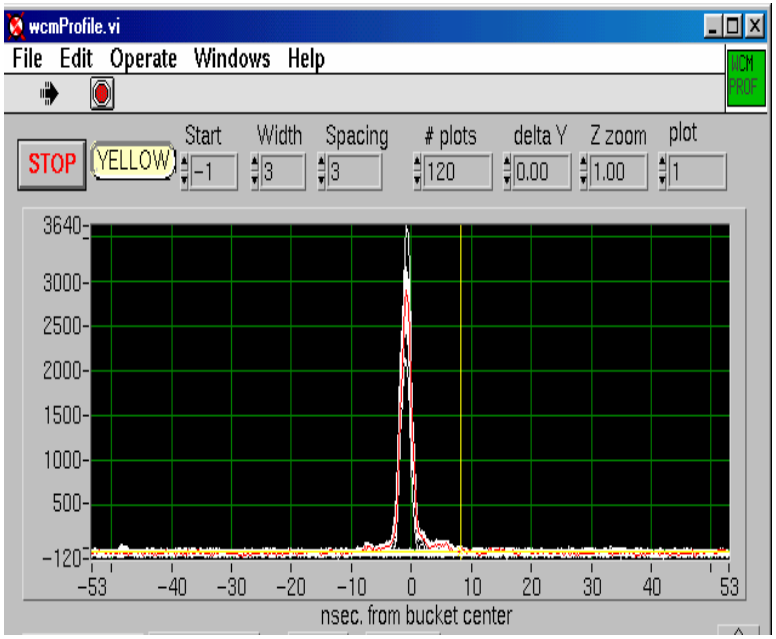
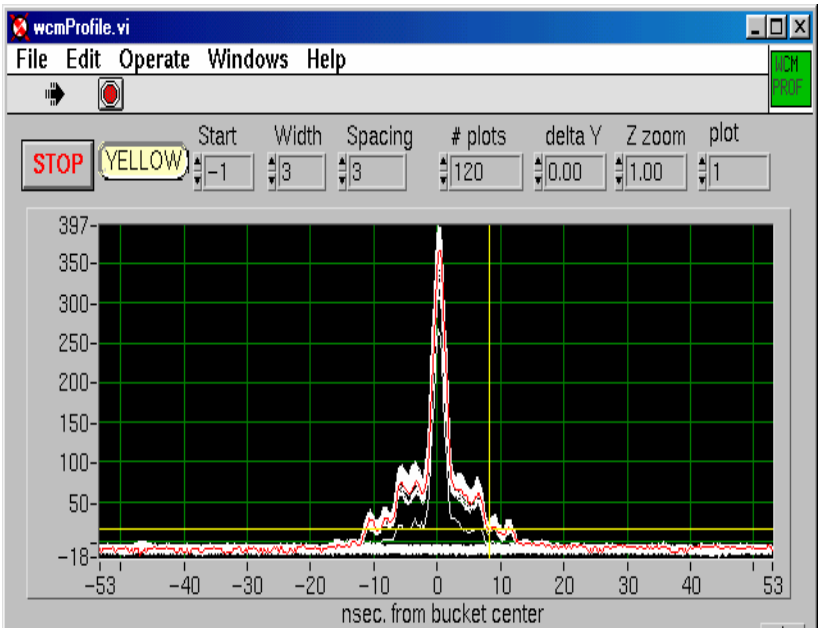
Stochastic Cooling Studies in RHIC

J.M. Brennan, M. Blaskiewicz, J. Wei
Brookhaven National Labs

- Motivation
- Schottky Spectra
- Beam Response Function
- Plans, near/far term

The Problem!





- Beginning of store
- Few hours into store

The Problem

- IBS
  - Emittance growth drives beam out of the bucket
    - Diminishes effective luminosity
    - Creates de-bunched beam, > dirty dumps
  - Can't FIX the problem (atomic scale)
    - Mitigate with bigger buckets (momentum aperture)
    - Emittance blowup strategies
    - Gap cleaning
  - Not a surprise
- Cooling in needed to `counteract IBS
  -

RHIC Design Manual

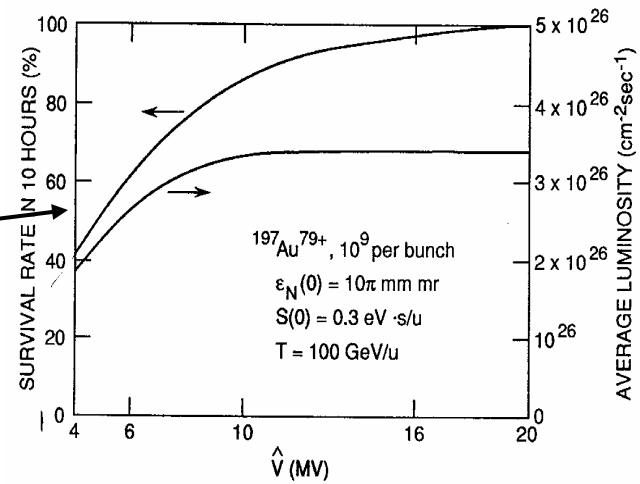


Fig. 7-3. Dependence of final beam survival rate and average luminosity on storage rf voltage after 10-hour operation, "constant voltage" scenario (courtesy J. Wei).

Bunched-beam Stochastic Cooling

- What would be required,
  - –Cooling time would have to be commensurate with de-bunching time, ~ few hours
  - –Cool only large ΔP particles (halo cooling)
- Consider coasting beam theory (full bucket)

$$\frac{1}{\tau} = \frac{W}{N_{eff}}\left[2g\left(1 - M^{-2}\right) - g^2\left(M + U\right)\right]$$

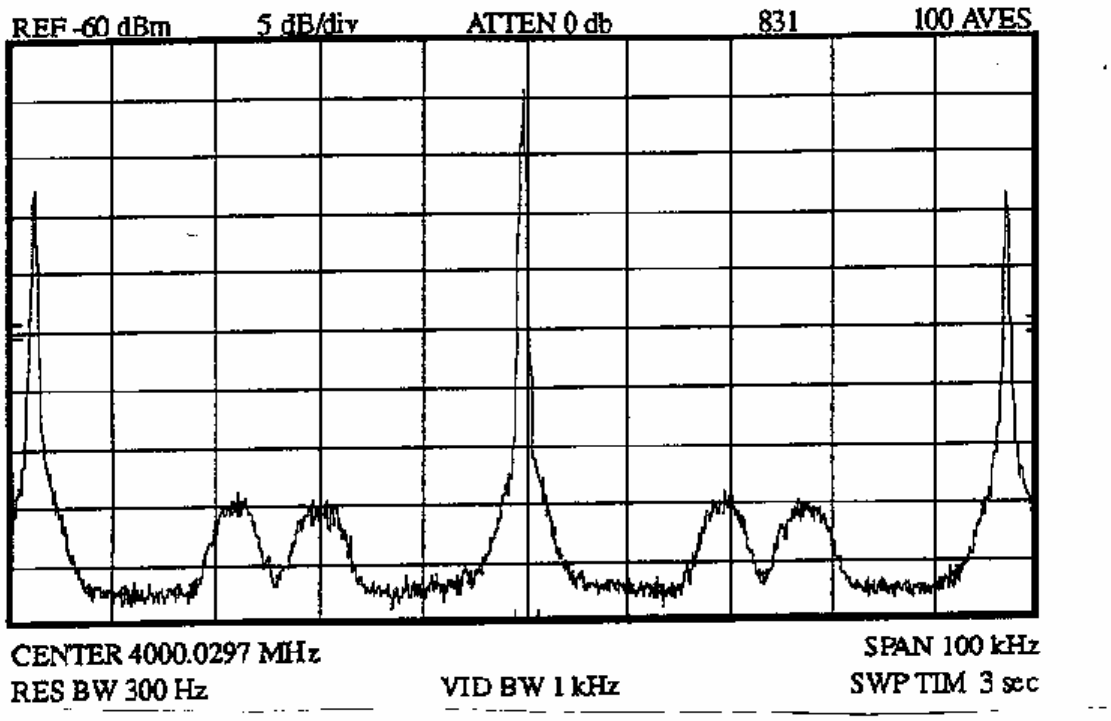
$$g_{optimum} = \frac{1 - M^{-2}}{M + U} \cong \frac{1}{5}$$

$$\frac{1}{\tau_{opt}} = \frac{W}{N_{eff}}\left[\frac{\left(1 - M^{-2}\right)^2}{M + U}\right] = \frac{1}{3000\ \text{sec}}$$

$$N_{effective} = \frac{10^9}{1.5\text{m}}3830\text{m} = 2.5\text{x}10^{12}$$

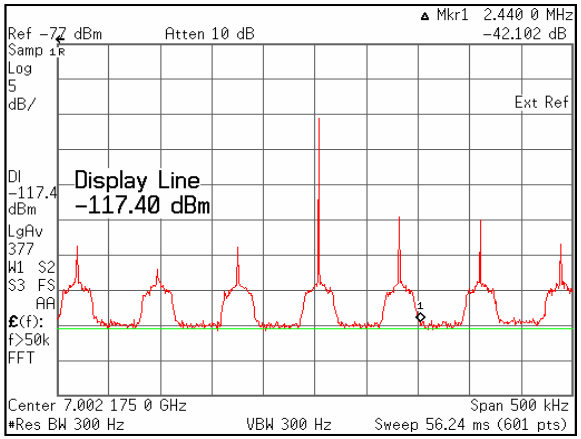
- Why wasn't stochastic cooling in the base line design for RHIC?
- High frequency bunched-beam stochastic cooling is required

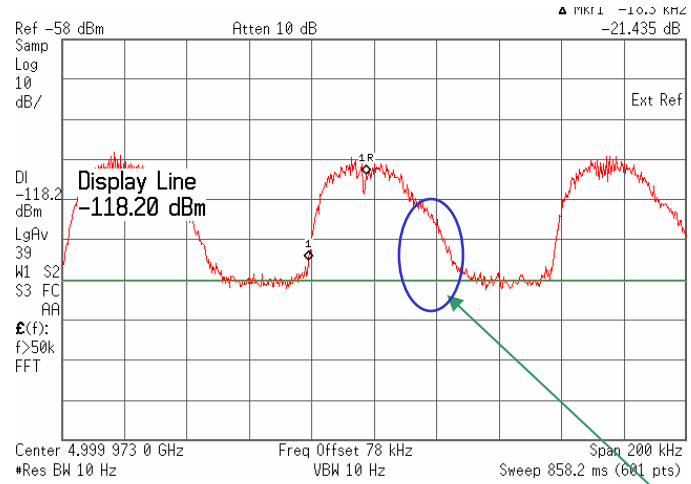
Spectrum from Tevatron



Schottky signals in the 4-8 GHz band

- Fermilab loaned to RHIC a pickup and kicker pair at 4-8 GHz
- Looking at the gold beam



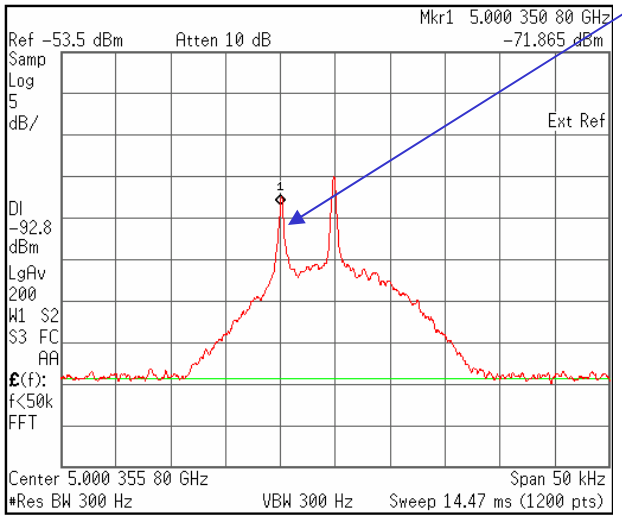


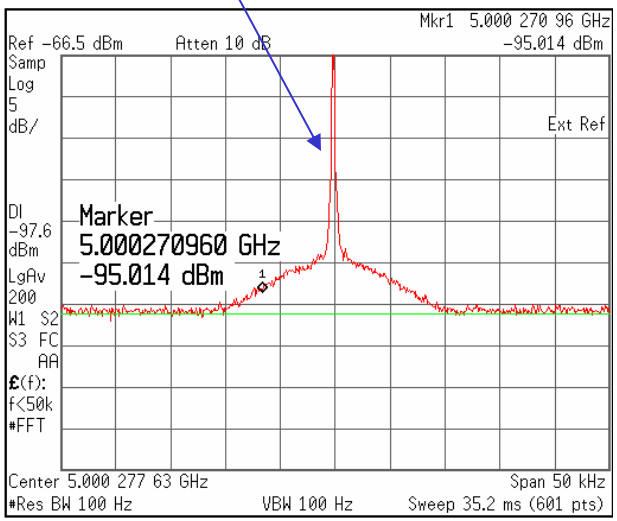
1. At 7 GHz early in a store, via 150 m cable
2. Coherence lines show up at harmonics of the bunch frequency
3. Even at 7 GHz the Schottky bands do not overlap,⇒ poor mixing

1. Late in the store at 5 GHz we see de-bunched beam, coasting on the low-energy side
2. The coherence has dissipated
3. The signal to noise ~ 30 dB

Protons (polarized)

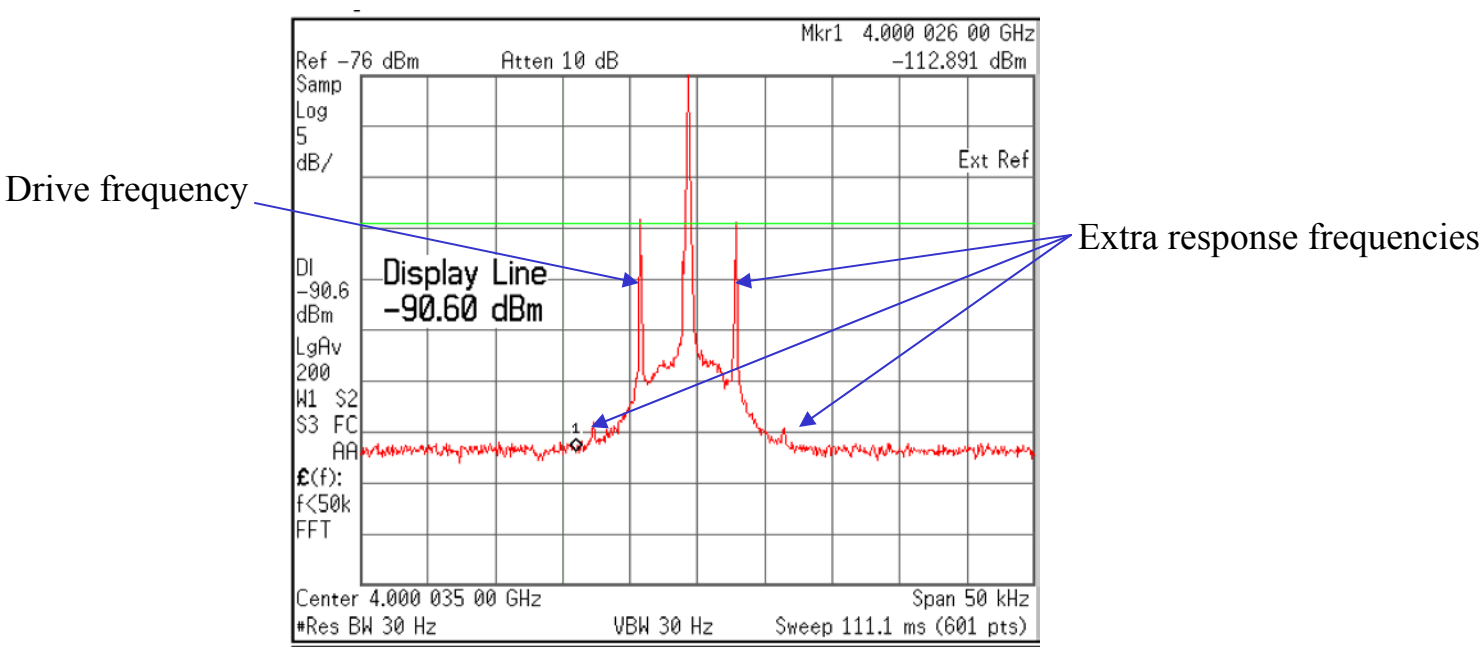
- Looking at the proton beam
- The significant difference in that the coherence lines do not dissipate
- This is consistent with experience at TEVATRON and SPS
- We also measured the longitudinal Beam Transfer Function by driving the kicker (5 Watts) at a single frequency within the distribution





The BTF in not always so straightforward

- Sometimes the response resembles low-frequency bunched beam BTF
- Generating mirror image frequencies at $\pm\Delta f$, $\pm 2\Delta f$,…
- Indicates creation of some long-lived ($>>\tau_{synchrotron}$) structures, eg: solitons
- This seems to be the key difference between protons and ions

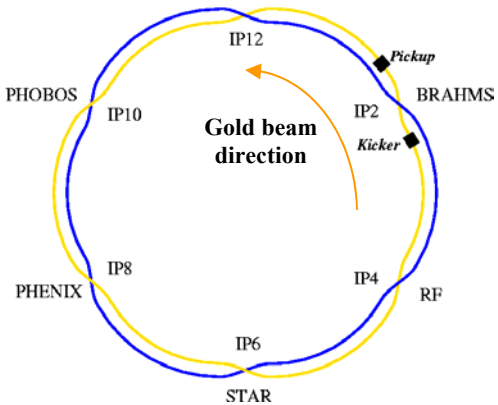


Longitudinal Beam Transfer Function

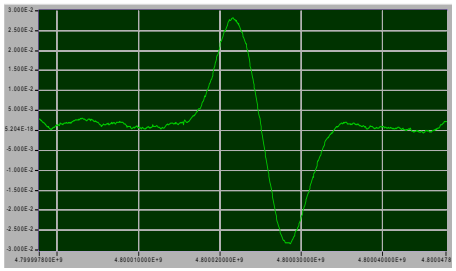
- The beam transfer function represents the beam's response to stimulus of the kicker
- It is a key part of feedback loop of a cooling system
- For a coasting beam it is given by the dispersion integral,

$$B(\omega) \propto j \int \frac{\frac{d\psi_0}{dE}}{\omega - n\omega_0 - nkE} dE$$

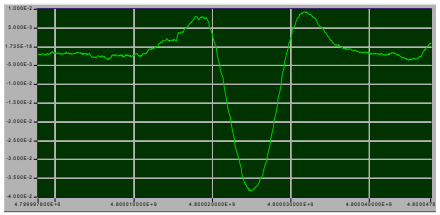
1. **Real part is anti-symmetric and proportional to the derivative of the energy distribution function**
2. **The imaginary part is symmetric and extends beyond the zero of the real part, where the interaction is pure reactive**
3. **The magnitude calibrates the impedance of the pickup and kicker**



Beam Transfer Function, 2×10^{12} protons

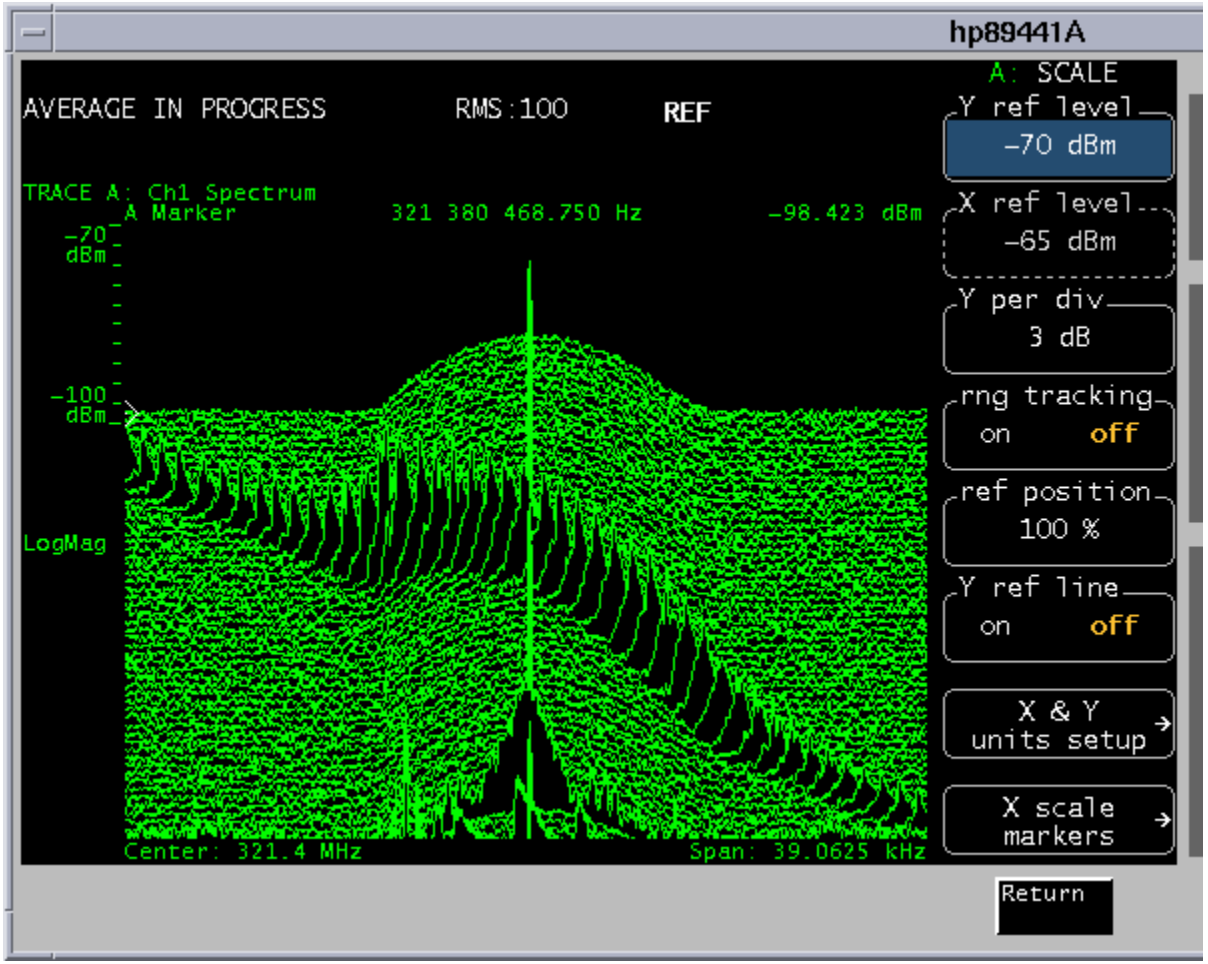


Real part, 5 GHz center frequency



Imaginary part, 50 kHz span

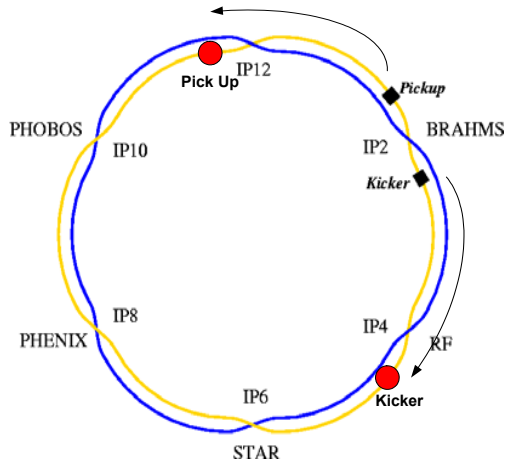
Beam Response, Protons Looking for Image Lines

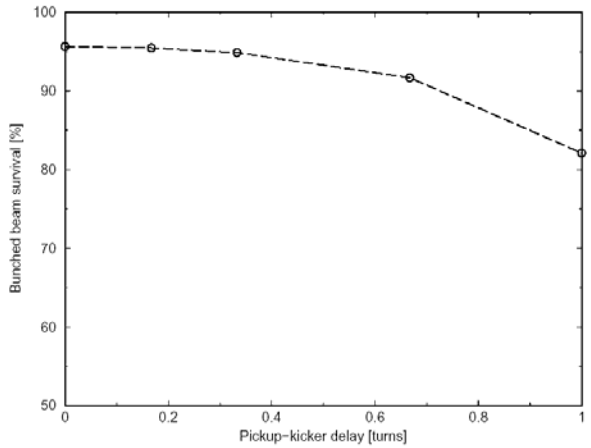


Stochastic Cooling Development Plans

1. Examine Schottky signals….. ✓
2. Measure Beam Transfer Function…. ✓
3. Demonstrate some cooling…….FY04
   a) Work with one bunch to limit power on kicker
   b) Use low-intensity bunch because of power limitation
   c) Work with witness bunch, concurrent with production stores
   d) Use Palmer cooling for simplicity
4. Design a practical momentum cooling system
   a. Frequency band , 4-8 GHz implies a 2/3 turn delay is OK
   b. Filter method, for halo cooling
   c. Kicker power requirements
      i. 10 kW = 2 M$ ball park
      ii. Higher impedance kickers (eg: slotted waveguide) [McGinnis at FNAL]
      iii. New concept, optimized for longitudinal
      iv. Power leveling (pulse expansion/compression) [proposed by F. Caspers]
      v. Fourier decomposition (only 20 lines are relevant) [proposed by Boussard for SPS]
5. In the long range, when RHIC is equipped with e-cooling, stochastic cooling would be a natural complement
   a. E-cooling works best on a cool beam. It tends to collect beam into a dense core
   b. Stochastic cooling works best on a hot beam. It could capture beam in the tails and contribute to the effective luminosity

PickUp-to-Kicker transmission goes via the Tunnel, 12 to 4 O'clock



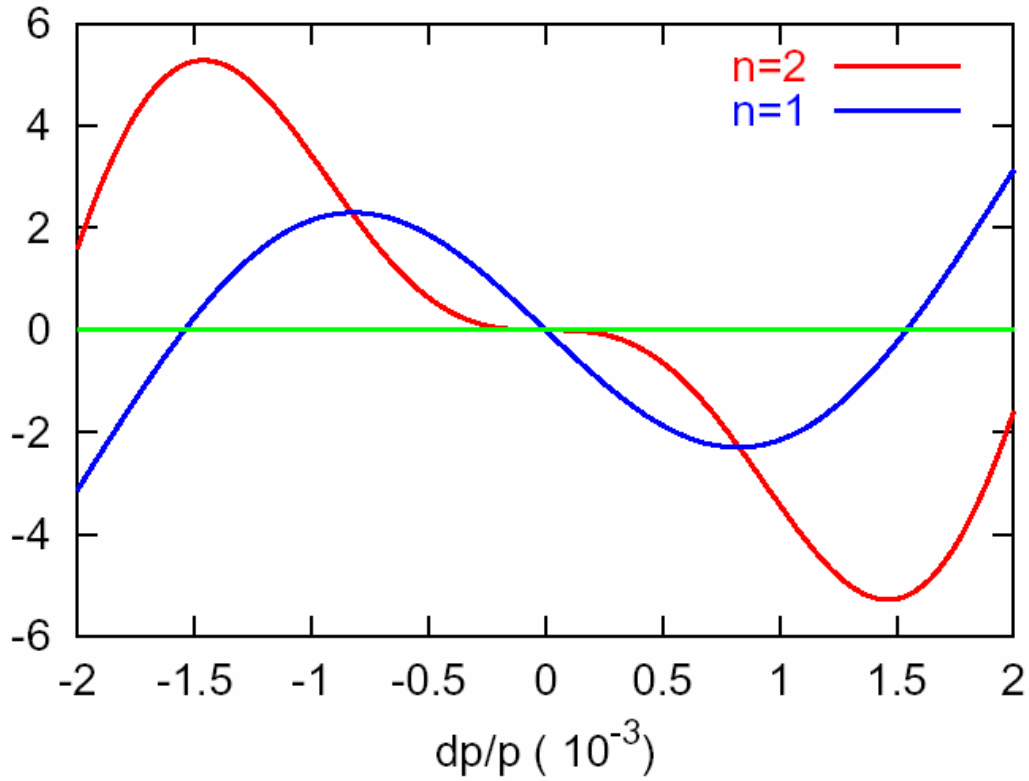


- Beam takes 8 micro seconds from 12 to 4 O'clock
- Fiber Optic line takes 6 Microseconds
- 2/3 turn delay gives only marginal reduction of cooling rate

Halo Cooling for IBS

- If the goal is to keep the beam bunched then we don't really want to cool the core, just keep the beam from crossing the separatrix
  - Cooling of the hot part of beam goes faster
    - Better mixing
    - Better signal to noise ratio
  - For a full bucket J. Wei showed (PAC 91 pp.1866) that coasting beam theory gives the correct results for cooling rate and stability limits
  - With a full bucket the synchrotron satellites completely overlap, giving good mixing
- We're not really looking to cool the beam (that will come with the electron cooling), we just need to keep it from escaping the bucket

Two-Turn Delay Filter for Halo Cooling (M. Blaskiewicz)



Kicker Size for RHIC

- 100 GeV/n, Q/A=79/197, e_{long}=1 eVs all tend to make for very large kicker voltage

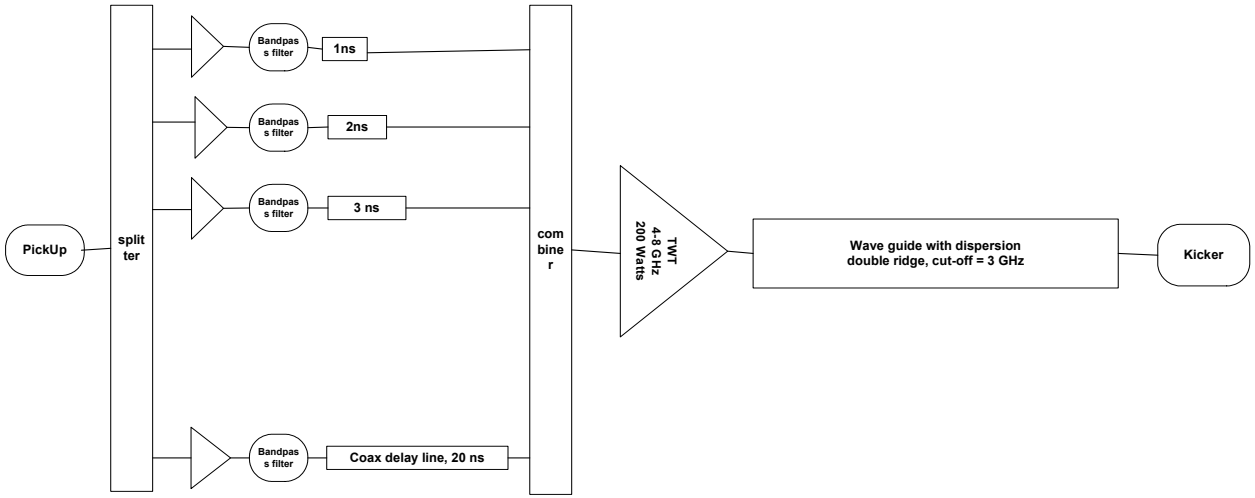
$$\delta E_{kick} = g_{opt}\frac{\sigma_E}{\sqrt{N_{sample}}} = g_{opt}\frac{\gamma A m_u \frac{\Delta p}{p}}{\sqrt{T_{sample}\frac{10^9}{5ns}}}$$

$$= \frac{1}{5}\frac{100\ x197x1GeVx10^{-3}}{\sqrt{125ps\frac{10^9}{5ns}}} = 800keV$$

$$Voltage = \frac{\delta E}{q\ x\#kickers} = \frac{8x10^5}{79x128} = 80Volts$$

$$Power = \frac{V^2}{2R}x\#kickers = 64Watts\,x\,128 = 8kW$$

Pulse Compression with a Waveguide



Challenges

- Higher impedance kicker
  - FNAL recently upgraded the stochastic cooling system for the pbar accumulator
  - Using slotted waveguide slow-wave kickers
  - We have more available insertion length (2x kickers⇒1/2 power)
- Pulse compressor (Fritz Caspers)
  - A waveguide with large dispersion (different frequencies travel at different speeds)
  - Stretch the 5 ns pulse before the TWT to 100 ns, then compress at high power before the kicker
  - Reducing the peak power by 20 reduce the cost by almost at much
  - Never been done!
- Use very many narrowband channels (Boussard SPS idea)
  - When the beam is bunched most of the spectrum is redundant information
  - 5ns bunches ⇒ kick can be constructed from Fourier components at 200 MHz
  - 4 GHz/200 MHz = 20 terms in the series
  - Make 20 narrowband, high impedance kickers

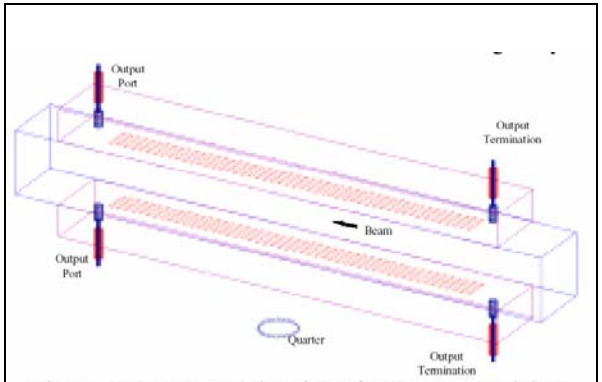
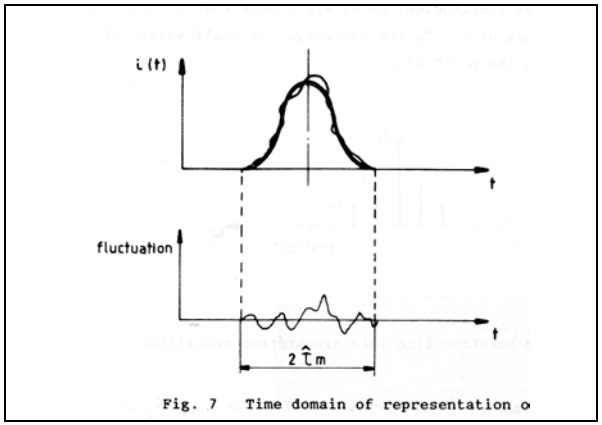



Figure 1: Conceptual drawing of a slow wave pickup