New Light Sources Reaching the Skies:
SRSs, FELs & ERLs

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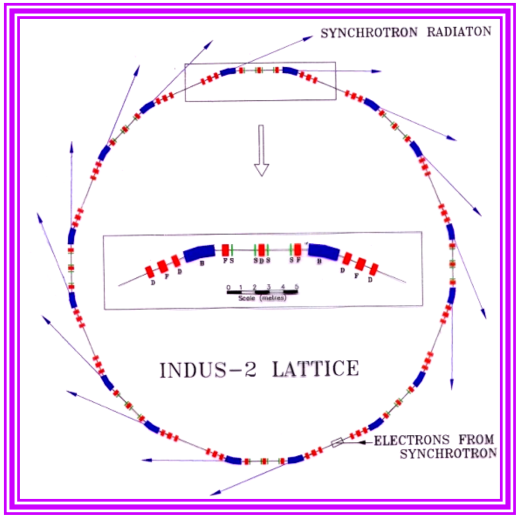
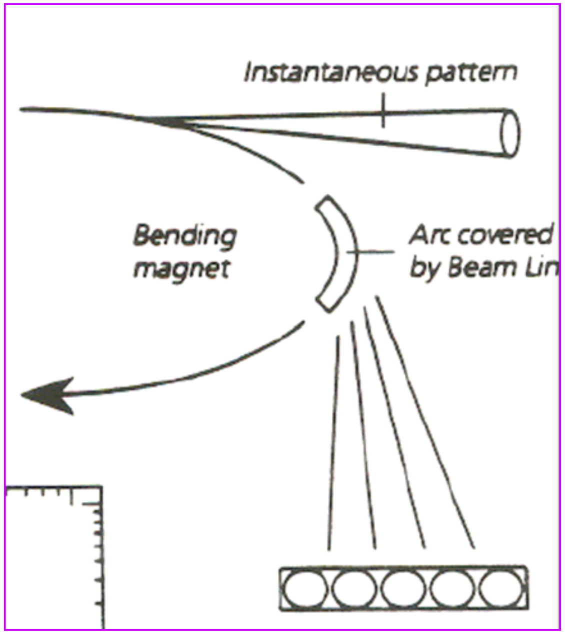
Profile of the talk:

1. A primer on SRSs
2. Spectral brightness of a source & parameters experimenters look for
3. More details about SRSs
4. Review of FEL, ERL programs planned or under execution in some labs abroad
5. Efforts at RRCAT in programs related to these areas
6. Concluding remarks

Synchrotron Radiation (SR) : A Primer



- In a synchrotron, charged particles move in closed orbits, along arcs of circles (under influence of magnetic field) & in straight sections. While passing through magnetic field they decelerate & emit SR.
- For light particles (eg electrons), SR emission is a dominant mechanism of energy loss & replenishment is done (in passage through a RF cavity) by an external electric field.
- Spectrum of the radiation and its spatial distribution as well as its polarization characteristics can all be worked out using classical electromagnetic theory. But some features need use of quantum mechanics.
- Over time these sources have seen a great variety of developments.



Synchrotron radiation sources have evolved through clearly defined generations:

1. In first generation sources, radiation produced in dipole bending magnets (BM) of accelerators used for other purposes, eg high energy physics facility, (like NINA, at Daresbury) was used parasitically .
2. Second generation sources: Dedicated electron accelrators producing SR from BMs.
3. Third generation sources are also dedicated; but in addition deploy IDs (wigglers/undulators) raising the source brightness by several orders.
4. Fourth generation sources involve use of Linac to accelerate electrons and exploit the FEL concept. There is also a variant ERL.

Spectral brightness of a SR source

Best way to quantify a synchrotron radiation source (SRS) is to measure number of photons emitted per sec, in a specified bandwidth, per unit solid angle, per unit area of the source.

But there is a confusion in literature about nomenclature!

IUCr concluded (*J. Synchrotron Rad.* ***12***,385(2005)) that the term *spectral brightness* best describes this quantity, since it is consistent with generally accepted concept of intensity per unit source size and divergence, while adjective *spectral* conveys the scientific importance of the number of photons in a given bandwidth.

Concerning units, IUCr thought it best to "maintain the units of photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)$^{-1}$" (not go to m^{-2} & rad^{-2} &100%$^{-1}$) "since they are so ensconced in the literature that a drive to change this would only lead to more confusion rather than more clarity……"

Spectral brightness .. (contd)

If we formally define brightness through function $F(x, y, \theta, \psi, \nu)$, which provides a measure of the photon flux, in terms of position coordinates on source area & angular coordinates (that give the direction of radiation), and also frequency dependence, then by integrating this function over all the variables, we can obtain the total power radiated ie

$$P = \int F(x, y, \theta, \psi, \nu)\, h\nu \, dx\, dy\, d\theta\, d\psi\, d\nu$$

Generally, in light sources that use electrical power, conversion efficiency of electrical to optical power is low ~0.1 to ~1 %. (eg 100 W lamp gives only ~100 mW optical output). Same holds for most lasers (except CO_2 & semiconductor lasers, having ~10 % and many tens of % efficiency respectively.)

SRSs (and lasers) are attractive since radiated power is highly directional & spectral brightness is high!

What users look for in light sources

Schematic arrangement of an experiment using monochromatic light from a white source

White source → Collecting optics → Dispersing elements → Focusing optics → Sample → Detector & electronics

Features of interest to users in actual sources:

High source strength.

High stability over long periods.

Low angular divergence → small optics.

Small source size, eg for microscopy.

Short pulse duration, useful for kinetics studies or other experiments, like, pump probe experiments etc.

For some uses, spatial & temporal coherence.

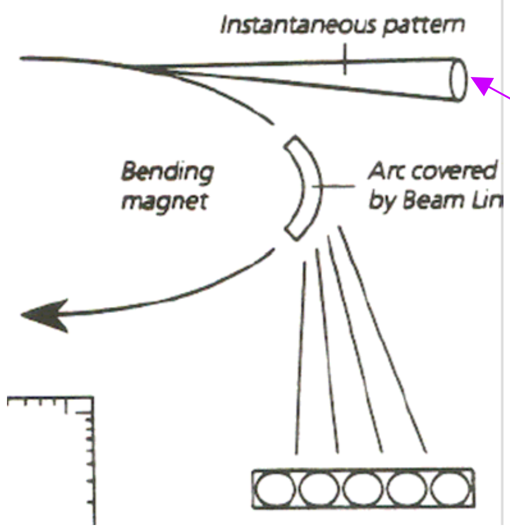
SR Sources & (FEL + ERL) score on all the counts.

Radiation from Bending Magnets

A relativistic electron of energy V, in passing through a bending magnet (of strength B), moves in a circular orbit of radius ρ,

$$\rho\,[m] = 3.3\; V\,[GeV]/B\,[T]$$

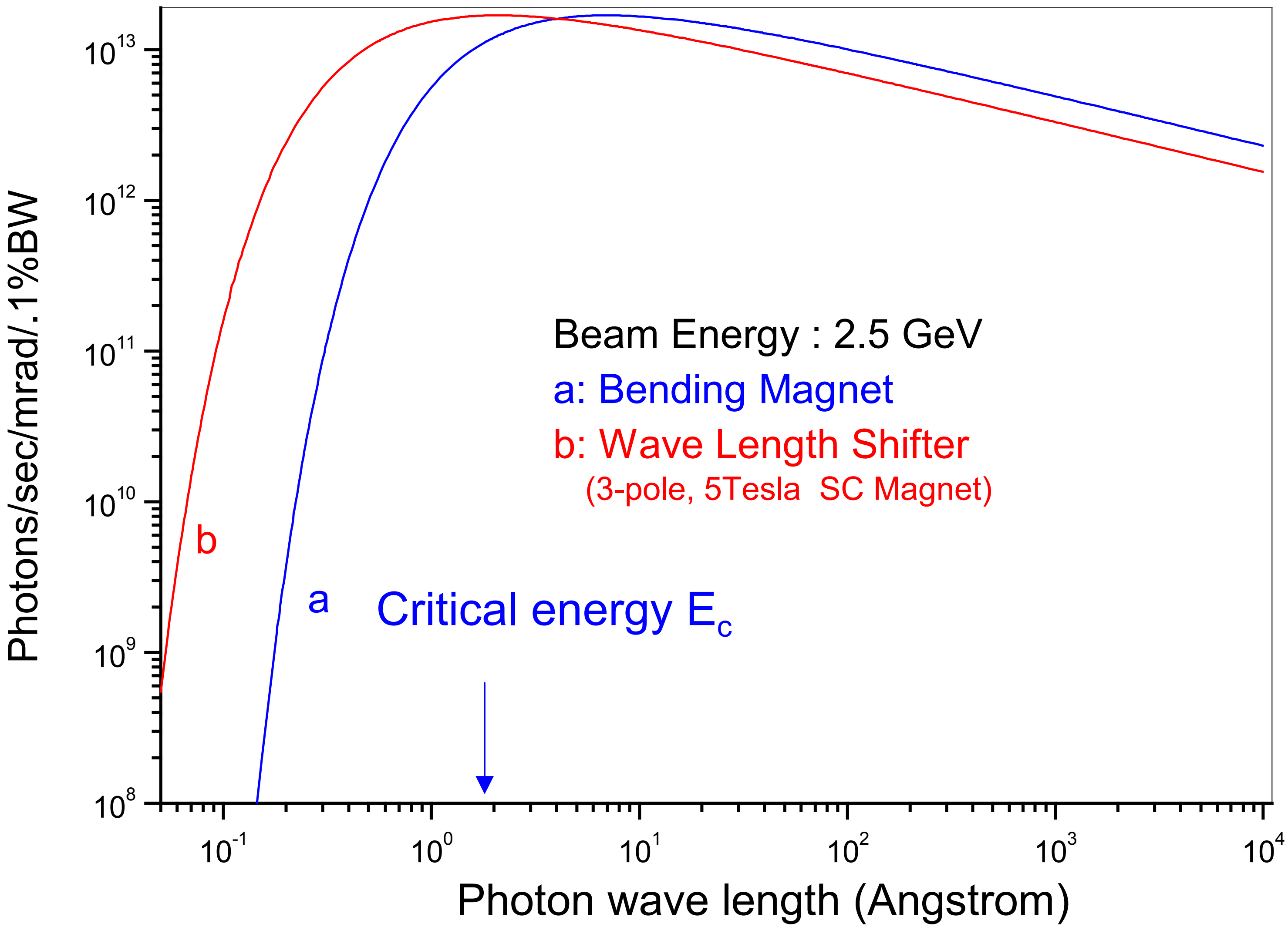
symbols in brackets indicate the units to be used. This motion produces a smooth spectral continuum emission (called SR), which is in the form of a cone, with a narrow vertical angular width and sweeps in the horizontal plane along the tangent to the orbit as the electrons pass through the bending magnet.



Vertical opening angle ~ 1/ γ *ie a fraction of a milli radian.*
 $\gamma = V/m_0c^2$.
Typically V ~ few GeV & m_0c^2 ~ 0.5 MeV.

Spectrum of Radiation from Indus-2 SRS

(Note the spectrum extends all the way from IR to x-rays!)



Radiation from BM (contd)

Angular distribution of radiation is given by,

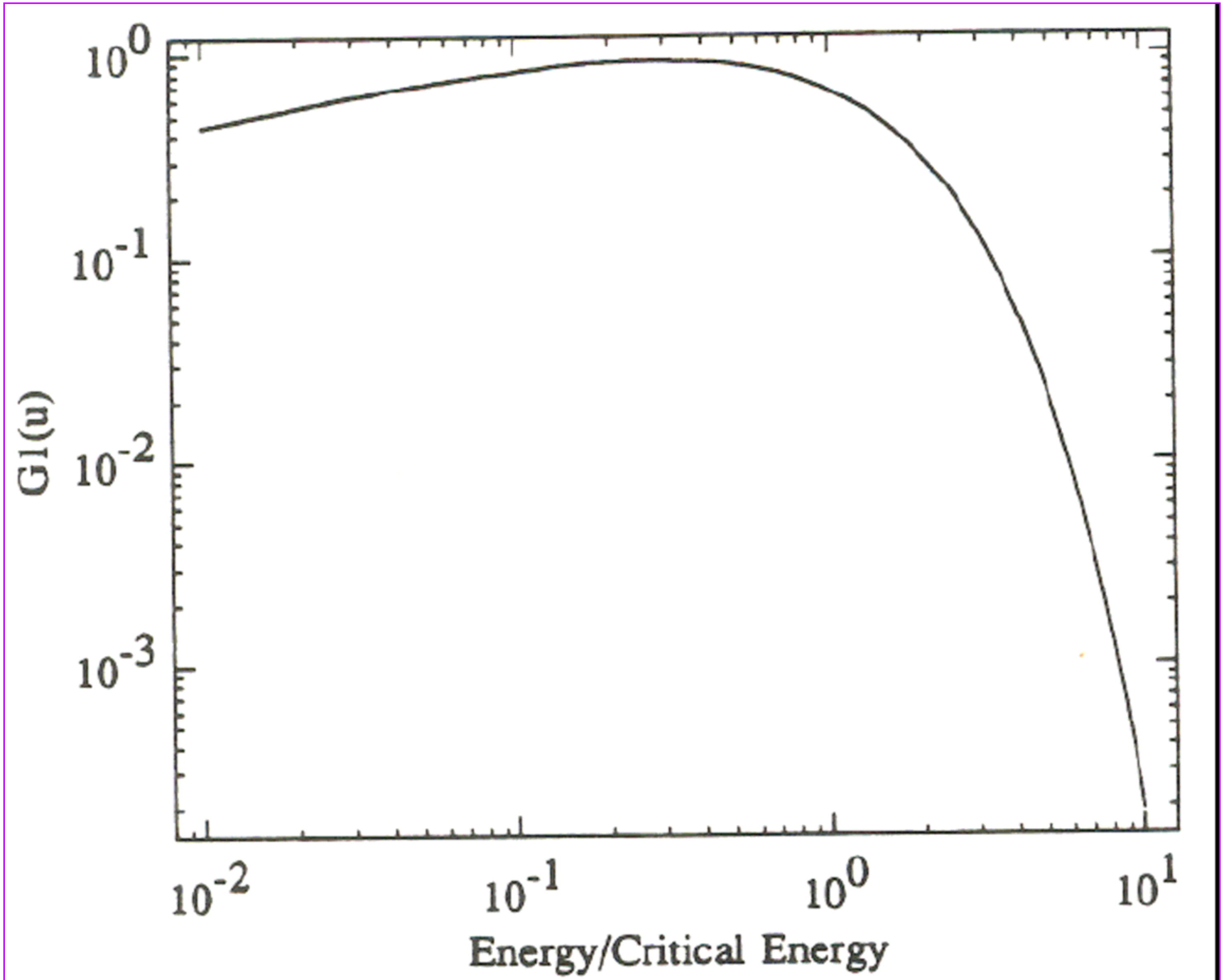
$$\frac{d^2F}{d\theta d\psi} = 1.327 \times 10^{13} V^2 [GeV]\, u^2 f_{\parallel}(u,\gamma\psi)\, f_{\perp}(u,\gamma\psi)$$

$$u = E / E_c \qquad E_c\,[eV] = 665 \times V^2\,[GeV]\, B\ \ [T]$$

E is photon energy, Ec, critical photon energy (divides emitted power into two equal halves); f describe angular dependence of the parallel & perpendicular components of polarization of the SR. The flux radiated per unit horizontal angle is obtained by integrating over vertical angle ψ & expressed in terms of a universal function G1(u) (see fig.) In practical units of photons sec-1 mrad-1(.1% bandwidth)-1Amp-1 radiated flux is given by,

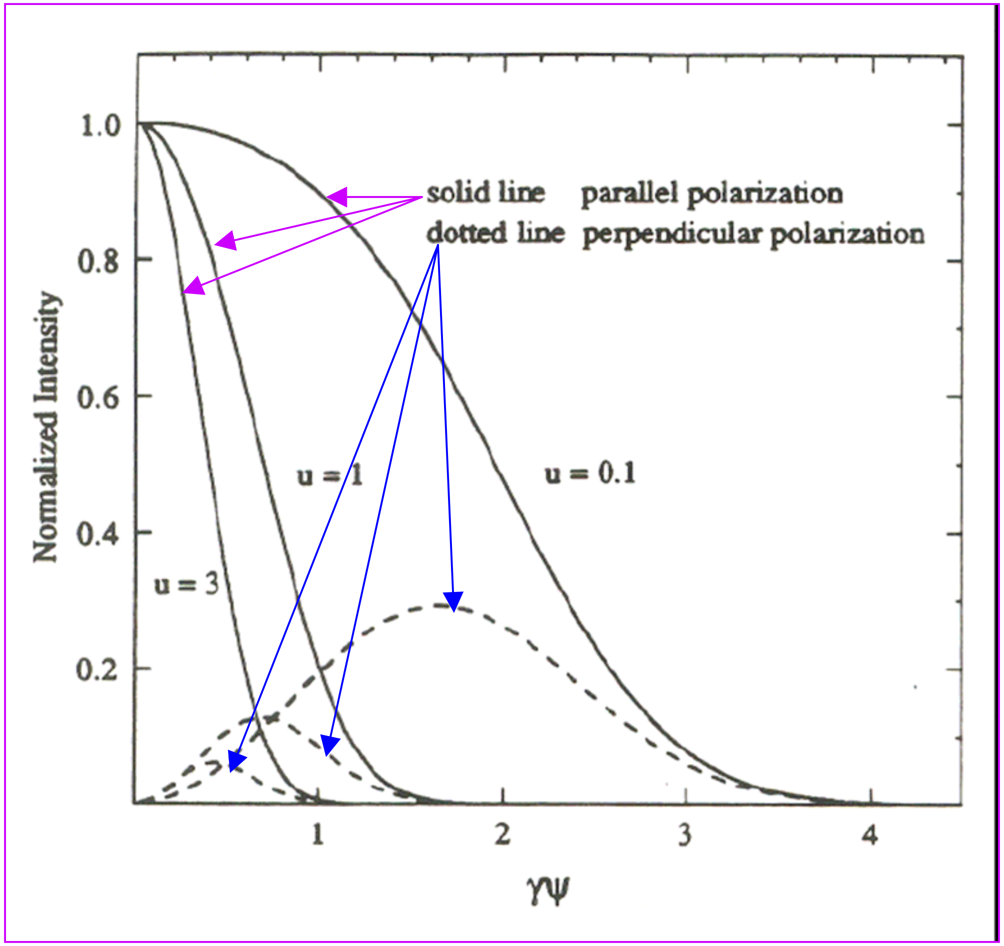
$$\frac{dF}{d\theta} = 2.457 \times 10^{13} \times V\ [GeV] \times G_1(u)$$

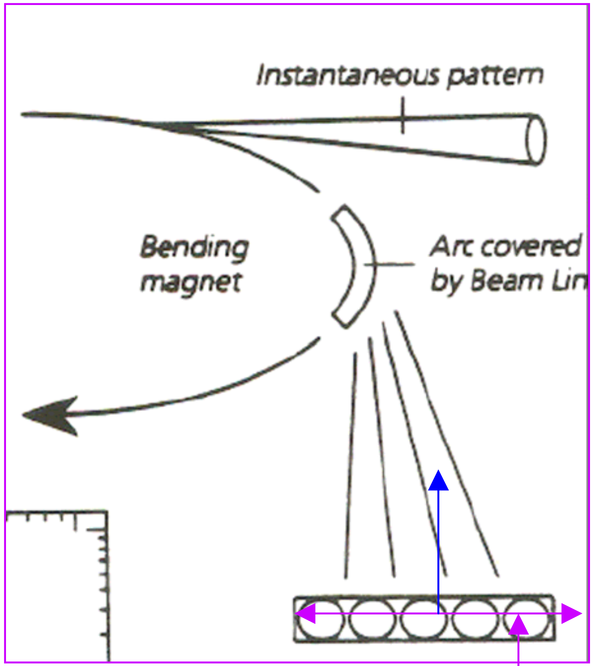
Radiation from BM (contd)



Radiation from BM (contd)

Normalized intensities of parallel & perpendicular polarization components as a function of observation angle for three values of u(=E/Ec). Note the opening angle is narrow for hard radiation; and **for ψ~0 light has only parallel polzn**.



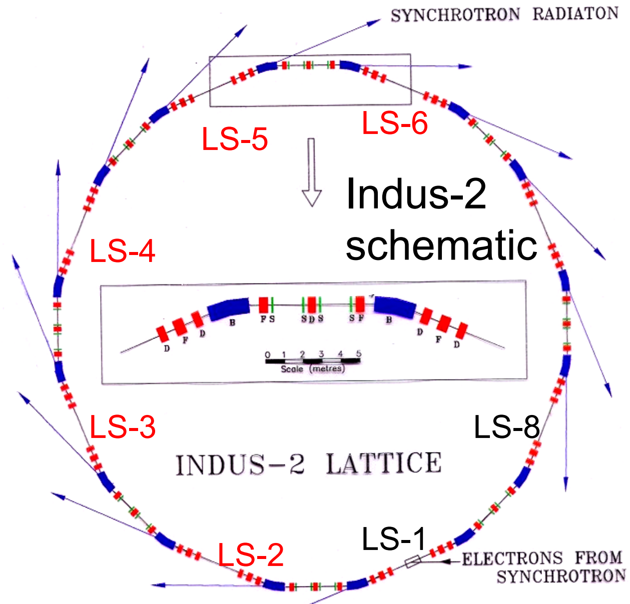


for ψ~0 light has only parallel polzn

Insertion Devices: Wigglers & Undulators

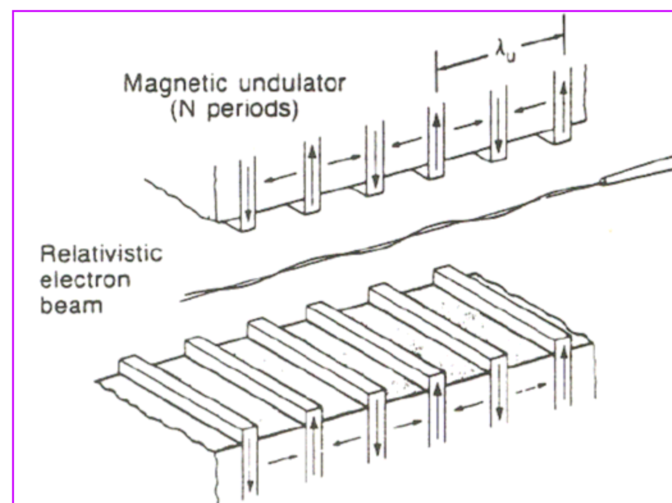
As noted before, a synchrotron has "bending sections" (made by BMs where "small bunches" of electrons move along arcs of circle) & "straight sections". In a real machine, higher energy photons (than in a BM) can be produced using a locally higher magnetic field in a device placed in straight section. Such a device is called a wiggler.

Wigglers are categorized by no of 'wiggles' or periods they impose on beam. Generally, a wavelength shifter is used to harden the spectrum to highest energy. It, therefore, usually, deploys a superconducting magnet.



LS-1:Injection; LS8- RF cavity

LS-2 to LS-6:LSS for IDs ie W/U.



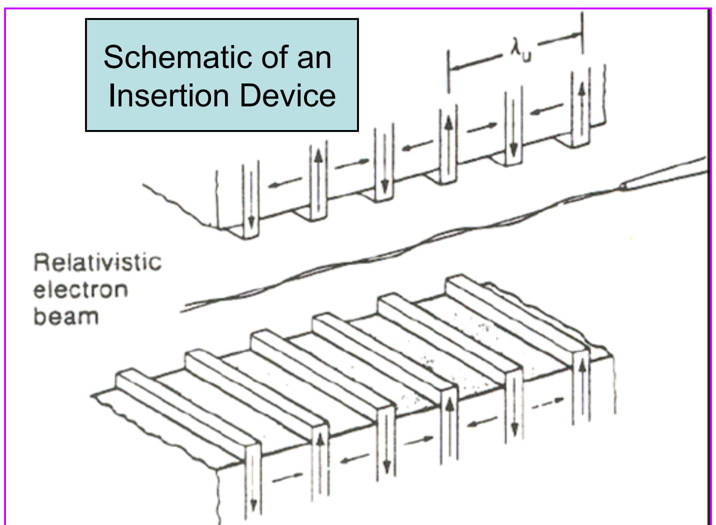
Insertion Devices: Wigglers/Undulators (contd)

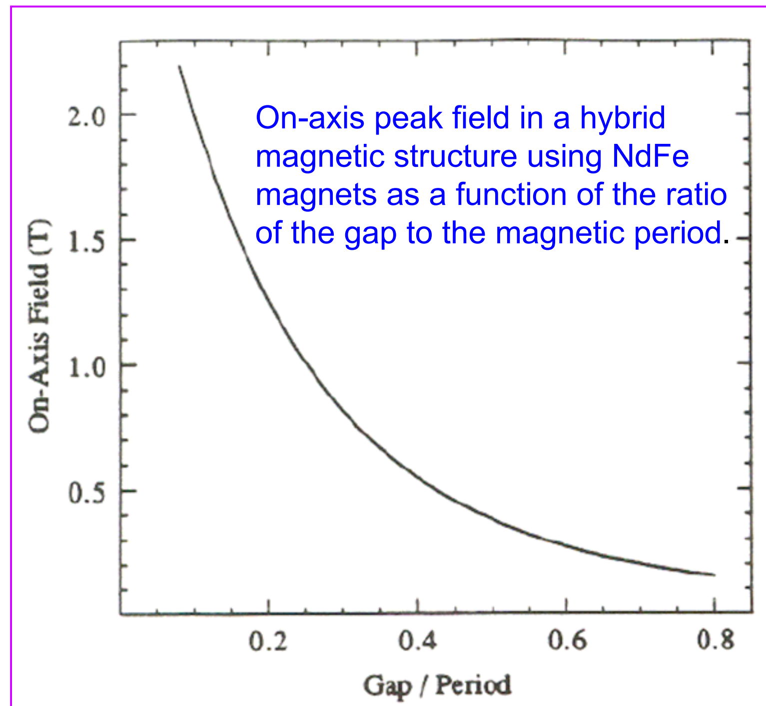
An important parameter characterizing motion of an electron in a periodic magnetic field (of W/U) is deflection parameter K given by, K= 93.4 $\lambda_u B_0$; here λ_u is the period of the magnetic oscillation & B_0 is the on-axis magnetic field.

K defines maximum amplitude of oscillation Xmax & maximum angular deviation x'max as,

$$x_{max} = \frac{K\lambda_u}{2\pi\gamma}$$

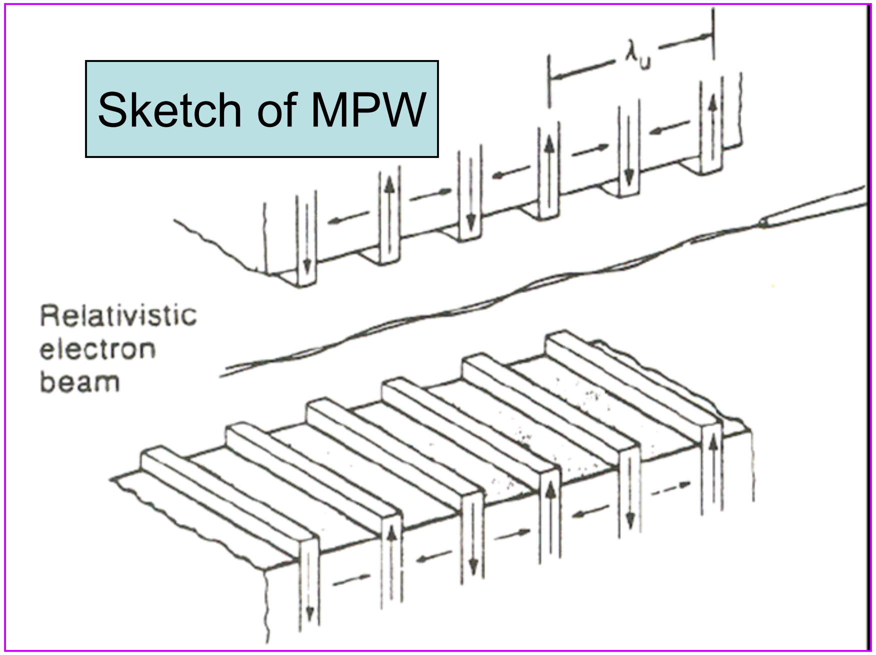
$$x'_{max} = \frac{K}{\gamma}$$





Insertion Devices: Wigglers/Undulators (contd)

Multipole wiggler uses many periods, usually of a lower peak field, to obtain an enhanced intensity from incoherent addition of radiation from each pole. These devices usually use an array of permanent magnets to produce oscillating magnetic field & can achieve a peak on-axis field higher than that created in dipole magnets.



Schematic of a multipole wiggler/undulator using a hybrid construction of permanent magnets and steel poles.

Insertion Devices: Wigglers/Undulators (contd)

If field in a MPW is reduced so much that the angular excursions of electron beam are less than angular width of natural instantaneous emission cone, light emitted from various parts of trajectory can interfere, leading to lower width of radiation cone & compression of smooth bending magnet spectrum into a series of sharp harmonics. The intensity goes as N^2 (N is the number of periods). This type of device is called an undulator .

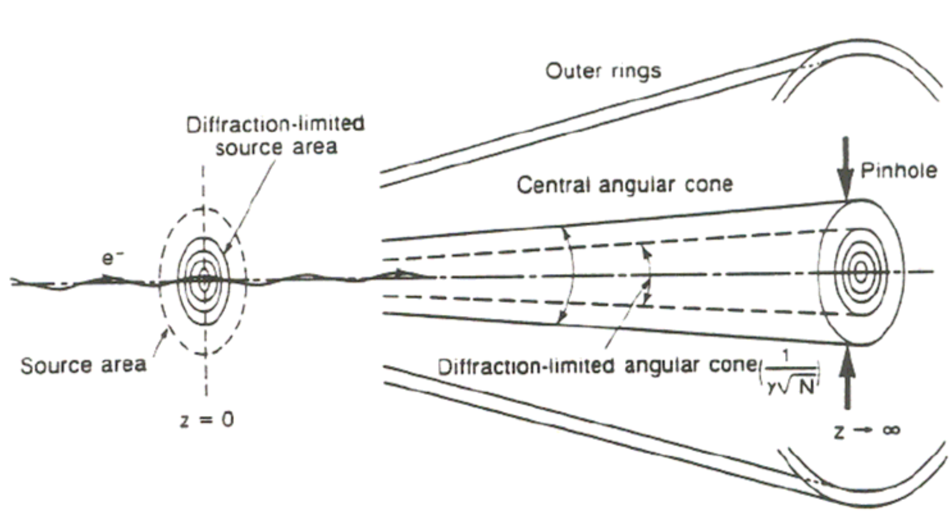


Illustration of the diffraction limited angular emission from an electron traversing an undulator structure. In practice the finite emittance of the beam increases the diffraction limited source area and divergence.

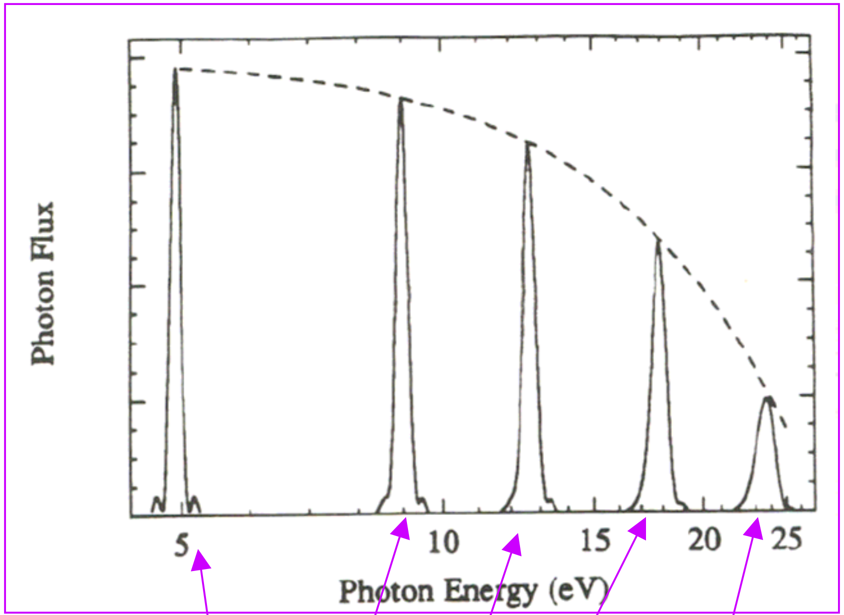
Insertion Devices: Wigglers/Undulators (contd)

If K is<1 & angular excursion of electron beam lies within the natural opening angle of radiation fan, light generated in various periods interferes, giving a spectrum that is not a continuum (as in a BM) but has sharp harmonics. Energy of harmonics is given by,

$$E_n\,[eV] = 9.5\, n \frac{V^2\,[GeV]}{(1+K^2/2)\,\lambda_u\,[m]}$$

and the relative bandwidth ΔE/E at the nth harmonic is l/nN where N is the number of periods.

This idea is also exploited in FEL (see later), using a linear accelerator as an injector into an undulator.



First harmonic peaks as a function of K for, left to right: K = 3.0, 2.0, 1.5, 1.0 and 0.5. Undulalor for this example has a period of 87 mm and 29 periods. V=0.5 GeV. Envelope of peaks gives tuning curve of the (variable gap) undulalor.

An appraisal of the SR, FEL & ERL

- In a storage ring, emittance & bunch length (decided by size of electron packet) are determined by equilibrium processes that take place over several kilo turns. To make major gains in emittance, bunch length etc is difficult & expensive.
- Very high energy rings have been built with many IDs (ESRF [6GeV]; APS[7GeV]; Spring8 [8GeV]). But cost a lot ~$1B!
- FEL & ERL based sources have been envisioned to offer dramatic gains: Greatly reduced emittance; Very short pulse durations; Large transverse coherence.
- In an ERL very small emittance beams (produced by using a laser based photo-injector) travel in the accelerator in “once through” mode, making only 1 round. This enables one to get extremely small (photon) source area, high transverse coherence & very small bunch lengths.

Why Experimenters want ERL X-ray Source?

A less expensive option than X-FEL & can give

Higher intensity– Study very weak effects.

Shorter pulses– Do pump-probe experiments with much smaller time windows.

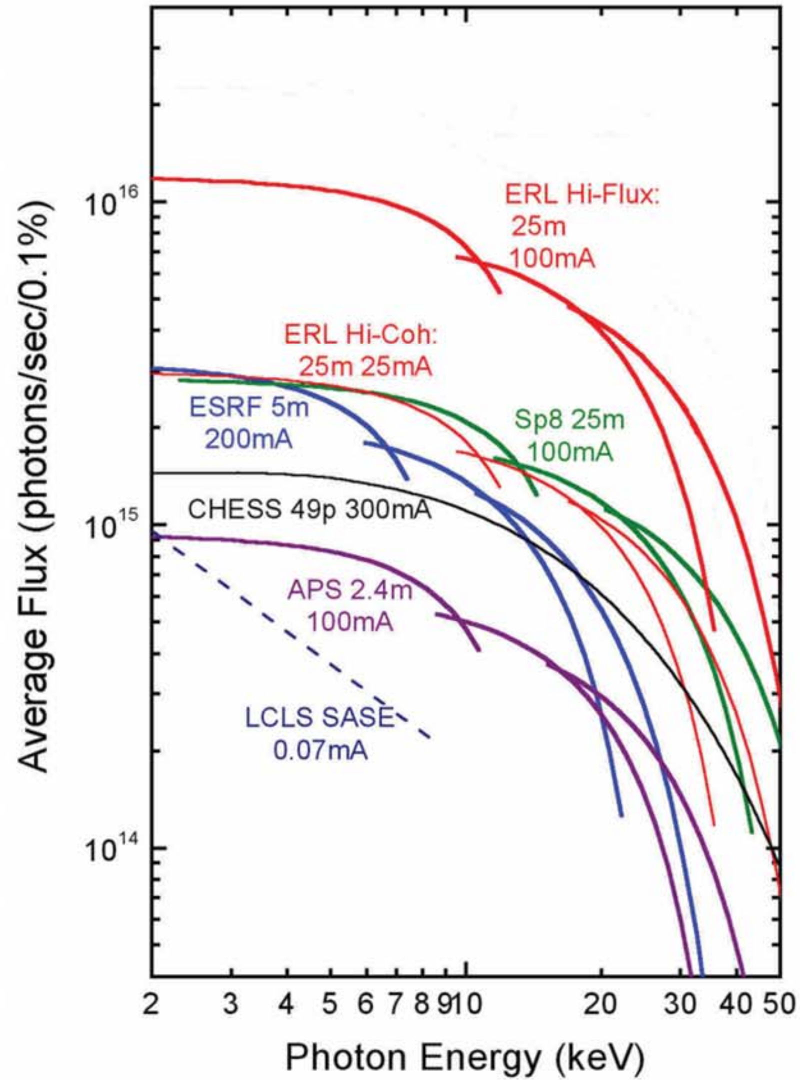
Higher coherent flux–To exploit coherent diffraction imaging.

Higher spectral brightness–To study samples of very small sizes.

All these advantages have great potential as we shall see next.

Using Higher Intensity ERL X-ray Beams for Experiments

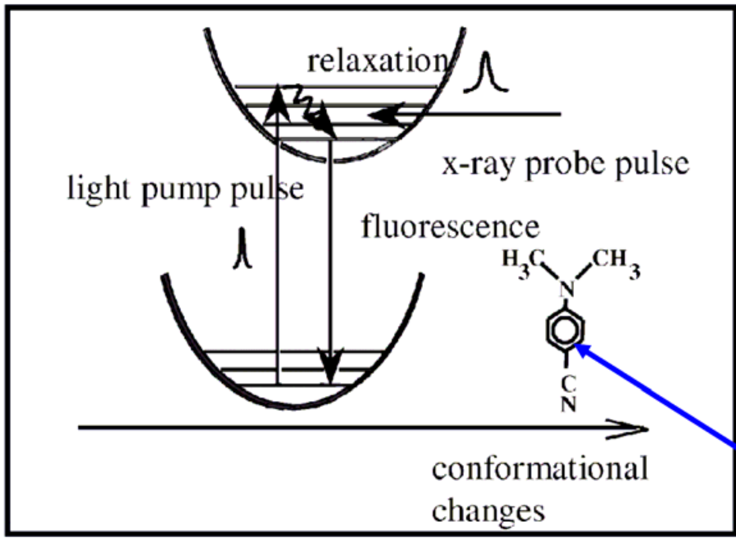
- Many experiments are x-ray photon starved:
  - inelastic x-ray scattering
  - powder diffraction from phase transitions
  - in diamond anvil cells, etc.
- Solution is many periods on the undulator (i.e. long IDs, go to short periods and narrow gaps), superconducting helical und.
- This may create heating problem on the crystal optics – so going without a monochromator may be feasible given enough periods (~ 1000 periods).
- We plan several 25 m long IDs for these purposes.

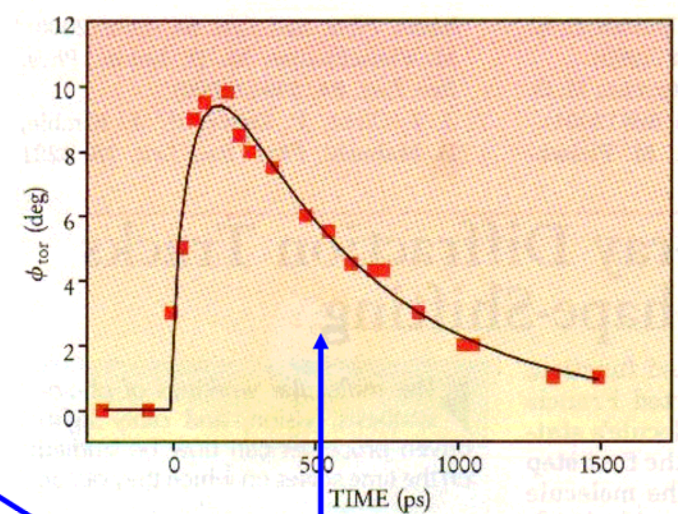


Studying kinetics at femto-sec

Scientific challenge is to understand the structural evolution of the "transition state(s)" intermediate between reactant and product species.

S. Techert, F. Schotte, and M. Wulff, Phys. Rev. Lett. **86**, 2030-2033 (2001).





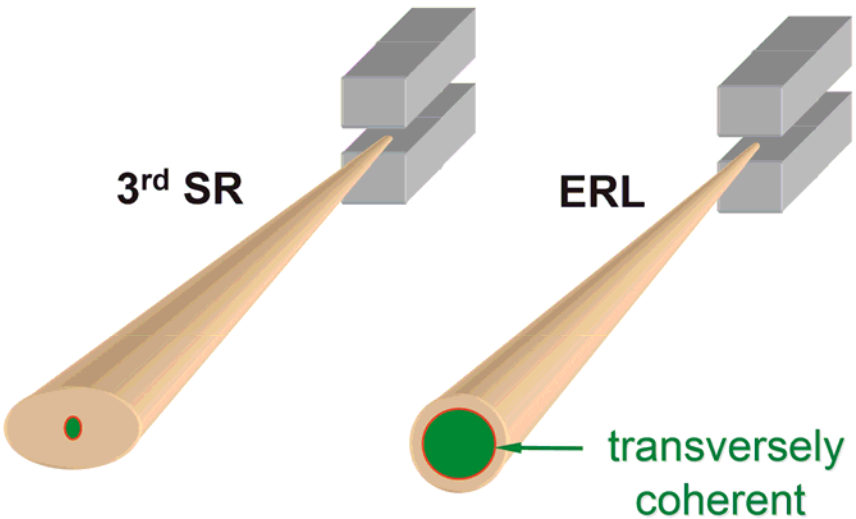
ERL can follow reactions on the 100's of femtosecond time scale.

ESRF expt. showed 10° of bond rotation over 100's of picoseconds

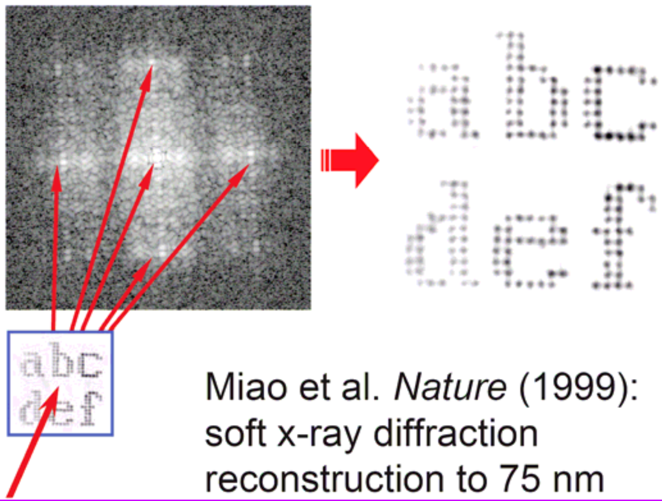
ERL Enables Following Structure of Ultrafast Chemical Reactions

Coherent X-rays for Molecular Imaging

- Molecular imaging requires much higher lateral resolution => limit on optics
- To go beyond the limit, lens less diffraction imaging using a transversely coherent beam is an attractive alternative
- Coherent diffraction imaging is similar to crystallography, but for noncrystalline materials



- Present Status: using a pin-hole to select a coherent x-ray beam
- Future ERL sources would change this dramatically:
  - ➔ almost fully coherent x-ray beams
  - ➔ 3,000 fold increase in coherent flux
- Open up structural science to noncrystalline materials



Miao et al. *Nature* (1999): soft x-ray diffraction reconstruction to 75 nm

FEL, ERL programs planned or under execution in some labs abroad

X-Ray & UV - FEL Projects:

**LCLS at SLAC 15 GeV beam producing 1.5 A to 15 A (8keV to 800 eV). Will use SASE principle.

**X-FEL at DESY; (There is also a proposal put up by BESSY for UV-FEL)

**ERL proposals at Cornell

**4GLS at Daresbury, UK will operate at three energies:15-50 MeV; 600 MeV;750-950 MeV to produce IR; UV & XUV. Will use ERL principle.

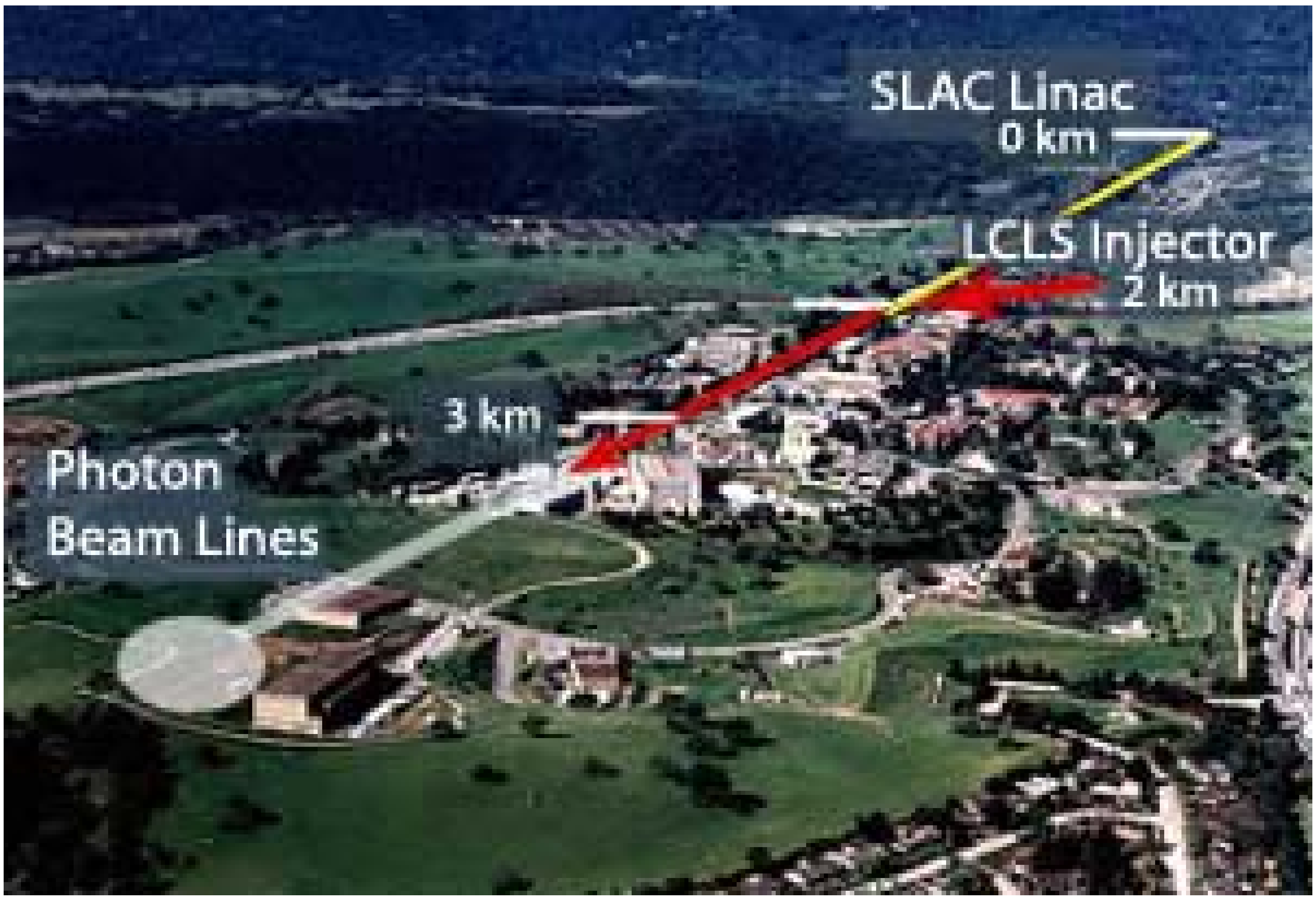
**ERL project at KEK, Japan

15 GeV Electrons

LCLS

1.5 Å X-Ray

Linac Coherent Light Source



- LCLS is a 4th Gen machine designed to produce radiation by FEL principle.

- LCLS will produce X-rays via electrons accelerated through a linear accelerator, which then go into a long periodic array of special magnets forming an "undulator" producing intense pulses of radiation lasting barely a trillionth of a second. It could image atomic motions, & shed light even on fundamental processes of life on an unprecedented scale.

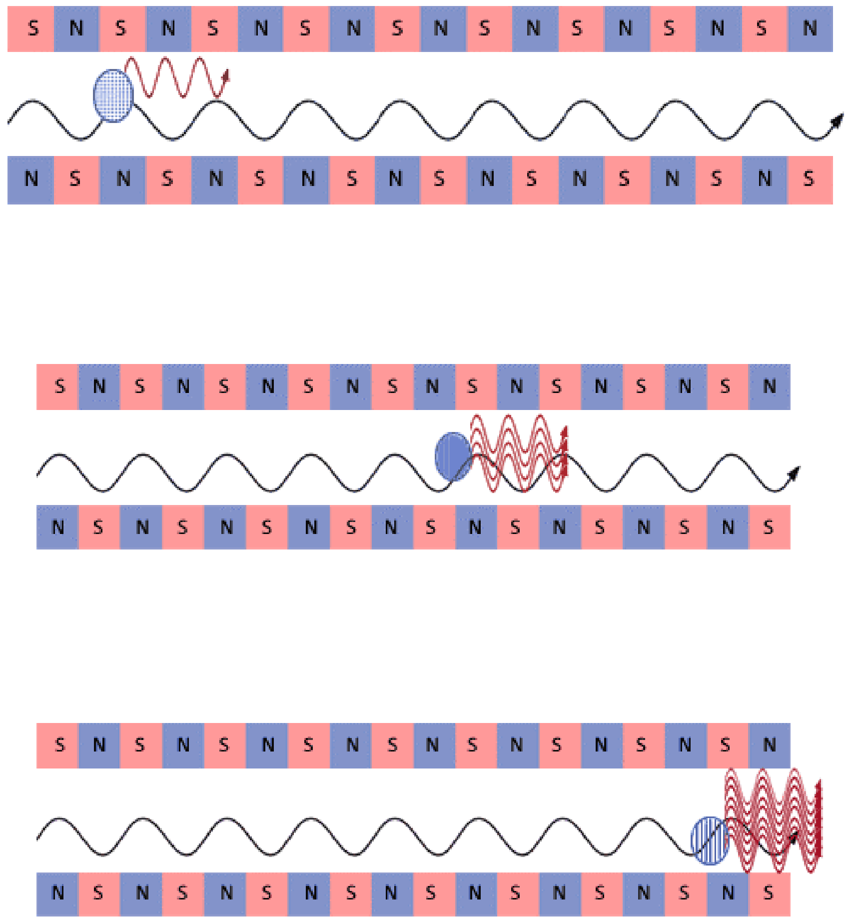
- SLAC Collaborators for LCLS project are: Argonne National Lab, Lawrence Livermore National Lab, & UCLA.

Self-Amplified Spontaneous Emission - SASE

An intense, highly collimated electron beam travels through an undulator magnet. Alternating north and south poles of magnet force the electron beam to travel on an approximately sinusoidal trajectory, emitting synchrotron radiation as it goes.

Electron beam & synchrotron radiation accompanying it interact so that motion of electrons get modified by e.m. field of its own emitted synchrotron light. Under joint influence of undulator & synchrotron radiation, the electrons begin to form micro-bunches, separated by a distance equal to wavelength of emitted radiation.

These micro-bunches begin to radiate as if they were single particles with immense charge. The process reaches saturation when the micro-bunching has gone as far as it can go.



European X-Ray Laser Project : X-FEL

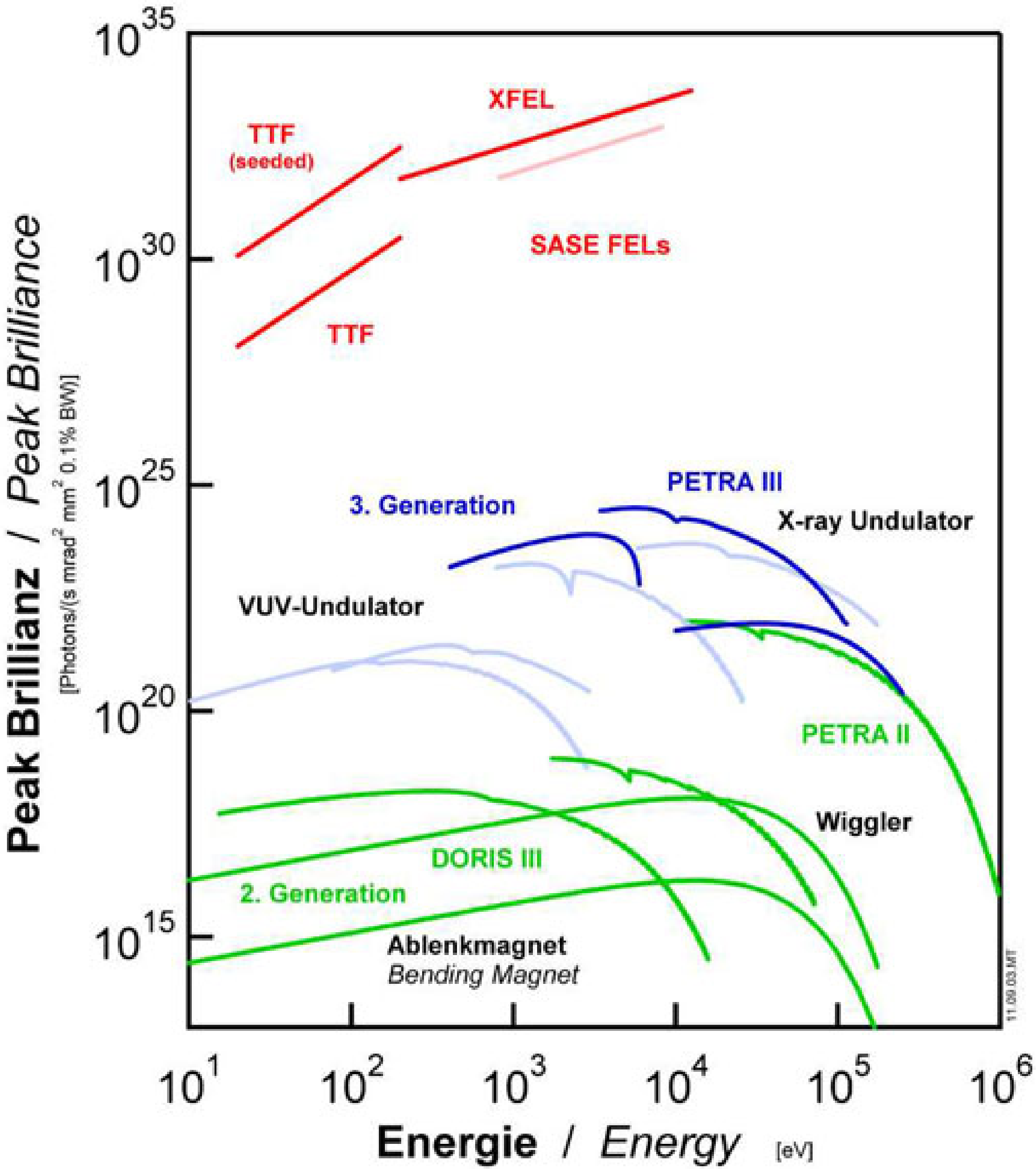
X-Ray Free-Electron Laser: A Superlative Light Source

In Feb. 2003, German Federal Ministry of Education & Research gave green signal for X-ray laser project, to be further developed with other international partners.

After a construction period of ~7years, commissioning could start ~ 2014. A team, “TESLA collaboration”, has developed & demonstrated X-FEL’s pioneering technology at a test facility set up in DESY,Hamburg.

While 2-250 GeV energy is possible, this X-ray laser will keep 2 options: (1) 13-27 GeV beam or (2) 20-50 GeV & a suite of undulators giving source of unprecedented brightness & a tool for extraordinary x-ray research .

Spectral Brightness in Comparison



This comparison of peak brightness of synchrotron radiation sources with free-electron lasers (FELs, red lines) shows the great leap in brightness offered by the FELs. (Source: DESY Hamburg)

Schematic of a Cornell University's ERL proposal with an electron energy of 5 GeV

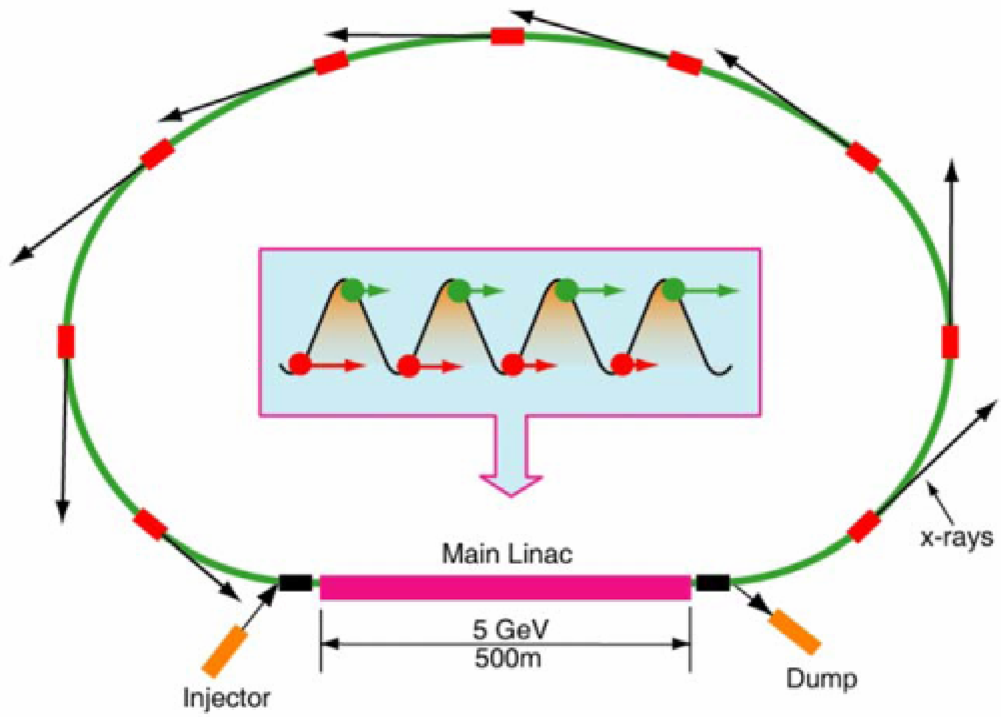
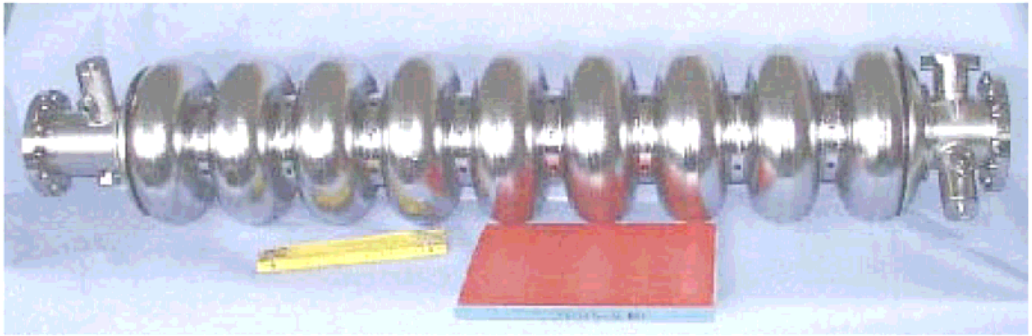
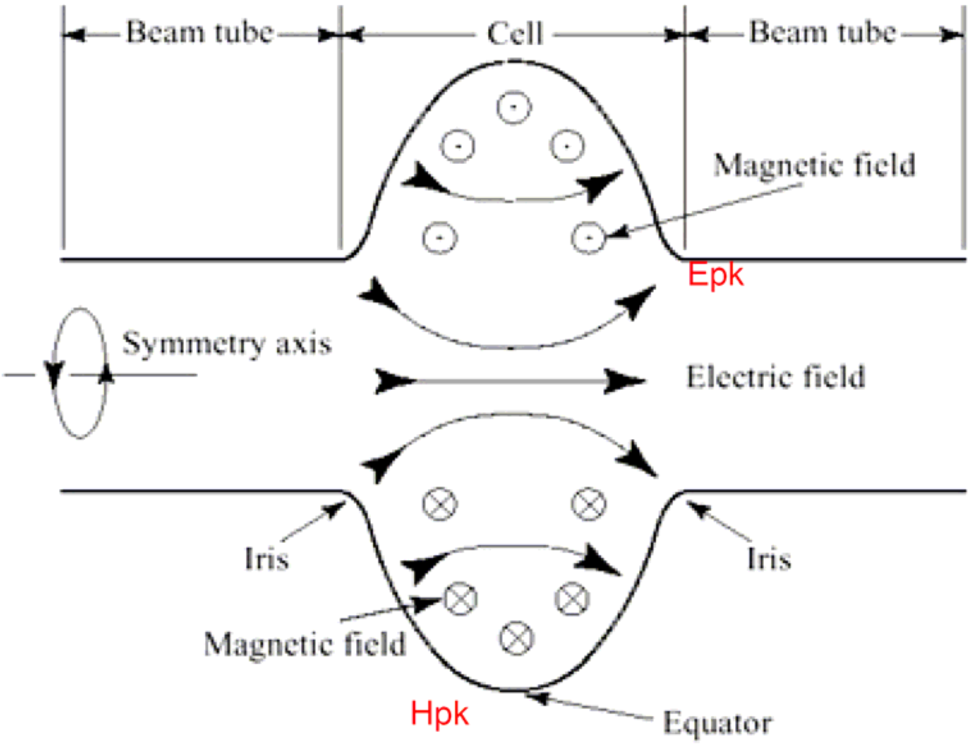


Figure 1. Schematic of an ERL light source. Low emittance electron bunches are produced in a photoemission electron injector and accelerated to about 10 MeV before injection into the superconducting main linac. The oscillating electric field in the cavities accelerates the bunches (green dots riding near the crest of the RF wave in the illustration above) to 5 GeV. The electron bunches produce x-rays in undulator magnets in the beam transport line. The path length of this transport line is such that the electron bunches arrive at the linac 180 degrees from their accelerating phase and are decelerated (red dots), to the injector energy (less the synchrotron radiation losses) and deflected to the beam dump. Each electron makes just one circuit around the machine in this layout. The electrons are accelerated (and decelerated) slightly off the maximum accelerating field to generate a time dependent energy spread across the bunch, allowing it to be temporally compressed to very short duration in the beam transport line.

Module of a Nb SC cavity of a Linac meant for ERL; EM field in the cavity





Note that the EM field will accelerate & impart energy to the electrons if they are in phase with the electric field. But if electrons see the electric field 180^0 out of phase, then EM field will decelerate them. Then the EM field will gain energy from the electrons. This is the “energy recovery” idea used in ERLs.

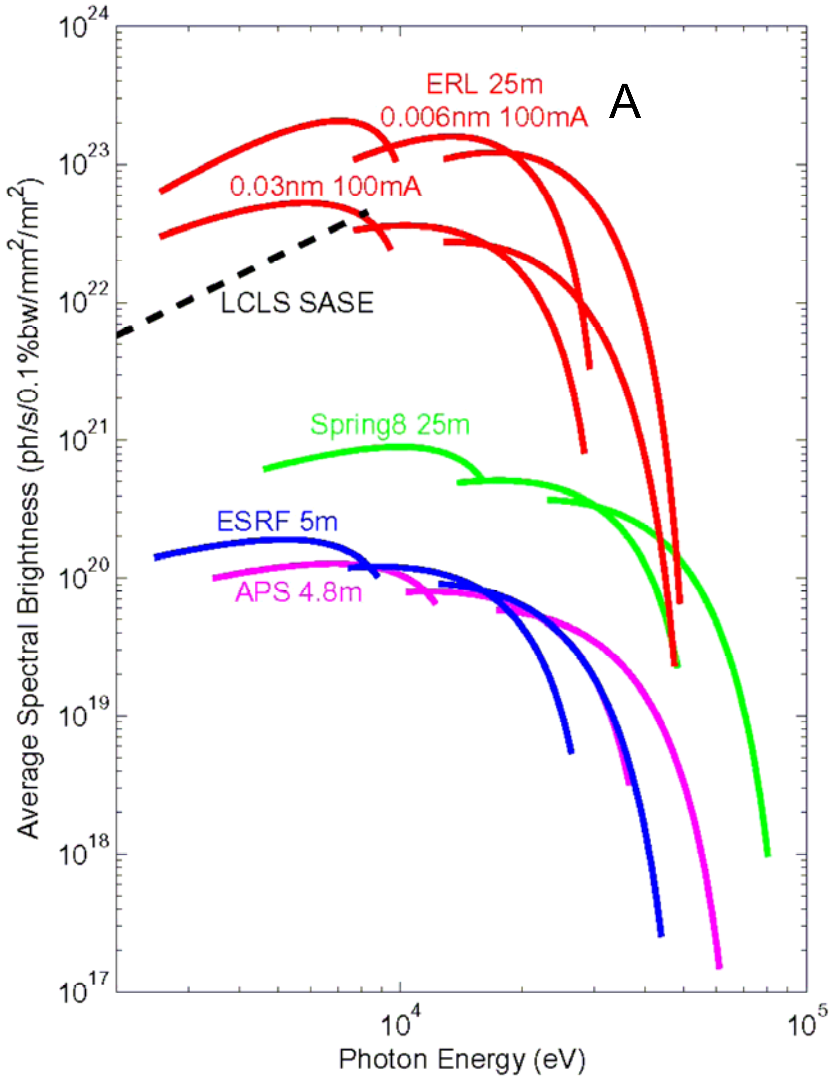
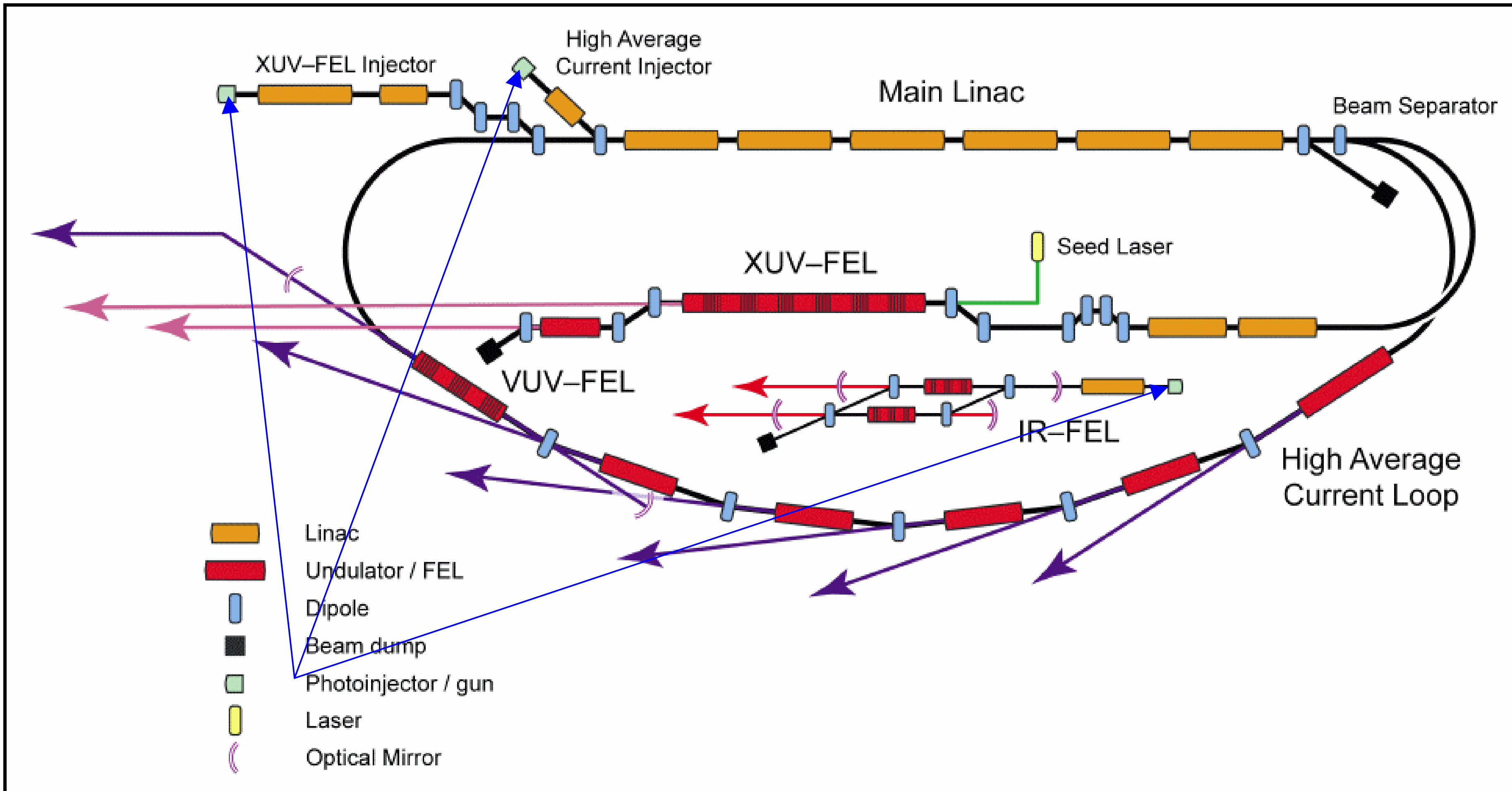


Figure A shows the average spectral brightness vs. photon energy for a 25 m long ERL undulator[16]. As can be seen in the top curves belonging to the ERL (red), the average spectral brightness will be several orders of magnitude higher than existing storage ring sources and even higher than the average (but not peak) brightness of the LCLS.

4GLS (15-50MeV;600 MeV;750-950MeV)

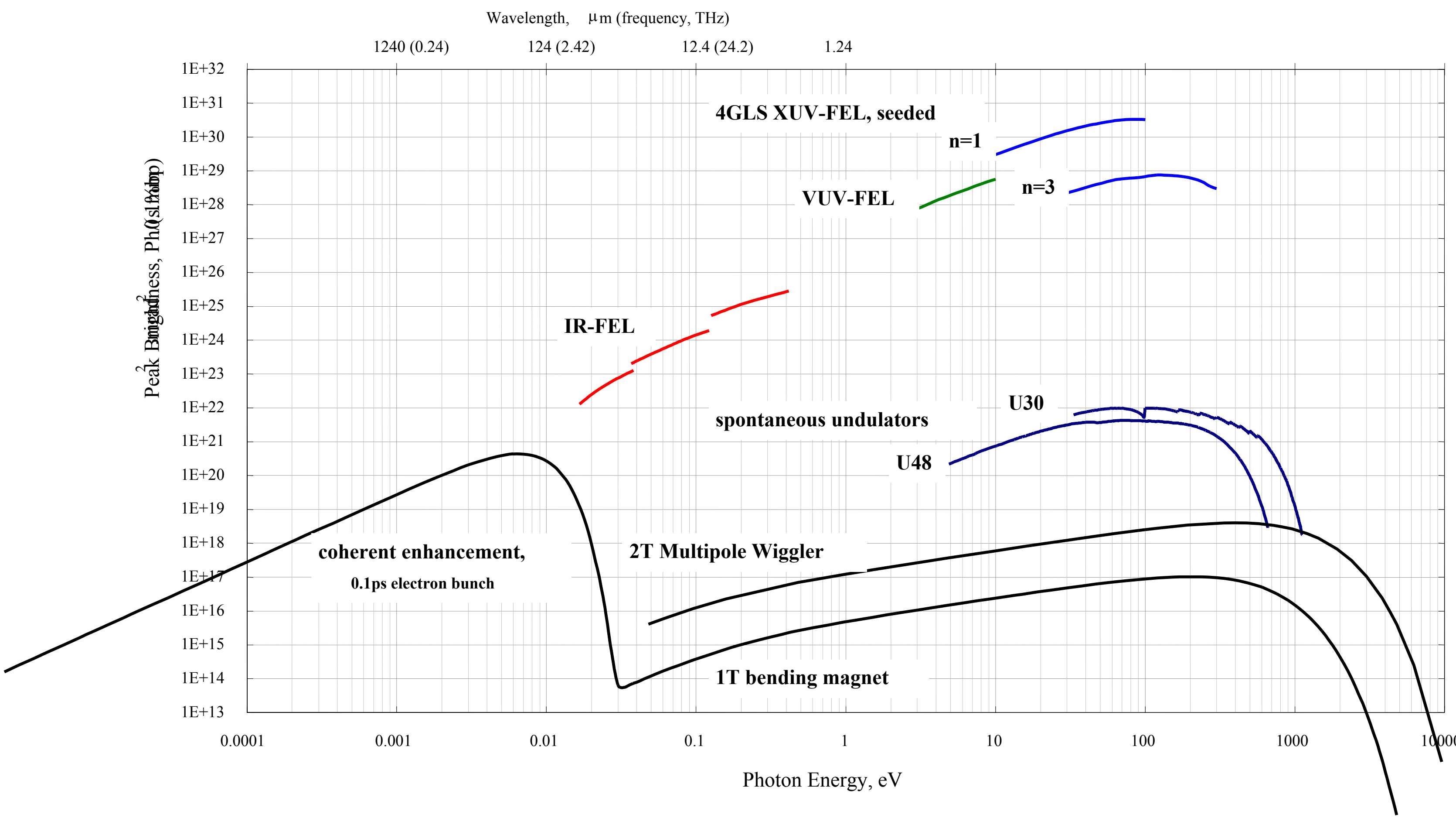


- The 4GLS facility will combine energy recovery linac (ERL) and free electron laser (FEL) technologies to deliver different synchronized state-of-the-art sources covering terahertz (THz) to soft X-rays.
- 4GLS is the leading energy recovery proposal in Europe and the most comprehensive in terms of utilization of combined sources. It is complementary to TESLA XFEL, to table-top lasers and to third generation sources available to researchers*i.e.* ESRF, SRS and DLS (near future).
- 4GLS will be a multi-user facility utilizing strengths of undulator sources, capturing potential of FELs and harnessing advantages of combining both.

4GLS machine parameters used for the tables and graphs.

	high average current branch			XUV FEL branch	IR FEL Branch
Operating mode	high average current mode	Timing mode 1	Timing mode 2	Same timing most modes	Timing mode 1
RF frequency (MHz)	1300	1300	1300	1300	1300
Electron energy (MeV)	600	600	600	750 - 950	15-50
charge per bunch (pC)	77	77	77	1000	200
repetition rate (MHz)	1300	6.5	0.001	0.001	13
average current (mA)	100	0.5	$8*10^{-5}$	0.001	2.6
normalised emittance (mm rad); e.g. 2mm mrad equates to 1.7 nm rad at 600MeV	2	2	2	2	10

Performance of 4GLS



SAMPLE UNDULATORS

mode	high average current mode		
Energy, eV	5	20	100
Wavelength, nm	248	62	12
undulator	5m U48	5m U48	5m U30
harmonic	1	1	3
rms pulse length, fs	100	100	100
photon/pulse	$1.1 * 10^{6}$	$1.0 * 10^{6}$	$8.6 * 10^{5}$
Energy per pulse, μJ	$8.6 * 10^{-7}$	$3.2 * 10^{-6}$	$1.4 * 10^{-5}$
peak flux, photons/s/0.1%	$4.4 * 10^{18}$	$4.1 * 10^{18}$	$3.4 * 10^{18}$
average flux, ph/s/0.1%	$1.4 * 10^{15}$	$1.3 * 10^{15}$	$1.1 * 10^{15}$
peak brightness, photons/s/0.1%/mm^2/mrad^2	$2.2 * 10^{20}$	$2.0 * 10^{21}$	$9.8 * 10^{21}$
average brightness, ph/s/0.1%/mm^2/mrad^2	$7.3 * 10^{16}$	$6.5 * 10^{17}$	$3.2 * 10^{18}$

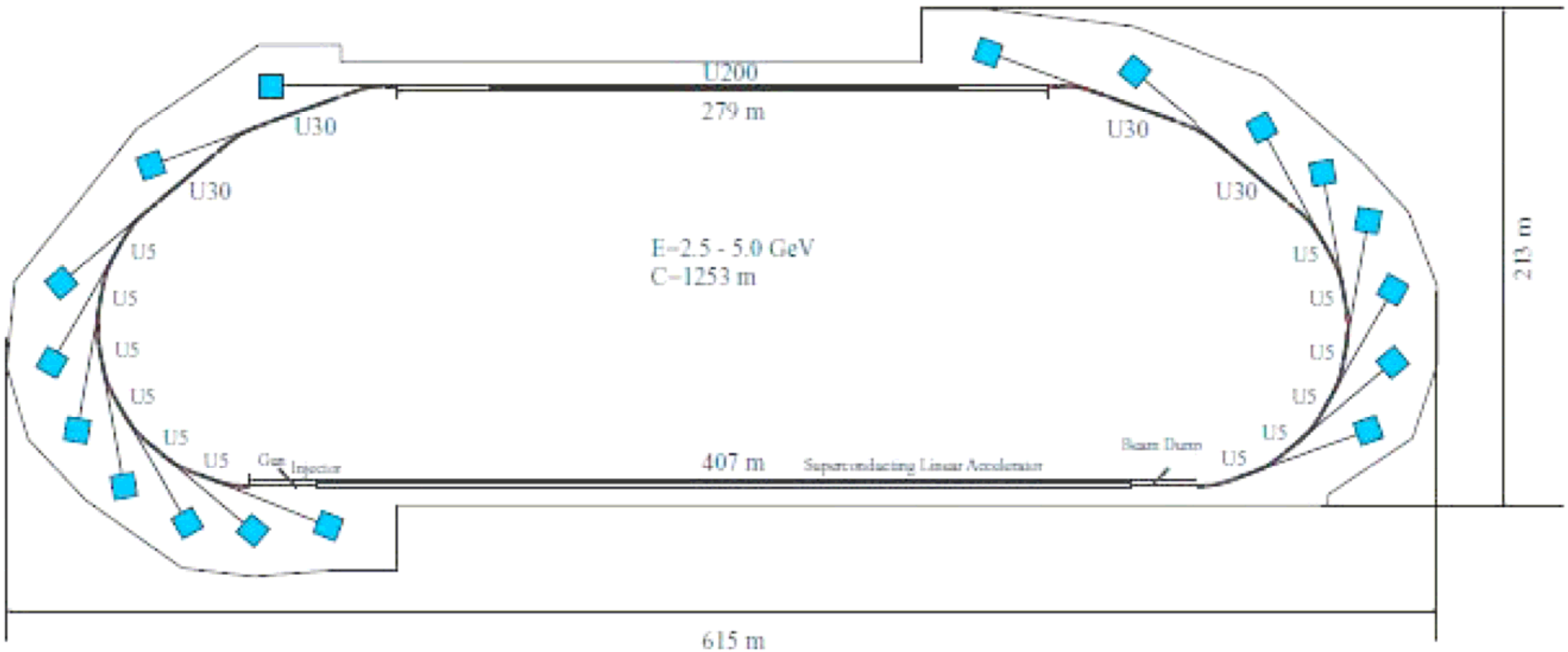


Figure 2. The 2.5 to 5 GeV, 100 mA Energy Recovery Linac under consideration at KEK is designed to provide next generation capability for users of the Photon Factory. Seventeen x-ray beamlines from 5 and 30 meter long undulators are shown in this schematic layout.

Our programs at RRCAT related

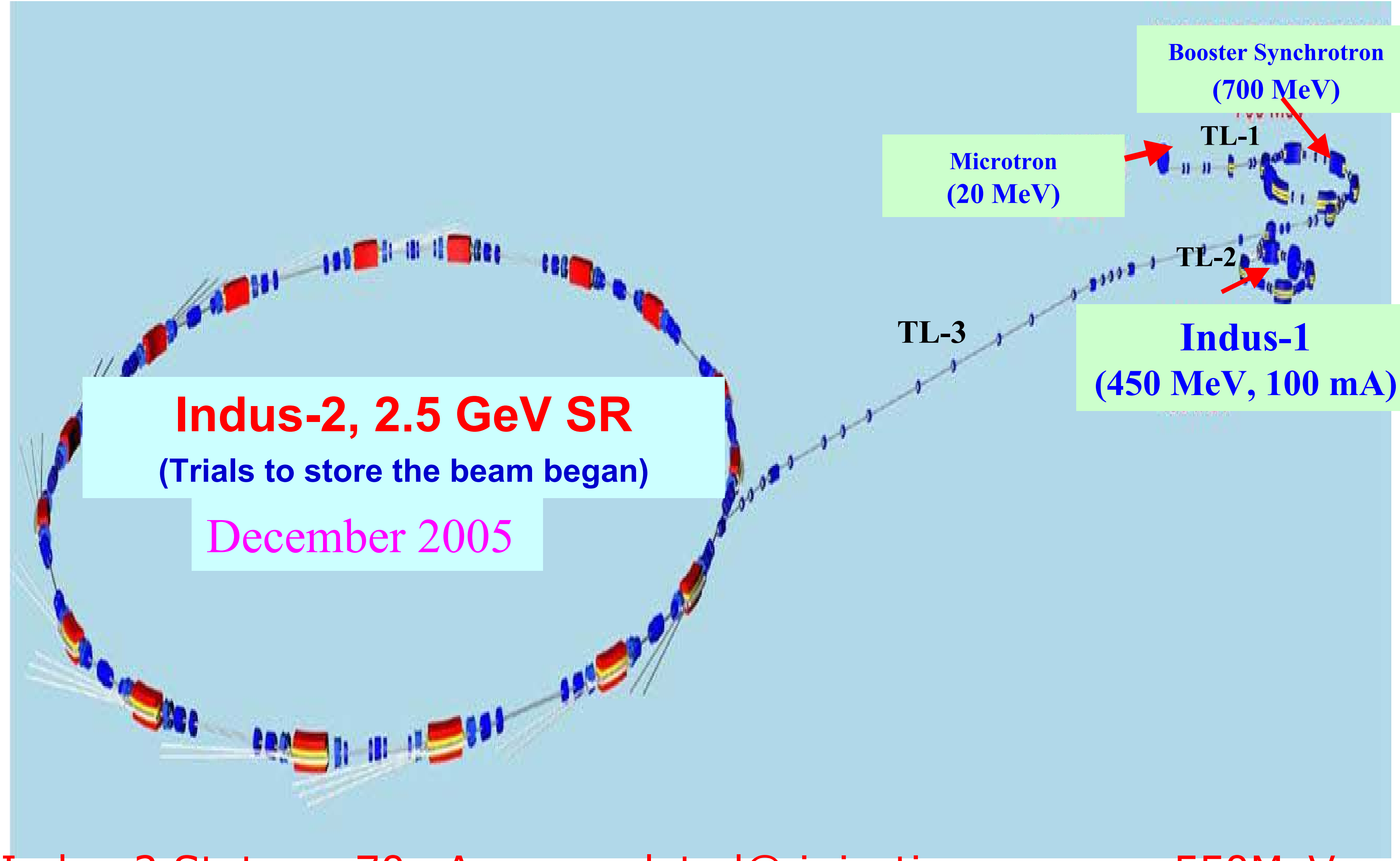
to

light sources

&

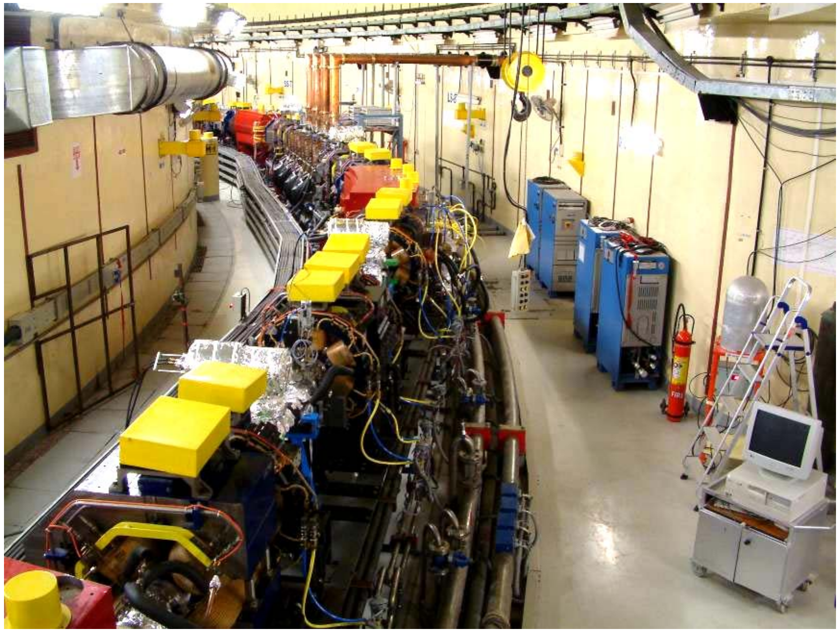
the journey ahead

SCHEMATIC VIEW OF INDUS COMPLEX



Indus-2 Status:~70mA accumulated@ injection energy ~550MeV.
Now being operated @2GeV.(Max energy reached so far 2.4 GeV.)

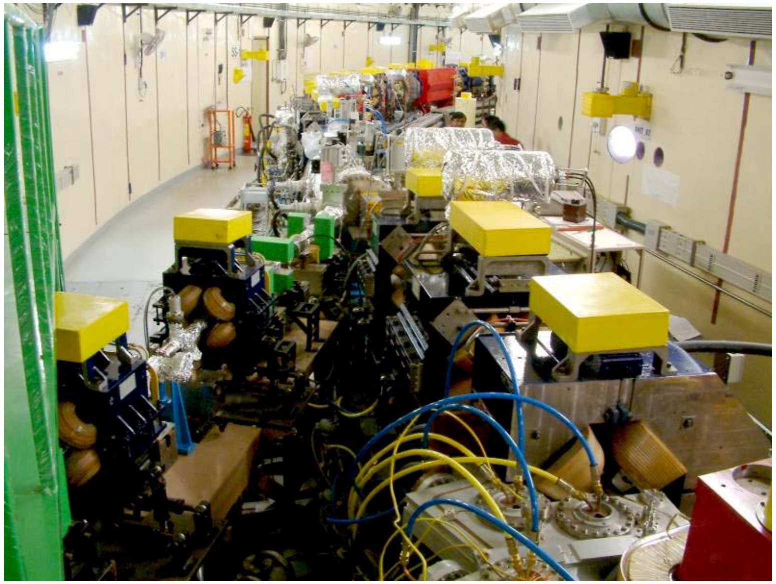
Assembly of Indus-2 Ring in the Tunnel



RF Cavities installed in Indus-2 Ring

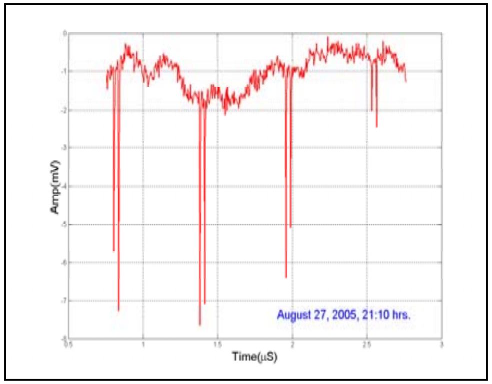
Long Straight Section LS-6 Assembly

Transport Line-3 Joining on to Indus-2



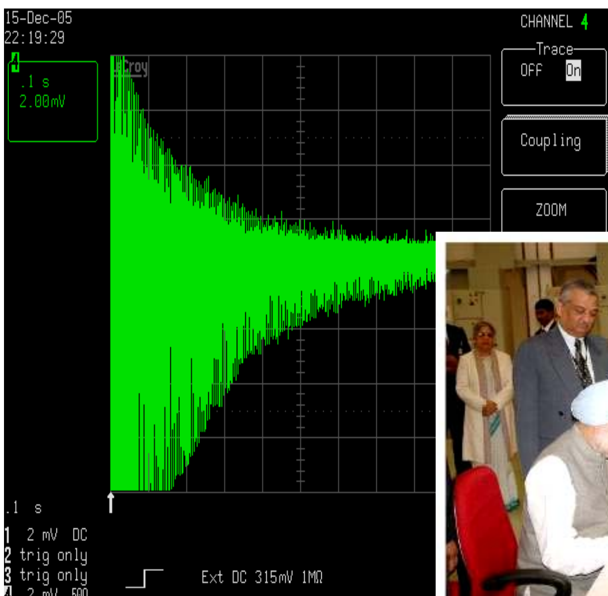
Major Events in the 2nd Half of 2005

(a) **4** turn beam circulation seen on wall current monitor on 27th August,2005



(b) First SR light from Indus-2 recorded on Dec. 2, 2005 with CCD camera on sighting beam line.

(c) Beam circulation up to **1 second** reached on **15th December, 2005**



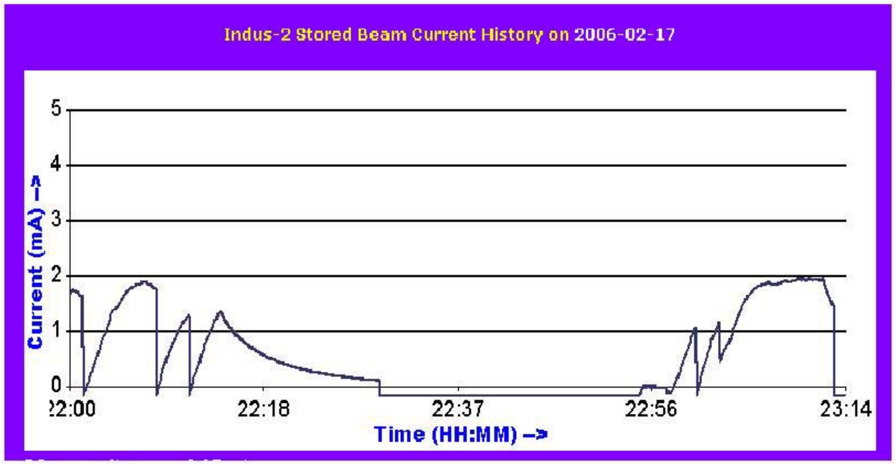
(d) **Prime Minister dedicated Indus-2 to the Nation on 17th December, 2005**

Modern science and technology have opened up enormous opportunities for human development. The Dept of Atomic Energy has been a path finder in this regard. This is a tribute to the leadership provided by people like Dr Raja Ramanna.

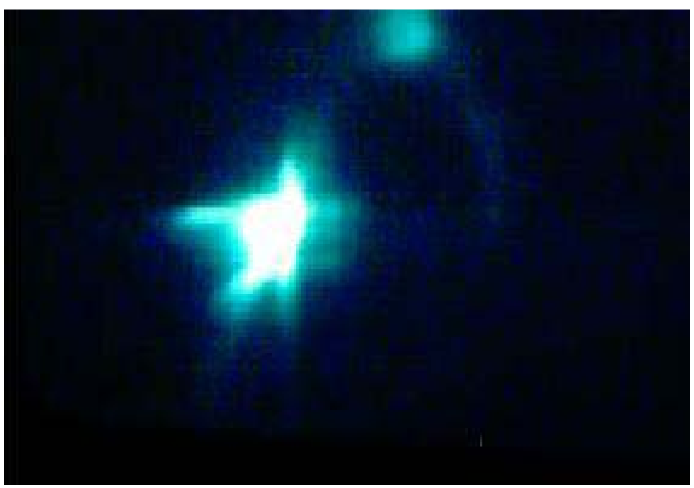
Manmohan Singh
17.12.2005

Major Events in 2006 (I)

First current accumulation in Indus-2 seen using DC Current Transformer) (17 Feb 2006)

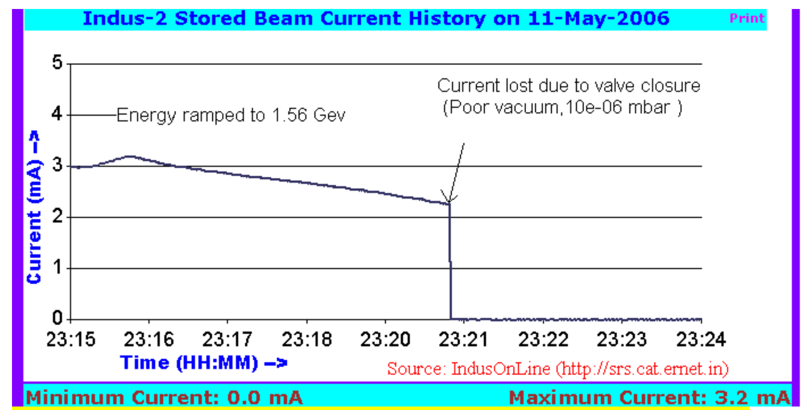


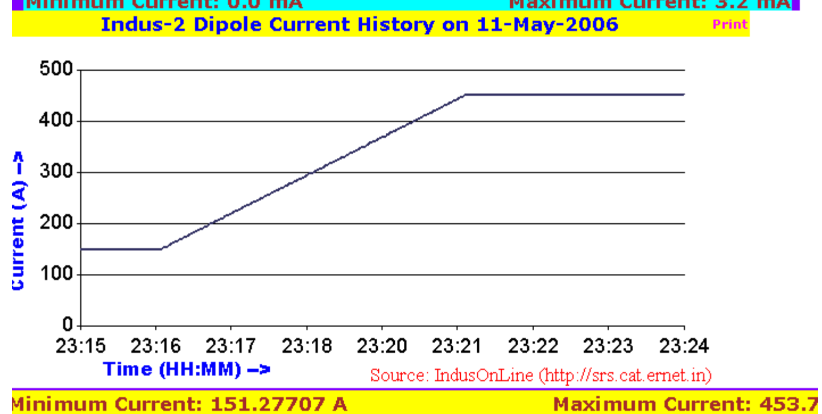
Maximum Current= 2.1 mA



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

Successful energy ramping >1.5 GeV (May 11,2006) in Indus-2: 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.

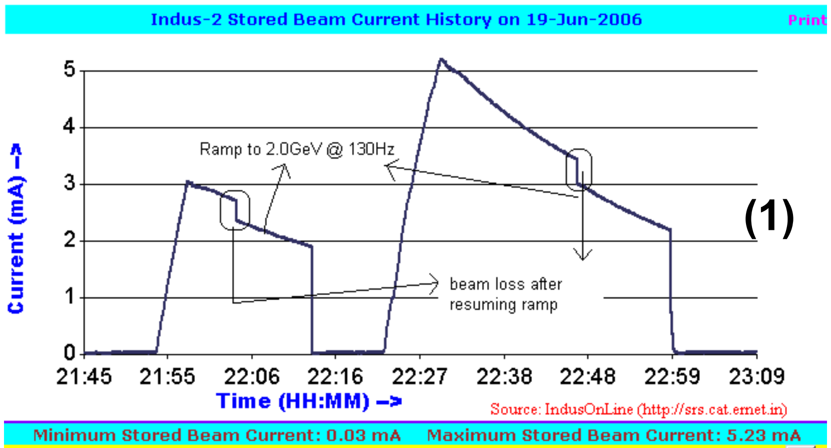




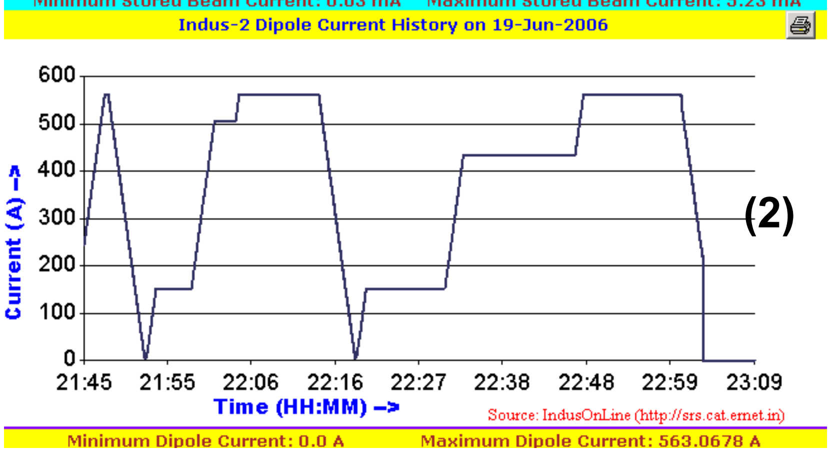
Major Events in 2006 (II)

Energy ramped to 2 GeV (19/6/ 2006).
(1) shows current in Indus-2;

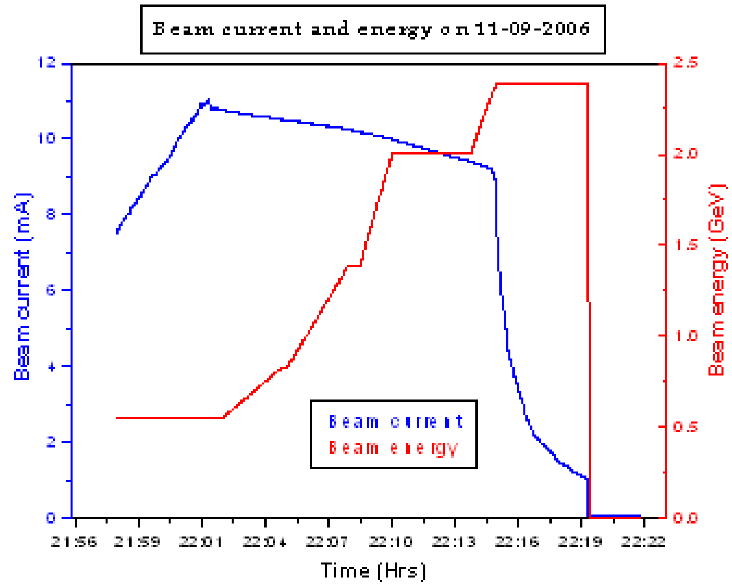
(2) shows current in the dipole magnets.
150 Amps corresponds to 543 MeV; ~550 Amps corresponds to ~2 GeV.

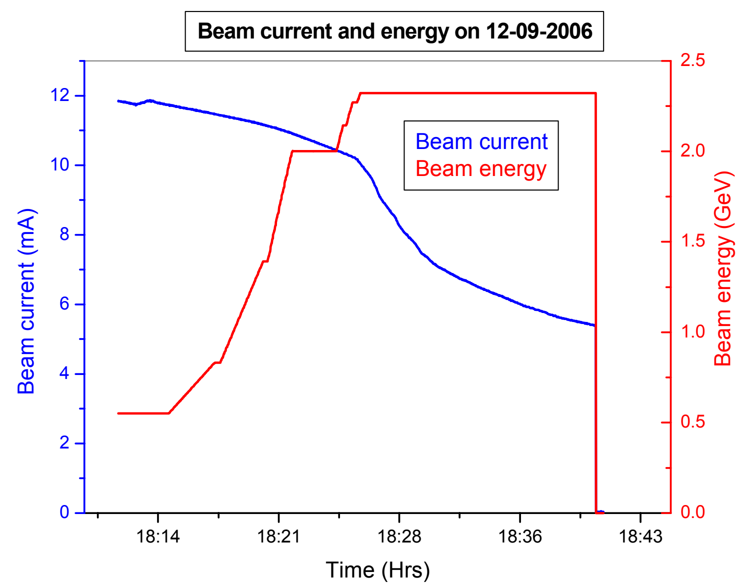


(1)



(2)





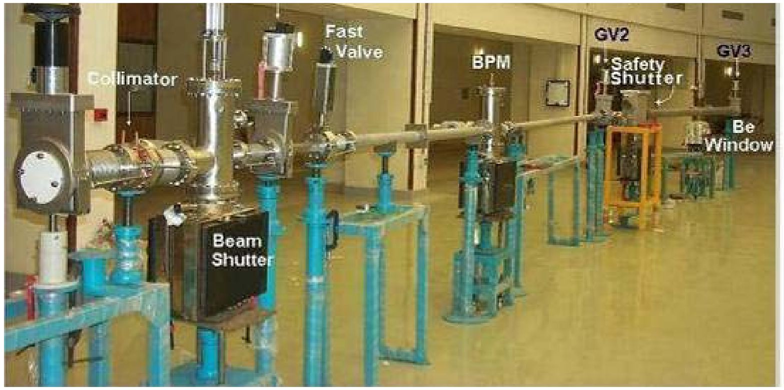
Beam-lines being built/designed/planned

	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

(# Action towards beam line installation in experimental hall has started)

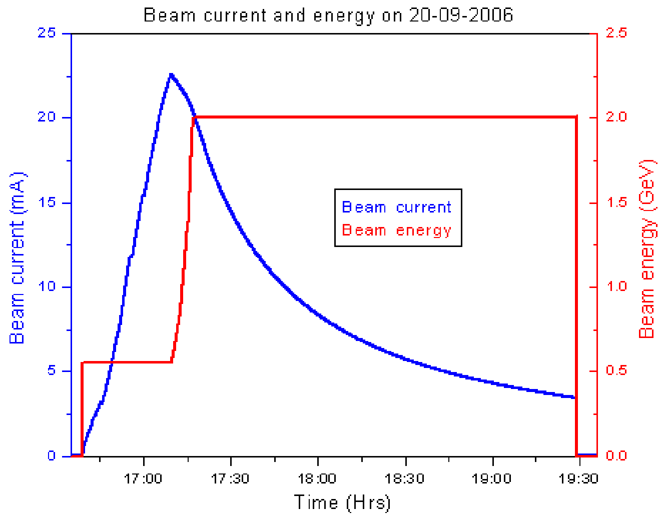
Major Events in 2006 (III)

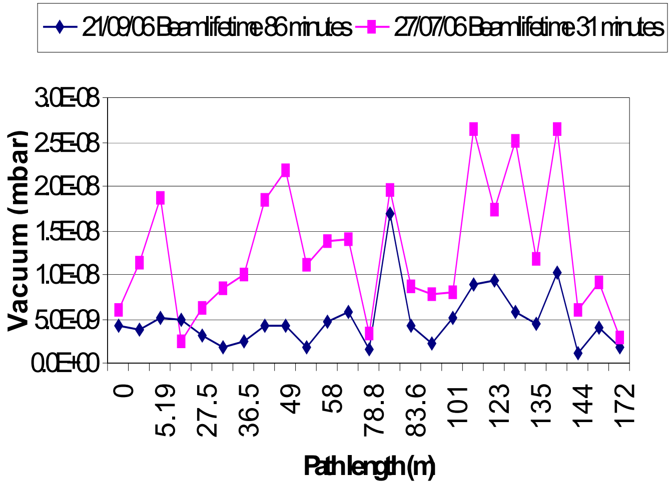
Prototype Front-end of Indus-2 Beam-line Built



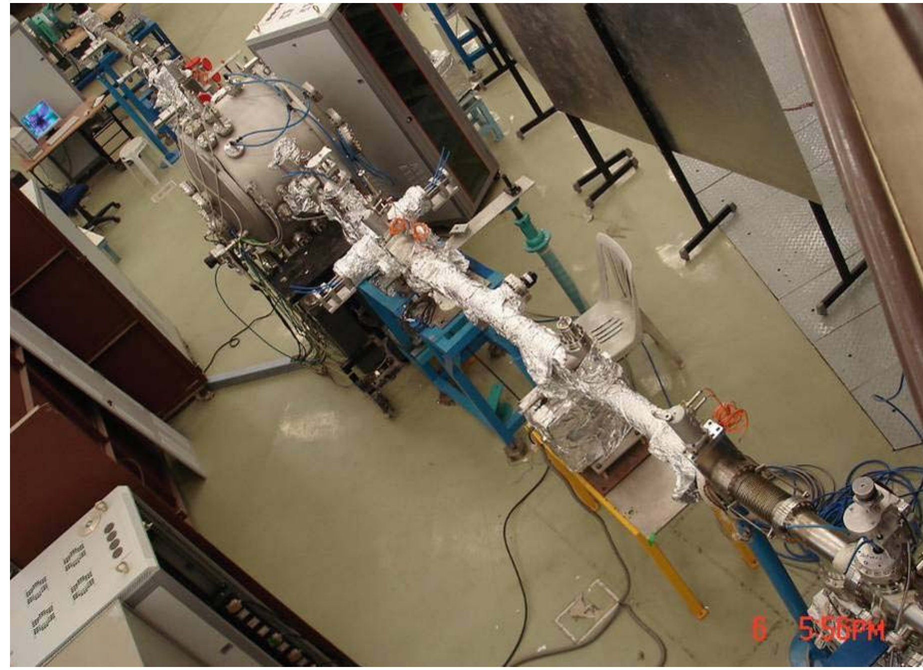
First front end on XRD BL Indus-2 installed

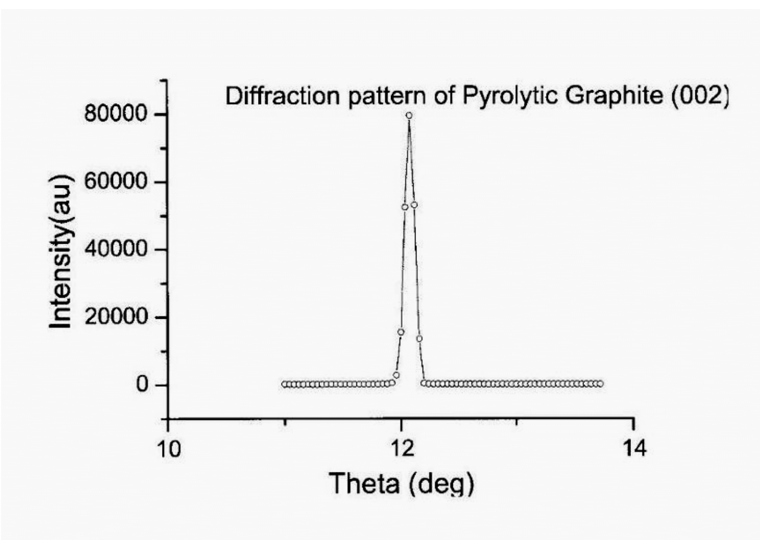
Experimental operation @ 2 GeV





Major Events in 2006 (IV)-XRD BL Progresses





First x-ray diffraction record with SR from Indus-2 using XRD BL12 on 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. Collecting and focusing mirrors were not yet in place.

Major Events in 2006 (V)

simomura osamu <simomura@post.kek.jp>

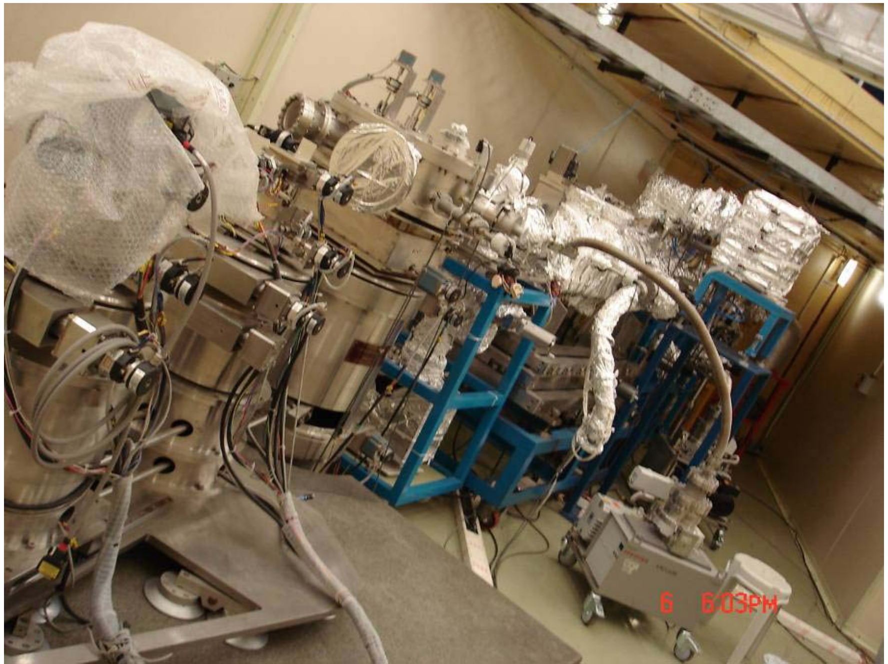
Thursday, October 05, 2006 5:22 AM

Dear Dr. Sahni, Dr. Kotaiah and Dr. Nandedkar,

On behalf of the Japanese Society of Synchrotron Radiation Research, and also on behalf of the Photon Factory, I would like to express my sincere congratulation to you and your colleagues on the success of hard X-ray diffraction at INDUS-II. When I visited INDUS about 10 years ago, INDUS-I was just in operation and the place for INDUS-II was digging out. Since then, you have made a tremendous effort to this great milestone. I much appreciate your enthusiasm to construct SR facility in India. I expect you will present your excellent result at the first workshop of Asia-Oceania Forum held at KEK, Tsukuba in this November,

It is my pleasure to look at the new activity at INDUS-II next week.

Major Events in 2006 (VI)- EXAFS BL Installed



Major Events in 2007 (I)- Work on PES BL Started

Main parameters

Energy range : 0.85 keV to 15 keV,

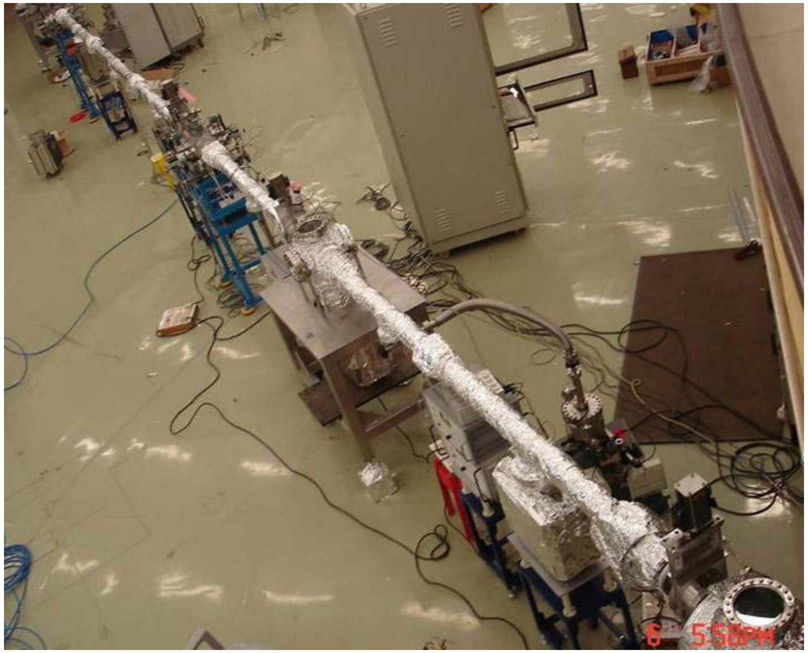
Resolution : $\sim 10^{-4}$

Overall Pressure : $< 5\text{x}10^{-10}$ mbar

Crystals : (1) Si (111), 2d = 6.271 Å ,

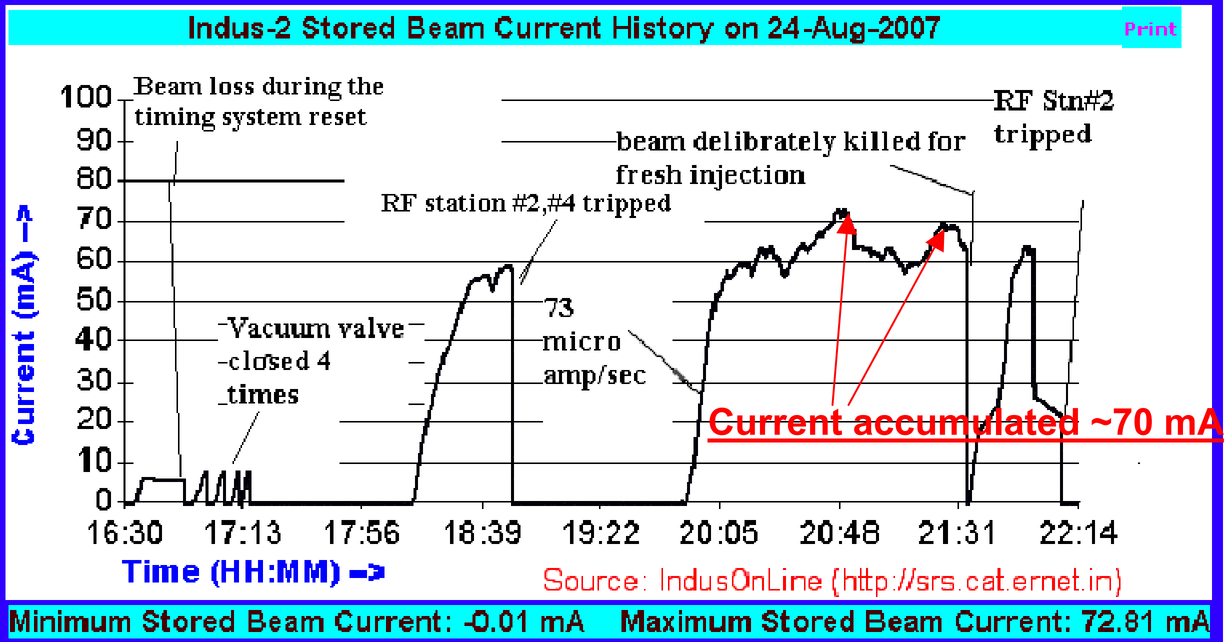
(2) Beryl (1010), 2d = 15.954 Å

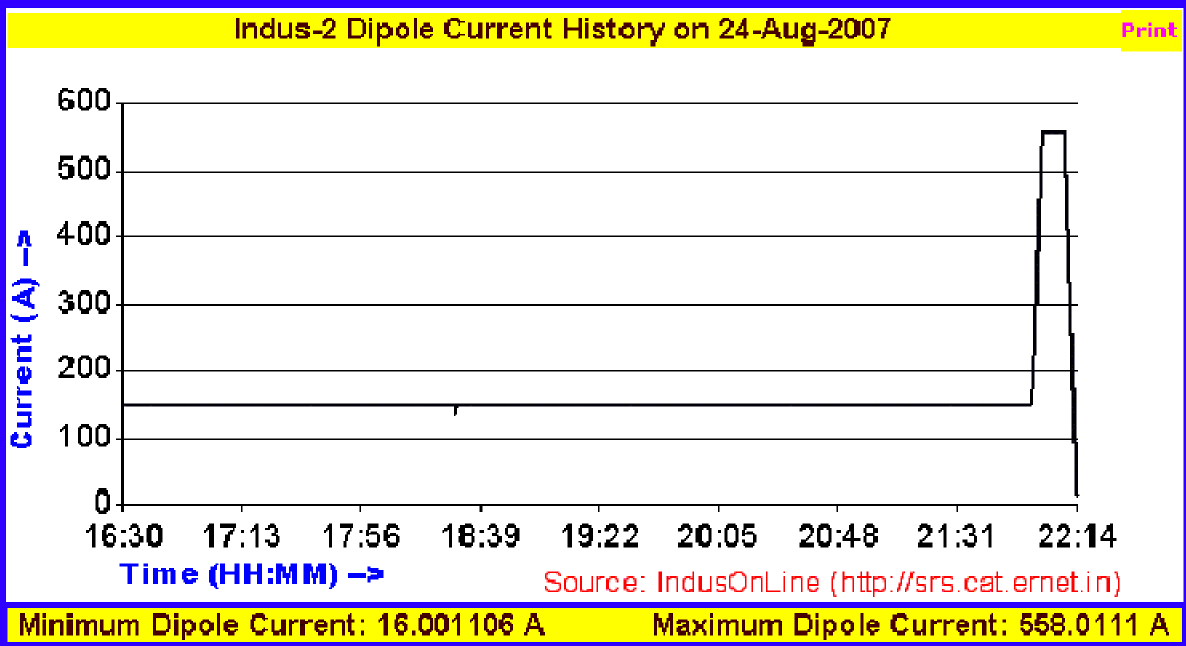
Spot on Sample :~ 250 μm x 250 μm



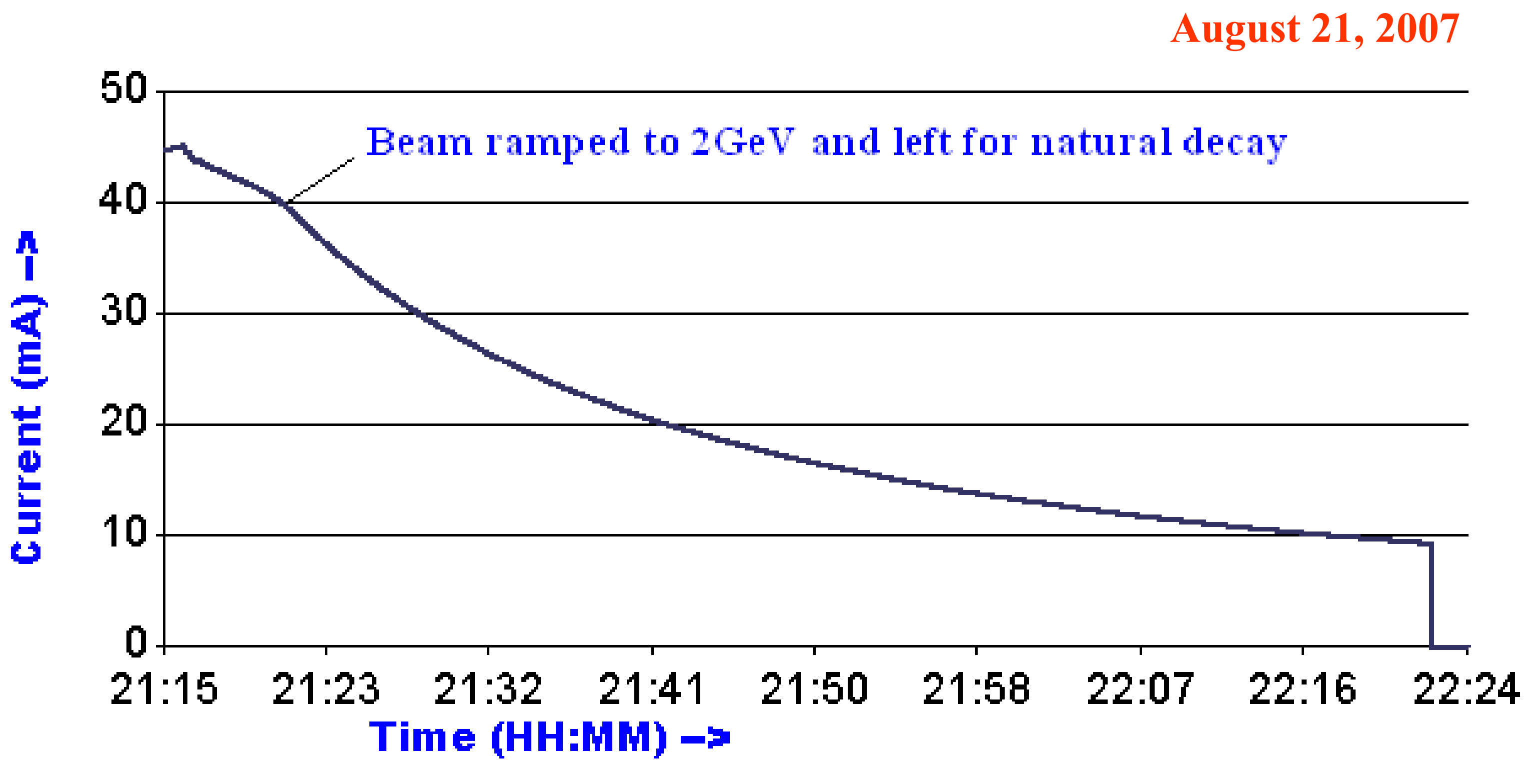
Salient Features:

- Home built DCM, slit assemblies & HSA for electron-energy analysis.
- All subsystems computer controlled.
- Sample temperature 10 - 1100 K.
- Insitu thin film preparation facility.
- Pre-characterization by LEED/ AUGER
- Arrangement for depth profiling.
- Software developed for data acquisition and analysis.


Indus-2 Stored Beam Current History on 24-Aug-2007
Print
Beam loss during the timing system reset
RF Stn#2 tripped
beam delibrately killed for fresh injection
RF station #2,#4 tripped
73 micro amp/sec
Vacuum valve closed 4 times
Current accumulated ~70 mA
Current (mA) -->
Time (HH:MM) -->
Source: IndusOnLine (http://srs.cat.ernet.in)
Minimum Stored Beam Current: -0.01 mA
Maximum Stored Beam Current: 72.81 mA

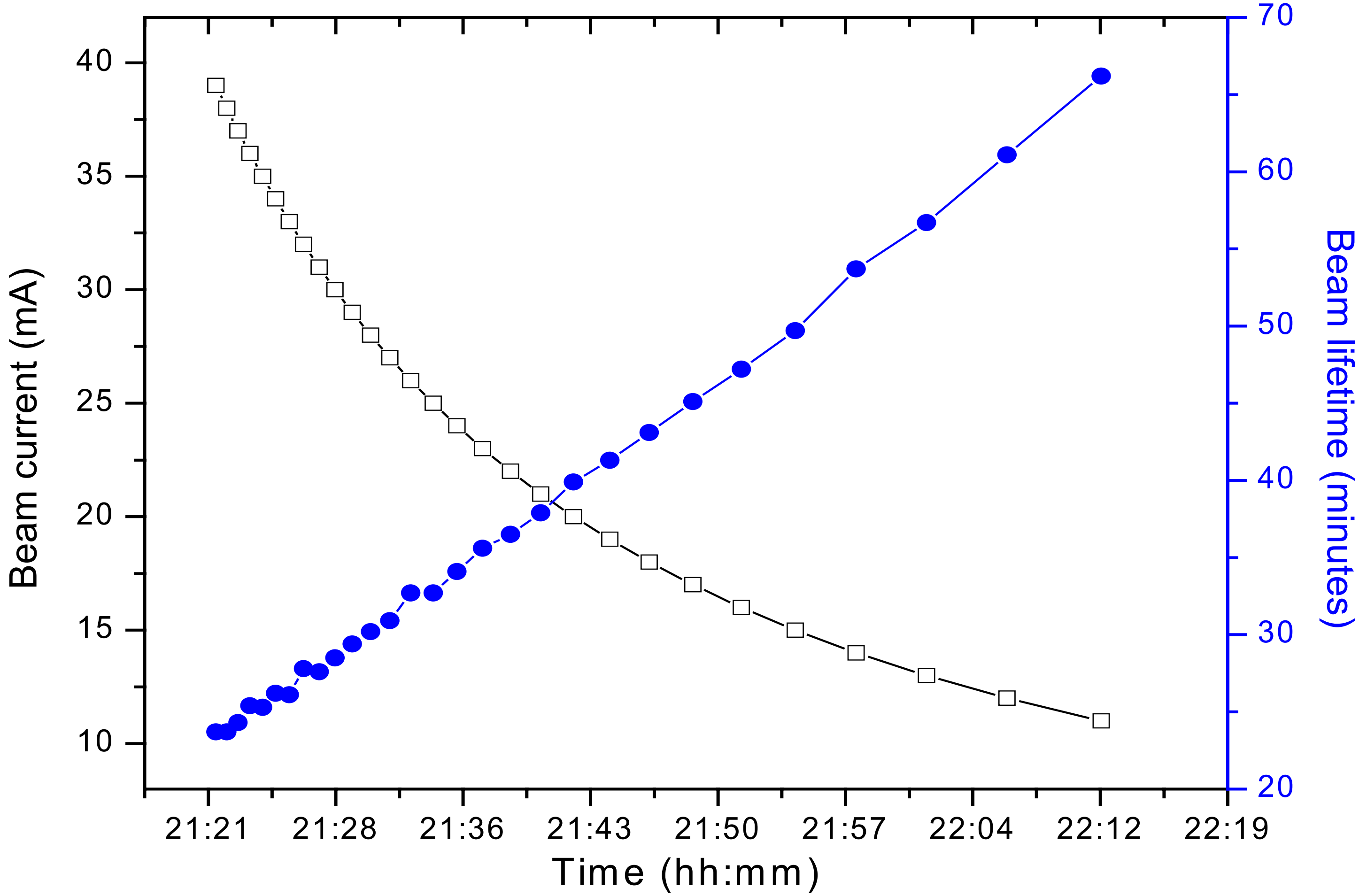

Indus-2 Dipole Current History on 24-Aug-2007
Print
Current (A) -->
Time (HH:MM) -->
Source: IndusOnLine (http://srs.cat.ernet.in)
Minimum Dipole Current: 16.001106 A
Maximum Dipole Current: 558.0111 A

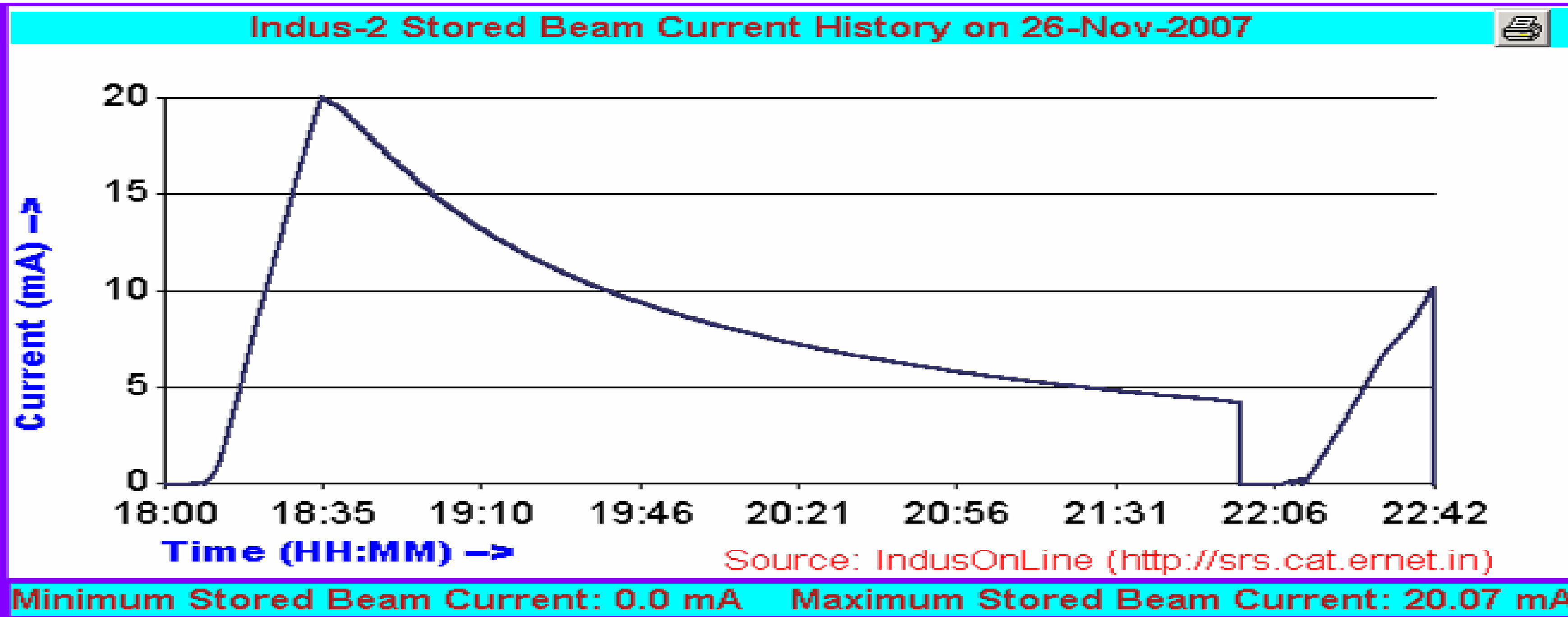
Beam current decay with time at 2GeV

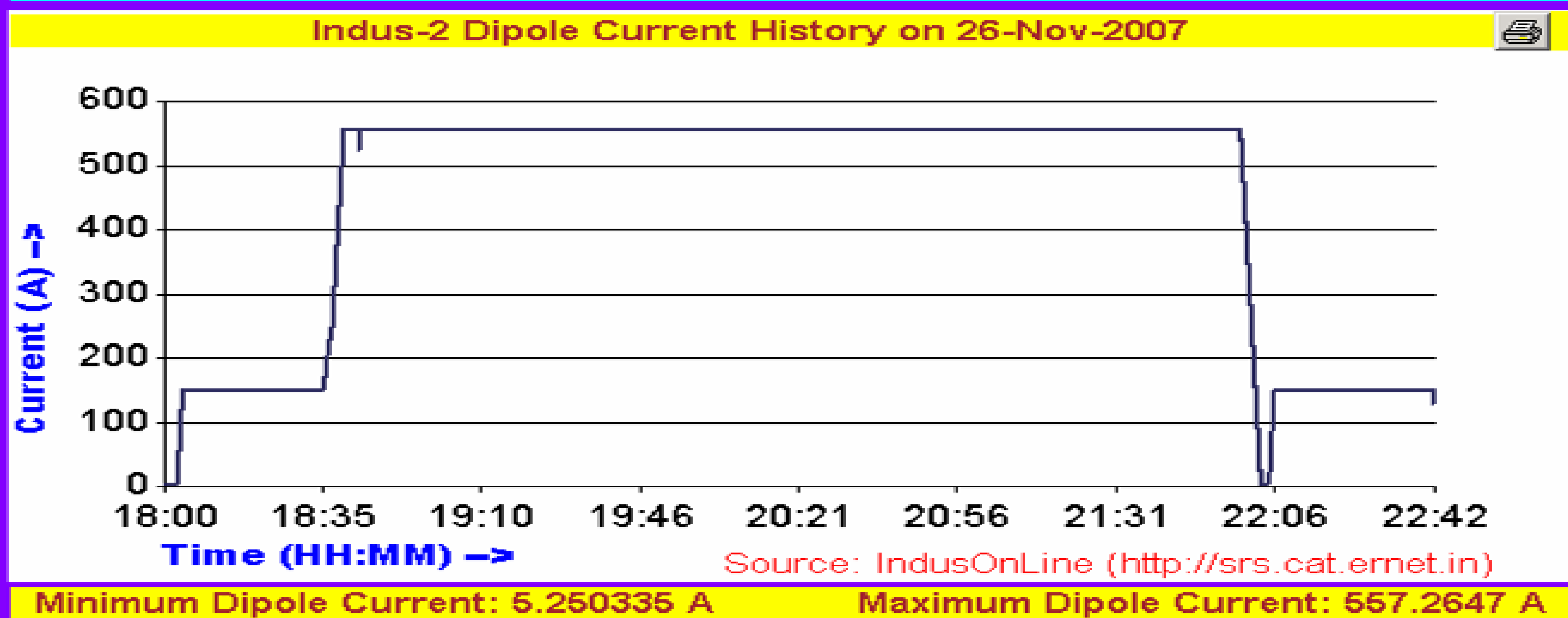


Beam lifetime at 2GeV

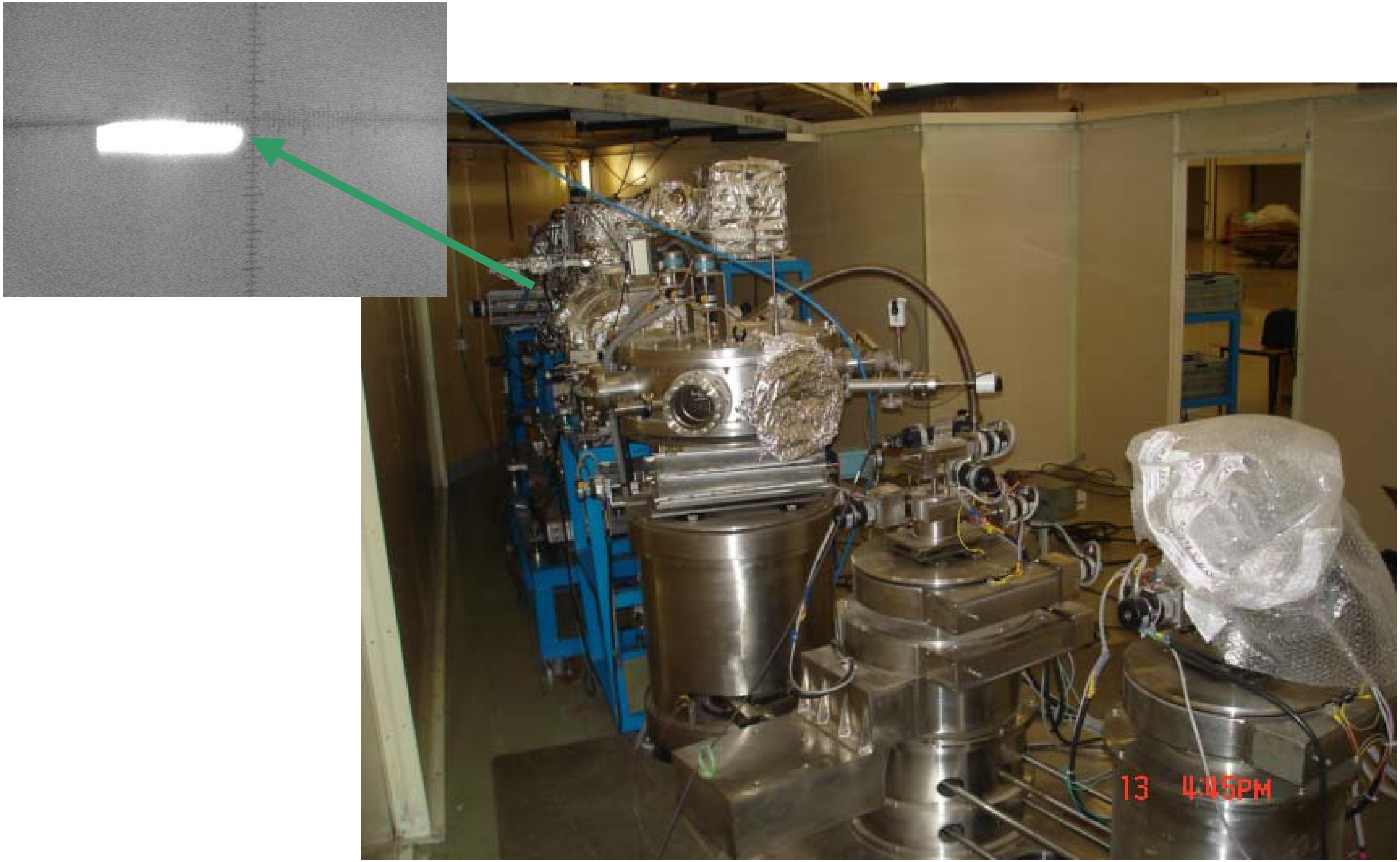
August 21, 2007



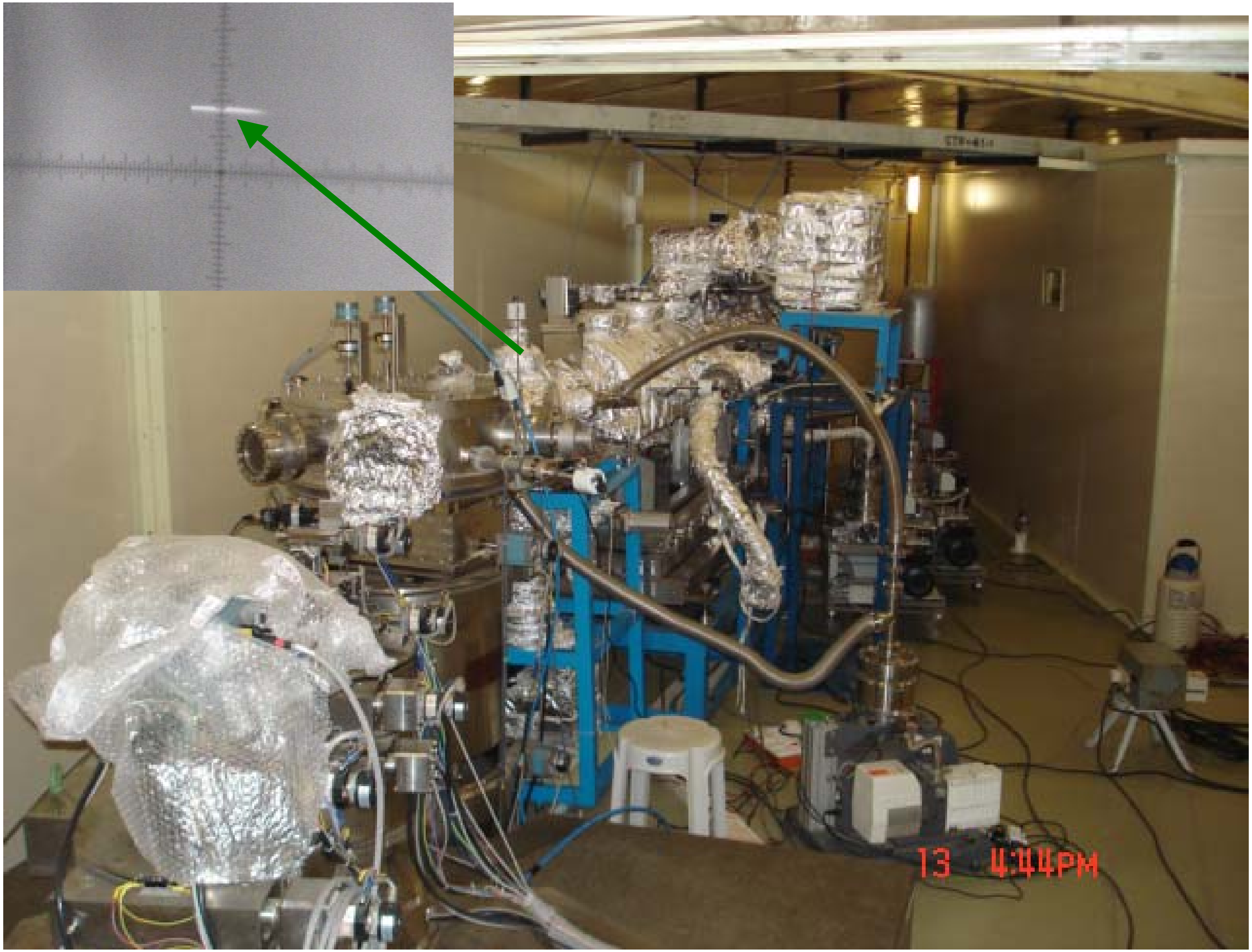

Indus-2 Stored Beam Current History on 26-Nov-2007
20
15
10
5
0
Current (mA) -->
18:00
18:35
19:10
19:46
20:21
20:56
21:31
22:06
22:42
Time (HH:MM) -->
Source: IndusOnLine (http://srs.cat.ernet.in)
Minimum Stored Beam Current: 0.0 mA
Maximum Stored Beam Current: 20.07 mA

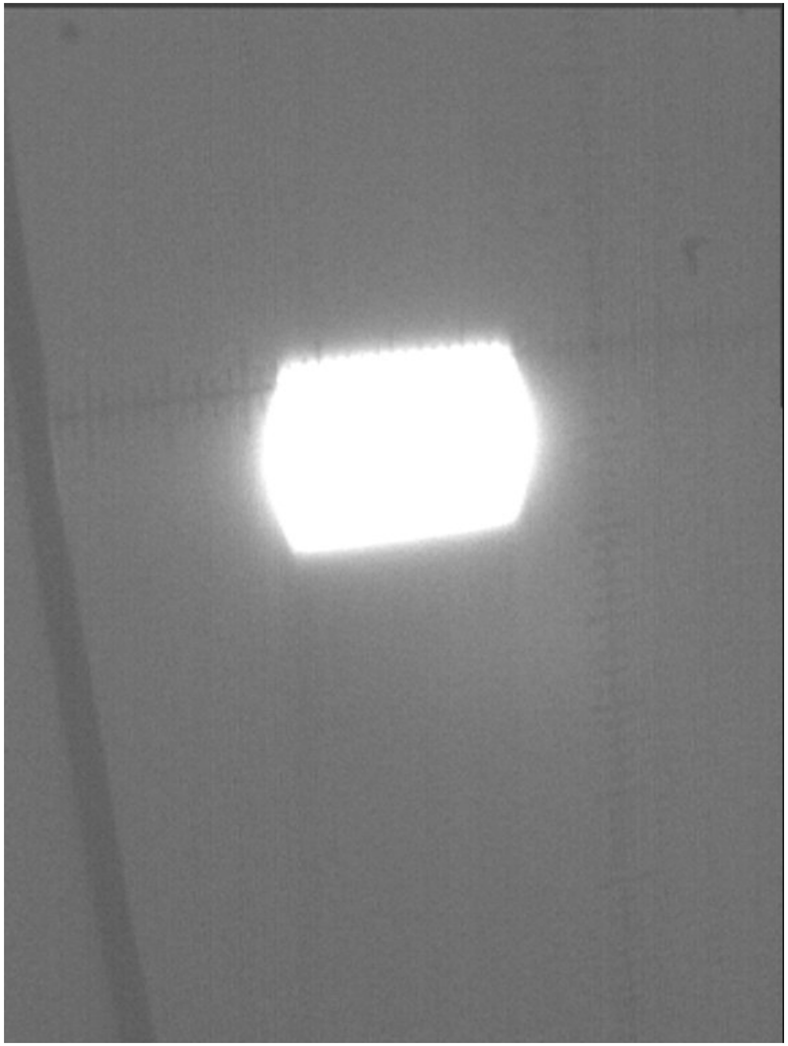

Indus-2 Dipole Current History on 26-Nov-2007
600
500
400
300
200
100
0
Current (A) -->
18:00
18:35
19:10
19:46
20:21
20:56
21:31
22:06
22:42
Time (HH:MM) -->
Source: IndusOnLine (http://srs.cat.ernet.in)
Minimum Dipole Current: 5.250335 A
Maximum Dipole Current: 557.2647 A

SR Beam footprint at Beam Viewer-1 (before Mirror) of BL-8, EXAFS beam line obtained on 22.11.2007 @5mA/2 GeV Beam from INDUS-2



SR Beam footprint at Beam Viewer-2 (between Mirror & polychromator) of BL-8 obtained on 23.11.2007 @3mA/2 GeV Beam from INDUS-2





SR as seen on the Be window of the EDXRD beam line (BL11). Picture taken on 27-11-2007.

As you see, user efforts are now well under way on three beam lines (XRD, EXAFS & EDXRD) and work is also on to build two more beam lines (PES & GIMS) so that we should be able to produce some data in the coming months, even as capability of these beam lines is improved.

As for GenIV light sources, RRCAT has started a project concerning core technology ("SCRF") that is required.

Proposed XI Plan Project of RRCAT on

Development of Superconducting Cavities and Associated Technologies for High Energy Accelerators & their Applications

Project Identification Code: 11-R&D-CAT-4.08-0300

Financial Outlay: Rs 9135 Lakhs

(XI Plan: Rs 8410 Lakhs; XII Plan Rs 725 Lakhs)

Team

S B Roy : Superconducting Materials

S C Joshi : Engineering of SCRF cavity

P K Kush : Cryogenics Facility/ Support

S Krishnagopal : Accelerator Physics

Main Aim of this project:

Develop SC RF technology for particle accelerators

Charged particles can be accelerated by (1) Either static (DC) fields or by (2) Alternating (AC at Radiofrequency (RF)) fields.

But DC voltages are limited by corona formation & discharge; so to reach very high energies only RF fields are used. But with RF fields, metallic structures that confine particle beams, cause parasitic power loss.

This power loss can be avoided by using superconducting cavities.

Status of SCRF cavity related developments in India:

A SC LINAC booster has been built to boost energy of heavy ions in BARC-TIFR Pelletron at Mumbai. This booster uses a lead coated (2 μm) copper quarter wave resonators.

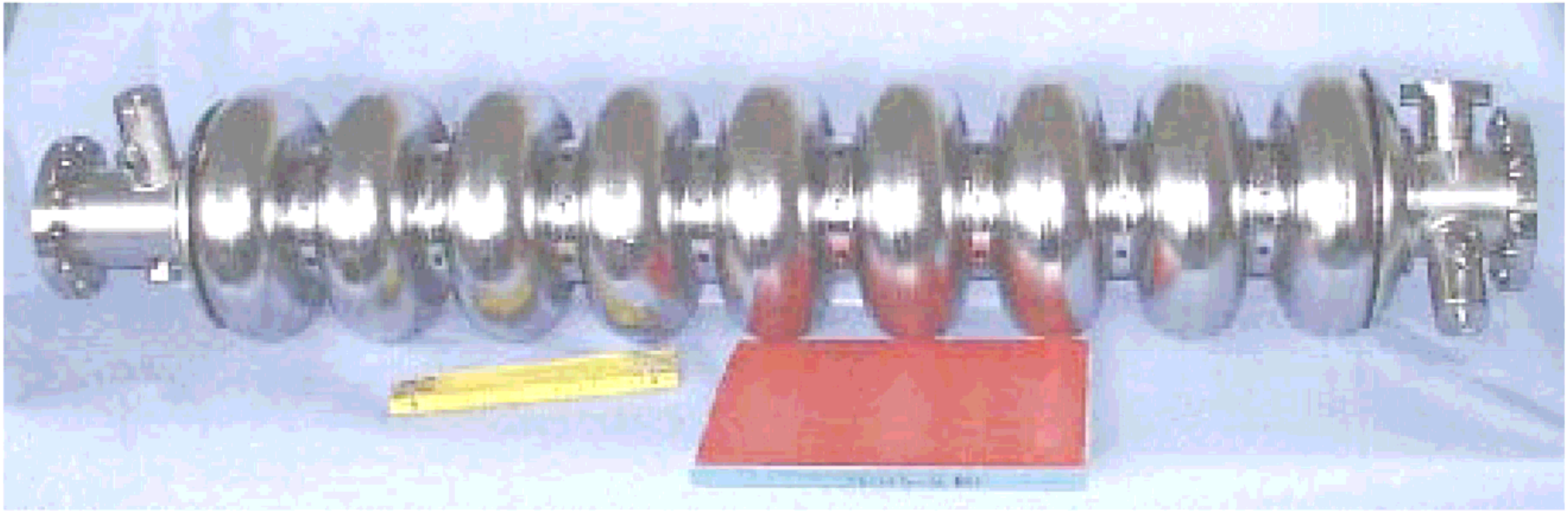
IUAC, New Delhi has built a SCRF-LINAC booster for its existing Pelletron Accelerator. Program aim: Indigenously fabricate bulk niobium superconducting resonators.

Major objectives of this R&D project at RRCAT

- Develop technology and set up infrastructure for the bulk Nb SCRF cavity fabrication, chemical processing, cleaning, assembly & also test the single and multi cell cavity structures.
- Upgrade cryogenic infrastructure at RRCAT.
- R&D in bulk/thin film superconducting materials (Nb & others).
- Using a superconducting post-accelerator set up a THz coherent IR source at wavelengths down to ≈ 30 microns.
- Gear up to be able to take part in the R&D related to International projects such as X-FEL & ILC.

Amongst the final aims : Develop module of a Nb SC cavity for a Linac

In the first phase we will develop the infrastructure to build single and multicell cavities, eventually make a multi cell cavity of the type as shown below



New Facilities Planned to be Set Up at RRCAT

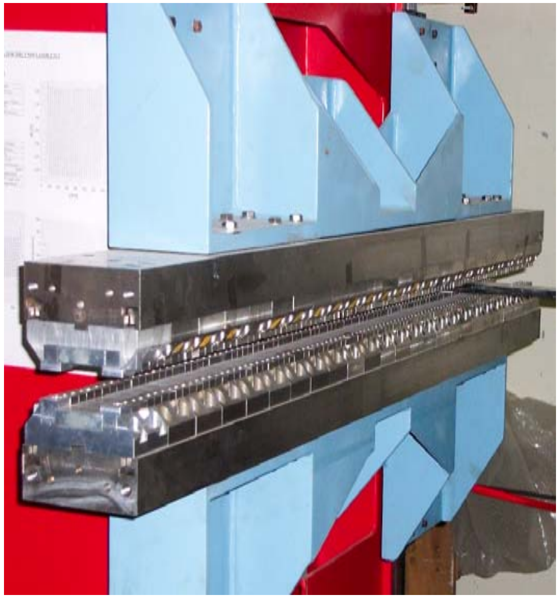
- Put up SCRF cavity making infrastructure (eg hydraulic press, set up to make parts of Nb cavities, EBW Machine etc.), plus chemical processing facilities (eg, EP/BCP/BP, HPR & annealing furnaces etc.), assembly & testing set up. (clean-room, test cryostats, RF sources etc.)
- Add to cryogenic infrastructure, (Bigger liquid He plant, Liquid N_2 plant and accessories for larger cryogen & gas handling systems etc.)
- Augment experimental facilities for superconducting materials research. Add to presently available (magnetic, electrical & thermal conductivity measurements) by new set ups to evaluate materials.

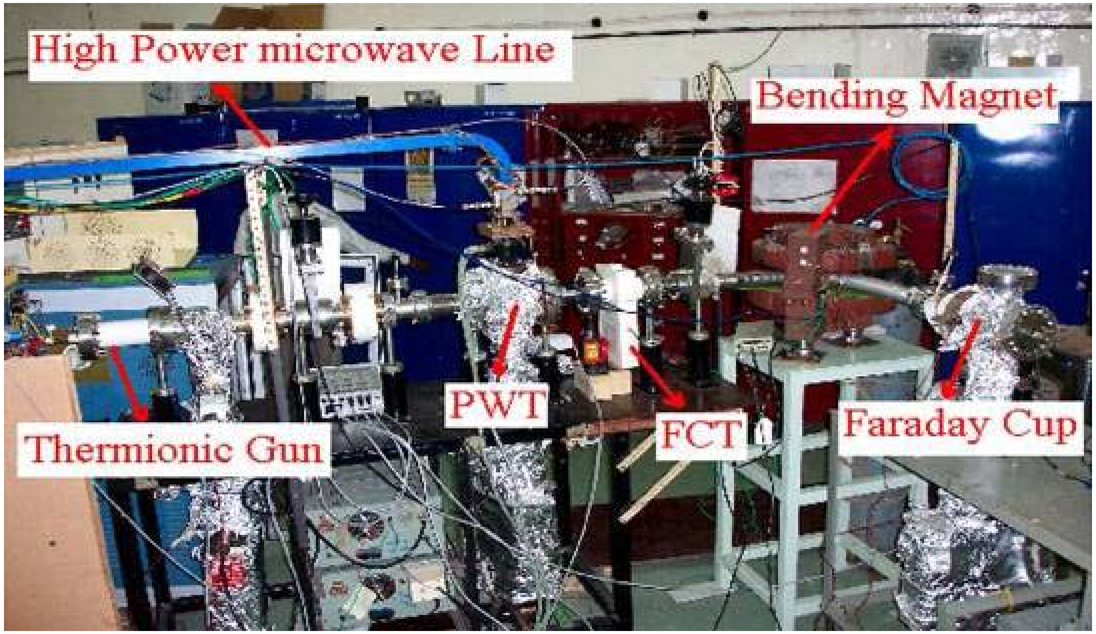
Overall long term benefits to DAE programs:

- Learning to make reliable and reproducible SC-RF cavities.
- Gain knowledge and experience to work on SCRF accelerating structures that we will require for later stages of Gen IV light sources & HIPA needed for ADS program.

Parts of PWT Linac for THz Source

Variable Gap PM Undulator





Status:

PWT has been built; beam accelerated and passed through Undulator, producing First THz radiation signal @ ~500μ.

Concluding remarks

- We have covered the basics of synchrotrons & reasons that underlie experimentalists interest in building the SRSs, FELs & ERLs.
- SR from Indus-2 is now in trial usage stage. We want to give thrust to it & eventually turn Indus-2 into a top class facility by adding IDs on straight sections.
- Meanwhile we will prepare the base in SCRF technology so that in the next decade we can launch a program to develop next generation of light sources of the FEL/ERL variety.
- I hope RRCAT will become a hub for light sources and I want you to join us in this journey.

Thank You