Study on 2K Heat Exchanger for Superfluid Helium Cryogenic Systems at KEK

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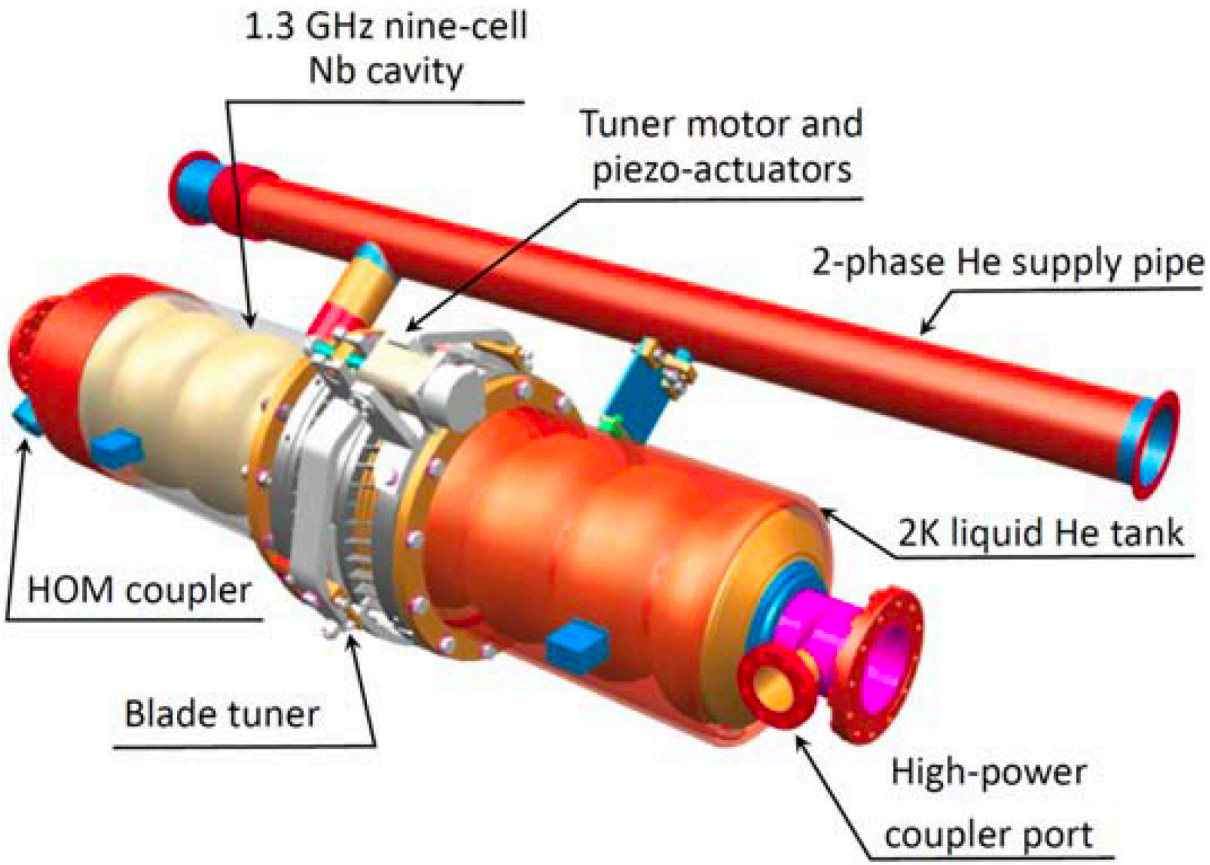
Contents

Introduction

Accelerators with Superconducting Technologies

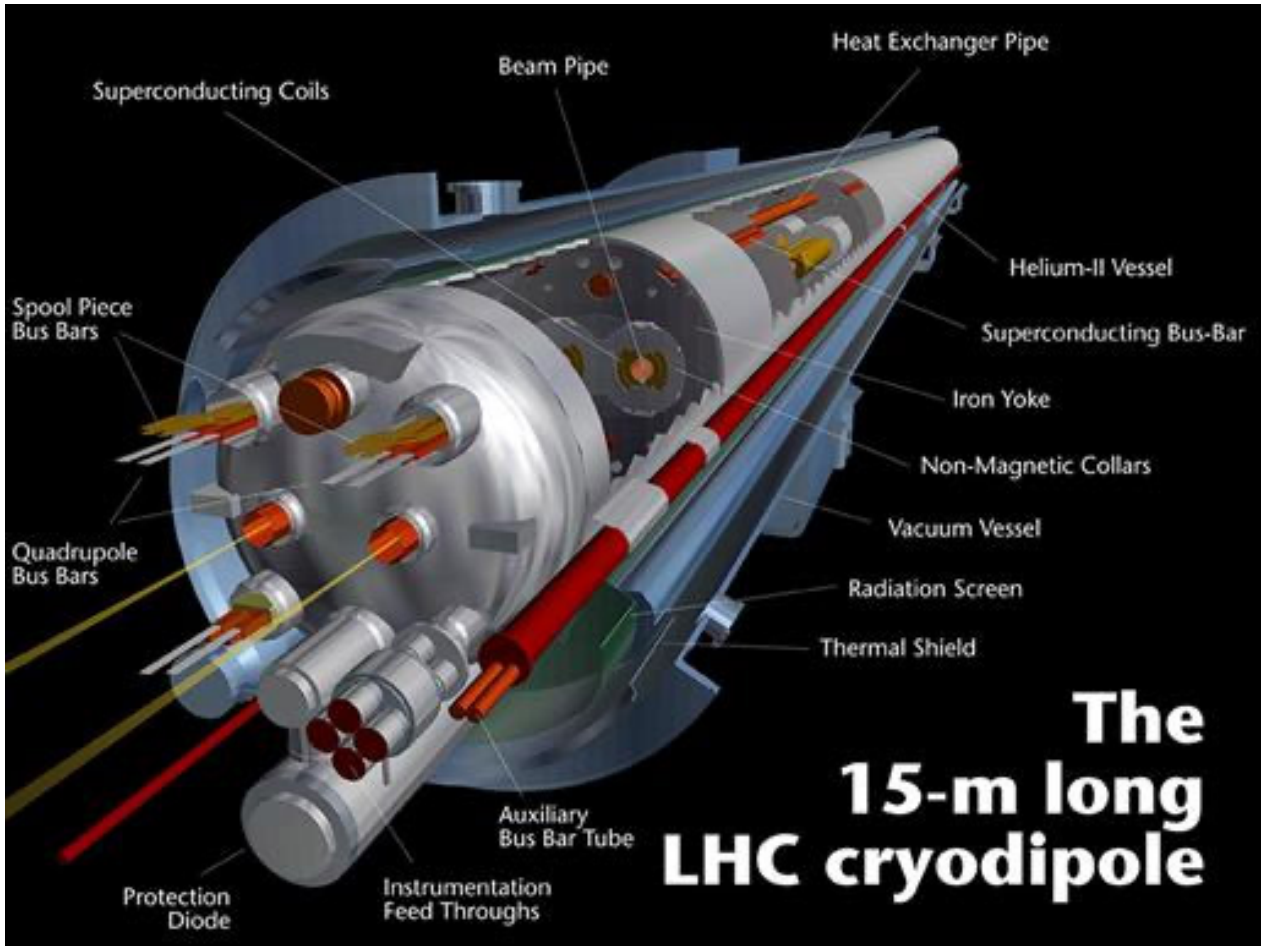
- SRF cavities accelerates particle beams in facilities such as XFEL (DESY), LCLS (SLAC), STF (KEK), etc.
- Superconducting magnets bends and focus the particle beams in LHC (CERN).
- Usually operated at < 2.0 K temperature, cooled with Superfluid Helium (He II).

Nb Superconducting Cavity System



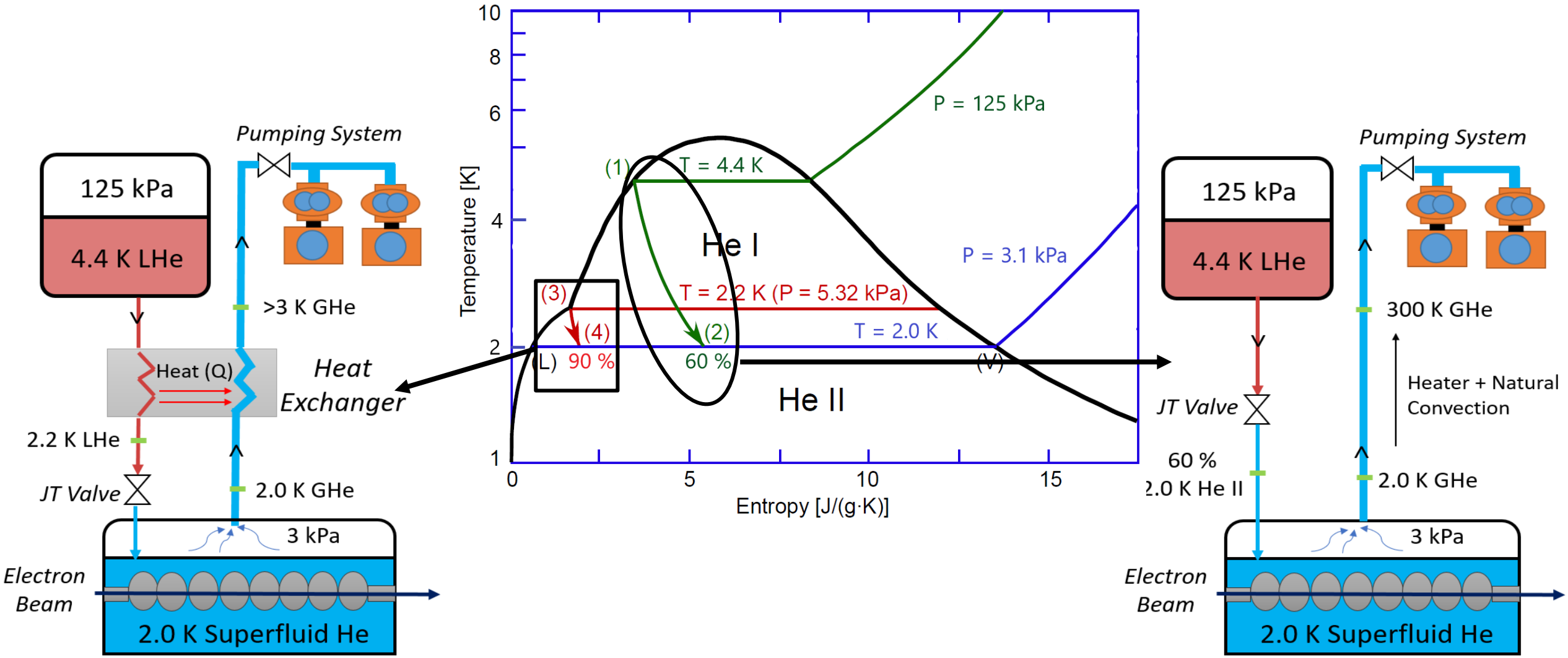
Cited from: New J. Phys. 20 (2018) 11301

LHC Superconducting Magnet System



http://www.supraconductivite.fr/en/index.php?p=applications-accelerateurs

Superfluid Helium Production Techniques

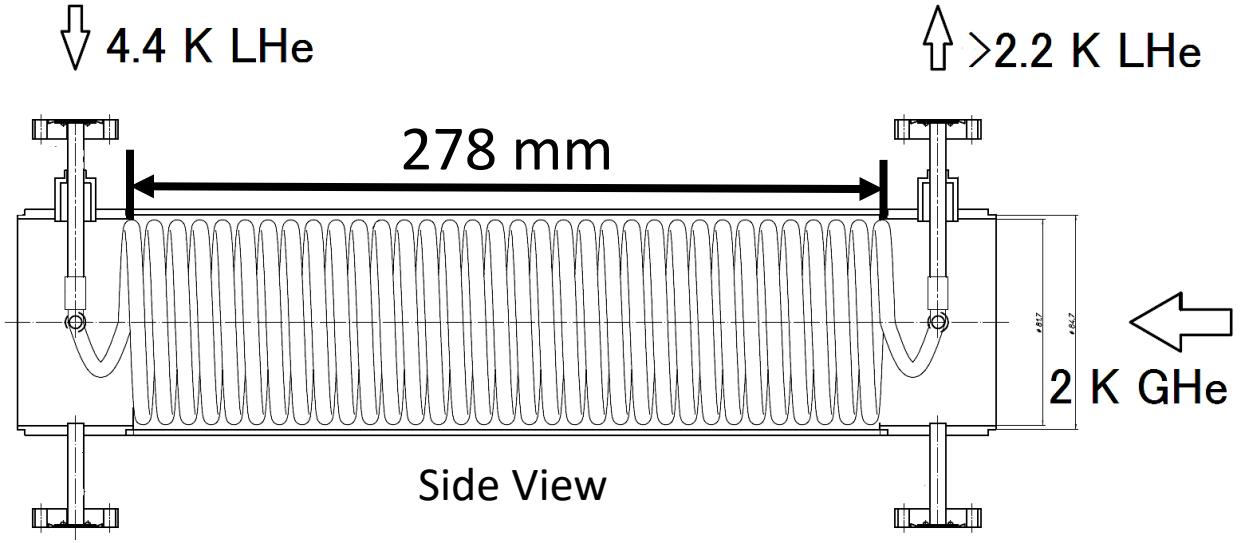


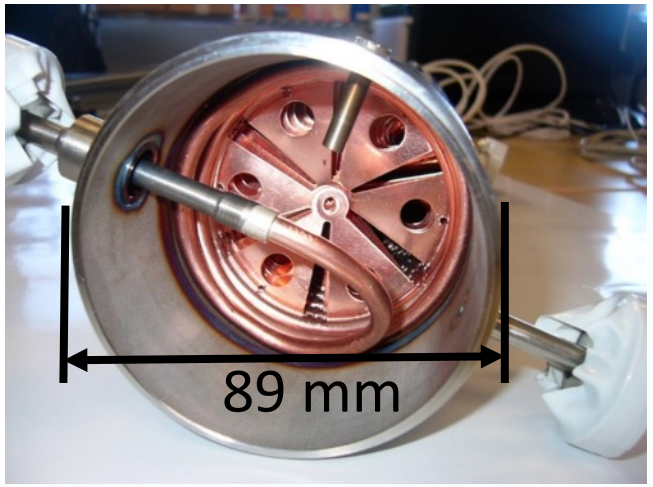
Superfluid Helium Cryogenic System at KEK

Cited from J. Yoshida et. Al, “Development of STF Cryogenic System in KEK”.

2K Heat Exchanger

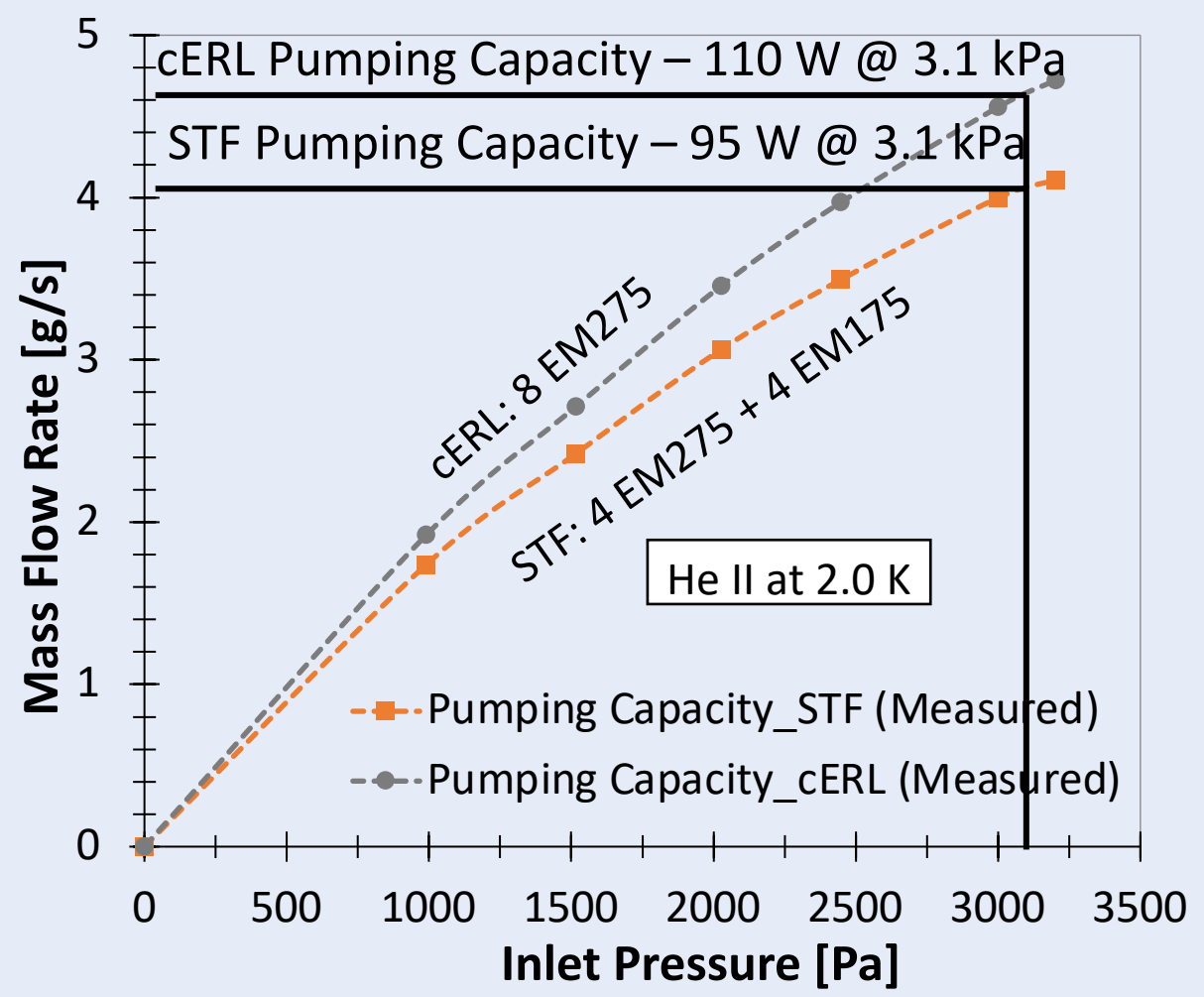
- Cools liquid helium (LHe) from 4.4 K to >2.2 K.
- Uses sensible heat capacity of gaseous helium (GHe) at 2.0 K.
- Decrease vapor flash loss for LHe after Joule Thomson (JT) valve.
- Effectiveness > 84% to achieve subcooled 2.2 K LHe.

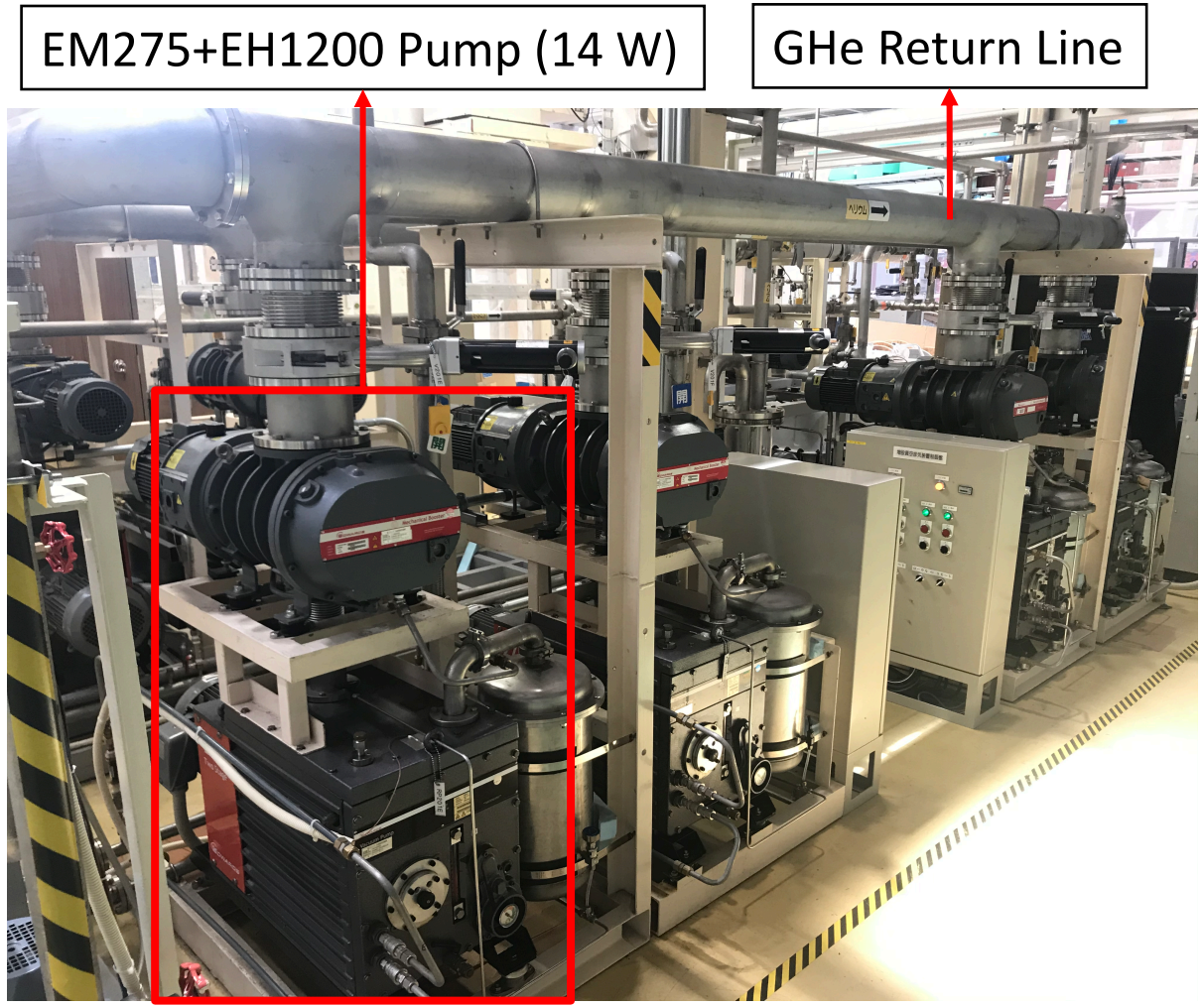




Designed by Prof. K. Hosoyama

GHe Pumping System

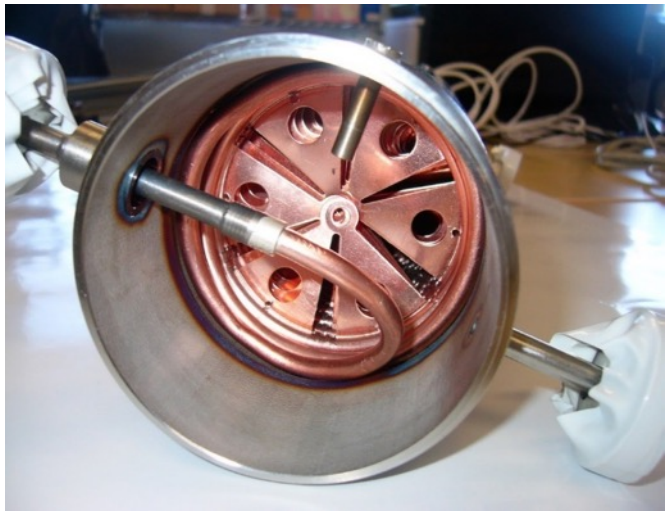




cERL GHe Pumping System

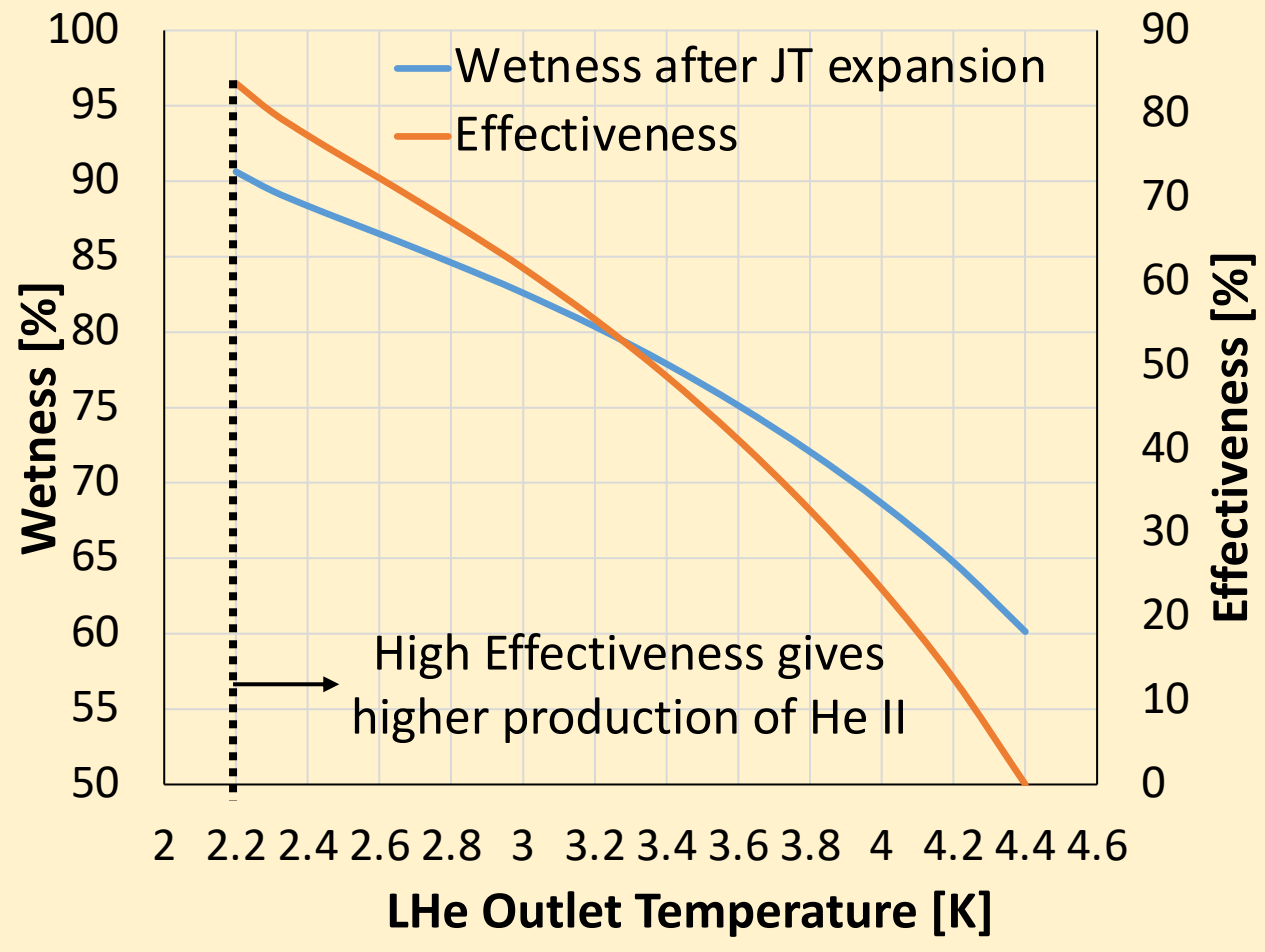
Objective of the Study

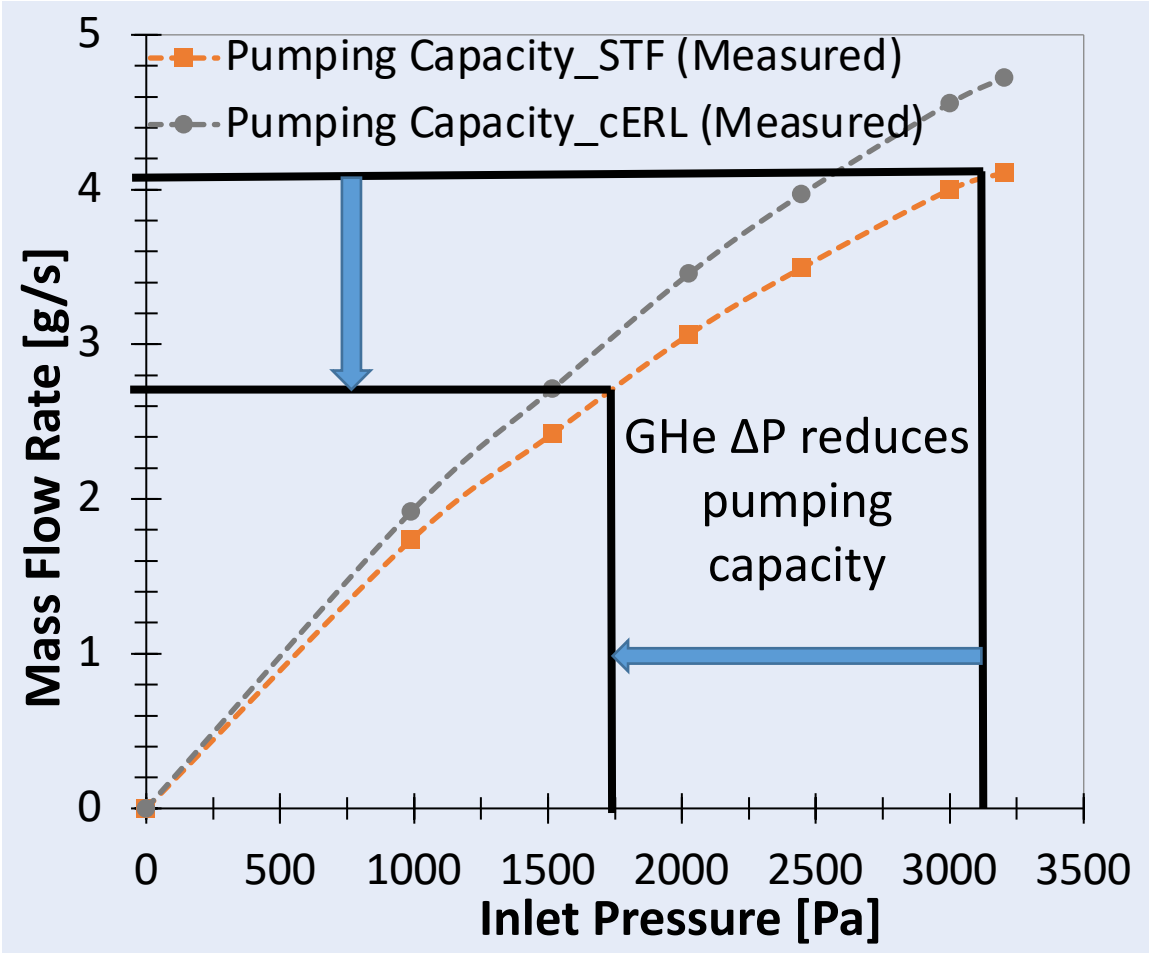
- Determine the performance of 2K heat exchanger.
- Performance is determined by a factor known as ***Effectiveness***.
- Determine GHe pressure drop through 2K HX.
- Optimize the design to maximize He II production rate from the cryogenic systems.



2K HX_1

Importance of Effectiveness and GHe Pressure drop





Methodology for Effectiveness Analysis

Problem Specification

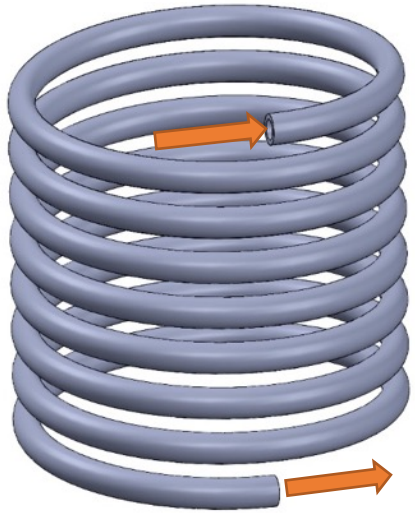
Determine heat transfer coefficient (h)

Thermal Conductance (UA)

Temperature Profile (FDM)

Effectiveness

LHe Flow inside helical tube (Empirical Relations)



$\dot{Q}$

GHe Flow ⊥ to fin

Thermal Resistance, LHe = $\frac{1}{(hA)_h}$

Thermal Resistance, GHe = $\frac{1}{(hA)_c}$

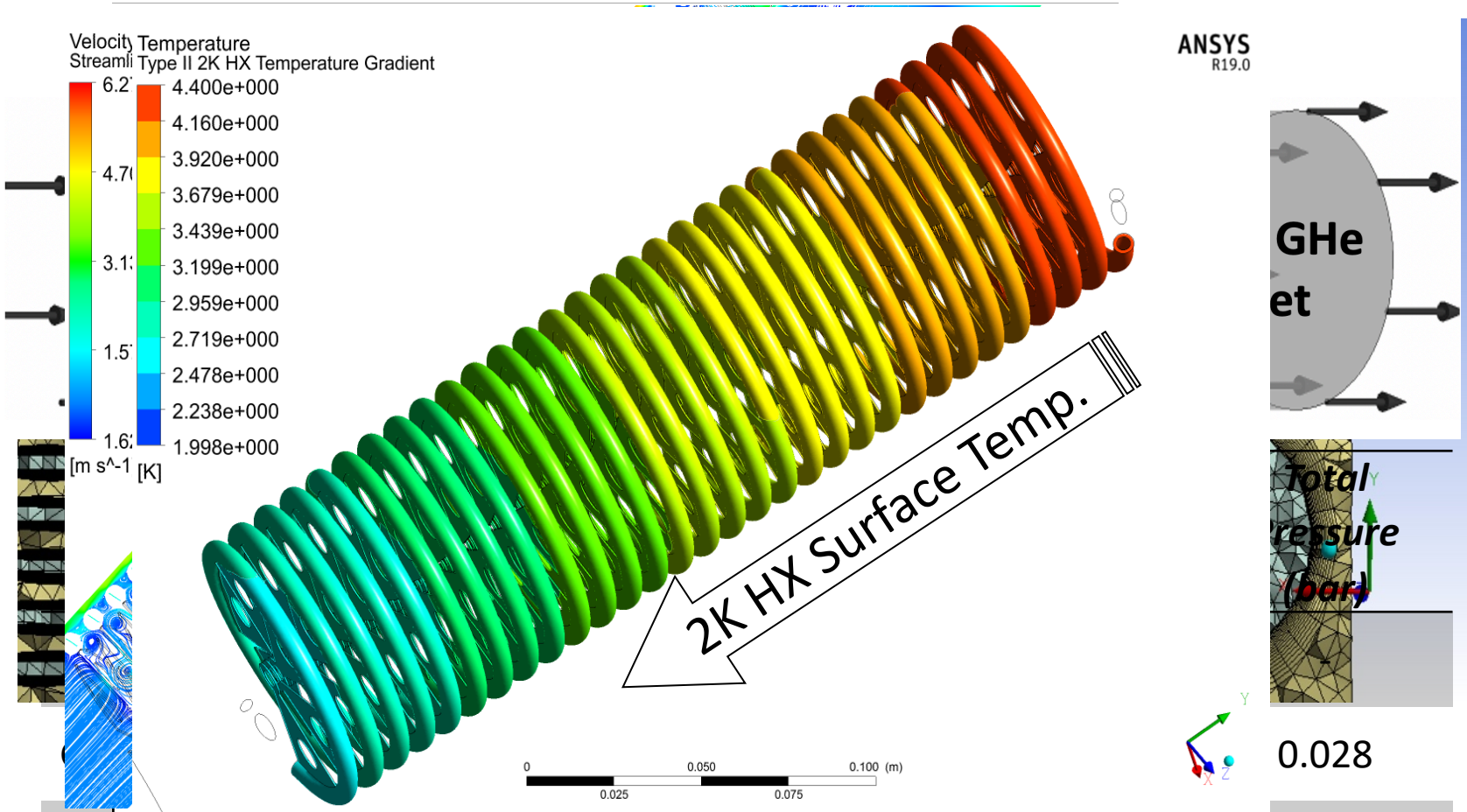
$$\frac{1}{UA} = \frac{1}{(hA)_h} + R_w + \frac{1}{(\eta_o hA)_c}$$

$$\dot{m} C_{p,h/c} \frac{dT_{h/c}}{dx_{h/c}} + \frac{UA_{h/c}}{l_{h/c}} (T_h - T_c) = 0$$

$$\text{Effectiveness, } \varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{\dot{m}(H_{h,i} - H_{h,o})}{\dot{m}(H_{h,i} - H_{h@T_{c,i}})}$$

Computational Fluid Dynamics

- Geometry Generation
- Meshing
- ANSYS CFX Pre
- ANSYS CFX Solver
- ANSYS CFD Post



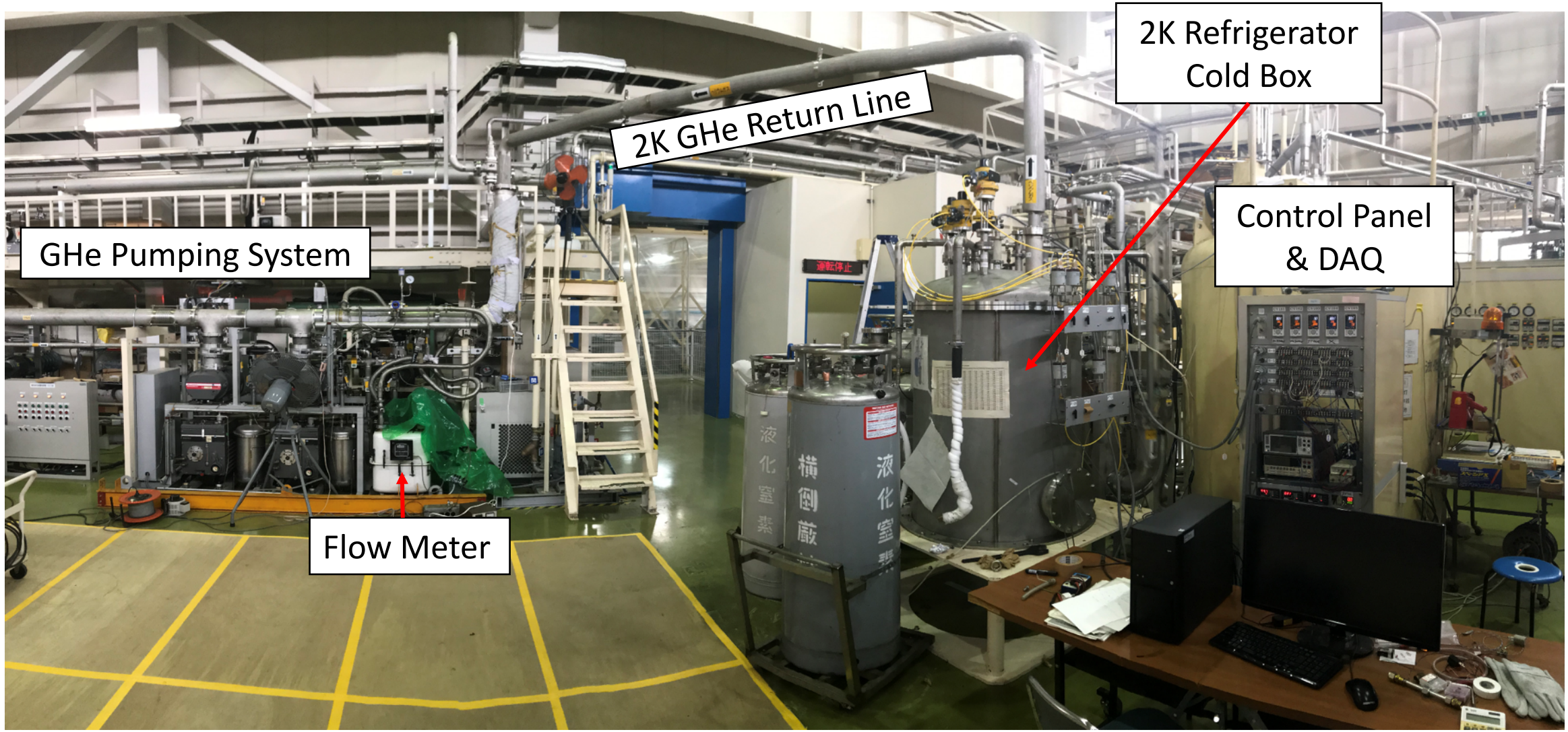
Velocity streamline contour of 2K HX surface Temperature contour of 2K HX surface

Post processor for analyzing and visualizing the results

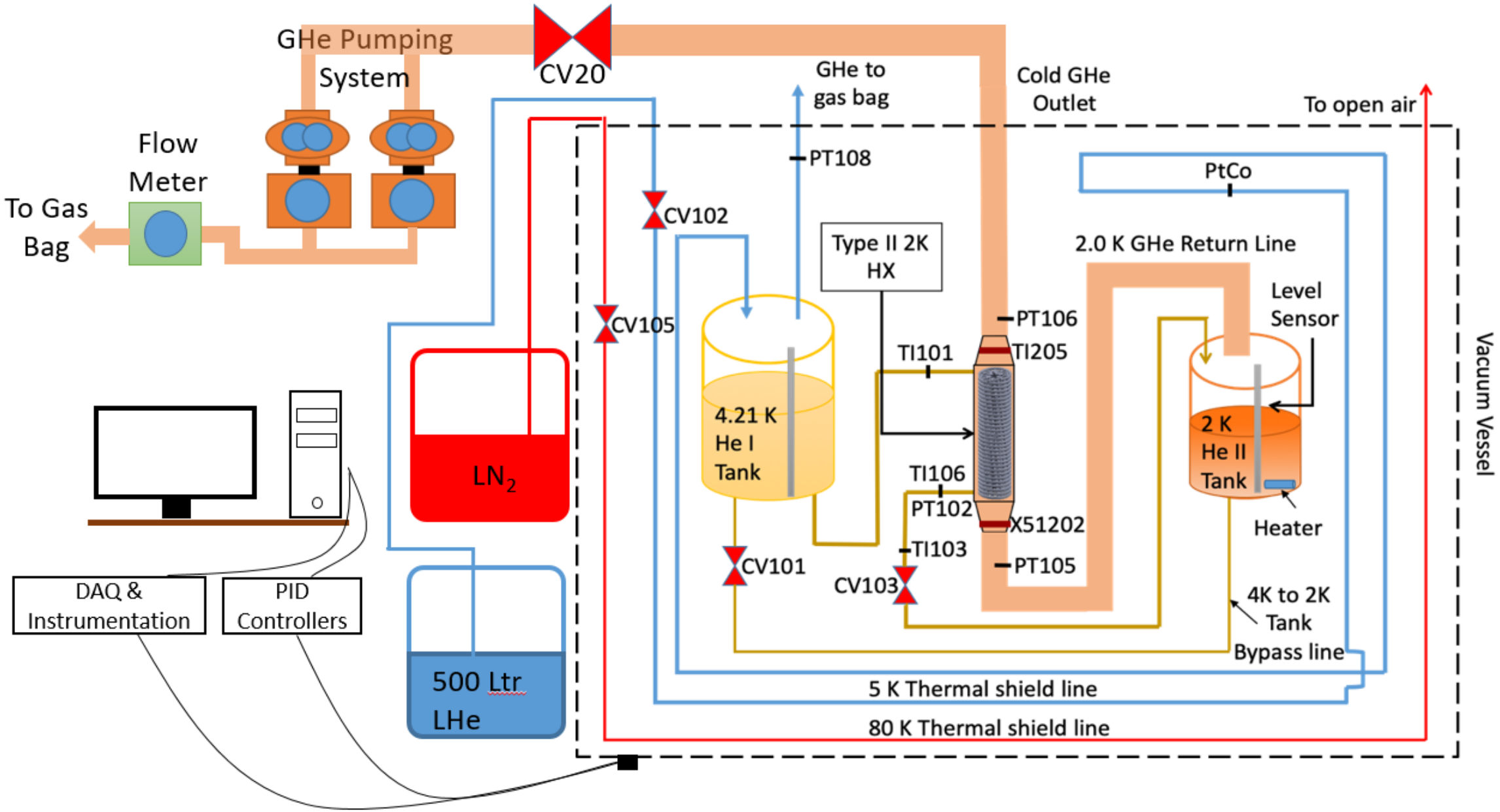
s, etc.

Experimental and Numerical Performance of the 2K HX_1

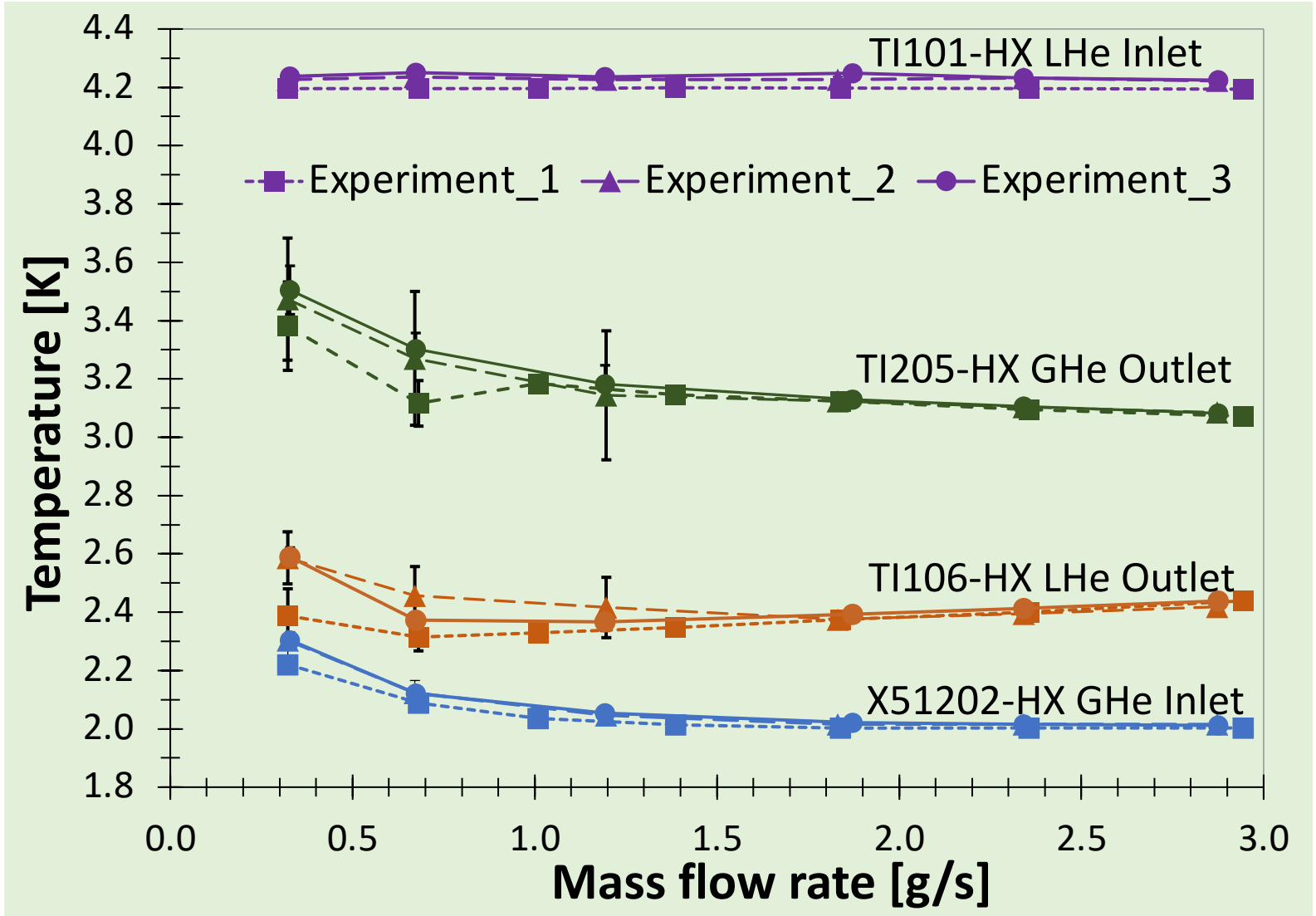
2K Heat Exchanger Test Stand

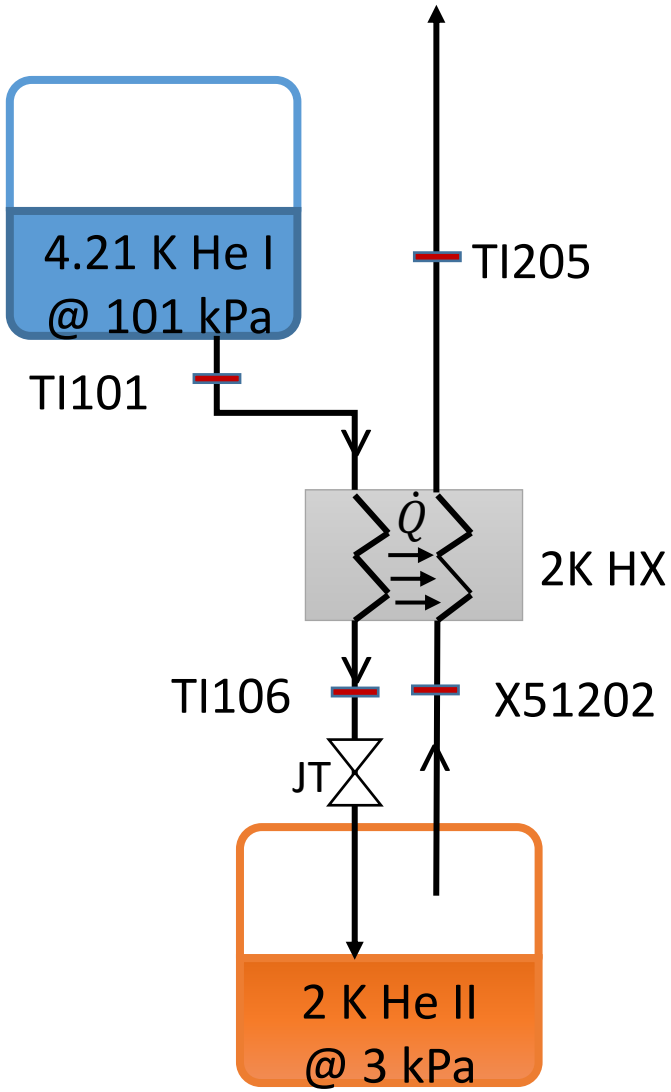


Schematic Diagram of Heat Exchanger Test Stand

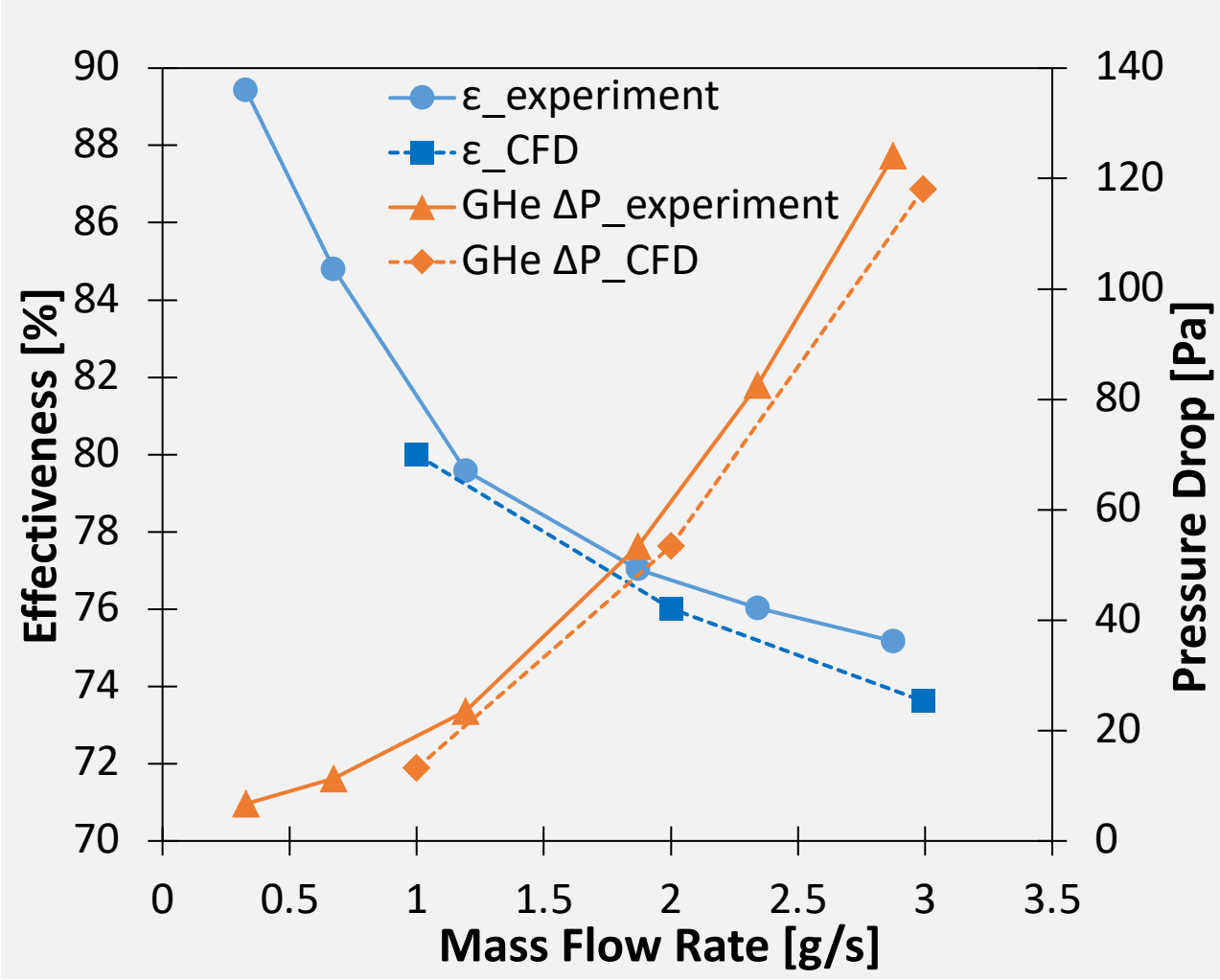


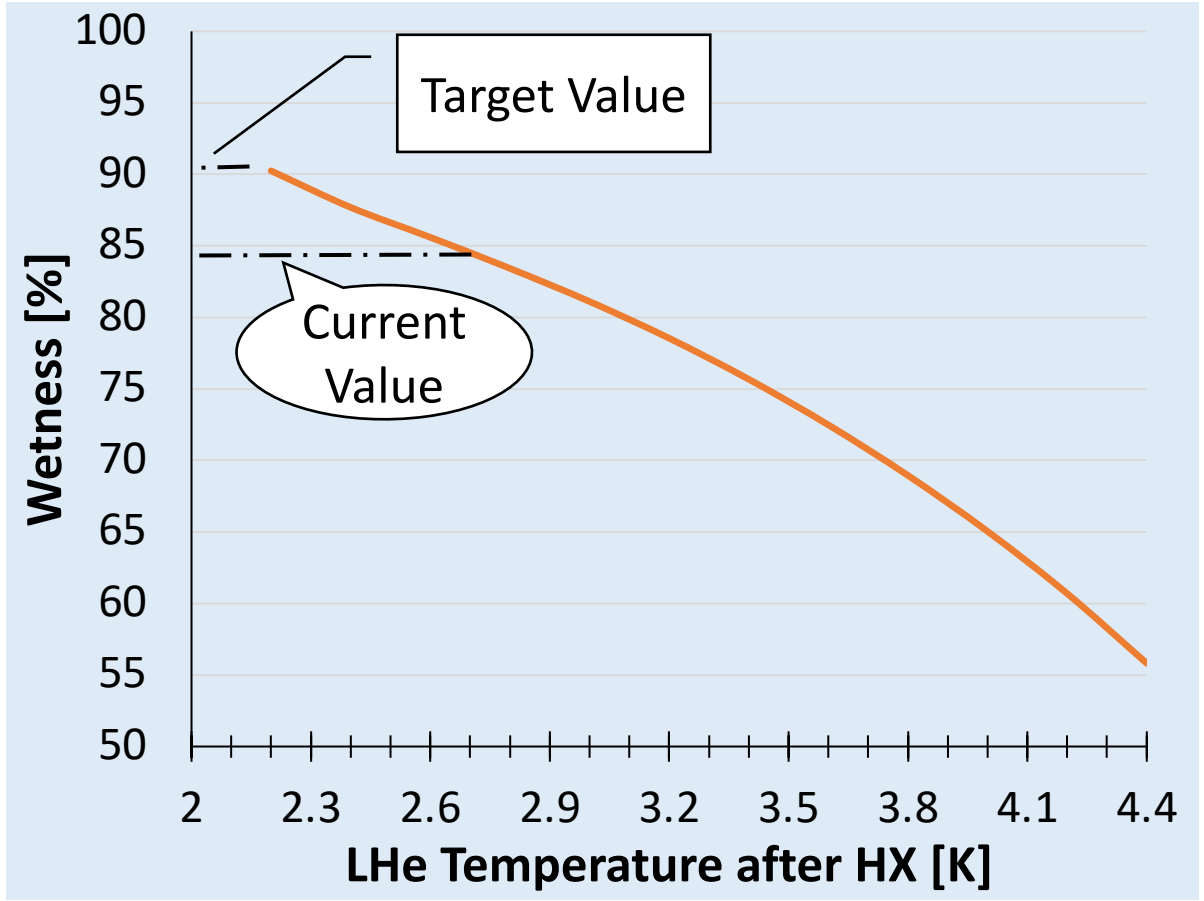
Experimental Results





Effectiveness of the 2K HX_1





Observations

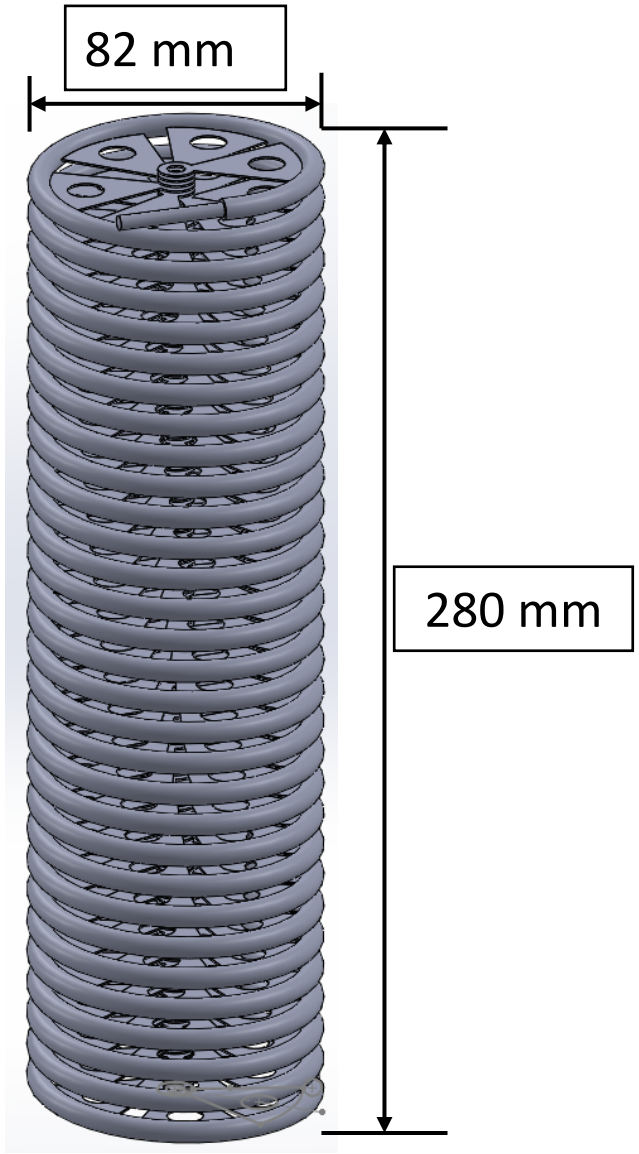
Performance Parameters	2K HX_1	
	Experiment	Numerical
Effectiveness @ 3 g/s	75%	73%
GHe ΔP @ 3 g/s	135 Pa	118 Pa
LHe outlet temperature @ 3g/s	2.5 K	2.57 K
Wetness after JT Valve	87.5%	86.8%

- Effectiveness always reduces with increasing flow rate.
- GHe pressure drop is directly proportional to square of mass flow rate($\dot{m}^2$).

Parametric Study of the 2K HX_1

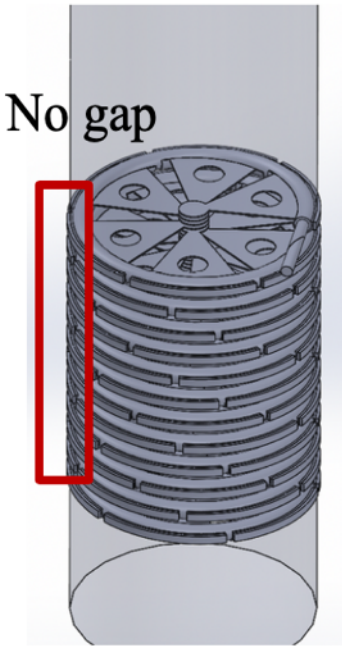
Objective and Methodology

- Improve the performance of the 2K HX_1.
- Set of parameters studied to improve the design.
- Overall size of the 2K HX is kept similar, initially.
- Helix diameter and fin design cannot be changed.
- Simulations performed at 3 g/s flow rate.

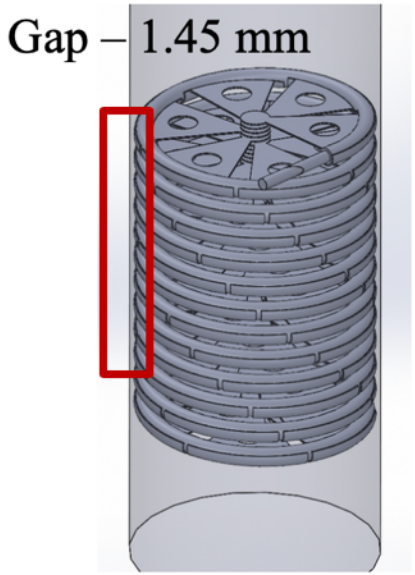


Design Factors

Bypass Area

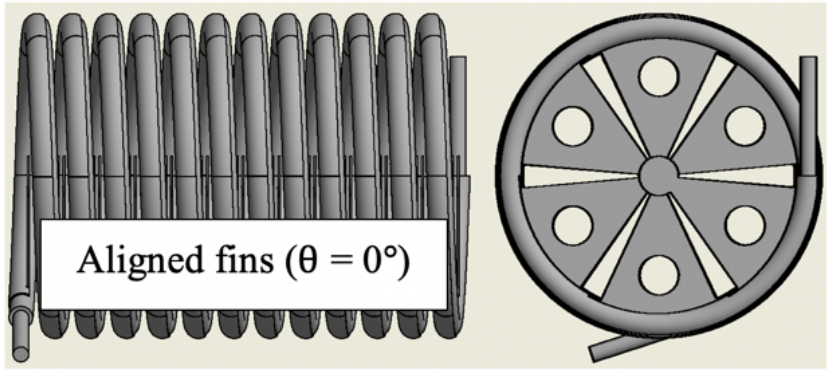


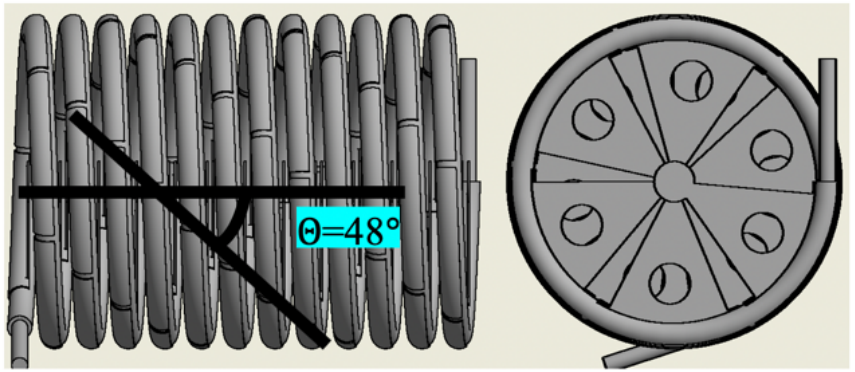
Bypass area – 0%



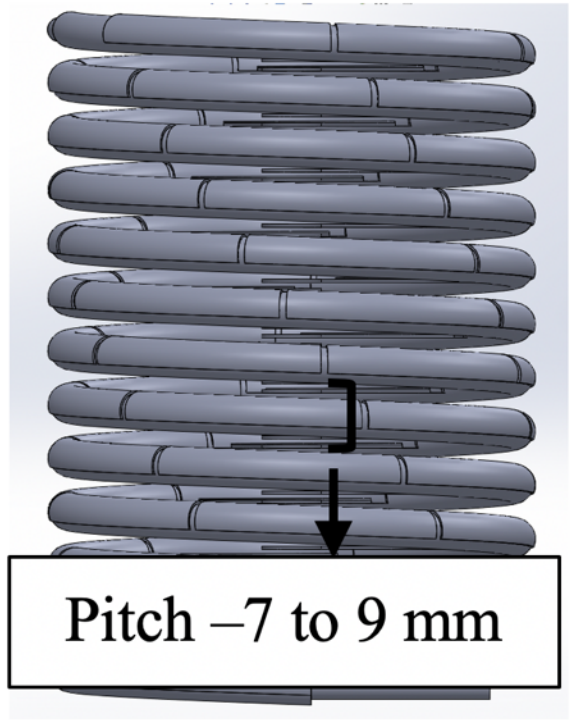
Bypass area – 7.2%

Helix Angle





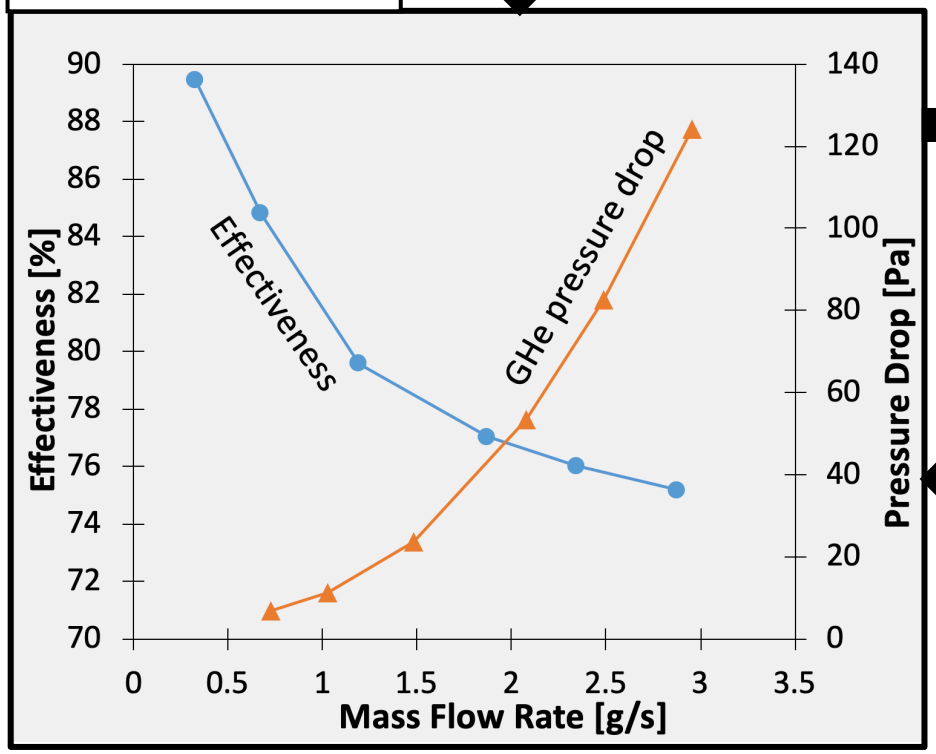
Helix Pitch



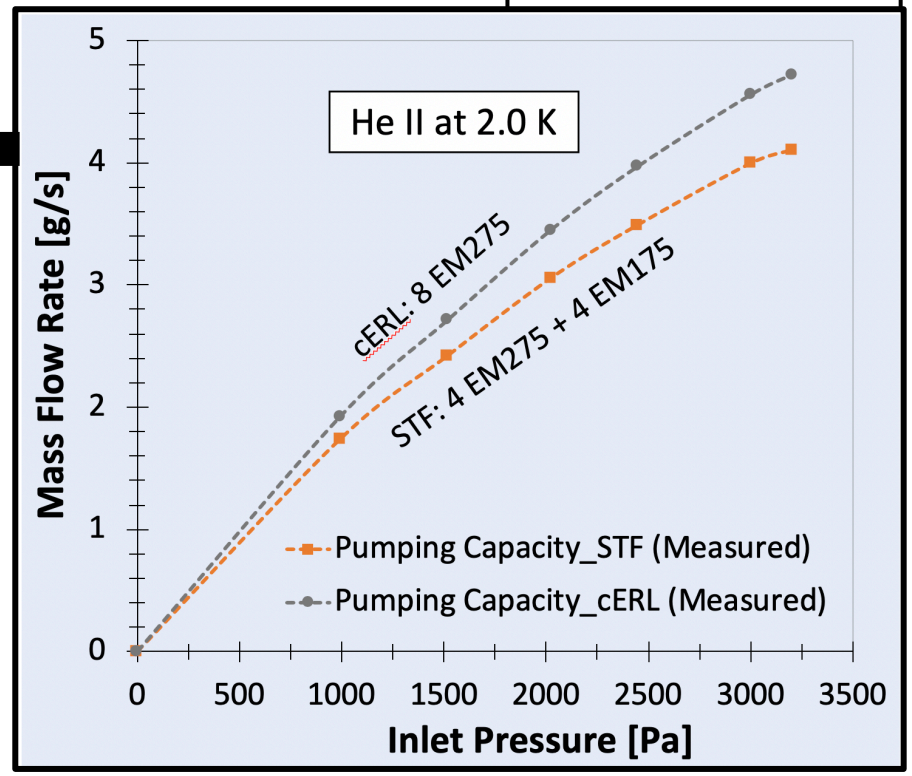
Optimization Methodology

Database of Improved 2K HX designs

ε and GHe ΔP



GHe Pumping System capacity



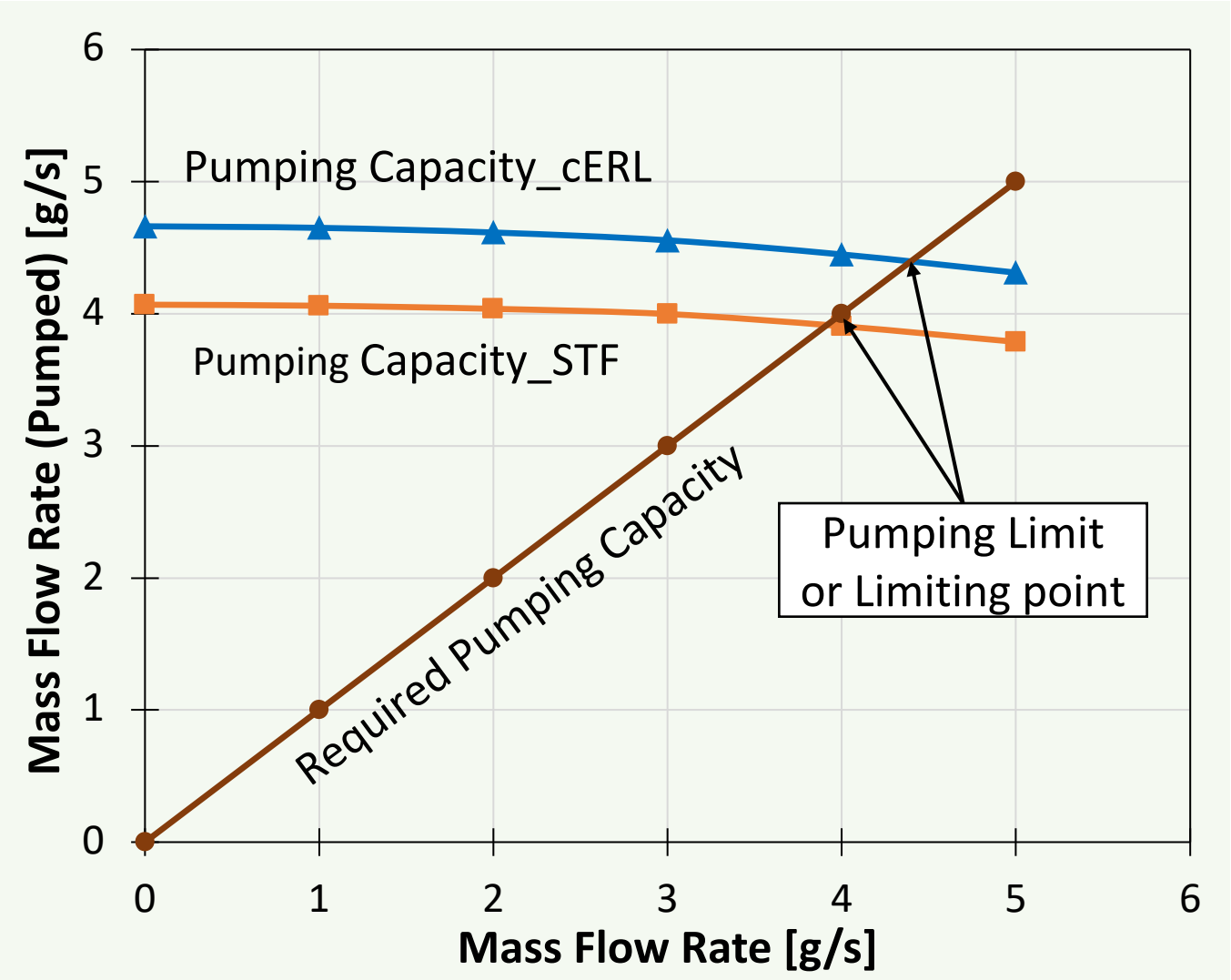
No

If He II production rate maximized

Yes

Optimized 2K HX Design

Cooling Capacity of STF and cERL Cryogenic Systems



Required Pumping Capacity

$$\dot{m} = \dot{m}_{He\ II} + \xi \times \dot{m}$$

Flash Loss (from Effectiveness)

$$\xi = \frac{\dot{m}_v}{\dot{m}} = \frac{\left[h_{h,o} - h_{h@\ sat.}\right]}{h_{fg}}$$

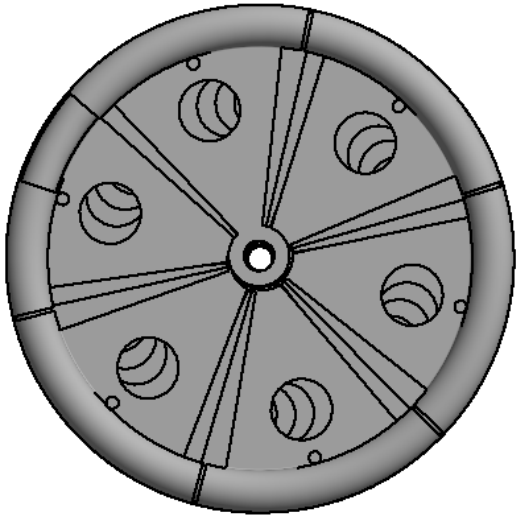
He II Production Rate

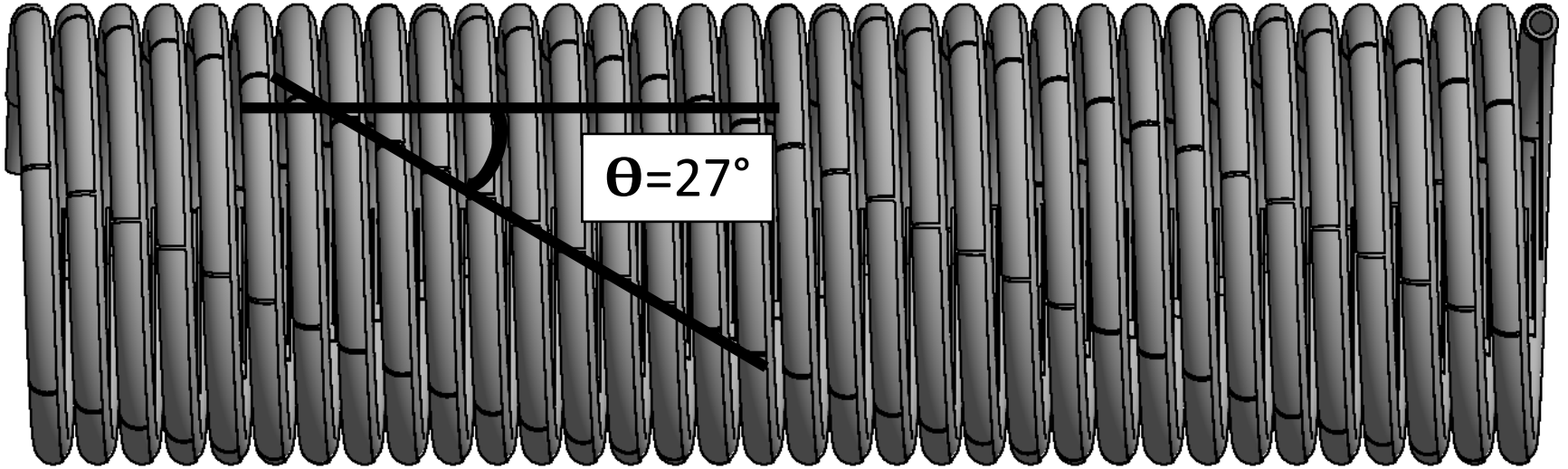
$$HPR = \dot{m}_{He\ II} \times \text{Latent Heat @ 2.0 K}$$

Summarized Results

Performance Parameters	2K HX_1 (in STF and cERL)	2K HX_1	2K HX_2 (with axial restriction)	2K HX_3 (w/o axial restriction)
		Helical tube parameters		
Tube OD (thickness)	Φ6 (1) mm	Φ6 (1) mm	Φ6 (1) mm	Φ6 (1) mm
Helix diameter (pitch)	75 (9) mm	Φ75 (9) mm	Φ75 (8) mm	Φ75 (8) mm
Number of loops	60	30	34	65
Helix angle	Unknown	13°	26°	OPTIMIZED DESIGN
		Total dimensions		
2K HX axial length	554 mm	277 mm	279 mm	520 mm
2K HX diameter	Φ82 mm	Φ82 mm	Φ82 mm	Φ82 mm
Bypass Area	Nil	Nil	4.7%	4.7%
		Performance Parameters		
Effectiveness @ 3 g/s	84%	75%	78.4%	84%
GHe ΔP @ 3 g/s	600 Pa	135 Pa	97 Pa	140 Pa
LHe outlet temperature @ 3g/s	2.2 K	2.5 K	2.36 K	2.2 K
Cooling capacity_STF @ limiting point	70 W	78.5 W	81.3 W	82.1 W
Cooling capacity_cERL @ limiting point	80 W	88 W	91.5 W	92 W

Experimental Verification of Optimization Study

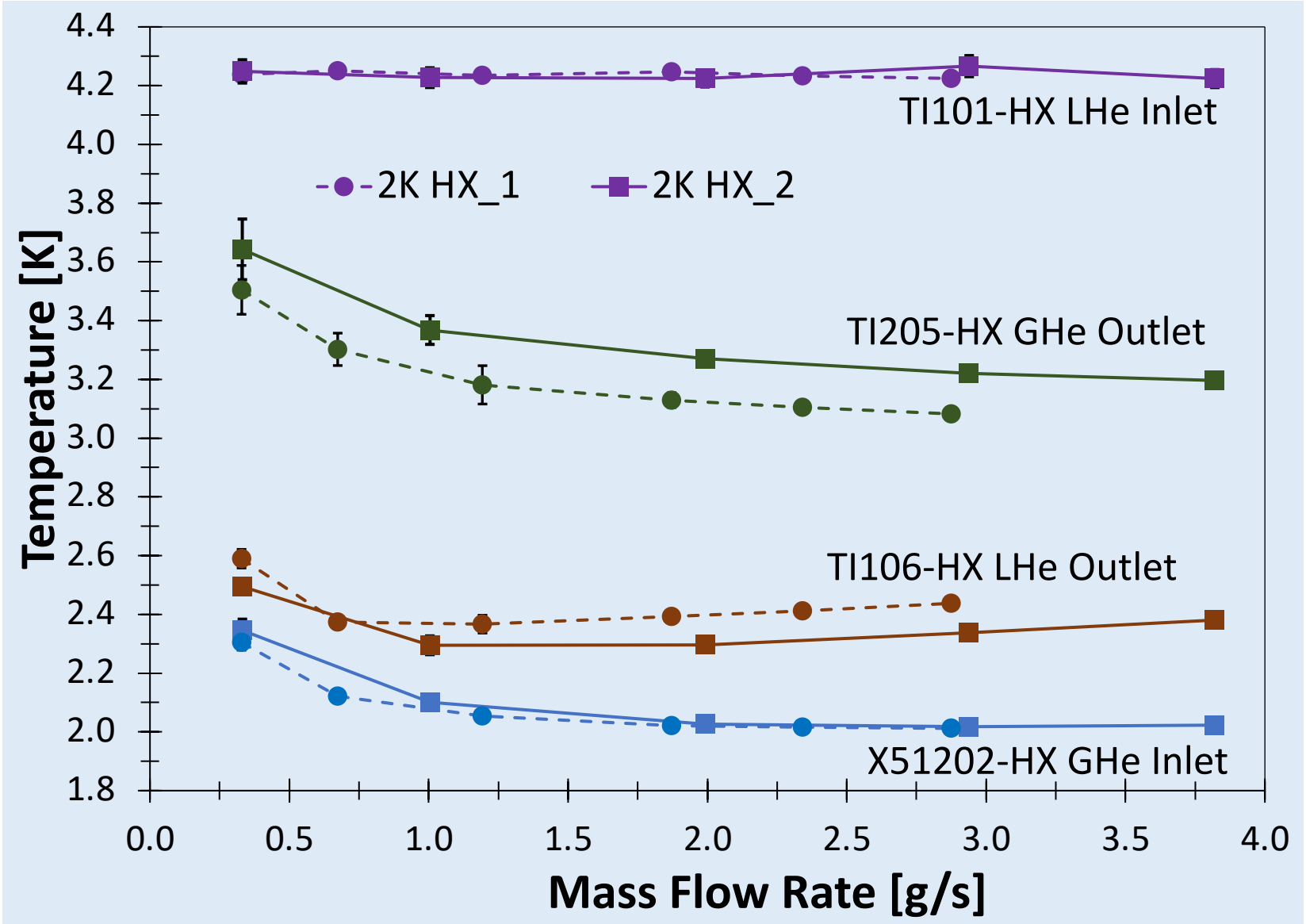


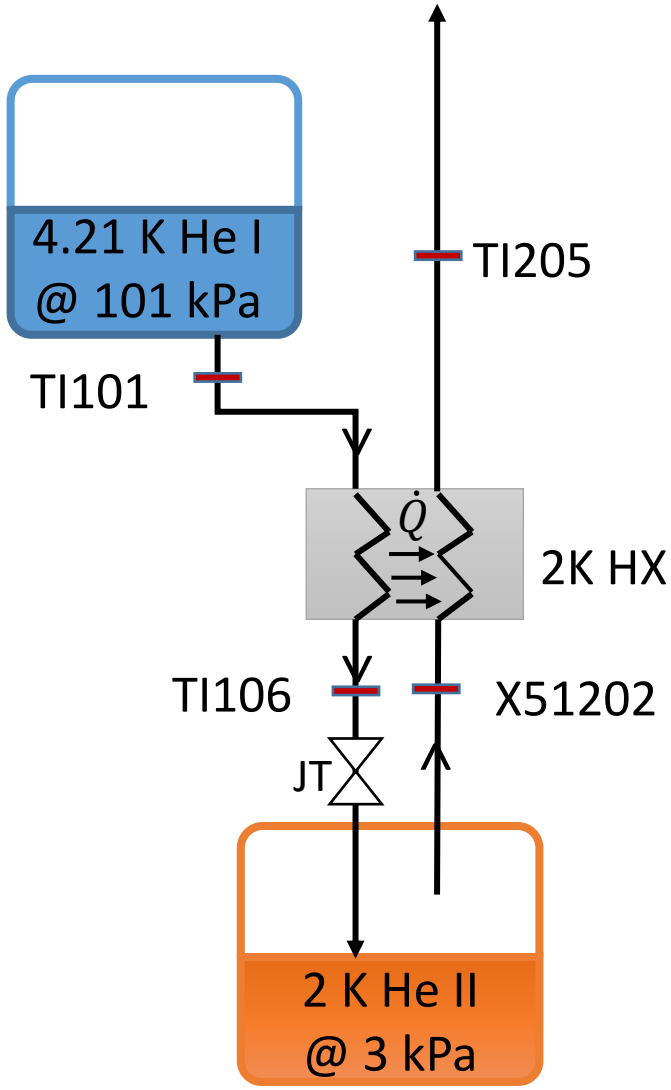


83 mm

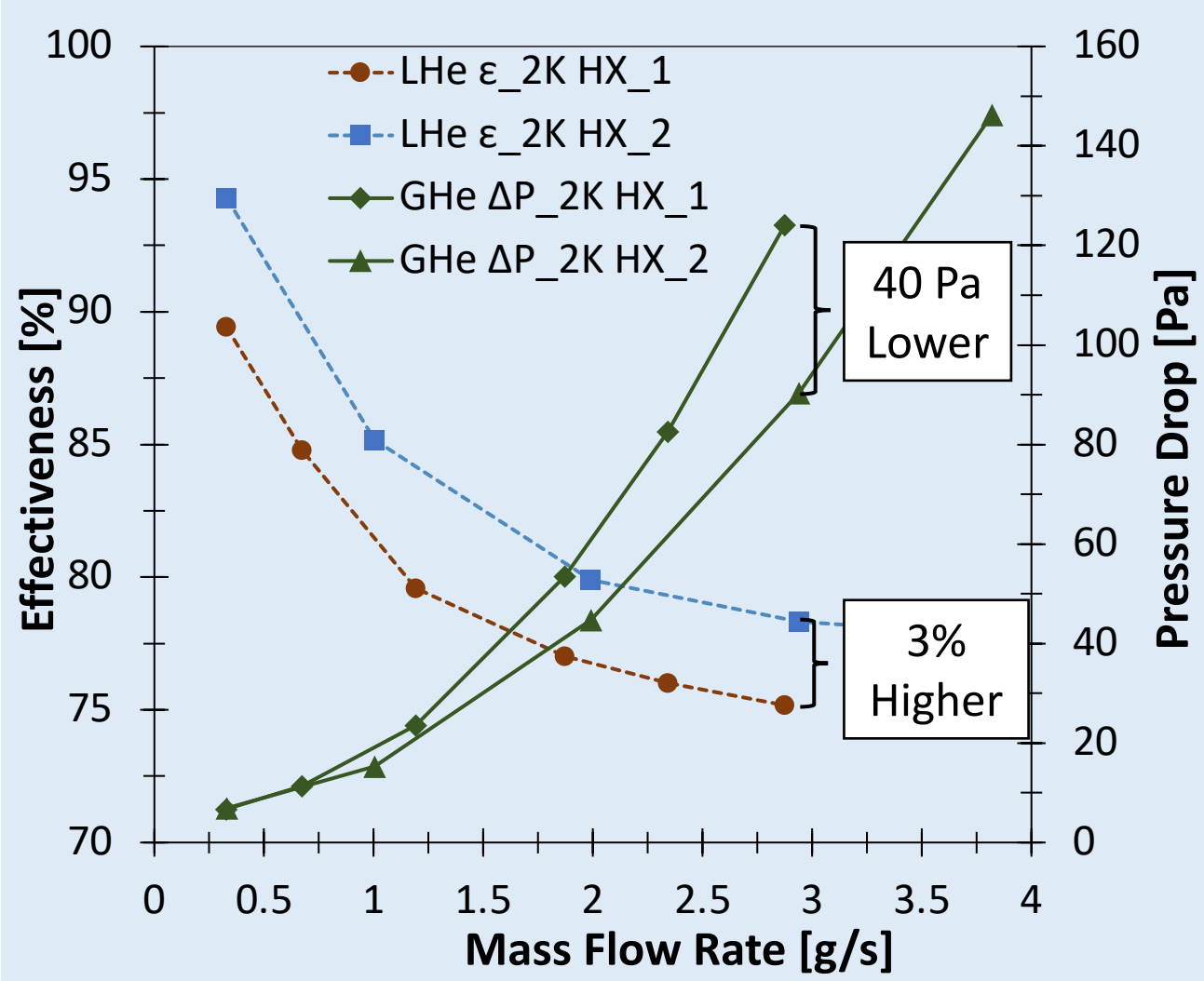
279 mm

Experimental Results

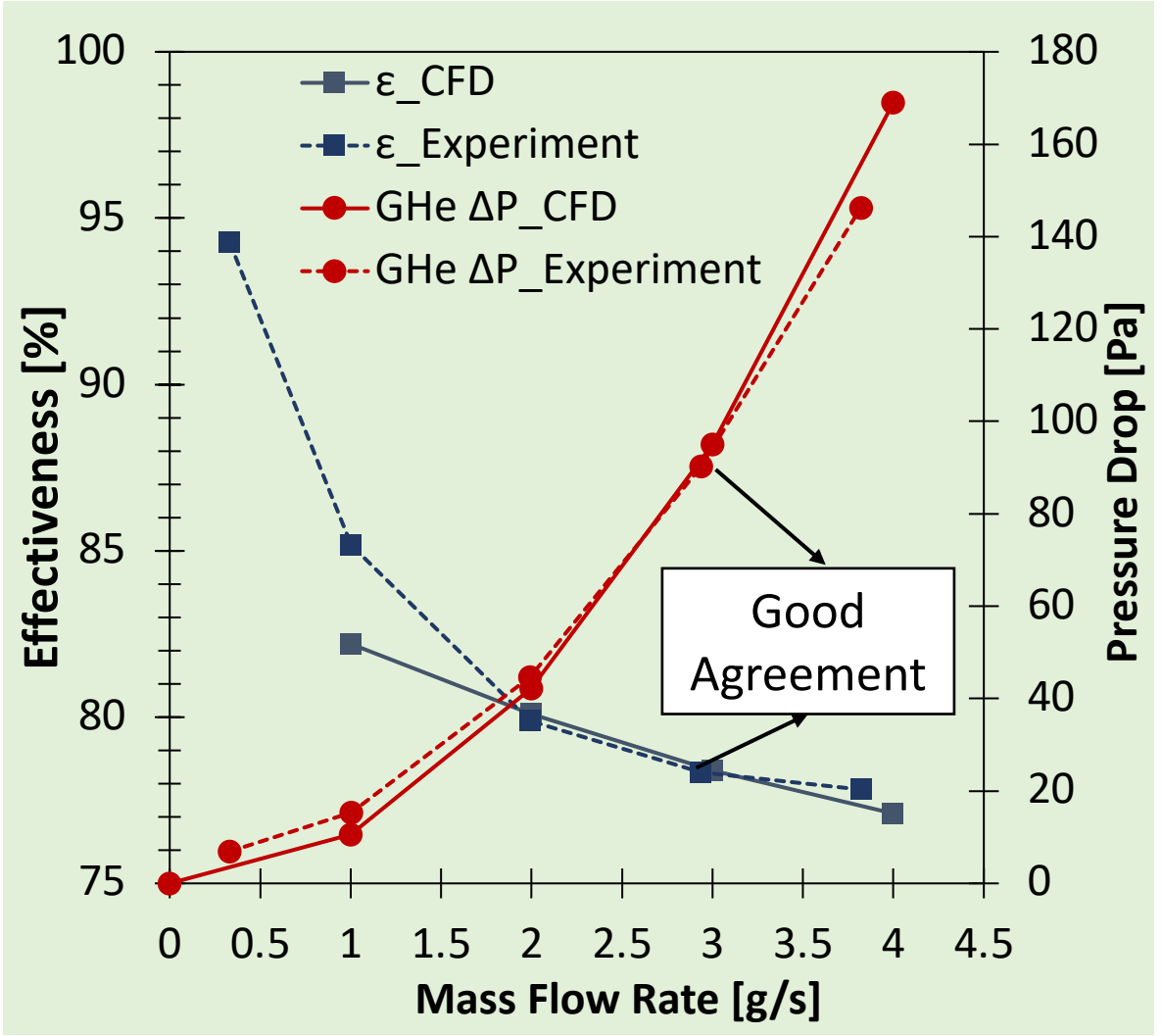




Comparison of 2K HX_2 with 2K HX_1



Performance comparison of 2K HX_2 with its numerical results



Conclusions

Conclusion

- Cryogenic plants (Sulzer TCF200) produces 250 Ltr/hr (180 W) of He I.
- Pumping systems capacity at 2.0 K is limited (max. 110 W).
- He II production is hindered by the *GHe pressure drop* through the 2K HX.
- GHe pressure drop was reduced by almost 4 times to improve the He II production rate.
- Two 2K HX_1 in series at STF and cERL facility provides 70 W and 80 W of cooling capacity respectively at 2.0 K and Optimized 2K HX_3 should increase the cooling capacity of cryogenic systems by 15% to 82.1 and 92 W, respectively.
- Cost saving with purchasing extra pumps to improve the He II production rate.

Thank you for your attention!