Commissioning of Indus-2 Storage Ring

V.C.Sahni
RRCAT & BARC

Talk Delivered at the APAC2007
Raja Ramanna Centre for Advanced Technology, Indore
January 30, 2007

Profile of the talk:

1. Background of the Indian SRS program

2. Start of RRCAT

3. Synchrotron related activities

- ***Short Digest on Injectors & Indus-1***
- ***Lattice of Indus-2 & Sub-system Development***
- ***Facets of Indus-2 Commissioning Activities***
- ***Indus-2 & Its Beam-line Activities***

4. Indus-2 program ahead & benefits for upcoming partnership programs with accelerator labs abroad

5. Concluding remarks

Indian SRS Program: Chronology of events

- 1978 Dr. H.N.Sethna, Secretary, DAE constitutes AHEAF committee with Dr. P.K.Iyengar as Chair.
- 1980 AHEAF committee recommends setting up of Synchrotron radiation sources (SRS).
- 1981/82 Survey of prospective users & decision to build separate low energy & high energy rings.
- 1983 onwards All possible options explored and Brookhaven NSLS model adopted.
- 1983 Dr. R.Ramanna issues the Office Order to start CAT at Indore.
- 1984 Foundation stone of CAT, Indore was laid.
- 1986 CAT activities start with modest facilities.
- 1987 Decision to start building injector accelerators for SRSs: 20 MeV microtron & 450-700 MeV booster synchrotron.

Government of India
Department of Atomic Energy

C.S.M. Marg
Bombay-400 039

No. 25/34/83(BARC)-R June 27, 1983.

OFFICE ORDER

Sub :- Centre for Advanced Technology at Indore, MP.

...

The Department of Atomic Energy has decided to set up a Research Centre for Advanced Technology at Indore. The Centre will initiate coordinated activities in the fields of inertially confined fusion research, plasma physics, advanced high energy accelerators, laser technology and other related areas such as laser isotope separation,

The department of atomic energy has decided to set up a research centre for advanced technology at Indore. The centre will initiate coordinated activities in the fields of *inertially confined fusion research, plasma physics, advanced high energy accelerators, laser technology and other related areas such as laser isotope separation, industrial laser, cryogenics, ultra high vacuum technology, optical and x-ray instrumentations, nuclear detectors, RF systems and microelectronics* etc.

1. Shri C. Ambasankaran, Director, E & I Group, BARC. .. Chairman
2. Dr. V.K. Moorthy, Director, Planning Cell, BARC. .. Member

...2

3. Dr. D.D. Bhawalkar, Head, Laser Section, BARC. .. Member
4. Shri A.D. Mathure, C & A Division, BARC. .. Member
5. Dr. V.K. Rohatgi, Head, Plasma Physics Divn., BARC. .. Member
6. Dr. N.S. Satyamurthy, Head, Nuclear Physics Division, BARC. .. Member
7. Shri R.C. A. Jain, Director, DAE. .. Member
8. Dr. G. Venkataraman, RRC. .. Member
9. Shri I.A. Lakshminarayanan, I.F.A., BARC. .. Member
10. Shri B.K. Banerjee, R-5 Project, BARC. .. Member-Secretary

f) All matters relevant and ancilliary to the implementation of this project.

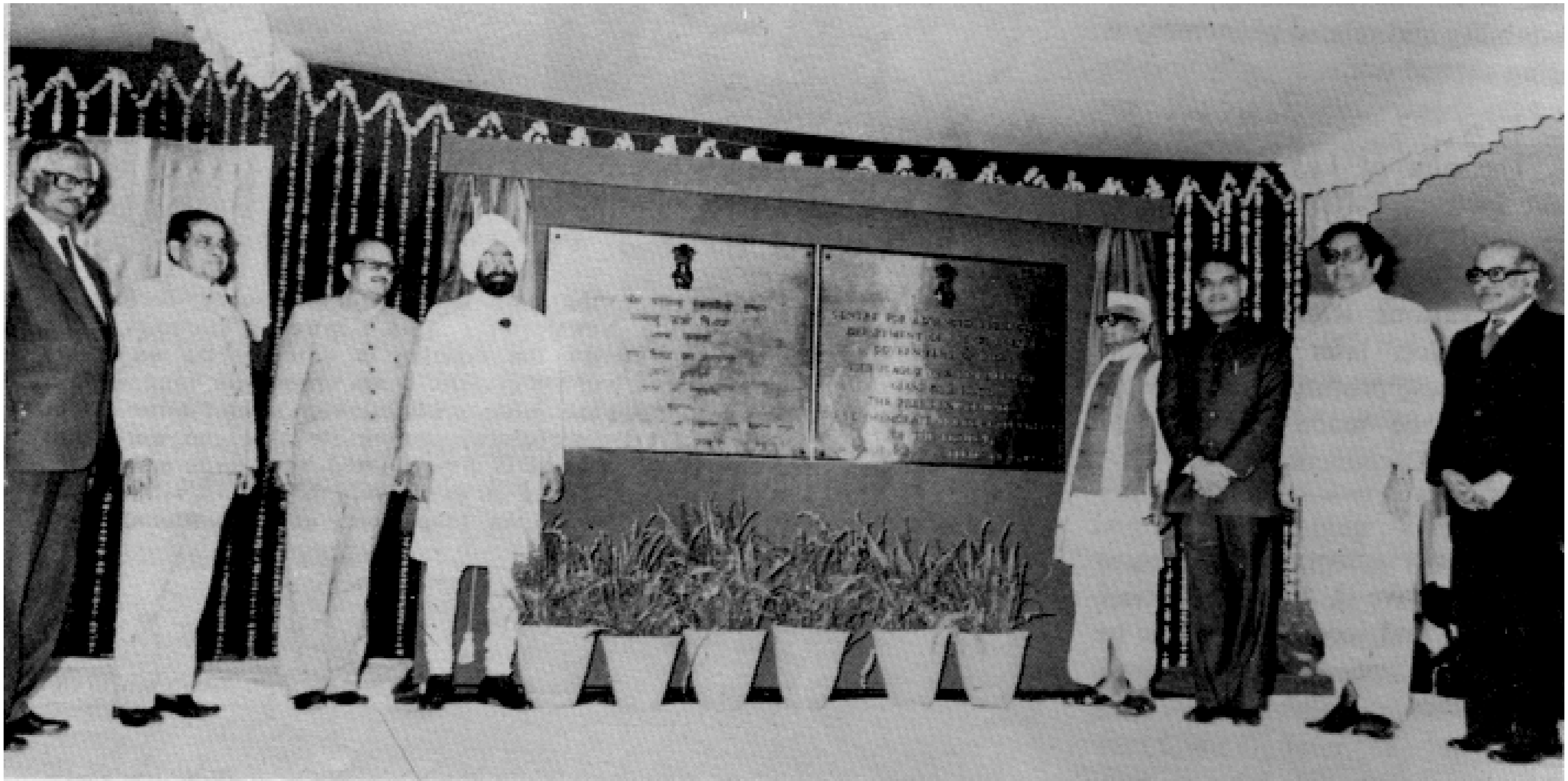
The Committee will be responsible to and report to Director, BARC and Secretary to Government of India.

Sd/-

(R. Ramanna)
Secretary to the Govt.of India

19-1492
-7-83

RRCAT's Foundation Stone Laying Function
19th February 1984



Inauguration of CAT by President Giani Zail Singh. Seen along with him (L to R) are—Dr. R. Ramanna, Chairman, Atomic Energy Commission; Shri P.C. Sethi, Union Home Minister; Shri Arjun Singh, Chief Minister of M.P.; Shri Bhagawat Dayal Sharma, Governor of M.P.; Shri Shivraj Patil, Union Minister for Energy; Shri Rajendra Dharkar, Mayor, Indore Municipal Corporation & Shri C. Ambasankaran, Chairman, P&IC, CAT.

Electron accelerators for radiation processing R&D

Developed 300-750 keV ~20kW DC accelerator

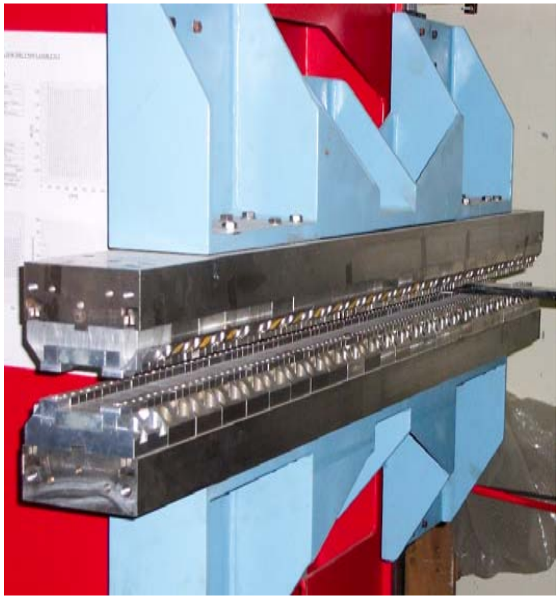
It has been used for polymer degradation, polymer grafting, medical sterlization, surface irradiation of potatoes, seeds.

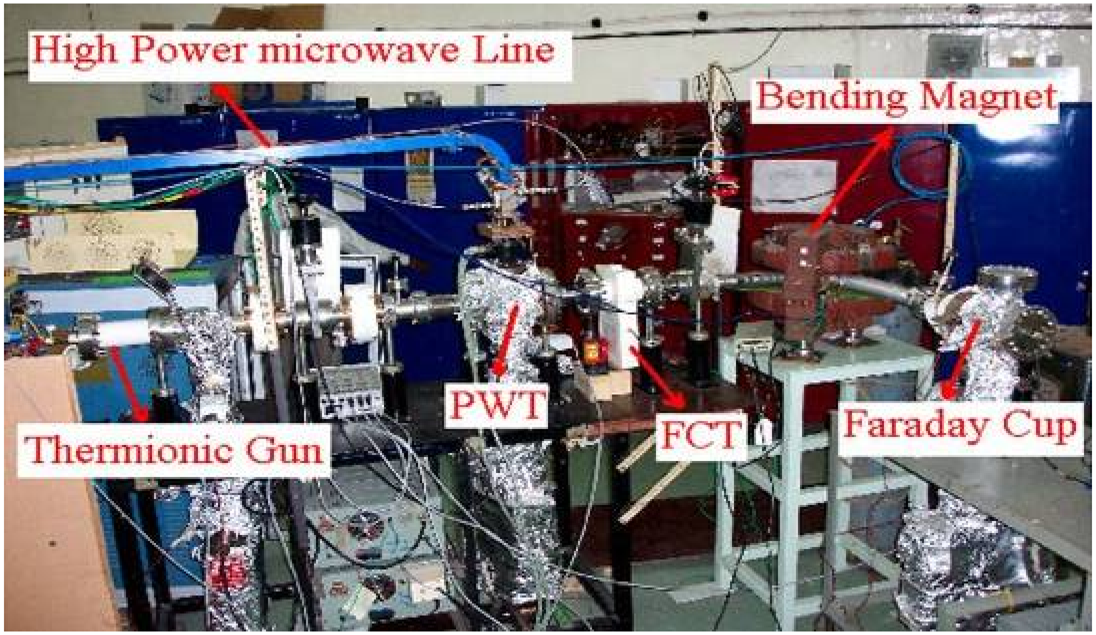
10MeV, 10kW electron LINAC

6MW, 2856 MHz MICROWAVE SOURCE

Parts of PWT Linac for THz Source

Variable Gap PM Undulator





Status (as of Nov 06):
PWT has been built;
beam accelerated and
passed through Undulator,
producing First THz
radiation signal @ ~500μ.

Fully indigenous
He Liquefier 15 l/ hr Development

Indigenous Development of Turbo Molecular Pump of ~150- 350 l/s Pumping Speed

Single & Two stage Cryo-coolers giving ~10K

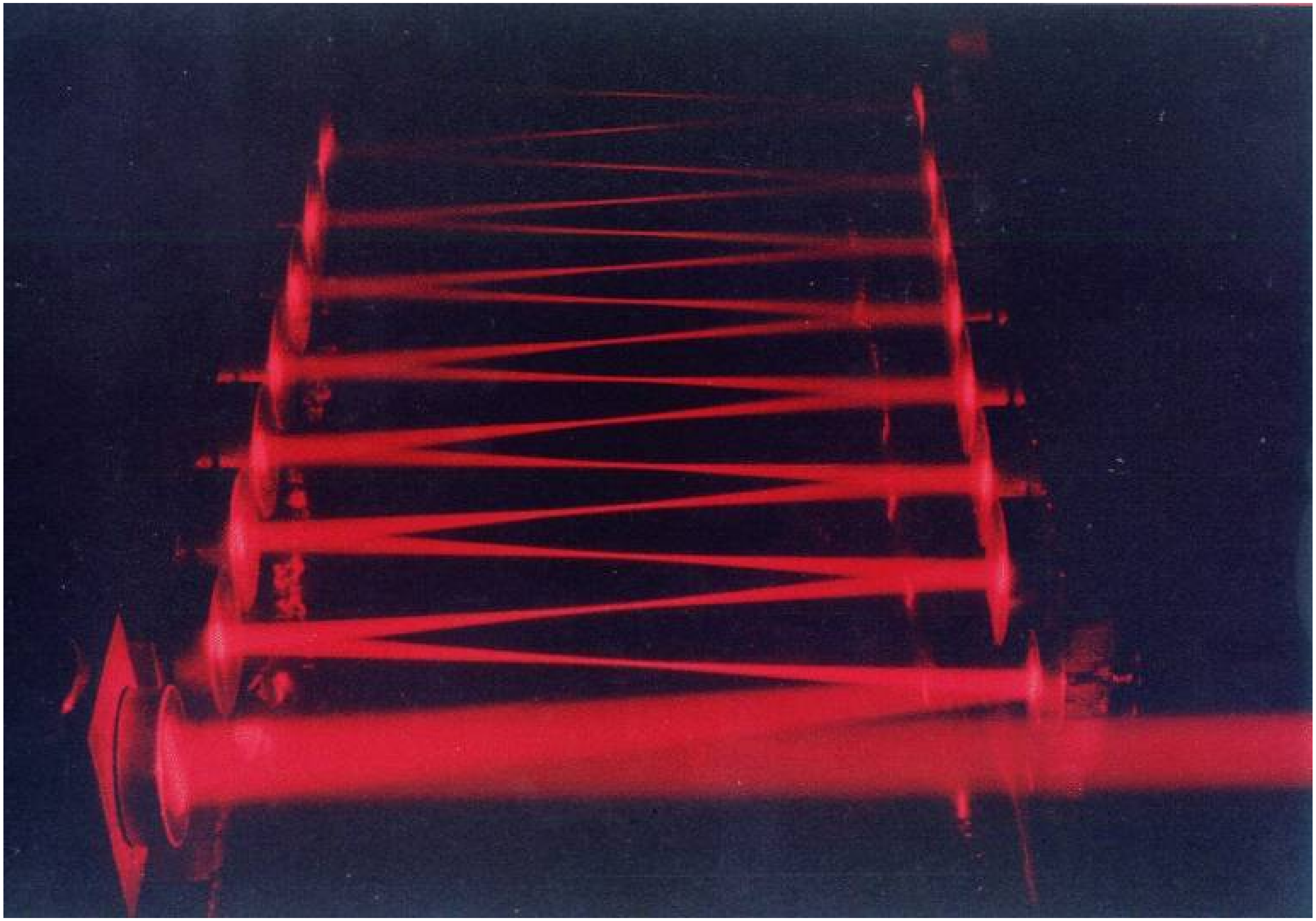
Copper vapour laser developed

3.5 kW CW CO2 Laser with CNC Workstation

High Rep. Rate TEA CO_2 Laser

20 kW CW CO_2 Laser

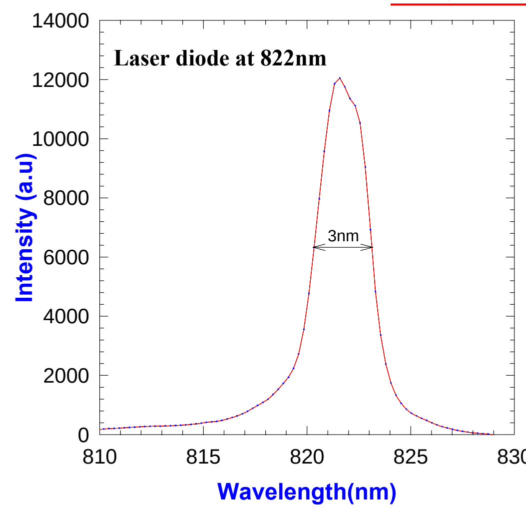
Multi-pass set up for isotopic enrichment of C13 using carbon dioxide laser. The arrangement gives nearly doubly efficient photon utilization.

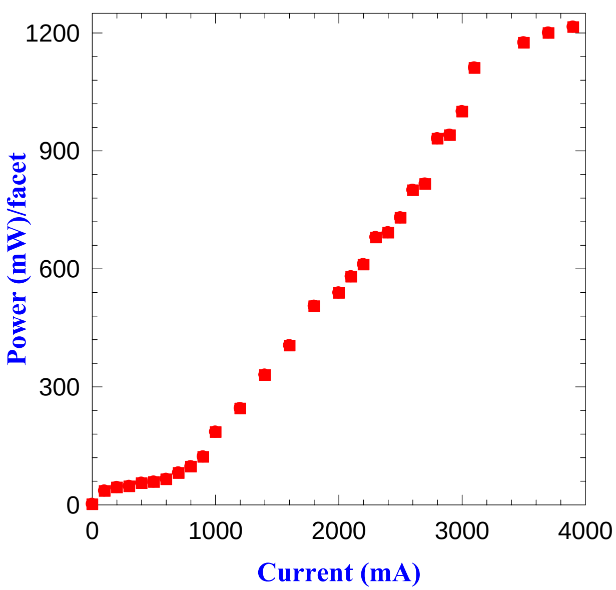


Typical MOVPE growth conditions

Growth Temperature
~ 770/600 °C for AlGaAs/GaAs
Growth rate
~ 5/2.5 Å/s for AlGaAs/GaAs
V/III ratio
~ 100/150 for AlGaAs/GaAs
Reactor Pressure
~ 50 mbar
Precursors
TMGa,TMAl & TMIn and AsH_3 , PH_3
DEZn & SiH4 for doping

Laser Spectrum of First Laser Diode





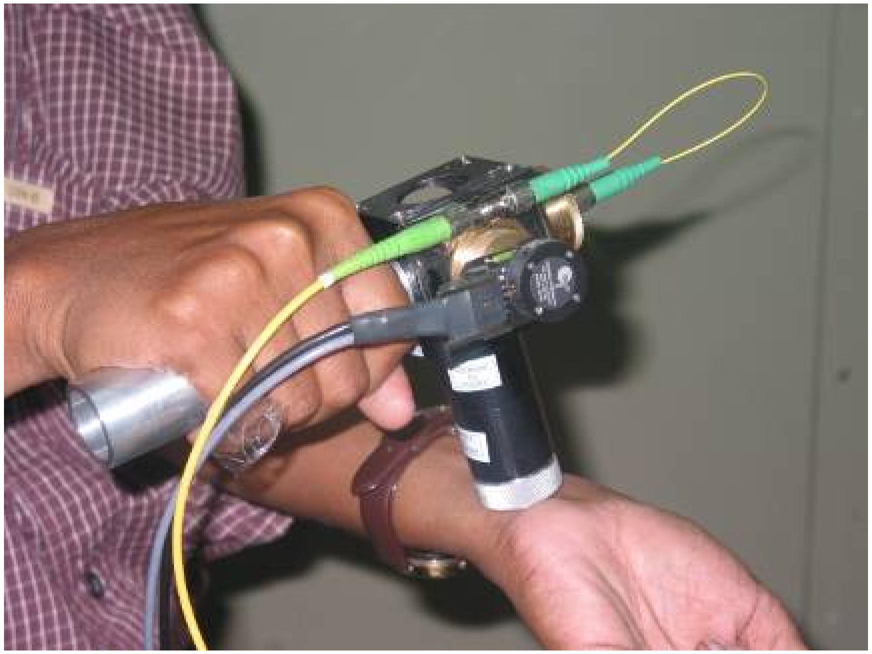
Laser Action in First Semiconductor Diode Structure grown in RRCAT

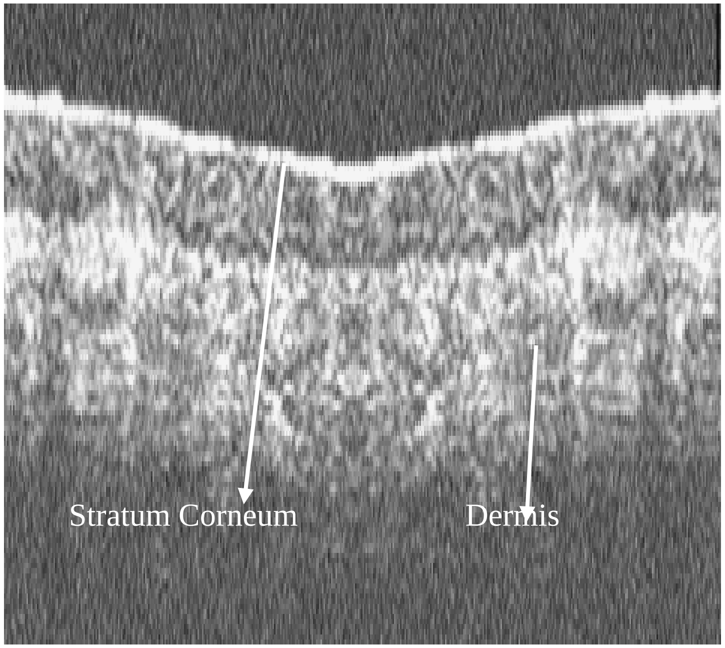
Diagnosis of Cancer Using Laser Induced Fluorescence

Studies on human tissues done to assess its potential for cancer diagnosis

	Training Set		Validation Set	
Diagnostic Algorithm	Sensitivity (%)	Specificity (%)	Sensitivity (%)	Specificity (%)
PCA	83	66	80	58
FLD	83	99	73	92
MRDF	93	96	95	96
SVM	90	96	87	96
RVM	86	97	85	97

Handheld probe for real time imaging using Optical Coherence Tomography





* Records 8 frames per second

Axial and lateral resolution ~18μm

Nd:YAG Laser based bellow-lips cutting & welding set up for use in PHWRs. (4 systems given to & used at NAPS)

Laser cutting mock-up for bellow lip

Salient features

- MANREM reduction
- Ease in system handling
- Time saving
- Reliable operation

Separated bellow lip

Bellow lip cutting fixture

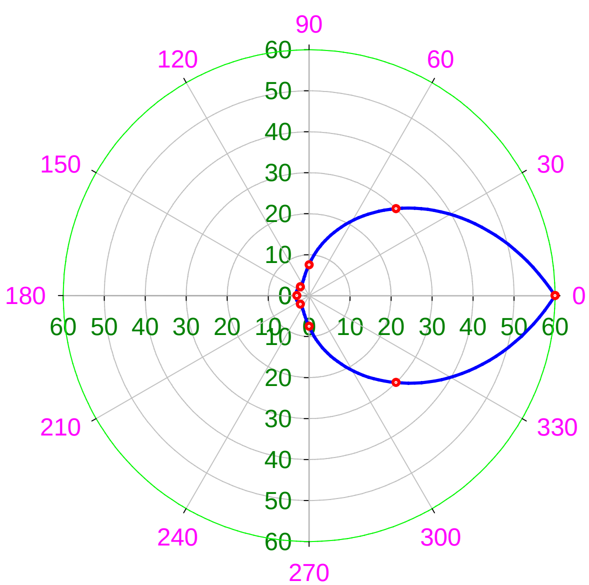
Welded bellow lip

Ultra-high Intensity Laser-Plasma Interaction

10 TW Titanium Sapphire Laser

Pulse duration	48 femtoseconds
Pulse energy	150 mJ (500mJ)
Pulse repetition rate	10 Hz
Pulse power	3 TW (10TW)
Beam waist radius	9 μm
Intensity at the focus	> 10^{18} W cm^{-2}
M^2 parameter	1.3

X-ray dose from Cu target

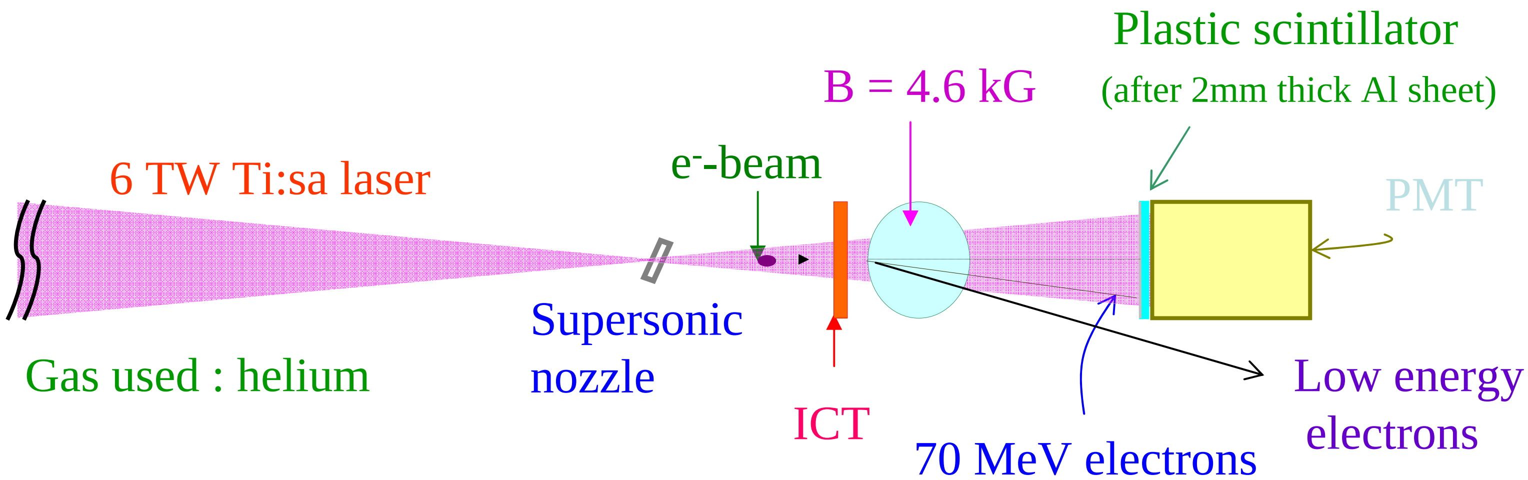


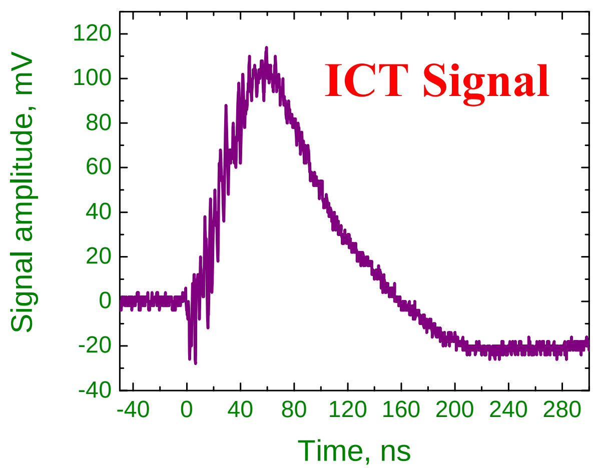
Through 12mm Al

Angular distribution

Maximum 60 mR/hr

Laser based Electron Acceleration





Electron energy > 70 MeV

Total charge: 2.7 nC

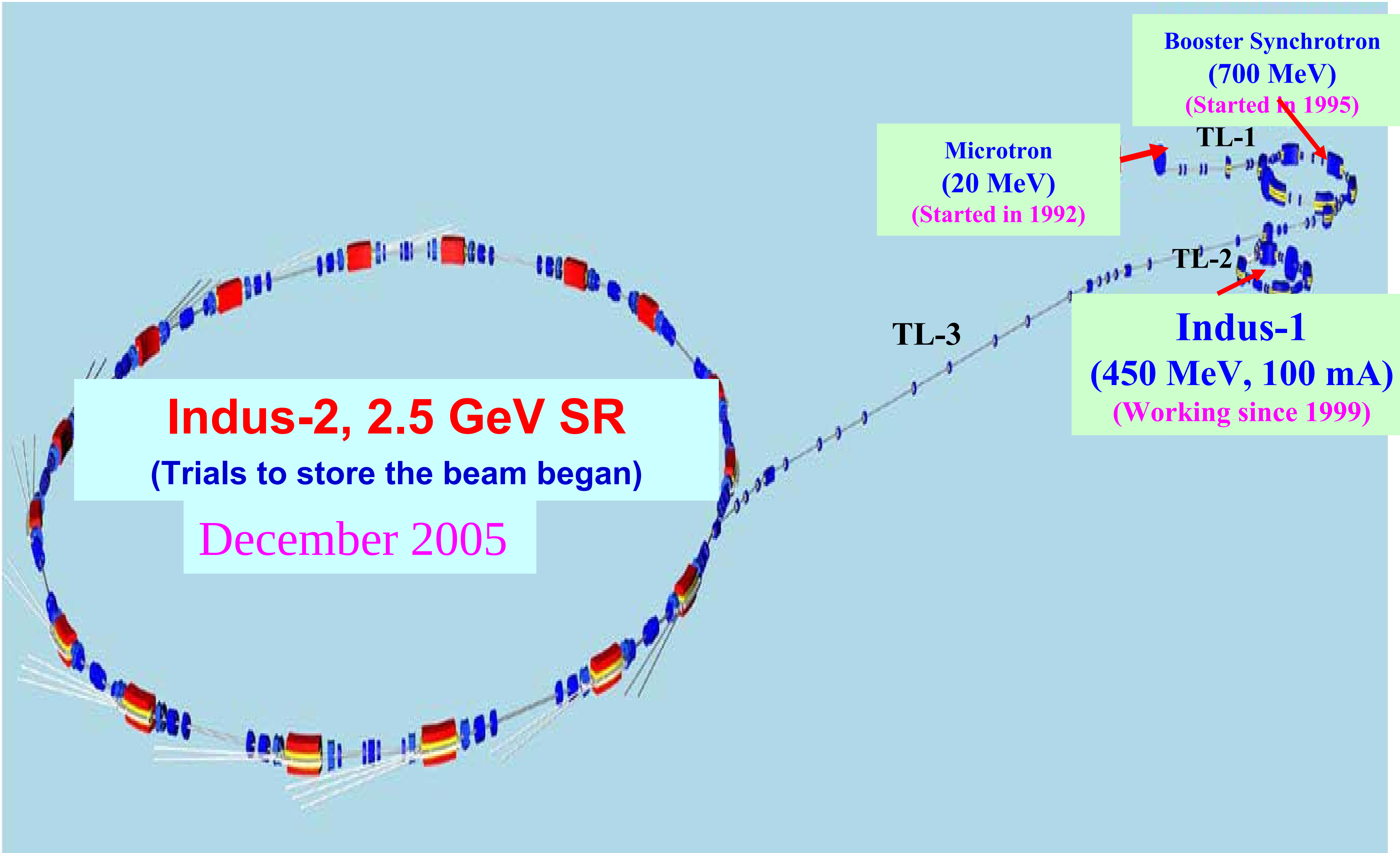
No. of electrons ~ 1.7×10^{10}

SRS Program at RRCAT

Hallmark of Our SRS Program is

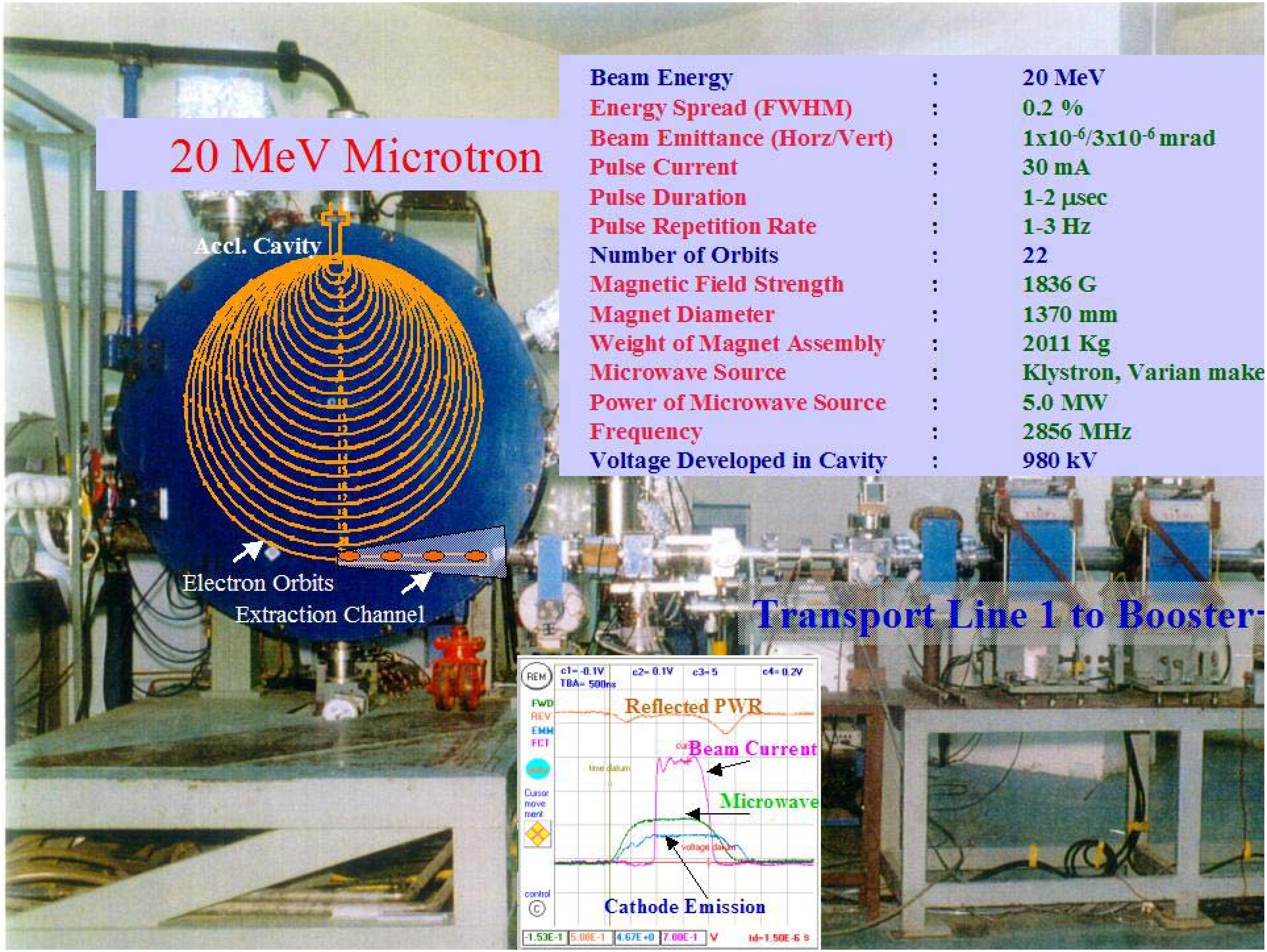
- Intense focus on ***indigenous development & qualification*** of **most of the sub systems** through **home based efforts**.
- These include the magnets & their power supplies, vacuum chambers, ion pumps & gauges, beam diagnostic accessories, RF driver and control systems etc.
- ***Vendor development*** for many high quality components for these accelerators.

SCHEMATIC VIEW OF INDUS COMPLEX



Status:Indus-2, TL-3 Fully Integrated;~35 mA accumulated.
Injection @550MeV, beam energy ramped up to 2.4 GeV.

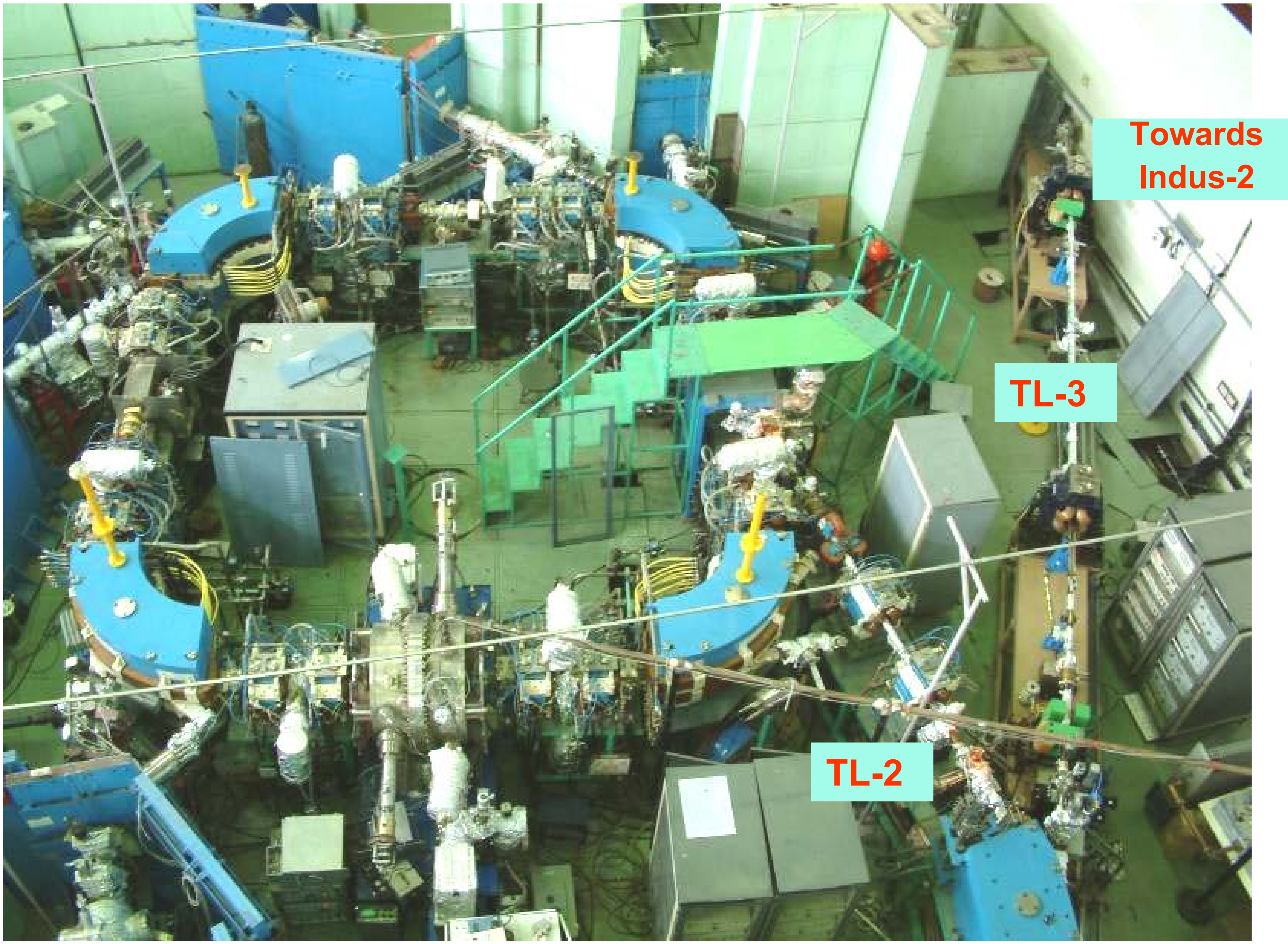
20 MeV Microtron



Beam Energy	:	20 MeV
Energy Spread (FWHM)	:	0.2 %
Beam Emittance (Horz/Vert)	:	$1x10^{-6}/3x10^{-6}$ mrad
Pulse Current	:	30 mA
Pulse Duration	:	1-2 μsec
Pulse Repetition Rate	:	1-3 Hz
Number of Orbits	:	22
Magnetic Field Strength	:	1836 G
Magnet Diameter	:	1370 mm
Weight of Magnet Assembly	:	2011 Kg
Microwave Source	:	Klystron, Varian make
Power of Microwave Source	:	5.0 MW
Frequency	:	2856 MHz
Voltage Developed in Cavity	:	980 kV


700 MeV Booster Synchrotron
TL-1

Indus-1 Hall, Beam-lines, TL-2 & TL-3



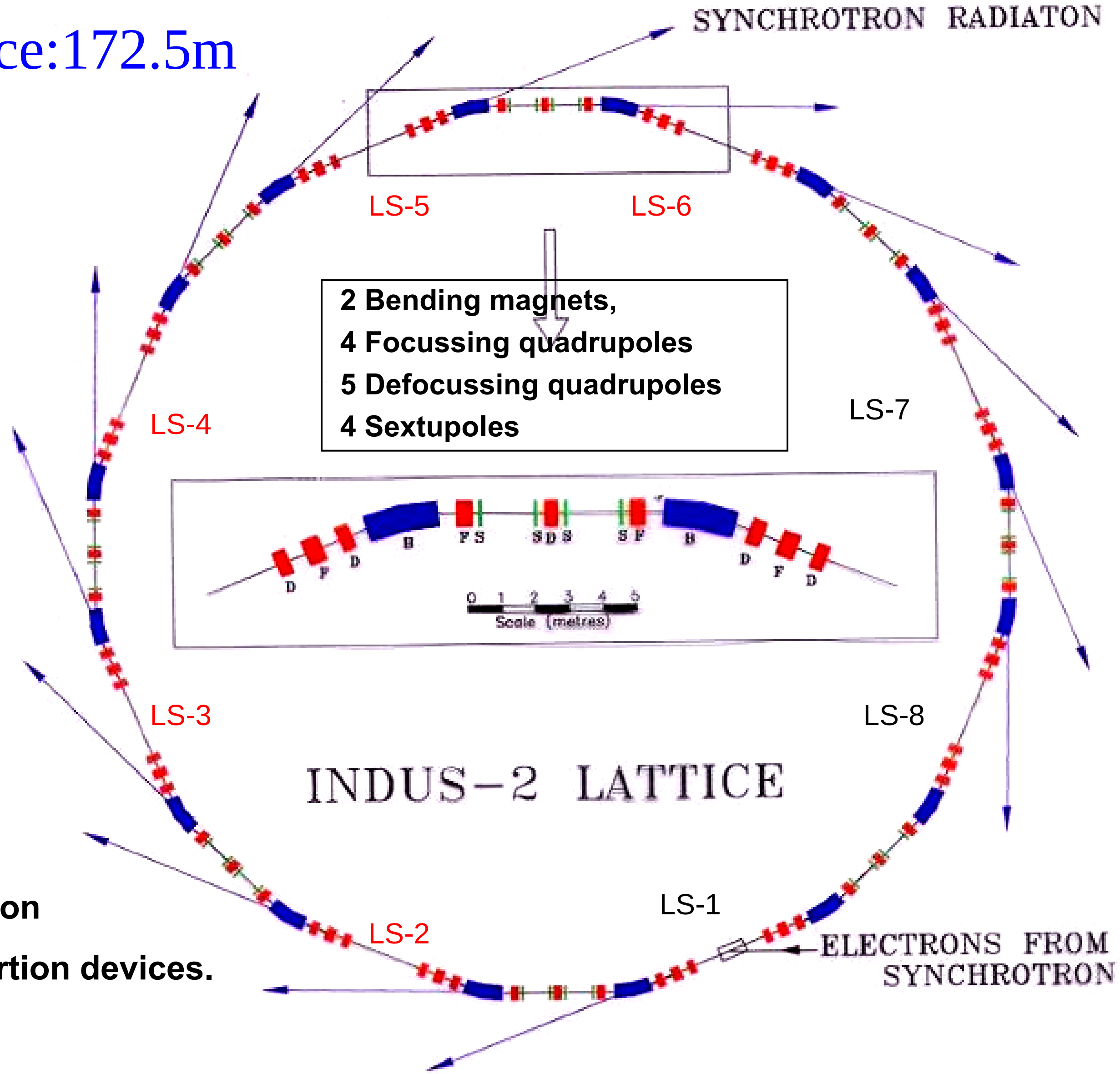
Indus-2 Program

&

Related Developmental Activities

Indus – 2 lattice & its components

Circumference:172.5m



LS-1: used for injection

LS-2 to LS-6: for insertion devices.

LS-7: Unusable

LS-8: for RF cavities

PARAMETERS OF Indus-2

Maximum energy		:	2.5 GeV
Maximum current		:	300 mA
Lattice type		:	Expanded Chasman Green
Superperiods		:	8
Circumference		:	172.4743 m
Bending field		:	1.502 T
Typical tune points		:	9.2, 5.2
Beam Emittance	εx	:	5.81×10^{-8} mrad
	εy	:	5.81×10^{-9} mrad
Available straight section for insertion devices		:	5
Maximum straight length available for insertion devices		:	4.5 m
Beam size	σx	:	0.234 mm
(Centre of bending magnet)	σy	:	0.237 mm
Beam envelope vacuum		:	$< 1 \times 10^{-9}$ mbar
Beam life time		:	15 Hrs
RF frequency		:	505.812 MHz
Critical wavelength		:	1.98 Å (Bending Magnet) 0.596 Å (High Field Wiggler)
Power loss		:	186.6 kW (Bending magnet)

Magnets:

Dipoles : 16; Q'poles: 32 focusing & 40 defocusing type; S'poles: 32

Indus-2 Overview

1997 : Decision to make 2.5 GeV energy machine

1998- 2002 : Civil construction, adding infrastructure; design of major components & prototype development; material procurement for in-house production & vendor identification for series production etc.

2000-2004 : Subsystem fabrication/evaluation phase.

2004-2005 : Installation & final commissioning in tunnel.

2006 : Beam storage & energy ramping (up to 2.4 GeV)

Cost : ~Rs. 95 Crores (Cost of machine & building).

Indigenous Systems Developed : Vacuum chambers, magnets, power supplies, beam diagnostics and RF power system etc.

Imported Items: RF cavities & Klystrons.

Main Dipole Magnet of Indus-2

Coil winding, assembly & testing at CAT (Yoke made by Godrej)

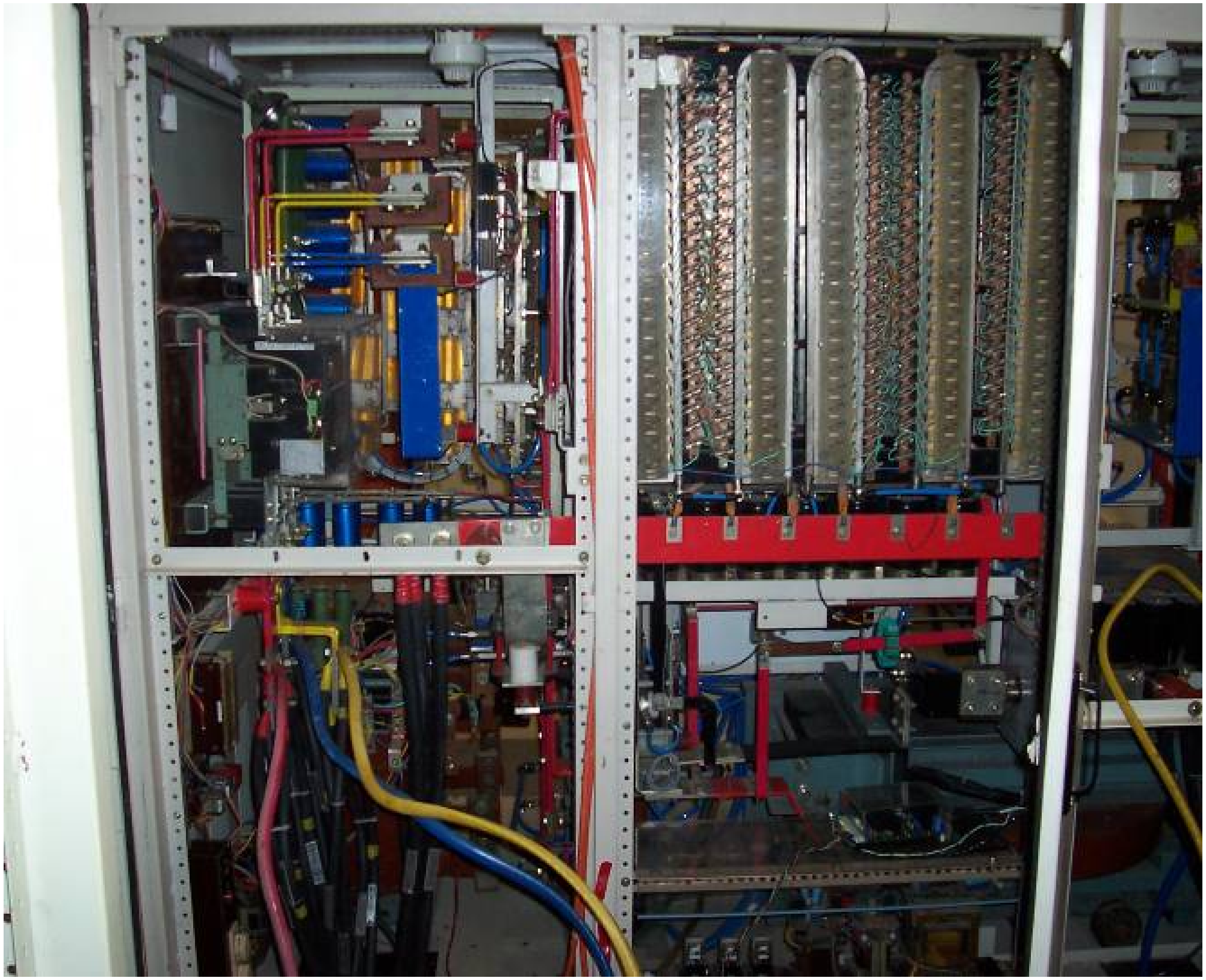
(Pole Gap: 50mm, Tolerance<50μm,flatness, parallelism<10 μm, Core length 2m±0.5mm; Field: 1.5T, NI: 70,000 Amp turns)

Indus-2 Q'poles & S'poles made by CMTI & CAT

(Q'p: Field:16T/m; NI:13,000 A turns; Gap: 85 mm)
(S'p: Field: 400T/m2; NI: 5,700 A turns; Gap: 92 mm;
Tolerance on Geometry: pole gap < 50 μm)

Indus-2 Dipole Power Supply

One P/S for 16+1 dipole magnets, **Current 200 - 900 Amp, Stability ~ ± 50 ppm & ripple ~ ± 100 ppm**; Max Voltage 680 Volts

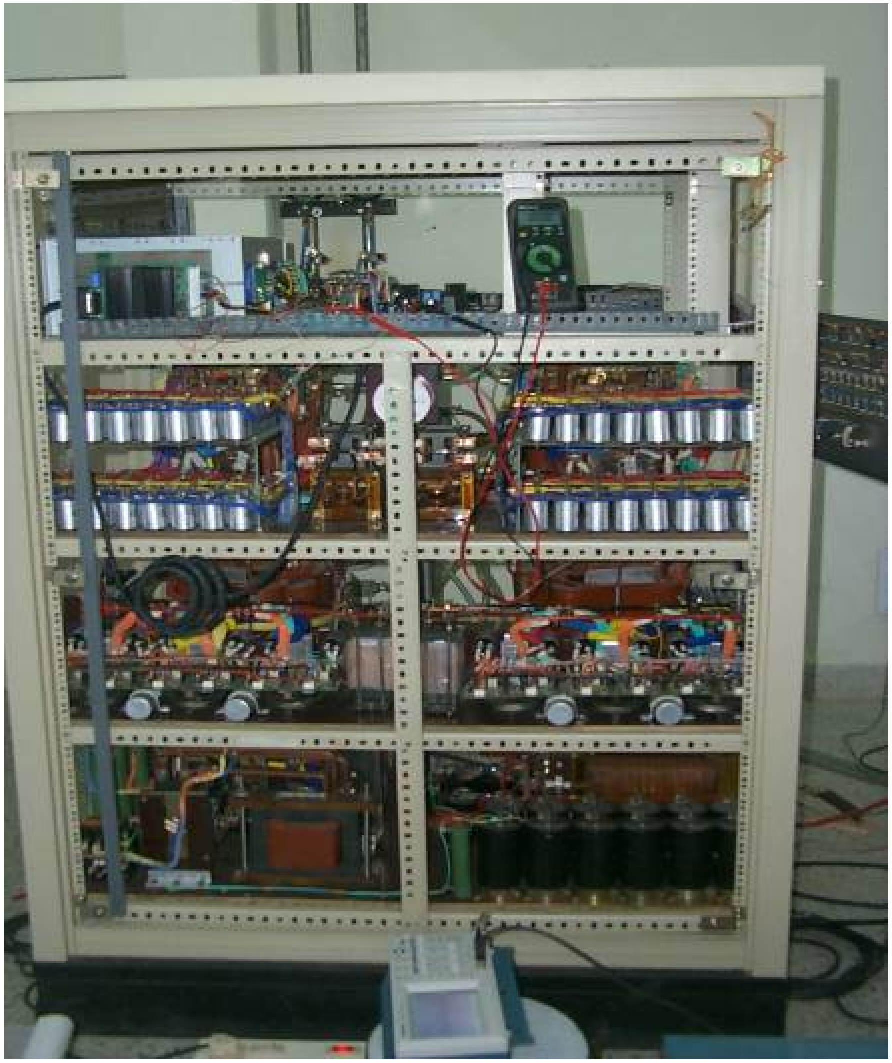


Indus-2 Q/P-1,2,3 Magnet P/S

8+8+8 P/S for Q-pole magnets, **Current 30-180 Amp, Stability ~ ± 50 ppm & ripple ~ ±100 ppm;** Max Voltage 87 - 119 Volts

Indus-2 Sextupole Magnet P/S

Two P/S for 32 Sextupoles magnets, **Current 40-230 Amp,**
Stability ~ ± 500 ppm & ripple ~ ±500 ppm; Max Voltage 300 Volts



RF System

Co-axial Line, Circulator & Klystron

Klystron Tube & Auxiliary PS / Interlock

Solid-state Driver Amplifier

Indus –2 RF Power System

Dipole Chambers

- Material: Aluminium alloy A5083-H321 (Machining of 2 halves done by HAL; Welding plus leak checking etc. done at CAT)
- Two beam ports at 5^0 and 10^0 in each dipole chamber
- Additionally, port at 0^0 is also provided in five dipole chambers for insertion devices

DETAILED INSIDE VIEW OF SEPTUM CHAMBER

Beam diagnostics

- Devices developed & deployed:

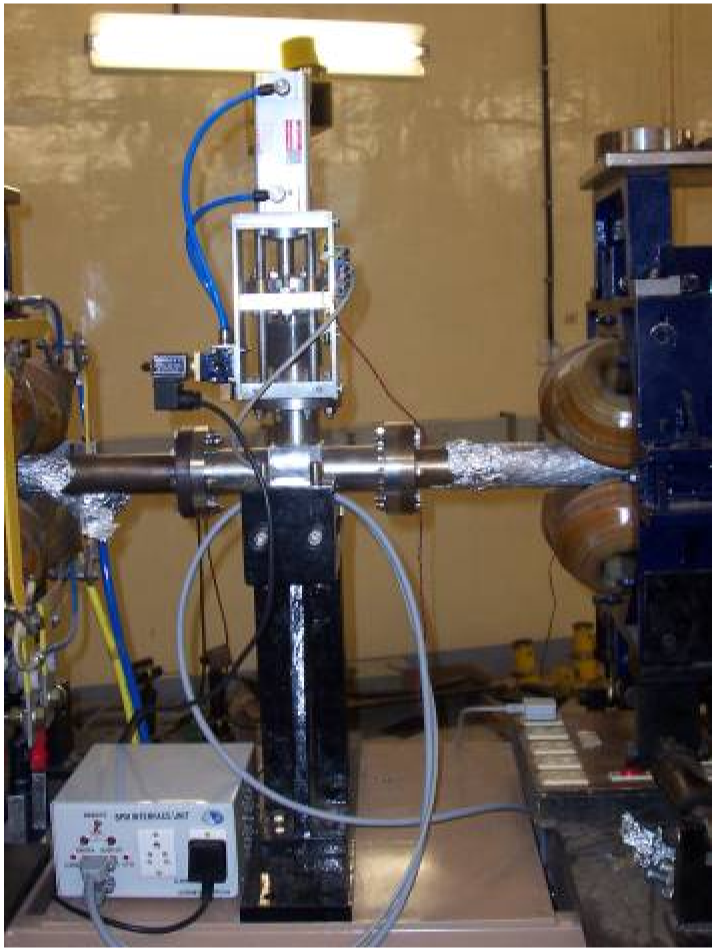
(1) Beam position monitors (electrostatic pick-up),
(2) Beam profile monitors
(3) Strip-line monitors
(4) DCCT
(5) Beam scrapers,
(6) Wall current monitors
(7) Secondary emission wire monitors
(8) Sighting beam-line: for visible & X-ray diagnostic.

- Main features are:

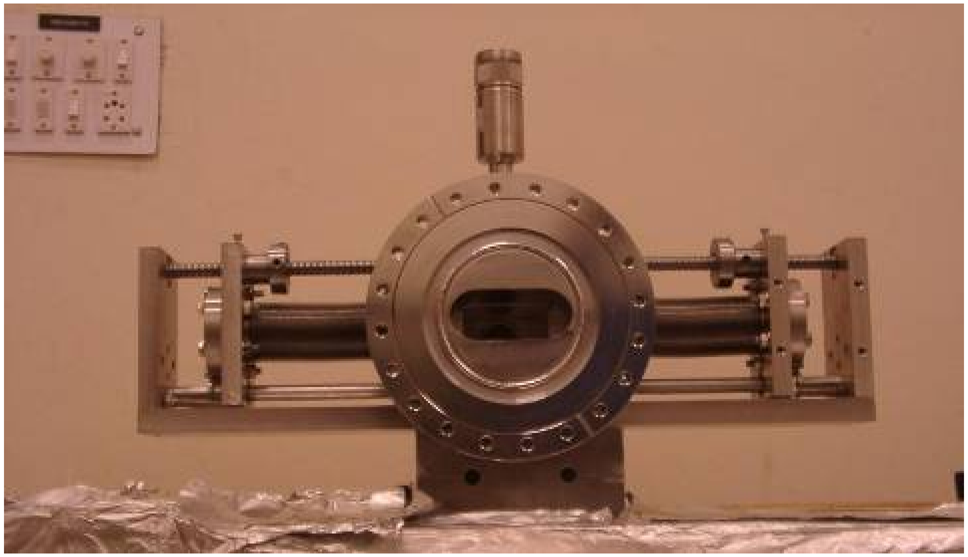
(1) UHV compatibility
(2) Precision fabrication/ assembly
(3) Fast signal processing capability etc.

Beam Diagnostic Components

Beam profile monitor



Horizontal Scraper during assembly



- Photon Absorber
  - To absorb unwanted photon x-ray radiation and protect the vacuum chambers
  - Material: OFHC Copper

Control System Boards

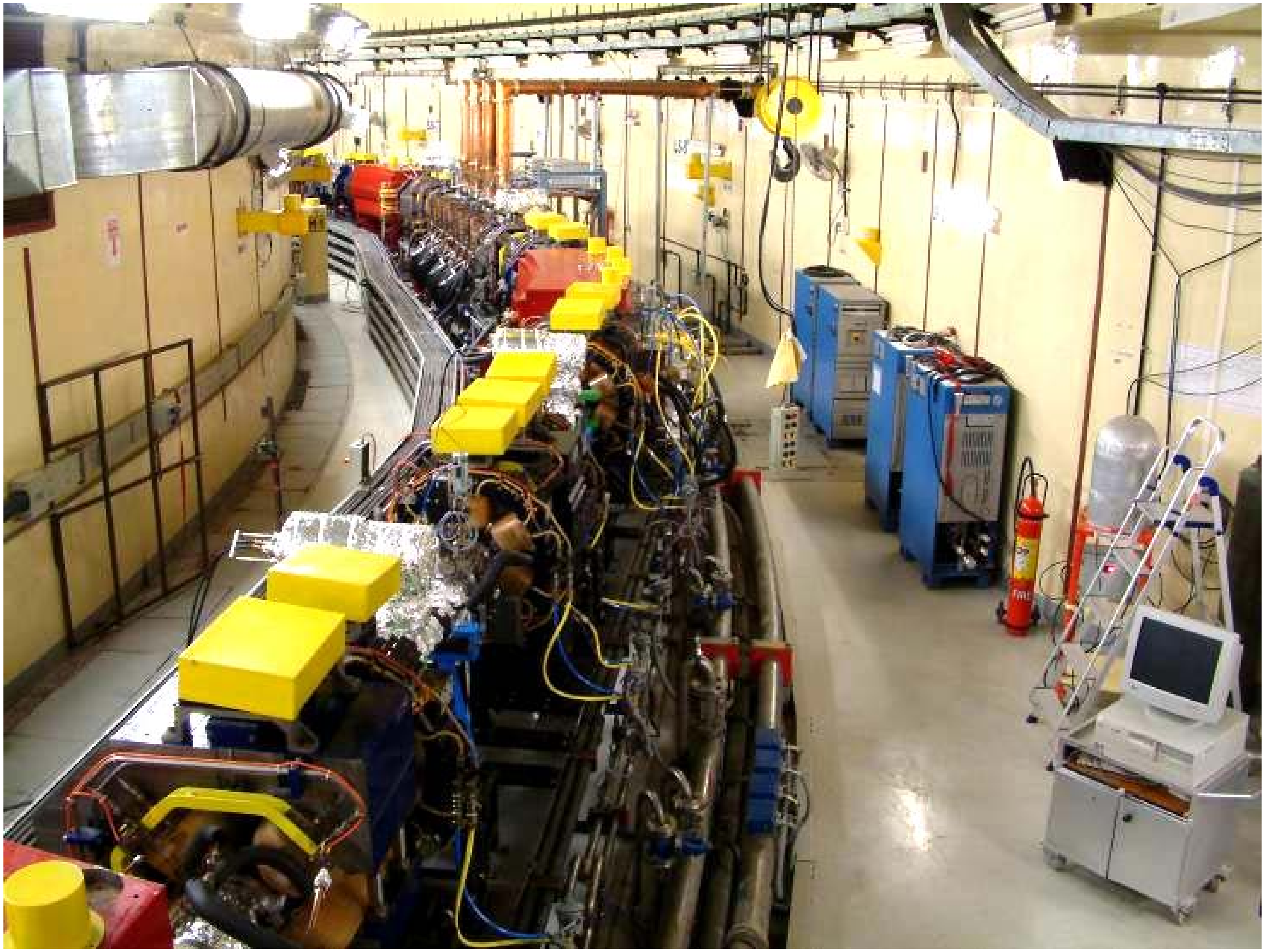
Various VME boards

Subsystem Qualification and Installation Details

1. All vacuum chambers were baked to get ~10^{-9} to 10^{-10} mbar before assembling in the ring.
2. All p/s were tested with dummy loads.
3. Field mapping done on each magnet. Data was used **to optimize magnet locations ie "which one to place where"for best performance of ring**.
4. This optimization was arrived at using the simulated annealing algorithm.
5. All Transfer Line (TL-3) & Indus-2 components were installed after full qualification.

Transport Line TL-3 under Assembly

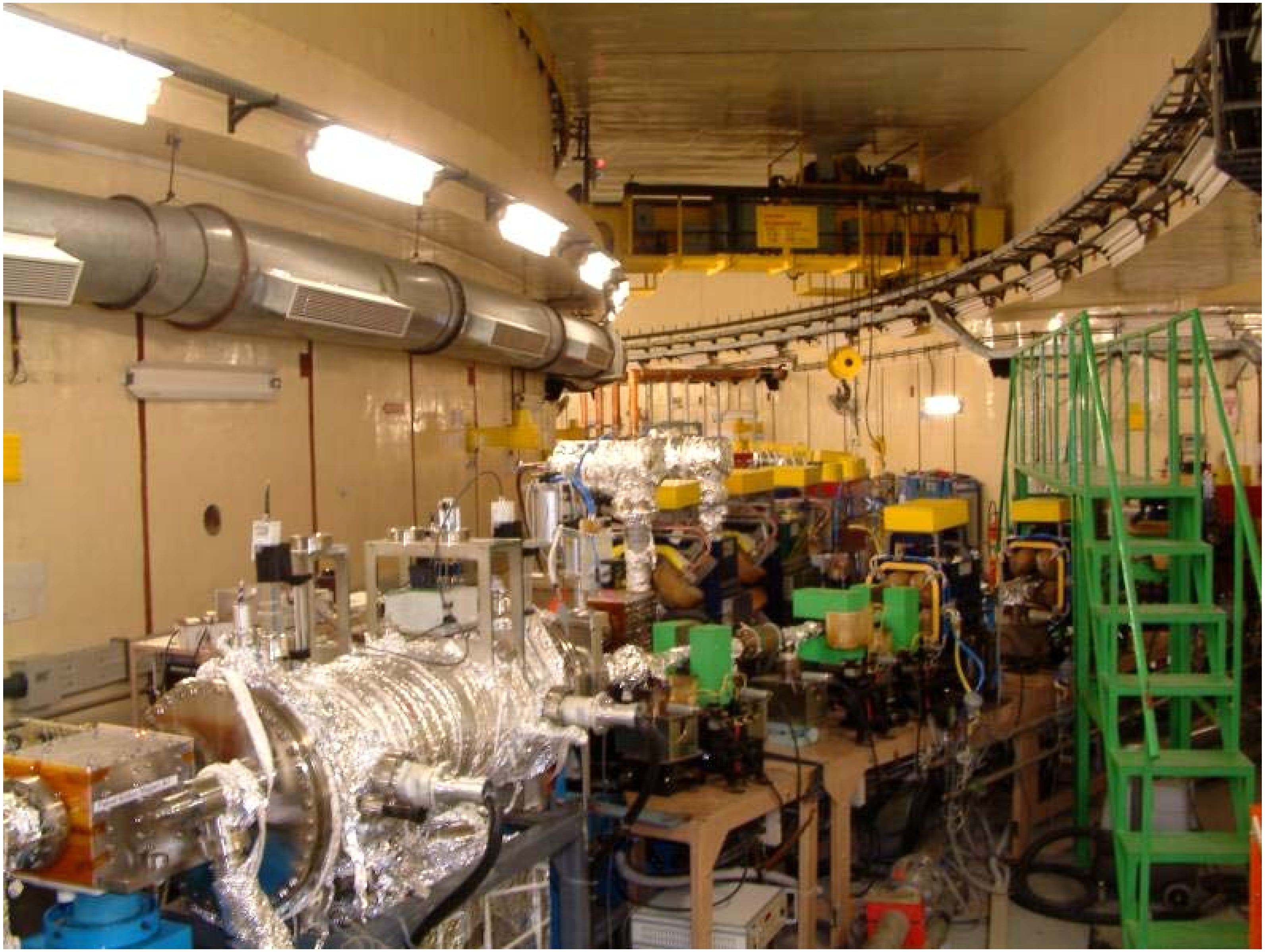
Assembly of Indus-2 Ring in the Tunnel



RF Cavities Commissioned in Indus-2 Ring

Long Straight Section LS-6 Assembly

Septum and Kicker



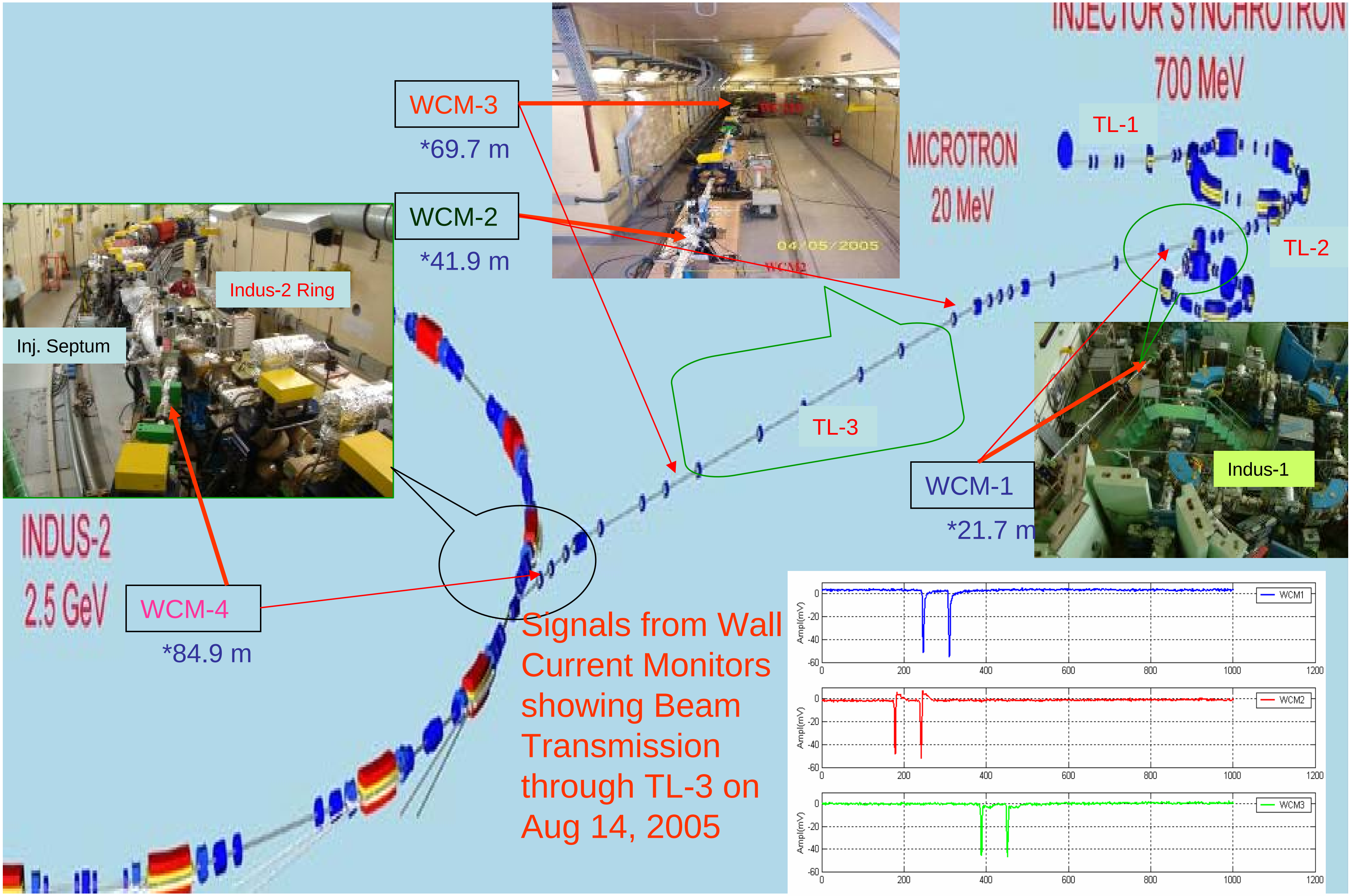
Transport Line-3 Joining on to Indus-2

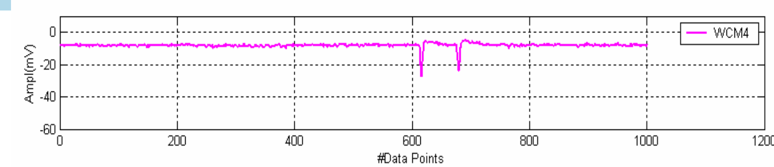
Control Room for Indus-1 & Indus-2

Details of Commissioning

Get SET Go

Photograph of Indus-2 team taken in the experimental hall on 11.08.05 after getting AERB's consent to start trial beam injection into the storage ring.

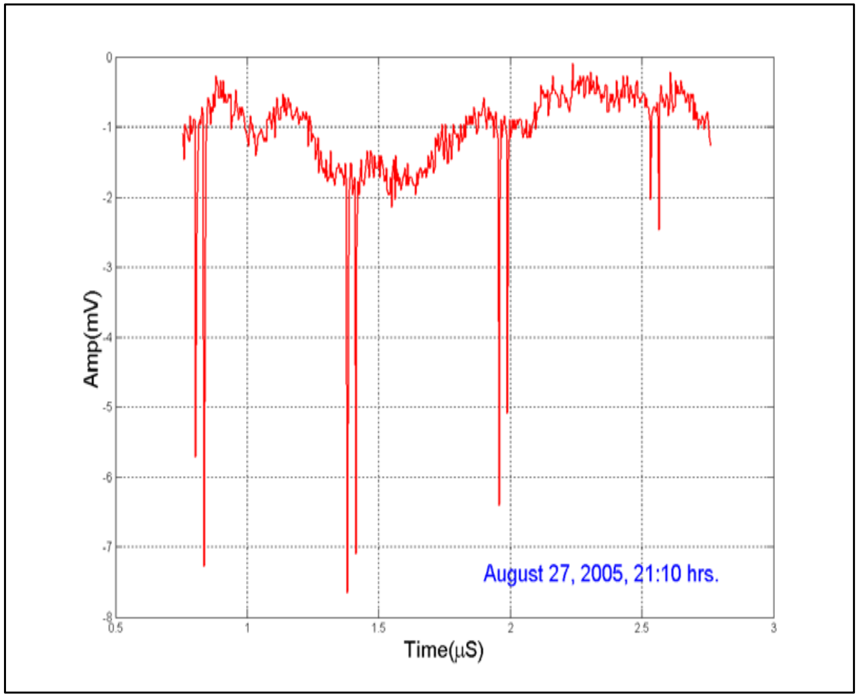




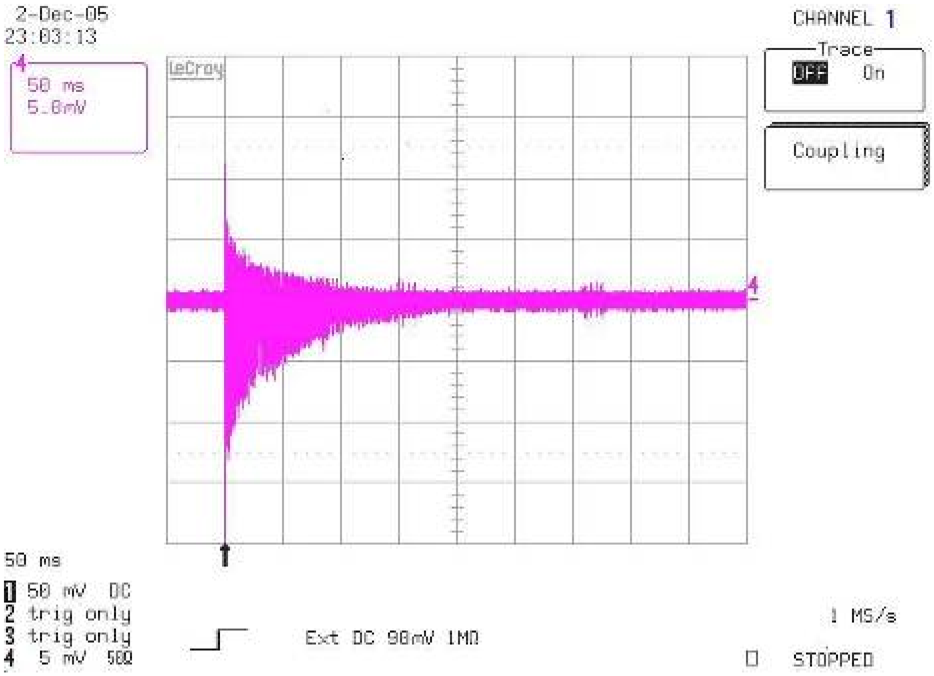
* Number designates the distance from extraction point on Booster Synchrotron

Four Turn Beam Circulation in Indus-2

- Four turn beam circulation seen on wall current monitor (WCM) signal on 27th August,2005

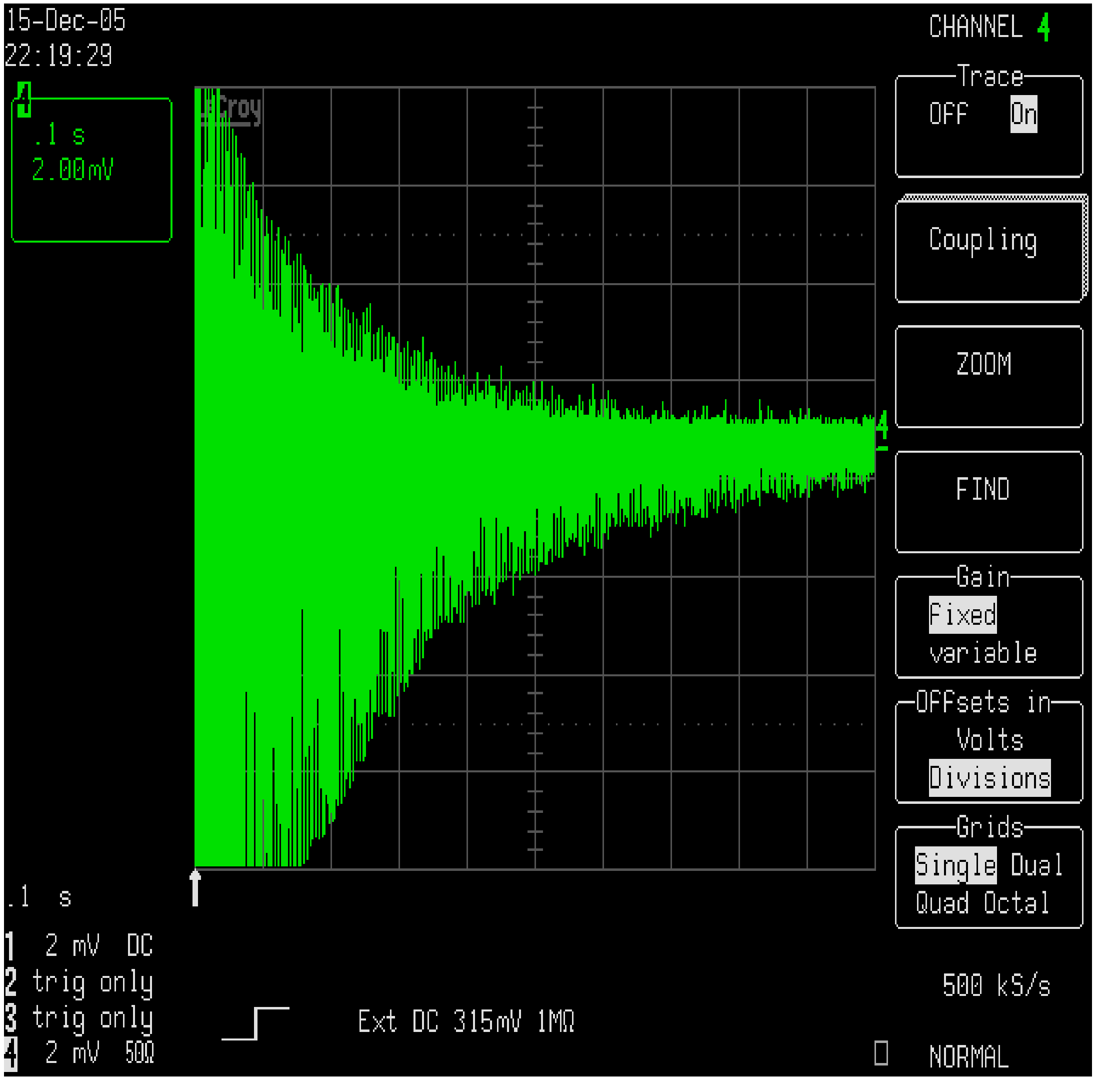


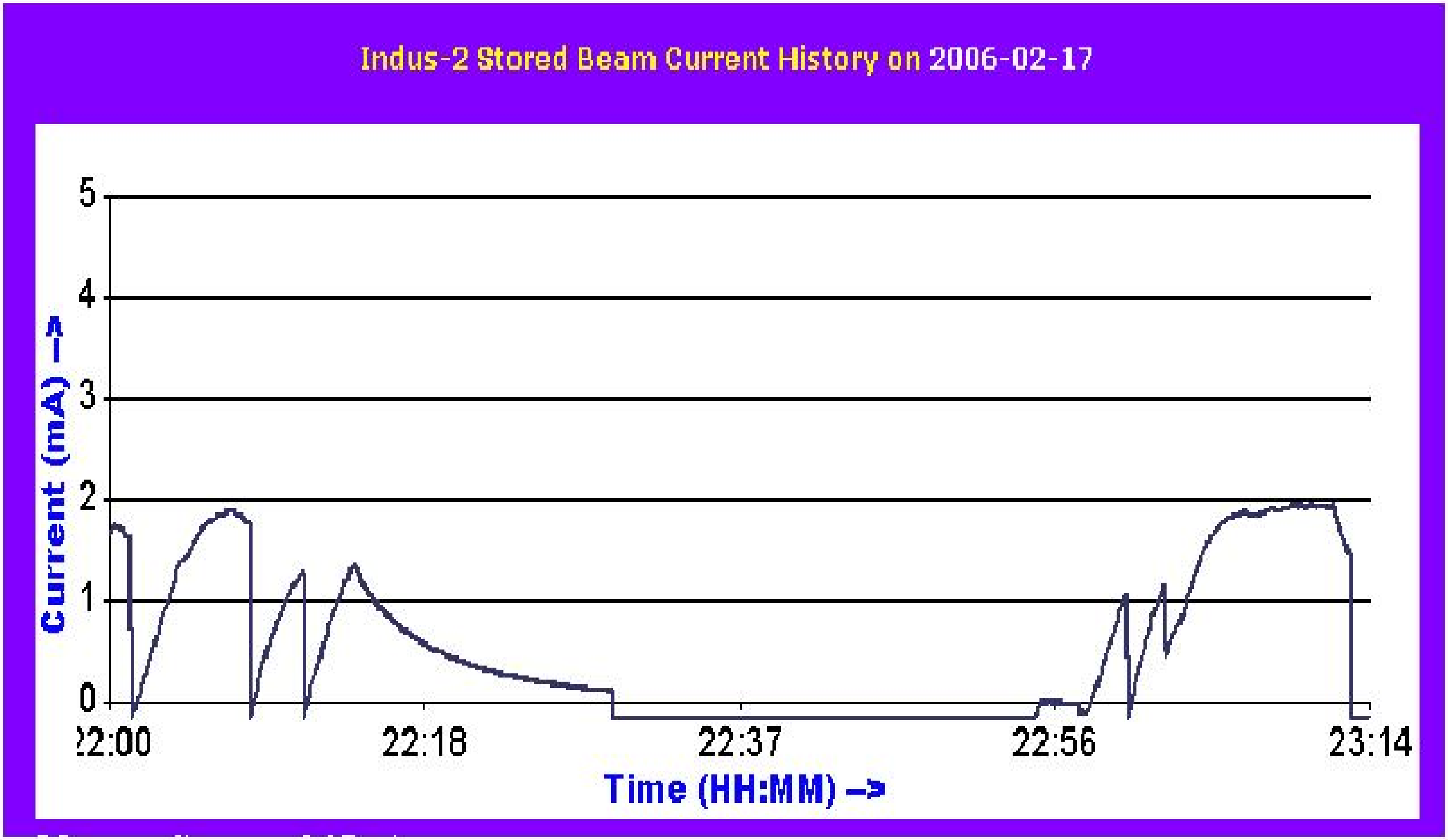
FIRST SYNCHROTRON LIGHT OUT OF INDUS-2
RECORDED ON DEC. 2, 2005
USING CCD CAMERA ON THE "SIGHTING BEAM-LINE"



CURRENT MONITOR SIGNAL INDICATING
SURVIVAL OF BEAM UPTO 200ms

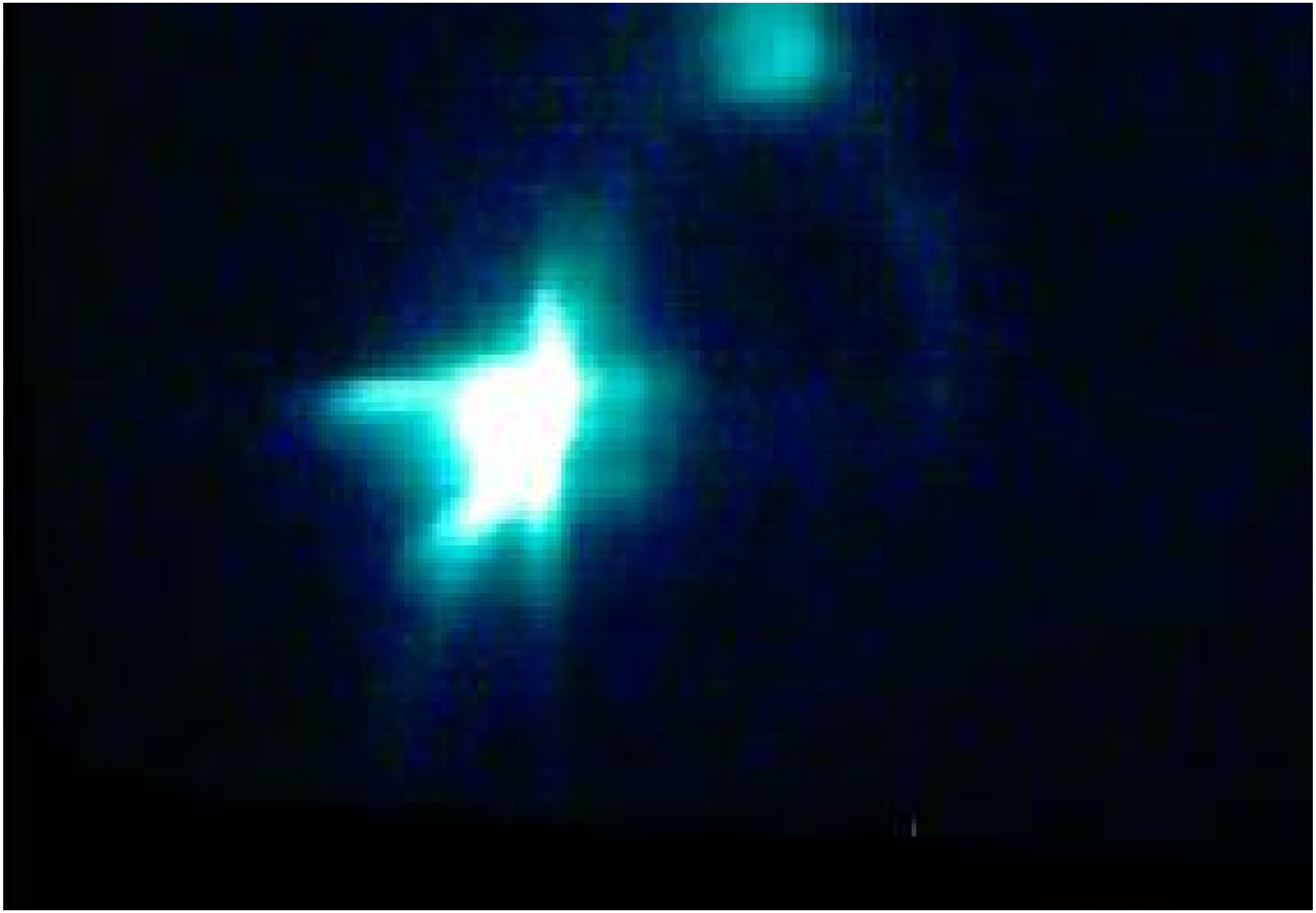
Beam circulation up to **1 second** was seen on wall current monitor on **15th December, 2005**





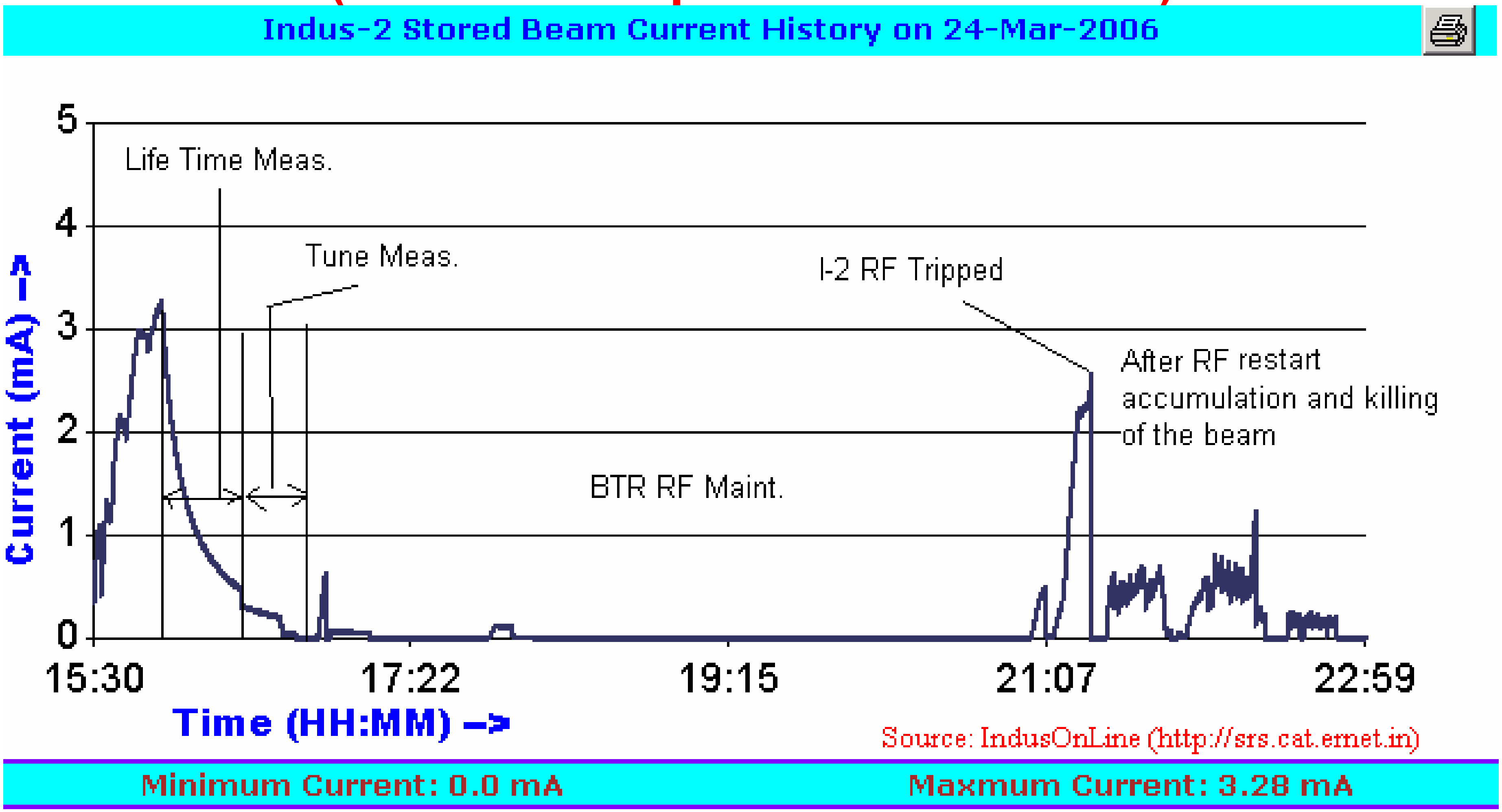
Maximum Current= 2.1 mA

Average Current recorded on DCCT (DC Current Transformer)

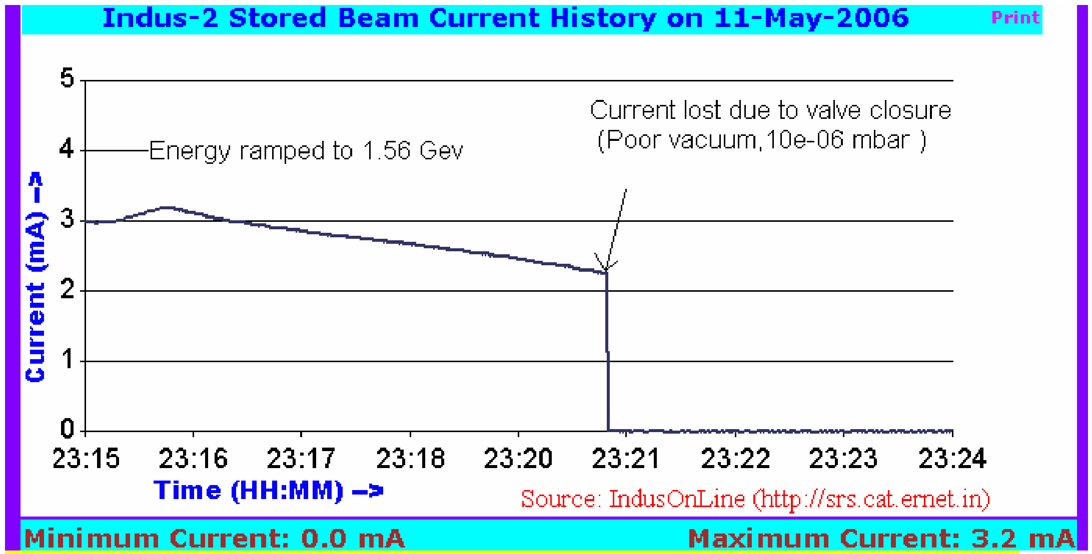


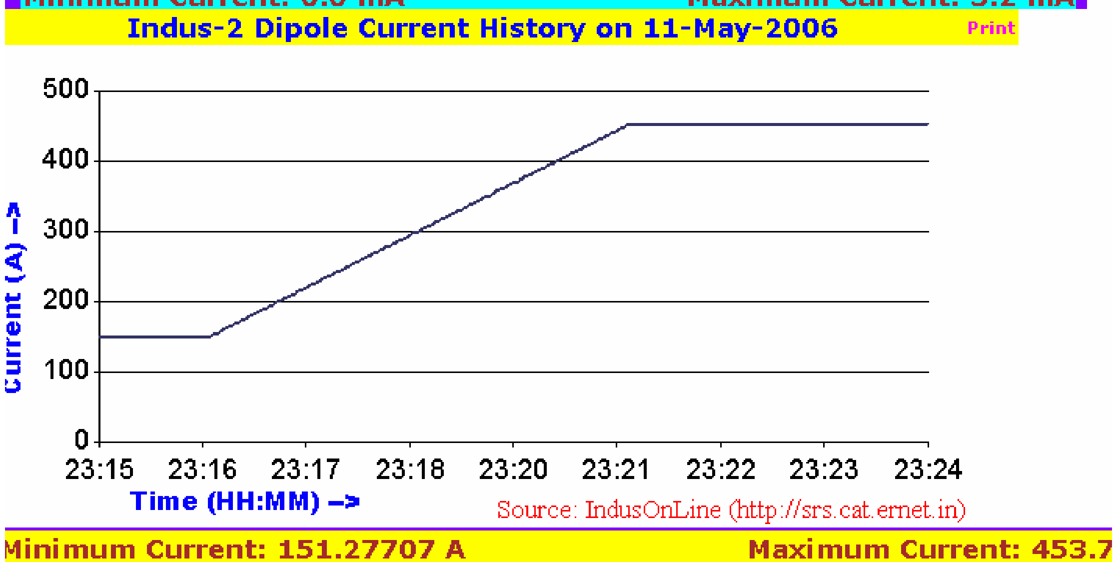
Synchrotron Light at 2mA Beam Current as seen by CCD onsighting beamline on Feb 17, 2006

Beam injected @ 543 MeV; Energy ramped to 590 MeV
(Results of experiments in Mar 06)

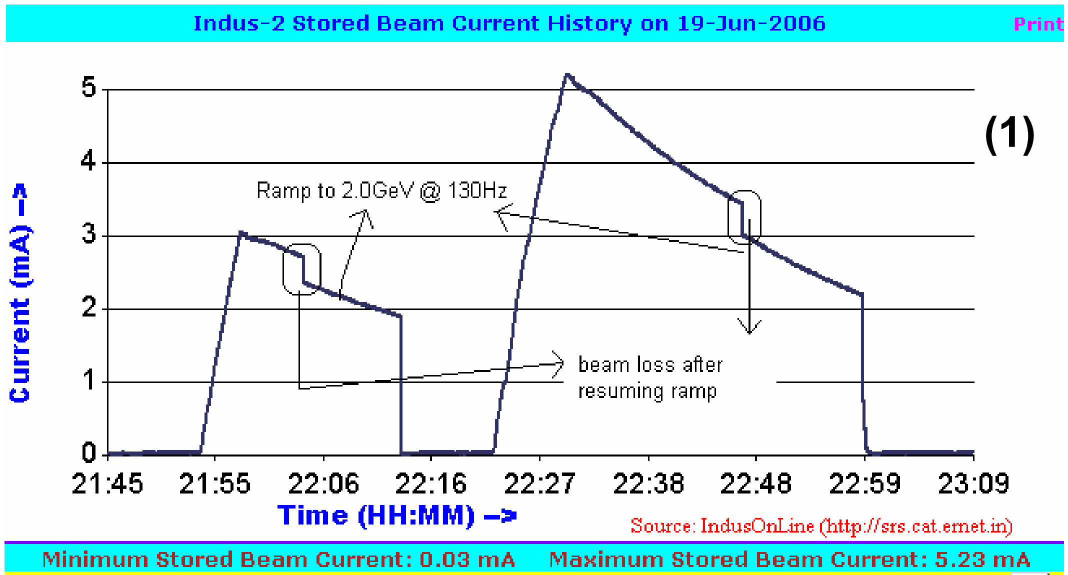


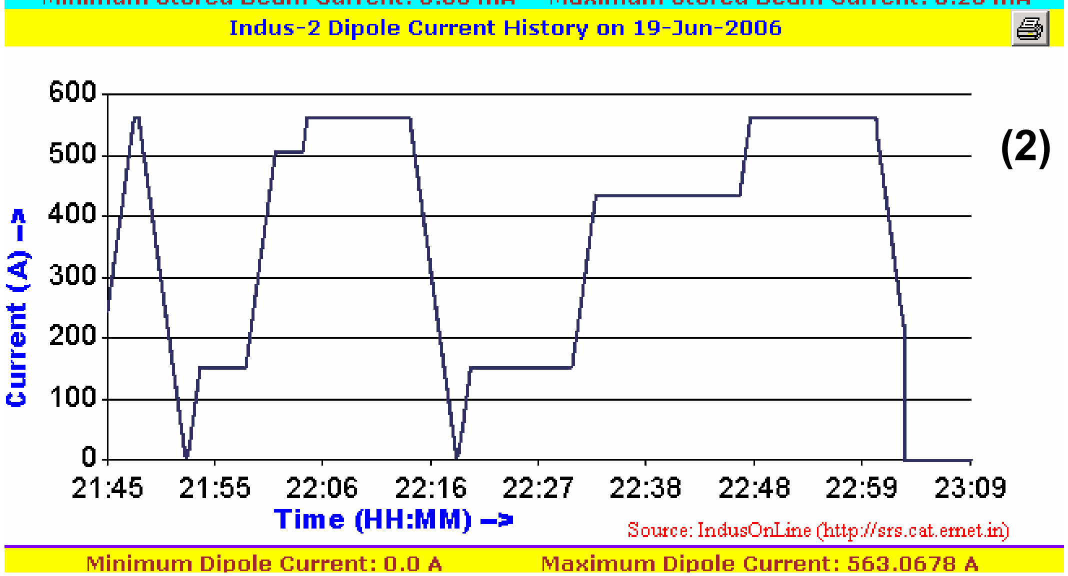
Successful energy ramping to >1.5 GeV in Indus-2 (May 11, 2006). Upper trace shows current in Indus-2; lower trace shows current in the dipole magnets. 150 Amps corresponds to 543 MeV ~450 Amps corresponds to 1.56 GeV.

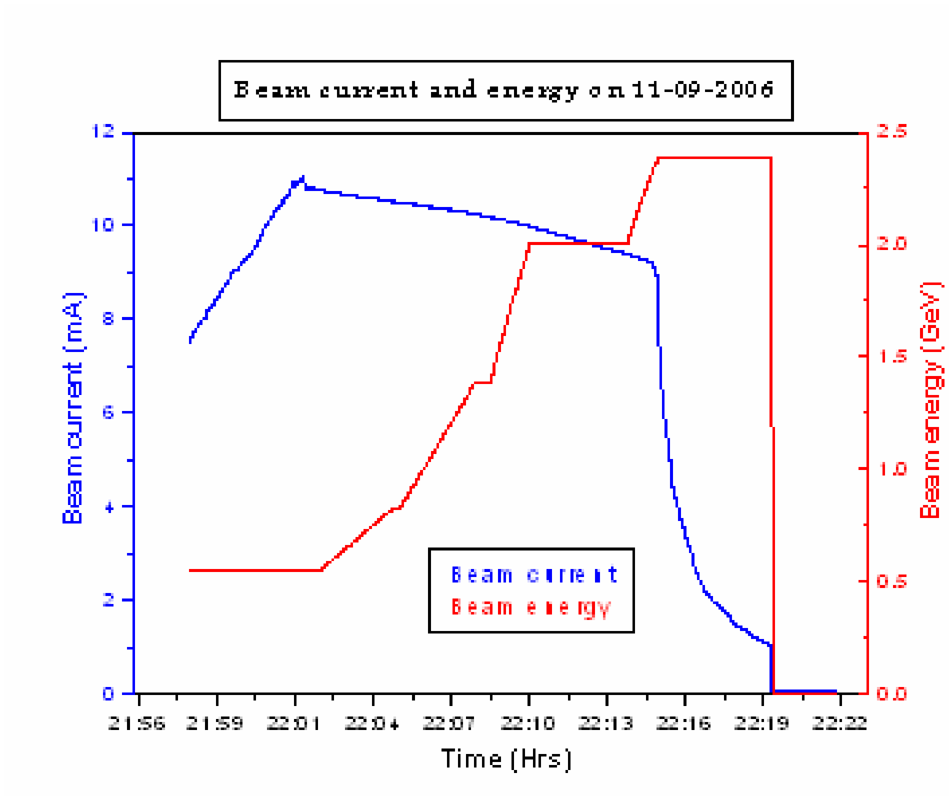




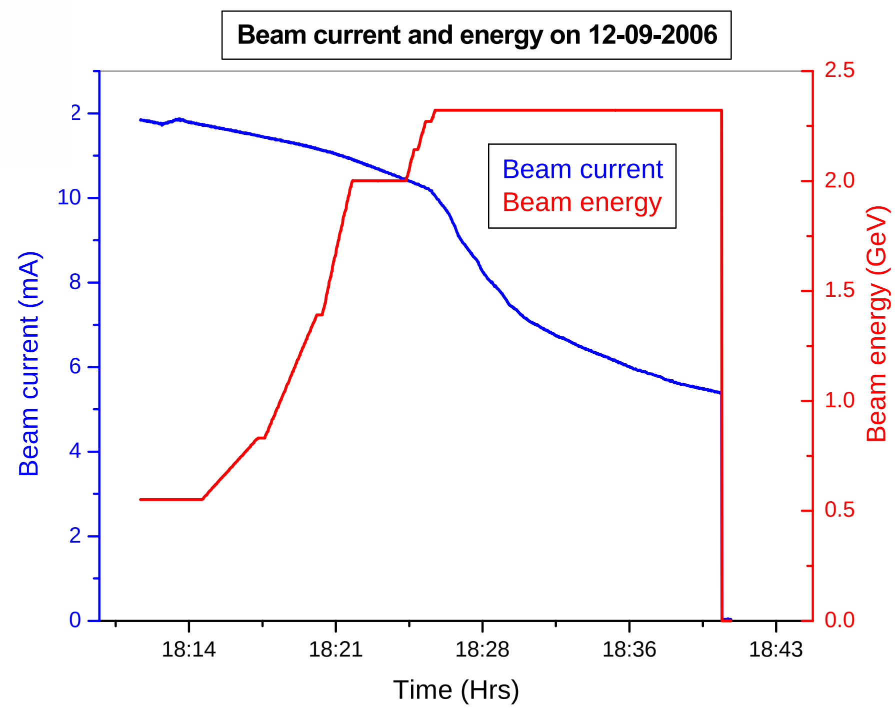
Successful energy ramping to 2 GeV (19/6/ 2006). (1) shows current in Indus-2; (2) shows current in the dipole magnets. 150 Amps corresponds to 543 MeV; ~550 Amps corresponds to ~2 GeV.



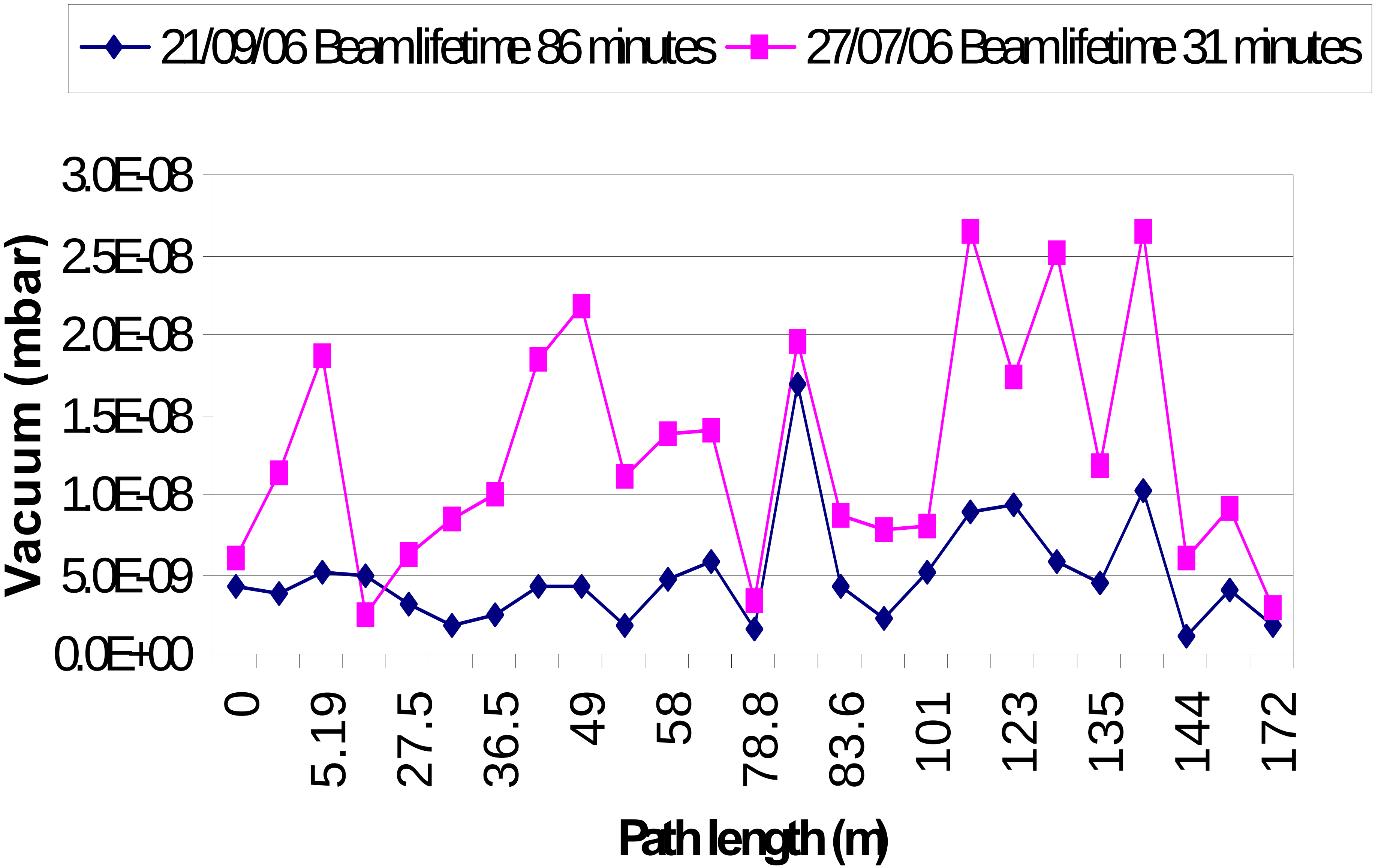




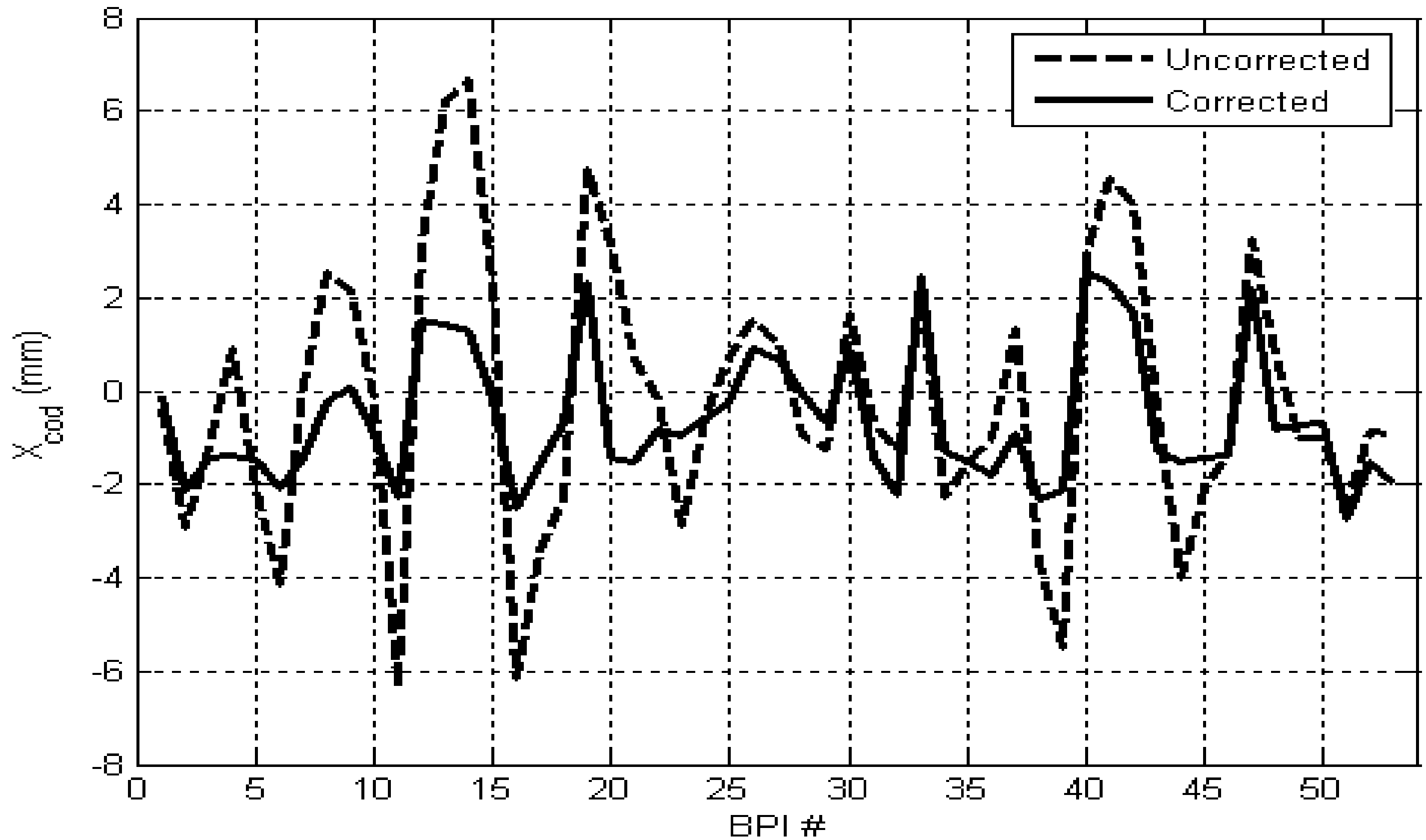
Beam current and energy on 11-09-2006
Beam current (mA)
Beam energy (GeV)
Beam current
Beam energy
Time (Hrs)
21:56
21:59
22:01
22:04
22:07
22:10
22:13
22:16
22:19
22:22



Beam current and energy on 12-09-2006
Beam current (mA)
Beam energy (GeV)
Beam current
Beam energy
Time (Hrs)
18:14
18:21
18:28
18:36
18:43

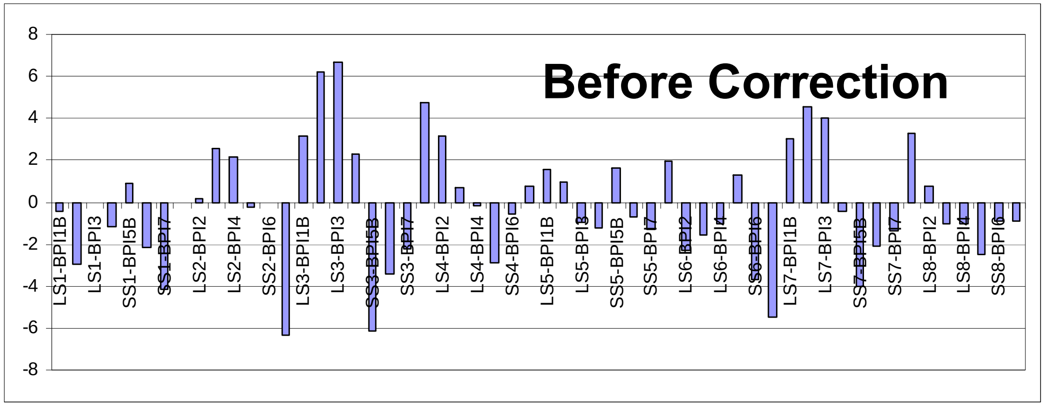


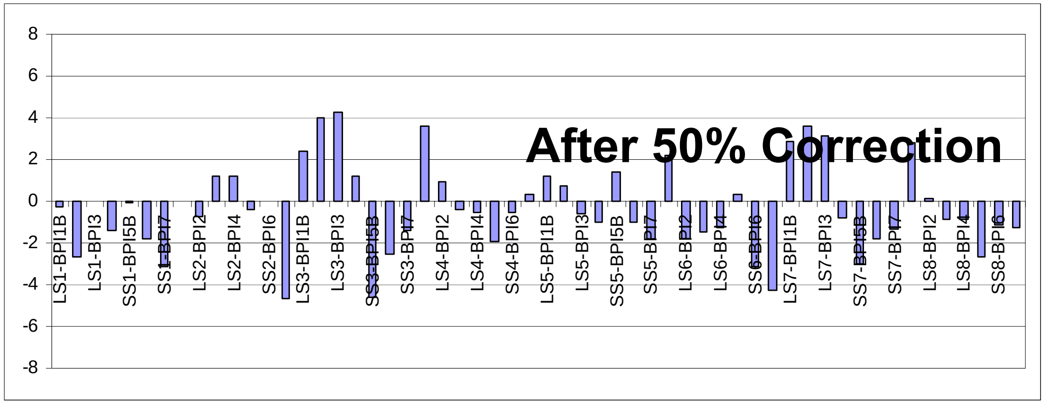
21/09/06 Beamlifetime 86 minutes
27/07/06 Beamlifetime 31 minutes
Vacuum (mbar)
3.0E-08
2.5E-08
2.0E-08
1.5E-08
1.0E-08
5.0E-09
0.0E+00
0
5.19
27.5
36.5
49
58
78.8
83.6
101
123
135
144
172
Path length (m)

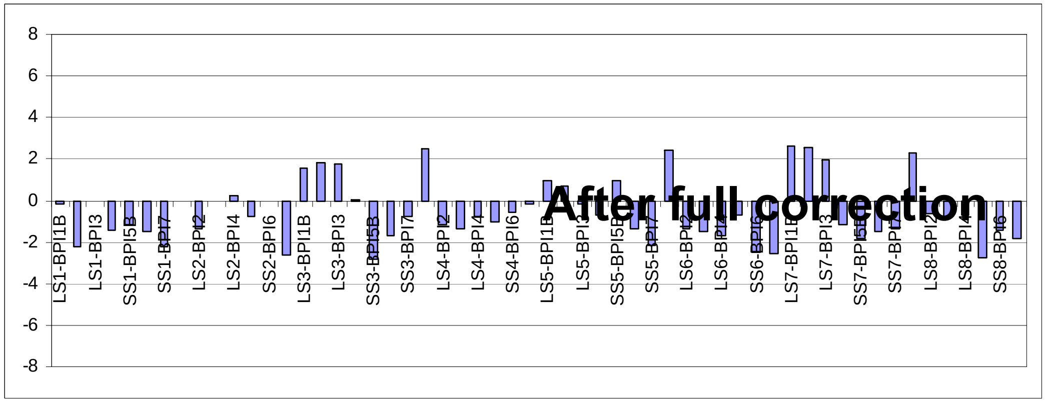


COD_x	Uncorrected	Corrected
Absolute Max (mm)	6.7	2.75
RMS(mm)	2.9	1.54

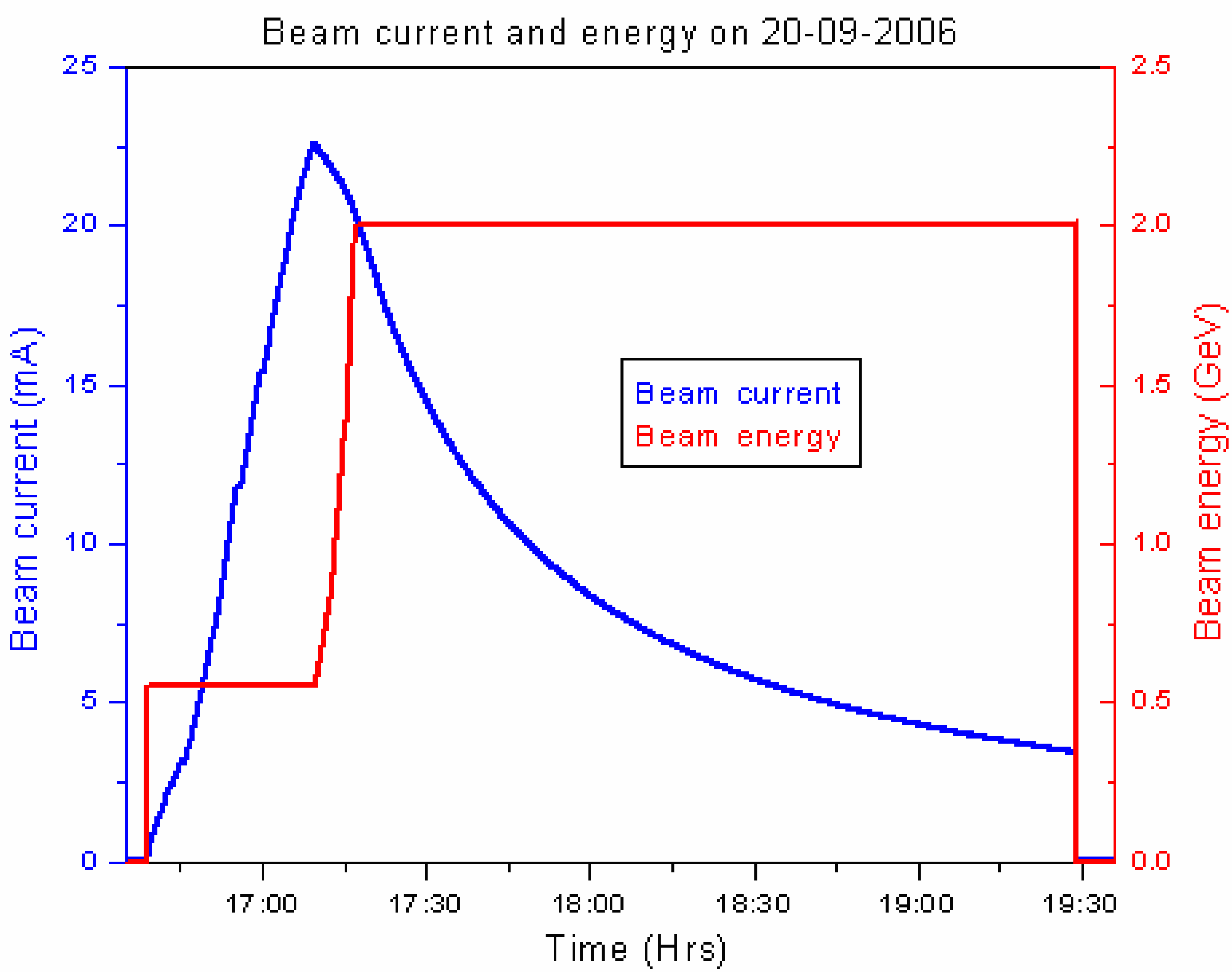
July 30 2006







Note the peak value of horizontal orbit correction is reduced from uncorrected value of 6.6 mm to 2.8 mm after correction using sixteen horizontal correctors .



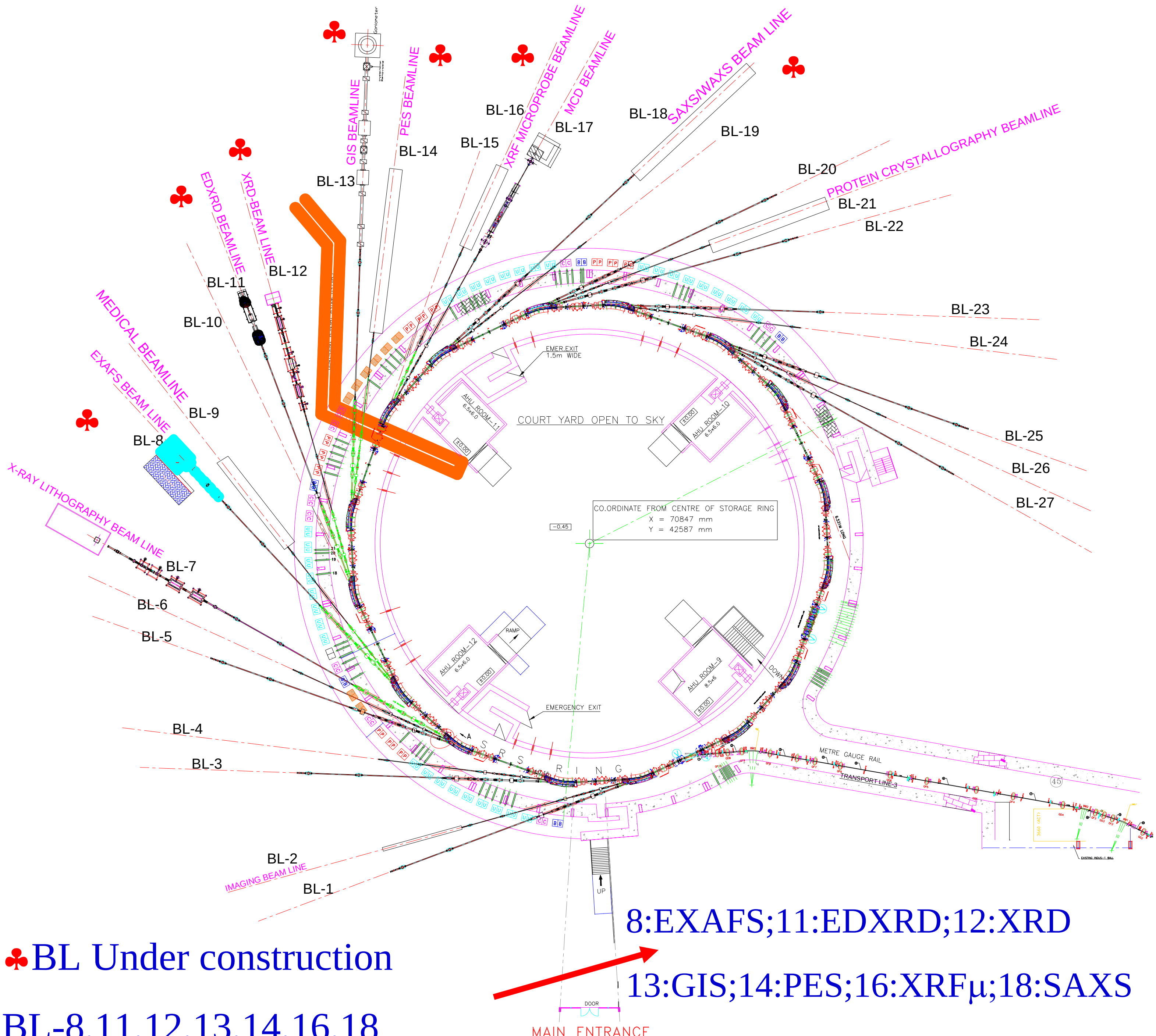
Beam current and energy on 20-09-2006
Beam current (mA)
Beam energy (GeV)
Time (Hrs)
Beam current
Beam energy
0
5
10
15
20
25
0.0
0.5
1.0
1.5
2.0
2.5
17:00
17:30
18:00
18:30
19:00
19:30

Program Related to Indus-2 Usage

- Work has been done to indigenously make bending magnet beam-line front-ends.
- Efforts are on at BARC & RRCAT to make beamline parts including DCM, mirrors & the movement mechanisms, UHV chambers, slits, beam stoppers, mirror bender, beam viewer, beam position monitor etc.
- There are 7 groups currently engaged in building various Indus-2 beam-lines.

Beam-lines being built/designed/planned (updated 10-2-06)

	Range (KeV)	Groups
Being built		
XRD powder diffraction (Installed)	5 – 25	RRAT
XRF-microprobe	2 – 20	RRCAT
Energy Dispersive – XRD	10 – 70	BARC
EXAFS (Installed)	5 – 20	BARC
Grazing incidence mag scattering	5 – 15	SINP, Kolkatta
PES (With high resolution at ~6keV)	.8 - 15	BARC
Small angle X-ray scattering (SAXS)	8 - 16	BARC + IGCAR
Being designed		
Protein Crystallography	6 – 25	BARC + UGC-DAE-CSR
White-beam lithography	1 – 10	RRCAT
MCD/PES on bending magnet	0.03 – 4	UGC-DAE-CSR
Medical imaging beam-line	10 – 35	BARC + UGC-DAE-CSR
Planned		
IR-beam-line	2 – 100 μm	BARC
Undulator-MCD	0.1 – 1.5	RRCAT
X-ray beam diagnostics	6.2	RRCAT
Visible beam diagnostics	Visible	RRCAT



♣BL Under construction

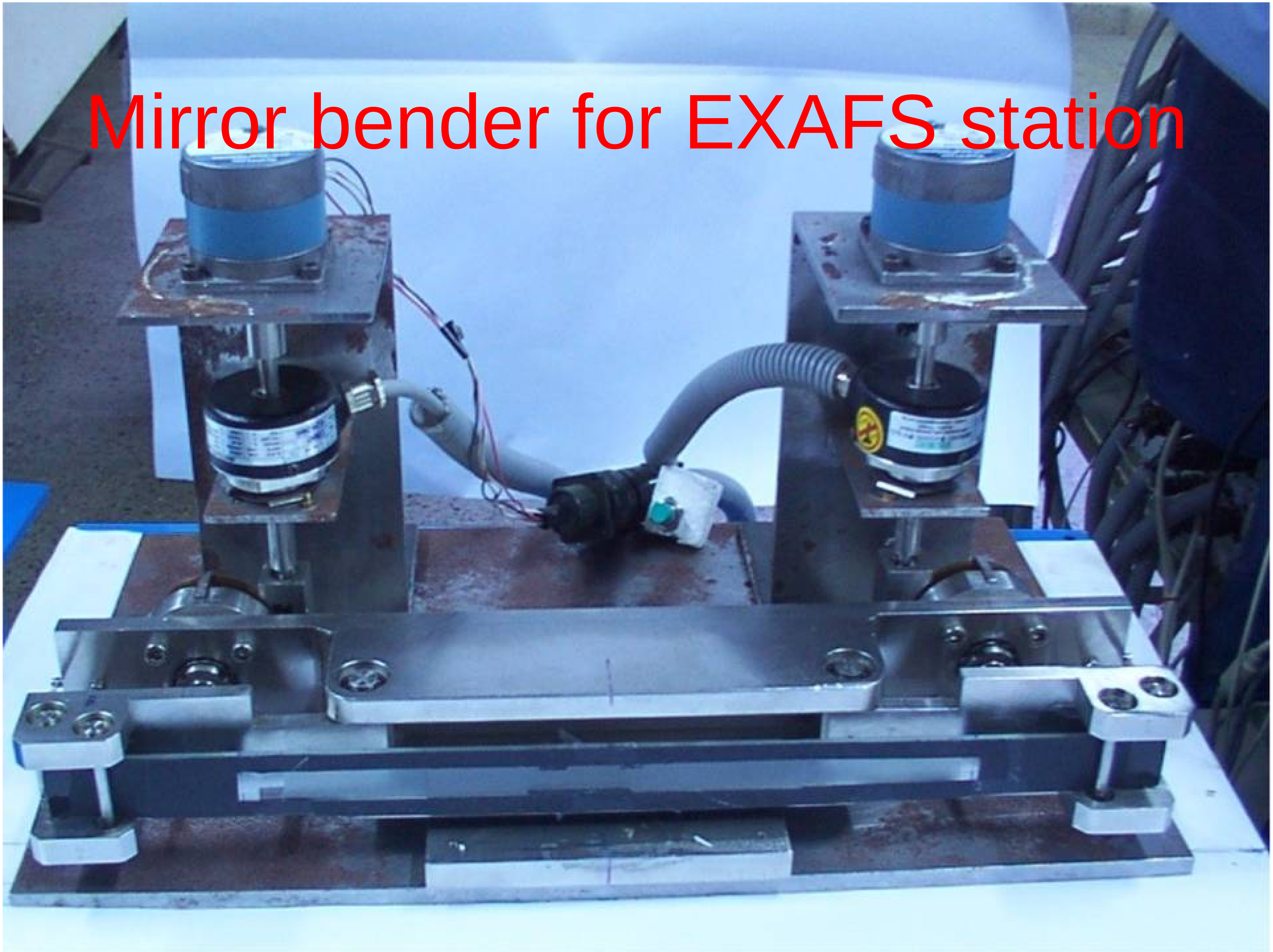
BL-8,11,12,13,14,16,18

8:EXAFS;11:EDXRD;12:XRD

13:GIS;14:PES;16:XRFμ;18:SAXS

Prototype Front-end of Indus-2 Beam-line

Mirror bender for EXAFS station



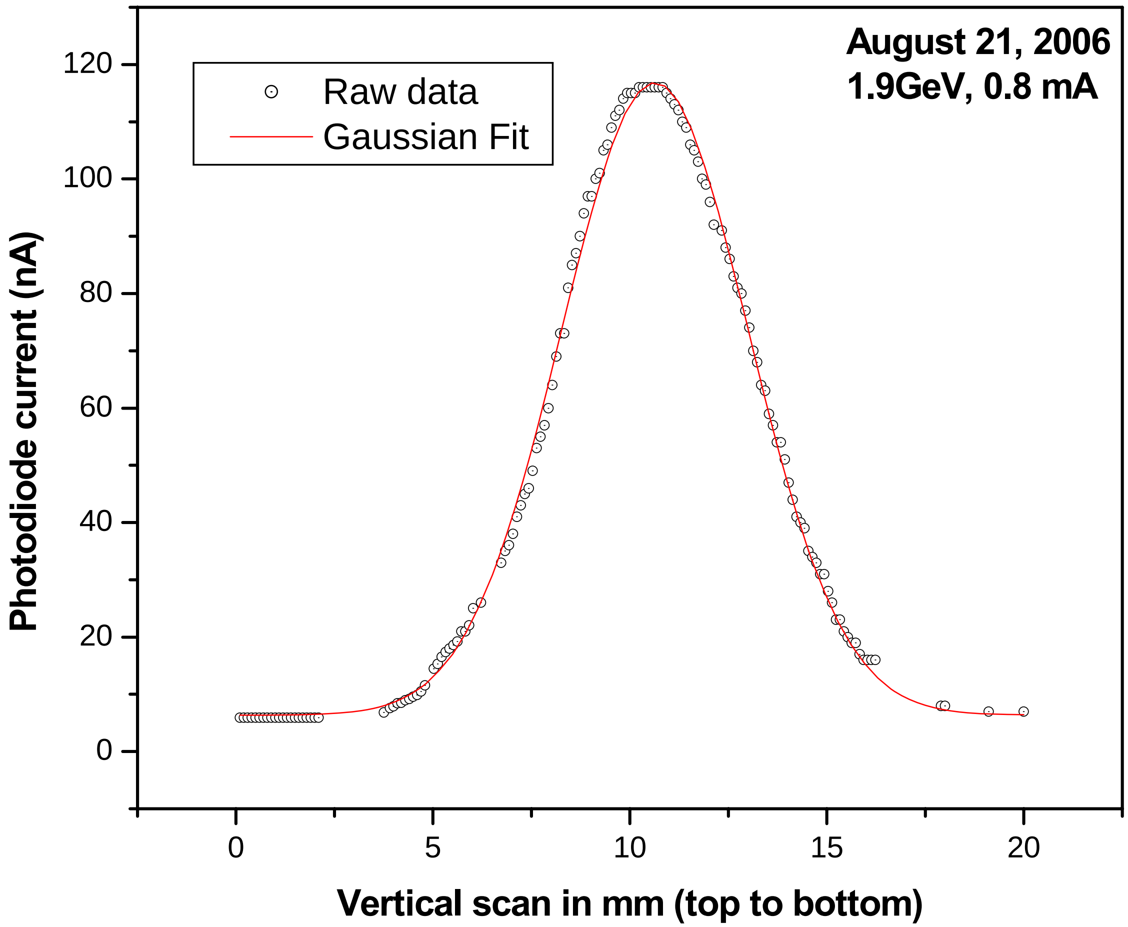
First front end on Indus-2

This front end has been installed on BL-12, a "High resolution x-ray diffraction beam line" of Indus-2.

After qualifying it, front ends for five other beam lines, being built by RRCAT / BARC, will be installed.

Part of XRD beam line in Indus-2 hall: It shows DCM & place where beam was monitored during beam line alignment.

Beam profile measurement on the beamline-12 for XRD



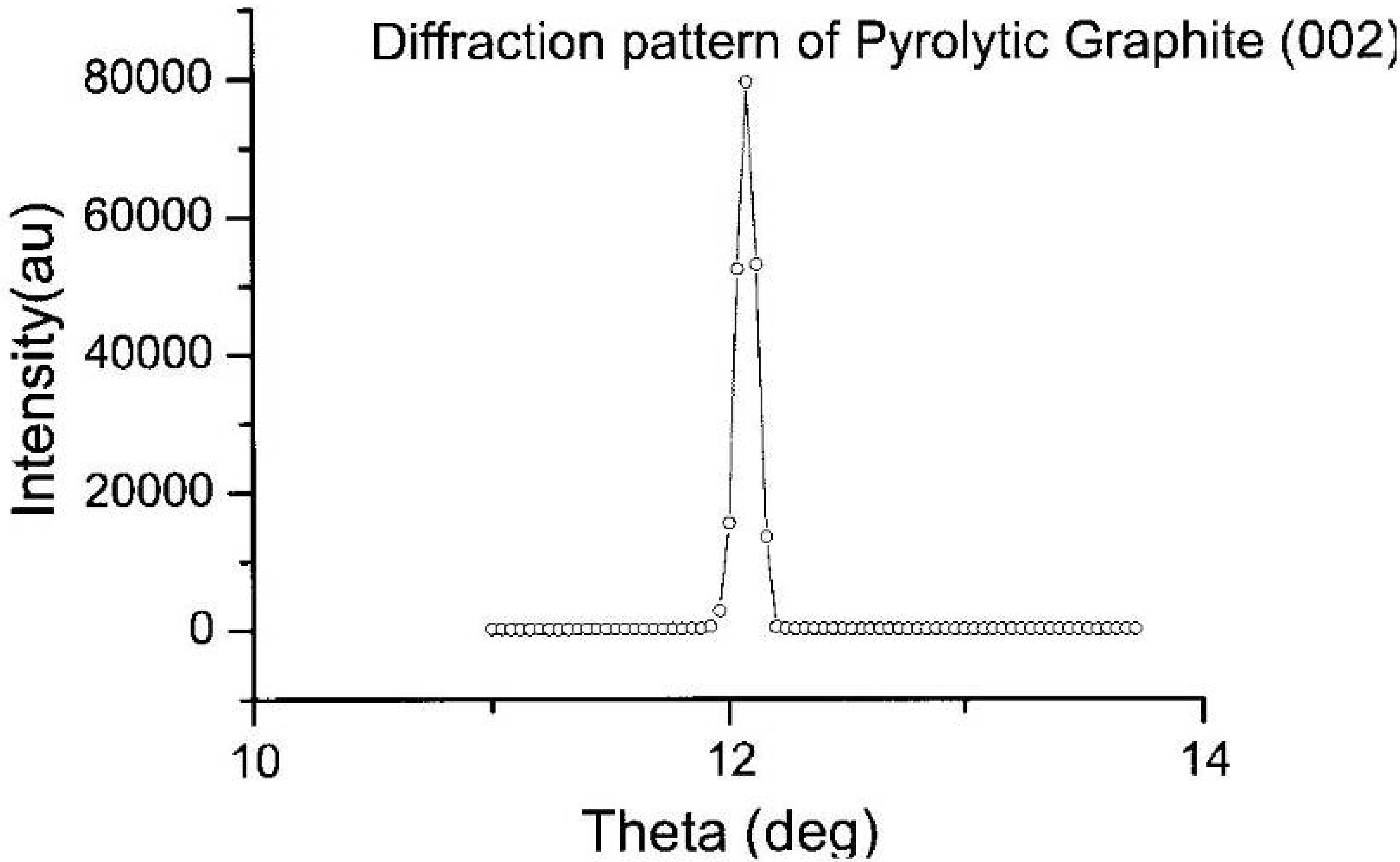
Above SR profile was measured at 21 meters from tangent point in the ring on beam line BL-12 meant for XRD. The FWHM of ~ 4 mm corresponds to ~0.1 mrad (1 σ) in the vertical plane.

Integrated photons/s = 10^9 /mrad/mA ring current

First record of the x-ray diffraction with SR from Indus-2 using beam line 12

Date:Sept 28, 2006; Indus-2 beam energy was 2 GeV & current ~4 mA.

DCM was aligned to get monochromatic SR out but calibration was still on.

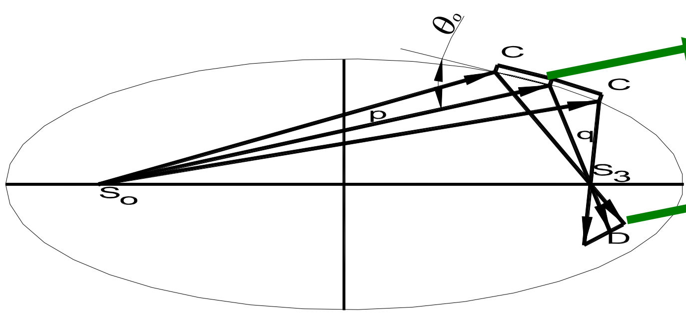


Multi Channel EXAFS Beamline for INDUS-2 Synchrotron Source

Being developed by Spectroscopy Division, B.A.R.C.

It involves measuring the x-ray attenuation coefficient in a material just above the absorption edge of a particular atom using **Energy Dispersive Mode**

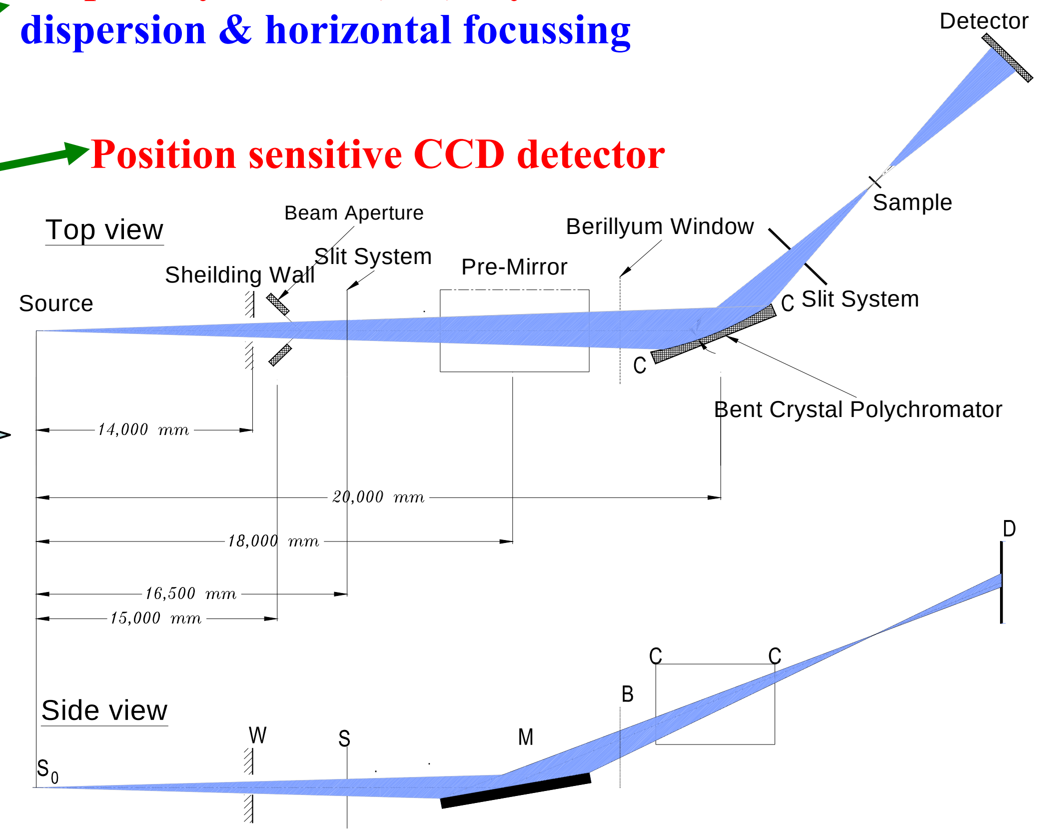
Fast Technique → Average data acquisition time : 300 msec
Suitable for in-situ, fast and time-resolved processes



Elliptically bent Si (111) crystal for dispersion & horizontal focussing

Position sensitive CCD detector

Optical Layout →



Specifications

Energy Range: 5-20 keV

Bandwidth : 1 keV @ 10keV

Resolution (E/ΔE): 10^4

Picture of EXAFS beamline (BL-8) under installation

Indus-2 Program Ahead

&

Benefits for

Upcoming Partnerships

with CERN

& Other labs

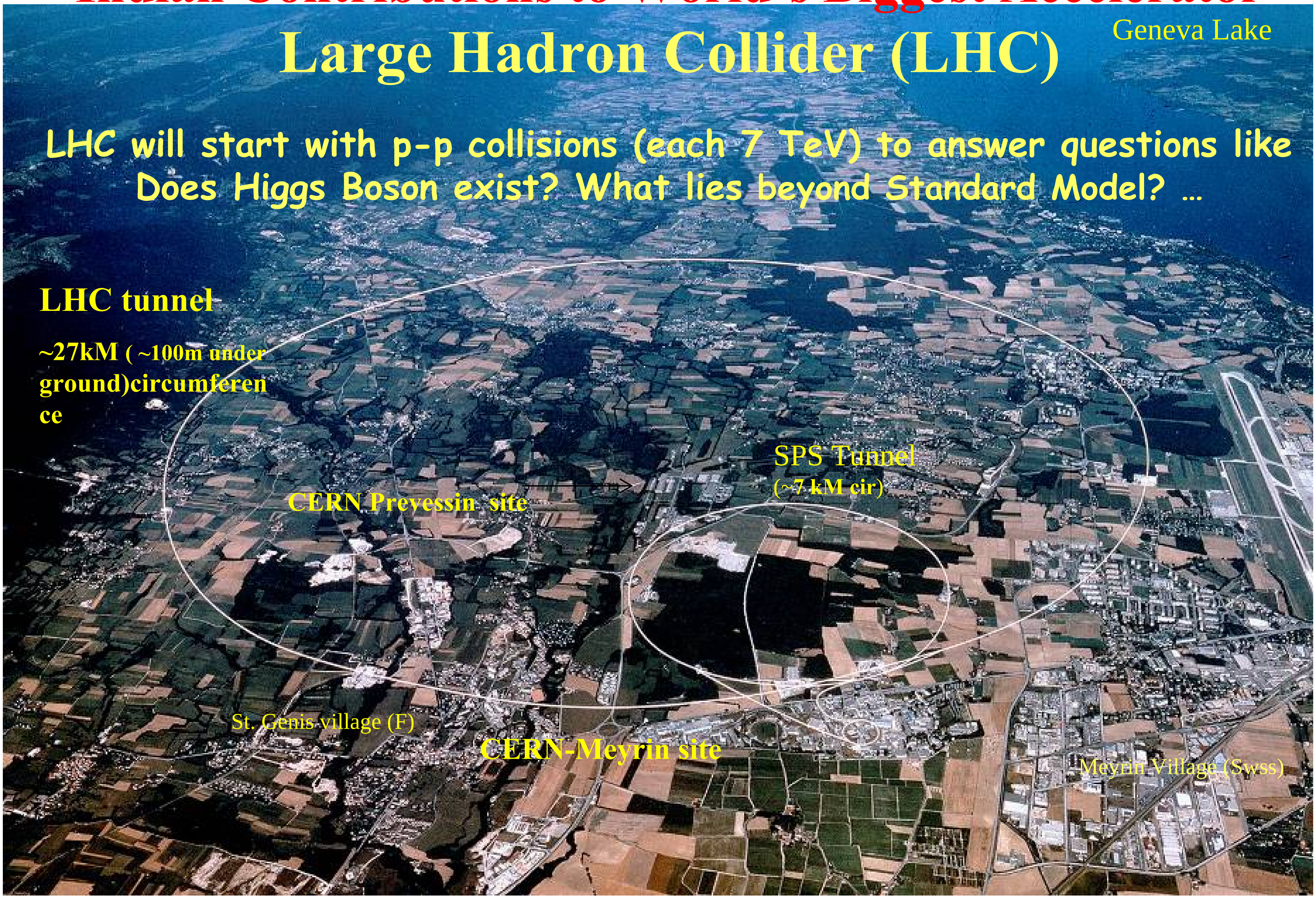
in

International Accelerator Programs

Plans ahead for Indus-2

- Enhance beam energy. Will need more power. MPSEB (the utility company) has been approached.
- Bring down closed orbit deviations.
- For stable performance of ring, power conditioning system would be added. Power trips cause dipole current to plummet rapidly, resulting in large force on dipole vacuum chambers. Some of the connecting bellows have been damaged.
- Give thrust to developing beam line components: DCM, mirrors & their movement systems, slits, mirror bender, beam position monitor etc.
- Build or acquire IDs and install as per users' interests.

Indian Contributions to World's Biggest Accelerator



DAE-CERN COLLABORATION for LHC

LHC is being built by CERN with International support. India joined it in 1996. RRCAT is DAE's Nodal Agency.

We have given many components & subsystems for LHC & provided skilled manpower support at CERN. Many organizations have contributed.

India has been accorded "Observer State" status; Others are: Israel, Japan, Russian Federation, USA etc.

Precision alignment JACKS for LHC cryomagnets (weighing 32 Tons)

6800 PMPS Jacks + 280 Motorizable & Higher Precision-All delivered

Test Set-up to demonstrate setting resolution of 0.02 mm

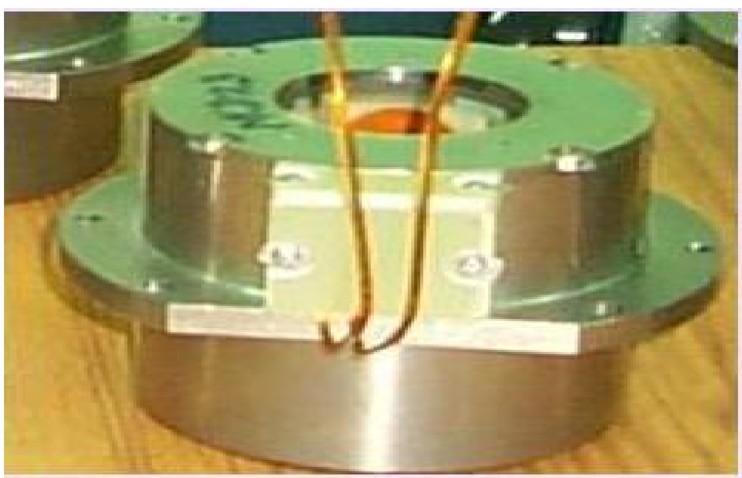
Indian made PMPS Jacks being installed in LHC

Cryogenic test facility at CAT, Indore

Warm magnet measurement setup at CAT

MCS & MCDO ready for despatch

Mass Production of MCS (1146 Units-All Delivered) & MCDO (616 Units-All Delivered)



Decapole & Octupole corrector magnet assembly

Local Protection Units for LHC SC Magnets, (Prototype:I&CD,RRCAT; Manufacture:ECIL)

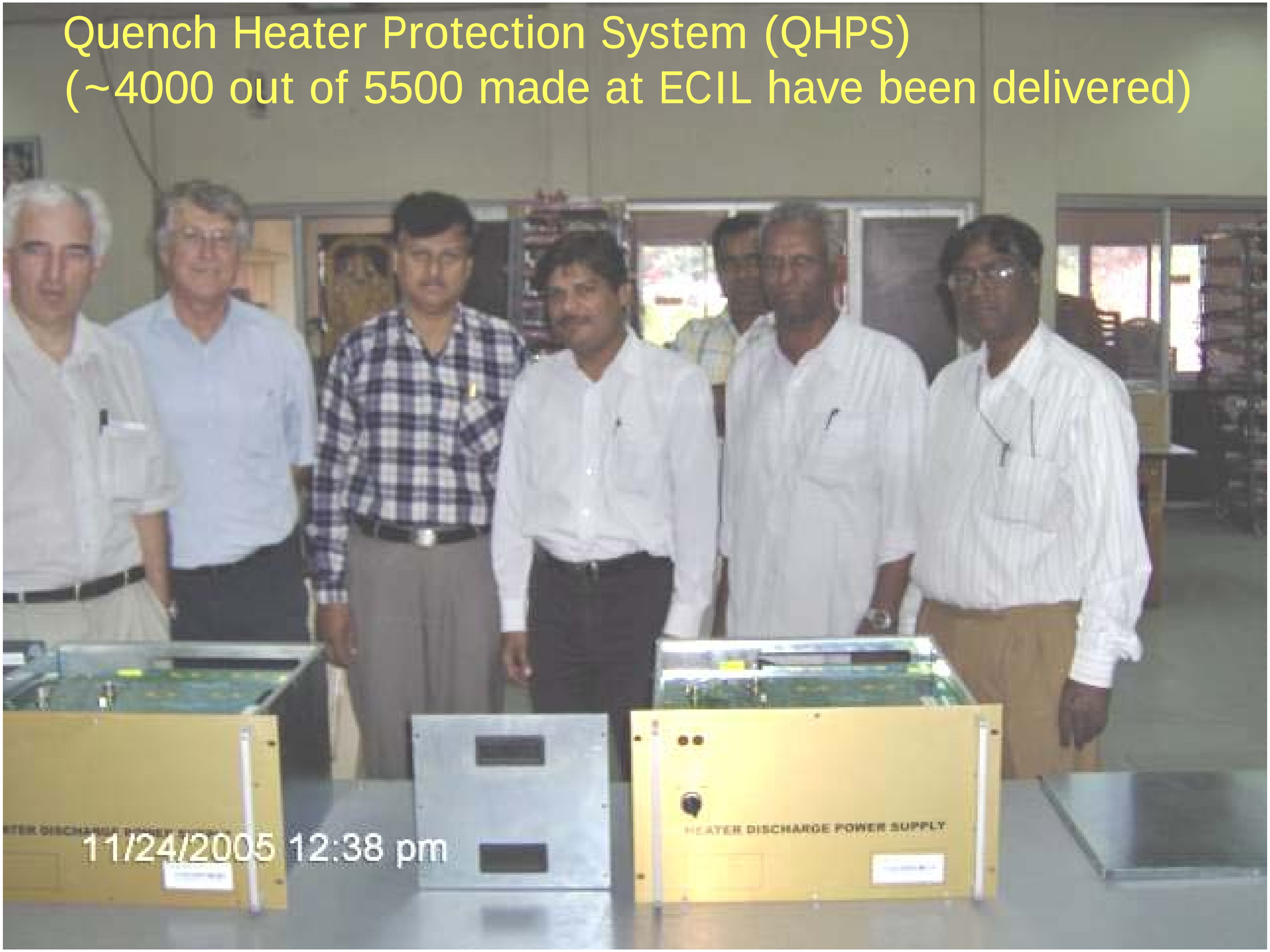
Requirement : 1435 Units

1090 Units for Dipole Magnets

345 Units for Quadrapole Magnets

All delivered

Quench Heater Protection System (QHPS)
(~4000 out of 5500 made at ECIL have been delivered)



Encouraged by LHC related success, DAE-CERN have initiated a new cooperation on **Novel Accelerator Technologies**

CERN to help our upcoming projects:

- **Spallation Neutron Source (SNS) at CAT, Indore**
- **Accelerator Driven System (ADS) at BARC**

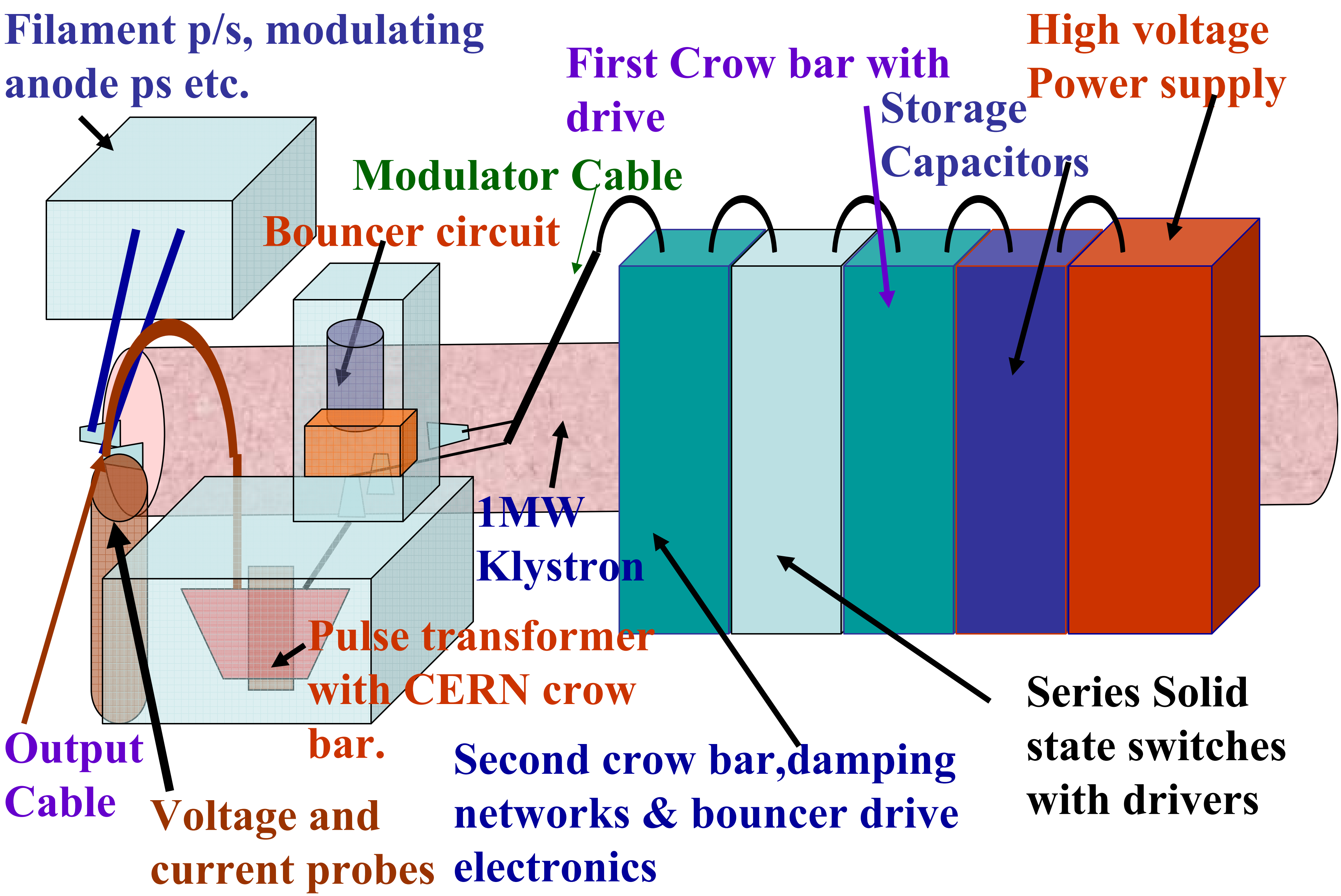
DAE to join CERN's Novel Accelerator Projects :

- **SPL, especially LINAC-4, the front end of SPL.**
- **Compact Linear Collider (CLIC) Test Facility CTF3.**

We have identified our contributions after discussions with CERN scientists:

For LINAC4 we are building a modulator and for CTF3 (design of TL-2, supply of Al alloy vacuum chambers, magnets etc.)

Layout of klystron modulator for LINAC 4



Concluding remarks

- We have created a good indigenous base during the course of building synchrotron sources.
- This will serve as a launching pad to build bigger machine for our domestic programs & enable us to join advanced international accelerator projects, like, CTF3, Linac-4, ILC, X-FEL etc which will integrate our home efforts with world wide activities.

Thank You