Time Resolved Cryogenic Cooling Analysis of the Cornell Injector Cryomodule

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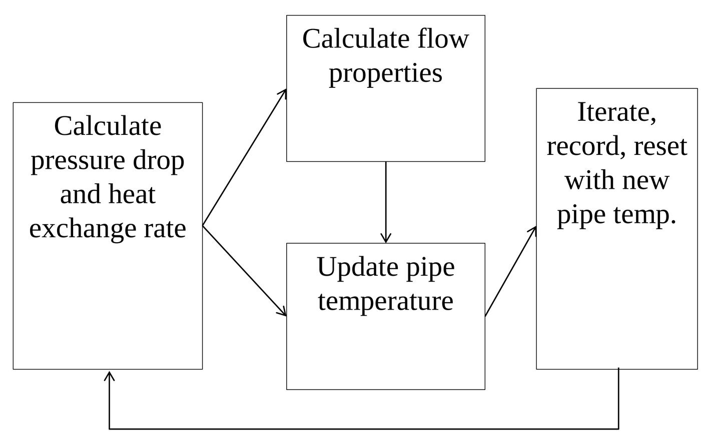
Abstract

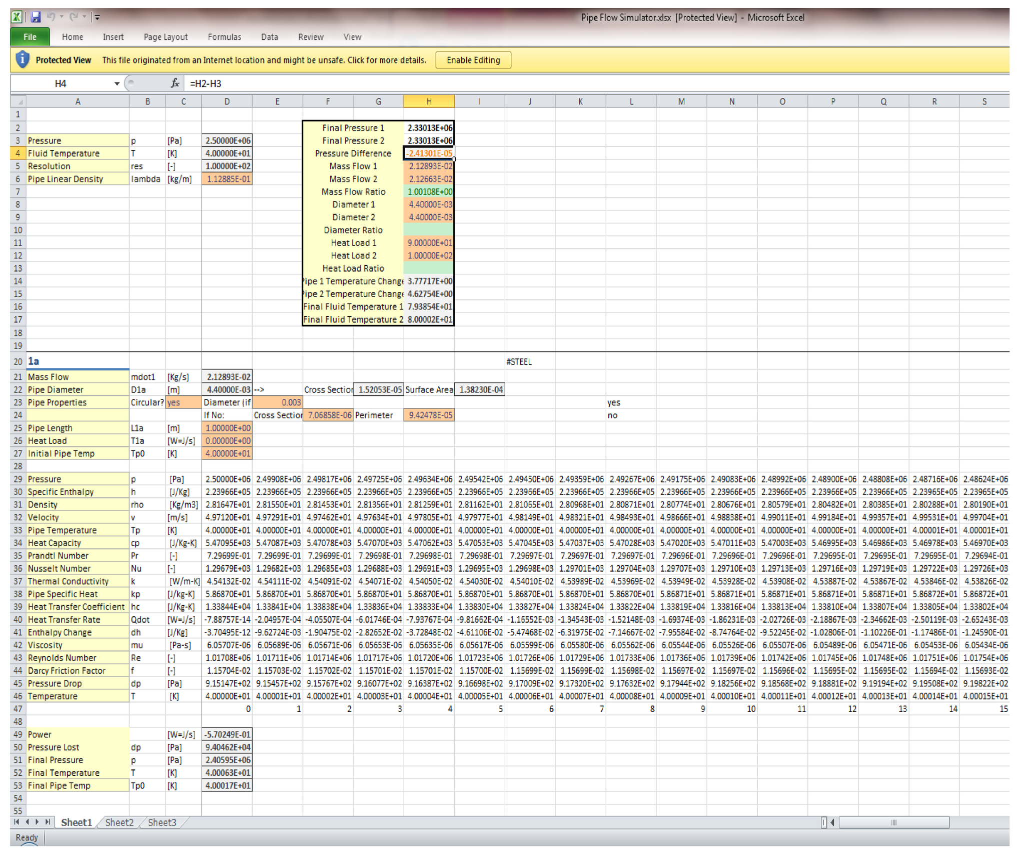
Managing parallel cryogenic flows has become a key challenge in designing efficient and smart cryo-modules for particle accelerators. In analyzing the heating dynamics of the Cornell high current injector module a power-full computational tool has been set-up allowing time resolved analysis and optimization. We will describe the computational methods and data sets we have used, report the results and compare them to measured data from the module being in good agreement. Mitigation strategies developed on basis of this model have helped pushing the operational limitations.

Calculation set-up

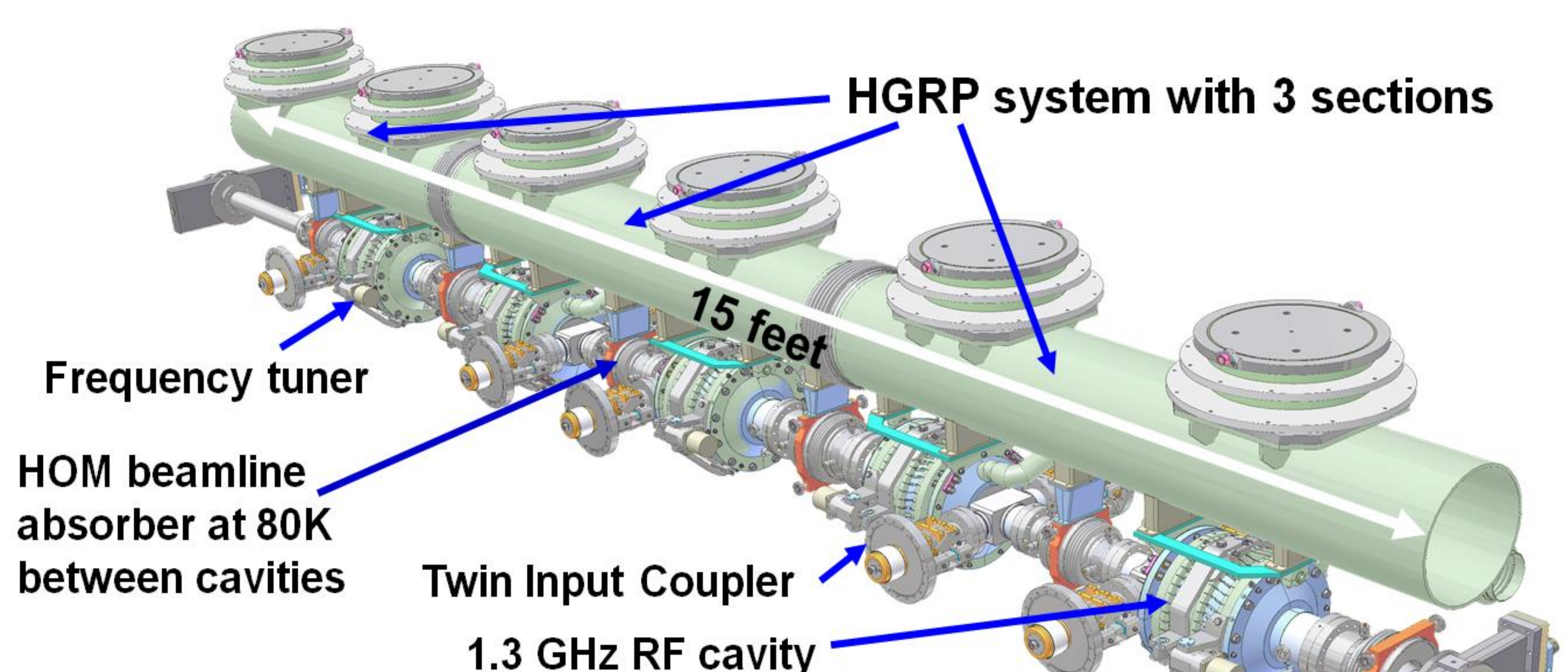


Pressure (p): Input or $p - \Delta p^*$
Enthalpy (h): HEPAK or $h + \Delta h$
Density (ρ): HEPAK
Velocity (v): $\frac{\dot{m}}{A\,\rho}$
Pipe Temperature (T_p): $T_p + \Delta T_p$
$= T_p + \frac{P}{v\,r\,\lambda\,C_p} - \frac{\dot{Q}}{v\,\lambda\,C_p}$
Pipe Specific Heat (C_p): Fit to empirical data from N.I.S.T
Fluid Specific Heat Capacity (C_f): HEPAK
Prandtl Number (Pr): HEPAK
Fluid Thermal Conductivity (k): HEPAK
Heat Transfer Coefficient (h_c): $\frac{k\,Nu}{D}$
Nusselt Number (Nu): $0.023\,Re^{0.8}\,Pr^{0.4}$
Heat Transfer Rate ($\dot{Q}$): $h_c\,A_S\,(T_p - T_f)$
Enthalpy Change (Δh): $\frac{\dot{Q}}{\dot{m}}$
Dynamic Viscosity (μ): HEPAK
Reynolds Number (Re): $\frac{D\,v\,\rho}{\mu}$
Friction Factor (f):
$Re < 2300 \rightarrow f = {}^{64}/_{Re}$;
$2300 < Re < 2 \times 10^4 \rightarrow f = 0.316\,Re^{-0.25}$;
$Re > 2 \times 10^4 \rightarrow f = 0.184\,Re^{-0.20}$

Pressure Drop (Δp): $\frac{f\,L\,v^2\rho}{2\,r\,D}$
Fluid Temperature (T_f): HEPAK

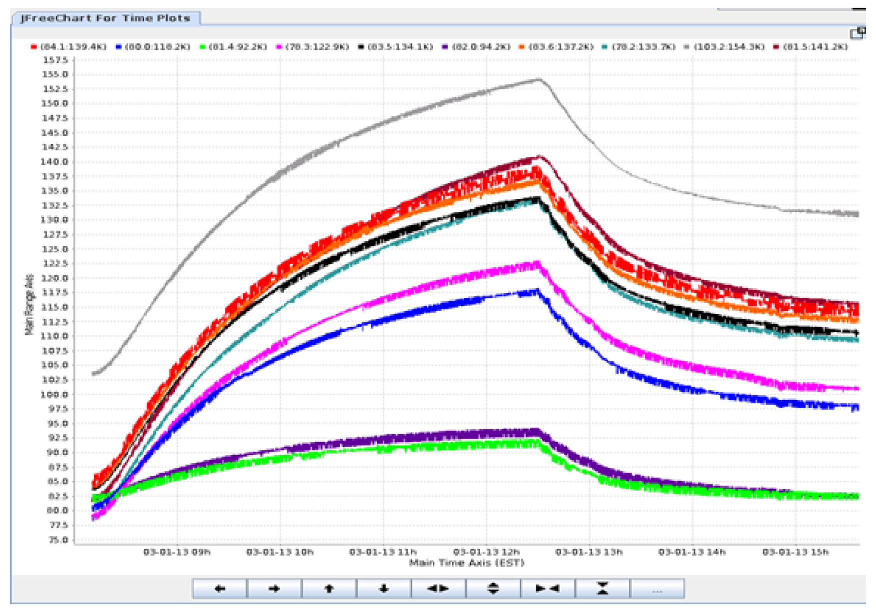


Injector Cryomodule



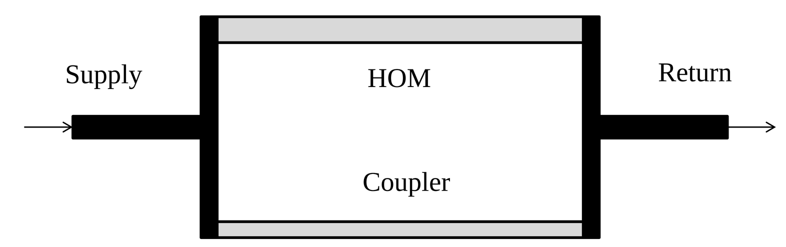
- Number of 2-cell cavities 5
- Acceleration per cavity 1 – 3 MeV
- Accelerating gradient 4.3 – 13.0 MV/m
- R/Q (linac definition) 222 Ohm
- Q_{ext} $4.6\times10^4 – 4.1\times10^5$
- Total 2K / 5K / 80K loads: 30W / 60W / 700W
- Number of HOM loads 6
- HOM power per cavity 40 W
- Couplers per cavity 2
- RF power per cavity 120 kW
- Amplitude/phase stability 10^{-4}/ 0.1° (rms)
- ICM length 5 m

Comparison to Experimental Findings



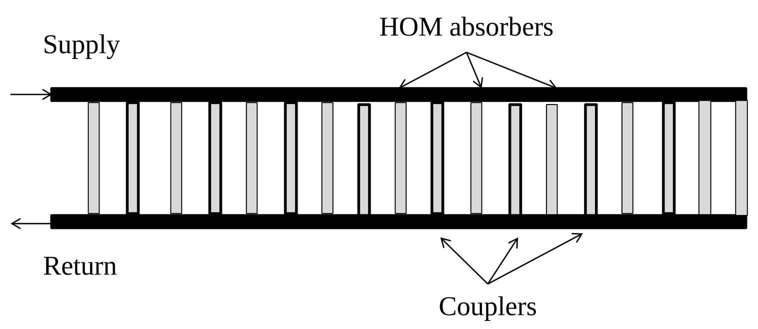
Temperatures reach equilibrium in 4 hours

Simplified model of cryogenic scheme

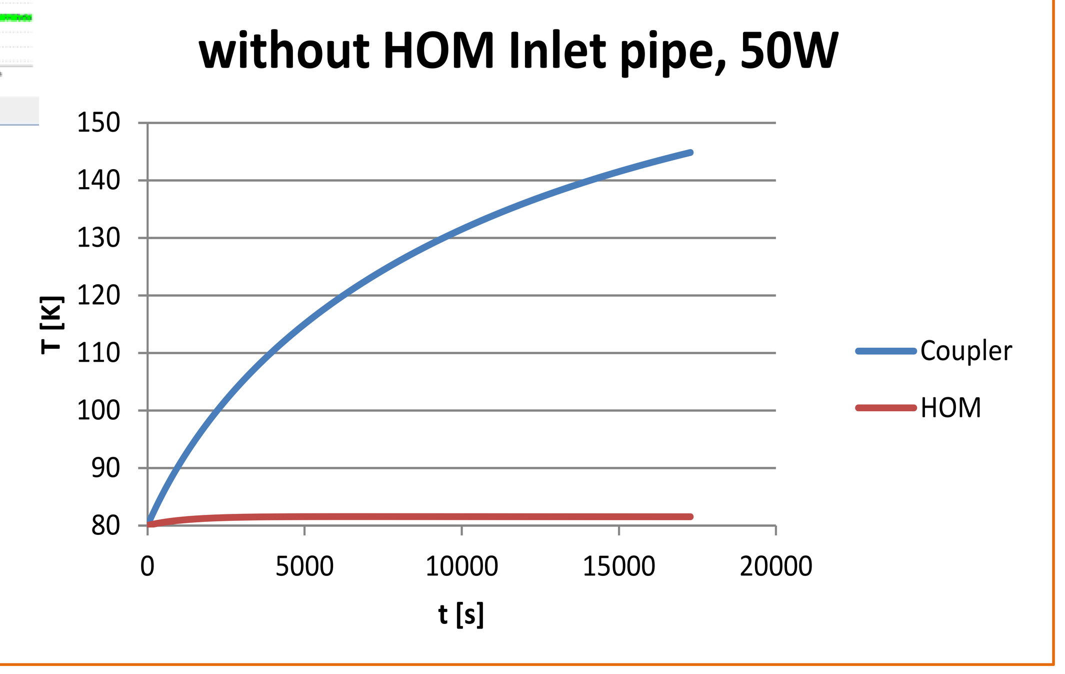


Two pipe model of the problem, exploiting the identity of the HOM and coupler channels

80 K circuit of the ICM



The flow to the HOM's and couplers are in parallel, but we discovered the coupler tubing is too small. So the HOM's get more flow, and the couplers less than designed for.



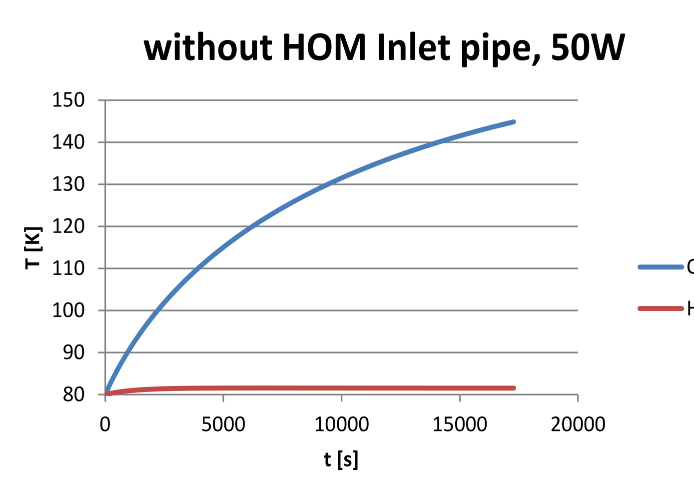
Simulation Parameters

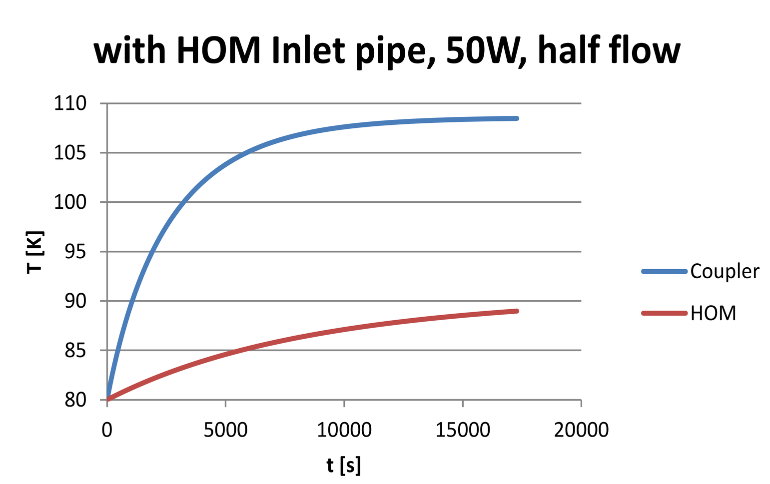
Input parameters for the simulation. The blue table specifies the system properties, the red table specifies the physical properties of the cryomodule

Pipe	Inner Diameter	Length	Mass
HOM	5.94 mm	68.6 cm	200 g
Coupler	3.88 mm	83.8 cm	200 g
Inlet	2.00 mm	50.0 cm	N/A

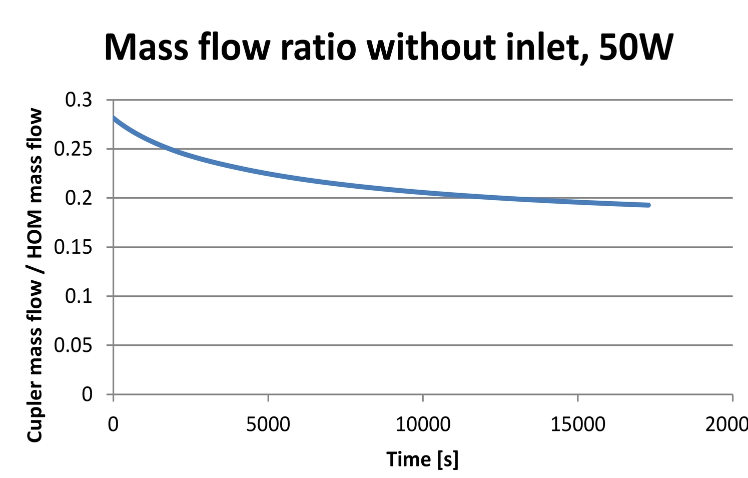
Regime	HOM Heat Load	Coupler Heat Load	Input Pressure	Mass Flow Rate	Initial Fluid Temp
No inlet	5 W	50 W	30 bar	9 g/s	80 K
Inlet	5 W	50 W	30 bar	4.5 g/s	80 K
High Heat (inlet)	5 W	120 W	30 bar	6 g/s	80 K

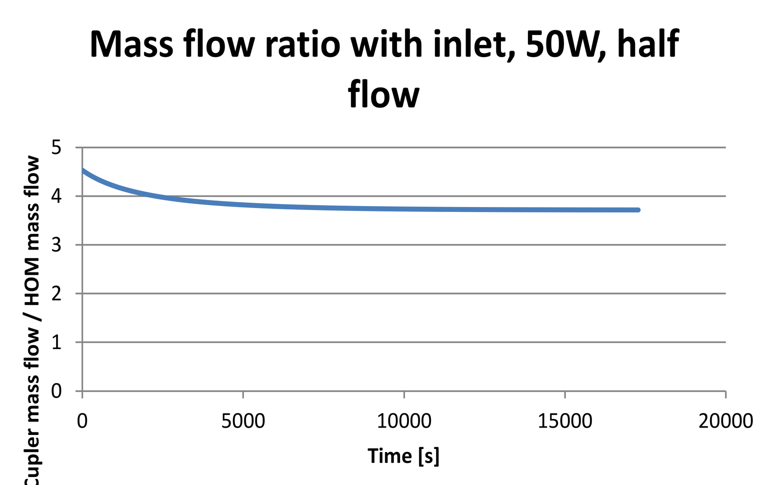
Effect of the Inlet Pipe

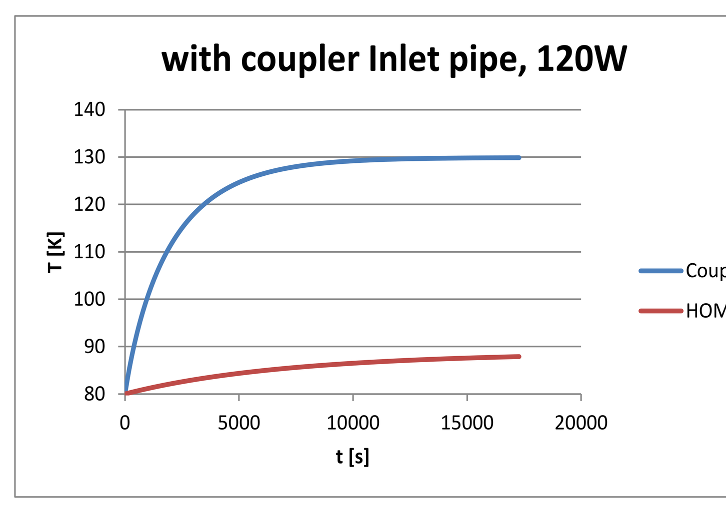




Including the inlet pipe allows more cryogen to flow through the couplers, greatly improving system performance







It also allows the system to operate with substantially larger heat loads

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