

## TWENTY-FIVE YEARS OF STOCHASTIC COOLING EXPERIENCE AT FERMILAB\*

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### *Abstract*

In the early 1980s, it was decided that Fermilab would build a proton antiproton collider to search for the top quark following the success at CERN with the discovery of the W and Z bosons in the SPS pbar p collider. The effort was designated the Tevatron I project. Design of the antiproton source began in earnest in 1981 with a construction start in 1983. The Tevatron started fixed target operations that same year. The first antiprotons were delivered to the Tevatron in October of 1985 and first collisions were observed in the CDF detector. The Antiproton Source consists of two 8 GeV kinetic energy accelerators, the Debuncher and Accumulator. The Debuncher ring performs bunch rotation and pre-cooling, the Accumulator ring utilizes stochastic cooling for antiproton collection. The addition of the Recycler ring (also 8 GeV) in 2003 as a depository for antiprotons changed the scope of cooling in the Accumulator. This paper will present the chronology of the cooling systems development from those early days to the current record setting performance.

### DEBUNCHER COOLING SYSTEMS

The original design of the stochastic cooling systems in the Debuncher included only transverse cooling operating from 2-4 GHz.[1, 2] Incoming flux was predicted to be  $3 \times 10^7$  pbars per second, but was significantly lower due to insufficient protons on target. Bunch rotation and longitudinal cooling takes the incoming 4.25% momentum spread and reduces it to 0.037%. The acceptance of the Debuncher was designed at  $20\pi$  mm-mrad in both planes and has been improved with lattice modifications and careful placement of aperture restricting devices to  $35\pi$ . The horizontal and vertical cooling reduces the beam to under  $2\pi$  mm-mrad. With the expected flux, it was clear from the outset that front-end effective noise temperature of the stochastic cooling systems would need to be significantly below tunnel temperature of 311<sup>o</sup>K. The original Debuncher stochastic cooling systems employed liquid nitrogen to cool the pickups and amplifiers to 80<sup>o</sup>K. Total front-end effective noise temperatures were of the order of 120<sup>o</sup> K.

A significant upgrade to the cooling system was begun in 1996 and completed in 1998 with increased bandwidth to 4-8 GHz. [3] The octave band is split into eight 500 MHz wide bands for the pickups then combined to four 1 GHz bands for the kickers utilizing slotted waveguide structures. [4] This decision was based on minimizing the number of cold to warm transitions on the cryogenic

pickups, and the need for more kicker drive ports. The slotted waveguide structure bandwidth is dependent on the length of the array, facilitating this requirement. Liquid helium cooled pickups, amplifiers, and components [5] are responsible for a front-end effective noise temperature ranging from 10<sup>o</sup>K to 30<sup>o</sup>K. [6] This four to ten fold decrease in effective noise temperature dramatically improved cooling performance. With an enhanced S/N ratio, it was now possible to make beam transfer function measurements with pbars. Prior to this upgrade, the only way transfer functions could be measured was to reverse magnet polarity and inject forward protons, a cumbersome effort taking two to three days to complete.

Momentum cooling was realized by using the same pickups and kickers simultaneously in sum and difference mode. Unlike the accumulator, where high dispersion straights are available for utilizing Palmer cooling, notch filter cooling was implemented for momentum cooling. The first notch filter consisted of four independent Bulk Acoustic Wave (BAW) delays. Momentum spread now became sufficiently narrow that small drifts in notch filter frequency between the four systems became problematic limiting the asymptotic momentum spread. A solution was to combine all four bands of momentum cooling into one trunk, then passing through an octave wide optical notch filter, splitting back into separate bands, effectively eliminating notch frequency drift between bands. The Debuncher Momentum system has been upgraded to a single/double turn optical notch filter. After the first second of the cooling cycle, a single turn delay is switched to a double turn increasing the gain near the central momentum. The resulting momentum spread being 3.26 MeV/c (0.037%). An automated tuning program is run periodically to adjust the filter to the correct revolution frequency, typically only a few picoseconds of adjustment.

Because the tune of the Debuncher is close to the three quarter integer, it is possible to improve system signal to noise in the transverse cooling with the addition of two turn delay notch filters. These filters suppress any common mode signal from the pickup and notch thermal noise between bands where no Schottky signal exists, all while providing balanced gain and phase to the desired transverse Schottky signal.

The upgrade consists of eight each cryogenically cooled pickup tanks and water-cooled kicker tanks. Sixty-four 200 Watt traveling wave tube amplifiers (TWT) running at the 1 dB compression point drive the kicker tanks.

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## ACCUMULATOR COOLING SYSTEMS

The Accumulator cooling consists of the Stacktail [7, 8] and core cooling systems. [9] The original Stacktail system operated from 1-2 GHz and core systems operated from 2-4 GHz. Stacktail horizontal and vertical transverse systems were also part of the original design operating from 1-2 GHz. The pickups for the Stacktail betatron system were the same as the momentum system by taking the difference signal from the medium energy pickup plates for vertical and edge coupling for horizontal. Pickups for the Stacktail are located in high dispersion and momentum cooling uses the Palmer method of energy dependent pickup response. Due to the high momentum spread of the beam in the Stacktail, the Stacktail betatron system had difficulty resolving betatron motion from momentum spread. This coupled with the nonlinear distribution of beam in the stack made the betatron system more of a momentum cooling system. It was never very effective for stacking and was abandoned when the Stacktail was upgraded to 2-4 GHz in 1999. [10]

Core cooling consists of two transverse and two momentum cooling systems. The original 2-4 GHz momentum system was augmented with the addition of a 4-8 GHz core momentum system in 1989. Pickup to kicker delay for this momentum system is half the revolution period. The gain slope and dispersive effects of this length of coaxial cable were detrimental to system bandwidth. An equalizer was designed to relieve some of this effect, but the required 40 dB gain slope compensation also negatively affected system signal to noise. In 2006, this system was upgraded to optical fiber transmission between pickup and kicker, which eliminated gain slope and dispersion. This is the only cooling system that has sufficient beam transition time between pickup and kicker that would allow for the slow propagation velocity of fiber (67% velocity of light). The 4-8 GHz momentum system is now being upgraded by the addition of two new planar loop kicker arrays.

When the Stacktail was upgraded to 2-4 GHz, the core transverse cooling was also upgraded to 4-8 GHz. The initial 4-8 GHz upgrade utilized planar loops in one octave band. Gain slope and phase dispersion due to cable delays across the ring reduced system performance. As an R&D project for signal transmission in the Recycler, a free space optical link was installed between pickups and kickers in the Accumulator. [11] This proved successful and eliminated the need for equalizers. With the recent success of slotted waveguide arrays in the Debuncher, it was decided in 2000 to upgrade core transverse cooling to the higher sensitivity of slotted waveguides and transverse cooling became six separate cooling systems in three bands covering the frequency span. These narrower bands did not have the gain slope or dispersion extremes of the full octave and the optical free space link could be decommissioned. Core transverse heating from the Stacktail kicker power was a considerable problem with the 1-2 GHz system and was overcome by taking four of the kickers and adding transverse feedback to combat the heating. Transverse

kickers were also included in the 2-4 GHz Stacktail upgrade, but proved un-necessary in operations due to Stacktail kicker centering (eight short vacuum vessels as opposed to three long tanks from the original system) and improved transverse core cooling.

The accumulator exhibits saturation effects as the stack size approaches an excess of  $1 \times 10^{12}$  antiprotons. This was mitigated by increasing the stacking cycle time and reducing Stacktail power resulting in a commensurate decrease in stacking rate. Cores of that size exceed a system dynamic range of 60 dB and notch filters lose their effectiveness. With the addition of the Recycler, stacks rarely exceed  $4 \times 10^{11}$  and the stacking rate is maximized. The Stacktail system continues to be the most complicated of all cooling systems and has taken considerable effort to optimize.[12]

## RECYCLER COOLING

At the outset of Recycler commissioning, only stochastic cooling was available. [13] Due to the lattice of the synchrotron and a low revolution frequency, the cooling frequency bands are limited to avoid Schottky signal band overlap. The Recycler has the original four cooling systems: two longitudinal systems covering 0.5-1 GHz and 1-2 GHz plus two transverse systems H&V 2-4 GHz.

The Recycler is seven times the circumference of the Accumulator and required a transmission scheme other than optical fiber (propagation too slow) or coaxial cable (insertion loss too large) to connect the pickups to the kickers. Two choices were pursued: an over-moded circular waveguide transmission line or free space laser link.

AT&T developed the over-moded waveguide years before optical fiber systems were practical. Low loss at a very high carrier frequency (60-80 GHz) and several GHz wide bandwidths were obtainable. A proof of principle was the signal collection for the VLA radio telescope in Socorro New Mexico. [14] Some two kilometers of "spare" waveguide was made available to FNAL from NRAO for the Recycler link, but after twenty years of outside storage, inspection showed only 10 percent of the waveguide was not corroded. The fabrication of new waveguide was financially impractical.

With the success of the Accumulator free space link, it was decided this was the best scheme to span the 550-meter chord between pickups and kickers. With the use of expanding lenses and telescopes, three links were built in temperature controlled environments and the laser beam transmitted in an evacuated 24 inch diameter pipe buried between pickup and kicker. One of the laser links has the 0.5-1 GHz longitudinal and the 2-4 GHz vertical system multiplexed. The lack of gain slope and phase dispersion allows for maximum cooling bandwidth. Free space optical transmission has proven to be robust and requires only periodic remote control alignment of the laser beams to compensate for mechanical/thermal laser beam drift.

## PICKUPS/KICKERS

The initial electrode design for pickups and kickers consisted of a three dimensional antenna with a pocket ground plane. [15,16] These arrays proved functional for the first years of operations, but did experience several difficulties. The arrays were delicate and expensive to fabricate. Kicker overheating caused the solder connections to fail on several occasions, resulting in a loop falling into the beam aperture.

As higher frequency systems were designed, three-dimensional technology proved less sensitive at frequencies above 4 GHz. With the advent of improved computer aided microwave design tools, it was possible to develop printed circuit planar antennas. [17,18,19] The 4-8 GHz core momentum system first employed three-dimensional loops but has since been modified with planar kickers. The Stacktail system uses planer loops throughout. An added benefit with this technology is the combiner/splitter network is integrated into the same circuit board, providing an inexpensive and robust design. Planar arrays (as they became known) are fabricated in octave bands from 0.5 to 8 GHz.

When it was decided to replace the Debuncher cooling electronics in 1996, the required sensitivity of the pickups to achieve the required cooling rates left two options. The first was to use plunging planar arrays, the plunging necessary to follow beam size to maintain S/N as the beam cooled rapidly. This technique had been successfully implemented in the CERN ACOL ring.[20] Mechanical requirements of a moving pickup at cryogenic temperatures did not appeal to the FNAL design team. With octave bandwidths still required, it was decided that the frequency response could be met with multiple narrower bands. The innovation of slotted waveguide arrays was chosen for the upgrade. Bandwidths of in excess of 500 MHz were attainable with sensitivities an order of magnitude greater than previously used methods. No moving parts allowed for easier cryogenic cooling to 4°K. These same slotted structures are used for the kickers. In the Debuncher, two 200-Watt TWTs are used to drive each array one each transversely and longitudinally. The absorptive loads in the waveguide were brazed to water cooled heat sinks and cooled with 13°C water to minimize any out gassing due to heating.

Slotted waveguide technology was utilized in the Accumulator core 4-8 GHz transverse cooling systems in 2002. These waveguide pickups were also employed in 2003 for 1.7 GHz Schottky systems in both the Recycler and Tevatron and four 4.8 GHz Schottky systems in the CERN LHC in 2005. [21,22,23]

## ELECTRONICS

The electronics for stochastic cooling are required to gain/phase shape signals, provide amplification, and precisely control timing delays between pickups and kickers. Front-end signal to noise is critical with the only free parameter (once bandwidth has been chosen) being the effective noise temperature. Commercially available

low noise amplifiers did not meet the necessary effective noise temperature requirements in 1983 and LBL was commissioned to work on cryogenically cooled front end amplifiers and components.[24] These amplifiers operated from 1-4 GHz in two separate octave bands. Due to the nature of limited electron mobility in silicon at cryogenic temperatures, physically separate bias networks were required. By the time of the Debuncher cooling upgrade, commercially available cryogenic amplifiers with effective noise temperatures in the range of 5°K to 25°K in the 4-8 GHz band were purchased from Miteq Inc. During the initial testing, it was discovered that these amplifiers were not stable at all temperatures between room and liquid helium temperatures. The ensuing instability destroyed the amplifiers, requiring Fermilab to implement a redundant interlock system to ensure amplifiers were not powered during cool down or warm up. Since the interlocks were installed, no amplifiers have failed due to this unstable operating mode.

Signal processing requires taking the sum and difference of both pickup and kicker signals. Commercial hybrids perform admirably, but did not provide adequate common mode rejection performance. A Fermilab patented hybrid [25] has been included in many cooling applications with excellent difference mode performance and power handling capabilities.

After the first few years of operations, it became clear that system equalization could improve cooling performance at very low cost. Today, most systems have a custom equalizer designed in-house and fabricated at local circuit board vendors.[26,27]

The Antiproton Source tunnel is quite warm and power dissipation in electronics became a subtle problem. Driver amplifiers heat sunk to ambient temperatures would endure a graceful decline in gain over a period of years. A simple fix was chilled water-cooling of all such amplifiers. Once implemented, stable gains have resulted in worry free operation.

Power amplifiers are the most expensive electronic part of a cooling system. The cost per watt can be as high as several hundred dollars. Fermilab has one of the largest installations of TWT amplifiers at 112 with a total power capacity of 22.4 kilowatts. The critical timing required for stochastic cooling necessitates having the TWTs located very close to the kickers to minimize insertion loss and transmission delay. The TWT power supply is the weakest link in reliable operations. All supplies are located in service buildings as far as 100 meters from the TWT. The added cable capacitance and regulation requirements required tight tolerance on the power supply design. Ready access is required to facilitate supply replacement.

## NOTCH FILTERS

Fermilab has pioneered a variety of technologies for the fabrication of recursive notch filters required for Stochastic Cooling. The original design for the Stacktail system was based on superconducting delay lines. [28,29]

The availability of coaxial cables made from superconducting material was very limited. The first cable used consisted of a niobium center conductor and a lead outer conductor. The 83-meter length available was not commensurate with the delay required for the accumulator filter, but was adequate for initial testing. In collaboration with KEK, negotiations with Furukawa industries of Japan produced required quantities of 1.6 mm diameter lead plated copper coax. At the outset of development, it was known that intermodulation distortion from the TWT power amplifiers would be detrimental to cooling. A significant effort was directed to passing power through the superconducting cable in an effort to put the notch filter after the power source, mitigating the intermods. The maximum achievable power transfer was twenty-five watts before inducing a quench. Forty watts minimum was required, so this approach was abandoned. Superconducting notch filters have the best performance of all filter technologies. Due to low insertion loss and wide bandwidth, these notch filters produce the deepest notches with the maximum dynamic range and low dispersion due to lack of skin effects. The operational costs of the liquid helium plant is the only draw back.

A subsequent notch filter technology was the use of BAW delay lines, [30] a technology developed for radar applications after World War II. The BAW consists of a quartz or sapphire crystal with surface printed antenna to transform electrical energy to acoustic waves in the crystal. The slower propagation velocity of acoustic waves yields a delay on the order of one microsecond per centimeter of crystal. Sapphire is the preferred material due to its lower temperature coefficient. The impedance match to the crystal has a very high voltage standing wave ratio (VSWR) as is typical with all piezo electric materials, hence the manufacturer supplied the delay line with circulators and an equalizer. BAW notch filters are realized with a passive circuit requiring only temperature stability of the oven that housed the device. Operating costs are significantly below that of superconducting filters, but have the limitation of a high insertion loss (40-60 dB) and a limited dynamic range of 30-50 dB set by signal to noise ratio. BAW filters are best suited to frequencies below 6 GHz and delays less than a few microseconds.

The last notch filter technology implemented was the use of fiber optic delays. [31] With the expansion in telecommunications hardware, wide band fiber optic links became commercially available as a viable means of creating longer delays than achievable with either coax or BAW techniques. This was particularly necessary for notch filters in the Recycler, where delays approached 12 microseconds. Fiber optic links operate in the communication wavelengths of 1330 and 1550 nanometers. The first optical notch filters were fabricated for the Debuncher cooling systems. [32] Optical links have bandwidths exceeding the cooling system requirements, but the higher the bandwidth utilized, a reduced dynamic range is incurred. For filters with

octave bandwidths between 1-8 GHz, dynamic range is limited to approximately 40 dB or less. Optical links have both an active laser transmitter and photo diode receiver. For applications requiring location in the tunnel due to beam time of flight requirements, radiation shielding is a prudent precaution for extending link life.

Fourteen notch filters are now in use: one Debuncher momentum (optical), eight Debuncher transverse (four BAW, four optical), three Stacktail (two BAW, one superconducting), two Recycler (both optical).

## PBAR ACCUMULATION PERFORMANCE

The original accumulation specifications were for a stack size of  $4.3 \times 10^{11}$  pbars and a stack rate of  $1 \times 10^{11}$  per hour. [33] This lofty goal for stack rate was not achieved until August 2001. Most recent records are a maximum stack size of  $3.13 \times 10^{12}$  in February 2008 and stacking rate of  $2.85 \times 10^{11}$  per hour in December 2008. Run II operations routinely have stack sizes less than  $4 \times 10^{11}$  at stacking rates exceeding  $2.5 \times 10^{11}$  per hour with transfers to the Recycler every hour. [34] Current plans are to continue the collider experiments through 2010 and perhaps 2011 depending on operations at CERN with the LHC.

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