T.2: Precise survey and alignment of accelerator machines

Vijendra Prasad (vijen@rrcat.gov.in) and R.K. Sahu

Introduction

Major accelerator machines at RRCAT are 450 MeV Indus-1 and 2.5 GeV Indus-2. Both the machines use a 450/550 MeV booster synchrotron and 20 MeV pre-injector microtron for injection. A systematic and proper methodology of survey and alignment has been adopted to accurately transform the designed shapes and positions of these accelerators into real world. This demanded involvement of survey and alignment team right from the building construction stage. Among the various metrological techniques and instruments, a suitable combination of them was selected based on shape and size of our accelerators to meet the specified accuracy. In this article, we discuss the role of survey and alignment in building accelerator machines at RRCAT. We then discuss the methodology adopted and provide a brief description of the instrumentation and softwares used. A short report on the calibration facility, which had been set up during the Xth plan is also presented in this article.

Planning, Toolings, and Instruments

1. Planning : The work of alignment started with the building construction and the accuracy continued to improve in steps to the specified values, till start of machine operation. Thereafter also, survey and alignment is required for periodic checks and analysis of stability of various supports / foundations.

Survey and alignment features like network monuments for horizontal and elevation control, openings for visibility among control points, embedded pipes for synchrotron beam lines etc. were incorporated in building during construction stage. Their positional accuracies were controlled within 2.5 cm. In the next step, footprints of the girders and magnets were marked and the positions of the embedded plates for them were controlled within 15 mm accuracy while casting in the floor. The supporting jacks and girders were positioned within 5 mm followed by the UHV assemblies, and finally the beam sensitive components were positioned to their specified accuracy as given in Table.T.2.1.

Another important work which was accomplished with precision, before placing components in the machine was fiducialization. It is the process of representing the active features like magnetic axis, optical axis, median planes etc. of the components in physical forms, which are accessible and visible when the components are in their final position and over which survey targets or instruments can be mounted.

Table. T.2.1: Alignment tolerances for Indus-2 (Units: δS, δX, δZ-mm, $\delta\theta_s$, $\delta\theta_x$, $\delta\theta_z$-mrad)

Object	δS	δX	δZ	$\delta\theta$s	$\delta\theta$x	$\delta\theta$s
Dipole	0.1	0.2	0.1	0.2	0.5	0.5
Quadrupole	0.1	0.1	0.1	0.2	0.5	0.5
Sextupole	0.5	0.1	0.1	0.2	1.0	1.0
Steering magnet	1.0	1.0	1.0	2.0	2.0	2.0

2. Toolings : Various types of toolings are required for representation of active features, measurements of positions of components, and mounting of measuring instruments. They are normally custom made depending on the shape and size of components and instruments. The main toolings are : targets, target holding devices, and instrument mounting devices. Different types of targets used for survey and alignment are shown in Figs. T.2.1 and T.2.2. These targets have precise centre mark and when mounted on target holding devices, define the position accurately. The target holding devices have either conical base or precise hole, in which targets can be mounted.

For mounting instruments like theodolite and DISTINVAR®, alignment sphere with standard 30 mm diameter hole and a conical surface, as shown in Fig.T.2.3, was used. The hole and conical surface have common axis. The conical surface facilitates mounting of optical targets on the same axis.

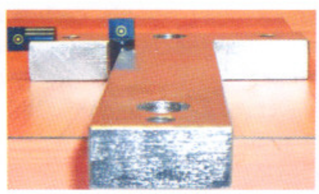
With optical mark at centre

With concentric circle

With centred reflecting prism

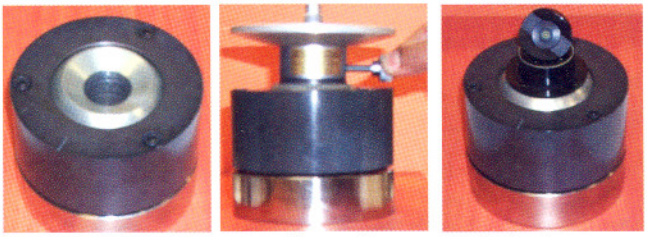
Fig. T.2.1: Diameter 88.9 mm optical targets (1 and 2), and retro-reflective target (3)

Target for pipe axis



Target for edges

Fig. T.2.2: Targets and level plate



Assembly to generate vertical bore of Φ30 mm on desired axis | *Expanding hydraulic shank to mount theodoloites* | *Optical target on same assembly*

Fig.T.2.3: Φ30 mm hole as fiducial and its uses

3. **Instruments and Softwares :** Following measuring instruments are being used for survey and alignment:

- Angle measurement: Precision digital theodolites Leica TDA5005, TDM5000 and TM5100. For Indus-1 E2 theodolites were used.
- Distance measurement: Distinvar® with calibrated invar wire, Laser Interferometer as distance standard, Total station Leica TDA5005 and TDM5000.
- Levelling and elevation: Wild N-3 optical level.
- Tilt: Electronic Inclinometers Leica Nivel-20, Wyler precision spirit levels.
- Softwares: SNAAPS[3] for survey data collection, their least square adjustment, on-line coordinate measurements, alignment error analysis, curve fittings, coordinate transformations, stake out, resection etc, Axyz™ for online coordinate measurements and analysis.

In order to ensure the accuracy of distance measurements by Leica TDA5005, they are calibrated using laser interferometer. Calibration files having the coefficients of Fourier fitting are prepared and used for on-line correction of distances measured at site.

Alignment of Booster Synchrotron and Indus-1

The booster synchrotron is hexagonal in shape having six super-periods, each consisting of a 60° bending magnet and a straight section of length 2853.8 mm having a quadrupole doublet. It was the first machine for installation, so its average centre and orientation was decided by taking rough reference from the points established during civil work. This average centre was marked on the central monument and was taken as the origin for X, Y and Z. The line joining this centre to an apex of machine hexagon was chosen as X direction in horizontal plane. This primarily defined the coordinate system for installation of booster synchrotron. During initial installation no proper network was established since the machine was small, it was easy to control the shape and size as well as the positions of various components in a single setup of instruments. However, afterwards, a proper network was established by mounting brackets on the wall and their coordinates were determined in the originally defined coordinate system. This network now facilitates measurement and alignment of any individual component during maintenance etc. For deciding the positions of the microtron, TL-1, TL-2 and Indus-1, the booster synchrotron was taken as the reference. A footprint of the complete machine was marked on the floor. Installation and rough alignment of these machines were carried out by using these marks. The precise alignment of

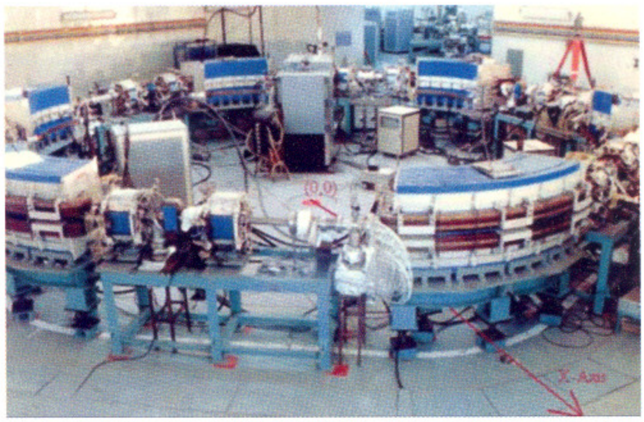


Fig. T.2.4: Booster synchrotron showing originally defined coordinate system

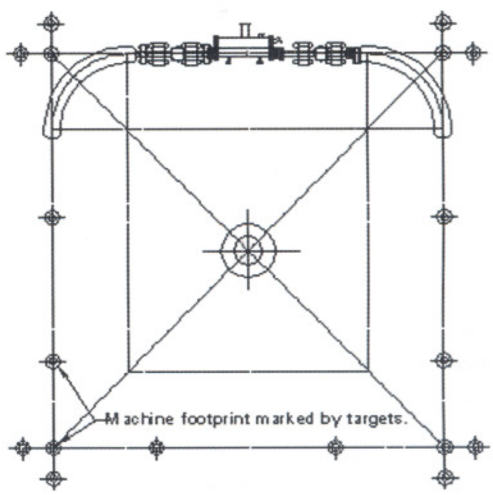


Fig. T.2.5: Indus-1 machine footprint marked using adhesive targets.

components in the booster synchrotron, Indus-1, TL-1 and TL-2 were carried out by using online coordinate measurement system ECDS along with an optical level N-3 for controlling elevations separately.

Survey and alignment of Indus-2

Indus-2, with a circumference of 172.47 m, consists of 16 dipole magnets, 72 quadrupoles, 32 sextupoles, 48 steering magnets, 56 beam position monitors, and some special components like injection septums, injection kickers, and RF cavities. The booster synchrotron acts as the injector for Indus-2. Hence, before start of construction of the building for Indus-2, it was necessary to mark the centre of building and fix the central monument with respect to the booster synchrotron. Since Indus-2 is housed in a narrow over-ground tunnel of 5.2 m width, the visibility of machine is limited to a very small zone. So it was decided to adopt a network approach of alignment for controlling the overall shape and size of the machine and at the same time to align all the components within specified tolerances. For this, three control networks, namely primary control network, secondary control network, and elevation control network were established.

1. Primary control network : The primary control network defines the coordinate system of Indus-2 and acts as a reference for the secondary control network. It consists of 11 control points in the form of 400 mm diameter concrete pillars (monuments), with forced centering sockets over them for mounting survey instruments and optical targets. They are distributed inside the ring tunnel and in the open area and are named M0 through M9 and MS. Their locations were decided in such a way that each control point was visible from at least two other control points. The location of M9 was decided with the consideration to have a control over TL-3. The coordinates of these monuments were determined by least square adjustment of repetitive redundant distance and direction measurements.

2. Secondary control network : The secondary control network is in the form of 42 uniformly distributed brackets fixed with the inner and outer wall of the tunnel [see Fig.T.2.6]. These brackets were equipped with conical bases for mounting survey instruments and optical targets. Their locations were decided after considering the parameters like focusing distances of theodolites, visibility of components, and uniform positional strength in all directions. The coordinates of these network points were determined by repetitive distance and direction measurements using a calibrated TDA5005™ and a TM5100™.

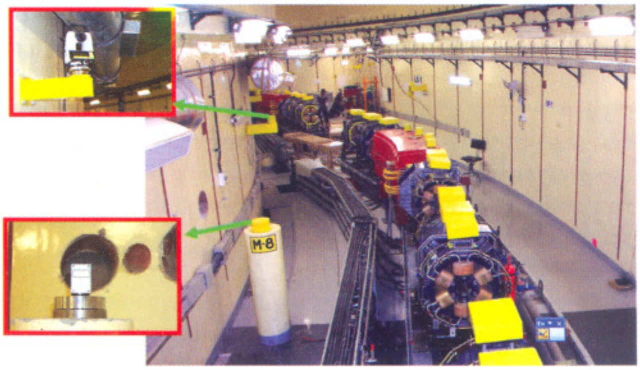


Fig. T.2.6: Indus-2 tunnel showing primary control network monument, secondary control network brackets, and magnet fiducials protected by yellow coverings

3. Elevation Control Network: The elevation control network is also in the form of 24 wall brackets fixed to the inner and outer walls of the tunnel. They were also equipped with conical bases for mounting optical targets. Elevation of each bracket was determined by their repetitive survey using a Leica N-3™ optical level.

Stages of survey and alignment of Indus-2

A. Installation and pre-alignment

In order to have the full range of movement of girder jacks during final alignment, all jacks were fixed at their designed locations within ±5 mm. Subsequently, the straight sections and dipole girders were installed and aligned. The dipoles were installed first and individually aligned by taking reference from nearby network points.

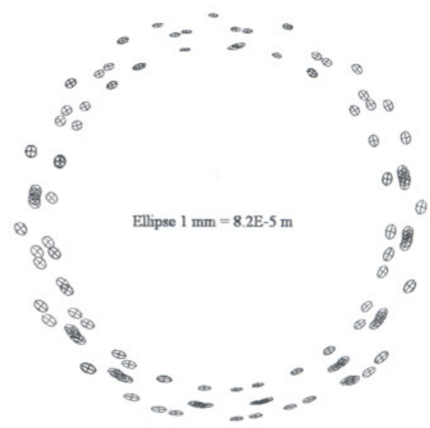


Fig. T.2.7: Absolute Error Ellipses (Dipoles and Secondary Control Network points).

After completion of alignment of all dipoles, they were surveyed together to determine the relative positions and overall shape. Based on the results of this survey, 5 out of 16 dipoles were readjusted to obtain better relative alignment and smooth shape of the machine. After this, all the dipoles along with the secondary control network points were re-surveyed. The absolute error ellipses of this survey are shown in Fig.T.2.7.

The results of this survey were within acceptable limit and no further refinement in positions of dipoles was attempted. Over the straight section girder, quadrupoles and sextupoles were supported on six-strut support system for their individual alignment. The upper halves of all the quadrupoles and sextupoles were required to be opened for assembly of vacuum chambers. Before removing the upper half, the magnets were pre-aligned within ±1 mm to facilitate the assembly of vacuum chambers. The beam position monitors (BPM) and beam position indicators (BPI) are part of vacuum envelope and required a precise alignment. So before connecting to adjacent vacuum chambers, they were aligned and fixed.

B. Precise alignment

Precise alignment of multipoles started after completing the assembly of vacuum chambers and re-assembly of upper halves of multipoles. All the quadrupoles and sextupoles on individual girder were first precisely aligned within the specified tolerances by using N-3 optical level, precision tilt level, and two theodolites together, oriented in machine coordinate system by using the coordinates of nearby 5-6 secondary network points. For elevation control, references were taken from nearby elevation control network points. This helped not only in controlling the relative alignment of multipoles on a girder within the specified tolerance, but also the absolute position of girder in the machine. The same procedure was followed for all 16 straight sections. After this, a full survey of the machine was carried out and approximately 1866 directions and 766 distances were measured by using motorized theodolite TDA5005. This data was processed by least square adjustment. During the adjustment, the coordinates of two primary control points, namely M1 and M3, which are in the tunnel, were assumed fixed. After adjustment, the largest size error ellipse was found to have major axis of the order of 0.2 mm. The most probable coordinates obtained from this adjustment were used to analyze the overall shape of the machine, the orientation of the straight sections with respect to each other and nearby dipoles etc. Based on the results of this survey, three girders were realigned and again a complete survey run was performed. The results of this survey were quite satisfactory and the calculated circumference deviated by only 1.8 mm (2σ) from design value. Hence, further refinement in the alignment was not attempted.

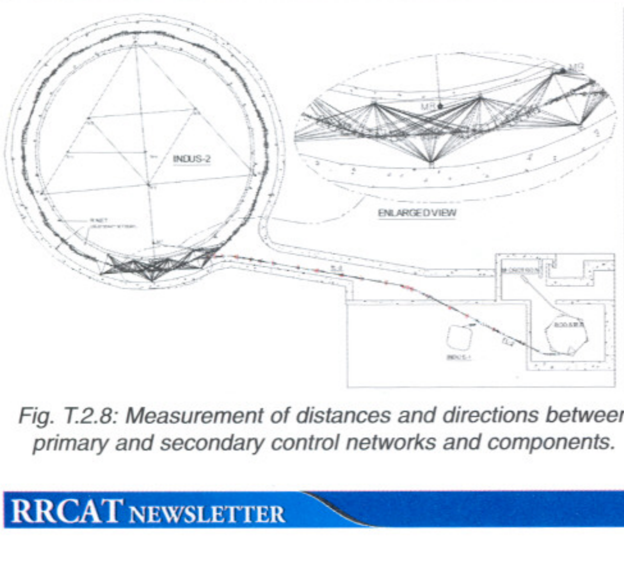
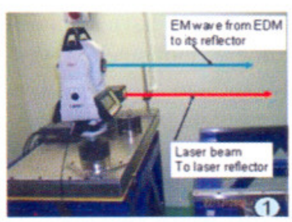


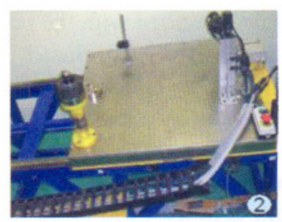
Fig. T.2.8: Measurement of distances and directions between primary and secondary control networks and components.

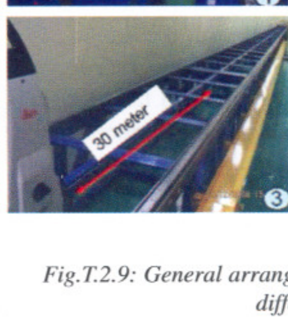
Distance calibration facility

In accelerator machines, to meet required accuracy over large distances, electromagnetic distance meters (EDM) and Distinvar™ must be calibrated periodically. For first use at Indus-2, these instruments were calibrated at CERN. For periodic use in future, a distance calibration facility has been set up at RRCAT. It comprises of a system for measurement of distances by the instrument to be calibrated, as well as by the laser interferometer as standard, and a precision temperature control system.

1. Scheme and general arrangement : The complete system is housed in an underground tunnel (3.3 m wide x







1. *EDM integrated in theodolite and laser interferometer mounted on a fixed Table at one end*
2. *Carriage with reflector*
3. *Liner motion system for 30 meter carriage movement*

Fig.T.2.9: General arrangement of the calibration bench in different views.

33.7 m long) at Alignment Laboratory, RRCAT. This improves temperature stability by resisting thermal loading from outside. The calibration bench is essentially a 3-axis CNC table of large range of X movement and very small range of Y-Z movement. It is equipped with a laser interferometer at one end which provides a standard for distance measurement. A motorized carriage provides movement to the two retro-reflectors, of which one is aligned to EDM and another to the laser beam. The system can measure and calibrate distance upto 30 meters. Fig.T.2.9 shows the general arrangement of the calibration bench.

2. Subsystems :

a) Linear Motion (LM) system: The X motion for carriage is obtained by two parallel standard linear motion guides separated by 800 mm. These two guides are made of standard elements joined together by specific attachment systems integrated into the profile to build the total travel of 30 m. One is chosen as rack for transmission of motion and other is a plain rail of the LM system. At about every two meters between the base and these two guides, adjustable sleepers are provided to adjust parallelism, straightness and roll of the guides. LM guides (LM rail and LM block) are of THK make. On the floor, embedded plates (EPs) of steel leveled within ± 3 mm of free floor level (FFL) were provided to install the bench structure. Salient features of calibration bench are as follows:

Parameter	**Value**
Transverse tolerances for X-carriage (75 kg of test-load)	< ± 0.1 mm (Y or Z) per meter (X) but < ± 1.0 mm in X, Y and Z axes, accumulated over 30 m of X- travel
Positioning accuracy of Y -Z translation stage.	± 0.05 mm absolute on their respective scales. Independent of X-carriage.
Controller specifications:	
Modes of motion	Jogging, point to point, 3 axes linear interpolation
Feed (max)	10 m/min (G0), 3 m/min(G1)
Motors and Encoders	Servo motor with in-built rotary encoder with correction mechanism at pinion
Drivers	Motor dependent
Homing cycle	Run time home with marker search process
Breaks	Electro-magnetic on all axes

b) Carriage (X) and stage (Y-Z) movements :

Carriage can be moved in X by a command from the PC. Retro-reflector can be moved by few mm in Y & Z, simultaneously with X, using translation stage. This

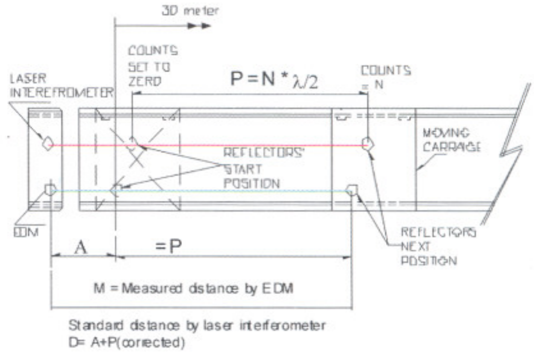


Fig. T.2.10: Definition of variables used

corrective transverse movement to the reflector can be useful in future in maintaining the alignment of the reflector with laser beam and hence the signal strength of interference over 30 m travel. Standard distance measured by the laser interferometer and its online correction are taken to PC using a software developed in-house.

3. Algorithms :

Fig.T.2.10 depicts and defines the variables used. Initial distance (A) between an instrument and its reflector on carriage is measured by conventional contact measurement. For a carriage movement (X), the instrument to be calibrated measures absolute distance (M) between itself and its reflector, whereas laser interferometer measures incremental distance P. Thus (A+P) is the standard distance D for the

Table.T.2.2: Calibration data

Laser Distance D (m)	EDM Dist M (m)	Diff(D-M) (m)	Residual after Linear regression (m)	Residual after Fourier regression (m)

12.12892	12.09415	0.03477	-0.00105	0.00006
12.17897	12.14425	0.03472	-0.00110	0.00000
12.22892	12.19415	0.03477	-0.00105	0.00006
12.27900	12.24435	0.03465	-0.00117	-0.00005
12.32899	12.29435	0.03464	-0.00118	-0.00008
------	.	.	.	.

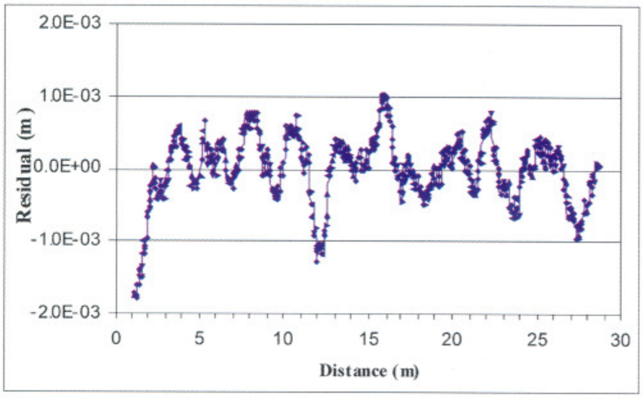


Fig. T.2.11: Residual after linear regression

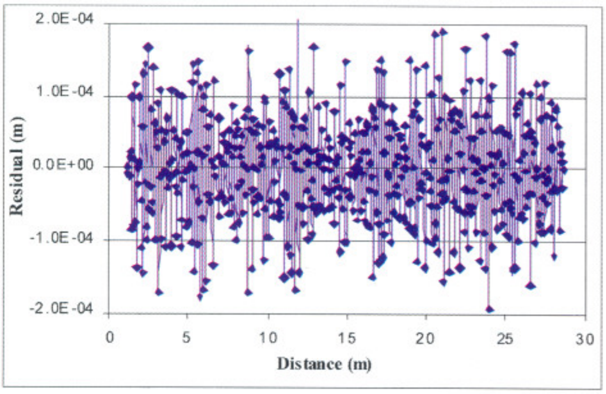


Fig. T.2.12: Residual after Fourier regression

distance (M) measured by the instrument. (D-M) is the error which can be as high as ± 2 mm at any particular distance but repeats itself within ± 0.1 mm for repeated measurements. So this error is modelled using Fourier transformation to reduce residual (D-Mcorrected). To achieve this, measurements were taken at each 0.1 m step and corrected as explained above. A part of measured data for EDM of theodolite TDA5005 is given in Table.T.2.2. Residual after linear regression and after the Fourier regression are depicted in Fig.T.2.11 and Fig.T.2.12 respectively.

Following Fourier model is used for variation of the measured distance M to get $M_{corrected}$ for getting minimum residual (D- $M_{corrected}$) :

$$M_{corrected} = \alpha M - a_0 - \left[\sum_{j=1}^{d} a_j \cos(j\varphi) + \sum_{j=1}^{d} b_j \sin(j\varphi) \right]$$

α : Scale factor

a_0 : First Fourier coefficient

a_j to b_j : Other Fourier coefficients

d : Order of the Fourier series

M : EDM distance corrected for temperature,

φ : pressure and humidity

$$\varphi = \left(2\pi/_U\right)\left(M - U * FLOOR\left(M/_U\right)\right)$$

where U (m) is the wavelength chosen for Fourier expansion. This facility is being used to determine the zero and cyclic errors of EDM instrument-reflector pairs. The result is a calibration curve. A Fourier series can model this calibration curve and it is found that residuals with respect to a modelled curve are generally less than 0.1 mm. This curve is used to correct the measured distances. Using these corrected distances in the least squares adjustment of the machine network, there is a net improvement in the standard deviation for distance.

Conclusion

Alignment of the booster synchrotron and Indus-1 was carried out mostly using on-line coordinate determination system, because of their small sizes. However for Indus-2, a network approach was adopted. In order to achieve the specified tolerances we had to control the various sources of errors, perform precise survey and rigorous data analysis. With these, it has been possible to align Indus-2 successfully, which is reflected in the proper operation of the machine. The distance calibration facility, which has been recently commissioned, will enhance the accuracy of alignment in future.

References

1. R.K.Sahu et al, Proceedings of InPAC-2003, 613 (2003).
2. Vijendra Prasad et al, Proceedings of InPAC-2005, 496 (2005).
3. Vijendra Prasad, Proceedings of InPAC-2003, 609 (2003).
4. Vijendra Prasad et al, Proceedings of APAC07, 761 (2007).