Fermilab

MAGIS-100

Pulse Efficiency Simulations Update

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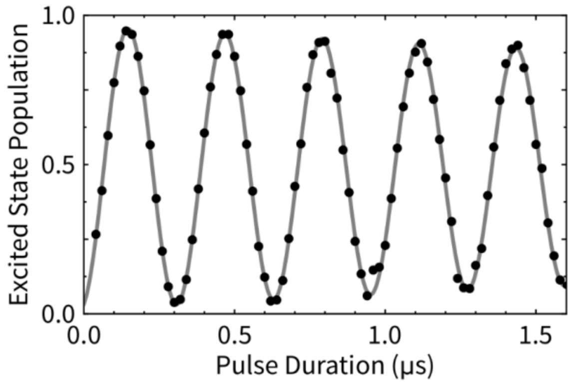
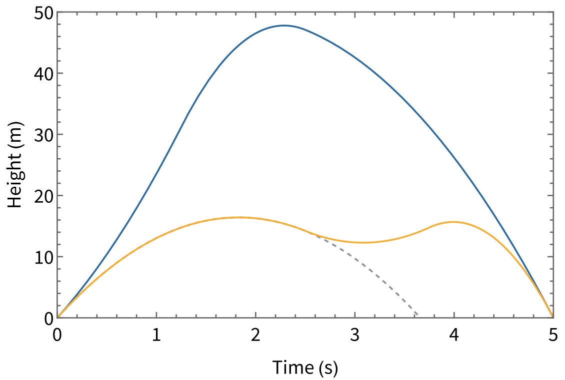
Recap

- Efficient pulses (LMT enhancement) is crucial
- Previously presented key factors for pulse efficiency
    - Spontaneous emission from excited state
    - Off-resonant scattering
    - Detuning errors (Doppler shifts, laser noise,..)
    - **Inhomogeneous intensity (size ratio, dynamics)**
- Boundary conditions for prelim. simulations
    - Size of detector
    - Available measurement time
    - Available laser power
    - Approximate size of atom cloud
- Results
    - Compared and optimized different (composite) pulses
    - Found diverging strategies

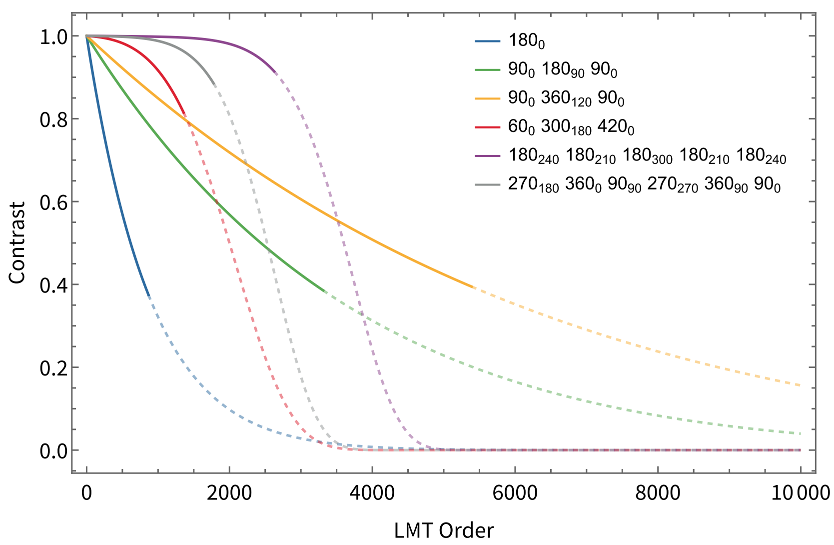


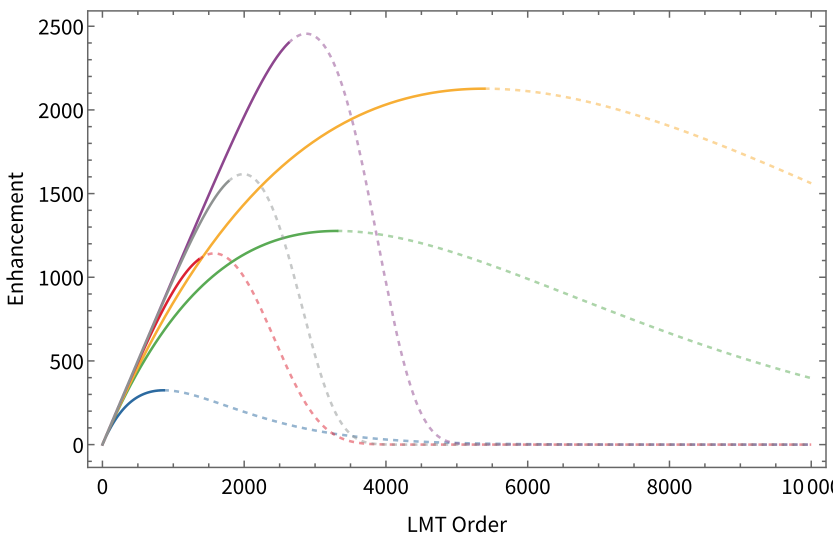


Recap

- Two families:
  - Large cloud, larger beam, very cold (size const.)
  - Small cloud, small beam, not as cold (size doubles)

- Issues:
  - No firm boundary on beam size
  - No firm boundary on temperature
  - Cloud dynamics (expansion) more complicated for fermions





Outline

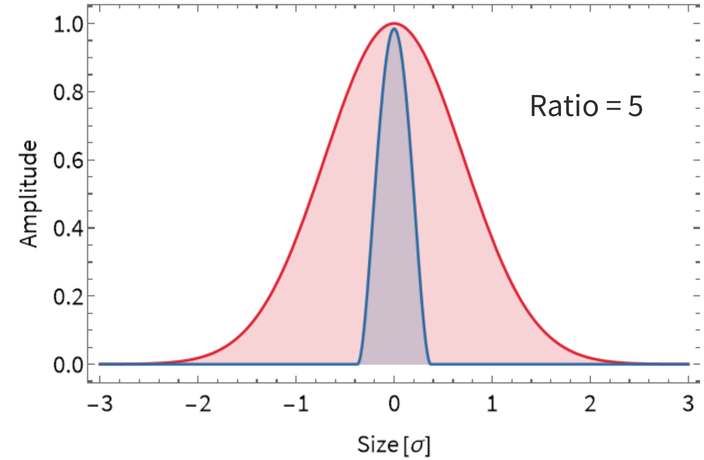
- What is the required size ratio between atom cloud and laser beam?
- What is the largest beam we can accommodate?
- How big is a cloud of fermions and how fast does it expand?

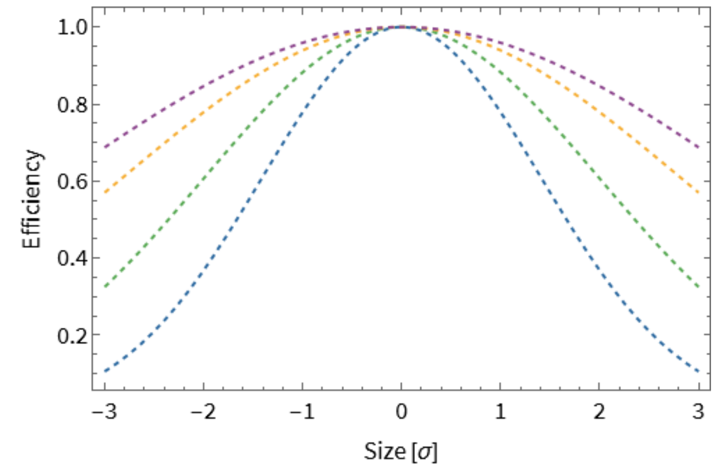
Size Ratio

- Intensity of Gaussian beam varies with ~r^2
- Transfer efficiency error varies with ~r^4

$$\left(\frac{\Omega}{\sqrt{\Omega^2+\Delta^2}}\,\mathrm{Sin}\left[\frac{1}{2}\sqrt{\Omega^2+\Delta^2}\,\tau\right]\right)^2$$

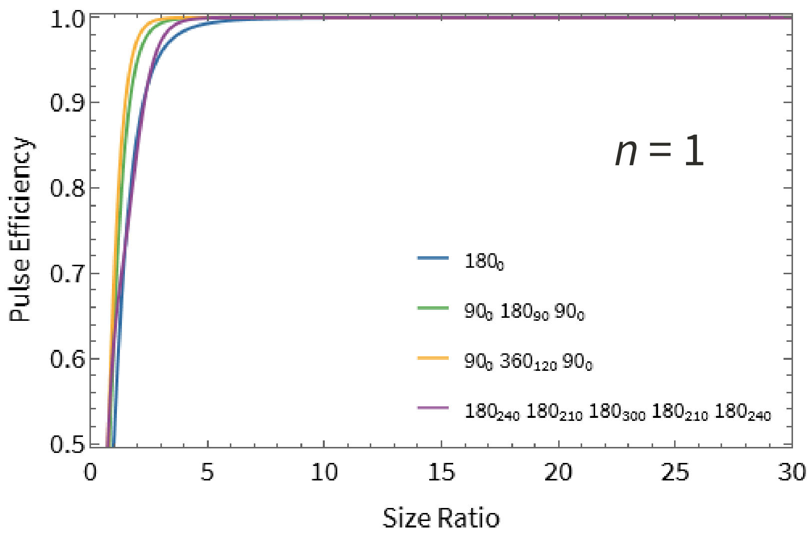
- Average transfer efficiency over whole cloud
- Other (composite) pulses have more homogeneous response (r^8, r^{12}, ..)
- Size of the cloud not constant, depends on (effective) temperature

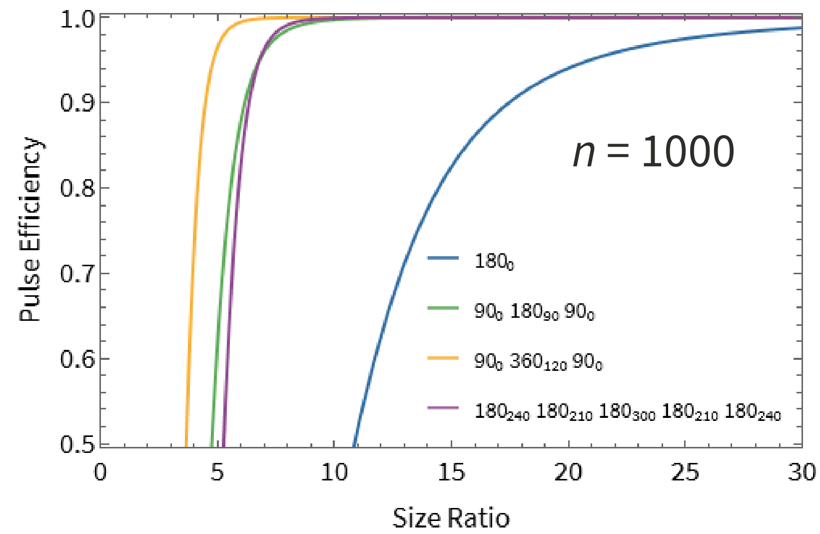




Size Ratio

- Integrated transfer efficiency over size ratio
- Single pulse vs. 1000 pulses
- (Plain pulses are already ruled out)
- Abrupt cutoff in transfer efficiency

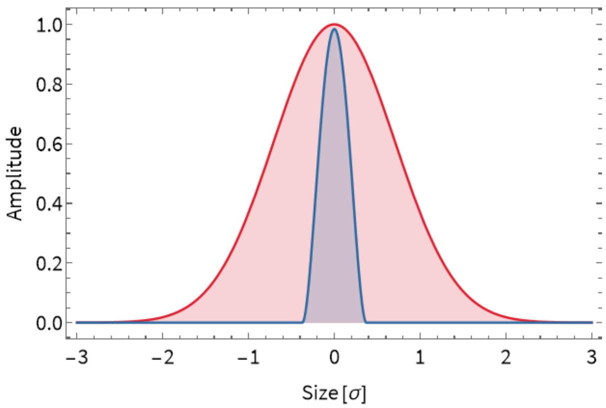


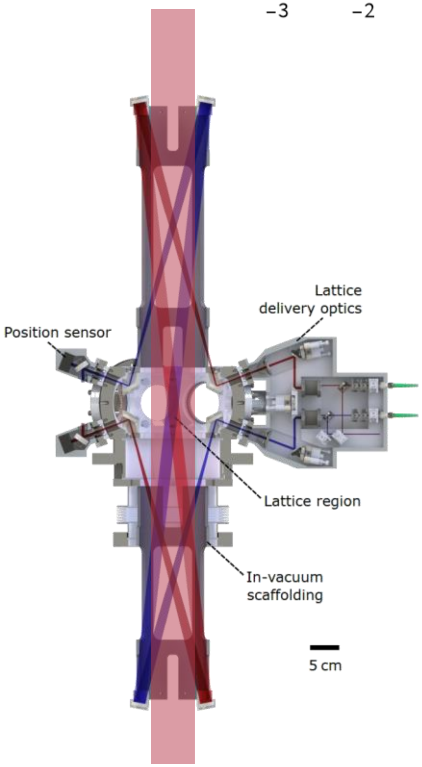


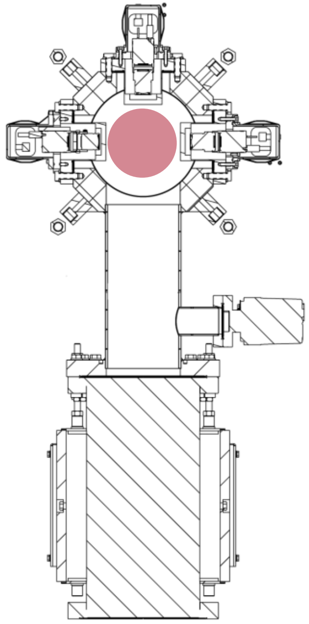
Beam Size

- Fundamentally limited by tube diameter
- Other obstacles: in-vacuum optics, viewports
- Objects in beam/apertures lead to diffraction and interference
- We may want to simulate this

- Closest object to the center of the tube: lattice launch optics (⌀ 87mm)
- Bucket windows (⌀ 100mm)
- Assuming free aperture of ±3σ
- Max. cloud size: ~1.5mm radius (ratio of 10)
  ~2.0mm radius (ratio of 7)







Ultracold Atoms & Lensing

- How do you control the size of a cloud for ~10s?
- Do you need degenerate atoms?
- Do you need bosons?

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PAPER

Atomic source selection in space-borne gravitational wave detection

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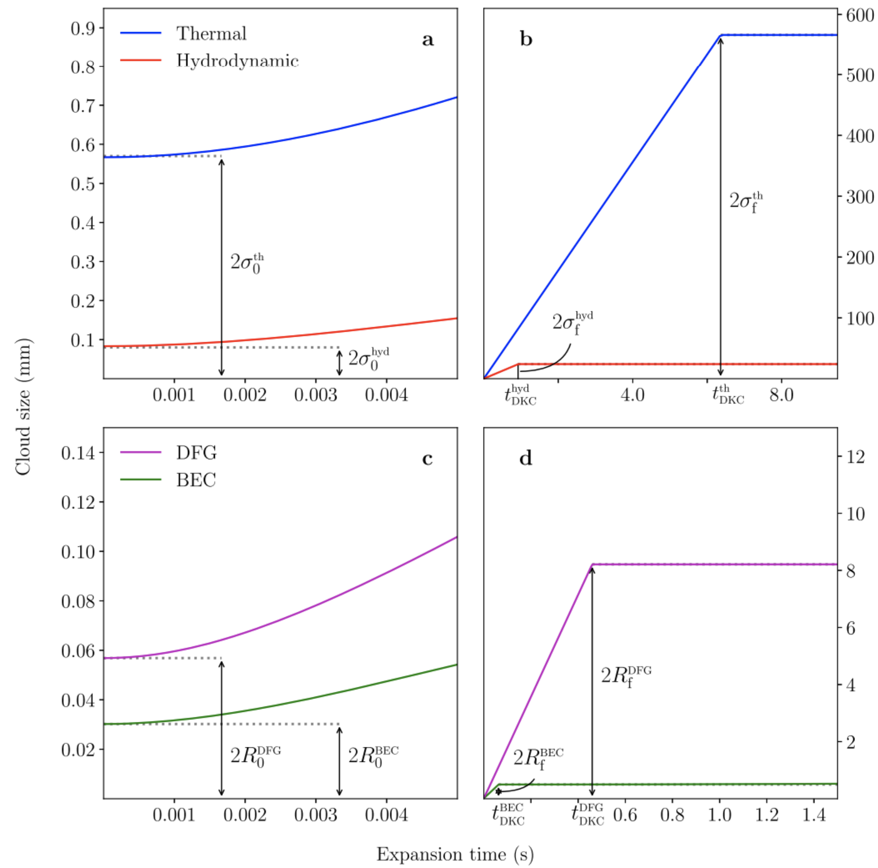
Ultracold Atoms & Lensing

- Comparison between thermal, hydrodynamic, condensed atoms
- BEC vs. DFG
- Target (effective) temperature: 10pK
- 7x10^6 atoms (degenerate)

- Initial size (left) vs. size at lens (right)
- Thermal clouds way too big
- Fermions ~10x larger than Bosons
- Cloud radii of ~6mm at 10pK (^{87}Sr)



Ultracold Atoms & Lensing

- Numbers are challenging!
- Paper assumes plain pulses, other pulse strategies can help
- Need to relax temperature requirements
- Important: size scales with atom number

3D expansion rate $T_{\mathrm{eff}} = 10$ pK	BEC		DFG	
	^{174}Yb	^{84}Sr	^{171}Yb	^{87}Sr
Number of atoms	7×10^6		7×10^6	
Trapping frequency (2π Hz)	50		50	
Critical temperature (μK)	0.431		0.834	
Initial size $2R_0$ (μm)	30.2	41.8	56.86	81.86
Pre-DKC expansion time (t_{DKC}) (ms)	63	61	460	460
Size at lens $2R(t_{\mathrm{DKC}})$ (mm)	**0.50**	**0.67**	**8.21**	**11.82**
Final size $2R(t_{\mathrm{DKC}} + 2T)$ (mm)				
$T = 40$ s	9.27	13.34	12.86	18.51
$T = 100$ s	23.15	33.32	26.07	37.53
$T = 160$ s	37.03	53.31	40.43	58.20

Ongoing Work & Status

- Free expansion and lensing of Fermions is more complicated
- Need to simulate DFG lensing with realistic sizes

- Include lens/collimation as optimization parameters for pulse efficiency
- Search for LMT strategy that works with the beam sizes we can support

- (Future) How do the kinematics for the launch and lens sequence work?
- (Future) Do we need to model the laser light diffraction along the tube?
- (Future) Do we want to look into Bosons and LMT with 3-photon transitions?