OVERVIEW OF THE ACCELERATOR PROGRAMS AT THE INDIAN LABORATORIES

Vinod C. Sahni#
Bhabha Atomic Research Centre (BARC), Mumbai-400 085 &
Raja Ramanna Centre for Advanced Technology (RRCAT), Indore-452 013, India

Abstract

Particle accelerator programs being pursued by the Indian labs cover a broad range, encompassing accelerators for nuclear physics research (NPR) (in the low and intermediate energy range), construction of synchrotron radiation sources (SRS) as well as participation in international accelerator projects, especially those related to high energy physics. Machines for NPR include 14MV Pelletrons, augmented by home built superconducting linac boosters to enhance the energy & mass range of the ion beams, and a superconducting cyclotron which is currently undergoing commissioning at Kolkata. Two SRS, namely, a 450 MeV ring Indus-1 and 2.5 GeV booster cum light source, Indus-2, have been indigenously constructed and set up at Indore. A program is also on to develop a high current proton accelerator that will eventually be used for R&D linked to ADS. Regarding our international collaborations, Indian labs have contributed to setting up of LHC at CERN, are associated with the CLIC Test Facility 3 & Linac-4 and the FAIR project at Darmstadt besides working with Fermilab on ILC/Project-X R&D. The paper gives an overview of some of the recent developments related to these activities.

INTRODUCTION

Accelerator related activities are being mainly pursued at four major locations in India, namely, Indore, Kolkata, Mumbai and New Delhi. While some small machines are also in use elsewhere, here we cover the work being done in these places. Presently the primary activity at Indore is geared towards providing synchrotron radiation to the condensed matter community, while other three locations mainly meet the requirements of the nuclear physicists. In this paper we will focus our attention mostly on the work going on at the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, (earlier known by the name Centre for Advanced Technology (CAT)), since the author is more closely associated with it as the Director, RRCAT. Some recent developments at the other three places are also briefly discussed.

SYNCHROTRON RADIATION PROGRAM

Branching off from its parent institution, the Bhabha Atomic Research Centre (BARC), Mumbai, CAT was created in the mid 1980s as a separate nodal laboratory of Indian Department of Atomic Energy (DAE) primarily to develop the technology required for accelerators (and lasers) in the country. This was done as a sequel to the decision to build synchrotron radiation sources (SRS) in India. An early survey of the various interested SRS users in the country revealed two types of requirements: one for the VUV/soft x-ray spectroscopic community, for which a low energy ring of about 400 to 500 MeV was appropriate, second type of users (mostly material scientists) needing harder x-rays and a higher energy ring. After the launch of SRS program, work commenced on setting up the infrastructure required for building accelerators and design of the injector accelerators - a 20 MeV microtron and a 400 to 700 MeV energy range booster synchrotron- was taken up.

Initially DAE received funds from the Government (in the late 80s) for the injector accelerator system and a 450 MeV storage ring Indus-1. It was also visualized that after more funds are available, a 2 GeV machine (Indus-2) and a 2.5 GeV machine (Indus-3) would be taken up. The injector accelerator system built completely indigenously was ready in early 1990s, but infrastructural constraints delayed the booster commissioning by about two years. Finally, Indus-1 started operating in 1999. Meanwhile work did start on the originally envisioned 2 GeV SRS Indus-2. But in November 1997, an International Panel advised that it would be better to build one machine operable right up to 2.5 GeV. Design work on the components of the enhanced energy ring was started in 1998 along with civil construction of the building. Development of prototype components and their large scale manufacture, partly in industry and partly in house, was spread over the next five years. The installation of Indus-2 & transport line (TL-3) connecting it to the booster was finished by mid 2005. By the end of 2005 we had started accumulating electrons in Indus-2 (at an injection energy of 450 MeV) and the first signatures of the SR from Indus-2 were recorded.

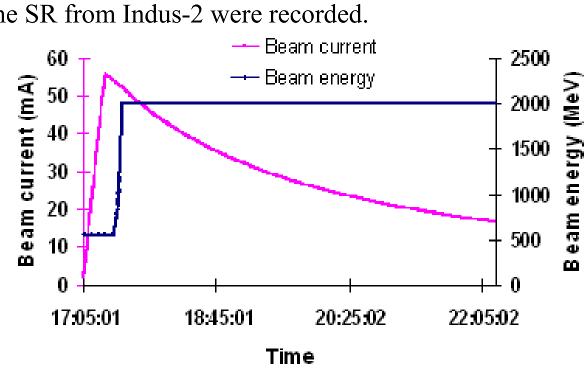

Figure 1: Illustrative trace showing Indus-2 performance.

vcsahni@barc.gov.in

As Indus-2 is a booster cum storage ring, experiments to accumulate current (at injection energy of 550 MeV) started in early 2006 and by mid 2006, energy ramping trials were successfully completed to reach 2 GeV beam energy. Over last three years we have steadily progressed on the installation of Indus-2 beam lines. Since May 2008 Indus-2 is operating up to its highest energy of 2.5 GeV. with the Atomic Energy Regulatory Board (AERB), (the agency regulating radiation protection responsibilities in India) permitting its operation up to 50 mA (see fig. 1 as an illustration). Presently work on building three beam lines has been completed and that on three more beam lines is advancing well. An account of most of these developments has been recently presented [1].

COLLABORATION WITH CERN

Formal collaboration between Indian DAE and CERN began with a cooperation agreement in 1991, which was followed up by a 1996 protocol that led to DAE's participation in the construction and utilization of LHC. The protocol envisioned "in kind" contributions in the form of hardware delivery and expert manpower support with RRCAT serving as the nodal DAE lab for the LHC construction part of the collaboration. This partnership has worked well and Table 1 summarizes the major elements of our contribution.

The successful completion of LHC related activities led CERN to invite Indian DAE in 2006 to join its other ("Novel Accelerator Technology" (NAT)) programs. An additional protocol (along same lines as before for LHC contribution) was signed by Dr. R. Aymer, DG, CERN and Dr. Anil Kakodkar, Chairman AEC, India. This has paved the way for Indian participation in CLIC (Compact Linear Collider) & Linac-4 (a project meant to upgrade LHC luminosity), details of which are described below.

High energy physicists are unanimous that for precision physics studies, a e^--e^+ collider must follow LHC, with a centre of mass energy, ECM, in TeV range. Even as study of International Linear Collider (ILC) with ECM of 0.5 TeV is on, CERN is exploring an alternate (CLIC) technology that may reach a E_{CM} of up to ~ 3 to 5 TeV and is pursuing it as an international collaboration, where RRCAT is a partner. As part of CLIC R&D, CLIC Test Facility 3 (CTF3) has been set up for which, RRCAT has (i) Designed the Transport Line 2 (TL-2) of CTF3, (ii) Delivered 61vacuum chambers & 5 dipole magnets & (iii) Contributed to creating Control Software for CTF3.

TL2 carries the high current "drive beam" into the power extraction & transfer structures (PETS) and its optics has to ensure an excellent control of bunch length over a wide tuning range. This is achieved by tuning the R56 parameter (which relates the path length of particles to their momentum deviations), over the range from -0.30m to +0.30m. The design also needs to conform to constraints, like, using some existing hardware (like, quadrupole & sextupole magnets) & fitting TL-2 into LEP pre-injector building. Another requirement is to suppress the second order dependence (T566) of path length on the momentum deviations by introducing sextupole magnets in TL-2. But as the optical functions in the tuneable R_{56} arc were not symmetric, sextupoles could dilute transverse emittance due to geometric and magnetic constraints. To mitigate this difficulty a scheme (for sextupoles) was evolved so that even in the absence of symmetrical optical parameters, emittance dilution could be kept very low. The design, meeting these demands was completed in early 2008 [2] and by May 2008 hardware, as per details below, had also been shipped to CERN.

Table 1: Major Indian Contributions to LHC.

	Details of Indian Contributions	Qty
1	50000 litres Liquid Nitrogen tanks.	2
2	Superconducting corrector magnets Sextpole (MCS) Decapole and Octupole (MCDO)	 1146 616
3	Precision Magnet Positioning System (PMPS) Jacks	7080
4	Quench Heater Power Supplies QHPS	5500
5	Integration of QHPS units into racks	6200
6	Control electronics for circuit breakers of energy extraction system	70
7	Local protection units (LPU)	1435
8	SC Dipole magnet tests/measurements, expert support in Man years	100
9	Manpower for Commissioning LHC Hardware, like, Cryogenics, Controls Power converters, Protection systems.	20 Man years
10	Data management software upgrade, Data analysis software projects.	In all about 41 Man years
11	Development of JMT-II software	
12	Software development-slow control of Industrial Systems of LHC	
13	Design and calculations for Vacuum system for beam dump line	
14	Analysis of cryo-line jumper and magnet connections	

The 61 vacuum chambers made by RRCAT included (i) 5 Dipole vacuum chambers (ii) 31 Cylindrical straight vacuum chambers (iii) 22 Racetrack straight vacuum chambers (iv) 3 Cylindrical bent chambers. All of them were UHV qualified, as per a CERN test procedure. TL-2 uses 7 dipole and a few quadrupole magnets. As CERN already had 2 dipole magnets, 5 more dipole magnets, were required. These were fabricated and supplied within a tight schedule. The magnet cores were fabricated from 1.5 mm thick low carbon steel sheets by adopting a laser cutting process to cut low carbon steel sheets in place of usual die-punch set & punching operation. This could save lot of time and helped meet tight schedule of CERN. We compensated for the limitations in accuracy &

repeatability of laser cutting of lamination, (compared to die-punch) by CNC milling/boring operation performed after assembling the complete stacking of laminations. This way we achieved better dimensional control of laminations than reached by the die punch method.

The magnet coils, formed from hollow conductor of OFHC copper were assessed at each stage for dimensions, resistance & inductance values. The detailed magnetic field profile was measured on assembled magnet at different current levels varying from 160 to 340 A. The magnets were shipped to Geneva, tested and accepted by CERN and are working satisfactorily. Fig 2 shows a few pictures of the RRCAT supplied hardware installed in CTF3 at CERN. In September 2008, RRCAT scientists also took part in the commissioning of TL-2 and successful transport of beam through it.

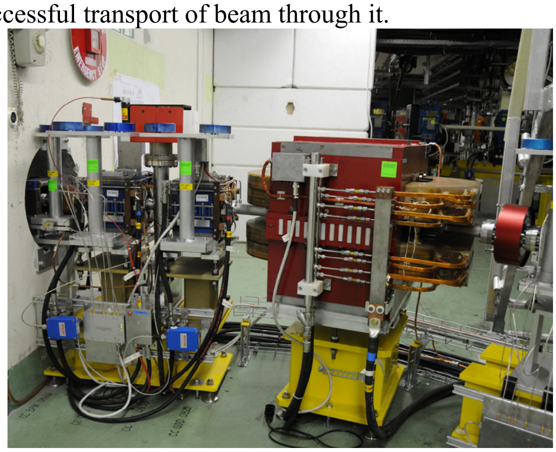

Figure 2: Dipole magnet (red) and dipole vacuum chamber installed in TL2 at CERN

The control software was developed for the following sections of CTF3: (a) LINAC to TL1 portion (b) Delay Line, (c) Combiner Ring (d) Transport Line 2 & CLEX elements: It involved development of Java Swings and JAPC (JAVA APIs for Parameter Control by CERN) based orbit and trajectory display Graphical User Interface (GUI) applications so that the intensity and beam position array data could be extracted from the output of beam diagnostics devices. The GUI offers options like: (1) Freeze and take screenshot by a click, (2) Error log panel to view any error, (3) Archive the data and save in database, (4) Multiple trace display to show intensity and position of all BPMs, (5) Separate settings panel to select/deselect trace, display difference between two traces, display average trace, (6) Facility to change acquisition window start, and interval property of the position monitors. The software has been successfully developed, installed, tested & is in use at the CTF3 controls site. These can be viewed at the following URL: http://indico.cern.ch/getFile.py/access?contribId=46&sessionId=9&resId=1&materialId=slides&confId=47771

We next turn to the other part of NAT program, viz., relating to Linac4. CERN is building a 352.21 MHz 3 MeV RFQ based test stand as part of Linac-4. For this RRCAT had agreed to design and develop a high voltage pulsed modulator for 1 MW LEP klystrons. RRCAT had proposed three design schemes, of which an all solid state bouncer compensated modulator was chosen for follow up development work. Main design demands were to avoid gas tube crowbar on the HV side, have low rise and fall times and to realize high voltage stability of the flat top. The output voltage and current are rated up to 110kV/24A, with pulse duration 800μs, repetition rate of 2Hz, <1% droop and <0.1% ripple on pulse top with energy restricted to 10J in case of klystron arc. Using this design, CERN built a modulator that has been tested with a klystron, while another unit built at RRCAT is going through final evaluation. Details of this development were presented at LINAC08 conference in Vancouver, Canada. Figure 3 shows picture of the unit built by RRCAT.

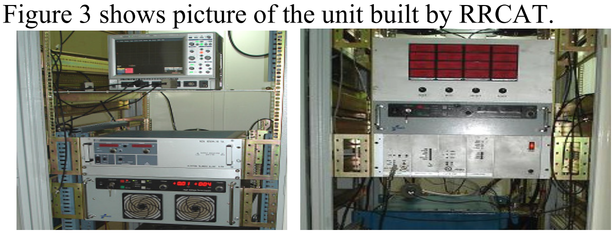

Figure 3: Photo on left: Charging/Filament Supplies Photo on right: Trigger, controls and interlock system of modulator at RRCAT.

R&D IN SUPERCONDUCTIVITY RELEVANT TO SCRF CAVITIES

The proposed International Linear Collider, the X-FEL at DESY, Project-X at Fermilab have all triggered world wide interest in making Niobium based superconducting radio frequency (SC-RF) cavities. The main aim is to reach high gradients and superior cleaning procedures devised in recent years have led to such cavities reaching gradients (without field emission) in the 25-30 MVm^{-1} range. But that is still way below the maximum estimated gradient of 55 MVm^{-1} for an elliptical shaped Nb cavity. Often the limitation on reaching accelerating gradient above 25-30 MVm^{-1} is linked to a rapid drop in the cavity quality factor [3]. In fact, a study involving a Nb SCRF cavity operating in the TE011 mode (where there is no surface electric field) has shown that the "Q-drop" is related to the peak magnetic field HPeak experienced by the cavity surface [3]. This prompted us to undertake a study [4] of the superconducting properties of some test samples of technical Nb material that are actually used for SC-RF cavity fabrication. We particularly focused attention on the field at which magnetic flux first penetrates the sample and have examined (1) fine-grain (FG) polycrystalline Nb samples with 50 microns average grain size, and with varying Ta content & (2) large-grain (LG) polycrystalline Nb samples with average 1mm grain size, and with ~400 ppm Ta content. Samples were divided into three categories: (1) Sample S1: pristine samples as received from various vendors, (2) Sample S2: samples subjected to the same buffer chemical polishing (BCP) as is employed in the standard chemical processing of SC-RF cavities, which is followed by annealing at 600 C for 10 hours, and (3) Sample S3: samples subjected to a

120 C bake out for 10 hours over and above the standard chemical and thermal treatments. These samples were obtained from same mother ingots that were actually used for fabrication of some SC-RF cavities at Jlab, USA. For the sake of uniformity we used the same sample sizes - roughly 2mm x 2mm x 2mm- throughout. We used a vibrating sample magnetometer (VSM; Quantum Design, USA) for magnetization measurements.

Results of our measurements showed that (1) the estimated onset temperature of superconductivity in LG pristine material is 9.2K, while that for the FG pristine sample (measured under same experimental protocol) is 9.26K. Samples involving BCP treatment & a subsequent annealing at 600C showed a distinctly lower estimated superconducting onset temperature of 9.05K. We have observed same behaviour in other BCP treated samples of technical Nb including large-grain, fine-grain and oriented single crystals with different degrees of purity.

More detailed measurements showed that the field for the first flux line penetration Hp, identified as the field where virgin isothermal M-H curve departs from linearity and the upper critical field are affected by the grain size and the chemical treatment. In figures 4 & 5 we show typical data of our measurements. Values of different parameters for various BCP treated technical-Nb samples (both large-grain and fine-grain) clearly show that at 2K the flux-lines start penetrating these samples around 1000 Oe, and the complete Meissner state tends to get destroyed. The loss associated with the flux-line dynamics provides a natural explanation of the observed high-field Q-drop in the Nb SC-RF cavities in the field range 900-1200 Oe. We propose that the earlier penetration of the flux-lines in the BCP treated samples, is possibly linked to the lower gradients realized in cavities made out of such technical Nb materials. We conclude that the lowered superconducting parameter values for the BCP treated samples correlate well with the reported severe degradation in the Q-factor observed in the such Nb SC-RF cavities. We believe a careful prior estimation of the field for first penetration in the technical

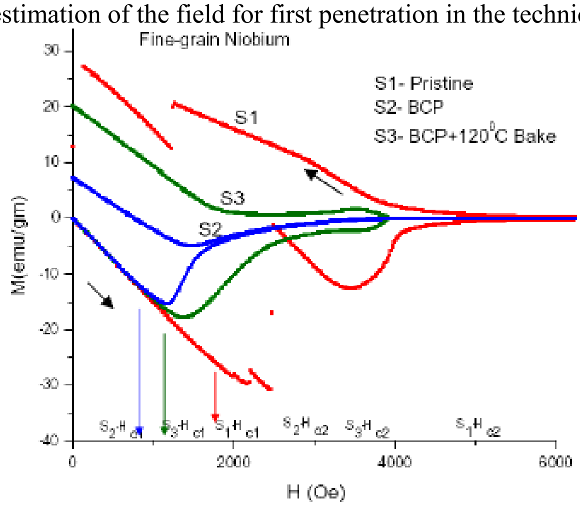

Figure 4: M vs H to obtain H_p in fine grain samples.

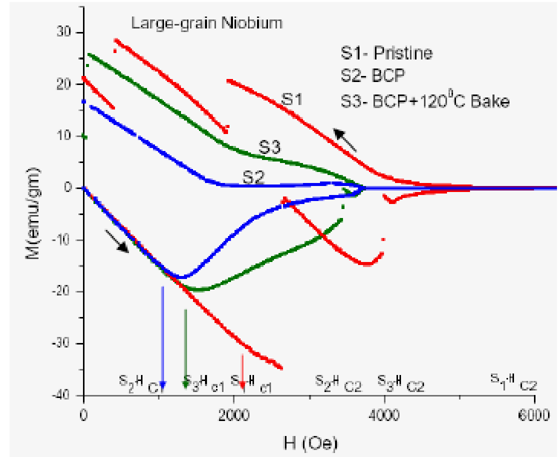

Figure 5: M vs H to obtain H_p in large grain samples.

Nb samples (which are to be used in a SC-RF cavity fabrication) after these samples are subjected to various surface treatments (used typically during actual SC-RF cavity fabrication and processing) and thermal treatments (annealing and baking), can be a good way for judging the SC-RF cavity fabrication processes.

FERMILAB–DAE COLLABORATION INVOLVING SCRF TECHNOLOGY

In Jan 2006, six Indian labs {BARC, RRCAT, VECC, TIFR, IUAC & Delhi University} & 4 US labs {Fermilab (interested in ILC & Project-X), SLAC, Cornell & Jlab} had signed a MoU with a view to collaborate, amongst other things, in the areas of accelerator science. Since then we have progressed with 6 Indian scientists visiting Fermilab to participate in SCRF cavity & cryomodule R&D. Indian labs are partnering Fermilab in Project-X and the gains so far realised are as follows:

- Finished improvements on the design of the 1.3 GHz cavity fabrication tooling, including the die set. One set of tooling delivered to Fermilab and will be used for cavity fabrication in collaboration with TRIUMF.
- Constructed several Nb and copper prototype, 1-cell, 1.3 GHz cavities; performed RF tests to check fabrication techniques.
- Proposed and prototyped a new end group design for the 9-cell, 1.3 GHz cavity using block Niobium.
- Started study on Type-IV cryomodule being built at Fermilab; proposed several value engineering design changes to the cryomodule design and fabrication.
- IUAC is in the process of fabricating two spoke resonator cavities for the HINS project at Fermilab.
- Discussions are on to construct Vertical &Horizontal test stands for use in Fermilab and Indian labs.

This collaboration also aims at joint work on the design & development of parts of beta = 0.8 cavity/cryomodule.

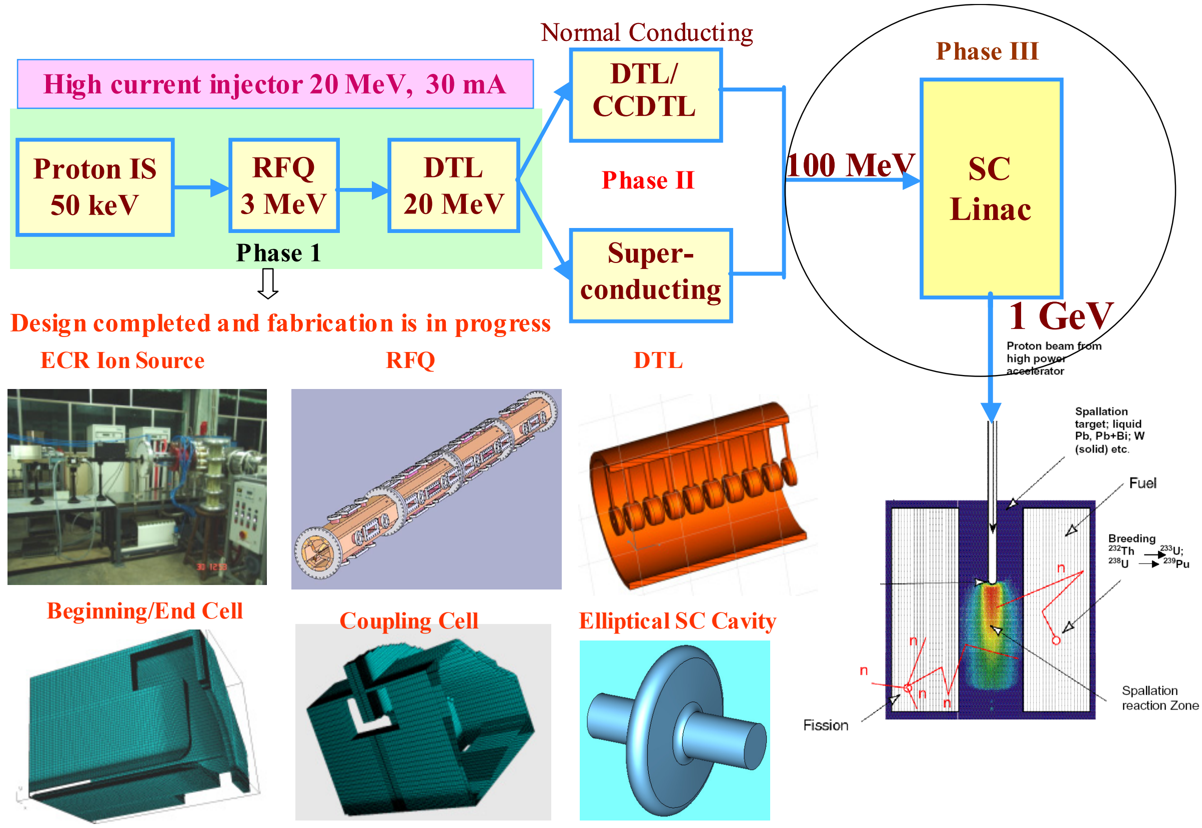

Figure 6: Scheme of high intensity proton accelerator started by BARC for ADS linked R&D. Work on phase I is on.

ACCELERATORS FOR NUCLEAR PHYSICS & ENERGY PROGRAMS

A number of accelerators are available in India for research in nuclear physics in the low and medium energy range. Prominent amongst these are located in Kolkata, Mumbai and New Delhi. At Kolkata, Variable Energy Cyclotron Centre operates a home built cyclotron and has also set up a K=500 superconducting cyclotron due to soon start operations [5]. A program on Radioactive Ion Beams is also on [5] and progressing well. At Mumbai, Bhabha Atomic Research Centre & Tata Institute of Fundamental Research have added a (quarter wave resonator based) superconducting linac booster to double the energy of the beams available from their 14 MV pelletron. BARC has also launched a program on high current proton machine that would be useful for R&D on ADS, and fig 6 shows its schematic [6]. Inter University Accelerator Centre in New Delhi has set up a number of advanced facilities and also built a superconducting linac booster. For an update on all these developments, one can consult the proceedings of InPAC2009.

CONCLUDING REMARKS

We reviewed the capability of major Indian accelerator labs built up over the past two decades, especially the work done at RRCAT, Indore. Current and recent activities, where Indian DAE labs are partnering CERN & Fermilab were described. The SCRF based upcoming international accelerator projects, attractive to us due to Indian interest in R&D on Accelerator Driven Sub-critical reactors (ADS) were touched upon. The accelerator related developments in India have now entered a new phase and in the coming years we hope to strongly integrate with worldwide efforts in this area.

ACKNOWLEDGEMENT

Work described here is the effort of many scientists & engineers at RRCAT, BARC, IUAC & VECC. Author is grateful for the help given to him by all of them.

REFERENCES

[1] V.C. Sahni, Proceedings of APAC2007 and see also Proceedings of International Meeting on Frontiers of Physics, (IMFP2009) Kualalampur, Malaysia, Jan 12-16, 2009 (to be published by APS).

[2] Amalendu Sharma, Abdurrahim, A.D. Ghodke and Gurnam Singh, Nuclear Instruments and Methods in Physics Research Section-A, 602, 342 (2009).

[3] G. Ciovati & P.Kneisel, Phys. Rev. Special Topics, 9, 42001 (2006); G. Ciovati, P. Kneisel & A. Gurevich, Phys. Rev. Special Topics, 10, 62002 (2007).

[4] S.B. Roy, G.R. Myneni and V.C. Sahni, Supercond. Sci. Techno. 21, 65002 (2008); & another paper that has been submitted.

[5] See the invited talks delivered by R. K. Bhandari, S. Som and Alok Chakrabarty in InPAC2009.

[6] See invited talk by P. Singh at InPAC 2009.