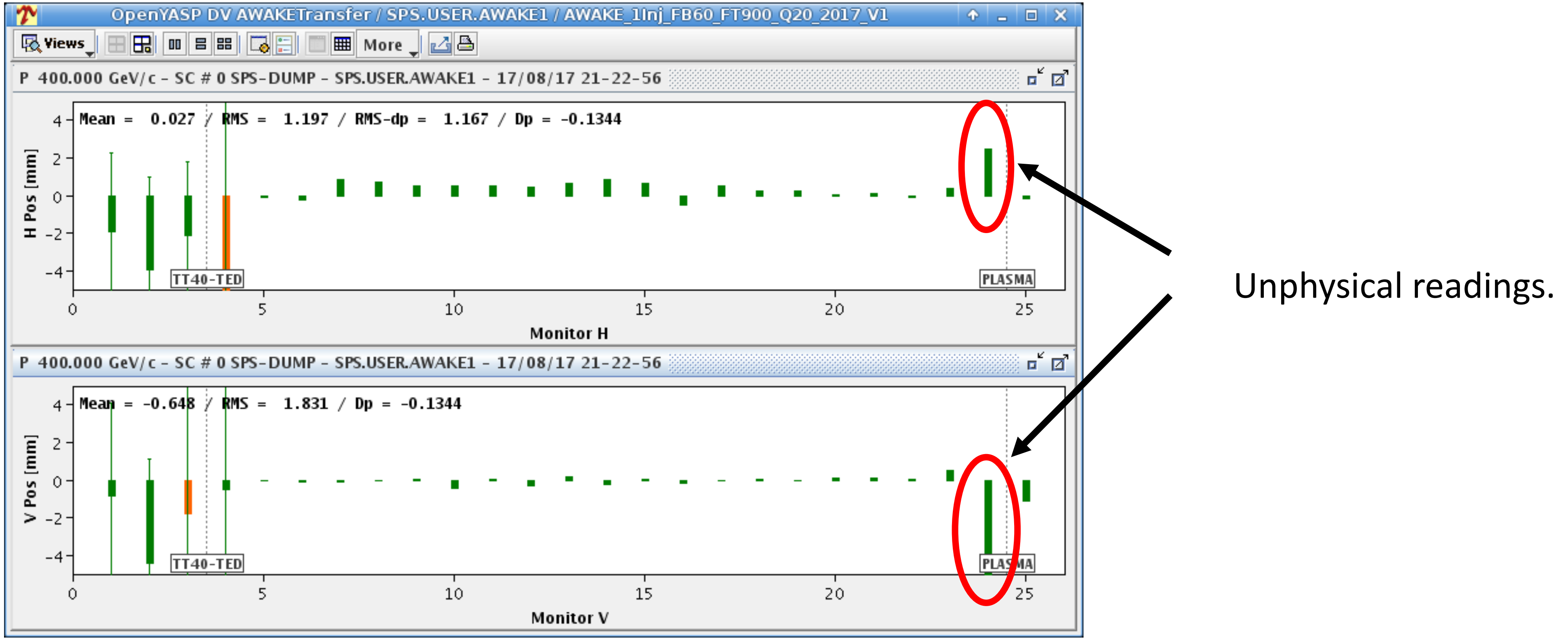
Results of BPM Tests at AWAKE

S. Gessner, A.-M. Bachmann, J. Moody, M. Wendt, T. Bogey

20 August, 2017

Motivation for tests



In the presence of Rb plasma, the BPMs just upstream and downstream of the plasma show record unphysical values for the beam trajectory.

What causes the readout errors? The leading hypothesis is that it is a build up of Rb ions on the button electrodes.

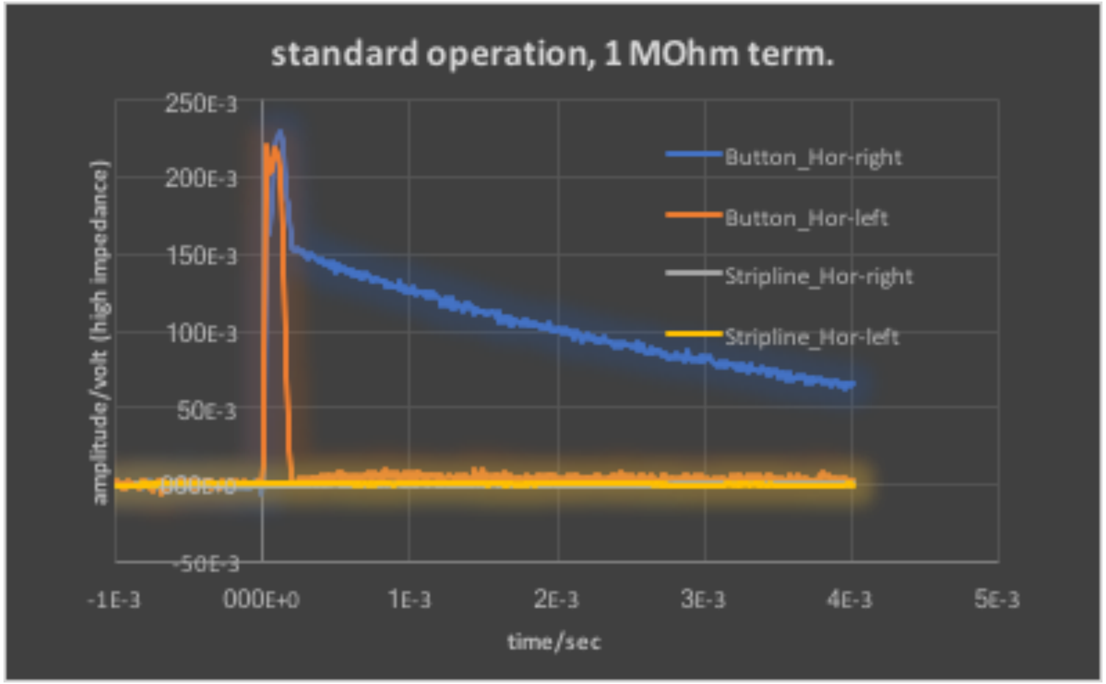
Observation of long time-scale signals on BPMs

In April, we performed a test where we fired the high power laser in the presence of Rb (no proton beam) and observed the resulting signal on button and strip line BPMs.

The button BPMs show an extremely long (order ms) response, perhaps from Rb ions landing on the button. The strip line BPMs saw no signal.

It was later determined that the laser had been firing on the valve of the plasma cell, rather than directly into the Rb vapor.

M. Wendt proposes adding inductors to the BPM pickups to provide a path to ground for the built up charge on the pickup.



M. Wendt, T. Bogey, April 2017

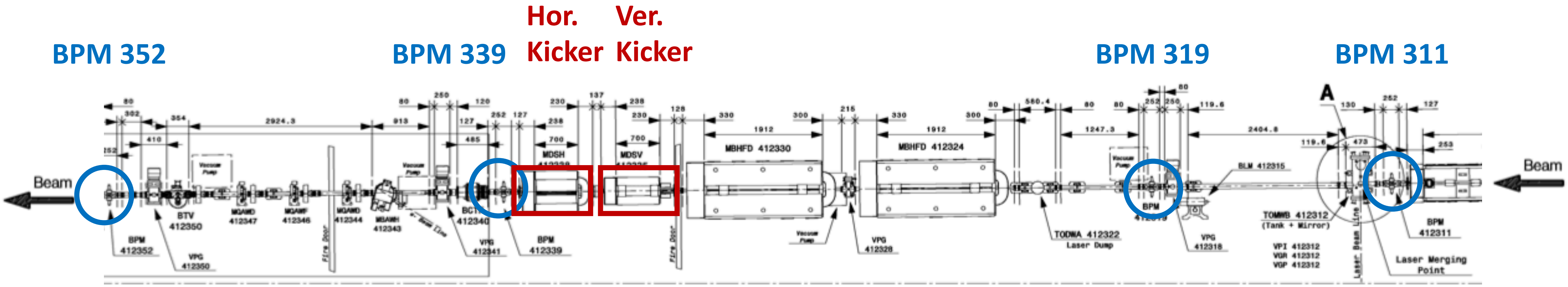
BPM Calibrations: Orthogonal scans

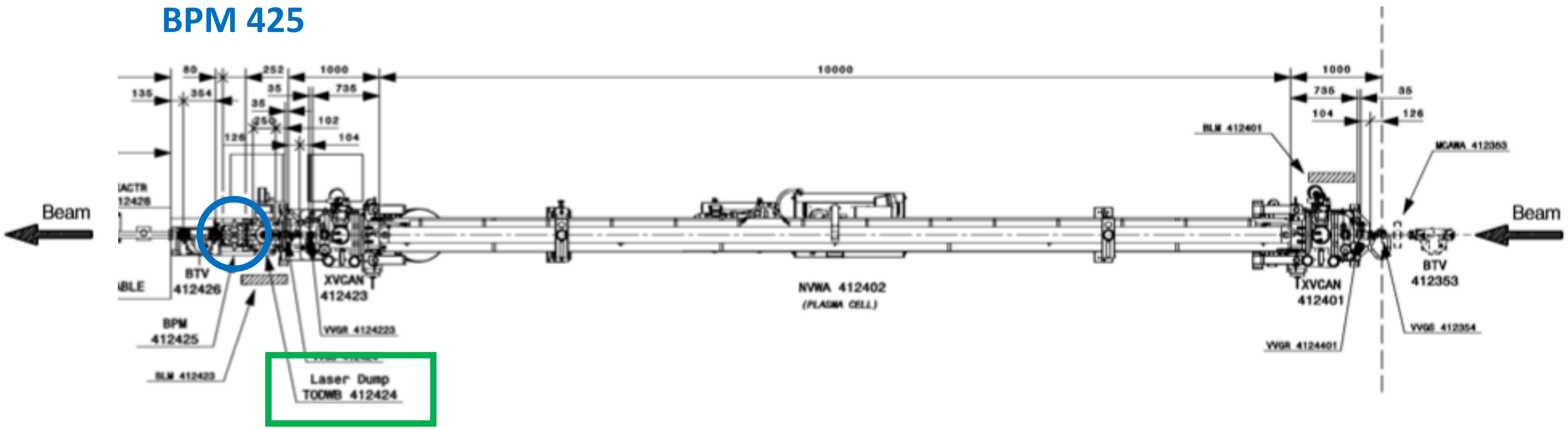
Before adding inductors to the BPMs, we can calibrate their response by performing orthogonal scans.

In the orthogonal scan, two kickers are used to create a “bump”. The upstream kicker is used to displace the beam by a given amount, and the downstream flattens the trajectory so the beam has a parallel offset in the plasma cell.

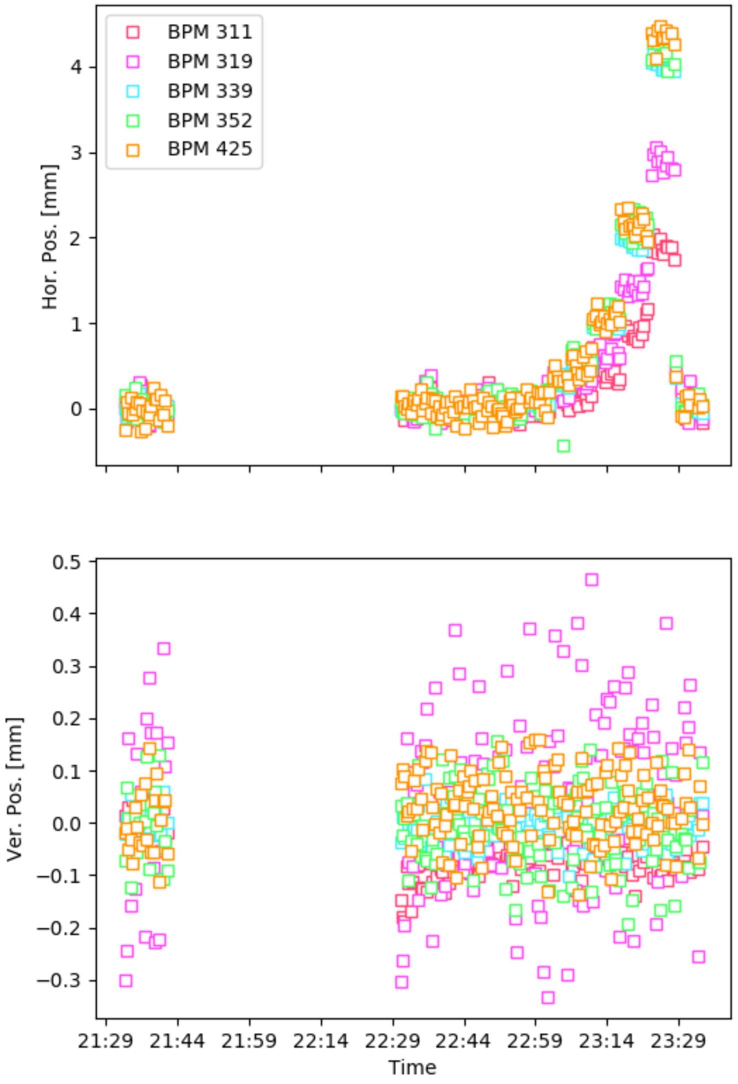
There are three BPMs downstream of the second kicker. These BPMs move in parallel during the orthogonal scan.

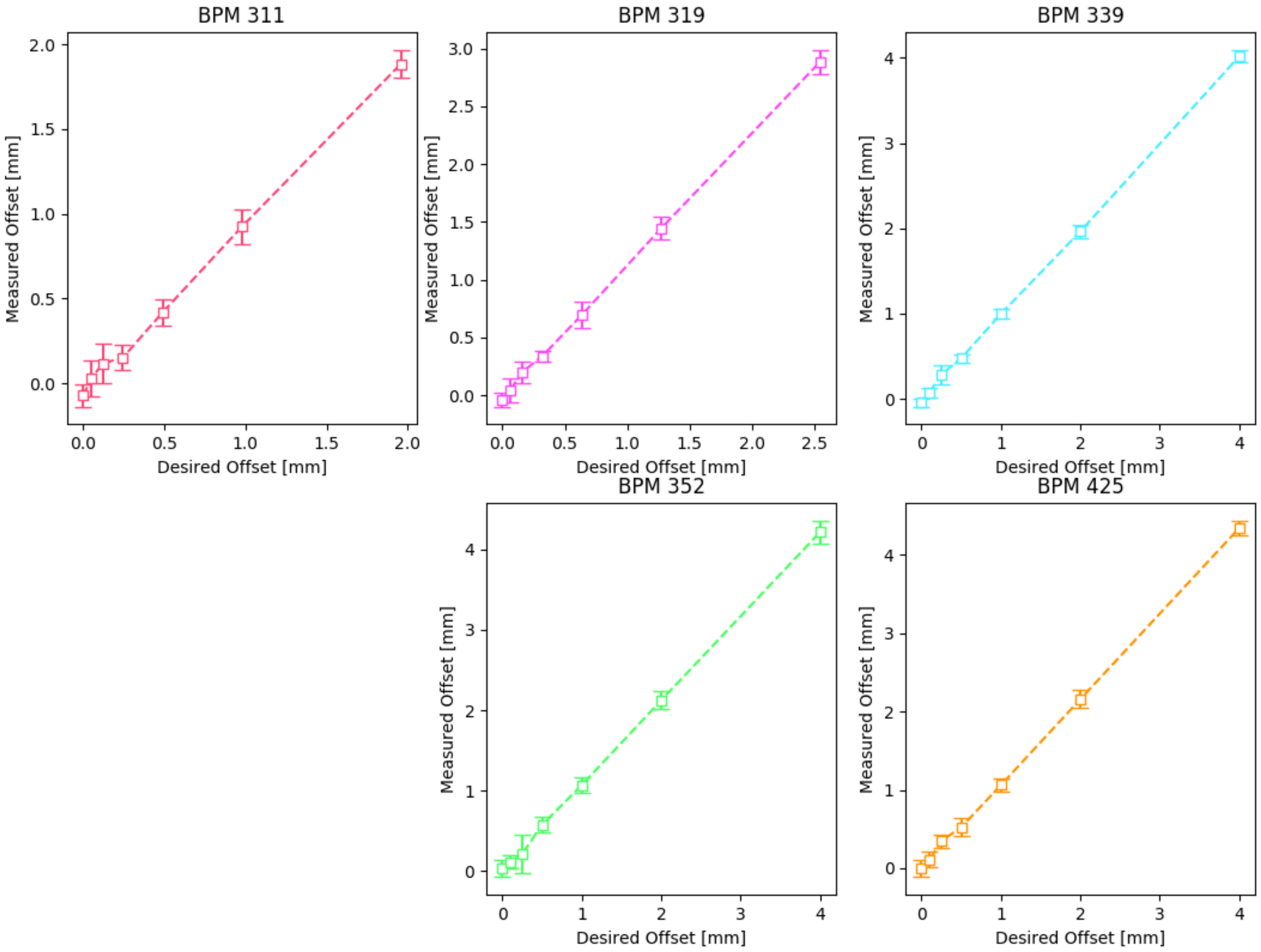
Beamline layout



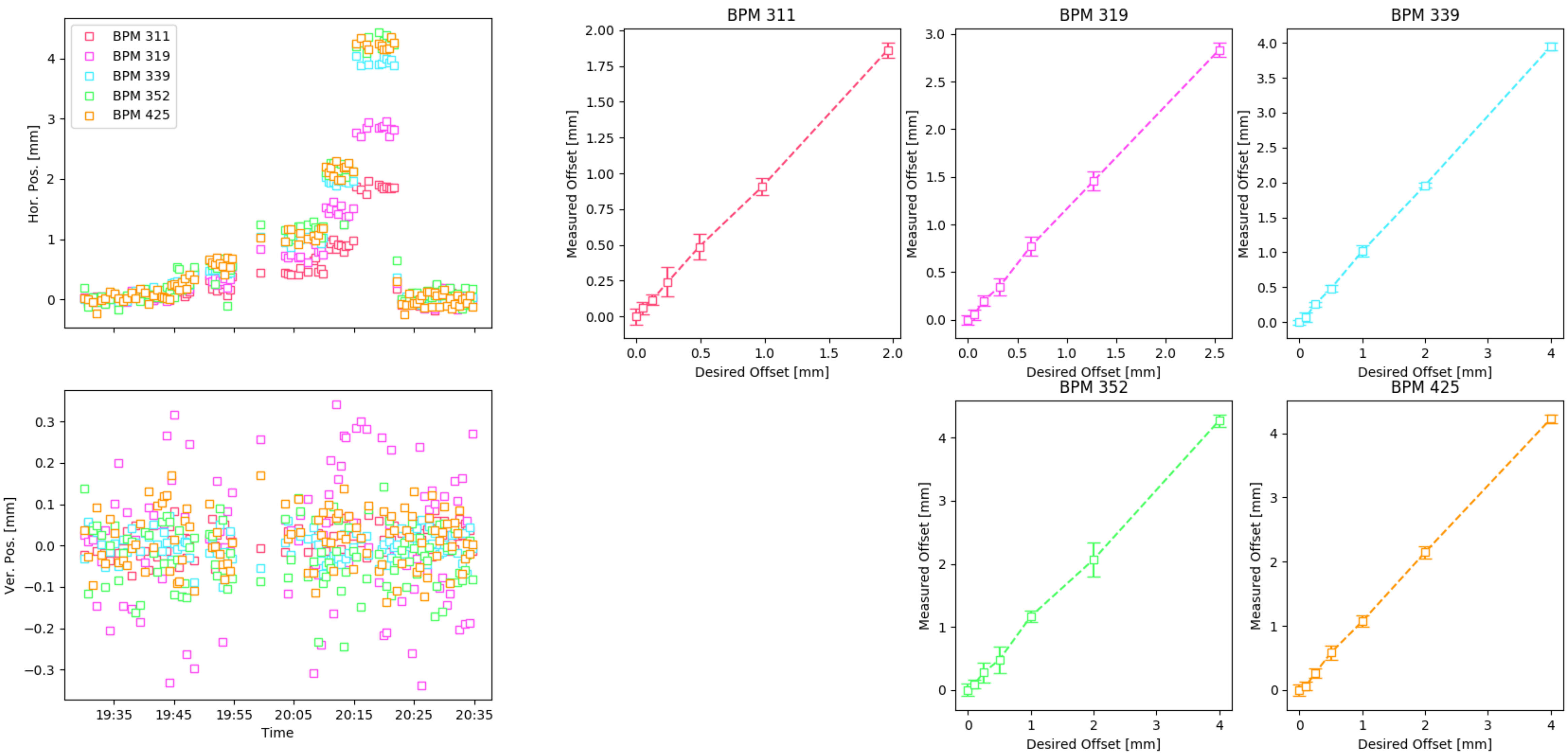


Horizontal scan, no inductor



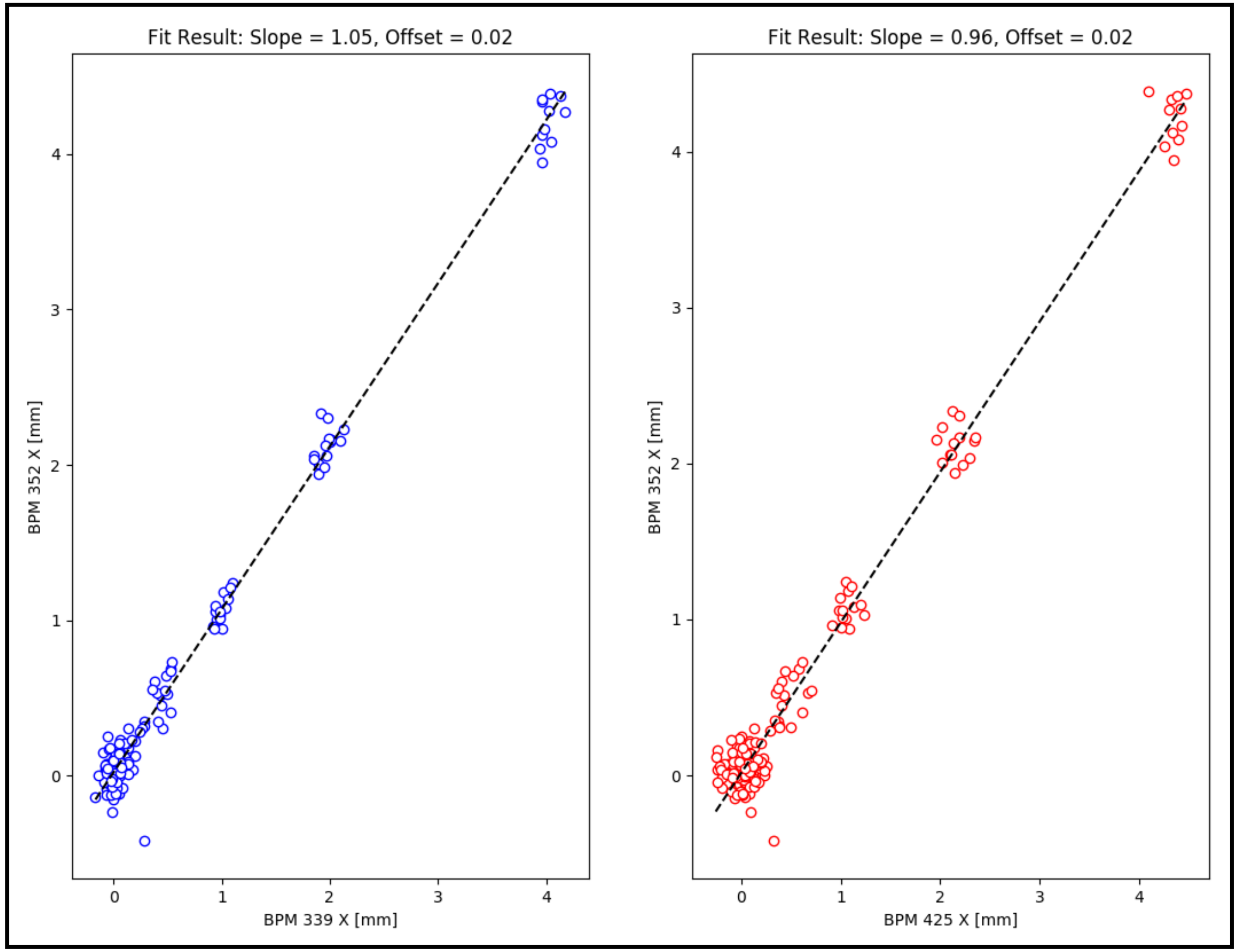


Horizontal scan, with inductor on BPM 352

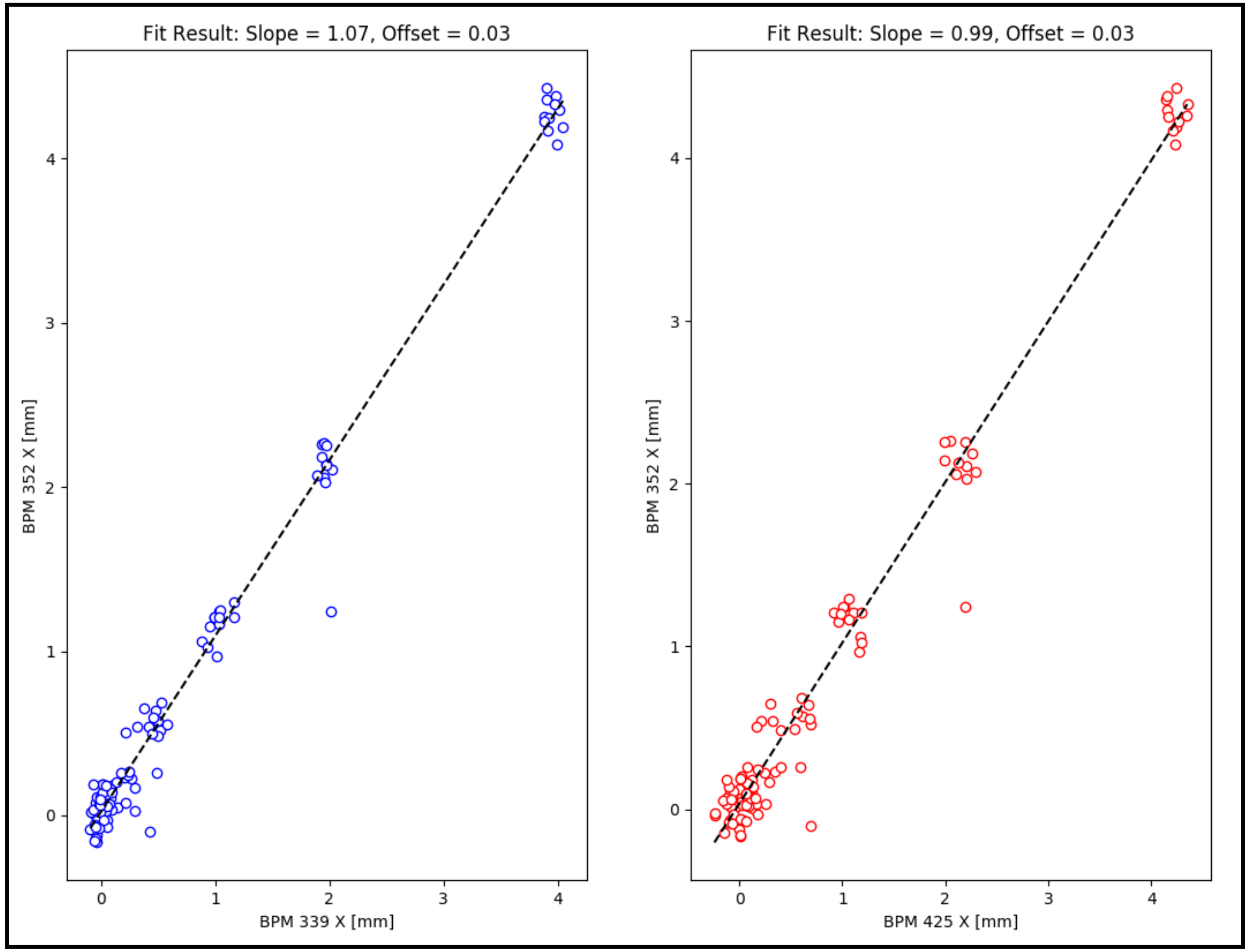


Horizontal scan, correlations

No inductor

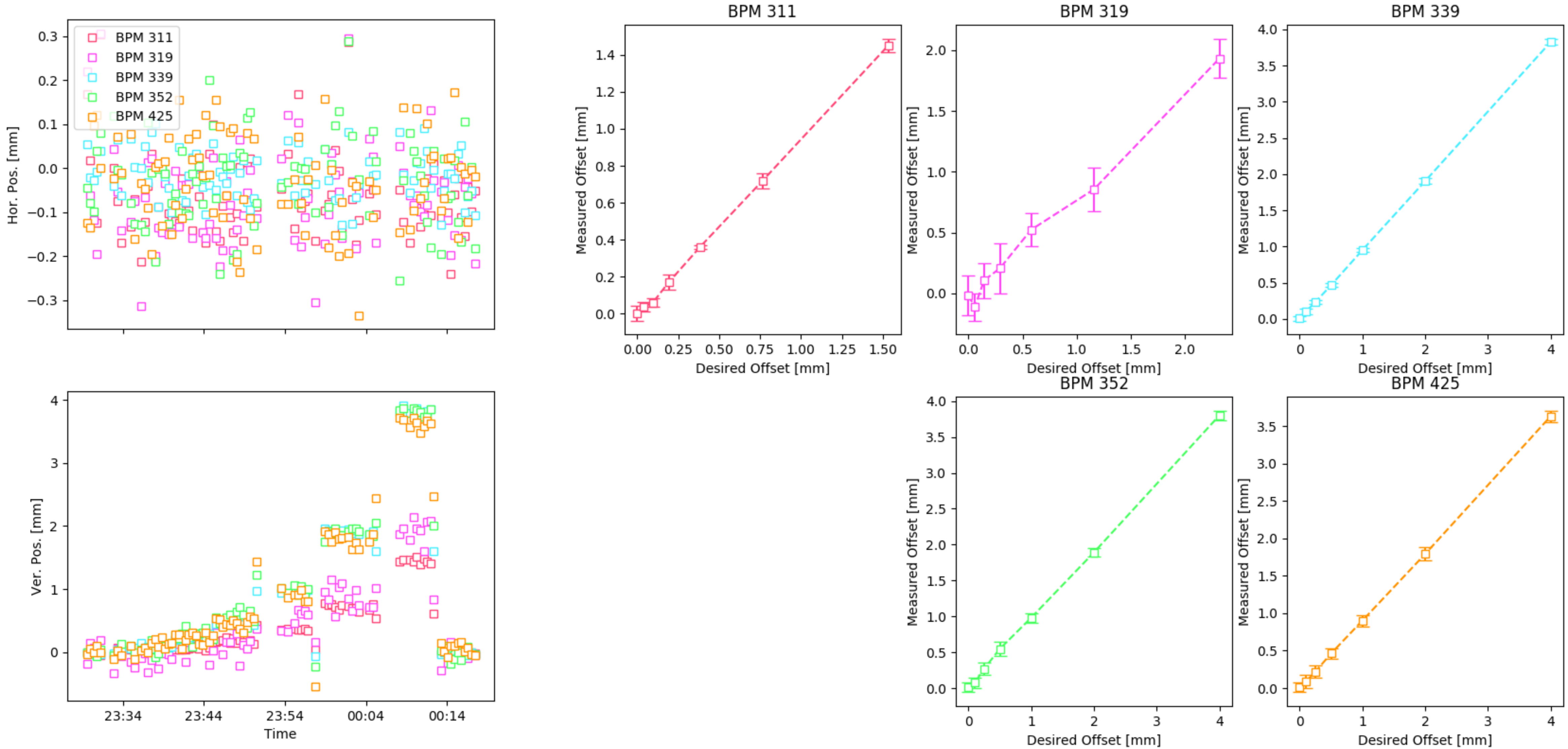


With inductor

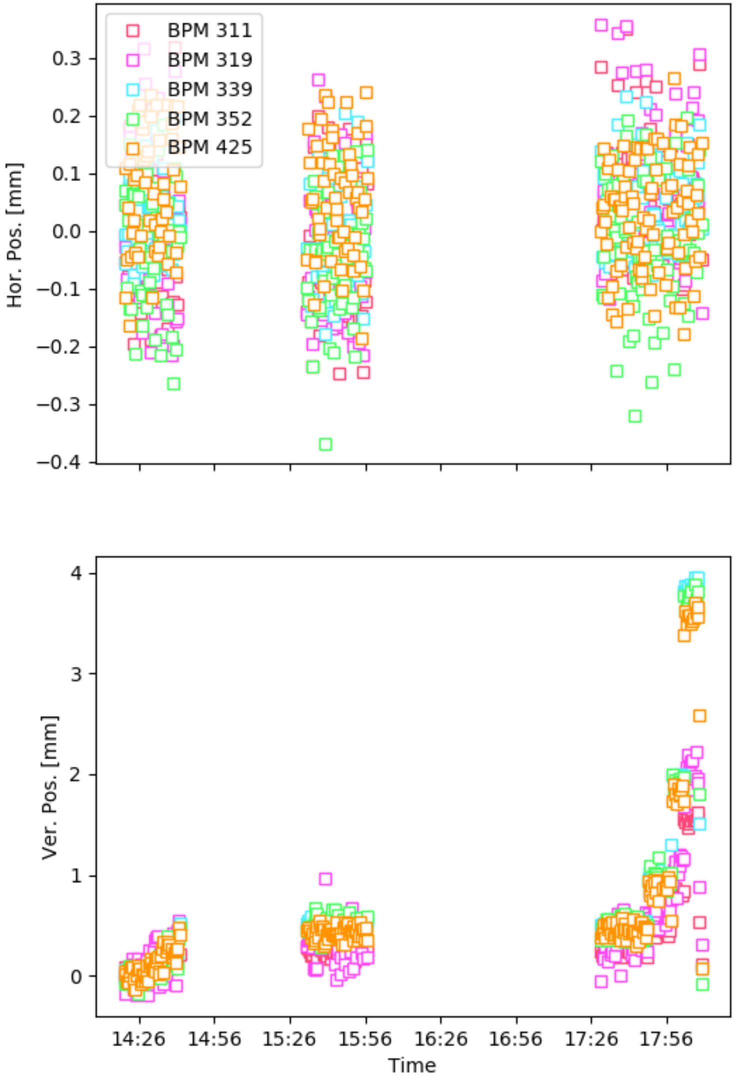


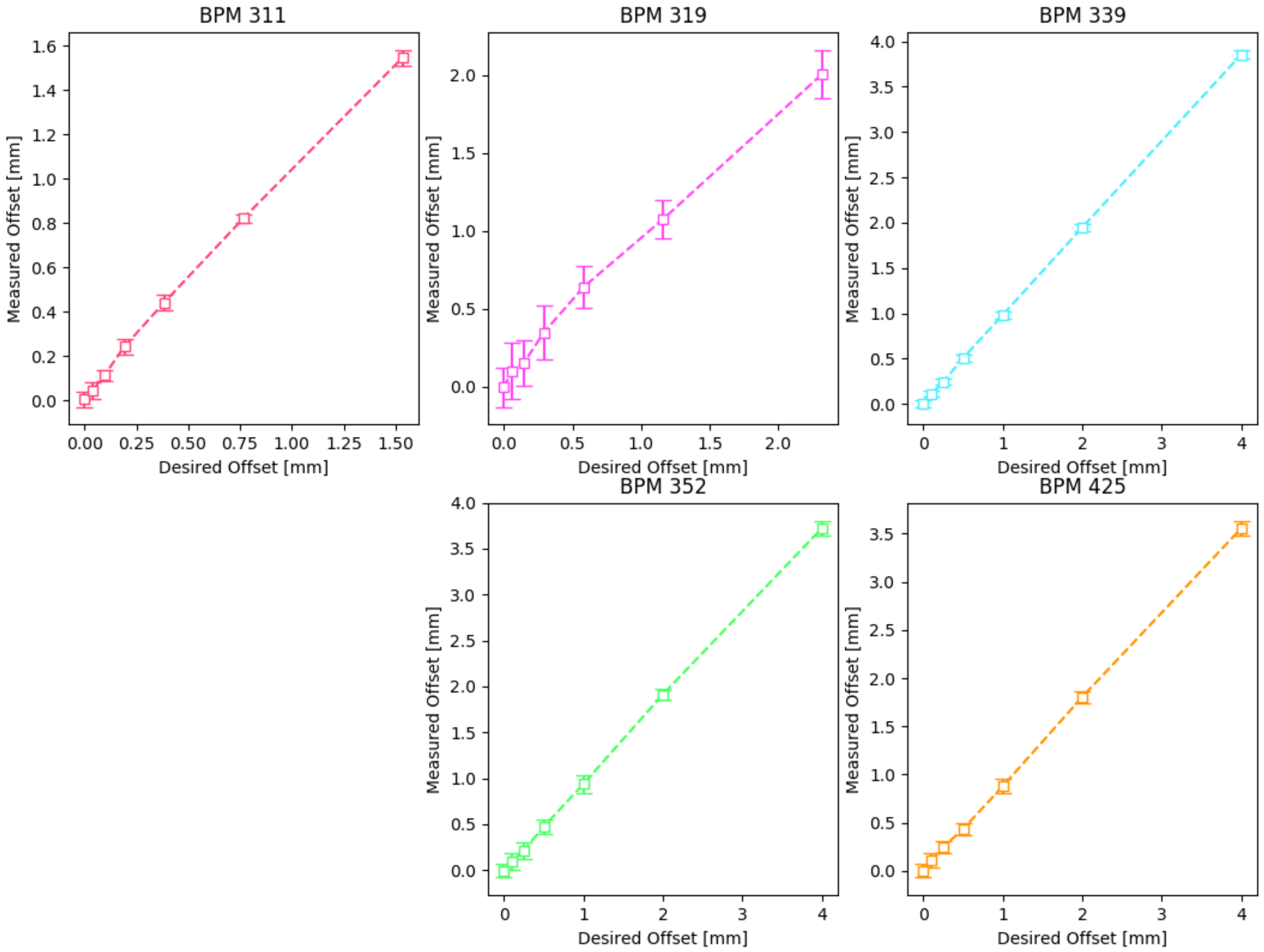
No change in result when inductor added to BPM 352.

Vertical scan, no inductor



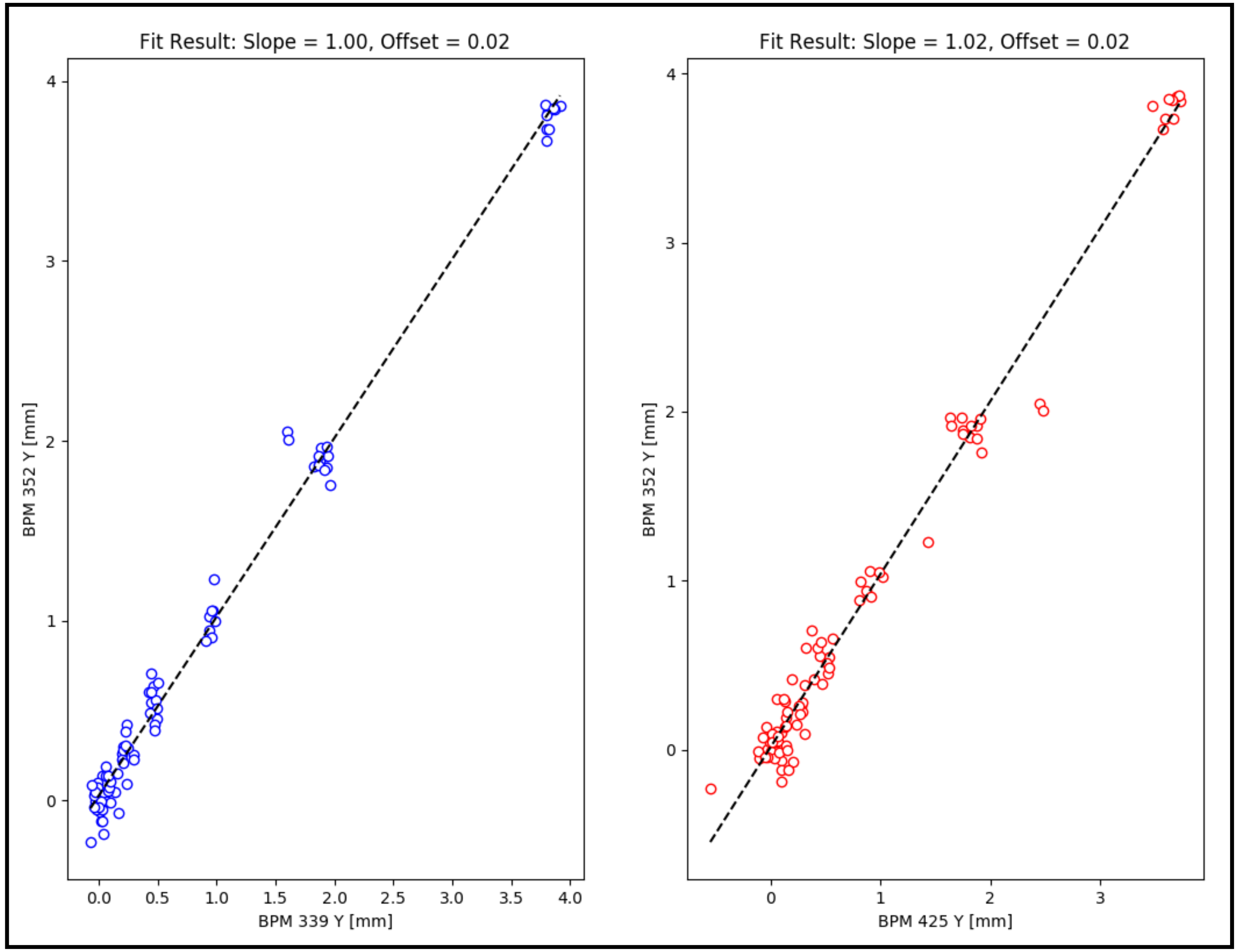
Vertical scan, with inductor on BPM 352



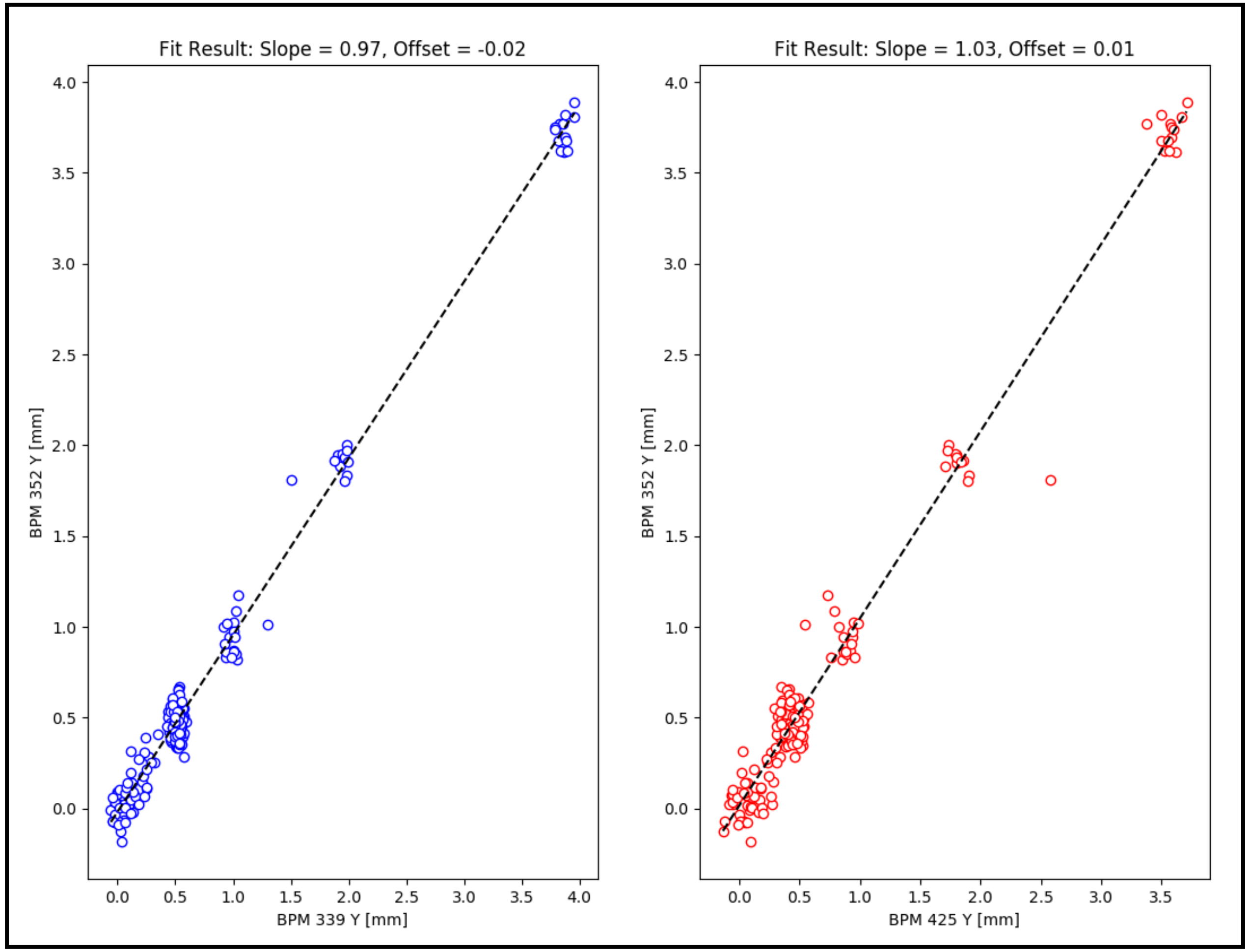


Vertical scan, correlations

No inductor



With inductor



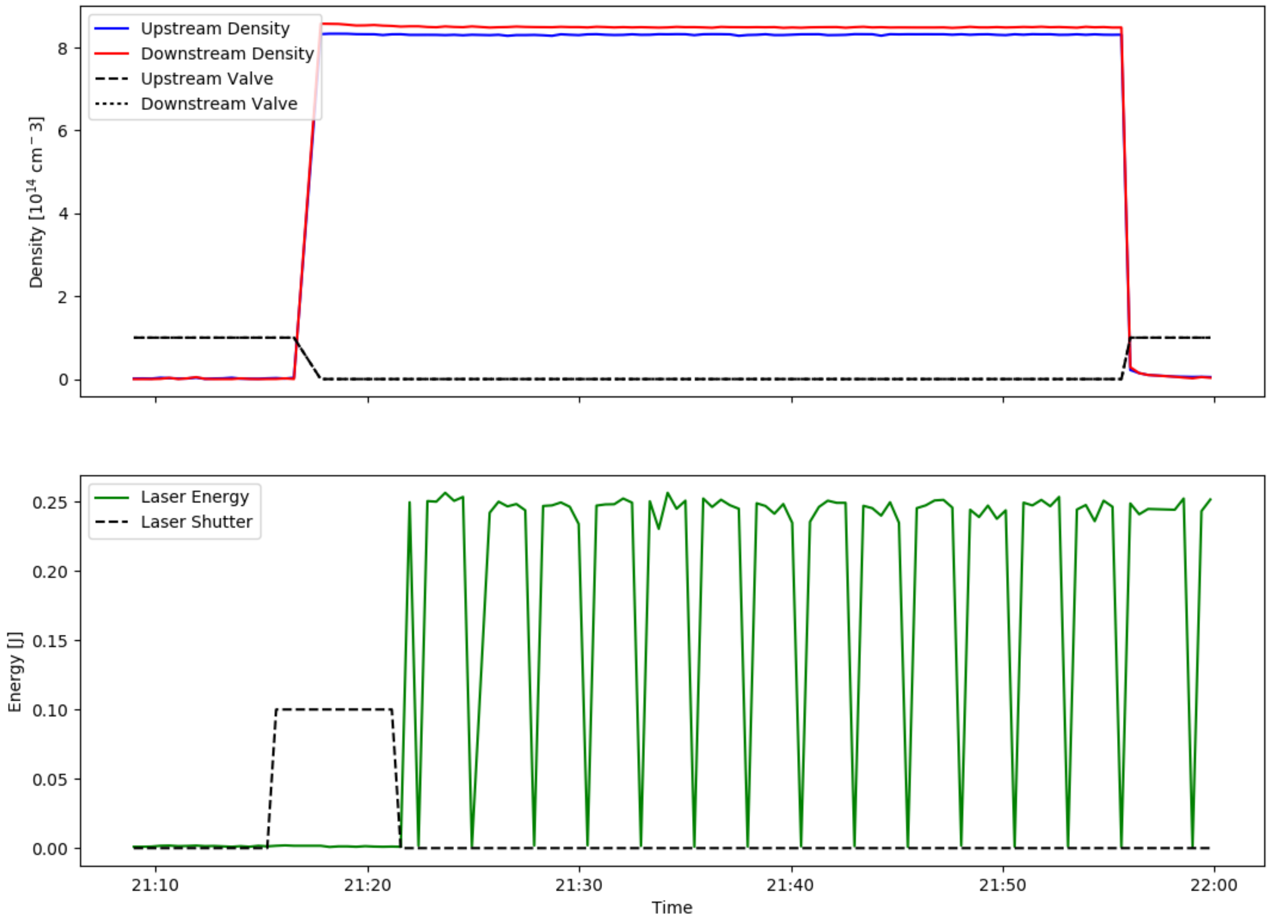
No change in result when inductor added to BPM 352.

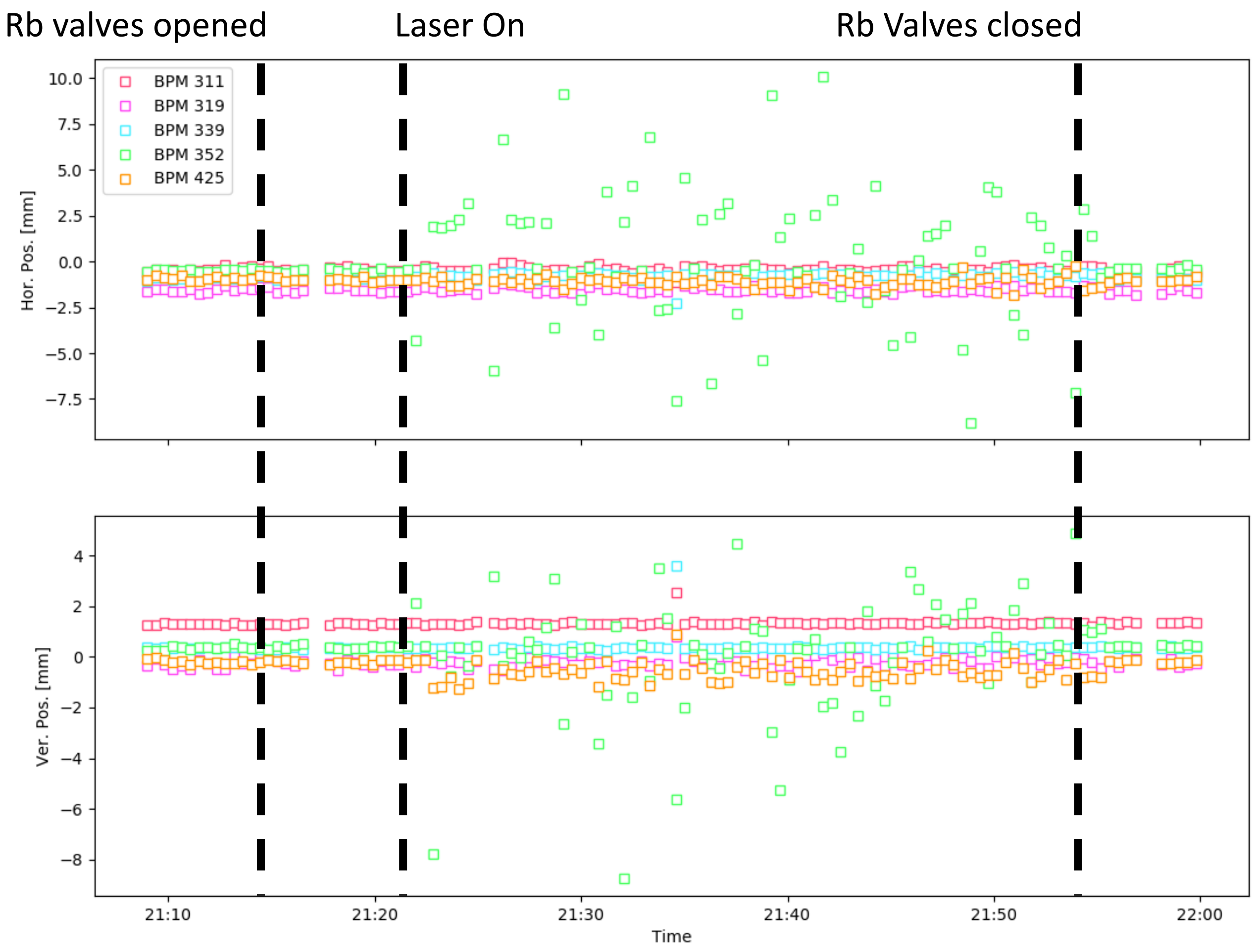
Tests with Plasma

After we verified that the inductor did not affect the no-plasma measurement, we moved on to tests with Rb.

For this test, the Rb density was 8E14 cm^{-3} and the laser was operated such that once every 5 events the laser shutter was closed.

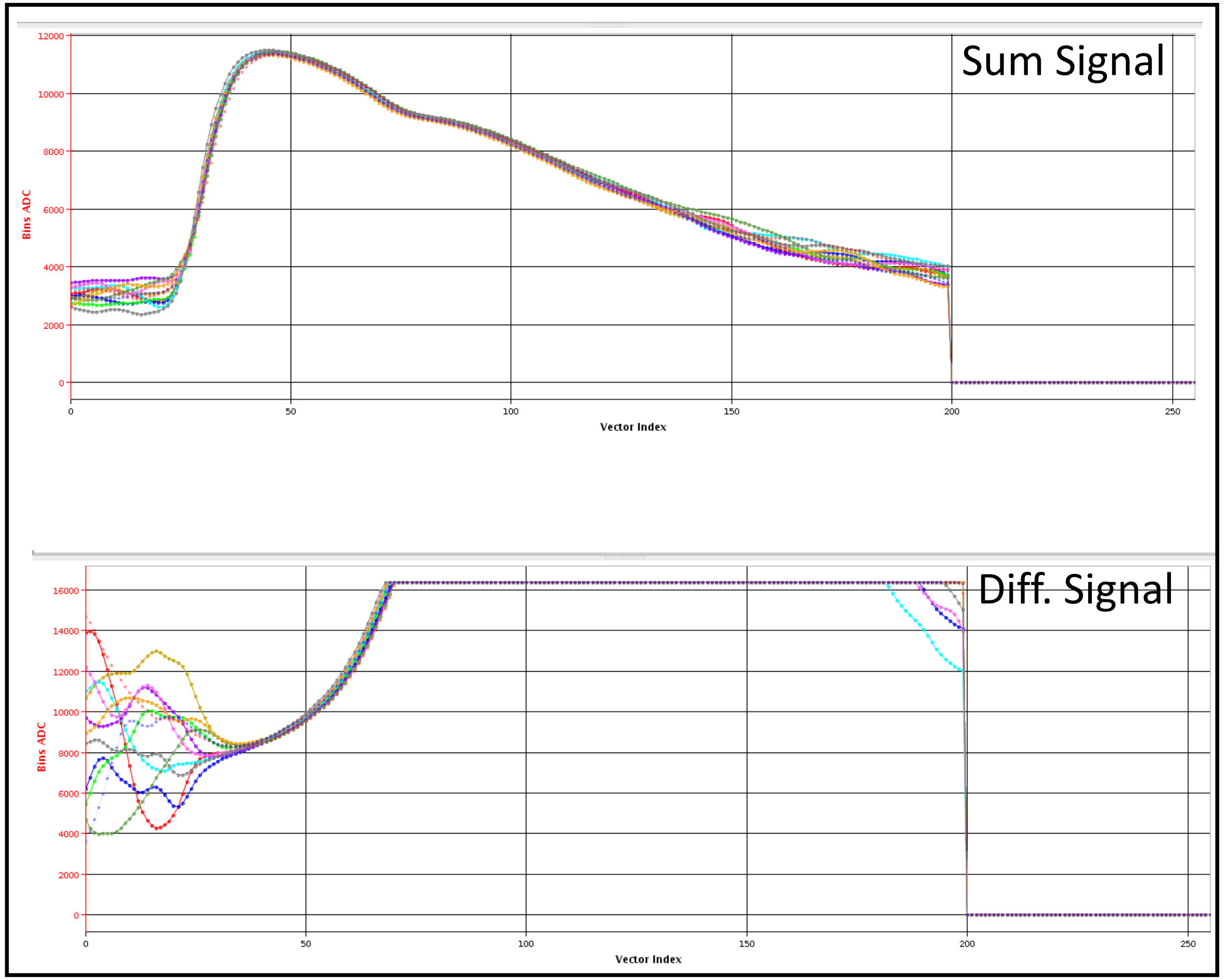
Results with Plasma



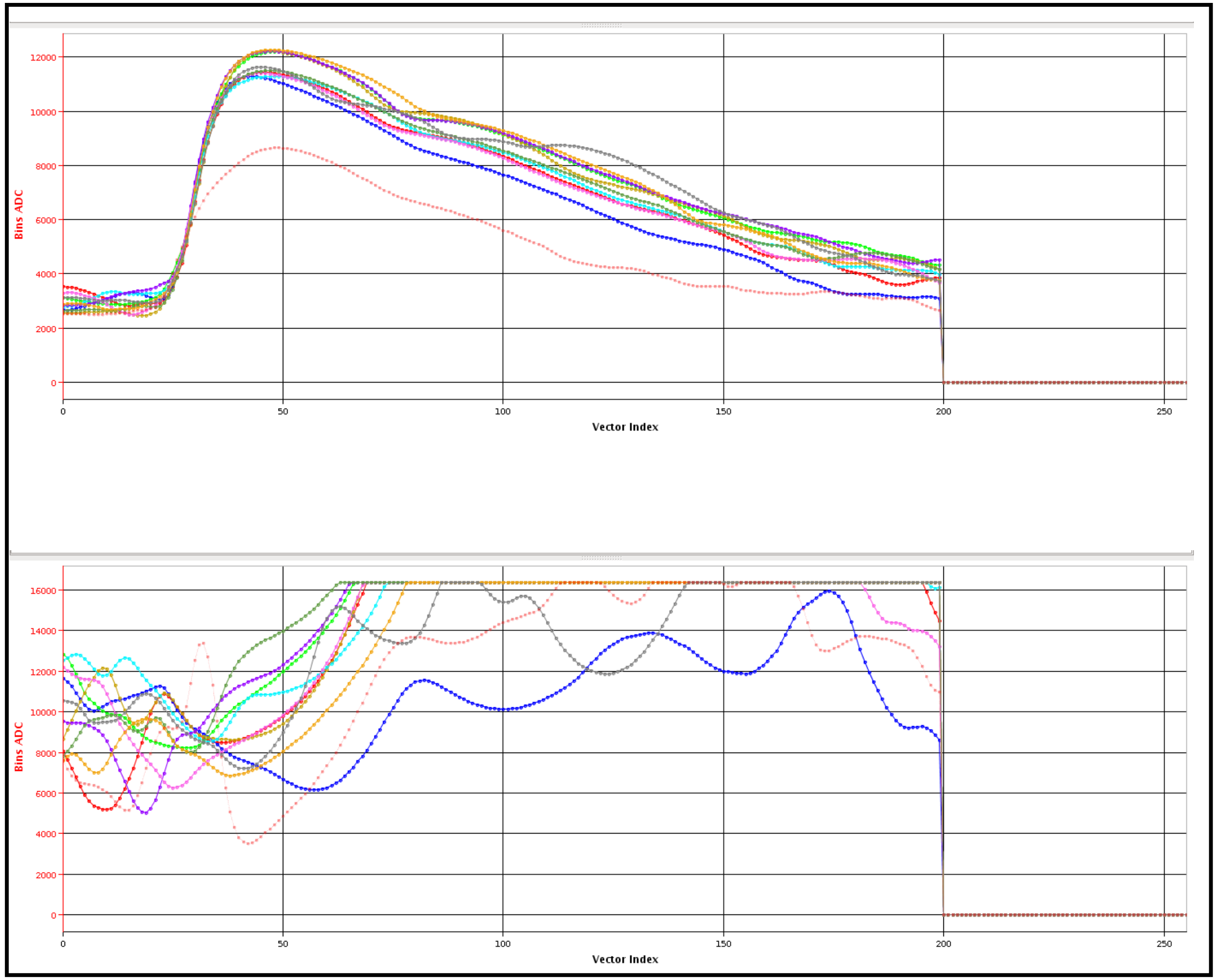


Raw BPM Signals

No plasma



Plasma



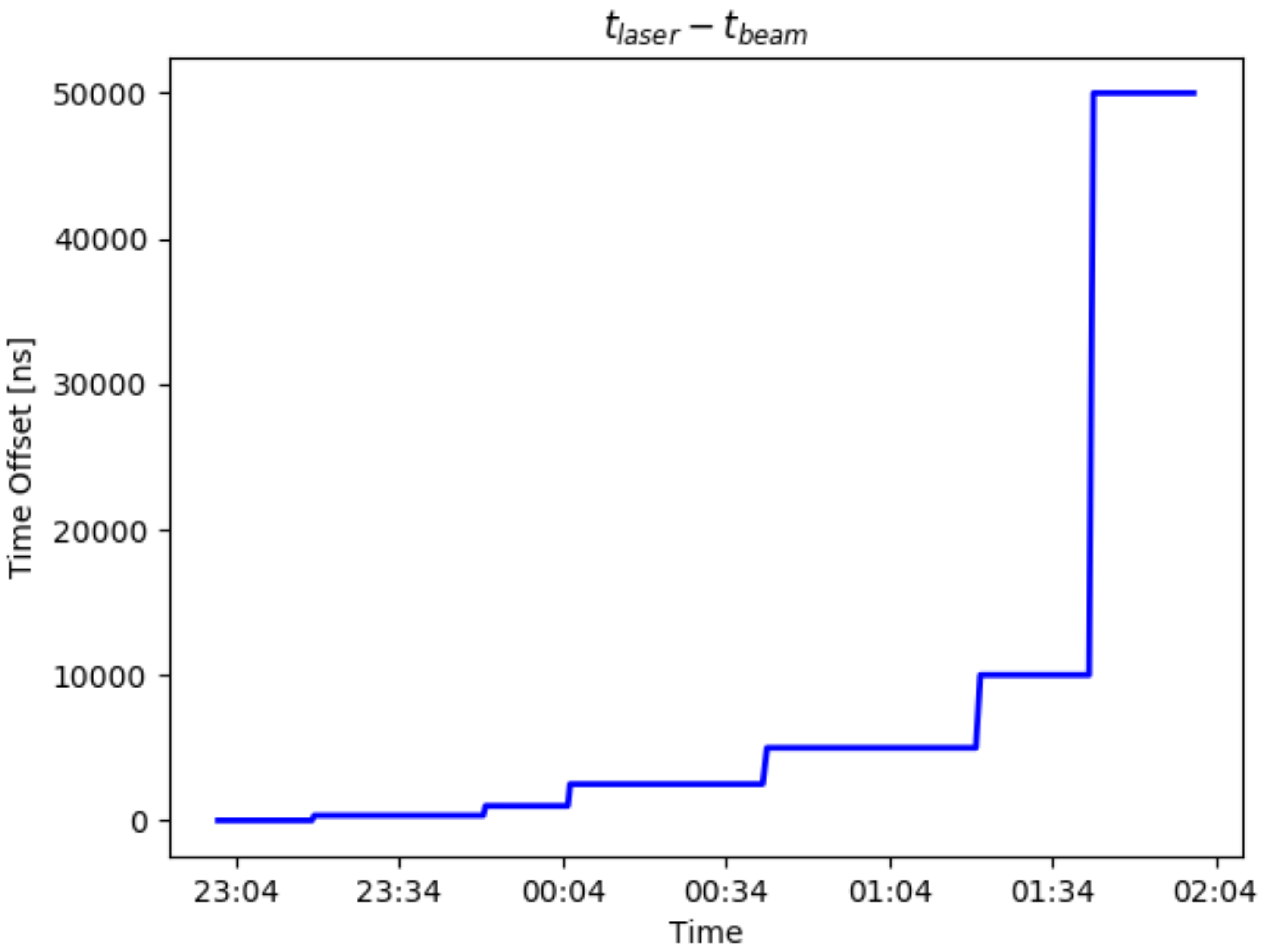
M. Wendt

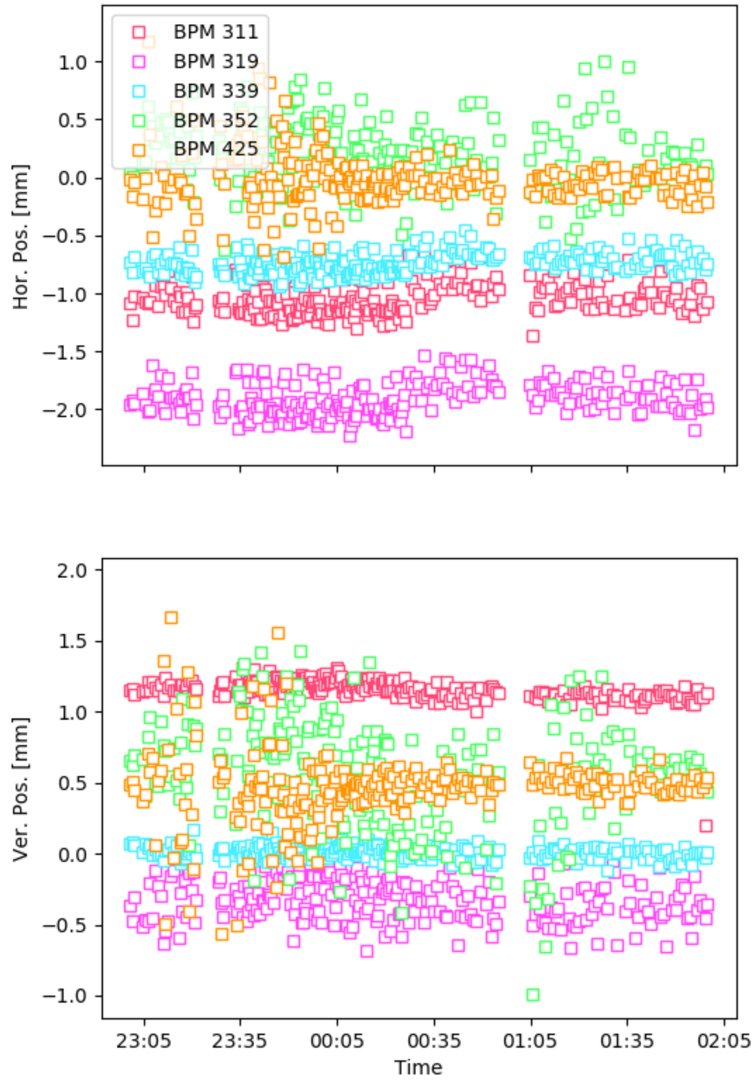
Results with Plasma

Hor. Measurements	BPM 311	BPM 319	BPM 339	BPM 352	BPM 425
No Rb, No Laser, Avg. [mm]	-0.41	-1.54	-0.91	-0.49	0.94
No Rb, No Laser, Std. [µm]	118	129	84	71	104
Rb, No Laser, Avg. [mm]	-0.41	-1.57	-0.93	-0.46	-1.01
Rb, No Laser, Std. [µm]	109	124	86	94	96
Rb and Laser, Avg. [mm]	-0.41	-1.52	-0.73	0.56	-1.12
Rb and Laser, Std. [µm]	131	140	74	**3868**	307

Ver. Measurements	BPM 311	BPM 319	BPM 339	BPM 352	BPM 425
No Rb, No Laser, Avg. [mm]	1.30	-0.26	-0.35	-0.37	-0.19
No Rb, No Laser, Std. [µm]	33	177	31	83	69
Rb, No Laser, Avg. [mm]	1.32	-0.25	-0.38	-0.39	-0.19
Rb, No Laser, Std. [µm]	36	150	27	57	58
Rb and Laser, Avg. [mm]	1.33	-0.21	-0.36	0.43	-0.69
Rb and Laser, Std. [µm]	35	178	43	**2425**	308

Effect present with large laser-proton beam delay

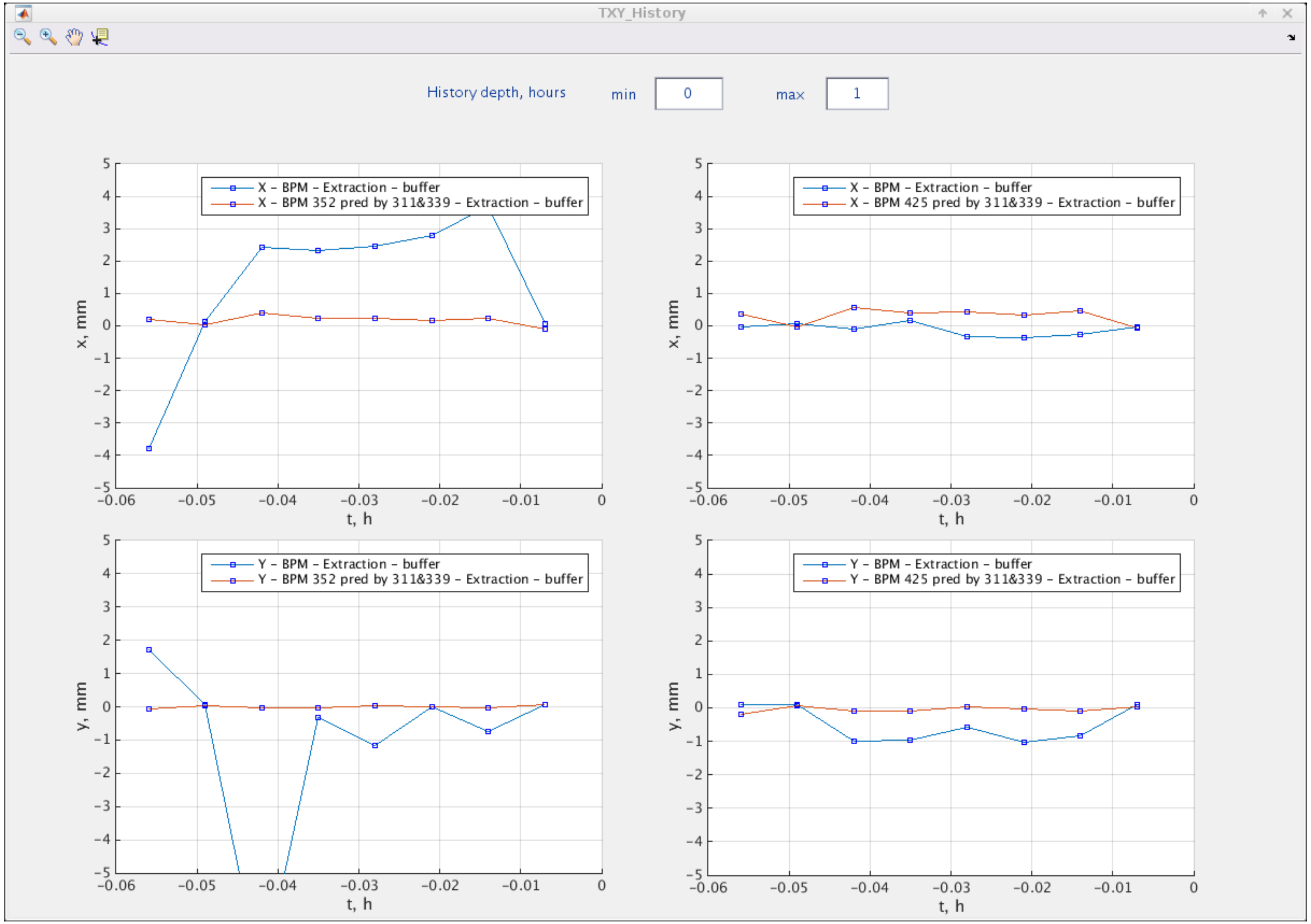




Future Tests

- Check to see if TRIUMF stripline BPMs give a reasonable measurement using CERN 30 MHz readout hardware.
- Check to see if TRIUMF stripline BPMs give a reasonable measurement using TRIUMF readout hardware with an additional 30 dB attenuation.
- Check to see if adding negative voltage bias to BPM buttons can suppress signal.
- Check if using the plungers and/or fast valves has an impact on the signal.

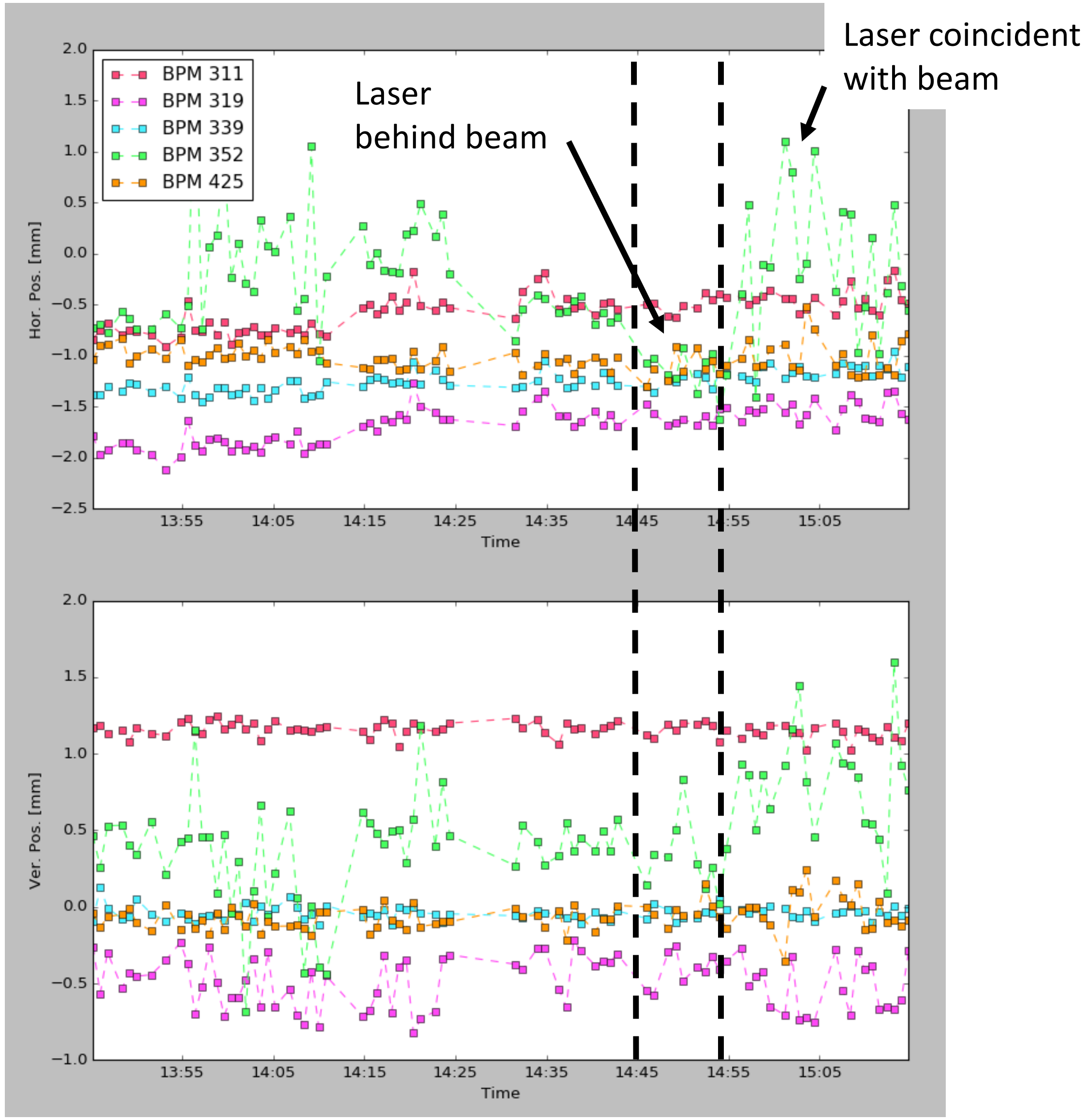
Near-term solution

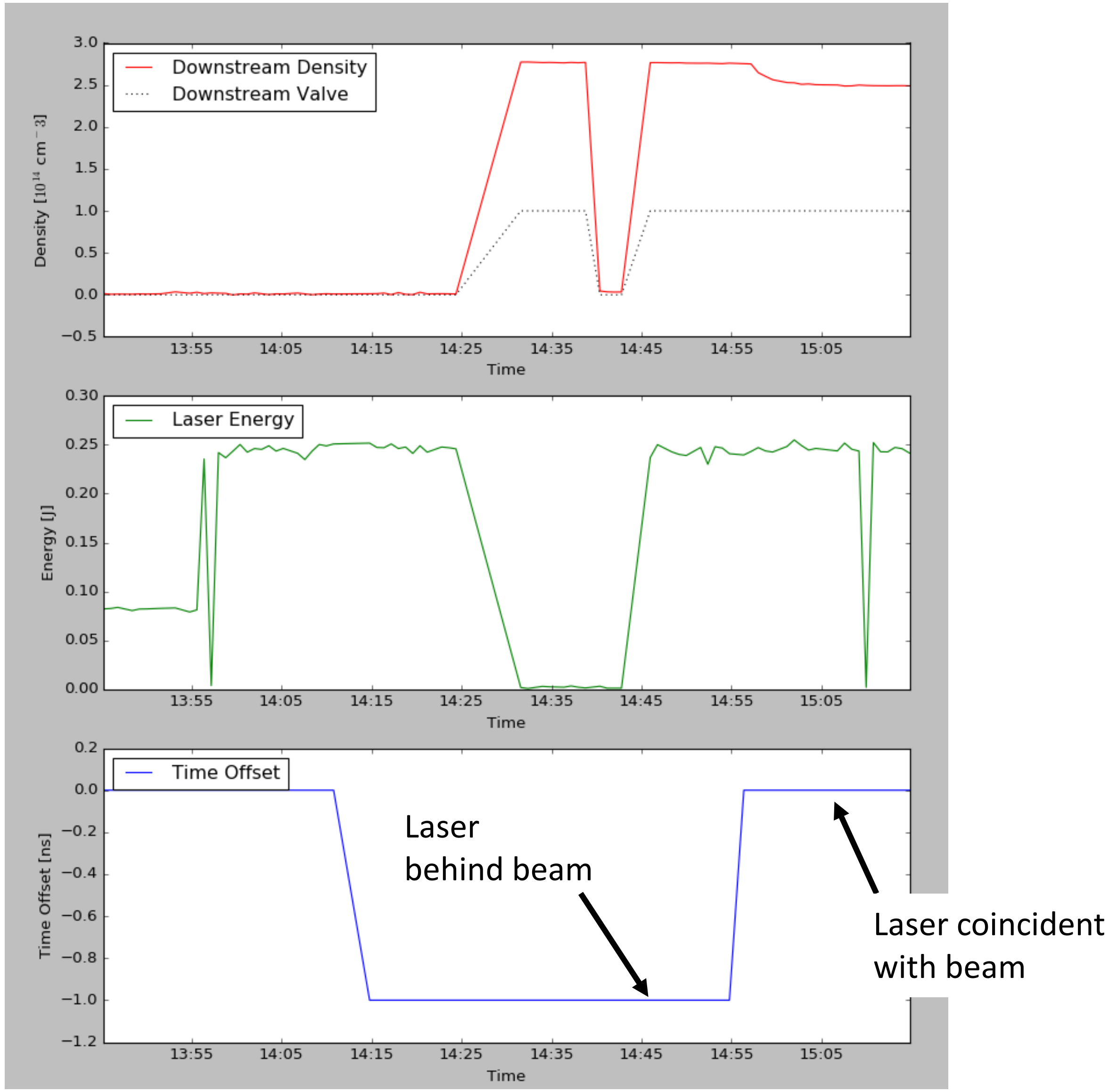


- Anna-Maria has developed a prediction of the beam position based on BPMs 311 and 339.

More Stuff . . .

Laser after proton beam





Delaying the laser with respect to the beam appears to suppress the spurious readings at BPM 352.

Rb density at BPM 352

From E. Oz:

Flow rate through pipe at BPM 352 = 0.08 mg s^{-1} m^{-2}

Flow velocity = 220 m s^{-1}

Rb density = 2.5E9 cm^{-3}

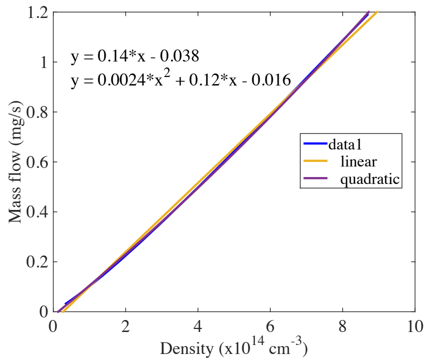


FIG. 1. Rb flux vs measured density and a linear and quadratic fit.

Estimate of Rb deposition 2 m away from the orifice

E.Öz, Max Planck Institute for Physics

August 22, 2017

The mass flow rate from an orifice into vacuum is

$$\dot{M} = W\dot{M}_0 \tag{1}$$

where $\dot{M}_0 = -\frac{\sqrt{\pi}a_o^2}{v_m}P_2$ is the flow rate that corresponds to free molecular regime $\delta = 0$, and $W = 1 + \frac{0.4733+0.6005/\sqrt{\delta}}{1+4.559/\delta+3.094/\delta^2}$ with $\delta = \frac{a_o P}{\mu v_m}$. Where $v_m = \sqrt{\frac{2kT}{M}}$ is the most probable speed. P is the pressure corresponding to the Rb density diagnostic. $a_o = 0.5$ cm is the orifice radius. Rb viscosity at around 480 K is taken to be $\mu = 1.22\times 10^{-5}$ Pas. Using this equation we plot the mass flow vs measured density in Fig. 1.

Mass flux into a solid angle of $d\omega$ is given by

$$dM_e = \Gamma \cos\phi \frac{d\omega}{\pi} dA_e dt. \tag{2}$$

Where $\Gamma = P\sqrt{\frac{m}{2\pi kT}}$ is the mass flow rate per unit area. Total condensed mass over an area located at $r_c = 2$ m is then

$$M_c = \int\int\int\int \Gamma \cos\phi \frac{d\omega}{\pi} dA_e dt \tag{3}$$

$$= T\pi r_o^2 \Gamma \int_0^{\phi_c}\int \cos\phi \frac{\sin\theta\cos\phi}{\pi} d\theta d\phi \tag{4}$$

$$= T\pi r_o^2 \Gamma \int_0^{\phi_c} 2\sin\phi\cos\phi d\phi \tag{5}$$

$$= T\pi r_o^2 \Gamma \int_0^{\phi_c} \sin 2\phi \tag{6}$$

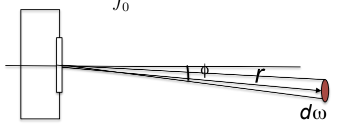


FIG. 2. Φ is the angle between the normal at the orifice and position vector, r.

$$= T\pi r_o^2 \Gamma \frac{1-\cos 2\phi_c}{2} \tag{7}$$

Here we assumed a constant flux over time T. $\phi_c = atan(r_w/r_c) = 0.01$ where $r_w = 2$ cm is the pipe radius. A simple estimate by taking for a high density mass flow rate, $\pi r_o^2 \Gamma = 1$ mg/s from Fig. 1 for $T = 2$ weeks gives total condensed mass 2 meter away as $M_c = 120$ mg.

Plasma Effects at BPM 352

For a background density of 2.5E9, we have a plasma skin depth of approximately 10 cm.

The standard AWAKE beam has a charge of 3E11, a bunch length of 12 cm, and spot size of 100 microns. BPM 352 is very close to focus.

The peak bunch density is 2E13 cm^{-3}. We expect the beam to “blow-out” the plasma.

In order to neutralize the beam charge, the background plasma must rearrange itself so that the total number of ions in the bubble is equal to the bunch charge. We assume this happens over the 12 cm length of the bunch.

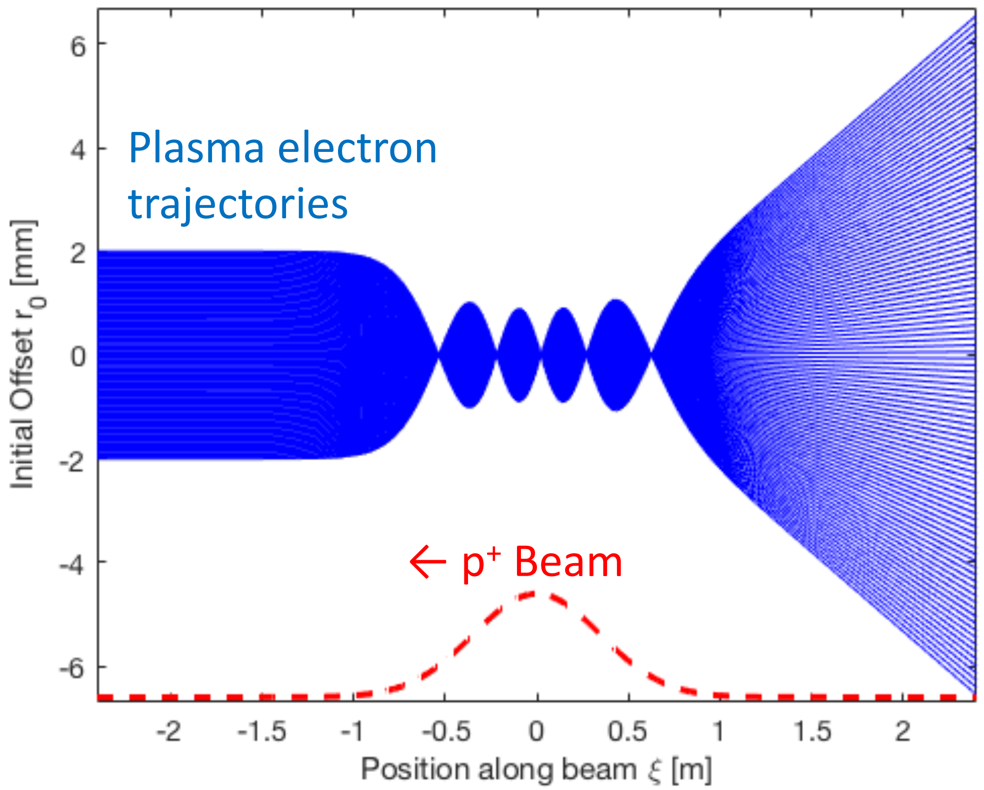
This gives a blowout radius of about 1.8 cm -> almost the size of the beam pipe!

But the laser does not ionize out to this radius. . .

Modeling Plasma Electron Energy Spectrum

Assumptions:

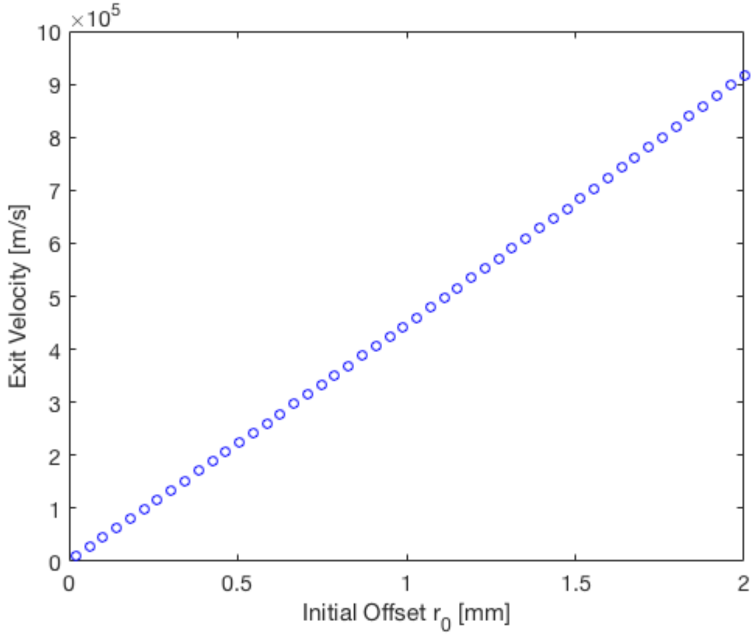
- Non-relativistic
- All motion radial
- All plasma electrons start within ionized region
- All plasma electrons start with zero transverse velocity
- Plasma electrons experience transverse force due to proton beam and plasma ions
- Plasma electrons do not experience force from other plasma electrons (poor assumption).

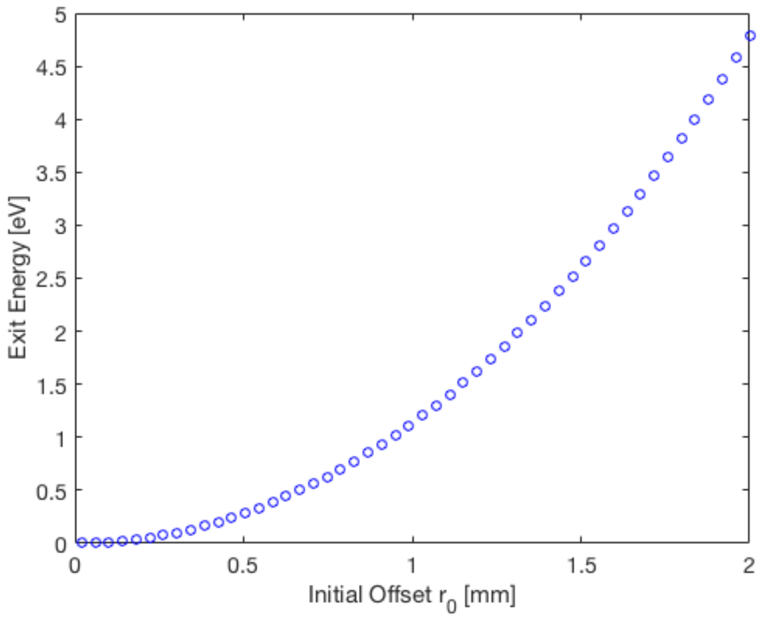


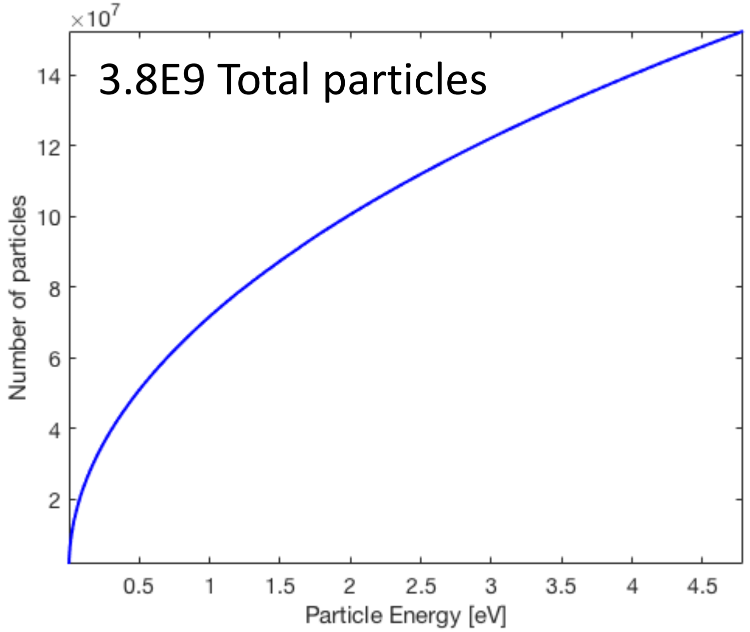
N_p = 3E11
σ_z = 12 cm
σ_r = 100 µm

n_0 = 2.5E9 cm^{-3}
r_i = 2 mm
r_i is the initial ionized radius

Modeling Plasma Electron Energy Spectrum







Plasma electrons exit plasma with velocity that depends on their initial offset from the beam axis. The particles travel at up to 1E6 m/s and reach the BPM buttons within 20 ns of when the beam passes.

The particles are fast, but non-relativistic. They have a maximum energy of 5 eV.

More particles start at larger radii. There are about 4E9 plasma electrons in the 12 cm × 2 mm tube for this example.