Bunched Beam Stochastic Cooling at RHIC

Mike Brennan and Mike Blaskiewicz

COOL07

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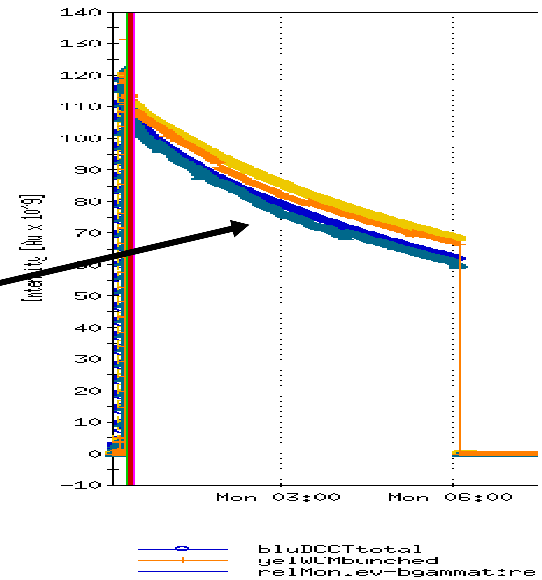
Motivation and Context

- Stochastic cooling is a mature and effective technique for reducing phase space volume
  - Antiproton accumulation at SppS and Tevatron
  - Precooling heavy ions before electron cooling

- At RHIC we want to counteract IBS during stores to increase integrated luminosity
- Prevent de-bunching (halo cooling)
- The challenges for RHIC S.C. are:
  1. A cooling time of about 1 hour is required
  2. Beam energy is 100 GeV/nucleon
  3. **The beam is bunched to 5 ns in 200 MHz rf buckets**



Why S.C. for bunched beam is different from coasting beam

1. High particle density
2. Synchrotron motion affects mixing
3. Coherent components in the Schottky spectrum

Particle density is high for bunched beam

- The standard cooling rate formula becomes;

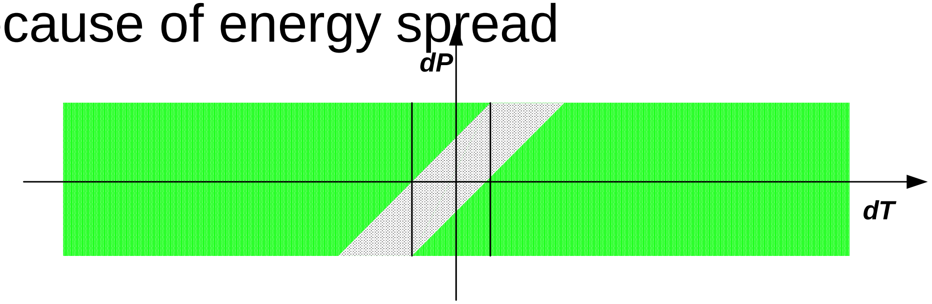
$$\tau_{cool} = \frac{1}{g_{opt}} \frac{N_{effective}}{2BW} \quad \text{where}: N_{effective} = \frac{N_{bunch}}{\text{bunch length}} X\, 2\pi R$$

- For RHIC @ 10^9 per bunch $N_{effective} = 2 \times 10^{12}$
- BW=3 GHz $> \tau_{cool} \approx$ ½ hour, OK for IBS growth rate

Synchrotron motion affects mixing

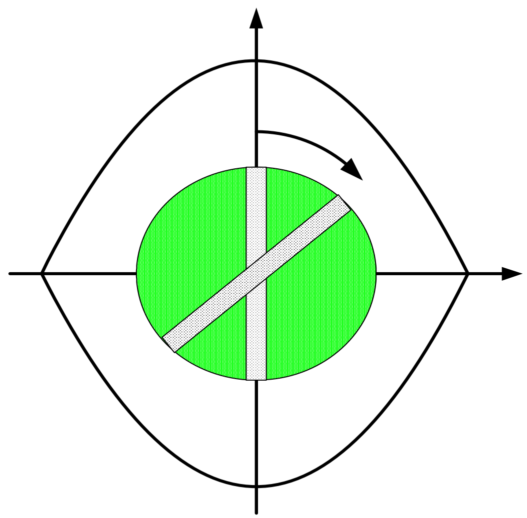
- In a coasting beam mixing comes from frequency slip
- Particles drift out of the "sample" because of energy spread

$$\frac{\Delta T}{T_{rev}} = \left(\frac{1}{\gamma^2} - \frac{1}{\gamma_{T_r}^2}\right)\frac{\Delta P}{P}$$



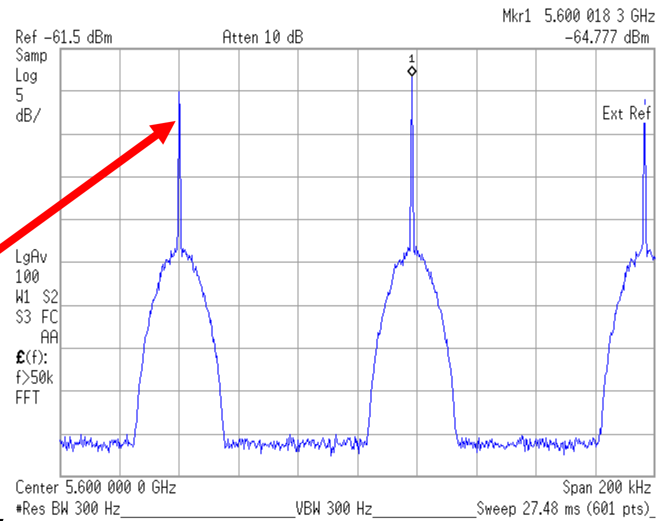
•For bunched beam, motion in synchrotron space is correlated and the samples are not random, the same particles reappear in the sample after a few milliseconds with the same neighbors

•In RHIC we have a full bucket and although the beam is bunched it behaves more like coasting beam because of the spread in synchrotron frequencies



Coherent Components in the Schottky Spectrum

- The Schottky spectrum is the (small) “AC signal from a DC beam”
- For bunched beam the Schottky signal competes with the coherent bunched signal

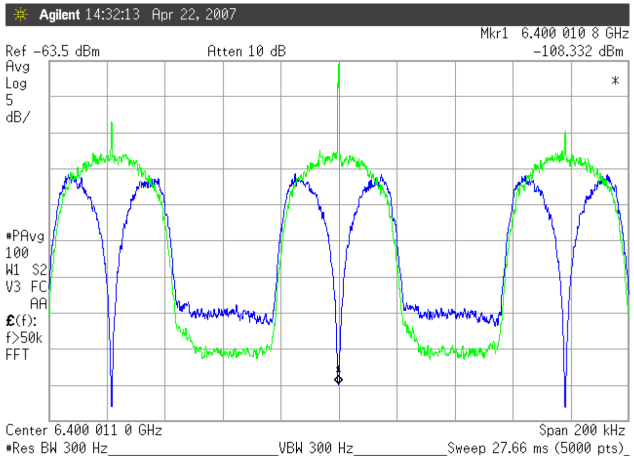


- Since the signal is weak we must work at high frequency where the beam is quasi-DC
  - 8 GHz implies 40 wavelengths in the bunch
  - for a Gaussian bunch, σ=1ns, the coherent signal is 100 dB below the Schottky
- In reality it can be 30 dB **above** the Schottky

Coherent components are THE technical challenge to bunched beam S.C.

- They are not “anomalous”
  - Not caused by solitons or instabilities
  - Manifestation of the bunch shape
- We have to cope with them
- See extra slides

To cope with coherent components we have to filter the pick up signal

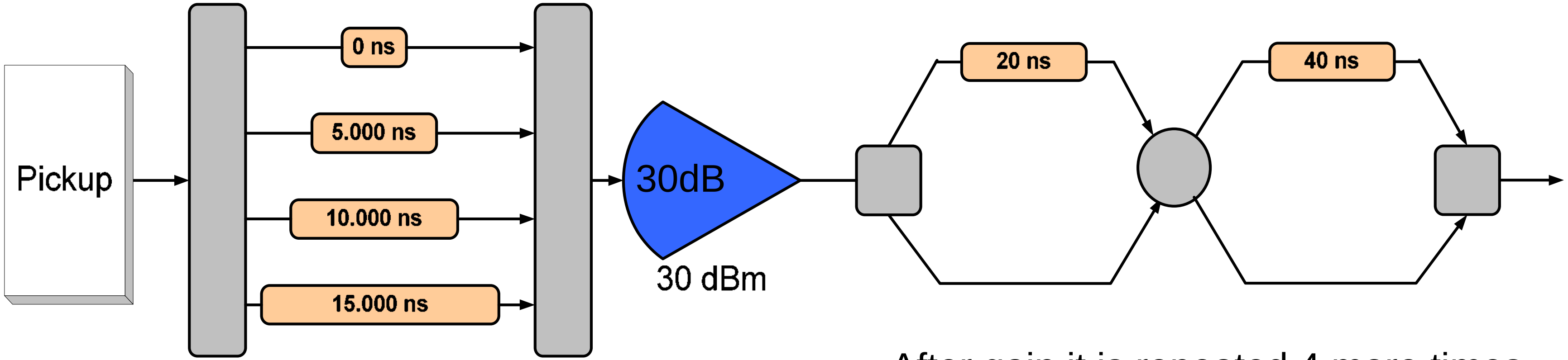


$$V_{out} = gV_{in}(1+\varepsilon V_{in}^2)$$

$$f = f_1 + f_2 - f_3$$

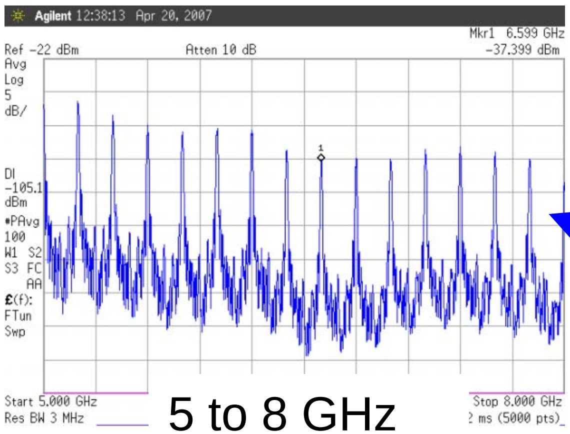
- We use a notch filter for momentum cooling, so what's the problem?
  - Real information could be lost before the filter is applied
  - Inter-Modulation Products (three wave mixing) can corrupt the signal
  - It's a time-domain problem, high peak voltages
  - We must filter before any active stage, gain or fiber optic (used for the notch)

Solution to the Coherent Line Problem



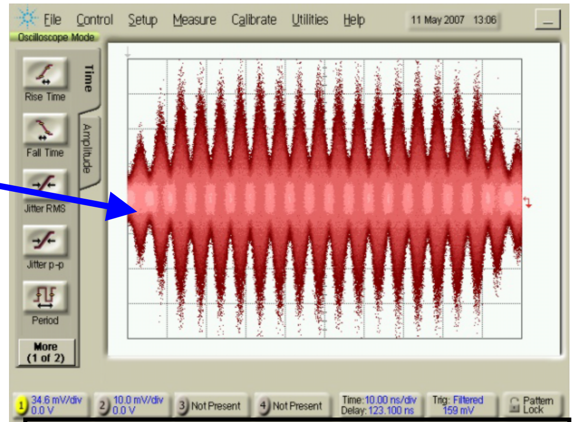
The 5 ns bunch signal is split and delayed 4 times, reducing the peak by ¼, 20 ns out

After gain it is repeated 4 more times, to 80 ns. The time between bunches.



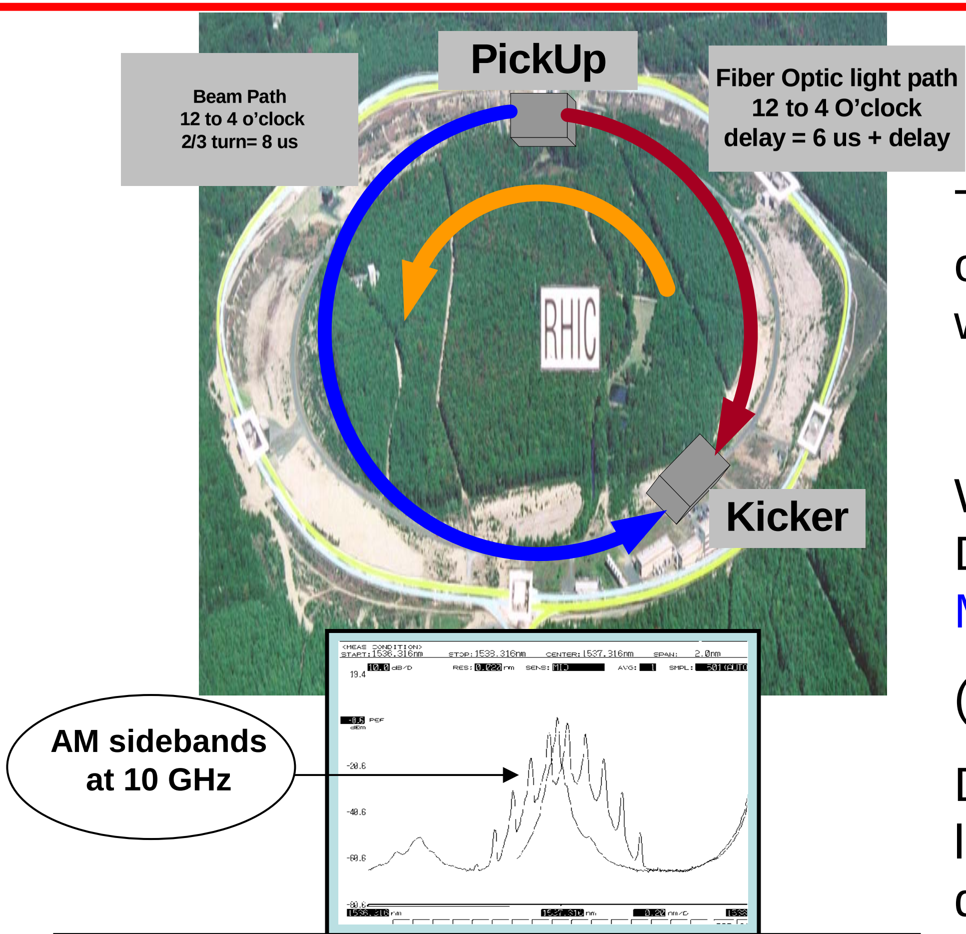
Time domain

Frequency domain



Output of traversal filter for 5 ns bunch, 10 ns/Div

The signal is sent from Pickup to Kicker via Fiber Optic (v/c=0.7)



Spectrum of optical carrier at 1550 nm

The dynamic range in the analog fiber optic link from pickup to kicker is the weak link in the signal processing.

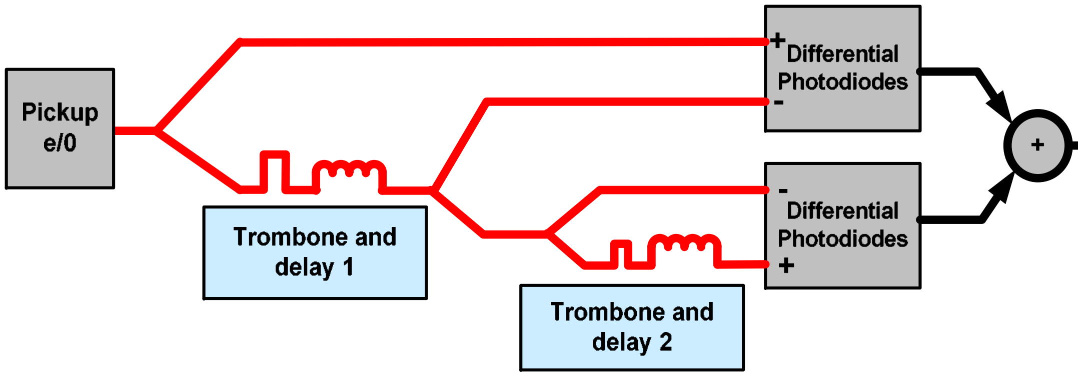
We switched from "Direct Modulation" DFB laser to "Electro-Absorption Modulation" DFB laser @1550 nm.

(PHOTONICSystems, Inc.)

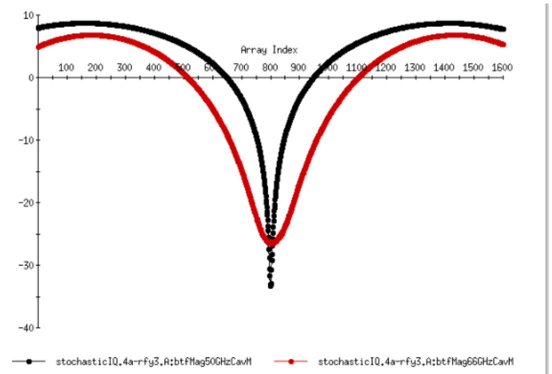
Direct modulation introduces a very large chip on the light and the dispersion in 3 km of fiber makes strong distortion

Two-Turn Filter for Halo Cooling

$$S(\omega) = (1 - e^{-i\omega T_{rev}})^2$$

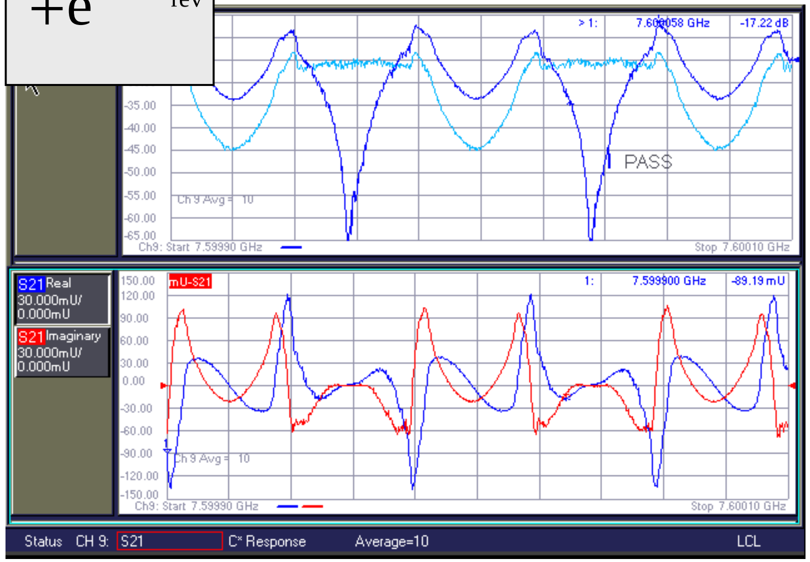


$$1$$
$$-e^{i\omega T_{rev}}$$
$$-e^{i\omega T_{rev}}$$
$$+e^{i2\omega T_{rev}}$$



Black: single turn, Red: two turn

- Two turn filter extend momentum reach and prevents de-bunching
- Differential photodiodes (Discovery Semiconductor) with >35 dB CMR give deep notches across 5 – 8 GHz band with no equalizer



BTF, Real part (blue) changes sign about Frev

Cavity Kickers

- The voltage that the kicker has to provide is given by the size of the energy fluctuation detected by the pickup
- 3 kV with a 50 Ohm kicker would take 90 kW
- We can exploit the fact that the beam is bunched
- Use the time between bunches for "pulse compression"
- We use high-Q cavity kickers
- ~ 20 Watts each for 16 cavities

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

$$= \frac{1}{5} \frac{100 \text{ x } 197 \text{ x} 1GeV \text{x} (0.3 \text{x} 10^{-3})}{\sqrt{125ps \frac{10^9}{5ns}}} = 250 \text{ keV}$$

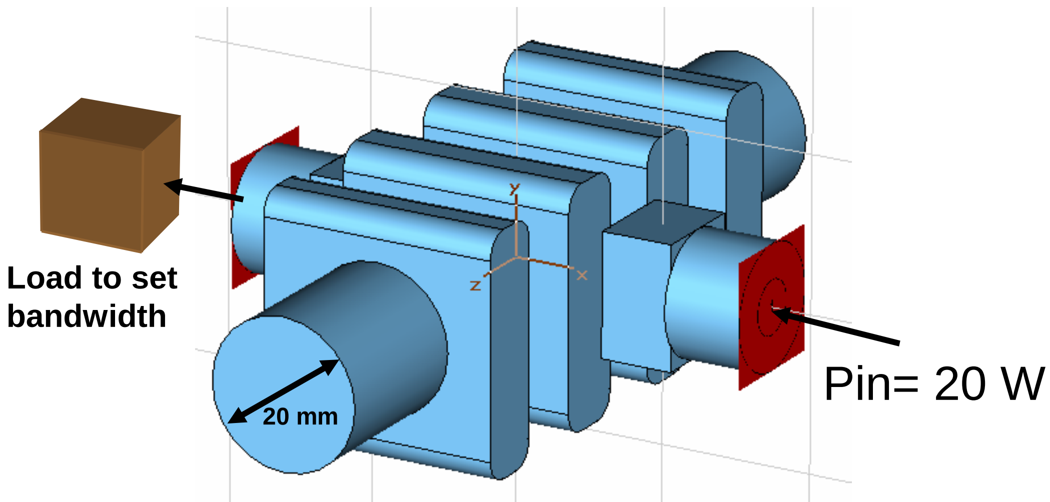
$$V_{kicker} = \frac{\delta E_{kick}}{79} = 3kV$$

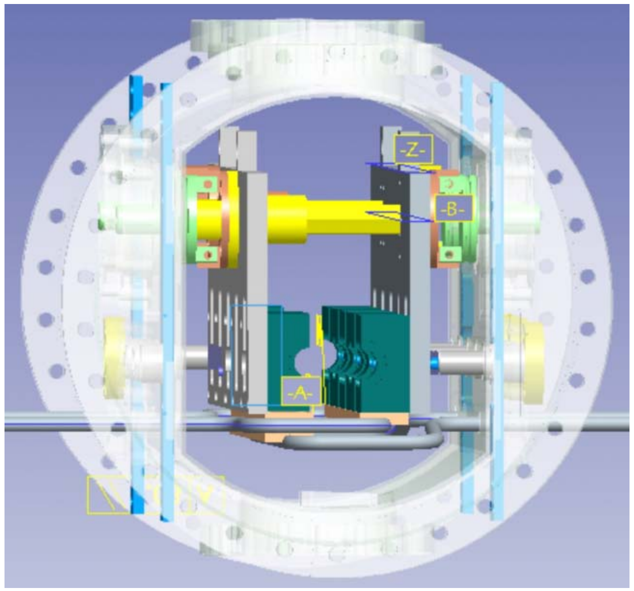
High Q and Broadband (?)

- Expand the kick signal in a Fourier series. The lowest frequency needed is 1/bunch length = 200 MHz
- Bandlimit the series to 5 – 8 GHz and there are only 16 lines (recall the traversal filter at the pickup)
- We have a cavity for each line.

Kicker Cavities

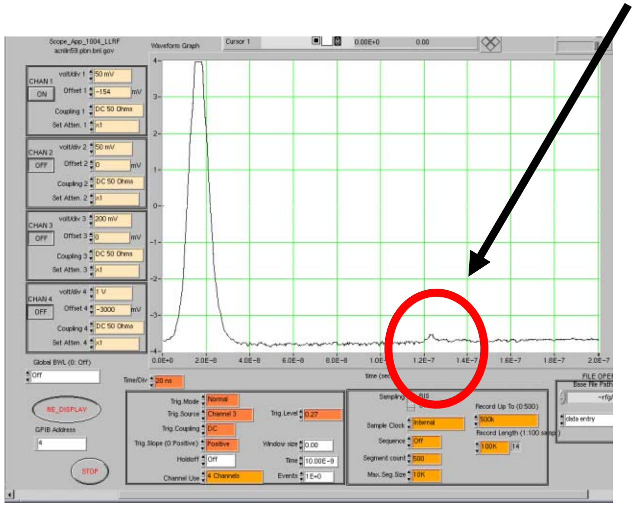
- Fill-time (bandwidth) is limited by the time between bunches, =100 ns > 10 MHz > Q~800
- Maximize R/Q (100 ohm) with four-cell cavities
- Open the 20 mm bore for filling and ramping

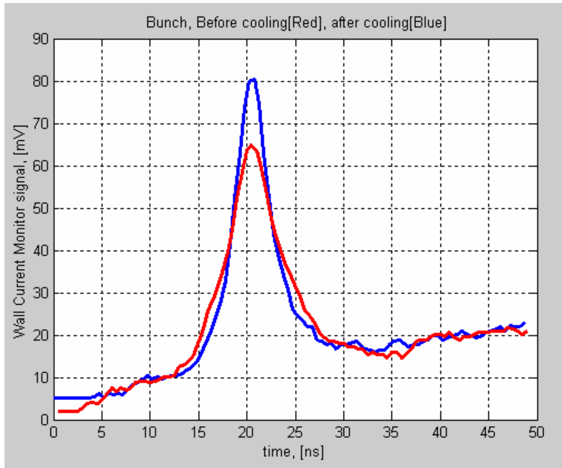




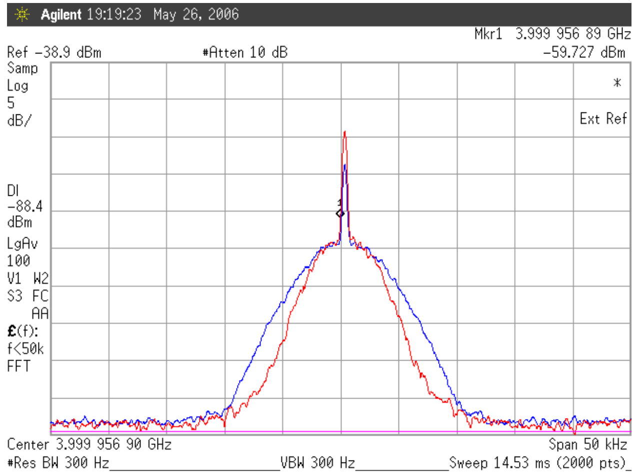
Results, with protons

- In FY06 RHIC ran with protons only
  - 10^{11} per bunch = 100 x ions
  - Prepared one test bunch with 10^{9} particles as analog of an ion bunch
- Cooling of the test bunch was successful





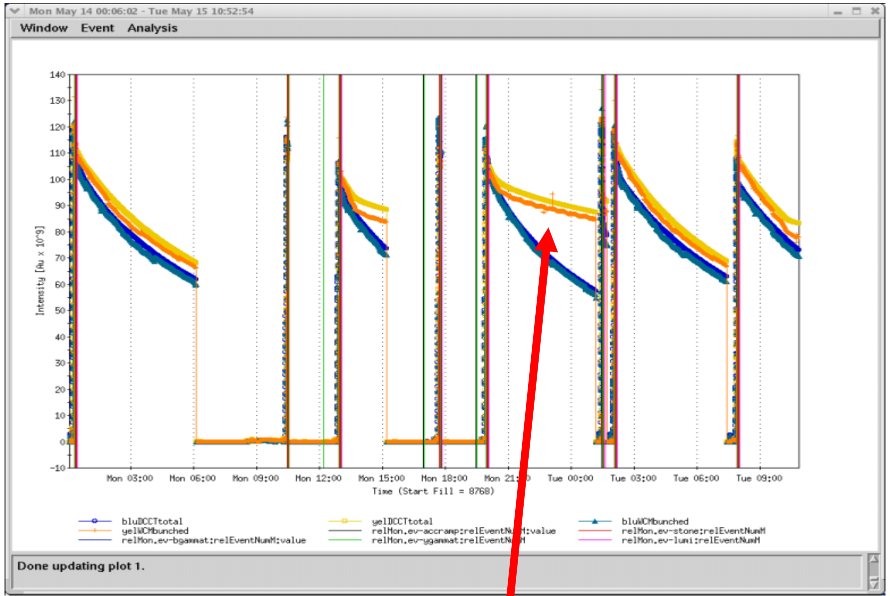
Wall current monitor of cooled test bunch (blue)



Schottky spectrum of cooled test bunch (red)

Results, with Gold Ions

- In FY07 RHIC operated with gold ions
- The stochastic cooling system in one ring was commissioned and turned over to operations
- The beam loss rate has been reduced to the “burn off” level (beam is lost to collisions only)
  - Cooling prevented de-bunching
  - Gated off during abort gap

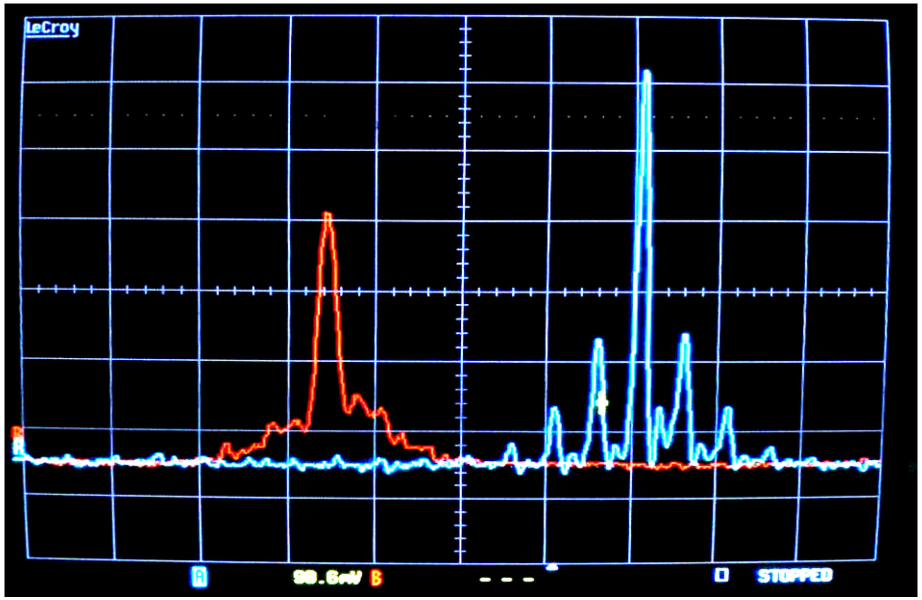


This was the first store with cooling running in the Yellow ring

Beyond Halo cooling

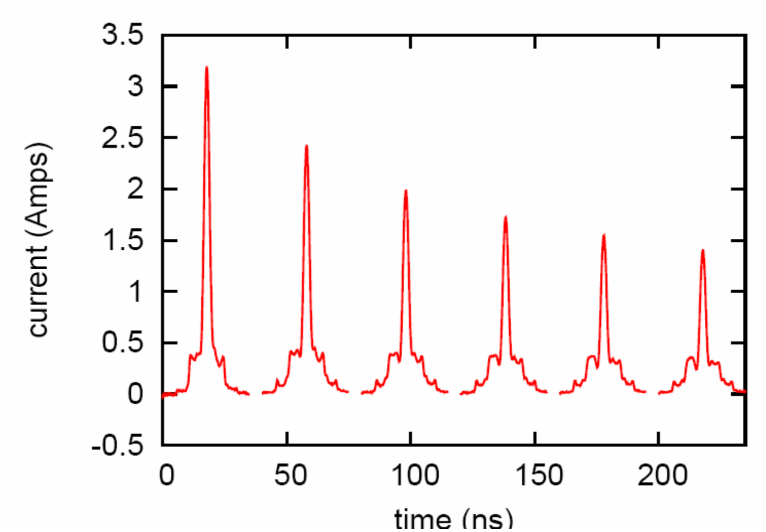
- The longitudinal emittance is **reduced**
- Compare cooled and un-cooled bunches

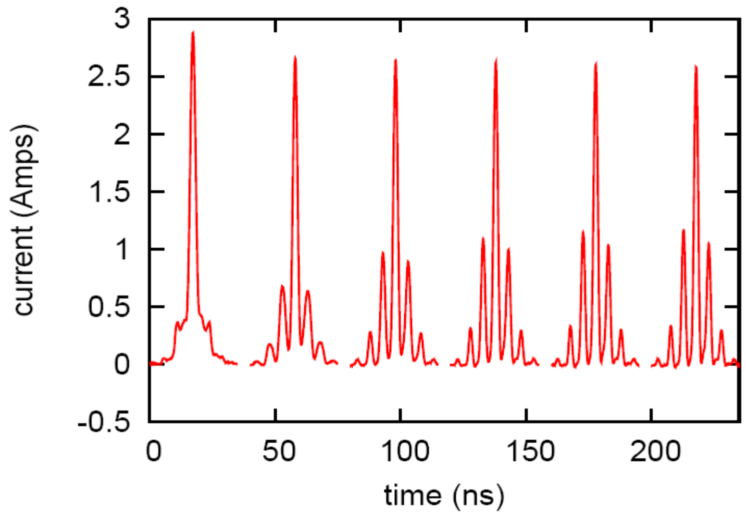
Cooling was applied to half of the bunches



The peak current increased.
Beam in the satellites was cooled

Evolution of a bunch over 5 hour store, without and with cooling





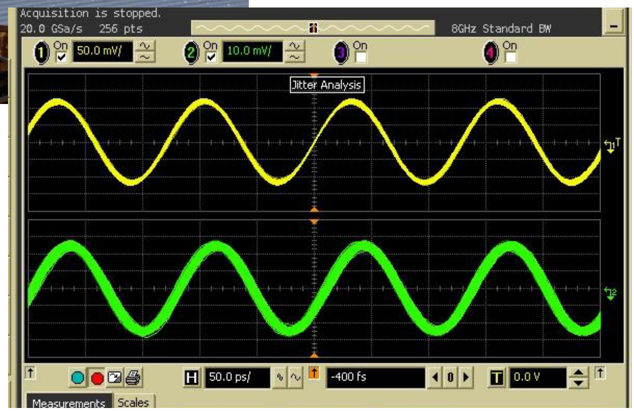
- Wall current monitor measurements of bunch shape
- Un-cooled on left, cooled on right
- Each profile to the right is one hour later
- Beam in the satellite buckets remains a challenge

Plans

- Cut the chord in the blue ring this year

Cutting the Chord, core cooling

- Microwave link (70 GHz)
  - Suggested by Fritz Caspers @ cool05
  - Can use one-turn filter
  - Higher frequency>more particles
  - Installed and tested with beam
- Timing w.r.t beam: ok
- Stabilized with pilot tone: ok
- Signal-to-noise: not ok



10 sec sample @ 8 GHz

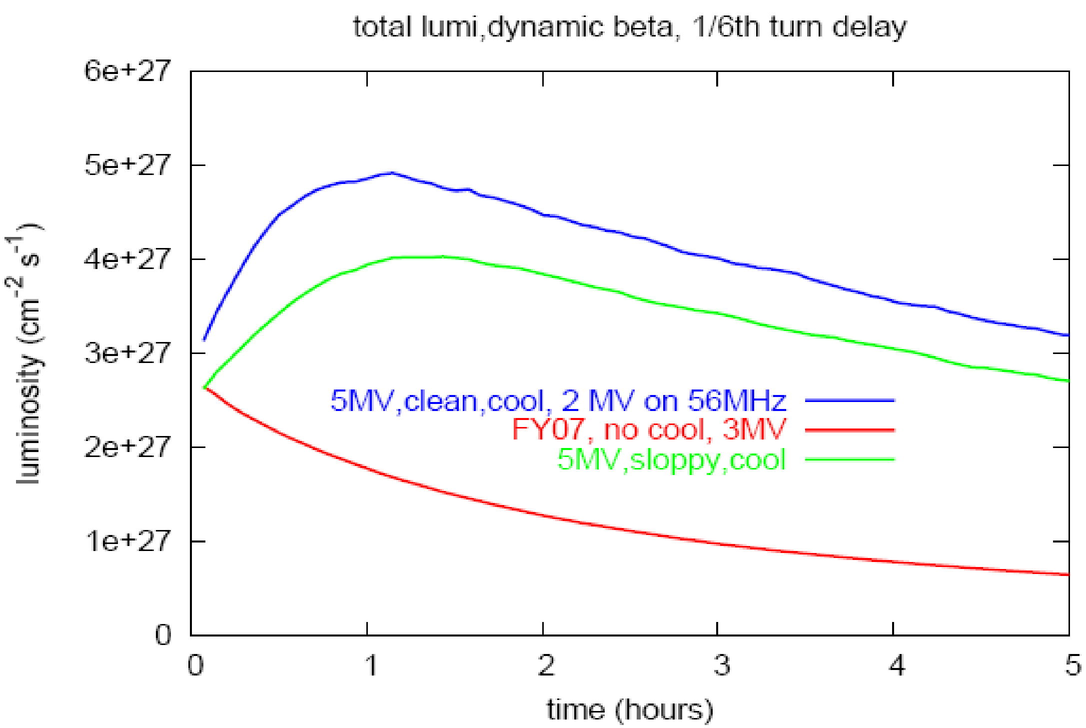
Se

Plans

- Cut the chord in the blue ring this year
- Transverse cooling, one plane, one ring, is planned for next year, FY09 run

Projected Luminosity Improvement with Transverse and Longitudinal Cooling

- Transverse and longitudinal interact via IBS
- Mike Blaskiewicz has done simulations (talk on Wednesday)
- X 4 increase in luminosity
- FY09 test with one plane



Simulations of luminosity for a 5 hour store with; red=no cooling, green=cooling, blue=harmonic cavity

Plans

- Cut the chord in the blue ring this year
- Transverse cooling, one plane, one ring, is planned for next year
- Address satellite bunches
  - Better rebucketing by reducing emittance growth
  - Considering adding a SRF 2nd harmonic cavity
- New pickups
- Higher frequency kickers

Summary

- Bunched beam stochastic cooling is operational in one ring of RHIC at 100 GeV/n
- The loss rate has reached the “burn-off” level
- We will finish longitudinal cooling in the blue ring next run (cut the chord)
- We will move on to cooling in the transverse plane in FY09

Extra slides

Outline

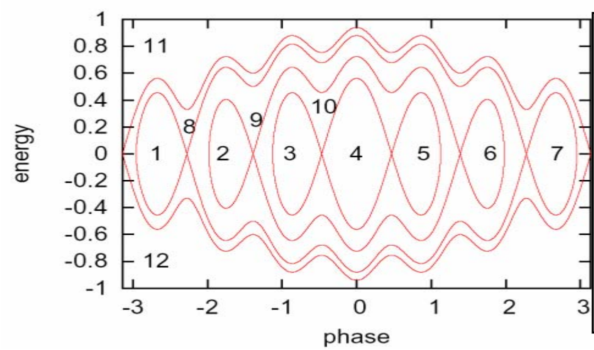
1. Motivation and Context
2. Technical challenges and Coherent lines
3. System description/Hardware
4. Results
5. Plans
6. Conclusions

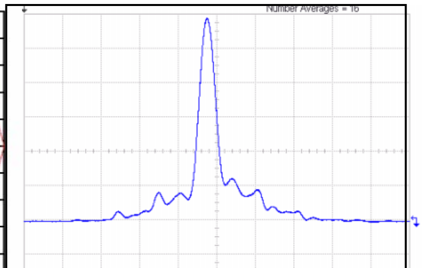
Coherent components are THE technical challenge to bunched beam S.C.

•We know that in RHIC for ions the **bunch shape** has Fourier strength at 8 GHz

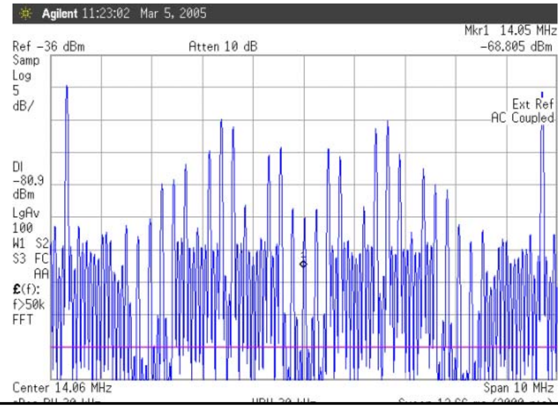
- •The low frequency spectrum reflects the bunch filling pattern, abort gap, missing bunches, etc.
- •The high frequency spectrum looks the same
  - •All bunches contribute coherently
  - •Are locked to rf

•The bunch shape arises from the dual harmonic rf buckets and the "rebucketing" gymnastic, h=360/2520

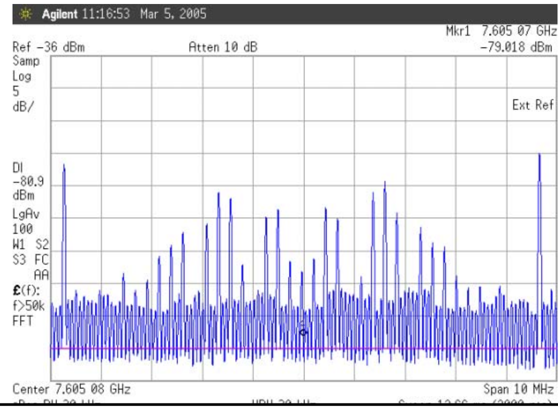




Bunch profile 5 ns/div

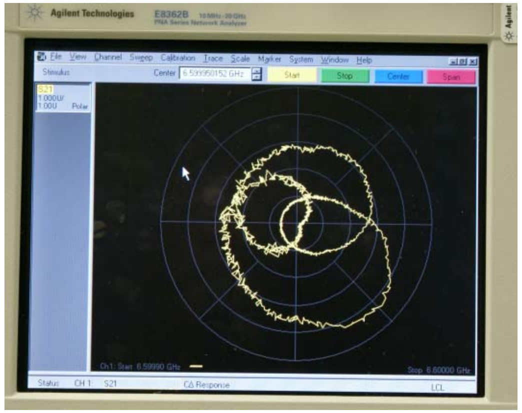


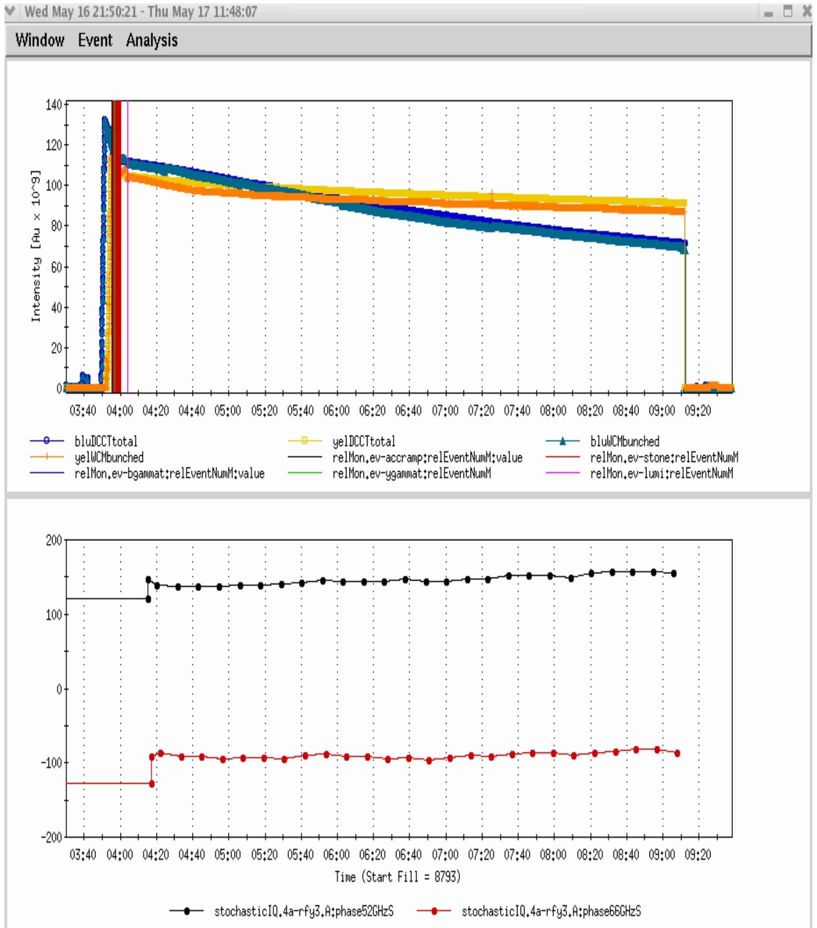
Bunch signal spectrum at 10 MHz



Bunch signal spectrum at 8 GHz

Network Analyzer is in Charge





Kicker Cavities