Feedback as a Method to Control Beam Instabilities in the SPS

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Overview

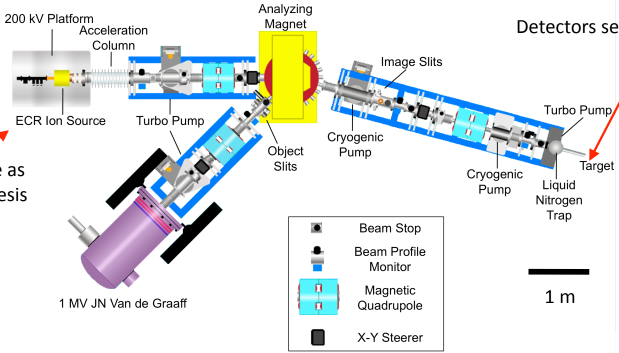
1. My background
2. Toohig fellowship
3. Electron cloud instability
4. Feedback as part of the HiLumi LHC project
   - SPS bunch excitation MDs
   - Bunch-excitiation synchronization
   - Kicker design study
5. Summary

Education, background, previous experience

- Undergraduate studies completed at John Carroll University in Cleveland, OH. BS in Physics, 2005
- Trained as a nuclear physicist at the University of North Carolina in Chapel Hill, NC. MS, 2008; PhD, 2011
- Masters thesis - design and construct a high intensity, low-energy proton source
- Applications in nuclear astrophysics, measuring nuclear reactions important for stellar burning
- Need very intense beams to probe very small nuclear cross sections
- Goal: produce 1 mA average proton beam on target at 200 keV

Laboratory for Experimental Nuclear Astrophysics

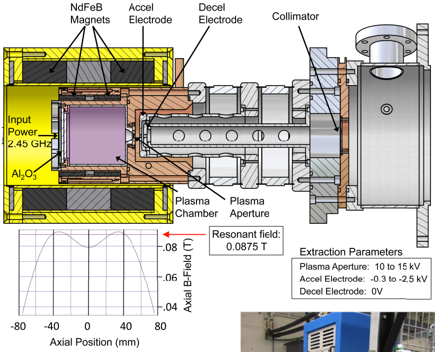
Detectors setup here

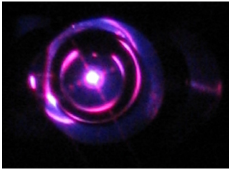


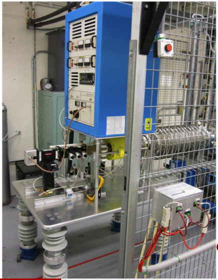
Built on-site as Master's thesis

Low-energy facility solely devoted to making measurements of astrophysical importance
Student operated and maintained

LENA ECR Ion Source and 200 kV Accelerator





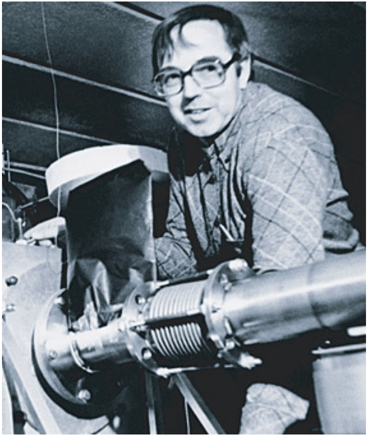


- Compact ion source to fit on isolated, high potential table top
- Utilizes NdFeB permanent magnets to produce the 875 G mirror field on axis to drive electron cyclotron resonance
- Plasma driven with microwave frequency of 2.45 GHz
- Beam extracted at 15 kV and accelerated electrostatically up to 200 kV
- Produces 1.5 mA proton beam on target at $E_p = 100 - 200$ keV
- Emittance: 0.19 π-mm-mrad
- Used this new accelerator for a measurement of $^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$ at astrophysical energies - PhD thesis

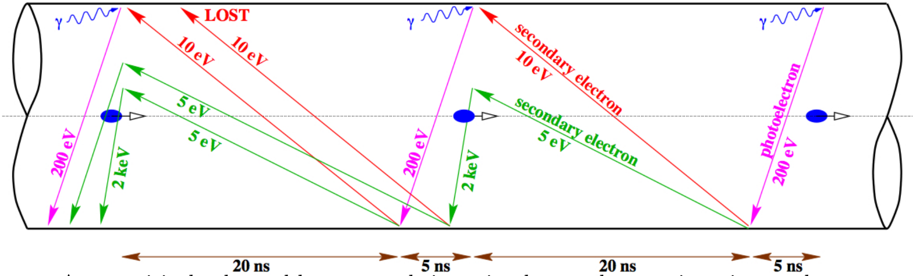
Cesaratto et al. *Nucl. Instrum. Meth. A* **623**, 888 (2010).

Dr. Timothy Toohig, S.J.

- As many of you know, through LARP, Toohig fellows participate in LHC research and operations.
- Fellowship is in honor of Dr. Timothy Toohig, S.J., physicist and Jesuit priest.
- Provides young PhDs a unique opportunity to participate in research at a US national laboratory and at CERN.
- November 2011, I joined LARP in the accelerator research division at SLAC National Accelerator Laboratory.
- With very broad interests, I began working with the feedback and dynamics group.



Electron cloud instability



- As a positively charged beam travels in a circular accelerator, it emits synchrotron radiation or interacts with residual gas producing secondary electrons.
- The synchrotron radiation produces photoelectrons from interaction with the beam pipe walls.
- These secondary and photoelectrons are accelerated by the beam and can hit the beam pipe walls creating more electrons, an avalanching effect - "cloud"
- The interaction of this cloud with the beam can cause bunch instabilities, i.e., unstable transverse motion, emittance blowup, bunch lengthening, and vacuum pressure increase
- Intensity dependent effect! Limits the beam intensity in the machine.

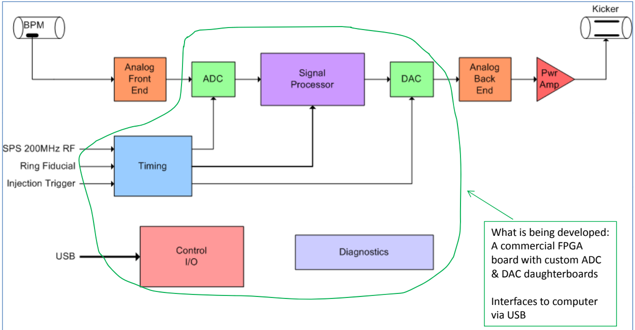
F. Ruggiero and X. Zhang, AIP Conf. Proc. 496 p. 40 (1999).

Beam instabilities in the SPS

- Studies over the last decade have shown the presence of the electron cloud effect in the SPS
  - Emittance blowup
  - Unstable bunch motion
  - Tune shift
  - Intensity loss
- For the LHC to reach the luminosity increase desired, a factor of 10 beyond designed luminosity, these effects must be suppressed and/or mitigated
- Several proposed methods:
  - Beam scrubbing - conditioning the accelerator
  - Operate with alternative operating parameters, Q20 vs. Q26 optics
  - Beam chamber coatings with amorphous carbon or other low secondary emission yield (SEY) materials
  - Clearing electrodes
  - Feedback systems
- Feedback could be used to address transverse mode coupling instability (TMCI)

Feedback effort

- Provide another method to control beam instabilities, used in conjunction with the above proposed methods
- Non-permanent, active, so it can be turned on/off as necessary

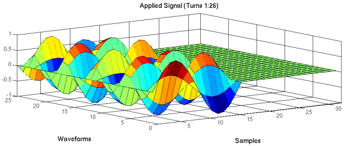


SPS Bunch Slice Feedback Demo System – Block Diagram

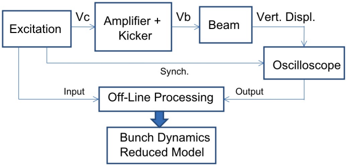
- Back end of system can be used as beam diagnostic
  - Excitation of intra-bunch motion, head-tail, higher order modes
  - Understand complex bunch dynamics
  - Excitation with band filtered random noise

Beam excitation MDs

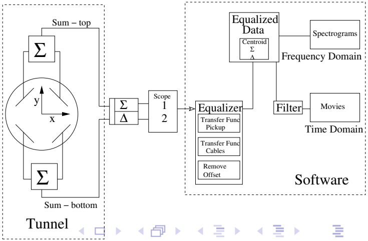
- Apply amplitude modulated RF signals to the bunch at 3.2 GS/s with excitation system, wideband amplifiers and bandwidth limited exponential tapered stripline



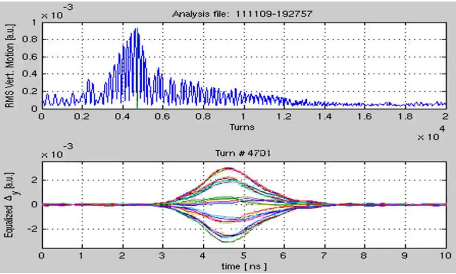
- Single bunch excitation measurements performed to date, will expand to multibunch
- Measure beam response with exponentially tapered stripline, hybrid coupler to produce the sum and difference (vertical) signals.
- Sum/difference acquired at 20 GS/s by oscilloscope

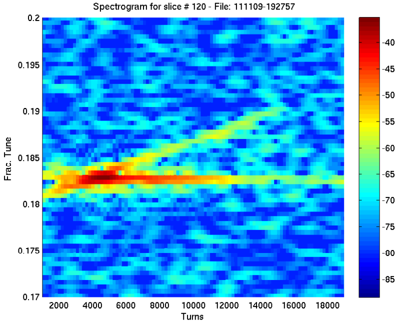


- Signal is synchronized with SPS RF clock, revolution fiducial, and injection trigger
- These beam excitation studies help to understand the stable bunch dynamics under perturbation



Excitation study results - Mode 0





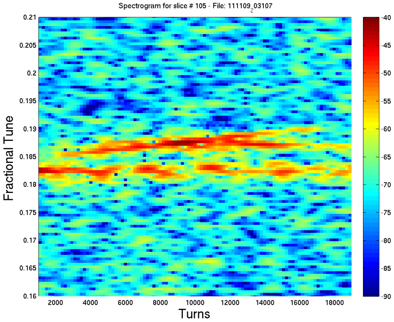
- Viewing the BPM signal in the time domain is nice, but our eyes are not so good at resolving the frequency content.
- Use FFT to identify modes in frequency domain.
- Excitation signal swept in frequency through betatron tune and first synchrotron sideband
- Strong coupling with mode 0

Excitation study results - Mode 0

Play

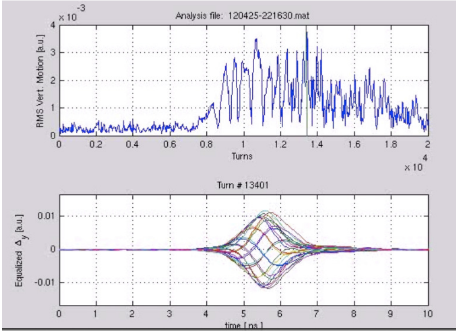
Excitation study results - Mode 1

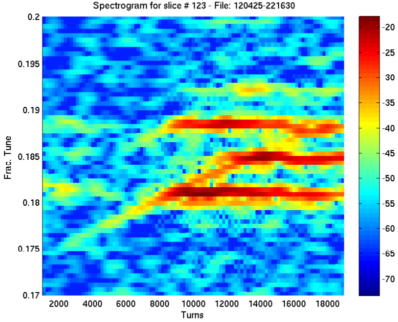
Play



- Excitation signal swept in frequency through the first synchrotron sideband
- Strong coupling with mode 1 at turn 9000, head-tail motion
- Can see mode 0 excitation from accelerator/lattice parameters, not from excitation signal
- Vector representation of motion, beam slice at model frequency - blue → mode 0, green → mode 1

Excitation study results - Many modes



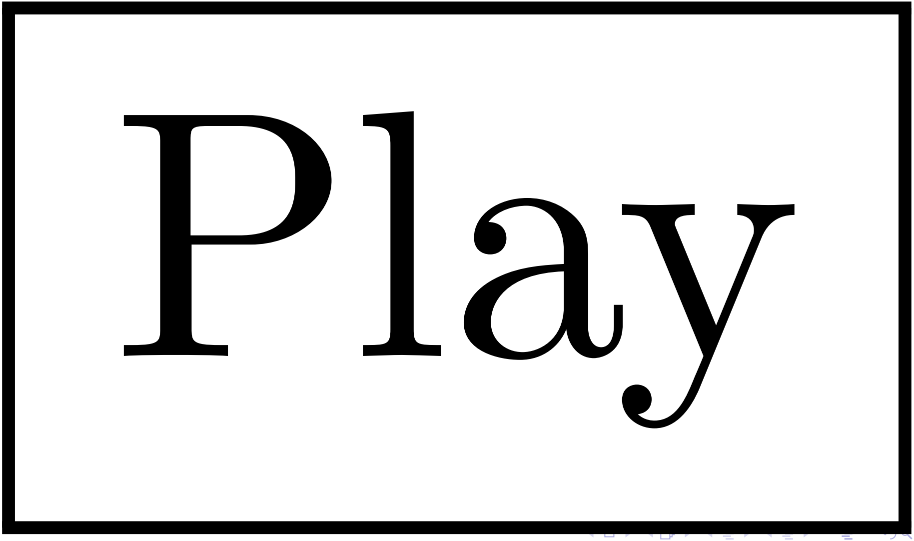


- In this example, clearly excite 4 modes, from ν_{β_y} to $\nu_{\beta_y} + 3\nu_s$
- Beam on verge of instability enables us to excite multiple modes!
- Very complicated motion, still trying to understand motion
- Motion dependent upon accelerator setup, in addition to any perturbations we impart

Excitation study results - Many modes, time domain

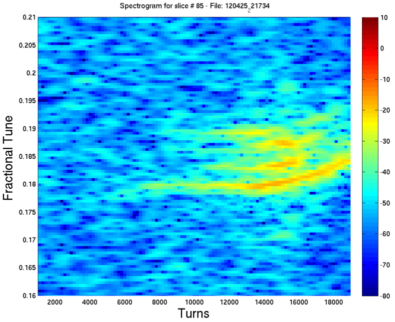
Play

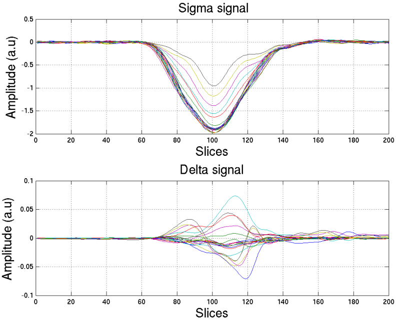
Excitation study results - Many modes, frequency domain



Drive beam to instability

- Very low chromaticity beam
- Drive the beam to instability at 15k turns
- Loss of beam intensity, notice sigma signal from pickup
- Observe by slice: slice 105 shows +/- modes symmetric at turn 8k
- Slice 135 shows as high(low) as mode +6(-3), negative modes





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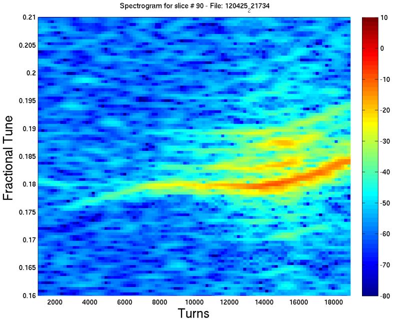

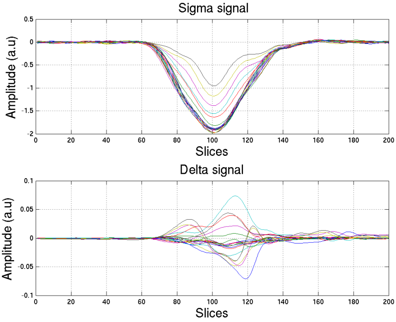

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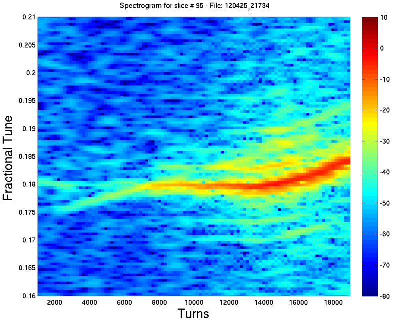

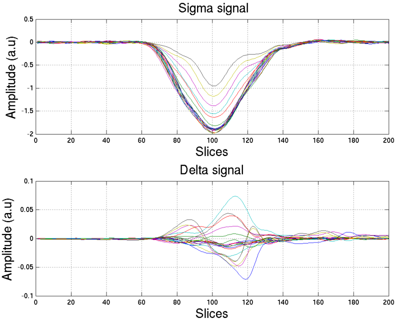

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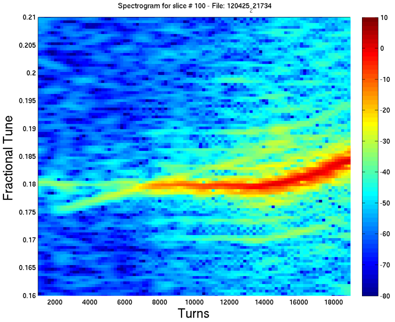

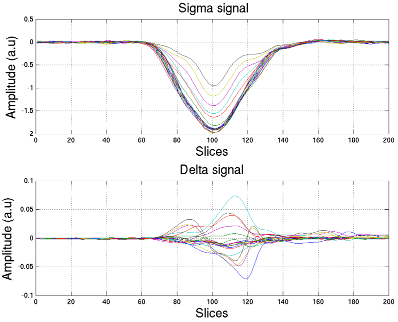

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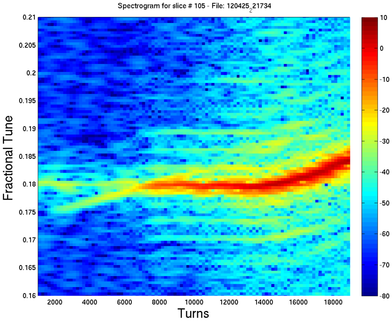

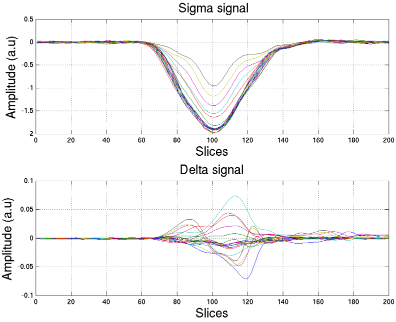

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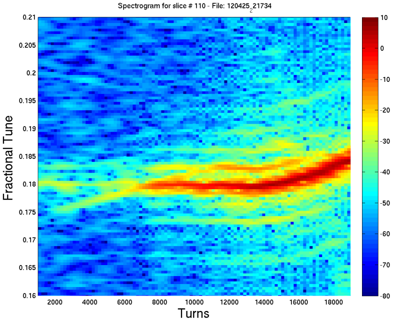

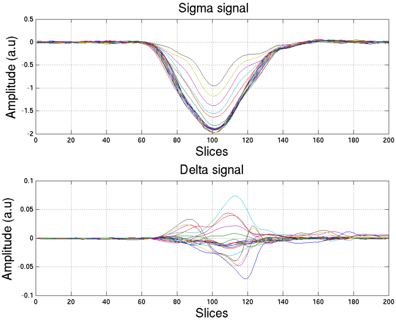

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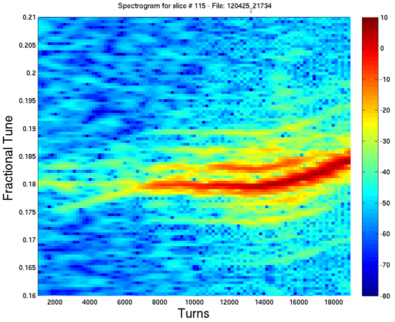

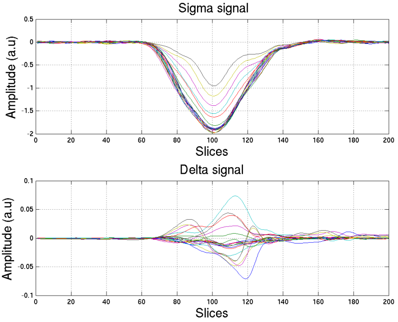

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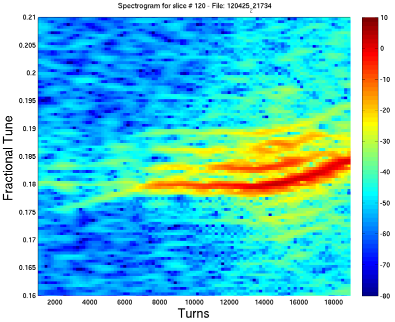

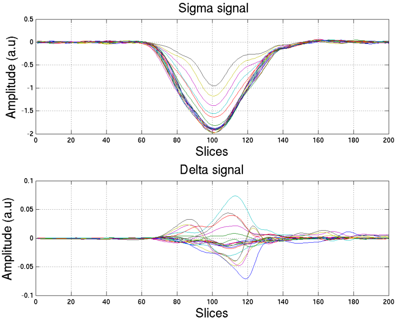

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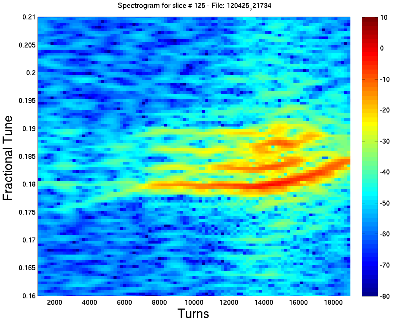

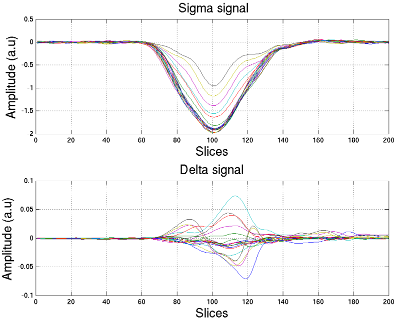

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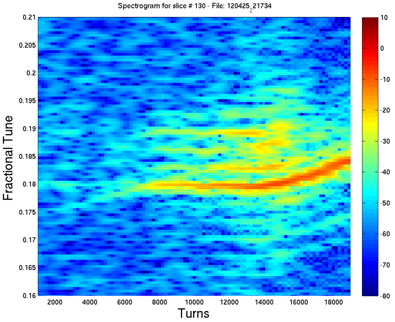

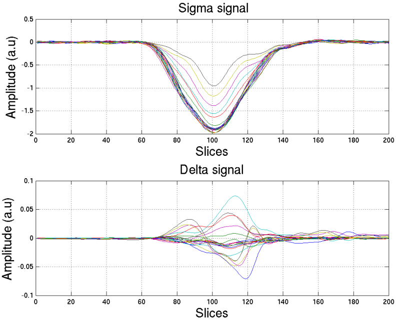

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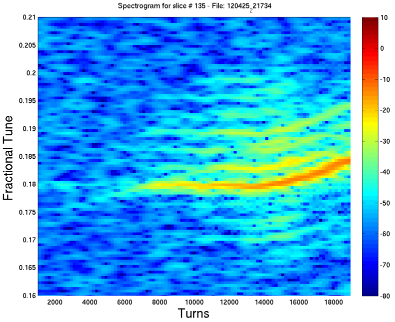
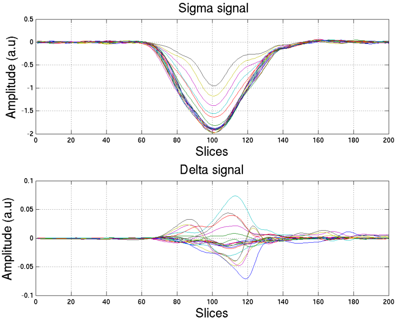
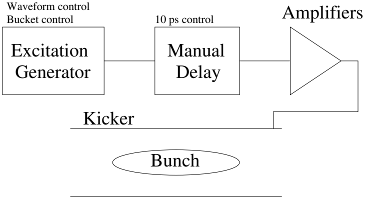
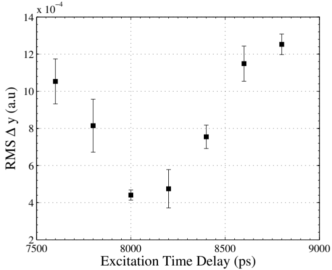


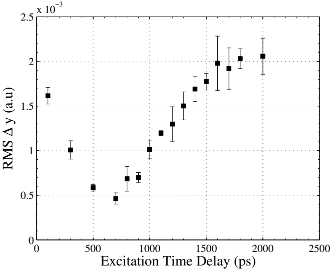


Properly timing the kick

- Excitation of particular bunch modes depends on the frequency at which the bunch is driven
- The efficiency at which you can couple energy into the bunch will depend on synchronization of the bunch with the excitation signal.
- MDs to properly synchronize the bunch with the excitation signal.
- Sweep in time with amplitude modulated sine 200 MHz chirp signal across bucket
- Monitor the RMS motion of the centroid of the bunch to determine proper synchronization
- A minimum in the RMS corresponds to a properly synchronized signal
- Working on methods to improve speed and efficiency





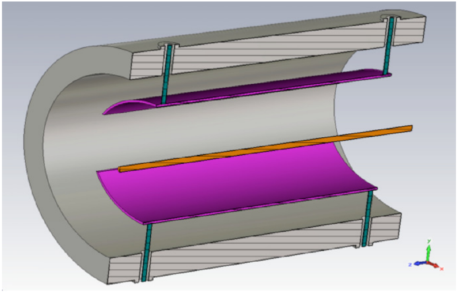


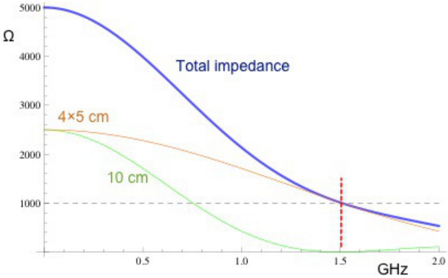
Wideband kicker design study

- Multilab effort between SLAC, LBNL, and LNF to evaluate different kicker structures to be used as a prototype for the wideband feedback project
  - Stripline structures - relatively wideband
  - Damped cavities - High shunt impedance
  - Slotted structures - Used in stochastic cooling, high shunt impedance
- Bandwidth of the kicker structure determined by simulation studies, $f =$ DC – 1 GHz desirable.
- Particular initial considerations are shunt impedance, broadband beam coupling impedance, and bandwidth.
- Studies so far show that more than one kicker will necessary to cover such a large band, e.g., a low band and high band.
  - Array of striplines
  - Stripline & slotted structure
  - Stripline & cavities
- Define options and a path to fabrication for CERN SPS kicker

Stripline

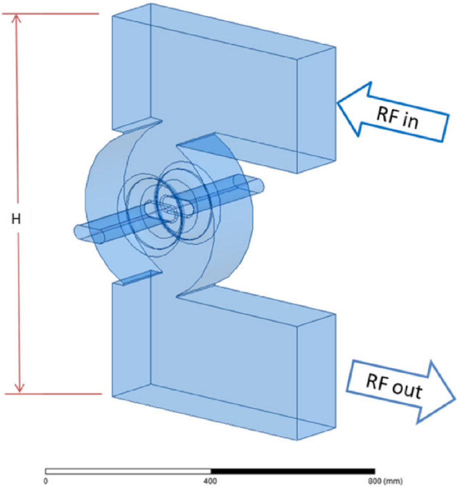
- Efforts by S. DeSantis and Z. Paret at LBNL
- Estimates of shunt impedance and coupling impedance
- Attractive for low band, say DC - 500 MHz
- A single stripline, 10 cm in length, could provide coverage up to 750 MHz
- An array of 4 $\times$ 5 cm striplines could provide coverage up to 1.5 GHz
- At this point looks very necessary for implementation





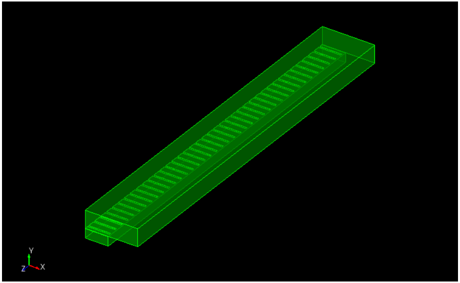
Cavities

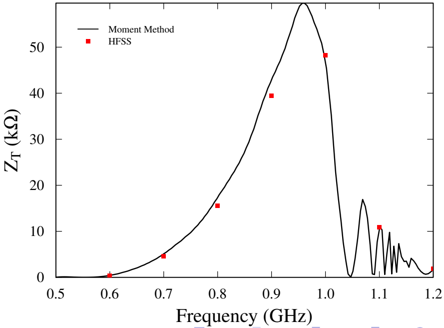
- Efforts by F. Marcellini and A. Gallo at LNF
- Used in conjunction with a stripline kicker
- Use multiple narrow band cavities at harmonics of fundamental frequency, $\omega_0 = 2\pi/\tau_b$
- Very attractive for shunt impedance
- Interesting processing model, decompose kick into a few modes, N independent outputs and power stages
- Time between bunches adequate for filling cavity



Slotted structures

- Efforts by LNF, SLAC, and LBNL
- Co-propagate kick signal with bunch, waveguides couple to beam pipe by slots
- 1 m long structure evaluated with 40 slots.
- High shunt impedance show with HFSS and moment method calculations
- Calculation of broadband beam coupling impedance with ACE3P and GdfidL
- Attractive option to cover high band, with reasonably large bandwidth





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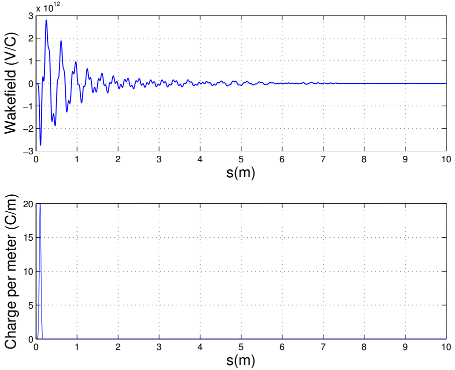
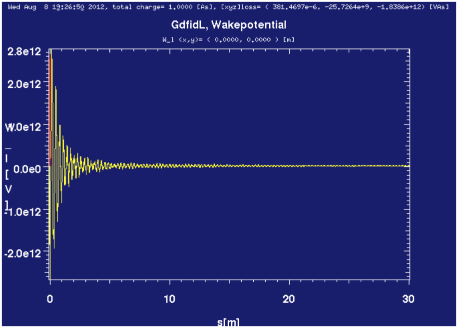
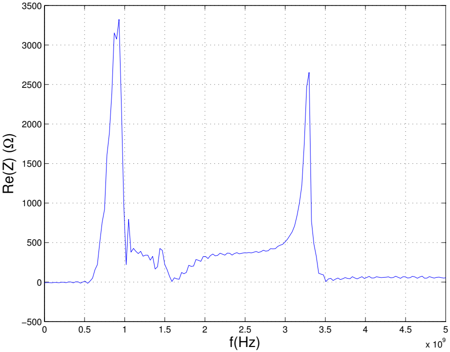
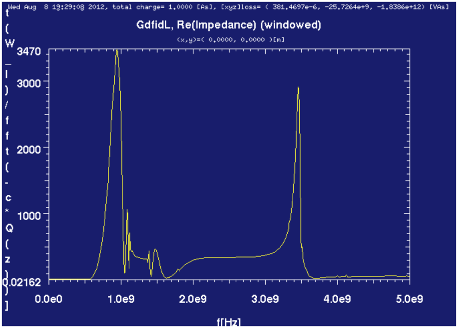




Slotted structures

- Efforts by LNF, SLAC, and LBNL
- Co-propagate kick signal with bunch, waveguides couple to beam pipe by slots
- 1 m long structure evaluated with 40 slots.
- High shunt impedance show with HFSS and moment method calculations
- Calculation of broadband beam coupling impedance with ACE3P and GdfidL
- Attractive option to cover high band, with reasonably large bandwidth





Feedback project in summary

- The SPS wide band transverse feedback project has many diverse areas of accelerator research and development
  - Simulation of feedback varying gain, bandwidth, etc.
  - Beam excitation measurement for characterizing the dynamics of the system
  - Electromagnetic design of wide band kickers
  - Signal processing studies and algorithm development
  - ...
- As a Toohig fellow, this opportunity has afforded me to work with scientists from the US and Europe, to learn and collaborate with the best in the business
- Bring collaborations together, expertise from various areas
- For a project like this, many active areas of research and development, many tasks to complete, just remember...

Rome ne s'est pas faite en un jour