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# MEASUREMENT AND OPTIMIZATION OF THE LATTICE FUNCTIONS IN THE DEBUNCHER RING AT FERMILAB*.

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*Abstract*

Tevatron Run-II upgrade requires substantial increase of antiproton production. The central step towards this goal is maximizing the Debuncher ring admittance which necessitates detailed understanding of the Debuncher optics and aperture limitations. The method of the response matrix optimization has been used to determine quadrupole errors and to build a model of machine optics. We estimate that the model predicts beta-functions with accuracy of about 5% mainly limited by Beam Position Monitor system resolution and small number of steering elements in the machine. The improvements of optics model were used to redesign Debuncher optics so that the beam envelopes would be minimized at regions with small aperture.

## INTRODUCTION.

The Debuncher is the first of two Antiproton source. The goal of the Debuncher is to reduce a very large phase space of the beam in all 3 dimensions in order to fit acceptance of the second ring, the Accumulator. First, the momentum spread is reduced using RF bunch rotation and adiabatic debunching. During the rest of Debuncher cycle (about 2 sec) the beam is cooled using transverse and longitudinal stochastic cooling.

The best production rate of the Antiproton source in Run-I was $7\cdot10^{10}$ hour$^{-1}$. In 2005 peak stacking rate reached $17\cdot10^{10}$ hour$^{-1}$, which is still well below of $30\cdot10^{10}$ hour$^{-1}$ anticipated by the Run II upgrade plan. Therefore, massive efforts were taken in the end of 2005 to raise the stacking rate and the work described below was part of these efforts. The acceptance of the Debuncher ring was one of few critical places to be improved. The best measured horizontal/vertical ring acceptances in 2005 were $30\pi/25\pi$ mm·mrad whereas the acceptances corresponding to the physical aperture were $34\pi/31\pi$ mm·mrad. The goal of the Debuncher acceptance upgrade was to reach $35\pi$ mm·mrad in both planes. Earlier simulations [1] have shown that together with an upgrade of Lithium lens this would gain about 60% for antiproton yield. Initially, the Debuncher upgrade plan anticipated an increase of physical aperture of two stochastic cooling tanks that have had major aperture limitation. After lattice measurements and analysis were performed we found that Debuncher optics modification would be an easier way to achieve the required acceptance. It also eliminated risks of deterioration of stochastic cooling systems.

## DEBUNCHER LATTICE

The Debuncher ring has a periodicity of 3, and mirror symmetry in each of 3 sectors. It has 3 straight regions and 3 arcs. The magnet structure consists of 57 FODO cells each with ≈60° phase advance. Straight sections accommodate stochastic cooling tanks, RF cavities and injection/extraction septa. The regularity of FODO structure is only slightly perturbed in straight sections. This is important for maximizing the dynamic aperture and acceptance of the ring. Figure 1 shows the beta-functions and the dispersion in the ring.

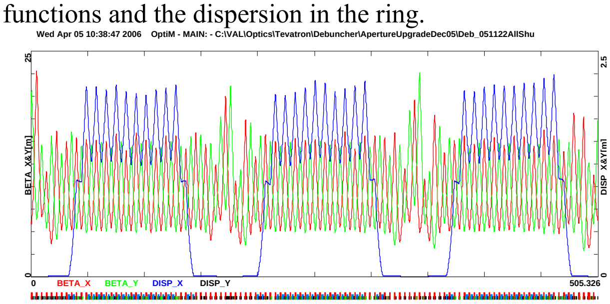


Figure 1. Beta-functions (red line – horizontal, green line – vertical) and dispersion (blue line) in Debuncher. The plot starts at antiproton injection kicker. Horizontal units are meters.

Natural chromaticity is compensated by two families of sextupoles bracketing all arc quads. There is also a considerable non-linearity introduced by the dipoles. In order to include those nonlinearities into optics model, we fit the model predictions to the measured tune dependence on momentum and found that the sextupole and decapole components make major contributions ($B_2/B_0$=-3.6· $10^{-5}$ cm$^{-2}$, $B_4/B_0$=$1.6\cdot10^{-5}$ cm$^{-4}$). Figure 2 presents these data and the fit. Sextupole correction has been applied to make the tunes flat in the central part of the region shown. Figure 3 shows calculated variation of beta-functions and dispersion with momentum. As one can see they have moderate dependence on momentum and, consequently, have little effect on the Debuncher momentum acceptance. Direct tracking simulations have shown negligible effect of machine non-linearities on the Debuncher acceptance for both on- and off-momentum particles.

The free drift space in the straight sectors is very tightly packed with stochastic cooling devices. In order to accommodate them, some of the dipole correctors were

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removed from the ring. There remain 10 horizontal and 7 vertical correctors in the entire Debuncher.

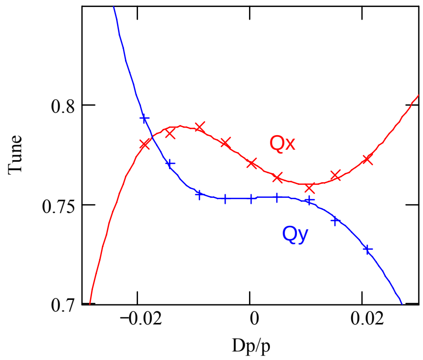


Figure 2. Dependence of tunes on momentum computed using Debuncher optics model (solid lines) and measured (crosses).

Major aperture limitations are the stochastic cooling pickups and kickers for bands 3 and 4, and the injection kicker. The maximum momentum spread is limited by scraping in arcs at high dispersion regions (D≈2.2 m) and is about ±0.03. Additionally, the extraction kicker limits the momentum spread for particles with large betatron amplitude resulting in 7% decrease in number of captured antiprotons.

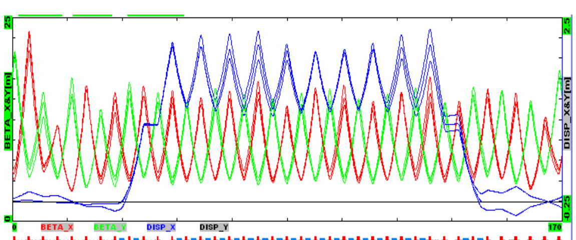


Figure 3. Calculated variation of beta-functions and dispersion with momentum; curves present data for Dp/p = -0.029, 0 and +0.029. Only the first third of Debuncher ring is shown.

## *Lattice measurement method*

Lattice measurement and calculation are made via fitting of the response matrix (RM) – the Beam Position Monitor (BPM) vector response to closed orbit excitation produced by each of the corrector elements [2]. Finding the best model for the lattice description is equivalent to finding the best fit between the calculated and measured response matrices. For the model calculations we used the OptiM program [3]. This program supports 6D calculations for the coupled motion and the nonlinear transport. The *SRLOCOFitting* program was used for the fit. This program was developed at ANL and then successfully extended to the Tevatron [4] and to the Debuncher. The parameters of the model that were varied included individual BPM and trim gains, rolls, quadrupole gradient errors and power supply error factors. The difficulties of accurate lattice measurements in the Debuncher are related to the limited accuracy of BPMs and the small number of correctors. *SRLOCOFitting* is using the robust method of Singular Value Decomposition (SVD), which is beneficial in our case of low data redundancy.

## *Measurement, data analysis, accuracy*

Orbit measurements in the Debuncher were done using reverse protons injected from the Main Injector via Accumulator. As efficiency and stability of the fit critically depends on the measurement accuracy, the precision was the main focus of data taking. Typical BPM resolution in the Debuncher is about 50 μm with a sampling time a little above 1 sec. To get better resolution we took large number of samples (20-25). BPM response had been recorded as a difference of positions between positive and negative kicks for each corrector. This approach was used to minimize such effects as slow machine drifts, BPM nonlinearities and hysteresis-like effects. For the dispersion measurements, the RF frequency was scanned in 5 steps equivalent to Dp/p=0.1% between steps, and orbits recorded for each step. The dispersion was then computed as the slope of a straight line fitting the data. As the data taking application runs on the controls network and analysis is done on the LINUX farm, application creates the data in a format suitable for *SRLOCOFitting* and then that data are transported to the farm. The difference between the measured and calculated orbits before and after the fit is shown in Figure 4. Typical residual errors of the final response matrices are 10μm.

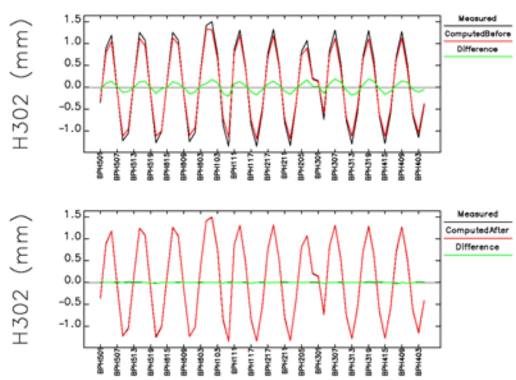


Figure 4. Measured and calculated orbit comparison before and after the RM fitting. Green line shows the residual error of the fit at each BPM.

The key point of the SVD method is to exclude degenerate combinations by means of removing (zeroing) small Singular Values (SV). One has to decide on the threshold of SV rejection. Cutting out too many eigenvectors would make the solution space incomplete and resolution would suffer. Leaving in too small SVs will make the solution unstable. Figure 5 shows the plot of SVs arranged in the descending order. On the same plot the residual RMS in X and Y planes and the RMS of the quad errors are also shown versus the number of SVs left in. This shows that the solution is surprisingly stable for a wide range of selected thresholds. We chose to set the number of selected SVs at 450 which correspond to minimal SV~1.

The accuracy of resulting beta-functions was estimated using simple and naive calculations from the residual RMS to be 3%. A more solid way to do this, although still an estimate of the lower limit was to compare computed new functions with those measured the same way after the lattice change. This also results in ~3% in RMS difference.

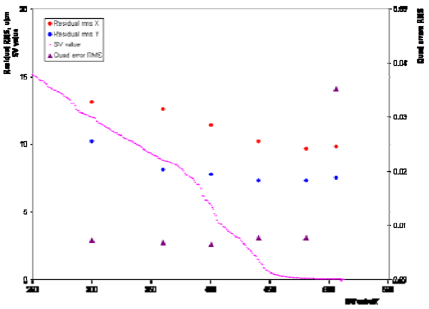

Figure 5. Singular values (in descending order). Shown are also residual RMS and quad errors RMS depending on the number of SV selected.

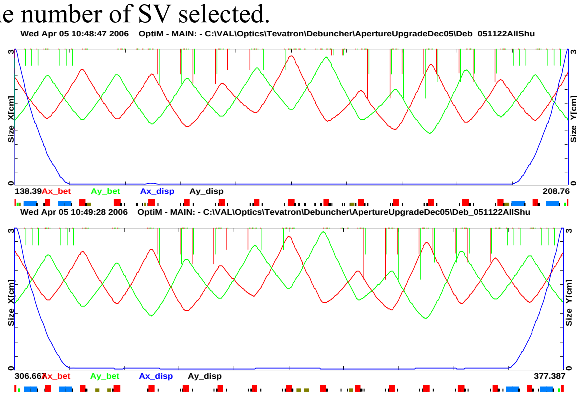


Figure 6. Beam envelopes in the AP-10 (top) and AP-30 (bottom) straight sectors for acceptances of 40.5 and 37.5 π·mm·mrad for horizontal and vertical planes, correspondingly; red line – horizontal beam envelope, green line – vertical beam envelope, and blue line – the contribution to beam size due to momentum spread of 0.03. Vertical lines present aperture limitations with color corresponding to the curve of the same plane.

### *Lattice optimization*

Original optics design had regular behavior for beta-functions, and the stochastic cooling tanks with smallest aperture were the major aperture limitation. We modified the optics so that to minimize the beam size in these tanks. The acceptance increase was limited by the beam size growth in larger aperture tanks. Lattice changes were also constrained by preservation of the tunes (9.764, 9.785) and the slip factor (0.006). This optics modification should result in Debuncher acceptances of 40.5 and 37.5π mm·mrad for horizontal and vertical planes, correspondingly. These numbers are greater than the apertures of the Run II design. Additionally, it also resulted in better conditions for the stochastic cooling due to beam size increase in large aperture tanks. Figure 6 presents the beam envelopes and physical apertures in the AP-10 and AP-30 straight sections where the stochastic cooling pickup and kickers are located. One can see that beam envelope nicely fits within the aperture limitations.

The implementation of new optics was strongly supported by our ability to perform high precision optics measurements. It also required reconfiguration of quadrupole shunts so that the independent current regulation would be possible for each quad.

### *Aperture increase*

The new lattice has been implemented in the Debuncher in the end of the last winter study period in January 2006. This resulted in the best achieved acceptance of 35.3/34.6π mm·mrad, which reaches the design goals. Therefore we do not need to do costly stochastic cooling tanks upgrade with potentially negative impact on their performance. Increasing the Debuncher admittance was only a part of a big effort that resulted in a new stacking rate record of $20.1\cdot10^{10}$ $hr^{-1}$ set in February 2006. Its major significance is opening the road for new substantial production improvements. A number of issues need to be solved in order to get the full benefit of the larger Debuncher aperture, such as beam line and injection channel acceptance, larger momentum aperture in the Debuncher extraction kicker and stochastic cooling performance. All those issues were planned to be addressed during the 2006 Tevatron complex shutdown and the year after that.

## CONCLUSIONS AND FUTURE PLANS

A successful Debuncher lattice measurement and optimization has been performed which resulted in a substantial opening of the Debuncher physical aperture. It brings a potential of 60% increase in the antiproton yield after corresponding optimization in the beam lines and injection channel. It also eliminated the need to make an upgrade of the stochastic cooling tanks. Still new degrees of freedom were added to the lattice design after adding more quad shunts during the 2006 shutdown. We will try to use it to compensate the insufficient aperture for off-momentum particles in the extraction kicker which upgrade has been postponed beyond the shutdown.

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