Fermi National Accelerator Laboratory

FERMILAB-Pub-97/049

Stochastic Cooling at Fermilab

Mike Church

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

February 1997

Submitted to *Nuclear Instruments and Methods in Physics Research A*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

Disclaimer

Distribution

Reference number: 3.3

STOCHASTIC COOLING AT FERMILAB

Mike Church
Fermi National Accelerator Laboratory[1]
Batavia, IL 60510 USA

Abstract

Fermilab now has over 10 years of operational experience with stochastic cooling systems. New techniques and refinements of old techniques continue to push the state of the art. I will discuss recent developments which include strategies for new pickup and kicker arrays, laser signal processing, recent measurements on system performance, bunched beam cooling, new calculational/modeling techniques, and requirements for future Accelerator upgrades.

Corresponding author: Mike Church
MS 341 Fermilab, Batavia, IL 60510 USA
Ph. (630)-840-2382, FAX (630)-840-8737
EMAIL: CHURCH@FNAL.GOV

PACS numbers: 29.20.Dh, 29.27.-a,41.75.-i

Keywords: stochastic cooling, storage ring, pickups, kickers

---

[1]Operated by the Universities Research Association under contract with the U.S. Department of Energy

Introduction

The Fermilab Antiproton Source has been able to stack up to 220×10^{10} antiprotons at peak rates of 7.2×10^{10}/hour [1]. Numerous improvements and additions to the original stochastic cooling systems in both the Debuncher ring and Accumulator ring have helped make this possible. In the near future, with the commissioning of the Main Injector Ring, the flux of protons on the antiproton production target will increase by at least a factor of 2.7, and perhaps by a factor of 5 or 6 [2]. To meet the luminosity requirements of Collider Run II with the Main Injector, the Antiproton Source will be required to stack 20×10^{10}/hour for up to 1 hour before transferring beam to the newly proposed Recycler Ring [3]. The addition of the Recycler as the final storage ring for antiprotons will eliminate the need to store very large antiproton stacks in the Accumulator, but the stochastic cooling systems in the Debuncher and Accumulator will still be required to increase the phase space density of the antiprotons by about 6 orders of magnitude. Calculations, and a recent study stacking protons [4], indicate that the maximum flux the current systems can handle is about 12-15$\times 10^{10}$/hour. Further into the future, proposals to reach luminosities of 10^{33} cm^{-2}sec^{-1} in the Tevatron (TEV33) will require an antiproton stacking rate approaching 100×10^{10}/hour. Hence, there is abundant motivation to improve the performance of the stochastic cooling systems at Fermilab.

Figure 1 shows schematically the stochastic cooling systems currently in use in the Antiproton Source. The Debuncher has 3 separate systems: 2-4 GHz vertical, horizontal, and longitudinal. The Accumulator has 9 separate systems: 1-2 GHz ("stacktail") vertical, horizontal, and longitudinal; 2-4 GHz core vertical, horizontal, and longitudinal; and 4-8 GHz core vertical, horizontal, and longitudinal. The original TEV I design had two Debuncher cooling systems (no longitudinal), three stacktail systems, and three 2-4 GHz core systems.

Debuncher Cooling Systems

Every 2.4 seconds a pulse of 6.7×10^7 antiprotons is injected into the Debuncher, bunch rotated, stochastically cooled, and then extracted a few milliseconds before the next injection. The beam is cooled longitudinally from $\Delta p/p_{95\%}$ =.30% to .17% and transversally from 16 π-mm-mrad to 4 π-mm-mrad (95%) in this period. The original 3 dimensional loop couplers [5] are still used for the pickups and kickers, and each transverse system uses 128 pickups and 128 kickers. Momentum cooling is obtained by shaping the sum mode signal from the pickups with a notch filter and applying this signal to the kickers in sum mode. The transverse cooling rate is well understood and well predicted by the transverse cooling rate formula:

$$-\frac{1}{\varepsilon_\perp}\frac{d\varepsilon_\perp}{dt} = F_0 \sum_l \left\{ g_l T_l - \frac{N}{2} |g_l T_l|^2 (M_l + U_l) \right\}, \text{ where}$$

$$\text{signal suppression} = T_l = \frac{1}{1 + .5 N g_l M_l} \text{ for a gaussian beam.}$$

The inputs to this equation can be directly measured. The noise/signal ratio U_l is measured from Schottky signals in the 2-4 GHz band; the mixing factor M_l is extracted from a measurement of the beam momentum profile; and the gain g_l is obtained from open loop network analyzer measurements and/or signal suppression measurements. These systems are each limited to 1000W of output power due to the power-handling limitation of the kicker arrays, and 95% of this power is thermal. They are operating at only 20% of optimum gain due to this power limitation.

An upgrade plan, due to be completed by the Main Injector startup, has already been initiated. It consists of the following items: 1) plunged planar pickups and kickers to follow the shrinking beam profile during the cooling cycle; 2) pickups and combiner boards cooled to 4°K with liquid He (the current pickups are cooled to 80°K) together with lower temperature preamps (25°K); 3) increased power handling capability of the kicker tanks to 1600W; and 4) ramped Debuncher lattice parameter η from -.006 to -.009 during the cooling cycle to improve the mixing factor. The predicted transverse cooling rate due to these upgrades, compared to the case of no upgrade, is shown in Figure 2.

Accumulator Cooling Systems

A new pulse of 5.4×10^7 antiprotons is injected into the Accumulator every 2.4 seconds.

(The Debuncher to Accumulator transfer efficiency is typically 80%.) This beam is then rf displaced to the central orbit where it is then stochastically stacked into a core with a 90% efficiency [5]. Figure 3 shows a typical longitudinal profile of an Accumulator stack. With the simplifying assumptions of a static density distribution, no signal suppression, and "perfect" gain functions, the theoretical maximum stacking rate is given by [6]

$$\phi_{\max} = \frac{1.4 \bullet W^2 E_d |\eta|}{P \bullet F_0} = 21\text{x}10^{10}/\text{hour},$$

where W=bandwidth and E_d=characteristic energy ($\varphi \propto \varphi_0 e^{\delta E/E_d}$). In practice, the major difficulties which limit performance below this optimum are the following:

1) Transverse heating of the core by the stacktail system: When the core reaches a size of about $40\text{x}10^{10}$ the core cooling systems can no longer adequately offset the transverse heating effects of the stacktail system, and the pulse repetition rate must be reduced to compensate. The stacktail systems generate about 1000W of output power, and a small amount of this signal will appear in difference mode on the longitudinal kickers, overwhelming the few 10's of watts of power in the core transverse cooling systems. The source of this transverse signal is primarily from imperfect microwave hybrids, although some transverse heating originates from beam misalignment in the longitudinal kickers and non-zero dispersion at the kickers. During Collider Run 1b, the 4-8 GHz core transverse cooling systems were partially replaced by 2-4 GHz core transverse cooling systems, which effectively cool a wider part of the stacktail system. This upgrade (or retrofit in this case) substantially reduced this transverse heating problem.

2) Bad mixing: The unavoidable phase slope due to the notch filters in the system and the beam delay across the stacktail energy introduce non-optimum phase advance through the system, which can not be completely compensated for by two sets of kicker arrays.

3) Overall complexity: The current longitudinal stacktail cooling system has 11 independent, tunable free parameters. It is difficult to find the optimum settings under varying machine conditions.

4) Schottky band overlap: The transverse sidebands of the core overlap the longitudinal Schottky profile of the stacktail at regions of high gain over the upper half of the microwave band. These signals are picked up by the stacktail pickups near the core and further "pumped" up by signal suppression which then distort the longitudinal power spectrum at the stacktail kickers. This signal also contributes to heating the core transversally. During Collider Run 1b a "compensation" pickup placed near the core was used to subtract out this core transverse signal from the stacktail longitudinal signal.

5) Intermodulation distortion in the TWT's (Traveling Wave Tube amplifiers) fills in the notch filters [7], which contributes to longitudinal heating of the core. At low power, the 2-4 GHz notch filters are 30 dB deep, and at 80W they are only 21 dB deep.

In the Main Injector era, the Accumulator stacktail system will be upgraded from 1-2 GHz to 2-4 GHz and the lattice will be modified to change the slip factor η from -.023 to -.0119 to avoid Schottky band overlap. These changes will in principle increase the maximum possible stack rate by a factor of 2. The core cooling systems will remain at 4-8 GHz, with some improvements noted below. Simulations using a new macro particle Monte Carlo technique [8] with realistic gain functions indicate that a stacking rate of at least 24×10^{10}/hour is possible (see Figure 4).

Microwave technology

Advancements in microwave signal processing have been made over the years to improve stochastic cooling performance:

1) We have developed new hybrids (Δ and Σ mode combiners) which can handle 200W of power and have less than .1 dB of gain variation, and less than 1° of phase variation across the 2-4 GHz bandwidth in Δ mode. These will be used in both the Debuncher and Accumulator cooling upgrades. 4-8 GHz hybrids are under development.

2) Phase variation across the microwave band due to cable dispersion is a major problem, especially in the 4-8 GHz band. Optical fibers were used for signal delay in the Tevatron bunched beam cooling project [9,10], with essentially linear phase and flat gain across the 4-8 GHz band,

however because of the slow signal transmission speed in optical fibers (.6c) these cannot be used in the Antiproton Source or Recycler Ring. However, we have recently tested 4-8 GHz signal transmission via line-of-sight lasers with good results, and these will be incorporated into the Accumulator 4-8 GHz cooling systems and the Recycler cooling systems.

3) The development of planar pickup structures [11] has made the fabrication of pickups much simpler. The planar pickups have similar sensitivity to the 3-dimensional loop couplers in the 2-4 GHz range. However, no pickup array structure (pickups plus microstrip combiners) has yet been made at Fermilab which has good sensitivity across the entire 4-8 GHz band -- the currently used pickups at Fermilab have very low sensitivity above 6.5 GHz, in large part due to insertion losses in the microstrip combiner boards. An R&D effort has been initiated to design and test 4-8 GHz slot arrays [12]. These pickups would each have relatively narrow band (1 GHz) and signals would be combined in a slow wave (Floquet) waveguide structure. In principle, such an array would have substantially higher gain x sensitivity. In addition, if a pickup is placed in a high dispersion region, in a tilted configuration with respect to the beam, it can compensate for at least some of the bad mixing due to beam delay from pickup to kicker. A prototype "phase-compensated" 2-4 GHz pickup has been tested on the bench to have the expected phase characteristics, and such a pickup could prove advantageous in the Accumulator stacktail system.

Future Directions

Stochastic cooling remains an active field at Fermilab. The push towards higher luminosities in proton-antiproton collisions in the Tevatron requires higher antiproton production rates which challenge the current state of the art in stochastic cooling. The newly proposed Recycler ring will use exclusively stochastic cooling systems before high energy electron cooling can be commissioned. Antiproton stacking rates of over 30×10^{10}/hour will require an additional Debuncher cooling upgrade to 4-8 GHz, which will require the development of pickup arrays with good sensitivity in this frequency range. If this is successful, it may open the way to higher bandwidth pickup structures. This may reopen the possibility of bunched beam cooling in the

Tevatron, which will probably require a cooling bandwidth in the range 16-32 GHz to obtain cooling times comparable to emittance growth times.

References

[1] S Werkema, "Performance of the Antiproton Source During Run 1b" Fermilab Pbar Note 559 (1996)

[2] S Shukla, *et al.*, "TEV33 Working Group Summary" in *Proceedings of the 1996 Snowmass Meeting* (to be published)

[3] J MacLachlan, these proceedings

[4] M Church, "Summary of Proton Stacking 2/96" Fermilab Pbar Note 560 (1996)

[5] *Design Report for Tevatron I Project*, Fermilab (1984)

[6] J Bisognano, C Leeman, "Stochastic Cooling" in *AIP Conf Proc #87, Fermilab Summer School on Acc. Physics* p583 (1981)

[7] R Pasquinelli, "Bulk Acoustic Wave (BAW) Devices for Stochastic Cooling Notch Filters" in *1991 IEEE Particle Accelerator Conference* San Francisco p1395 (1991)

[8] A Gerasimov, *Fermilab-Pub-94/376* "Macroparticle Simulation for Stochastic Cooling", Fermilab (1994)

[9] R Pasquinelli, "Bunched Beam Cooling for the Fermilab Tevatron" in *1995 IEEE Particle Accelerator Conference* Dallas p2379 (1995)

[10] G Jackson, "Analysis of the Tevatron Collider Beam Spectrum for Bunched Beam Stochastic Cooling" in *1995 IEEE Particle Accelerator Conference* Dallas p2931 (1995)

[11] J Petter, *et al.*, "Novel Stochastic Cooling Pickups/Kickers" in *1989 IEE Particle Accelerator Conference* Chicago p636 (1989)

[12] F Caspers, "Planar Slotline Pickups and Kickers for Stochastic Cooling" *IEEE Trans. on Nuclear Science*, Vol. NS-34 p1866 (1987)

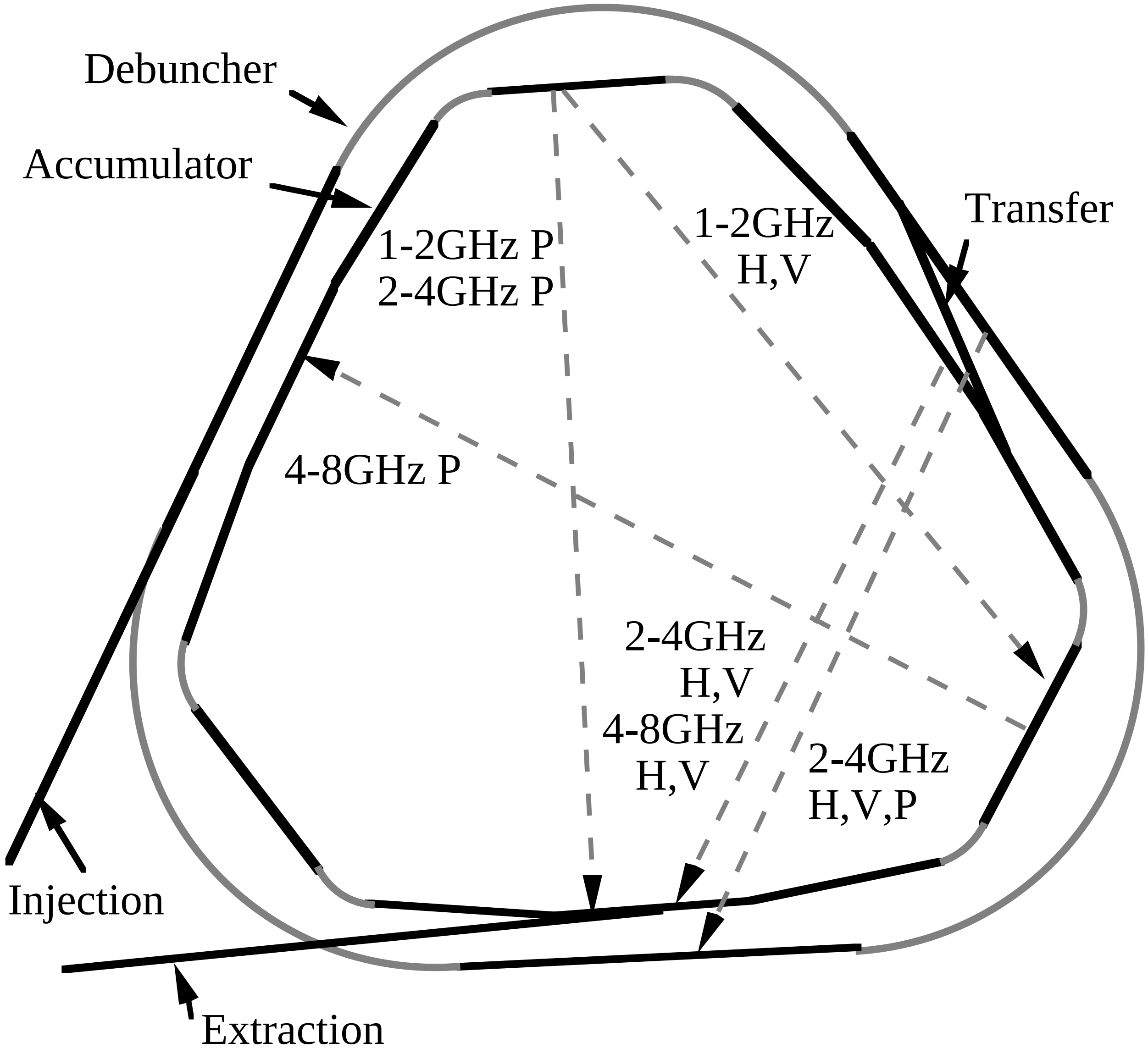

Figure 1. Accumulator and Debuncher stochastic cooling layout

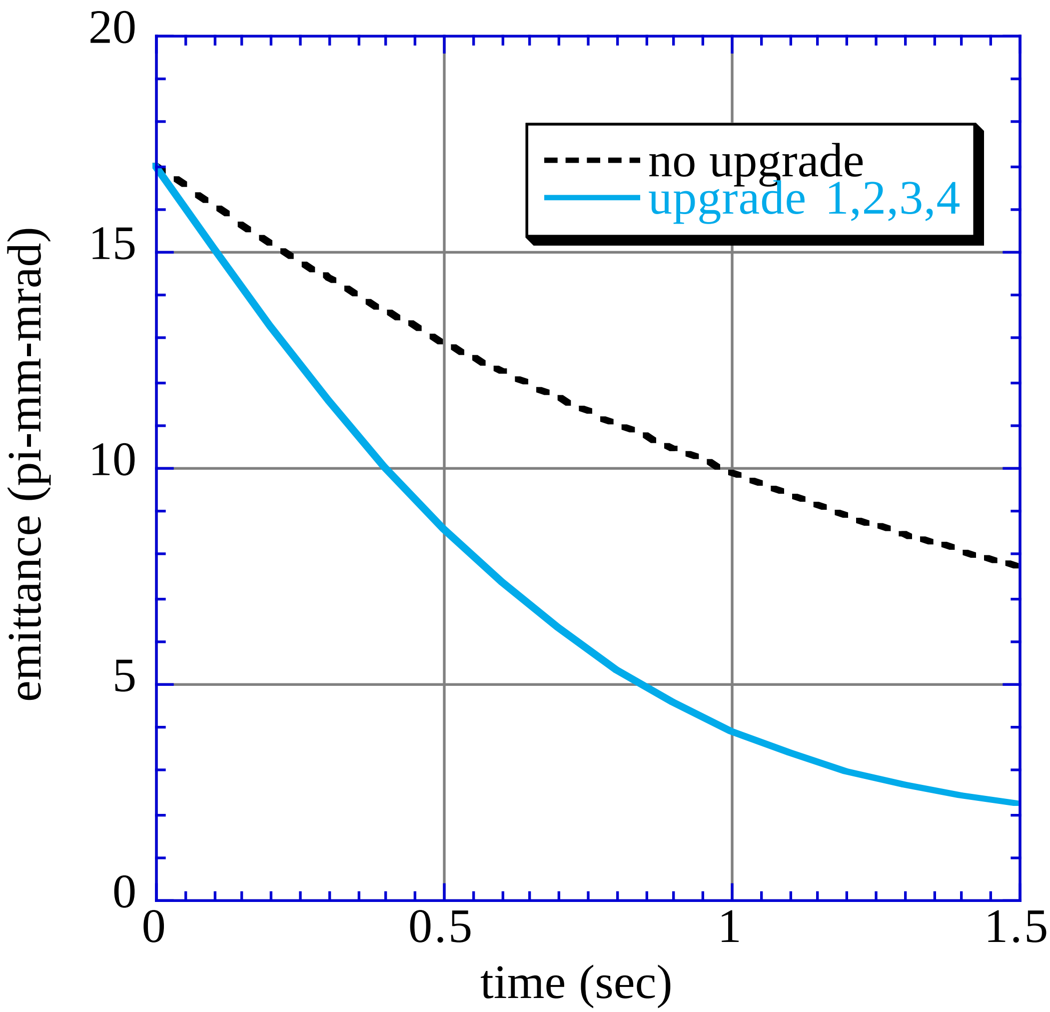

Figure 2. Calculated transverse emittance vs. time in the Debuncher

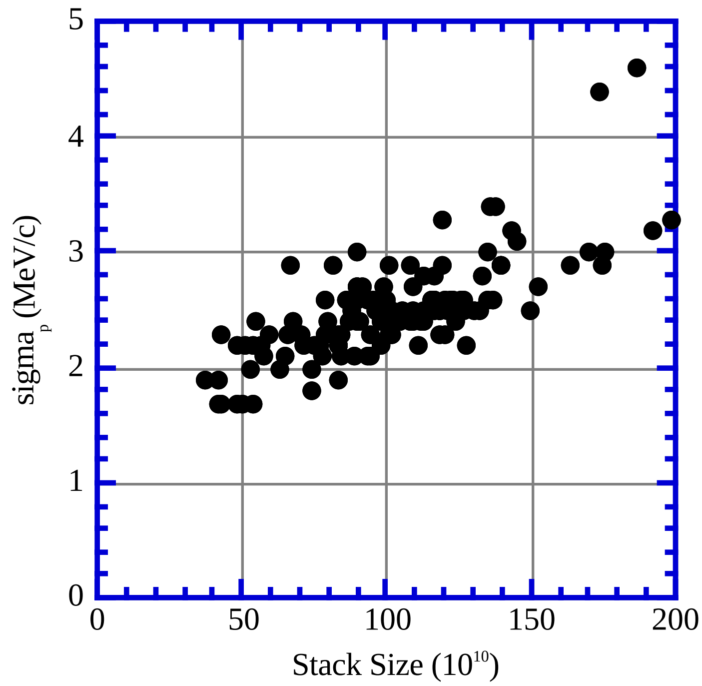

Figure 3. Accumulator longitudinal profile during stacking

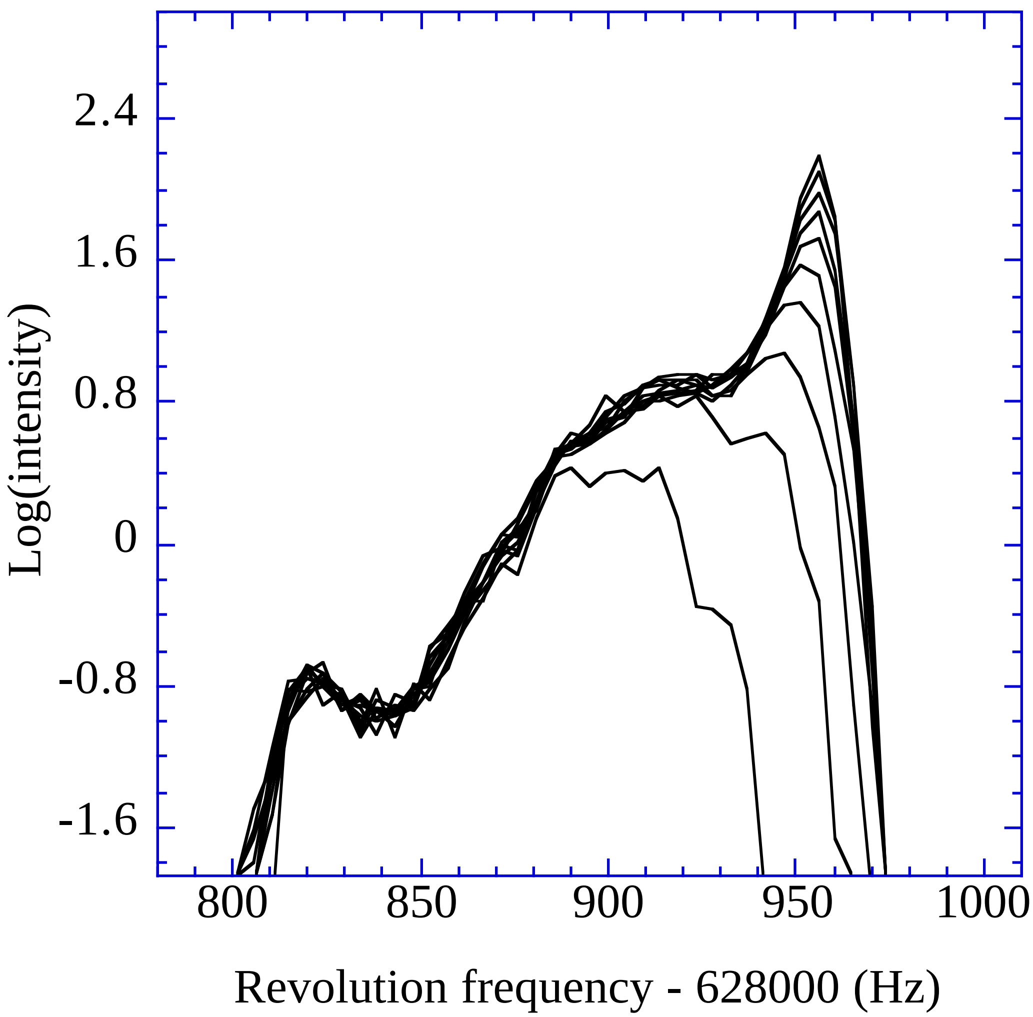

Figure 4. Macroparticle simulation of 2-4 GHz stacktail cooling in the Accumulator. The contours show the longitudinal profile in 3 minute intervals.