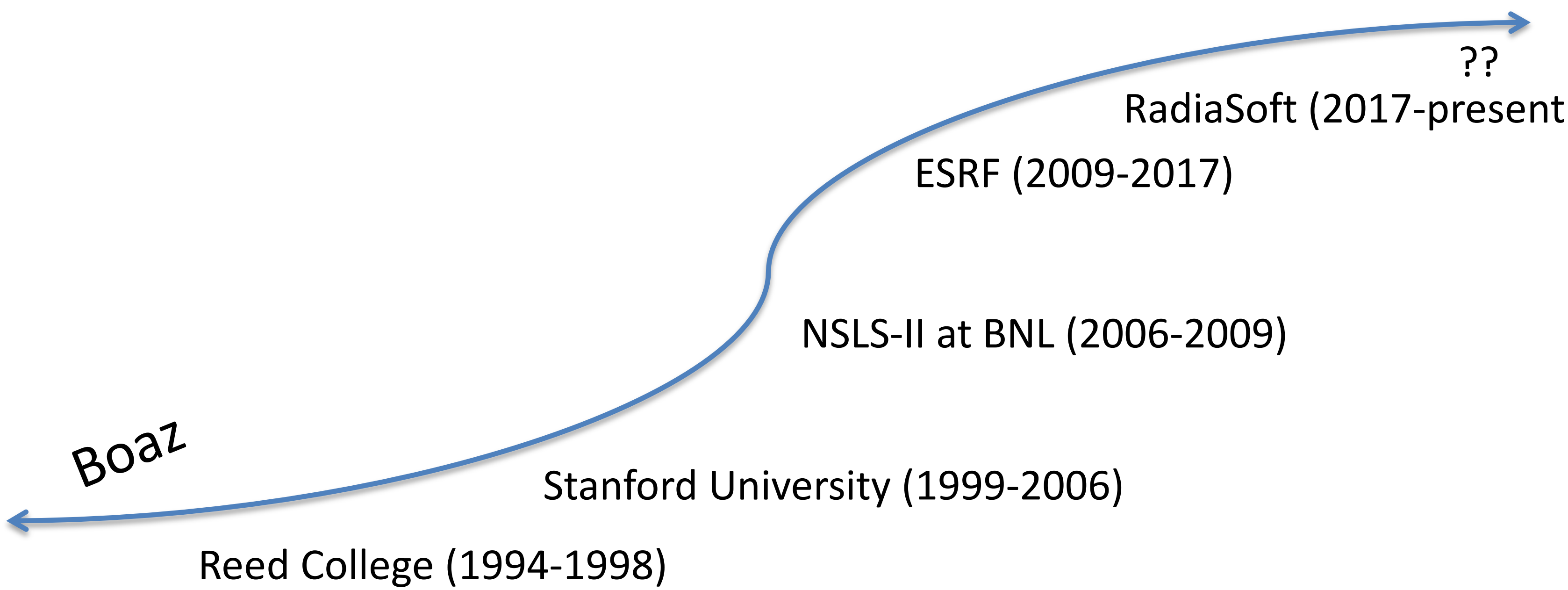
Intrabeam scattering, coupling and electron storage rings: experience from my PhD with Alex Chao

Boaz Nash
RadiaSoft LLC

Outline

- How did I get into accelerator physics?
- Finding Alex as a supervisor
- Research projects with Alex
- After the PhD

My journey so far in accelerator science



Part I: Reed College (1994-1998)

- My father Peter Nash went to Reed College

- I was a math and physics major, but also took a lot of humanities classes, as required

- I came in as a biology major and left as a math/physics major

  - Senior Thesis: Getting from here to there: "Adiabatic Transport of Single Particle Periodic Systems" with Thomas Wieting (math) and Nicholas Wheeler (physics)

My Reed College Thesis

Getting from Here to There:
Adiabatic Transport of Single Particle
Classical Periodic Systems

A Thesis
Presented to
The Division of Mathematics and Natural Sciences
Reed College

In Partial Fulfillment
of the Requirements for the Degree
Bachelor of Arts

Boaz E. Nash

May 1998

My Reed thesis (continued)

What happens to a system when it is transported from A to B?

Can one move it gently enough that it will be unaffected? Which aspects will inevitably change during transport? What does it mean to transport a system “adiabatically”?

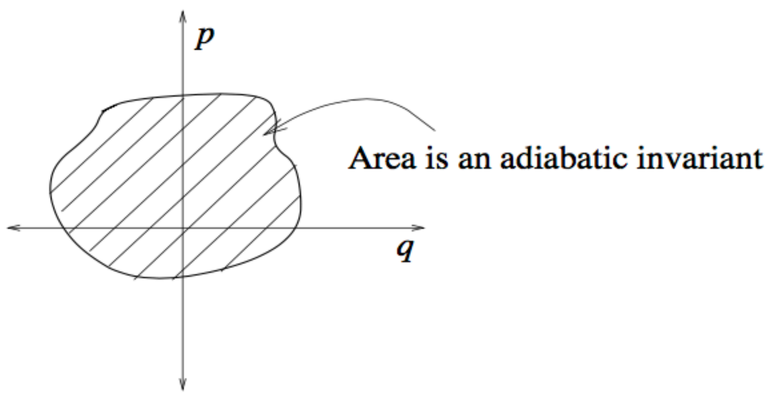
systems treated: Foucault pendulum

a mechanical clock on a rocket ship

Coulomb potential

Lots of fun
Classical mechanics!

Reed Thesis (continued)



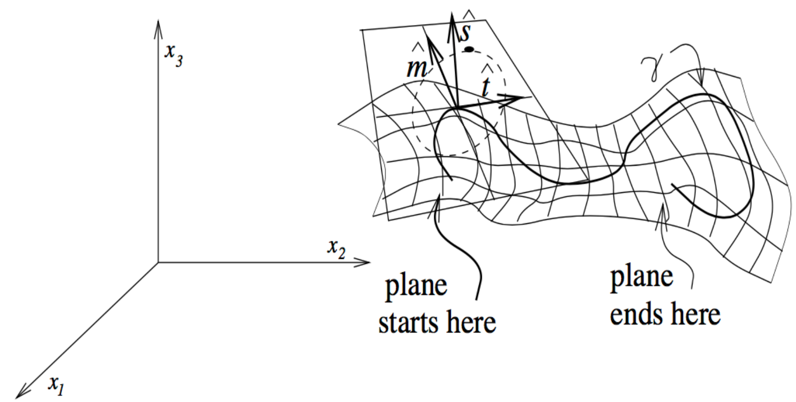


Figure 4.1: Surface, S with inscribed γ, and particle constrained to a plane moving along it.

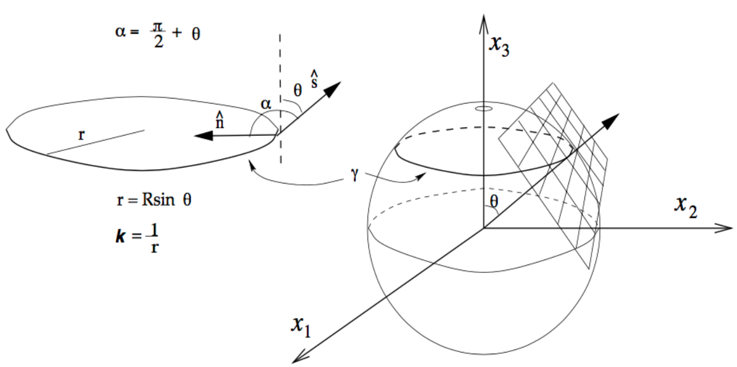


Figure 4.2: Geometry for Foucault Pendulum

Adiabatic transport
Geometric phases, etc.

Transition to Stanford

- I was so involved in my senior thesis, that I did a poor job preparing to get into graduate school (applications, GREs, etc.)

- I took a year off, working for Dr. Richard Crandall working on some topics for Pixar such as lossless compression and efficient solid noise generation in computer graphics

Richard Crandall (1947-2012)

- I improved my score on the physics GRE and got into Stanford and a few other physics graduate programs!!

What to work on at Stanford?

- I'd never heard of accelerator physics as a discipline. I thought I would study particle physics or condensed matter physics.

- I'd never heard of accelerator physics as a discipline. I thought I would study particle physics or condensed matter physics.

- Stanford had an open day where different professors talked about their work. I told people about my thesis experience, and someone (who??) suggested I speak to Ron Ruth!

- I gave a talk on my Reed thesis work at ARDA, and afterwards started discussing with Alex about working together.

First physics topics with Alex

SLAC–AP–125
July, 2000

Searching for Transverse Sawtooth in Strong Head-Tail Instability by Adding Landau Damping*

Boaz Nash and Alex Chao
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

SLAC–AP–136
March, 2000

Solenoid Fringe Optics[1]

Boaz Nash
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

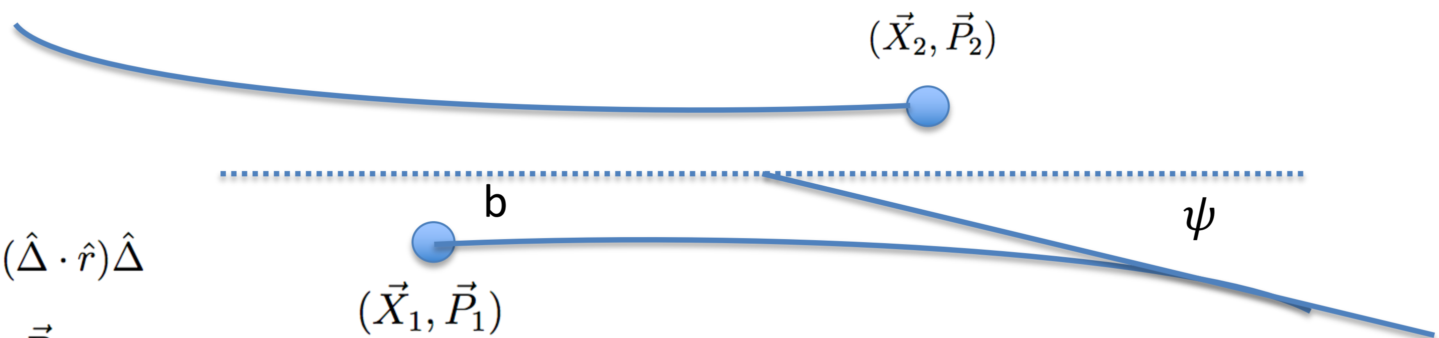
SLAC–PUB–8726
December 2000

Possible Quantum Mechanical Effect on Beam Echo*

Alex Chao and Boaz Nash
Stanford Linear Accelerator Center, Stanford Unversity, CA 94309

PHD topic formulation

$$\tan\left(\frac{\psi}{2}\right) = \frac{2(mc)^2 r_0}{\Delta^2 b} = \frac{2k}{\Delta^2 b} \qquad k = (mc)^2 r_0 \qquad (6.21)$$



$$\vec{b} = \vec{r} - r(\hat{\Delta}\cdot\hat{r})\hat{\Delta}$$

$$\vec{\Delta} = \vec{P}_1 - \vec{P}_2.$$

$$t_{\rm min} = -\frac{mr}{\Delta}\hat{\Delta}\cdot\hat{r} \qquad 0 < t_{\rm min} < \Delta t$$

This picks out a subset of the scattering
Particle pairs to integrate over

With Alex's help, I was able to take this simple picture and rederive all the different formulations of IBS in the literature as special cases! This formulation has no logarithmic divergence!

PAC '03 paper on IBS

Proceedings of the 2003 Particle Accelerator Conference

A NEW ANALYSIS OF INTRABEAM SCATTERING*

Boaz Nash†, Juhao Wu, Karl Bane, Alex Chao, SLAC, Menlo Park, CA, 94025

Very dense! Should have been expanded into a full publication.

Equilibrium Electron beams

My IBS work was almost enough for my thesis, but not quite.

I continued with the study of how to describe the electron distribution in a storage ring with the damping and diffusion effects of synchrotron radiation.

Alex proposed that I study synchrobetatron resonances and gave me some examples, such as dispersion at an RF cavity, and crab cavities.

I constructed the matrices and looked at what happened near linear resonances.

Perturbation theory near resonance

What does it mean to be near a linear resonance?
It means that two of the eigenvalues become equal.

Thus, to treat perturbation theory near resonance, one needs to do **degenerate perturbation theory**.

I applied degenerate perturbation theory from quantum mechanics (Hermitian matrices) to Hamiltonian mechanics of storage rings (Symplectic matrices).

Combining this with the diffusion and damping from synchrotron radiation, I derived equilibrium emittances and beam sizes near linear resonances.

2006 Paper on eigen-emittance near SB coupling resonances

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **9**, 032801 (2006)

Equilibrium beam distribution in an electron storage ring near linear synchrobetatron coupling resonances

Boaz Nash,* Juhao Wu, and Alexander W. Chao

SLAC, Menlo Park, California 94025, USA

(Received 2 October 2005; published 8 March 2006)

Linear dynamics in a storage ring can be described by the one-turn map matrix. In the case of a resonance where two of the eigenvalues of this matrix are degenerate, a coupling perturbation causes a mixing of the uncoupled eigenvectors. A perturbation formalism is developed to find eigenvalues and eigenvectors of the one-turn map near such a linear resonance. Damping and diffusion due to synchrotron radiation can be obtained by integrating their effects over one turn, and the coupled eigenvectors can be used to find the coupled damping and diffusion coefficients. Expressions for the coupled equilibrium emittances and beam distribution moments are then derived. In addition to the conventional instabilities at the sum, integer, and half-integer resonances, it is found that the coupling can cause an instability through antidamping near a sum resonance even when the symplectic dynamics are stable. As one application of this formalism, the case of linear synchrobetatron coupling is analyzed where the coupling is caused by dispersion in the rf cavity, or by a crab cavity. Explicit closed-form expressions for the sum/difference resonances are given along with the integer/half-integer resonances. The integer and half-integer resonances caused by coupling require particular care. We find an example of this with the case of a crab cavity for the integer resonance of the synchrotron tune. Whether or not there is an instability is determined by the value of the horizontal betatron tune, a unique feature of these coupling-caused integer or half-integer resonances. Finally, the coupled damping and diffusion coefficients along with the equilibrium invariants and projected emittances are plotted as a function of the betatron and synchrotron tunes for an example storage ring based on PEP-II.

DOI: 10.1103/PhysRevSTAB.9.032801 PACS numbers: 29.27.Bd, 29.20.Dh, 29.27.Eg, 41.85.−p

SB coupling paper continued

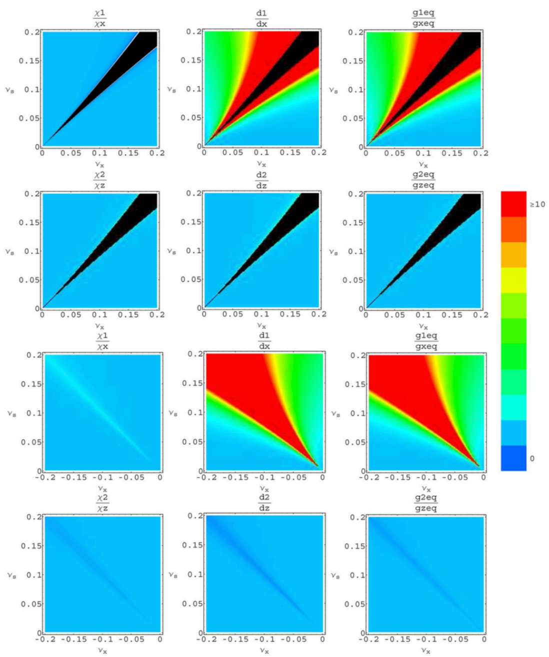


FIG. 1. (Color) In this figure, we plot global damping, diffusion, and equilibrium invariant values for coupling due to a dispersion of 1 m at an rf cavity near the sum/difference resonances. The upper two rows are the sum resonance, and lower two are the difference resonance. The parameters are otherwise drawn from Table VI based on the PEP-II LER. The quantities are plotted as a function of the betatron tune ν_x and the synchrotron tune ν_s which is positive and equal to $-\nu_z$, thus giving an inversion of sum and difference resonances. χ_1 and χ_2 are global damping decrements expressed in Table V. $\bar{d}_1$ and $\bar{d}_2$ are global diffusion coefficients expressed in Table IV, and $\langle g_1 \rangle_{eq}$ and $\langle g_2 \rangle_{eq}$ are one half the ratio of these quantities as given by Eq. (47). All quantities have been divided by their uncoupled values so that the blue region with the value of 1 represents no effect from coupling. The region of instability due to the Hamiltonian dynamics is black. There is also an extremely small region of antidamping instability outside the symplectic instability region for the sum resonance where the damping decrement χ_1 is negative. This region is indicated by white.

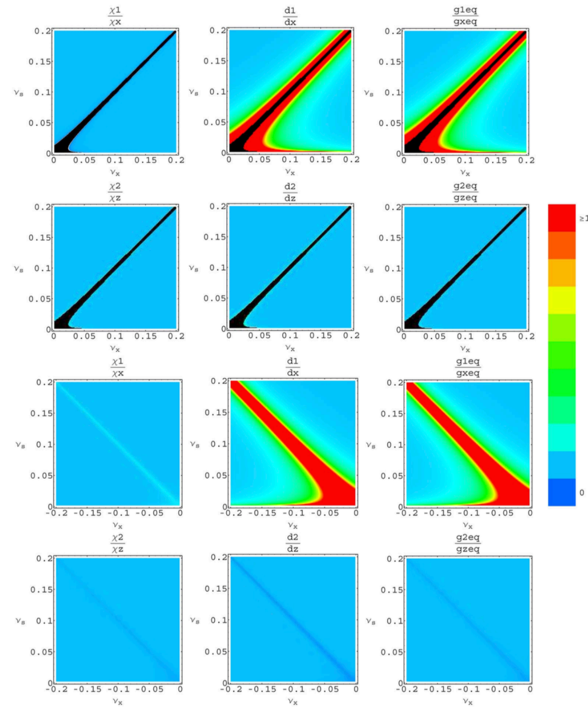


FIG. 2. (Color) In this figure, we plot global damping, diffusion, and equilibrium invariant values for coupling due to a crab cavity with $\xi_c = 0.003$ near the sum and difference resonances. The dispersion at the crab cavity is set to 0 in this example. Because the coupling strength ξ is inversely proportional to $\sqrt{\nu_s}$, the instability broadens for smaller ν_s. χ_1, χ_2, $\bar{d}_1$, $\bar{d}_2$, $\langle g_1 \rangle$ and $\langle g_2 \rangle$ are the same as in Fig. 1. As in Fig. 1, the small region of antidamping for χ_1 near the sum resonance is colored white.

Emittances, damping and diffusion and tunes near sum and difference Resonances for RF cavity dispersion and crab cavity

> 350 equations!!

Final Thesis

ANALYTICAL APPROACH TO EIGEN-EMITTANCE
EVOLUTION IN STORAGE RINGS

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF PHYSICS
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Boaz Nash
May 2006

Thanks to others during this time

Juhao Wu: helped a lot both with talking through the concepts, and with implementation of the equations to get concrete numerical results

Karl Bane helped with the work on IBS

Members of the BIG group in ARDA:

Sam Heiffets, Ron Ruth, and Gennady Stupakov

Graduation!

After my PhD

- I had to decide between postdoc offers
- Mathematical, abstract work at University of Maryland, or design project at BNL/NSLSII?

- Alex advised I get involved in practical design work. Followed this advice to work at NSLS-II from 2006-2009

Postdoc at NSLS-II (2006-2009)

I moved from linear dynamics to non-linear dynamics. Computing dynamics aperture and momentum aperture (for Touschek lifetime) for the NSLS-II design.

Here, I really got into the questions of particle tracking codes, working with Johan Bengtsson and his Tracy code.

Here, I learned about the opposite direction than seeking simple explanations for complex phenomena. Here I learned about starting with a well understood simulation code, and progressively adding more and more imperfections, to try to prepare for the real world in the design.

Second postdoc and scientist at ESRF
8 years in France!
(2009-2017)

My work had two orientations during these 8 years:

Electron beam dynamics on a running machine and upgrade:

I got to work on a real machine, and then, again work on a design project. It was time to jump into a new code: Accelerator Toolbox. I again sought to build a collaboration to find a standardization. I helped build atcollab.

Photon science, and bridging the gap between the storage ring and the photons at the sample. X-ray optics beamline modeling codes!

Lecture series: Accelerator Physics for x-rays

Lecture 1:

Fast Electrons

B. Nash

January 13, 2015

Lecture 2:

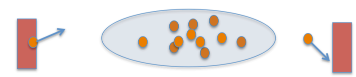
Surfing the Ring

B. Nash
27 Jan. 2015

Lecture 3:

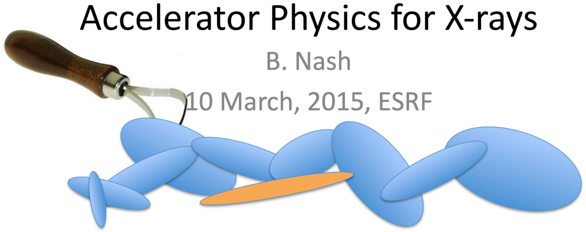
Collective Survival

B. Nash
February 24, 2015

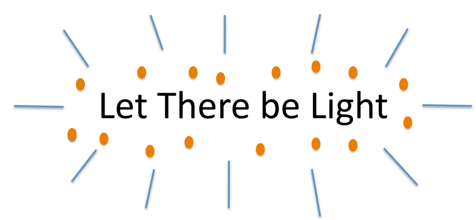


Lecture 4:

Sculpting the beam
Lecture 4
Accelerator Physics for X-rays
B. Nash
10 March, 2015, ESRF



Lecture 5:



Accelerator Physics for X-Rays, Lecture 5
B. Nash
ESRF, ASD
31 March, 2015

RadiaSoft (2017 – present)

I’ve been at RadiaSoft (Boulder, CO) for the past 2 years.

Research and software topics:

X-ray optics: SRW/Sirepo, fast maps for beamlines

Spin tracking for EIC: Zgoubi code use and development

Magnetic undulator design: Radia code development

Some conclusions

- I wouldn't have followed this path if not for the good fortune of meeting Alex and his PhD supervision
- Accelerator science remains active, with a bright future
- Alex's approach of finding clear simple explanations underlying complex phenomena is an important heritage he has given all of us

Thanks for your attention!