SpinQuest Target Overview

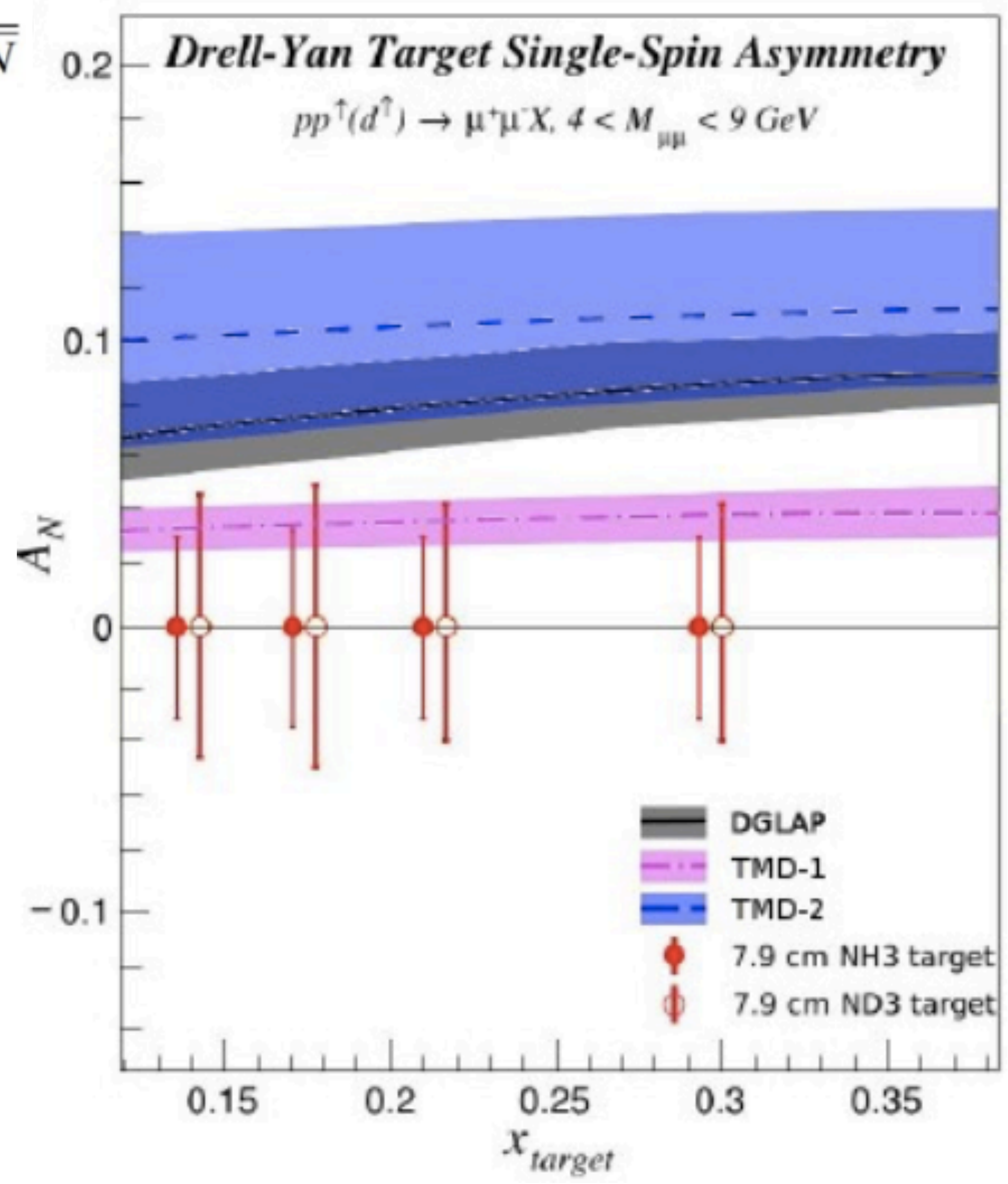
E1039 Polarized target system and cryogenics

D. Keller

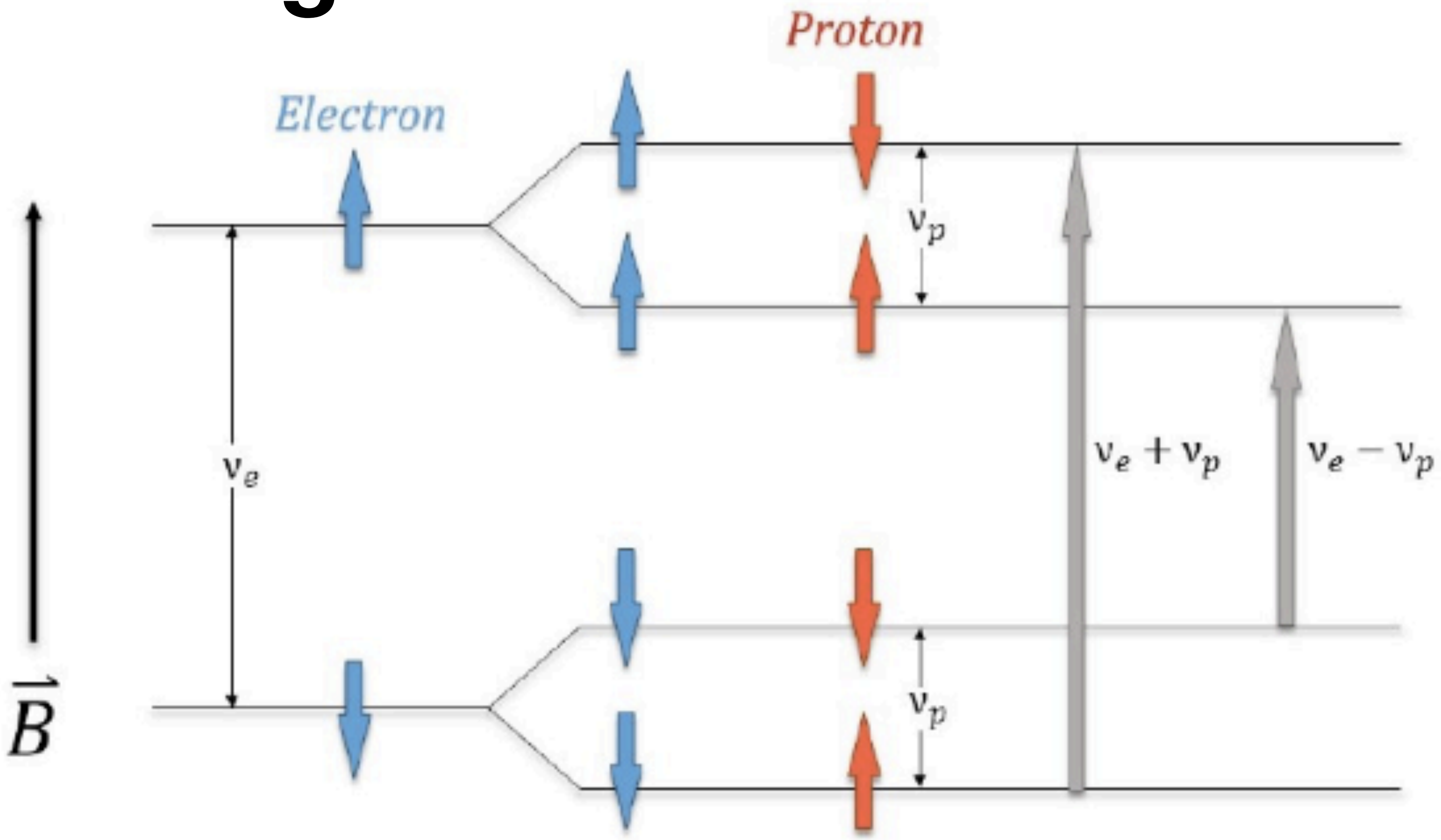
Expected Uncertainties

- Statistical: 3%-5% absolute error
    - Dependent on polarization, dilution, events
    - Dependent on run time
- Systematic: Mostly relative error, some absolute. Numbers listed hopeful upper bounds
    - Target: ~6/7% (P/D)
        - Dilution: 3%
        - Packing Fraction: 2%
        - Density: 1%
        - Polarization: 2.5%/4.5% (P/D)
        - Polarization Homogeneity: 2%
        - Uneven Decay: 3%
        - Alignment: small absolute possible
    - Beam: 2.5%
        - Relative Luminosity: 1%
        - Drifts: 2% (Absolute possible)
        - Scraping: 1%
    - Detector: 1% (Some relative, Absolute possible)

$$\Delta A_N = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N}}$$

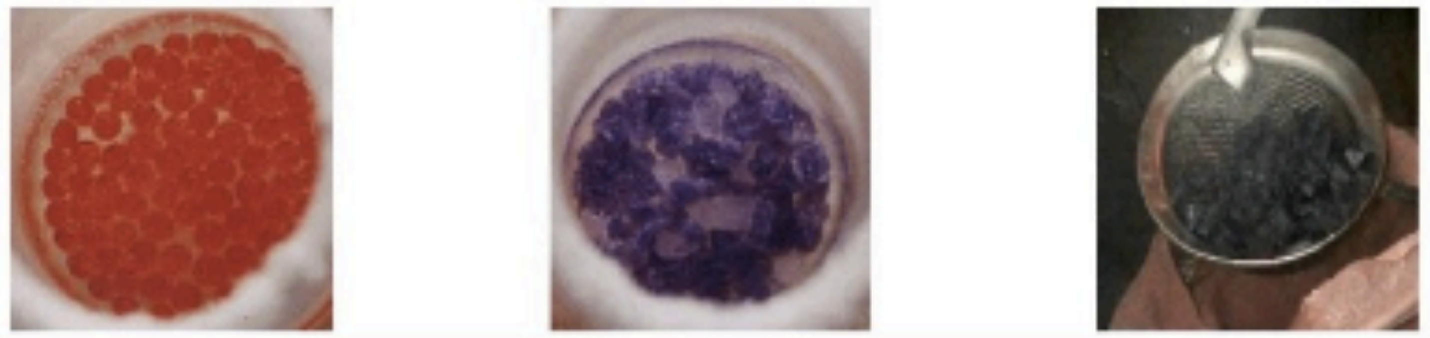


DNP Target



Successful material for DNP characterized by three measures:

1. Maximum polarization
2. Dilution factor
3. Resistance to ionizing radiation



Material	Butanol	Ammonia, NH_3	Lithium Hydride, ^{7}LiH
Dopant	Chemical	Irradiation	Irradiation
Dil. Factor (%)	13.5	17.6	25.0
Polarization (%)	90-95	90-95	90
Material	D-Butanol	D-Ammonia, ND_3	Lithium Deuteride, ^{6}LiH
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	40	50	55
Rad. Resistance	moderate	high	very high
Comments	*Easy to produce and handle*	*Works well at 5T/1K*	*Slow polarization, but long T_1*

- Dynamic Nuclear Polarization
  - Dope target material with paramagnetic centers:

chemical or irradiation doping to just the right density (10^{19} spins/cm^3)

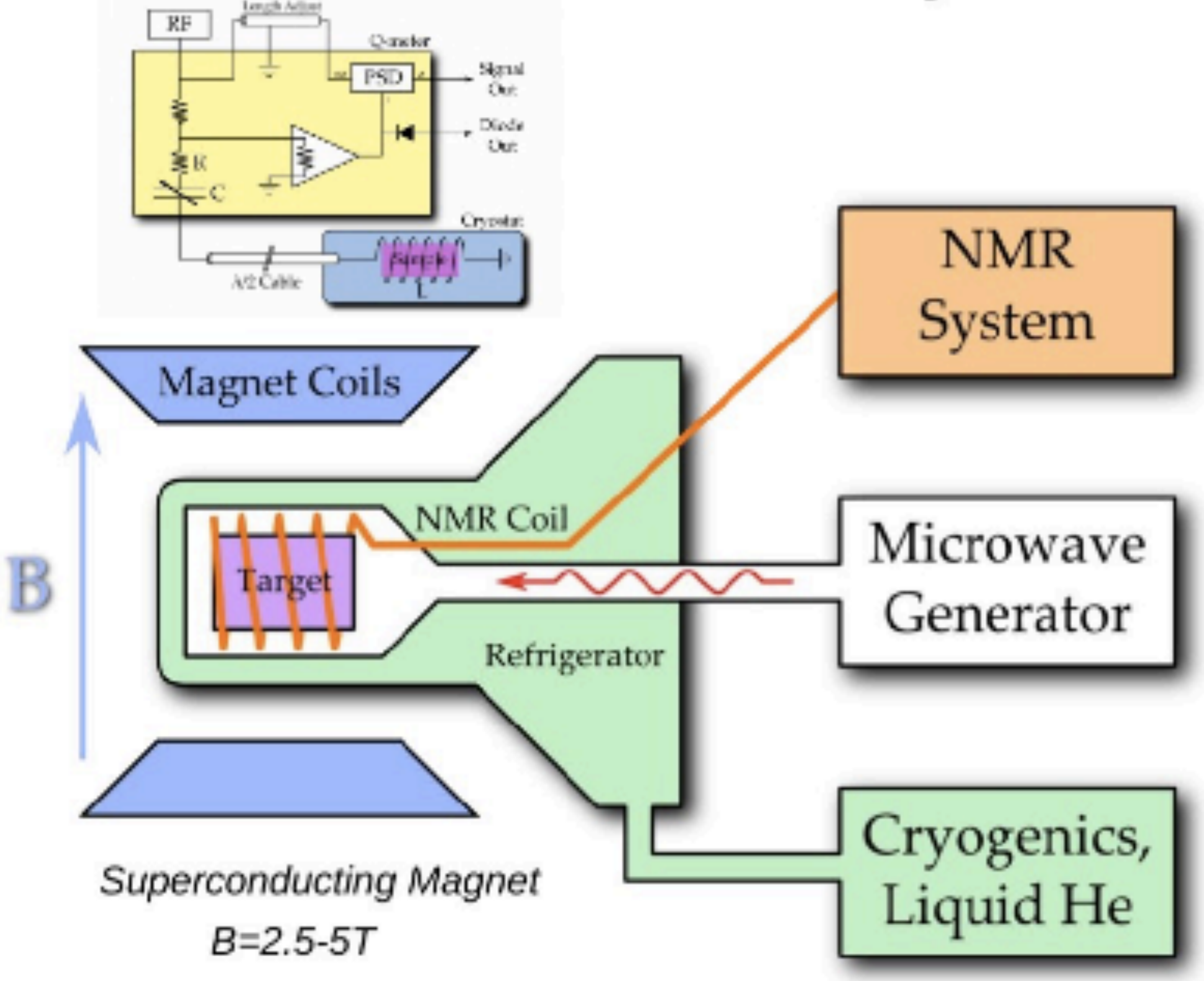
  - Polarize the centers: Just stick it in a magnetic field
  - Use microwaves to transfer this polarization to nuclei:

mutual electron-proton spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other

- Optimize so that DNP is performed at *B/T* conditions where electron t_1 is short (ms) and nuclear t_1 is long (minutes or hours)

$$P_{TE} = \frac{e^{\frac{\mu B}{kT}} - e^{\frac{-\mu B}{kT}}}{e^{\frac{\mu B}{kT}} + e^{\frac{-\mu B}{kT}}} = \tanh\left(\frac{\mu B}{kT}\right)$$

General System



Superconducting Magnet

B=2.5-5T

Polarization Detection

Tuned To Larmor of spin species

Proton (42.6 MHz/T)

Larmor-ESR

50-185 GHz

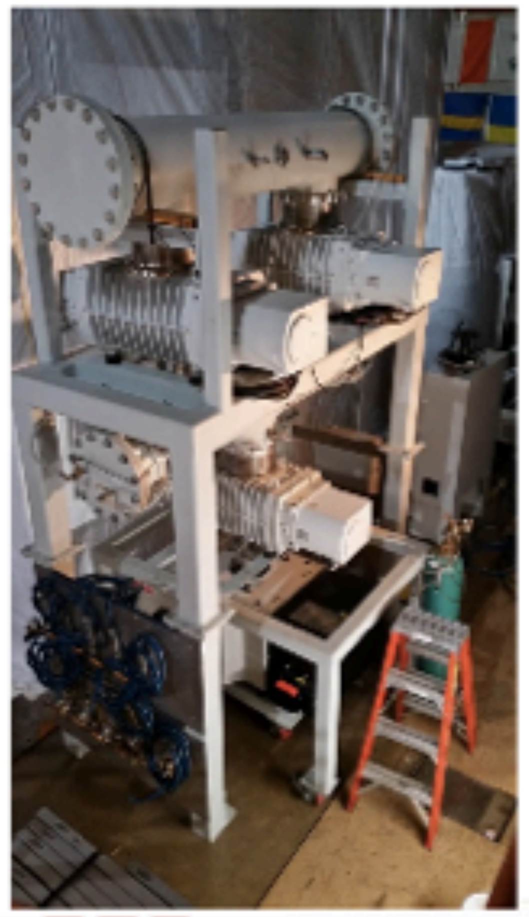
~140 GHz at 5T

T=0.03-1K

Polarized Target Subsystems

UVA-LANL: Three completely new NMRs

NMR



oerlikon

Pumps

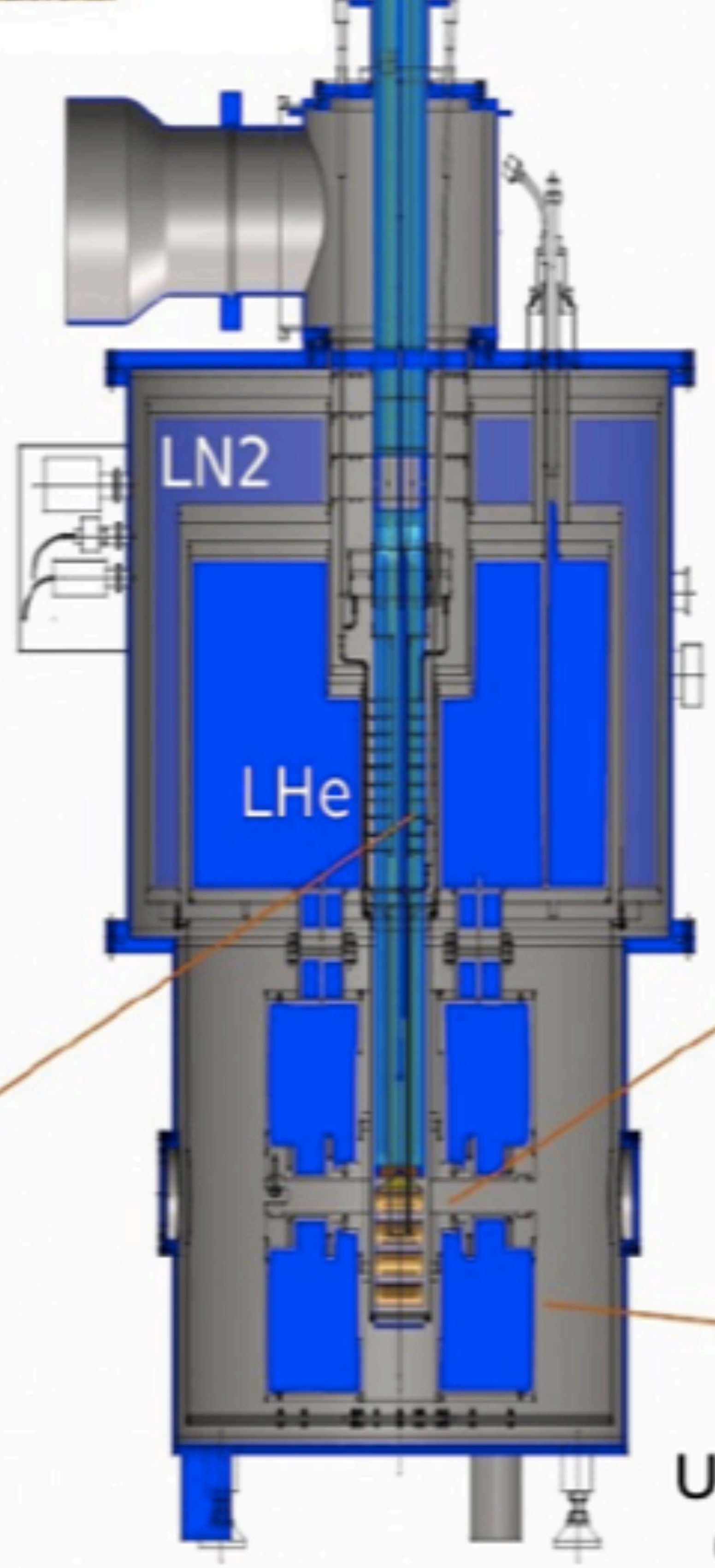
14,000 providing the highest cooling power for 1K system

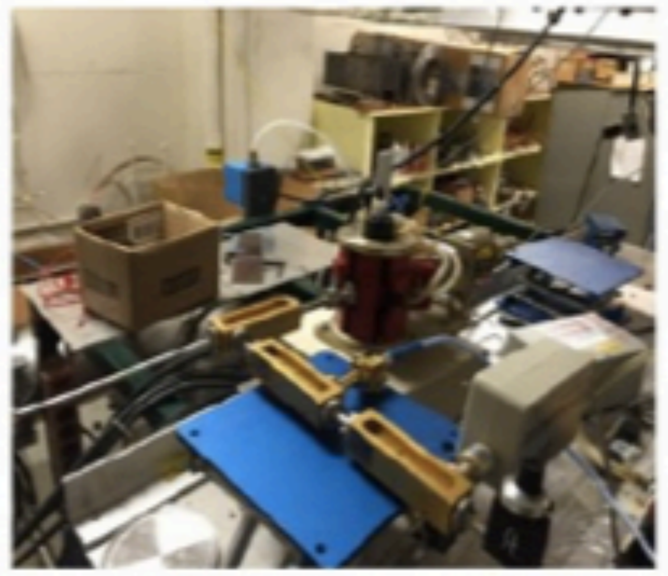
UVA: Configure Fridge and Insert, Commission for Optimal running, setup with Actuator

Fridge

UVA: Design

Insert





CPI

UVA: Tune System and Automation

Microwave

NIST National Institute of Standards and Technology U.S. Department of Commerce

Target material

UVA: Target Insert with longest cell at 8 cm for 5T

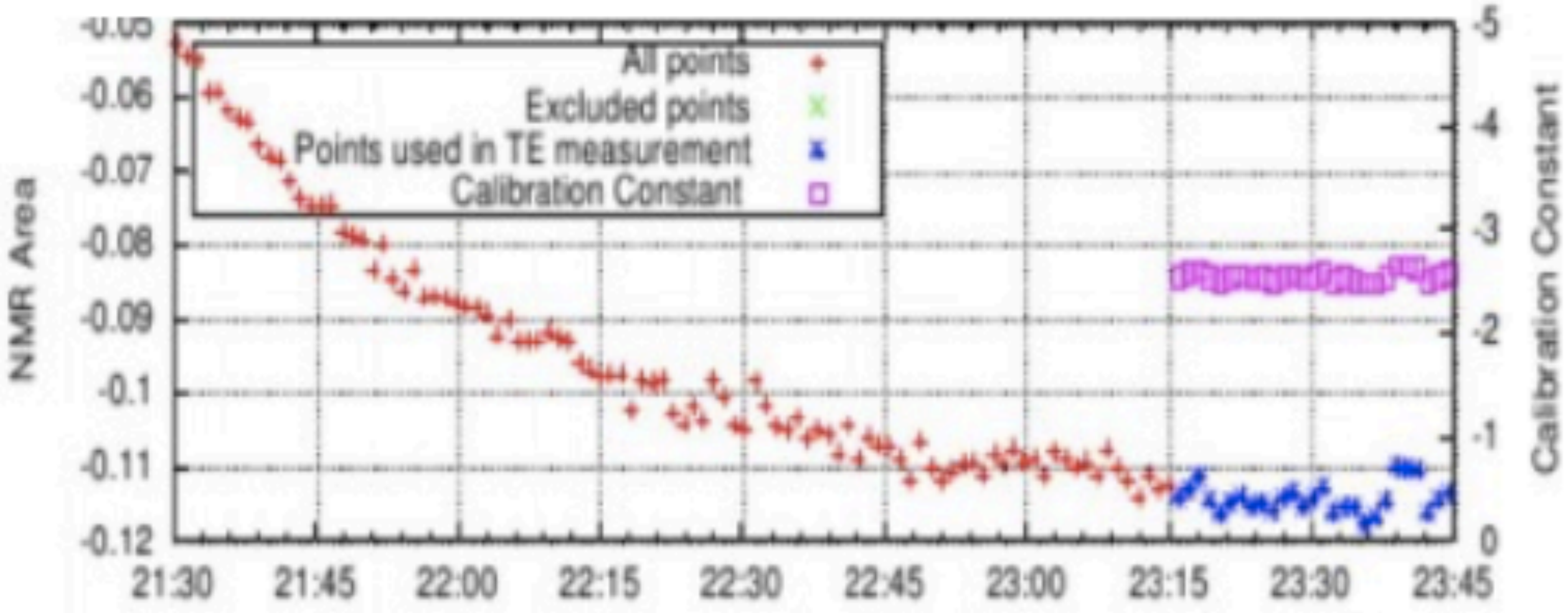
Magnet

OXFORD INSTRUMENTS

UVA: Commissioning, Slow Controls, Quench Study,

Material	Dens. (g/cm^3)	Length (cm)	Interaction Length (cm)	Dilution Factor	Packing Fraction	$< P_z >$
NH_3	0.867	7.9	91.7	0.176	0.6	80%
ND_3	1.007	7.9	82.9	0.3	0.6	32%

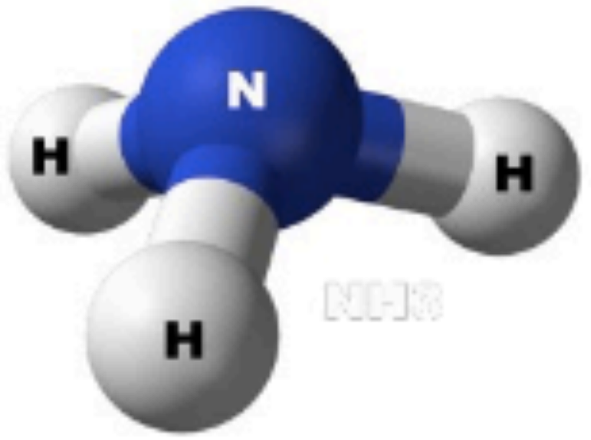
- 3 probes over length of target.
- NMR expected to have 2-3% error for proton 4-5% for deuteron. Deuteron signal order of magnitude smaller.
- If coils moved outside cup, possible increase in uncertainty for deuteron.
- Need time to thermalize. Need 3xt1 (relaxation rate, ~10 min for proton, 1 hour for deuteron). 2-3x more error if rushed.
- Built-in error for neutron polarization from deuteron.



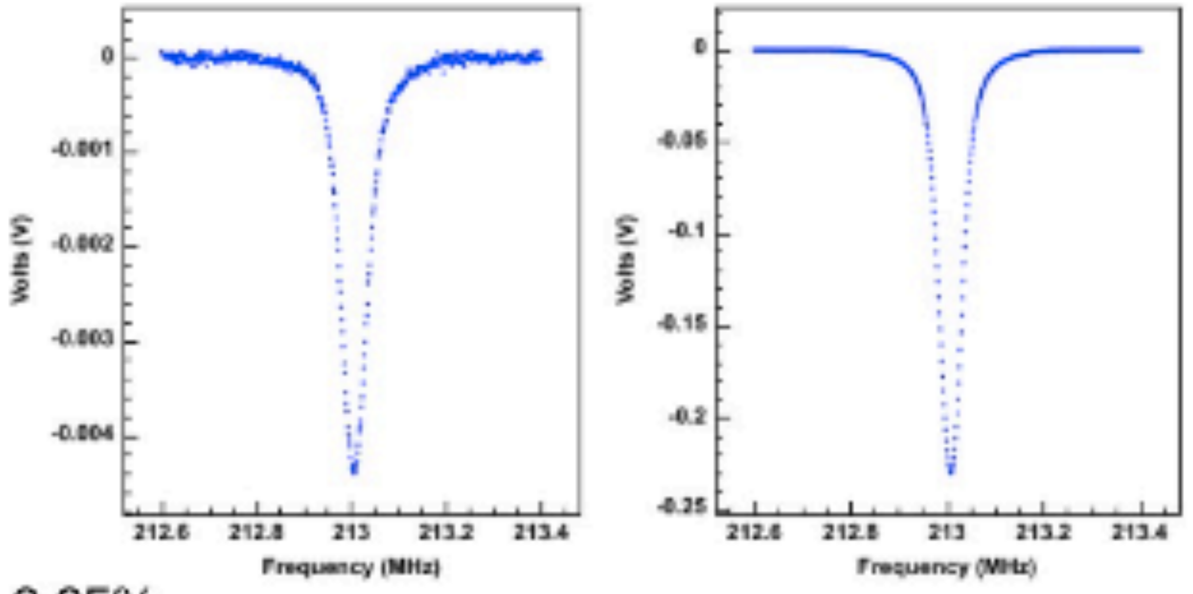
$$\Delta A_N = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N}}$$

$$f \equiv \frac{N_{p,polarizable}}{N_p + N_n} = \frac{p \times 3}{p \times (7+3) + n \times 7} = \frac{3}{17}$$

$$f \equiv \frac{N_{p,polarizable}\ \sigma_{\pi p}^{DY}}{N_p \sigma_{\pi p}^{DY} + N_n \sigma_{\pi n}^{DY}}$$



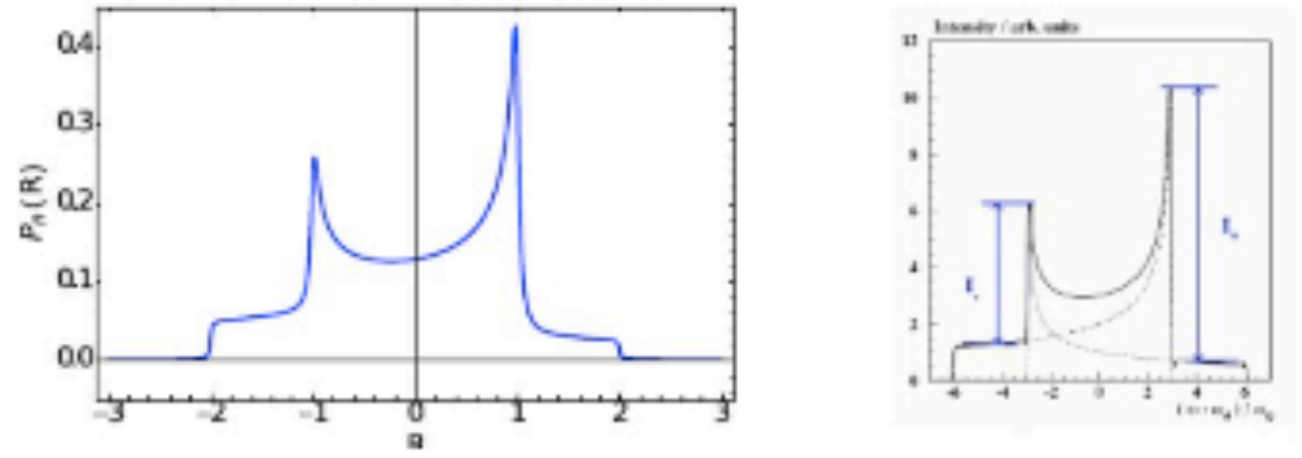
~0.3%



Proton

$$P_{TE} = \tanh\left(\frac{\mu B}{kT}\right)$$

~0.05%



Deuteron

$$P_{TE} = \frac{4+\tanh\frac{\mu B}{2kT}}{3+\tanh^2\frac{\mu B}{2kT}}$$

$$P_z = \frac{R^2-1}{R^2+R+1}$$

Neutron

$$P_n = (1 - 1.5\alpha_D)P_d \approx 0.91 P_d$$

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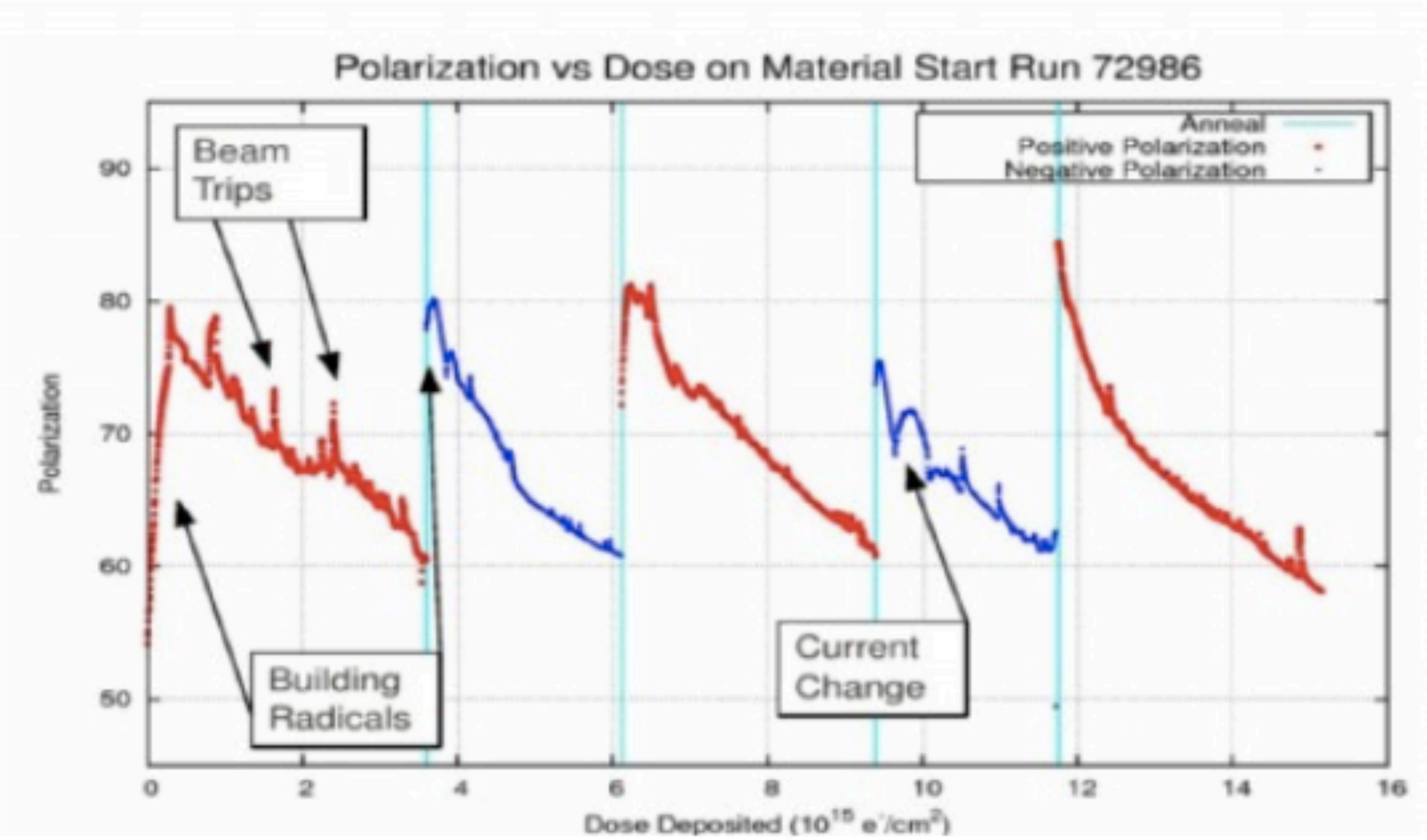
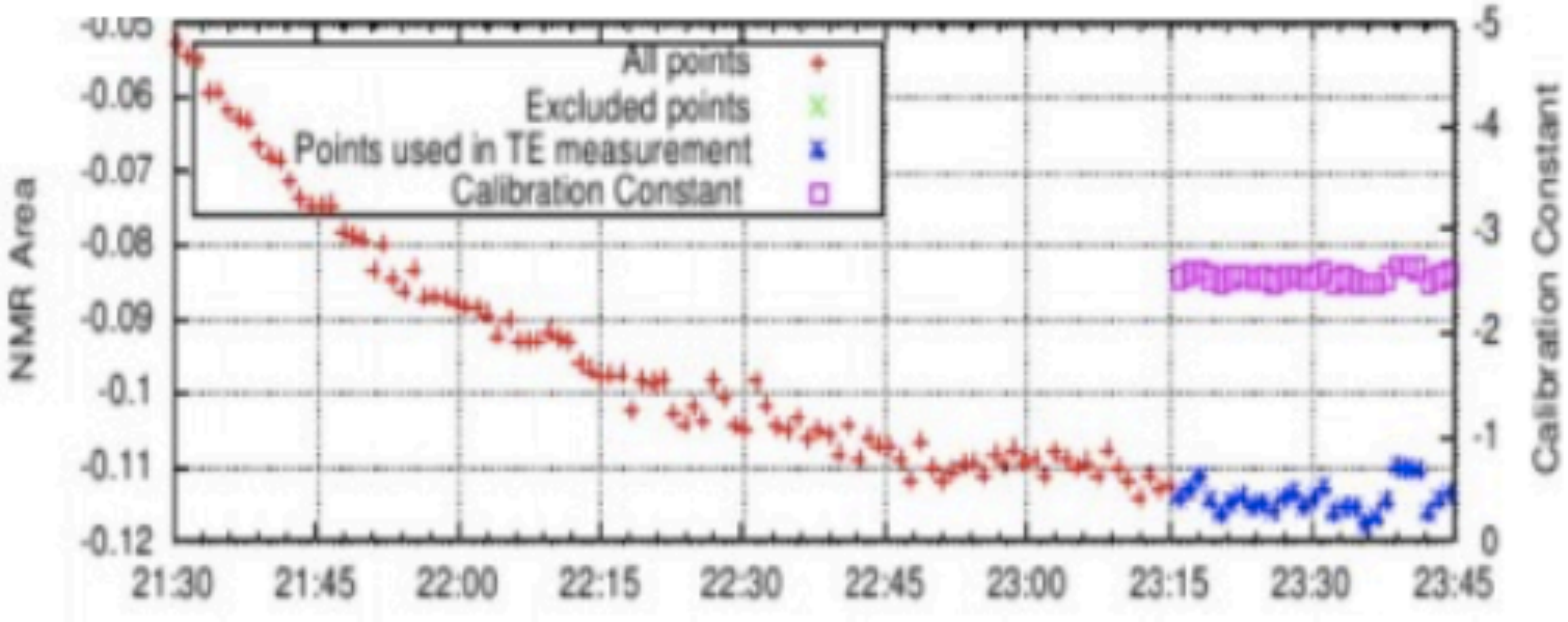
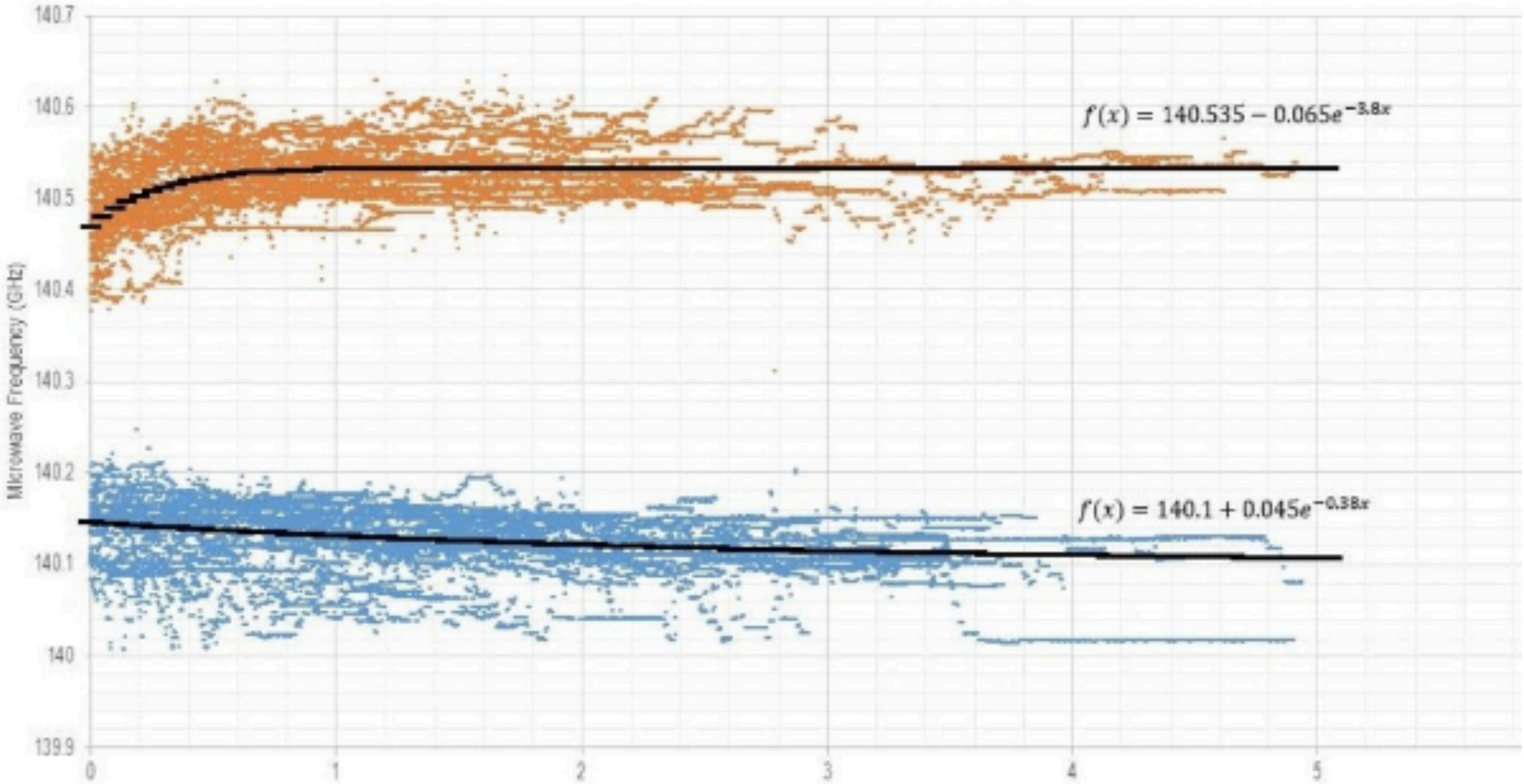






SpinQuest

A target system to operate at the proton intensity frontier

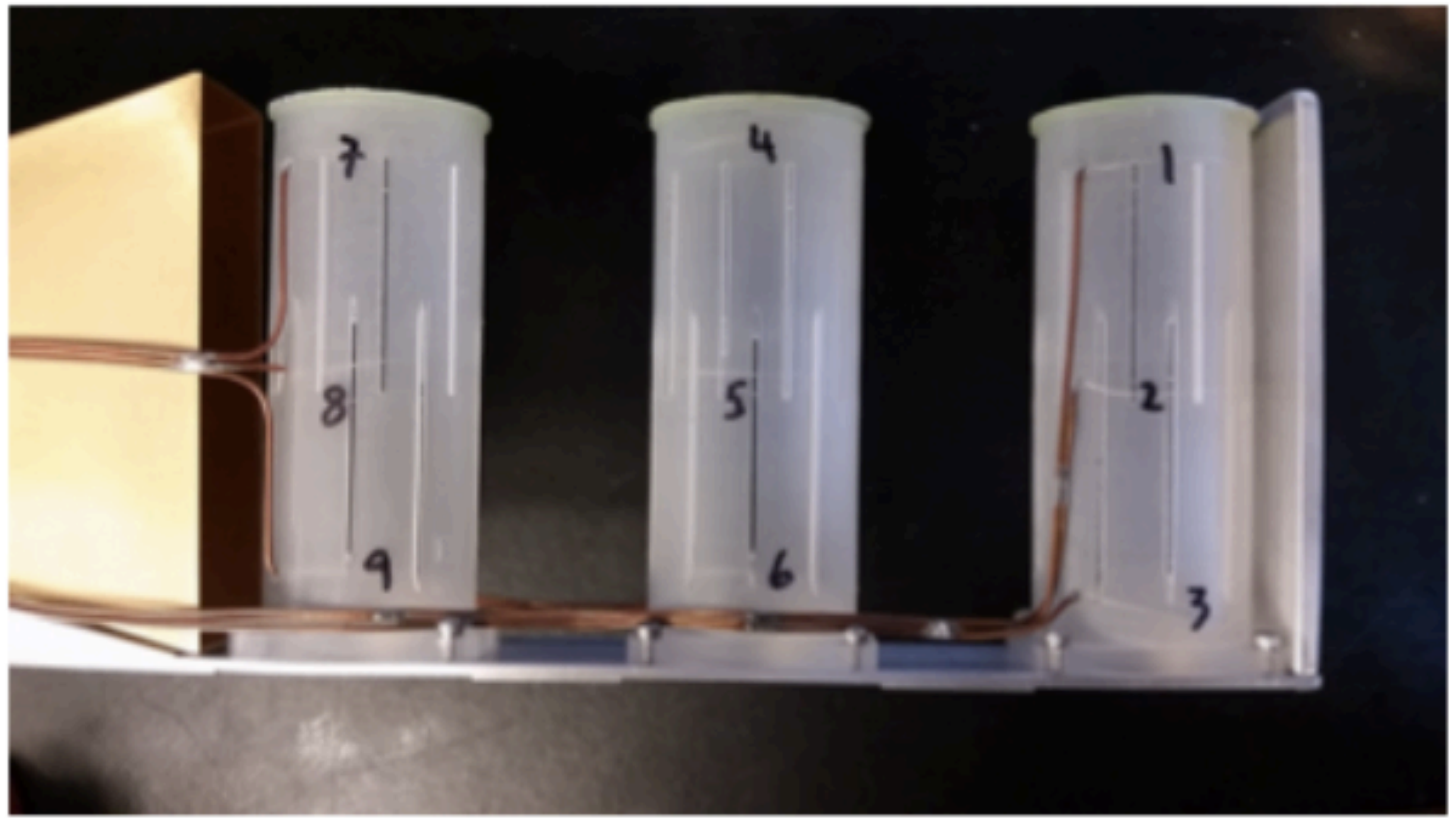
- At least 3×10^{12} protons/spill
- 8 cm long target of NH_3 and ND_3
- Several Watts of cooling available: 14000 $m^3/hour$ pump
- 5T vertically pointing field (close to critical temperature each spill)
- Luminosity of $2 \times 10^{35} cm^{-2} s^{-1}$

Target Insert


Carbon fiber with copper heat sink

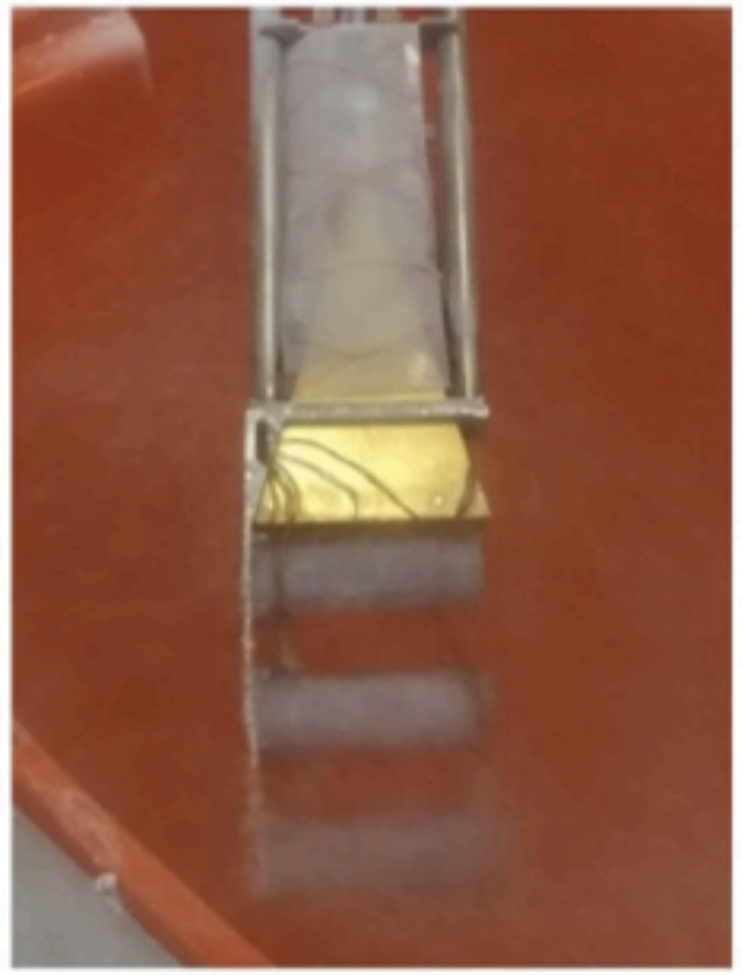
20X27 mm elliptical cells

long cell length microwave horn



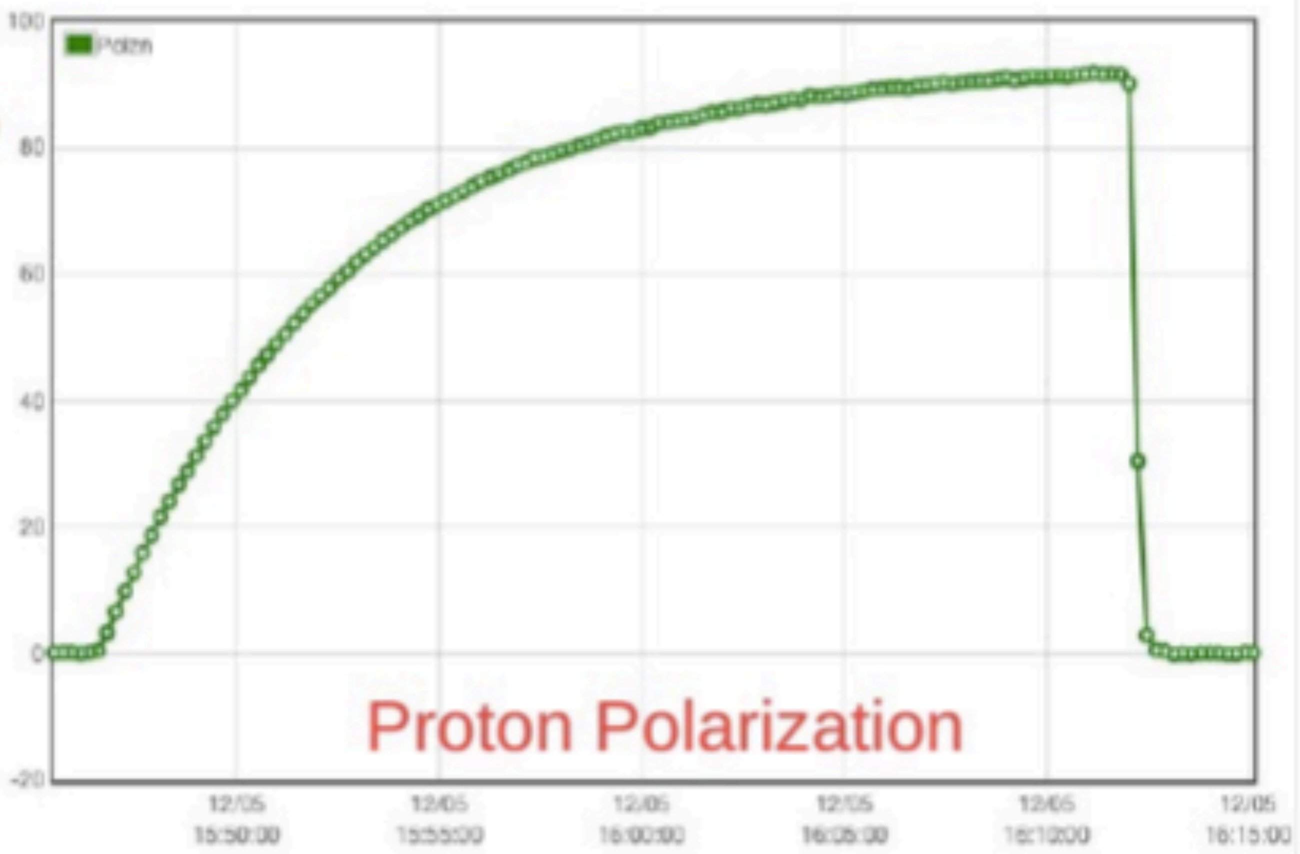
- 3 NMR coils per cell
- 8 cm long target cell of solid:
  NH_3 and ND_3
- Standard Insert has 3 cells
- One centering cell
- Elliptically shaped to match profile

Last Target Polarization at UVA



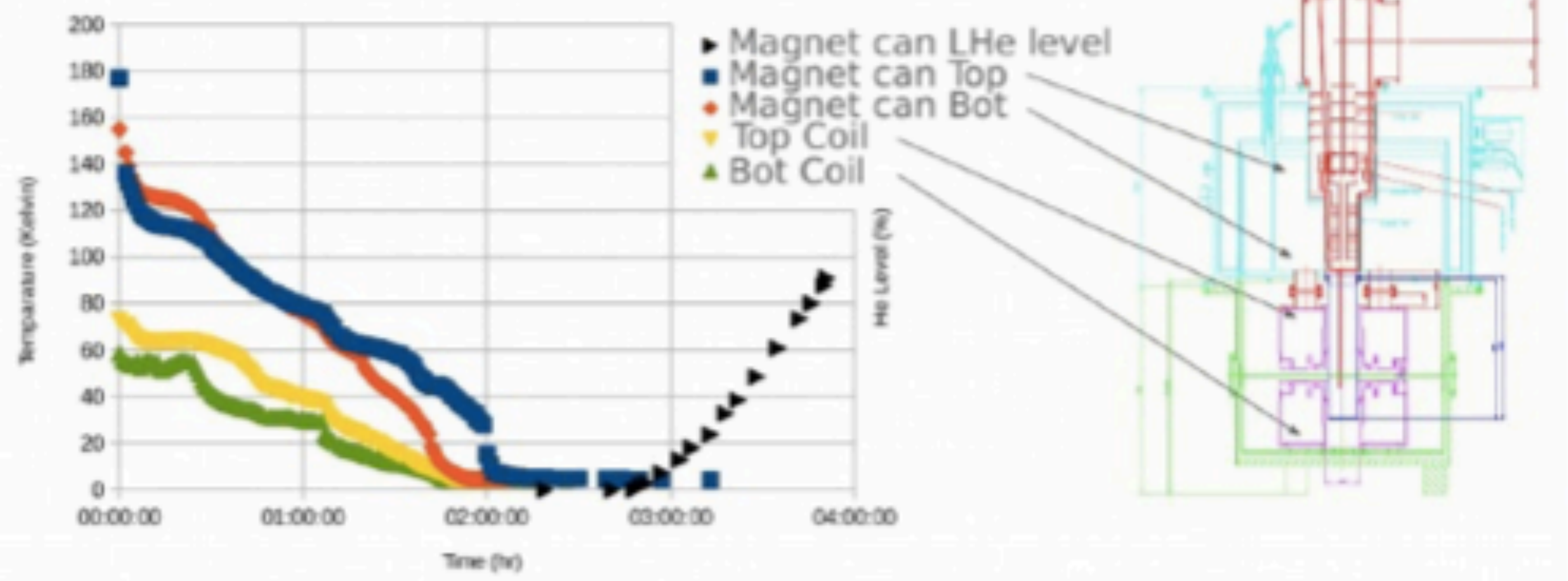
Insert in LN2

95%

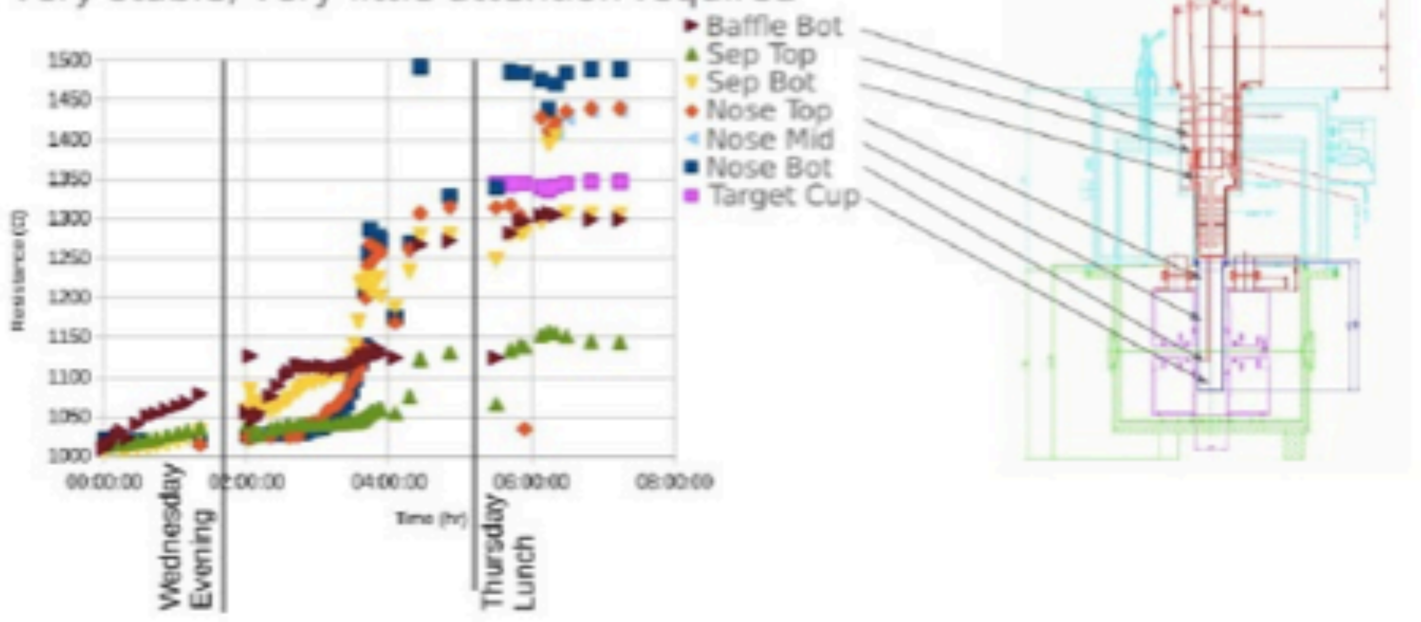


~2.5

~1 hr to to fill magnet can

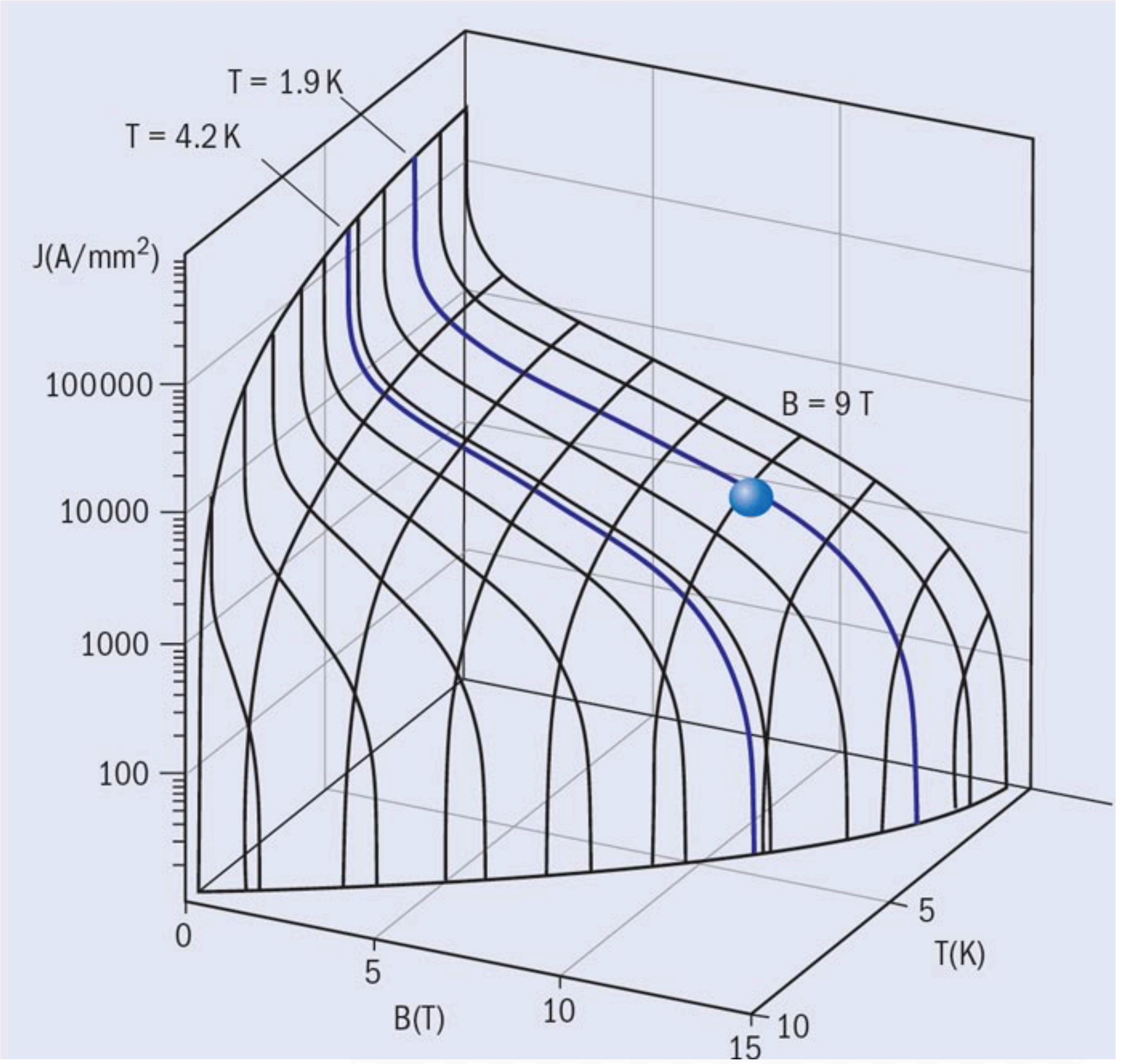


~1hr to fill the nose after a night on standby
very stable, very little attention required



Superconducting Magnet

Introduction: Quench definition



The critical surface is defined from the temperature (T), magnetic field (B), and the surface current (J)

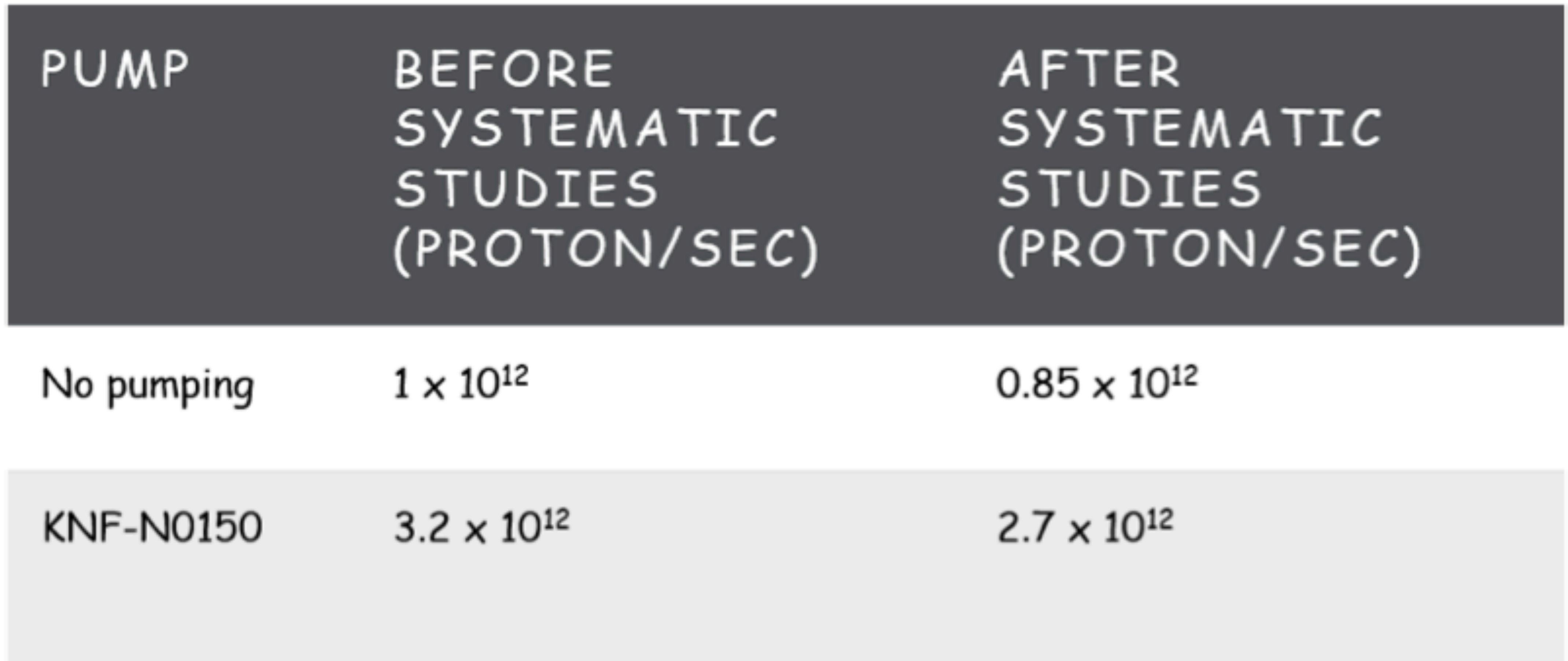
Magnet quench if the T, B or J lie outside the critical surface

For B = 5 T, The maximum temperature that the magnet can hold is around 7.2 K

Quench Studies

Primary Intensity Boundary

- Very Limited Experimental Information
- Use Monte Carlo and Finite Element Analysis
- Match Measured Field and Simulated Field

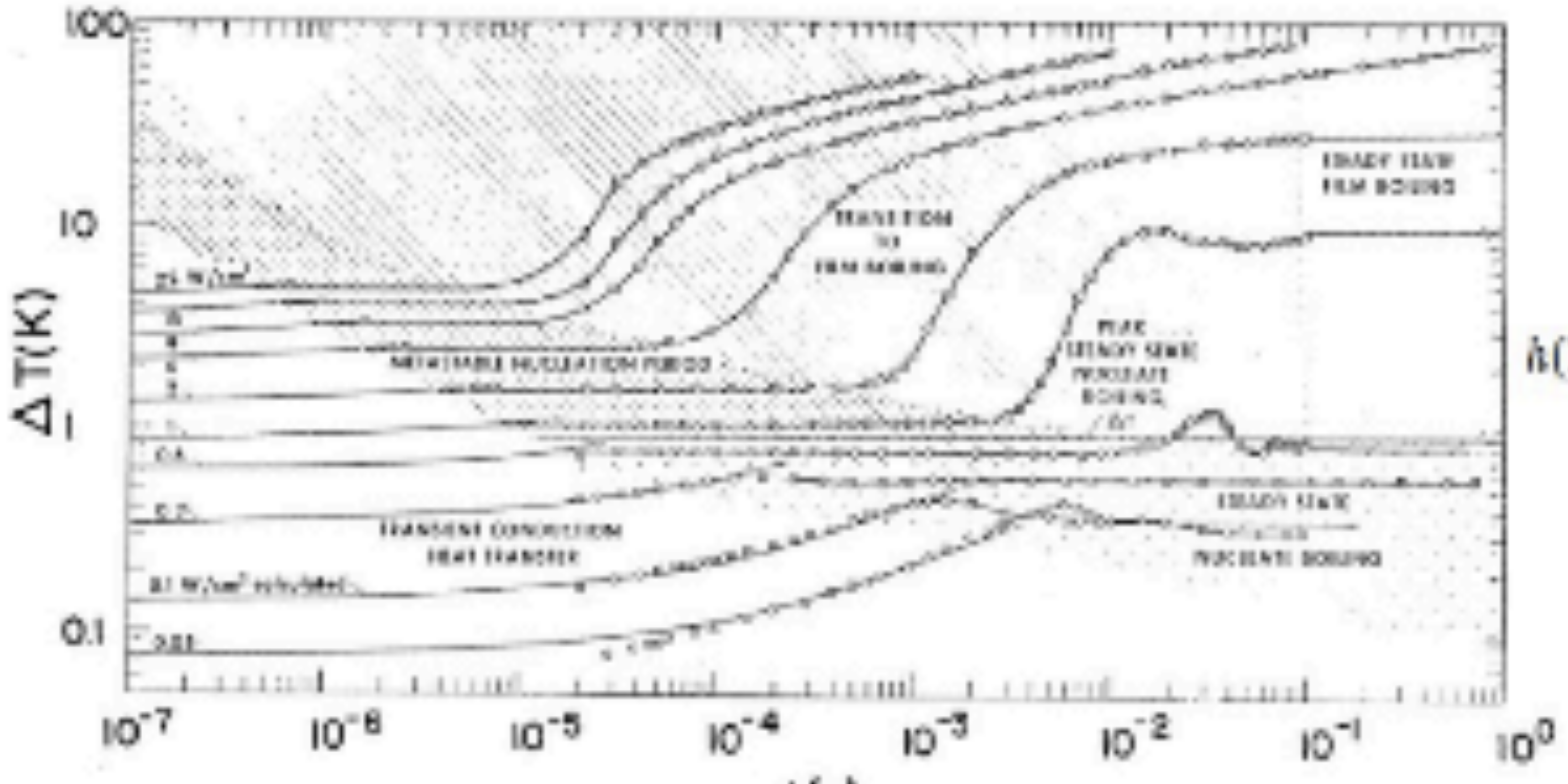


PUMP	BEFORE SYSTEMATIC STUDIES (PROTON/SEC)	AFTER SYSTEMATIC STUDIES (PROTON/SEC)
No pumping	1×10^{12}	0.85×10^{12}
KNF-N0150	3.2×10^{12}	2.7×10^{12}

- coils
- e Running
- Use Estimate to Make Quench Commissioning Plan

https://confluence.its.virginia.edu/display/twist/Quench+Commissioning

Approximation Strategy

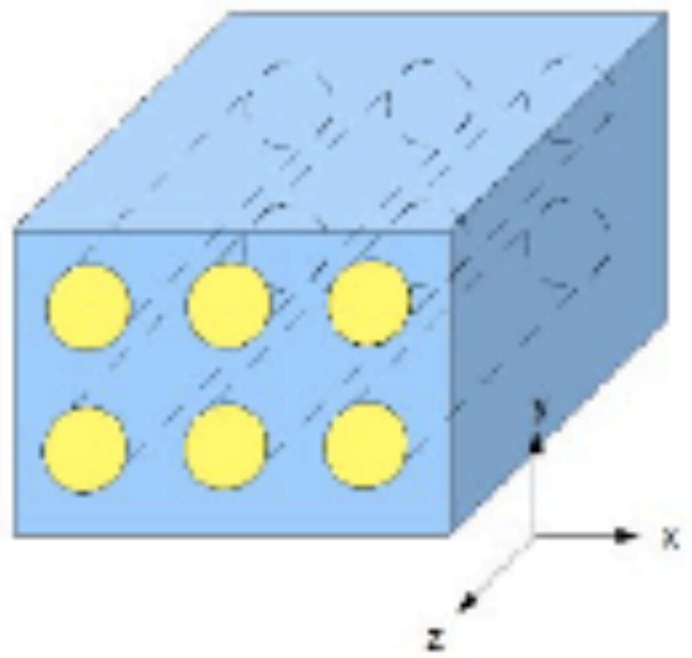


Various regimes of the heat transfer from solid to LHe

First, Steady state Film boiling regime is applied

$$h(T_s, T_{He}) = a_{FB,I}(T_s - T_{He}).$$

Second, we consider the superconducting magnet as a composite material with the effective thermal parameter



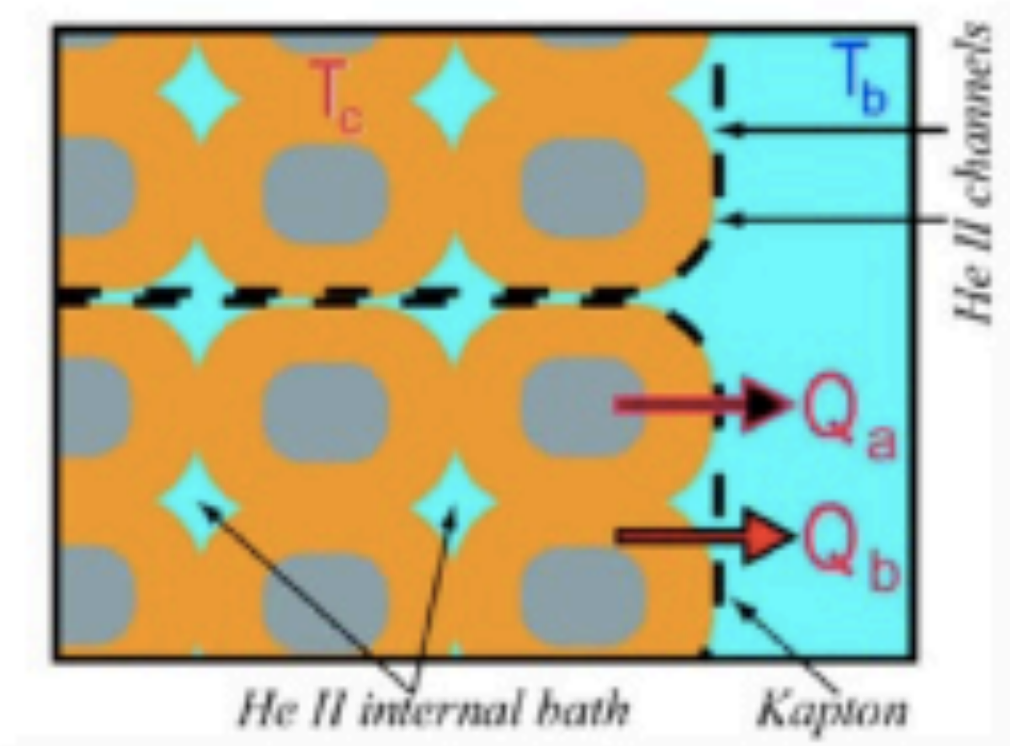
Rayleigh's model consist of parallel cylinders embedded in a continuous matrix

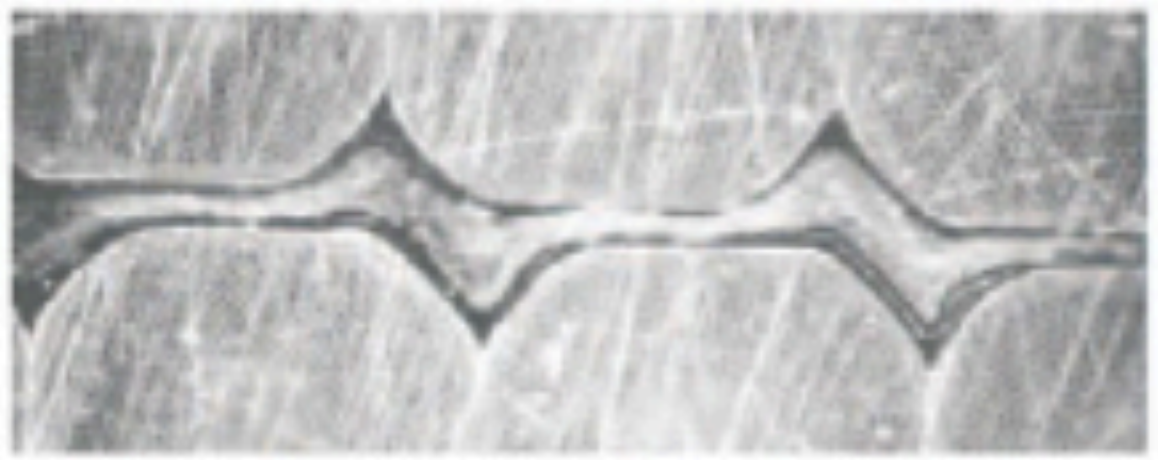
Rayleigh's formula

$$\frac{k_{eff}}{k_m} = 1 + \frac{3\phi}{\left(\frac{k_1-2k_m}{k_1-k_m}\right) - \phi + 1.569\left(\frac{k_1-k_m}{3k_1-4k_m}\right)\phi^{\frac{10}{3}} + \ldots}$$

Third, we parameterize some of the unknown properties by the effective surfaces that are in direct contact with the LHe:

- Perimeter of the He void
- Insulation
- Former





Microscopic view of the cable

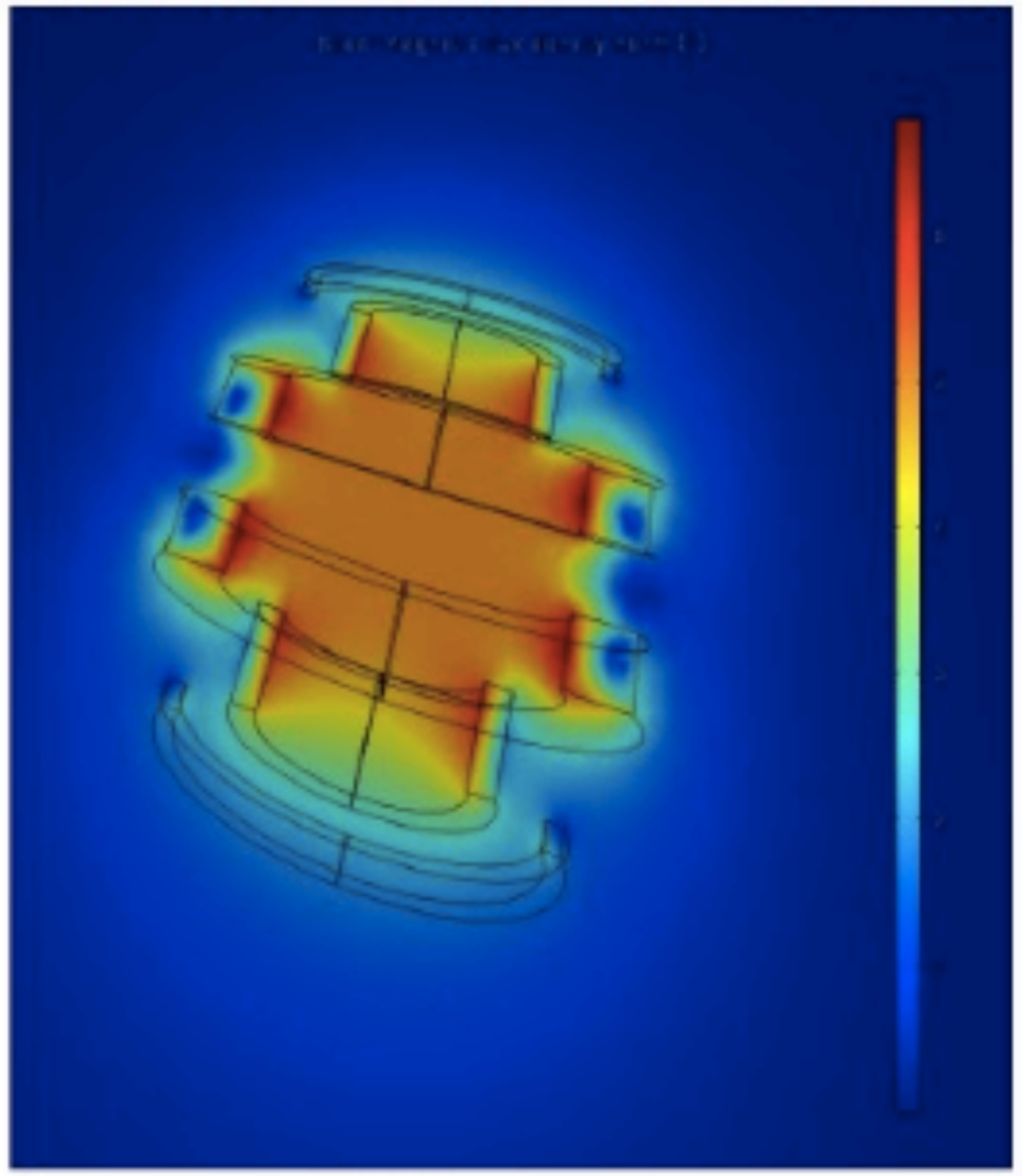
Field Measurement and Map

Measure Homogeneity using NMR and Hall Probe

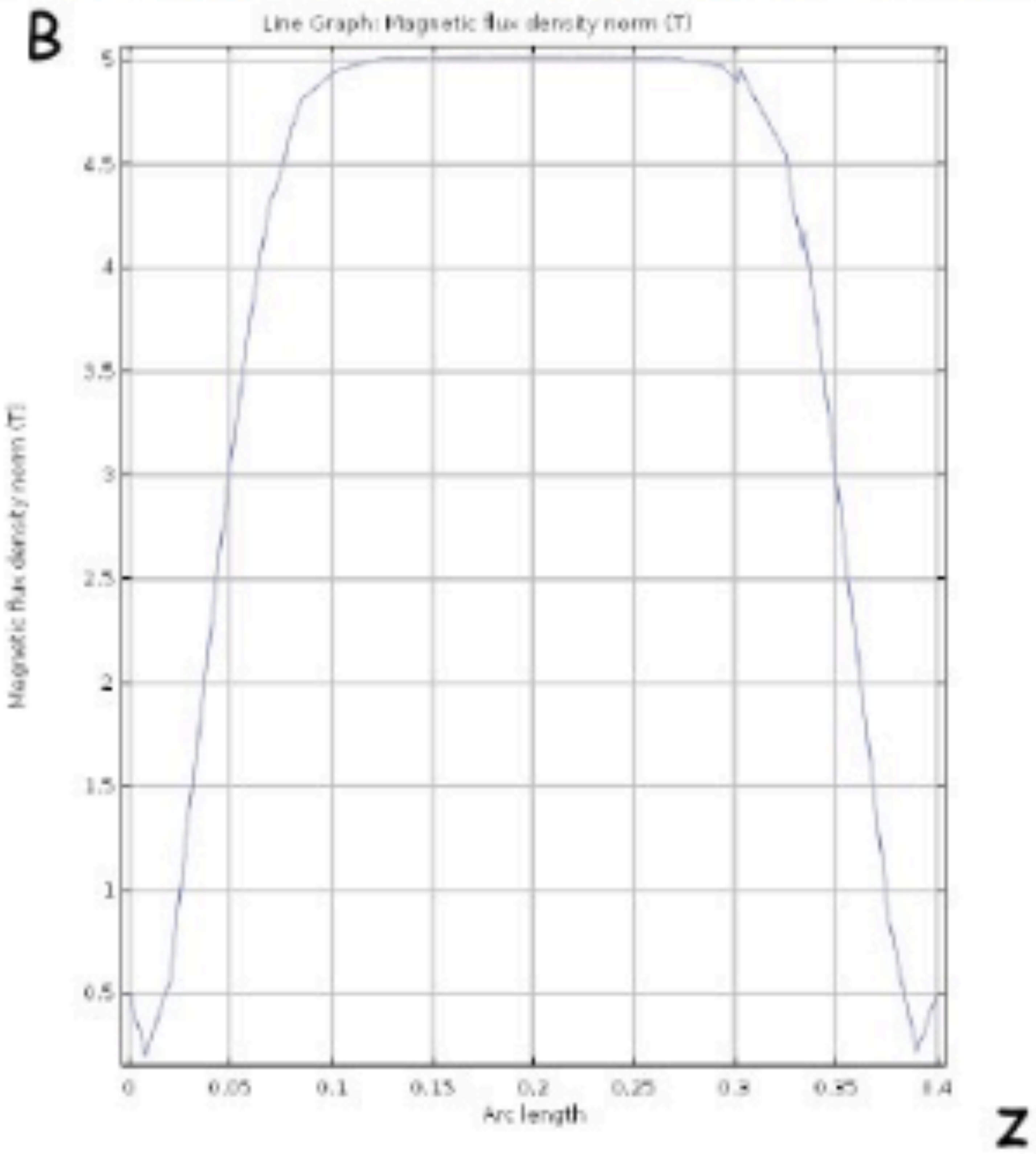
Accurate Field Map ✓

Measure outside fringe field and map to simulated field

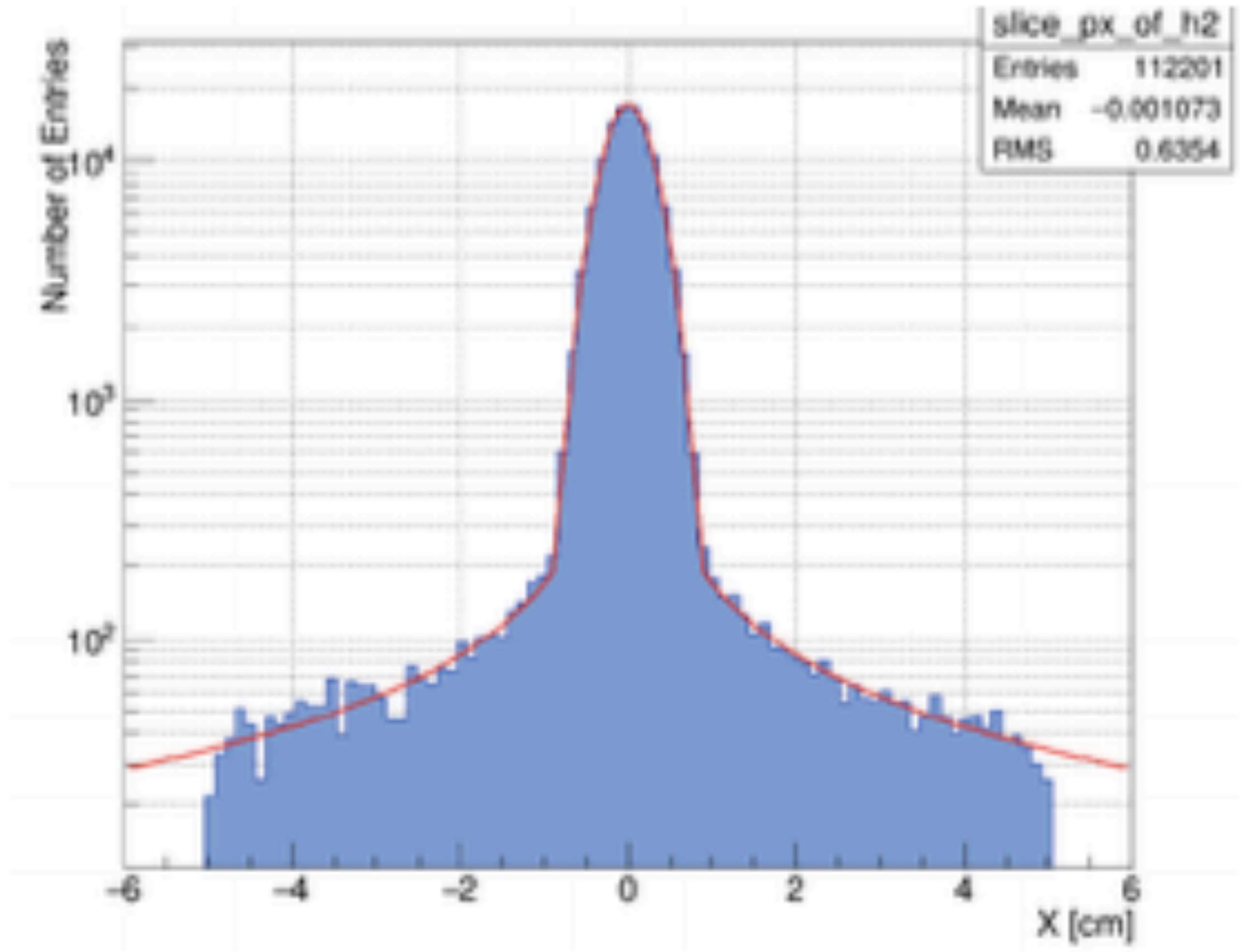
We achieve a high level of homogeneity around the target area & along the beam line:

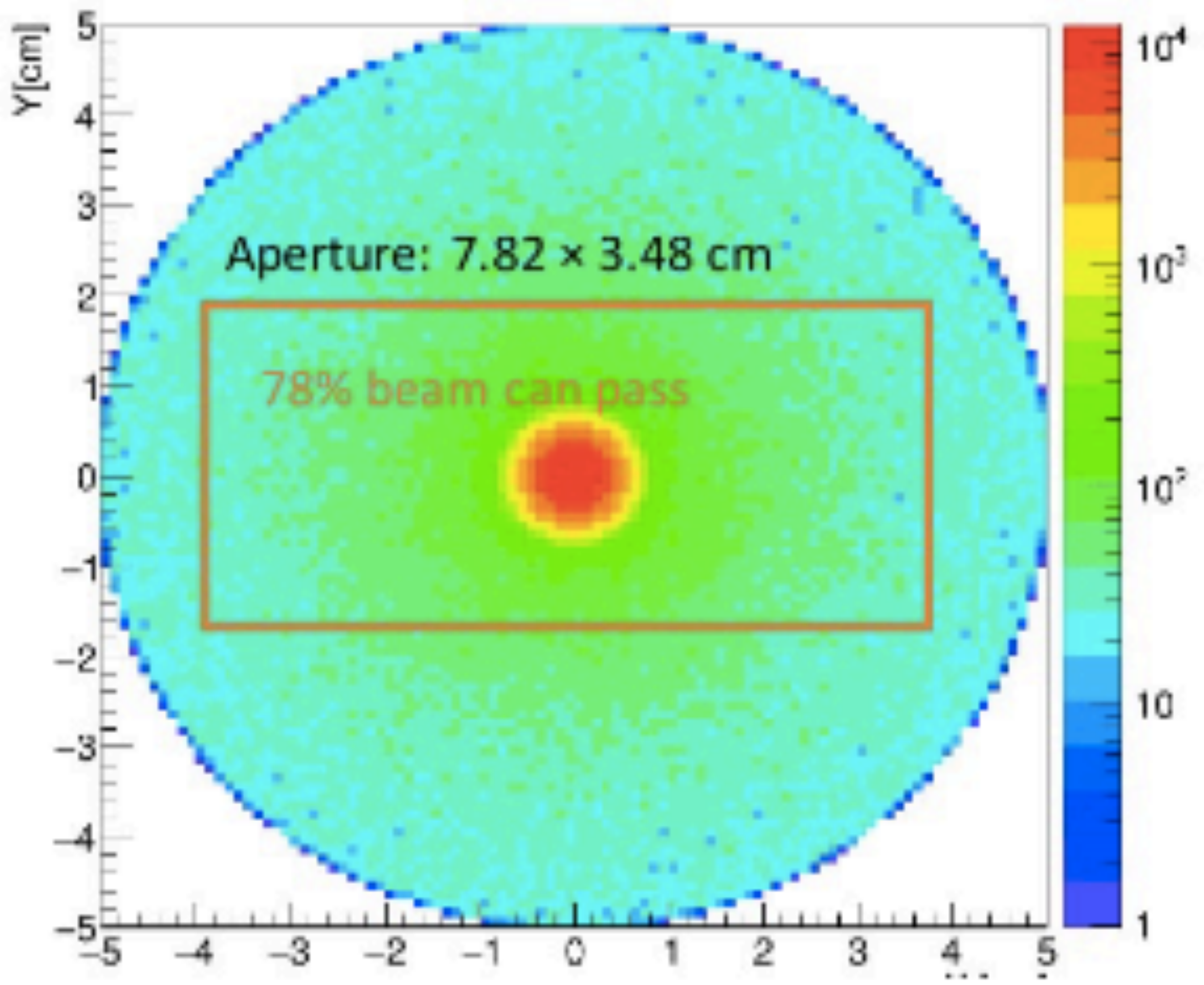


High level of homogeneity in the target area

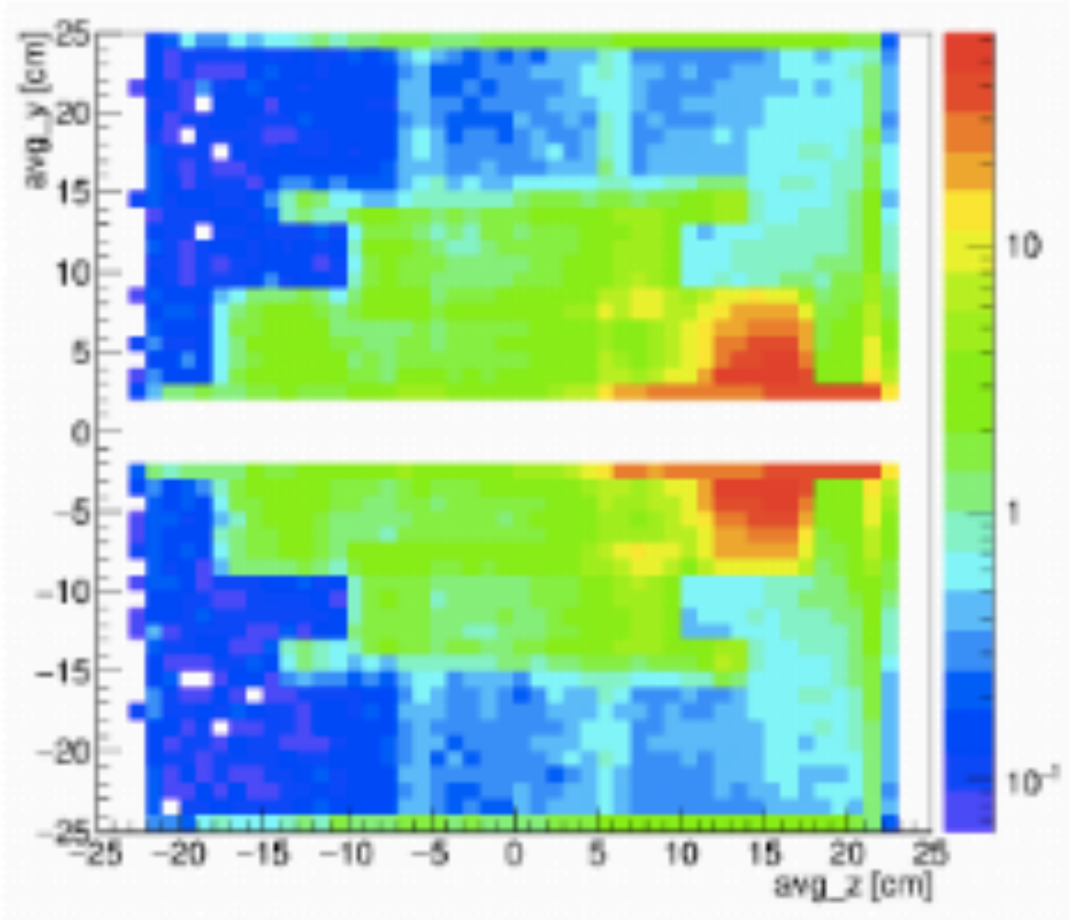


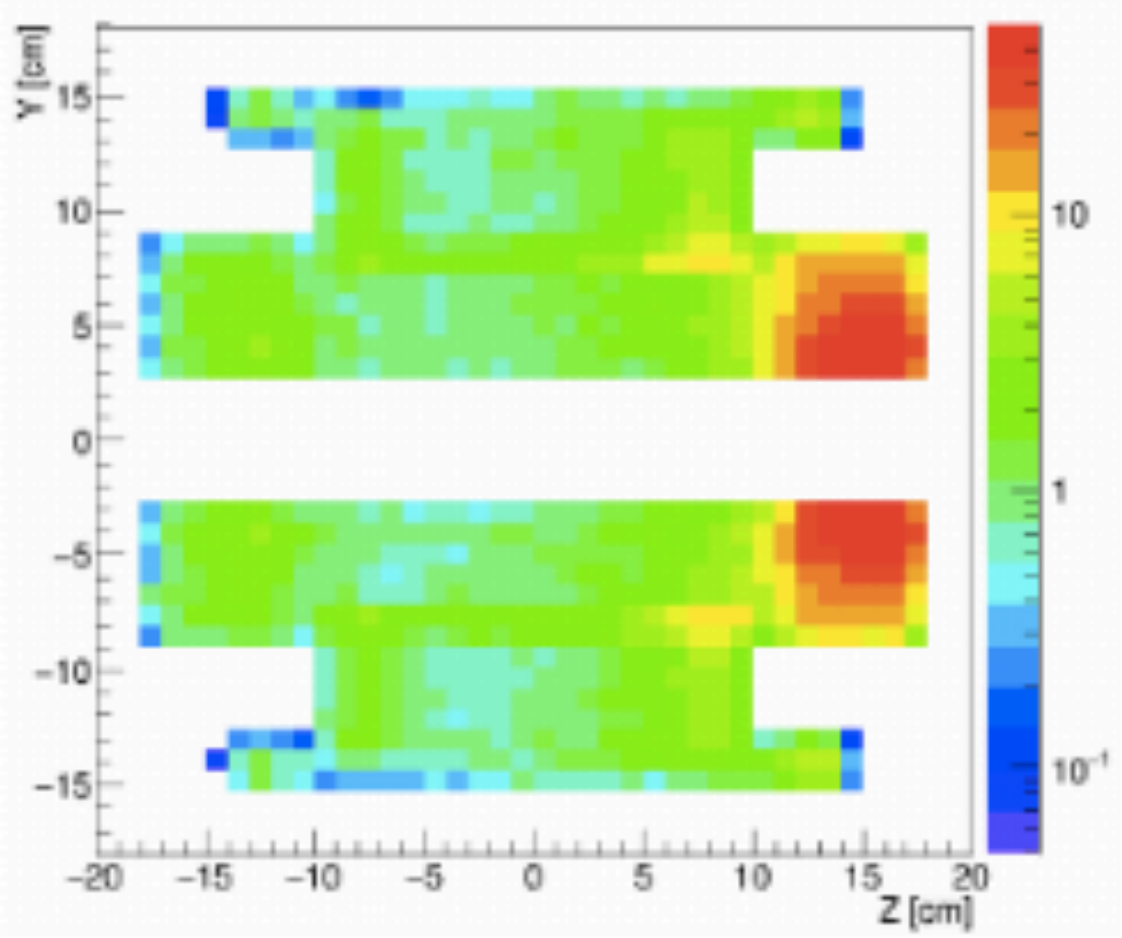
Geant → COMSOL

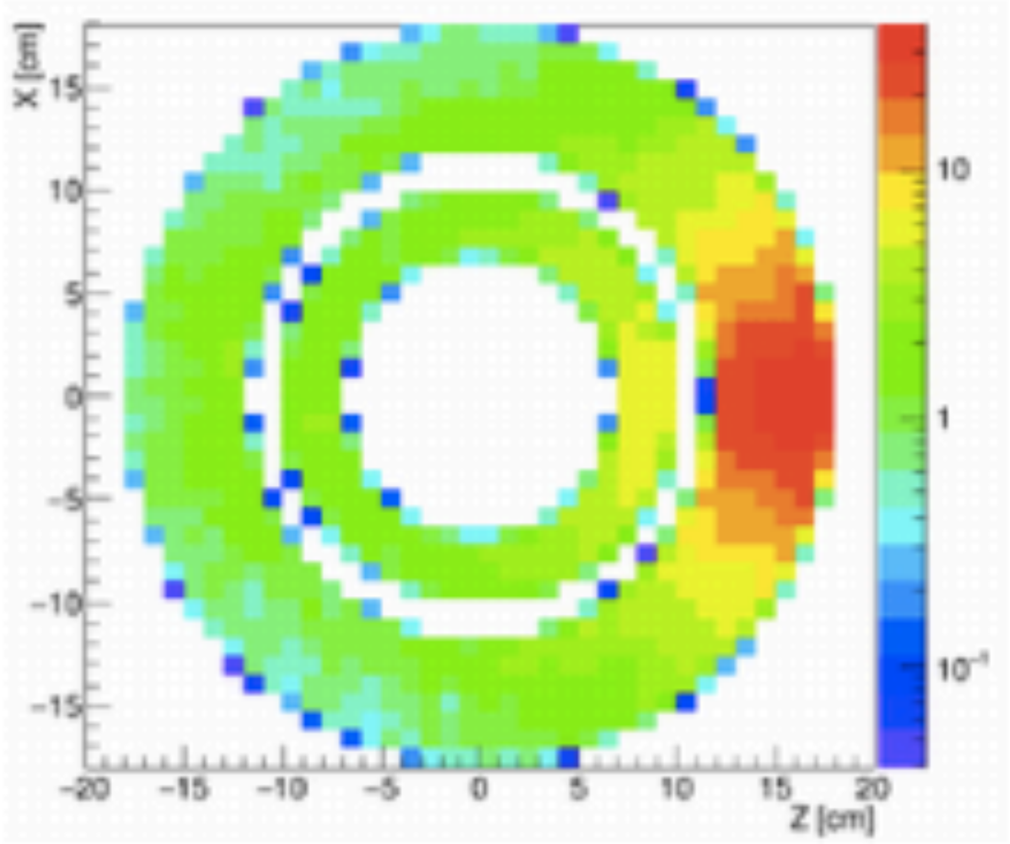



Aperture: 7.82 × 3.48 cm

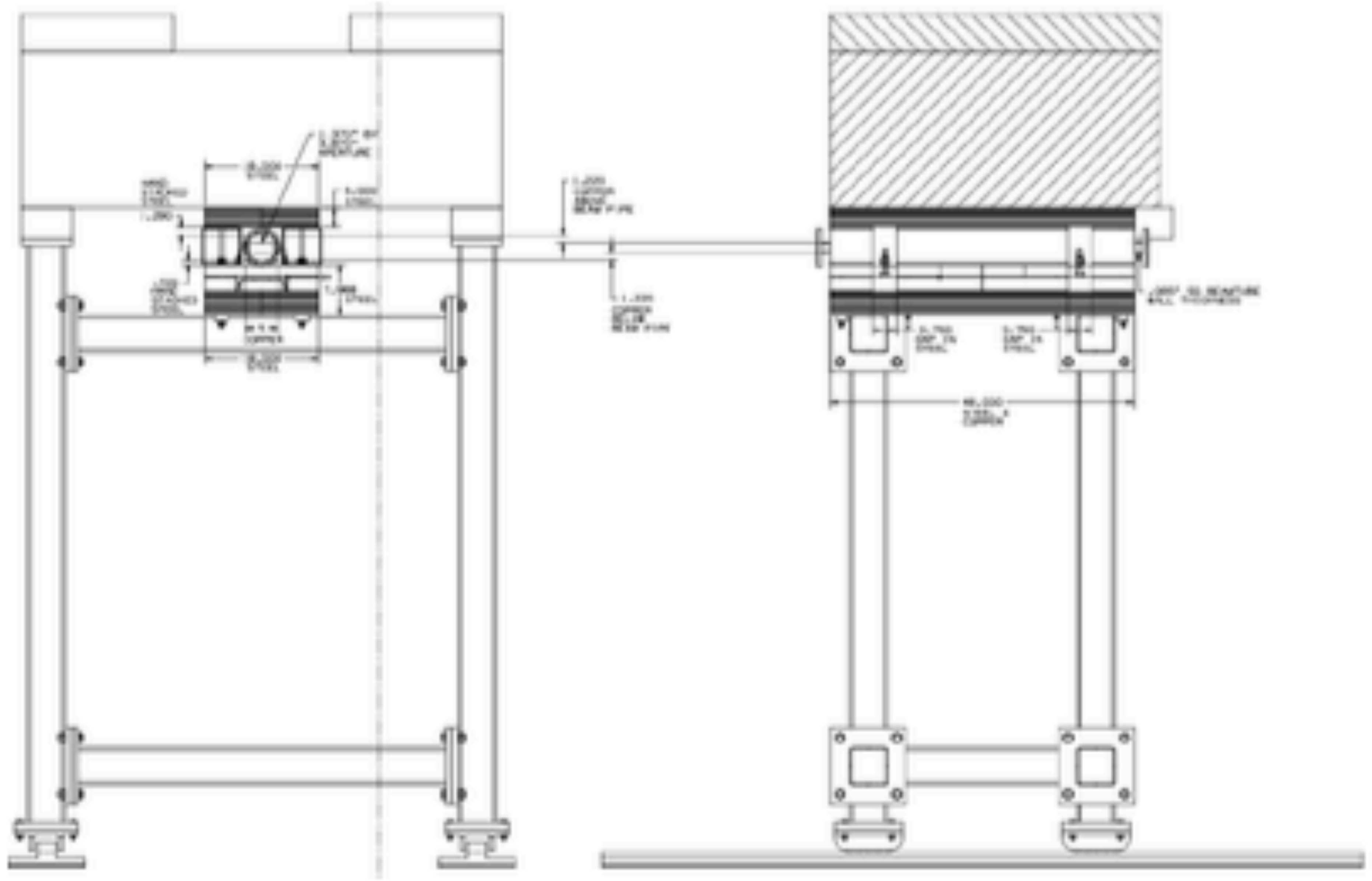
78% beam can pass

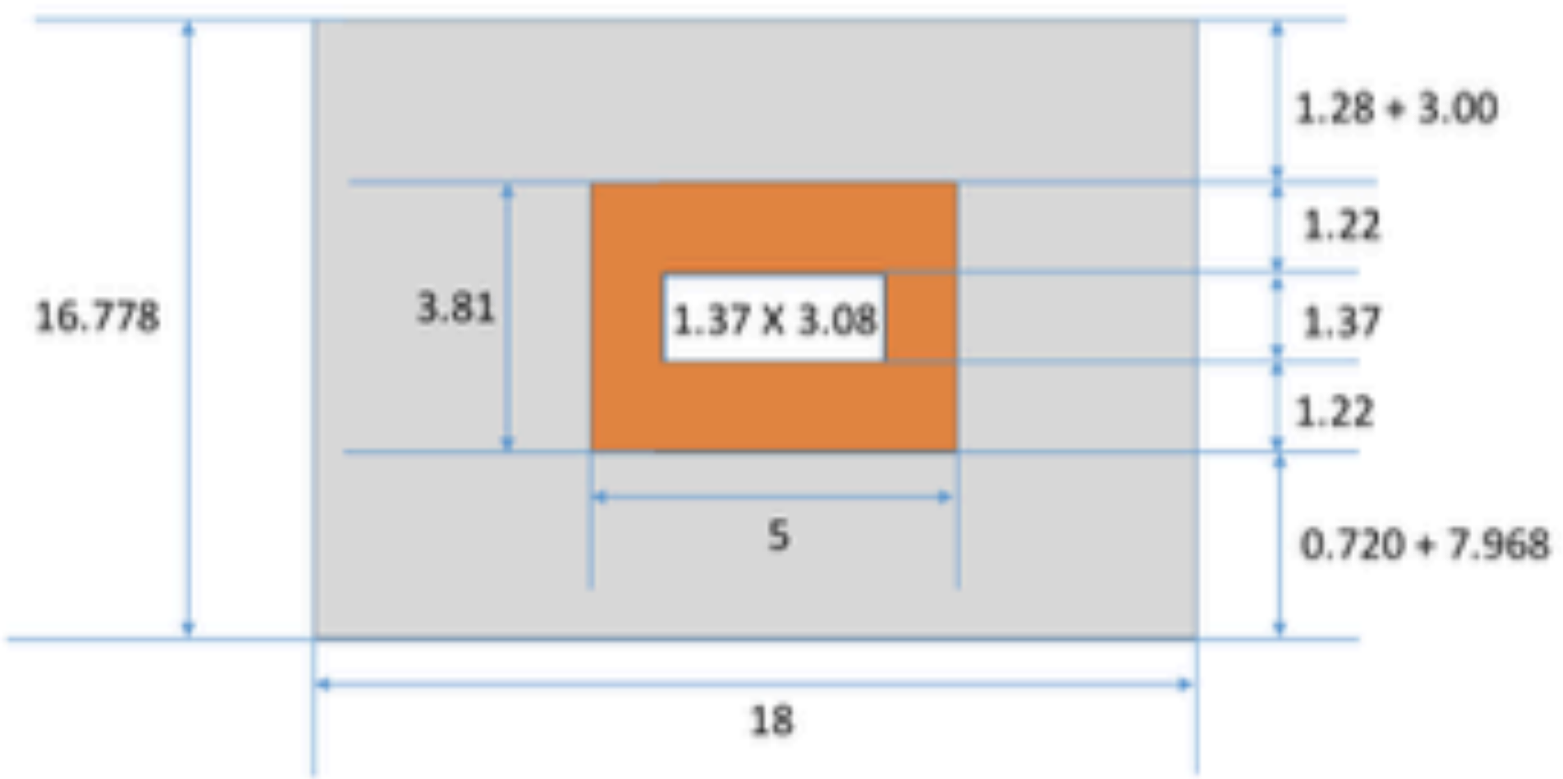


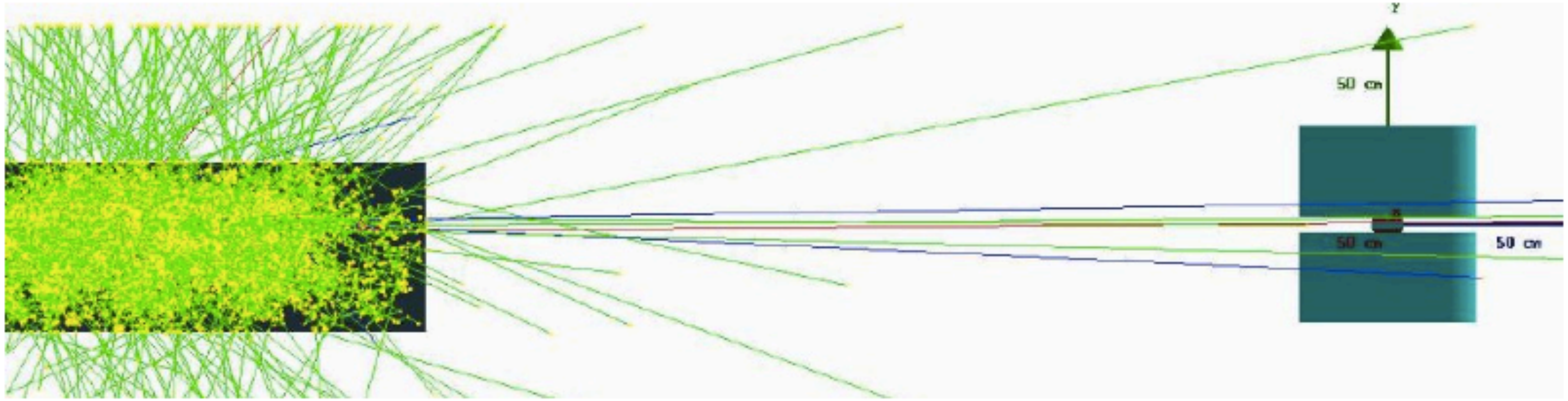




Collimator

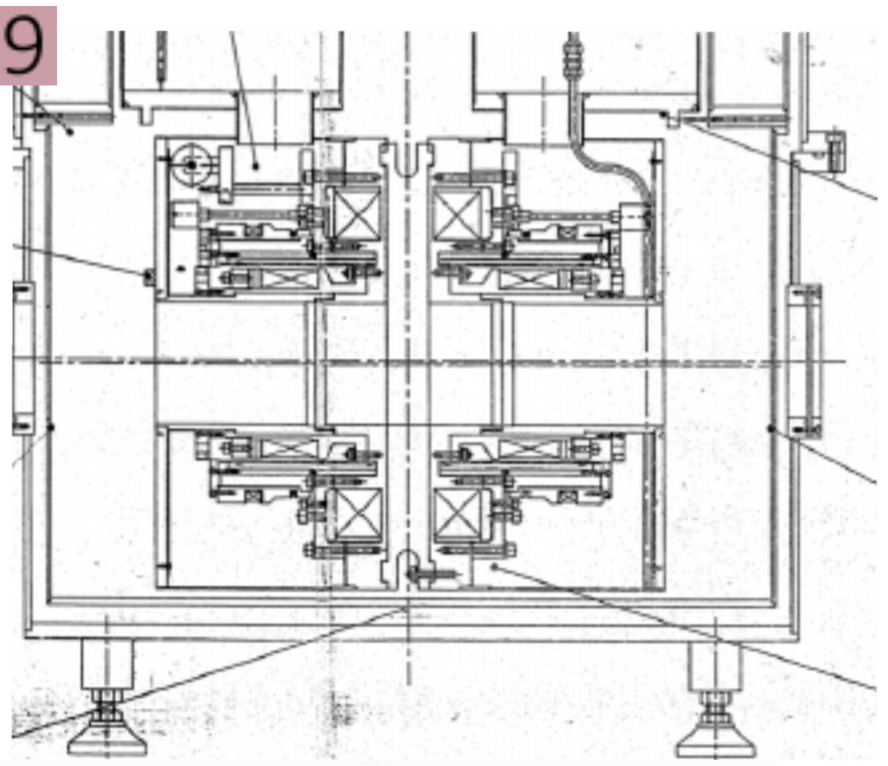



16.778
3.81
1.37 X 3.08
5
18
1.28 + 3.00
1.22
1.37
1.22
0.720 + 7.968

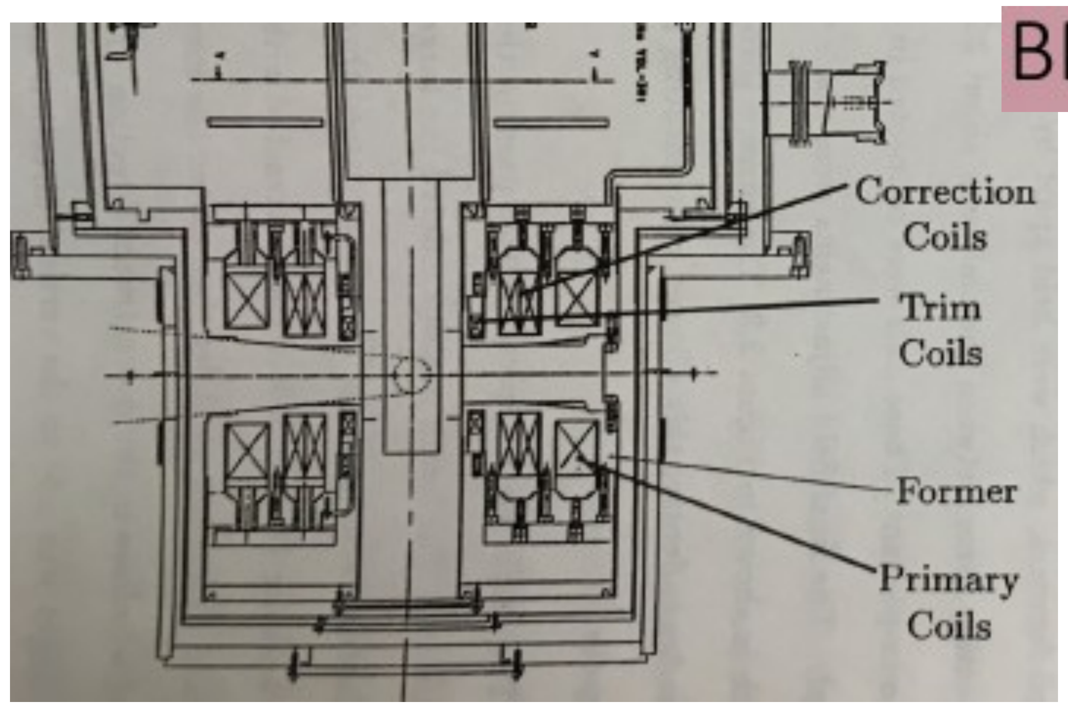

Y
50 cm
50 cm
50 cm

Magnet Comparison

E1039

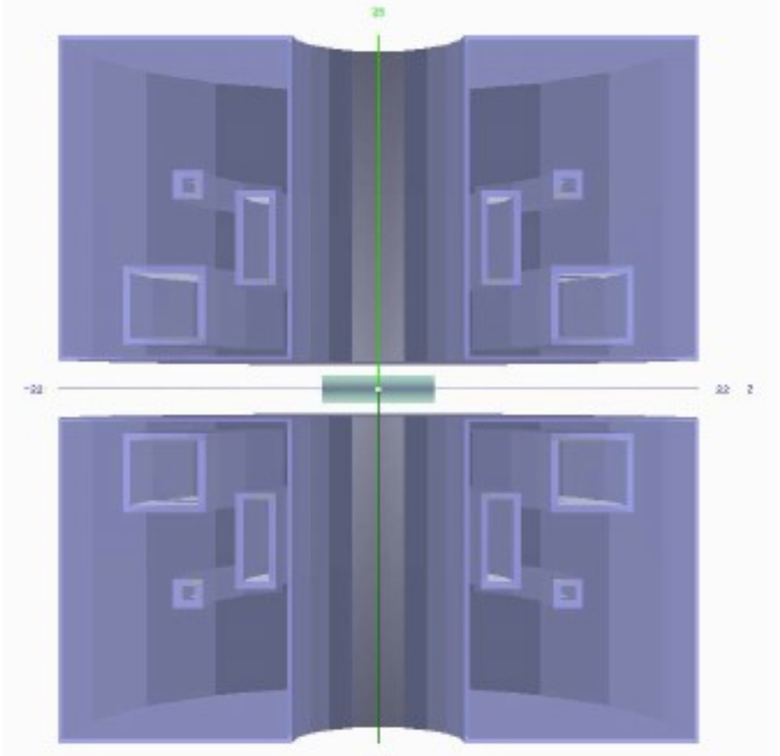


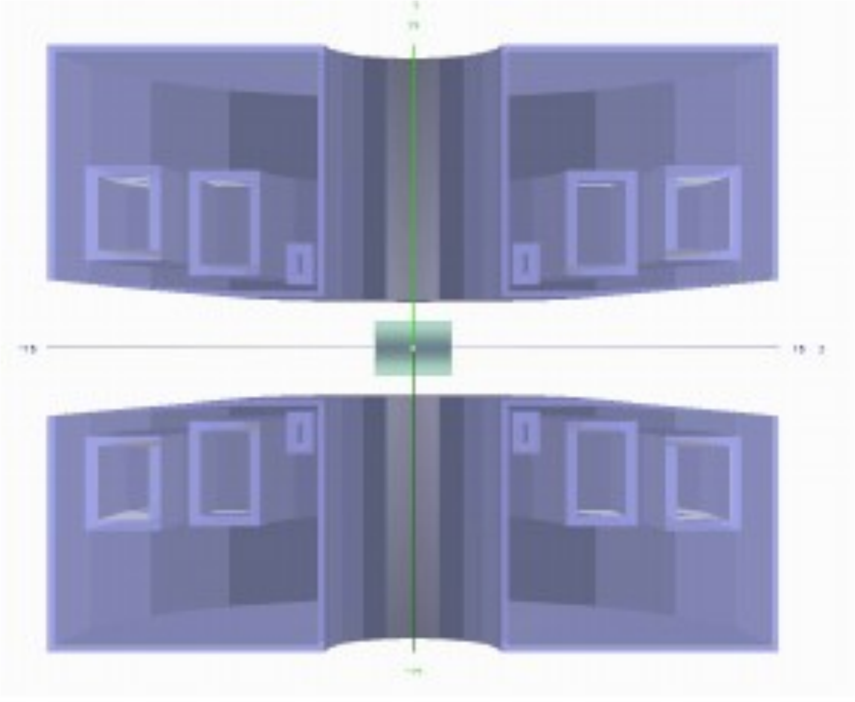
BNL target



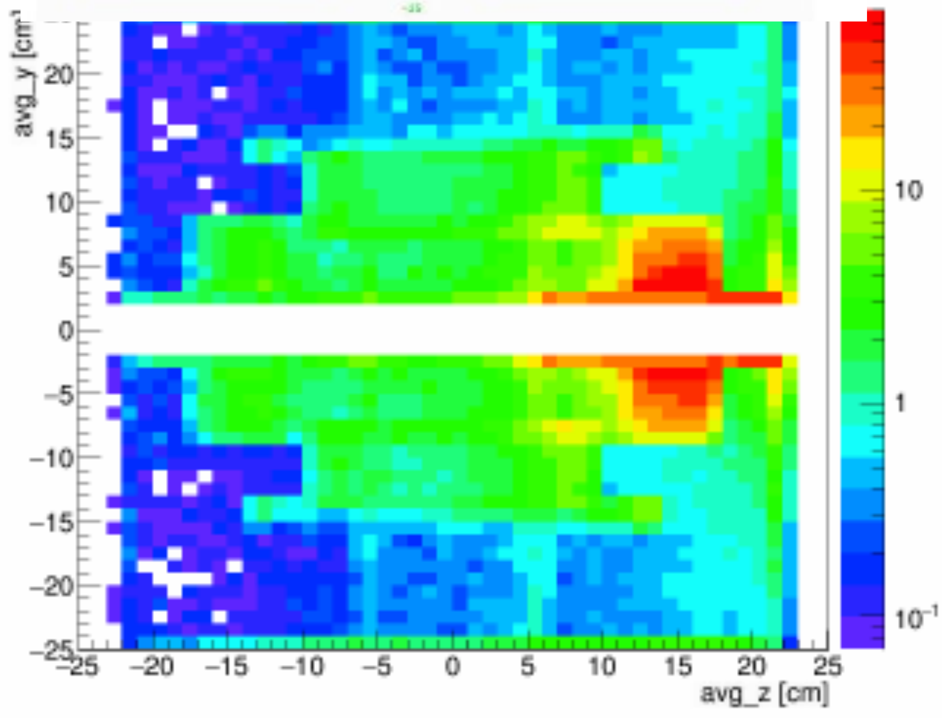
Solidworks → Geat4

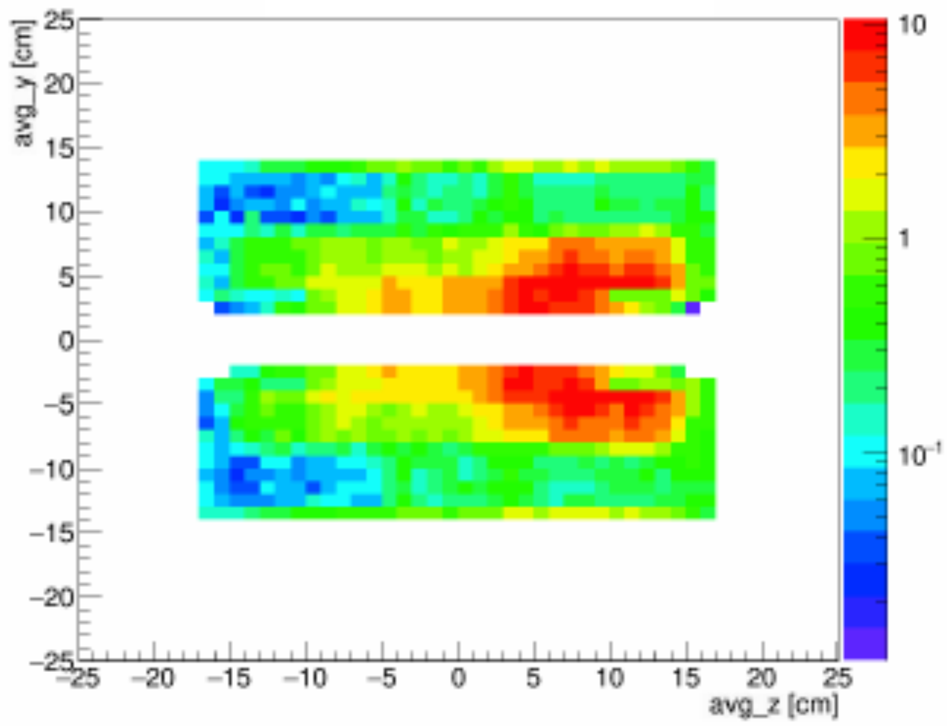
Based on drawings and measurements





Simulation contain SS former, LHe, vessels, target cell, target material

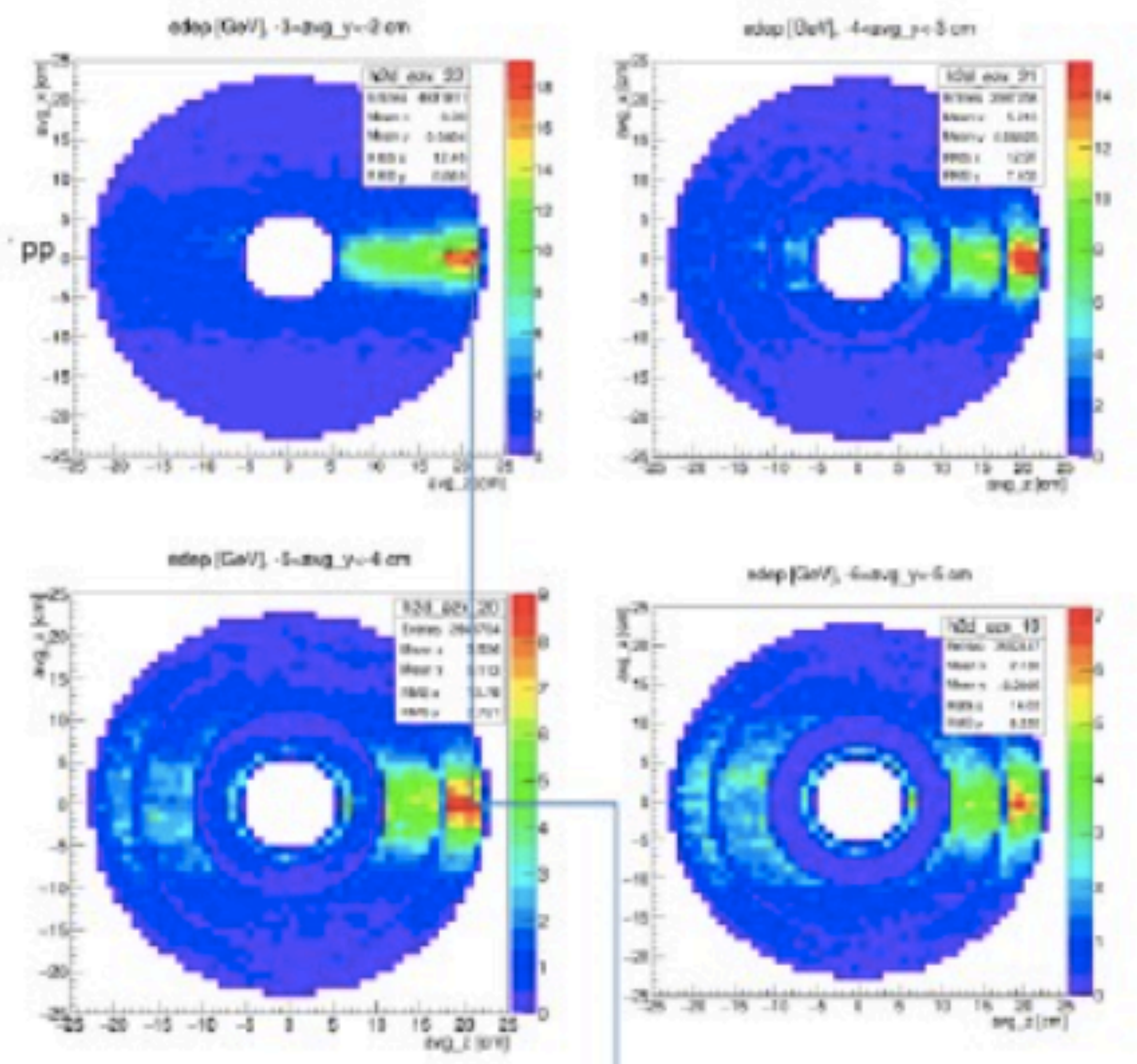




Then look at energy deposition in the SC coils

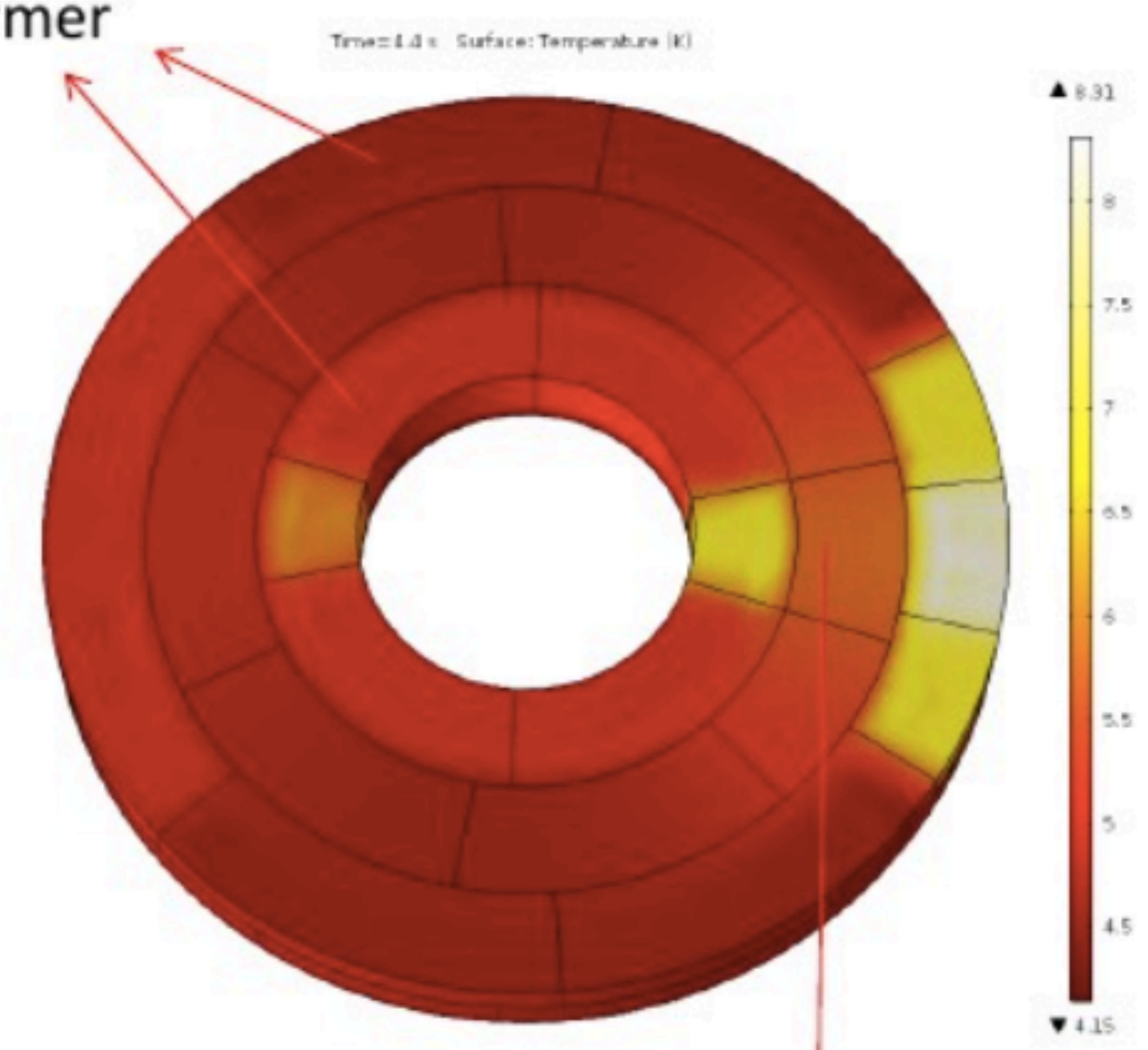
Quench Simulations

What we have currently



Maximum hot spot
around 18000 W/m^3

Former

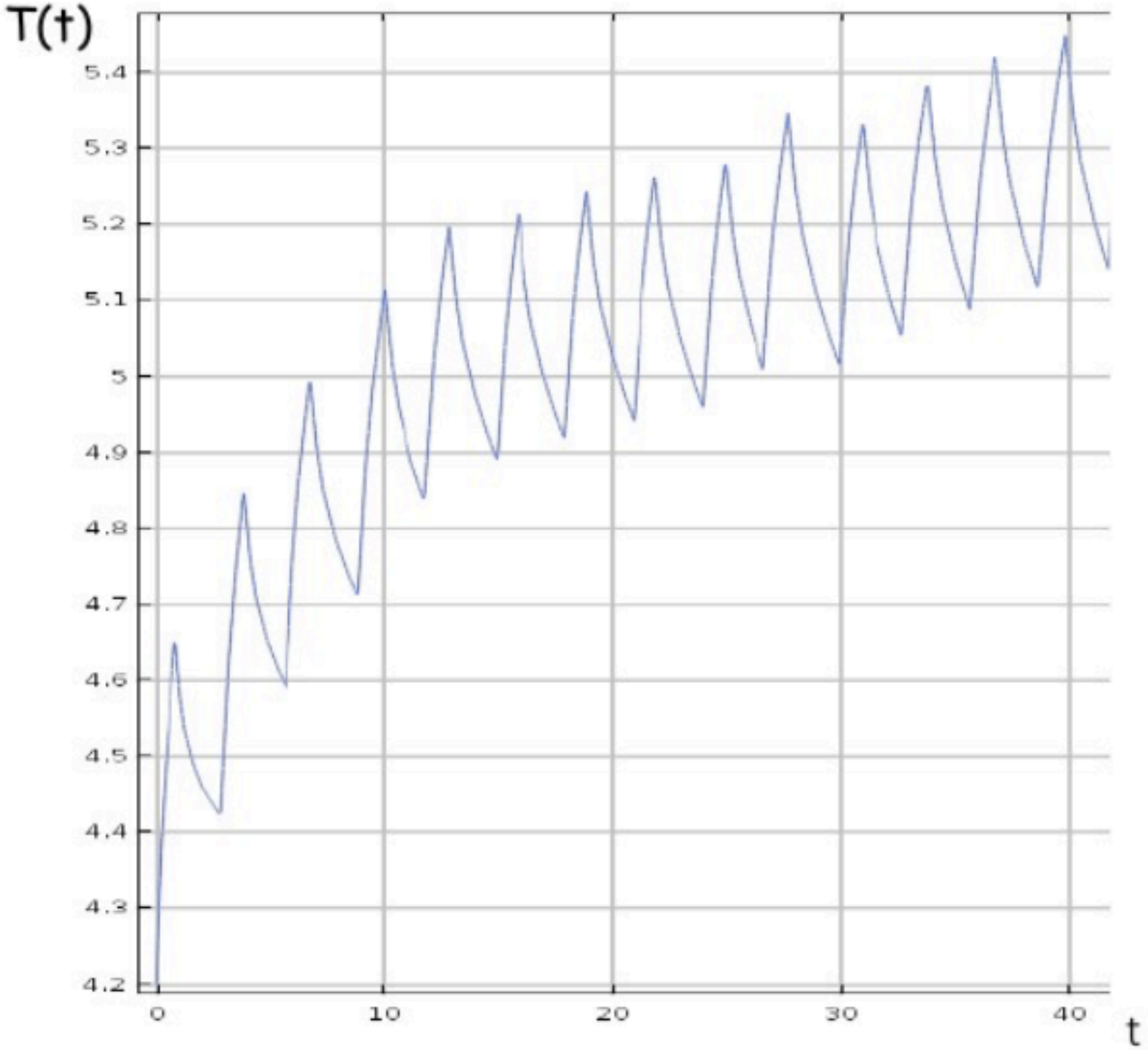


Simulation result

Maximum temperature of
coil around 5.7 K

Results on BNL experiment

The maximum temperature of the coil as a function of time



Maximum Temperature profile Tmax(t) for BNL:

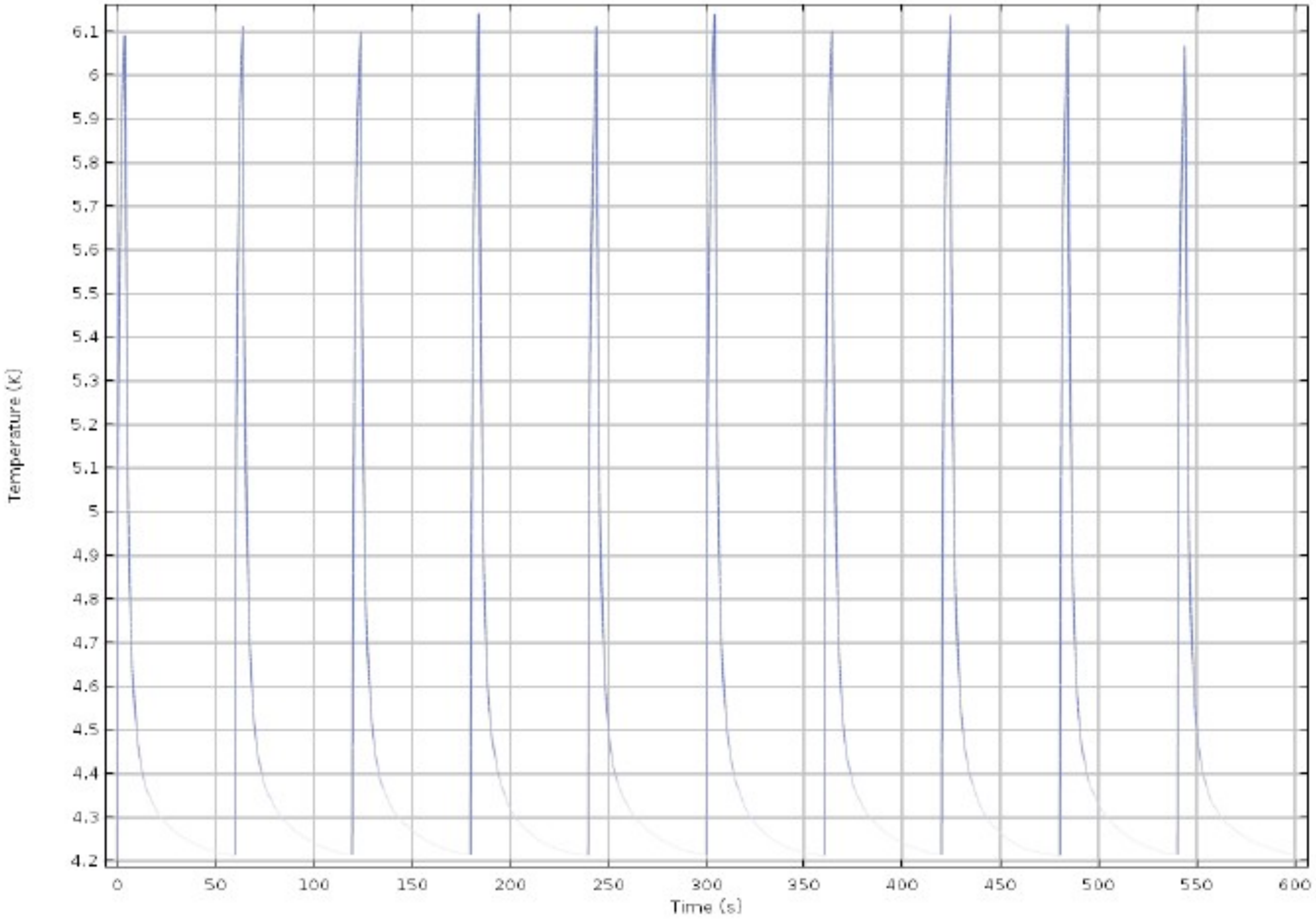
- 24 GeV proton
- 2e11 proton/s
- Teflon Target

Notes:

- The BNL magnet was quenched in this setup (Teflon target & 2e11 proton/s)
- The simulation results “indicate” quench -> The heat is accumulated over time
- There is an issue about numerical convergence issue for longer run that need to be fixed -> require extremely fine Mesh and time step

SpinQuest Target Magnet

The maximum temperature of the coil as a function of time



Maximum Temperature profile Tmax(t) for E1039:

- 120 GeV proton
- 1e12 proton/s
- NH3 Target

Conclusion: It is save to run at 1e12 proton/s but I recommend this intensity to be considered as the upper limit

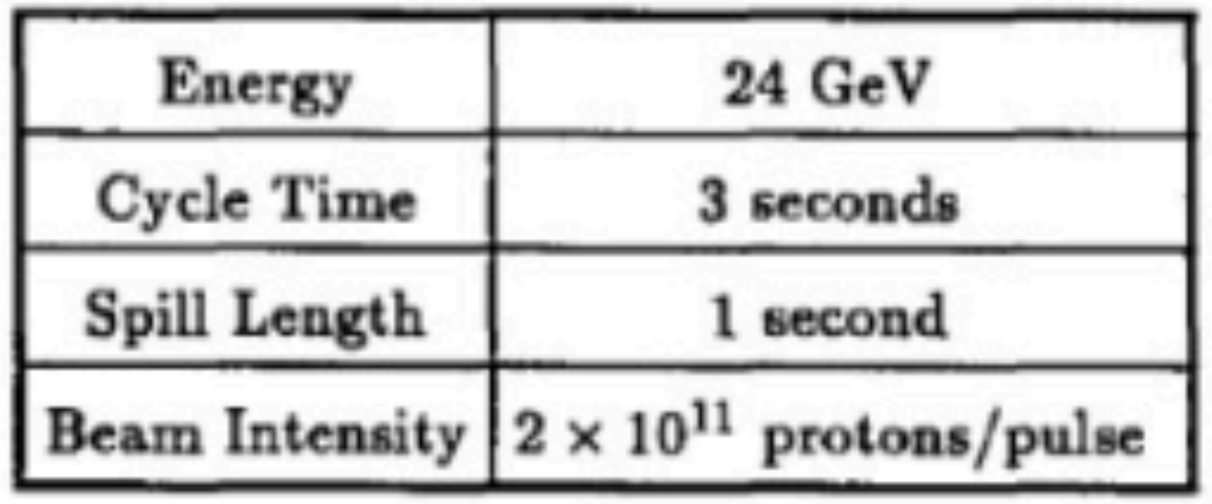
Superconducting Magnet Quest Studies

SpinQuest

- Cycle Time: Every 55.6 seconds
- Spill Length: 4.4 seconds
- Beam Intensity: $1.0\text{X}10^{12}$ protons/sec

vs

BNL:



Energy	24 GeV
Cycle Time	3 seconds
Spill Length	1 second
Beam Intensity	2×10^{11} protons/pulse

Limiting Factors: - Fridge Cooling Power

- Heat load to SC Magnet
- Cycle Time

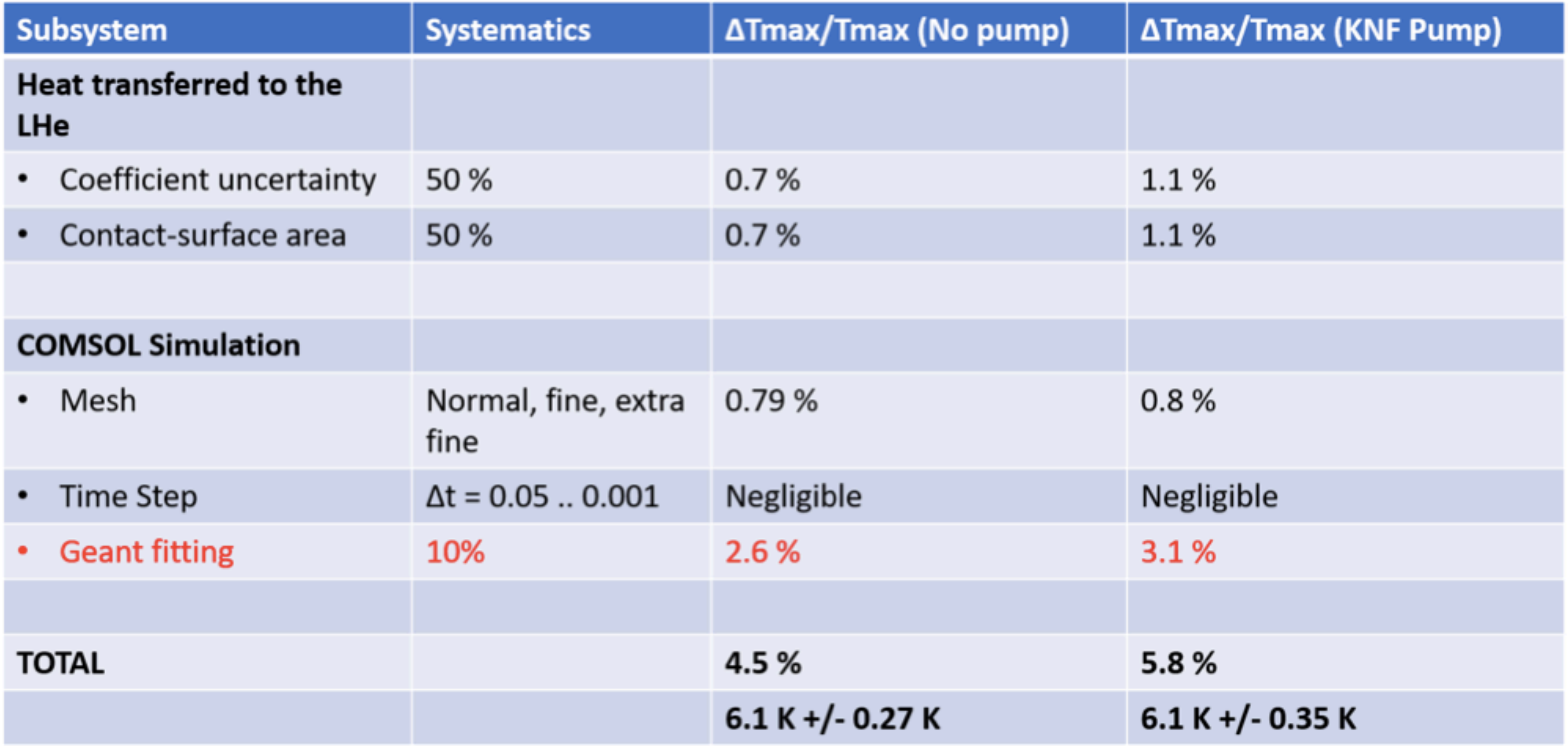
BNL : $4.0\text{X}10^{12}$ protons/min - 4 cm

FNAL : $5\text{-}4.4\text{X}10^{12}$ protons/min - 8 cm

Highest Cooling Power DNP Evaporation System:

- Running at 20 SLPM have 1.4 W of cooling power
  - For 4.4 sec receive 0.4 W of heat load from protons
  - Continuous DNP microwave heat load 0.65 W
- Super conducting magnet critical temperature 7.5 K @ 5T
- Cycle gives time to cool

Systematic Uncertainties



Subsystem	Systematics	ΔTmax/Tmax (No pump)	ΔTmax/Tmax (KNF Pump)
Heat transferred to the LHe			
- Coefficient uncertainty	50 %	0.7 %	1.1 %
- Contact-surface area	50 %	0.7 %	1.1 %
COMSOL Simulation			
- Mesh	Normal, fine, extra fine	0.79 %	0.8 %
- Time Step	Δt = 0.05 .. 0.001	Negligible	Negligible
- Geant fitting	10%	2.6 %	3.1 %
TOTAL		**4.5 %**	**5.8 %**
		6.1 K +/- 0.27 K	**6.1 K +/- 0.35 K**

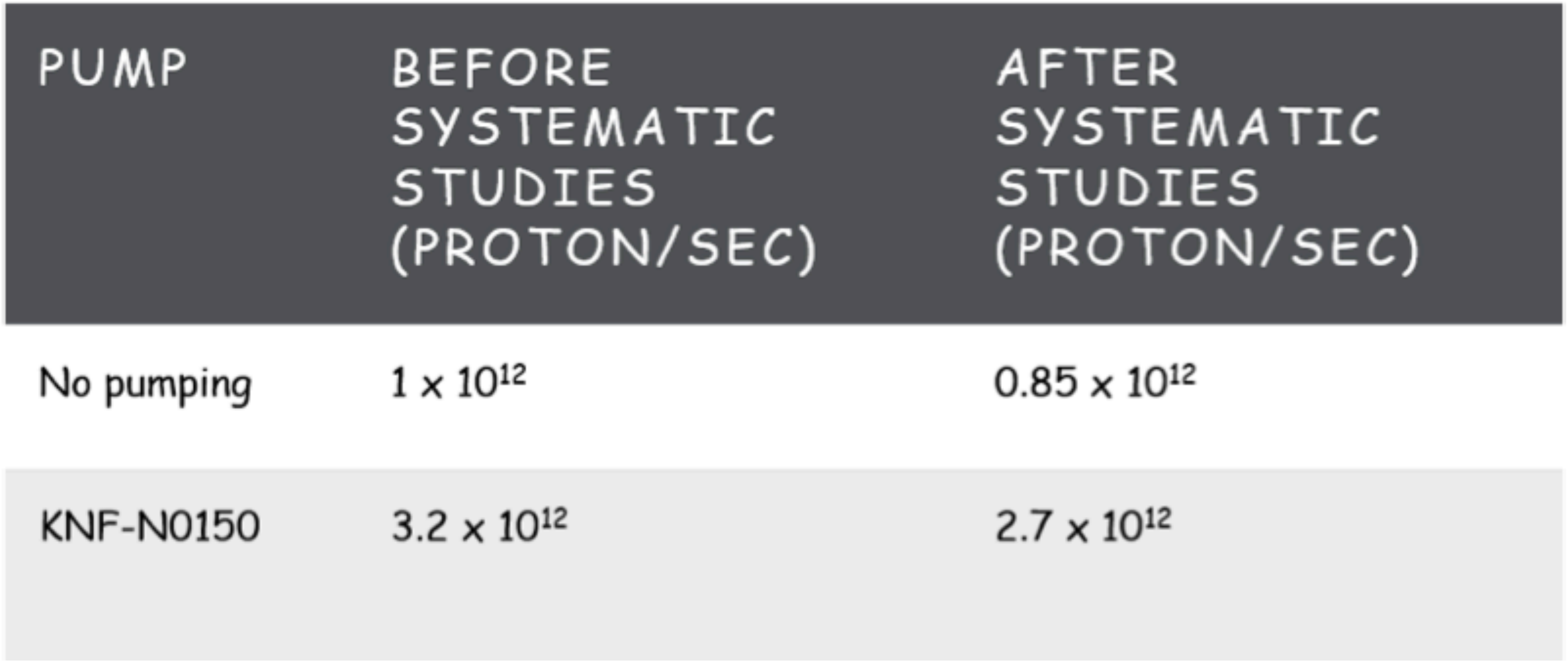
External Magnet Temp Sensor

Type-T Thermocouples Cu-CuNi

Estimated Quench Threshold

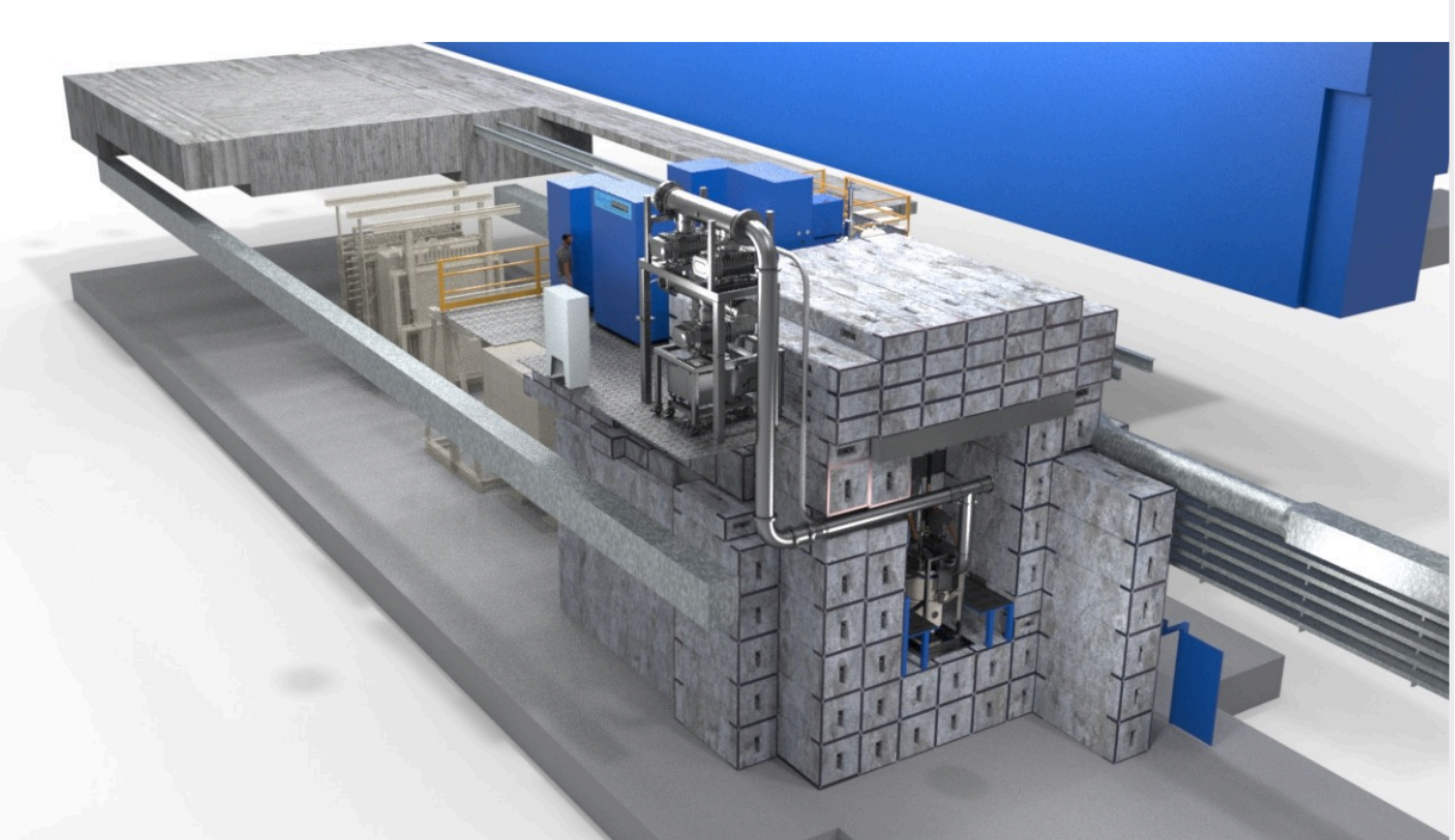
Based on a series of MC systematics studies

- Assume no other intensity constraints
- Assume unlimited LHe

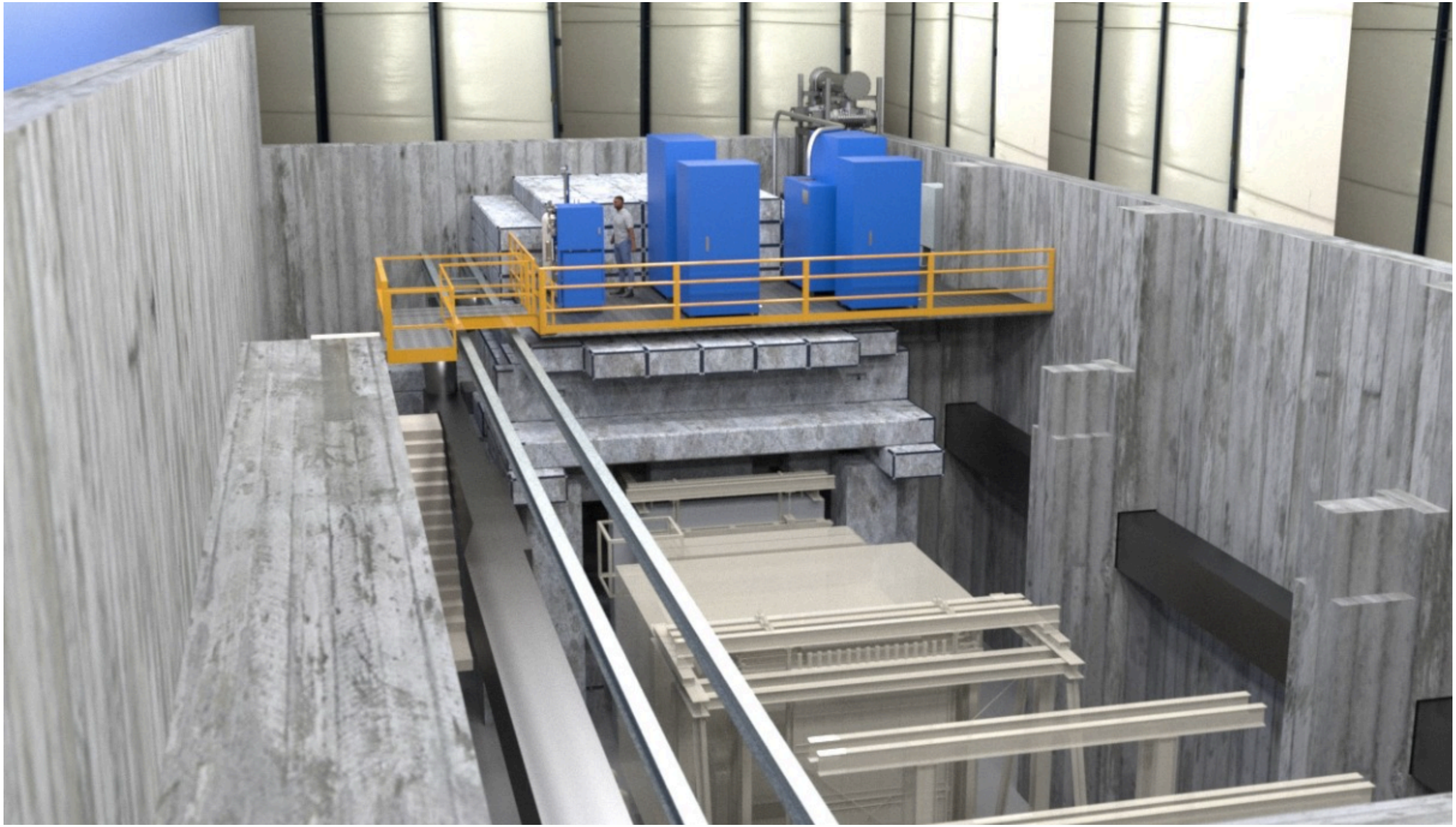


PUMP	BEFORE SYSTEMATIC STUDIES (PROTON/SEC)	AFTER SYSTEMATIC STUDIES (PROTON/SEC)
No pumping	1×10^{12}	0.85×10^{12}
KNF-N0150	3.2×10^{12}	2.7×10^{12}

SpinQuest Experimental Hall



NM4 Experimental Hall

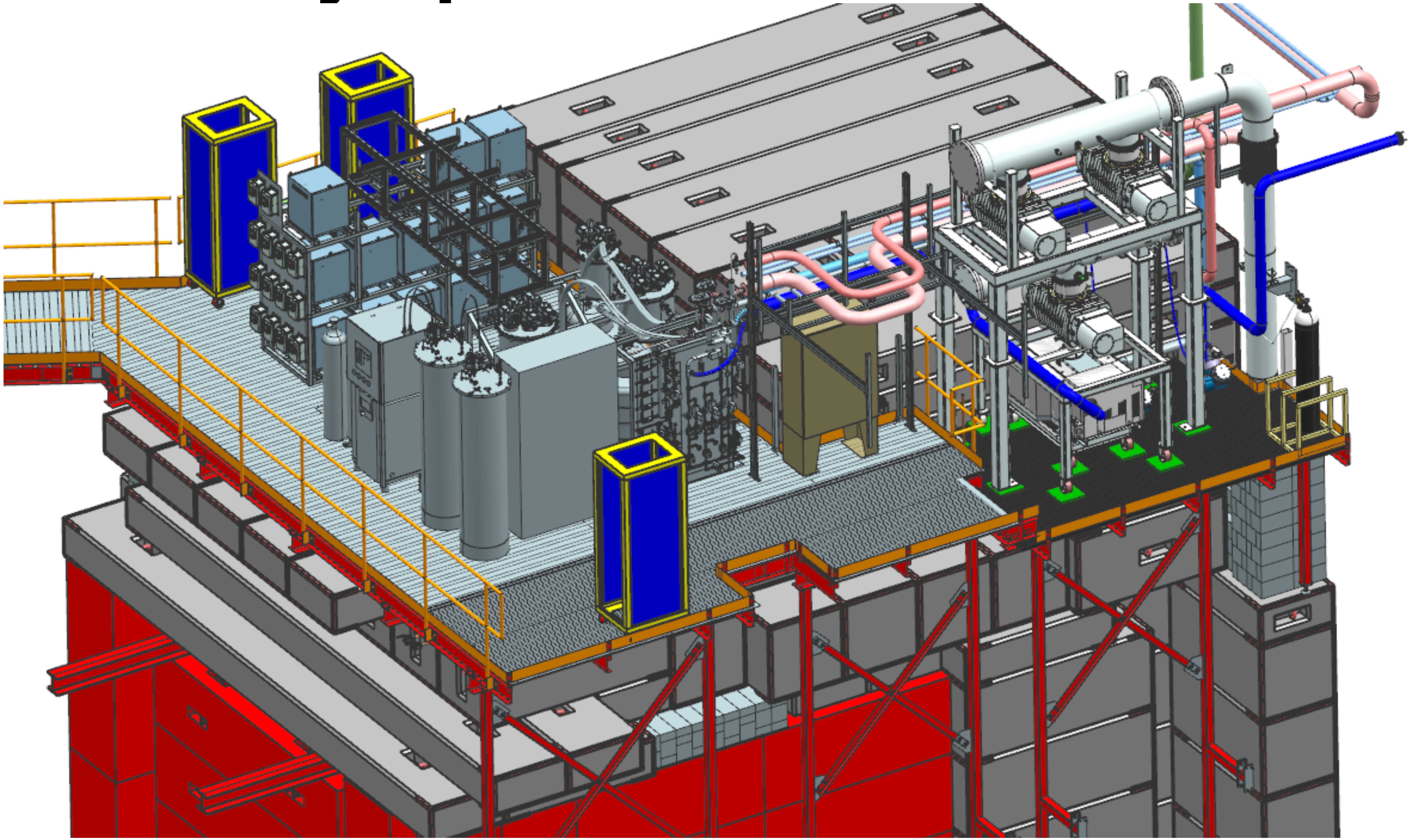


Cryo-platform

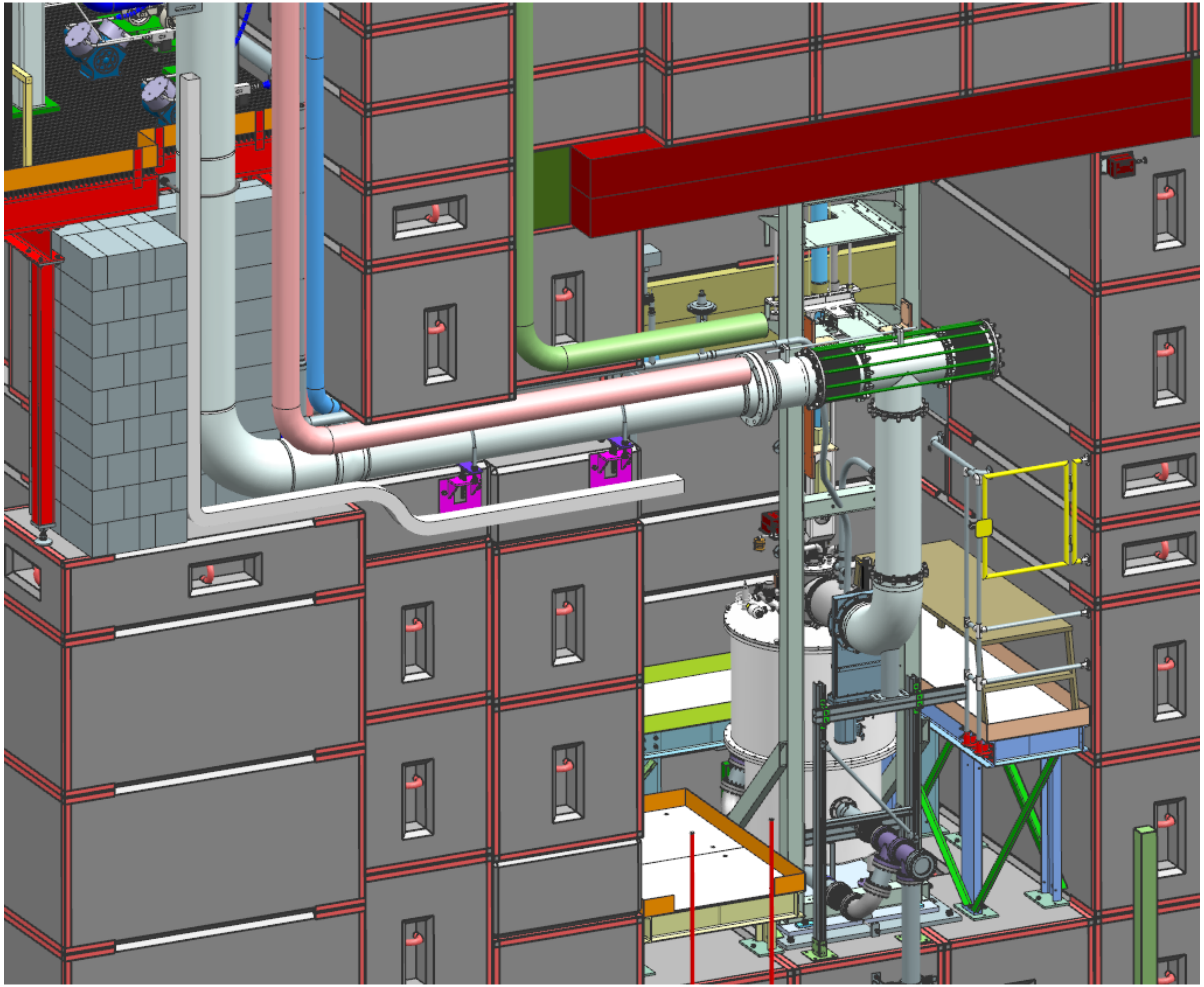
Top of Target Cave

Target Cave and Cryo-platform

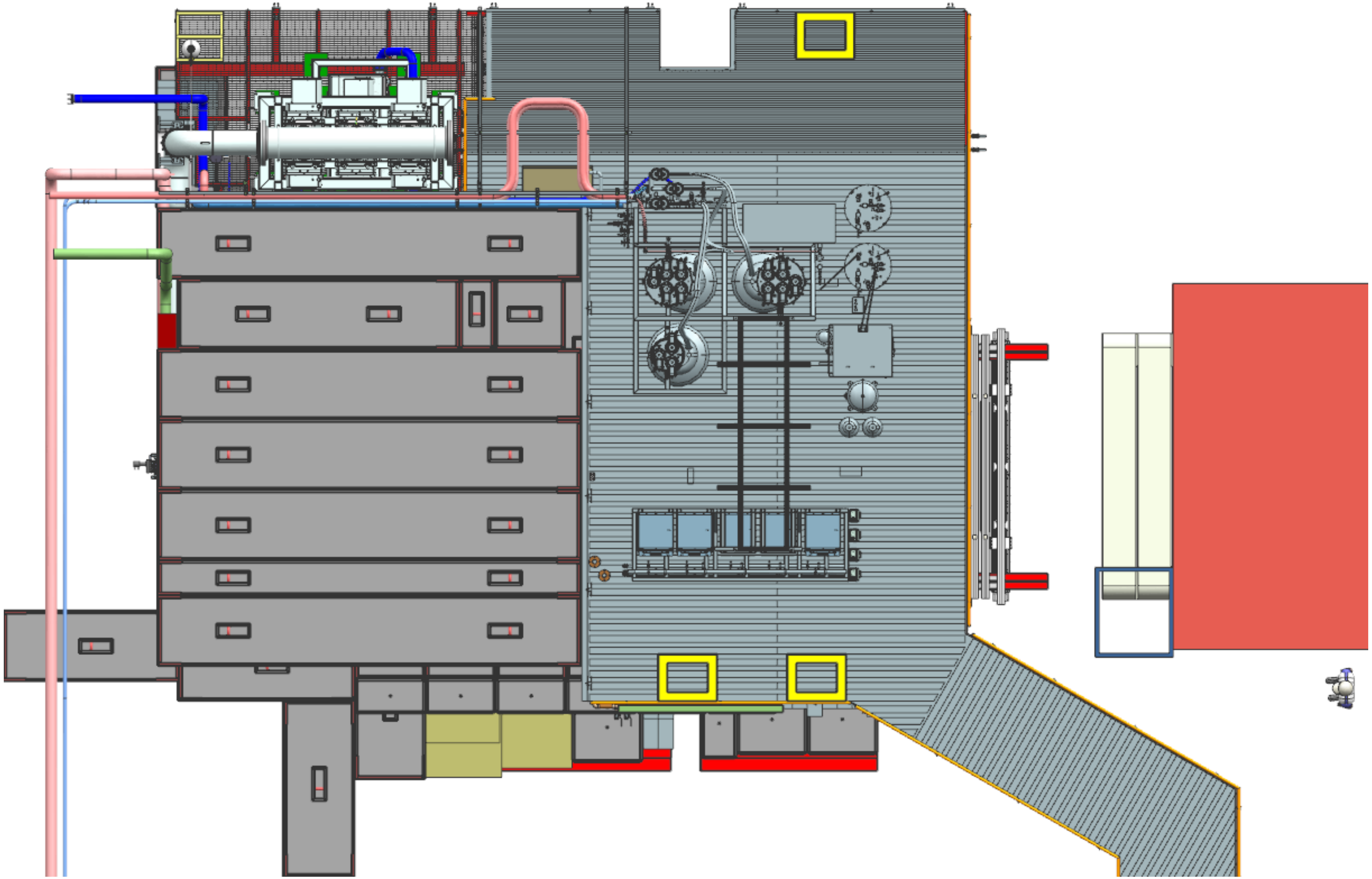
New Cryo-platform



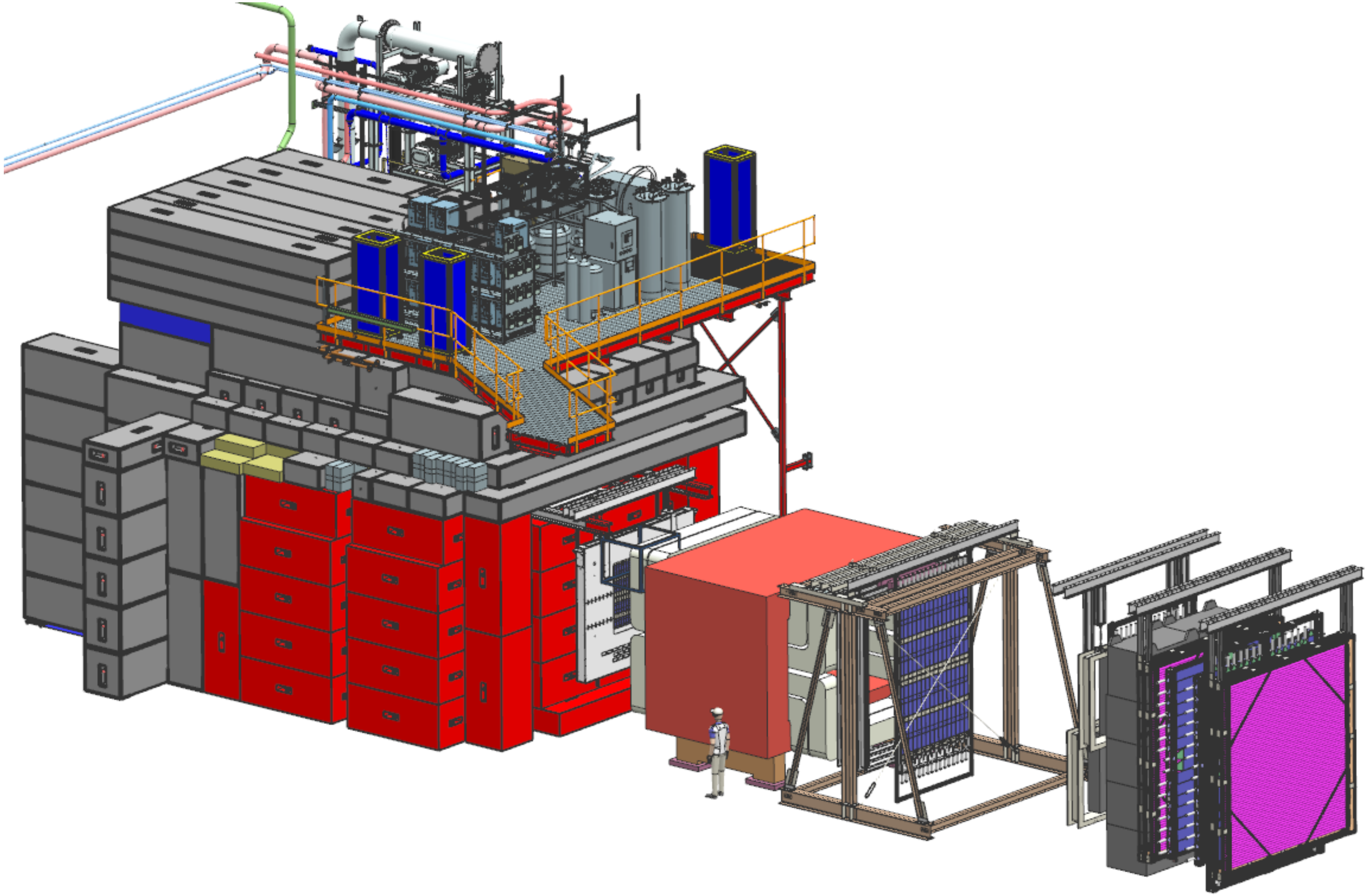
Target Alcove



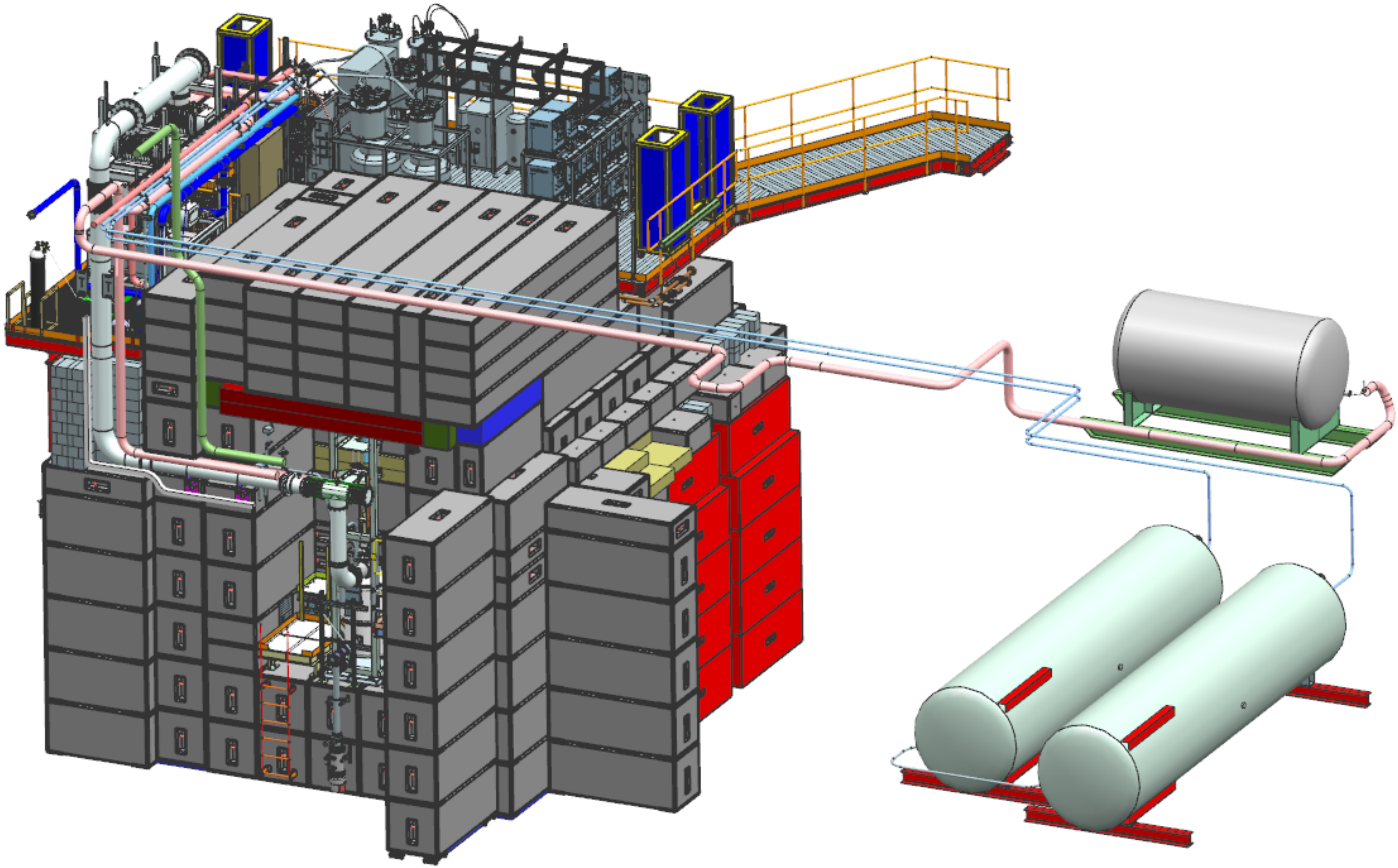
Overhead view of Cryo-platform



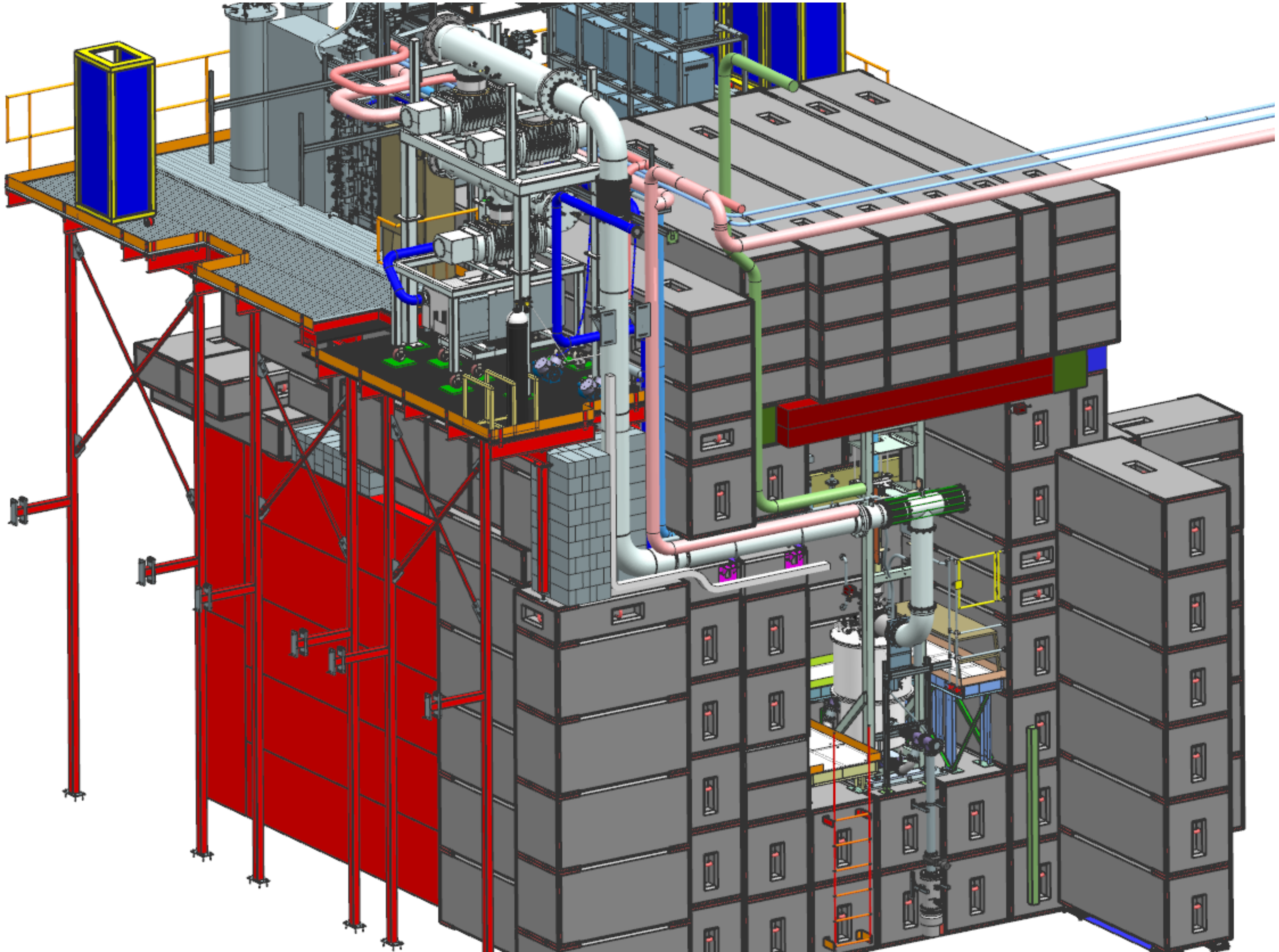
Full Detector and Target



Helium and Nitrogen Supplies

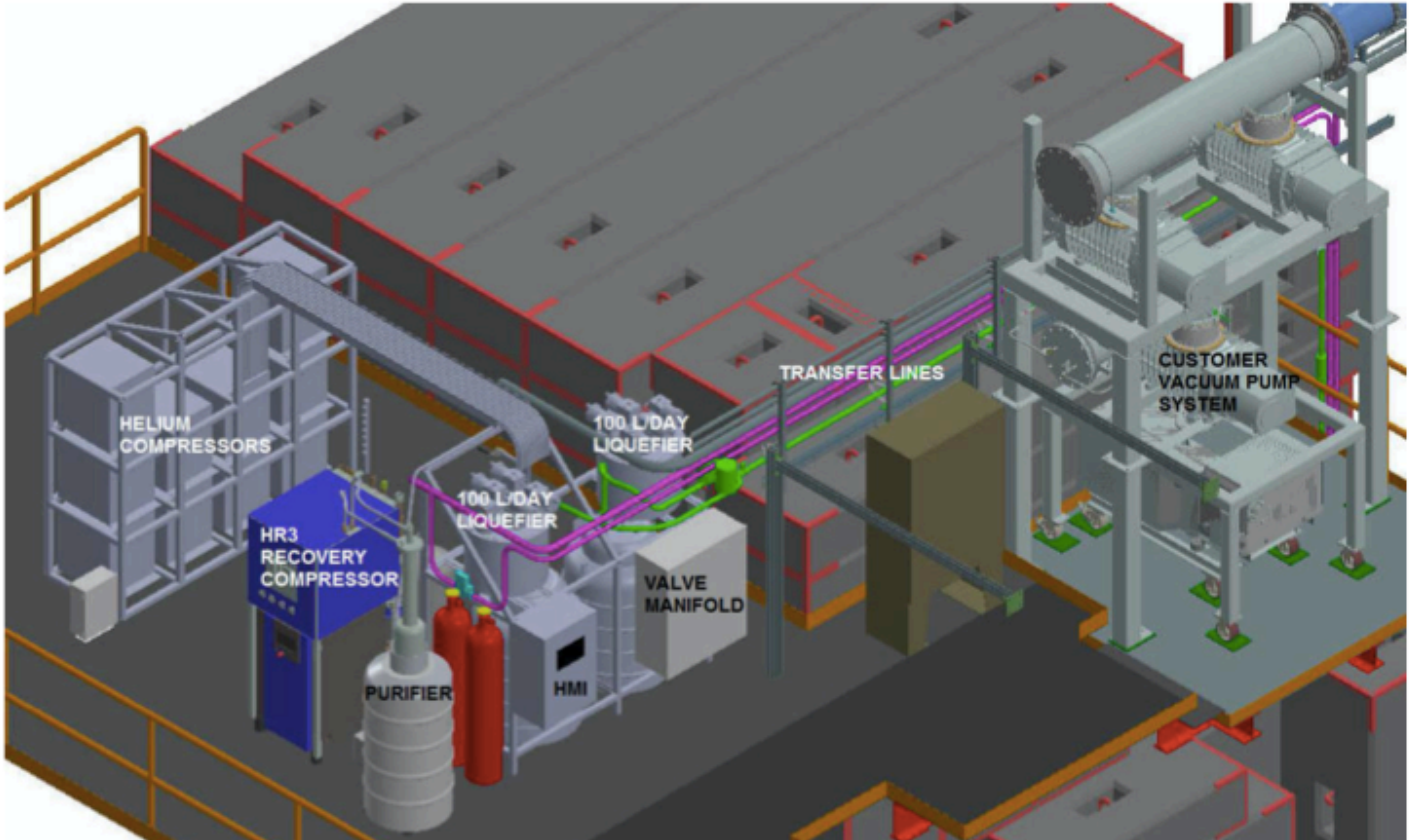


West View of Target Cave



QT Liquefier

Set of components



Quantum Technology Corp Liquefier

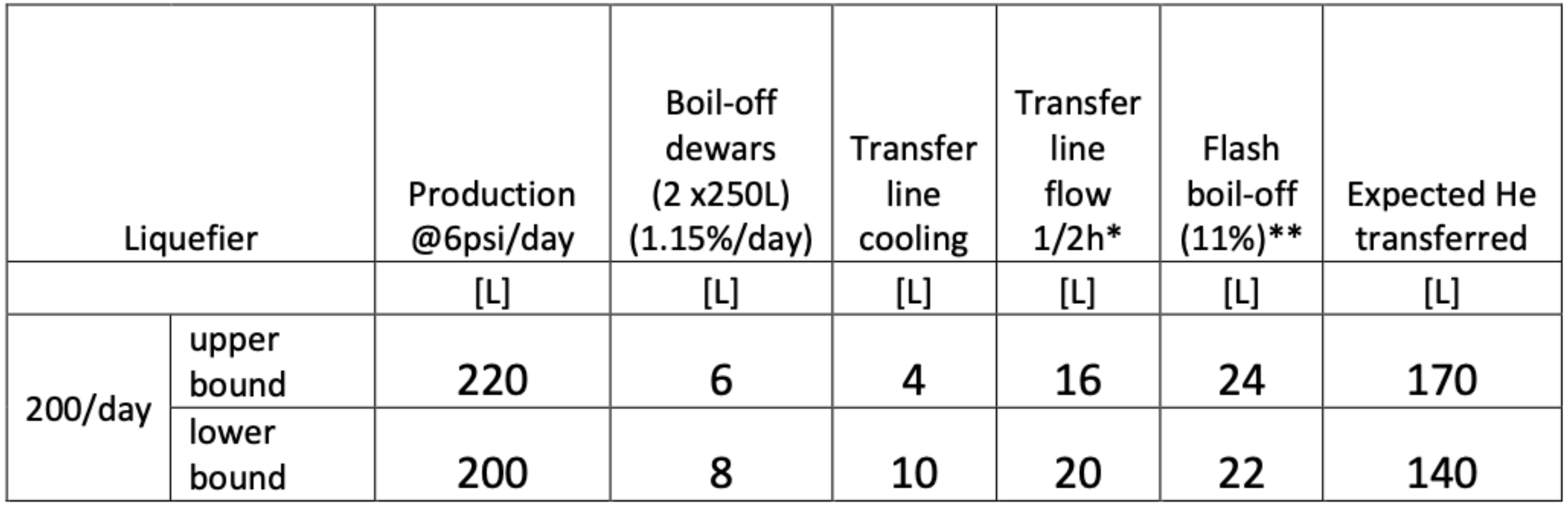
A DOE-UVA Purchase for SpinQuest

Model QDHRR100 Helium liquefier **2 units, for a total of 200 LPD**

Liquefaction Rate: 100 liters/day
Dewar Capacity: 250 Liters
Compressor Package Model (five units): QDC6000V (Available water cooled only)
Compressor Package Weight: 1320 LB
Power Consumption: 37.5 kW 3 Phase 480V / 60Hz
Cooling Water: Minimum flow 9.5 GPM @ 80ºF
Ambient Temperature Range: 45ºF to 100ºF (7 to 38ºC)
Gaseous helium requirement: Purity 99.99%

- Quntumpure Purifier
- Helium Gas Purity Meter
- Custom liquid helium transfer line
- Custom liquefier and liquid helium transfer system

Liquefier System



Liquefier		Production @6psi/day	Boil-off dewars (2 x250L) (1.15%/day)	Transfer line cooling	Transfer line flow 1/2h*	Flash boil-off (11%)**	Expected He transferred
		[L]	[L]	[L]	[L]	[L]	[L]
200/day	upper bound	220	6	4	16	24	170
	lower bound	200	8	10	20	22	140

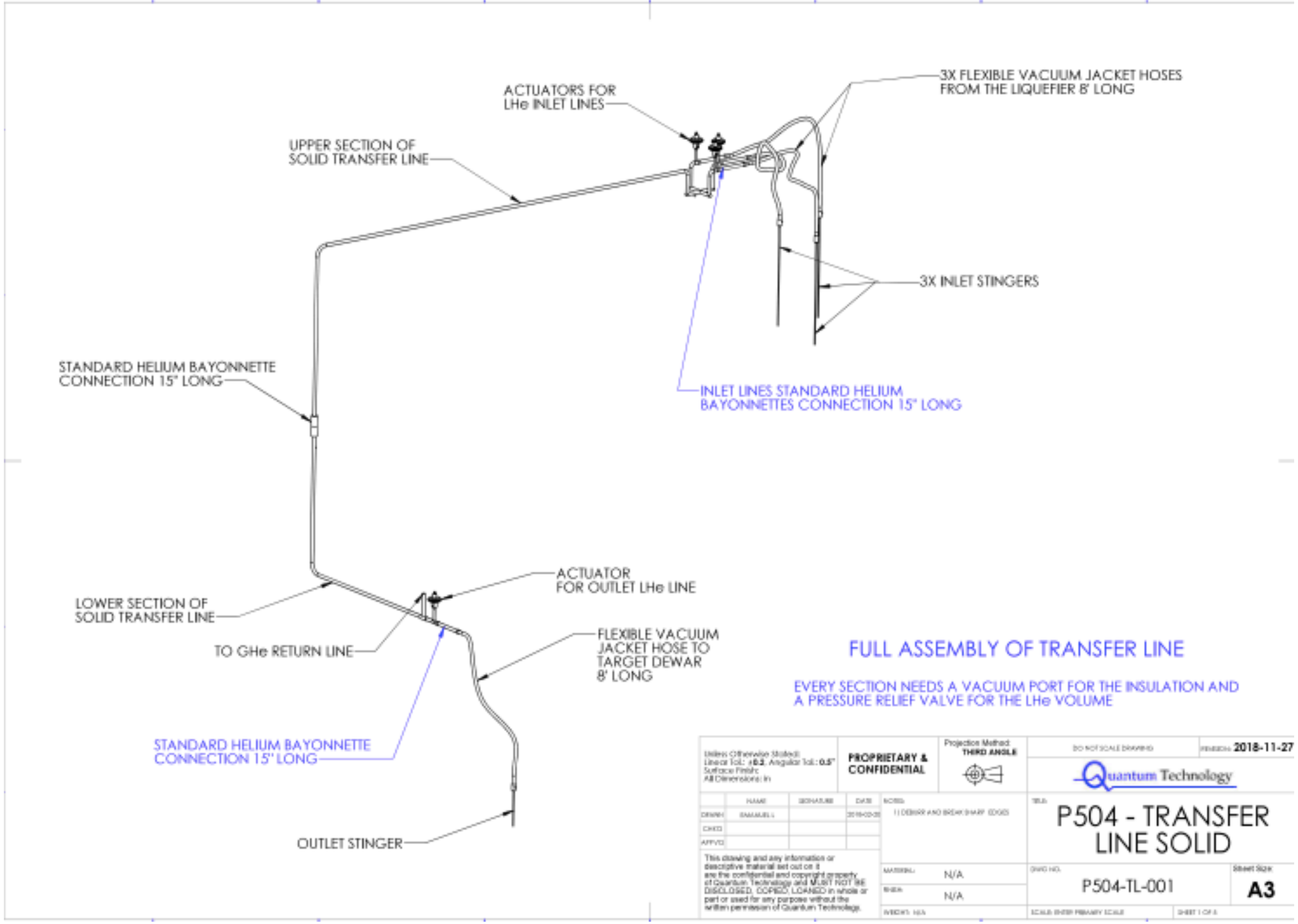
- Requested 135 L/day at the target magnet (67% efficient when transferring over 60 min.)
- Based on studies at UVA this is more than sufficient for continuous running with no beam
- Additional pumping on the magnet will likely be required to run at the beam intensity of interest
- Less efficiency is expected due to safety modification of system, magnet and fridge
- These numbers are very much dependent on the efficiency of the transfer line meeting expectation

Liquid Helium Transfer

QT Transfer to the target

- Initial Cooldown 100% boil-off at 1700 slpm
- QT recovery compressor can handle 1500 slpm
- Loss of 200 slpm
- Using rigid non-LN2 shielded (just vacuum) with flexible ends
- Initial fill at 80K requires at least the full 500L of stored LHe
- Refill ~135L (200L) should be delivered over 60 minutes
- Can only store 2X250 at a time

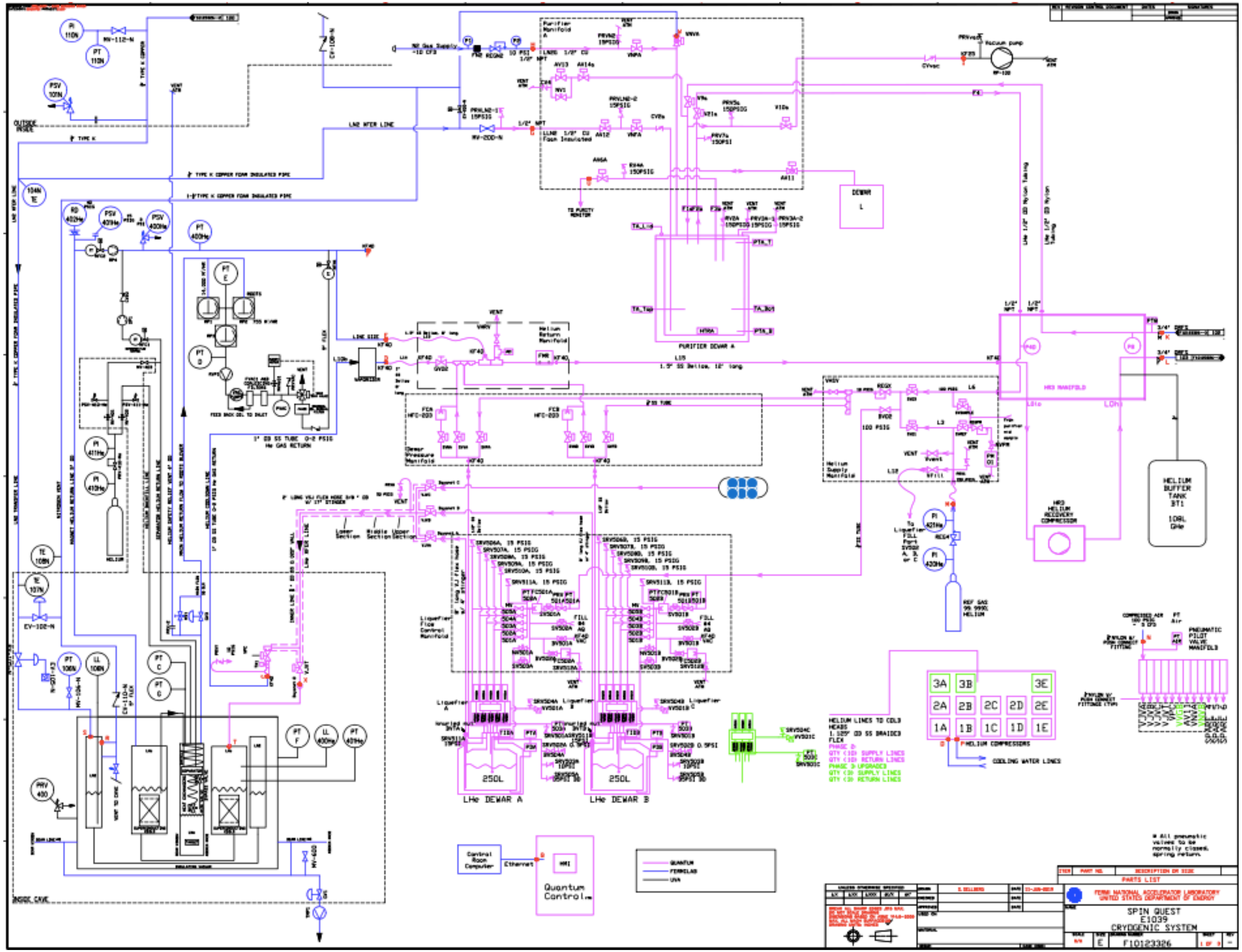
QT Transfer Line into Cave

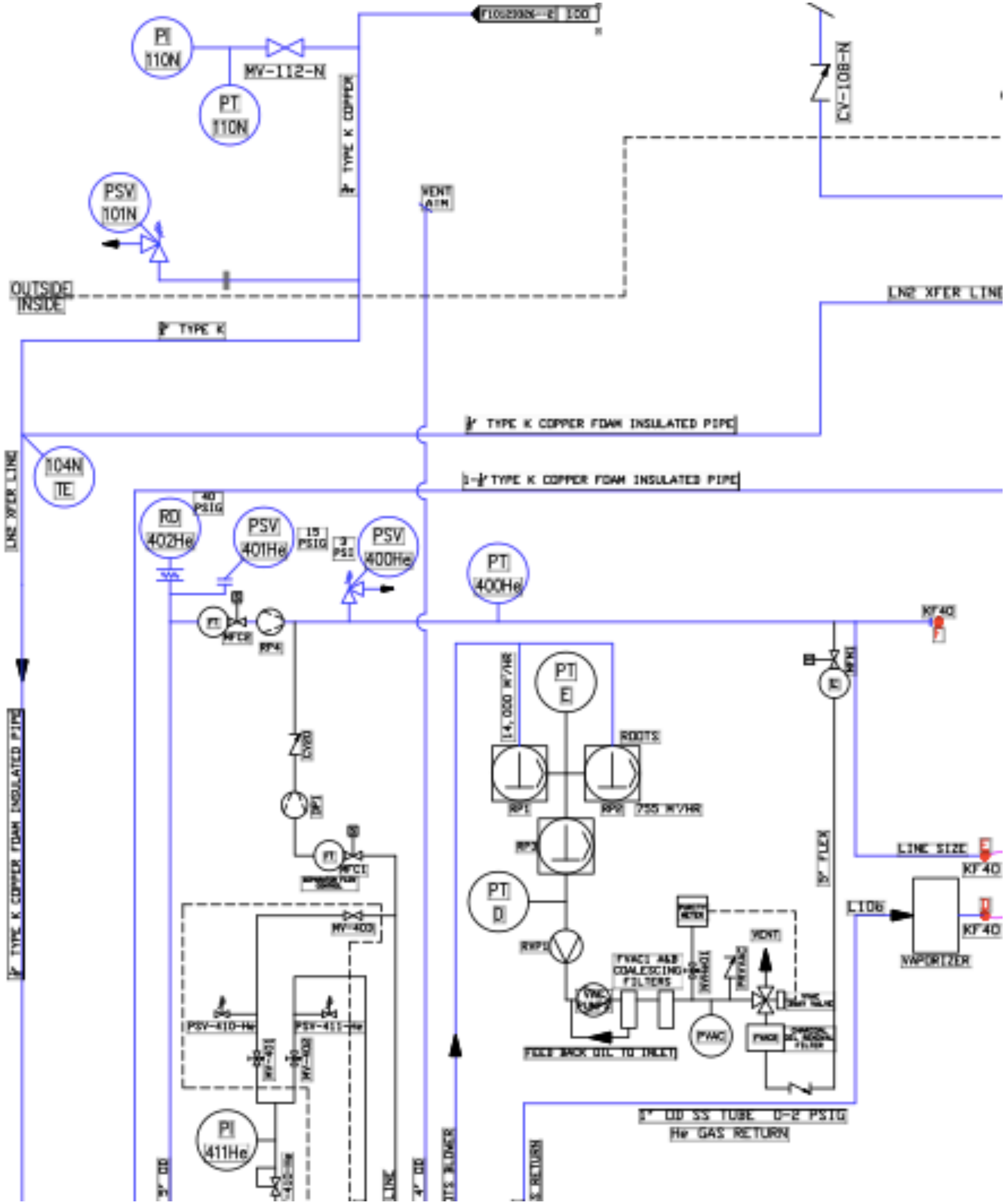


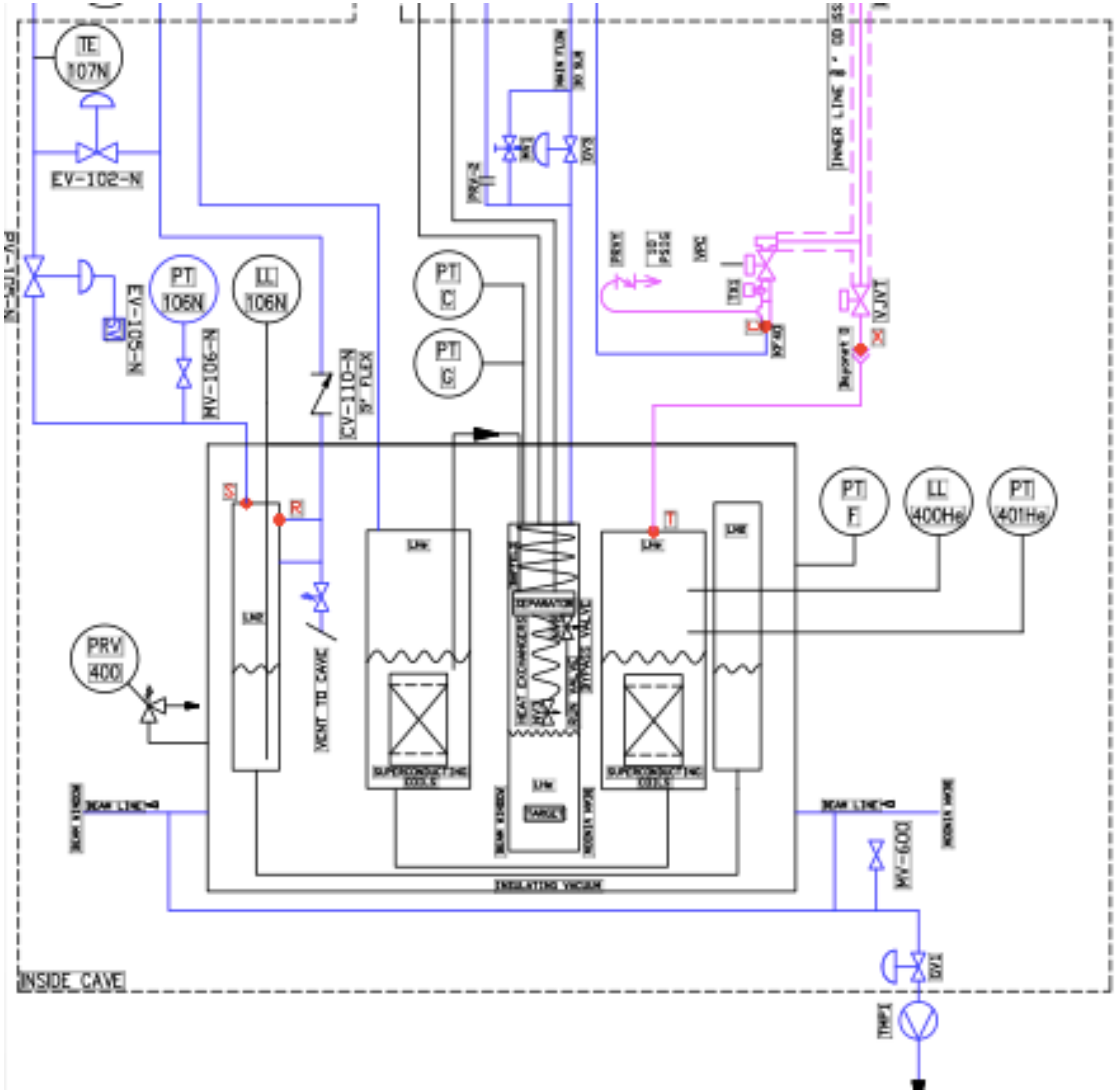
Target Magnet Pumping

Intensity vs Helium budget

Intensity	$3 \times 10^{12} p/s$	$10 \times 10^{12} p/s$
Daily Consumption	135 l/day	175 l/day
Additional Daily Requirements	0 l	40 l/day
250L	0	5 days


Purifier Manifold A
N2 Gas Supply ~10 CFS
LN2 WTER LINE
OUTSIDE
INSIDE
Vacuum pump
DEWAR L
PURIFIER DEWAR A
Helium Return Manifold
VAPORIZER
L15
1.5" SS Bellow, 12" long
HRS MANIFOLD
Helium Supply Manifold
Dewar Pressure Manifold
Liquefier Flow Control Manifold
HELIUM BUFFER TANK BT1
HRS HELIUM RECOVERY COMPRESSOR
REF GAS 99.999% HELIUM
250L
LHe DEWAR A
250L
LHe DEWAR B
HELIUM LINES TO COLD HEADS
1.125" OD SS BRAIDED FLEX
PHASE 2:
QTY (10) SUPPLY LINES
QTY (10) RETURN LINES
PHASE 3 UPGRADES
QTY (3) SUPPLY LINES
QTY (3) RETURN LINES
3A
3B
3E
2A
2B
2C
2D
2E
1A
1B
1C
1D
1E
HELIUM COMPRESSORS
COOLING WATER LINES
PNEUMATIC PILOT VALVE MANIFOLD
Control Room Computer
Ethernet
HMI
Quantum Controls
QUANTUM
FERMILAB
UVA
INSIDE CAVE
* All pneumatic valves to be normally closed, spring return.
PARTS LIST
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
SPIN QUEST
E1039
CRYOGENIC SYSTEM
E
F10123326


PI
110N
PT
110N
MV-112-N
TYPE K COPPER
100
PSV
101N
VENT
ATM
CV-108-N
OUTSIDE
INSIDE
TYPE K
LN2 XFER LINE
TYPE K COPPER FOAM INSULATED PIPE
1-TYPE K COPPER FOAM INSULATED PIPE
104N
TE
LN2 XFER LINE
TYPE K COPPER FOAM INSULATED PIPE
RD
402He
40
PSIG
PSV
401He
15
PSIG
3
PSI
PSV
400He
PT
400He
PT
MFC2
RP4
KF40
F
14,000 M³/HR
PT
E
ROOTS
RP1
RP2
755 M³/HR
RP3
PT
D
MFC1
MV-403
PSV-410-He
PSV-411-He
PI
411He
RWP1
FVAC1 A&B
COALESCING
FILTERS
VENT
FVAC
LINE SIZE
E
KF40
L106
D
KF40
VAPORIZER
5" FLEX
FEED BACK OIL TO INLET
5" OD SS TUBE 0-2 PSIG
He GAS RETURN
4" OD
LINE
BLOWER
RETURN


TE 107N
EV-102-N
PV-1?5-N
EV-105-N
PT 106N
MV-106-N
LL 106N
CV-110-N
5' FLEX
PT C
PT G
PRV-2
INNER LINE
VJVT
X
S
R
T
LHe
LN2
VENT TO CAVE
HEAT EXCHANGER
SEPARATOR
BYPASS VALVE
SUPERCONDUCTING COILS
TARGET
BEAM WINDOW
BEAM LINE
INSULATING VACUUM
PRV 400
PT F
LL 400He
PT 401He
MV-600
TMP1
INSIDE CAVE

Cryosystem status

- **Target**
  - *Roots pump*: Electrical work likely complete
    LCW setup near complete
    Leak check complete
    ORC writeup in process

  - *Target Slow Controls*: LabView Meeting- Organize subsystem, Readout/control, NMR system, Microwave, Actuator, cryocontrols
    Electronics\interlocks- separate effort to come

  - *Target Magnet:* In place
    Final survey is week after next
    Vacuum piping to come
    Access walkway to come
    Electrical through West penetration to come

  - Refrigerator : Preparing system for safety modifications
    Back to UVA for machining
    Install hopefully around late Oct

  - *QT Liquefier*: Everything in place
    Several system connections still required
    Helium + Nitrogen lines must be in place (FNAL+UVA)
    Can not yet arrange for QT visit (COVID-19)

Target Team

UVA Spin Physics and Polarized Target Group

- Team Leader
- Research Scientist (hiring in process)
- 2 postdocs
- Slow Controls
- 1 Target Technician (hiring in process)
- 3 grad students
- undergrads

Challenges

Past and Present

- No full-time cryo-engineer to help prepare for FNAL cryosafety review
- Major infrastructure additions/modification to meet safety standards
- Additional modifications driven by safety still in process
- FNAL Cryo-engineers can not guarantee a pass (at any price)
- Training target experts requires a running target