Update on the RHIC Stochastic Cooling

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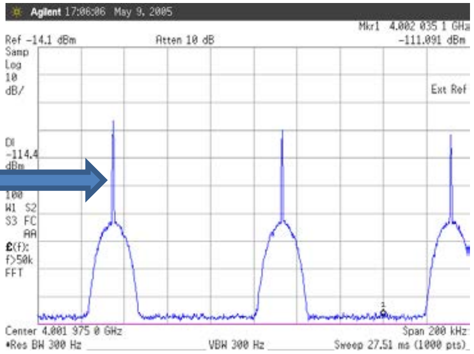
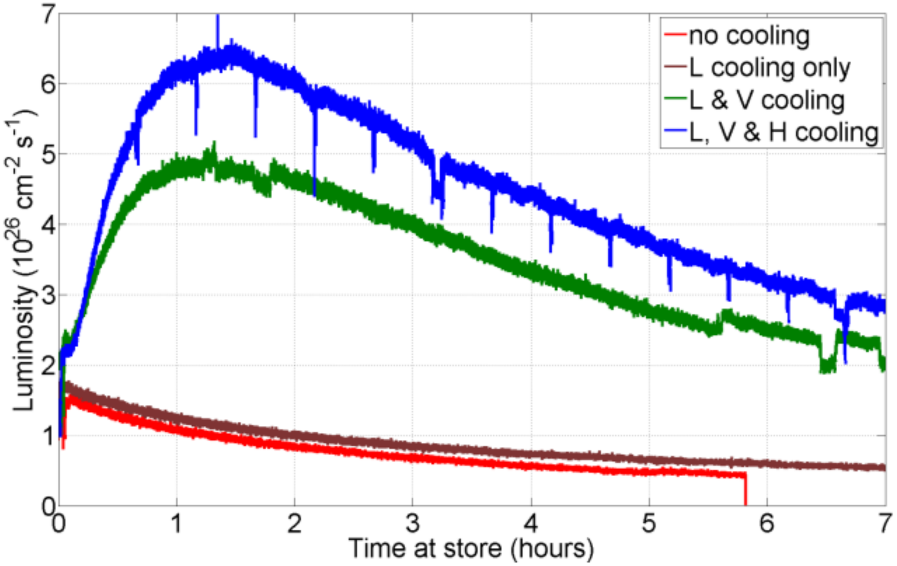
What are the unique challenges of the RHIC cooling system?

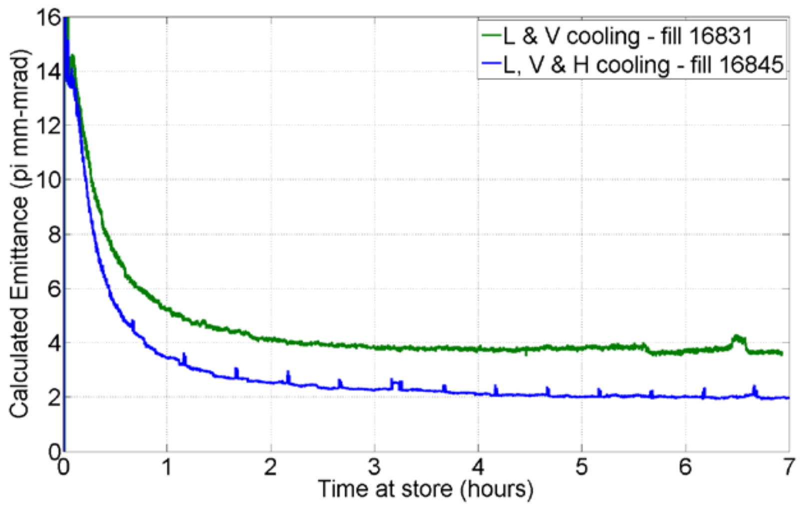
- Bunched beam
  - High local particle density
    - 1.8 x 10^9 ions per bunch >high bandwidth
    - 5 ns bunches
  - Coherent lines in the Schottky spectrum
- 100 GeV/n
  - We need ~ 2 kV kick at 5-9 GHz



- Strong Intra-Beam Scattering with fully stripped ions
- Not an optimized lattice for cooling. Eta is too small for good mixing (about 4 turns)
- Beam aperture for pickups and kickers ≥ 20 mm

Results: RHIC Luminosity production



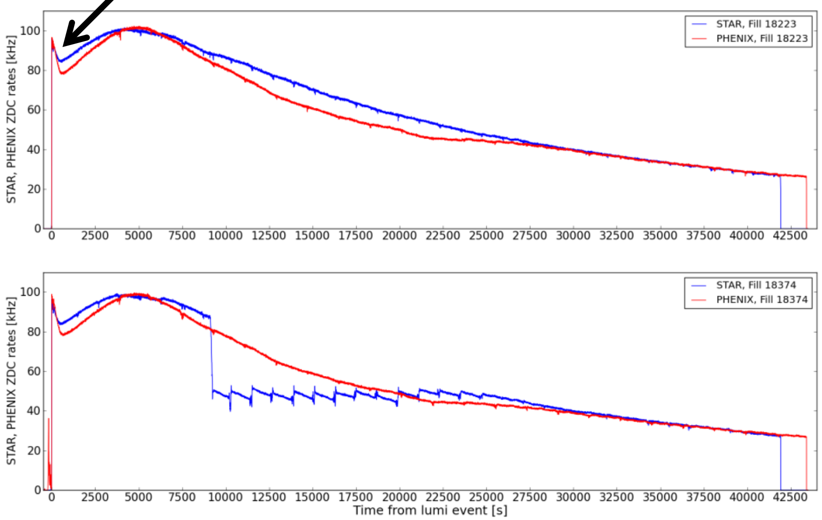


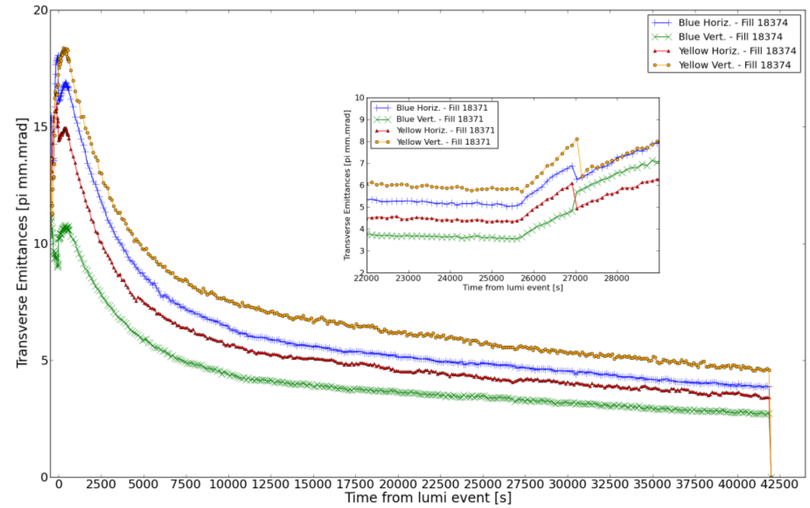
For Uranium-on-Uranium collisions the cooling increased the integrated luminosity per store by a factor of 5

The transverse emittances were reduced by x 4 with a cooling time of ½ hour

Gold-Gold at 100 GeV/n

Before cooling starts





- For Gold-Gold collisions rates (STAR and PHENIX) with 1.8 x 10^9 ions per bunch
- No stores without cooling
- Beam loss dominated by burn-off

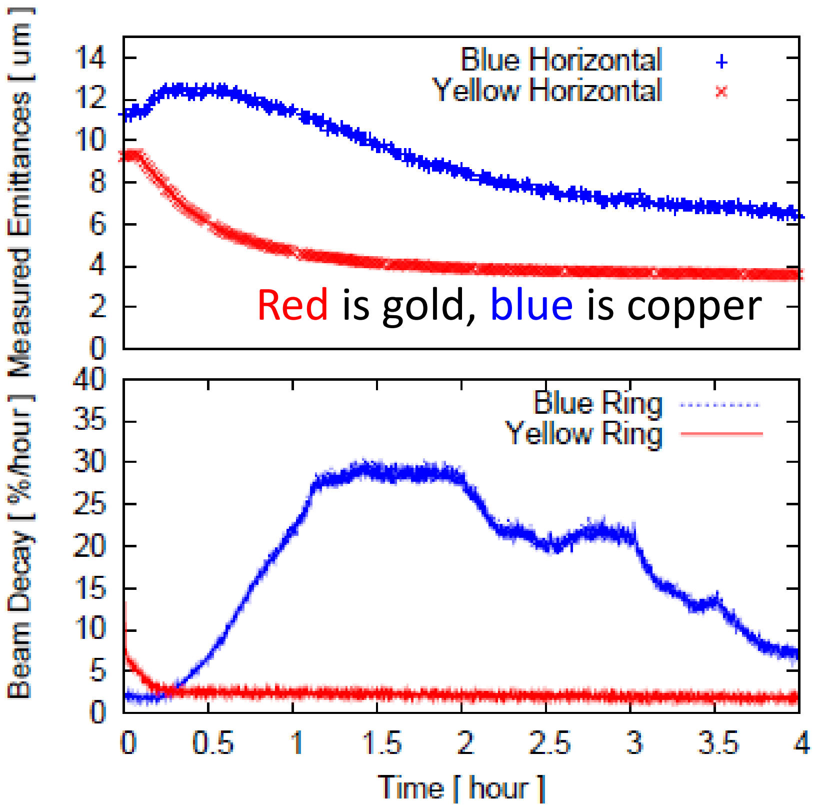
- Transverse emittances for all four planes, with cooling
- Insert: cooling off for 50 minutes, emittances double

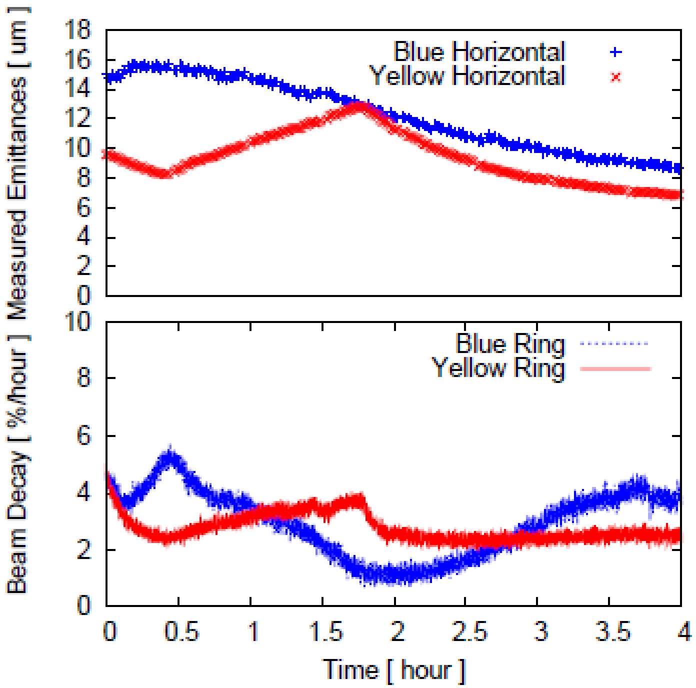
Copper-Gold collisions $4x10^9$ and $1.3x10^9$ per bunch

- IBS growth rate for copper is ½ that for gold
- At 4e9 per bunch copper ions the cooling rate is 1/3 that for gold
- Therefore the gold is cooled more that copper and the size difference between gold and copper beams enhances the beam-beam tune shift.[*] The loss rate is greater for the larger beam
- To maximize the integrated luminosity the cooling rate of the gold beam was reduced by switching off one plane of transverse cooling and adjusting the cooling gain to keep the beam sizes about equal

* Y. Luo et al. PAC2013

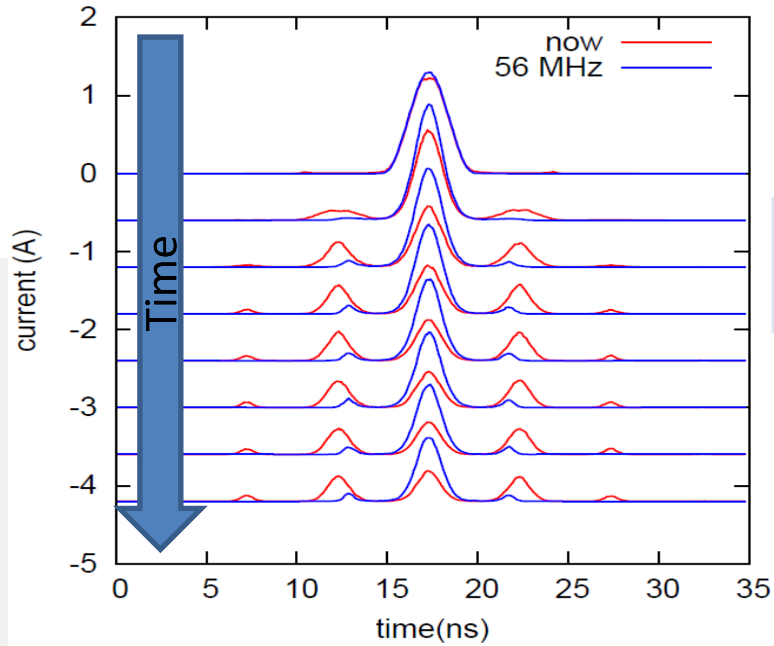
Adjusting cooling rate for Gold to match beam size for copper



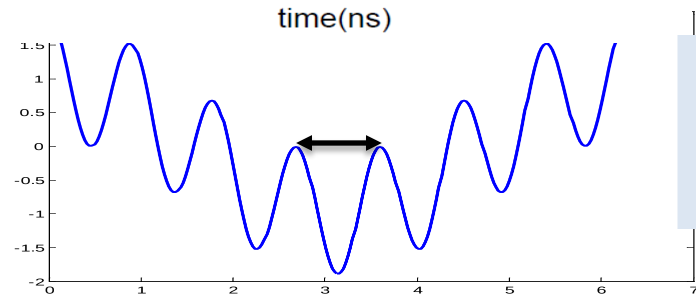


Longitudinal Cooling and Bunch Profile

- The RF bucket during the store has two harmonics, 28 MHz and (7 x 28 MHz)
- While cooling, the beam develops satellites bunches at ± 5ns. Red curve
- The solution is 56 MHz SRF cavity at 2 MV. Blue curve*



Evolution of bunch shape during store

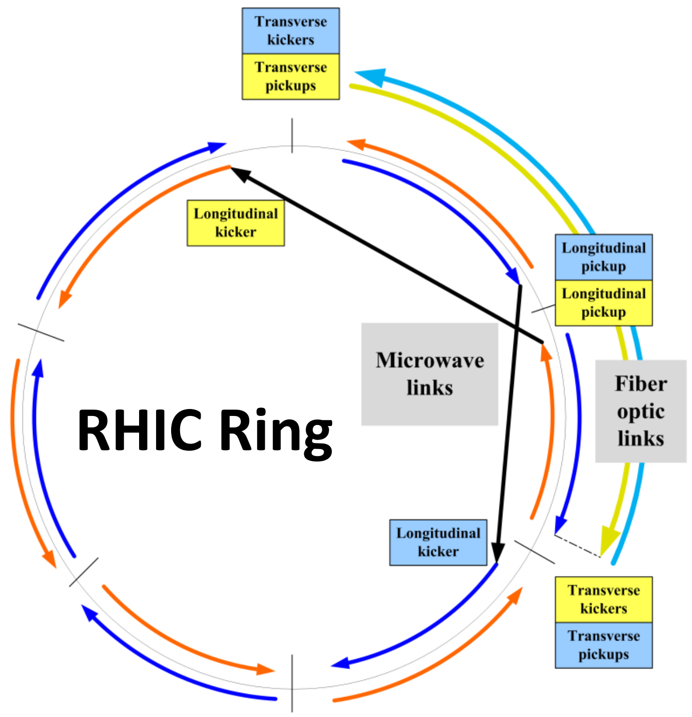


Potential well for two harmonic bucket

* Simulation by Blaskiewicz, COOL13

The cooling equipment

1. Kickers
2. Pickups
3. Signal processing
4. Operation



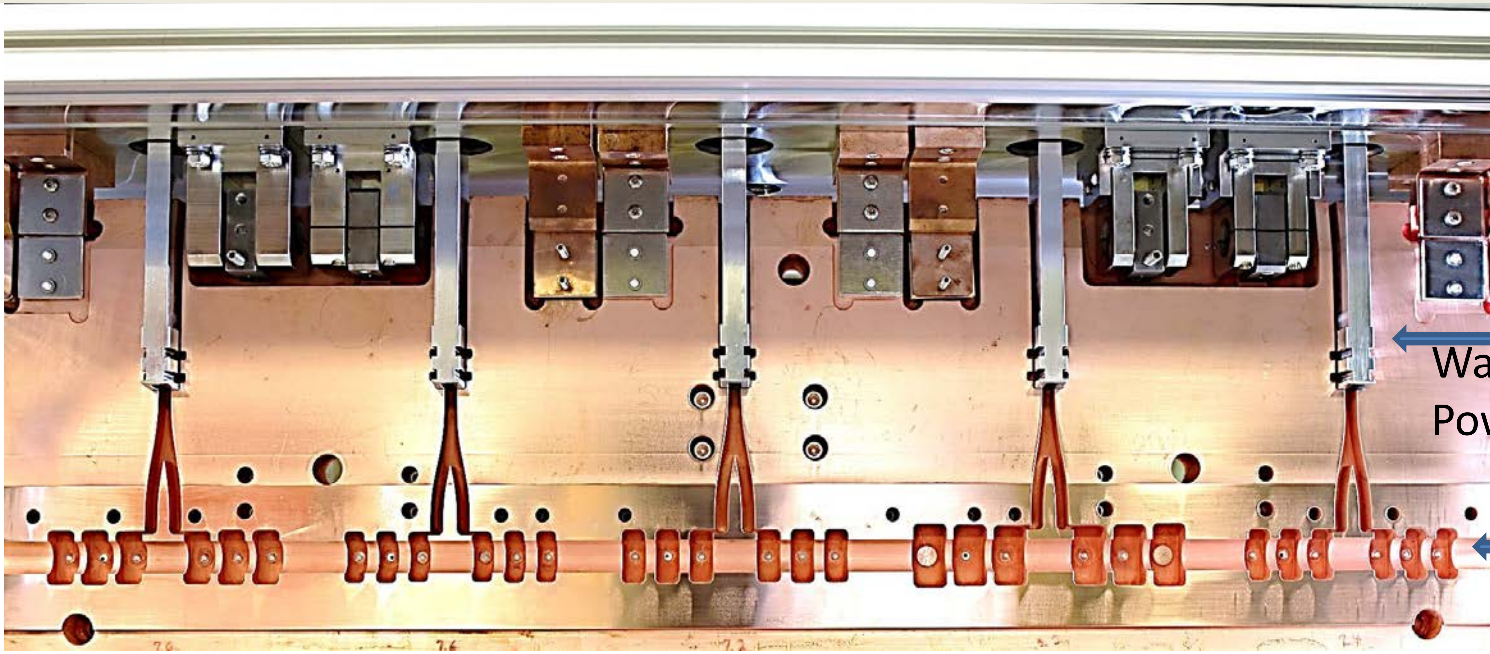
Layout of cooling equipment. Transverse signal via fiber optics. Pickup-to-kicker delay is 2/3 turn. Longitudinal signal via microwave links. Delay is 1/6 turn.

Kickers

- Kickers are realized by high Q, narrow band, cavities.
  - 16 cavities synthesize a Fourier composition of the kick
  - Cavities bandwidth matches time between bunches
  - With bunch length of 5 ns the cavity frequencies are multiples of 200 MHz between 5-8 GHz for transverse and 6-9 GHz for longitudinal
  - Kickers open to 80 mm clear aperture for injection and ramping
  - Close to 20 mm aperture for operation
- Each cavity is driven by a 40 Watt linear solid state amplifier
- Power feed is coax cables for transverse and waveguide for longitudinal kicker cavities

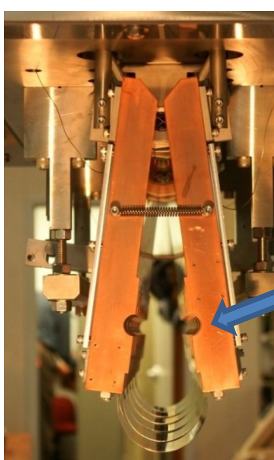
Five 6-cell cavities of longitudinal kicker.

Right half shown, copper plated aluminum, 1 meter long.



Waveguide
Power feed

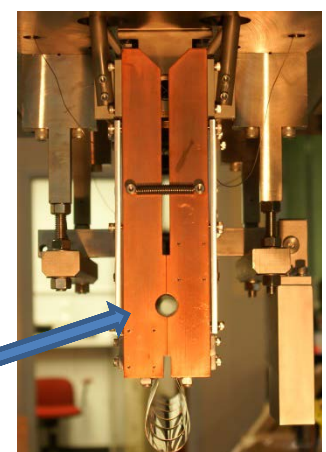
Beam



End view of the kicker.

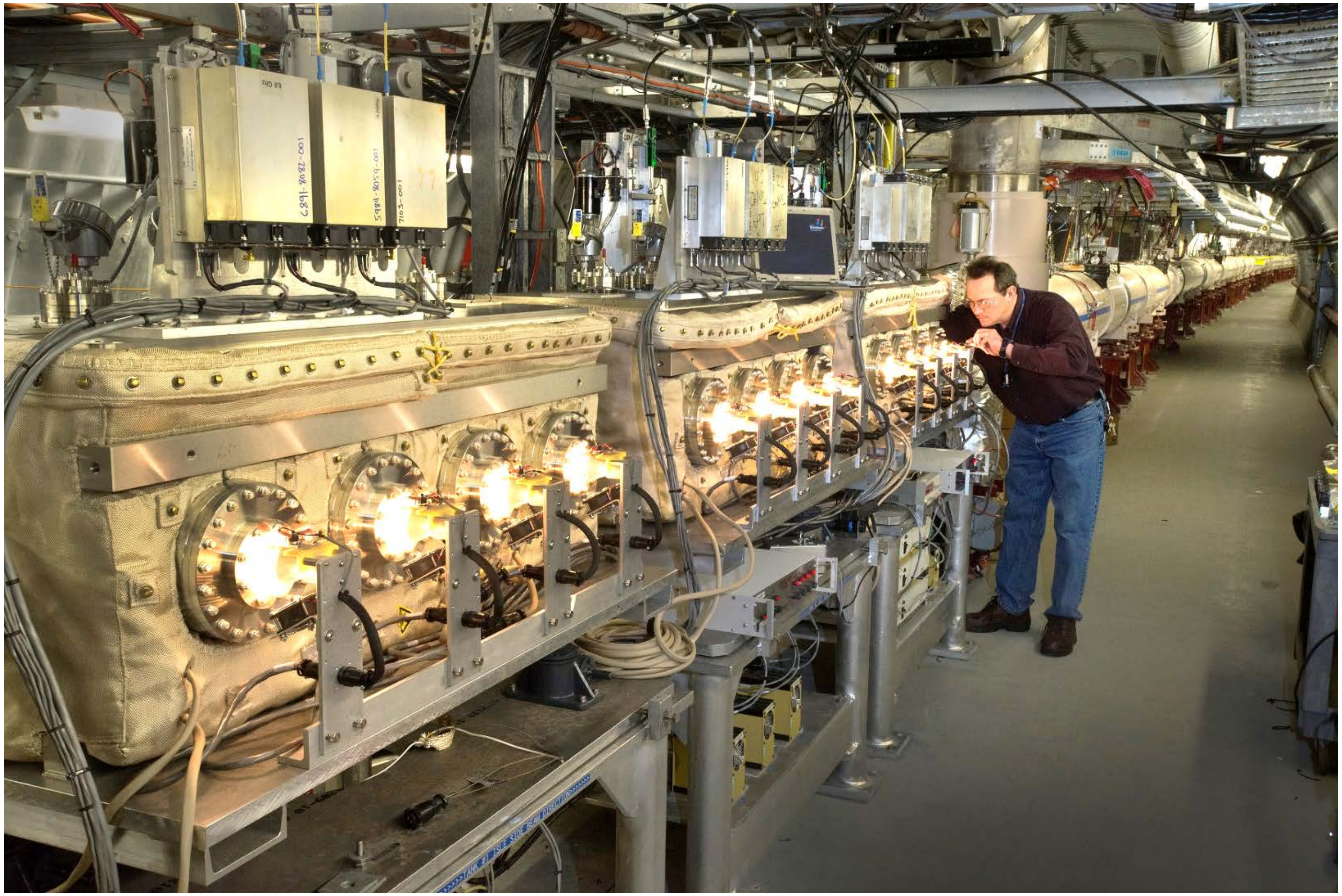
Shown in;
Open position for
injection and ramping

Closed for operation



Cavities are heated by light bulbs(40 C),

when the rf switches on the light power is reduced for constant temperature/frequency



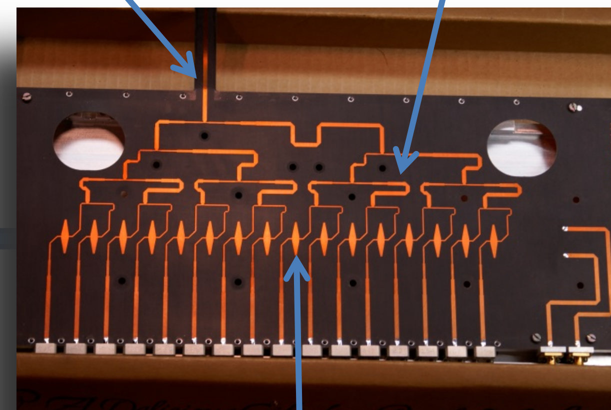
Pickups - Transverse

- Planar arrays (from the Tevatron*) are used for transverse pickups
- Common mode rejection is the challenge
- Best performance when the two arrays are close enough to cut off waveguide modes below operating frequency (~30 mm)

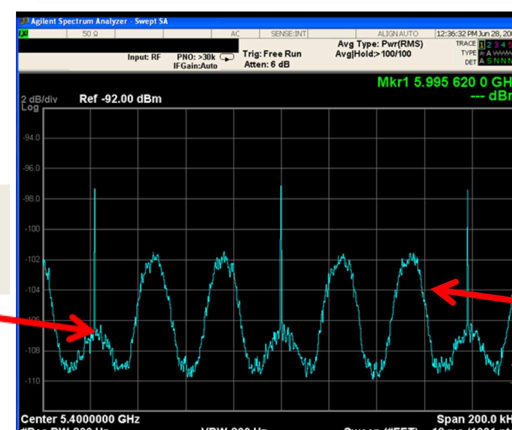
Output goes to 180^0 combiner

Signals are combined in phase via meander lines

Beam



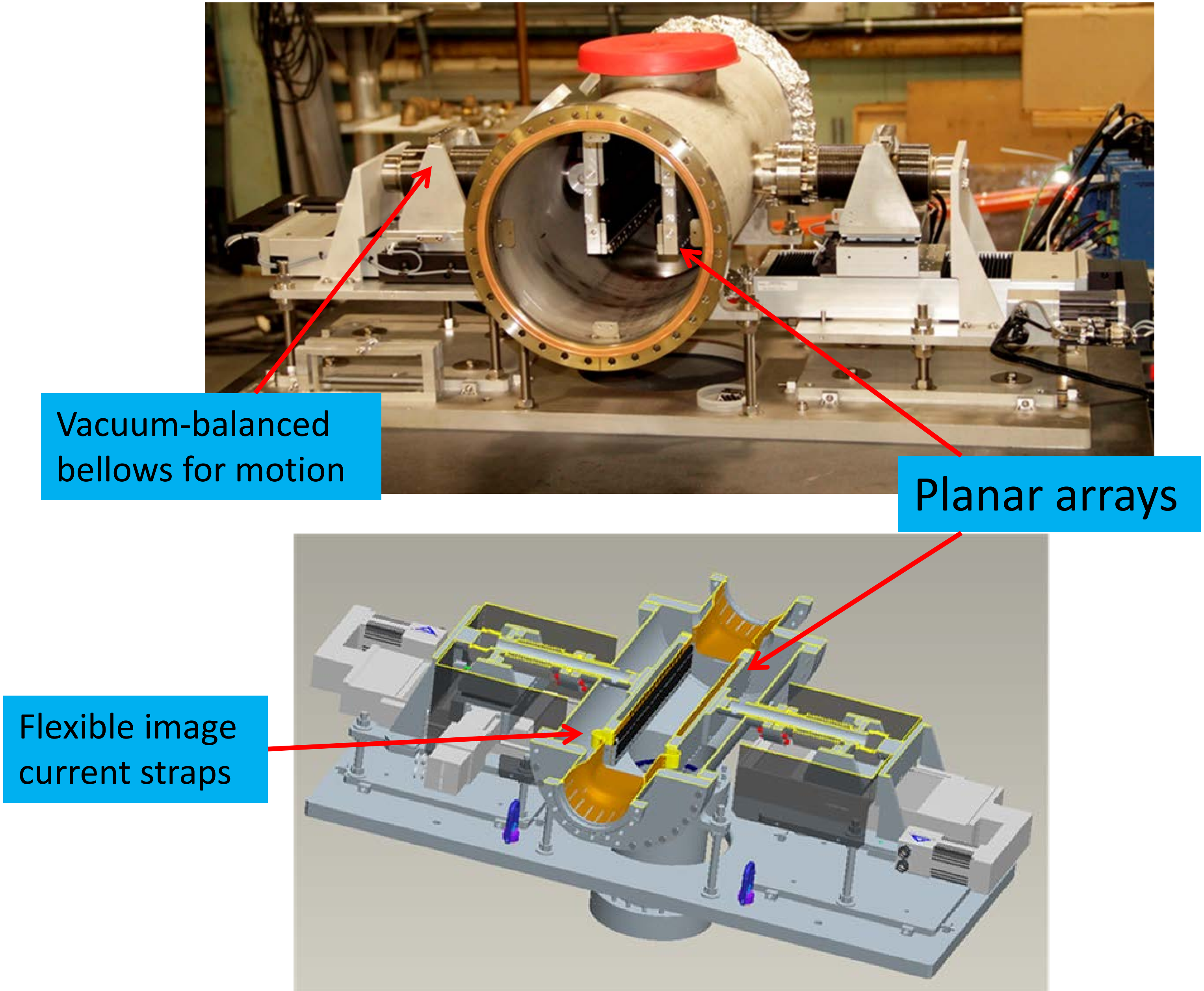
16 antennas see the beam through the dielectric



Common mode lines at revolution harmonics

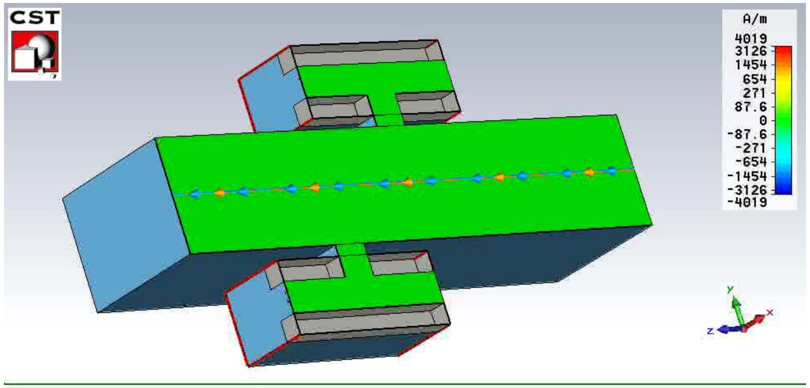
Betatron lines

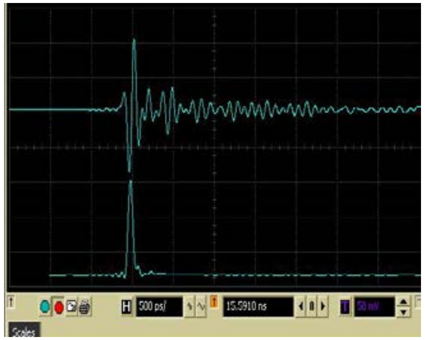
* McGinnis, et al; PAC91 p.1389


Vacuum-balanced bellows for motion
Planar arrays
Flexible image current straps

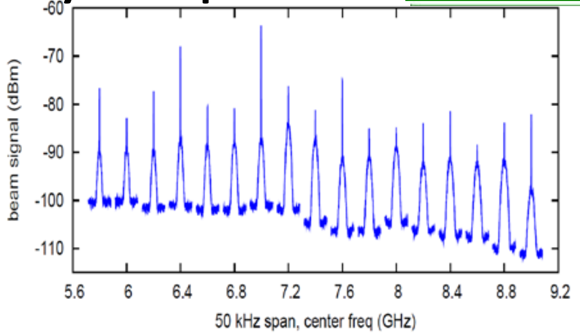
Longitudinal Pickup

- Keyhole shape
- Consistent frequency response

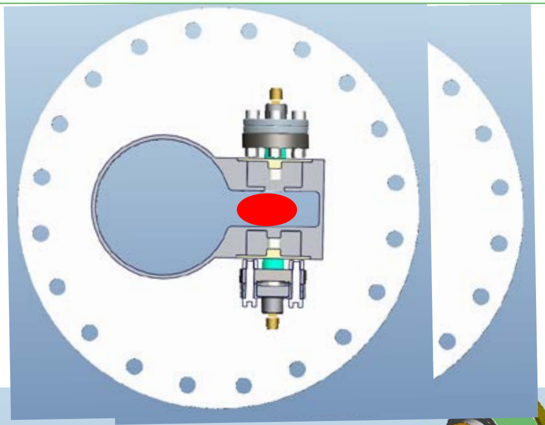


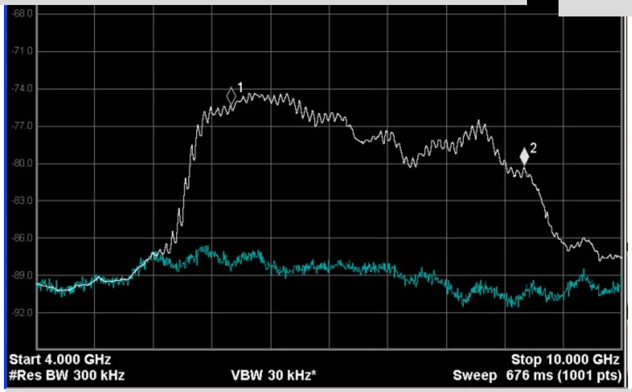


Wire test of pickup.
50 ps risetime pulse, 500 ps/div

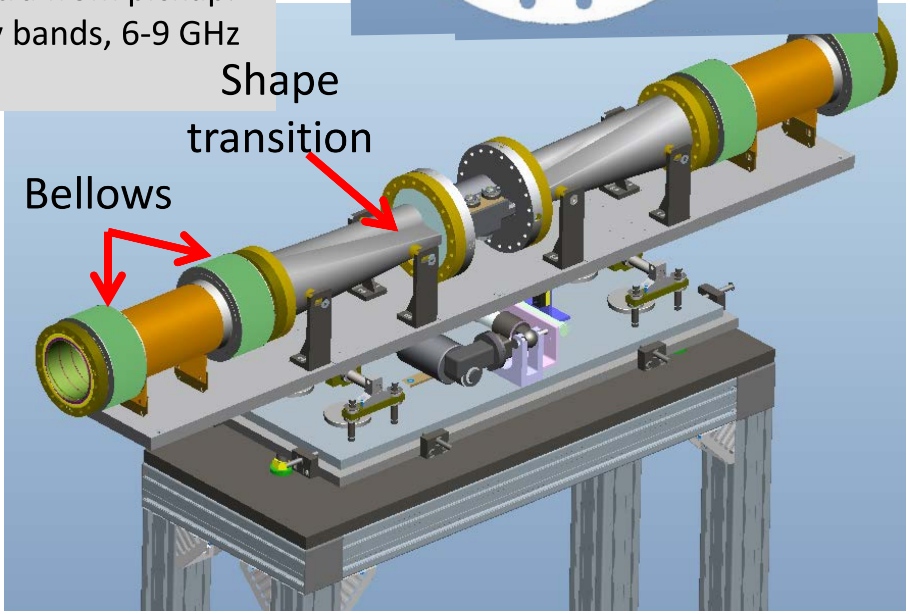


Beam spectra from pickup.
16 Schottky bands, 6-9 GHz





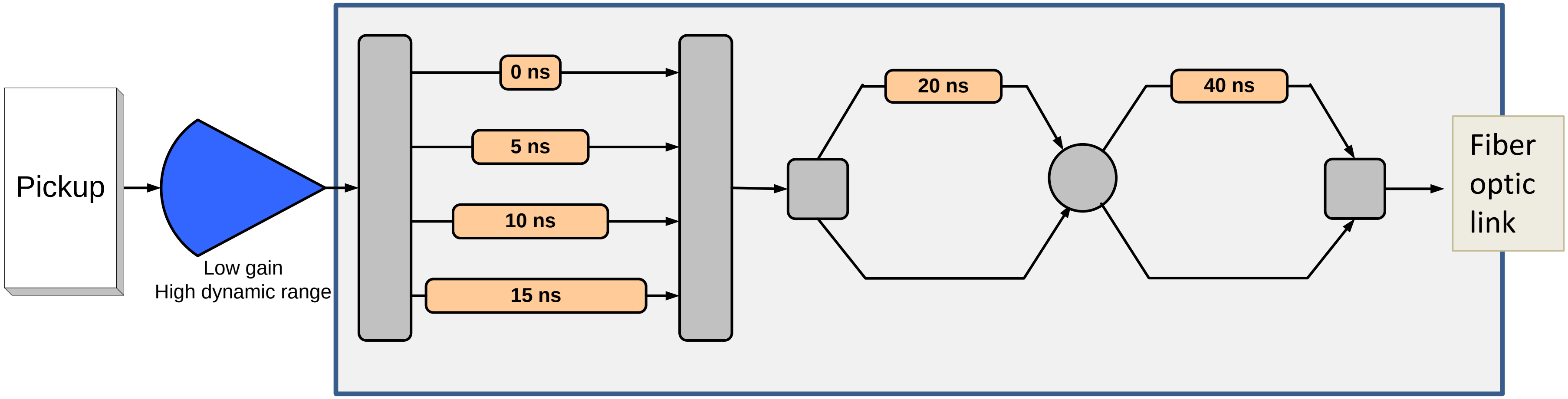
Spectrum from wire test.
Markers at 6 and 9 GHz, 3 dB/div



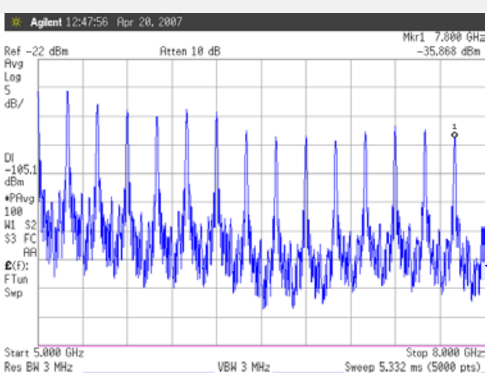
Signal Processing

- Wide dynamic range is required to cope with the coherent components in the Schottky signals from the pickups
- But high frequencies and long distances mandate fiber optics for signal transmission
  - The noise figure of fiber optic links is about 40 dB
  - Requires active gain before the link input
  - Non-linearity and saturation cause inter-modulation distortion with un-wanted products in-band
  - The Schottky signals have to filtered before the gain stage

Solution to the Coherent Line Problem

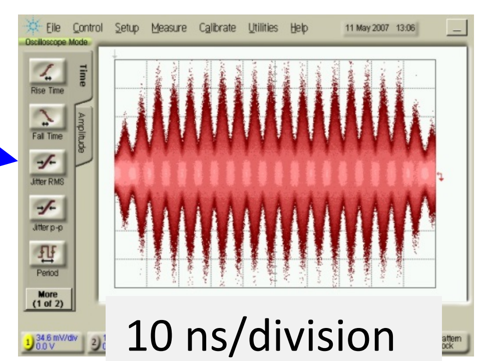


- A traversal filter with 16 delays of 5.000 ns reduces the peak signal value but has passbands at 200 MHz intervals.
- It is realized passively with only coax cables. So it is linear.
- After this filter the signal goes into the fiber optic analog link to the surface.
- This stretched pulse ultimately drives the kicker cavities to fill them between bunches



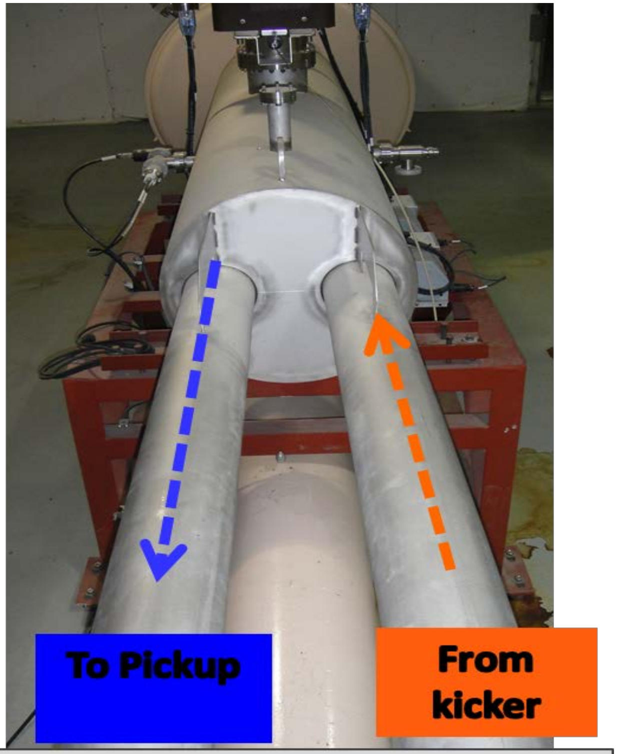
Time domain

Frequency domain

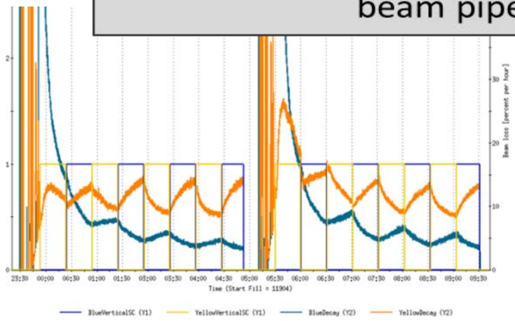


Cross talk between rings

- We observed cross talk between the cooling systems of the two RHIC rings
- Operation in the Yellow ring would corrupt the signals in the Blue ring.
- Signals propagated in the beam pipe from the kickers to common chamber, then back to the pickup of the other ring.
- In the first run we had to ping-pong between cooling in the two rings every ½ hour
- The solution is to operate the rings at different frequencies
  - Yellow: 4.8, 5.0, 5.2…7.8 GHz
  - Blue: 4.7, 4.9, 5.1…7.7 GHz



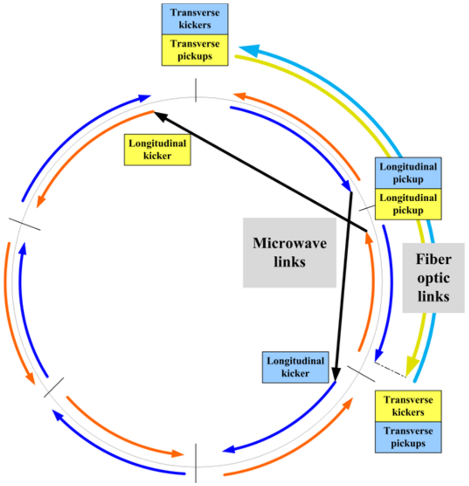
Propagating waveguide modes in the beam pipe



Loss rates while ping-ponging between rings

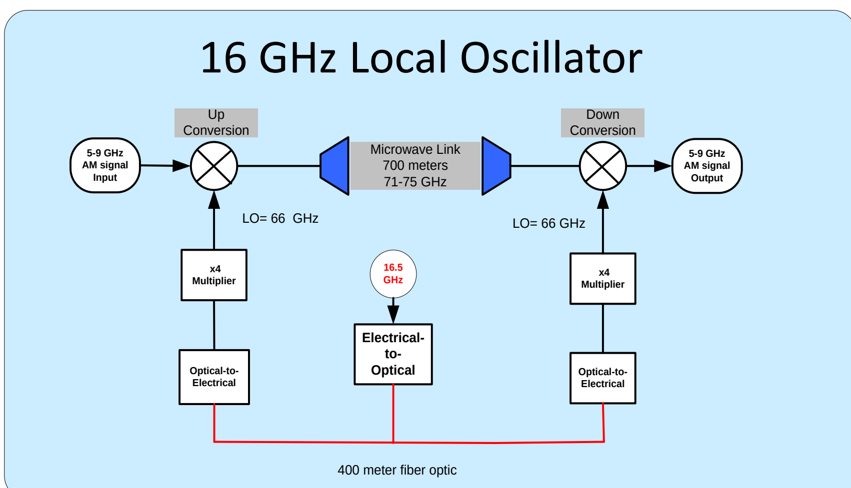
Signal Processing

- Wide dynamic range is required to cope with the coherent components in the Schottky signals from the pickups
- But high frequencies and long distances mandate fiber optics for signal transmission
- For the longitudinal systems we need to minimize the pickup-to-kicker delay
  - The notch filter for momentum cooling adds group delay
  - Microwave links sends signals across the ring

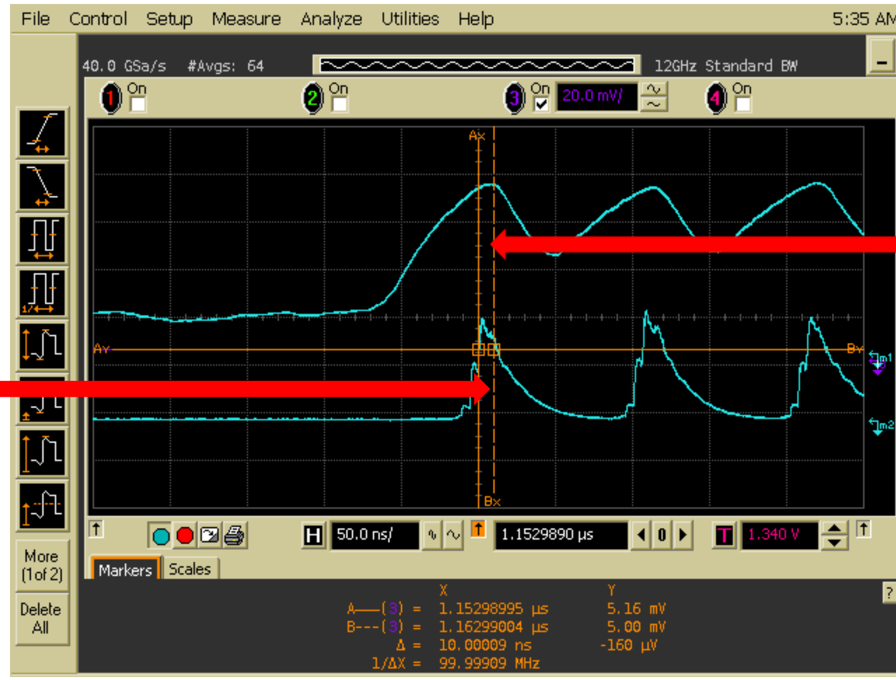


Longitudinal pickup to kicker via Microwave link

- Microwave link (70 GHz carrier)
- Stabilized by phase feedback from a pilot tone at 4.7 and 9.4 GHz (fast fluctuations)
- Local oscillator for up and down conversion recently upgraded from 100 MHz to 16 GHz



Pickup to Kicker Timing



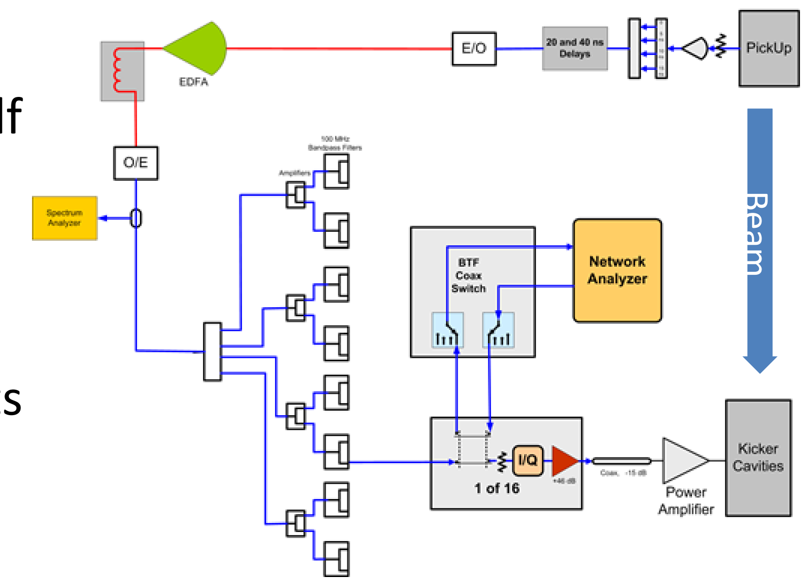
1. We observe the signal induced on a cavity by beam
2. Each cavity has a monitor port
3. Cavity drive amplifiers are off

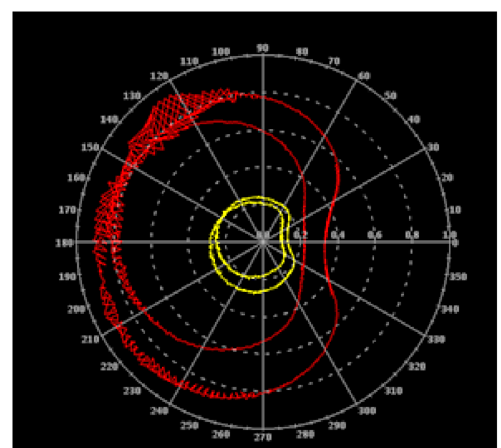
1. With the amplifiers on
2. We observe the voltage in the cavity from the cooling system
3. Adjust time delay

Operation

- The basic principle of low-level control is that each plane automatically re-tunes itself every ~10 minutes
- This tracks drifts due to temperature, and changing beam emittance and intensity
- A transfer switch in the signal path connects a network analyzer to measure the open loop transfer function with beam
- The measured transfer function is compared to a reference and adjustments are send to amplitude and phase modulators
- Only one of the 16 frequencies are measured so the other 15 continue cooling

Stochastic Cooling Low Level Block Diagram

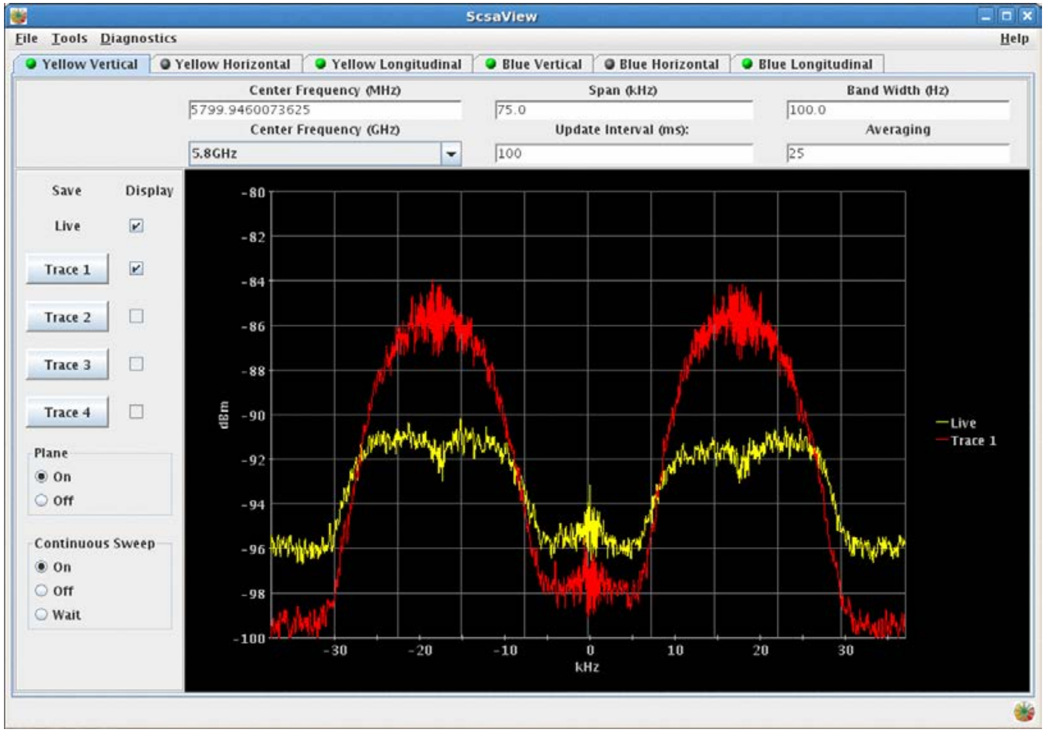




Open loop transfer function, reference and measured

Signal Suppression

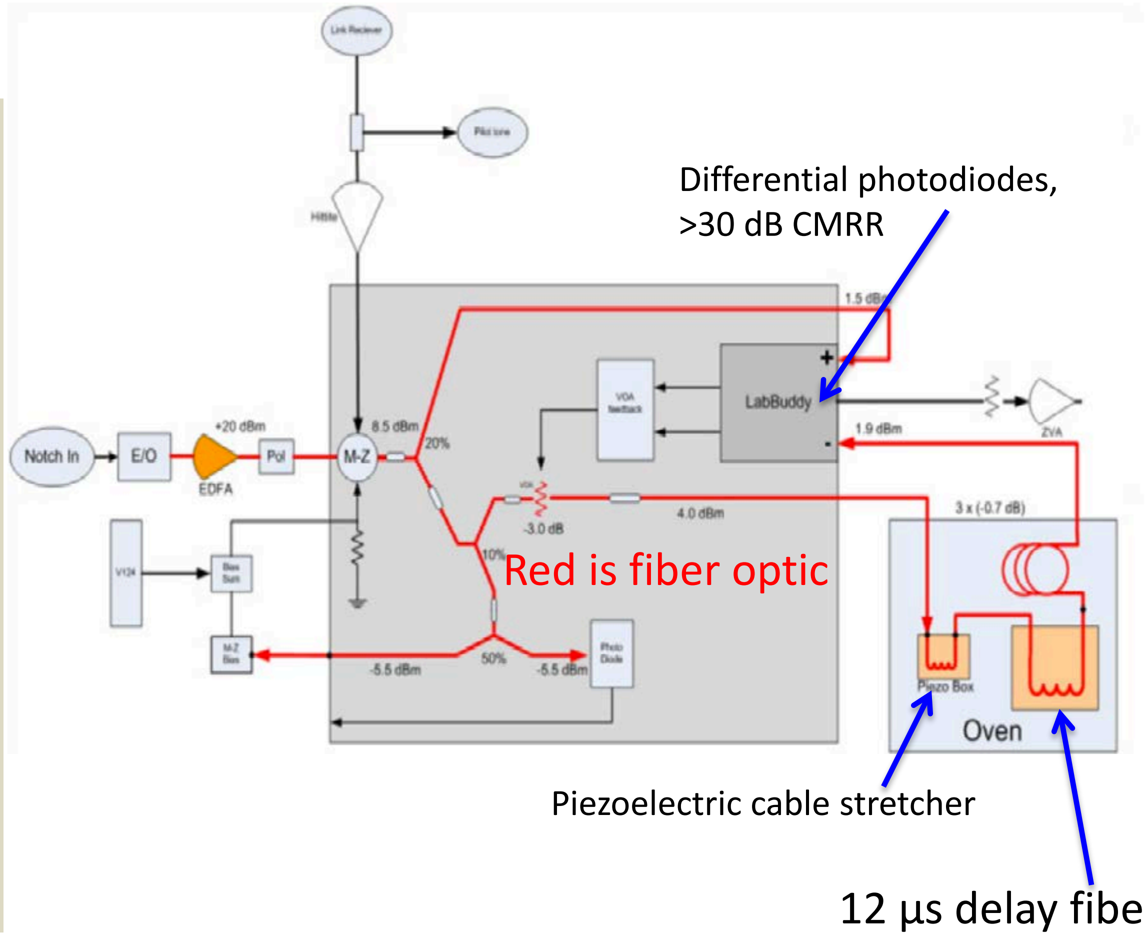
- The reference transfer functions are obtained by observing and optimizing **signal suppression**
- Whereas 6 dB is optimal for cooling the system is typically operated with less, ~3dB
- The network analyzer measurements have a systematic error because they are CW as opposed to beam driven excitement of the kicker cavities



Spectrum analyzer display of Schottky signals from a transverse pickup. Red is cooling off, Yellow is cooling on

Longitudinal Cooling Uses a One-turn Delay Notch Filter

- One-turn delay realizes a derivative of the revolution frequency, giving the sign of energy correction kick
- The delay is created with a **fiber optic cable**
- The delay value is constantly adjusted with a Piezoelectric line stretcher
- Control of the Piezo comes from Network Analyzer measurements of the notch frequencies



Summary

- Bunched beam stochastic cooling in 5-9 GHz range is operational at RHIC
- The challenges of coherent components in the Schottky signals and high voltage/high frequency kickers have been met by specially adapted devices
  - Analog passive traversal filters reduce signal dynamic range
  - High Q cavity kickers synthesize a Fourier composition of the correction kicks and reduce power requirements
- Automated system tuning and corrections are obtained with real-time Network Analyzer measurements and calculated parameter adjustments
- Bottom line: the collider integrated luminosity for physics production has been increased by up to a factor of five for some beams