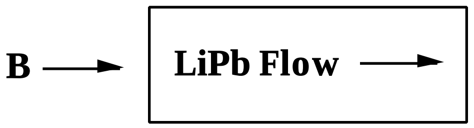
Plasma-side



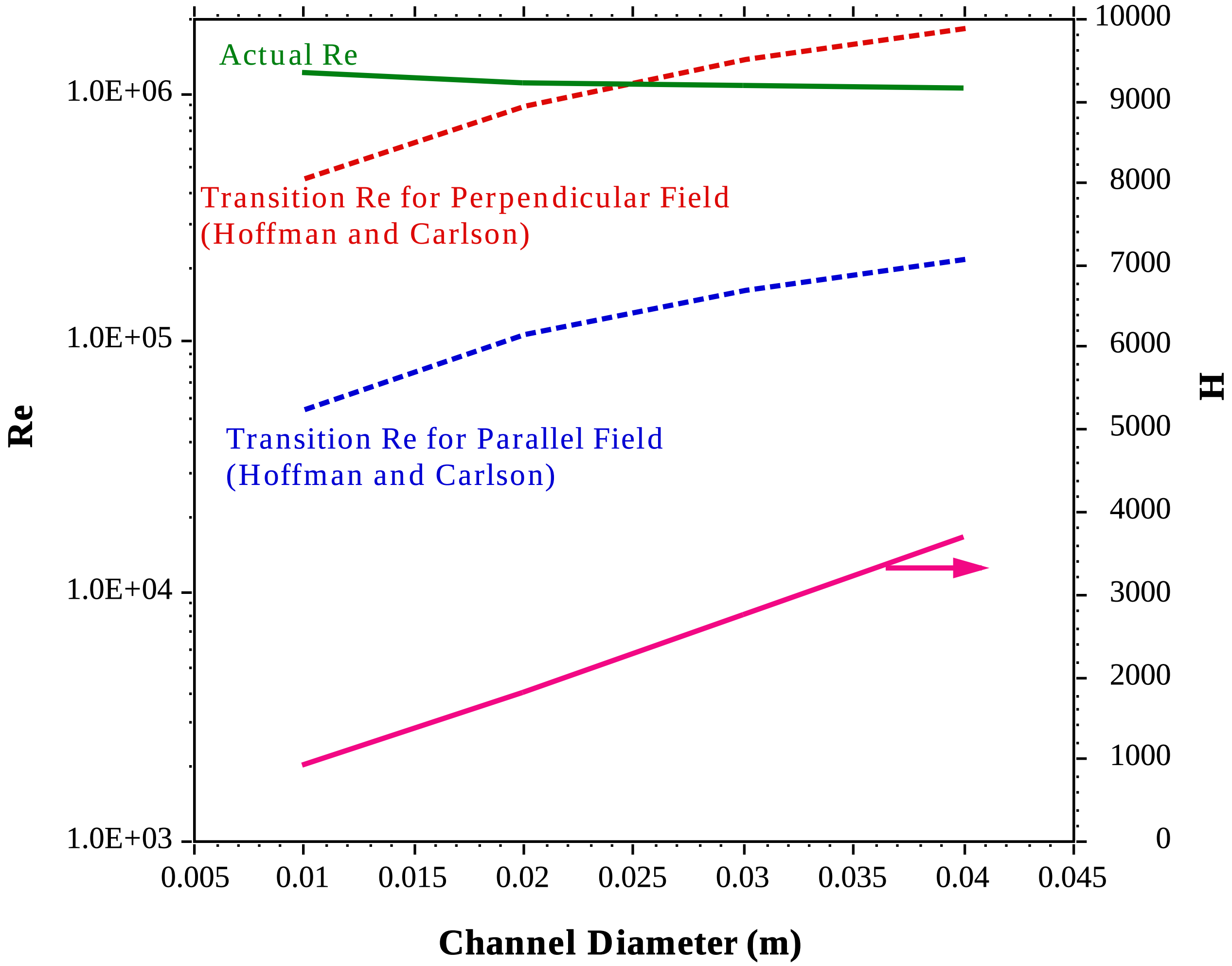
Hartmann and Reynolds Numbers as a Function of FW Channel Diameter



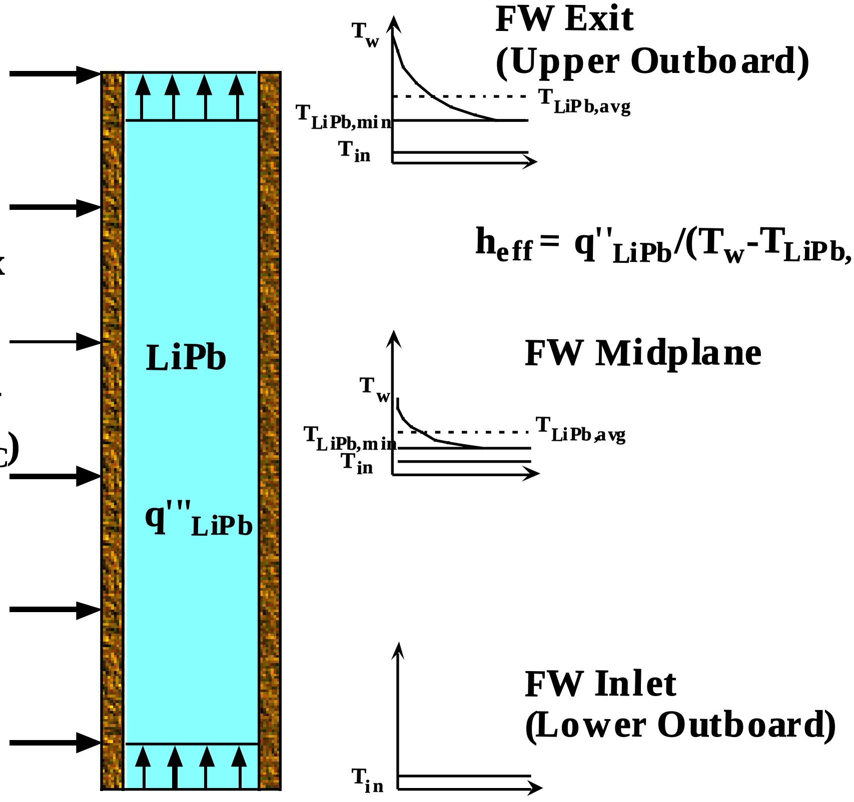
Flow Perpendicular to Field



Flow Parallel to Field



LiPb Temperature Distribution in FW Poloidal Channel under MHD Laminarization Effect



FW Exit
(Upper Outboard)

FW Midplane

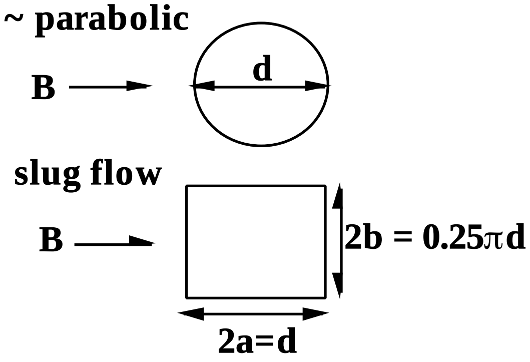
FW Inlet
(Lower Outboard)

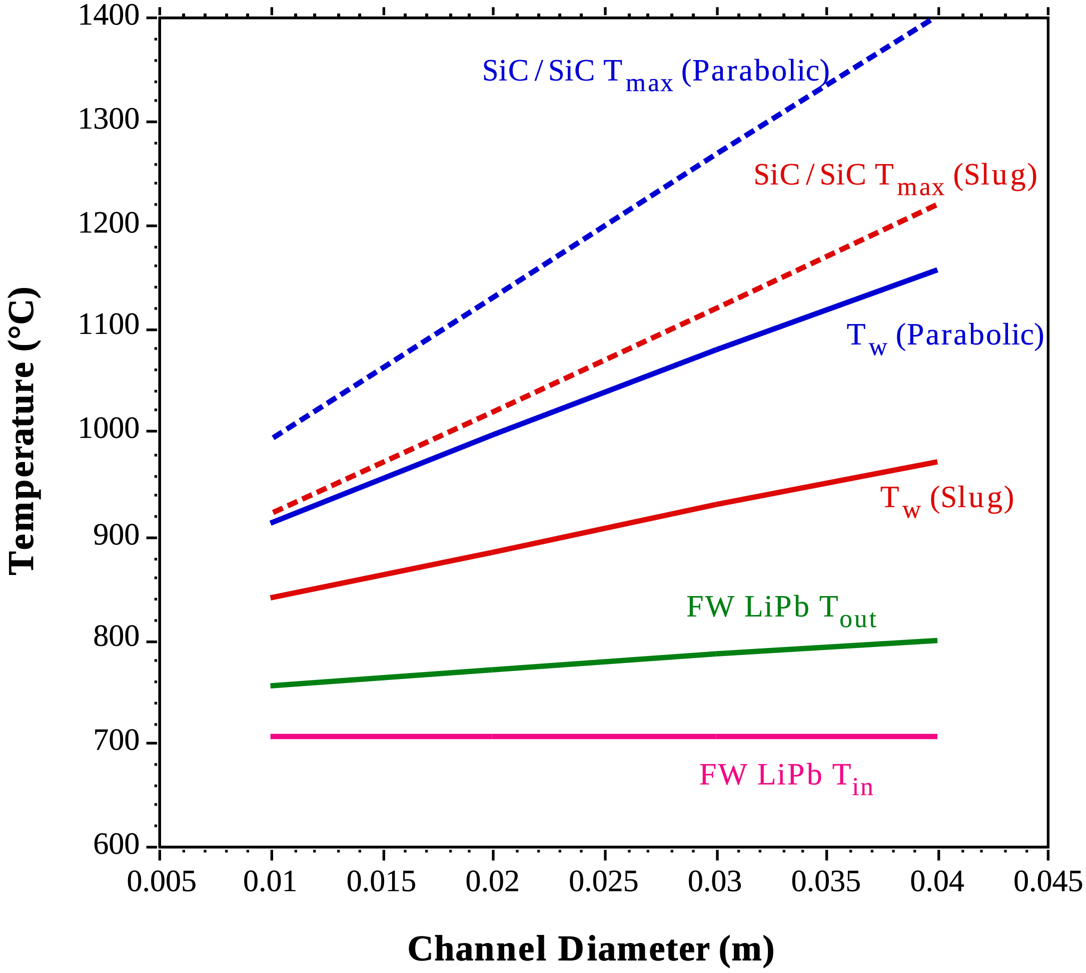
Effective Heat Flux to LiPb ($q''_{LiPb} = q''_{plasma} + q'''_{SiC}\,\delta_{SiC}$)

$$h_{eff} = q''_{LiPb}/(T_w - T_{LiPb,min})$$

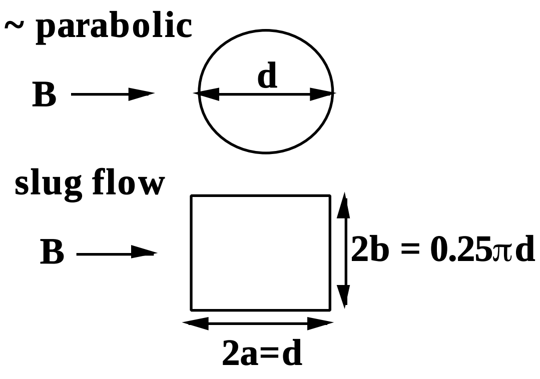
FW LiPb and SiC Temperatures as a Function of FW Channel Diameter for Slug and Parabolic Velocity Profiles

h_{eff} (parabolic) ~ 0.54 h_{eff}(slug)
(by analogy to regular laminar flow)

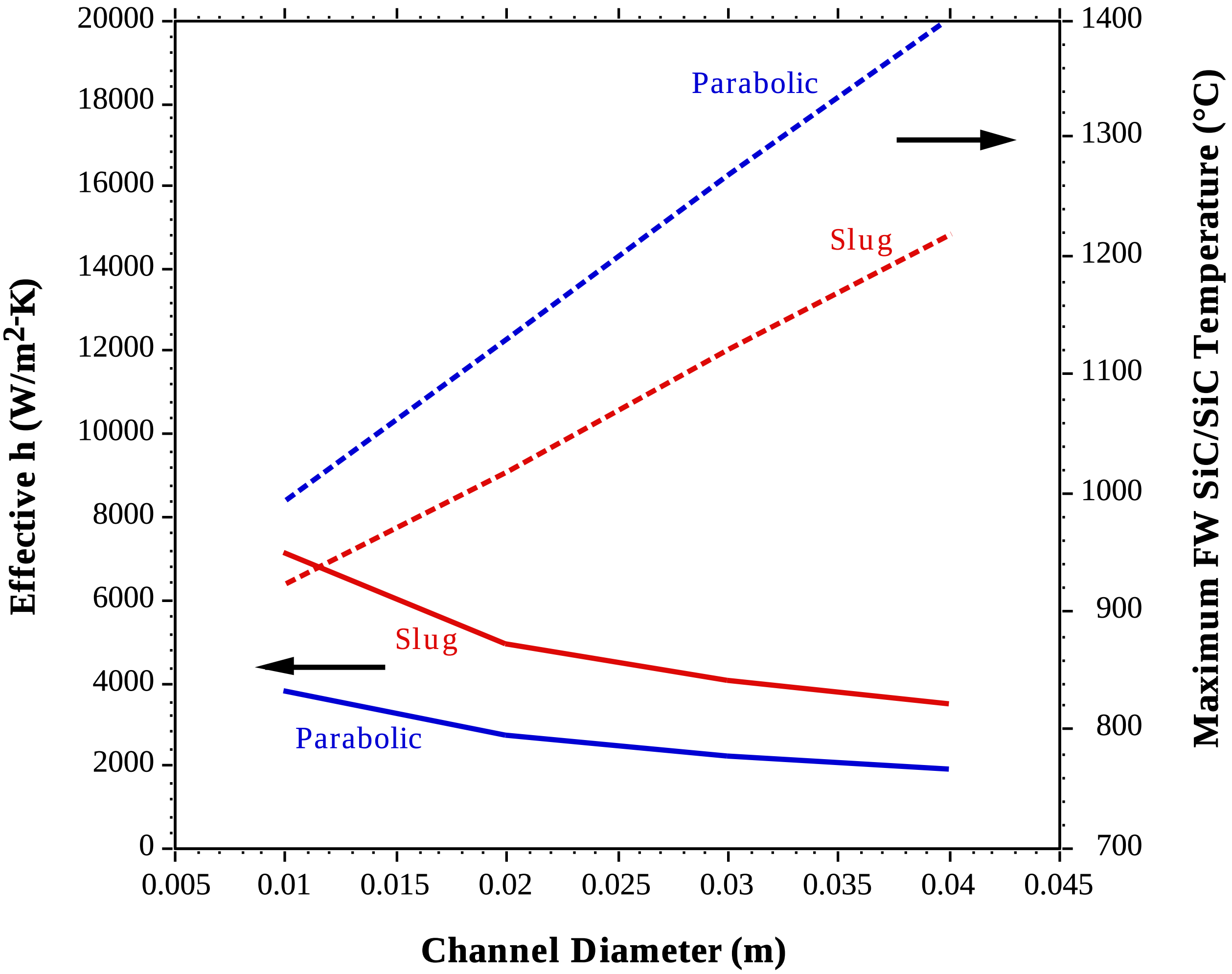




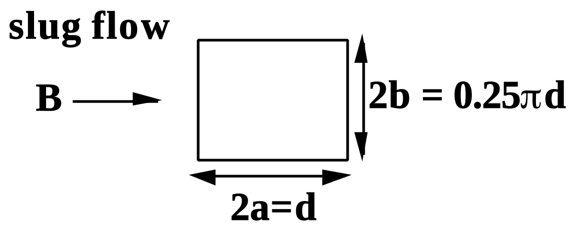
Effective h and Maximum FW SiC Temperature as a Function of FW Channel Diameter for Slug and Parabolic Velocity Profiles

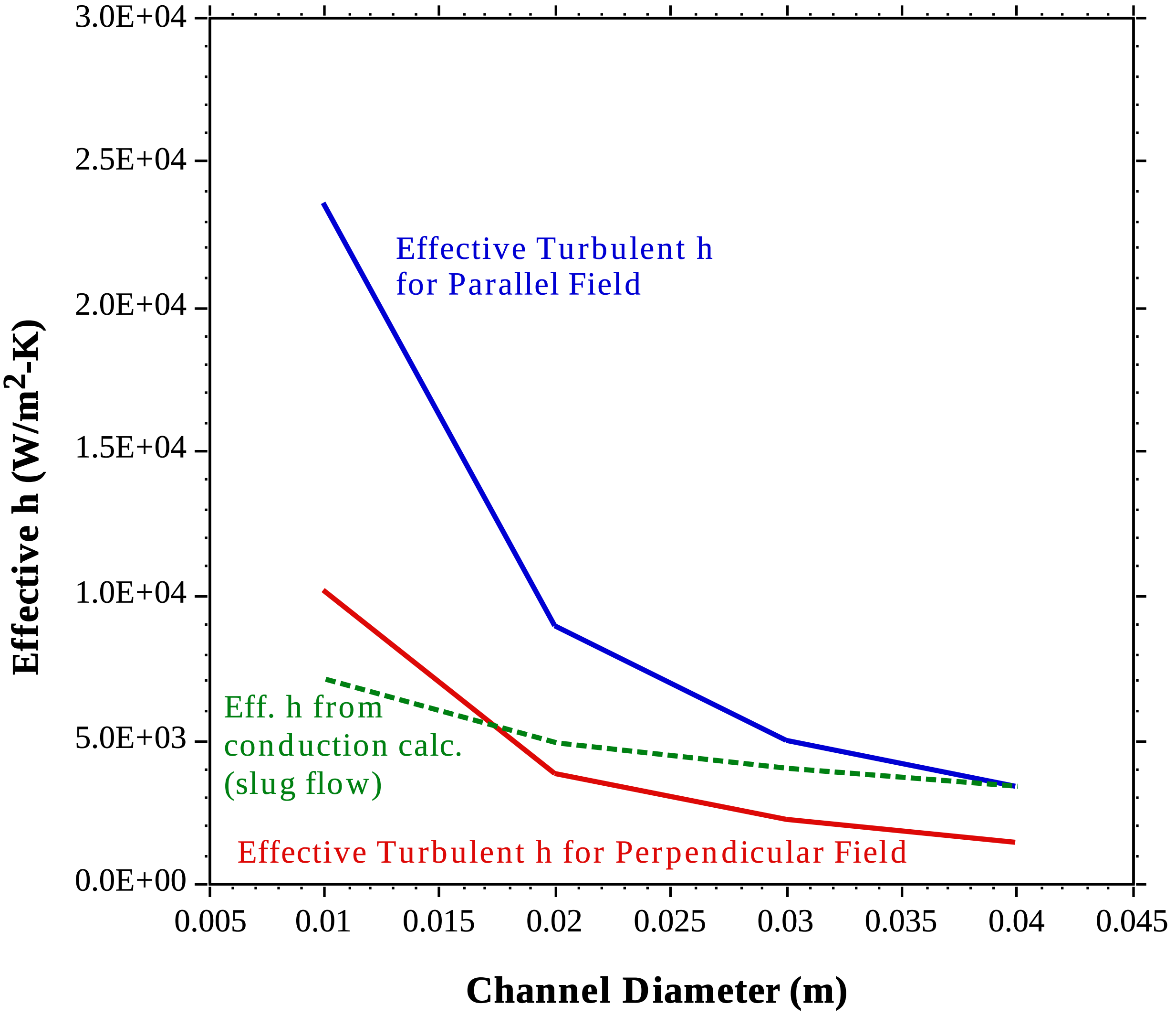


h_{eff} (parabolic) ~ 0.54 h_{eff}(slug)
(by analogy to regular laminar flow)

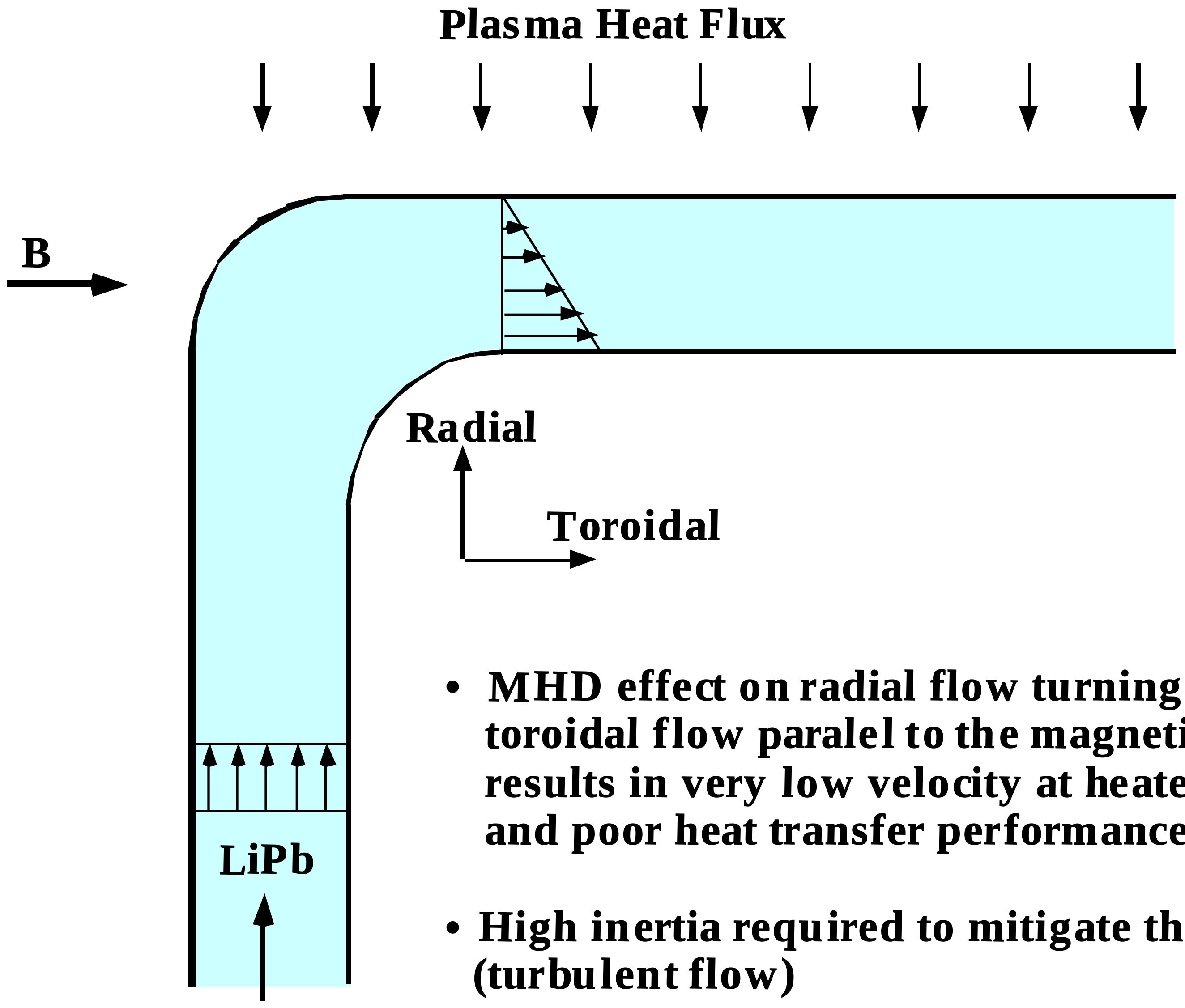


FW Effective h for Turbulent Flow and Calculated from Conduction Analysis





LiPb Radial/Toroidal Flow

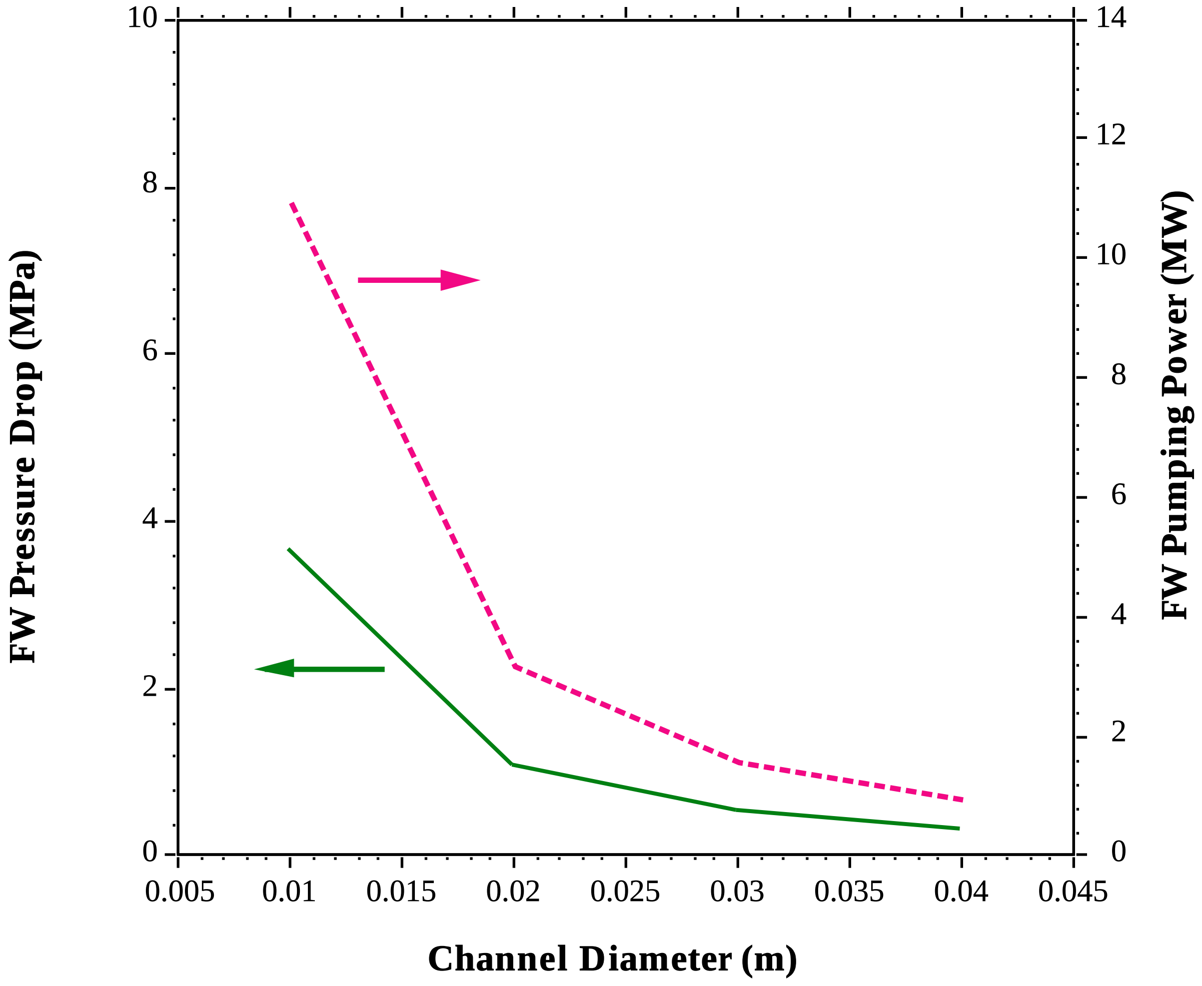


- MHD effect on radial flow turning to toroidal flow paralel to the magnetic field results in very low velocity at heated FW and poor heat transfer performance

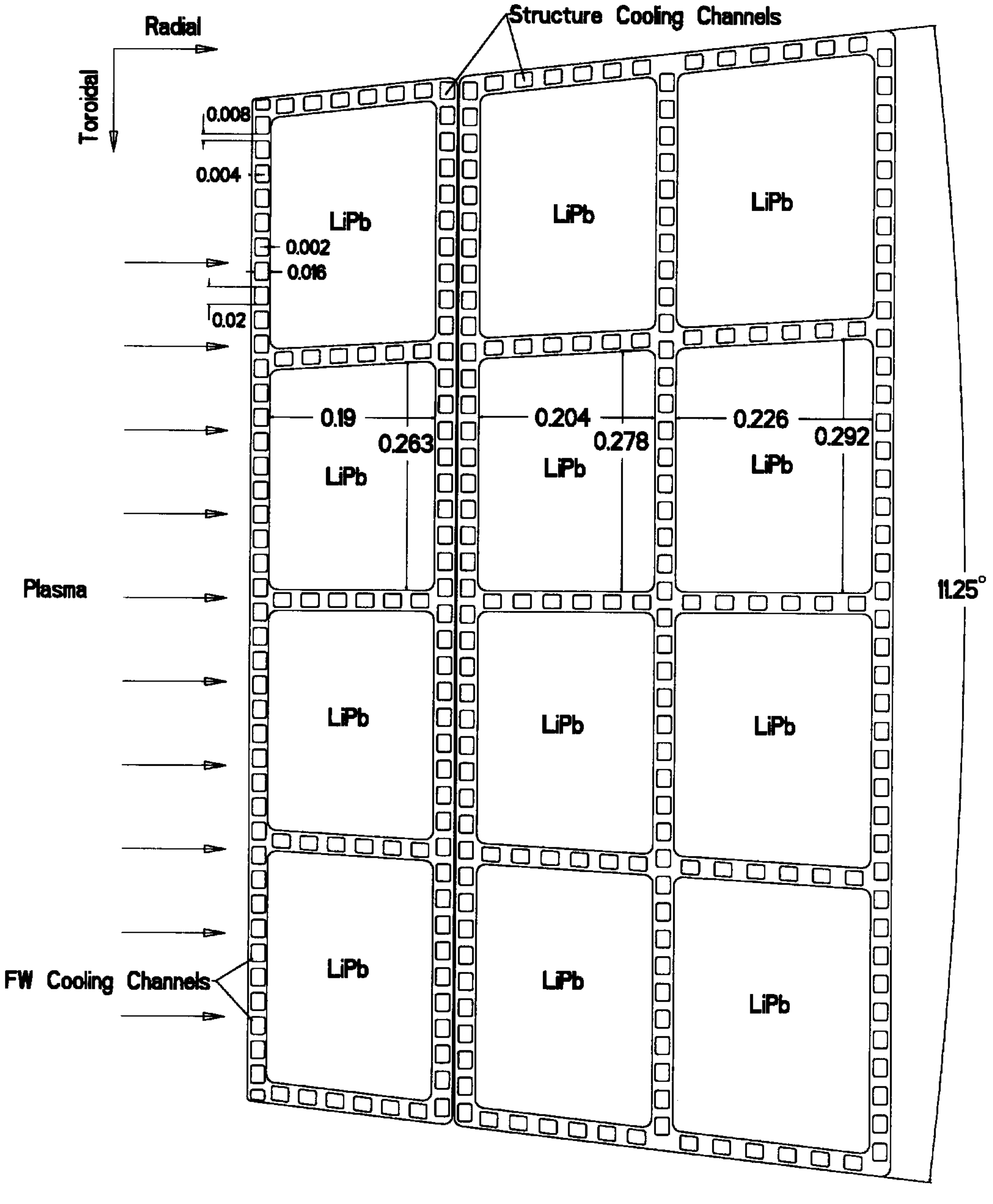
- High inertia required to mitigate this effect (turbulent flow)

FW LiPb Pressure Drop and Pumping Power as a Function of Channel Diameter

Poloidal Length = 6 m



ARIES-AT LiPb Cooled FW/Blanket Configuration
(Midplane)



Blanket Parameters for Example Design Point

Brayton Cycle Parameters	
Cycle T_{He} at Recuperator Exit (°C)	6.10E+02
Cycle $T_{He,max}$ (°C)	1.05E+03
Total Compression ratio	2.99E+00
Cycle Gross Efficiency	5.86E-01
Blanket Region Radial Thicknesses (m)	
Replaceable FW/Blanket Region	2.50E-01
Permanent FW/Blanket Region	4.50E-01
FW + Blanket Coolant	LiPb
Mass Flow Rate (kg/s)	2.36E+04
Inlet Temperature (°C)	7.05E+02
Outlet Temperature (°C)	1.09E+03
Pressure Drop (MPa)	1.11E+00
Pumping Power (MW)	3.33E+00
First Wall Assuming Tapering Channels	
OB Midplane Channel Toroidal Dimension (m)	2.00E-02
Outboard Midplane Channel Pitch (m)	2.80E-02
FW Region Radial Thickness (m)	2.60E-02
LiPb Velocity (m/s)	4.69E+00
Effective Heat Transfer Coefficient (W/m^2-K)	4.97E+03
Pressure Drop (MPa)	1.07E+00
Maximum SiC Temperature (°C)	1.02E+03
SiC/SiC Rib + Wall	
Thickness (m)	3.40E-02
Channel Dimension (m)	3.00E-02
Channel Pitch (m)	3.50E-02
LiPb Velocity (m/s)	4.01E-01
Effective Heat Transfer Coefficient (W/m^2-K)	6.97E+02
Pressure Drop (MPa)	3.40E-02
Maximum SiC/LiPb Temperature (°C)	9.38E+02
Main LiPB Channels (In Replaceable Section)	
Average Toroidal Dimension (m)	2.28E-01
Hydraulic Diameter (m)	2.13E-01
LiPb Velocity (m/s)	1.47E-01
Effective Heat Transfer Coefficient (W/m^2-K)	4.34E+02
Pressure Drop (MPa)	7.30E-03

Summary and Future Effort

- **High Performance SiC/SiC + LiPb Blanket**
  - Major impact in lowering COE
  - Attractive safety features

- **Converge on final design for detailed analysis**
  - Balanced approach: High performance but credible fabrication, reliability, maintenance
  - Maintain reasonable margins as a measure of reliability
  - Develop maintenance scheme
  - Fabrication procedures
  - HX tube material
  - Update design as SiC material data become available (in particular SiC/LiPb compatibility)

- **Develop Compatible Divertor Design**