Upgrade ACME III electron EDM search with a molecular lens

Xing Wu

CFP colloquium, Northwestern University,

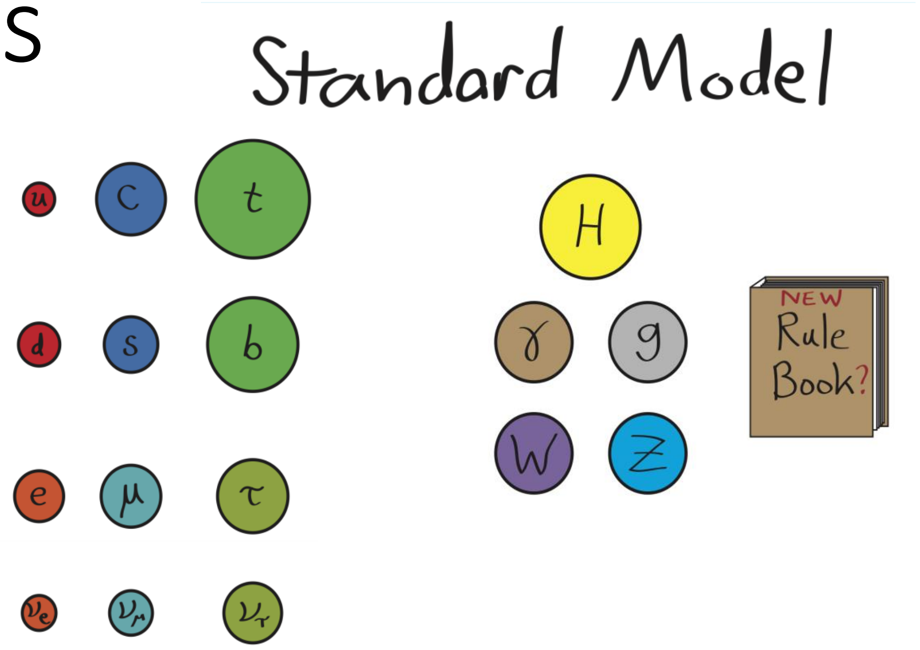
01/28/2020

Outline

- Motivation & overview
- Molecular properties of ThO & result from ACME II
- Upgrade ACME III with electrostatic lens
  - Good electronic state: Q ($^3\Delta_2$) state
  - Robust state preparation with STIRAP
  - Efficient electrostatic focusing of molecule beam
  - Other associated technical upgrades
- Conclusion

EDMs probe TeV scale physics

- New theories predict particles at the TeV energy scale.



EDMs probe TeV scale physics

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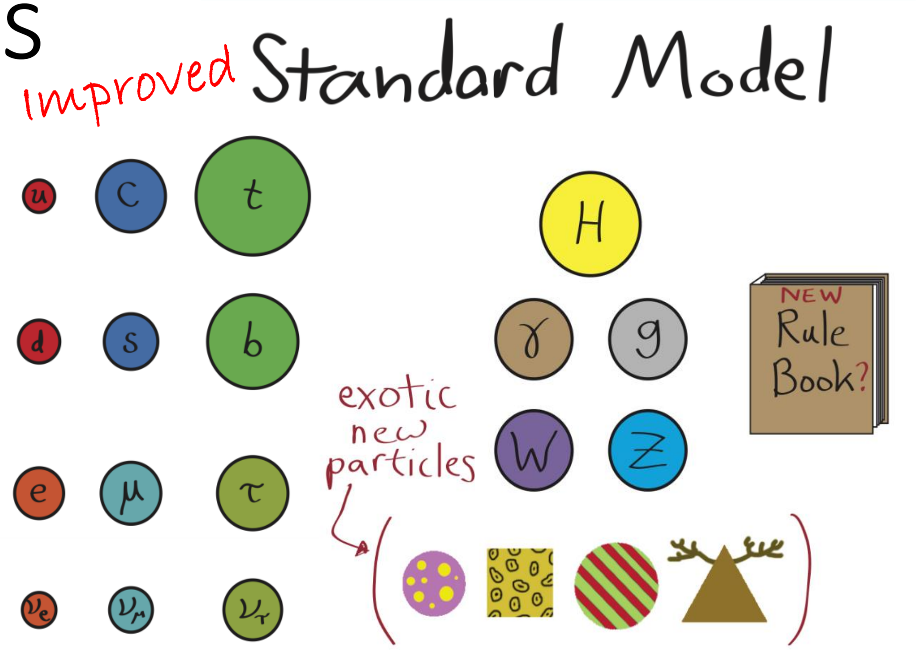
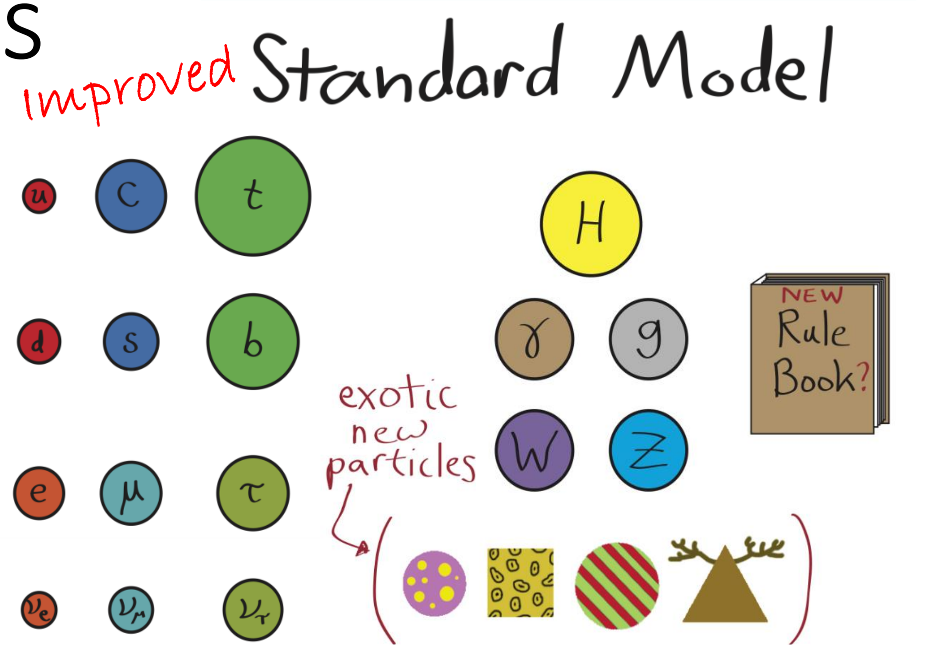
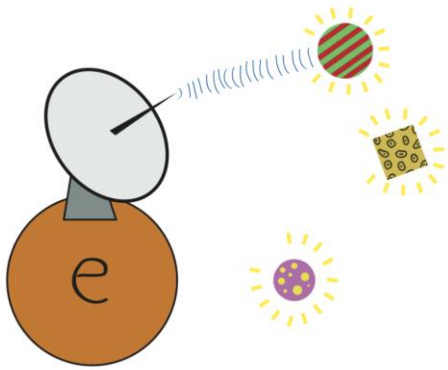
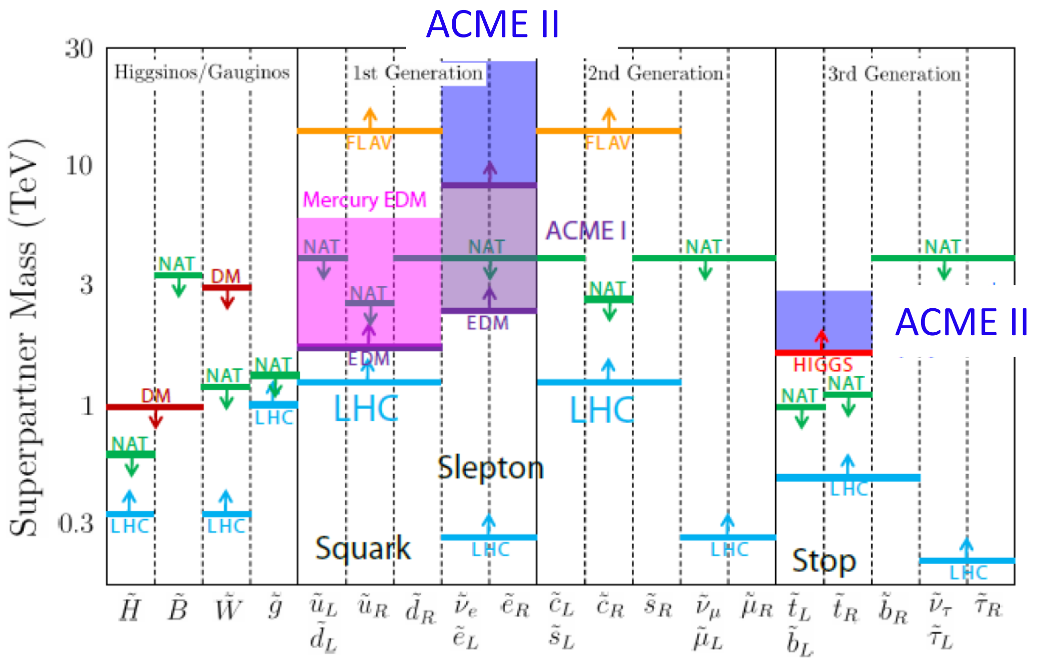


EDMs probe TeV scale physics



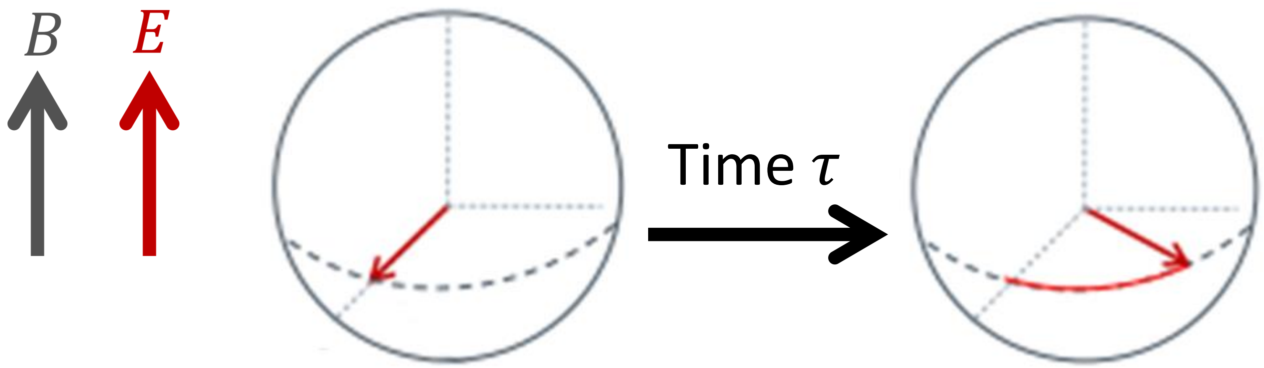
- New theories predict particles at the TeV energy scale.
- Electron EDM sensitive to coupling with T-violating interactions with particles at the 3-30 TeV scale.





EDM measurement scheme

$$H = -\mu \cdot B - d \cdot E$$



$$\phi_+ = \mu B\tau + dE\tau$$

EDM measurement scheme

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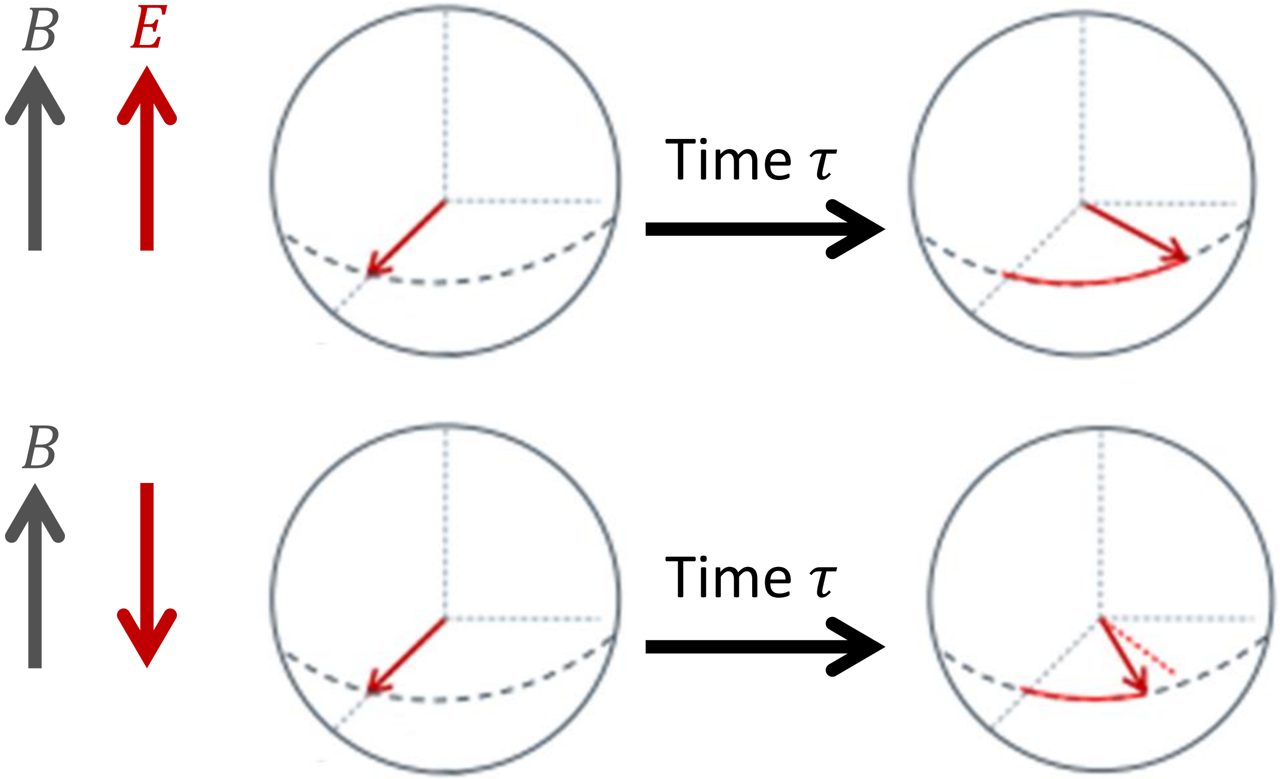


$$\phi_+ = \mu B\tau + dE\tau$$

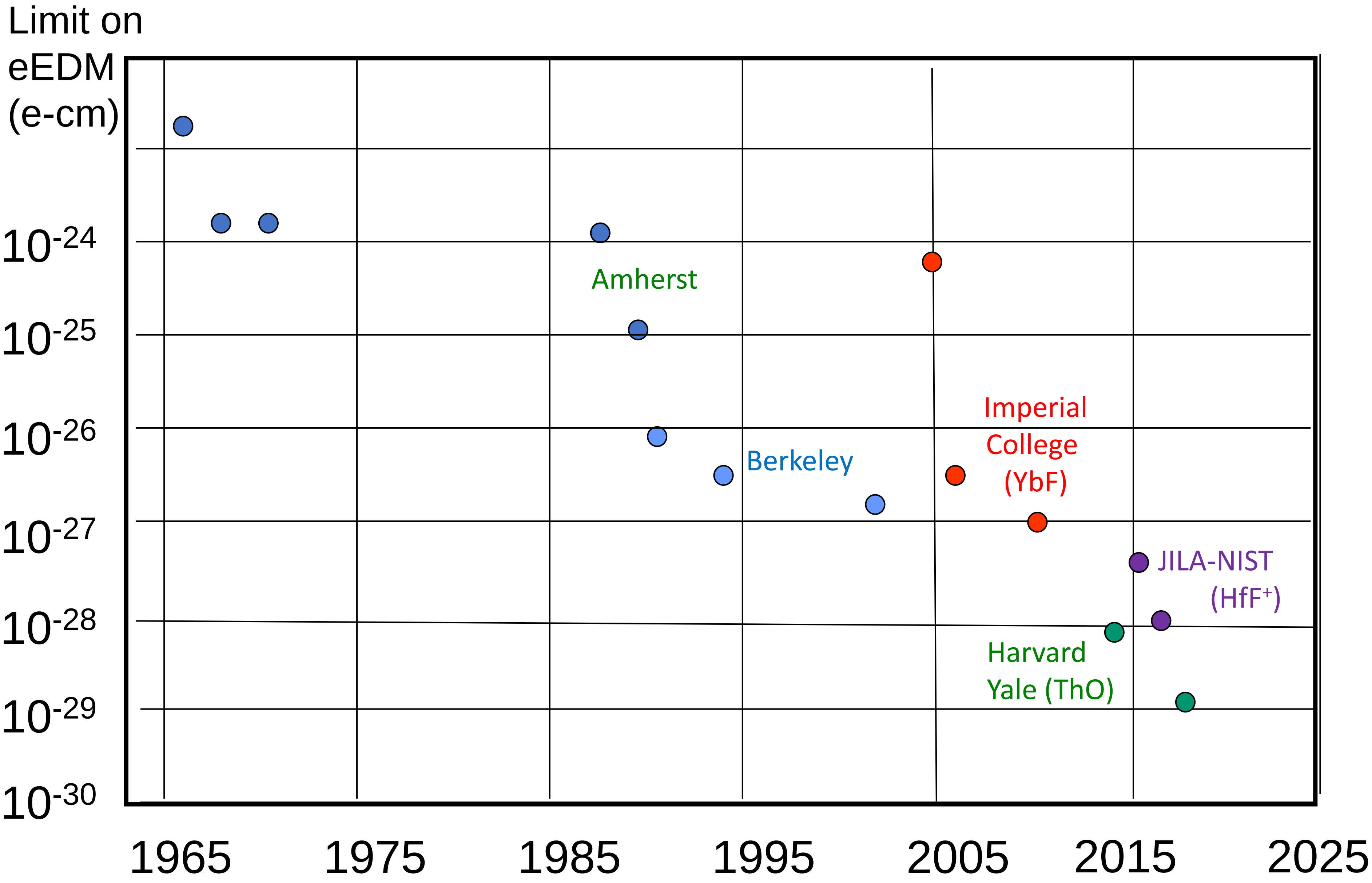
$$\phi_- = \mu B\tau - dE\tau$$

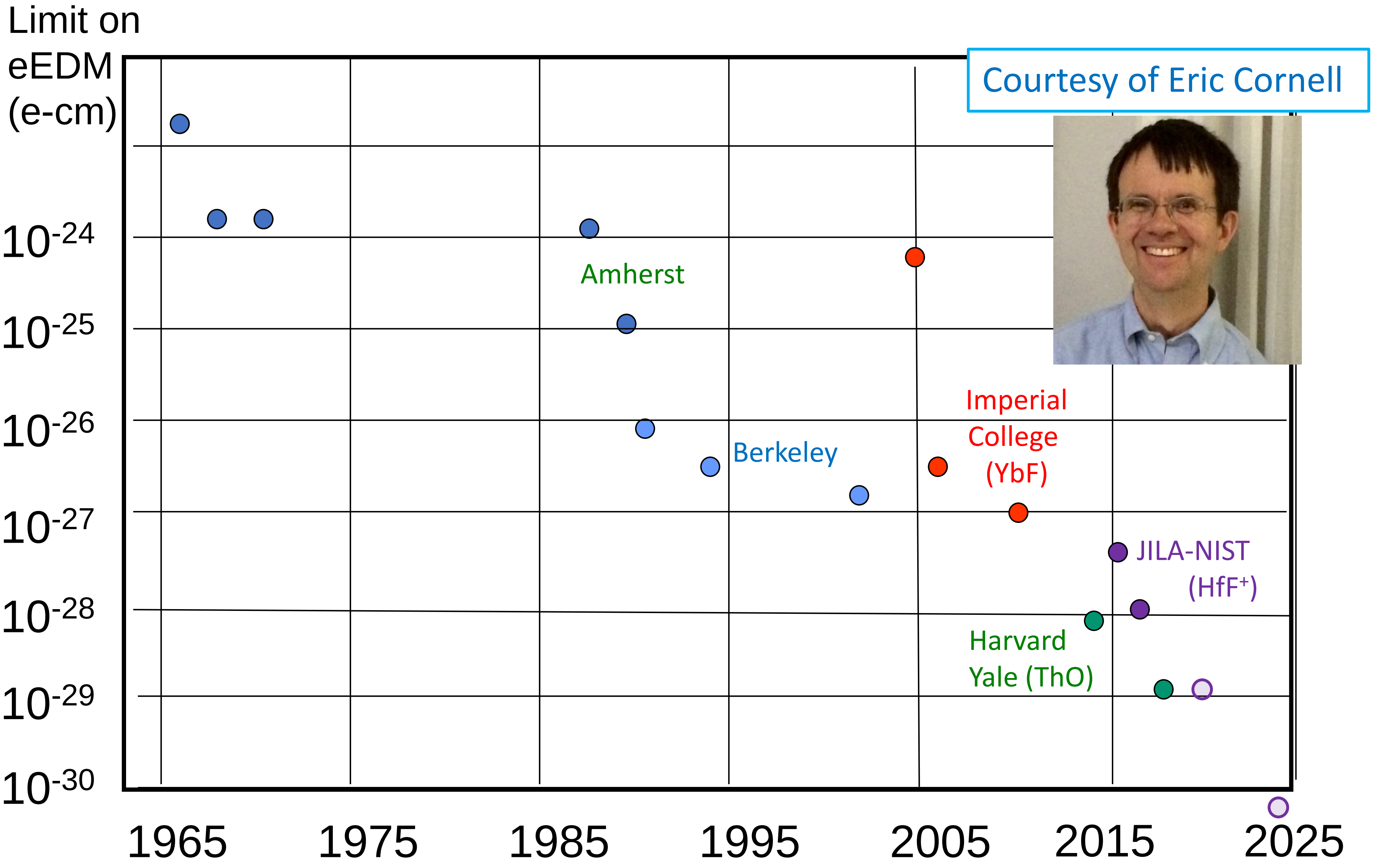
Figure of merit:

$$\frac{1}{\Delta d} \propto E\tau\sqrt{\dot{N}T}$$

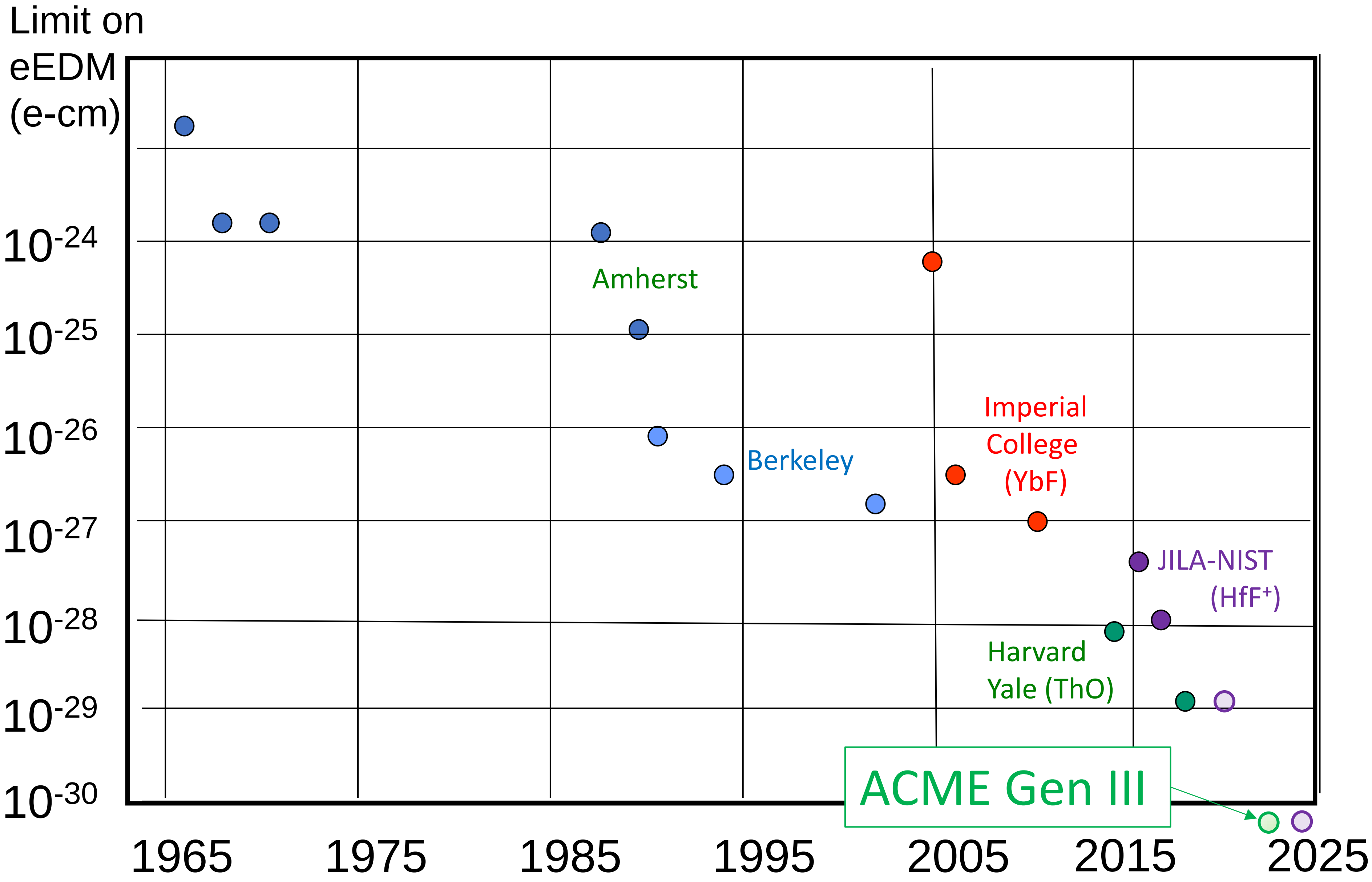
E = electric field
τ = precession time
$\dot{N}$ = experiment repetition rate
T = integration time

$$\boxed{d \propto \phi_+ - \phi_-}$$


Limit on eEDM (e-cm)
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
1965
1975
1985
1995
2005
2015
2025
Amherst
Berkeley
Imperial College (YbF)
JILA-NIST (HfF^+)
Harvard Yale (ThO)



Courtesy of Eric Cornell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Harvard Yale (ThO)
ACME Gen III

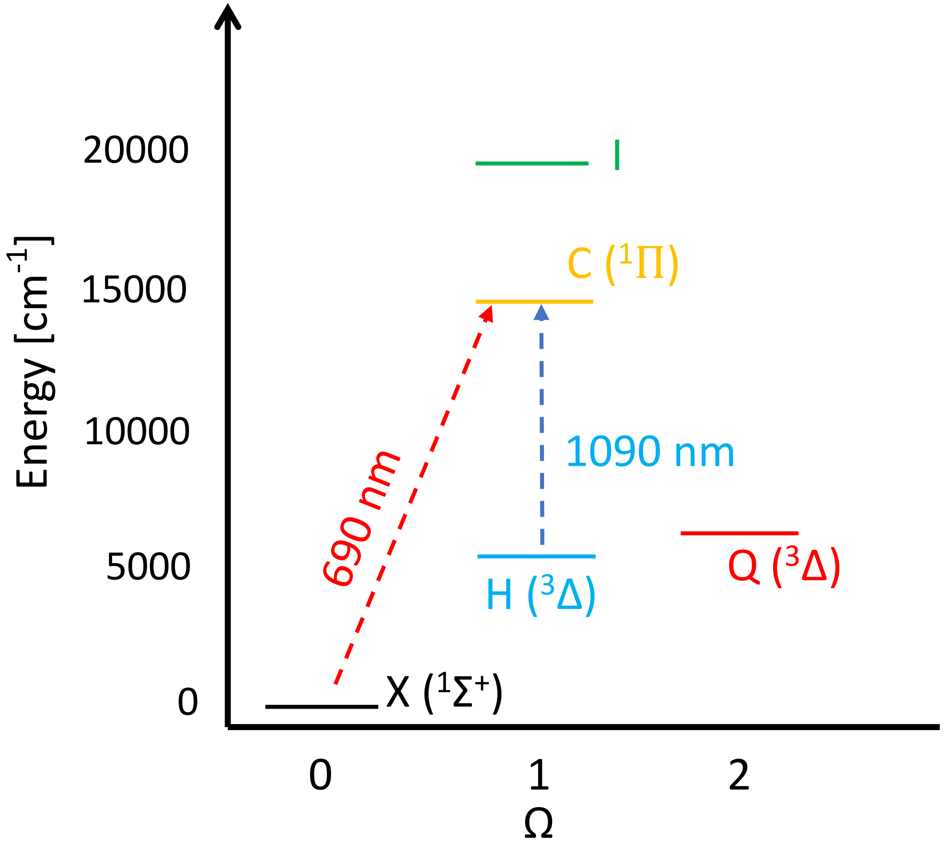
The ThO $H\,^3\Delta_1$ state

Label for electronic state

Triplet: S=1

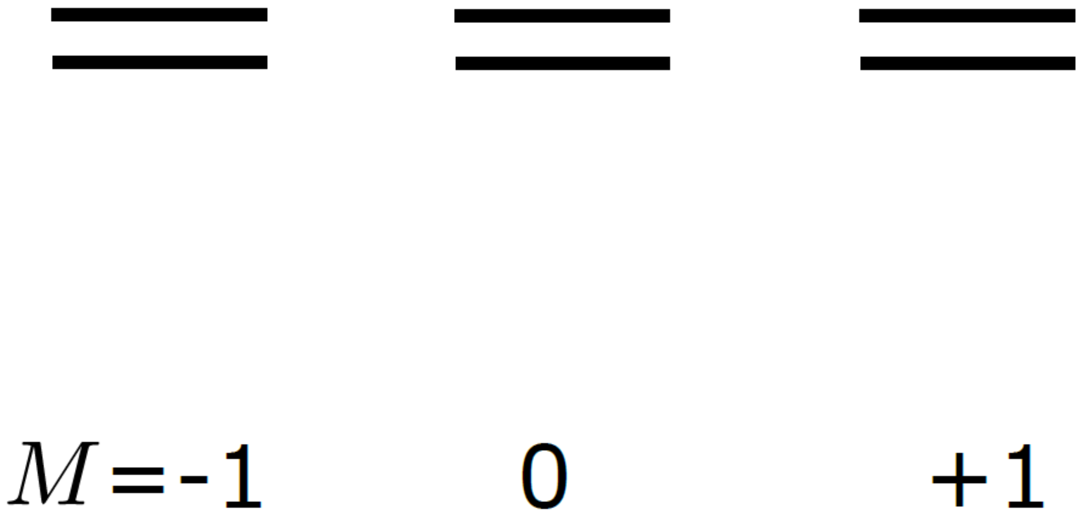
Λ=2, projection of orbital angular momentum on molecular axis (analog. l=2 as *d-orbital* in atom)

Sum of Ω = Λ + Σ (projection of spin on molecular axis).
Ω = 1 and Λ=2 → Σ = -1, i.e. here spin is anti-aligned with Ω



The ThO $H\ ^3\Delta_1$ state

- High effective field.
- Can be easily polarized.
- Low magnetic noise sensitivity.



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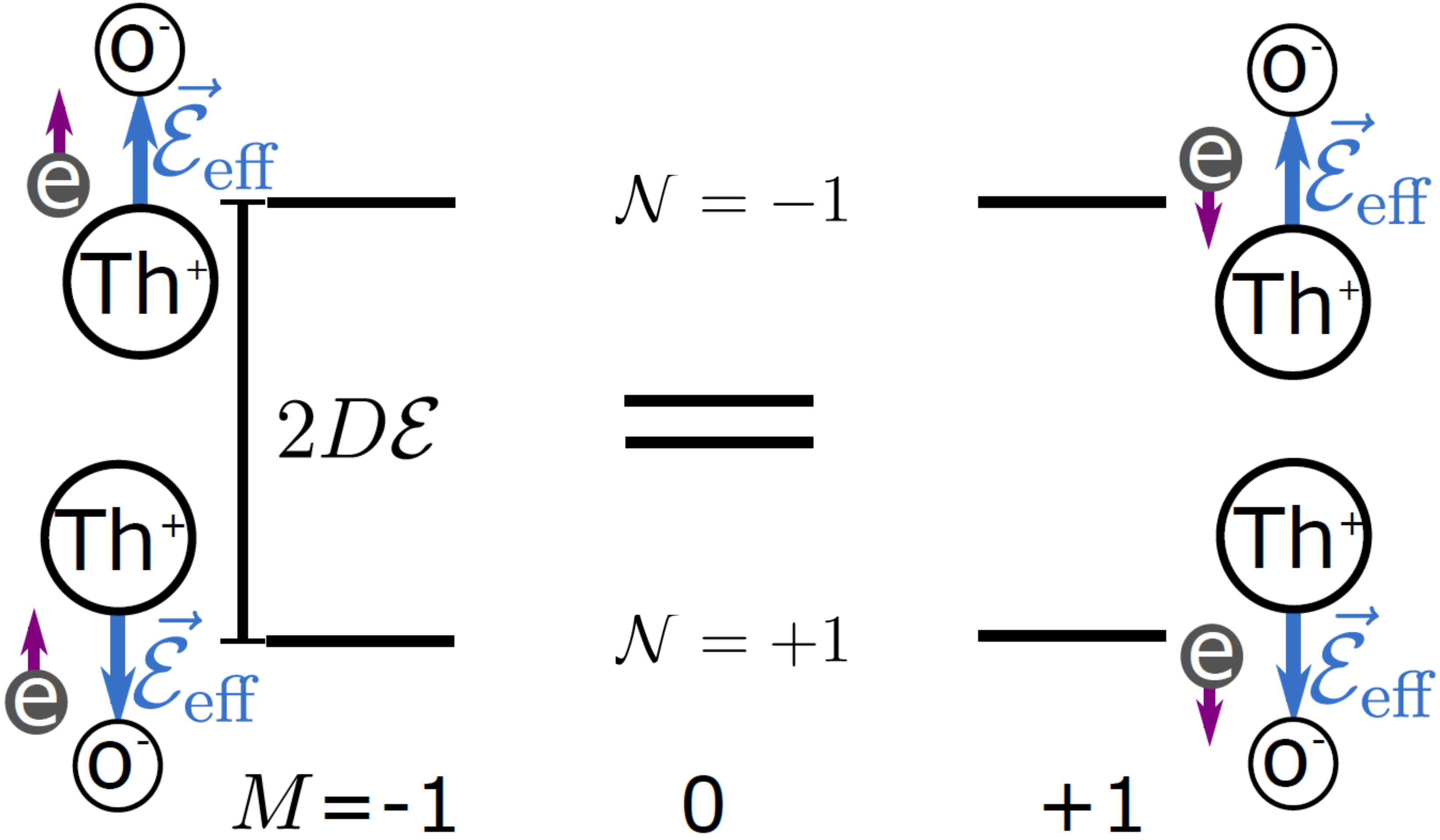

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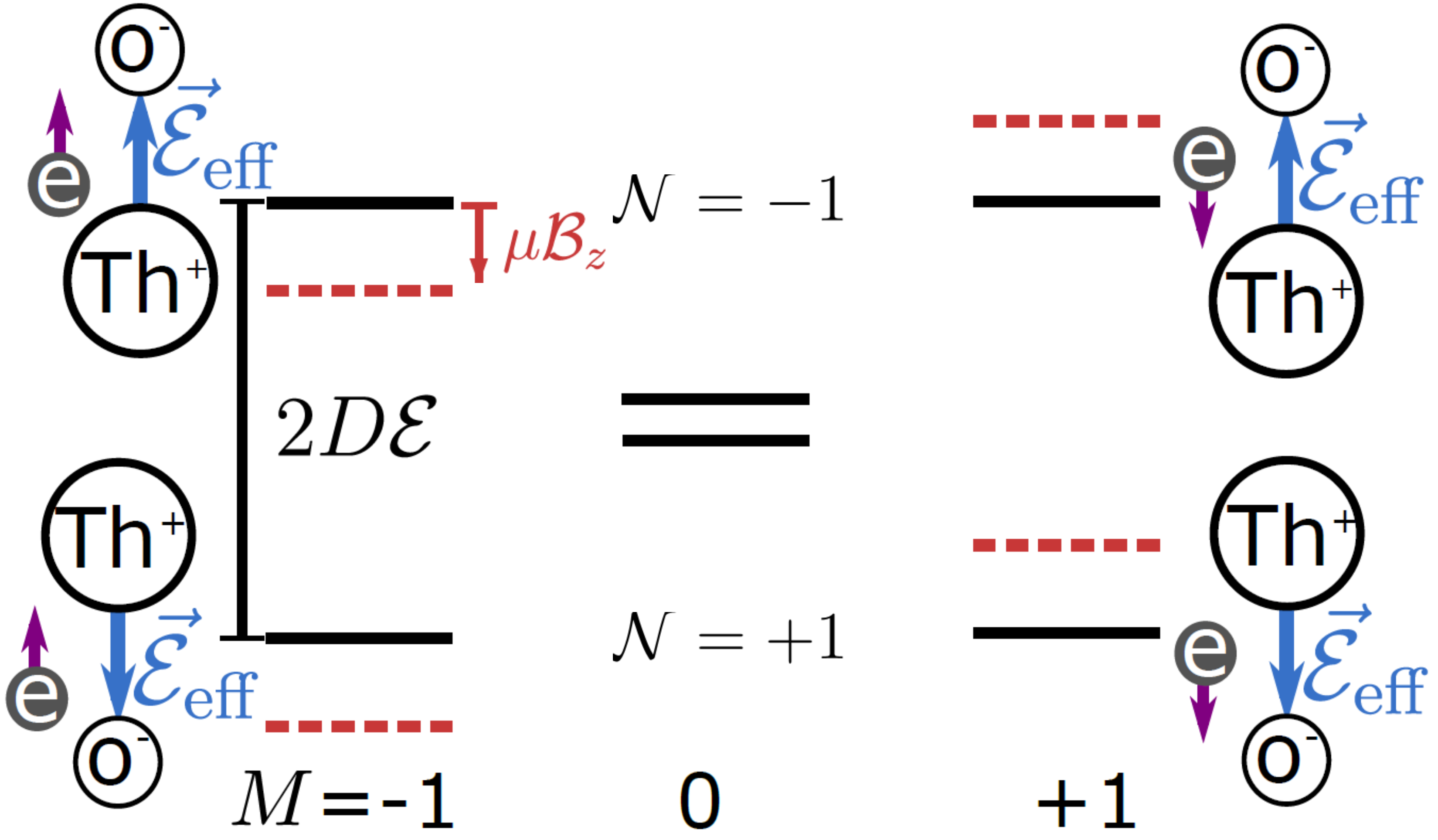

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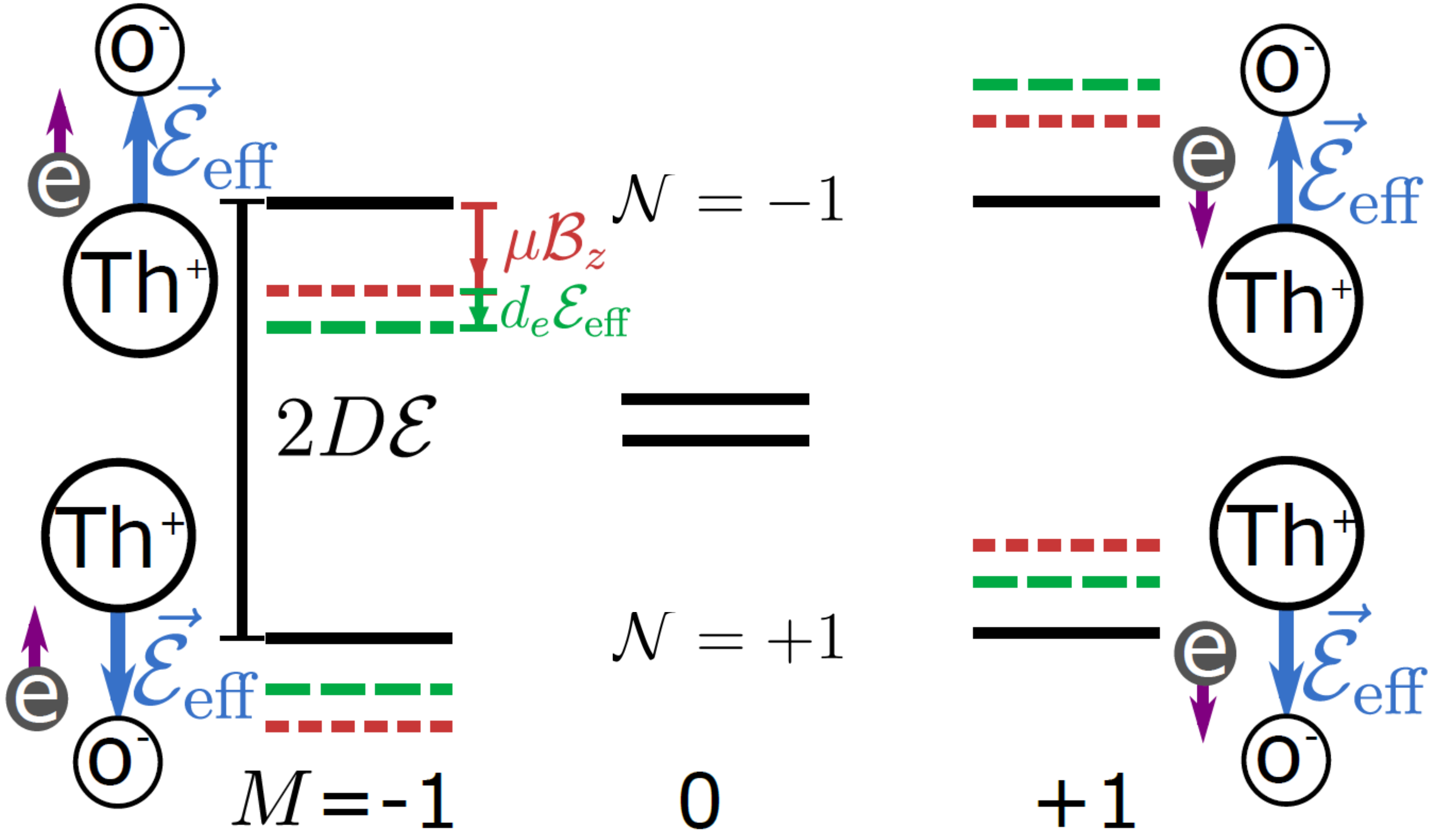

The ThO $H\ ^3\Delta_1$ state

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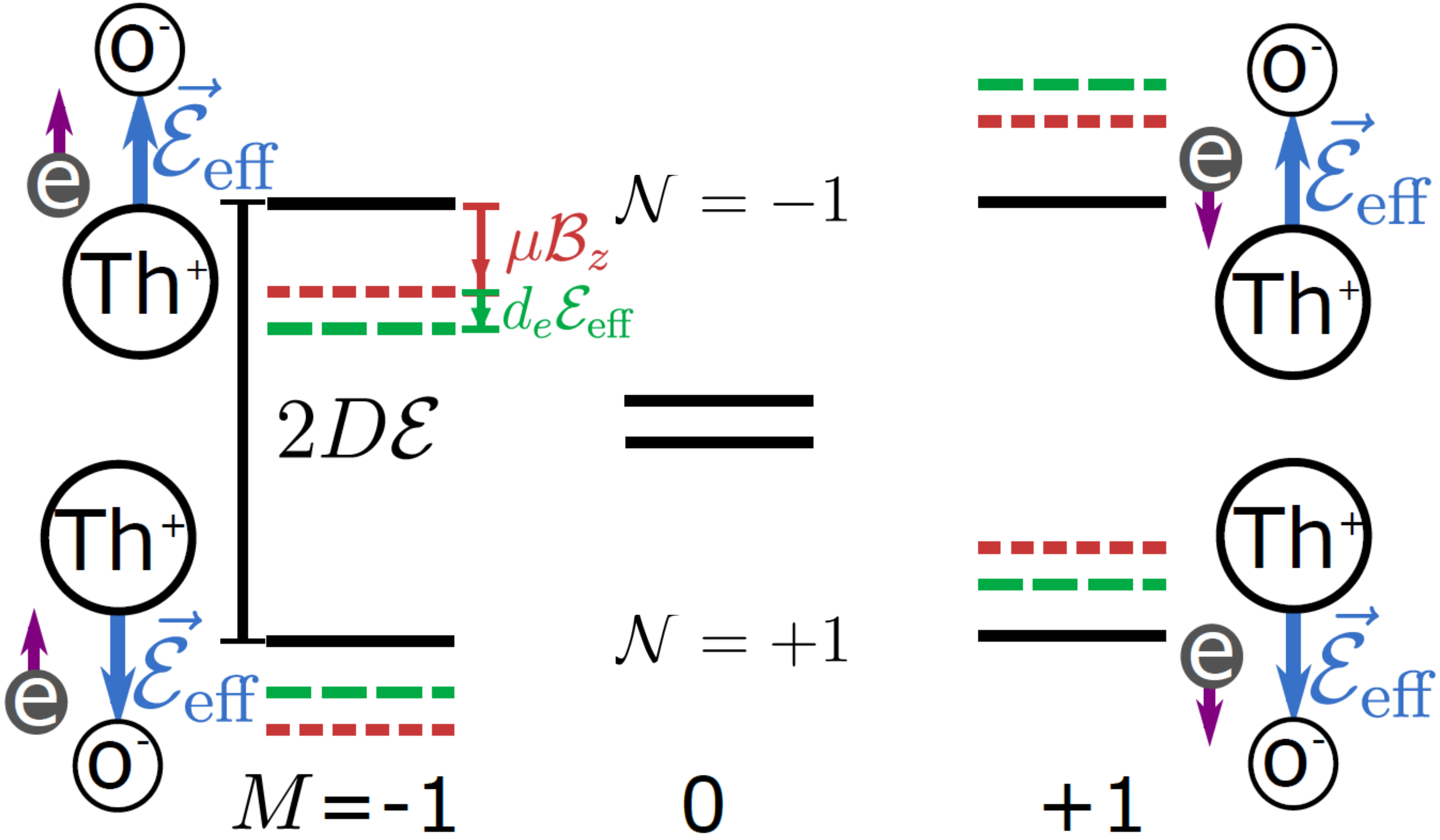
Can reverse the direction of $\vec{\mathcal{E}}_{\text{eff}}$ either by reversing:

- The lab electric field, E.
- The internal electric field, N.



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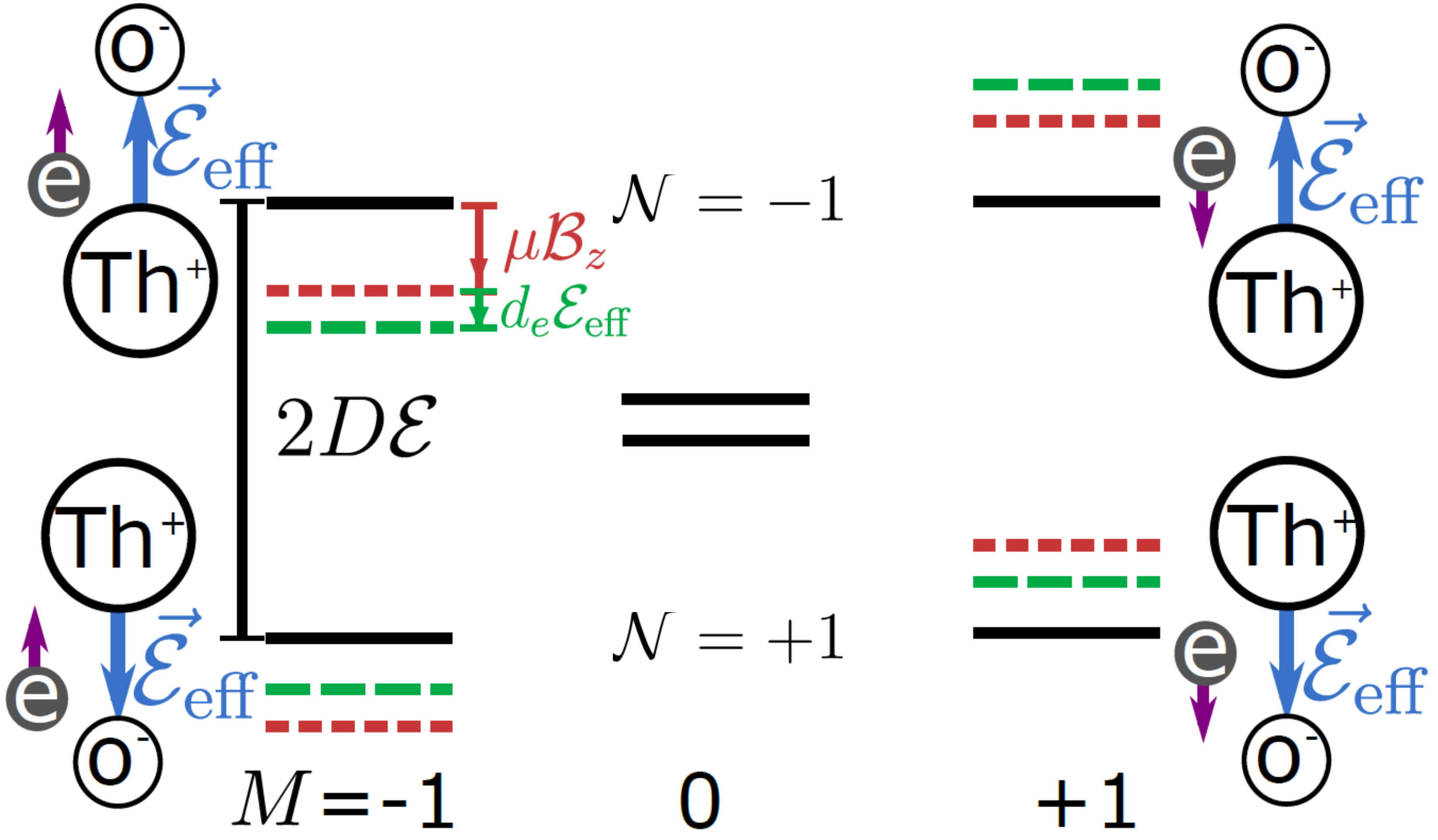
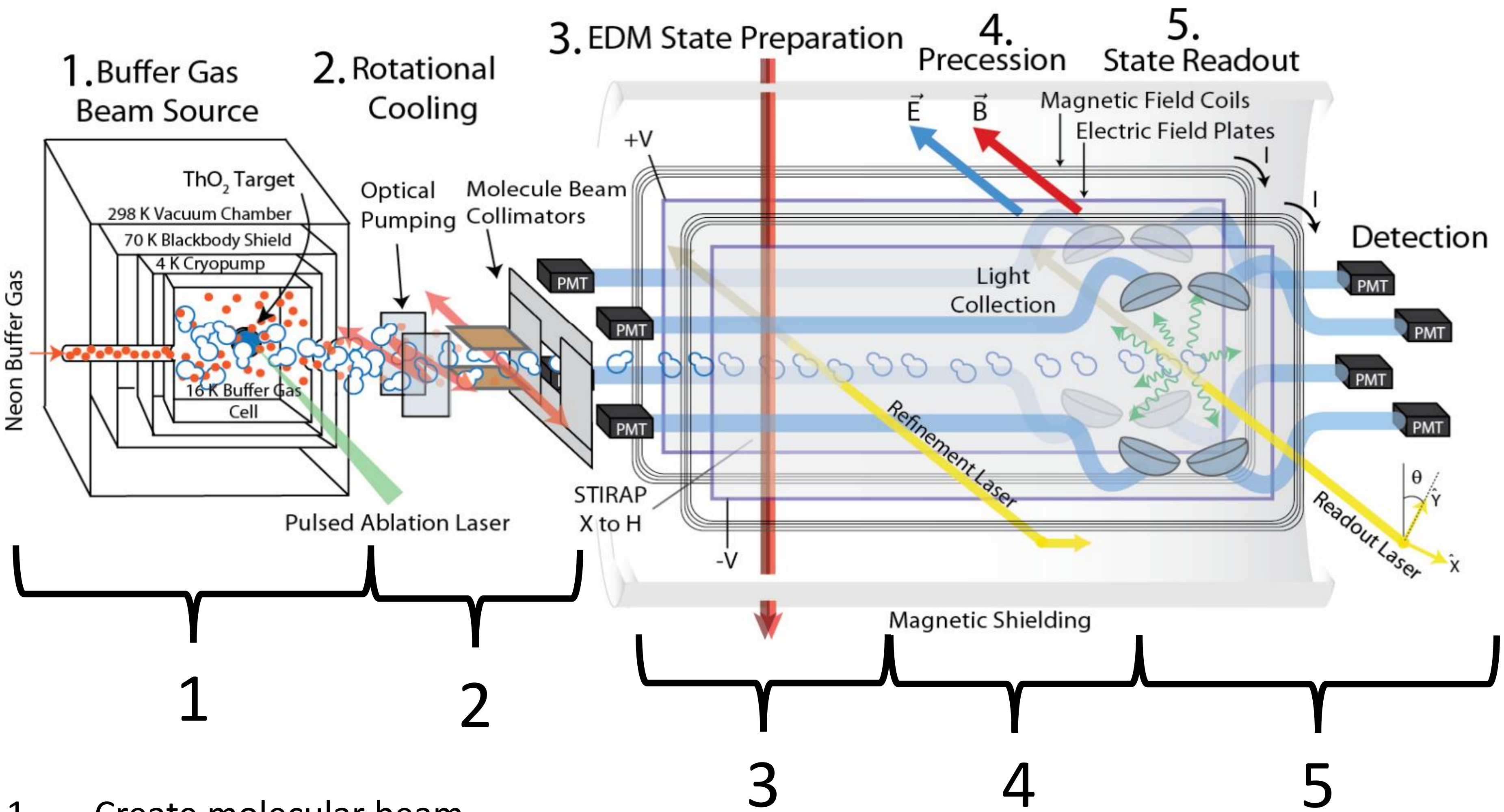
Measure EDM energy shift, NE correlated frequency $\omega^{\mathcal{N}\mathcal{E}}$.

$$d_e\mathcal{E}_{\text{eff}} = -\hbar\omega^{\mathcal{N}\mathcal{E}}$$



Apparatus for 2nd generation ACME

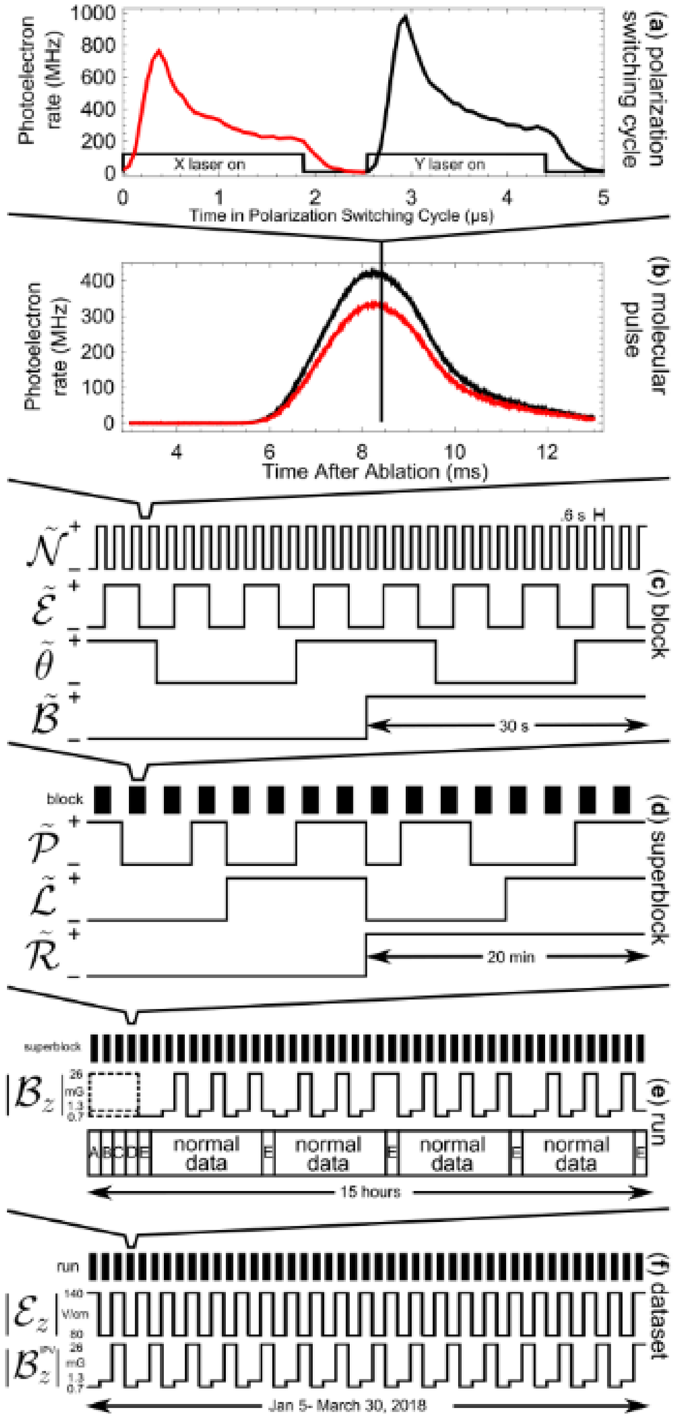


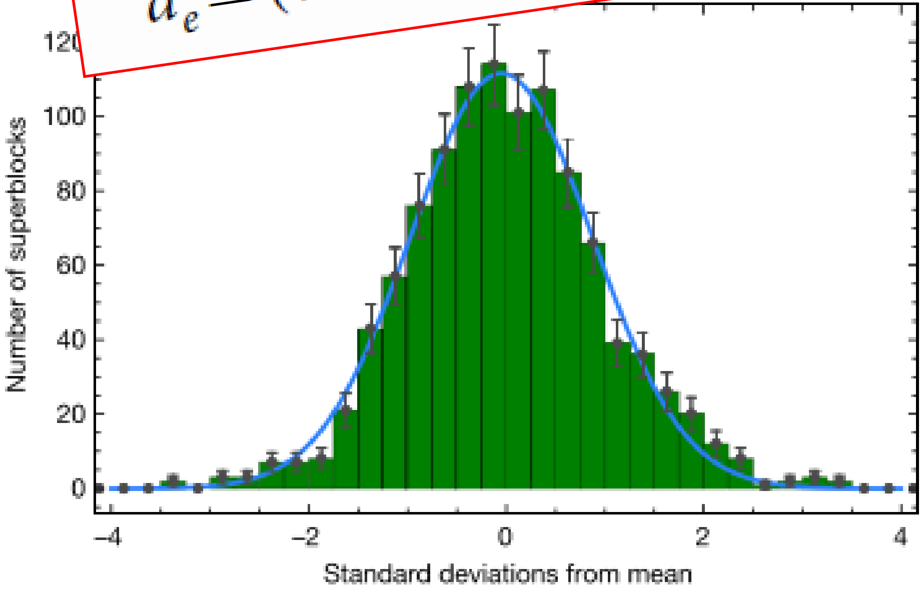
1. Create molecular beam
2. populate single quantum state
3. STIRAP transfer to science state
4. spin precession
5. Read out precession phase

ACME II final result

- Fastest switch 200kHz: Resolve relative population in two orthogonal states (quantum phase measurement)
- Two ways of reversing electric field interaction with eEDM
- Slower switches to distinguish systematic errors
- ACME II data set: 3 months of EDM data (after ≈1 year of systematic error searches)

$$d_e = (4.3 \pm 3.1_{\text{stat}} \pm 2.6_{\text{syst}}) \times 10^{-30}\, e\ \text{cm}$$





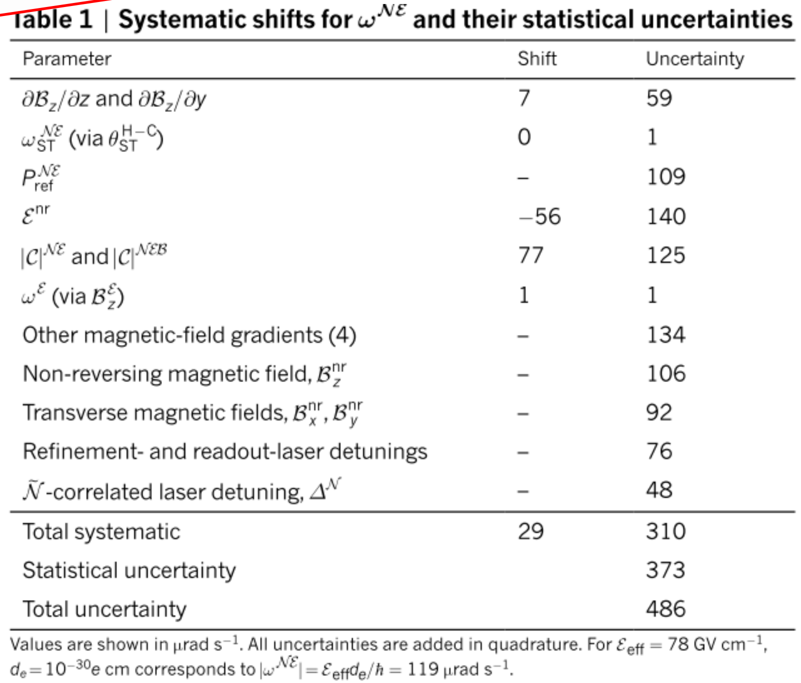
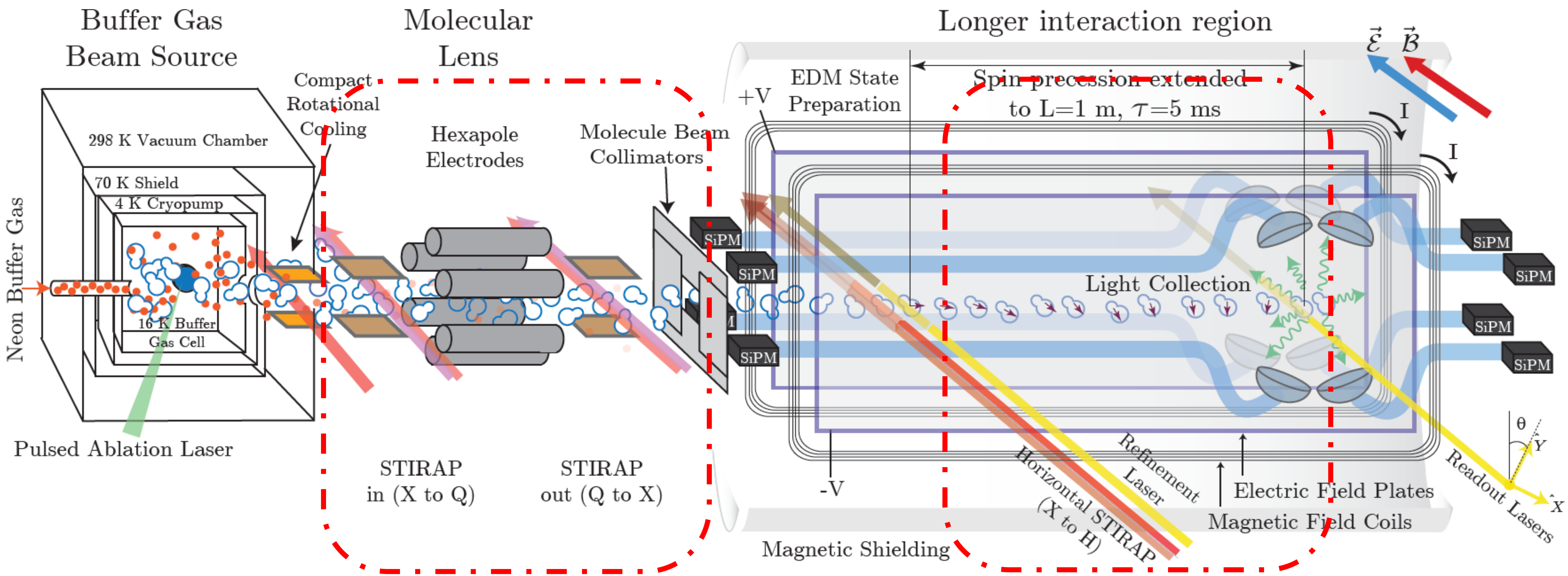


Table 1 | Systematic shifts for $\omega^{\mathcal{N}\mathcal{E}}$ and their statistical uncertainties

Parameter	Shift	Uncertainty
$\partial\mathcal{B}_z/\partial z$ and $\partial\mathcal{B}_z/\partial y$	7	59
$\omega_{\text{ST}}^{\mathcal{N}\mathcal{E}}$ (via $\theta_{\text{ST}}^{\text{H-C}}$)	0	1
$P_{\text{ref}}^{\mathcal{N}\mathcal{E}}$	–	109
$\mathcal{E}^{\text{nr}}$	−56	140
$\lvert C\rvert^{\mathcal{N}\mathcal{E}}$ and $\lvert C\rvert^{\mathcal{N}\mathcal{E}\mathcal{B}}$	77	125
$\omega^{\mathcal{E}}$ (via $\mathcal{B}_z^{\mathcal{E}}$)	1	1
Other magnetic-field gradients (4)	–	134
Non-reversing magnetic field, $\mathcal{B}_z^{\text{nr}}$	–	106
Transverse magnetic fields, $\mathcal{B}_x^{\text{nr}}$, $\mathcal{B}_y^{\text{nr}}$	–	92
Refinement- and readout-laser detunings	–	76
$\tilde{\mathcal{N}}$-correlated laser detuning, $\Delta^{\mathcal{N}}$	–	48
Total systematic	29	310
Statistical uncertainty		373
Total uncertainty		486

Values are shown in μrad s^{-1}. All uncertainties are added in quadrature. For $\mathcal{E}_{\text{eff}} = 78$ GV cm^{-1}, $d_e = 10^{-30}$e cm corresponds to $\lvert\omega^{\mathcal{N}\mathcal{E}}\rvert = \mathcal{E}_{\text{eff}} d_e/\hbar = 119$ μrad s^{-1}.

Apparatus for ACME III



Much bigger molecular flux!

Longer Coherent Time!

Projected sensitivity gain for ACME III

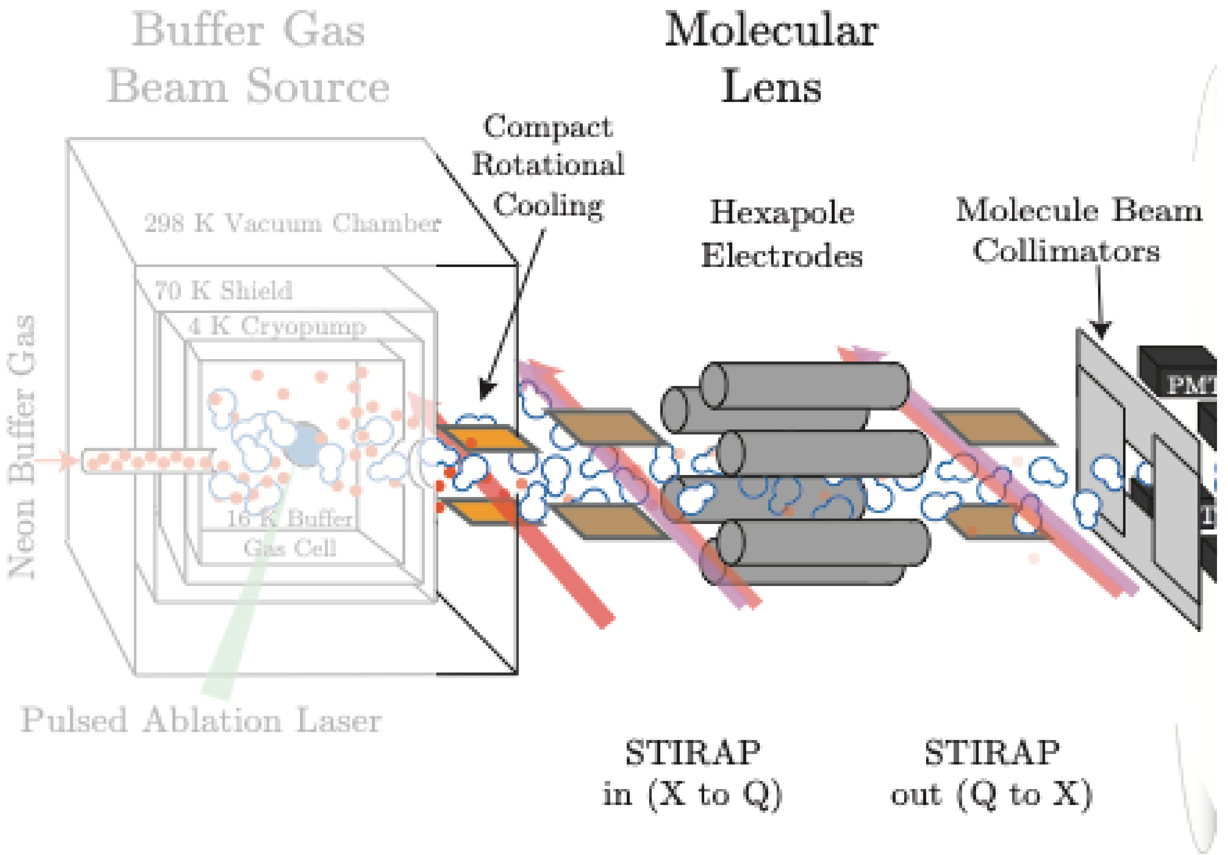
$$\delta d_e = \frac{1}{2T\mathcal{E}_{eff}\sqrt{N}}$$

Already include practical constraints, e.g. the demonstrated state preparation efficiency

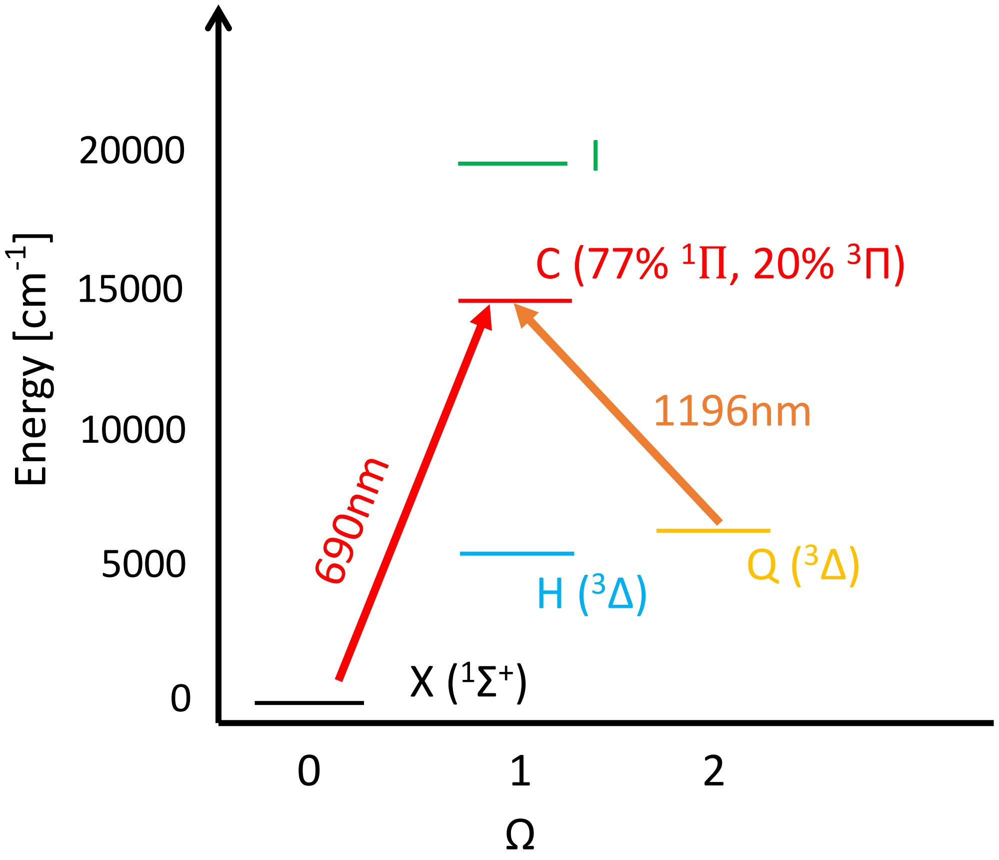
Improvement	Signal Gain	EDM Sensitivity Gain
Increased Precession Time	0.20	2.3
Electrostatic Lens	15	3.9
SiPM Detector Upgrade	2.3	1.5
Timing Jitter Noise Reduction	1	1.7
Total	7.4	23

4 important aspects of molecular lens

- Good electronic state for lensing
  - Q ($^3\Delta_2$) state of ThO
- Robust state preparation
  - 90% sequential STIRAPs
- Efficient molecular beam focusing
  - Hexapole electrostatic lens, x19 times flux enhancement
- Rotational cooling upgrade, etc
  - more compact
  - cover broader Doppler distribution



Q ($^3\Delta_2$) state: a new resource for the ACME e$^-$EDM search



Made first measurement on the relevant properties of Q state, and showed it is ideal for molecular lens:

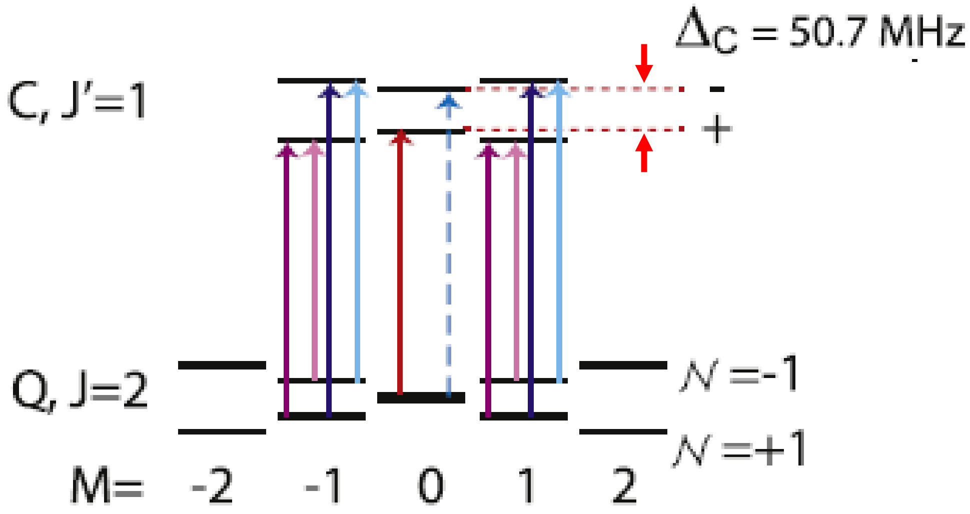
✓ Stark shift:	linear, $D_Q = 4.1$D
✓ Zeeman shift:	$g_Q = 2.07\mu_B$
✓ Transition strength:	$d_{Q\text{-}C} = 1.0$D
✓ Life time (90% c.l.):	$\tau > 62$ms

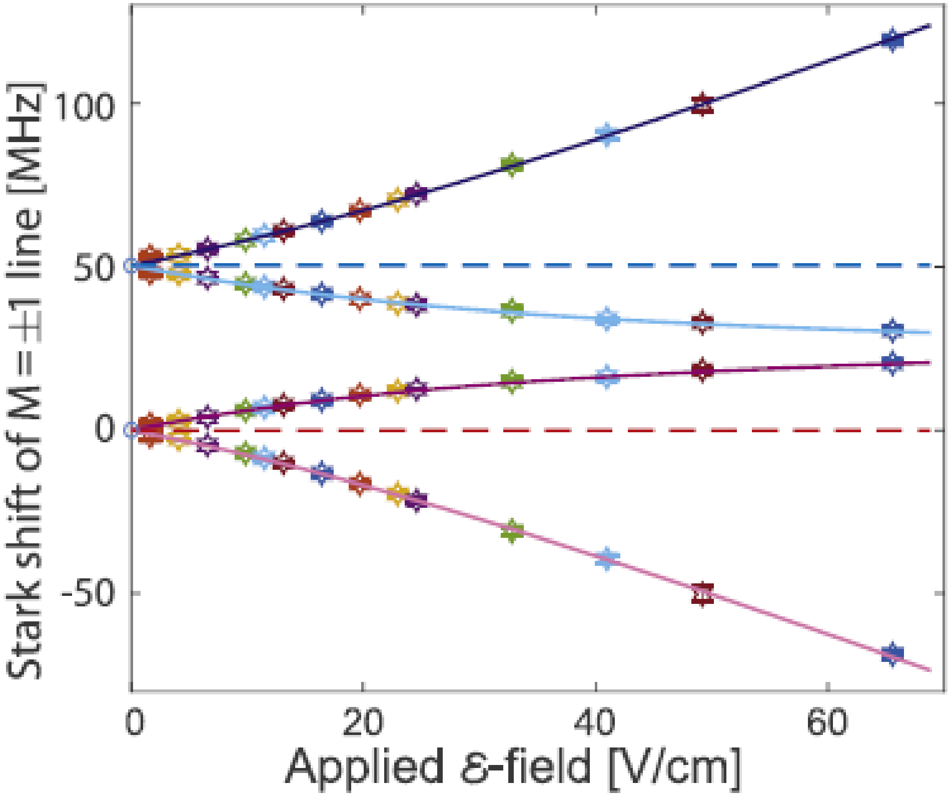
X. Wu et al, *NJP* (2020) arXiv:1911.03015

Q ($^3\Delta_2$) state molecule-frame electric dipole

- Differential Stark-shift measurement of Q—C transition

X. Wu et al, *NJP* (2020) arXiv:1911.03015



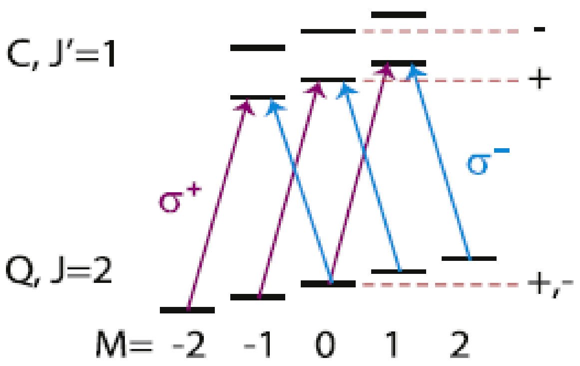


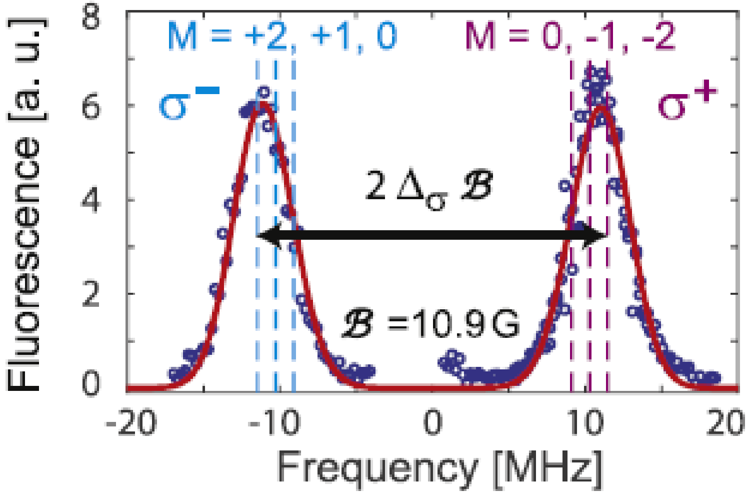
$$d_Q = 4.07(6)\text{D and } d_C = 2.60(4)\text{D}$$

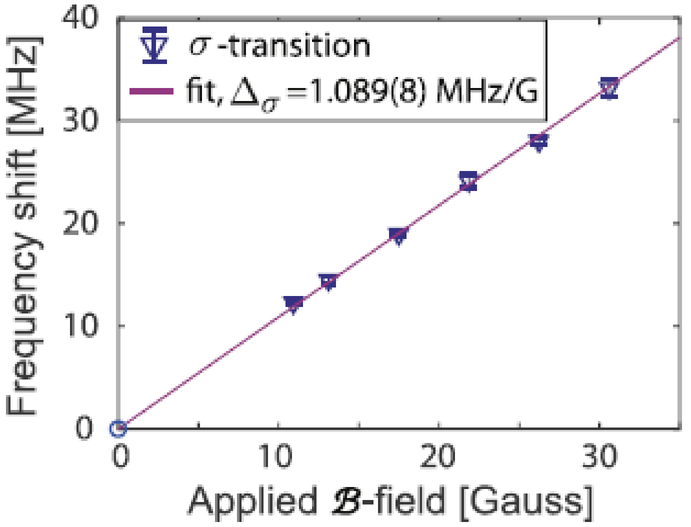
Q ($^3\Delta_2$) state molecule-frame magnetic dipole

- Differential Zeeman-shift measurement of Q—C transition

X. Wu et al, *NJP* (2020) arXiv:1911.03015







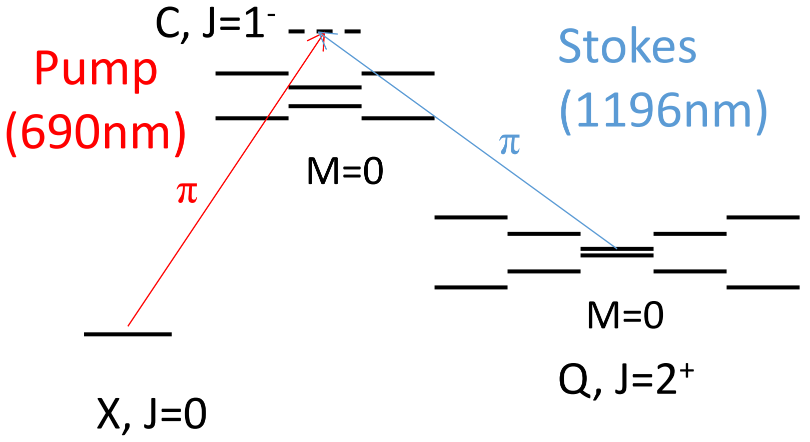
Together with transition with π-polarization

$$g_Q = 2.07(11)$$
$$g_C = 1.24(6)$$

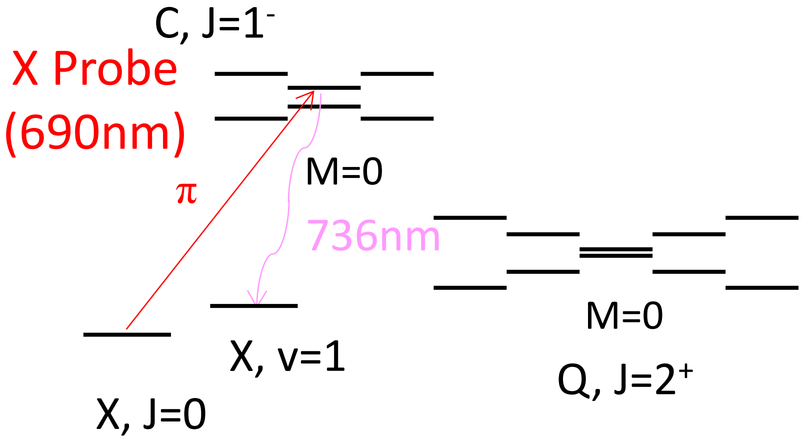
How well can we transfer population into Q state?

STIRAP and Probe Level Scheme in Test Setup:

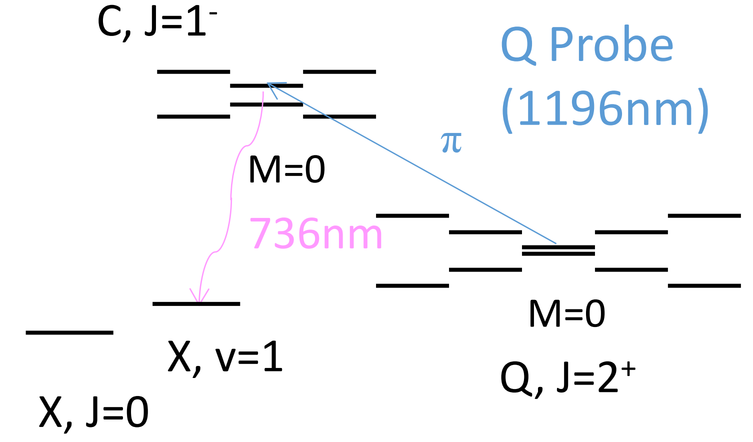
STIRAP Scheme:



Probe X state:



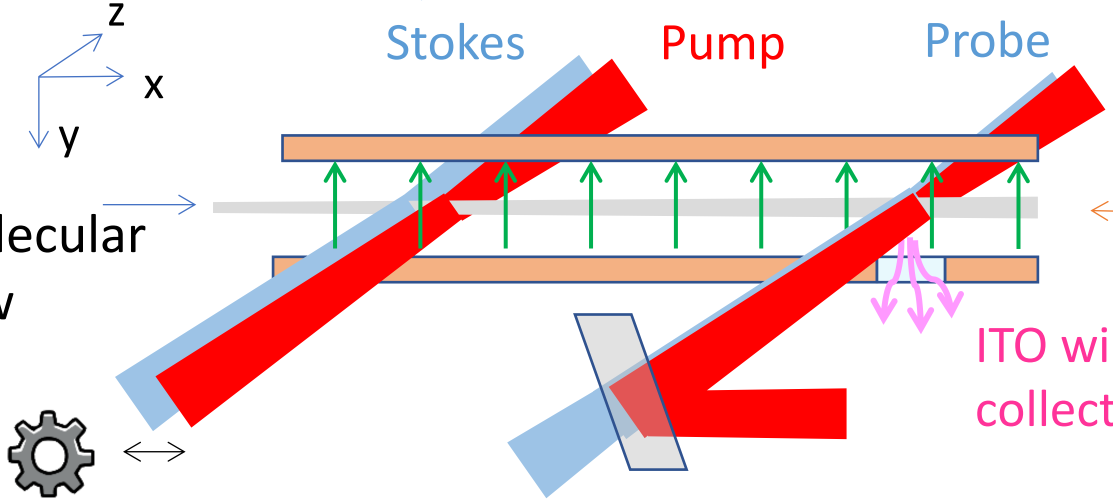
Probe Q state:



✓ Detect 736nm off-diagonal decay from C—X (v=1), helps a lot to suppress background scattering

✓ Both probes excite to EXACTLY the same C state sublevel, so allows direct comparison between population in X and in Q

STIRAP Setup



STIRAP

Probe

Q-C
Stokes

X-C
Pump

Q state
Probe

X state
Probe

Molecular
flow

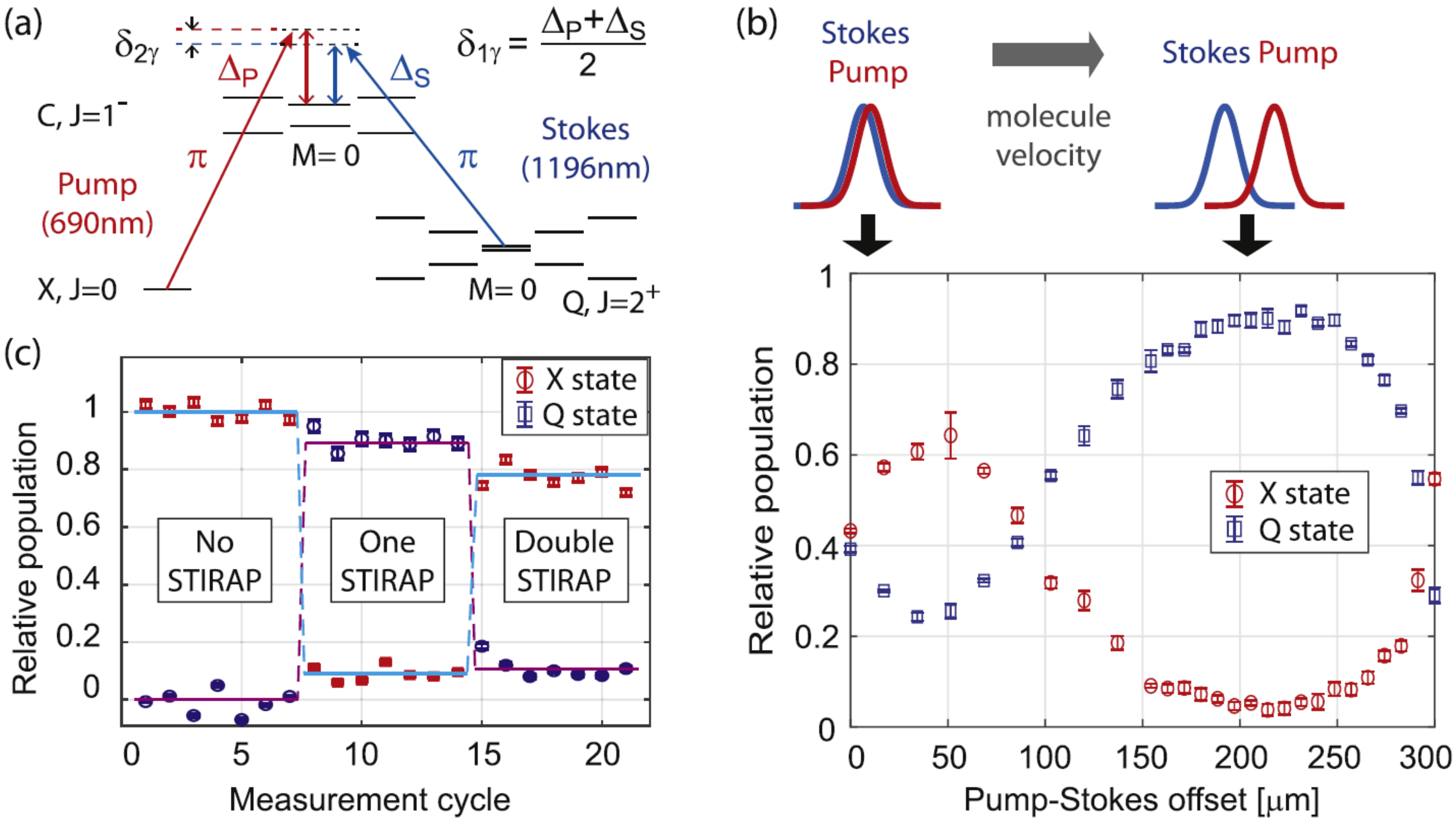
Continuous, homogeneous,
quantizing E-field

ITO window for fluorescence
collection

Offset adjustable

Overlap two probe beams,
switch between X/Q state

Efficient population transfer into and out of Q state: 90% STIRAP efficiency



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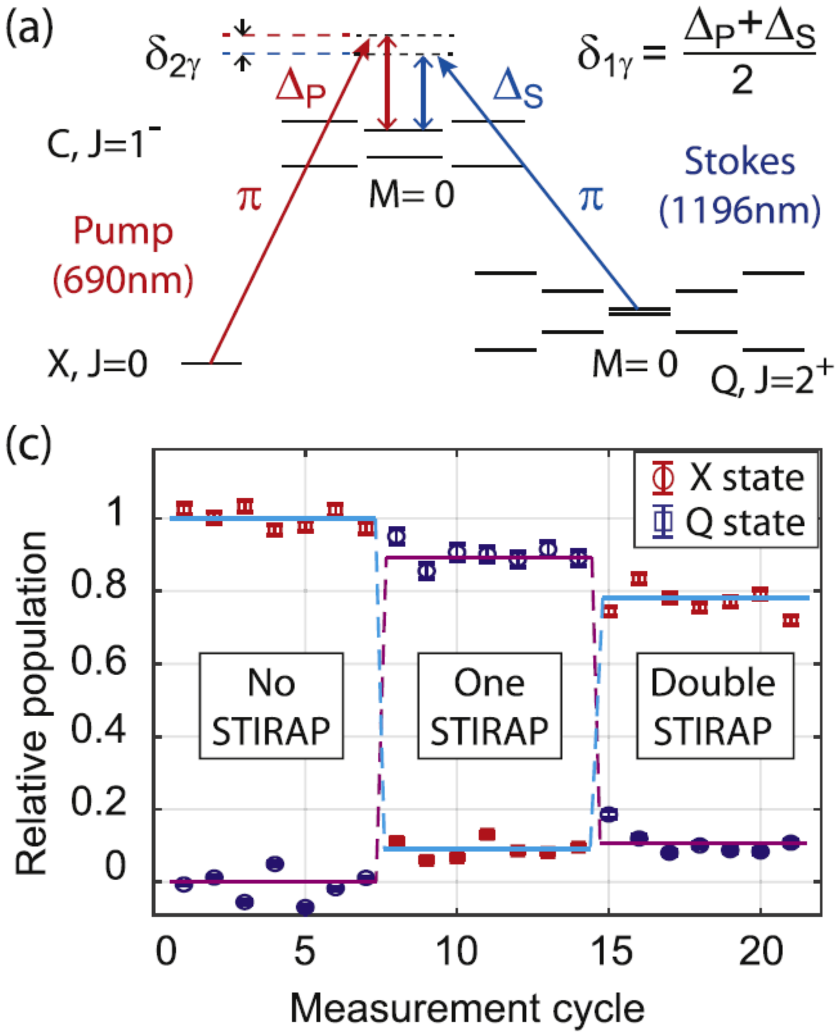
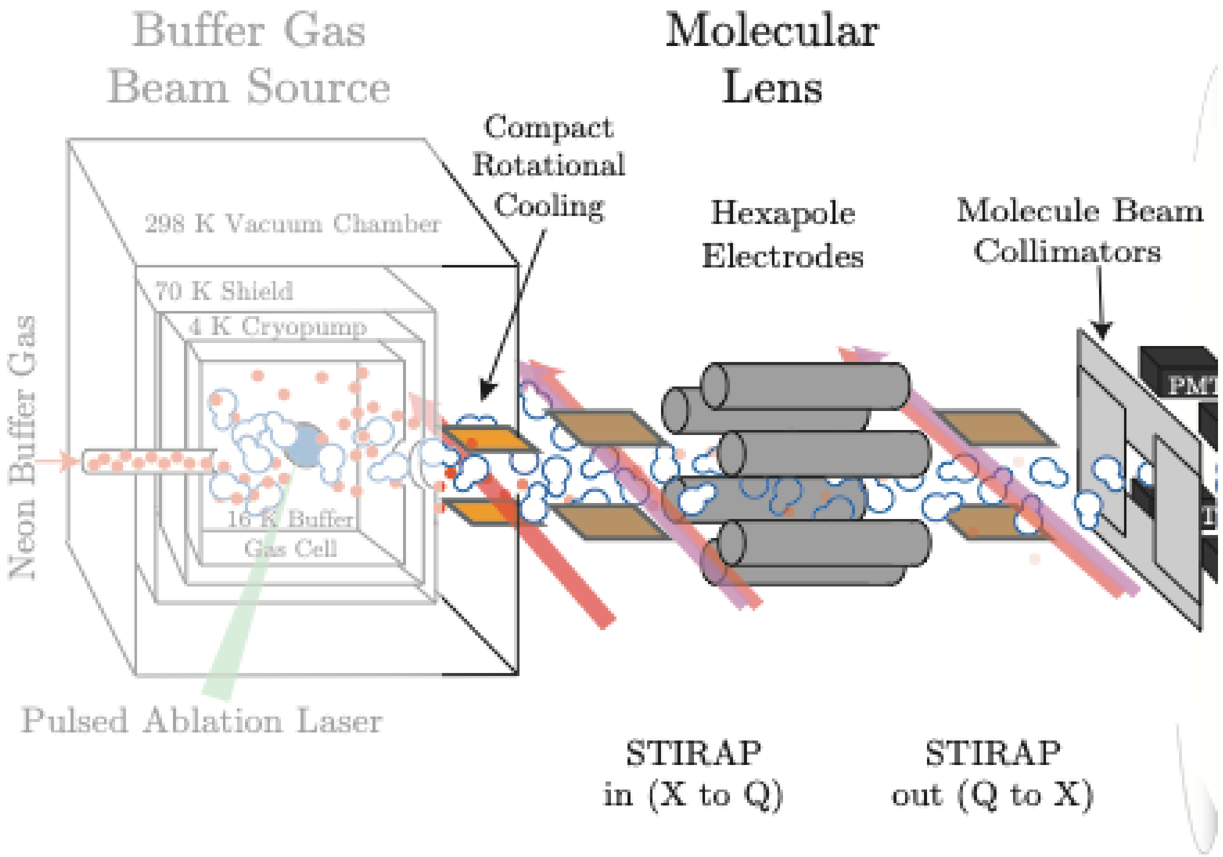
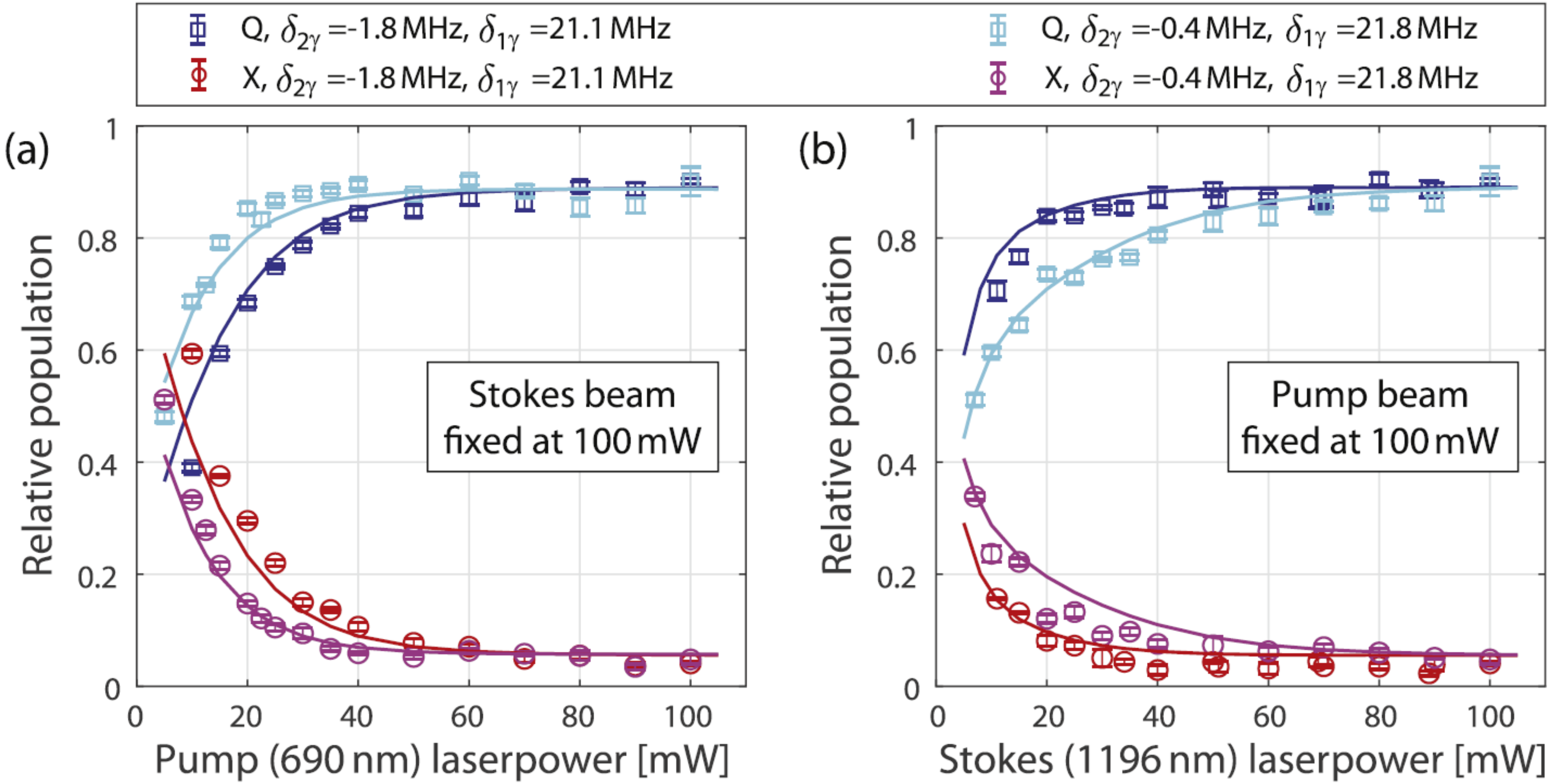


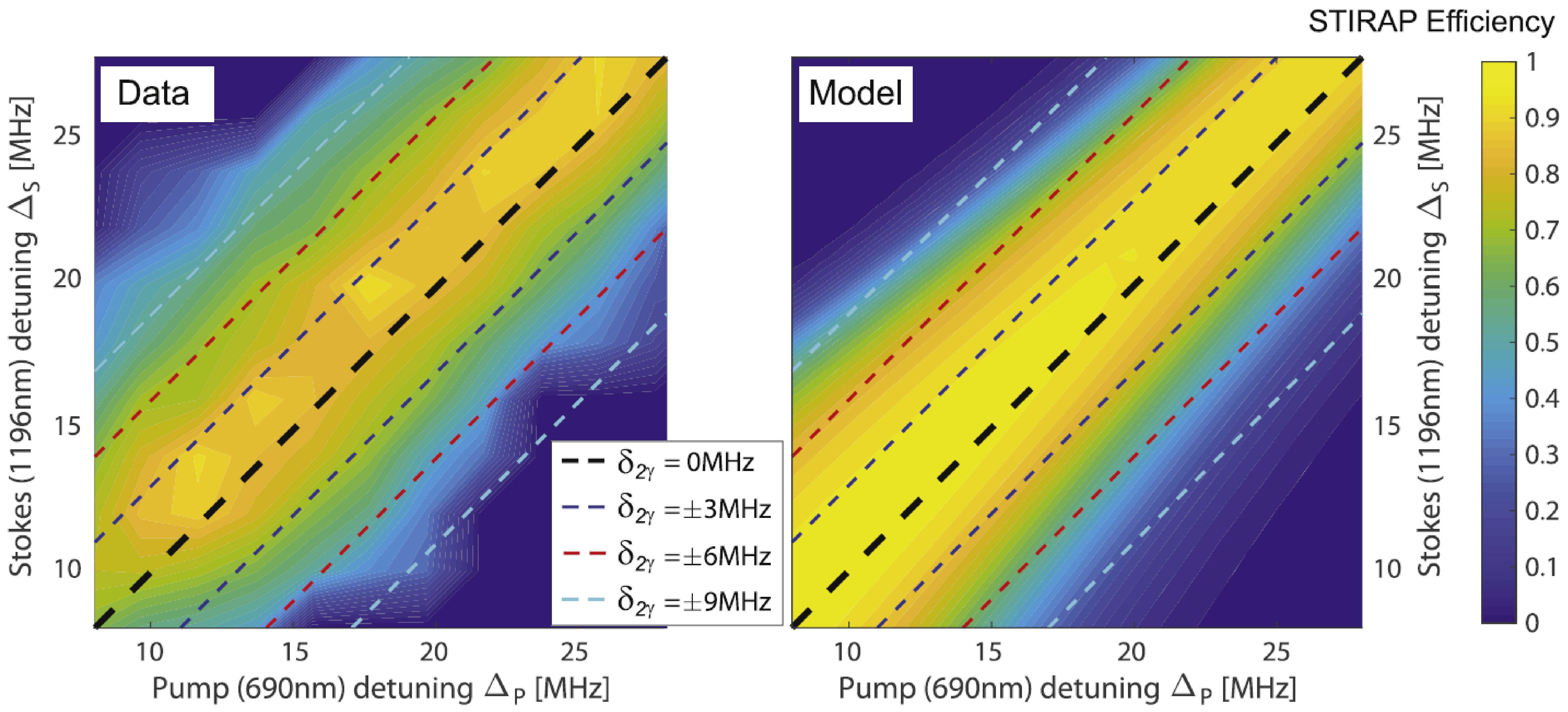


Power saturation scan for STIRAP laser (both Pump & Stokes)



Population transfer fully saturated!!

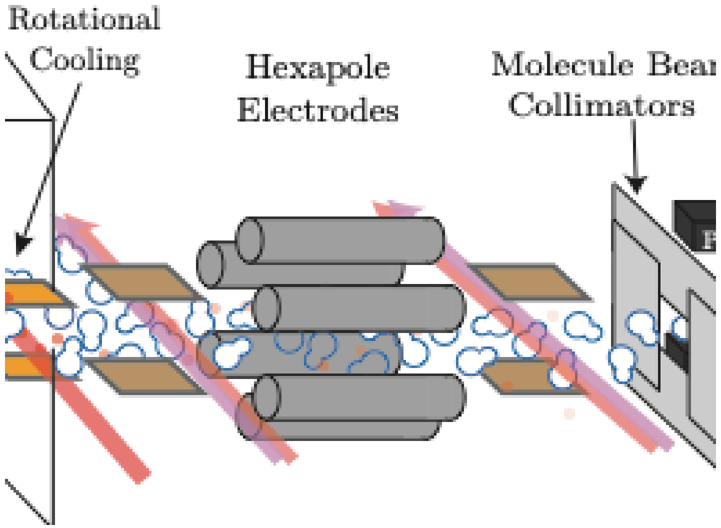
STIRAP efficiency vs. 2-photon detuning scan

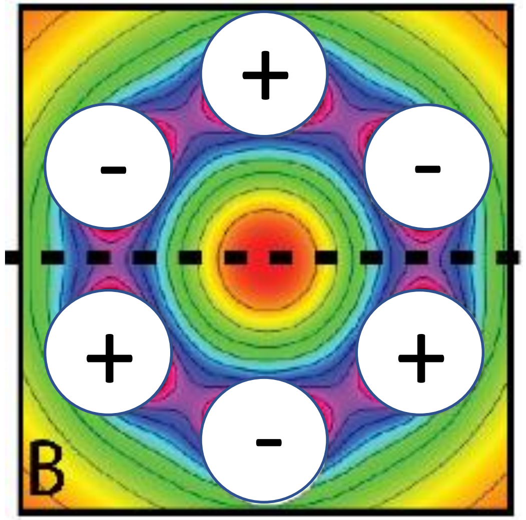


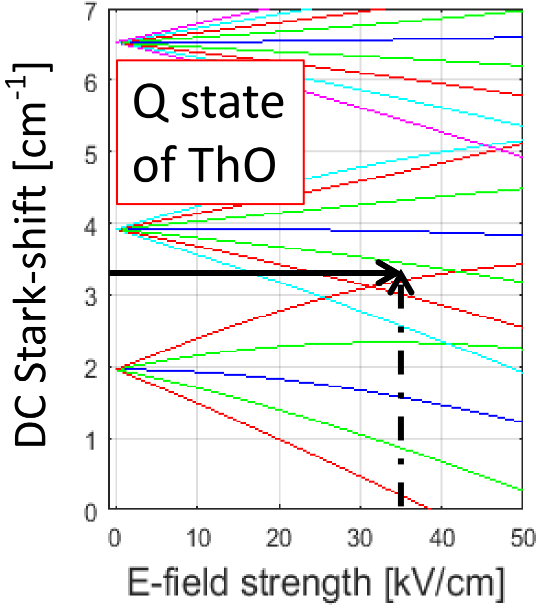
Electrostatic Focusing

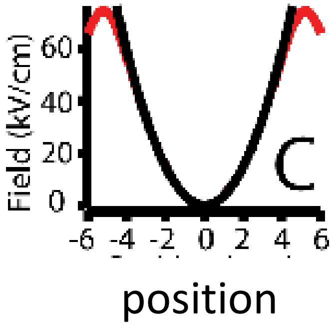
Hexapole electrostatic lens

- Quadratic E field distribution
- Harmonic potential for states with Linear Stark-shift
- ±22kV, 1.5” diameter: 1.8K trap depth, Δv_{tran}=±10m/s capture range

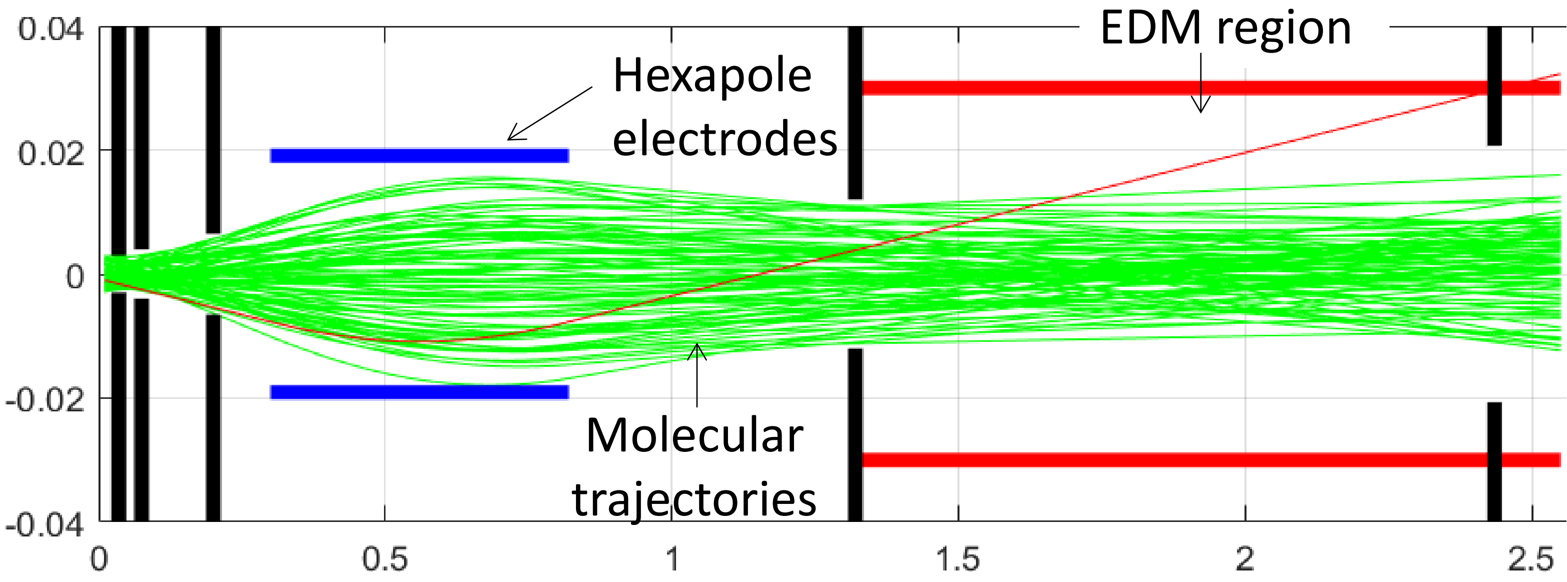








Electrostatic focusing for ThO molecules

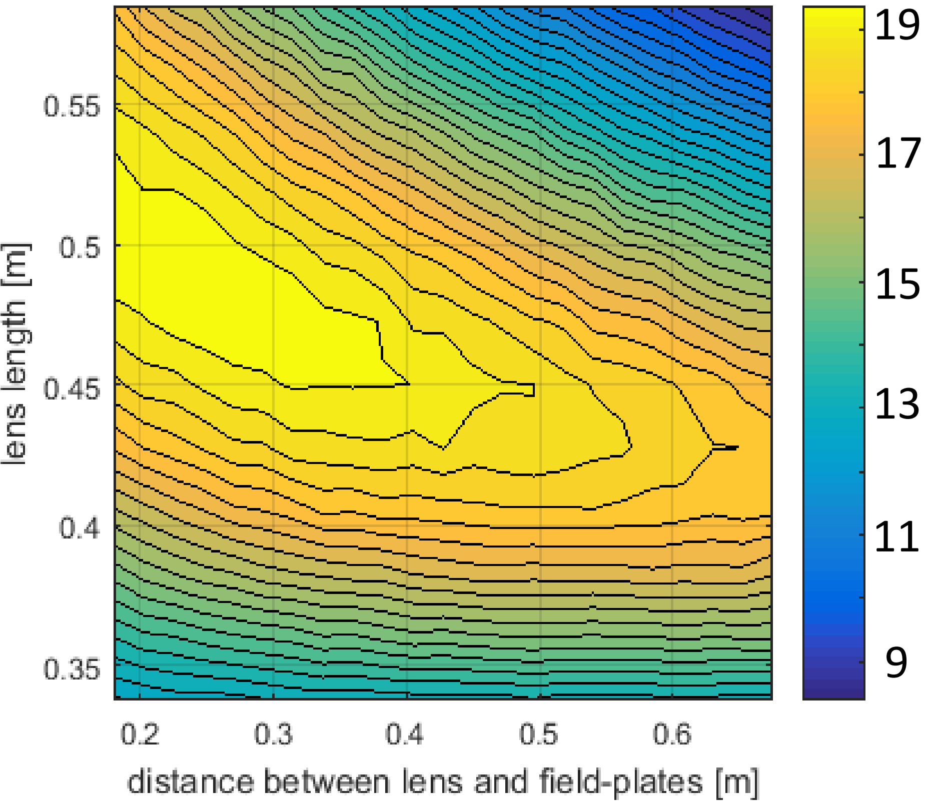


EDM region

Hexapole electrodes

Molecular trajectories

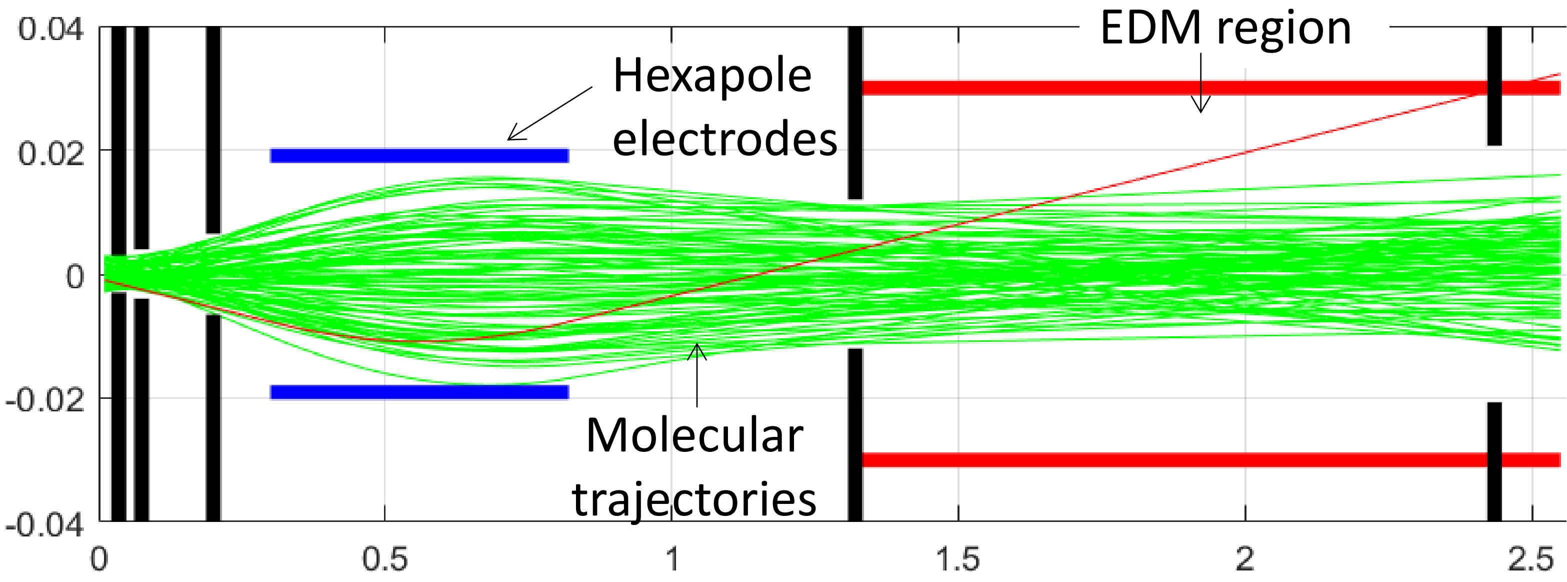
flux gain from molecular lens (trajectory simulation)

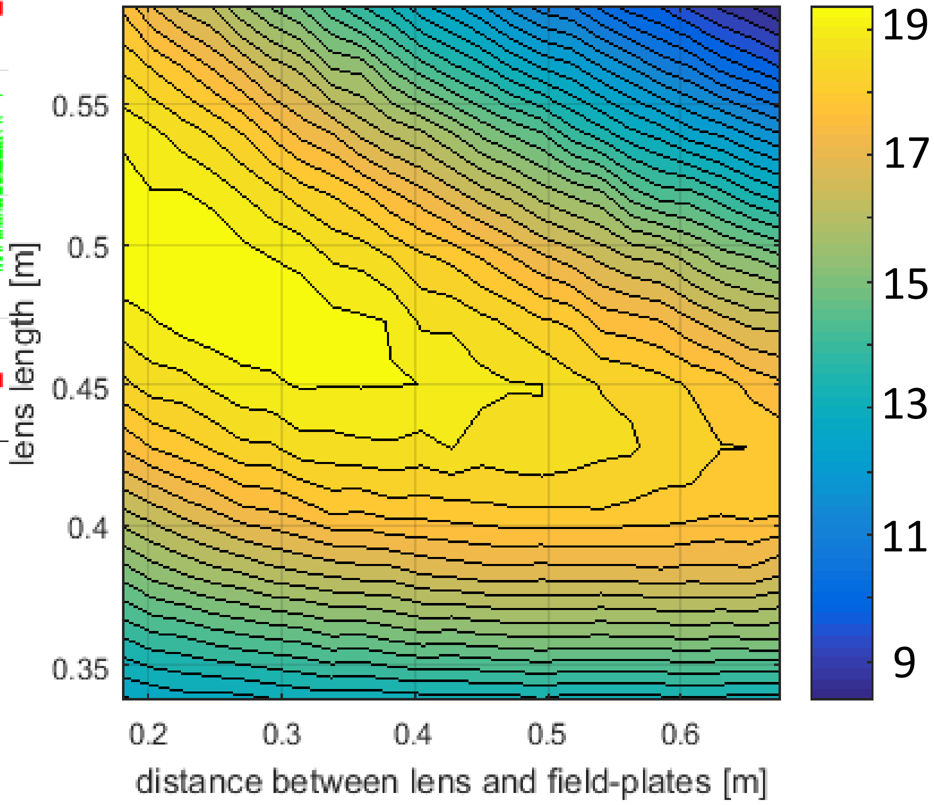


- Without lens, fewer than 0.04% of the molecules make it.

- Electrostatic lens focuses molecules into the EDM region, giving > x15 gain in signal (including the efficiency of ‘double’-STIRAP)

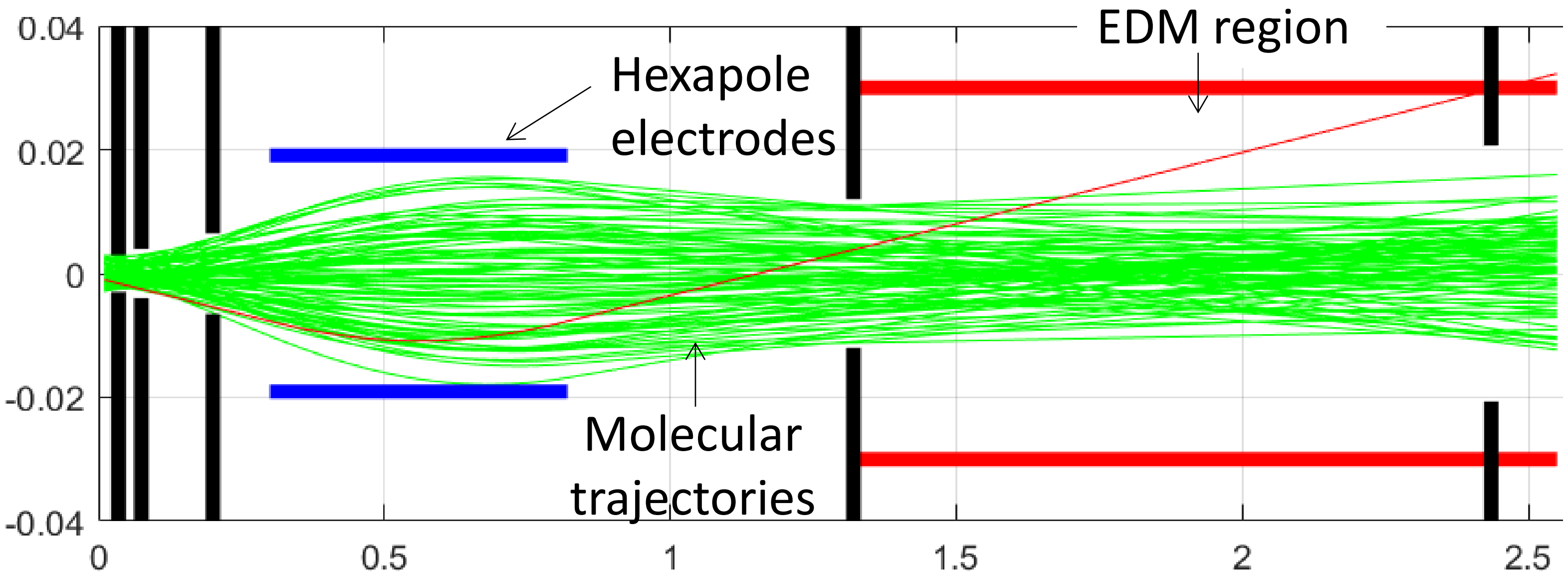
Electrostatic focusing for ThO molecules

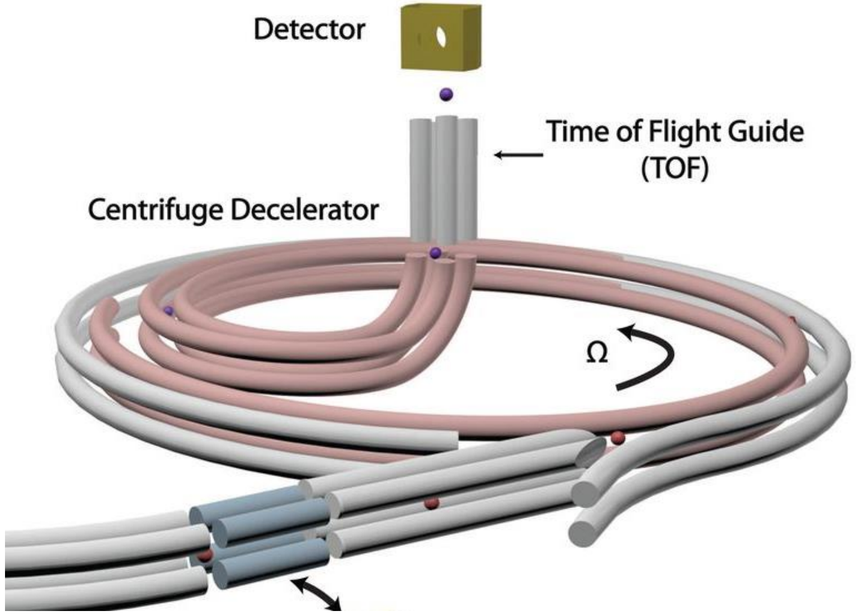



flux gain from molecular lens (trajectory simulation)

- Are these numbers / simulation reliable?????

Electrostatic focusing for ThO molecules





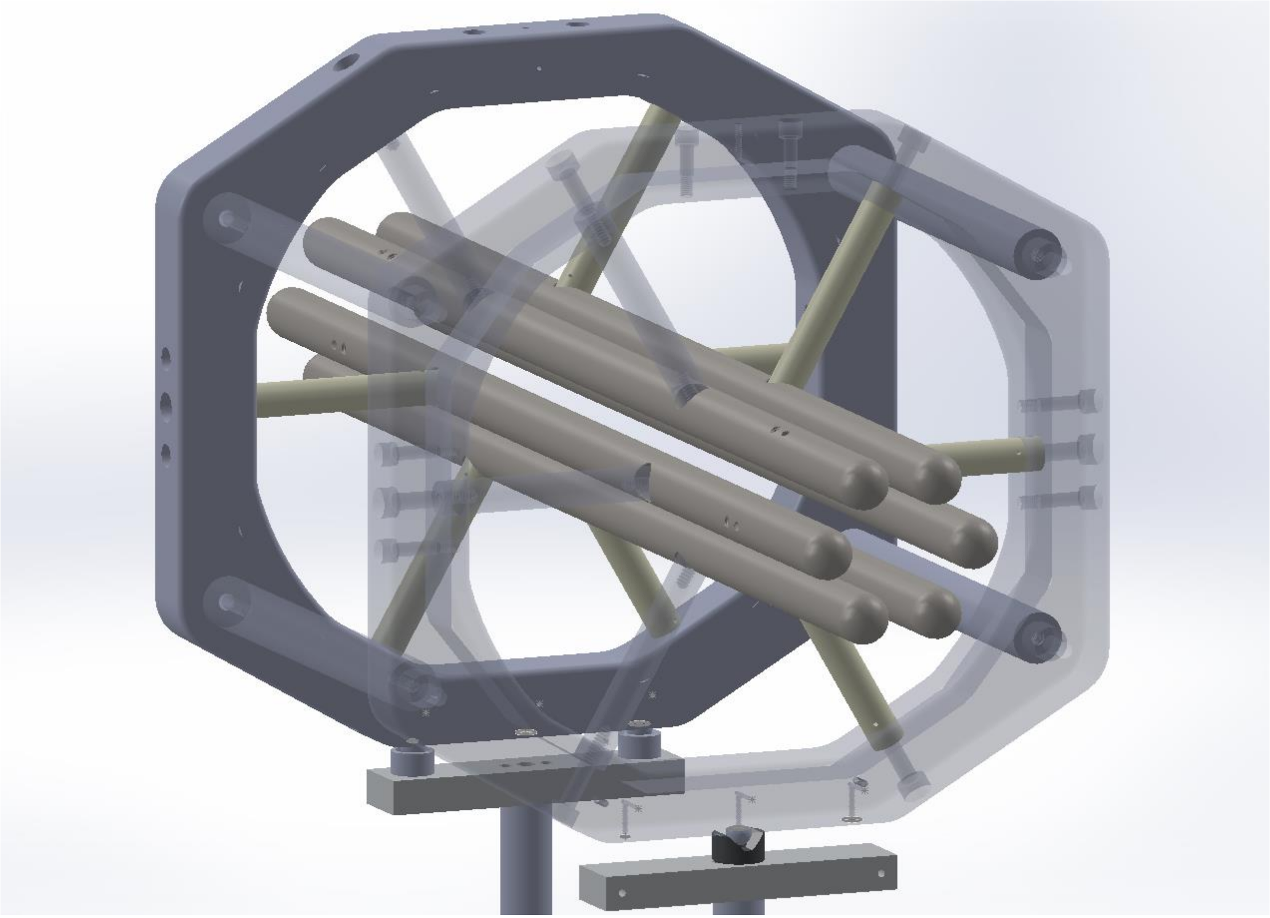
- Are these numbers / simulation reliable?????

- Simulation method / package very well understood. Validated multiple times before

X Wu, *et al, Science* 358, 645 (2017)

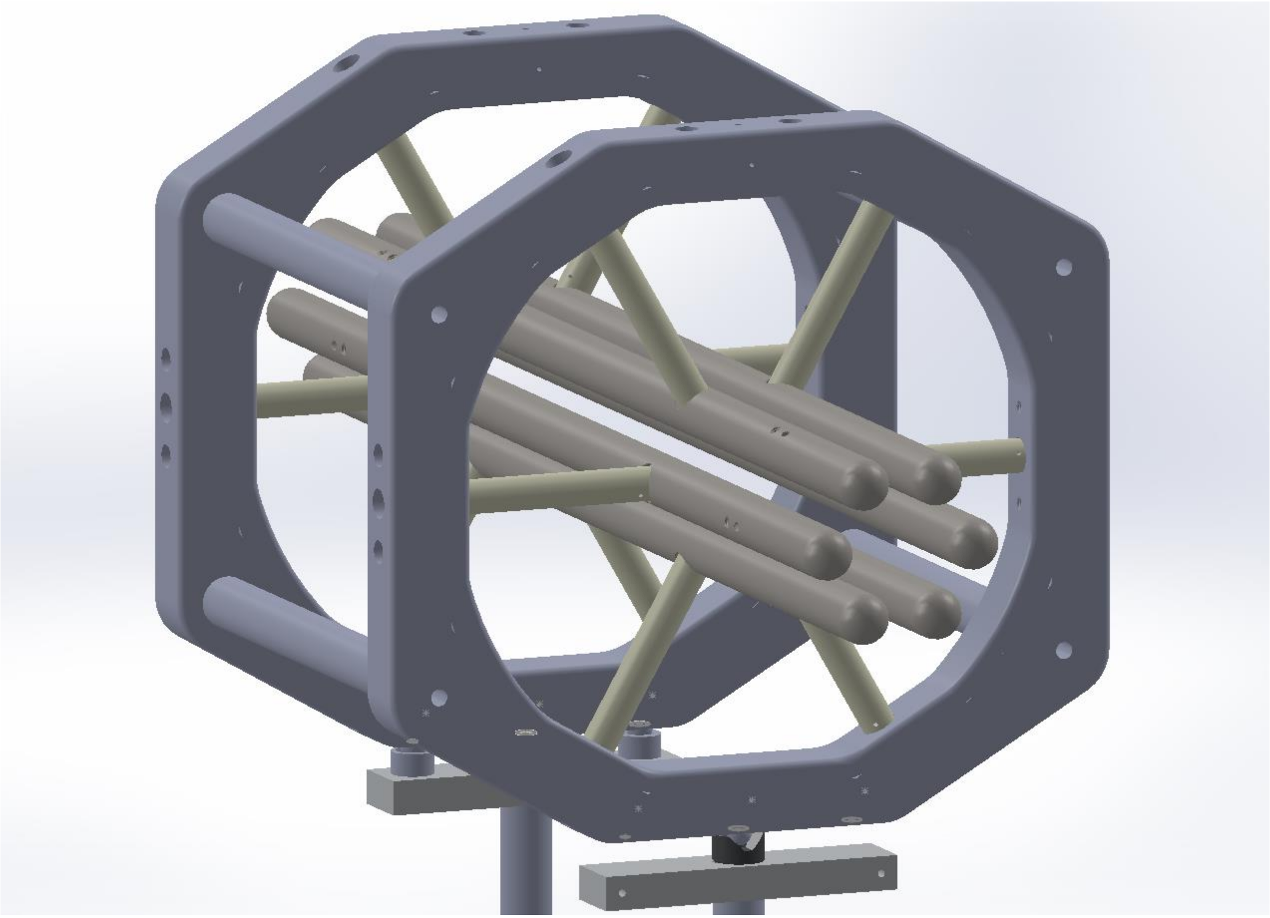
X Wu, *et al, ChemPhysChem* 17 (22), 3631-3640 (2016)

Mechanical Design



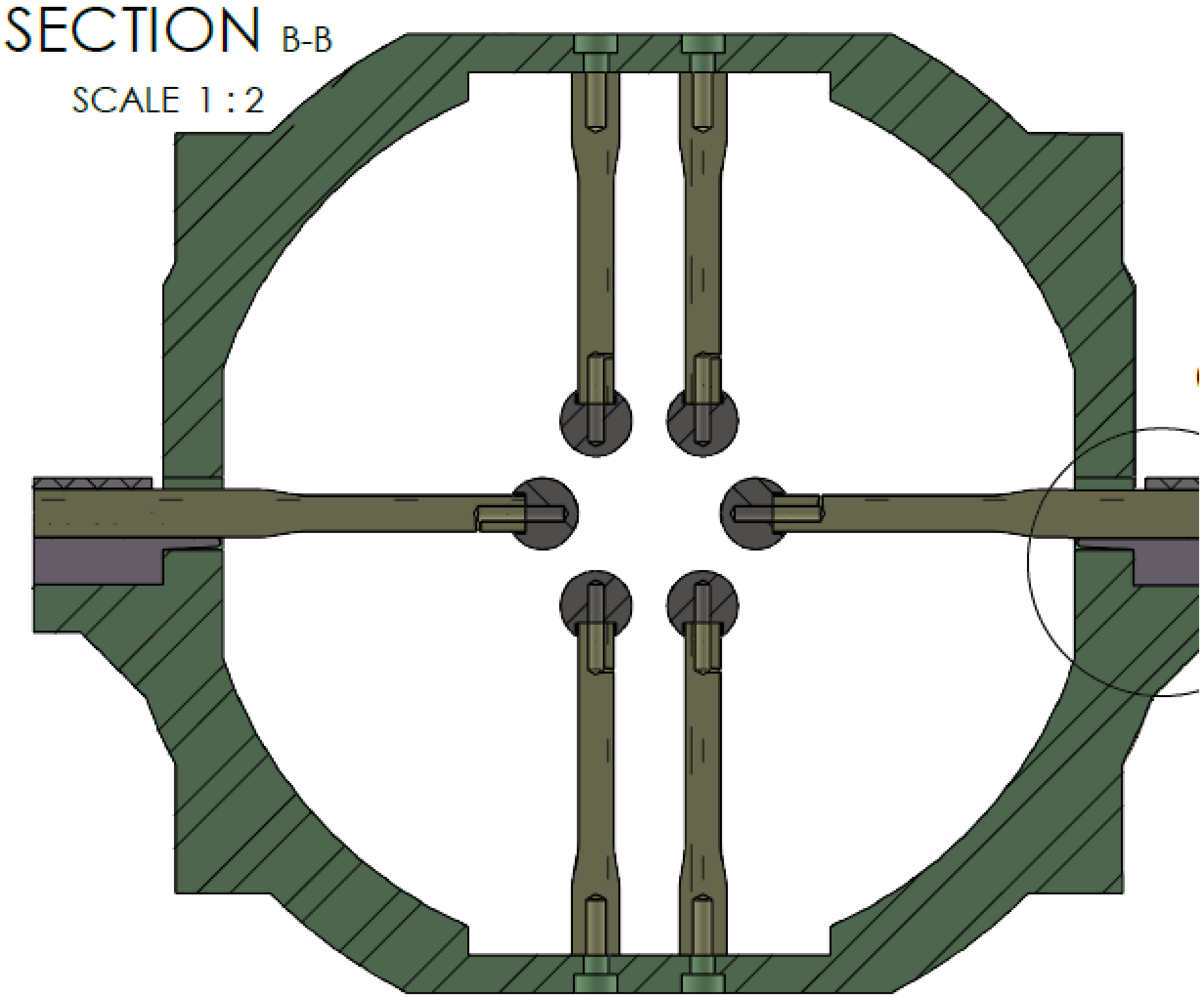
Electrode diameter = 19mm

Mechanical Design



Electrode mounted on Macor stand

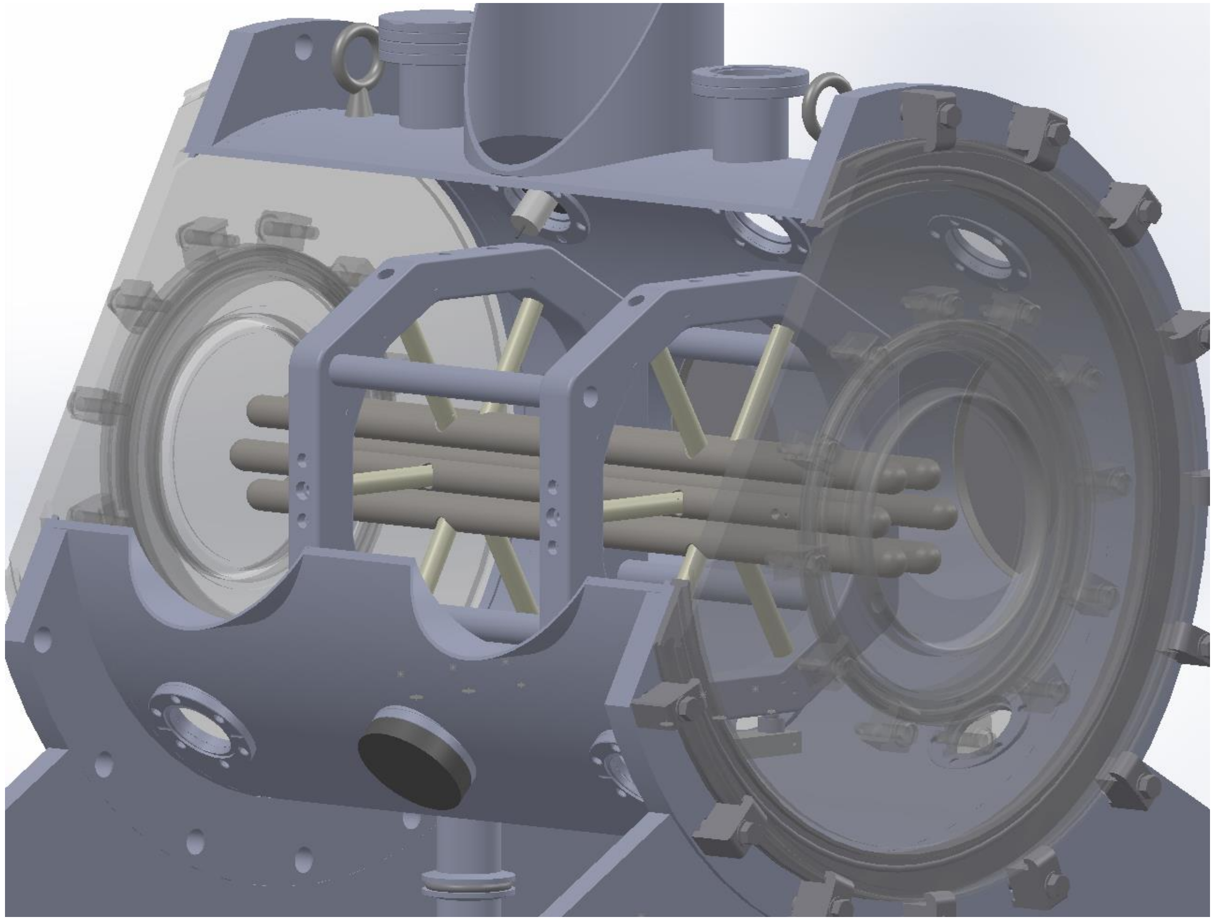
Mechanical Design



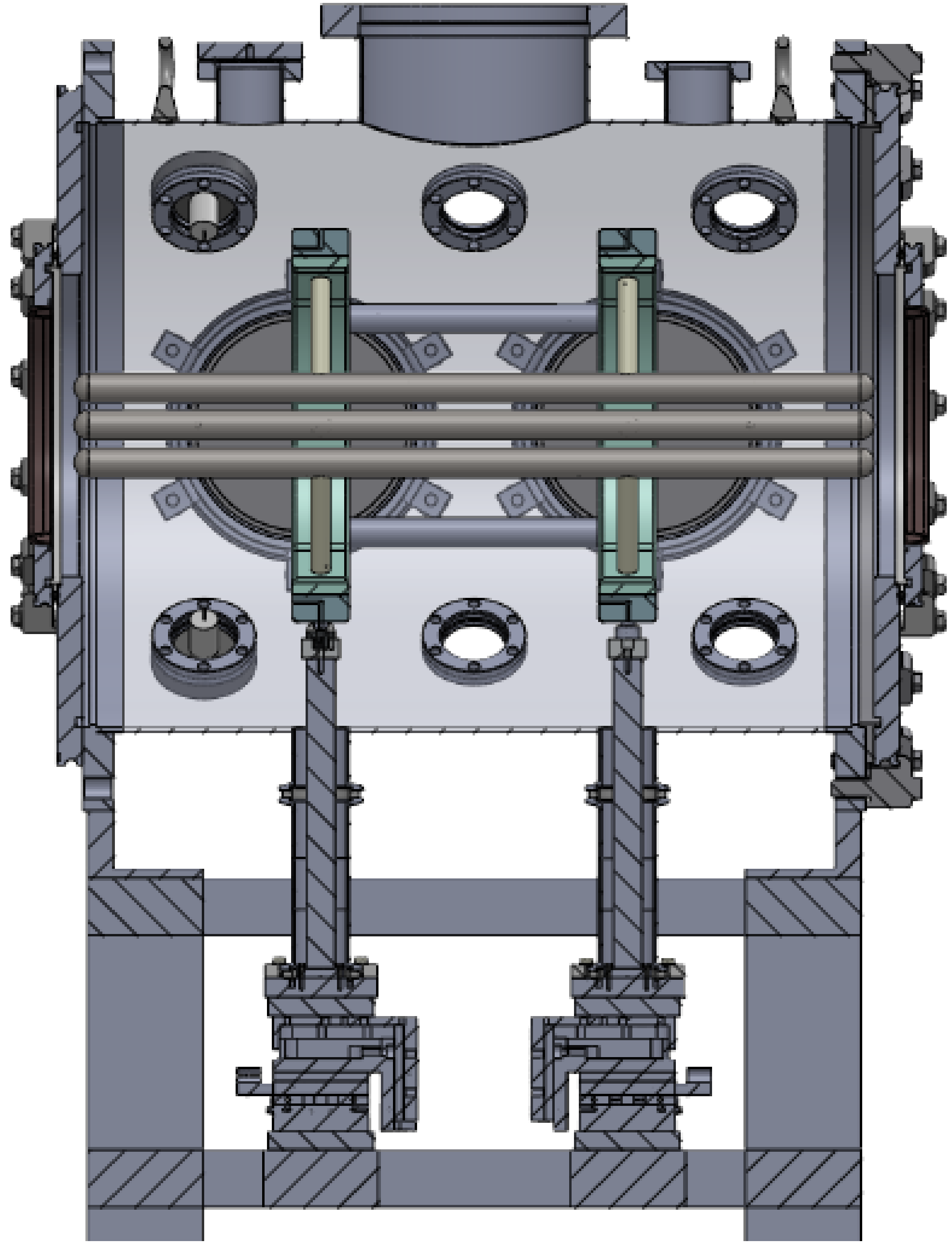
Electrode diameter = 19mm

Spacing = 9.5mm

Mechanical Design



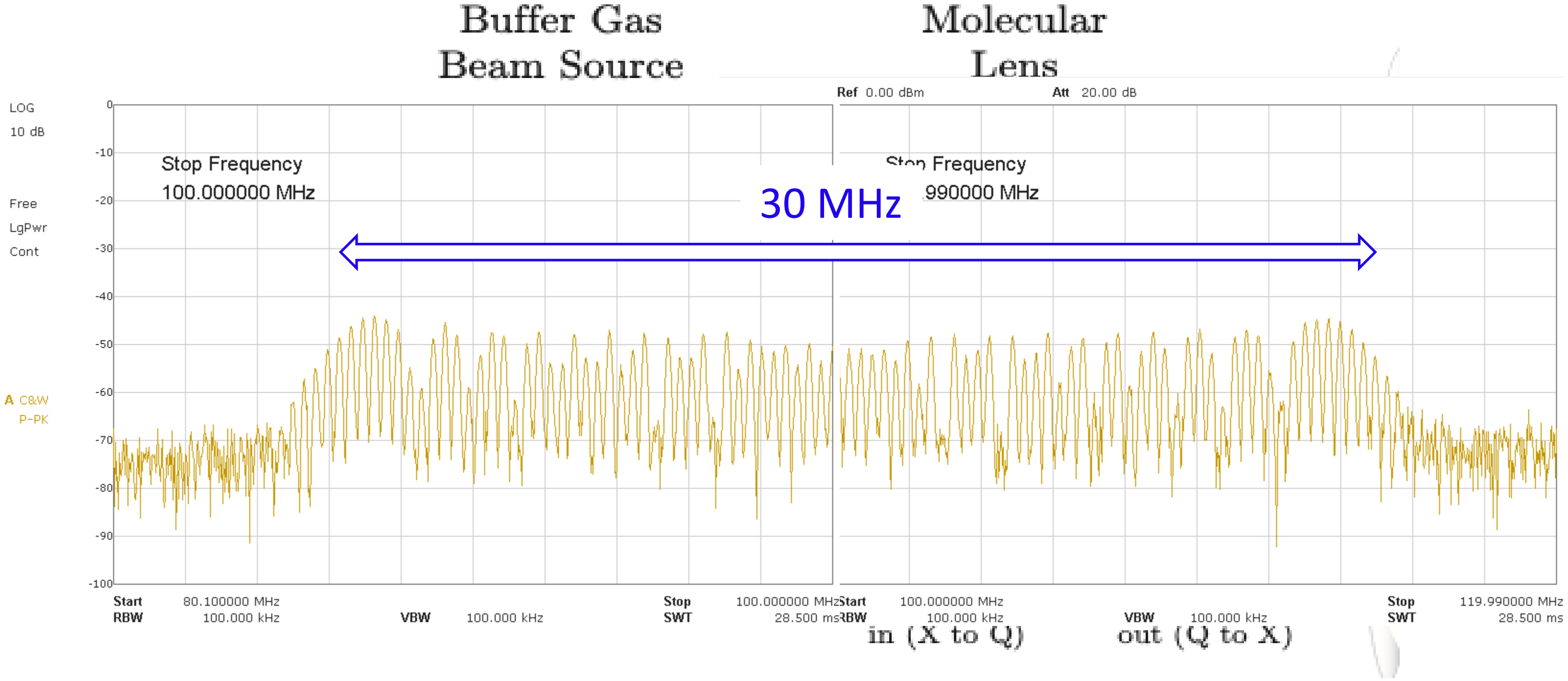
Cross section view

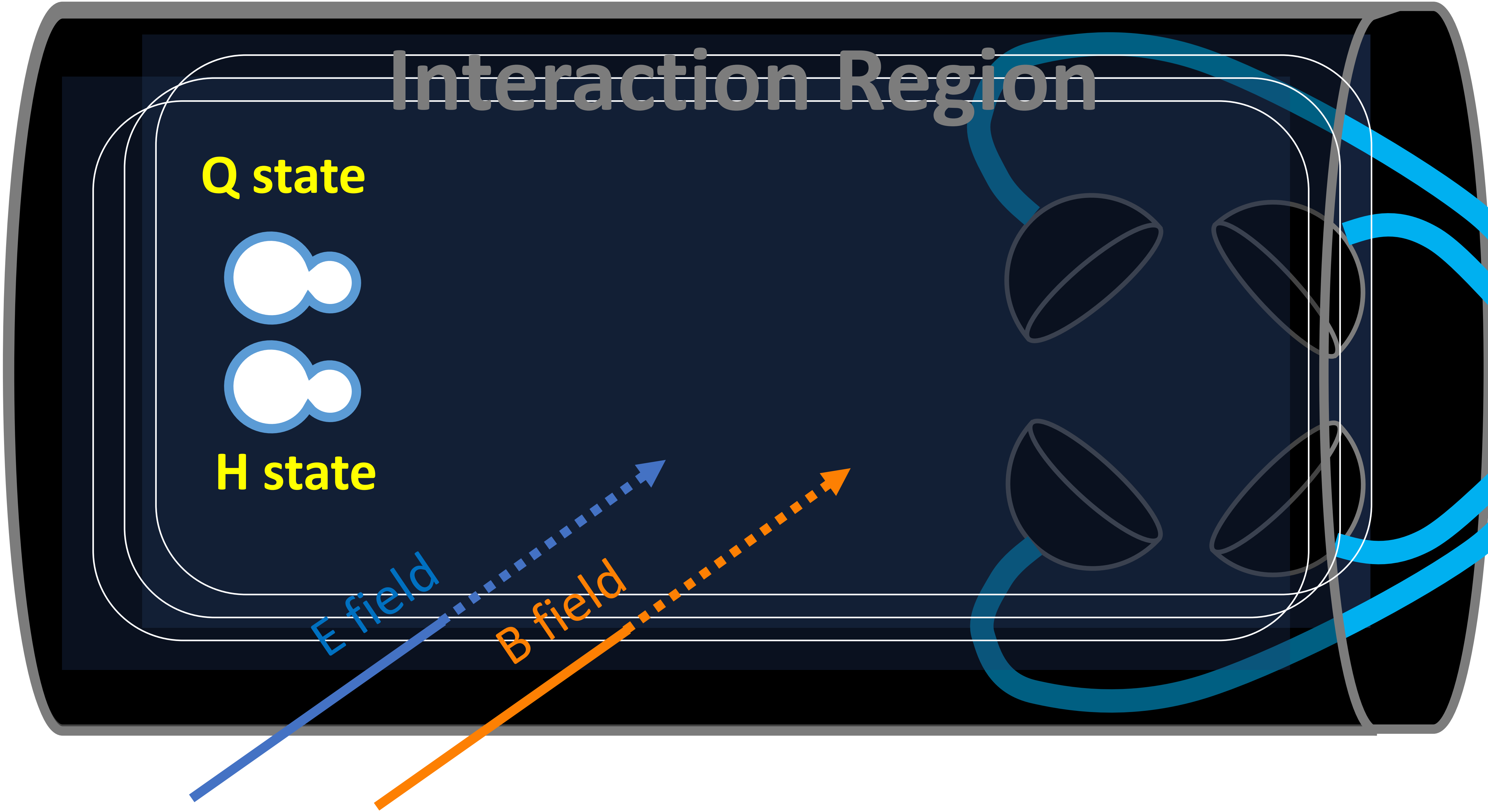


Electrostatic lens mounted on 3-axis translational stage

Other technical upgrades

- Rotational-state cooling for x6 broader linewidth, in more compacted space
- Sideband modulation (90 sidebands, spacing = 330kHz)

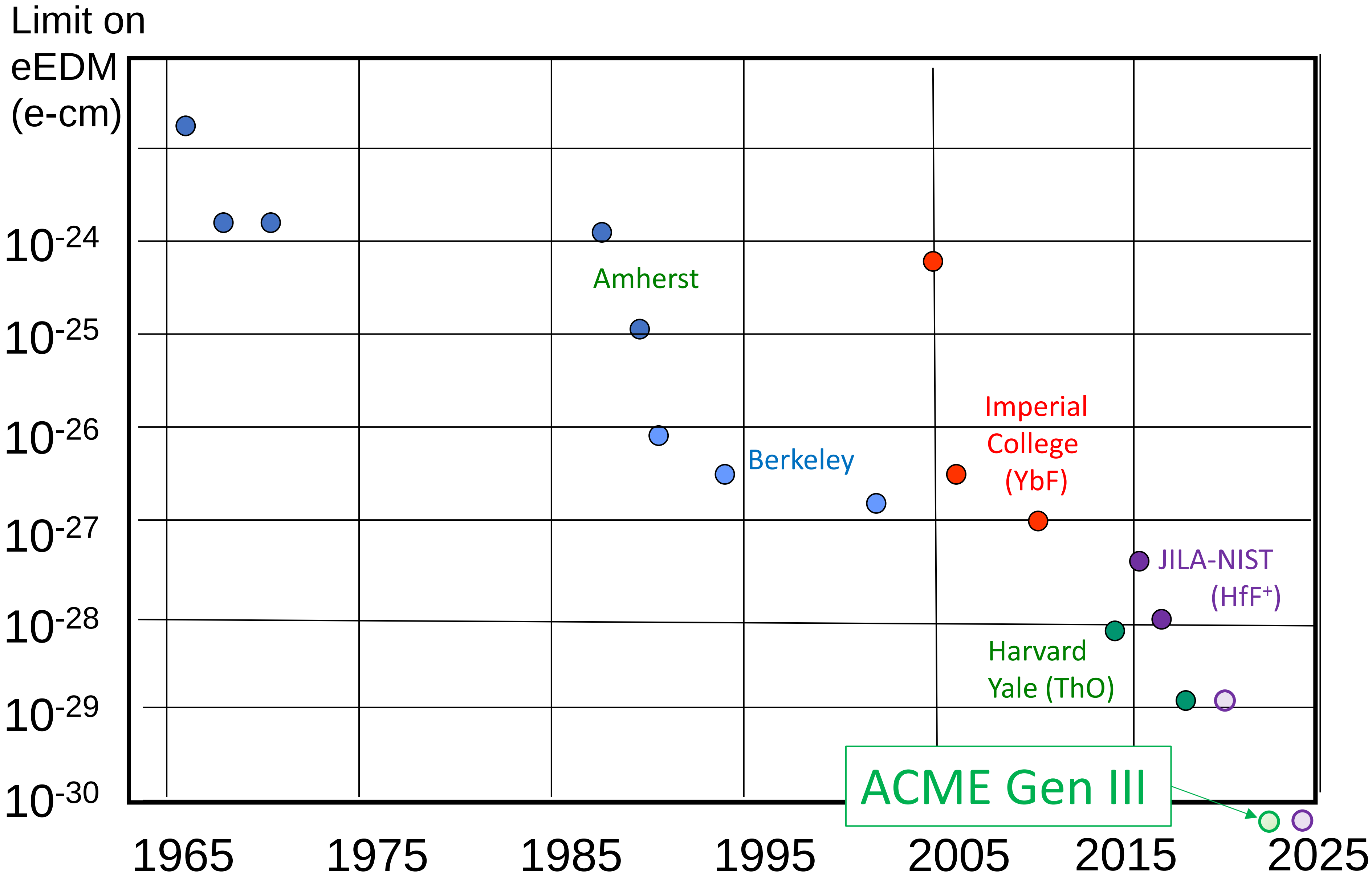



Interaction Region
Q state
H state
E field
B field

Conclusion

- Upgrade with electric hexapole lens
  - Ideal state properties in Q state: 4.1D, 2.07μ_B, >62ms lifetime
  - State preparation efficiency: 90% with STIRAP
  - Electrostatic focusing: x19 times gain in flux
  - Overall gain: > x15 in signal
- Total EDM sensitivity gain: over one order of magnitude

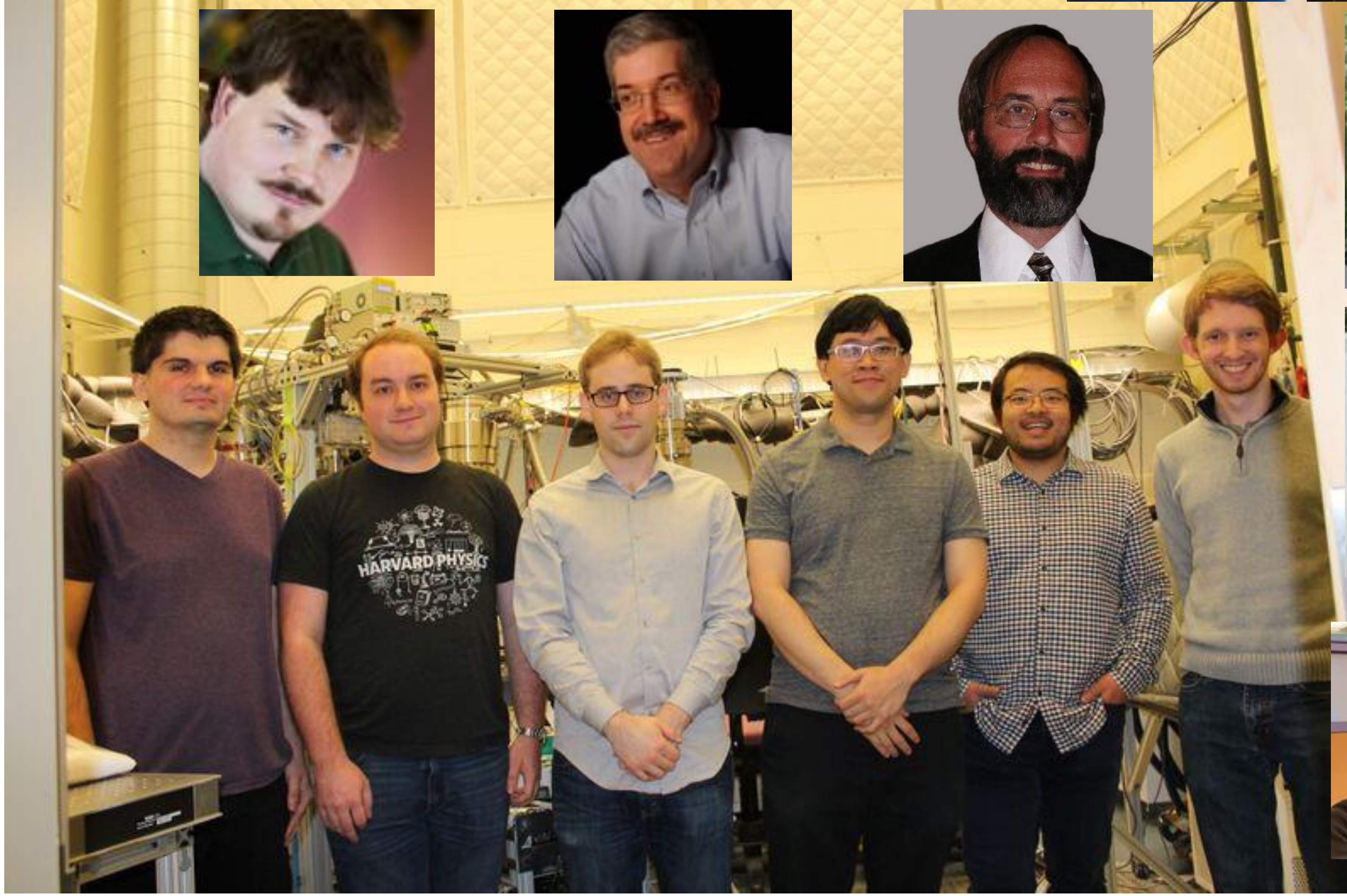
Improvement	Signal Gain	EDM Sensitivity Gain
Increased Precession Time	0.20	2.3
Electrostatic Lens	15	3.9
SiPM Detector Upgrade	2.3	1.5
Timing Jitter Noise Reduction	1	1.7
Total	7.4	23

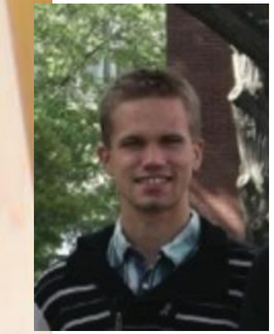

Limit on eEDM (e-cm)
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
1965
1975
1985
1995
2005
2015
2025
Amherst
Berkeley
Imperial College (YbF)
JILA-NIST (HfF^+)
Harvard Yale (ThO)

ACME Gen III

ACME Gen II







PI's (left to right)

David DeMille

John Doyle

Gerald Gabrielse

Graduate students
(left to right)

Cris Panda

Cole Meisenhelder

Zack Lasner

Daniel Ang

Xing Wu

Jonathan Haefner

(right upper corner)

Adam West

Brendon O'Leary

Vitaly Andreev

Elizabeth Petrik

Nick Hutzler

ACME Collaboration

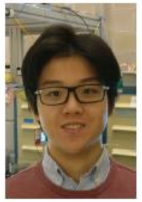
Yale
David DeMille (PI)
Xing Wu (postdoc)
James Chow (grad student)
Zhen Han (grad student)

Harvard
John Doyle (PI)
Xing Wu (postdoc)

Northwestern
Gerald Gabrielse (PI)
Daniel Lascar (Research Asst. Prof.)
Daniel Ang (Harvard grad student)
Cole Meisenhelder (Harvard grad student)
Siyuan Liu (grad student)
Bingjie Hao (grad student)


David DeMille


James Chow


Zhen Han


Xing Wu


John Doyle


Gerald Gabrielse


Dan Lascar


Siyuan Liu


Bingjie Hao


Cole M.


Daniel Ang

Collaborators:

@Okayama:

Takahiko Masuda

Noboru Sasao

Satoshi Uetake

Koji Yoshimura

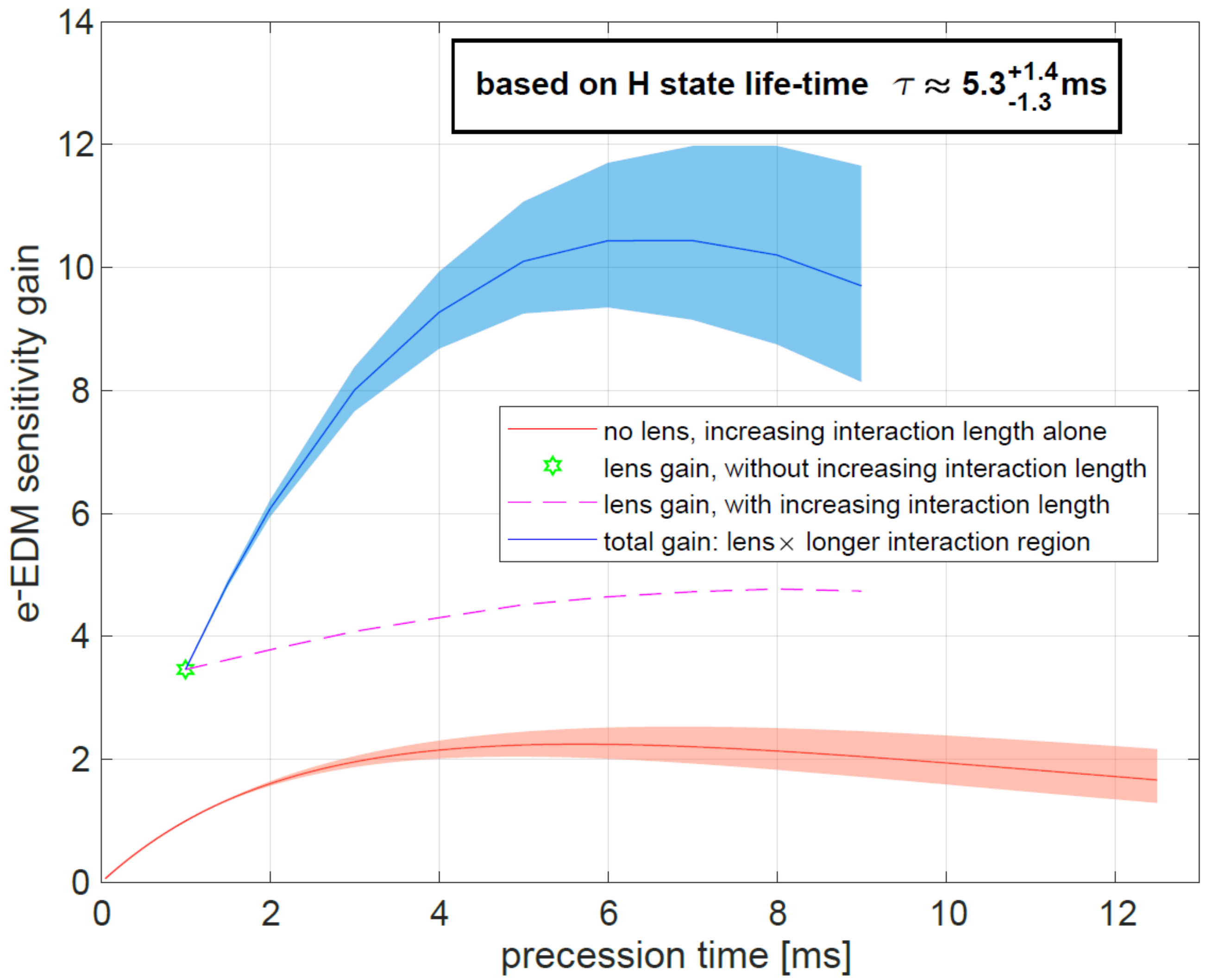
@Caltech:

Nick Hutzler

@Berkeley:

Cris Panda

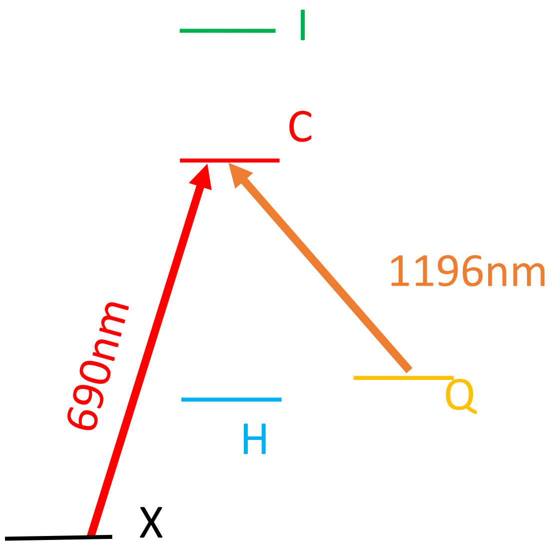
EDM sensitivity gain vs. interaction length

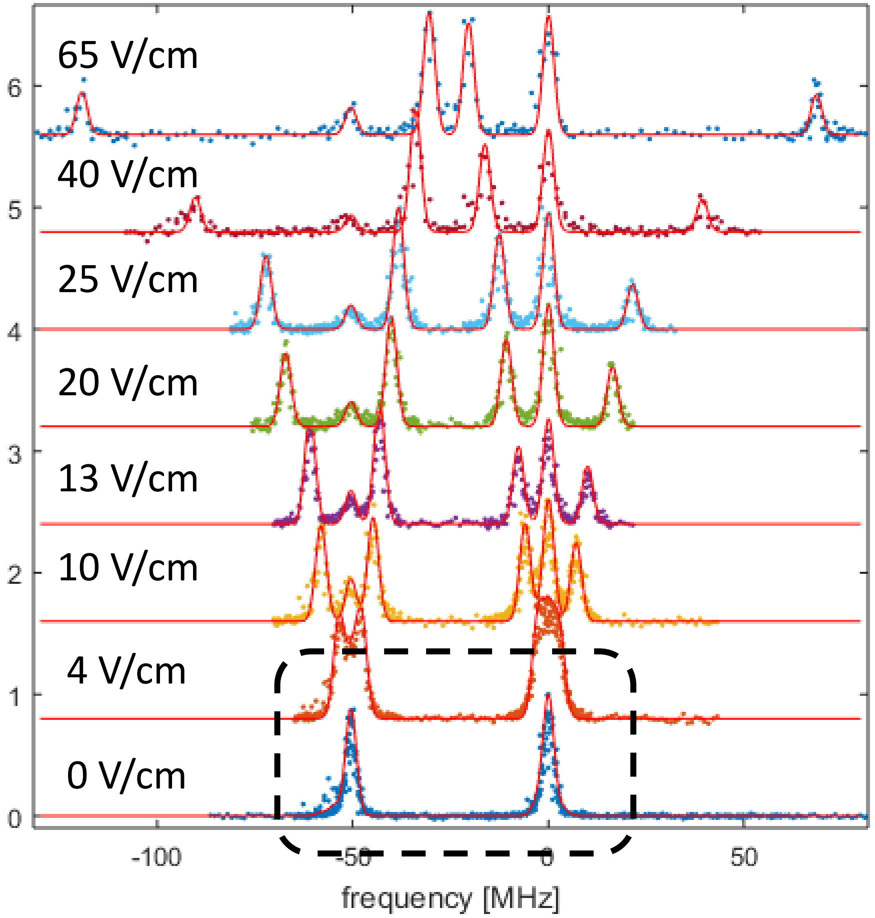


Not including gains from

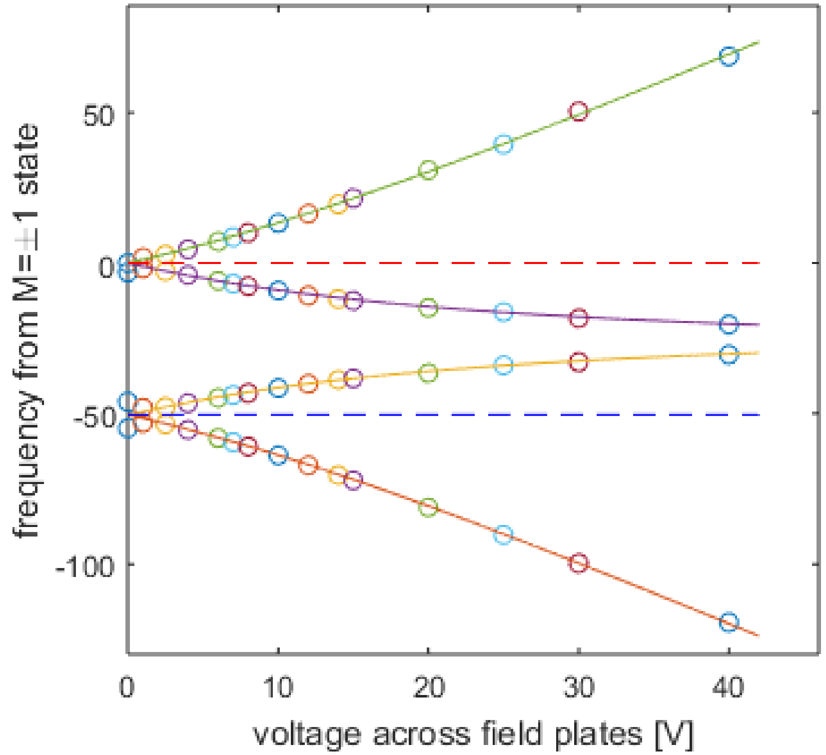
- SiPM upgrade: x1.5
- Ex. Noise Suppresion: x1.7

Stark shift of Q—C transition



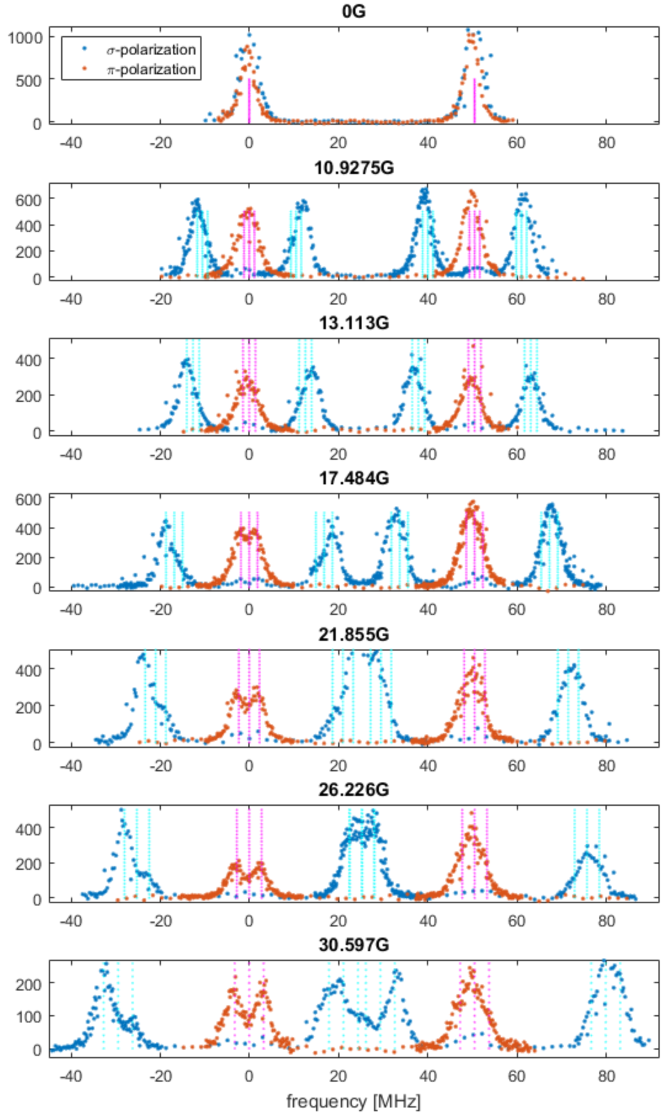


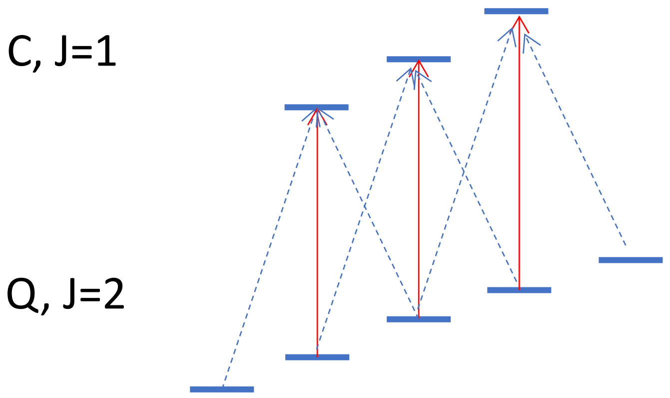
Λ-doublet of C: 51 MHz
Q state doublet is unresolved (<<100kHz)

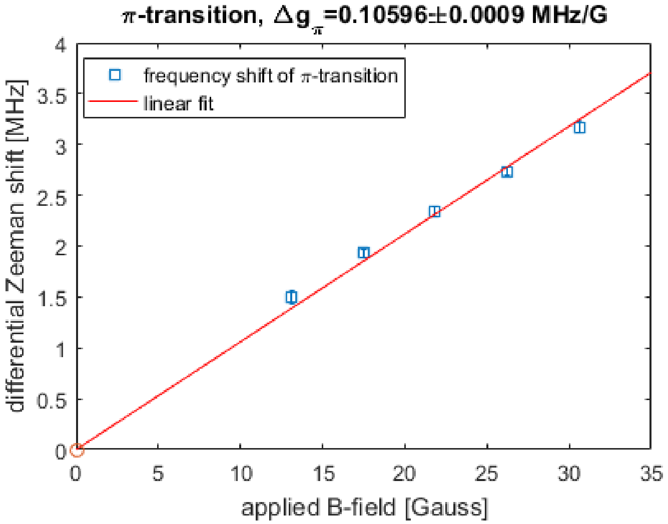


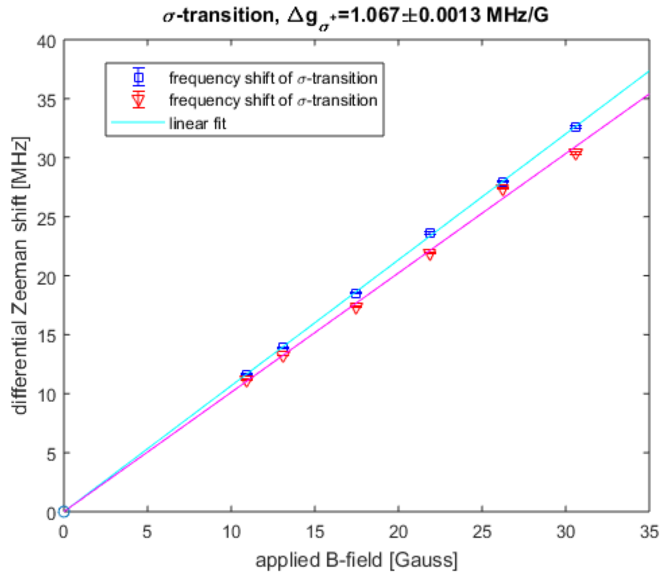
- D_Q=4.07D (Q state)
- D_C=2.60D (C state)

Zeeman shift of Q—C transition





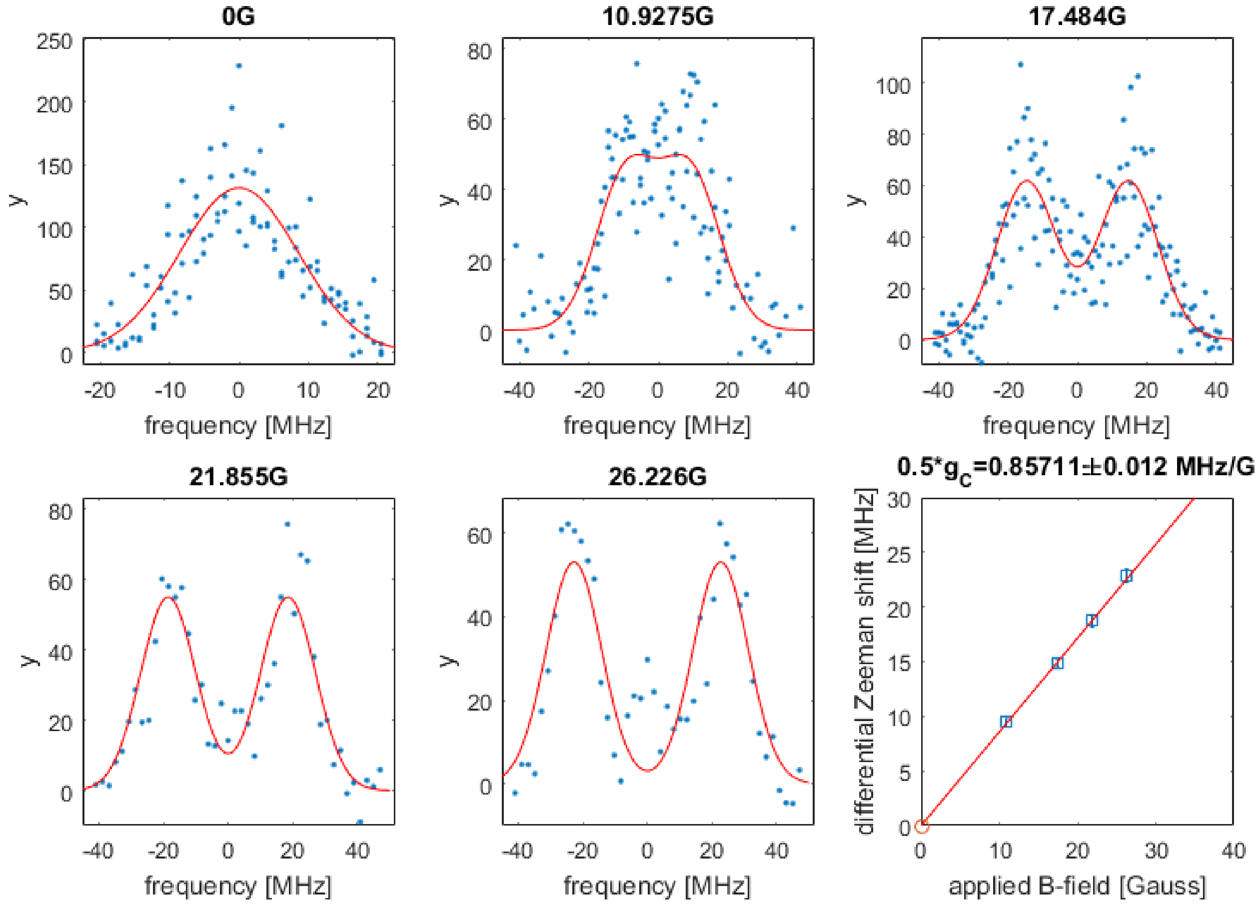


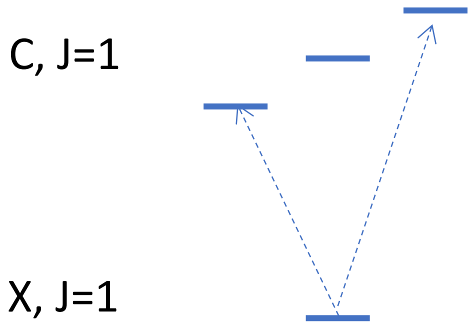


$G_Q = 2.061 \pm 0.004\ \mu_B$

$G_C = 1.222 \pm 0.003\ \mu_B$

A quick cross check of g_C via X—C transition



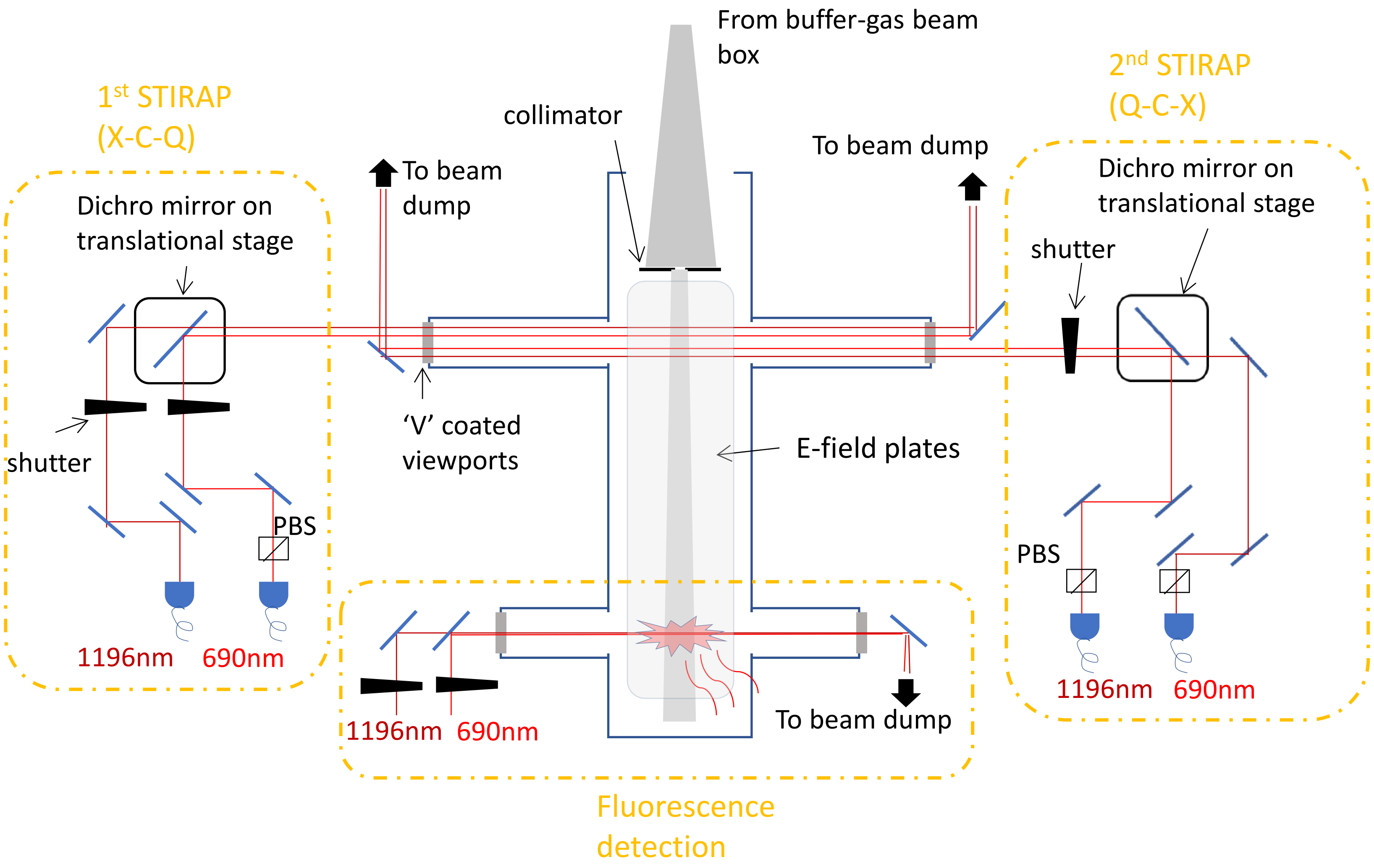


- X state has only ~10^{-3} μ_B
- $G_C = 1.71 \pm 0.02$ MHz/G,

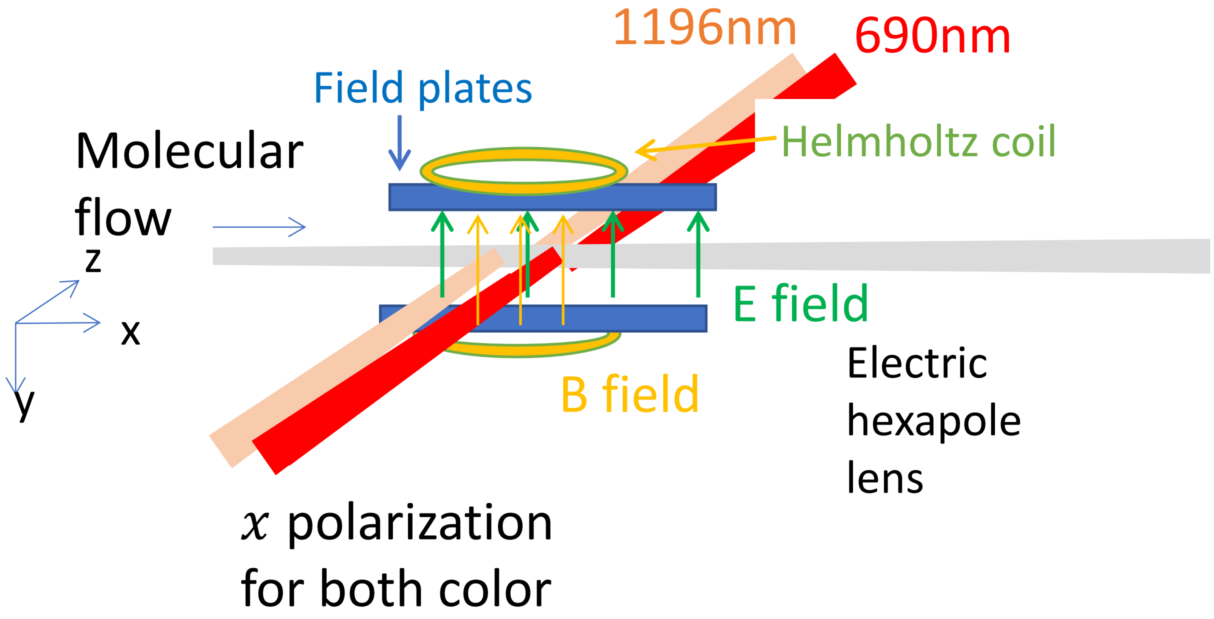
  1.22 ± 0.02 μ_B
- Agrees with the value from Q—C transition

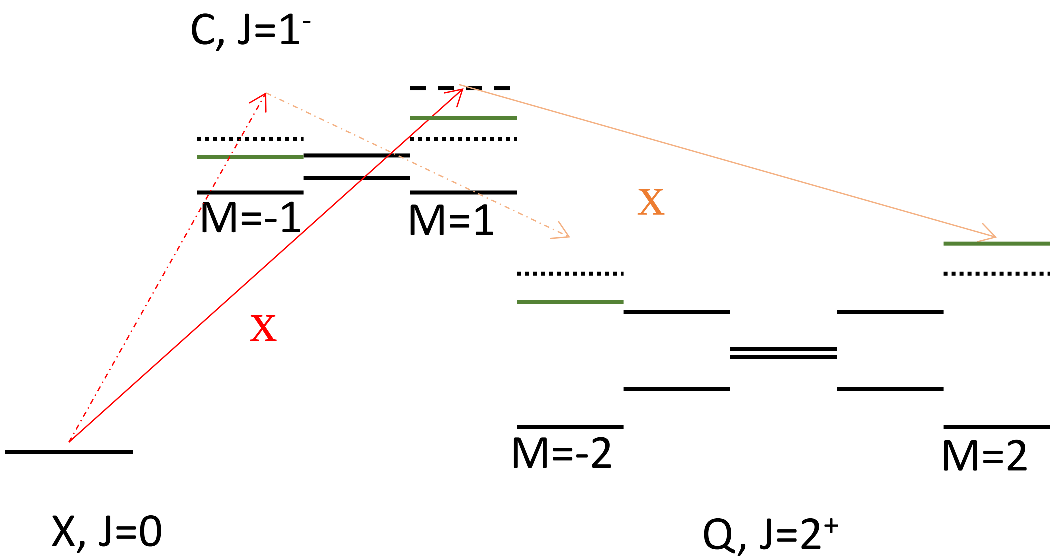
STIRAP setup

- Continuous E-field applied from STIRAP to detection region
- Switch between X-C (690nm) and Q-C (1196nm) probing lasers
- Detect 735nm photon from X-C (v=1) decay for both probes



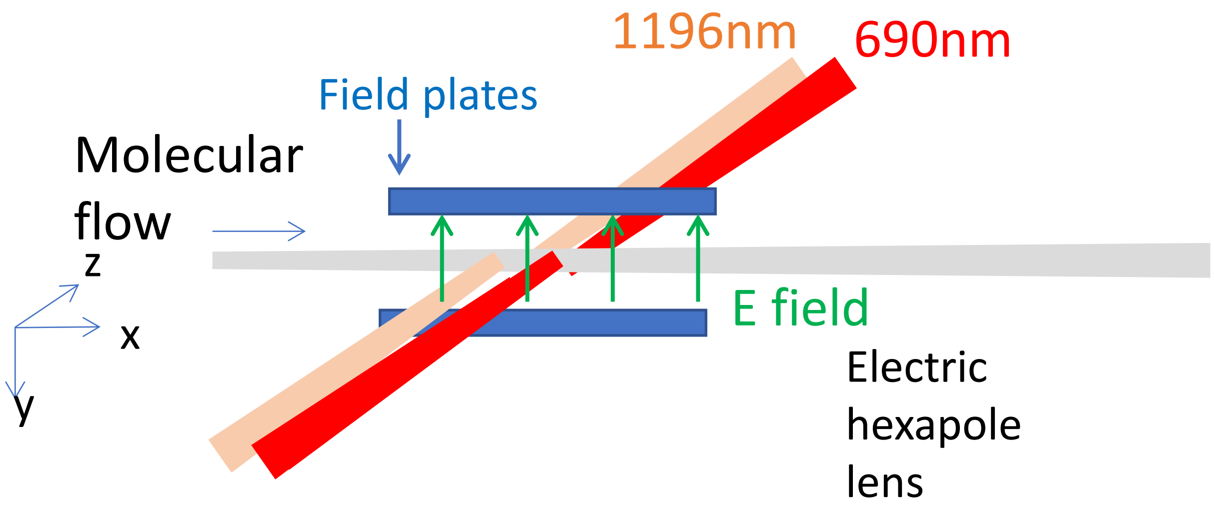
STIRAP scheme for actual Lens



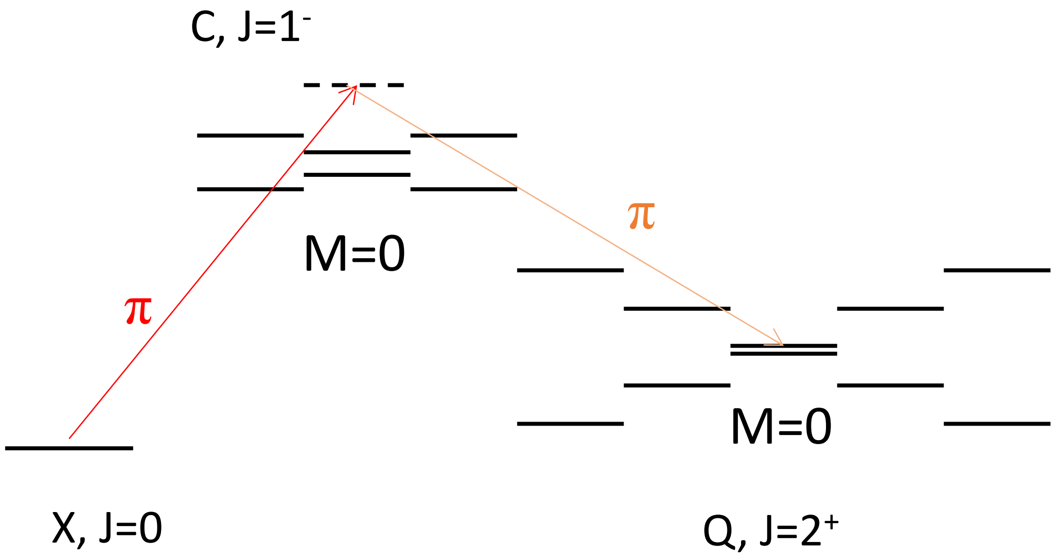


- For test: X |JM>=|00> to C |JM>=|10> to Q |JM>=|20>
- For actual lens setup: we need to go to Q, |JM>=|22>
  - Apply B offset field
  - Use lasers with x-polarization
  - Need twice the laser power

STIRAP scheme for 1st demonstration

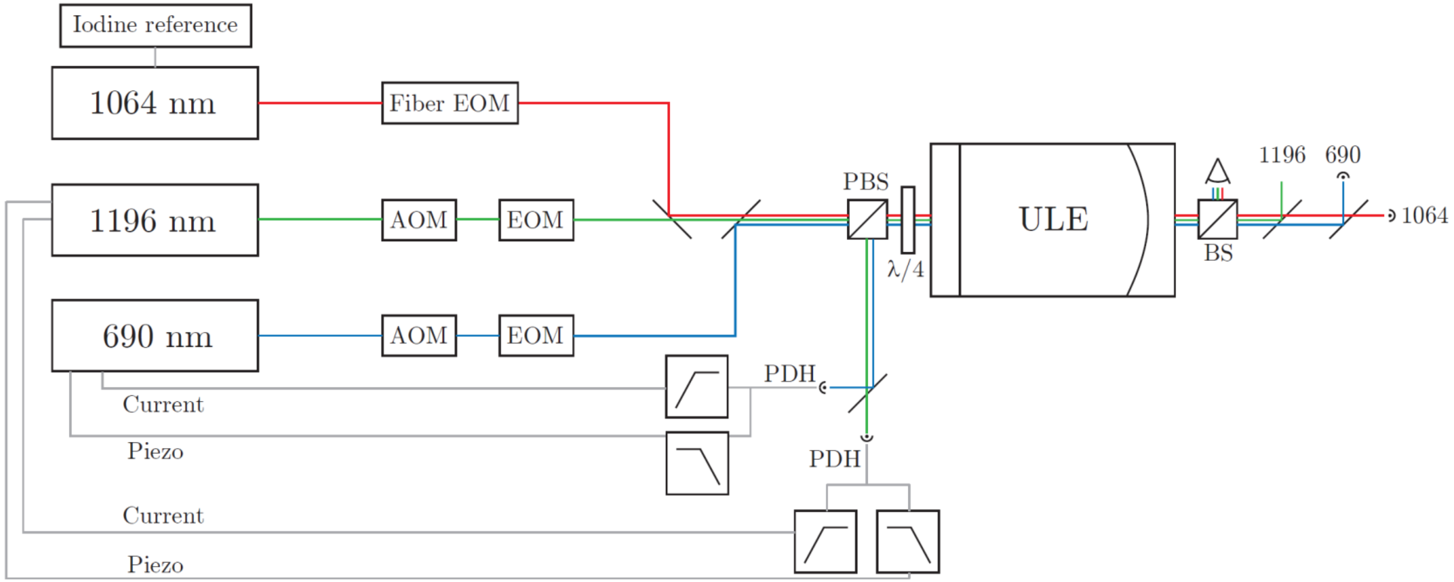


π polarization
for both color

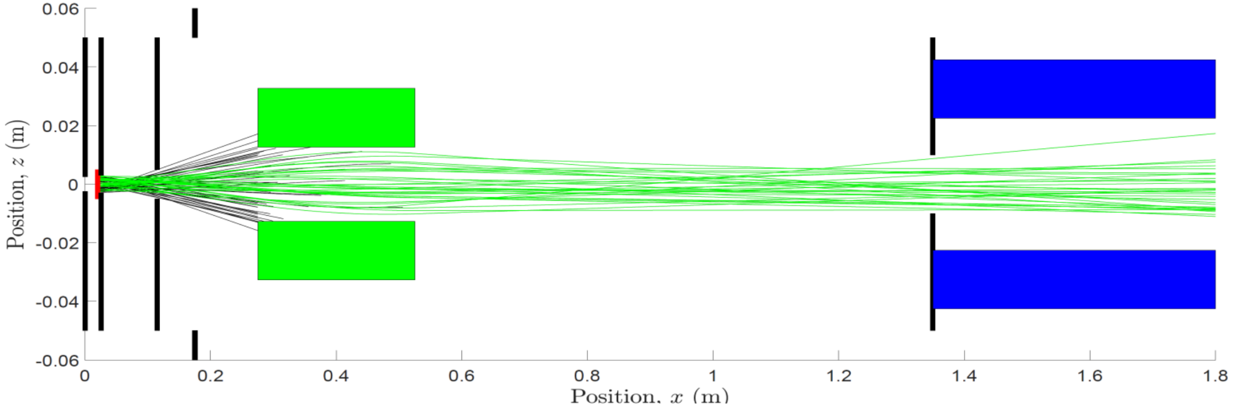


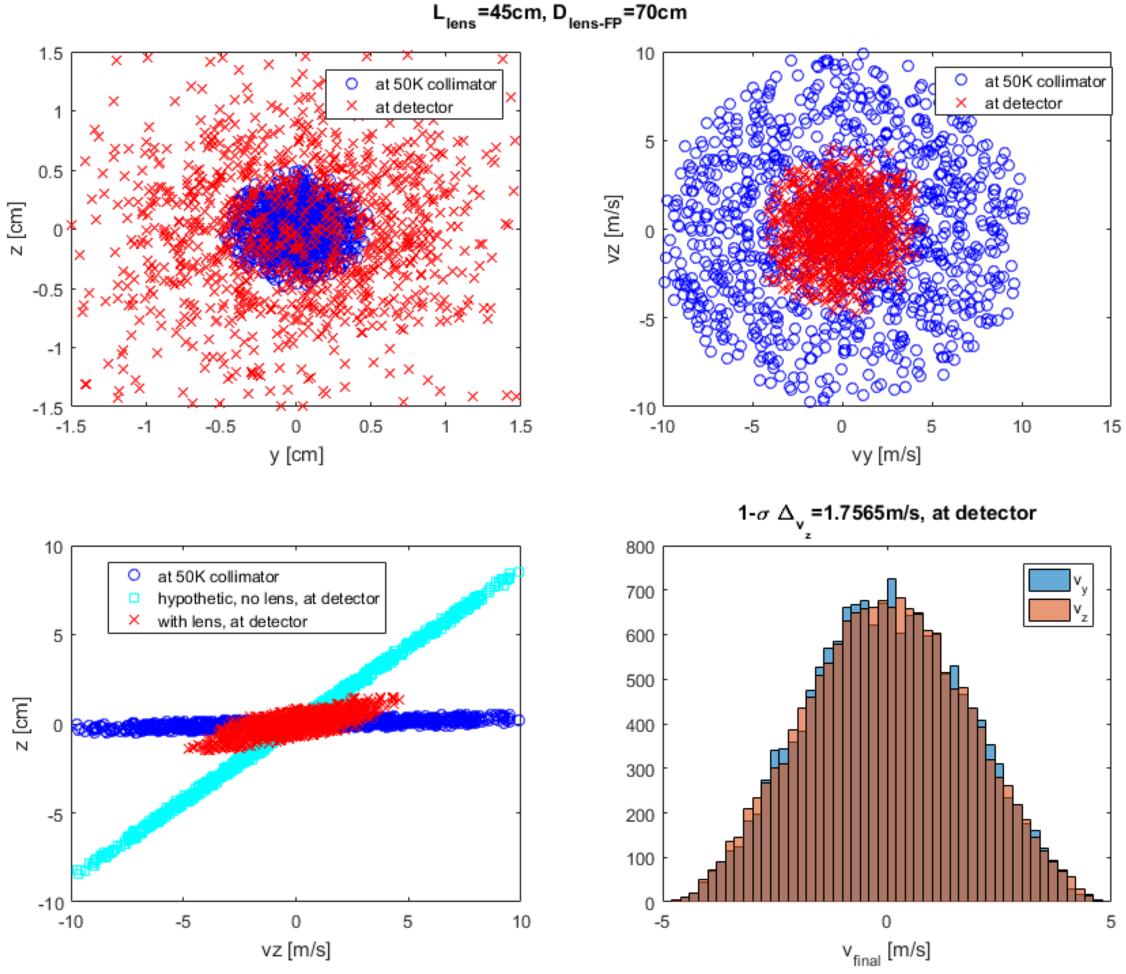
Available Laser power for
X-C-Q STIRAP:

- ✓ 160mW for 690nm
- ✓ 900mW for 1196nm



Manipulating the phase space distribution





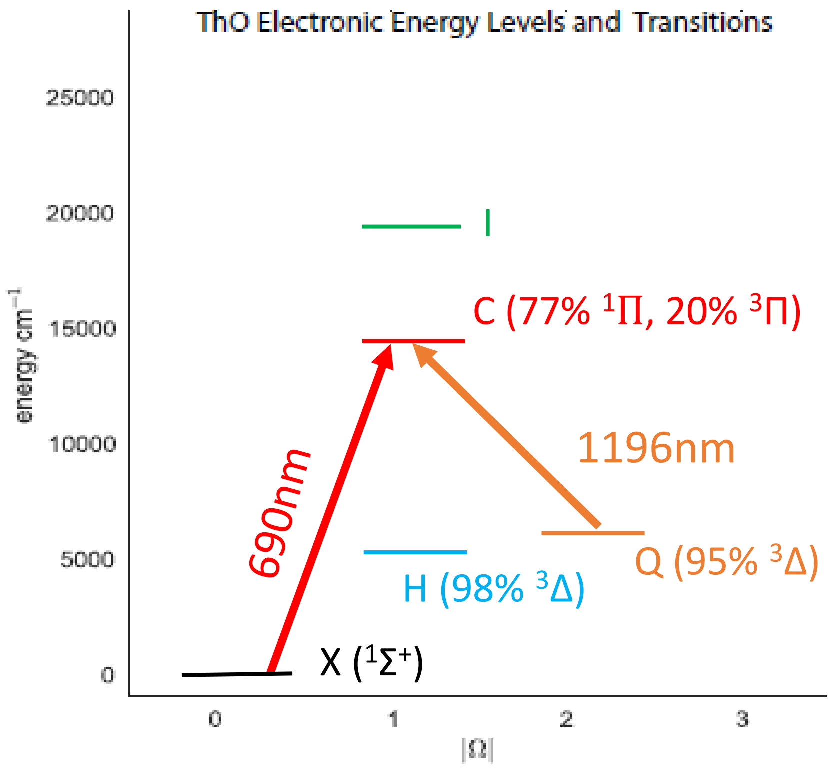
Key Question we try to answer

- Do we have enough laser power to saturate double STIRAP between X and Q state of ThO?

Molecular beam property	Before Lens Entrance
Vertical extent	2 cm
Transverse velocity width (FWHM)	13.5m/s (*19.6MHz* @690nm, *11.3MHz* @1196nm, *8.3MHz* for 2-ν linewidth

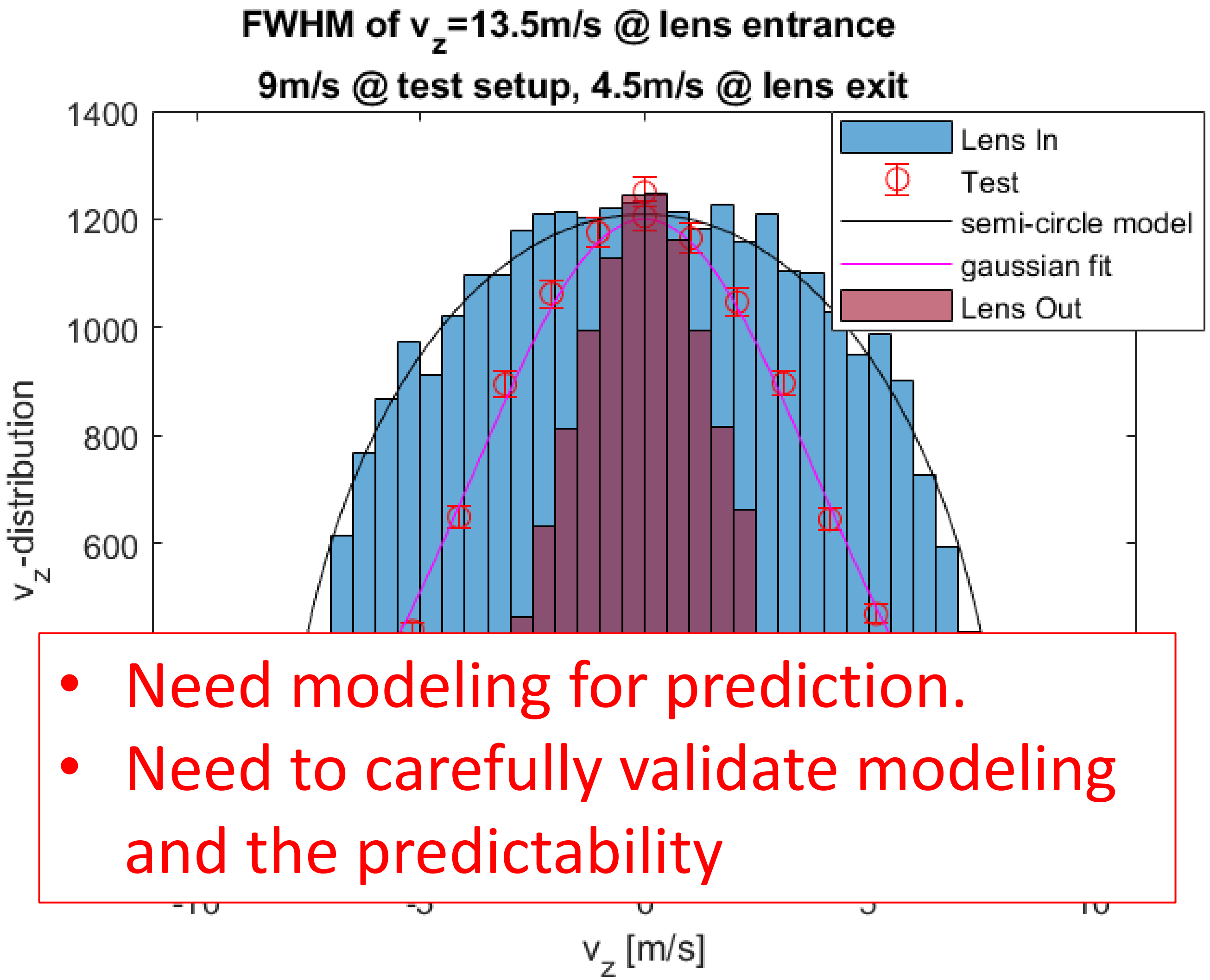
- Previously, showed 90% transfer efficiency each way. Here, demonstrate saturation of STIRAP in Test setup.

- Show that from Test results + modeling: infer we can saturate the power for the actual Molecular Lens



Different Velocity Distributions between Test and Lens, even after Maximizing Collimator Opening

- Test Setup
  - Molecule collimator fully opened, but limited by fluorescence collection (1” ITO window)
  - Gaussian shape, FWHM=9m/s, (5.5MHz in 2-ν linewidth)
- Lens entrance
  - Semi-circle shape (verified by trajectory simulation)
  - FWHM=13.5m/s, (8.3MHz in 2-ν linewidth)
- Lens exit
  - Trajectory simulation, FWHM = 4.5m/s
  - fully covered by Test
- Only efficiency vs. V_z at Lens Input is in question

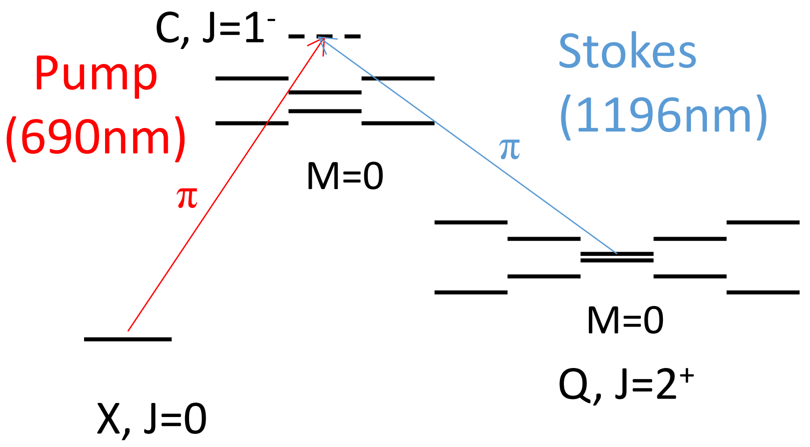

FWHM of v_z=13.5m/s @ lens entrance

9m/s @ test setup, 4.5m/s @ lens exit

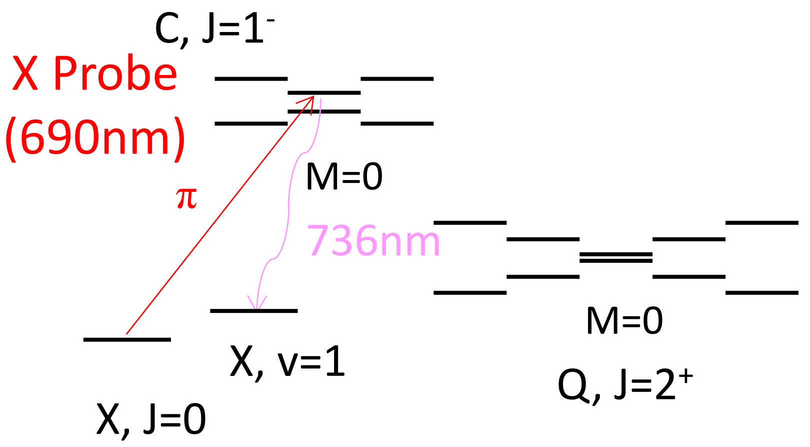
- Need modeling for prediction.
- Need to carefully validate modeling and the predictability

STIRAP and Probe Level Scheme in Test Setup:

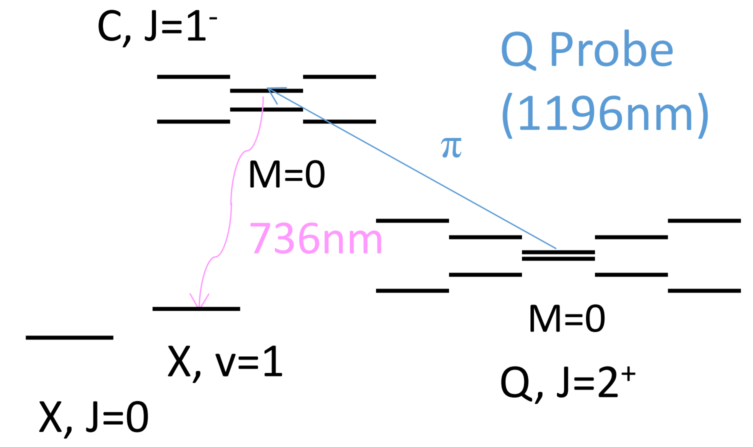
STIRAP Scheme:



Probe X state:



Probe Q state:

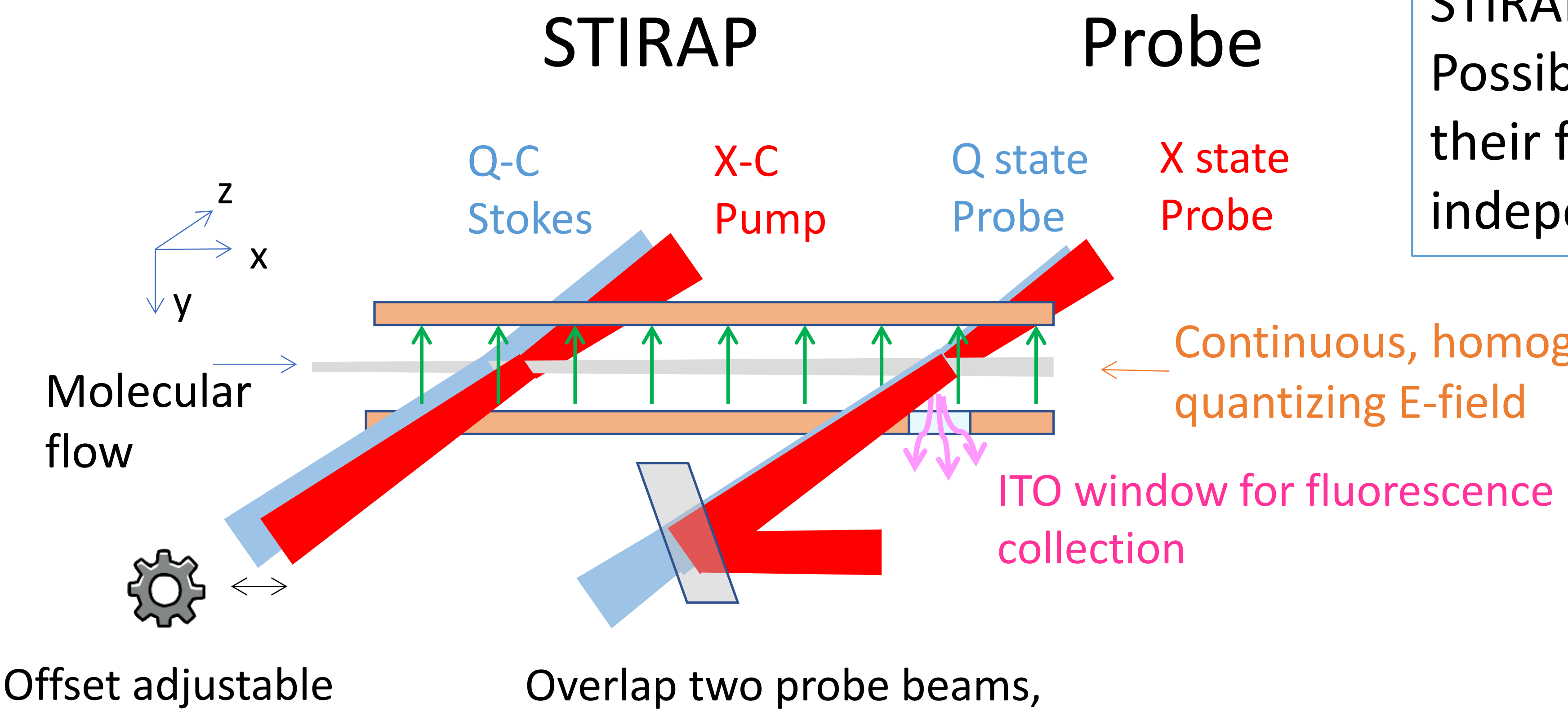


✓Detect 736nm off-diagonal decay from C—X (v=1), helps a lot to suppress background scattering

✓Both probes excite to EXACTLY the same C state sublevel, so allows direct comparison between population in X and in Q

STIRAP Setup

Q-probe is derived from Q-C STIRAP beam:
Possible, but tedious to tune their frequency and power independently



Molecular flow

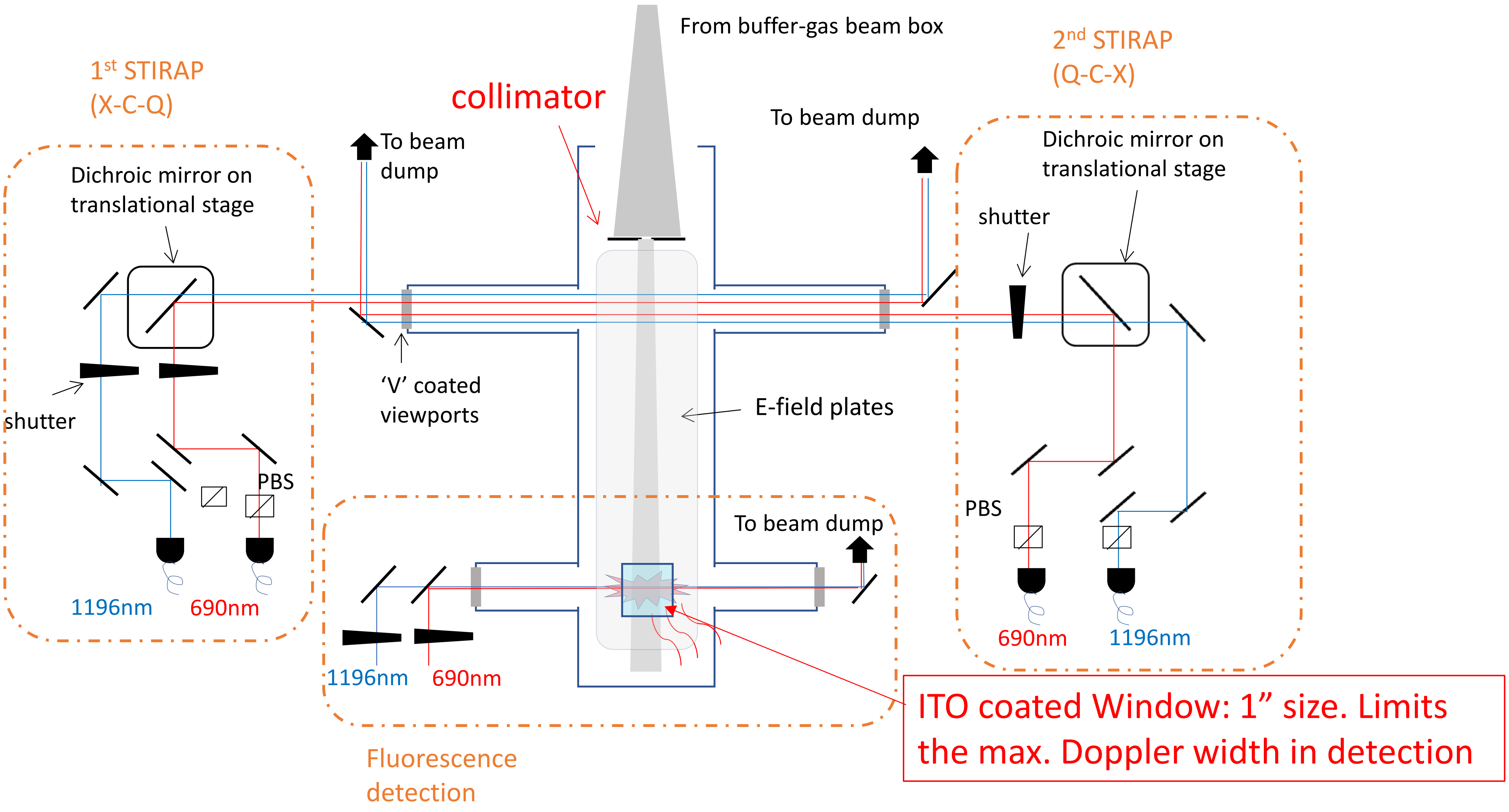
Continuous, homogeneous, quantizing E-field

ITO window for fluorescence collection

Offset adjustable

Overlap two probe beams, switch between X/Q state

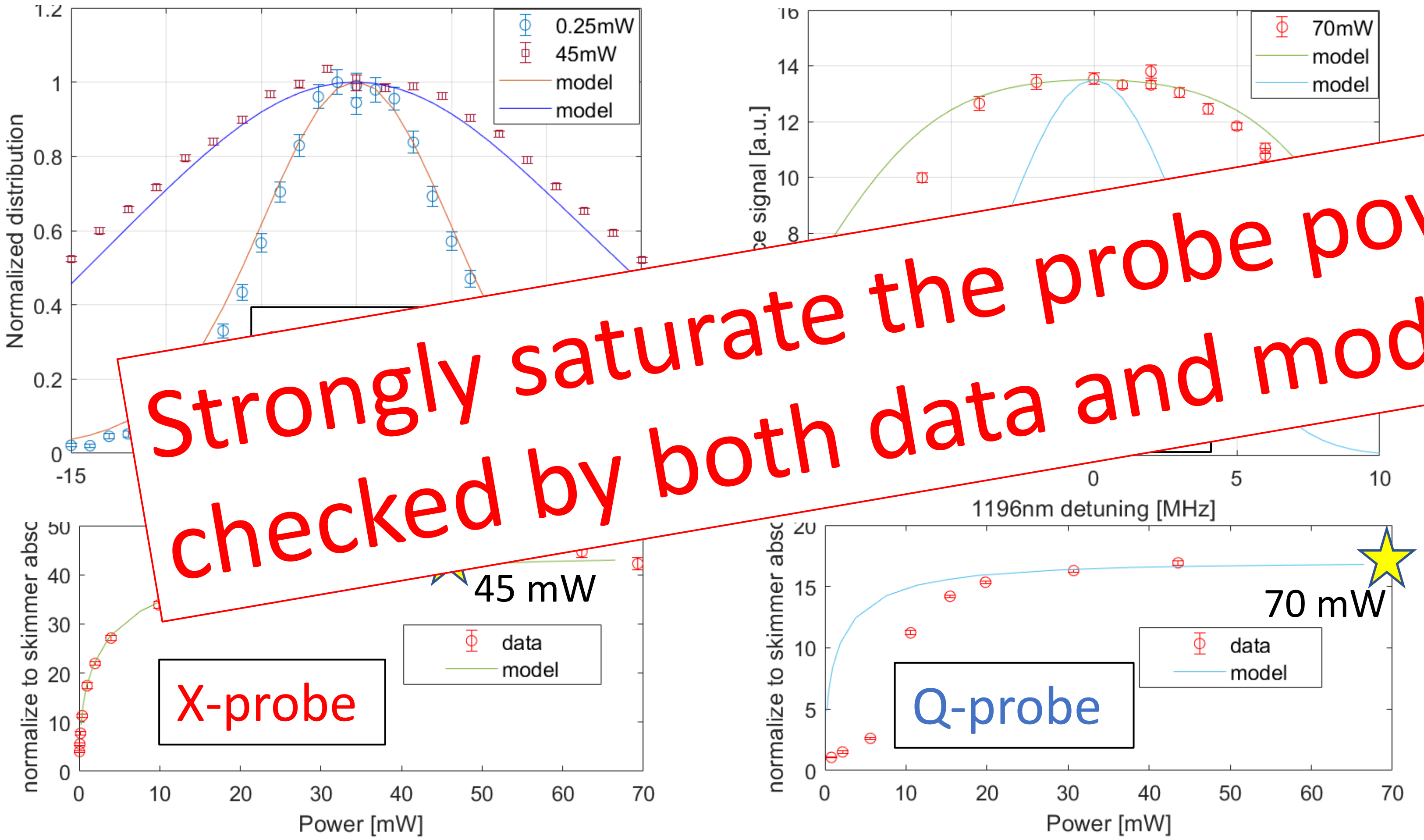
STIRAP Setup



ITO coated Window: 1" size. Limits the max. Doppler width in detection

To Measure STIRAP Saturation: Make Sure Probe Beams Saturate Entire Doppler Width

- General strategy: use max available probe power to get most signal from molecules with large v



Strongly saturate the probe power, checked by both data and modeling

- Verify with power b dening scan & hape modeling (t parameter)
- y with power saturation scan & modeling (no fit parameter)

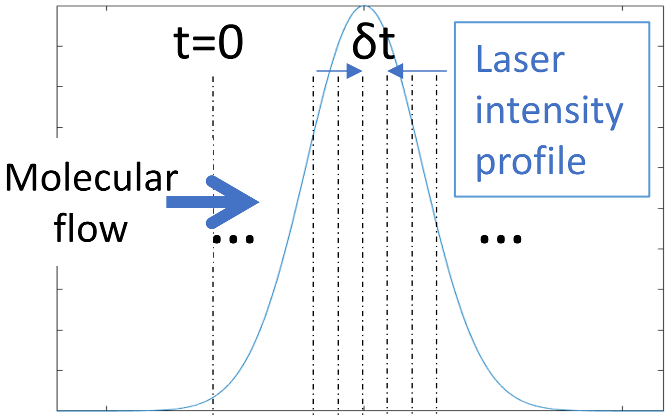
☆ : indicates where STIRAP measurements were made

Lineshape/Power-scan Modeling: Optical Bloch Equations

- Model input:
  - Laser intensity profile; transition dipoles/branching ratios of X-C, Q-C; laser detuning; Doppler distribution; Laser power
- Time integration of Optical Bloch Equation
  - captures dynamics in the transient process, e.g. 50% decay from C to X, J=0
- Modeled detection efficiency vs. v_z

✓ High efficiency even at edges of v-distribution, as desired to simulate situation with lens

- Convolute (integrate) with (over) v-distribution gives lineshape (saturation percentage)



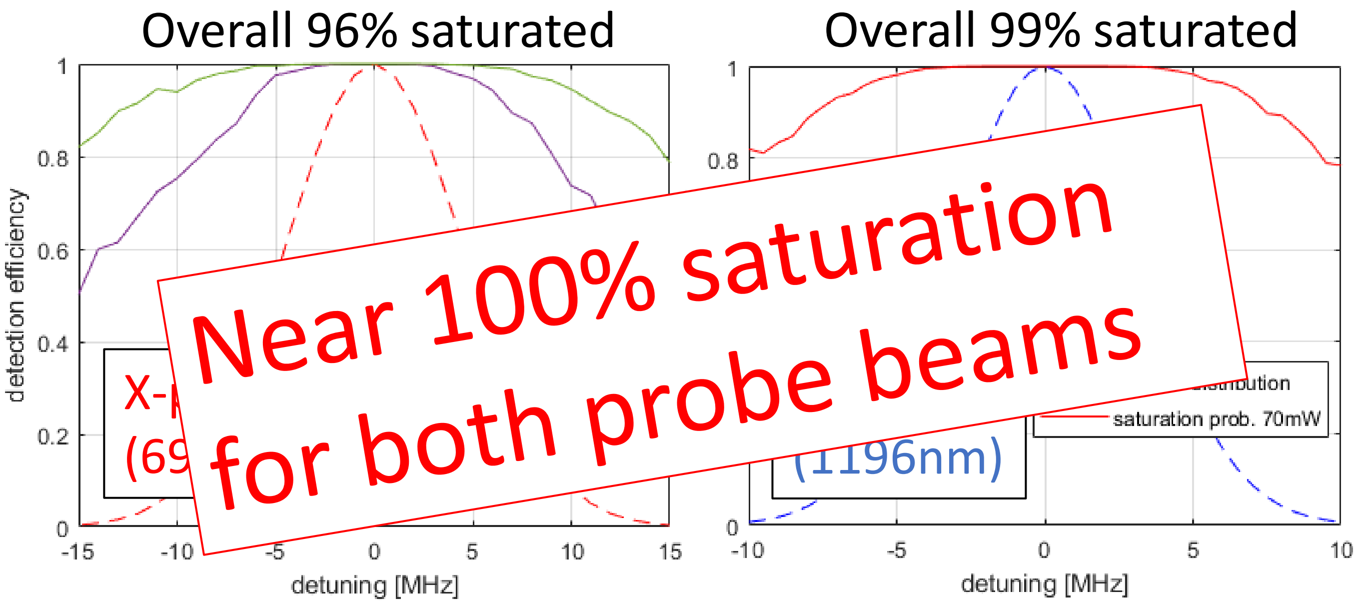
$$\dot{\rho}_{ee} = i\frac{\Omega}{2}(\rho_{eg} - \rho_{ge}) - \Gamma\rho_{ee}$$

$$\dot{\rho}_{gg} = -i\frac{\Omega}{2}(\rho_{eg} - \rho_{ge}) + \xi'\Gamma\rho_{ee}$$

$$\dot{\rho}_{ge} = -(\frac{\Gamma}{2} + i\delta)\rho_{ge} - i\frac{\Omega}{2}(\rho_{ee} - \rho_{gg})$$

$$\Omega = \frac{dE}{\hbar}, \qquad d = D_{X-C,v=0} \cdot f_{HL} \cdot f_{CG}$$

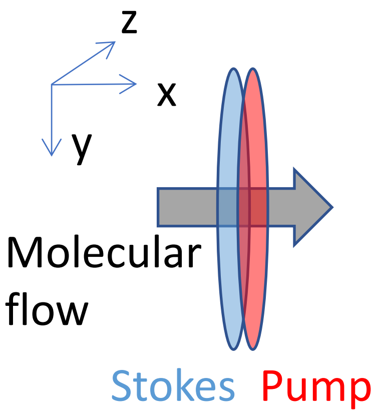
$$\Gamma = \frac{1}{490ns}, \quad \xi' = \xi \cdot \frac{2}{3}, \quad \xi \propto \frac{D^2_{X-C,v=0}}{\lambda^3_{X-C,v=0}}\frac{1}{\Gamma}$$

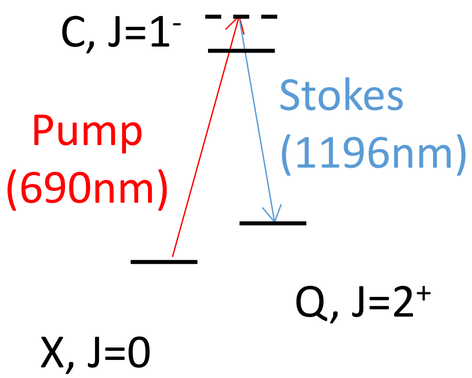

Overall 96% saturated

Overall 99% saturated

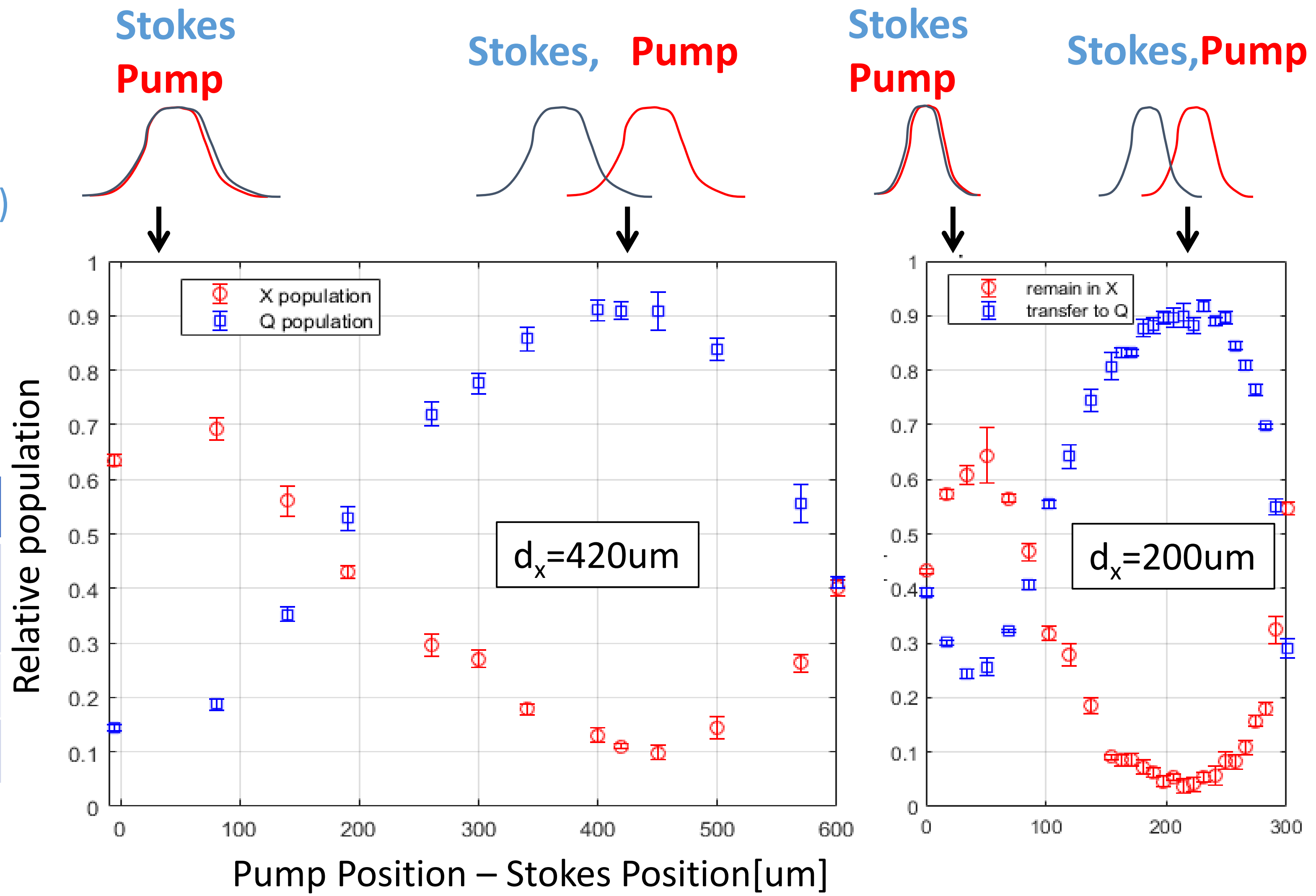
Near 100% saturation for both probe beams

Same STIRAP Efficiency at Narrow 200um Beams as Wider Beams, but with Lower Power



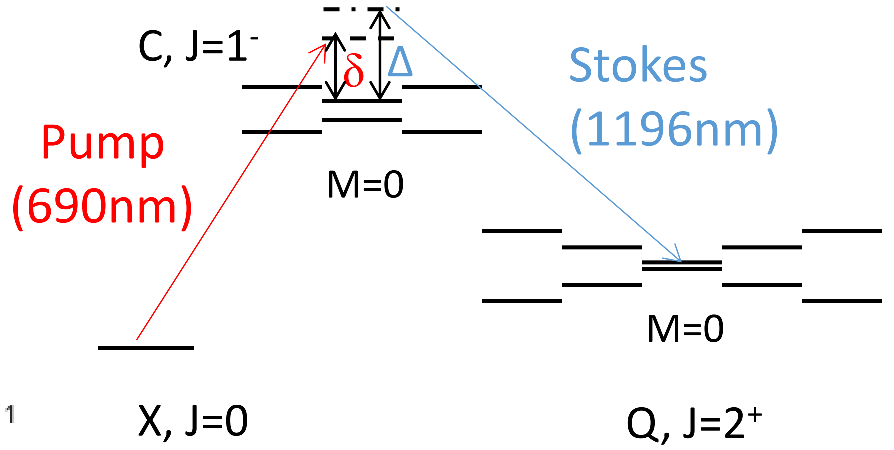


Test condition	
Laser beam (1/e2 diameters)	Molecule beam
d_y≈1.5cm	D_y=5mm
d_x≈420um & 200um	Δv_z=9m/s (FWHM)

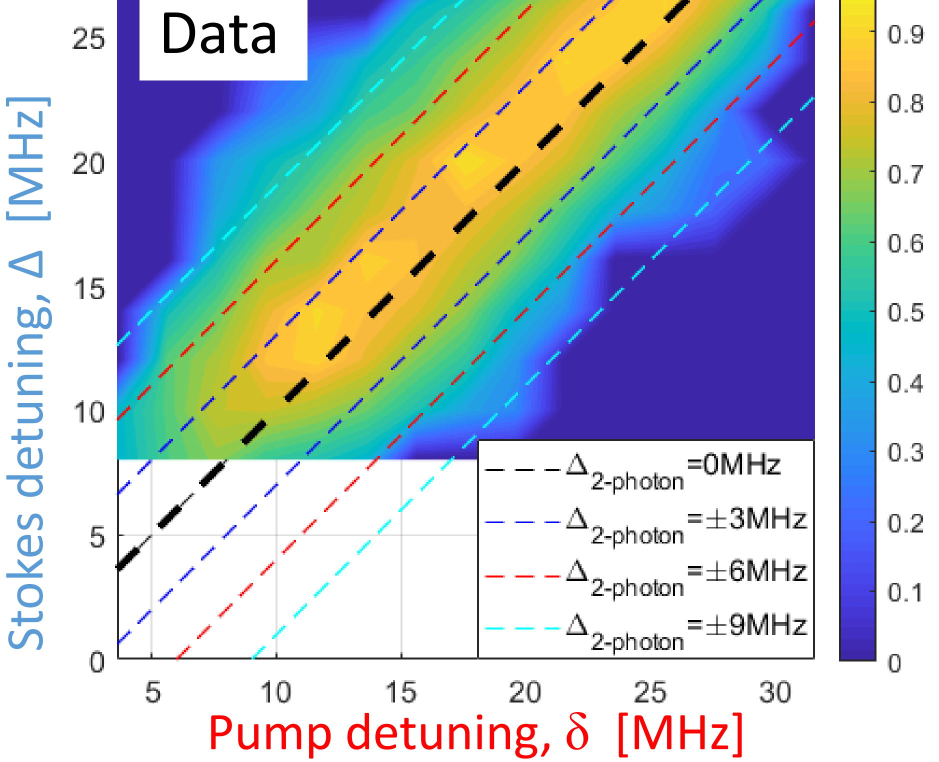


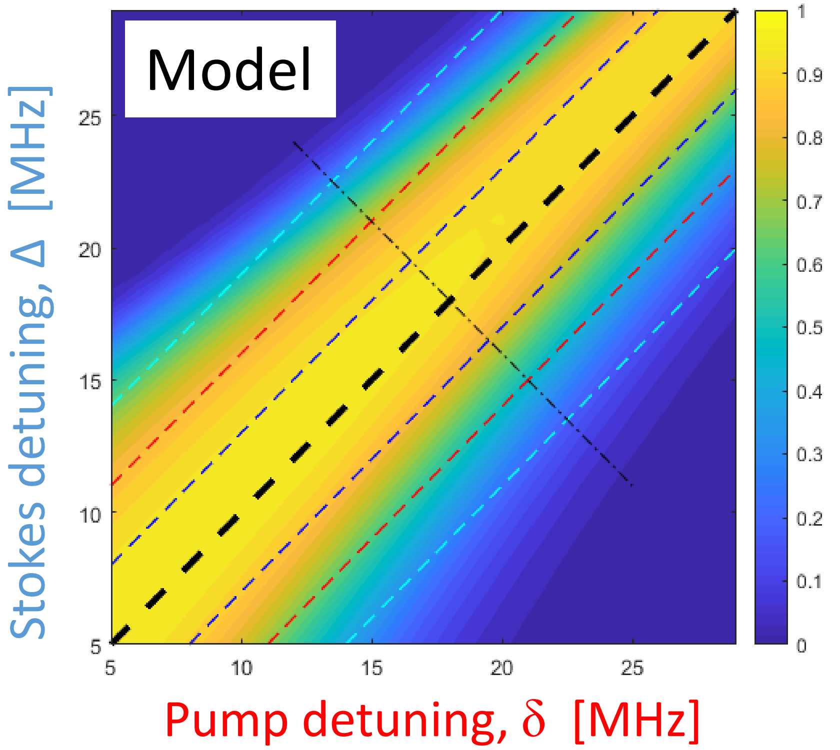
A curiosity: asymmetry in STIRAP vs 2-ν Detuning

- Both X/Q-probe beams saturate the Doppler distribution: Δv_z=9m/s (FWHM)
- Blue shift 1-photon detuning, to avoid complication from other states/polarizations



- ○ Data and model match well qualitatively
- ○ Peak efficiency is asymmetric w.r.t. 2-ν resonance

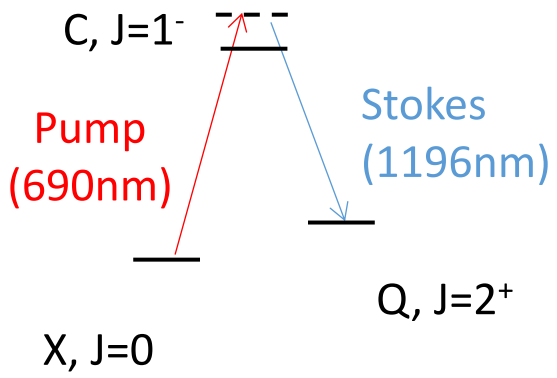


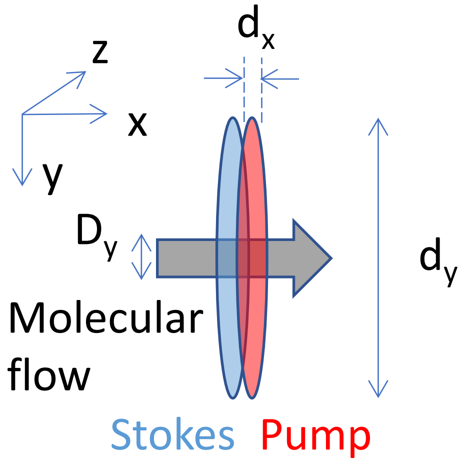


How Well Quantitatively Can Modeling Describe/Predict STIRAP?

STIRAP Modeling & Corrections

- Hamiltonian: 3-level system, coupled by 2 laser fields. Input parameters all from measurements:
  - Molecule beam size, D_y=5mm
  - transverse Doppler profile, FWHM=9m/s
  - laser beam profile (1/e^2 $d_y \approx$1.5cm, d_x=420um, 200um)
  - Actual $\delta_{1-\nu}$ & $\delta_{2-\nu}$ detuning in the scan
  - X-C & Q-C transition strength measured previously





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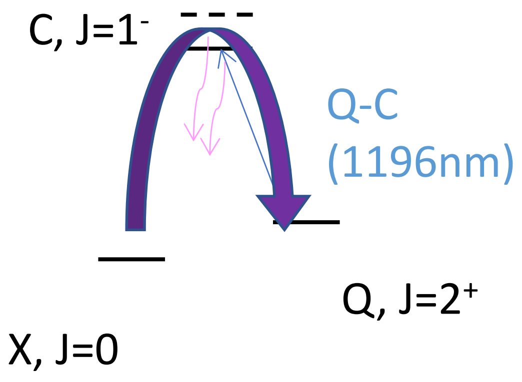
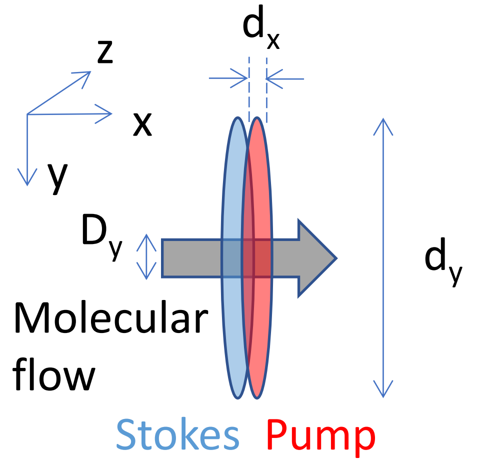
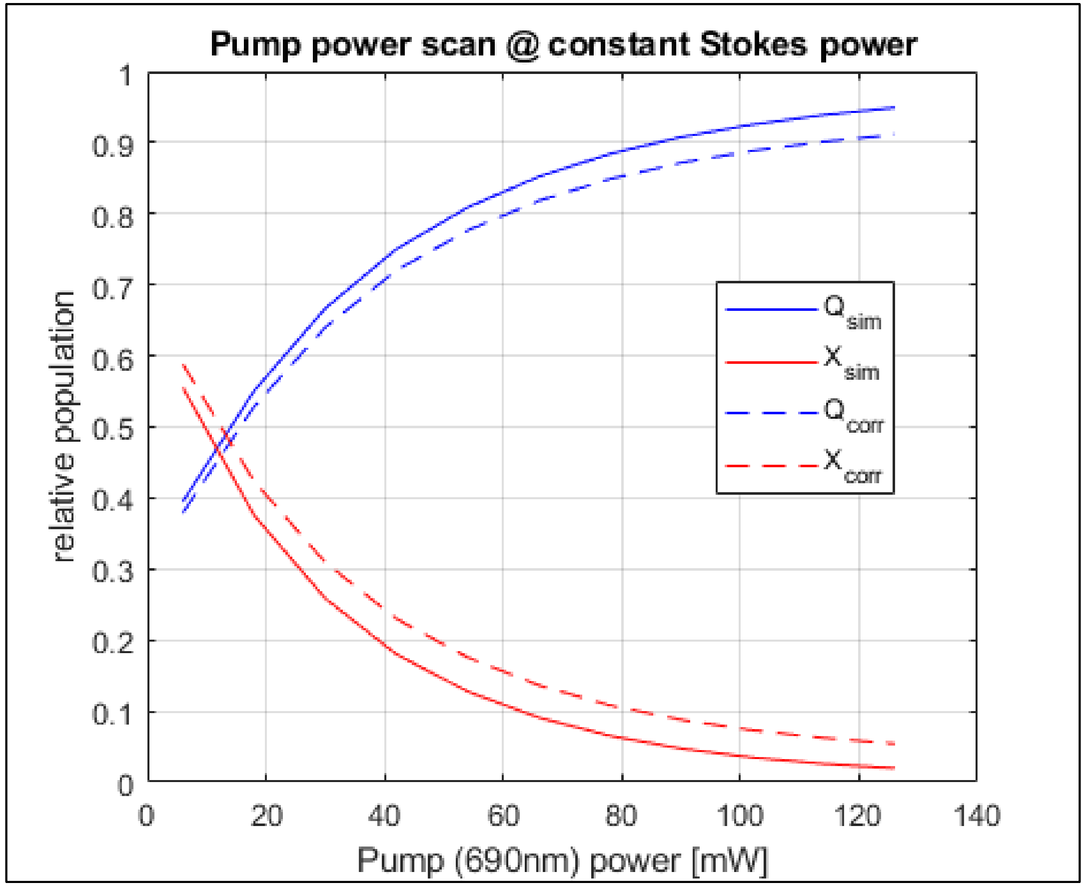
  - Molecule beam size, D_y=5mm
  - transverse Doppler profile, FWHM=9m/s
  - laser beam profile ($1/e^2$ $d_y \approx$1.5cm, d_x=420um, 200um)
  - Actual $\delta_{1\text{-}\nu}$ & $\delta_{2\text{-}\nu}$ detuning in the scan
  - X-C & Q-C transition strength measured previously
- Correction:
  - Higher remaining X population: decay out of 3-level system not captured by the Hamiltonian, but 50% of them is back to X ground state
  - Lower Q population: Q-C optical pumping by Stokes beam imperfection





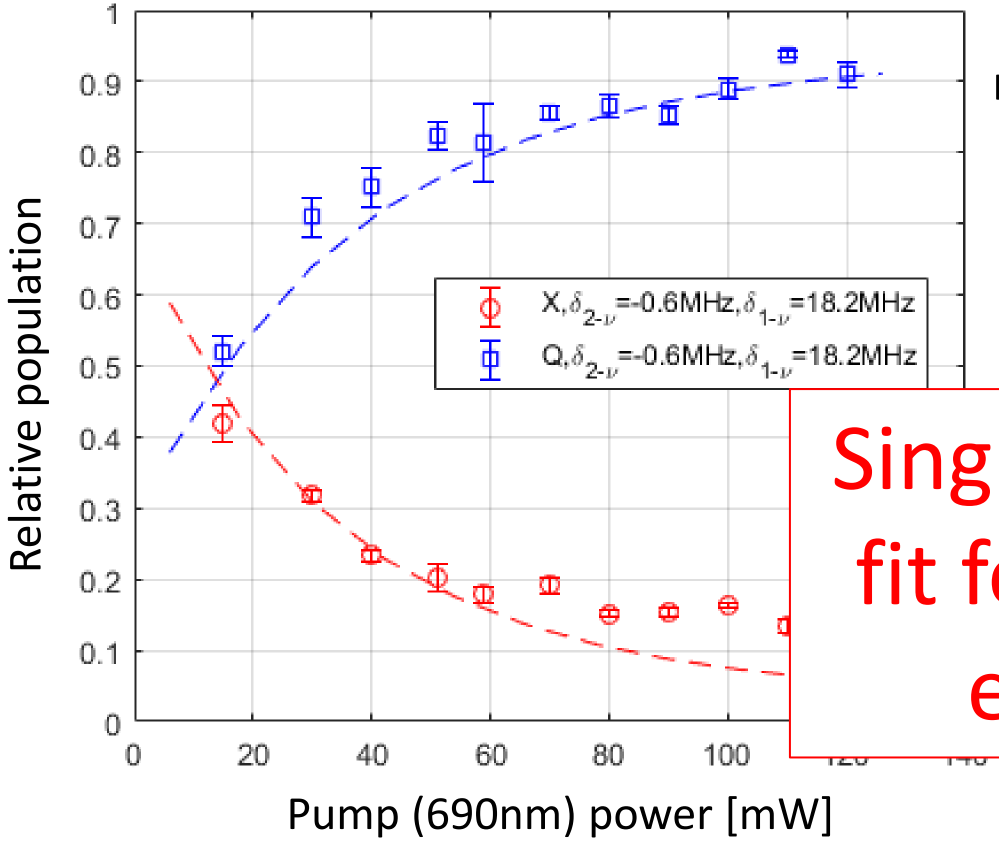
Correction in STIRAP Modeling, Part 1:



- Correction to Q population
  - $Q_{corr}=Q_{sim}*\eta$, where constant rescaling factor, $\eta < 1$ (but ≈ 1)
  - Justified when Stokes beam power held constant, with imperfection pumps Q out.
- Correction to X population
  - $X_{corr}=X_{sim}+(1-X_{sim}-Q_{sim})*0.5+Q_{sim}*(1-\eta)*0.5$
  - $(1-X_{sim}-Q_{sim})$ is the population decay out of the 3-level system via C state
  - $Q_{sim}*(1-\eta)$ is the amount of Q population pumped out

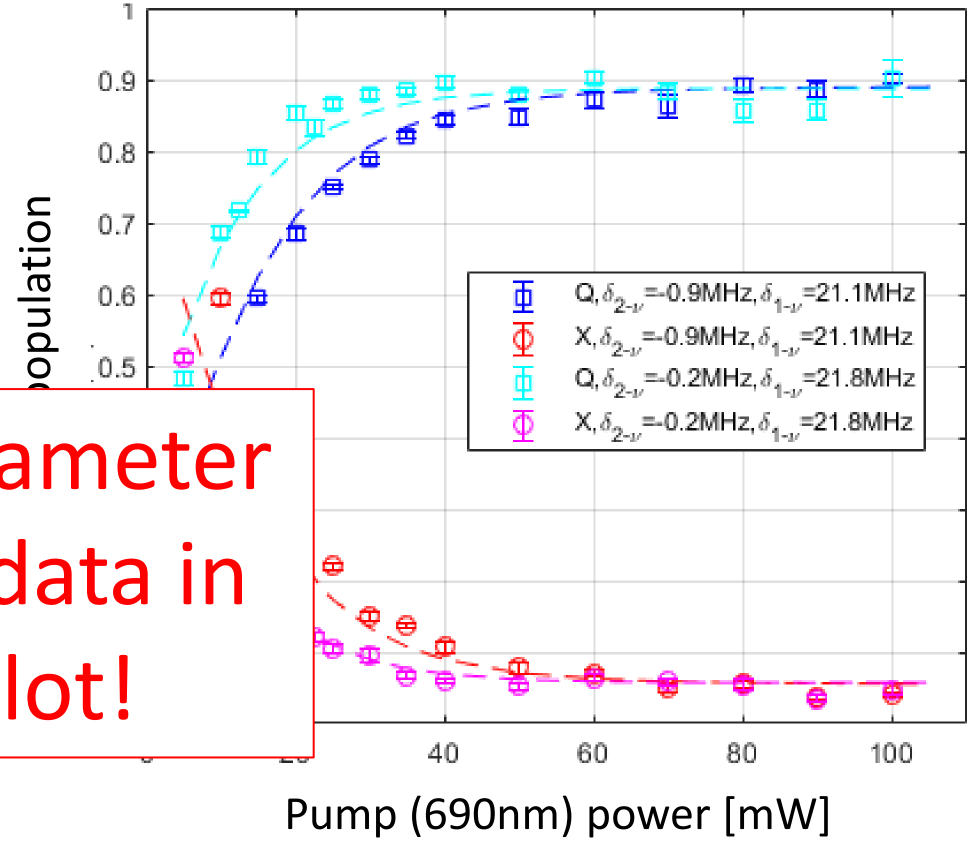
Verify STIRAP Modeling, Part 1: Population Transfer vs X-C Pump Power

Simulation vs. Data
soft focus d_x= 420um



η =0.96

Simulation vs. Data
tighter focus d_x= 200um



η =0.90

Single parameter fit for all data in each plot!

Correction in STIRAP Modeling, Part 2:

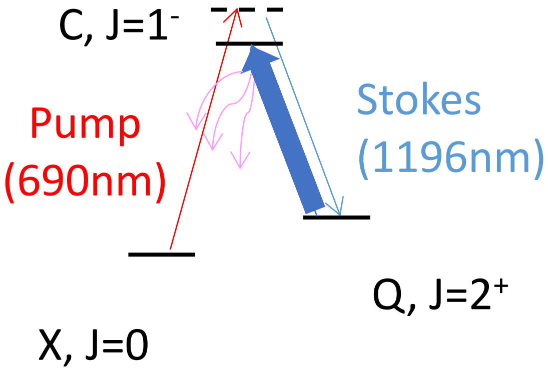
- Correction for Stokes (Q-C) power scan
  - $Q_{corr}=Q_{sim}*\eta$, with constant η, NO longer valid
  - Power dependence captured by rate equation of Q-C pumping
  - Solution approximated by simple exponential behavior:

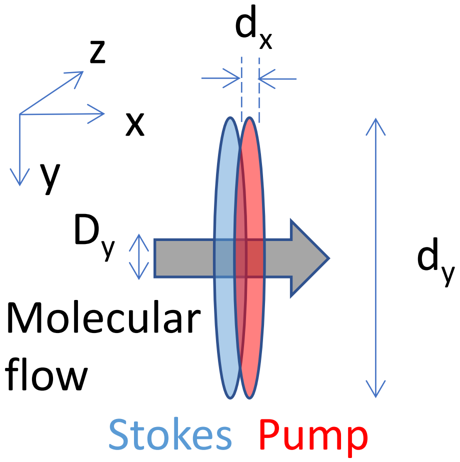
    $Q=Q_{sim}*(\eta+\exp(-Power/P_{sat.})*(1-\eta))$,

  where $P_{sat.}$ is the only additional fit parameter, represents 1/e saturation power of Q-C pumping,

  while η is the same as in Pump (X-C) scan

- Correction to X population modified accordingly

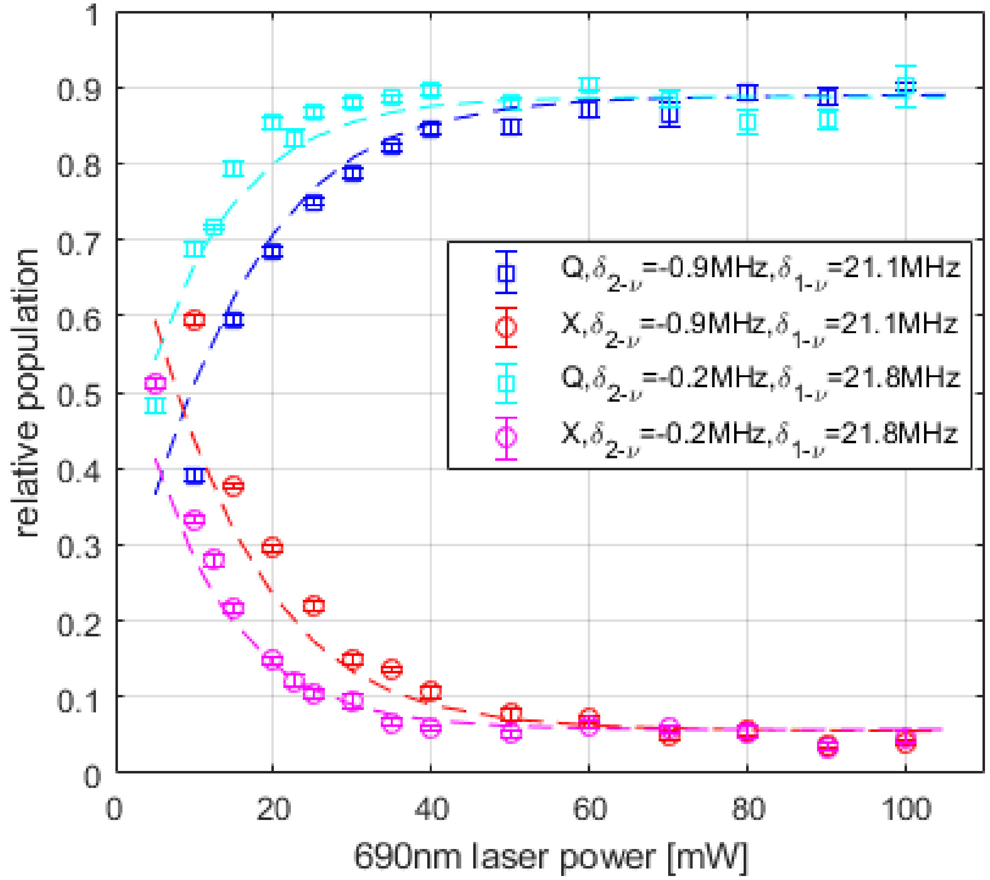




Verify STIRAP Modeling, Part 2: d_x=200um Laser Beam

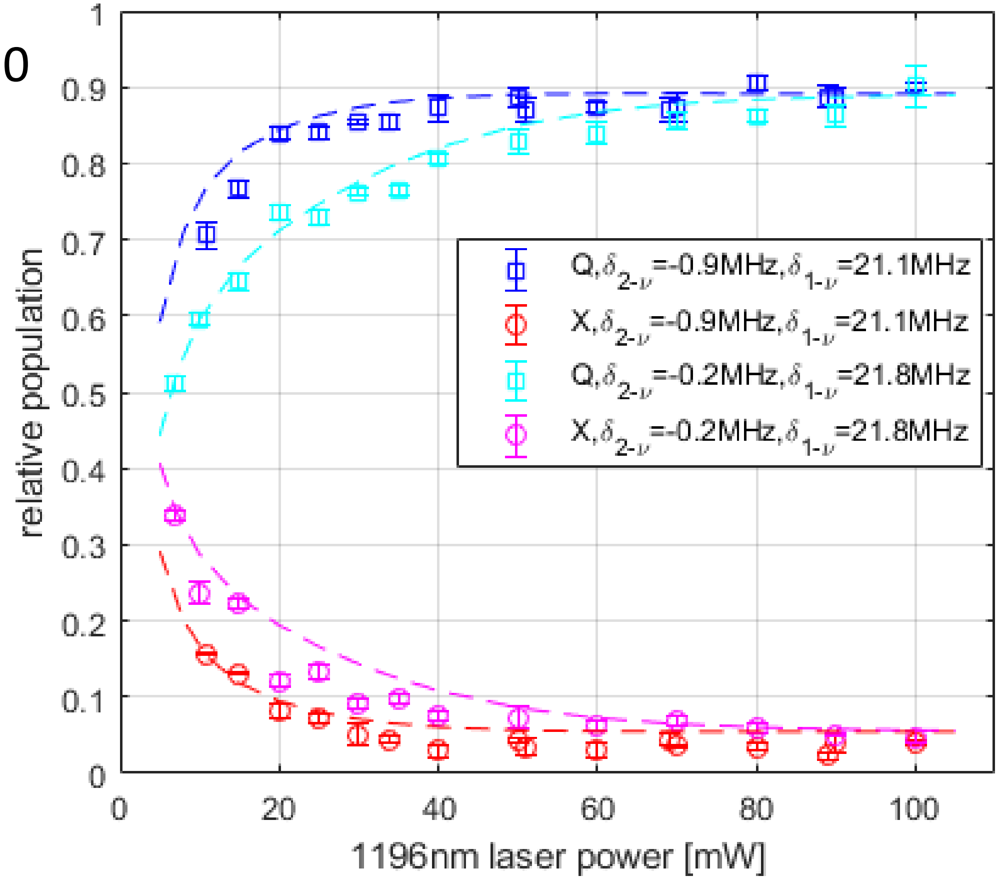
η held as constant between the two. Same saturation Stokes power are used

Pump (X-C) power scan



η =0.90

Stokes (Q-C) power scan



η =0.90

$P_{sat.}$=25mW

Comparable to what we know from Q—C transition strength measurement. For a direct optical pumping, need ~x100 less intensity to saturate.

Summary for Modeling

- excellent agreement between model and measurement, using ‘1.5’ fitting parameters
- Verified with 2 different laser beam focus size, 3 different values of detuning, across broad range of Pump and Stokes powers
- Demonstrate predictive power with the 200um focus measurement
- Gives confidence on extrapolating to real Lens condition

Differences in Transition Strength: Test vs Lens

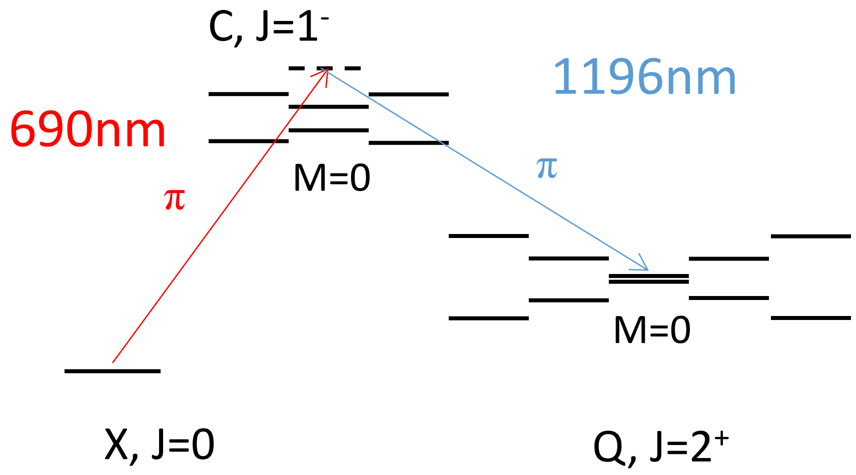
- Keep 200um diameter focus, as in Test
- Clebsch-Gordan coefficients ^{2} (Transition moment $\propto$ CG factor^2)

	Test	Lens	Power required
690 nm	1/3; No E-field mixing	1/3; small E-field mixing	X ~1.25 to 1.5 times
1196 nm	2/15; No E-field mixing	3/15; x1/2 from full E-mixing	X 1.33 times

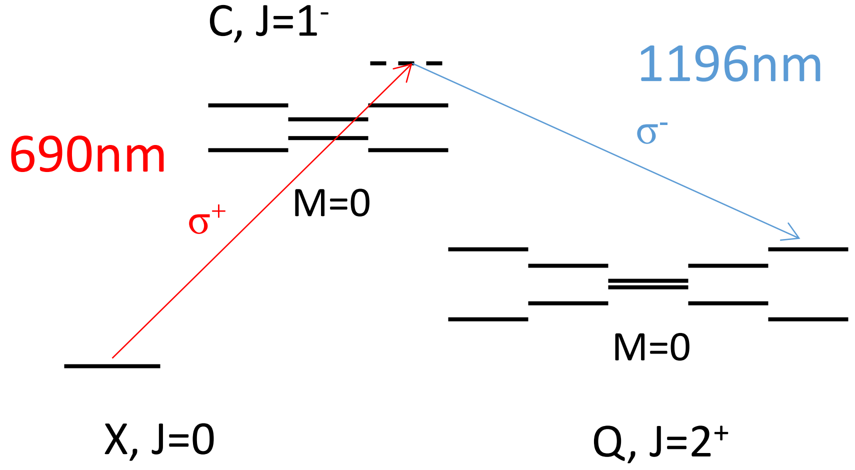
Depends on E-field: 50 to 100V/cm, or 15 to 40MHz Stark shift (using worst scenario for model)

Only for keeping a continuous E-field towards Lens

Test Setup:

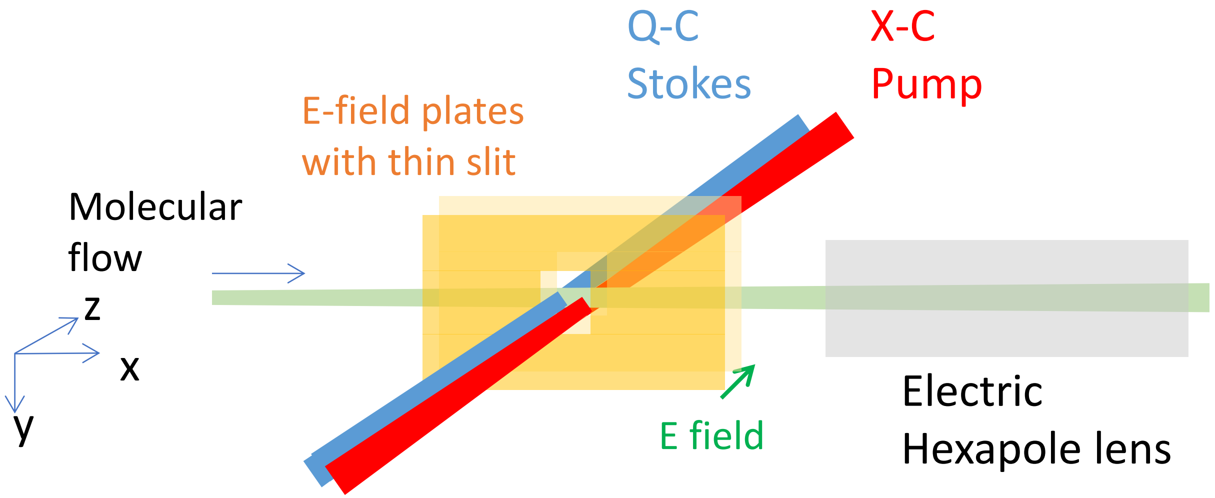


Actual Lens:

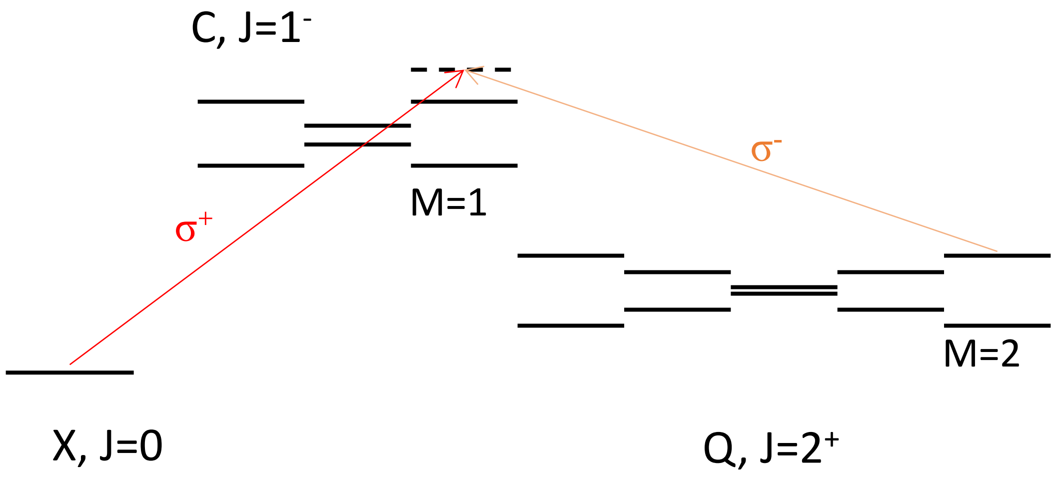


B-field along quantization axis can help eliminate issues from 'wrong' polarization

Proposed Actual STIRAP Setup Geometry



σ^- and σ^+ polarization for Stokes (1196nm) and Pump (690nm)



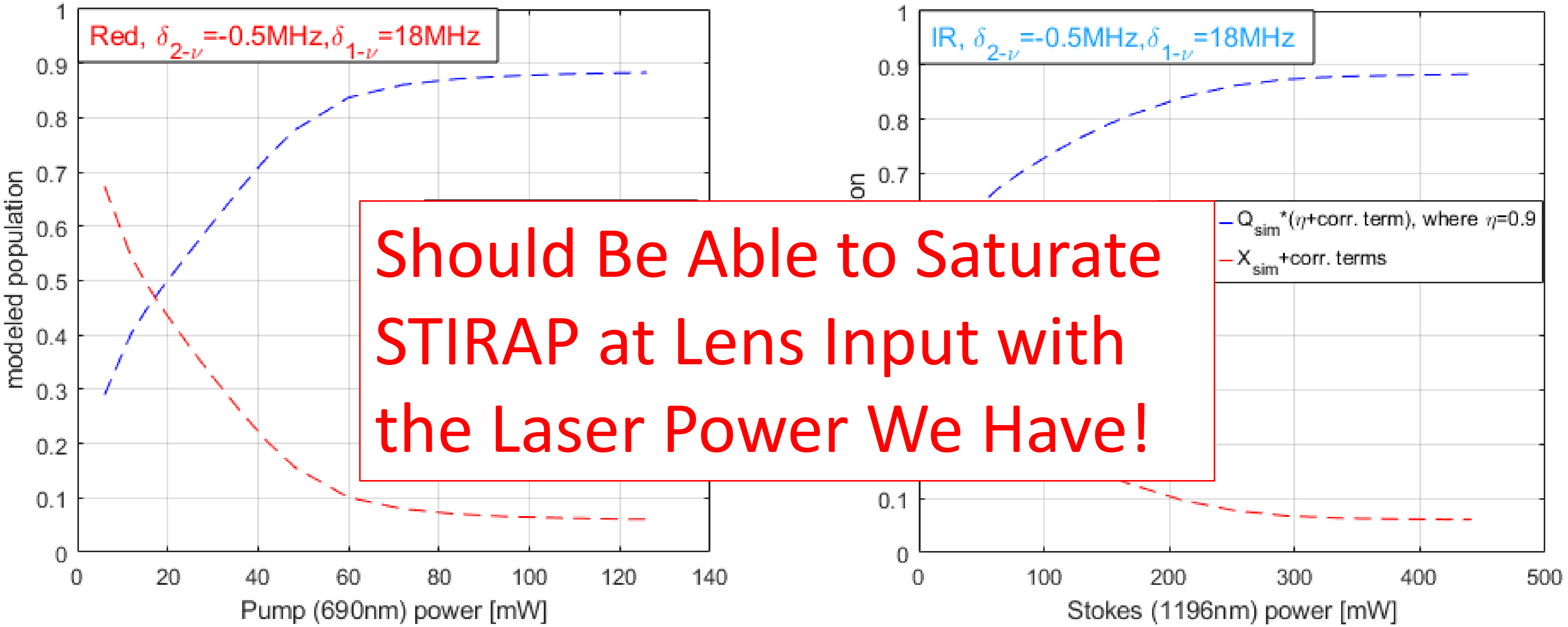
- Field plates dimension (based on field simulation.
    - L x H ≈ 6cm x 6cm
    - Spacing = 3cm
    - Slit 2mm x 40mm

  Might want narrower slit for more homogeneous E-field

- E-field: 50 to 100V/cm, depending on the matching to Hexapole lens. For maintain Stark splitting >> 100kHz parity splitting of Q-state in region between STIRAP and lens
- Need 2” diameter quarter-wave plate to make correct polarization
- B-field of ~7G is sufficient to detuning the ‘wrong’ polarization

Projection of saturation power for Lens

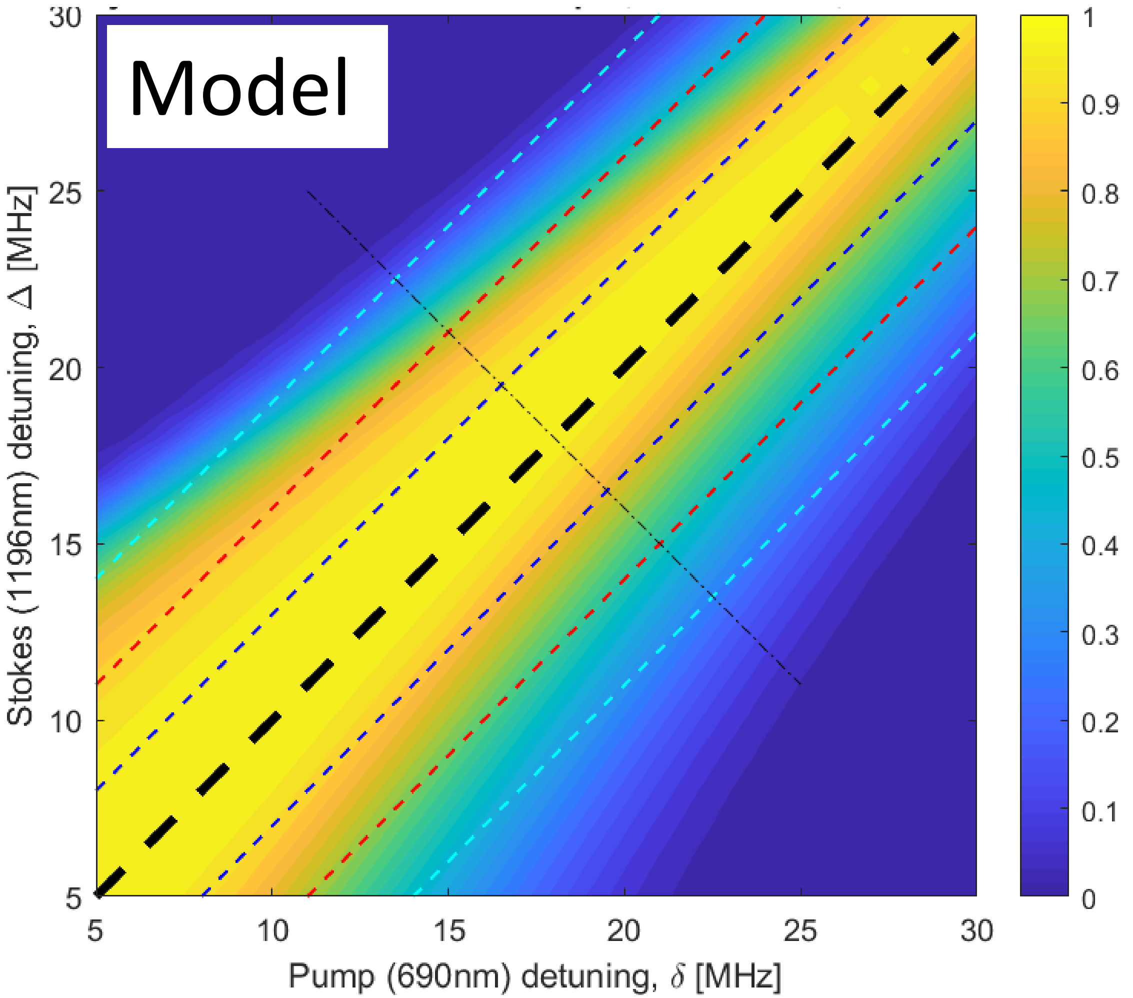
- Modeling with the actual v_z distribution at Lens Input, and actual transition strength (including parity mixing)
- Beam diameter H=3cm, D=200um,
- Including the η=0.9 imperfection factor

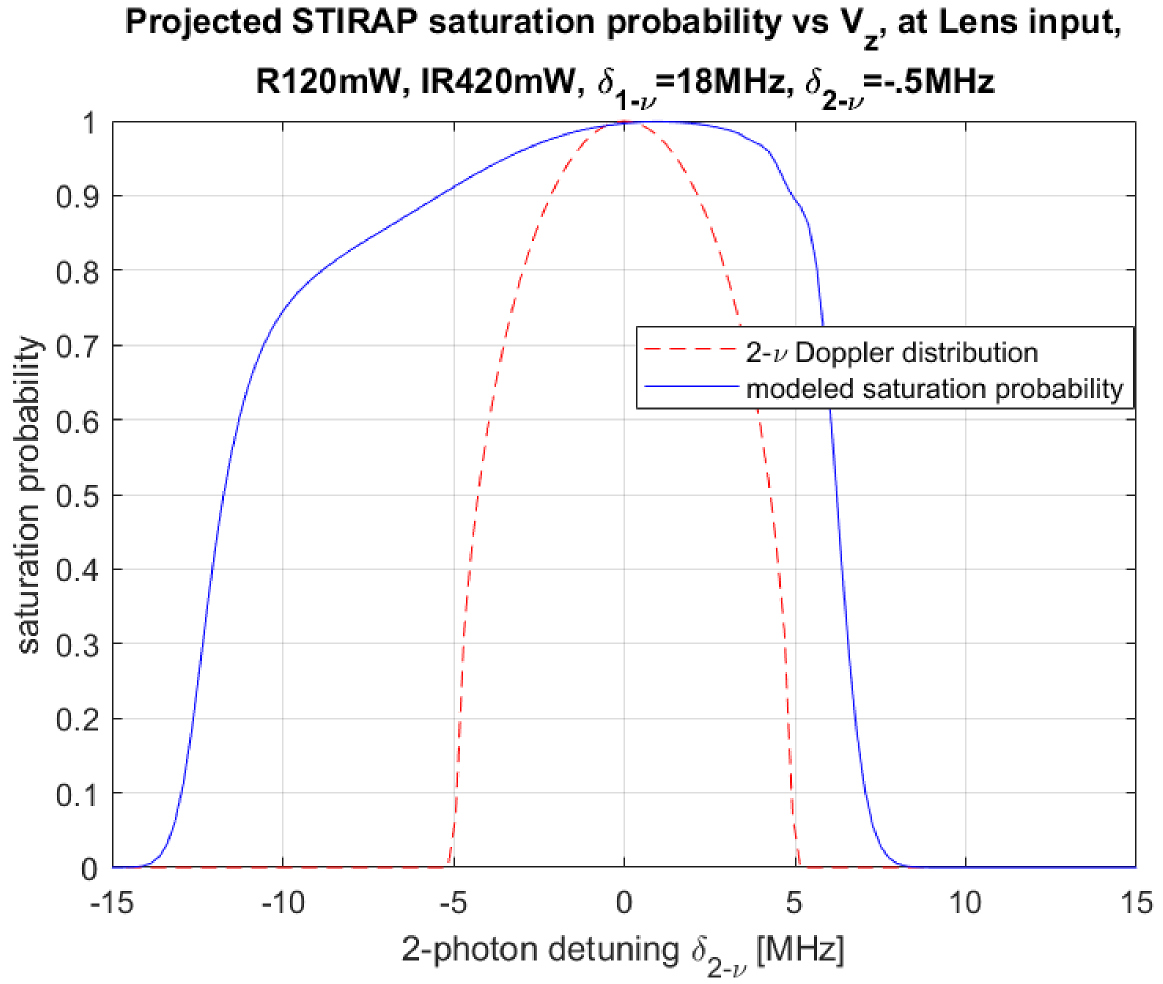


Should Be Able to Saturate STIRAP at Lens Input with the Laser Power We Have!

The **Entire V_z Distribution** at Lens Input Can Be **Well Saturated**

- We are able to look for optimized $\delta_{2\text{-}\nu}$ with modeling




Projected STIRAP saturation probability vs V_z, at Lens input, R120mW, IR420mW, $\delta_{1\text{-}\nu}$=18MHz, $\delta_{2\text{-}\nu}$=-.5MHz

Conclusion: Laser Power Necessary to Saturate STIRAP is Covered by Current TAs

- STIRAP Power requirement
  - Pump (X-C, 690nm) need 120mW x 2 for Lens Input and (less at) Lens Output. **Covered** by 2x 690nm TAs.
    - get 270mW from each TA, 120mW after fiber
    - Toptica claims their 690nm TA will come online (at earliest) the end of the year
  - Stokes (Q-C, 1196nm) need 300mW x2 for Lens Input & Output. **Covered** by 1x 1196nm TA (900mW after fiber).
- STIRAP Geometry
  - Require STIRAP beam going along quantization axis (through E-field plates, and along Helmholtz coil axis)
  - Space before Lens is compatible with a 30cm Source—Lens distance

Order-of-magnitude estimate

Attenuation factor is linear with interaction length, 0.4%x5=2%, assuming the same bg pressure in ACME III. 0.4% is from ACME II

hypothetical

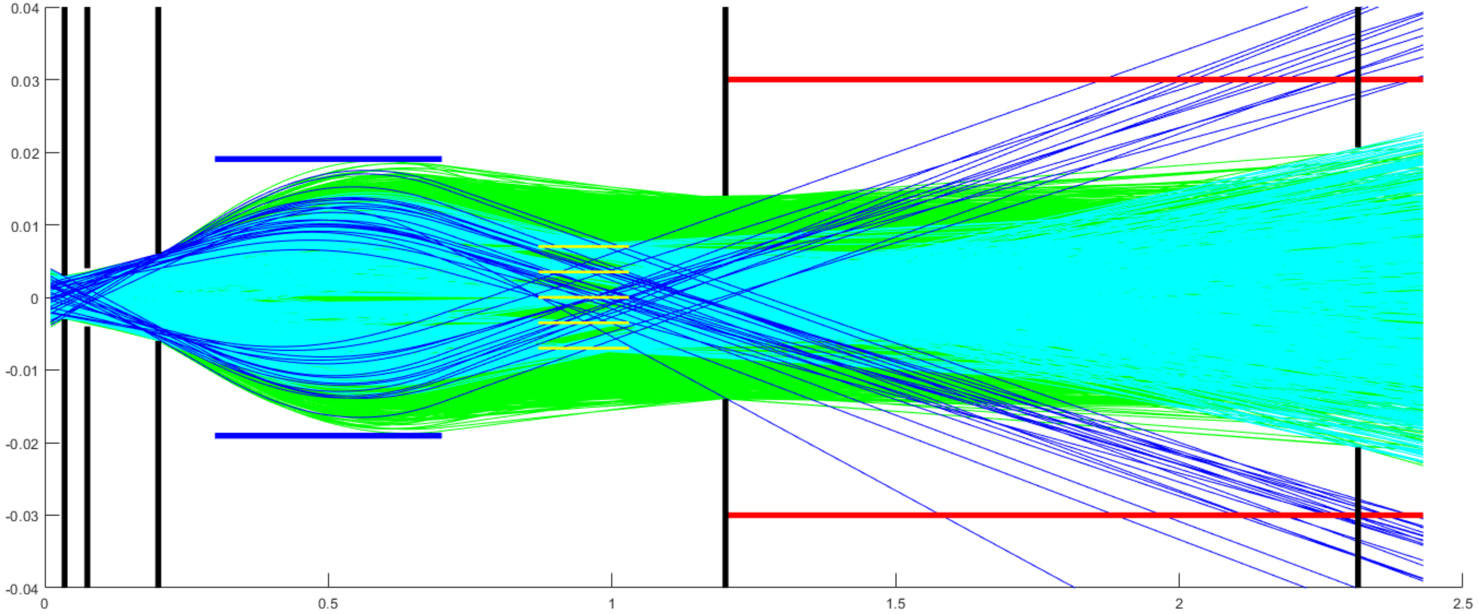
Baseline

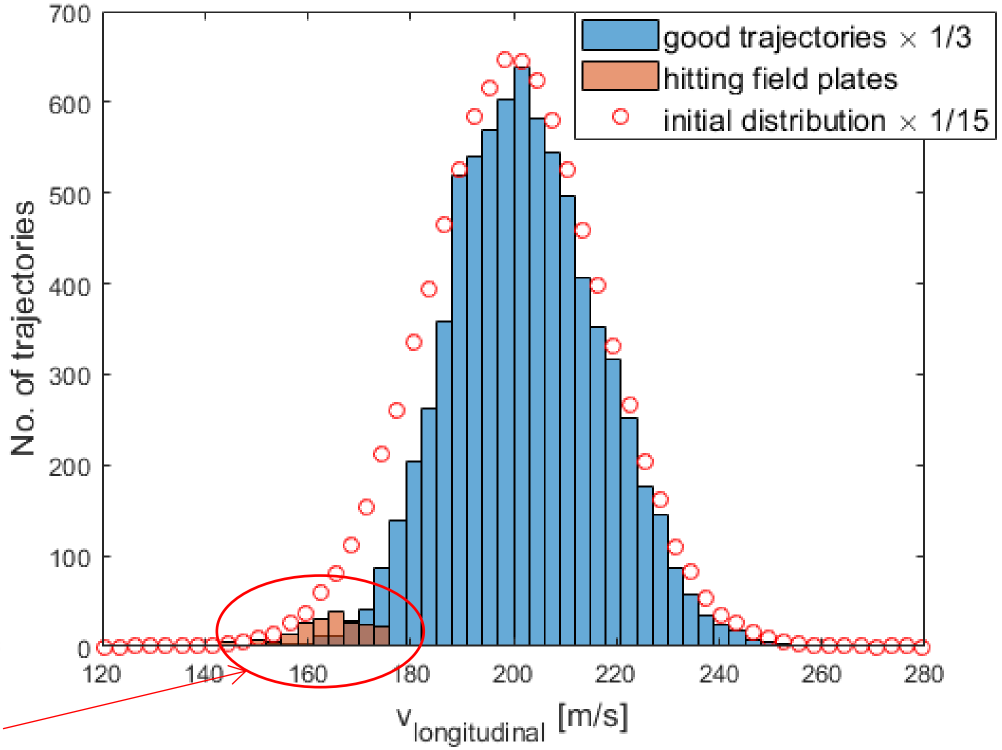
Scenario	ACME II, direct 'head-on' exposure	ACME II, finite vacuum scattering)	ACME III, overfocus by lens	ACME III, finite vacuum scattering
particle flux density [moleucles/s/cm^2]	Φ_0= 1e8 [only ThO in J=0]	Φ_0*0.4% =4e5 [attenuation calib.]	(Φ_0*16)*0.5% =1.6e9*0.5%=8e6	(Φ_0*16)*2%=3e7 [only ThO in J=0]
Coating area		20cm*5cm*2	30cm*28cm*2	100cm*28cm*2
Running time	1.3e7 second [10hrs/day, 1 yr of continuous running]			
Sticking probability	100%			
Number/cm^2 in 1year	1.3e15	1.3e11	6e11	2e12
ThO monolayer latt. size	6e14 /cm^2 [4 Angstrom lattice constant]			
No. monolayer per year	2	2e-4	1e-3	3e-3

Scenario	ACME II, direct 'head-on' exposure	ACME II, finite vacuum scattering)	ACME III, overfocus by lens	ACME III, finite vacuum scattering
particle flux density [moleucles/s/cm^2]	Φ_0= 1e8 [only ThO in J=0]	Φ_0*0.4% =4e5 [attenuation calib.]	(Φ_0*16)*0.5% =1.6e9*0.5%=8e6	(Φ_0*16)*2%=3e7 [only ThO in J=0]
No. monolayer per year	2	2e-4	1e-3	3e-3
Particle flux density	Underestimated by up to 1 order of magnitude (diff. J, diff. species)	Underestimated by up to 1 order of magnitude (diff. J, diff. species)		Underestimated by up to 1 order of magnitude (diff. J, diff. species)
Attenuation probability		factor of 0.4% overestimated by likely 1~2 orders of magnitude		factor of 2% overestimated by likely 1~2 orders of magnitude
Percent of 'too slow'			factor of 0.5% underestimated by likely 1 order of magnitude	
More realistic No. monolayer per year	2~20	2e-5	<1e-2	3e-4

Looking at the trajectories

- Major difference between good & bad: longitudinal velocities

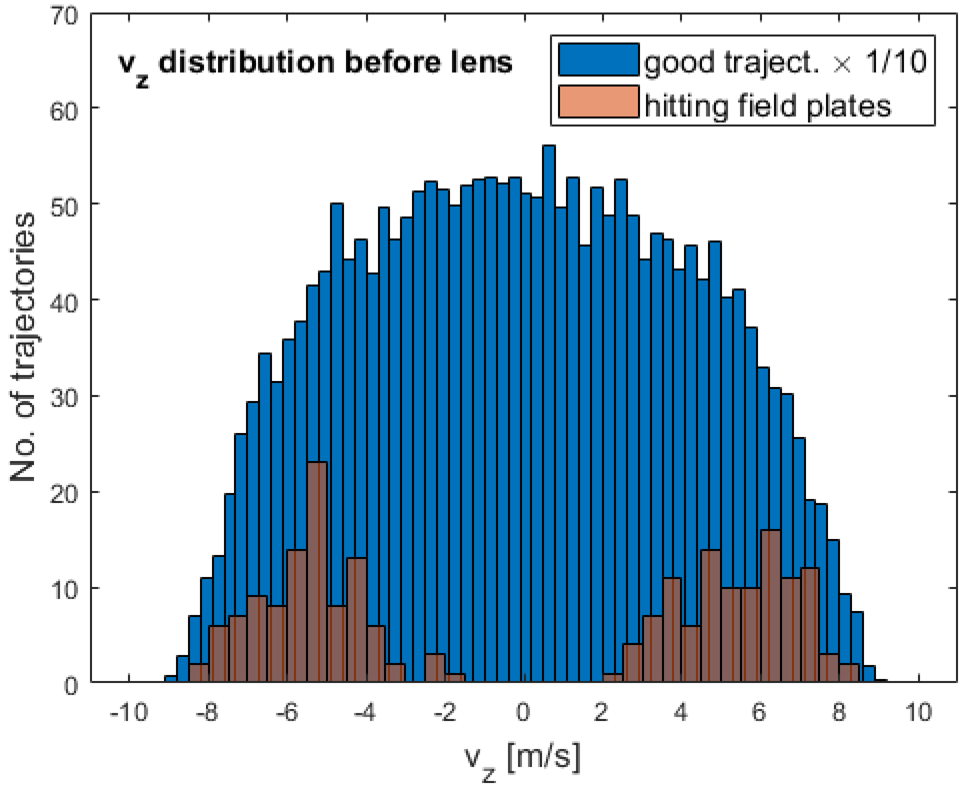


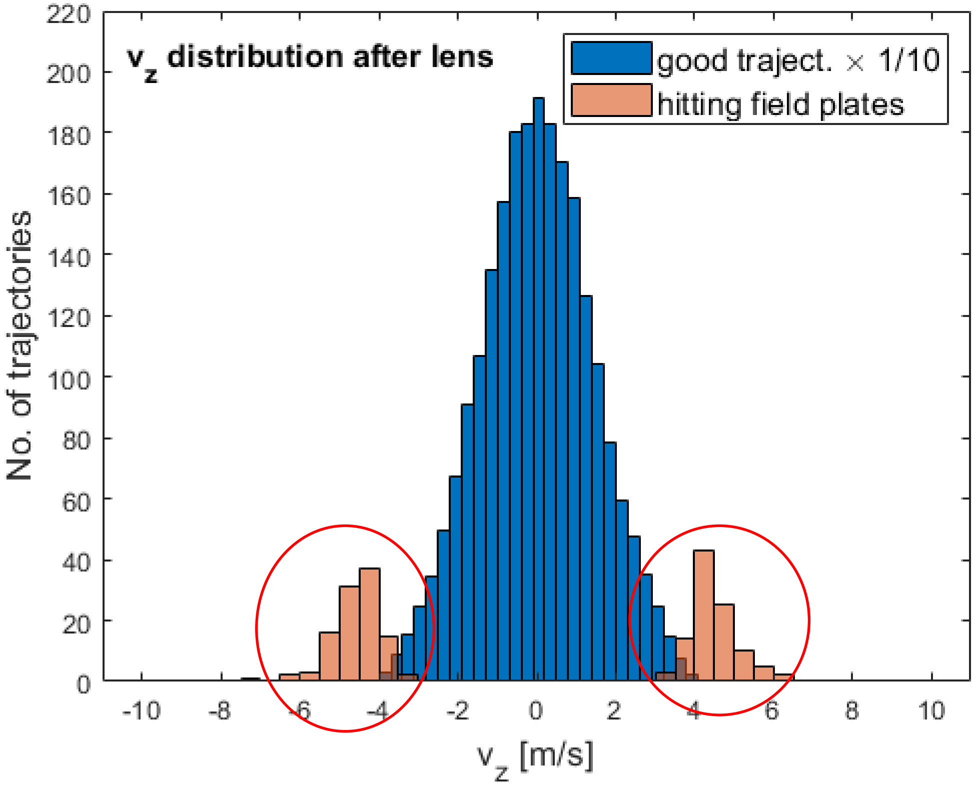


About 0.5% of all trajectories that make into the interaction region

Transverse velocity (v_z) (z is the same as defined in ACME II)

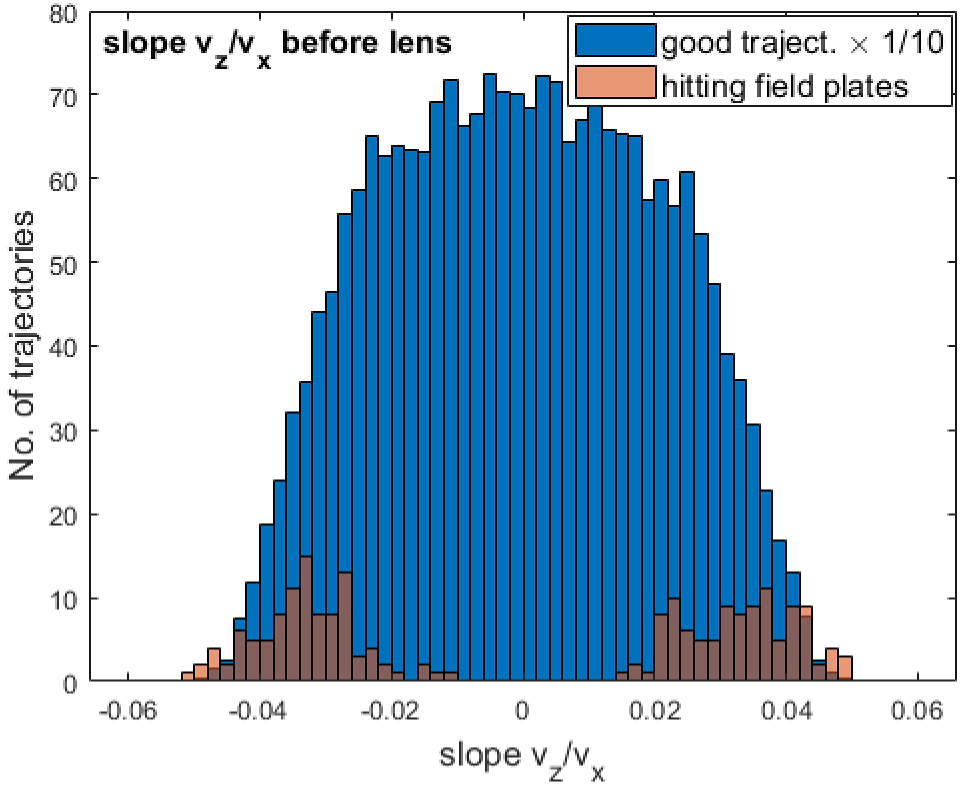
- Cannot differentiate good & bad trajectories in v_z before lens. But they get separated after lens because the bad ones are all slower in v_x and hence spend

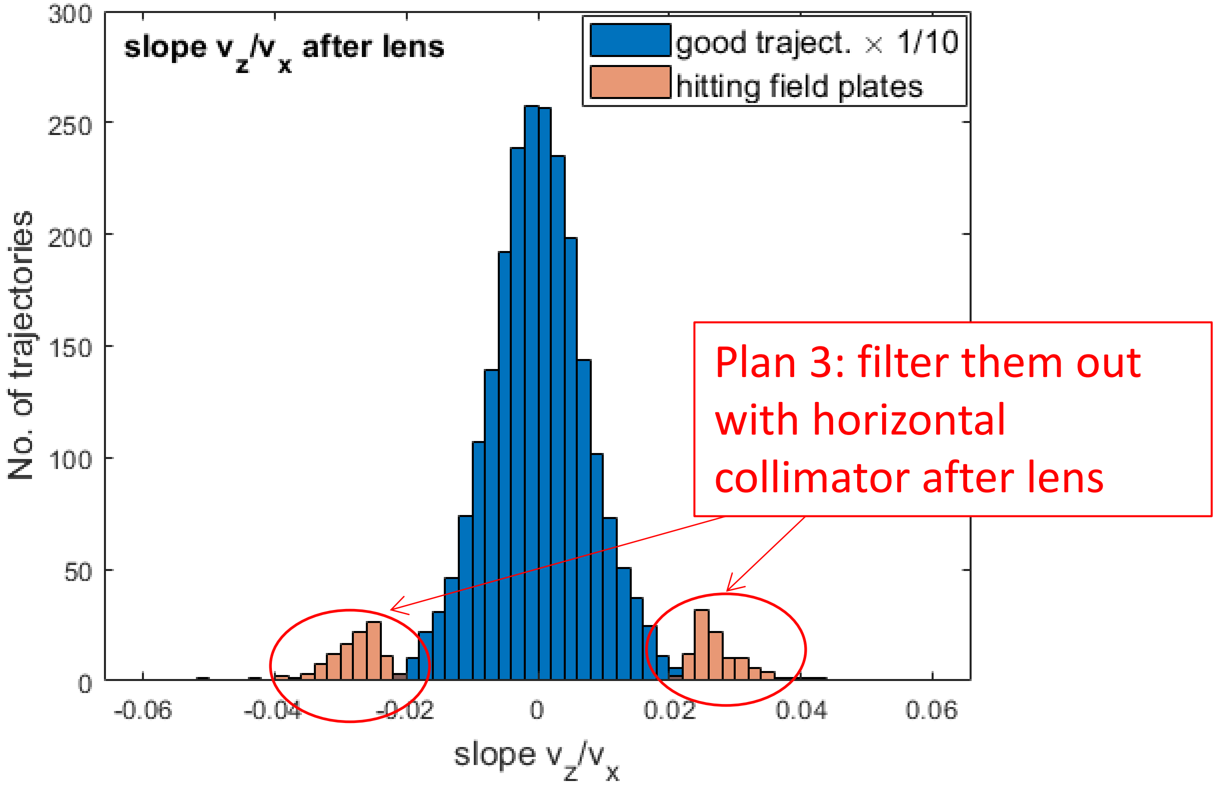




Trajectory slope (v_z/v_x)

- The differentiation gets ‘doubly’ enhanced by looking at the slope (v_z/v_x).





Plan 3: filter them out with horizontal collimator after lens

Estimate on the monolayer deposit rate

- ACME II molecule flux density:
  - Phi = [photoelectron rate]/[detection efficiency]/[state prep efficiency]*[rep rate]/[beam cross-section]

    = [7e5 cnt/shot]/[5%]/[75%]*[50 shot/s]/[10cm^2]

    = 1e8 molecules/s/cm^2

Interaction region collimator: 2.4cm x 2.4cm
detection region: 3.1cm x 3.1cm

  - Suppose insert ITO coated surface directly onto molecule beam (‘head-on’), assuming 100% sticking probability, continuous running for 10hr/day for 1yr

    Number density on surface: N = Phi*[1.3e7 sec]=1.3e15 molecules/cm^2
  - Typical monolayer size: 10^14/cm^2. ThO lattice constant is know, 4 Angstrom: 6e14 molecules/cm^2

    Thus, 2 monolayer for one year continuous running at 100% duty cycle

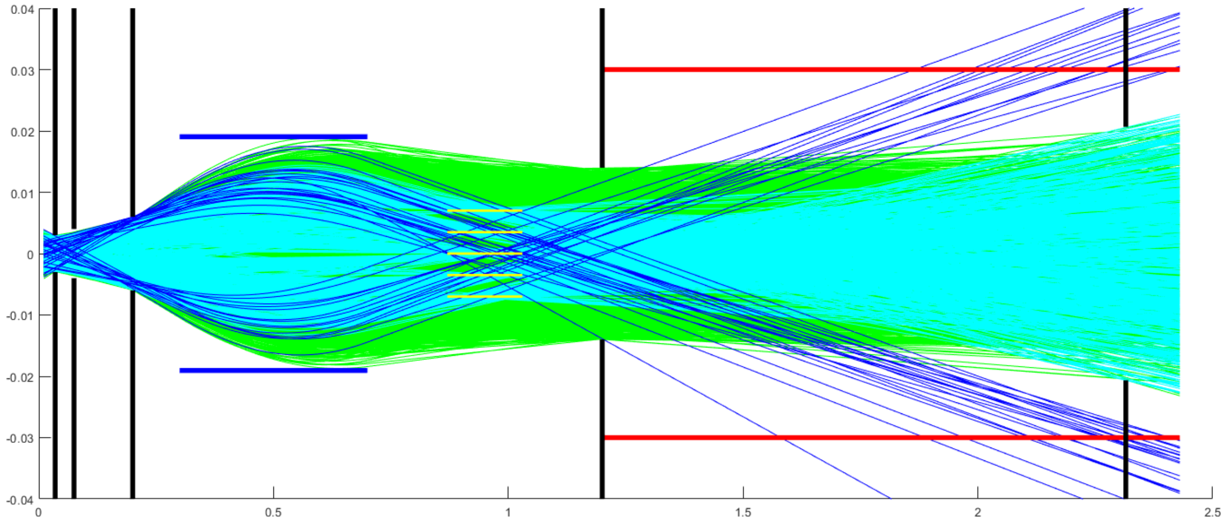
Estimate on the monolayer deposit rate

- ACME III molecule flux density, and the 0.5% overfocused molecules:
  - Lens increase flux by x16 times: Phi’=Phi*16=1.6e9 molecules/s/cm^2
  - 0.5% of the trajectories focused into interaction region gets over-focused onto the last 30cm part of the field plates
  - N’ = [0.5%]*Phi’*[1.3e7 sec]*[beam cross-section]/[coated area on ITO]

    = [0.5%]* [1.6e9 /s/cm^2]*[1.3e7 sec]*[10cm^2]/[30cm*28cm*2]

    = 6e11 molecules/cm^2

  - 6e14 per cm^2 for ThO monolayer
  - 1e-3 monolayer in 1 yr



Estimate on the monolayer deposit rate

- **Baseline analysis:** ACME II ThO monolayer deposition from background scattered molecules (Beer’s law of beam attenuation)
  - P=3e-7 Torr interaction region.
  - Attenuation is calibrated to be exp(- [length]/14m*[pressure]/uTorr)
  - For 20cm long (shorter in ACME II), exp(-.2/14*0.3)=99.6%. Thus, .4% attenuation of the beam.
  - Assuming these scattered molecules evenly distributed on 20cm long 5cm wide stripes in all 4 site of the molecule beam
  - Surface density: N’’= [.4%]*Phi*[1.3e7 s]*[10cm^2]/[20cm*5cm*4]
    = 1.3e11 /cm^2

Phi= 1e8 /s/cm^2, for ACME II

  - This is 0.2e-3 monolayer in 1 yr.
  - Overfocused trajectories in ACME III: N’ = 6e11/cm^2 , x5 of Baseline value
  - Both values scale linearly with Phi, so N’/N” ≈ 5 is independent from Phi calibration error

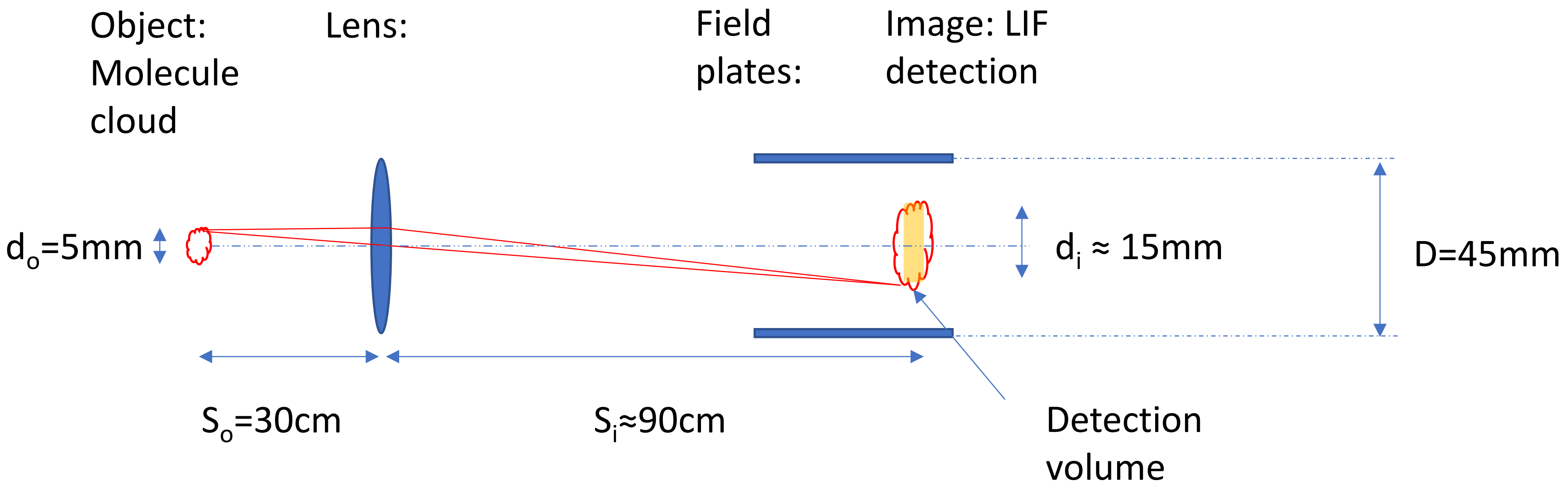
Estimate on the monolayer deposit rate

- ACME III, ThO monolayer deposition from background scattered molecules (Beer’s law of beam attenuation):
    - X16 larger flux compared to ACME II
    - length factor drops out in the [attenuation factor]/[coated length]
    - Thus, the coated surface density N’’’=16*N’’= 16*[1.3e11/cm^2]=2e12/cm^2
    - The deposit rate is N’’’/[6e14/cm^2]=3e-3 monolayer in 1 yr
    - Overfocused trajectories in ACME III: N’ = 6e11/cm^2 = .3* N’’’

- It seems the background scattering in ACME III deposit monolayer on ITO surface at x3 higher rate than the overfocused molecule trajectories

To avoid hitting the extended field plates

- ‘0^{th} order’ approximation:
  - Using ideal lens formula, and object has finite size (no aberration, no fuzziness)
  - Magnification=di/do=Si/So



To avoid hitting the extended field plates

- ‘0th order’ approximation:
  - Using ideal lens formula, and object has finite size (no aberration, no fuzziness)
  - Magnification=di/do=Si/So
- Longer field plates → larger image. If take aberration (i.e. ‘fuzziness’ of the image) into account:
  - → smaller signal for a given finite detection volume (we already knew)
  - → more likely to hit the field plates

‘Desirable’ feature:

- Lens-to-field-plates distance as short as possible
- bigger field-plates separation, D

Object: Molecule cloud

Lens:

Field plates:

Image: LIF detection