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A. Asseev et al.

Fermi National Accelerator Laboratory
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First Observation of Luminosity-driven Extraction Using Channeling with a Bent Crystal

A. Asseev[7], S. I. Baker[1], S. A. Bogacz[2†], V. Biryukov[7], R. A. Carrigan[4], Jr.,
D. Chen[4*], D. Cline[2], B. Cox[12], J. A. Ellison[5], W. Gabella[11], V. Golovatyuk[12¶],
G. Jackson[4], A. Khanzadeev[6], A. McManus[12**], N. Mokhov[4], C. T. Murphy[4],
B. Newberger[9§], T. Prokofieva[6], S. Ramachandran[2‡], J. Rhoades[2],
J. Rosenzweig[2], V. Samsonov[6], H.-J. Shih[8||], G. Solodov[6], A. Taratin[3],
E. Tsyganov[10]

[1]*Argonne National Laboratory, Argonne, IL 60439*
[2]*University of California at Los Angeles, Los Angeles, CA 90024*
[3]*Joint Institute for Nuclear Research, Dubna, Russia*
[4]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[5]*The University of New Mexico, Albuquerque, NM 87131*
[6]*Petersburg Nuclear Physics Institute, Gatchina, Russia*
[7]*Institute for High Energy Physics, Serpukhov, Russia*
[8]*Superconducting Super Collider, Dallas, TX 75237*
[9]*The University of Texas, Austin, TX 78712*
[10]*The University of Texas Southwestern Medical Center at Dallas, Dallas, TX 75235*
[11]*Vanderbilt University, Nashville, TN 37235*
[12]*The University of Virginia, Charlottesville, VA 22901*

Abstract

Luminosity-driven channeling extraction has been observed for the first time from a 900 GeV circulating proton beam at the Fermilab Tevatron. The extraction efficiency was found to be of the order of 30%. A 150 kHz beam was obtained during luminosity-driven extraction with a tolerable background rate at the collider experiments, and a 900 kHz beam was obtained when background limits were doubled. This is the highest energy at which channeling has been observed.

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Since the original suggestion of bent crystal channeling [1] there has been interest in exploiting the technique for accelerator extraction. While the planar channeling critical angle is small, 5.8 μrad at 900 GeV for the Si(111) plane compared to the Tevatron beam divergence of ~10 μrad, this is less of a limitation than might be thought. Many unchanneled particles multiple scatter in the crystal and remain in the accelerator to channel on a later pass, since the rms multiple scattering angle is only 10.8 μrad. Such multiple-pass extraction was first seen as an effect in simulations [2] and confirmed in experiments at CERN [3].

For channeling extraction a bent crystal placed near the beam edge can extract some portion of the beam. This method is particularly interesting for colliders where there is enough halo to create significant external beams with little impact on the luminosity. During the SSC planning stage such a technique was proposed for construction of a 20 TeV proton beam for beauty production [4]. The experiment reported here, E853 at the superconducting Tevatron, was undertaken to investigate that possibility at 900 GeV.

The E853 layout is shown in Fig. 1. The bent crystal was located 60 m upstream of the C0 center in place of a kicker magnet at the beginning of an existing beam abort line. The extracted beam was monitored at air gaps 20 m and 60 m after the C0 center with scintillators to count the entire beam and thin "finger" counters to measure the beam widths. A pair of scintillators called the "interaction monitor" was also positioned below the crystal to count inelastic interactions of the beam with the crystal.

Crystals were prepared at the Petersburg Nuclear Physics Institute[5] from a dislocation-free silicon crystal boule obtained from Wacker Corporation. One crystal was mounted in a goniometer with four degrees of freedom so that it could be translated and rotated with small step sizes. The crystal was cut so that the (111) atomic plane was parallel with the top optical surface of the crystal. The beam side was optically flat. The 39 mm long, 3 mm high, 9 mm wide crystal was bent through a vertical angle of 642±5 μrad with a four point bender (see Fig. 1). The angle of the (111) plane was prealigned to within 300 μrad of the nominal beam angle.

Several mechanisms were available to drive halo beam onto the crystal. A fast kicker magnet at E17 could provide transverse kicks of 0.5 mm at the crystal for an individual bunch. Results of these studies have already been published [6]. Noise sources such as beam-gas scattering, power supply modulation, and magnetic field non-linearities also produced beam growth, called natural diffusion. Diffusion could be stimulated with an RF electrical horizontal damper. Most significantly, proton-antiproton collisions at the collider detectors created halo.

In operation the crystal was gradually moved horizontally into the halo from the outside of the ring. Note that in contrast with the CERN experiment, the crystal moved into the beam in the horizontal plane, but bent the beam up, so that any lack of parallelism between the atomic planes and the top optical surface would not reduce the extraction efficiency.

Fig. 2 shows a vertical beam profile obtained with a finger counter scan. The beam width was $\sigma_V = 0.25$ mm after correcting for the height of the finger counter. The width expected, based on the critical angle and the beam optics, was $\sigma_V = 0.23$ mm. A tail is visible below the beam resulting from such factors as horizontal misalignment and dechanneling. The bottom of the tail was cut off by the Lambertson magnets. The number of particles in the visible tail is 20% of the peak, twice that expected on the basis of a simulation of the experiment [7].

The crystal was aligned to the circulating beam by scanning the crystal through the vertical angle Θ_V. Fig. 3 (bottom) shows a two air gap scintillator coincidence distribution. The width of the Θ_V distribution for diffusion mode is due mostly to the effect of multiple scattering from crystal multiple passes convoluted with the angular distribution of the circulating beam and the critical angle. The simulation [7] predicts a σ_V of 21 to 24 μrad compared to the 32 μrad measured in Fig. 3.

We have measured extraction rates under three conditions: extraction driven by natural diffusion during proton-only stores, RF noise-driven diffusion during a proton-only store, and luminosity-driven extraction during proton-antiproton stores.

In a typical proton-only store, 10^{11} protons were circulating in six bunches. The maximum extraction rate achieved was 200 kHz. Higher rates could have been achieved by moving the crystal even closer to the beam, but with only six bunches, a rate of 287 kHz corresponded to extracting on average one proton per bunch, and the counters could not count more than one particle per bunch. The crystal edge was between 4 and 6 times the beam width (σ_H) from the beam center.

To mitigate this limitation, a special proton-only store was arranged with 10^{11} protons circulating in 84 bunches. Additional diffusion was induced by transverse RF horizontal noise using an electrical damper, creating an rms diffusion rate at the crystal of 0.023 μm per turn. The extraction rate achieved was greater than 450 kHz.

In the luminosity-driven stores, typically 10^{12} protons were circulating in six bunches. The maximum extraction rate achieved was 150 kHz. In this mode the limitation was the impact of particles scattered from the crystal in creating backgrounds for the operating collider experiments. The D0 "lost protons" monitor, which was 1/6 of the ring downstream from the crystal, reached the limit set by that experiment at an extraction rate between 50 and 150 kHz. The crystal edge was between 5 and 8 times σ_H from the beam center.

This limitation was removed during a special store with 36 proton bunches and 3 antiproton bunches during which D0 was not taking data. There were 3×10^{12} protons circulating, and an extraction rate of 900 kHz was achieved. The D0 lost proton monitor exceeded its upper limit by a factor of two.

During that same store, the extraction rate was also studied as a function of luminosity. Only 6 of the proton bunches were colliding with antiprotons. Colliding and non-colliding proton bunches were observed during the same counting interval. The extracted beam rate increased by factors of 4 to 8 for proton bunches that were colliding with antiprotons.

Another purpose of this experiment was to measure the extraction efficiency. Efficiencies up to 15.4% were measured in a recent CERN 120 GeV experiment [3]. "Efficiency" in this context is defined in two ways. One practical definition, which we call the "extraction efficiency", is the extraction rate divided by the increase in the total circulating beam loss rate after the crystal was inserted. This definition was used by CERN.

The major contribution to lowering this efficiency was from protons which interacted inelastically with the crystal (8.8% of an interaction length) on one of their several passes through the crystal. A second contribution is from protons which dechanneled after being bent through approximately 50 to 350 μrad. A third contribution is from protons which were fully channeled but left the crystal through the beam-side surface because they had a large negative horizontal angle, called hereafter the "surface loss" contribution.

While the numerator was straight-forward to measure, determining the change in the total loss rate from the accelerator was difficult. The variation with time of the loss rates before the crystal was inserted usually exceeded the difference between the crystal out and in loss rates. No successful measurements of this efficiency were achieved.

A second way to measure the efficiency is to compare the number of protons that interact with the crystal when its vertical angle is not aligned to the beam with the number that interact when it is correctly aligned for maximum channeling. Fewer interactions are observed when the crystal is well aligned with the beam because the channeled protons do not come close to nuclei[8]. We call this the "channeling efficiency" and define it as the difference between the aligned and unaligned interaction monitor rate, divided by the unaligned rate.

The "surface loss" mentioned above does not lower this efficiency, and the dechanneling losses contribute only partially (once a proton has dechanneled after channeling through part of the crystal, it has less than 8.8% probability of a nuclear interaction). Thus we expect this efficiency to be slightly higher than the extraction efficiency.

In operation, the interaction counter rates were sensitive to fluctuations arising from such effects as small horizontal deviations of the circulating beam. Some of these effects could change in an unpredictable way in the time it took to do a typical Θ_V scan. To mitigate this time dependence, the best measurements were obtained by moving the crystal quickly back and forth from an aligned to a very unaligned vertical angle. An example of such data is shown in Fig. 3 (top). These data were taken within minutes after the Θ_V scan shown in Fig. 3 (bottom). The crystal was moved repeatedly to three different angles, one at the peak of the Θ_V scan, and one angle each in the left and right tail of the Θ_V scan.

In two stores in which the extraction was luminosity driven, the weighted average channeling efficiency was 32±4%. During the 84-bunch proton-only fill, the efficiency was 32±15%. The errors in these efficiences are derived from the rms scatter of the many data points about their average value [9]. The simulation [7] predicted an extraction efficiency of 35% for a realistic crystal.

In summary, this experiment has observed luminosity-driven crystal extraction and demonstrated crystal extraction in a superconducting accelerator for the first time. It is noteworthy that this is the highest energy channeling experiment ever carried out. There was no evidence of problems resulting from dislocations or radiation damage. The extraction efficiency has been measured under several conditions and found to be consistent with simulations incorporating multiple-pass extraction.

Crystal extraction efficiencies are high enough to make this technique an interesting candidate for several applications. One such possibility is using a crystal as an active primary collimator [10]. The use of crystals to extract protons to generate neutrino beams has also been investigated [11]. A continuous 1 TeV proton beam of order 1 MHz could be extracted from the upgraded Tevatron collider into the fixed target areas with no significant impact on collider detector operations [12]. This might be quite useful as a test beam for LHC detectors. One analysis [13] has suggested that an experiment operating in such a beam could produce 10^7 charm candidates a year. A proposal for a B physics experiment using such a system was considered for the LHC at CERN. The proposal was rejected because of uncertainties about channeling extraction in TeV-scale superconducting colliders. With the completion of this experiment these concerns should now be significantly reduced.

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[*] Present address: AT&T,Middletown, NJ 07748.

[†] Present address: Thomas Jefferson National Accelerator Facility, Newport News, VA 23606.

[‡] Present address: BACG, Lisle, IL 60532.

[§] Present address: Winstead Sechrest & Minick, P.C., Austin TX 78701.

[||] Present address: Affiliated Computer Services, Inc., Dallas TX 75204.

[¶] Present address: University and INFN of Lecce, Lecce, Italy.

[**] Present address: AT&T, West Long Branch, NJ 07764.

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Figure Captions:

1. Schematic of the channeling extraction apparatus. The bent crystal deflects protons up through the quadrupoles into the field-free region of the Lambertson magnets. The protons are detected with a system of scintillators in two air gaps separated by 40 m. The inset shows the location of the crystal extraction system, the fast kicker, the RF damper, and the collider experiments at B0 and D0.

2. Vertical profile of the extracted beam taken with a thin finger counter. Note the tail extending below the main peak. To better illustrate this tail, the values have been multiplied by 20 and replotted (diamonds - see right ordinate). The solid line is a Gaussian fit to the data.

3. The lower data set (right ordinate) is the counting rate in a coincidence between scintillators in the two air gaps as the vertical angle of the crystal was varied. The curve is a fit to a Gaussian plus a flat background. The upper data set (left ordinate) is the counting rate in the interaction monitor at three different vertical angles. The curve is a Gaussian with the same width and central value as the curve in the lower half of the figure.

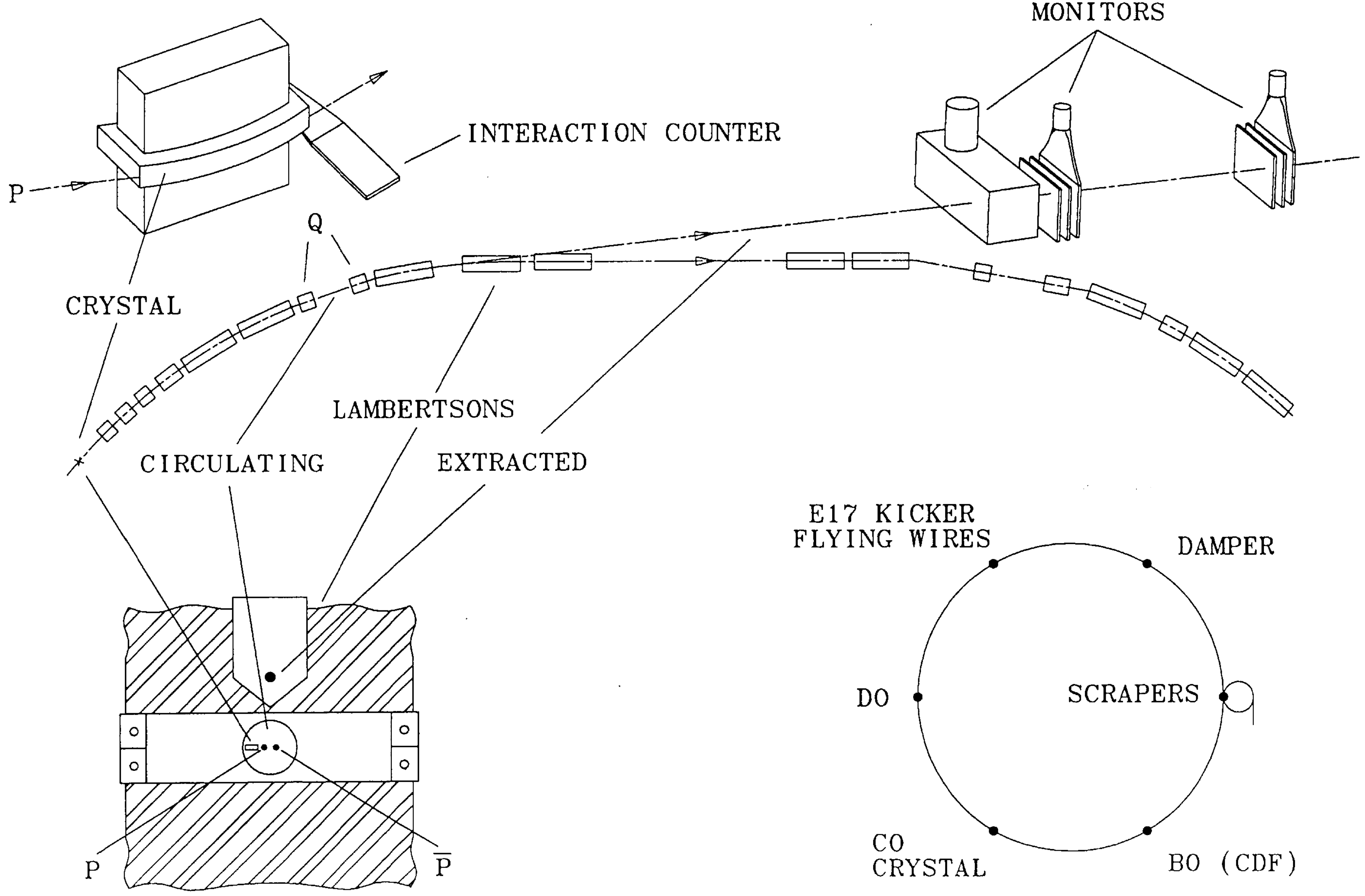
MONITORS
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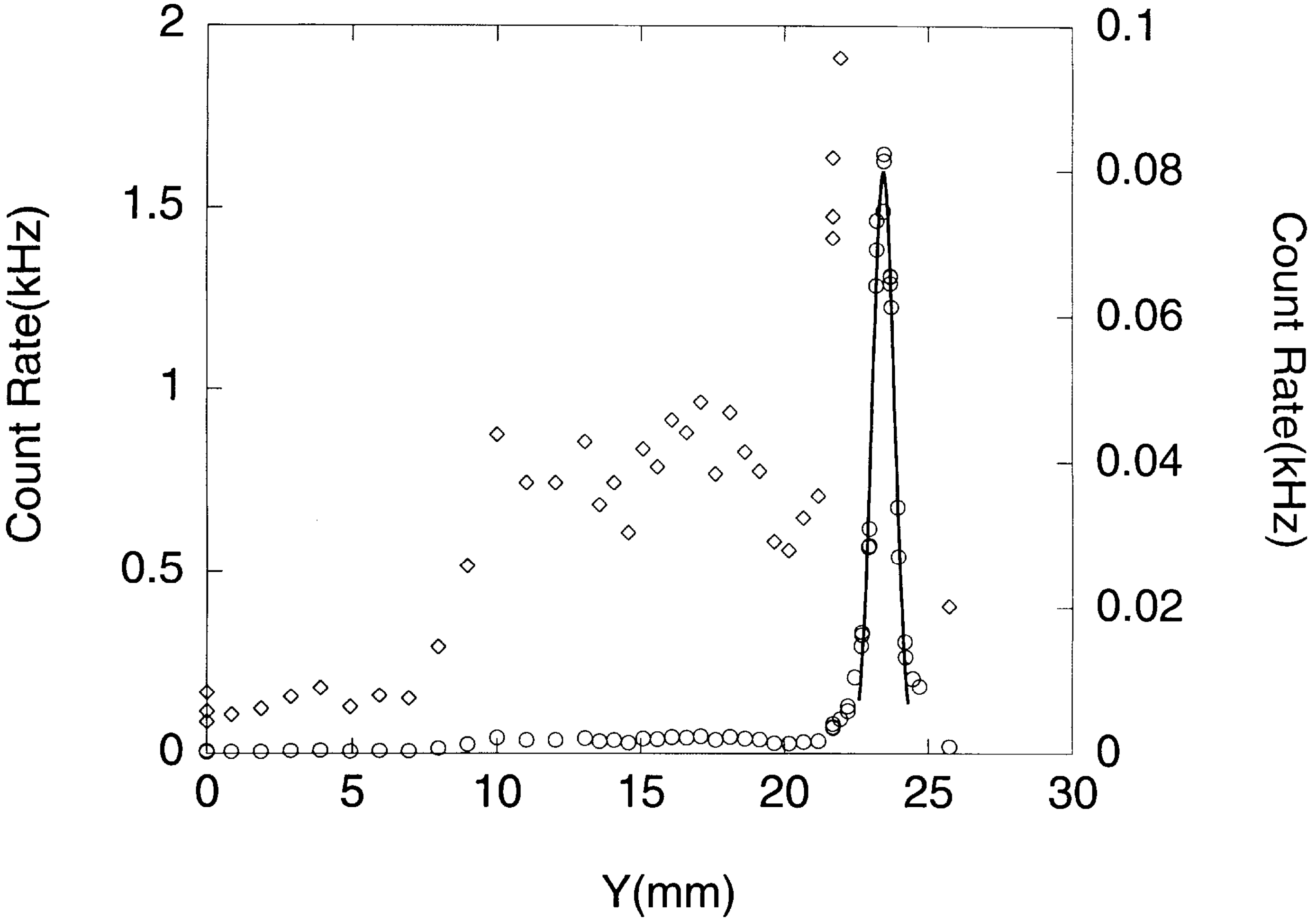
Fig. 1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1
0.5
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0.1
0.08
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0.04
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0
Count Rate(kHz)
0
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30
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Fig. 2

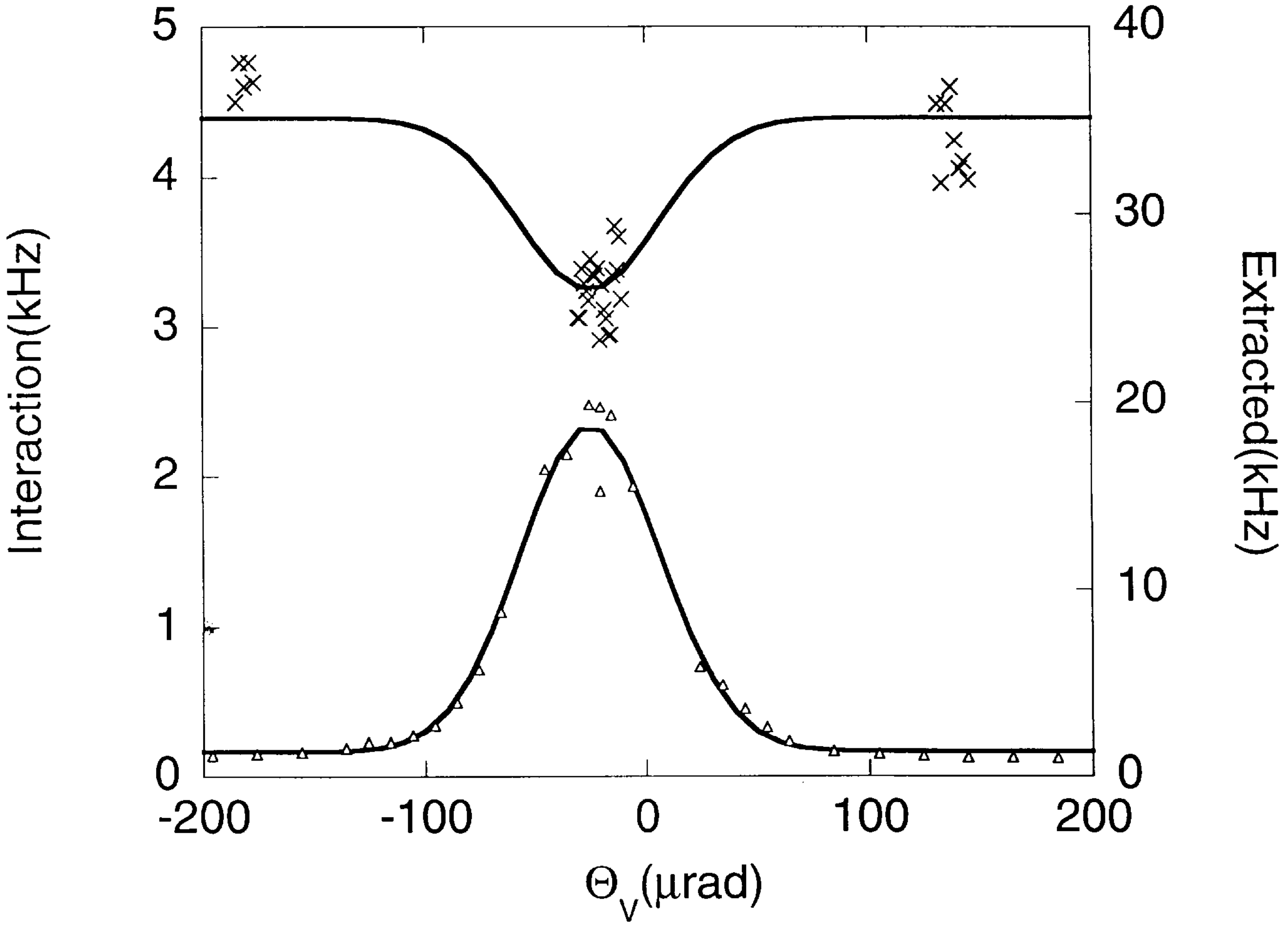
Interaction(kHz)
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Fig. 3