RFQ Energy Measurements

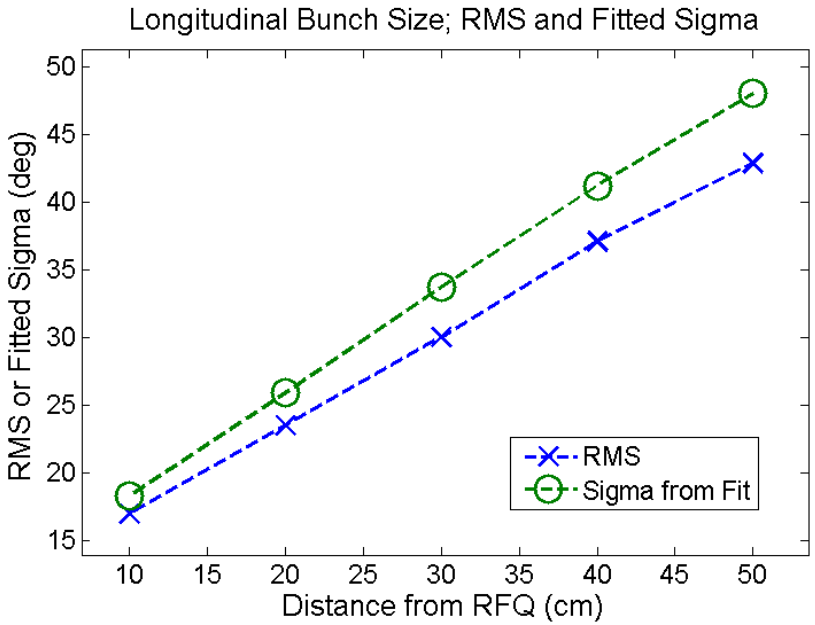
Which technique?

1. Energy spectrometer?
   - Fairly straight forward
   - Lots of pieces, complicated
2. Time of Flight (ToF)?
   - Simpler setup
   - Usually needs a good edge to get absolute energy
   - If velocity is constant then can infer absolute energy using multiple BPMs

Our choice – Three BPM time-of-flight setup

- Two close BPMs for gross energy
- Two further apart BPMs for finer energy resolution

ToF Design



What is BPM spacing?

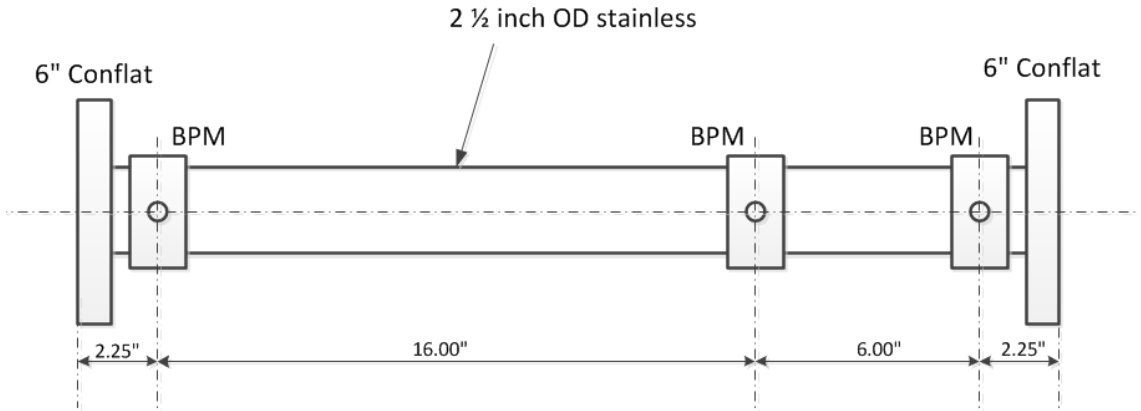
- Can not go too far from RFQ because bunches decohere longitudinally

For 750 H- beam:

- Velocity = 1.198e7 m/s
- $\beta = 0.0400 \rightarrow \gamma = 1.0008$
- RF = 201.25 MHz → 1/RF = 4.969 ns

So make BPM spacing 6" and 16"

- L12 = 6" → ToF = 12.771 ns → 2.5734 RF cycles = 2 cycles + 206.43 degrees
- L23 = 16" → ToF = 33.806 ns → 6.8035 RF cycles = 6 cycles + 289.27 degrees
- L13 = 22" → ToF = 46.578 ns → 9.3895 RF cycles = 9 cycles + 138.77 degrees



Calculated Energy Sensitivities

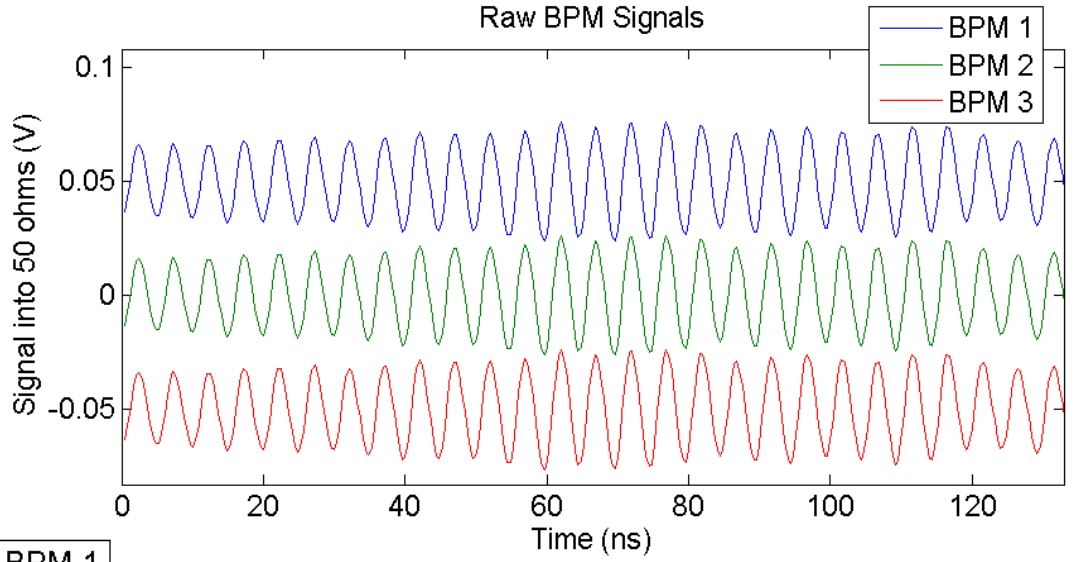
	dVel/dE ((m/s)/keV)	dE/dL (keV/mm)	dt/dE (ps/keV)	dE/dt (keV/ps)	dPhase/dE (deg/keV)	dE/dPhase (keV/deg)
BPM 1 to 2	7.983e3	9.846	-8.471	0.118	-0.613	-1.631
BPM 2 to 3	7.983e3	3.692	-22.589	0.044	-1.635	-0.612
BPM 1 to 3	7.983e3	2.685	-31.06	0.032	-2.248	-0.445

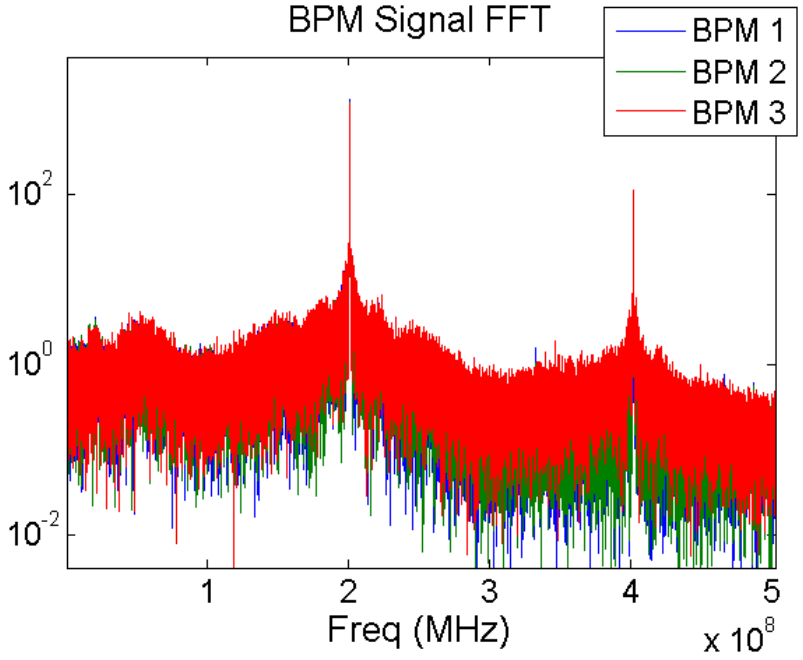
How much does the energy change if you pick the wrong number of RF cycles?

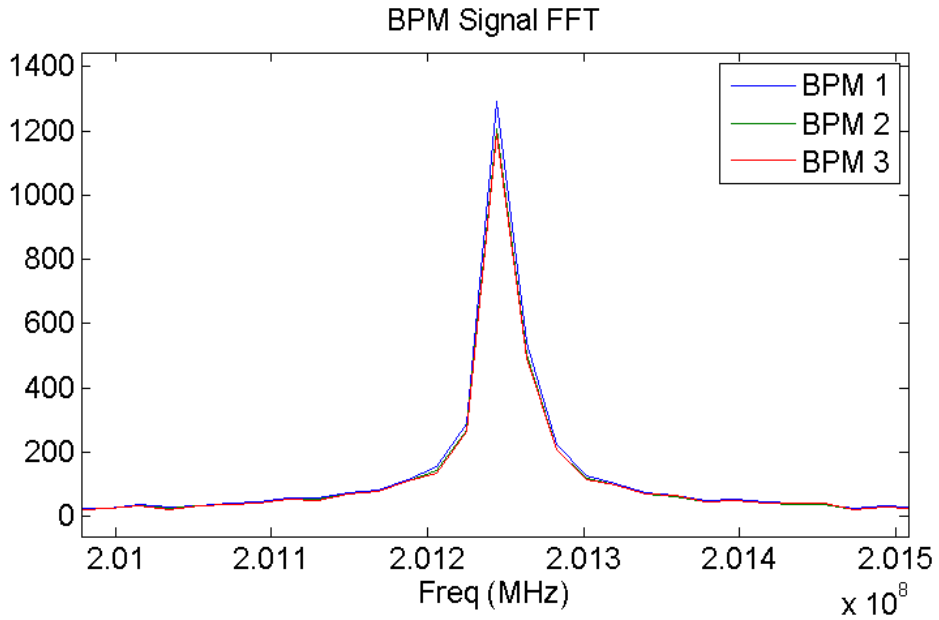
	N0	E @ N0 – 1	E @ N0	E @ N0 + 1
BPM 1 to 2	2	2016 KeV	750 KeV	389 KeV
BPM 2 to 3	6	1032 KeV	750 KeV	571 KeV
BPM 1 to 3	9	941 KeV	750 KeV	613 KeV

BPM Signals

Look at BPM signals using 500 MHz analog BW scope

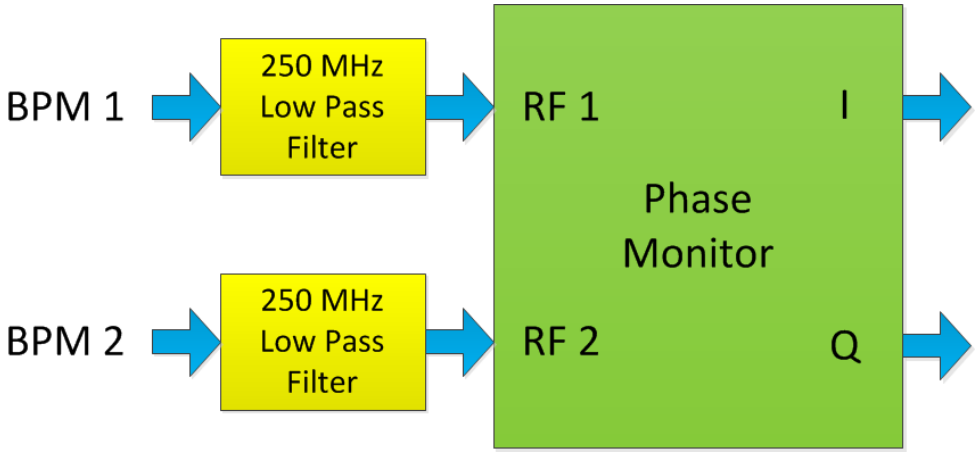


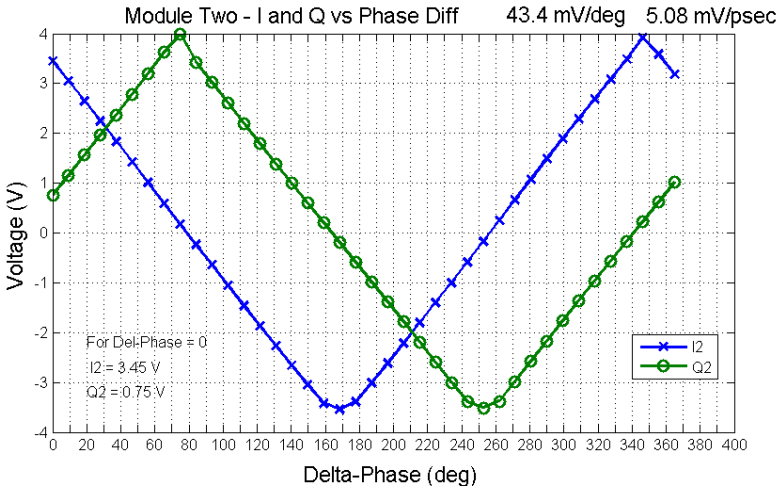




(1) ToF Using Phase Monitor

Feed BPM signals through low-pass filters into phase monitor





	Del-Phase (deg)	N0	ToF (ns)	Vel (m/s)	Beta	Gamma	Energy (KeV)
BPM 1 to 2	224	2	12.771	1.157e7	0.0386	1.0007	701
BPM 1 to 3	235	9	46.578	1.163e7	0.0388	1.0008	708

(2) Direct Scope Measurements

All three BPM signals into scope – *no filters, no phase monitor*

- Capture many bunches → FFT → unwrap phase from 201.25 MHz FFT component
- Measurements at different RFQ power levels

Phase Difference (degrees) VS RFQ Power

* Wrap around to next RF cycle

	233 KW	220 KW	212 KW	206 KW	182 KW	162 KW
BPM 1 to 2	227.2	227.4	227.5	227.2	234.2	260.2
BPM 2 to 3	15.9	17.9	15.4	13.3	4.7	329.2*
BPM 1 to 3	243.2	245.3	242.8	240.5	238.8	229.4

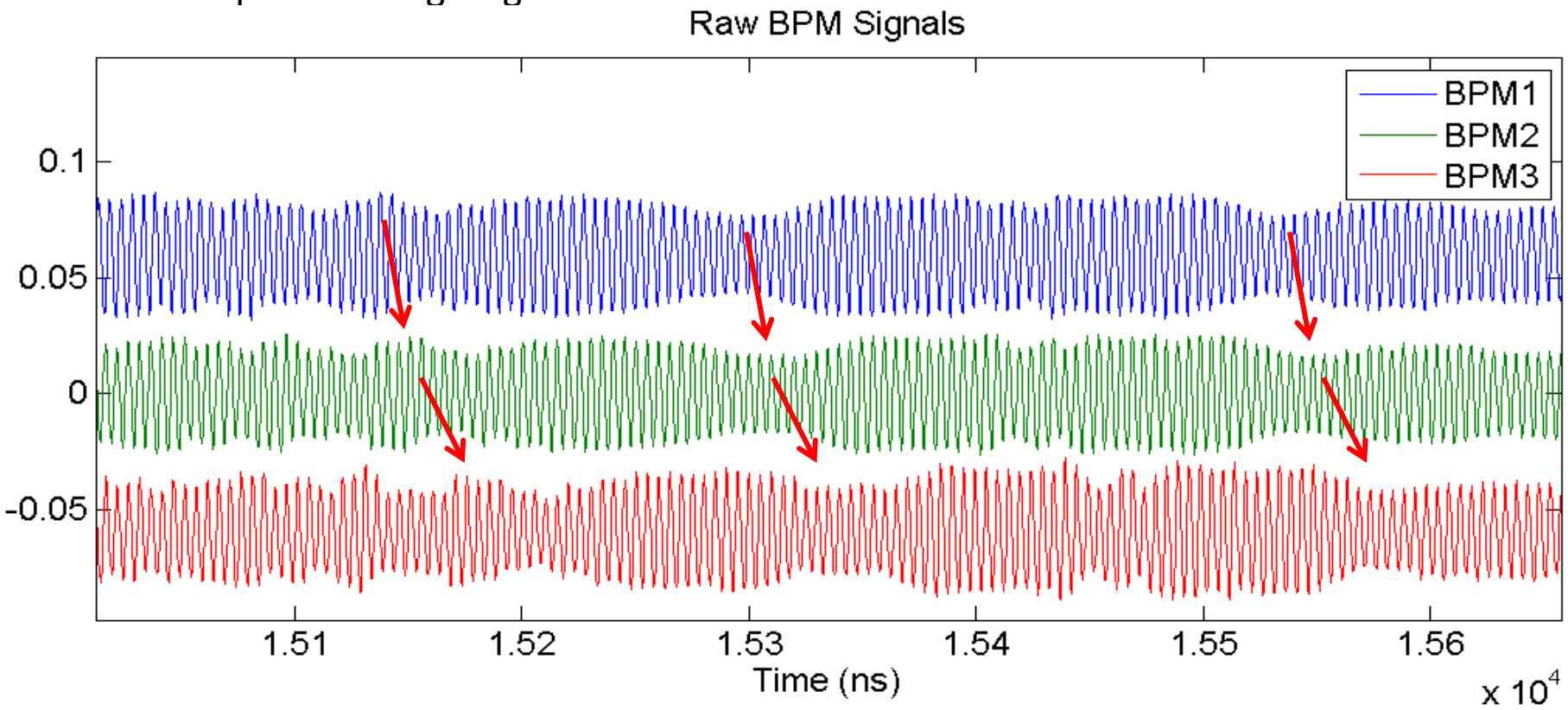
Beam Energy VS RFQ Power

RFQ Power (KW)	Beam Energy (BPM 1 to 2) keV	Beam Energy (BPM 1 to 3) keV	Beam Energy (BPM 2 to 3) keV
212	0.716	0.705	0.701
220	0.716	0.704	0.699
233	0.716	0.705	0.700
206	0.717	0.706	0.702
182	0.706	0.706	0.707
162	0.669	0.710	0.556

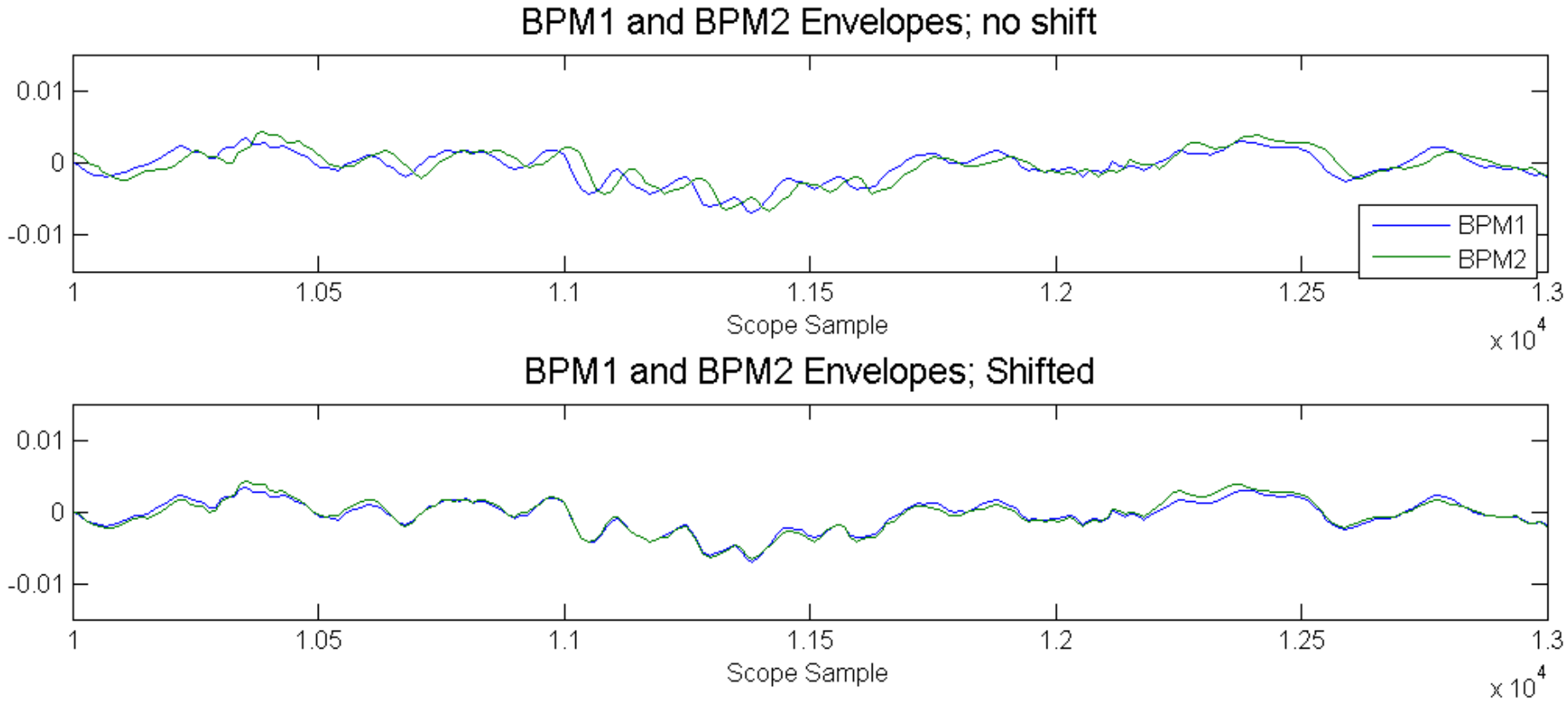
(3) Energy from Time of Flight using Slow-Wave Structures in BPM Signals

Can we correlated similar slow-wave structures in the BPM signals to determine the RFQ energy through time of flight (ToF)? – *poor mans chopper*

- Try and correlate BPM signal envelopes to determine ToF
  - Minimize difference in envelope structure to determine the shift in time required to align signals from different BPMs



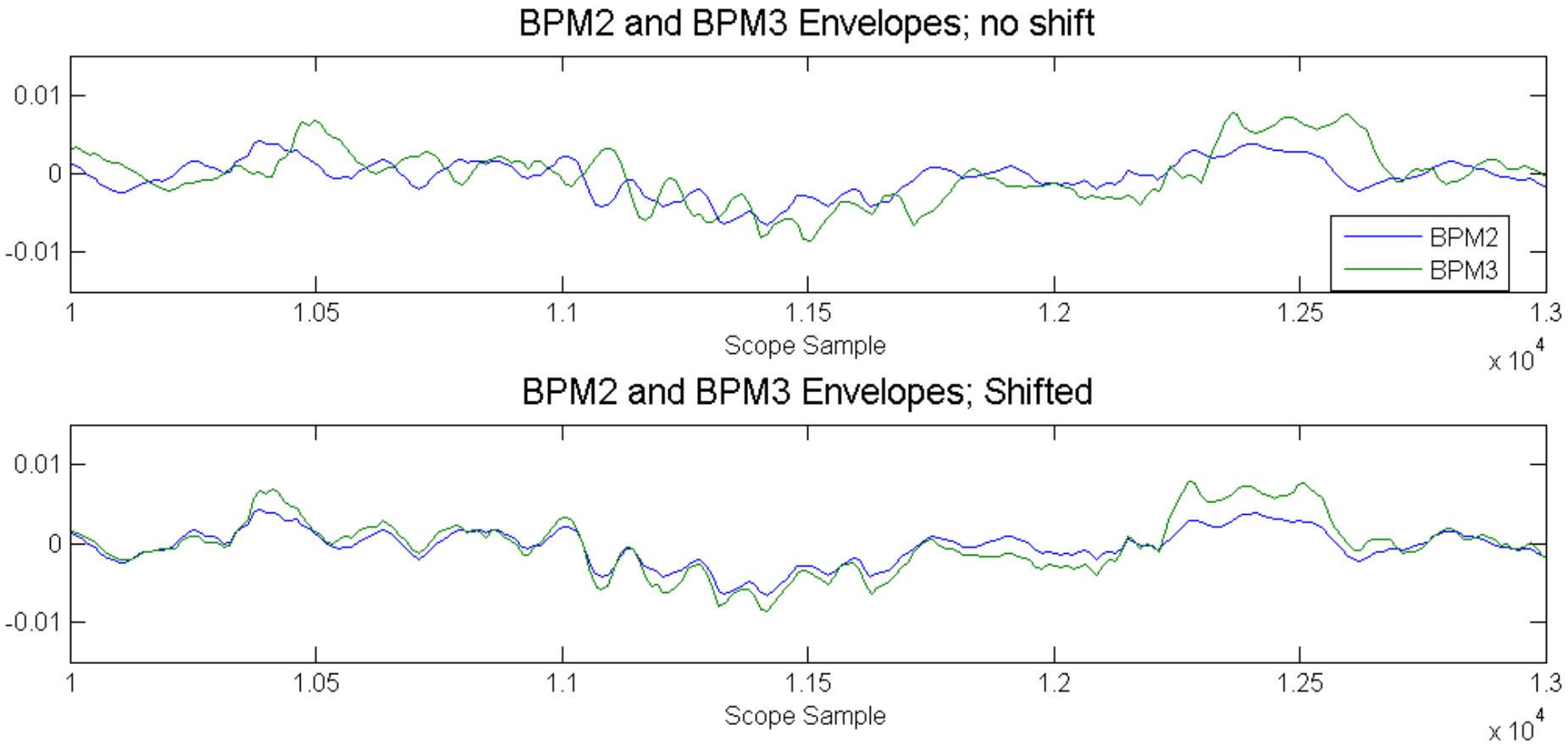
Aligning BPM 2 to BPM 1



Shift BPM 2 data 13.2 ns for best alignment to BPM 1
ToF = 13.2 ns → Velocity = 1.160e7 m/s → β = 0.0387

Gives a beam energy of 703 keV +/- ~40 keV

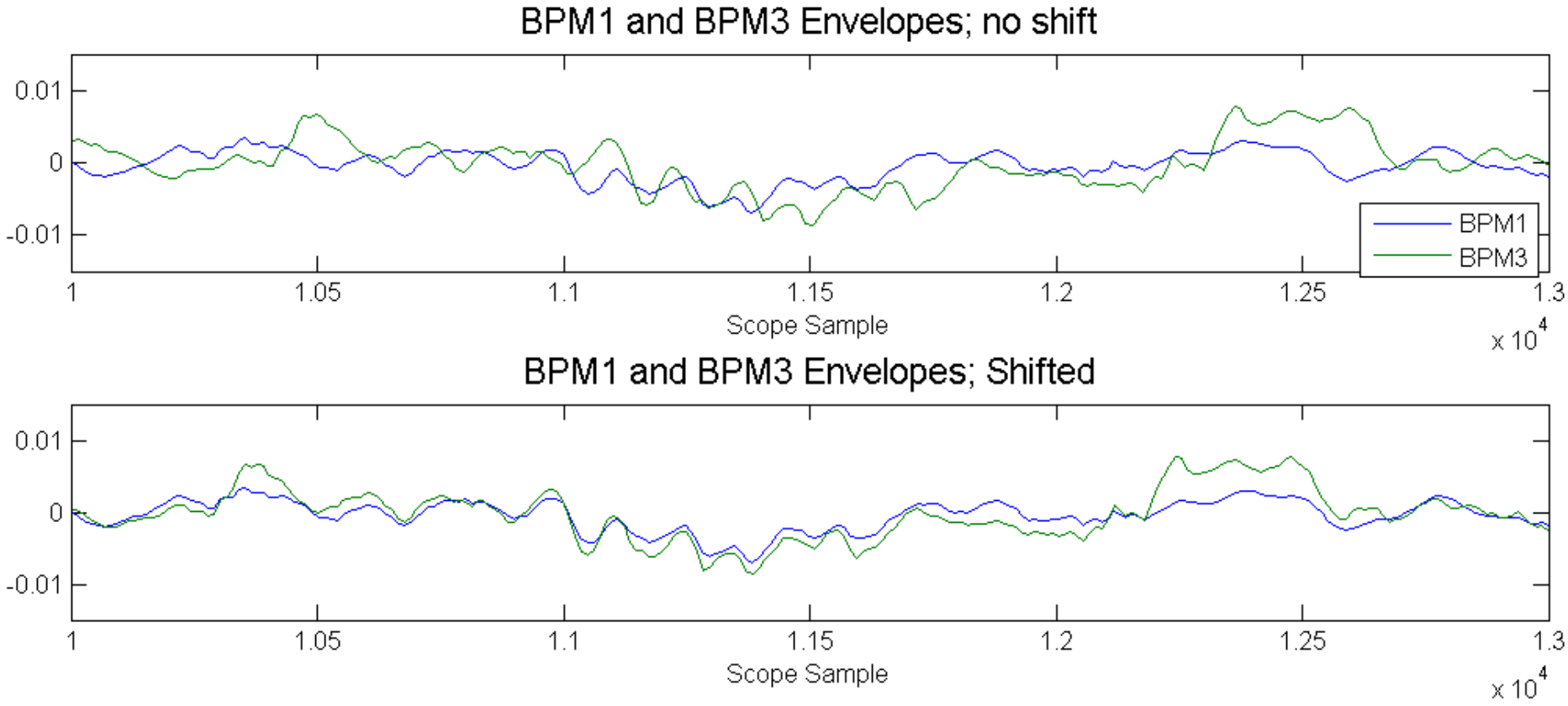
Aligning BPM 3 to BPM 2



Shift BPM 3 data 34.8 ns for best alignment to BPM 2
ToF = 34.8 ns → Velocity = 1.164e7 m/s → β = 0.0388

Gives a beam energy of 709 keV +/- ~16 keV

Aligning BPM 3 to BPM 1



Shift BPM 3 data 48.0 ns for best alignment to BPM 1

ToF = 48.0 ns → Velocity = 1.163e7 m/s → β = 0.0388

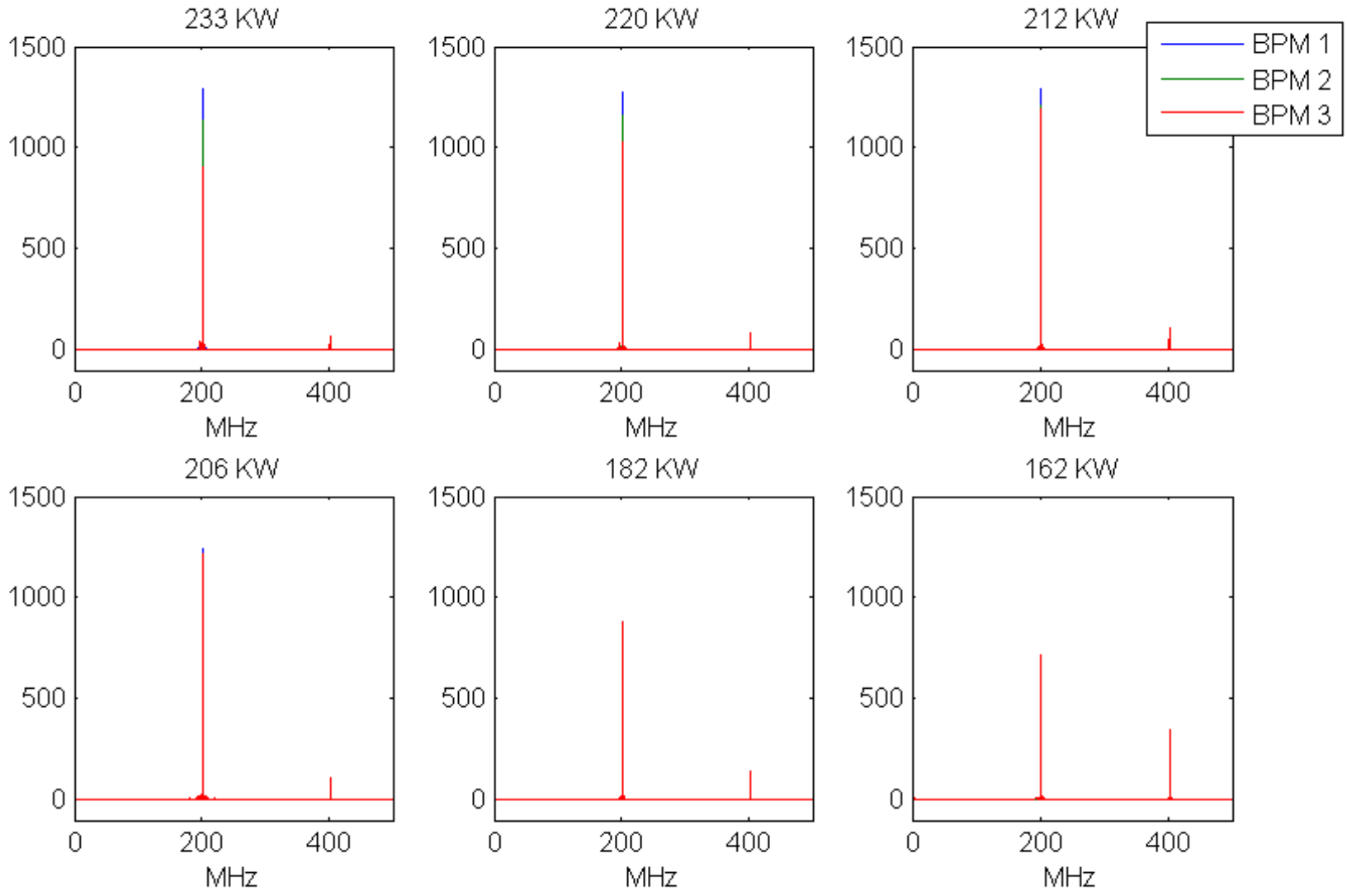
Gives a beam energy of 707 keV +/- ~11 keV

RFQ Beam Energy from Slow-Wave Structures in BPM Signals

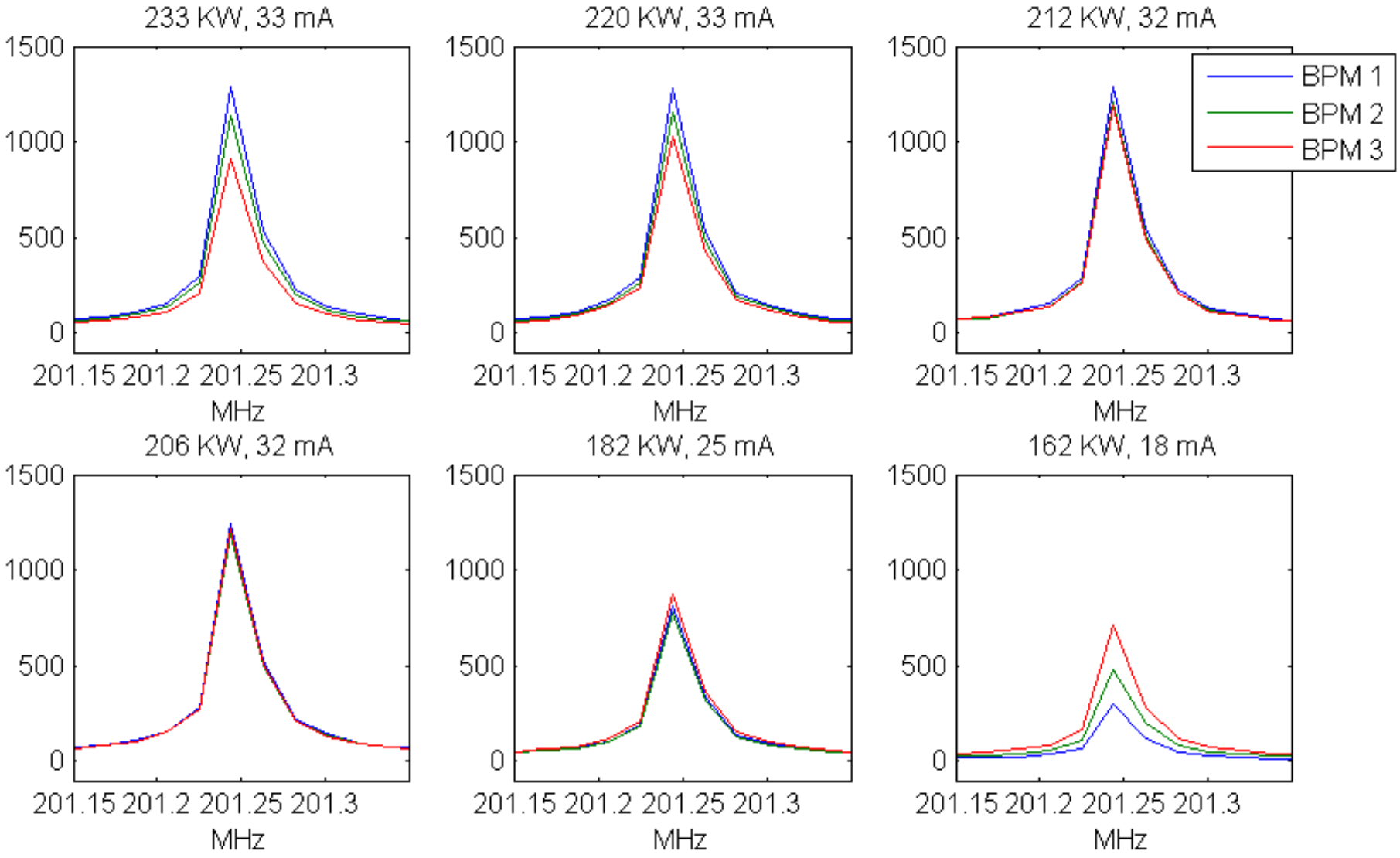
	Time of Flight (nsec)	Velocity (m/s)	Beta	Beam Energy (keV)	Energy Error* (keV)
BPM 1 to 2	13.2	1.160e7	0.0387	703	+/- ~ 40
BPM 2 to 3	34.8	1.164e7	0.0388	709	+/- ~ 16
BPM 1 to 3	48.0	1.163e7	0.0388	707	+/- ~ 11

* Note: Energy error is a “best estimate” from alignment of BPM waveforms.

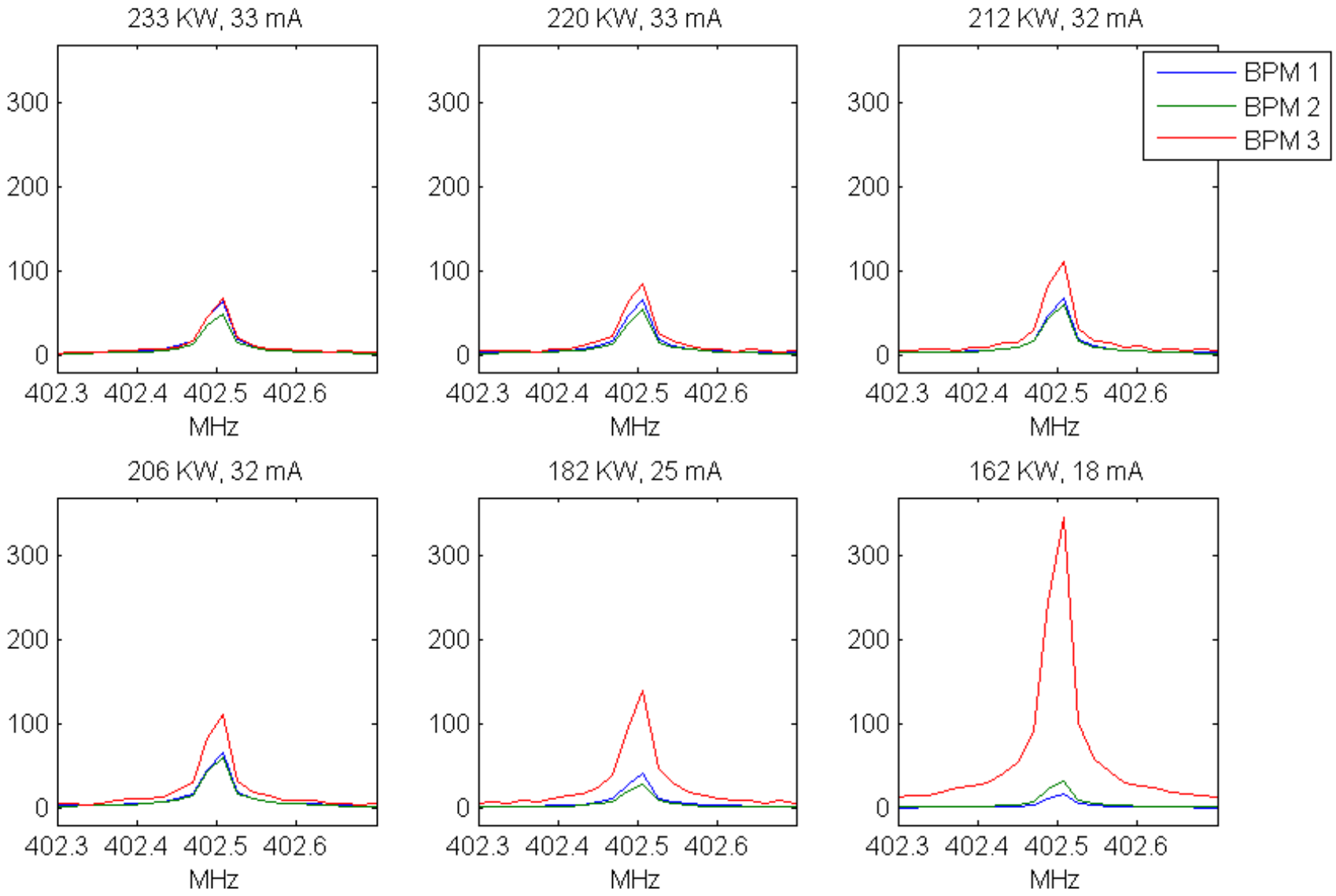
201.25 MHz Component VS RFQ Power



201.25 MHz Component VS RFQ Power



402.5 MHz Component VS RFQ Power



201.25 MHz Component VS RFQ Power