Electron Cloud Studies in the Fermilab Main Injector using Microwave Transmission

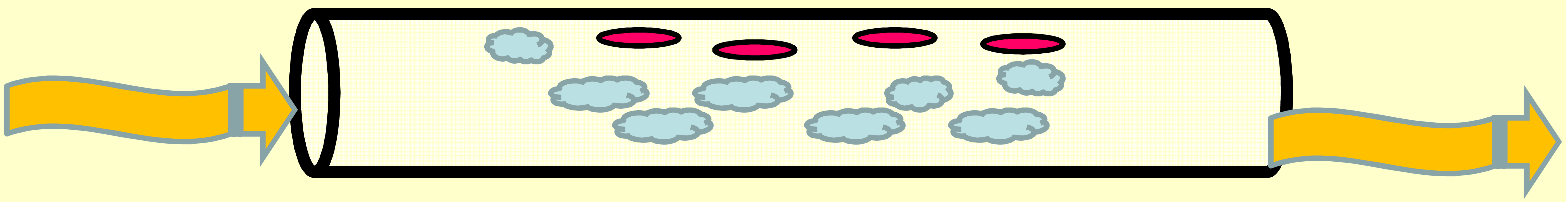
J. Charles Thangaraj

on behalf of

E-cloud team @ Fermilab (B. Zwaska, C. Tan, N. Eddy,..)

Microwave measurement principle

The wind and the waves are "*always*" on the side of the ablest navigators

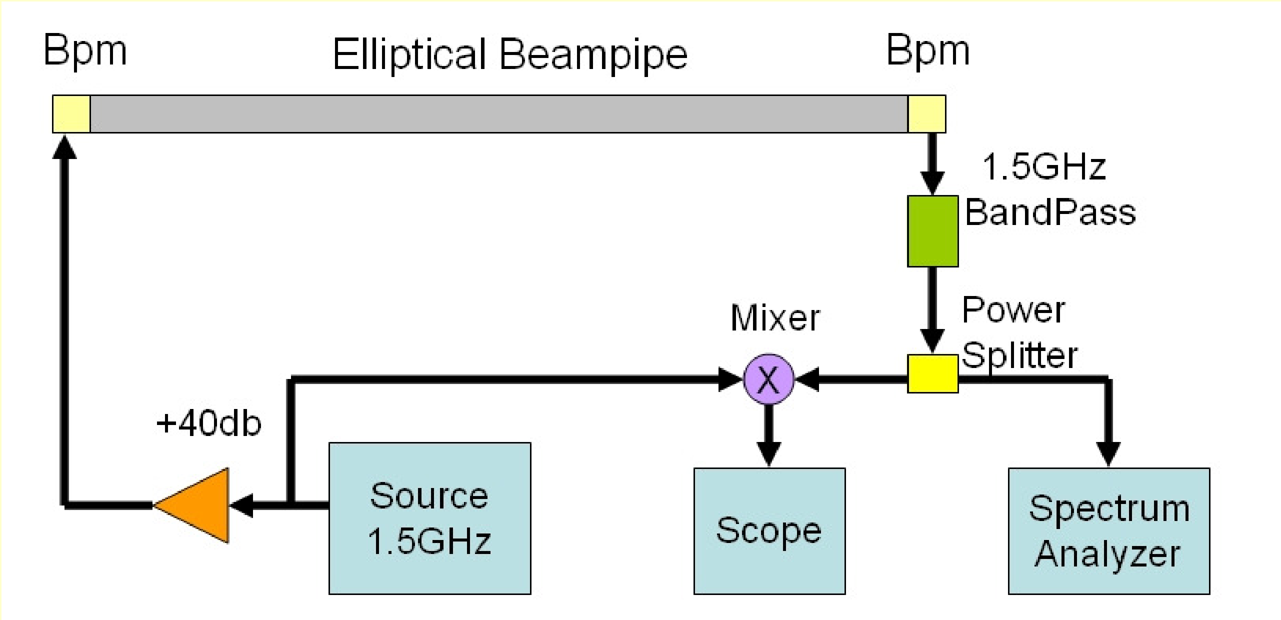


$$k^2 = \frac{\omega^2 - \omega_c^2 - \omega_p^2}{c^2}; \qquad \omega_p^2 = 4\pi \rho_e r_e c^2;$$

- The phase shift depends on the plasma frequency, which depends on the density.
- The phase shift per unit length is given by

$$\frac{\Delta\phi}{\Delta L} \approx \frac{\omega_p^2}{2c\sqrt{(\omega^2 - \omega_c^2)}}$$

Measurement setup and method



- Three different methods
    - Direct phase shift
    - Sideband spectrum
    - Zero span

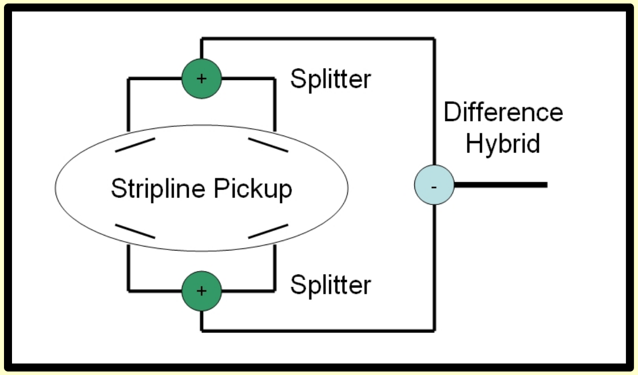
Measurement Techniques

- Sideband spectrum
  - Send a carrier wave (1.5 GHz)
  - Any phase modulation, then would show up as a sideband.
  - Sideband *dbc = 20 log (A/2)*, where A is the amplitude of phase modulation

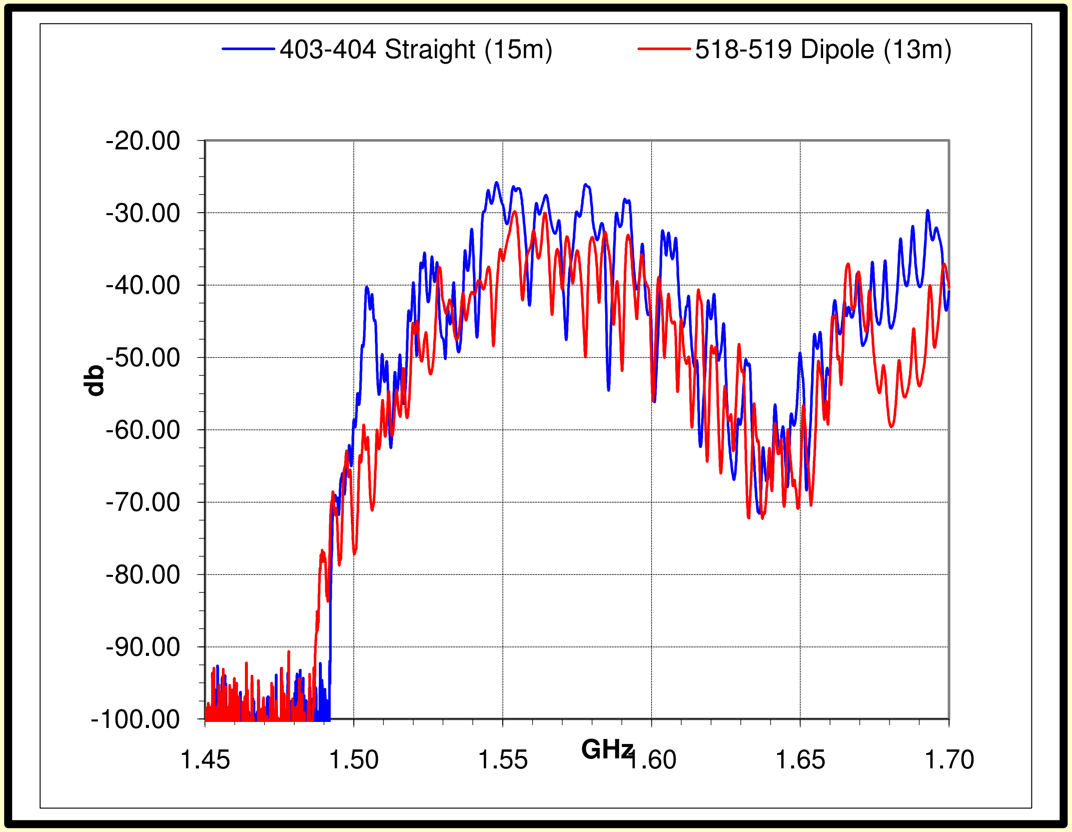
- Zero span
  - Set the spectrum analyzer to the expected sideband frequency
  - Collect data over the full injector cycle.
  - The signal amplitude would show a increase in case of phase modulation

- Direct phase shift
  - "Microwave interferometry"
  - Convert the signal to baseband and record and average out the beam signals over a single machine turn.

Measurement Pickups

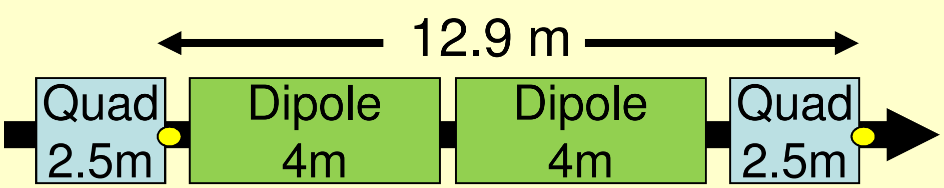


- Pickups are optimized to couple to TE_{11} mode
- Cutoff for the beam pipe just below 1.5 GHz

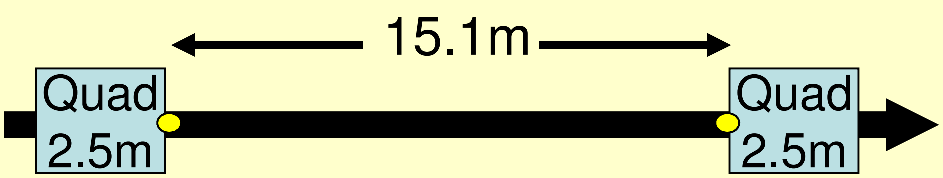


Measurement Location

MI 52 BEND REGION

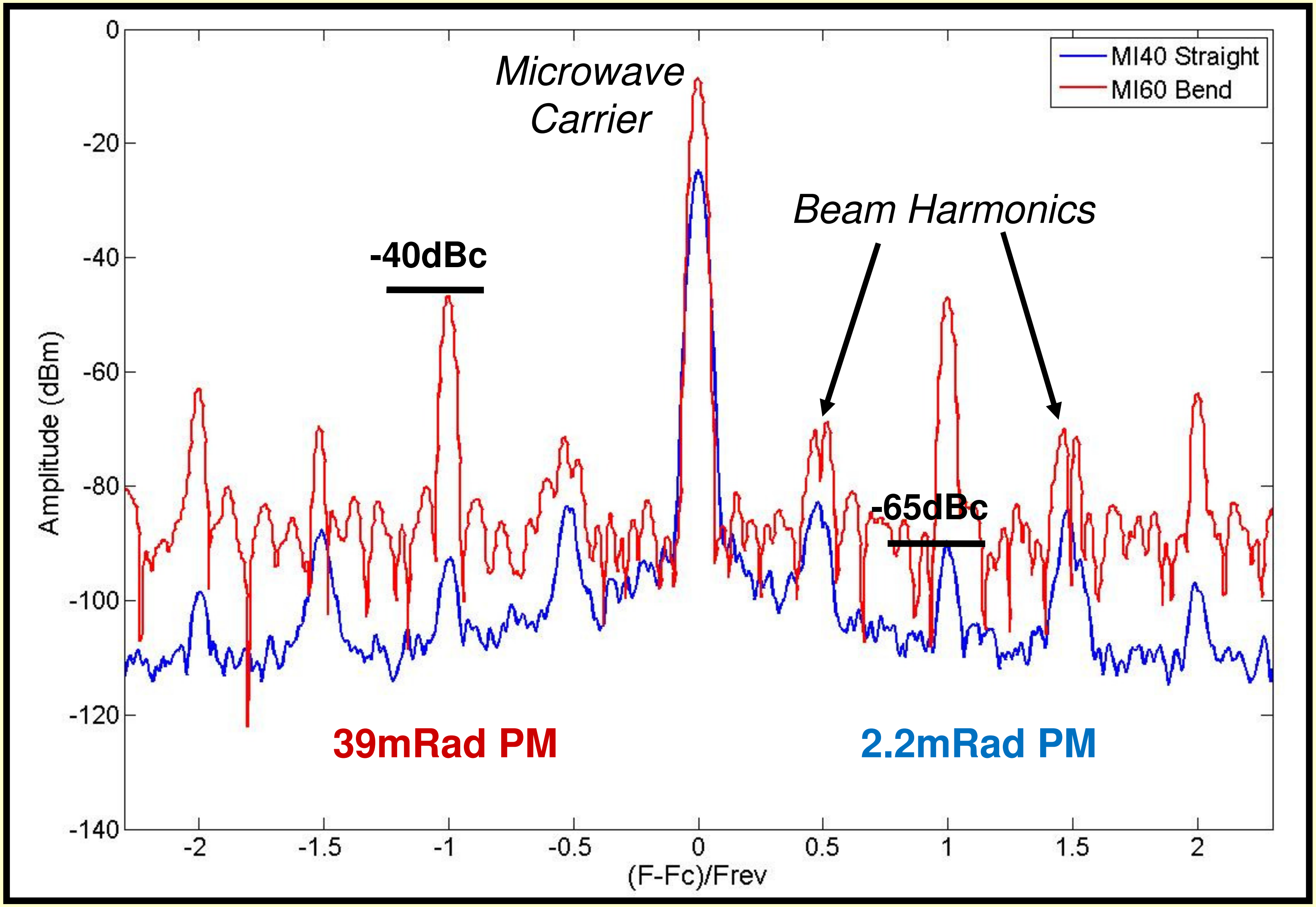


MI 40 BEND REGION

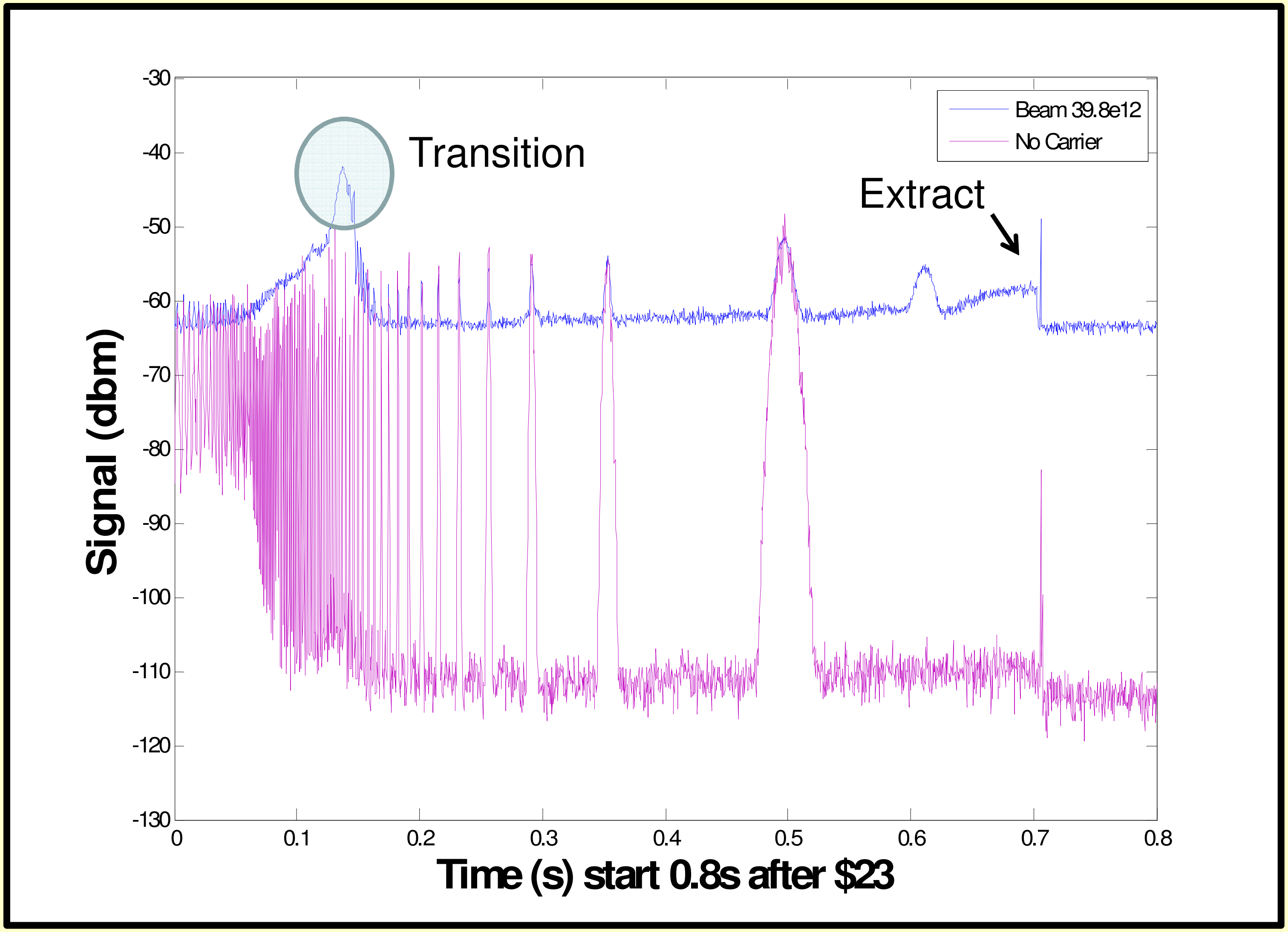


- Standard elliptical beam pipe
- At MI40 no magnetic field
- Heliax cable
- We get reflections…

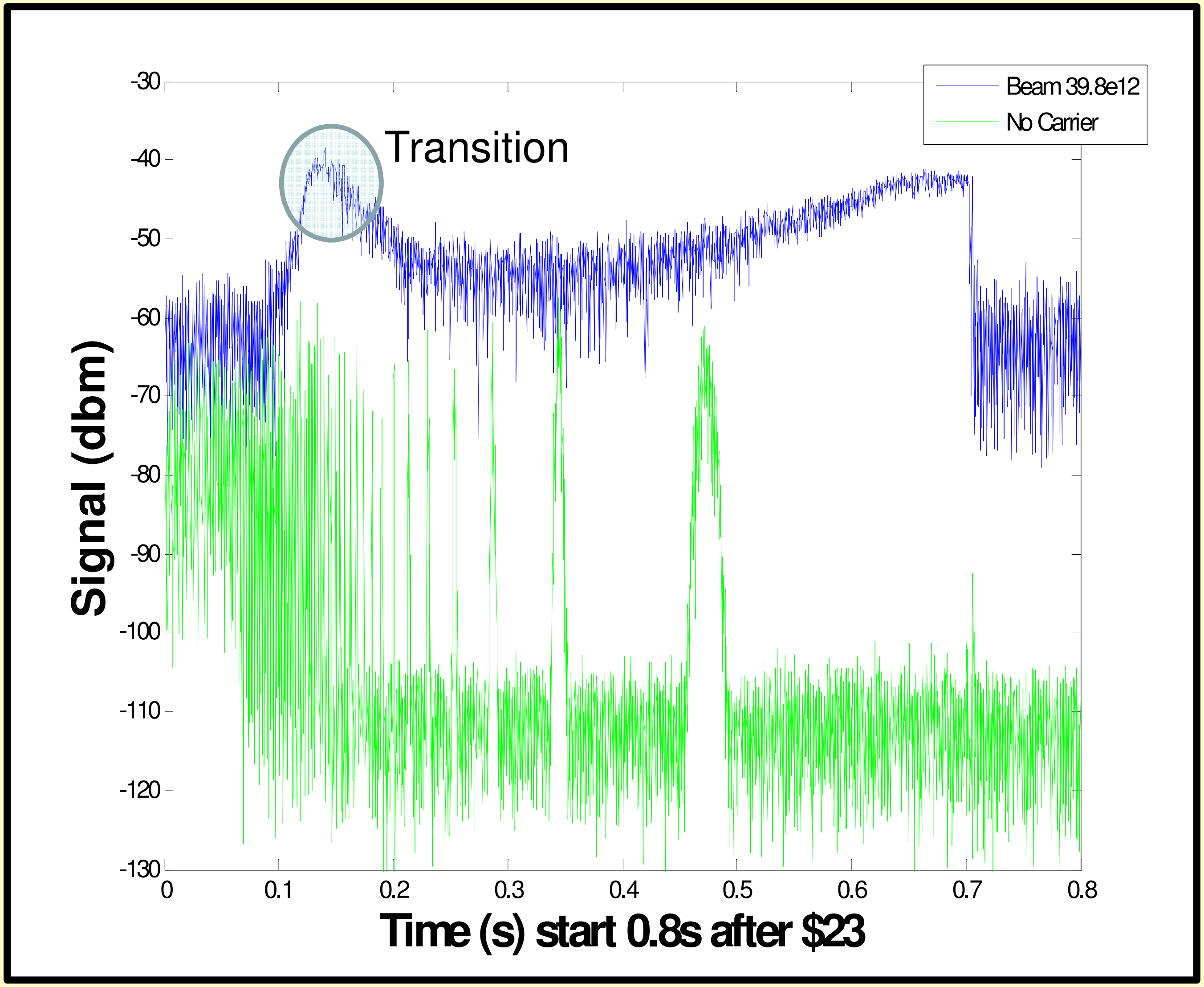
Sideband spectrum measurements



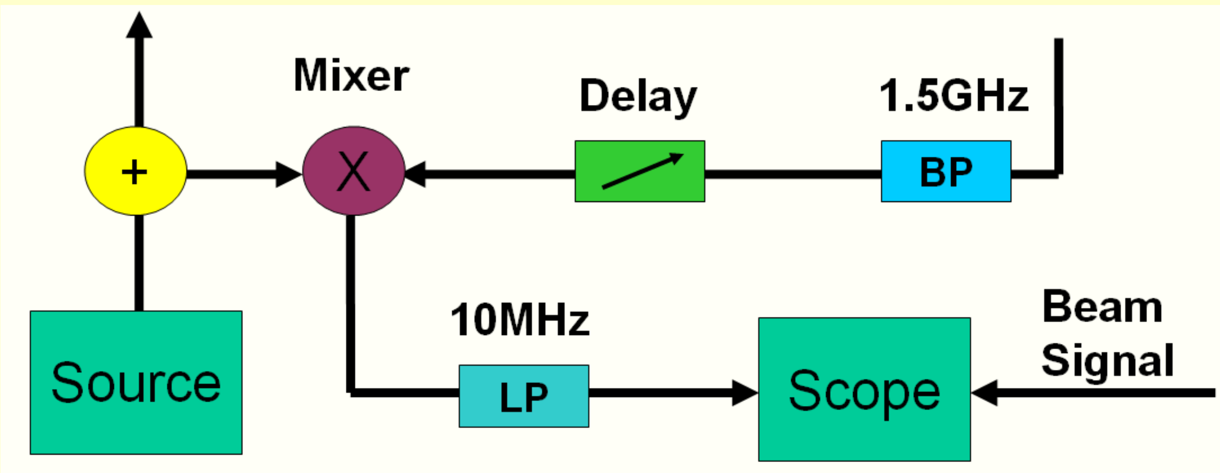
Zero span sideband MI 52 BEND

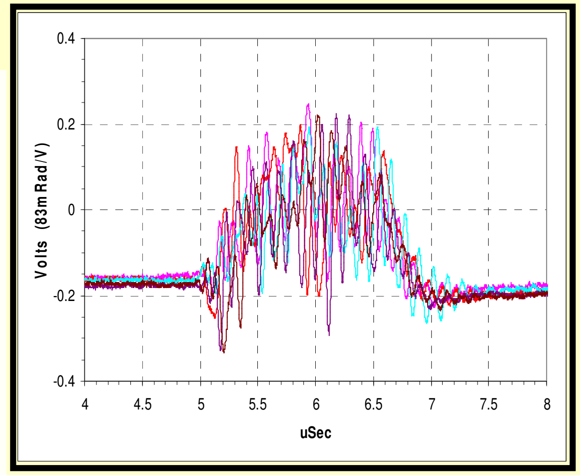


Zero span sideband MI-40 STRAIGHT



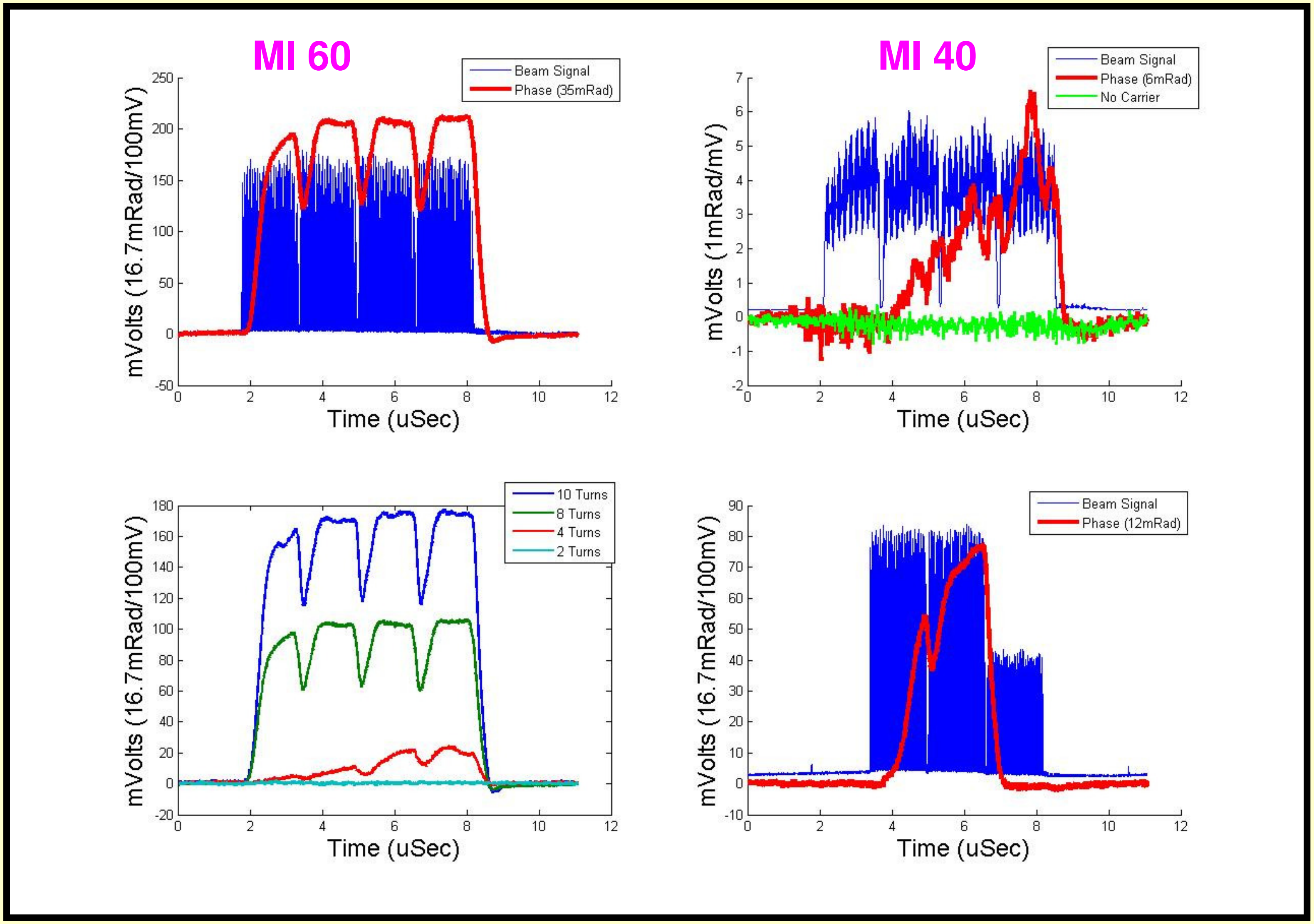
Direct Phase Shift Measurement



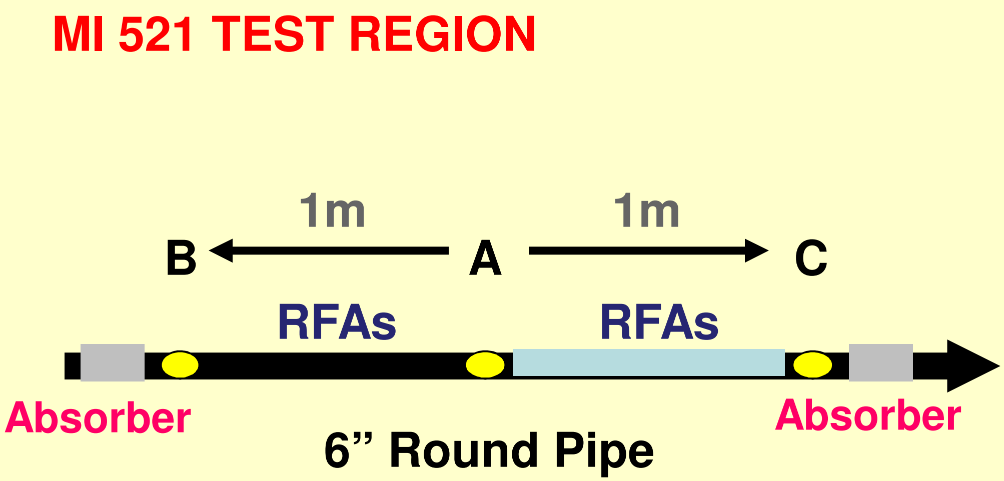


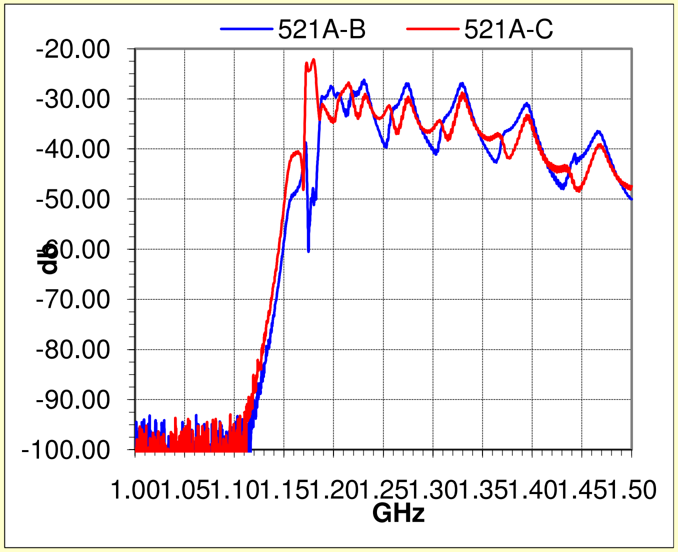
- Down convert the transmitted microwave to baseband
  - Phase shift by 90^0 using delay to cancel input.
  - Turn-by-turn carrier frequency & phase should remain constant
  - Beam harmonics average out after many turns
  - Though the direct beam harmonics are large, the are not correlated with the microwave carrier and so average in time domain

Direct Phase Shift Results



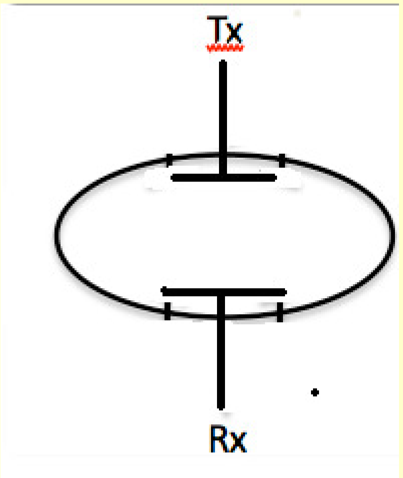
New e-cloud test lattice





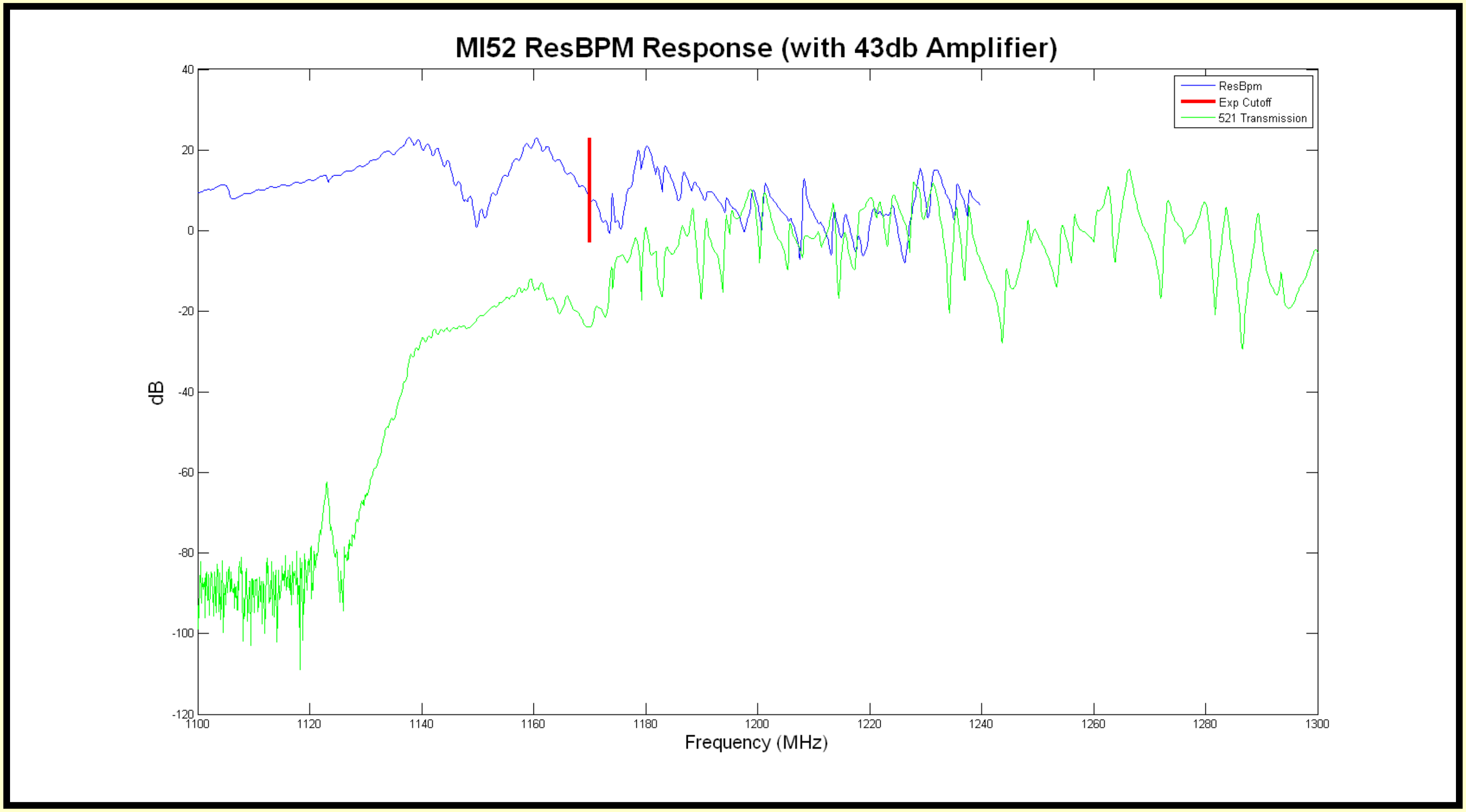
- Round beam pipe
- Short distance (1 m) for propagation
- Comparison with other diagnostics (RFAs)
- Cutoff frequency 1.2 GHz
- The ends of the beam pipe are elliptical and so reflection. a CAVITY!

Resonant BPM

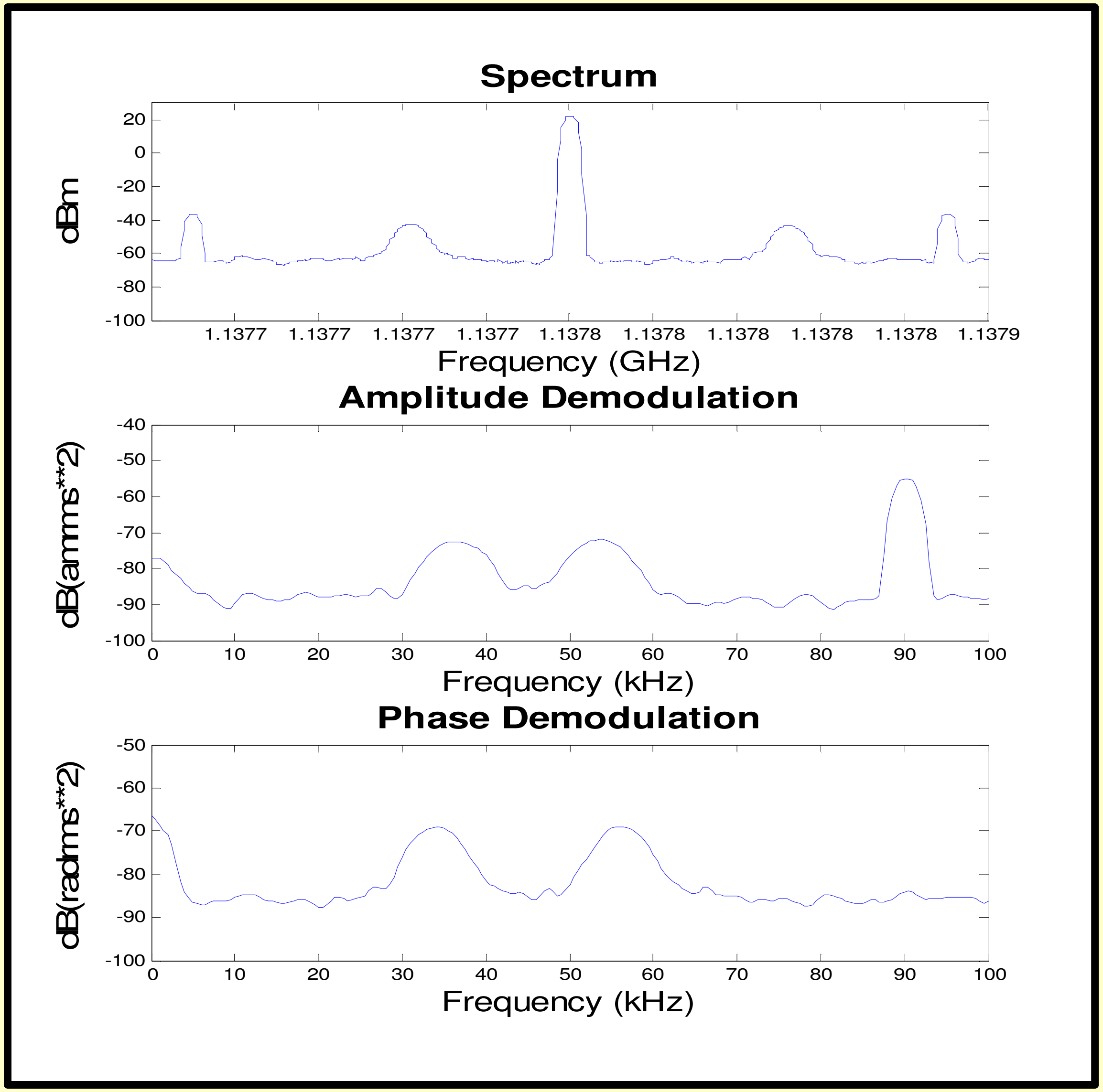


- Immune to reflections
- Carrier frequency just below the cutoff for the trapped mode

Resonant BPM response

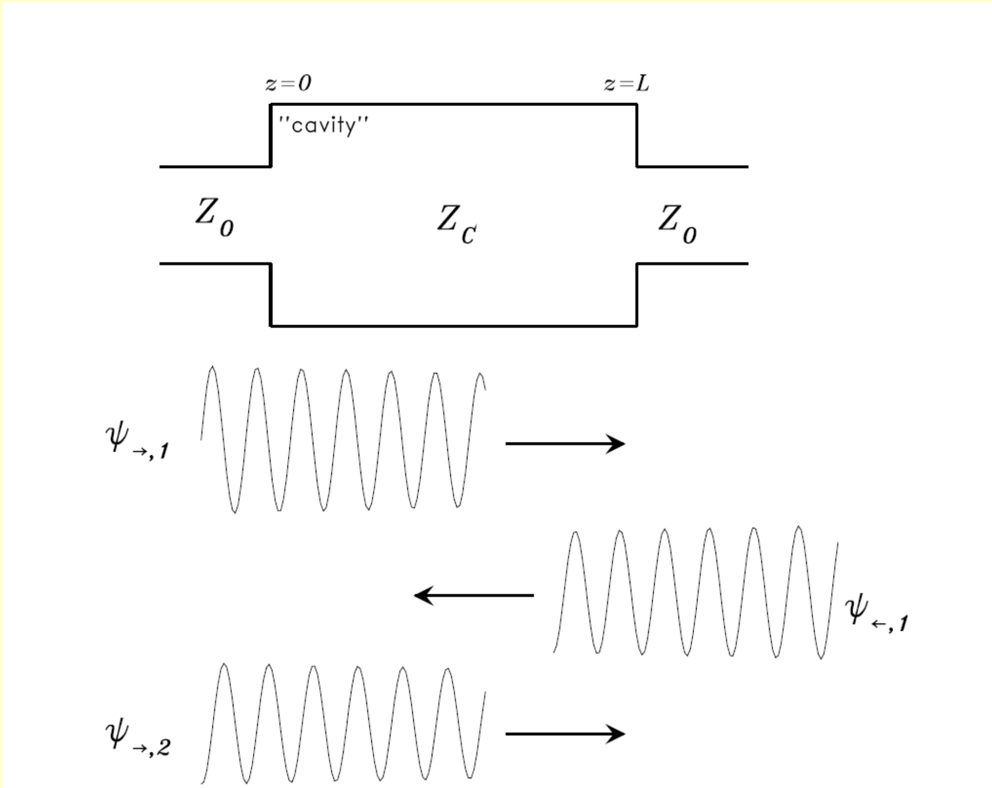


Resonant BPM measurements MI 521



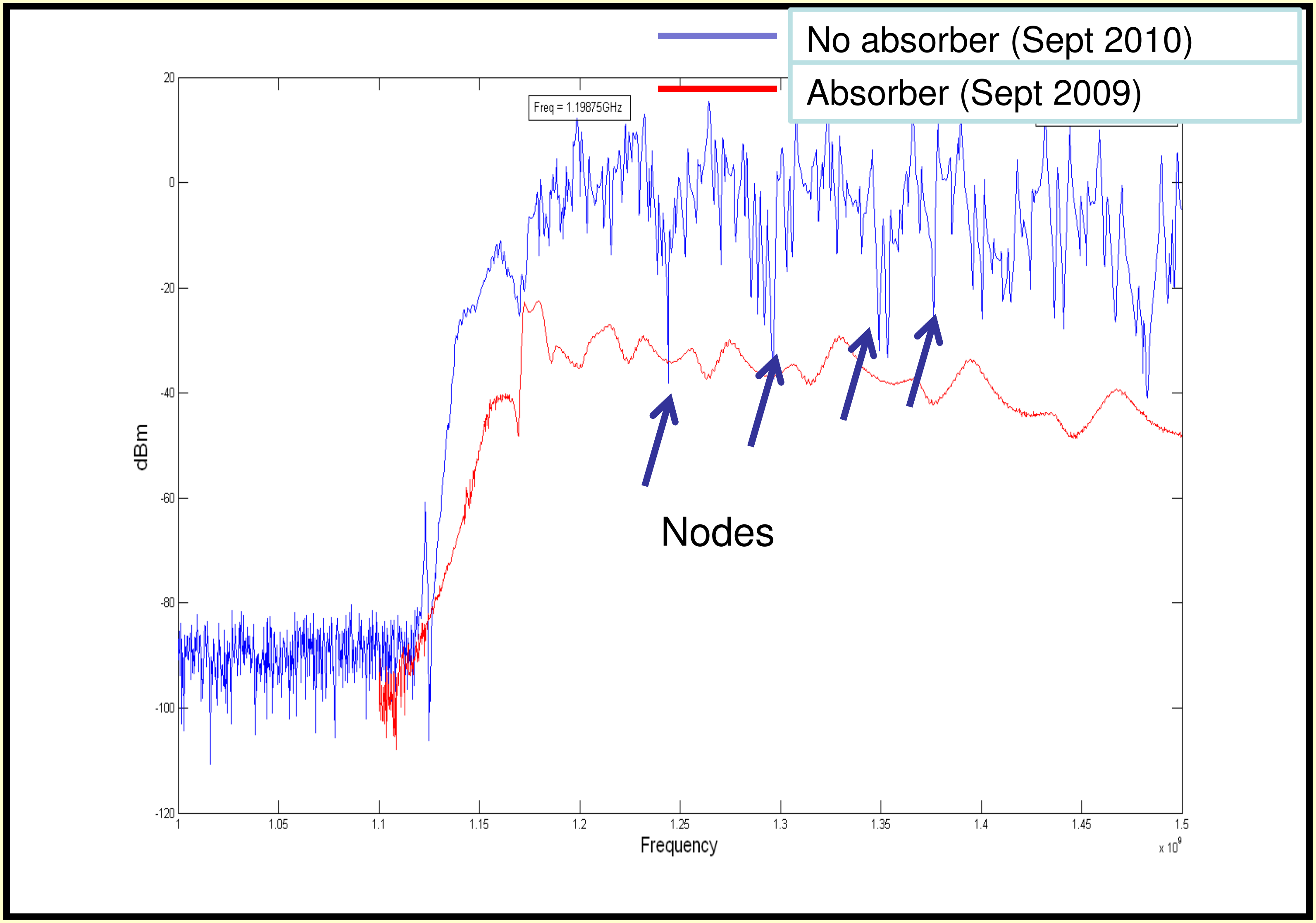
- No phase modulation observed

FNAL reflection method

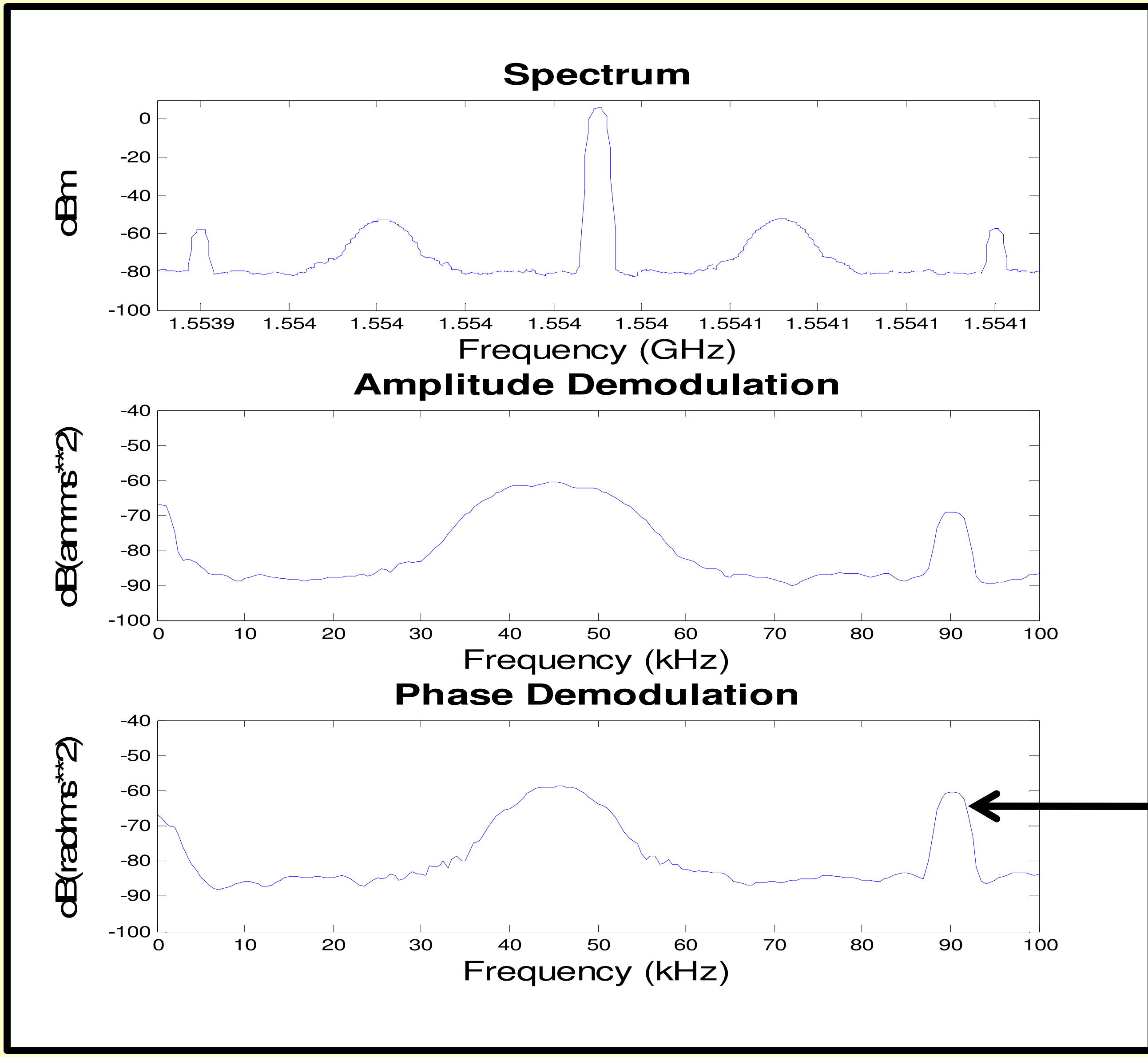


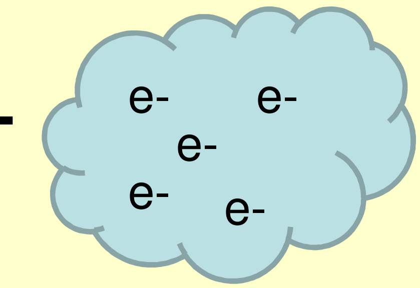
(C. Tan Tech Note FERMILAB)

Transmission with and without absorbers

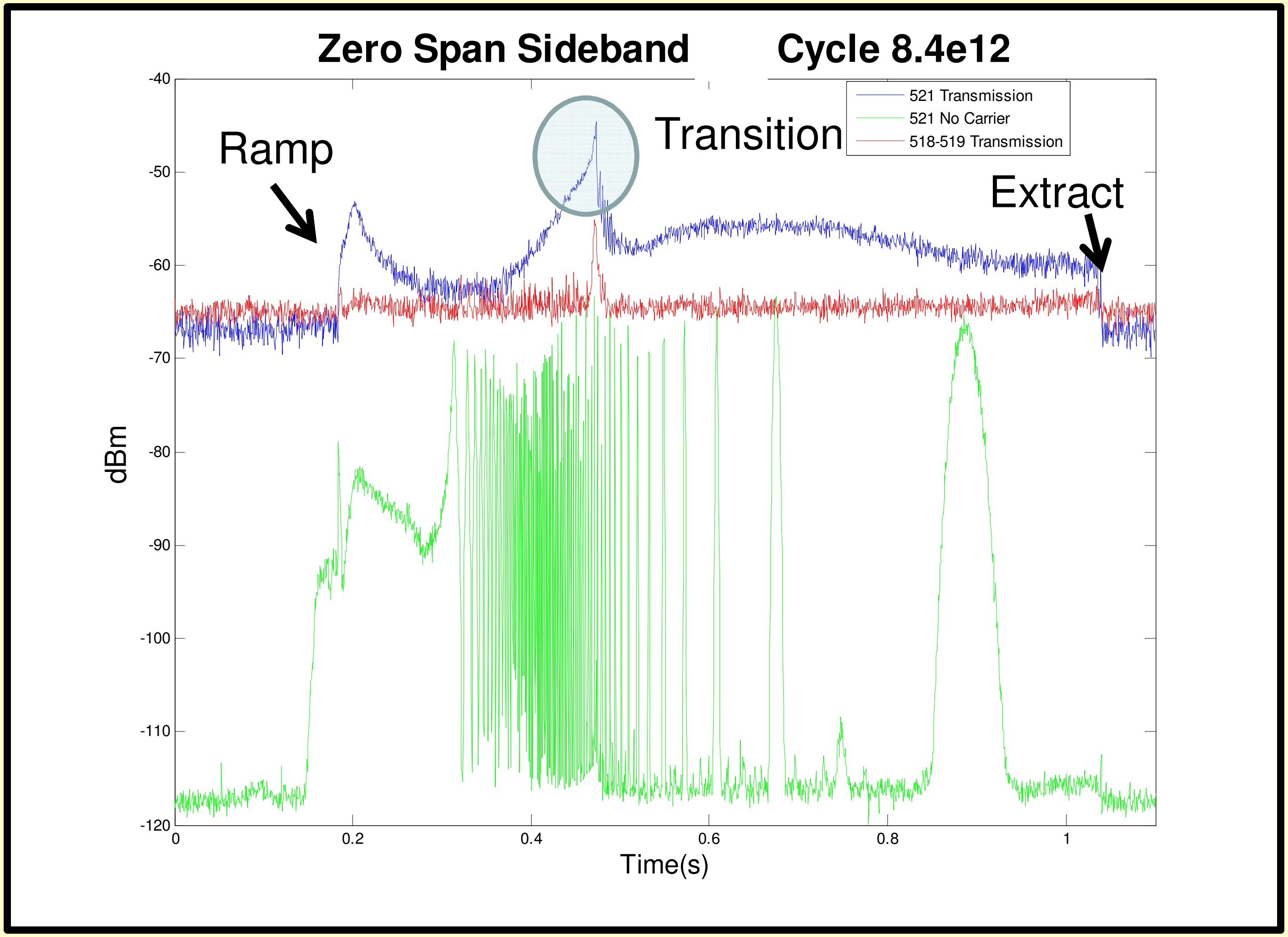


Sideband spectrum measurements MI 521





Zero span sideband MI 521



Laser detection of e-cloud: My two cents

- Can we use a laser to measure e-cloud?
  - Challenge: very small phase shift
    Solution : Cavity type interferometry
  - Could be sent through a dipole for measuring polarization changes?
  - Could also be used to construct spatial profile

Summary

- Evidence of e-cloud at different locations established by three different methods
- Challenges remain: Non-homogenous e-cloud, magnetic fields, reflections
- We plan to redo the resonant BPM technique and start on a small scale testing new detection of e-clouds

Thank you

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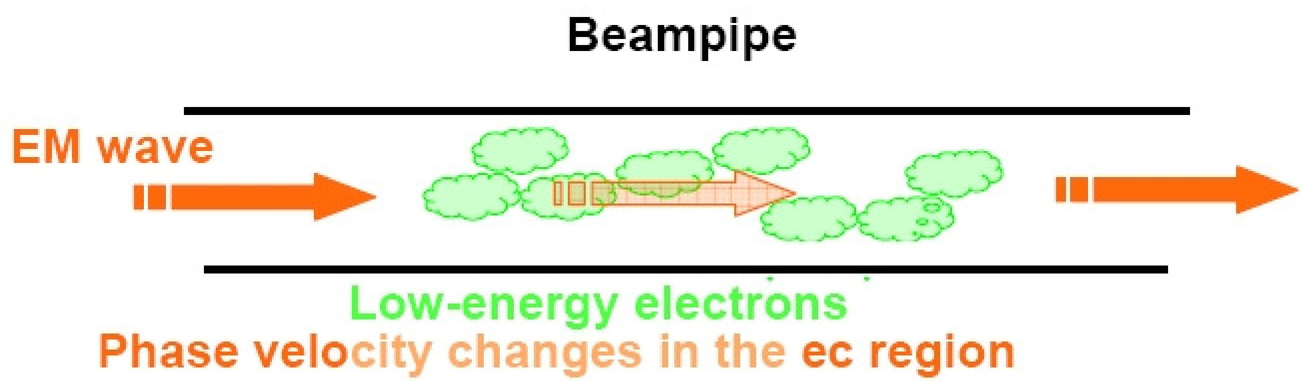
Status of Microwave Measurements in the Main Injector

Nathan Eddy

EC Meeting

Oct 22, 2009

Microwave Transmission Theory



$$\Delta\phi = [\sqrt{(\omega^2 - \omega_c^2)} - \sqrt{(\omega^2 - \omega_c^2 - \omega_p^2)}]\frac{\Delta L}{c}$$

From plasma physics, expect a microwave travelling down a waveguide to experience a phase shift due to a homogeneous plasma

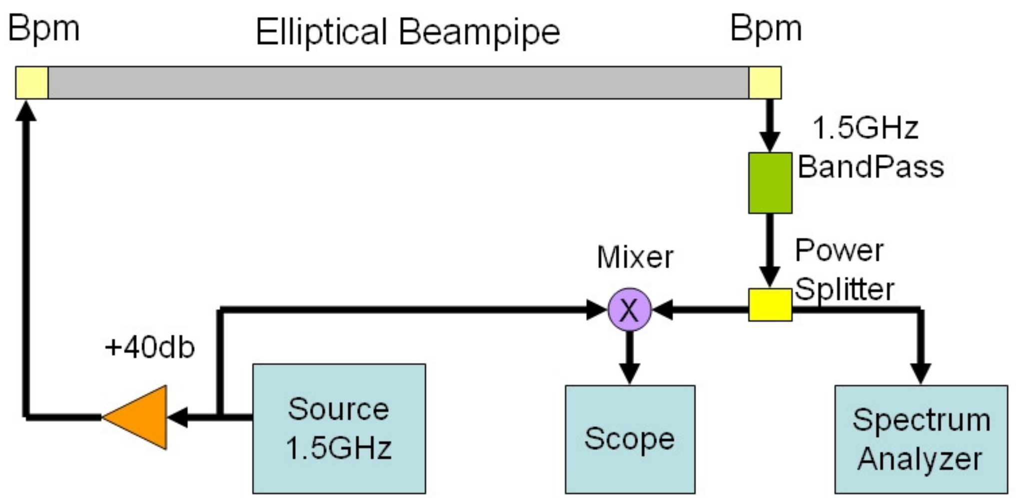
From the microwave dispersion relation

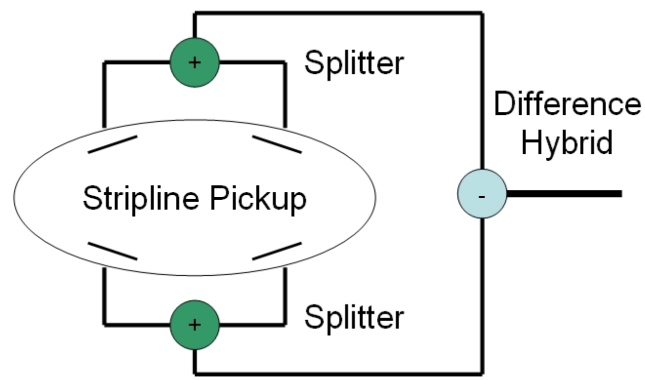
$$\frac{\Delta\phi}{\Delta L} \approx \frac{\omega_p^2}{2c\sqrt{(\omega^2 - \omega_c^2)}} \Rightarrow \frac{\Delta\phi}{l} = \frac{\omega_p^2}{2c\sqrt{\omega^2 - \omega_c^2}}$$

$$\frac{\pi}{2}$$

For an electron cloud $\omega_p^2 = 4\pi\rho_e r_e c^2$ is proportional to *e* density

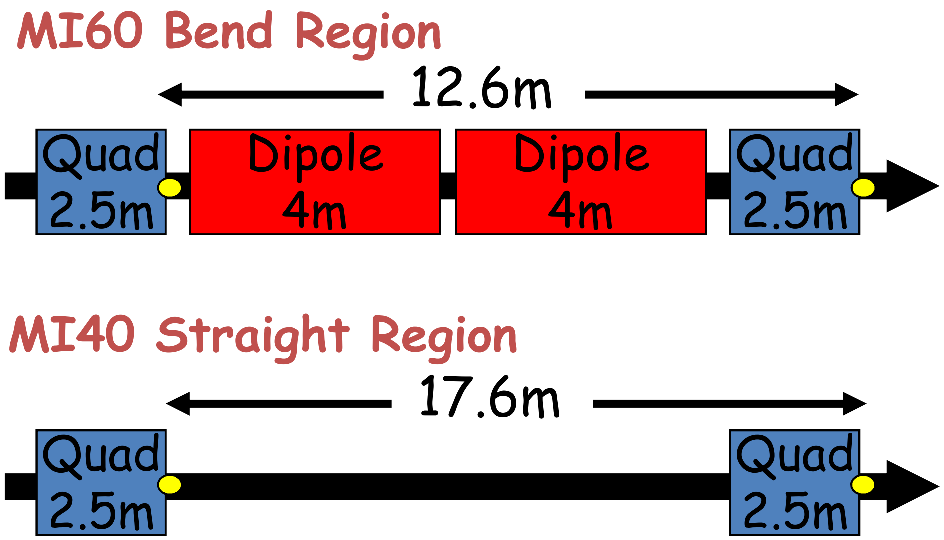
Measurement Setup

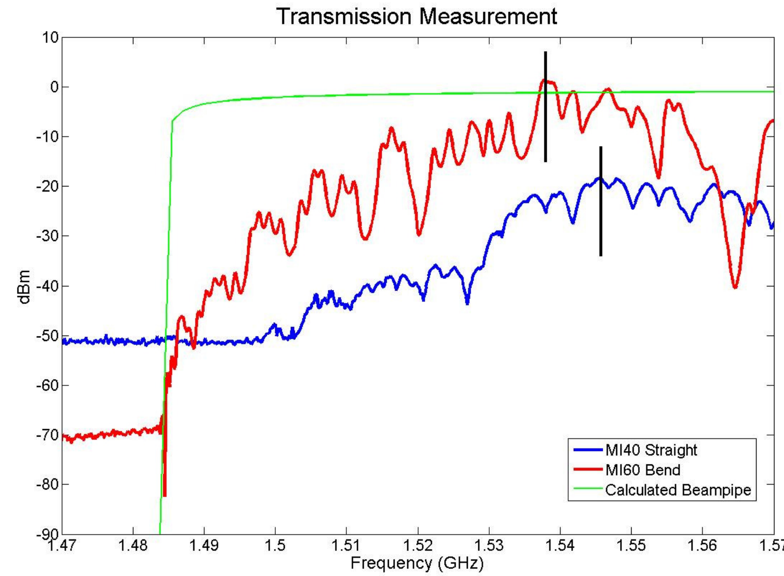




- Made three different measurements of the phase shift
  - Measure sideband spectrum of 1.5GHz carrier with SA
  - For phase modulation of amplitude β, sideband dbc = $20\log(\beta/2)$
  - Measure 1st sideband over a full MI ramp (800ms) in zero span mode with SA
  - Mix down to baseband and record IF with deep memory scope (10MHz BW)
- Pickup connections to optimize coupling to TE_{11} mode
  - Measure -20db transmission for two pickups and 15m of beam pipe
  - Cutoff for beam pipe is just below 1.5GHz

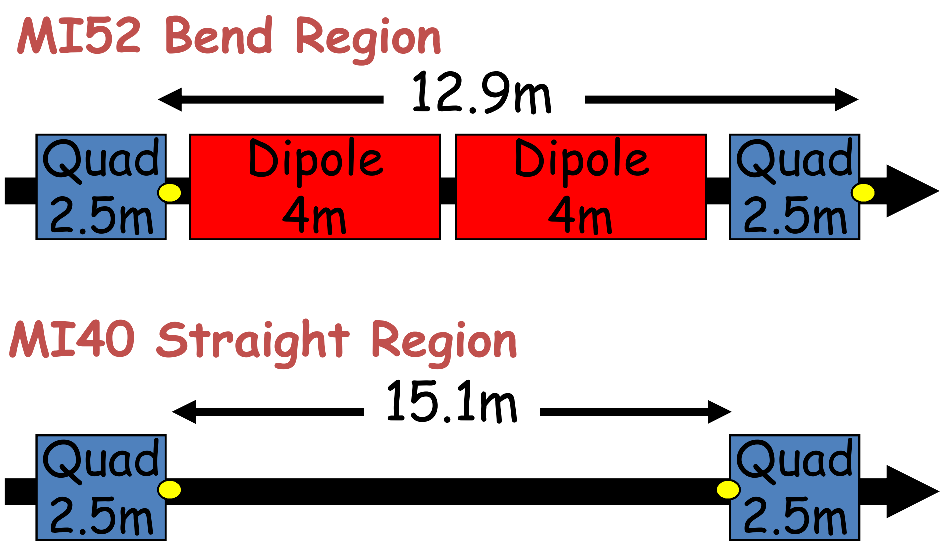
Previous Measurement Locations

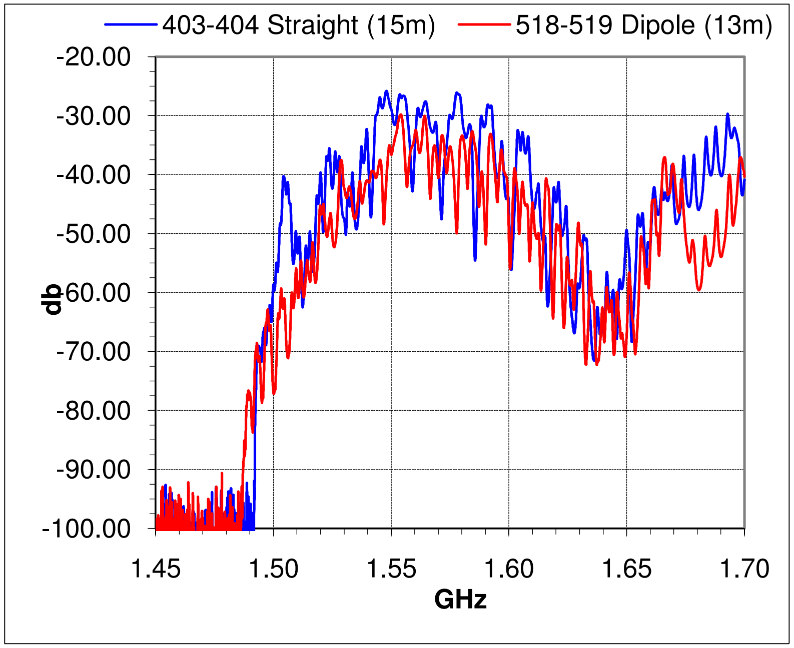




- At MI60 Bend Region able to use spare Heliax cable
- At MI40 Straight Region have to use RG8 bpm cable
  - See an addition 20db of attenuation on transmitted signal
  - Appear to get coupling between the cables
  - Put the 40db drive amplifier in the tunnel at this location

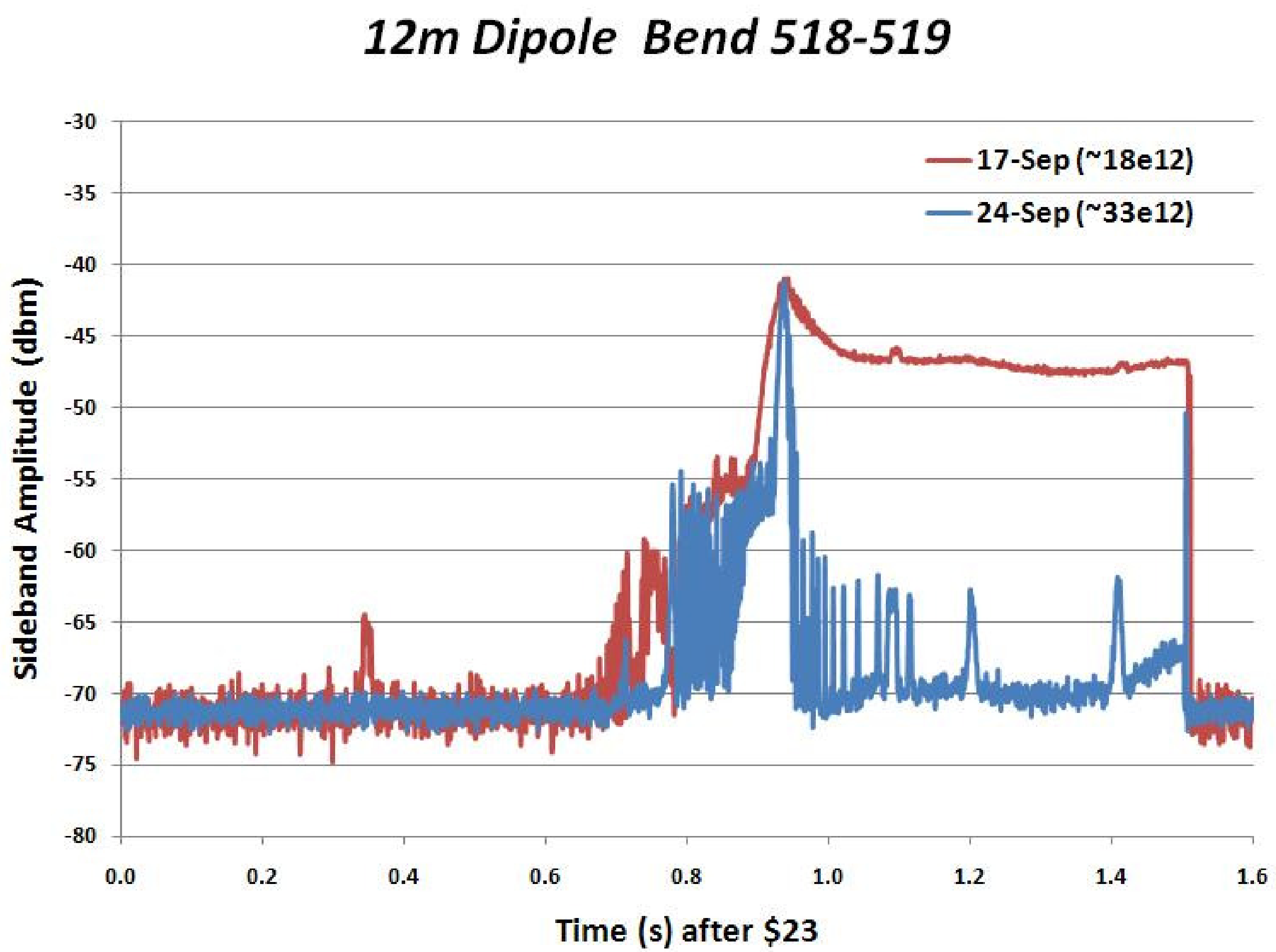
New Dedicated Pickups





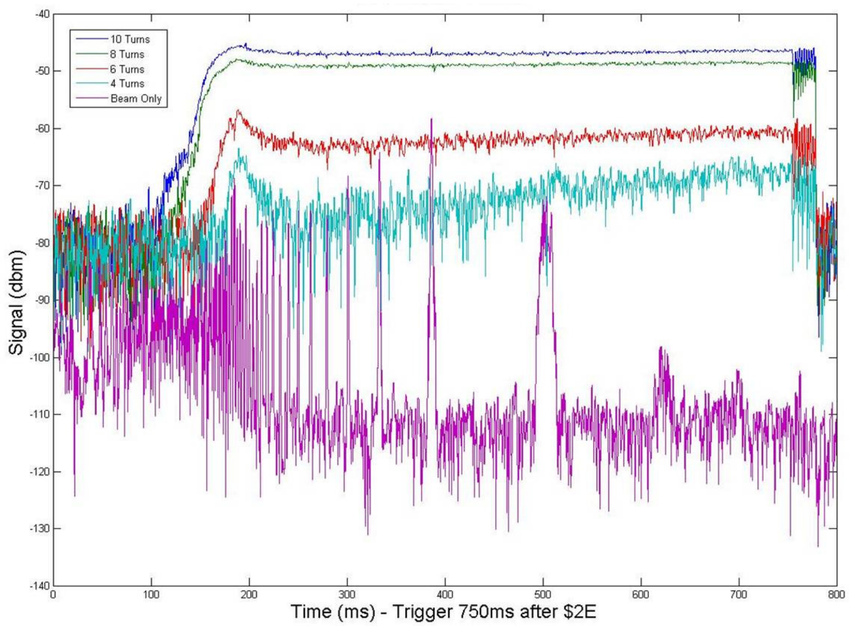
- Dedicated BPMs installed at MI52 Bend and MI40 Straight
  - Standard elliptical beam pipe and pickups
  - Completely field free at MI40 straight
- Good quality heliax cable pulled for each BPM
  - Expect improved sensitivity for MI40 Straight

Zero Span Sideband in Dipole at MI52

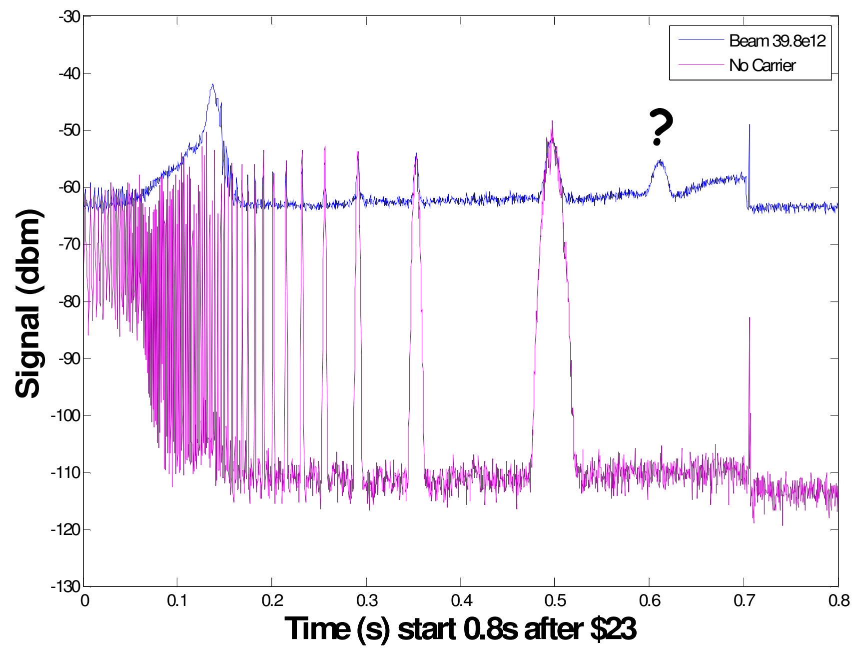


Zero Span Sideband in Dipole

MI60 Bend



MI52 Bend

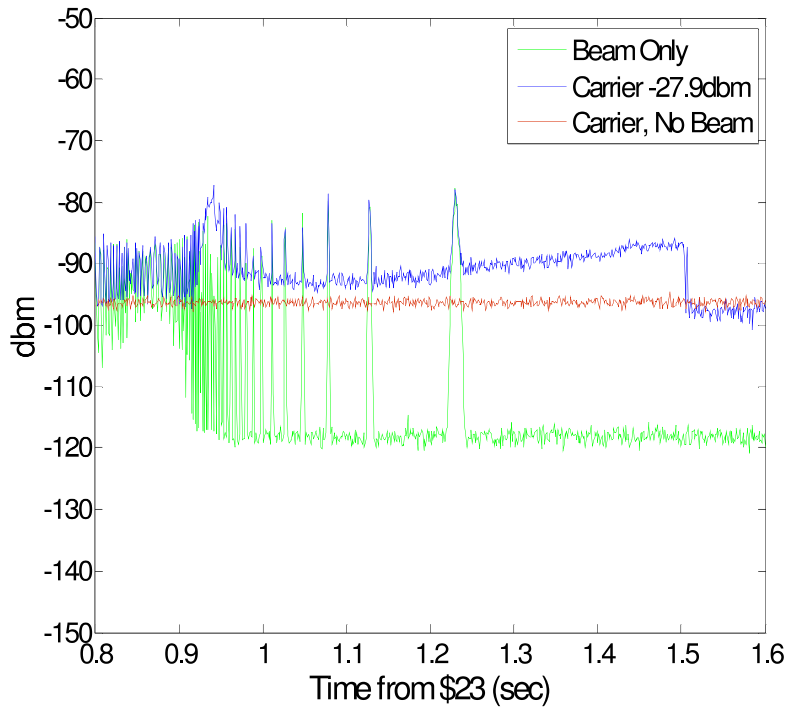


MI60 was measured from 532 to 601, MI52 from 518 to 519
Drastically different response is not understood

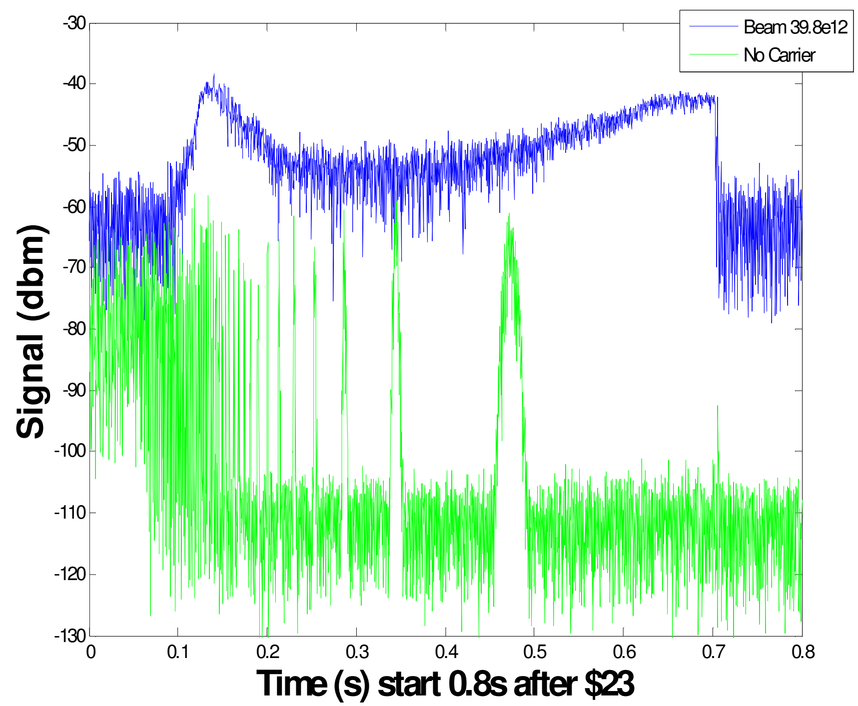
- Beam Conditions or Location Dependency (Lattice)
- Propose remeasuring MI60 if possible

Zero Span Sideband in Straight

MI40 Before

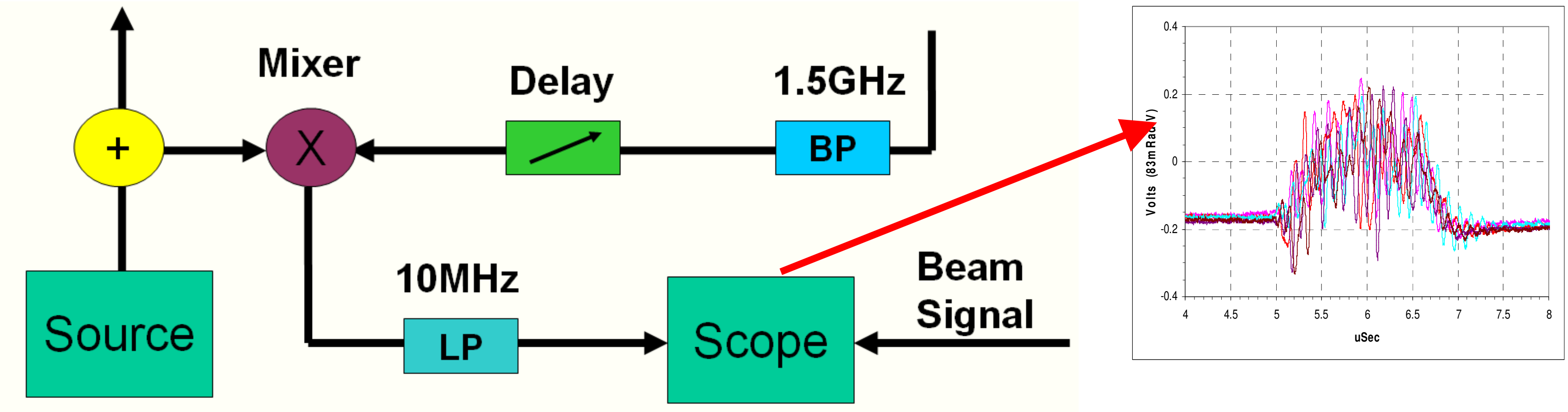


MI40 Now



Difference due to improved signal from better cables
See roughly same behavior

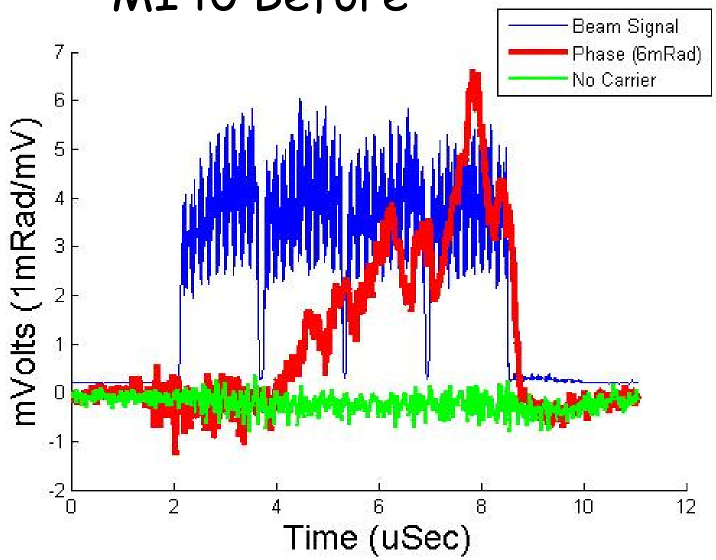
Direct Phase Shift Measurement



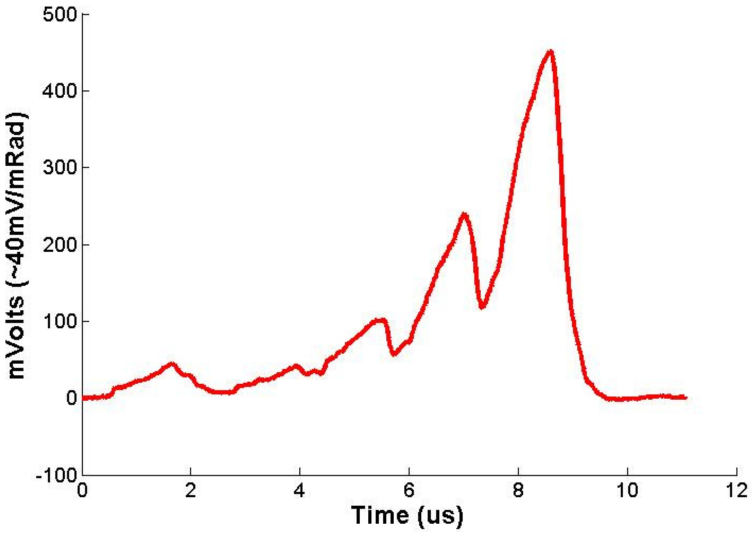
- Mix the transmitted microwave signal to baseband
  - Use the delay to effect 90° phase shift (zero DC offset)
  - Theoritically, should only see PM modulation as AM cancels
- Scope aquires from 2ms to 20ms sampling at either 500MS/s or 100MS/s respectively
  - Expect eCloud induced phase shift to be the same each turn
  - The beam harmonics behave as noise which averages away
    - Use 100 turn average at MI60 and 1700 turns at MI40
  - Size of the beam harmonics impacts the dynamic range

Direct Phase Shift Results

MI40 Before



MI40 Now

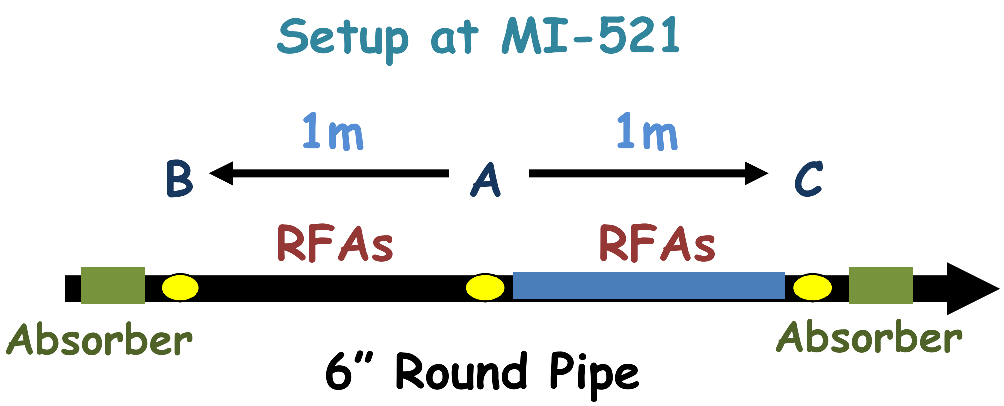


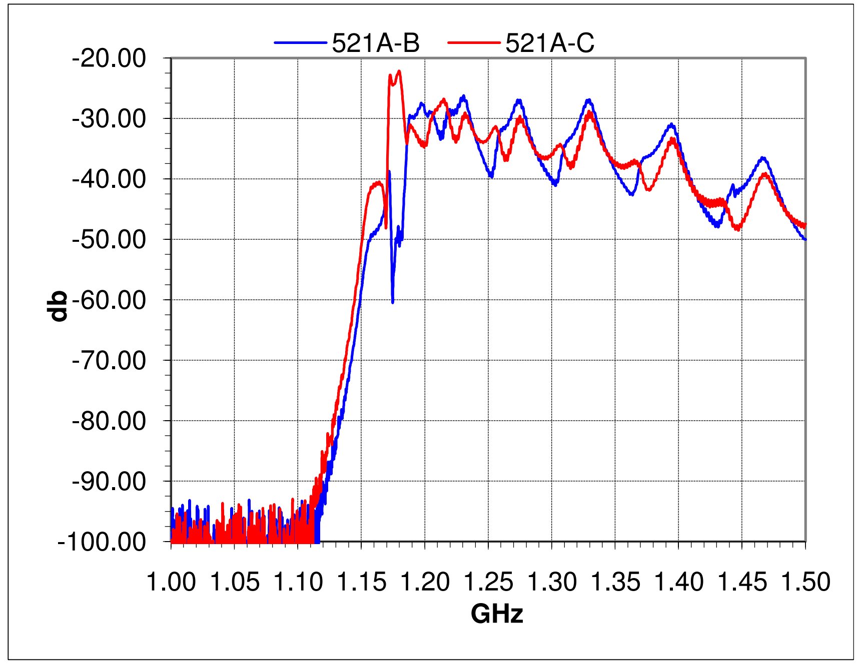
Need to calibrate response for current measurements

mV/mRad good to ~3

Again see reasonable agreement

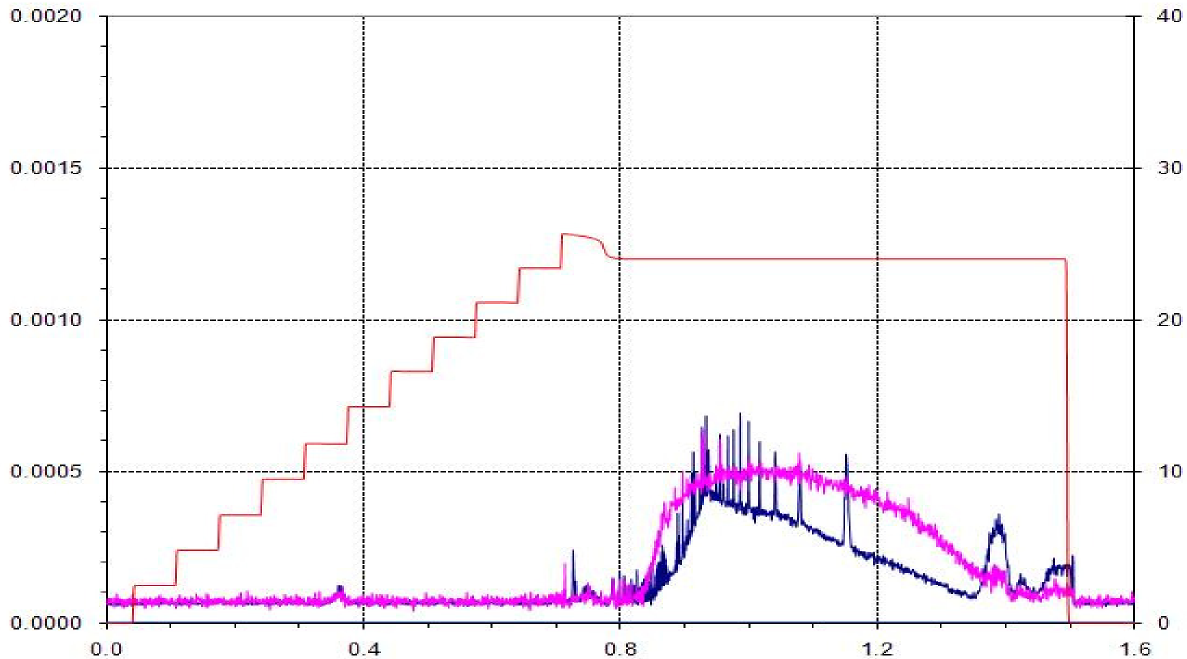
Coated Pipe/RFA Comparison





- Three Large Aperture BPMs have been installed around 1m long test pipes at MI-521
  - Cutoff for the 6" round pipe is just below 1.2GHz
  - As measured phase shift is proportional to length ⇒ -23db sensitivity
- Will provide direct comparison with RFA
  - Expect to be very useful in understanding $\Delta\varphi$ ⇒ *e* density

Initial Response at 521



Initially saw response during first beam (~20e10)
Have not seen any signal since > 30e10
Resonant measurement?

Summary

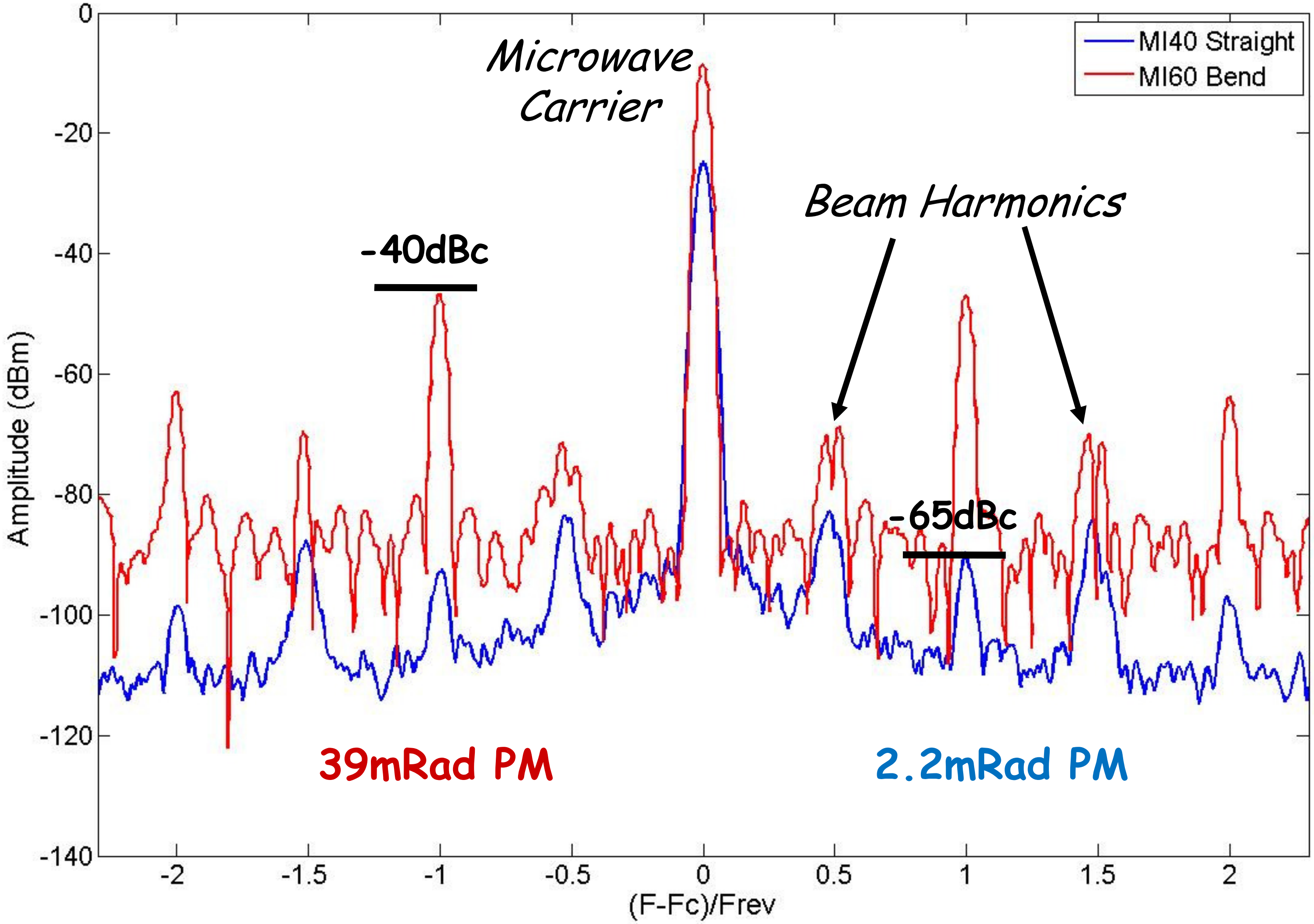
- Demodulate transmitted signal to separate PM & AM
  – Verified we are observing Phase Modulation
  – Verified expectation of no Amplitude Modulation

- Current response in MI52 dipole is not understood
  – Would be nice to remeasure at MI60

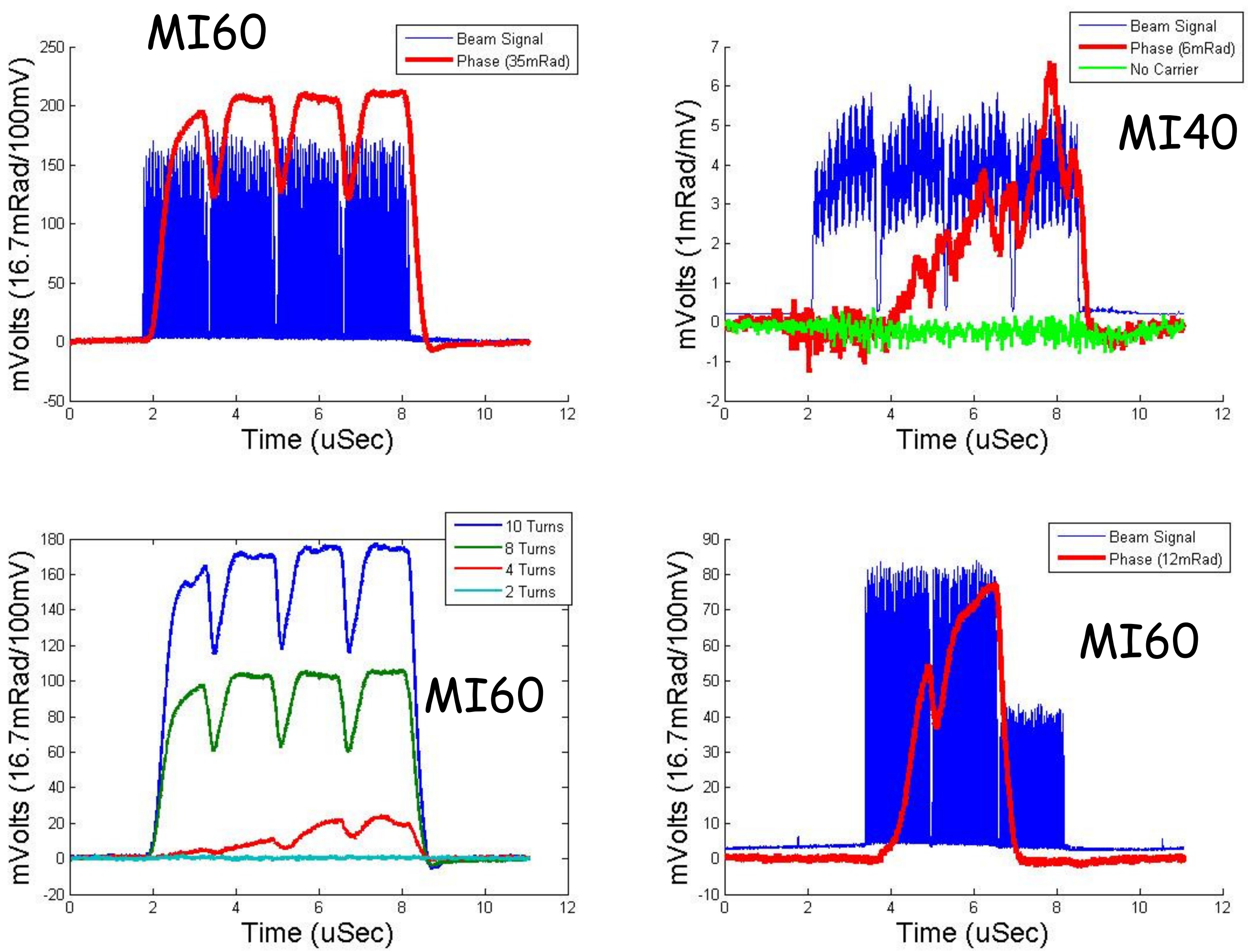
- Results from MI40 straight are as expected

- Calibrate phase shift to electron density
  – Comparison with RFA measurements
  – Comparison with simulation results

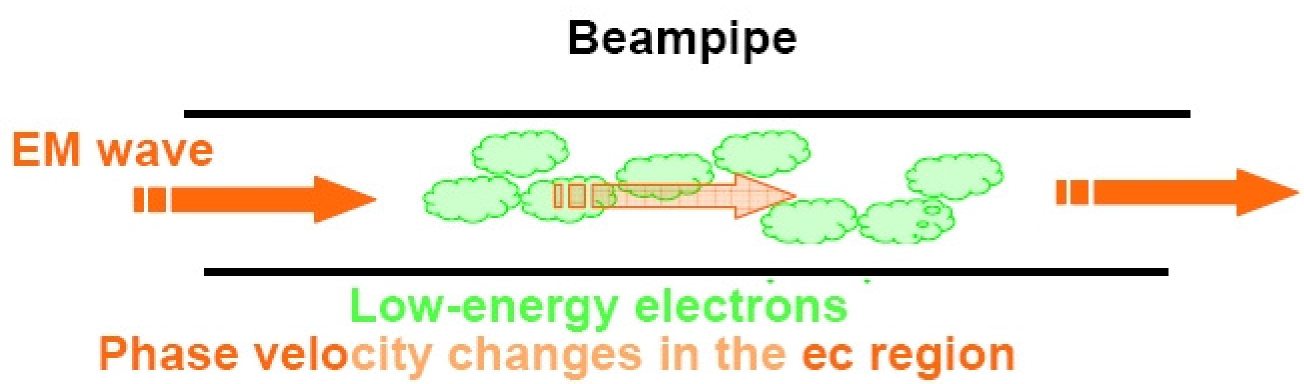
Sideband Spectrum Measurement



Direct Phase Shift Results



Simple Model for Transmission



From plasma physics, expect a microwave travelling down a waveguide to experience a phase shift due to a homogeneous plasma
From the microwave dispersion relation

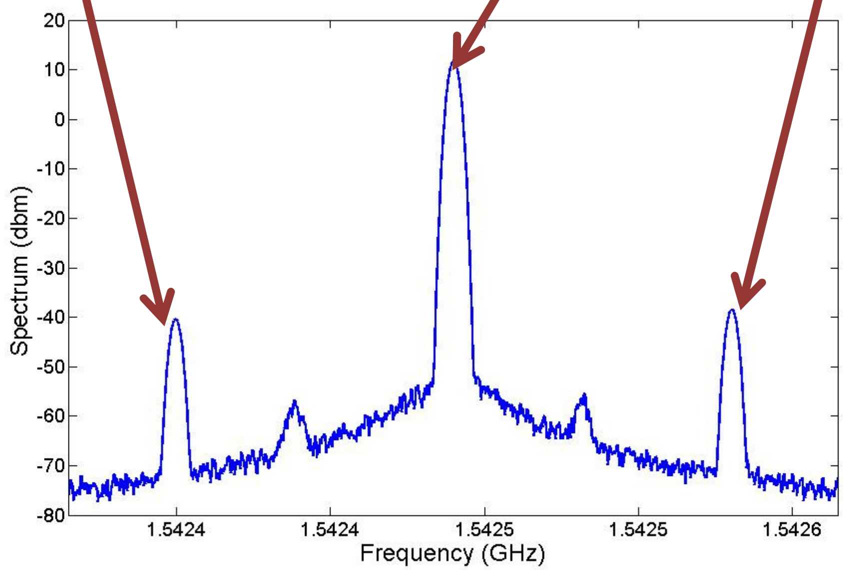
$$k^2 = \frac{\omega^2 - \omega_c^2 - \omega_p^2}{c^2} \Rightarrow \frac{\Delta\phi}{l} = \frac{\omega_p^2}{2c\sqrt{\omega^2 - \omega_c^2}}$$

For an electron cloud $\omega_p^2 = 4\pi\rho_e r_e c^2$ is proportional to *e* density

Phase Modulation Measurement

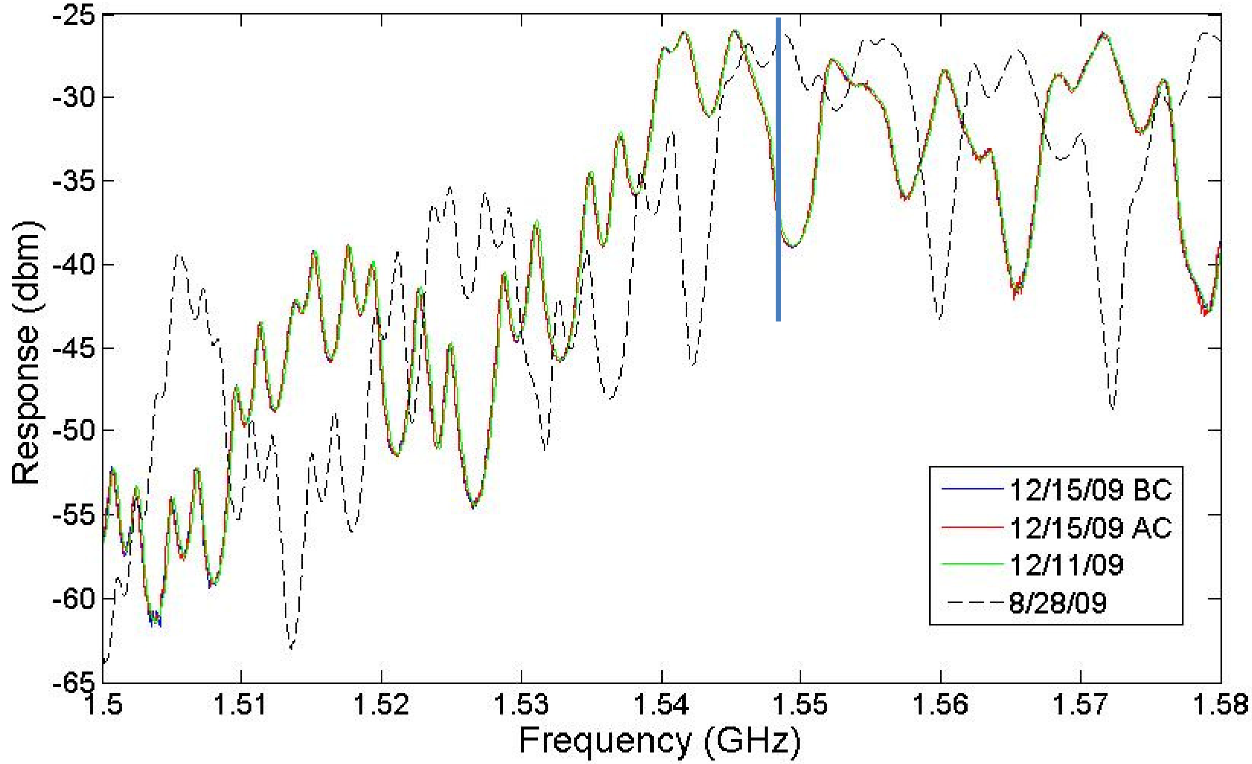
$$e(t) = A\cos(\omega_c t + \beta \sin(\omega_m t + \phi_m))$$

$$e(t) \approx A\left[-\frac{\beta}{2}\cos((\omega_c - \omega_m)t - \phi_m) + \cos\omega_c t + \frac{\beta}{2}\cos((\omega_c + \omega_m)t + \phi_m)\right]$$



=> Dbc – db wrt carrier is proportional to pm amplitude

MI40 S21 Measurements



Beam measurements on 9/24/09 show opposite change!

see +3db change on carrier transmission at 1.547871GHz

Found N-connector upstairs mistreaded – fixing did not change response

perhaps was effecting earlier measurements?

Any changes to beamline in this region?

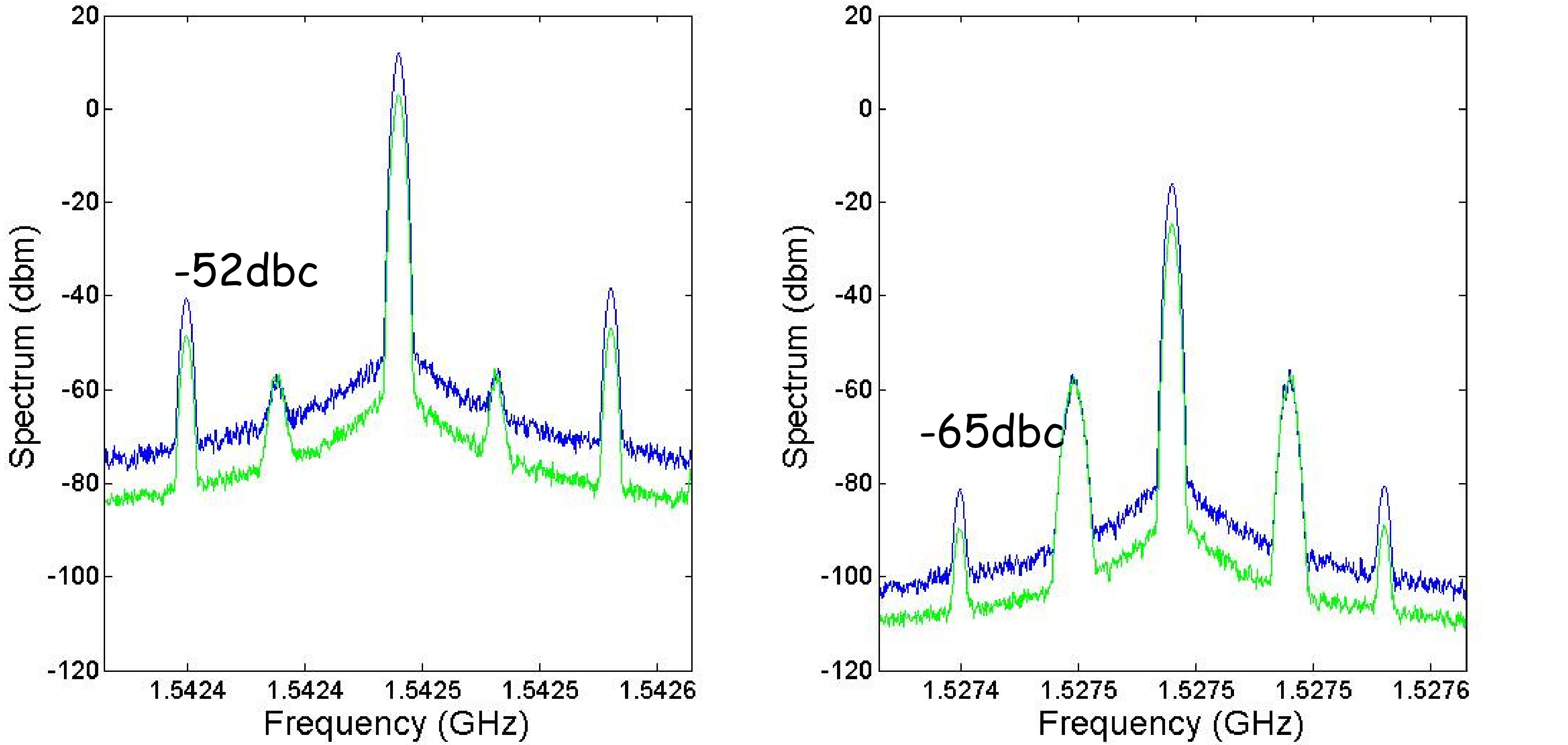
Perhaps beam valve was closed in August? -> remeasure with valve closed

Do not see any change at MI52…

Are Reflections an Issue?

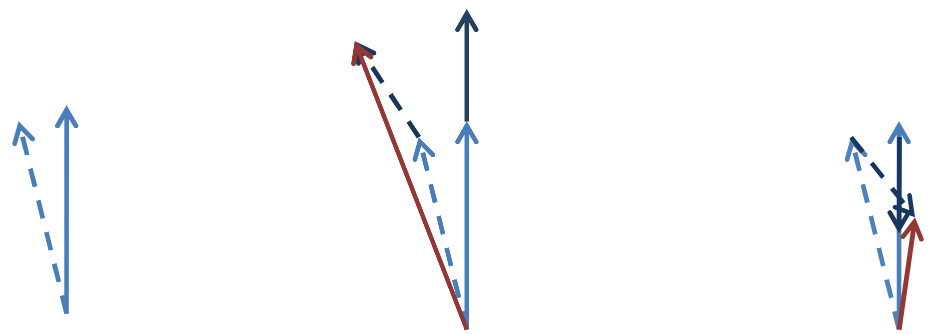
- Attempted to look at step/pulse response but very difficult to interpret without very fast/short pulse
- Structure of S21 measurement suggests complicated system
  - Do not expect observed structure from simple waveguide and bpm response
- Idea to look at PM measurements at different frequencies

PM Measurements



Change of 13db or about a factor of 4 in phase shift
Concrete evidence we do not have simple transmission

Oversimplified Examples



No Interference

Constructive

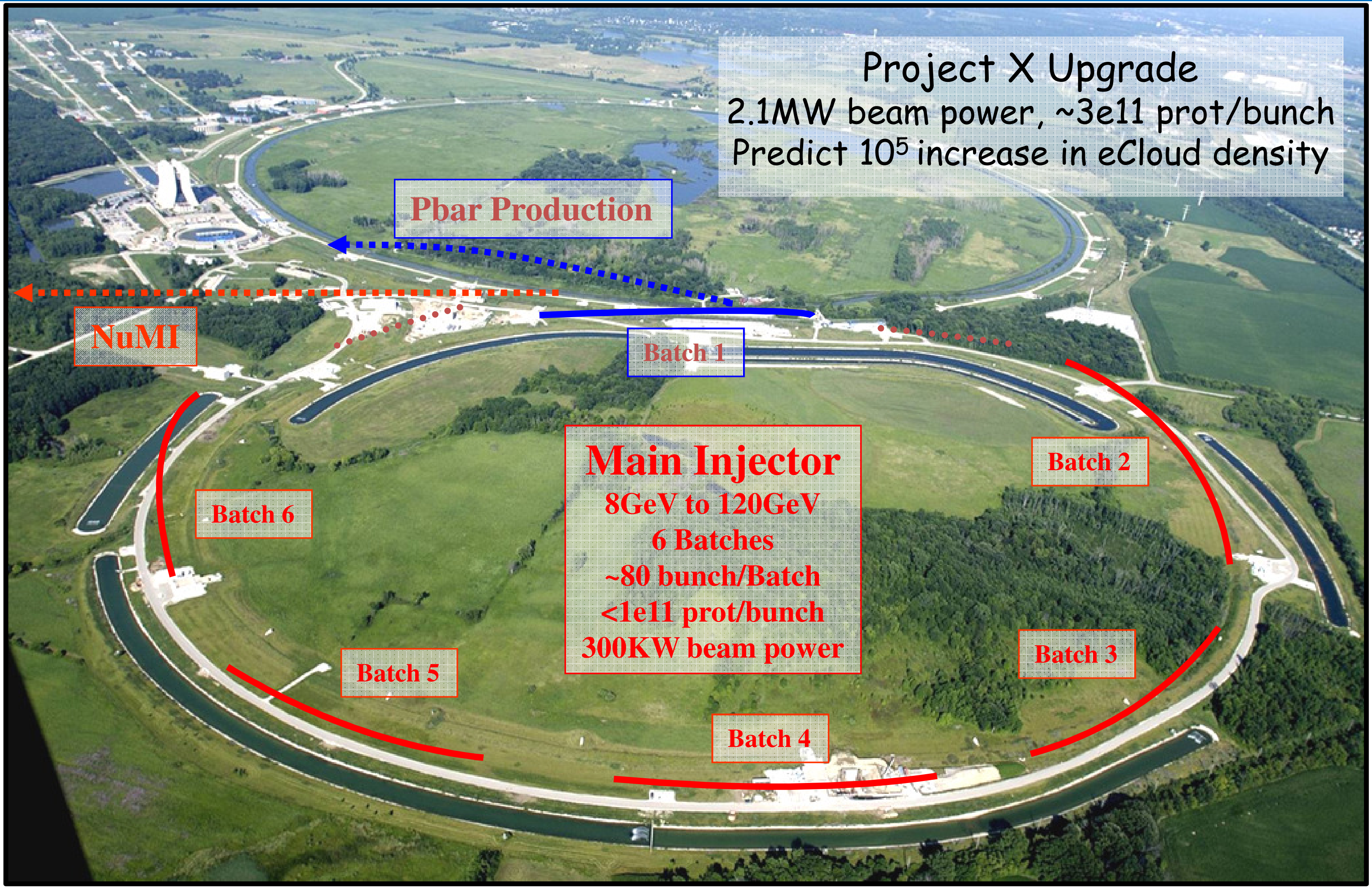
Destructive

Measurement of ecloud Development in the Fermilab MI using Microwave Transmission

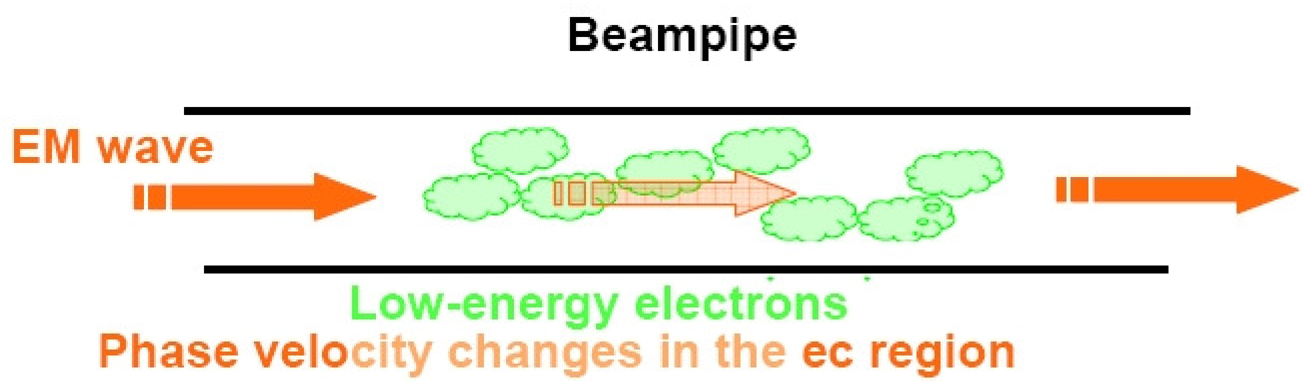
Nathan Eddy, Jim Crisp, Ioanis Kourbanis,
Kiyomi Seiya, Bob Zwaska, *FNAL*

Stefano De Santis, *LBNL*

Fermilab Main Injector



Microwave Transmission



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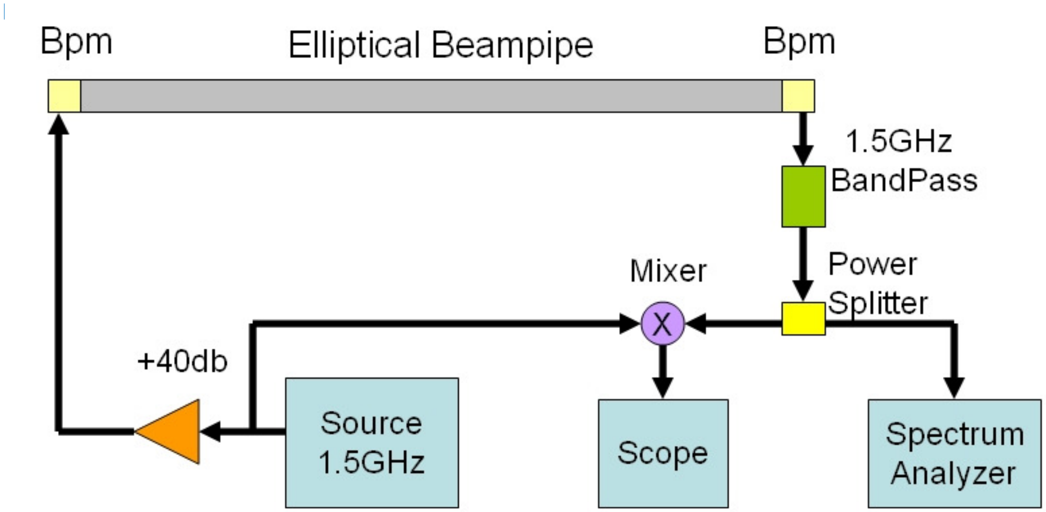
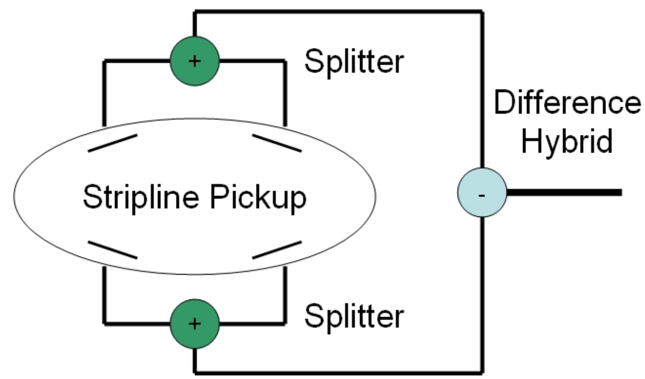
For an electron cloud $\omega_p^2 = 4\pi\rho_e r_e c^2$ is proportional to *e* density

Measurement Setup



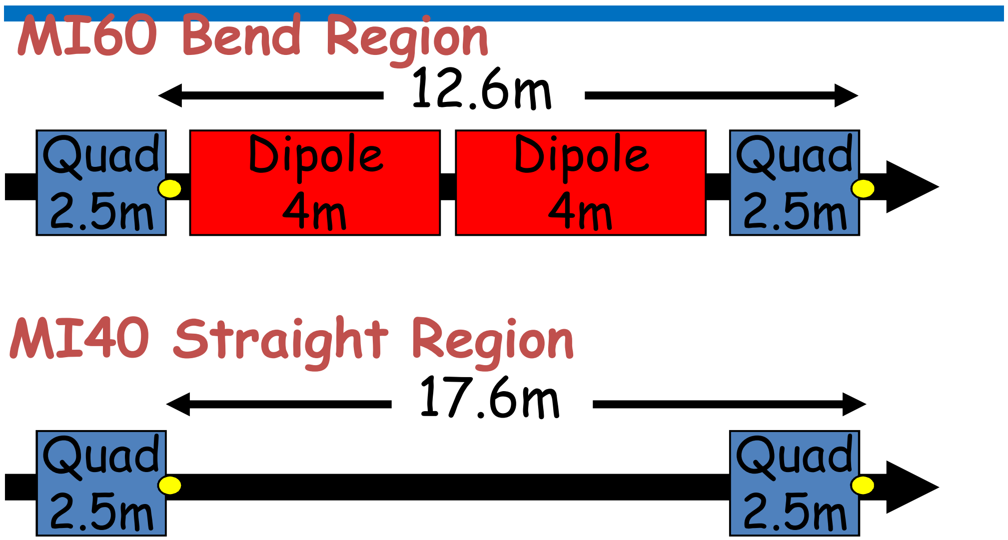


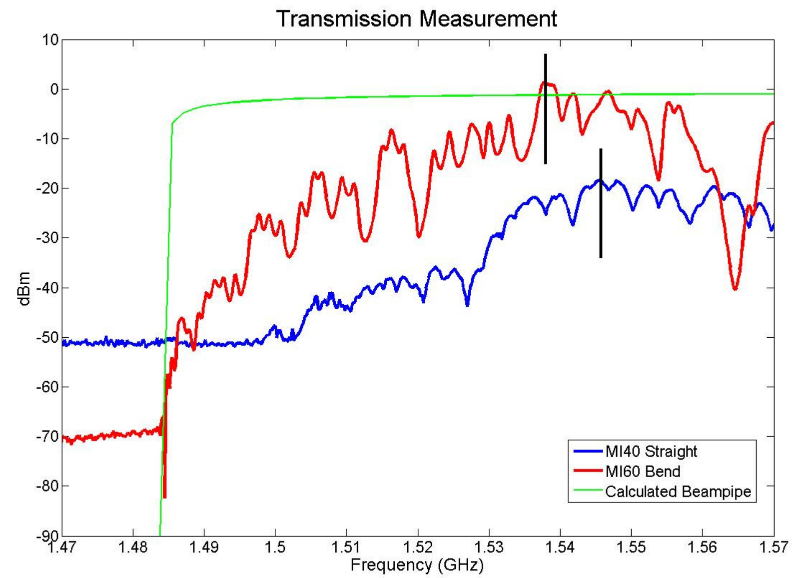
- Made three different measurements of the phase shift
  - Measure sideband spectrum of 1.5GHz carrier with SA, for Phase Modulation

$$e(t) \approx A\left[\cos\omega_c t + \frac{\beta}{2}\cos((\omega_c + \omega_m)t + \phi_m) - \frac{\beta}{2}\cos((\omega_c - \omega_m)t - \phi_m)\right]$$

  - Where β is the phase modulation amplitude, sideband dbc = 20log(β /2)
  - Measure 1st sideband over a full MI ramp (800ms) in zero span mode with SA
  - Mix down to baseband and record IF with deep memory scope (10MHz BW)
- Pickup connections to optimize coupling to TE_{11} mode
  - Measure -20db transmission for two pickups and 15m of beam pipe
  - Cutoff for beam pipe is just below 1.5GHz

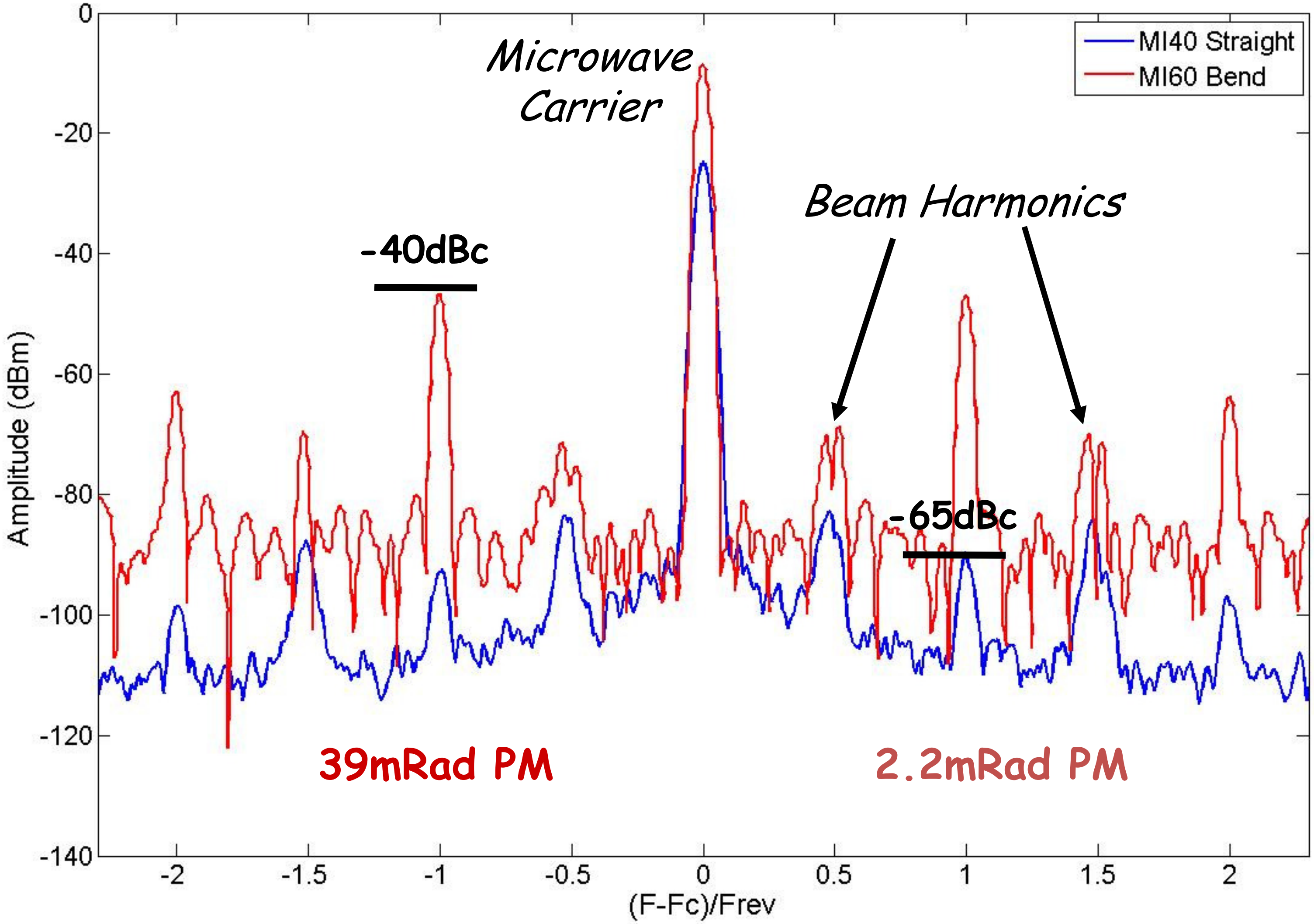
Measurement Locations



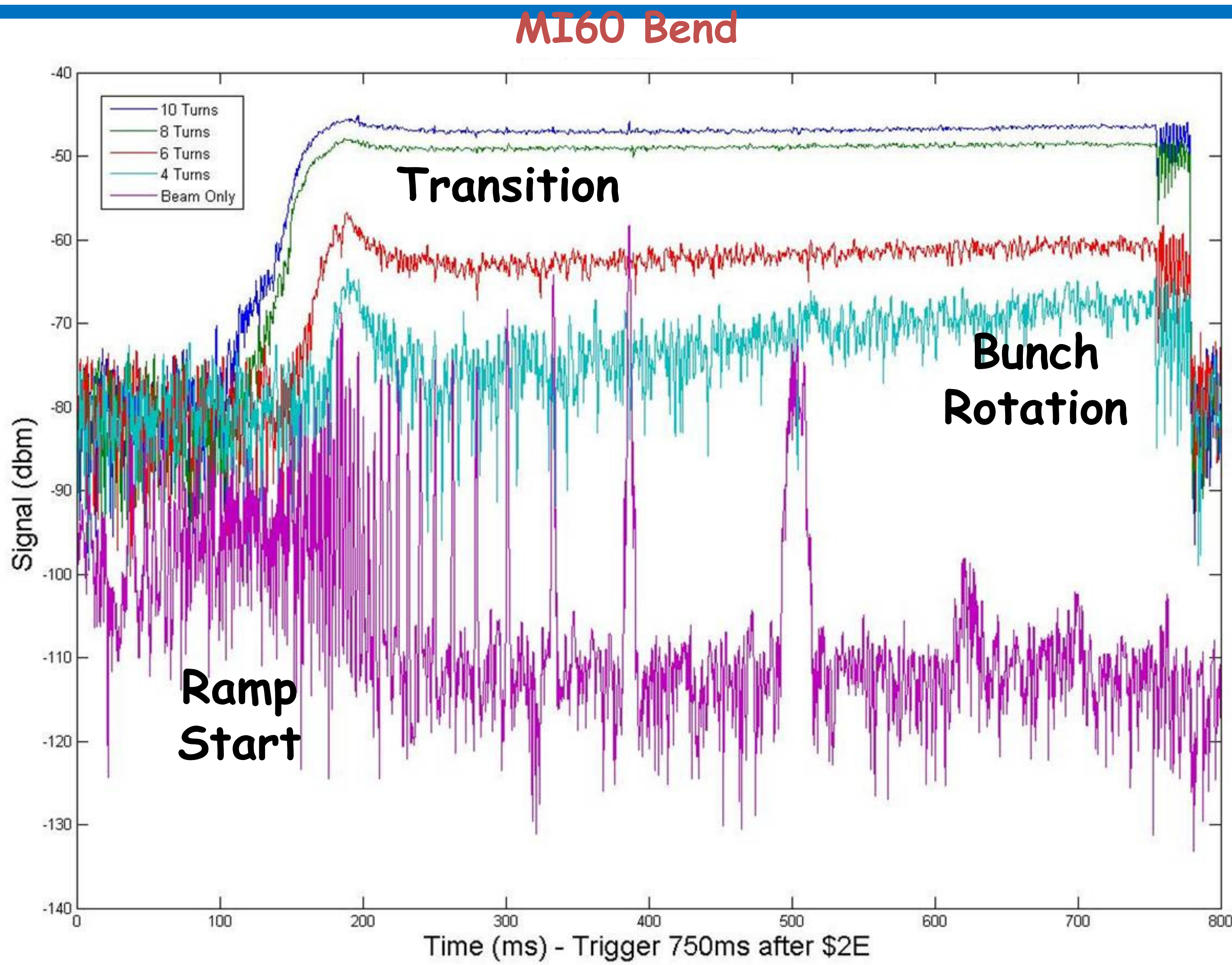


- Necessary to access MI Tunnel to reconfigure bpms
  - Bpms no longer available for operation
  - Can be months between MI access opportunities
  - Severely limits which bpms are available
- At MI60 Bend Region able to use spare Heliax cable
- At MI40 Straight Region have to use RG8 bpm cable
  - See an addition 20db of attenuation on transmitted signal
  - Appear to get coupling between the cables
  - Put the 40db drive amplifier in the tunnel at this location

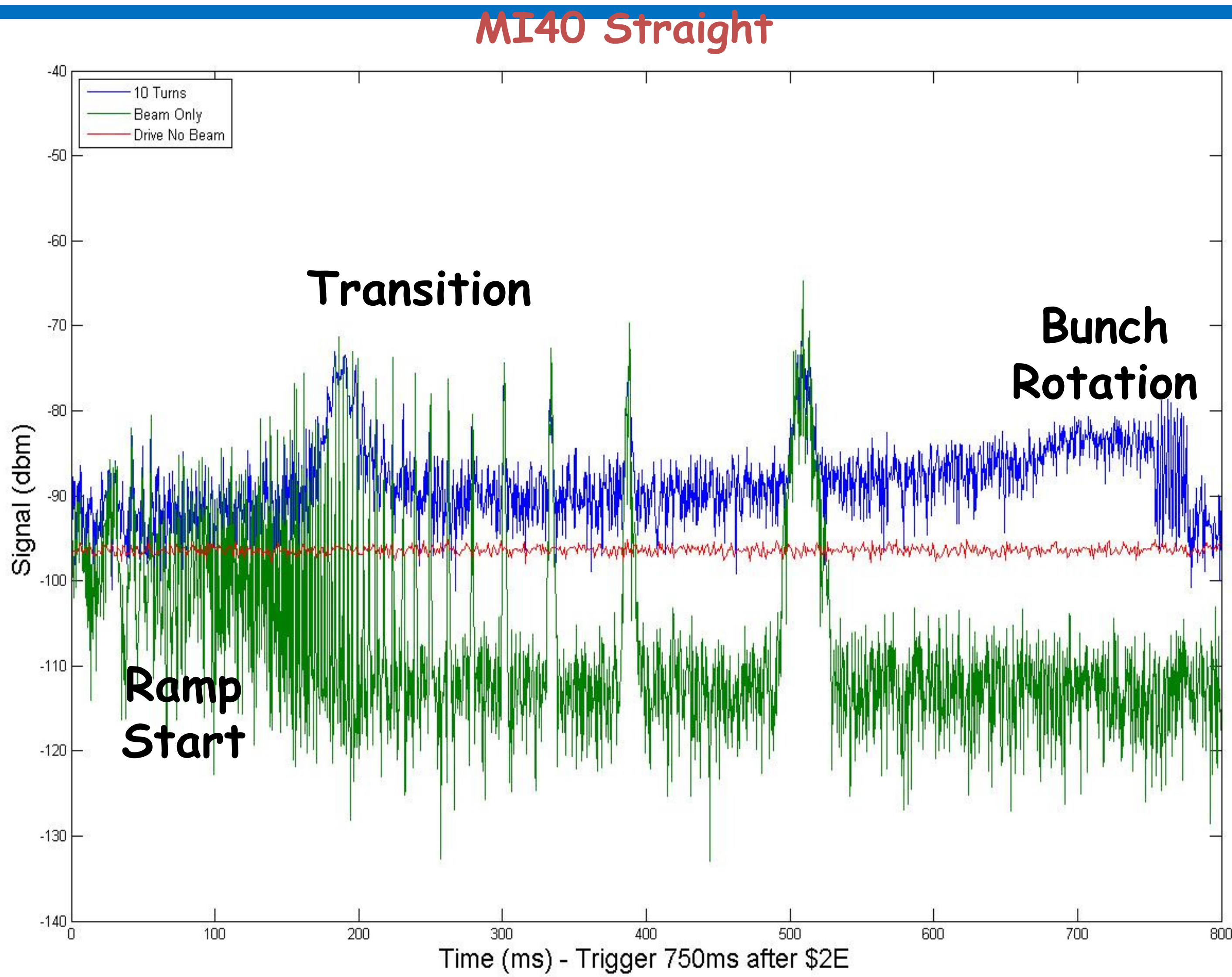
Sideband Spectrum



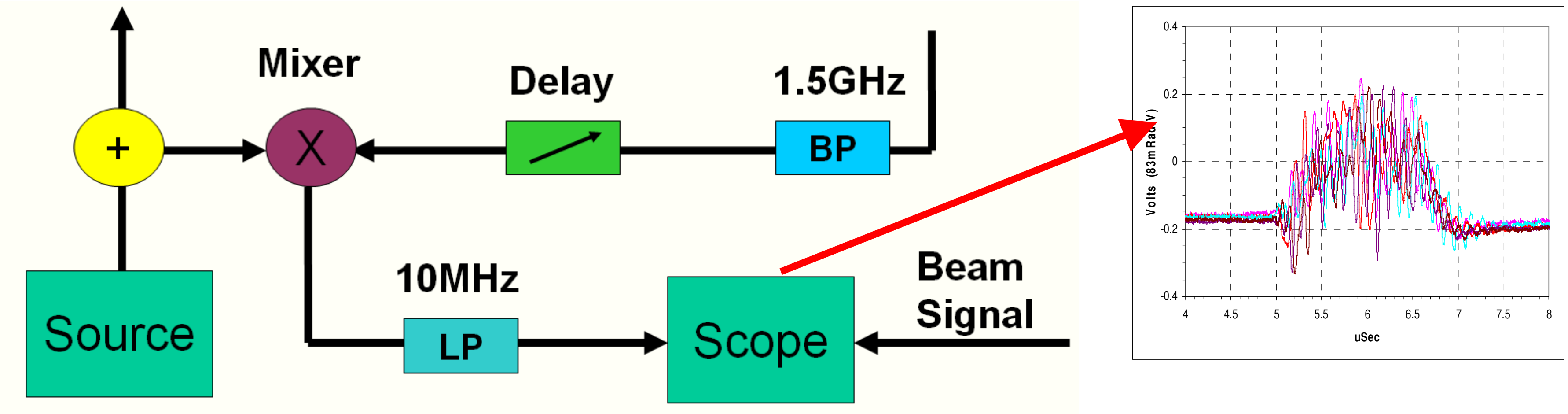
Zero Span Sideband



Zero Span Sideband

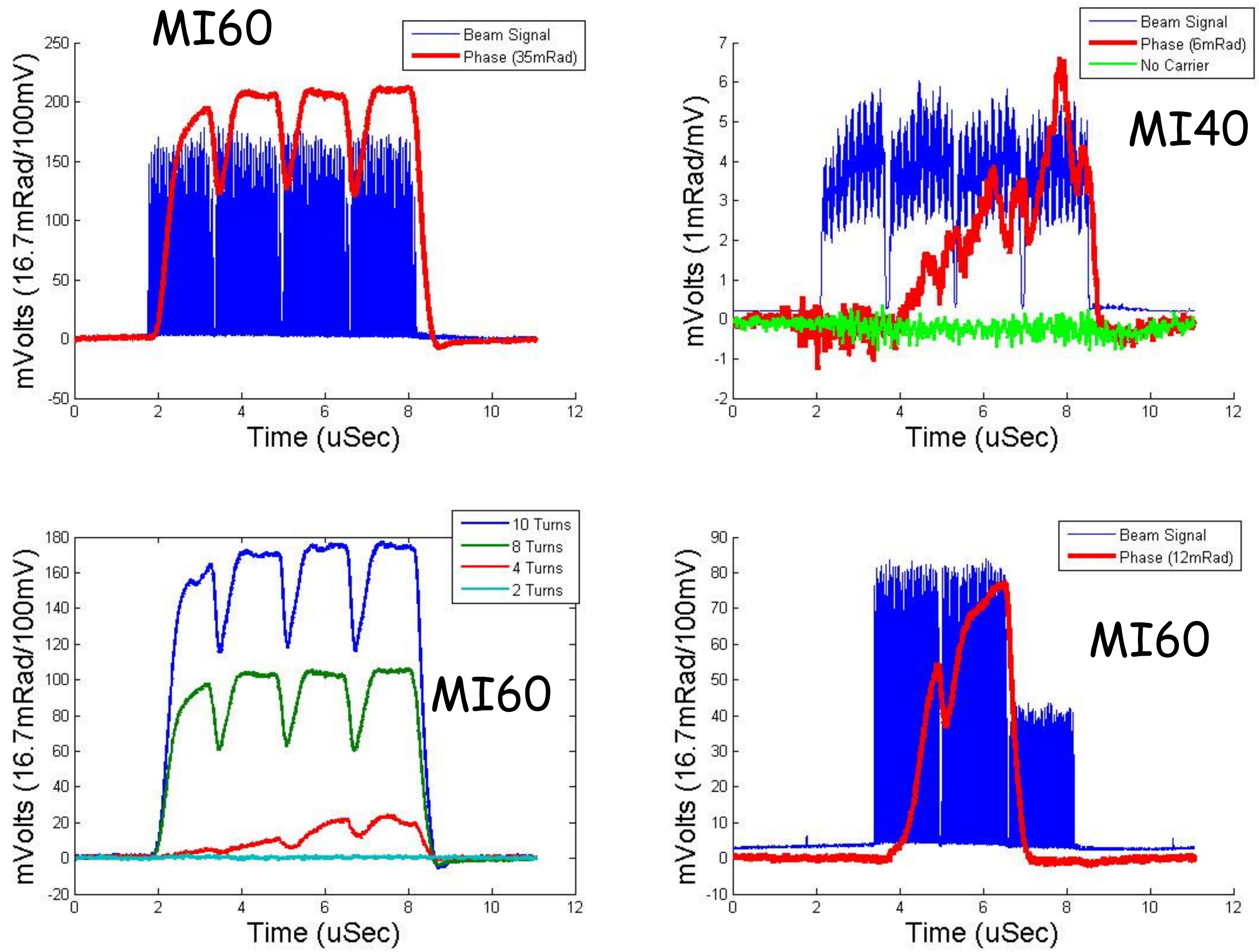


Direct Phase Shift Technique



- Mix the transmitted microwave signal to baseband
  - Use the delay to effect 90° phase shift (zero DC offset)
  - Theoritically, should only see PM modulation as AM cancels
- Scope aquires from 2ms to 20ms sampling at either 500MS/s or 100MS/s respectively
  - Expect eCloud induced phase shift to be the same each turn
  - The beam harmonics behave as noise which averages away
    - Use 100 turn average at MI60 and 1700 turns at MI40
  - Size of the beam harmonics impacts the dynamic range

Direct Phase Shift Results



Summary and Plans

- To calculate the eCloud density is difficult
  - Non-homogeneous plasma, magnetic fields, possible reflections
  - Efforts underway to simulate the microwave transmission
  - See TH5PFP019 and FR5PFP089
- Right now, have very interesting measurements of microwave phase shifts under a variety of beam intensities
  - Strong evidence that these are eCloud induced
  - Use demodulation to uniquely identify PM and AM
- The end goal is to see good agreement between measurements and simulation for current MI intensities
  - Must rely upon simulation to predict what measures are needed to mitigate the eCloud for Project X
  - The direct phase shift in the time domain can be directly compared with the simulation of a single machine turn
  - See TH5PFP032
- During the upcoming summer shutdown, a dedicated system will be installed
  - 2 pickups in dipole bend, 3 pickups in ~2m straight where two 1m coated beam pipes are being installed along with absorbers
  - Facilitate ease of measurements
  - Implement dedicated digital receiver – measure only PM, improve S/N

Backup Slides

Mixing Phase Modulated Signal

$$e(t) = A\cos(\omega_c t + \beta \sin(\omega_m t + \phi_m))$$

$$e(t) \approx A\left[\cos \omega_c t + \frac{\beta}{2}\cos((\omega_c + \omega_m)t + \phi_m) - \frac{\beta}{2}\cos((\omega_c - \omega_m)t - \phi_m)\right]$$

$$RF = e(t) \quad LO = \cos(\omega_c t + \phi_L)$$

$$neglect\ 2\omega_c\ terms$$

$$IF = RF\ x\ LO = \frac{A}{2}\left[\cos(\phi_L) + \frac{\beta}{2}\cos(\omega_m t + \phi_m - \phi_L) - \frac{\beta}{2}\cos(\omega_m t + \phi_m + \phi_L)\right]$$

$$= \frac{A}{2}\left[\cos(\phi_L) + \beta \sin(\phi_L)\sin(\omega_m t + \phi_m)\right]$$

Full Transmission Response