Gas Cooling of Divertors

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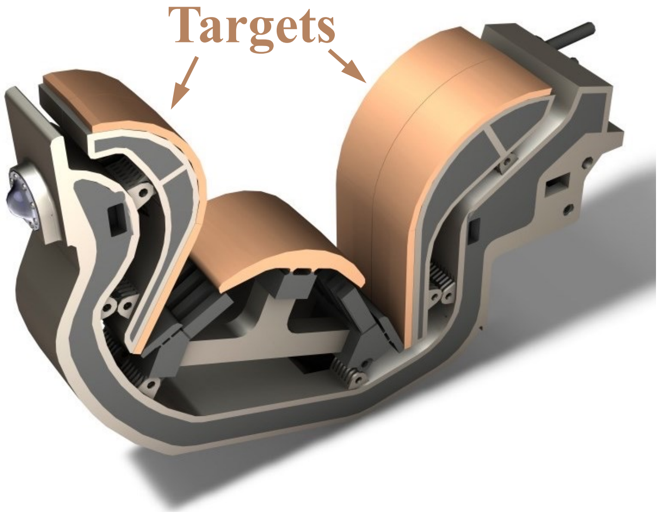
INTRODUCTION

- **Power handling/exhaust in plasma-material interactions (PMI)**
  - Divertor configuration: confine core plasma with poloidal magnetic field
    - Exhaust ~20% of energy onto divertor targets (plasma-facing components, or PFC) near X-point(s)
    - Targets remove plasma impurities and fusion products from scrape-off layer, converting kinetic energy to heat ⇒ subject to extremely high heat fluxes
  - ITER divertor specifications
    - Steady-state heat fluxes $q'' = 10$ MW/m^2
    - "Slow transients": $q'' = 20$ MW/m^2 over 10 s
  - Lower (< 2 MW/m^2) heat load on first wall
  - Actual divertor (and first wall) heat load specifications TBD
  - Candidate coolants for long-pulse reactors: He, water (DEMO), liquid metals



Georgia Tech Studies

Aim: evaluate thermo-fluids performance of gas-cooled solid-tungsten (W) divertors

- **Experiments complemented by numerical simulations**
  - Tests in He loop on stainless + WL10 test sections: consider pressure boundary (*vs.* W PFC/tile) at prototypical pressures, nearly prototypical temperatures and heat fluxes
    - Measure cooled surface temperatures T_s, pressure drops Δp, and incident heat flux q'' (from He energy balance) over a range of He mass flowrates $\dot{m}$
    - Dimensionless heat transfer coefficient, Nusselt number Nu, from (T_s, q''): correlations for $Nu(Re)$ [Reynolds number Re dimensionless $\dot{m}$]
    - Dimensionless pressure loss coefficient K_L from Δp: correlations for $K_L(Re)$
  - Experimental data validate numerical models in commercial CFD software (ANSYS Workbench)
  - Develop performance curves for maximum heat flux on target plates

OVERVIEW

Updates on current research

- **"Flat design" finger-type divertor update**
  - Revised pressure loss coefficients K_L
- **CO_2, *vs.* He, cooled divertors**
  - Thermo-fluids performance of finger-type (= "HEMJ minus the HE") divertors
- **Helium-cooled flat plate (HCFP) experiments**
  - "Short" HCFP test section in small ($\dot{m} \leq 10$ g/s) GT He loop

Finger-Type Divertors

- **Helium-cooled multijet (HEMJ) divertor**
  - 25 (24 ⌀0.6 mm + 1 ⌀1.04 mm) impinging jets of (600 °C, 10 MPa) He cool curved inner surface of PFC across $H = 0.9$ mm gap
  - $\dot{m} = 6.8$ g/s; tile area ≈ 2.8 cm^2
- **Task 1 of PHENIX: optimize cooling**
  - Developed "flat" design to simplify HEMJ: 7 (⌀1.18 mm) impinging jets cool flat inner surface across $H = 1.25$ mm gap
  - Experiments in small GT He loop
    - Incident heat fluxes $q'' \leq 7.1$ MW/m^2
    - He conditions at inlet: $T_i \leq 400$ °C, $p_i \approx 10$ MPa
    - Reynolds number $Re \leq 5.4\times10^4$ (*vs.* prototypical $Re_p = 2.2\times10^4$)

Ihli *et al.* 05

Zhao *et al.* 17

Flat Design Parameters

- **Reynolds number *Re* dimensionless He mass flow rate**
  - Jet diameter D_j = 1.18 mm; jets area A_j = 766.4 mm^2
  - Prototypical $Re_\mathrm{p} = 2.2\times10^4$

$$Re = \frac{4}{\pi}\frac{\dot{m}D_\mathrm{j}}{\mu(T_\mathrm{i})A_\mathrm{j}}$$

- **Average heat transfer coefficient (HTC) *h***
  - Heat flux q'' from He energy balance
  - $\bar{c}_\mathrm{p}$ = specific heat evaluated at $(T_\mathrm{o}+T_\mathrm{i})/2$
  - Area of heated, cooled surfaces A_h = 227 mm^2, A_c = 154 mm^2
  - $\bar{T}_\mathrm{c}$ average cooled surface temperature

$$q'' = \dot{m}\bar{c}_\mathrm{p}(T_\mathrm{o}-T_\mathrm{i})/A_\mathrm{h}$$

$$h = \frac{q''A_\mathrm{h}}{(\bar{T}_\mathrm{c}-T_\mathrm{i})A_\mathrm{c}}$$

- **Nusselt number *Nu* dimensionless HTC**
  - $\bar{k}$ = He thermal conductivity evaluated at $(T_\mathrm{o}+T_\mathrm{i})/2$
  - Develop correlation assuming power law for $Nu(Re)$ since test section uses actual divertor materials

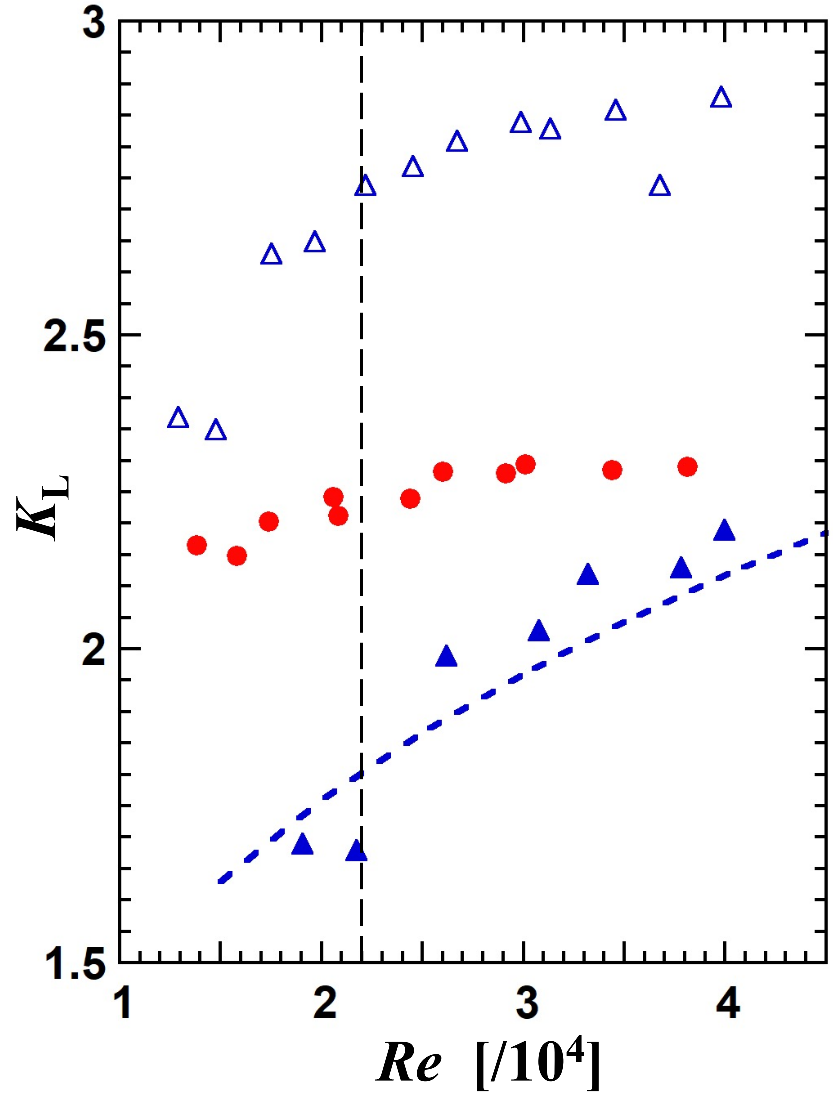
$$Nu = \frac{hD_\mathrm{j}}{\bar{k}}$$

UPDATED PRESSURE DROPS

- **Pressure loss coefficient K_L dimensionless Δp**
  - $\bar{V}$ average speed

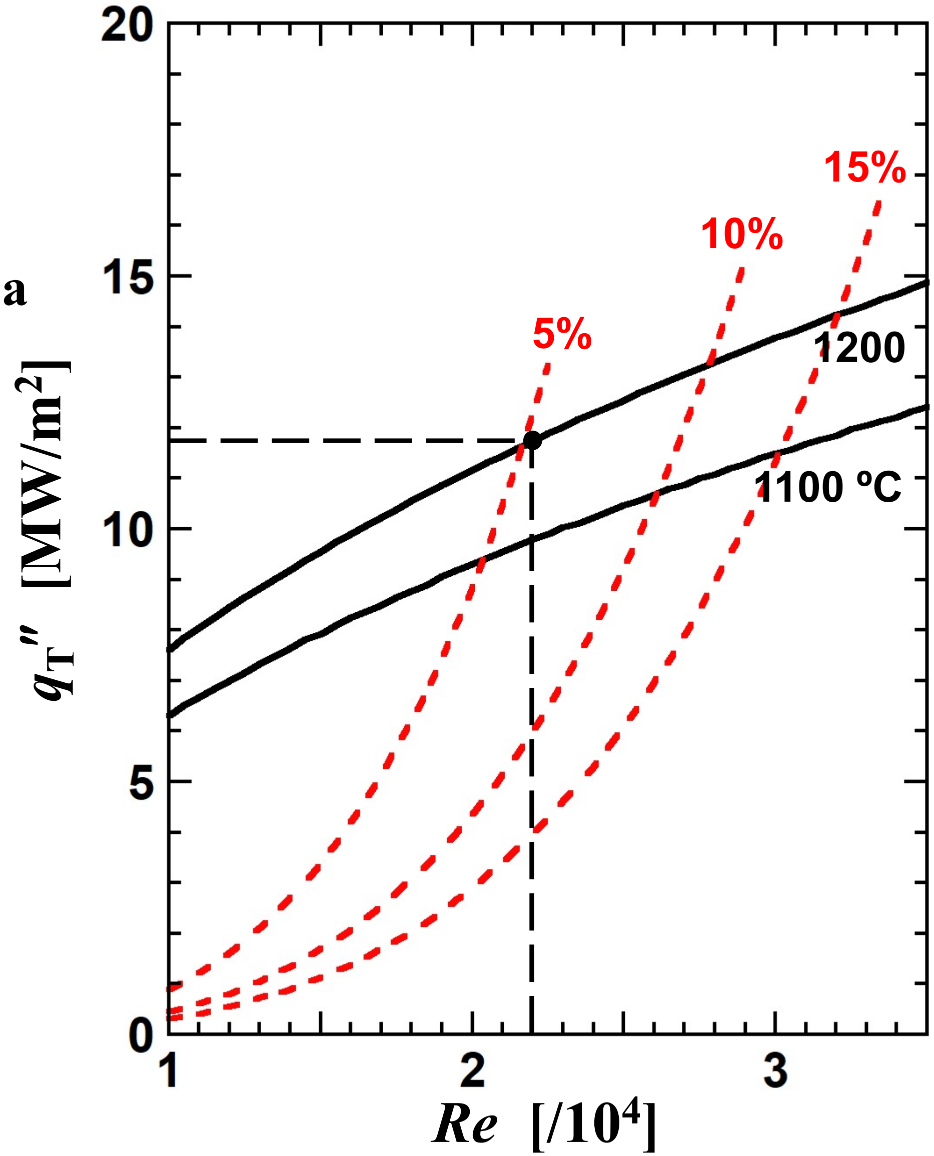
$$K_L = \frac{\Delta p}{\rho \bar{V}^2/2}$$

- **Flat design results**
  - Original K_L (●) Zhao *et al.* 18
  - Initial tests with new test section gave much higher K_L (△) Lee *et al.* 21
  - Tests with new manifold (and same test section) give lower K_L (▲): at Re_p, $K_L = 1.7$, *vs.* 2.3 for HEMJ
  - Correlation: $K_L = 0.125 Re^{0.267}$ (- - -)
- **Extrapolate *Nu*, K_L correlations to prototypical conditions**
  - $Nu = 0.145\, Re^{0.685}$ $T_i \geq 300$ °C



PERFORMANCE CURVES

- **Estimate maximum incident heat flux on tile q''_T (A_T = 281 mm²) removed at prototypical conditions: T_i = 600 °C, $p \approx$ 10 MPa**
  - Average pressure boundary temperature (based on 1D conduction) **T_s = 1100 °C, 1200 °C**
  - Helium pumping power (as fraction of thermal power) **β = 5%, 10%, 15%**
  - At $Re_p = 2.2\times10^4$: q''_T = 11.7 MW/m², β ≈ 5%
- **Based on updated K_L results, flat design and HEMJ have similar thermal-fluids performance**



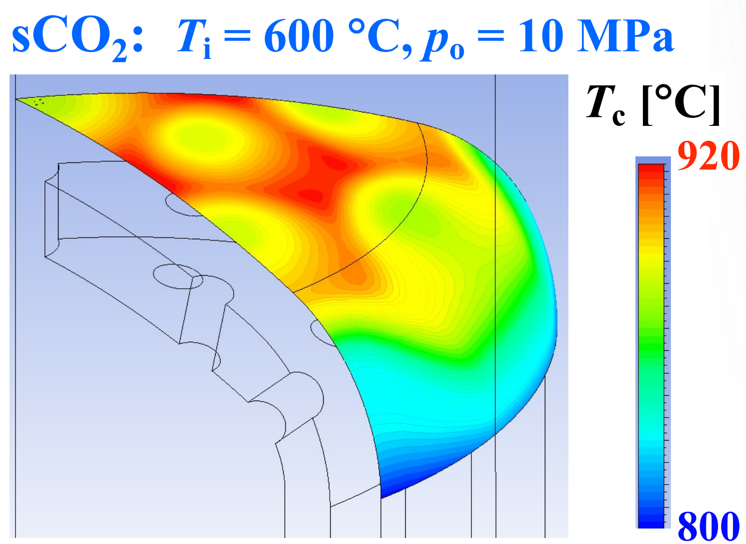
Other Gaseous Coolants

Objective: evaluate supercritical carbon dioxide (sCO_2) *vs.* He as a divertor coolant

- **Fission reactors have used two gaseous coolants: He and CO_2**
  - CO_2 coolant for Magnox (1950s), Gen II AGRs (1970s)
    - AGRs: dissociation of CO_2 into CO and O_2 (especially at higher temperatures > 600 °C) results in oxidation of graphite, metals
- **Focus on supercritical CO_2: critical point (7.38 MPa, 31 °C)**
  - High densities ⇒ compact, high efficiency power cycles
    - Evaluation of various sCO_2 power cycles using heat from DEMO **Stepanek *et al.* 20**
  - Evaluate thermo-fluids performance of sCO_2 as (last?) part of the FESS Next Study
    - Nu, K_L ⇒ estimate maximum heat flux and pumping power under prototypical conditions
    - Exploit existing validated numerical models of HEMJ

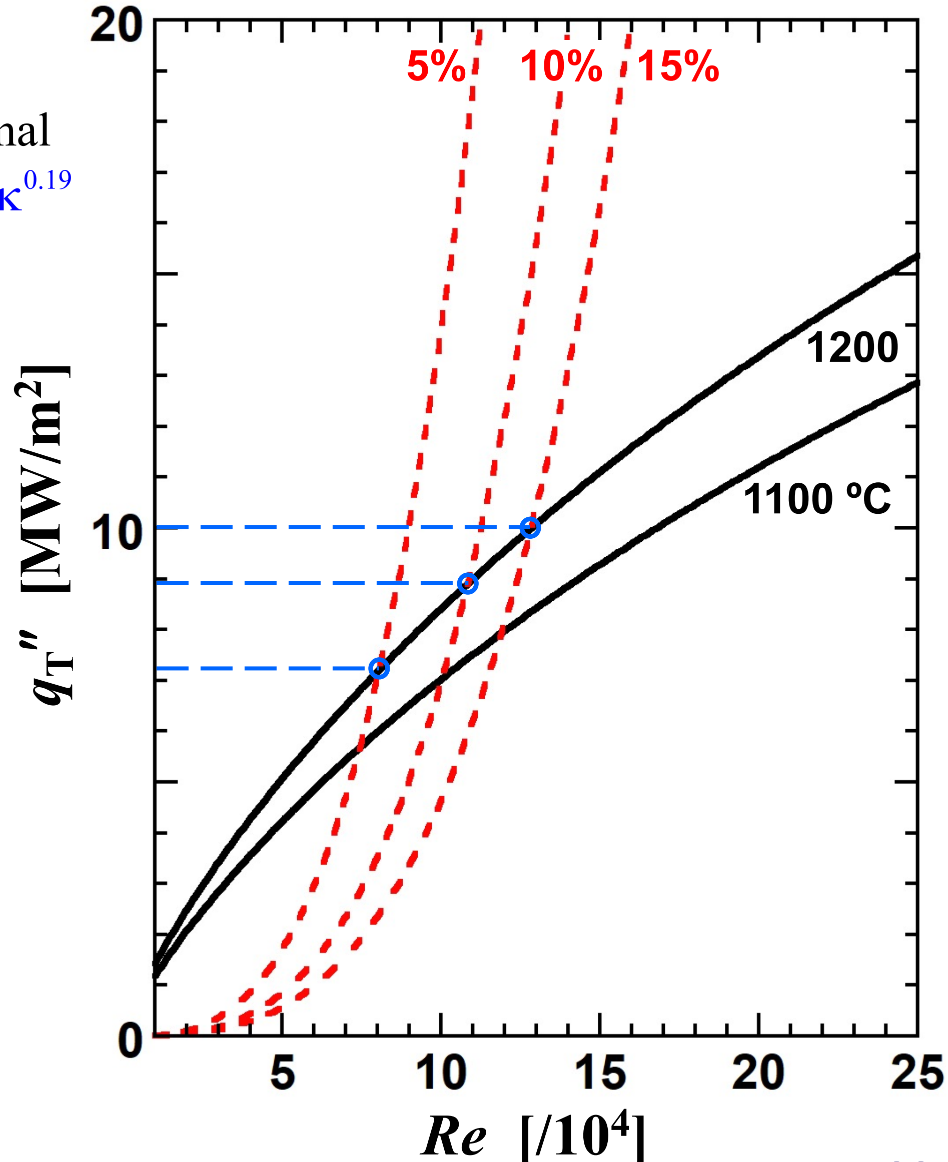
sCO_2 Simulations

- **Numerical model of 60° wedge of HEMJ**
  - Commercial CFD software (FLUENT)
    - Unstructured hexahedral mesh with enhanced wall functions: 6.2M elements
    - Standard k-ε turbulence model
    - Specify q'', $\dot{m}$, T_i, p_o; adiabatic walls (except top wall)
- **Constrained by temperature limits on materials**
  - For sCO_2, much higher mass flow rate $\dot{m}_C$ = 59 g/s ($Re = 2\times10^5$) to match cooled surface temperatures T_c to those for He at $Re_p = 2.2\times10^4$
    - Higher HTC with He



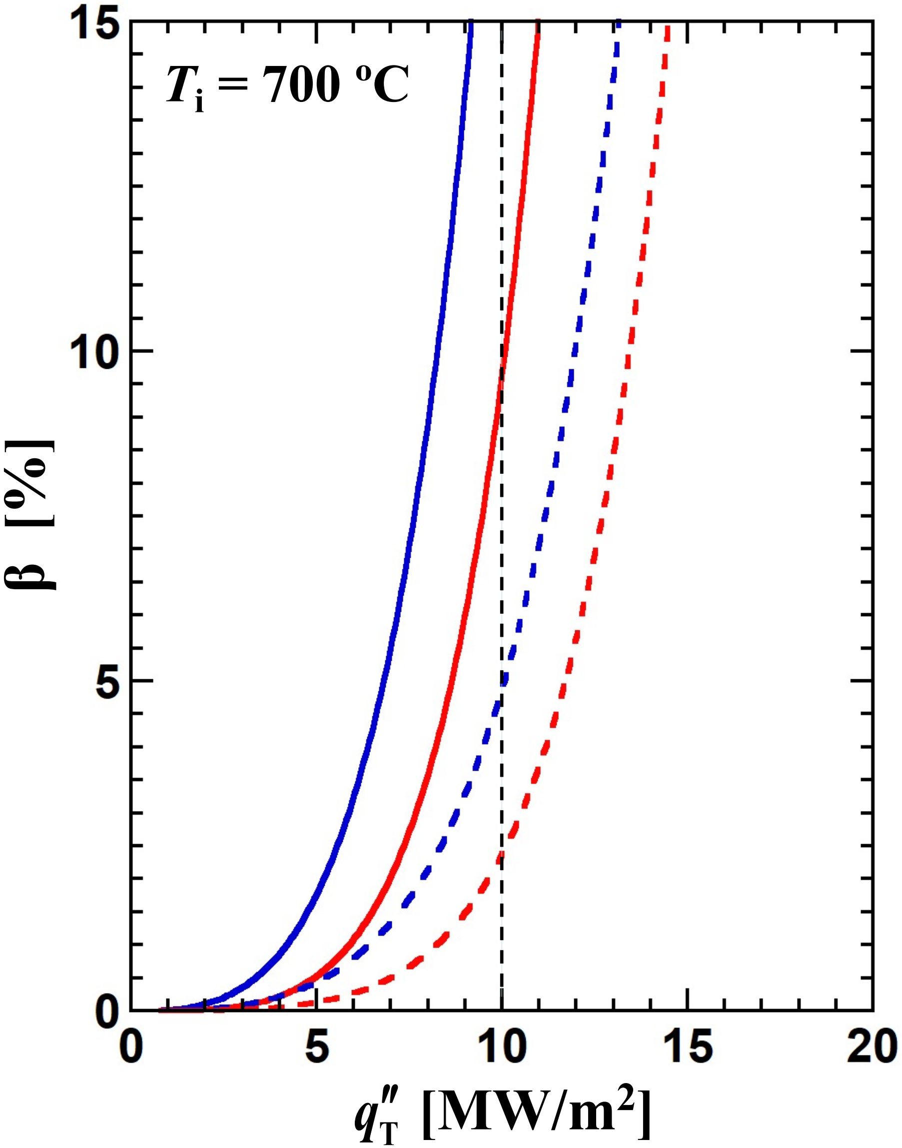
sCO_2 Performance Curves

- **Simulation results at p_o = 10 MPa**
  - $Nu = 0.00626 Re^{0.837} \kappa^{0.19}$ ($\kappa \equiv k_s / k$ thermal conductivity ratio), *vs.* $Nu = 0.0377 Re^{0.687} \kappa^{0.19}$ for He
  - $K_L \approx 1.84$, *vs.* 1.73 for He
- **Estimate maximum incident heat flux on tile q''_T removed at T_i = 600 °C, $p \approx$ 10 MPa**
  - Max. average pressure boundary temperature T_s = **1100 °C, 1200 °C**
  - sCO_2 pumping power fraction **β = 5%, 10%, 15%**
- **New performance curves**
  - For given T_s, determine $\beta(q''_T)$
    - *Re* increases as β and q''_T increase



New Performance Curves

- **Pumping power fraction β as a function of max. incident heat flux on tile q''_T removed for constant T_s = 1200 °C**
  - sCO$_2$ *vs.* He for p = 10 MPa (—) and 20 MPa (– –) at T_s = 1200 °C
  - β higher for sCO$_2$ for given set of conditions ⇒ He has better thermo-fluids performance



sCO_2 vs. He

- Heat flux on tile q''_T (and *Re*) at p_o = 10 MPa

T_i = 600 °C

	β = 5%		β = 10%	
	T_s = 1100 °C	T_s = 1200 °C	T_s = 1100 °C	T_s = 1200 °C
sCO_2	7.0 MW/m² (9.9×10^4)	8.8 MW/m² (1.1×10^5)	8.6 MW/m² (1.3×10^5)	10.8 MW/m² (1.4×10^5)
He	9.1 MW/m² (2.0×10^4)	11.3 MW/m² (2.2×10^4)	10.5 MW/m² (2.7×10^4)	13.1 MW/m² (2.9×10^4)

T_i = 700 °C

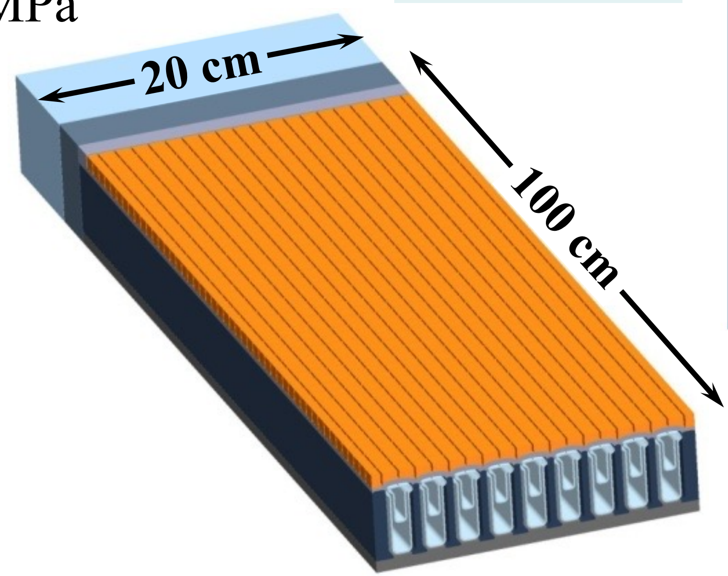
	β = 5%		β = 10%	
	T_s = 1100 °C	T_s = 1200 °C	T_s = 1100 °C	T_s = 1200 °C
sCO_2	5.2 MW/m² (7.8×10^4)	6.8 MW/m² (8.5×10^4)	6.3 MW/m² (1.0×10^5)	8.3 MW/m² (1.1×10^5)
He	6.6 MW/m² (1.6×10^4)	8.7 MW/m² (1.7×10^4)	7.8 MW/m² (2.1×10^4)	10.1 MW/m² (2.3×10^4)

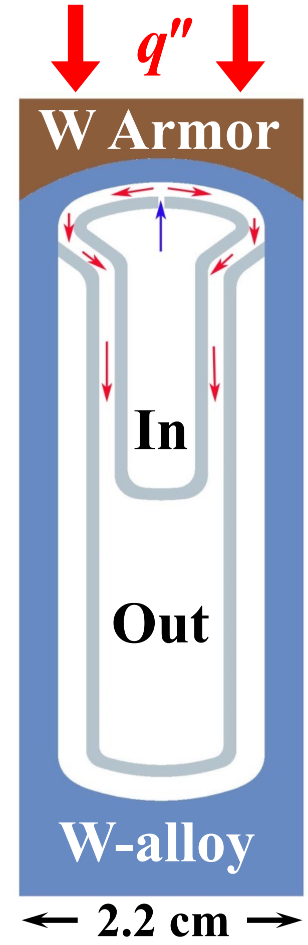
He-Cooled Flat Plate

- **Helium-cooled flat plate (HCFP) divertor**
  - Cool large areas, but at lower $q'' < 8$ MW/m^2

    Hermsmeyer & Malang 02; Wang *et al.* 09
    - $O(10^2)$ plate modules required to cool 150 m^2 target plate, *vs.* $O(10^5)$ "fingers"
  - Experimental studies of HCFP in small GT He loop
    - $\dot{m} \leq 10$ g/s $\Rightarrow$ "short" test section with $L \approx 3$ cm slot to achieve prototypical $Re = 3.3\times10^4$
    - First studies with He at $p \approx 10$ MPa
    - Heat fluxes $q'' < 2$ MW/m^2 from electric cartridge heaters
    - Inlet temperatures $T_i \leq 100$ °C
    - Experiments complemented by numerical simulations at prototypical conditions

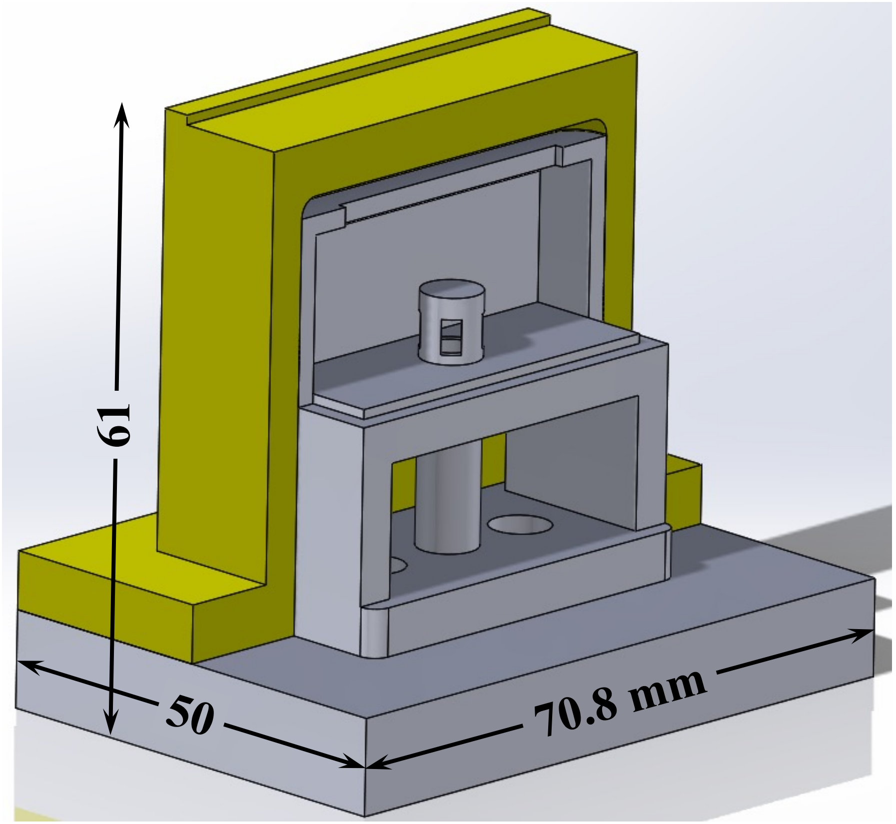
$$Re = \frac{2\dot{m}}{\mu(T_i)L}$$

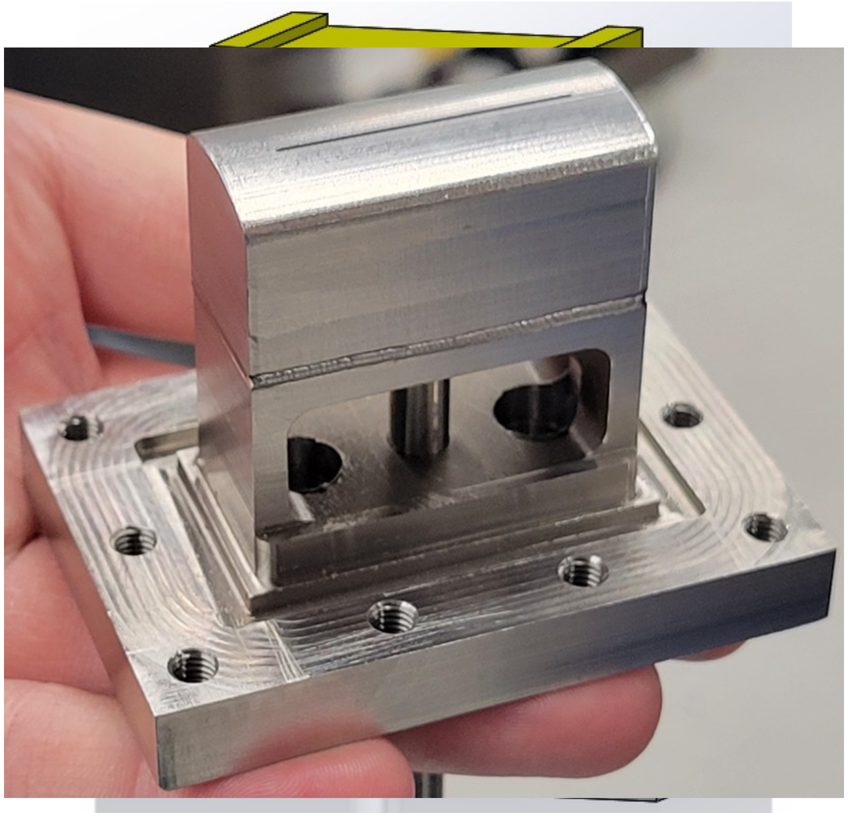




HCFP Test Section

- **Fabricating "short" HCFP test section**
  - Slot: width $W = 0.5$ mm (width) × length $L = 29.8$ mm
  - Stainless 316 inner cartridge + Ampcoloy 944 (Cu-Ni) outer shell





FUTURE WORK

Next steps

- **Reexamine performance curves**
  - Base on maximum (*vs.* average) pressure boundary temperature imposed by material limits
  - Add limits imposed by maximum thermal stresses
- **Helium-cooled flat plate (HCFP) experiments**
  - Develop Nu and K_L correlations and performance curves based on experimental data + numerical simulations at prototypical conditions
- **Numerical analysis: integrate multiple divertor units with first wall**
  - "Tile" outboard side of first wall sector model with individual T-tube units
  - Nonuniform heat flux distribution: curve-fit to simulations by T. D. Rognlien
  - Variations in He mass flow rates to each unit