

A Polarized ${}^{6,7}\text{Li}$ Ion Source for the EIC

Wolfgang Korsch

(University of Kentucky)

Chao Peng, Zein-Eddine Meziani

(Argonne National Lab)

EPIOS Collaboration Meeting

March 18, 2026



Physics Motivation (short)

${}^6\text{Li}$ physics at the EIC: Quark-Gluon Structure in Bond Deuterons

Triple differential cross section using a polarized electron beam and a polarized nuclear spin-1 target:

$$\frac{d^3\sigma(\lambda_e)}{dx dQ^2 d\phi} = \frac{4\pi\alpha^2}{xQ^4} \left\{ \begin{array}{l} \text{unpolarized beam, unpolarized target} \\ xy^2 F_1(x, Q^2) + \left(1 - y - \frac{\gamma^2 y^2}{4}\right) F_2(x, Q^2) \\ \text{unpolarized beam, tensor-polarized target} \\ - \frac{1}{6}(3 \cos^2 \theta - 1) \left[xy^2 b_1(x, Q^2) + \left(1 - y - \frac{\gamma^2 y^2}{4}\right) b_2(x, Q^2) \right] \\ \text{polarized beam, transversely vector-polarized target} \\ + \frac{1}{2}(1 - y) \sin^2 \theta \Delta(x, Q^2) \cos(2\phi) \end{array} \right\} + \lambda_e \frac{4\alpha^2}{Q^4} y \left\{ \begin{array}{l} \text{polarized beam, longitudinally vector-polarized target} \\ S_L \left[\left(1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4}\right) g_1(x, Q^2) - \frac{\gamma^2 y}{4} g_2(x, Q^2) \right] \\ \text{polarized beam, transversely vector-polarized target} \\ - S_T \cos \phi \gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left[\frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right] \end{array} \right\}$$

or in DIS with tensor-polarized targets:

$$\sigma = \sigma_0 + P_z \sigma_{vector} + P_{zz} \sigma_{tensor}$$

S. Kumano, Phys. Rev. D 82, 017501 (2010)

P. Hoodbhoy, R.L. Jaffe, Aneesh Manohar, Nucl. Phys. B312 (1989) 571-588

${}^6\text{Li}$ physics at the EIC: Quark-Gluon Structure in Bond Deuterons

Form asymmetries:

vector-polarized target: $A_z = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$

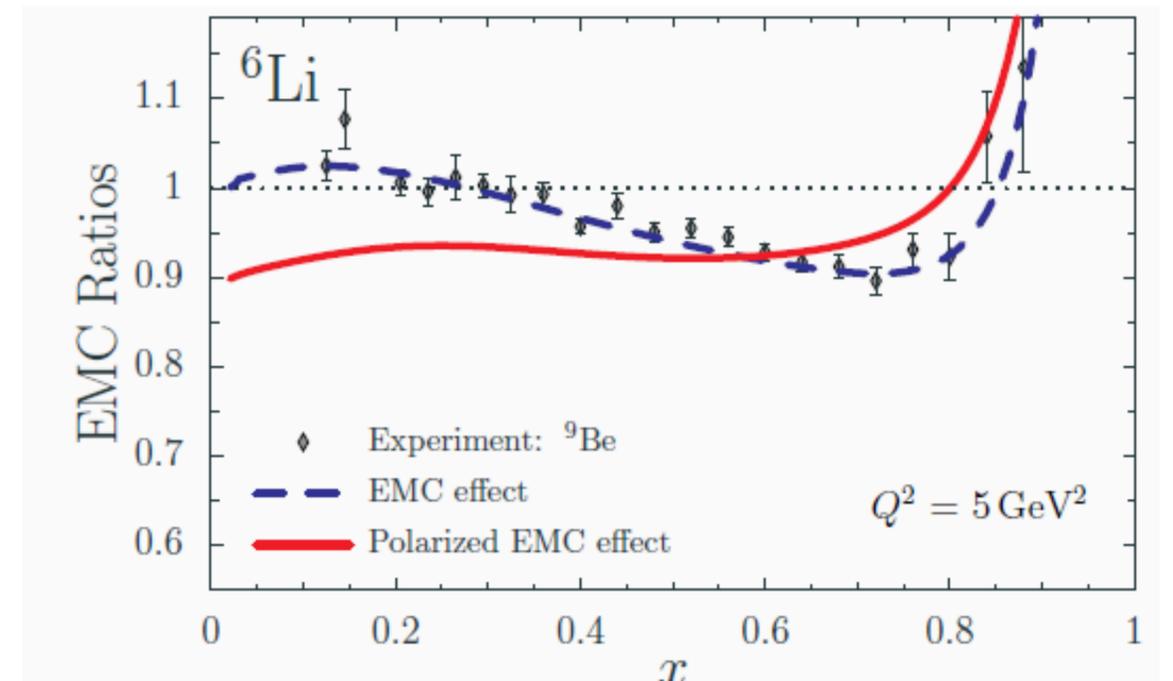
tensor-polarized target: $A_{zz} = \frac{\sigma_{+1} + \sigma_{-1} - 2\sigma_0}{\sigma_{+1} + \sigma_{-1} + 2\sigma_0}$

Structure function	helicity change	comment
F_1, F_2	0	
g_1, g_2	1	
b_1, b_2	tensor polarization	
Δ	2	$\cos(2\phi)$ modulation, double helicity flip

Polarized EMC effect:

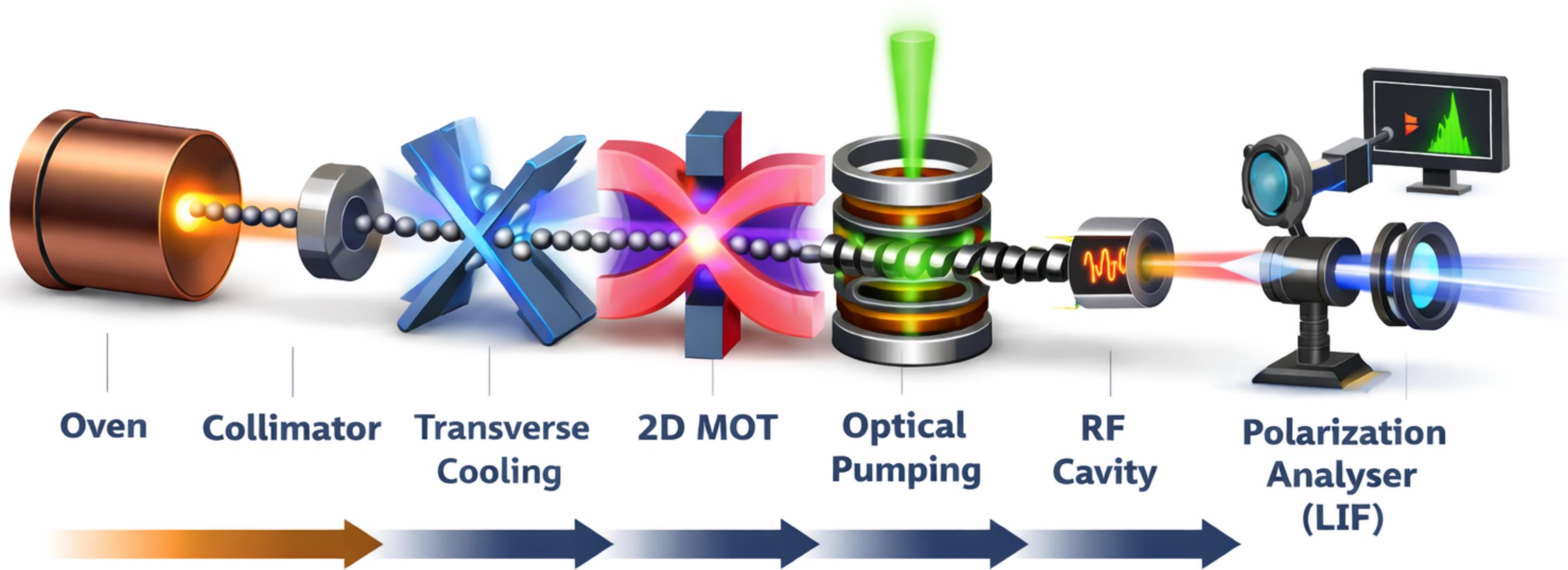
$$\Delta R(x) = \frac{g_{1A}(x)}{P_p g_{1p}(x) + P_n g_{1n}(x)}$$

I. C. Cloe, W. Bentz, A. W. Thomas Phys.Lett.B642:210-217,2006



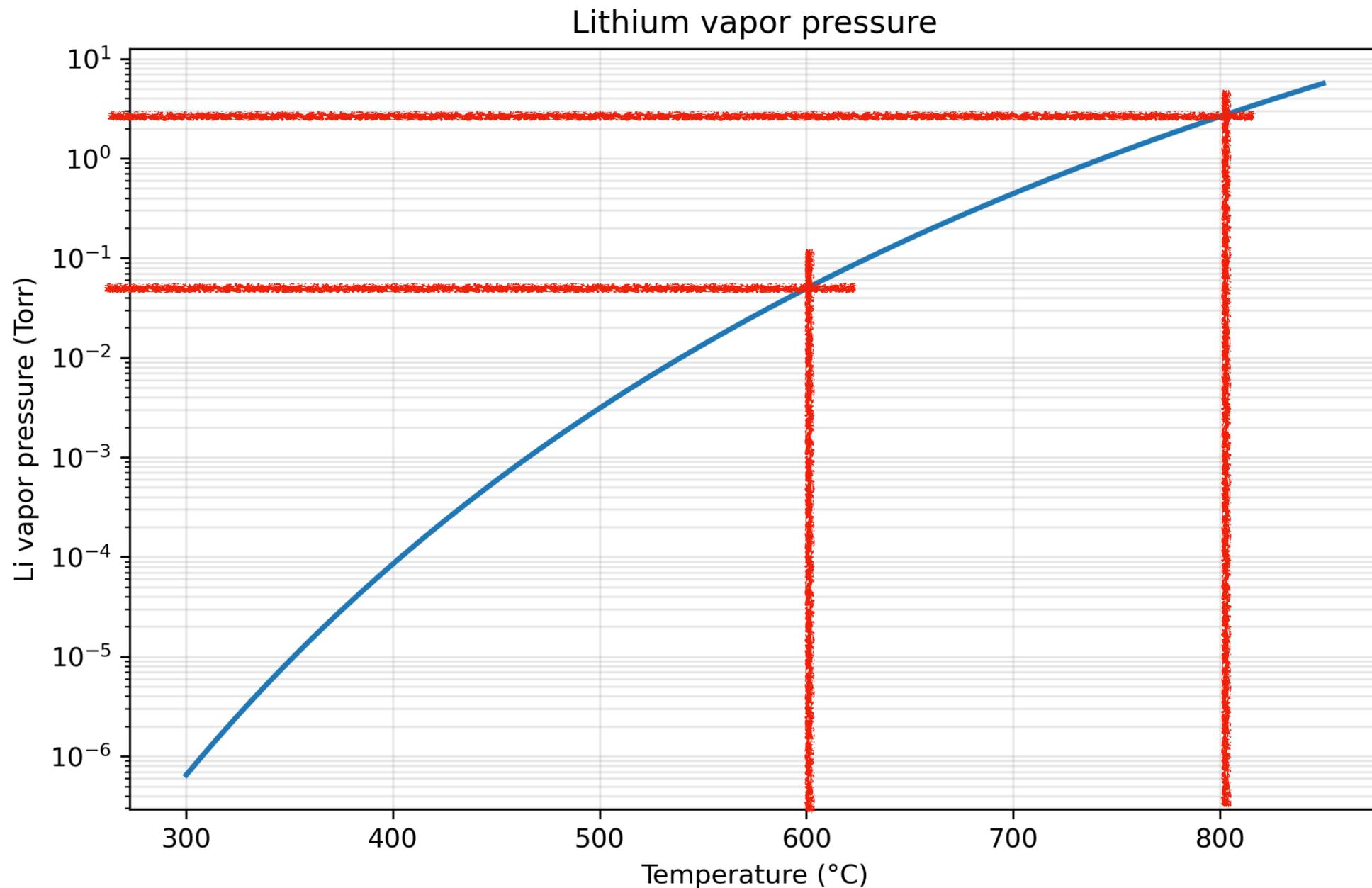
Conceptual Design of a Polarized $^{6,7}\text{Li}$ Atomic Beam Source

Artistic (ChatGPT) View of A Modern Polarized Li Source



Component Overview: Oven

Typical oven temperatures: ~600 °C → ~800 °C

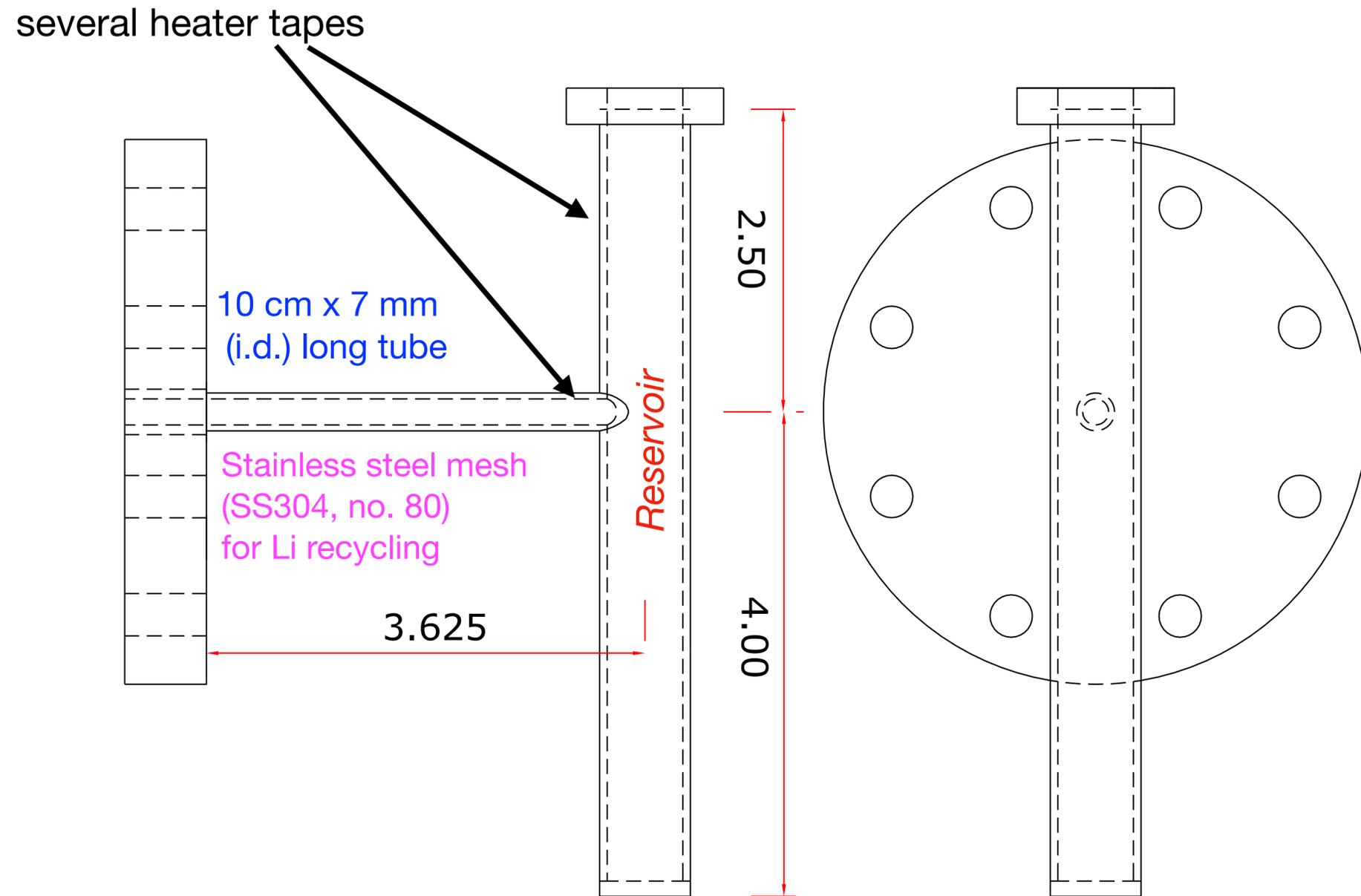


Oven pressure $\lesssim 10$ torr

- too low for efficient de Laval nozzle gas expansion?
- risk of clogging the nozzle if the smallest diameter of the single-channel pipe is ~2 mm?

Component Overview: Oven

Possible design: R.G. Hulet et al., Rev. Sci. Instrum. 91, 011101 (2020)



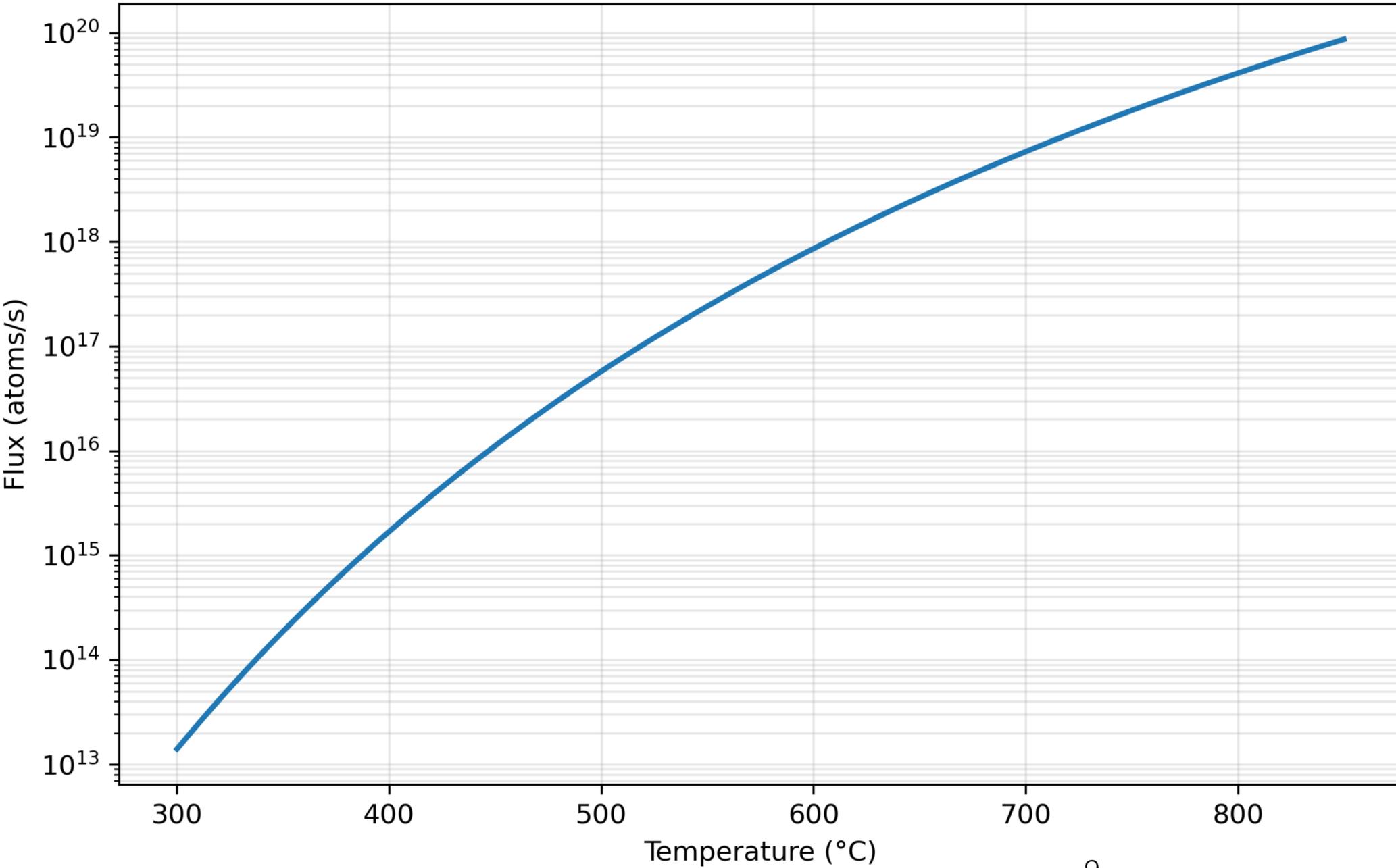
- UHV compatible
- Estimate run oven for 5 years with 10 g or lithium!!

Operating temperature: 500 °C

Component Overview: Oven

Possible alternative: R.G. Hulet et al., Rev. Sci. Instrum. 91, 011101 (2020)

Li oven flux through 10 cm x 7 mm exit tube



Without recycling mesh:

Temperature: 600 °C

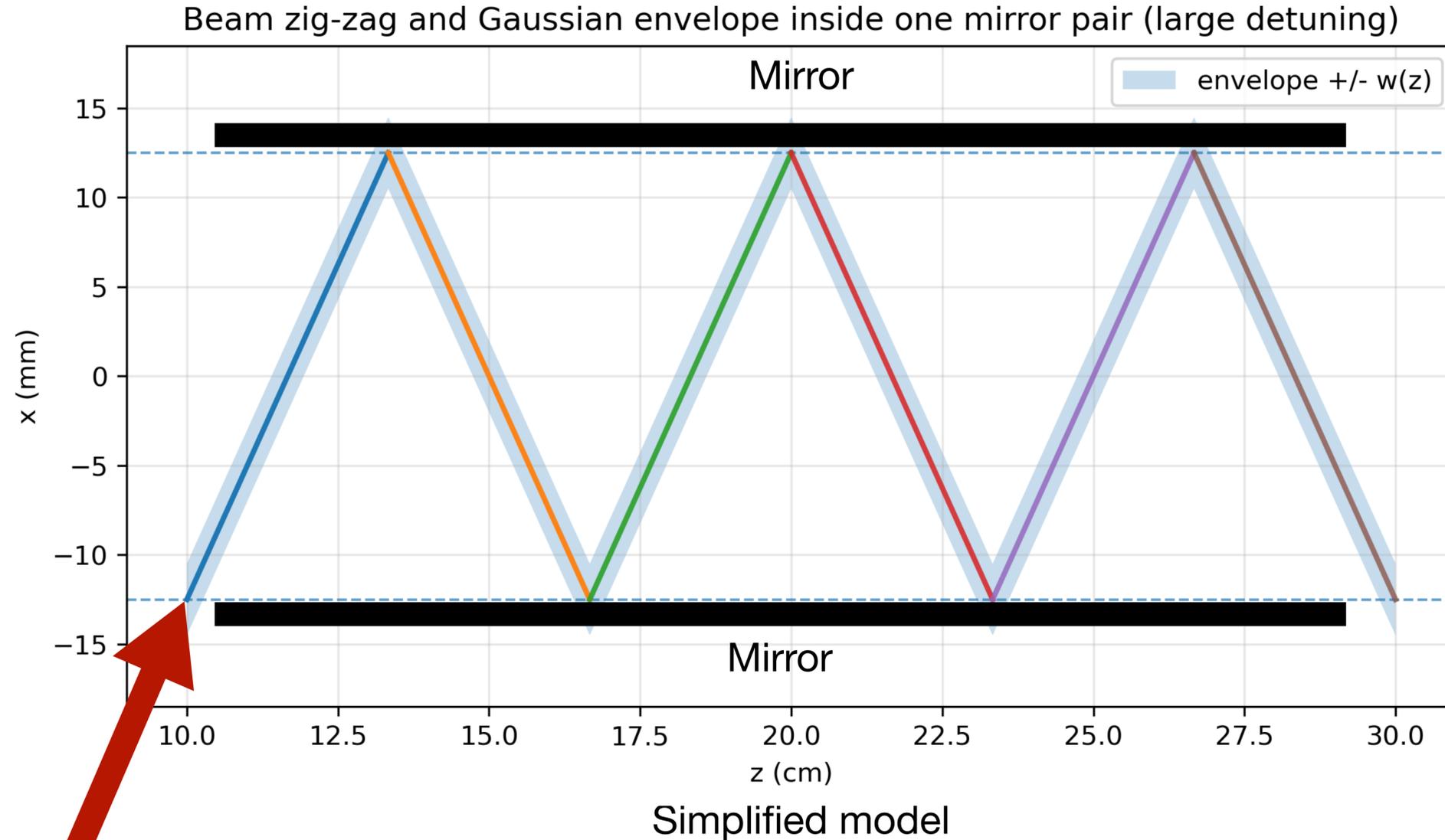
Flux : 8.61×10^{17} atoms/s

Molar rate : 1.43×10^{-6} mol/s

Lithium usage: 3.09×10^{-2} g/hour
 7.43×10^{-1} g/day

Seems reasonable

Beam Formation: Transverse Laser Cooling

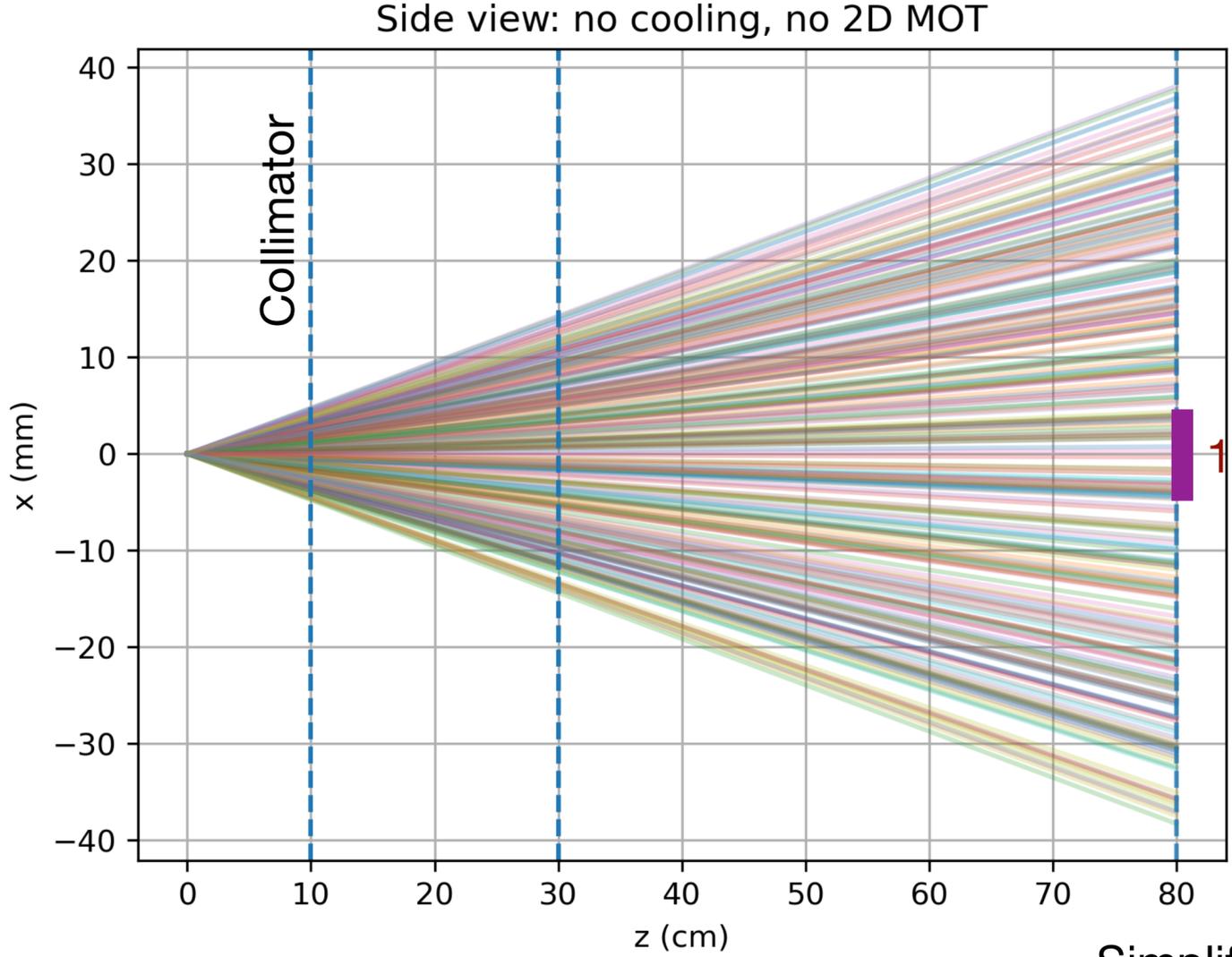


**Place mirrors at $x = \pm \sim 12$ mm
 $y = \pm \sim 12$ mm, $L \sim 20$ cm**

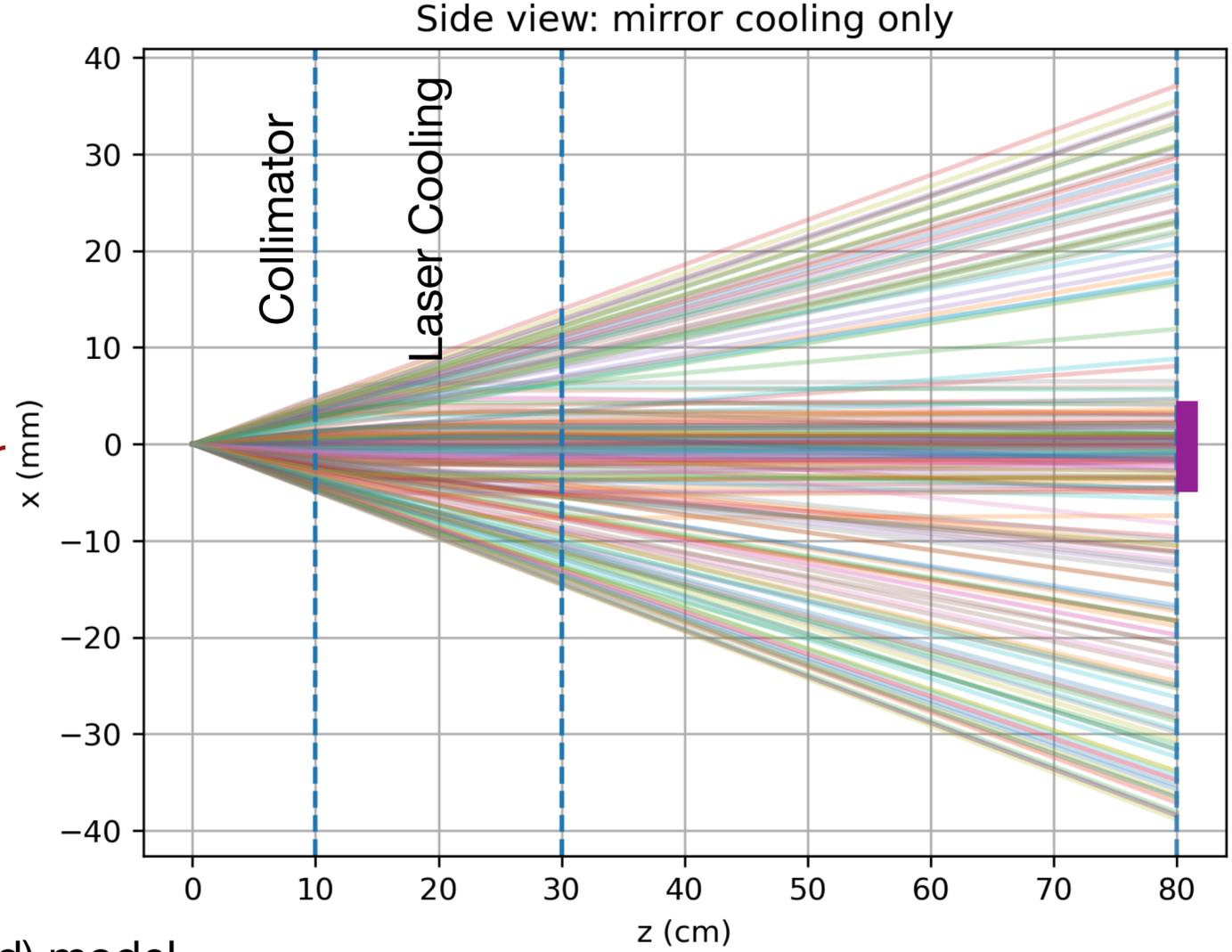
Caution: Carefully collimate the incoming beam and maintain sufficient mirror spacing to prevent lithium deposition on the mirrors.

Laser beam in (671 nm)

Beam Formation: Transverse Laser Cooling



Simplified (idealized) model

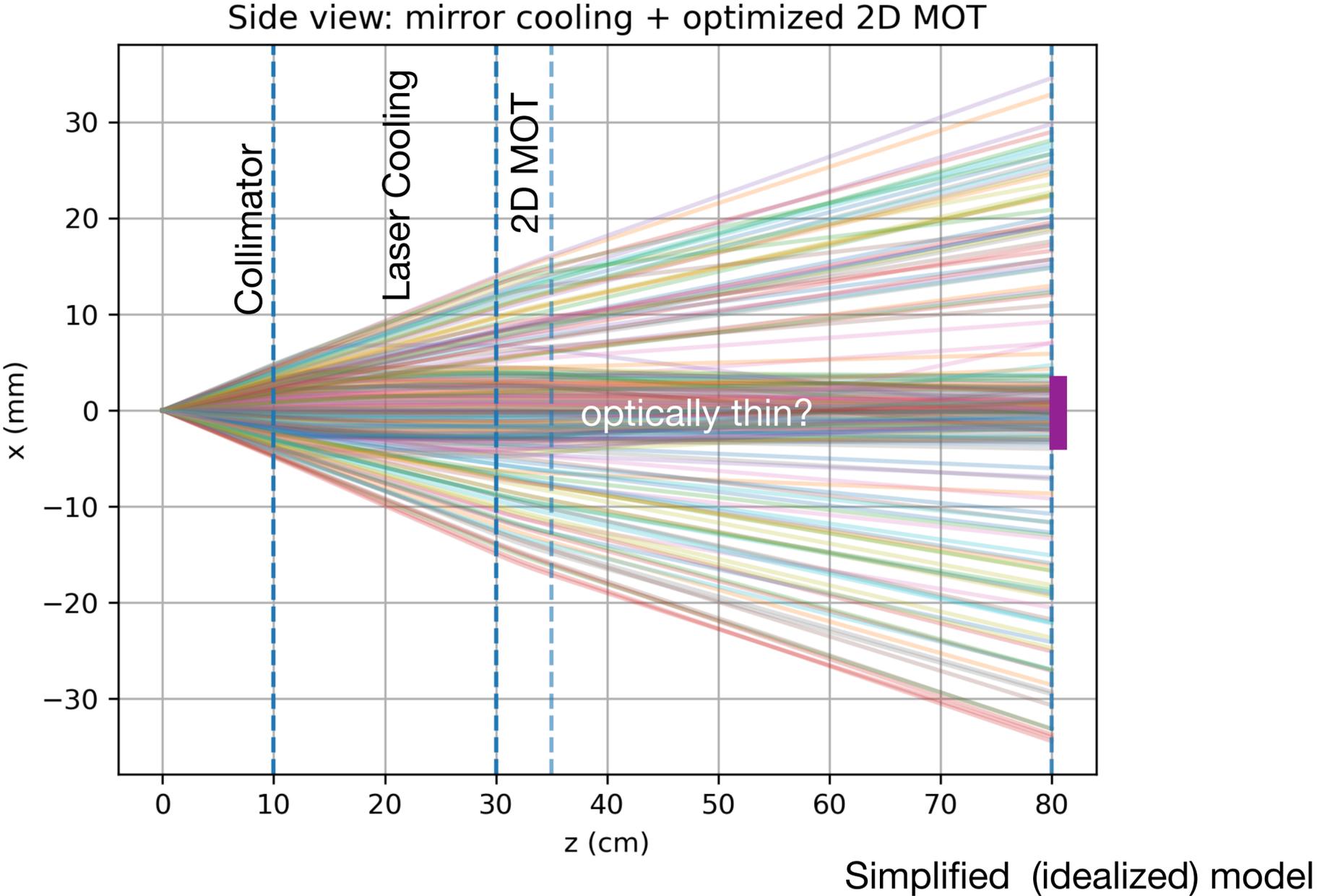


No cooling : 6.8×10^{11} atoms/s (in 1-cm circle)
 Transvers Cooling : 9.9×10^{12} atoms/s (gain: 14.545x)

Beam Formation: Transverse Laser Cooling

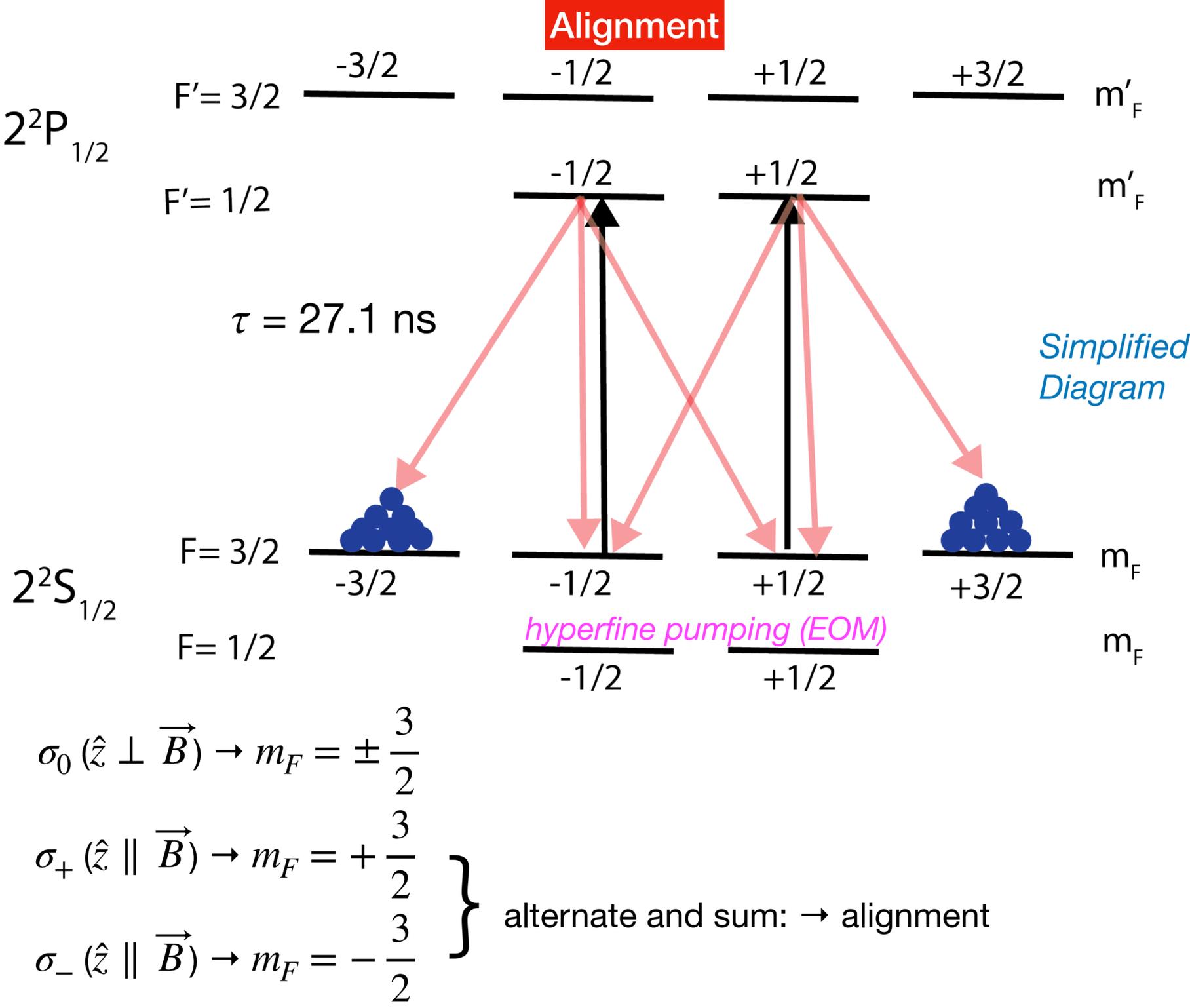
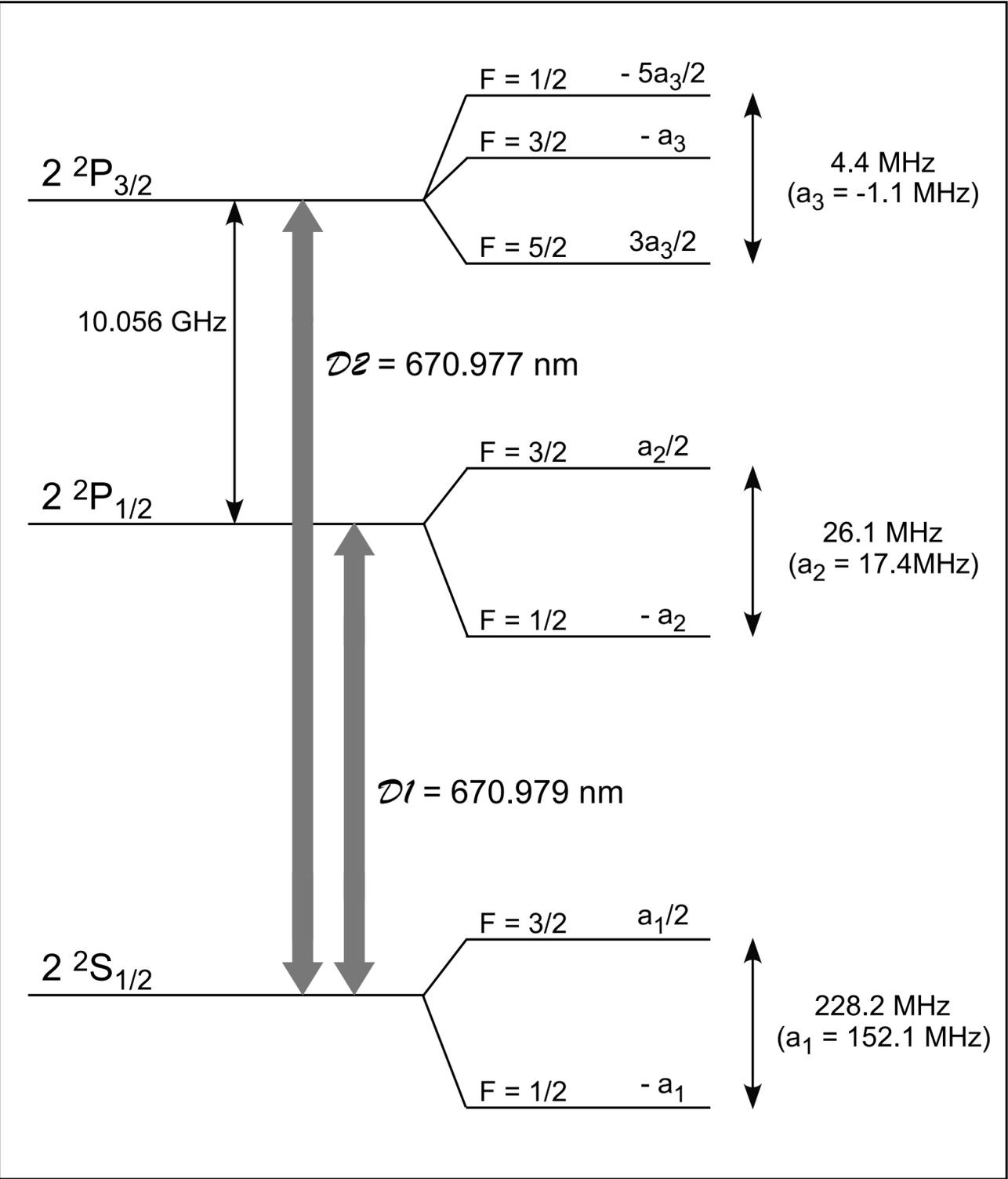
Collimator + Transverse Laser Cooling + 2D MOT

Note: A 2D MOT is a quadrupole B-field configuration but it is not a (strong) spin filter since $dB/dr \sim 10^3$ G/cm, not $\sim 10^4$ G/cm



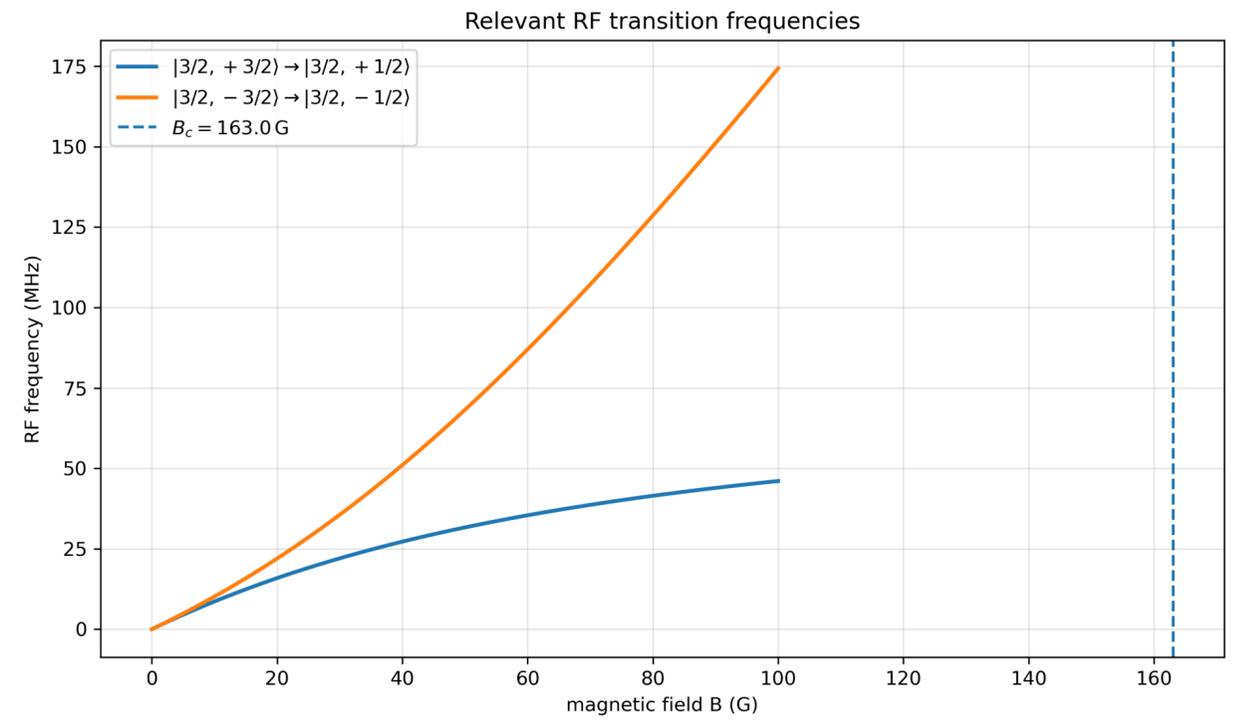
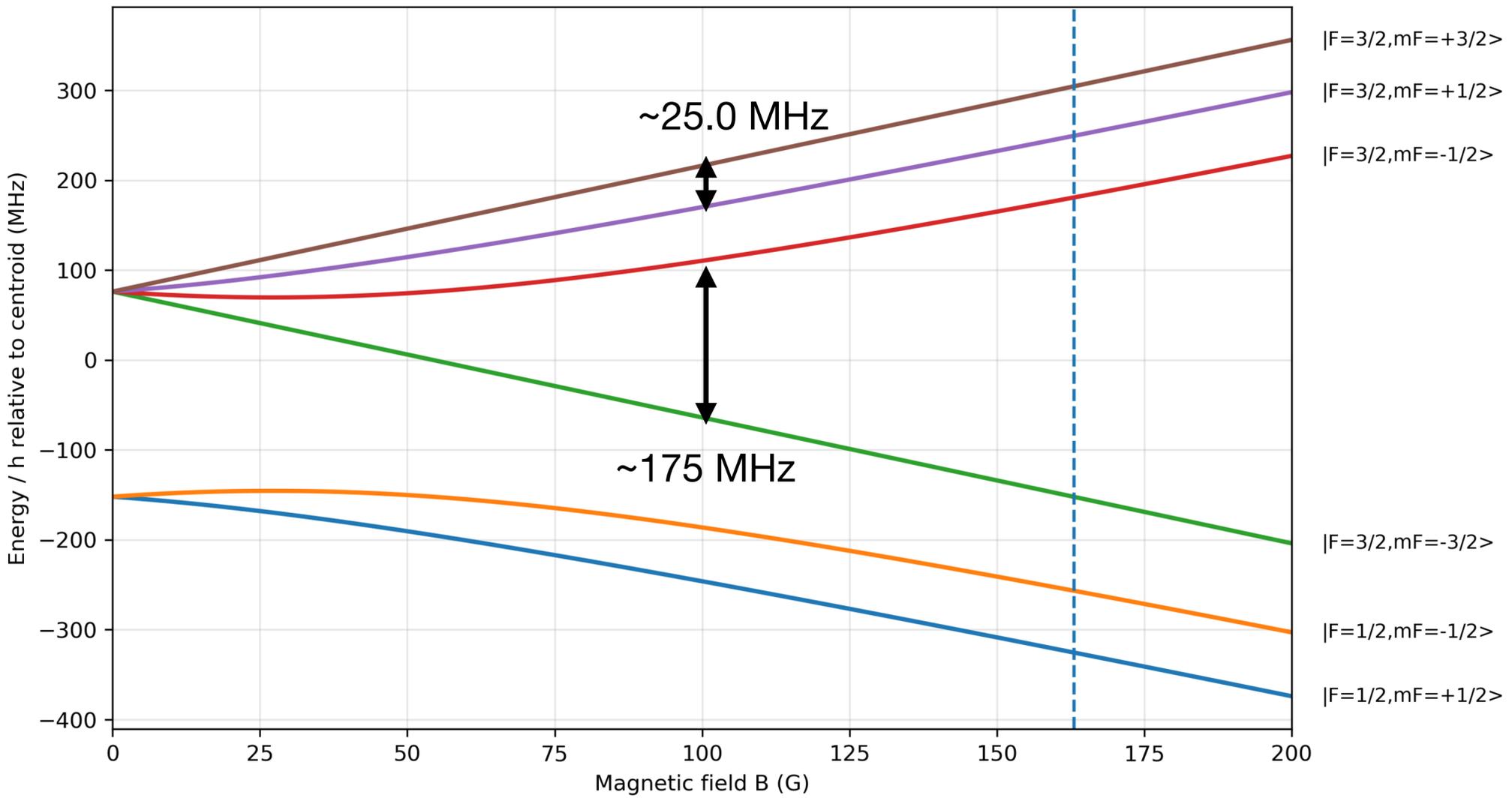
No cooling	: 6.8×10^{11} atoms/s (in 1-cm circle)
Transverse cooling	: 9.9×10^{12} atoms/s (gain: 14.545x)
Cooling + best 2D MOT flux:	1.35×10^{13} atoms/s (gain vs cooling: 1.366x, total gain: 19.862x)

Polarizing the Atoms: Optical Pumping



Polarizing the Atoms: RF transitions for ${}^6\text{Li}$

${}^6\text{Li}$ ground-state Breit-Rabi diagram

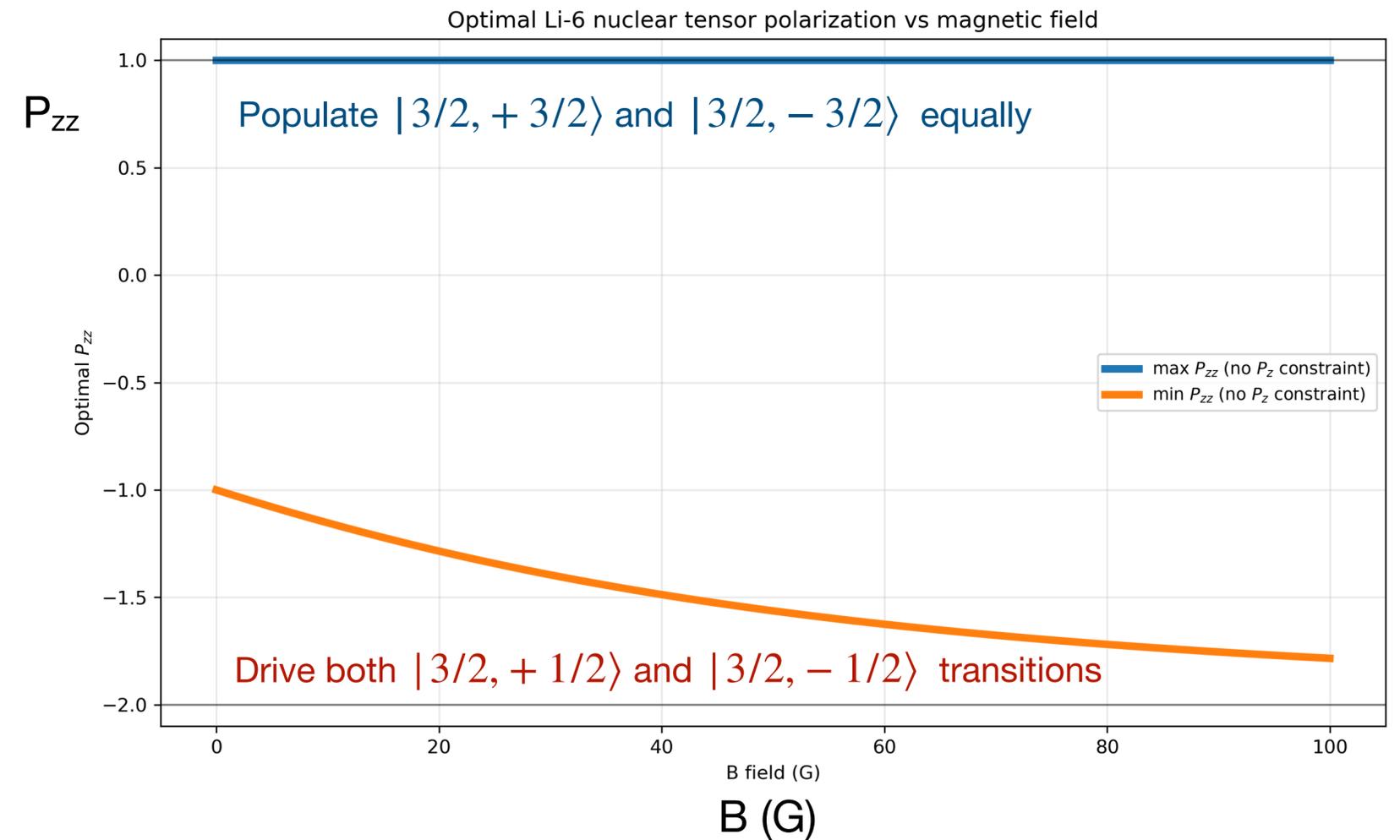


Polarizing the Atoms: RF transitions for ${}^6\text{Li}$

$$P_z = \frac{\langle I_z \rangle}{I} = \frac{N_{+1} - N_{-1}}{N} \quad N = \sum_m N_m$$

$$P_{zz} = \frac{3\langle I_z^2 \rangle - I(I+1)}{I(2I-1)} = \frac{N_{+1} + N_{-1} - 2N_0}{N}$$

State preparation	N_+	N_0	N_-	P_z	P_{zz}
$m_I = +1$	1	0	0	1	1
$m_I = -1$	0	0	1	-1	1
$m_I = 0$	0	1	0	0	-2



Preliminary!

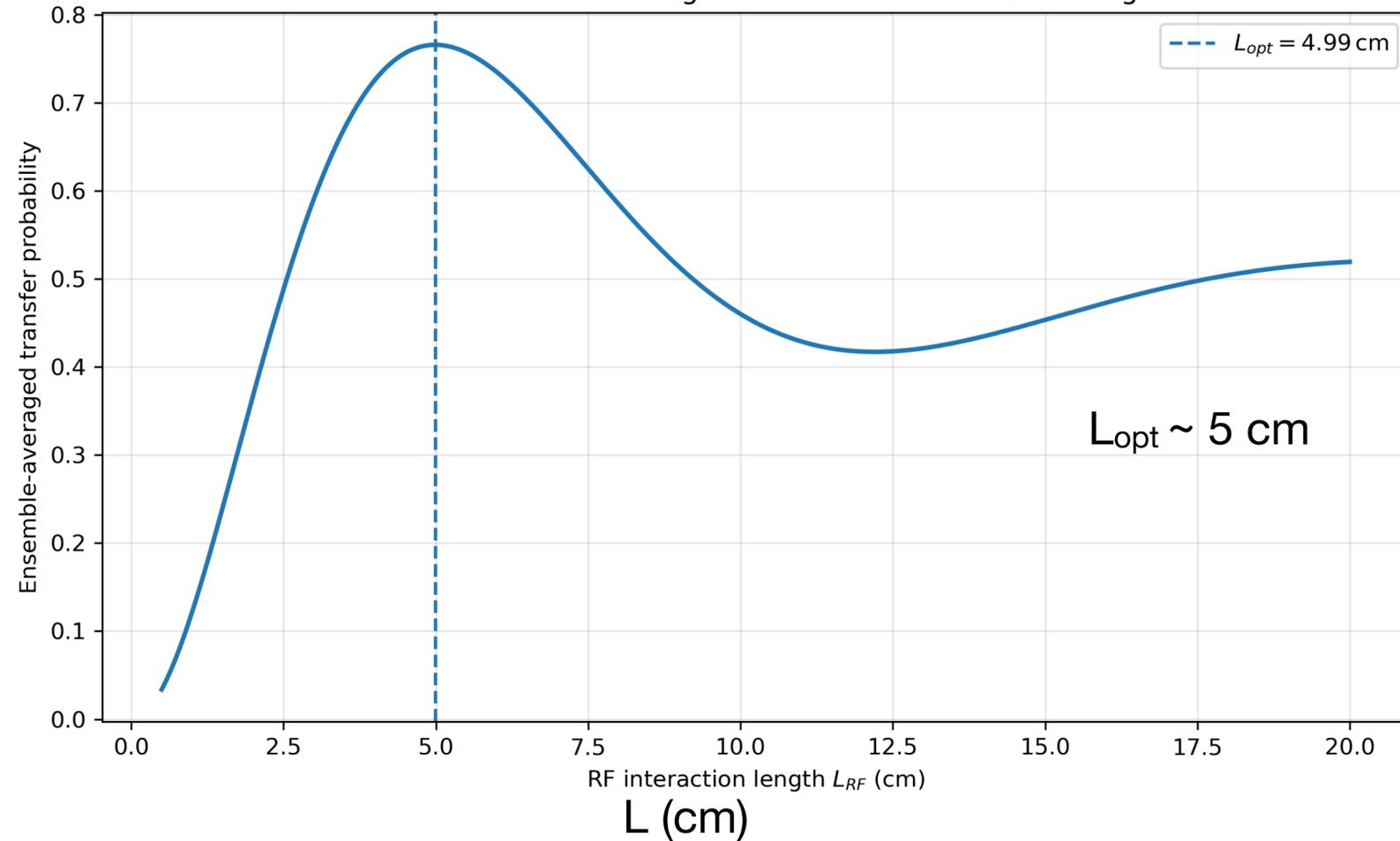
Polarizing the Atoms: Optimizing RF Cavity

Example: $|3/2, +3/2\rangle \rightarrow |3/2, +1/2\rangle$ transition: length of cavity corresponds to π -pulse for v_{mp} ($T = 600\text{ }^\circ\text{C}$)

$B_0 = 100\text{ G}$

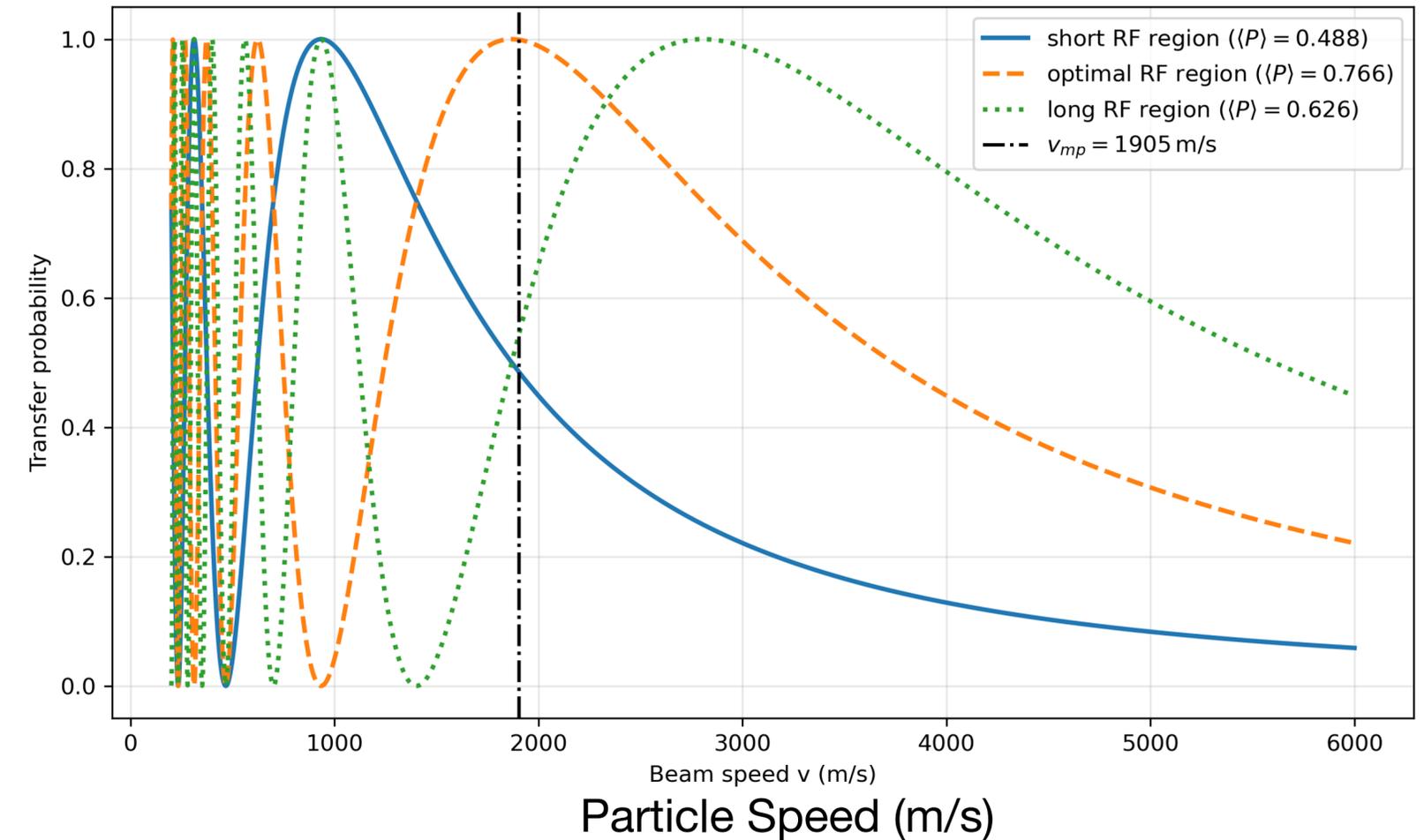
Length Optimization (thermally averaged beam)

Continuous beam: average transfer vs RF interaction length



Transition Probabilities (thermal beam)

Continuous beam: effect of RF interaction length on transfer



Preliminary!

Best $\langle P_T \rangle = 0.766$ for $L = 5\text{ cm}$

Polarizing the Atoms: Optimizing RF Cavity

Example: $|3/2, +3/2\rangle \rightarrow |3/2, +1/2\rangle$ transition: length of cavity corresponds to π -pulse for ν_{mp} (T = 600 °C)

$B_0 = 100$ G

Thermally averaged beam

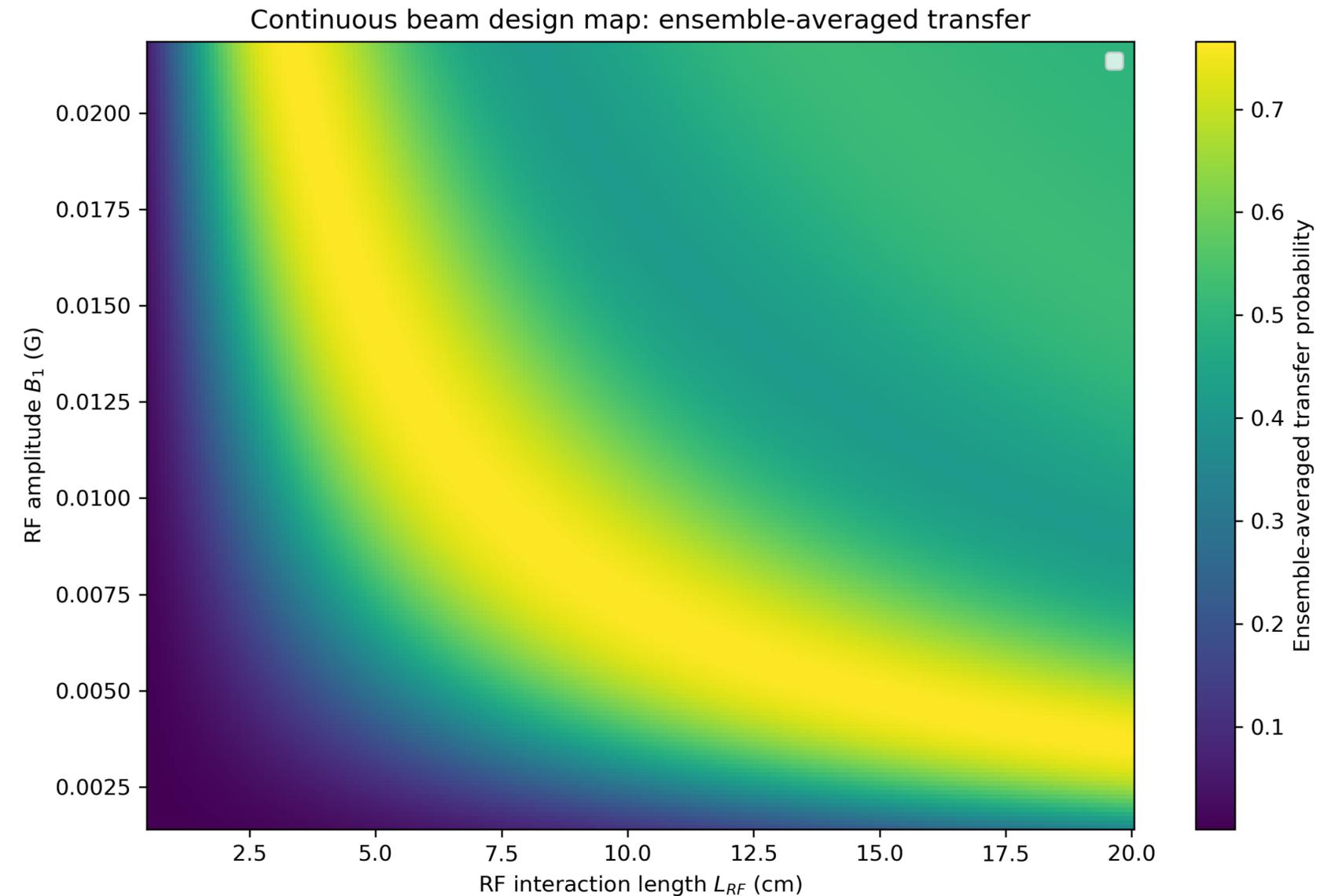
RF amplitude vs RF cavity length scan

Will need two cavities:

- WFT: ~25 MHz ($|3/2, +3/2\rangle \rightarrow |3/2, +1/2\rangle$ transition)
- SFT: ~175 MHz ($|3/2, -3/2\rangle \rightarrow |3/2, -1/2\rangle$ transition)

+ magnetic guiding fields (~few Gauss)

+ adiabatic tapering?



Preliminary!!!

⁷Li Operation

$$J = 1/2, I = 3/2$$

$$\text{vector polarization: } P_z = \frac{(N_{+3/2} - N_{-3/2}) + 1/3(N_{+1/2} - N_{-1/2})}{N} \rightarrow \begin{cases} P_z = +1 & (N_{-3/2} = N_{\pm 1/2} = 0) \\ P_z = -1 & (N_{+3/2} = N_{\pm 1/2} = 0) \end{cases}$$

$$\text{tensor polarization: } P_{zz} = \frac{(N_{+3/2} + N_{-3/2}) - (N_{+1/2} + N_{-1/2})}{N} \rightarrow \begin{cases} P_{zz} = +1 & (N_{\pm 1/2} = 0) \\ P_{zz} = -1 & (N_{\pm 3/2} = 0) \end{cases}$$

$$N = \sum_m N_m$$

- Oven, laser cooling, 2D-MOT, optical pumping identical to ⁶Li (slightly different laser frequencies)
- RF units need to be replaced

Polarimetry etc.

Atomic Beam Polarimetry:

Options:

- Laser Induced Fluorescence (LIF)
- Breit-Rabi Polarimeter
-

Injection into EBIS:

- Polarization transport
- Phase-space matching
-

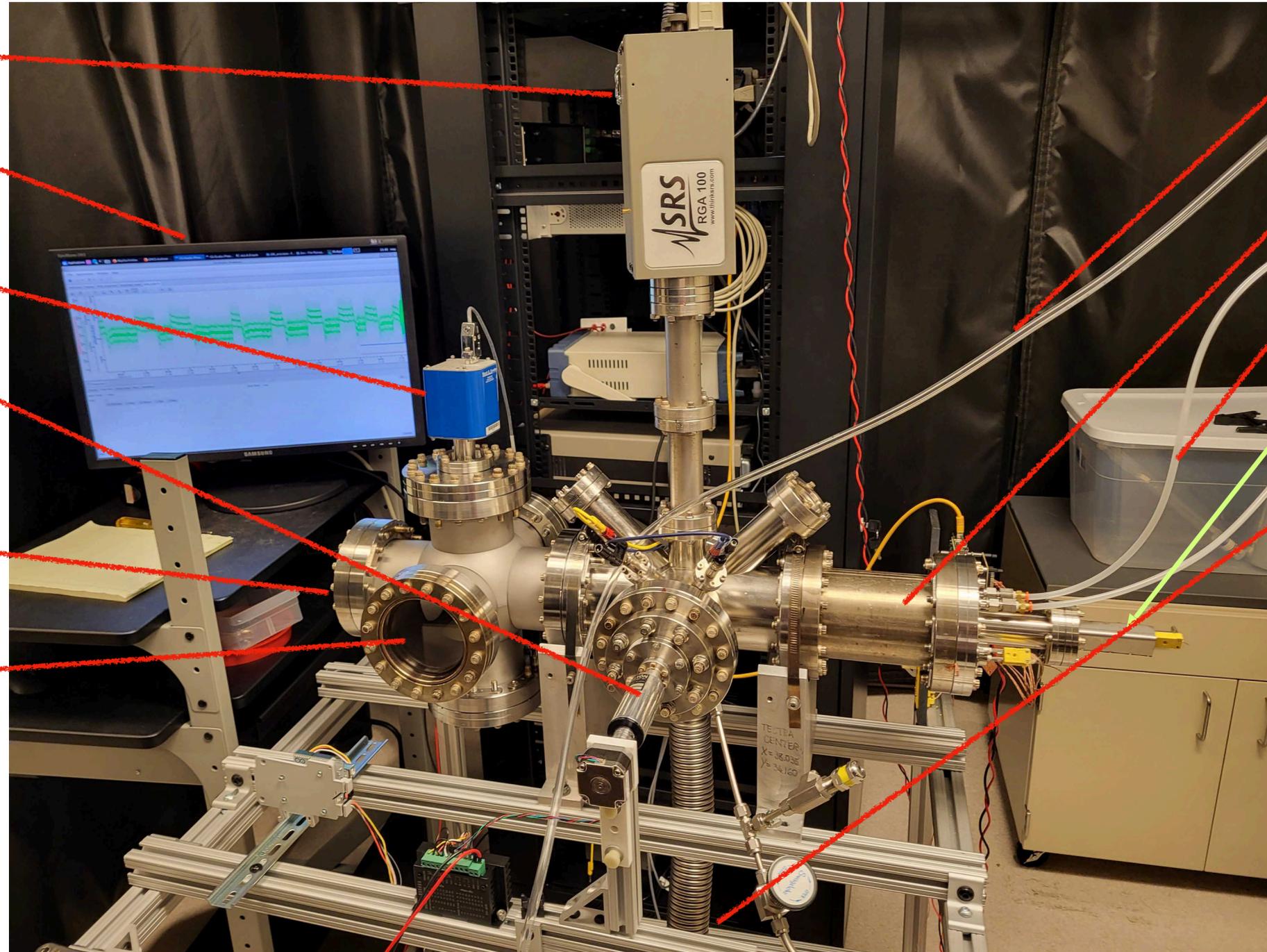
Ion Polarimetry at Higher Energies:

- Work closely with polarized deuteron group(s)

Infrastructure and Workforce

Current Experimental Setup at ANL

RGA
Controlling computer
(with EPICS)
Vacuum gauge
1st wire-scanner
End viewport
(visual measurement)
2nd wire-scanner
(will be installed)

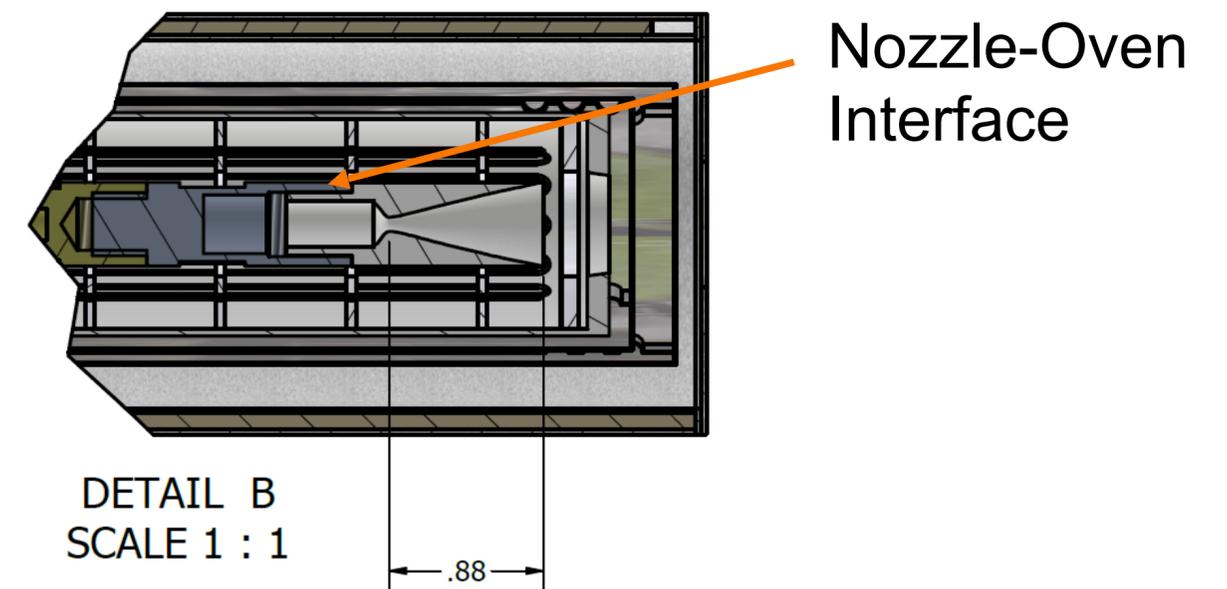
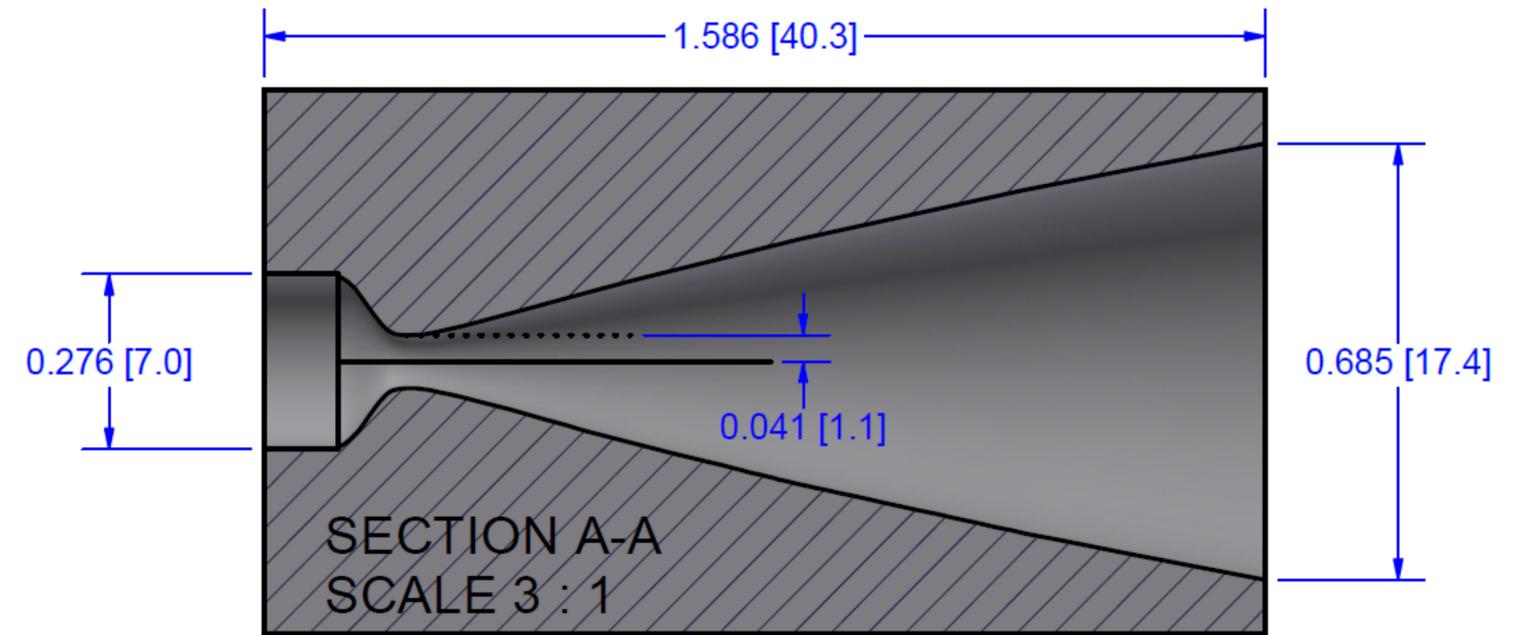


CO2 Gas line
(flushing chamber)
Oven and nozzle
Water lines
Temperature sensor
Vacuum pump

+ Toptica DLC PRO
Laser System (671 nm)

Beam Formation: Convergence-Divergence Nozzle

- De Laval Nozzle
 - Replaceable
 - Fully contained in the heating filaments (prevent for clogging)
 - Convert the Lithium vapor into a non-divergent beam
- Inner contour design
 - 2-mm-diameter throat
 - Initial design from Computational Fluid Dynamics (CFD) simulation
 - Will be further optimized after benchmarking simulation with real profile measurements

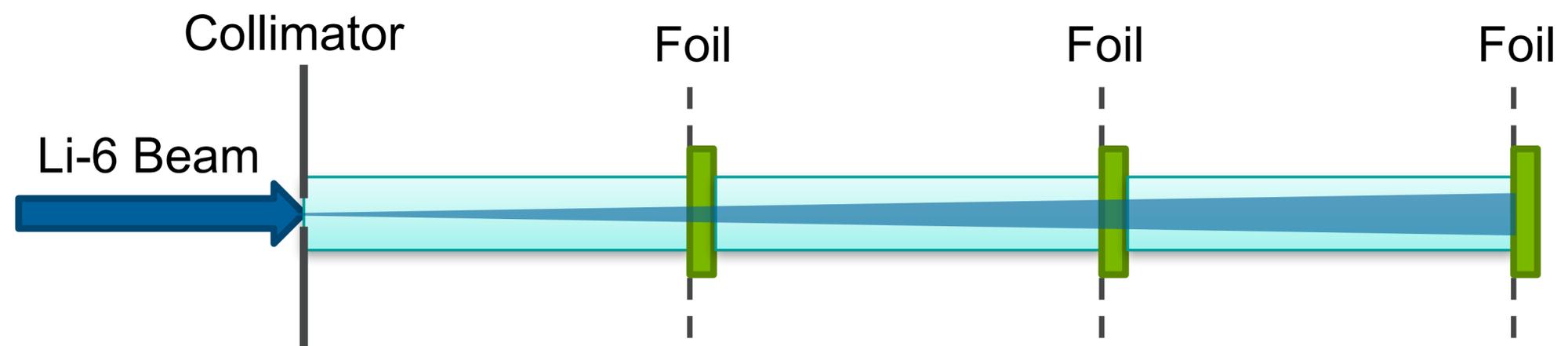


Beam Profile Measurements

- Benchmark the simulation
- Design and preparation for the measurements
- Visual measurement: transverse deposit of Li-6 beam
- Wire scan measurement
 - **Ionizer-wire scan** (thermal ionization)
 - **Laser-wire scan**

↓
Appl. Opt. 49, 6816-6823 (2010)

↓
Nuclear Instruments and Methods in Physics Research A242 (1986) 196-200



Schematic of the visual measurement at different locations



Rhenium wire used in the measurement

Workforce and Funding

Chao Peng, Zein-Eddine Meziani, partial postdoc — (ANL)

Peter Müller (ANL): advising (laser and spectroscopy expert)

Wolfgang Korsch, Dustin Pigg (graduate student will join project this summer) — UKy

Engineering support from ANL

Machine/Electronic shop support from UKy

Funding:

- Chao Peng (ANL) - applied for DOE grant: Advanced Technology R&D for the Office of Nuclear Physics (NP) — 2025
- Wolfgang Korsch (UKy): EPSCoR grant: 2024 - 2025

Summary

- ***Strong physics case for a polarized $^{6,7}\text{Li}$ source***
 - access to novel spin observables and nuclear structure effect
- ***Opportunity to leverage modern laser-based techniques***
 - efficient optical pumping and high polarization
- ***Initial (0th-order) conceptual source design presented***
 - oven, collimation, cooling, optical pumping, RF transitions
- ***Significant R&D remains***
 - optimization of flux, polarization, polarimetry, and system integration