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The TUCAN next generation UCN source

overview and some details

R. Picker

2020-02-06

Discovery, accelerated

Topics

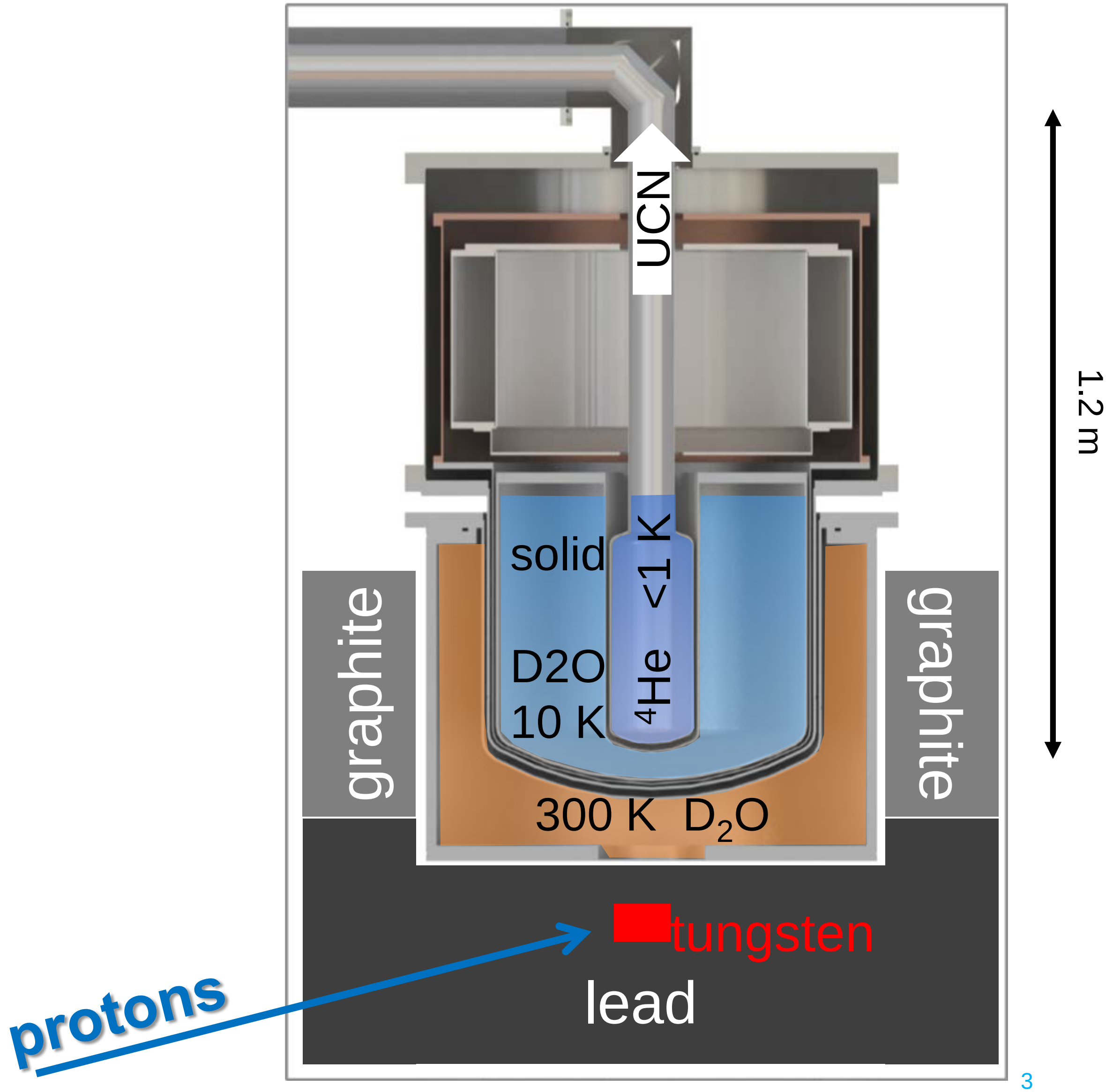
Manpower:
C. Davis, B. Franke, C. Gibson, K. Hatanaka,
T. Higuchi, S. Horn, S. Kawasaki, S. Imajo, T. Kikawa,
A. Konaka, F. Kuchler, T. Lindner, Y. Makida,
R. Mammei, C. Marshall, J.W. Martin, R. Matsumiya,
K. Mishima, T. Okamura, R. Picker, D. Rompen,
W. Schreyer, S. Sidhu, S. Vanbergen

- UCN source key numbers
- Source components and model
- Schedule
- Monte Carlo Optimization of UCN components
- Gas handling systems, pumps and transfer line

TUCAN UCN source recipe

using the prototype source as example

1. 480 MeV protons on tungsten create **spallation neutrons**
2. lead, graphite, heavy water, (deuterium) **moderate** fast neutrons (MeV) to cold neutrons (meV)
3. **^{4}He** at around 1 K **converts** 1 meV (9Å) neutrons **to UCN**
4. **Extraction** to experiments via material guides



Vertical UCN source cryostat cooling scheme

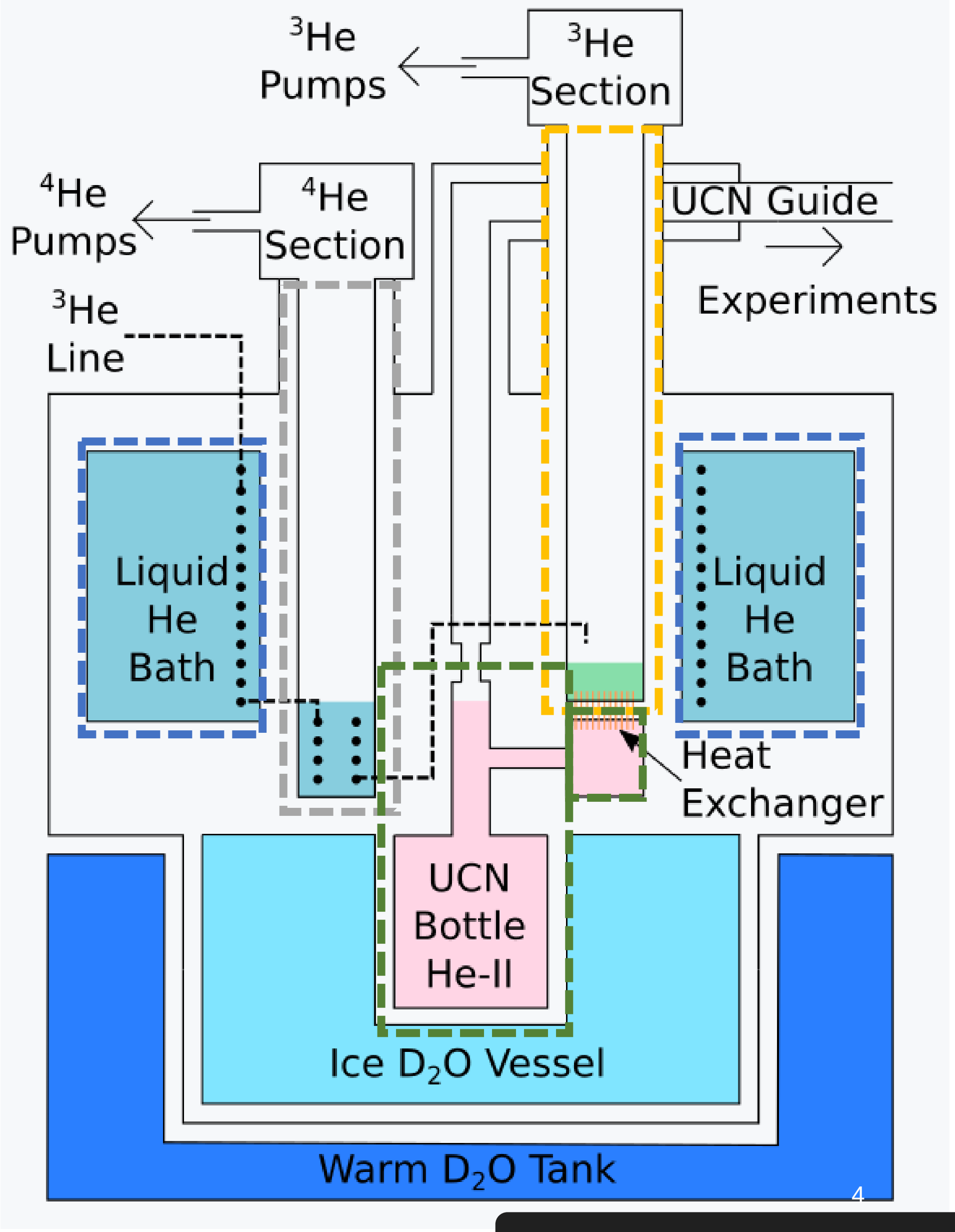
from KEK/RCNP, Japan

3 cooling stages, heat exchanger to cool isopure ^{4}He UCN converter

- lHe bath cryostat (4.2 K)
- ^{4}He pumping section (1.6 K)
- ^{3}He pumping section (< 1.0 K)
- Isopure ^{4}He UCN converter cooled via heat exchanger

⇨ Running nominally at 1 µA beam (as at RCNP).

W. Schreyer, tomorrow

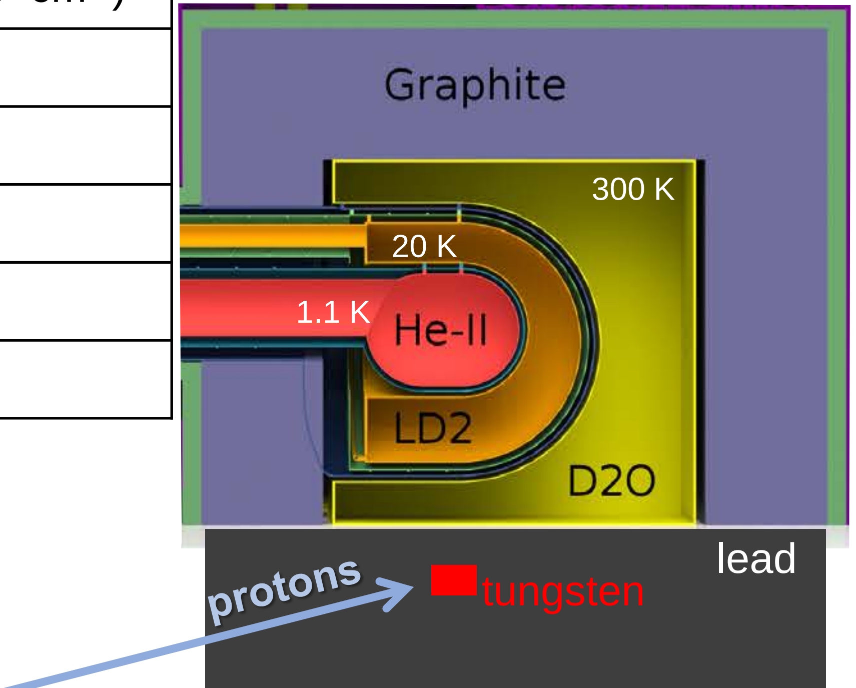


Ryohei Matsumiya, Shinsuke Kawasaki

TUCAN Next generation UCN source strategy

Similar basic layout with major improvements:

Parameter	**Prototype source**	**Next gen source**
Beam current	1 μA	40 μA (480 MeV)
Production volume	8 L	27 L
Cold moderator	sD_2O	LD_2
Production rate	$2x10^5$ /s	$1.4\text{-}1.6x10^7$/s (500 $s^{-1}cm^{-3}$)



TUCAN Next generation UCN source strategy

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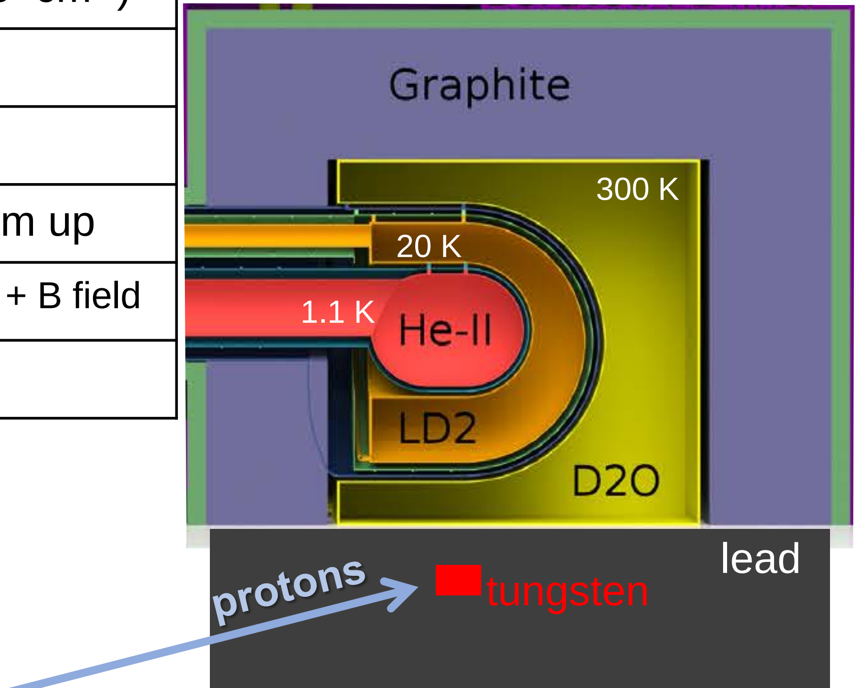
Production volume	8 L	27 L
Cold moderator	sD_2O	LD_2
Production rate	$2x10^5$ /s	1.4-$1.6x10^7$/s (500 $s^{-1}cm^{-3}$)
Cooling power	0.3 W	10 W
He-II temperature	0.9 K	1.1 – 1.15 K
Extraction	Vertical by 1.2 m	Near horizontal 0.3 m up
Vacuum separation	No foil	Warm vacuum sep foil + B field
Position of cryostat	On top of source	2.5 m away



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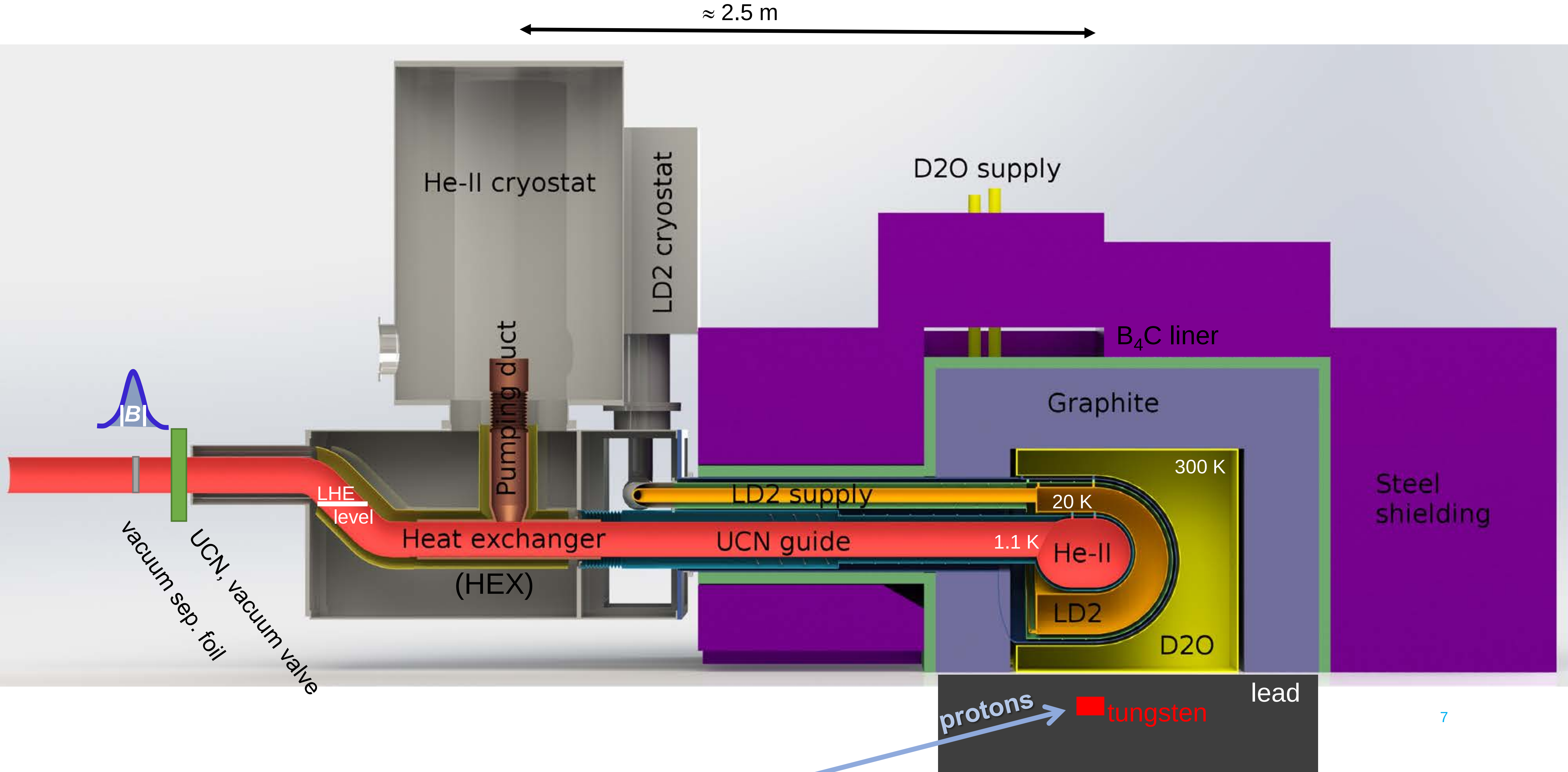
Next generation UCN source basics



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Main challenges and solutions

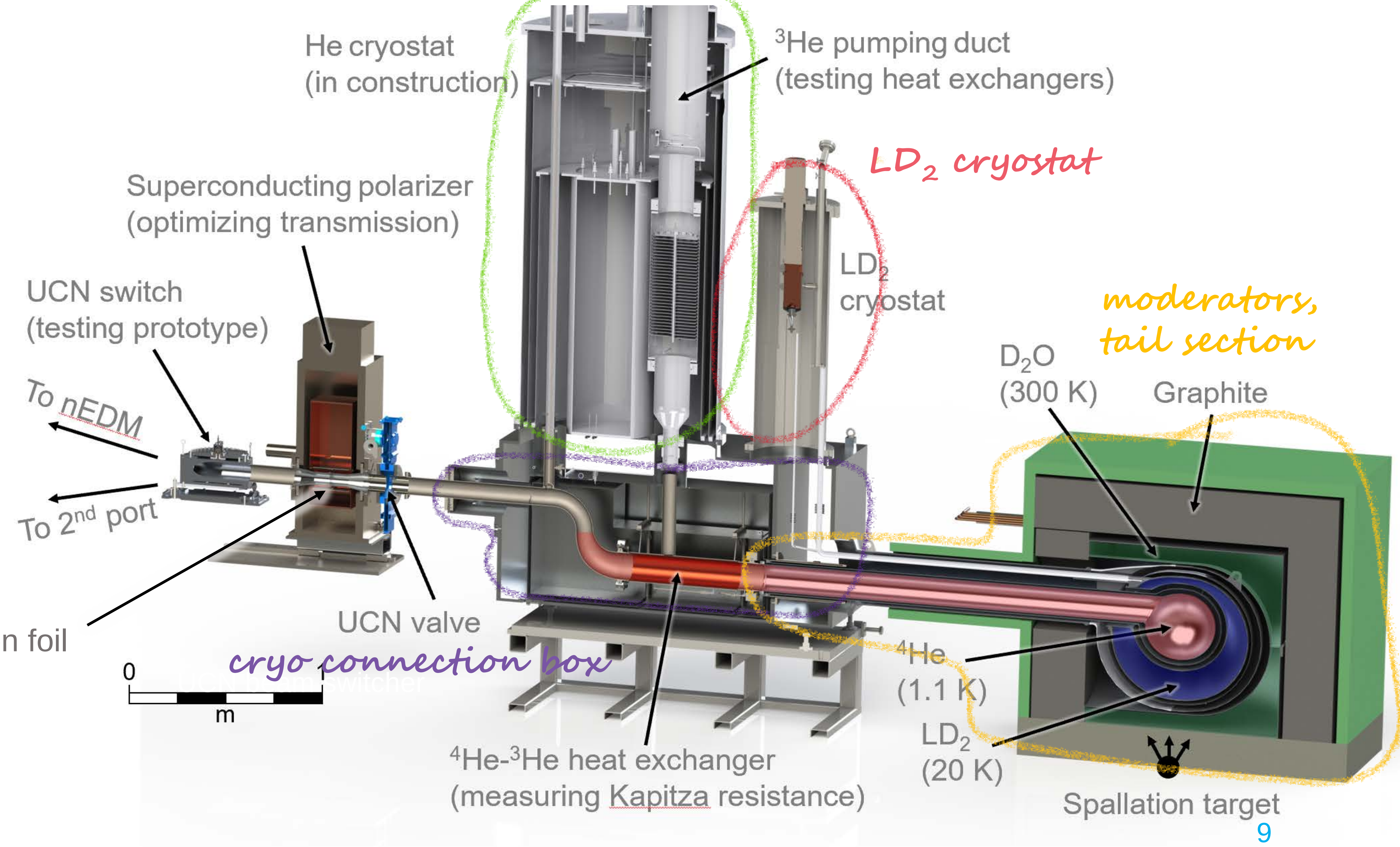
Covered in presentations by

- Large cold flux in UCN production volume ⇒ D_2O, LD_2 moderators, graphite reflector C. Marshall W. Schreyer
- Large thermal load from spallation source ⇒ lead shield plus geometry optimization W. Schreyer

https://doi.org/10.1016/j.nima.2020.163525

- **More material, more heat ⇒ near-spherical shape of UCN production volume** C. Marshall
- Large cooling power below 1 K ⇒ pumping on ^{3}He (10000 m^3/h ⇒ 10 W) S. Kawasaki
- Incompatibility of ^{3}He with UCN ⇒ UCN friendly ^{3}He-^{4}He heat exchanger (flat surface inside) S. Kawasaki
- **^{3}He very expensive ⇒ staged HEX approach and “cheap” ^{3}He?** S. Kawasaki
- **Kapitza resistance large at 1 K ⇒ large HEX surface (approx. 0.3 m^2)** S. Kawasaki
- Cannot put cryostat right on top of target ⇒ UCN guide ≡ heat conduction channel (2.5 m long) S. Kawasaki
- **Low heat conductivity of He-II at 1 K ⇒ large UCN guide diameter (15 cm)** S. Kawasaki
- Freeze-out on cold vacuum separation foil ⇒ warm vacuum separation foil (inside B field) RP
- Containment of liquid helium ⇒ (small) vertical rise in liquid filled UCN guide (23 cm) This presentation
- **Limited supply of liquid helium ⇒ design efficient cryostat** S. Kawasaki, C. Gibson
- **Large amount of deuterium required ⇒ inherent and/or redundant safety systems (safety approval)** C. Marshall
- **Radiative heat input to SF LHE surface ⇒ testing UCN friendly radiation heat suppressors** RP, W. Schreyer

More detailed UCN source model



He cryostat

He cryostat
(in construction)

^{3}He pumping duct
(testing heat exchangers)

LD_2 cryostat

Superconducting polarizer
(optimizing transmission)

LD_2
cryostat

UCN switch
(testing prototype)

moderators,
tail section

To nEDM

D_2O
(300 K)

Graphite

To 2nd port

vacuum separation foil

UCN valve

cryo connection box

^{4}He
(1.1 K)

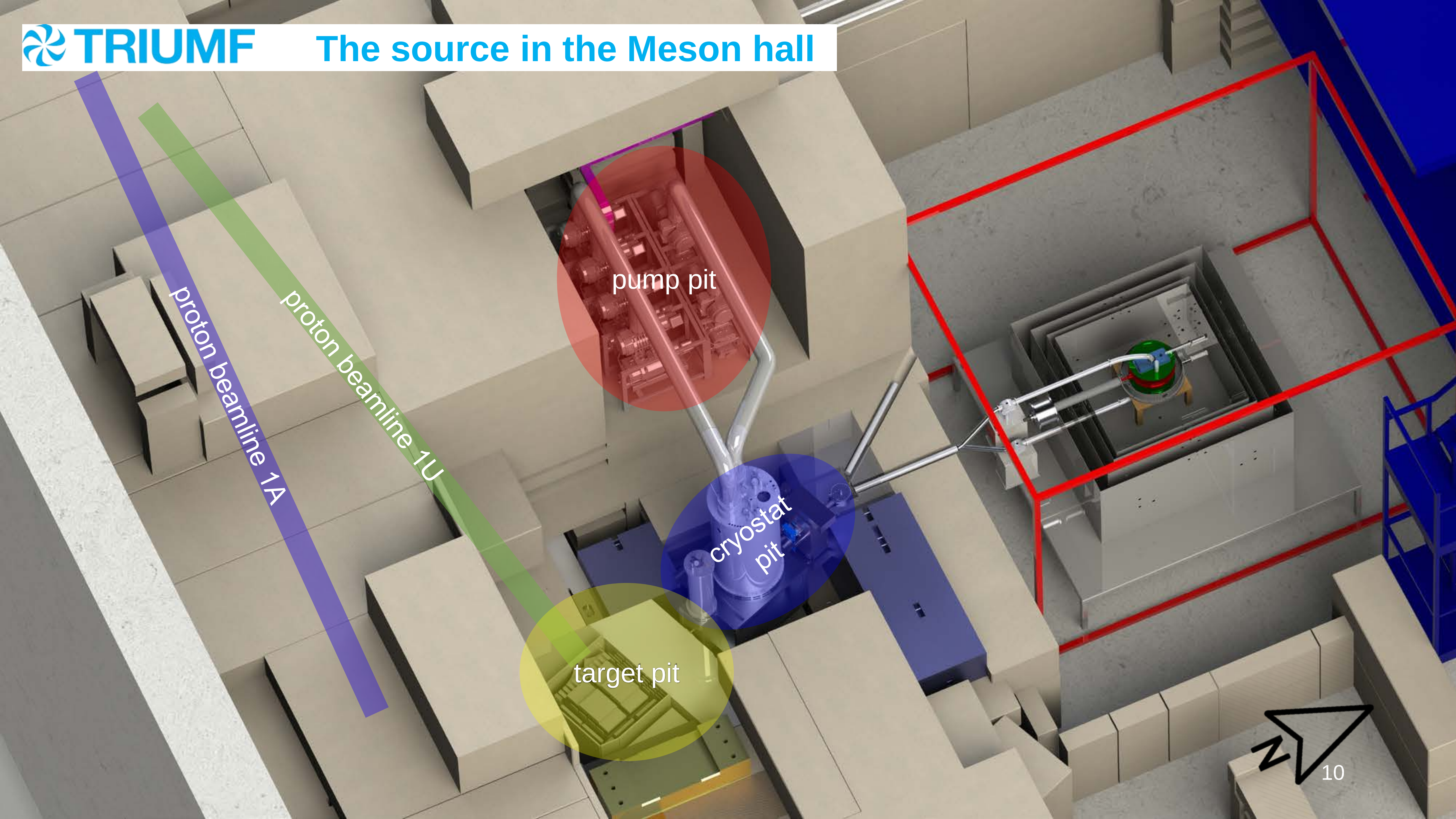
0 1
m

LD_2
(20 K)

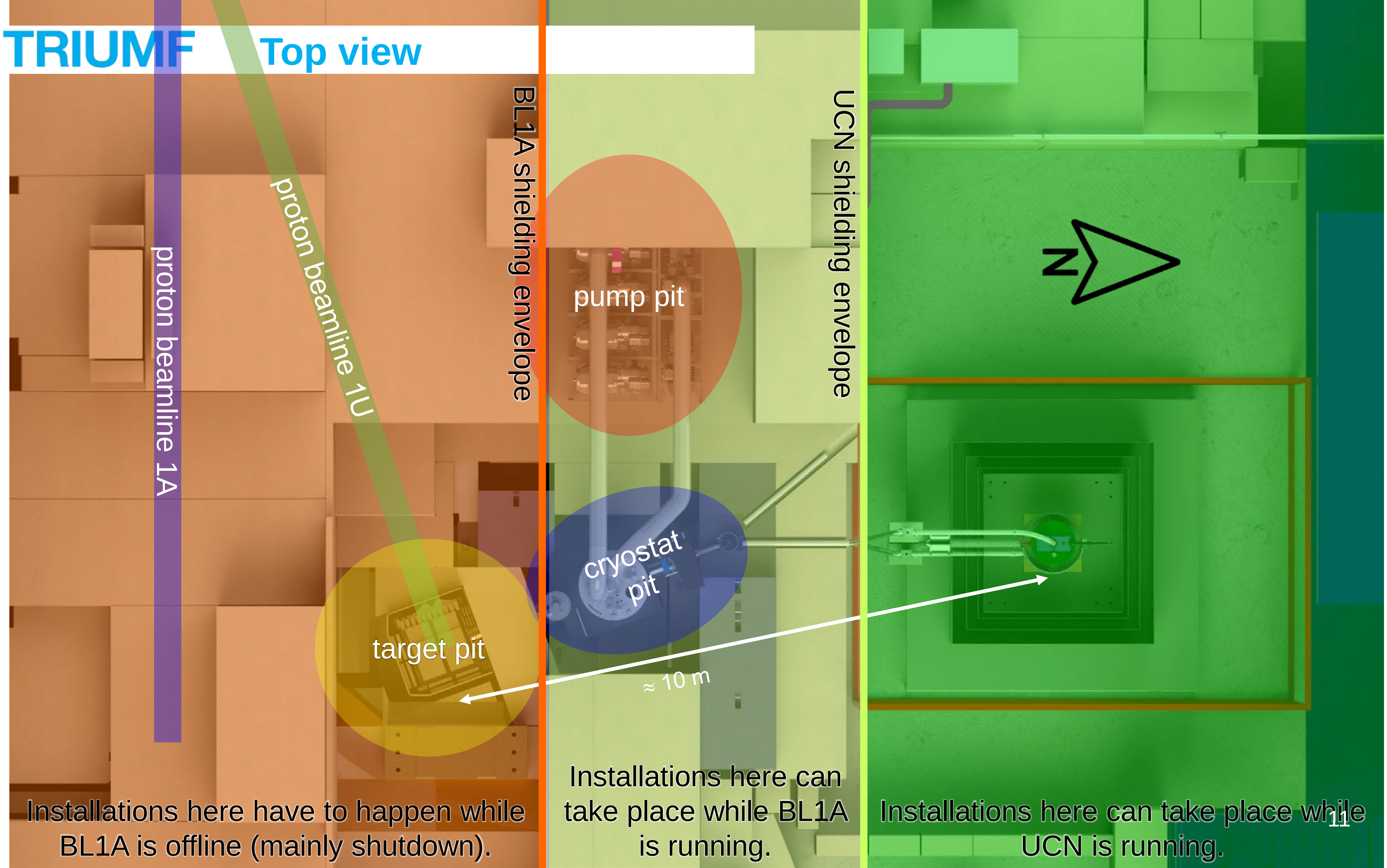
^{4}He-^{3}He heat exchanger
(measuring Kapitza resistance)

Spallation target

The source in the Meson hall



Top view



Installations here have to happen while BL1A is offline (mainly shutdown).

Installations here can take place while BL1A is running.

Installations here can take place while UCN is running.

Some estimates for relevant numbers

Mostly coming from MC (MCNP, PENTrack)

TUCAN source

(engineering stage)

- Production 1.4-1.6 x 10^7 UCN/s
- Source helium temp 1.03 K to 1.13 K
- Cooling power 10 W (3He fridge)
- Source storage lifetime 28 s
- Figure of merit $P\tau = 4.5 \times 10^8$
- Density in the source 3 x 10^3 UCN/cc
- Total number in the source 3 x 10^8 UCN
- Initial polarized density in 70 l EDM experiment 200 UCN/cc (> 10 m of guide)
- Counted at the end of cycle 2 x 10^6

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Recent Milestones

copied from https://ucn.triumf.ca/meetings-and-workshops/review-meetings/2020-02-eac-review-meeting/documentation-for-eac-review/New_UCN_Source_Status_2020-2019-12-20.pdf

Summer 2018

- **JSPS** (Japan Society for the Promotion of Science) **funding** for the helium cryostat has been grantedat 152 MJPY.
- Final decision to go for **^{3}He cryostat** (not ^{4}He direct pumping).
- Initial System Engineering Design (System Block Diagram, Top level Requirements, nEDM Experiment Requirements, He Cryostat Requirements, LD_2 Subsystem Requirements, Initial Spec Sheetsgeneration)
- **Preliminary LD2 Safety Report** Released
- Initial release of UCN yield versus moderator and source design report
- Released designs for UCN experiments in Fall 2018
- Released **schematics** (P&IDs) for He-II Subsystem, LD2 Subsystem
- Released initial **design concept for biological shielding**

Fall 2018

- **Tested first components for the new UCN source** during 1-month of UCN beamtime at TRIUMF (UCN friendly vent port, UCN source valve, superconducting polarizer)
- Performed UCN storage tests with a mock-up UCN production volume (NiP coating on aluminum) and determined that a bake out temperature of 100 C is sufficient.
- Liquid deuterium system conceptual design received positive concept review from the safety authority Technical Safety BC.
- Additional **requirements documents** released: He-II Subsystem, Simultaneous Spin Analyzer Subsystem
- Some **cryogenic calculations** completed for He-Cryostat and LD2 Subsystem

Winter 2019

- Additional requirements documents released: remaining source subsystems, nEDM Cell, UCN Guidance
- Initial **3D concept of LD_2** Subsystem
- Initial stress calculations and 3D Model for the multi-layered source vessel containing LD_2 and superfluid helium
- Early orders for D2O

Spring 2019

- Finished the bulk of UCN and **cryogenics related calculations** necessary to start detailed design.
- Measurements at KEK confirm the **Kapitza conductance** at the 3He to 4He heat exchanger is in good agreement with our models.
- Additional requirements documents released: Internal magnetometry
- TRIUMF **design review of biological shielding** passed.
- TRIUMF **design review of He cryostat pumping** system passed
- Positive initial discussions with Technical Safety BC about LD2 system safety
- **Hemispherical production volume** and moderator geometry chosen

Summer 2019

- Target protect monitor (TPM) of BL1U commissioned
- **Detailed design of helium cryostat** completed, start of production in Japan.
- Confirm **superleak tightness** of a new designed **helicoflex seal** flange at KEK (it will be used for junction of the HEX1, which is the main heat exchanger, and the UCN guides.
- Confirm superleak tightness of a **junction of aluminum and stainless** steel at KEK (it will be used for UCN guide upstream of the helium cryostat)
- **HEX7 test** successfully completed at KEK (counterflow gas heat exchanger from room temperature to 10 K)

Fall 2019

- **UCN source storage valve** upgrade tested successfully during UCN beamtime.
- **TRIUMF design review of He cryostat** passed.
- Important interfaces between He cryostat and remainder of He-II subsystem confirmed
- **UCN Y switch** completed

Winter 2020

- **HEX5 test** successfully completed at KEK (counterflow gas heat exchanger in the 1K pot pumping tube)

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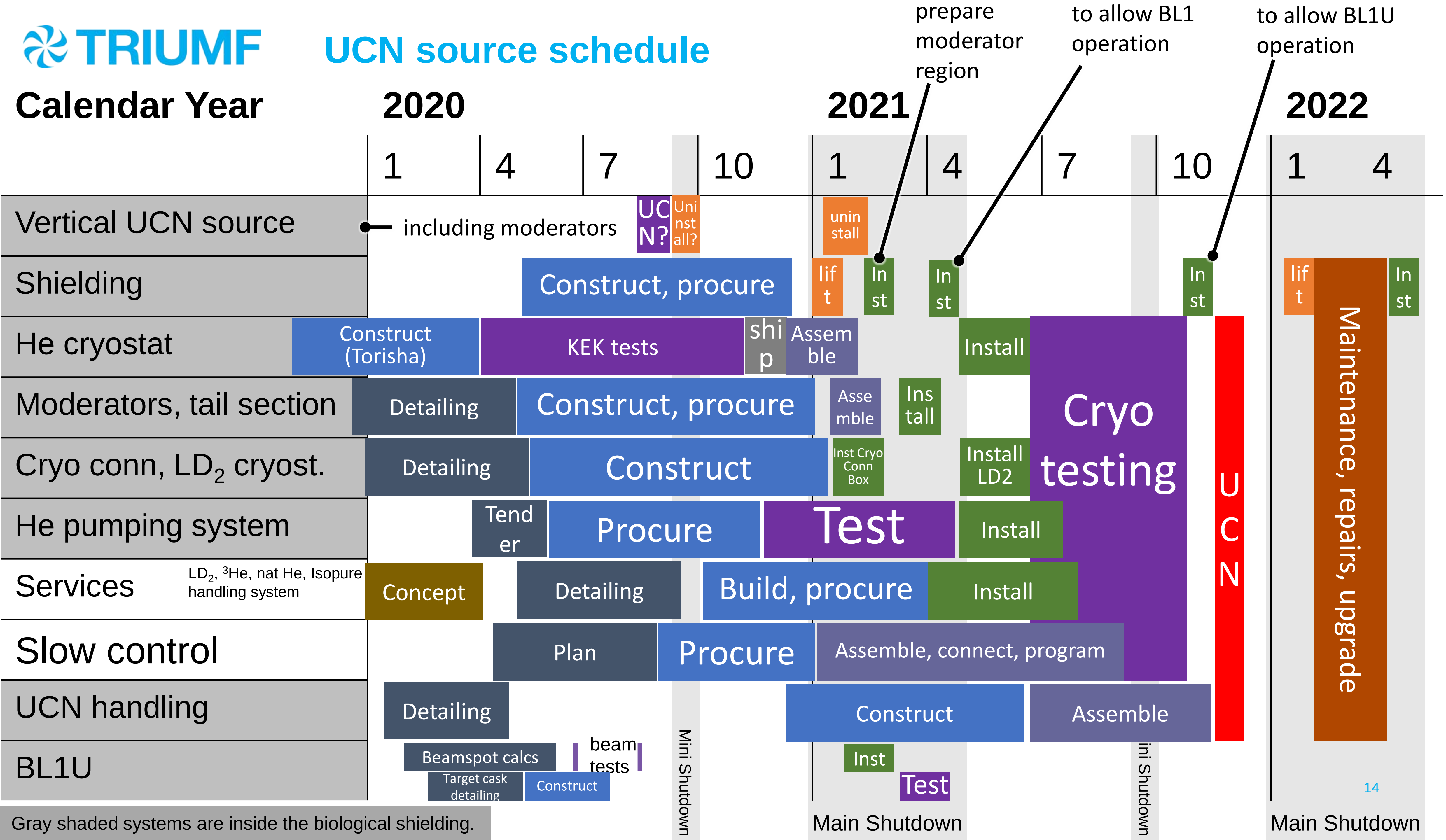
UCN source schedule



Calendar Year 2020 2021 2022

1 4 7 10 1 4 7 10 1 4

Vertical UCN source — including moderators: UCN? | Uninstall? | uninstall

Shielding: Construct, procure | lift | Inst | Inst | Inst | lift | Inst

He cryostat: Construct (Torisha) | KEK tests | ship | Assemble | Install

Moderators, tail section: Detailing | Construct, procure | Assemble | Install

Cryo conn, LD_2 cryost.: Detailing | Construct | Inst Cryo Conn Box | Install LD2

He pumping system: Tender | Procure | Test | Install

Services (LD_2, ^{3}He, nat He, Isopure handling system): Concept | Detailing | Build, procure | Install

Slow control: Plan | Procure | Assemble, connect, program

UCN handling: Detailing | Construct | Assemble

BL1U: Beamspot calcs | Target cask detailing | Construct | beam tests | Inst | Test

Cryo testing

UCN

Maintenance, repairs, upgrade

prepare moderator region

to allow BL1 operation

to allow BL1U operation

Mini Shutdown

Main Shutdown

Mini Shutdown

Main Shutdown

Gray shaded systems are inside the biological shielding.

UCN source test plan

General remarks

- He cryostat components are tested pre-assembly at KEK (2019/2020)
- Extensive cryo testing of all components planned for 2021
- He cryostat can be cooled down without cooling LD_2 system
- Currently developing a more detailed installation and testing plan

Planned test campaigns

LD_2

- LD_2 handling system test with N_2
- LD_2 cryostat cooldown

He cryostat

- Cryo testing at KEK (no ^{3}He)
- 1K pot pumping
- ^{3}He pot pumping, probably with ^{4}He first
- HEX1 only test (if possible)
- Connect tail section
- Connect downstream UCN guide

S. Sidhu, W. Schreyer, RP

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Optimizing the UCN handling from source to EDM

Goal: minimize the measurement time to reach a sensitivity $d_n \leq 10^{-27} e$cm

Starting point

- Well known **statistical sensitivity formula**

$$\sigma(d_n) \approx \frac{\hbar}{2\alpha T_{\mathrm{Ramsey}} E \sqrt{N_{\mathrm{det}}}}$$

- Naively one thinks you can only improve N_{det} by improving the geometry using UCN MC simulations…
- … but the energy spectrum also influences the optimal T_{Ramsey} and more…

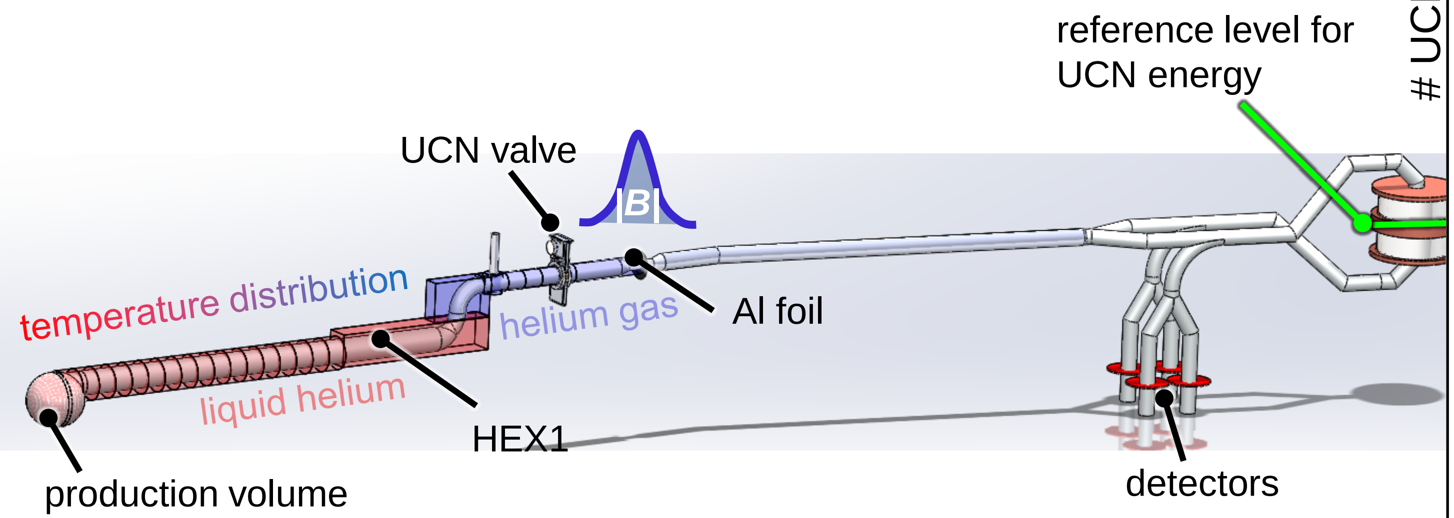
α visibility ∝ polarization
T_{Ramsey} free spin precession time
E electric field
N_{det} # of UCN detected

Steps:

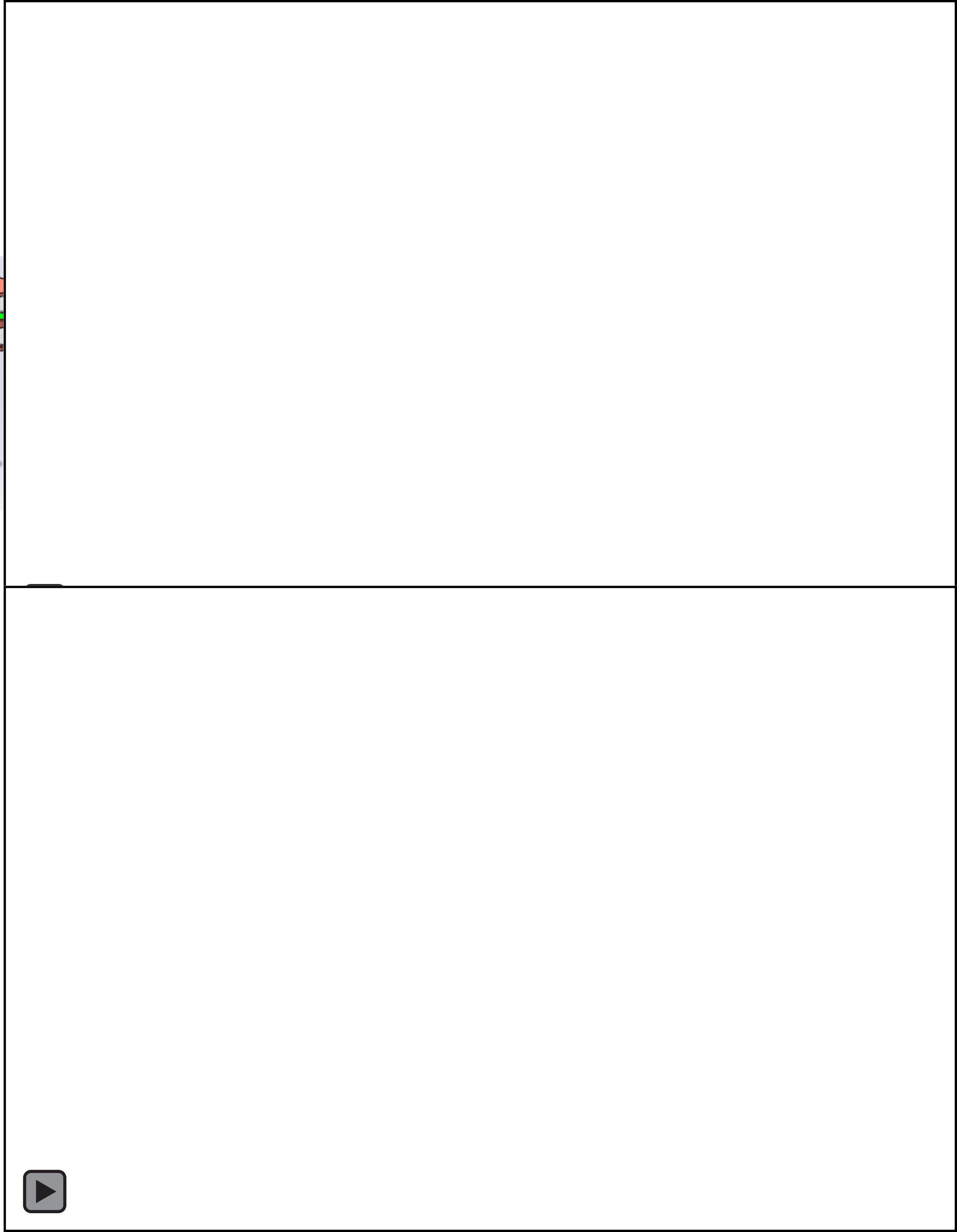
1. Perform three separate MC simulations (relevant durations)
   A. Simulate filling of EDM cells from UCN source ($T_{accumulate}$ and T_{fill})
   B. Simulate storage in EDM cells (T_{Ramsey})
   C. Simulate emptying of EDM cells to detectors (T_{count})
2. Calculate $\sigma(d_n)$ for one cycle
   Inputs: T1, T2, detector efficiency etc
3. Calculate number of cycles needed for $d_n \leq 10^{-27} e$cm
4. Calculate required calendar days
   Inputs: a certain up time per day (≈16 hr), degaussing time, E field reversal etc
5. Then vary the four durations above to minimize the measurement time. (differential evolution algorithm from the SciPy library)

next slides

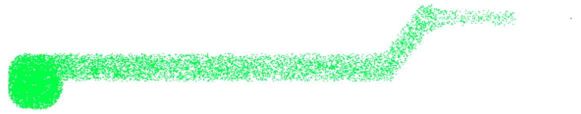
(A) Filling Simulation



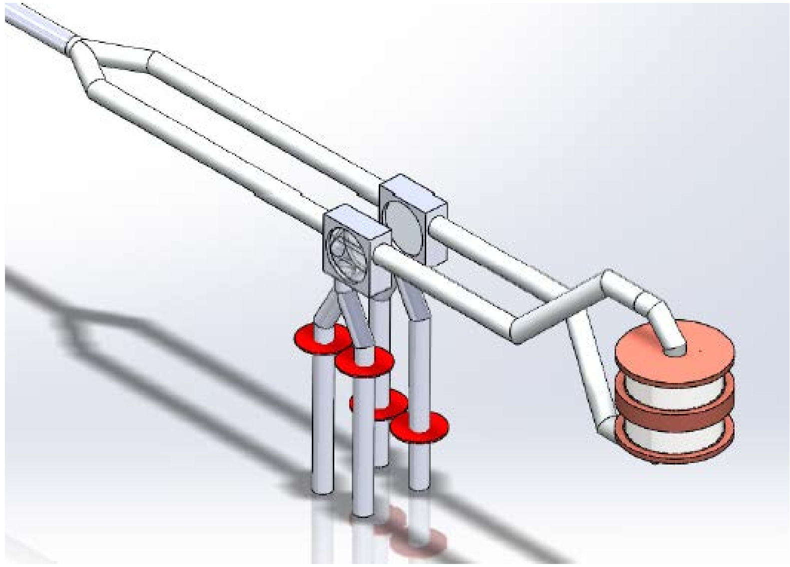
1. Spawn UCN inside production volume at constant rate with UCN valve closed (Maxwellian tail spectrum) $T_{accumulate}$
2. Open UCN valve to start EDM cell filling, keep spawning UCN T_{fill}
3. Record UCN energy distribution in EDM cell every second



Color: UCN production time



(B) Storage in cells



1. Spawn all UCN inside EDM cells at T=0 with a constant energy distribution
2. Store UCN with EDM cell valve closed for 300 s T_{Ramsey}
3. Record energy distribution every second

(C) Counting simulation

1. Spawn neutrons inside EDM cells at T=0 with constant energy distribution, EDM cell valve open and EDM switch connecting to detectors
2. Record energy distribution of neutrons collected in the detectors every second T_{count}

(C) Counting simulation

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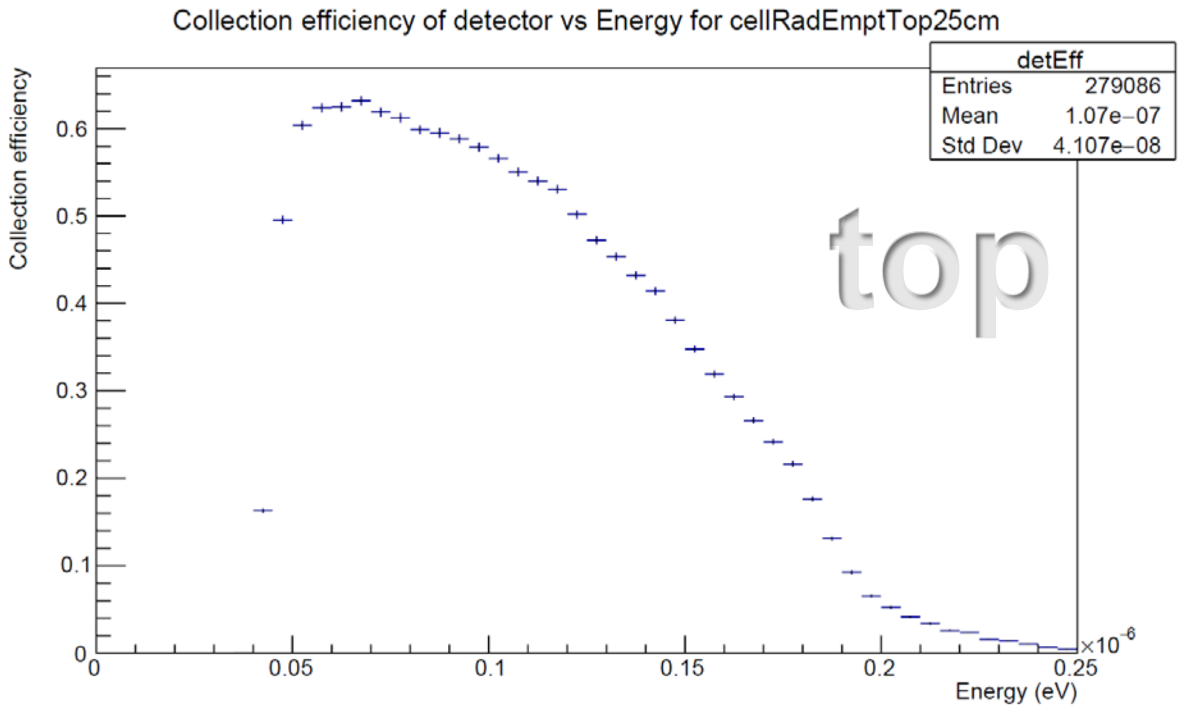
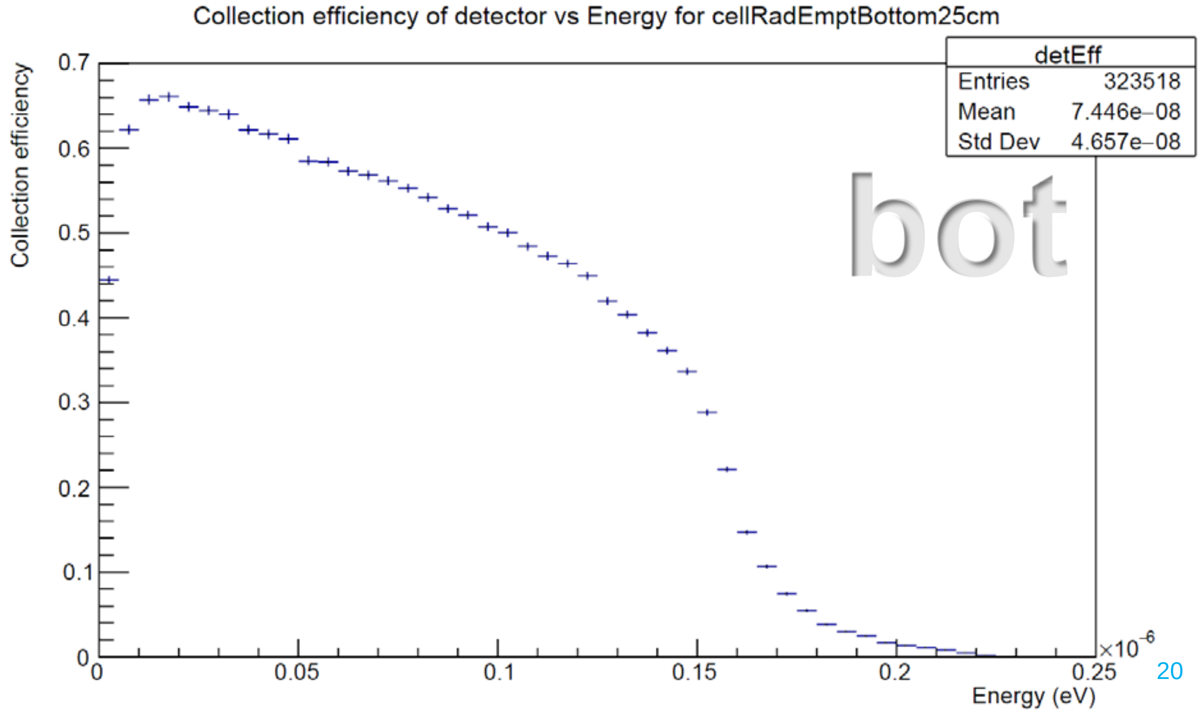




Remarks on the general optimization results

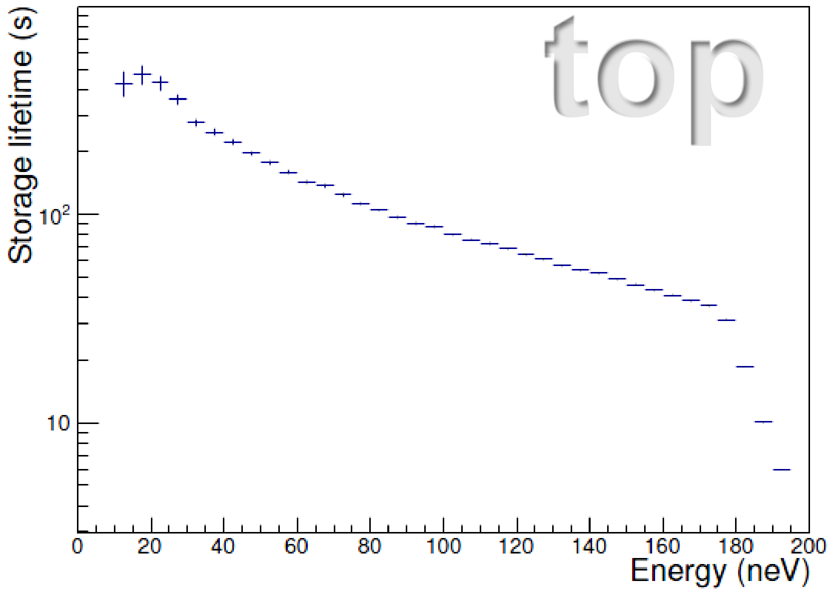
Optimal timings

- Accumulation time $T_{accumulate} = 26$ s
- Fill time $T_{fill} = 96$ s
- Storage time $T_{Ramsey} = 129$ s
- Counting time was $T_{count} = 88$ s

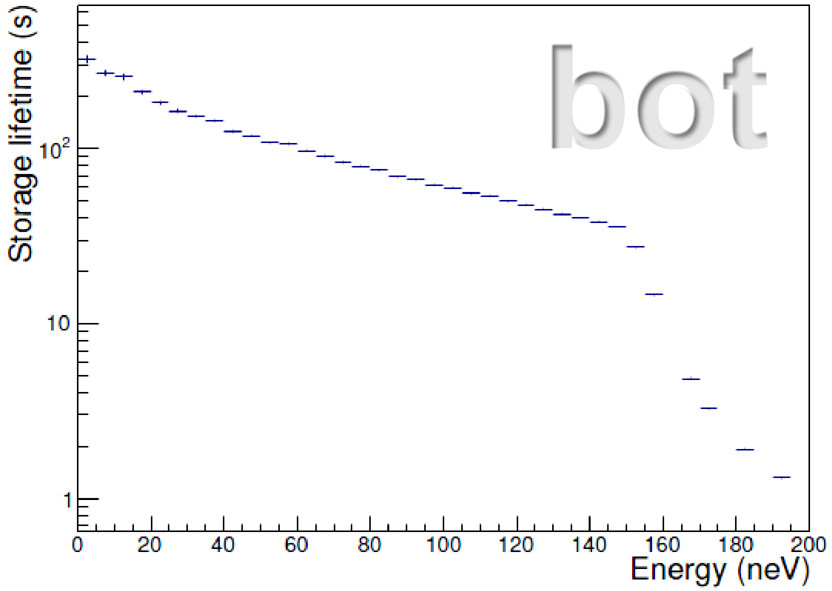
Conclusions

- These times are quite a bit longer than originally anticipated.
- Transport timings are longer for lower energy neutrons. These have
  - longer storage lifetime in EDM cells and
  - a better collection efficiency.
- This increases T_{Ramsey} and N_{det}

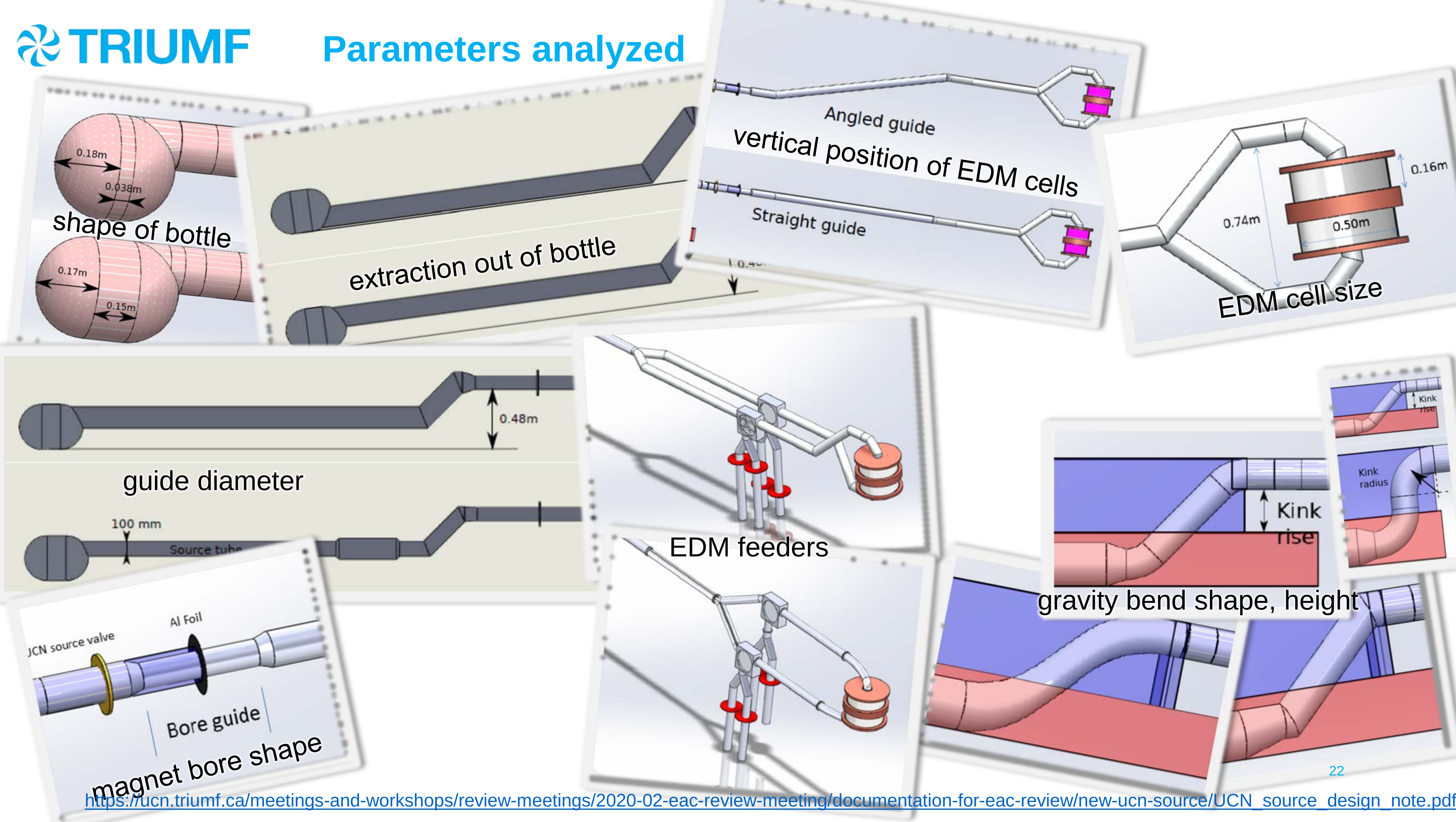
Top cell



Bottom cell



Parameters analyzed



shape of bottle

extraction out of bottle

vertical position of EDM cells

EDM cell size

guide diameter

EDM feeders

gravity bend shape, height

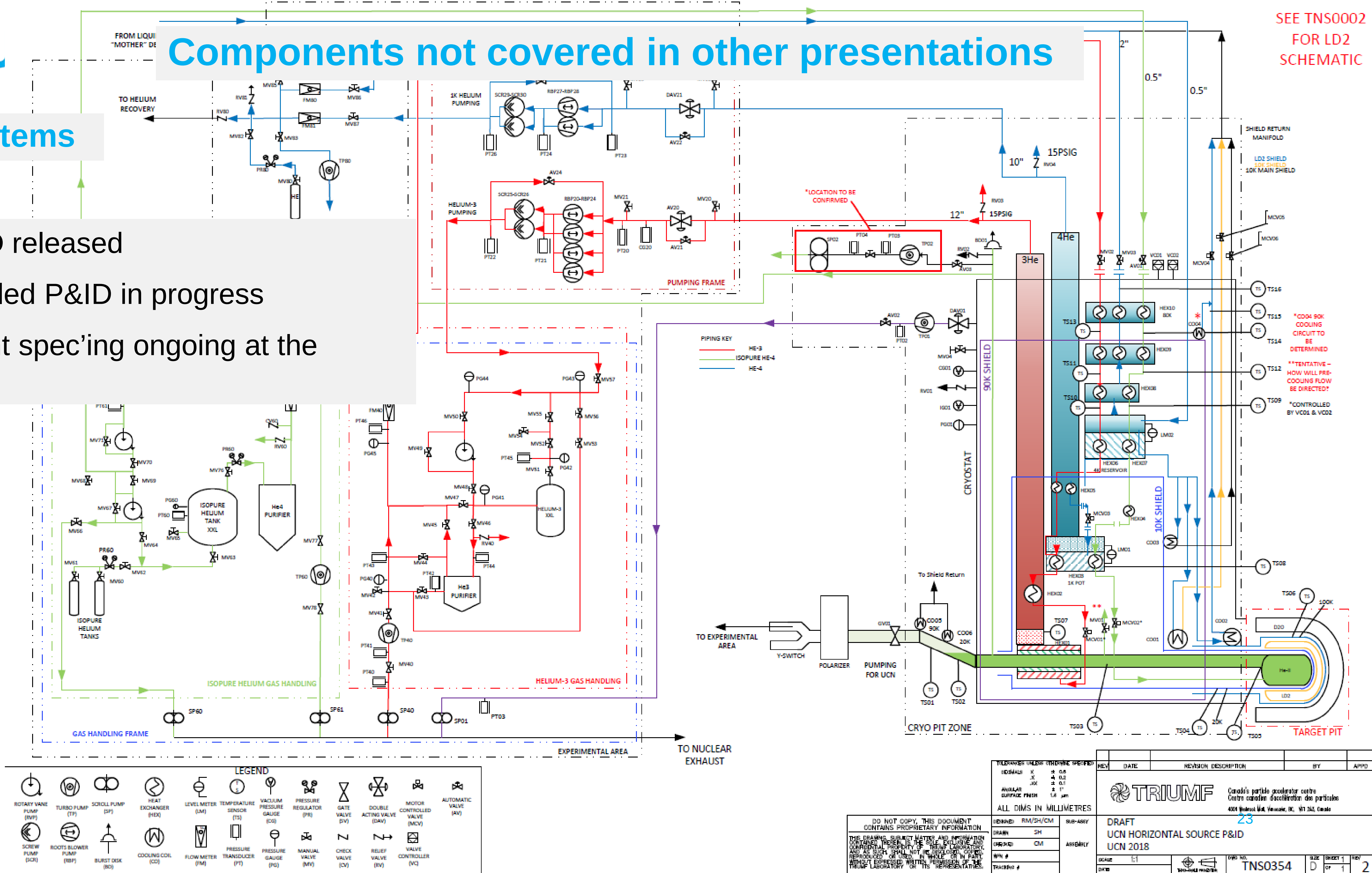
magnet bore shape

https://ucn.triumf.ca/meetings-and-workshops/review-meetings/2020-02-eac-review-meeting/documentation-for-eac-review/new-ucn-source/UCN_source_design_note.pdf

Components not covered in other presentations

He gas systems

- Initial P&ID released
- More detailed P&ID in progress
- Component spec'ing ongoing at the moment



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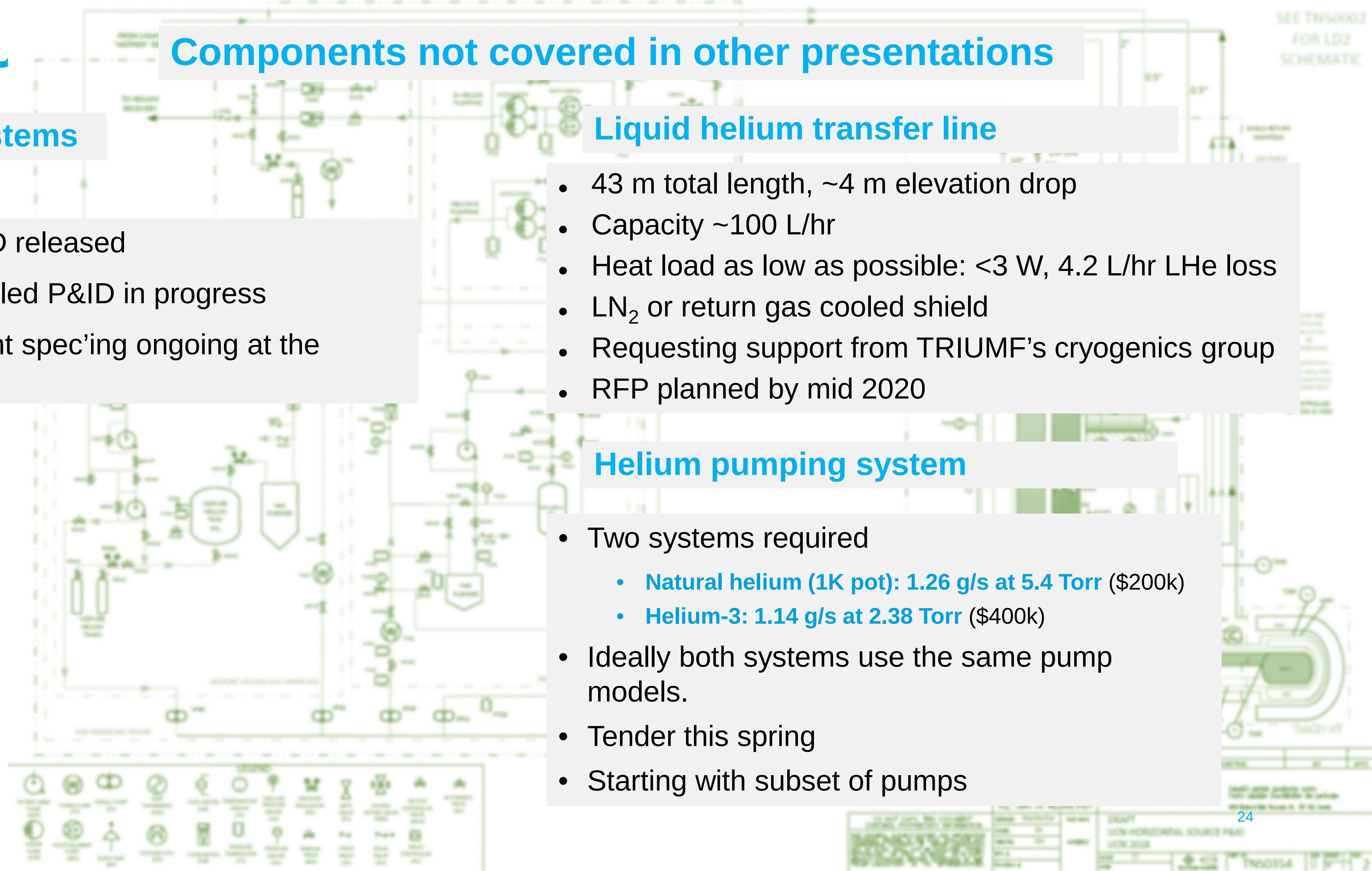

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Liquid helium transfer line

- 43 m total length, ~4 m elevation drop
- Capacity ~100 L/hr
- Heat load as low as possible: <3 W, 4.2 L/hr LHe loss
- LN_2 or return gas cooled shield
- Requesting support from TRIUMF’s cryogenics group
- RFP planned by mid 2020

Helium pumping system

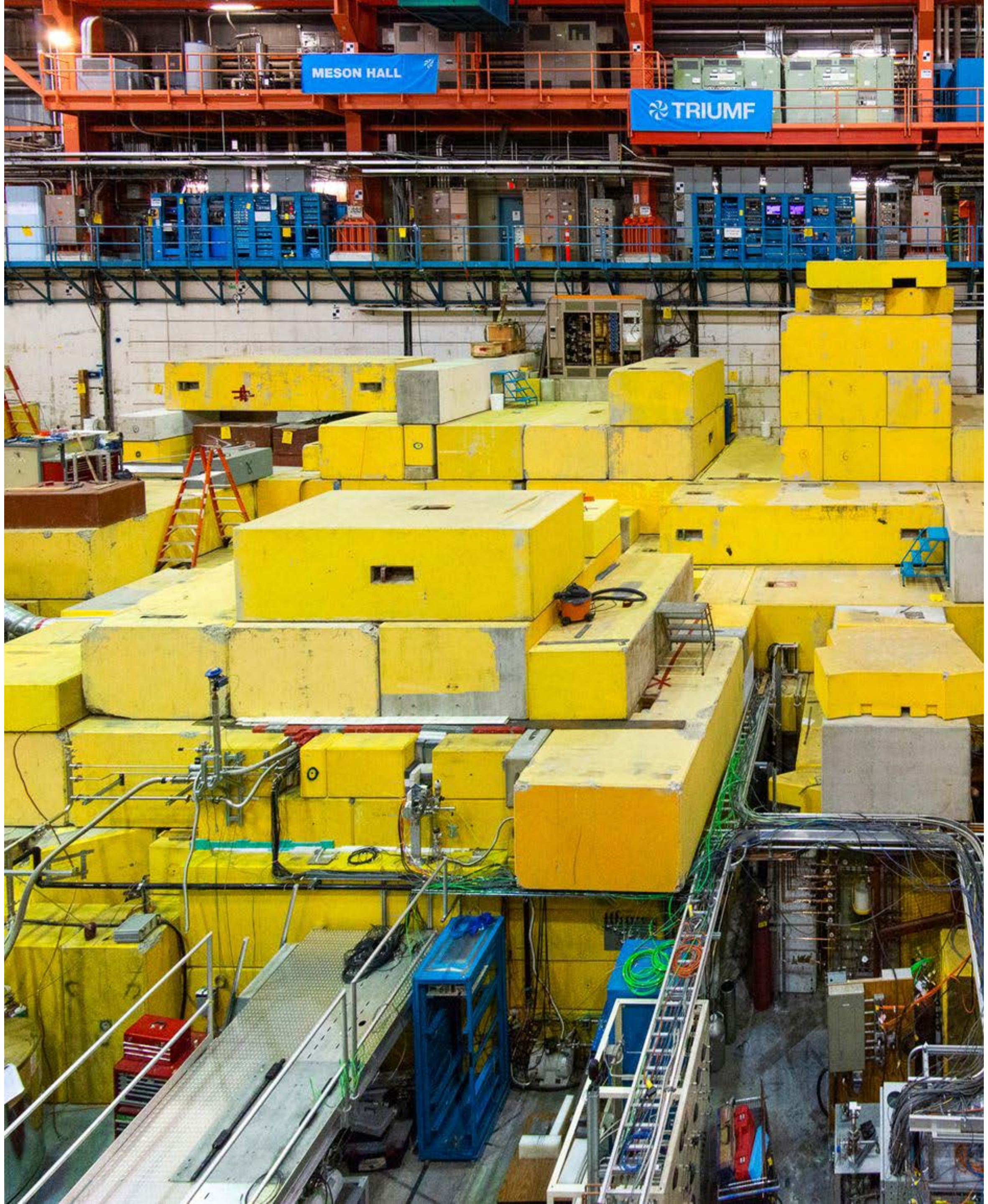
- Two systems required
  - **Natural helium (1K pot): 1.26 g/s at 5.4 Torr** ($200k)
  - **Helium-3: 1.14 g/s at 2.38 Torr** ($400k)
- Ideally both systems use the same pump models.
- Tender this spring
- Starting with subset of pumps

Summary

- We have solved nearly all major challenges posed by the TUCAN next generation source.
- We are making good progress and have achieved major milestones.
- We plan to install it in 2021 and perform first beam tests the same year.
- This is highest priority of the TUCAN collaboration!

We have very challenging and demanding 2 years ahead of us to have many different components come together on time!

Thank you
Merci



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Discovery, accelerated

Some relevant numbers (compared to inverse geometry source)

TUCAN source

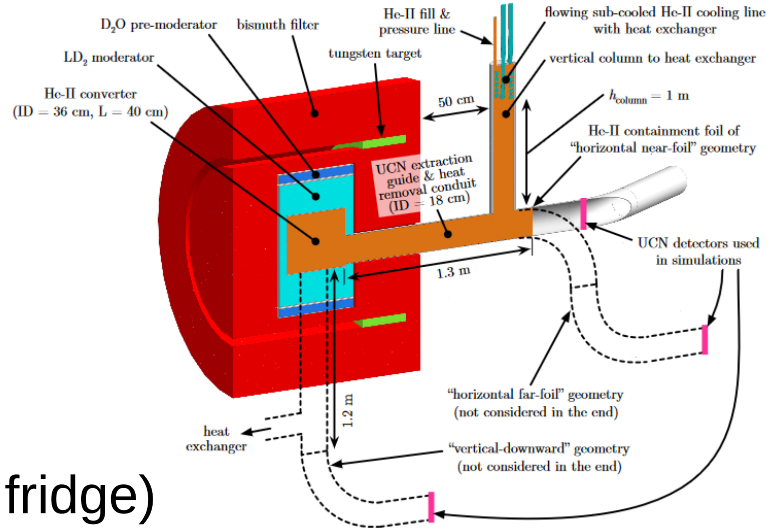
(engineering stage)

- Production 1.4-1.6 x 10^7 UCN/s
- Source helium temp 1.03 K to 1.13 K
- Cooling power 10 W (3He fridge)
- Source storage lifetime 28 s
- Figure of merit Pτ = 4.5 x 10^8
- Density in the source 3 x 10^3 UCN/cc
- Total number in the source 3 x 10^8 UCN
- Initial density in 70 l EDM expt 200 UCN/cc
- Counted at the end of cycle 2 x 10^6

Inverse geometry source

(conceptual stage)

- Production 1.8 x 10^9 UCN/s
- Source helium temp 1.6 K
- Cooling power 100 W (4He fridge)
- Source storage lifetime 2 s
- Figure of merit Pτ = 3.6 x 10^9
- Density in the source 5 x 10^4 UCN/cc
- Total number in the source 6.5 x 10^9 UCN
- Initial density in 100 l perfectly matched expt 10000 UCN/cc

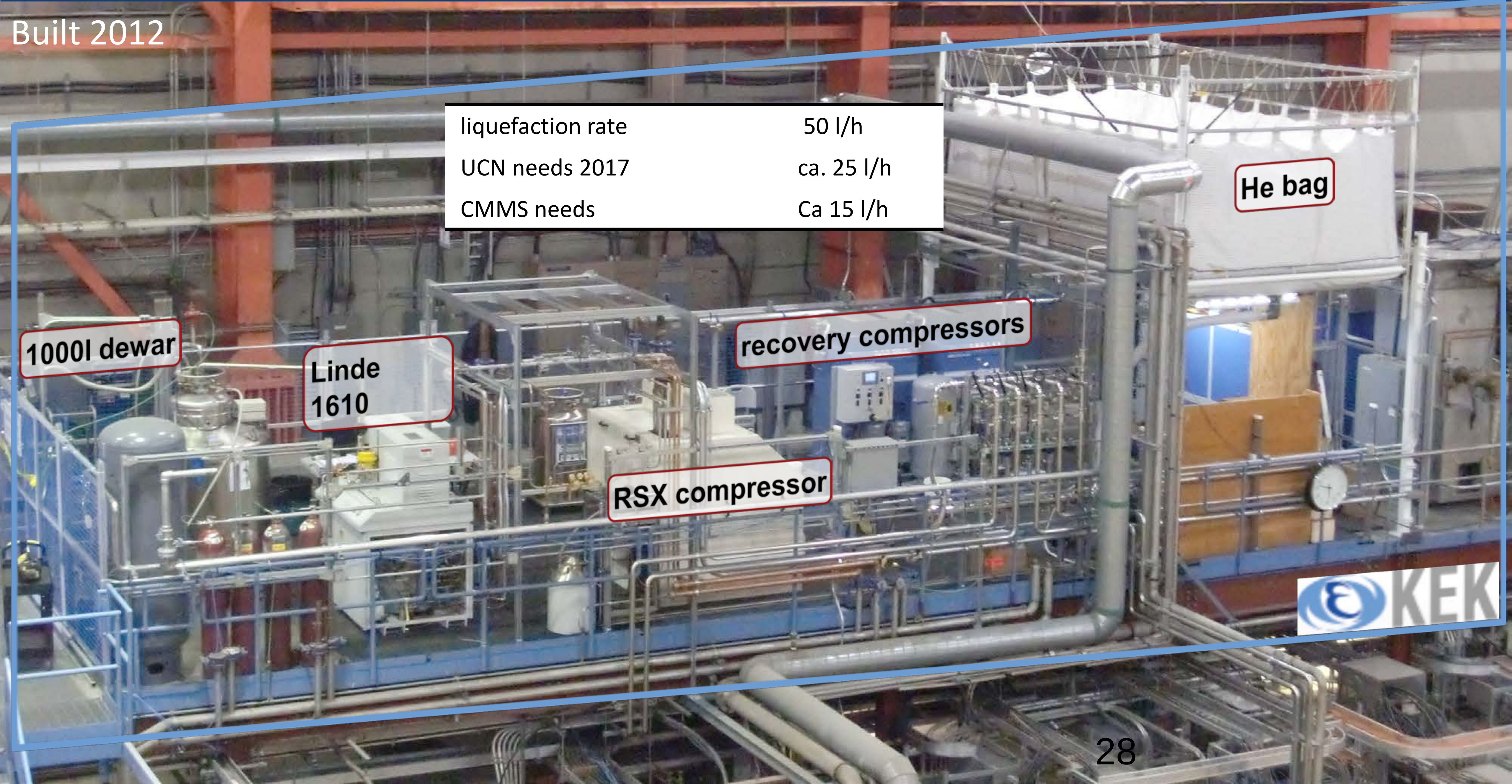


https://arxiv.org/abs/1905.09459

Meson hall He liquefier

Built 2012

liquefaction rate	50 l/h
UCN needs 2017	ca. 25 l/h
CMMS needs	Ca 15 l/h



(C) Counting simulation

1. Spawn neutrons inside EDM cells at T=0 with constant energy distribution, EDM cell valve open and EDM switch connecting to detectors
2. Record energy distribution of neutrons collected in the detectors every second T_{count}

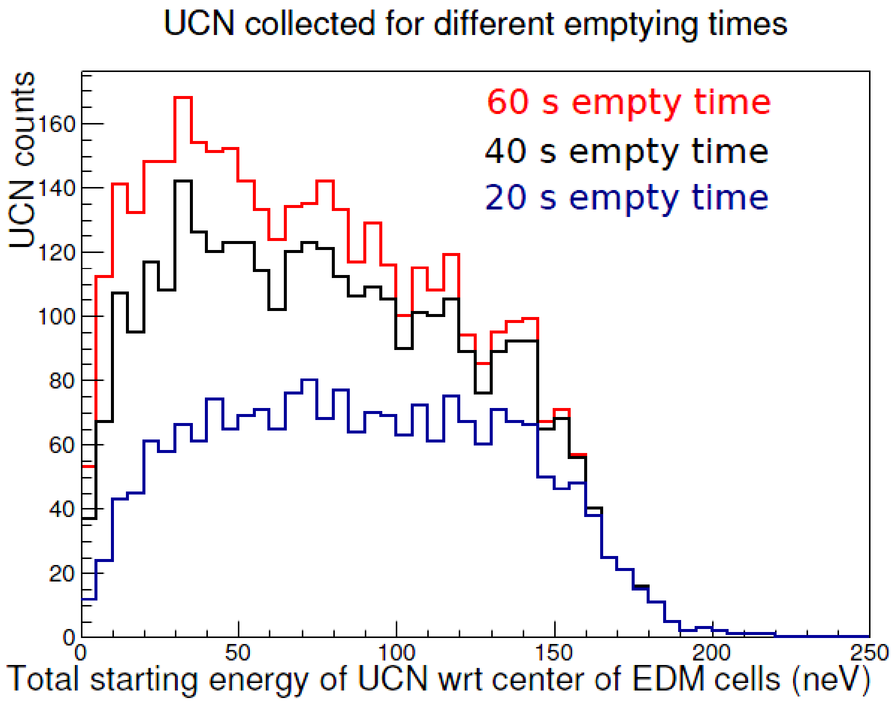


Figure 11: UCN collected by the detectors vs Total starting energy in the EDM cells in the cell emptying simulations. As emptying time increases the total number of UCN collected by the detectors increases and the average UCN energy decreases.

S. Sidhu

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Simulation results summary

Parameter Studied	**Values**	**Optimum**	**Spread from optimum (%)**	**Remarks**	**Concept Design**
He bottle shape	Cyl (r=170 + 150), sph (r=180 + 38)	Spherical	~5%	~3% better	Cylinder
He bottle material	Al6061,Al2219,AlBeMet	AlBeMet	~25%	~17-20% better	Al6061
Bottle extraction	Low, mid, high	high	~13%	dbl kink ~ 5% better than high	High extraction
Source tube diameter (mm)	100,125,150,180	150	~7%	150 ~ 4% better than 125	150
21.7KG HEX diameter (mm)	125,150,180,200	180	~60%	(KG = 21.7) 180 ~ 50% better than 150, 200	148
35KG HEX Diameter (mm)	125,148,180,200	148	~6%	148 and 125 are roughly the same	148
Funnel shape	Symmetric, asymmetric, eccentric	eccentric	~7%	eccentric ~ 4% better than Asymmetric	eccentric
Kink rise (cm)	18,23,28,33,38,43	18	~ 8%	18 ~ 2% better than next best	18
Kink radius (cm)	15,22,29,36,43,50,57	no clear optimum	~ 0	no significant difference	20
Kink angle (deg)	45,50,55,60,65,70,75,80,85,90	no clear optimum	~ 0	no significant difference	90
UCN guide diameter (mm)	86, 95,100,125	125	~10 %	95 ~ 7% better than 86, ~ 2% worse than 125	100
Bore guide diameter (mm)	40,45,50,55,60,67	67	~15 %	200 mm fixed length	70
Spider location	On 45 deg kink, on and out side 90 deg kink	no clear optimum	~1 %	no significant difference	out side of 90deg kink
Cell radius (cm)	18,20,22,25,28,30,40,50	50	~100 %	30cm ~ 20% better than 25cm	25

EDM sensitivity

$$\sigma(d) = \frac{\hbar}{2\alpha E \; T_{Ramsey}\sqrt{N_{det}}}, \qquad (1)$$

where

$$\alpha = \alpha_0 * e^{-t_{EDM}/T_2 - (t_{wait}+2*t_{\pi/2})/T_1} * \epsilon_{depol} * P_{analyzer}$$

with an initial visibility of $\alpha_0 = 0.95$, depolarization (5 %, $\epsilon_{depol} = 0.95$), efficiency of the spin analyzers ($P_{analyzer} = 0.90$). For the simulations:

$$N_{\mathrm{det}} = N_{\mathrm{coll}} * \epsilon_{\mathrm{det}} * 0.5 * P_{real}/P_{sim} * e^{-t_{storage}/\tau_{Xe}},$$

where $\epsilon_{\mathrm{det}} = 0.90$ detector efficiency, and N_{coll} includes

$$N_{\mathrm{surv}} = \sum_E N_{\mathrm{det}}(E) * e^{-t_{storage}/\tau(E)}$$

Days to reach 10^{-27} *ecm*

The cycles to reach a sensitivity of 1×10^{-27} $e \cdot cm$ is given by

$$CTR = \left(\frac{\sigma_d}{8 * \ 1 \times 10^{-27}} \right)^2 \tag{2}$$

The cycles per day are thus given by:

$$CPD = \frac{t_{stable}}{8 * (t_{irrad} + t_{fill} + t_{EDM} + t_{empty}) + 2 * t_{flipPol} + t_{degauss}/10} \tag{3}$$

$$days = \frac{CTR}{CPD}.$$

S. Sidhu

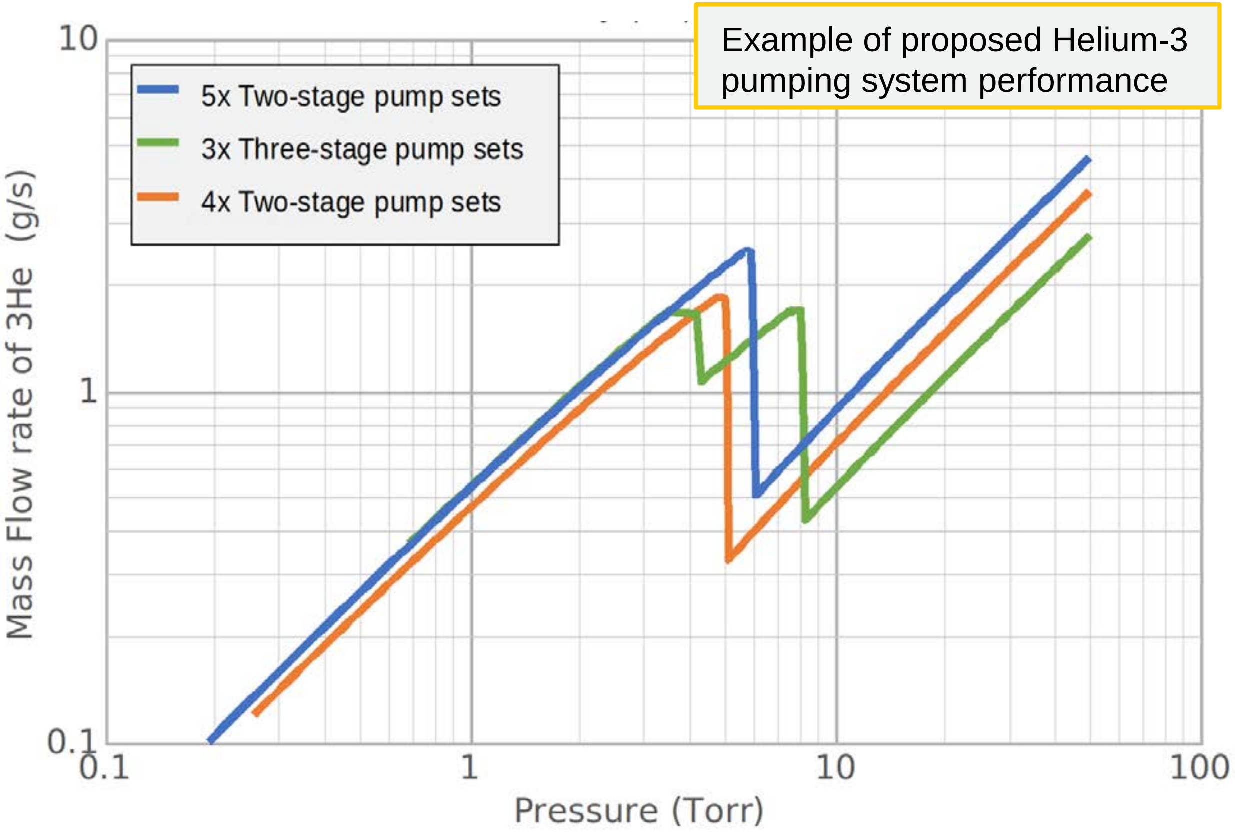
TUCAN UCN source pumping systems

Natural helium (1K pot): 1.26 g/s at 5.4 Torr

- well known pumping performance, low risk
- cost about 200 kCAD

Helium-3: 1.14 g/s at 2.38 Torr

- pumping performance only estimated
- minimize additional helium-3 for purges
- cost about 400 kCAD
- ideally both systems use the same pump models



Example of proposed Helium-3 pumping system performance

Status

- discussion with three suppliers, 1-2 promising proposals
- TRIUMF conceptual design review in May 2019
- preparation of RFP ongoing
- approach to purchase minimal system first (possibly for Helium-3 only, use current pumps for Natural helium)

TUCAN UCN source liquid helium supply line

Natural helium supply

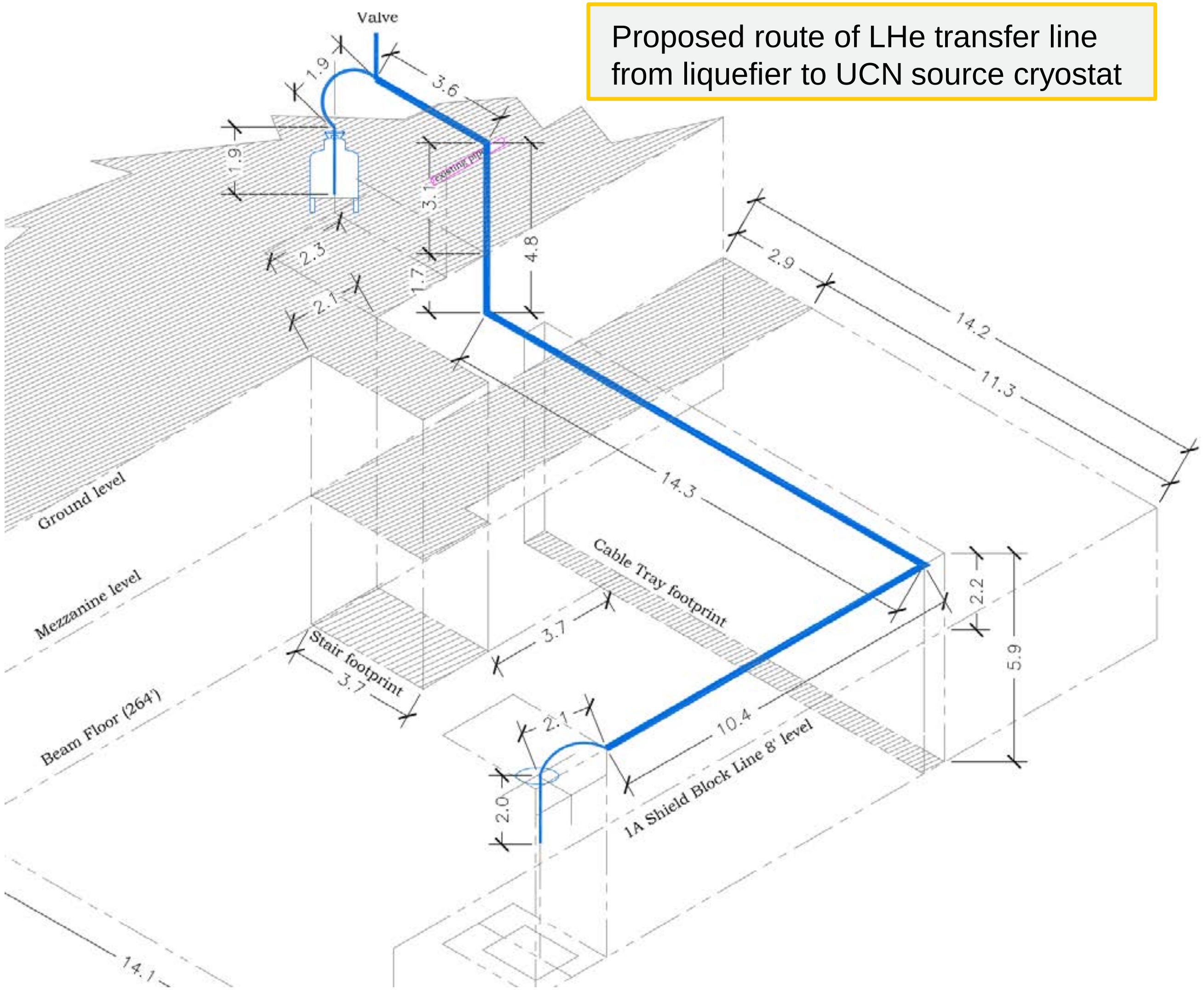
- liquefier production currently 50-55 L/hr
- Full, reliable operation requires upgrade of production rate and mother dewar capacity

Natural helium transfer line

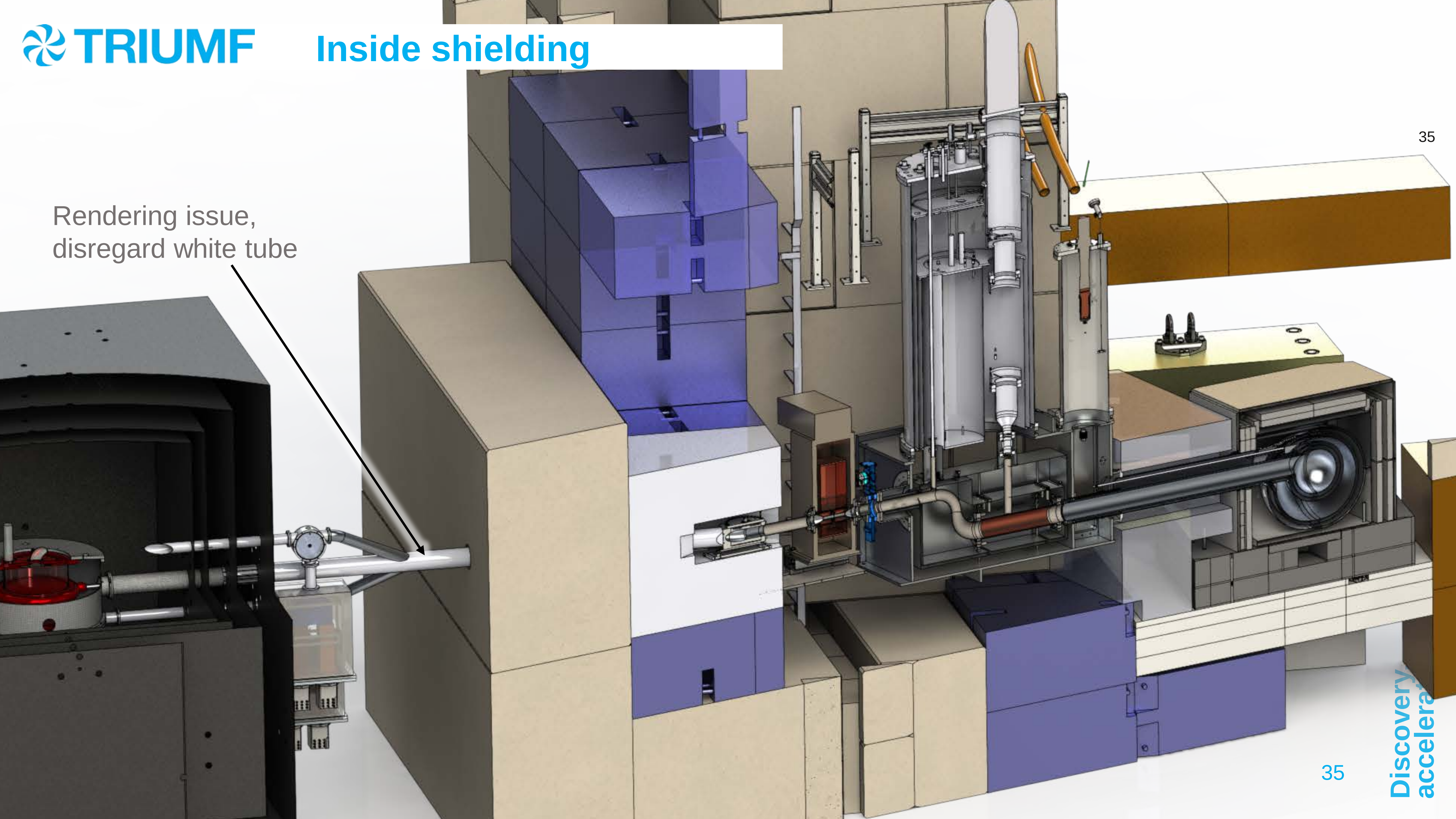
- 43 m total length, ~4 m elevation drop
- UCN source avg consumption 10W, 35% duty: 31 L/hr
- LHe supply line capacity ~100 L/hr
- Heat load <3 W, 4.2 L/hr loss (as low as possible)
- LN2 or return gas cooled

Status

- Request support from TRIUMF’s cryogenics group
- RFP planned by mid 2020


Proposed route of LHe transfer line from liquefier to UCN source cryostat

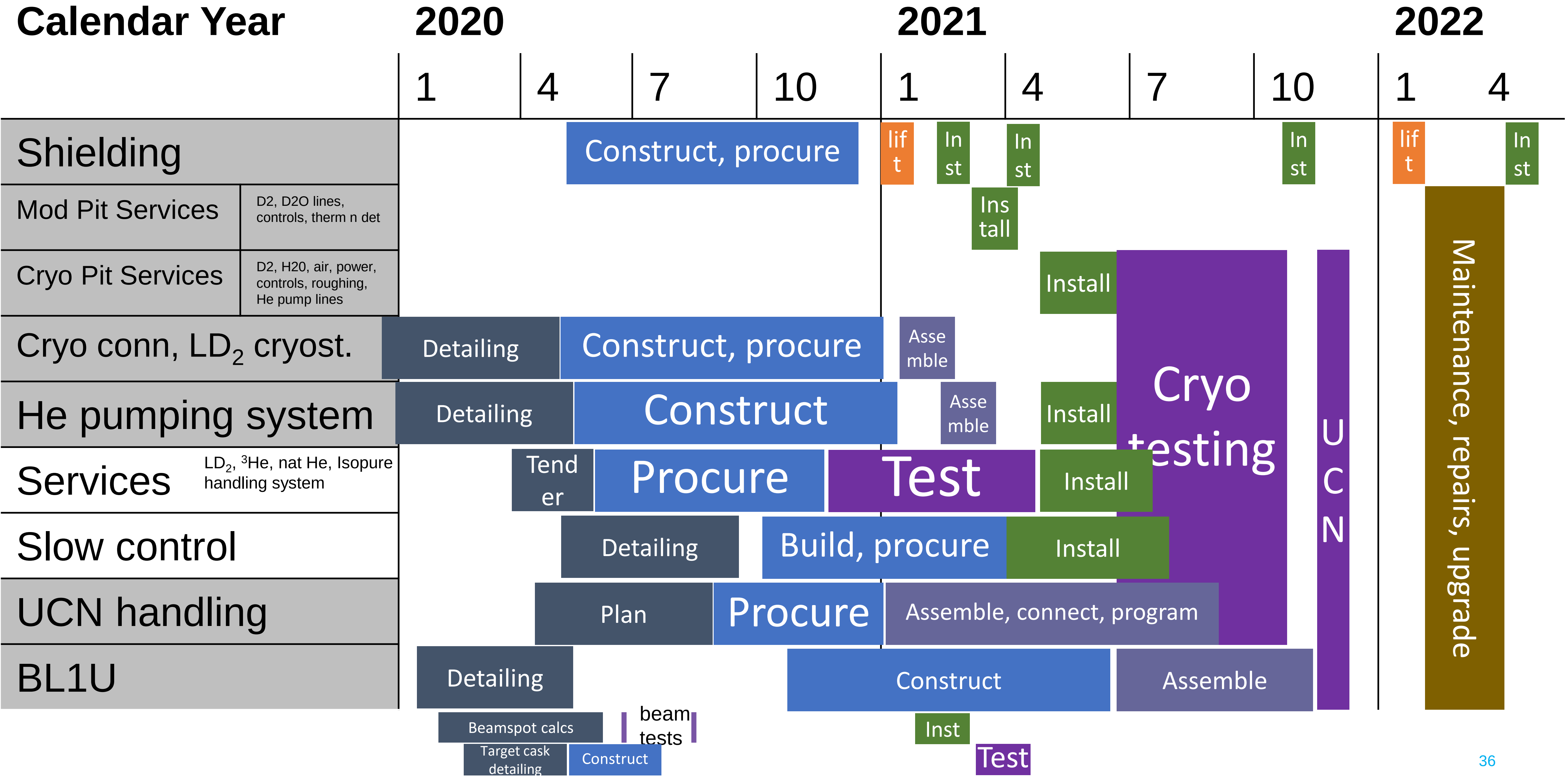
Inside shielding



Rendering issue, disregard white tube

TRIUMF

UCN services schedule (will go to appendix…)



Calendar Year 2020 2021 2022

1 4 7 10 1 4 7 10 1 4

Shielding: Construct, procure; lift; Inst; Inst; Inst; lift; Inst

Mod Pit Services (D2, D2O lines, controls, therm n det): Install

Cryo Pit Services (D2, H20, air, power, controls, roughing, He pump lines): Install

Cryo conn, LD_2 cryost.: Detailing; Construct, procure; Assemble

He pumping system: Detailing; Construct; Assemble; Install

Services (LD_2, ^3He, nat He, Isopure handling system): Tender; Procure; Test; Install

Slow control: Detailing; Build, procure; Install

UCN handling: Plan; Procure; Assemble, connect, program

BL1U: Detailing; Construct; Assemble

Beamspot calcs; Target cask detailing; Construct; beam tests; Inst; Test

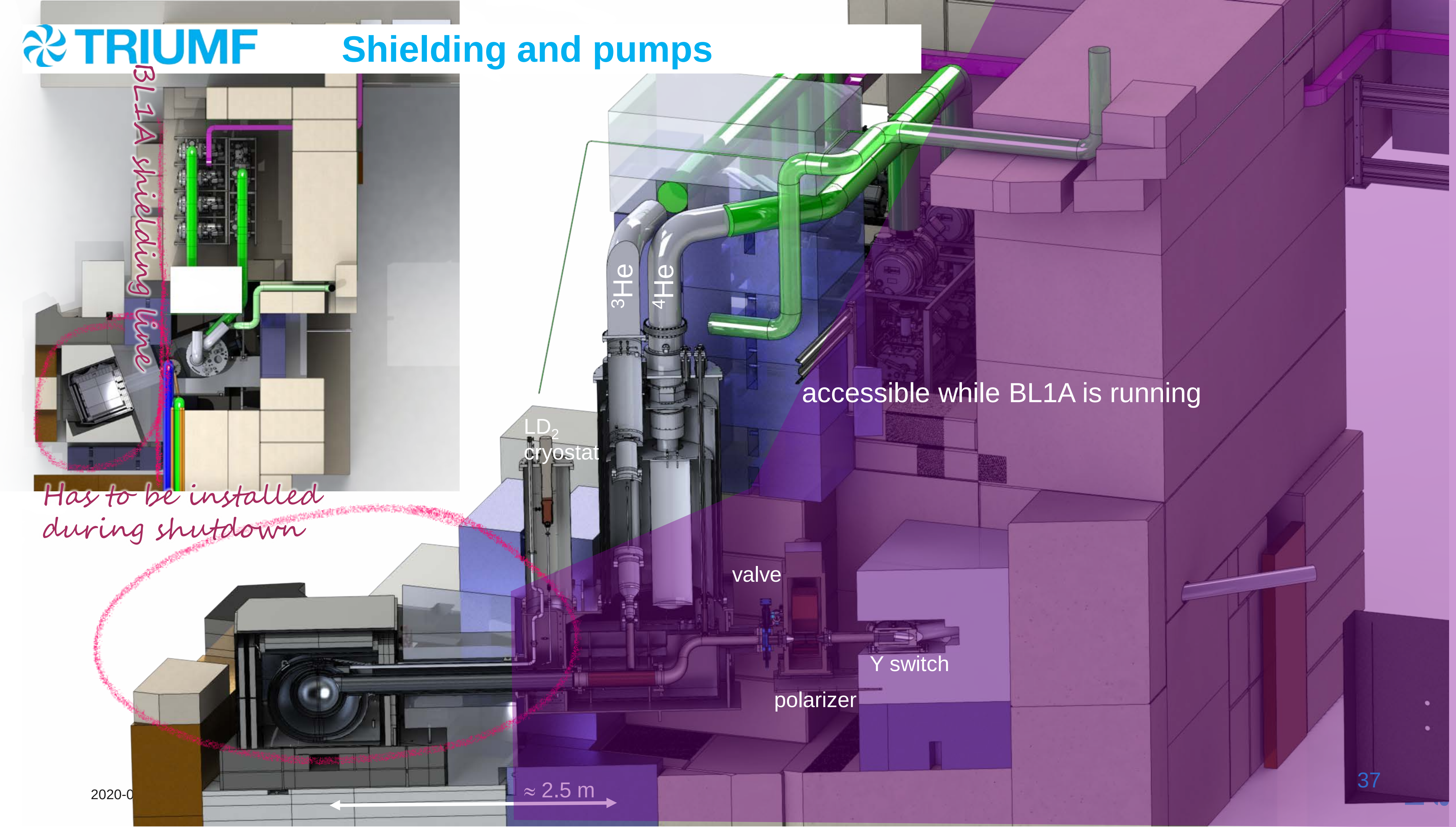
Cryo testing

UCN

Maintenance, repairs, upgrade

Gray shaded systems are inside the biological shielding.

Shielding and pumps



accessible while BL1A is running

Has to be installed during shutdown

Technology choices for converter and cold moderator

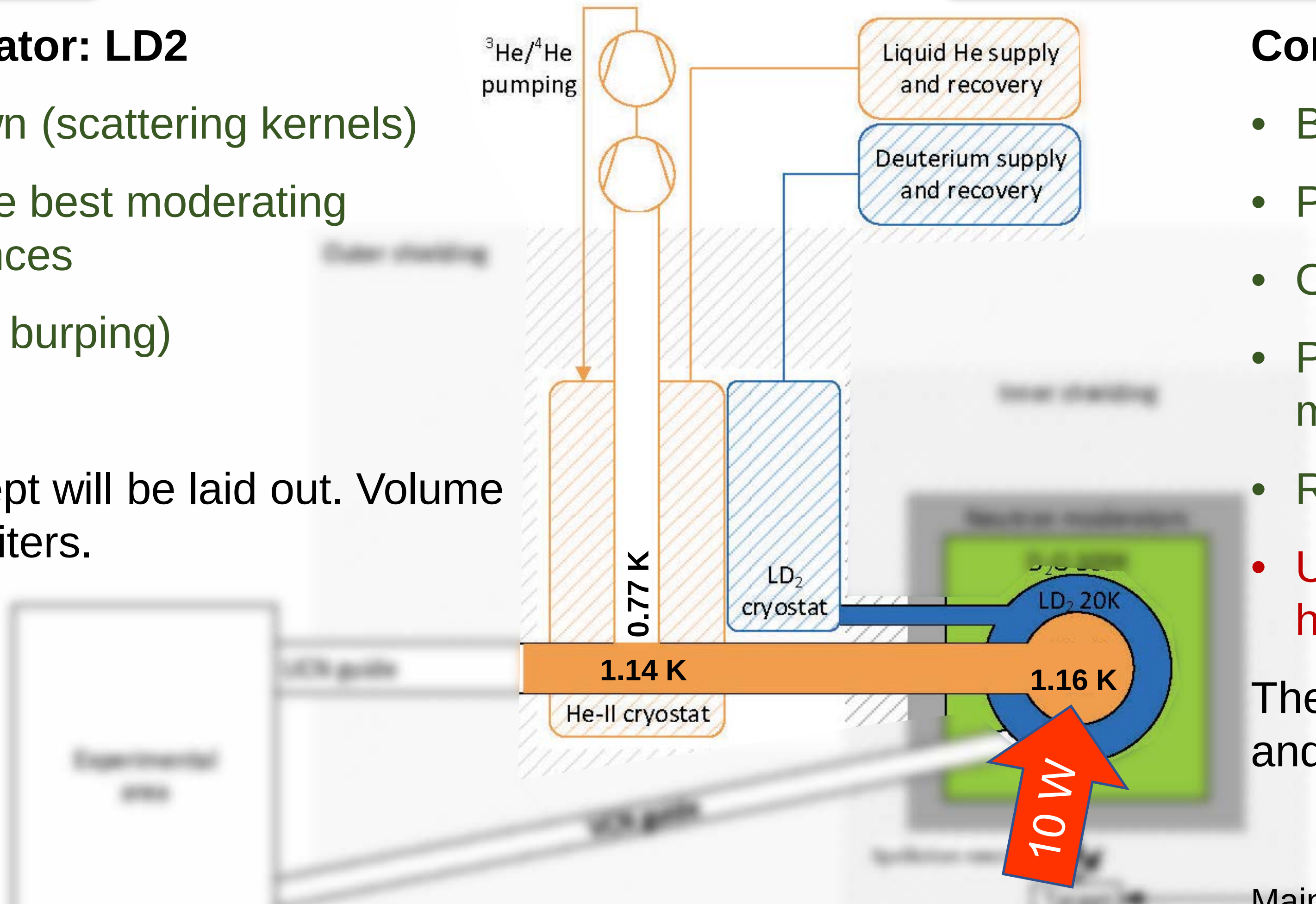
Cam Marshall

Shinsuke Kawasaki Ryohei Matsumiya Takahiro Okamura

Cold moderator: LD2

- Well known (scattering kernels)
- Among the best moderating performances
- Liquid (no burping)
- Explosive

Safety concept will be laid out. Volume < 150 liquid liters.



0.25 W static load, K_g=22, a=2.6, VanSciver

Converter cryostat: ^{3}He pumping

- Best cooling performance < 1 K
- Proven technology
- Own expertise
- Pressure drop in pumping duct manageable.
- Reasonable pumps required.
- Uncertainty in surface and superfluid helium conductivity

These uncertainties have been studied and are being experimentally tested.

Main disadvantages of 4He direct pumping:

- huge pumping power
- pressure drop very critical

What is taken into account in the analytical model?

Analytical model useful to study many more parameter options than possible in simulation.

This is taken into account…

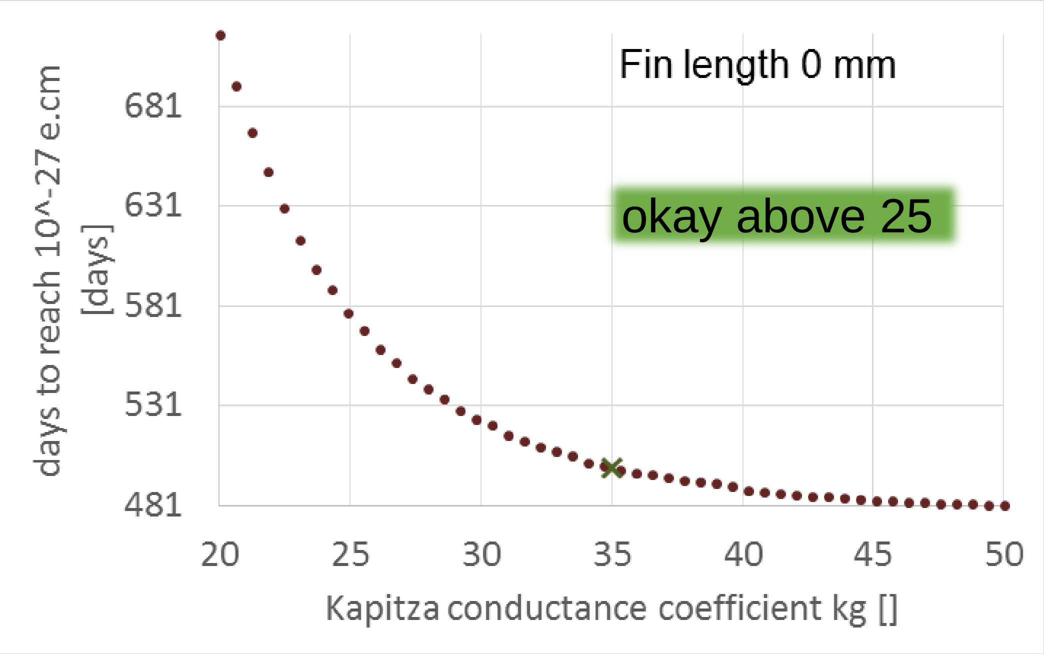
- UCN production/heat input from MCNP simulations
- Cryostat performance (pumps, pressure drop, HEX, heat conductivity)
- Neutron storage lifetime in source (He liquid + vapor)
- Phase space reduction due to wall Fermi potential and height differences
- Dilution of neutron “gas”
- Simple model of Ramsey cycle
- Probable stable daily measurement period
- Times for E field change, degaussing etc

This is not… or not so well…

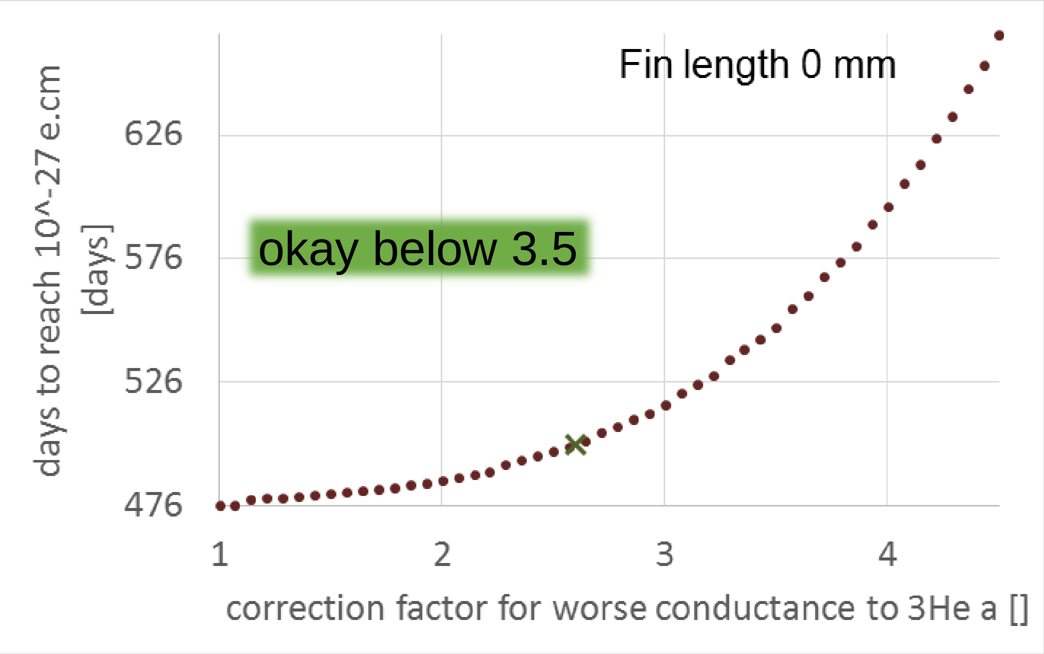
- Magnetic field of polarizer (it is in MC)
- Transport is only modelled via loss per meter, bend, foil etc
- Depolarization of UCN during transport (assuming 5% total)

Heat exchanger sensitivity

Kapitza resistance parameter K_G

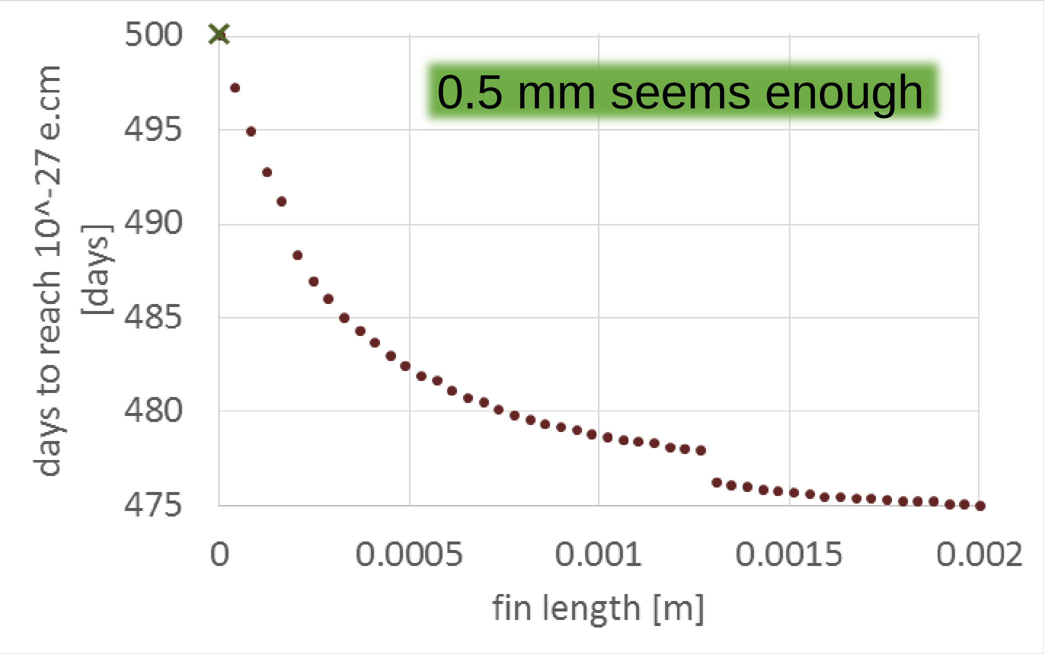


^{3}He Kapitza correction factor



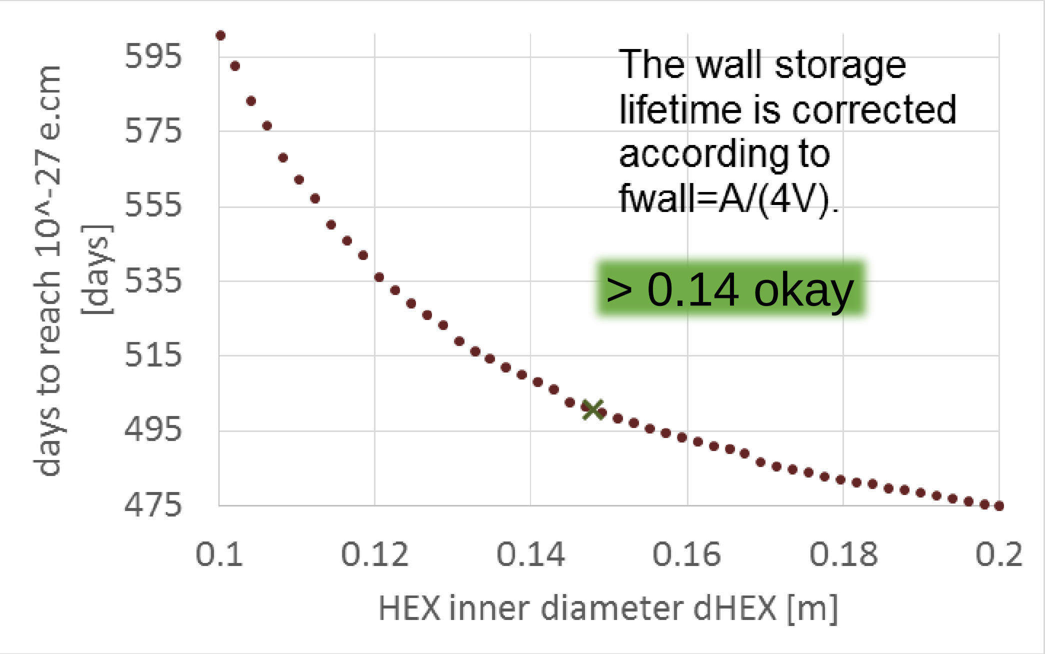
Heat exchanger sensitivity continued

Fin length



Heat exchanger sensitivity continued

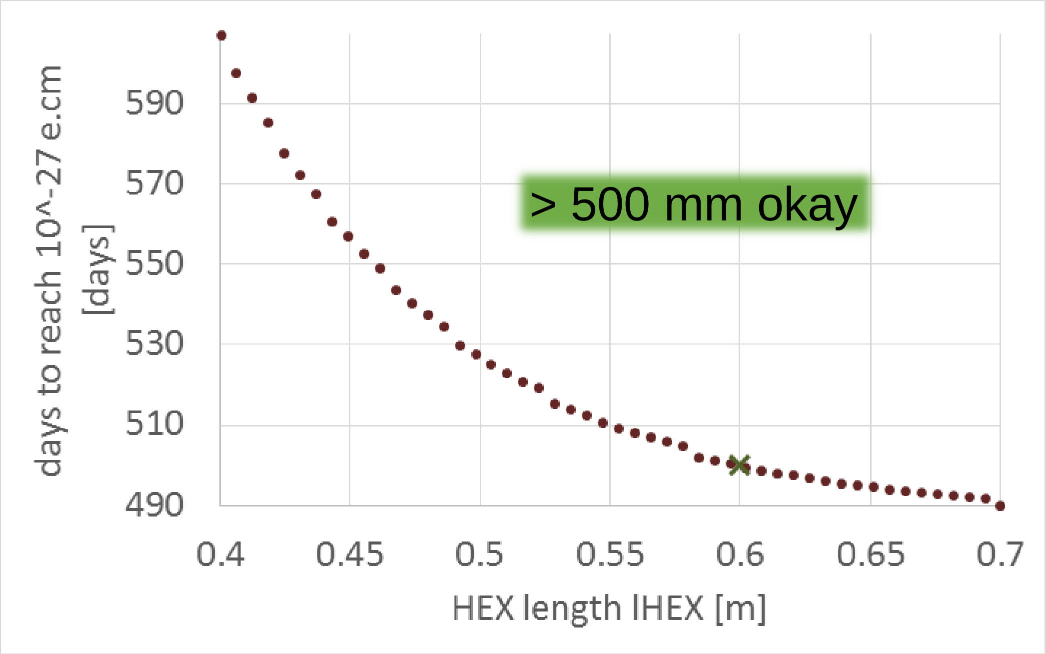
HEX1 inner diameter



The wall storage lifetime is corrected according to fwall=A/(4V).

> 0.14 okay

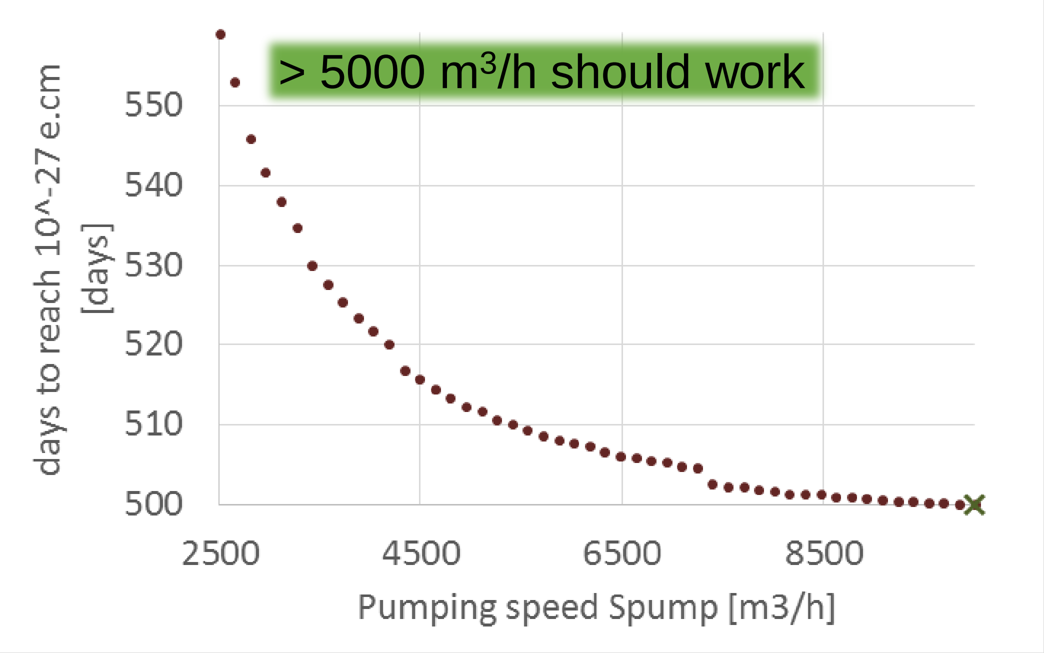
HEX 1 length



> 500 mm okay

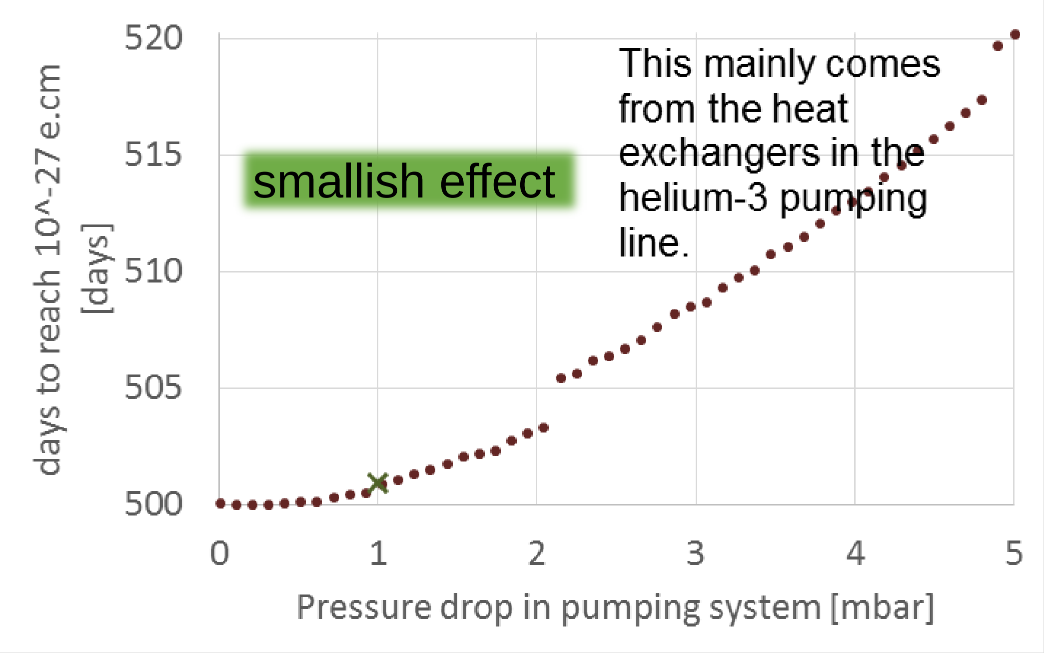
Helium-3 pumping system

Pumping speed



> 5000 m^3/h should work

Pressure drop in helium-3 pumping line

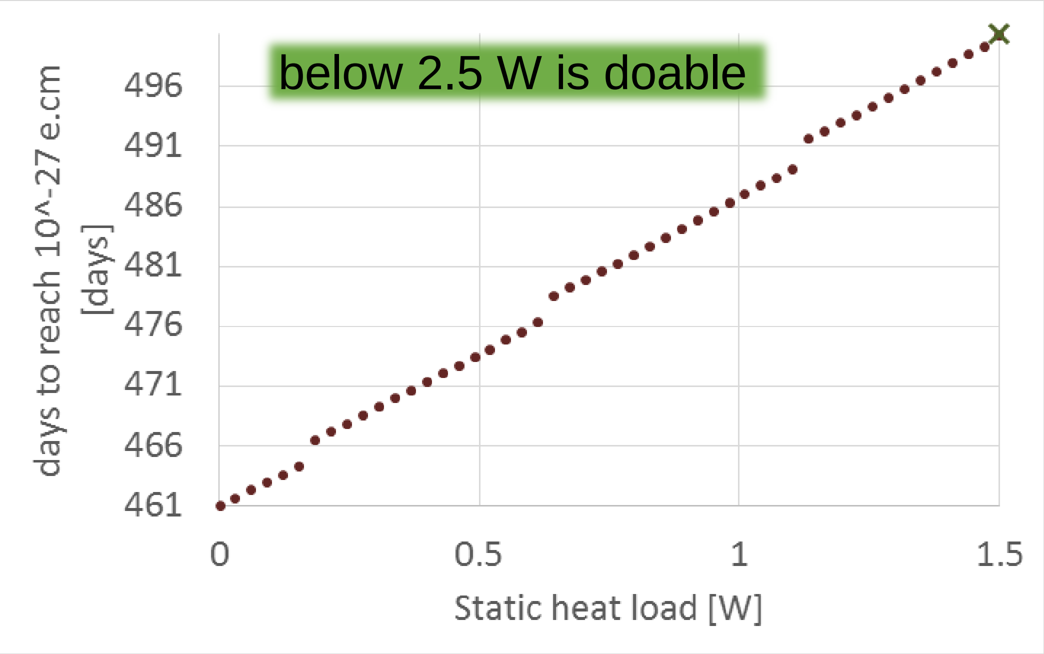


smallish effect

This mainly comes from the heat exchangers in the helium-3 pumping line.

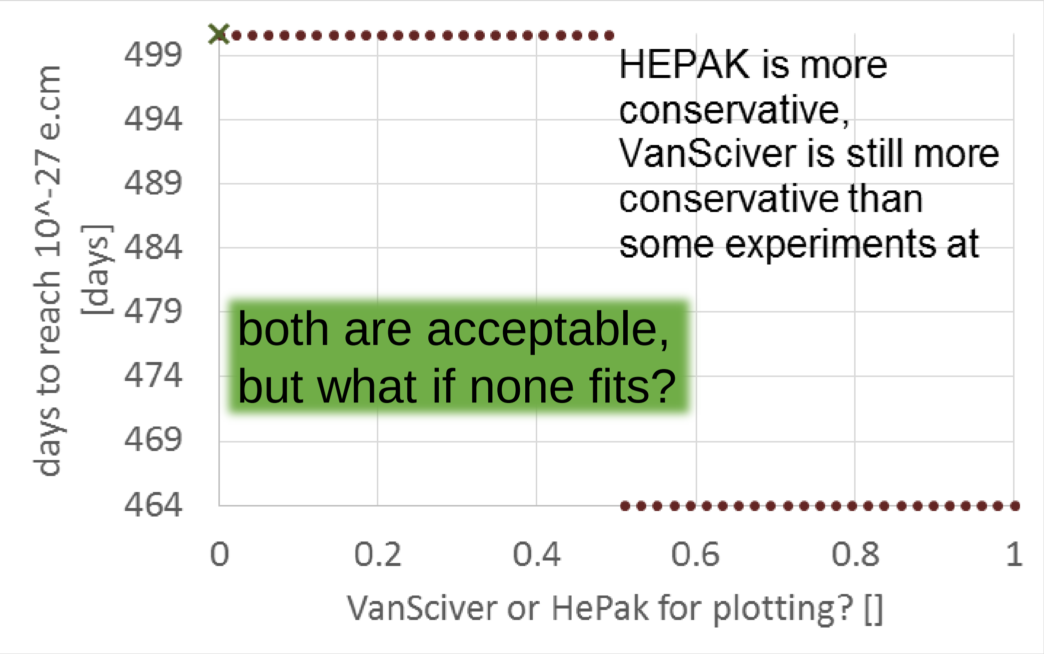
Heat input and conduction

Static heat input



below 2.5 W is doable

Model dependence

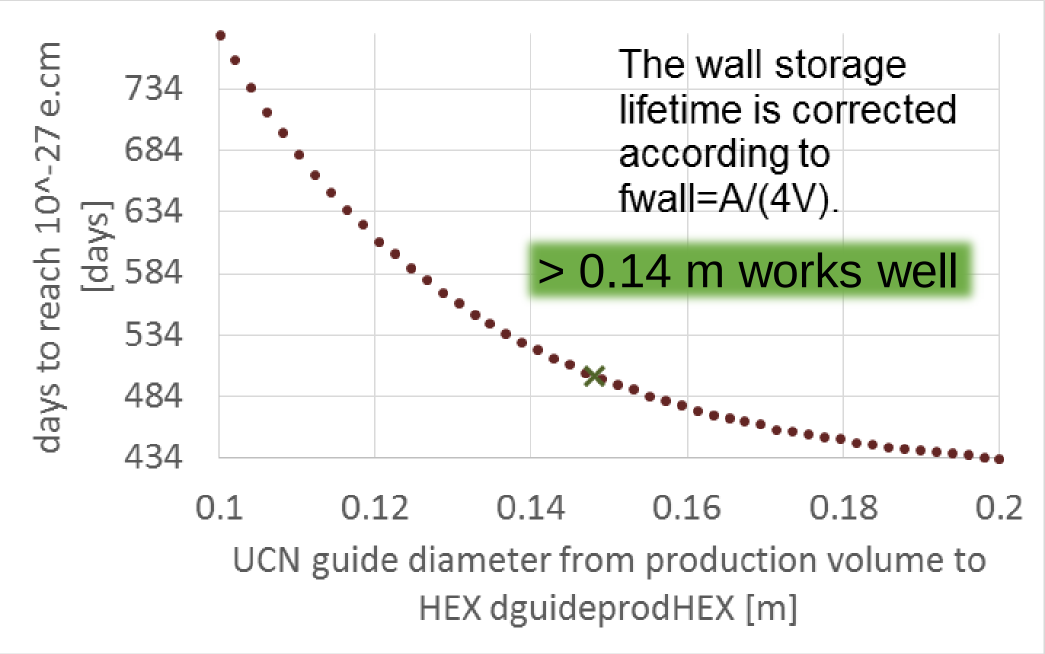


HEPAK is more conservative, VanSciver is still more conservative than some experiments at

both are acceptable, but what if none fits?

Heat conduction continued

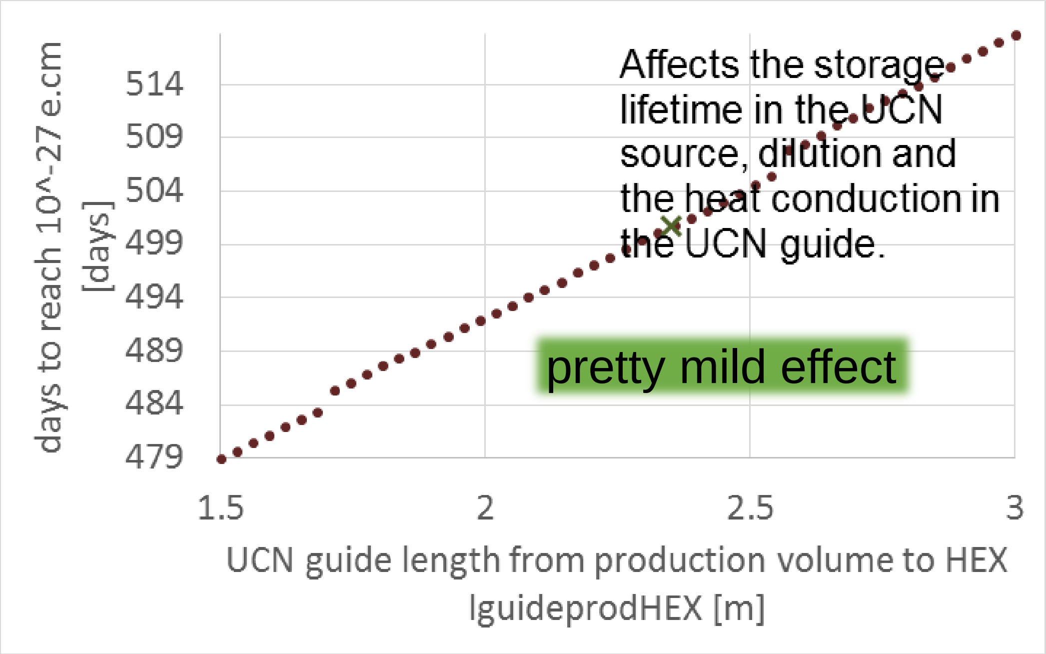
UCN guide and heat conduction channel diameter



The wall storage lifetime is corrected according to fwall=A/(4V).

> 0.14 m works well

Length of the same

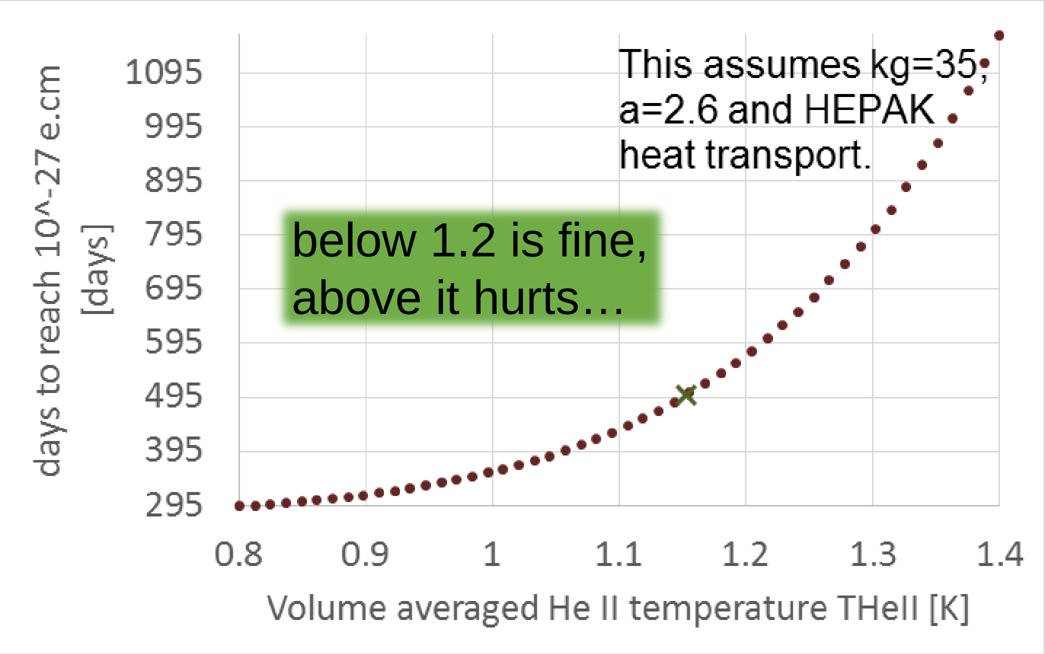


Affects the storage lifetime in the UCN source, dilution and the heat conduction in the UCN guide.

pretty mild effect

General temperature dependence

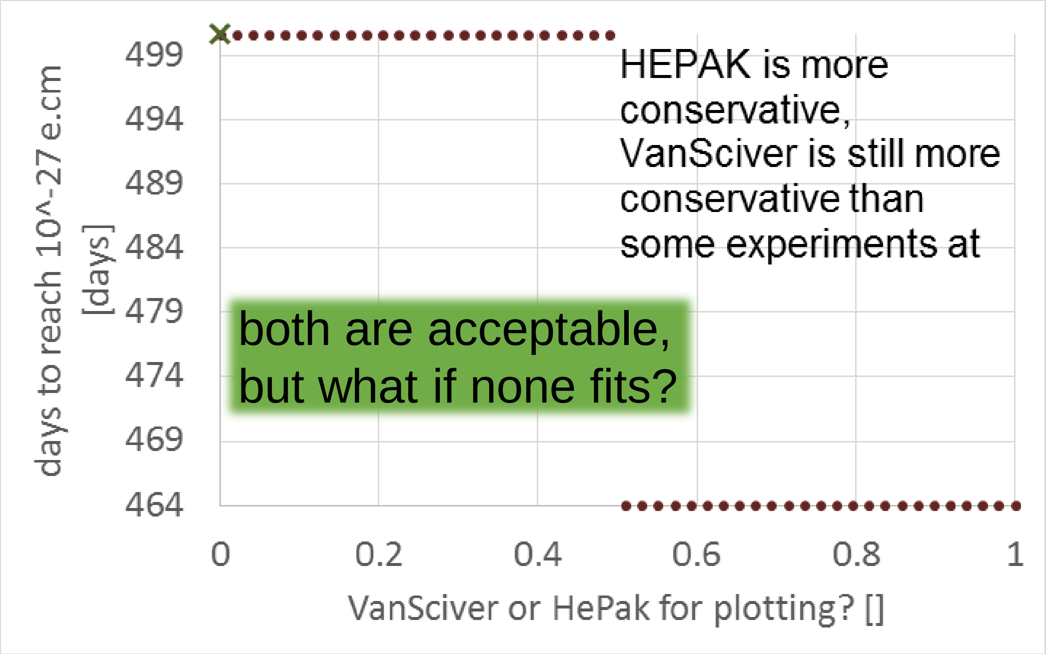
Volume averaged isopure helium temperature



This assumes kg=35; a=2.6 and HEPAK heat transport.

below 1.2 is fine, above it hurts…

Model dependence



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General temperature dependence

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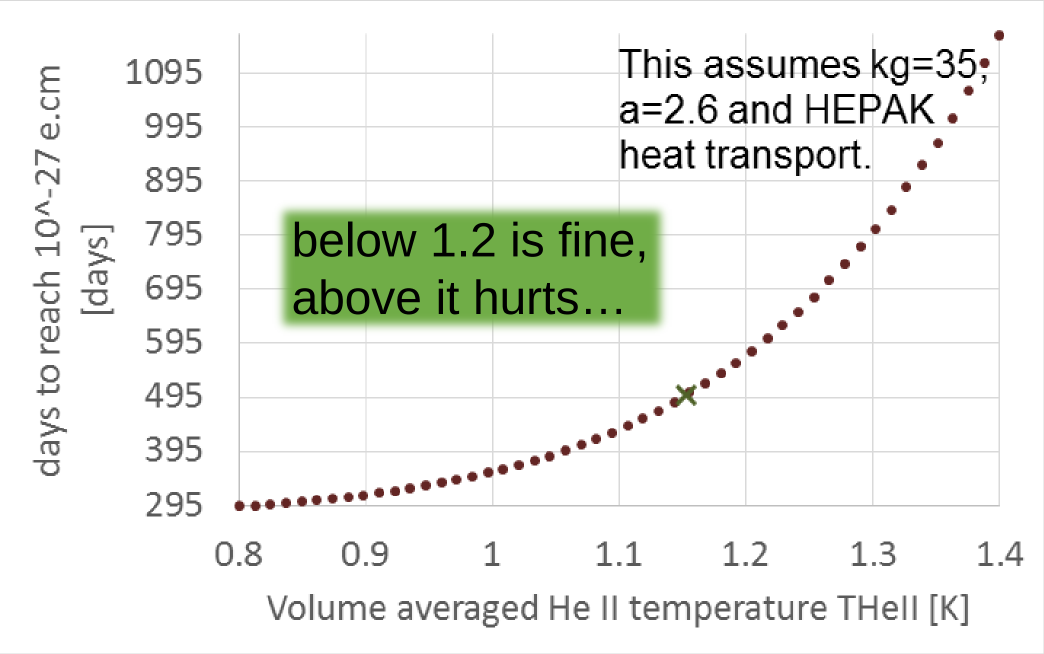

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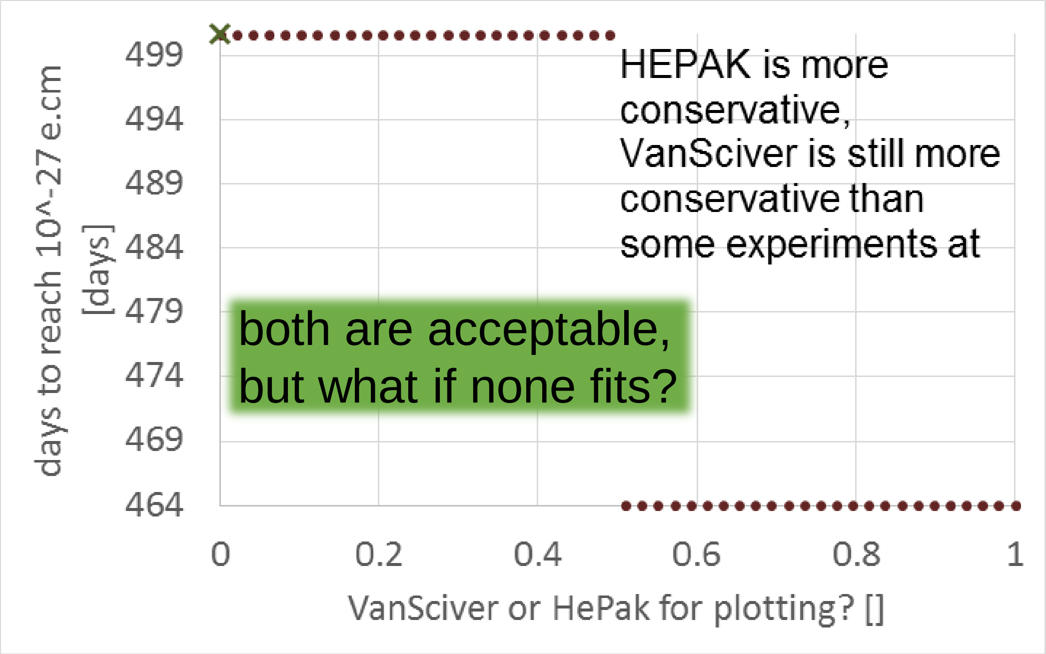
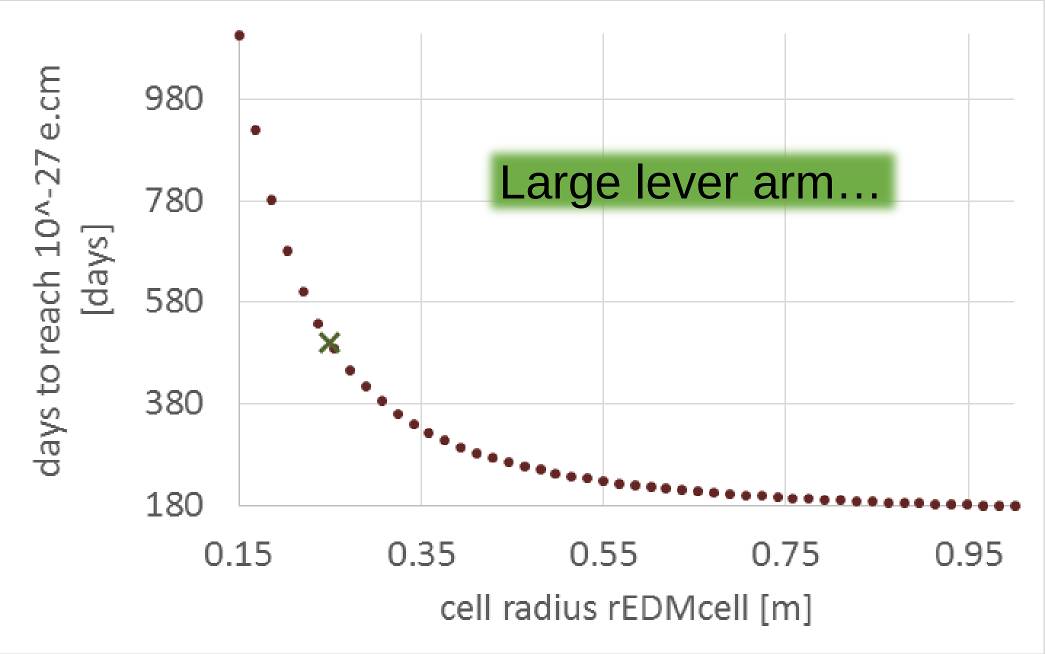


HEPAK is more conservative, VanSciver is still more conservative than some experiments at

both are acceptable, but what if none fits?

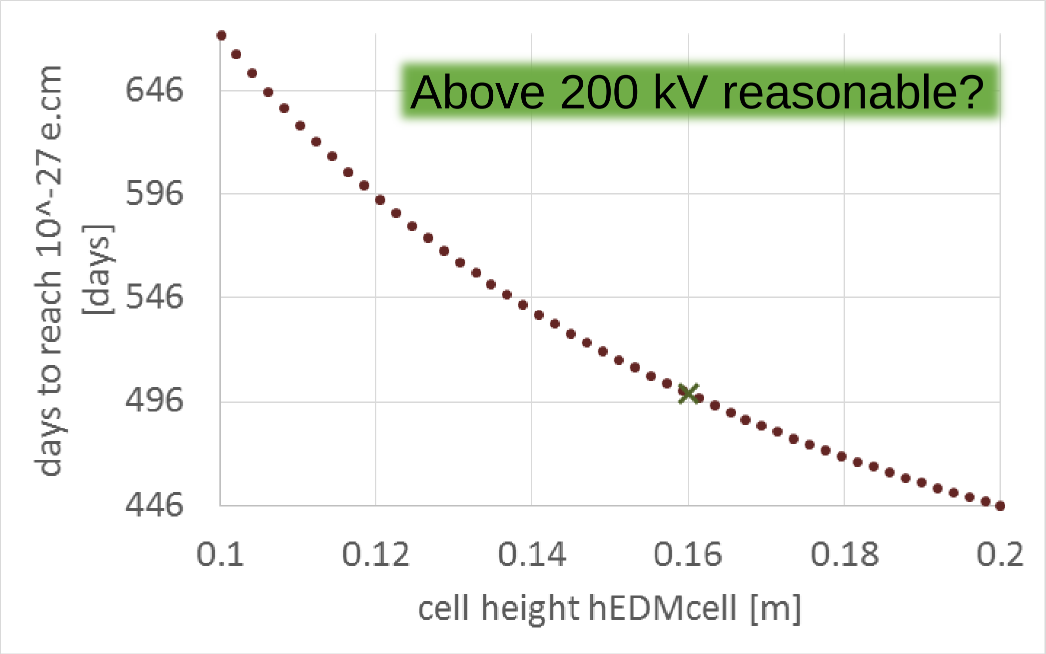
nEDM parameter sensitivity

EDM cell radius



Large lever arm…

EDM cell height (E field kept at 13 kV/cm)



Above 200 kV reasonable?