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2019 NISHIKAWA TETSUJI PRIZE TALK

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Abstract

The talk is given at the IPAC19 on the occasion of acceptance of the Nishikawa Tetsuji Prize for a recent, significant, original contribution to the accelerator field, with no age limit with citation "for original work on electron lenses in synchrotron colliders, outstanding contribution to the construction and operation of high-energy, high-luminosity hadron colliders and for tireless leadership in the accelerator community."

TRIBUTE TO PROF. NISHIKAWA

It is a great honour for me to receive the 2019 ACFA/IPAC Nishikawa Tetsuji Prize. Prof. Nihsikawa – see Fig.1 - was among the pioneers of particle accelerators who shaped our field at its early stage. After making a significant contribution to the BNL linac in 1964-1966, he moved to Japan and established Japan National Lab for High Energy Physics in 1969 (now KEK) and later was instrumental in inception, design, construction, commissioning and operation of such remarkable facilities as the 12 GeV proton synchrotron [1], neutron facility J-PARC, the 500 MeV cancer treatment synchrotron, the KEK Photon Factory, and TRISTAN electron-positron collider. Prof. Nishikawa was also a man of great integrity and an active supporter of the international cooperation, in particular, between Japan and the US [2].

Figure 1: Tetsuji Nishikawa (1926-2010).

Below I will briefly outline the activities of myself and my teams noted in the prize citation and discuss the progress of my current research topics.

ELECTRON LENSES

I got PhD in accelerator and beam physics from BINP (Novosibirsk, Russia) in 1994, and worked in leading accelerator laboratories in Protvino (Russia), the SSCL (USA) and DESY (Germany) before joining Fermilab in 1996 where I shortly thereafter initiated the project of beam-beam compensation with *Tevatron Electron Lenses* [3,4,5]. Since then the electron lenses - a novel instrument for high-energy particle accelerators – have been added to the toolbox of modern beam facilities, being particularly useful for the energy frontier superconducting hadron colliders ("supercolliders") [6]. The physics mechanism of the electron lens is the space-force of liny beam of low energy electrons, immersed in strong longitudinal magnetic field. The space-charge force effectively acts on accelerator's high energy beam moving along (or colliding) with the electron beam while the effect of longitudinal magnetic field is usually a minor, correctable imperfection. Transverse motion of electrons is essentially frozen along the magnetic field lines which therefore assures outstanding stability of the electron beam.

Given that the electron beam transverse shapes and longitudinal current modulation patterns can be broadly varied (usually, created at an electron gun) [7] the electron lenses have become a uniquely flexible instrument. In the Fermilab Tevatron 2 TeV proton-antiproton collider two TELs were built and installed in 2001 and 2004 (see Fig. 2), operated till the end of the Run II in 2001 and used for :a)

compensation of long-range beam-beam effects (the TELs varied tune shift of individual 1 TeV bunches by 0.003-0.01) [8]; longitudinal collimation – removal the DC beam particles from the abort gaps - for 10 years in regular operation [9]; studies of head-on beam-beam compensation [10,11]; demonstration of halo scraping with hollow electron beams [12, 13]. Since 2015 two electron lenses are installed in RHIC at BNL and very successfully used for head-on beam-beam compensation leading to doubling the luminosity in proton-proton collisions [14]

World-wide efforts on the electron lenses currently cover several areas of research: a) hollow electron beam collimation of protons in the HL-LHC [15, 16]; b) long-range beam-beam compensation with electron lenses as current-bearing "wires" in the HL-LHC [17, 18, 19]; c) generation of nonlinear integrable lattices with special transverse current distribution $1/(1+r^2)^2$ – first proposed in [20, 5] - eg in the IOTA ring [21, 22]; d) to generate tune spread for Landau damping of broad spectrum of coherent instabilities [12,23] in, e.g., the LHC, FCC-hh (where electron lens can outperform some 10,000 octupoles), or FNAL Recycler; e) to compensate space-charge effects in modern high-intensity RCSs [24, 25].

The electron lenses usually employ low energy (~10kV), high current (1-10 A) sub-mm size magnetized electron

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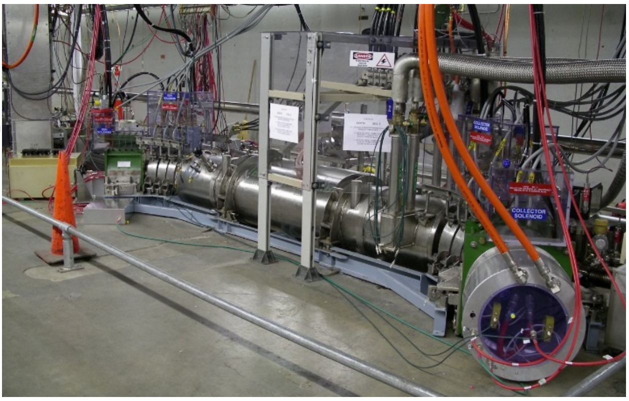

Figure 2: Tevatron electron lens in the colliders' tunnel.

beam to affect beneficially high energy beam of hadrons (protons, antiprotons). The design of the lenses required advancing several technologies: high field quality solenoids and correctors (sometimes SC up to 4-6 T), high brightness electron beam generation and low loss transport (gun, collector, etc), fast HV gun anode modulator (10kV, 100 us and multiples of the machine revolution frequency, e.g. 50 kHz in the Tevatron), sophisticated power recirculation electrical scheme, ultra-high vacuum and beam diagnostics system.

Together with other R&D needs, further research on the electron lenses motivated construction of a dedicated accelerator test facility – IOTA (Integrable Optics Beam Accelerator) ring at Fermilab [26]. The ring – see Fig.3 - has been commissioned in 2018 and the first experimental run with electrons has taken place in Oct. 2018 – Mar. 2019, providing many excellent results in key experiments on the nonlinear integrable optics, single-electron tomography and many others – see, e.g., related reports at this Conference [27-44]. The experiment on space-charge compensation with electron lens is being prepared with goal to be ready for the IOTA operation with protons in 2020-2021.

COLLIDING BEAMS AND METHODS

Over more than three decades in accelerators, I have been involved in, contributed to or led design, construction or operation of a number of forefront accelerators and colliders, such as Tevatron, VLEPP, TESLA, UNK, HERA, PIP-II, LHC, Muon Collider, ILC, etc. The most extensive work was done for the Tevatron collider which took over a decade [45-48]. Through computer modeling and series of dedicated beam studies we had greatly advanced the understanding of a number of critical beam physics phenomena creating impediments on the collider's luminosity, such as long-range and head-on beam-beam effects [49], beam injection optics matching, control of coherent beam instabilities, two-stage halo collimation, novel collimation methods by hollow electron beams collimation method [11] and bent crystals [50]. First ever two-stage beam halo collimation system using bent Si crystals had been installed, tested, demonstrated predicted excellent performance and introduced into operation of the Tevatron collider [51]. Since then, the bent crystal systems were developed and installed in the LHC where they demonstrated excellent performance as well. Beam diagnostics was greatly improved over the collider Run II years of 2001-2011 (Schottky detectors, ionization profile monitors, new BPMs, etc) [52] and the orbit stability issues due to the ATL-type of the ground diffusion [53] were addressed and resolved. More than two decades of vibrations and ground motion studies [54] for accelerator tunnels, development of advanced instruments [55] resulted in solid experimental confirmation of "the ATL law" of the ground diffusion and comprehensive understanding of its practical implications for operation of all large accelerators. Luminosity upgrade of the Tevatron proton-antiproton collider and corresponding beam physics tests and studies resulted in ~40 fold improvement of then world's most powerful accelerator [56]. Accelerator physic and technology advances implemented in the course of the Tevatron operation have been comprehensively summarized in our book [57] and were of big help during beam commissioning of the LHC at CERN.

Figure 3: IOTA (Integrable Optics Test Accelerator) is in operation at Fermilab since 2018.

Already during the Tevatron years I got involved in the design studies, experimental tests and leadership of the Fermilab Muon Collider Task Force and later, in the US Muon Accelerator Program. These studies were focused on the muon ionization cooling, NC RF in strong magnetic fields and overall machine design and established the accelerator physics feasibility of the muon collider – an alternative cost- and power-efficient energy frontier machine for the future particle physics research [58, 59]. Now the muon colliders are under active consideration for the European particle physics strategy, with especially attractive concept of a 14 TeV c.m.e. μ+μ- collider in the LHC tunnel 60]. Related activity was the development of the HTS based fast cycling magnets which could offer economical way to build rapid cycling synchrotrons for particle physics (e.g., proton sources and muon accelerators), neutron spallation sources and other applications [61, 62]. In 2018 we have achieved ramping rate of 12 T/s in a dual bore HTS magnet prototype, exceeding the previous world record rate for SC magnets by a factor of 3 [63].

As part of the FNAL Accelerator Physics Center (APC) mission (see below), since 2009 we constructed FAST facility which besides the IOTA ring had a 300 MeV 1.3GHz SC RF electron linac [26]. In Fall 2017, we achieved the world record-high superconducting RF beam accelerating gradient of 31.5 MeV/m [63] - that was the first ever demonstration of average beam accelerating gradient matching the International Linear Collider specifications. That accomplishment greatly boosted the confidence in the technical feasibility of the ILC – the supercollider project to push elementary particle physics beyond LHC and which is now in the final stage of the approval by the Japanese government. The FAST linac was also commissioned as an electron injector to IOTA ring and already supports users research [64]. Of note here is that my involvement in the linear colliders' R&D began in 1990's back in Russia and in DESY and, e.g. I was part of the group which for the first time demonstrated ns-scale HV pulse (~5kV, high rep rate) travelling wave injection/extraction kickers for multi-bunch storage rings and other accelerator applications [65], thus, paving the way to many modern pulsed ns HV systems based on MOSFETs, FIDs and other fast switches and allowing to shorten the circumference of the damping rings of the future *e+e-* linear colliders from 10-20 km to about 3 km. Also at DESY I came out with the idea of even faster beam-beam kicker [66] and co-authored seminal paper on the theory of coherent synchrotron radiation [67].

In 2005-2007 I led the Accelerator Systems section of the US LARP (LHC Accelerator Research Program) and either supervised and participated or led the beam physics analysis, technical design, construction or operation of such systems as high frequency Schottky detectors, rotatable collimators, simulations of the beam-beam effects and their compensation by electron lenses, etc. All these studies helped the LHC and its upgrades as well as future proton supercolliders [68].

ACCELERATOR PHYSICS CENTER

Accelerator construction, operation and research by necessity involves large teams of physicists, engineers and technicians. Over more than 20 years at Fermilab I led the beam-beam compensation project group (1997-2001), was the Head of the Tevatron Department (2001-2006) and was appointed the inaugural Director of the Fermilab Accelerator Physics Center (2007-2018) [69]. APC was a unique organization created in June 2007 with mission to carry out R&D to keep the US leading high-energy physics laboratory at the forefront of accelerator science, technology and facility operation. In support of the FNAL high-energy physics research mission, APC scientists and engineers conducted accelerator R&D aimed at next-generation and beyond accelerator facilities; provided accelerator physics support for existing operational programs and the evolution thereof; trained accelerator scientists and engineer and established experimental programs for a broad range of accelerator R&D that can be accessed by both Fermilab staff and the US and world HEP community. APC was a centerplace for in-depth design, research and development efforts which allowed the Laboratory to make intelligent decisions on the ILC in the US, on the Muon Collider, as well as originate projects such as PIP-II (through the Proton Driver/Project-X work), LHC-AUP (via LARP) and the IOTA/FAST R&D facility. The results were published in 215 peer-review articles and were used as an input for the discussions of the Fermilab Steering Group, of the P5 (Particle Physics Project Prioritization Panel) in 2008, during the 2014 HEPAP P5 process and the 2015 HEPAP Accelerator R&D Subpanel meetings. Important contributions were made to the ILC CRD and TDR, to the Muon Collider design studies [see the JINST collection of reports and papers on muon accelerators], as well as in the Project-X CDR and the PIP-II CDR, the High-Luminosity LHC Upgrade project and the IOTA/FAST R&D facility CDR.

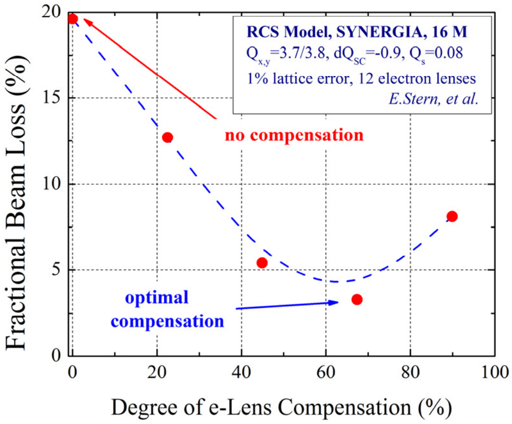

Figure 4: Fractional loss of proton beam with $dQ_{SC} \sim -1.0$ after 1000 in a model RCS with 12 electron lenses vs the degree of SC compensation (PIC simulations data courtesy E.Stern).

Experimental beam physics R&D was carried out at the operational accelerators at Fermilab and CERN as well as at a number of dedicated beam test facilities developed, constructed or supported by APC for the purpose of accelerator R&D: the Fermilab NICADD Photoinjector Laboratory with an 18 MeV electron linac; the MuCool Test Area with a 201-MHz test cavity installed next to 5 T solenoid, also used for testing the smaller 805-MHz cavities under impact of 400 MeV proton beam; the Muon Ionization Cooling Experiment (MICE) at RAL (UK) which operated with 200 MeV muons; 325 MHz HINS RFQ that accelerated protons and H- particles to 2.5 MeV; 1.3 GHz SRF 300 MeV electron injector at FAST and IOTA ring operating with up to 150 MeV/c electrons and 70 MeV/c protons.

. APC was also the birthplace and host of many national and international collaborations and several educational and training programs in beam physics resulted in 27 PhD theses. Besides the Office of US PAS, APC hosted several programs in Accelerator and Beam Physics education and training such as: Lee Teng Internship – jointly with ANL; International Summer Internship/PARTI, later - Helen Edwards Internship; and Joint Fermilab-University PhD Program in Accelerator Physics. APC hosted 5 Joint Appointments with NIU and IIT, as well 11 Peoples Fellows, 3 US LARP Toohig Fellows and 2 ICL Fellows, two out of 27 students in the PhD program won the APS DPB Outstanding Doctoral Thesis Research in Beam Physics Award. In 2007-2018, APC hosted more than 100 visitors and PhD or

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MSc students, over 100 summer students in the Lee Teng and Helen Edwards programs, about 3000 people attended semi-annual US PAS sessions.

NEXT STEPS

At present, I carry out two research projects: the first is modelling of the space-charge compensation with electron lenses [24] in ultimate-intensity synchrotrons with $dQ_{SC} \sim -1.0$ (jointly with E.Stern, A.Burov and Yu.Alexahin). The simulation results show great promise of about order of magnitude reduction in the beam losses with electron lenses – see Fig.4 [70]. The other project is an initial exploration of the ultimate high gradient acceleration of muons in crystals and nanostructures – the idea that may potentially open the path to PeV class colliders [71]. In collaboration with the pioneer of the method, Prof. T.Tajima, we organize "Workshop on Beam Acceleration in Crystals and Nanostructures" this year at Fermilab [72].

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I would like wholeheartedly thank those who nominated me and many colleagues I had fortune to work with over many years on the electron lenses, the Tevatron collider and many interesting and important topics from beam-beam effects to bent crystal collimation, ground motion and orbit stabilization, head-tail instability and super-fast HV pulsers, future collider designs and construction of IOTA ring, beam commissioning of the worlds' best ILC cryo-module and very fast cycling HTS magnet. I'd like to pay special tribute to my late collaborators D.Wildman (FNAL), G.F.Kuznetsov (BINP/FNAL), M.Tiunov (BINP) and V.Danilov (ORNL).

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