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HEAT TRANSFER ANALYSIS IN A HIGHER ORDER MODE WAVEGUIDE FOR THE ELECTRON – ION COLLIDER AT BNL

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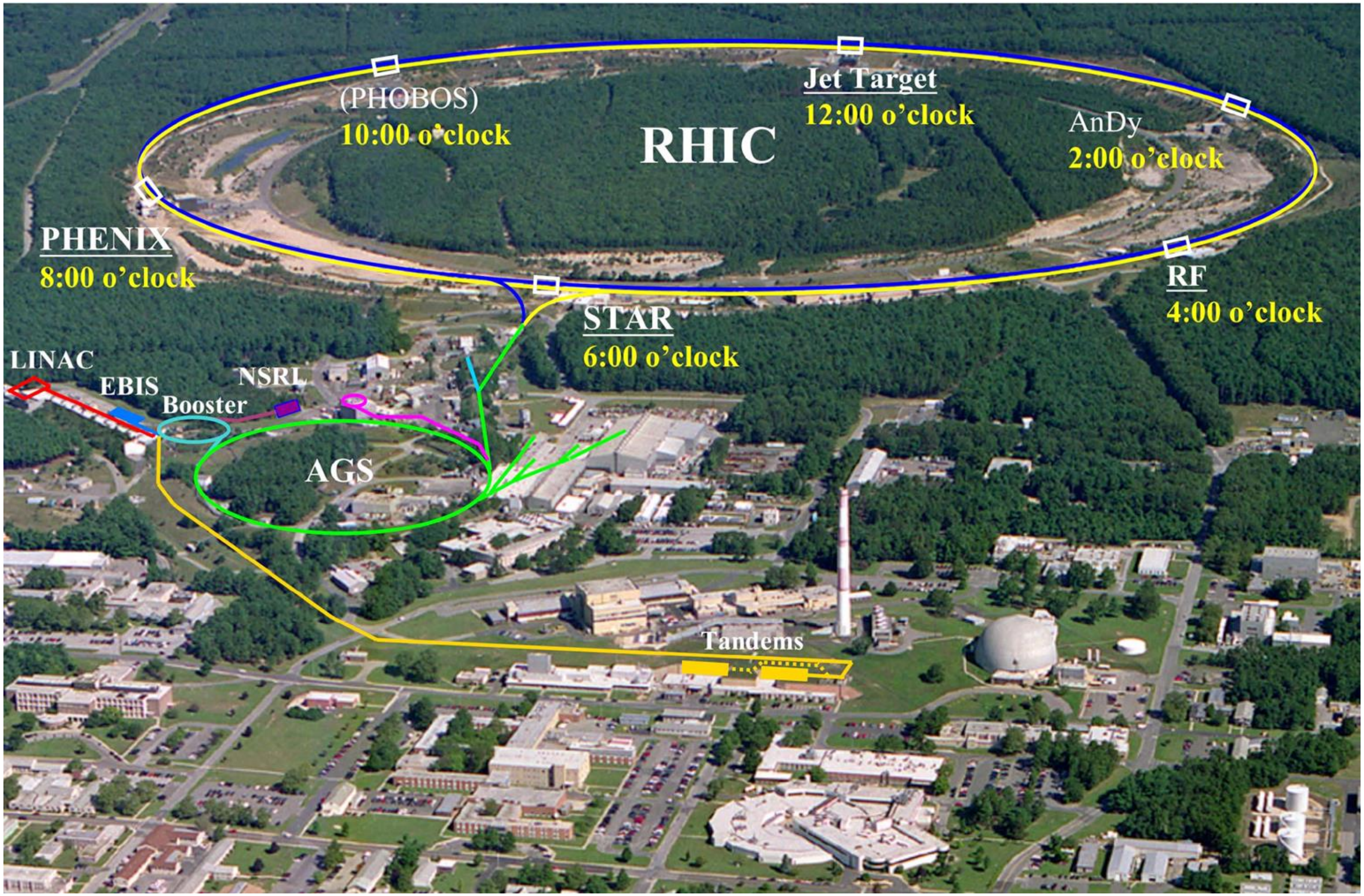
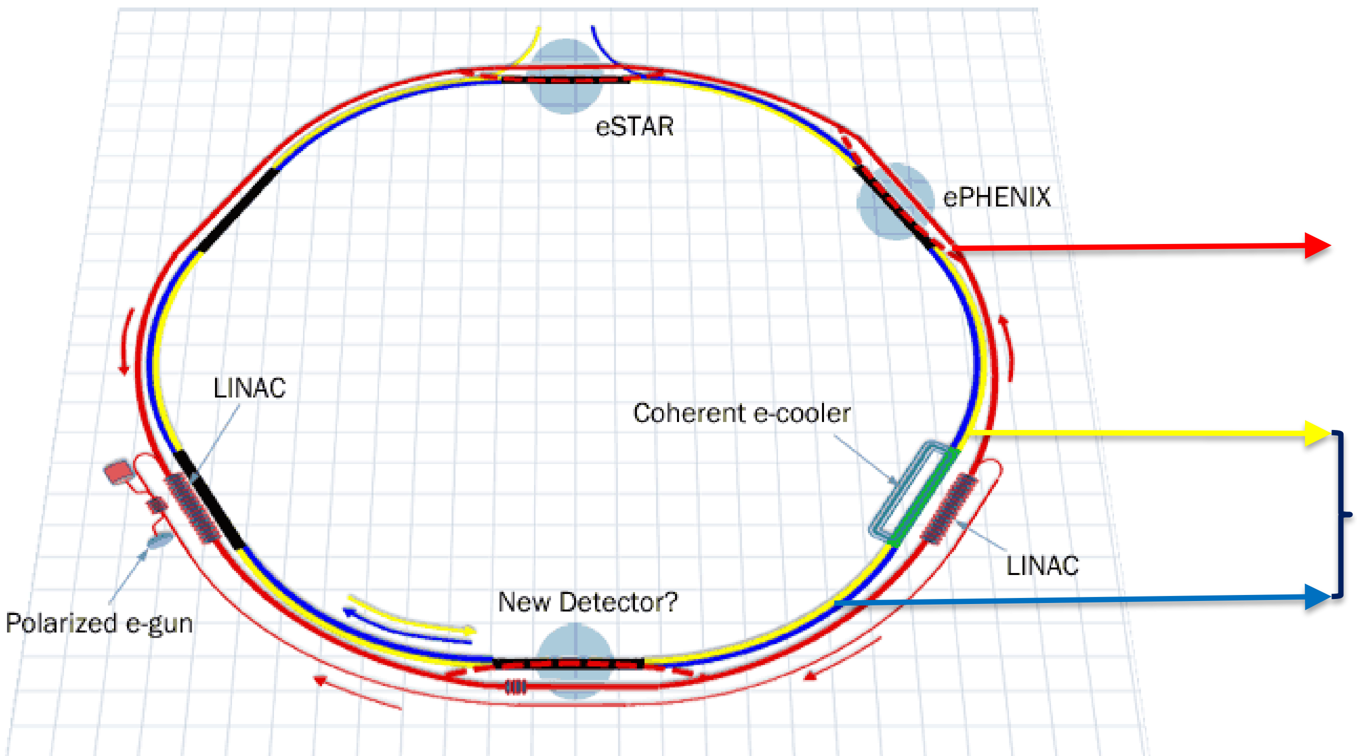
Stony Brook University

The Relativistic Heavy Ion Collider (RHIC)



Upgrading to an Electron-Ion Collider (EIC)

- Add *linear accelerator* (LINAC) to RHIC for electrons
- Heavy ions collide with electrons

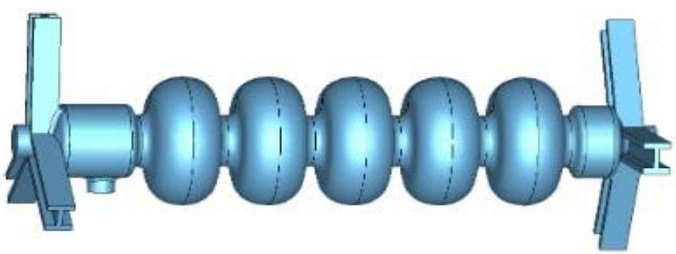


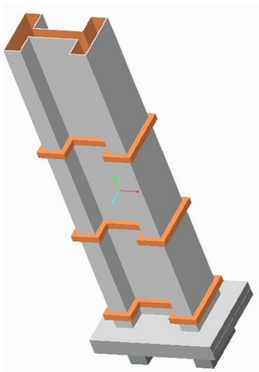
New e^- ring

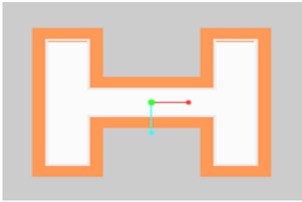
Existing ion rings

Upgrading to an EIC

- LINAC: superconducting RF cavities for acceleration (Nb)
  - Operating temp: 2.1 K; Cooled by superfluid He.
  - RF volume – High vacuum (10^{-10} mbar)
- Fundamental mode is at 650 MHz
- Charged-particle beams interact with EM field in cavity; generate *higher-order modes* (HOM) that impedes beam
- Waveguide channels HOM energy from 2 K







Problem Description

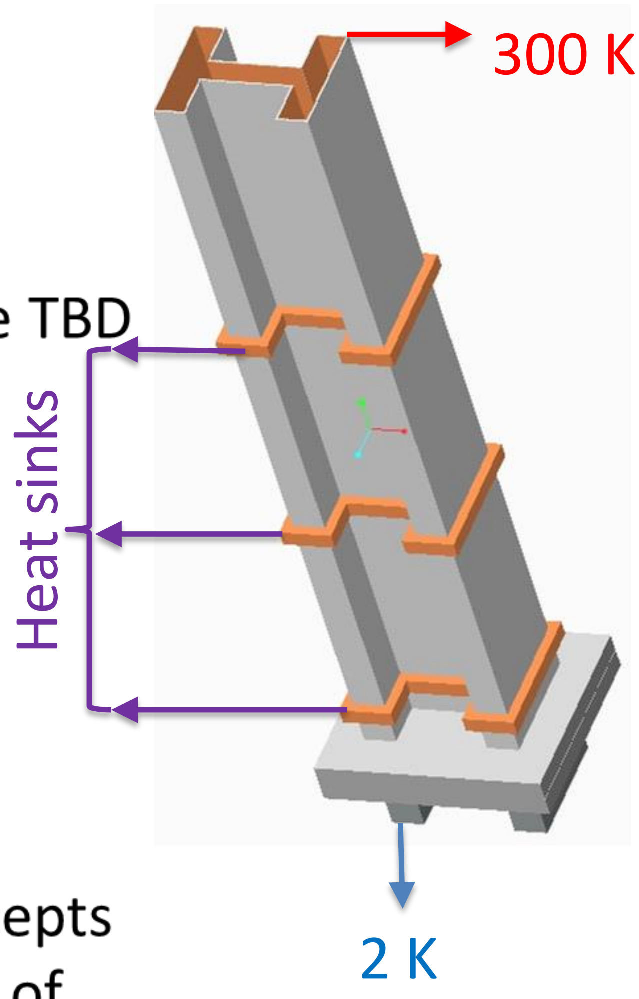
- 1.2 mm stainless steel wall w/ 20 μm Cu coating (minimizing RF heating)
- Goal: minimize cryogenic load and provide adequate cooling.
- Multiphysics problem
  - Thermal conduction and radiation
  - RF heating from fundamental mode field

MODELLING

- Model the boundary value problem:
  - Cu coated SS end at 300 K, Nb at 2 K
  - Heat sinks used to intercept most heat; number (2 or 3), location and temperature TBD
  - RF heating calculated from

$$P = \frac{1}{2}\int H^2\, R_s\, ds$$

- Thermal radiation is modelled using ANSYS
- Assumptions
  - Operating temperatures of thermal intercepts are ~3 to 5 K higher than the temperature of returning Helium.

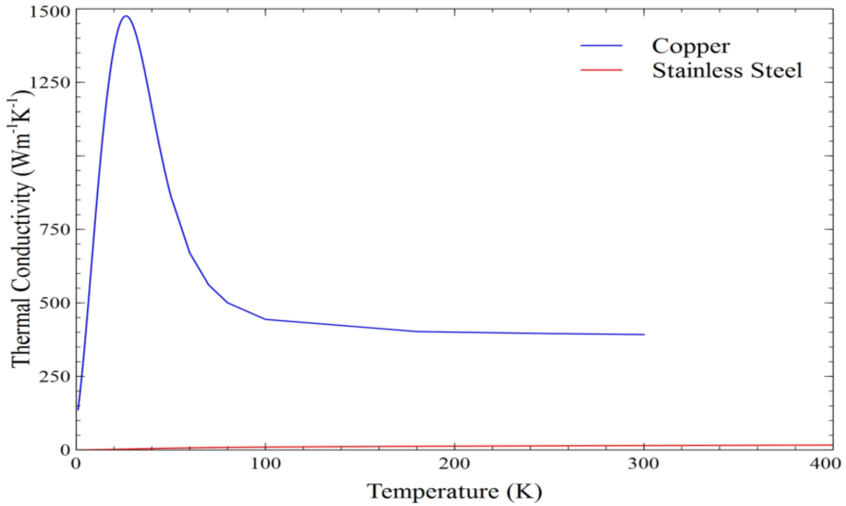


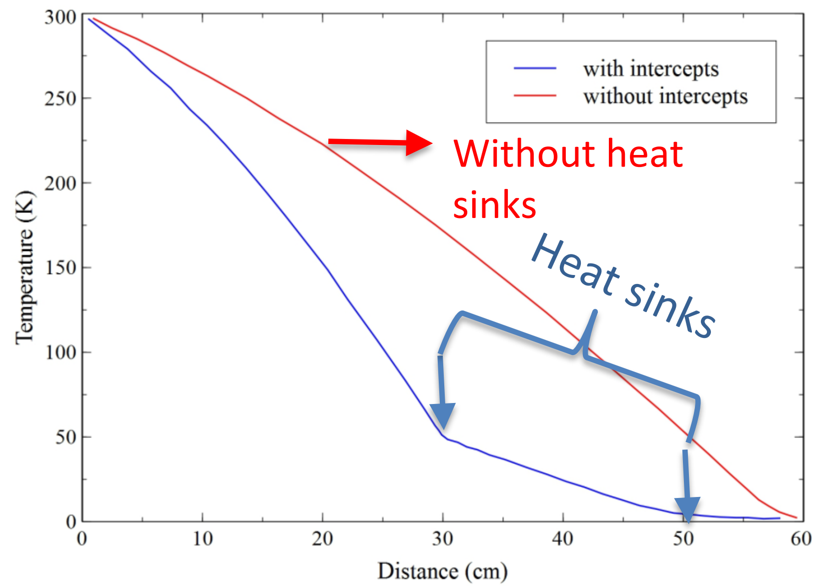
ANLAYTICAL CALCULATIONS - I

- Static load (no RF):
  - Dictated by thermal conductivity and temperature gradient
  - Non-linear: changes in thermal conductivity cannot be ignored: $k = k(T)$,
  - Static heat flow, $\dot{Q}$, computed analytically:

$$\dot{Q} = \frac{A_{cond}}{dx} \int_{2}^{300} k(T)\, dT$$

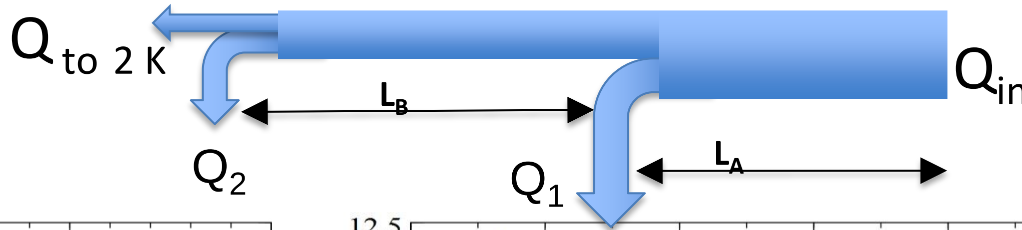
  - $\dot{Q}_{Cu} + \dot{Q}_{SS} \cong 12.7W$
  - Temperature distribution obtained from equation.
  - Starting point for temperature and location of heat intercepts

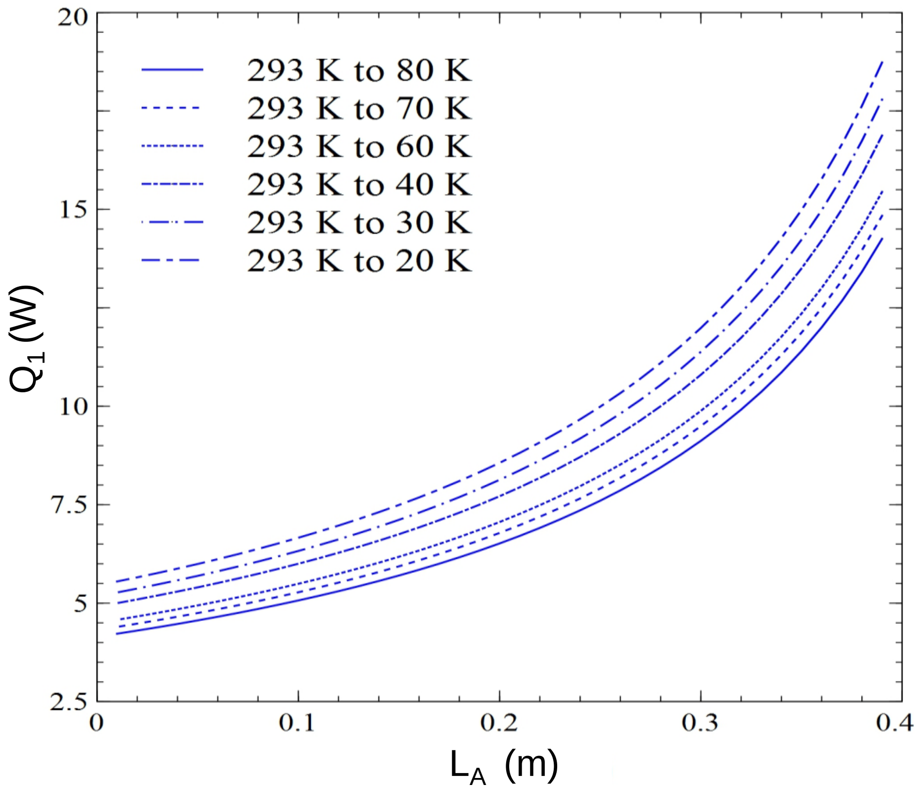


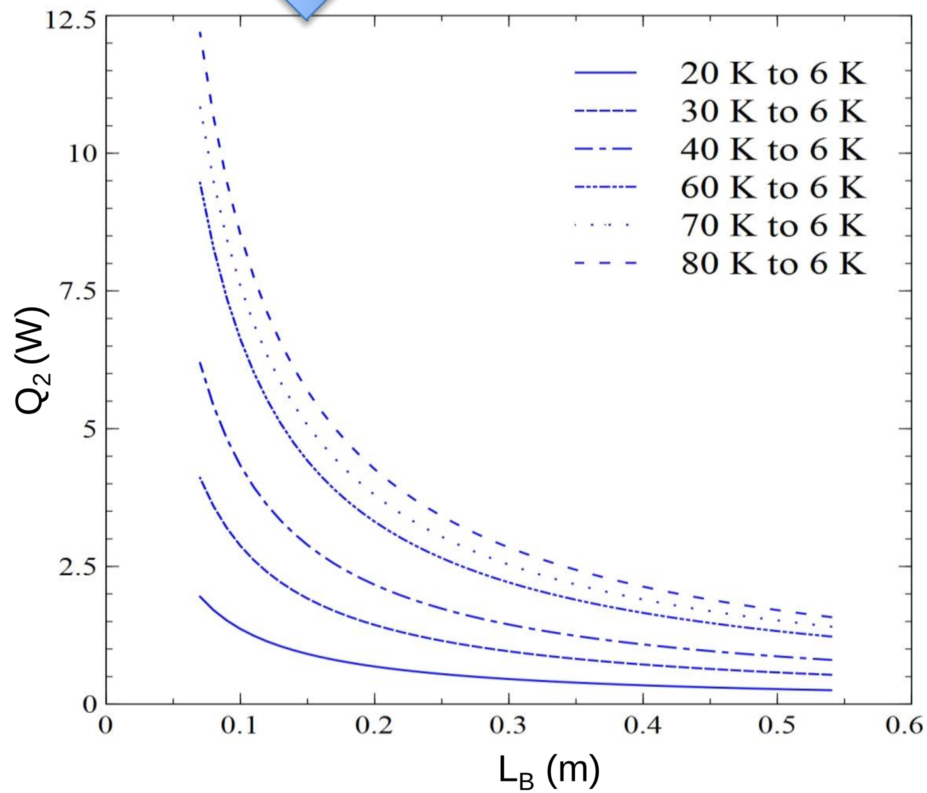


ANALYTICAL CALCULATIONS (2-HEAT-SINK CASE)

- Heat sink temperature vs. heat load
  - Second heat sink temperature fixed at 6.5 K (providing gradient to He return pipes)

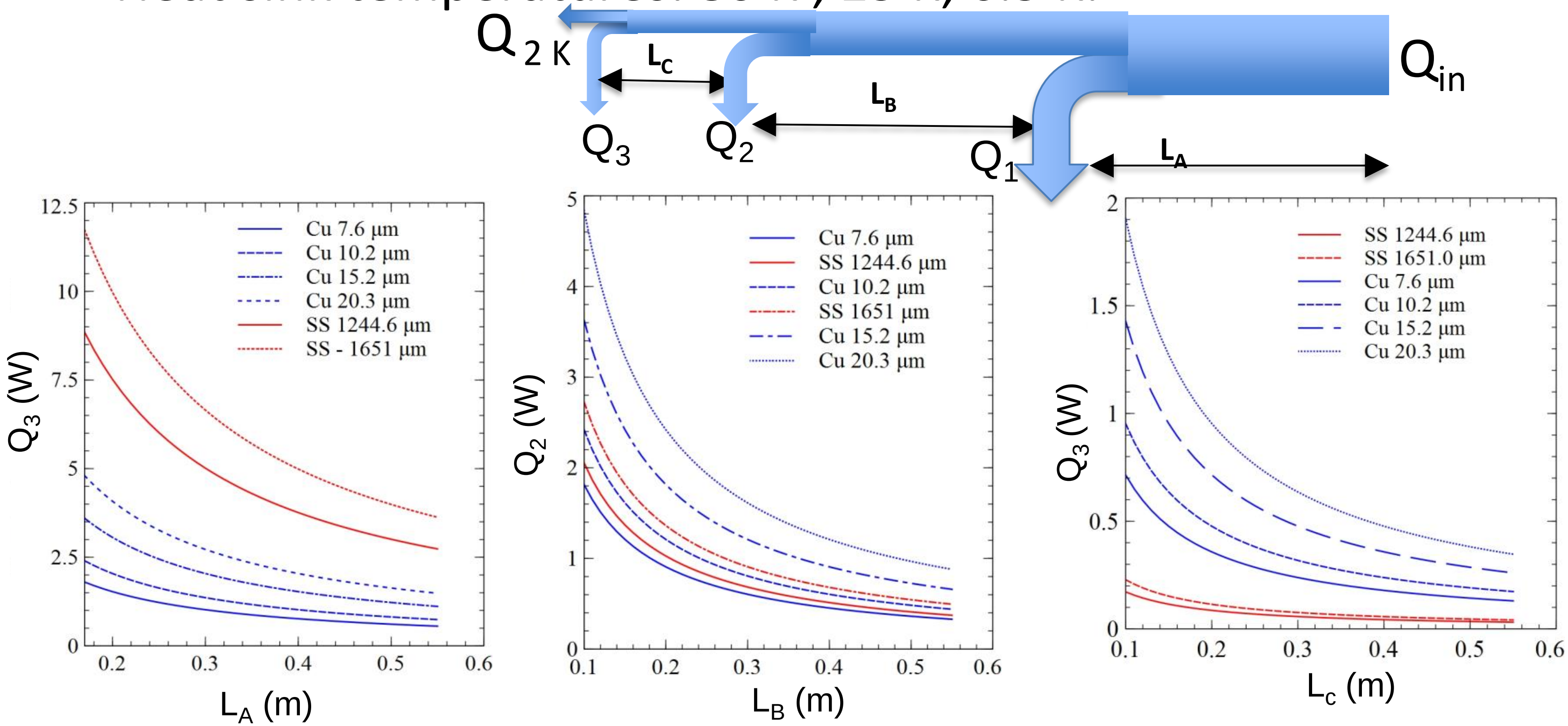






ANLAYTICAL CALCULATIONS (3-HEAT-SINK CASE)

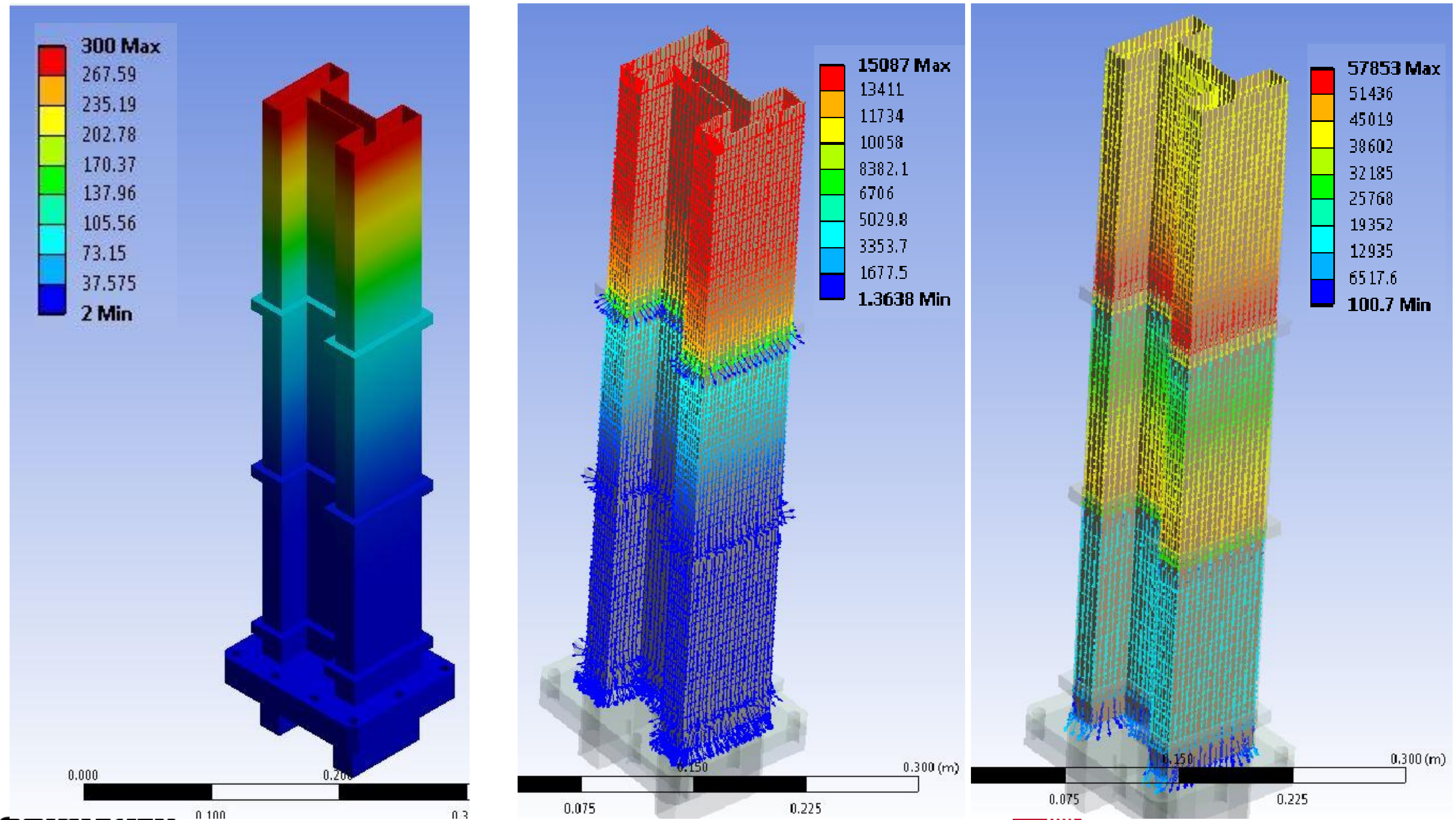
- Heat sink temperatures: 80 K , 25 K, 6.5 K.



- Controlling heat removed at different temperatures facilitates better cryogenic system design
- Parametric study performed documenting effect of varying thicknesses of Stainless steel and Cu

NUMERICAL ANALYSIS – STATIC LOAD ONLY

- Temperature and heat flux were solved using ANSYS with respective boundary conditions.



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ANALYTICAL CALCULATIONS: DYNAMIC LOAD

- No HFSS; have to come up with other ways
- Trial 1: False – convection for q (T) using q = h(T) (T_surf – T_amb)

y location on the waveguide	Temperature (K)	H actual	Rho (T) Ohm-M	Rho_surface(T) (Ohm)	Q/A (W/m^2)	A = 0.013692, Q =	h'
0	2	100	8E-10	0.001432494	7.162468247	0.124197199	-0.021836793
0.03	4.05	76.931	8E-10	0.001432494	4.239019995	0.073504607	-0.013005123
0.06	4.969	58.86	8E-10	0.001432494	2.481436838	0.043028115	-0.007634462
0.09	6.5015	45.1	8E-10	0.001432494	1.456853204	0.025261835	-0.004503431
0.12	9.425	34.52	8E-10	0.001432494	0.85350149	0.014799716	-0.002662408
0.15	13.571	26.44	8E-10	0.001432494	0.500709246	0.008682298	-0.001582375
0.18	17.541	20.25	8.10164E-10	0.001441565	0.295565842	0.005125112	-0.000945935
0.21	21.333	15.5	8.3333E-10	0.00146203	0.175626328	0.003045361	-0.000568983
0.24	25.005	11.85	8.7009E-10	0.001493928	0.104890585	0.001818803	-0.000343909
0.27	33.484	9.07	1.05755E-09	0.001647019	0.067745922	0.001174714	-0.000228473
0.3	45.758	6.96	1.43032E-09	0.001915421	0.046393037	0.000804455	-0.000163217
0.33	57.8	5.323	1.912E-09	0.002214581	0.03137434	0.000544031	-0.000115262
0.36	69.603	4.9	2.57618E-09	0.002570608	0.030860146	0.000535115	-0.000118512
0.39	81.085	3.1171	3.3651E-09	0.002937966	0.014273096	0.000247495	-5.73412E-05
0.42	97.405	2.3915	4.7405E-09	0.003487063	0.009971731	0.00017291	-4.28716E-05
0.45	132.72	1.83	6.9632E-09	0.00422622	0.007076595	0.000122708	-3.58708E-05
0.48	167.51	1.4	9.11068E-09	0.004834183	0.0047375	8.21482E-05	-2.91556E-05
0.51	201.69	1.071	1.1169E-08	0.005352478	0.003069756	5.32296E-05	-2.39245E-05
0.54	235.2	0.81	1.4216E-08	0.006038602	0.001980963	3.43499E-05	-2.08962E-05
0.57	267.97	0.6291	1.71376E-08	0.00663014	0.001311995	2.275E-05	-2.1151E-05
0.6	300	0.4813	0.00000002	0.007162468	0.000829592	1.43851E-05	-2.76531E-05
						0.303271336	

- Creepy ANSYS results
- Conduction load is now 13.557 KW. Cannot be unless cold end is getting colder. But Convection load is + 0.03 W
- Used ANSYS APDL script instead to specify q (T)

Numerical analysis – Static and dynamic load

- Dynamic heat loads: RF dissipation included
- Static and Dynamic heat loads are shown below

TABLE I. Static Heat load

Boundary condition	Temperature (Kelvin)	Heat flow (Q) (Watts)
Warm end	300	12.17
Intercept	85	-7.55
Intercept	25	-3.15
Intercept	6.5	-0.94
Cold end	2	-0.53

TABLE II. Dynamic Heat load

Boundary condition	Temperature (Kelvin)	Heat flow (Q) (Watts)
Warm end	300	11.20
Intercept	85	-8.29
Intercept	25	-2.79
Intercept	6.5	-0.66
Cold end	2	-1.20
Dynamic load		1.74

- Preliminary results: thermal radiation load

TABLE III. Radiation load

Surface	Emissivity (ϵ)	Net radiation (Watts)
SiC	0.9	0.44
Cu plating	0.05	-0.38
Nb waveguide	0.9	-0.01
Cold Nb surface	0.9	-0.00357

Conclusions

- A thermal study has been carried out for the RF HOM Waveguide on the RHIC upgrade at BNL
- Multiple heat sink configurations were explored
- Static and dynamic loads are calculated.
  - Dynamic heat flow ~ 10% of static heat flow
- Contribution from radiation is small
  - ~ few mW (negligible)