High-Power Density Target Design and Analyses for Accelerator Production of Isotopes

W. David Pointer
Argonne National Laboratory
Nuclear Engineering Division

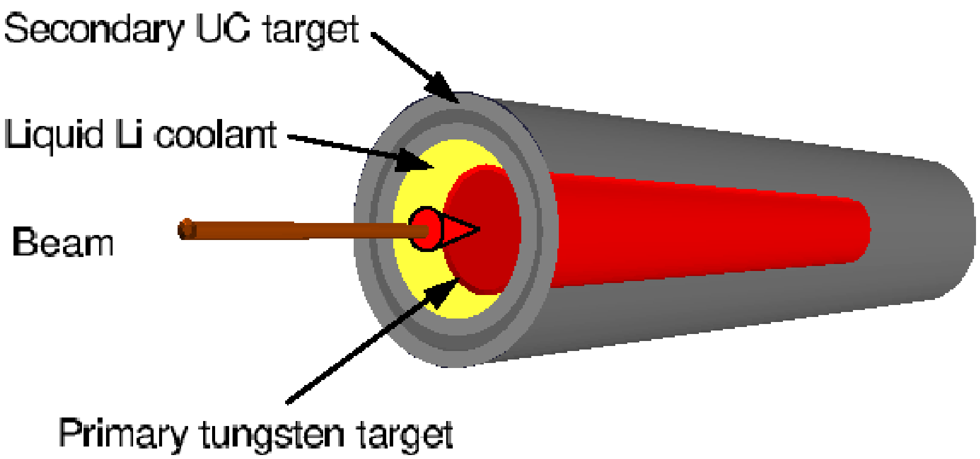
Workshop on Applications of High Intensity Proton Accelerators
Fermi National Accelerator Laboratory
October 20, 2009

Outline

- Purpose
- Design Challenges
- Design Options
- Solid Target Concepts
  - Lithium-cooled Tungsten Pebble Bed
  - Lithium-cooled Tungsten Plate
- Liquid Target Concepts
  - Lead Bismuth Eutectic

Purpose

- Develop a high-power accelerator target concept for use as the primary stage in a two stage isotope production target
  - Neutrons are generated in primary target stage
    - Spallation of heavy metal target material by high energy charged particles
      - Protons, Deuterons, or Helium-3
  - Neutrons are absorbed in second stage
    - Fissioning and decay processes produce desired isotopes in Uranium Carbide target
    - High temperature (~2000 C) maintained in second stage to encourage fission and decay products to diffuse out of second stage target



Design Challenges

- Primary stage target must meet a number of engineering constraints and challenges
  - Physical Constraints
    - Must produce sufficient neutrons to power second stage isotope production target
    - Must be small in size to maximize efficiency of neutron use
      - Ideally cylindrical, <5 cm in diameter and ~9cm long
      - Beam will be approximately 1 cm in diameter with uniform cross-section
  - Structural Constraints
    - Must isolate coolant and target material from vacuum in beam line
      - Must satisfy mechanical stress limits
  - Thermal Constraints
    - Sufficient heat removal needed to maintain structure within acceptable limits
      - Total beam power of ~400kW at 1 GeV
        - » ~1/3 of power deposited in small target
    - Must be thermally isolated from high temperature second stage

Target material/coolant considerations

- Solid Target Options
  - tungsten
    - Good neutron yield
    - Good heat transfer and structural characteristics in new target material
    - High melting point (3422 °C)
    - May be clad when in contact with water or alkali metals
  - uranium alloys
    - Better neutron yield than tungsten
    - Poorer heat transfer in new target material
    - Lower melting point (1000-1400 °C)
    - Many alloys compatible with alkali metals. Likely must be clad in water or air cooled systems
    - Higher decay heat load and longer-lived decay heat load than tungsten target

- Solid Target Coolant Options
  - Air
    - Low heat capacity limits applicability
  - Water
    - Low boiling point → must account for two-phase flow
    - Corrosion management
  - Lithium
    - Excellent conductivity, but low heat capacity compared to other coolants
  - Sodium
    - Better heat capacity than lithium
  - Mercury
    - Power generation in coolant limits applicability
    - Potential for two-phase and non-wetting issues
  - Lead or Lead-Bismuth Eutectic
    - Power generation in coolant limits applicability

Target material/coolant considerations

- Liquid Target Options
  - mercury
    - Good neutron yield
    - Good heat transfer characteristics
    - Low boiling point (357 °C) → may have two phase flows
    - Liquid at room temperature
    - Does not wet many materials well → careful surface preparation required
  - lead
    - Better neutron yield per proton, but longer stopping distance than mercury
    - Higher boiling point (1749 °C)
    - High melting point (327.46 °C)
    - Erodes structural materials in high speed turbulent flows
    - Wets most structural materials
  - Lead-Bismuth Eutectic
    - Similar neutron yield to pure lead
    - High boiling point (~1700 °C)
    - Low melting point (123.5 °C)
    - Erodes structural materials like lead
    - Wets most structural materials like lead
    - Higher polonium production → higher decay heat load

Design Options

Liquid Lead-Bismuth Eutectic Target vs. Lithium-Cooled Solid Tungsten Target

	Advantages	Disadvantages
Lithium-Cooled Solid Tungsten	• Short stopping distance yields more neutrons in small target length • Most spallation products are contained within solid target material • High thermal conductivity and heat capacity in solid target • High thermal conductivity in coolant • Potentially simplified target handling procedures	• Small stopping distance leads to much higher power density • Coolant channels must be built into target, increasing target length • Higher activity in waste products, decay heat removal issues • Low heat capacity in coolant • Oxygen content must be controlled to prevent fire • Interaction between liquid lithium and common structural materials largely unknown • Tungsten must be clad in stainless steel
Liquid Lead-Bismuth Eutectic	• Higher neutron yield per incident proton • Single coolant and target material • No need for complex structure to accommodate coolant channels • Good thermal conductivity and heat capacity • Very high boiling point • Spallation products can be removed on-line using cold trap technology • No danger of fire with oxygen exposure	• Longer stopping distance requires longer target • Oxygen content must be carefully controlled to limit corrosion • Fluid velocities must be carefully controlled to prevent erosion • High density coolant requires more robust structure • Potentially more complex target handling procedures

Solid Tungsten Target Design

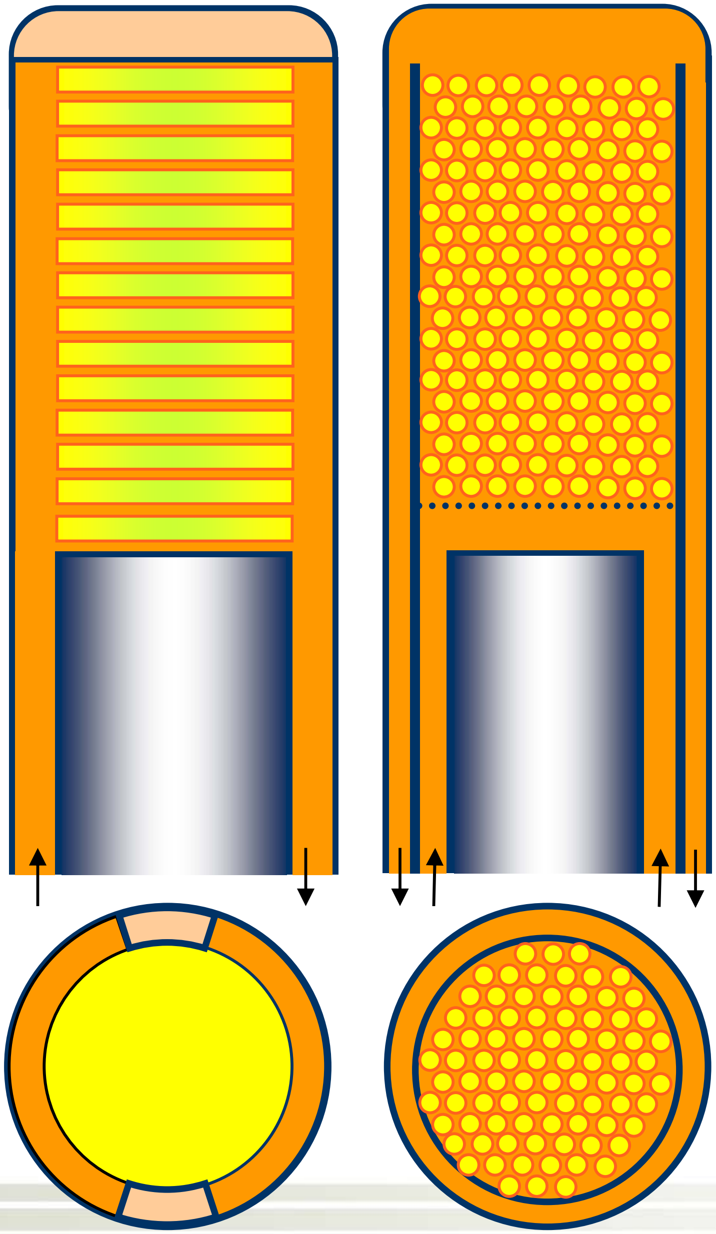
Tungsten Plate Target vs. Tungsten Pebble Bed Target

Advantages

- Simple Construction
- Low Pressure Drop
- Separate Window Cooling Channel

Disadvantages

- Low Volume Fraction of Target Material
- Plate Deformation Limits Target Life



Advantages

- High Volume Fraction of Target Material
- Annular Design Provides Thermal Isolation
- Target Material Can Deform Freely

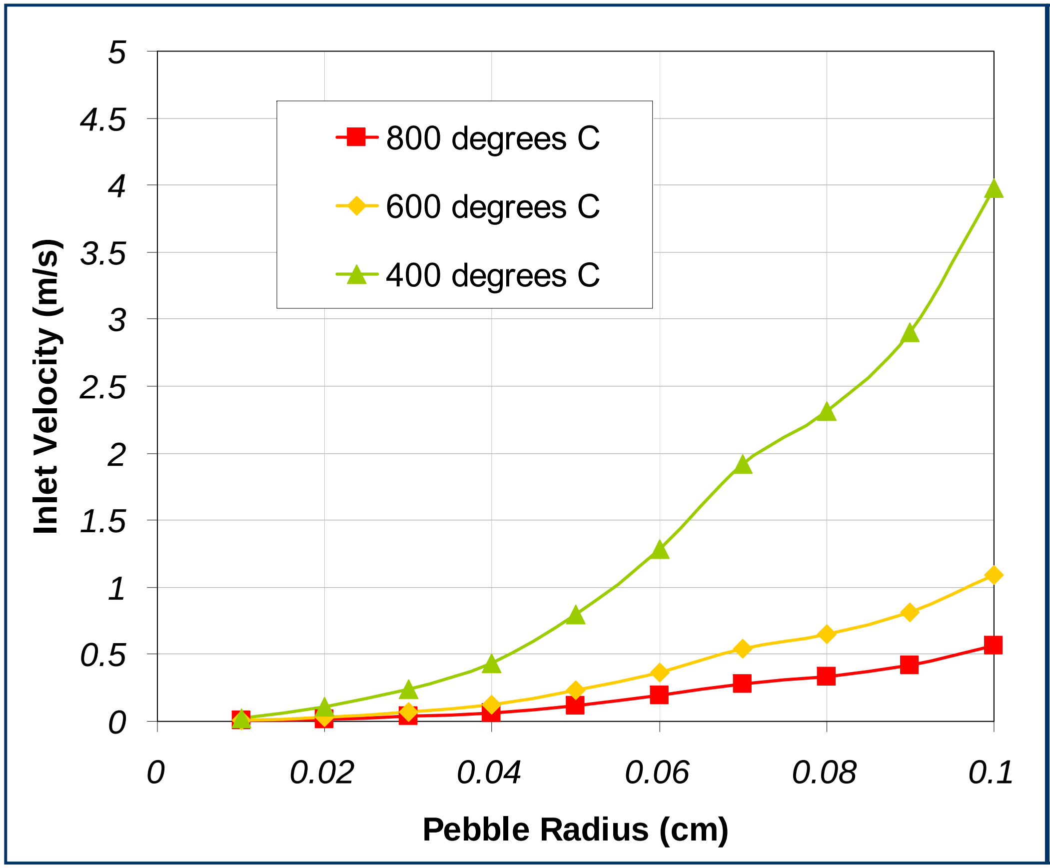
Disadvantages

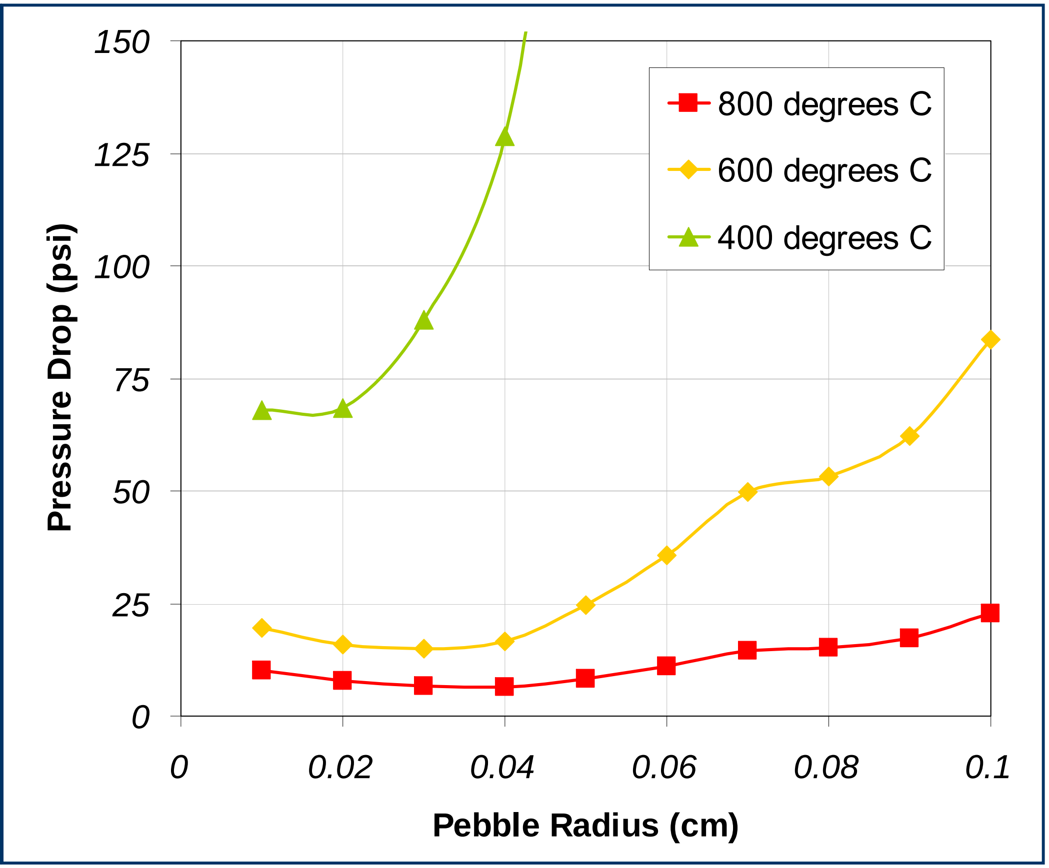
- More Complex Construction
- Manufacture of Very Small Pebbles May Not Be Feasible
- High Pressure Drop
- Integrated Window Cooling

Heat Transfer In Tungsten Pebble Bed Target

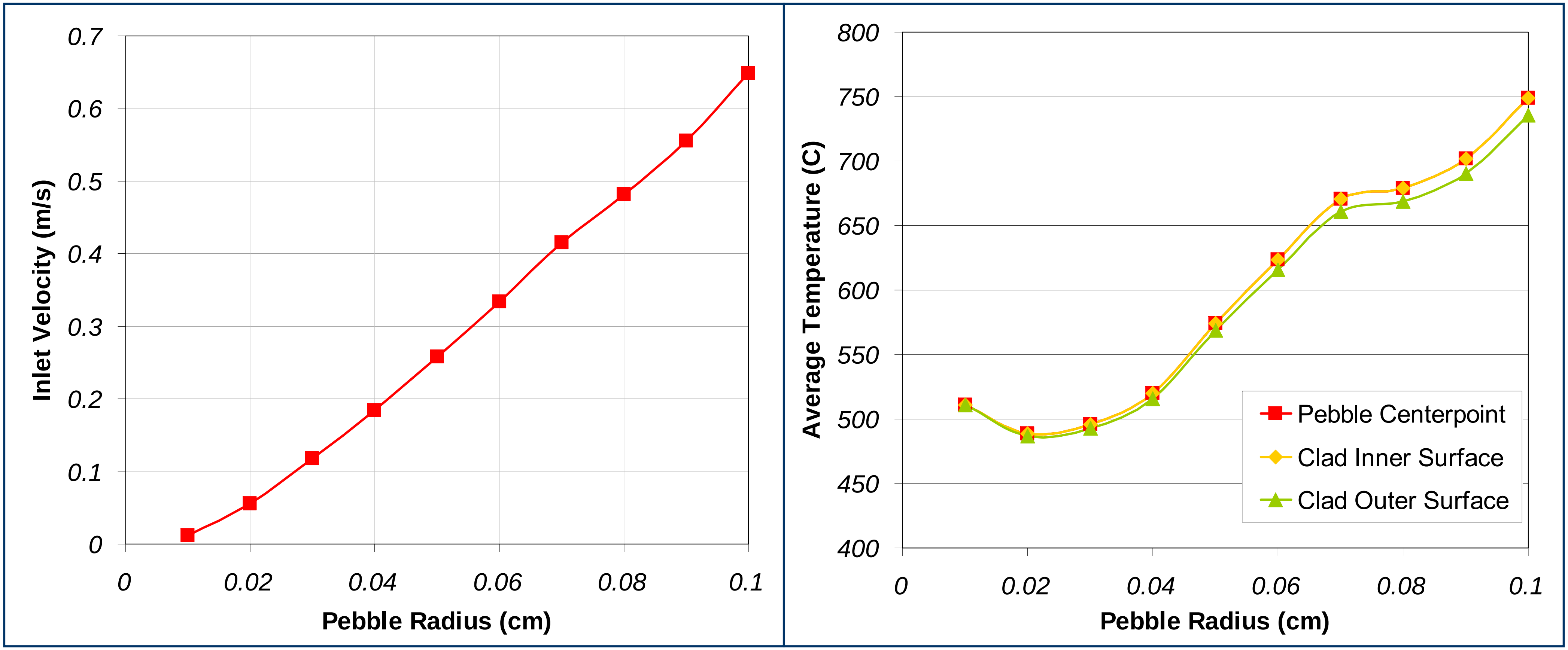
- Assumptions
  - Use average heat generation rate within beam radius throughout target (130 kW)
    - Total target power is over estimated
    - Peak target power is underestimated
  - Neglect conduction between pebbles
  - Calculated pebble-averaged temperatures
    - Does not account for hot spots at contact points
  - Coolant Inlet Temperature = 523 K
    - ~50 K above melting point
  - Cladding Thickness = 0.1 mm
- Consider three limiting cases to examine effects of pebble size on performance
    - Constant centerline temperature
    - Constant pressure drop
    - Constant inlet fluid velocity

Pebble Bed – Constant Centerpoint Temperature



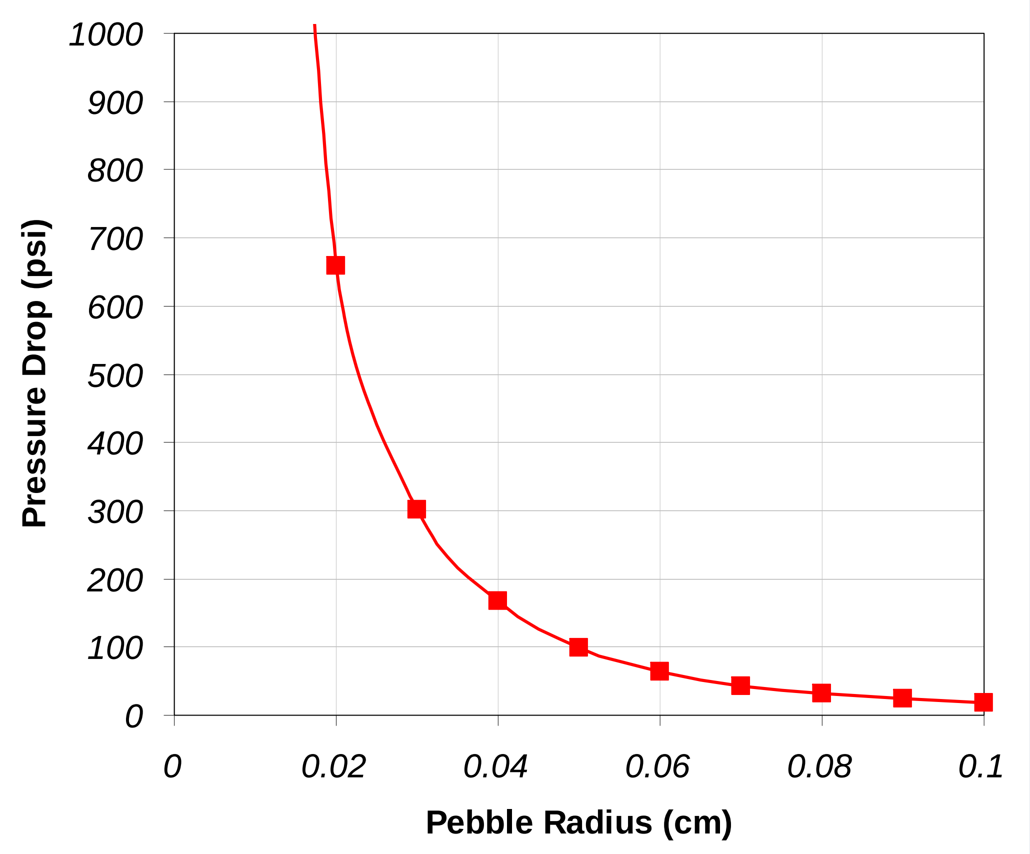


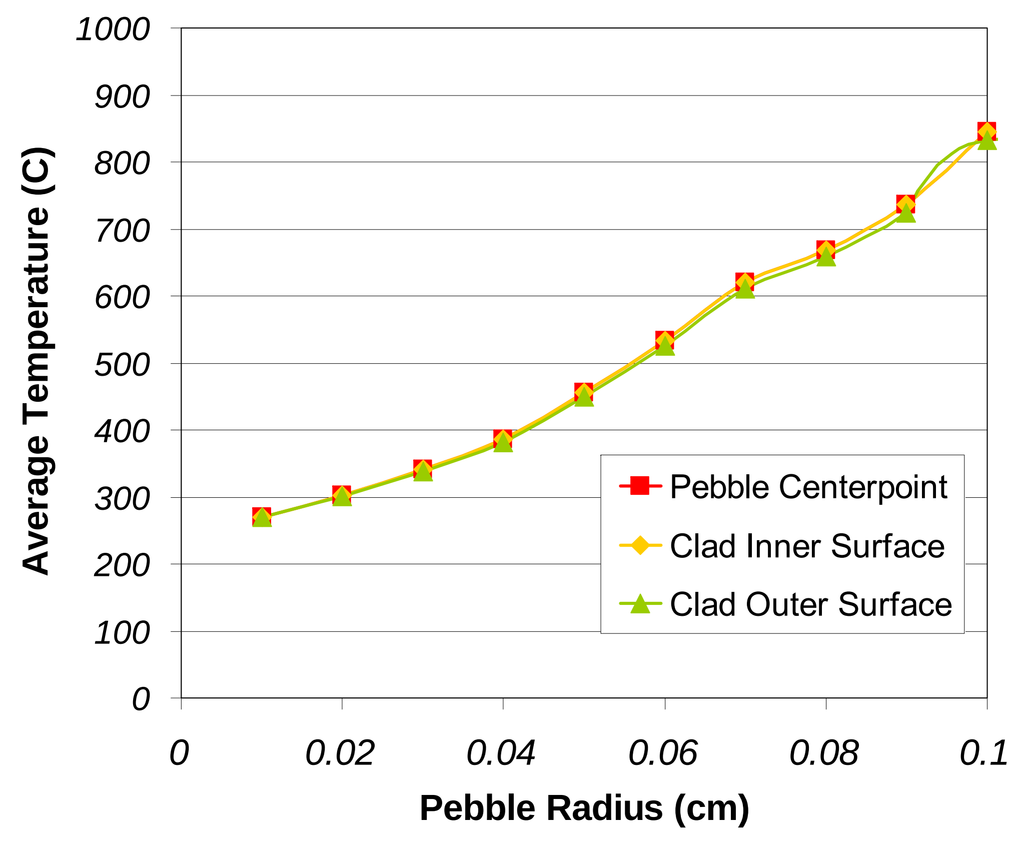
Pebble Bed – Constant Pressure Drop



Target Pressure Drop = 30 psi

Pebble Bed – Constant Inlet Velocity





V = 0.5 m/s

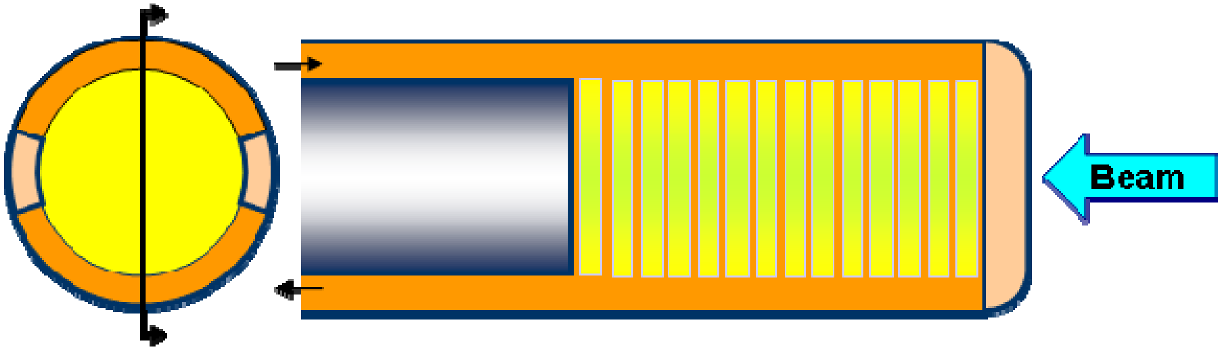
Pebble Bed Target Concept Conclusions

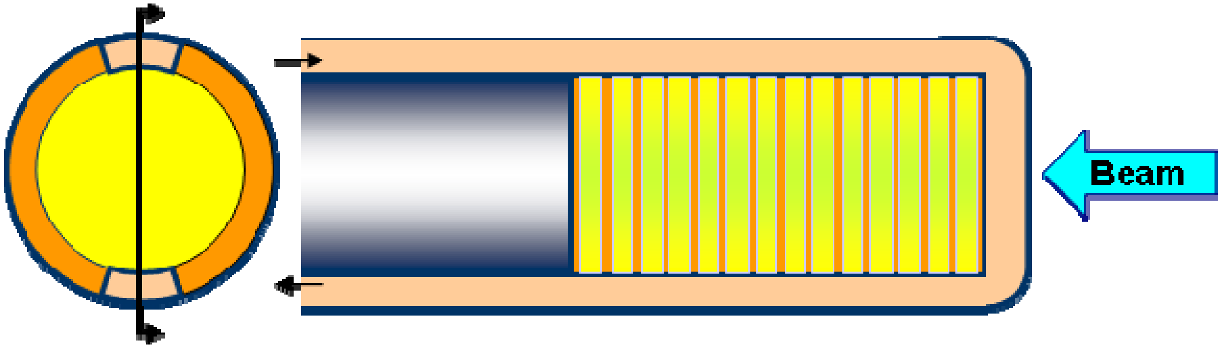
- Pebble bed target could be developed to satisfy thermal requirements
- Many manufacturing challenges
  - Construction of steel clad tungsten pebbles
    - Diameter less than 1 mm
  - Arrangement of small pebbles in target
    - Randomly distributed pebble beds introduce large uncertainties
      - Neutron production
      - Thermal performance
- Many development challenges
  - Analysis of peak temperatures
    - Contact points between pebbles
    - Heat deposition distribution
  - Analysis of mechanical behavior of pebble/clad
- Pursue plate-type target as primary option

Tungsten Plate Target Concept

- Easy to construct
- Plates are easily clad if necessary
- Lower pressure drop than a pebble bed

- Less surface area available for heat removal
- Lower target material volume fraction than a pebble bed
- Must give special attention to beam window cooling

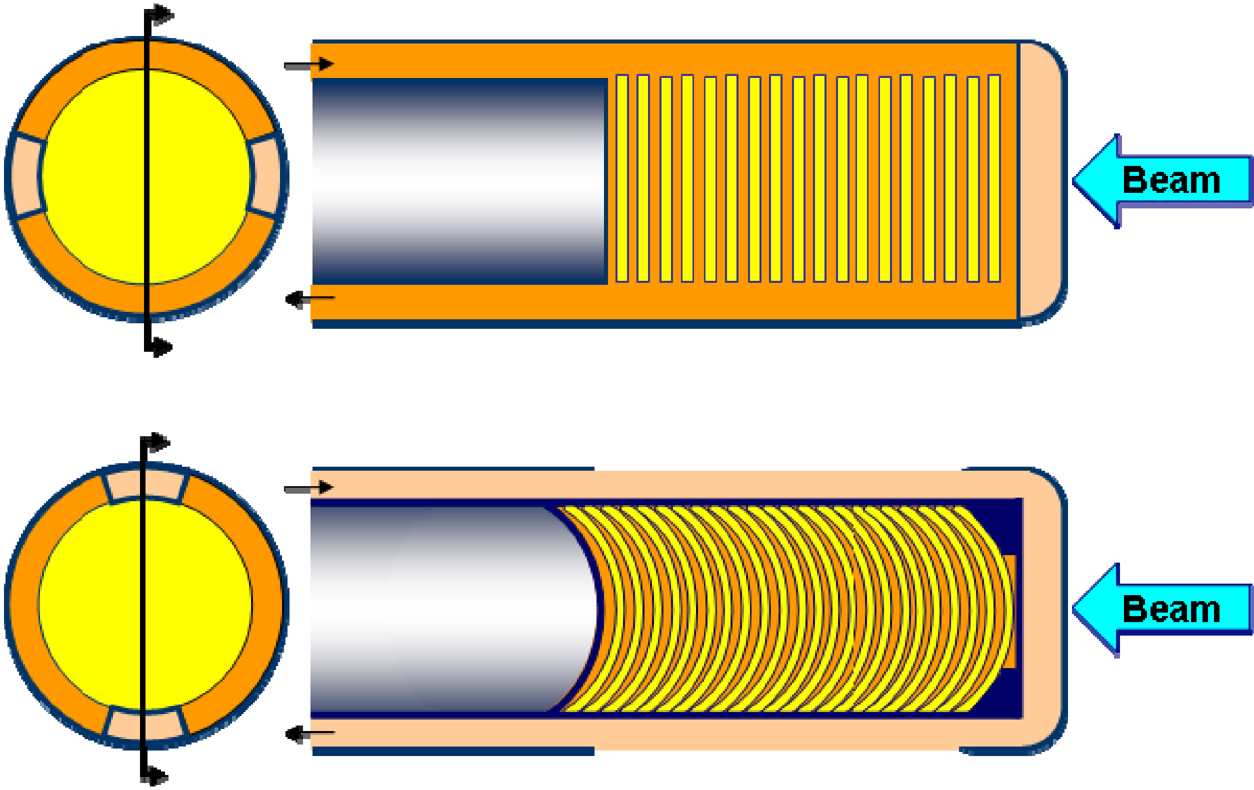




Tungsten Plate Target Concept

- Easy to construct
- Plates are easily clad if necessary
- Lower pressure drop than a pebble bed

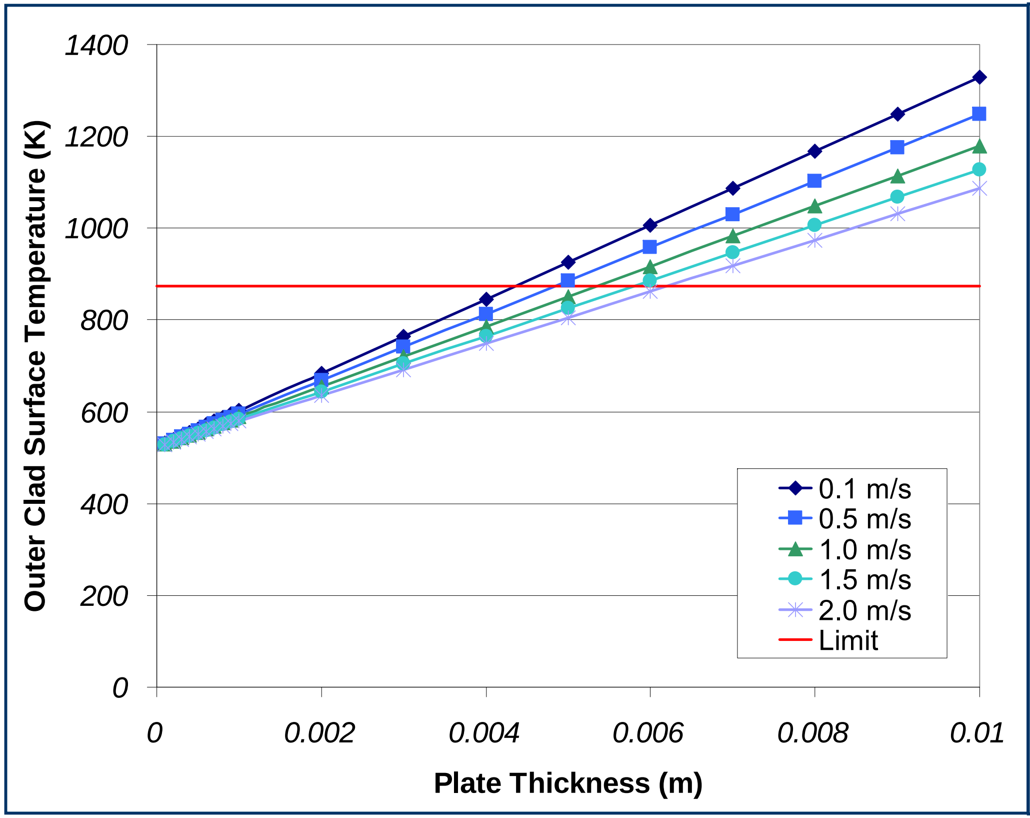
- Less surface area available for heat removal
- Lower target material volume fraction than a pebble bed
- Must give special attention to beam window cooling

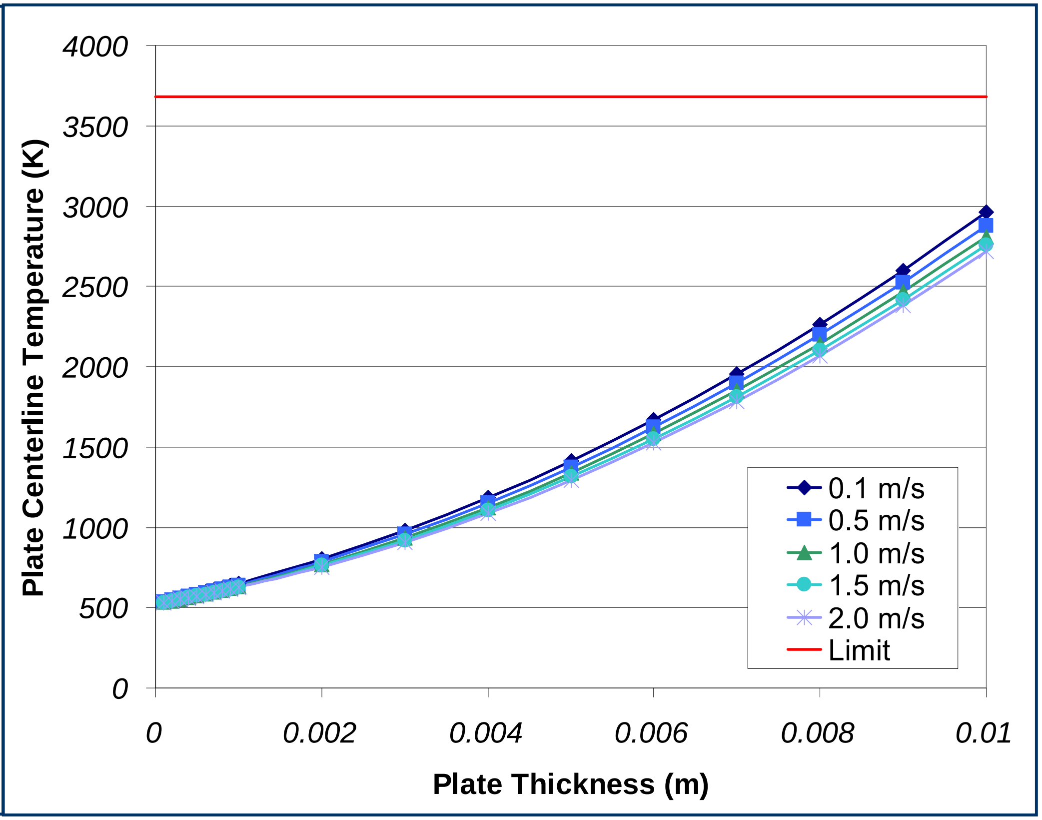


Heat Transfer In Tungsten Plate Target

- Assumptions
  - Use average heat generation rate within beam radius throughout target
    - Total target power is over estimated
    - Peak target power is underestimated
  - Calculate plate-averaged temperatures
    - Does not account for radial temperature distribution
  - Coolant Inlet Temperature = 523 K
    - ~50 K above melting point
  - Cladding Thickness = 0.1 mm
- Consider effects of four parameters on performance
    - Plate thickness
    - Inlet velocity
    - Coolant gap width
    - Clad thickness

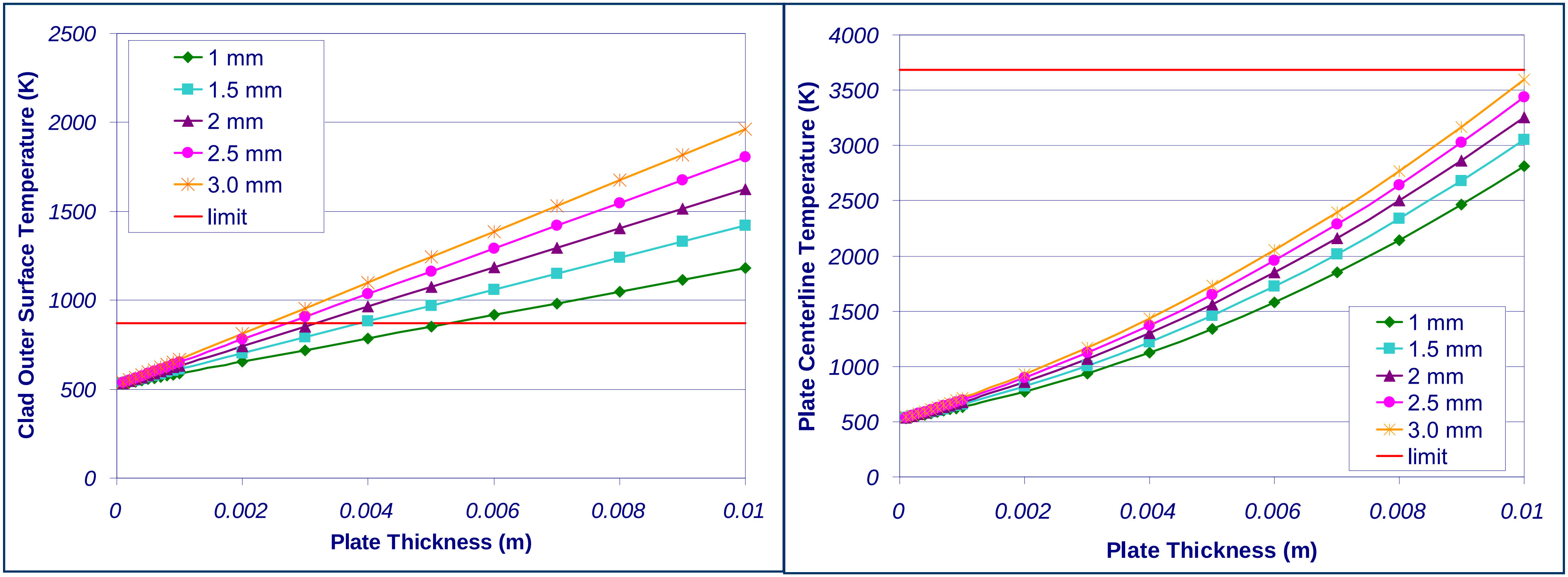
Plate Target – inlet velocity and plate thickness





Clad thickness = 0.1 mm
Gap width = 1.0 mm

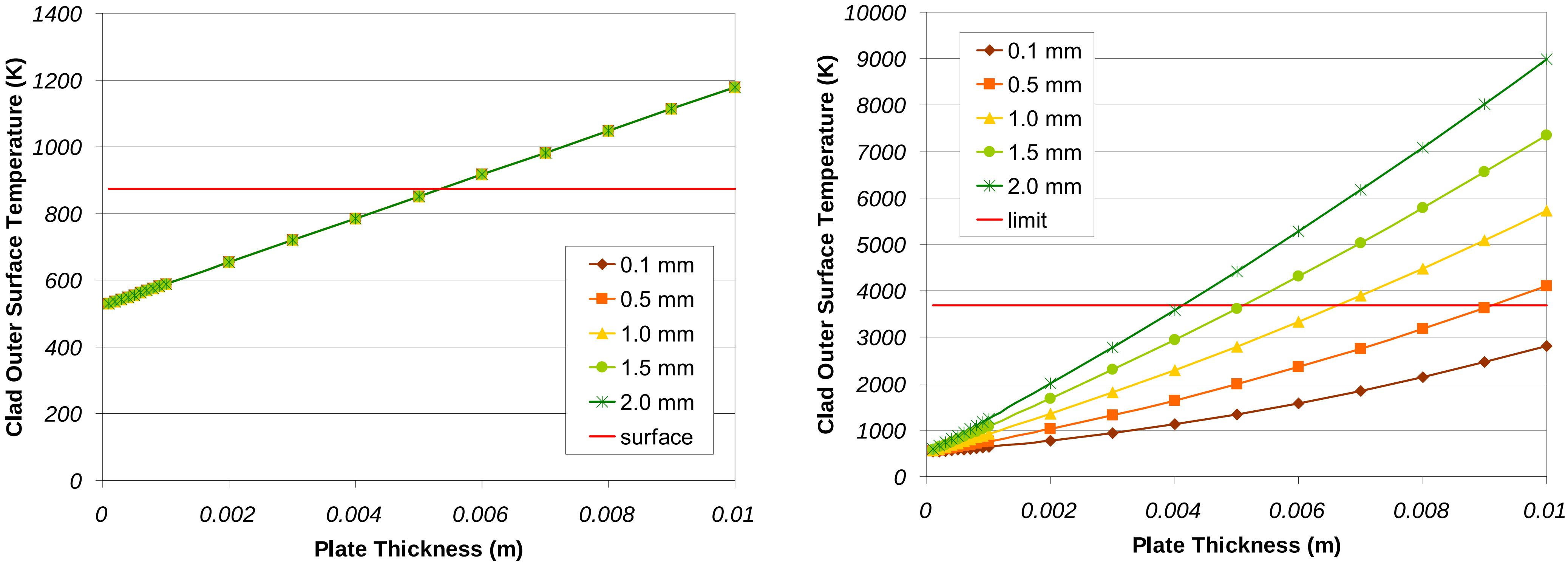
Plate Target – gap width and plate thickness



Clad thickness = 0.1 mm

Inlet velocity = 1.0 m/s

Plate Target – clad thickness and plate thickness



Gap width = 1.0 mm

Inlet velocity = 1.0 m/s

Channel width optimization for fixed coolant channel velocity

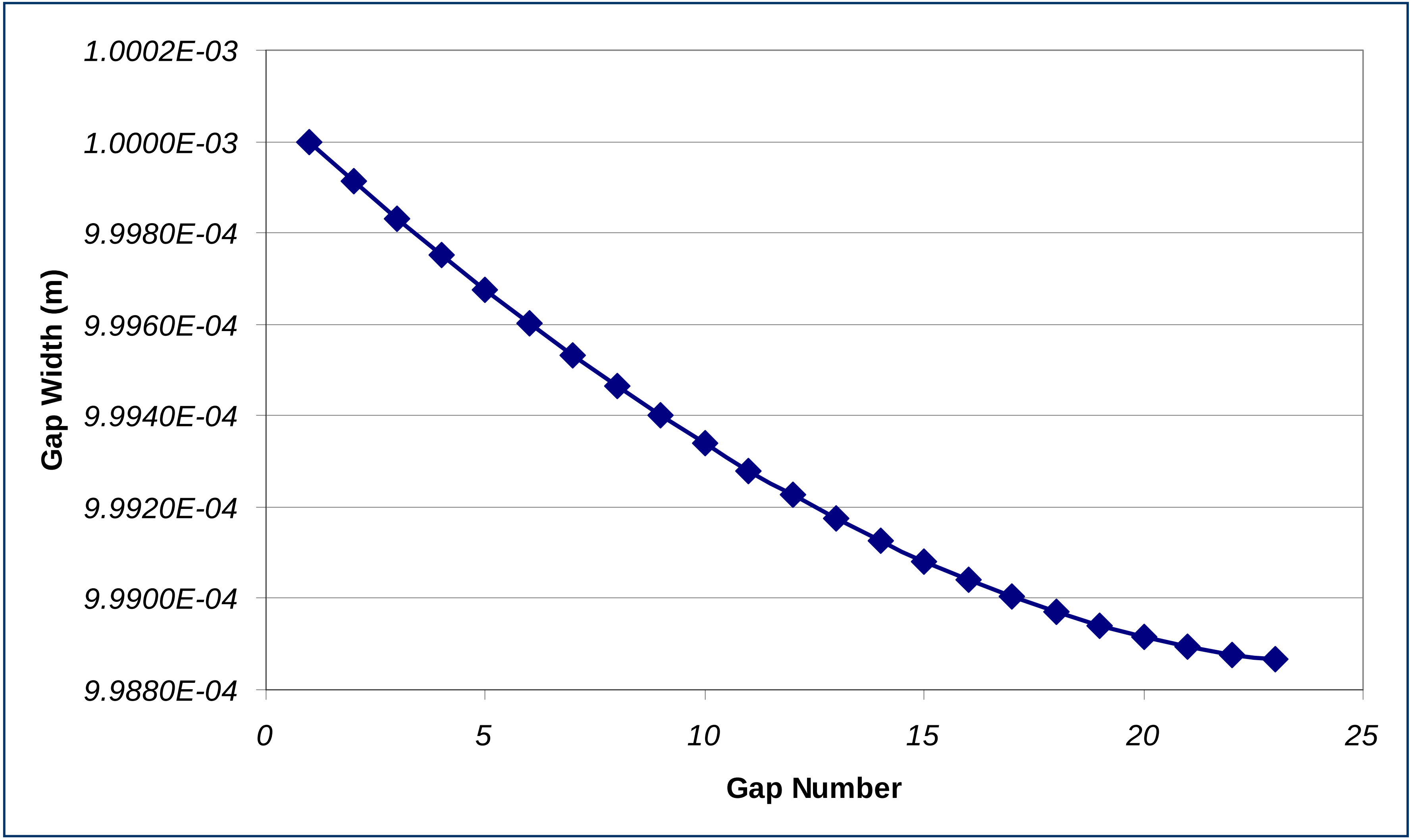


Plate thickness = 3 mm
21 plates

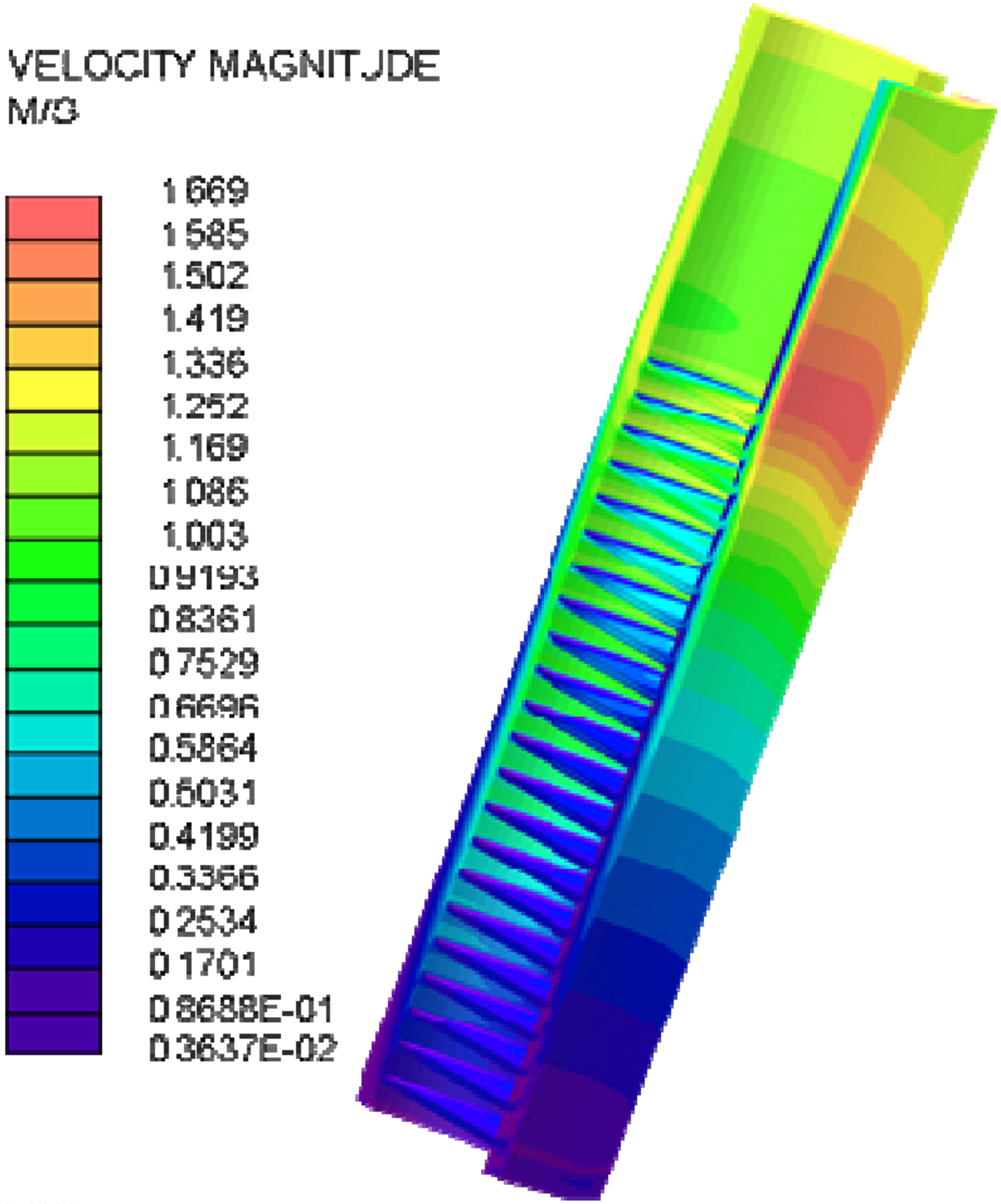
Channel Velocity = 1.0 m/s
Pressure Drop = ~800 Pa

Computational Fluid Dynamic Studies

- Use the commercial CFD code Star-CD
- Apply 3-dimensional CFD simulations for
  - Confirmation of conclusions drawn from scaling studies
  - Evaluation of effects of radial conduction of heat in solid components and convection of heat in the coolant away from the region heated by the particle beam
  - Approximation of localized peak temperatures
- Modeling Strategy
  - Solid Target
    - Consider tungsten plate cooling and beam window cooling separately
    - Consider one symmetric half of the target geometry
  - Liquid Target
    - Consider a 10° wedge of the target geometry
- Modeling assumptions
  - Uniform volumetric heat source in target materials
    - Limited to region actually heated by the particle beam
  - Constant velocity condition at model inlet
  - Zero gradient condition at model outlet

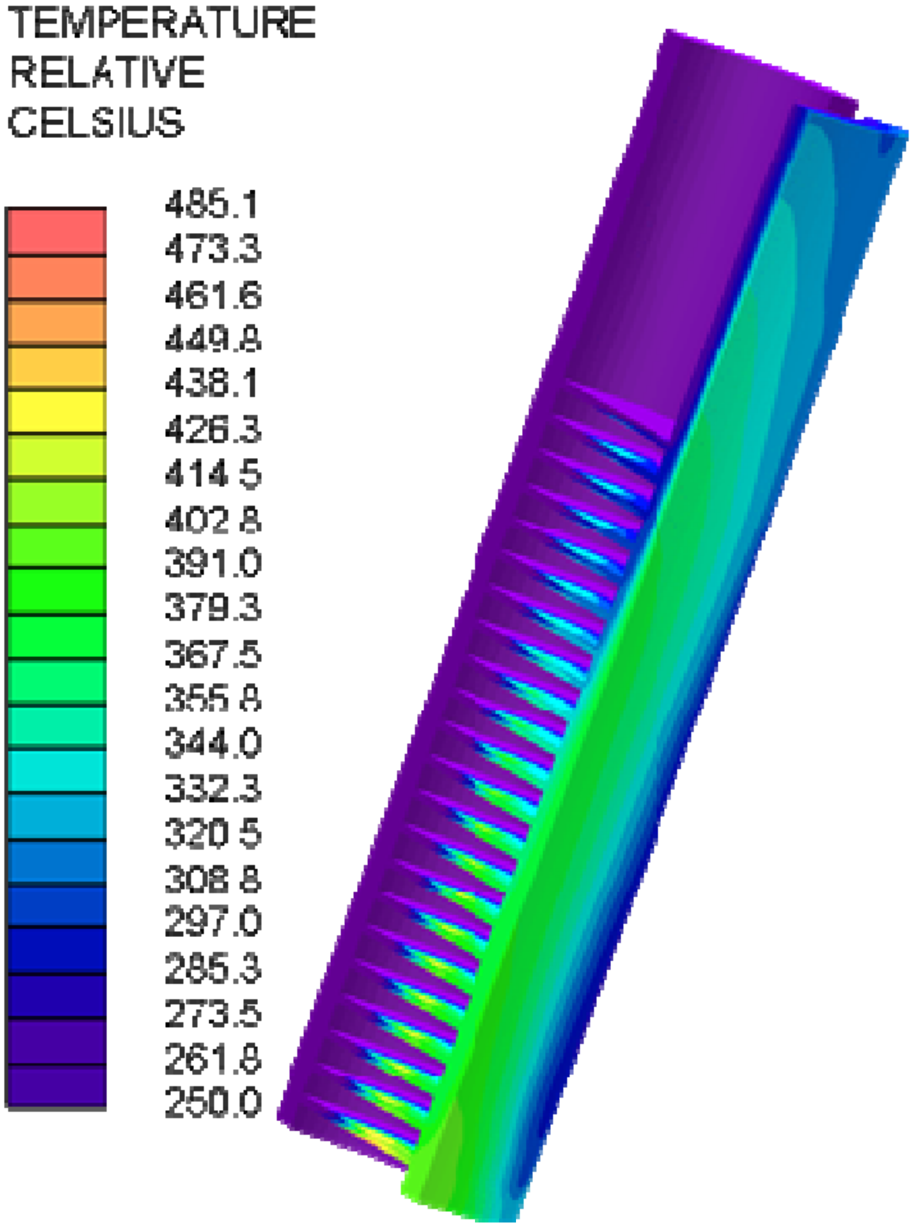
Solid Target Plate Cooling

- Model
  - Approximately 300,000 computational volume elements
  - $V_{in} = 1$ m/s
  - $T_{in} = 250$ °C
- Results
  - Channel velocities
    - $0.1 < V_C < 1.1$ m/s
  - Peak surface temperature
    - 485 °C
  - Peak solid temperature
    - 527 °C



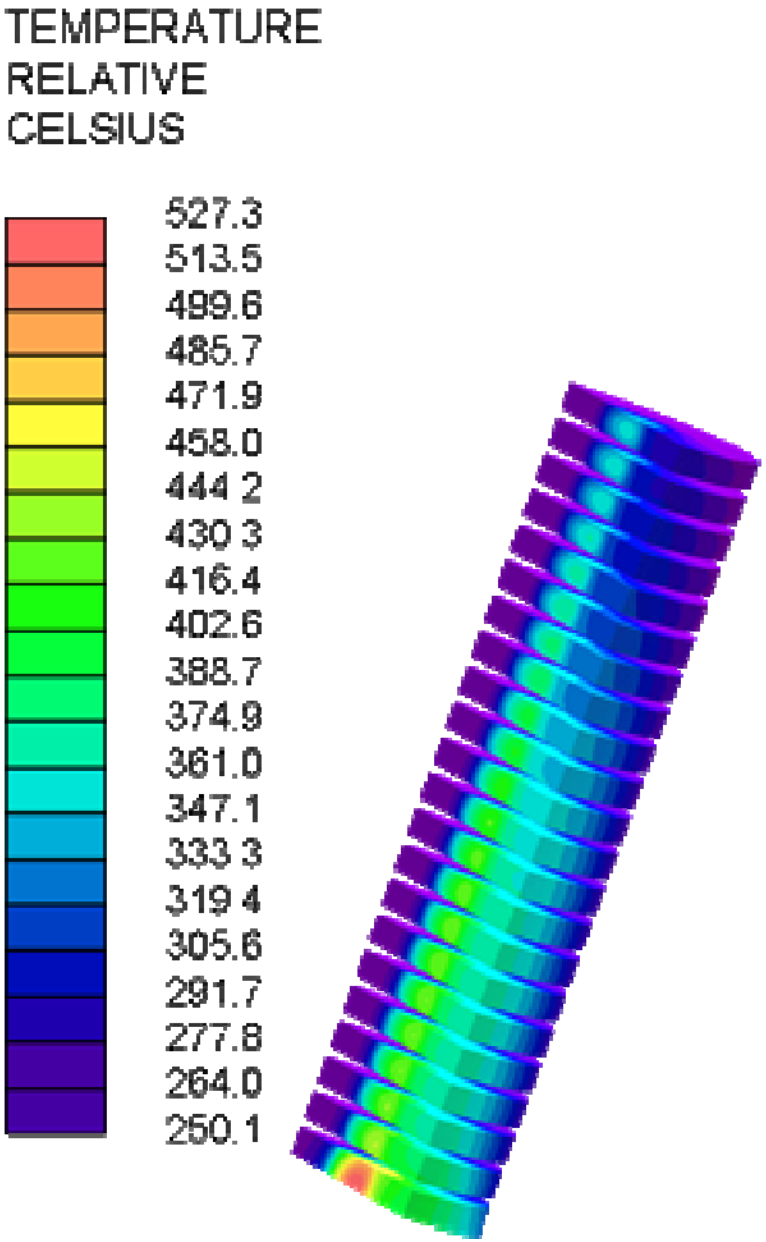
Solid Target Plate Cooling

- Model
  - Approximately 300,000 computational volume elements
  - V_{in}= 1 m/s
  - T_{in}= 250 °C
- Results
  - Channel velocities
    - $0.1 < V_C < 1.1$ m/s
  - Peak surface temperature
    - 485 °C
  - Peak solid temperature
    - 527 °C



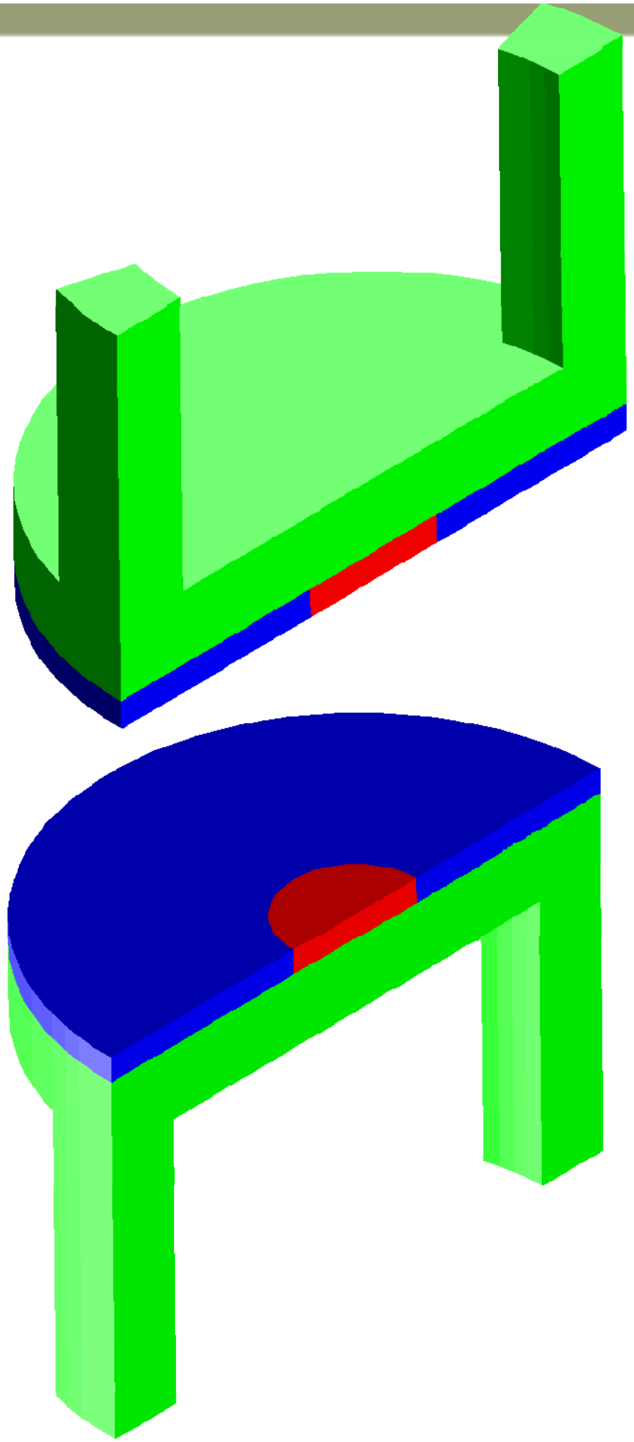
Solid Target Plate Cooling

- Model
  - Approximately 300,000 computational volume elements
  - V_{in}= 1 m/s
  - T_{in}= 250 °C
- Results
  - Channel velocities
    - $0.1 < V_C < 1.1$ m/s
  - Peak surface temperature
    - 485 °C
  - Peak solid temperature
    - 527 °C



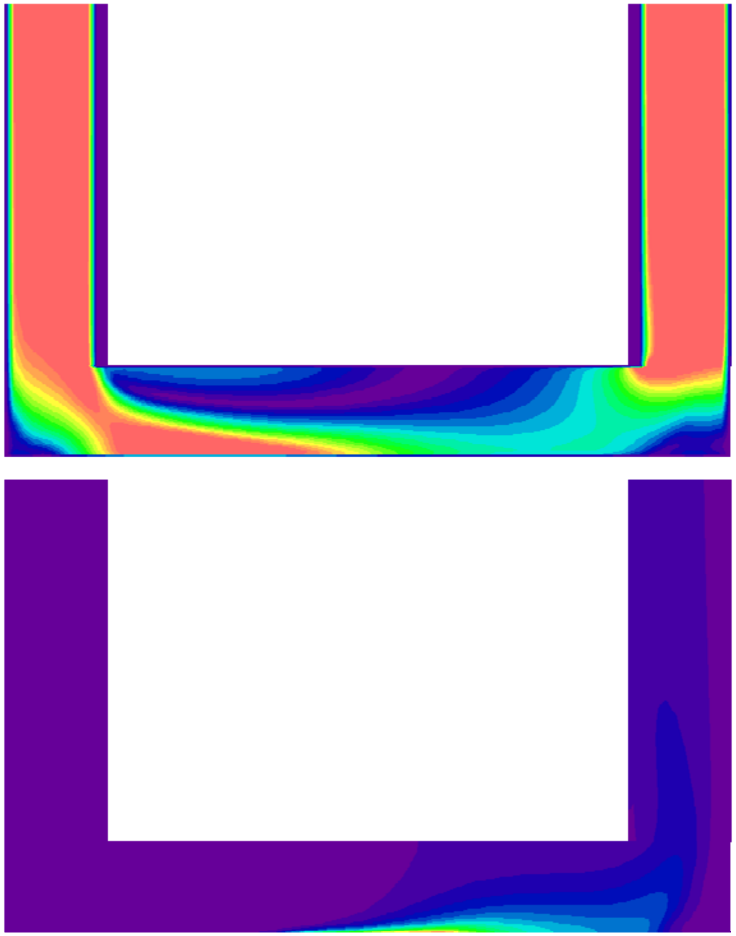
Solid Target Window Cooling

- Model
  - Approximately 125,000 computational volume elements
  - One symmetric half of geometry
  - Parametrically evaluate effect of stainless steel beam window thickness
- Result
  - Limit thickness to no more than 2.0 mm



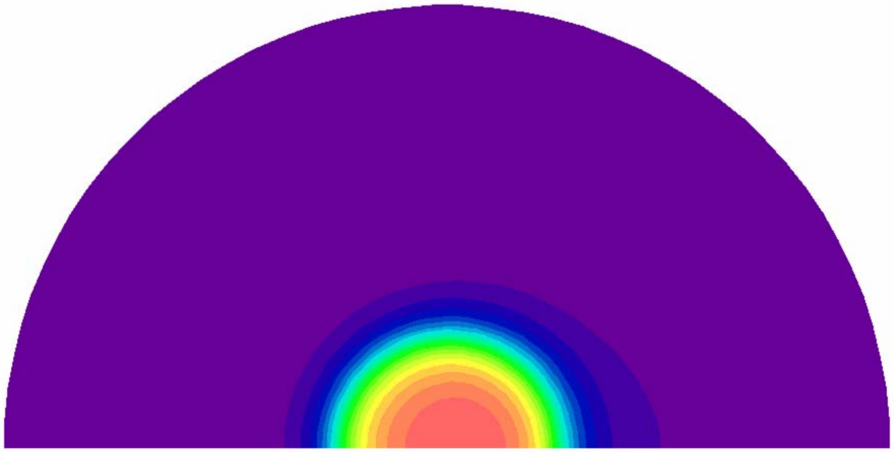
Solid Target Window Cooling

- Model
  - Approximately 125,000 computational volume elements
  - One symmetric half of geometry
  - Parametrically evaluate effect of stainless steel beam window thickness
- Result
  - Limit thickness to no more than 2.0 mm

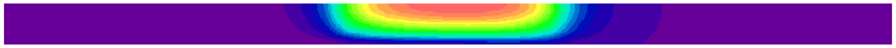


Solid Target Window Cooling

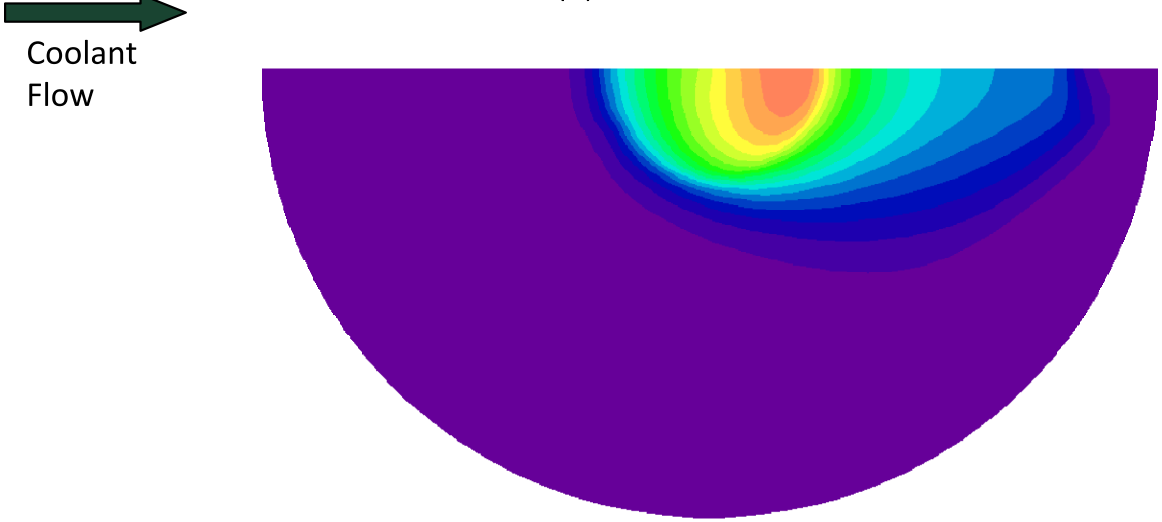
- Model
  - Approximately 125,000 computational volume elements
  - One symmetric half of geometry
  - Parametrically evaluate effect of stainless steel beam window thickness
- Result
  - Limit thickness to no more than 2.0 mm



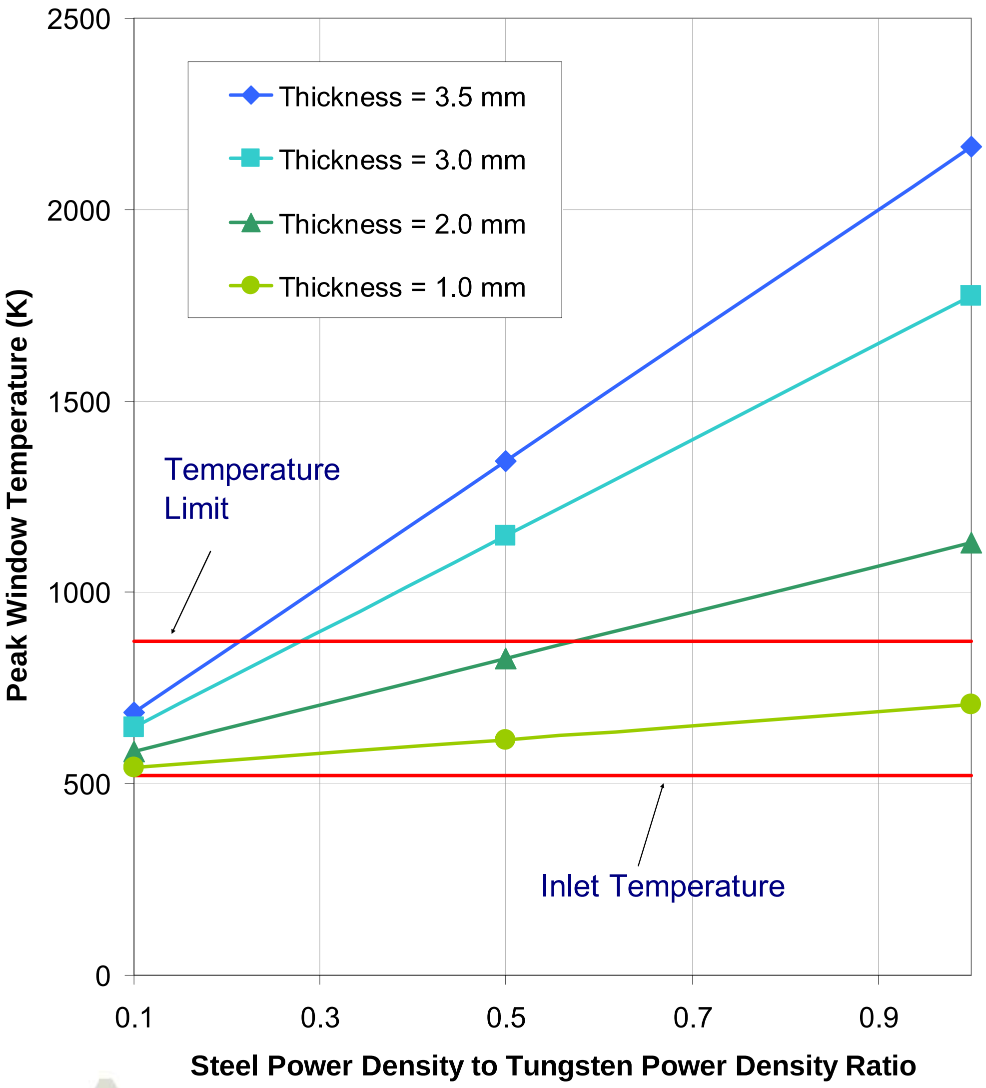
(a) Adiabatic Surface

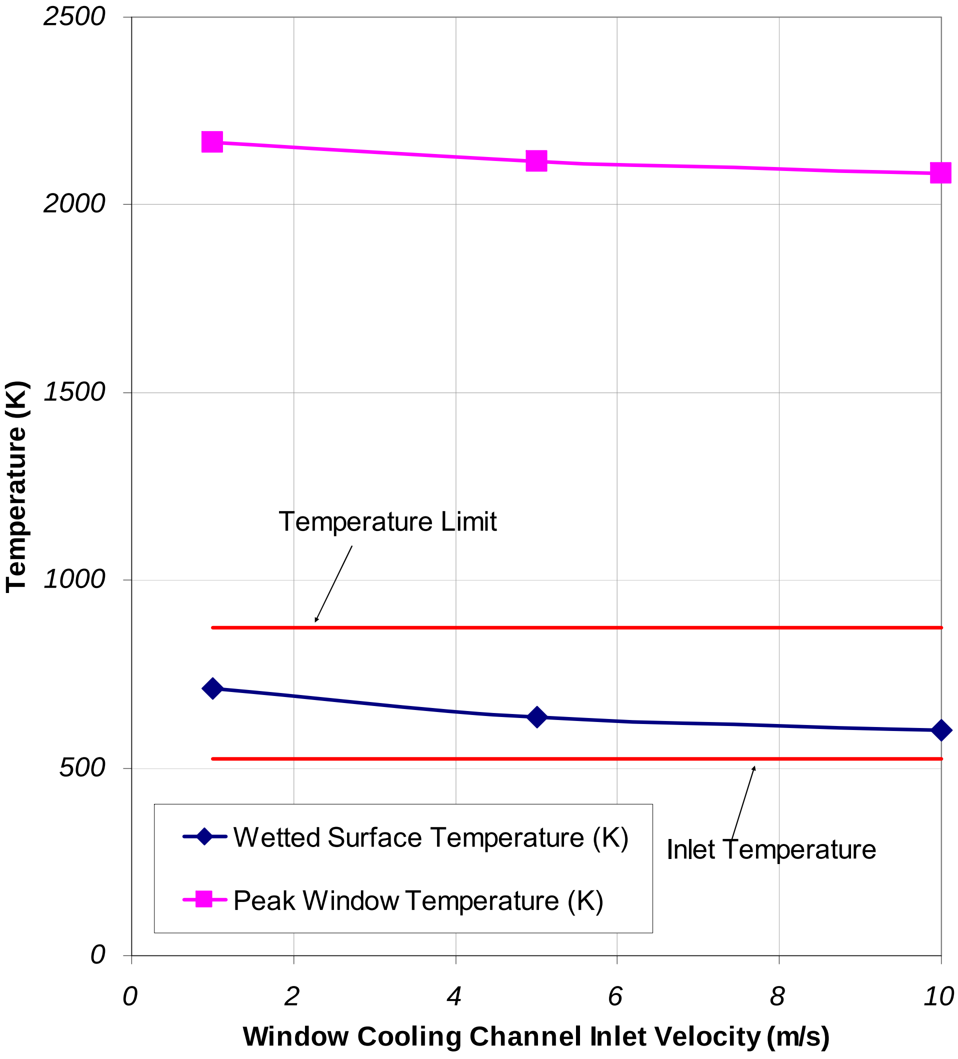


(b) Cross Section



Beam Window Performance





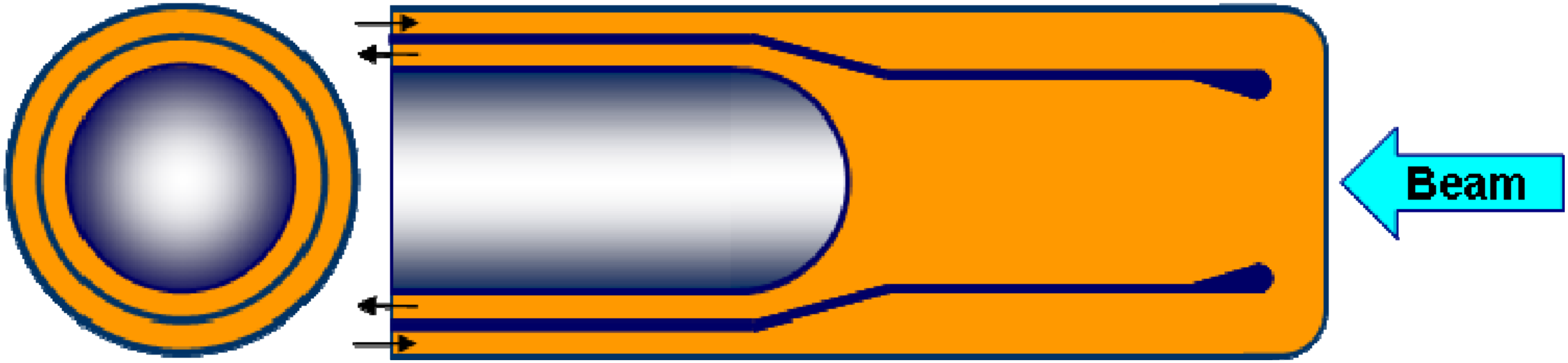
Tungsten plate target concept conclusions

- Tungsten plate target concept can potentially satisfy thermal requirements
  - Plate thickness ≈ 3.0 mm
  - Clad thickness < 0.5 mm
  - Gap width ≈ 1.0 mm
  - Channel velocity ≈ 1.0 m/s
- No real need to optimize gap width for target of this size
- Need to consider realistic power distribution
  - Optimize plate thickness

Liquid Lead-Bismuth Eutectic Target Concept

- High neutron yield per proton
- Coolant is target material
  - No stress issues in target material
- Simple design

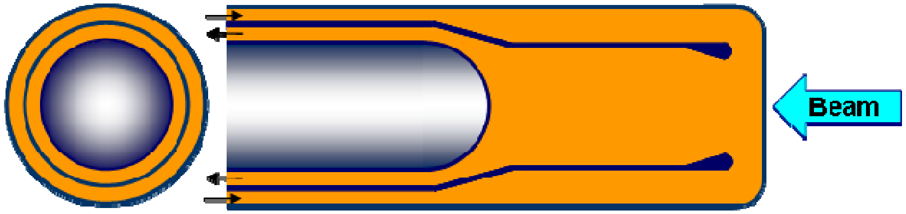
- Need careful oxidation control
- Lower density → less target material per unit volume
  - Nearly equivalent to lithium cooled tungsten plate concept

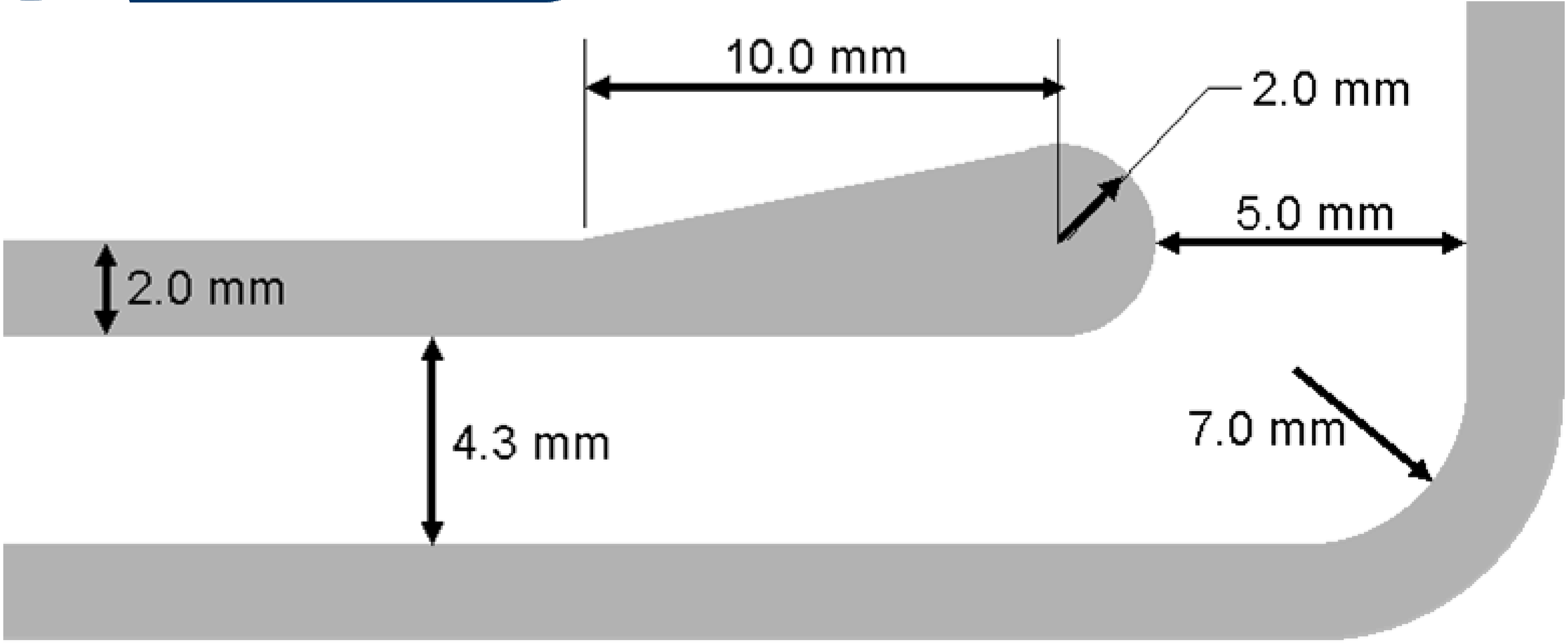


LBE target scaling studies

- Assume uniform volumetric heat source in LBE
- Thermal analyses
  - Target coolant temperature rise = 40 °C
    - Average inlet velocity = 2 m/s
    - Mass flow rate = 3.6 kg/s
    - Can be reduced to 20 °C
      - Mass flow rate = 8.0 kg/s
      - Increase total target diameter from 4.0 to 4.5 cm
- Stability analyses
  - Annular turning flows are inherently unstable
    - Leads to flow induced vibration issues when using heavy liquid metal
    - Follow stability guidelines from Idelchik's Handbook of Hydraulic Resistance
      - Develop turning vane concept for leading edge of central flow baffle.

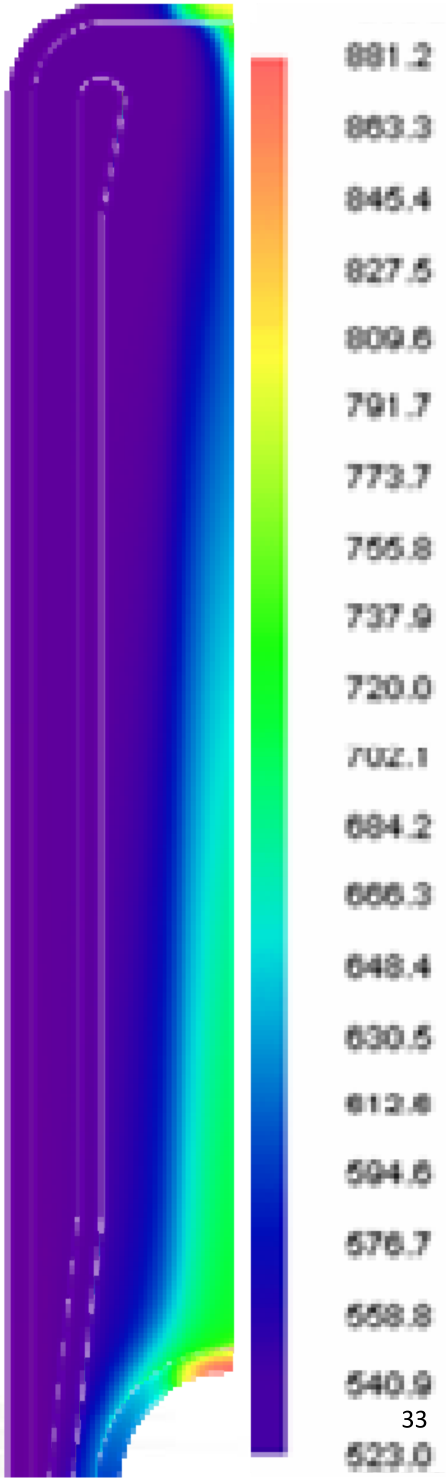
LBE target turning vane





LBE Target Cooling

- Model
  - Approximately 35,000 computational volume elements
  - V_{in}= 2.0 m/s
  - T_{in} = 250 °C
- Results
  - Peak velocity occurs at inlet and outlet
    - Implies good fairing design
  - Peak surface temperature
    - 493 ° C
  - Peak temperature
    - 608 ° C
- Detailed physics analyses needed to provide enthalpy source distribution for further optimization



Conclusions

- The high power density neutron converter will drive the two-stage ISOL target
- Many design options were considered in the development of a conceptual design
- A lithium-cooled tungsten concept has been developed for application as the neutron converter stage of a two-stage high-Z ISOL target
- A liquid LBE target is being developed as one alternate to the lithium cooled neutron converter concept

Questions?