



Echoes of Friendship and A Shared Journey:
*Colliding Protons, Spinning Electrons, Growing
Waves and Shrinking Phase Space*

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Alex Chao Fest:

Kavli Institute, SLAC
October 25, 2019



NATIONAL
ACCELERATOR
LABORATORY



Special Topics in
Accelerator Physics

Celebrating the Distinguished Career
of Professor ALEX CHAO



ACKNOWLEDGEMENTS

- I want to thank Yun-hai Cai, Zhirong Huang, Tor Raubenheimer and all other members of the symposium organizing committee for inviting me as a speaker to this symposium.
- It is an honor for me to speak at Alex's retirement event.

**Impeccable Academic Pedigree and Tutelage with
Formidable Mentors and a Remarkable Mentee**

C. N. Yang (Yang, Chen-Ning)

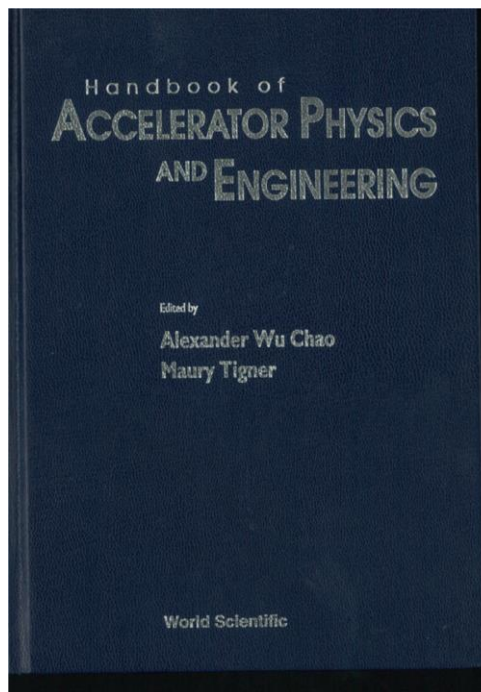
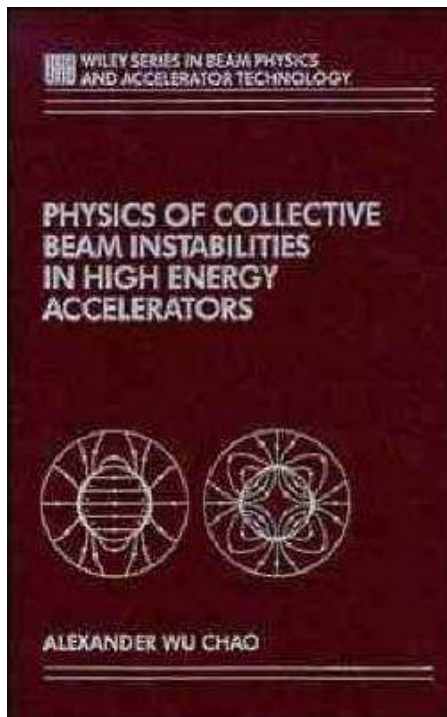
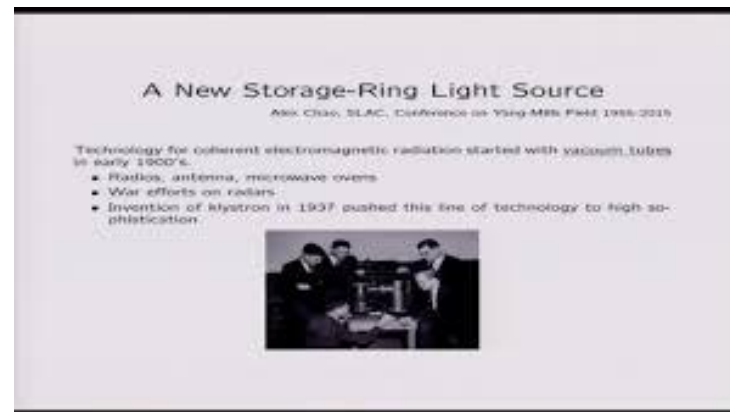
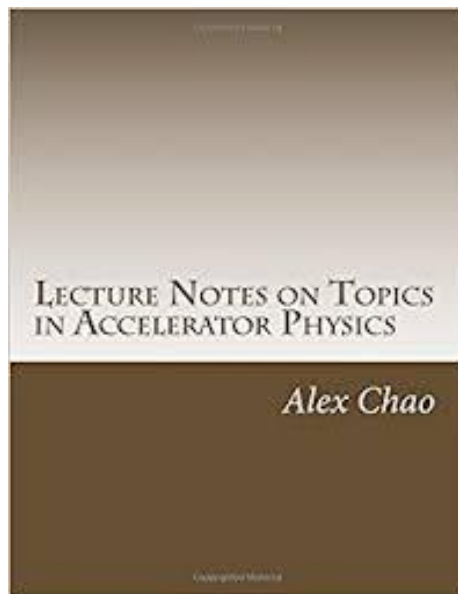
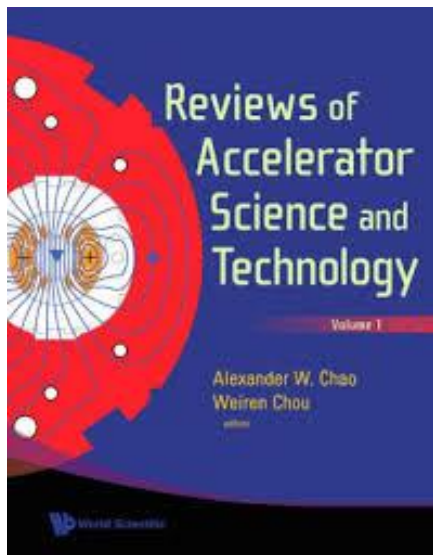
and

Ernest Courant



ACCOMPLISHMENTS

- **USPAS Prize**
- **APS/DPB Wilson Prize**
- **IPAC European Physical Society Prize**
- **Editor of Particle Accelerator Physics and Engineering Handbook with Maury Tigner (World Scientific)**
- **Editor-in-Chief of Reviews of Accelerator Science and Technology with Weiren Chou (World Scientific)**
- **Author of “Physics of Collective Beam Instabilities in High Energy Accelerators”**
- **Inventor of a new storage-ring light source exploiting “microbunching”**
- **Contributions to all SLAC accelerators, SSC, ILC, novel acceleration methods, beam echo schemes, polarization in storage rings, nonlinear dynamics,....**
- **International involvement in the accelerator enterprise worldwide: US, CERN and Europe, Asia (China, Taiwan, Korea, Japan,...)**
- **.....**



Alex's Professional and Personal Characteristics

- A formidable theoretical physicist with impressive mathematical prowess, but applied only when necessary
- Alex's approach is 'SIMPLICITY' in modelling, retaining only the essential physics, not encumbered with unnecessary and nonessential complications
- Always anchored to extracting actual estimations relevant to experimental facts and observations
- Precision in problem statement but qualitatively optimized in modelling to yield useful results
- Kind, generous to colleagues and peers and forgiving to junior mentees as supervisor or boss
- Highest personal and professional integrity

Colliding Protons

My association with Alex started in 1984 when many of us at Berkeley:

Christoph Leemann, Tom Elioff, Joe Bisognano, David Douglas, Alpert Garren, Etienne Forest, myselfet al

were busy with the conceptual design of the SSC in the accelerator physics team led by Alex under Maury Tigner as the SSC-CDG director.

The LBL-team members were hand-picked by the LBL director David Shirley as Berkeley's FTE contribution to the SSC design effort as the Central Design Group got established in Berkeley.

But I had two masters!

Alex Chao for SSC-CDG assignment

And

Max Cornacchia for the assignment of ALS at Berkeley!

Conceptual Design of the Advanced Light Source -- to be built at my own laboratory LBL at Berkeley and which was to be the world's first "third generation" high brightness soft x-ray synchrotron radiation source at that time!!

Busy 1980s, but I survived two bosses! [Serving three bosses at CERN during 1982-1984 – Rubbia, van der Meer and Boussard – prepared me well!]

Alex's Assignment to me:

- Evaluate all possible collective and coherent instabilities potentially limiting SSC performance, design proper feedback systems to remedy them and establish ultimate 'intensity' performance to maximize luminosity
- Evaluate all possible 'beam Lifetime' and 'Luminosity Lifetime' mechanisms: interbeam scattering, Touchek scattering, RF diffusion, nonlinear diffusion and halo, beam-beam effects, etc.
- Establish an Impedance budget for the ring
- Was polarized proton a possibility?
- Critical evaluation of aspects of the nonlinear dynamical aperture of the SSC rings

All this added up to Chapters 3,4,5 and parts of 6 in the CDR.

My vulnerability:

- I was new at the game --- fresh off PhD from Berkeley and 2-year stint at CERN
- **So it had to be scrutinized by venerable wise men as experts!**
- Ernest Courant, Don Hartill and Robert Siemann were assigned as my scrutinizers
- **All okay, except calamity with Ernie!**
- Ernie had an entire collider design programmed on his HP calculator --- his program was giving him intra-beam scattering lifetime of SSC proton colliding beams of seconds while I had many hours in my design! Ernie was most UNHAPPY and asked me to look into alternate lattices and reported this to Alex
- **I was almost sure that I had lost my job at the SSC-CDG !!**

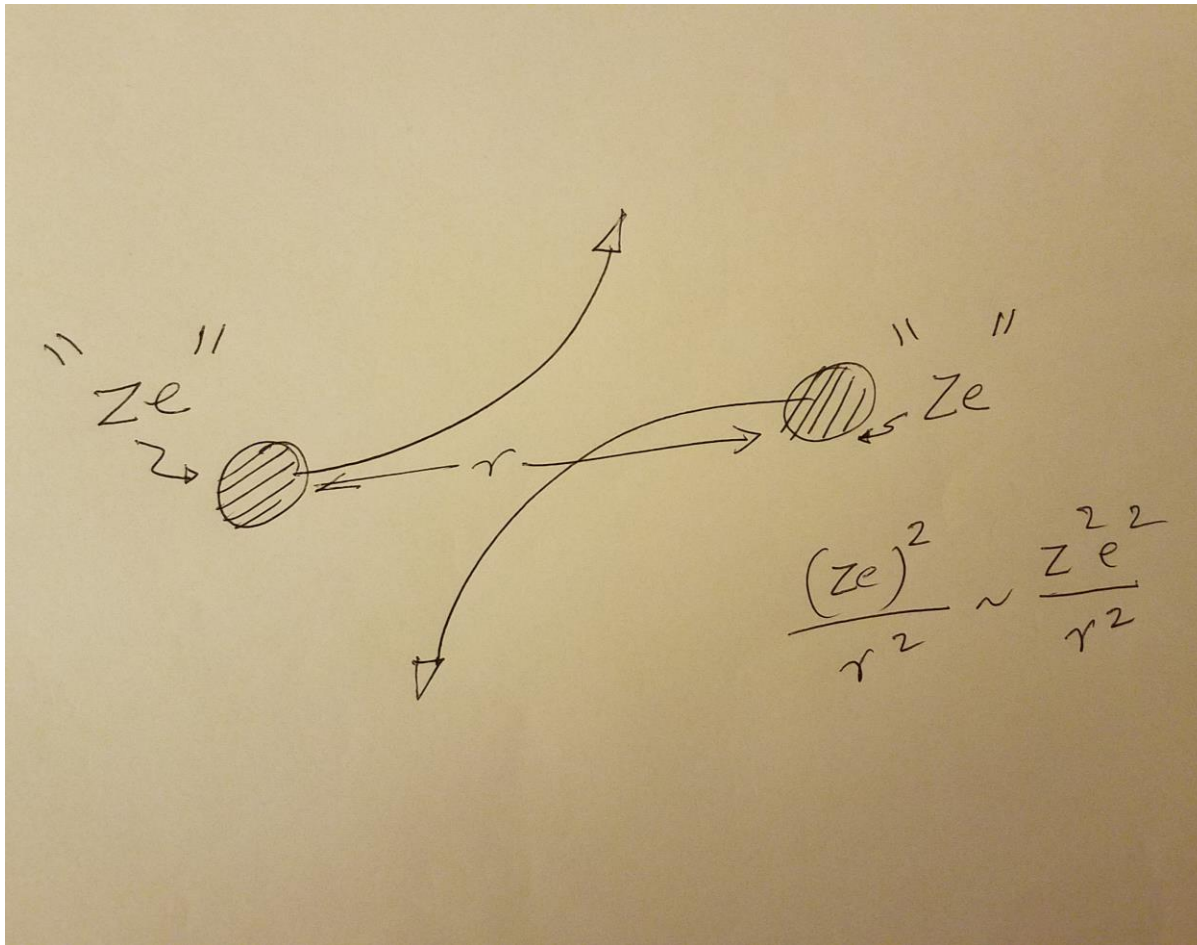
My meetings with Ernie:

- I simply did not understand such a big discrepancy!
- Every time I sat down with Ernie, he would input all the parameters into his HP hand calculator and voila! --the answer was always catastrophically short lifetime!
- At the end of the day, I was sure that Alex will have fired me tomorrow, if not solved. Before leaving for home , I called Alex to beg off extra time to look into it and he told me that I had all the time I needed, but that Ernie was an important man!
- As I was walking home, it struck me that a special number '79' kept appearing on Ernie's HP! A light bulb lit up inside me! Ernie is a quintessential BNL man, preoccupied at that time with a possible heavy ion collider with gold-on-gold collisions for quark-gluon plasma studies! A fully stripped gold ion as a charge state of $Z = 79$!
- I went back to Ernie's office and asked him meekly that could it be that he had the proton mass but a fully stripped gold charge in his program?
- And you should have seen Ernie's face! I thought I did not loose my job after all.

Intra-beam Scattering collision between two “Ze” charged state ions : Z = 1 for protons, Z = 79 for fully stripped Gold ions:

$$Z \times Z = 79 \times 79 = 6241$$

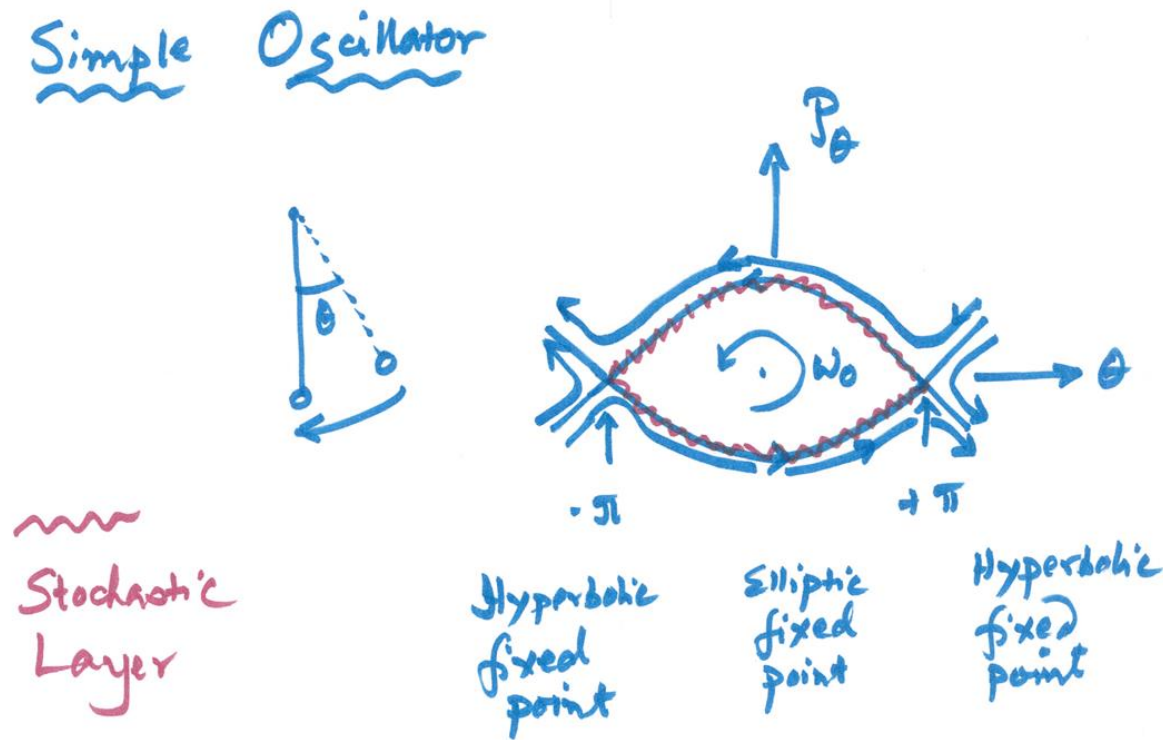
10 hours \rightarrow \sim 6 seconds !! for same mass, worse for lighter mass.



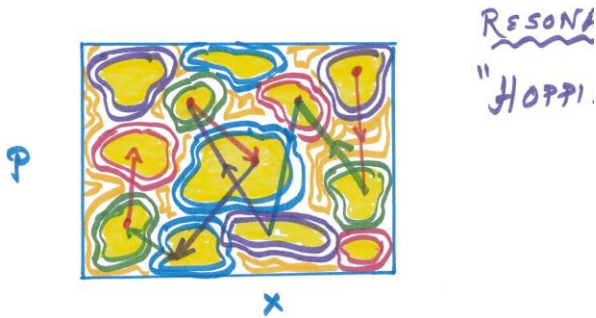
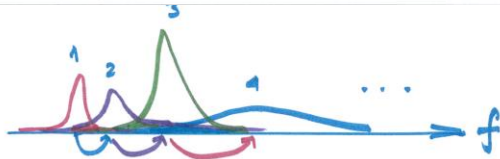
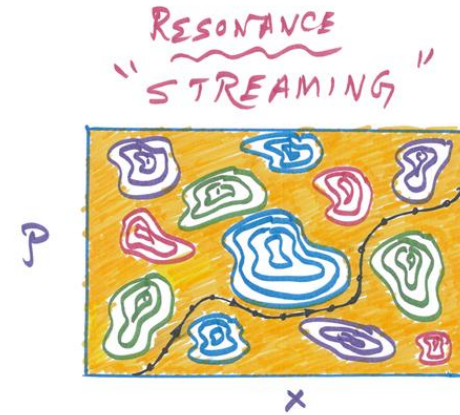
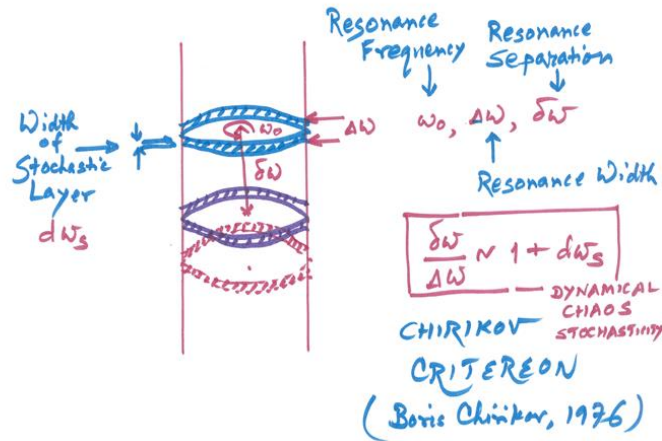
MORAL:

Alex was the most considerate, kind and tolerant supervisor that I could have hoped to have worked for!!

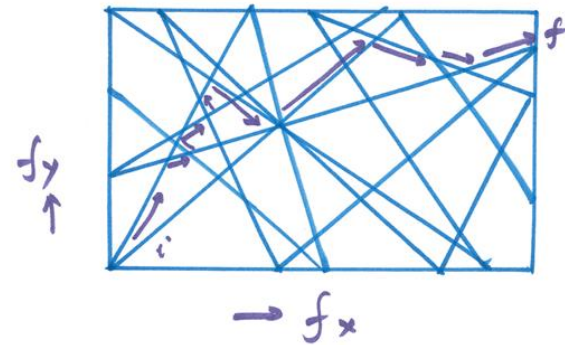
DYNAMIC APERTURE was a big issue in the SSC....so Resonance Dynamics in Rings and proper particle tracking codes were critical!



We studied various Resonance Dynamics in Rings through computing and theoretical analysis



ARNOLD'S WEB
ARNOLD Diffusion



**Much later,
Alex and Nonlinear Dynamics, ARCIDOSSO, 1994**



Spinning Particles: Polarized Protons, anti-protons and electrons

*Alex has done significant research on polarized electron beams, spin polarization dynamics, written codes etc. But in the context of the SSC, he also entertained the idea of collisions of **polarized protons!!***

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PARTICLES
AND FIELDS
SERIES 34

POLARIZED
BEAMS AT SSC
ANN ARBOR, MI 1985

POLARIZED
ANTIPROTONS
BODEGA BAY, CA 1985

EDITORS: A. D. KRISCH, A. M. T. LIN & O. CHAMBERLAIN

Ultimately kept 'on hold' as required too many "Siberian Snakes" and limited by SSC estimated overall cost!!

POLARIZED PROTONS AT THE SSC

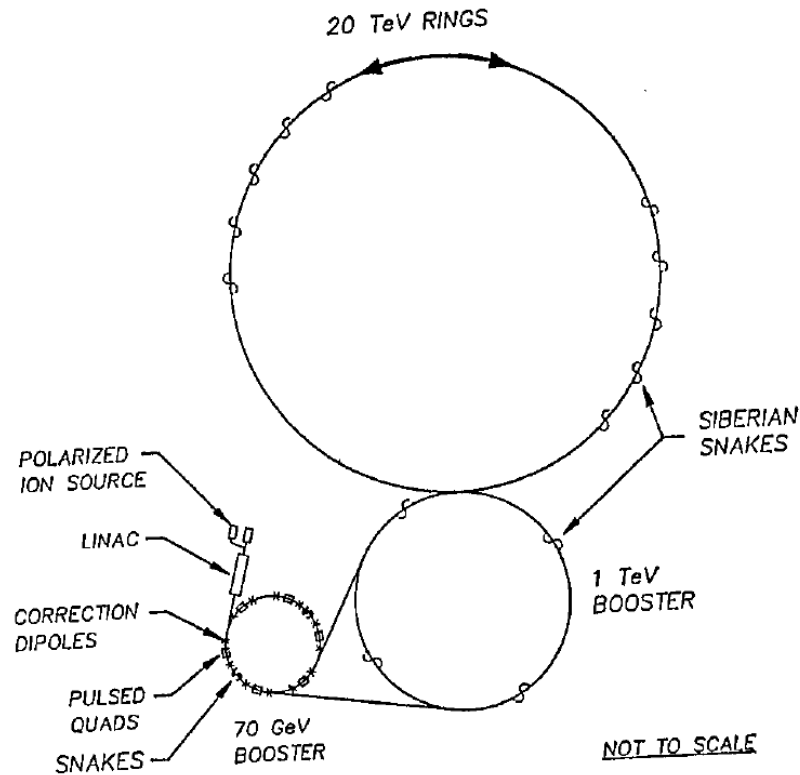


Fig. 1 Acceleration of Polarized Protons at the SSC.

**Ernest Courant, John David Jackson,
Owen Chamberlain and Alan Kirsch
having a heated discussion on the
possibility of polarized protons in the
SSC**



**Alex with Klaus Steffen
discussing Polarization in SSC**



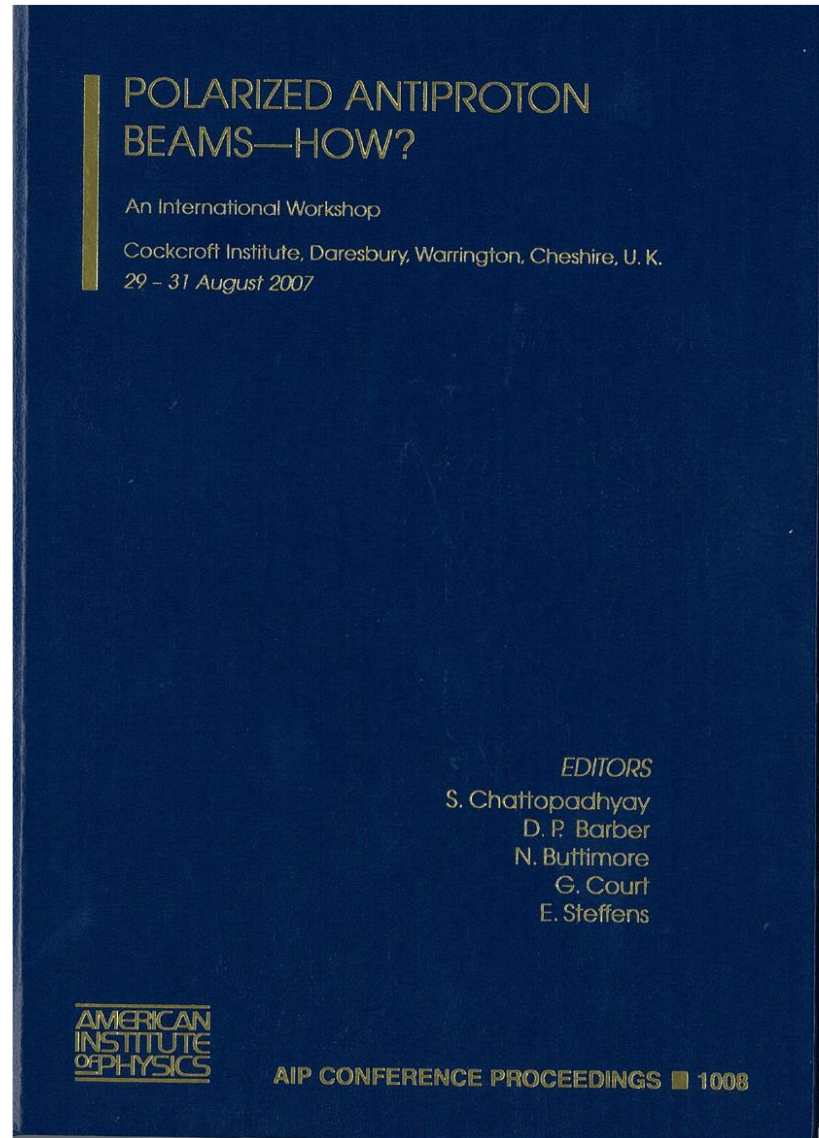
Polarized Beam at SSC workshop in Ann Arbor, Michigan

[Ron Ruth, Ernie Courant, Alex Chao, Swapan
Chattopadhyay, Klaus Steffen, Dave Jackson, Owen
Chamberlain,.....]



... C. Betner, R.D. Ruth, B.W. Montague,

Years later, this motivated me to look into further possibilities of polarized antiprotons!!



Growing Waves

GROWING WAVES

Charged Particle beams are plagued with various “coherent”, intensity-dependent “collective instabilities”, determined by the *electromagnetic response of the environment* to the beam’s charge-current density and its feedback on the beam, characterized by the “Beam Coupling Impedance”, which includes the full spectrum of excited electromagnetic modes of the beam-vacuum chamber system, including radiation coupling and synchrotron radiation of the beam to very high frequencies beyond the beam-pipe cutoff. Proper modeling of this is critical to maximizing the supported beam intensity, beam brightness and consequent synchrotron radiation brightness or colliding beam luminosity i.e. maximizing the threshold current for beam instability

→ Critical contribution by Alex, often overlooked!

“Chao-Gareyte” Scaling law (Jacques Gareyte)

for very small bunches experiencing coupling Impedance beyond storage ring cut-off frequency (based on SPEAR-ring).
Applicable and relevant to most Synchrotron Radiation Storage rings: ALS, APS, SPEAR-III, NSLS-II, SOLEIL, DIAMOND,.

$$\left| \frac{Z_{\parallel}}{n} \right|^{BB} = \left| \frac{Z_{\parallel}}{n} \right|_0^{BB} \quad \left(\epsilon \leq \epsilon_c \right)$$

$$= \left| \frac{Z_{\parallel}}{n} \right|_0^{BB} \left(\frac{\omega}{\omega_c} \right)^{-1.68} \quad \left(\epsilon > \epsilon_c \right) .$$

$$\left| \frac{Z_{\parallel}}{n} \right|^{BB} = \left| \frac{Z_{\parallel}}{n} \right|_0^{BB} \left(\frac{\sigma_{\ell}}{b} \right)^{1.68} \quad \left(\sigma_{\ell} < b \right)$$



I had the good fortune to have worked with both Alex and Jacques Gareyte on various collective beam dynamics problems at SLAC and CERN



Shrinking Phase Space

Phase Space Cooling

→ With my experience in bunched beam stochastic cooling at CERN, I asked Alex whether one should look into stochastic cooling at hadron colliders.

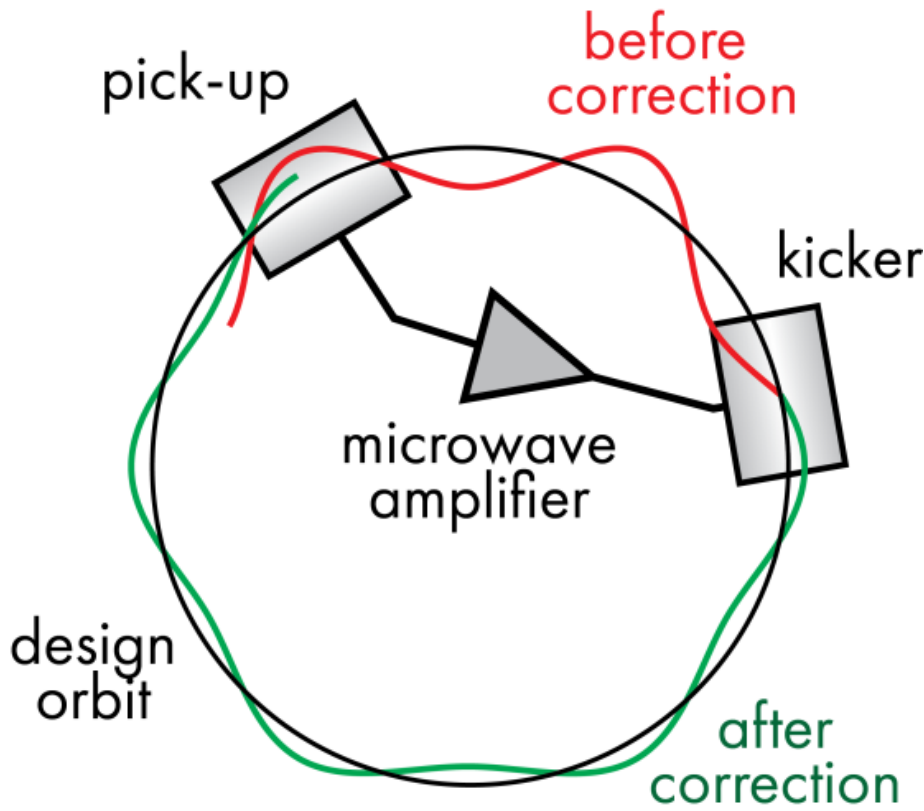
→ Alex thought it better be demonstrated at a working collider first before an all-out design.

→ Many years later, I proposed a bunched beam stochastic cooling for the Fermilab Tevatron, since they were having severe luminosity limitations in their chase for the top quark. But the cost of implementations was approximately \$10 M, so it was dropped.

→ But it was picked up by my student and mentee, Michael Blaskiewicz at BNL RHIC and was successfully implemented in gold-on-gold collisions.

→ Today we are looking forward to a demonstration of an optical stochastic cooling experiment in the experimental ring IOTA at Fermilab!

SC: a powerful technique but limited to GHz BW



Simplified stochastic cooling system

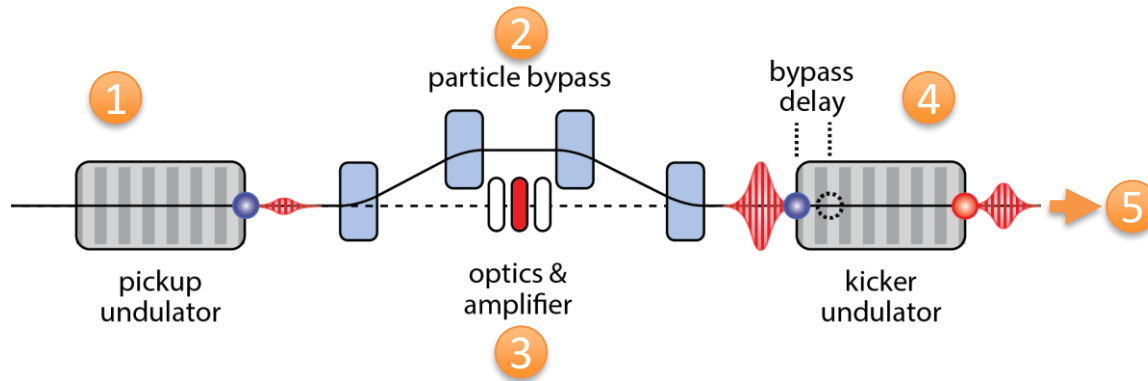


$$\mathcal{L} \sim \frac{f N_b N^2}{4\pi\sigma_x^* \sigma_y^*}$$

1984 Nobel: van der Meer/Rubbia

- 1) We can increase beam brightness if we have granular information about particle ensemble.
- 2) Bandwidth of feedback system controls cooling rate

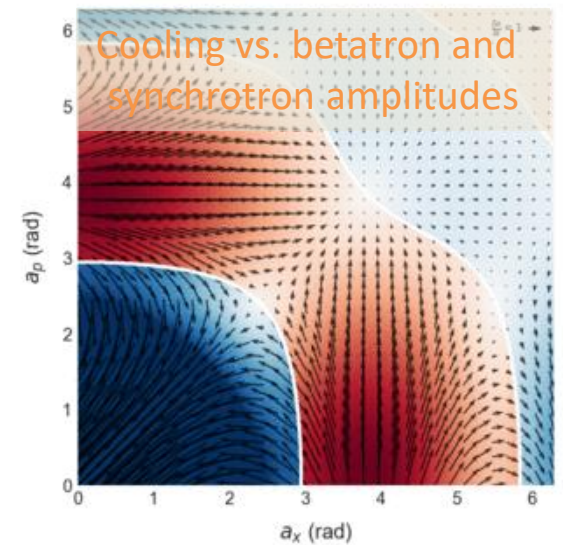
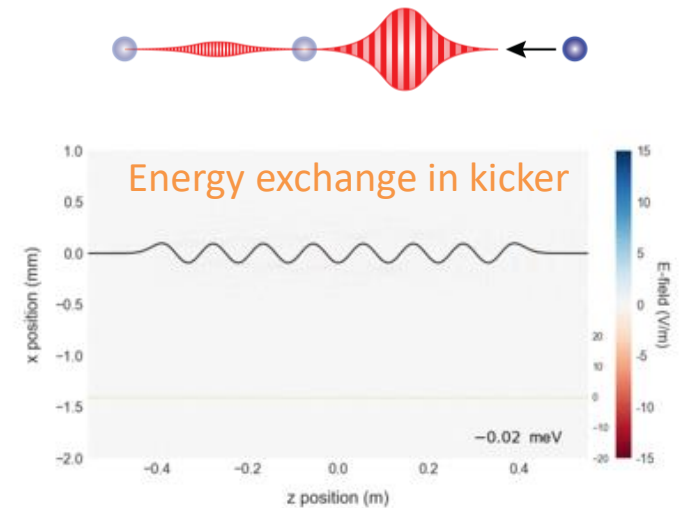
Optical Stochastic Cooling: optical bandwidth



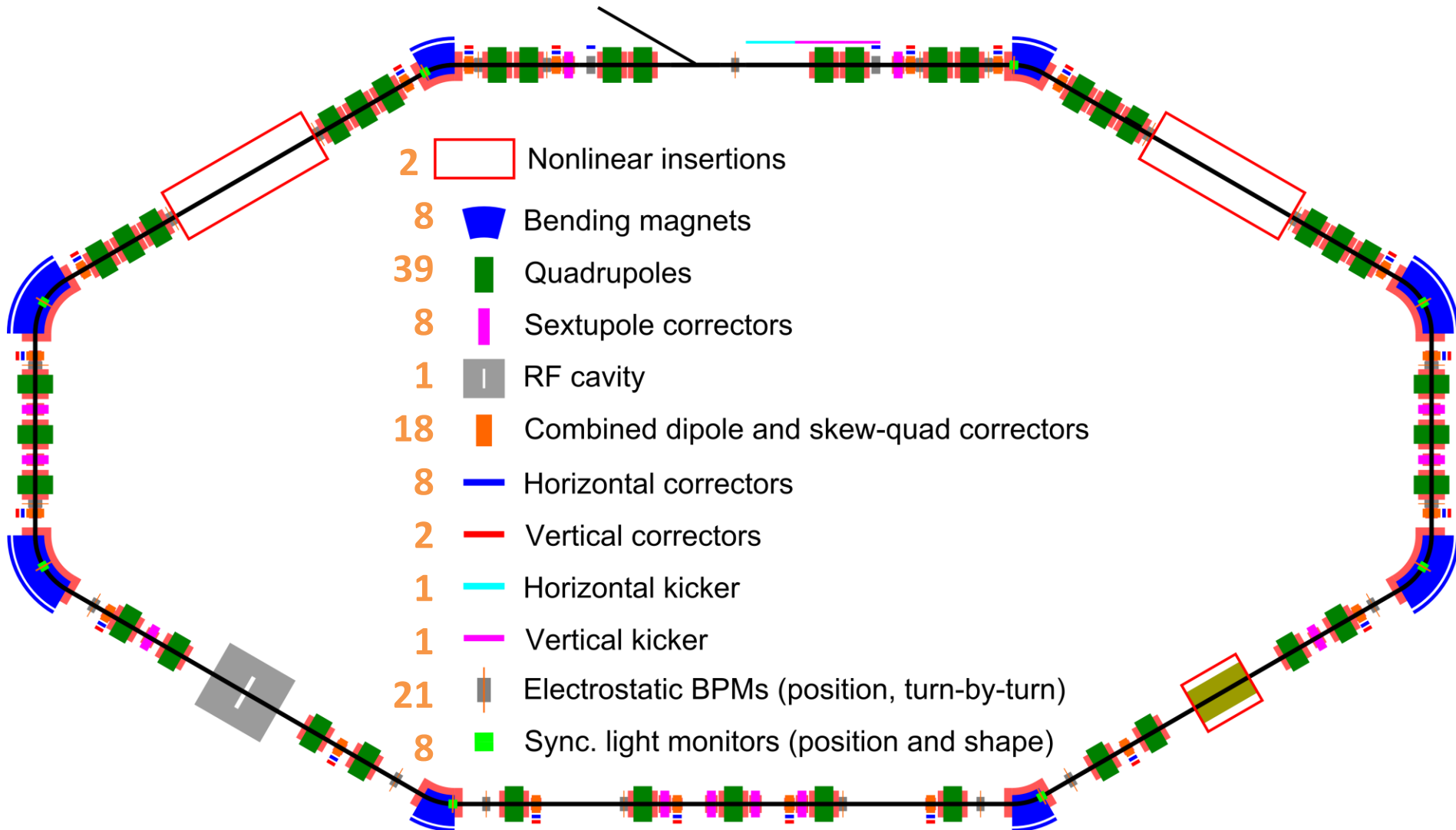
1. Wavepacket generated
2. Particle delayed in bypass
3. Wavepacket amplified and focused
4. Corrective kick applied
5. Cooling accumulates over many passes

$10^3 - 10^4$ increase in cooling rate over SC and extension into an energy range where no cooling solutions exist

Collaborator: Jonathan Jarvis



IOTA Layout - Elements



Other personal shared journeys....

Alex and me in School on Beam Physics in Bangalore, India, January, 1997

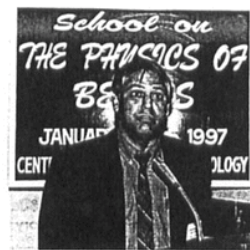
MEETING REPORTS

School on the Physics of Beams



School participants pose at the venue for a picture.

A School on the Physics of Beams was held from January 13–25, 1997, at the Centre for Advanced Technology (CAT), Indore, the premier accelerator physics laboratory in



Prof. Span Chattopadhyay, Head, Beam Physics Group, LBNL, delivering the keynote address.

India. The School was sponsored by the Indian Department of Science and Technology. This was the first School of its kind in the country, following in the tradition of the Particle Accelerator schools held regularly in the United States, Europe and Japan. The School was organized by Srinivas Krishnagopal and A. S. Raja Rao of CAT.

There were a total of 53 registered students at the School, representing 15 universities and 5 national laboratories. The backgrounds of the students ranged from first-year Masters students to young professionals in the field. In spite of the varying backgrounds, the common thread amongst the students was that none of them had had a formal, pedagogical exposure to the physics of beams. There were 12 lecturers at the School, including 3 from abroad: Alex Chao from SLAC, Alex Dragt from Mary-

land and Swapan Chattopadhyay from LBNL. The course contents were divided into core topics and special topics. The former were short courses, typically of five hours, and included: (i) introduction to accelerators; (ii) introduction to storage rings; (iii) nonlinear dynamics in accelerators; (iv) introduction to coherent instabilities; (v) introduction to free-electron lasers; (vi) introduction to ion sources. The latter were in the form of single seminars, designed to "fill in the gaps" and give the students a perspective on the field. Topics included: (i) accelerators for high-energy physics; (ii) future accelerators for condensed-matter physics; (iii) beam-plasma interaction; (iv) synchrotron radiation sources; (v) utilization of synchrotron radiation; (vi) synchrotron radiation work at Daresbury; and others.

The response to the School sur-

Personal Friendship: Alex and Pat spending a relaxing day in the wine country --- visiting me and my wife in Sonoma



*Congratulations Alex on your happy
retirement!!!*

*And a fistful of THANKS for many years of
fruitful collaboration and friendship which
continues unimpeded!!!!*

*The accelerator physics community
is enriched because we have you
amongst us!!*