BUNCHED-BEAM STOCHASTIC COOLING PROJECT FOR RHIC

COOL05

September 2005

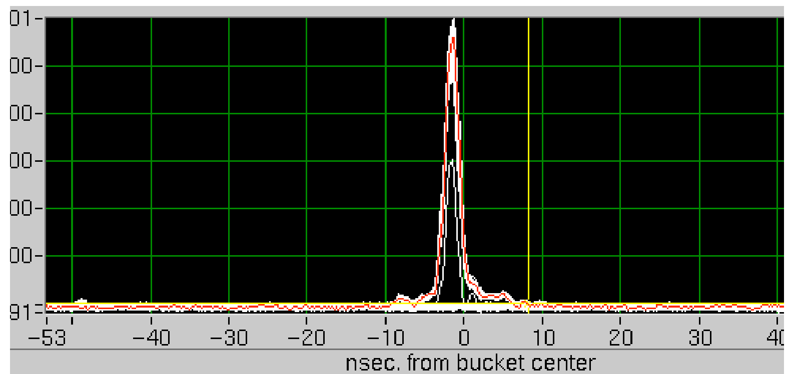
J. Mike Brennan and Mike M. Blaskiewicz

Outline

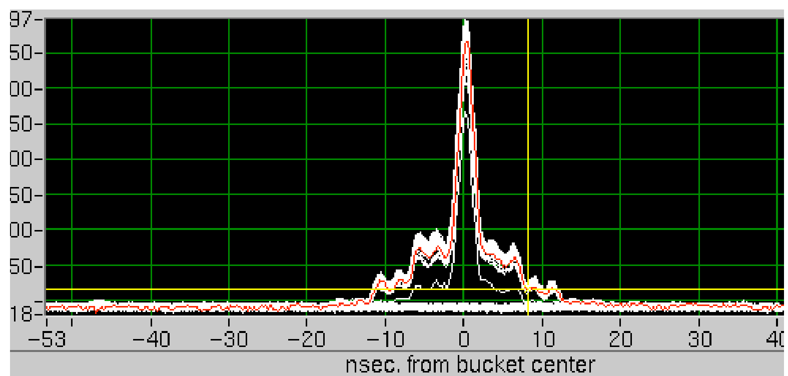
- Motivation and Approach
- Main challenges
  - Coherent lines in Schottky spectrum
  - High voltage for the kicker
  - Bunched beam (high effective number of particles)
  - Ring lattice (disadvantageous mixing)
  - Not cutting the cord (pickup-to-kicker)
- Solutions
  - Filters, coax and optical
  - Discrete frequency, high-Q cavities
  - Halo cooling and two-turn delay filter
  - Pickup-to-kicker via fiber optic link in tunnel
- Some results from the FY05 Copper ion run

Motivation for Cooling (Ions)

- Intra-Beam Scattering drives emittance growth and de-bunching
- Bunch is trapped in satellite bunches by the 28 MHz rf
- We want to stop beam from jumping the 200 MHz separatrix (momentum halo cooling)
- The time scale is hours
- The effective number of particles is:
  - $10^9/1.5$ m * 3830 m = 2.5×10^{12}



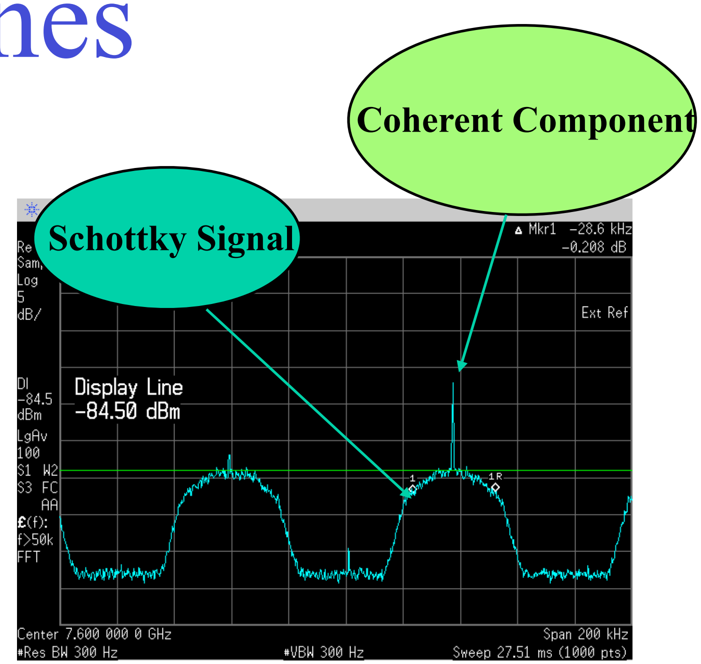
Gold beam at beginning of store



Gold beam at end of store (>5 hours)

Coherent Lines

- This has been Nemesis of bunched-beam cooling.
- Not as severe for ions as for protons.
- Nevertheless, can cause saturation and disable the electronics. The problem is high peak voltages in the time domain.

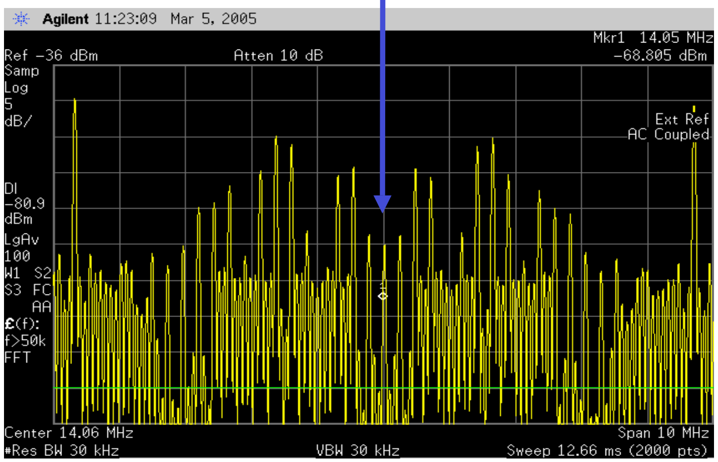


Spectrum of Copper ions in RHIC at 7.6 GHz, 100 GeV/n

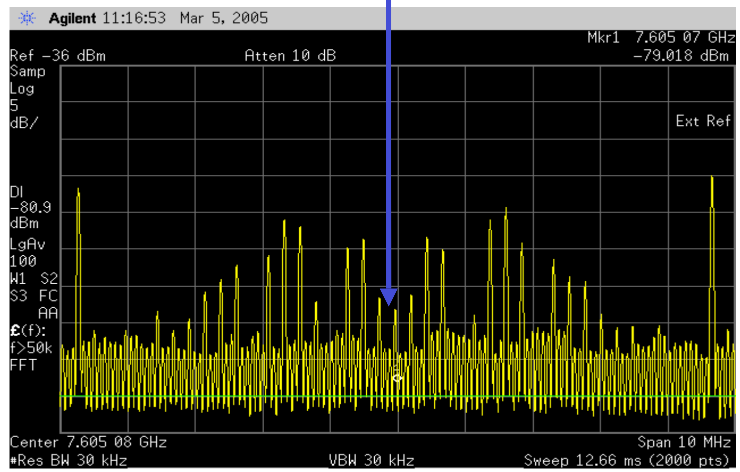
Origin of the Coherent Lines

- M. Blaskiewicz has a talk at this conference on our studies of the coherent lines.
- We believe the origin is different for **ions** and **protons** in RHIC.
  - The key difference is that ions are stored in completely filled buckets (large synchrotron frequency spread) and protons are short bunches in long buckets (28 MHz, Δf_s small)
  - For protons, the coherent signals come from the motion of the bunch.
  - For ions, they come from the shape of the bunch.
- The ion bunches have very high frequency structure because of the satellite bunches
  - The Fourier transform of the bunch shape in not negligible at 8 GHz
  - All bunches have the same shape so they contribute coherently to the spectrum
  - The low frequency spectrum envelope reflects the bunch fill pattern
  - As does the high frequency spectrum

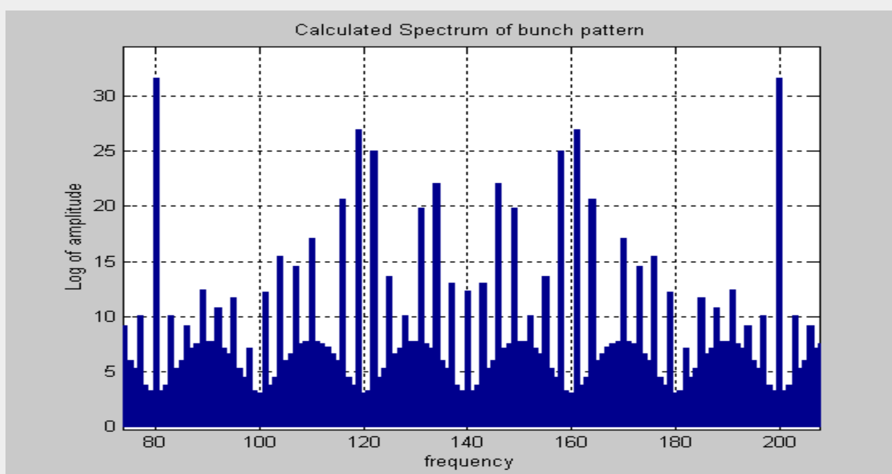
All bunches of copper ions have the same shape and are locked exactly to the revolution frequency



Spectrum at low frequency, 10 MHz from Wall Current Monitor



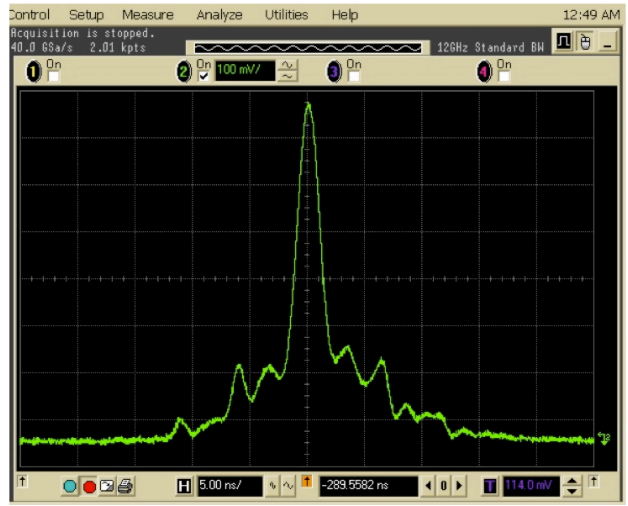
Spectrum at 7.6 GHz from stochastic cooling pickup



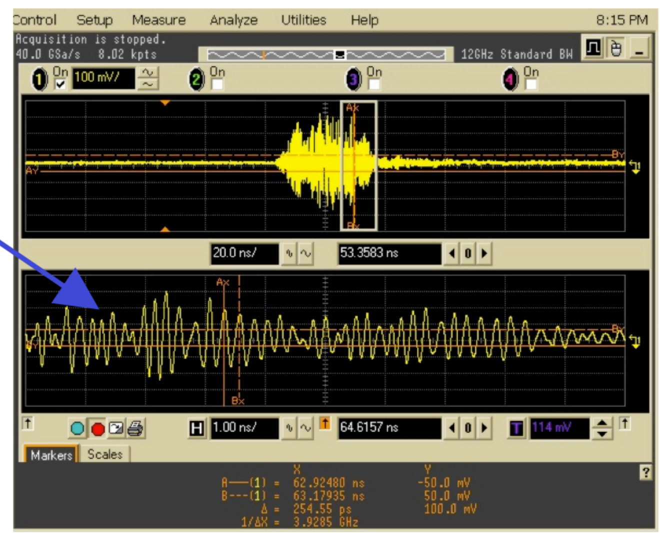
Calculation of delta-function bunches from the bunch filling pattern. Mix of 60 and 120 bunch patterns

We looked at the pickup signal with the superscope (40 Gs/s, thanks Agilent)

- Indeed the bunch does have structure at 4-8 GHz
- The pickup electronics rings at 4 GHz
- The features of the signal are stationary, not fluctuating

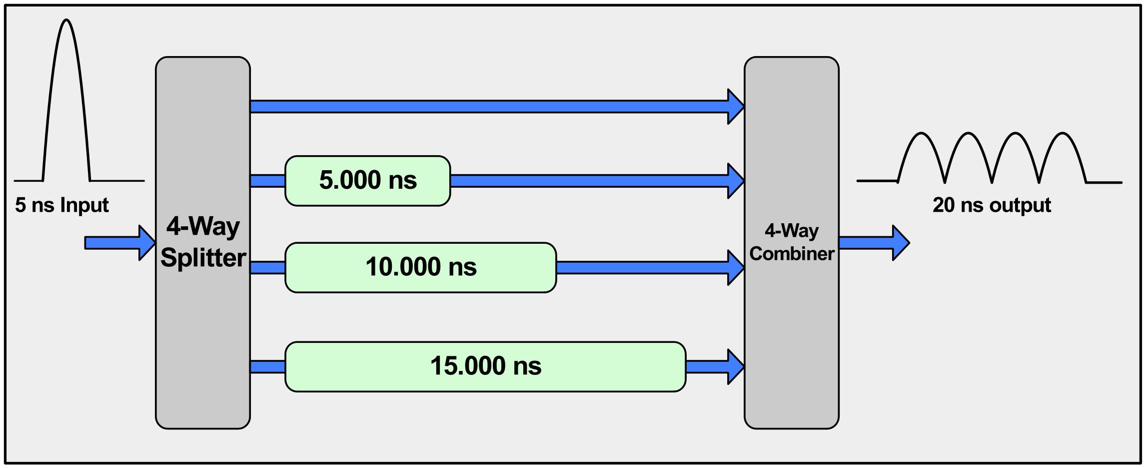


Bunch profile from wall current monitor, 0-500 MHz

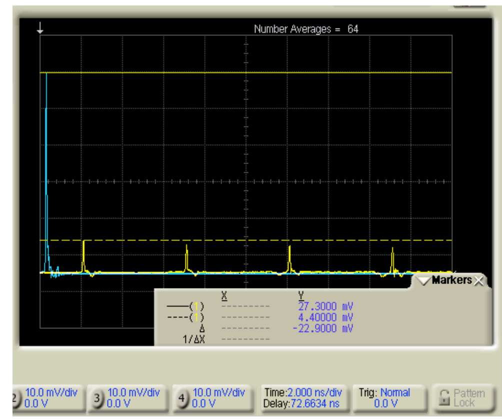


Signal from stochastic cool pickup, 4-8 GH

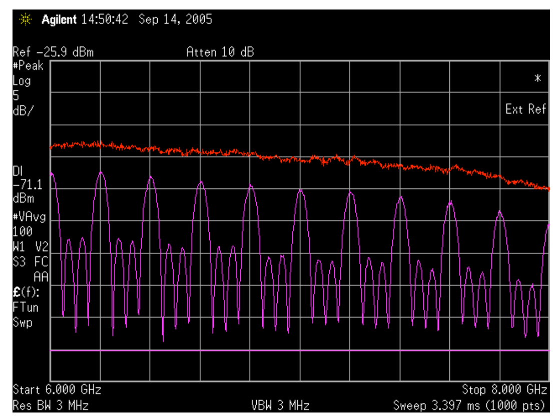
We need to reduce the dynamic range of the pickup signal



- We can take advantage of the bunched beam
- A passive delay-line filter reduces the peak voltage by x 8
- Only 6 dB loss in frequency domain
- We can do this because of our kicker scheme.



200ps test pulse, Vout/Vin=1/8



Spectrum Analyzer of noise diode, 6 to 8 GHz

Insertion loss = 6 dB

Kickers Voltage Requirement

- The kicker must correct 1/5 of the measured fluctuations per kick. The optimum gain is given by mixing, = 1/5.
- Fluctuations are proportional to sqrt(N_{sample})
- 8 GHz system gives 125 ps sample
- 3 kV with a 50 Ohm kicker would take 90 kW

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

$$= \frac{1}{5} \frac{100 \text{ x } 197 \text{ x1GeVx}(0.3\text{x}10^{-3})}{\sqrt{125ps \frac{10^9}{5ns}}} = 250 \text{ keV}$$

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

Because the beam is bunched we can exploit energy averaging

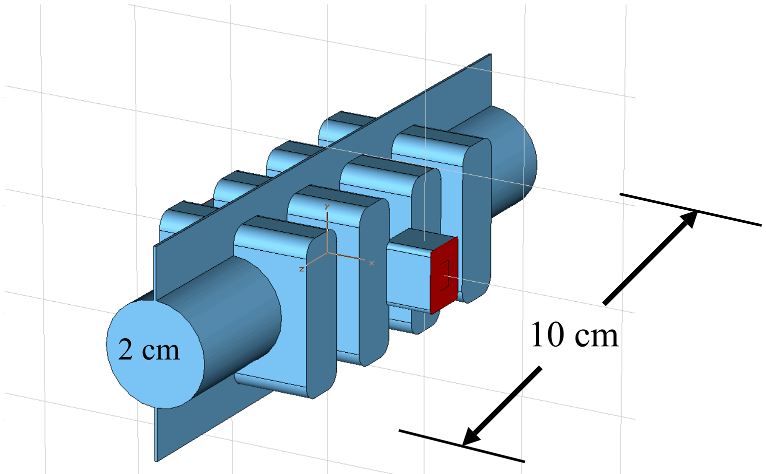
- One pays for the peak power. With a bunched beam the power is off most of the time.
- Some form of pulse compression can reduce the peak power and therefore the cost by a factor of ~ten.
- Our approach to pulse compression is high-Q cavities for the kicker
- How can one use high-Q cavities for a BROADBAND kicker?
- Just because the beam in bunched!

If we synthesized our kicker pulse with a Fourier series

$$V_{kick}(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\omega_0 t + \vartheta_n)$$

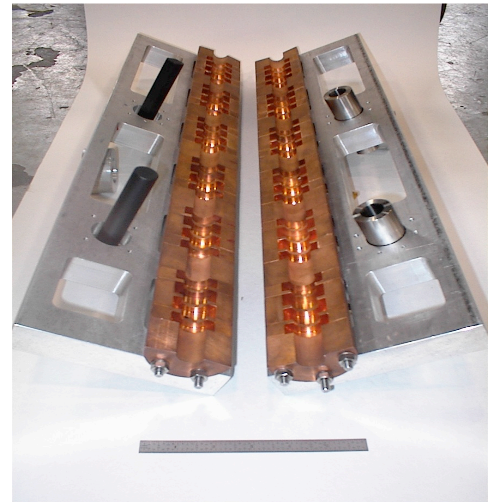
$$\omega_0 = \frac{2\pi}{\text{bunch length}} = 2\pi \; 200\,\text{MHz}$$

- Since our system bandwidth is 4-8 GHz we only need the 20 discrete lines in this band
- Each line is realized with a dedicated high-Q cavity
- The Q is limited by the time between the bunches, 100 ns. BW=10 MHz, Q ~ 600.
- Cavities have R/Q = 120 Ohm $\Rightarrow$ Power = 10 Watts

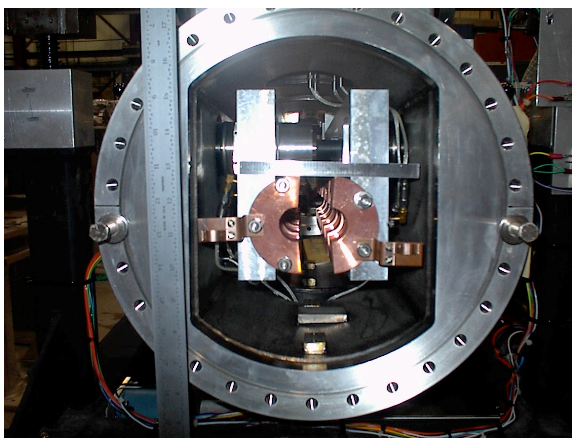


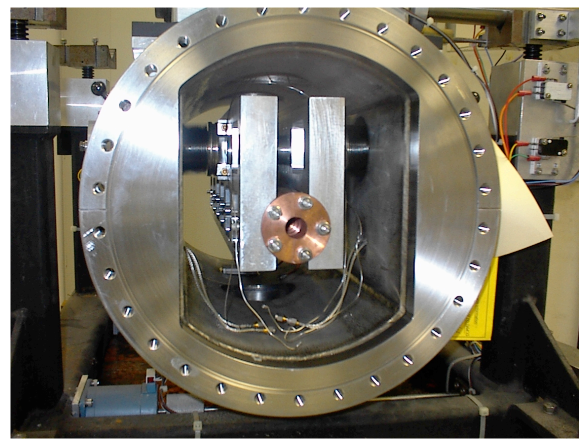
Cavities are designed with CST MicroWave Studio

R/Q = 120 Ω, f = 5.0, 5.2,….7.8, 8.0 GHz



They are split to open during the ramp for aperture



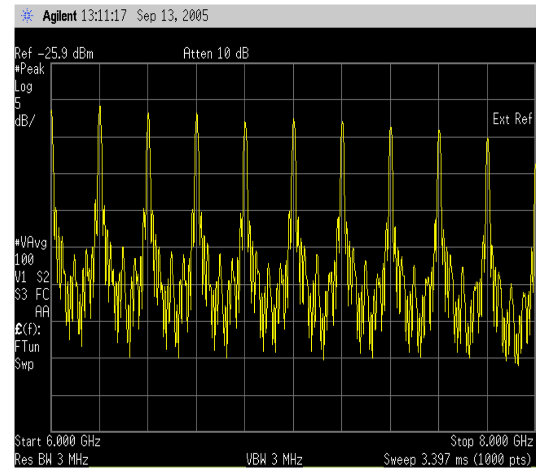


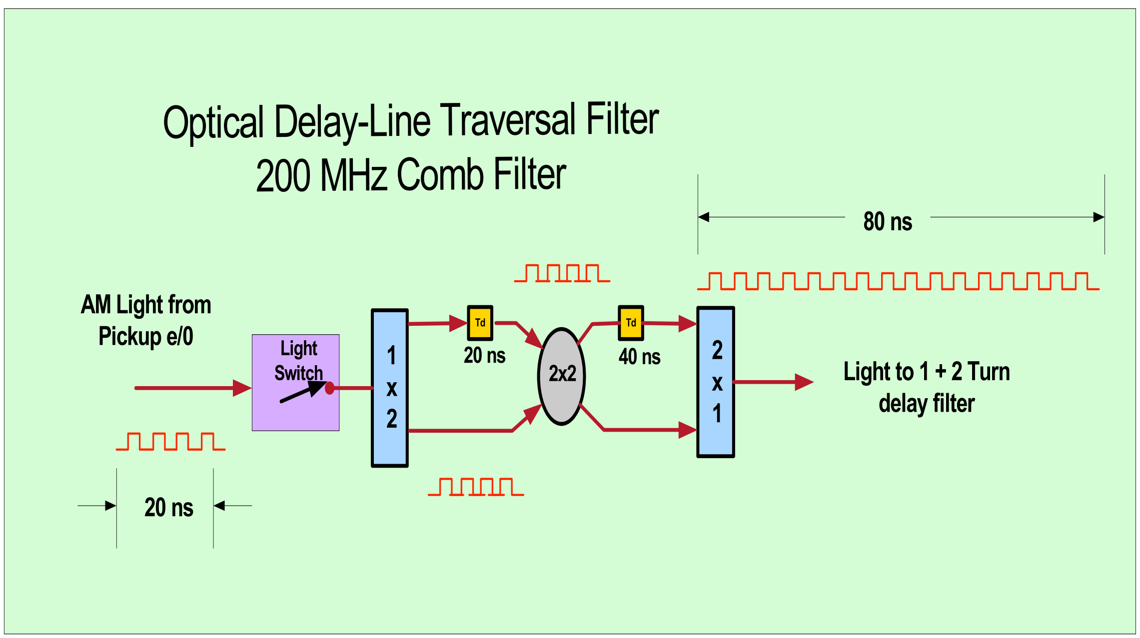
Assembled into tanks with drive mechanisms from FERMILAB

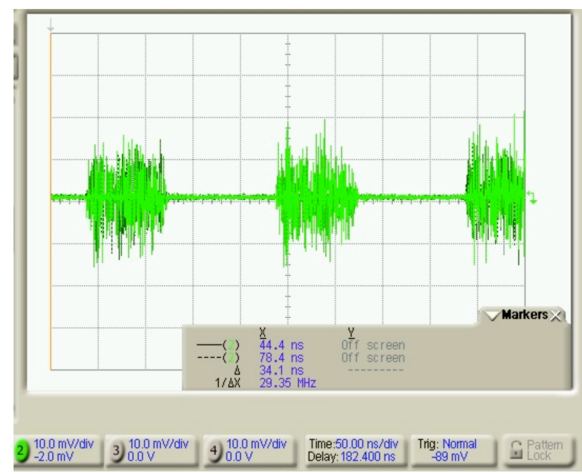
Close to 20 mm diameter aperture during store

Drive signal to the cavities

- We need to start filling the cavities 80 ns before the beam arrives
- The filter shown above stretches the 5 ns beam pulse to 20ns
- A fiber optic filter extends it to 80 ns
  - Fiber optics avoids dispersion over the 4-8 GHz band
  - The filter is realized directly in light

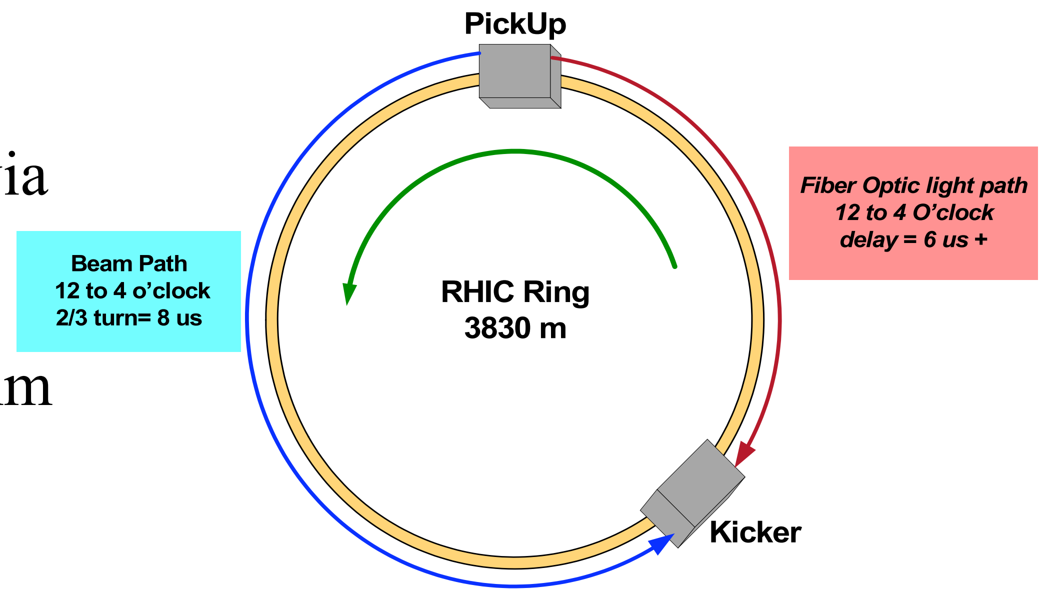


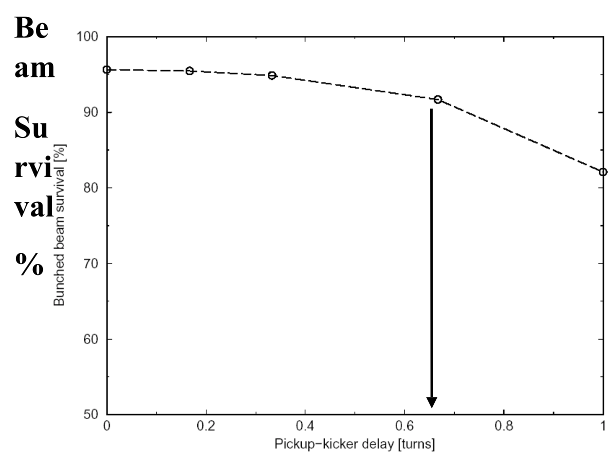




PickUp to Kicker Delay

- Fiber optic link runs via the tunnel against the beam
- V_{light}=c/1.47 @ 1550nm
- Effectively 2/3 turn delay
- Mixing factor is about 4 turns
- Simulations (J. Wei) indicate that >90% beam is still bunched after 10 hours



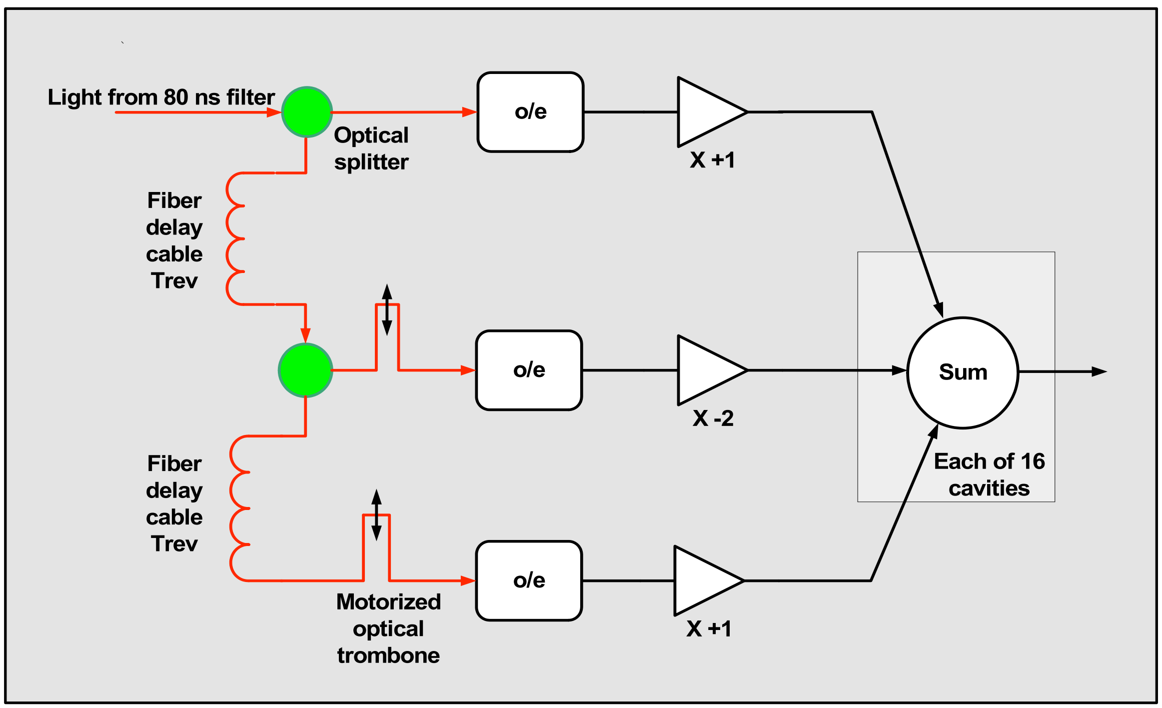


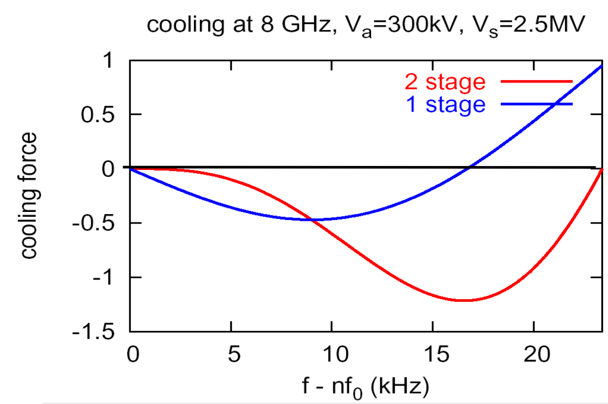
Pickup to kicker delay, turns

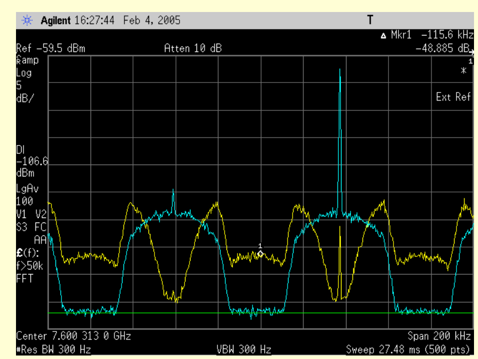
The Cooling Filter

- The filter does two jobs:
  - Generates the correct phase kick for cooling
  - Suppresses the coherent component
- A 1 + 2 turn delay filter shapes the momentum distribution

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







Two-turn filter at 7.6 GHz

Cooling simulation (coasting beam calc.)

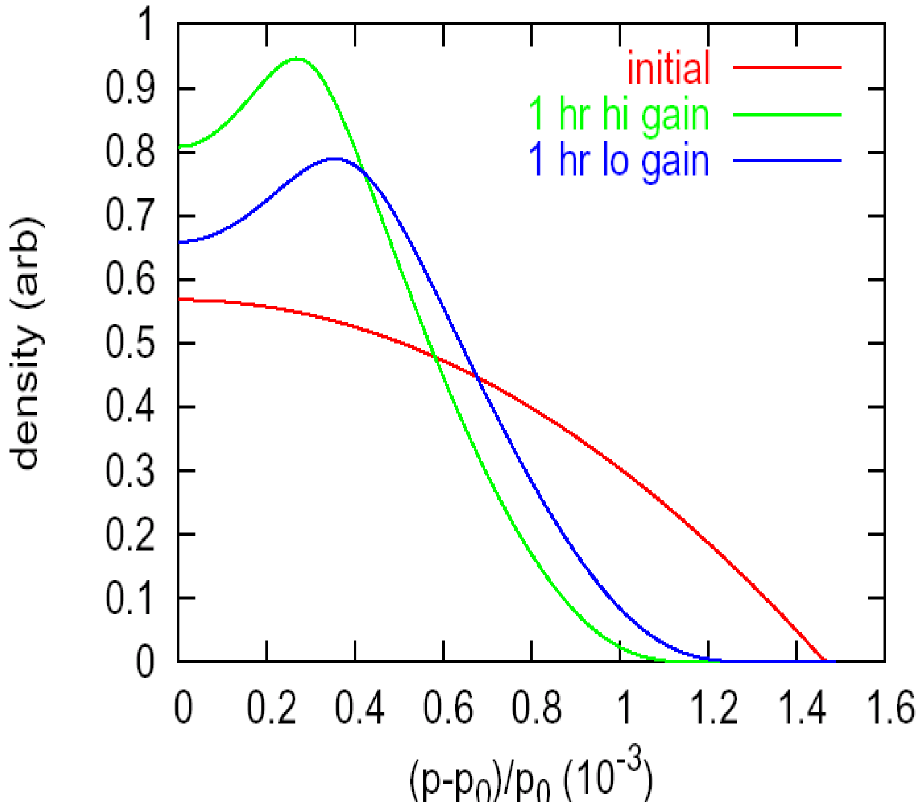
Coasting beam cooling rate calculations based on peak particle density

Au^{+79}, 100 GeV/n

IBS was included.

Numerical integration of Fokker-Planck equation

$$\frac{\partial \Psi}{\partial t} = \frac{\partial}{\partial \omega}\left[-F(\omega)\Psi(\omega,t) + D(\omega,t)\frac{\partial \Psi}{\partial \omega}\right]$$



Beam Transfer Function

- The BTF measures the entire loop
  - Calibrates kickers (corrected for duty factor)
  - Obtains beam response
  - Determines loop phase (stability)
  - Reveals filter response

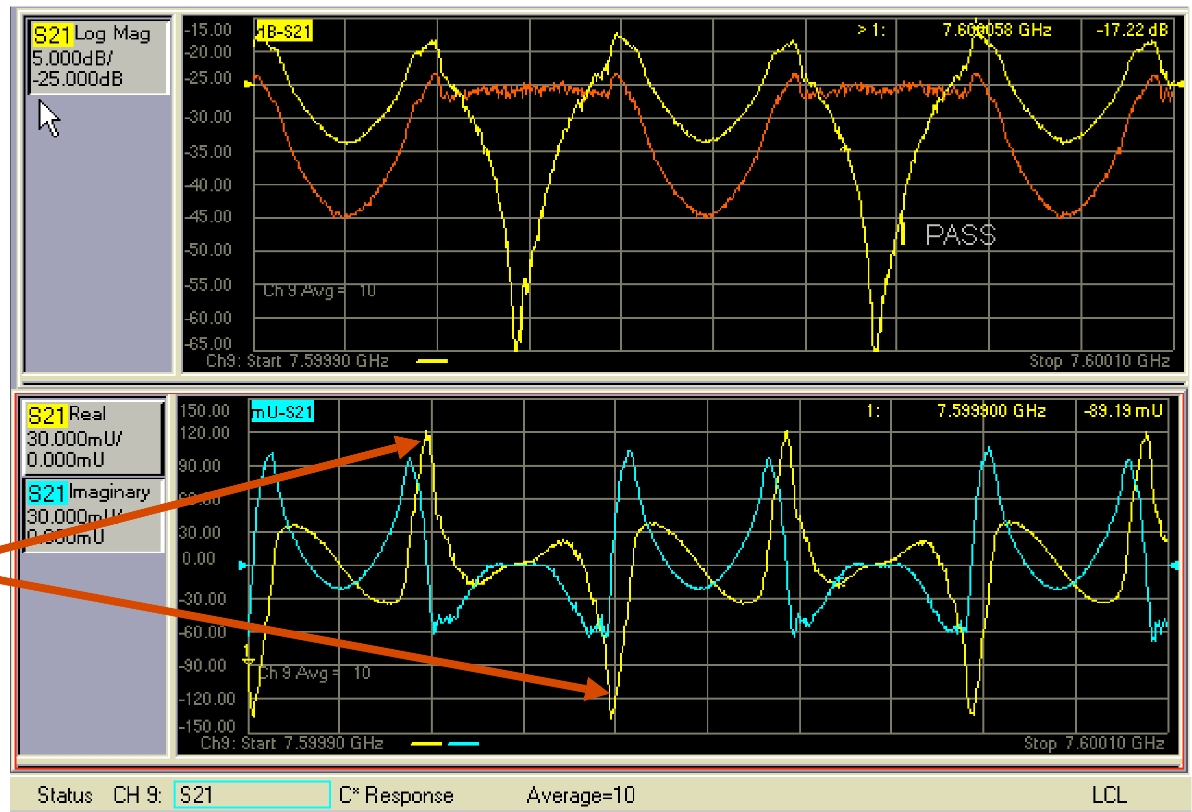
•The filter flips the sign of the real part at each Frev

•The phase is stable on the 10-minute time scale

•Run-time BTFs will be used to correct drifts

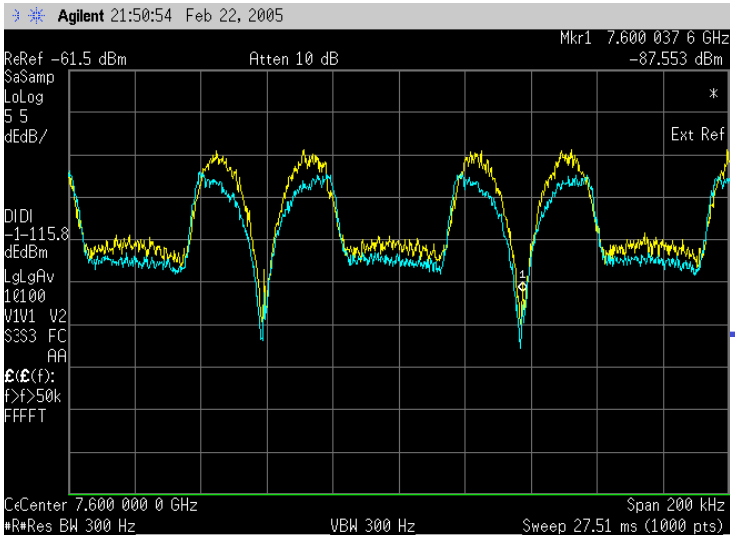
Magnitude: red is no filter, yellow is with 2-turn filter

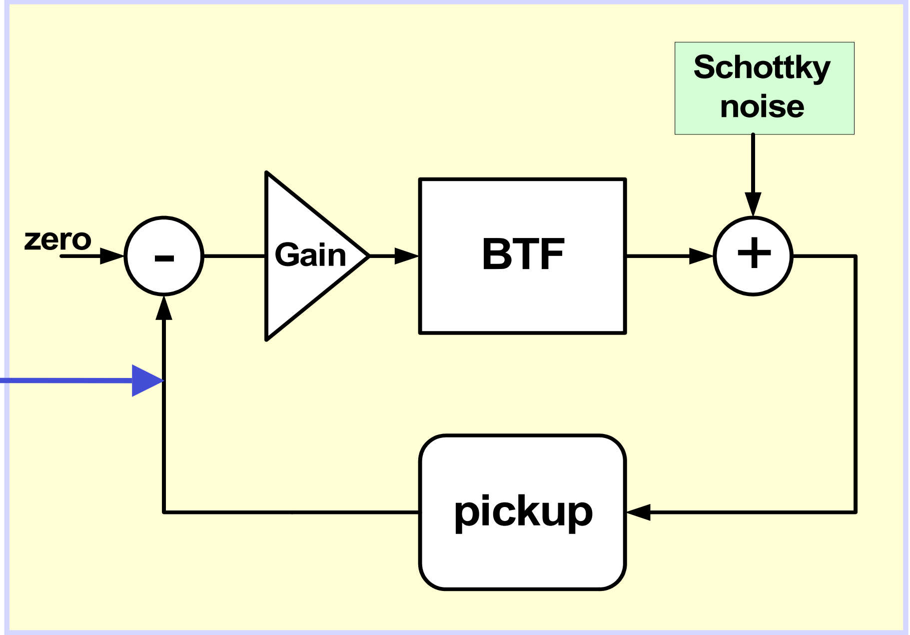
Real (yellow)and Imaginary parts. Real part changes sign at Frev



Signal Suppression

- The cooling system imposes onto the beam the negative of the Schottky noise
  - The kicker must be strong enough
  - The phase must be correct and stable
  - The "peaking" implies we must reduce momentum spread
  - Signal suppression extends beyond the bandwidth of the kicker





Summary

- Unusual features
  1. Halo cooling only, to counteract IBS
  2. High-Q cavity kickers
  3. 2/3 turn delay, pickup to kicker via beam tunnel
  4. Filters realized in fiber optic networks
  5. Run-time BTFs
- Status/Plans
  1. Coherent line problem is manageable
  2. Closed-loop measurements with copper ion have demonstrated signal suppression
  3. Intend to have an operation cooling system for the next RHIC ion run