Free Electron Laser based Delhi Light Source (DLS) project at IUAC, New Delhi

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Inter University Accelerator Centre (IUAC), New Delhi

On behalf of FEL team of IUAC and collaborators

Project is jointly funded by BRNS, DAE and IUAC

Plan of Presentation

- Introduction
- Concept of DLS and major developments of sub-systems
  - Beam optics calculation
  - Cavity fabrication and testing
  - RF System
  - Laser design and development
  - Photocathode deposition system - design, fabrication, testing
  - Undulator – design
- Time chart
- Conclusion

Inter-University Accelerator Centre (IUAC) Delhi

Established in 1984

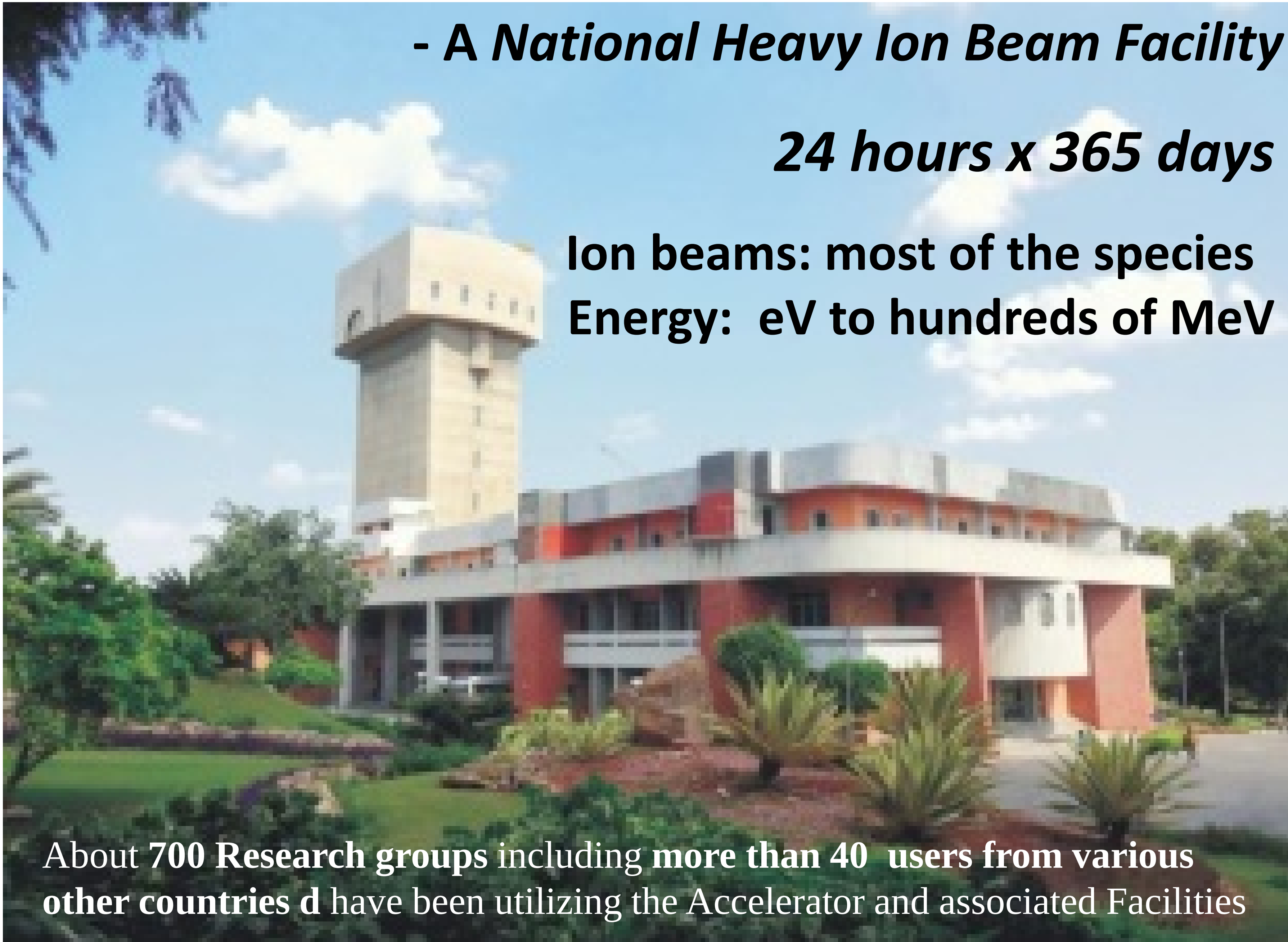
as the first Inter-University Centre (IUC) in India

Mission:

"To provide within the university system world class facilities for accelerator based internationally competitive research in focussed areas of several disciplines, e.g., Nuclear Physics, Materials Science, Atomic & Molecular Physics, Earth Sciences and Radiation Biology."

www.iuac.res.in

Inter-University Accelerator Centre (IUAC)



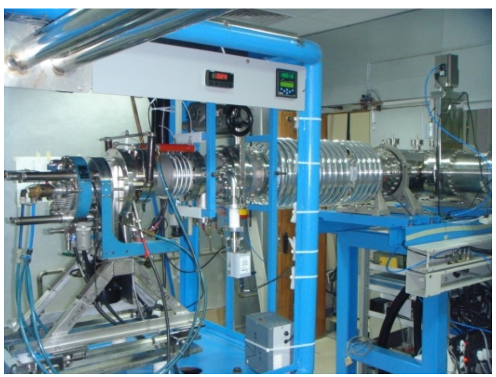
ACCELERATORS AT IUAC

16 MV Pelletron

Nb QWR based Superconducting LINAC

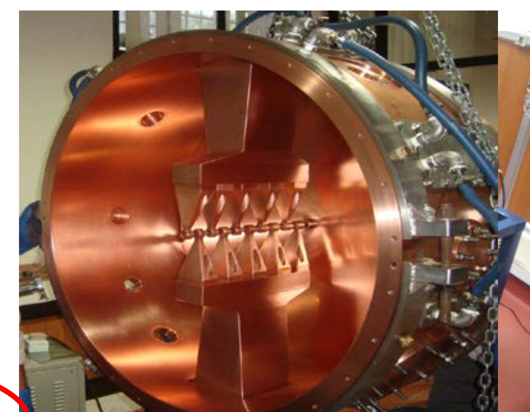
1.7 MV RBS Facility

Dedicated AMS Facility



MC-SNICS
Negative Ion Facility

ECR
Positive Ion Facility

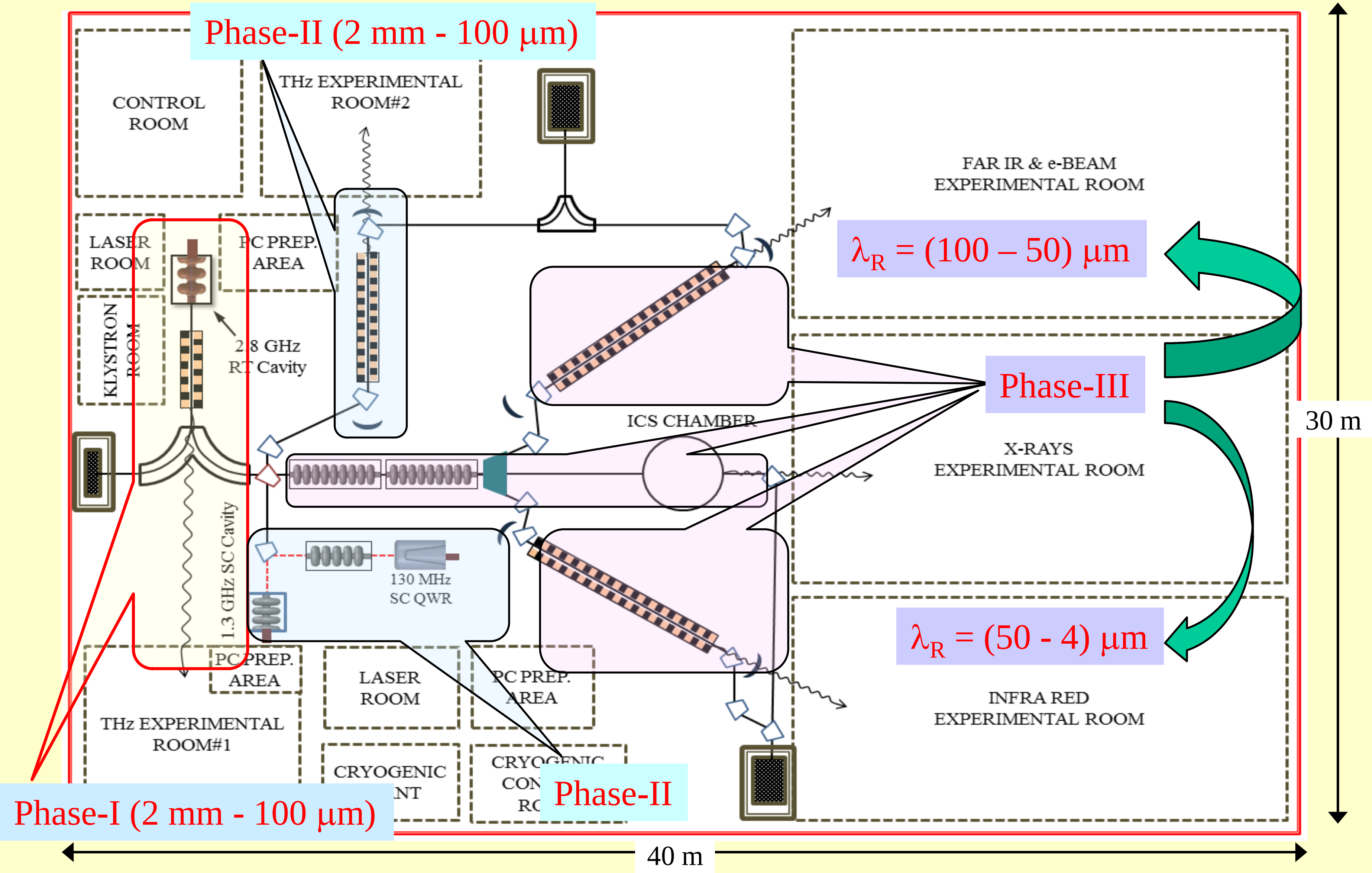


Drift tube Linac

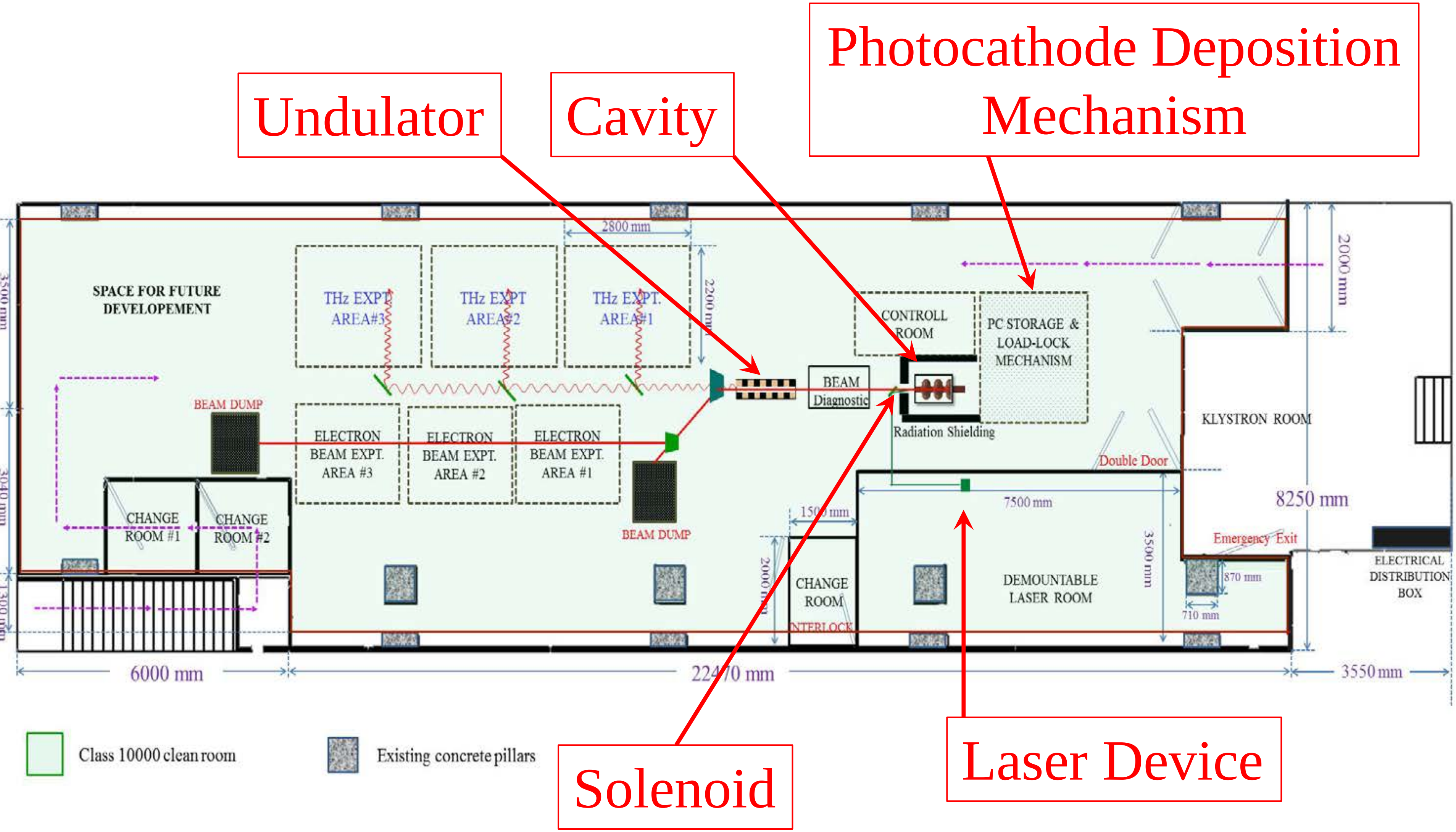
Light source is planned to serve more number of inter disciplinary research

FEL BASED DELHI LIGHT SOURCE (DLS)

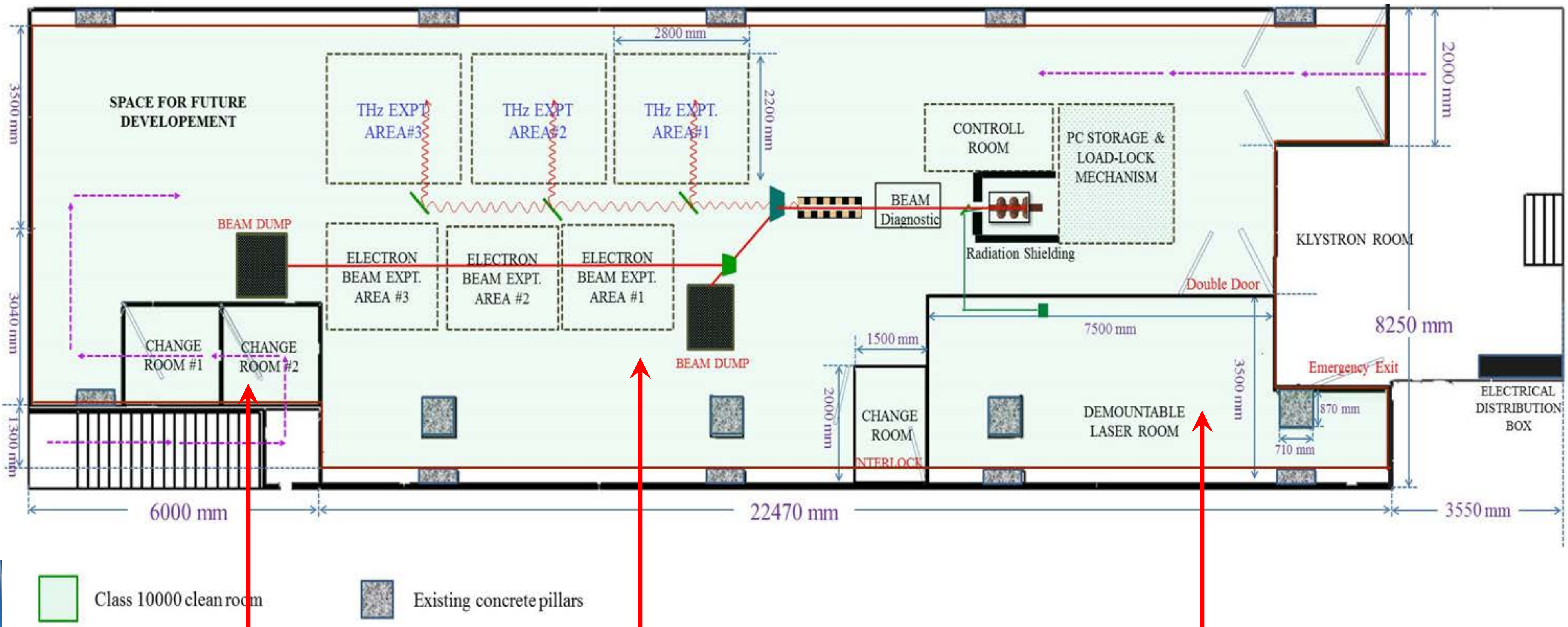
Layout of Delhi Light Source (DLS)



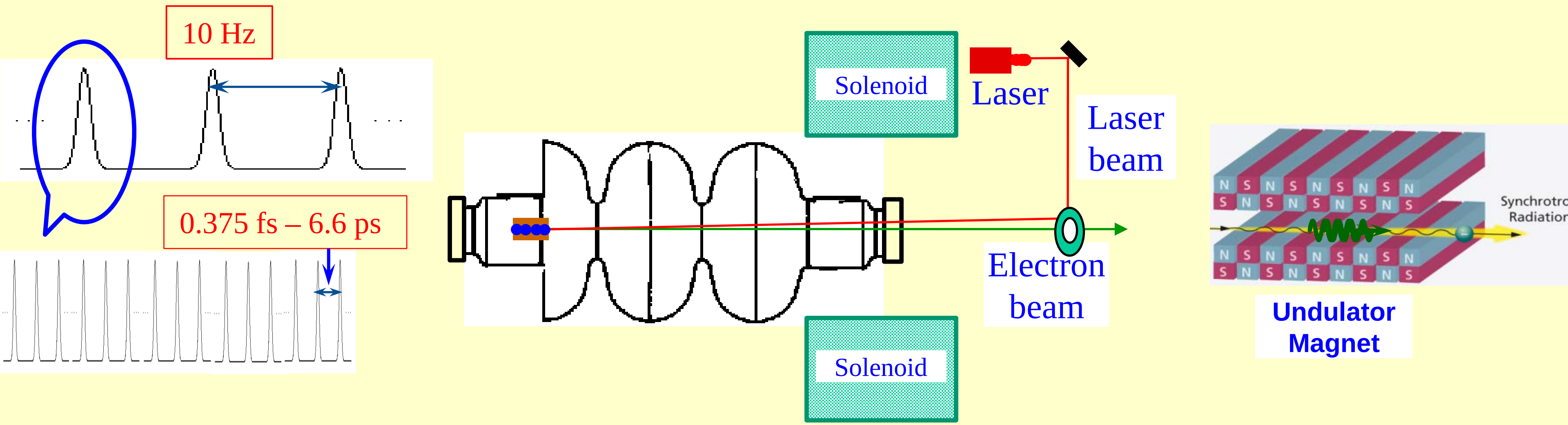
Phase-I of the project: complete layout with expt. stations



Class 10000 clean room to accommodate the complete facility



Major components of FEL – Pre-bunched FEL



1. An electron gun – laser operated PC & a resonator powered by klystron/modulator
2. A laser system – produce the electron bunches – single pulse is split into many
3. Photocathode preparation device
4. Solenoid – focus electron beam – Cavity to Undulator
5. High Power RF system
6. Electronics and Control system
7. An Undulator magnet – to produce e.m. radiation
8. Beam diagnostic and e.m. radiation detector systems

Development of Phase-I

Physics Design

- Wavelength range
- Energy
- Optics and Radiation

- f = 0.18 to 3 THz
- Energy ~ 8 MeV
- Optics, Radn. simulation

Choice of Accel. Components

- RF cavity, Frequency
- Photocathodes
- Laser
- Klystron, Modulator
- Solnd, Undulator, etc.

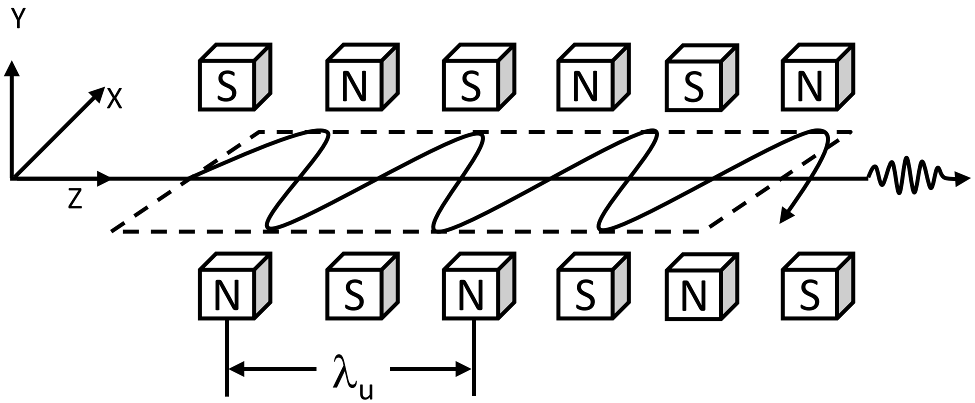
RF cavity – 2860 MHz, Ready, Collab. with KEK
Photocathodes – Design - IUAC, Fabrication - BNL
Laser – Finalized param., Ist part done, IUAC+KEK
Klystron, Modulator - Order placed, del. ’18 Spring
Solnd, Undulator, etc. – Order Placed, Design over

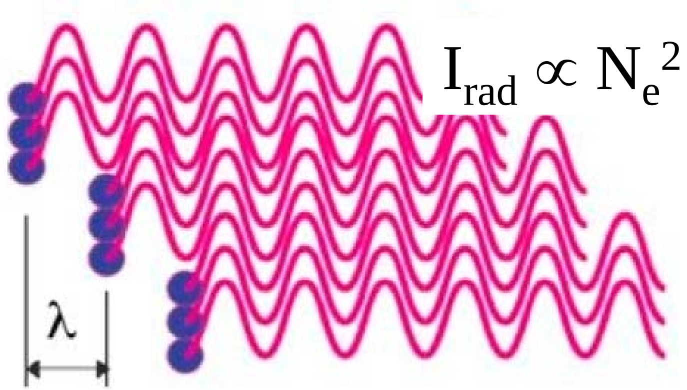
Electronics and Control

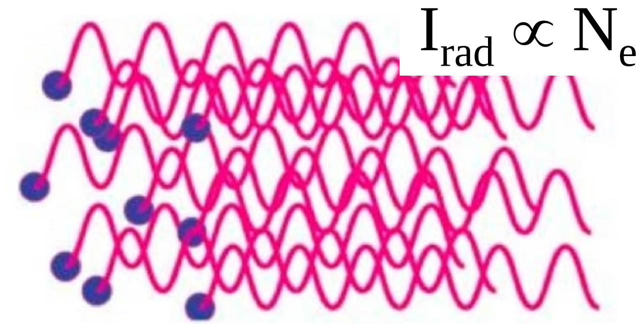
- Time synchro syst
- LLRF
- For Diagnostics & Meas. System
- Control system

- Design
Using commercial instruments and indigenous development

Conventional FEL – Oscillator, Seeded & SASE





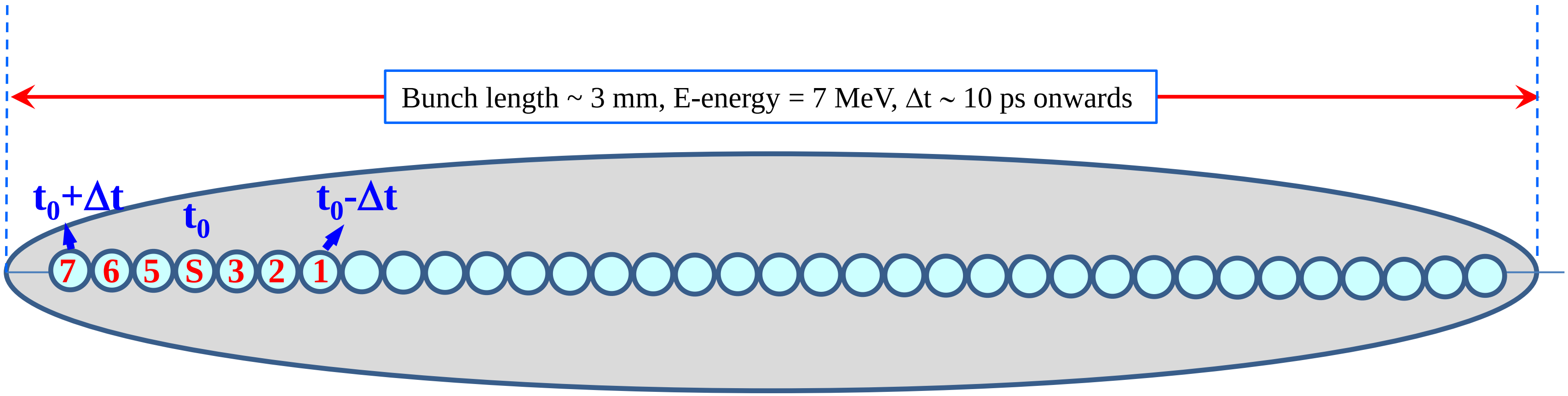


Major points:

- Relativistic electron
- Approaching Undulator magnet, λ_U
- λ_U - length contracted to $\lambda_U^* = \lambda_U/\gamma$, $\gamma = E/E_0$
- λ_U^* = Emitted wavelength from the electron
- Wavelength (lab fr.) = $\lambda_R = \lambda_U^*/2\gamma = \lambda_U/2\gamma^2$, relativistic Doppler effect
- Including the parameter of Undulator, wavelength measured will be

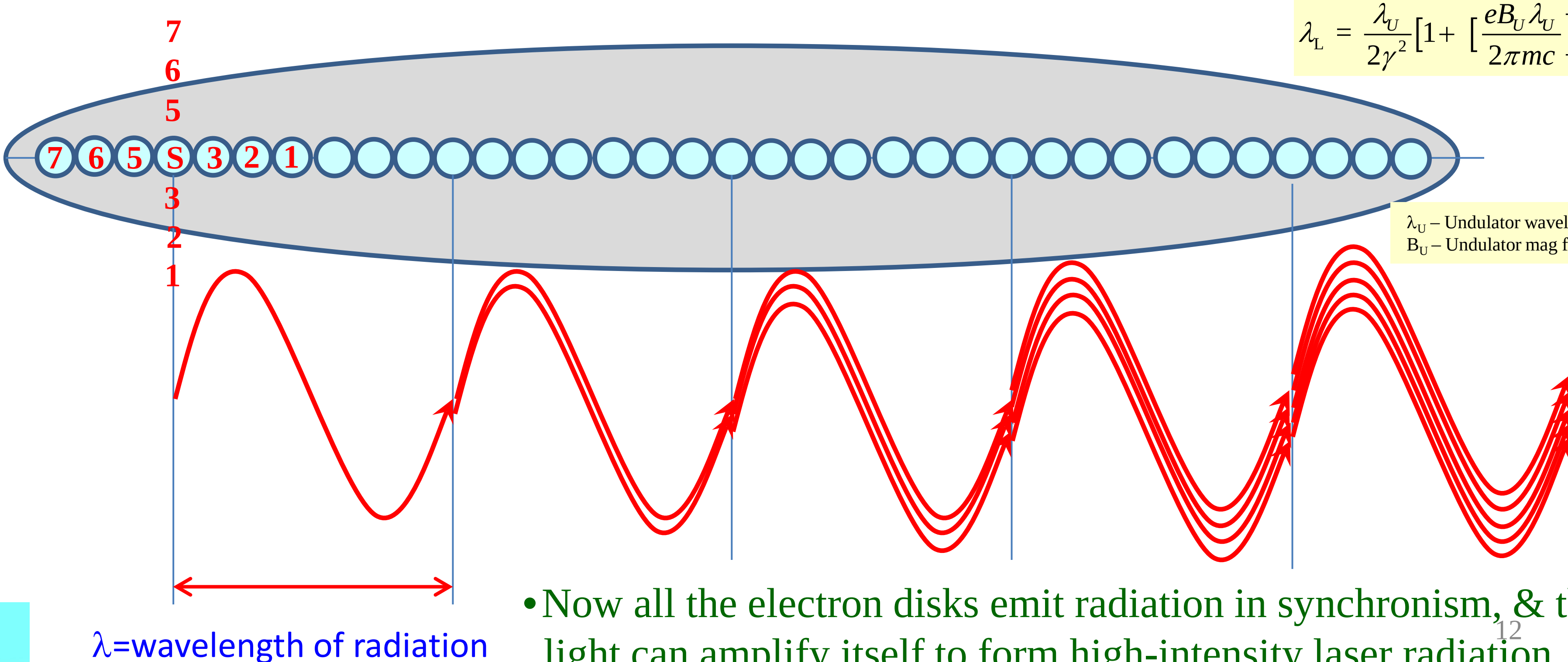
$$\lambda_R = \frac{\lambda_U}{2\gamma^2}[1+\frac{K^2}{2}]\ where\ K = 0.934 Bu(T)\boldsymbol{\lambda}_U(\text{cm})$$

Microbunching in FEL (Osc., Seeded and SASE)



Interaction of Photon and wiggling electron inside undulator magnet

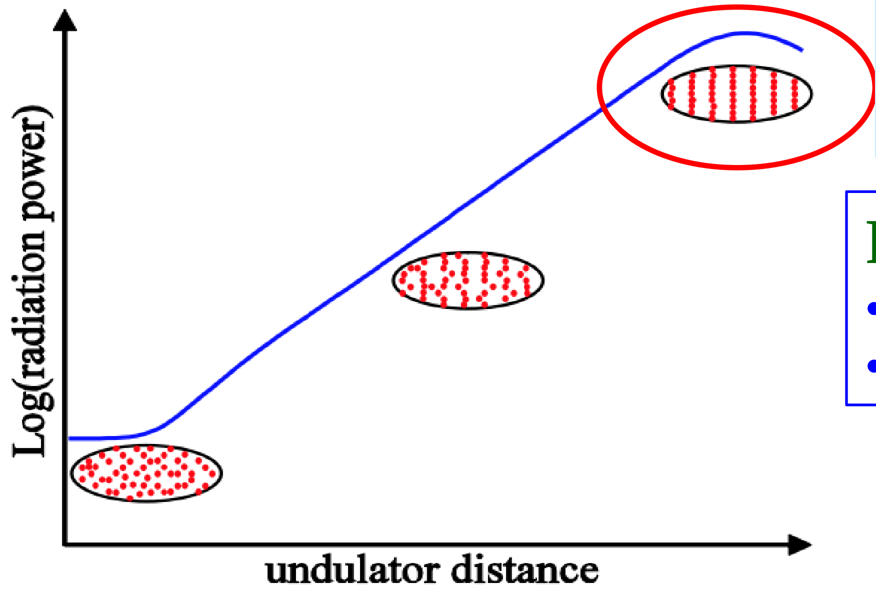
$$\lambda_L = \frac{\lambda_U}{2\gamma^2}\left[1 + \left[\frac{eB_U\lambda_U}{2\pi mc}\right]^2\right]$$



λ_U – Undulator wavelength
B_U – Undulator mag field

- Now all the electron disks emit radiation in synchronism, & the light can amplify itself to form high-intensity laser radiation.

Pre-bunched FEL - How is it different from conventional FEL

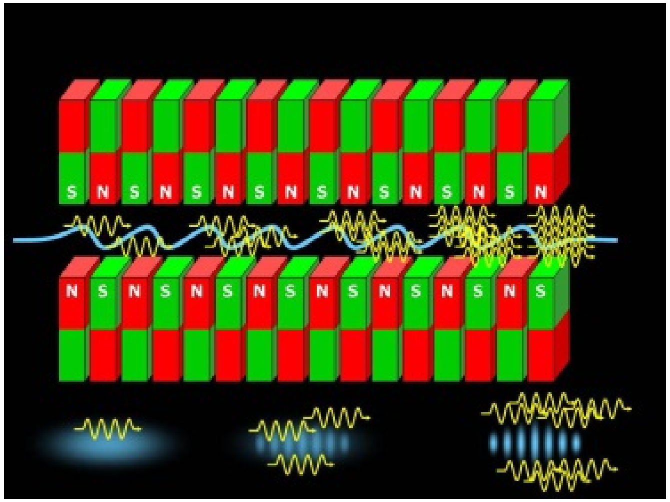


Starting point of Delhi Light Source

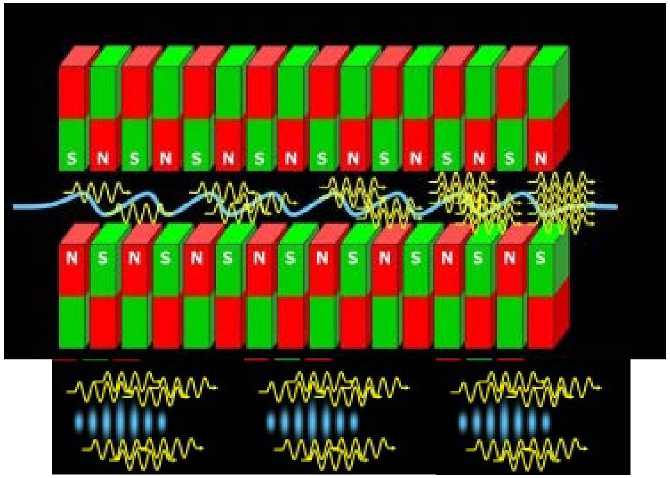
Requirement:

- **Electron disc formation**
- **Separation equal to λ_R**

$$\lambda_L = \frac{\lambda_U}{2\gamma^2}\left[1 + \left[\frac{eB_U\lambda_U}{2\pi mc}\right]^2\right]$$



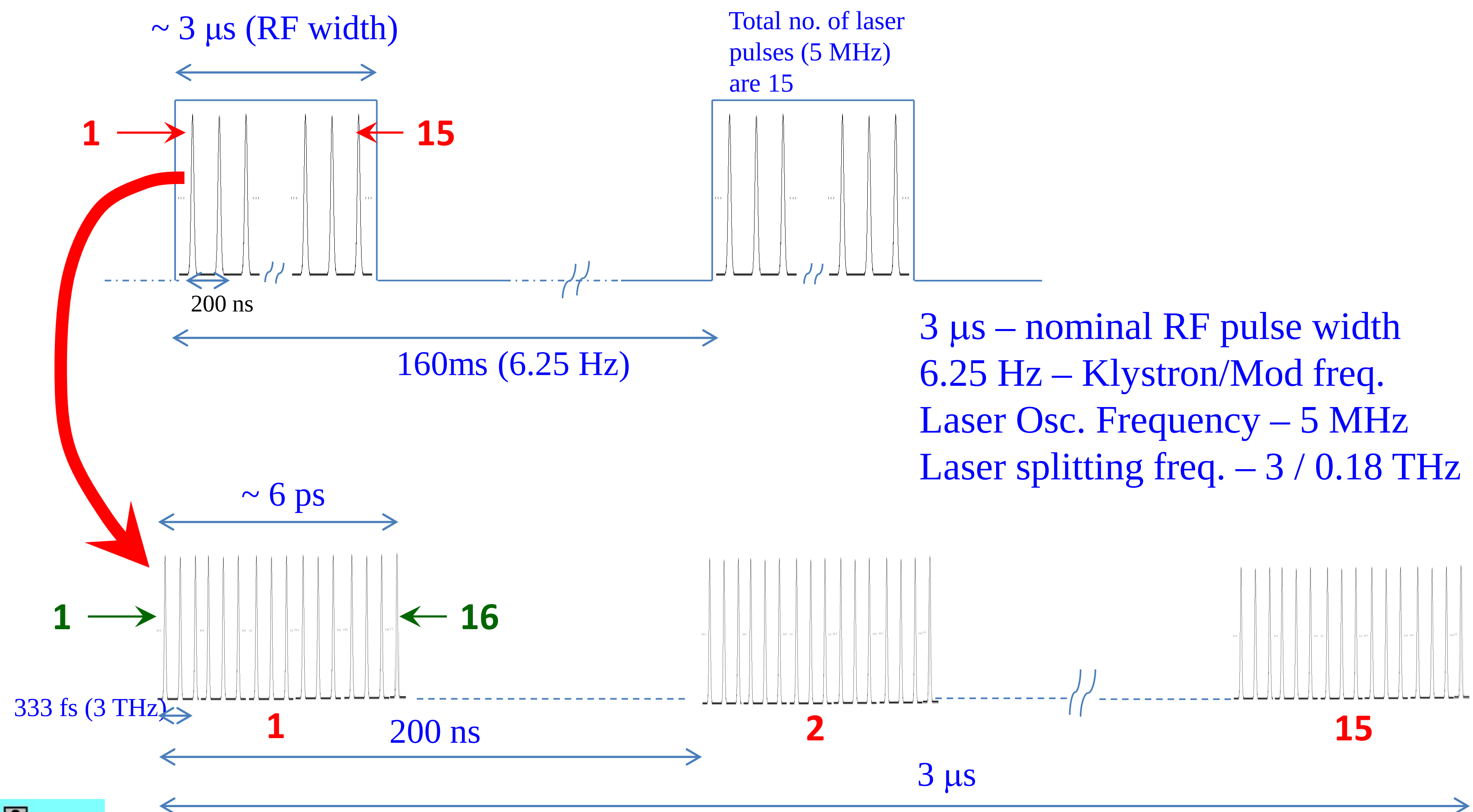
Conventional FEL



Prebunched FEL (Phase-I of DLS)

Progress in Beam optics calculation

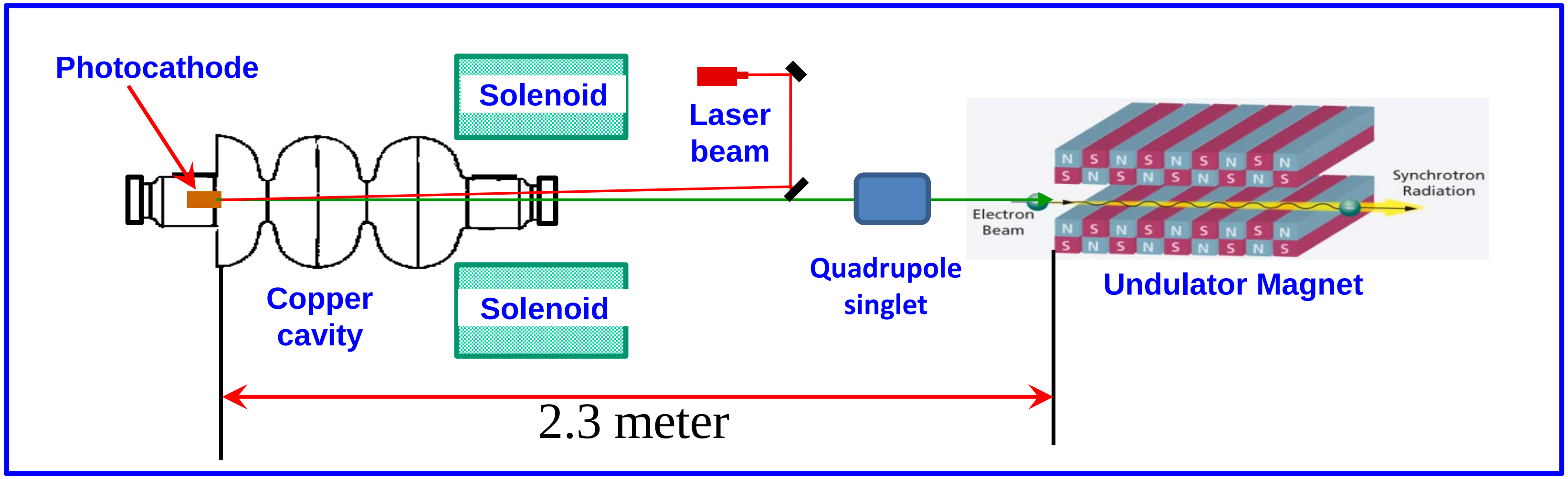
Generation of laser pulses and electron beam - multi-micro bunch train



3 μs – nominal RF pulse width
6.25 Hz – Klystron/Mod freq.
Laser Osc. Frequency – 5 MHz
Laser splitting freq. – 3 / 0.18 THz

So total no. of laser micropulses and e-bunches 15 × 16 × 6.25 = 1500 pulses/sec

Beam optics calculation



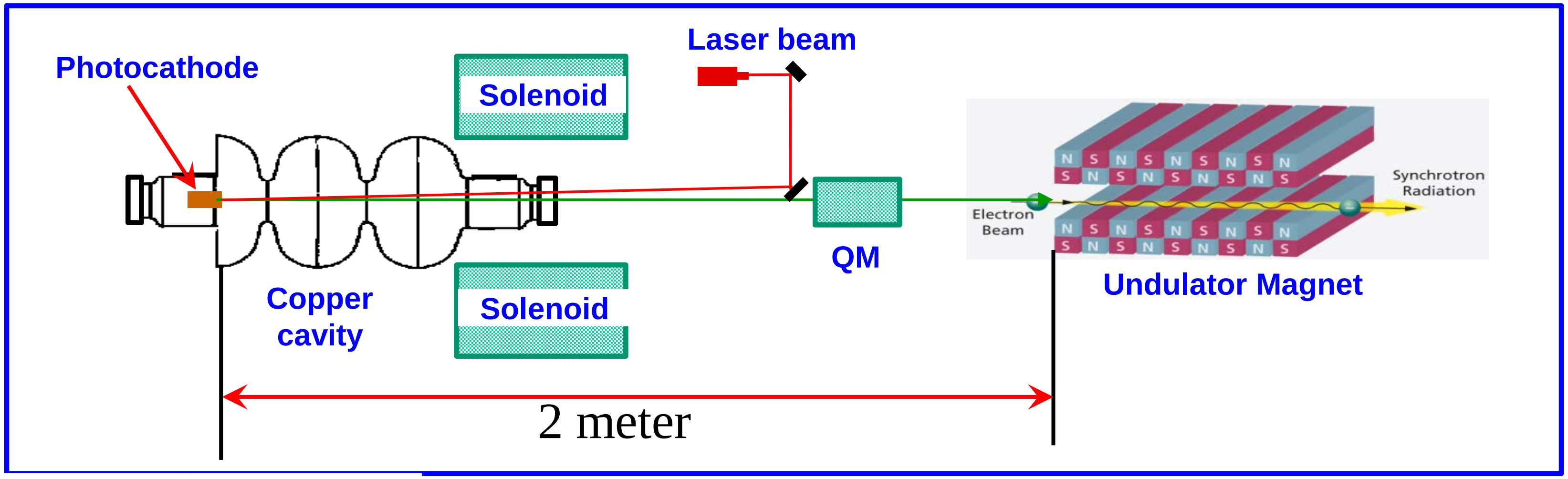
1. Photocathode, Laser
2. Cavity
3. Solenoid
4. Quadrupole - singlet
4. Undulator

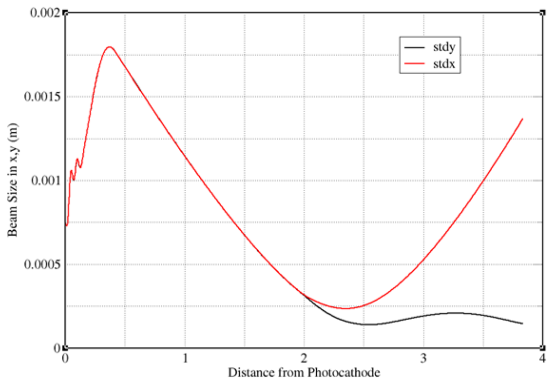
Parameters at rf gun and solenoid:
- Laser injection phase (RF phase what electron sees at the photocathode)
- Max possible E field of gun
- Optimize B field of Solenoid

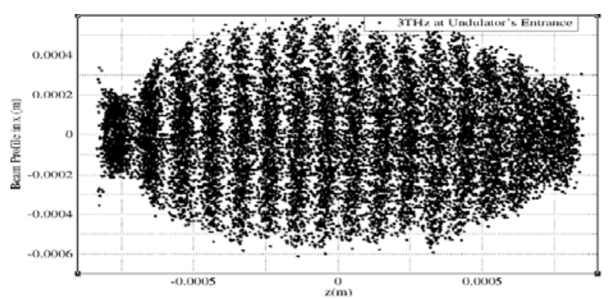
Parameters at cathode:
- Laser spot size
- Bunch emission time
- Charge/e-bunch
- Initial transverse emittance

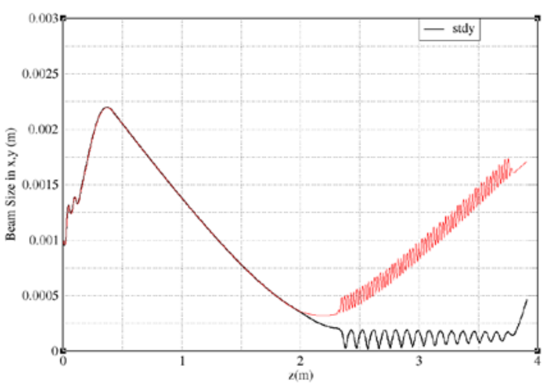
Results (important parameters):
- Transverse emittance
- Spot size
- Bunch time spread
- Energy
- Energy spread

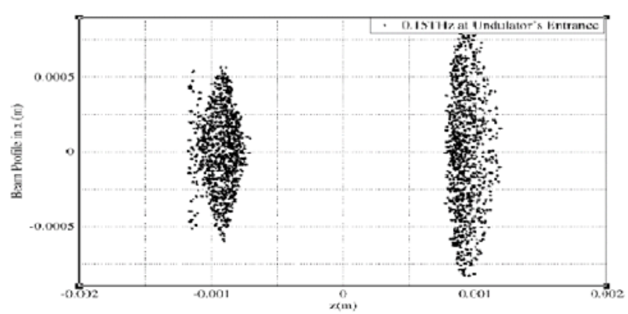
Beam optics calculation of Phase-I (GPT)









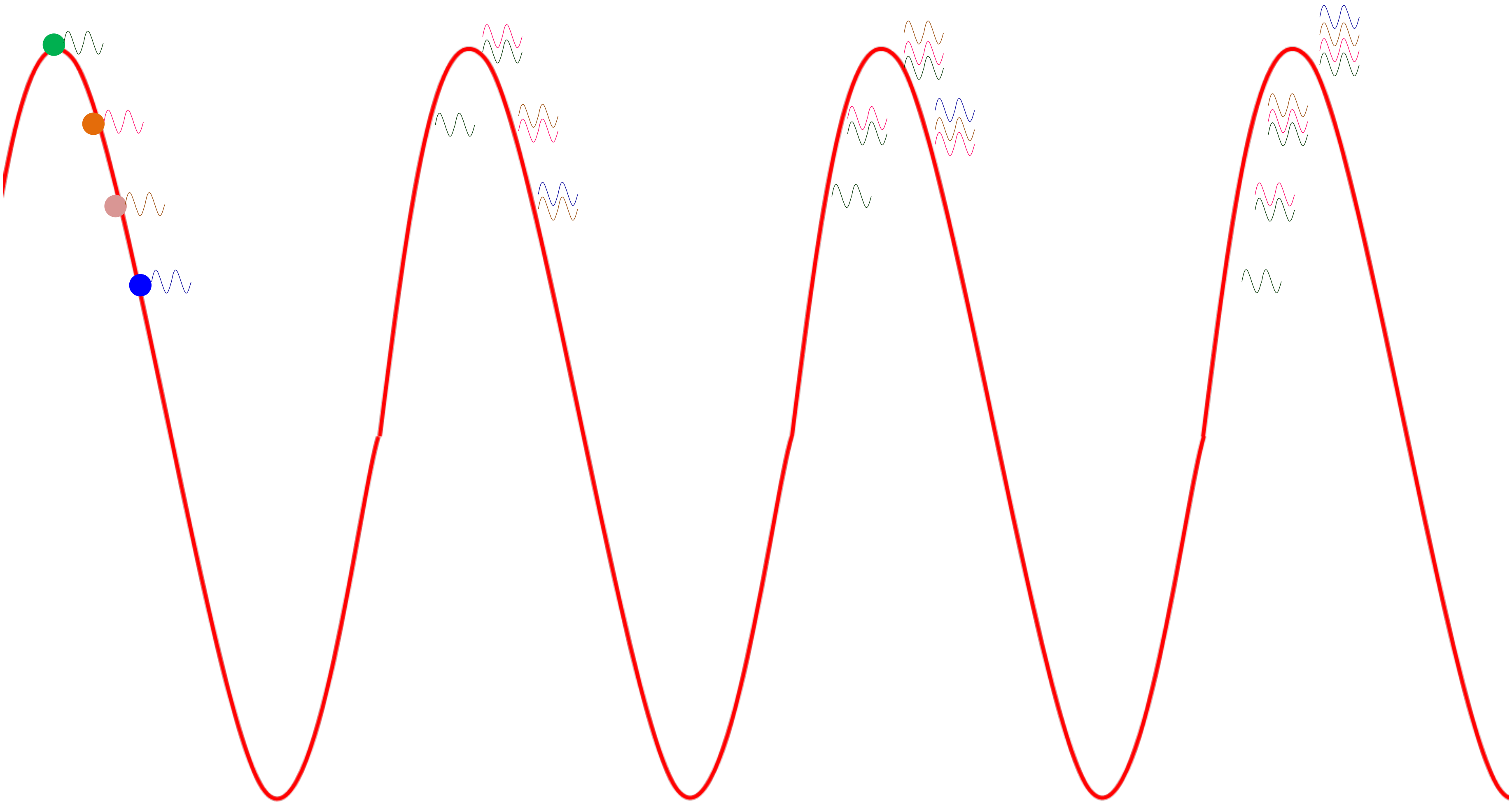


Radiation frequency range (THz)	0.18	3
Accelerating field (MV/m)	59	112
Launching phase (deg)	41	30
Electron Energy (MeV)	4.0	8.2
Energy spread (%)	1.1	0.68
e-beam FWHM @ cathode (fs)	200	200
Total charge (pC)/microbunch	15	15
Number of microbunches	2	16
Av. microbunch separation at undulator's entrance (ps)	6.6	0.345
Peak Current (A) at und. entrance	20	75
$\sigma_{x,y}$ (mm) at undulator's entrance	1.75, 0.25	0.7, 0.35
Normalised emittance (x, y) π mm-mrad at undulator's entrance	3.0, 3.2	4.2, 4.8

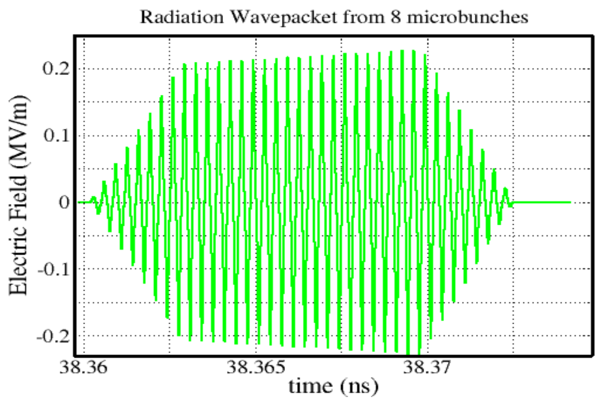
Where Photon meets Electron

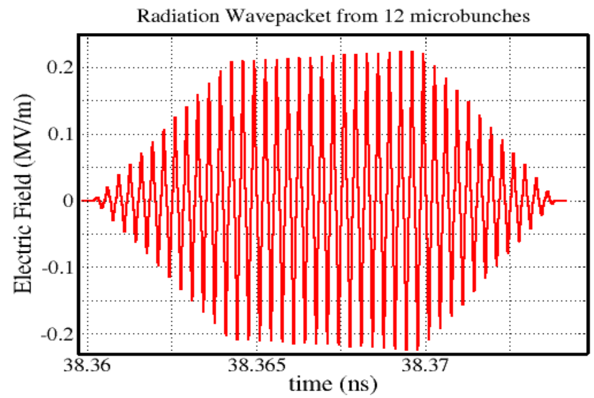
$$v_z = c \times [1 - \frac{(1+\frac{K^2}{2})}{2}$$

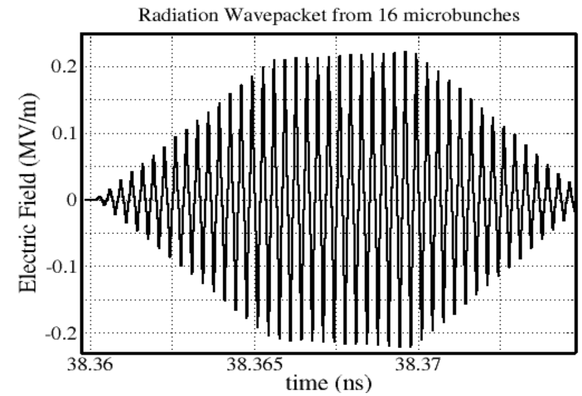
$$\frac{\lambda_U}{c} = \frac{\lambda_U - \lambda_R}{v_z} \text{ or } \lambda_U = \frac{\lambda_R \times c}{c - vz}$$

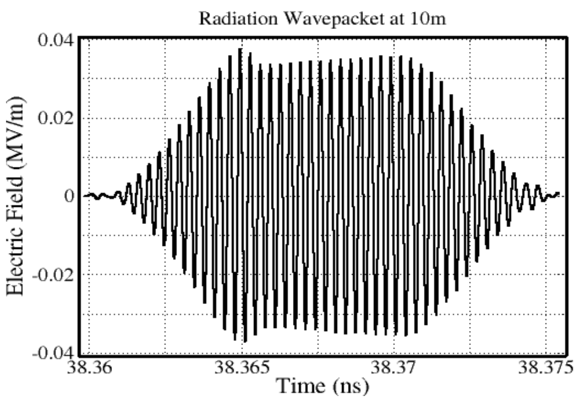


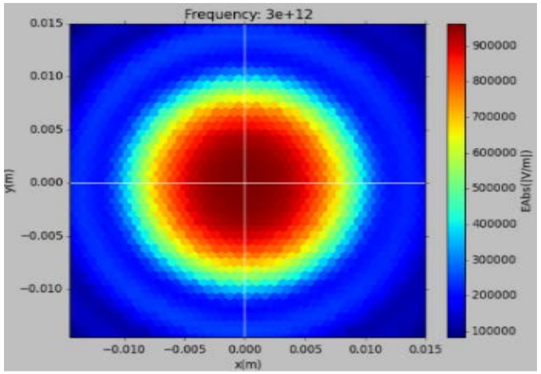
Radiation simulation

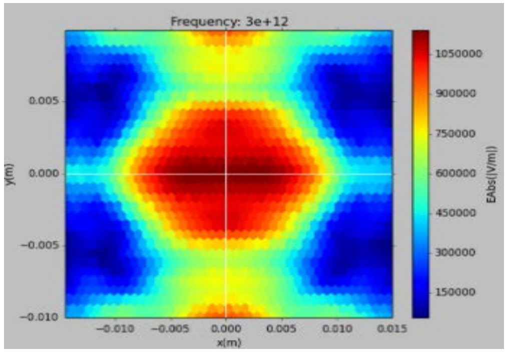






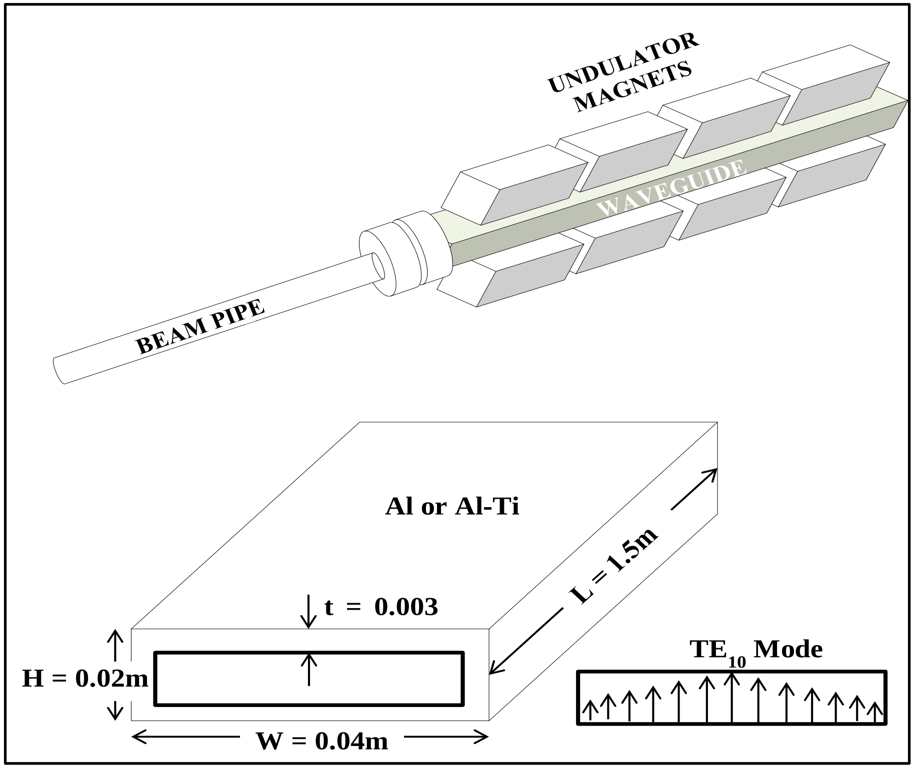


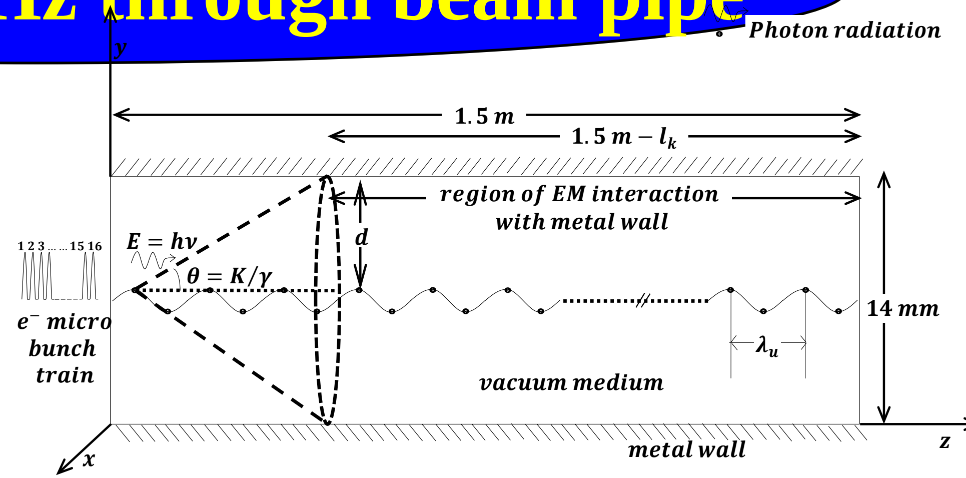




Time width	Number of electrons	Total electron current	Energy content of 3 THz (μJ)	Remarks
~ 200 fs	9.3×10^{7}	75 A	< ~ 1	Single e-bunch.
~ 6 ps	1.5×10^{9}	40 A	~ 12	Train of 16 e-bunches.
~ 3 μs	2.25×10^{10}	1.2 mA	~ 180	Train of 15 no. of 16 e-bunches.
1 sec.	1.4×10^{12}	22.5 nA	~ 1125	Train of 15 no. of 16 e-bunches arriving 6.25 times in a sec.

Transportation – THz through beam pipe





$$\alpha_c = \frac{2R_s}{b\eta\left\{1-\left(\frac{f_c}{f}\right)^2\right\}}\left[1+\frac{b}{a}\left(\frac{f_c}{f}\right)^2\right]$$

$$P_u = \sum_{k=1}^{N_u} P_k e^{-2\alpha_c z_k}$$

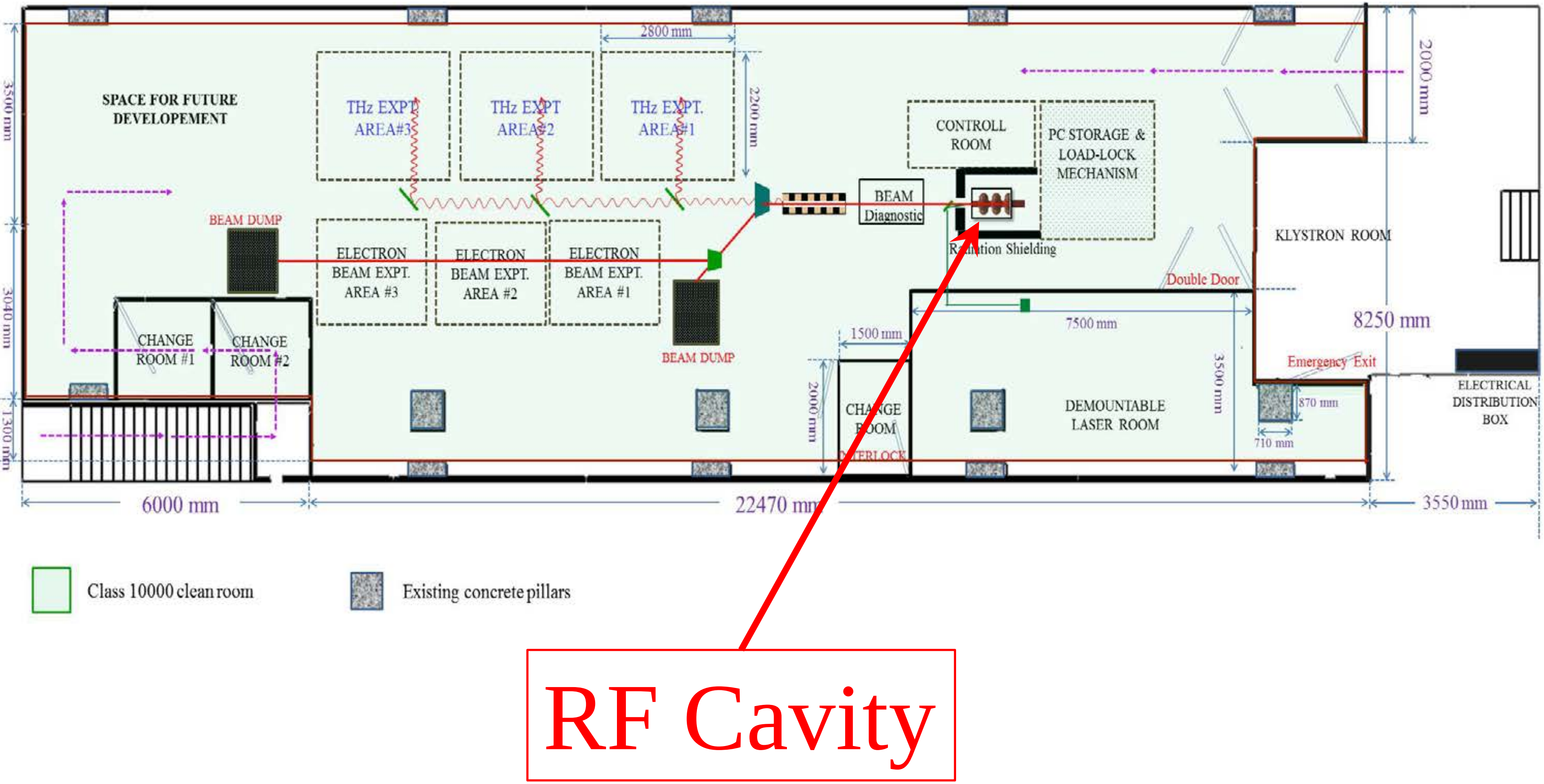
$$P_k = \begin{cases} (k^2).P_1, 1 \le k \le N_b \\ (N_b^2).P_1, N_b+1 \le k \le N_u \end{cases}$$

$$loss\ (dB) = 10log_{10}\left(P_u \Big/ \sum_{k=1}^{N_u} P_k\right)$$

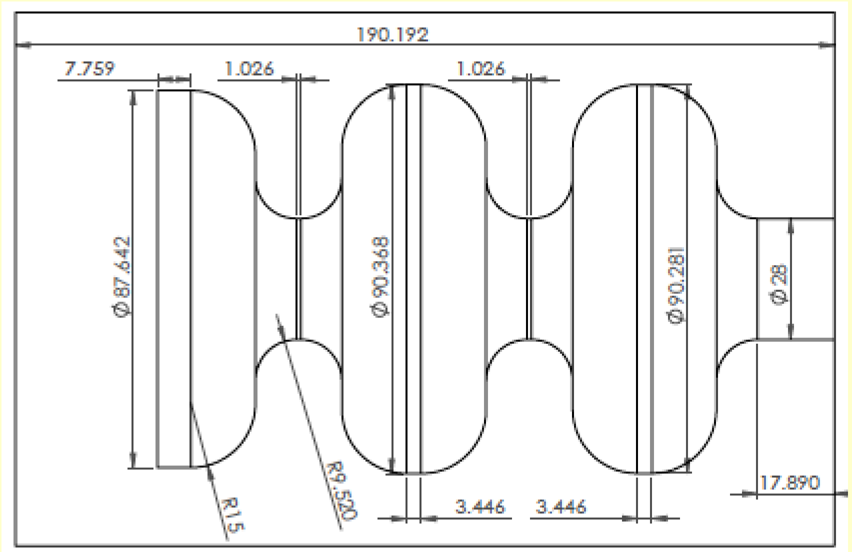
Material	Attenuation Constant (Np/m)	
	0.18 THz	3 THz
Al	0.1185	0.1618

Waveguide	Loss @ 0.18 THz	Loss @ 3 THz
Al	0.17 dB	0.51 dB

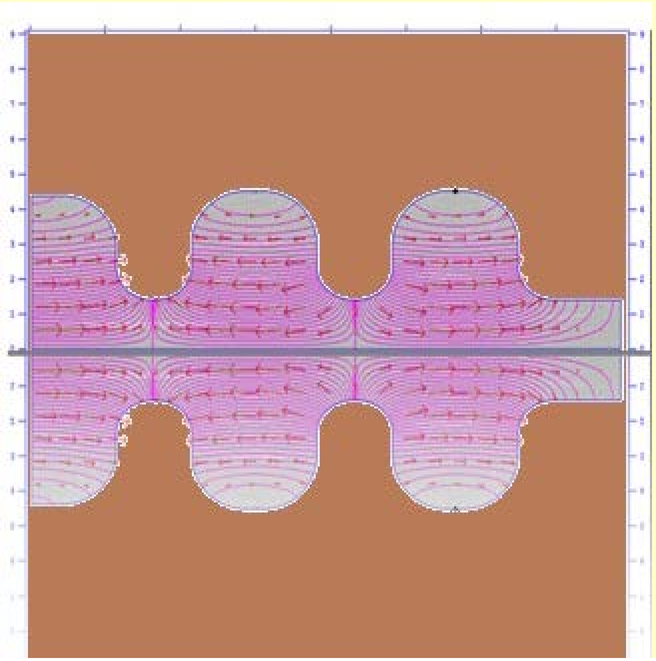
Phase-I of the project: complete layout with expt. stations

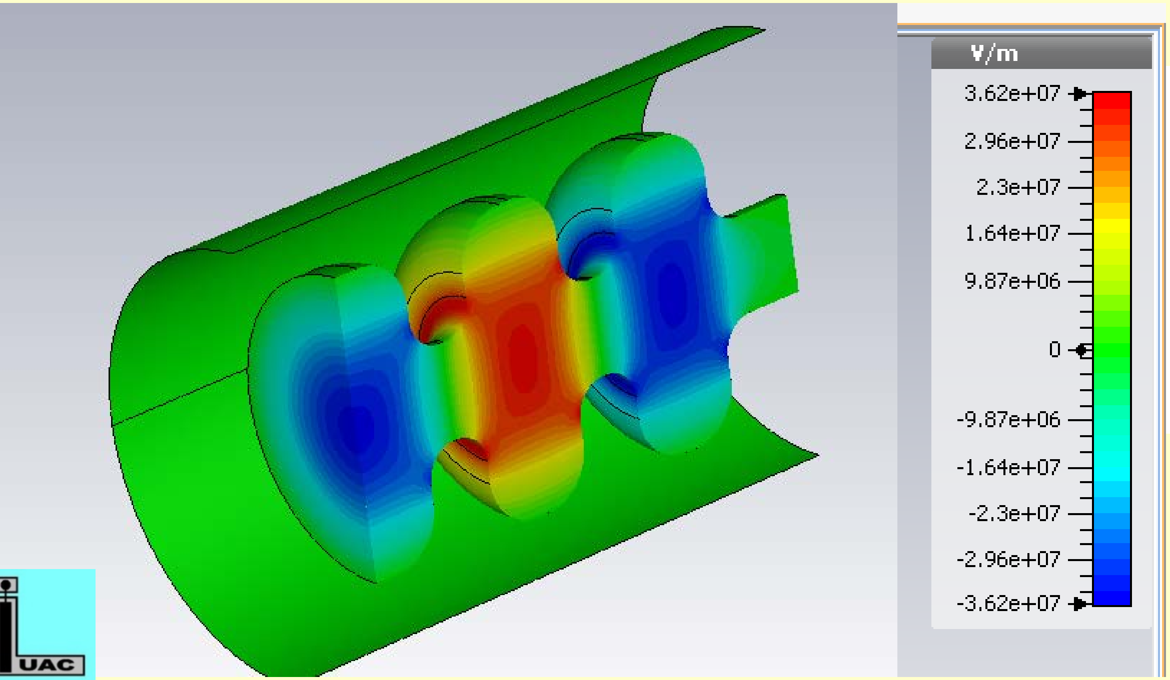


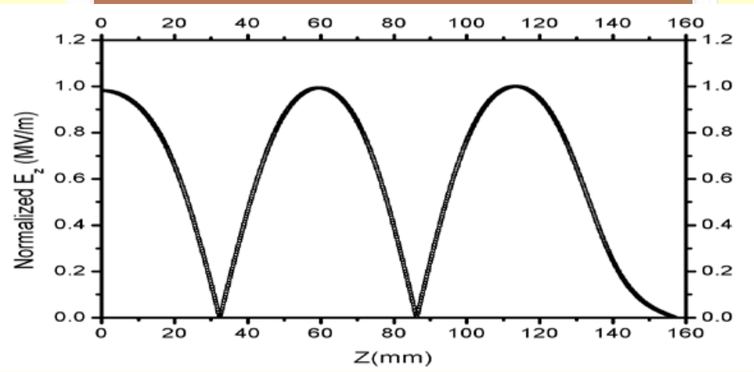
RF cavity as e-gun – Design and Simulation



Beam Axis



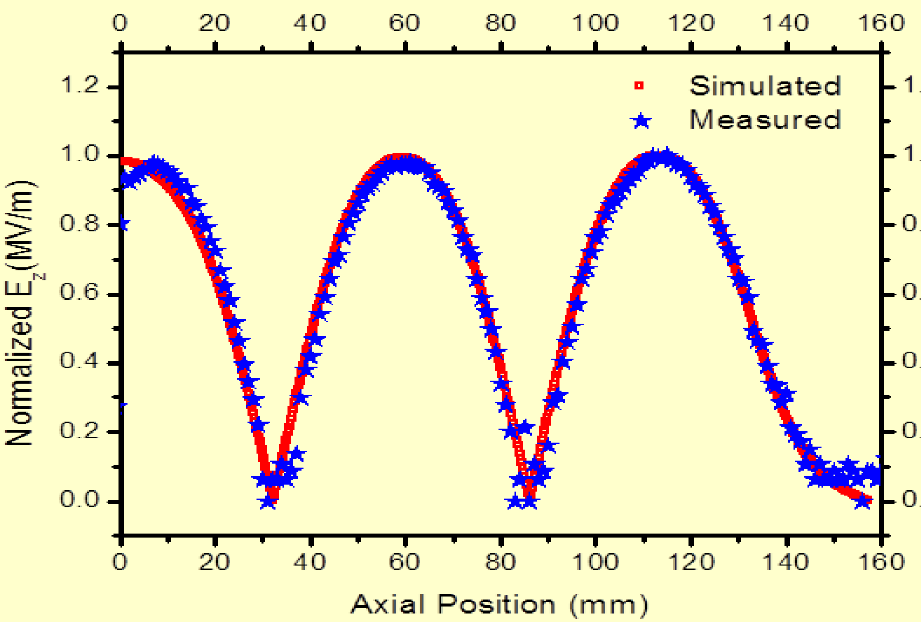




RF Gun at IUAC

- OFHC copper, water cooled
- Resonance freq. – 2860 MHz
- Quality factor (meas.) ~ 15,200

Central frequency=2859.795 MHz @ 24.8C
β = 0.904, Metal bead dia ~ 1.89 mm

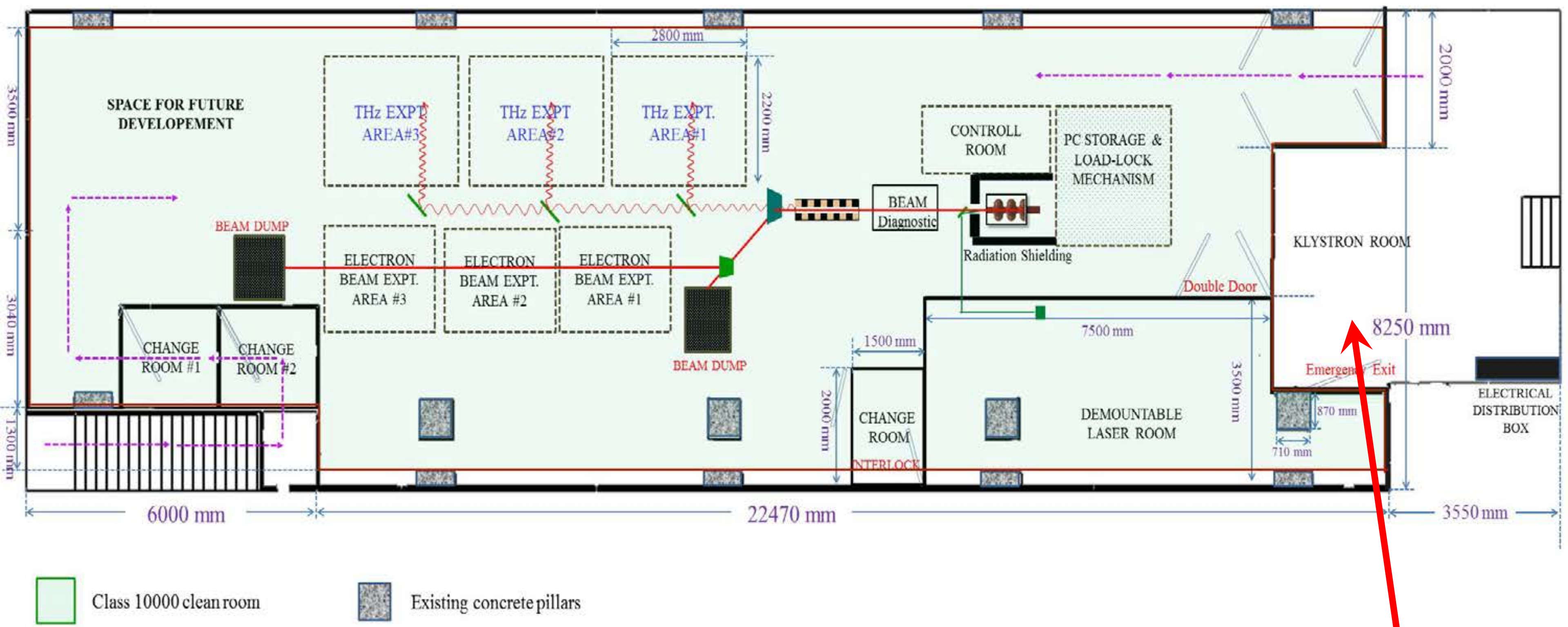


Accelerating Field profile Measured (bead pull) & simulation

Developed in Collaboration with KEK, Japan

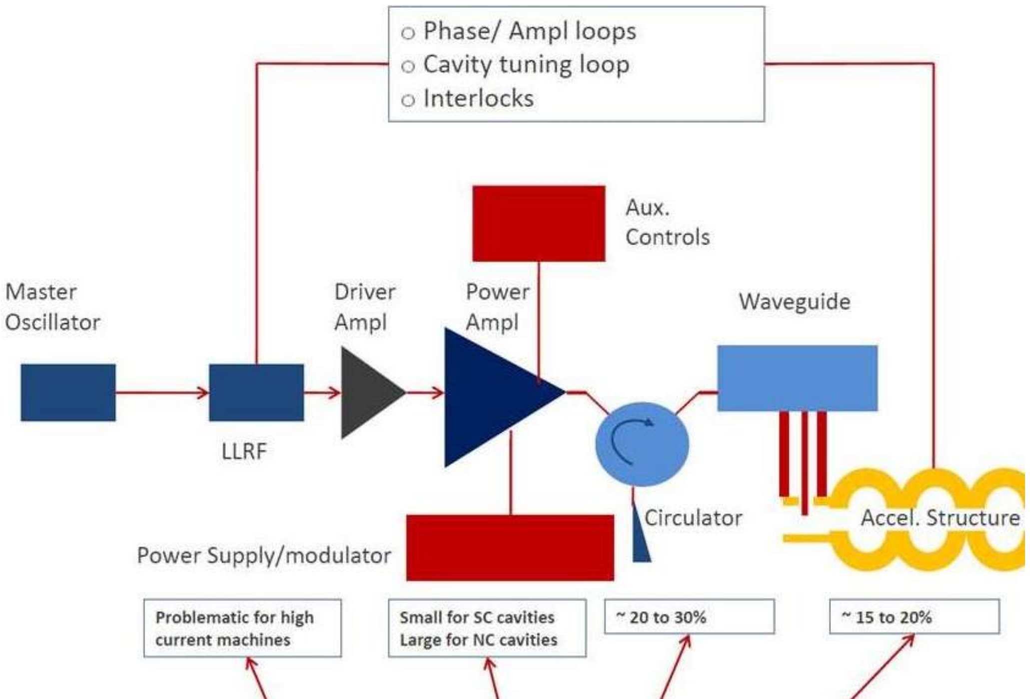
Progress in High power RF System

Phase-I of the project: complete layout with expt. stations



Klystron/Modulator

High Power RF System for Delhi Light Source



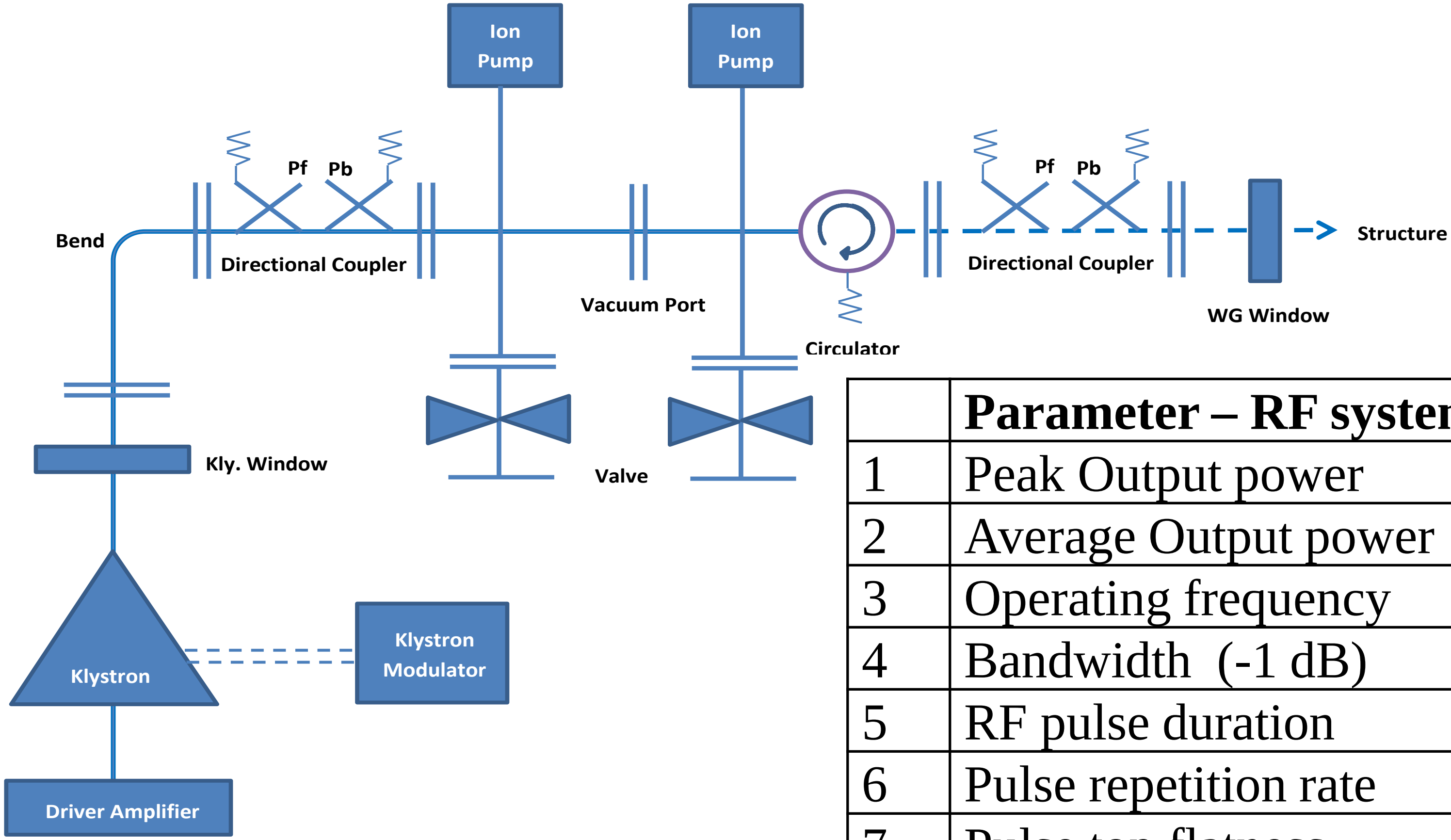
$$P_{RF} = P_{beam\ loading} + P_{cav\ loss} + P_{wg\ loss} + P_{overhead}$$

2860 MHz Normal conducting 2.6 Cell RF photocathode

Klystron based high power RF system to power cavities in pulsed mode.

Solid state Modulator for pulsed mode operation

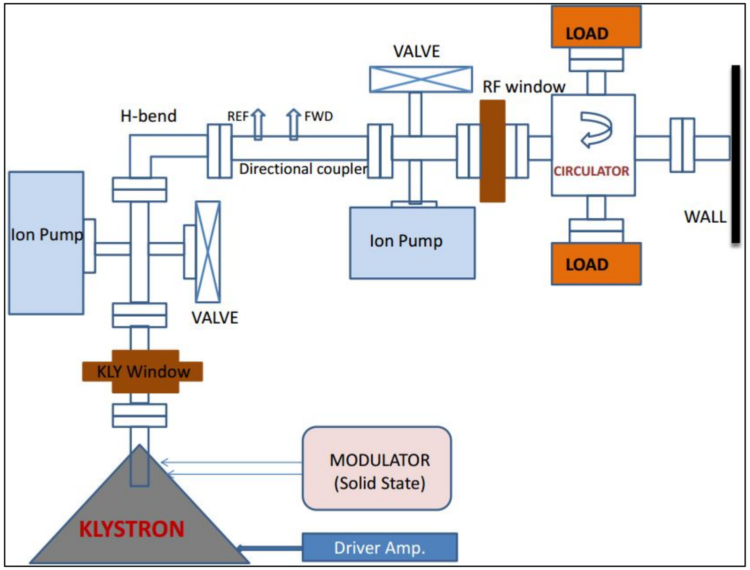
Klystron and Modulator with circulator

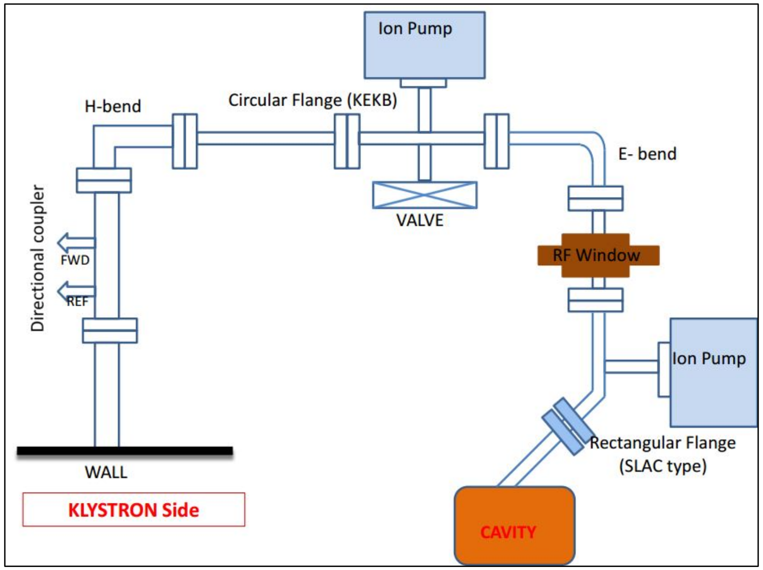


	Parameter – RF system	Value
1	Peak Output power	≥ 25 MW
2	Average Output power	≥ 5 kW
3	Operating frequency	2860 MHz
4	Bandwidth (-1 dB)	± 1MHz
5	RF pulse duration	0.2 µs to 4 µs
6	Pulse repetition rate	1-50 Hz
7	Pulse top flatness	±0.3%
8	Rate of rise and fall of modulator output voltage	200-250 kV/µs
9	Long term stability	±0.05 %

Under development: Scandinova (& Toshiba)

Klystron based high power RF source

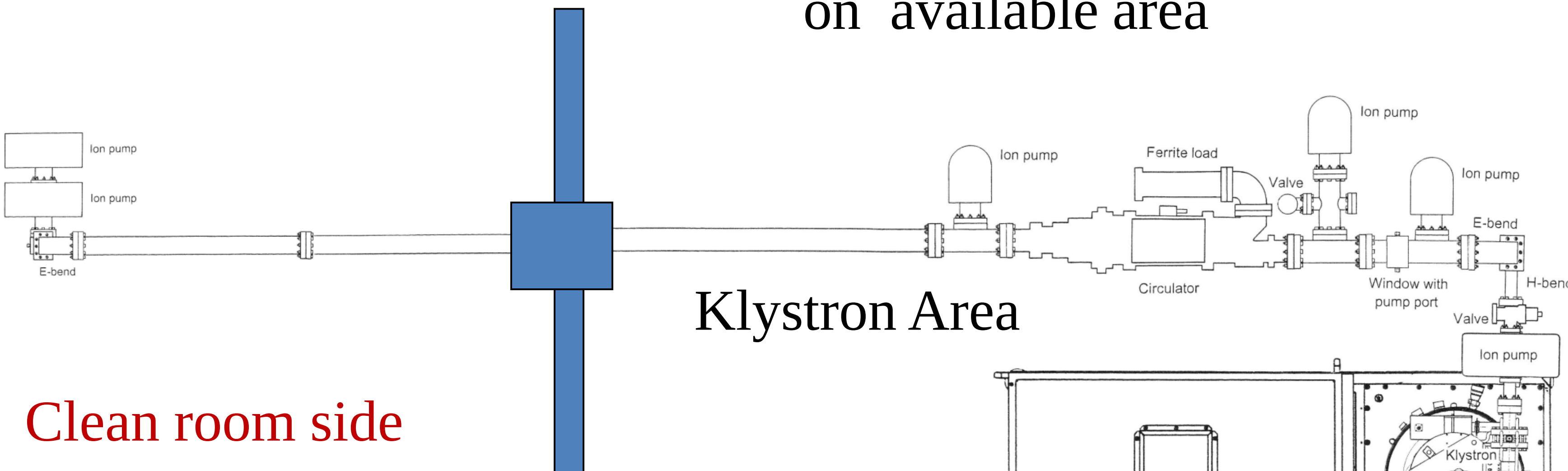




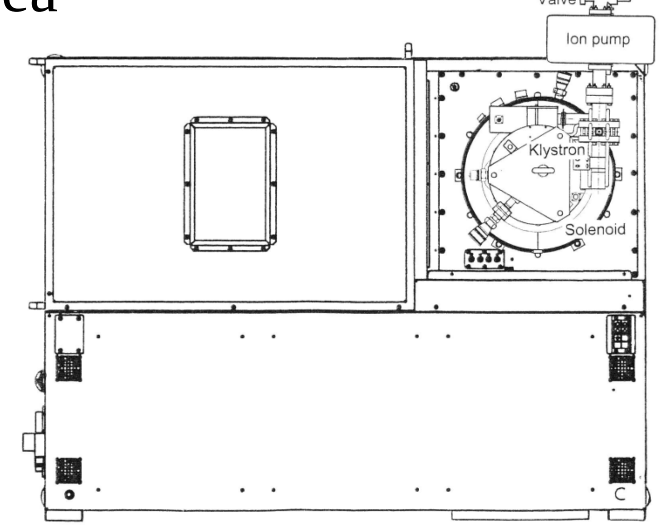
Layout of RF system for DLS

Final design of RF system based on available area

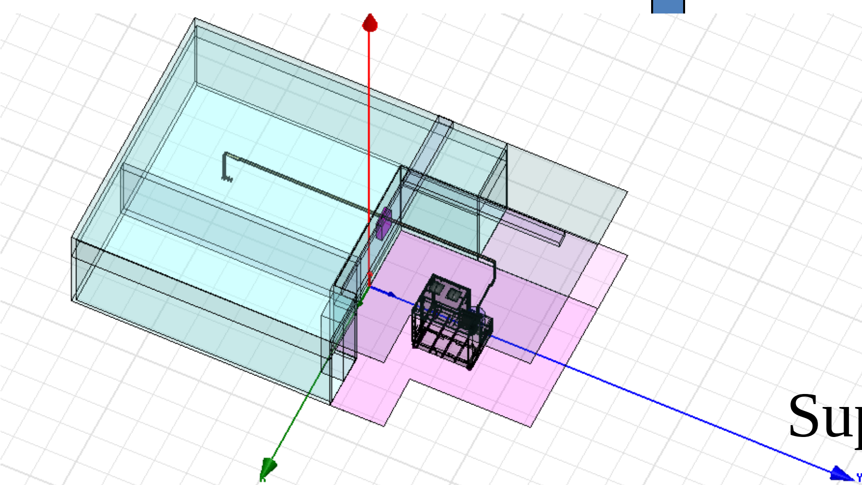
Clean room wall



Klystron Area

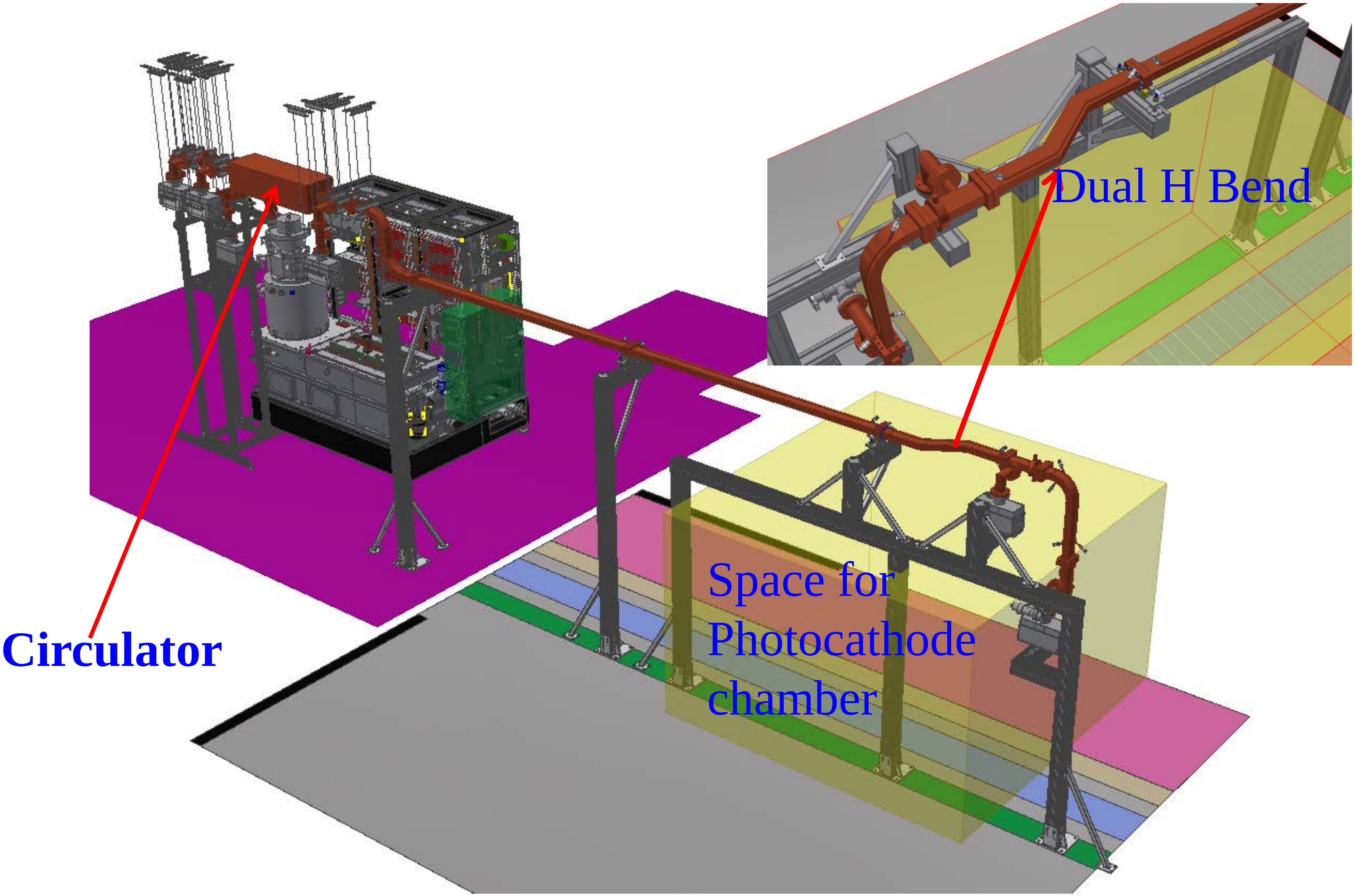


Clean room side

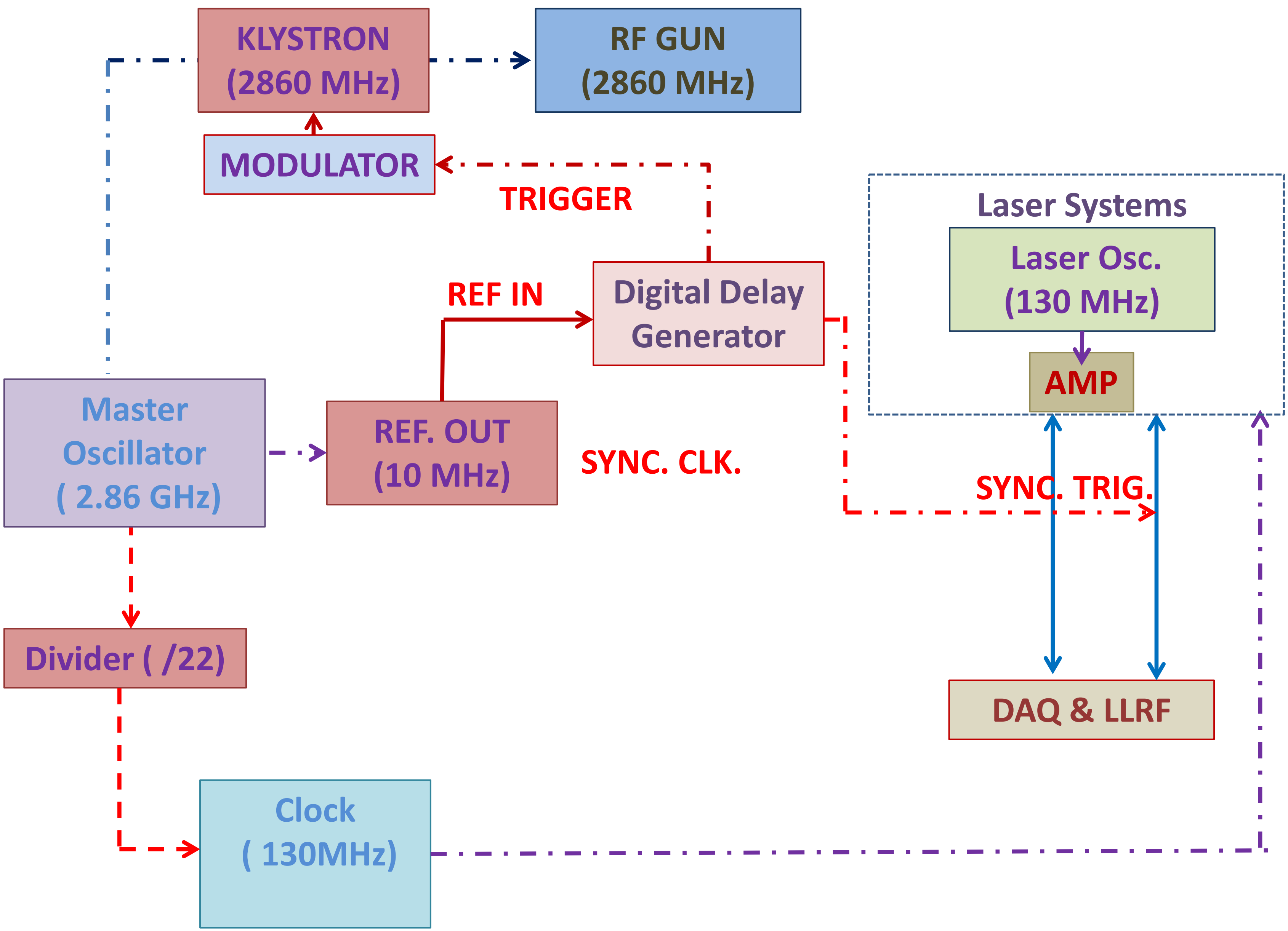


Supporting systems are being planned

Wave guide design for High power RF system



Clock distribution Scheme for RF and Laser System



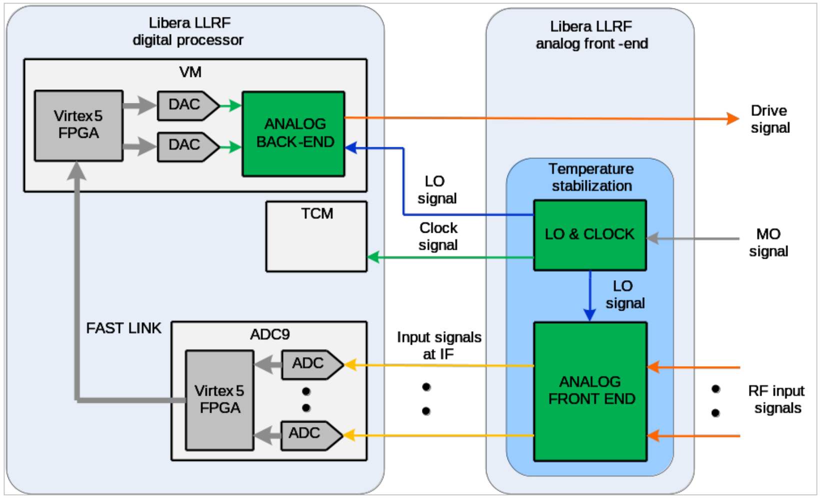
LLRF requirements for Delhi Light Source

Require stable Pulsed RF system for 2.86 GHz photo cathode conditioning along with interlocks for klystron and modulator.

Phase and Amplitude stabilization of accelerating structure with phase stability ± 0.1 degree and amplitude stability better than 0.1% during pulse on period.

Synchronization of Laser to RF with phase stability better than ± 0.1 degree.

Libera LLRF model



LLRF for initial testing

Design based on a number of RF modules like splitter , amplifier, pulse modulator

CAMAC based trigger generator for synchronization or SRS Delay generator module

Signal generator used as master clock

EPICS control for overall monitoring and control.

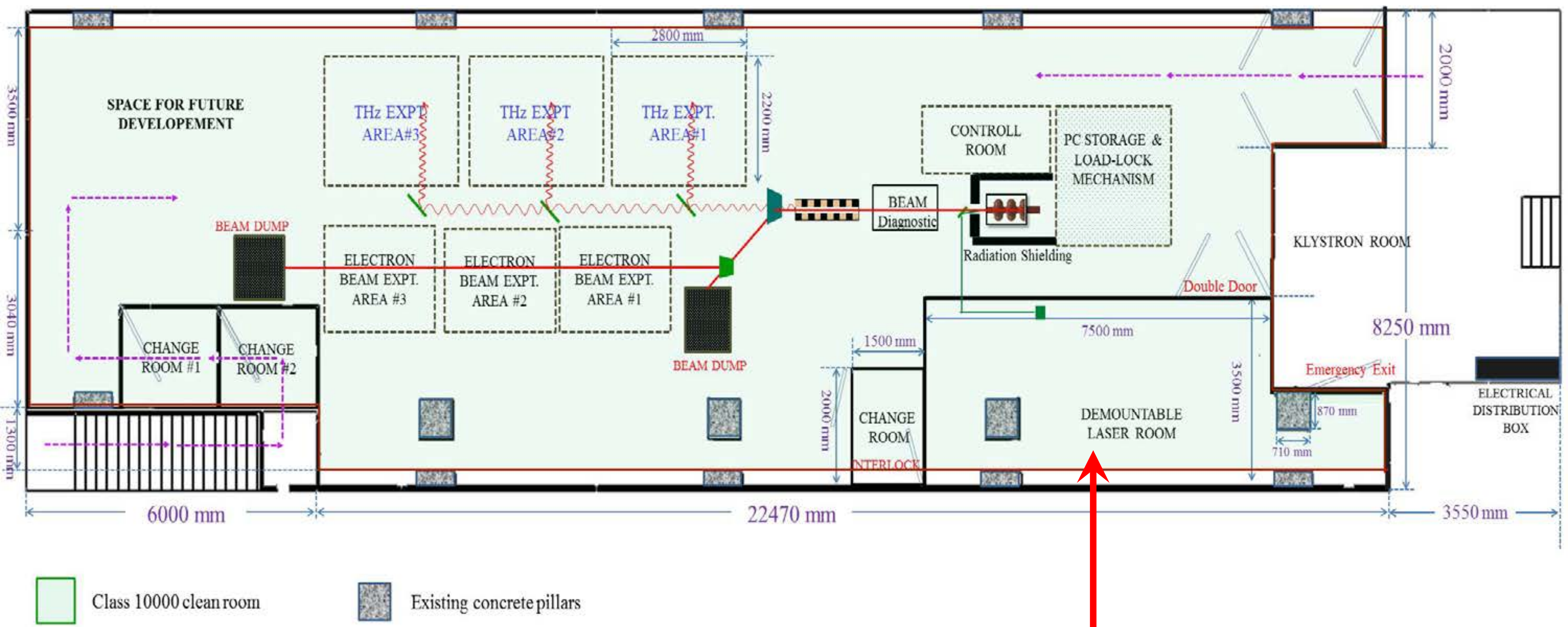
Analogue control modules for synchronization.

Performance:

Resolution of the system for measuring and controlling the RF field better than 0.1% RMS for the amplitude and 0.01deg RMS for the phase

Long Term stability equal or better than 95fs at ambient temperature of 24±2 deg

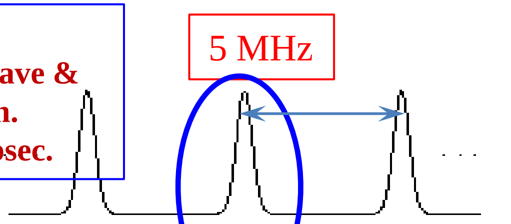
Facility layout with expt. stations

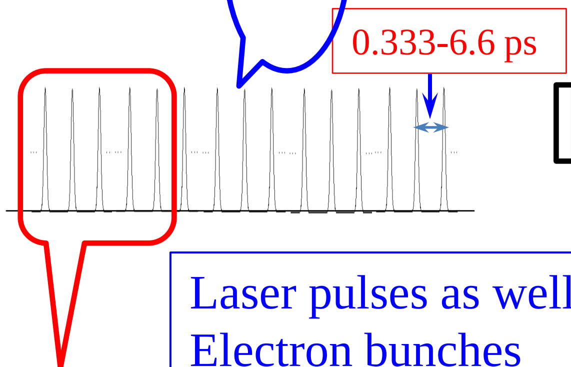


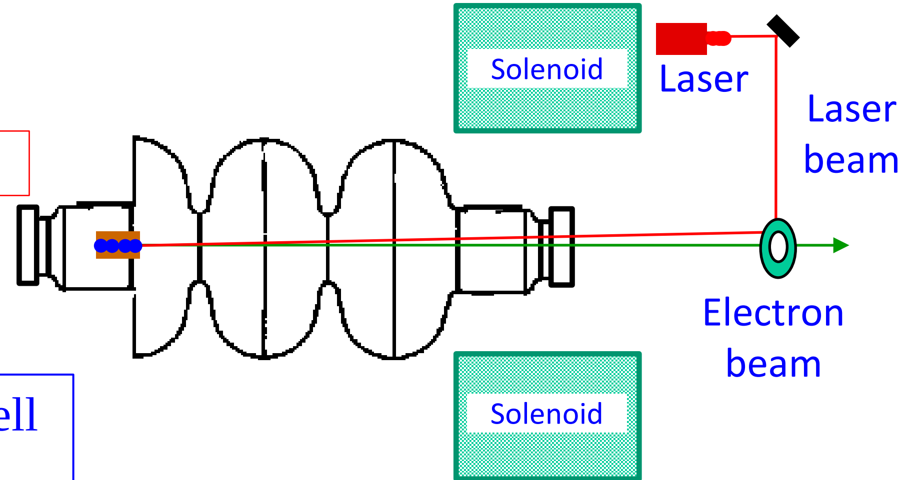
Laser Device

Laser system of DLS

- ½ w plate rotates S-wave by 45º.
- Polarizing beam splitter makes S-wave & P-wave by reflection & transmission.
- 16 micro bunched laser within 6-7 psec.

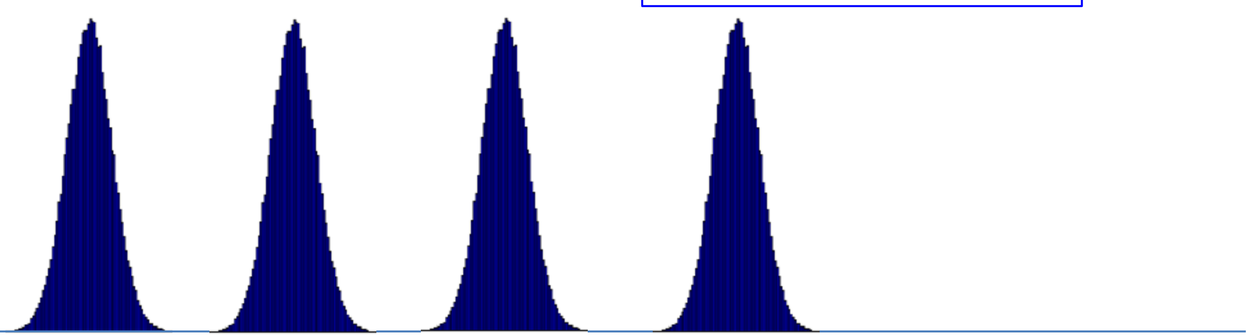


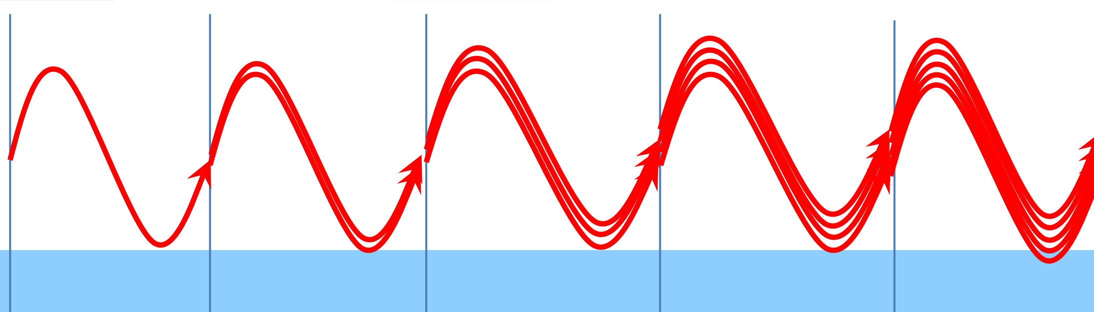




f ~ 3 – 0.18 THz
T = 333 fs to 6.6 ps
λ = 100 μm to 2 mm

Laser pulses as well Electron bunches





$$\lambda_L = \frac{\lambda_U}{2\gamma^2}\left[1 + \left[\frac{eB_U\lambda_U}{2\pi mc}\right]^2\right]$$

$$\gamma = \frac{E}{E_o} = \frac{8}{0.5} = 16$$

λ_U – Undulator wavelength
B_U – Undulator mag field

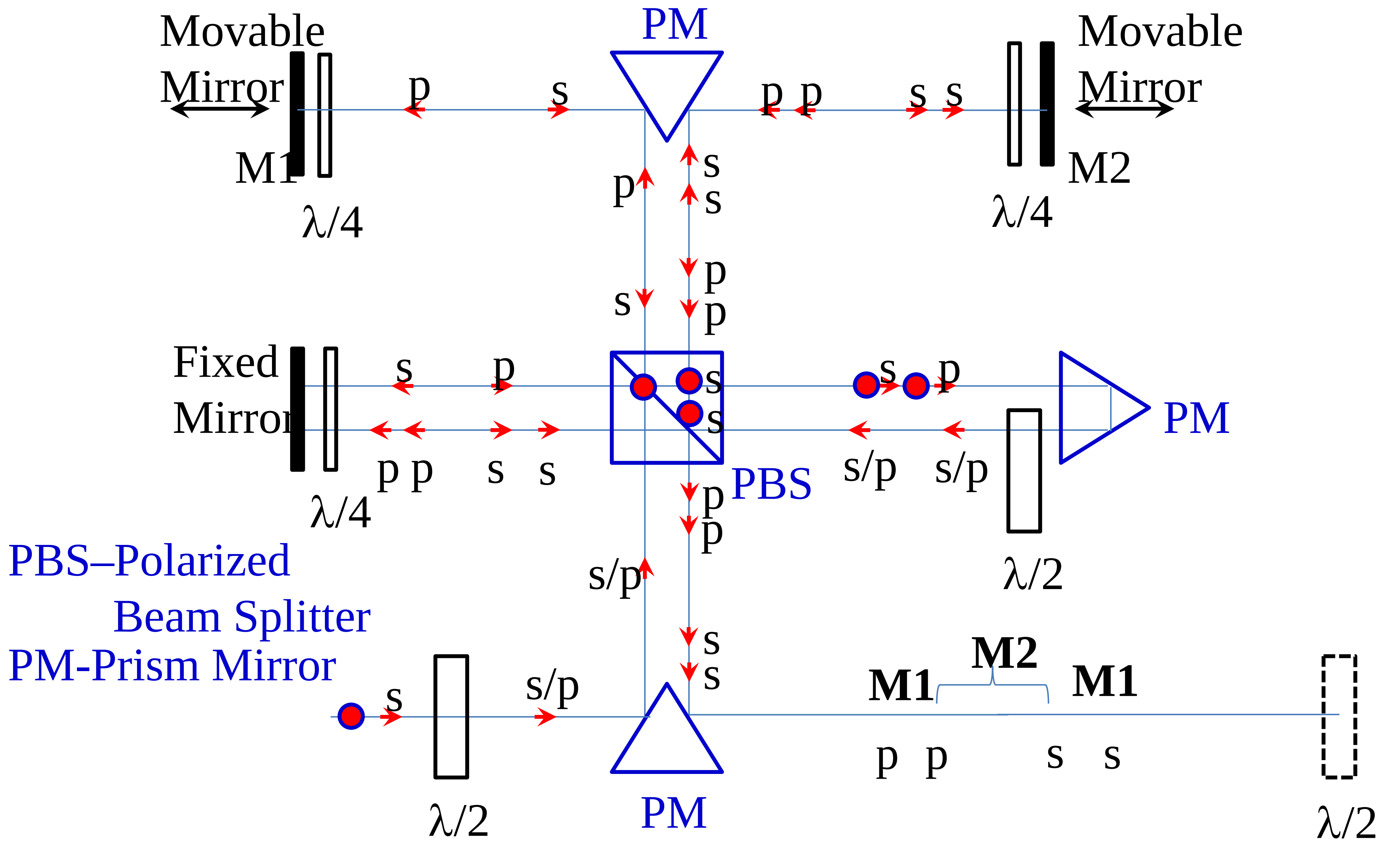
Power of the fiber laser and total charge from two photocathodes

Energy/ Pulse @ 258 nm @cathode	Total no. of micropulses to be produced	Pulse width of each micropulses	Photocathode & expected Q.E.	Charges produced from each one of 16 micropulses	Max Average Current (15x16 bunch structure @12.5 Hz rep rate)
10 μJ (Transient amplification)	1	200 fs	Copper & 0.0014%	20 pC	3.8 nA
0.1 μJ (Steady state)	1-16	200 fs	CsTe & 1%	200 pC	600 nA

First part of the system was tested and installed at IUAC.

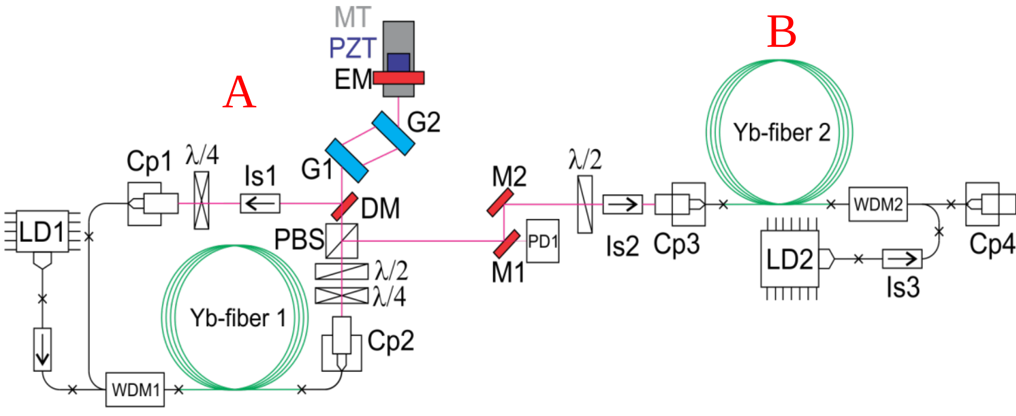
The remaining part will be integrated at IUAC during June/July 2018

A single laser pulse is split in to four laser pulses with variable separation

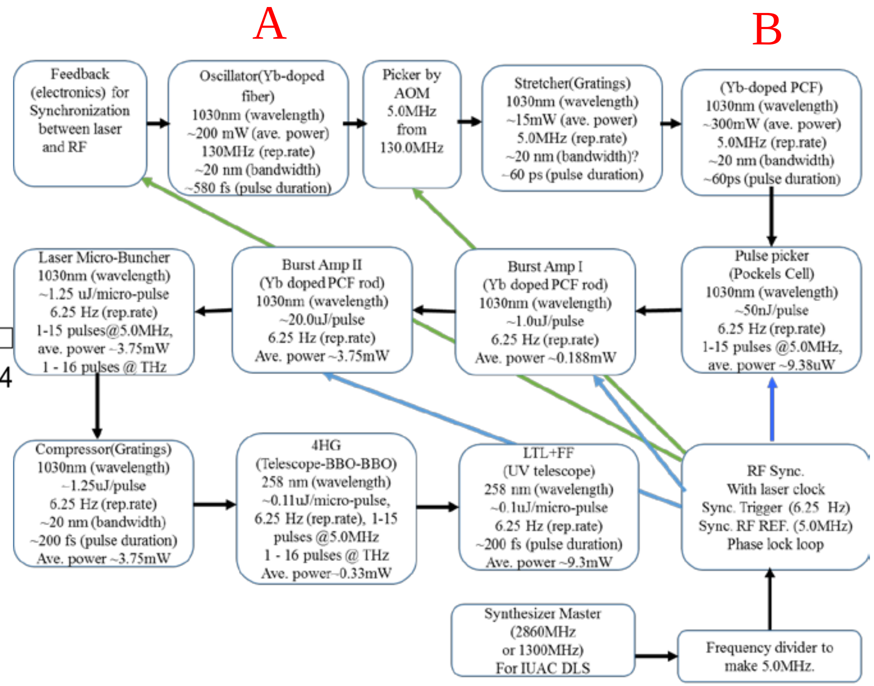


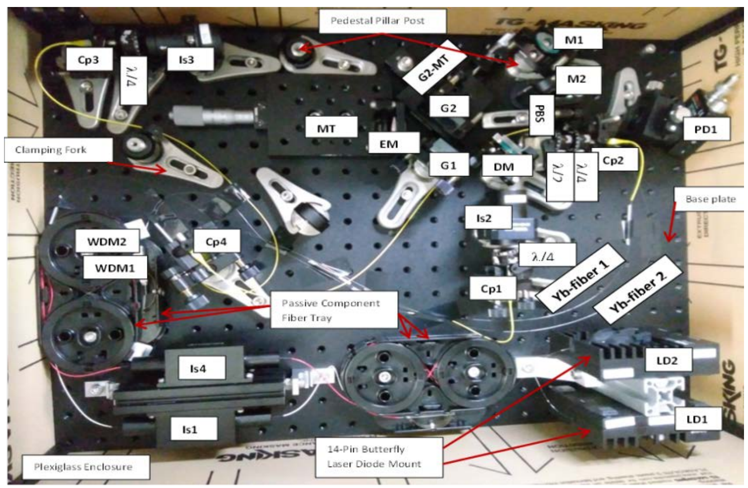
Courtesy: Dr. A. Aryshev

Testing and installation of Prototype Fiber oscillator + pre Amplifier



Schematic of Fiber Oscillator

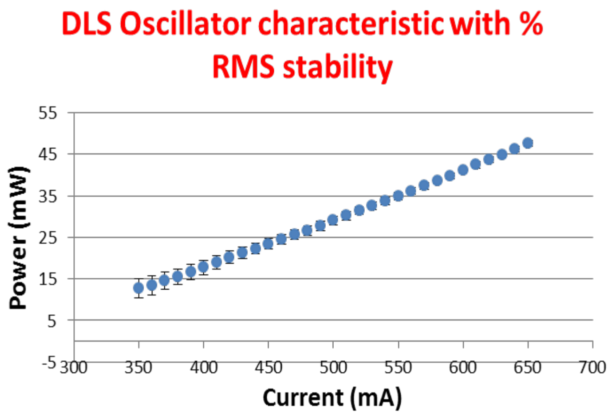


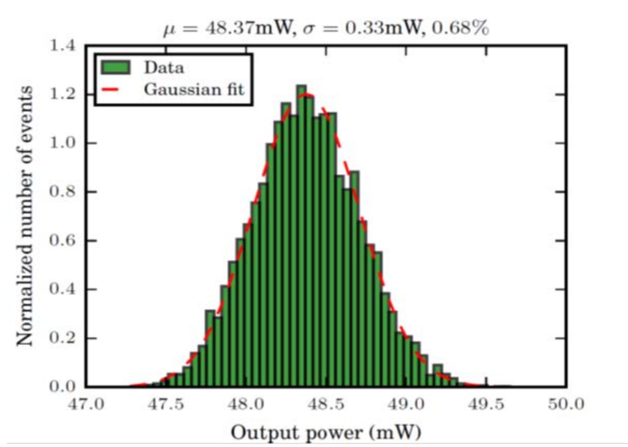


Oscillator + Pre amplifier

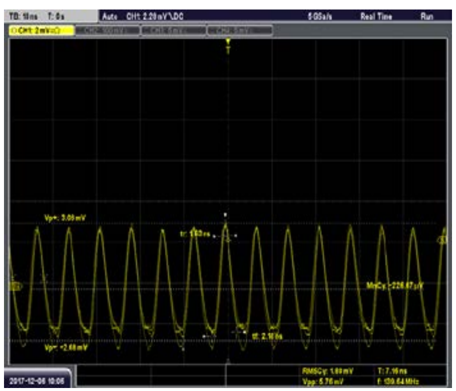
Power Stability : Without feedback
Oscillator Frequency : Master clock
Optical Bandwidth : Pulse width
RF bandwidth : Locking

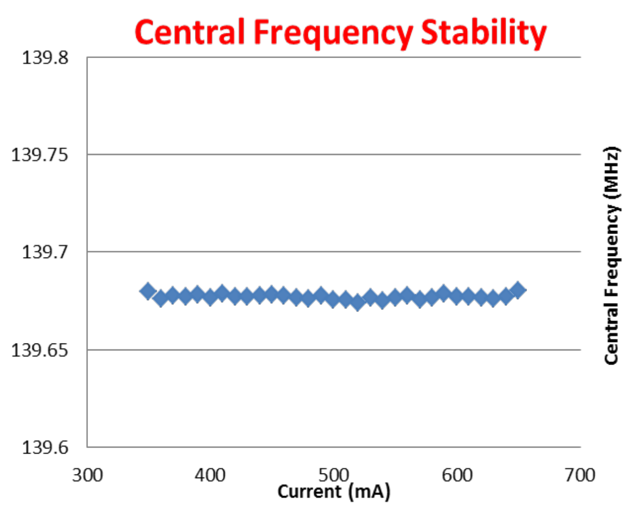
Prototype Fiber oscillator + pre Amplifier Measurement and results





Oscillator power stability





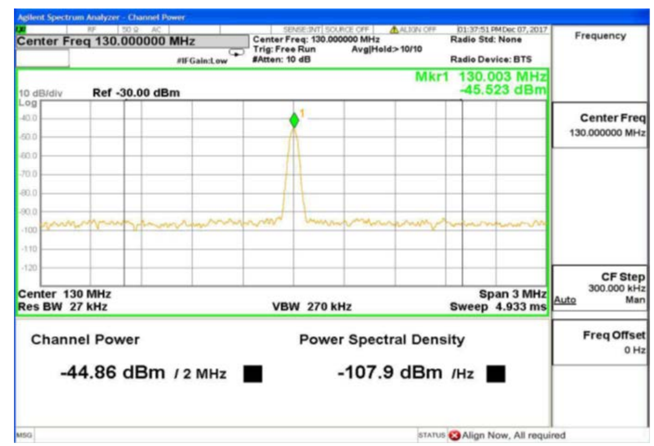
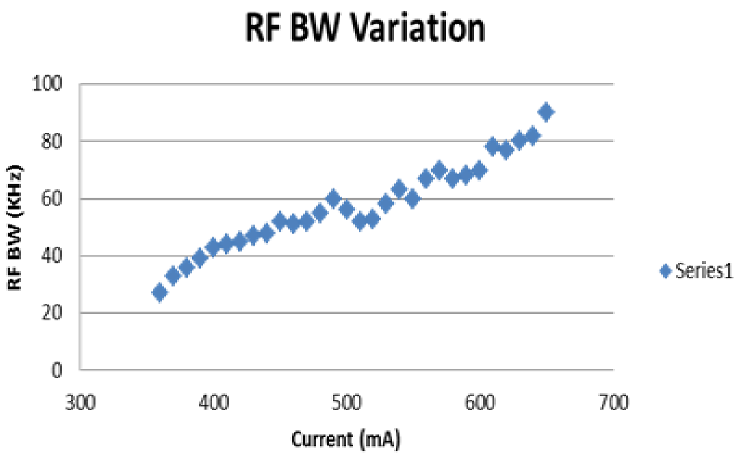


Photo diode output : Mode locked at 130 MHz

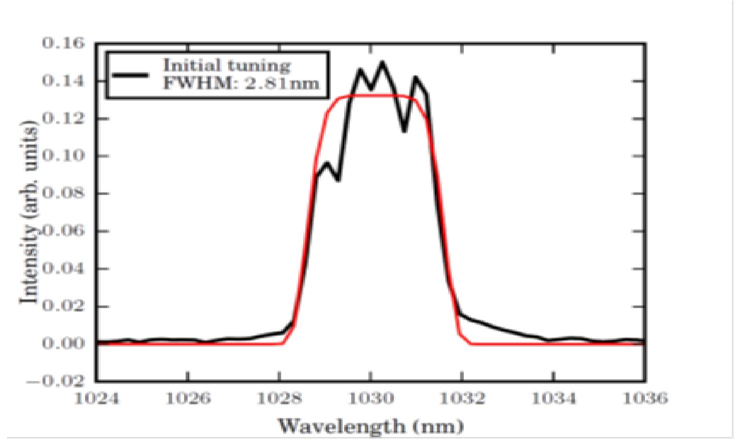
Oscillator rep rate stability

130 MHz oscillator rep rate measured in spectrum Analyser

Prototype Fiber oscillator + Pre-amplifier Measurement and results



RF Bandwidth

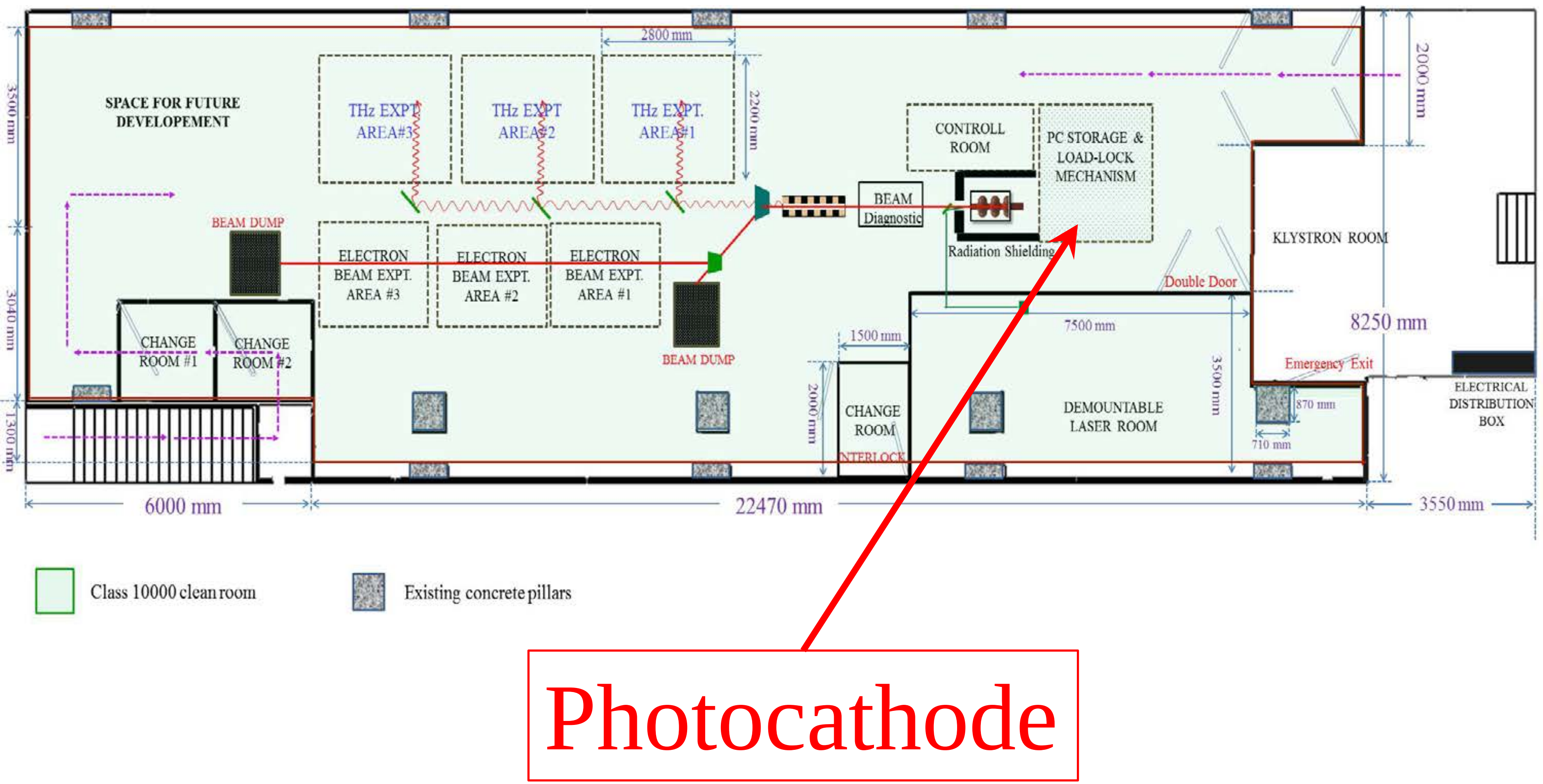


Optical BW fitted with Ocean Optics data

Parameter	Value	Notes
Output power	47.6 mW	
RMS power stability	0.68%	w/o enclosure and feedback, To be improved to another factor of 10
Center wavelength	1030 nm	Tunable in the current setup
Optical bandwidth	~2.8 nm	Need to increase to > 10 nm
Repetition rate	130MHz	Tunable in the current setup
Max RF BW (99%power)	90 kHz	
Pulse duration	~1.5 ps	Measured with Femtochrome FR-103XL/IR Autocorrelator

Photocathode Deposition system

Phase-I of the project: complete layout with expt. stations



Photocathode for Phase-I

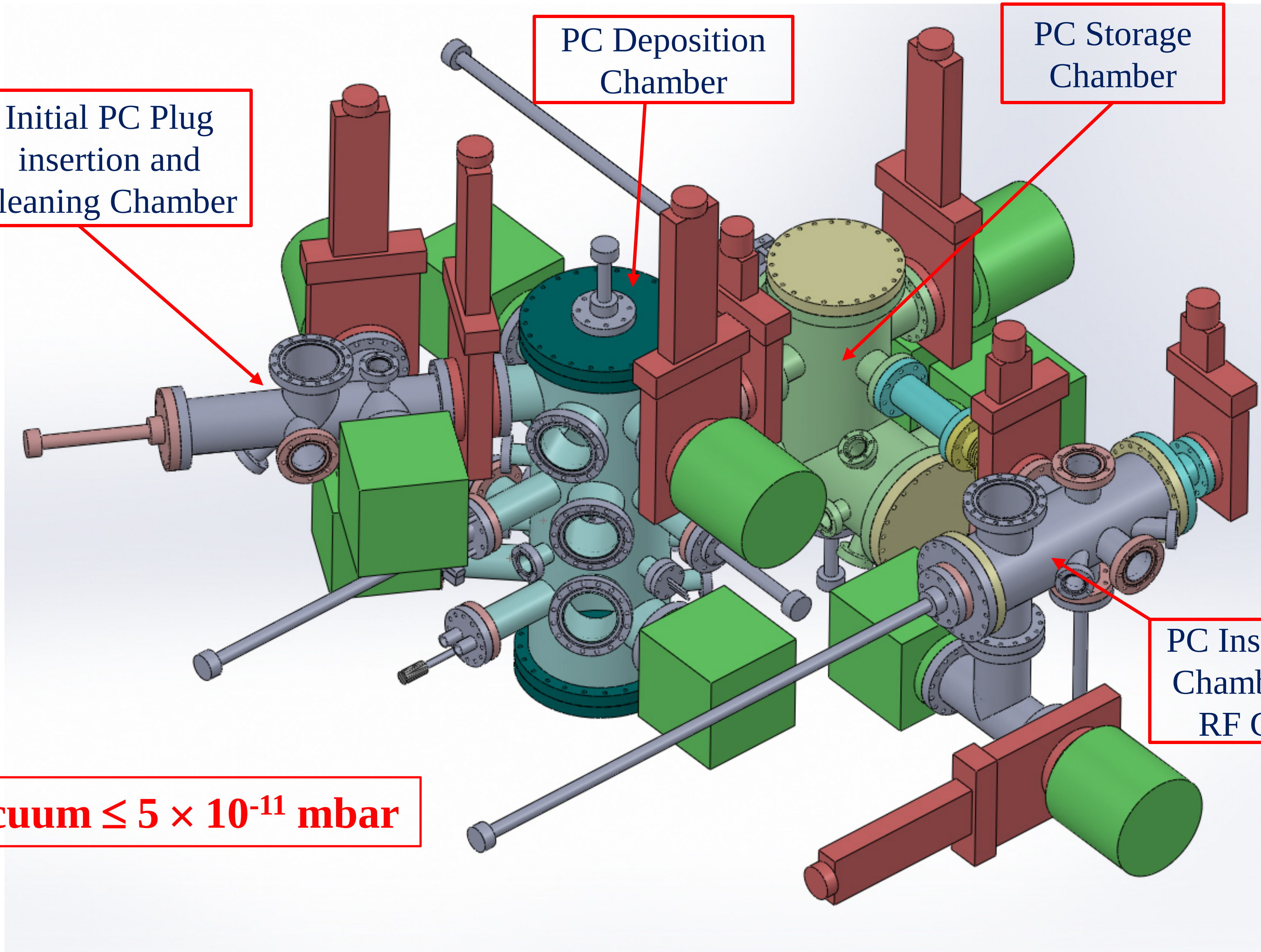
Initially:

Copper Photocathode – low QE, less no. of electrons for same laser beam
- 3 Photocathode were fabricated with cavity
- OFHC, Surface finish ~ few nm,
- Spring contact for RF

Finally:

Cs_2Te Photocathode & other advanced material – To be developed with help from BNL
- State of the art, performance varies
- Surface finish ~ few nm,
- Spring contact for RF

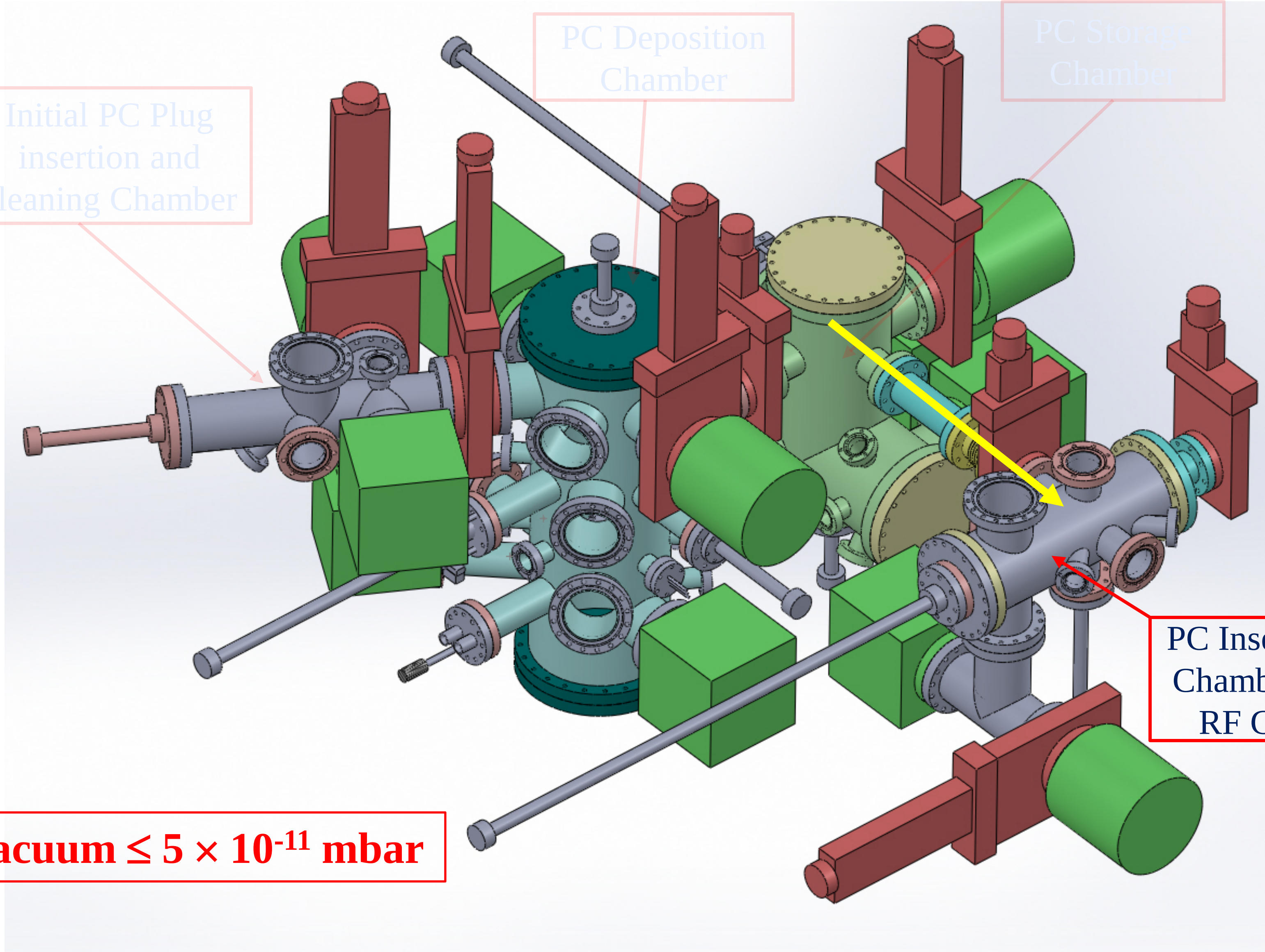
Photocathode deposition and transportation system



Base Vacuum ≤ 5 × 10^{-11} mbar

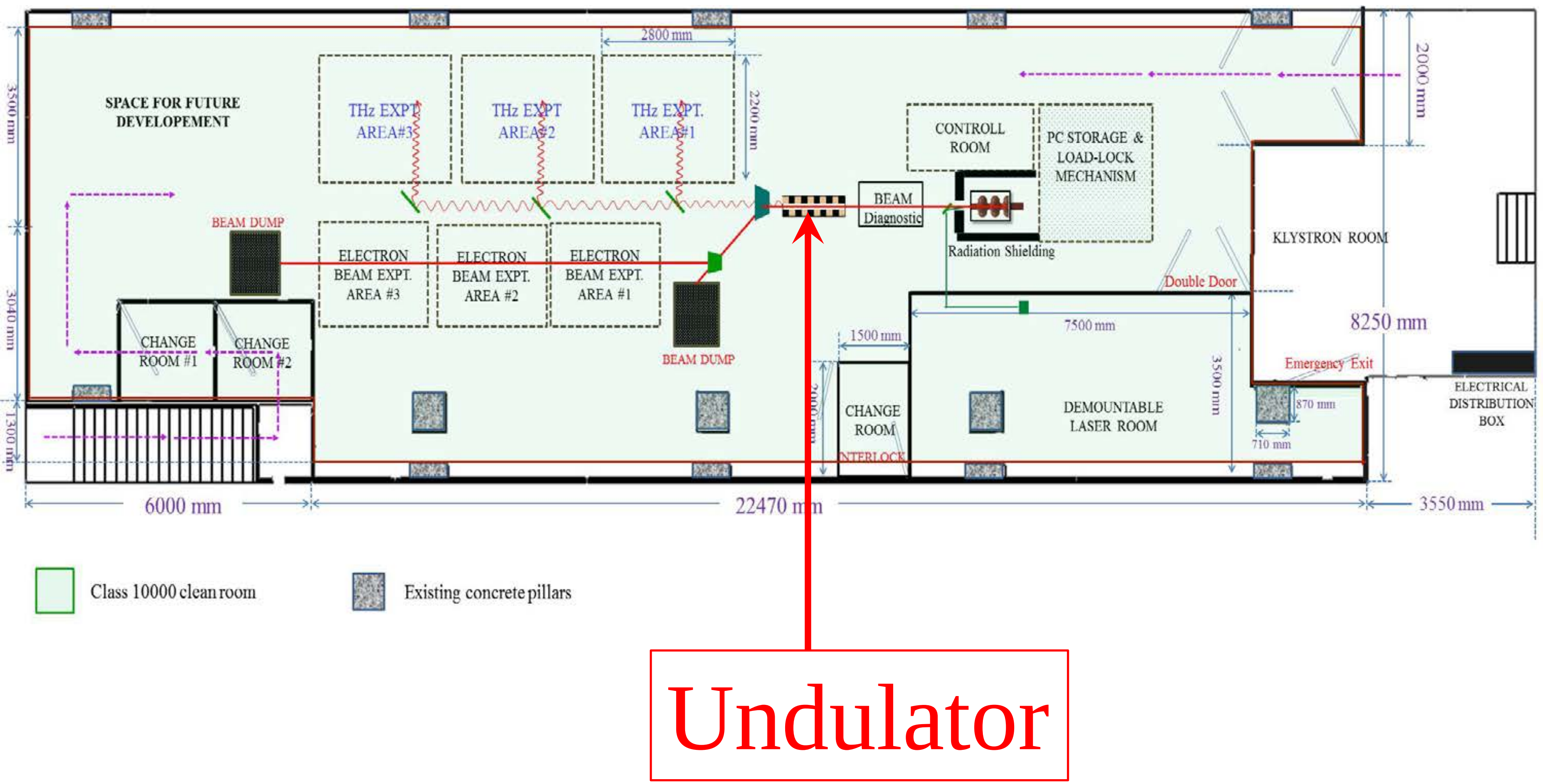
IUAC

Photocathode deposition and transportation system



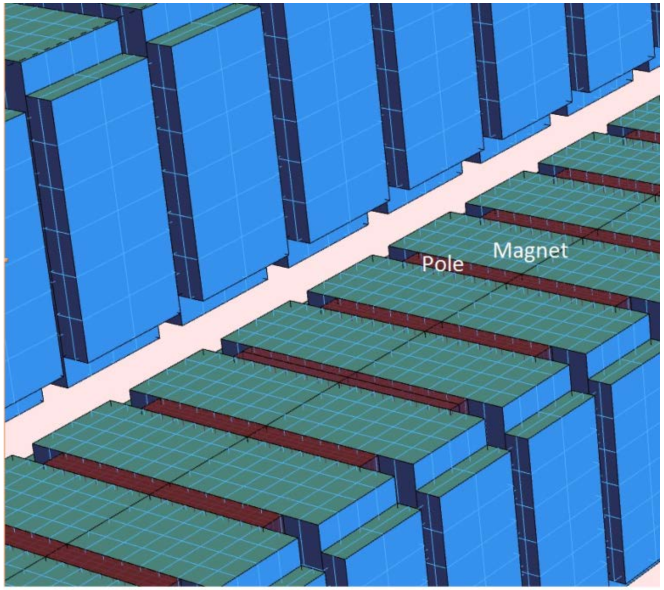
Base Vacuum ≤ 5 × 10^{-11} mbar

Phase-I of the project: complete layout with expt. stations



Design of undulator magnet by RADIA

Hybrid Undulator – NdFeB - magnet, Vanadium Permendur - pole



Period length (λ_u)= 50mm

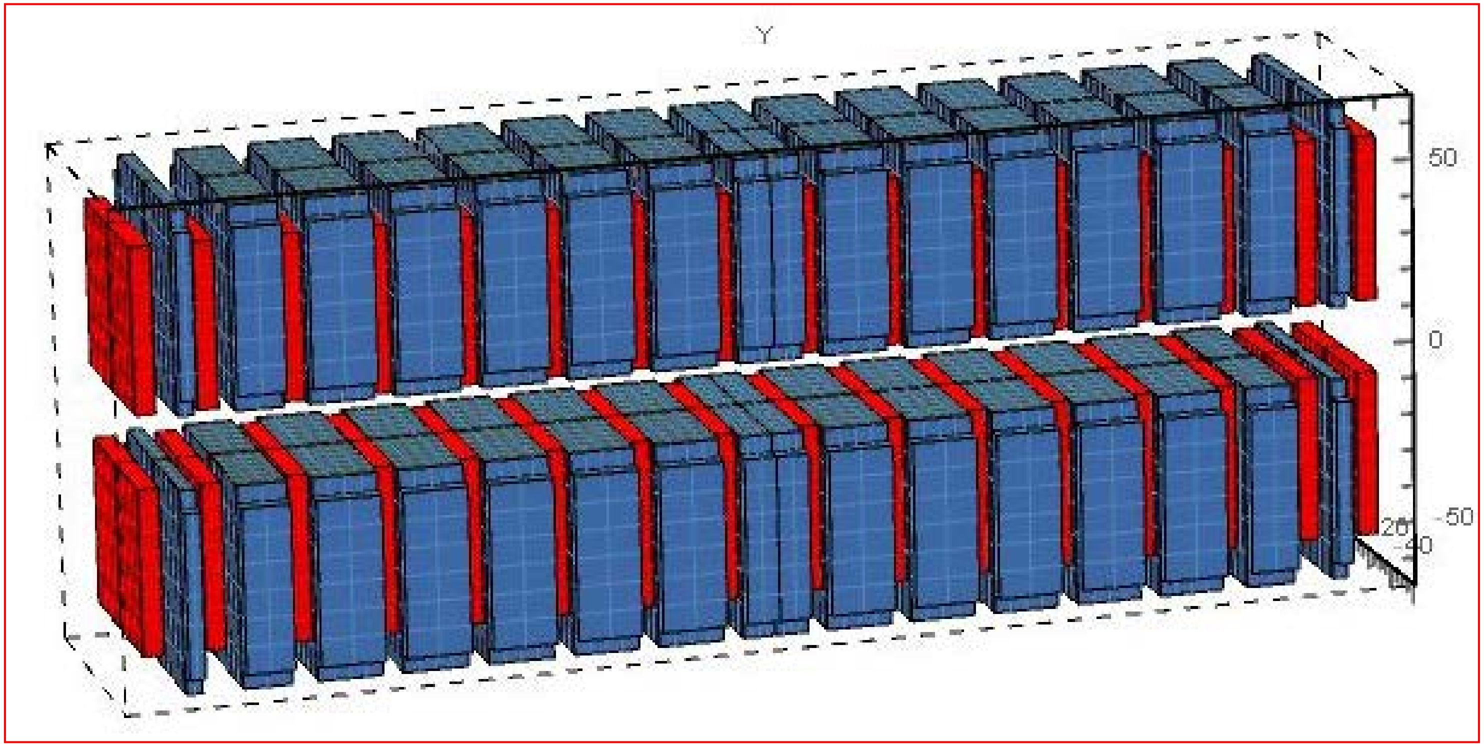
Device length = ~ 1.5m

NdFeB Magnet size
Width = 19.00mm
Height = 55.00mm
Length = 80.00mm

Vanadium permendur pole size
Width = 6.00mm
Height = 45.00mm
Length = 60.00mm

λ_R (~mm)	Freq. to be Produced (THz)	Electron Energy (MeV)	λ_U (mm)	K – value	B_u (T)	Required gap (mm)
1.67	0.16	4.1	50	2.89	0.62	20
0.1	3	8.2	50	0.6	0.1	45

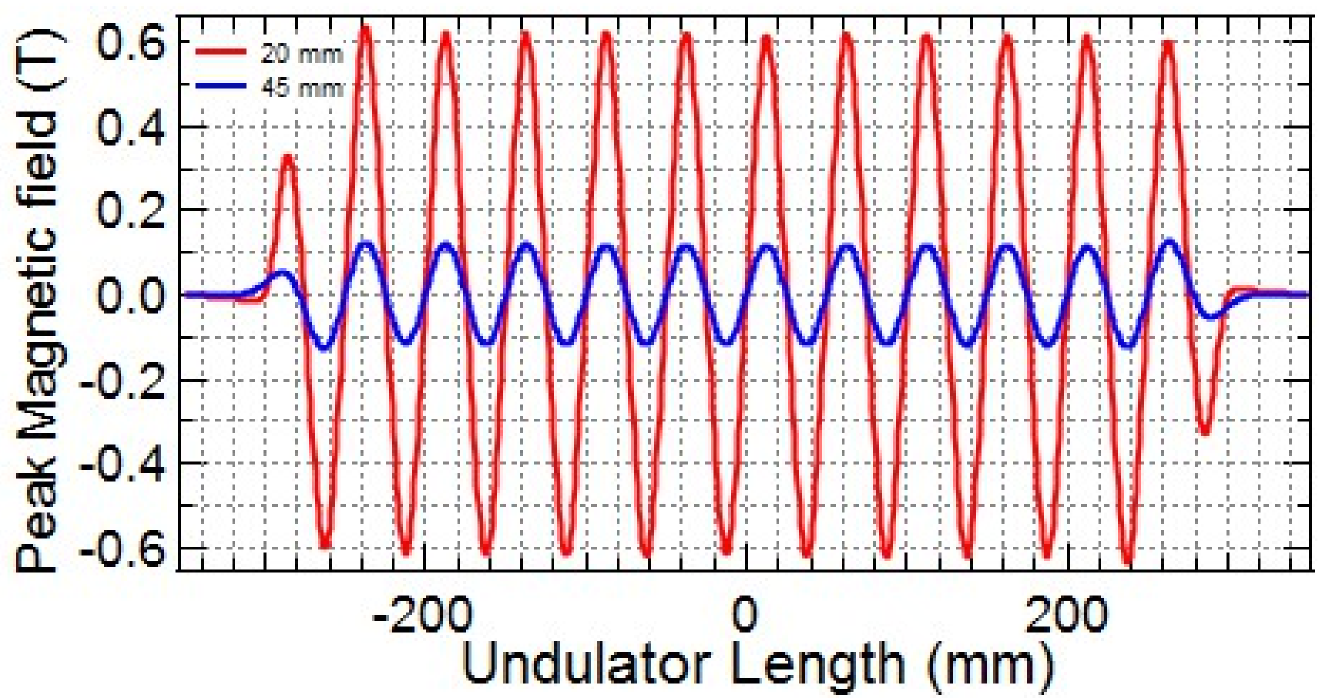
Optimization of undulator parameters by RADIA



Design: Undulator for DLS with full 5 periods and end structure.

The End Structure: 1 : 3/4 : 1/4 magnet configuration

Undulator field profile from RADIA

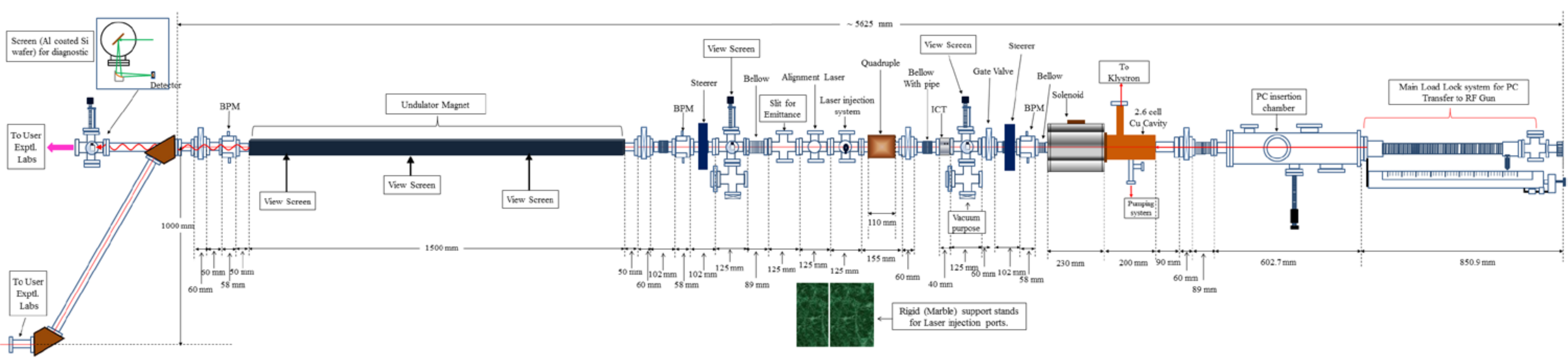


Undulator Gap= 20mm ; Peak mag. Field= 0.62T
Gap= 45mm ; Peak mag. Field= 0.11T.

$$B_u = 2.806 \exp\left[-3.941 \frac{g}{\lambda_u} + 0.493 \left(\frac{g}{\lambda_u}\right)^2\right]$$

For IUAC's hybrid undulator made from NdFeB magnet with $0.1 < \frac{g}{\lambda_u} < 0.9$

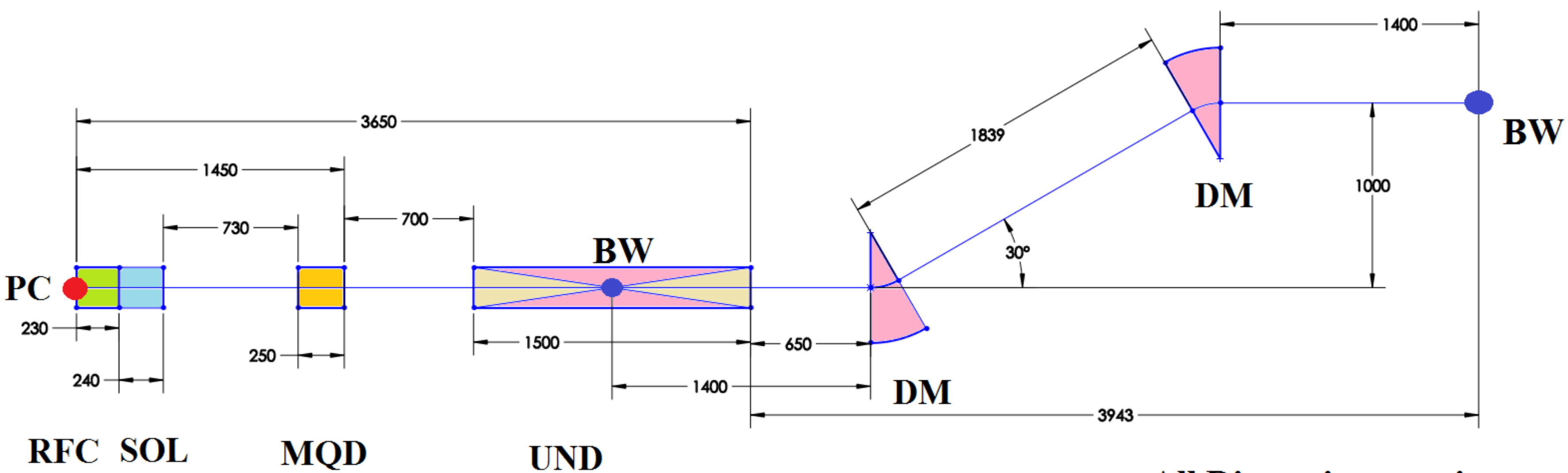
Beam line of Phase-I



ELECTRON BEAM TRANSPORT AFTER UNDULATOR

Acronyms:

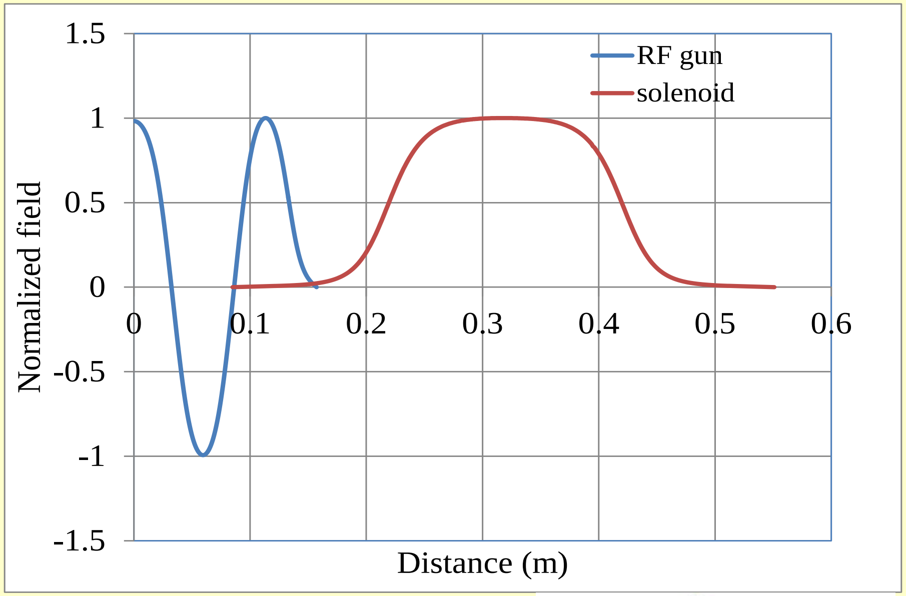
- **PC: Photo cathode**
- **RFC: Radio Frequency Cavity**
- **SOL: Solenoid**
- **UND: Undulator**
- **DM: Dipole magnet**
- **MQD: Magnetic Quadrupole Doublet**
- **BW : Beam Waist**



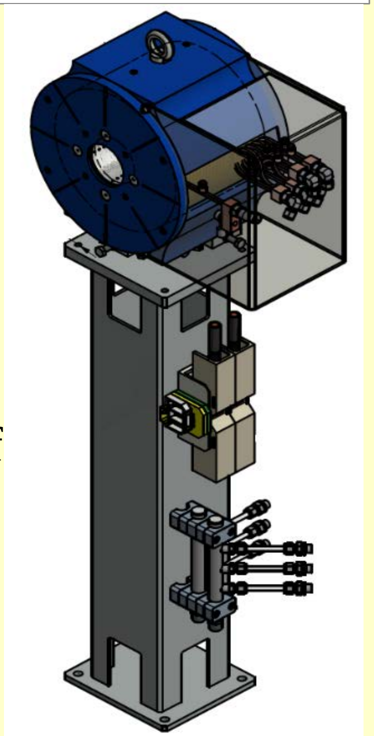
All Dimensions are in mm

Beam transport device – Solenoid (NC)

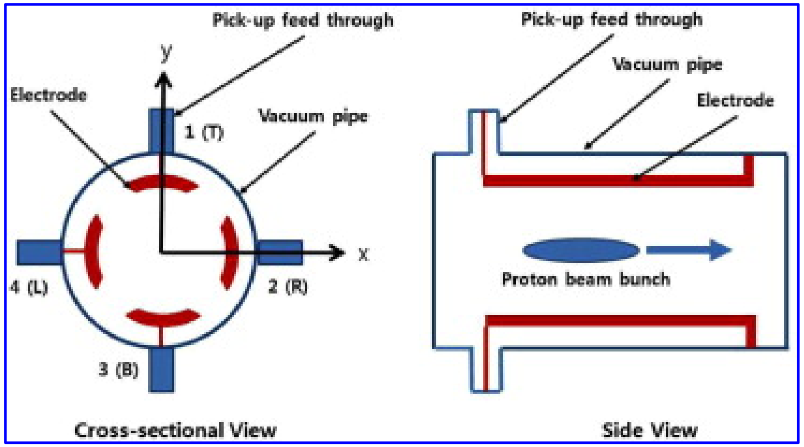
Parameters	Values
Maximum magnetic Field at the Centre of the solenoid magnet	0.35 T
Physical Length including return yoke	≤ 240 mm
Overall Diameter	≤ 480 mm
Effective Length	~ 200 mm
Bore Diameter	76 mm, fit over 2.75” flange
Alignment marks	Yes
Longitudinal alignment Tolerance	≤ 0.25 mm
Transverse alignment Tolerance	≤ 0.025 mm
Axial Field at a distance of 200mm from the centre of the solenoid magnet	< 30 Gauss
Cooling Water requiremnt	~ 5 l/min
Operating temperature of solenoid magnet	~ 20 $^oC \pm 1\ ^oC$
Water Pressure required in Cu Coils	~5 bar
Field Homogeneity	~ 5 x 10^{-3} within ± 20 mm around the middle of the solenoid along the transverse and longitudinal direction



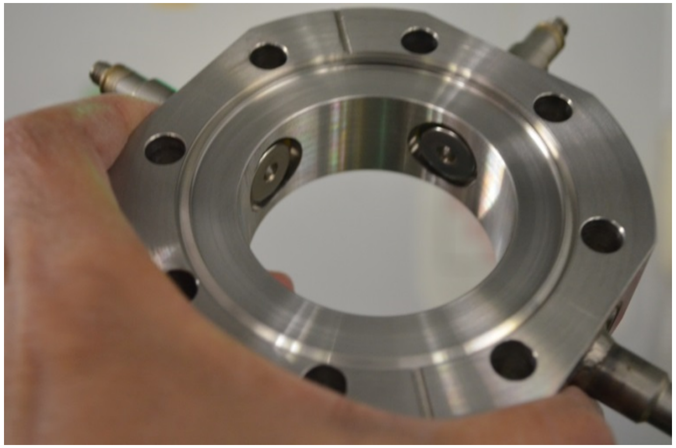
3D technical design of solenoid magnet (from Danfysik) Shipped to IUAC



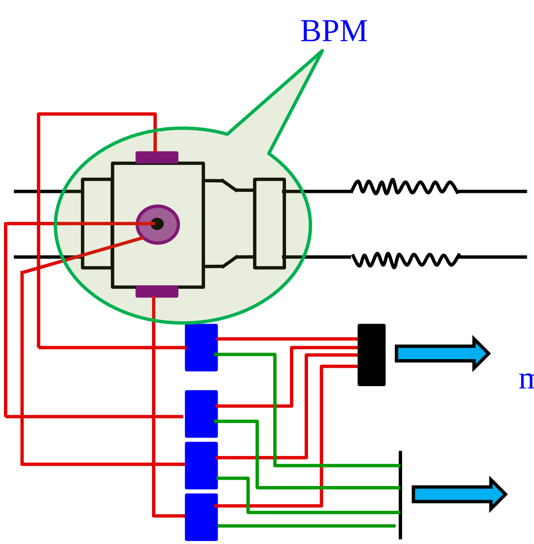
Beam Diagnostics and measurement



Stripline BPM



Button BPM



Schematic of the Beam position measurement layout.

Stripline BPM

- Position of each microbunch of a 16 bunch train can't be resolved
- Position of macro-bunches (5 MHz) containing 2, 4, 8 or 16 microbunch train can be resolved

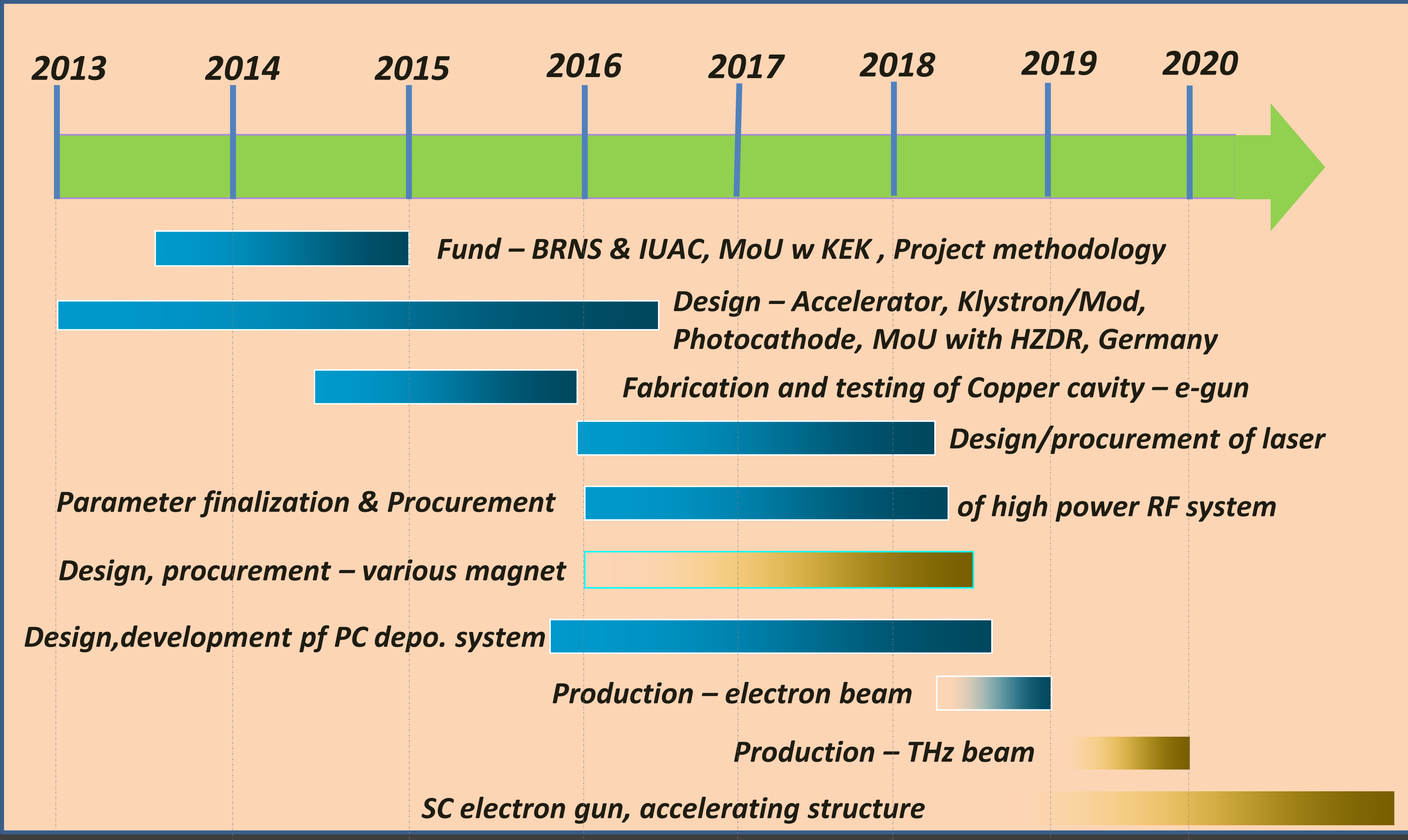
Parameter finalization is going on, to be purchased soon

Status of DLS: January 2018

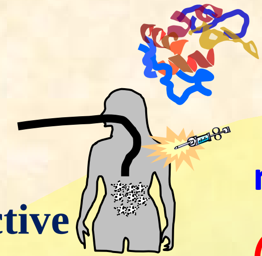
- Copper cavity is fabricated, is waiting to be installed.
- Deposition of semiconductor PC (CsTe) is being developed in collaboration with BNL
- Spec. for Klystron/Modulator - finalized, Tender floated, order placed, Delivery – April.'18
- Beam transport simulation is performed and finalized
- Class 10000 clean room is fabricated (28 × 8 meters), installation will be started soon
- Type of Laser device is finalized, design is frozen, first part is developed and tested.

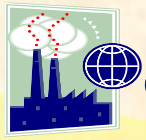
  Complete system to be operational in July 2018
- Beam diagnostic components are being chosen & development/procurement will start
- Development of electronics and control system is started
- Beam line design is frozen, various beam diagnostic devices are to be procured/developed
- Simulation of THz production is in the final stage
- Design of Undulator is in the final stage, procurement process to be started
- Expected to demonstrate electron beam & THz by Dec. 2018 and Dec. 2019

Time chart – for Phase I of DLS



THz-wave region and possible applications





Bio-medical Engineering

protein analysis.

medicine and food inspection

Environmental

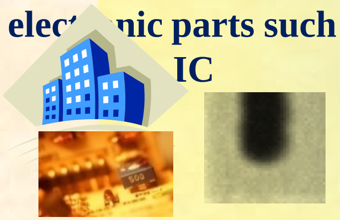
deleterious chemical detection

Oil and gas detection

Non-destructive Inspection

buildings study for cracks,

electronic parts such as IC



Organic

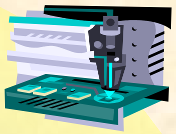
molecules orientation,

molecular interactions

Semiconductor

Phonon,

impurity energy level (donor, accepter)



Process Monitoring

molecular defects, polymorphism

Physical properties and function in THz region

Ceramic

soft phonon mode

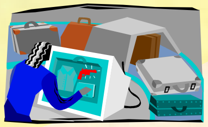
capacitor

Metal

plasmon

THz spintronics

Harmful Material mixture inspection



THz communication

carrier, modulation

Monitoring

dangerous substances underneath the land, aging of polymer

Safe Society

dangerous weapons and explosives identification

Coming years could be Golden Years for Terahertz

Publication on DLS

Nuclear Instruments and Methods in Physics Research B 402 (2017) 358–363

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BEAM INTERACTIONS WITH MATERIALS AND ATOMS

Status of the development of Delhi Light Source (DLS) at IUAC

CrossMark

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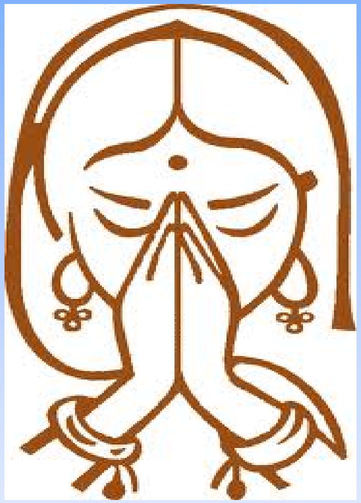
Photocathode
THz radiation
Electron gun

ABSTRACT

A [illegible] a compact [illegible] photo-cathode [illegible] at In[illegible] New Delhi, India. In this facility, the short laser pulses from a high power laser system will be split into many pulses (2–[illegible]) commonly known as 'Comb beam' and will strike the photocathode material (metal and semiconductor) to produce electron beam bunches. The electrons will be accelerated up to an energy of ~8 MeV by a copper cavity operated at a frequency of 2860 MHz and the beam will be injected into a compact, planar permanent undulator magnet to produce THz radiation. The radiation frequency designed to be tuned in the range of 0.15–3 THz by varying the magnetic field of the undulator and/or changing the energy of the electron. The separation of the laser micro-pulses will be varied by adjusting the path length difference to alter the separation of the electron micro-bunches and to maximise the radiation intensity.

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