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Evaluation of NuMI Decay Pipe for 1 MW Beam Operation

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TSD Topical Meeting

June 18, 2020

Outline

Presented here is a collection of work from Abhishek Deshpande (Des), Igor Rakhno, Zhijing Tang, Bob Wands, Jim Hylen, and Mike Campbell

- **Overview of the Decay pipe and RAW system**
  - Mechanical structure
  - RAW system capacity (Des)

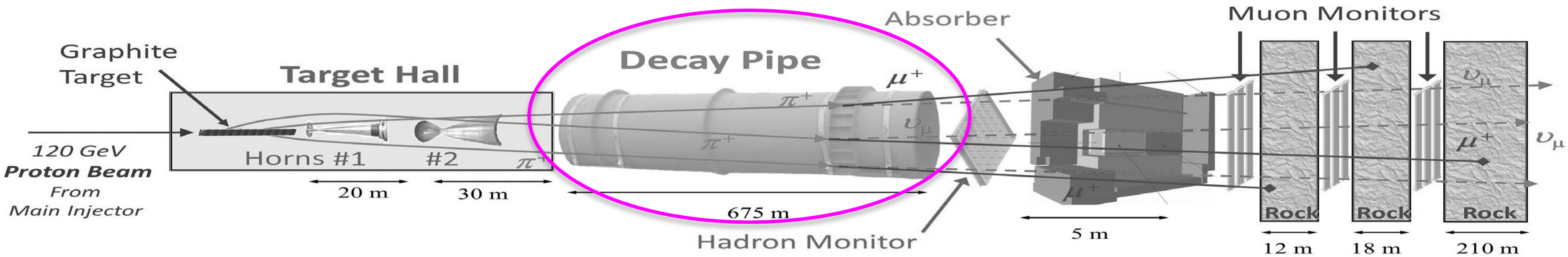
- **MARS simulations** (Igor Rakhno)

- **FEA report** (Zhijing Tang)
  - Reference: Bob Wands' FEA for 2.3 MW beam
  - FEA for 1 MW beam
  - Temperatures, stresses, and summary

- **Decay pipe US window repair mechanism** (Mike Campbell)

More information: NuMI-AIP Decay Pipe SharePoint page

Introduction of NuMI Decay Pipe

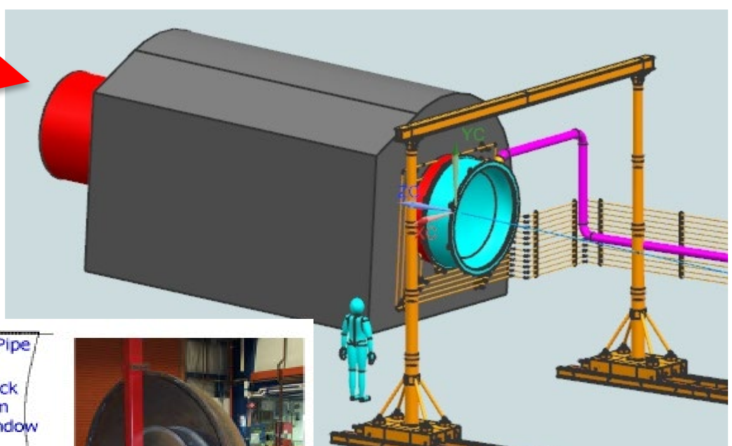


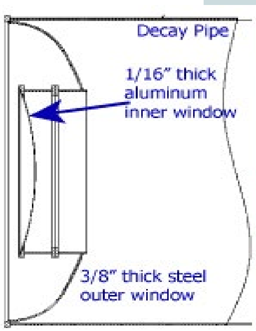
Ø2m, 1 cm wall, 675m steel pipe

Provides a large space for secondary beam pions to decay into muon-neutrinos

- with sealed beam entrance and exit windows
- Under vacuum prior 2007
- filled with 0.9 atm helium gas since 2007
- Water cooled

Beam





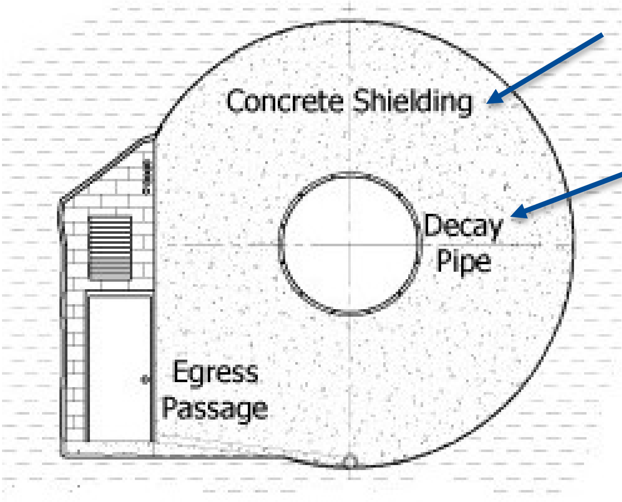
US Window

DS Window

Pump port

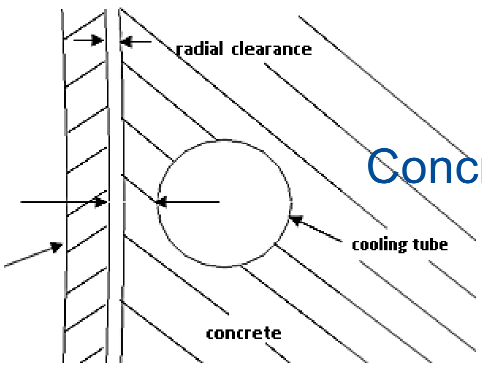
Cooling lines

Decay Pipe Mechanical Structure



Protect groundwater (varying from Ø4.6m to Ø6.3m)

Ø2 m A36 steel pipe, 0.375” thick, 670m



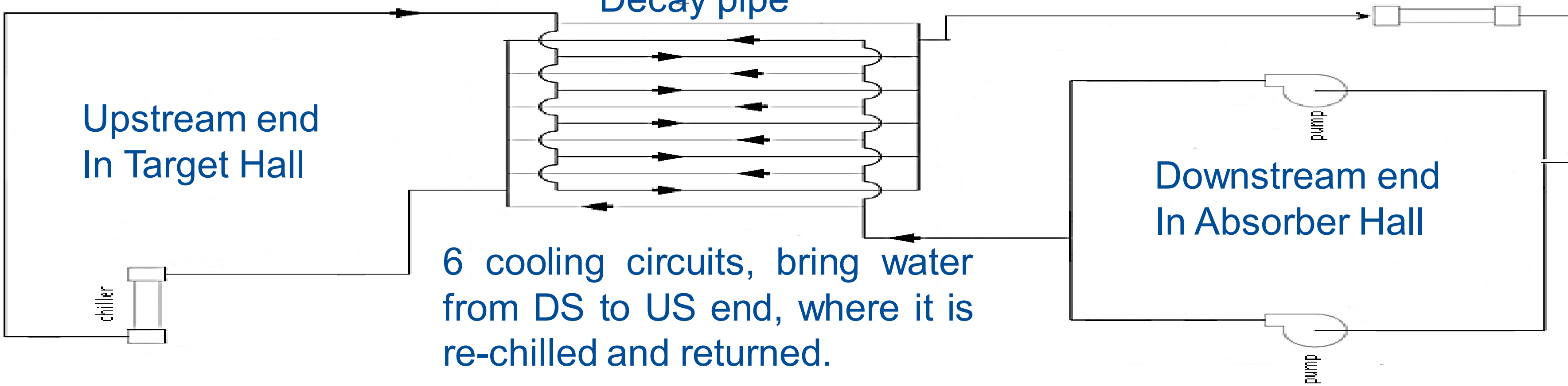
Stiffening ring

12 of Ø1” tubes , evenly spaced azimuthally, and running parallel to the steel pipe, but attached directly to the pipe only at the stiffening rings, which are spaced 10’ apart.

Evaluation effort for 1 MW beam operation:

- safely dissipate increased heat load
- RAW system capacity
- MARS simulations – Edep data
- FEA of the entire Decay pipe

RAW System



Upstream end
In Target Hall

Downstream end
In Absorber Hall

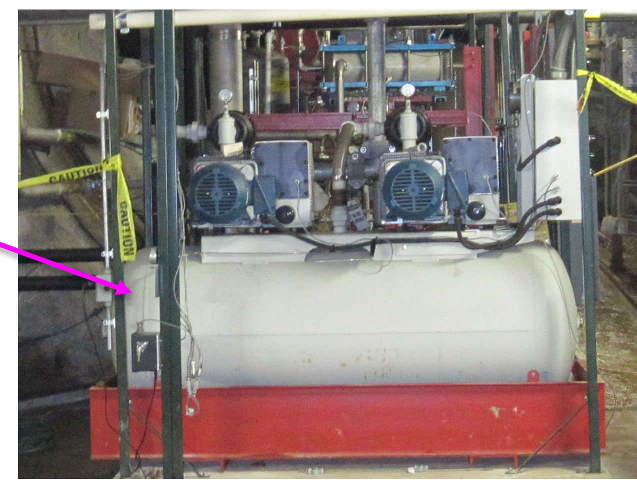
6 cooling circuits, bring water from DS to US end, where it is re-chilled and returned.

US RAW system

Evaluation effort: is it necessary to increase the cooling capacity?

DS RAW system

The DS Chiller has never been used for NuMI operations.



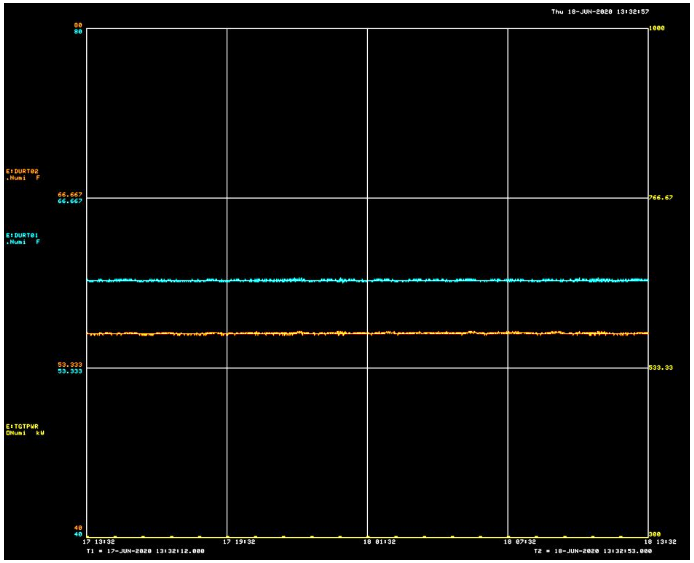
RAW System Operation Measurements and Capacity (Des)

~ 4.0 gpm flow measured @US end

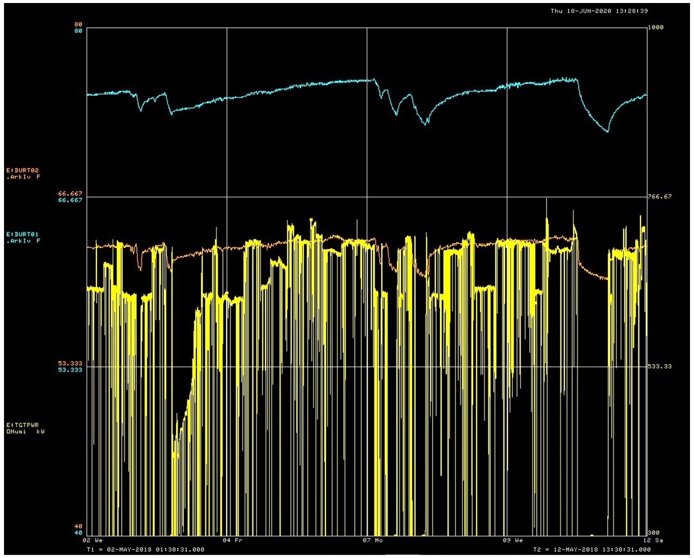
Pipe location (degree)	Flow in	Flow out
0	3.1 gpm	4.5 gpm
60	3.9 gpm	3.9 gpm
120	3.6 gpm	4.0 gpm
180	3.7 gpm	4.0 gpm
240	3.9 gpm	3.5 gpm
300	3.7 gpm	3.8 gpm

- RAW capacity ~70 kW
  - ~40 kW is removed by RAW system for 750 kW beam operation
  - Remaining heat load is removed by groundwater
- Water discharge pressure is 150 psi, whereas the pressure at suction is 20-30 psi
- Flow is limited by pipe size

Temperature in US RAW w/o beam
Supply: 56 F, Return: 60 F



Temperature in US RAW w/ beam @750 kW
Supply: 75 F, Return: 63 F



Energy deposition calculations for NuMI-AIP decay pipe with MARS15 code

Igor Rakhno

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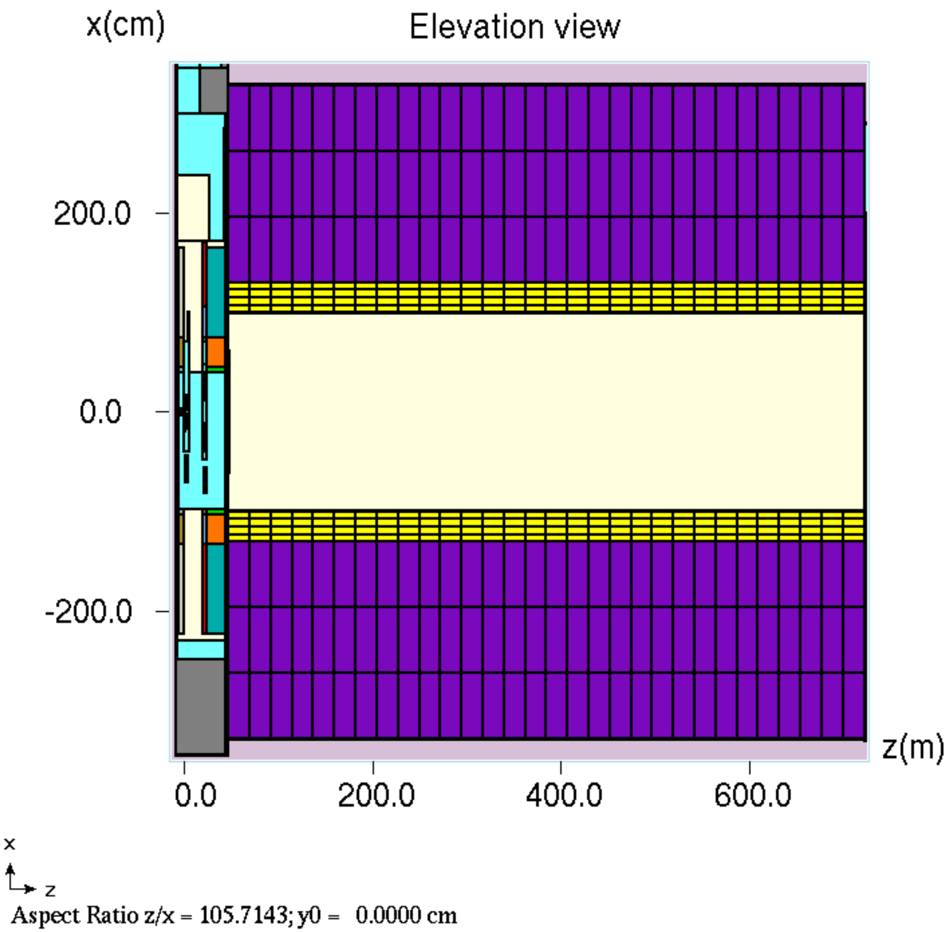
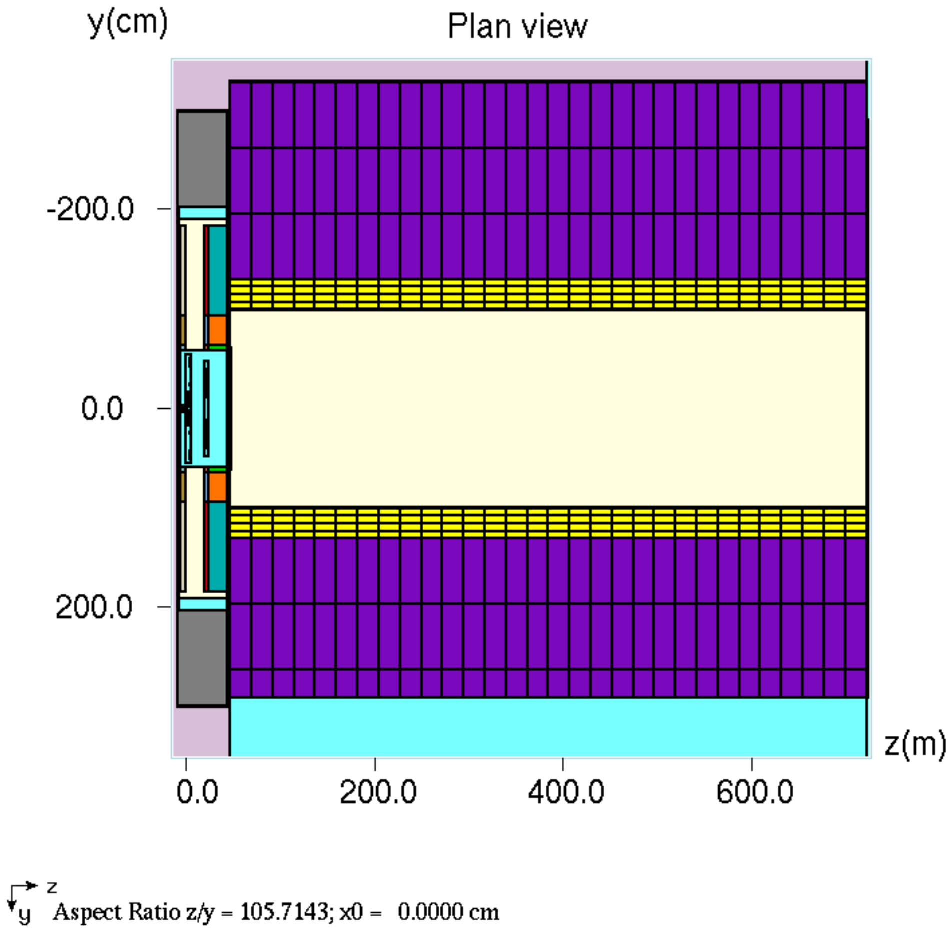
Model updates and assumptions

- A 3D binning has been added to the previously built model of decay pipe.
- Non-uniform radial bins, smaller bins at inner side.
- Two features are responsible for breaking symmetry in azimuth:
  (i) alignment of the decay pipe relative to the target hall (elevation);
  (ii) existence of a passageway on right side.
- Bins in azimuth were introduced as well.
- A couple of iterations has been done to properly adjust the sizes of radial and longitudinal bins as well as bins in azimuth.

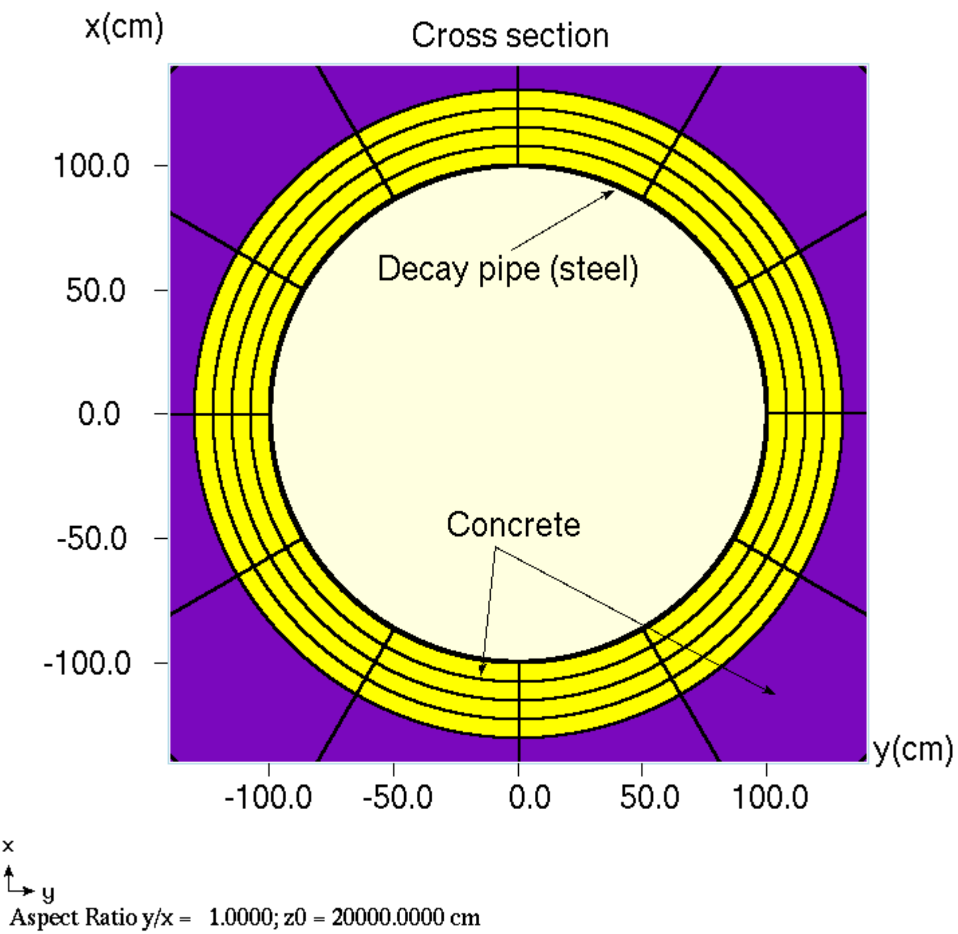
- Energy threshold for neutrons and charged hadrons is 10^{-3} eV and 100 keV, respectively.
- Distribution of incoming protons upstream of the target is assumed to be a Gaussian (both in energy and angle), without energy-angle correlations.
- A comparative study has been done to see if any essential difference in calculated distributions can be observed due to energy-angle correlations in the proton source used. A special modeling routine has been used for that purpose.

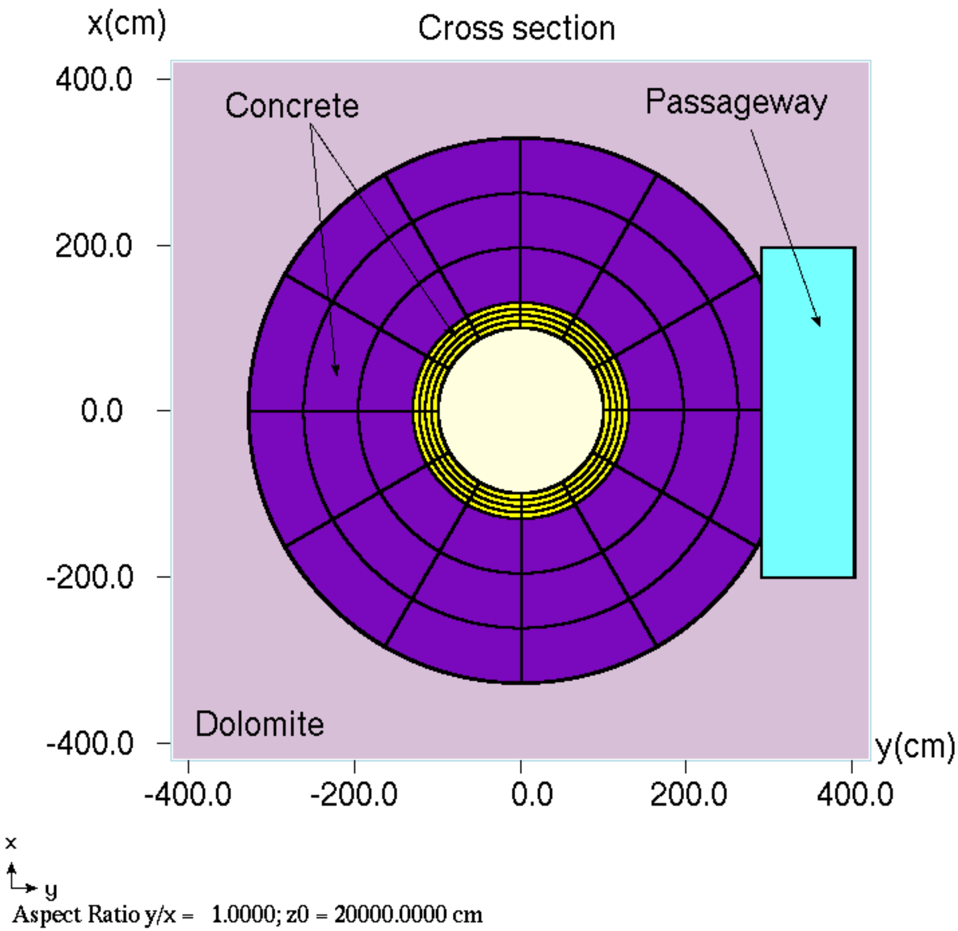
Both yellow and violet colors correspond to concrete. A thin steel layer is an innermost layer (not visible at this scale).





Cross section of the inner part (left) and the entire decay pipe with passageway (right)

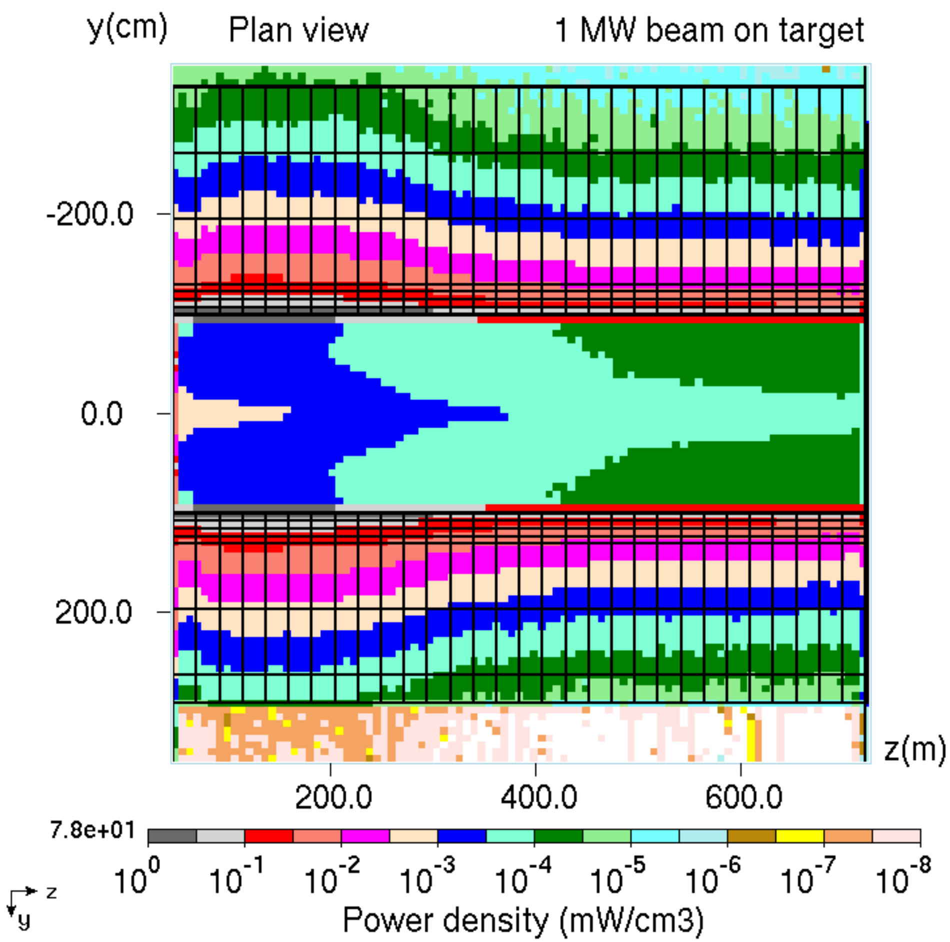




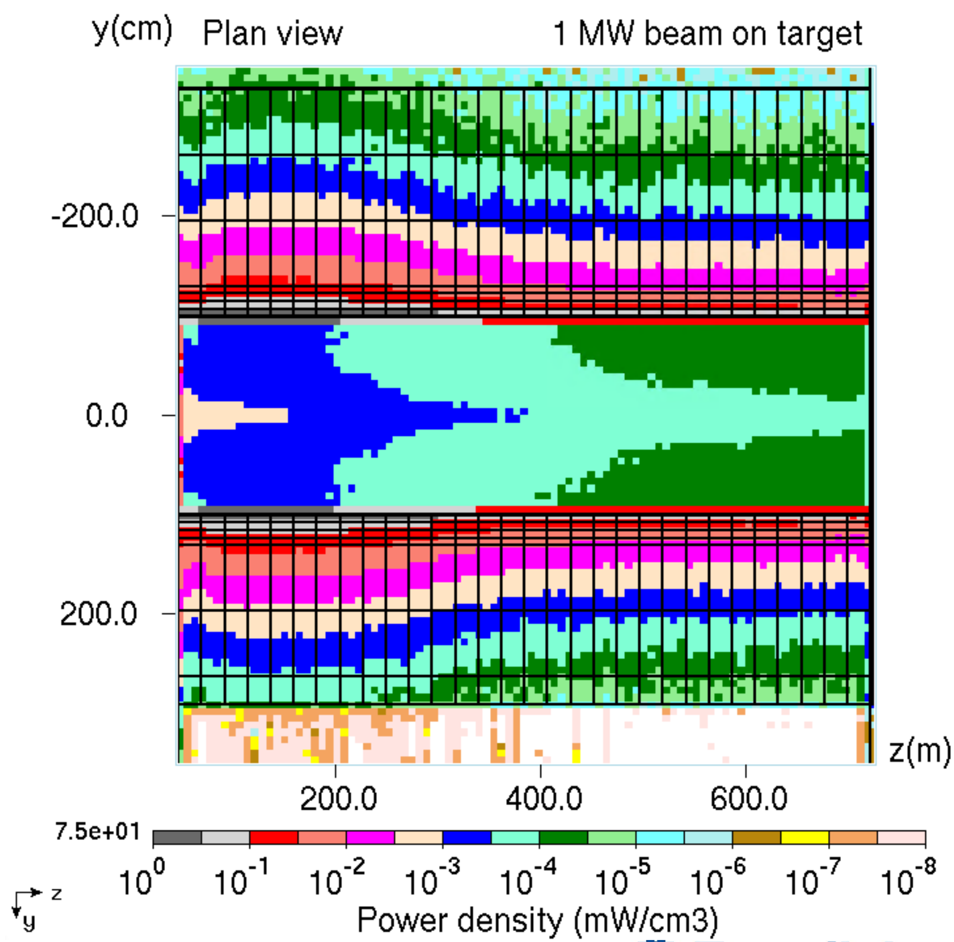
Energy deposition in Decay Pipe

Effect of correlations between spatial and angular coordinates in incoming beam

W/o correlations



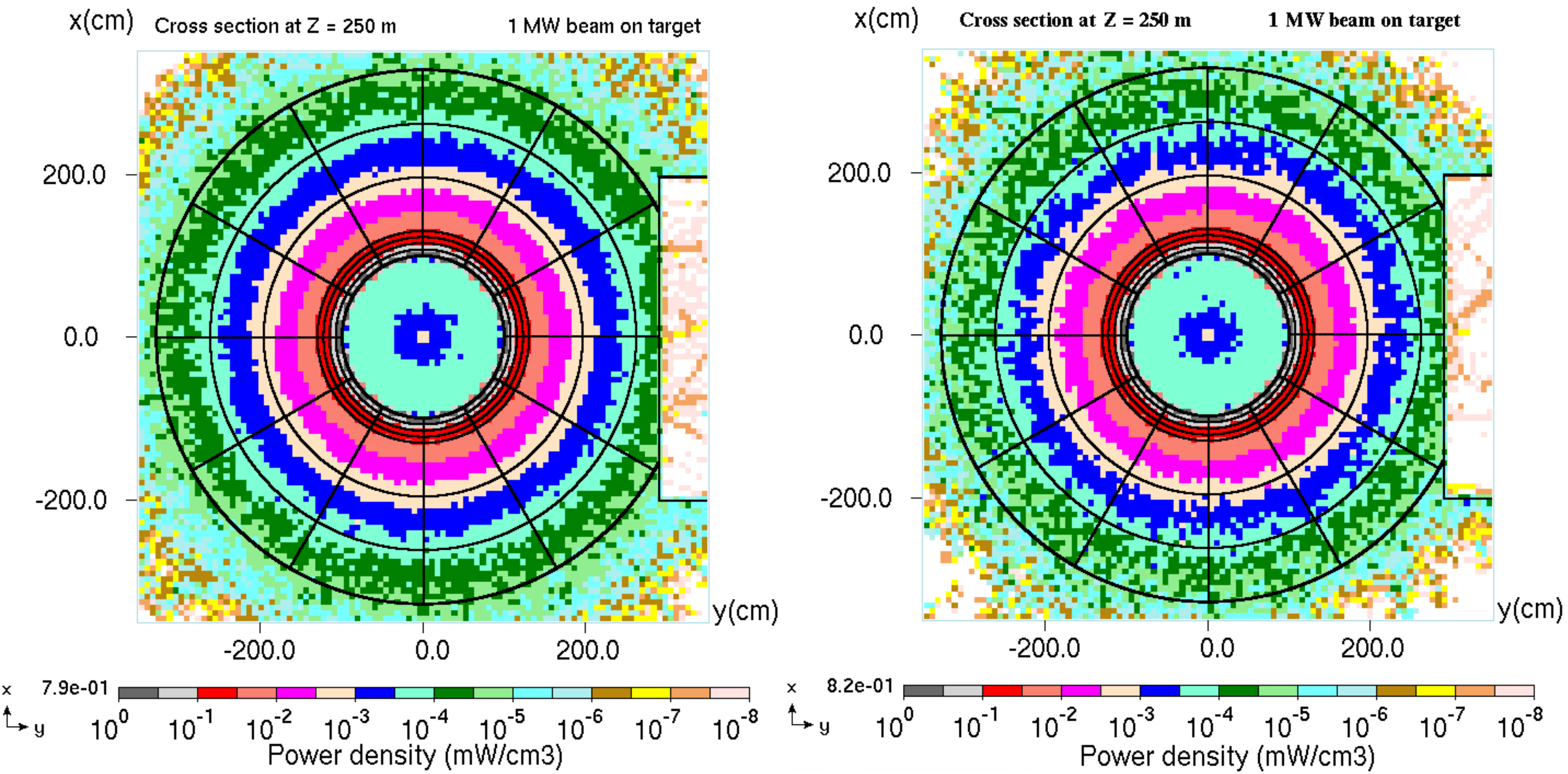
With correlations



Energy deposition in Decay Pipe

Effect of correlations between spatial and angular coordinates in incoming beam

W/o correlations | With correlations



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Energy deposition in a fragment of Decay Pipe at Z = 250 m (peak region) (arbitrary units)

Effect of correlations between spatial and angular coordinates in incoming beam

	W/o correlations	With correlations
1-cm thick beam pipe	**4.765 ± 0.019***	**4.689 ± 0.040**
Adjacent concrete layer	**0.3464 ± 0.0016**	**0.3487 ± 0.0034**

*** The statistical uncertainty is 1σ.**

Conclusions

- **The calculated energy deposition distributions (ready-to-use formatted tables) have been sent to Z. Tang.**

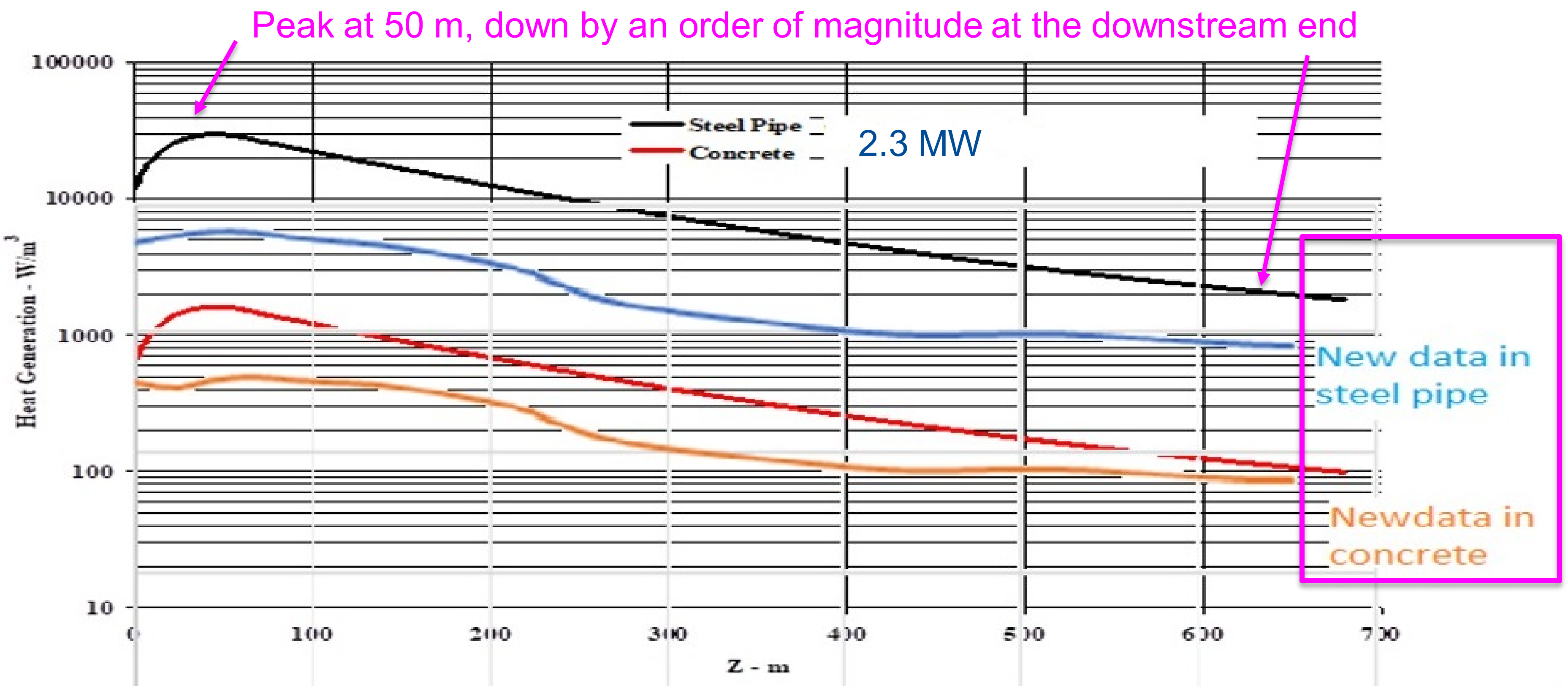
- **The effect of energy-angle correlations seems to be lost after several (a few?) collisions in matter. In this case target itself provides such collisions. Also, the scoring bins are pretty big.**

FEA Report from Zhijing Tang

- Heat load profile
- Bob Wands' FEA for 2.3 MW beam (750 kW in Decay pipe)
- FEA for 1 MW beam (250 kW in Decay pipe)
- Summary

Heating Loads (@1 MW Beam vs. @2.3 MW Beam)

	@1 MW	@2.3 MW	@400 kW	@700 kW
Steel pipe	103 kW	390 kW	63 kW	110 kW
Concrete shielding	144 kW	360 kW	52 kW	91 kW
% of total beam power	25%	32%	29%	29%



Boundary Conditions (Bob Wands)

Parameters most directly affecting the stresses in the decay pipe

Description	Assumptions
Radial clearance between steel pipe and concrete	0, or 1 mm
Degree of axial constraint at the ends of decay pipe	Fixed
Outer boundary cooling provided by ground water	25 C, h = 20 W/m2-C
Flow rate and temperature of water in cooling tubes	9 gpm / 25 C per 2.3 MW case 4.5 gpm / 31 C per 1 MW case
Inside steel pipe	Vacuum per 2.3 MW case 0.9 atm Helium per 1 MW case

- The two materials have the same thermal expansion coefficient, the vast bulk of concrete stays relatively cool, preventing substantial expansion at the inner radius, where it contacts the steel pipe, and hence limits the total thermal expansion, tend to produce higher hoop stresses in the steel pipe
- If axially unconstrained, and raised by 50 C, the pipe/concrete unit would increase nearly 0.4 m.
- If axially constrained, this tendency to expand results in axial stresses.

Main reference: *The Numi Decay Pipe Under Proton Driver Loads*

by Bob Wands, April 11, 2005

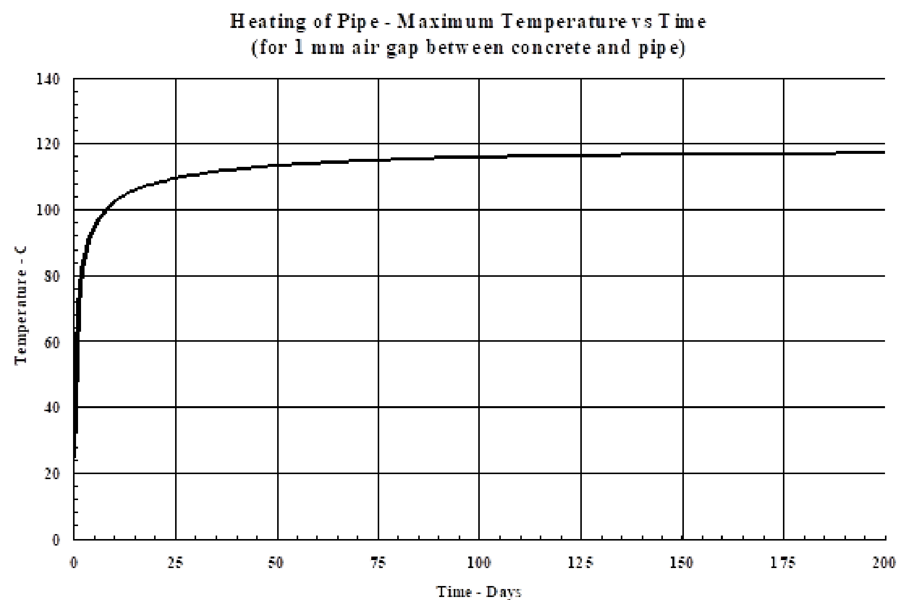
Total heat dumped in the decay pipe: 750 kW

Model	Radial clearance between steel pipe and concrete
Model 1	zero, i.e., perfect contact between concrete and steel pipe
Model 2	1 mm for both thermal and structural calculations
Model 3	1 mm for thermal calculation, zero for structural calculation

Conclusions of Wands' Study:

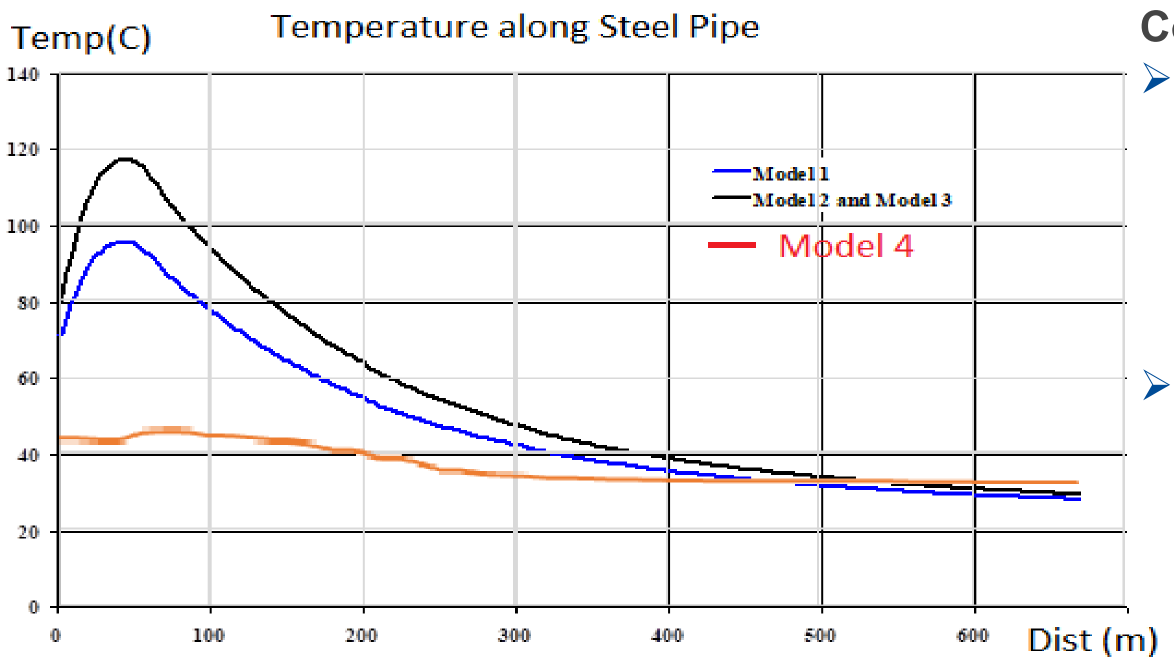
- Maximum temperature will reach 117 C (with 1 mm gap) or 96 C (without gap)
- It will take about 200 days to reach equilibrium temperature.
- Thermal stress will not cause the yield nor buckling of the steel pipe.
- Even though there may be some local cracks in concrete, they will be saturated with ground water, and will not affect the thermal operation of the decay pipe.

Figure 11



Temperature Comparison (@1 MW vs. @2.3 MW)

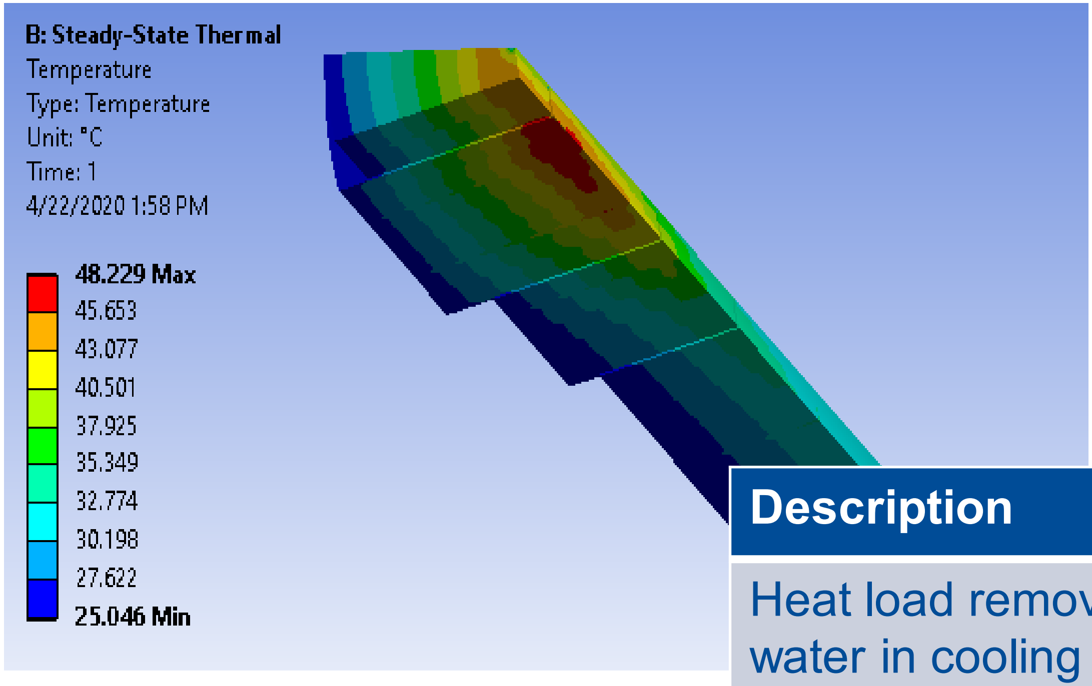
Model	Radial clearance between steel pipe and concrete
Model 1	zero, i.e., perfect contact between concrete and steel pipe.
Model 2	1 mm for both thermal and structural calculations
Model 3	1 mm for thermal calculation, zero for structural calculation
Model 4	Zero. 0.1 atm negative pressure on steel pipe inner surface; cooling tube: h = 2500 W/m^2-C, T_b = 31 C



Comments from Jim Hylen:

- Cooling water will be picking up heat from the hot spot but re-depositing a significant part of that heat in the rest of the decay pipe for a significant period after turn-on
- Measured temperature of the water emerging from the decay pipe is not a measurement of the maximum water temperature or the heat it is carrying away from the hot spot.

Static Temperature @1MW Beam Operation



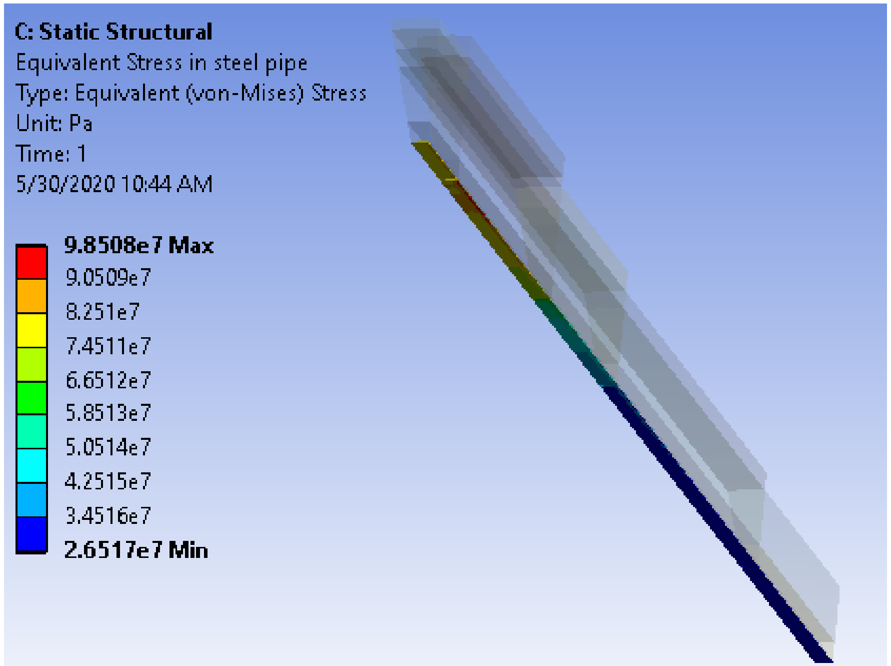
Max. temperature 48 C
(a 15 degree segment of the decay pipe)

FEA Model heat balance check

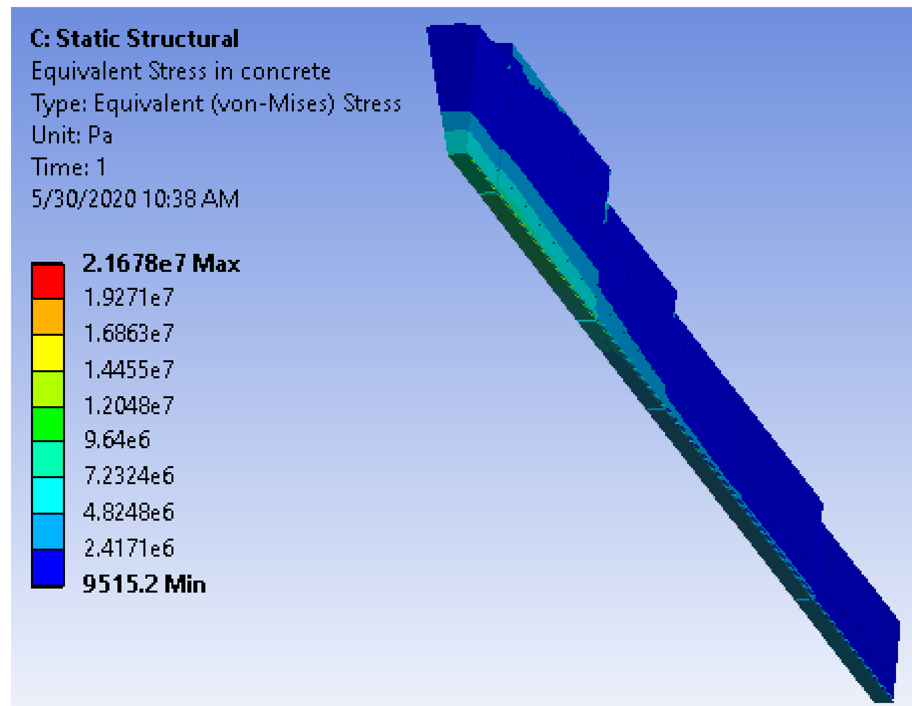
Description	Value
Heat load removed by water in cooling tubes	7891.5 W (67%)
Heat load removed by ground water	3876.8 W (33%)
Total heat load	282.44 kW (15% more than the MARS data)
Water temperature rise after absorb heat load	13.5 C

Equivalent Stresses @1MW Beam Operation

Steel pipe: 98.5 MPa



Concrete: 21.7 MPa



Summary

Model	Max. Steel Pipe Temperature (°C)	Max. Concrete Temperature (^{0}C)	Max. Steel Pipe Hoop Stress- (ksi)	Max. Steel Pipe Axial Stress – (ksi)	Max. Concrete Stress- (ksi)
1	96	96	-17.3	-22.1	5.4
2	117	116	-1.7	-23.7	8.9
3	117	116	-25.9	-30.6	6.9
4	46.10	48.23	-16.92	-10.59	3.14

Material properties

Property	Steel	Concrete
Young's Modulus	29e6 psi (200 GPa)	3.48e6 psi (24 GPa)
Density	7849 kg/m^3	2500 kg/m^3
Thermal Conductivity	43 W/m-C	1.2 W/m-C
Specific Heat	450 J/kg-C	3300 J/kg-C
Thermal Expansion Coefficient	0.117e-4 m/m-C	0.117e-4 m/m-C
Yield Strength	36 ksi (248 MPa)	1000 psi (69 MPa)

- Concrete in the decay pipe contains much more water than conventional concrete, and much less cement;
- The "yield" stress can only be estimated;
- The properties used for the concrete are thought to be conservative choices from among the range of typical values.

Conclusion: thermal stress will not cause the yield nor buckling of the steel pipe.

Decay Pipe Upstream Window (Mike Campbell / Zhijing Tang)

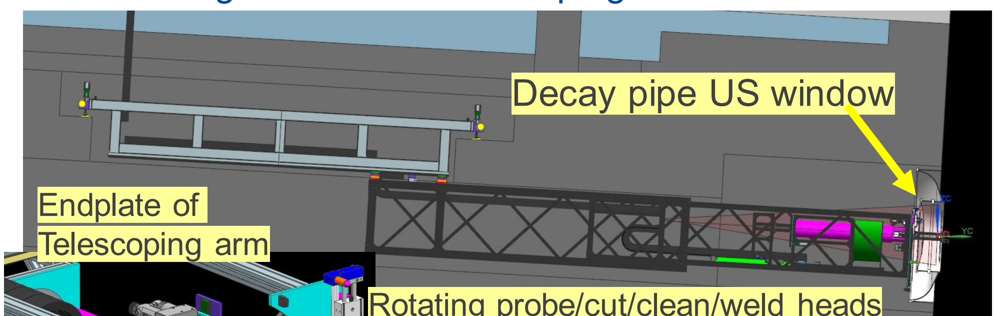
A window replacement concept is developed in the event US window fails

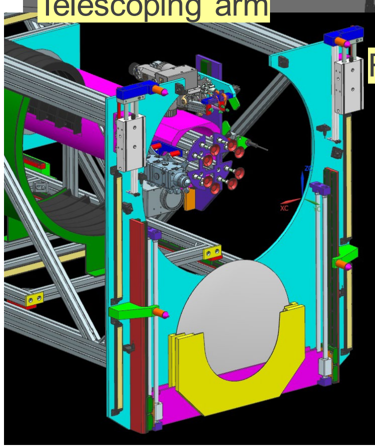
- Suspected corrosion was found on the window at beam spot center in 2007
- Since then, decay pipe was filled with 0.9atm helium gas

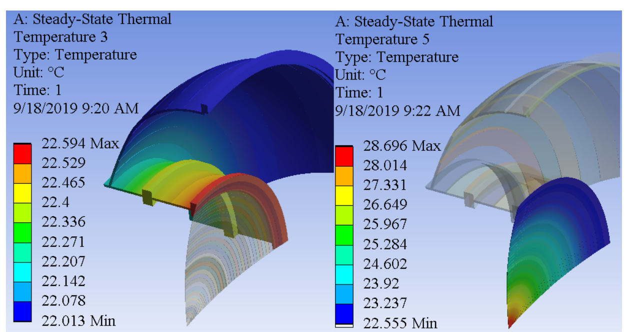
Activities performed

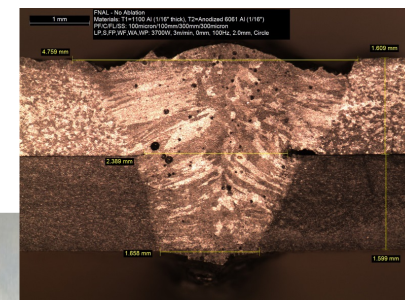
- Repair mechanism concept Robot laser ablation welding testing
  - Weld repair patch (Al 5083 or 5052) over failed section (Al 6061)
  - Samples, welding, testing & characterize properties
- FEA thermo-structural analysis

Uses a 2-stage motorized telescoping arm to reach out 23.5’









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Summary

- The current RAW system provides the cooling needed for decay pipe to run for 1 MW beam operation. There is no need for an upgrade of the RAW system. (today's talk)

- Per risk mitigation, a window replacement concept is developed for the US window. (previous talk)