Interaction Region Optics

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March 29, 2017

1 Summary

Table 1 shows a summary of the possible schemes for performing the $\hat{k} \cdot \hat{z}$ switch.

Items Not Duplicated	**Cost/Savings**	**Items Moved During $\hat{k} \cdot \hat{z}$ Switch**	**Comments**
None (Full Duplication)	\$27k/\$33k (with/without 2 dump cameras)	None	
943 nm Optics	-\$1k	None	Fiber launcher, mirrors, retro optics. Only used during microwave spectroscopy/checking STIRAP.
Cleanup/Readout Waveplates	-\$12k	Waveplates and associated rotation stages	Expensive items that (to a good approximation) do not deflect beams — easy to move without affecting alignment.
Beam Dump Side Diagnostics	-\$3k/\$9k (with/without 2 dump cameras)	Cleanup/Readout monitor (mirrors etc., PD/QPD, camera)	PD/QPD/camera a little more difficult to align, lose consistency between switches.
Everything	\$250	All	None

I am not considering us to need beam profilers for monitoring. If you think we do, add \$8k to the costs in all schemes (including moving).

2 Introduction

2.1 Purpose

The interaction region optics must serve the following purposes:

- **State cleanup:** following STIRAP transfer we wish to ensure that the correct state within the H state manifold is prepared. This is performed by optical pumping on the H to I transition (703 nm). For this laser beam we must precisely control/monitor:
  - Beam shaping — cylindrical lenses used to elongate beam in y while being collimated in x; beam profiler possibly used to analyse beam shape
  - Beam pointing — piezo-controlled mirrors used to tune pointing; reflected light from field plates used to ensure perpendicularity; QPD used to monitor pointing
  - Beam polarisation — half-wave and quarter-wave plates in precision rotation stages used to carefully define the polarisation

- **State readout:** following spin precession we must read out the state of the molecules — this will happen in the same manner as Gen. 1, except on the H to I transition (703 nm). We must precisely control/monitor:
  - Beam shaping — cylindrical lenses used to elongate beam in y while being collimated in x; beam profiler possibly used to analyse beam shape
  - Beam pointing — piezo-controlled mirrors used to tune pointing; reflected light from field plates used to ensure perpendicularity; QPD used to monitor pointing
  - Beam polarisation — need to perform polarisation switching with AOMs. After the polarisations are combined we must use half-wave and quarter-wave plates in precision rotation stages to carefully define the polarisation
- **Optical pumping:** we wish to use the Gen. 1 method of state preparation (optical pumping from X to H through A) for some tests such as microwave spectroscopy or checking efficiency of STIRAP. For this beam we must control:
  - Beam shape — cylindrical lenses
  - Beam pointing — not critical, but must retroreflect offset in x
  - Beam polarisation — does not have to be precisely defined, must be approximately orthogonal on retroreflection

Note that I am not consider us to need beam profilers to monitor beams — I believe photodiodes and quadrant photodiodes will suffice for continuous monitoring.

2.2 The $\hat{k} \cdot \hat{z}$ switch

In Gen. 1, we had two significant systematic errors which we deducted from the $\omega^{\mathcal{N}\mathcal{E}}$ channel. One we understood: an accumulated Stark shift phase due to the combination of a polarisation ellipticity gradient in the state preparation beam and a non-reversing electric field component. One of them we didn't really understand, but attributed to interference between E1 and M1 transition amplitudes. The model we constructed for the latter predicted that the accumulated phase should be odd under reversal of our laser beams, which we observed. We later realised that the model would also predict that this effect should 'average away' over the lengthscale of our molecule beam width. As such, we don't understand the cause of the systematic but we will definitely want to investigate it in Gen. 2 and this will involve switching the laser beam directions at some (or, more likely, several) points.

3 Moving Optics

This scheme obviously requires significantly more work to perform. It is also slightly non-trivial because the $\hat{k} \cdot \hat{z}$ requires a mirror reflection in the molecule beam ($\hat{x}$) axis, whereas when one e.g. moves breadboards from one side to the other the setup is being rotated about $\hat{y}$. Any such scheme should account for this.

3.1 Setup

A scheme where the optics necessary for performing the experiment are moved from one side to the other is shown in Fig. 1. The scheme is essentially the same as we have anticipated all along, but with some tweaking to make the $\hat{k} \cdot \hat{z}$ switch a little easier to perform. In particular, we assume that optics are always put on breadboards to minimise the necessary alignment, e.g. the readout beam shaping is on a separate breadboard to the readout polarisation switching. I have highlighted in yellow circles the things that would need to be moved/realigned when performing the $\hat{k} \cdot \hat{z}$ switch. These are necessary due to the disparity between the required mirror reflection, and the rotational flip that is actually performed. We would need to flip three mirrors and a PBS on the state preparation, due to a change in relative position of the two associated breadboards. We would need to move the 943 nm retroreflection and the mirrors which pick off the cleanup beam for monitoring. Again this is because of a relative position change, this time between 943 nm and cleanup.

In Fig. 2 we can see the setup of the breadboards. Only one half of the setup is shown, i.e. the part required to prepare the laser beams is shown on both sides. The optics required to monitor/retroreflect beams is omitted since it is much simpler/smaller. I have marked the positions where a laser beam exits a breadboard with a white circle. In particular, note that the breadboard for polarisation switching and pointing control has two such circles.

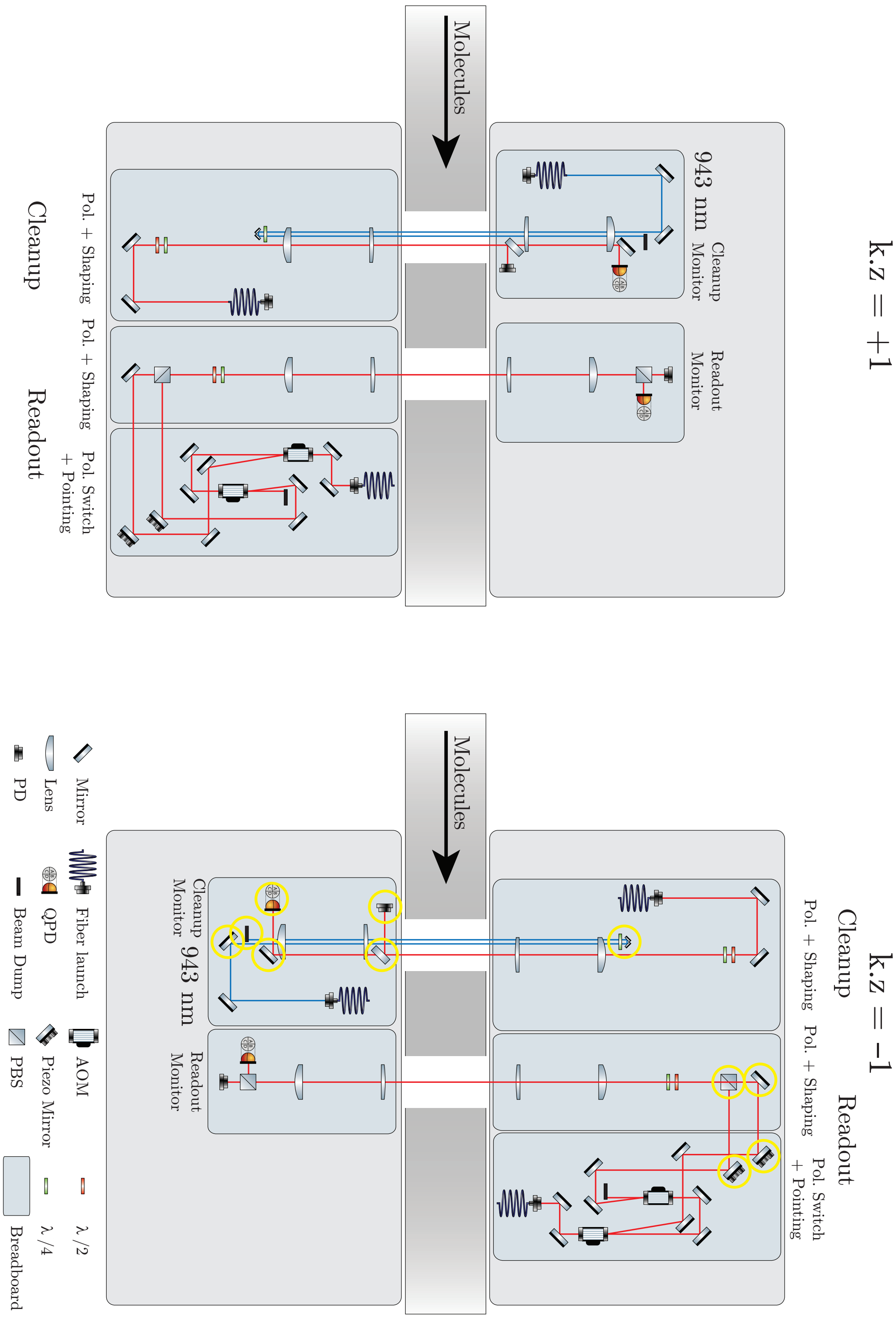

Figure 1: Proposed scheme for the interaction region optics where the setup is moved between east and west sides. The items in yellow circles are those which will need to be realigned by hand under this scheme.

Depending on which side of the experiment this breadboard is placed, the direction of the laser beam will change. Note also that the laser beams exit the other two breadboards centrally (in x). This allows the breadboards to fit together in the same way independent of which side of the experiment they are on. The widths of the breadboards were also chosen with this in mind.

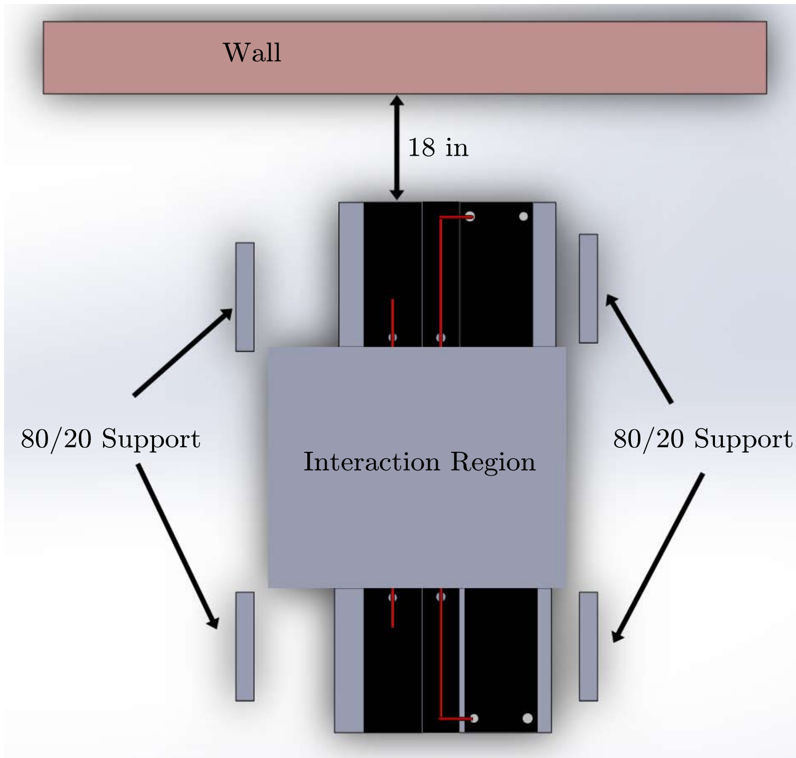

Figure 2: Birds-eye view of the experiment showing the positions of breadboards/tables. We see that with the larger breadboard/table there is 18 in of room between the optics table and the wall. We see that everything fits inside the 80/20 structure that supports the interaction region/shields. We also see that we can move everything from one side to the other using 3 breadboards, where we have to flip the direction of one of the beams. The white circles show where a laser beam leaves a breadboard.

3.2 Cost

This option has no cost associated with it, except for perhaps one or two breadboards ($\sim$ \$250).

3.3 Function

I do not think that any function in the experiment is lost by opting for this scheme, indeed it is what we did in Gen. 1 and how we had planned to run in Gen. 2 before considering the $\hat{k} \cdot \hat{z}$ switch.

Another aspect to consider is space within the room. In the 'duplication' scheme we will need to have the same size table/breadboard on both sides. This will mean a larger table/breadboard on the west side than we currently have. On the east side we currently have a $3' \times 2'$ table. To see how much space this leaves, I mocked it up in Solidworks — see Fig. 2. We can see that there is only 18 inches of space left between the optics table/breadboard and the west wall (accounting for the power conduit as well). Personally this seems like enough space to me (it is the same amount of space as between the north optics table and the wall), but it might make it a 'PI-free' zone...

4 Full Duplication

Under this scheme we have nominally identical copies of the optical setup on each side of the experiment. I assume we would have to change some electrical connections (e.g. from piezo controllers to piezo-actuated mirrors) — since there is no alignment, this task has almost zero time associated. One possible difficulty is that there would be less space for optics for analysing beams after they pass through the interaction region.

4.1 Setup

A proposed scheme, wherby the optics necessary for performing the experiment is present on both sides of the interaction region, is shown in Fig. 3.

I will briefly explain the different sections of the setup, which are highlighted by coloured boxes:

- Cleanup: Light is launched from a fiber, aligned with two mirrors then passes through a pair of waveplates in precision rotation stages which tune the polarisation state. A pair of cylindrical lenses are used to shape the beam. On the other side of the chamber the light passes through an identical setup which 'undoes' the shaping. After which it can be diverted for monitoring.
- Cleanup monitor: A flipper mirror can be used to divert light for monitoring — exactly what is used here is somewhat in flux, but will likely consist of a quadrant photodiode and/or camera/beam profiler.
- 943 nm: Light is launched from a fiber, aligned with a pair of mirrors and then passes through the same lenses as used for the cleanup beam. Due to the wavelength difference these lenses will not be ideal for both beams; if there is room we could opt for using different lenses for cleanup/943 on one side of the telescope. On the other side of the chamber, the light passes through an identical setup. This 'undoes' the beam shaping and then the light passes through a quarter-wave plate before being retroreflected, offset in x and passes back through the chamber. It is likely that we won't need to duplicate this, but I include it for completeness.
- Readout polarisation switching/pointing: Laser light is launched from a fiber and passes through a pair of AOMs. The deflected (and frequency shifted) light from each of the two AOMs is later combined on a PBS. Within this setup are two piezo-controlled kinematic mounts which are used to correct/induce/monitor beam pointing.
- Readout polarisation/shaping: Following polarisation switching, light of opposite polarisations is combined and then passes through a pair of wave plates in precision rotation mounts in order to tune the polarisation state. The light then passes through a pair of cylindrical lenses to shape it. The light passes through an identical setup on the other side of the chamber which 'undoes' the beam shaping, allowing the light to be diverted to be monitored.
- Readout monitor: A flipper lens is used to divert light to be monitored — exactly what is used here is somewhat in flux, but will likely consist of a quadrant photodiode and/or camera/beam profiler.

The scheme which I describe above allows for absolutely everything to be set up at the same time. One aspect which may end up being imperfect is where beams pass through cylindrical lenses after passing through the chamber; if the two sides aren't perfectly aligned this might lead to distortion of the shape. However, this is not a critical element of the experiment — the light is simply monitored after passing through these lenses. It is also possible we will want to 'pick off' the light after passing through the chamber but before the cylindrical lenses in order to analyse its shape. I have not shown this in the diagram.

4.2 Cost

I have made an estimate of this in a spreadsheet, available at this link. I have made fairly conservative estimates of the equipment needed to duplicate the setup. This includes breadboards and all the optics/stages. For the moment, I have assumed we don't already have any of this equipment. Please feel free to make corrections to this document if necessary. The overall cost is around $27k. The column 'Include in Grand Total?' allows you to compare for yourself how the total cost varies if you omit some items.

I believe that all of the items that we need are in stock except for the precision rotation stages which currently show as having a 4 week lead time. I do not include 80/20 in the cost since we have a huge amount stockpiled.

As I previous mentioned, I am not considering us to need beam profilers for monitoring. If you think we do, add $8k to the costs in all schemes (including moving).

4.3 Function

As far as I can tell, this setup does not limit what we can do in the experiment at all. It would be more cramped than in the 'moving' option as there will be twice as much optics, but I think this should not be a problem. Perhaps re-assessment after getting everything set up on one side would be useful.

In addition, the considerations regarding space from Section 3.3 also apply here.

k.z = +/−1

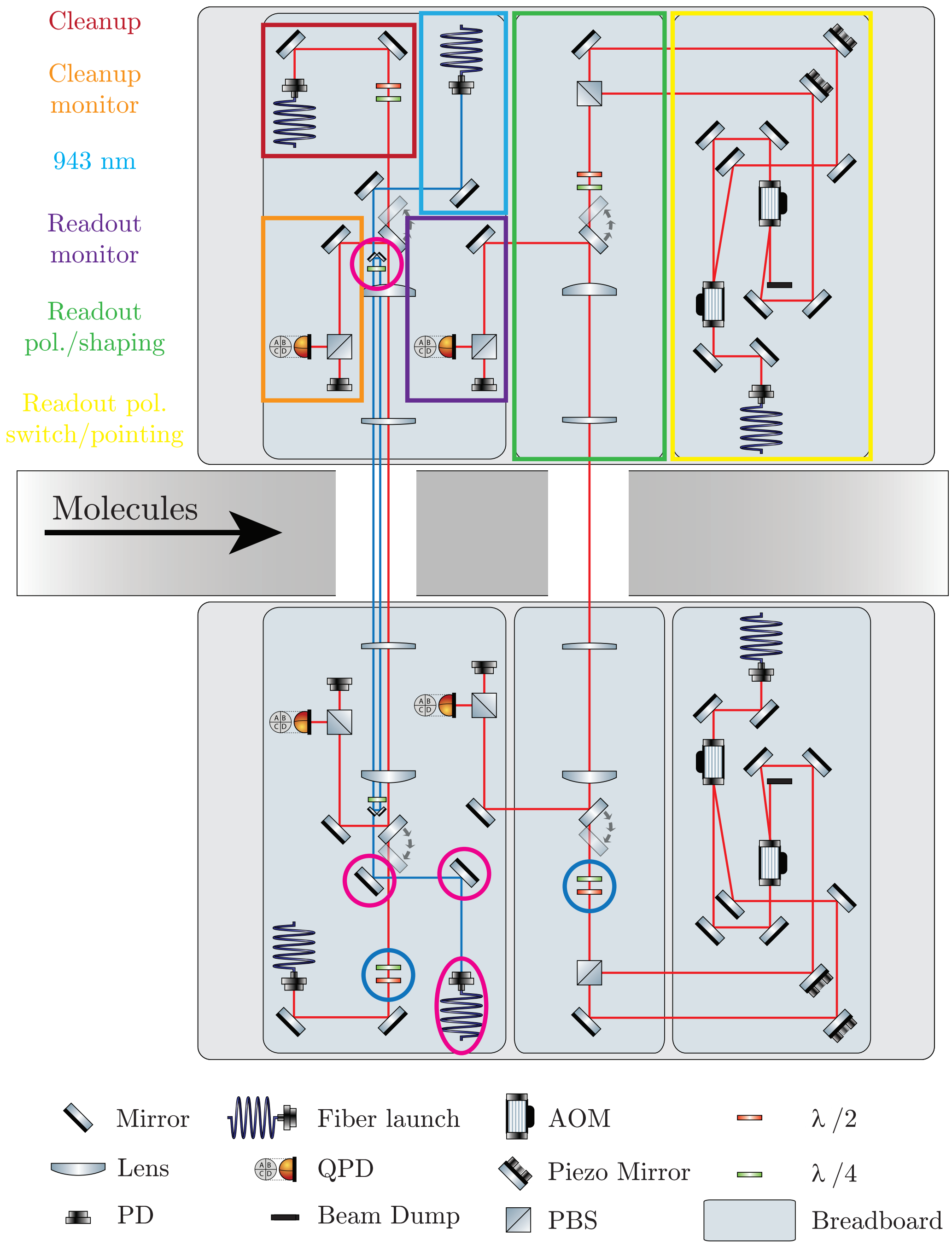

Figure 3: Proposed scheme for the interaction region optics where the setup is duplicated on east/west sides. The items in pink circles are omitted under the 'Partial Duplication I' scheme. The 'cleanup monitor' and 'readout monitor' items are also omitted under 'Partial Duplication II'.

5 943 nm Beam

One can make an argument that we don't need to duplicate the optics associated with this laser beam. We only plan to use it when performing microwave spectroscopy, or to check on STIRAP efficiency. I have highlighted the associated items with pink circles in Fig. 3. I also highlight them in pink on the spreadsheet.

The total cost associated with these items is about \$1.3k.

6 Cleanup/Readout Polarisation

It is possible that we can save a significant amount of money by not duplicating the items associated with controlling the polarisation states of the cleanup and readout laser beams. In particular the rotation stages are very costly (the waveplates aren't particularly cheap either). Instead, we could move these rotation stages by hand since they do not require precise alignment. I have highlighted these items with blue circles in Fig. 3 and also in blue on the spreadsheet.

The total cost associated with these items is about \$12k.

7 Cleanup/Readout Monitoring

We could opt to not duplicate the elements associated with monitoring the cleanup and readout beams: mirrors, lenses, photodiodes, quadrant photodiodes. These are labelled in the orange and purple boxes in Fig. 3. Again, since the alignment of these is not crucial, the work associated with moving them is small, but not insignificant.

The total cost associated with these items is about \$2.9k.

Again, note that I am not considering us needing beam profilers for monitoring in any of these schemes.

8 Laser Parameters

In general we should always anticipate that there will be properties of our laser beams which are correlated with $\hat{k} \cdot \hat{z}$.

- Shape/size: will definitely be slightly different on either side due to differences in beam shaping lens positions. We can analyse this with beam profilers.
- Polarisation: we can probably only expect this to change by a small amount. The linear angle of the polarisation is probably limited by the rotation stages or by the angle of the optical table surface(!). The purity of the state is likely limited by the PBS's. The ellipticity will be limited by birefringence in optical elements. We can perform polarimetry to analyse this.
- Pointing: if we use the reflection from the field plates we can ensure the beams on either side are highly parallel, probably to around 10 μrad (assuming the field plate surfaces are locally parallel). We should use QPDs to analyse if there are short timescale variations above this level.

For all of these properties, we will expect their $\hat{k} \cdot \hat{z}$-correlated components to remain constant in the case of full duplication. We might expect the $\hat{k} \cdot \hat{z}$-correlated components of polarisation to change wich each $\hat{k} \cdot \hat{z}$ switch in all the other cases, since changing the positions of the waveplates might effect the polarisation (Vitaly probably has a better idea about this). For the 'Moving' scheme we should expect all $\hat{k} \cdot \hat{z}$-correlated components to vary each time we perform the $\hat{k} \cdot \hat{z}$ switch.

9 Other Issues

I have not considered here the space that we will require for performing polarimetry. From talking to Vitaly it sounded like the setup doesn't take up a great deal of space, perhaps 12 in. by 6 in.

10 Verdict

I think that duplication is a reasonable path forward, given the relatively low cost; I think \$14k is a reasonable cost for what I see as a low-effort way of performing the $\hat{k} \cdot \hat{z}$ switch. My assessment of this makes some assumption about how frequently we will perform the switch. If we only ever do it once or twice, then I might change my mind. However, this is unlikely to be the case, and we certainly don't know it to be the case.