Stochastic Cooling Studies in RHIC

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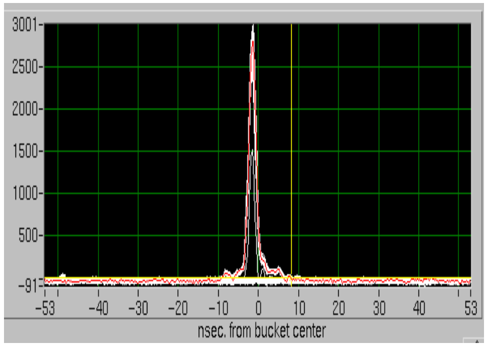
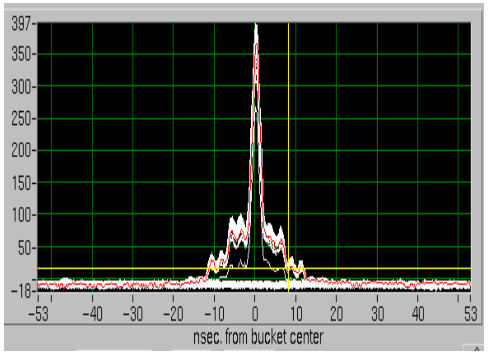
- Motivation
- Schottky Spectra
- Beam Response Function
- Status

Motivations

- RHIC luminosity is limited by:
  - Bunch intensity (~10^9 ions)
    - Instabilities (single bunch, transverse)
    - Beam-beam interaction (strong-strong regime)
  - Number of bunches (55/ring)
    - Vacuum breakdown at 110 bunches
    - Time between crossings (< 100 ns)
  - Emittance growth
    - Magnet non-linearities
    - Beam-beam interaction
    - Intra-Beam Scattering
- Longitudinal emittance growth (IBS) leads to De-bunching



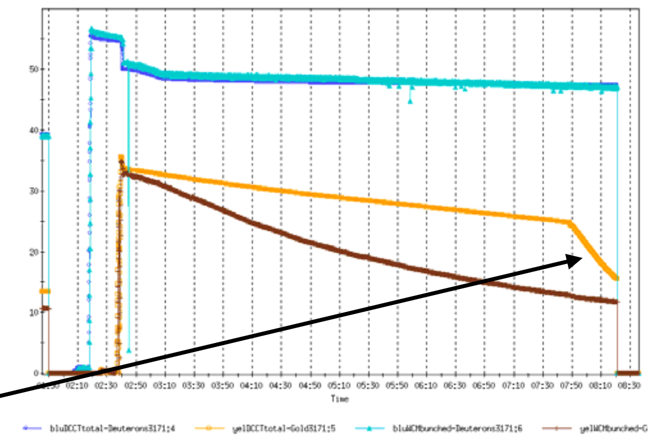
Bunch in 197 MHz bucket at start of store



Five hours into store beam has escaped the bucket and is confined by 28 MHz bucket

De-Bunching

- Particles escape the separatrix by IBS
  - Reduces the useful luminosity
  - Increases background
  - Populates the abort gap (⇒gap cleaning)



Deuteron and Gold beam during a store.
Yellow is DC gold, brown in bunched gold

•This is not news. IBS calculations for RHIC indicated 60% beam bunched beam lost in a typical store

•Calculations also showed that momentum cooling could counteract IBS and increase integrated luminosity by x 2-3

[J. Wei and A.G. Ruggiero, AD/RHIC-71 1990]

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)

$$\frac{1}{\tau} = \frac{\mathbf{W}}{\mathbf{N_{eff}}}\left[2\mathbf{g}\left(1-\tilde{\mathbf{M}}^{-2}\right)-\mathbf{g}^2\left(\mathbf{M}+\mathbf{U}\right)\right] \qquad \mathbf{g_{optimum}} = \frac{\mathbf{1}-\tilde{\mathbf{M}}^{-2}}{\mathbf{M}+\mathbf{U}} \cong \frac{\mathbf{1}}{\mathbf{5}}$$

$$\frac{1}{\tau_{opt}} = \frac{\mathbf{W}}{\mathbf{N_{eff}}}\left[\frac{\left(1-\tilde{\mathbf{M}}^{-2}\right)^2}{\mathbf{M}+\mathbf{U}}\right] = \frac{1}{3000\ \mathrm{sec}} \qquad \mathbf{N_{effective}} = \frac{\mathbf{10^9}}{\mathbf{1.5m}}\mathbf{3830m} = \mathbf{2.5x10^{12}}$$

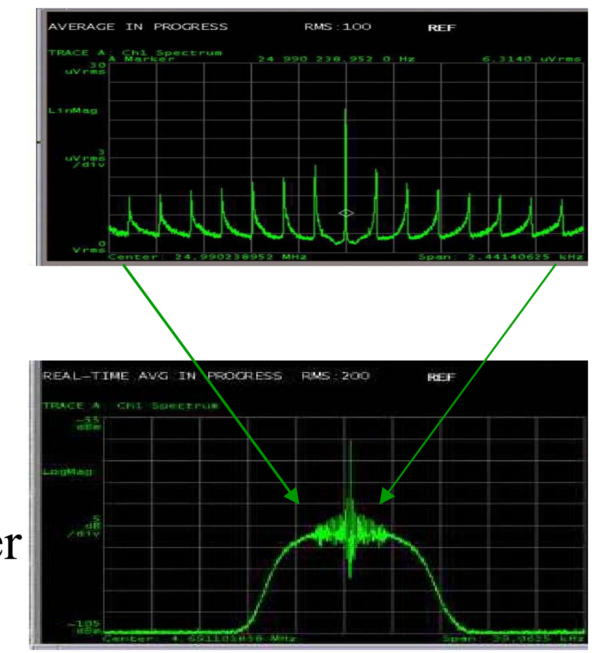
- Why wasn't stochastic cooling in the base line design for RHIC?
- High frequency bunched-beam stochastic cooling is required

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

Schottky Spectra

- *"if you want to find out if cooling can work look at the Schottky signals"* (consensus of experts)
  - Signal to noise ratio
  - Mixing situation
  - Anomalous coherence

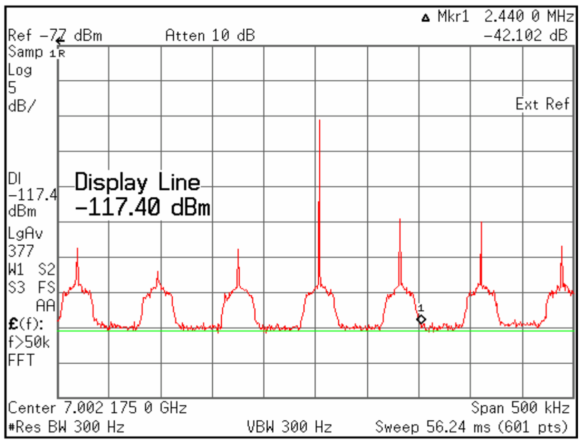


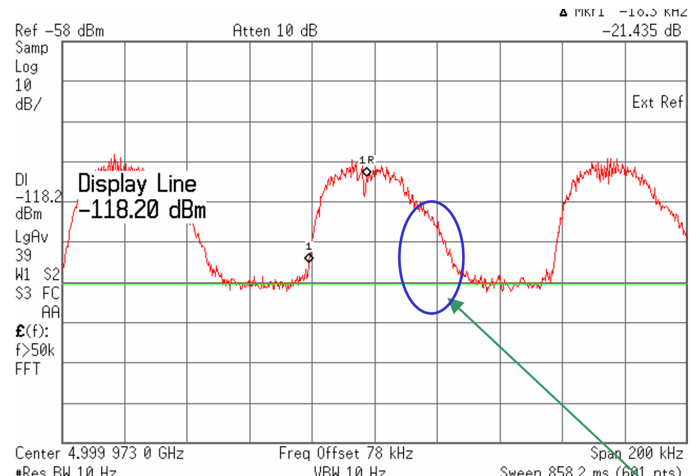
- The signal to noise ratio is high for ions
  - For the same number of charges in the ring the Schottky power from ions is Q times larger than from protons

Schottky signals from 2.7 GHz narrowband pickup. Many synchrotron sidebands are resolved. Signal to noise ration > 25 dB.

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



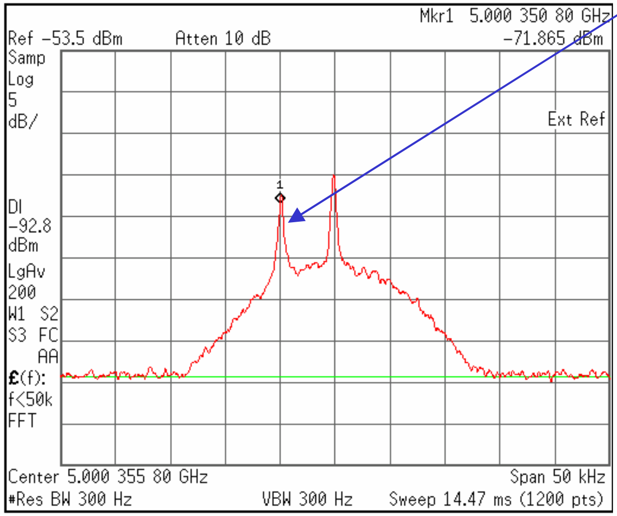


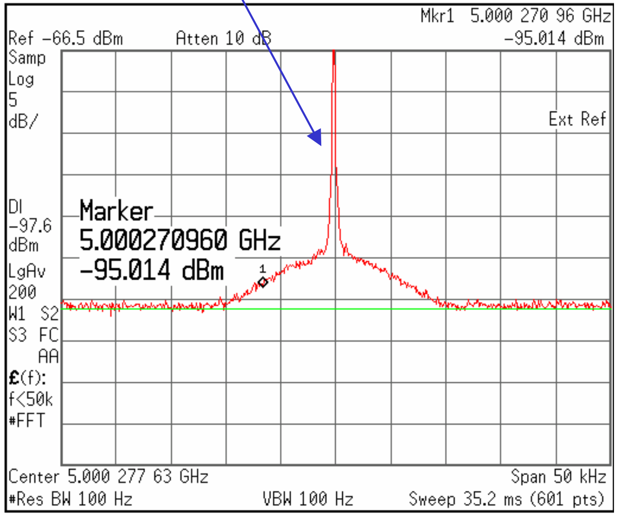
1. At 7 GHz early in a store, via 150 m cable
2. Coherence lines show up at harmonics of the bunch frequency

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





Longitudinal Beam Transfer Function

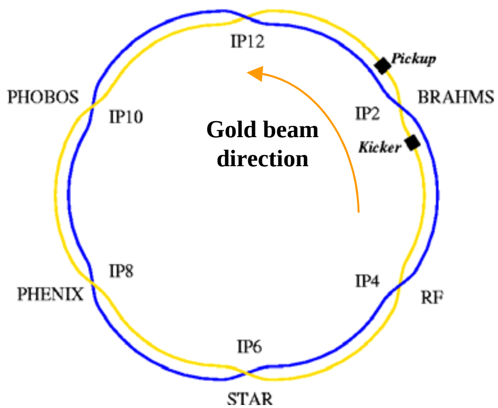
• The beam transfer function represents the beam's response to stimulus of the kicker

• It is a key part of feedback loop of a cooling system

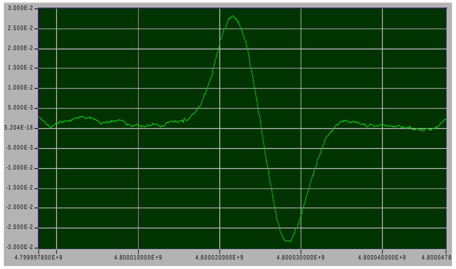
•For a coasting beam it is given by the dispersion integral,

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

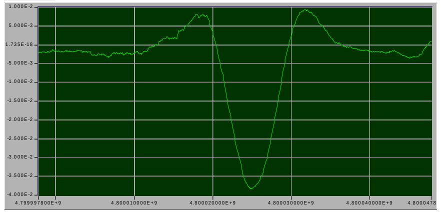
1. **Real part is anti-symmetric and proportional to the derivative of the energy distribution function**
2. **The imaginary part is symmetric and extends beyond the zero of the real part, where the interaction is pure reactive**
3. **The magnitude calibrates the impedance of the pickup and kicker**



Beam Transfer Function, $2\text{x}10^{12}$ protons



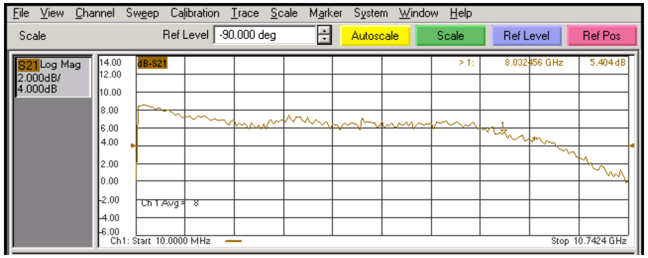
Real part, 5 GHz center frequency



Imaginary part, 50 kHz span

Tests Now in Progress

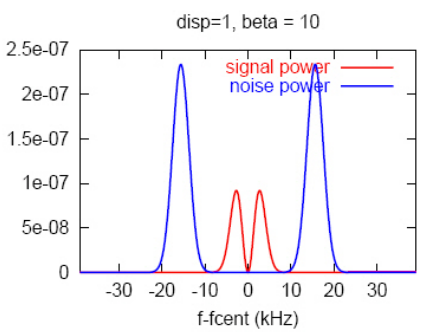
- Plans for FY04 Run
  - Relocation of pickup and kicker (2/3 turn delay)
  - TWT amplifier in tunnel
  - Fiber Optic cable from Pickup to control room
    - Signal delay measured to be acceptable



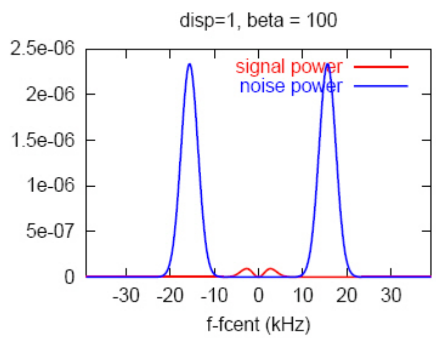
  - Gating on one bunch
    - Kicker power limit overcome
    - Parasitic studies (low intensity bunch)
  - Palmer cooling experiment (attractive for its simplicity)
    - Not viable with available lattice (dispersion/beta function)

Palmer cooling turns out not to be an option

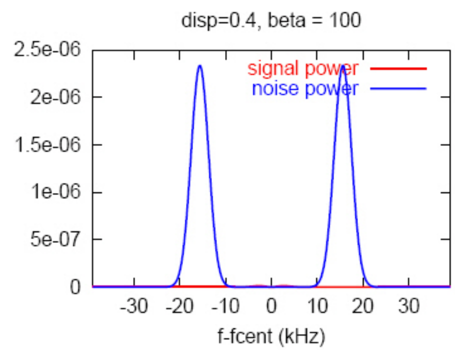
- Lattice problem for dispersion outside an arc
- Calculation of signal (longitudinal) to noise (betatron) for realizable lattice shows difficulty



Original plan

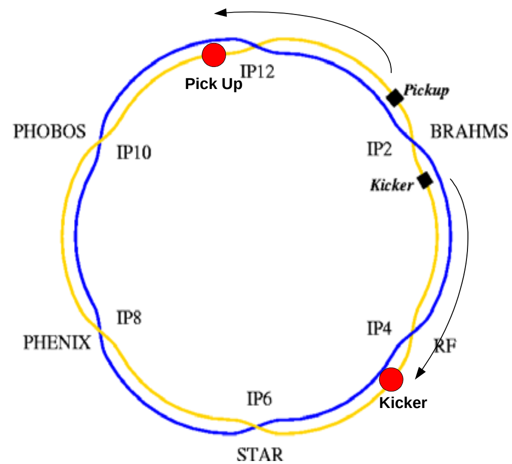


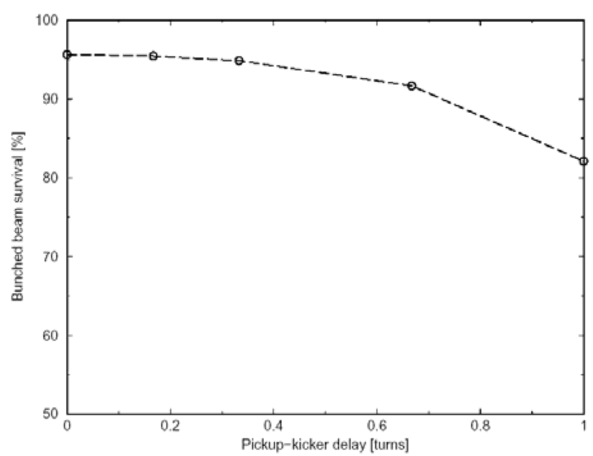
Compromise plan



Realizable lattice

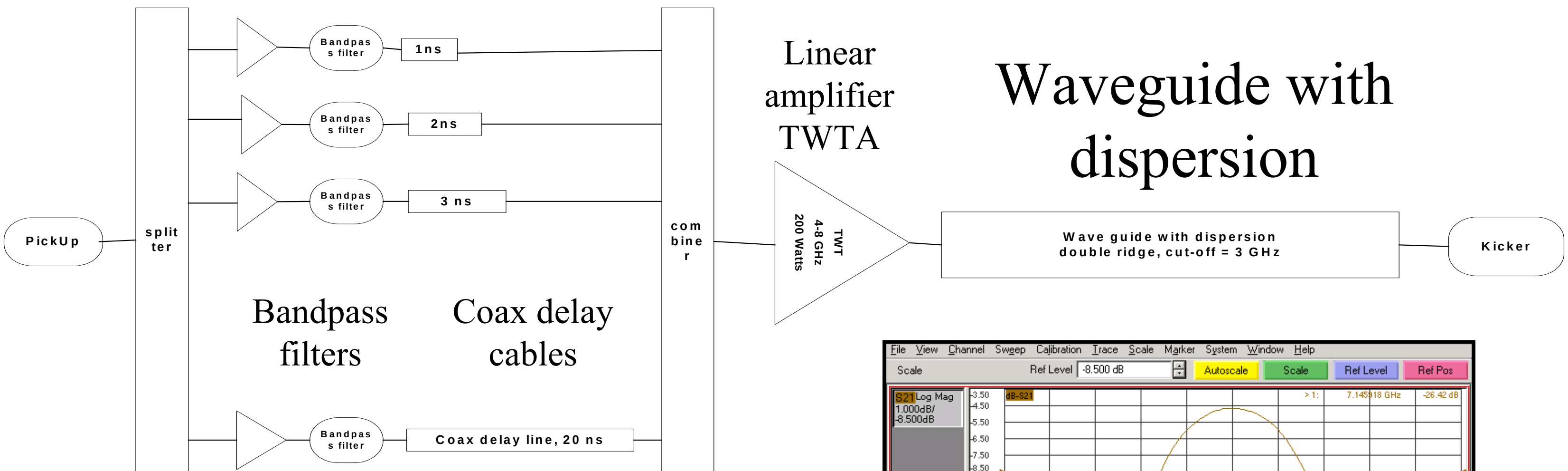
PickUp-to-Kicker transmission goes via Fiber Optics in the Tunnel, 12 to 4 O'clock

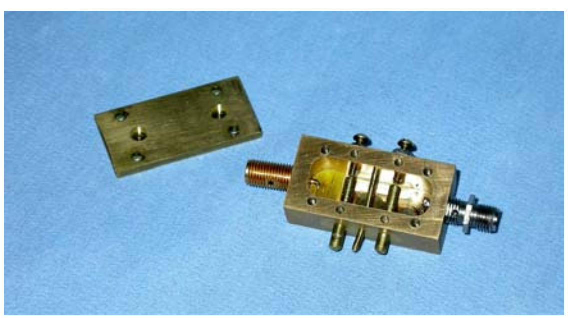




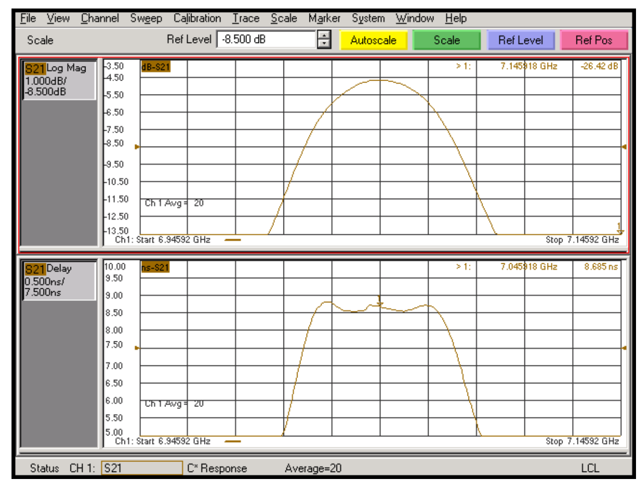
- Beam takes 8 micro seconds from 12 to 4 O'clock
- Fiber Optic line takes 7.5 Microseconds
- 2/3 turn delay gives only marginal reduction of cooling rate

Pulse Compression with a Waveguide and Discrete Frequency Bands





Home-made filter



Flat group delay

An extension of this concept is discrete frequency (narrowband) kickers

- Because the beam is bunched the "information" in the S.C. signal can be resolved into a discrete set of Fourier components

- The fundamental frequency is 1/bunch length= 200 MHz

- 20 components span 4 – 8 GHz

- 20 high Q cavities can synthesize the kick

- R/Q=100, Q= 1000, -> 5 Watts

EMPOWER RF SYSTEMS, INC. | MBM65709K 6.5 – 7.0 GHz / 8 W Amplifiers

FEATURES

- P-1 dB: 39 dBm
- Noise Figure: 4.5 dB
- IP3: 47 dBm
- Bias Condition: 4700 mA @ 12 V
- Small Signal Gain: 41 dB

DESCRIPTION

The MBM65709K is an 8 W power amplifier designed for high linearity applications in the 6.5 to 7.0 GHz frequency range. This amplifier utilizes high power devices that provide excellent linearity, high gain and wide dynamic range. Exceptional performance operation is achieved by using hybrid MIC designs and advanced GaAs PHEMT devices. The Empower ISO9001 Quality Assurance Program assures consistent performance and the highest reliability.

ELECTRICAL SPECIFICATIONS at 25 ° C

Parameter	Symbol	Min.	Typ.	Max.	Unit
Frequency Range	FREQ	6.5		7.0	GHz
Small Signal Gain	SSG	41*			dB
Small Signal Gain Flatness	GOF		± 0.5	± 0.75	dB
Output Power at 1 dB Gain Compression	P-1 dB	38	39		dBm
Output Power at 3 dB Gain Compression	P-3 dB	39	40		dBm
Third Order Intercept Point	IP3	46	47		dBm
Noise Figure	NF		4.5	5	dB
Input / Output VSWR	S11 / S22		1.5:1	1.7:1	-
DC Supply Voltage	Vdc		12		Volt
Current Supply	Idc		4.7	4.9	A
Operating Temperature Range	OTR	-30		60	°C

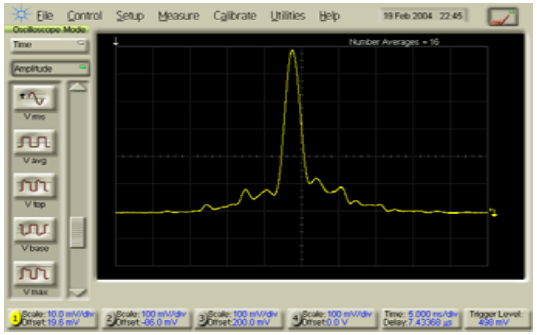
* Actual gain and current depend on configuration.

MECHANICAL SPECIFICATIONS

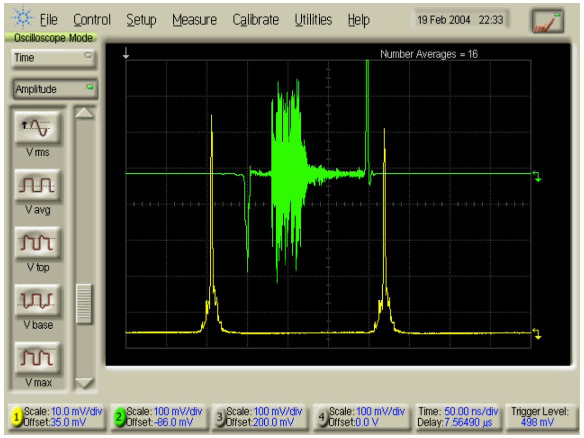
Parameter	Value	Units	Limits
Dimensions	2.9×2.34×0.63	Inch	Max
RF Connectors In/Out	SMA Female		

The Coherent Problem

– Understanding pickup response
  - Looking in the time domain
  - The bunch structure stimulates “resonances” in the pickup
  - They are very large signals
  - Will require time domain filtering

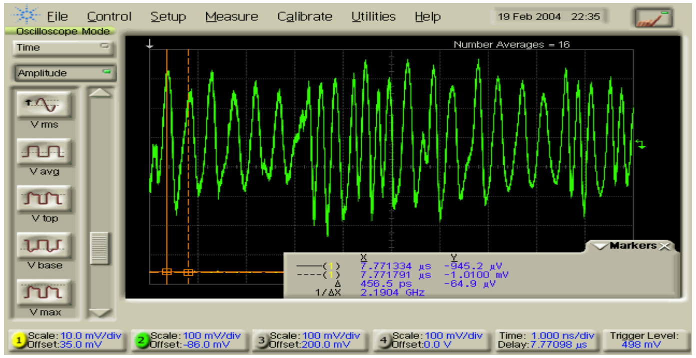


Complicated bunch structure due to satellites



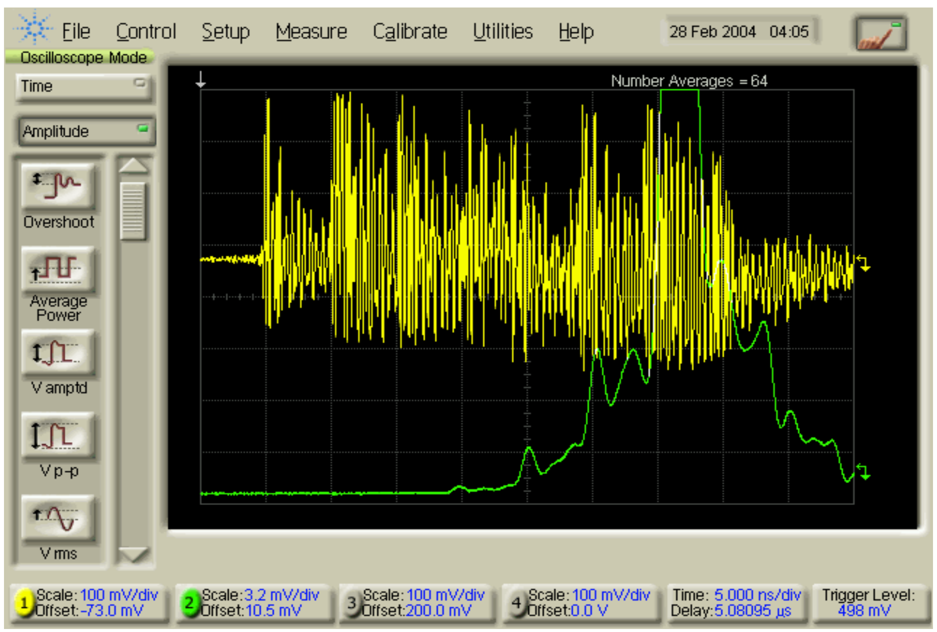
A burst of signal from the pickup,

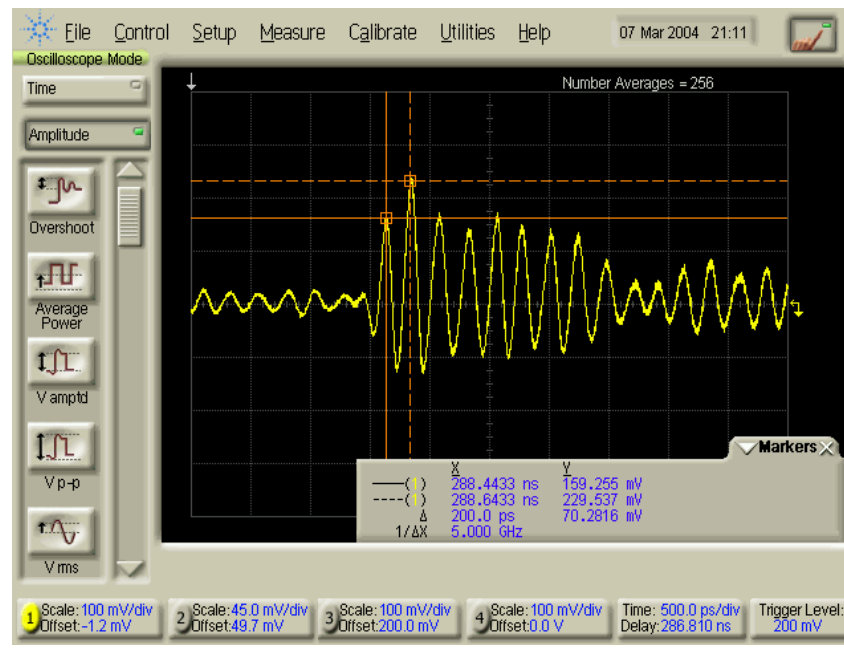
And the bunch profile



Very high frequency structure is stationary at the revolution frequency

Very High Frequency Components in the Bunch Dominate the Response

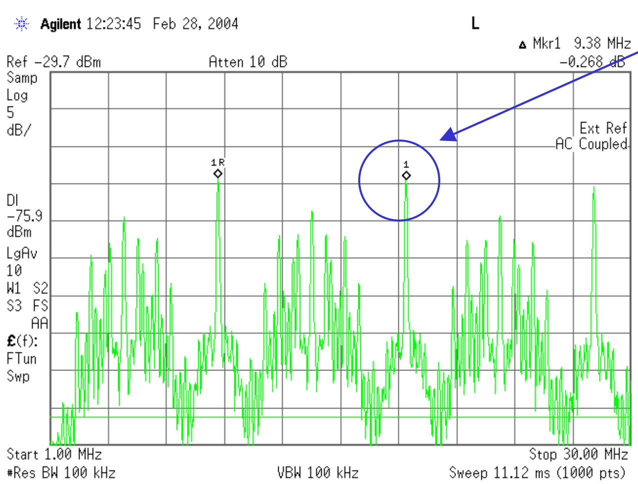




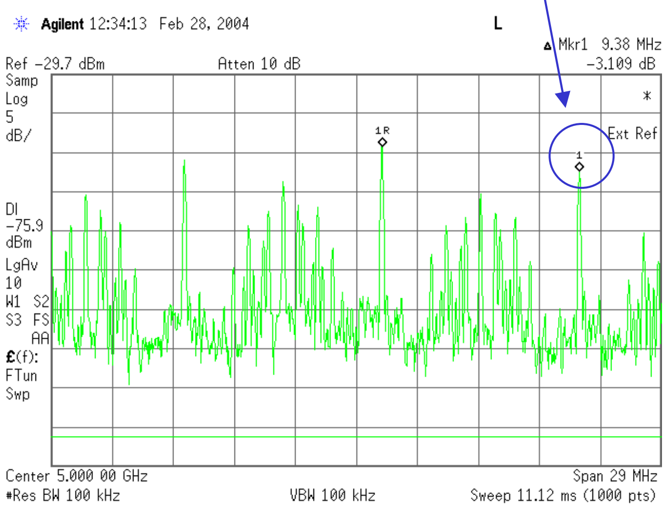
Bunch structure (high gain) and Pickup response (5 GHz ringing)

The Frequency Domain Corroborates this Interpretation

- The ratio of the coherent part (bunch frequency harmonics) to Schottky part is the same at 10 MHz and 5 GHz



10 MHz

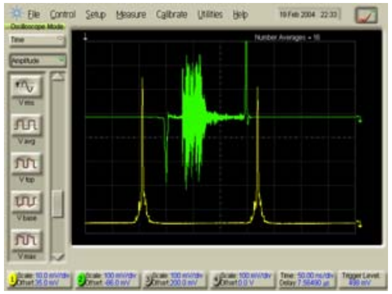


5 GHz

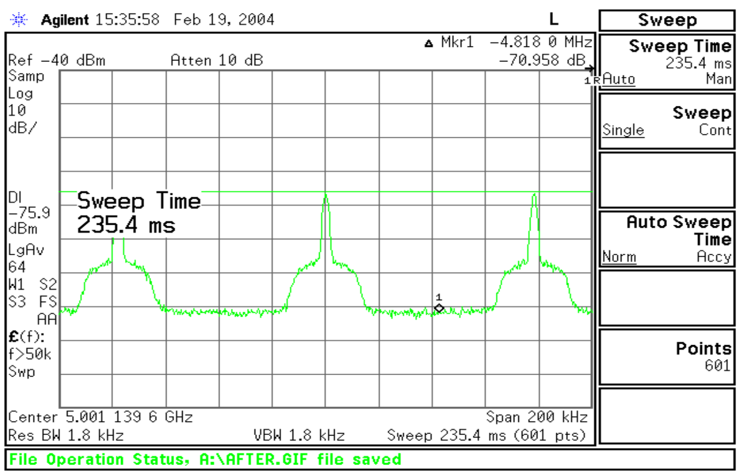
Coherent signals contribute as $N^2_{particles}$

– Equivalently, gating one bunch or measuring all bunches gives a reduction of the coherent component by

$$□ \sqrt{N_{\text{bunches}}} = 18\text{dB}$$

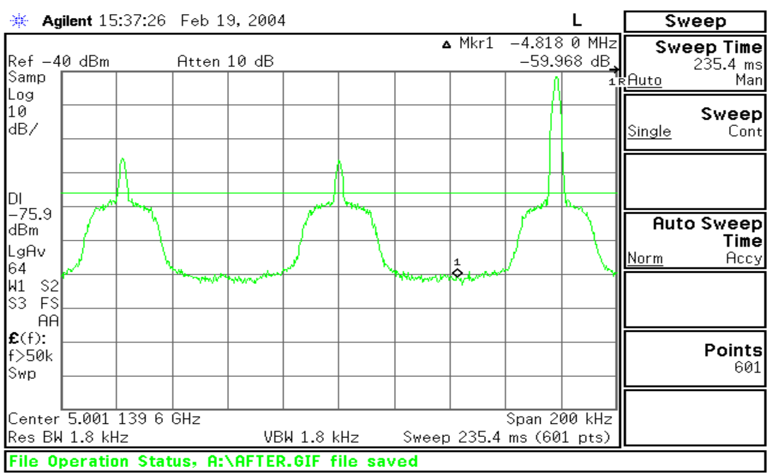


Gated bunch



Each bunch has a coherent part

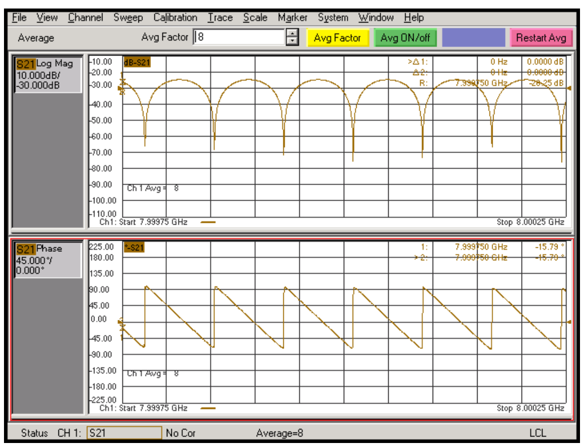
(contributes as N)



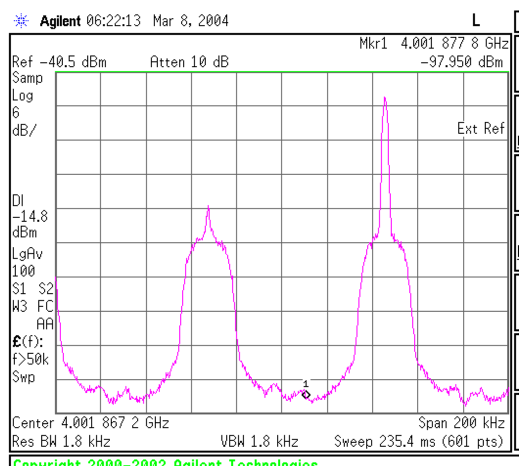
At the bunch frequencies they add coherently (contributes as N^2)

The Fiber Optics are use to make a one turn delay correlator filter

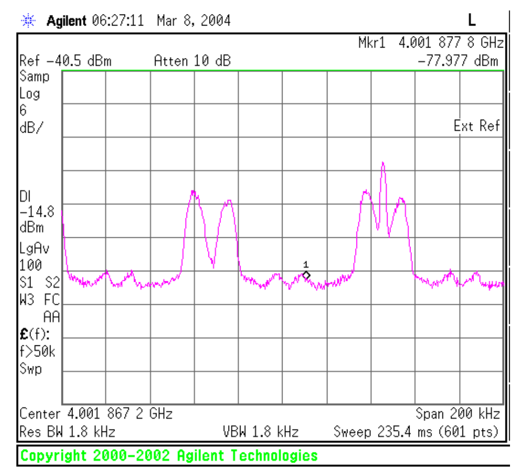
- The filter solves the coherent signal problem
- It also replaces Palmer cooling as the feedback technique
- Fiber Optics provides 12.78889 microseconds of delay



Delay line Filter



Unfiltered beam



Filtered Beam

Stochastic Cooling Development Plans

1. Examine Schottky signals…..
2. Measure Beam Transfer Function….
3. Demonstrate some cooling…….FY04 (well, maybe not)
4. Design a practical momentum cooling system
    a. Filter method (Palmer cooling ruled out)
        i. Halo cooling by optimized filter
        ii. Removes "coherent signal"
    b. Frequency band
        i. 4-8 GHz implies a 2/3 turn delay is OK
        ii. 9 GHz is max without 'cutting a cord"
    c. Kicker power requirements
        i. 10 kW = 2 M$ if we don't do anything new
        ii. Higher impedance kickers (slotted waveguide) [McGinnis at FNAL]
        iii. Power leveling (pulse expansion/compression) [proposed by F. Caspers]
        iv. Fourier decomposition (20 narrowband kickers) [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

Conclusions

- Bunched-beam stochastic cooling continues to look promising for counteracting IBS driven debunching
- Our technology and expertise continues to develop due to practical experience with beam
- The cost driver of an operational system is kicker (power amplifier) technology. There is still a wide range of options and the concentration of effort for the next phase will be here.
- The possibility of eventually implementing transverse cooling remains open.