# SpinQuest Target Overview

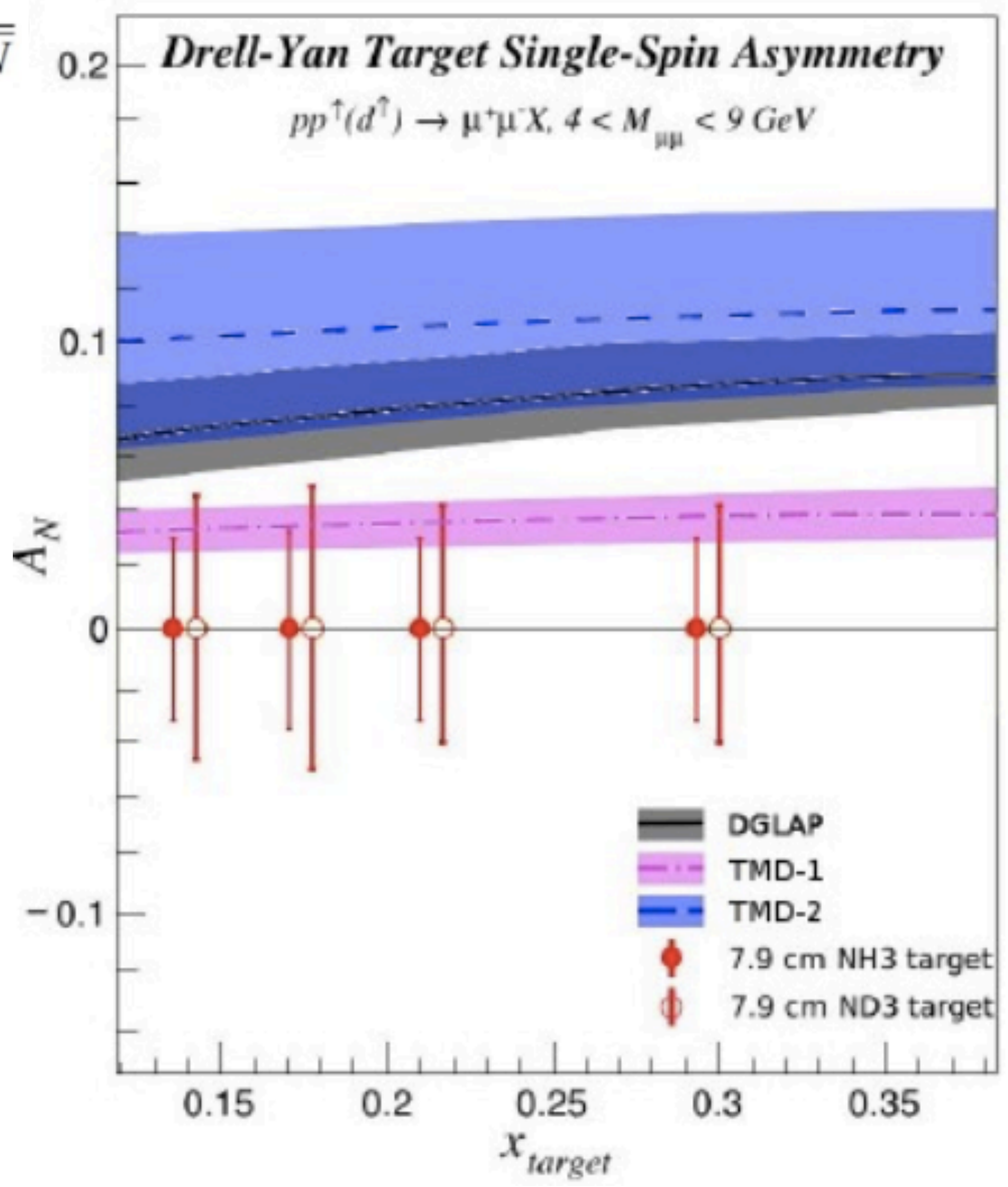
## E1039 Polarized target system and cryogenics

**D. Keller**

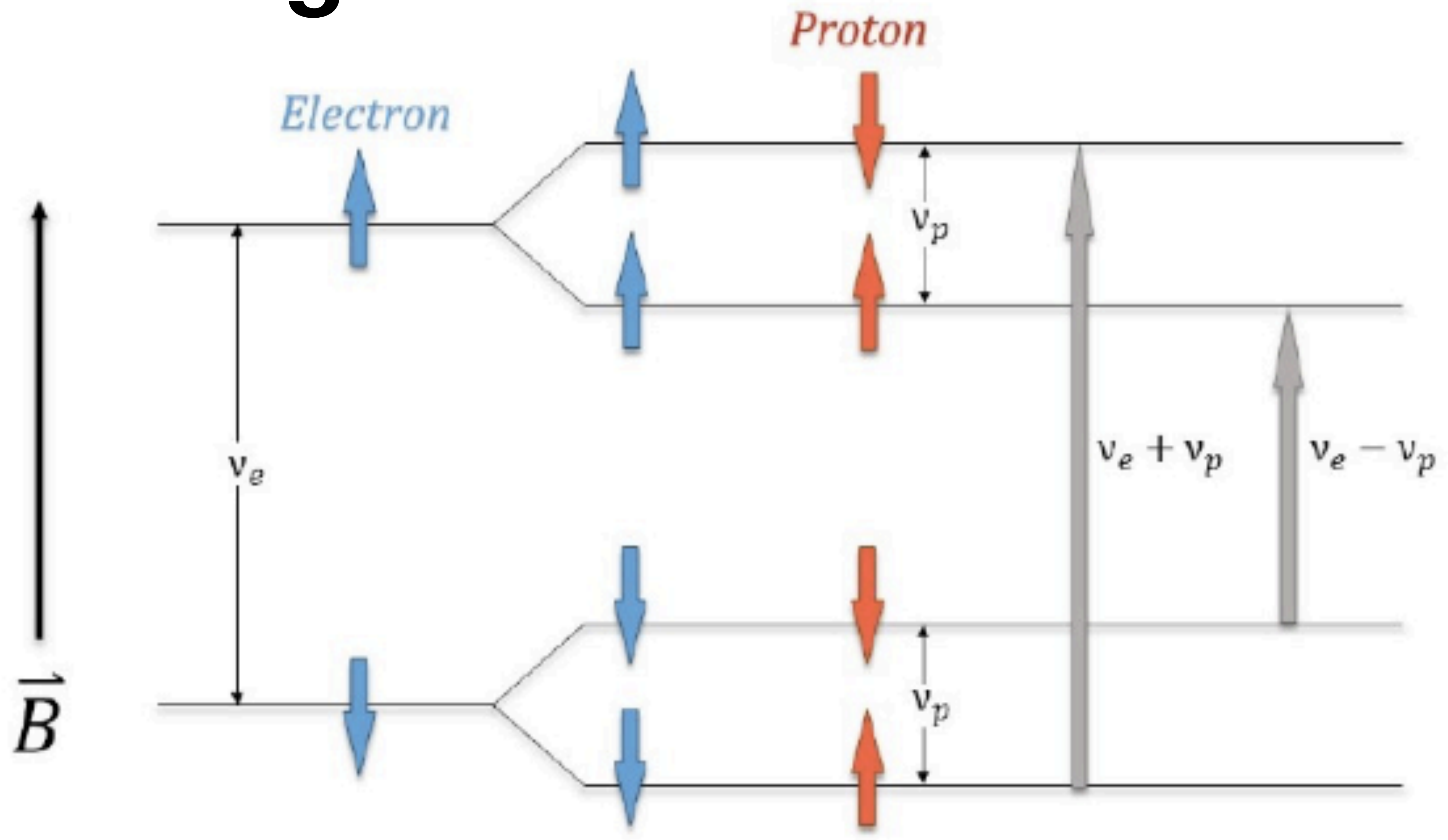
# Expected Uncertainties

- 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)

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

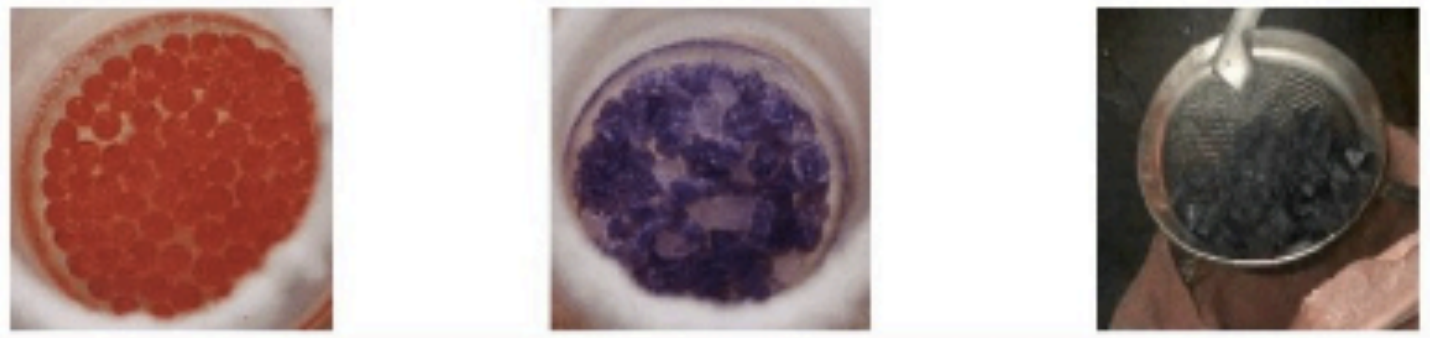


# DNP Target



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, $^7LiH$ |
|---|---|---|---|
| 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 $T_1$* |

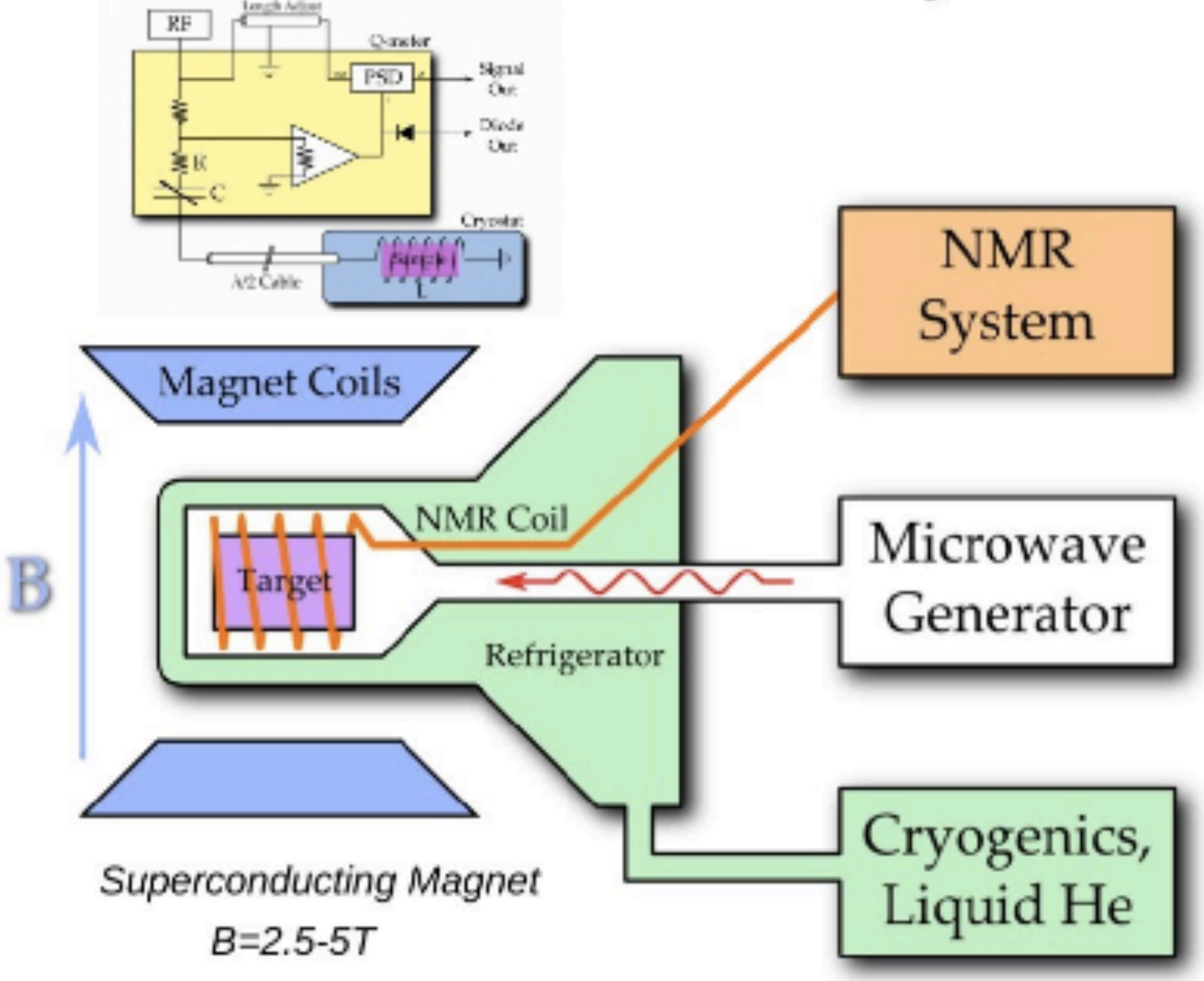
- Dynamic Nuclear Polarization
  - Dope target material with paramagnetic centers:

    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



*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*

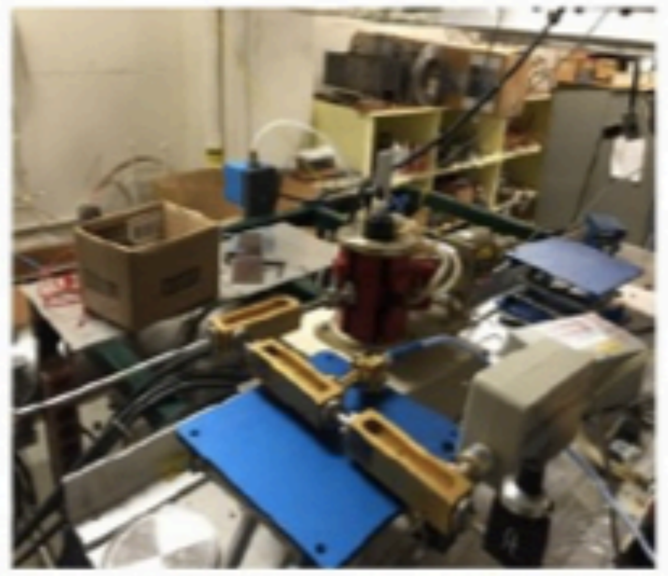
*Superconducting Magnet*

*B=2.5-5T*

# Polarized Target Subsystems

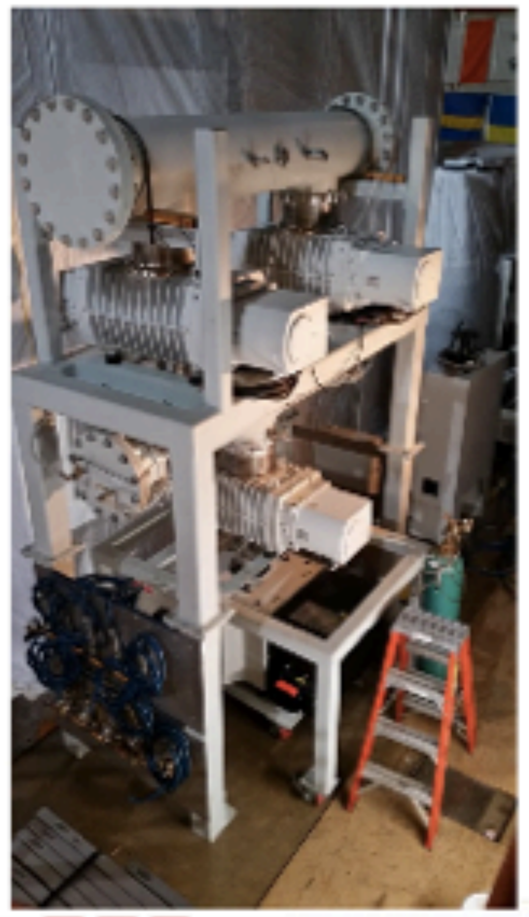
UVA-LANL: Three completely new NMRs

UVA: Design



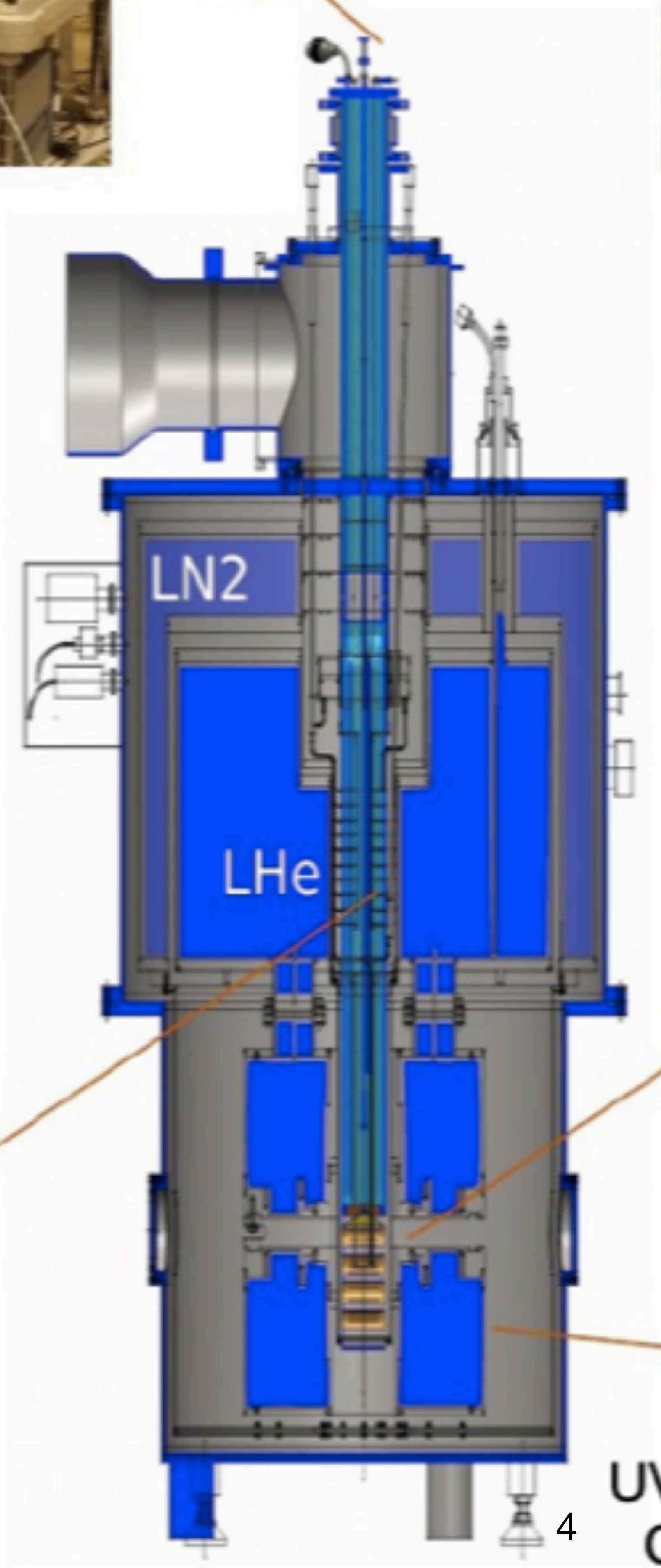
CPI

UVA: Tune System and Automation



oerlikon

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



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

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

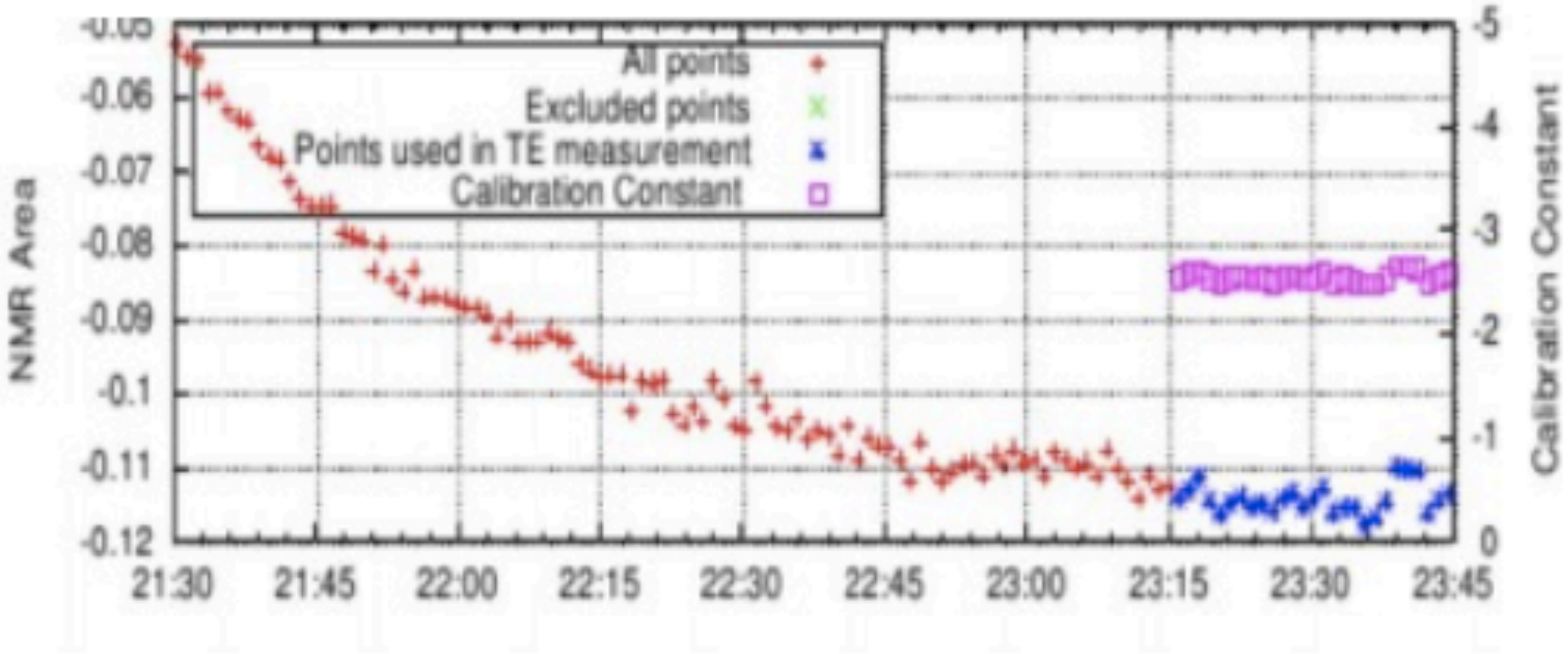
UVA: Configure Fridge and Insert, Commission for Optimal running, setup with Actuator

OXFORD INSTRUMENTS

UVA: Commissioning, Slow Controls, Quench Study,

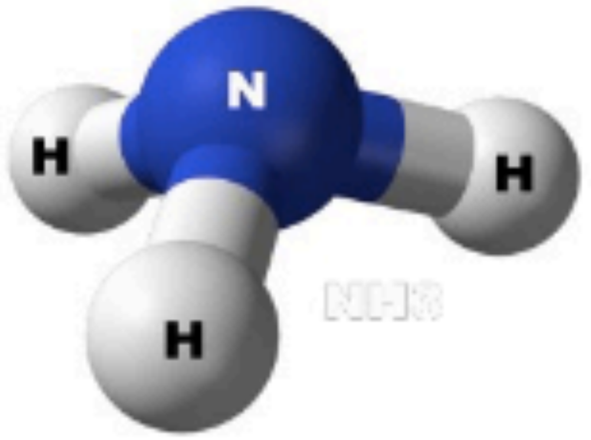
| Material | Dens. (g/cm$^3$) | Length (cm) | Interaction Length (cm) | Dilution Factor | Packing Fraction | $< P_z >$ |
|---|---|---|---|---|---|---|
| $NH_3$ | 0.867 | 7.9 | 91.7 | 0.176 | 0.6 | 80% |
| $ND_3$ | 1.007 | 7.9 | 82.9 | 0.3 | 0.6 | 32% |

- 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.

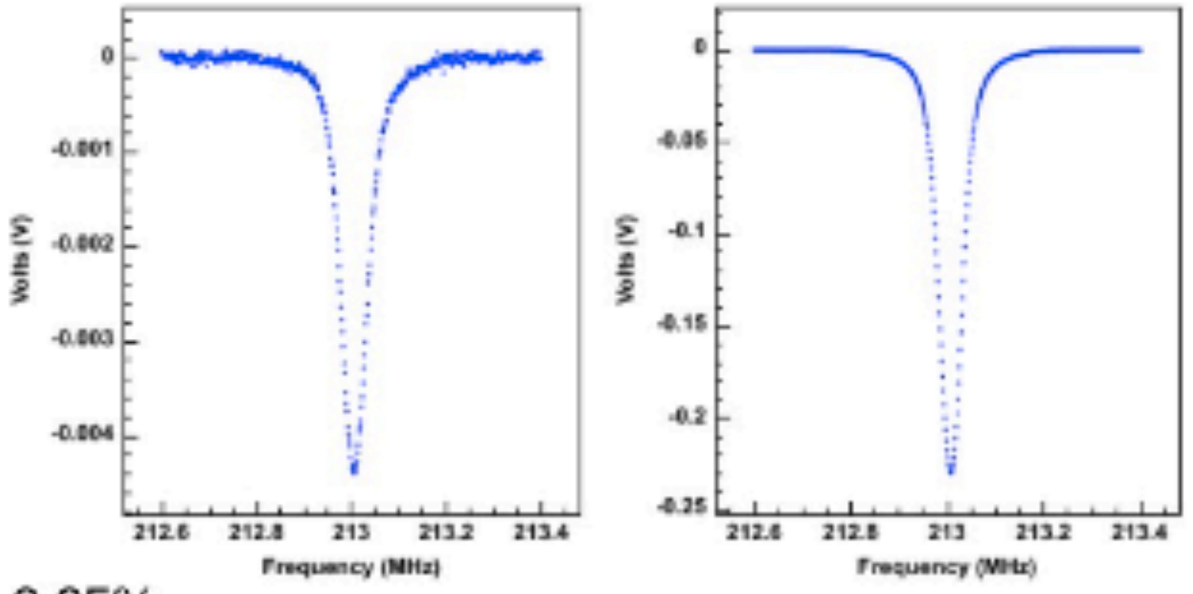


$$\Delta A_N = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N}}$$

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



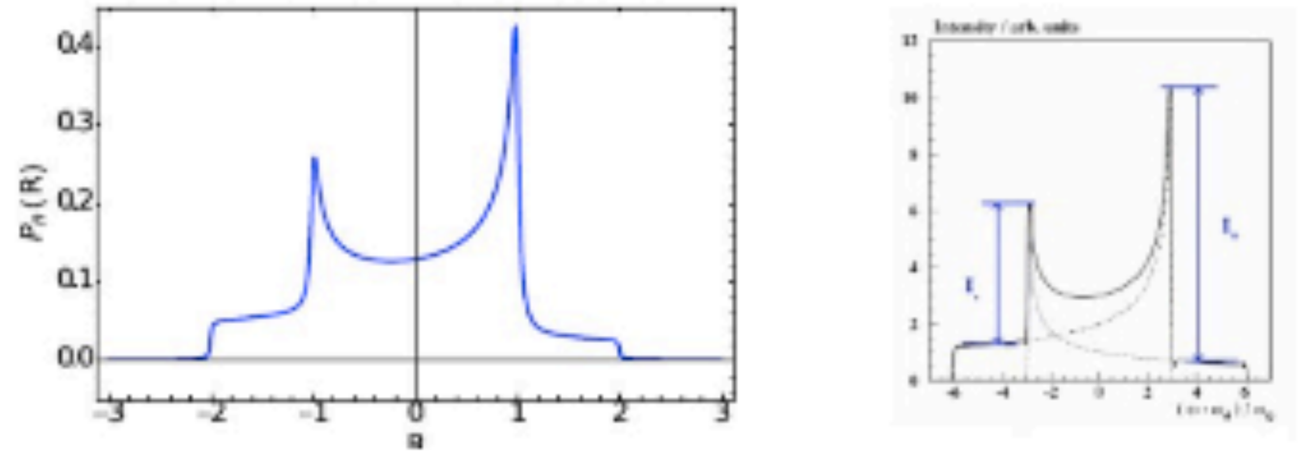
~0.3%



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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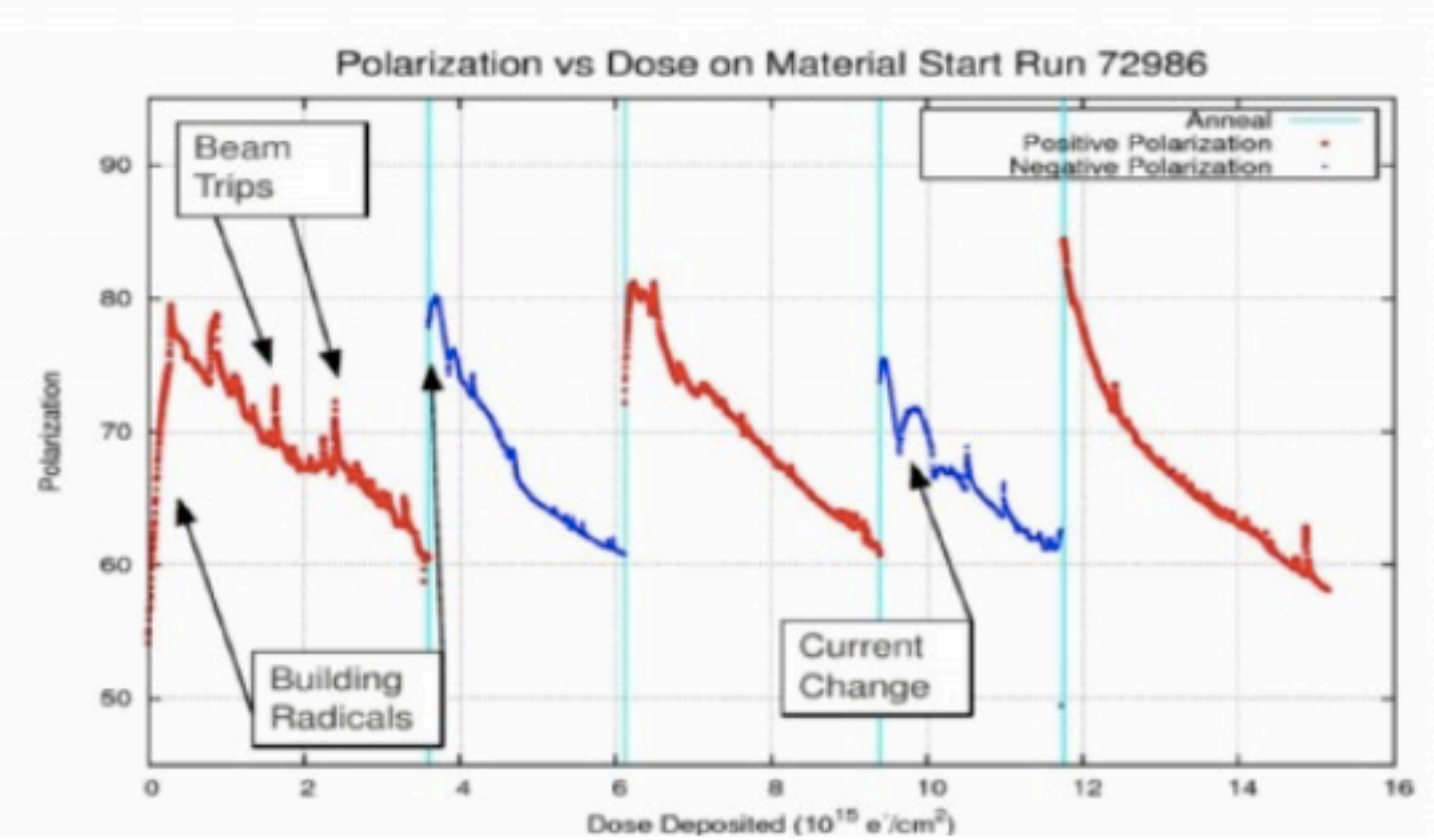
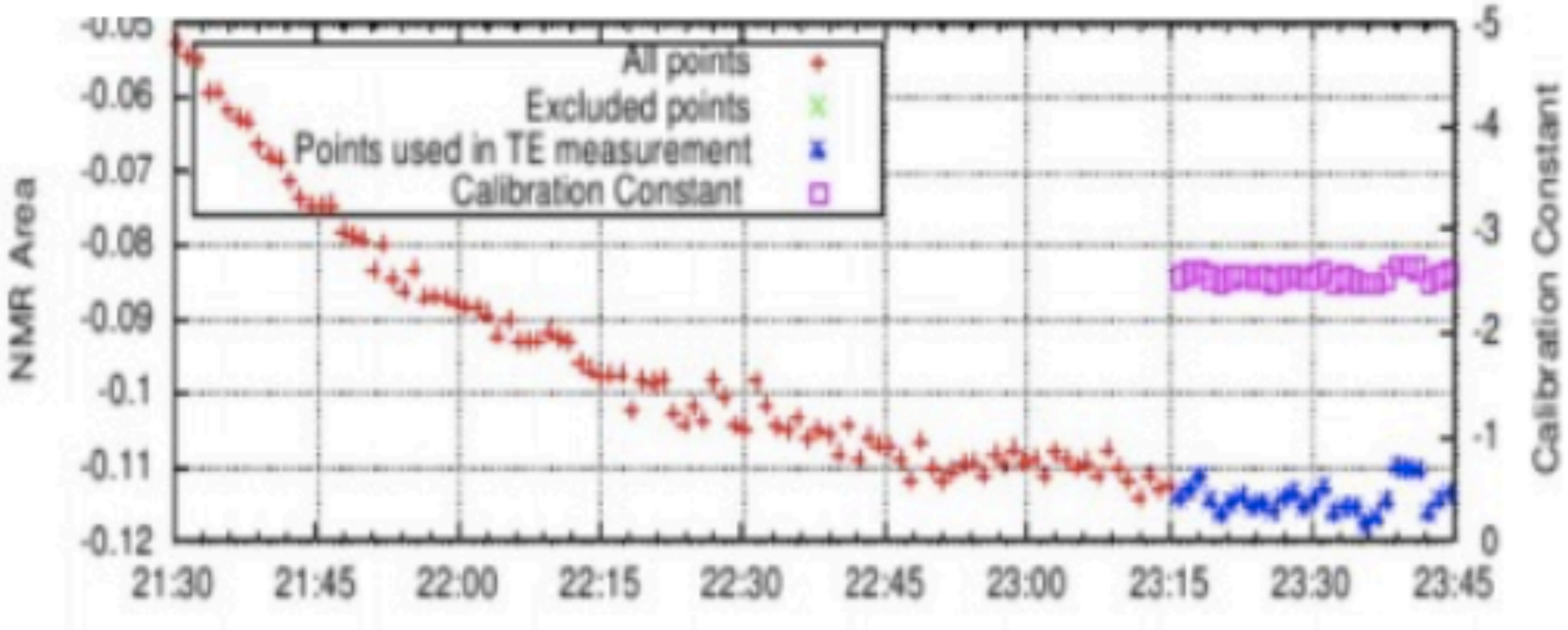
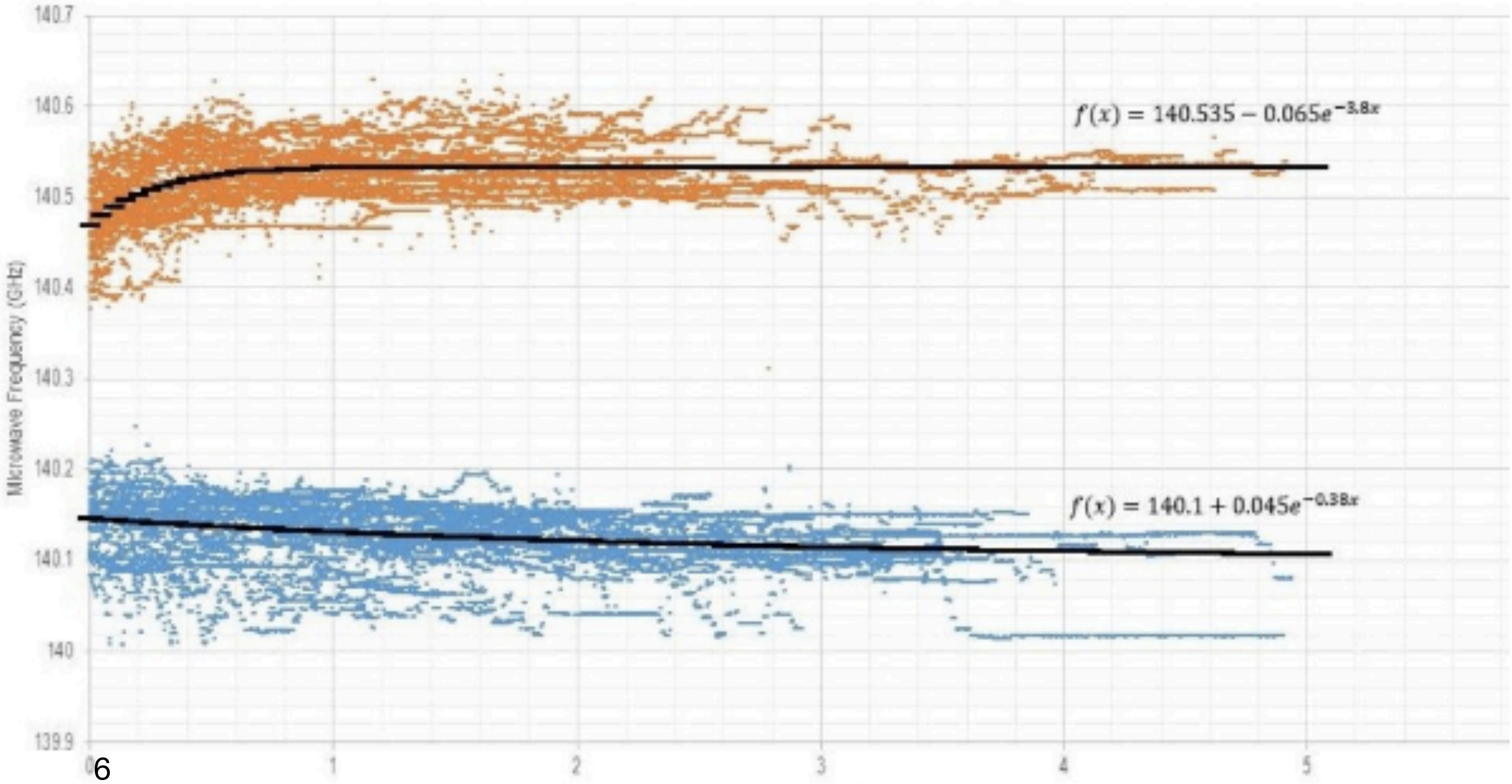






$f(x) = 140.535 - 0.065e^{-3.8x}$

$f(x) = 140.1 + 0.045e^{-0.38x}$

# SpinQuest

## A target system to operate at the proton intensity frontier

- At least $3 \times 10^{12}$ 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$^{-1}$

# DNP Refrigerator

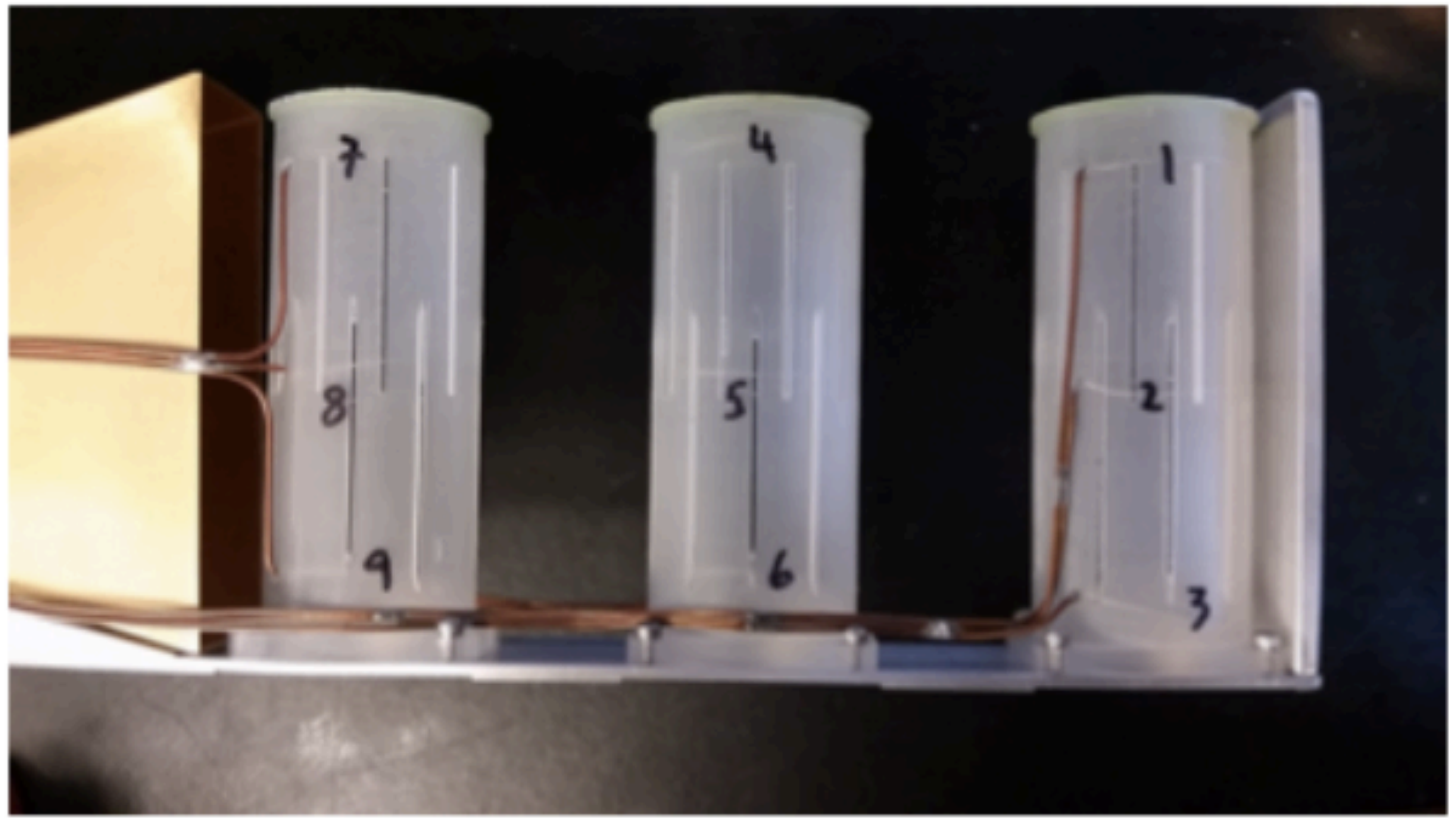
## High Cooling Power Evaporation System

# Target Insert

Carbon fiber with copper heat sink

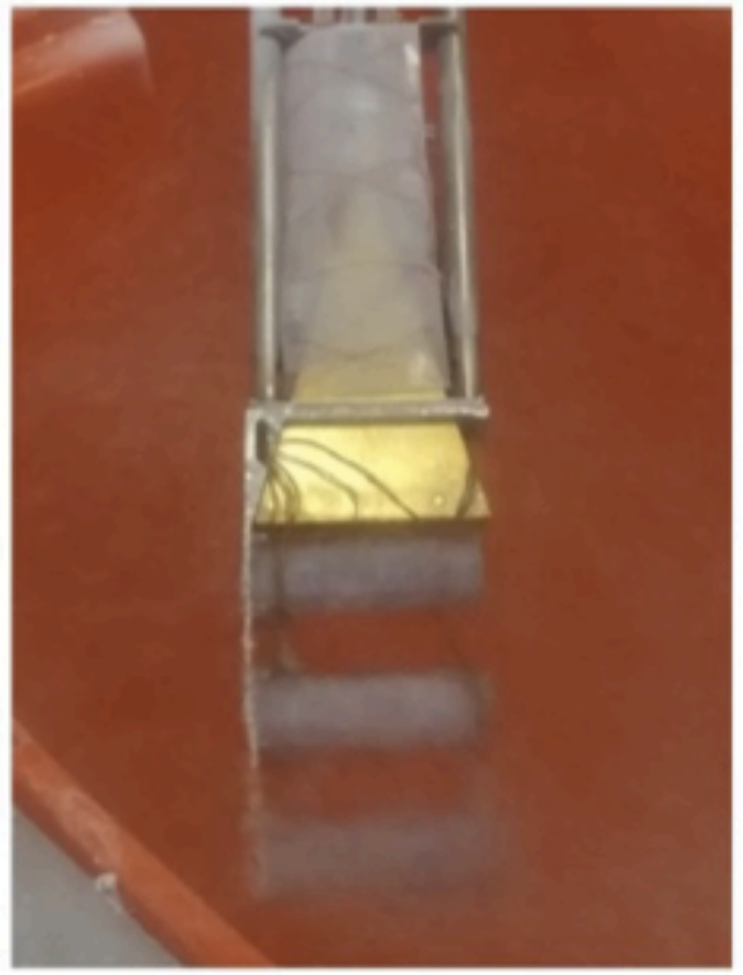
20X27 mm elliptical cells

long cell length microwave horn

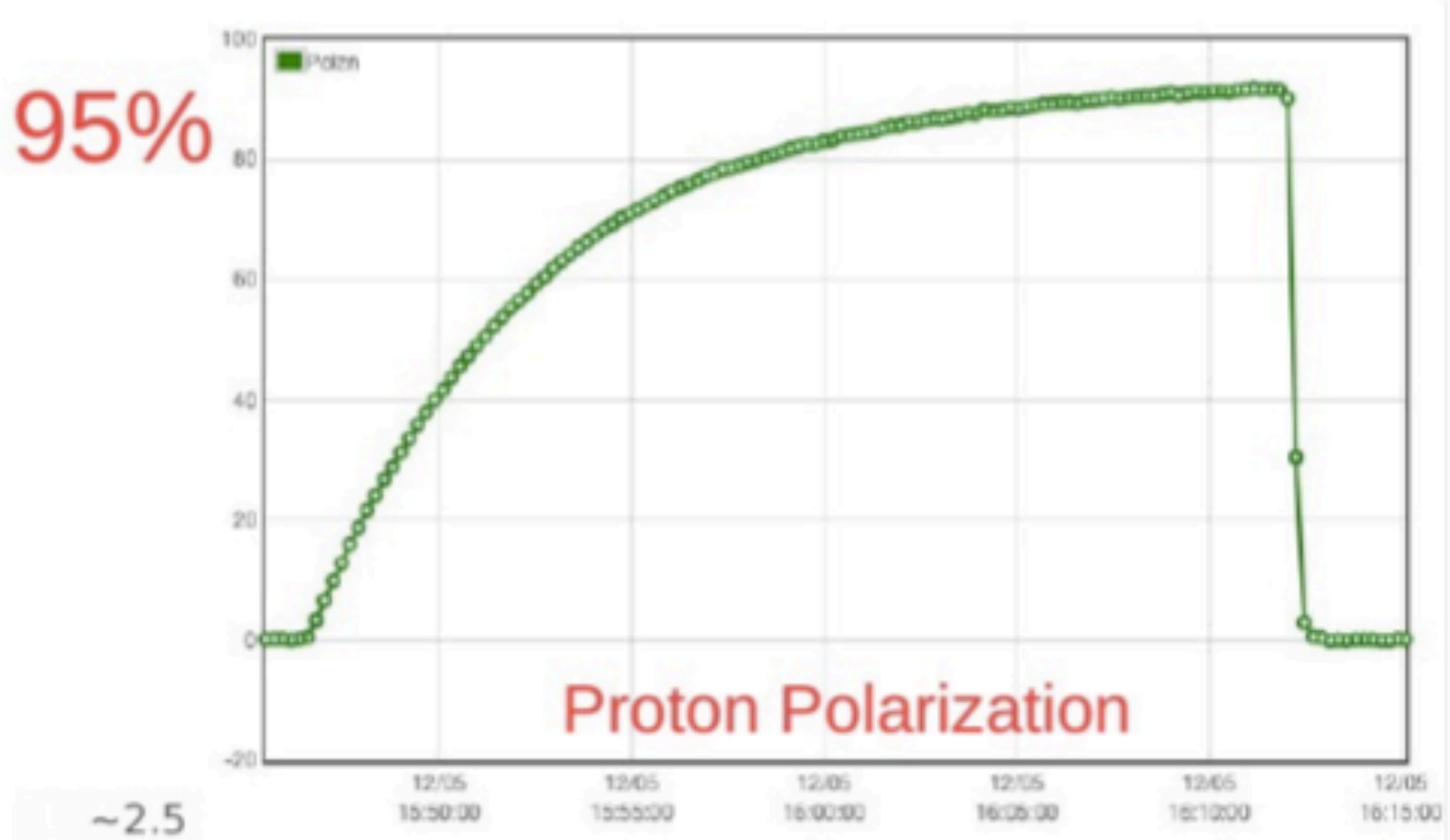


- 3 NMR coils per cell
- 8 cm long target cell of solid: $NH_3$ and $ND_3$
- Standard Insert has 3 cells
- One centering cell
- Elliptically shaped to match profile

# Last Target Polarization at UVA

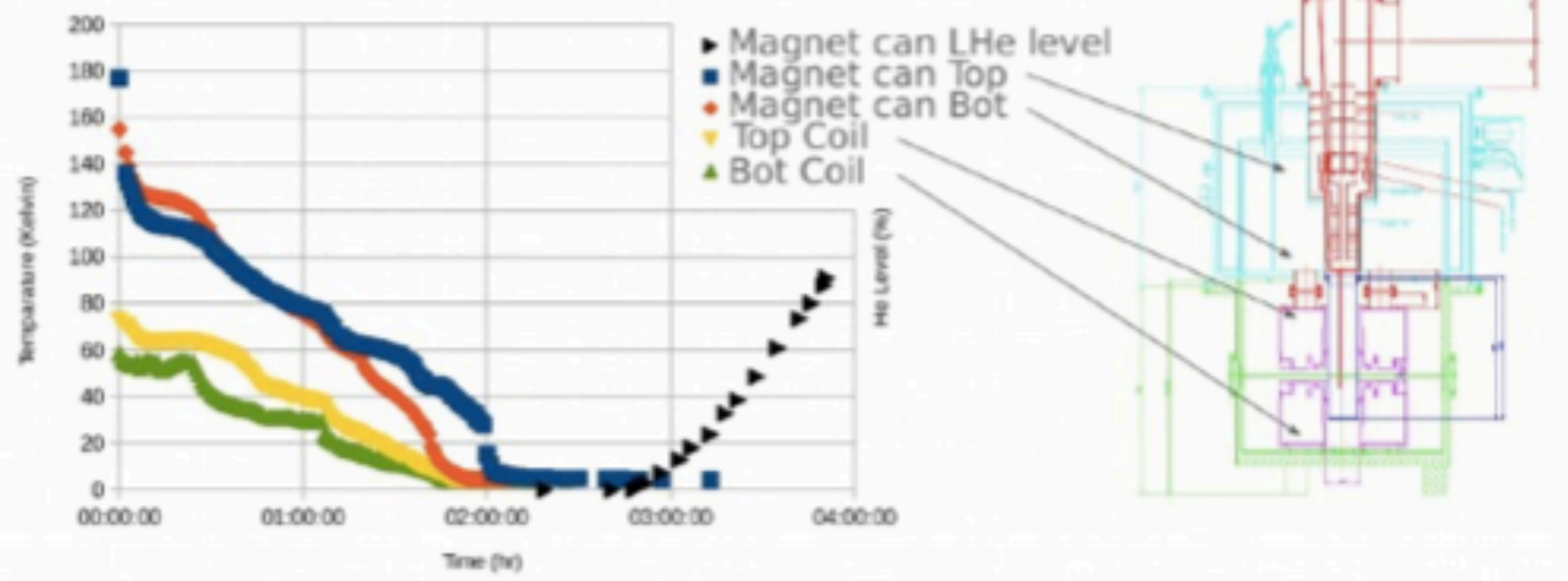


Insert in LN2



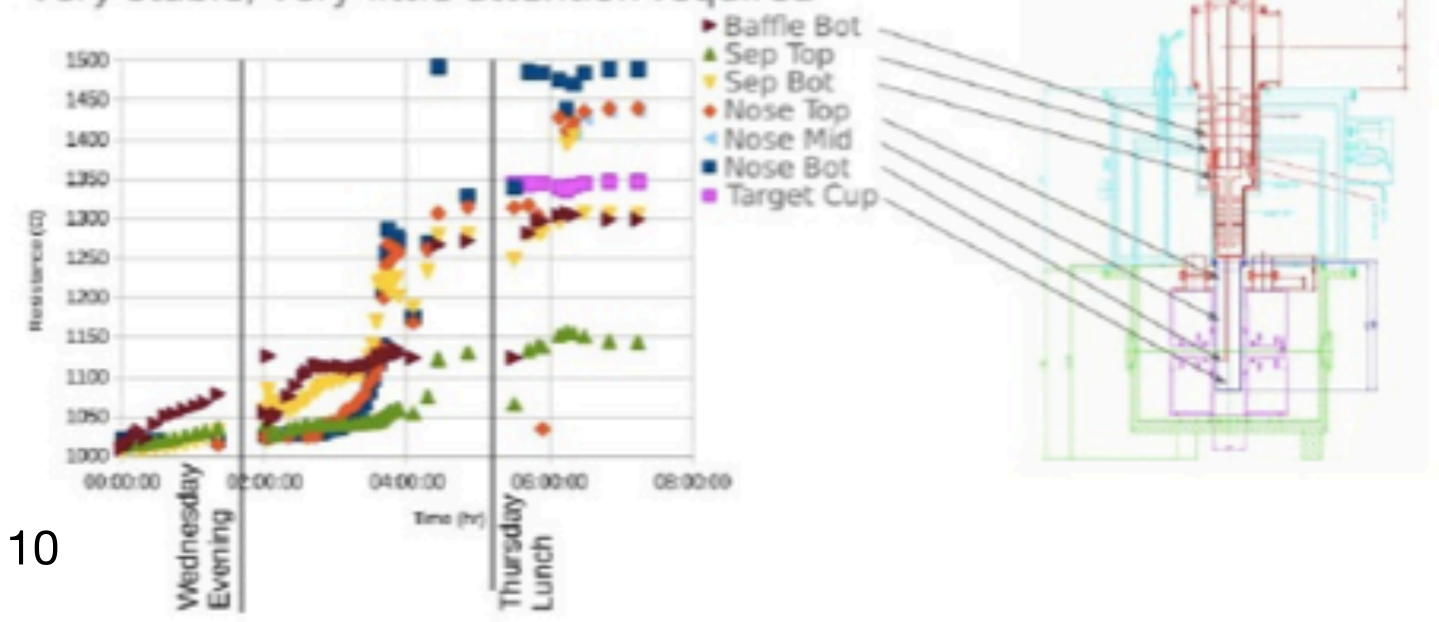
~2.5

~1 hr to to fill magnet can



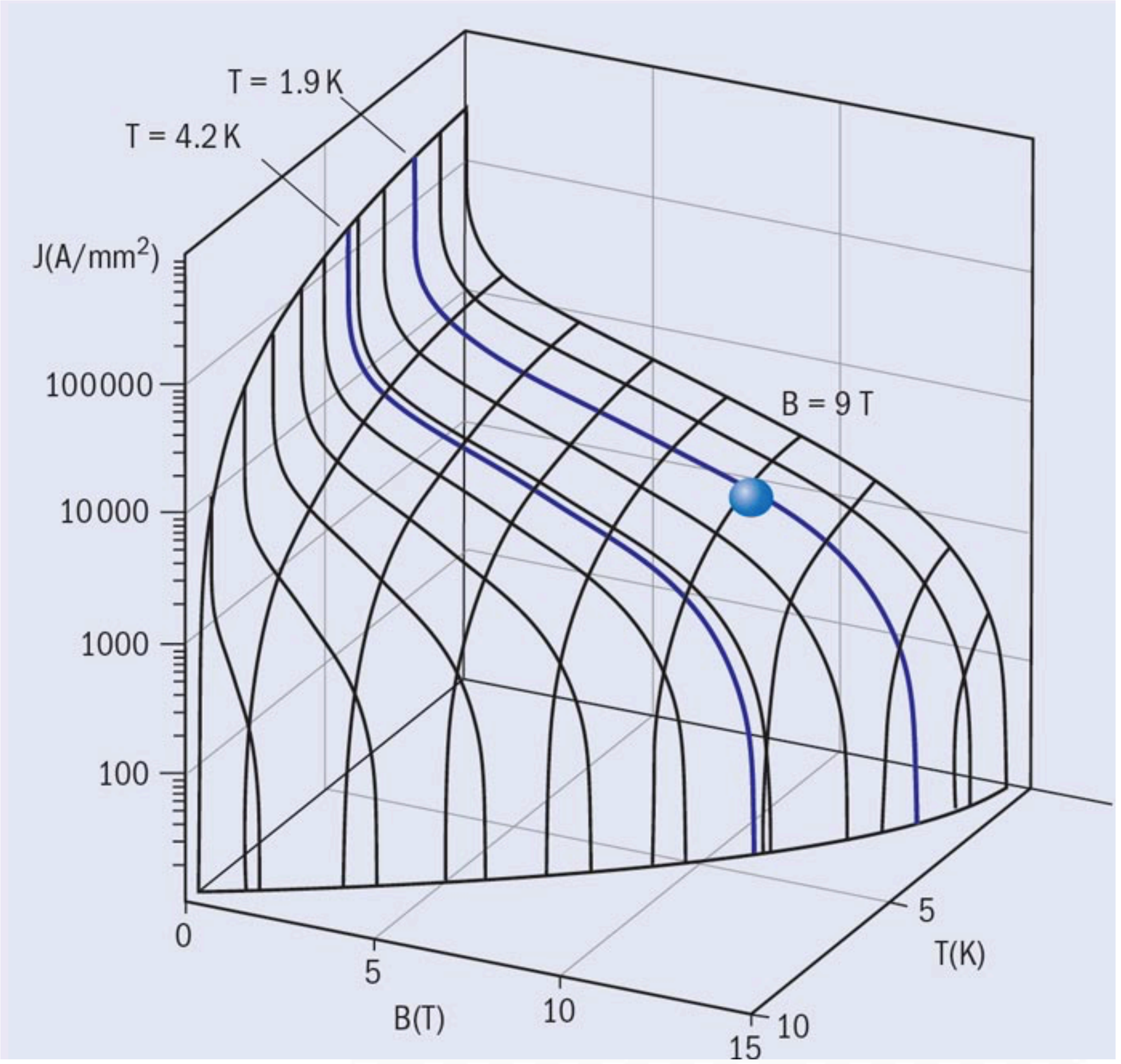
~1hr to fill the nose after a night on standby

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

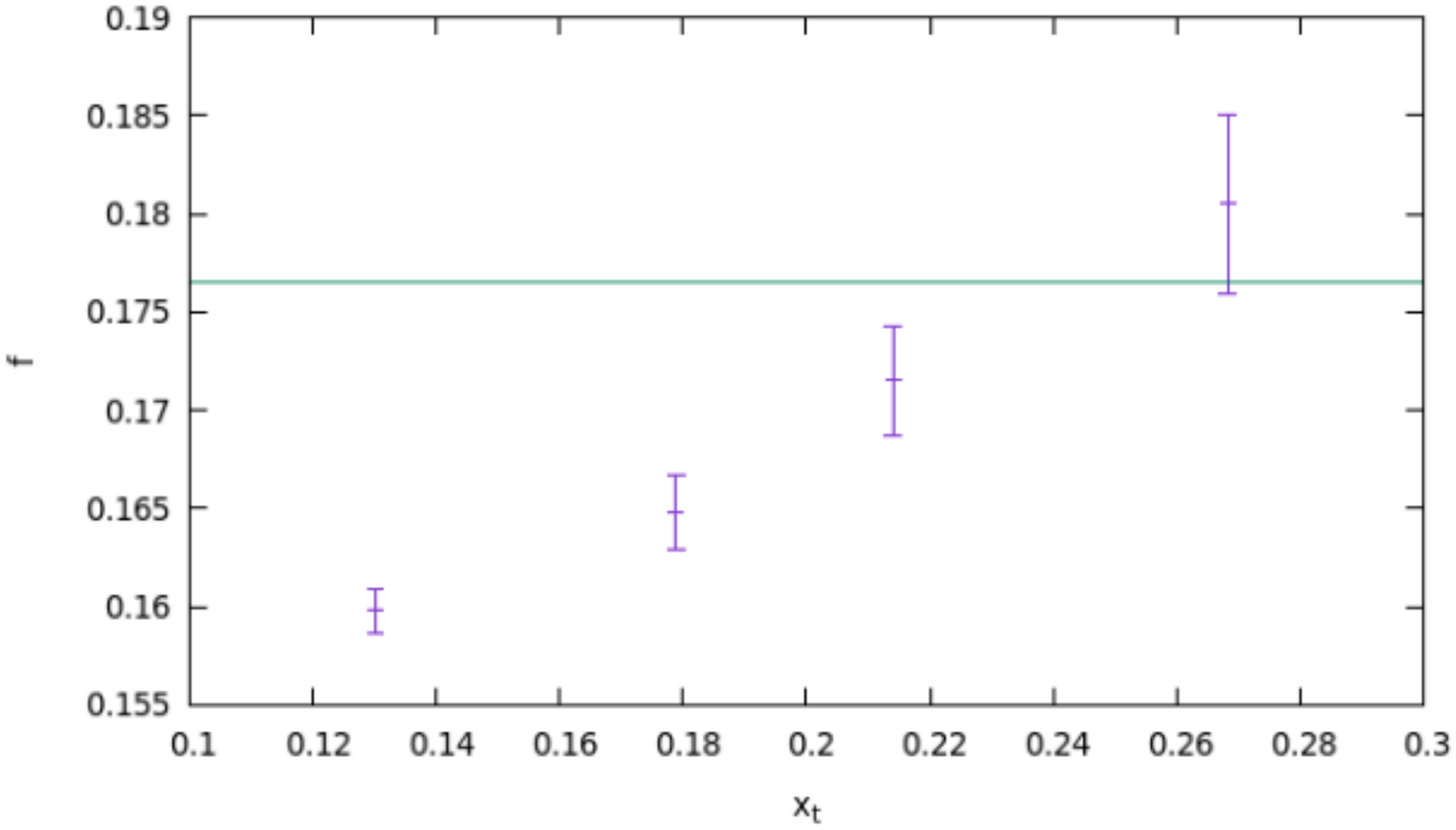
# Novelty Issues

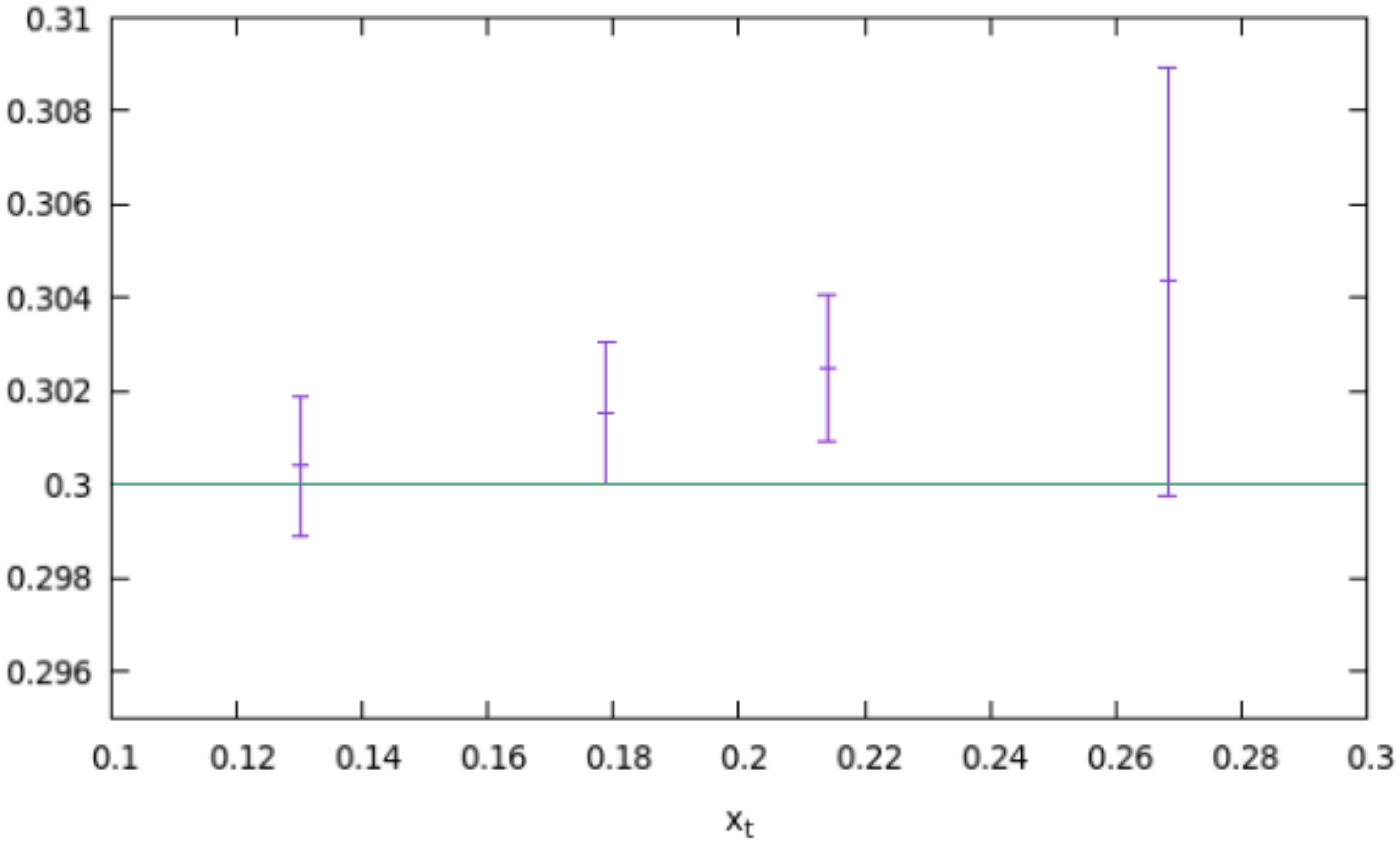
## Polarized Target on the Intensity frontier

- 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 Drell-Yan on $NH_3/ND_3$ (dilution factor, cycling)
- Magnet heat-load limits

# Dilution Factor

## Kinematic sensitivity





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

# Quench Studies

## Primary Intensity Boundary

- Very Limited Experimental Information
- Use Monte Carlo and Finite Element Analysis
- 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

# Update to Projected Error bars

**Beam(2.5%):**

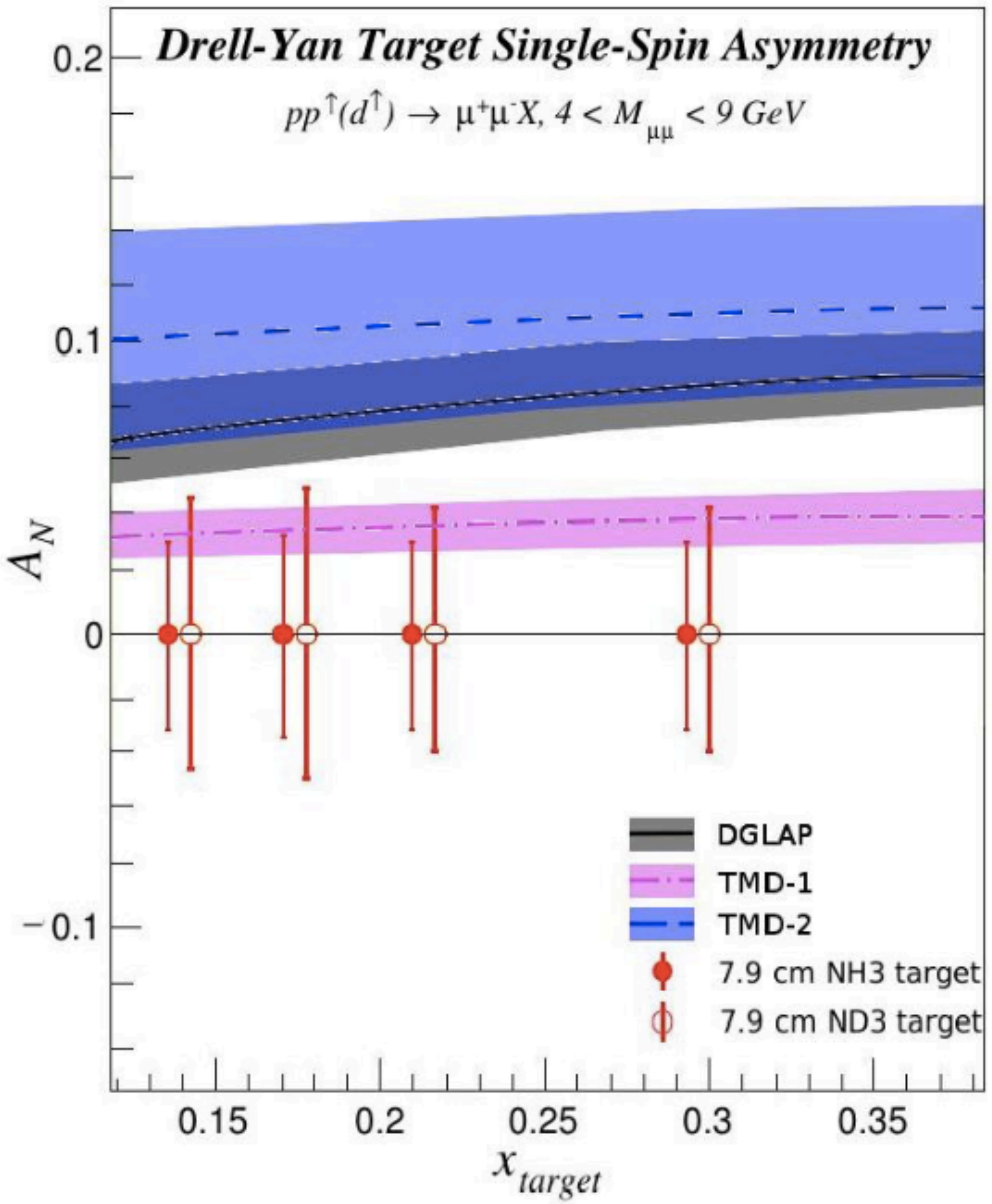
- Relative Luminosity (~1%)
- Drifts (<2%)
- Scraping (~1%)

**Analysis sources(3.5%):**

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

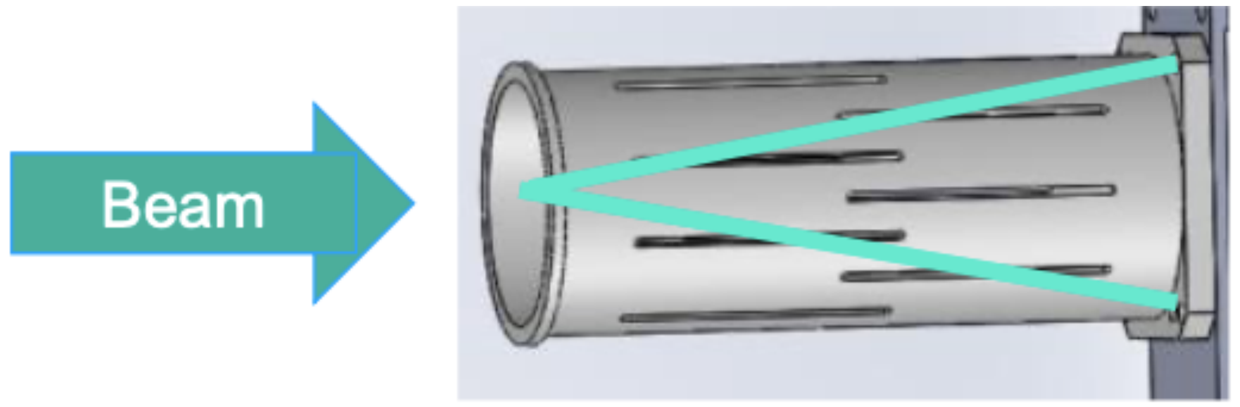
**Target(6-7%)**

- 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%)

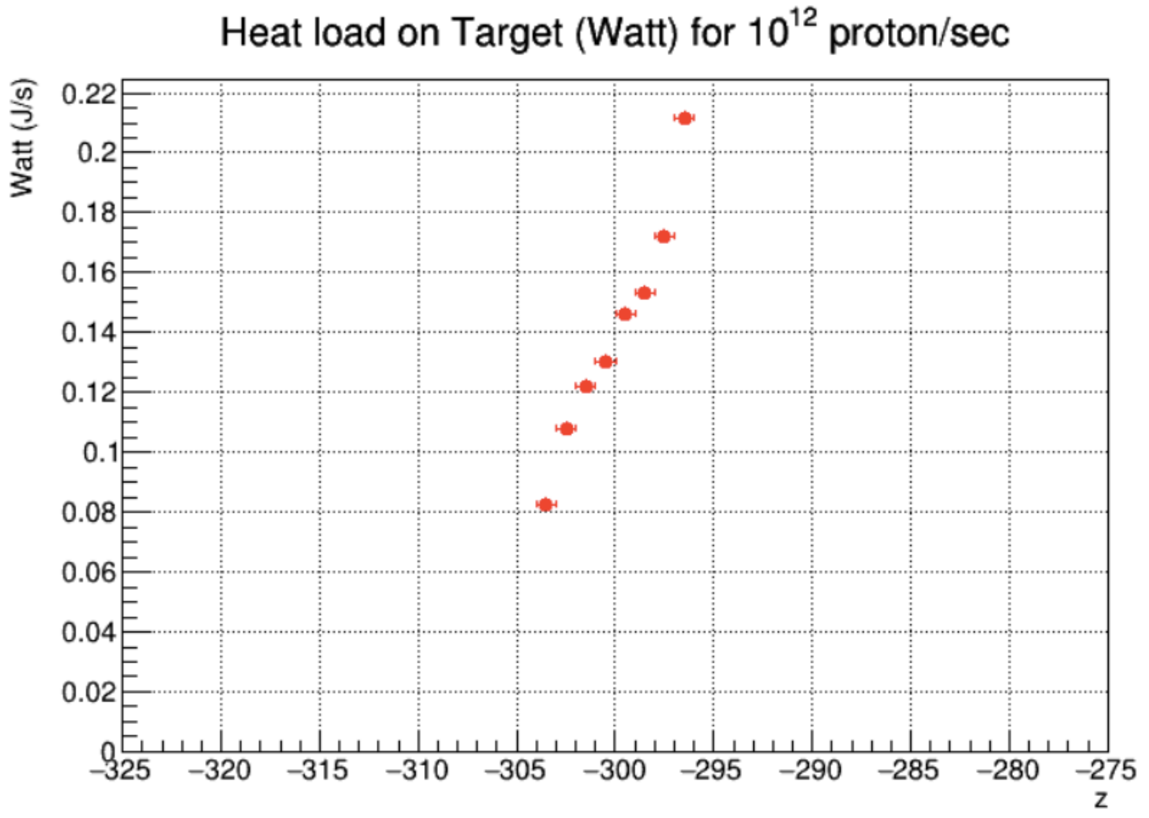


DGLAP: M. Anselmino et al arXiv:1612.06413
TMD-1: M. G. Echevarria et al arXiv:1401.5078
TMD-2: P. Sun and F. Yuan arXiv:1308.5003

# 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

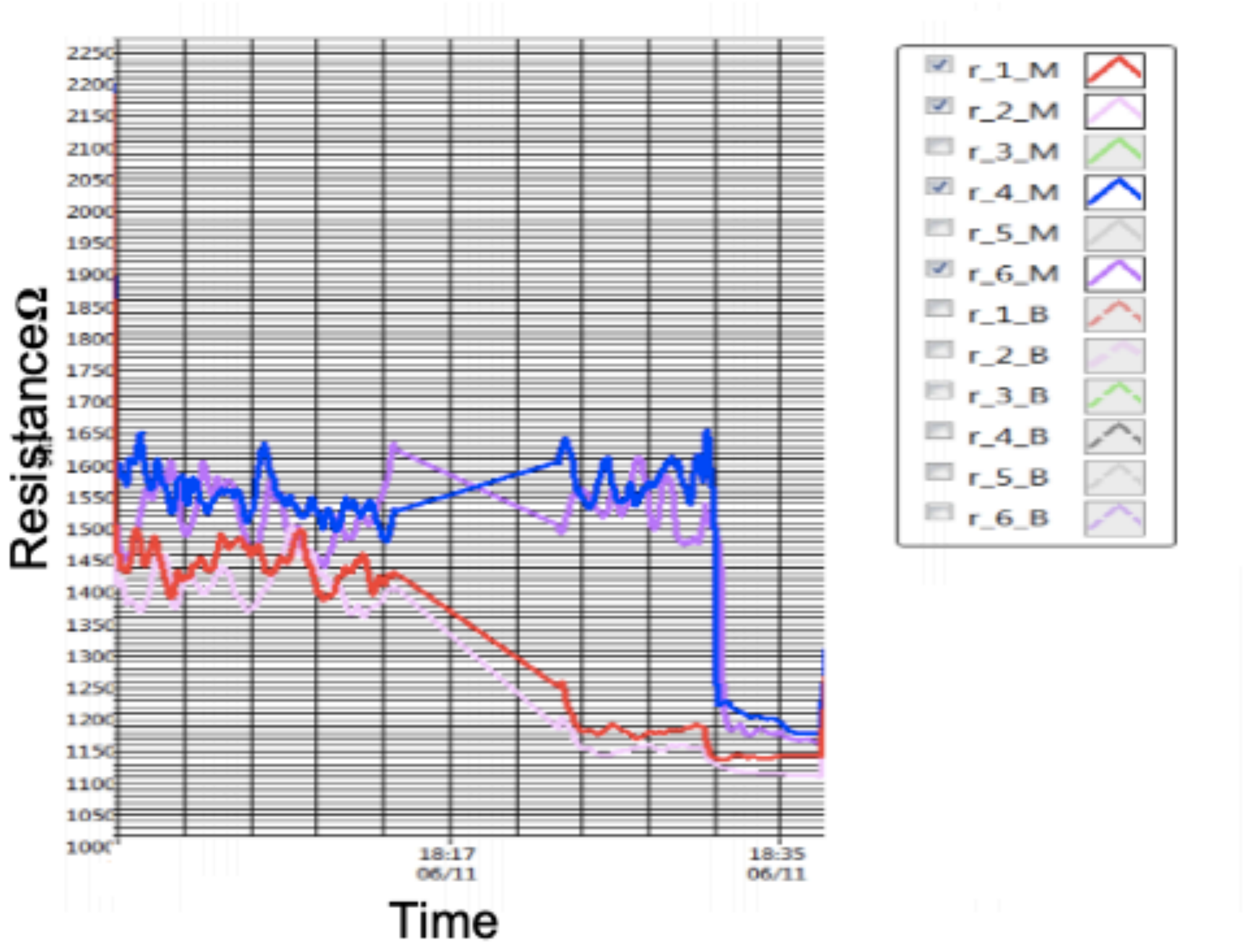


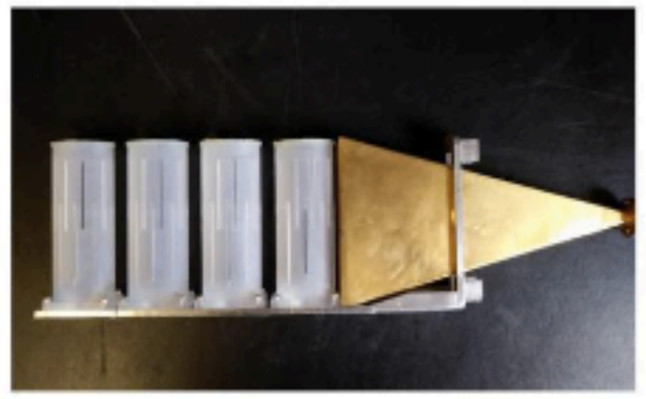
- Microwave distribution intensity along the target
- To test this 4 thermal sensors placed along-z and studies at varied frequency
- The NMR coils only measure 3 points along-z
- Using simulations and empirical data to interpolate microwave power profile
- Distribution being $P(z)$
- The average polarization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

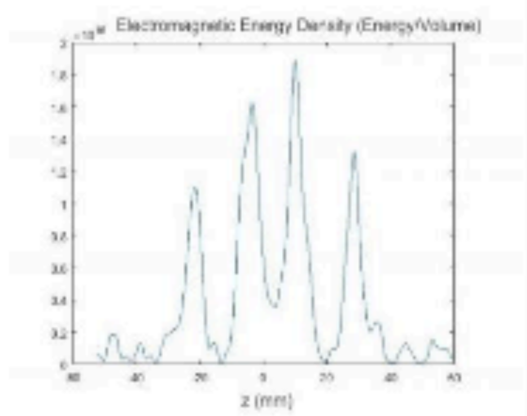
$$p_{avg} = \frac{p_1 + p_2 + p_3}{3}$$

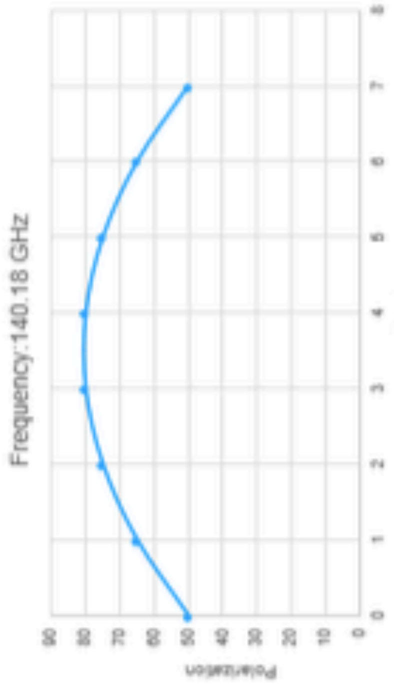
The error: $$\Delta A = \frac{P(Z) - P_{avg}}{P(z)}$$

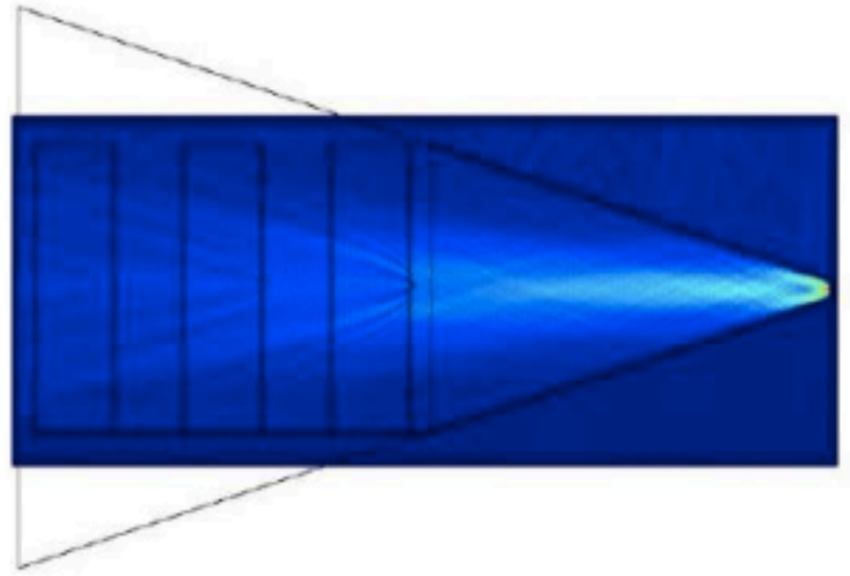
**The error can be reduced by knowing the power profile**

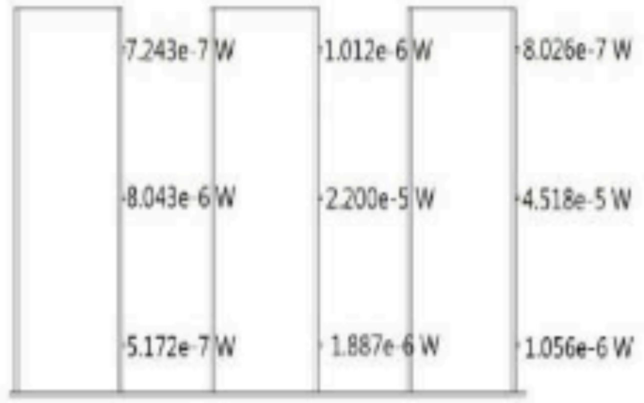


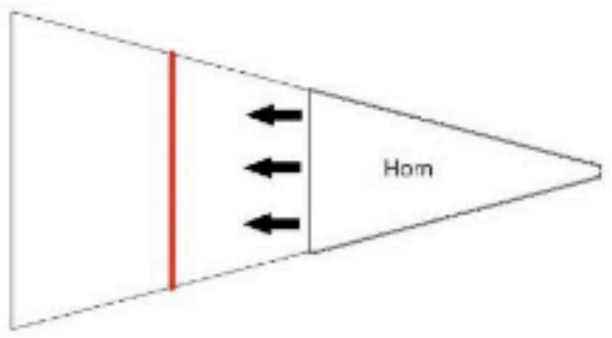






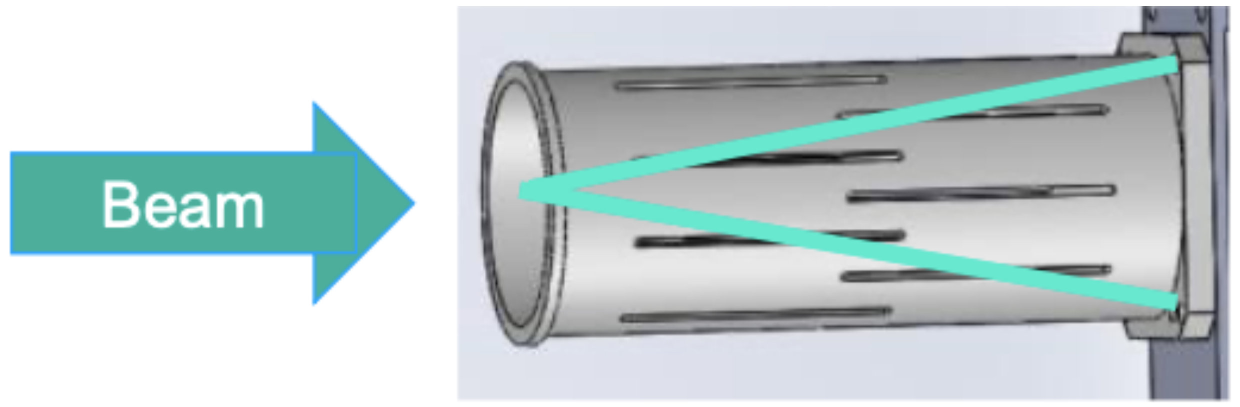






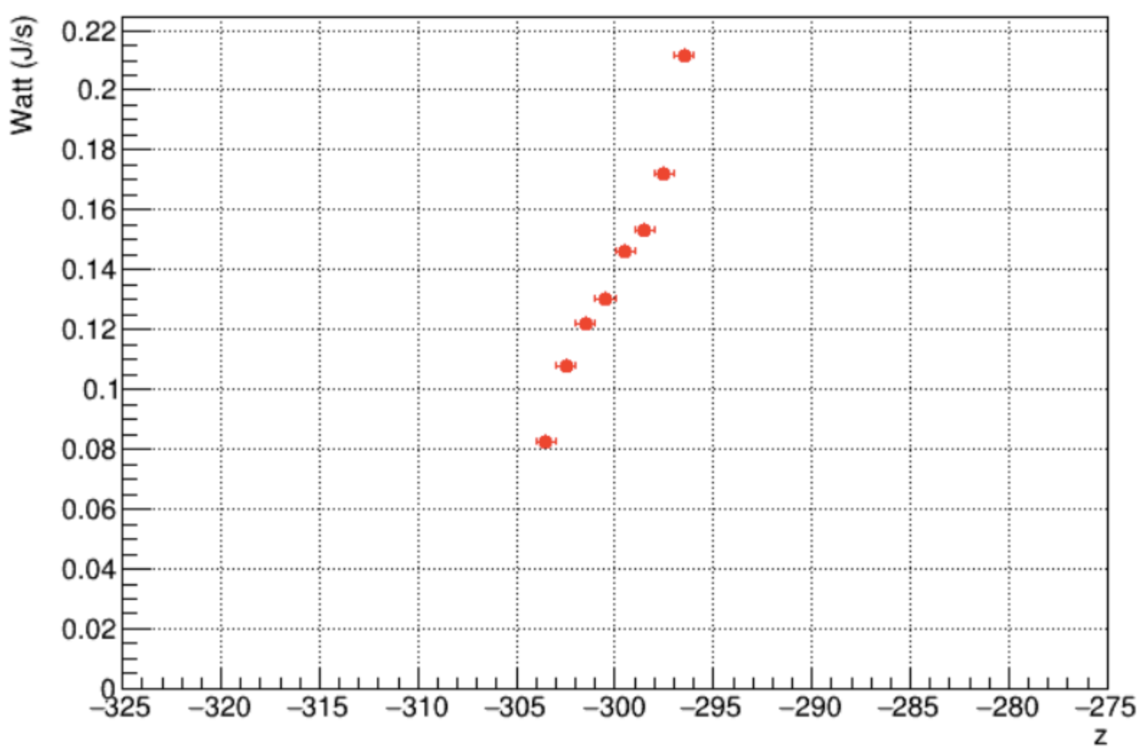
Simulations using RF module in Comsol multiPhysics simulation package

# Challenges of a long Target



- Anneals : $2 \times 10^{16}$ protons
- Replace: $1.5 \times 10^{17}$ protons
- Higher average requires more target maintenance
- Details required to know target overhead

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



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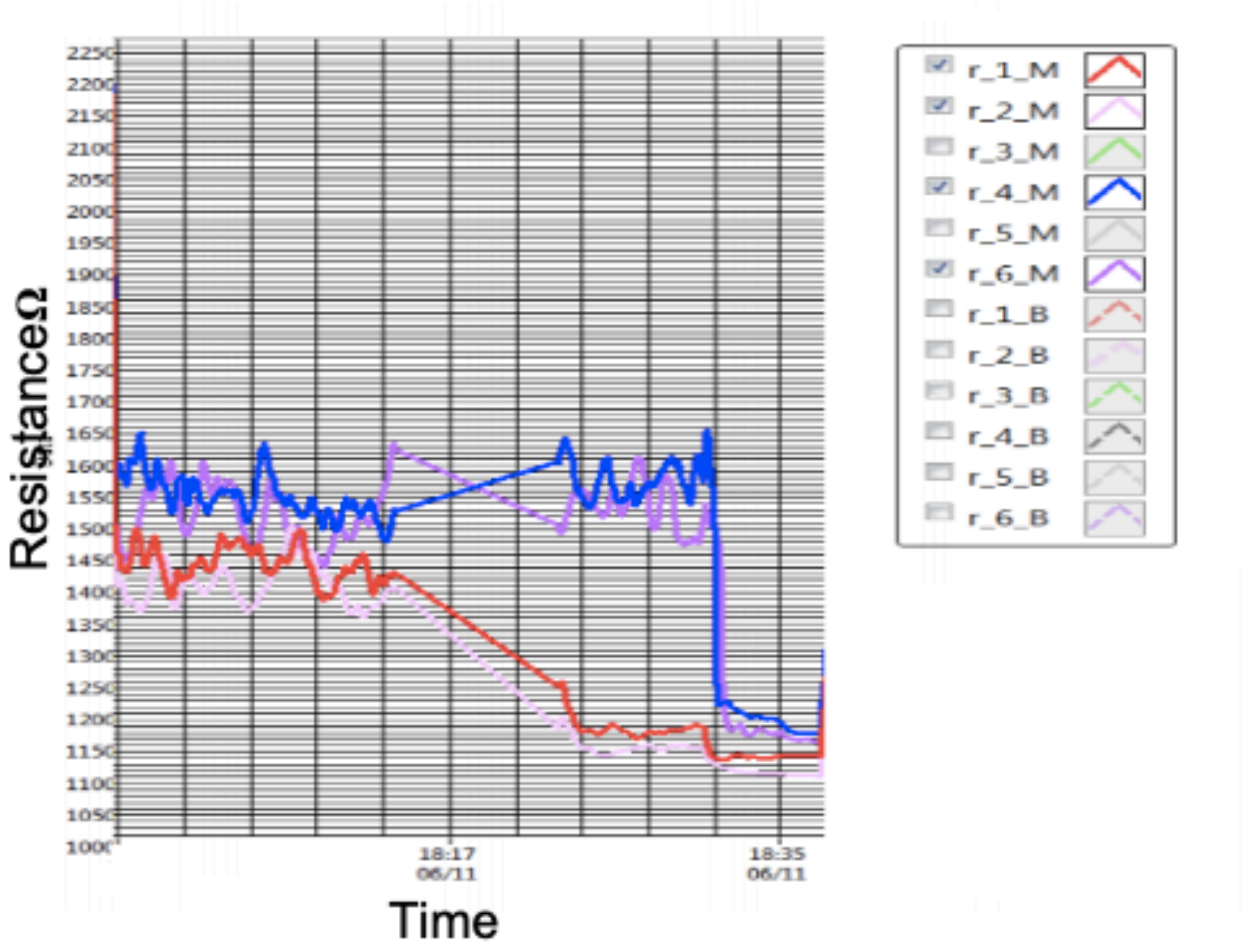
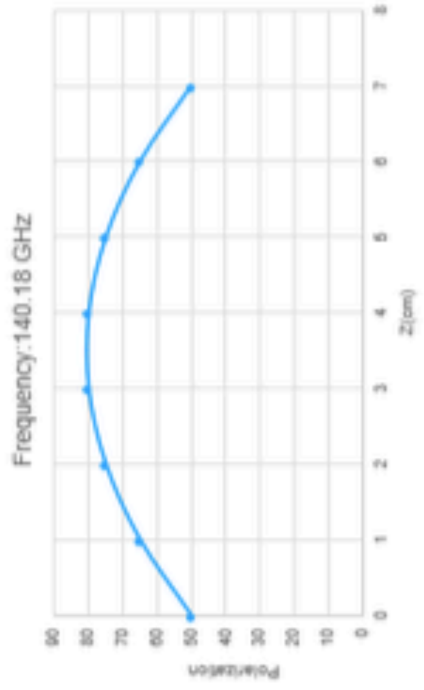
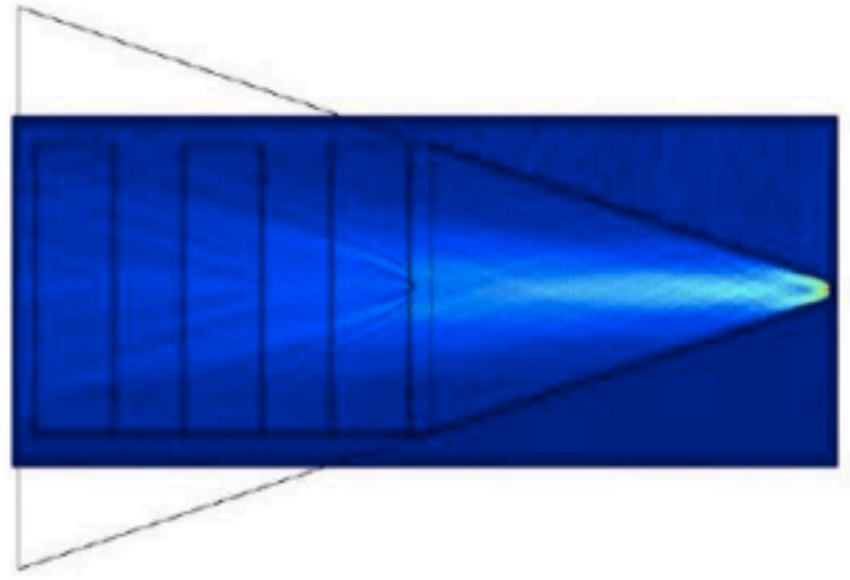
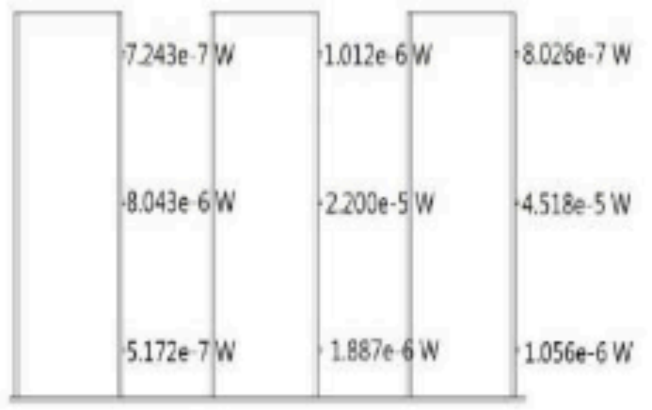
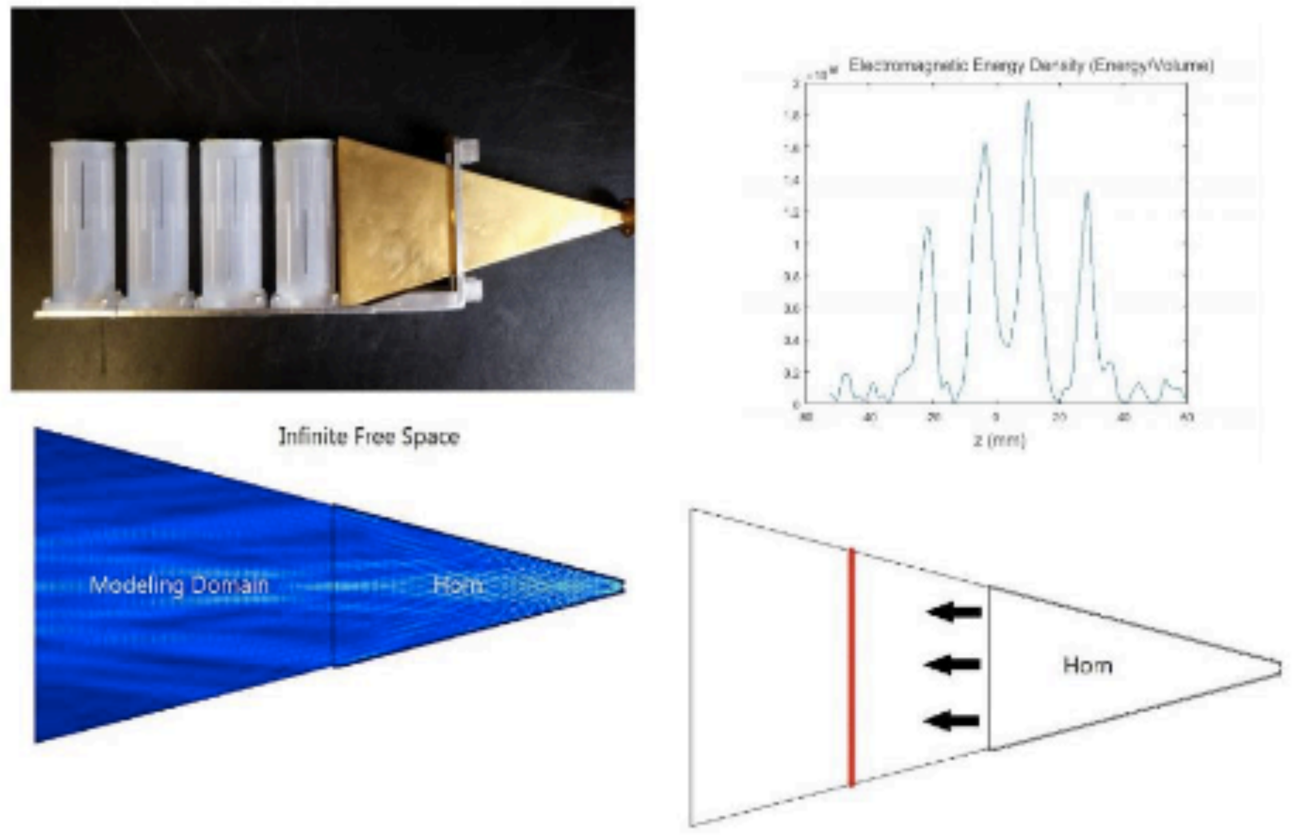




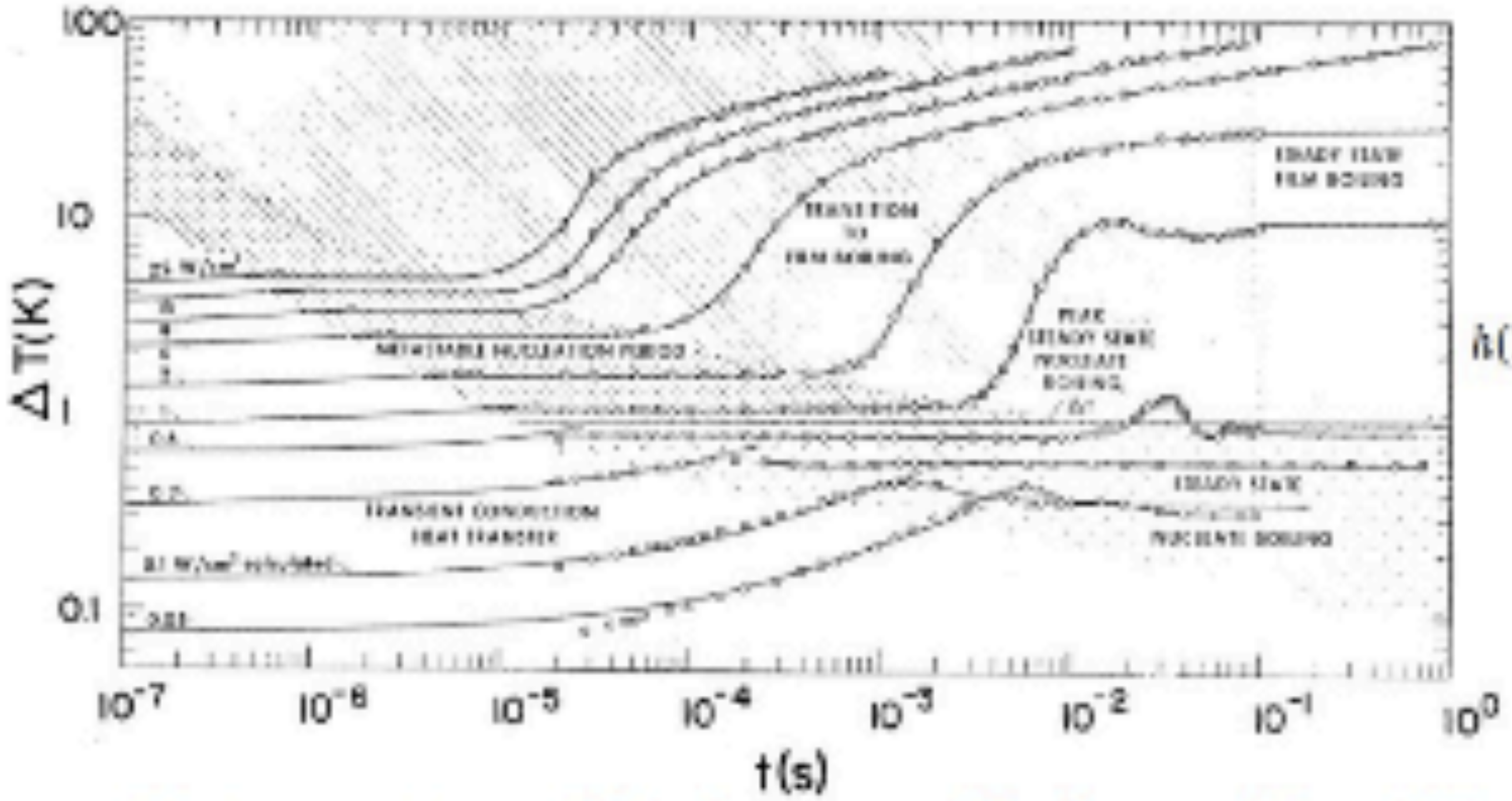






Simulations using RF module in Comsol multiPhysics simulation package

# Approximation Strategy

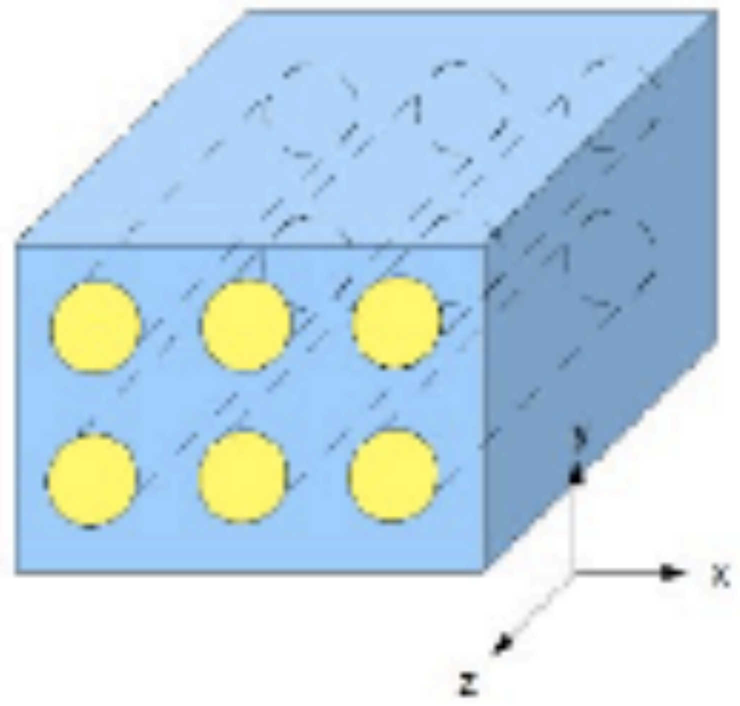


Various regimes of the heat transfer from solid to LHe

First, Steady state Film boiling regime is applied

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

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



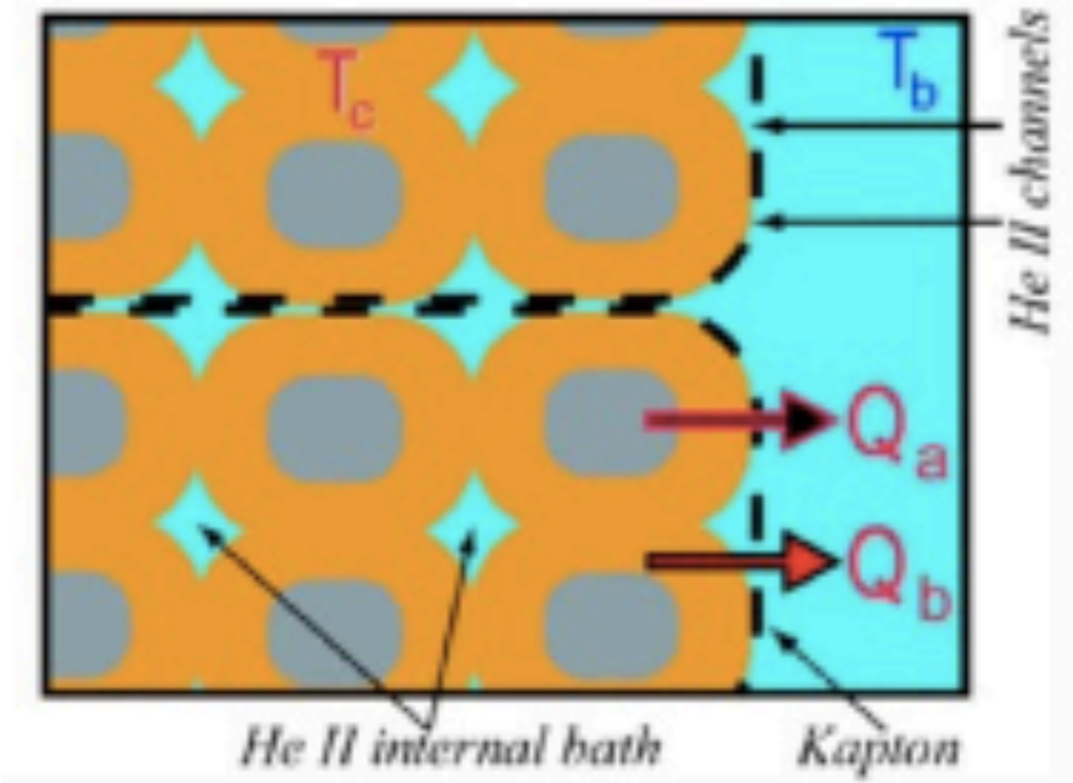
Rayleigh's model consist of parallel cylinders embedded in a continuous matrix

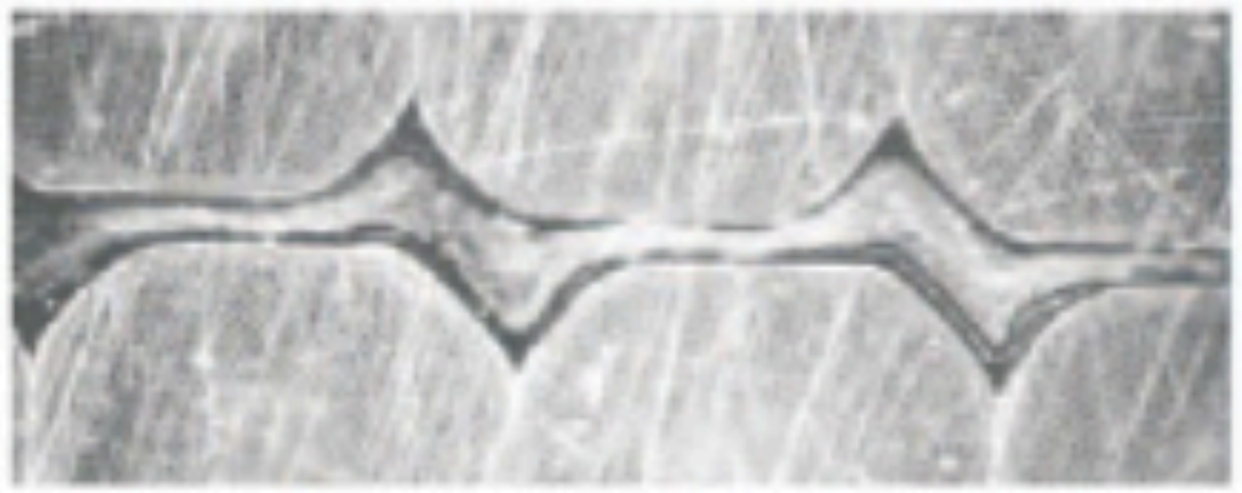
Rayleigh's formula

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

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

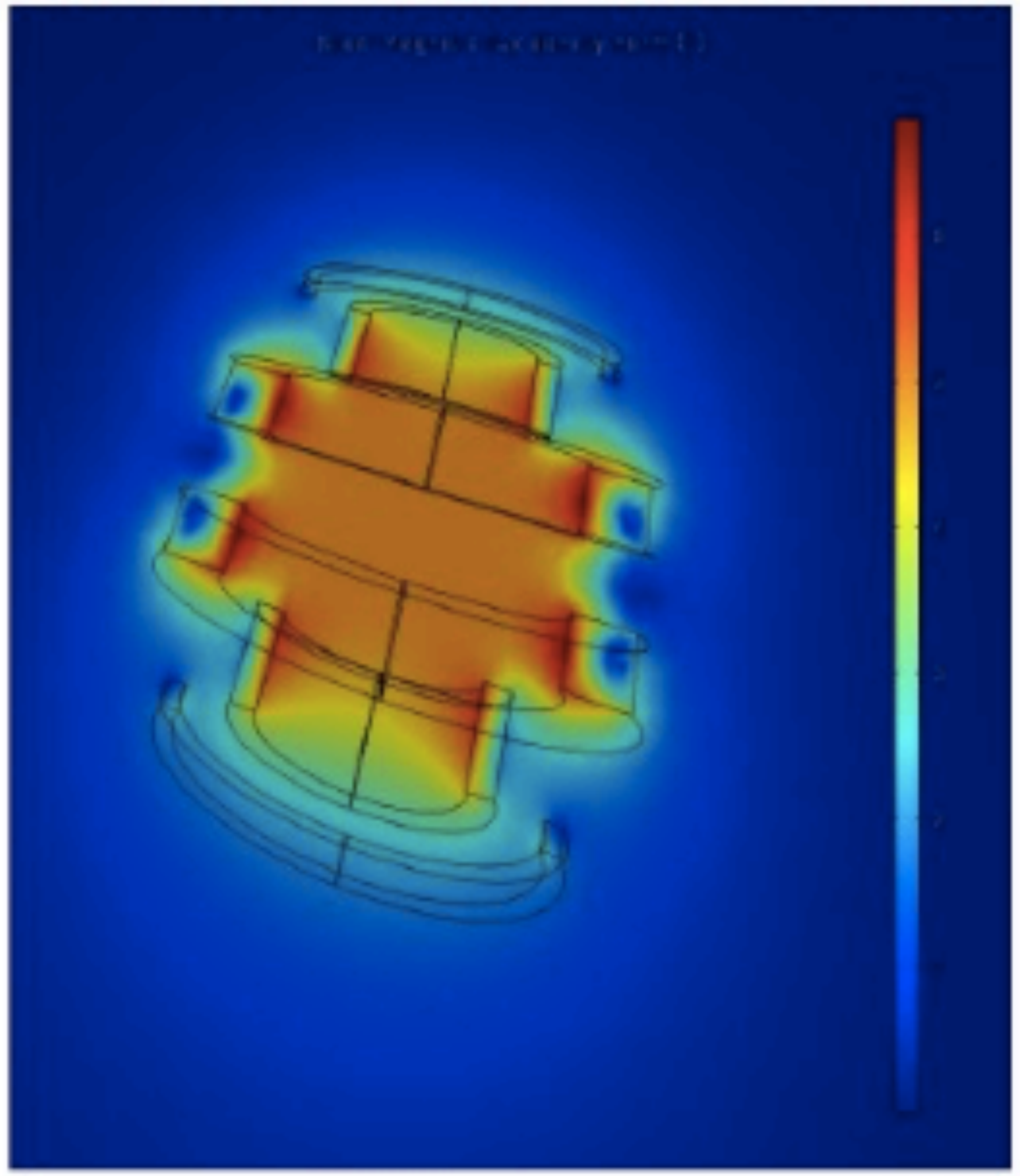
# Field Measurement and Map

Measure Homogeneity using NMR and Hall Probe

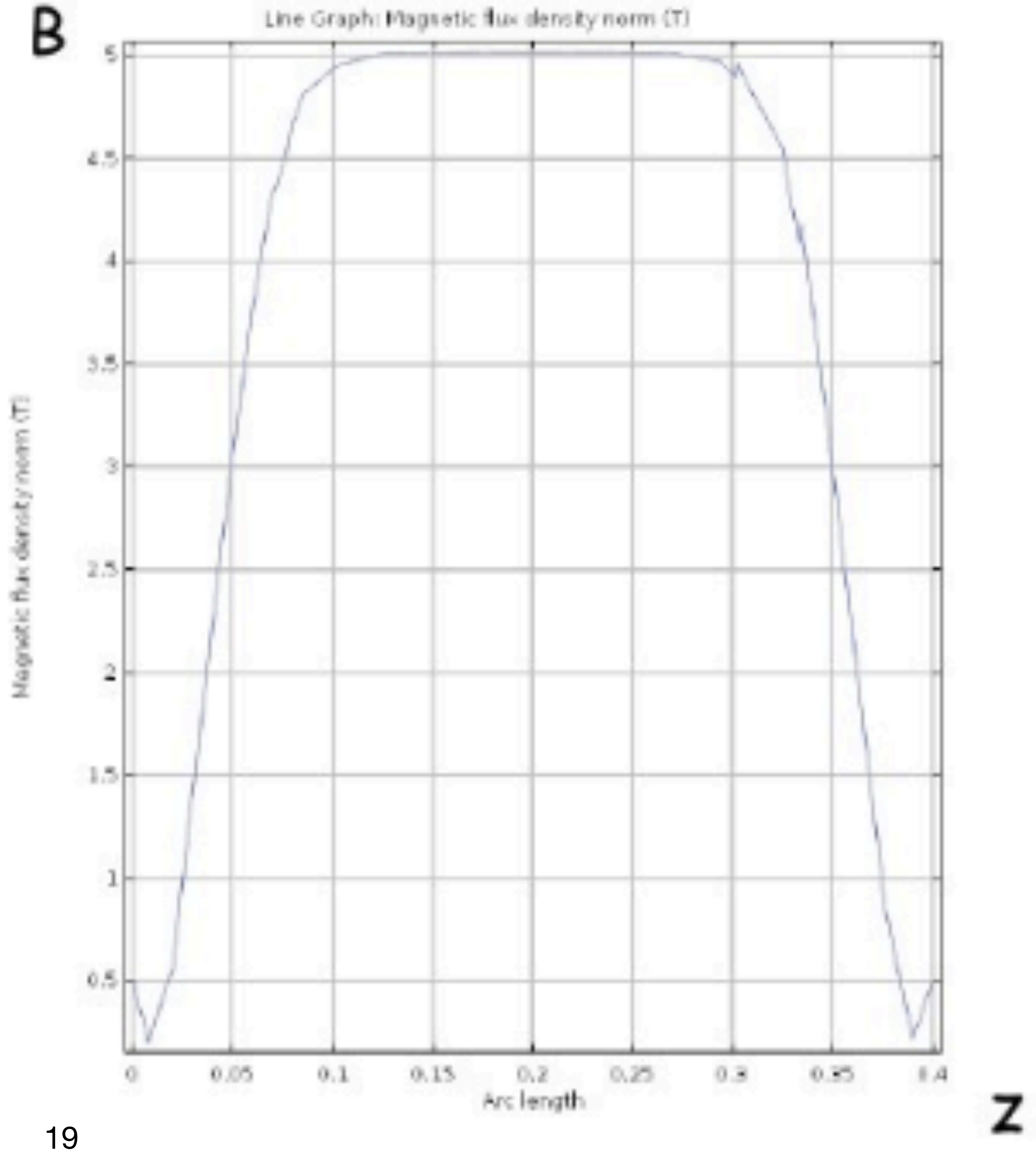
Accurate Field Map ✓

Measure outside fringe field and map to simulated field

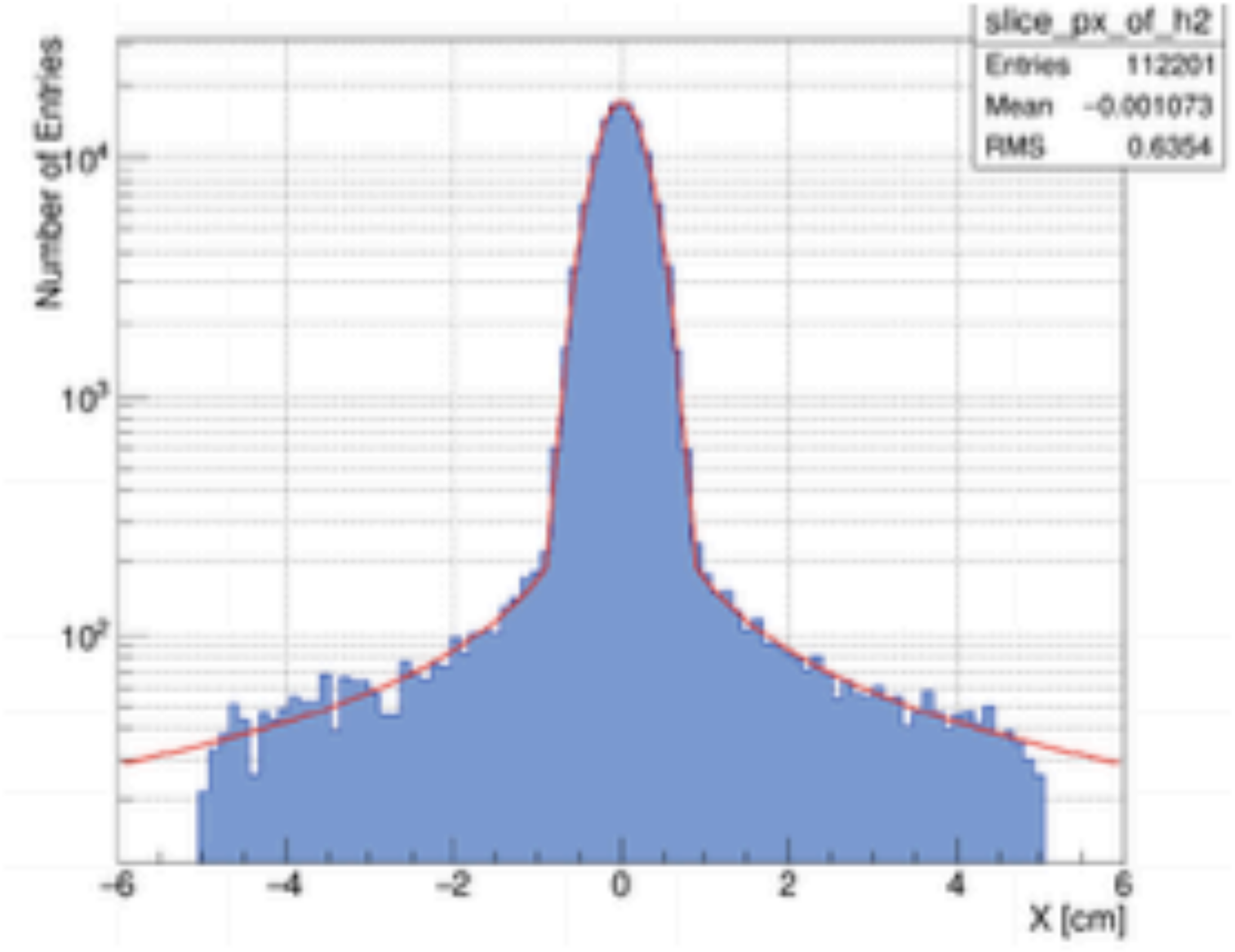
We achieve a high level of homogeneity around the target area & along the beam line:

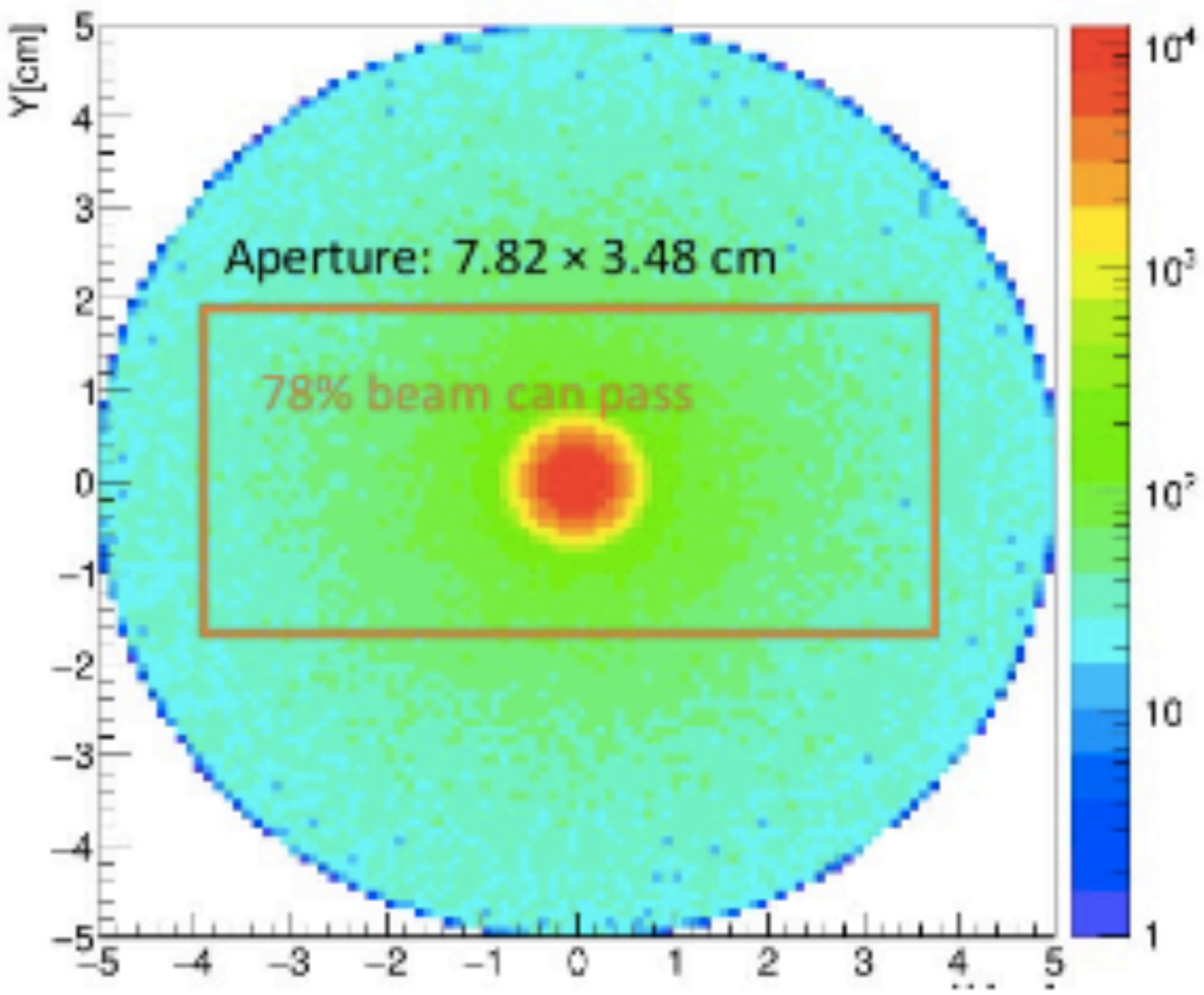


High level of homogeneity in the target area

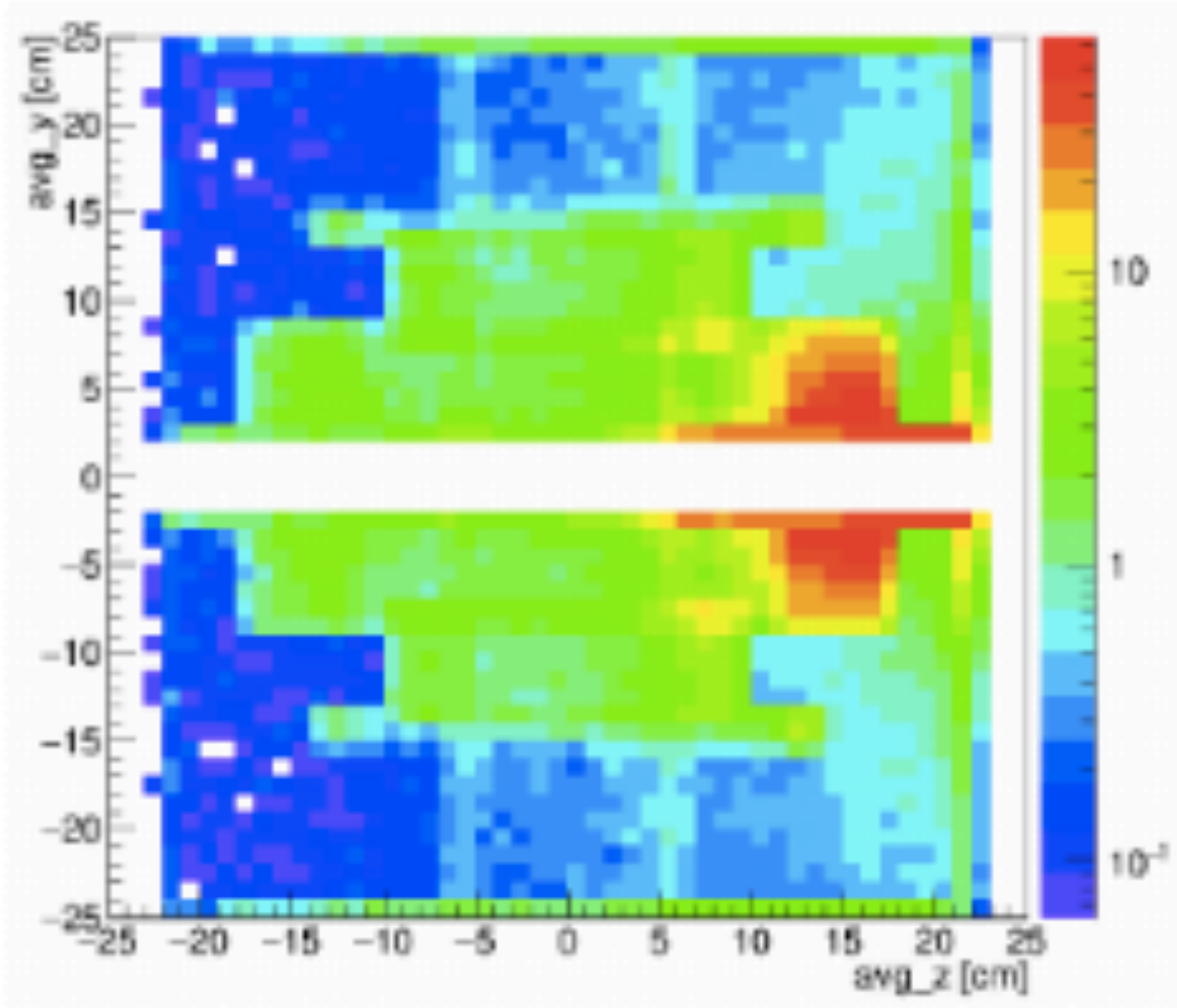


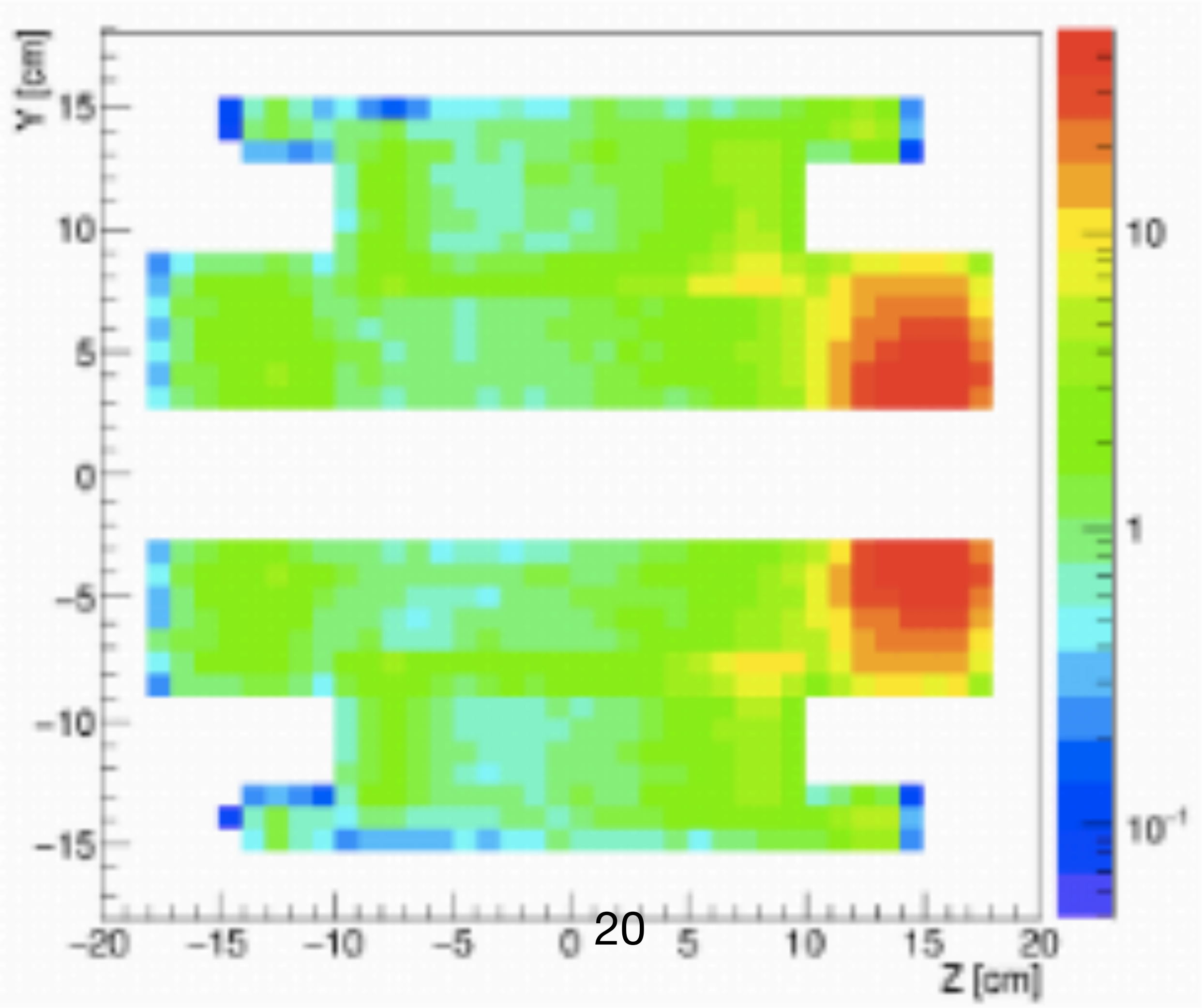
# Geant → COMSOL

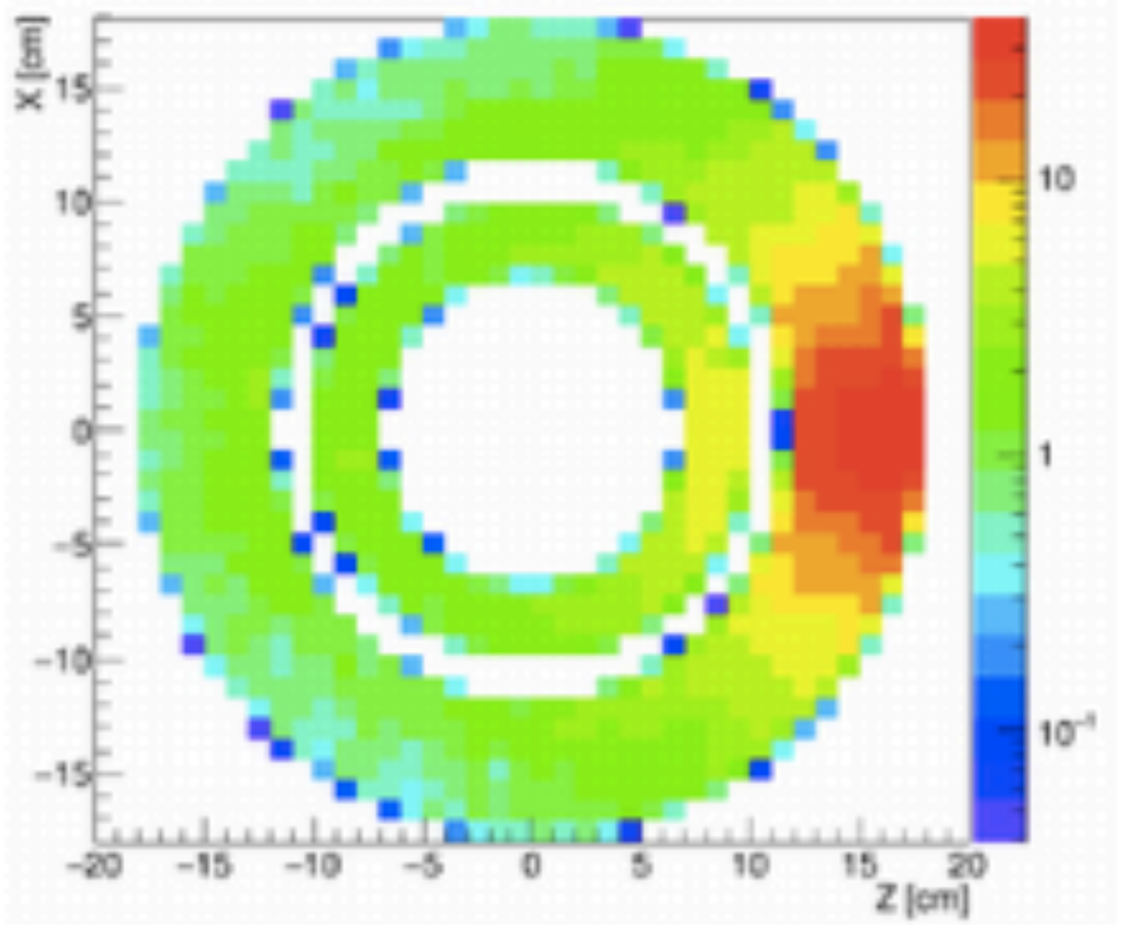



Aperture: 7.82 × 3.48 cm

78% beam can pass

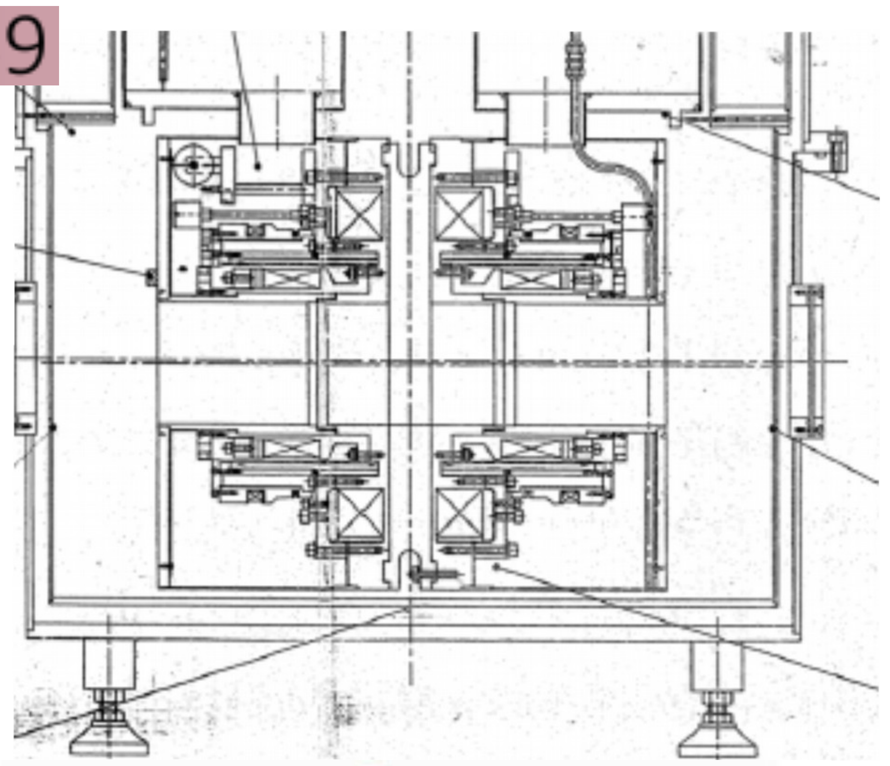


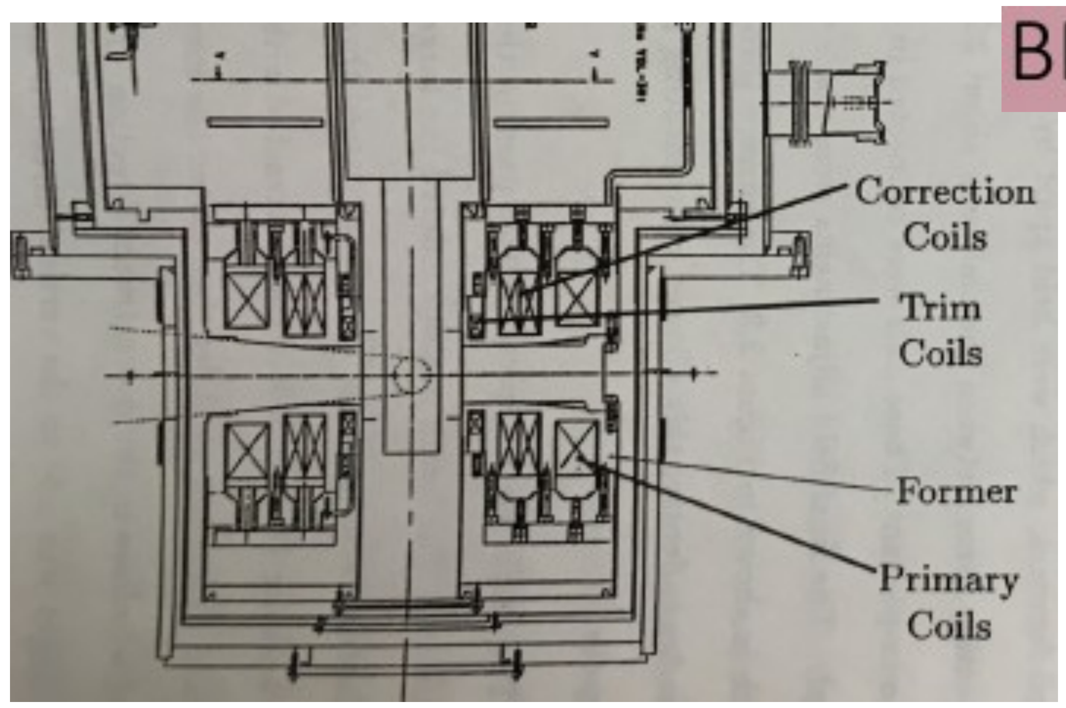




# Magnet Comparison

E1039

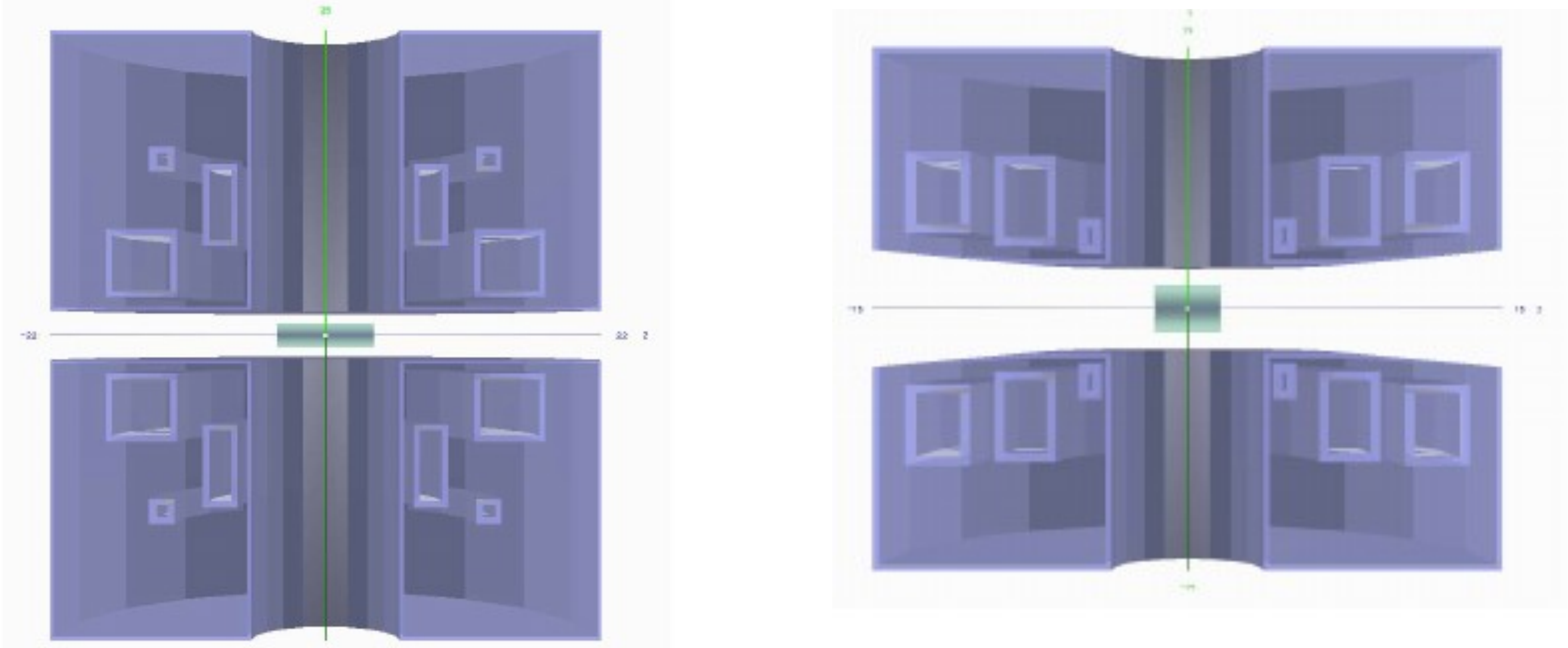




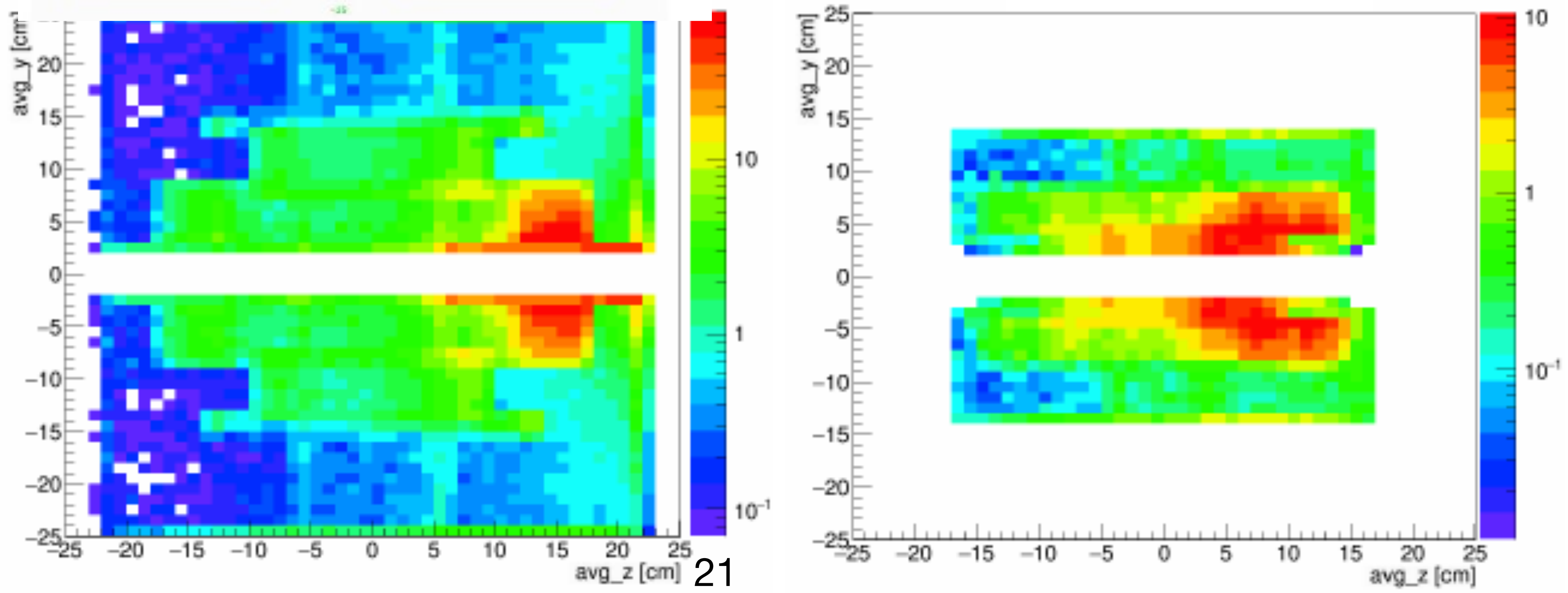
BNL target

Solidworks→ Geat4

Based on drawings and measurements



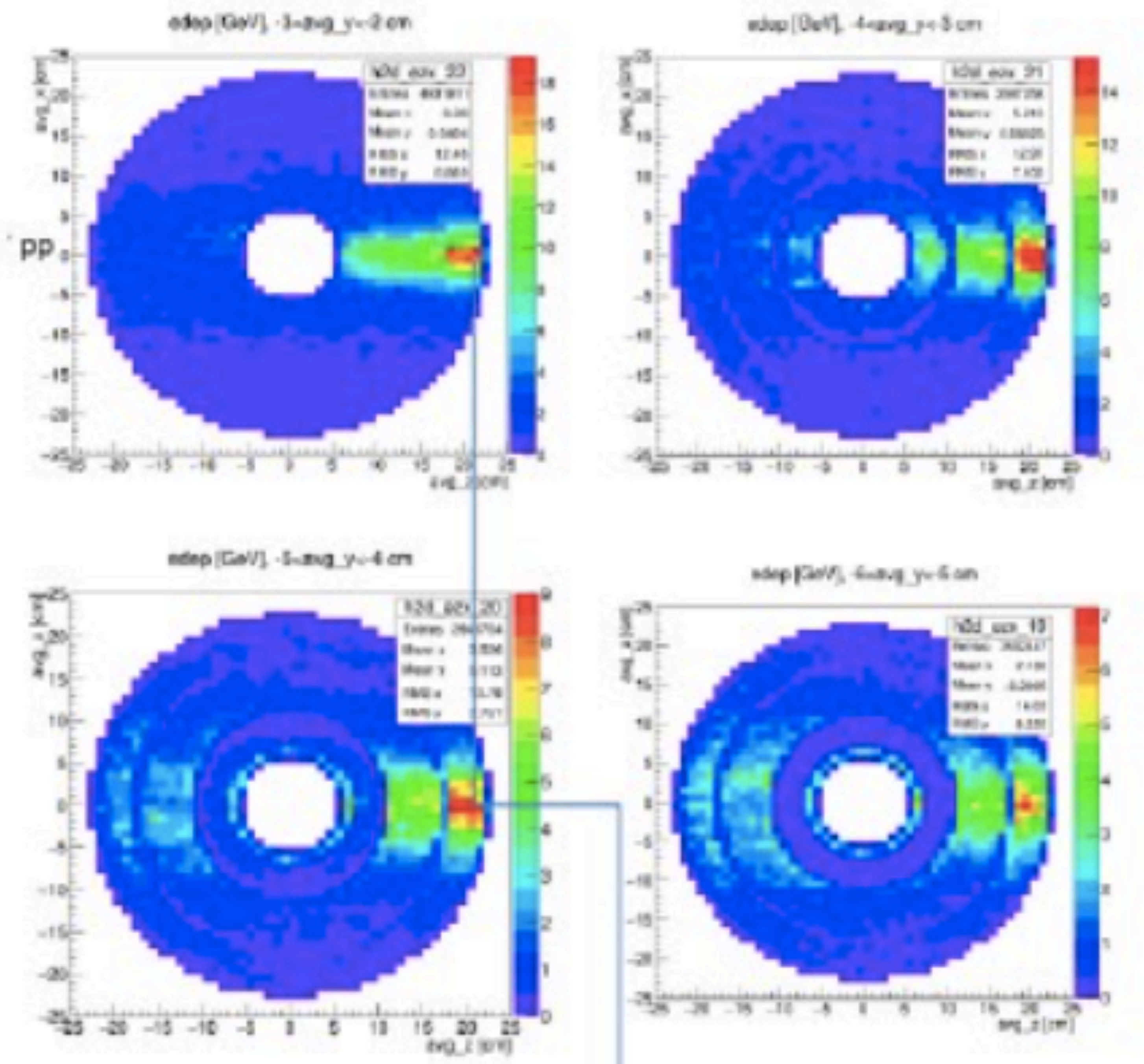
Simulation contain SS former, LHe, vessels, target cell, target material



Then look at energy deposition in the SC coils

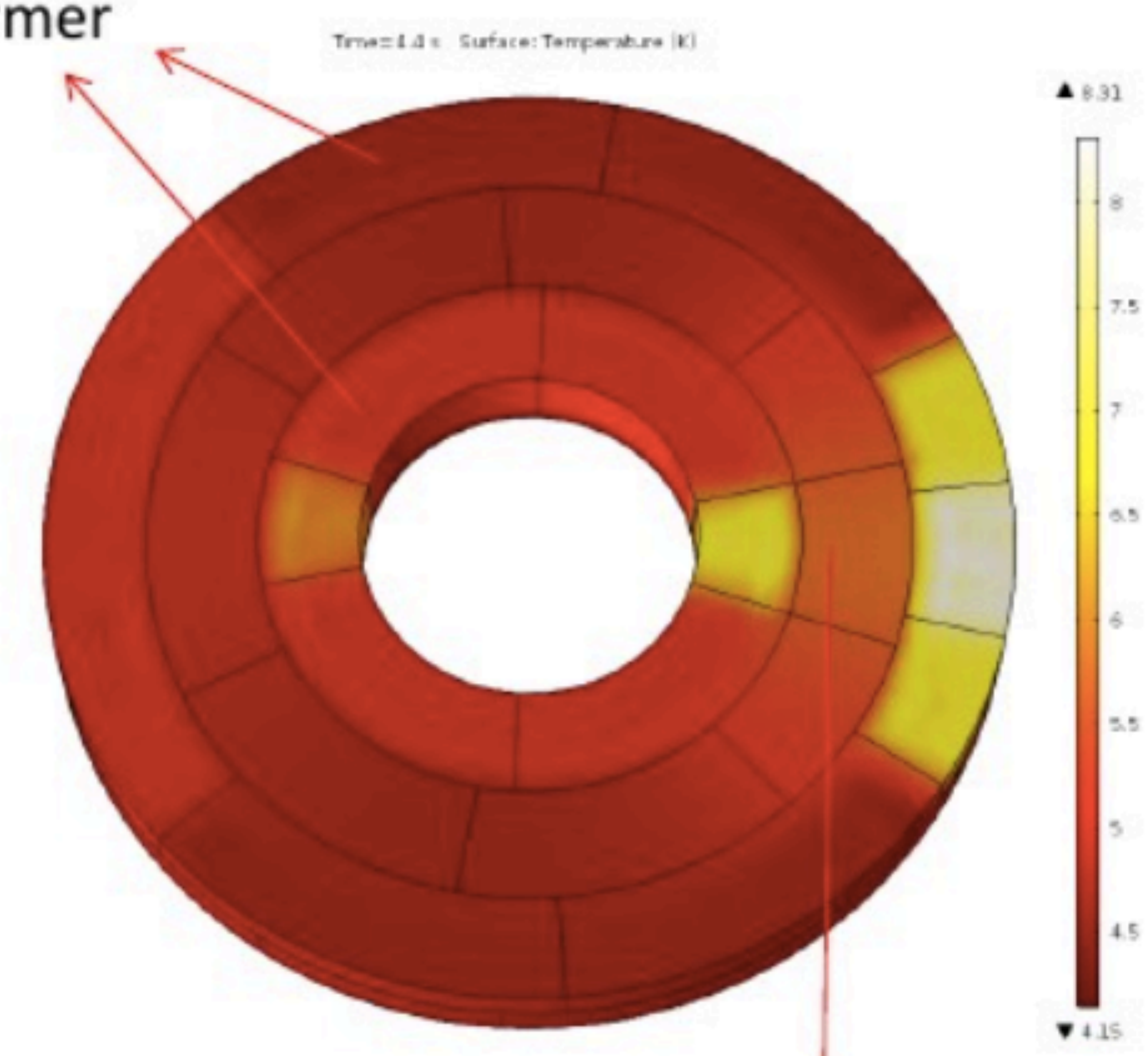
# Quench Simulations

What we have currently



Maximum hot spot
around 18000 W/m^3

Former

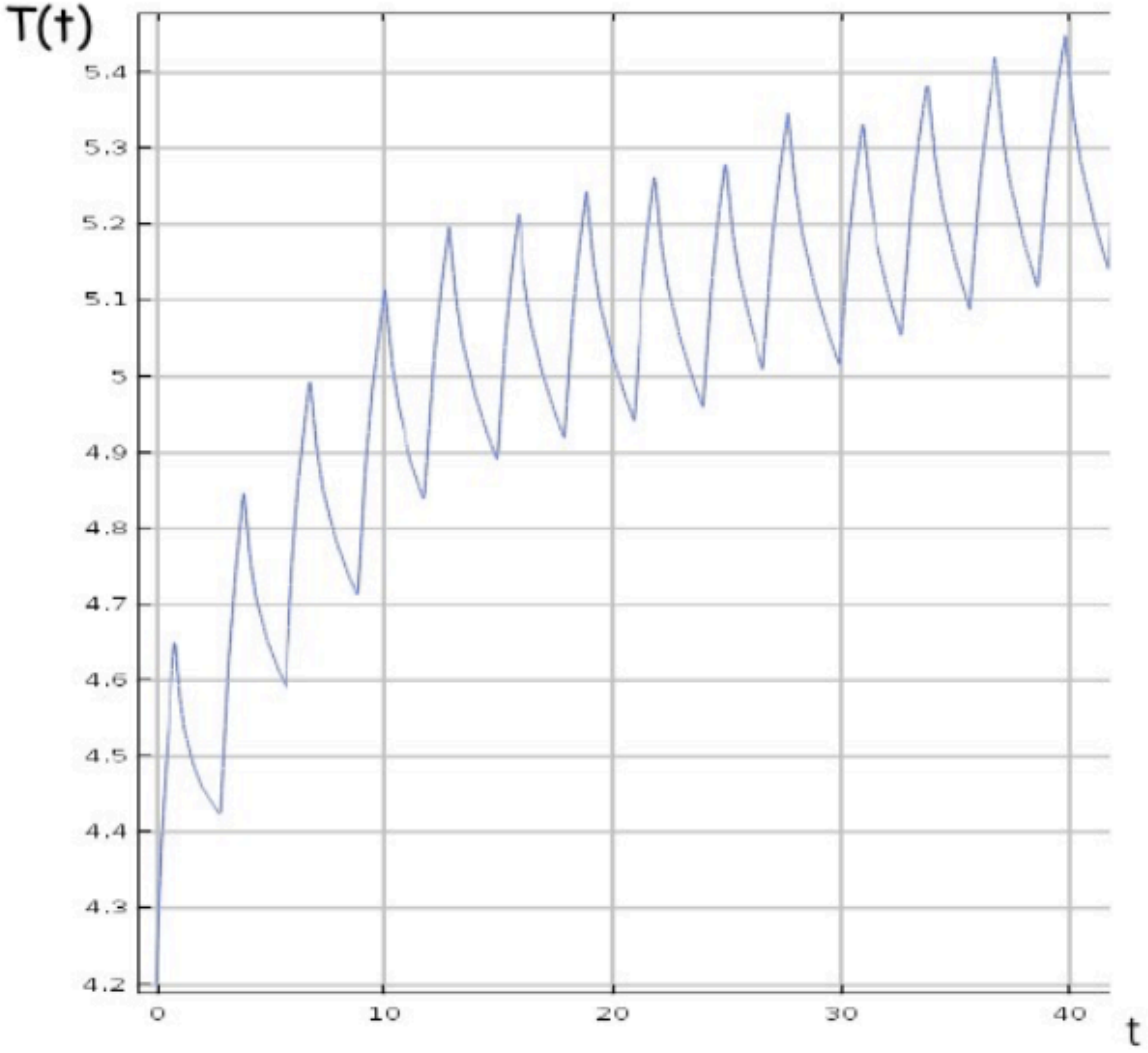


Simulation result

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:

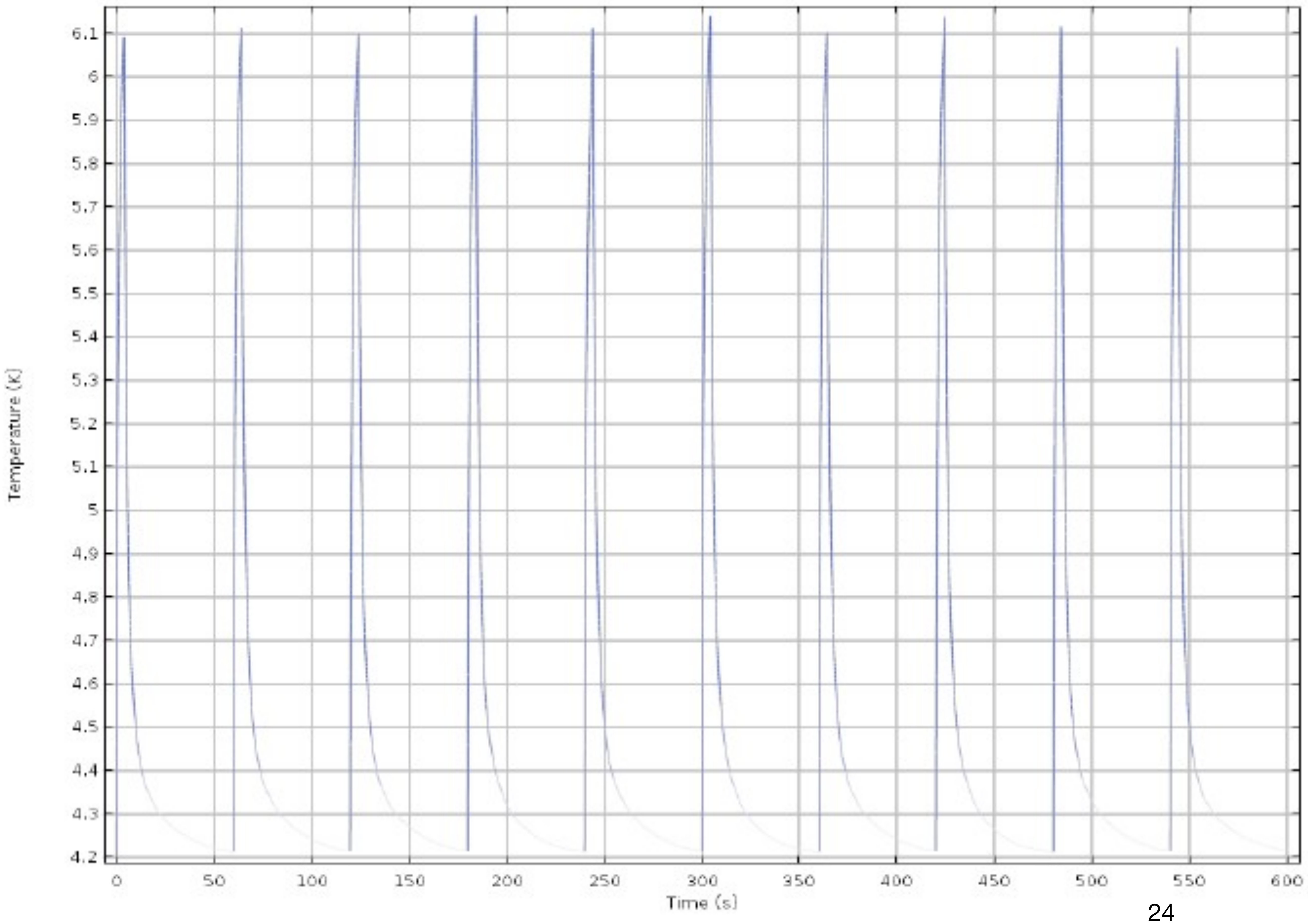
- 24 GeV proton
- 2e11 proton/s
- Teflon Target

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

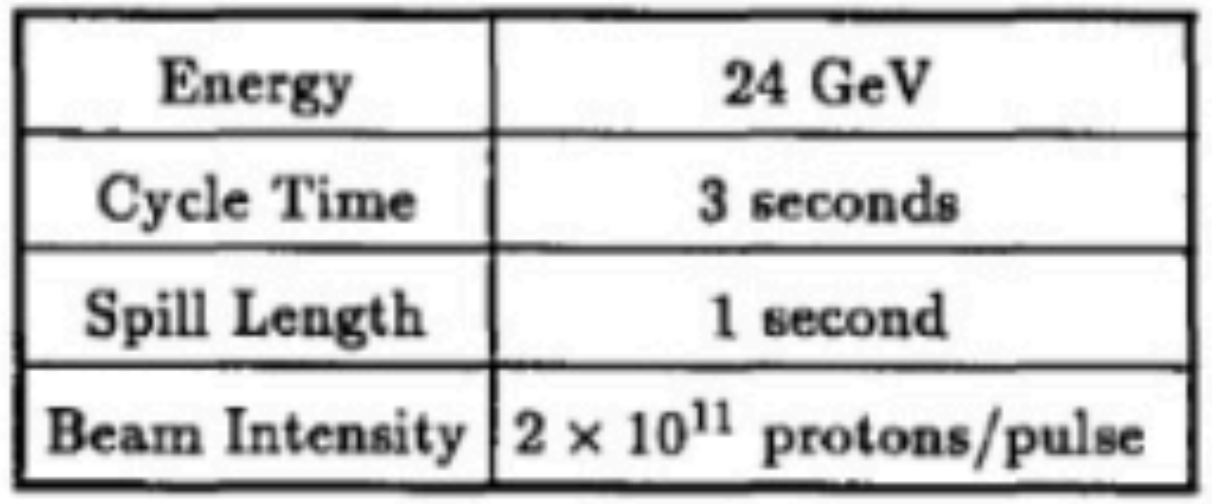
# Superconducting Magnet Quest Studies

**SpinQuest**

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

vs

BNL:



| Energy | 24 GeV |
|---|---|
| Cycle Time | 3 seconds |
| Spill Length | 1 second |
| Beam Intensity | $2 \times 10^{11}$ protons/pulse |

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

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

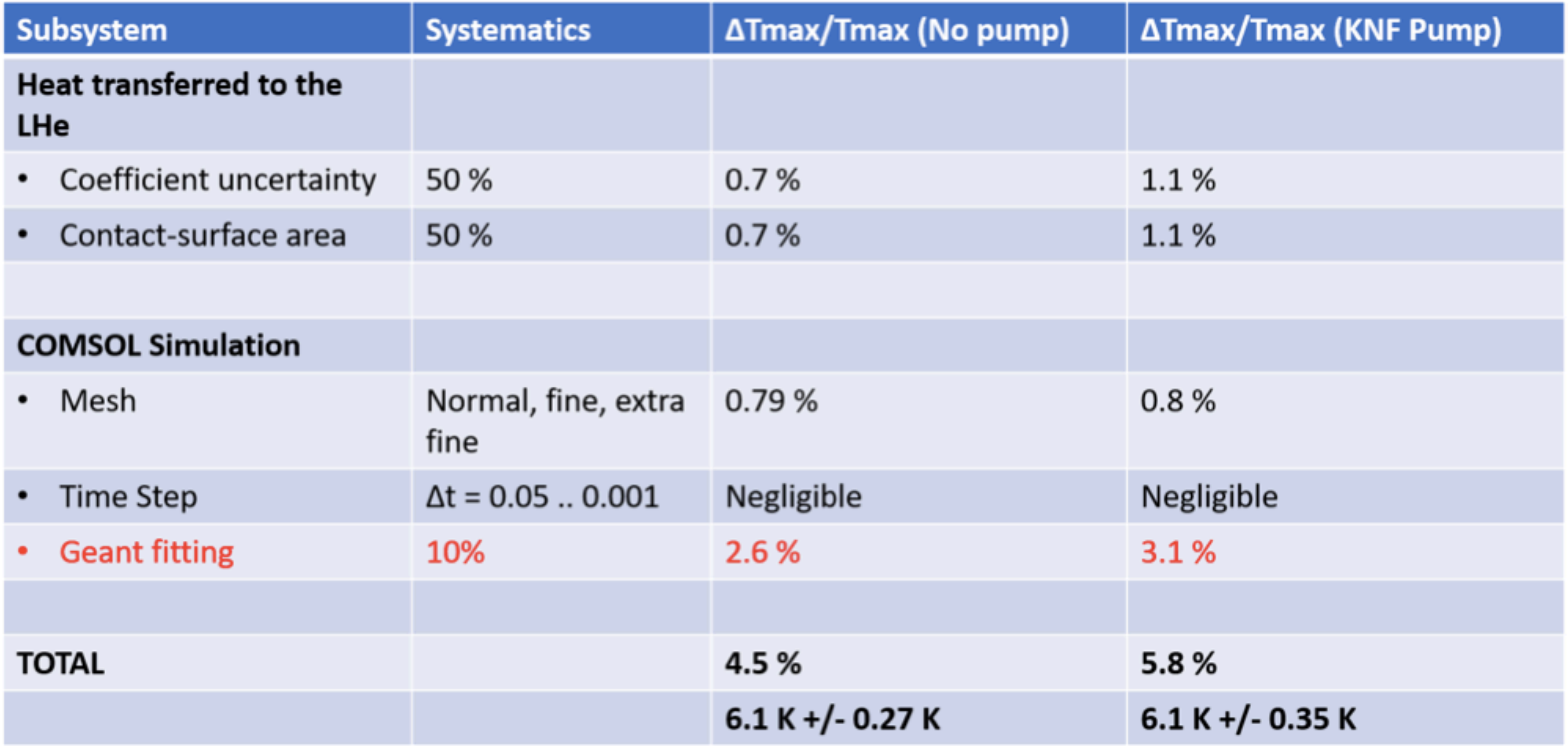
Highest Cooling Power DNP Evaporation System:

- 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

# External Magnet Temp Sensor

Type-T Thermocouples Cu-CuNi

# Systematic Uncertainties

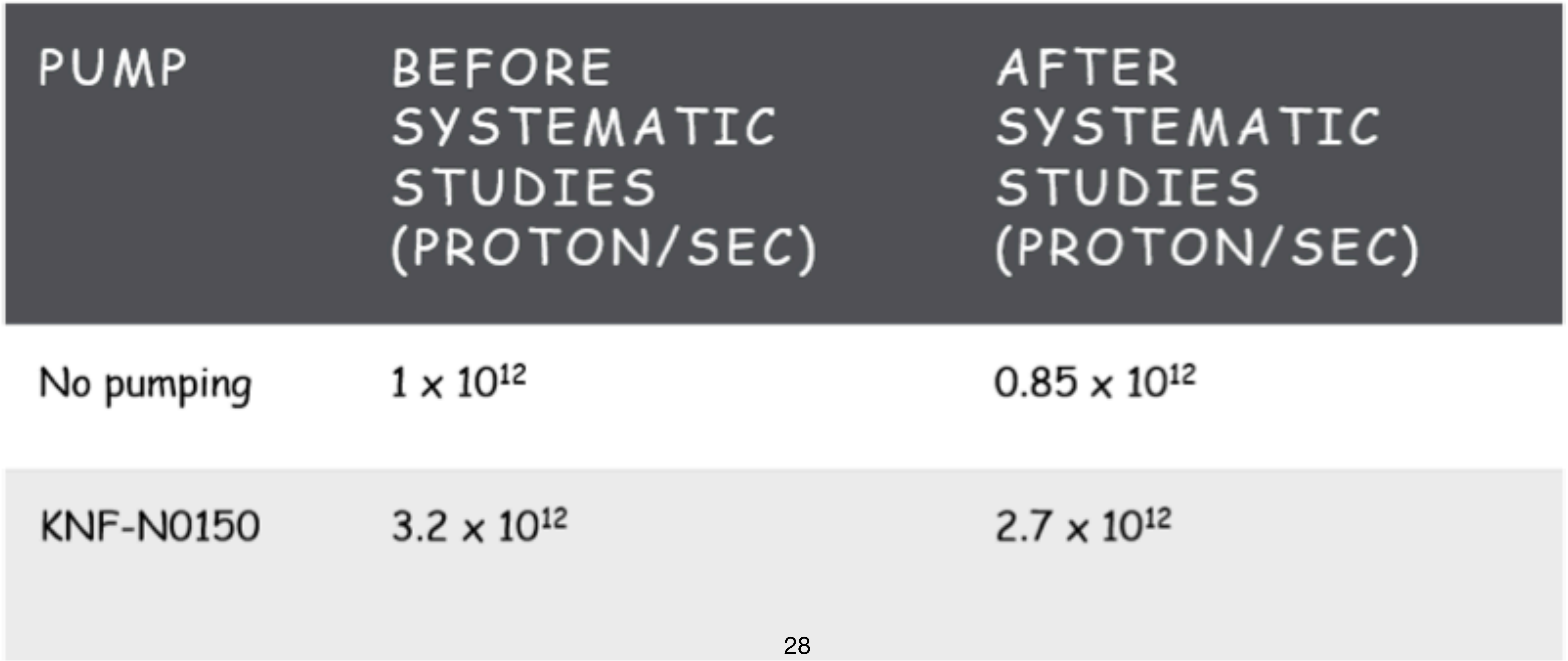


| Subsystem | Systematics | ΔTmax/Tmax (No pump) | ΔTmax/Tmax (KNF Pump) |
|---|---|---|---|
| **Heat transferred to the LHe** | | | |
| • Coefficient uncertainty | 50 % | 0.7 % | 1.1 % |
| • Contact-surface area | 50 % | 0.7 % | 1.1 % |
| | | | |
| **COMSOL Simulation** | | | |
| • Mesh | Normal, fine, 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** |

# Estimated Quench Threshold

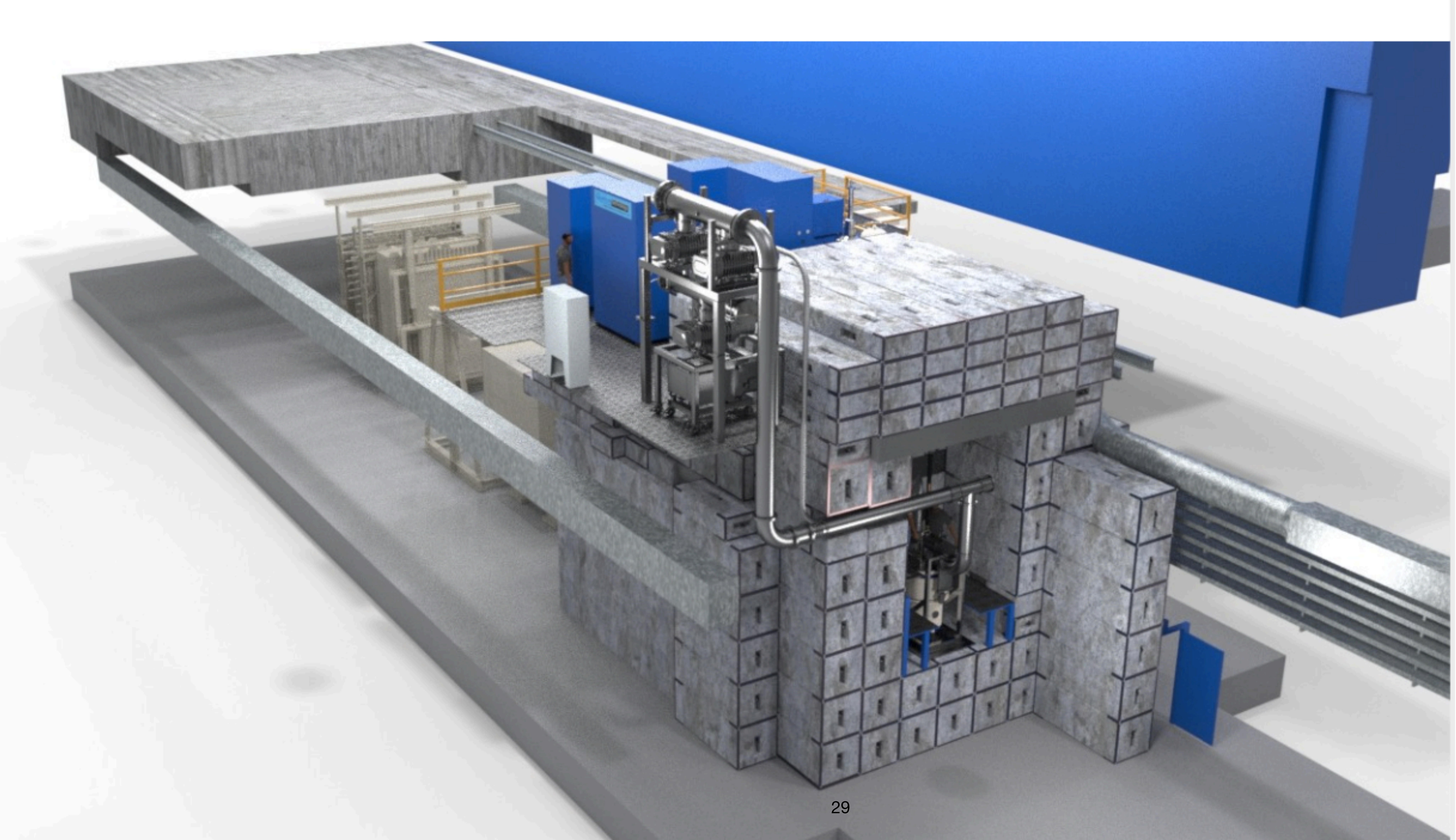
## Based on a series of MC systematics studies

- Assume no other intensity constraints
- Assume unlimited LHe

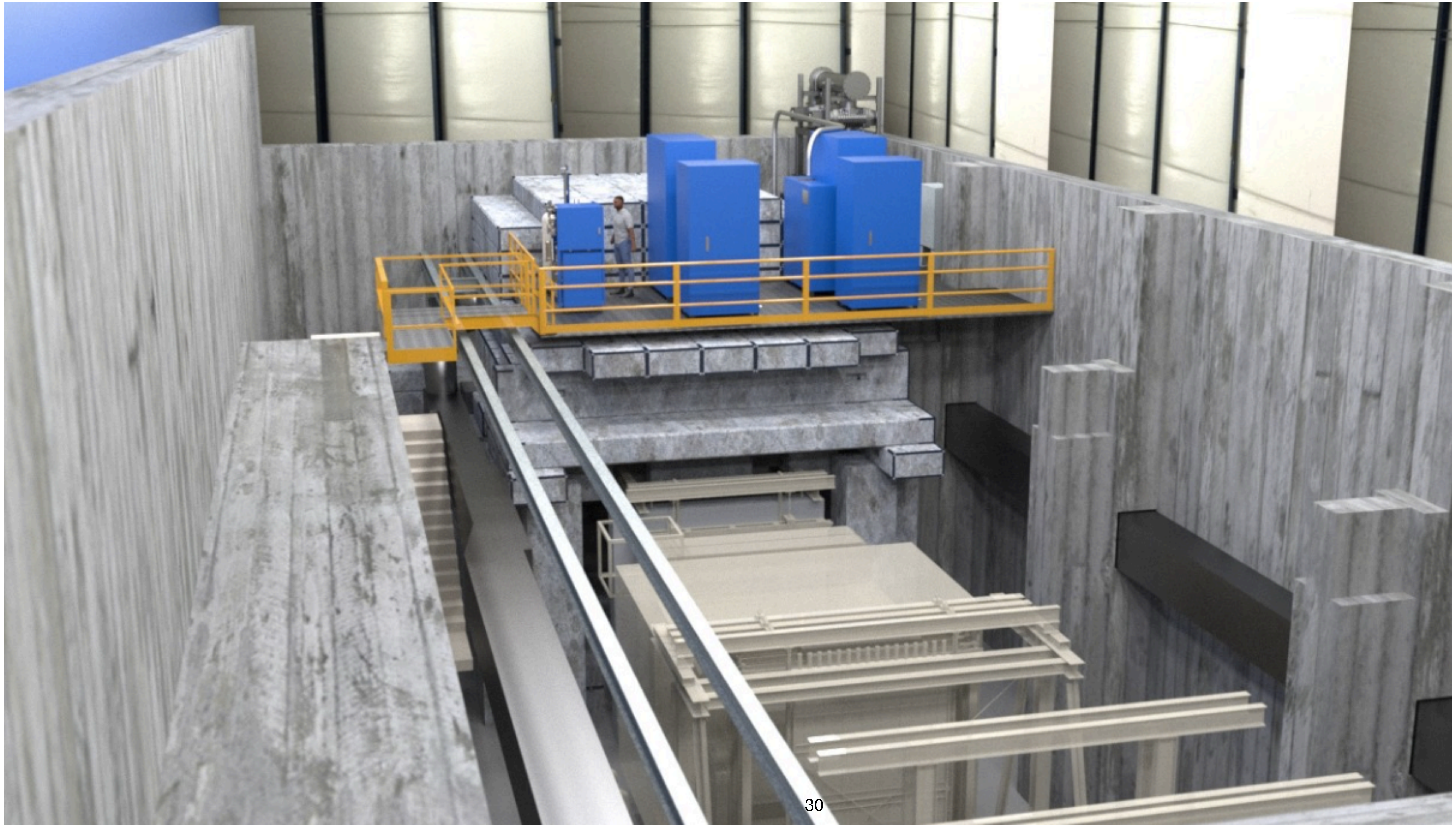


| PUMP | BEFORE SYSTEMATIC STUDIES (PROTON/SEC) | AFTER SYSTEMATIC STUDIES (PROTON/SEC) |
|---|---|---|
| No pumping | $1 \times 10^{12}$ | $0.85 \times 10^{12}$ |
| KNF-N0150 | $3.2 \times 10^{12}$ | $2.7 \times 10^{12}$ |

# SpinQuest Experimental Hall



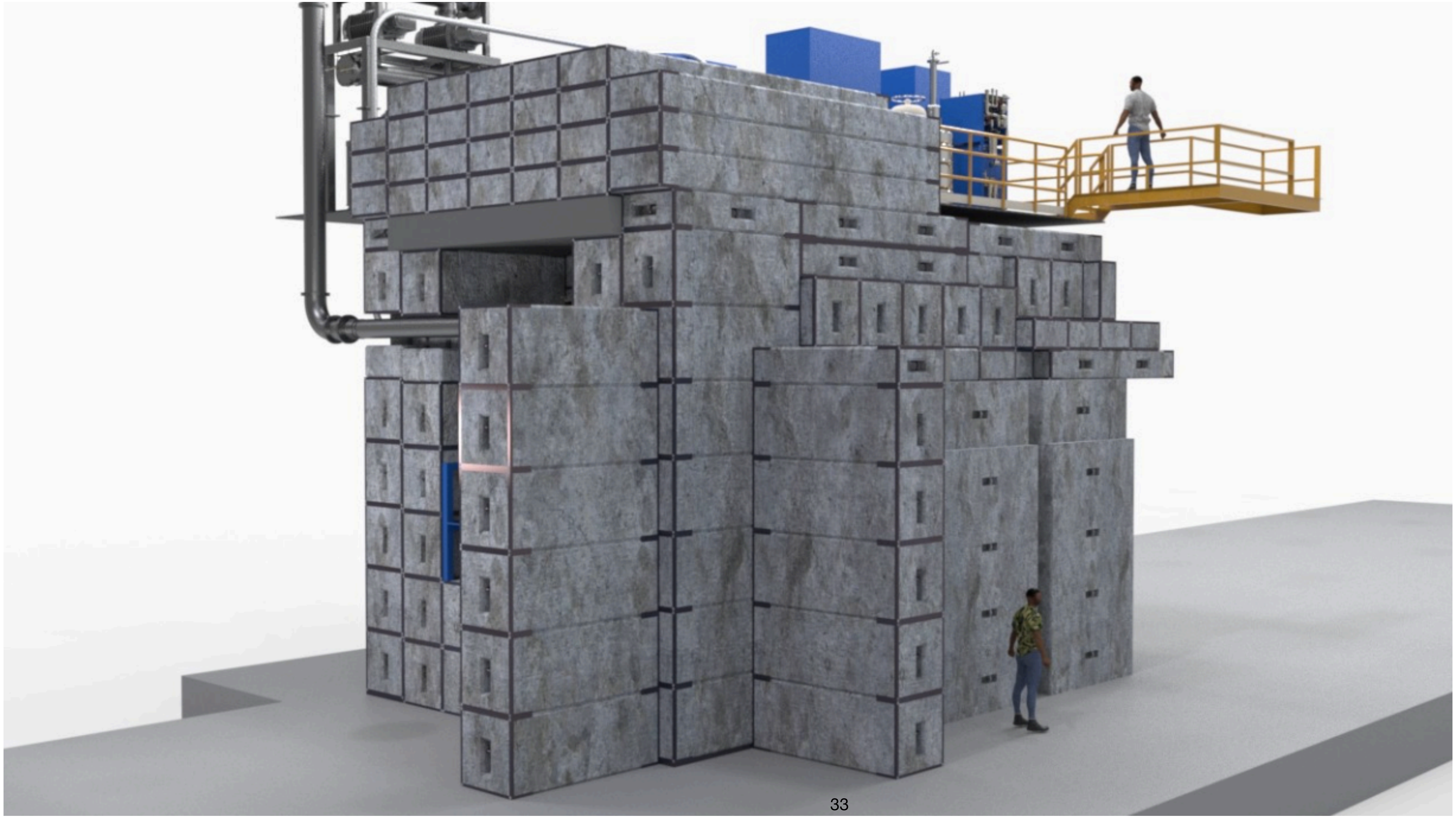
# NM4 Experimental Hall



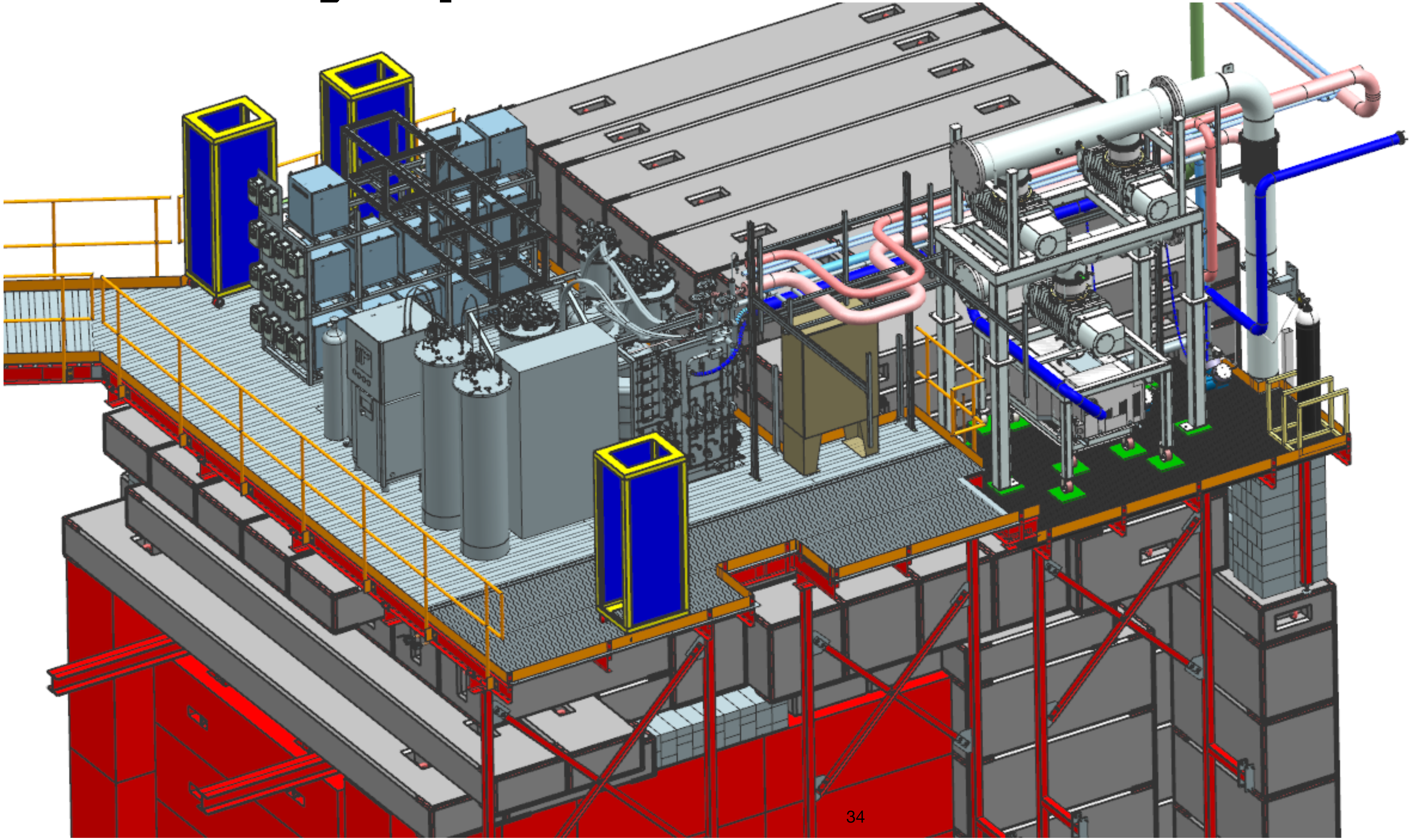
# Cryo-platform

# Top of Target Cave

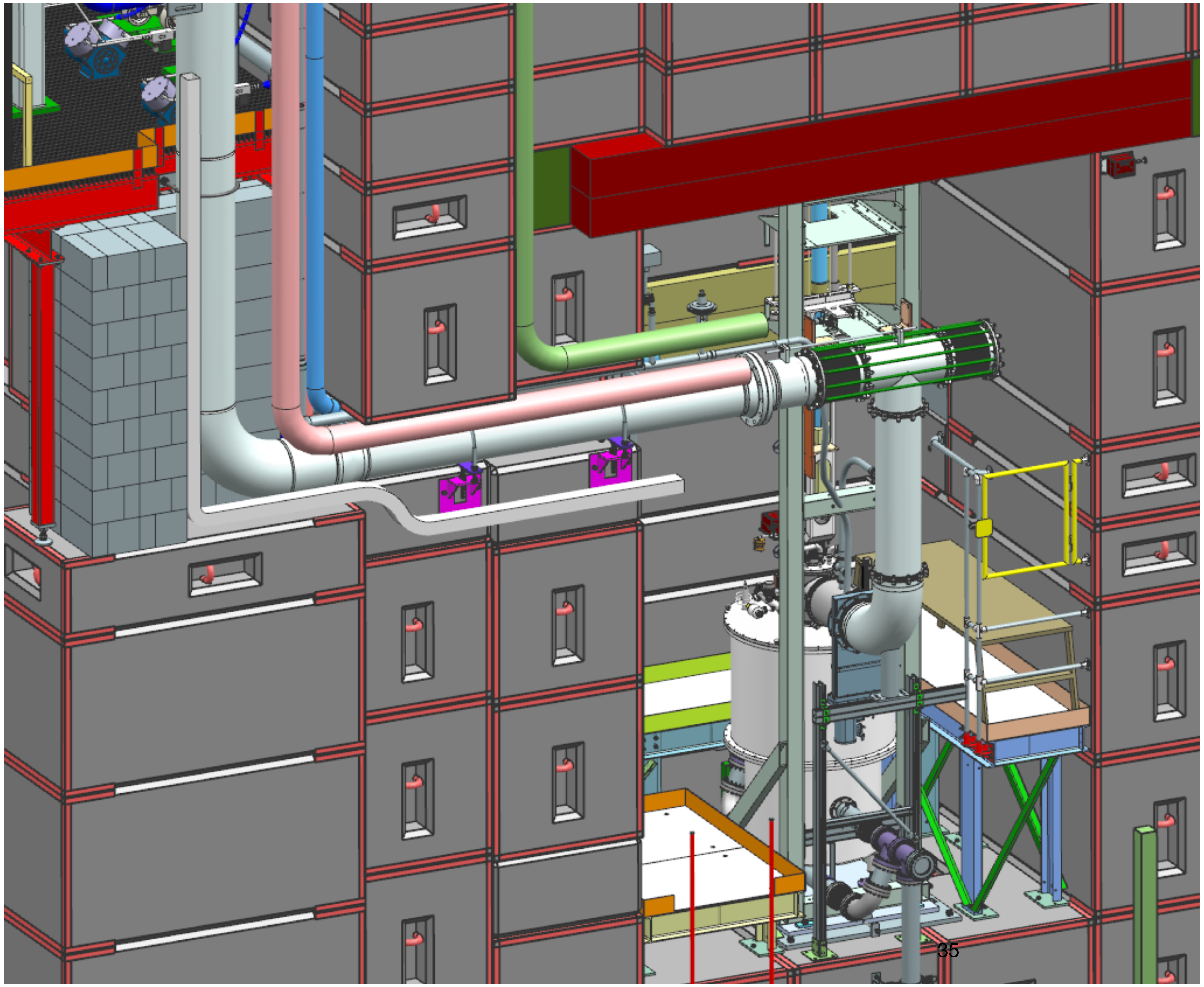
# Target Cave and Cryo-platform



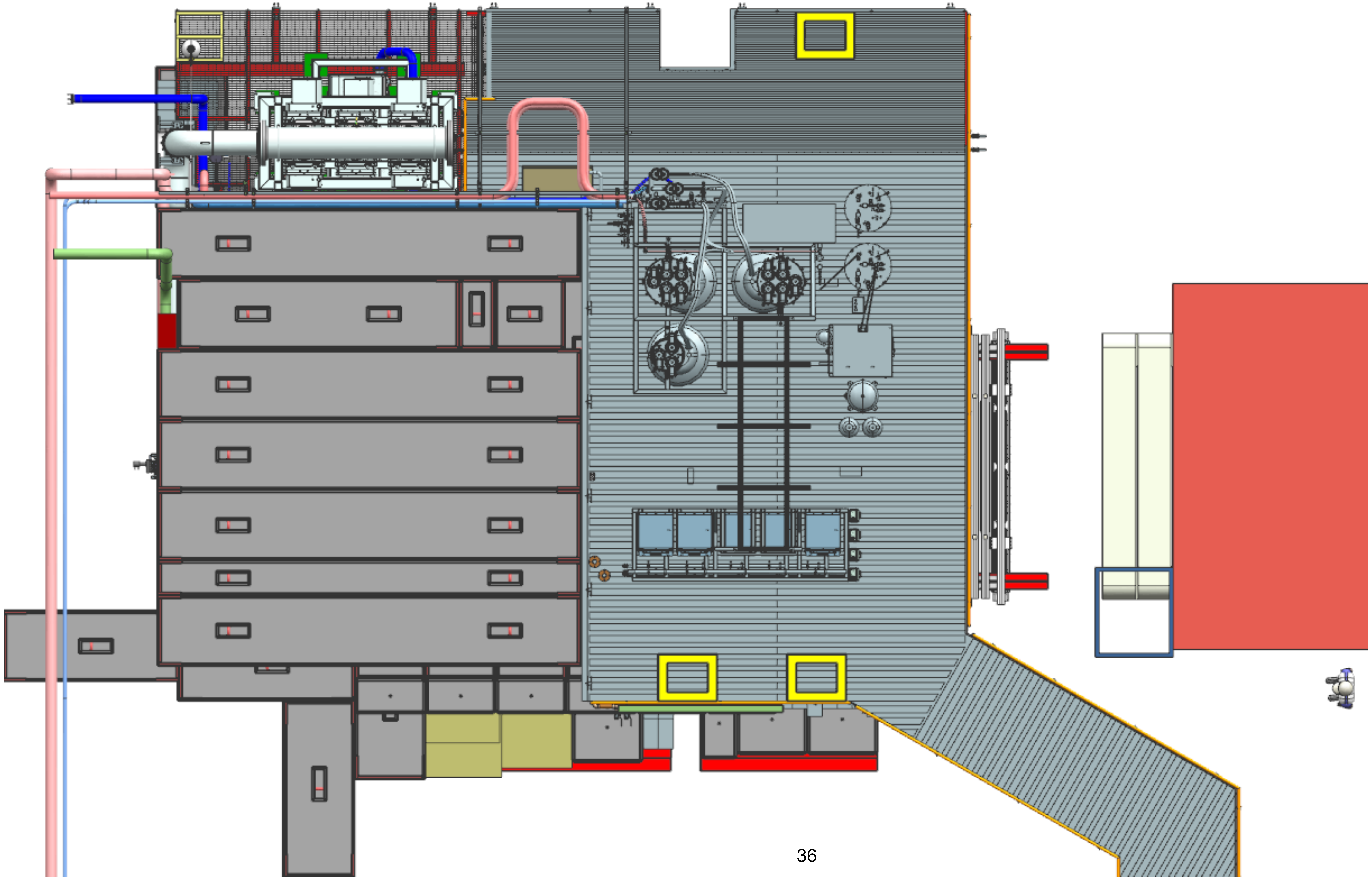
# New Cryo-platform



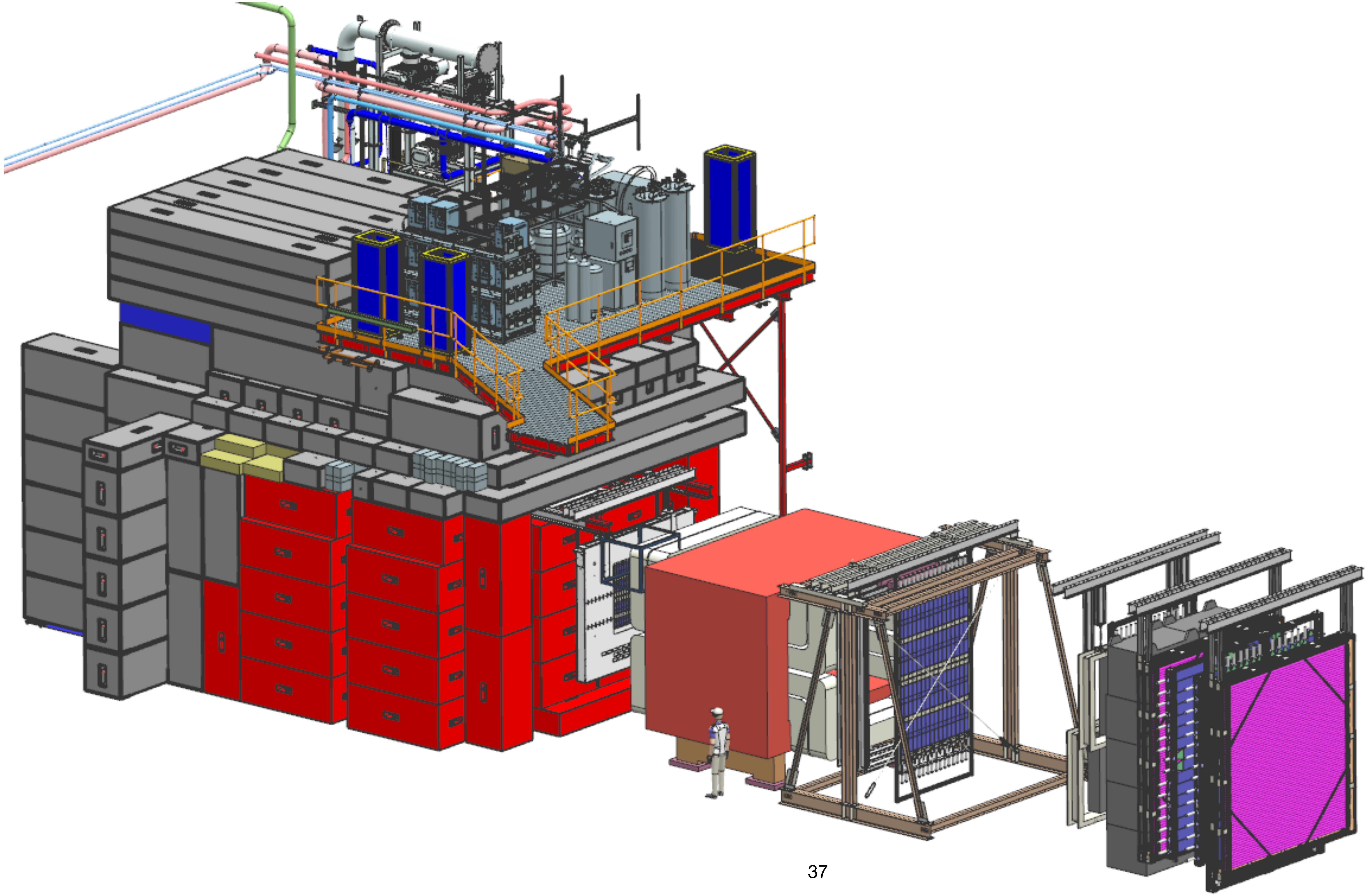
# Target Alcove



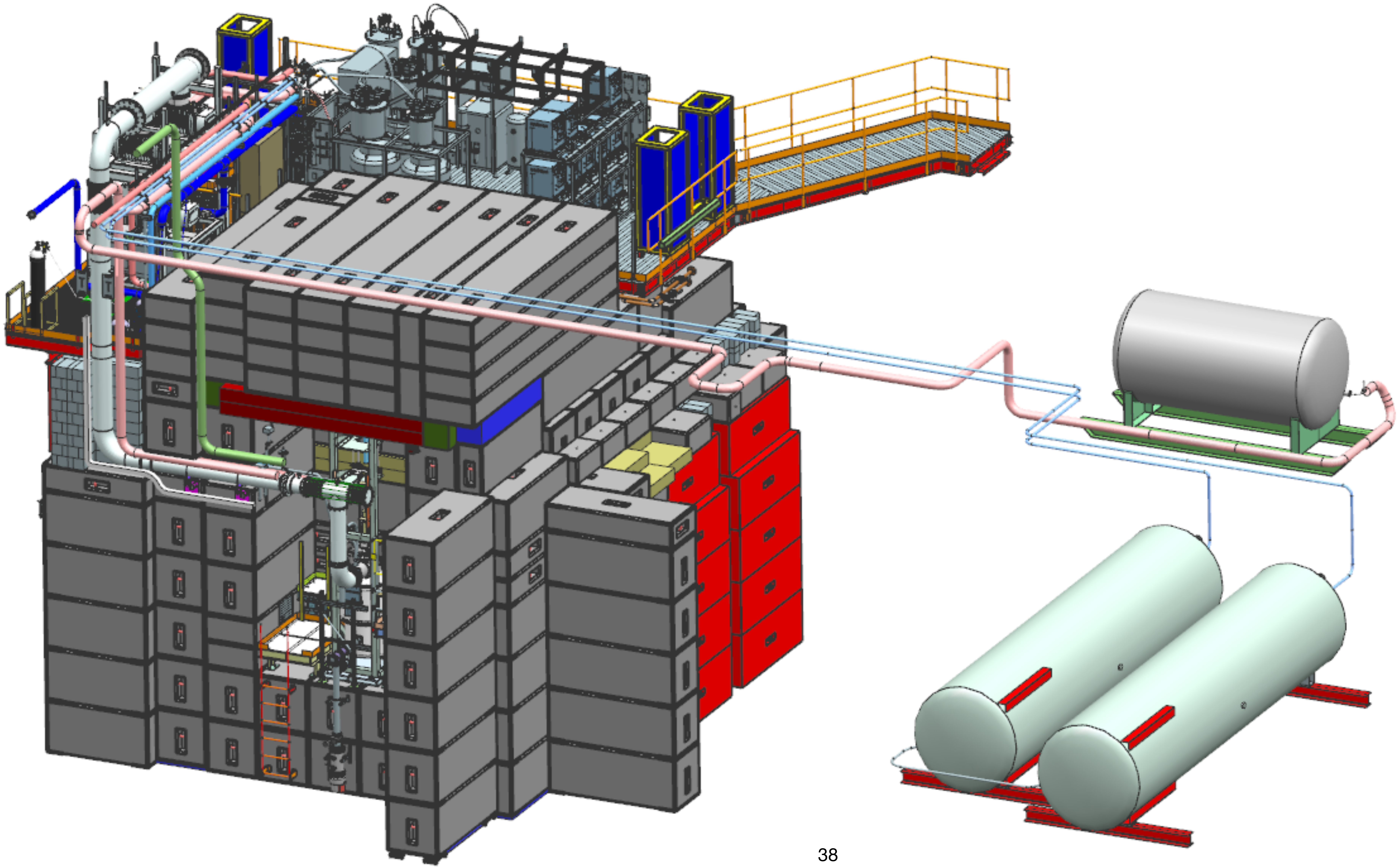
# Overhead view of Cryo-platform



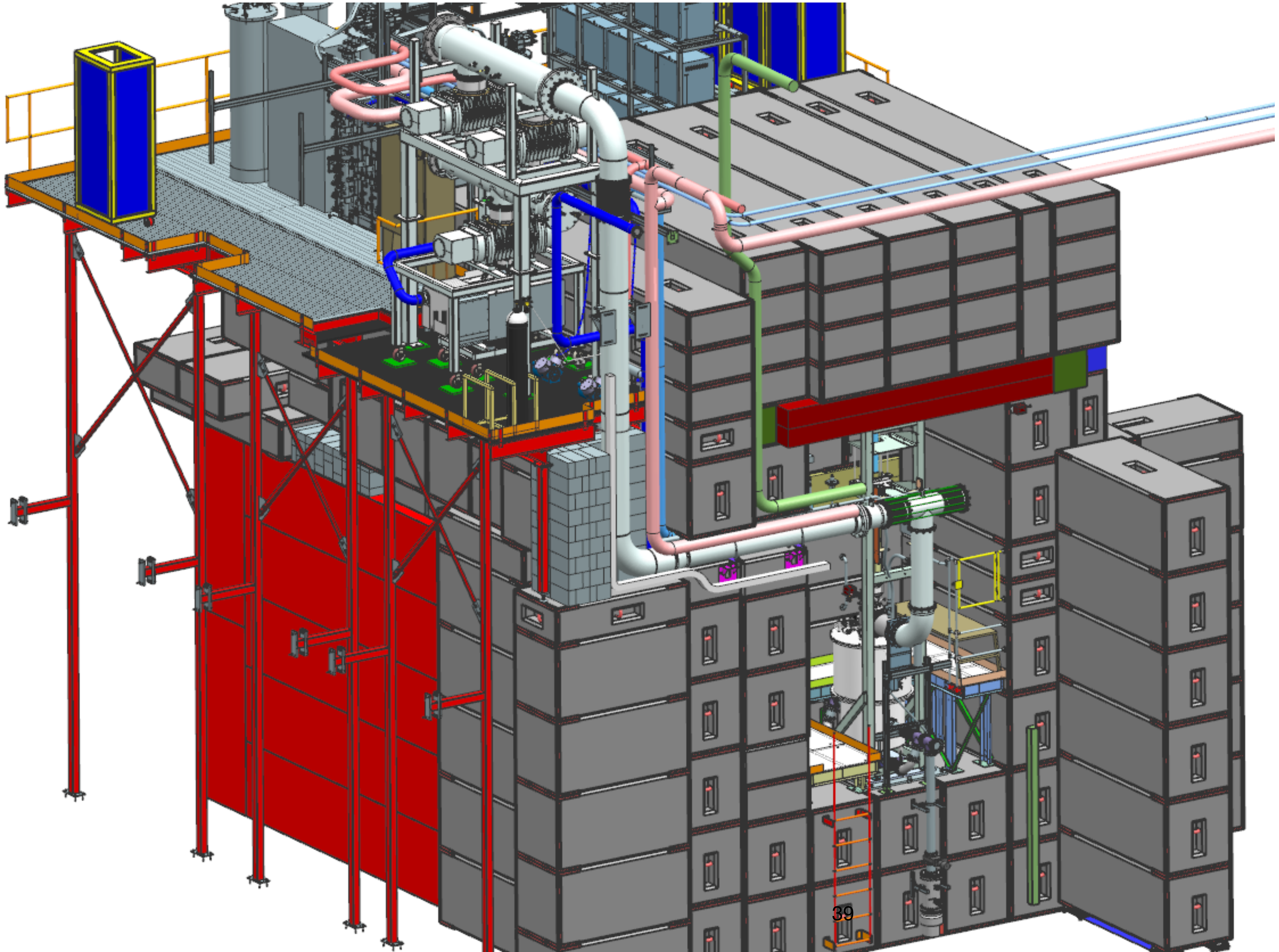
# Full Detector and Target



# Helium and Nitrogen Supplies

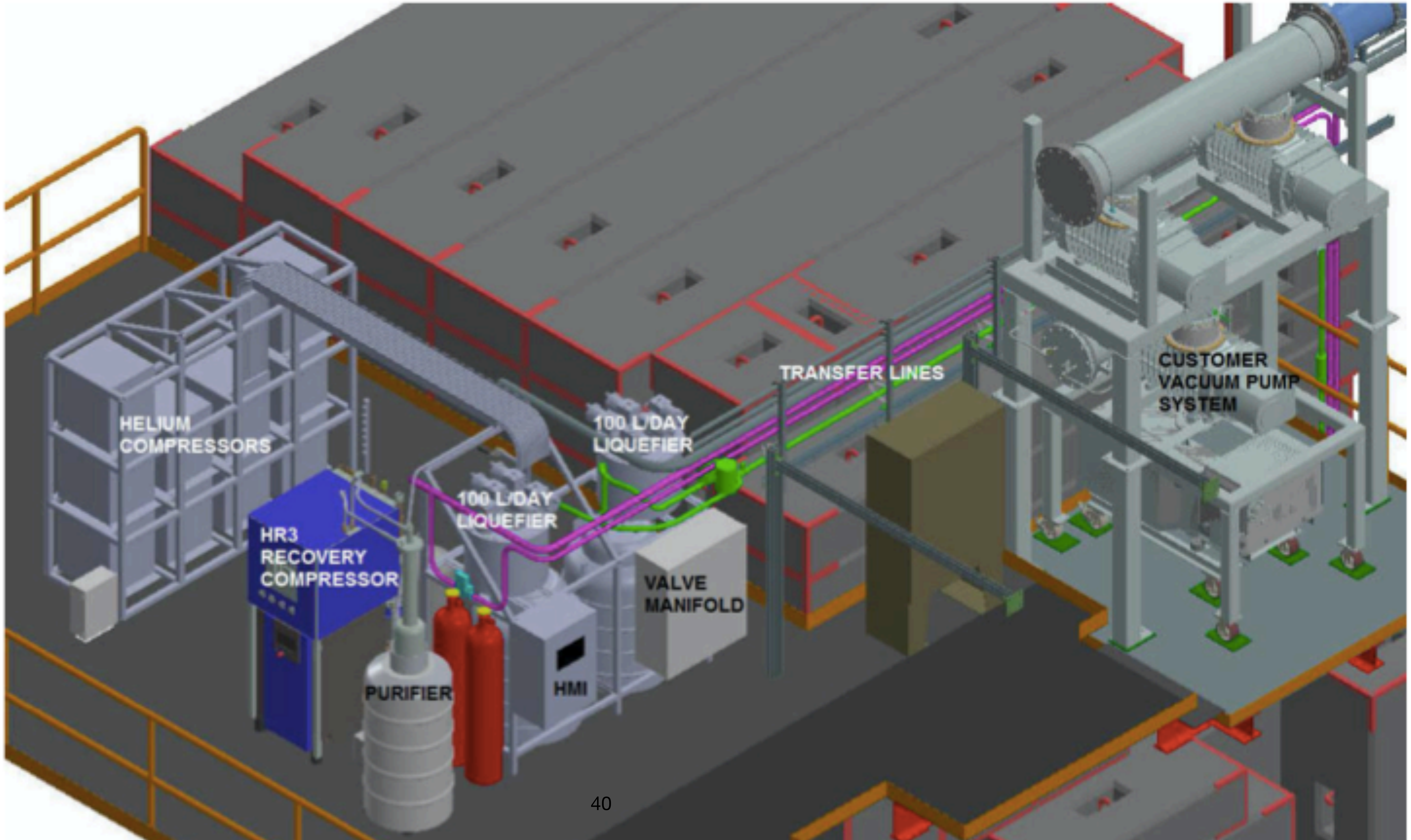


# West View of Target Cave



# QT Liquefier

## Set of components



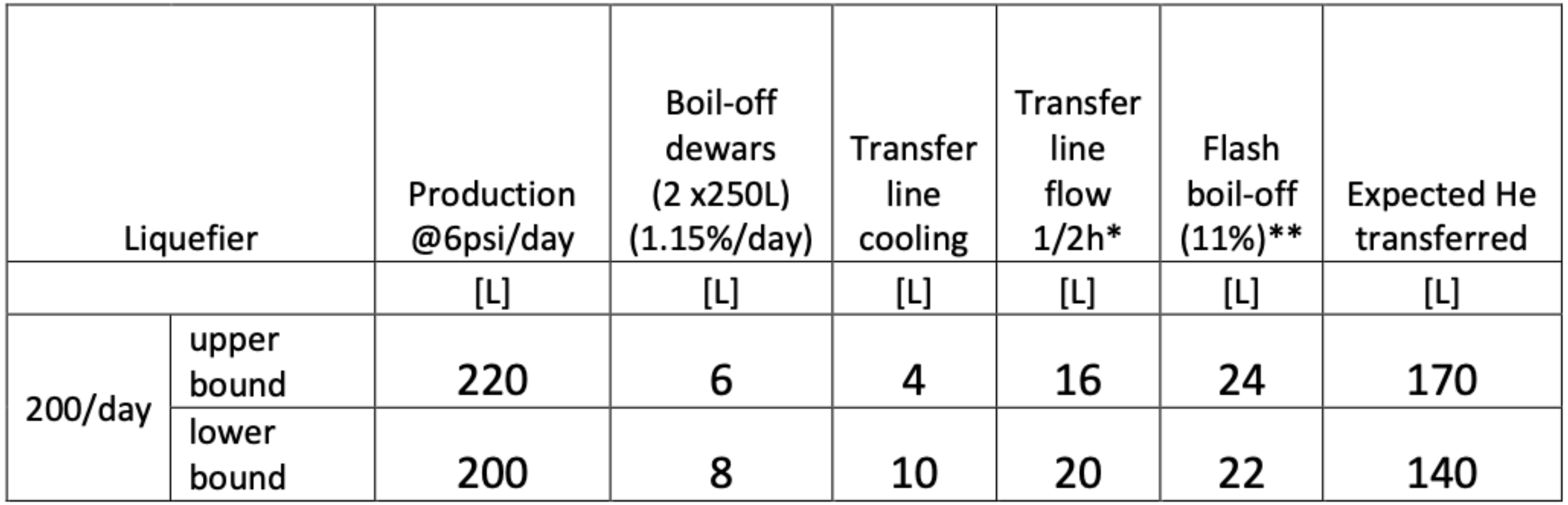
# Quantum Technology Corp Liquefier

## 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 |

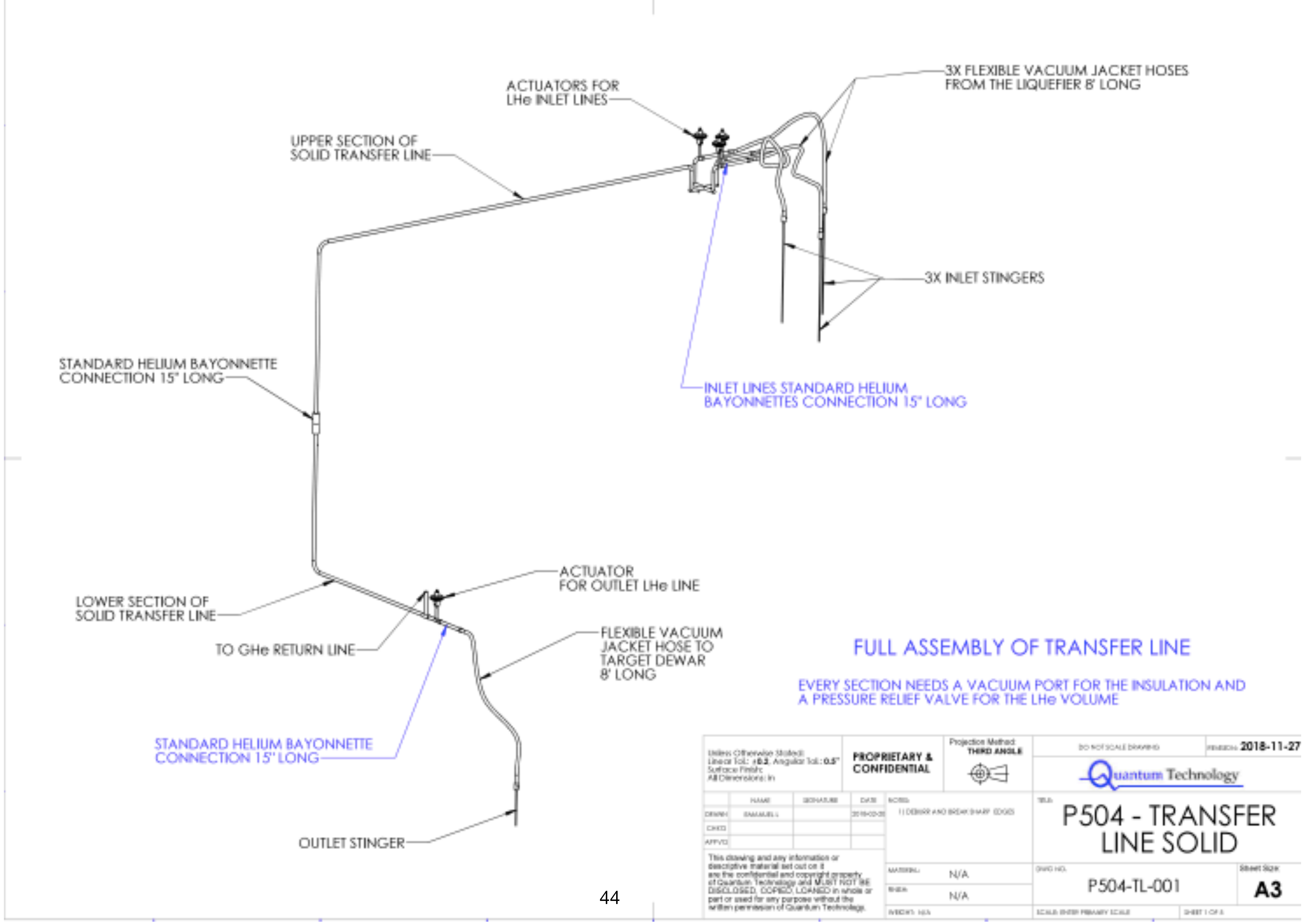
- Requested 135 L/day at the target magnet (67% efficient when transferring over 60 min.)
- Based on studies at UVA this is more than sufficient for continuous running with no beam
- Additional pumping on the magnet will likely be required to run at the beam intensity of interest
- Less efficiency is 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



FULL ASSEMBLY OF TRANSFER LINE

EVERY SECTION NEEDS A VACUUM PORT FOR THE INSULATION AND A PRESSURE RELIEF VALVE FOR THE LHe VOLUME

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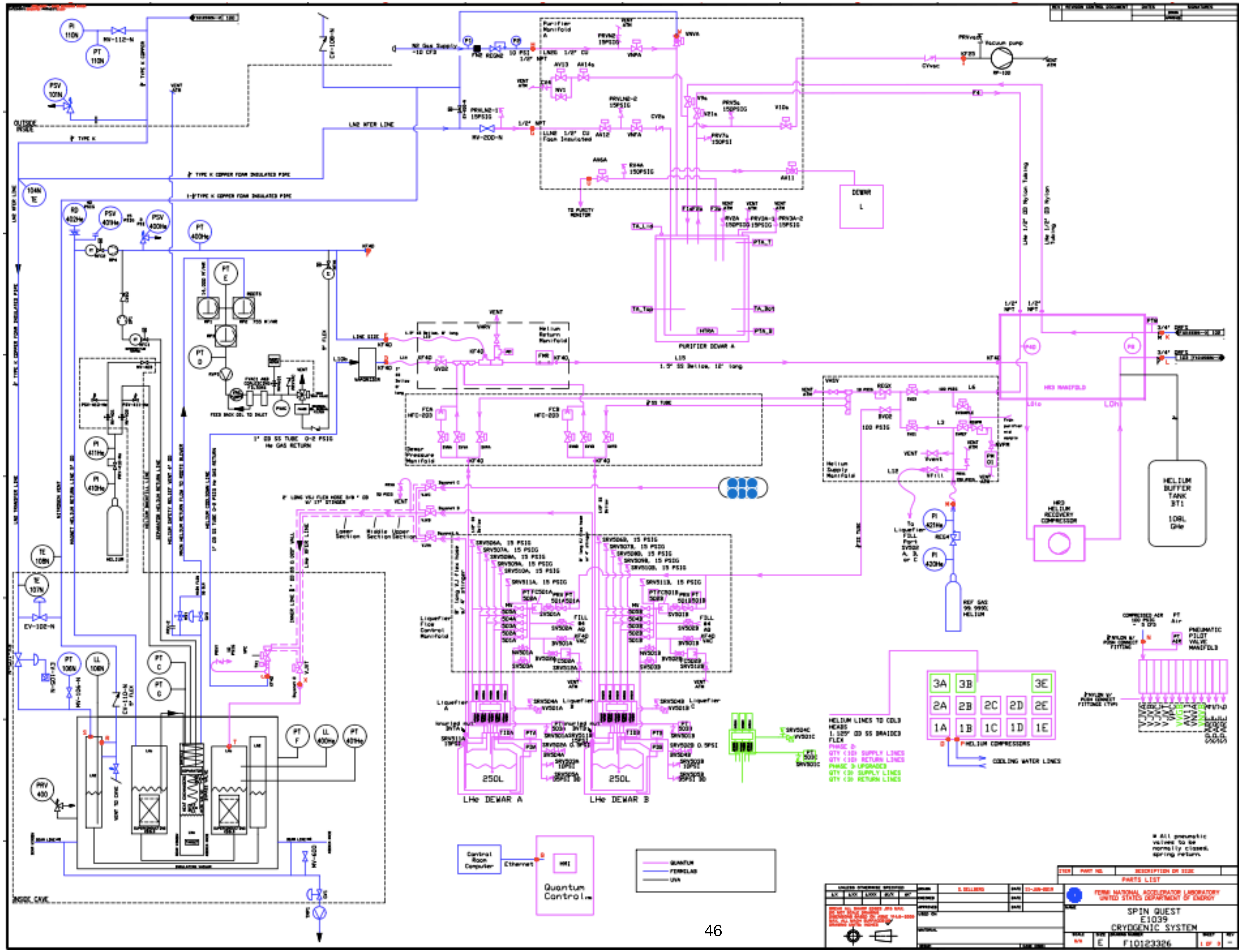
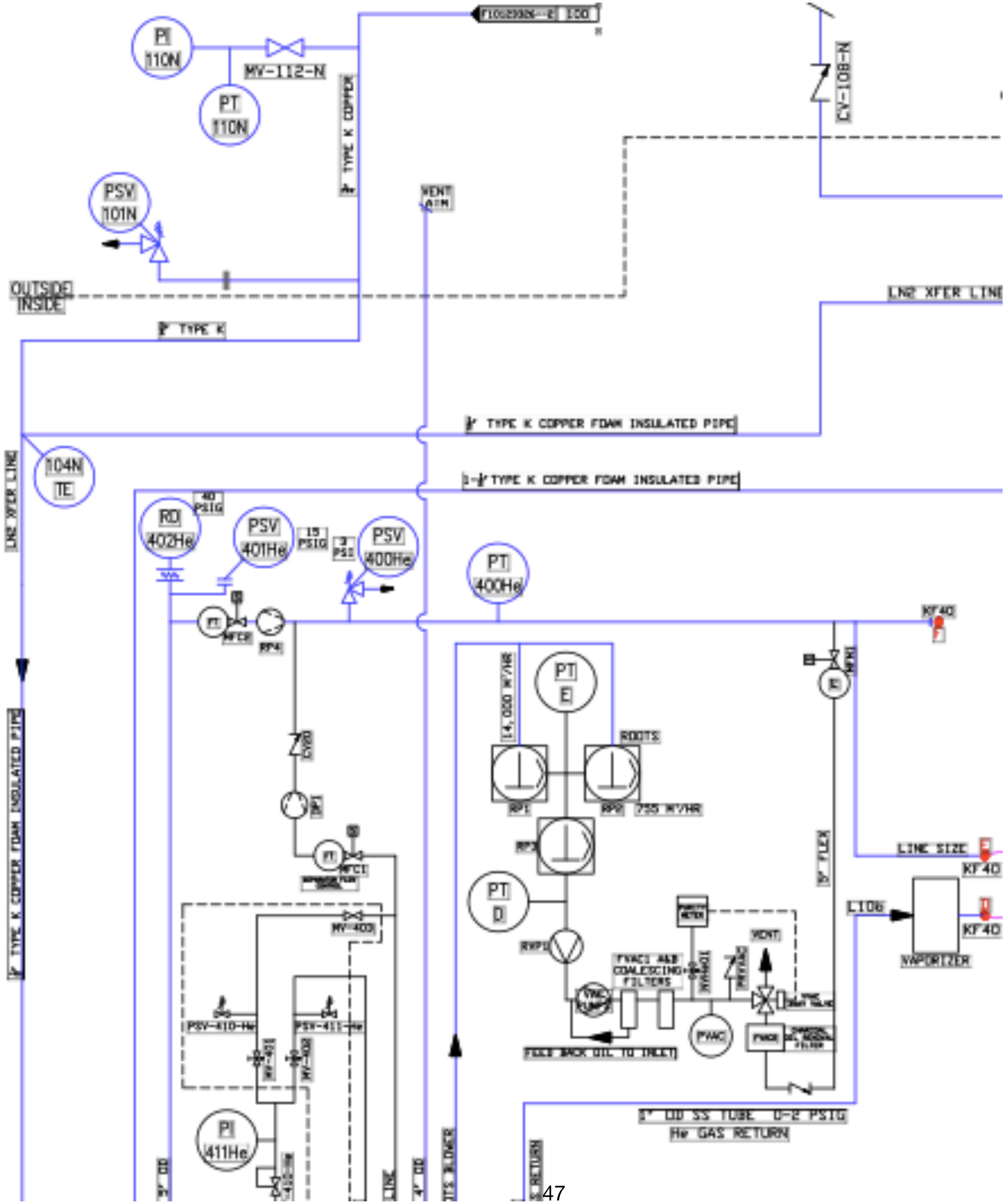
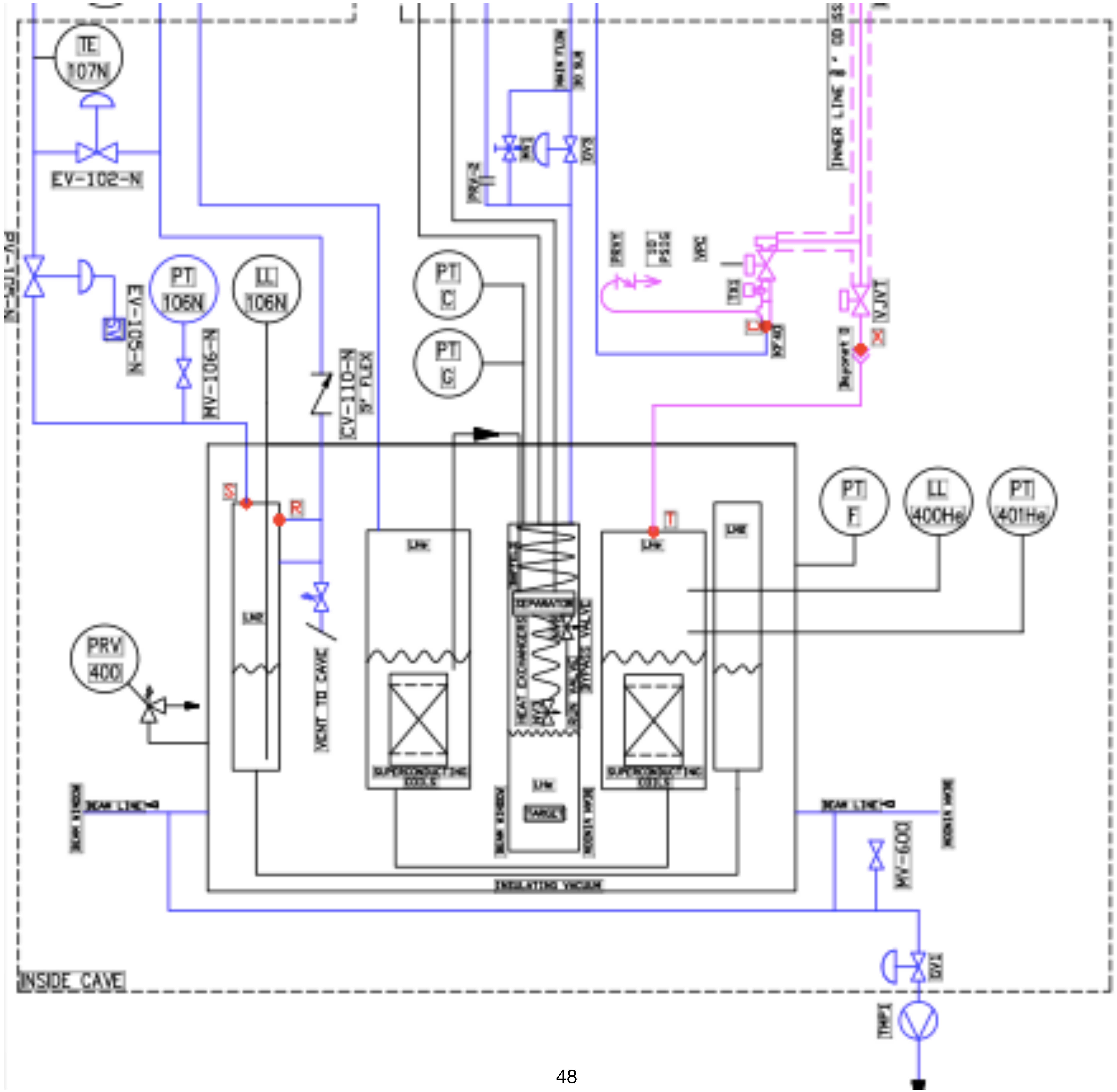
# Target Magnet Pumping

## 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/day | 40 l/day |
| **250L** | 0 | 5 days |


N2 Gas Supply
Purifier Manifold
Vacuum pump
DEWAR
PURIFIER DEWAR A
Helium Return Manifold
LN2 WTER LINE
1.5" SS Bellow, 12' long
HRS MANIFOLD
HELIUM BUFFER TANK BT1
HRS HELIUM RECOVERY COMPRESSOR
Dewar Pressure Manifold
Helium Supply Manifold
Liquefier Flow Control Manifold
REF GAS 99.999% HELIUM
250L
LHe DEWAR A
250L
LHe DEWAR B
HELIUM LINES TO COLD HEADS
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
OUTSIDE
INSIDE
INSIDE CAVE
* All pneumatic valves to be normally closed, spring return.
ITEM
PART NO.
DESCRIPTION OR SIZE
PARTS LIST
UNLESS OTHERWISE SPECIFIED
DRAWN
S. DELLBERG
DATE
CHECKED
APPROVED
USED ON
MATERIAL
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
SPIN QUEST
E1039
CRYOGENIC SYSTEM
SIZE
E
F10123326
SHEET
REV
-


PI
110N
PT
110N
MV-112-N
TYPE K COPPER
PSV
101N
VENT
OUTSIDE
INSIDE
TYPE K
CV-108-N
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
FT
MFC2
RP4
CV
FT
MFC1
MV-403
PSV-410-He
PSV-411-He
PI
411He
KF40
PT
E
14,000 M³/HR
ROOTS
RP1
RP2
755 M³/HR
RP3
PT
D
RWP1
FVAC1 A&B
COALESCING
FILTERS
VENT
FVAC
FEED BACK OIL TO INLET
FLEX
LINE SIZE
KF40
L106
KF40
VAPORIZER
1" OD SS TUBE 0-2 PSIG
He GAS RETURN
4" OD
RETURN


TE
107N
EV-102-N
PV-1RE-N
EV-105-N
PT
106N
LL
106N
MV-106-N
CV-110-N
5" FLEX
PT
C
PT
G
PRV-2
MV1
CV3
MAIN FLOW
INNER LINE
PRV
VRC
TX1
VJVT
X
S
R
T
LHe
LN2
SEPARATOR
HEAT EXCHANGERS
BYPASS VALVE
SUPERCONDUCTING COILS
TARGET
BEAM WINDOW
INSULATING VACUUM
PRV
400
VENT TO CAVE
PT
F
LL
400He
PT
401He
BEAM LINE
MV-600
CV1
TMP1
INSIDE CAVE

# Target Team

## UVA Spin Physics and Polarized Target Group

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

# Thank You