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STORAGE RINGS FOR SCIENCE WITH: ELECTRON-POSITRON COLLISIONS, HADRON COLLISIONS AND SYNCHROTRON LIGHT

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Abstract

On the occasion of receiving the Robert Wilson Prize, recollections by the recipient on his achievements in Japan and the US will be presented.

INTRODUCTION

The author is honored to receive the 2009 Robert Wilson Prize and the recognition that comes with it. The citation for the prize reads, "For his outstanding contribution to the design and construction of accelerators that has led to the realization of major machines for fundamental science on two continents, and his promotion of international collaboration." In this article, he will discuss the two construction projects, which he led, one (TRISTAN e^+e^- Collider at KEK) in Japan and the other (RHIC at BNL) in the USA, covering project issues and lessons learned from these projects. Although both of them were built on separate continents, it is interesting to note that they are both built on long off-shore islands. He will also add comments on his recent engagement in the development of the Conceptual Design for the National Synchrotron Light Source II (NSLS-II).

TRISTAN e^+e^- Collider

The initiative to building TRISTAN as a world frontier machine in Japan was proposed by our Japanese colleagues in 1974. This led to the construction of its phase-I accelerator complex, an e^+e^- Collider in the collision energy of 60 GeV, at KEK in 1981–1987. The TRISTAN Accelerator complex [1] consists of four connected accelerator systems. A 400 m long S-Band linac (2.5 GeV) that has been in operation since 1982 as an injector for KEK "Photon Factory", a new high current (~10A) 200 MeV electron linac located near the upstream end of the 400 m linac for positron production, an 8 GeV synchrotron (377 m in circumference) to accumulate and accelerate positrons and electrons from the linac to 8 GeV, and the main ring that accelerates and stores counter rotating electron and positron beams at top energy and collide. Incidentally, this 8 GeV ring was designed also to serve as a synchrotron light source, and it has been working as such to date.

The main ring was built in a tunnel, 3 km in circumference, which filled the northern part of the KEK site that measures only 1 km wide. The question here was how to build a 30 GeV electron storage ring on such a small site, considering the sizable energy loss by the synchrotron radiation. The answer was to build four linacs that were connected by short arcs. In this case, the storage ring was configured with four 200 m long straight sections connected by four 550 m long arc sections. The aerial photo of the TRISTAN facility shortly after completion is shown in Fig. 1. These long straight sections accommodate an approximately 100 m long linear accelerator, each operating at the RF frequency of 508.6 MHz, generating ~ 380 MV of RF acceleration voltage to replenish 290 MeV of energy loss by the synchrotron radiation per turn at the beam energy of 30 GeV. Two bunches of electrons and positrons are stored in the ring rotating in opposite directions and collide at the middle of four straight sections, where the collision detectors were located.

Fig.1 View of KEK and the TRISTAN complex from the north

Technologies used for the design and construction of TRISTAN are more or less conventional and well established at that time, except for the use of superconducting RF and magnet technology as add-on components. Of 413 m of the RF system, 360 m was outfitted with room temperature cavities with the Alternating Periodic Structure, relatively conventional technology. This system, driven by 26 1 MW CW klystrons, was installed during the construction period and used for the commissioning of the ring at 28 GeV beam energy.

In parallel, vigorous R&D was carried out to develop superconducting RF systems operating at the same frequency to supplement additional RF power needed to reach 30 GeV. This notion was partly driven to save the enormous wall plug power the additional room

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temperature system would demand, but also driven by the novelty of the technology. Shortly after the initial commissioning of the ring,, ~97m of the superconducting RF acceleration system was installed to reach 30 GeV. It should be noted that this was the first deployment of a large scale superconducting RF system in an actual accelerator in the world. The room temperature and superconducting RF systems installed in the TRISTAN main ring are shown in Fig. 2 and Fig. 3.

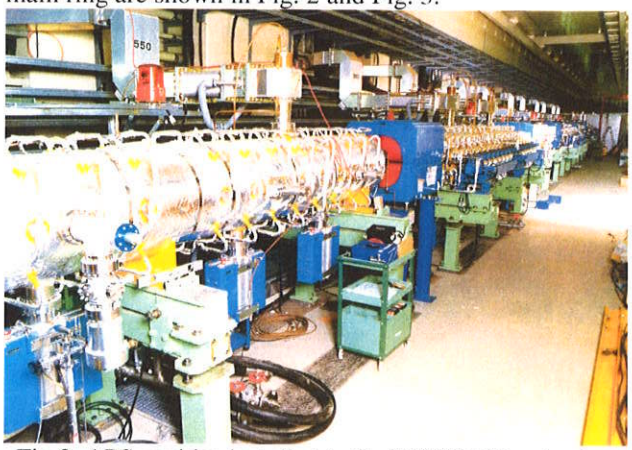

Fig.2 APS cavities installed in the TRISTAN main ring

Fig.3 Superconducting RF system installed in the TRISTAN main ring

Notes on the TRISTAN Project

- TRISTAN, then the highest energy e^+e^- collider, was built using accelerator science and technology capability, both at laboratories and industry in Japan, nurtured through construction of small scale accelerators over years, starting with Dr. Nishina's cyclotron at RIKEN in 1937 and including KEK 12 GeV PS in 1976.
- Detector design and construction was supported by many physicists who were trained in overseas labs, such as under the US-Japan Collaboration in High Energy Physics.
- The AMY experiment that was led by a US team was the forerunner of large scale international collaborations and helped open the door for Japan to foreign researchers.
- The most important accomplishment of this Project was establishing the foundation of modern accelerator physics and technology that opened the way for Japan to compete and collaborate in the international arena.

Lessons Learned from TRISTAN

- The Japanese Industry was very eager to engage in the technological development for the Project, but their success rate was much better where the Laboratory had technical and engineering capability.
- We made a lot of mileage by treating the industry as a partner in the Project and not as a vendor with adverse relationships.
- The overall design of the accelerator system was conservative relying on the proven technology, but introducing a small number of new ideas through the R&D process before it became a critical component of the system.
- Maintaining the schedule is the way to control the project cost and people's moral.

Relativistic Heavy Ion Collider (RHIC)

RHIC is the flagship of the US DOE Nuclear Physics Research Facility which was conceived as part of the U.S. Nuclear Science Advisory Committee's Long Range Plan in 1983. In 1989 the Conceptual Design Report was updated and in 1991 the actual conception began. Construction began using the partially completed ISABELLE tunnel and its infrastructure. The construction was completed and its functionalities verified in 1999, and the relativistic heavy ion collision experiments began in the year 2000.

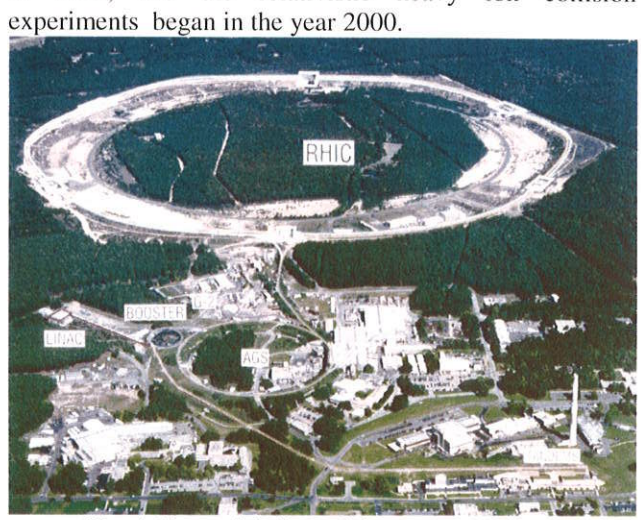

Fig. 4 The aerial view of the RHIC complex

RHIC [2] is a two-ring high energy hadron collider, initially for heavy ion collisions. Later with the support of the RIKEN Laboratory in Japan, the ability to accelerate and to collide polarized protons was added for the Spin Physics program. In both cases the AGS complex, which already existed, serves as the injector. The aerial view of the RHIC complex is shown in Fig. 4. Unlike an e^+e^- or anti-proton proton collider like TRISTAN and the Tevatron, the RHIC collider consists of

two magnet rings because heavy ions can be available only in positive charge. Superconducting magnets were used because the magnetic field required for dipoles is 3.5 TESLA that is beyond the saturation point of the iron.

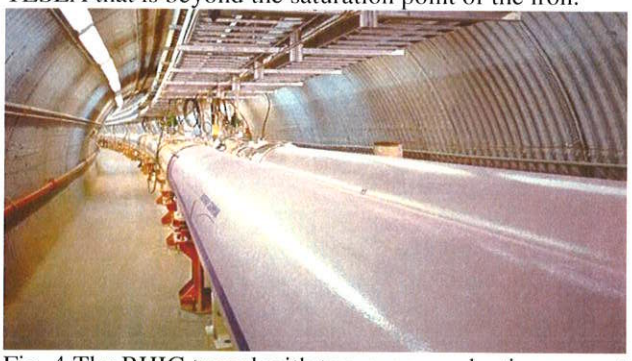

Fig. 4 The RHIC tunnel with two superconducting magnet rings for counter rotating hadron beams

The RHIC acceleration scenario for Au ion beams is shown in Fig. 6 and that for polarized proton beams is shown in Fig. 7. Unlike the case with proton beams, a generation of heavy ion beams requires a cascade of accelerators that increase the energy of ions in steps, and successive stripping of electrons to reach the fully stripped ions for storage and collisions. This process for Au ion beams is depicted in Fig. 6.

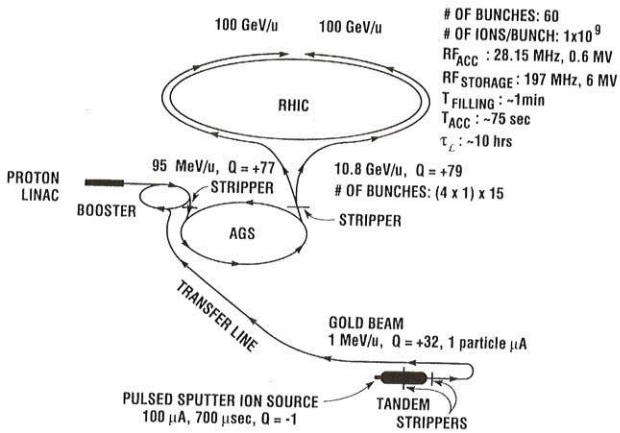

Fig. 6 The RHIC acceleration scenario for Au ion beams:

Negatively charged gold ions from the pulsed sputter ion source at the Tandem Van De Graaff are partially stripped of their electrons with a foil at the Tandem's high voltage terminal, accelerated to the energy of 1 MeV/u by the second stage of the Tandem. The gold ions, charge selected by bending magnets, are delivered to the Booster Synchrotron, accelerated to 95 MeV/u, and are stripped again at the exit from the Booster to reach the charge state of + 77, a helium-like ion, for injection into the AGS and acceleration to the RHIC injection energy of 10.8 GeV/u. Gold ions are re-bunched to increase the bunch intensity in the AGS and transferred to RHIC one bunch at a time after having been fully stripped to the charge state of +79 at the exit from the AGS.

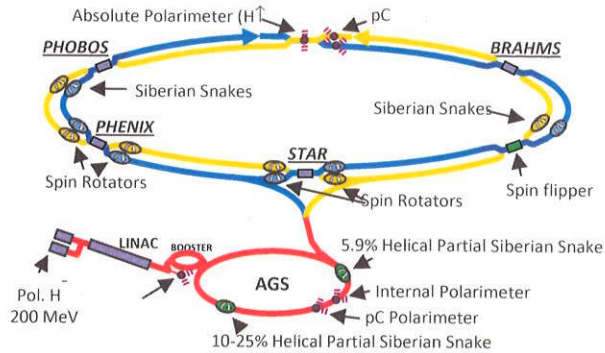

Fig. 7 RHIC Configuration of Polarized Proton operation: Siberian Snakes are sets of helical dipoles and manipulate the spin of protons and either maintain the-polarization through the de-polarizing resonances or change the orientation of proton spin at the collision points.

Notes on the RHIC Project

- It was thought that collisions of very high energy heavy ion beams might create a microcosm of hot and dense matter that might have existed shortly after the Big Bang. RHIC experiments indeed found that Au-Au collisions at top energy can create a hot and dense state of matter that behaves like perfect fluid, not a plasma like substance.(SQGP).
- There has been a puzzle as to where the nucleon spin comes from. Since the earlier observations indicated that the contribution from quark is very small, the hope was to find the gluon to the contributor. The preliminary observations with 200 GeV polarized proton collisions at RHIC now indicate that the gluon contribution is also negligible.
- The accelerator physics challenge was to cross the synchrotron phase transition with a slow acceleration of a superconducting ring, and to make short bunches from the long bunches in the AGS and maintain them short (~25 cm) to fit the detector's acceptance zone.

Lessons Learned from RHIC

- As in the case of TRISTAN, I found that a strong in-house technical knowledge and capability and the idea of partnership with industry helped smooth out accelerator component procurement.
- Expertise on superconducting magnets that had been built up at BNL since the early 1980's was indispensable for the success of the RHIC Project.
- A change in the funding profile, even though relatively small, after the major contract was signed made the management of the project very difficult, resulting in the stretch-out of baseline schedule and cost.

The NSLS-II Project

NSLS-II is a new medium energy third generation storage ring light source that is under construction at BNL as the light source that will replace the existing 25 years old NSLS. The basic mission of this Project is to build a synchrotron light source for x-rays that will allow studies

with ~1 nm spatial resolution and 0.1 meV energy resolution with the single atom sensitivity. These mission statements translated into the requirement that the NSLS-II must be a high performance storage ring light source with ultra-high brightness and stability. The energy of the storage ring is 3 GeV with a target value for the stored current of > 500 mA ±1% with Top-off injection. The design calls for an Ultra-small emittance such as <1.0nm (achromatic) for horizontal and diffraction limited emittance @12 keV for vertical. The target stability is ≤10% of beam size, and since expected vertical beam size is ~300 nm, this led to the vertical beam stability of ~30nm.

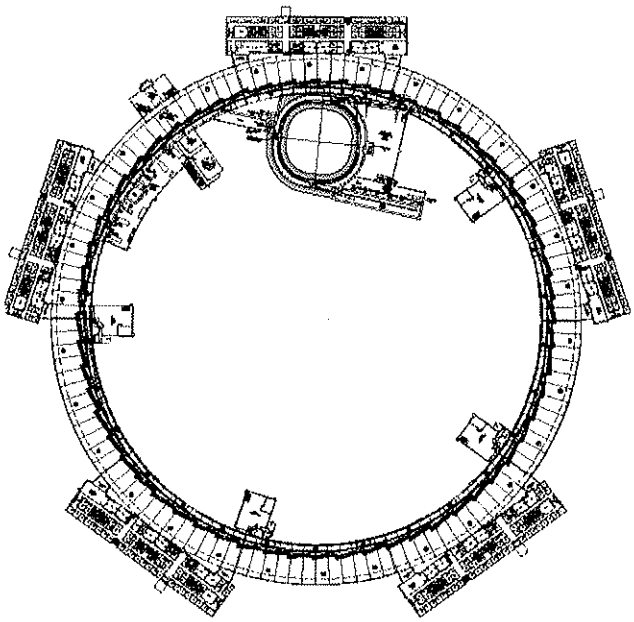

Fig. 8 Accelerator layout of NSLS-II with 200 MeV injector linac, 3 GeV booster for top-off injection and 791.5 m main storage ring.

A new 3 GeV electron storage ring has 30 Double Bend Achromatic cells with a corresponding number of straight sections for insertion devices and accelerator service elements. In fact, there are 15 long straights with high beta function and 15 short straights with low beta function, particularly suitable for narrow gap insertion devices for ultra high brightness photon beams. A decision was made in the Conceptual Design stage that damping wigglers which are often used in high energy physics machines, will be used to control the emittance. This idea was further coupled with the use of a large bending radius, as large as 25 m, for dipole magnetic fields to make emittance control by damping wigglers more effective [3]. Consequently, the circumference of the ring became as large as 791.5 m, quite large for a 3 GeV storage ring. An additional feature of the lattice is that three of 30 cells will have a pair of dipole magnets with a large aperture in order to enable a large solid angle extraction of infer-red beams. The details of the NSLS-II storage ring lattice will be discussed by S. Krinsky at this conference [4]. An accelerator layout of the NSLS-II facility is shown in Fig. 8. Following the Conceptual Design Review and Preliminary Design Review [5], the NSLS-II Project received approval to begin construction in January 2009. Formal completion and start of operation is planned for June 2015, but with the possibility of starting operations about one year earlier.

Technical Challenges

One of the lessons I have learned in working on the NSLS-II is that the technical requirements for the electron storage ring for a synchrotron light source are much more demanding that those for a collider. For instance, for a collider, the stability requirement of the beam orbit is only relative to the other beam and localized in the vicinity of the collision point, whereas for the light source the requirement is absolute relative to the ground and all around the ring. Other challenges are:

- How to deal with insertion devices such as in-vacuum undulators, elliptical undulators, superconducting undulators and damping wigglers, which impact on dynamics of beam.
- Impact of large gap IR vacuum chambers and small gap (5 mm) ID tapers, etc on the impedance budget of the ring, and
- Lattice design that ensures a healthy dynamic aperture and energy acceptance in spite of impacts mentioned above.

ACKNOWLEDGEMENT

The author sincerely thanks the APS and its Division of Particle Beams for their recognition of his work and awarding him this prestigious Robert Wilson Prize. He also appreciates having been given this opportunity to speak on the history of these projects he was involved in on two continents. Thanks are due to the Directors of KEK and BNL, and their funding agencies, for their trust in him and giving him the opportunity to work on the construction of their major and critical research facilities. Of course, what he accomplished is the results of team work, and thanks are also due to his colleagues at respective Laboratories and the user communities whose hard work brought these projects to their success. In closing, he wished to thank his wife, Yoko, for her steady support throughout these trying periods.

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