Mean forward velocity from ACME II & its implication on electric Lens design / operation / performance

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The last conceptual difficulty about Lens design

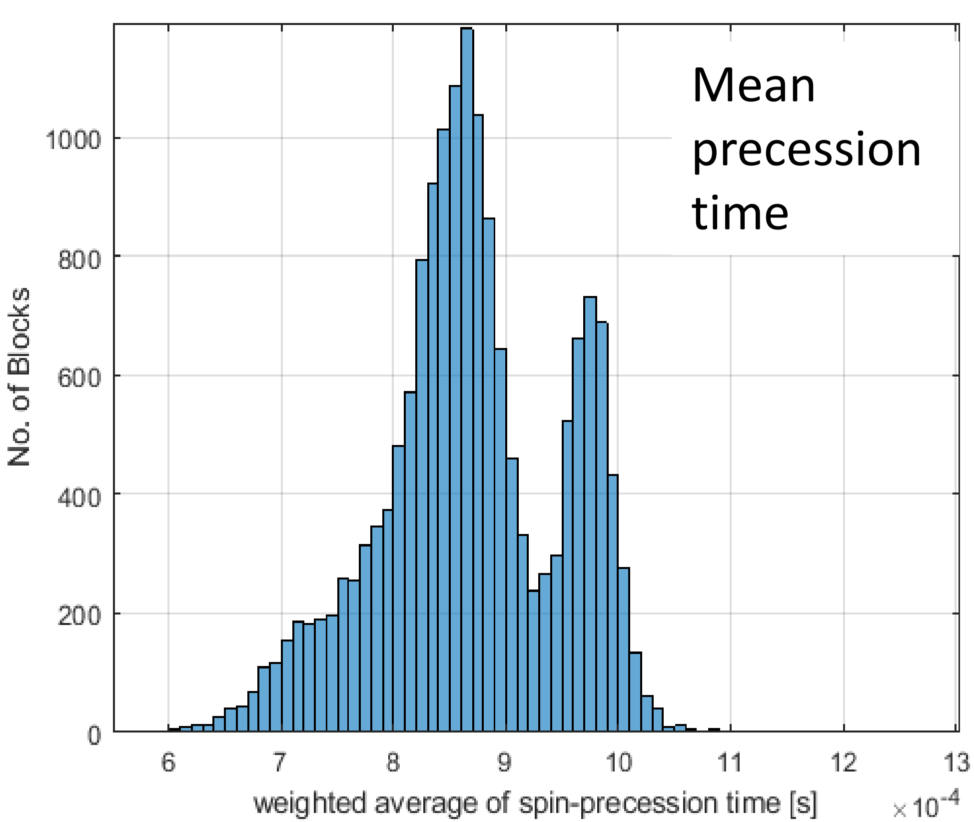
- What mean forward velocity should we choose as target velocity?
  - Faster beam → shorter ‘focusing’ time → longer lens electrode required
- How big is the variation of mean forward velocity on the time scale of blocks/days/weeks?
  - It would influence the Lens design & operation

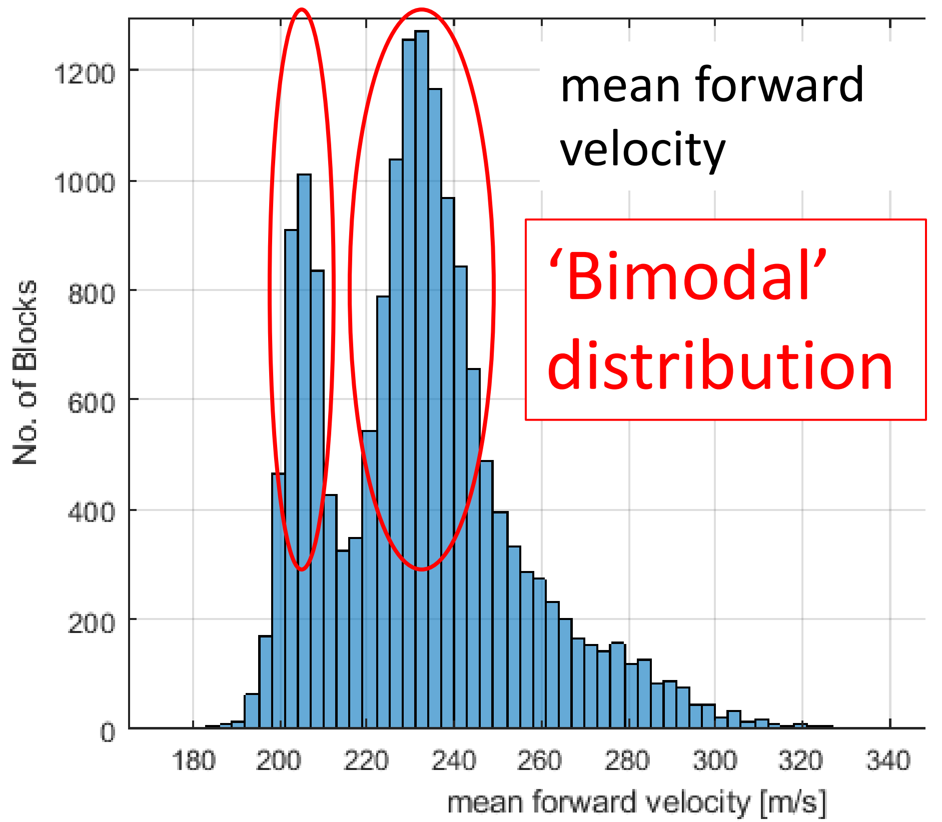
Outline

- Review the mean forward velocities (mean v_x) in the ACME II final run
  - Based on our radiation work record: big jumps in precession time (hence, v_x) is associated with target change and cell change
- Lens operation with a fixed voltage
  - Flux gain vs. mean v_x is relatively flat
  - But, Doppler width (Δv_z) after lens, and # of ‘bad’ trajectories hitting field plates are sensitive to mean v_x
- Lens operation with a variable voltage (‘slow’-feedback)
  - Seems a safe operational strategy, in combination with the approach of ‘stick to new cell’ and ‘stick to downstream targets’
  - A tentative Look-up table for the ‘slow’-feedback is worked out

ACME II runs (~3 months, 16675 blocks)

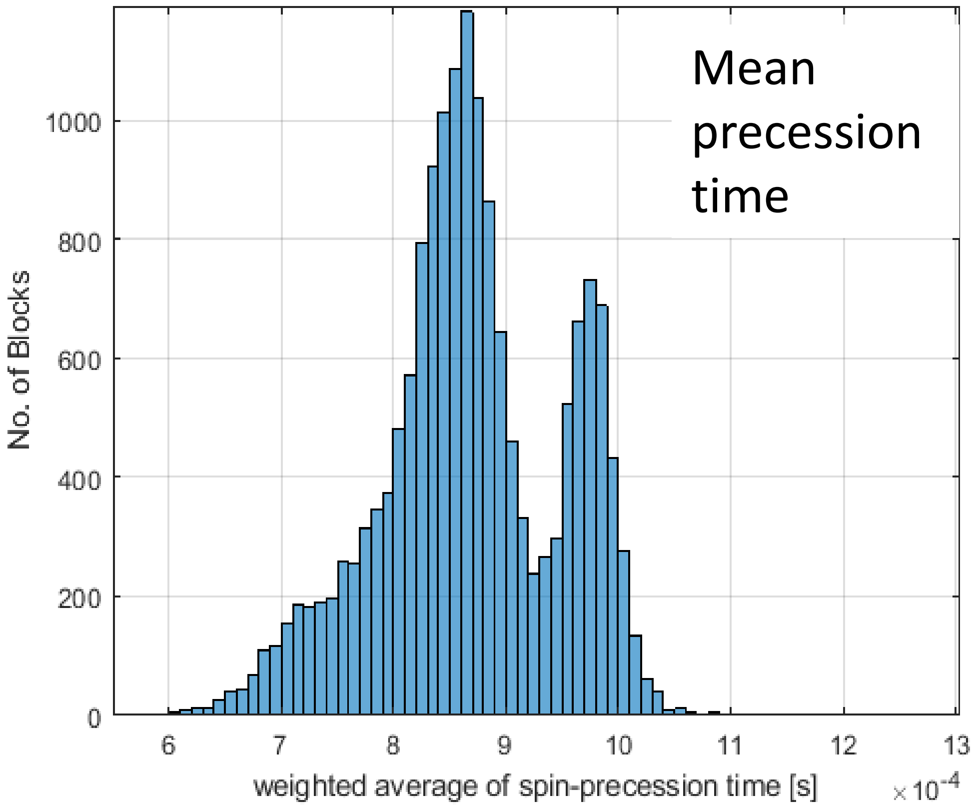
- Extract forward velocity information from spin-precession time of each block
- More accurate than the time-of-flight measurement → no convolution with temporal profile

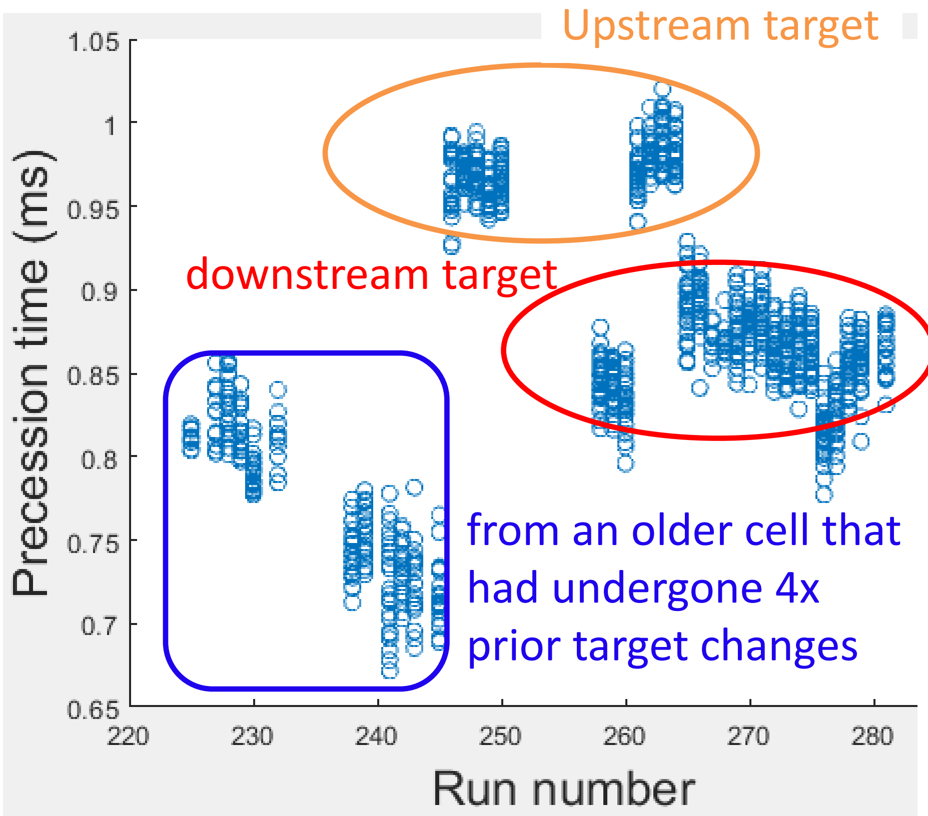




Bimodal distribution: upstream & downstream targets

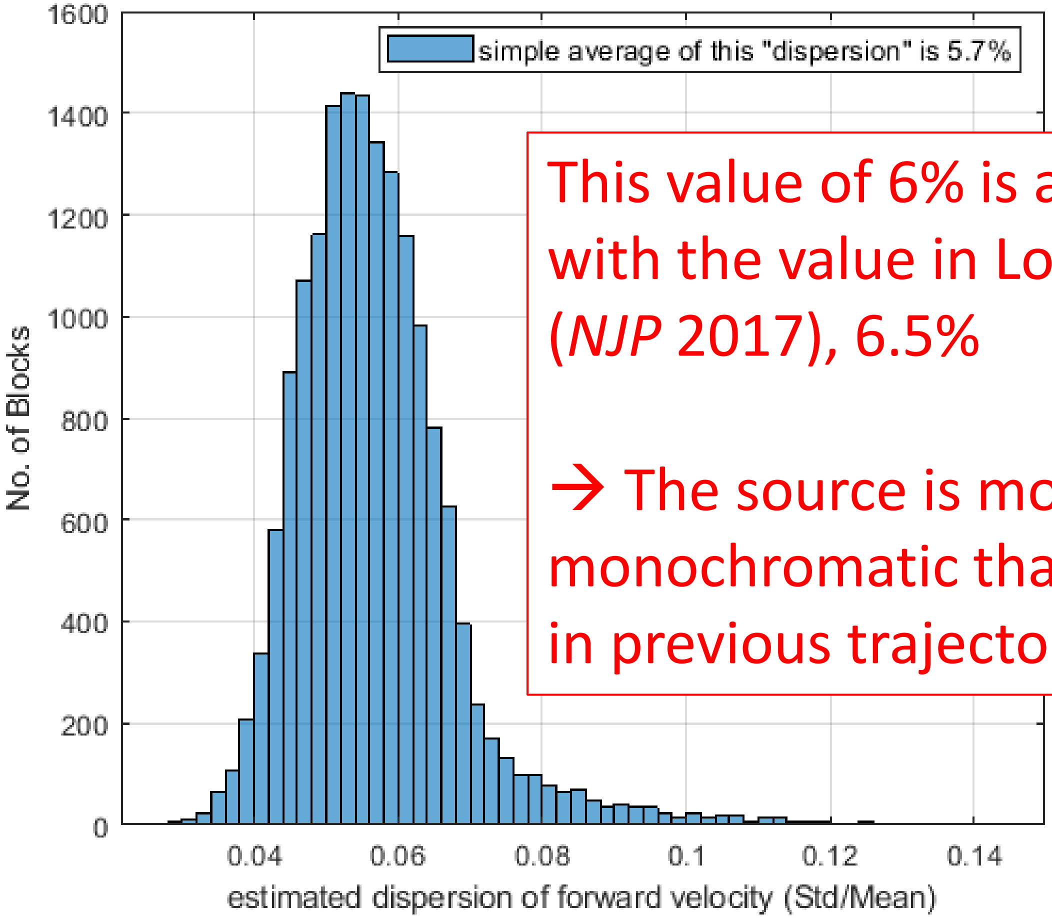
- Jumps in precession time vs Run number (c.a. Days) corresponds to target changes!!!





Additional information on forward V

- Estimate dispersion by (std/mean) of forward V
- Dispersion is narrower (6%) than I thought (10%)



This value of 6% is also consistent with the value in Long ACME I paper (*NJP* 2017), 6.5%

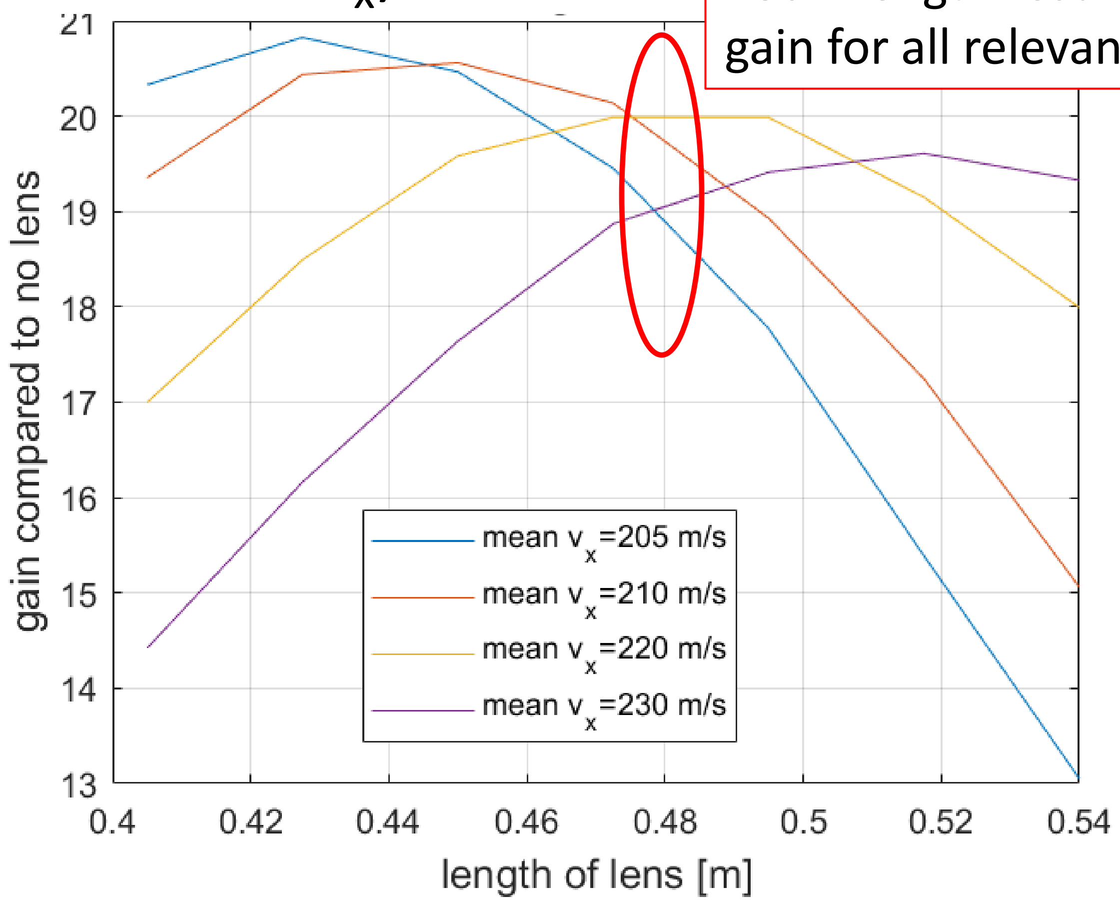
→ The source is more monochromatic than I have assumed in previous trajectory simulation

Proposal 1:
fixed length & fixed voltage on electrodes?

For fixed voltage (+/-22.5kV)

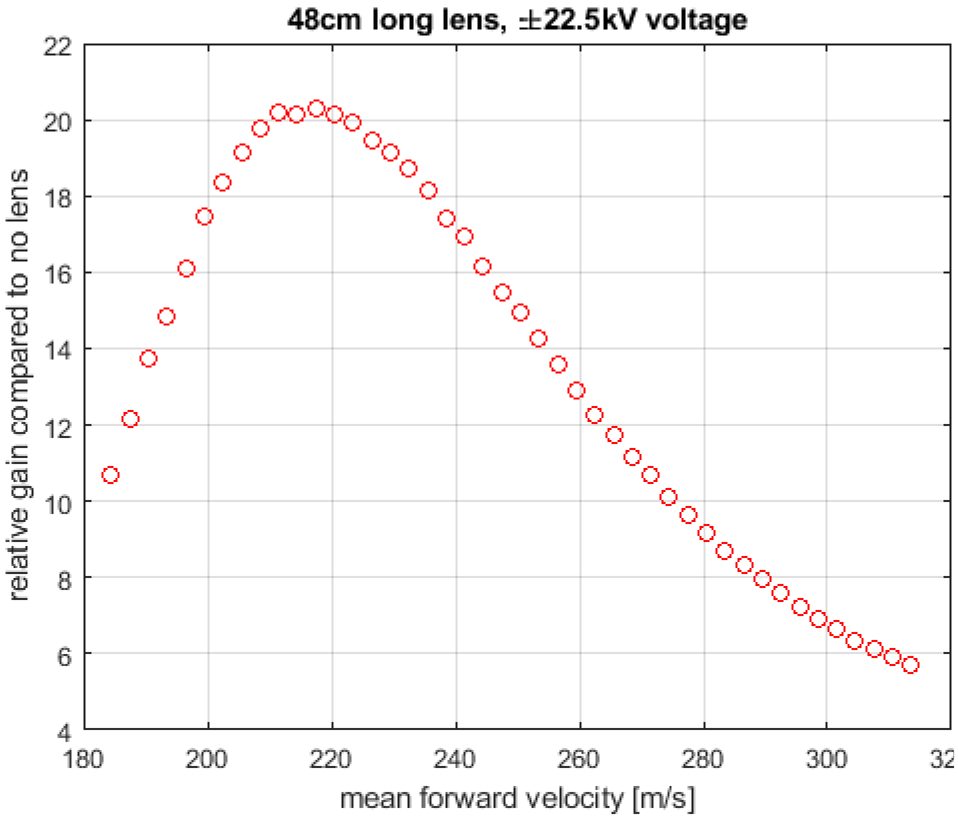
- Lens gain vs. length of electrodes: relatively flat, for various mean forward velocities (assuming 6.5% dispersion for all v_x)

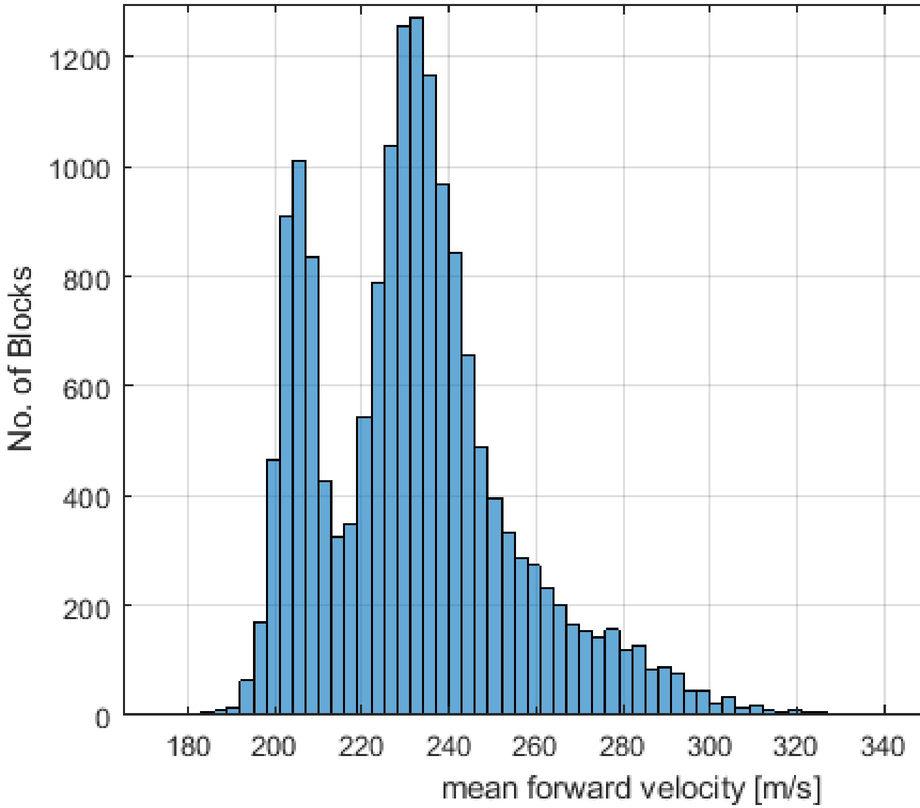
48cm length results in good flux gain for all relevant mean v_x



Fix the electrode length to 48cm

- For fixed voltage at +/-22.5kV: averaged gain factor of 17.2, over the entire ACME II mean forward velocity distribution

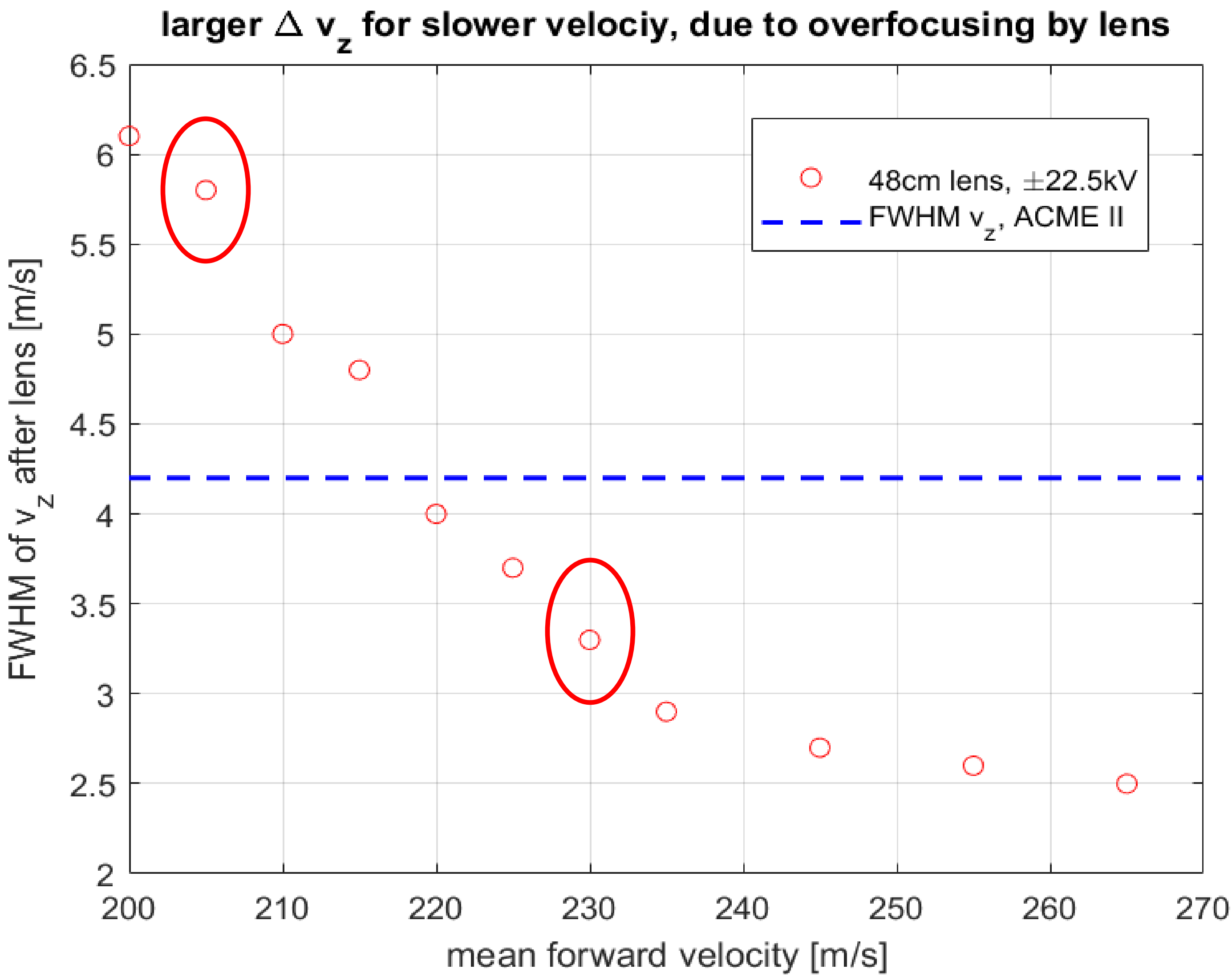




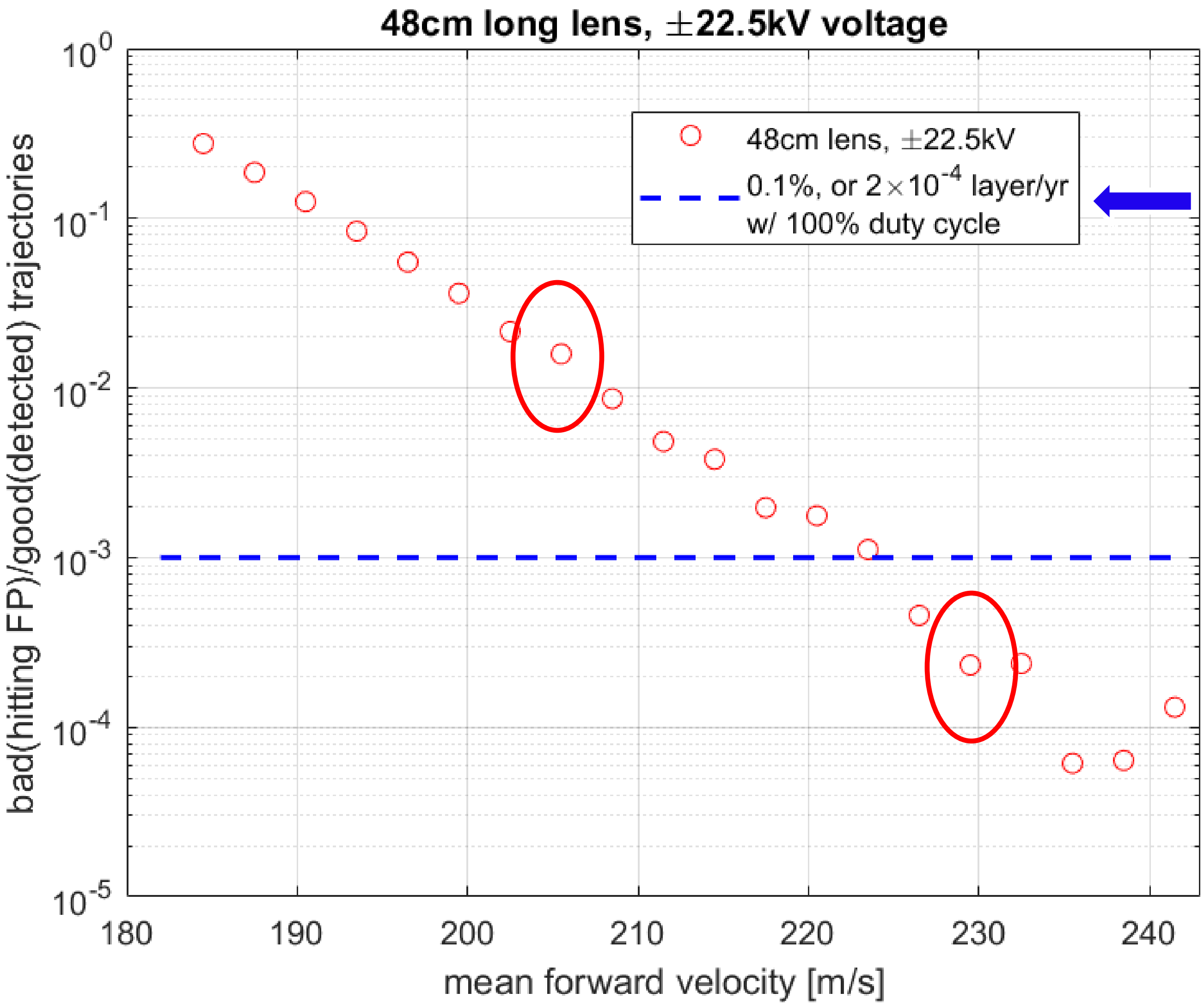
Problems with fixed voltage at fixed electrode length

- Doppler widths after lens:
  - varies by a factor of 2 due to changing from overfocusing (at v_x= 200m/s) to underfocusing (v_x= 230m/s)
- Number of overfocused trajectories hitting the field plates:
  - also varies by 2 orders of magnitude due to the change of focusing effect

Doppler width after lens



number of overfocused trajectories hitting the field plates



- Assuming v_x has normal distribution.
- It's a conservative estimate: fewer slow molecules (outside 2σ from mean v_x) seen in precession time from ACME II runs.
- Not including the effect of the 'additional' horizontal filter or the active optical pumping of the slow molecules

Proposal 2:
fixed length & variable voltage on electrodes (with slow feedback)

Strategy: combination of the following two approaches

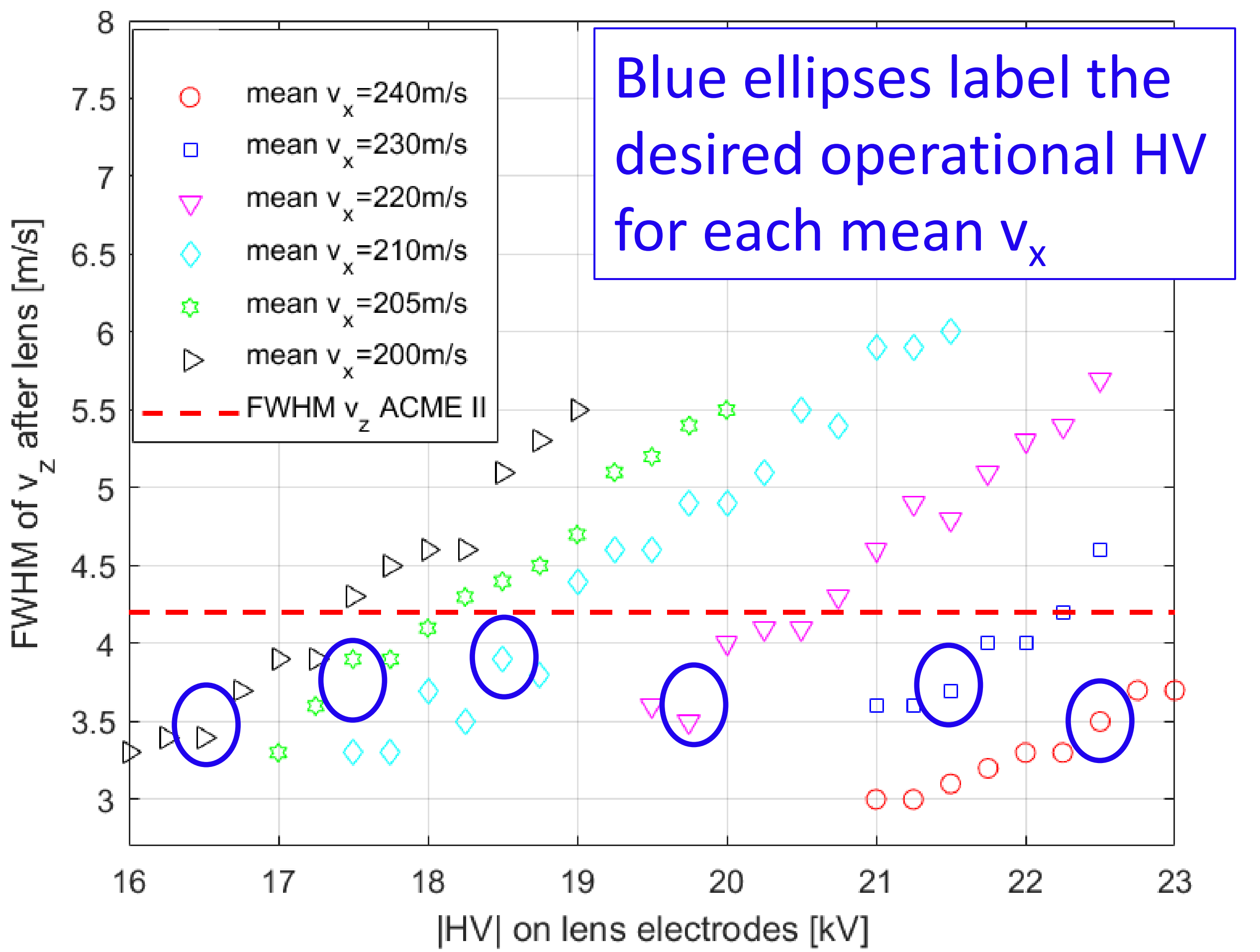
- Always use a relatively new cell (less dusty inside) & Stick to the downstream ablation target
  - So that the forward velocities are most likely around 230m/s
- A 'slow' feedback: the precession time is relatively stable for the same ablation target
  - Design the lens length & max. HV for a faster velocity (v_x=240m/s), and lower the HV based on the velocities measured from the precession time

Three criteria for choosing HV

- Keep the Doppler width (v_z) after lens consistently narrow (or at least comparable to ACME II, FWHM v_z=4.2m/s), for all v_x
  - → slight underfocusing is desirable
- Keep the number of 'bad' trajectories hitting field plates low (ratio to good trajectories $\lesssim$ 0.1%, or equivalent to 2×10^{-4} monolayer/yr of ThO, w/ 100% duty cycle), for all v_x
  - → slight underfocusing is desirable
- Keep the flux gain consistently high, for all v_x
  - Easy to satisfy, given the flat gain curve

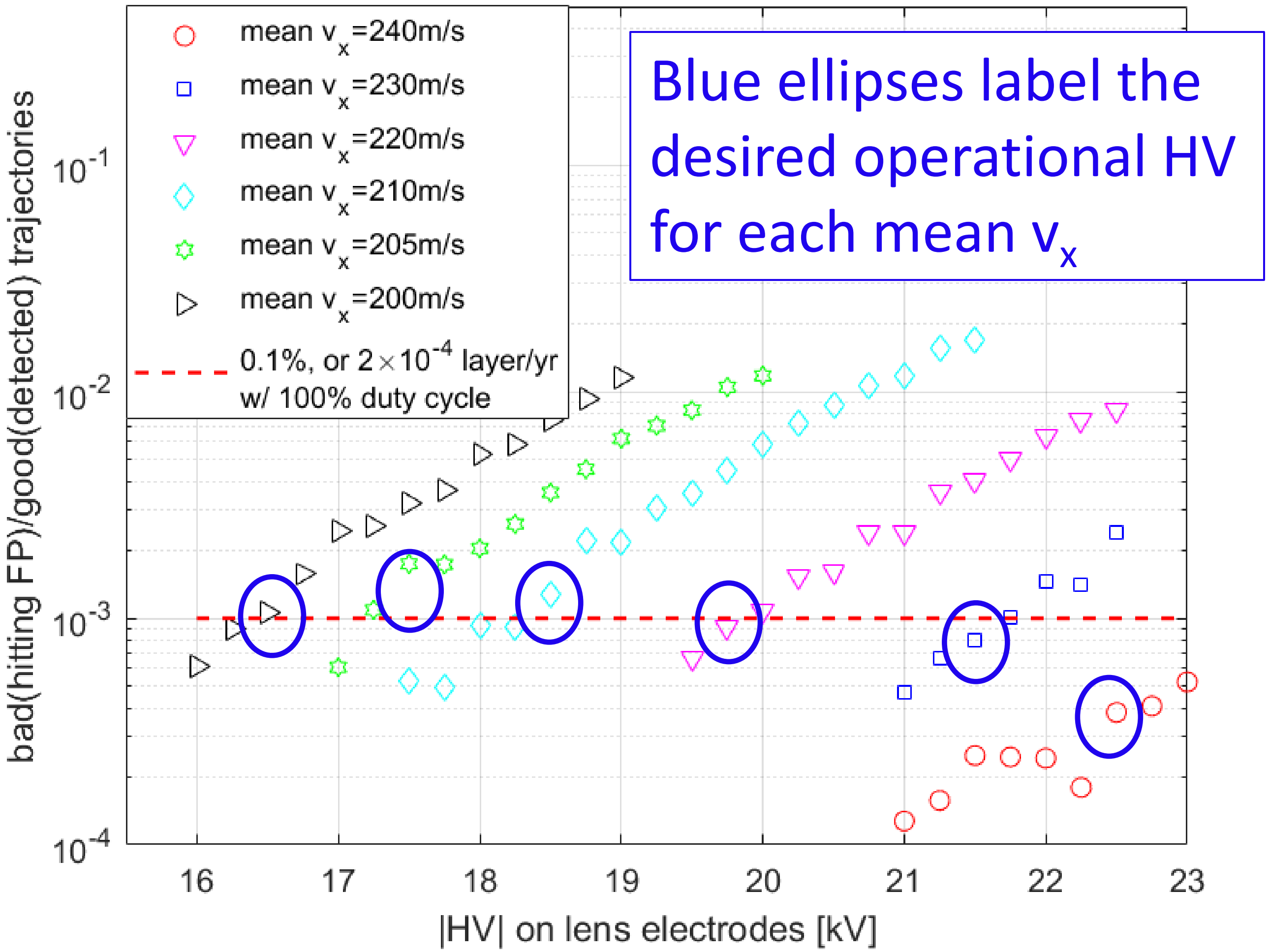
Fix the length at 52cm, vary the HV (max. +/-22.5kV for 1.8K trap depth)

- FWHM after lens vs. HV, for various forward v



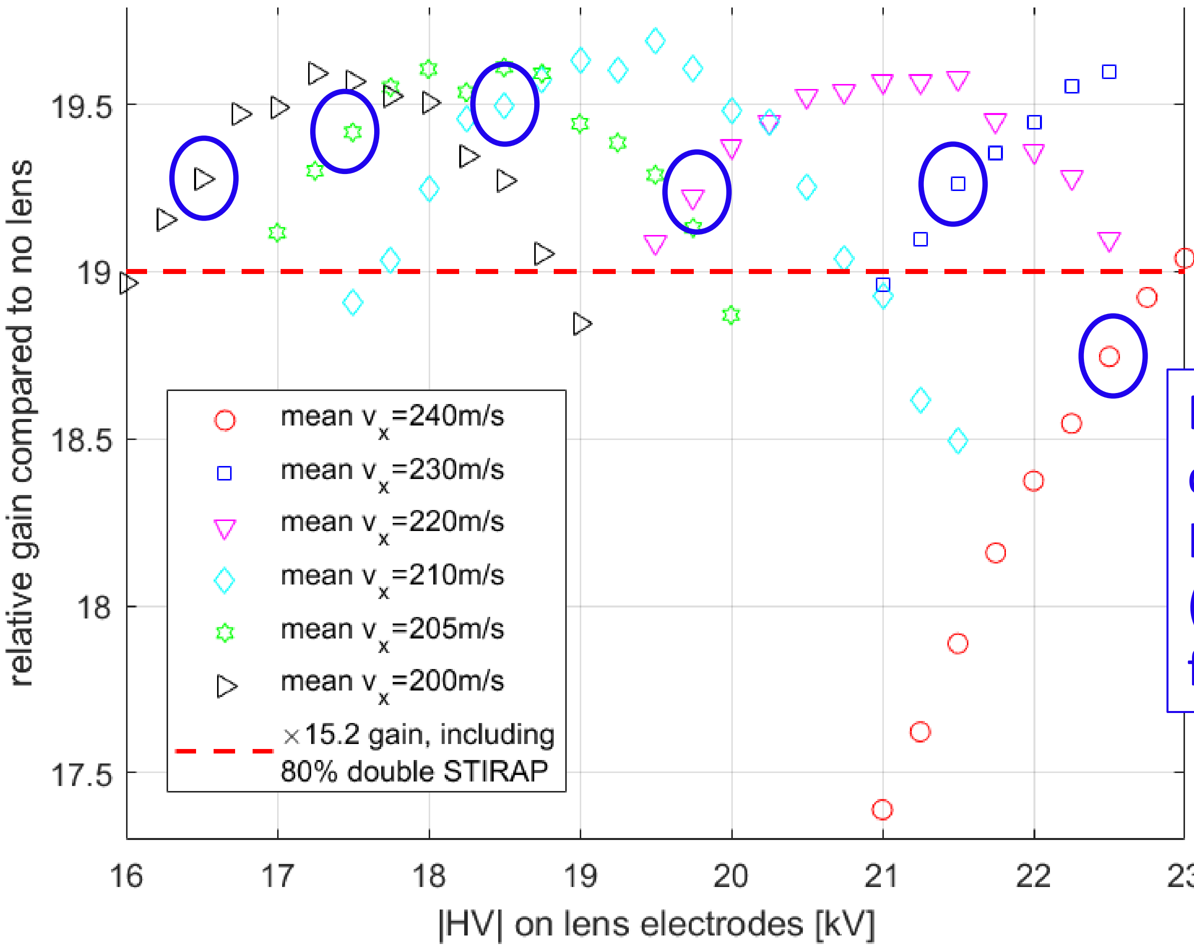
Fix the length at 52cm, vary the HV (max. +/-22.5kV for 1.8K trap depth)

- Number of overfocused trajectories vs. lens HV



Fix the length at 52cm, vary the HV (max. +/-22.5kV for 1.8K trap depth)

- Flux gain vs. HV, for various mean forward velocities



Blue ellipses label the desired operational HV (slight underfocusing for each v_x)

Operational look up table for HV

Mean vx [m/s]	200	205	210	220	230	240	ACME II
Precession time [ms]	Tbd (depending on the interaction length design)						-------------
Preferred |HV| [kV]	16.5	17.5	18.5	19.75	21.5	22.5	---------------
Estimated FWHM v_z after lens [m/s]	3.5	3.7	3.9	3.8	3.7	3.5	4.2
Est. flux gain (w/o including stirap)	19.3	19.4	19.5	19.2	19.3	18.7	----------------
Ratio of bad over good trajectories*	0.11%	0.2%	.13%	.09%	.08%	.04%	----------------
Est. Monolayer/yr 100% duty cycle	2e-4	4e-4	3e-4	2e-4	2e-4	1e-4	< 2e-5**

* Assuming normal distribution of v_x in each molecule pulse: conservative estimate because fewer slow molecules (than normal distribution) are seen in the precession time data

**0^{th} order approximation gives 2e-4. Two major corrections: 1) particle flux underestimated by upto 1 order of magnitude (to include other J states and other species); 2) background gas scattering rate for big angles overestimated by 1~2 orders of magnitude. Thus, including 1) and 2), <2e-5 seems reasonable

Conclusion

- The velocity variation problem seems solvable by the combination of the two approaches:
  - Stick to new cell, and stick to the downstream target
    - Based on previous experience, we also knew the upstream targets give lower yield and fewer days of stable running & new cells perform better than old cells
  - ‘Slow’ feedback on the lens electrode HV, based on the precession time measurement.
    - Numerical simulations suggest a stable FWHM of v_z (comparable to ACME II), around 2e-4 monolayer/yr ThO layer, and x19 flux gain are feasible for all reasonable v_x
    - A tentative Look-up table is on the previous slide