THE JOY OF ACCELERATOR PHYSICS*

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Abstract

Since being introduced to accelerator physics, I have had the privilege to study and work with some of the best physicists on some of the most exciting projects. My first assignment was to simulate transition-crossing in RHIC in which a shocking 86% beam loss led to a redesign of its RF system which later earned me a Ph.D. To participate in the design, R&D, construction, and the commissioning of RHIC not only introduced me to the fascinating world of accelerator physics but also gave me the opportunity to be trained as a physicist for accelerator projects. Since then, I have had the chance to work and lead teams of physicists and engineers on accelerator projects: US-LHC/AP, SNS/AP, SNS ring, CSNS, and now CPHS. The field of accelerator physics is uniquely rewarding in that ideas and dreams can be turned into reality through engineering projects, through which one experiences endless learning in physics, technology, teamwork and fostering friendships. Based on this experience the work on crystalline beams has developed as a hobby of mine for the past 18 years.

INTRODUCTION

In 1984 I left China with a borrowed $100 bill for Stony Brook, USA to pursue a Ph. D. degree in physics. Prof. C.N. Yang, believing that the future of high-energy physics relies on accelerator physics (AP), recommended that I study with Dr. E.D. Courant - thus beginning one of the most rewarding experiences of my life.

During the past 24 years, I have had the opportunity to work on several accelerator projects including the Relativistic Heavy Ion Collider (RHIC) and the US part of Large Hadron Collider (US-LHC) at BNL, the Spallation Neutron Source (SNS) at BNL and ORNL, the China Spallation Neutron Source (CSNS) at IHEP, and the Compact Pulsed Hadron Source (CPHS) at Tsinghua, and to study several exciting hadron AP topics. I consider myself one of the most fortunate persons alive to be working and getting paid to do a job that brings me such a great deal of satisfaction.

RELATIVISTIC HEAVY ION COLLIDER

A big project is a huge training ground. After fourteen years on a single project, RHIC has transformed me from an ignorant graduate student to an accelerator physicist.

Ph. D. Thesis on Transition Crossing

Transition crossing is an old subject dating back to 1950's [1]. No one expected that there was going to be sufficient new work warranting a fresh Ph. D. thesis. Yet, RHIC is the first synchrotron with superconducting magnets of a slow ramping rate that is designed to cross transition. Contrary to common speculations, a higher accelerating voltage, though providing stronger focusing, increases the energy spread and enhances the chromatic effects. Analytical methods together with and TIBETAN [2] codes confirmed that with chromatic nonlinearity, bunch self-field mismatch, and collective instabilities greatly enhanced by the slow crossing, up to 86% of the gold beam would be lost (Fig. 1). Thus, the designed RF voltage was reduced from 1.2 MV to 0.3 MV, and a first-order transition jump was implemented by pulsing trim quads [3]. Theoretical predictions that led to the design changes were later confirmed by beam studies and by operational observations [4].

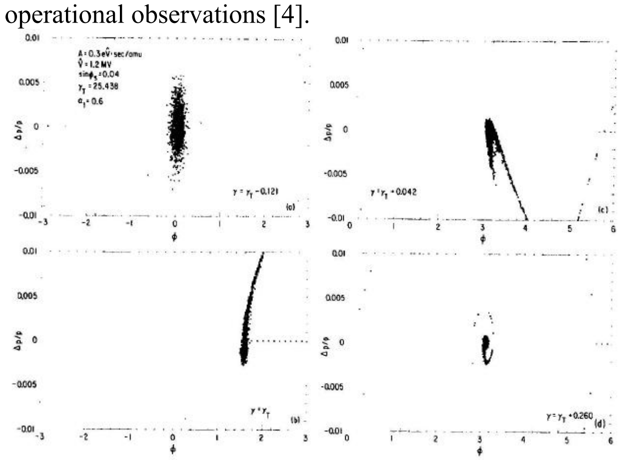

Figure 1: Longitudinal phase-space plots showing large beam loss upon transition with the original RHIC design.

Intra-beam Scattering (IBS)

While transition is the bottleneck with RHIC acceleration, IBS is the performance limiting effect at storage. Due to the fact that RHIC by design is a high-loss machine – about 40% beam loss is expected during the normal 10-hour storage cycle, the usual theory describing the change of moments [5] is not sufficient. A self-consistent Fokker-Planck (F-K) approach was developed for the density function evolution and beam loss due to IBS (Fig. 2). The theory was later confirmed experimentally at RHIC [6].

There exists four levels of sophistication of IBS theory: (1) scaling laws of the beam heating rates [7]; (2) heating rates calculated taking into account detailed machine lattice assuming Gaussian beam distributions [5]; (3) density evolution, heating rates, and beam loss calculation by iterating the IBS F-P equations [6]; (4) particle-by-particle simulation using the molecular dynamics (MD) methods. Level (1) scaling laws were frequently found to be handy in the design of new storage rings.

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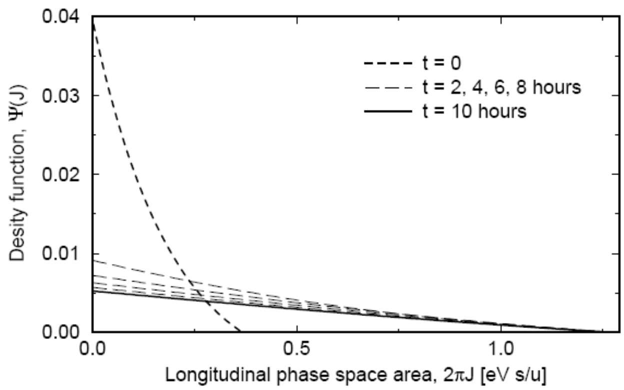


Figure 2: Evolution of the longitudinal density function during the 10-hour nominal store of the RHIC gold beam.

Stochastic Cooling

In early 1990's, stochastic cooling was identified as the most promising countermeasure to IBS (Fig. 3) [6, 8]. In 2000's it is implemented in RHIC and now proven to be the most important method to raise the collider luminosity [9].

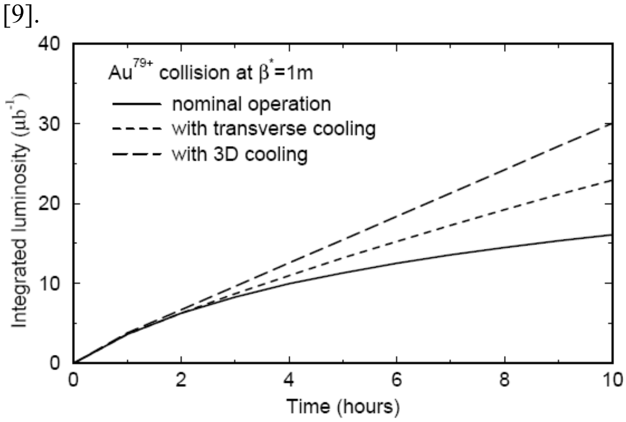


Figure 3: Luminosity improvement with stochastic cooling countering IBS predicted with the F-P approach.

Fringe Field and Interaction-region Corrections

More than 1700 superconducting magnets constitute the most part of RHIC storage rings. While at injection the machine performance is largely determined by the field quality of the arc dipoles and quads, at storage it is determined by the quality of the interaction-region (IR) quads. Due to the large variation of the beam amplitude across the magnet, magnet body and end fields, in particular systematic multipoles allowed by symmetry (dodecapole for quad), must be treated separately [10].

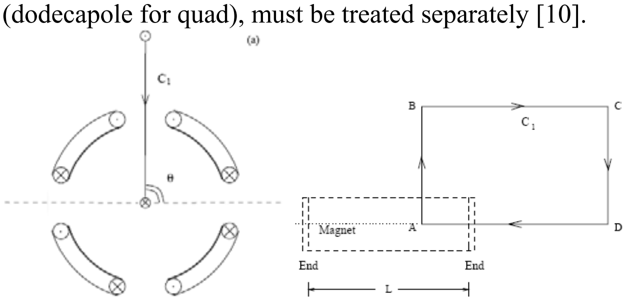
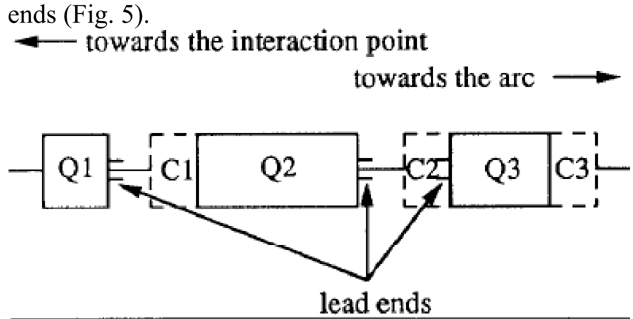


Figure 4: Loop of integration used to prove the fringe-field theorem in a non-solenoidal magnet [11].

Analysis of the magnet fringe field in RHIC is simplified by a theorem [11] stating that the relative impact of the longitudinal magnetic component is about the ratio between the beam emittance and the magnet length (Fig. 4). Thus, study based on multipole expansion of the transverse field components of the body and ends is adequate. Subsequently, a local IR correction scheme was developed based on action-kick minimization using body-end compensation with magnetic shims, and lumped correctors taking into account the orientation of magnet ends (Fig. 5).



ORDER, n	NORMAL, b_n	SKEW, a_n
0	C1 or C3	C3 or C1
1	-	C2
2	S, (C2)	S
3	S, C1, C3	S, (C2)
4	S, C1, C3	S
5	S, C1, C3	S, (C2)
6+	-	-

Figure 5: Implemented correctors in the RHIC IR triplet assembly from dipole (order 0) to dodecapole (order 5).

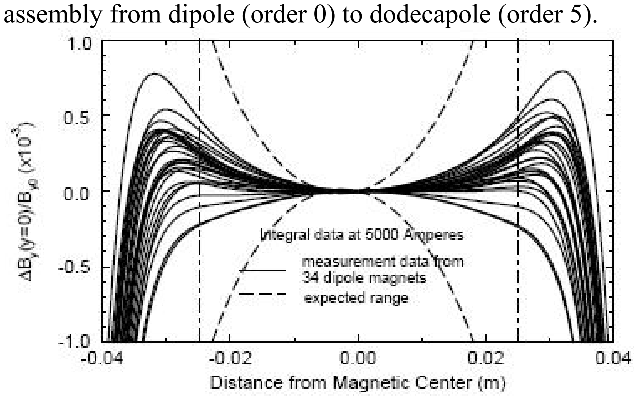


Figure 6: RHIC measured versus expected dipole magnet vertical field profile at horizontal mid-plane.

Magnet Acceptance and Sorting

The principle of magnet acceptance is an intimate collaboration between the accelerator physicists, magnet builders and surveyors to closely monitor the magnet measurement data, understand trends and issues, provide feedback for necessary improvements, evaluate the effects and minimize the negative impacts through sorting and matching. The aim is to assure optimal performance at minimized cost addition based on the expected field errors as opposed to rigidly enforcing specifications.

This work lasted for many years (Fig. 6) [12], and I truly enjoyed the weekly meetings, accepting the magnets, the bike rides around the RHIC tunnel ensuring proper placement, and orientation following the sorting decisions, as well as the sense of ownership of the machine.

Electron Cloud

The impact of e-cloud was not fully appreciated until RHIC operations as the nominal 216 ns bunch spacing was considered sufficiently long. Vacuum pressure rises, tune shifts, and e-flux were observed at injection, transition, and top energy. Emittance growth, fast instabilities, and beam loss at transition (Figs. 8 and 9) indicated e-cloud as the possible leading mechanism limiting RHIC intensity upgrades [13].

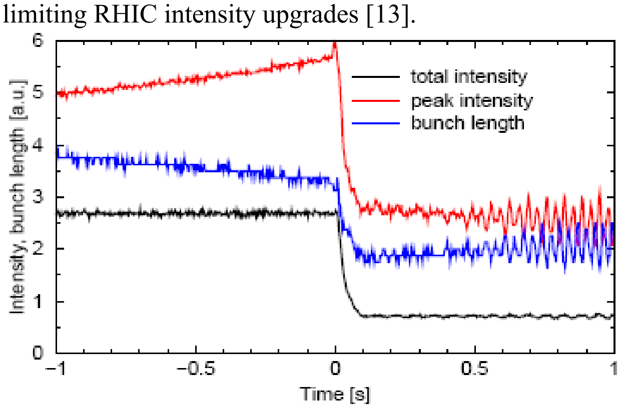


Figure 7: Loss of gold beam measured at RHIC transition due to e-cloud at 108 ns bunch spacing.

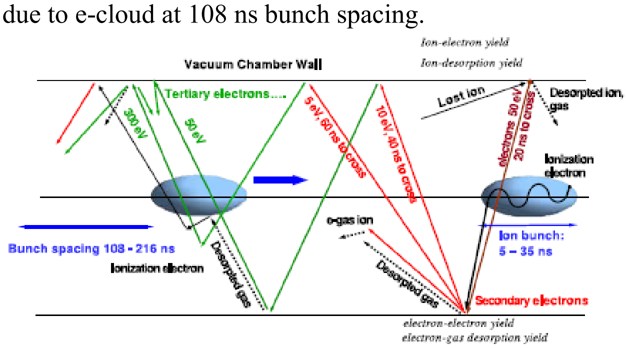


Figure 8: Mechanism of e-cloud interactions in RHIC.

CRYSTALLINE BEAMS

The study of Crystalline Beams began with my meeting Dr. A.M. Sessler and a six-month study on the theory of general relativity with numerical-algebra assisted derivation of the rotating-frame Hamiltonian. The most rewarding experience has been to understand physical mechanisms through principles first: discovering the condition of crystal formation from primitive simulations and back-of-envelope sketching; finding the phonon resonance relation and the maintenance condition; applying MD to a time-dependent system; finding the existence of maximum heating rates and the relation with IBS theory (Figs. 9 and 10) [14], and the pursuit of experimental verifications.

US-LHC ACCELERATOR PHYSICS

With the US-LHC project I experienced the joy of international multi-institutional collaboration. The AP role was to ensure the performance of US deliverables (Fig. 11). The IR correction scheme based on the action-kick minimization proposed for the LHC was a direct extension of the RHIC design [15]. Its effectiveness was later confirmed by CERN experts, even in the presence of beam-beam interactions.

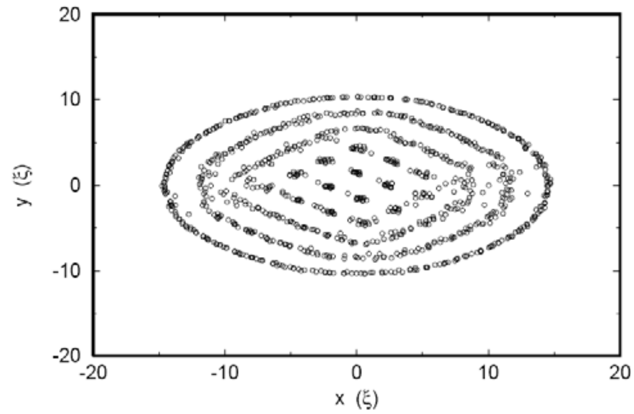


Figure 9: A multi-shell crystalline beam structure with particle positions projected into the transverse plane.

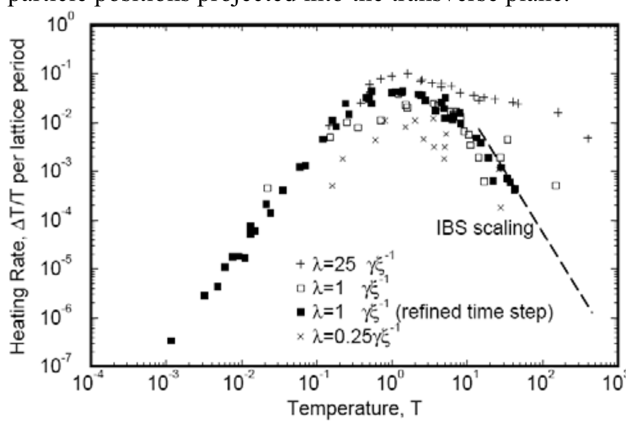


Figure 10: Typical heating rates as functions of temperature obtained by MD simulation.

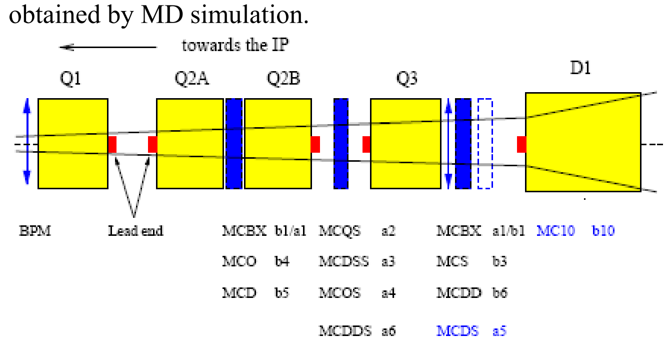


Figure 11: Proposed layout of the LHC inner triplet region including correctors up to the dodecapole order.

SPALLATION NEUTRON SOURCE

Accumulator-ring (AR) Project at Brookhaven

The beauty of the SNS AR, designed and built by BNL and ORNL physicists, was that it performed just as designed. The quick commissioning and the reach to 1 MW performance validated the 9-year effort from the early R&D to the final delivery in 2005.

A series of decisions were essential to this "easy" success: a month-long intensive study selected AR over a rapid-cycling-synchrotron (RCS) design; a 4-fold symmetry (Fig. 12) with dedicated functions; the doublet-straight/FODO-arc hybrid lattice; choice of admittance/emittance ratio to facilitate beam collimation; refined injection and extraction schemes; impedance minimization; instability damping by chromaticity control; preventive e-cloud mitigation including elaborated coating [16].

Even though I was ultimately responsible for the on-time, on-budget, on-performance delivery of the AR system (Fig. 13), the credit goes to the strong engineering team at BNL's Collider-Accelerator Department. I was fortunate to have the opportunity to work with the most intelligent and proficient engineers in the field.

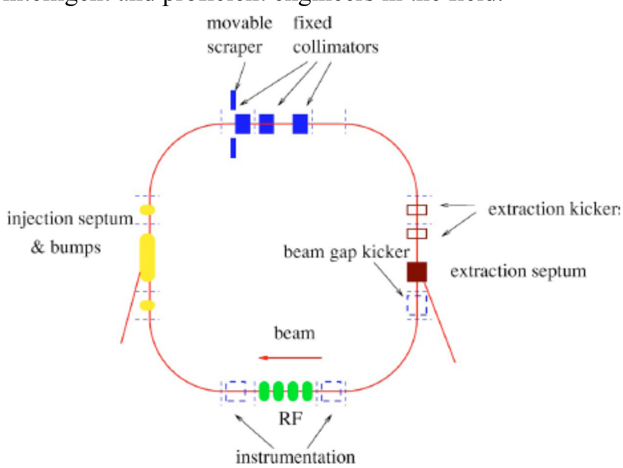


Figure 12: Design layout of the SNS ring with four dedicated straight sections of doublets and FODO arcs.

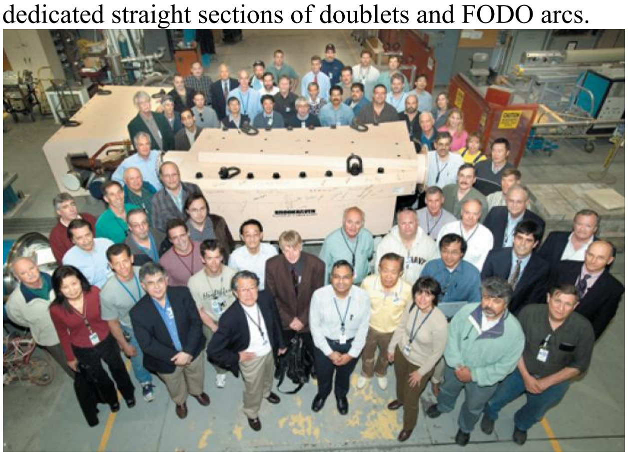


Figure 13: A ring dipole for SNS fabricated at BNL.

Accelerator Physics at Oak Ridge

The SNS project was a challenging collaboration among six US Department of Energy laboratories. The AP group at ORNL, which I helped establish over two years, played a crucial role in interfacing and integrating the physics design of the accelerator complex, leading to the successful commissioning of the machine (Table 1) [17]. It was a fascinating experience dealing with different team cultures at LBNL, LANL, JLAB, BNL, and ORNL, and quite rewarding as it resulted in mutual respect and friendships.

CHINA SPALLATION SOURCE, CSNS

During the three years that I had the honour of leading the project, CSNS received generous support from institutions around the world, e.g. ISIS on the H^- source, J-PARC on the linac and RCS magnets, BNL on the ring RF, vacuum, and magnets, and SNS on AP. The philosophy was to aggressively develop domestic technologies so that the CSNS could be built at minimal cost, to take advantage of China's cheaper labour, and to remain cutting edge through a worldwide collaboration. Among the most advanced designs were the RCS lattice, the rotating target station, and the capability for power upgrades and ADS extensions (Figs. 15 and 16) [18].

Figure 14: CSNS RCS dipole magnet and the stranded aluminium conductor (insert) fabricated in China (photo courtesy of Institute of High Energy Physics, CAS).

Table 1: SNS Design Beam Parameters from The Front End through The Linac and The Ring to The Target Station.

	Front End			Linac					Ring		
	IS/LEBT	RFQ	MEBT	DTL	CCL	SCL (1)	SCL (2)	HEBT	Ring	RTBT	Unit
Output Energy	0.065	2.5	2.5	86.8	185.6	391.4	1000	1000	1000	1000	MeV
Relativistic factor β	0.0118	0.0728	0.0728	0.4026	0.5503	0.7084	0.875	0.875	0.875	0.875	
Relativistic factor γ	1.00007	1.0027	1.0027	1.0924	1.1977	1.4167	2.066	2.066	2.066	2.066	
Peak current	47	38	38	38	38	38	38	38	9×10^4	9×10^4	mA
Minimum horizontal acceptance			250	38	19	57	50	26	480	480	πmm mr
Output H emittance (unnorm., rms)	17	2.9	3.7	0.75	0.59	0.41	0.23	0.26	24	24	πmm mr
Minimum vertical acceptance			51	42	18	55	39	26	480	400	πmm mr
Output V emittance (unnorm., rms)	17	2.9	3.7	0.75	0.59	0.41	0.23	0.26	24	24	πmm mr
Minimum longitudinal acceptance			4.7E-05	2.4E-05	7.4E-05	7.2E-05	1.8E-04		19/π		πeVs
Output longitudinal rms emittance		7.6E-07	1.0E-06	1.2E-06	1.4E-06	1.7E-06	2.3E-06		2/π		πeVs
Controlled beam loss; expected	0.05[a]	N/A	0.2[b]	N/A	N/A	N/A	N/A	5[c]	62[d]	58[e]	kW
uncontrolled beam loss; expected	70	100[f]	2	1	1	0.2	0.2	<1	1	<1	W/m
Output H emittance (norm., rms)	0.2	0.21	0.27	0.33	0.39	0.41	0.41	0.46	44	44	πmm mr
Output V emittance (norm., rms)	0.2	0.21	0.27	0.33	0.39	0.41	0.41	0.46	44	44	πmm mr

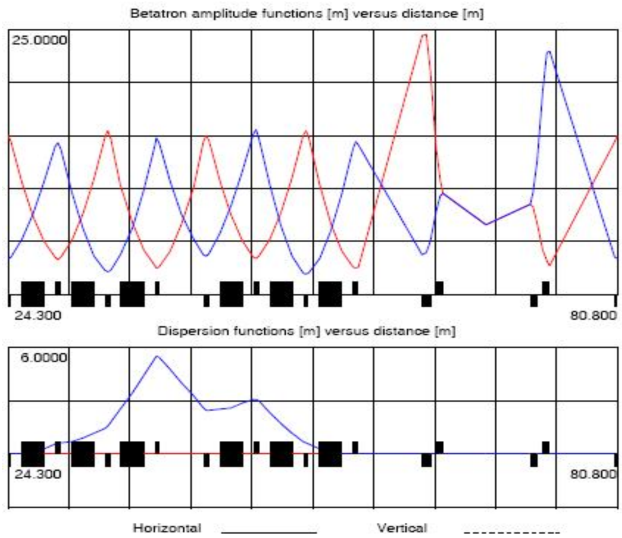


Figure 15: Proposed CSNS ring 4-superperiod lattice of doublet straight and FODO arc with single missing-dipole gap for optimized momentum collimation.

COMPACT PULSED HADRON SOURCE

After 25 years, I had the privilege of returning to Tsinghua to start a new team constructing the CPHS project. This university-based proton-neutron source complements the existing Thompson backscattering electron-laser source (TTX) with focus on education, user training, R&D of X-ray and neutronics instrumentation, and discovery science to a limited extent . It provides application platforms for radiography, scattering, and irradiation. It also serves as a technological link to future projects including ion-beam therapy, isotope production, ADS for nuclear energy and waste transmutation, and rare isotope application [19].

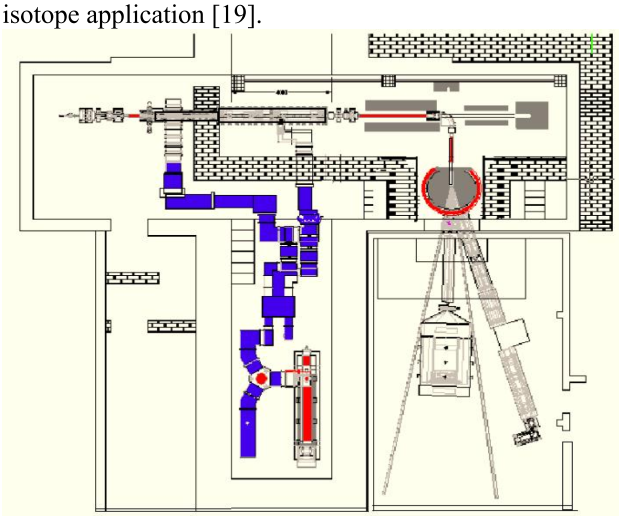


Figure 16: Layout of the CPHS linac, klystron room, target station, and neutron instruments at Tsinghua.

THOUGHTS AND ACKNOWLEDGMENTS

Accelerator physics works. It validates the discipline of accelerator physics and the role of accelerator physicists to design and build machines with well-understood signatures [20].

The accelerator profession is so uniquely rewarding in that a physical idea can be turned into reality through the execution of a construction project. Throughout its completion one experiences endless learning in physics, technology, teamwork, and creating friendships.

I would like to thank Profs. C.N. Yang and E.D. Courant for guiding me into the field, Dr. A.M. Sessler for his career-long mentoring to be a physicist, Prof. A. Chao for his crucial advice upon every career crossroad, Drs. M. Harrison and S. Peggs for teaching me to do projects, Prof. S.Y. Lee for modelling a physicist's dedication, Dr. A.G. Ruggiero for the introduction to several great topics, Drs. S. Ozaki, D. Lowenstein, and T. Roser for their never-ending trust and support, Tsinghua University for the most important part of my education, Stony Brook University for introducing me to the accelerator field, BNL for the opportunities to mature in my career, and to many of my friends and colleagues for their help and support throughout the years. Finally, I am indebted to my wife Ruimei and boys Alan and Benjamin for their sacrifice, understanding, and consistent support.

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