MECO Production Target Developments

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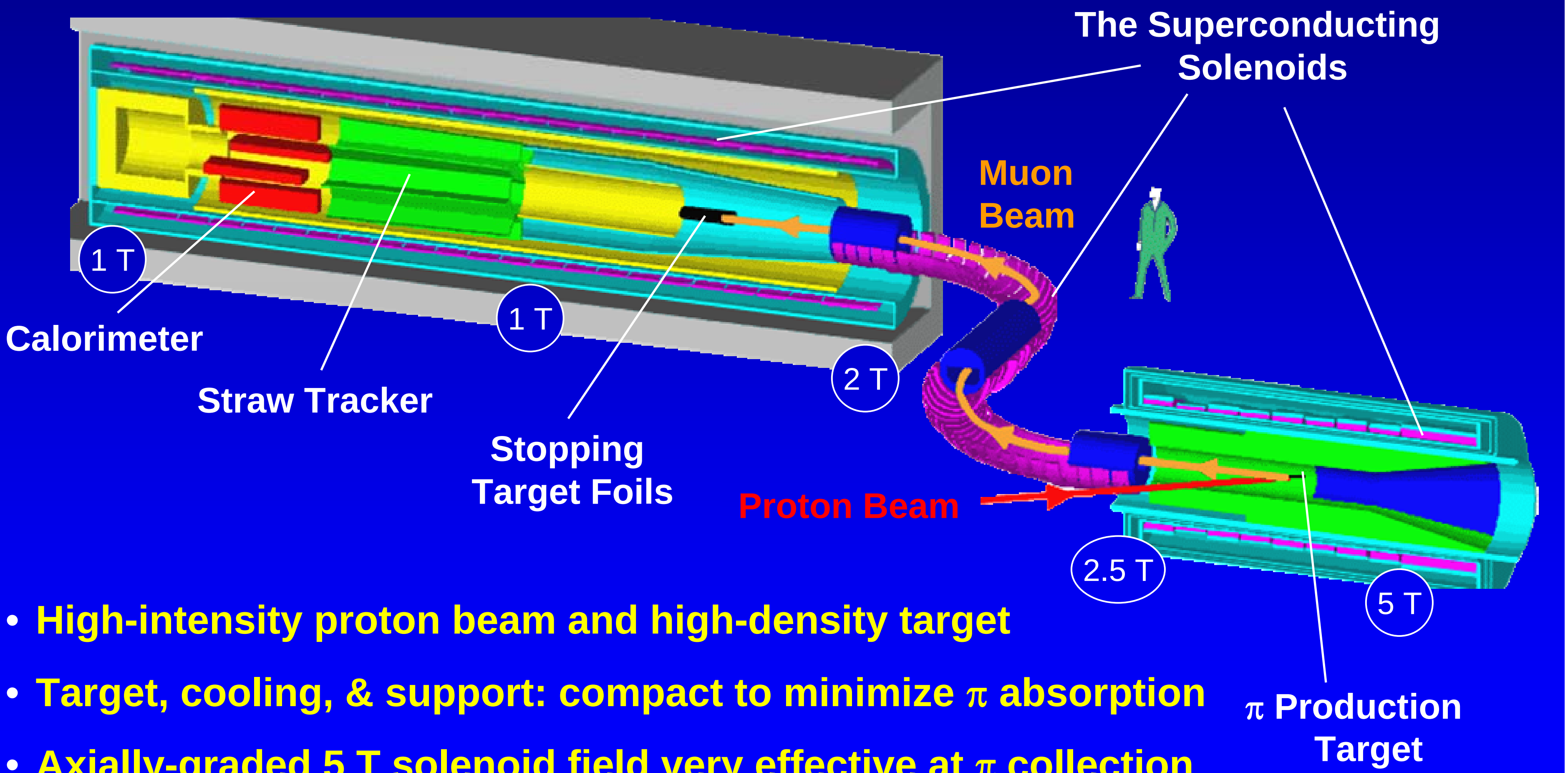
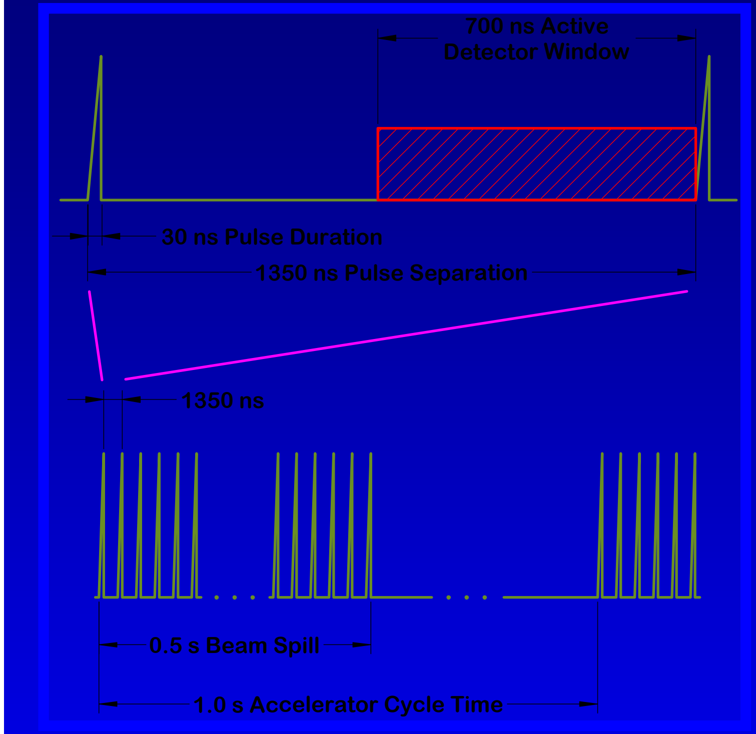
MECO Muon Beam Line at AGS

- **Goal: 10^{11} stopped μ^- / sec**
  - **1000-fold increase in μ beam intensity over existing facilities**

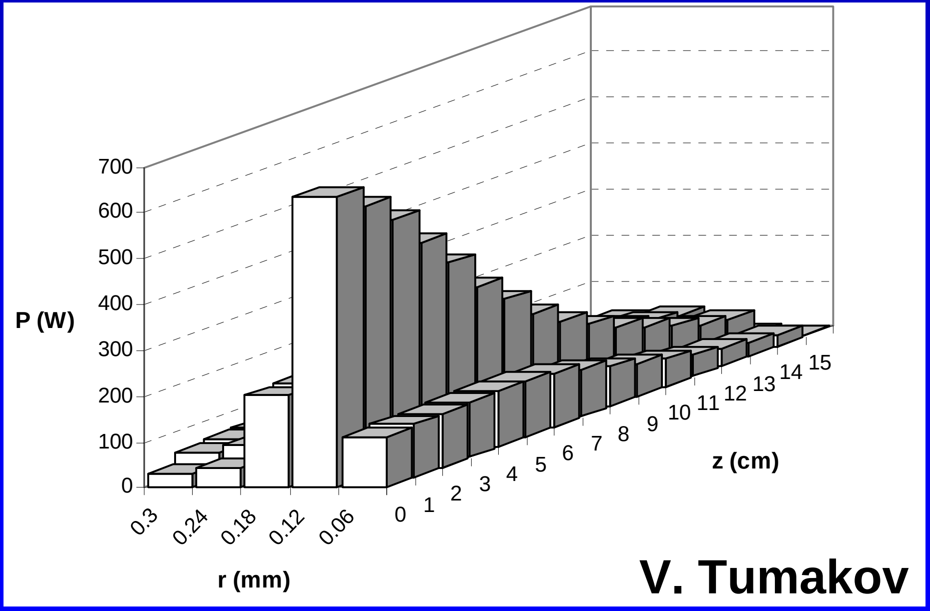


- **High-intensity proton beam and high-density target**
- **Target, cooling, & support: compact to minimize π absorption**
- **Axially-graded 5 T solenoid field very effective at π collection**

Target Heating



- Target: High density cylinder, L = 16 cm, R = 3-4 mm
- $4.0*10^{13}$ 7.5 GeV protons / sec from AGS
- Slow extraction, 0.5 s spill, 1.0 s AGS cycle time
- 2 RF buckets filled: 30 ns pulses, 1350 ns apart
- Total on-spill power deposition: 7500 - 9500 W
- On-peak energy deposition distribution:



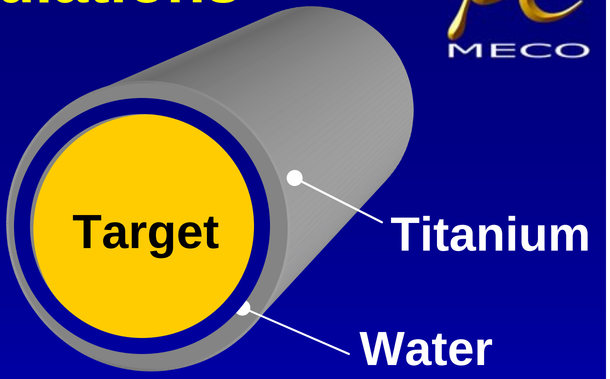
V. Tumakov

Production Target Cooling

- **Radiation**
  - **minimal material in production region to reabsorb π's**
  - **significant engineering difficulties to overcome**
    - high operating temperature, $T_{operation} = 2145 – 3000$ K
      - high thermal stresses
      - target evaporation
      - little hope of raising production rate beyond current goals
    - low-density materials: manageable stresses; but extended complex shapes, difficult to support & can lead to excessive pion reabsorption
- **Forced Convection w/ water as coolant**
  - **low operating temperature, $T_{operation} < T_{boil - water}$**
    - **negligible thermal stresses**
    - **hope for achieving greater sensitivity**
  - **minor impact on MECO sensitivity: cooling system absorbs π's**
  - **modest engineering difficulties handling coolant (water activation)**

Production Target Physics Simulations

Simulations of design parameters with GEANT3 indicate that both production target cooling methods can meet MECO physics requirements



Small water channel & thin containment tube costs 5% muon yield

Inlet & outlet pipes and target radius should be reoptimized

GEANT Simulations of Muon Yield

Water Thickness (mm)	Ti Wall Thickness (mm)	μ− Stops per Proton	Acceptance Loss (%) (+/- 1.5)
0	0	0.0050	0.0
0.5	0.5	0.0048	4.6
0.25	0.15	0.0048	4.1
0.2	0.15	0.0049	2.7
0.3	0.15	0.0048	4.5
0.4	0.15	0.0047	5.8
0.5	0.15	0.0047	6.3
0.25	0.2	0.0048	4.5
0.25	0.3	0.0047	6.7
0.25	0.4	0.0047	6.0
0.25	0.5	0.0047	5.4
2.35	0.76	0.0037	27.0
0.5	0.3	0.0041	17.8

Tungsten target
R = 3 mm, L = 16 cm

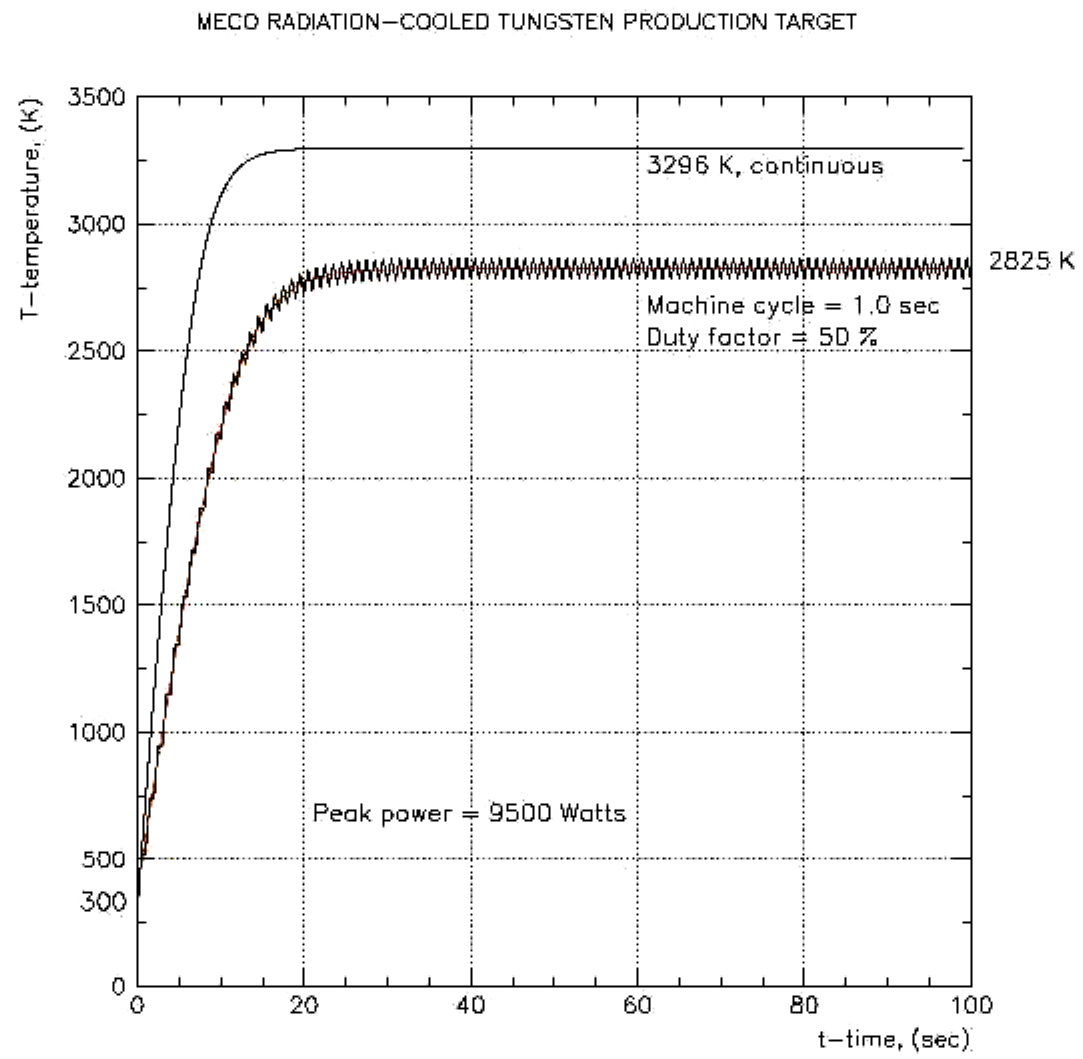
Radiation-cooled

All with 3 mm OD inlet/outlet pipes

Large inlet/outlet

UCI: A. Arjad, W.Molzon, M.Hebert, V.Tumakov, J.Popp

Radiation Cooling: Lumped Analysis of Heating Cycles



- **Tungsten cylinder**
- **R = 4 mm**
- **L = 16 cm**
- **Long time limit:**

$$T(t) = \bar{T}_{\max} + \delta h(t), \bar{T}_{\max} = 2825\ \mathrm{K}$$

$$f_{\mathrm{duty}} P_{\mathrm{peak}} \approx \sigma \varepsilon(\bar{T}_{\max}) \left(\bar{T}^4_{\max} - T^4_{\mathrm{ambient}} \right) A$$

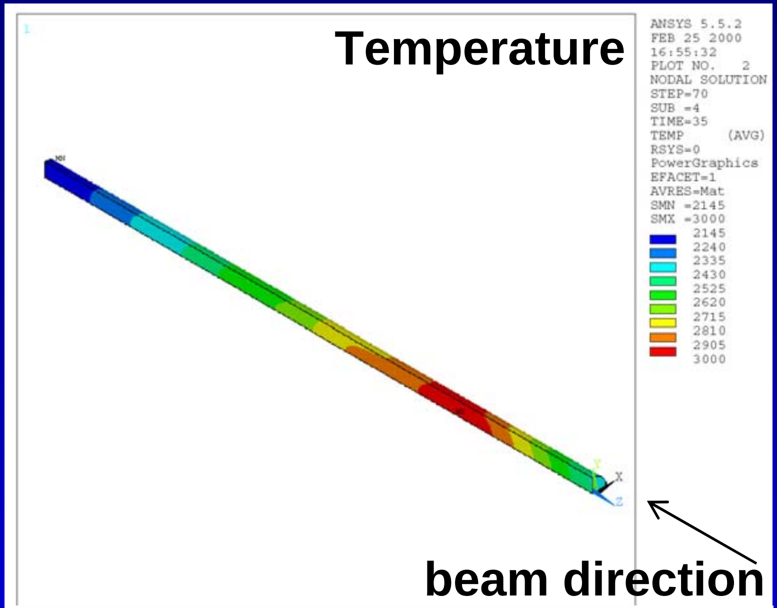
$$\delta = \frac{P_{\mathrm{peak}}\, f_{\mathrm{duty}} \left(1 - f_{\mathrm{duty}} \right) \tau}{2 C'_p (\bar{T}_{\max})},$$

$$\delta = 42\ \mathrm{K}$$

$$C'_p(T) = C_p(T) + T dC_p / dT$$

- **W: T_{melting} = 3683 K**

Radiation Cooling: On-Spill Temperature & Von Mises Stress



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RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =2145
SMX =3000
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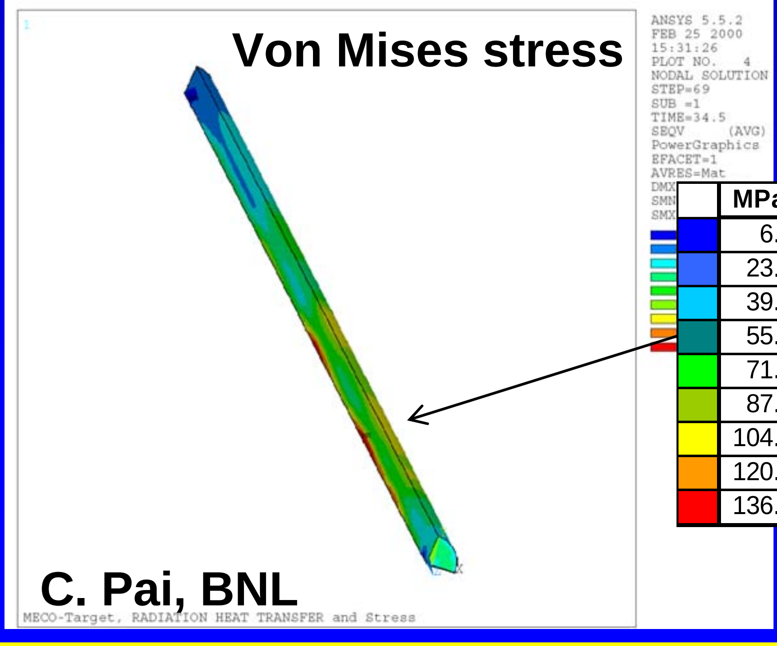
    2240
    2335
    2430
    2525
    2620
    2715
    2810
    2905
    3000
```

Temperature

beam direction



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PowerGraphics
EFACET=1
AVRES=Mat
DMX
SMN
SMX
```

MECO-Target, RADIATION HEAT TRANSFER and Stress

Von Mises stress

C. Pai, BNL

	MPa	--	MPa
🟦	6.9	--	23.1
🟦	23.1	--	39.3
🟦	39.3	--	55.5
🟦	55.5	--	71.6
🟩	71.6	--	87.8
🟩	87.8	--	104.0
🟨	104.0	--	120.2
🟧	120.2	--	136.4
🟥	136.4	--	152.6

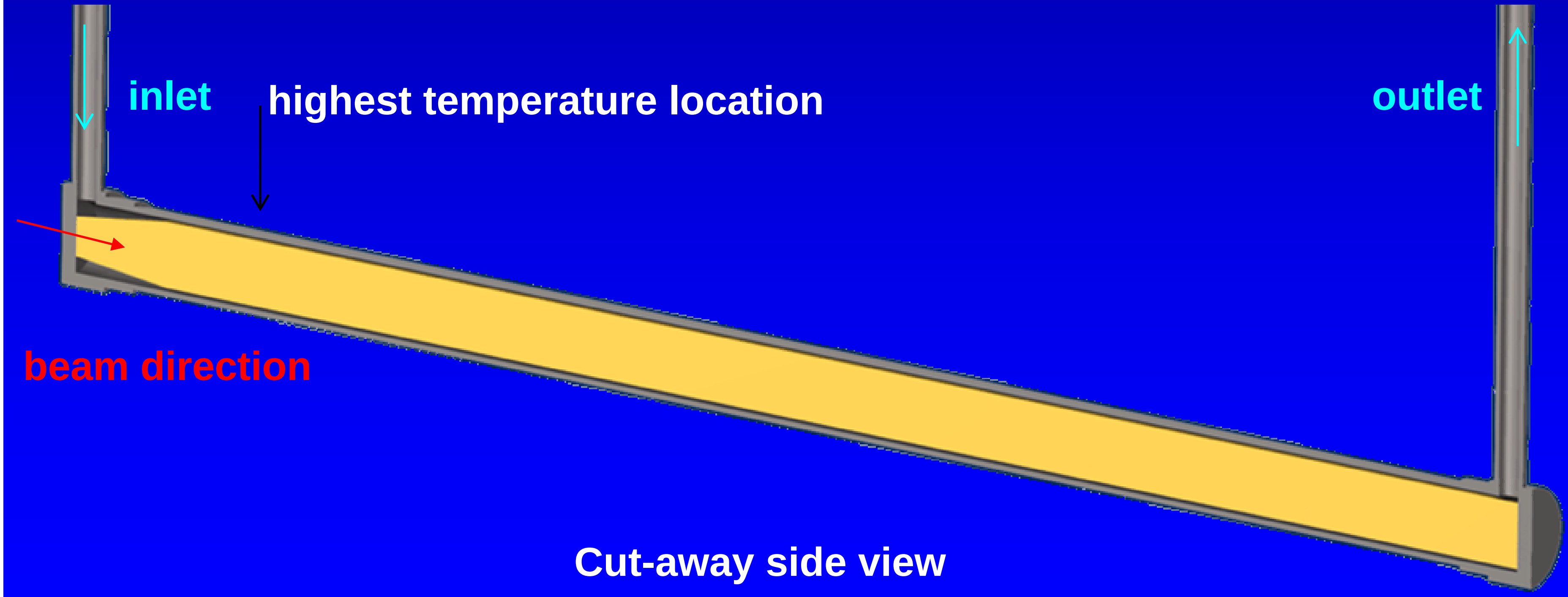
- **Tungsten cylinder, symmetry ¼**
- **L = 16.0 cm, R = 4 mm**
- **Power distribution: gaussian**
- **Thermal dependence: Properties W**

T(K)	300	500	1000	1500	2000	2500	3000
κ (W/cm K)	1.60	1.40	1.25	1.10	1.01	0.90	0.85
c_p (J/g K)	0.1313	0.138	0.1465	0.157	0.1723	0.1946	0.2255
α $(1/K)*10^{-6}$	0	4.04	4.42	4.82	5.22	5.61	6.01
E (Mpa)	41	38	36	34	32	28	23
σ_{Yield} (Mpa)	1519	150	110	75	40	20	N/A

- **Region of maximum Von Mises stress, σ_{Yield} = 20 Mpa or less**
- **Dividing up target into 0.1 cm slices, slotting $\perp$ & $\parallel$ to axis, spacing by 0.8 cm gives stability, but target size is unacceptable**

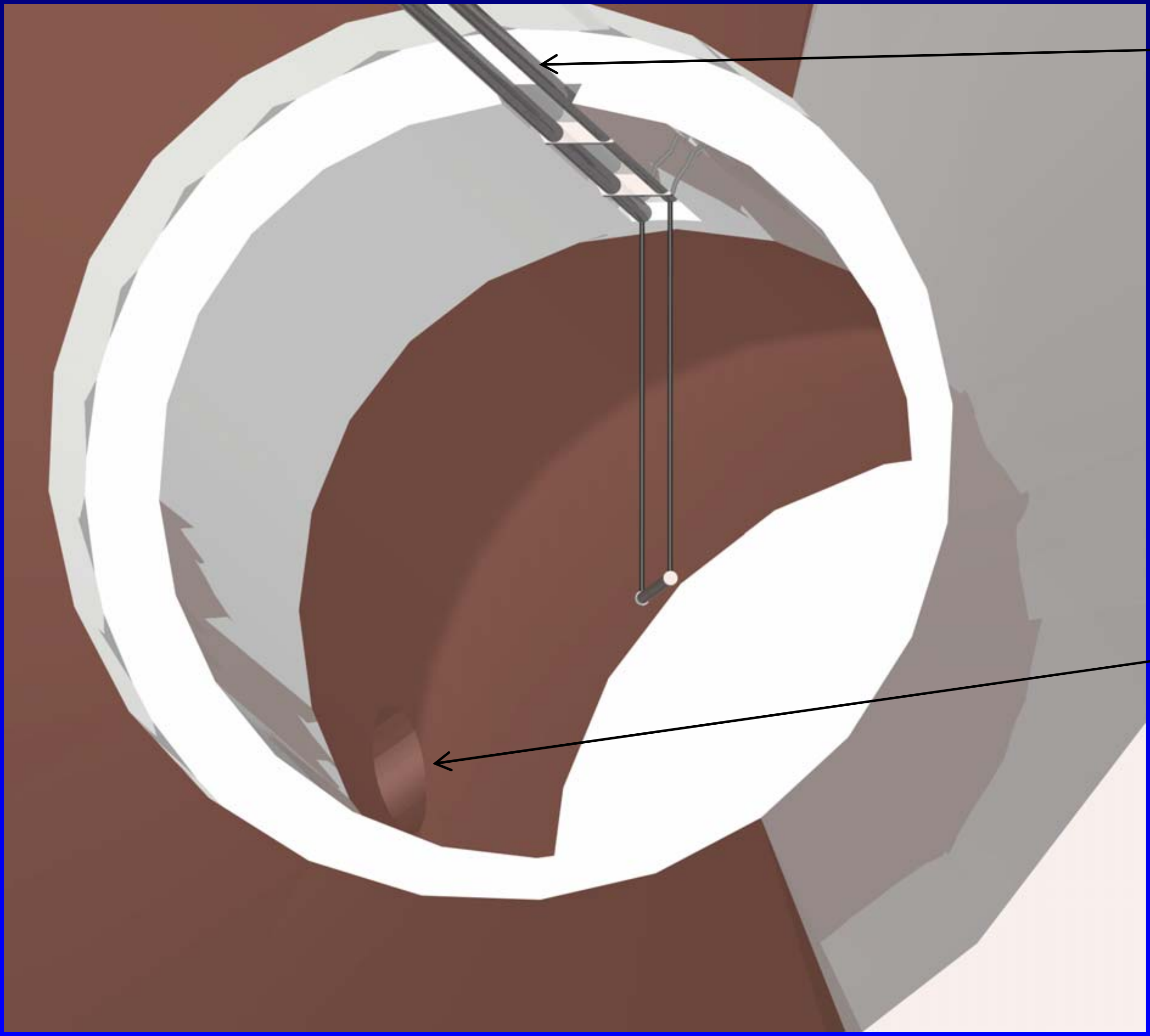
Current Water-Cooled Design

- Pt or Au cylinder: L = 16.0 cm, R = 3.0 mm
- Ti inlet & outlet pipes: 25 cm long, ID = 2.1 mm, OD = 3.2 mm
- Annular coolant channel: h = 0.3 mm
- Tapered inlet end reduces pressure drop across target
- Water containment shell: 0.5 mm wall thickness
- In MECO:



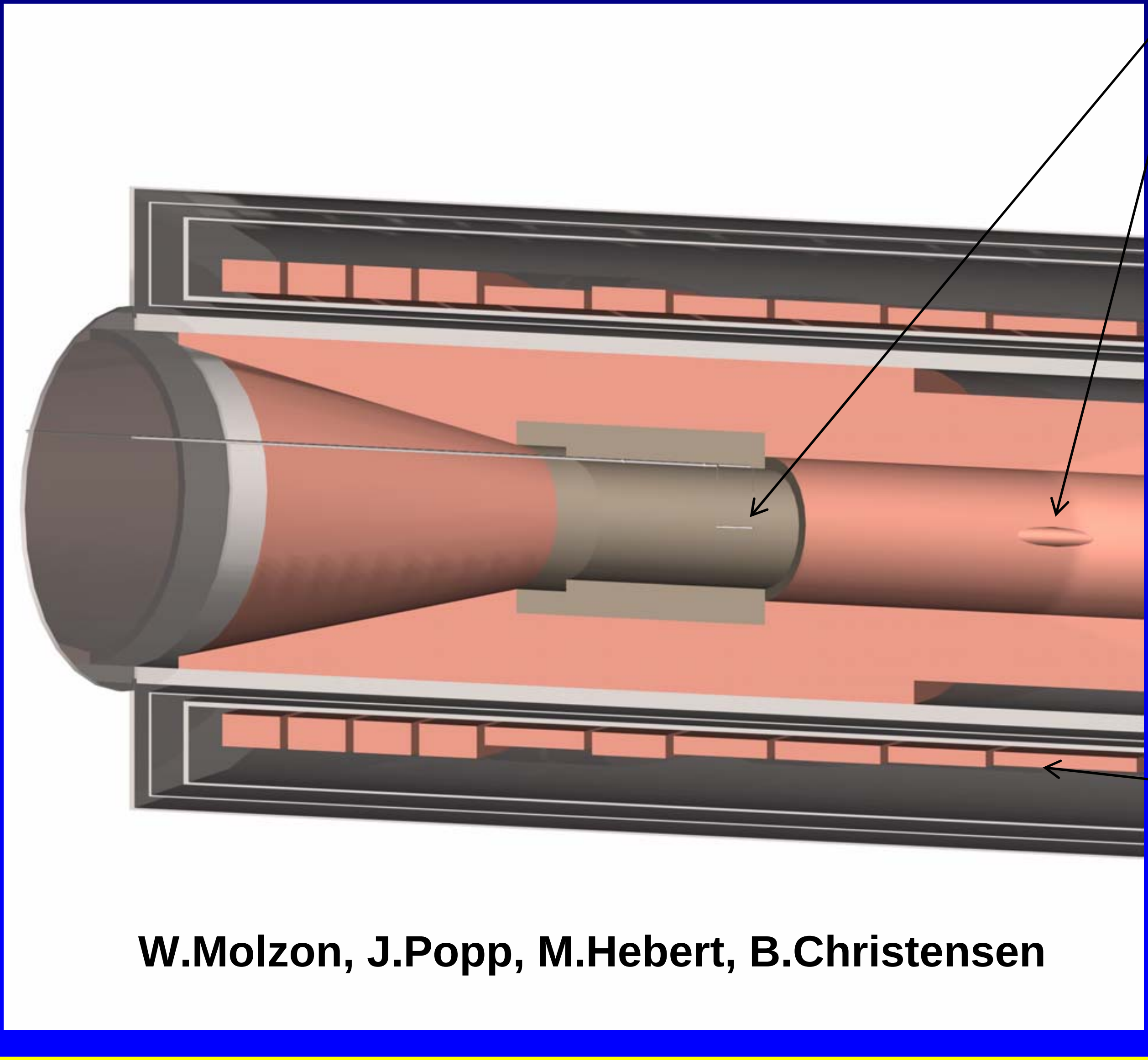
Cut-away side view

Target Installed in Production Solenoid



- 0.5” service pipes
- Slot in heat shield:
  - guide
  - positioning
- Simple installation:
  - robotic manipulation
  - no rotations need
  - total of 1 vertical & 2 horizontal translations required
- Opening in heat shield for beam entrance
- Target rotated slightly off-axis to be optimally oriented for the beam

Target Fully Installed: Cut-Away Wide View of Production Solenoid

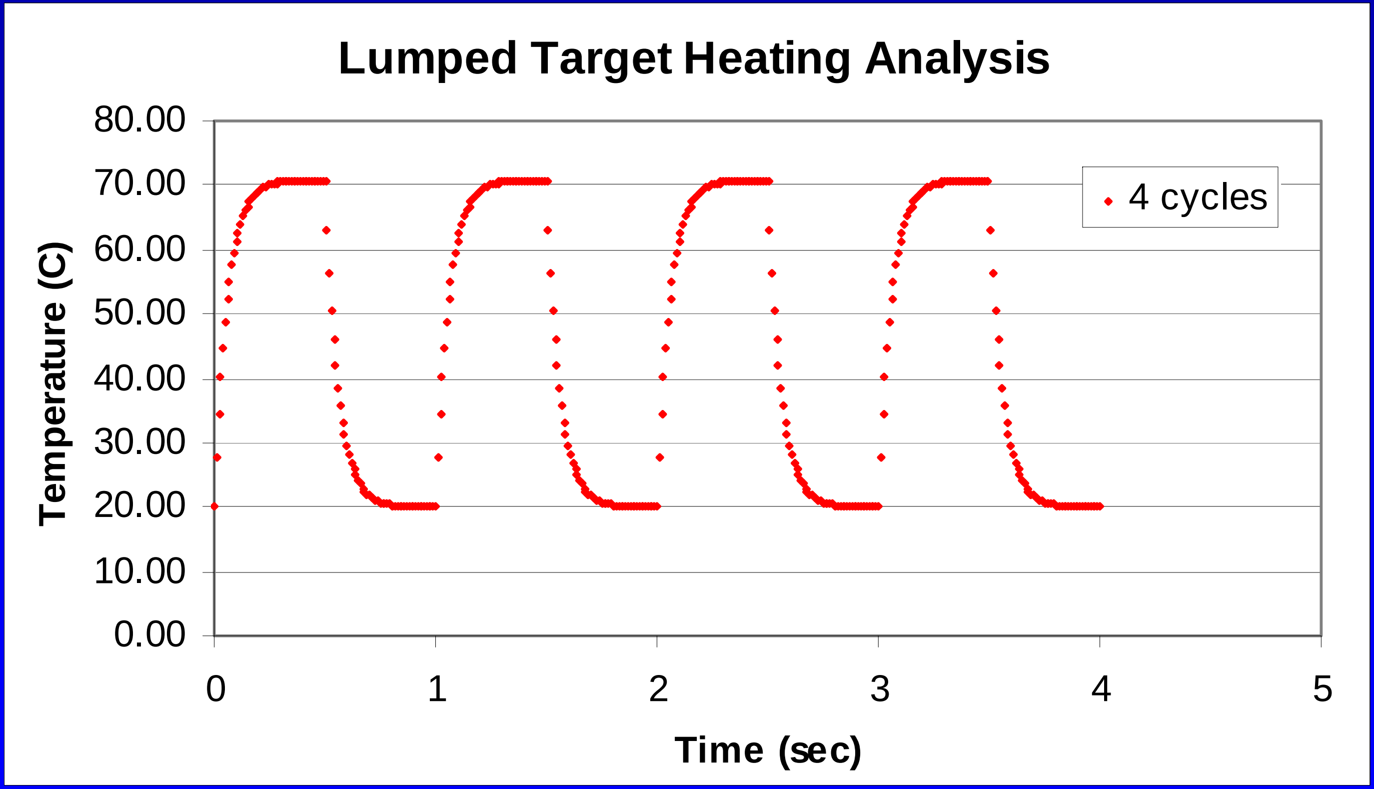


- Target
- Beam entrance
- Solenoid coil packs

W.Molzon, J.Popp, M.Hebert, B.Christensen

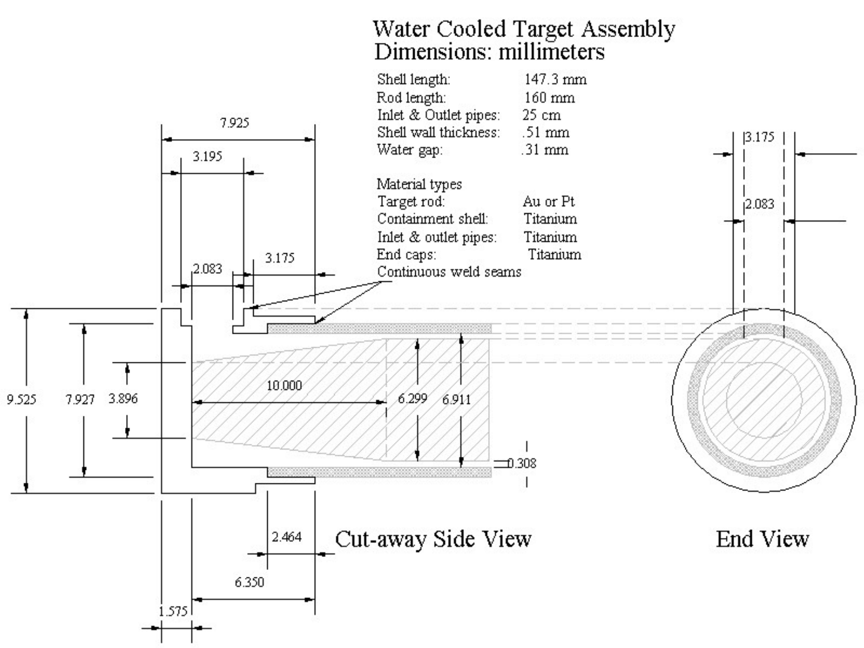
Water Cooling: Lumped Analysis of Heating Cycles

- Simple calculations and hydo code indicate large heat transfer coefficient
- Characteristic response time is of order AGS cycle time
- Target may reach steady state T on each cycle
- Time-dependent turbulent hydrodynamic simulations required to fully characterize the time behavior and more precisely the maximum coolant temperatures: CFDesign – suitable computational tool



Turbulent Flow in Annular Water Channel

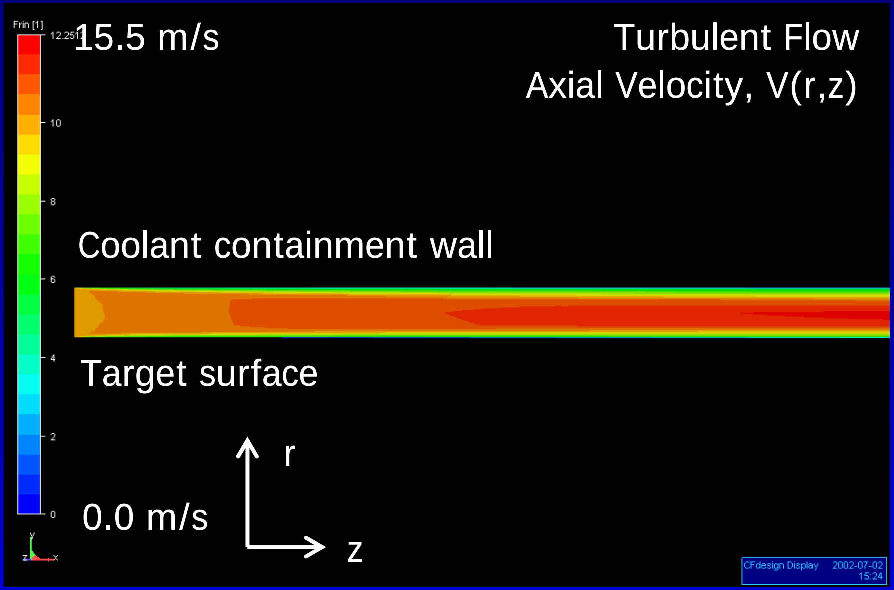
- **Worst case: steady state, 9500 W**
- **Inlet water conditions**
  - **temperature = 20 C**
  - **flow rate = 1.0 gpm**
  - **velocity = 10.6 m/s at inlet**
- **Flow channel**
  - **length = 16.0 cm**
  - **radius = 3.0 mm**
  - **gap = 0.3 mm**



Water Cooled Target Assembly
Dimensions: millimeters

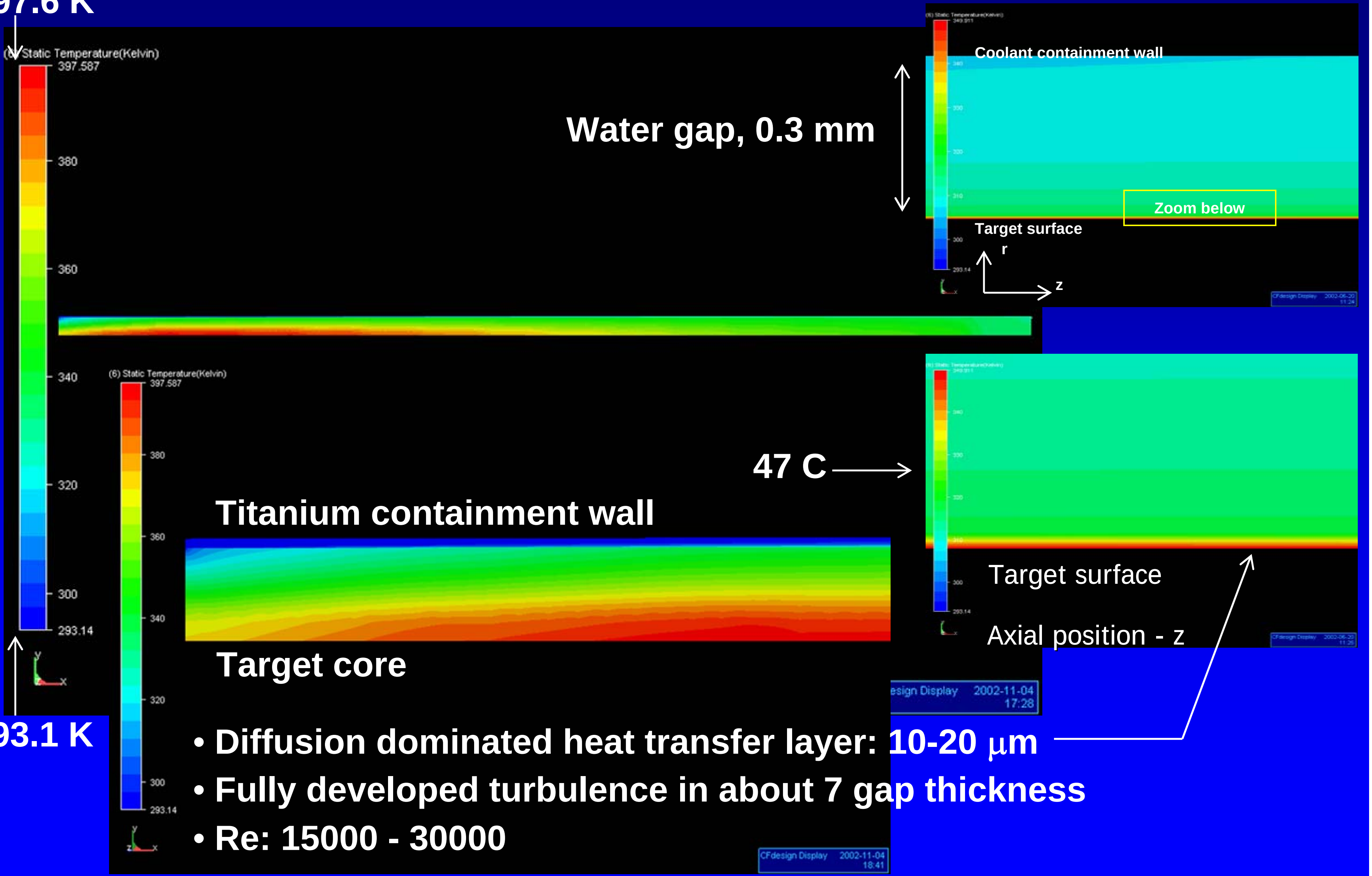
Shell length: 147.3 mm
Rod length: 160 mm
Inlet & Outlet pipes: 25 cm
Shell wall thickness: .51 mm
Water gap: .31 mm

Material types
Target rod: Au or Pt
Containment shell: Titanium
Inlet & outlet pipes: Titanium
End caps: Titanium
Continuous weld seams



- **Design parameters**
  - **target pressure drop = 127 psi**
  - **inlet pressure = 207 psi**
  - **outlet pressure = 80 psi**
  - **max. local water temp = 71 C**
  - **max. target temp (Au) = 124 C (core)**
  - **mean discharge temp = 56 C**
  - **stopped muon yield > 95% of rad. cooled**

Steady State Temperature Distribution Water-cooled Target



397.6 K

293.1 K

Water gap, 0.3 mm

47 C

Titanium containment wall

Target core

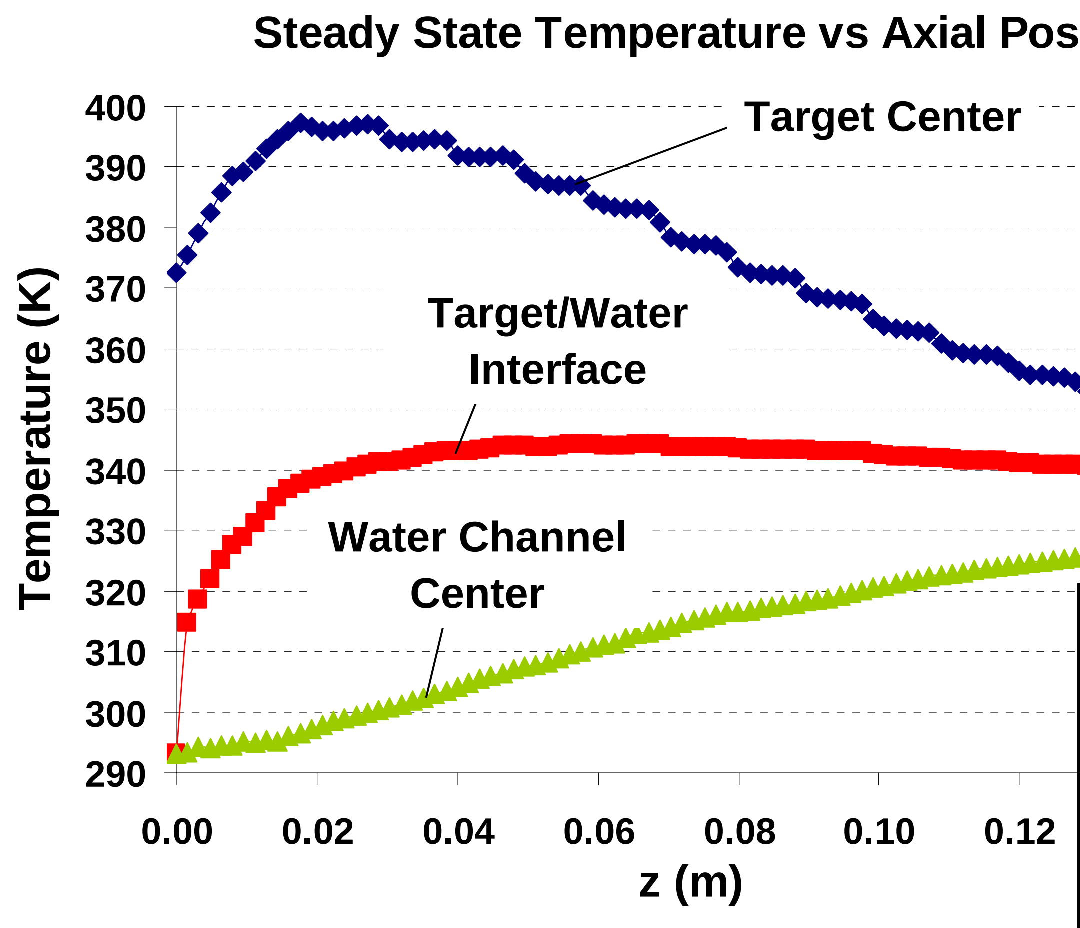
Target surface

Axial position - z

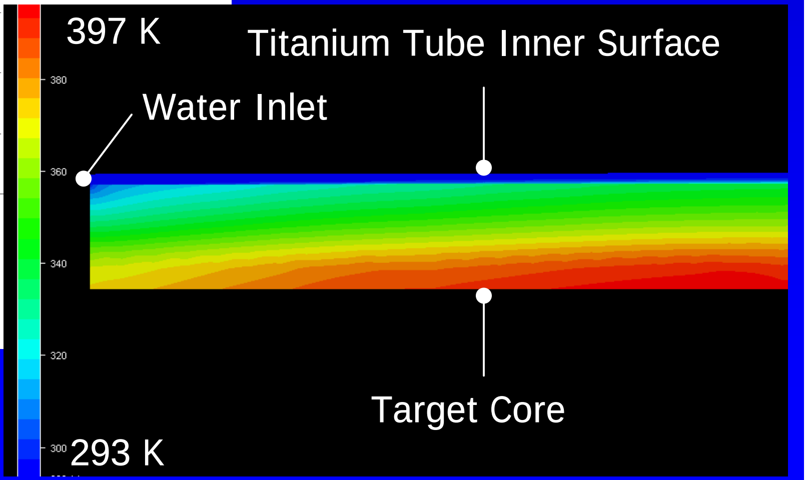
- Diffusion dominated heat transfer layer: 10-20 μm
- Fully developed turbulence in about 7 gap thickness
- Re: 15000 - 30000

Target and Water Temperature Under Turbulent Conditions

Heat transfer calculations for turbulent flow conditions demonstrate feasibility of the cooling scheme

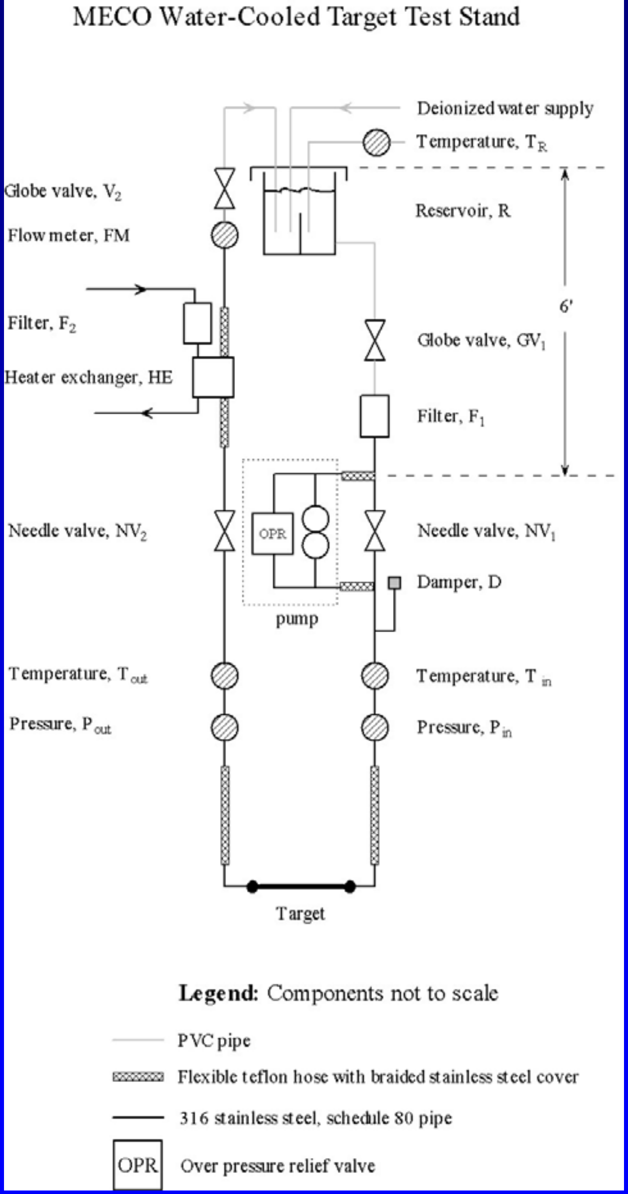


- **Turbulence calculation**
  - **unstable flow**
  - $\vec{v} = \langle \vec{v} \rangle + \delta\vec{v}, \ \langle \delta\vec{v} \rangle = 0$
  - **local fluctuations**
  - $\delta\vec{v}, \ \tau_{\text{turbulence}}$
  - **solutions to N-S eqs**
  - **time averaged, Δt**
  - $\tau_{\text{turbulence}} \ll \Delta t$



UCI:
J.Carmona, R.Rangel, J.LaRue, J.Popp, W.Molzon

Target Cooling Test Stand Diagram

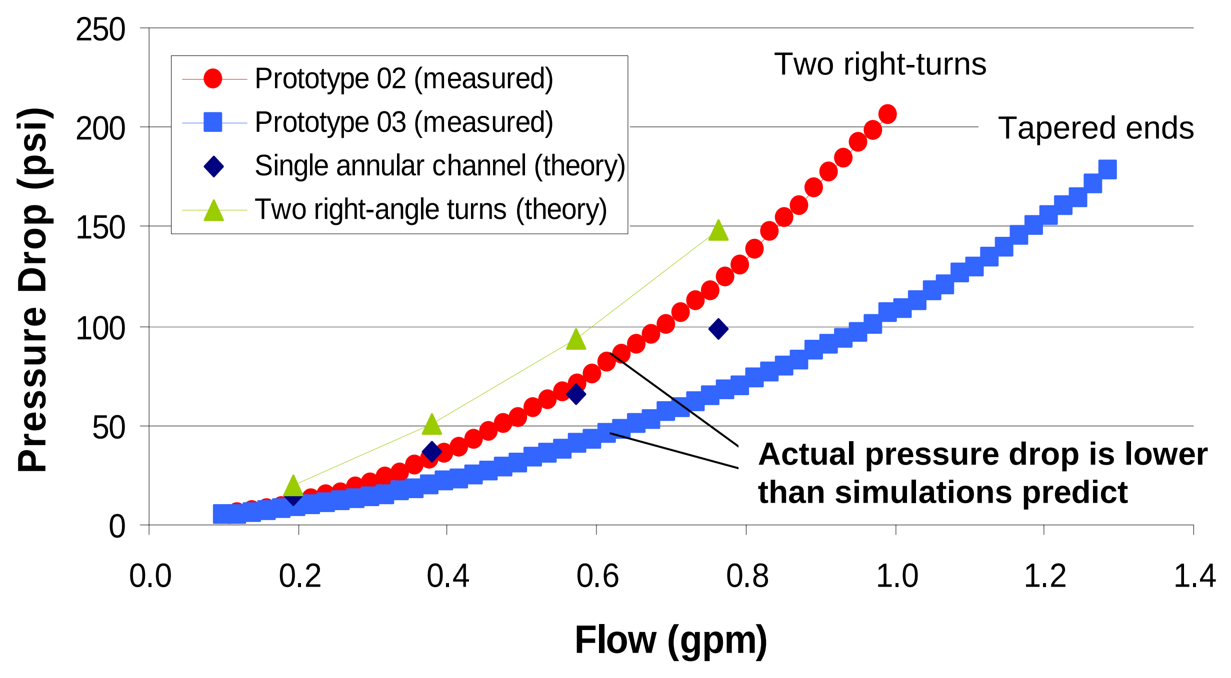


- Control: target geometry & flow rate
- Monitor: temperature & pressure:
  - target inlet & outlet
  - reservoir
  - target (not shown)
- Temperature probes:
  - thermistors
  - thermocouple
- Measurements of interest in heating tests:
  - power deposition in target
  - heat transfer coefficients
    - target
    - heat exchanger
  - target surface temperature
  - response times for power cycling

Target Prototype Tests

Water cooling effectiveness is being demonstrated via prototypes

- **Pressure drop vs. flow rate tests completed**
- **First induction heating test completed, next test June 2003**



Comparison of Prototype Data with HD Simulations

Two right-turns

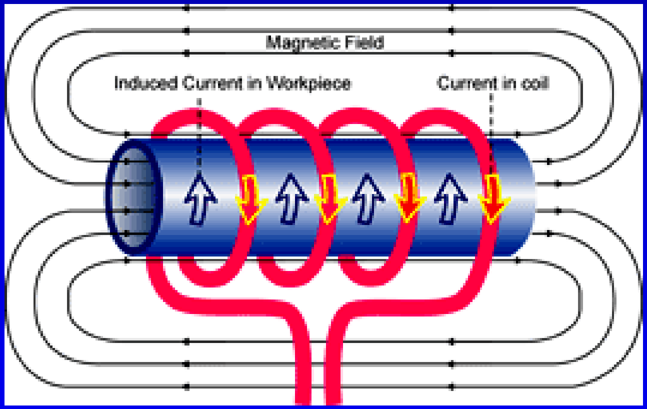
Tapered ends

Actual pressure drop is lower than simulations predict

UCI: J.Popp, B.Christensen, C.Chen, W.Molzon

Induction Heating

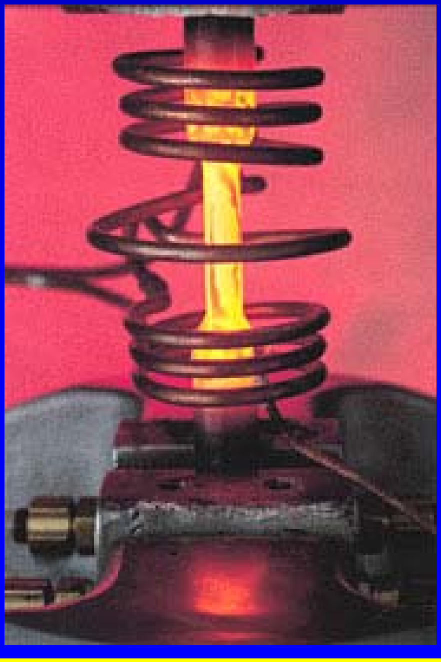
- Principle: Excite eddy currents which oppose changing magnetic flux, to obtain heating via $\langle \vec{J} \cdot \vec{E} \rangle$
- Apply AC current to coil wrapped around work piece (e.g., solid rod, billet,…):



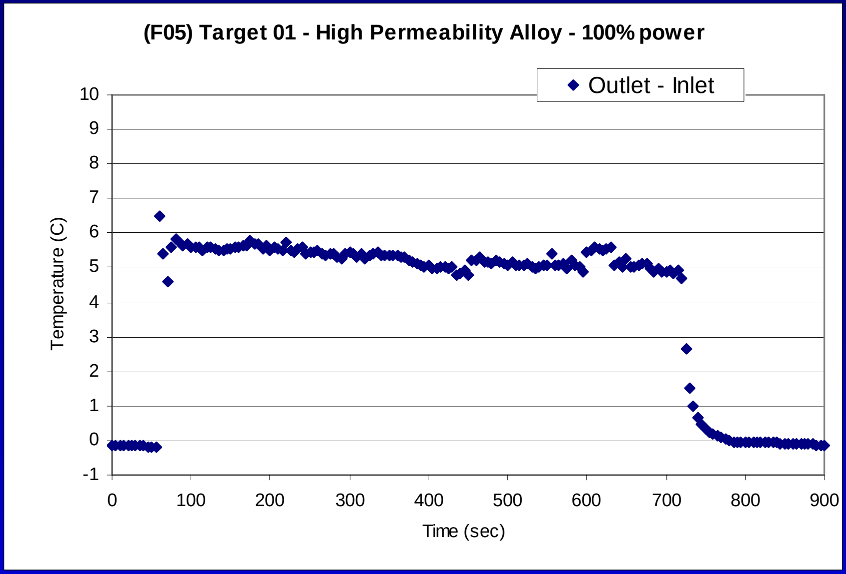
- H_0 = surface magnetic field intensity
- Solid cylinder:

$$P_{\mathrm{total}} / A_{\mathrm{rod}} = \frac{\rho H_0^2}{2\delta} f(R_{\mathrm{rod}}/\delta), \quad \delta = \sqrt{2\rho/\omega\mu}$$

- Ameritherm, Inc.; http://www.ameritherm.com
- Induction Heat Treet, Co.; Huntington Beach, CA
  - 20 kW, 175 kHz
  - 30 kW, 10 kHz
- Example: Tensile test for metals at extreme temperatures



Measured Power Deposition

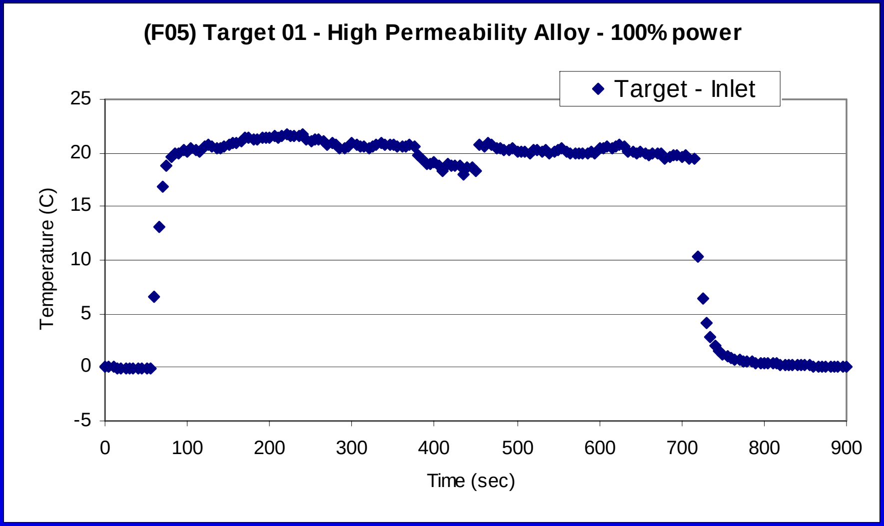


- Induction coil:
  - 152 turns/m
  - L = 23.6 cm, R = 3.8 cm
  - copper tubing: OD = 0.635 cm
- Power supply
  - Lepel 20kW unit
  - f = 175 kHz

- Solid rod:
  - R = 3.0 mm, L = 16.0 cm
  - Carpenter Technologies: High Permeability Alloy 49, 50/50 Fe/Ni
- Measured power deposited:
  - reservoir temperature rise
  - (outlet – inlet) temperature
- Approximately same result: 1450 W
- 264 W per K / unit discharge (gpm)
- Increase power deposition:
  - more turns per meter (coil w/ two close-packed layers)
  - reduce OD water containment shell
  - consider using higher-power unit

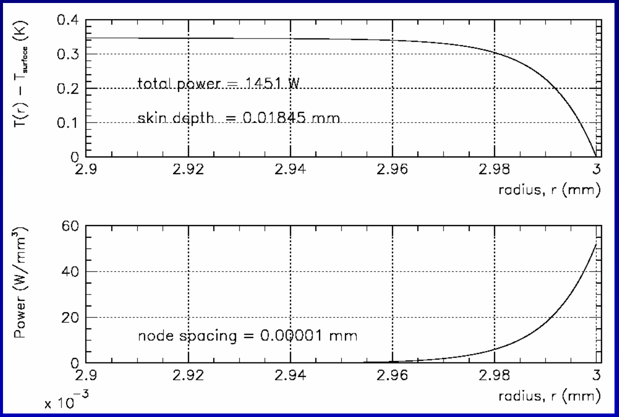
Measured Target Surface Temperature

- Annular water gap, h = 0.4 mm
- Flow rate = 1.0 gpm
- $\Delta P = 125$ psi



(F05) Target 01 - High Permeability Alloy - 100% power

- Skin depth: $\delta = 0.018$ mm
  - f = 175 kHz
  - relative permeability $\mu/\mu_0 = 2050$
- $T_{\text{target probe}}$:
  - probe radial position not critical
  - $T_{\text{core}} - T_{\text{surface}} \ll T_{\text{target probe}}$



- Probe near max surface T position:
  - 1.9 cm in from outlet end
  - > 0.5 mm below surface
- $T_{\text{target}} - T_{\text{inlet}} = 21.0$ C
- Scaled to MECO: $P_{\text{MECO}} = 7500$ W, $(T_{\text{target}} - T_{\text{inlet}})P_{\text{MECO}}/P_{\text{test}} = 108$ C
- Good approx.: $T_{\text{surface}} = T_{\text{inlet}} + 108$ C
- To maintain non-boiling condition
  - raise outlet pressure
  - chill inlet water
  - increase discharge rate

What next ?

- Opera calculations: redesign coil for greater power
  - two layers of coil windings
  - reduce OD of copper tubing, etc.
  - evaluate using 20 vs 30 kW unit (higher current & lower freq)
- 2nd heating test in June 2003
  - improved sensor operation
  - higher power deposition
  - gap size 0.4 mm, run at higher flow rate
  - gap size 0.3 mm, run at various flow rates
  - more precise positioning for target surface temperature probe
  - characterize response time of target
- Opera calculations: design coil for MECO longitudinal heating profile
- Redesign water containment shell to improve pressure drop
- More heating tests in July 2003