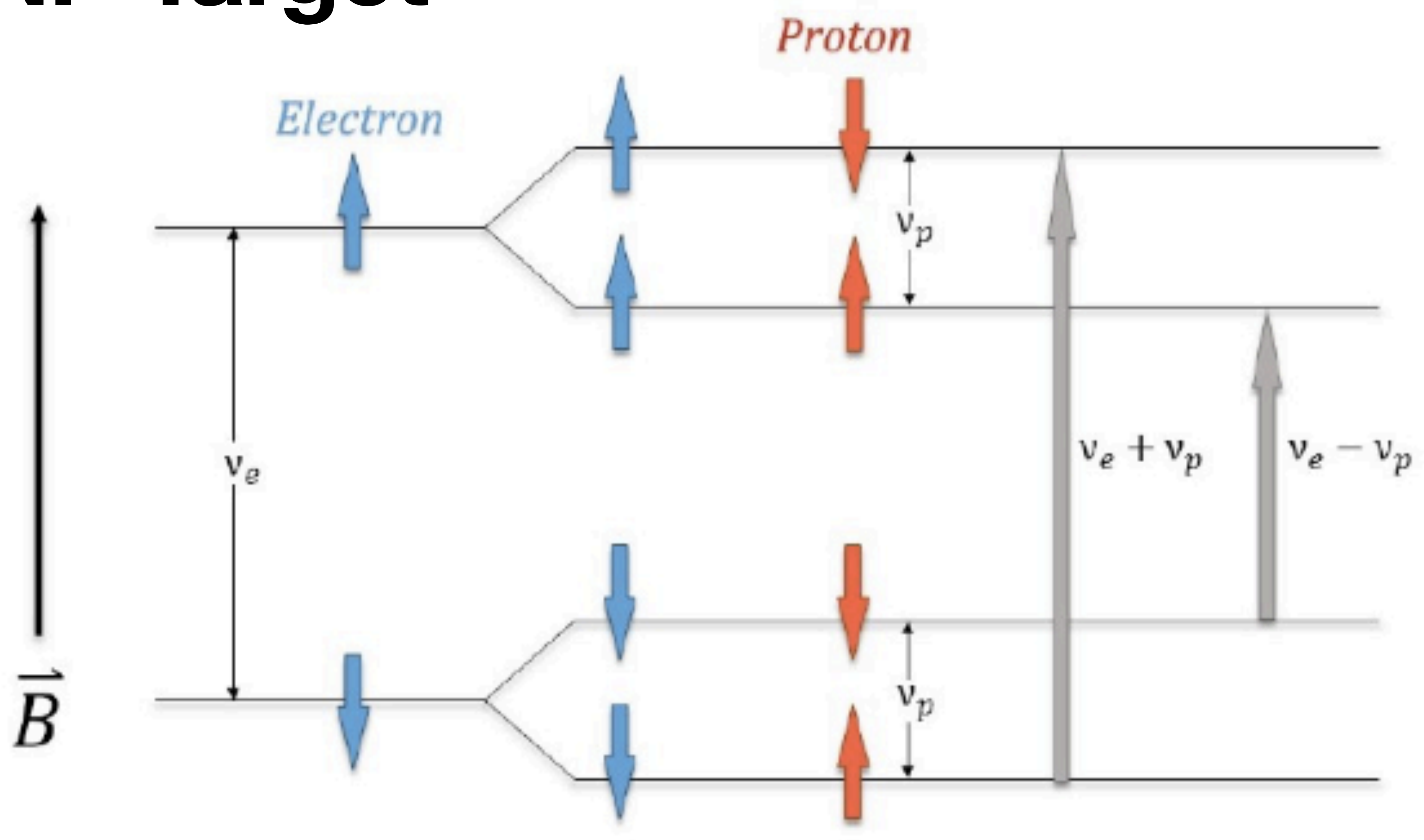
SpinQuest Target Overview

E1039 Polarized target system and cryogenics

D. Keller

DNP Target



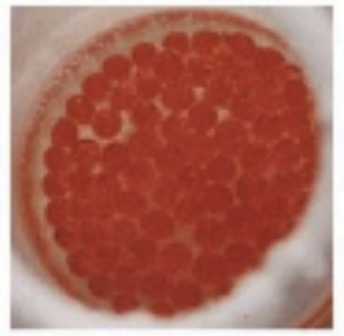
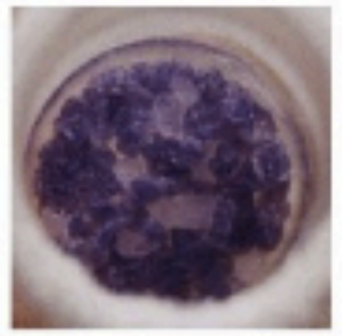
e-relaxation time: ~ms
p-relaxation time: ~10 mins

- 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)

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

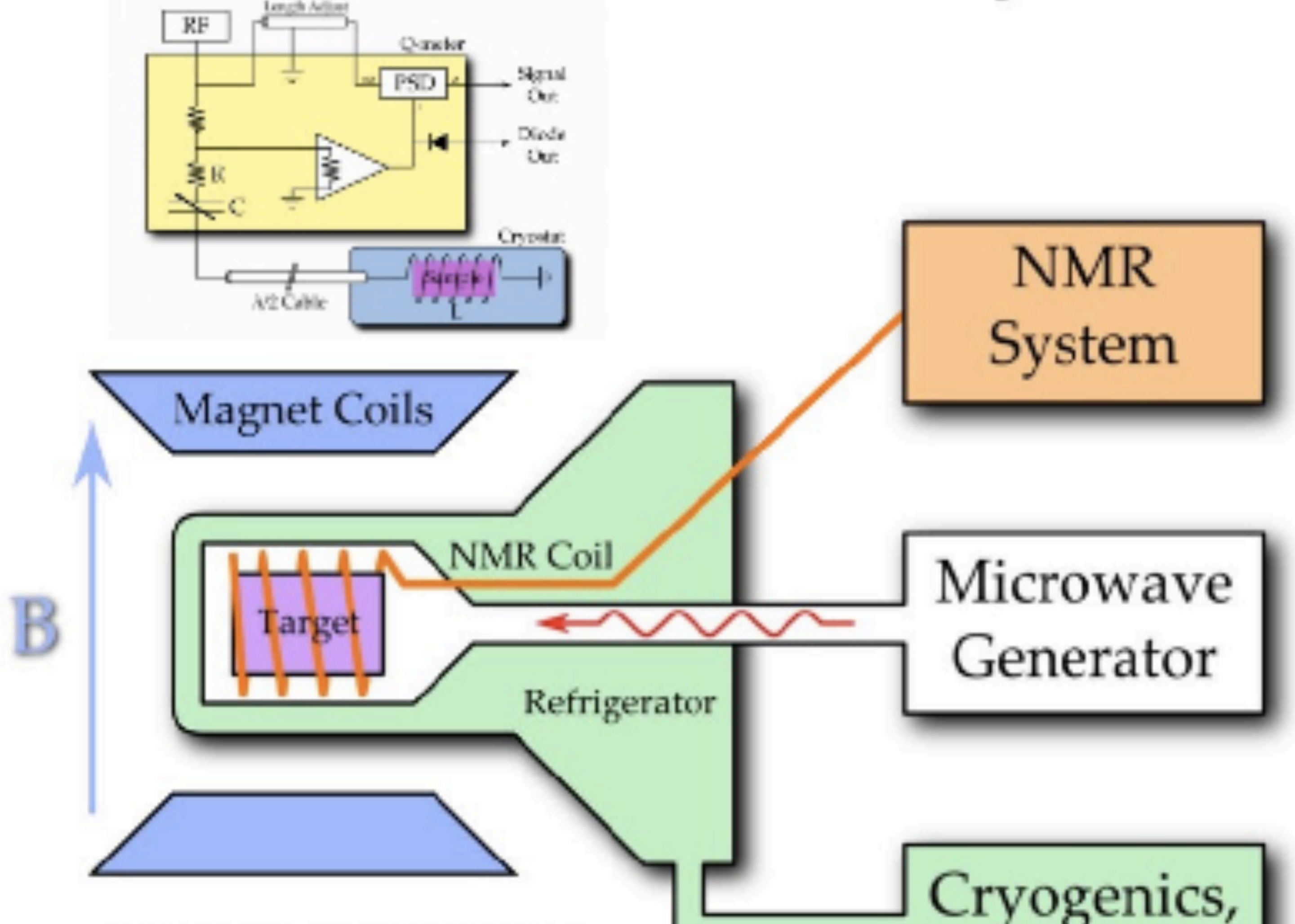
Successful material for DNP characterized by three measures:

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


Material	Butanol	Ammonia, NH_3	Lithium Hydride, ^7LiH
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, ^6LiH
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*

General System



Polarization Detection

Tuned To Larmor of spin species

Proton (42.6 MHz/T)

Larmor-ESR

50-185 GHz

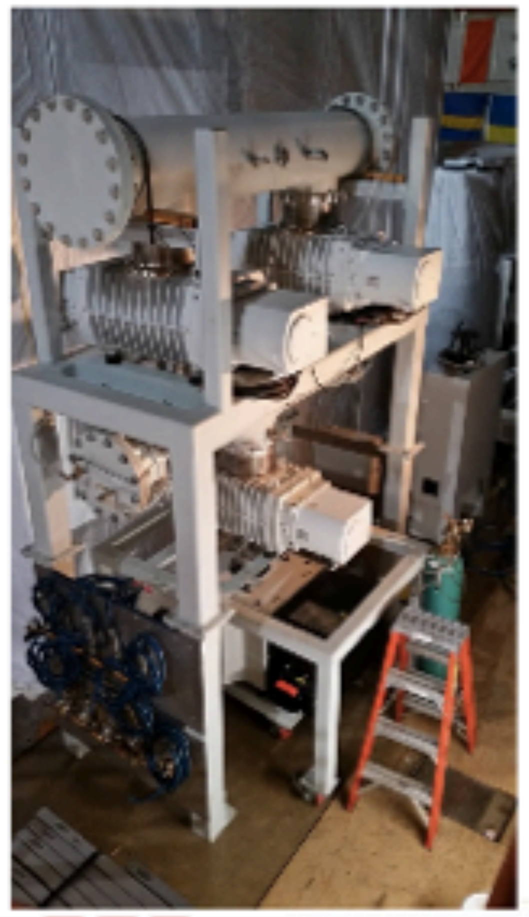
~140 GHz at 5T

T=0.03-1K

Superconducting Magnet

B=2.5-5T

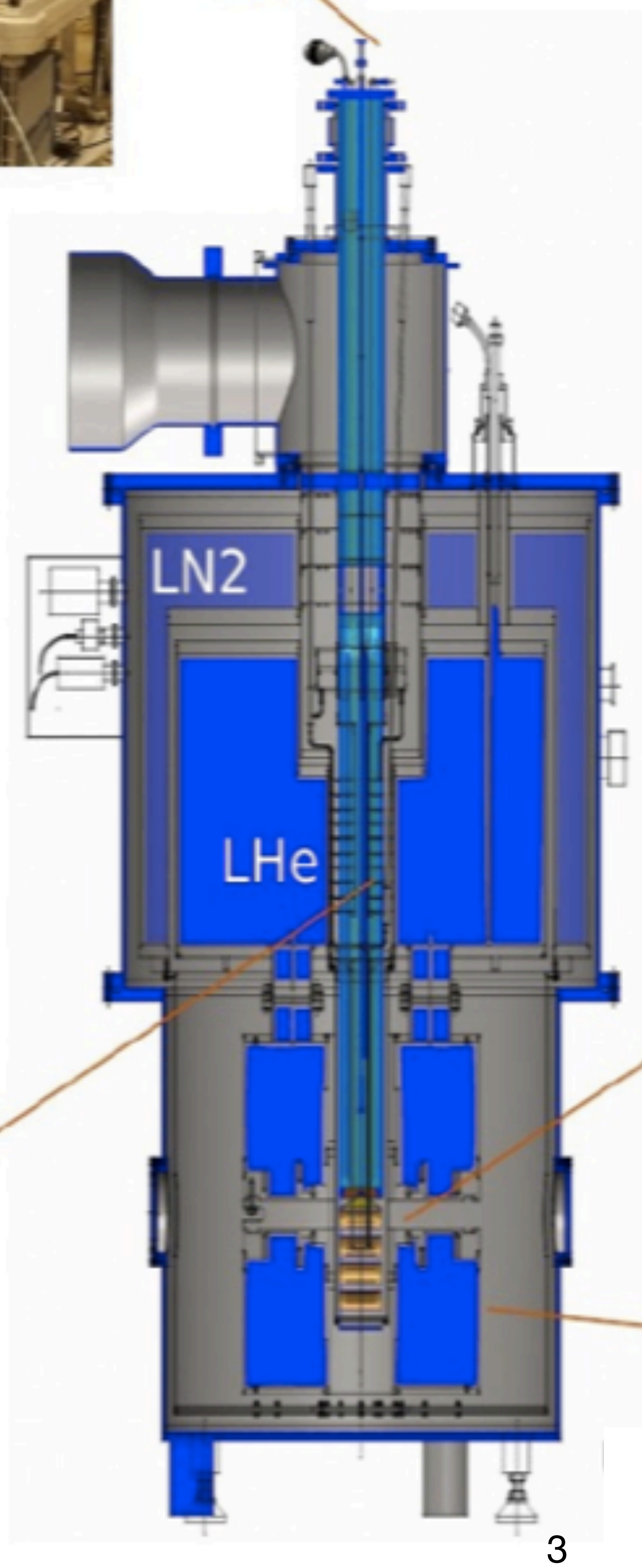
Polarized Target Subsystems

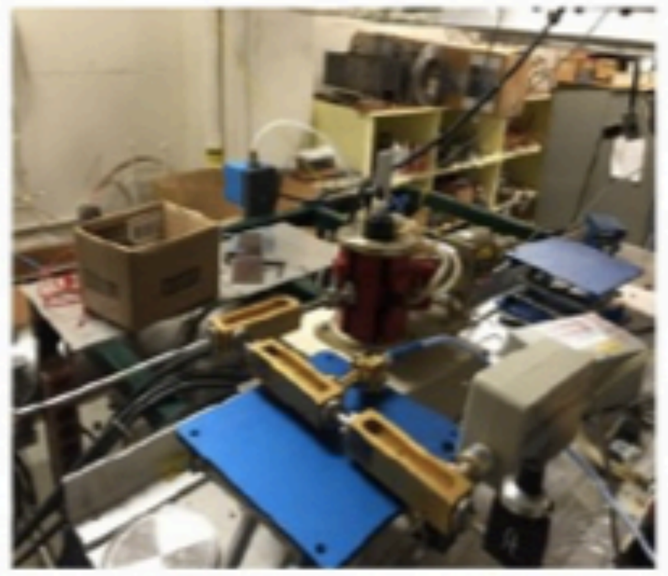


NMR

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

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

Magnet

OXFORD INSTRUMENTS

Update to Projected Error bars

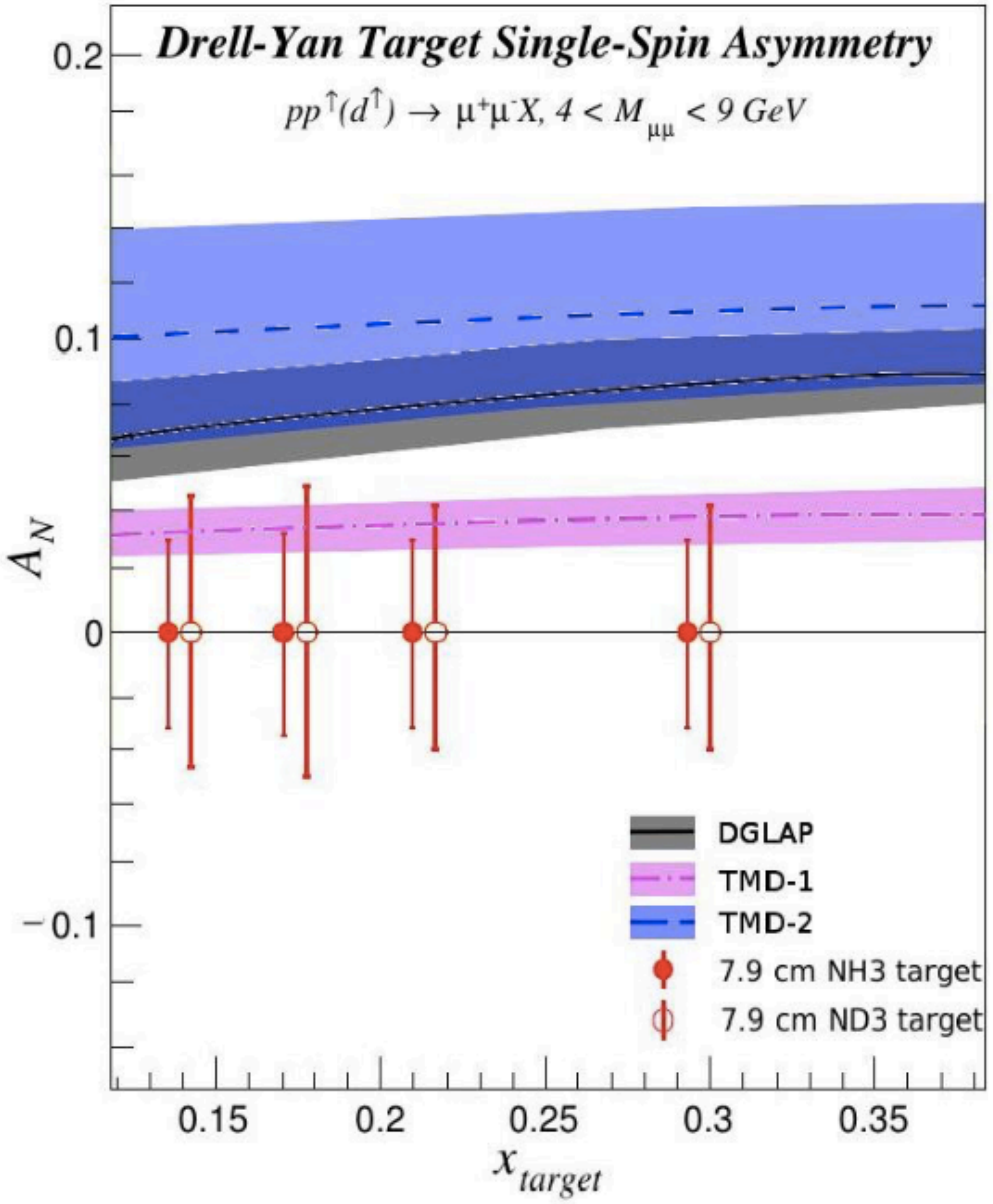
Beam(2.5%):
- Relative Luminosity (~1%)
- Drifts (<2%)
- Scraping (~1%)

$$\Delta A_N = \frac{1}{fP\sqrt{N}}$$

$$\delta A_N^{drifts} \sim \frac{2}{fP}\delta\xi$$

Analysis sources(3.5%):
- Tracking Efficiency (1.5%)
- Trigger and Geometrical Acceptance (<2%)
- Mixed background (3%)
- Shape of DY (~1%)

Target(6-7%)
- TE calibration (P-2.5% D-4.5%)
- Polarization inhomogeneity (2%)
- Density of target (ammonia) (1%)
- Uneven radiation damage (3%)
- Beam/target misalignment (0.5%)
- Packing fraction (2%)
- Dilution factor (3%)



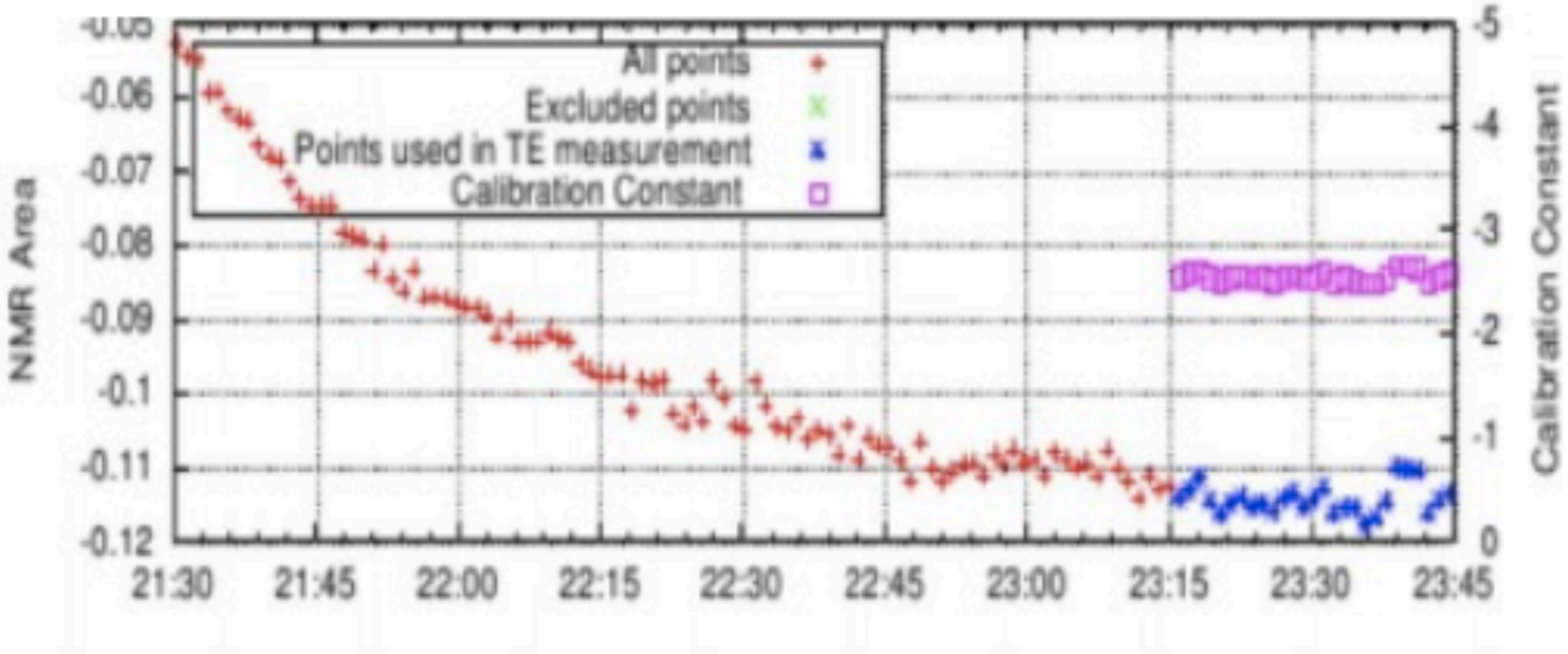
DGLAP: M. Anselmino et al arXiv:1612.06413
TMD-1: M. G. Echevarria et al arXiv:1401.5078
TMD-2: P. Sun and F. Yuan arXiv:1308.5003

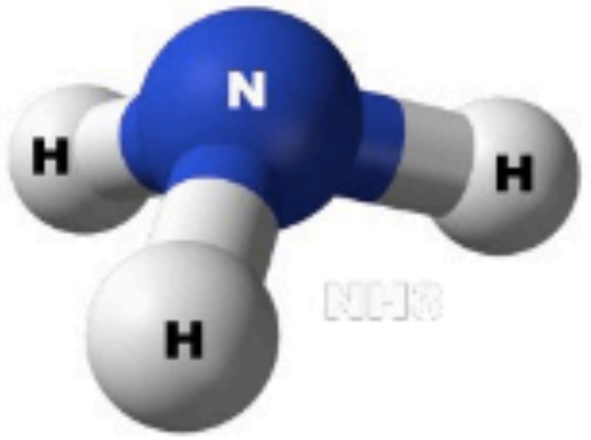
Material	Dens. (g/cm^3)	Length (cm)	Interaction Length (cm)	Dilution Factor	Packing Fraction	$< P_z >$
NH_3	0.867	7.9	91.7	0.176	0.6	80%
ND_3	1.007	7.9	82.9	0.3	0.6	32%

- 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.

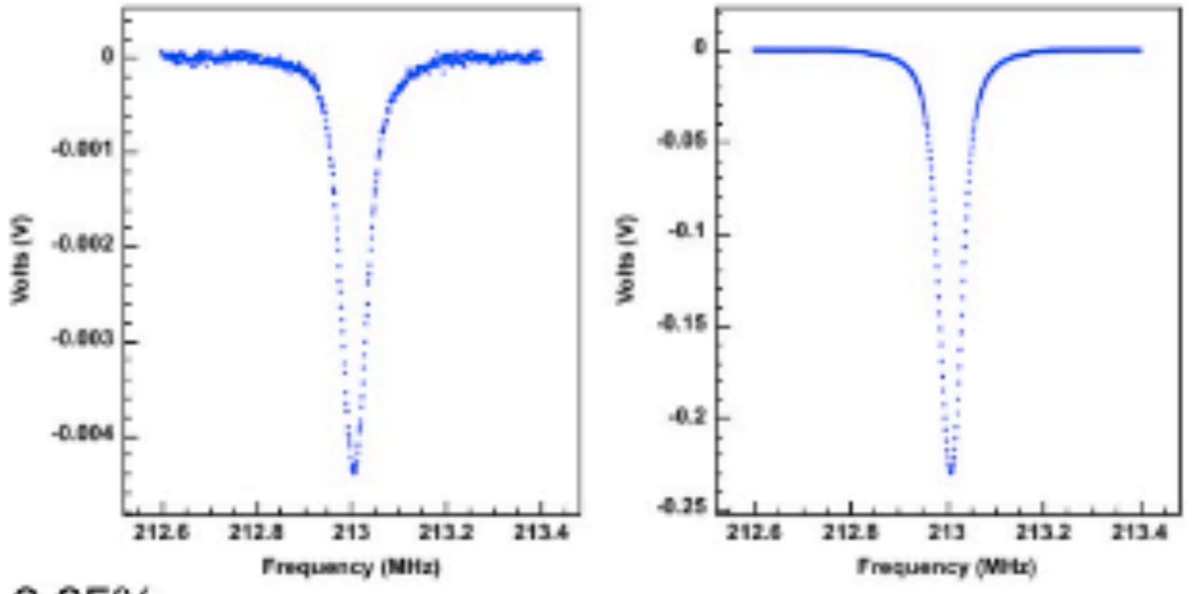
$$\Delta A_N = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N}}$$

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





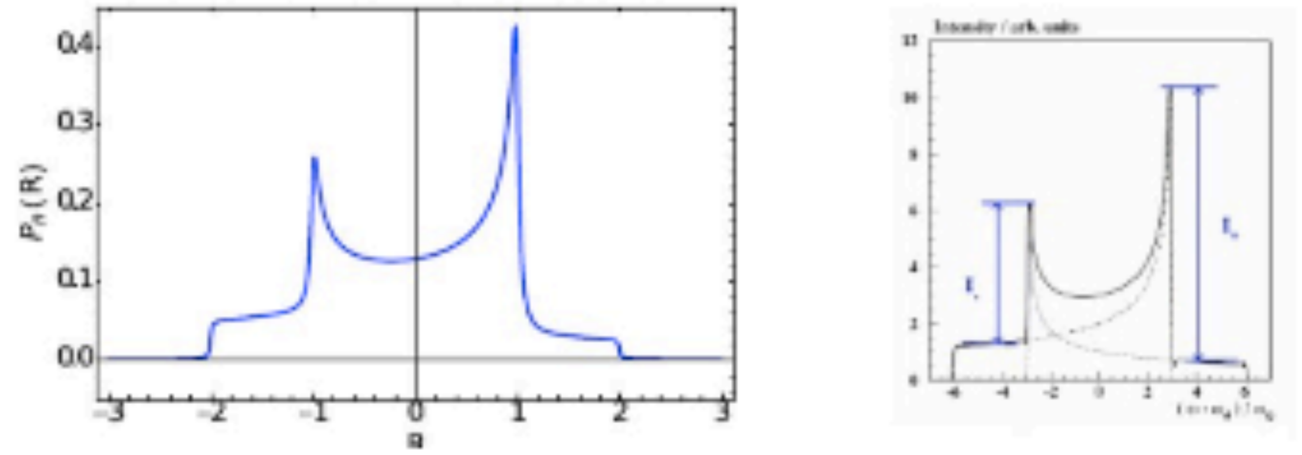
~0.3%



Proton

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

~0.05%



Deuteron

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

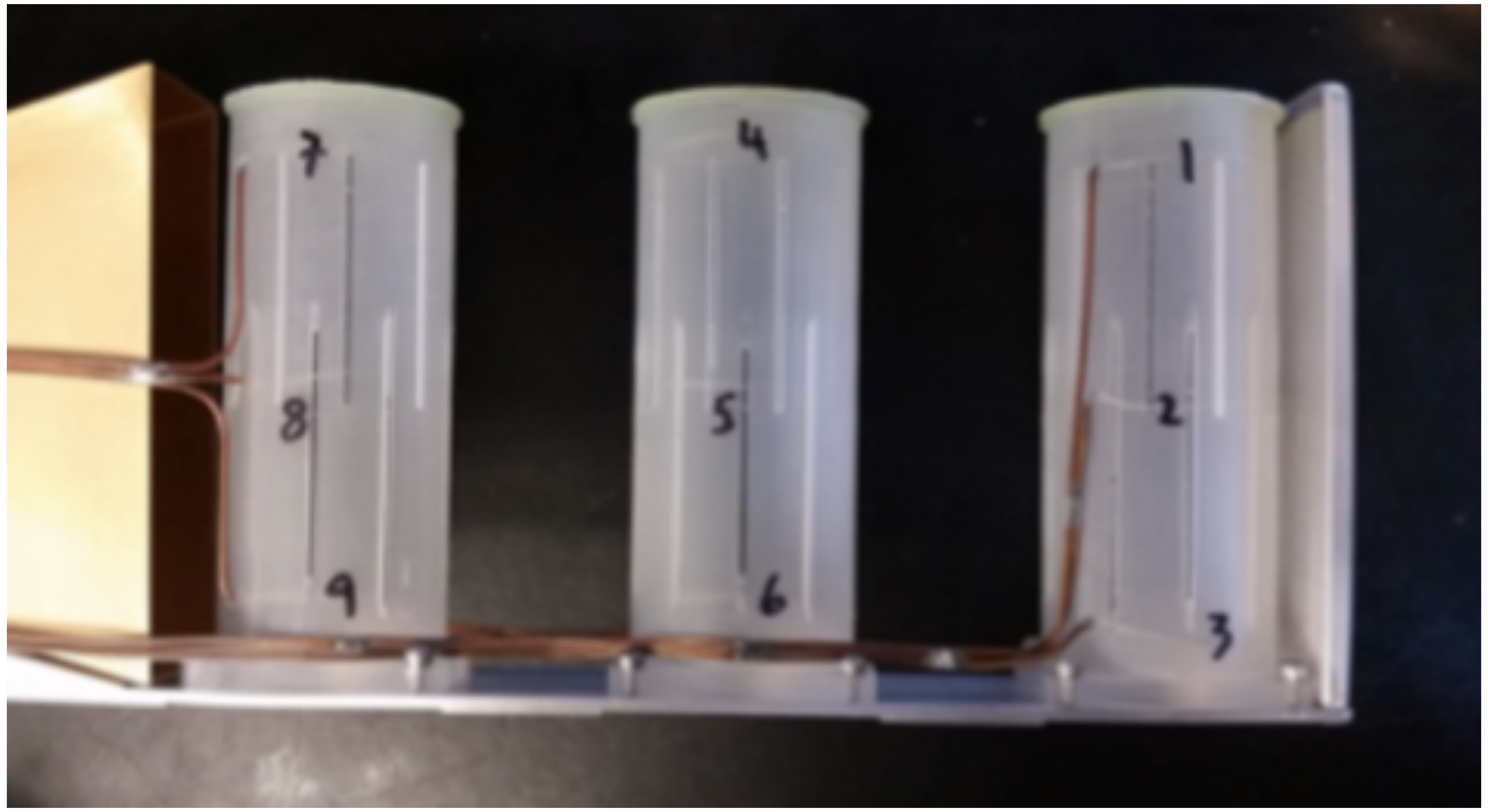
$$P_z = \frac{R^2 - 1}{R^2 + R + 1}$$

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

Target Insert

Carbon fiber with copper heat sink

- 27mm X 20mm elliptical target cell
- Shaped to match beam profile
- Long cell length microwave horn
- 3 cells per insert
- 3 NMR coils per cell
- Foil on either end



SpinQuest

A target system to operate at the proton intensity frontier

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

Novelty Issues

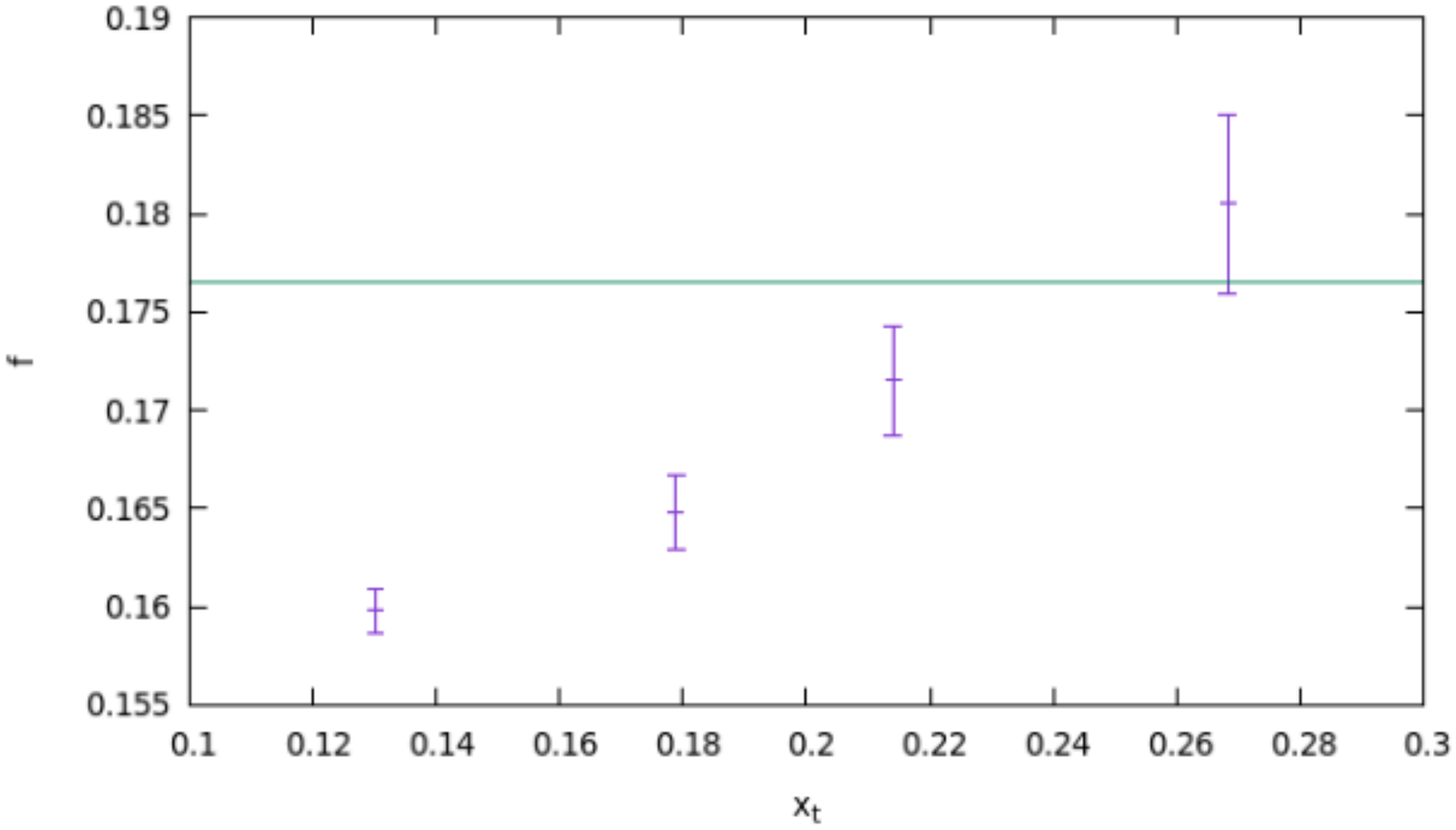
Polarized Target on the Intensity frontier

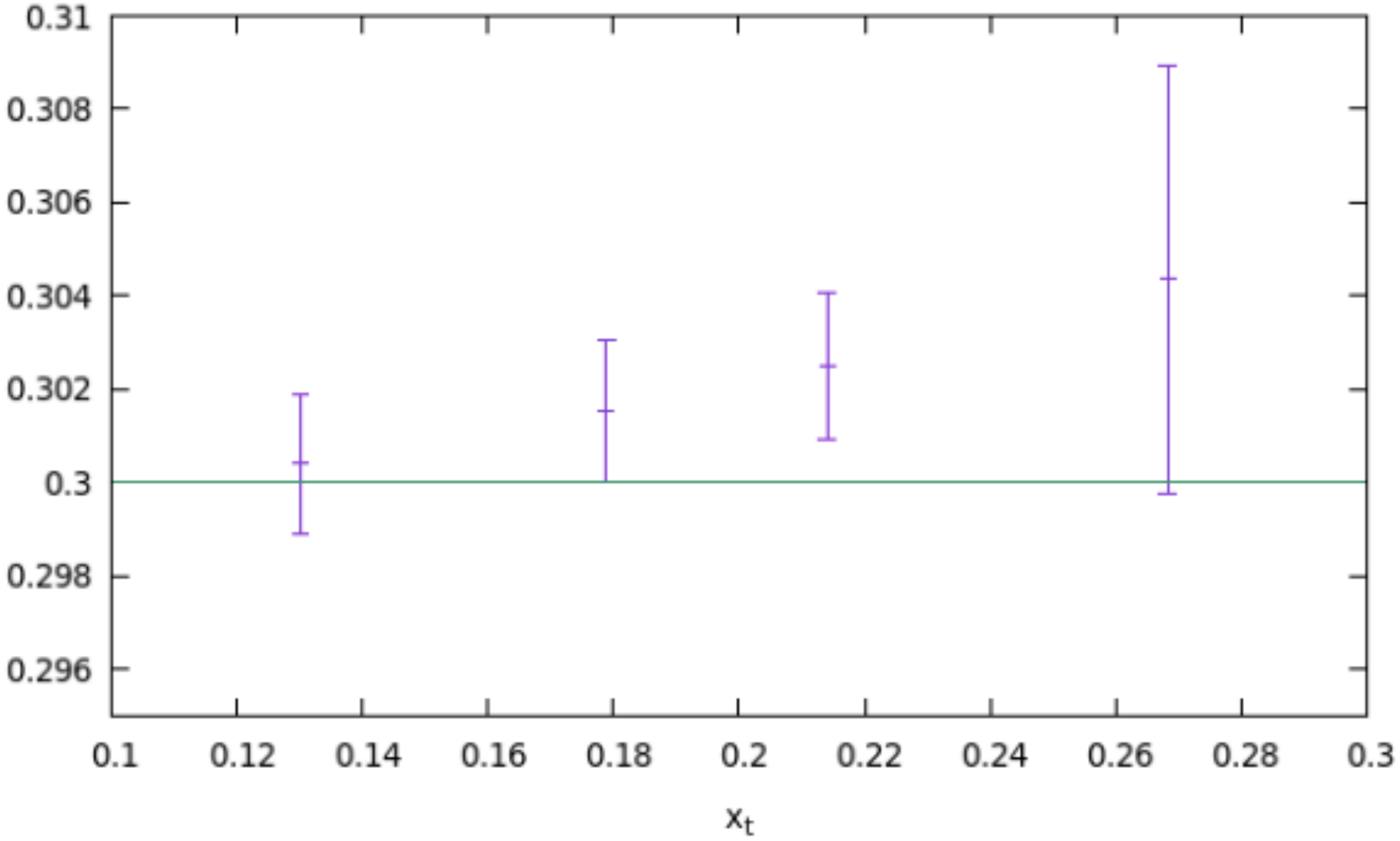
Optimize: Target length, field strength, degree of homogeneity, bore dimensions

- Proposed as the highest instantaneous proton intensity ever done
- Integrated over 1 second ~10^{12}
- Longest target cell used in an evaporation DNP system (decay, uniform)
- First proton beam Drell-Yan on NH_3/ND_3 (dilution factor, pol. level, cycle)
- Magnet heat-load limits, superconducting critical temperature
- Fridge heat-load limits (~1.1 Watts of beam heating alone)

Dilution Factor

Kinematic sensitivity (study with MCFM)





- Estimates based on MC
- H and D match to data well
- N not measured

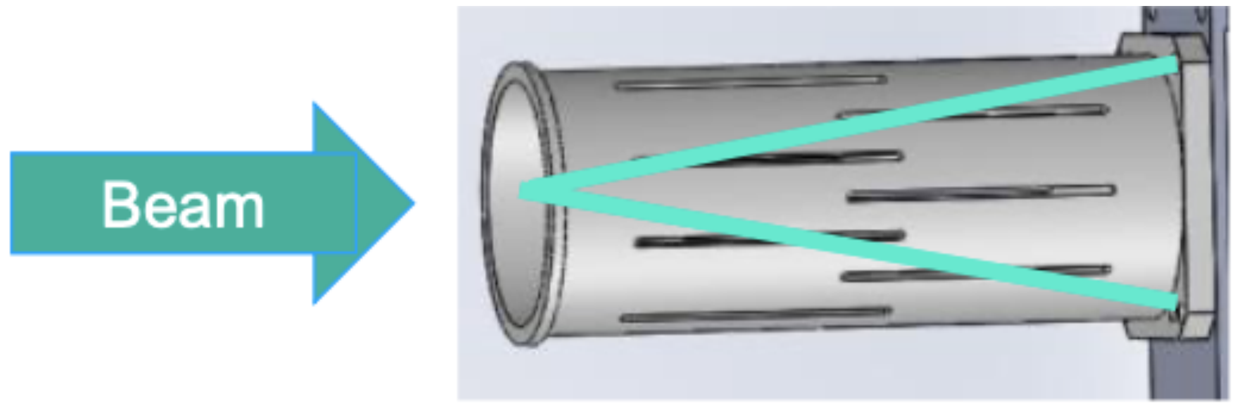
$$f(x_t) = \frac{3d\sigma_p^{DY}/dx_t}{3d\sigma_p^{DY}/dx_t + d\sigma_N^{DY}/dx_t}$$

$$fP(\mathrm{NH_3}) \sim 16\% \times 70\,\%$$

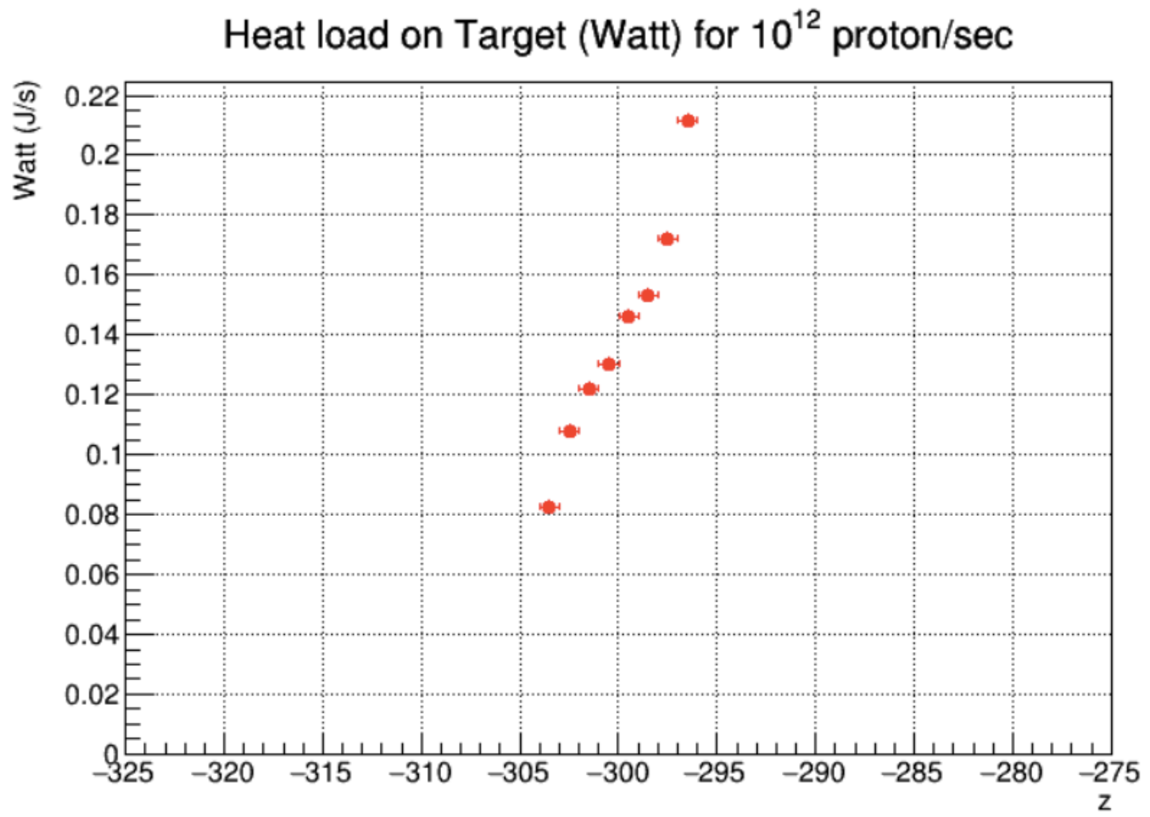
$$fP(\mathrm{ND_3}) \sim 30\% \times 35\,\%$$

$$\Delta A_N = \frac{1}{fP\sqrt{N}}$$

Challenges of a long Target



- Different decay along-z
- Microwave distribution
- 3 NMR coils
- Lower Average in NH3 (70%)(16%)
- Testing to gain insight and optimization required
- Details required to know target overhead

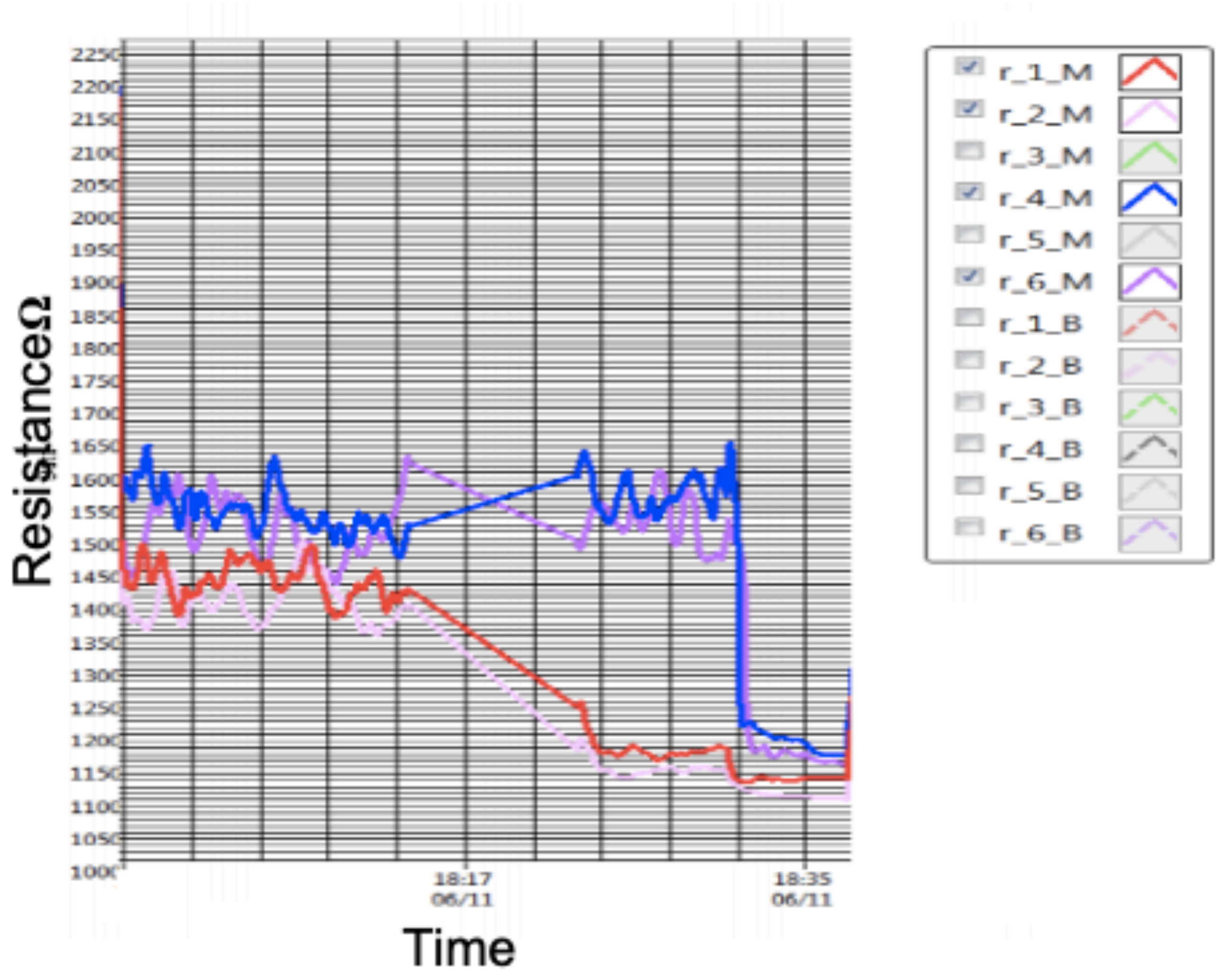

Heat load on Target (Watt) for 10^{12} proton/sec

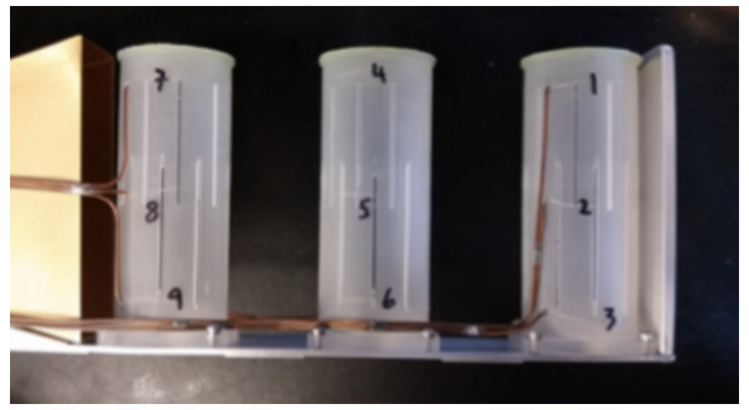
- Microwave distribution intensity along the target
- To test this 4 thermal sensors placed along-z and studies at varied frequency
- The NMR coils only measure 3 points along-z
- Using simulations and empirical data to interpolate microwave power profile
- Distribution being $P(z)$
- The average polarization will come out to be:

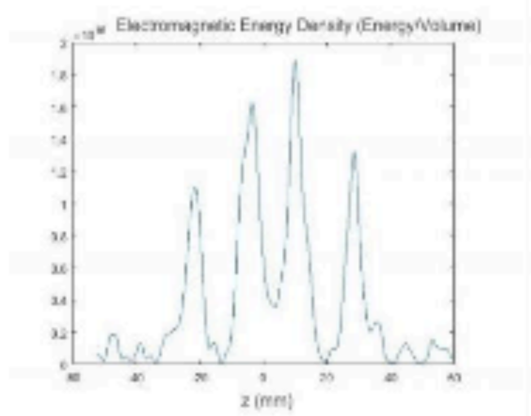
$$p_{avg} = \frac{p_1 + p_2 + p_3}{3}$$

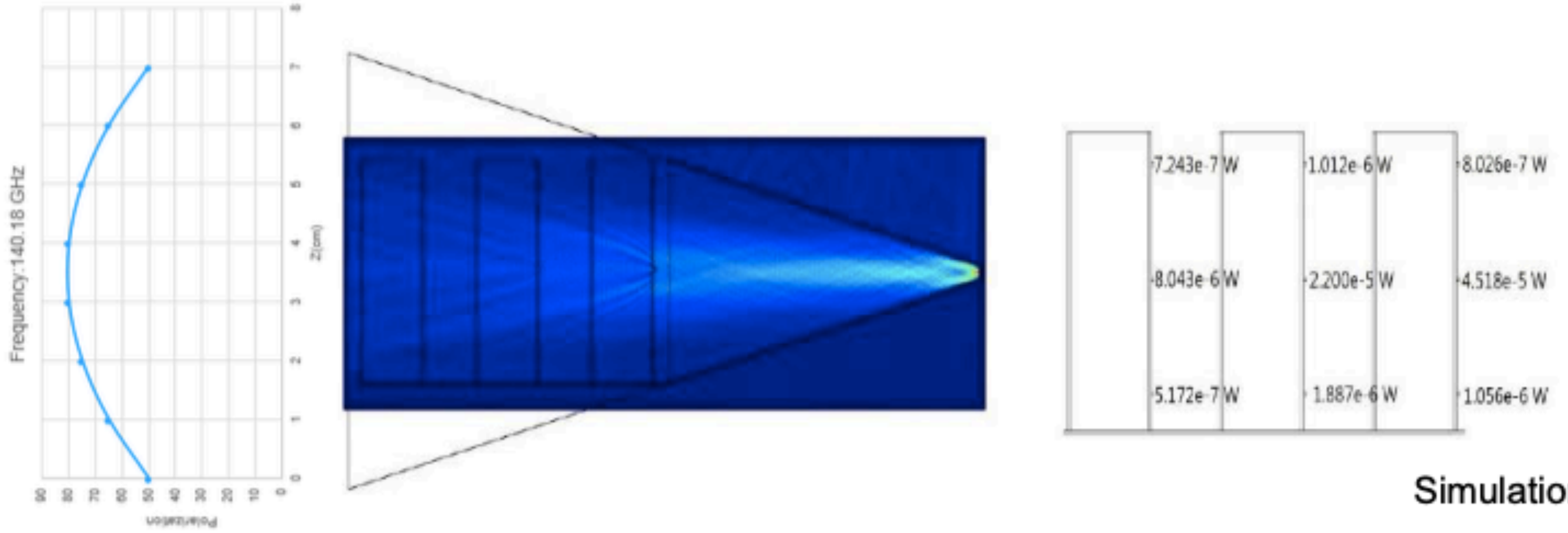
The error: $$\Delta A = \frac{P(Z) - P_{avg}}{P(z)}$$

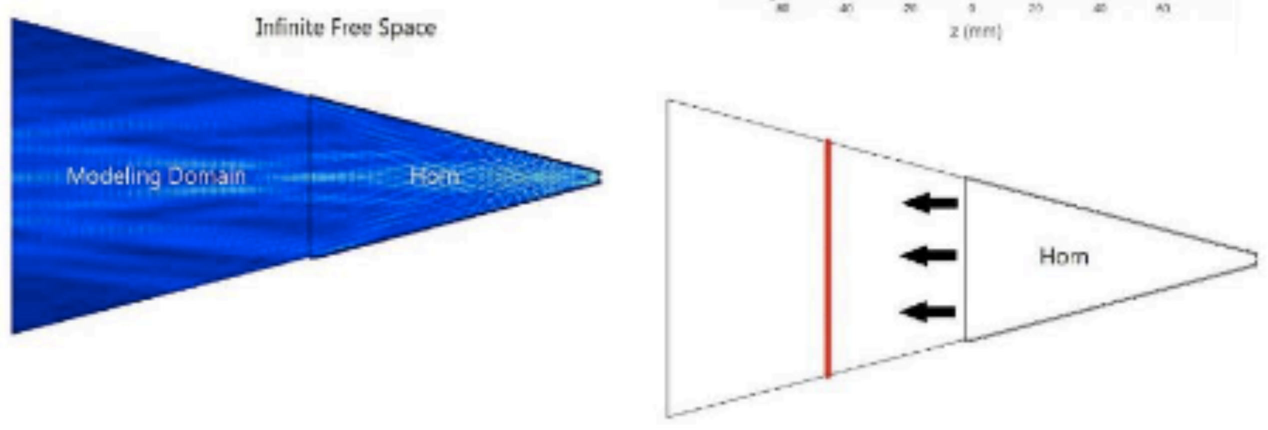
The error can be reduced by knowing the power profile





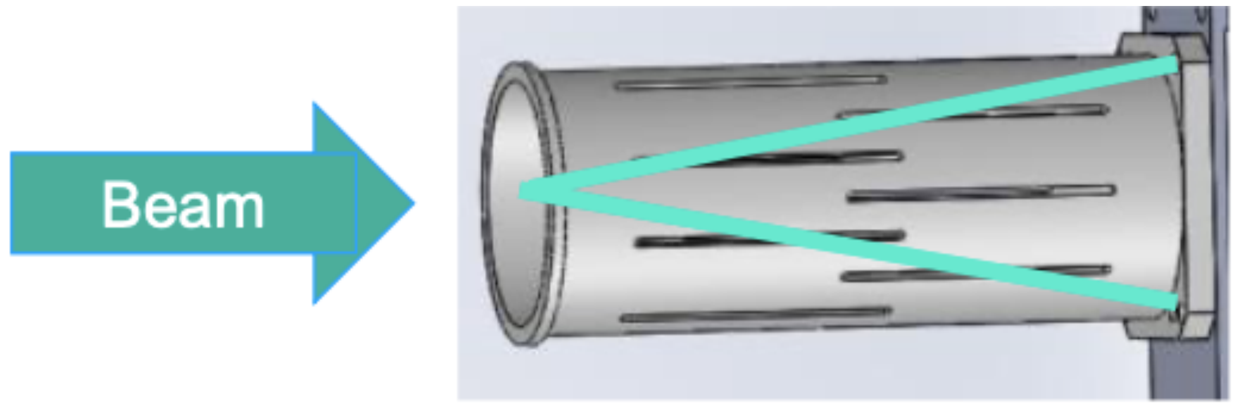




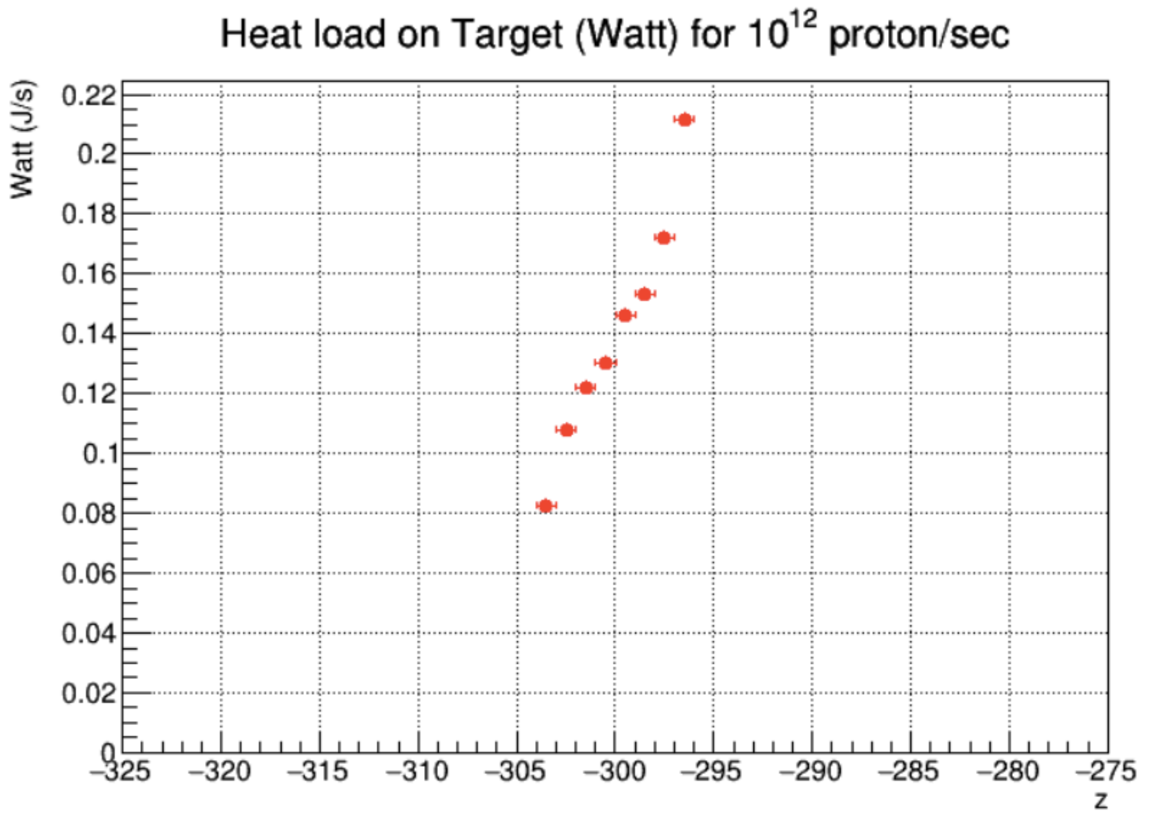


Simulations using RF module in Comsol multiPhysics simulation package

Challenges of a long Target



- At most (proton dose)
  - Anneals : 2×10^{16} protons
  - Replace: 1.5×10^{17} protons
- Higher average requires more target maintenance
- Details required to know target overhead



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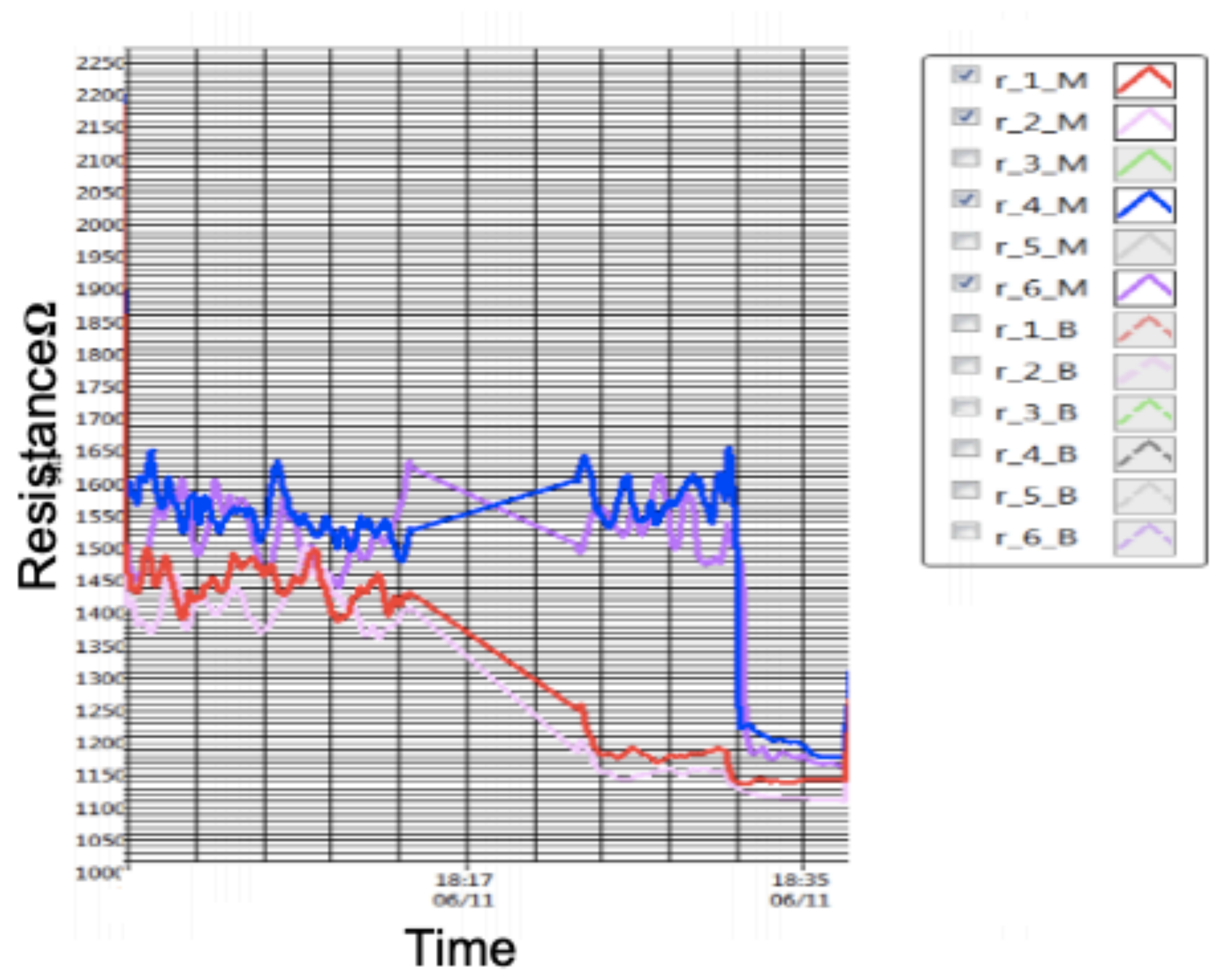
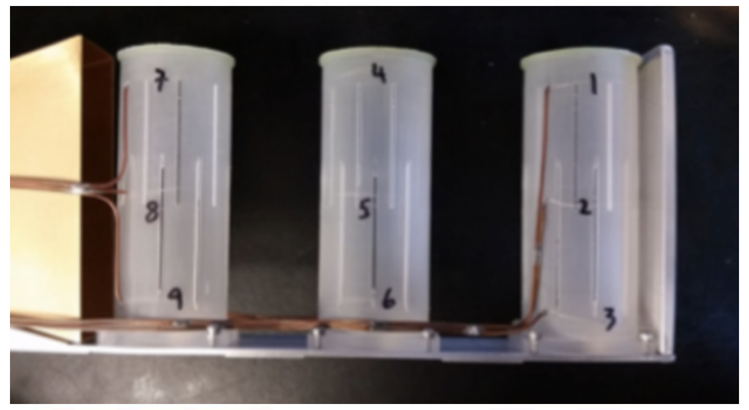
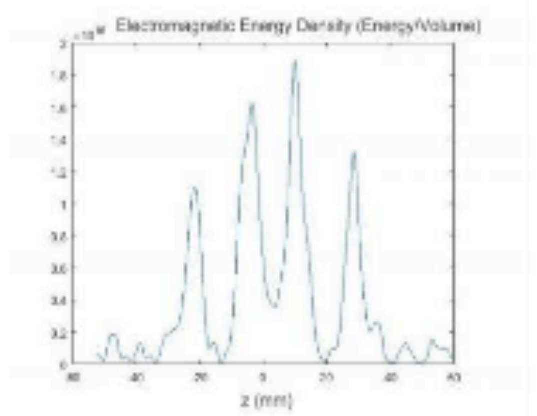
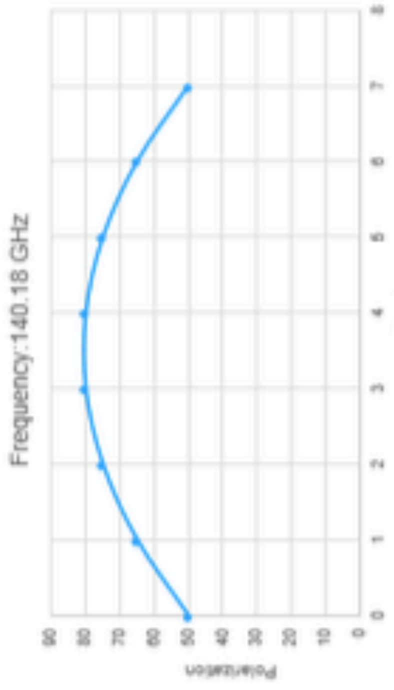
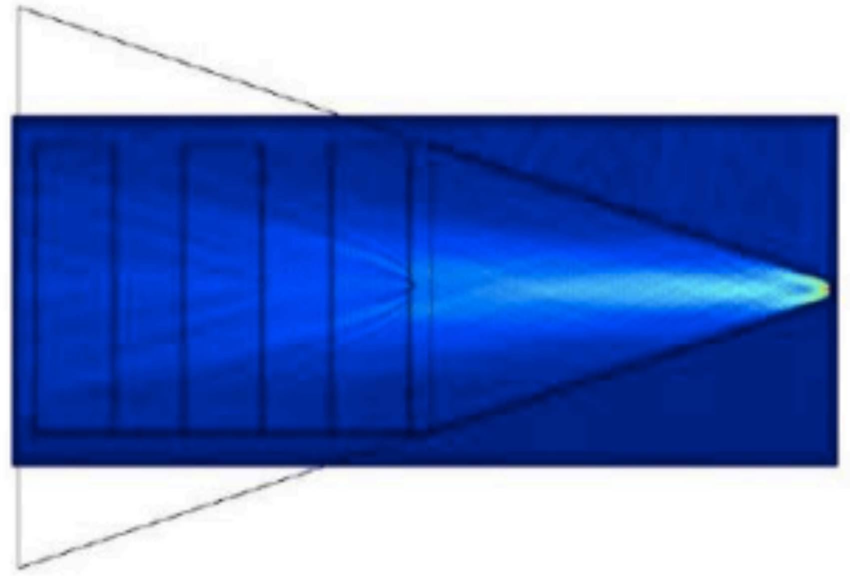
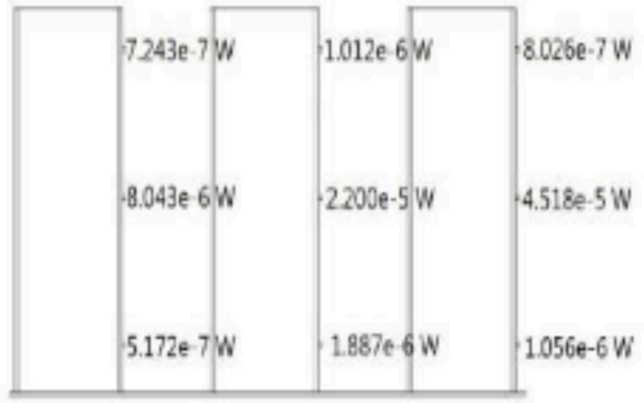


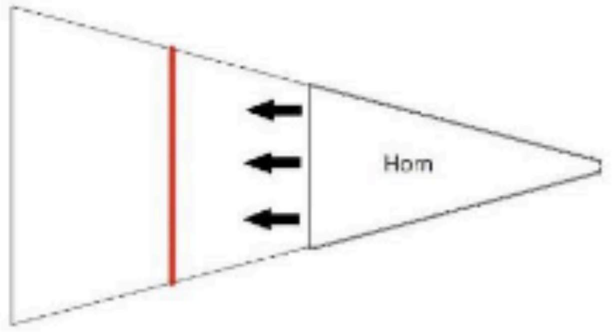








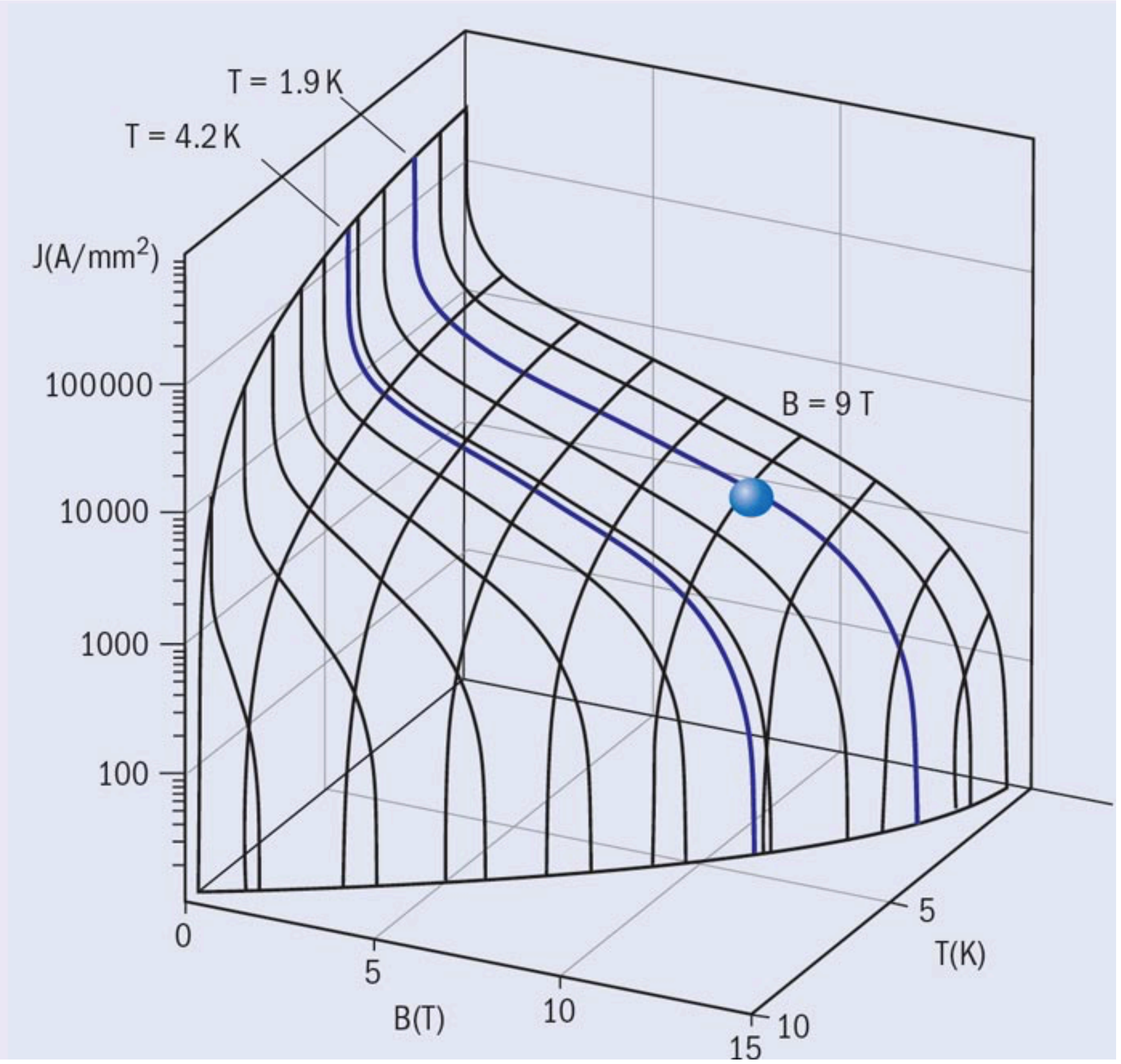




Simulations using RF module in Comsol multiPhysics simulation package

Superconducting Magnet

Quench Threshold



- Critical surface is defined by the temperature, field strength, surface current
- Quench if either of these is beyond the critical surface
- For 5T the maximum temperature is 7.2K

5T NbTi (Niobium-Titanium)

Quench Studies

Primary Intensity Boundary

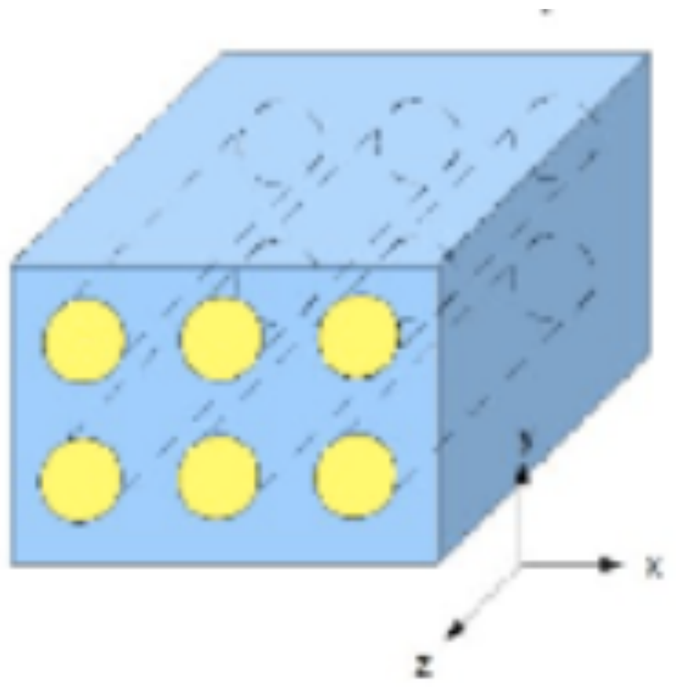
- Monte Carlo and Finite Element Analysis (limited exp info)
- Match Measured Field and Simulated Field
- Simulate Heat-load Cycle from Beam
- Calculate the heat propagation to the coils
- Estimate Quench Threshold for Stable Running
- Use Estimate to Make Quench Commissioning Plan

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

Simulation Strategy

Computational approach to superconducting magnet

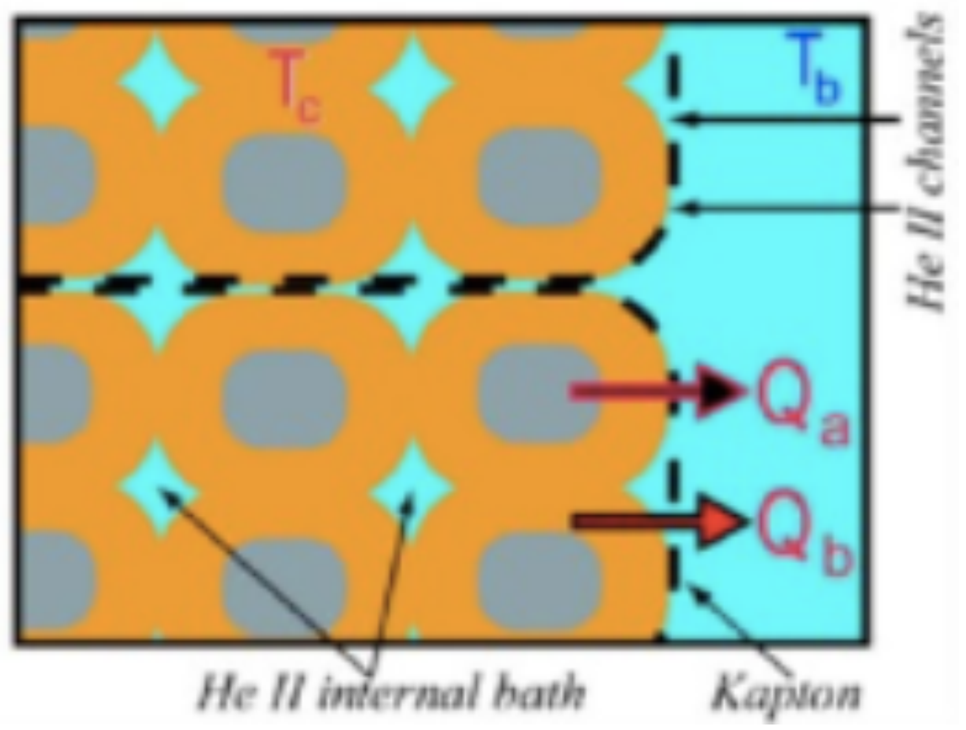
- Steady-state film boiling regime is applied
- Add composite materials with effective thermal parameters
- Parameterize of unknown properties of materials in contact with LHe

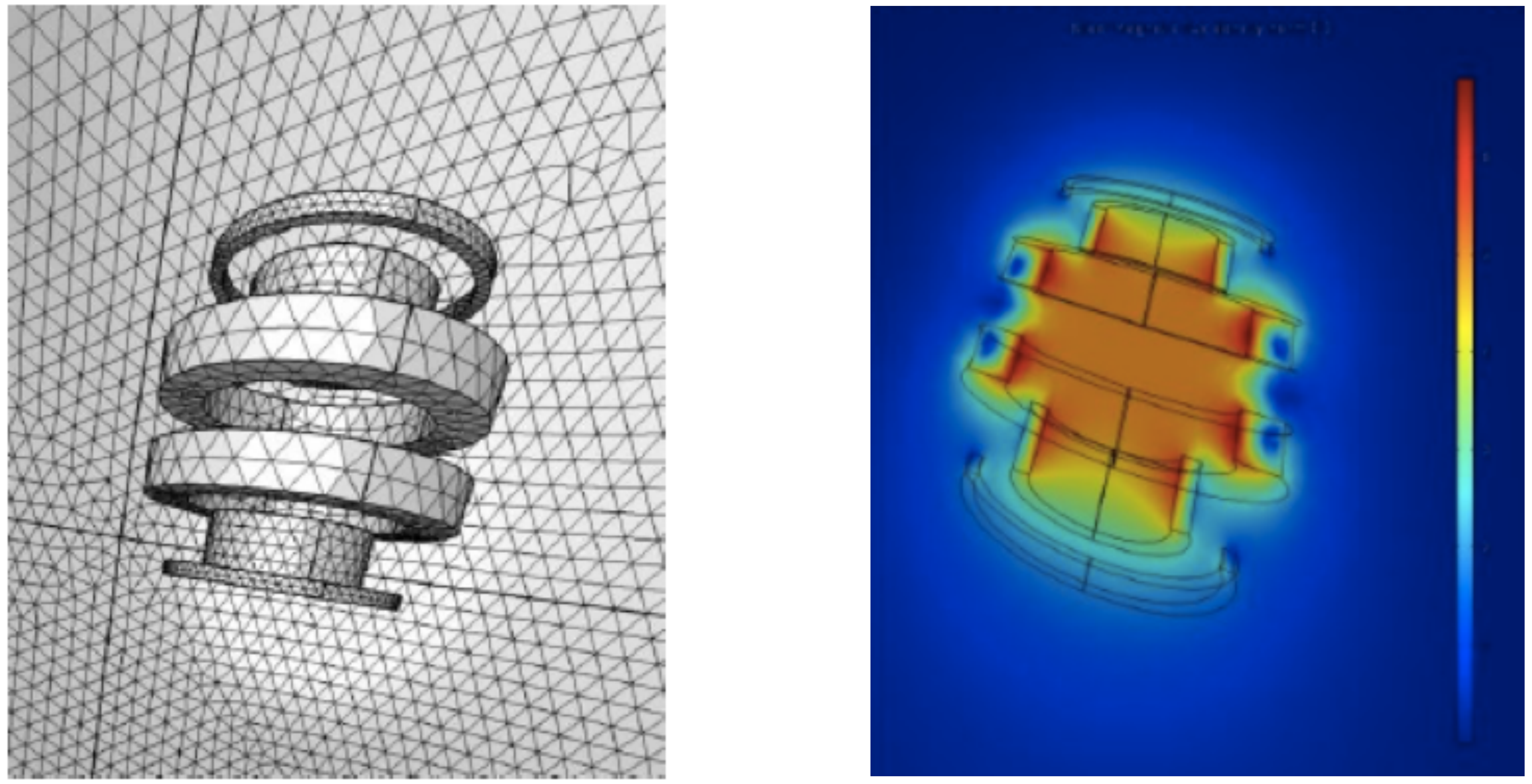


Rayleigh's model consist of parallel cylinders embedded in a continuous matrix

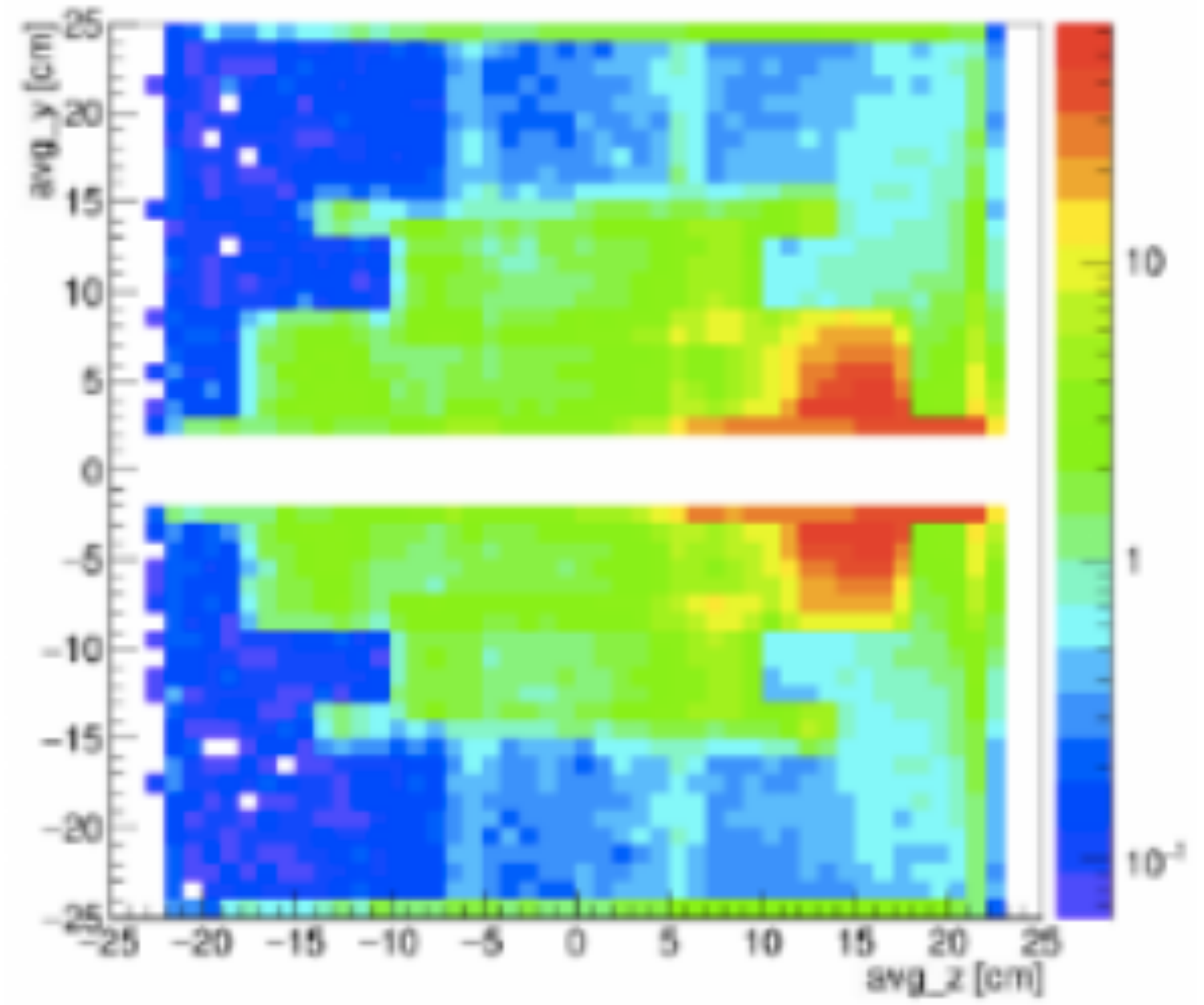
Rayleigh's formula

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



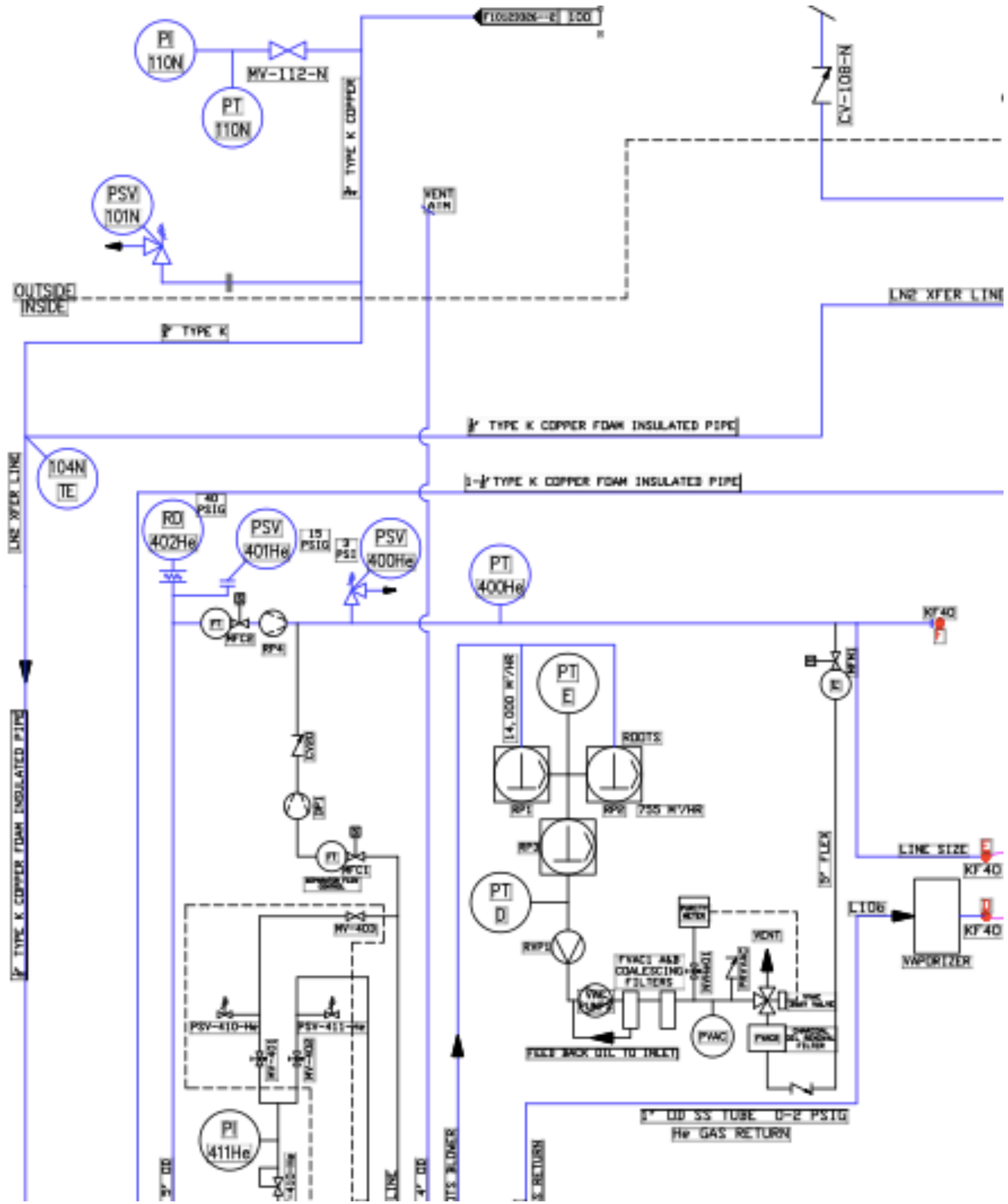


COMSOL Multiphysics Simulation Package



Geant4

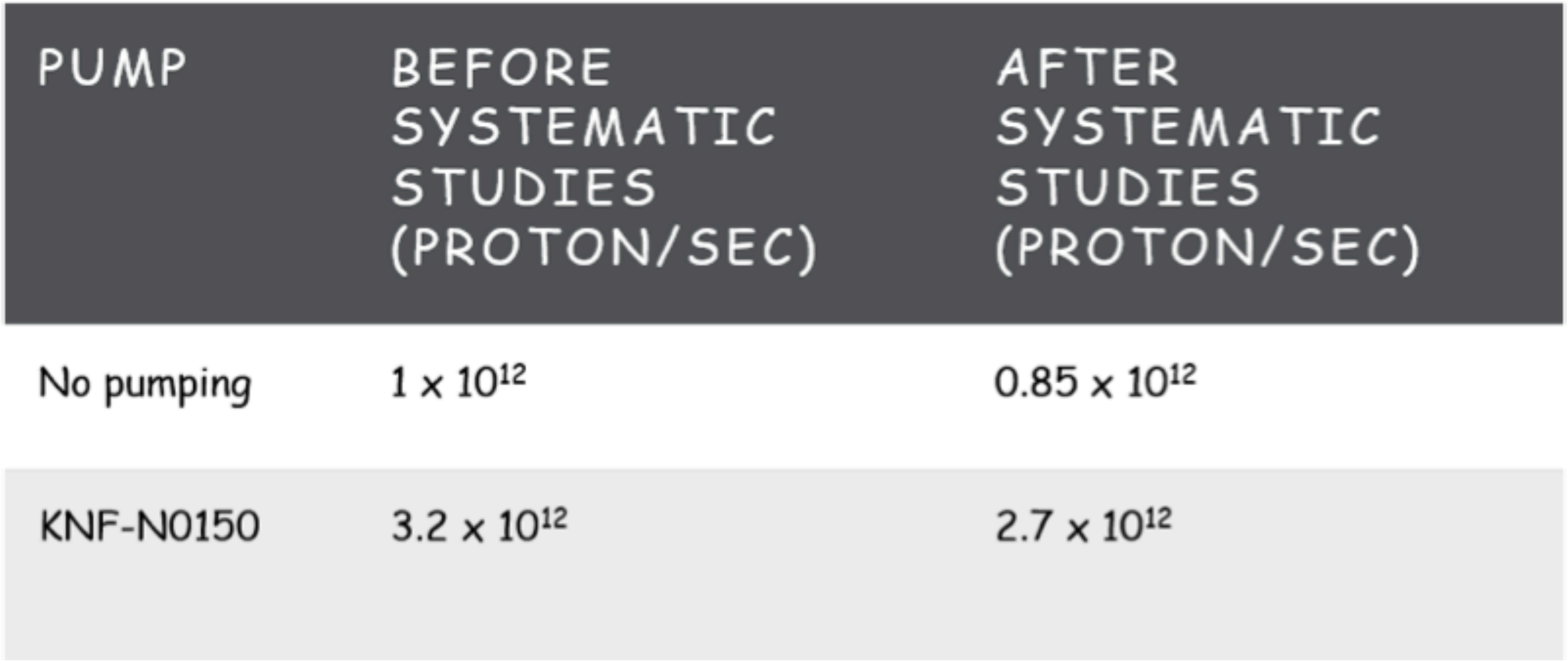
- Make field map
- Port to Geant4
- Acquire heat-load
- Check critical temp at different intensity
- Study different pumping scenarios



Estimated Quench Threshold

Based on a series of MC studies

- Assuming no other intensity constraints
- Assume unlimited LHe



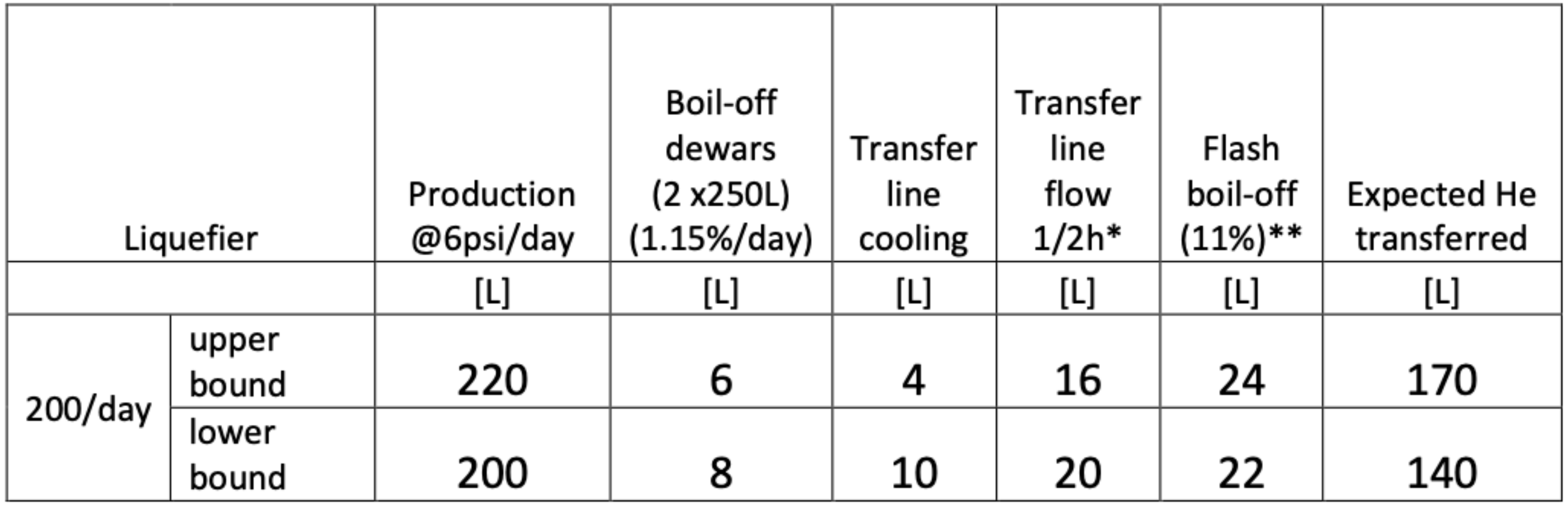
PUMP	BEFORE SYSTEMATIC STUDIES (PROTON/SEC)	AFTER SYSTEMATIC STUDIES (PROTON/SEC)
No pumping	1×10^{12}	0.85×10^{12}
KNF-N0150	3.2×10^{12}	2.7×10^{12}

Quantum Technology Corp Liquefier

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%

- Quantumpure 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 LPD 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 (using less than 120 LPD)
- 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

Target Magnet Pumping

Intensity vs Helium budget

Intensity	2×10^{12} p/spill	10×10^{12} p/spill
Daily Consumption	135 l/day	175 l/day
Additional Daily Requirements	0 l/day	40 l/day
250L	0	5 days

SpinQuest Target Team

- Team Leader
- 1 UVA Research Scientist (hiring in process)
- 2 UVA postdocs (general)
- 1 LANL postdoc (slow controls)
- 1 UVA Target Technician (hiring in process)
- 2-3 UVA grad students
- Multiple undergrads

Challenges

Past and Present

In addition PT at the intensity frontier

- No full-time cryogenic engineer to help prepare for cryogenic safety review
- Major infrastructure additions to meet safety standards
- Additional modifications driven by safety recommendations still in process
- Training target experts requires a running target (lots of people willing)

Thank You

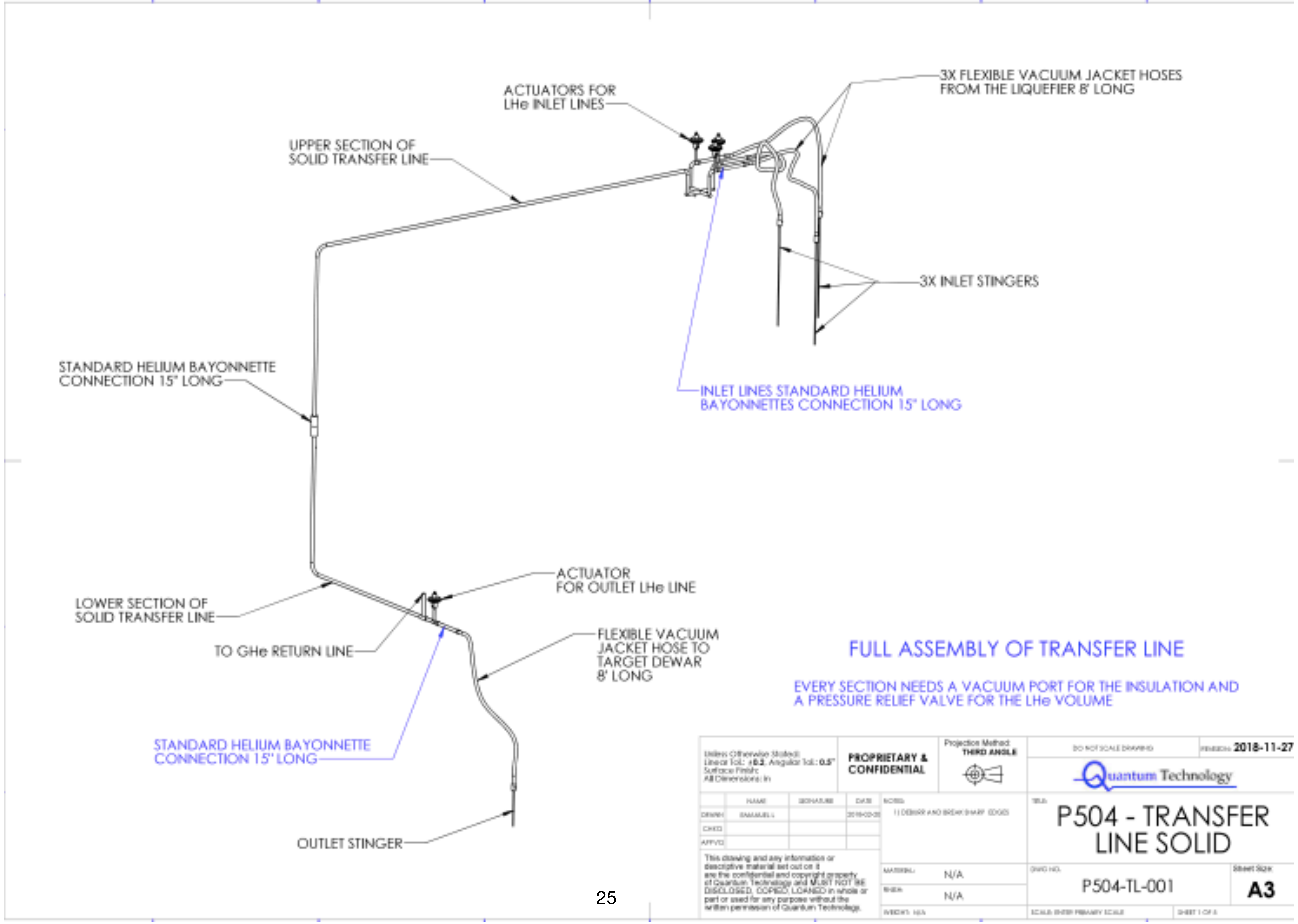
Backup Slides

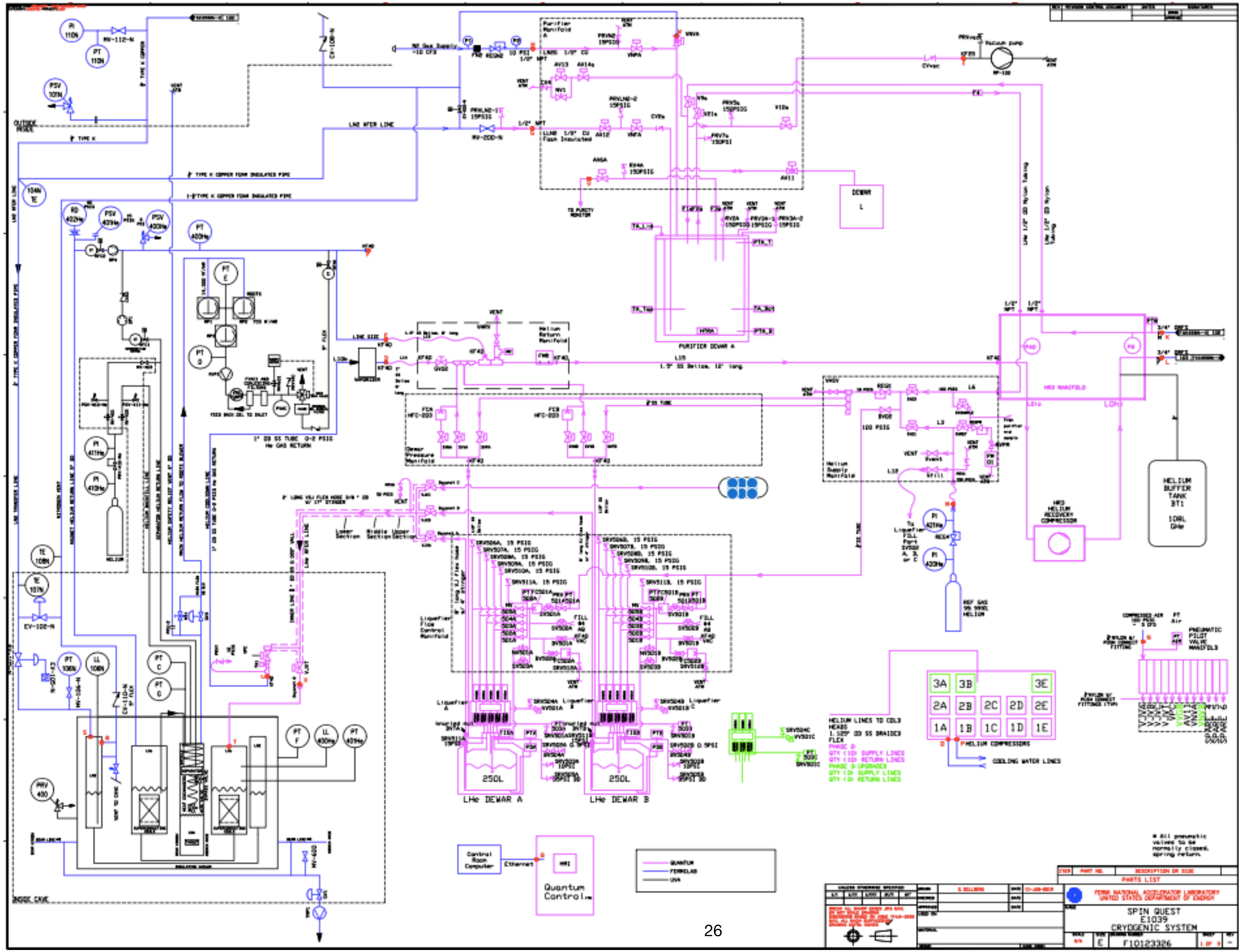
Liquid Helium Transfer

QT Transfer to the target

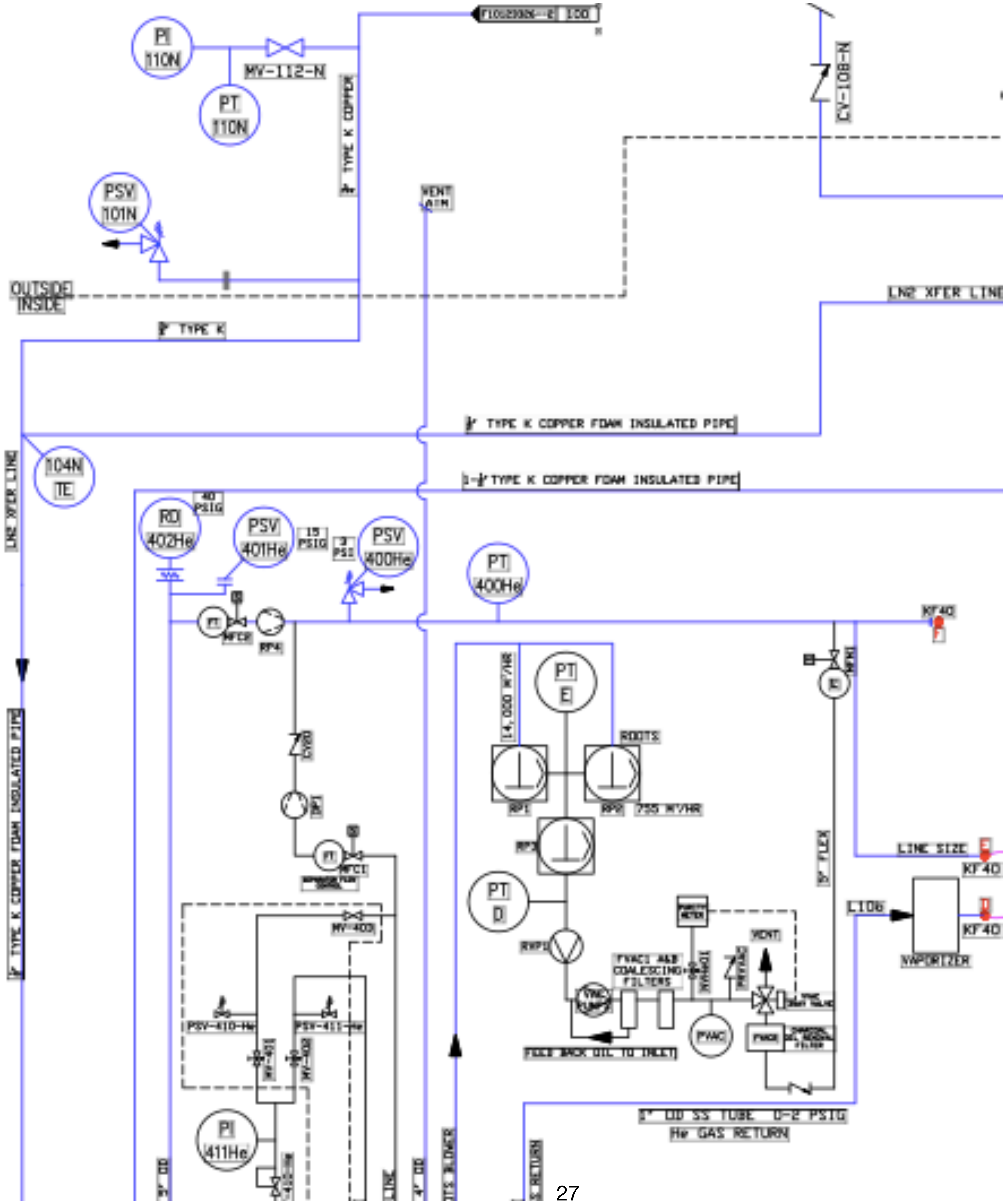
- Initial Cooldown 100% boil-off at 1700 slpm
- QT recovery compressor can handle 1500 slpm
- Loss of 200 slpm
- Using rigid non-LN2 shielded (just vacuum) with flexible ends
- Initial fill at 80K requires at least the full 500L of stored LHe
- Refill ~135L (200L) should be delivered over 60 minutes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

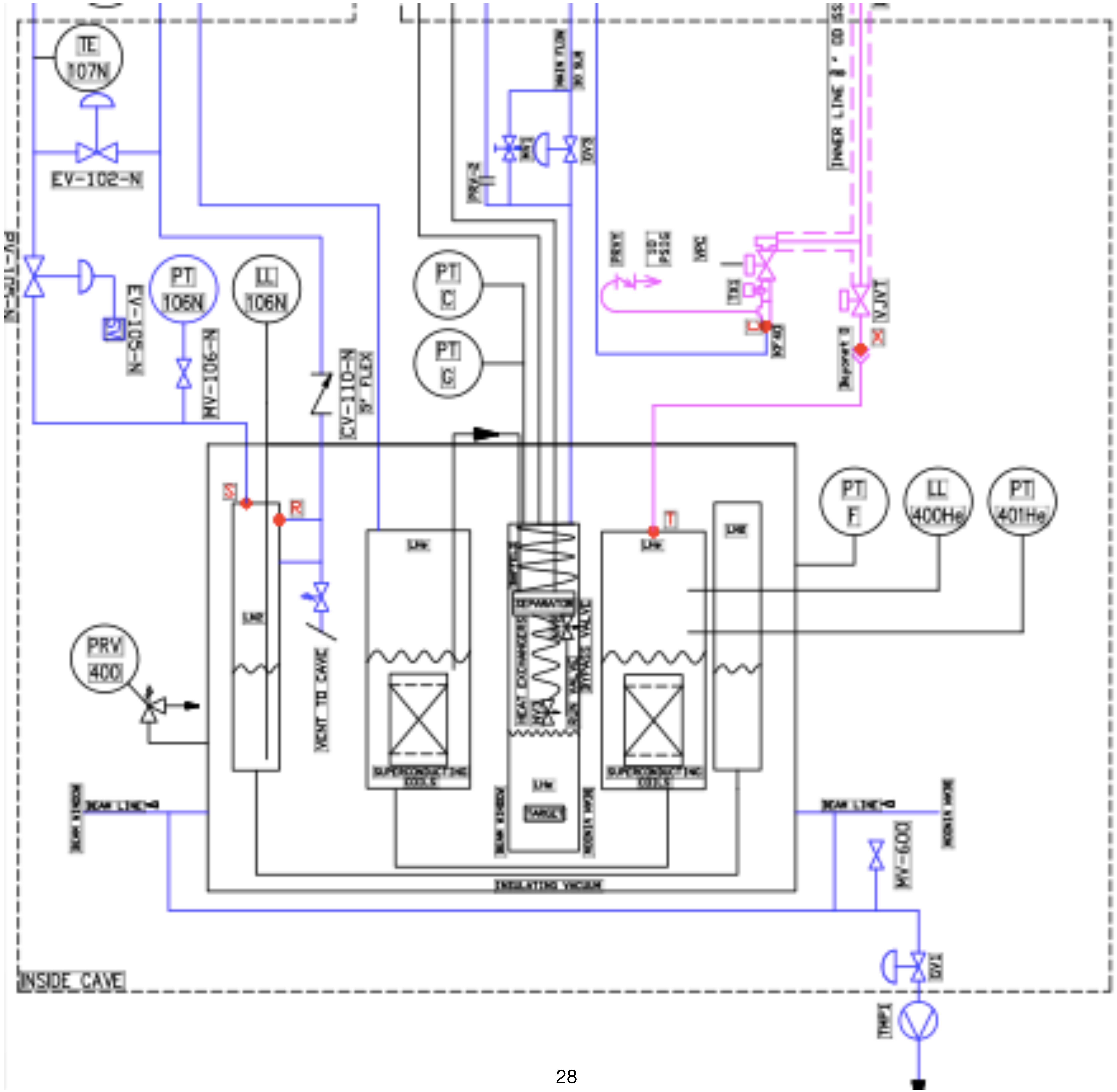
QT Transfer Line into Cave





OUTSIDE
INSIDE
N2 Gas Supply ~10 CFD
LN2 WTER LINE
Purifier Manifold A
PURIFIER DEWAR A
DEWAR L
Vacuum pump
LINE SIZE
Helium Return Manifold
1.5" SS Bellow, 12" long
L1/2" OD Nylon Tubing
1/2" NPT
HRD MANIFOLD
HELIUM BUFFER TANK BT1
HRD HELIUM RECOVERY COMPRESSOR
Helium Supply Manifold
Dewar Pressure Manifold
Lower Section
Middle Section
Upper Section
Liquefier Flow Control Manifold
Liquefier A
Liquefier B
Liquefier C
250L
250L
LHe DEWAR A
LHe DEWAR B
REF GAS 99.999% HELIUM
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.
ITEM
PART NO.
DESCRIPTION OR SIZE
PARTS LIST
UNLESS OTHERWISE SPECIFIED
DRAWN
E. DELLBERG
DATE
CHECKED
APPROVED
USED ON
MATERIAL
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
SPIN QUEST
E1039
CRYOGENIC SYSTEM
SCALE
SIZE
E
DRAWING NUMBER
F10123326
SHEET
1 OF 3
REV
-

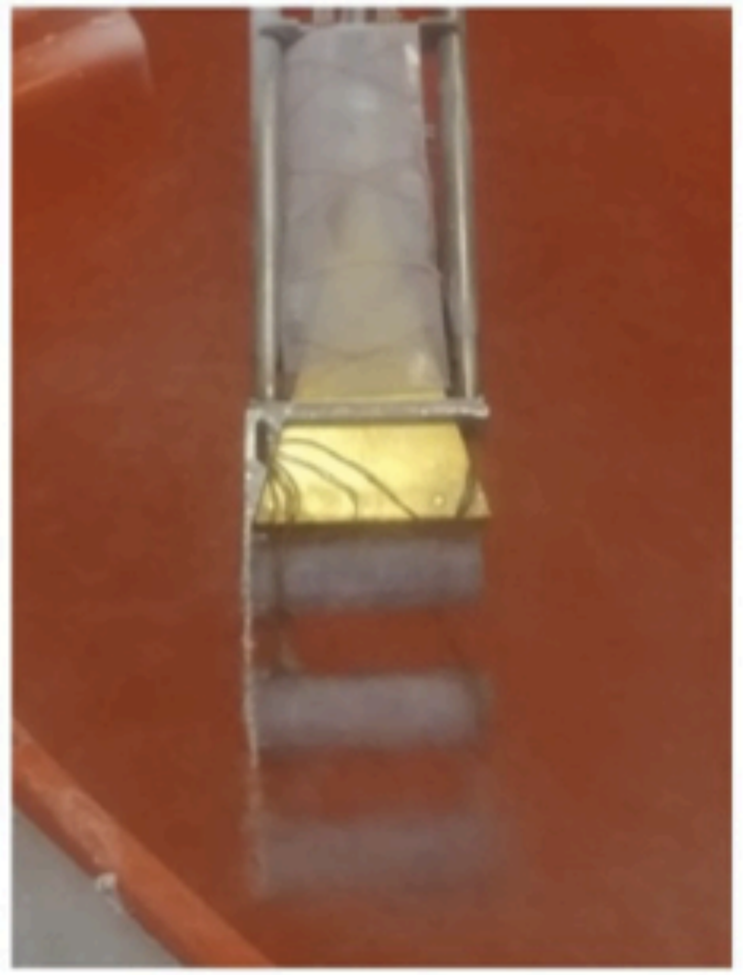

PI
110N
MV-112-N
PT
110N
TYPE K COPPER
PSV
101N
OUTSIDE
INSIDE
TYPE K
VENT
ATM
CV-108-N
LN2 XFER LINE
TYPE K COPPER FOAM INSULATED PIPE
1-½" TYPE K COPPER FOAM INSULATED PIPE
104N
TE
LN2 XFER LINE
TYPE K COPPER FOAM INSULATED PIPE
RD
402He
40
PSIG
PSV
401He
15
PSIG
3
PSI
PSV
400He
PT
400He
PT
MFC2
RP4
KF40
PT
E
14,000 M³/HR
ROOTS
RP1
RP2
755 M³/HR
RP3
PT
D
RWP1
FVAC1 A&B
COALESCING
FILTERS
FVAC
PUMP
VENT
FVAC
1" FLEX
LINE SIZE
KF40
L106
KF40
VAPORIZER
FEED BACK OIL TO INLET
1" OD SS TUBE 0-2 PSIG
He GAS RETURN
PT
MFC1
MV-403
PSV-410-He
PSV-411-He
PI
411He
3" OD
LINE
4" OD
ROOTS BLOWER
GAS RETURN


TE 107N
EV-102-N
PV-1??-N
EV-105-N
PT 106N
MV-106-N
LL 106N
CV-110-N
5" FLEX
PRV-2
MAIN FLOW
PT C
PT G
INNER LINE
VJVT
X
T
S
R
LN2
LHe
SEPARATOR
HEAT EXCHANGERS
BYPASS VALVE
SUPERCONDUCTING COILS
TARGET
BEAM WINDOW
INSULATING VACUUM
VENT TO CAVE
PRV 400
PT F
LL 400He
PT 401He
BEAM LINE
MV-600
TMP1
INSIDE CAVE

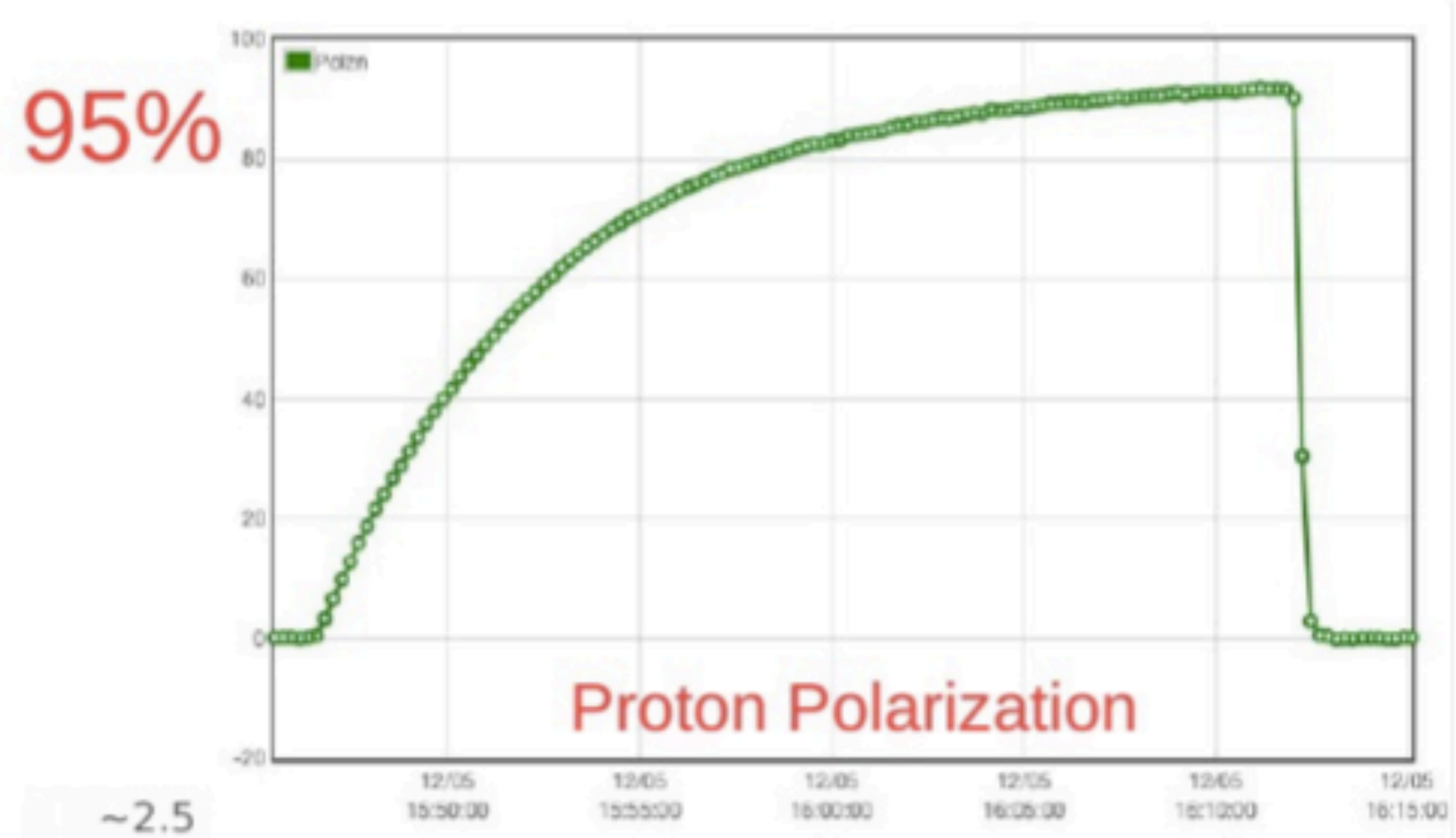
External Magnet Temp Sensor

Type-T Thermocouples Cu-CuNi

Last Target Polarization at UVA

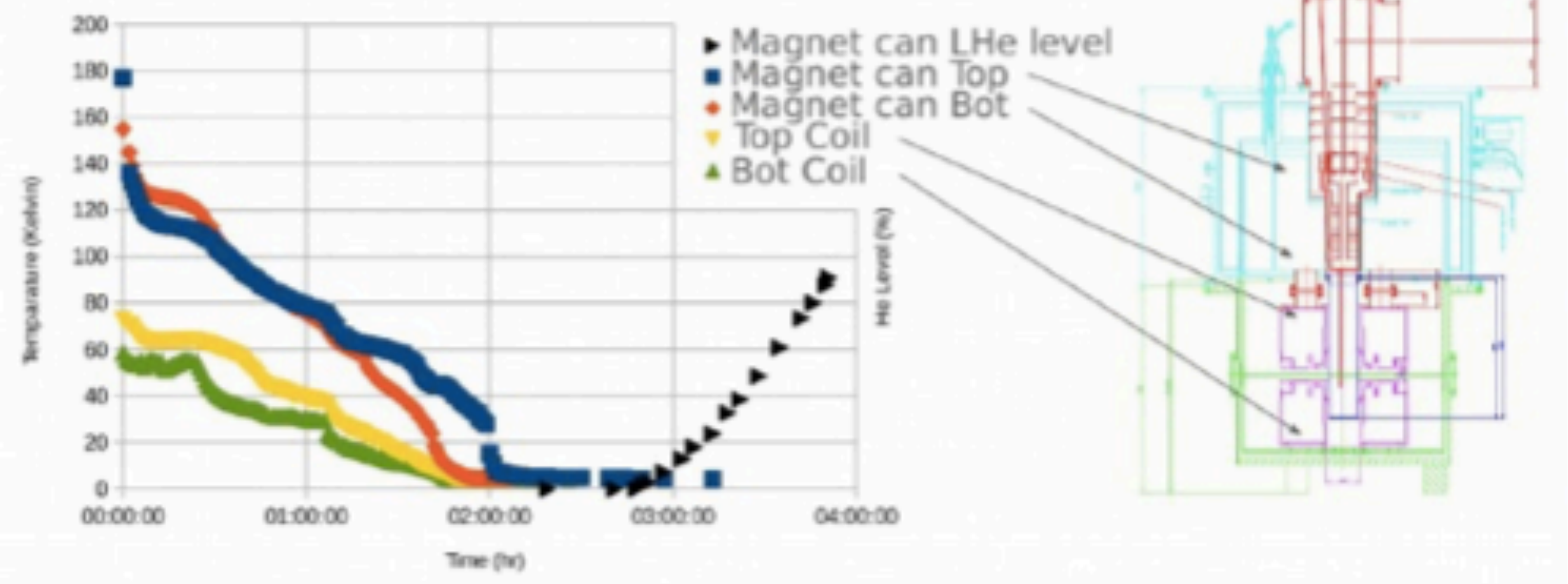


Insert in LN2



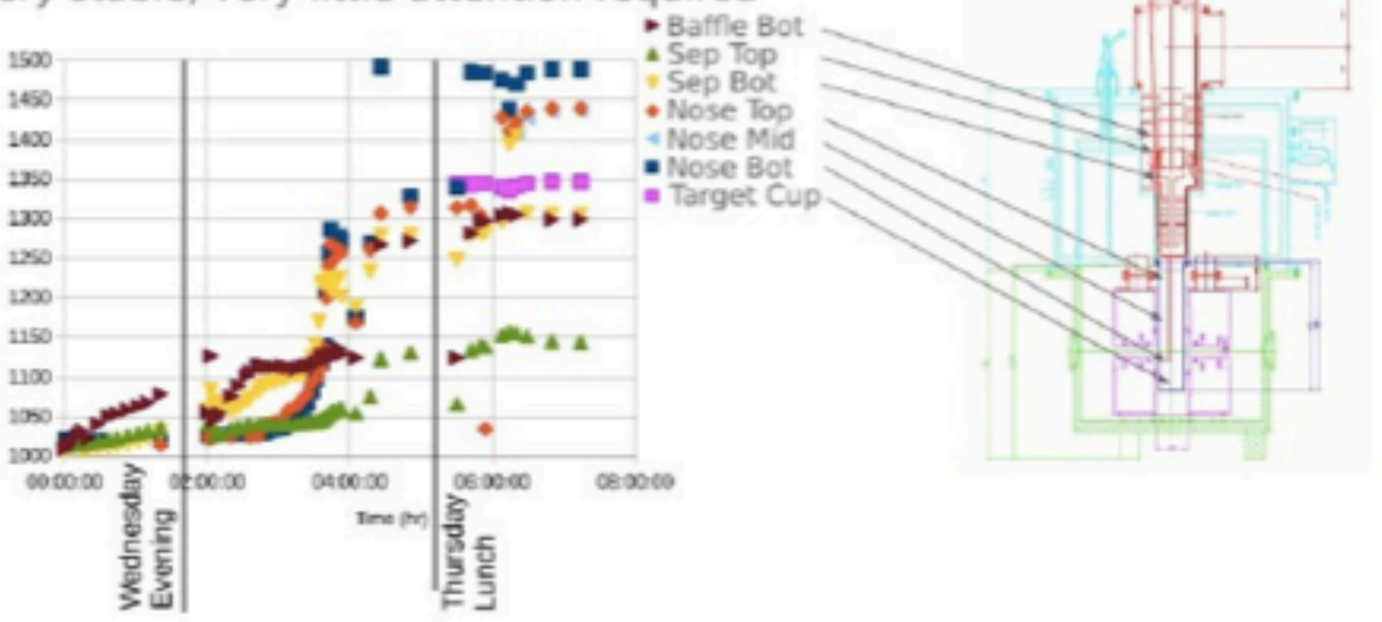
~2.5

~1 hr to to fill magnet can



~1hr to fill the nose after a night on standby

very stable, very little attention required

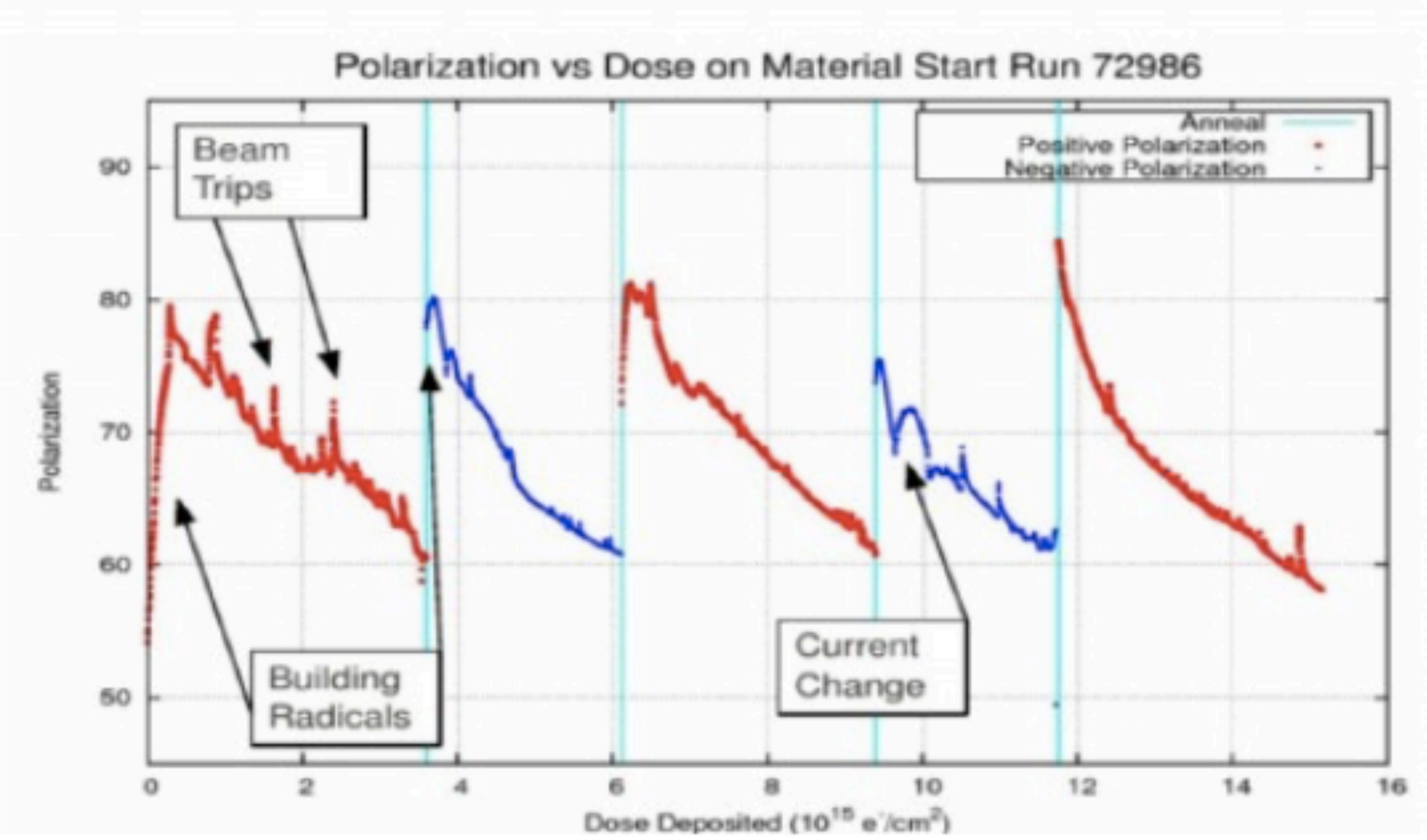


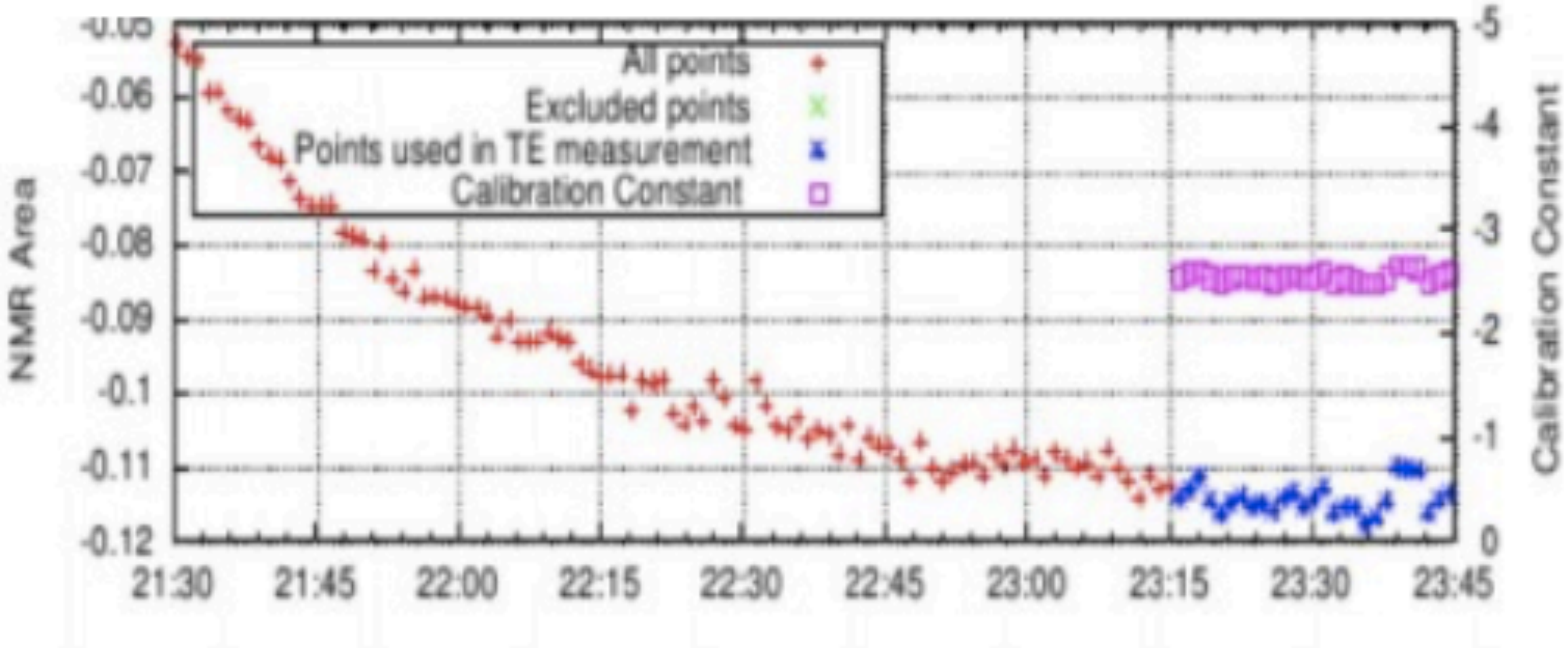
DNP Refrigerator

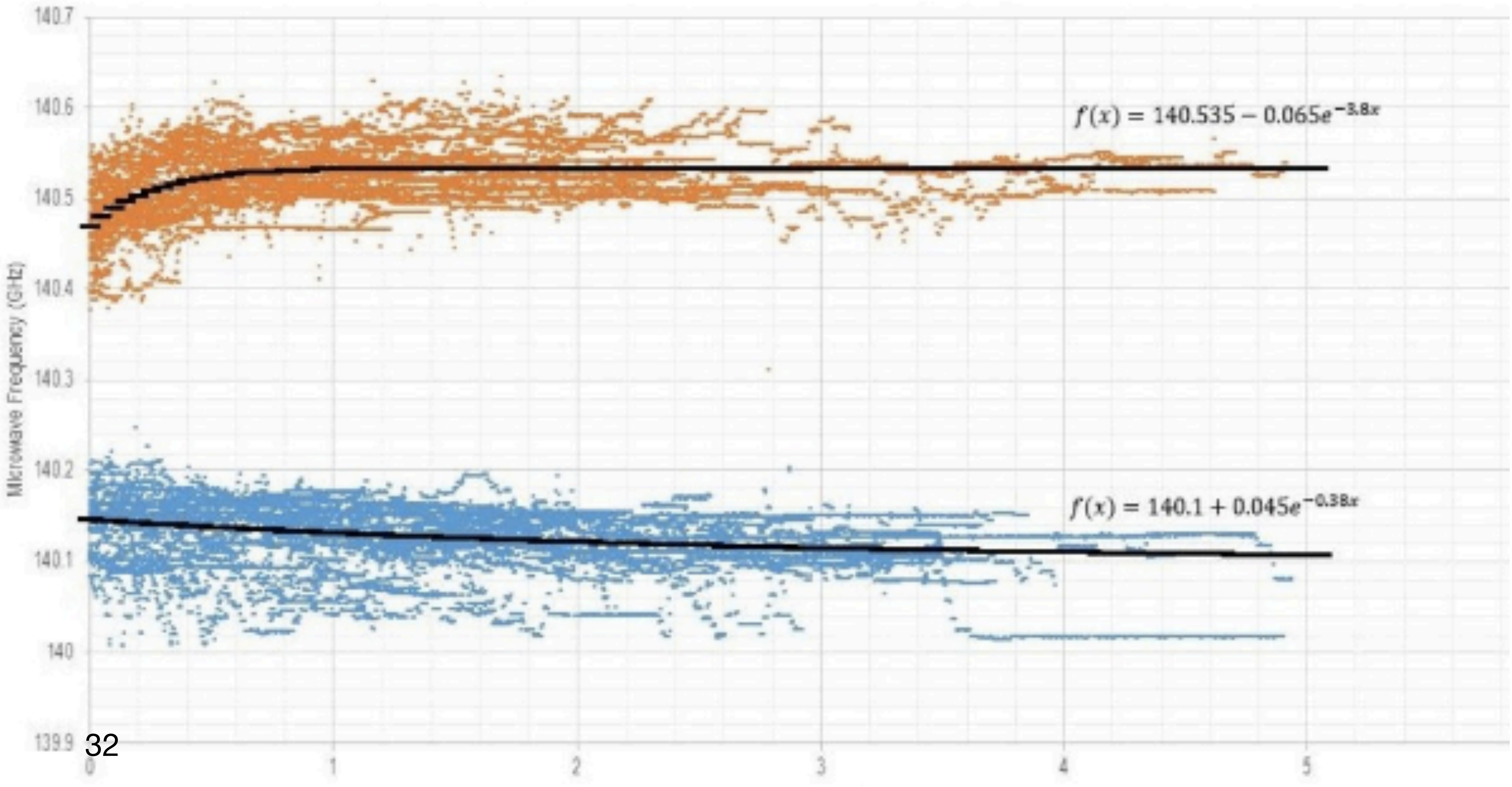
High Cooling Power Evaporation System

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.







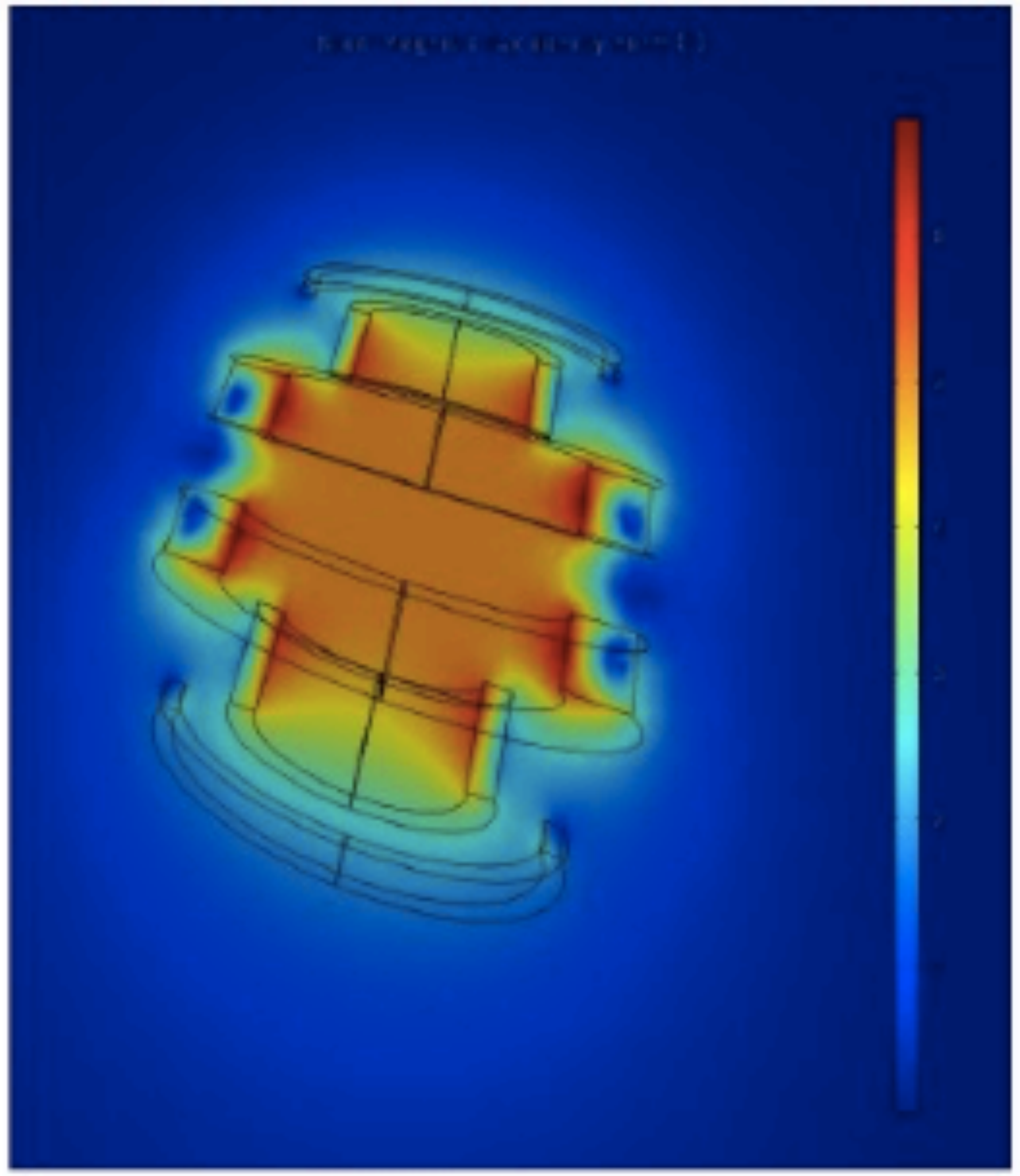
Field Measurement and Map

Measure Homogeneity using NMR and Hall Probe

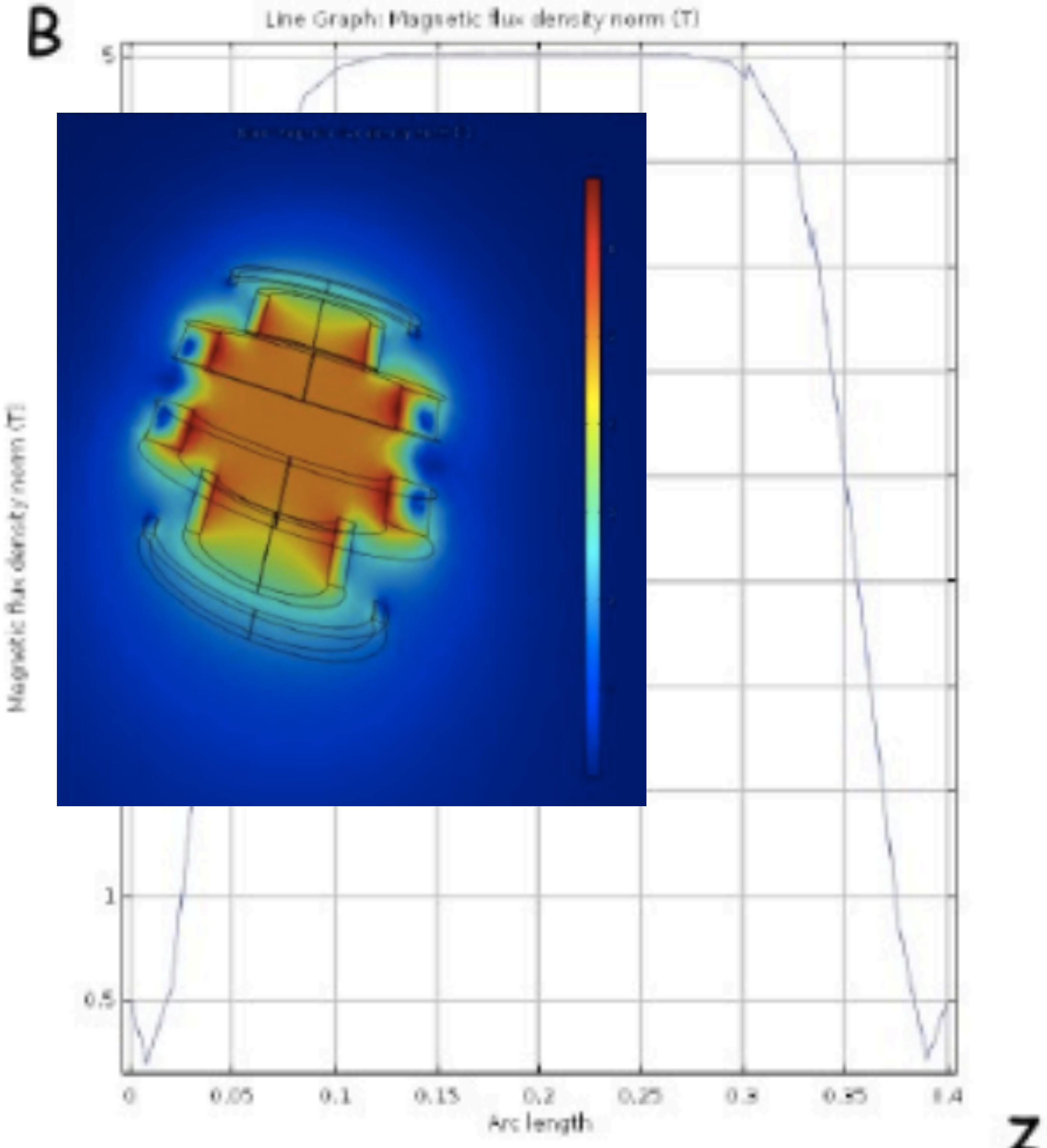
Accurate Field Map ✓

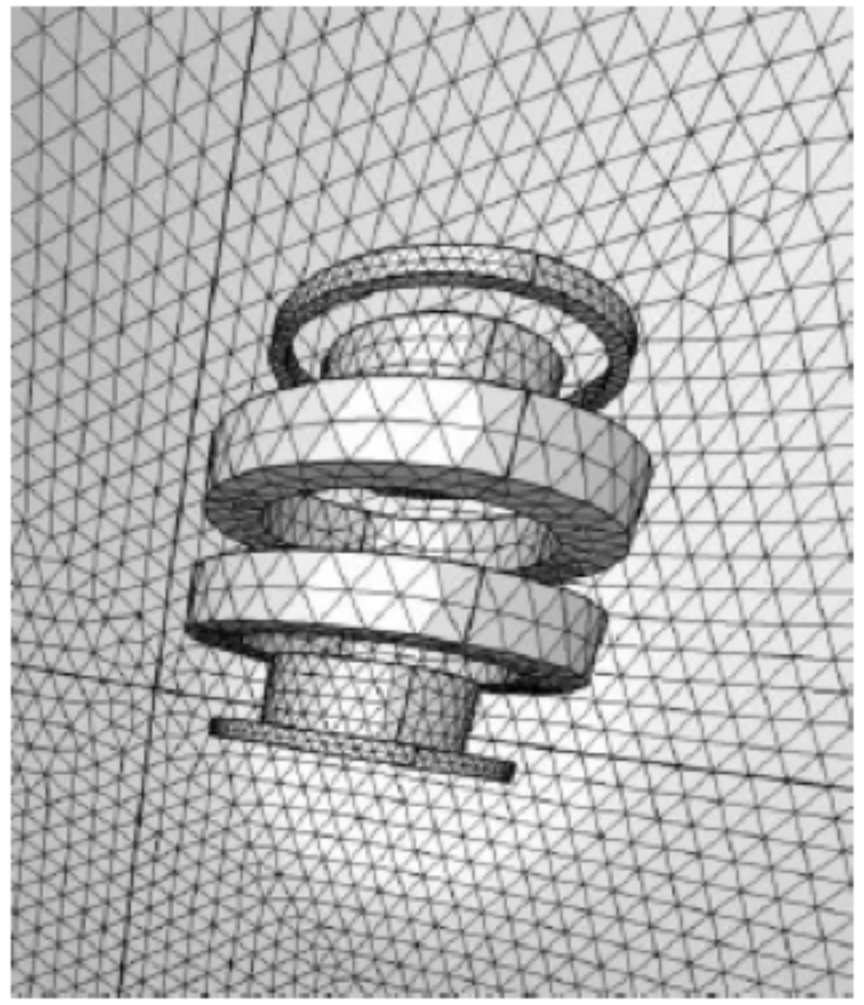
Measure outside fringe field and map to simulated field

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

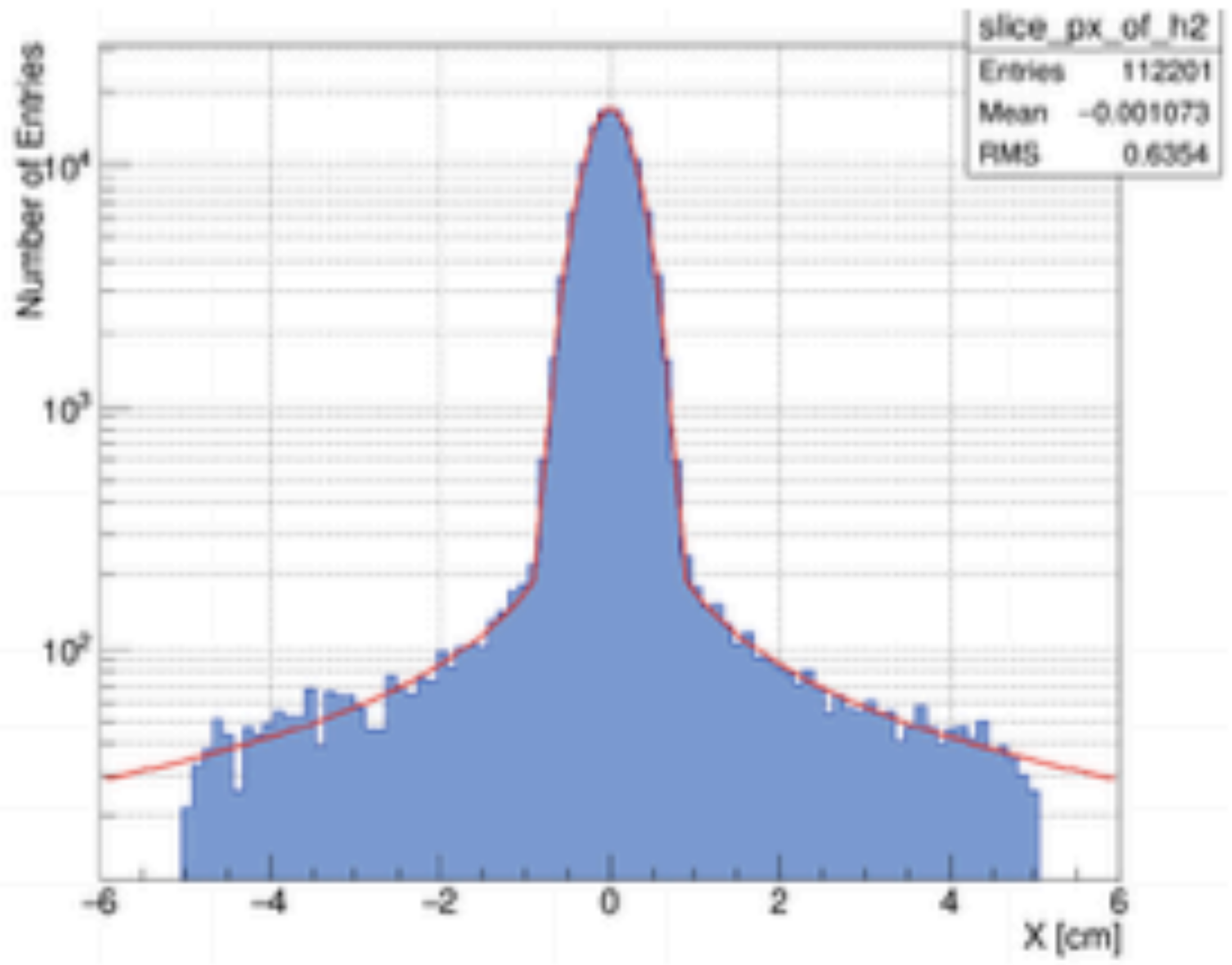


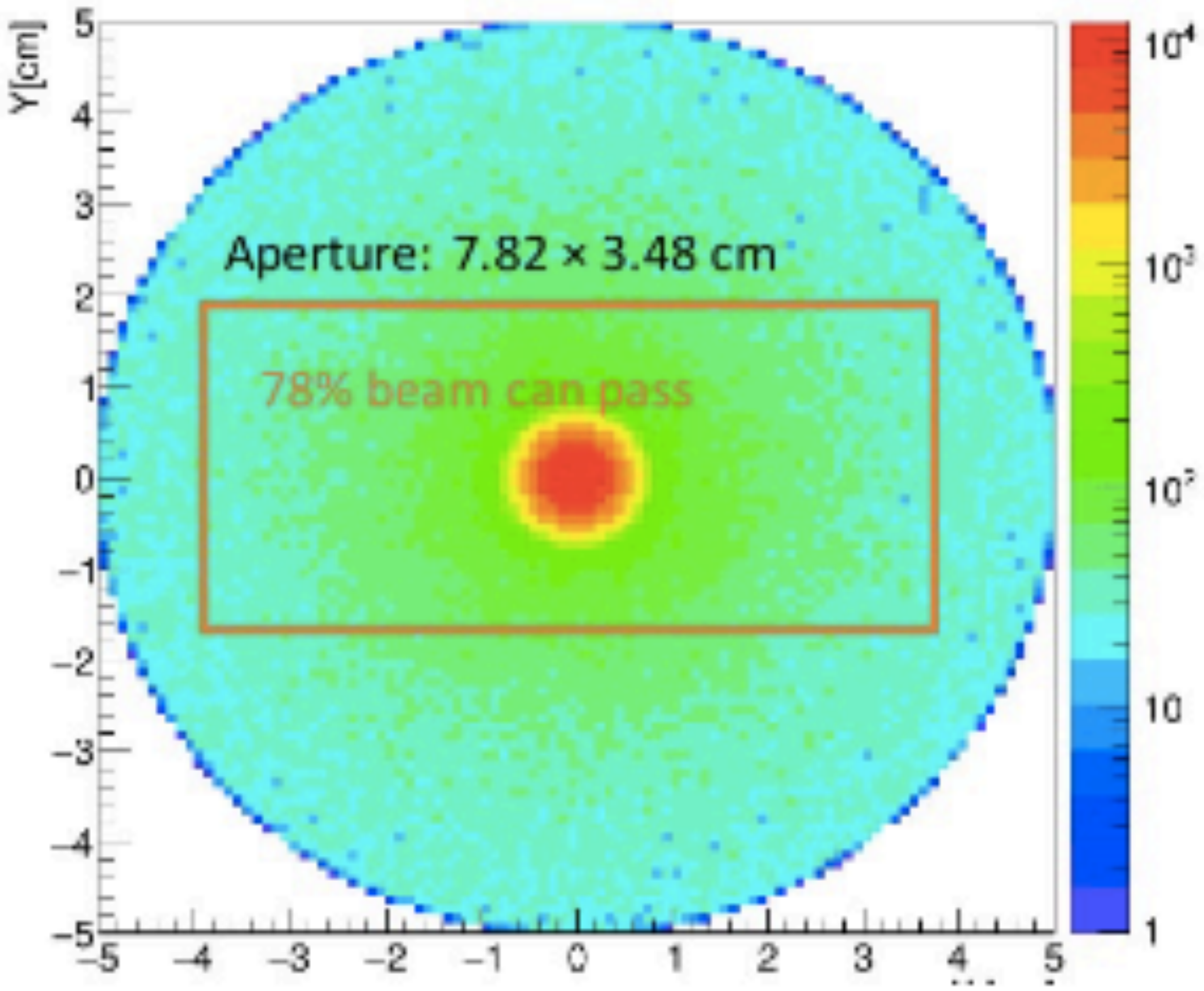
High level of homogeneity in the target area

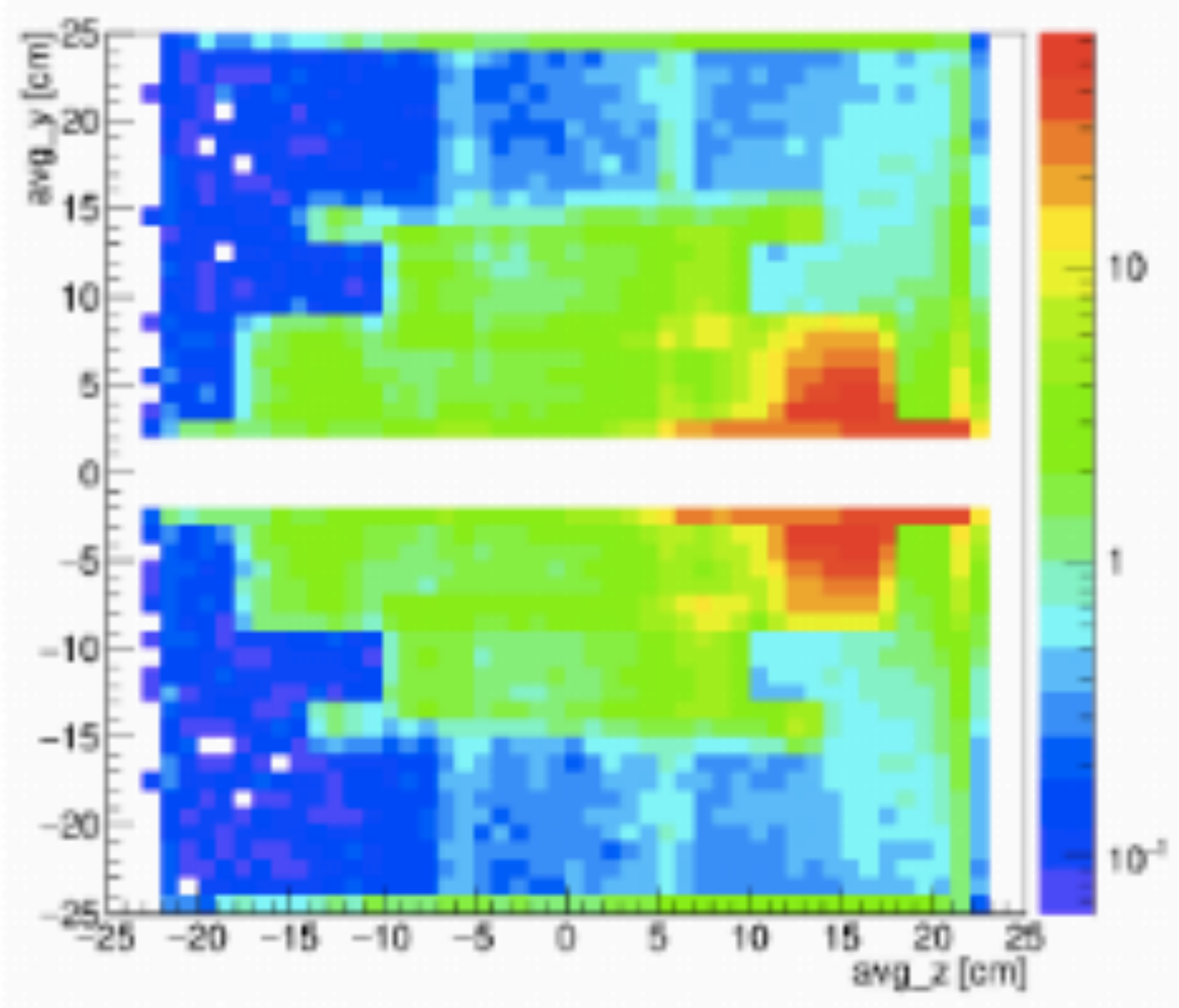


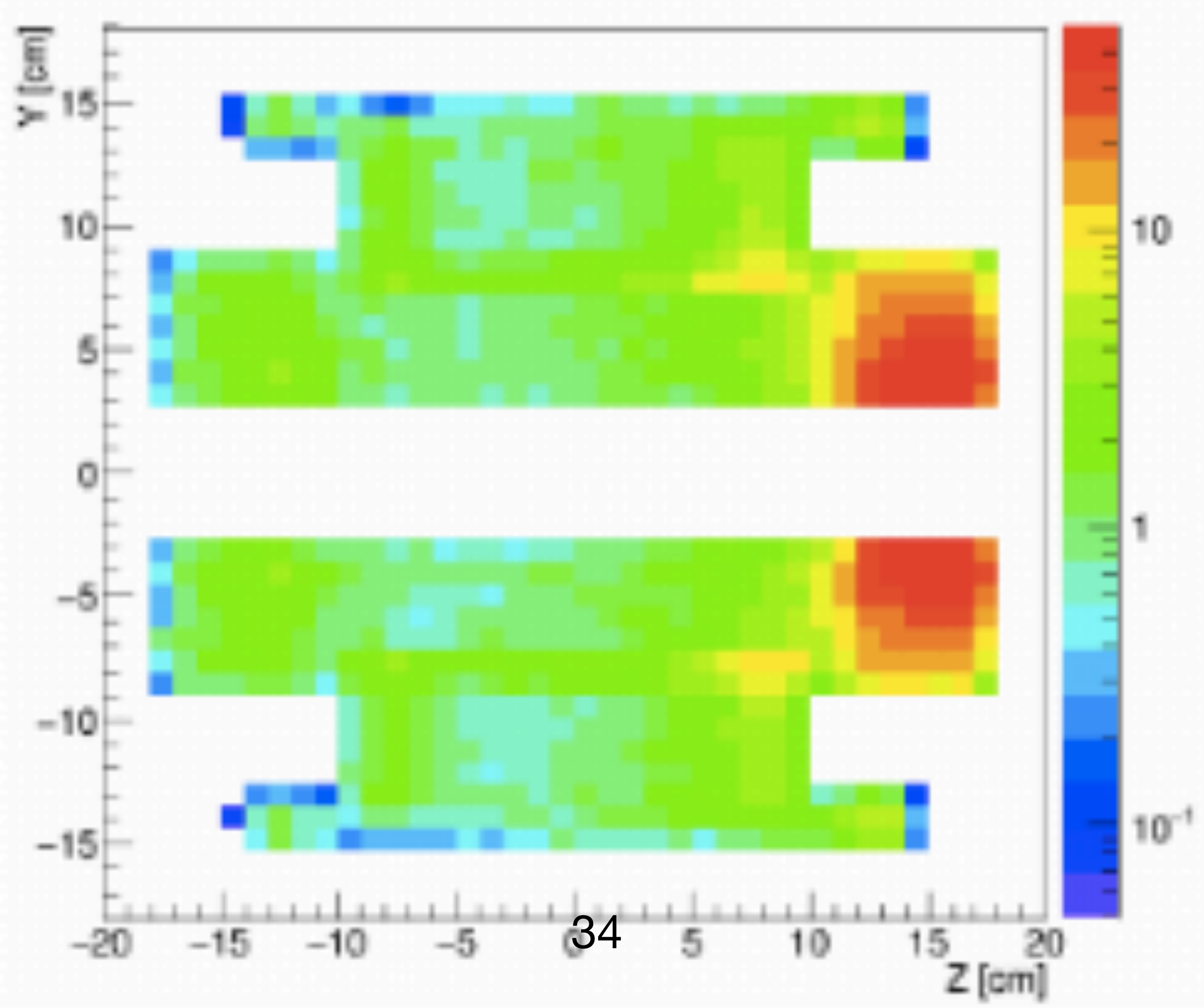


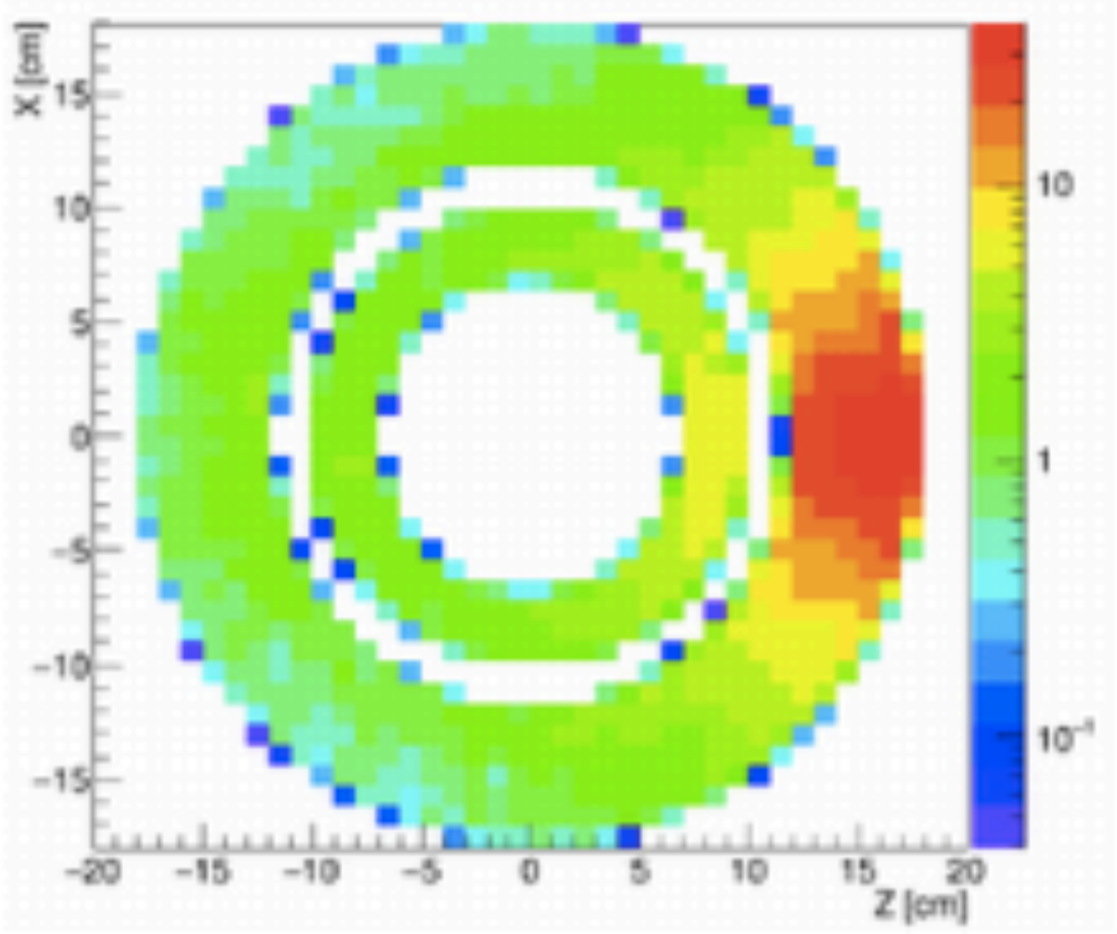
Geant → COMSOL





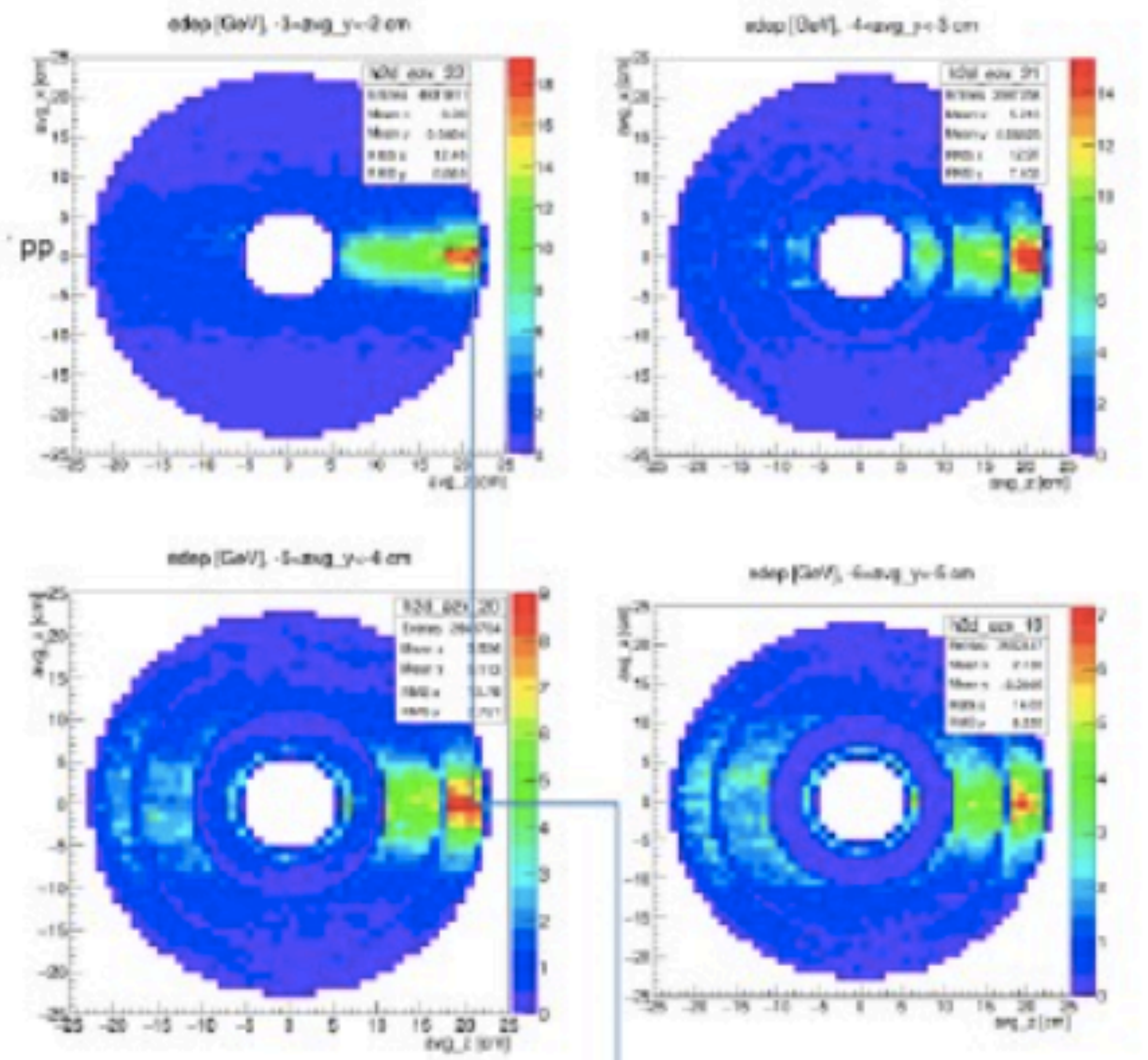






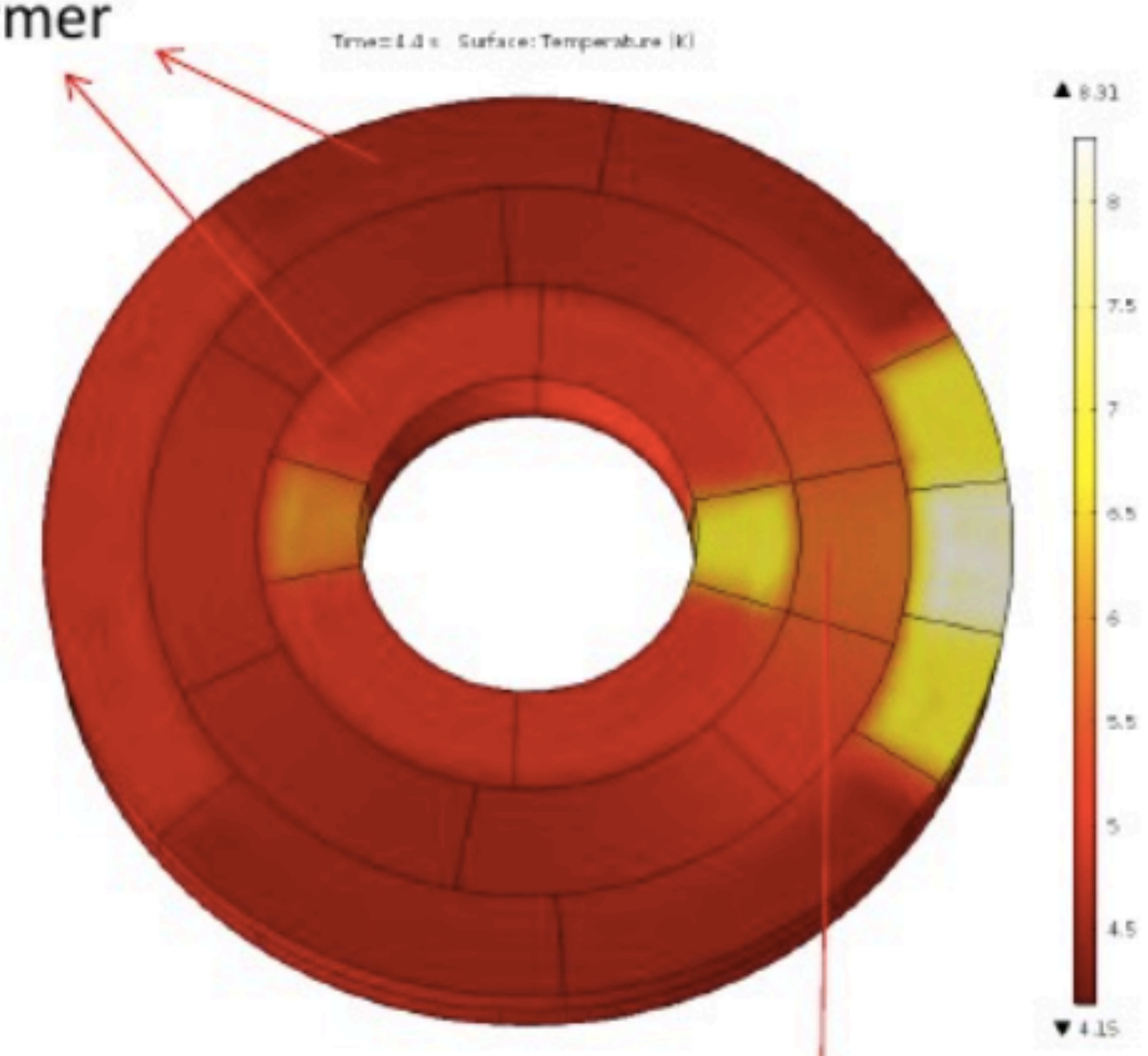
Quench Simulations

What we have currently



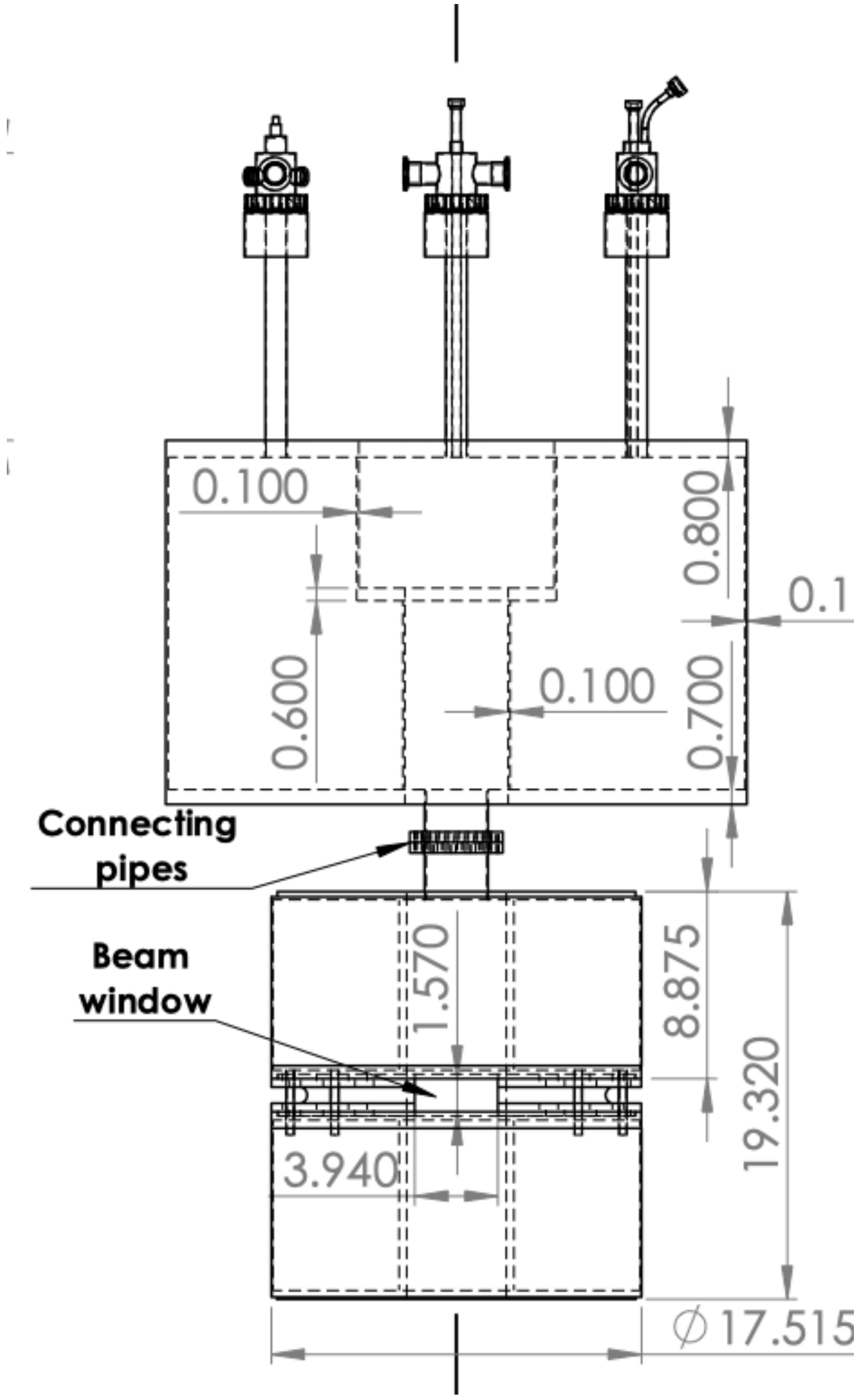
Maximum hot spot
around 18000 W/m^3

Former



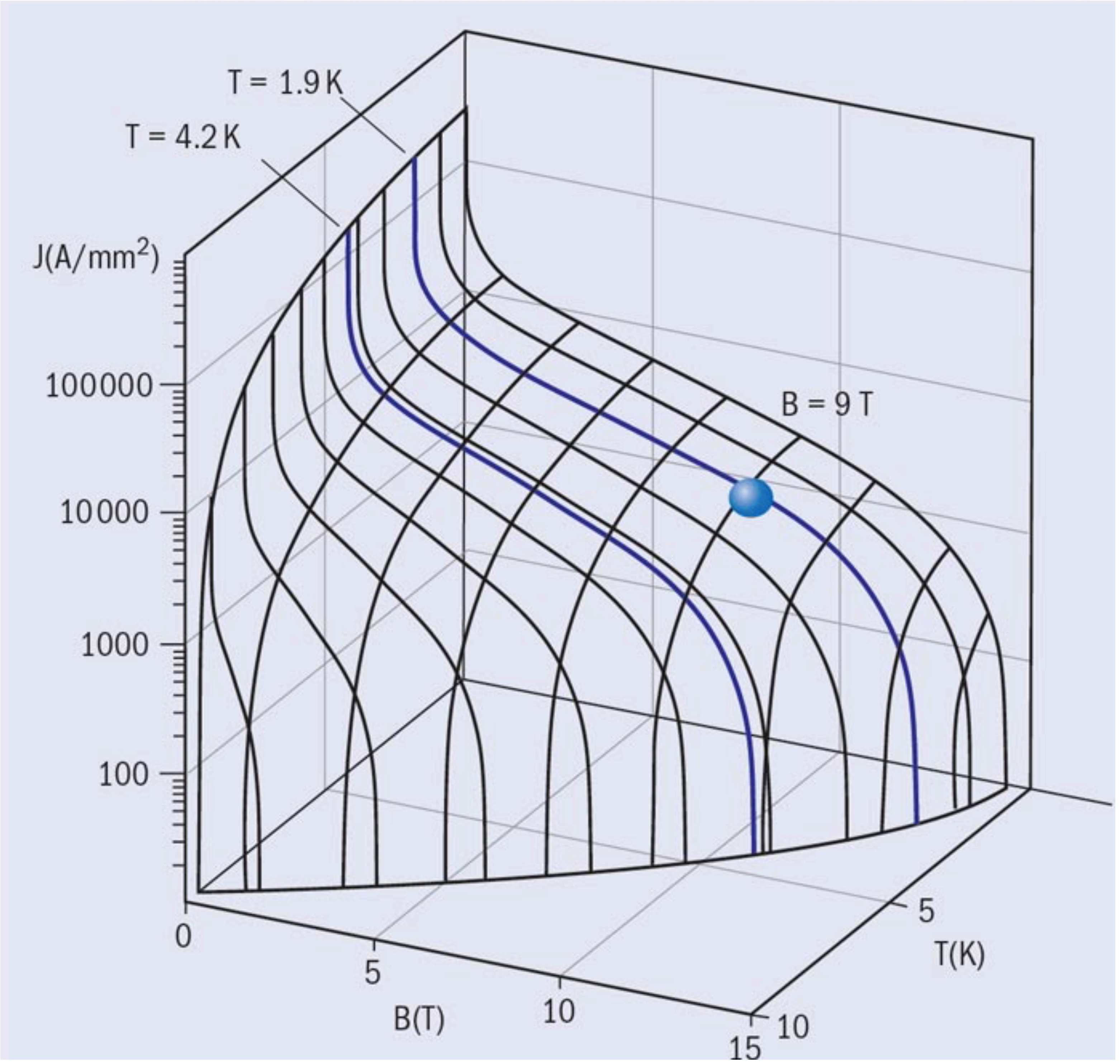
Simulation result

Maximum temperature of
coil around 5.7 K



Superconducting Magnet

Introduction: Quench definition



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

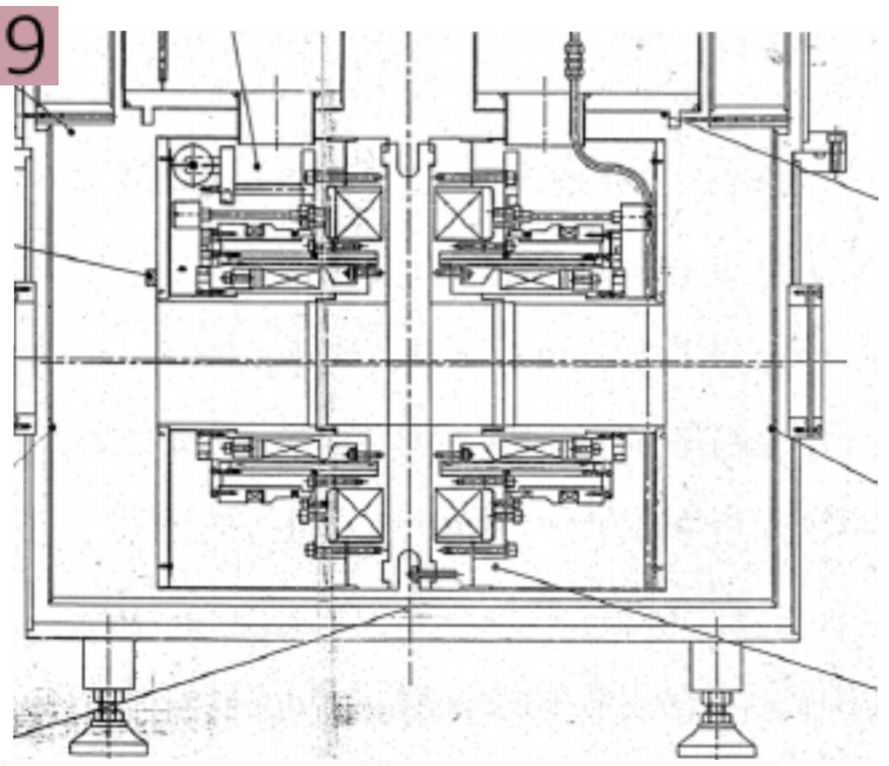
Magnet quench if the T, B or J lie outside the critical surface

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

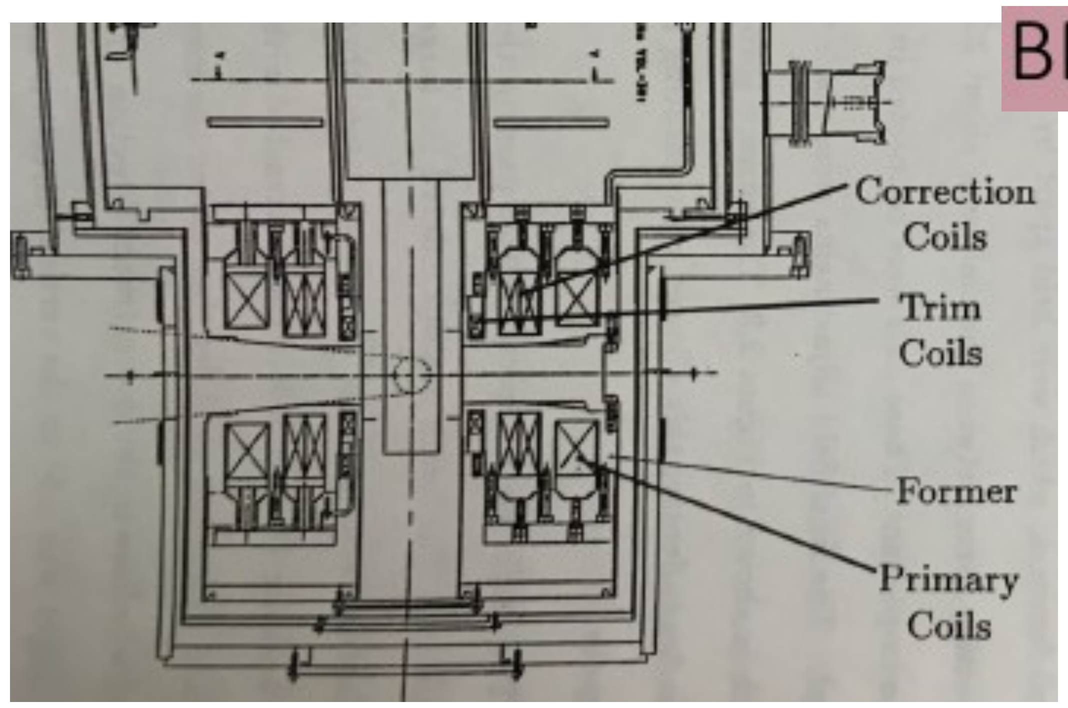
5T NbTi (Niobium-Titanium)

Magnet Comparison

E1039

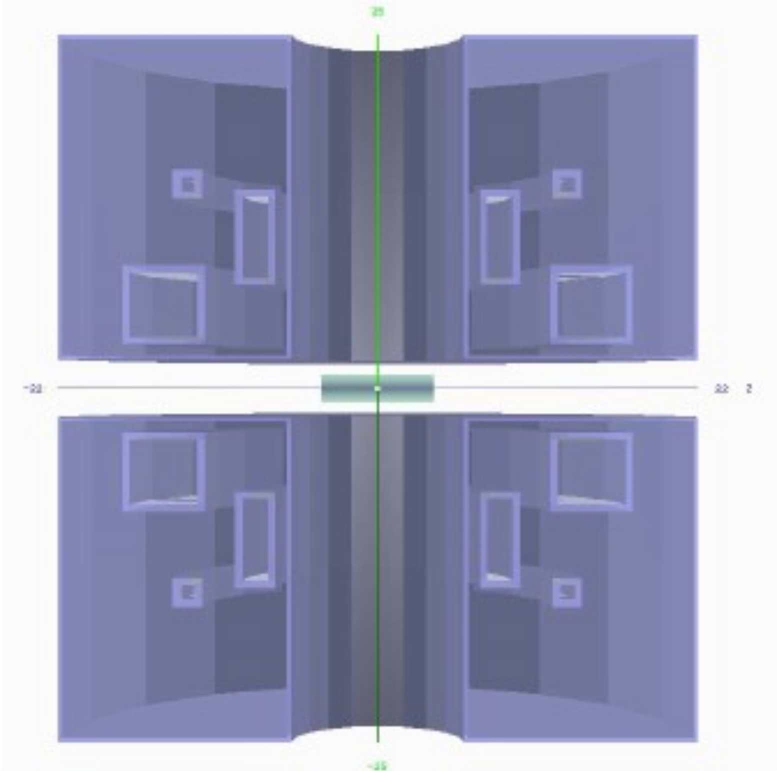


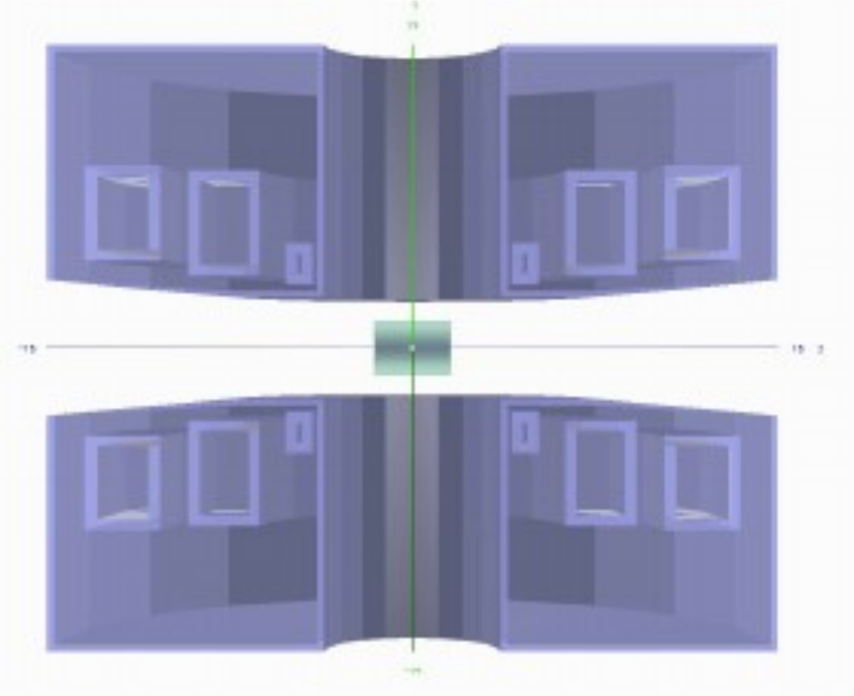
BNL target



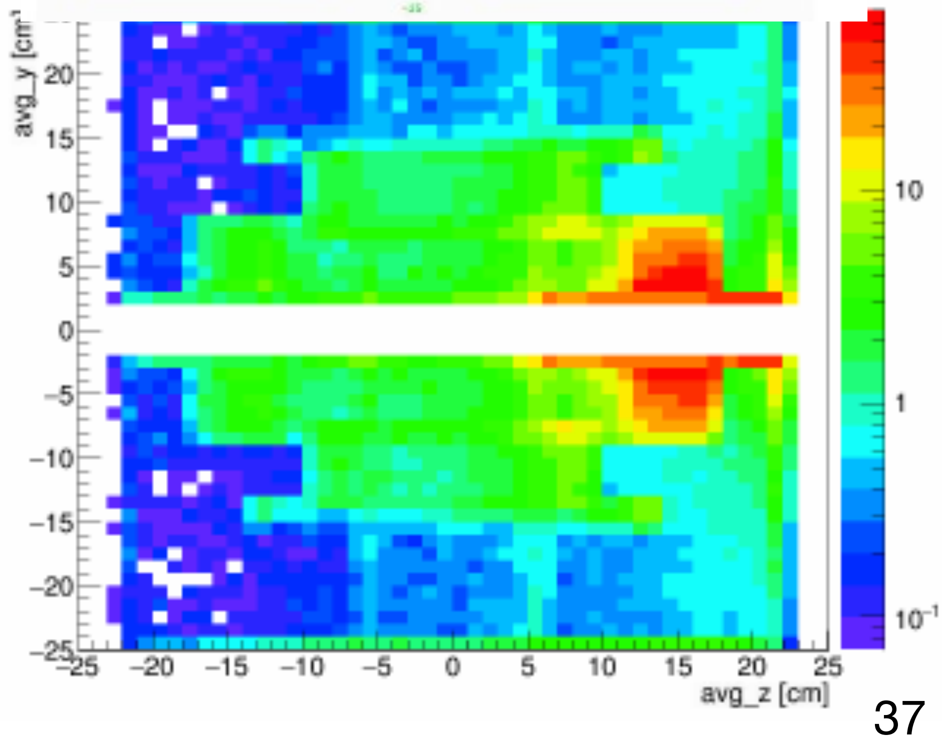
Solidworks → Geat4

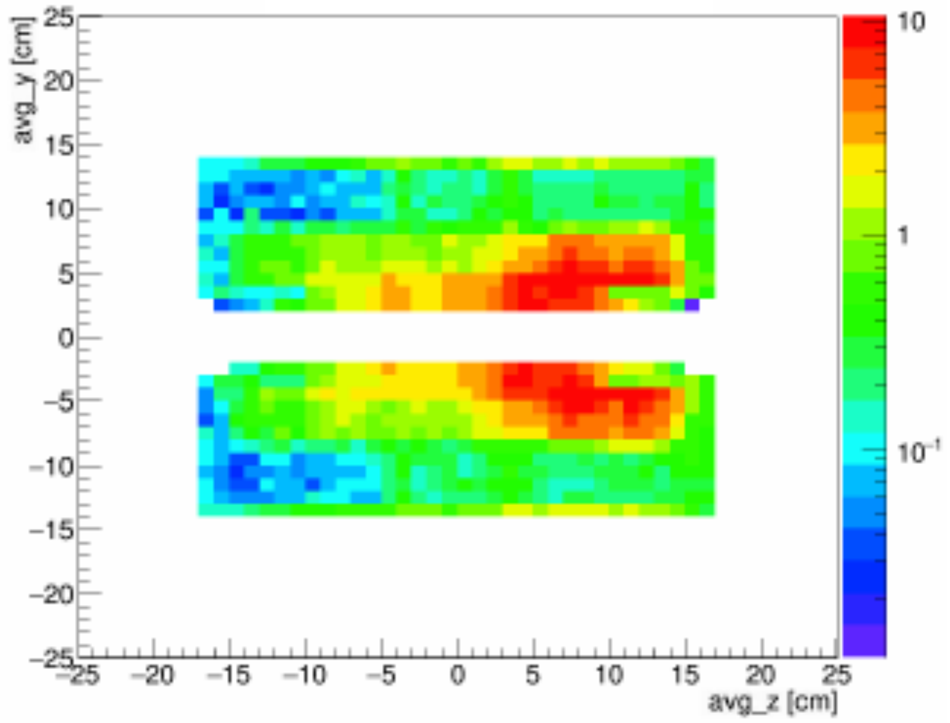
Based on drawings and measurements





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





Then look at energy deposition in the SC coils

Superconducting Magnet Quench Studies

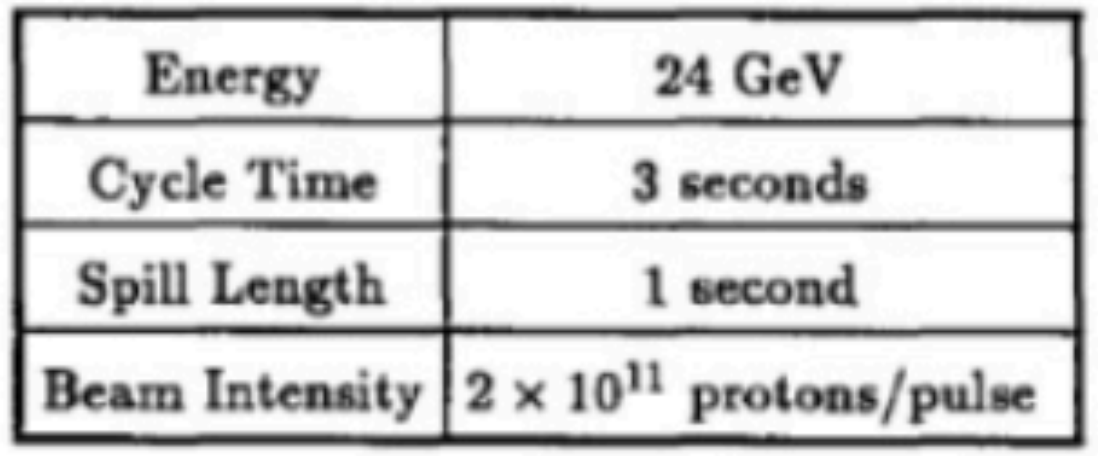
Comparison

SpinQuest

- Cycle Time: Every 55.6 seconds
- Spill Length: 4.4 seconds
- Beam Intensity: 1.0X10^{12} protons/sec

vs

BNL:



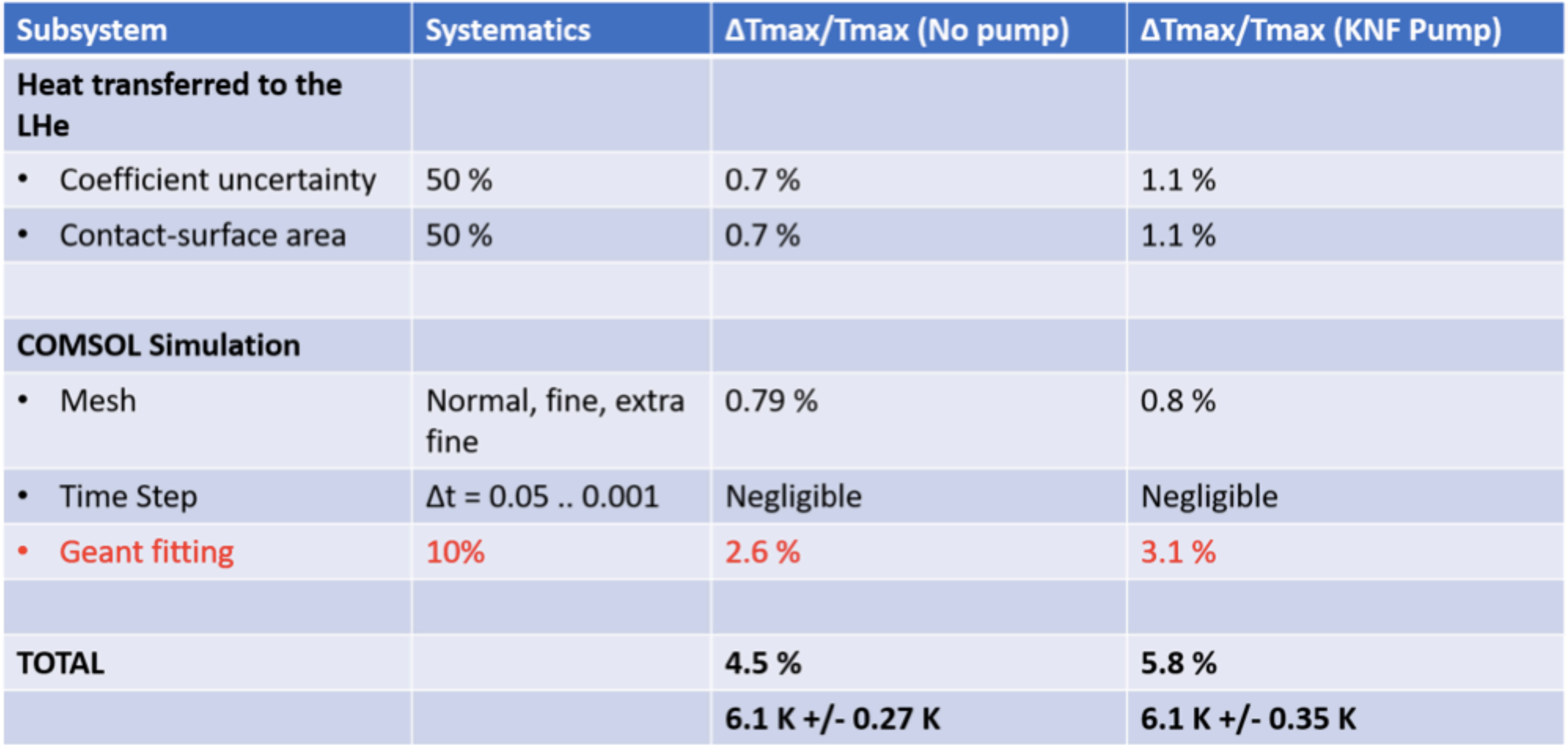
Energy	24 GeV
Cycle Time	3 seconds
Spill Length	1 second
Beam Intensity	2×10^{11} protons/pulse

Limiting Factors: - Fridge Cooling Power
- Heat load to SC Magnet
- Cycle Time

BNL : 4.0X10^{12} protons/min - 4 cm
FNAL : 5-4.4X10^{12} protons/min - 8 cm

- Running at 20 SLPM ~1.4 W
- For 4.4s ~1 W heat-load from beam
- DNP ~0.5 W heat-load from microwaves
- Superconducting magnet critical temperature 7.5 K at 5 T
- Beam cycle important factor

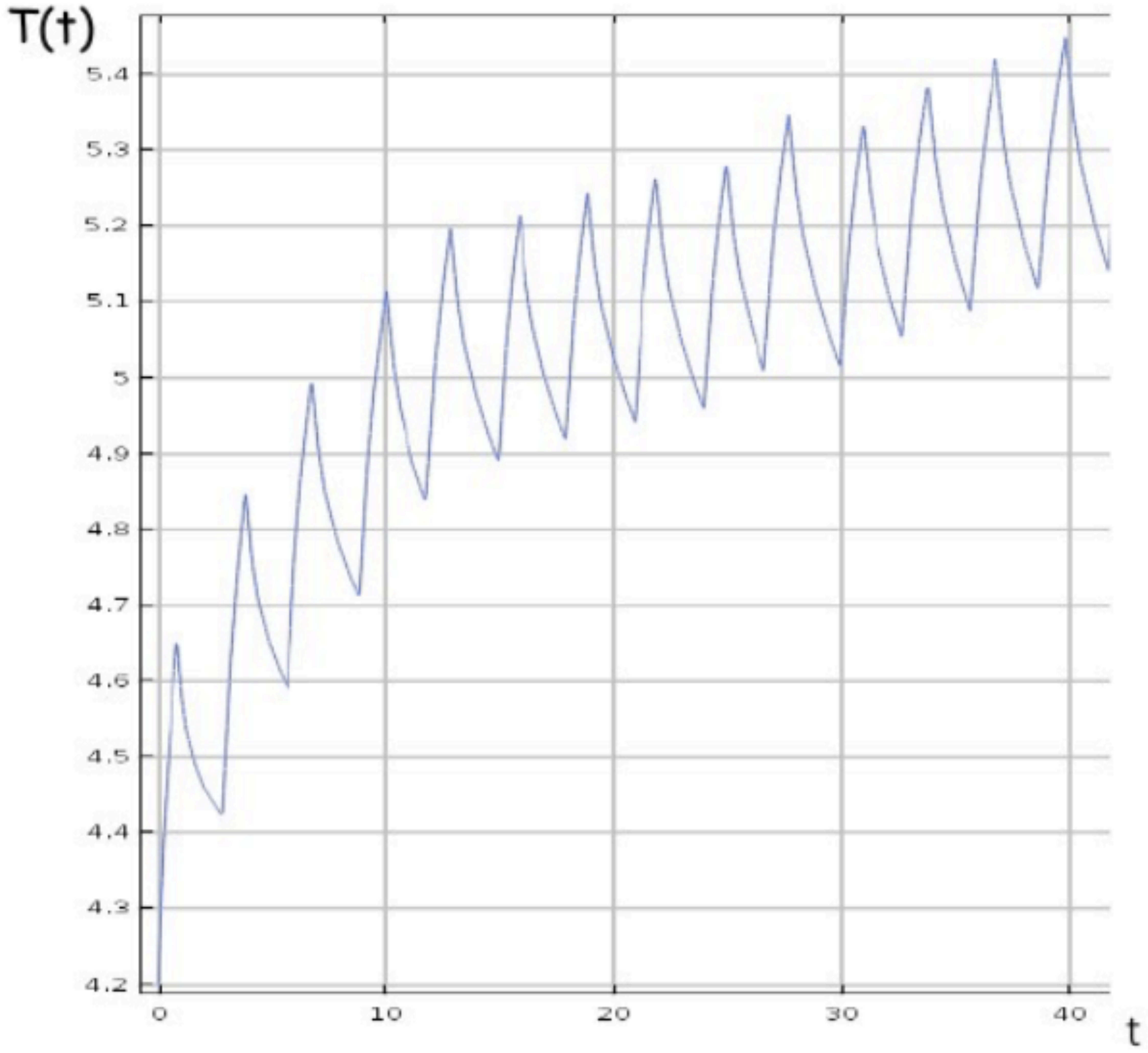
Systematic Uncertainties



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**

Results on BNL experiment

The maximum temperature of the coil as a function of time



Maximum Temperature profile Tmax(t) for BNL:

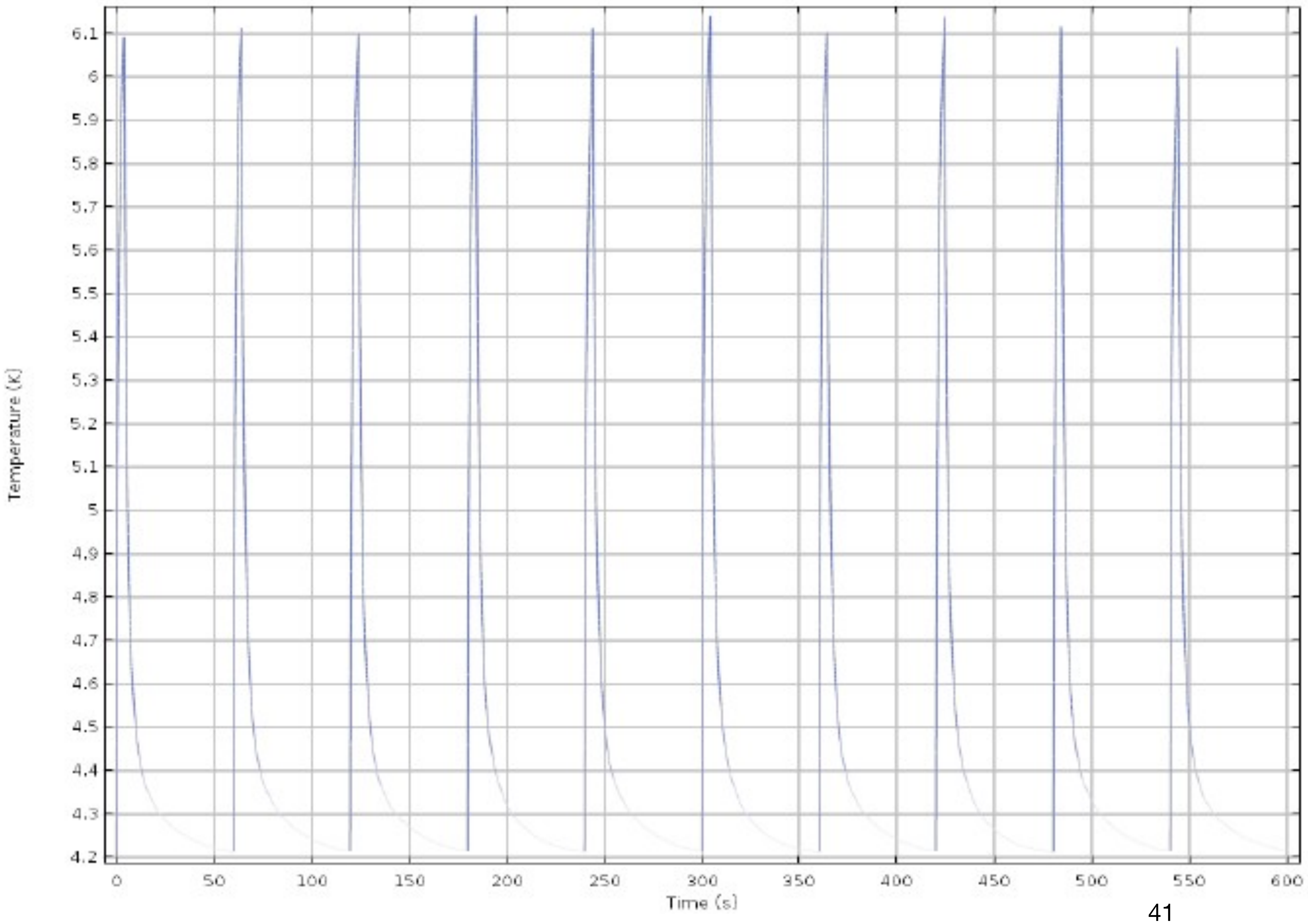
- 24 GeV proton
- 2e11 proton/s
- Teflon Target

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

SpinQuest Target Magnet

The maximum temperature of the coil as a function of time

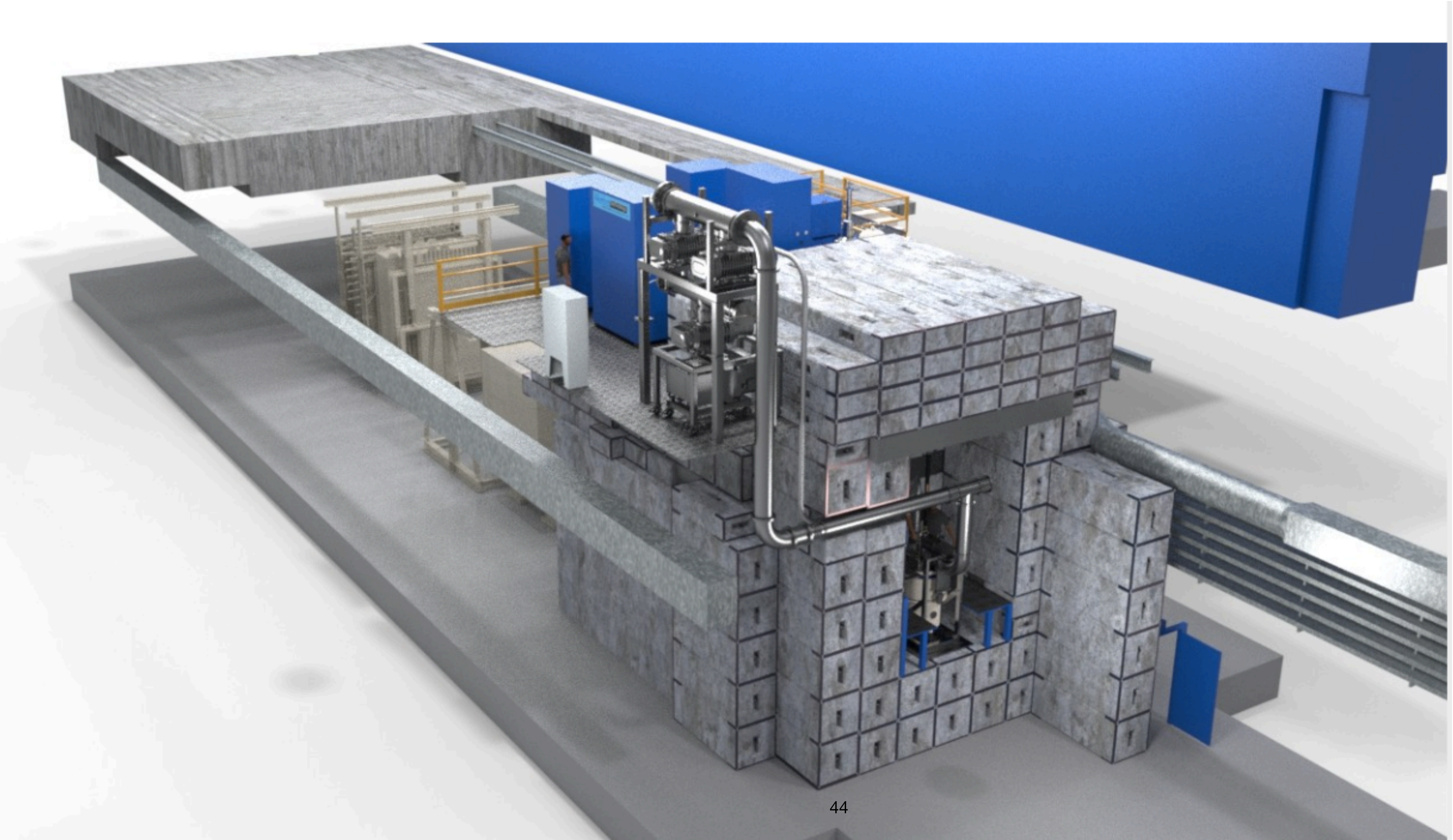


Maximum Temperature profile Tmax(t) for E1039:

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


Station 3
Upper
Low

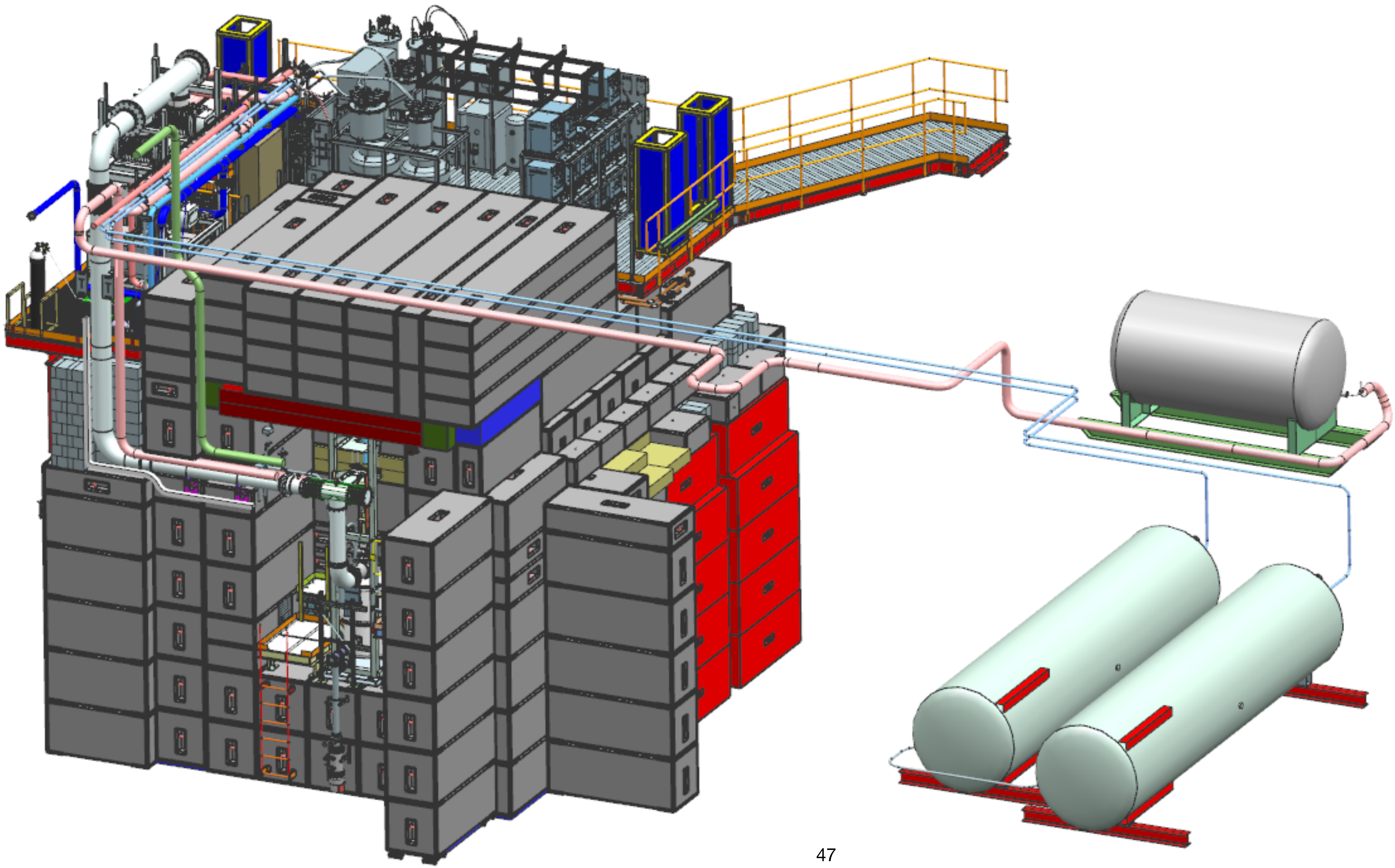
SpinQuest Experimental Hall



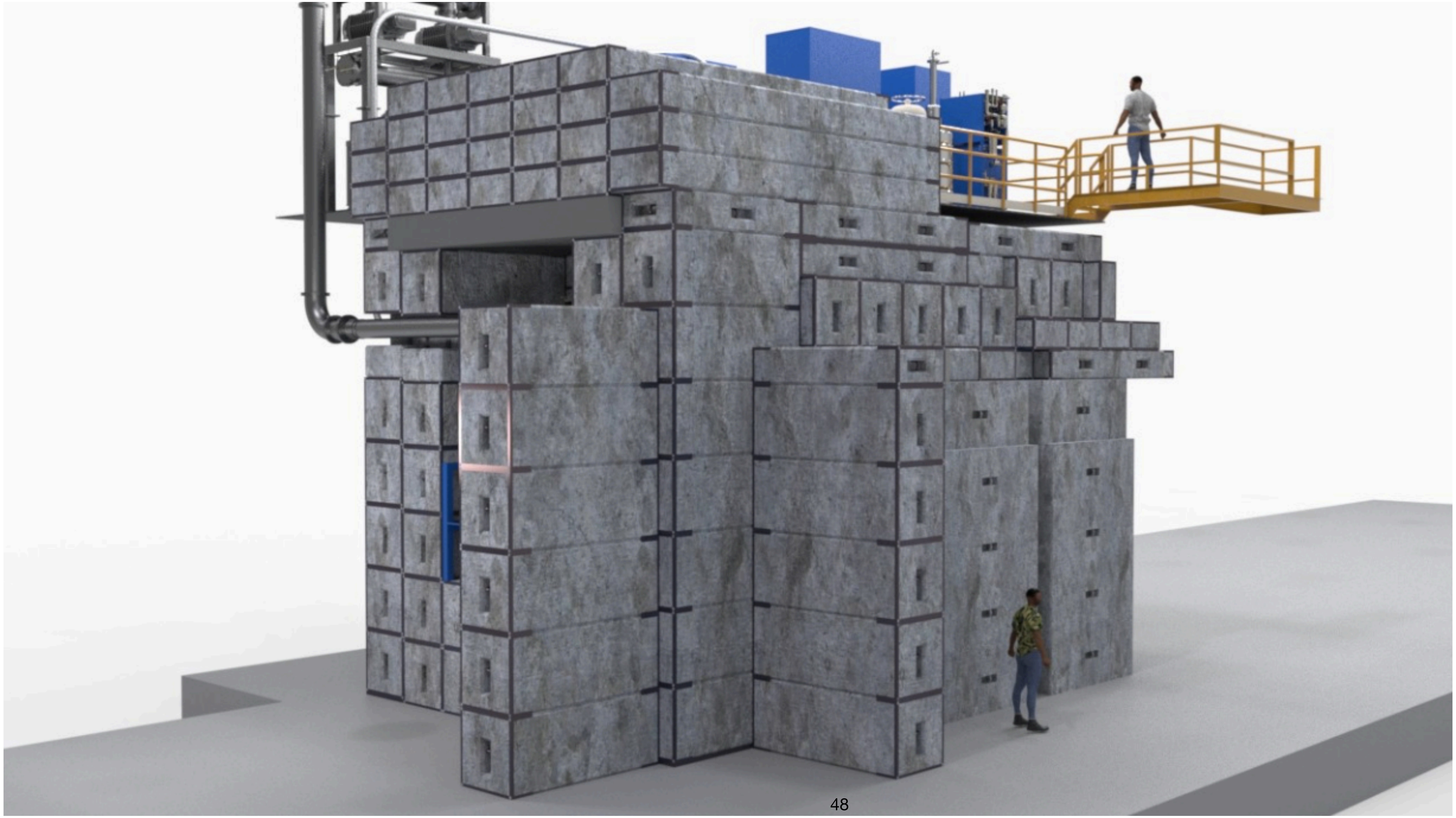
Cryo-platform

Top of Target Cave

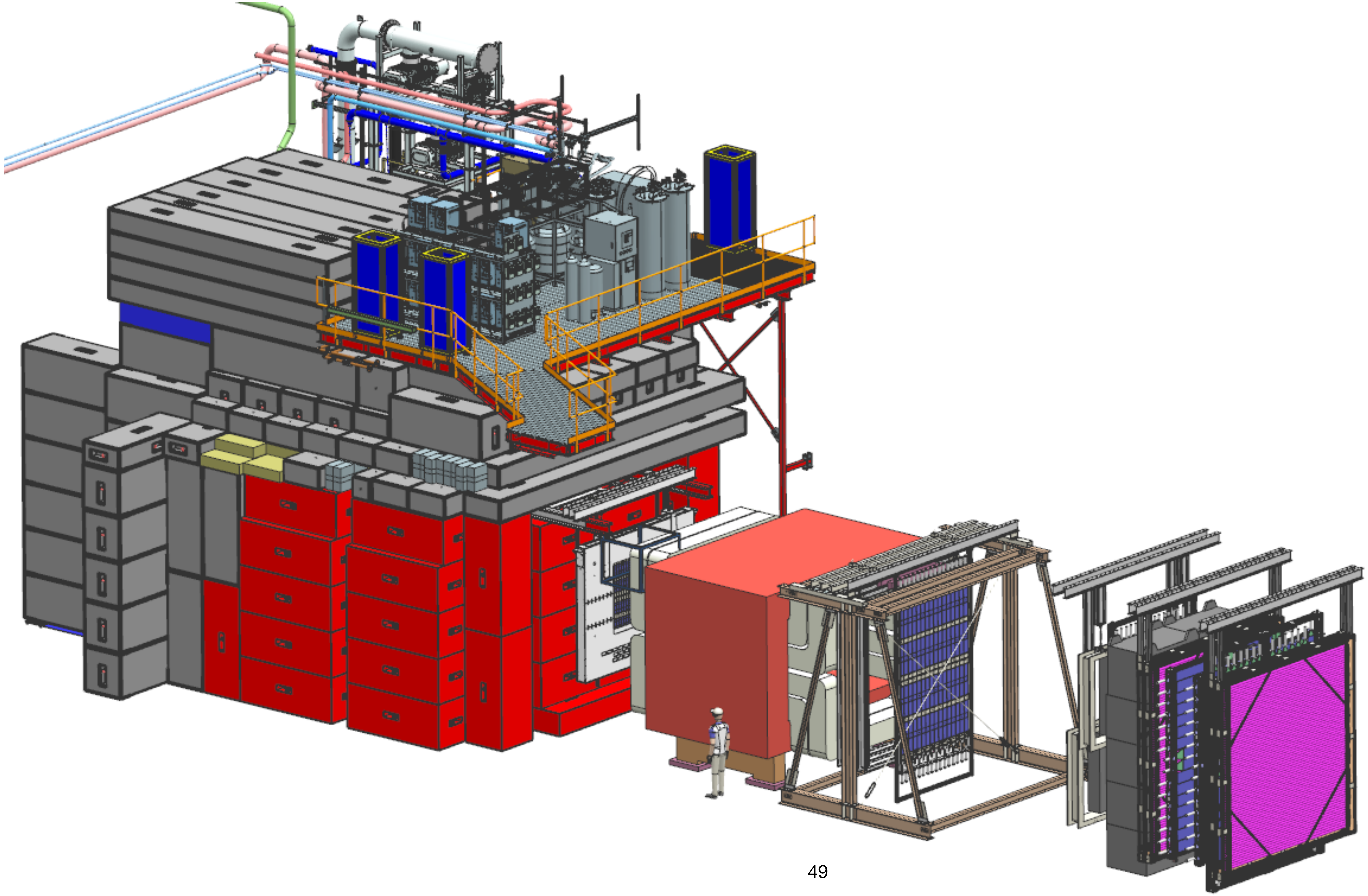
Helium and Nitrogen Supplies

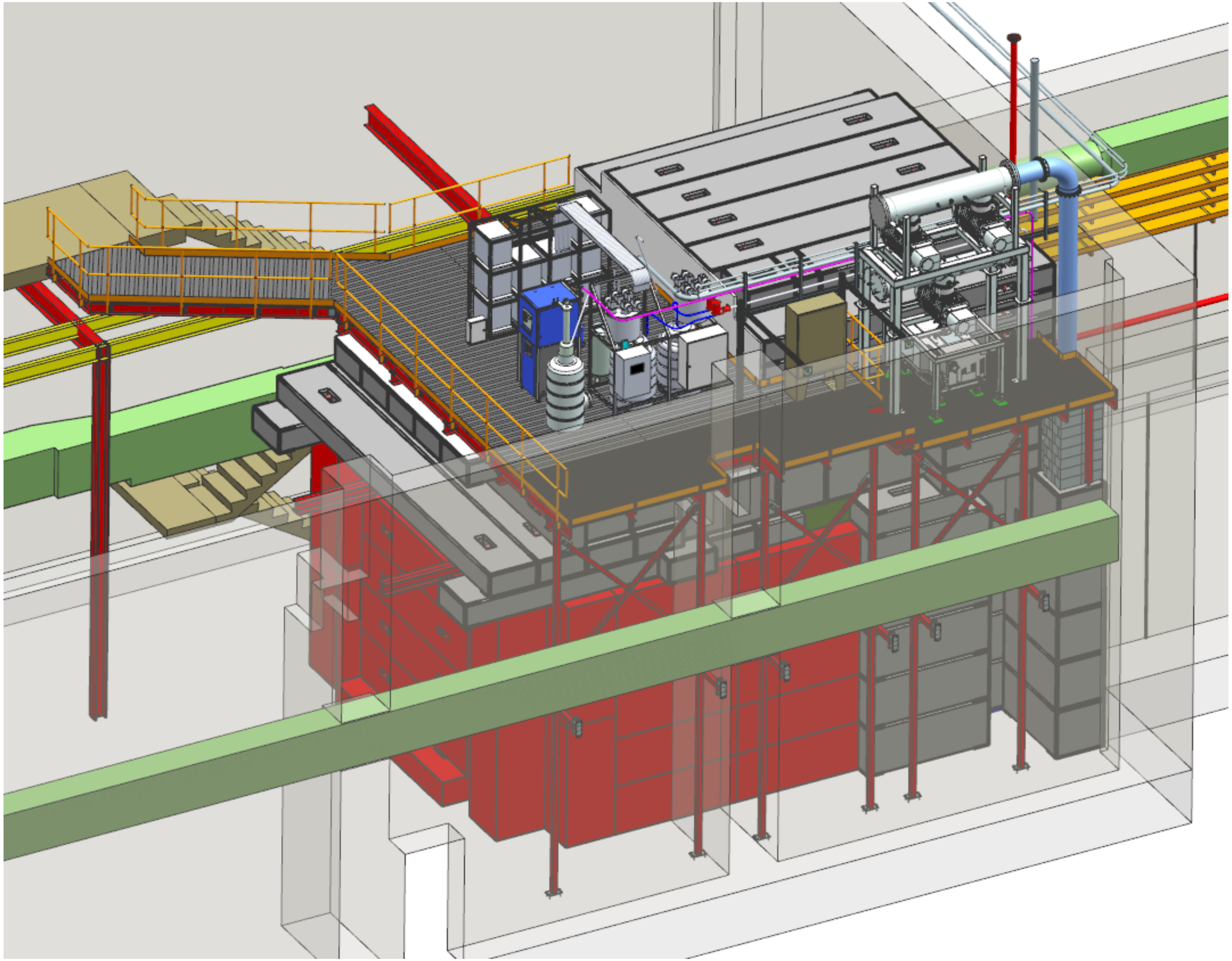


Target Cave and Cryo-platform

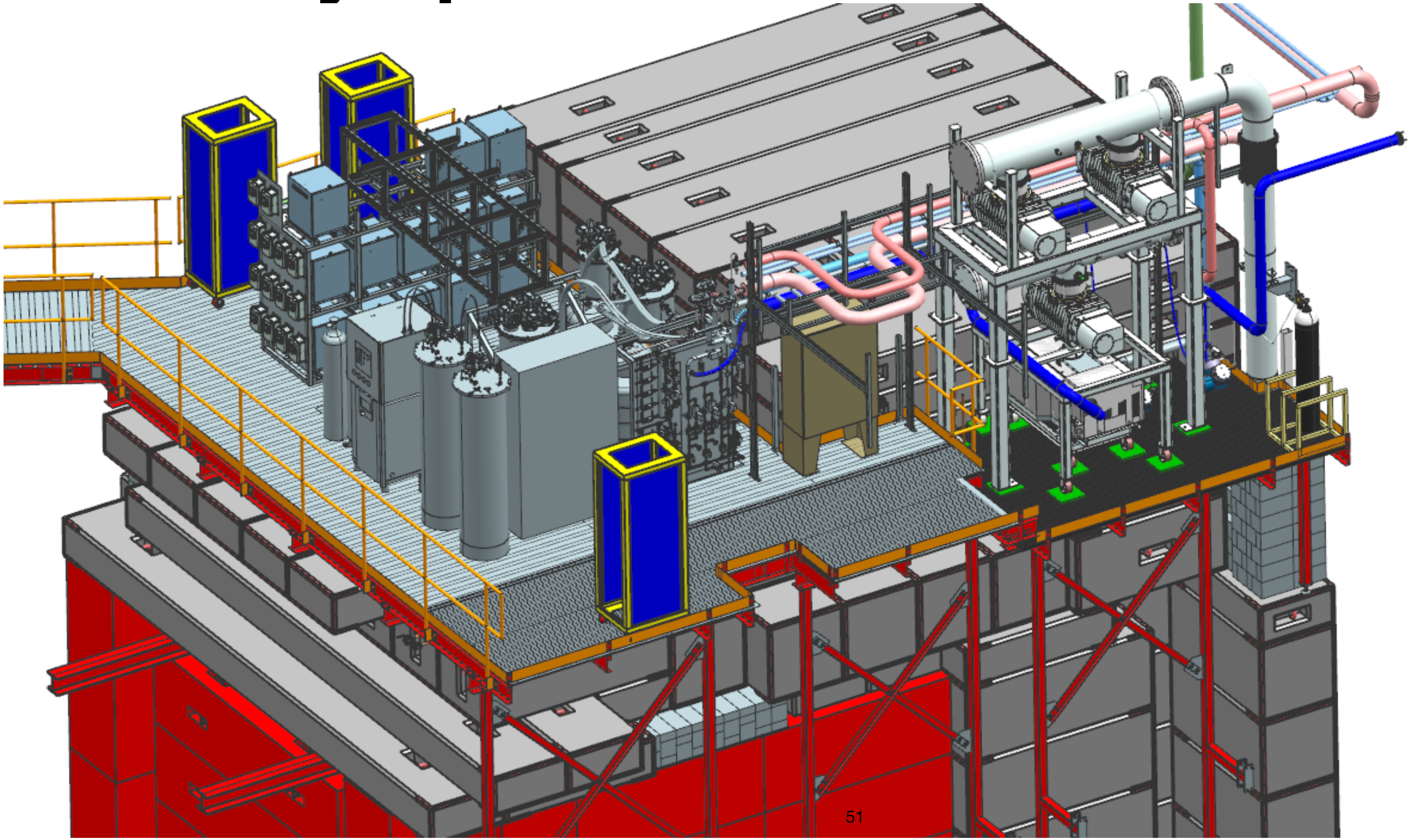


Full Detector and Target

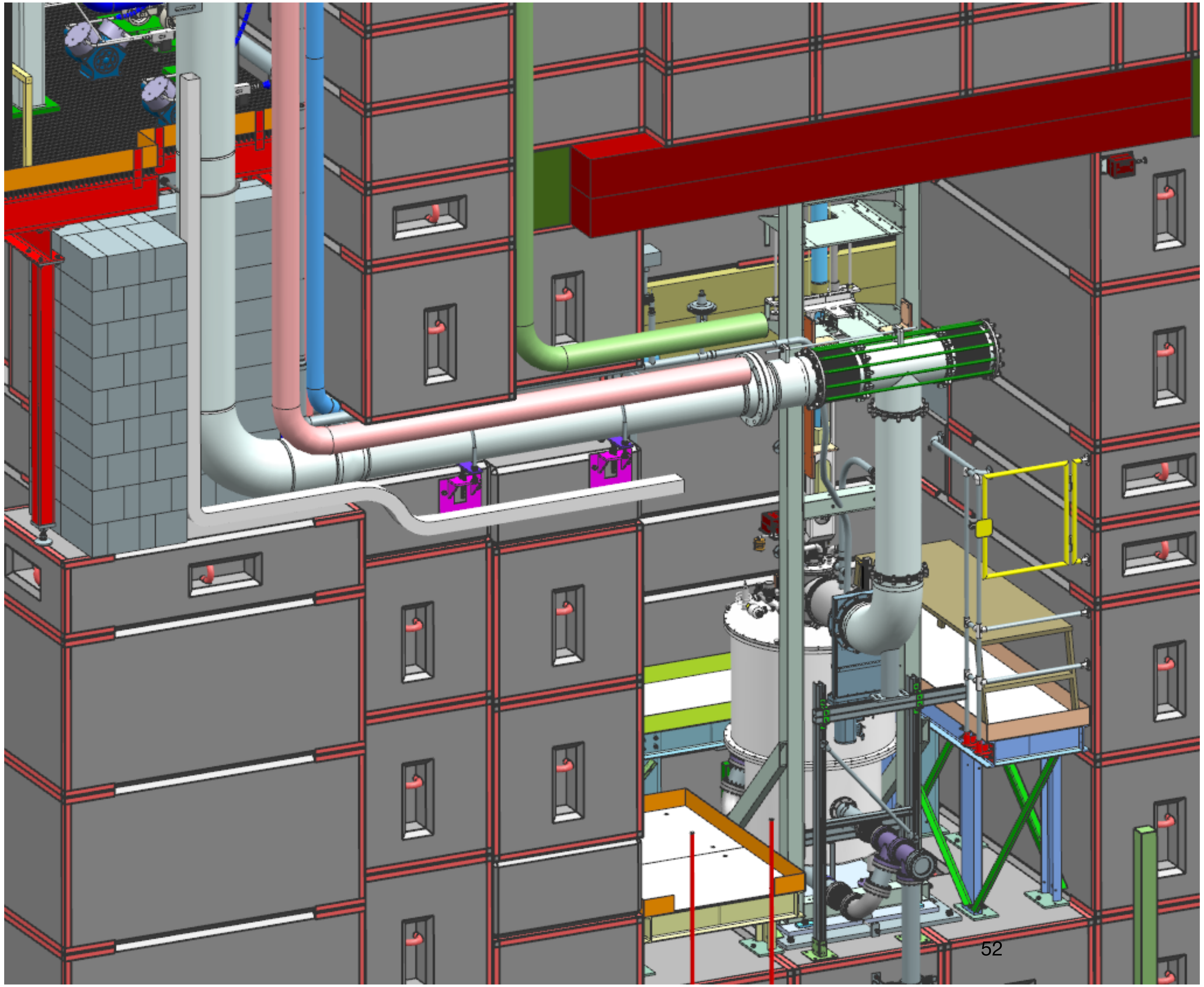


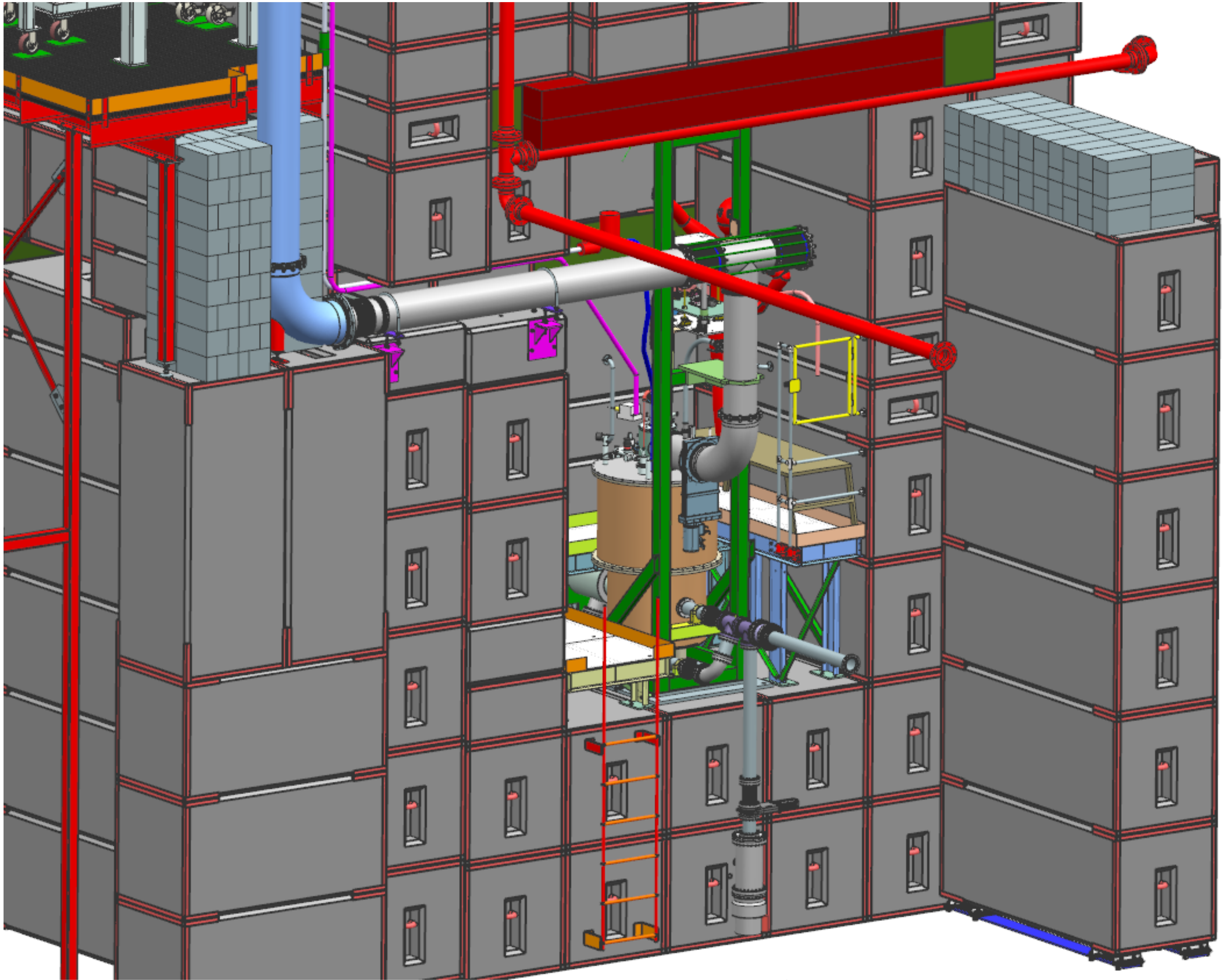


New Cryo-platform

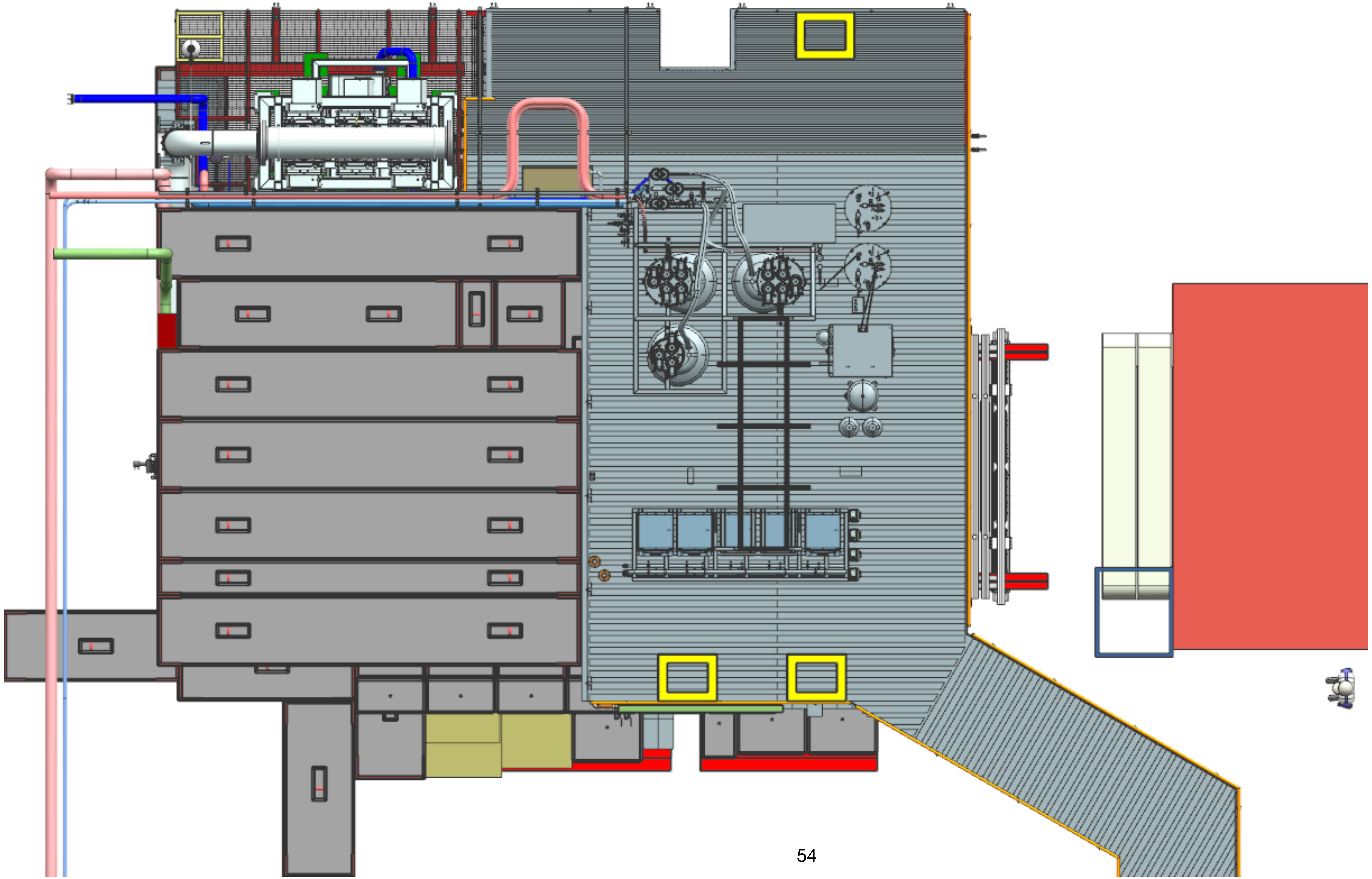


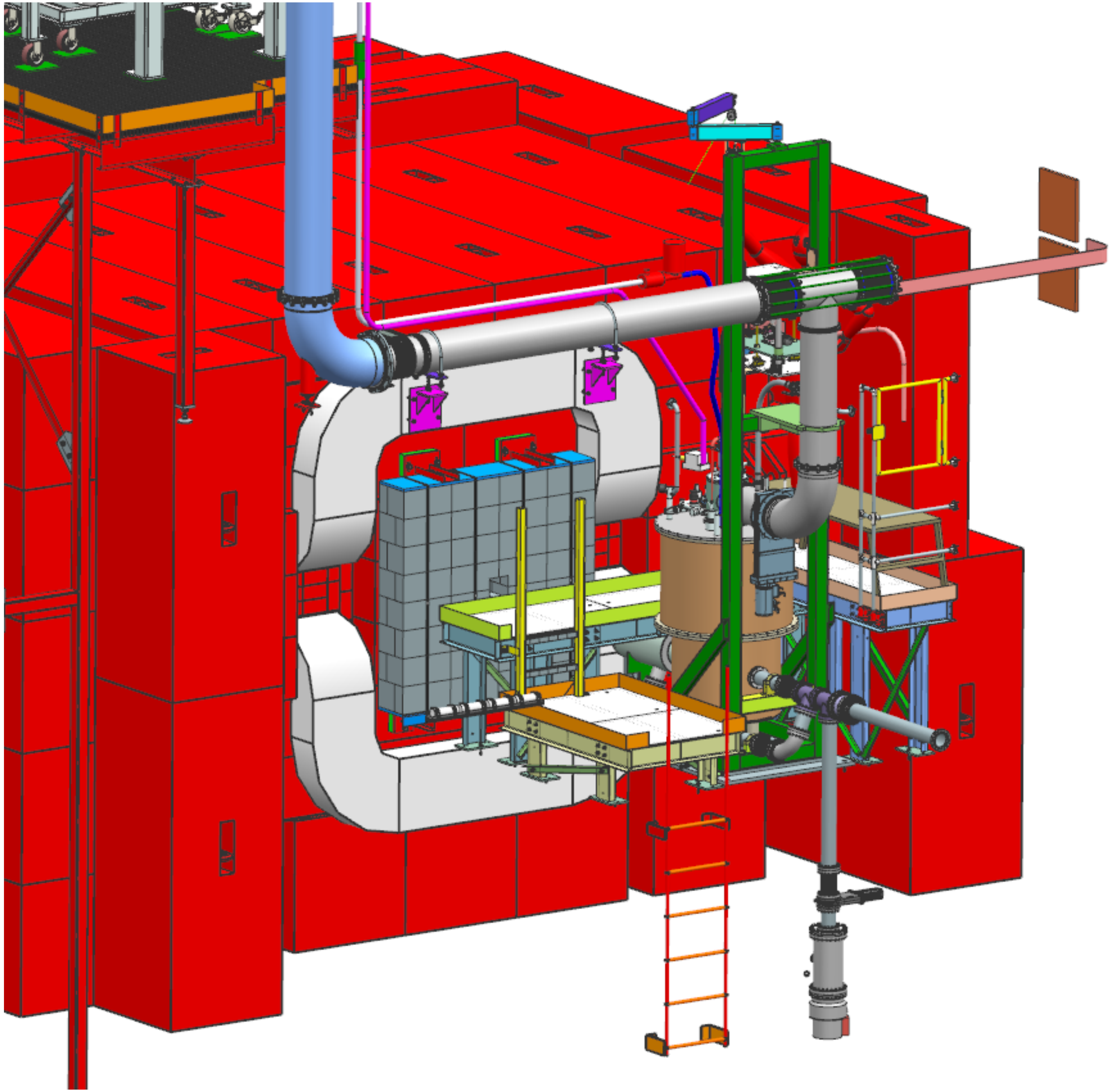
Target Alcove



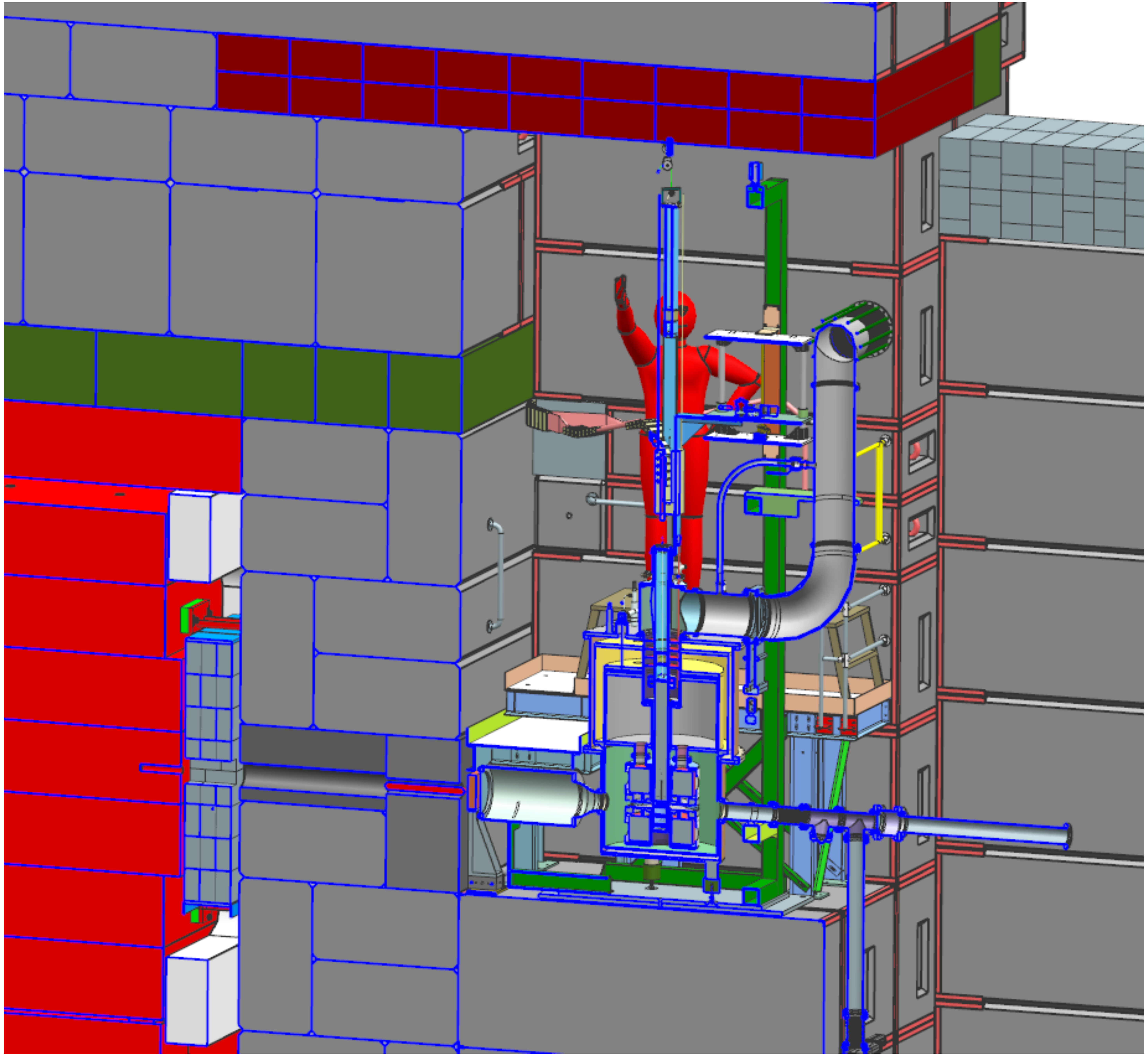


Overhead view of Cryo-platform

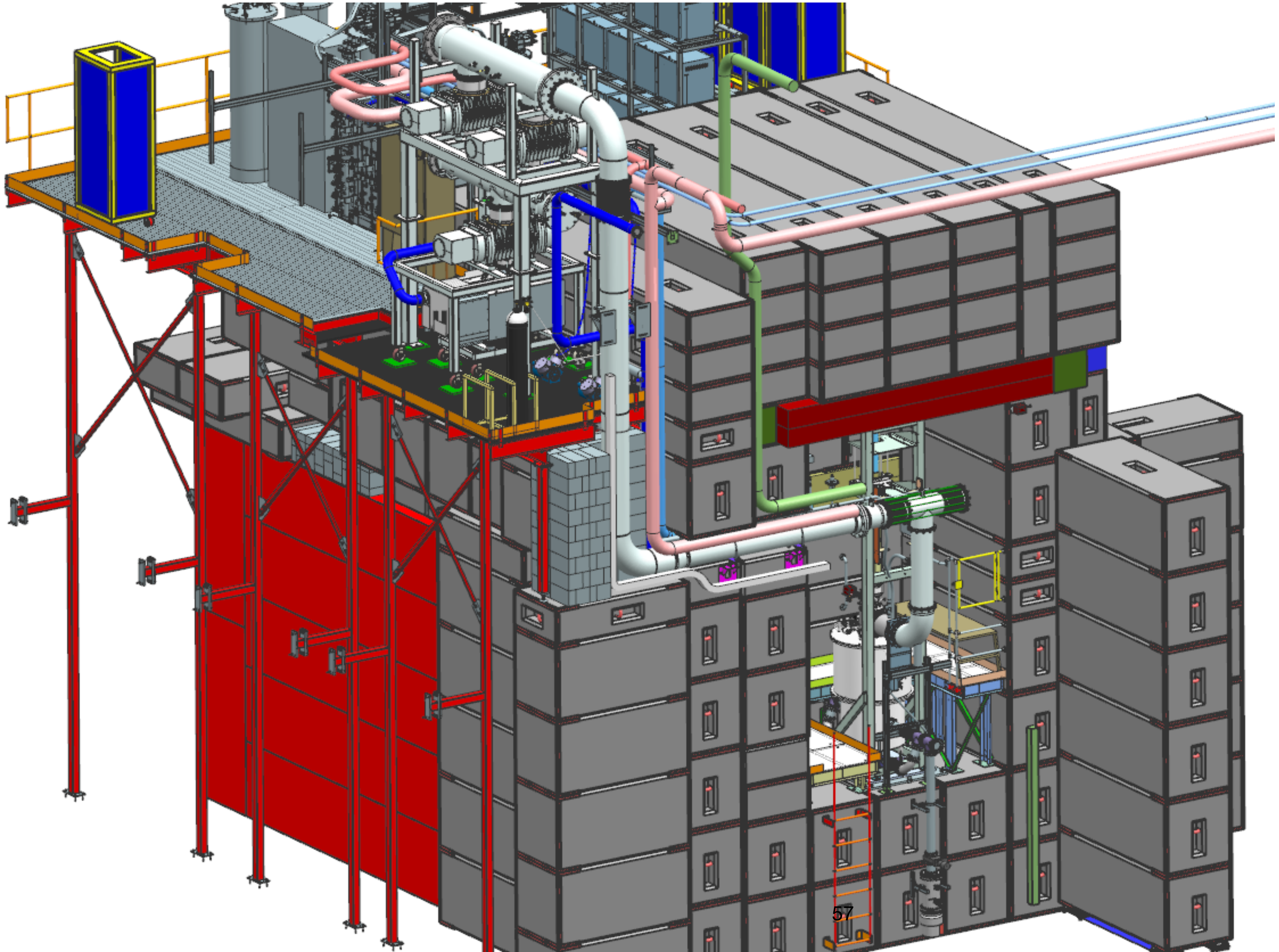




- F-mag field 1.8 T
- Target 3 meter upstream
- F-mag field 2 meters upstream ~3 Gauss
- SS curtain just upstream of F-mag
- Shielding block with reinforcing steel on the corners

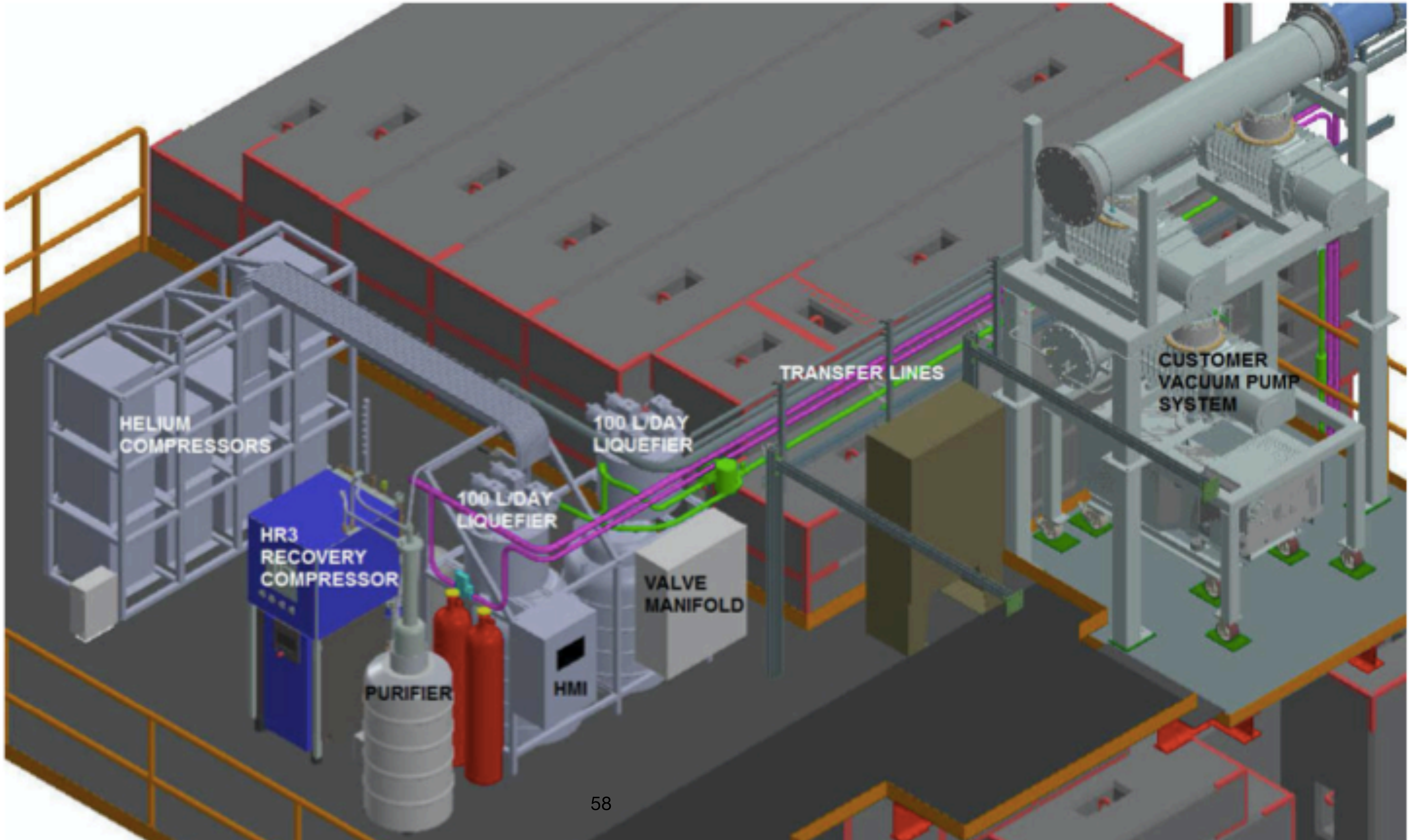


West View of Target Cave



QT Liquefier

Set of components



Thank You