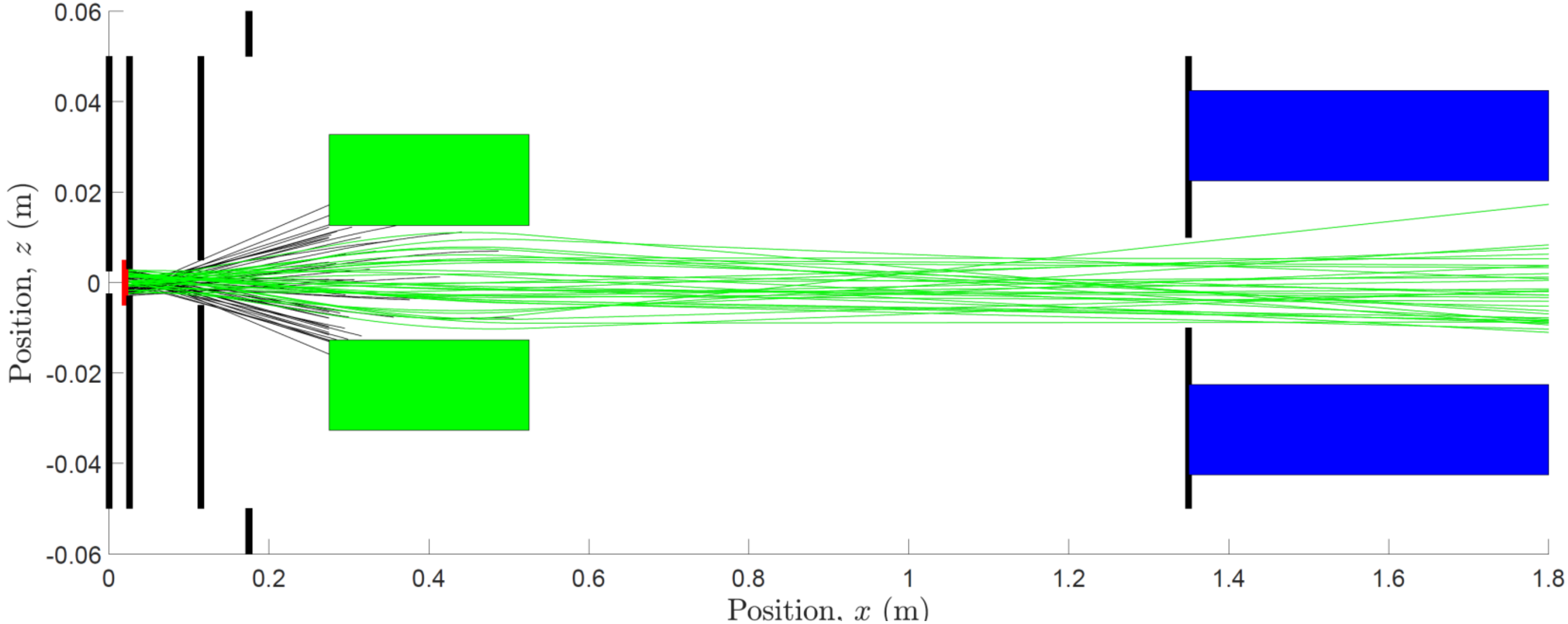
Magnetic Focussing of ThO

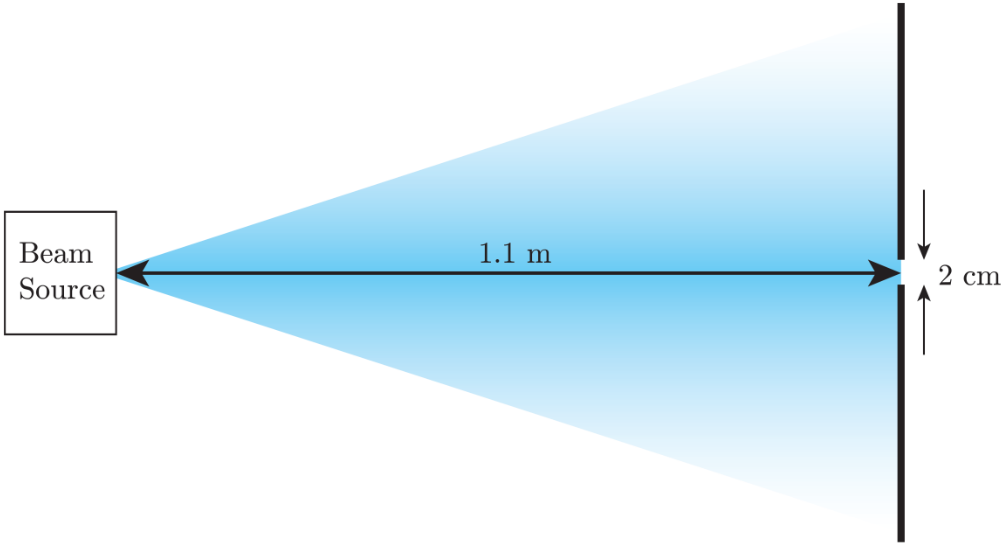


Adam West

Outline

- Motivation / Introduction
- Halbach arrays
- Magnetic focussing simulations
- State preparation considerations
- Outlook

Motivation



Solid angle subtended by interaction region = 0.00033 sr

Beam divergence = 39° FWHM
Solid angle = 0.45

Fewer than 0.1% of molecules make it.

For a point source with narrow longitudinal velocity, quadratic potential refocusses.

Harmonic oscillator – common T for all transverse velocity classes.

Fokussierung polarer Moleküle*.

Von

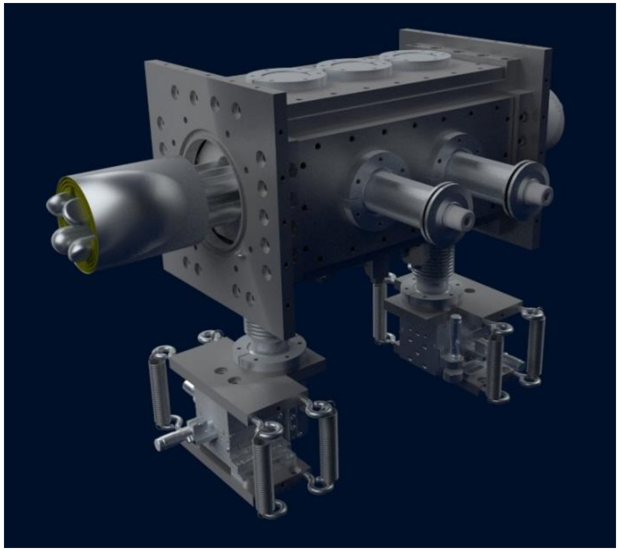
H. G. Bennewitz, W. Paul und Ch. Schlier.

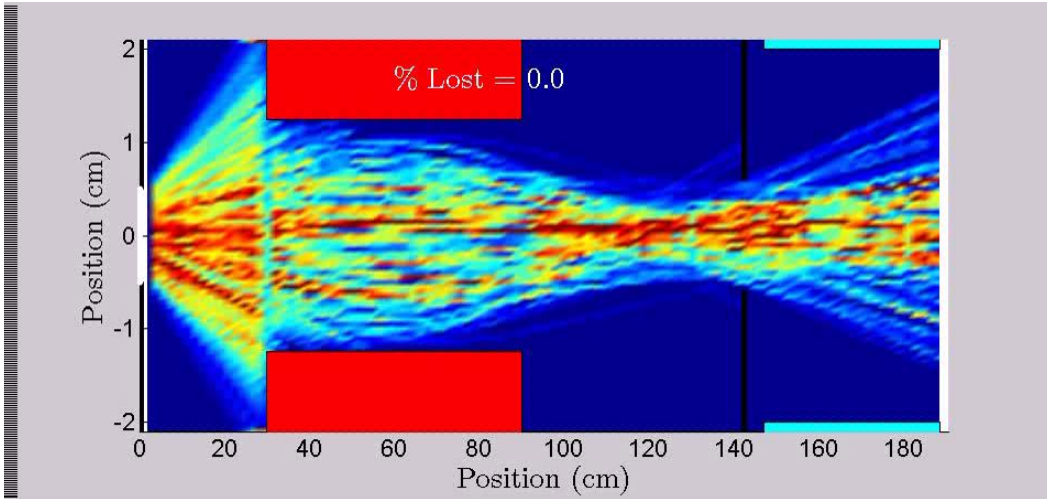
Mit 8 Figuren im Text.

(Eingegangen am 19. Januar 1955.)

Stark	Quadratic energy shift	x	Linear field	Quadrupole
Zeeman	Linear energy shift	x	Quadratic field	Hexapole

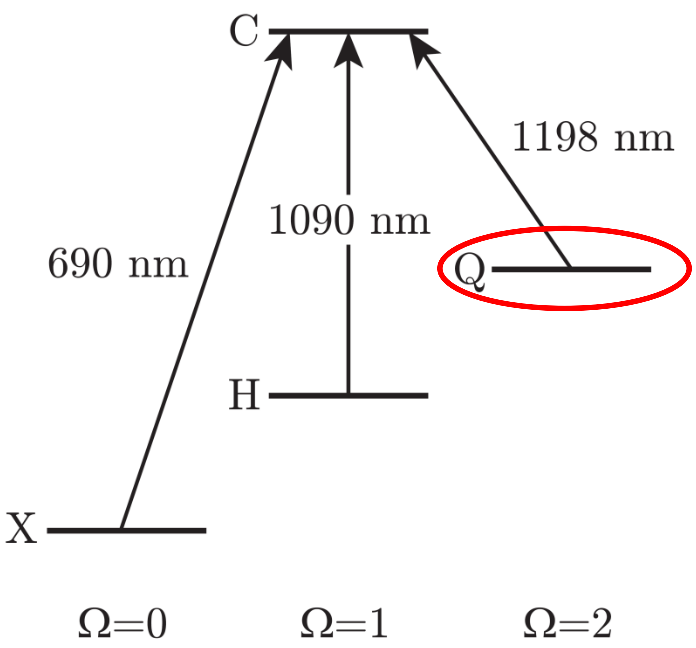
Motivation





AN UNDERAPPRECIATED RADIATION HAZARD FROM HIGH VOLTAGE ELECTRODES IN VACUUM

Q State



$$Q^3\Delta_2$$

$$S = 1, \quad \Lambda = 2, \quad \Omega = 2 \quad \Rightarrow \quad \Sigma = 0$$

$$G_{||} \approx (g_L \Lambda + g_S \Sigma) \approx 2$$

$$g(J) = \frac{G_{||}\Omega}{J(J+1)}$$

$$g(2) = 2/3$$

We can make an estimate of the capture range based on the maximum field:

$$M_J g(J) \mu_{\mathrm{B}} |B| / k_{\mathrm{B}} \approx 1.9 \text{ K}$$

By comparison, the potential depth from Stark shift is ≈ 1 K

Halbach Array

Locally enhances/suppresses magnetic field.

Linear array has many uses, e.g.

- Fridge magnet
- 'Wigglers'
- Atom optics

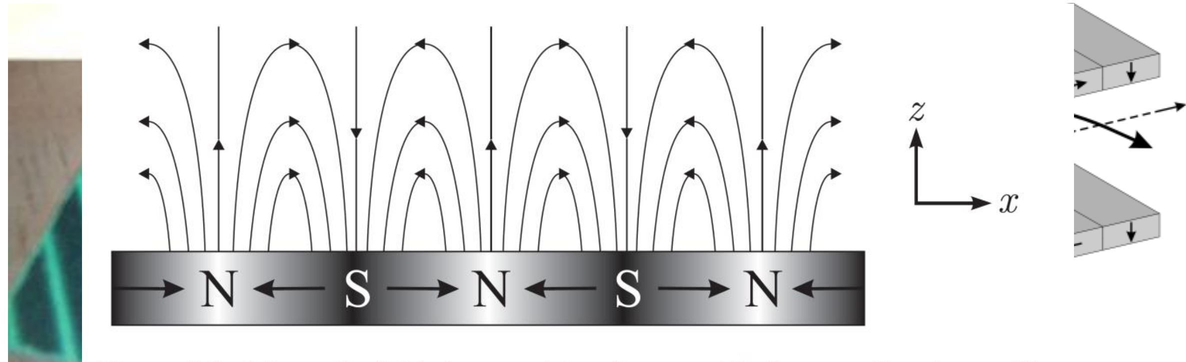
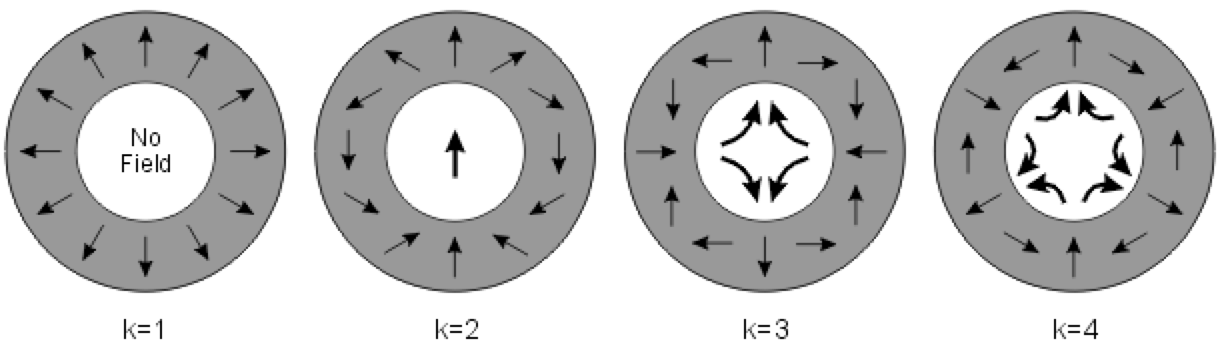


Figure 3.1: Magnetic field shape arising from an ideal magnetic mirror. The

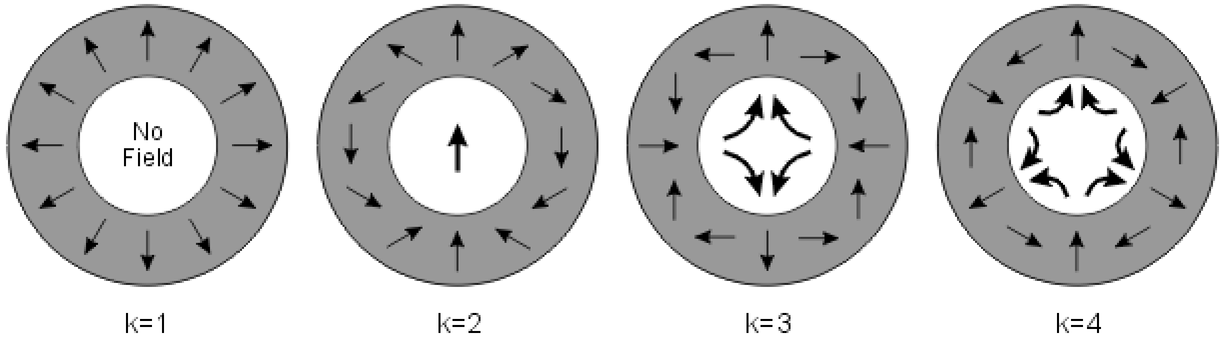


Cylindrical array follows the same principle.

Magnetisation rotates as move around the circumference.

Halbach Array

Dipole Quadrupole Hexapole



$$|B| = \frac{B_{\text{rem}}(k-1)}{k-2}\left[1-\left(\frac{R_i}{R_o}\right)^{k-2}\right]\left(\frac{r}{R_i}\right)^{k-2}$$

k = 4: $$|B| = \frac{3B_{\text{rem}}}{2}\left(1-\frac{R_i^2}{R_o^2}\right)\frac{r^2}{R_i^2}$$

$$R_i/R_o = 0$$
$$r = R_i$$

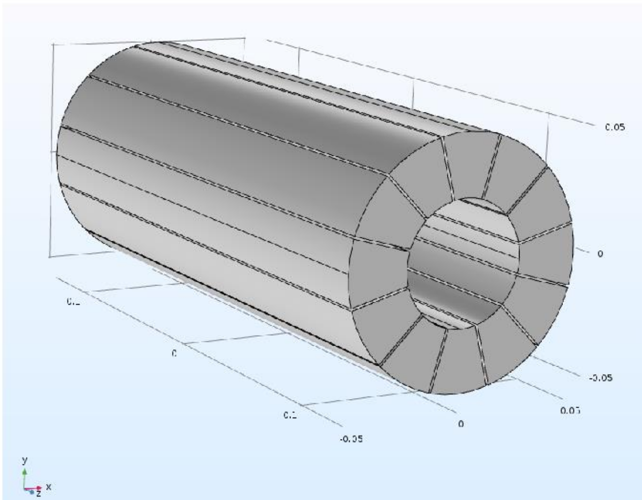
$$|B|_{\text{max}} = 3B_{\text{rem}}/2$$

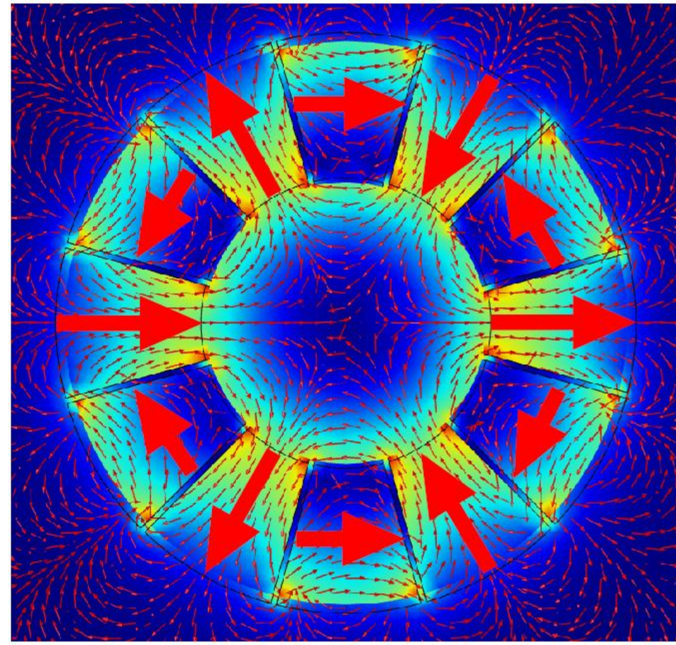
Dipole: $$|B| = B_{\text{rem}}\ln(R_o/R_i)$$

Halbach Array

In practice, continuous magnetisation rotation is difficult.

Use segmented structure instead.





$$\tilde{B}(z) = B_{\text{rem}} \sum_{\nu=0}^{\infty} \left(\frac{z}{r_i}\right)^{n-1} \frac{n}{n-1} \left[1 - \left(\frac{r_i}{r_o}\right)^{n-1}\right] K_n$$

$$z = x + iy \Rightarrow B_x = \Re(\tilde{B}), B_y = \Im(\tilde{B})$$

$$n = N + \nu M$$

$$K_n = \cos^n(\epsilon\pi/M)\frac{\sin(n\epsilon\pi/M)}{n\pi/M}.$$

N = multipole (3 for hexapole)
M = number of segments (12)

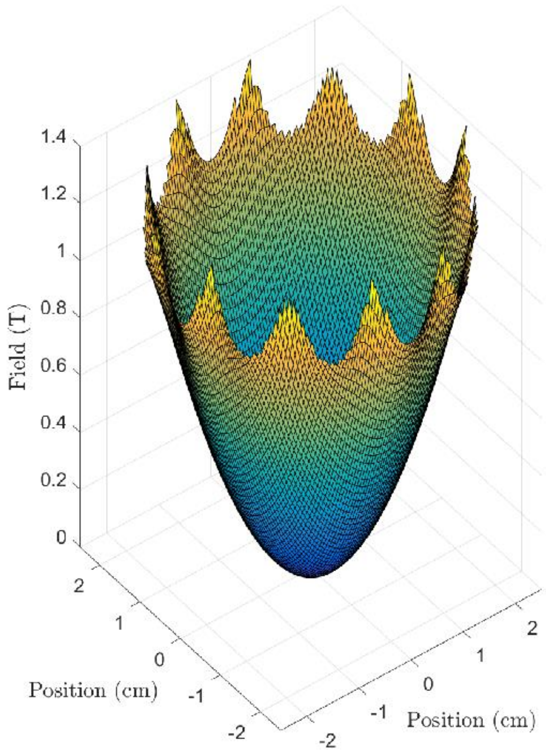
Nucl. Instr. Methods **169**, 1-10 (1980)

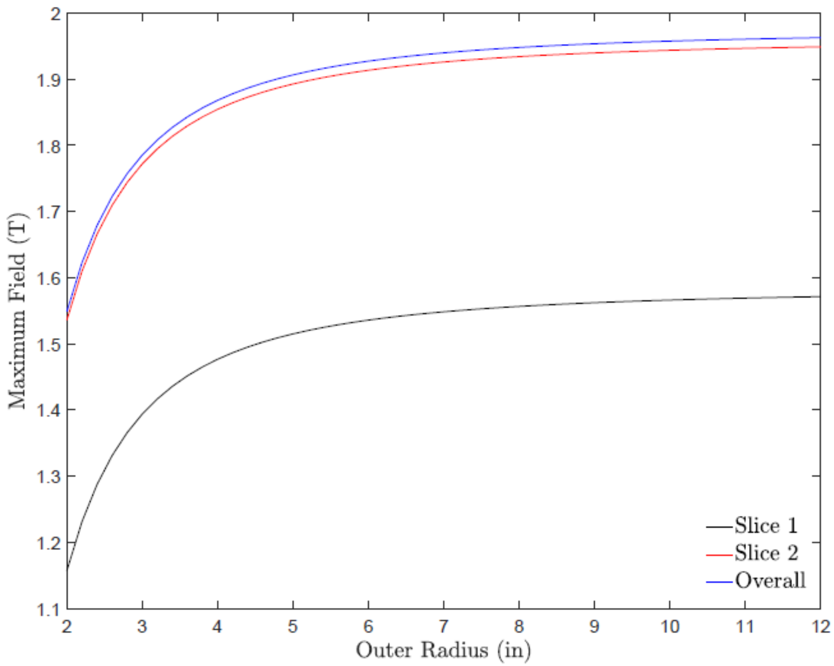
Halbach Array

Maximum field increases with outer radius.

Segmented array gives azimuthally varying field.

Maximum field is reduced for some angles.

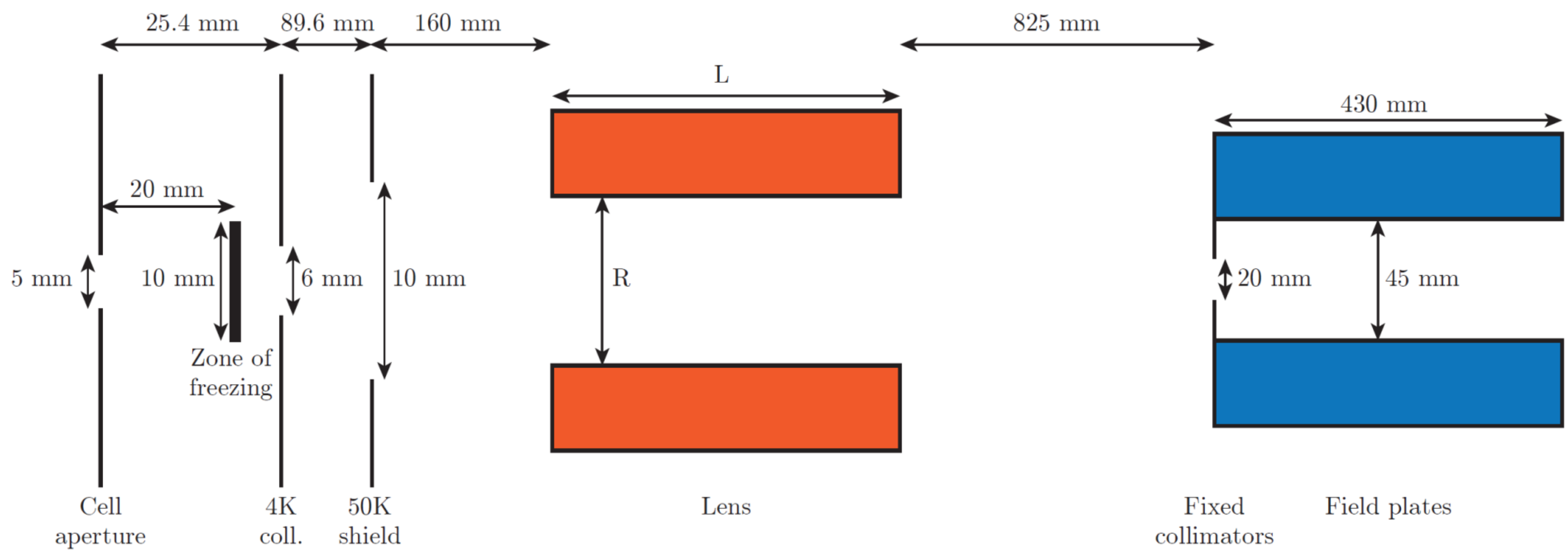




Slice 1: through 'troughs'
Slice 2: through 'peaks'

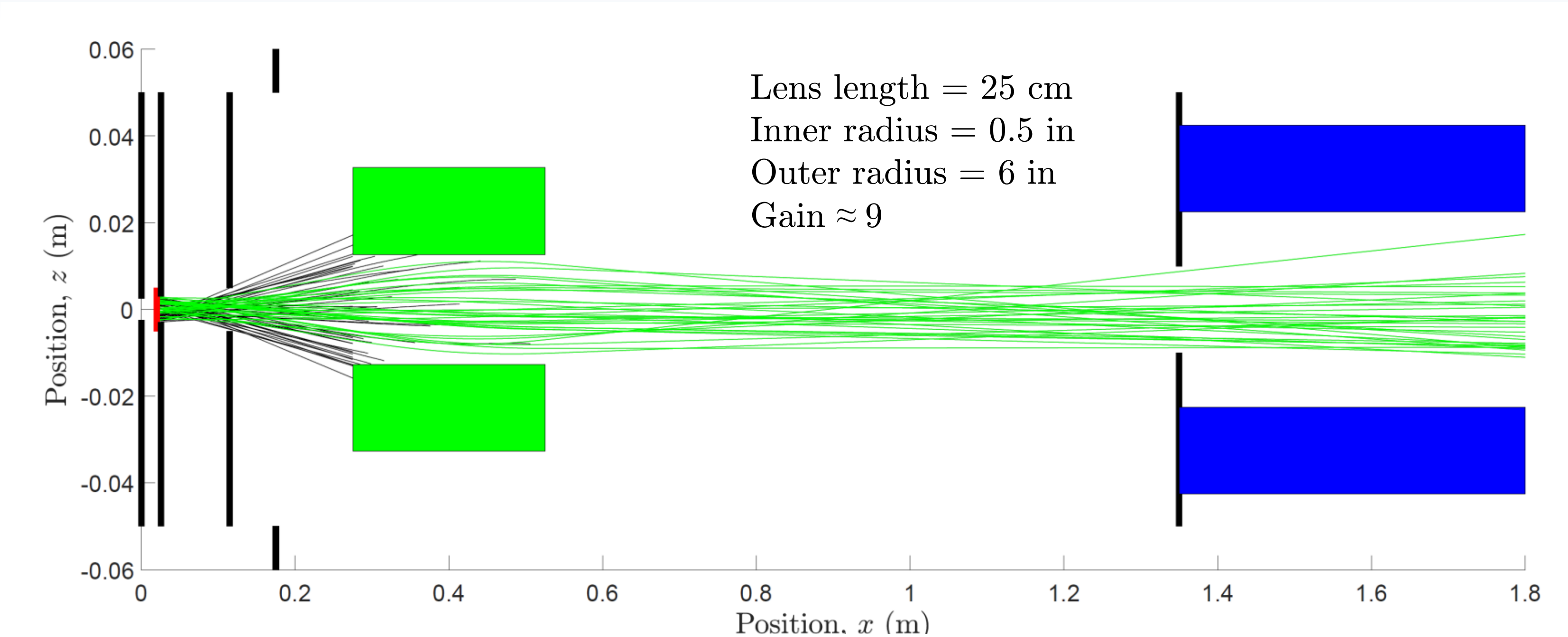
Trajectory Simulations

Beamline setup:



- Assume no axial dependence of field
- Molecules that make it to end of field plates are ‘good’
- Gain is multiplicative increase on no lens case

Trajectory Simulations

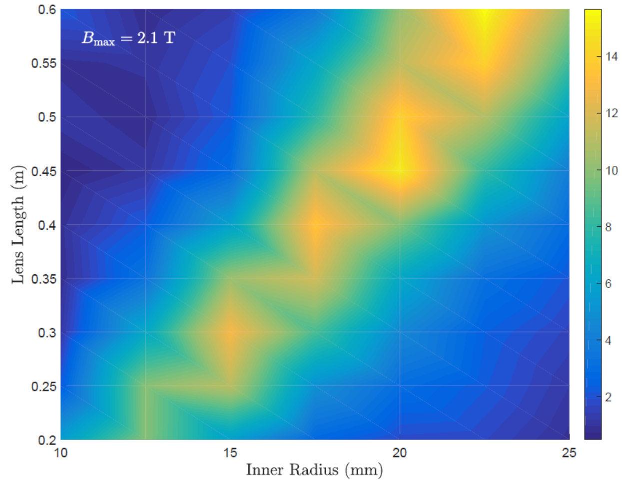


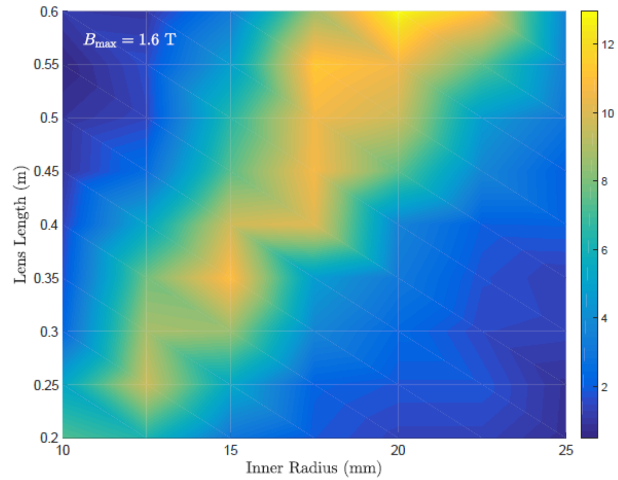
Optimising the length leads to weak focussing of molecules through collimator.

We find that no molecules hit the field plates.

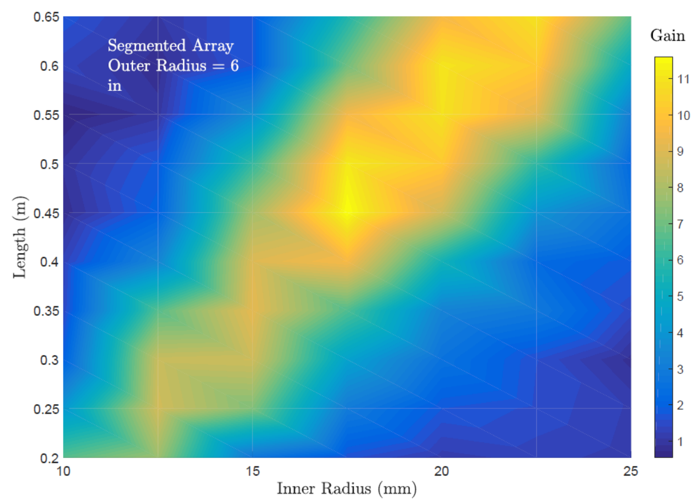
Trajectory Simulations

Continuous magnetisation rotation:

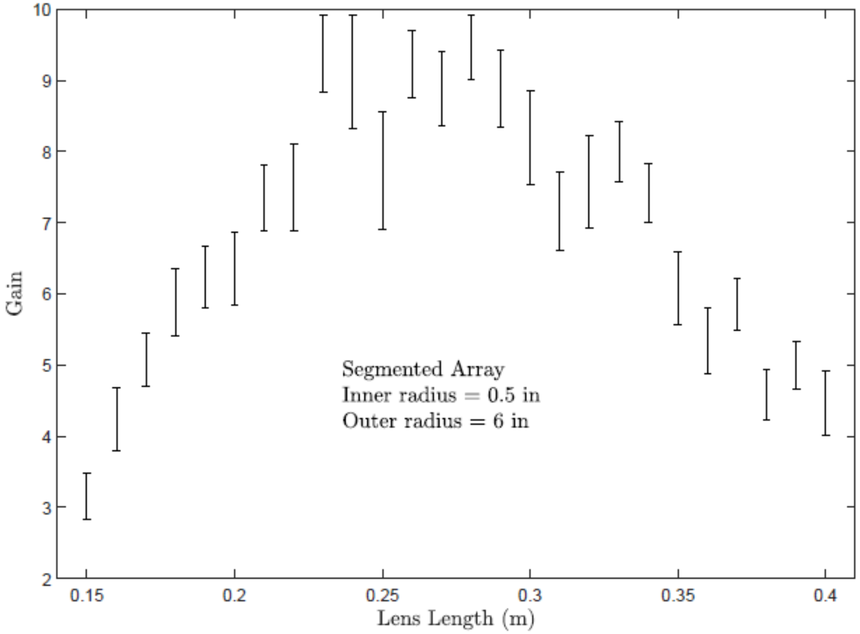


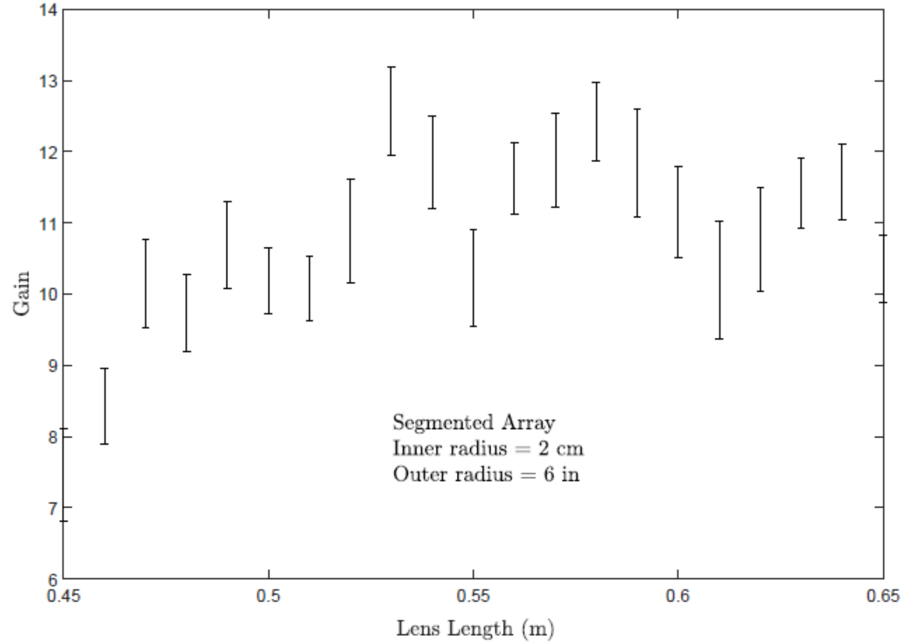


Segmented magnetisation:



Trajectory Simulations





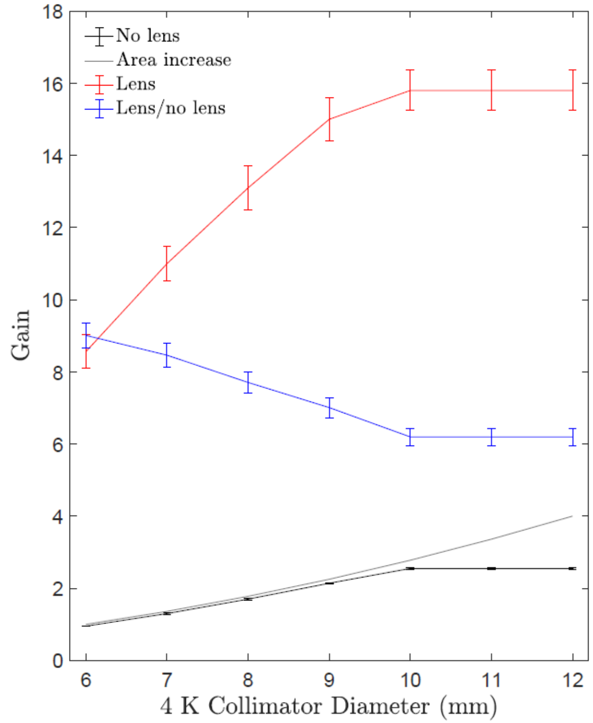
- An order of magnitude improvement seems feasible
- Increase bore:
  - Small gain improvement
  - Large increase in length

Trajectory Simulations

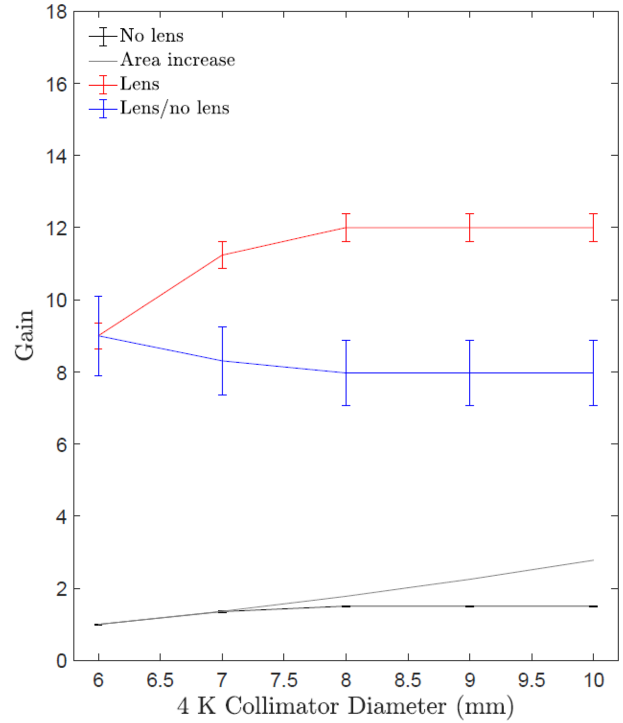
What if we open up the 4 K collimator?

Zone of freezing:

2 cm from cell exit
1 cm diameter



1 cm from cell exit
0.75 cm diameter



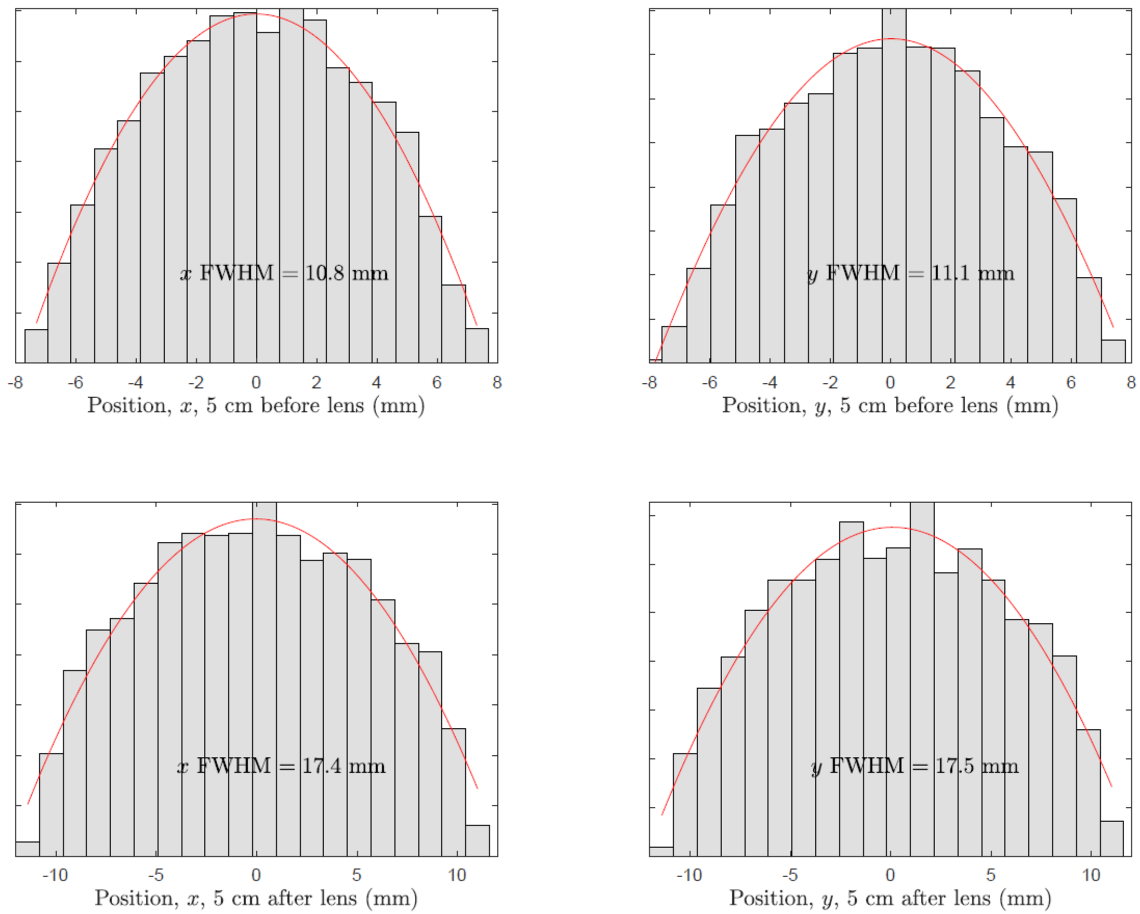
- Gain as area until ZOF and collimator same size (black traces)
- Extra gain from lens decreases as open collimator

Trajectory Simulations

Spatial distribution of ‘good’ trajectories.

Increase in spatial extent after lens.

Symmetric in transverse directions as expected.

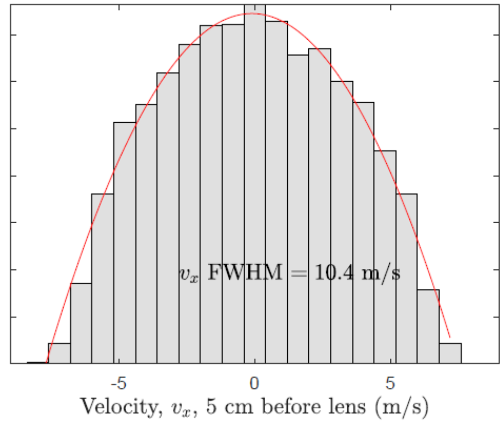


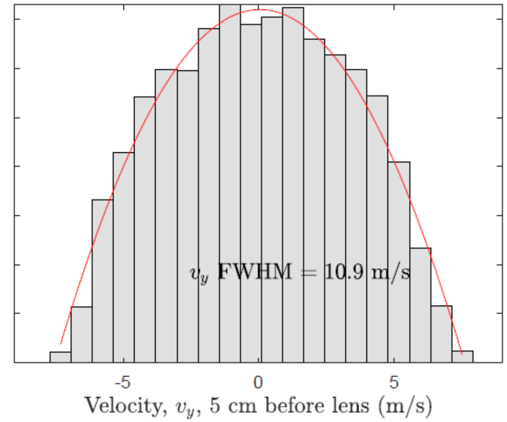
Trajectory Simulations

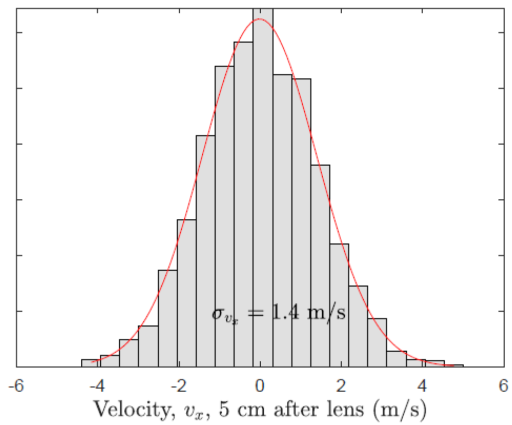
Velocity distribution of 'good' trajectories.

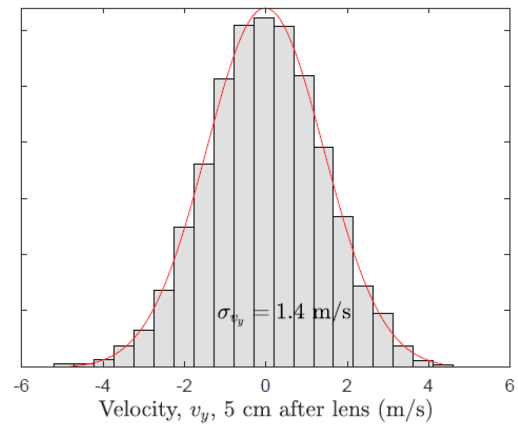
Significant decrease in velocity spread after lens.

Symmetric in transverse directions as expected.

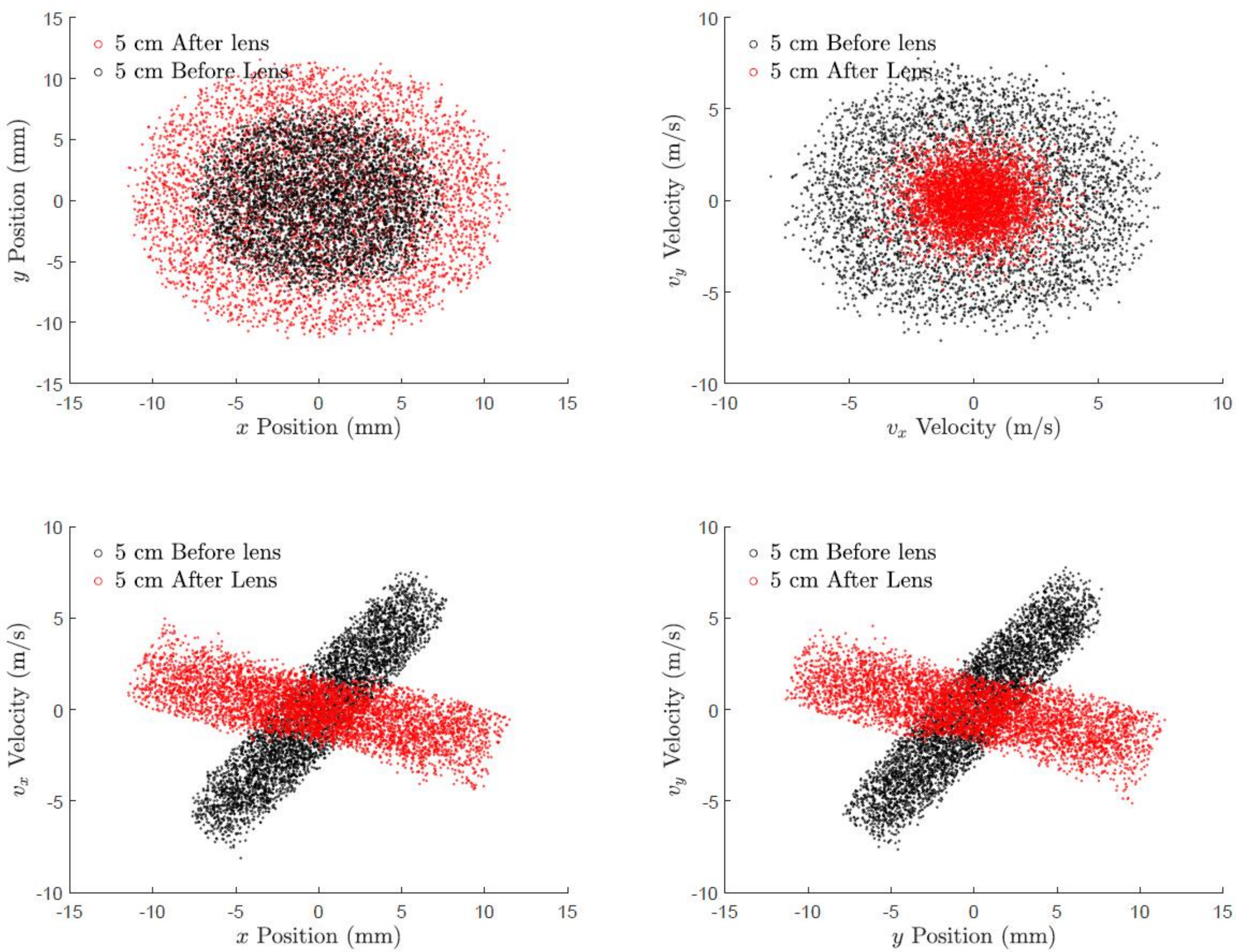








Trajectory Simulations



Given this distribution, can we prepare the required states?

State Preparation

State	Ω	Term Symbols	Pump (nm)	Pump μ (D)	Stokes (nm)	Stokes μ (D)	τ (ns)	P_1 (mW)	P_2 (mW)	P_3 (µW)	P_4 (µW)
X	0	$^1\Sigma^+$	-	-	-	-	∞	-	-	-	-
Q	2	$^3\Delta_2$	-	-	-	-	-	-	-	-	-
B	1	76.5% $^3\Pi$, 17.8% $^1\Pi$...	899		2000						
C	1	76.6% $^1\Pi$, 19.5% $^3\Pi$...	690	1.5	1196	≈ 1	468	3.9	0.2	103	36
D	1	74.5% $^3\Sigma^+$, 14.6% $^3\Phi$...	627		1018						
I	1		512	1.84	745	0.59	115	4.7	1.9	90	105
K	1		442		606						
L	1		402	2.94	536	1.42	17	3.0	33.5	31	18
M	1		460		641						
N	1		361		463						
U	1		397	1.08	526	1.28	57	22.7	22.1	119	31

All known Ω=1 states of ThO.

C state: possible intermediate, Q→C TDM estimate:

$$\mu = \sqrt{\frac{b}{3.137 \times 10^{-7} \nu^3 \tau}}$$

Phys. Rev. A **90**, 062503 (2014)

Lens captures larger range of velocities – how much power do we need for optical pumping/STIRAP?

State Preparation

Optical pumping:

To address entire Doppler width require: $$\sqrt{1+\Omega^2\tau^2} \gg \tau\sqrt{2}\sigma_{v_{x,y}}$$

$$\Omega \gg \sqrt{2}\sigma_{v_{x,y}} \qquad \Omega^2\tau^2 \gg 1$$

Power in beam: $$P = \frac{1}{2}\pi w_x w_y c\epsilon_0 \frac{\hbar^2\Omega^2_{\text{avg.}}}{d^2}$$

Inequality above exactly satisfied for: $$P_1 = \pi w_x w_y c\epsilon_0 \frac{\hbar^2\sigma^2_{v_{x,y}}}{d^2}$$

For linewidth larger than natural linewidth: $$P_2 = \pi w_x w_y c\epsilon_0 \frac{\hbar^2}{2\tau^2 d^2}.$$

State	Ω	Term Symbols	Pump (nm)	Pump μ (D)	Stokes (nm)	Stokes μ (D)	τ (ns)	P_1 (mW)	P_2 (mW)	P_3 (μW)	P_4 (μW)
X	0	$^1\Sigma^+$	-	-	-	-	∞	-	-	-	-
Q	2	$^3\Delta_2$	-	-	-	-	-	-	-	-	-
B	1	76.5% $^3\Pi$, 17.8% $^1\Pi$...	899		2000						
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State Preparation

STIRAP:

Adiabaticity criterion:

Transit time

$$\Omega_{\text{eff}}\delta t \gg 1$$

Assume equal power lasers:

$$P_{\text{Pump}} = P_{\text{Stokes}} = P$$

Effective Rabi frequency:

$$\Omega_{\text{eff}} = \sqrt{\frac{2P(d^2_{\text{Pump}} + d^2_{\text{Stokes}})}{\pi w_x w_y c\epsilon_0 \hbar^2}}$$

Consider when right-hand side exactly = 1:

$$\Omega_{\text{eff}}\delta t = \sqrt{\frac{2(d^2_{\text{Pump}} + d^2_{\text{Stokes}})}{\pi w_y c\epsilon_0 \hbar^2 v^2_{\parallel}}}\sqrt{P w_x}$$

$$P_3 = \frac{\sigma^2_{2\gamma}\pi w_x w_y \epsilon_0 c\hbar^2}{2\min(d_{\text{pump}}, d_{\text{Stokes}})^2}.$$

State	Ω	Term Symbols	Pump (nm)	Pump μ (D)	Stokes (nm)	Stokes μ (D)	τ (ns)	P_1 (mW)	P_2 (mW)	P_3 (μW)	P_4 (μW)
X	0	$^1\Sigma^+$	-	-	-	-	∞	-	-	-	-
Q	2	$^3\Delta_2$	-	-	-	-	-	-	-	-	-
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State Preparation

Also require 2-photon transition linewidth greater than 2-photon Doppler width

$$\delta = v(\lambda_{\text{Pump}}^{-1} - \lambda_{\text{Stokes}}^{-1}) \approx 0.6v \text{ MHz.}$$

v in m/s

Simple general expressions for 2-photon linewidth don't really exist

'Characteristic Rabi freq.'

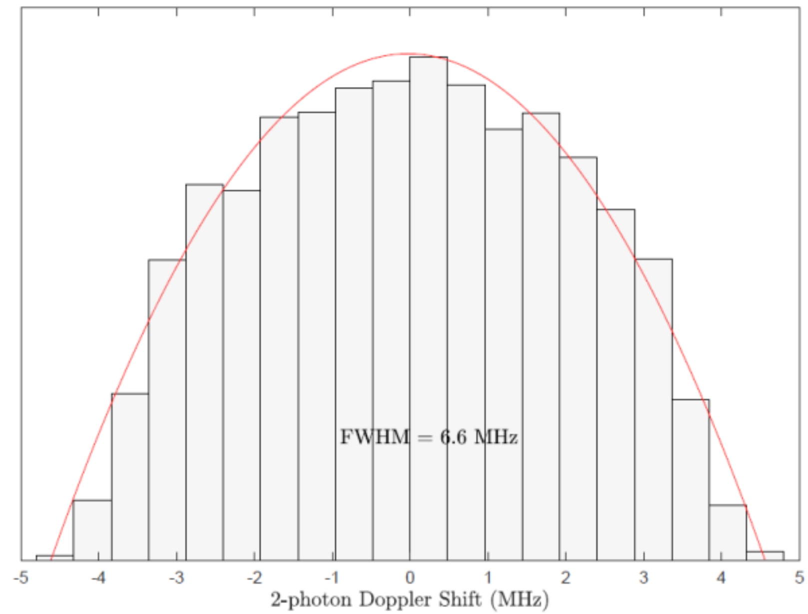
$$\sigma_{2\gamma}/2 = \frac{2V_{\text{m}}}{\sqrt{\gamma\delta t}} \qquad \gamma\delta t \gg 1,$$

Intermediate state decay rate

Not true!

In opposite regime:

$$\sigma_{2\gamma}/2 \approx 1.3V_m.$$



P4 makes this exactly true. Need more rigorous estimate though – using Cris' code.

State	Ω	Term Symbols	Pump (nm)	Pump μ (D)	Stokes (nm)	Stokes μ (D)	τ (ns)	P_1 (mW)	P_2 (mW)	P_3 (μW)	P_4 (μW)
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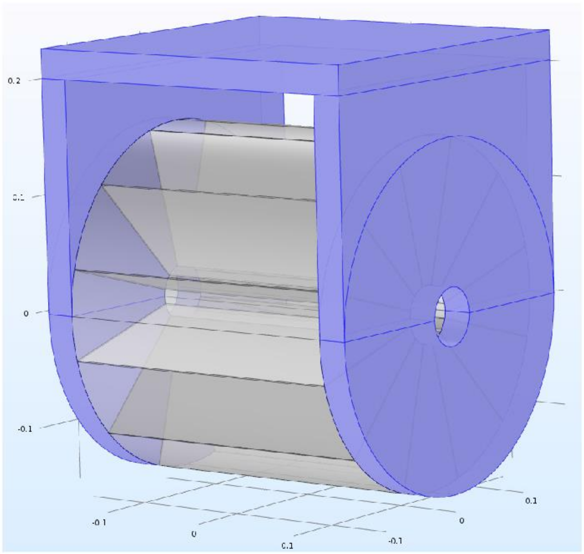
Q	2	$^3\Delta_2$	-	-	-	-	-	-	-	-	-
B	1	76.5% $^3\Pi$, 17.8% $^1\Pi$...	899		2000						
C	1	76.6% $^1\Pi$, 19.5% $^3\Pi$...	690	1.5	1196	≈1	468	3.9	0.2	103	36

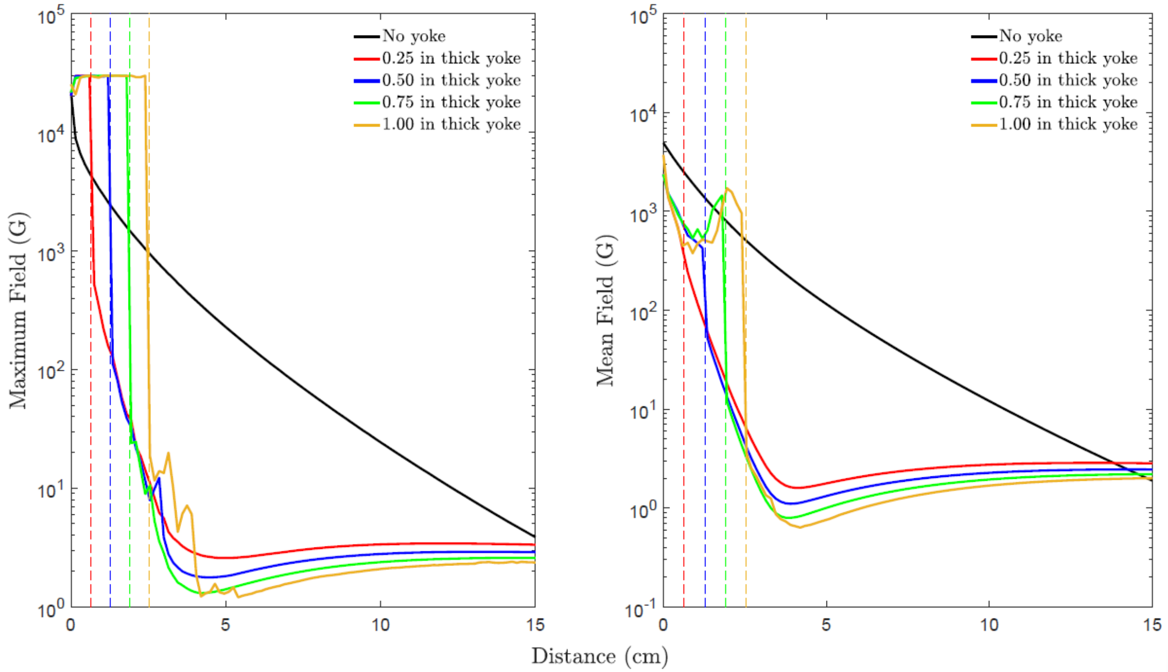
State Preparation

Will magnetic field affect state preparation?

- Should not be too big
- Should be non-zero
- Should have small variation

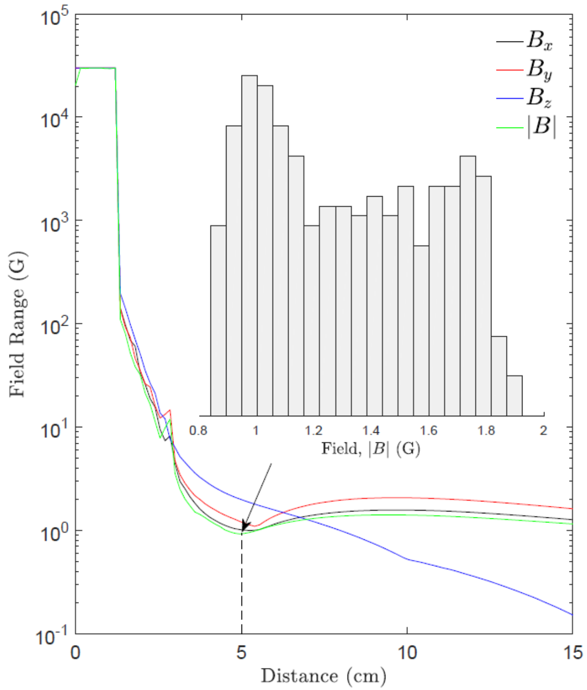
Adding yoke helps reduce field

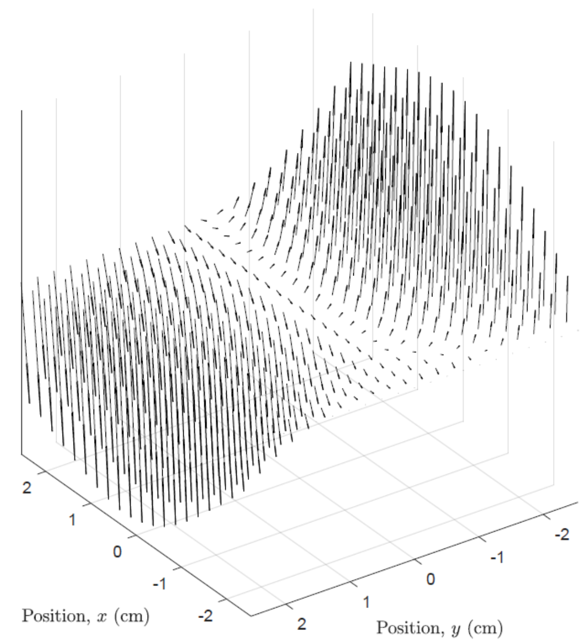




Suppression from 100 G to 1 G at 5 cm distance.

State Preparation





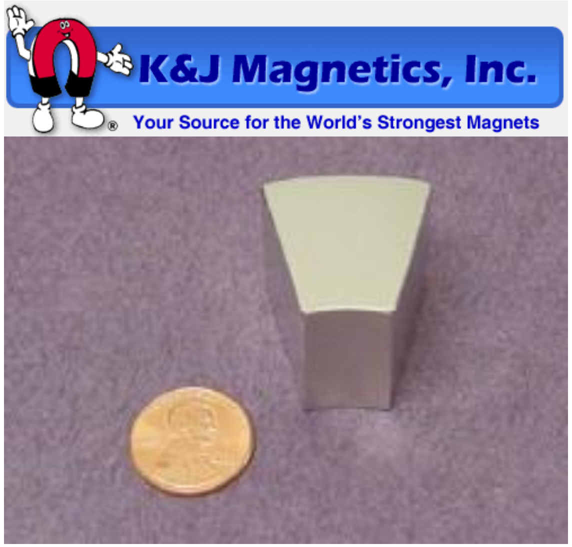
Around 1 G variation in field magnitude.

Corresponds to 1 MHz Zeeman broadening – less than Doppler width.

Asymmetric field shape due to magnetisation pattern/yoke.

Construction

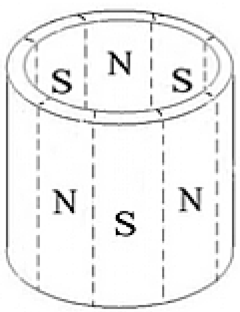
- Relatively cheap
    - 30 degree, 1 in thick segment costs \$30
    - For a 12 in long lens need 12 x 12 = 144 pieces = \$4k
- Tricky to assemble
    - Large forces
    - Tight tolerances(?)
- Easy to install
    - Can be warm
    - No electronics
    - Chance of X-rays = 0

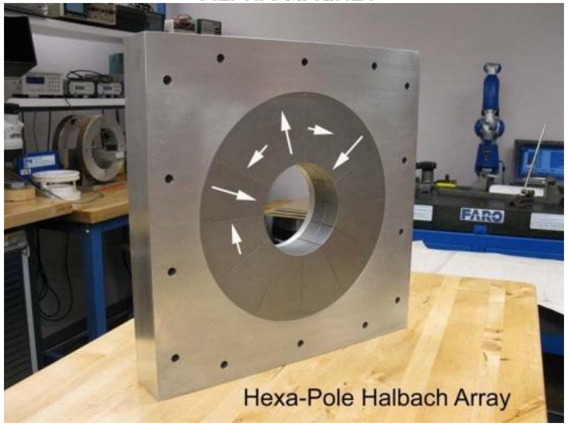


ALPHA MAGNET

Have quote for assembled array from Alpha Magnet

- 1 in inner radius
- 6 in outer radius
- 12 in length
- \$18k





Outlook:

- Simulations pretty much done
- Setting up laser to do spectroscopy on Q→C
- Apply electric field to avoid transitions between Omega doublets?
- Also thinking about alternatives – 'Winston cone' for molecules?

Questions?

Halbach Array