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Monte Carlo optimization of a next-generation ultracold-neutron source

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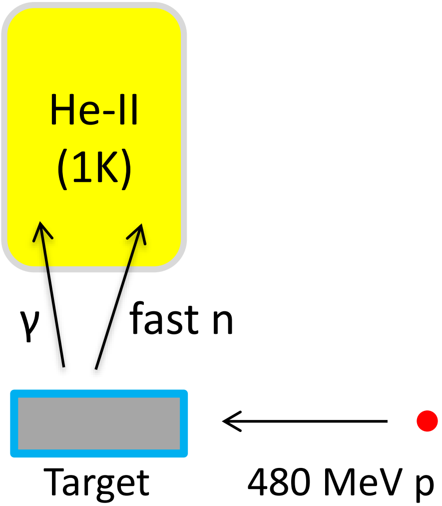
for the TUCAN collaboration

2017-10-18, nEDM 2017, Harrison Hot Springs

- Design parameters
- Optimization
  - FLUKA
  - MCNP
  - PENTrack
- Preliminary optimization results

Design parameters

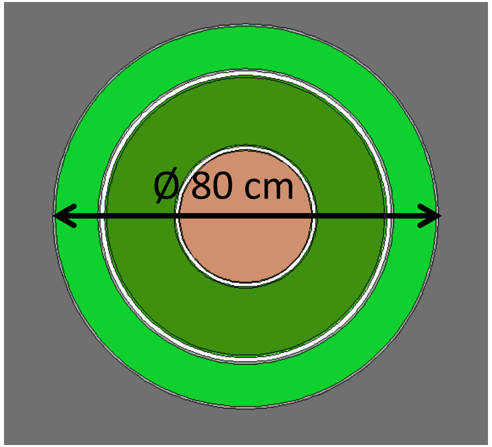
- Spallation source
  - Combination of neutron moderators
  - Radiation shielding
- Superfluid-helium converter
  - Heating by γs, neutrons, β electrons
  - Upscattering lifetime $\tau_{up} = 130\mathrm{K}^7\mathrm{s} \cdot T^{-7}$
- Geometry of ultracold-neutron guides

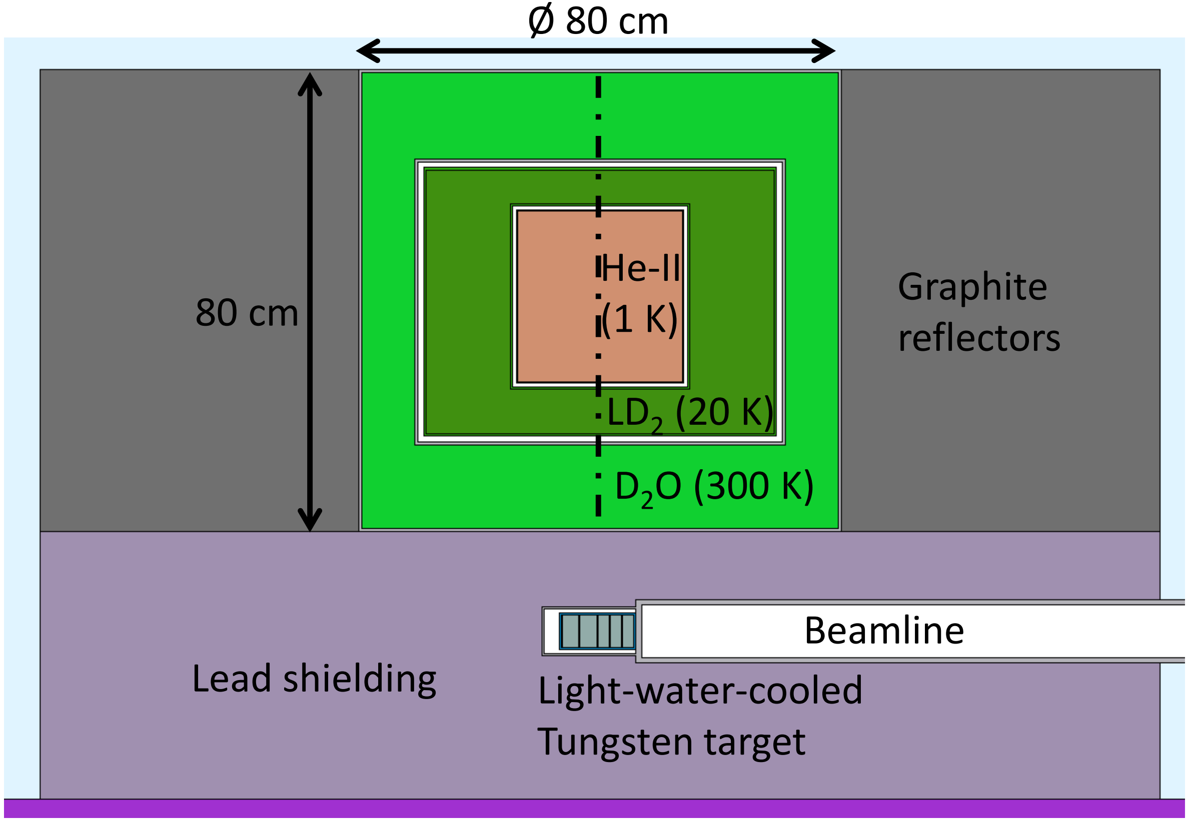


Optimization

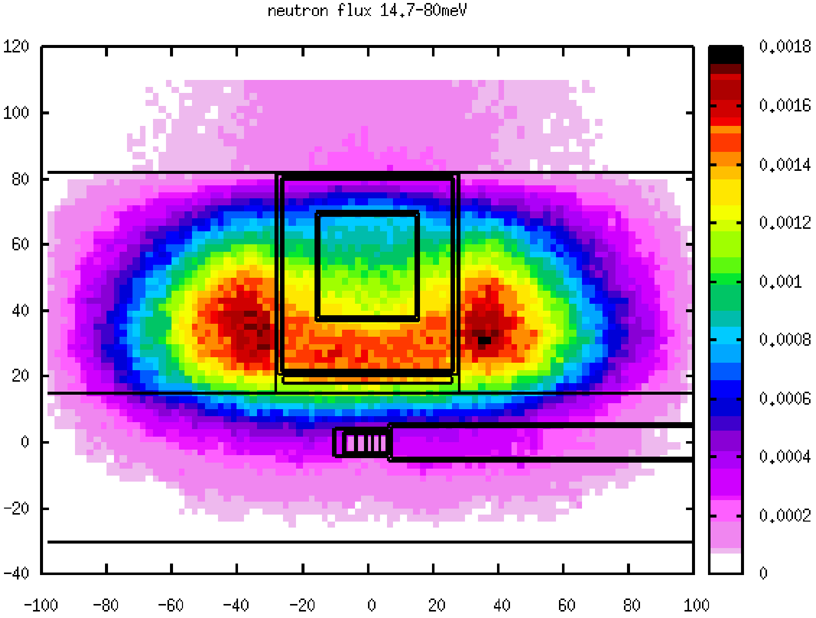
Starting geometry:

- Best use of symmetry
- Cylindrical aluminum vessels centered on target





FLUKA

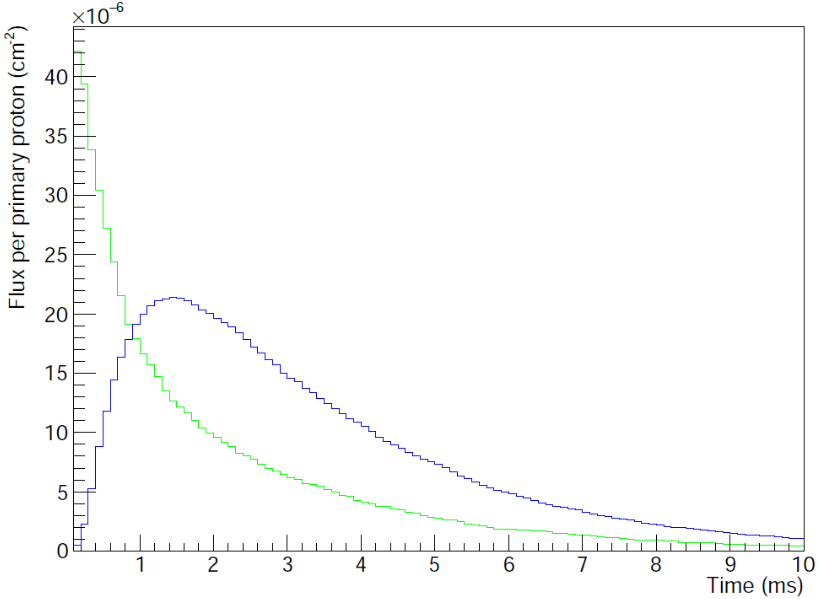


- fluka.org (Free)
- Monte Carlo simulation of **particle transport in matter**
- Including multi-group transport of low-energy neutrons
- **Neutron-scattering models for many isotopes** at 296K, some at 87K and 4
- Geometry as combination of basic shapes
- **Easy to use** thanks to flair (geometry builder, plotter)
- Can output particle flux in volume/over surface, production of radioactive nuclei, deposit of prompt and decay heat

MCNP

- mcnp.lanl.gov
- Much more **detailed nuclear-scattering** data
- Including many **specialized neutron moderators**
- Combinatorial geometry,
  can be exported from flair
- Detailed output of particle flux in volume/over surface, heat deposit, binned in energy, time, and directio
- Text-only configuration

Neutron flux <6 meV, 6-100 meV



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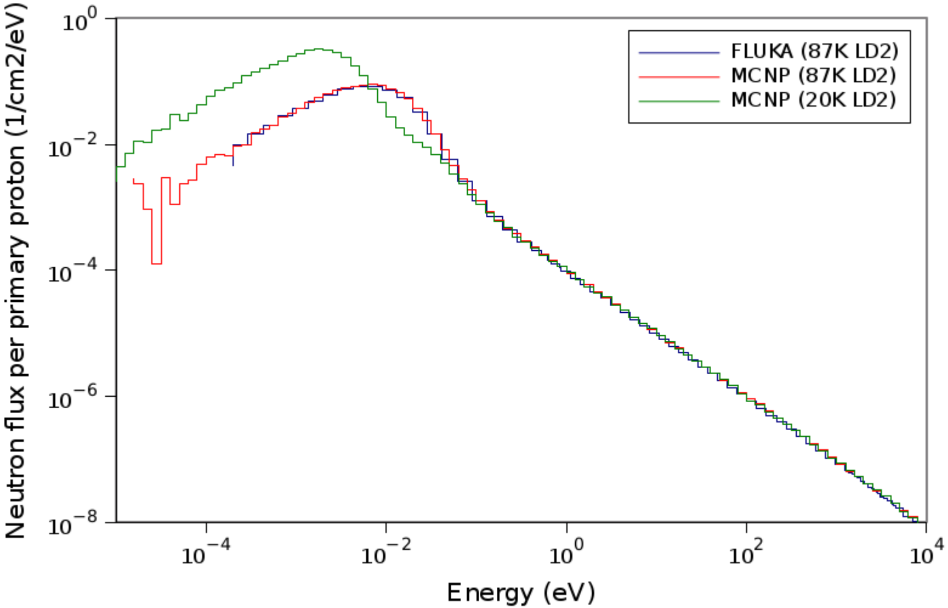
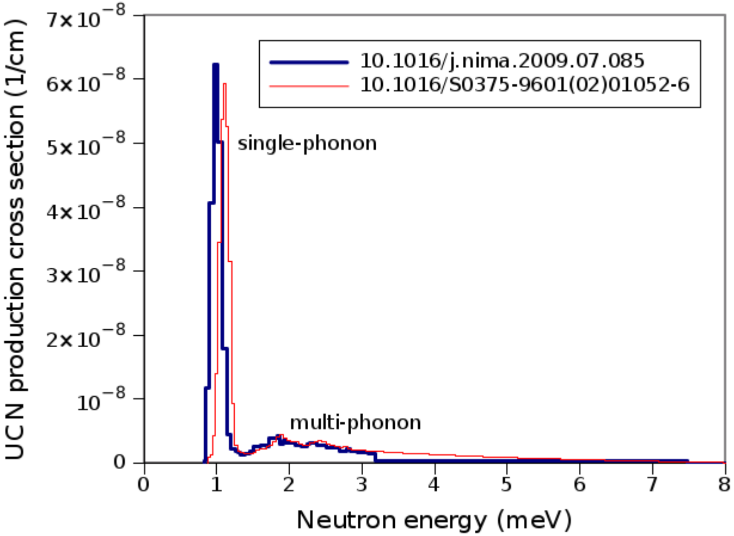
Comparison FLUKA and MCNP

- FLUKA has no scattering data for liquid deuterium at 20K
- Good agreement between MCNP/FLUKA for free-gas model at 87K
- Cold-neutron flux 10 times higher with 20K deuterium in MCNP



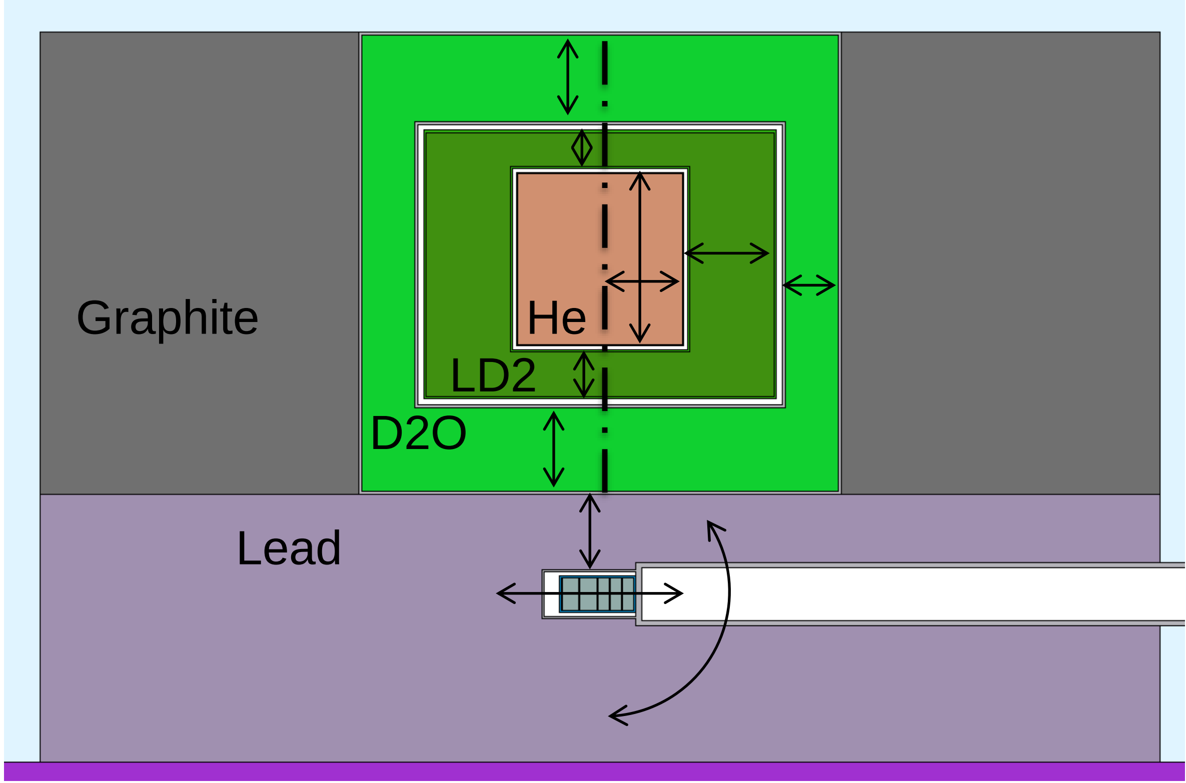
Optimization with MCNP

- Goal: maximize number of UCN available to experiment
- Constraints:
  - Cooling power at 1K: ~10W
  - Amount of cold moderators (liquid deuterium!)
- Simple model: maximize UCN production per heat P/Q
- Detailed model: maximize P·τ with $1/\tau = 1/\tau_{up}(Q) + 1/\ \tau_{wall} + 1/\ \tau_{\beta}$

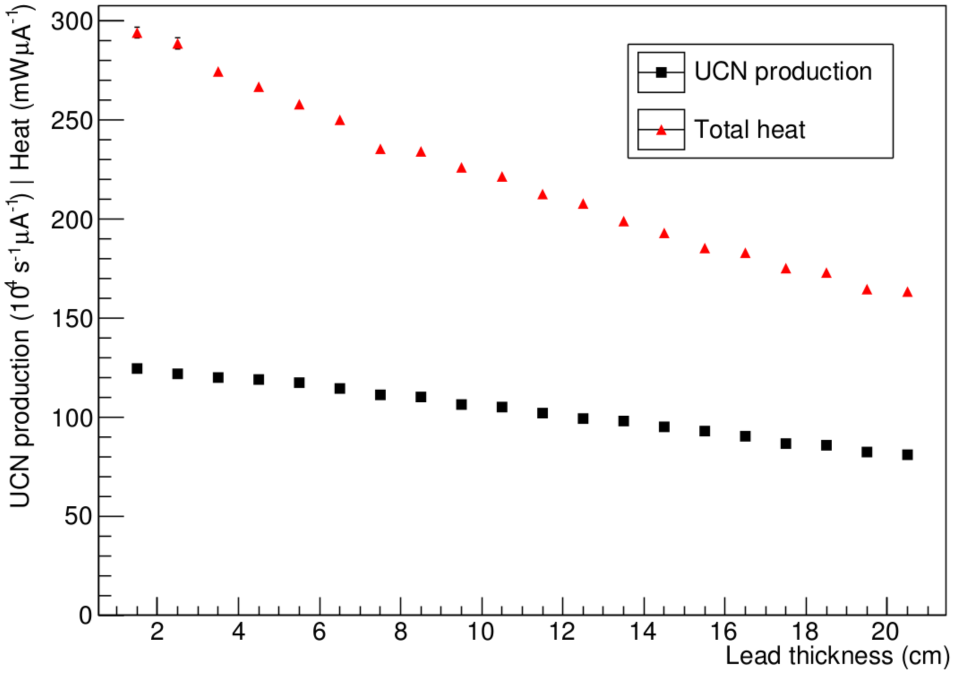


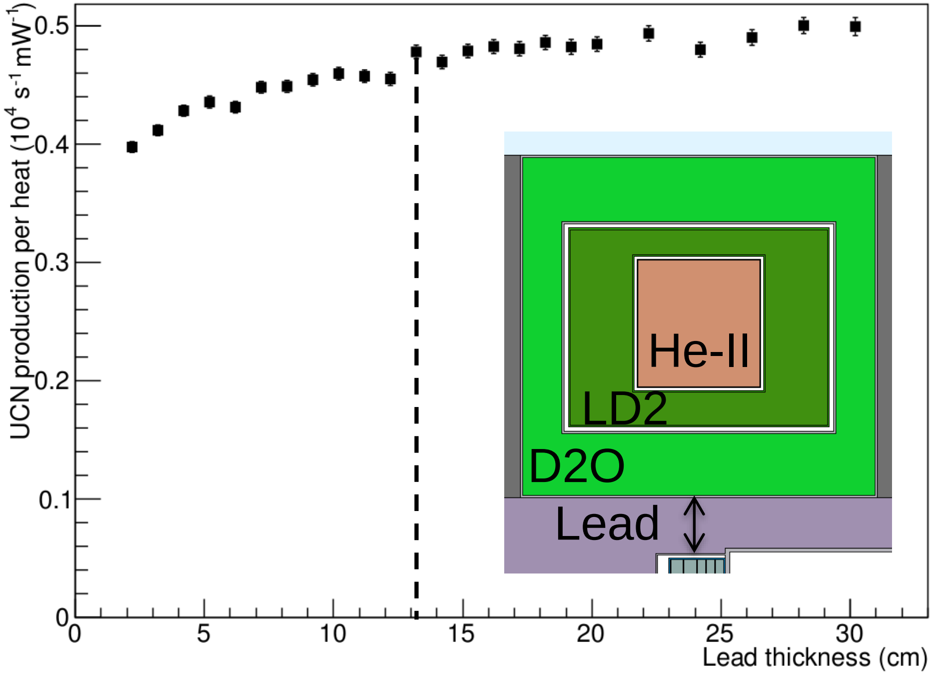
Optimization with MCNP

- Individually optimize
  - Thicknesses of moderators
  - Size of He-II bottle
  - Target position
- Iterate several times
- Manage configurations with git
- Ca. 15min runtime for each configuration on ComputeCanada cluster (100,000 p)



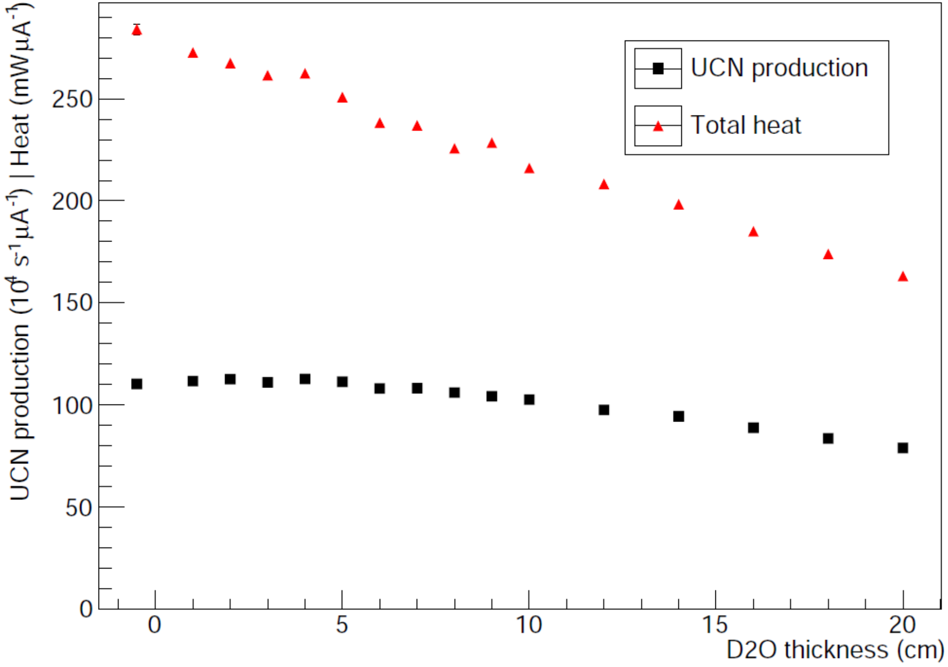
Lead layer above target

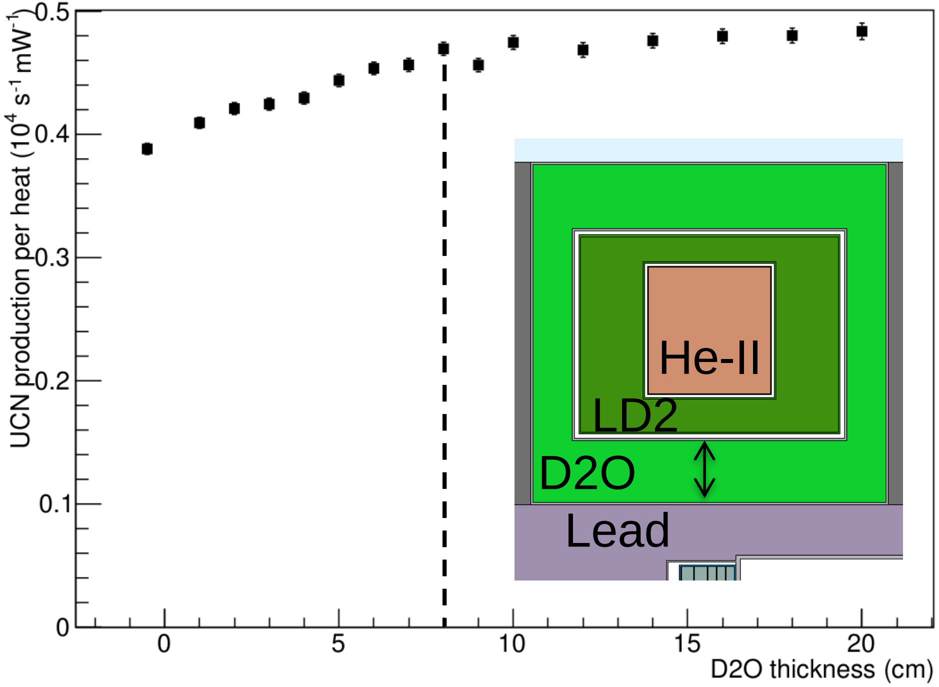




Optimization with MCNP

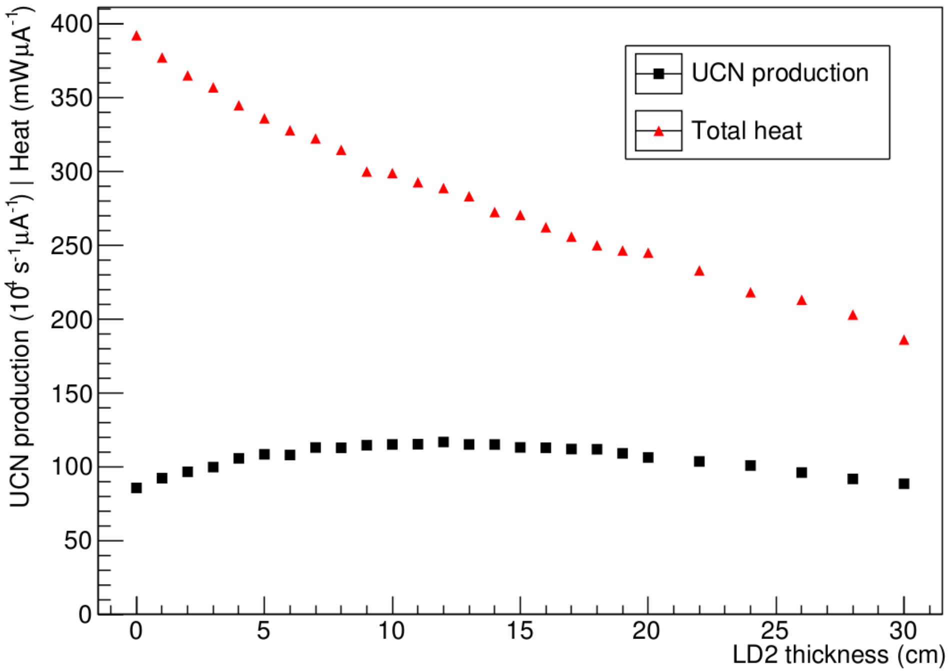
D_2O layer above target

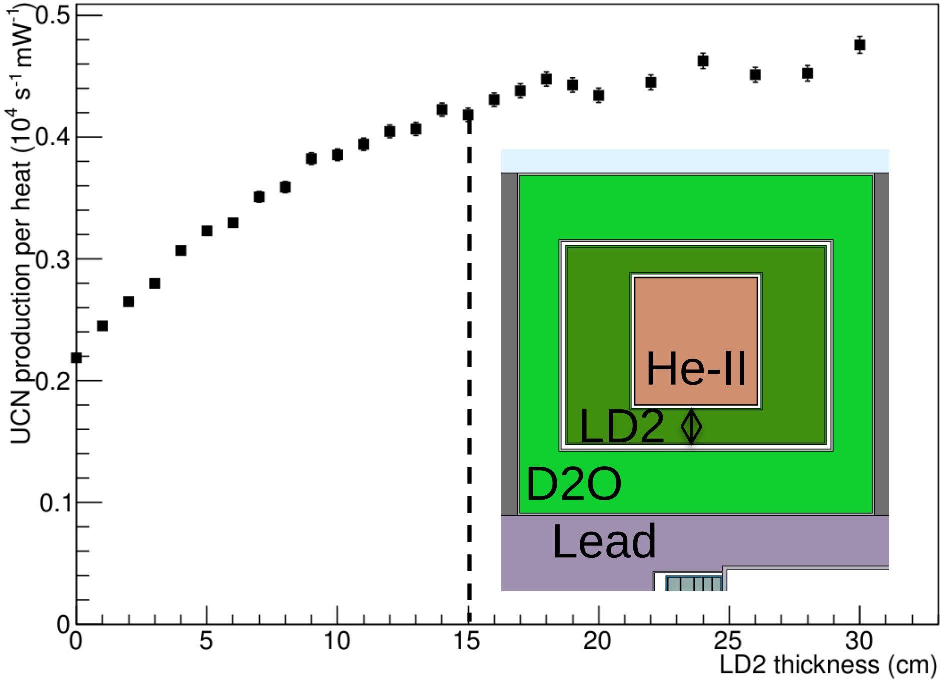




Optimization with MCNP

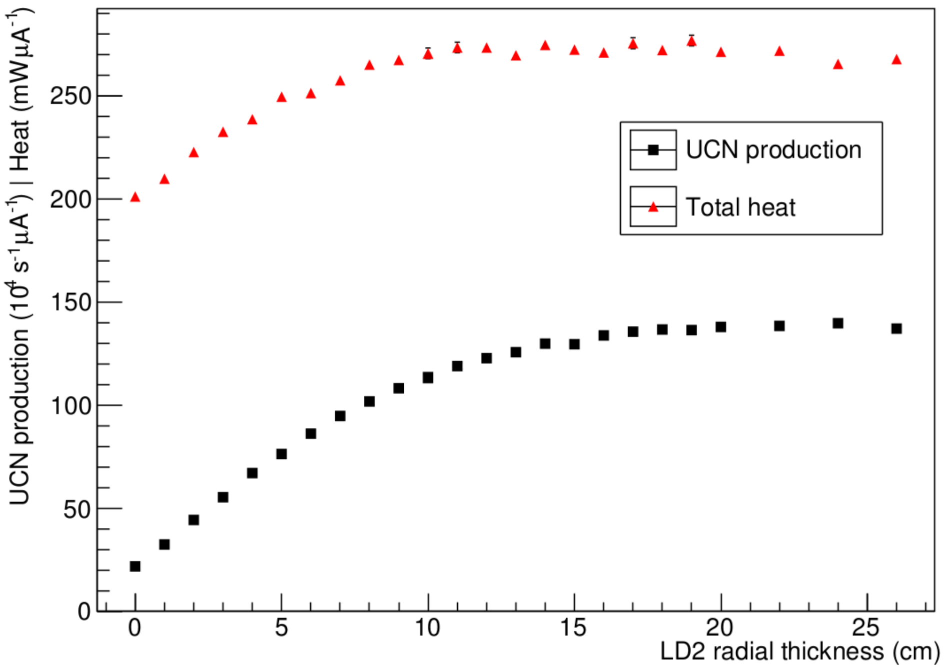
LD_2 layer above target

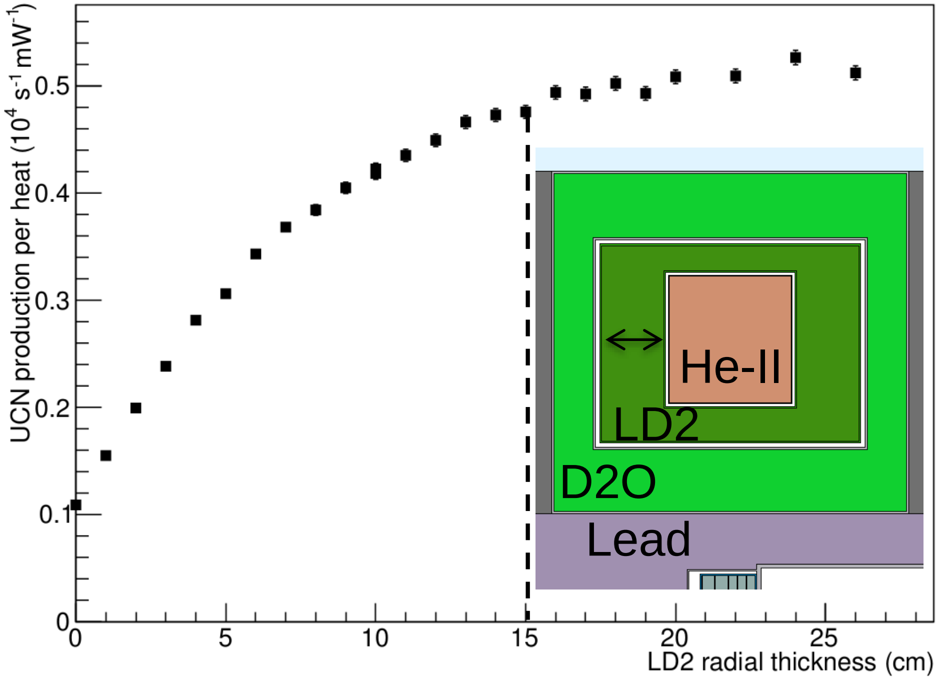




Optimization with MCNP

Radial LD_2 layer





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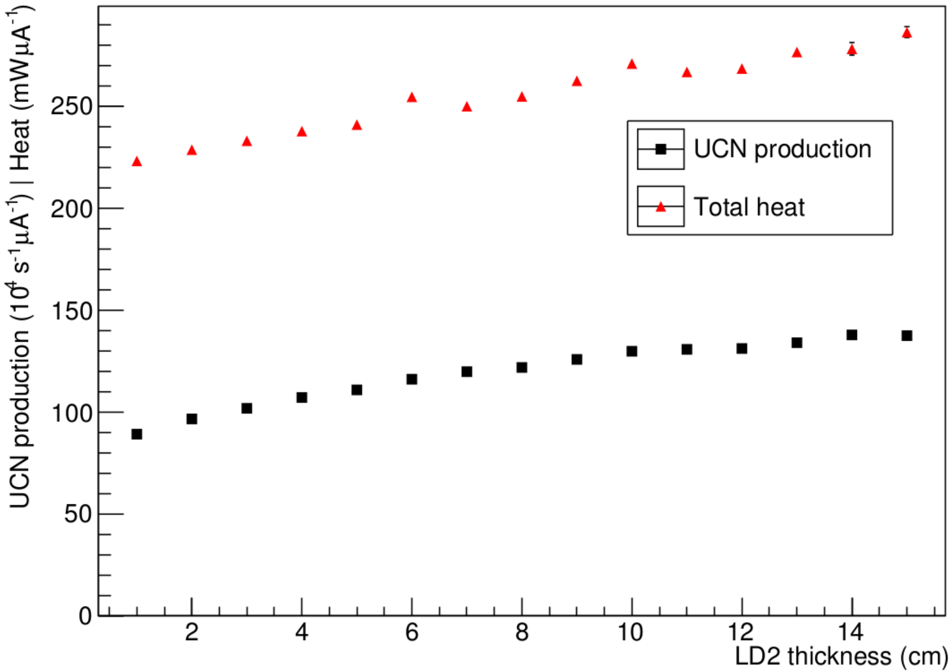
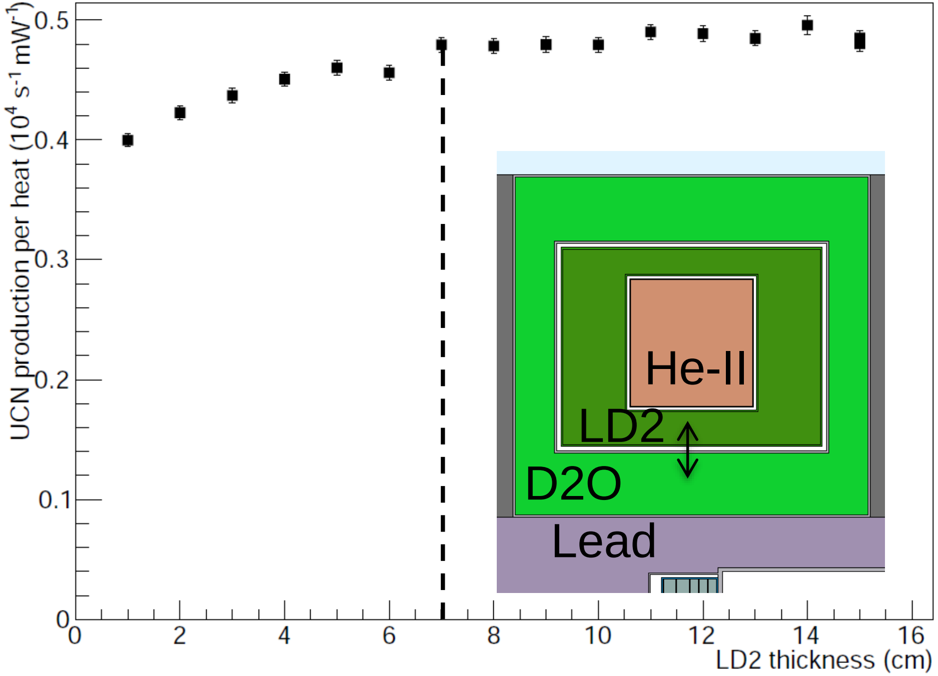
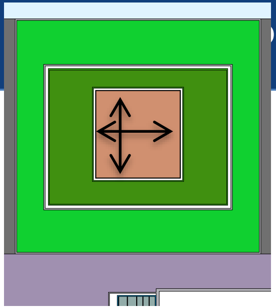
Optimization with MCNP

Trade-off between D_2O and LD_2 layer above target

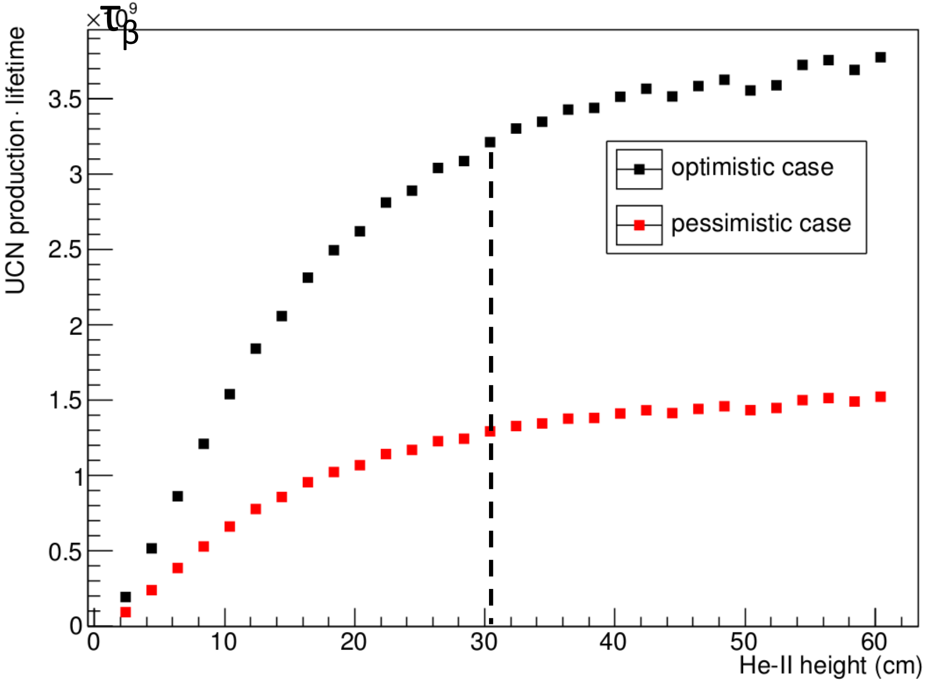


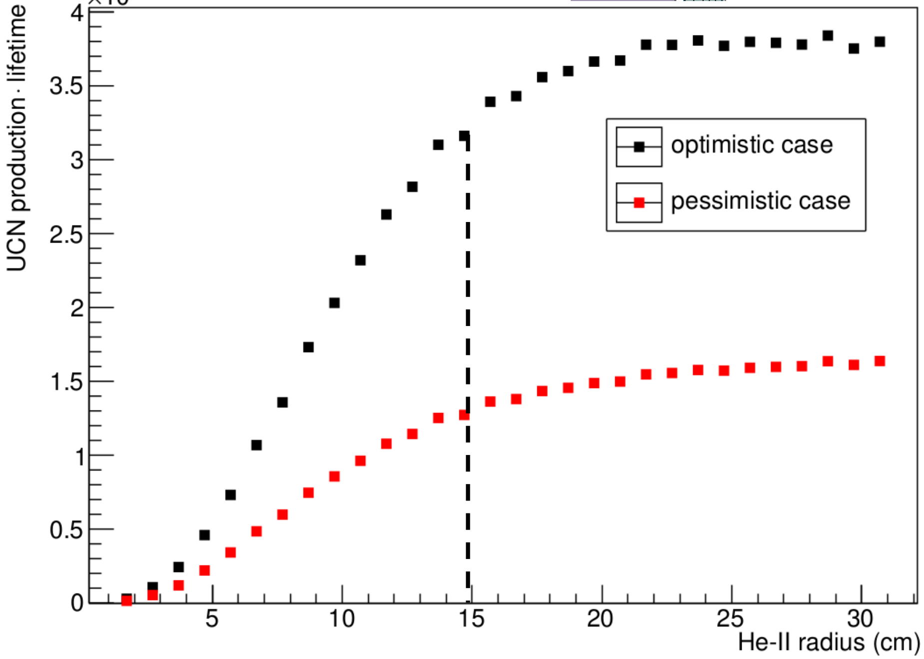


Optimization



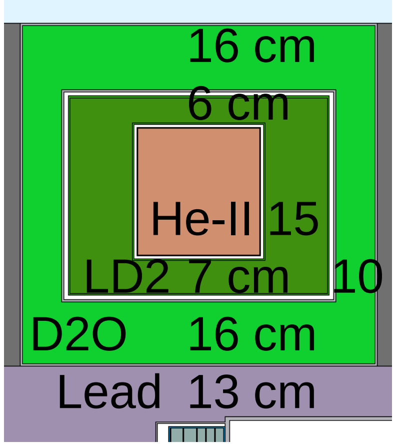
Height and radius of He-II bottle using improved model: P·τ with $1/\tau = 1/\tau_{up}(Q) + 1/\ \tau_{wall} + 1/\tau_{\beta}$

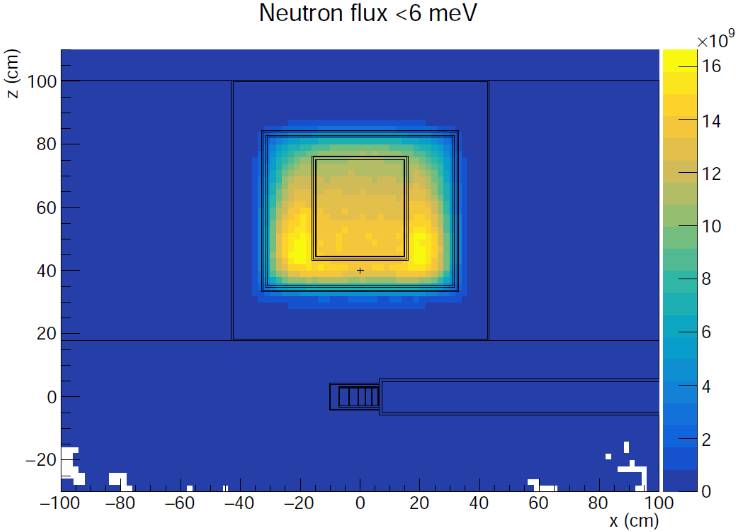




Preliminary results

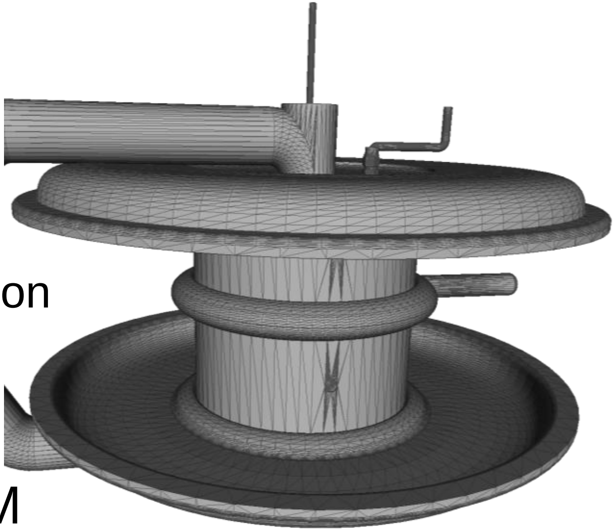
- Radial LD$_2$ layer more important than lower
- Best He-II-bottle height 30-40 cm, radius 15-20 cm (for current cooling scheme)
- Limited by amount of LD$_2$!
- For He-II height 30 cm, radius 15 cm, 40 μA beam:
  - 20.6 l He-II, 115 l LD$_2$
  - $3.9 \cdot 10^7$ UCN/s
  - 7.9 W max. heat in He-II
  - 65 W max. heat in LD$_2$
- Best strategy to reduce LD$_2$:
  reduce He-II size and go closer to target





PENTrack

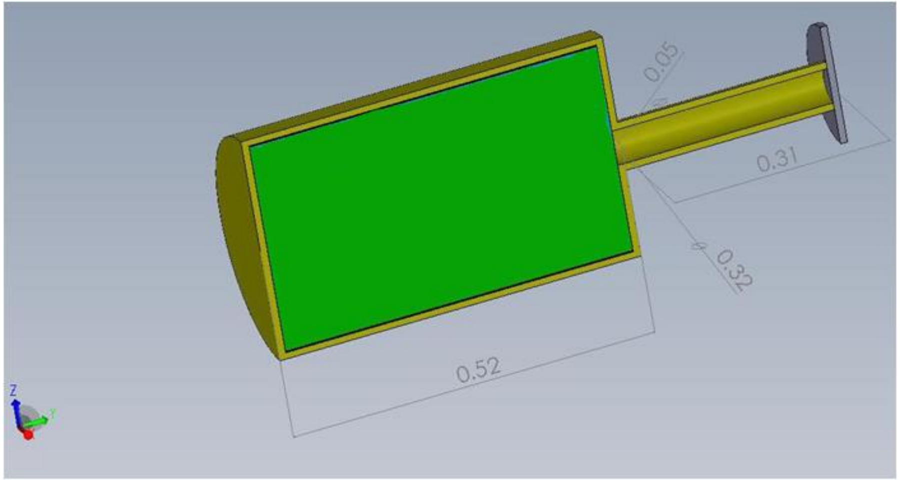
- Self-developed Monte Carlo **simulation for UCN** (+protons, electrons, comagnetometer atoms)
- Interactions:
  - Fermi-potential formalism, microroughness model
  - Magnetic moment in **strong magnetic fields**
  - **Precession of spins** in weak magnetic fields
  - **Fully relativistic** equations of motion, BMT equation
- **Geometry directly imported from CAD**, time-dependent (valves, etc.)
- Magnetic/electric field maps imported from FEM
- Open source: github.com/wschreyer/PENTrack.git
- Description: 10.1016/j.nima.2017.03.036

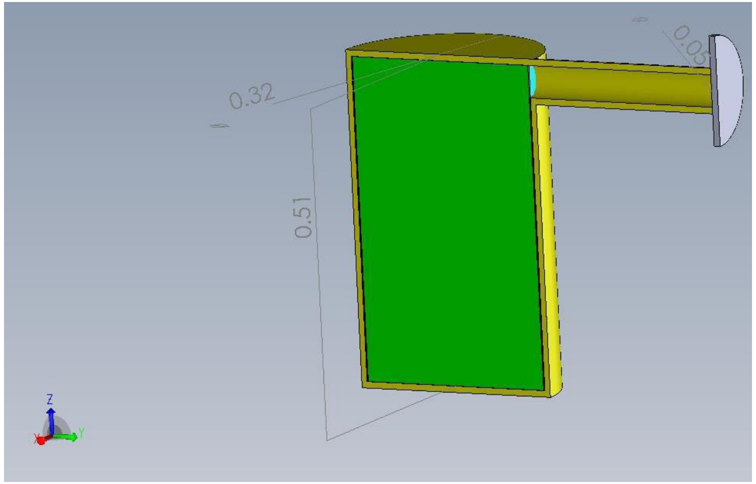


Optimization with PENTrack

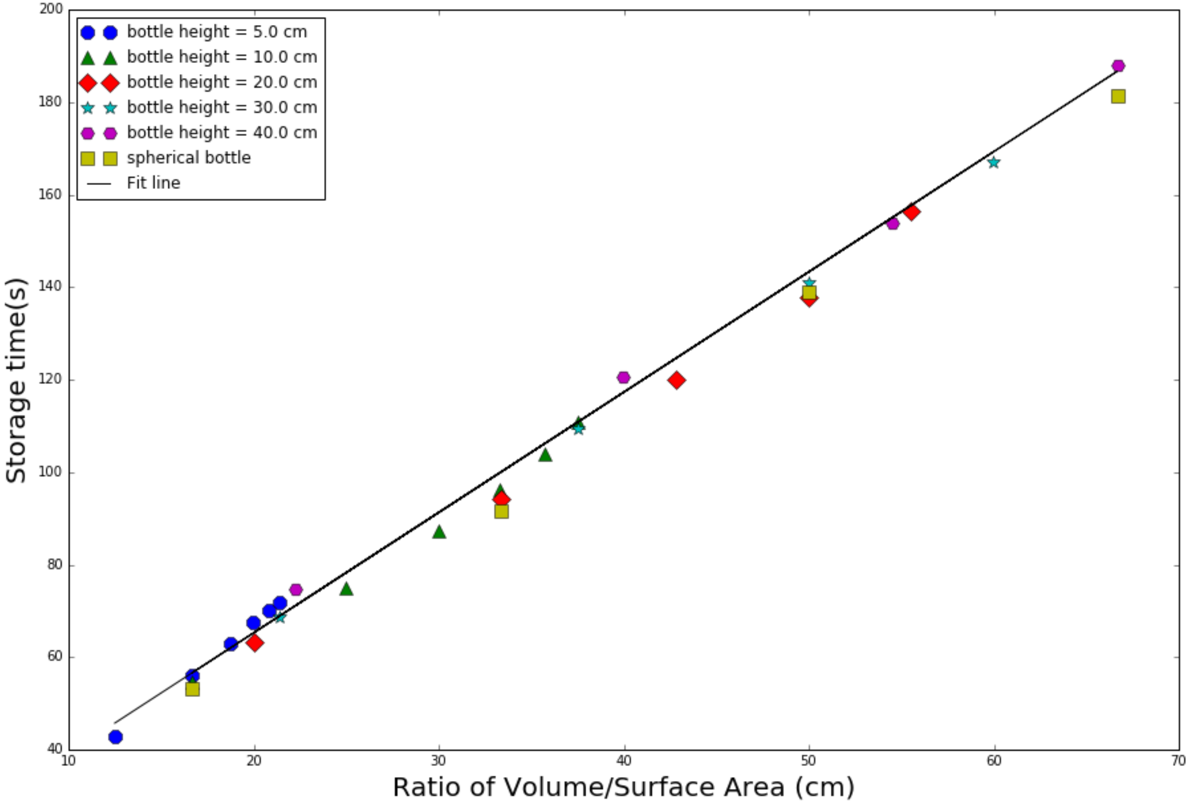
Steve Sidhu & Patricia Gnyp:

- Optimize geometry of UCN guides
- Compare storage and extraction time for different bottle shapes





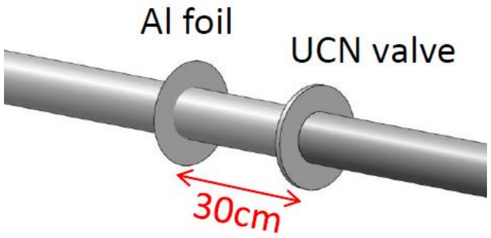
Optimization with PENTrack



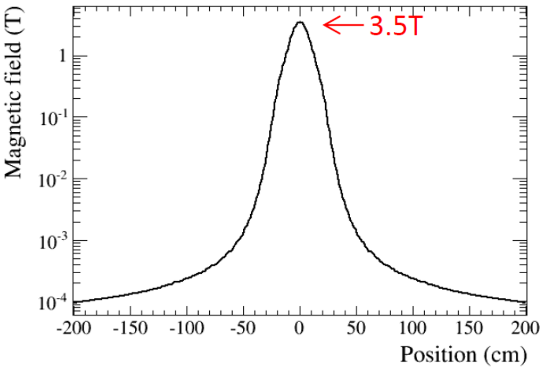
Optimization with PENTrack

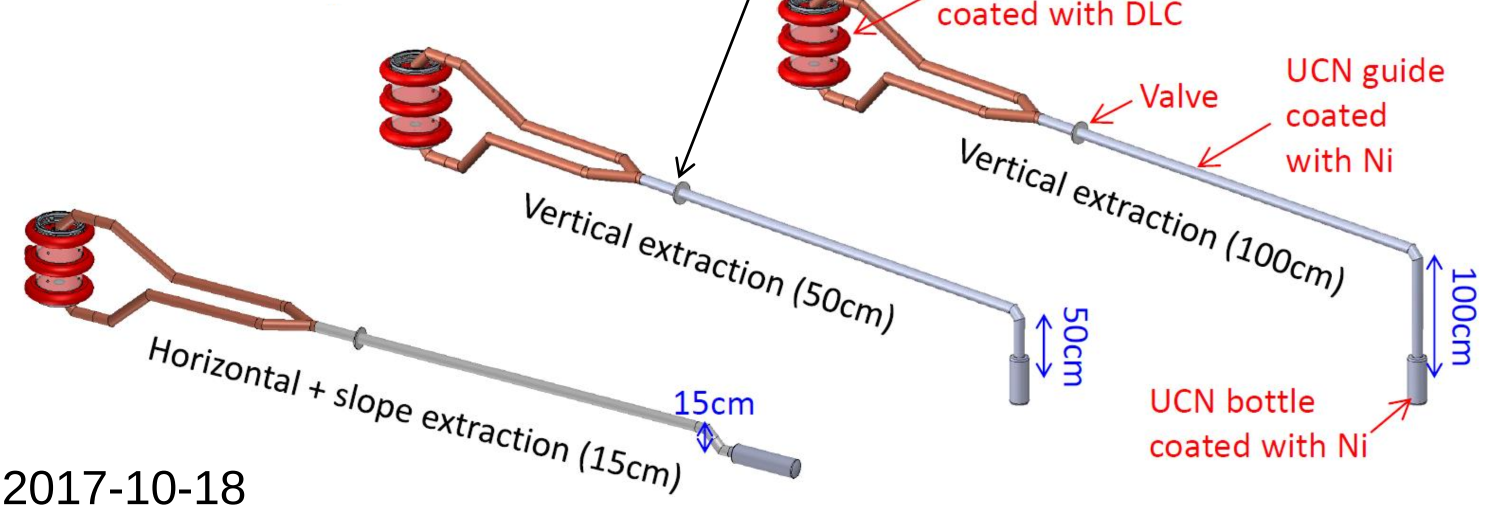
Tatsuya Kikawa:

- Optimize vertical extraction height
- Steady-state mode vs. batch mode



Magnetic field as a function of position from Al foil





Optimization with PENTrack

Tatsuya Kikawa:

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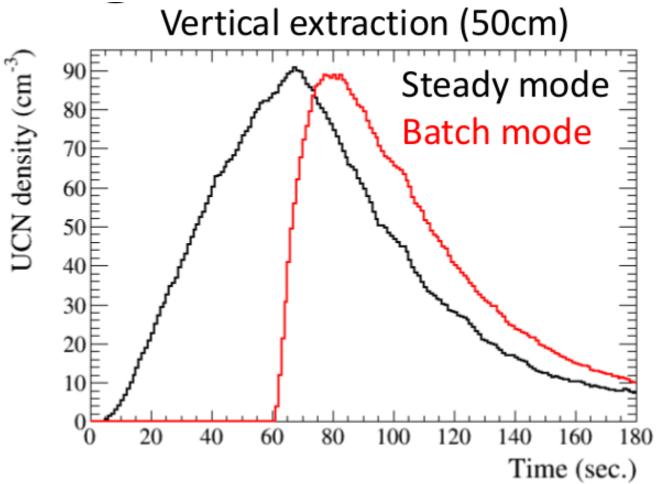
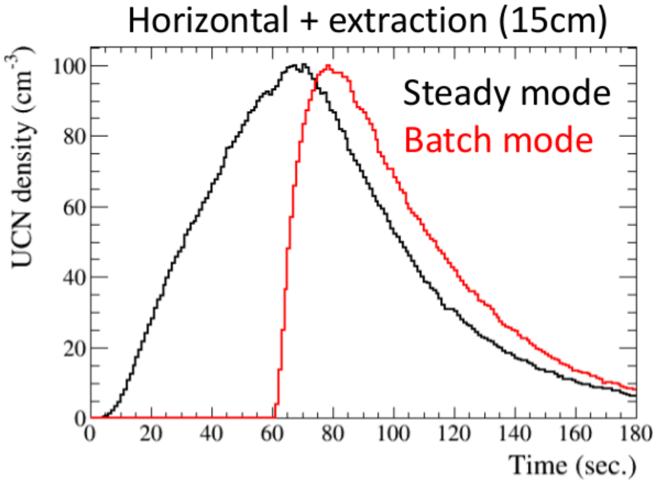
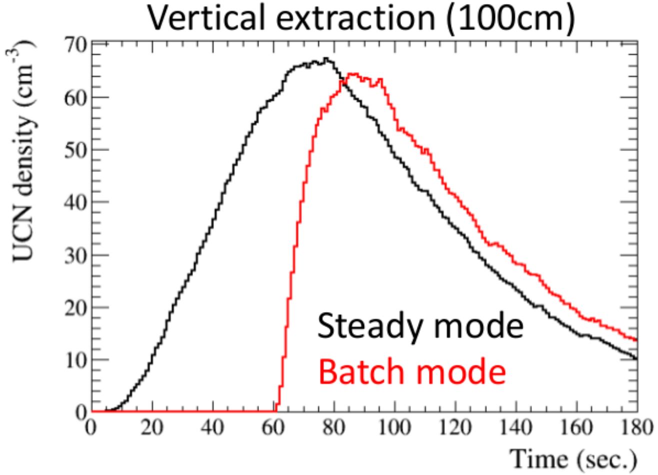
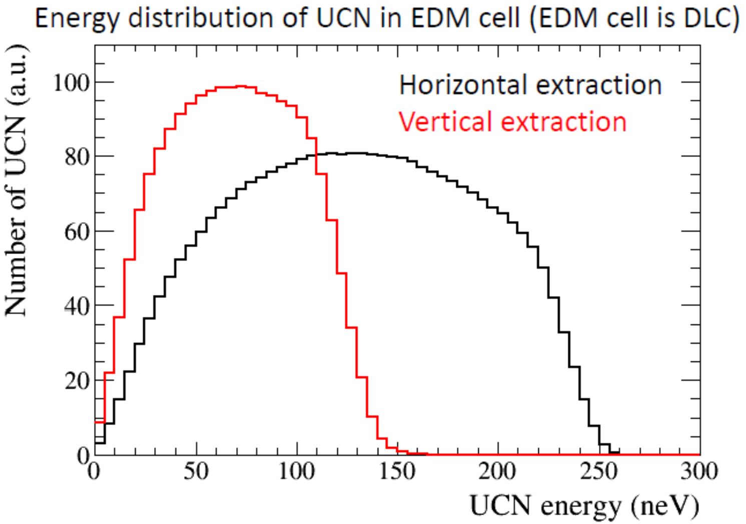

Vertical extraction (50cm)


Horizontal + extraction (15cm)


Vertical extraction (100cm)

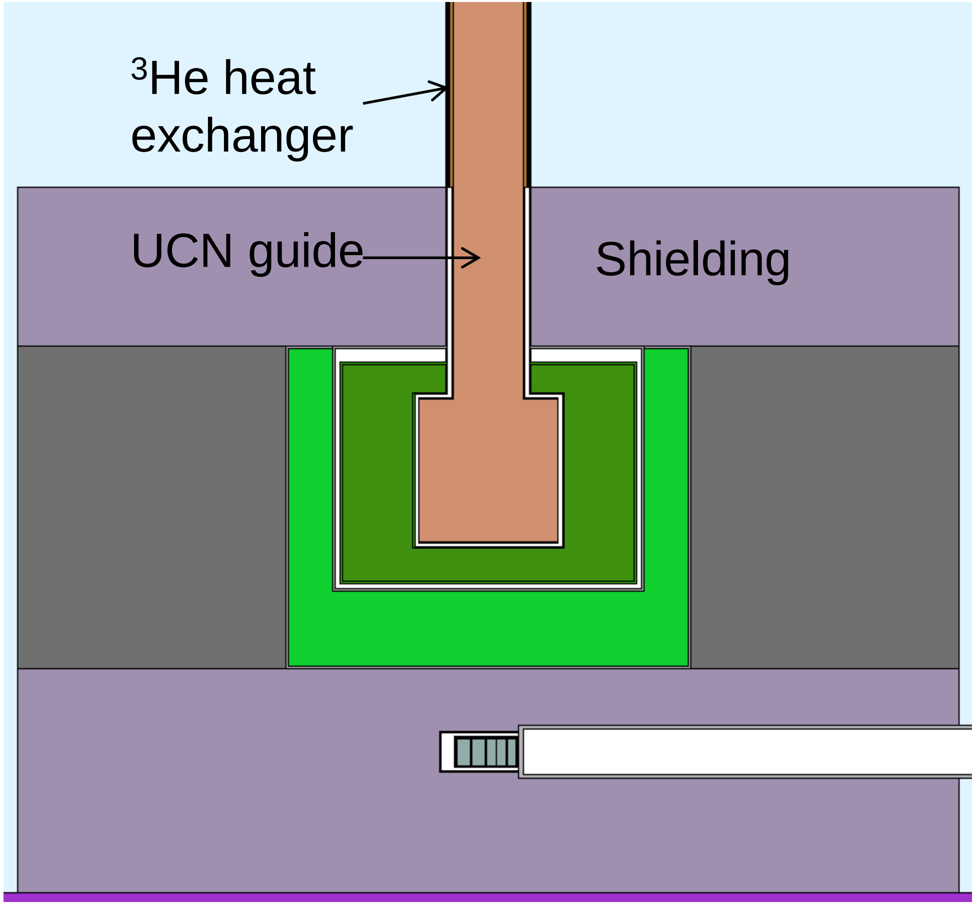
Preliminary results

- Vertical extraction of 50-100 cm seems best for nEDM experiment
- Work in progress, many unknown parameters
  - He-II temperature
  - Wall lifetime



Next steps

- More realistic source
  - UCN guides
  - Heat exchanger, ^{3}He
  - Cryostat
  - Shapes of pressure vessel
- Optimize shielding
  - Heat deposition in heat exchange
  - Activation of cryostat



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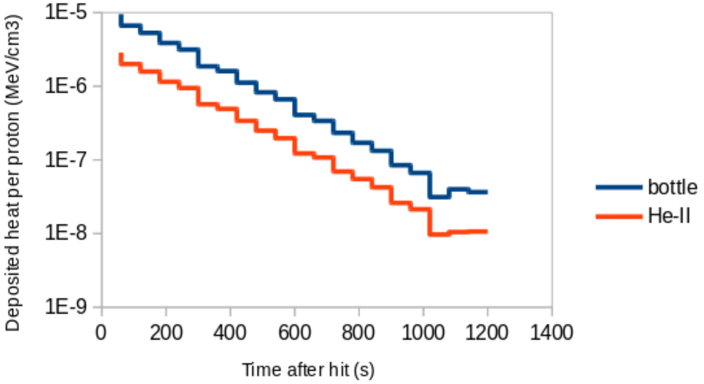
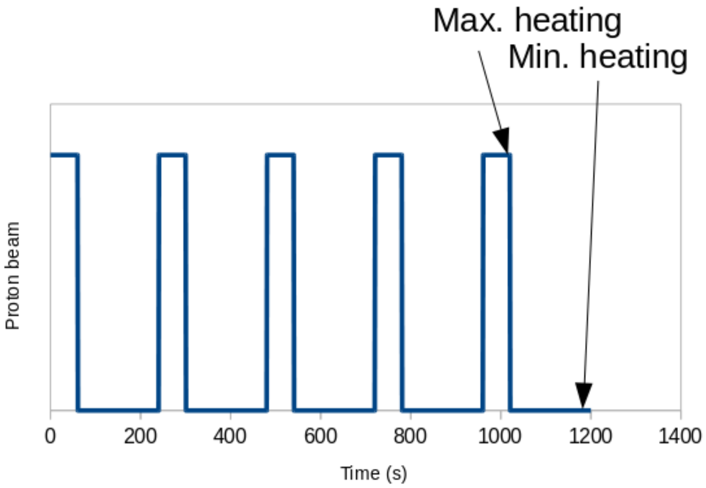
Delayed-heating model

- Decay constant ~200 s
- Assume 25% duty cycle
  1 min beam, 3 min no beam
- Use min./max. heat after 5 irradiations





Detailed storage-time model

- Detailed model: maximize P·τ with
  $1/\tau = 1/\tau_{up}(Q) + 1/\tau_{wall} + 1/\tau_{\beta}$
- $\tau_{up}(Q) \sim Q^{-1.2}$ to $Q^{-1.4}$

$$\tau_{wall} = \frac{4V}{A\langle v\bar{\mu}\rangle}$$

$$\langle v\bar{\mu}\rangle = \int_0^U v(E)\bar{\mu}(E)N(E)dE = \frac{3\sqrt{2}\pi W}{8\sqrt{mU}}$$

$$\bar{\mu}(E) = 2\frac{W}{U}\left(\frac{U}{E}\sin^{-1}\sqrt{\frac{E}{U}} - \sqrt{\frac{U}{E} - 1}\right)$$

$$N(E) = \frac{\sqrt{E}}{\int_0^U \sqrt{E}dE}$$