Swapan and the bunched beam cooling puzzle

Sergei Nagaitsev (Fermilab/U.Chicago)

Tangled Web of Quantum Sensors Symposium

April 30, 2021

Swapan's contributions to beam cooling

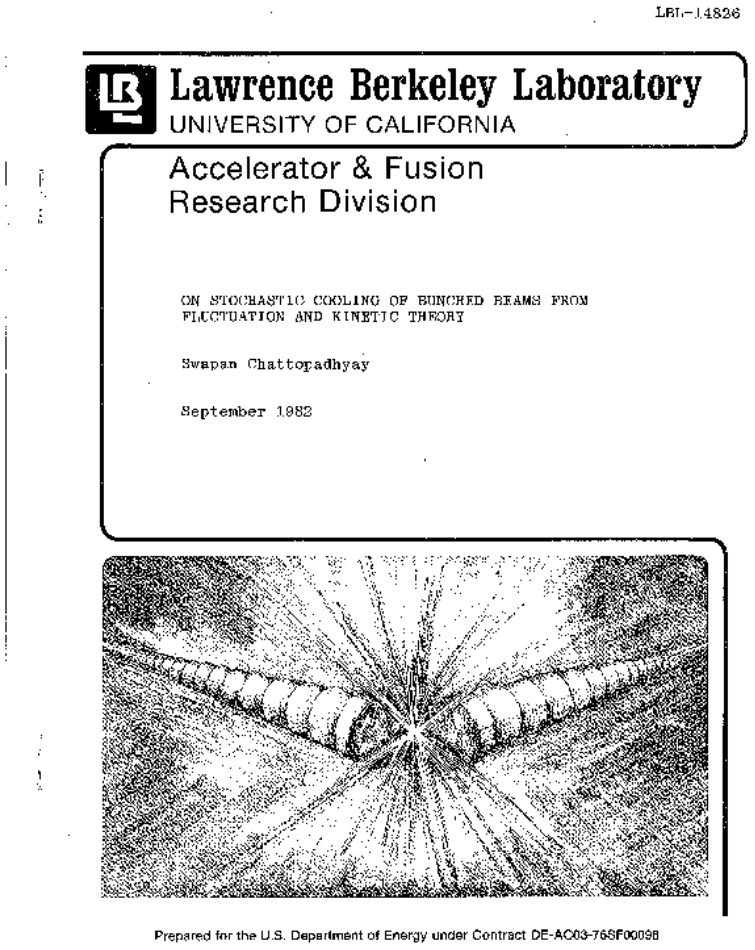
- As a freshly-minted Ph.D., Swapan made major contributions during 1982 – 1984, as a member of the group implementing **Stochastic Phase-space Cooling** in the colliding ring complex at CERN, Geneva, Switzerland where the W and Z Bosons were discovered during this period;

- Conceptual, theoretical , experimental and technological development of **"Bunched Beam Stochastic Cooling"** of protons, anti-protons and ions during 1978 till 1985, initial one-channel application at the SPS, and final validation in the recent implementation at the RHIC collider at the Brookhaven National laboratory (BNL);

Ph.D.: UC Berkley (1982)

Thesis Title: "On Stochastic Cooling of Bunched Beams from Fluctuation and Kinetic Theory" (1982)

Thesis Advisors: Prof. Joseph Bisognano, Prof. Owen Chamberlain, and Prof. Wulf Kunkel.



LBL-14826

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion
Research Division

ON STOCHASTIC COOLING OF BUNCHED BEAMS FROM FLUCTUATION AND KINETIC THEORY

Swapan Chattopadhyay

September 1982

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

Early predictions about bunched beam cooling

IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

STOCHASTIC COOLING OF BUNCHED BEAMS*

J.J. Bisognano and S. Chattopadhyay
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Numerical simulation studies are presented for transverse and longitudinal stochastic cooling of bunched particle beams. Radio frequency buckets of various shapes (e.g. rectangular, parabolic well, single sinusoidal waveform) are used to investigate the enhancement of phase space cooling by nonlinearities of synchrotron motion. The connection between the notions of Landau damping for instabilities and mixing for stochastic cooling are discussed. In particular, the need for synchrotron frequency spread for both Landau damping and good mixing is seen to be comparable for bunched beams.

This paper caught my attention in 2005!

An important conclusion:

No synch. frequency spread – no Landau damping and also no stoch. cooling!

Conclusions

Synchrotron frequency spread provides the necessary mixing mechanism for bunched beam cooling. In addition, it appears that the natural nonlinearities of a single, long full RF bucket can provide mixing comparable to a coasting beam for harmonics of higher frequency than those associated with the gross bunch structure. However, as the bunch length decreases degradation of cooling occurs as the mixing mechanism couples neighboring Schottky bands.[6]

First tests in the Tevatron: success is elusive

- Tevatron bunched beam cooling experiments, 1990-1995
- Observed strong coherent lines at each revolution frequency harmonic.
  - These strong coherent signals prevented bunched cooling;
  - Big mystery: no known reasons for them to exist!

Bunched Beam Stochastic Cooling in the Fermilab Tevatron Collider

G. Jackson, E. Buchanan, J. Budlong, E. Harms, P. Hurh,
D. McGinnis, R. Pasquinelli, D. Peterson, D. Poll, P. Seifrid
Fermi National Accelerator Laboratory*
P.O. Box 500 MS 341
Batavia, IL 60510

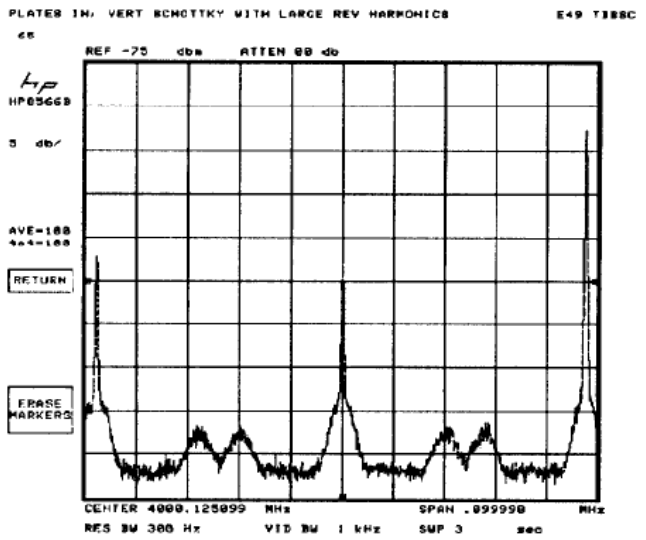


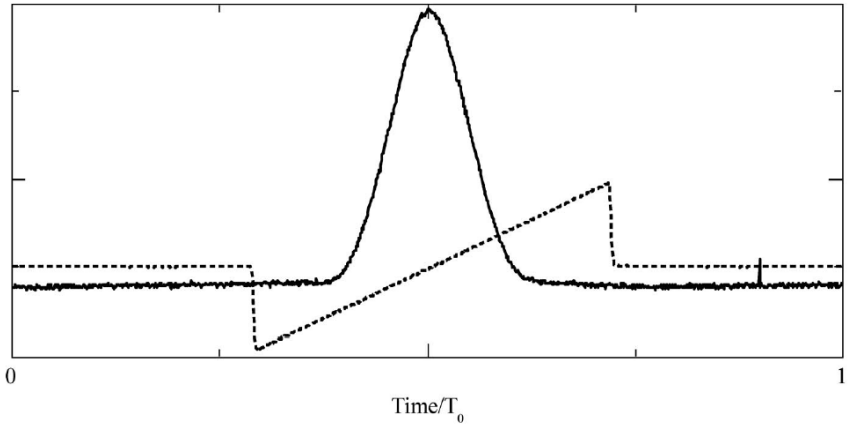
Figure 1: Measured beam spectrum from a vertical proton pickup. Note the large coherent lines at revolution harmonic frequencies at the left, center, and right. The betatron Schottky lines are clearly visible above the noise floor. The center frequency is 4 GHz and the scale is 10 kHz/div.

More bunched beam cooling research at Fermilab

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 124404 (2005)

Synchrotron frequency spread independence of bunched-beam stochastic cooling at the Fermilab Recycler

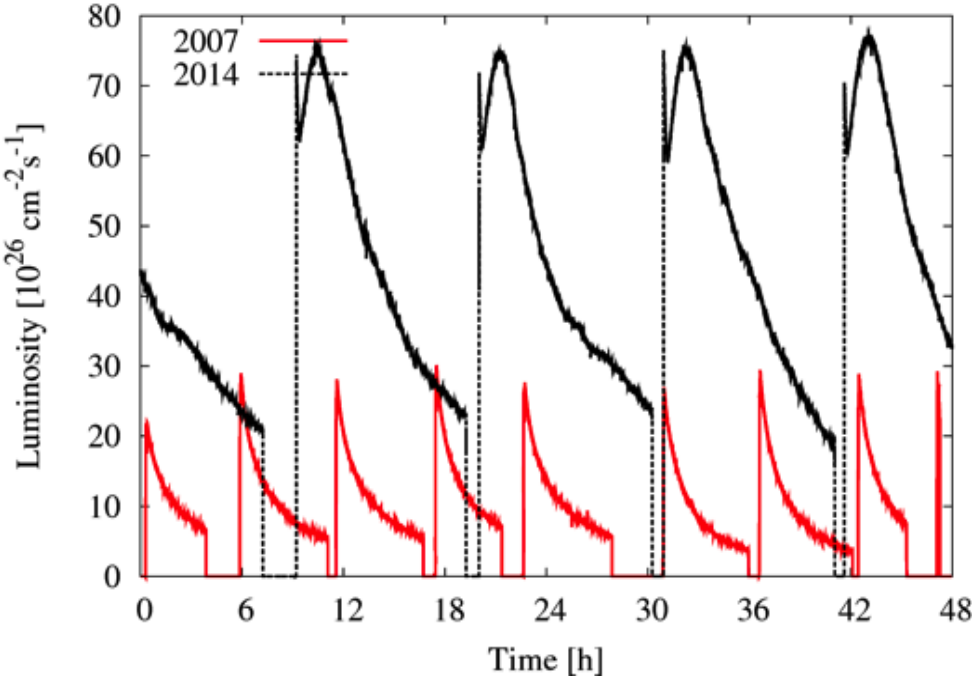
D. Broemmelsiek,* A. Burov, S. Nagaitsev, and D. Neuffer
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
(Received 12 October 2005; published 27 December 2005)



For certain conditions, the synchrotron frequency spread can be insignificant for bunched-beam longitudinal stochastic cooling. Namely, the synchrotron frequency spread plays no role when the sample randomization is determined by the diffusive motion of the cooled particles rather than the synchrotron frequency spread.

But still no explanation for the Tevatron results!

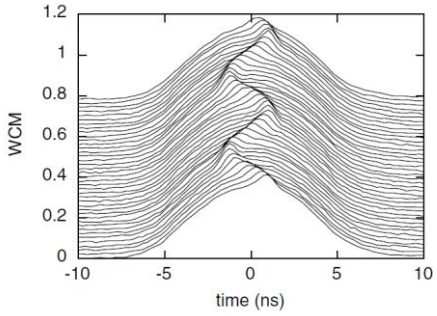
Au-Au stochastic cooling in RHIC: success, finally!



- 3-D stochastic cooling (5-9 GHz).
- ~5x U-U and ~ 4x Au-Au luminosity improvements.
  - Cooling led to first increase of instantaneous luminosity and smallest emittance ever in a hadron collider.
- Doesn't work with protons – same coherent lines as in the Tevatron!
  - Still an unresolved puzzle: why does it work with heavy ions and does not work protons?

Maybe they are solitons?

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 7, 044402 (2004)

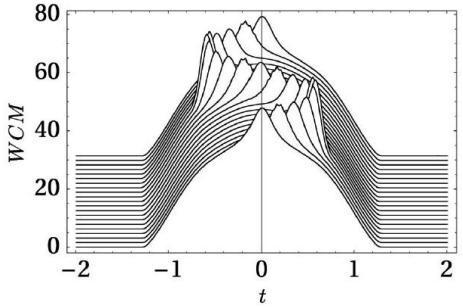


Longitudinal solitons in bunched beams

M. Blaskiewicz* and J. Wei
BNL, Upton, New York 11973, USA

A. Luque and H. Schamel
University of Bayreuth, 95440 Bayreuth, Germany

(Received 4 February 2004; published 28 April 2004)



Stable, coherent, longitudinal oscillations have been observed in several accelerators. Within the context of perturbation theory, the beam parameters and machine impedance often suggest these oscillations should be Landau damped. When nonlinear effects are included, long-lived, stable oscillations become possible for low intensity beams. In this paper we report observations of stable humps in bunched beams and present a theoretical framework for their description. Implications for bunched beam stochastic cooling are considered.

Finally, jump to 2021

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 011002 (2021)

Editors' Suggestion

Thresholds for loss of Landau damping in longitudinal plane

Ivan Karpov, Theodoros Argyropoulos, and Elena Shaposhnikova
CERN, CH 1211 Geneva 23, Switzerland

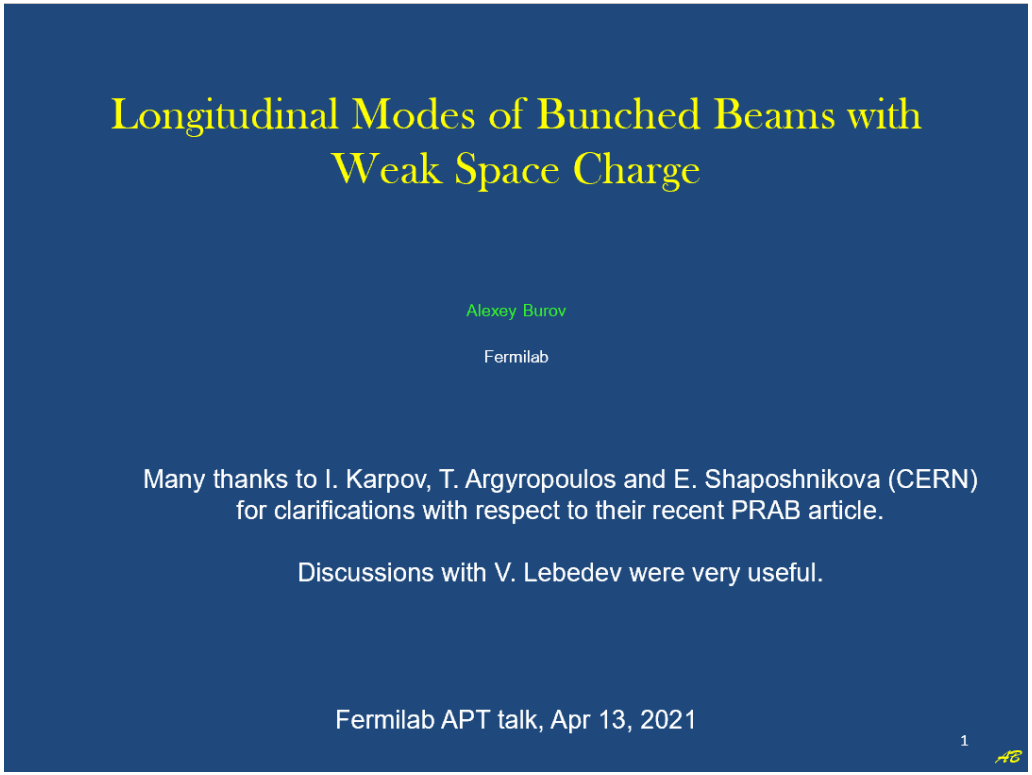
(Received 13 November 2020; accepted 11 January 2021; published 27 January 2021)

Summary: We have found that for the commonly used particle distribution functions, Landau damping vanishes in the presence of the constant inductive impedance Im(Z)/k above transition energy.

Both Tevatron and RHIC operate ABOVE TRANSITION!

Fermilab

Only very recently this phenomenon was fully elucidated!



- Loss of Landau damping leads to persistent longitudinal bunch oscillations with frequency spectrum extending to very high frequencies, ~10 GHz, unless they are damped by some other mechanism, like IBS

Finally, the community is starting to solve the bunched-beam cooling puzzle

- 1981: Swapan: Bunched beam cooling should work but synchrotron frequency spread is essential
  - No spread - no cooling and no Landau damping
- 1990-1995: Tevatron: persistent coherent lines prevent bunched beam cooling;
- 2005: Fermilab Recycler: bunched beam cooling works if bunches are very long (essentially coasting beam);
- 2006 – to date: RHIC: bunched beam cooling works with high-Z ions but not with protons (similar to Tevatron)
  - IBS diffusion seems crucial to damping coherent oscillations
- Finally, 2021: CERN: lack of Landau damping plus broad-band inductive impedance conspire to produce persistent oscillations up to very high frequencies!

Puzzle solved, finally!

- Just in time for Swapan's retirement!

- Congratulations and my best wishes to you and good luck with your next chapter!