Overview of the Accelerator Programs at the Indian Laboratories*

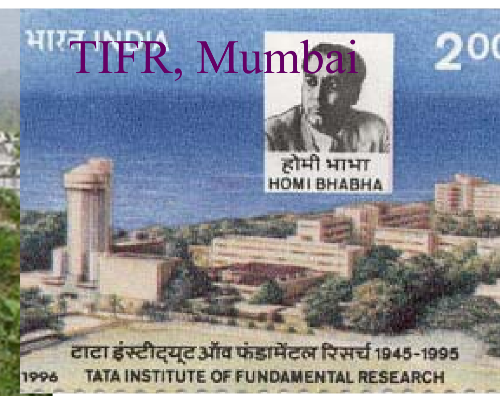
Vinod C. Sahni

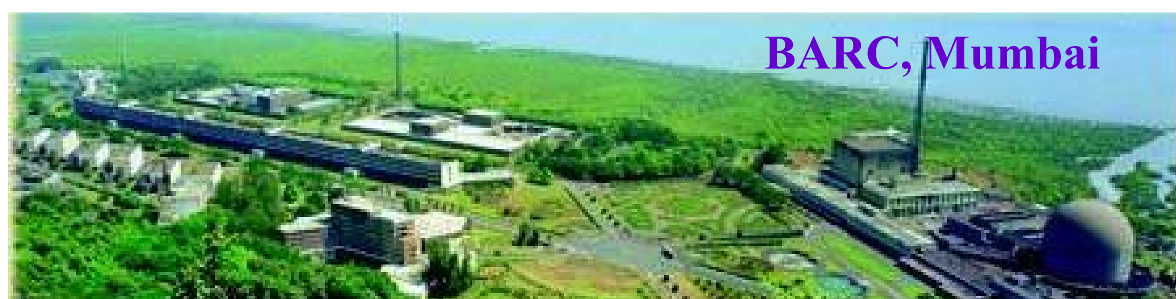
BARC, Mumbai-400 085 & RRCAT, Indore-452 013, India and

Raj G. Pillay

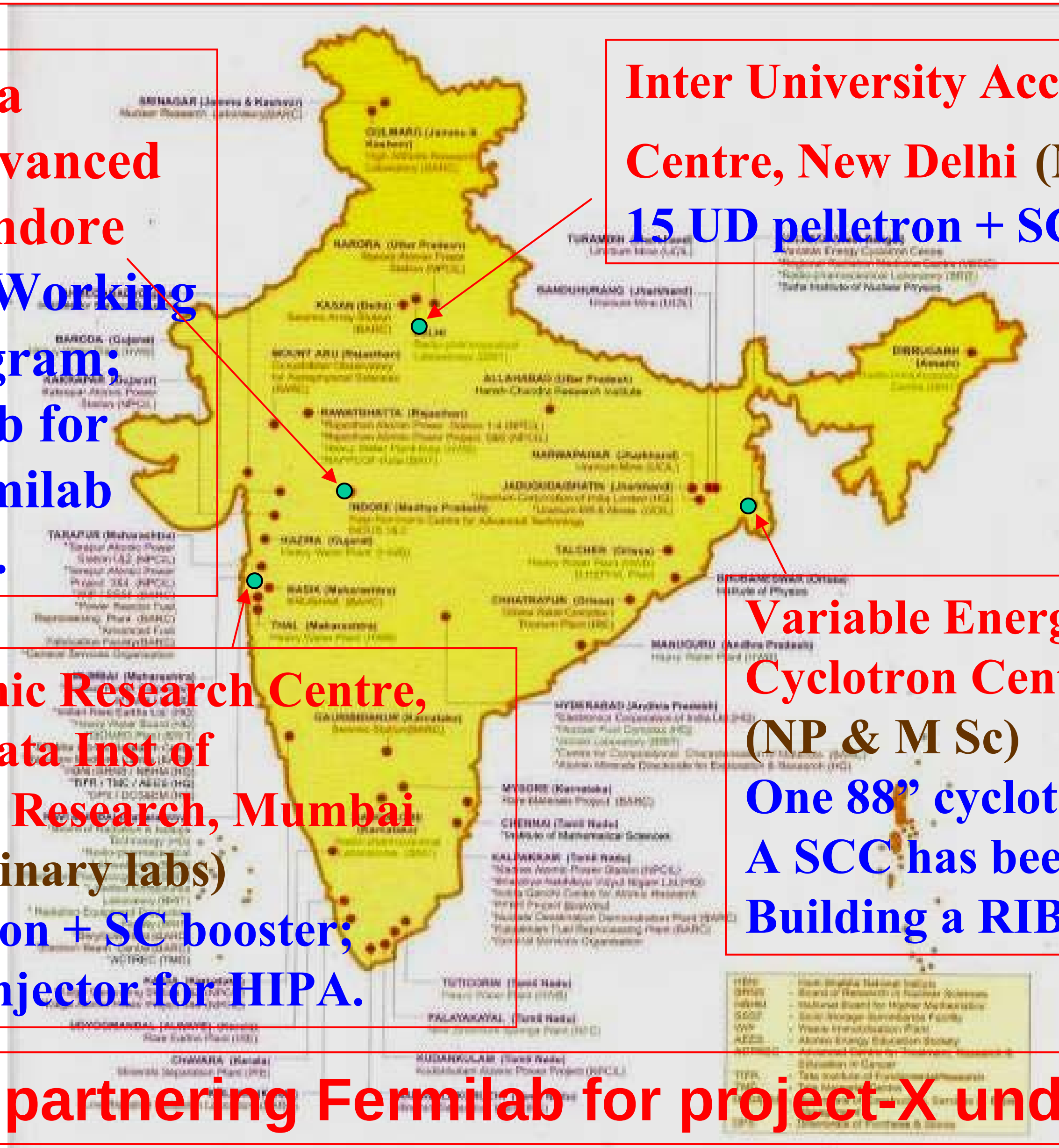
TIFR, Mumbai-400 005, India

***Invited talk at PAC 09, Vancouver, Canada, May7, 2009**





Major Indian Accelerator Labs & Their Prime Activities



Raja Ramanna Centre for Advanced Technology, Indore
Hosts 2 SRS; Working on SCRF program; Nodal DAE lab for CERN & Fermilab Collaboration.

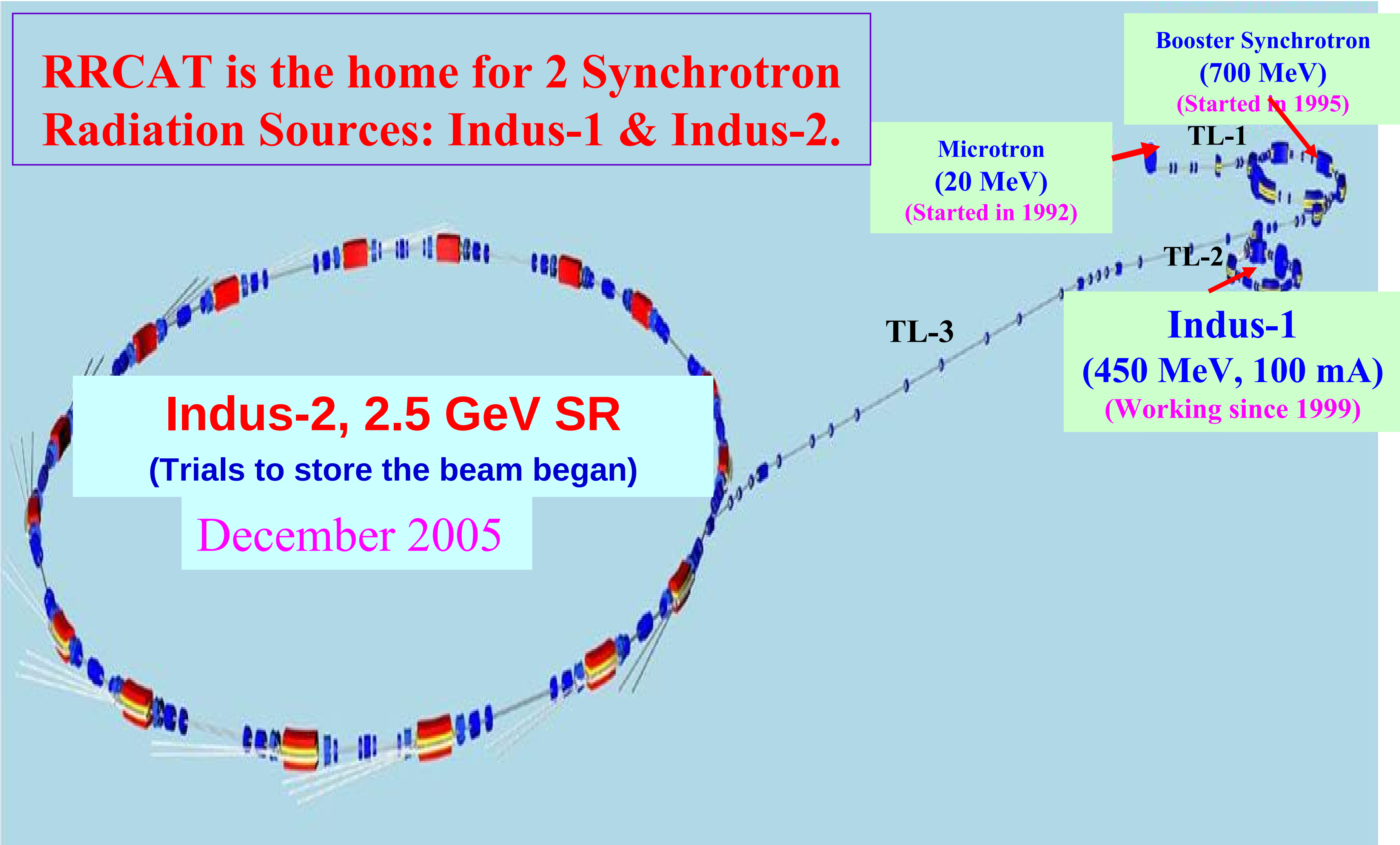
Inter University Accelerator Centre, New Delhi (NP & M Sc).
15 UD pelletron + SC booster.

Variable Energy Cyclotron Centre,Kolkata (NP & M Sc)
One 88” cyclotron;
A SCC has been set up;
Building a RIB facility.

Bhabha Atomic Research Centre, Mumbai & Tata Inst of Fundamental Research, Mumbai (Multi disciplinary labs)
14 UD pelletron + SC booster;
Building an injector for HIPA.

All labs are partnering Fermilab for project-X under an MoU

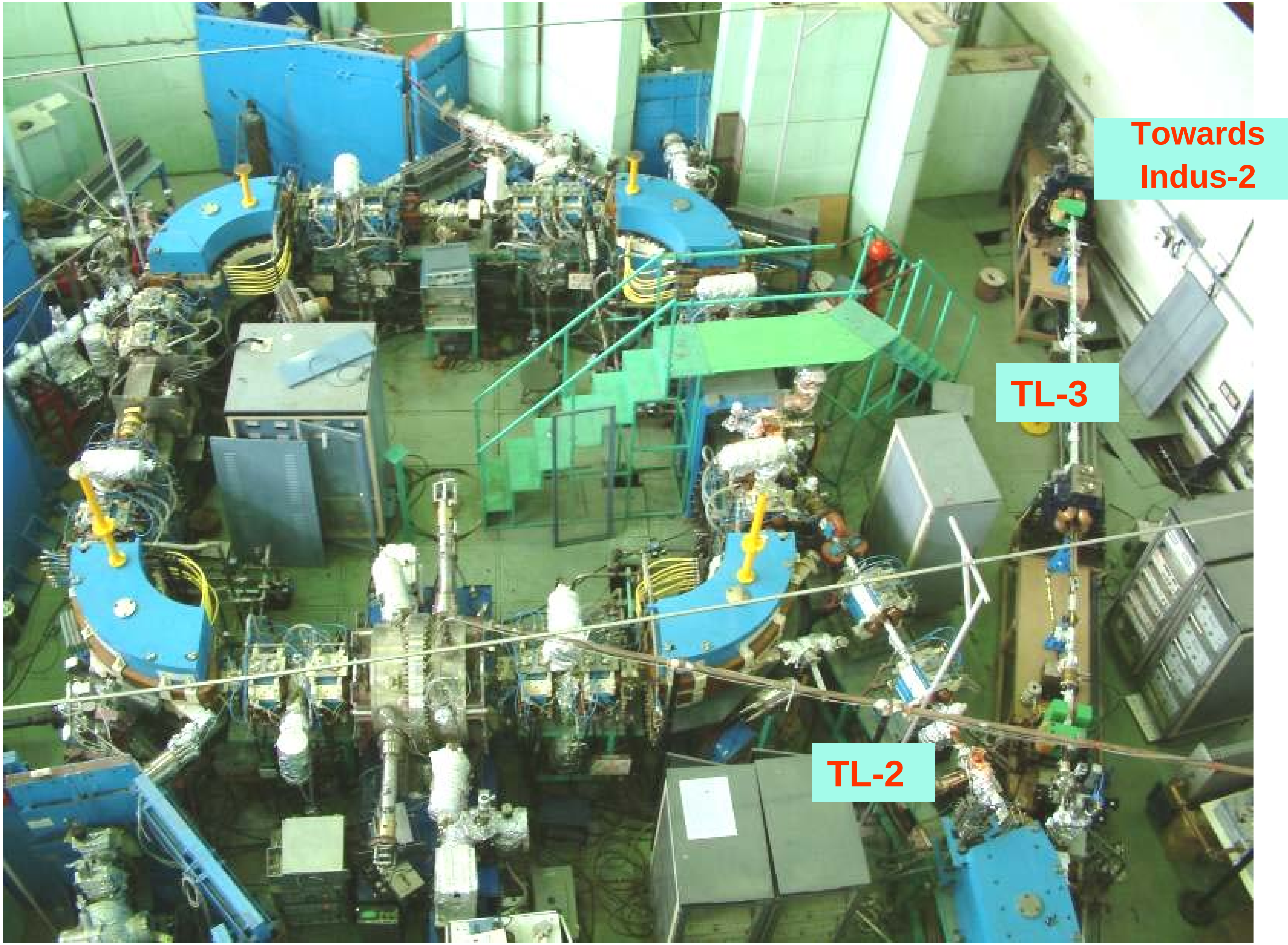
SCHEMATIC VIEW OF INDUS COMPLEX



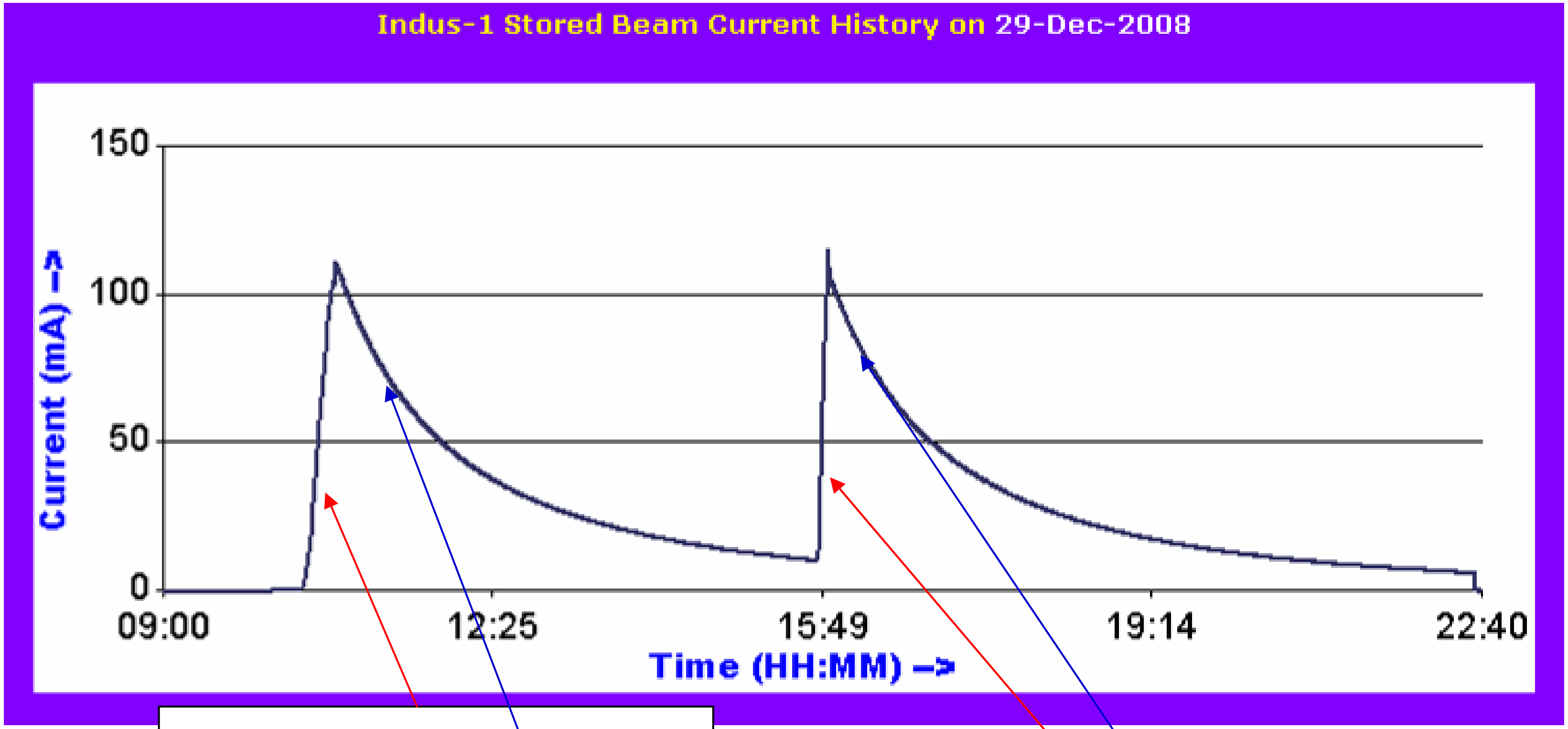
Timeline of Indus Accelerator Program

- → 1981-84 : Assessing SRS interest, new centre proposed & foundation stone of CAT laid.
- 1984-86 : Temporary structures set up at Indore & first accelerator teams identified.
- 1986 : Activities start with modest infrastructures, eg, 350 KVA / 11 kV Substation.
- → 1987-91 : Injector options discussed & Microtron + Booster Synchrotron decided. Components/subsystems for these built & bench tested. Indus-1 design work started.
- → 1992 : 20 MeV Microtron assembled & commissioned.
- 1989- 93 : Permanent civil construction & electrical infrastructure improvement.
- 1991-1995: Indus-1 components/subsystems built & bench tested. Developmental work also taken up for the 2 GeV design energy ring (originally envisioned for Indus-2).
- 1993 : Building for housing injector accelerators & other better facilities gets ready.
- 1994 : 132 kV, 1.25 MVA substation ready;enables operation of booster dipole magnets.
- → 1995 : Booster Synchrotron starts operation & first ramp up of the beam from 20 MeV to 450 MeV achieved in Sept. 1995.
- 1996 onwards : Indus-1 installation work started. Also infrastructure enhanced.
- → 1997: International Advisory Committee advised to raise energy of Indus-2 to 2.5 GeV.
- → 1999 : Indus-1 commissioned in April 1999.
- 1998 – 2002 : Civil construction of Indus-2 building.
- 2000-2004 : Components/subsystems of Indus-2 built, mostly bench tested & qualified.
- 2004 onwards : Indus-2 & TL-3 installation & integration of subsystems.
- → 2005 : First beam injection and four turns circulation in August 2005.
- → 2005 : RF and kicker system activated & first SR light seen on Dec 1, 2005 at 10.20 pm.
- → 2006 : AERB allows Indus-2 operation <2 GeV, 10mA. XRD recorded. Vacuum failure.
- 2007 : Vacuum failure resolved; new cavity for booster synchrotron; ring restarted.
- → 2008 : Operation up to 2.5 GeV, 50 mA; 3 beam lines made operational

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



Typical Indus-1 operation working 5 days/week and 2 shifts/day

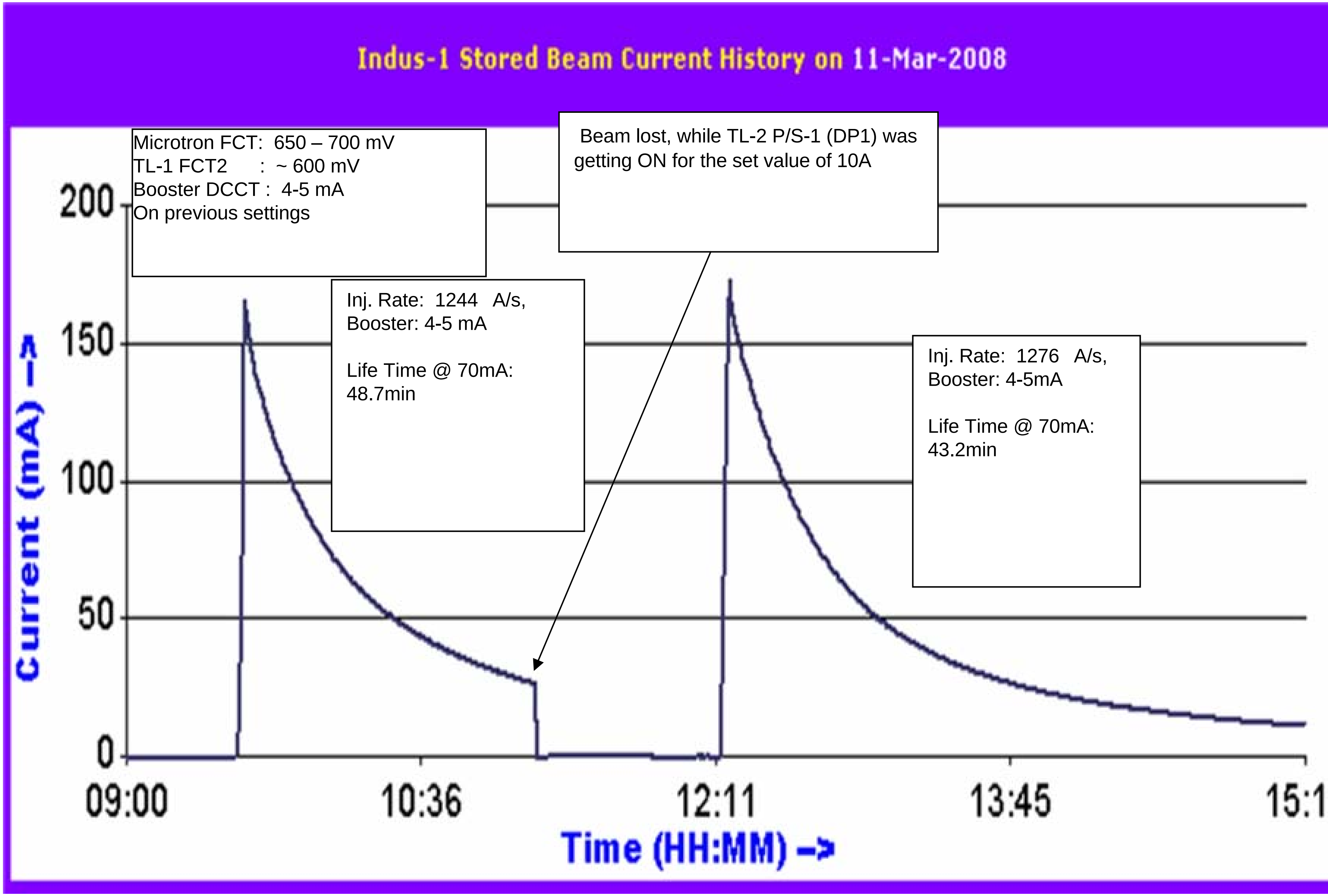


Accumulation rate= 100µA/s
Booster current: ~1-2mA

Lifetime @100mA=73minutes
Lifetime @ 70mA=84minutes

Accumulation rate=285µA/s
Booster current: ~2-3mA

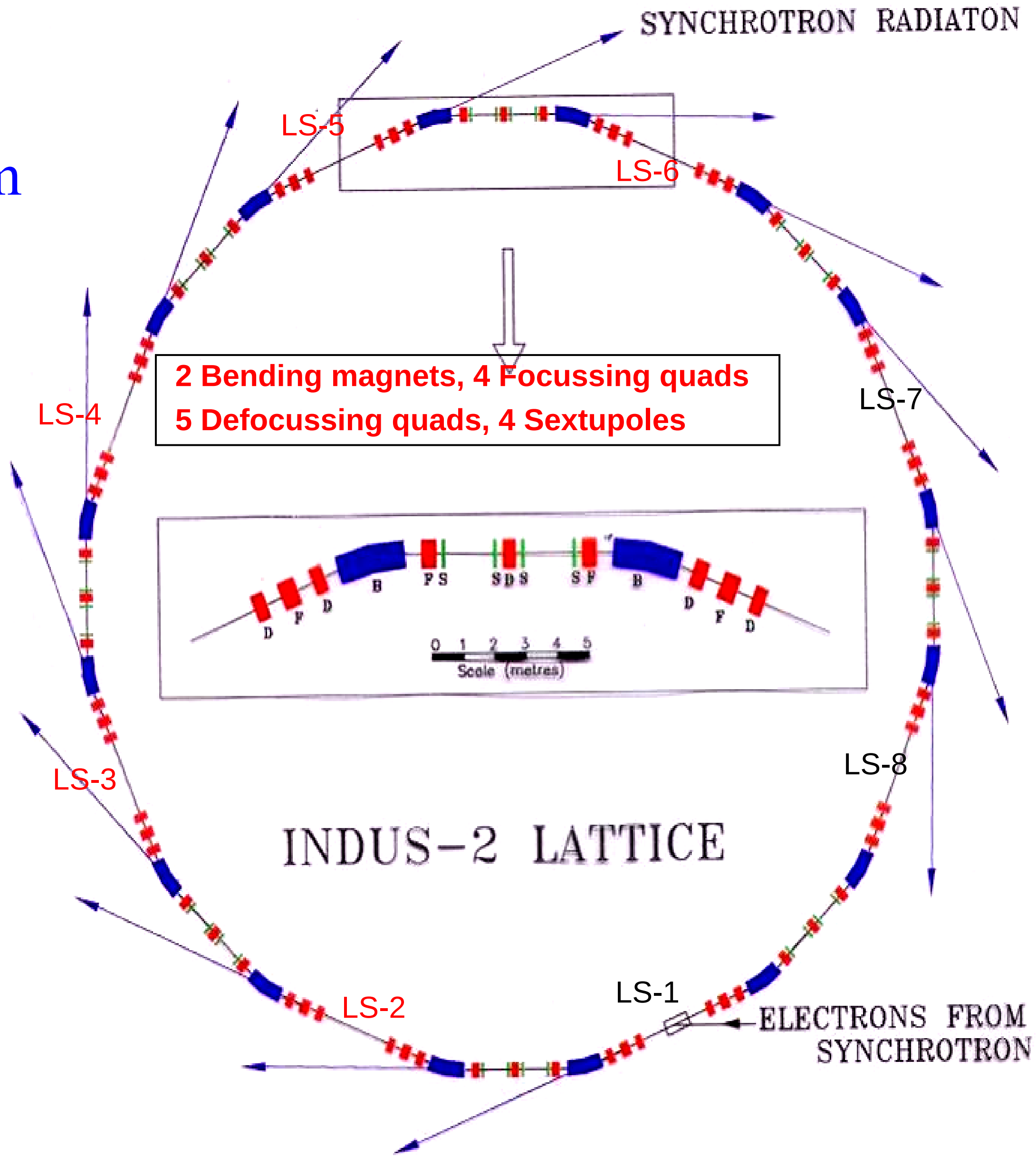
Lifetime @100mA=75minutes
Lifetime @ 70mA=88minutes



Indus-1 Stored Beam Current History on 11-Mar-2008
Microtron FCT: 650 – 700 mV
TL-1 FCT2 : ~ 600 mV
Booster DCCT : 4-5 mA
On previous settings
Beam lost, while TL-2 P/S-1 (DP1) was getting ON for the set value of 10A
Inj. Rate: 1244 A/s,
Booster: 4-5 mA
Life Time @ 70mA: 48.7min
Inj. Rate: 1276 A/s,
Booster: 4-5mA
Life Time @ 70mA: 43.2min
Current (mA) -->
200
150
100
50
0
09:00
10:36
12:11
13:45
15:19
Time (HH:MM) -->

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 IDs		:	5
Maximum straight length available for IDs		:	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		:	>12 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 of various subsystems in the tunnel.

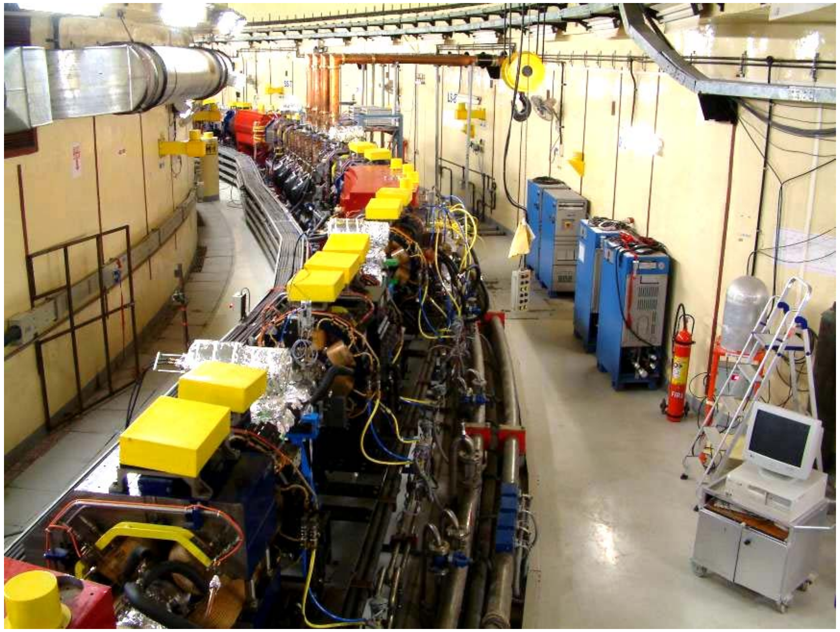
2006 onwards: Machine operation at 2 GeV & then 2.5 GeV.

Cost : ~Rs. 1 Billion (Cost of machine & building).

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

Imported Items: RF cavities & Klystrons.

Assembly of Indus-2 Ring in the Tunnel

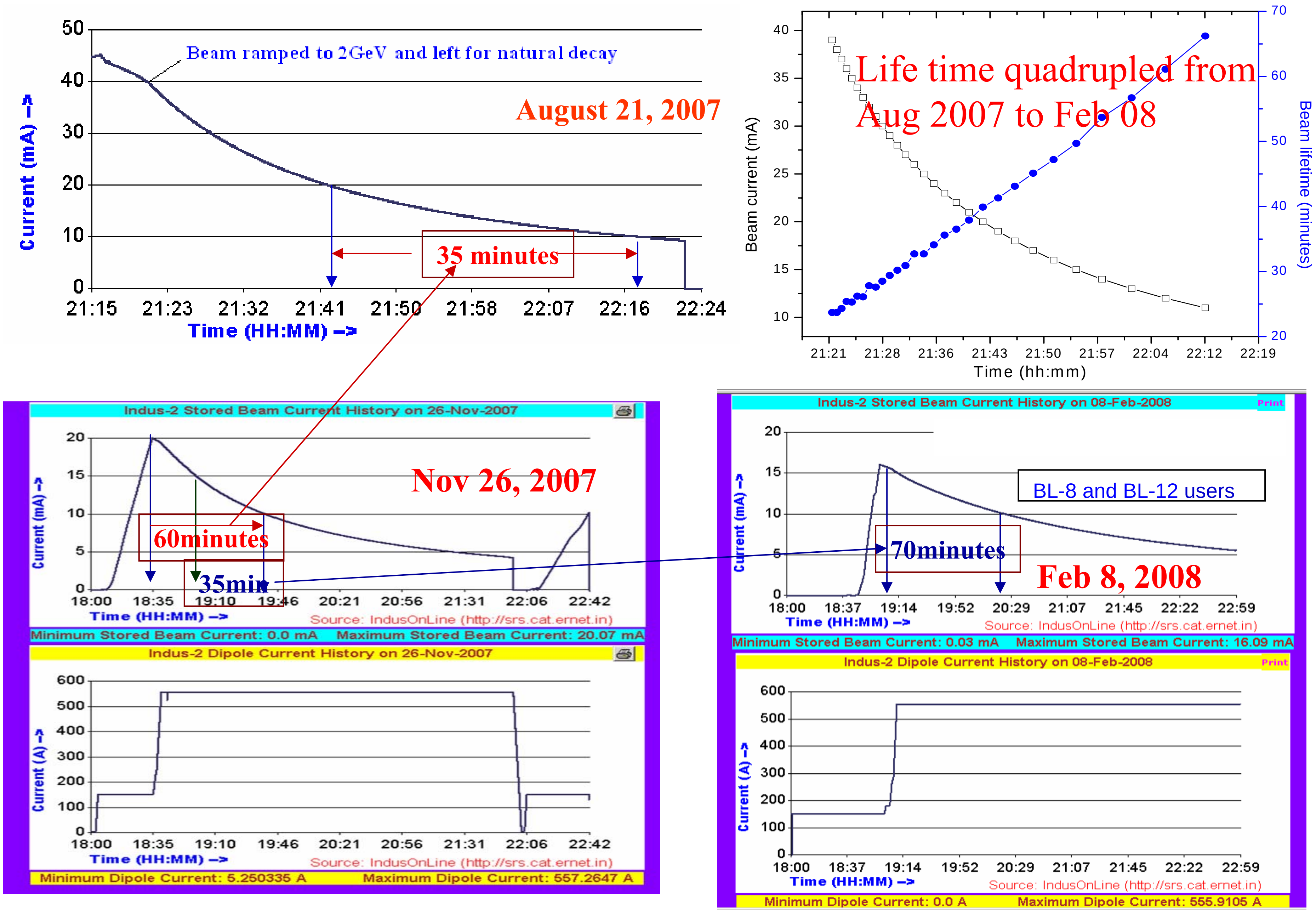


RF Cavities installed in Indus-2 Ring

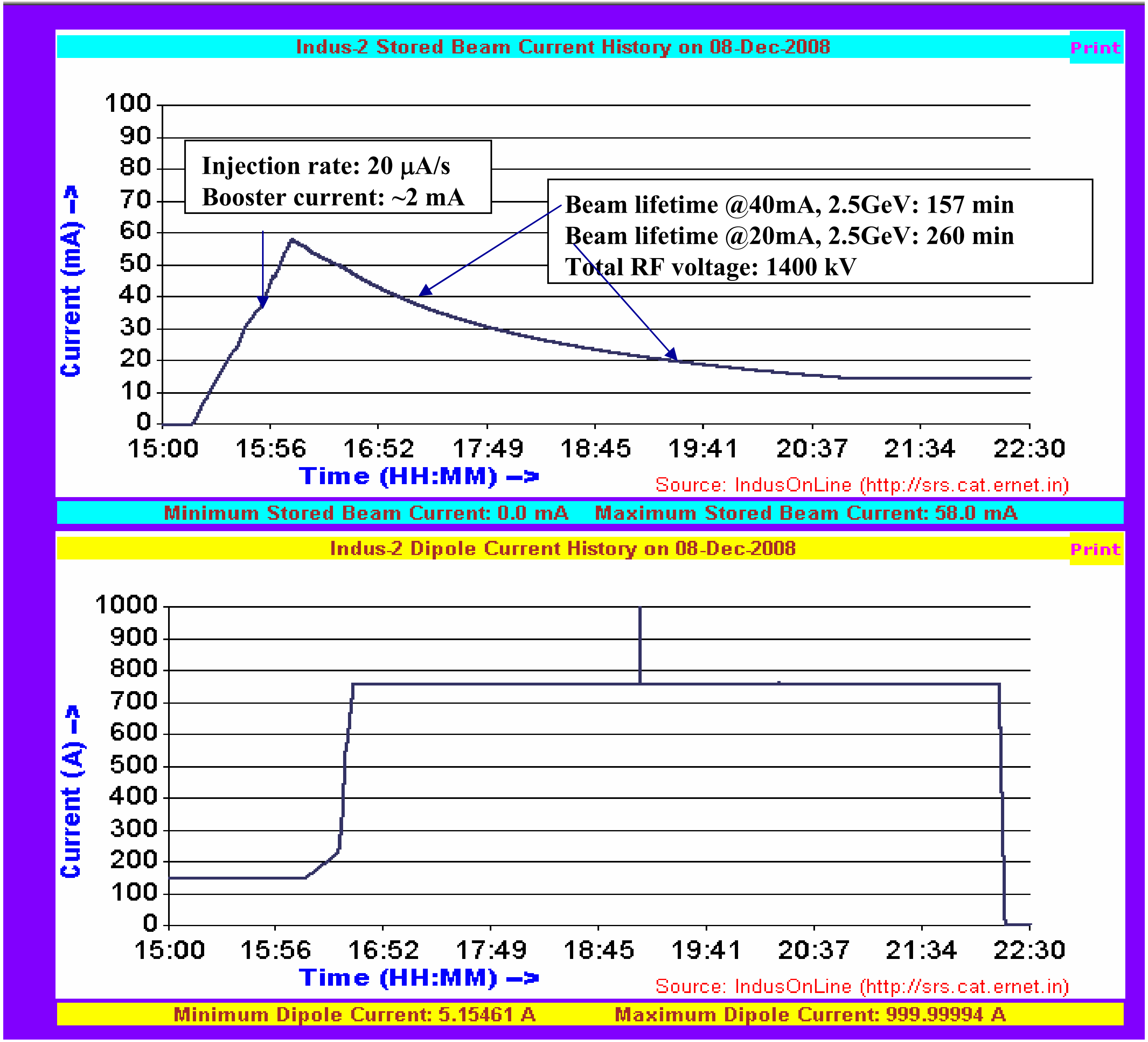
Long Straight Section LS-6 Assembly

Transport Line-3 Joining on to Indus-2

Beam lifetime improvement @ 2GeV



June 2008 : AERB permitted 2.5 GeV 50 mA operation. Daily run on 2 shift basis



Beam-lines Status (As of April 2009)

Purpose of beam line	Range (KeV)	Institutions involved
Already set up		
Sighting beam line (Installed)	Uses a CCD	RRCAT
EXAFS (Installed)	5 – 20	BARC
Energy Dispersive – XRD (Installed)	10 – 70	BARC
High resolution XRD (Installed)	5 – 25	RRAT
Under construction/partially installed		
XRF-microprobe	2 – 20	RRCAT
Grazing incidence magnetic scattering	5 – 15	SINP, Kolkatta
PES (With high resolution at ~6keV)	0.8 - 15	BARC
White-beam lithography	1 – 10	RRCAT
Protein Crystallography	6 – 25	BARC
Being designed		
Small angle X-ray scattering (SAXS)	8 - 16	BARC
MCD/PES on bending magnet	0.03 – 4	UGC-DAE-CSR
Medical imaging beam-line	10 – 35	BARC + UGC-DAE-CSR
Planned		
Undulator-MCD	0.1 – 1.5	RRCAT
X-ray beam diagnostics	6.2	RRCAT
Visible beam diagnostics	Visible	RRCAT

DAE- CERN Collaboration in Particle Accelerators

CO-OPERATION AGREEMENT

between

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

and

THE DEPARTMENT OF ATOMIC ENERGY (DAE)

OF THE GOVERNMENT OF INDIA

Article 10
Duration

This Agreement shall be in force for a period of five years from the date of its signature and will be automatically renewed for the same period unless six months' notice of termination is given by either party to the other.

Done at Geneva on 28 March 1991
in two copies in the English language.

For the Department of Atomic Energy of the Government of India (DAE)

P K Iyengar

P.K. Iyengar
Chairman, Atomic Energy Commission

For the European Organization for Nuclear Research (CERN)

Carlo Rubbia

C. Rubbia
Director-General

PROTOCOL

TO

THE 1991 CO-OPERATION AGREEMENT

between

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

and

THE DEPARTMENT OF ATOMIC ENERGY (DAE) OF THE GOVERNMENT OF INDIA

ARTICLE 13
Duration

1. This Protocol shall be in force for a period of ten years from the date of its signature, subject to a corresponding renewal of the Agreement. In case of non-renewal, the remaining amount in the India Fund will be utilised as per Article 3.3 (a). However, every three years the execution of the Protocol will be evaluated and the validity of the basic assumptions governing the Protocol will be assessed.

2. At least two years before the end of this period, the extension of this Protocol will be discussed with the aim of ensuring a continued access of Indian scientists to the CERN programme.

The present Protocol shall form an integral part of the Co-operation Agreement signed on 28 March 1991.

Done at Delhi, on 29th March 1996
in two copies in the English language.

For the Department of Atomic Energy (DAE) of the Government of India

R. Chidambaram

R. Chidambaram
Chairman, Atomic Energy Commission and Secretary, Department of Atomic Energy

For the European Organization for Nuclear Research (CERN)

C H Llewellyn Smith

C. H. Llewellyn Smith
Director-General

DAE-CERN Collaboration : LHC & Beyond

(RRCAT is the Nodal DAE Institute for this Collaboration)

DAE has given subsystems & skilled manpower support of 44 MCHF for LHC @ CERN; ***India is an Observer State.***

We continued helping CERN in LHC commissioning and

Participated in CERN's Novel Accelerator Projects :

*** Compact Linear Collider (CLIC)Test Facility CTF3.**

***Linac-4, front end of Superconducting Proton Linac.**

Reciprocally CERN has given hardware for our projects: One Klystron, one circulator for our use has already reached us. We had earlier received wave guide components.

 # Have made good progress in all collaborative programs during the last decade.

Major Elements of Contributions to LHC

Sn.	Detail	Status
1.	Corrector Magnets	616 MCDO & 1146 MCS supplied.
2.	Quench Heater Power Supply (QHPS) HDS units	All 5500 QHPS Supplied to CERN. Assembly of capacitors into 6200 QHPS completed.
3.	Manpower/expert support for magnetic meas.	Completed with 100 man-years
4.	PMPS Jacks 134 Adaptors	Total of 7080 supplied and accepted at CERN Supplied and accepted.
5.	Circuit breaker electronics	Full supply of 70 made to CERN.
6.	Local protection units (LPU)	1435 All completed.
7.	Man power support for LHC hardware commissioning	20 Man years. 22 officers identified for help starting September 2006, 13 officers deputed.

Precision Magnet Positioning System (PMPS) Jacks

MCS & MCDO

Magnetic measurements teams- ~100 Man-years

To mark DAE's contributions, CERN Gifted a Memento to Director, RRCAT on 20/3/07

Quench Heater Power Supplies(QHPS)

Local Protection Units

DAE's contributions installed in LHC Tunnel at CERN

DAE-CERN Joint Coordination Committee Meeting-March5, 08

P074/LHC

PROTOCOL

to

THE 1991 CO-OPERATION AGREEMENT

between

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

and

THE DEPARTMENT OF ATOMIC ENERGY OF THE GOVERNMENT OF INDIA (DAE)

concerning

THE FURTHER DEVELOPMENT OF NOVEL ACCELERATOR TECHNOLOGIES

2005

This Protocol shall form an integral part of the Co-operation Agreement dated 28 March 1991 and shall cancel the Statement of Intent signed on 25 May, 2005 by the Parties.

Done at Mumbai/Geneva on 15th February 2006 in two copies in the English language

For the European Organization for Nuclear Research (CERN)

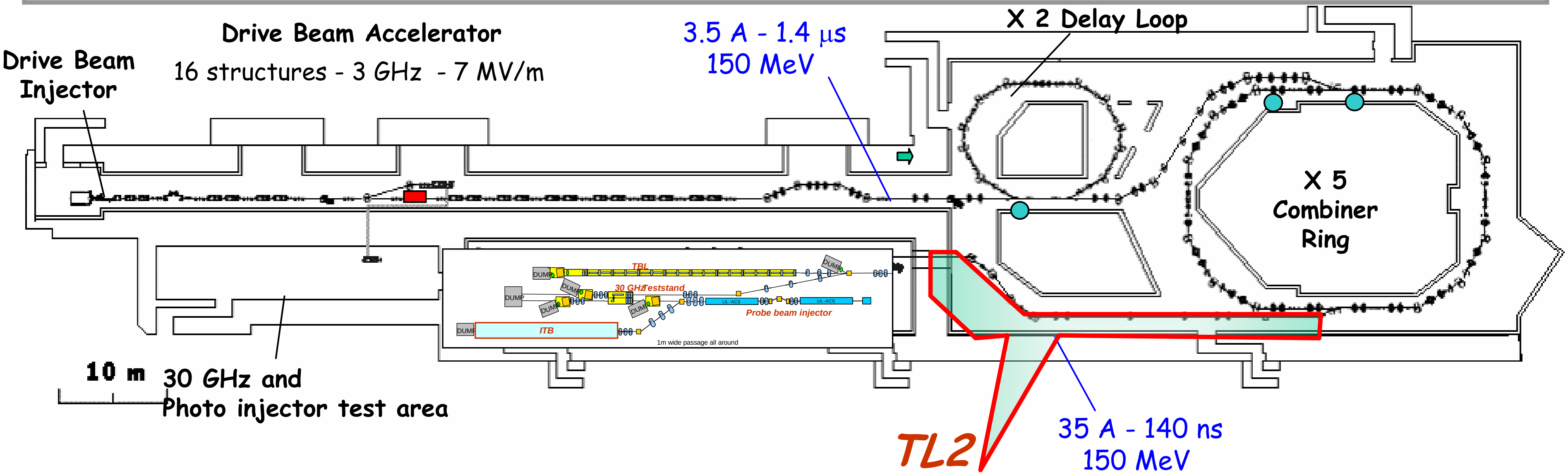
Robert Aymar
Director-General

For the Department of Atomic Energy of the Government of India (DAE)

Anil Kakodkar
Chairman, Atomic Energy Commission

NAT envisions DAE's participation in CERN's LINAC-4 & CLIC Test Facility-3 projects & CERN's contribution to DAE's programs by way of delivering hardware.

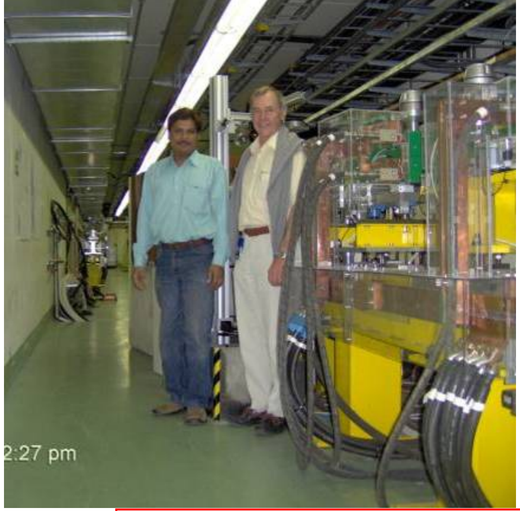
CLIC TEST FACILITY3 @ CERN *Aim: Establish principle of a 3-5 TeV e^+-e^- Collider using (1) A "drive beam" to create 12 GHz RF source",(2) Extract RF power via PETS & (3) Use RF power to accelerate e+-e- beams that will collide.*



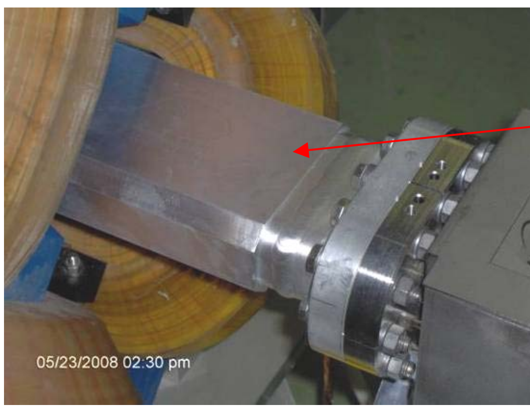
CTF3 Hardware Designed & Made at RRCAT & Shipped to CERN

Team with vacuum chambers

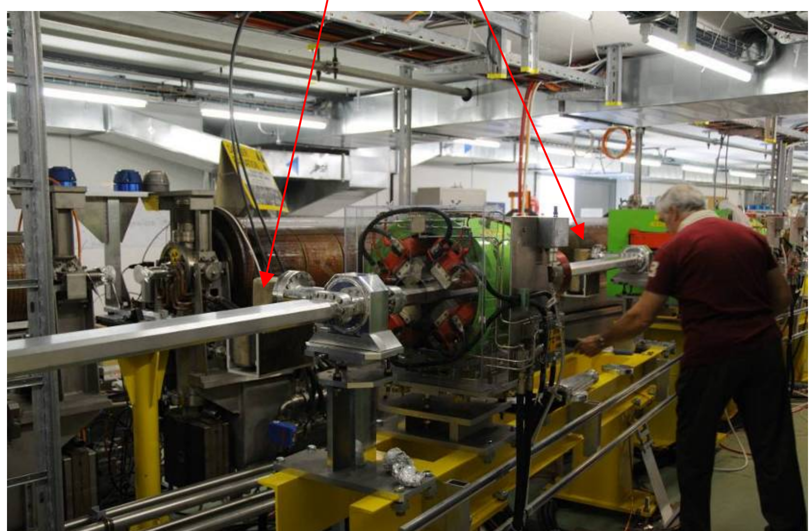
1/5 magnets for CTF3:Pic at RRCAT & CERN



Vacuum Chambers installed in TL2 of CTF 3 at CERN

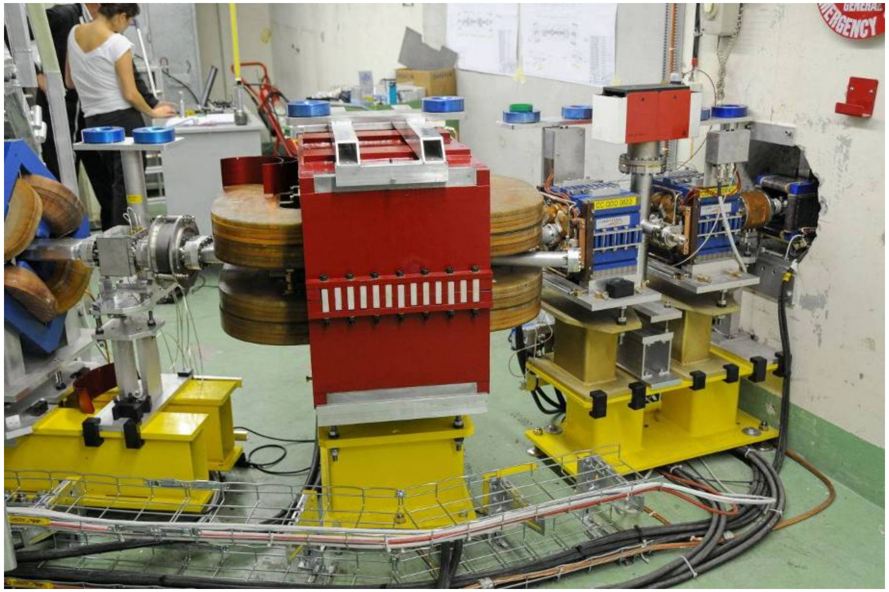


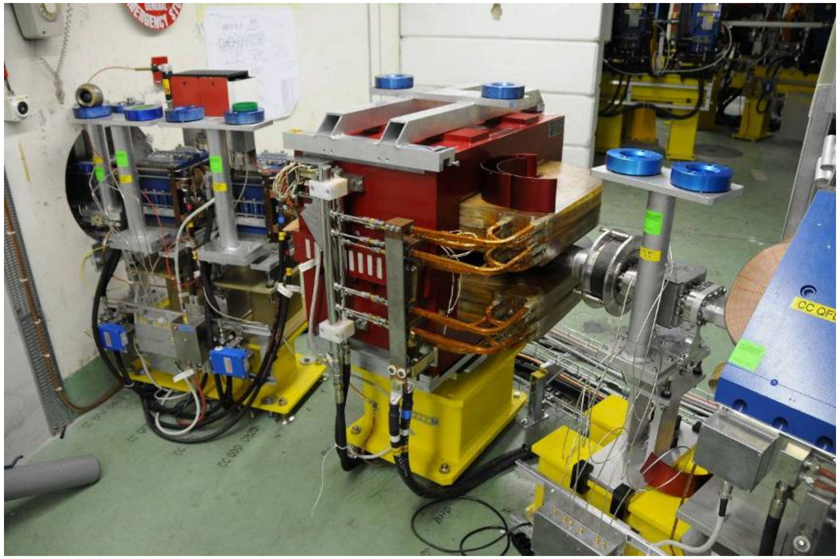
Race Track Profile Vacuum Chambers installed



End part of TL2 entering TL2' in CLEX area at CERN CTF3 Site

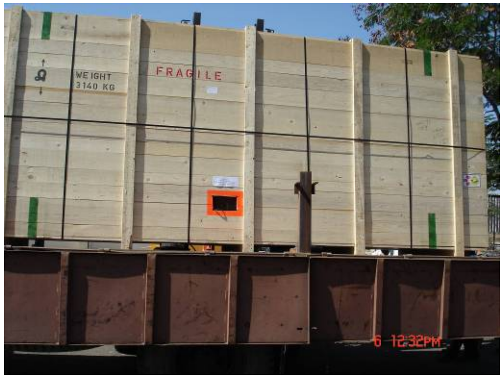
Circular Profile Vacuum Chambers installed





More pictures of RRCAT built CTF3 hardware installed @CERN

LEP Klystron from CERN to India



As received

Shifting to truck

Receipt & unloading of klystron at RRCAT

Shock detectors are intact; klystron is safely received

First LEP klystron & circulator from CERN have been received. Items are under installation in high power test stand set up at RRCAT to test these as well as the Solid State Bouncer modulator for LINAC 4 and the components developed at RRCAT.

Towards LHC's luminosity increase: Modulator for Linac 4 at CERN

DEVELOPMENT OF ALL SOLID STATE BOUNCER COMPENSATED LONG PULSE MODULATORS FOR LEP 1MW KLYSTRONS TO BE USED FOR LINAC4 PROJECT AT CERN*

Purushottam Shrivastava#, J. Mulchandani, V.C. Sahni
Raja Ramanna Centre for Advanced Technology, Indore, India
Carlos A. Martins, Carlo Rossi, Frédérick Bordry, CERN, Switzerland.

Abstract

CERN is building a 352.21 MHz 3 MeV RFQ based test stand as first part of LINAC 4. Extending its earlier collaboration with RRCAT, India, CERN had approached it to design and develop a high voltage pulsed modulator for 1 MW LEP klystrons, planning their reuse. RRCAT proposed three design schemes out of which an all solid state bouncer compensated modulator was chosen for follow up development work. The main considerations for the design were to avoid gas tube crowbar on the HV side, to 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. Based on these principles, a modulator has been developed and constructed at CERN and is currently undergoing tests with a klystron while another one with similar development is in the final stages of integration/evaluation at RRCAT. The present paper describes the topology, simulation results, protection strategy and briefly summarizes the results achieved.

INTRODUCTION

The 3MeV test stand will enable to explore the beam dynamics issues at the low energy end and comprises of 352.21 MHz, 3 MeV, 3-meter long RFQ, (part of SPL Front End) as the first part of the Linac4 [1], a new PS Booster injector proposed to improve the proton beam quality and availability for CERN users in the LHC era.

LEP 352.21 MHZ, 1 MW CW klystrons will be operated in pulsed mode with maximum average power up to 2 kW, to feed the RF sections of the linear accelerators. This requirement necessitated the development of new high voltage pulsed modulators tailored for operation at duty cycle of 0.1%.

Design considerations

The following issues were considered in the design:

- Crow-bar-less (no ignitron or thyratron) protection of klystron against arcing. The protection is assured by a) switching-off the main series switch very swiftly b) absorbing and dissipating the maximum of energy stored in the parasitic elements (stray capacitances, inductances, etc) inside the damping networks
- Low rise and fall time to limit the amount of wasted power
- High voltage stability of the flat top to assure the necessary phase stability of the RF output
- High reliability, minimum maintenance efforts and high lifetime due to solid-state construction.
- Modular structure to facilitate higher repetition rate up to 15 % duty at a later stage.
- The power supply interlock system able to be integrated into the CERN control and interlock system

purushri@rrcat.gov.in

* work supported by DAE of India under aegis of DAE CERN NAT Protocol___

TECHNICAL SPECIFICATIONS

The major requirements are listed in table 1.

Table 1 – List of modulator main parameters

Parameter	Design Targets
Klystron modulator type	Bouncer
High Voltage pulse amplitude	-10 kV to -110 kV
High Voltage pulse width measured at 70% to 70 % of peak.	800 µsec
Minimum Flat top available	600 µsec
Maximum current during pulse	24 A
Pulse repetition rate	2 Hz
Acceptable voltage drop	≤ 1.0 %
Allowed ripple on flat top (≥ 10 kHz)	≤ 0.1 %
Rise time/fall time	<100 µsec
Energy dissipated in klystron during klystron arc	<10 J

TOPOLOGIES CONSIDERED

At RRCAT we have designed and commissioned several modulators for klystrons based on the PFN topologies with step up pulse transformers, which have peak pulse power up to 15MW and mean power up to 90kW[2]. Few solid state switched modulators were also developed using RRCAT built stacked MOSFET/IGBT solid state switches, operating at 5kV/0.5A@10µsec/1Hz and 50kV/2A@10µsec/300Hz for pulsing driver klystrons and LINAC electron guns respectively. Looking into large reservoir of experience gathered on various topologies RRCAT took up the present project for CERN. Out of several schemes three options were found to be suitable and therefore an initial evaluation was restricted to: 1) Hard switched klystron modulator with high voltage programmable power supply for droop correction (active

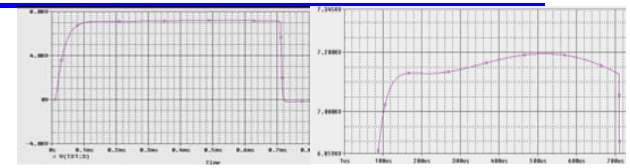


Figure 2 – Simulated waveforms (referred to primary) left: full pulse and, right: Zoomed at flat-top.

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

Figure 4 left: resistive load in oil tank (@110kv) connected to modulator; right: bouncer circuit elements pictures at RRCAT

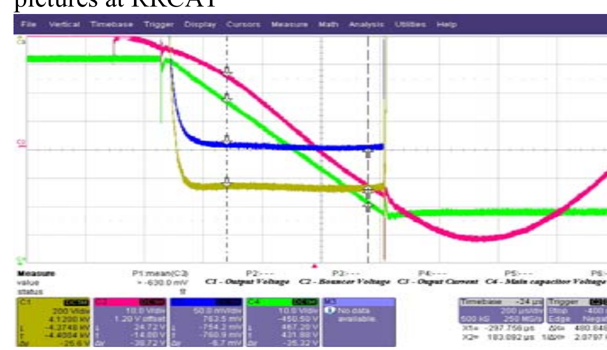
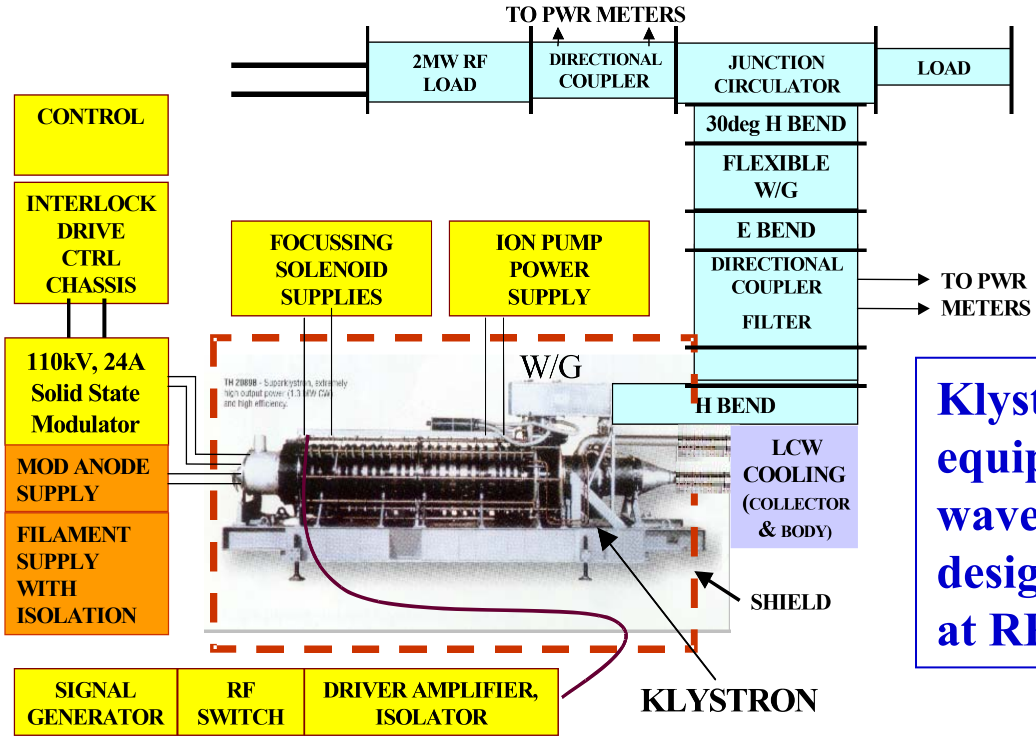


Figure 5 – Obtained output during initial run, at resistive load, representing klystron impedance. Waveforms represent C1:Output voltage C2: Bouncer voltage C3: Output Load current C4: Main Capacitor voltage



Schematic of 1.3 MW 352.2 MHz Test Stand at RRCAT

Klystron handling equipment & WR 2300 waveguide components designed and developed at RRCAT

LEP Klystron and circulatorr received from CERN being integrated with test stand at RRCAT

Modulator that has been designed (under test for CERN) would also serve our own proton accelerator development program.

Superconducting Cavity Developmental Activities at RRCAT

1. **Focus:Infrastructure to make Nb cavities for high energy/high power accelerators; building SCRF cavities, value engineering in cryomodule design and materials R & D**
2. **SCRF cavity infrastructure: Full fabrication set up, chemical processing, cleaning, assembly & test facility;**
3. **Cryogenic Infrastructure: Facilities to operate large systems.**
4. **Goal of superconducting materials R&D: Explore connection of cavity performance & basic superconducting properties.**
5. **Indian interests: High current proton accelerator to be used for R&D linked to ADS & take part in Project –X /ILC R&D; dialogue on regarding SPL@CERN.**
6. **Collaboration with: Fermilab, CERN & KEK.**
7. **Goal: Get accelerating gradients needed in these applications.**

US-Indian Accelerator Lab Collaboration

Memorandum of Understanding
between
US Universities & Accelerator Laboratories
and
Indian Universities & Accelerator Laboratories
concerning
Collaboration on R&D for Various Accelerator Physics and High Energy Physics Projects

January 9, 2006

1. Introduction

1.1 General Description

This Memorandum of Understanding (MOU) establishes a collaboration framework between various US and Indian Accelerator Laboratories and

4.2 Approvals
The following concur in the terms of this Memorandum of Understanding:

Piermaria Oddone, Director, FNAL	Vinod C. Sahni, Director, RRCAT
Date 1/9/05	Date March 8, 2006
Jonathon Dorfan, Director, SLAC	Bikash Sinha, Director, VECC
Date 1/23/06	Date March 9, 2006
Christoph Leemann, Director, TJNAF	Amit Roy, Director, IUAC
Date 1/18/06	Date March 9, 2006.
Maury Tigner, Director, Newman Lab	S. Bhattacharya, Director, TIFR
Date	Date April 17, 2006
	S. Banerjee, Director, BARC
Date	Date March 14, 2006
	Deepak Pental, Vice Chancellor, DU
Date	Date April 10, 2006

ADDENDUM
to the
Memorandum of Understanding
between
US Universities & Accelerator Laboratories
and
Indian Universities & Accelerator Laboratories
concerning
Collaboration on R&D for Accelerator Physics and High Energy Physics Projects

Addendum I: "Fermilab, RRCAT, BARC, IUAC and VECC Collaboration on ILC Main Linac SRF Accelerator Technology R&D"

October 2, 2007

1. Introduction

The work detailed in this document falls within the scope of the Memorandum of Understanding (MOU) between US and Indian Institutions dated January 9, 2006. It

7 Management and Approval:

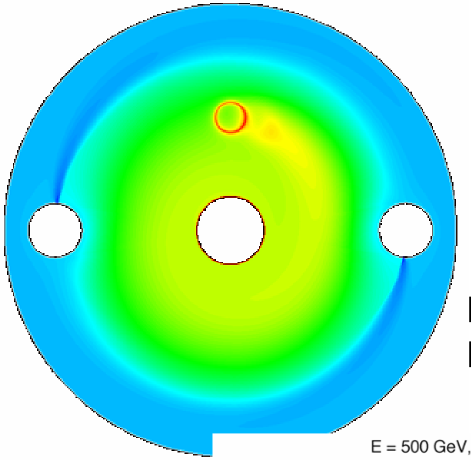
The work under this MOU will be jointly managed by Dr. Shekhar Mishra, Fermilab and Dr. Vinod C. Sahni, India. They represent the institutions in the respective countries and serve as a single point of contact.

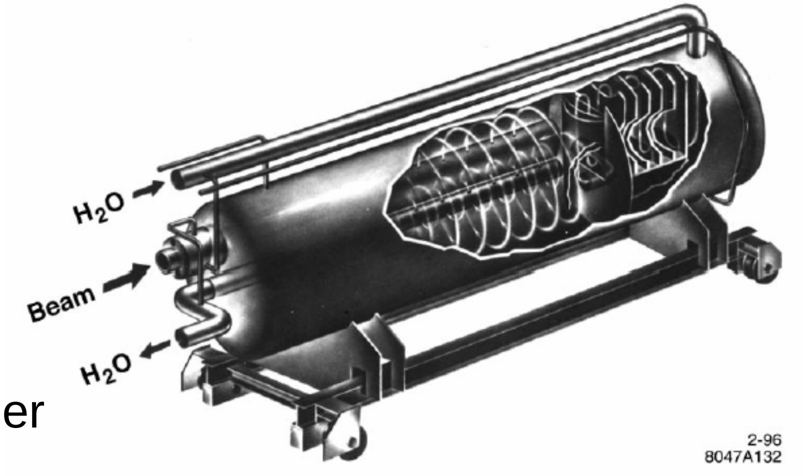
The following concur on the terms of this Memorandum of Understanding:

Dr Vinod C. Sahni, Director, RRCAT	Dr. Piermaria Oddone Director, FNAL
Date Oct 2, 2007	Date 10/2/07
	Dr. Shekhar Mishra Deputy ILC Program Director, FNAL
	Date 10/2/07

18MW Beam dump

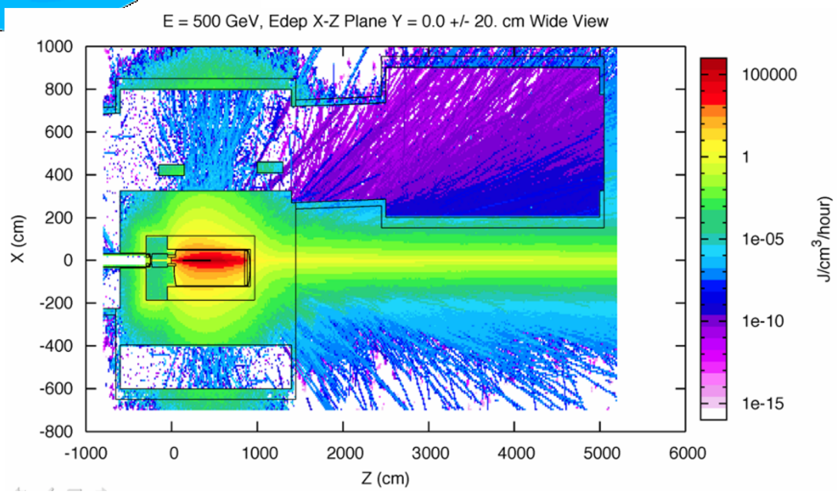
BARC, India, & SLAC, collaboration

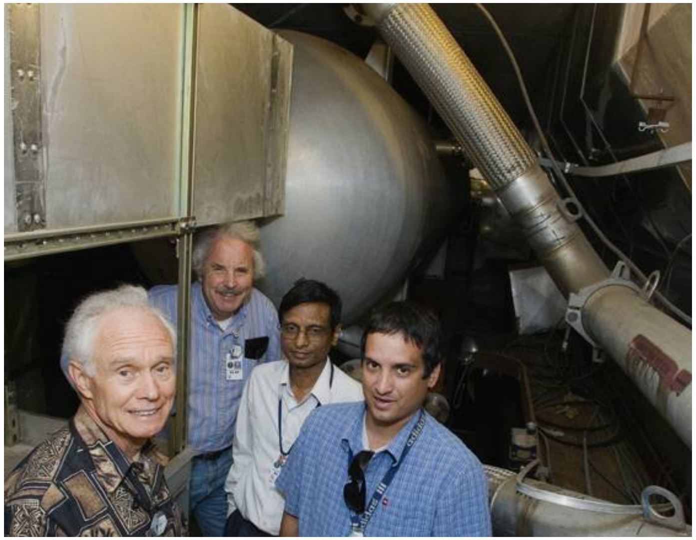




Beam dump with double header (Satyamurthy Polepalle et al, BARC-SLAC)

Maximum Temperature – 147^{0}C
Maximum delta T – 28^{0}C





Dieter Walz, Ray Arnold, Satyamurthy Polepalle (BARC, India), John Amann, at SLAC beam dump area (Feb 2008)

Planning for the next working meeting of the task force at SLAC in ~May 2009, to continue the work on beam dump design

ADDENDUM

to the

Memorandum of Understanding
between
US Universities & Accelerator Laboratories
and
Indian Universities & Accelerator Laboratories
concerning
Collaboration on R&D for Accelerator Physics and High Energy Physics Projects

Addendum III: "Fermilab and Indian Accelerator Laboratories Collaboration on High Intensity Proton Accelerator and SRF Infrastructure Development"

Feb 10, 2009

1. Authority and Limitations

Pursuant to the Memorandum of Understanding ("MOU") between the U.S. Universities & Accelerator Laboratories and Indian Universities & Accelerator Laboratories dated January 9, 2006, Fermilab and Indian Accelerator Laboratories (the "Parties") intend to undertake the work described in this Addendum III. The Parties acknowledge that their intended work shall be consistent with the terms and conditions of the MOU, the terms and conditions of their respective contracts and programs, and subject to the availability of appropriated funds as provided to them. The Parties further acknowledge and understand that their agreement with and signature to Addendum III does not create a legal, contractual obligation for either Party nor may form the basis of a claim for reliance thereon. The Parties agree to comport their activities under Addendum III in conformance with all applicable U.S. and Indian laws and regulations, including those related to export control.

2. Introduction

The work detailed in this document falls within the scope of the MOU cited above. It addresses in some detail the two key areas of collaboration mentioned in the main MOU, which are (i) Superconducting Radio Frequency (SRF) Acceleration Science and Technology, including setting up test facilities and a high current proton driver, and (ii)

Mishra, Fermilab and Dr. Vinod C. Sahni, India serve as the Collaboration Coordinators.

The Fermilab Associate Director Accelerators and the ILC/SRF Program Director in consultation with the appropriate Fermilab Division Head and the Fermilab Collaboration Coordinator will appoint a Project Manager for each of the projects described in this Addendum. Indian Institutions will also appoint a Project Manager in consultation with the Indian Collaboration Coordinator and assign a lead laboratory for each project to help coordinate the work.

The Project Managers have the responsibilities of developing and managing the technical design, budget and schedule of the project. They will provide technical leadership, negotiate for required labor, conduct project reviews, prepare needed safety documents, and get necessary safety approvals and certifications in order to carry out the work. Project Managers are also expected to manage the daily aspects of their projects and keep the respective Institutional Management and Collaboration Coordinators informed of progress.

The Collaboration Coordinator in consultant with the Project Managers will call for periodic reviews of the project. They, in consultation with their respective Institutional Management will approve the plans developed by the Project Managers and decide on future direction of a project.

The following concur on the terms of this Memorandum of Understanding Addendum:

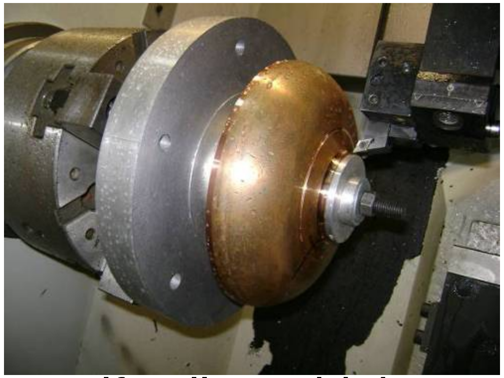
[signature] 10.2.2009	Feb 10, 2009	[signature]	2/10/2009
Dr Vinod C. Sahni, Director, RRCAT	Date	Dr. Piermaria Oddone Director, FNAL	Date
[signature]	Feb 11, 2009	[signature]	Feb 11, 2009
Dr Srikumar Banerjee, Director, BARC	Date	Dr Amit Roy, Director, IUAC	Date
Dr Bikash Sinha, Director, VECC	Date		


RRCAT, Indore
February 10, 2009
Dr. Shekhar Mishra
Dr. Anil Kakodkar
Dr.Piermaria Oddone
Dr. V. C. Sahni
Dr. R. K. Bhandari
Sh. C. K. Pithawa

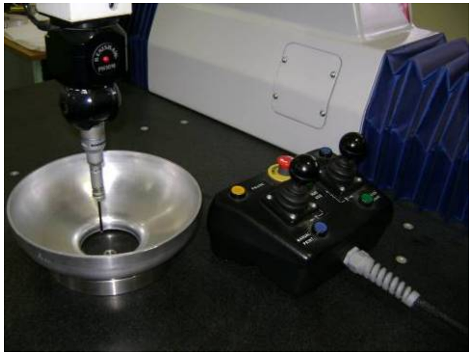
Development of 1.3 GHz Tesla Type Cavity Forming / Machining Tooling & Final Half Cells

- Manufactured, qualified one full set of forming and machining tooling (Mid half cell, Long end half cell, Short end half cell) and used to make trial pieces.
- Also one complete set of forming tooling made and shipped to Fermilab.
- Developed Niobium grade RRR 300 half cells for 1.3 GHz SC Cavity.

Forming tooling



Half cell machining



CMM inspection

Formed half cell

Parameter	Target Value	Obtained Value
Profile tolerance, mm	± 0.2	± 0.2
Parallelism of equator & iris faces, mm	0.02	0.03
Roundness of equator ID, mm	0.05	0.03
Roundness of iris OD, mm	0.05	0.01

First EB welding trial :1.5 GHz Al prototype cavity

Made in collaboration with Indian Industry, LTE, Coimbatore

EBW Machine : 6 kW, 60 kV;
M/s Techmeta, France
Chamber: 50cmx45cmx45cm

On way to 1.3 GHz single cell Nb cavity (EB welding trials joining half cell to pipe)

Made in collaboration with IUAC, New Delhi

EBW Machine : 15kW, 60 kV;
M/s Techmeta, France
Chamber : 2.5 m x 1 m x 1 m

Facilities for SCRF Program Set Up / Planned

For cavity fabrication:120 T Hydraulic press, Nb machining facility**,** EBW m/c etc.

For chemical & thermal processing: EP/BCP /CBP, HPR & annealing furnaces etc.

Support facilities: Software for cavity design, UTM, CMM, SIMS, Eddy Current Scanner etc.)

Assembly & testing set up: Clean-room, Test cryostats, RF sources etc.

Cryogenic infrastructure: large capacity liquid He plant, liquid N2 plant and accessories for larger cryogen & gas handling systems etc.

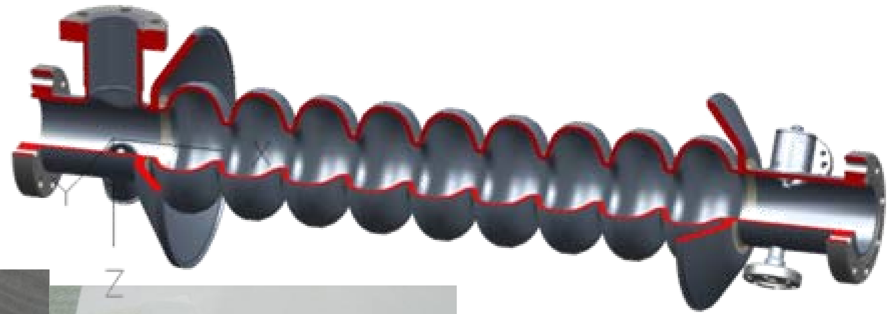
Facilities for superconducting materials R&D: Augment available magnetic, electrical & thermal conductivity measurement set up.

120 T Hydraulic Press

Al half cells

Progress towards economic manufacture of SC cavities

Alternate way to make the cavity "end groups"



M/S CRISP,Bhopal

Approach

- Machine entire end group from a single cylindrical block. Use EDM wire cut process. Solid part will be used to make other components like form teil housing.
- Extensive prototyping and testing.

Status

- Prototypes in Copper and Low RRR niobium block completed.

Qualification of Nb materials for SCRF cavity fabrication:

*Current approach: Focuses on improving the residual resistivity ratio (RRR) of the Nb. **Involves expensive Niobium refinement process.**

*High RRR + right cavity shape + surface treatment ⇒ Extrinsic (+ surface) defects are low & multipacting is reduced. But high RRR may **not** give good SC properties & at best gives indirect information on thermal conductivity.

***All cavities fabricated in the same way do not give high gradients and cavity gradients are often way below theoretical maximum ~55 MV/m.**

We explore effect of grain size, treatments & impurities on Nb SC properties ie how $H_{critical}$ changes for,

(1) Nb materials of different grain sizes and amount of Ta impurity,

(2) Different chemical treatments: EP or BCP treated,

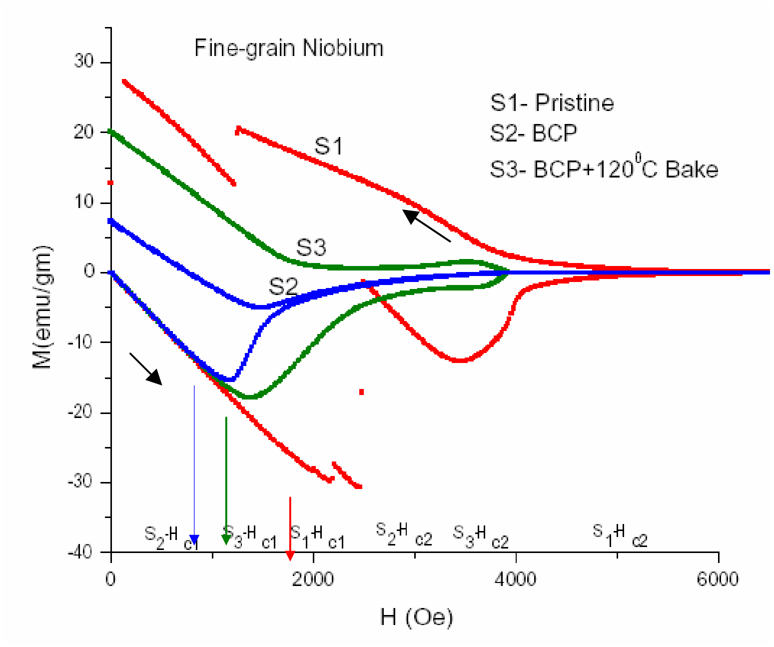
(3) Thermal treatment : annealing temperature and time.

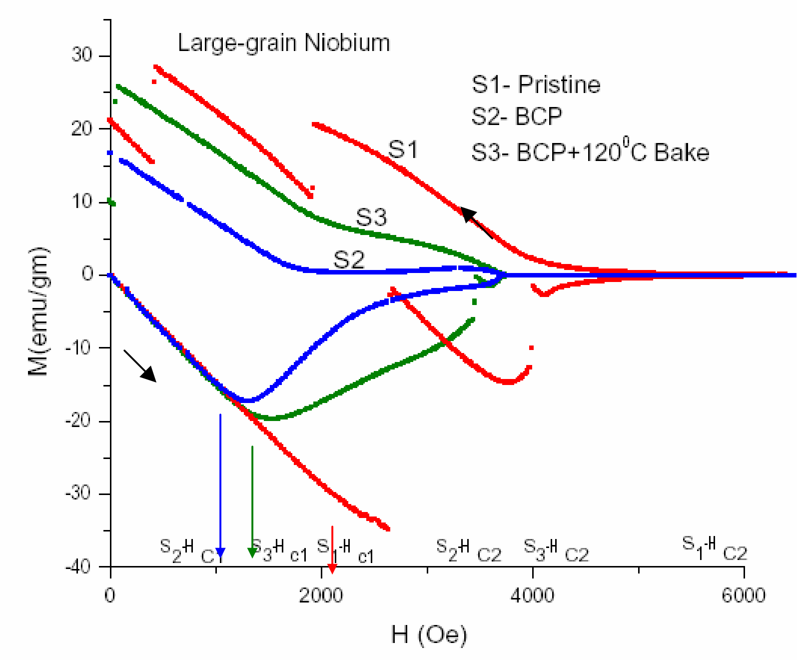
Goal was: Devise an improved Nb qualification scheme.

We find use of **H_{C1} / H_p gives better handle on accelerating gradients.**

Effect of BCP treatment on Nb samples

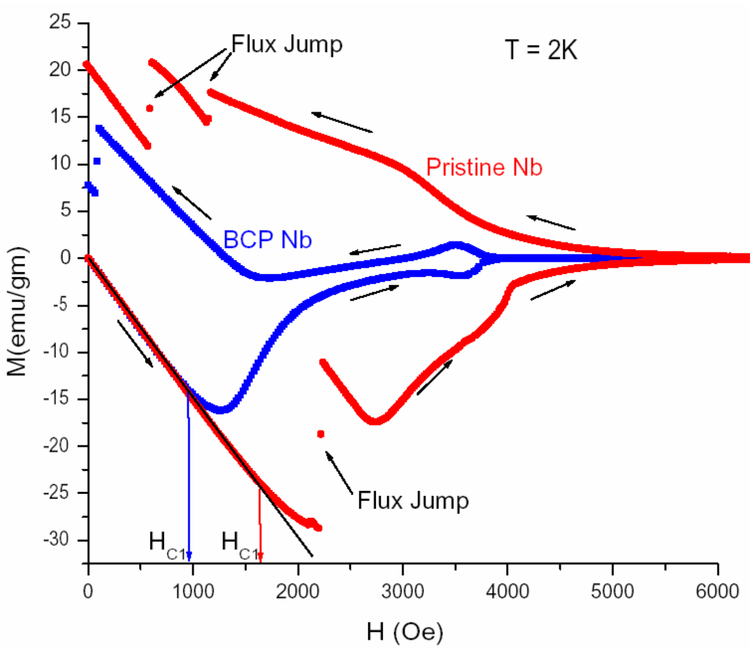
Nb samples obtained from the same batch that was used for making SCRF cavities at JLab, USA, subjected to same BCP and annealing treatments as was given to the SCRF cavities.

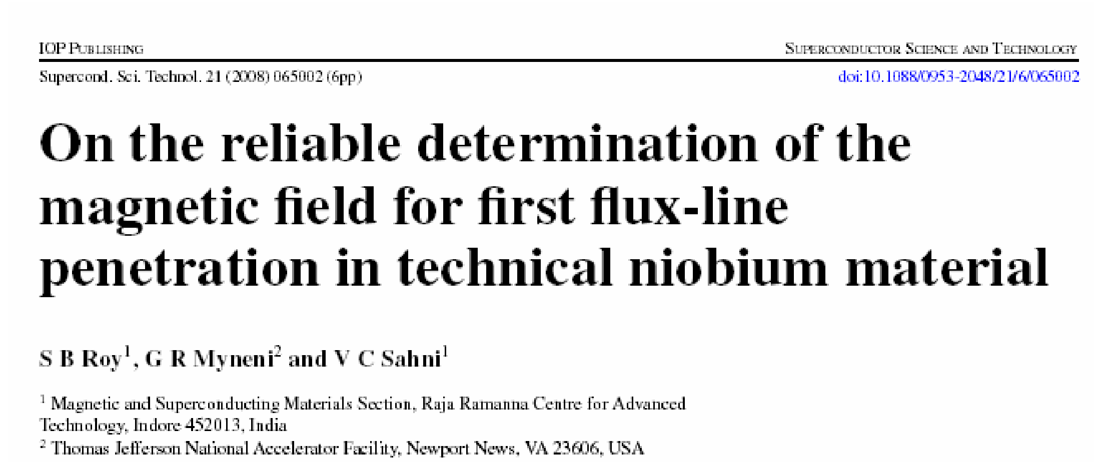




Note large grain material is better. Estimated H_{C1} of the BCP treated samples **correlates well** with the reported surface magnetic fields above which a severe degradation of the Q-factor is observed in the BCP treated Nb SC-RF cavities.

Main results in a nutshell





IOP PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY
Supercond. Sci. Technol. 21 (2008) 065002 (6pp) doi:10.1088/0953-2048/21/6/065002

On the reliable determination of the magnetic field for first flux-line penetration in technical niobium material

S B Roy[1], G R Myneni[2] and V C Sahni[1]

[1] Magnetic and Superconducting Materials Section, Raja Ramanna Centre for Advanced Technology, Indore 452013, India
[2] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

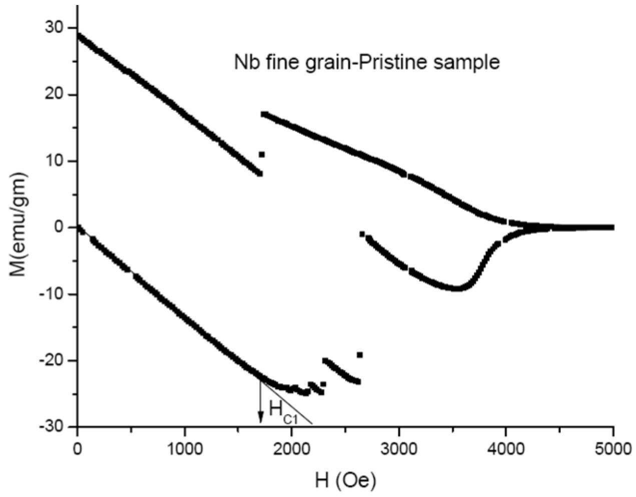
Note that in large grain Nb sample BCP treatment lowers the field at which magnetic flux lines enter the material as compared to that in pristine Nb.

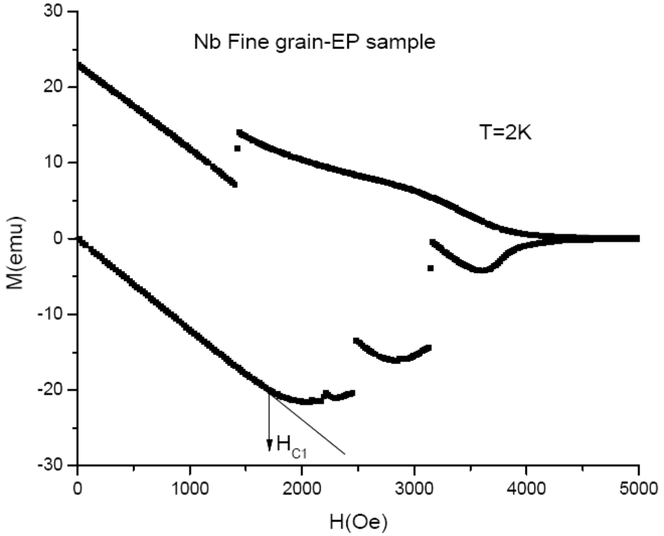
→

RF cavity prepared with such BCP Nb would reach maximum 30-32 MV/m

Effect of EP treatment on Nb samples

Samples from IUAC, New Delhi

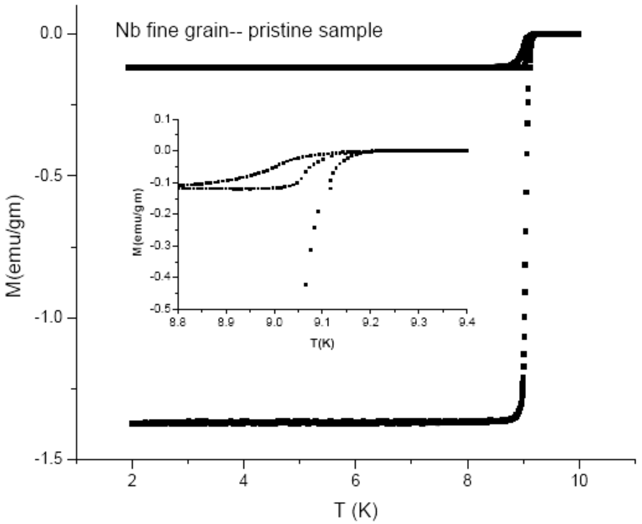


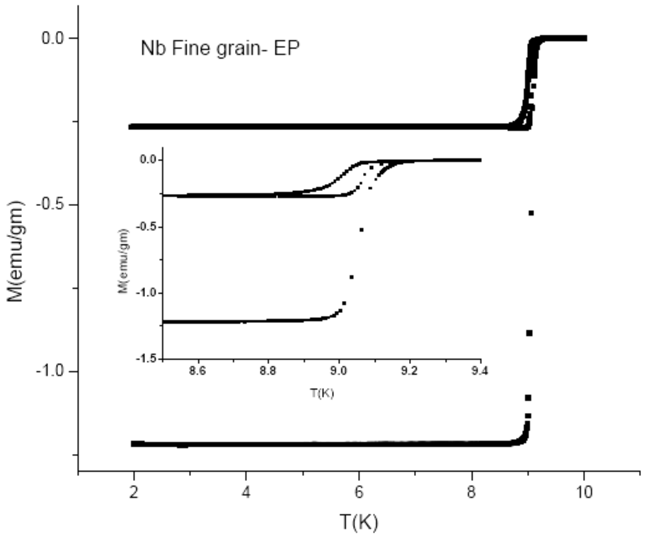


Conclusion:

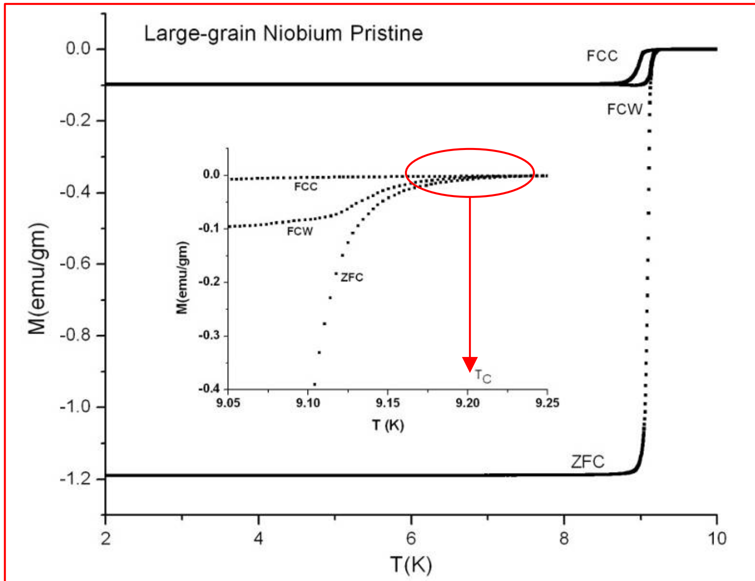
Effect of EP treatment on SC properties of Nb is rather small.

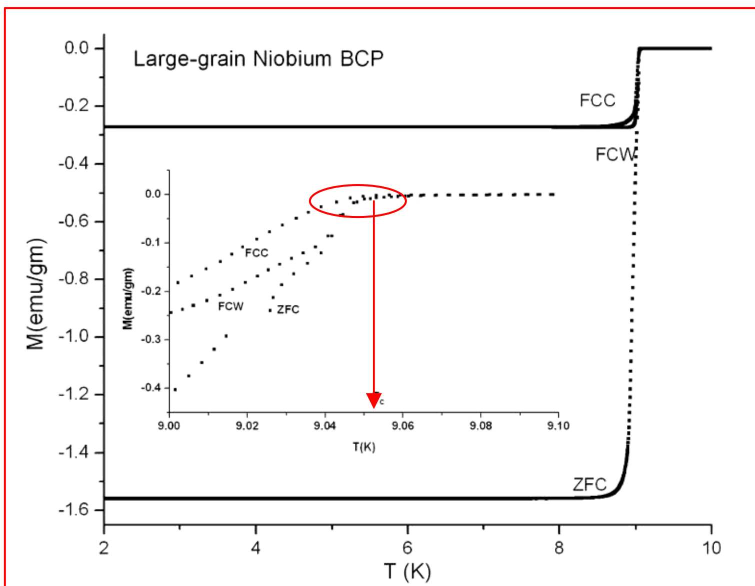
EP treatment is therefore preferable for handling Nb cavities.





Effect of BCP treatment on the T_C of Nb samples



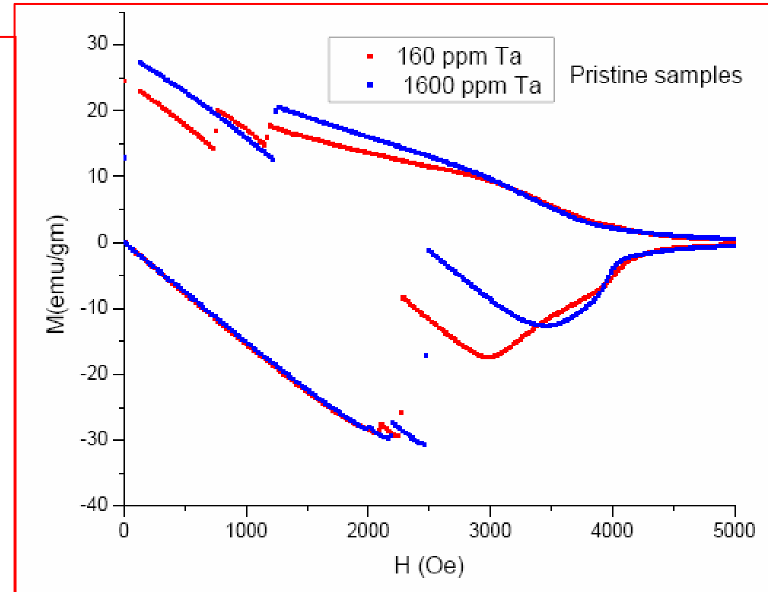


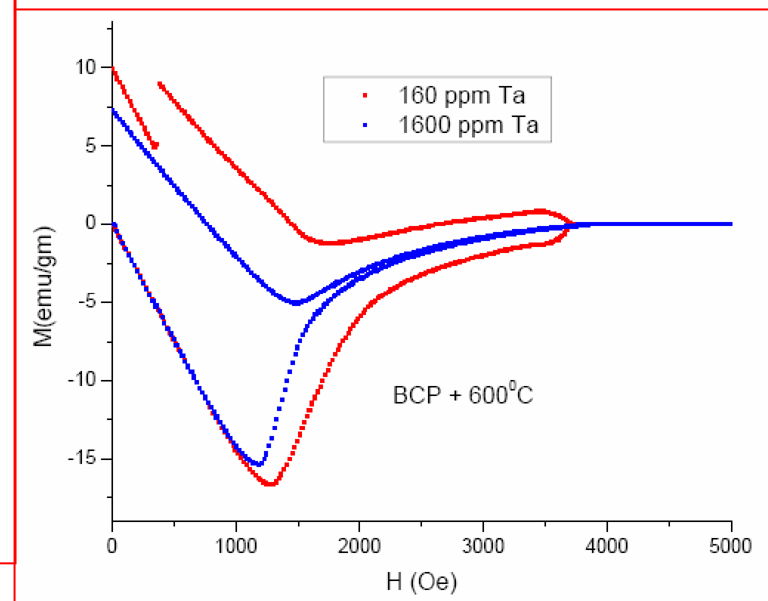
Conclusions

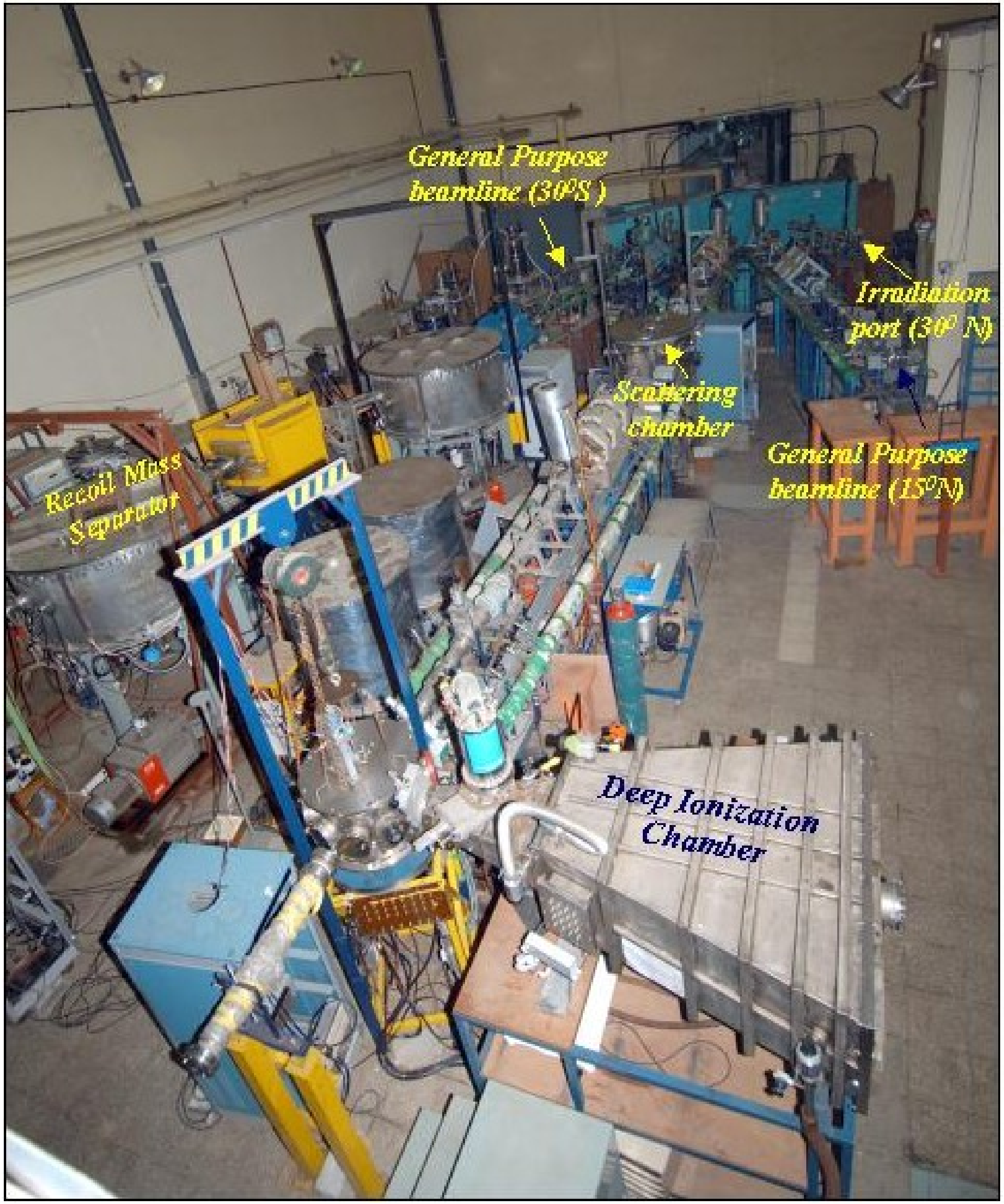
BCP lowers the Tc quite significantly. Hence not desirable.

High Ta impurity only marginally affects SC properties. So we can possibly use even less pure material to make cavities.

Effect of Ta impurities on the SC properties of Nb



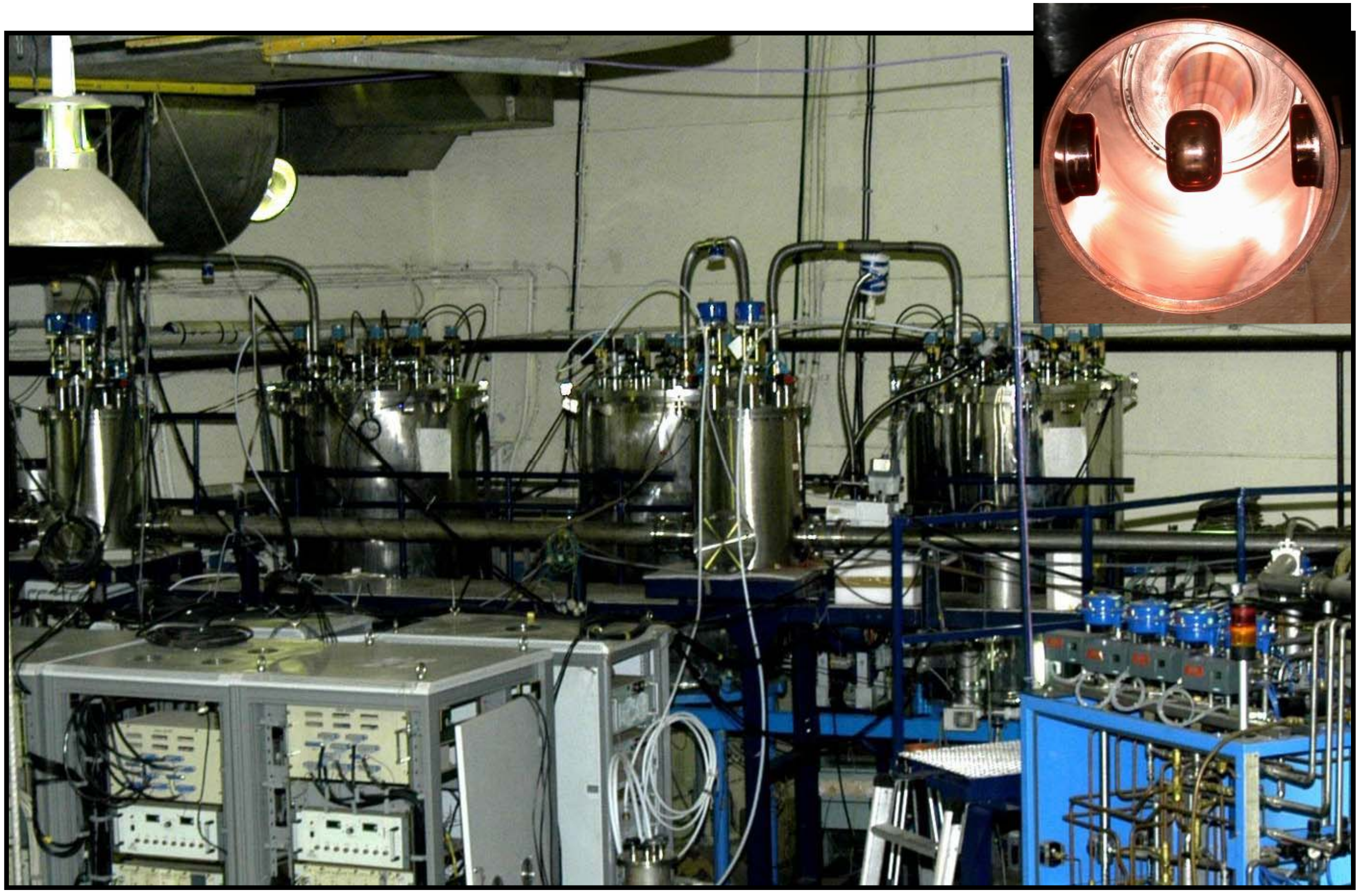




Set up as a BARC-TIFR collaborative project, Pelletron accelerator has been serving as a major advanced facility for nuclear physics research in India since its commissioning in 1989. Several facilities have also been added. Main areas of research are nuclear structure studies at high temperature/high angular momentum, elastic scattering & transfer reactions as well as fusion-fission reactions. It ***has been augmented with a superconducting LINAC booster to raise beam energy by ~ 5 –12 MeV/A****.*

A superconducting booster linac has been indigenously developed to raise the energy of the ions emerging from Pelletron. LINAC consists of 7 modules, each having four lead coated (2 μm) copper quarter wave resonators (QWR) immersed in liquid He cryostat & fed by RF power. A gradient of~2.5 MV/m is created in each module for acceleration.

If we used a room temperature LINAC rather than a superconducting one it would have been thrice as long & ten times more costly to operate. SC LINAC booster can provide an energy gain of 14 MeV/q and is on way to final commissioning.



Scheme for Accelerator Development for ADS

High current injector 20 MeV, 30 mA

Proton IS 50 keV → RFQ 3 MeV → DTL 20 MeV

Phase 1

⇩

Design completed and fabrication is in progress

Normal Conducting: DTL/ CCDTL

Phase II

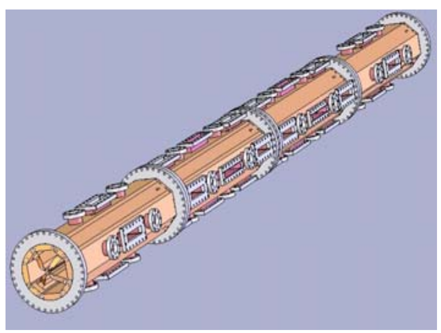
Super-conducting

100 MeV → Phase III: SC Linac

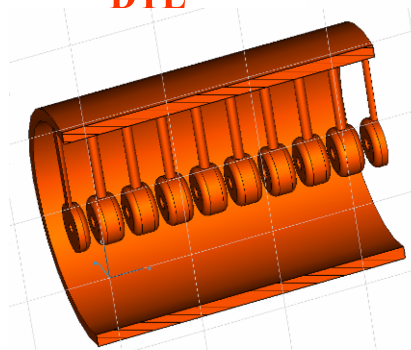
1 GeV

ECR Ion Source

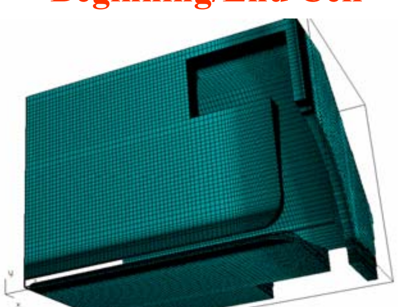
RFQ



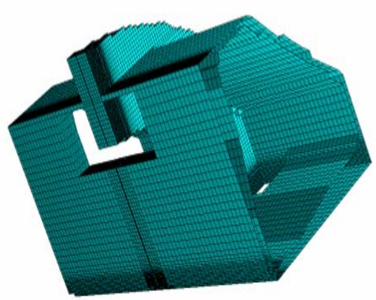
DTL



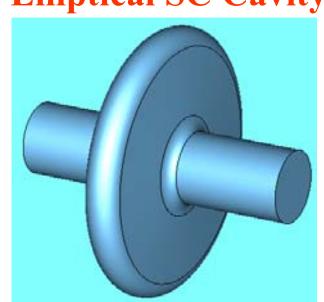
Beginning/End Cell

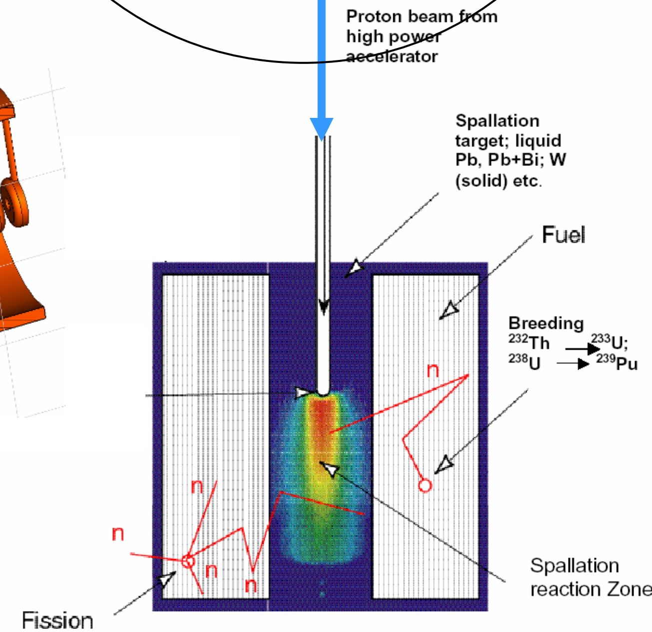


Coupling Cell



Elliptical SC Cavity





Parameters of RFQ, DTL, CCDTL and SC Linac

RFQ

Frequency	352.21 MHz
Energy	50 keV/ 3 MeV
Input current	30 mA
Vane voltage	80 kV
Peak surface field	32.8 MV/m
Length	4 m
Total RF power	500 kW
Transmission	98 %

DTL / CCDTL

	DTL	CCDTL
Energy Range (MeV)	3-40.1	40.1-100.2
Frequency (MHz)	352.21	704.42
Current (mA)	29.3	29.3
Focusing Lattice	FFDD	FODO
Quadrupole Gradient (T/m)	43	62.4-19.5
Avg. Acc. Gradient (MV/m)	2.5	1.37
Total Length (m)	22.66	69.57
Norm. Trans. Emitt. (πcm-mrad) ε_x ε_y	0.022-0.0232 0.022-0.0236	0.0232-0.0233 0.0236-0.0242

SC Linac (15 MV/m)

Parameter	β_G= 0.49	β_G= 0.62	β_G= 0.80
Energy Range (MeV)	100.2-197.2	197.2-421.3	421.3-1016.5
Frequency (MHz)	704.42	704.42	704.42
Current (mA)	29.3	29.3	29.3
Trans. Focusing lattice	Doublet	Doublet	Doublet
Lattice Period (cm)	304.27	607.90	810.47
Quadrupole gradient (T/m)	5.80-4.31	4.50-4.99	4.40
Eff. Length of Quad (cm)	35	40	45
Synch. Phase (degrees)	-30	-35.24	-34.37
Cavities/cryomodule	2	3	4
No. of Cryomodules	12	15	23
Aperture Radius (cm)	4.0	4.0	4.0
Total length (m)	34.76	88.15	183.33
Norm. Trans. Emitt. (πcm-mrad) ε_x , ε_y	0.023-0.030 0.024-0.027	0.030-0.033 0.027-0.030	0.033-0.037 0.030-0.031
Norm. Long. Emitt. (MeV-deg)	0.237-0.241	0.241-0.240	0.240-0.257

Transmission = 100% ; Total Length = 407 m (101 + 306)

A complete Linac cryostat with eight resonators and a solenoid magnet

Liquid He-vessel

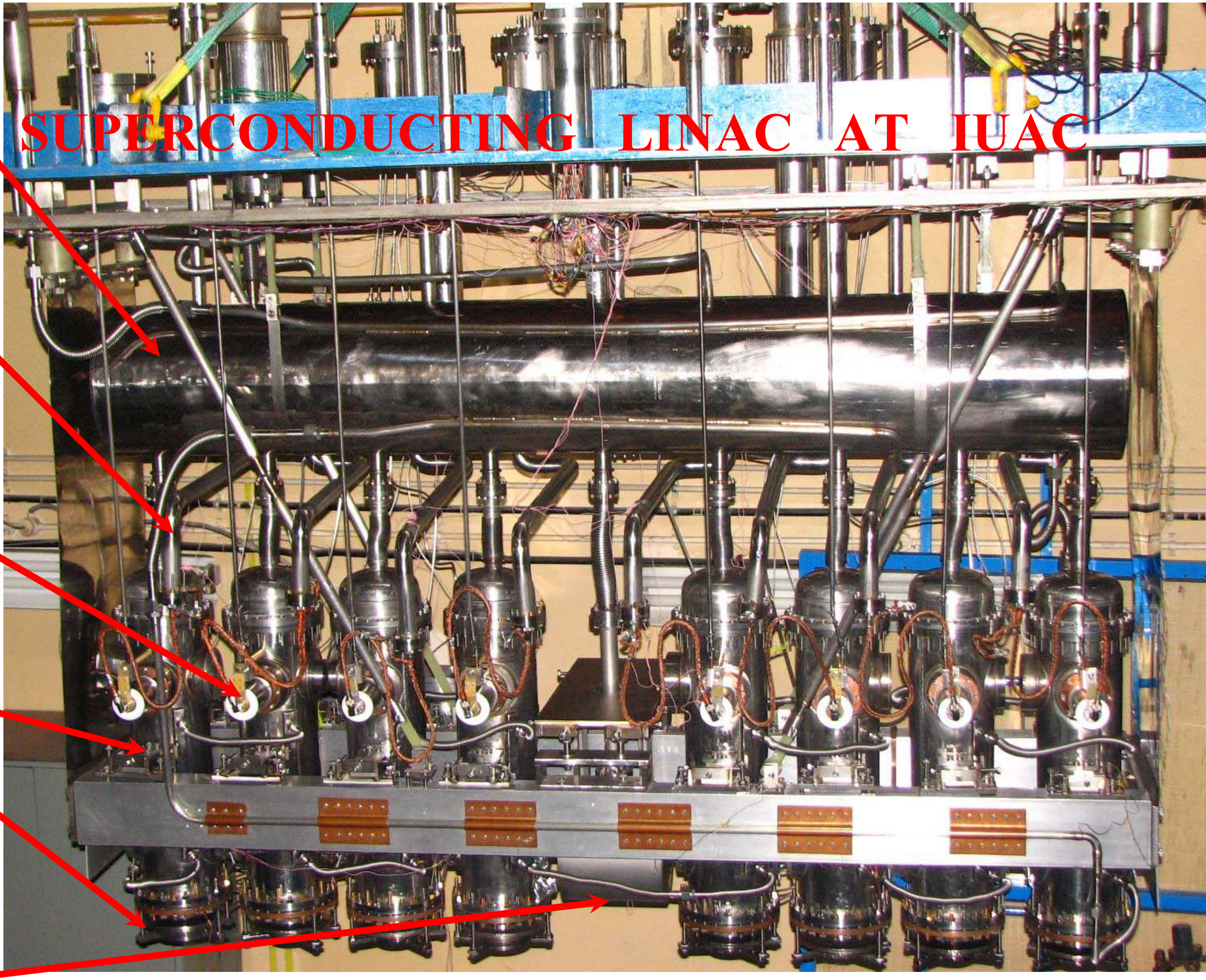
LN2 manifold to cool Power cable

Drive coupler

Resonators

Mechanical Tuner

Solenoid



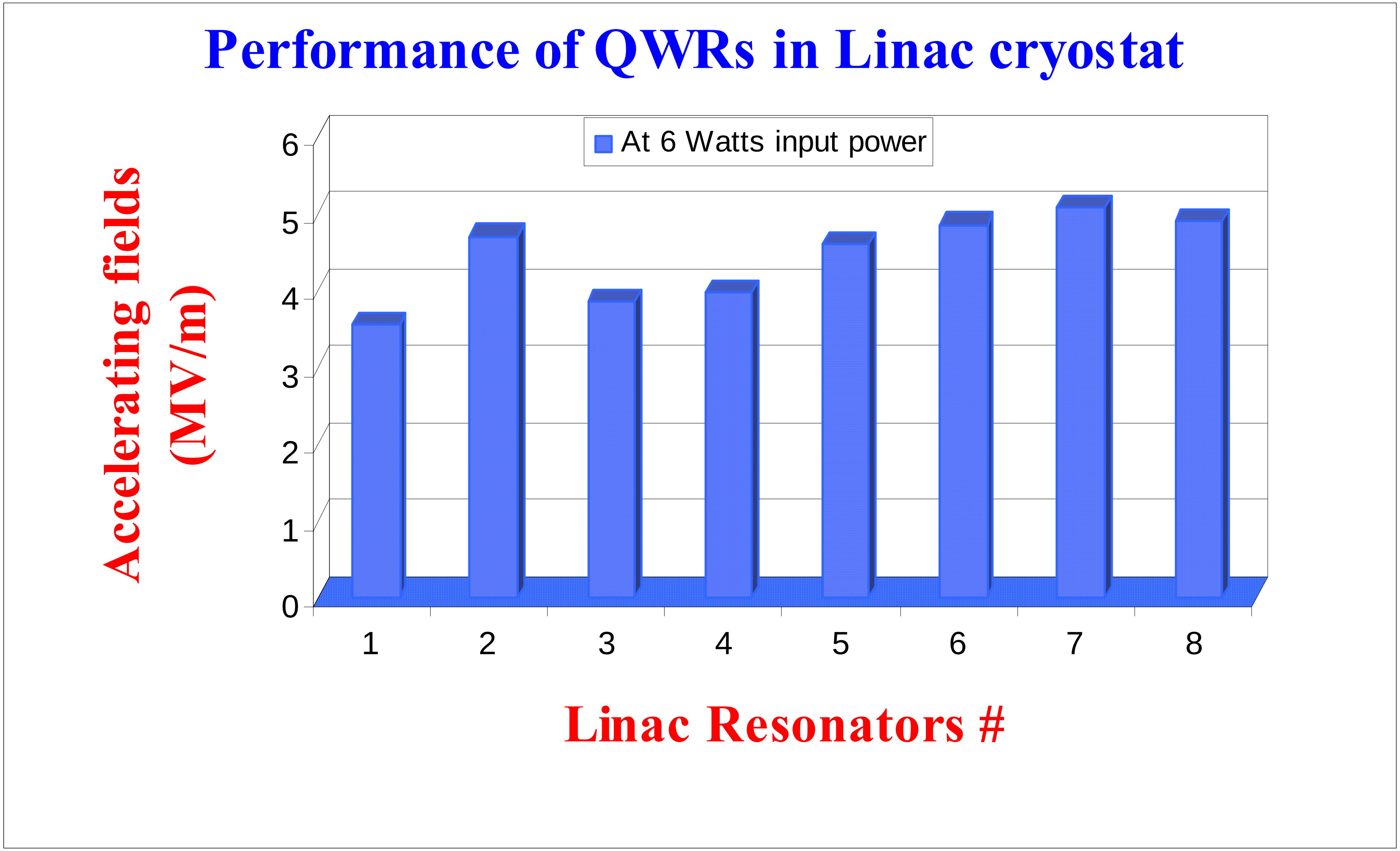
Results at liquid He temperature

Resonator test with damping mechanism in test and Linac cryostat

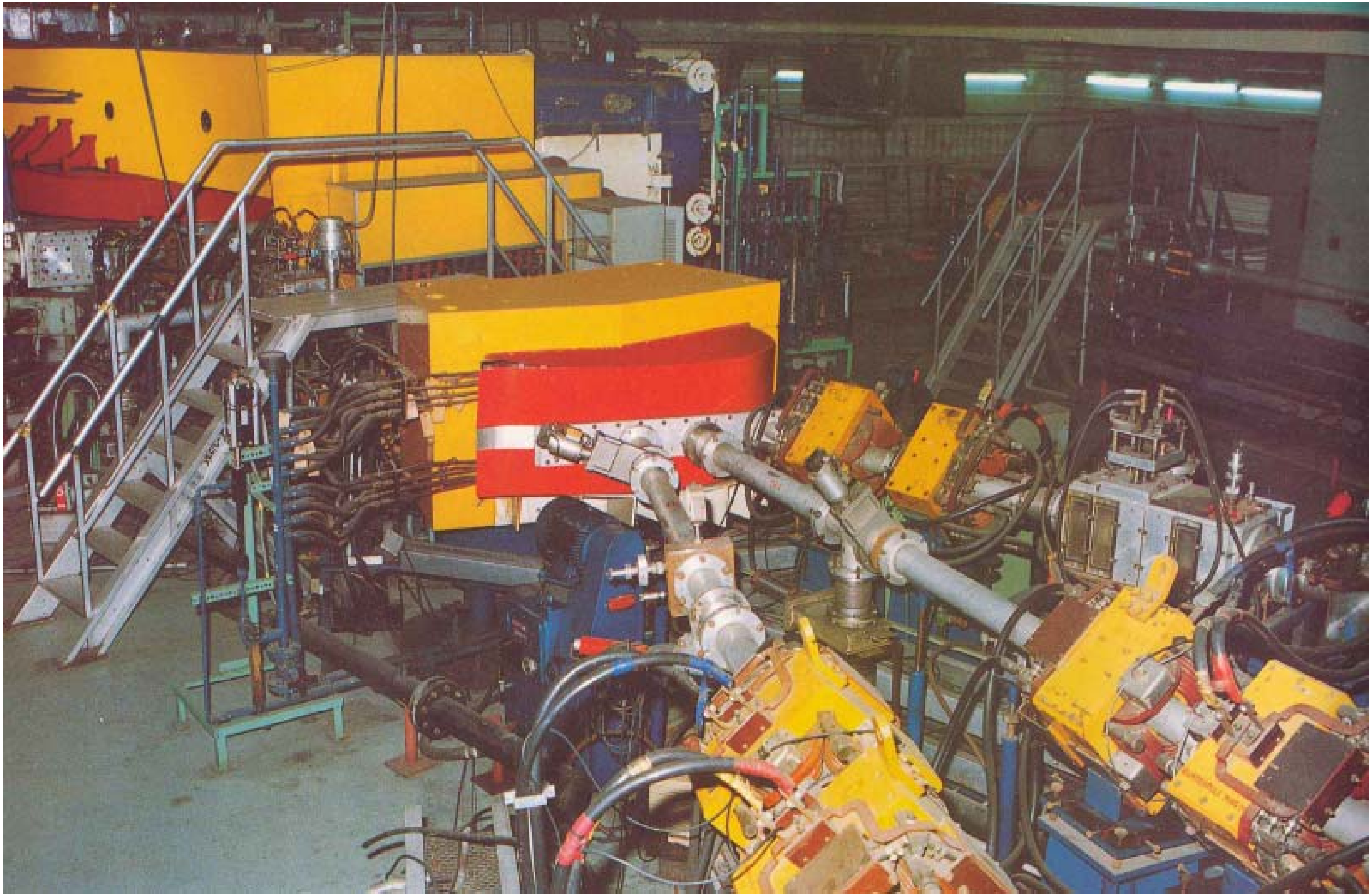
Cryostat	QWR	Q_0@ 6 Watts	E_{acc} (MV/m) @ 6 watt	E_{acc} (MV/m) during phase lock	Required power (W) without damping	Required power (W) with damping
Test	1	1.6×10^8	3.5	3.5	60	28
	2	4.7×10^8	6.0	5.0	80	35
Linac	3	2.1×10^8	4.0	3.1	218	90
	4	2.1×10^8	4.0	2.5	280	100

Physical Review – Special Topic –Accelerator and Beam, 10, 042002 (2007)

Recent Results (Jan – Feb 2009)



224cm Variable Energy Cyclotron@Kolkata



The superconducting cyclotron @ VECC, Kolkata

Parameters of the machine

K_{bend}= 520 (~B^2R^2), K_{foc}= 160

Accelerate heavy ion beams of energies:

80 MeV/nucleon for light ions
~10 MeV/nucleon for heavy ions

Radio-frequency system : 9-27 MHz

Maximum Dee voltage: 80 kV

Superconducting magnet field:

Average magnetic field ~ 5 Tesla

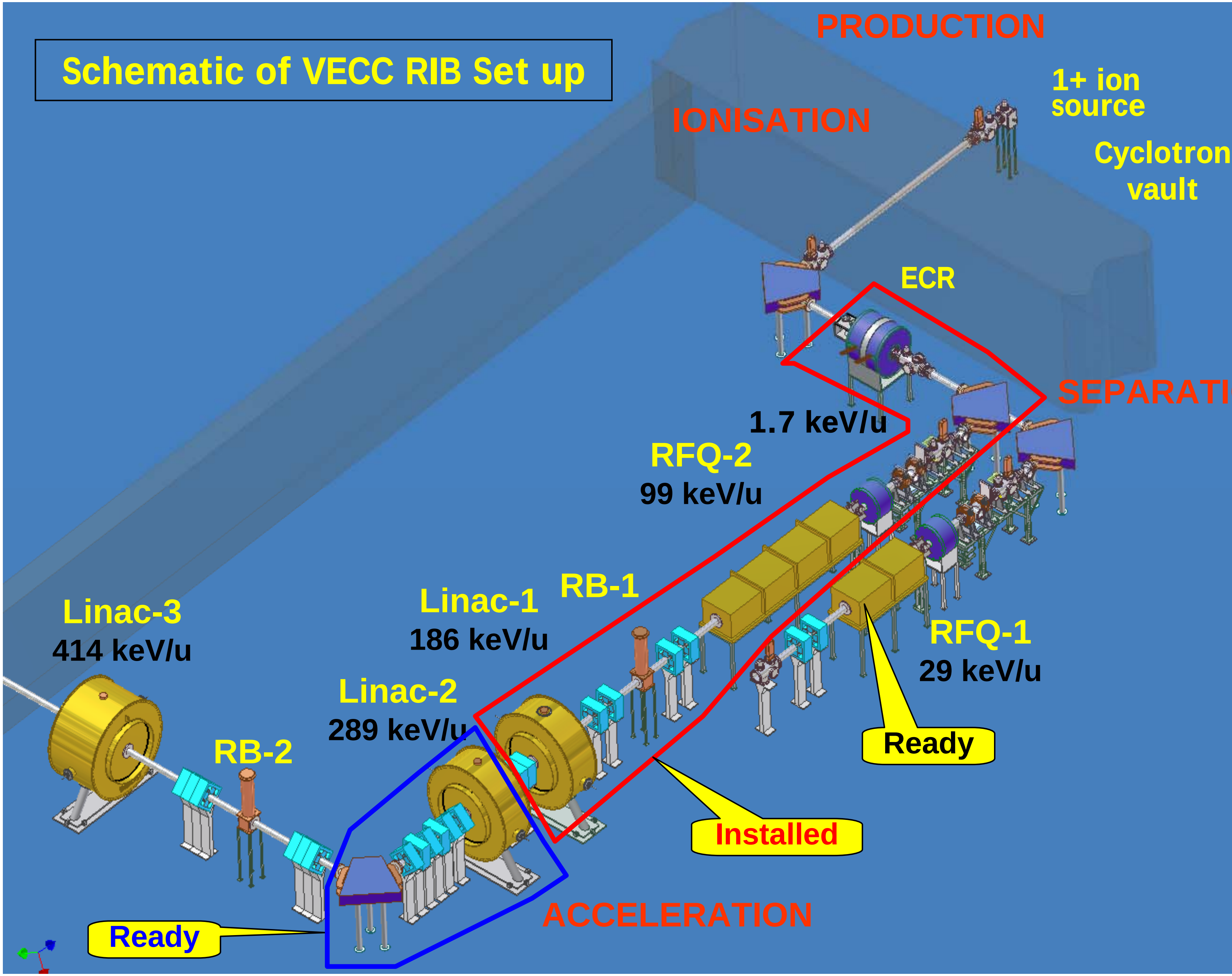
Other gross parameters:

100 Tonnes magnet iron
12.5 Tonnes cryostat

Magnet assembly with pole cap in lifted position - maximum lifting height of upper pole cap is 1143 mm.

VIEW OF THE SUPERCONDUCTING CYCLOTRON IN VAULT

ECR ION SOURCE AND INJECTION BEAM LINE



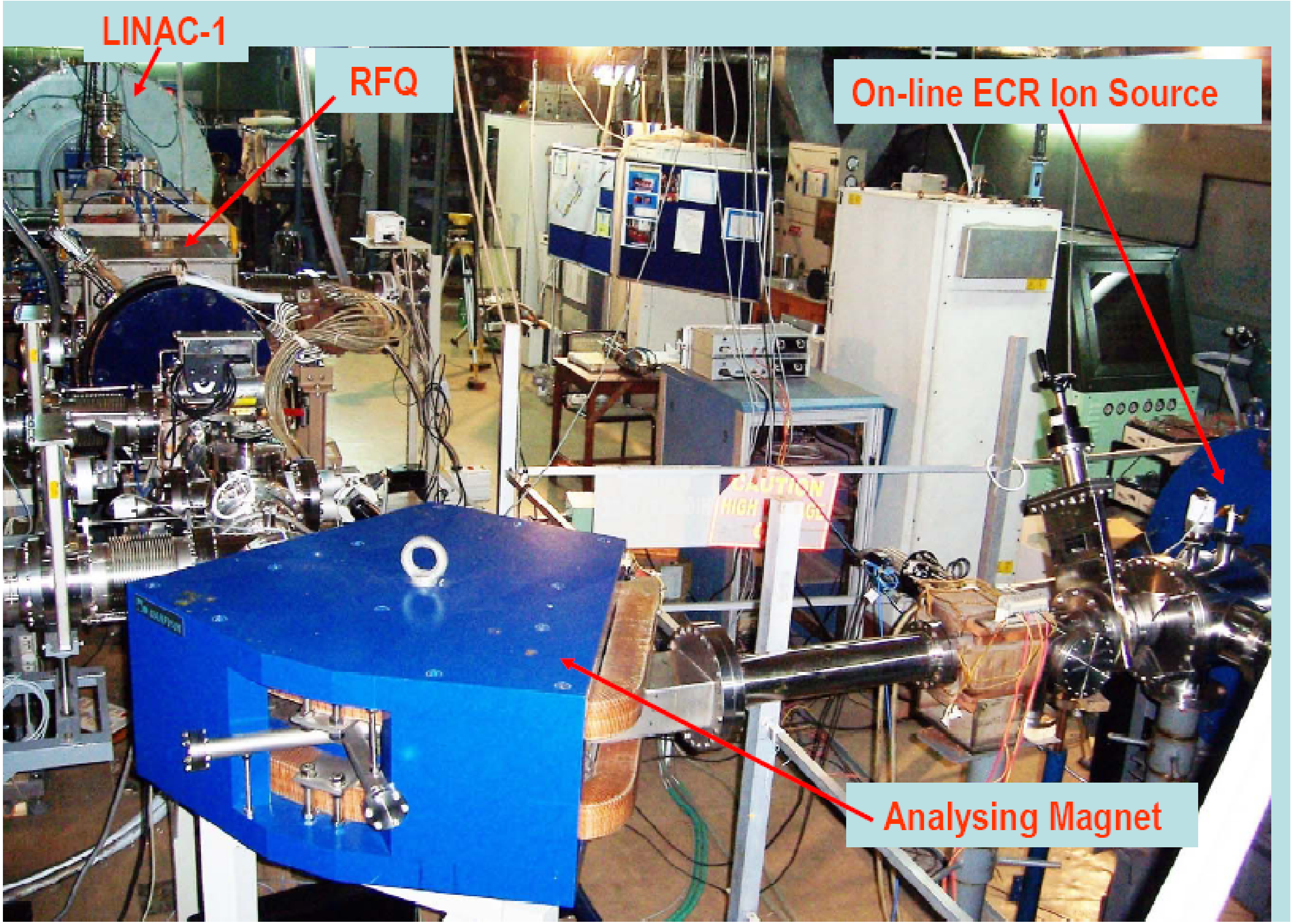
Schematic of VECC RIB Set up
PRODUCTION
1+ ion source
Cyclotron vault
IONISATION
ECR
SEPARATION
1.7 keV/u
RFQ-2
99 keV/u
RB-1
Linac-1
186 keV/u
RFQ-1
29 keV/u
Linac-3
414 keV/u
Linac-2
289 keV/u
RB-2
Ready
Installed
Ready
ACCELERATION

Important Parameters for the first three LINAC cavities :

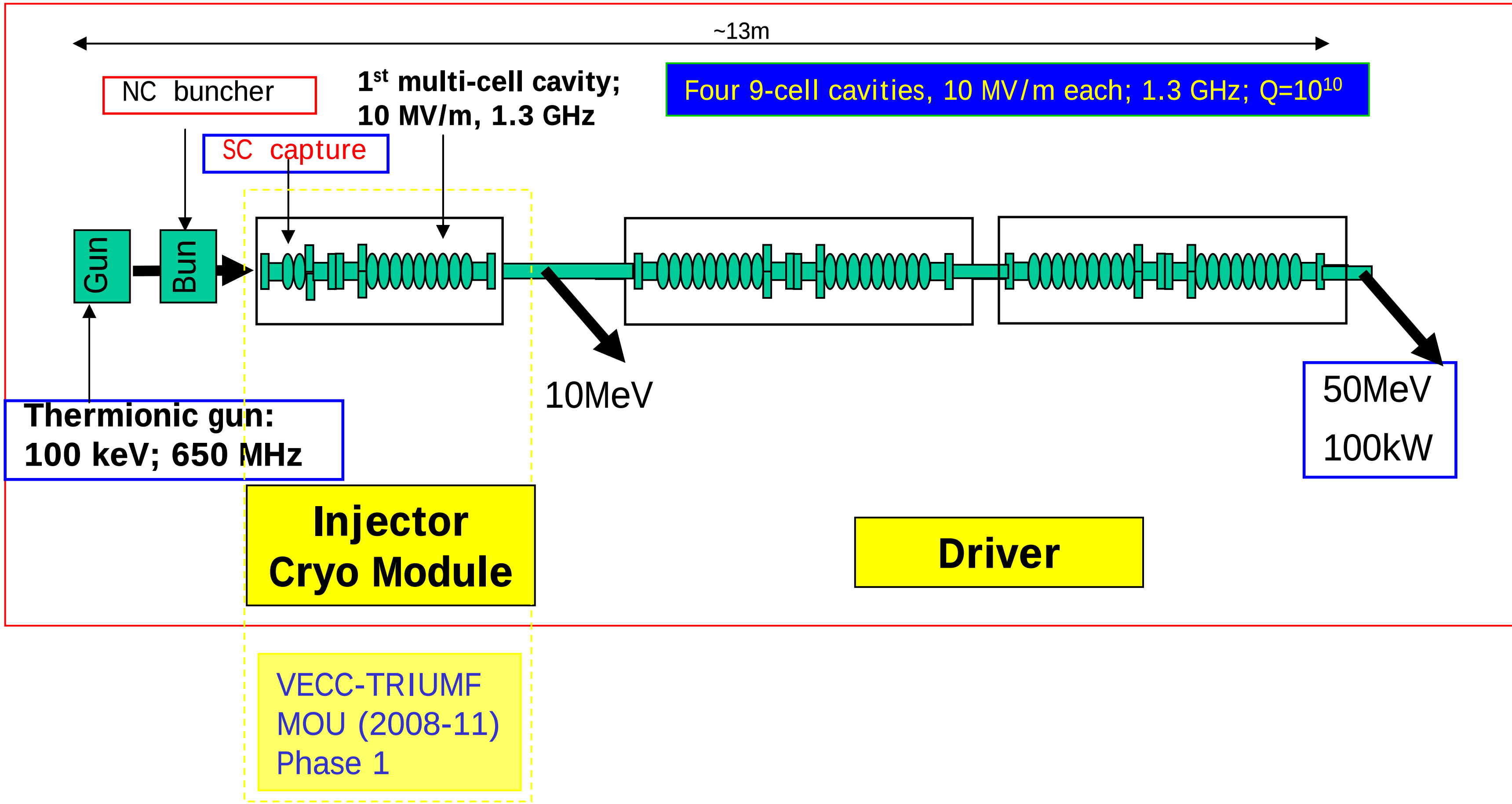
Parameter	Unit	Tank-1	Tank-2	Tank-3
Frequency	MHz	37.8	37.8	75.6
q/A	>=	1/14	1/14	1/14
E(in)→E(out)	KeV/u	98.8→186.2	186.2→289.1	289.1→413.9
β(in)→β(out)	%	1.46→1.99	1.99→2.49	2.49→2.98
# of Cells & gaps		9	10	17
Bore radius	cm	1.25	1.25	1.25
Gap length	cm	2.92	3.98	2.48
Cell length	cm	5.84→7.88	7.96→9.84	4.96→5.92
Peak Vol. On drift tubes	kV	±102.0	±107.8	±75.8
Transit Factor		0.79→0.85	0.80→0.85	0.78→0.82
Sync.Phase	Deg	-21.5	-25.6	-18
Cavity Length	m	0.618	0.871	0.913
Cavity I. Diameter	m	1.72	1.72	0.8
Acceleration Gradient	MV/m	2.13	1.79	1.99
Shunt Impedance (Calc.)	MΩ/m	342	432	474
Quality Factor (Calc.)		13772	18856	26284
Power (Calc. – Ideal)	kW	11.945	9.84	11.5

RF Parameters are ANSYS HF EM Calculations.

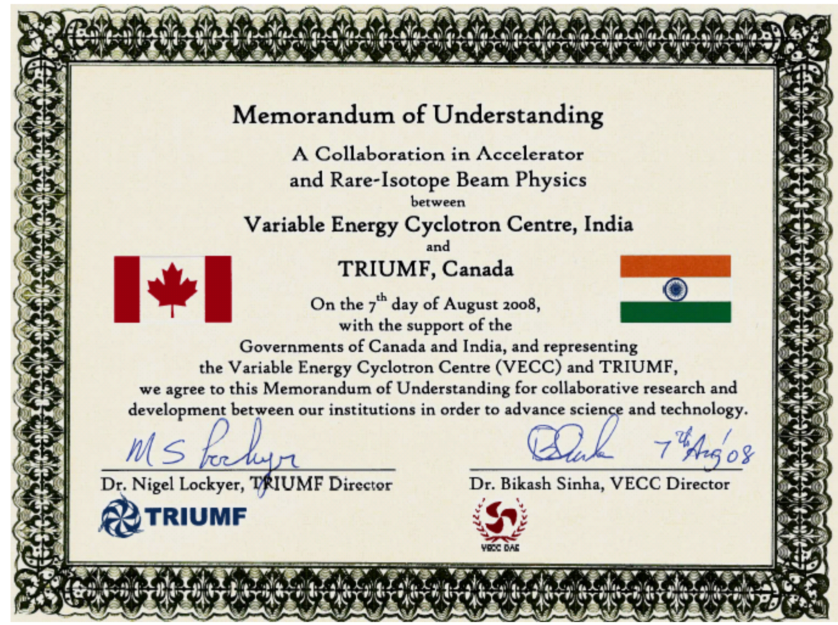
RIB site as on 6th February 2009



Schematic Layout of SC Electron Linac



MOU between VECC & TRIUMF



Memorandum of Understanding

A Collaboration in Accelerator
and Rare-Isotope Beam Physics
between
Variable Energy Cyclotron Centre, India
and
TRIUMF, Canada

On the 7th day of August 2008,
with the support of the
Governments of Canada and India, and representing
the Variable Energy Cyclotron Centre (VECC) and TRIUMF,
we agree to this Memorandum of Understanding for collaborative research and development between our institutions in order to advance science and technology.

Dr. Nigel Lockyer, TRIUMF Director

Dr. Bikash Sinha, VECC Director

7th Aug '08

- For Design & Development of a Superconducting Electron Linac
- Starts with the Development of an **Injector Cryo Module (ICM)**

Thank You