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Beam manipulatoion techniques, nonlinear beam dynamics, and space charge effect in high energy high power accelerators

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Summary of DOE Proposal DE-FG02-92ER40747

- Applicant: Indiana University
- Project Director: S.Y. Lee
- Project Title: Beam manipulatoion techniques, nonlinear beam dynamics, and space charge effect in high energy high power accelerators charge effect in high energy high power accelerators

Indiana University Center for Energy Exploration and Matter (CEEM) has built a Linac and an electron storage ring (ALPHA) for radiation effect experiments. The storage ring has been commissioned, and a 50 MeV high intensity linac will be completed by the summer of 2012.

The proposal was to investigate beam dynamics problems associated with high brightness high power accelerators; nonlinear beam dynamics; and applications in the generation of inverse Compton X-ray source, and possibly coherent light sources. Topics included were high power accelerators; space charge physics; synchro-betatron coupling; nonlinear beam dynamics and collective beam instabilities.

We had carried out a design of an ultimate storage ring with beam emittance less than 10 pico-meter for the feasibility of coherent light source at X-ray wavelength. The accelerator has an inherent small dynamic aperture. We will study method to improve the dynamic aperture and collective instability for an ultimate storage ring. Beam measurement and accelerator modeling are an integral part of accelerator physics. We will continue developing the independent component analysis (ICA) and the orbit response matrix method for improving accelerator reliability and performance. In collaboration with scientists in National Laboratories, we will also carry out experimental and theoretical studies on beam dynamics. Our proposed research topics are relevant to nuclear and particle physics using high brightness particle and photon beams.

In past three years, there are **eight** graduate students received Ph.D. degree in accelerator physics from Indiana University. Topics of our research include space charge beam dynamics, nonlinear beam dynamics, beam measurements and accelerator modeling, advanced beam manipulation techniques, beam cooling, design of compact medical synchrotrons, and high gain free electron lasers. These results have been employed to control and alleviate collective beam instabilities in high intensity storage rings. They also provide physics models to understand phenomena such as chaos, strange and limiting cycle attractors, and bifurcation characteristics of attractors. Our experimental and theoretical results have been used to improve beam quality, to provide design criterion for power supply ripple in high energy colliders, and to develop new methods for emittance preservation of high brightness beams.

The broader impacts of our research include training accelerator scientists, applications in high brightness beams for radioactive ion-beam accelerators, spallation neutron sources, heavy ion fusion, biochemistry and bio-medical, material science, high-tech industries, energy research, and defense research. The intellectual merit of our research covers fundamental understanding of nonlinear dynamics, chaos, beam cooling, and plasma physics. Some applications of high brightness beams are radioactive ion-beam accelerators, spallation neutron sources, heavy ion fusion, biochemistry and bio-medical, material science, and defense research.

A Results of the DOE Support

During the 3-year period, we have been funded by DOE grant DOE-FG02-92ER40747 to carry out research in accelerator and beam physics. We have participated electron cloud feedback experiment at PSR; we have measured and modeled the emittance evolution of a space charge dominated beams at the Fermilab Booster, and found that the emittance growth arisen essentially from linear coupling resonances; we have applied our space charge simulation program to study design criterion for the non-scaling FFAG high power accelerators; we have studied spin dynamics at the AGS and RHIC in BNL; we have introduced a new QBA low emittance electron-storage-ring design concept and achieved 1 nm natural emittance without using damping wiggler; we have studied the independent component analysis method and the orbit response matrix method in beam measurements and accelerator modeling, and collective beam instabilities. These beam dynamics research topics are listed as follows.

A.1 High Intensity and High power beams

A.1.1 Space Charge Effects

Space charge is important to all high power accelerators. Space charge can cause emittance dilution, beam loss, and radiation contamination to accelerator components. The emittance growth mechanisms may be different for different accelerators. For example, we found that possible emittance dilution mechanisms at the Fermilab Booster were the linear sum resonance induced by skew quadrupoles, and effect of the Monteque resonance [see e.g. X. Huang, S.Y. Lee, K.Y. Ng, and Y. Su, *Emittance measurement and modeling for the Fermilab Booster*, PRSTAB, **9**, 014202 (2006).]

Employing the multi-particle simulation code that we developed, we have carried out analysis of emittance growth due to resonance crossing. Defining the emittance growth factor (EGF) as the ratio of the final emittance to the initial one, we uncovered scaling laws of the emittance growth factor (EGF) vs the space charge parameter, the resonance strength, and the resonance crossing rate. We have found that the *systematic* space charge resonance induced by intrinsic beam size modulation can induce large emittance growth in high power accelerators [see. e.g. S.Y. Lee, *A Fundamental Limit of Non-scaling FFAG Accelerators*, Phys. Rev. Lett. **97**, 104801 (2006)]. We have also found a scaling laws for the EGF in passing through the half-integer and linear coupling sum resonances.

We developed an improved space charge code to provide reliable space charge calculation and study the 4th-order and the 6th-order systematic space charge resonances [6, 15]. We have also studied EGF of resonances driven by nonlinear magnetic fields. Possible beam dynamics experiments to verify these scaling laws would be of great interest to the beam physics community.

We have produced a fast-reliable space charge code that can integrated into a lattice design code and provide guidance in the design of high power accelerators. This is code is available for all accelerator physicists.

A.1.2 Nonlinear beam dynamics [18]

Nonlinear beam dynamics is important in high intensity and high power accelerators. We had studied the effect of crossing low order resonances and has attained scaling laws for resonance strength vs the crossing rate. In our first example, we study the effect of a 3rd resonance, where one can compare with available experiments and possible future experiments.

The Hamiltonian of a 3rd order resonance in the resonance rotating frame is $\tilde{H} = \delta I + \frac{1}{2}\alpha I^2 + G I^{3/2}\cos(3\psi)$ where J and ψ are the conjugate action-angle variables for betatron oscillations, $\nu = \nu_x$ is the betatron tune, $\alpha = \alpha_{xx}$ is the nonlinear betatron detuning parameter arising from higher order multipoles, $\delta = \nu - \frac{\ell}{3}$ is the proximity parameter of the betatron tune to the resonance with an integer ℓ, $G = |G_{30\ell}|$ is the resonance strength. Typical strengths of the 3rd order random resonances for FFAG accelerator designs are about 0.01 to 0.5 $(\pi\mathrm{m})^{-1/2}$, and $G = 2.2$ $(\pi\mathrm{m})^{-1/2}$ at the IUCF Cooler.

Particle motion in the Hamiltonian is characterized by the fixed points. Under certain conditions, the Hamiltonian has resonance islands. The island area in the asymptotic region: $|\delta| \gg G^2/\alpha$, where $J_{ufp} \sim J_{sfp} \approx -\frac{\delta}{\alpha}$ is

$$\text{Area} = \frac{16}{\pi}\, G^{1/2}|\delta|^{3/4}\alpha^{-5/4}. \tag{5}$$

The total island area (3 islands) indeed obeys a simple scaling property: $G^{-1/2}\alpha^{+5/4}$ proximity parameter for a number of resonance strengths and detuning parameters. At a given α and G, the effect of the third-order resonance becomes more important for a beam with a larger emittance because the beam covers a larger action.

When the tune of an accelerator is slowly changed due to acceleration or quadrupole manipulation, the Hamiltonian is quasi-adiabatic. If there were no resonance, the action of each particle and the emittance of the beam would remain constant. However, when the tune is ramped through a resonance line, the action of each particle will be perturbed. The fixed points and resonance islands of the resonance are time dependent. The particle motion will still follow the quasi-static resonance dynamics moving along the separatrix.

For $\alpha > 0$, the resonance occurs at the proximity $\delta < 0$. When the betatron tune ramps downward, i.e. proximity parameter varies from positive to negative, the resonance islands are creasted inside the beam and move outward in phase space. Particles will be trapped in the resonance islands and carry outward. We demonstrate this effect in multi-particle simulation shown in Fig. 9. Since particles are driven out of the center by the resonance and captured into resonance islands, the emittance will increase linearly with time shwon in Fig. 9.

For $\alpha < 0$ case, the resonance is locatd at $\delta > 0$. As the tune is ramped from a higher value to a lower value, large amplitude particles see the resonance first, and the resonance will drive particles outward along the separatrix and cause emittance growth. However, as the tune is ramped further downward, these resonance islands move inward in betatron phase space. After passing the bifurcation δ_{bif}, these resonance islands suddenly disappeared. An example is shown at the right plots of Figure 9, where a simulation of 5000 particles ramping through a third-order resonance with $\alpha < 0$. Note that the emittance begins to increase before the bare tune reaches the third-order resonance. After the resonance is crossed, the emittance becomes constant because no particle is trapped into resonance islands.

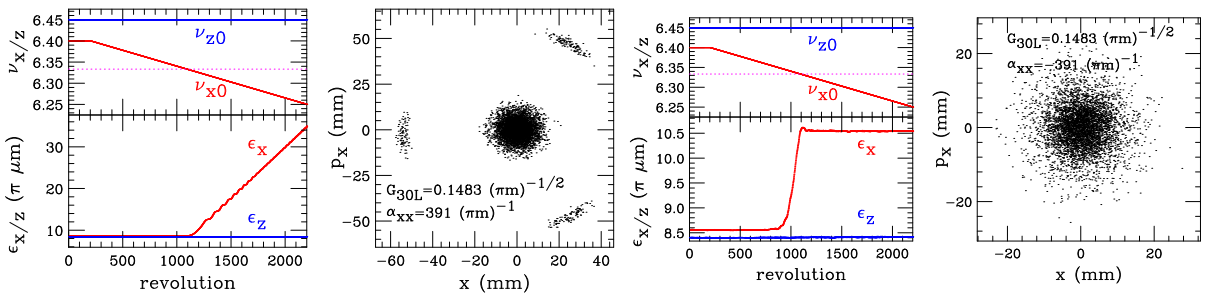

Figure 9: Left ($\alpha > 0$): Horizontal bare betatron tune is ramped downwards from $(\nu_x, \nu_z) = (6.40, 6.45)$ starting from turn 200 to $(6.25, 6.45)$ at turn 2200 (ramp rate -0.000075 per turn) through a third-order resonance $3\nu_x = 19$ at turn 1100. Red and blue curves are respectively the horizontal and vertical emittances. Resonsnce islands trap particles and move outward. Right ($\alpha < 0$): Horizontal bare betatron tune is ramped downwards from $(\nu_x, \nu_z) = (6.40, 6.45)$ starting from turn 200 to $(6.25, 6.45)$ at turn 2200 (ramp rate -0.000075 per turn), where the third-order resonances $3\nu_x = 19$ is crossed at turn 1100. Red and blue curves are respectively the horizontal and vertical emittances. Horizontal emittance increases before the bare tune crosses the resonance. There is no resonance islandi to trap particle after passiing the resonance.

We have systmatically studied effects of resonance crossing. The resulting emittance growth and particle capture into the third-order resonance islands are used to characterize the resonance. The phase space evolution depends on the sign of detuning coefficient. If the betatron tune is ramped downward, a negative detuning parameter α will produce emittance growth without particles being captured into resonance islands, and particles will be captured into resonance islands for the positive α case. These captured particles will move outward in phase space as the bare tune is further lowered as shown in the left plot of Fig. 9.

We use a 2.5% capture efficiency to define the critical resonance strength and find a simple scaling power-law for the critical strength vs as an universal function of the tune ramp rate and the initial emittance. We find that the *stationary phase condition* can provide a good criterion in solving Hamilton's equation of motion. The scaling law shows that the critical resonance of an octupole resonance scales like $\sim |d\nu/dn|^{1/2}\epsilon^{-1}$ and is nearly independent of the nonlinear detuning parameter. Our scaling law can be used in the design of high power accelerators, estimating the emittance growth in cyclotron, and requirement of slow beam extraction using the third-order resonance. A non-scaling FFAG has recently been commissioned. Our scaling law should be timely for experimental tests. Study of nonlinear resonance scaling law is important for future high power accelerators.

A.2 High Brightness storage ring and coherent light sources

A.2.1 Beam Dynamics of isochronous storage ring

The ALPHA project at IU/IUCEEM is building a linac and a storage ring. The storage ring is composed of 4 CIS dipoles (each 2 m long) separated by 3 m straight sections. Employing the gradient damping wigglers, we obtain tunable compaction factor and damping partition number with excellent dynamic aperture. We have recently installed 2 magnetic bumpers, two gradient damping wigglers, 1 rf cavity at 15 MHz and 8 BPMs. The facility is

shown in Sec. 4.3. We are currently commissioning the storage ring with damping wigglers [12, 16, 19, 20, 27, 29, 30, 31, 33, 34].

The first goal of the this 20-m storage ring is to provide beam debunching in one revolution. This debunching goal has been accomplished. The extracted beam has also been uniformized by nonlinear magnets, and verified by the experimental results [20]. The other goal of the storage ring is to accumulate linac pulses. We design to accumulate many linac pulses for a high charge of about 1000 nC at bunch length of the order of 40 ns. Once these goal is accomplished. The storage ring provides experimental ground for students in accelerator physics research. Some of these topics are (1) Touschek lifetime, (2) Intrabeam scattering, (3) beam dynamics in isochrous, (4) research in inverse Compton scattering.

A.2.2 Beam characterization of a linac beam [12]

The frequency spectra detected by a wide bandwidth BPM or wall gap monitor can be used to extract the characteristics of a beam. Let the beam current of a linac pulse be

$$I(t) = Qf(t)g(t); \qquad f(t) = \sum_{m}^{N} \delta(t - mT_0); \qquad t \in (0, T) \tag{6}$$

where Q is the total charge of a pulse, $g(t)$ is the normalized pulse function with $\sum_m g(mT_0) = 1$, and $T_0 = 1/f_{rf}$ with the rf frequency f_{rf}. For an S-band linac with $f_{rf} = 2.856$ GHz, we find $T_0 \approx 350$ ps. A linac pulse of a few microseconds may contain a few thousand micro-beamlets. The repetition rate is $1/T$, and Q/T is the average current. For a linac pulse, $g(t)$ is normally a square wave with time width ΔT, and $Q/(\Delta T)$ is the peak current. Figure 10 shows the procedure of the modulation-demodulation in the process of recovering the bunch profile of the linac source. Combination of the pulse shape and energy selection slits, one can reconstruct tomography of the beam.

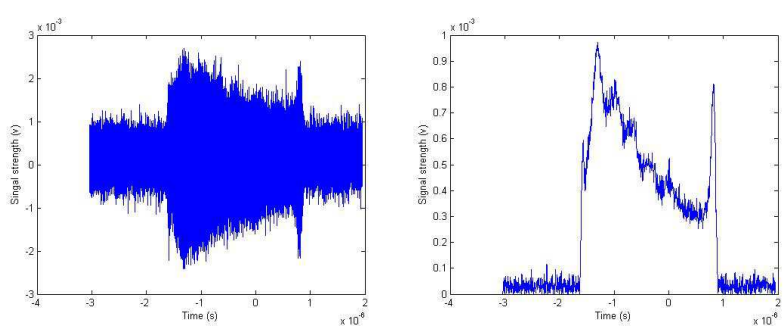

Figure 10: Left: digitized raw signal of a linac pulse after the band-pass filter around the 2.856 GHz, Right: The beam pulse after demodulation, i.e. inverse FFT of the band-pass filtered signal and frequency shift. The integrated area of the beam pulse will be used to obtain a total charge in a beam pulse.

A.2.3 Nonlinear beam spreader with octupole magnets

Employing octupole (or higher order multipole) magnets, one can transform a Gaussian beam profile to nearly uniform beam distribution in coordinate space without employing collimator for beam shaping. Figure 11 shows experimental data of beam shaping with octupole magnets. Using nonlinear multipoles for beam manipulation may also be important for the future high power accelerator in the secondary beam production.

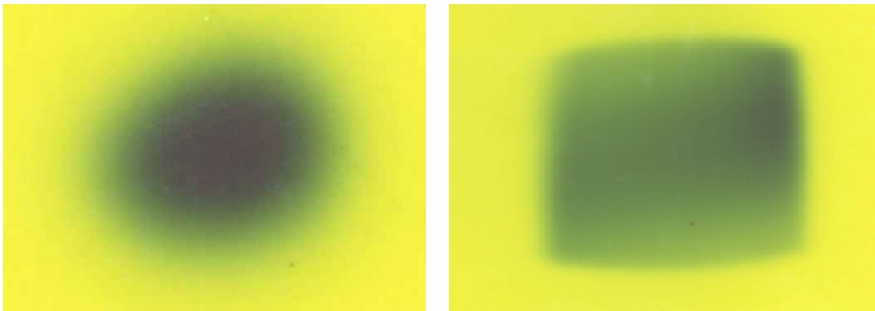

Figure 11: Left: The beam profile of a Gaussian beam. Right: The beam profile after the nonlinear spreader using octupoles in the ALPHA transport line.

A.2.4 Design and fabrication of a gradient damping wiggler [19]

A 3-pole gradient-damping wiggler (GDW) was developed for the ALPHA storage ring at Indiana University. The GDW is effective in modifying the momentum-compaction factor and the damping partition number in the ALPHA storage ring. The yokes of GDW are made by lamination of silicon steel sheet (50CS1300) with a thickness 0.5 mm. Glue (3M 2216) is used to paste the lamination sheets together become a block by a punch fixture. The C-shape structure and the pole profile of the damping wiggler are cut from the silicon-steel block with wire-cutting. One middle pole and two outer poles are assembled on the same girder as one set of GDW. The oblique of pole profile of middle and outer poles is different to obtain the same polarity of gradient field. The magnet gaps of the middle and outer poles are 40 and 35.87 mm; respectively to obtain the same dipole field strength. The field strengths of dipole and gradient-field of the middle (outer) pole are 0.67 T (-0.67 T) and 1.273 T/m (1.273 T/m), by keeping the integral ratio of $(dB/dx)/B = 1.9$ m^{-1} constant. The three combined functions of the dipole magnet can be charged in 1 Hz with a single power supply. There are trim coils on the three poles to adjust the first and second integral fields to zero. The good field region of the middle and outer poles along the transverse x-axis ($\Delta B/B$=0.1 %) are $\pm$50 and $\pm$40 mm. After fabrication of one set GDW magnet, a Hall probe measurement system was used to measure the magnetic field to verify the design and construction performance of the magnet.

A.2.5 The QBA low emittance lattice

We have systematically studied low emittance storage rings. Figure 12 shows a summary of all achieved design emittances vs the dipole numbers. The QBA lattices are shown as red symbols.

Our systematic studies show that the ratio of bending angles of the inner dipoles to that of the outer dipoles is numerically found to be about 1.5$\sim$1.6 for an optimal low beam emittance in the isomagnetic condition. The QBA lattice provides an advantage over the double-bend achromat or the double-bend non-achromat in performance by providing a small natural beam emittance and some zero-dispersion straight-sections. Since high field undulators installed in dispersion free straight sections can lower the beam emittance, the emittance of a QBA lattice will be further lowered when high field undulators/wigglers are installed in dispersion free straight sections. The QBA concept can be extended to nBA storage ring for ultimate storage rings.

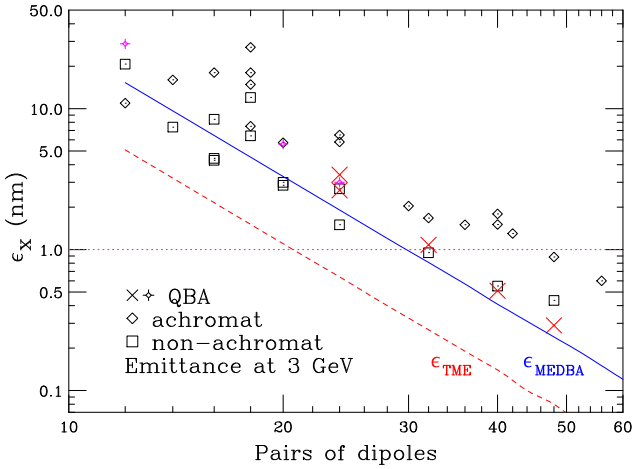

Figure 12: The natural emittances vs dipole numbers achieved for synchrotron light sources, where the square symbols are the non-achromatic lattices, the diamond symbols for the achromatic lattices. The blue solid and the red dashed lines are the minimum emittance for the DBA lattice and the theoretical minimum emittance (TME) respectively. For the nBA lattices, the pairs of dipoles is not equal to the number of cells, e.g. a lattice with 12(7BA) is equivalent to 42 pairs of dipoles. The red X and cross symbols are results from the QBA lattices.

A.2.6 Ultimate storage ring with emittance less than 10 pm [11, 32]

Ultimate storage rings aims to attain the best emittance achievable. In the summer of 2007, we have introduced a QBA lattice for small 3 GeV energy storage rings with emittance of the order of 1 nm. For X-ray light source, the emittance required for achieving coherent limit is an emittance of 10 pico-meter. We carried out the design of 10 pm storage ring. We choose an accelerator with 11-BA theoretical minimum emittance structure and obtain an emittance of aboout 9 pm. The design concept is to choose the dipole length such that the momentum spread is less than 10^{-3}, and emittance less than 10 pm. The resulting total circumference is long. Furthermore, the momentum compaction of the 11-BA lattice is given by $\alpha_c \approx \frac{1}{11\times 12}\left[4+9\times 3^{2/3}\right]\frac{\rho\theta_1^2}{R} \approx 0.172\frac{\rho\theta_1^2}{R}$ [1], where ρ is the bending radius of dipoles, θ_1 is the bending angle of the outer dipole, and R is the mean radius of the accelerator. To minimize cost, we study an option of using the combined function magnets. Although it can be matched to TME, the large gradient of the combined function dipole is too high. The resulting nonlinearity may be very large.

We use the 11BA structure to study nonlinear beam dynamics. Eight families of sextupoles were found to generate large nonlinear driving terms and tune shift with amplitude. The resulting dynamic aperture (DA) is very small. An implementation of ICA method shows the tracking particle at DA boundary experiences many resonances and the motion is chaotic. In the future, we will use the Genetic Algorithm (GA) to optimize the DA.

Due to the small momentum compaction factor of 10 pm storage ring, the microwave instability threshold occurs earlier than a typical 3rd generation light source. A single bunch microwave instability using Keil-Schnell formula is compared with the FEL parameter. The Intra-Beam Scattering effect can also be important on emittances and energy spread. Comparing these two effect, microwave instability is much more severe. Thus a smooth vacuum chamber is key in maintaining a good beam quality for ring operation and furthermore FEL process. A common difficulty in all ultra-low emittance storage rings is its small dynamic aperture. For example, we found that that the DA of USR is about 3 mm. The goal is to find an sextupole distribution scheme that can provide a dynamic aperture of about 15 mm.

A.3 ORM and ICA development

A.3.1 Orbit response matrix modeling (ORM)

The Orbit Response Matrix (ORM) has been successfully used in accelerator modeling. A dipole-kick θ_j at position s_j changes the closed orbit by $G(s, s_j)\theta_j$ and the circumference by $\Delta C = D(s_j)\theta_j$. The response matrix of the ORM experiment depends on the method of measurement:

Both Z. Liu and J. Kolski carried out experiments at SNS and PSR respectively and had verified that the orbit response matrix model can be better modeled with the constant momentum method for the proton accelerator, where the rf cavity is turned off during the experiment. Detailed analysis have been reported in their theses [8, 10].

A.3.2 Development of Independent Component Analysis

Since 2005, we have introduced the ICA method to the data analysis of beam measurements, and applied the method successfully to study the Fermilab Booster.The linear response of a dynamical system is represented by the relation between the m-dimensional observation vector $\mathbf{X}(t)$ and the n-dimensional source signal vector $\mathbf{s}(t)$ by

$$\mathbf{X}(t) = \mathbf{A}\mathbf{s}(t) + \mathcal{N}(t) \tag{7}$$

where $\mathbf{A} \in \Re^{m\times n}$ is the mixing matrix with $m \geq n$ (n is unknown *à priori*) and $\mathcal{N}(t)$ is the noise vector, assumed to be stationary, zero mean, temporally white and statistically independent of the source signal $\mathbf{s}(t)$. The task is to determine both the mixing matrix $\mathbf{A}$ and the source signals $\mathbf{s}(t)$ from the sample signal $\mathbf{x}(t)$.

Application of the ICA method at the Fermilab Booster was successful. For the first time, we can the measured betatron function, betatron tune, dispersion function, and synchrotron tune, for a regular Booster fast ramping cycle of 33 ms. We can measure the tune vs current during the ramp and derived impedance of the Booster Ring.

Vertical emittance characterization and correction [2]

The vertical beam emittance in an electron storage ring is mainly determined by two factors: the linear betatron coupling and the spurious vertical dispersion generated by magnet errors. Using the ICA method, we can precisely measure the vertical dispersion function and determine its contribution to the vertical emittance.

Using the independent component analysis (ICA) measurement method, we develop stop-band correction to reduce the vertical emittance. We demonstrate our method by making measurement and correction to a quadruple-bend achromatic (QBA) low emittance lattice. Six families of skew quadrupoles can effectively minimize both the vertical dispersion and the linear betatron coupling.

The ICA and nonlinear beam dynamics [6, 17]

The narrow-band filtering of ICA provides us methods to identify and extract information on the linear betatron and synchrotron motion, effects of wake fields, etc. We show that

the ICA is also a powerful tool to measure nonlinear magnetic field in accelerators to be demonstrated by the $2\nu_x$ mode for sextupole strength. Numerical simulations are used to demonstrate the ability to obtain sextupole strengths at high precision. The methods can be extended to other higher order multipoles.

We have developed the ICA method for the study of nonlinear betatron motion and compare the ICA measured nonlinear oscillation, $x_{2\nu}(s,t) = A_3(\phi)s_3(t) + A_4(\phi)s_4(t)$ of $2\nu_x$ modes, with the analytic solution of the Hill's equation of the $2\nu_x$ mode as shown in Fig. 13. This agreement provides us a method to extract sextupole strength.

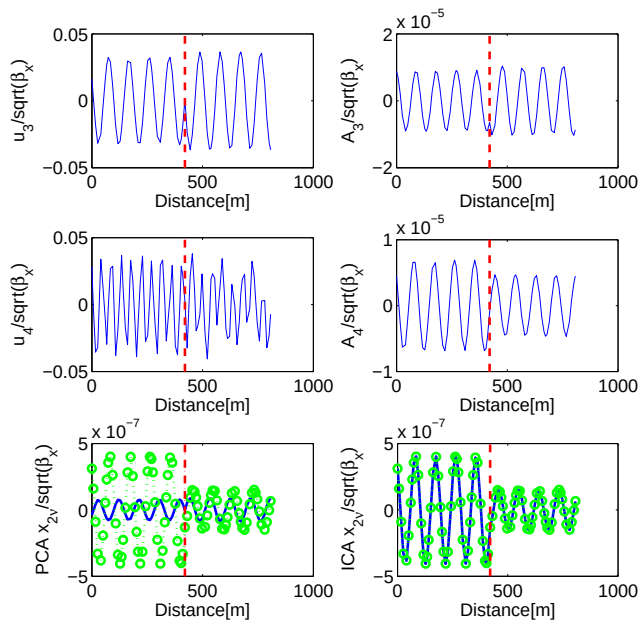

Figure 13: Right: Compare the analytic solution with wave function of the ICA $2\nu_x$ modes of the BPM data for one turn. This agreement continues for all turn numbers. In this calculation, one sextupole is placed at 420.37 m. The β_x at that location is 15.271 m. The action of $x_{2\nu}$ changes at sextupole locations. The action changes each time encountering the sextupole. The amount of action change can be extracted to obtain the sextupole strength. Left: the principal component analysis (PCA) wave function of $2\nu_x$ modes does not agree with theoretical result, and thus can not be used to extract sextupole strength.

A.4 e-p instabilities [10, 13]

The high intensity and high power ion beams can induce e-p instabilities. This phenomenon is induced by multipacting of Secondary Electron Yield from the vacuum chamber. The e-p instability has been carefully measured and documented at the PSR. This phenomenon may also limit the SNS proton beams intensity. We had form a collaboration to study the e-p instability feedback experiment at the PSR. Ms. Zhengzheng Liu has been working on electron cloud measurements at the SNS ring. Her Ph.D. thesis reports progresses in electron cloud measurements [10]. The e-p instability shows modes has streak moving toward high frequency. Much of this phenomenon is not properly modeled. We will continue to participate the experiment and and data analysis in the coming years.

A.5 Spin dynamics

Our students had participated research and development in RHIC on eRHIC [3] and electron source development [4]. In past few years, we have not participated polarized proton

development in RHIC. However, we have heavily involved polarized beam development in the past. Our research includes (1) spin matching, (2) linear coupling correction, (3) finding other innovative method of beam manipulation for polarized beam acceleration, (4) training graduate students in spin dynamics in accelerator physics, e.g. H. Huang (1995), M. Bai (1999), V. Ranjbar (2002), F. Lin (2007). In the coming period, we may participate RHIC polarized beam development if there is a need of collaboration.

A.6 Students received Ph.D. degree (2009-2012)

1. Chong Shik Park (graduated in 2009): *Investigations of electromagnetic space-charge effects in beam physics* (supervisor: Mark Hess).
2. Xiaoying Pang (2009): *Independent Component Analysis for Beam Measurement*
3. Wai-Ming Tam (2010): *Characterization of the proton ion source beam for the high intensity neutrino source at Fermilab*
4. Jeff Kolski (2010): *Lattice modeling and application of independent component analysis to high power, long bunch beams in the los alamos proton storage ring*
5. Xin Wang (2010): *Emittance Growth Mechanisms and Scaling Laws for Space-Charge Dominated Beams*
6. Zhengzheng Liu (2011): *Linear optics correction and observation of electron proton instability at SNS accumulator ring*
7. Yichao Jing (2011): *Design of an ultimate storage ring*
8. Tianhuan Luo (2011): *Instrumentation and beam dynamics study of advanced electron-photon facility in Indiana university*

B Publications of DOE award (2008-2012)

References

[1] S.Y. Lee, *Accelerator Physics*, 3rd Ed. (world scientific Pub. Co. Singapore, 2011).

[2] Fei Wang, *Vertical beam emittance correction with independent component analysis measurement method*, Ph.D. Thesis (Indiana University 2008)

[3] Yue Hao, *Beambeam interaction study in erl based erhic*, Ph.D. Thesis (Indiana University 2008)

[4] Qiong Wu, *Measurements and studies of secondary electron emission of diamond amplified photocathode*, Ph.D. Thesis (Indiana University 2008)

[5] Chong Shik Park, *Investigations of electromagnetic space-charge effects in beam physics*, Ph.D. Thesis (Indiana University 2009) (student under Prof. Mark Hess).

[6] Xiaoying Pang, *Independent Component Analysis for Beam Measurement*, Ph.D. Thesis (Indiana University 2009)

[7] Wai-Ming Tam, *Characterization of the proton ion source beam for the high intensity neutrino source at fermilab*, Ph.D. Thesis (Indiana University 2010)

[8] Jeff Kolski, *Lattice modeling and application of independent component analysis to high power, long bunch beams in the los alamos proton storage ring*, Ph.D. Thesis (Indiana University 2010)

[9] Xin Wang, *Emittance Growth Mechanisms and Scaling Laws for Space-Charge Dominated Beams*, Ph.D. Thesis (Indiana University 2010)

[10] Zhengzheng Liu, *Linear optics correction and observation of electron proton instability at sns accumulator ring*, Ph.D. Thesis (Indiana University 2011)

[11] Yichao Jing, *Design of an ultimate storage ring*, Ph.D. Thesis (Indiana University 2011)

[12] Tianhuan Luo, *Instrumentation and beam dynamics study of advanced electron-photon facility in indiana university*, Ph.D. Thesis (Indiana University 2011)

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