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

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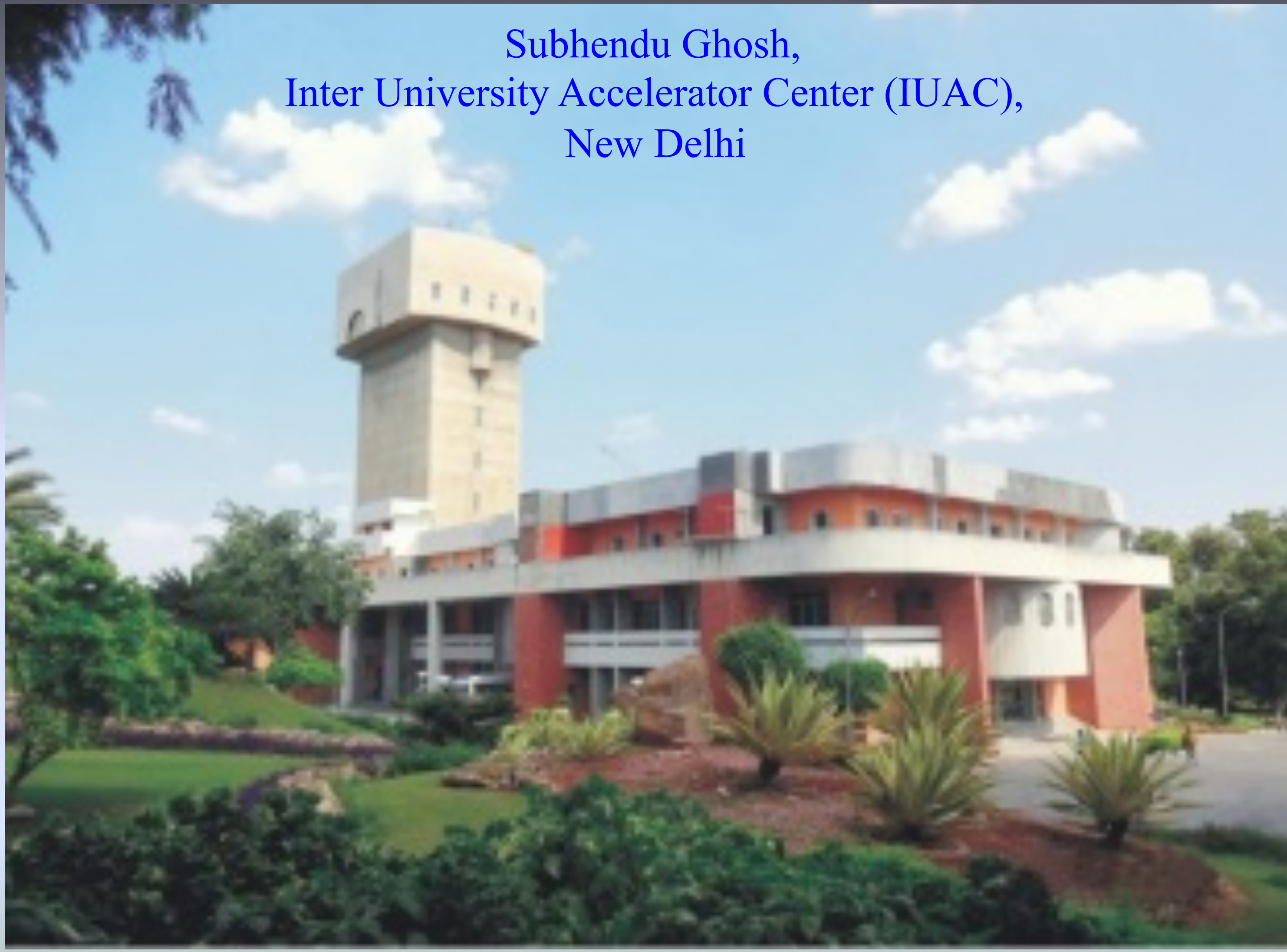


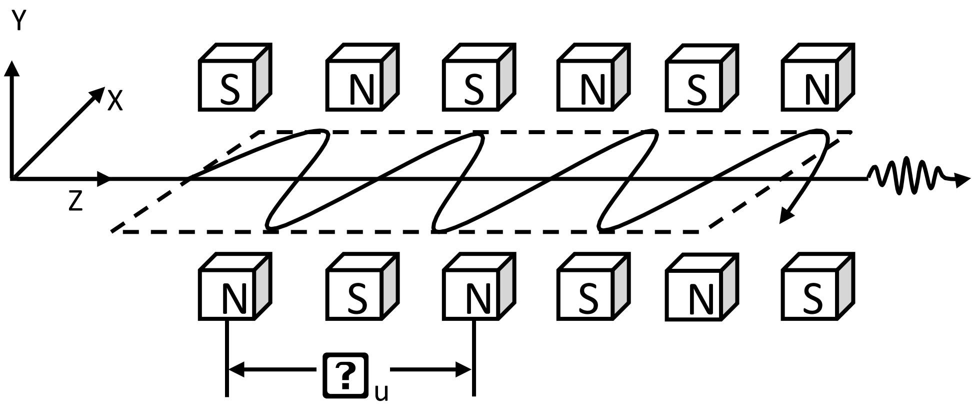
AGTaX Workshop - 30 Sept. 2017

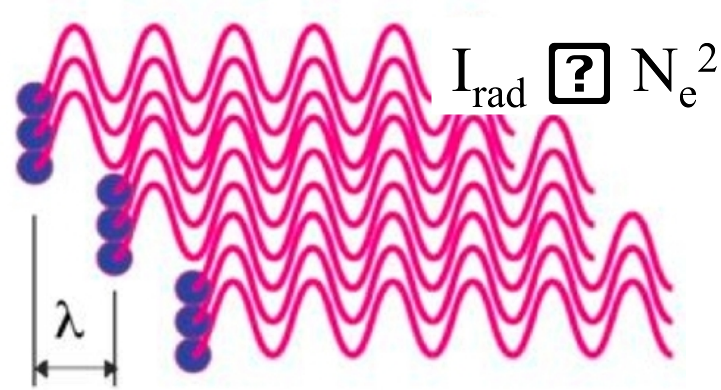
# DELHI LIGHT SOURCE (DLS)

## Plan of Presentation

- Short introduction to Free Electron Laser (FEL)
- Pre-bunched FEL (DLS) & how is it different from conventional FEL
- Developments of Phase-I of DLS in Collaboration with KEK, Japan and HZDR, Germany
- Time chart
- Conclusion

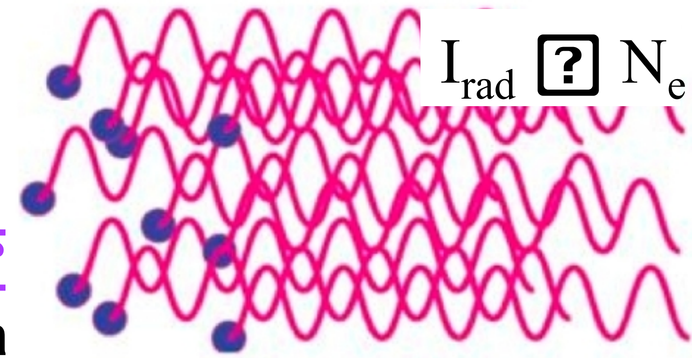
# Conventional FEL




## Major points:

- Relativistic electron
- Approaching Undulator magnet, $?_U$
- $?_U$ - length contracted to $?_U^* = ?_U/?$, ?
- $?_U^*$ = Emitted wavelength from the electron
- Wavelength (lab fr.) = $?_R = ?_U^*/2? = ?_U/2?^2$ , relativistic Dopple
- Including the parameter of Undulator, wavelength measured will be




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

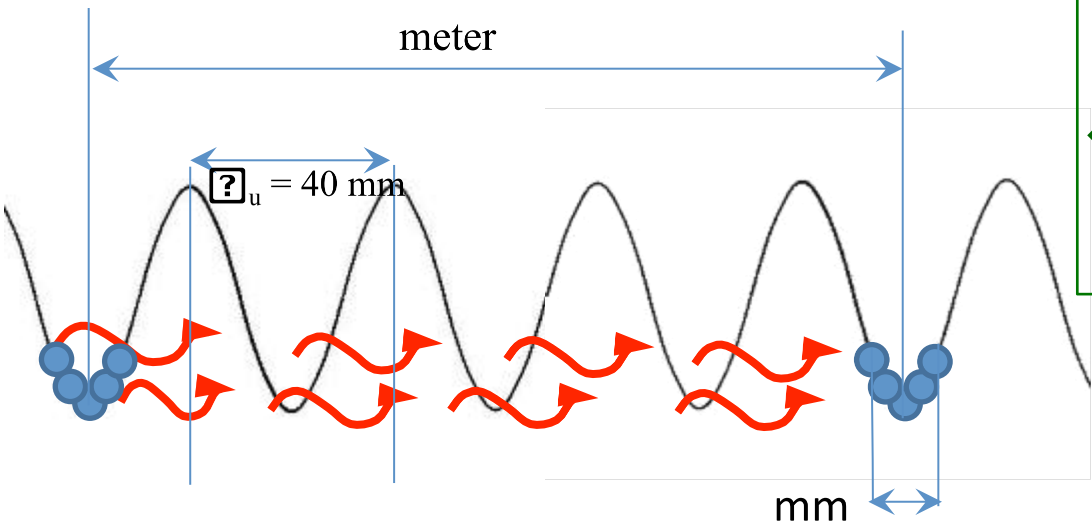
Electrons radiate spontaneously, now coherence is to be established

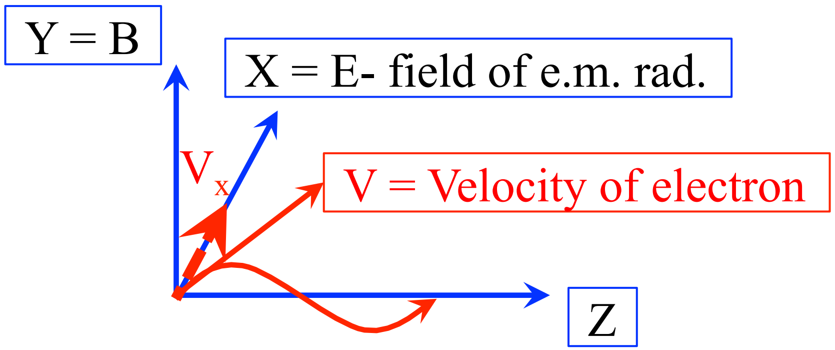
# How Coherent radiation is produced in FEL

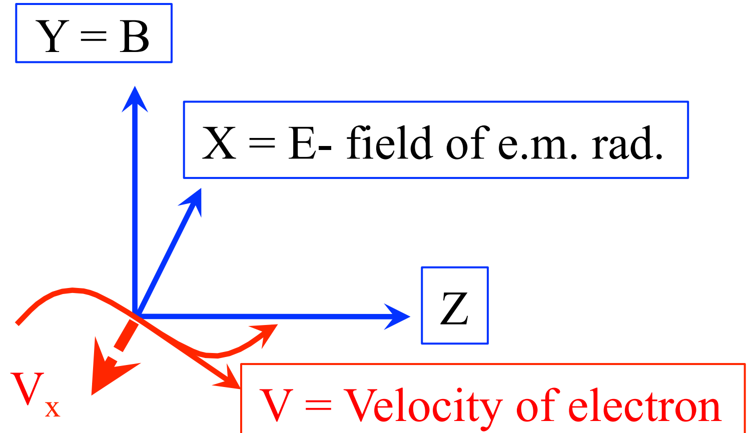
Electron velocity close to c
E-beam bunch length ~ mm (ps)
E-beam bunch separation ~ meter (MHz)

- Results to accl / deccel of electron
  ➡ Velocity modulation
- Electron are injected in bunches.
- Each bunch will be split in to microbunches due to velocity modulation.
- Process is known as

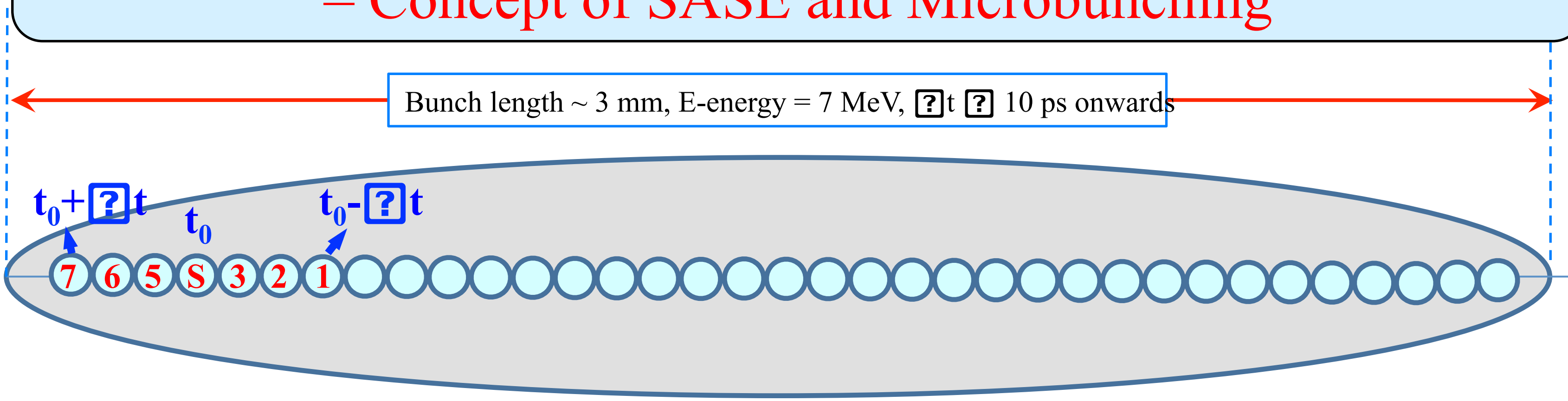
**Microbunching**



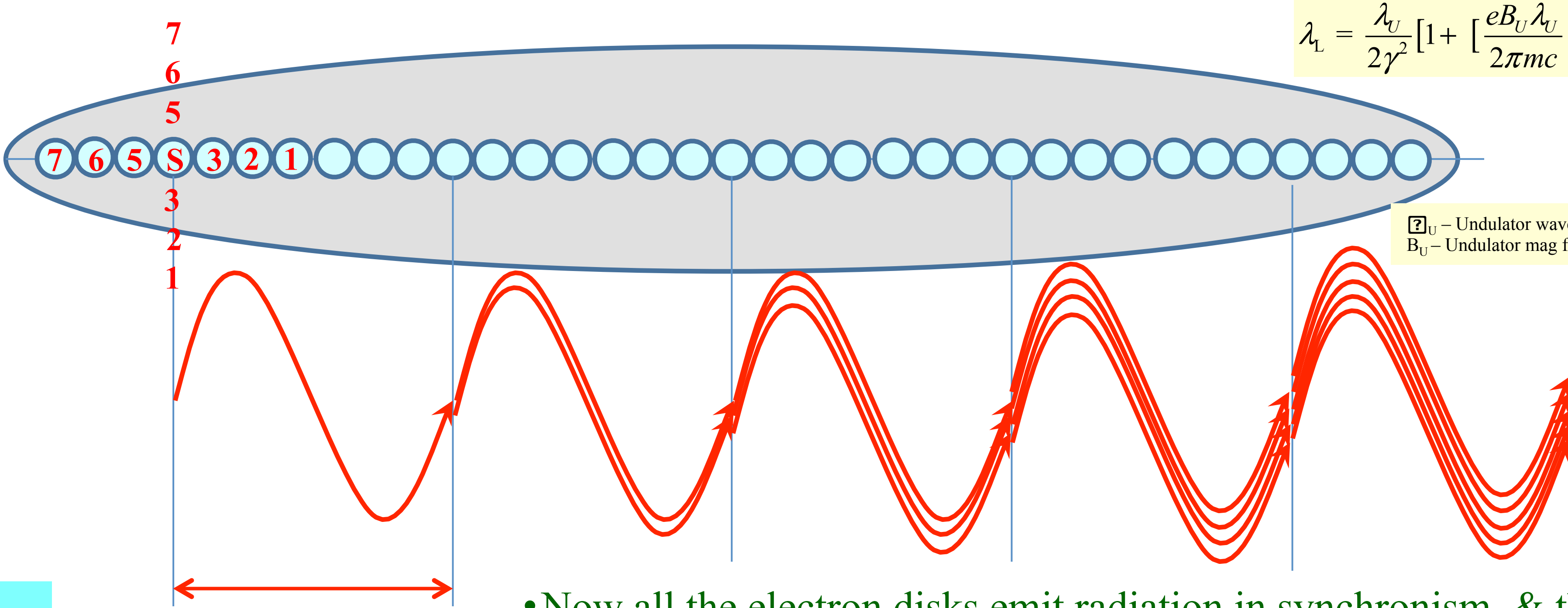
# How Coherent radiation is produced in FEL
## – Concept of SASE and Microbunching




**Interaction of Photon and wiggling electron inside undulator magnet**

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

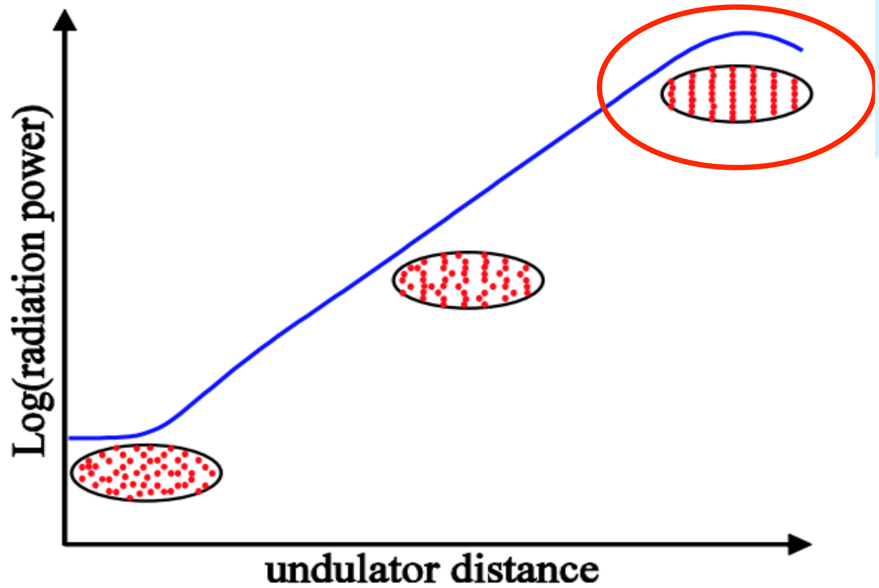
?$_U$ – Undulator wavelength
$B_U$ – Undulator mag field



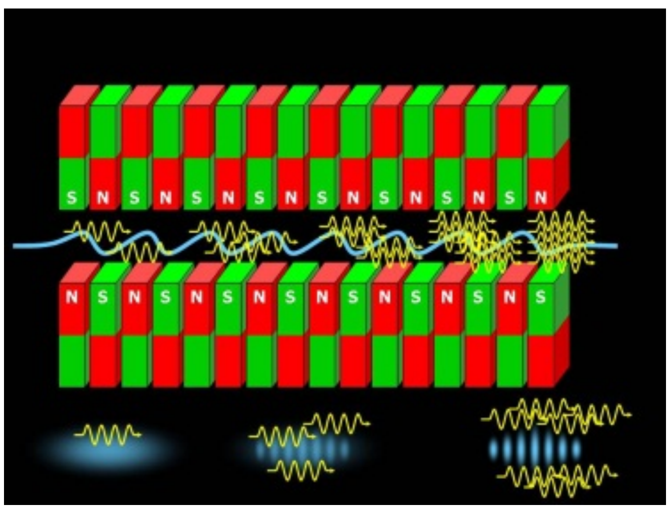

? =wavelength of radiation

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

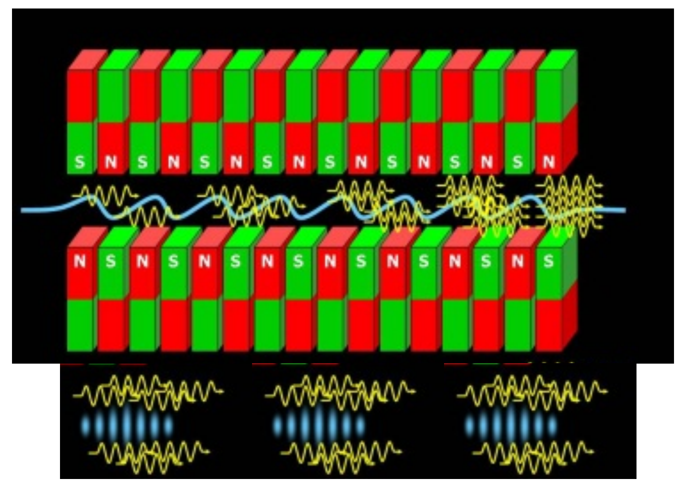
# Pre-bunched FEL - How is it different from conventional FEL




**Starting point of Delhi Light Source**



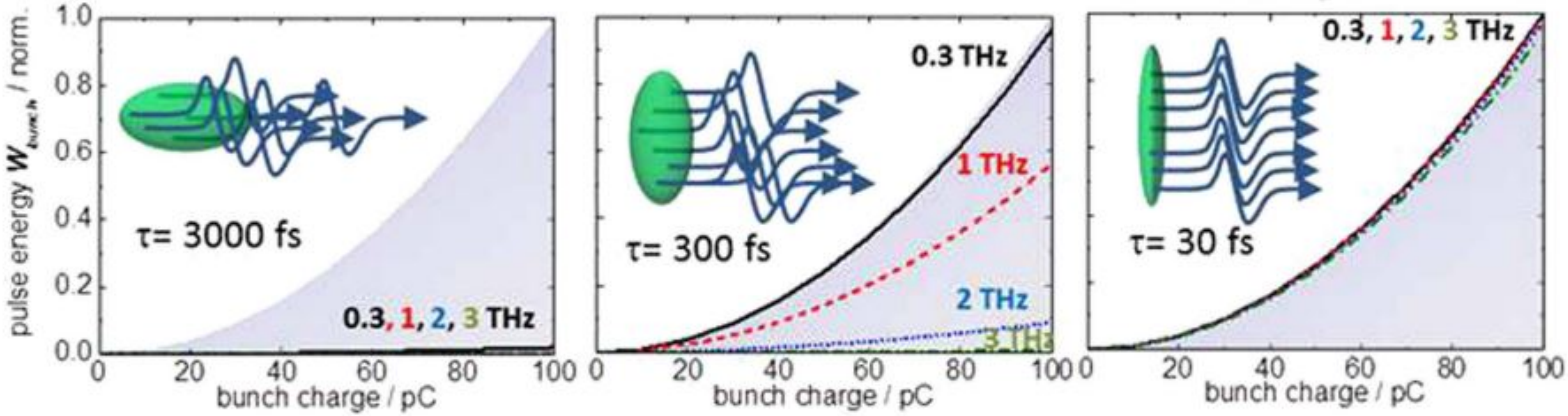

Conventional FEL




Prebunched FEL (Phase-I of DLS)

# Super-radiant radiation from microbunch train

## Super-radiant radiation




Superradiant radiation* – to produce frequencies when it is << 1/? [1/30 fs = 33.3 THz]

If the time width of the electron beam bunch is ~ 100 fs, then 1/? = 10 THz

**Delhi Light Source (DLS): Super-radiant with microbunch train**

- **e-bunches which is few hundred of fs (200 fs) – super-radiant (I ? $N_1^2$)**
- **In addition, train of microbunches (separation ~ 500 fs to a few ps) will be produced**
- **So I ? $(N_1 + N_2 + \ldots + N_{16})^2$**

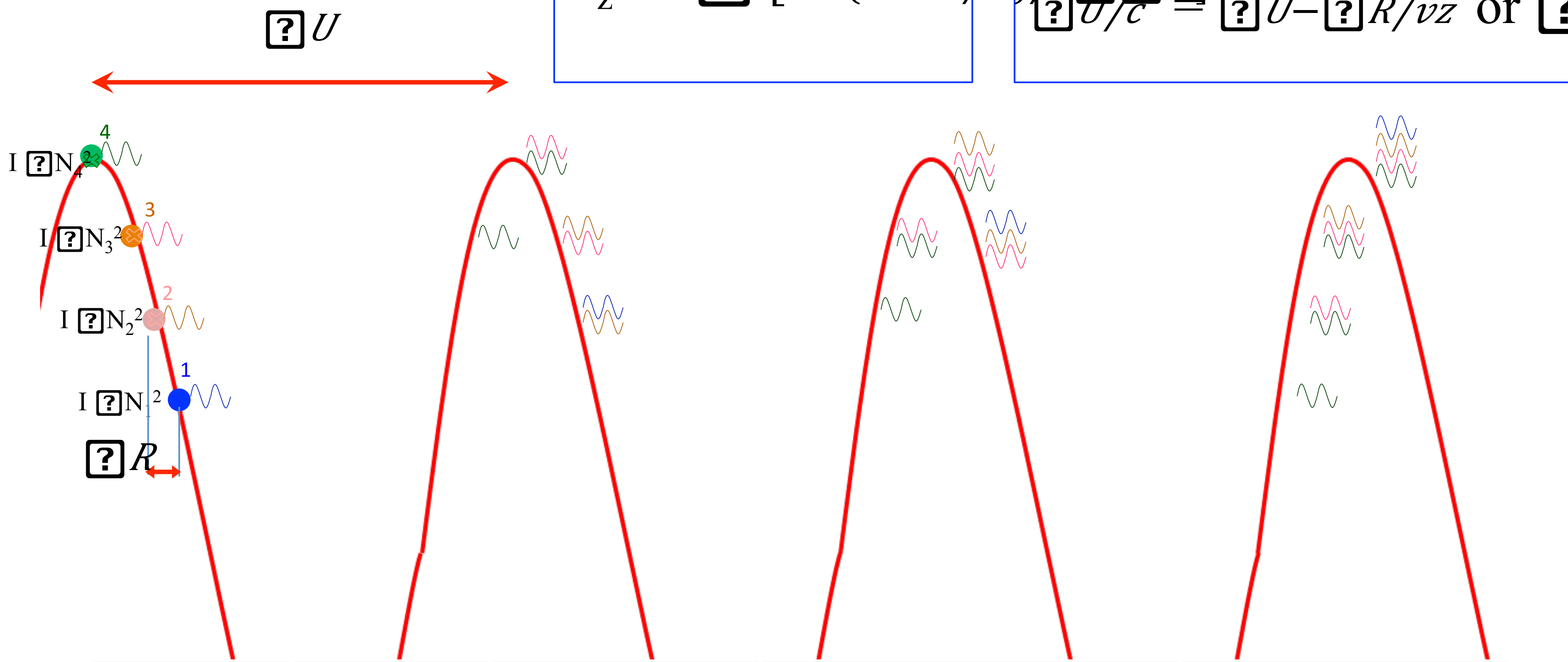
* B.Green et. al. www.nature.com/scientificreports(6:22256,DOI:10.1038)

# Where Photon meets Electron

?$R$=?$U/2$?2 [1+$K$2/2 ]

$v_z$= c ? [1- (1+$K$2/2 )/2??2 ]

?$U/c$ = ?$U$−?$R/vz$ or ?$_U$

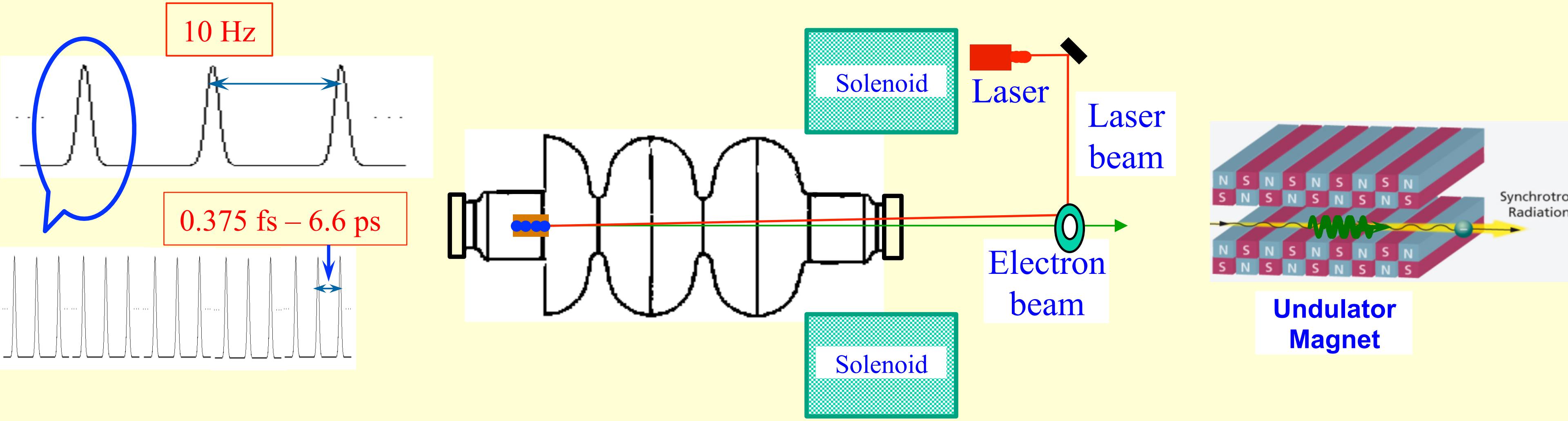



| freq (THz) | Energy (MeV) | K_undulator | Longitudinal Velocity of electron ($v_z$) m/sec | Undulator wavelength (m) |
|---|---|---|---|---|
| 0.15 | 4 | 2.982 | 2.8667E+08 | 0.045 |
| 0.6 | 6 | 2.032 | 2.9667E+08 | 0.045 |

I ? $(N_1+N_2+N_3+N_4)^2$ or I ? $N^2$

After 7 ?$_U$, 4 photon bunches with I @ separation of ?$_R$ are emitted & will

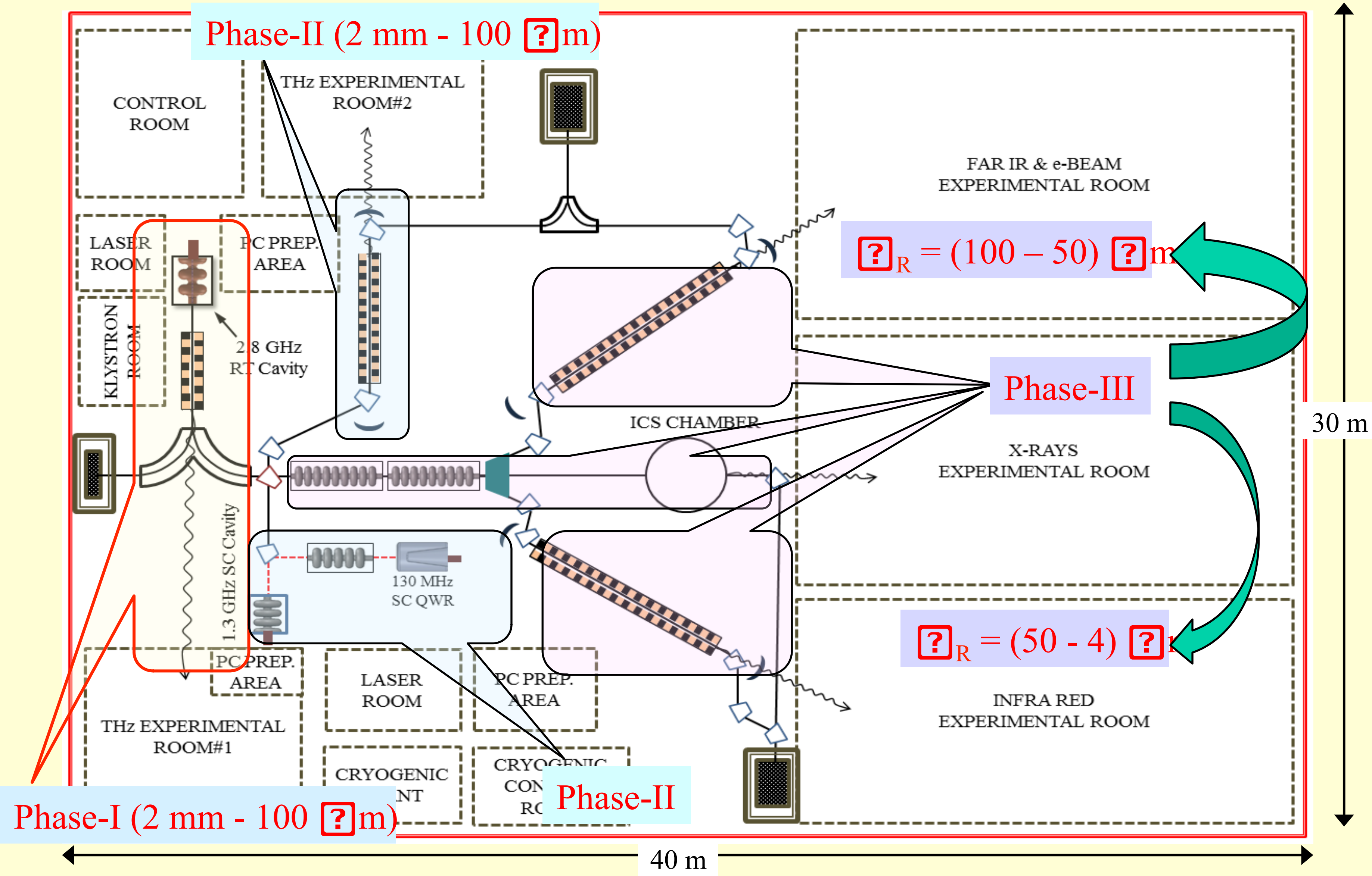
# Major components of DLS (Phase-I) – Pre-bunched FEL



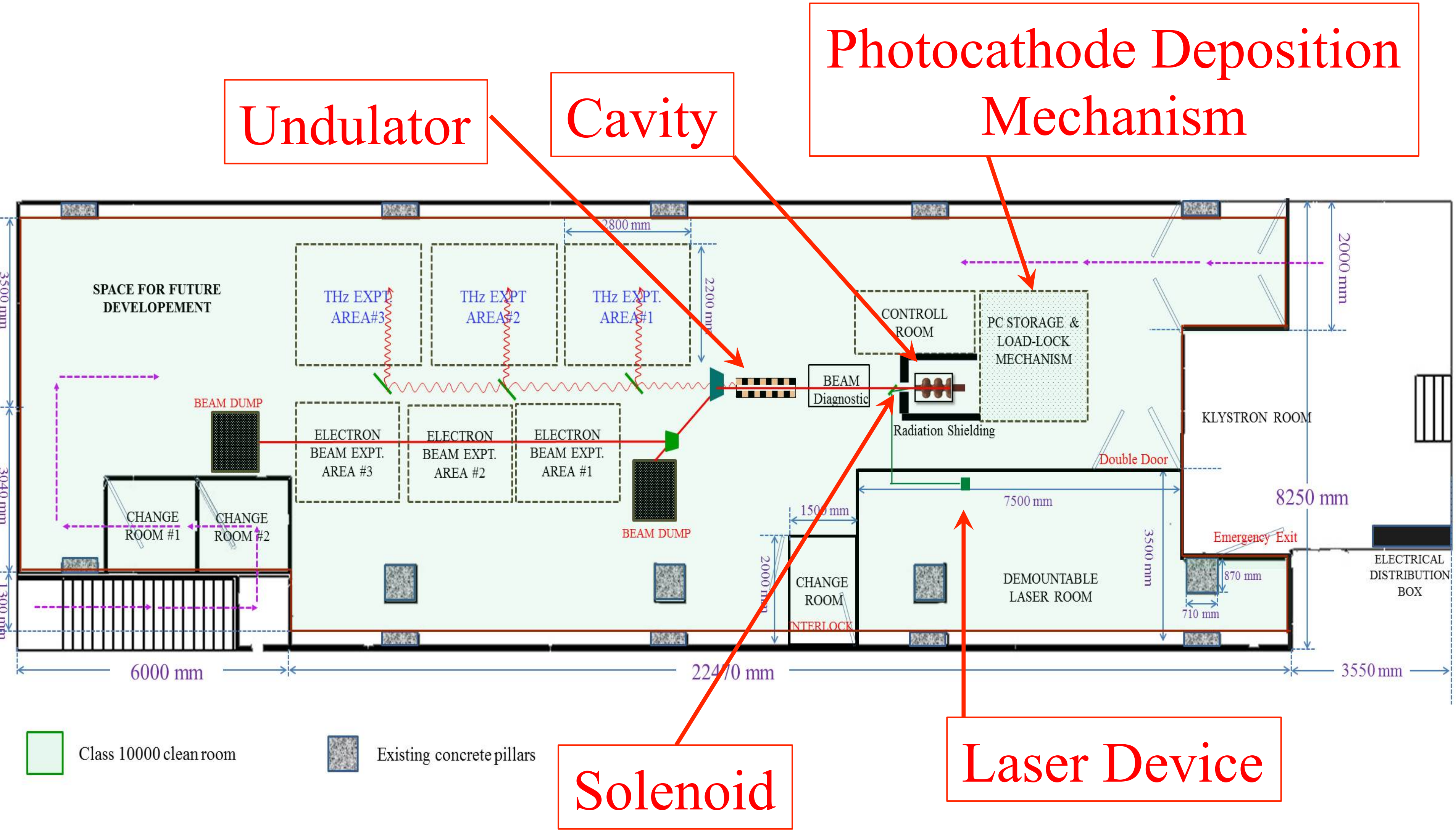

1. An electron gun – laser operated PC & a resonator powered by klystron/modulator
2. A laser system – produce the electron bunches – single pulse is split into many
3. Photocathode preparation device
4. Solenoid – focus electron beam – Cavity to Undulator
5. An Undulator magnet – to produce e.m. radiation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

# INTRODUCTION TO DELHI LIGHT SOURCE (DLS)

## Layout of Delhi Light Source (DLS)



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



# Development of Phase-I

## Physics Design

- Wavelength to be produced
- E-beam energy
- Beam optics design

Beam optics design is ready
Being validated

## Choice of Accel. Components

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

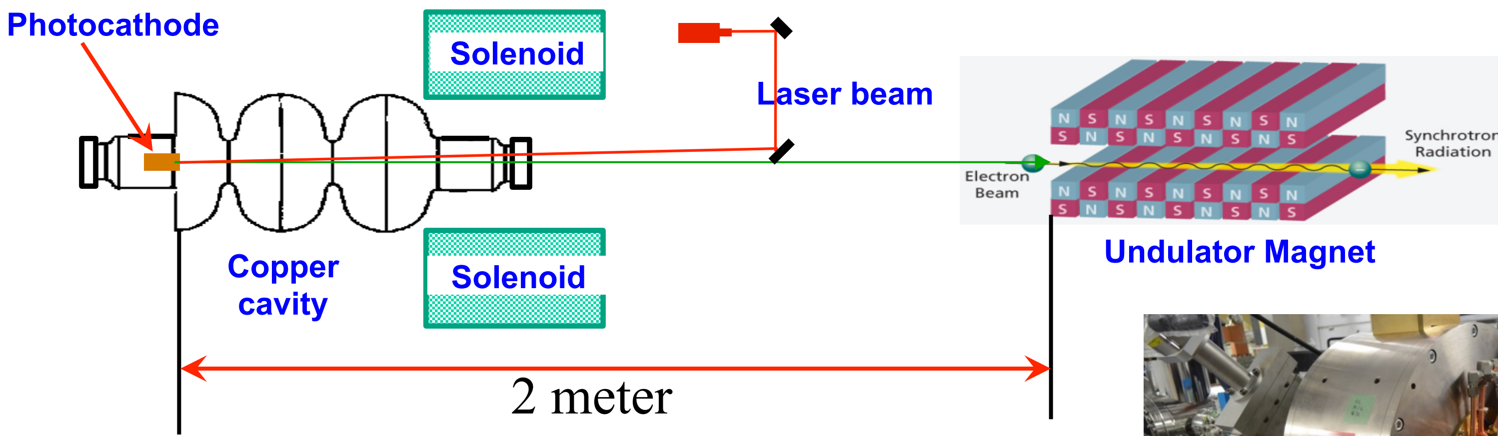
RF cavity – waiting to be installed
Photocathodes – Design frozen, tender preparation
Laser – Parameter finalized, development w KEK
Klystron, Modulator – Order to be placed – Oct '16
Solnd, Undulator, etc. – Tender floated, Designing

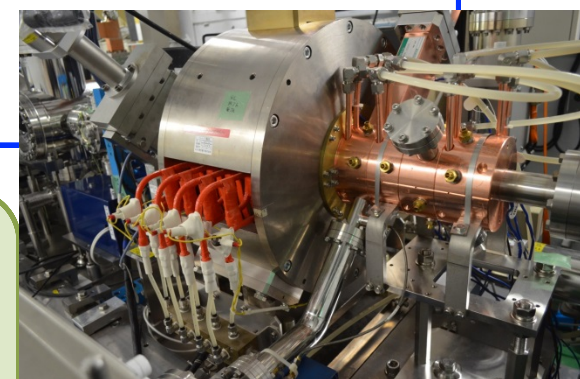
## Electronics and Control

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

- Preliminary design
- Collaboration w BARC
- Components being procured

# Beam optics calculation of Phase-I



1. Photocathode
2. Cavity
3. Solenoid
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:**

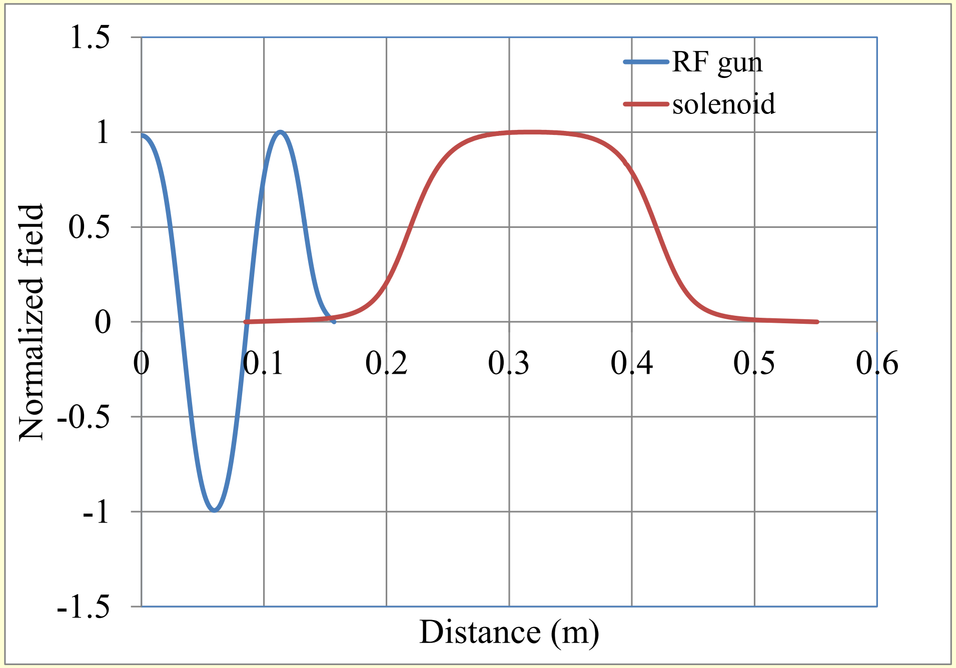
- Laser spot size
- Bunch emission time
- Charge/e-bunch
- Initial transverse emittance

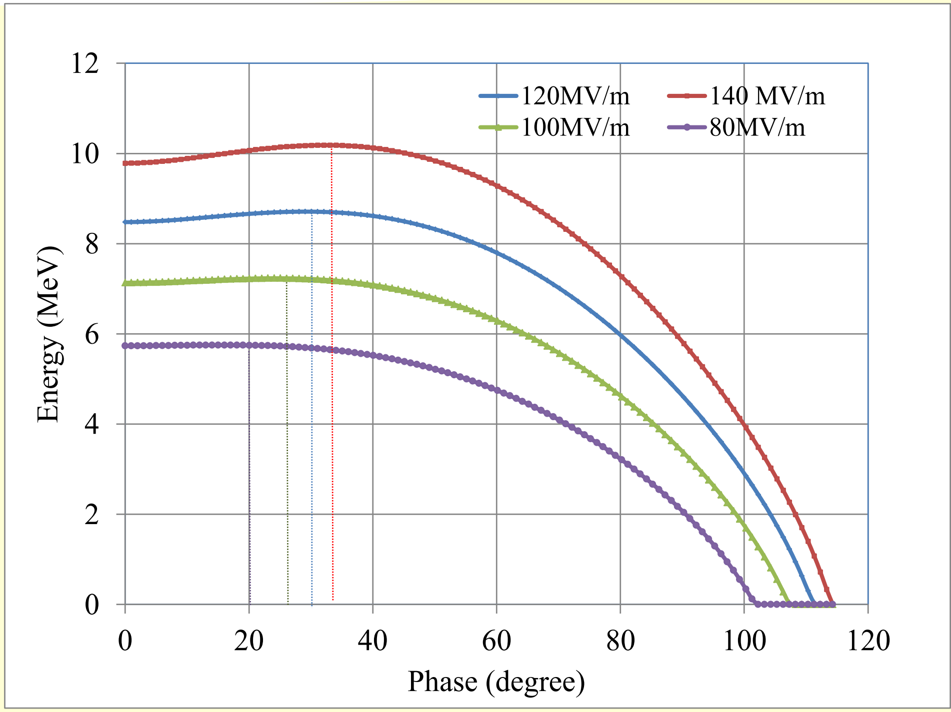
**Results (important parameters):**

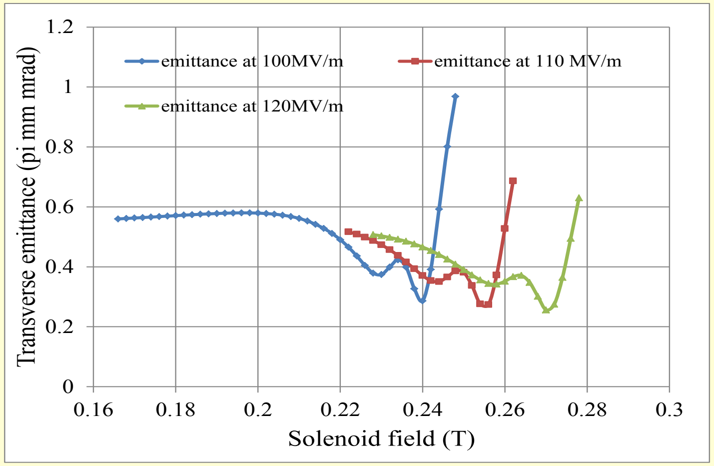
- Transverse emittance
- Spot size
- Bunch time spread
- Energy
- Energy spread

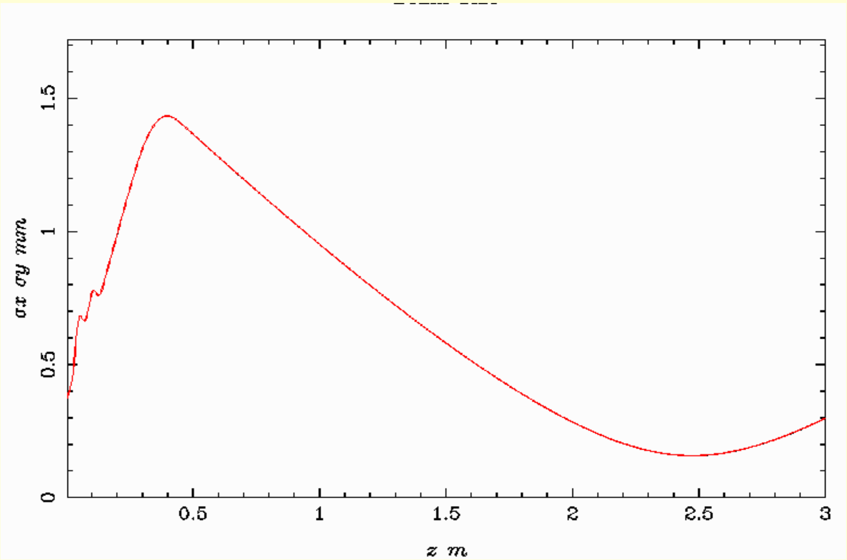
# Beam optics calculation

## Calculation with single bunch



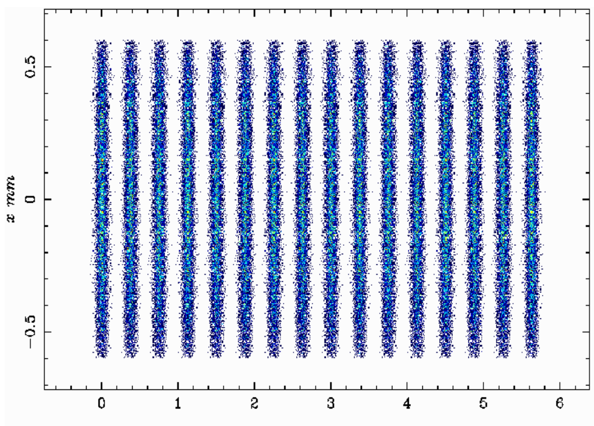



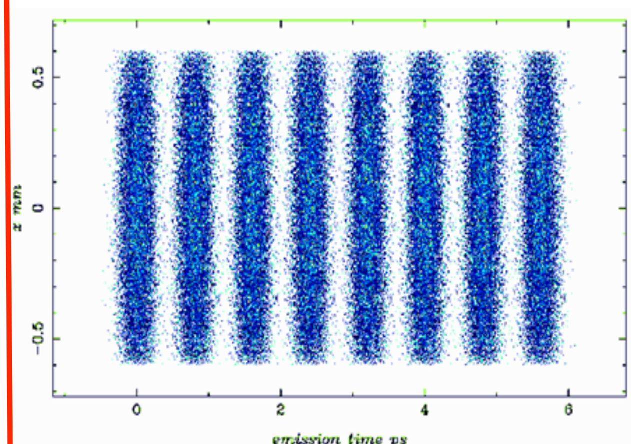
# Beam optics calculation

Energy of electron beam ~ 8.5 MeV
Microbunch FWHM at cathode: 100 & 300 fs
Microbunch separation at cath.: 375 & 800 fs

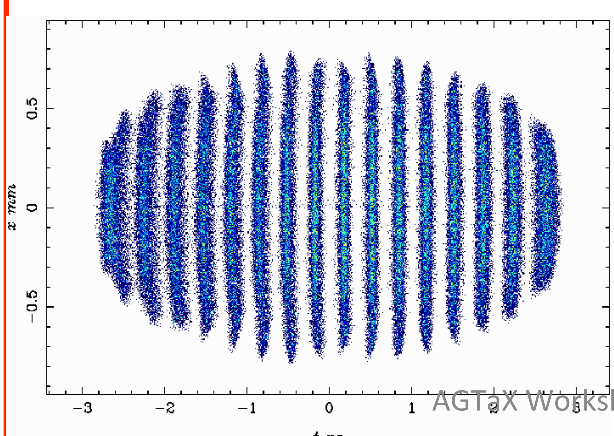
Cavity field: 120MV/m
Solenoid field: 0.273 and 0.270T
Injection phase: 35 degree

| **6 pC, FWHM/Sep - 100/375 fs** | **25 pC, FWHM/Sep - 300/800 fs** |
|---|---|
| At Cathode | At Cathode |

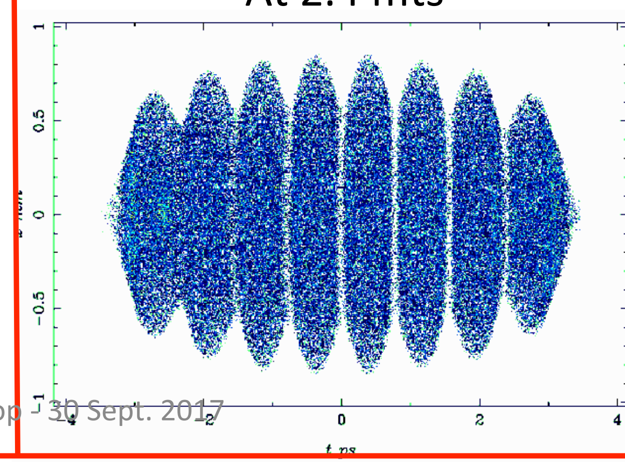


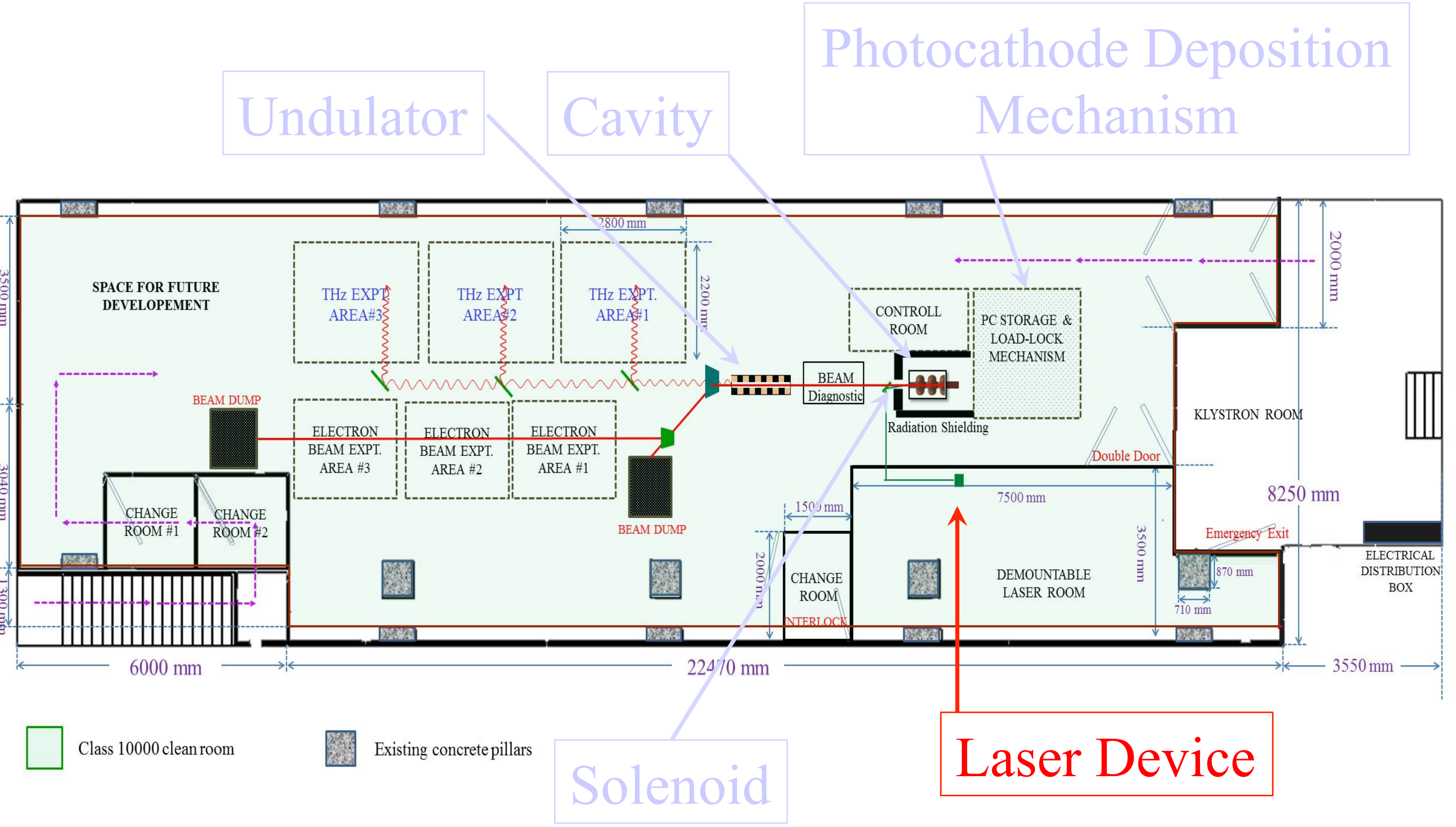

At 2.4 meter




At 2.4 mts

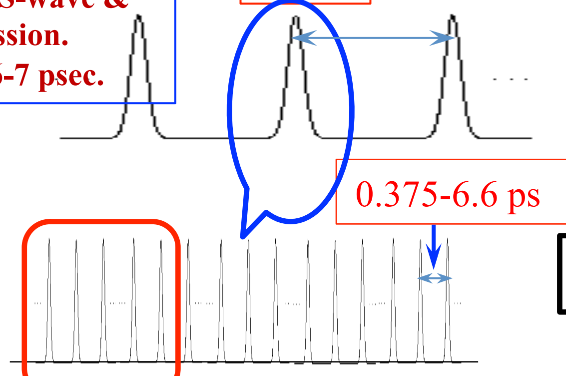


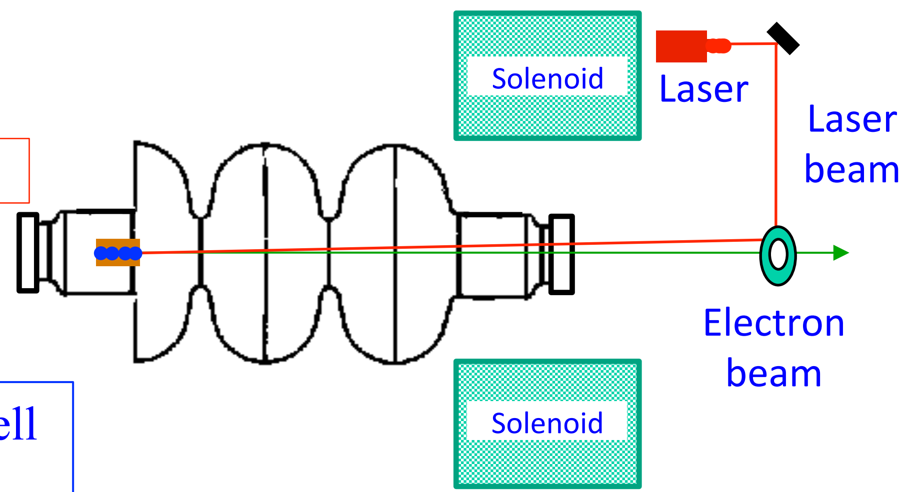
# Phase-I of the project: complete layout with expt. stations



# Laser system of Phase-I of DLS

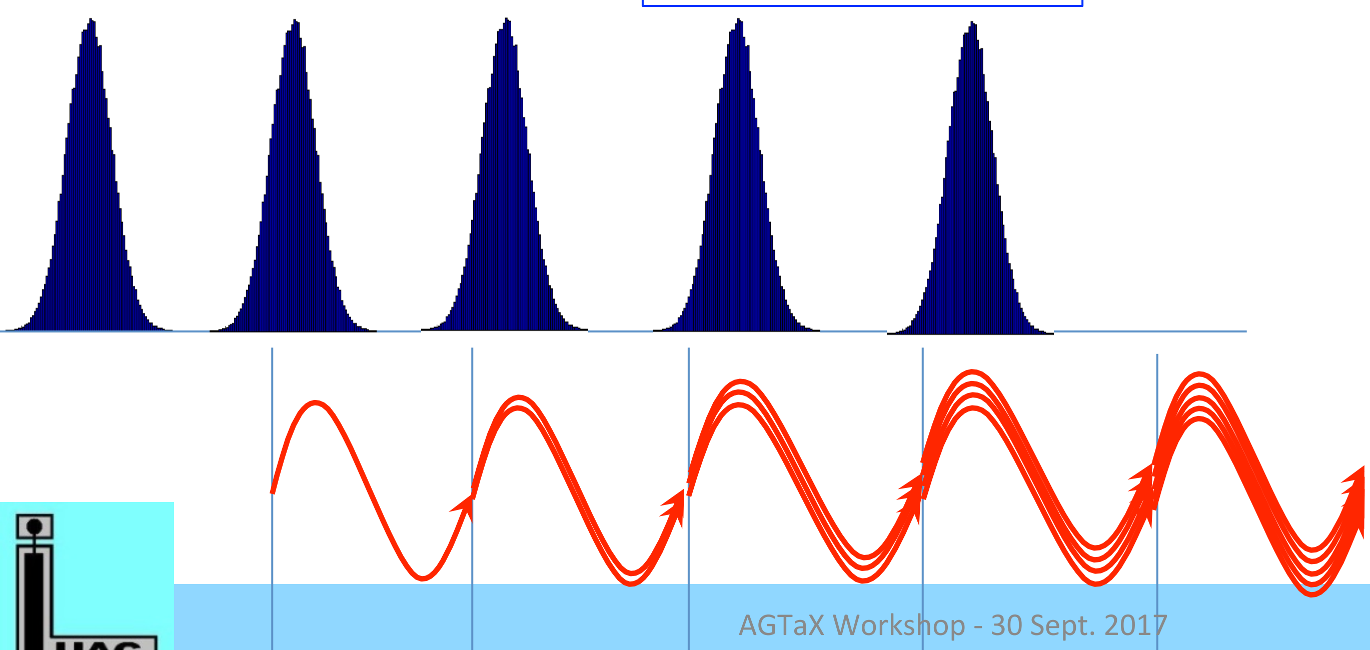
- ½ w plate rotates S-wave by 45°.
- Polarizing beam splitter makes S-wave & P-wave by reflection & transmission.
- 16 micro bunched laser within 6-7 psec.




f ~ 3 – 0.15 THz
T = 0.375 ps to 6.6 ps
? = 112 ?m to 2 mm

Laser pulses as well Electron bunches



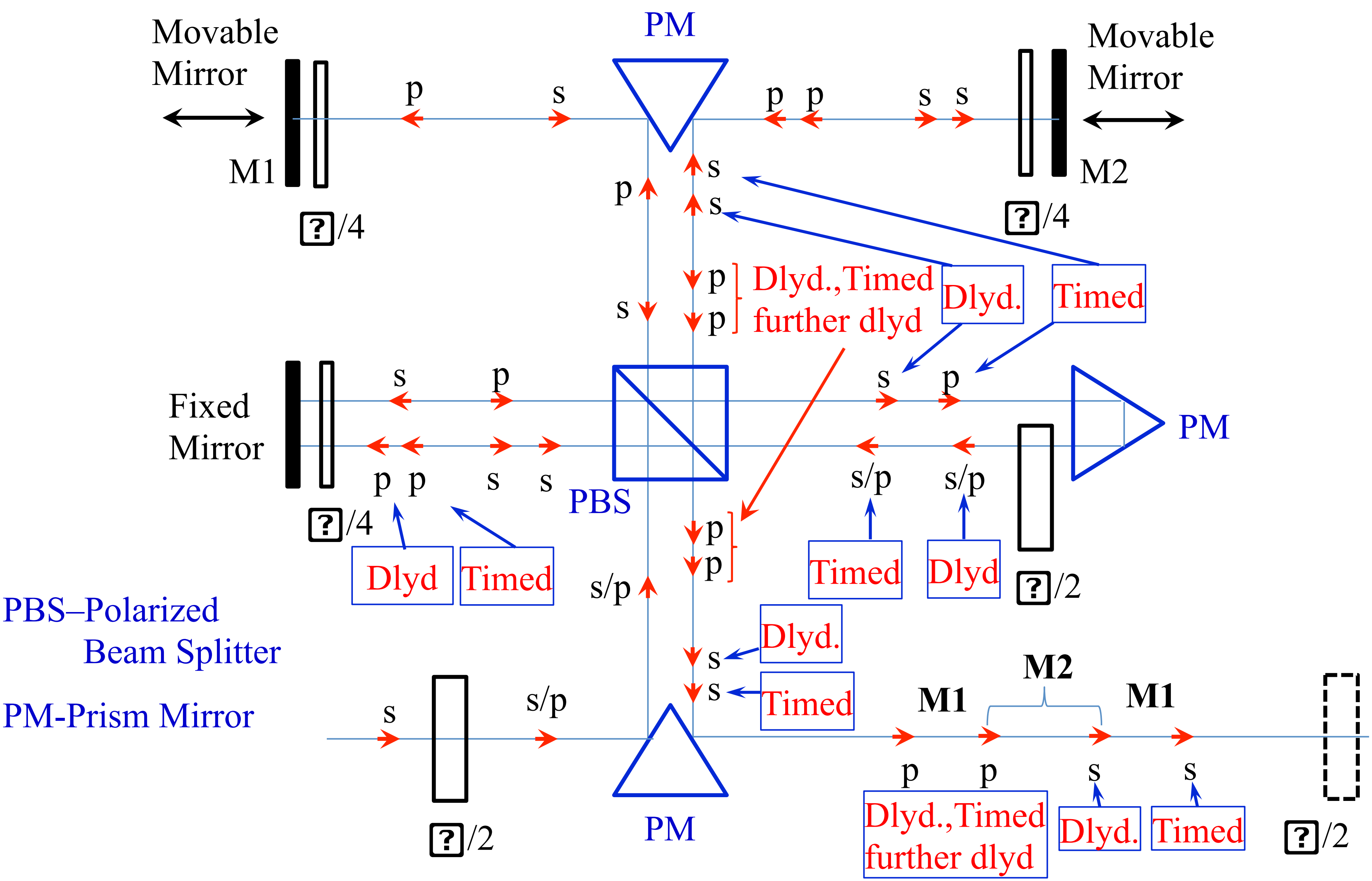
? R=? U/2?2 [1+

γ=E/E↓o =8/0.5 =16

?U – Undulator wavelength
$B_U$ – Undulator mag field

# Principle of splitting a single laser pulse in to many pulses

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



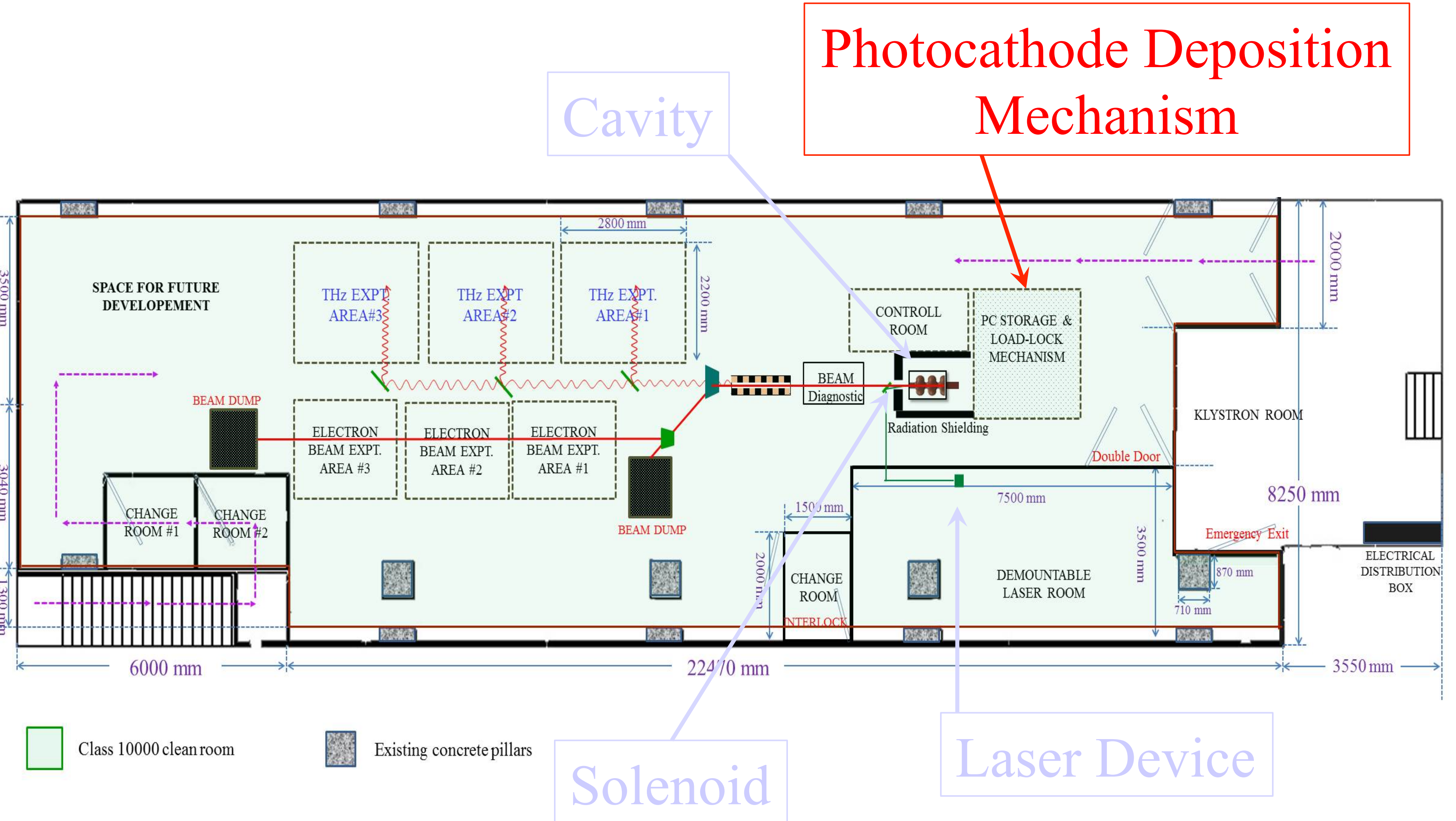
# Available laser power vs. Beam optics requirement

| Laser Specification | | | | | Beam optics Calculation | | | | |
|---|---|---|---|---|---|---|---|---|---|
| System | Energy/ pulse (UV) | Cathode | No of Microbunches | Available charge/ pulse | No. of Microbunches and Charge per microbunch | Laser system meet the requirement | Pulse width (fs) | Separation between microbunches (fs) | Frequency of THz to be produced |
| TANGERINE (Fibre) | 30 ?J | Cu | 2, 4, 8 & 16 | 28, 12, 4.5, 2.3 pC | 8 no, 4 pC | Yes | ~300 | 700 | 1.4 THz |
| | | $Cs_2Te$ | 2, 4, 8 & 16 | 13, 6, 3, 1.5 nC | 8 no, 6 pC | Yes | ~ 300 | 700 | 1.4 THz |
| S-Pulse 2 (Hybrid) | 200 ?J | Cu | 2, 4, 8 & 16 | 190, 84, 37, 15 pC | 4 no, 35 pC | Yes | ~ 500 | 1200 | 0.83 THz |
| | | $Cs_2Te$ | 2, 4, 8 & 16 | 95, 42, 18, 8 nC | 4 no, 80 pC | Yes | ~500 | 1800 | 0.55 THz |
| Ti:Sa (Solid State) | 1.5 mJ | Cu | 2, 4, 8 & 16 | 1.4, 0.6, 0.3, 0.1 nC | 16 no,6 pC | Yes | ~100 | 375 | 2.66 THz |
| | | $Cs_2Te$ | 2, 4, 8 & 16 | 710, 315, 140, 60 nC | 16 no, 6 pC | Yes | ~100 | 375 | 2.66 THz |
| Fiber Laser assembled @ KEK | 25uJ | Cu | 2, 4, 8 & 16 | 23, 10, 3.7, 2 pC | 16 no, 2 pC | Yes | ~200 | 400 | 2.50 THz |
| | | $Cs_2Te$ | 2, 4, 8 & 16 | 11, 5, 2.5, 1.2 nC | 16 no,6 pC | Yes | ~200 | 500 | 2.00 THz |

# Available laser power vs. Beam optics requirement

| Laser Specification | | | | | | |
|---|---|---|---|---|---|---|
| System | Energy/ pulse (UV) | Cathode | No of Microbunch es | Available charge/ pulse | Equipments to be supplied | Tentative Price |
| TANGERINE (Fibre) | 30 ?J | Cu | 2, 4, 8 & 16 | 28, 12, 4.5, 2.3 pC | Osc. + Amp. + Freq. Conv. + Synch. System (no splitting) | $ 425,000 |
| | | $Cs_2Te$ | 2, 4, 8 & 16 | 13, 6, 3, 1.5 nC | | |
| S-Pulse 2 (Hybrid) | 200 ?J | Cu | 2, 4, 8 & 16 | 190, 84, 37, 15 pC | Osc. + Amp. + Freq. Conv. + Synch. System (no splitting) | $ 360,000 |
| | | $Cs_2Te$ | 2, 4, 8 & 16 | 95, 42, 18, 8 nC | | |
| Ti:Sa (Solid State) | 1.5 mJ | Cu | 2, 4, 8 & 16 | 1.4, 0.6, 0.3, 0.1 nC | Osc. + Amp. + Freq. Conv. + Synch. System (no splitting) | $ 390,000 |
| | | $Cs_2Te$ | 2, 4, 8 & 16 | 710, 315, 140, 60 nC | | |
| Fiber Laser assembled @KEK | 25uJ | Cu | 2, 4, 8 & 16 | 23, 10, 3.7, 2 pC | Osc. + Amp. + Freq. Conv. + Synch. System + splitting **To be tested in KEK system** | $ 200,000 |
| | | $Cs_2Te$ | 2, 4, 8 & 16 | 11, 5, 2.5, 1.2 nC | | |

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



# Phase-I: RT e-gun

## Details of Photocathode

Photocathode:

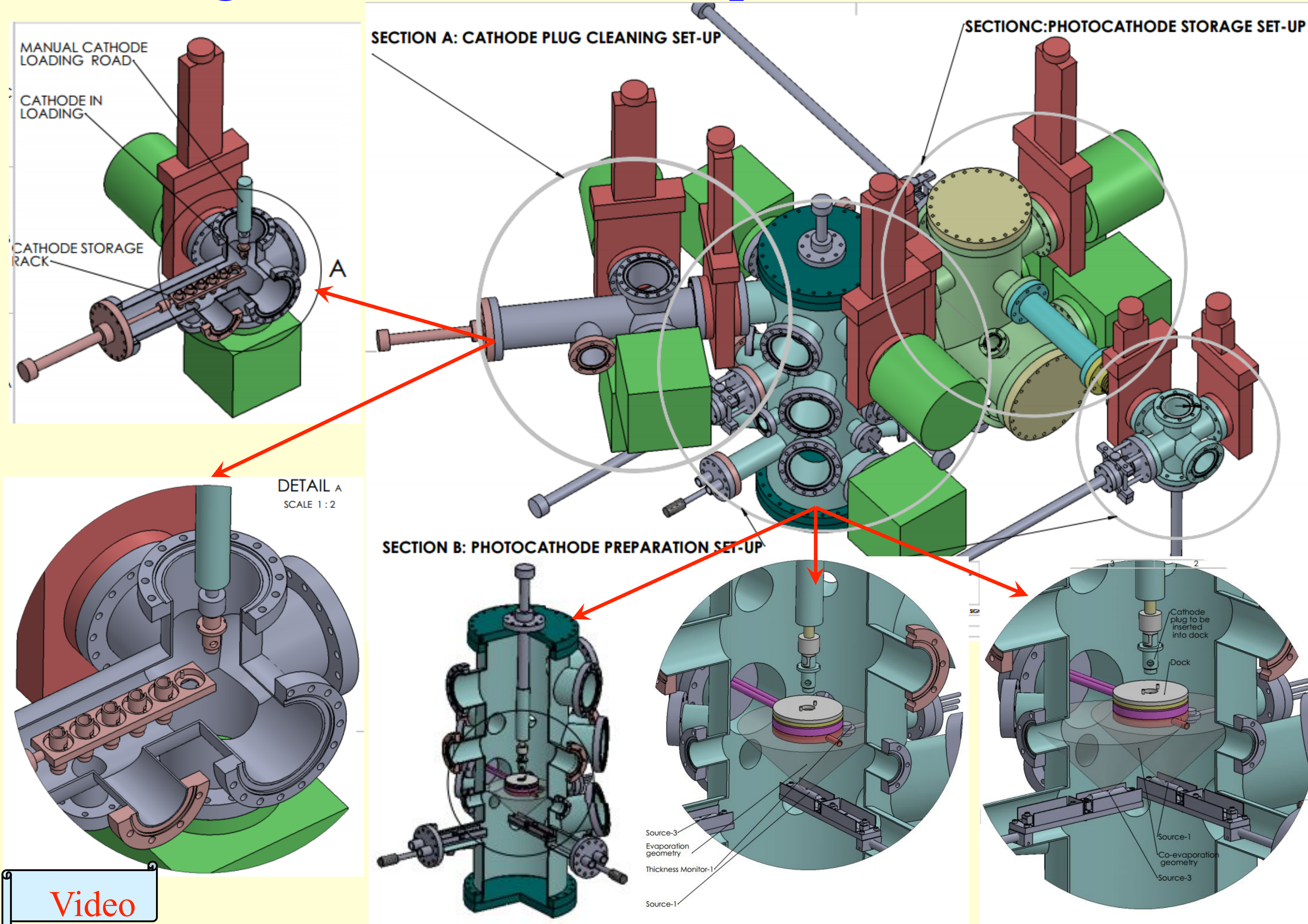
- Metal Photocathode e.g. Copper, Magnesium, Lead
- Semiconductor photocathode e.g. $Cs_2Te$, $K_2CsSb$, GaAs

To be developed at IUAC

| Cathode | Quantum Efficiency (%) | Photon Energy (eV) | Photon wavelength (nm) | Advantage | Disadvantage | Laser Energy for 1 nC/pulse (~ $10^9$ e/pulse) |
|---|---|---|---|---|---|---|
| Copper | 0.014 | 4.96 eV | 250 | Rugged, Long life, Less vac | Less QE, High Laser energy | 35.4 ?J |
| Magnesium | 0.62 | 4.66 eV | 266 | | | 9.2 ?J |
| Lead | 0.016 | 5.8 eV | 214 | | | 2.2 ?J |
| $Cs_2Te$ | ~10 | 4.66 eV | 266 | High QE, Less laser Energy | Delicate, Shorter life, UHV | 51 nJ |
| $K_2CsSb$ | ~10 | 2.33 eV | 533 | | | 23.3 nJ |
| GaAs:Cs | ~10 | 2.33 eV | 533 | | | 23.3 nJ |
| GaN:Cs<br>Thin layer of Cesium is deposited on GaN | ~15 | 4.77 eV | 260 | V. High QE robust (thk ~ 100-1000nm), QE is 50% back after 200C vac bakeout | New PC, not much data av. | 37 nJ |

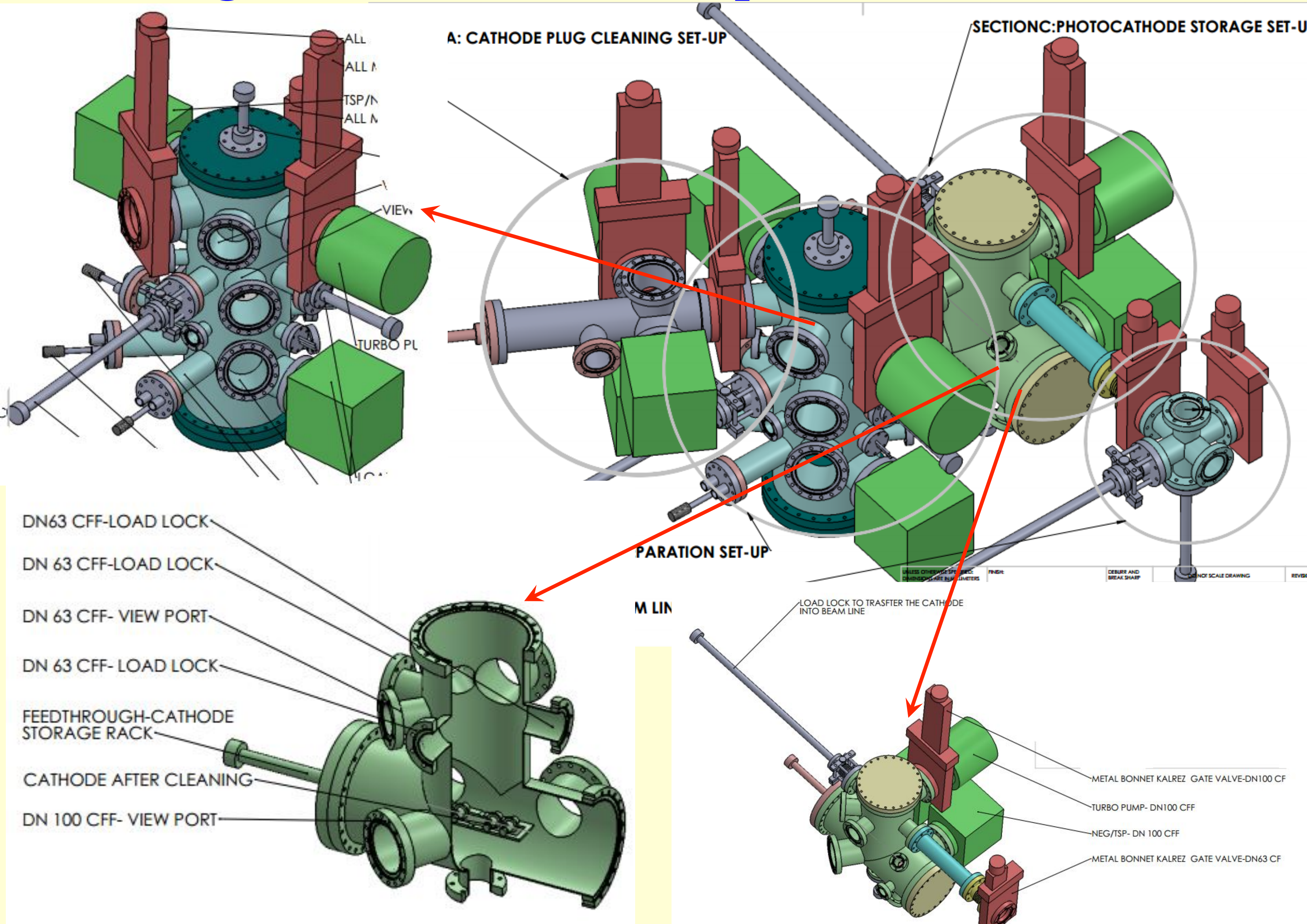
- Thickness of CsTe~ 100 nm, surface roughness ≤ 10-20 nm

# Design of Photocathode deposition mechanism

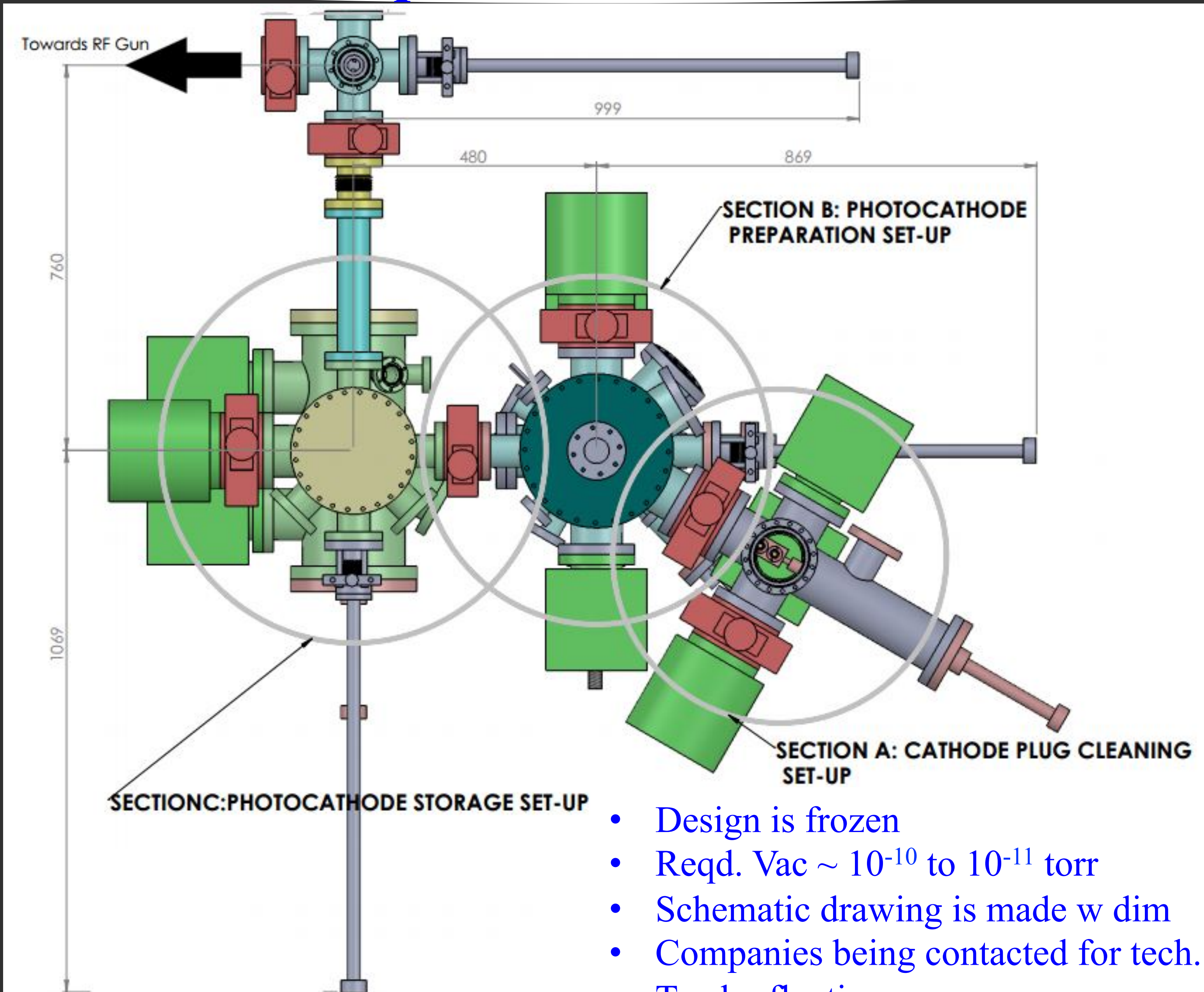



Video

# Design of Photocathode deposition mechanism

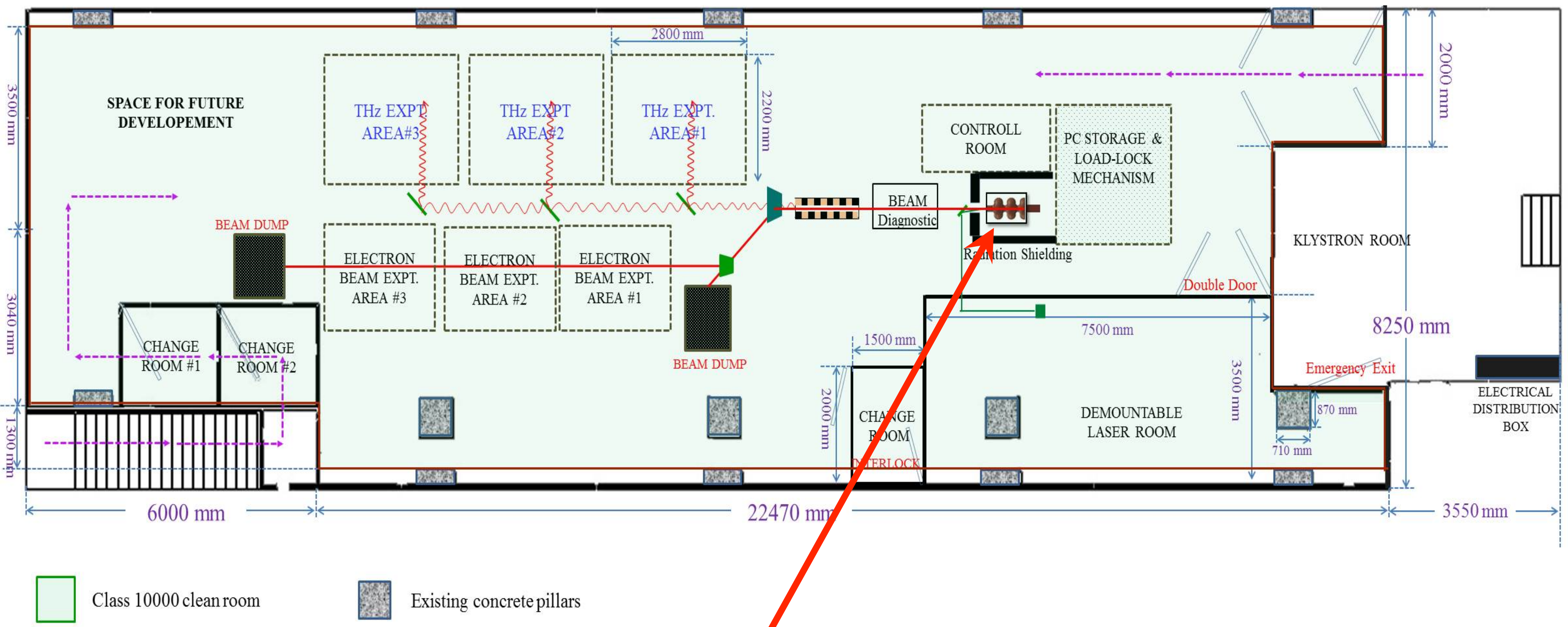


# Development of Photocathode



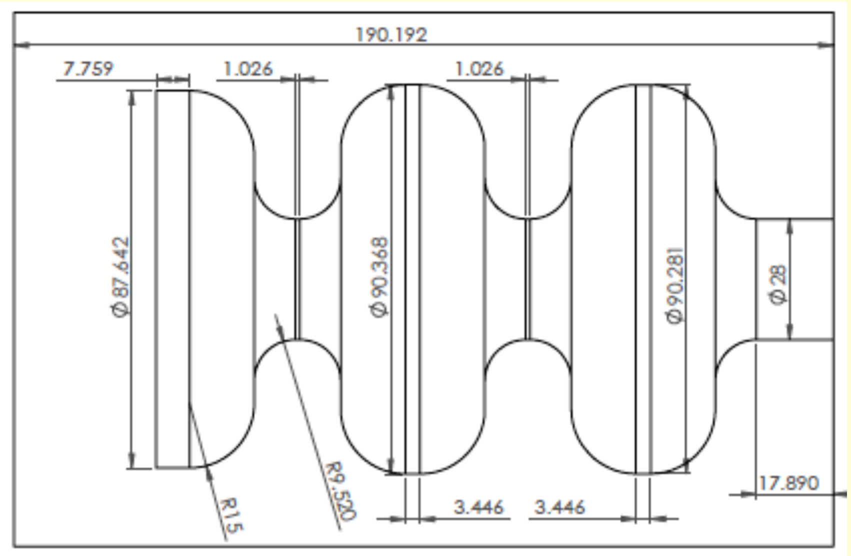

- Design is frozen
- Reqd. Vac ~ $10^{-10}$ to $10^{-11}$ torr
- Schematic drawing is made w dim
- Companies being contacted for tech. feedback
- Tender floating soon

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

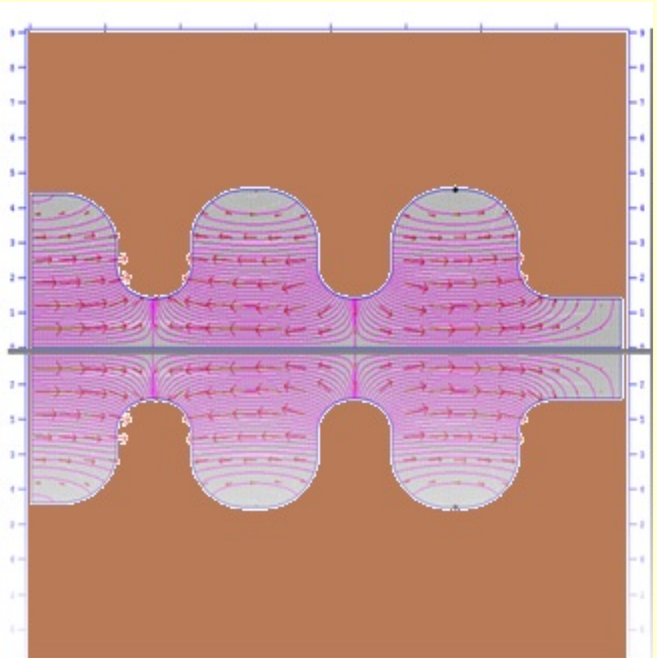


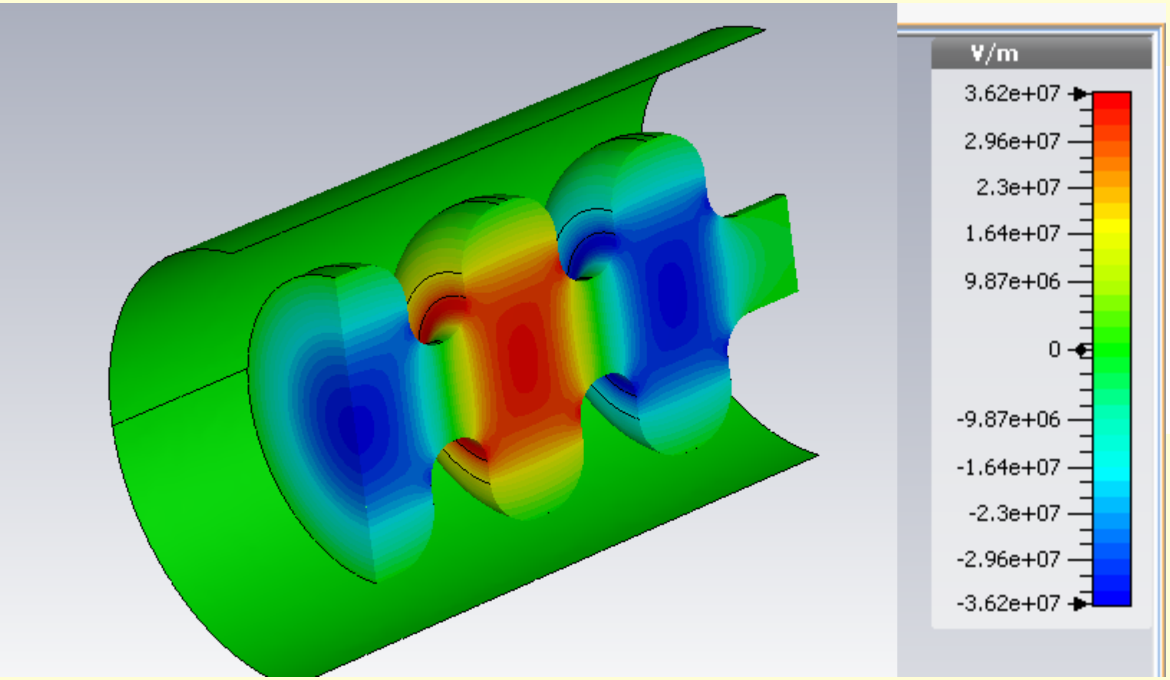

RF Cavity

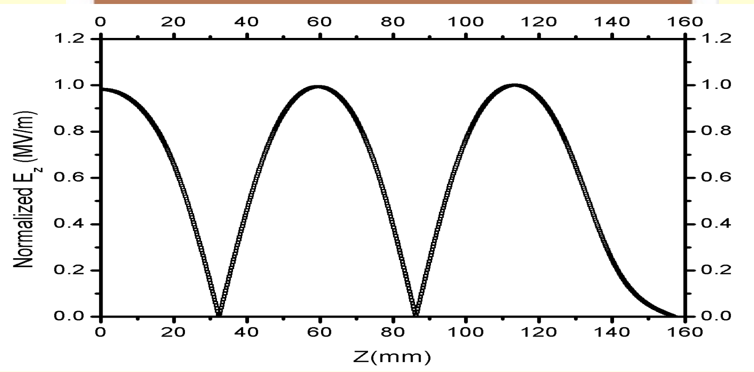
# RF cavity as e-gun – Design and Simulation



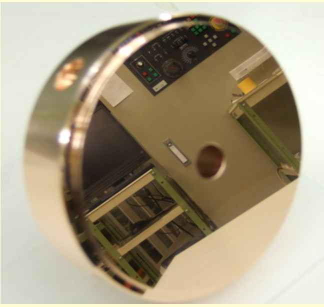

Beam Axis





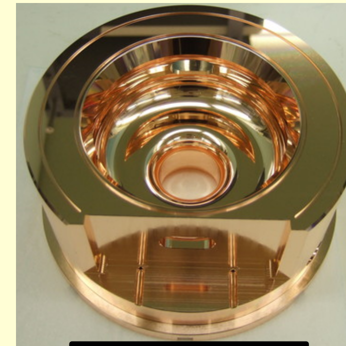
# RF cavity as the electron gun (fabrication at KEK)



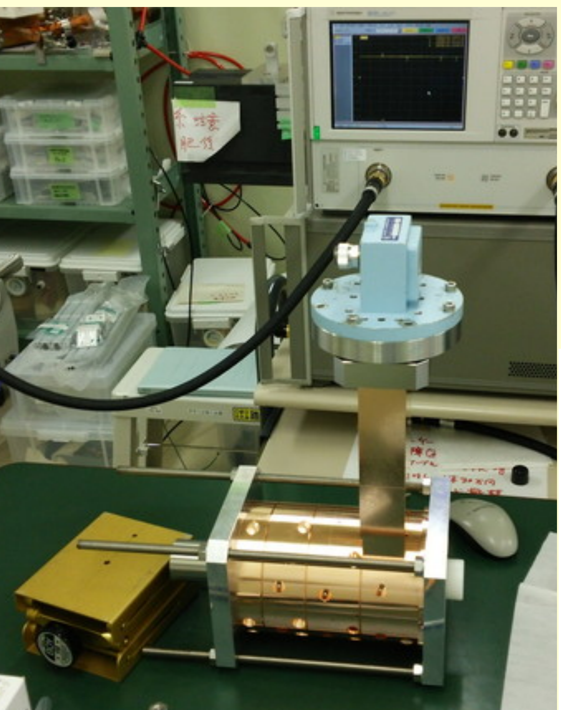
END PLATE

HALF CELL

MIDDLE CELL



FULL CELL

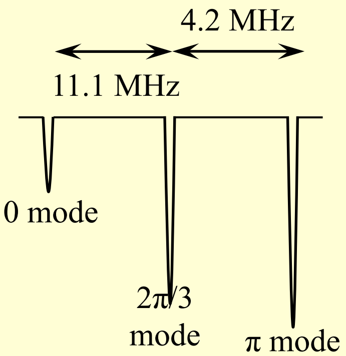


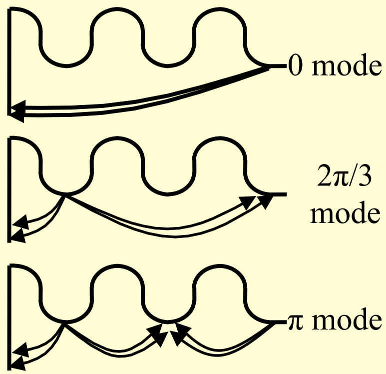
FULL CAVITY

WAVE GUIDE

| | m/c #1 | m/c #2 | m/c #3 | m/c #4 | m/c #5 |
|---|---|---|---|---|---|
| radius – HC | 43.370 | 43.71 | 43.83 | 43.85 | 43.85 |
| radius - FC1 | 44.515 | 44.99 | 45.12 | 45.14 | 45.18 |
| radius - FC2 | 44.515 | 44.84 | 44.91 | 44.95 | 45.14 |
| ? - mode | 2902.503 | 2871.267 | 2862.742 | 2860.585 | 2859.747 |

# Final testing of the RF cavity

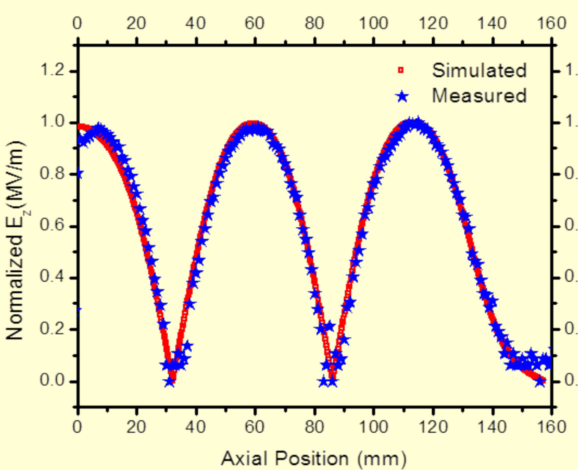


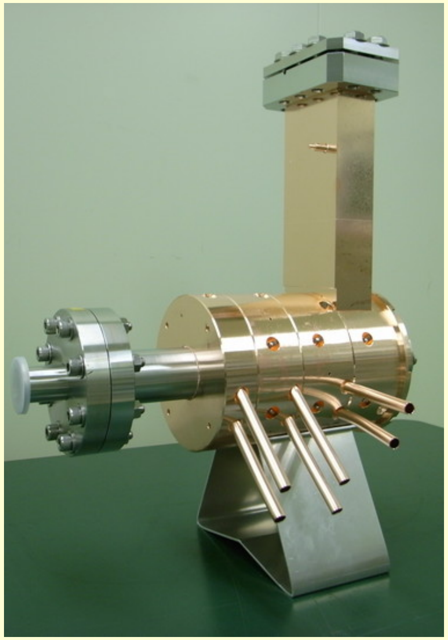




■ $1/Q_0 = 1/Q_L - 1/Q_{ext} = 1/7988 - 1/16822$ @@ $Q_0 = 15211$

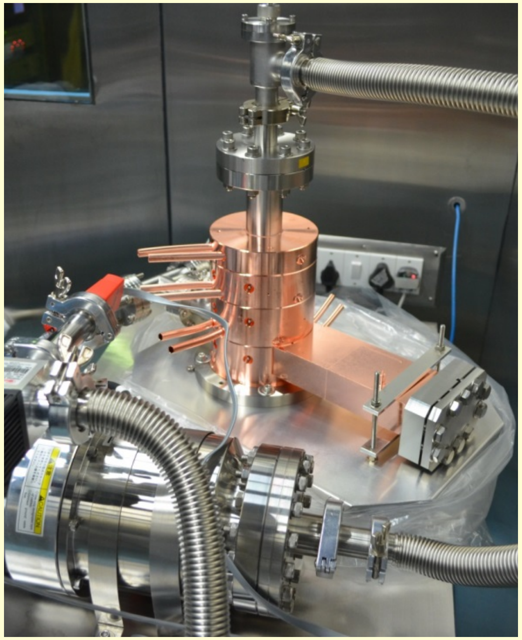
Central frequency=2859.795 MHz @ 24.8C

? = 0.904, Metal bead dia ~ 1.89 mm



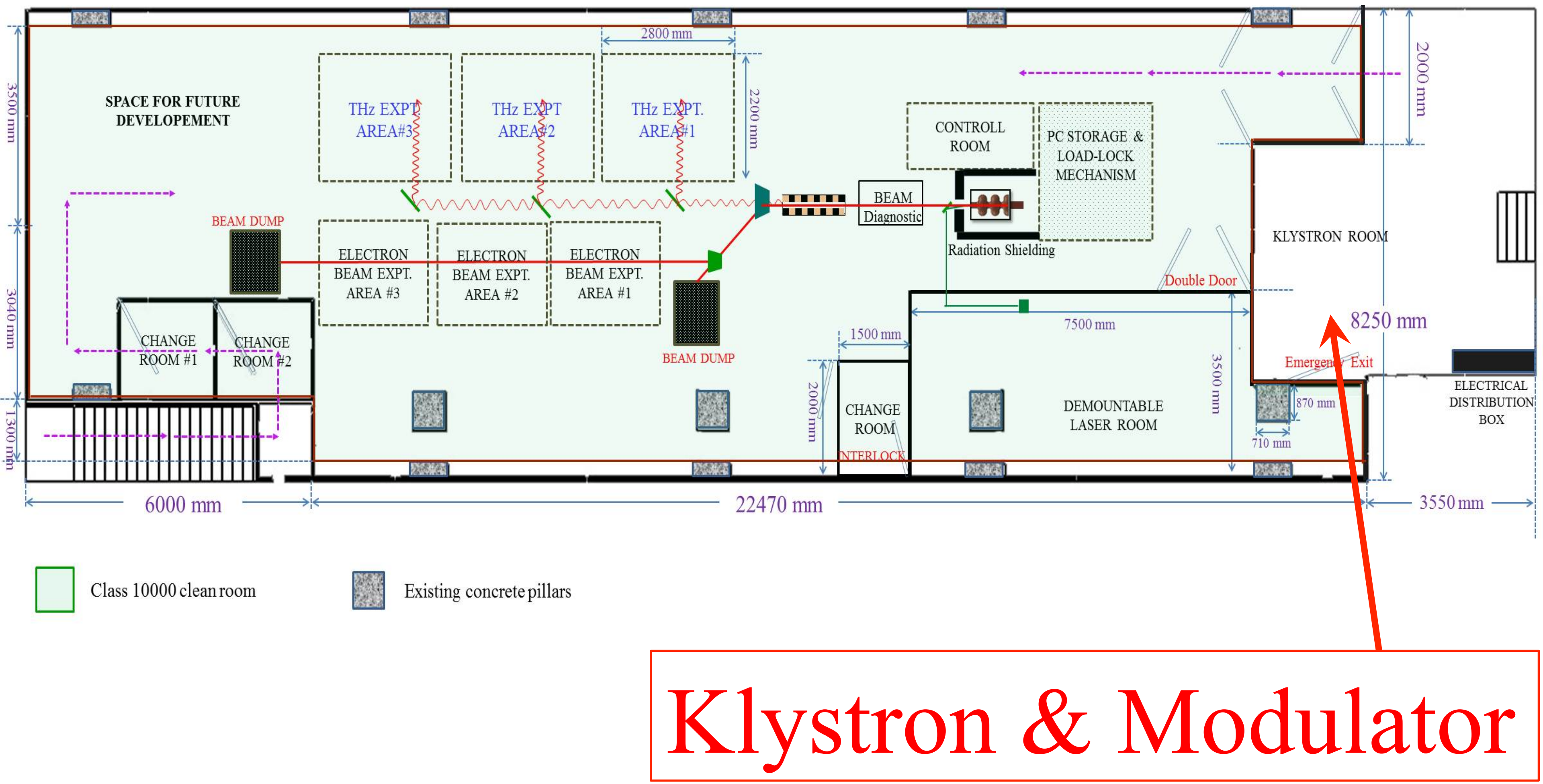



At KEK

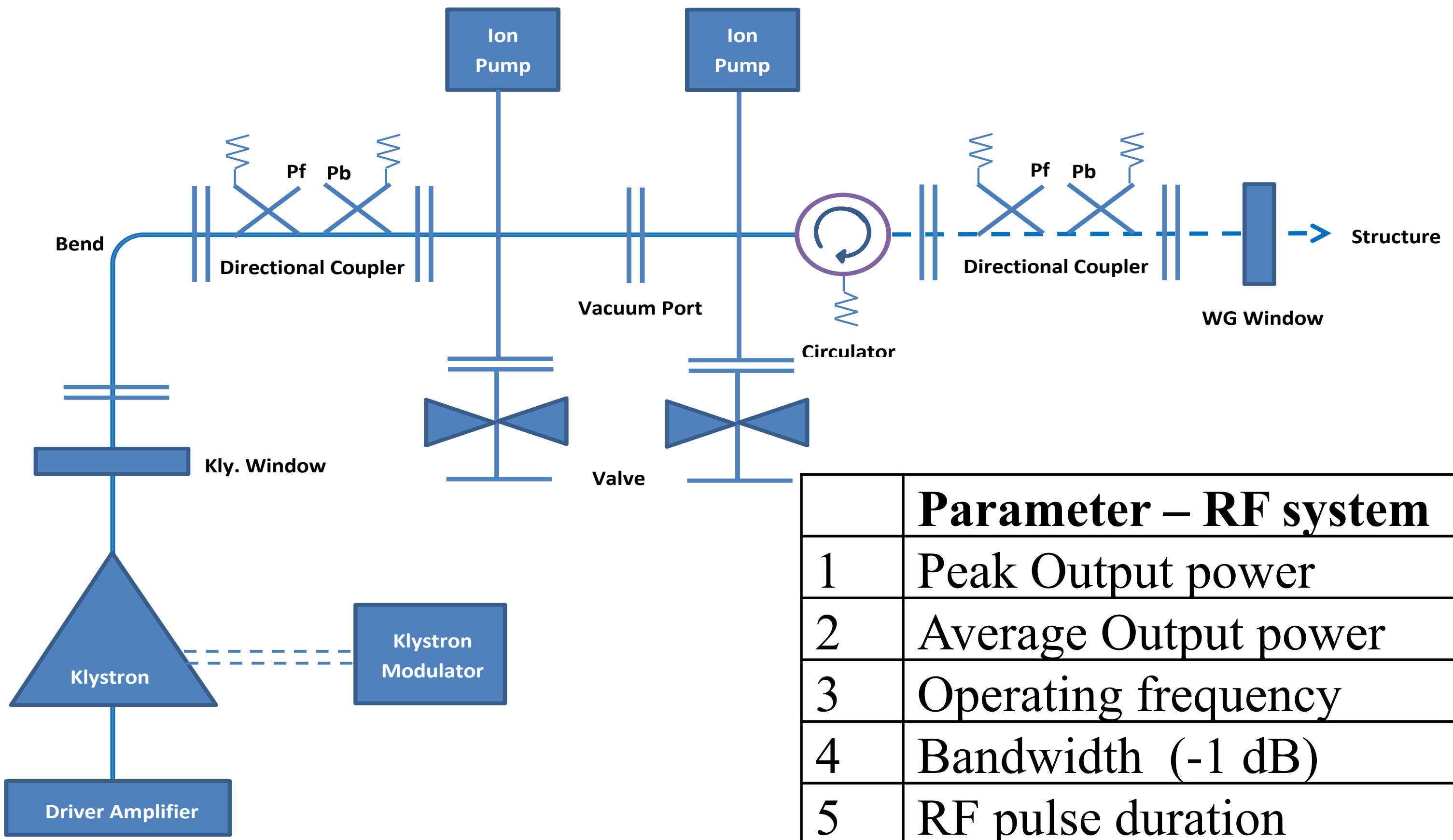


At IUAC

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



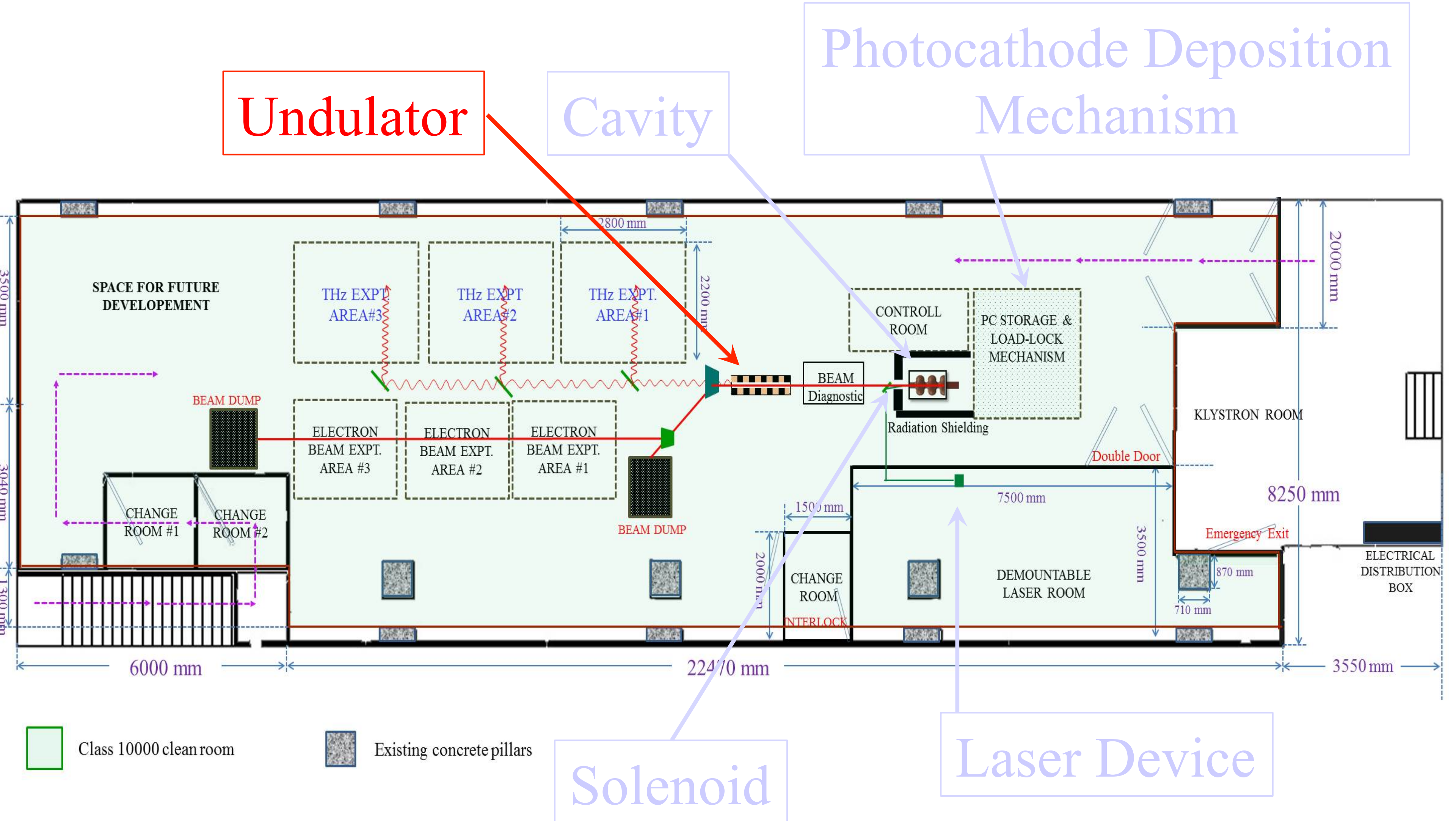
# Proposed RF system with circulator



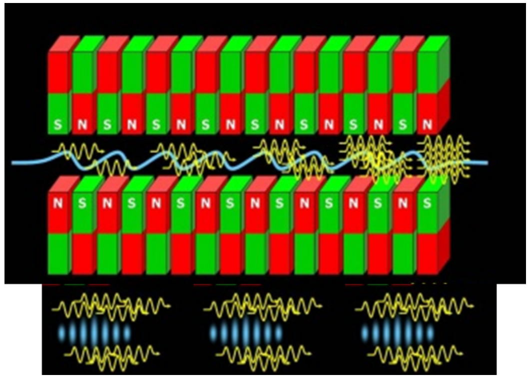

| | Parameter – RF system | Value |
|---|---|---|
| 1 | Peak Output power | ≥ 25 MW |
| 2 | Average Output power | ≥ 5 kW |
| 3 | Operating frequency | 2860 MHz |
| 4 | Bandwidth (-1 dB) | ± 1MHz |
| 5 | RF pulse duration | 0.2 µs to 4 µs |
| 6 | Pulse repetition rate | 1-50 Hz |
| 7 | Pulse top flatness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

**Order is being placed: Toshiba & Scandinova**

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



# Tentative undulator parameters for THz



| $\lambda_R$ (mm) | Freq. to be Produced (THz) | Electron Energy (MeV) | $\lambda_U$ (mm) | K – value | $B_u$ (T) | Required gap (mm) |
|---|---|---|---|---|---|---|
| 2 | 0.15 | 4 | 40 | 2.264 | 0.61 | 16 |
| 0.1 | 3 | 8 | 40 | 0.475 | 0.13 | 36 |

$K = e \times Bu \times \lambda u / 2\pi mc$

Structure: Planer with PM

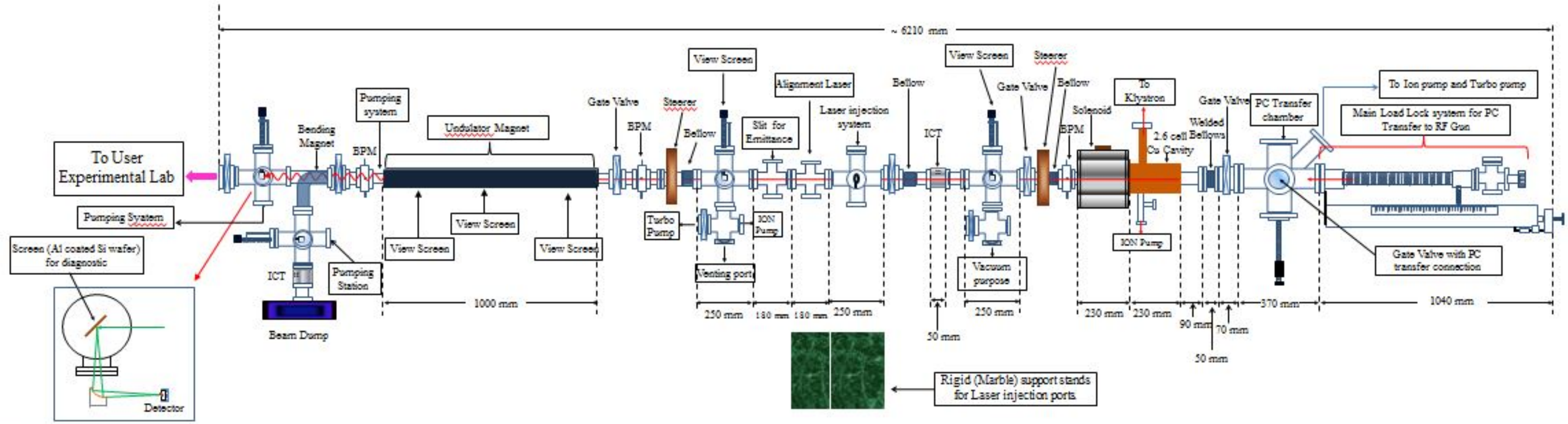
$\lambda_R = \lambda u / 2\gamma 2\ [1 + K2/2\ ]$

$\gamma = E/E0$

$B_u = 3.694 \exp[-5.068\ g/\lambda u + 1.52\ (g/\lambda u)^2]$

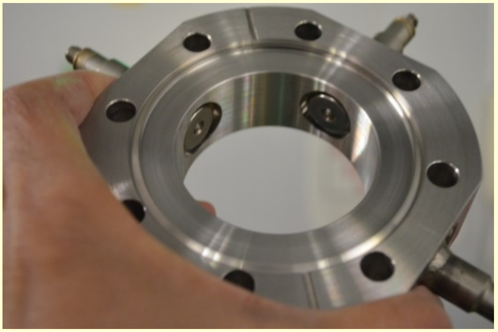
For hybrid undulator made from NdFeB magnet with $0.1 < g/\lambda u < 1.$

# Layout of the beam line of Phase-I

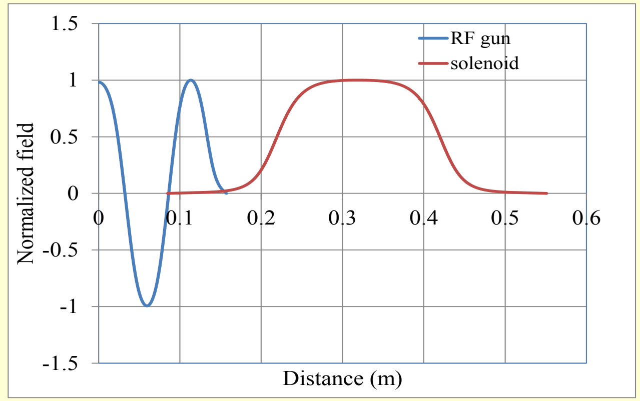


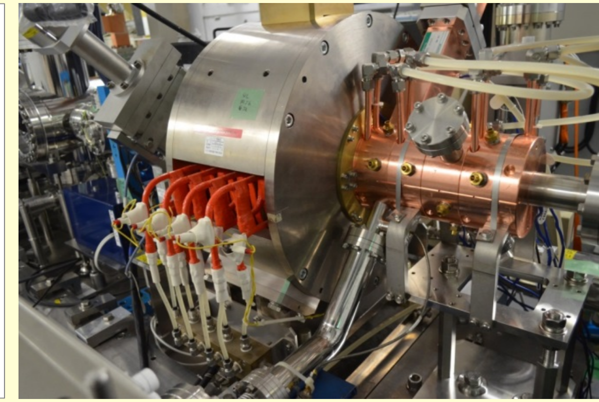
# Beam transport/diagnostic devices

## Beam Position Monitor

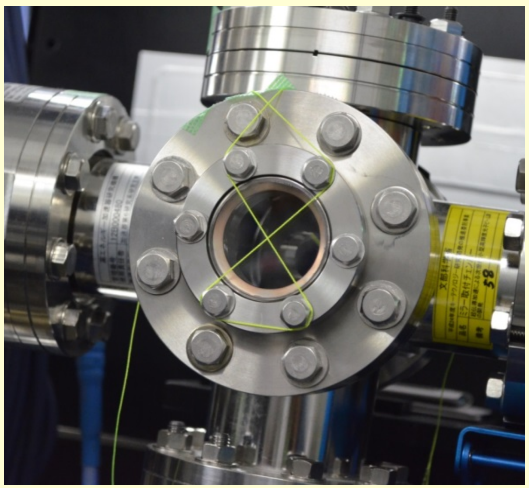


## Solenoid magnet to focus the beam

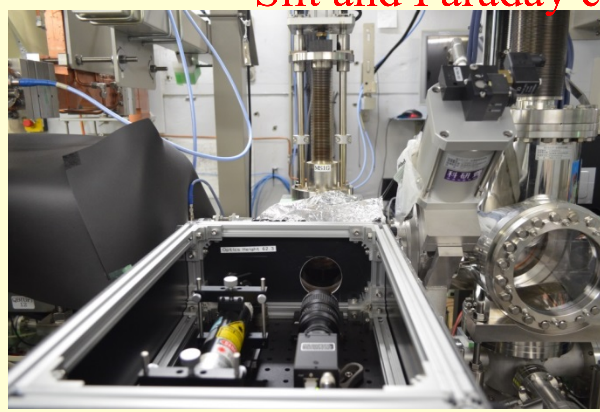


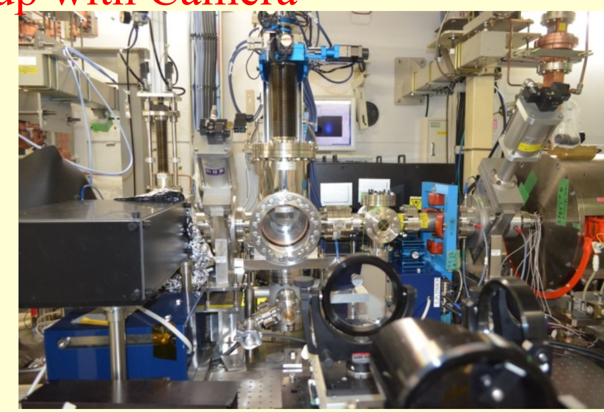



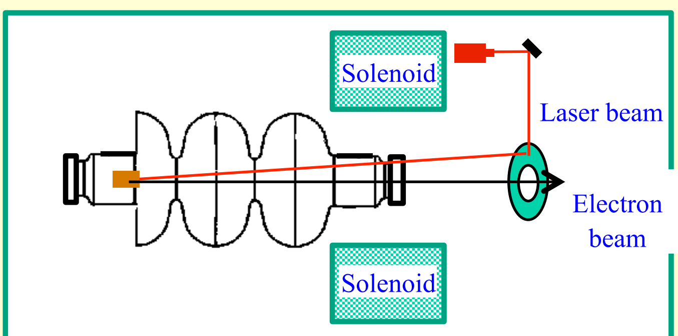
## Laser reflection mirror and beam passage



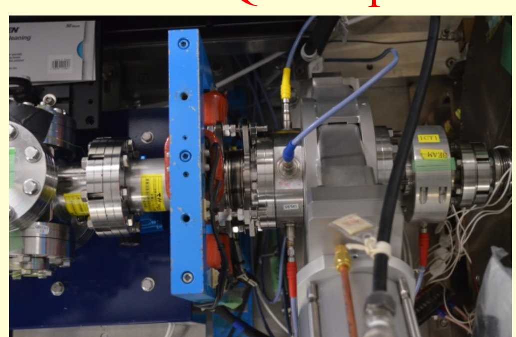
## Slit and Faraday cup with Camera

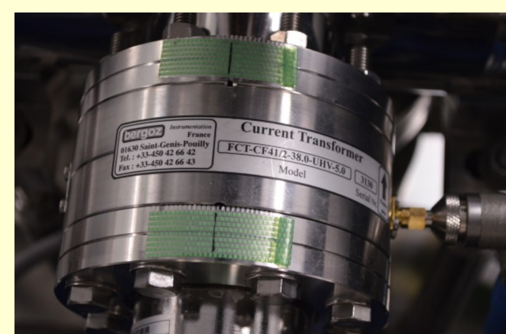




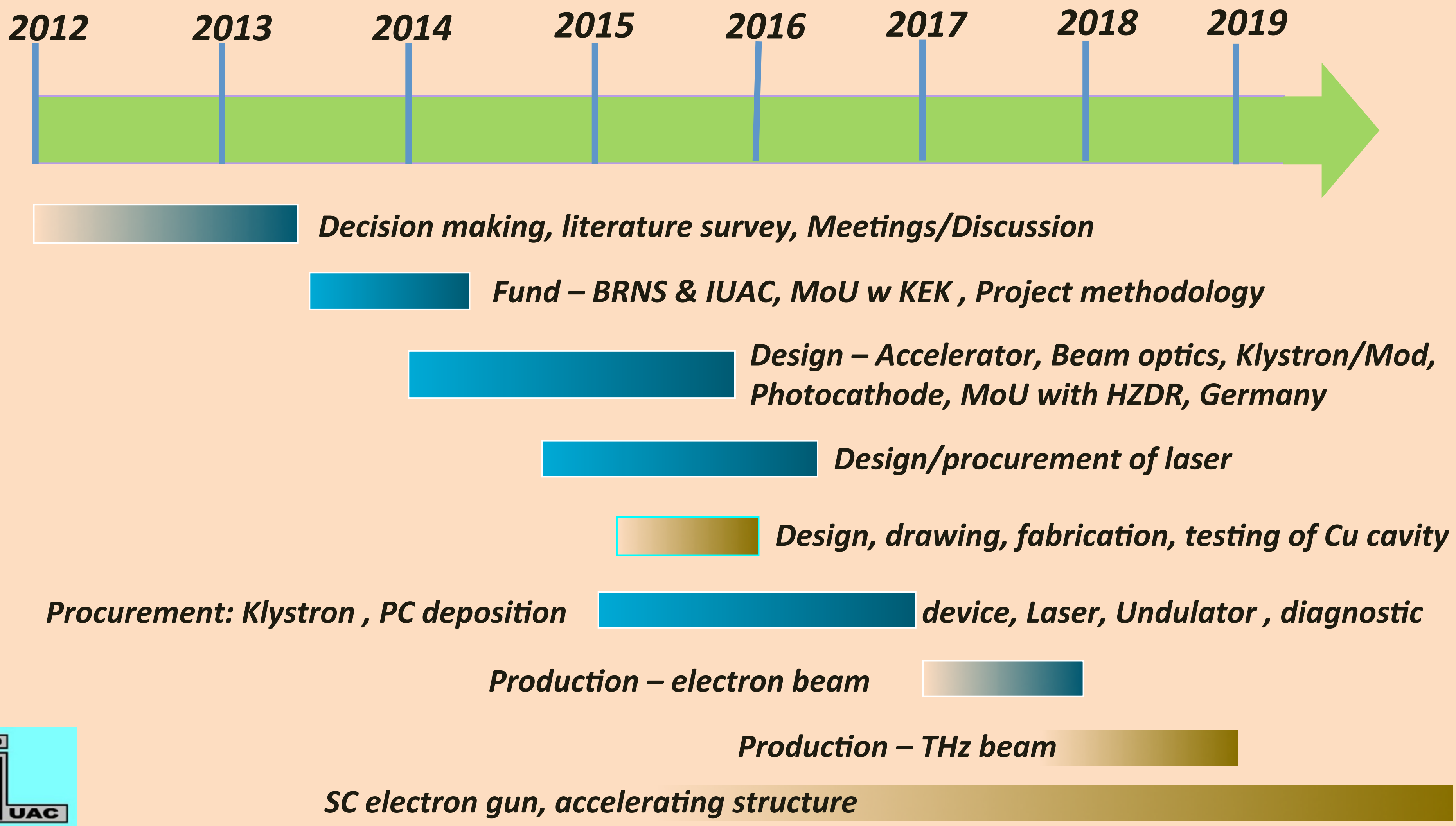



## Quadrupole magnet and ICT





# Time chart – for Phase I of DLS




IUAC

# Conclusion

- Status of the major components:
  - Copper cavity – Fabricated and tested (LLRF) at KEK, under evacuation at IUAC
  - Klystron/Modulator –order will be placed next month
  - Cu photocathode has been prepared. Design of dep. chamber for $Cs_2Te$ is being done
  - Beam optics simulation is done with ASTRA. Being validated by other GPT.
  - Laser system – Design finalized, development with KEK, Waseda soon
  - Beam line components:
    - Solenoid design is frozen, budgetary estimate is obtained, procurement soon
    - Design of other magnets is being started. Undulator – design stage
    - BPM, FC, other beam diagnostic elements are being procured
- Clean room and other utilities are being prepared. Will be ready by Oct. 2016
- 2016 – required for infrastructure development, equipment procurement, testing & installation
- 2017 – dedicated for generation for e-beam
- 2018 – dedicated for THz generation

# Core member of FEL team

### INDIAN INSTITUTIONS

1. Dr. D. Kanjilal, IUAC
2. Dr. R.K. Bhandari, IUAC
3. Dr. Gopal Joshi, BARC
4. Dr. S. Ghosh, IUAC
5. Dr. V. Naik, VECC
6. Dr. Manjiri Pande, BARC
7. Dr. A. Deshpande, SAMEER
8. Mr. B.K.Sahu, IUAC
9. Dr. D.Kabriraj, IUAC
10. Mr. P.Patra, IUAC
11. Mr. SRV Abhilash, IUAC
12. Mr. J.Karmakar, IUAC
13. Mr. B.Karmakar, IUAC
14. Dr. N.Kumar
15. Mr. V.Joshi
16. Mr. G.K.Chaudhary, IUAC

### JAPANESE INSTITUTIONS

1. Prof. J.Urakawa, KEK
2. Prof. N.Terunuma, KEK
3. Prof. S. Fukuda, KEK
4. Dr. M.Fukuda, KEK
5. Dr. A.Aryshev, KEK
6. Mr. T.Takatomi, KEK
7. Prof. Hirayama, KEK
8. Dr. K.Sakaue, Waseda Univ.
9. Prof. J.Yang, Osaka Univ.
10. Mr. I.Nozawa, Osaka Univ.

### OHER INSTITUTIONS

1. Dr. P. Michel, HZDR, Germany
2. Dr. T.Rao, BNL, USA

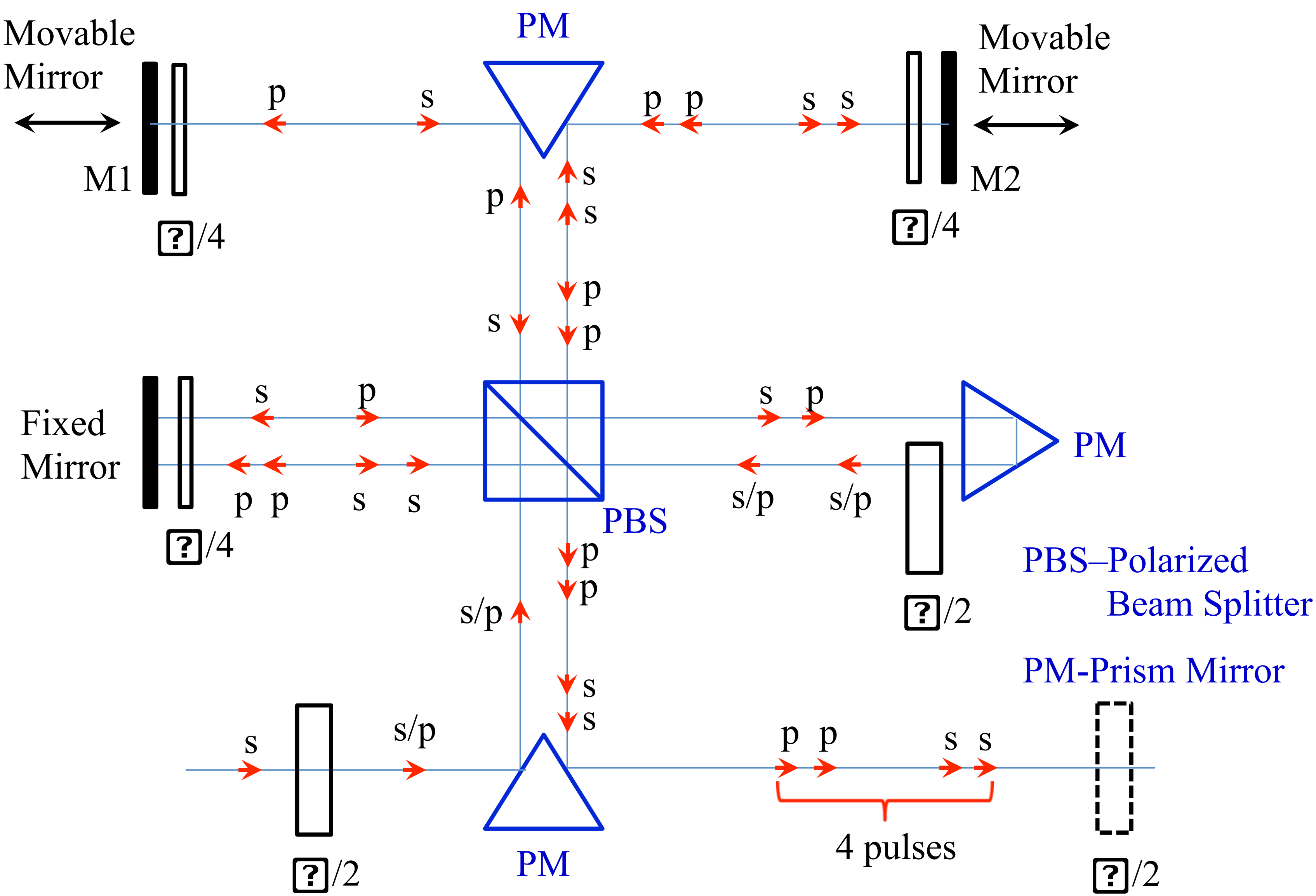
# Thanks for your patience

# Expected outcome – Phase-I of DLS

- **Electron beam (pulsed)**
  - Energy ~ 8 MeV (max), Emittance ~ 1 pi mm mrad
  - Peak current ~ tens to hundreds of Amps, Average current ~ nA
  - Time width ~ hundred of fs to a few ps,
  - microbunch train of 16 (max) @ 10 Hz

- **THz radiation (pulsed)**
  - Frequency range (tunable) ~ 0.15 to 3 THz
  - No. of photons per microbunch ~ $10^{26}$ (FWHM~500 fs, separation~ 700 fs, f~1.4 THZ)

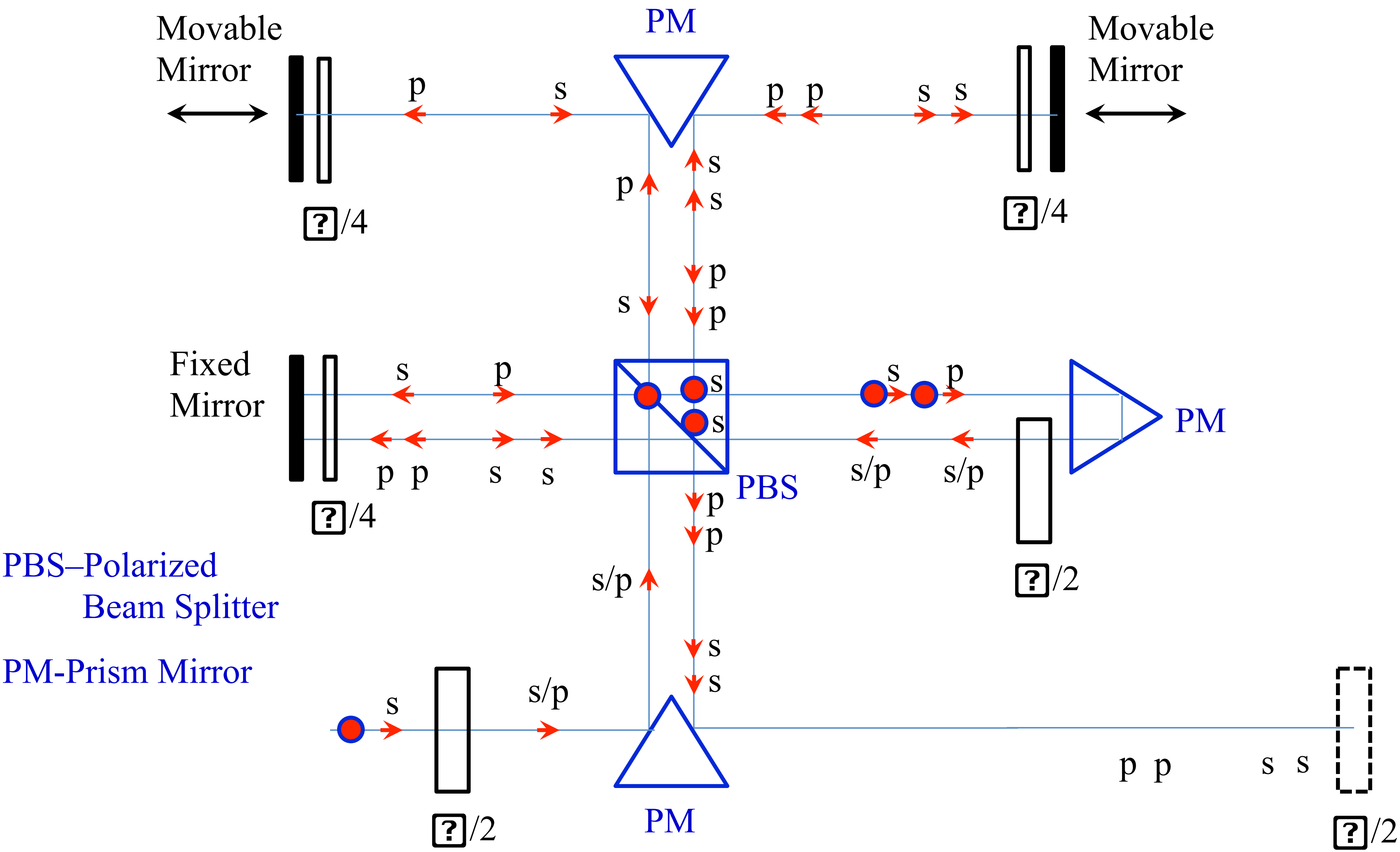
# A single laser pulse is split in to four laser pulses with variable separation






Courtesy: Dr. A. Aryshev

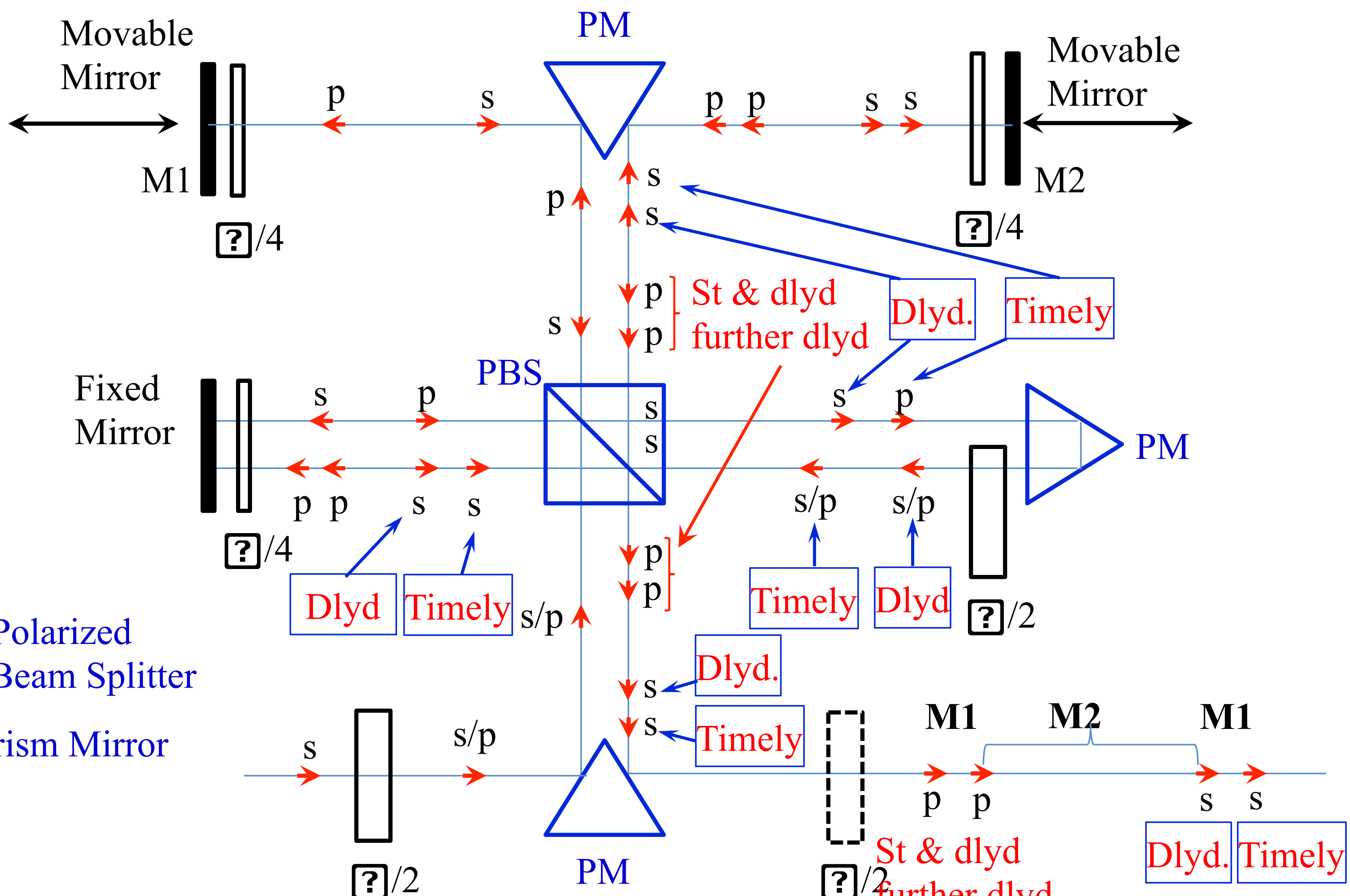
# A single laser pulse is split in to four laser pulses with variable separation






Courtesy: Dr. A. Aryshev

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



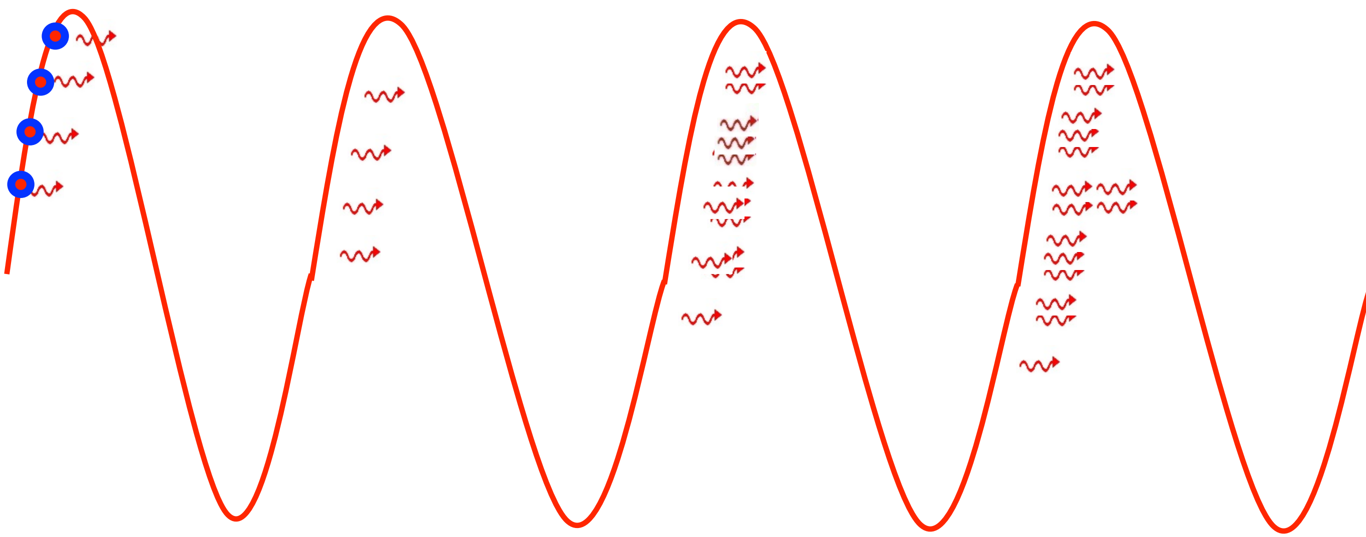

PBS–Polarized Beam Splitter

PM-Prism Mirror



Courtesy: Dr. A. Aryshev

# Where Photon meets Electron



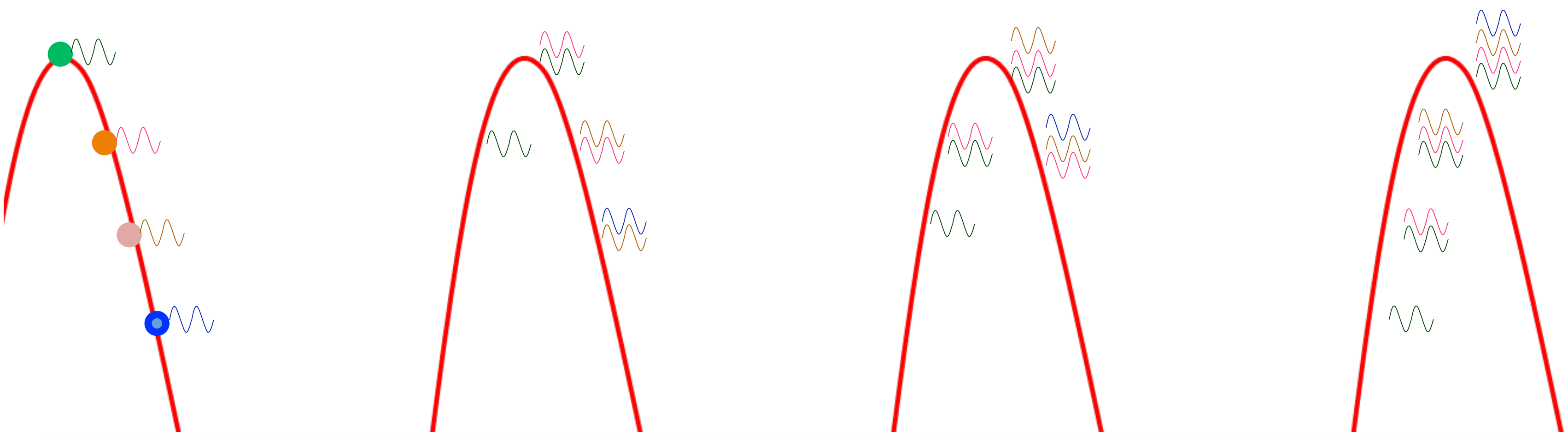
$v_z = c\,?\,[1 - (1+K2/2$

$? U/c = ? U - ?$

| freq (THz) | Energy (MeV) | K_undulator | Longitudinal Velocity of electron ($v_z$) m/sec | Undulator wavelength (m) |
|---|---|---|---|---|
| 0.15 | 4 | 2.982 | 2.8667E+08 | 0.045 |
| 0.3 | 5 | 2.552 | 2.9333E+08 | 0.045 |
| 0.6 | 6 | 2.032 | 2.9667E+08 | 0.045 |
| 1 | 7 | 1.733 | 2.9800E+08 | 0.045 |
| 2 | 7 | 0.709 | 2.9900E+08 | 0.045 |
| 3 | 8 | 0.423 | 2.9933E+08 | 0.045 |

# Where Photon meets Electron

$$?\,U/c = ?\,U - ?\,R/v_z \qquad v_z = c\,?\,[1 - (1+K^2/2)/2\,?\,?^2]$$



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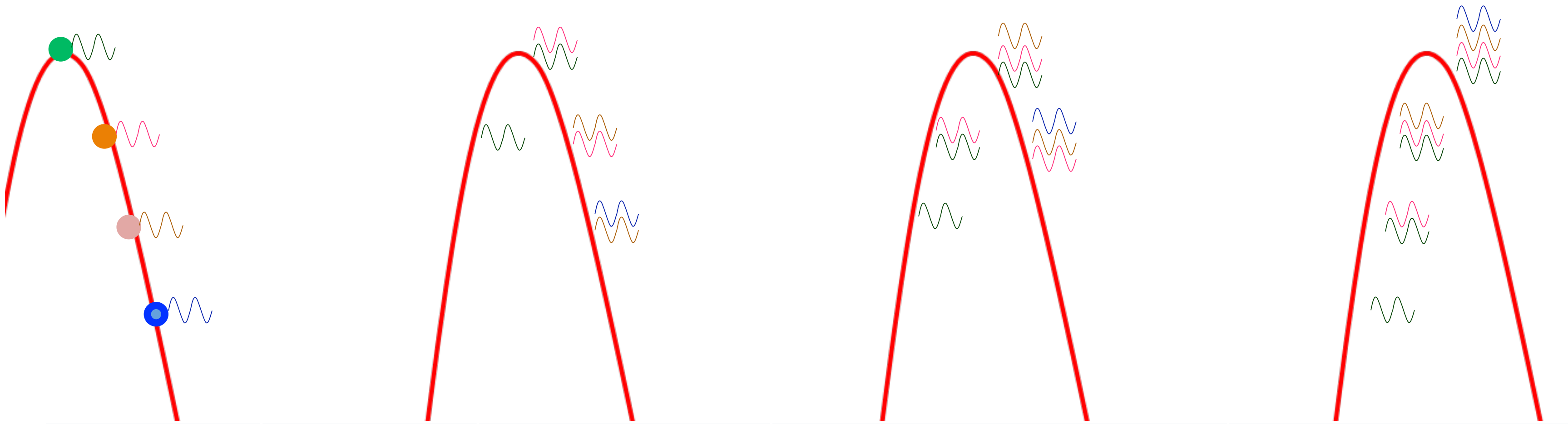
| 2 | 7 | 0.709 | 2.9900E+08 | 0.045 |
| 3 | 8 | 0.423 | 2.9933E+08 | 0.045 |

# Where Photon meets Electron

$I$ ? $(N_1+N_2+N_3+N_4)^2$ or $I$ ? $N^2$

Four bunches of photon with a separation of one radiation wavelength will be emitted



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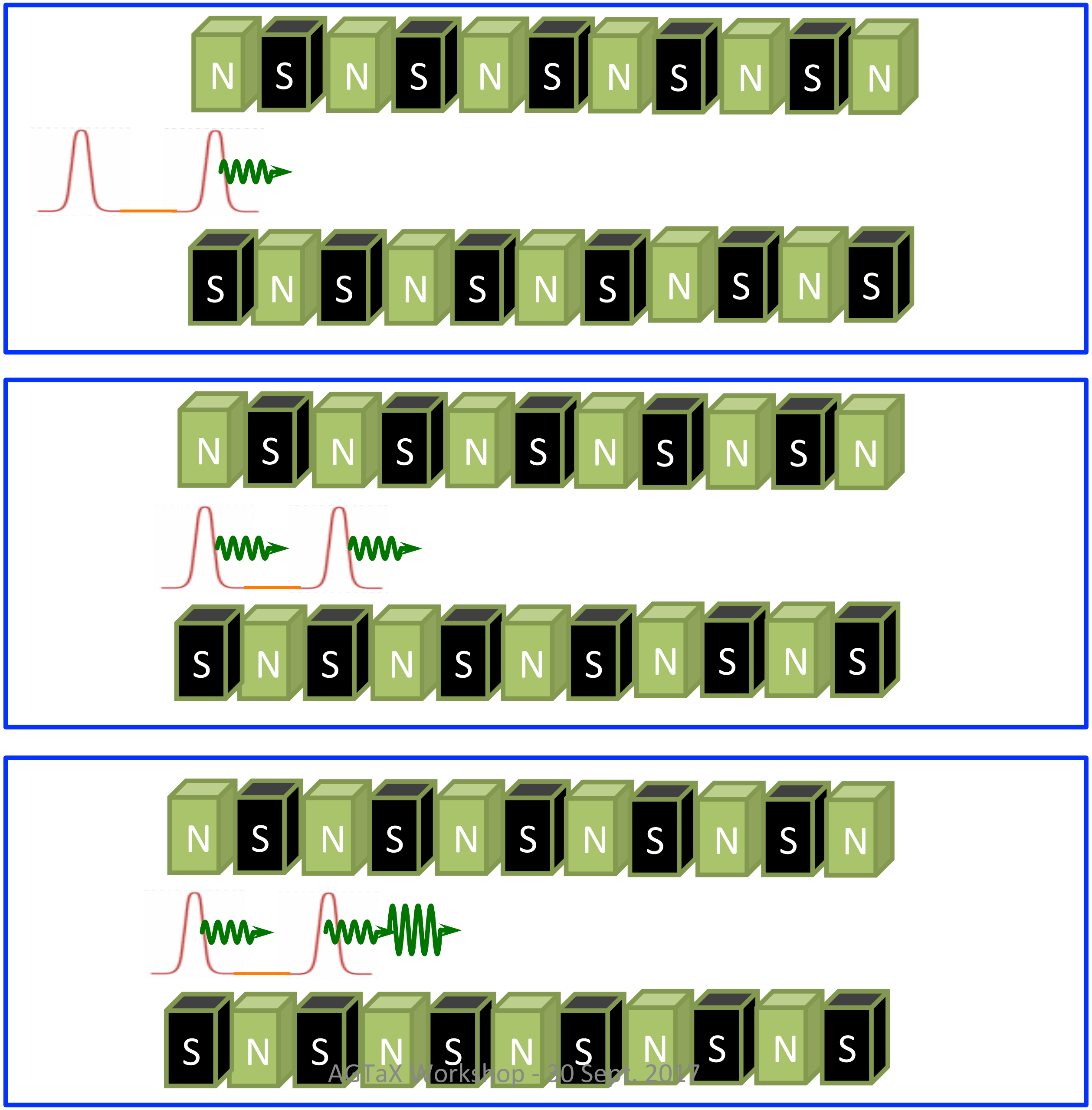
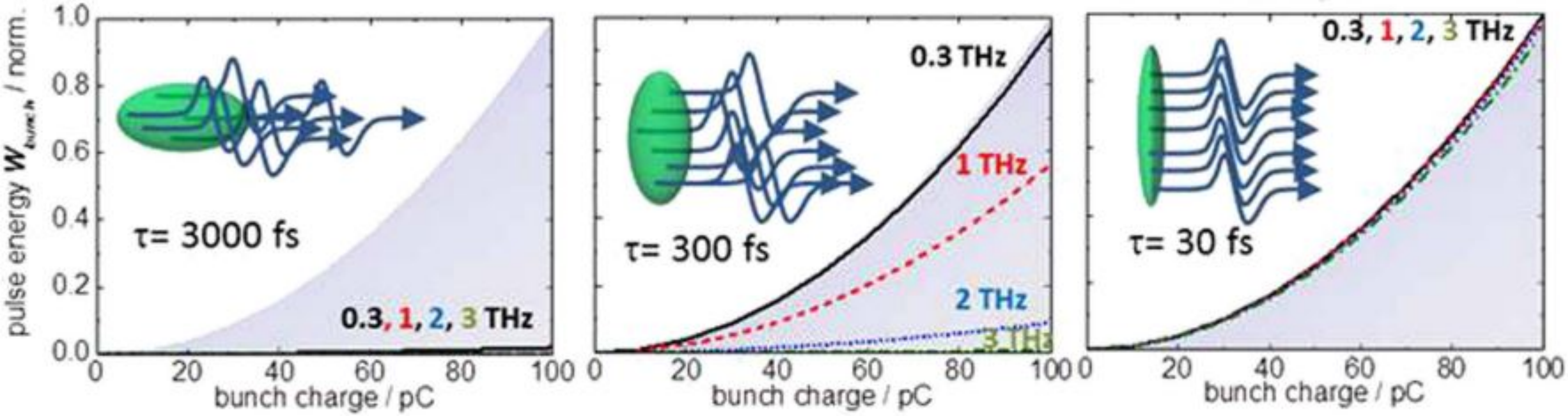
| 3 | 8 | 0.423 | 2.9933E+08 | 0.045 |

# Conventional FEL





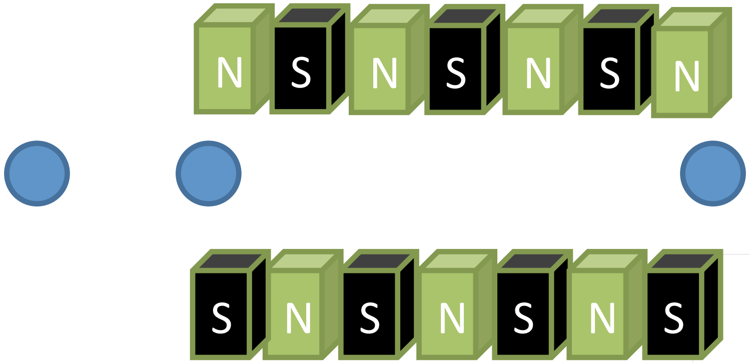

Superradiant radiation – Possible to produce frequencies when it is << 1/? [ 1/30 fs = 33.3 THz

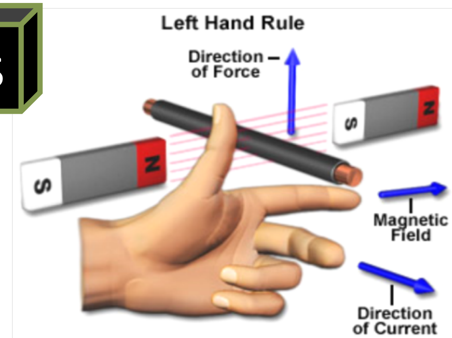
If the time width of the electron beam bunch is ~ 100 fs, then 1/? = 10 THz

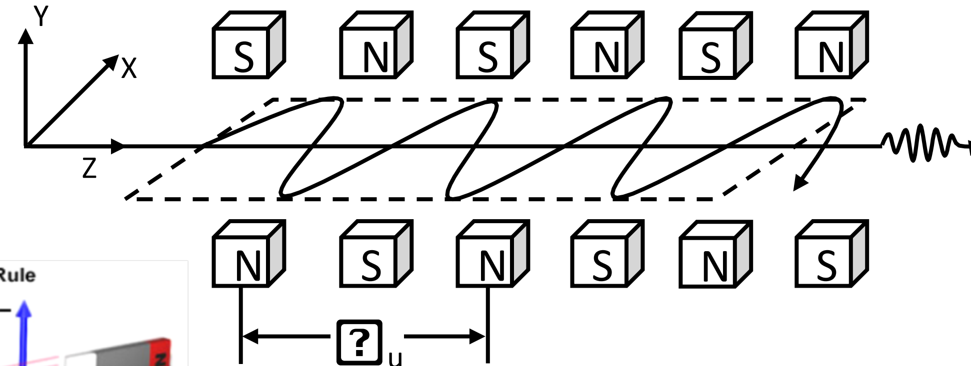
**Figure 2. Fundamental principle of superradiance.** Superradiant emission from electron bunches becomes significant for frequencies sufficiently lower than the inverse of the bunch duration τ. Following equation (1) the emission scales quadratically with the charge at low enough frequencies but diminishes at higher frequencies when a smaller fraction of the charge fits within the wavelength. This behavior can be described by the dimensionless form factor ***f***. (**a**) Form factors plotted for an assumed Gaussian bunch form with duration (FWHM) of 3000 fs, 300 fs and 30 fs (grey-shaded). (**b**) Corresponding dependence of the pulse energies at THz frequencies of 0.3 THz (black solid), 1 THz (red-dashed), 2 THz (blue-dotted) and 3 THz (green-dash-dot) on the bunch charge. For simplicity a "white" radiator with a frequency independent emission characteristic is assumed. The upper edge of the blue-shaded area corresponds to the case of a form factor equal to 1.

B.Green et. al. www.nature.com/scientificreports(6:22256,DOI:10.1038)

# Conventional FEL




*Electron energy = 5 MeV*

*? U = 30 mm*

*g = 10*

*? U * = 3 mm*

*? R = 3/20 = 150 ? m*

*= 2 THz*

## Major points:

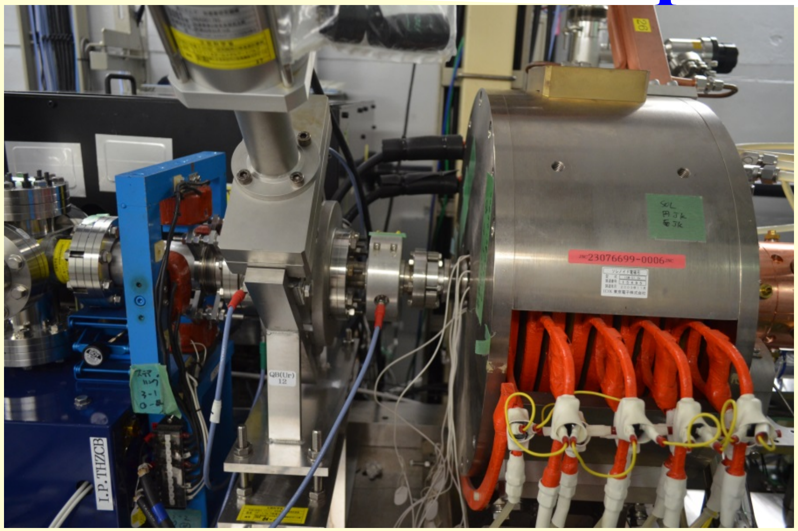
- Relativistic electron
- Approaching Undulator magnet, ?U
- ?U - length contracted to ?U* = ?U/?, ? = E/E0
- ?U* = Emitted wavelength from the electron
- Wavelength (lab fr.) = ?R = ?U* /2? = ?U /2?², relativistic Doppler
- Including the parameter of Undulator, wavelength measured will be

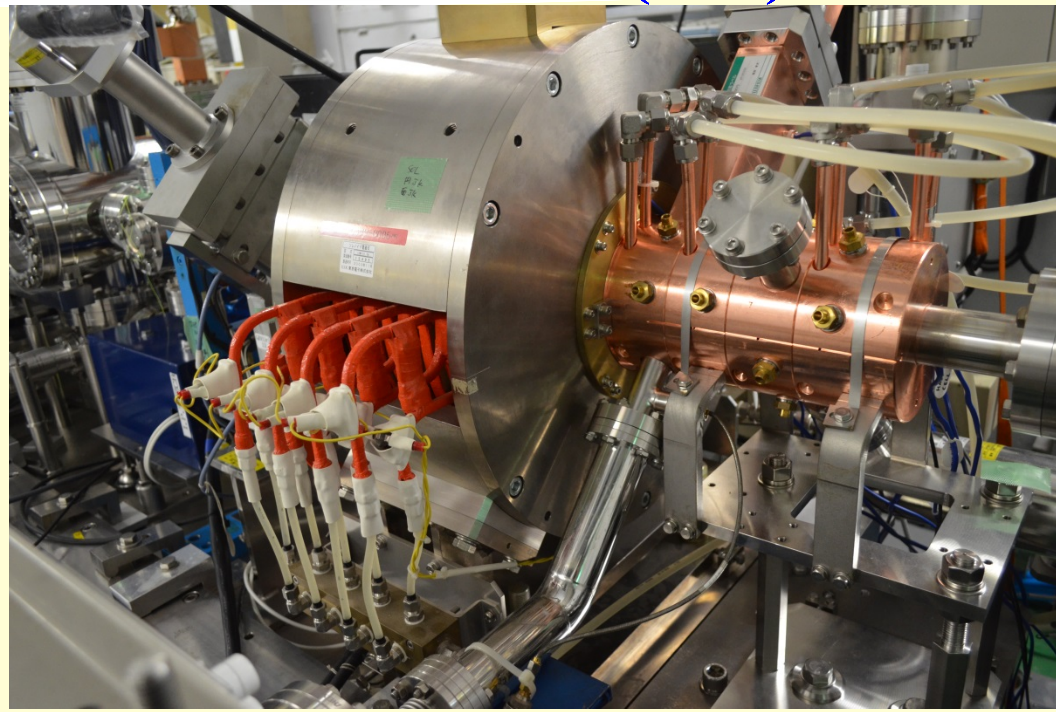
$$\lambda_R = \frac{\lambda_U}{2\gamma^2}[1+K^2] \; where \; K = \frac{eB_U\lambda_U}{2\pi mc}$$

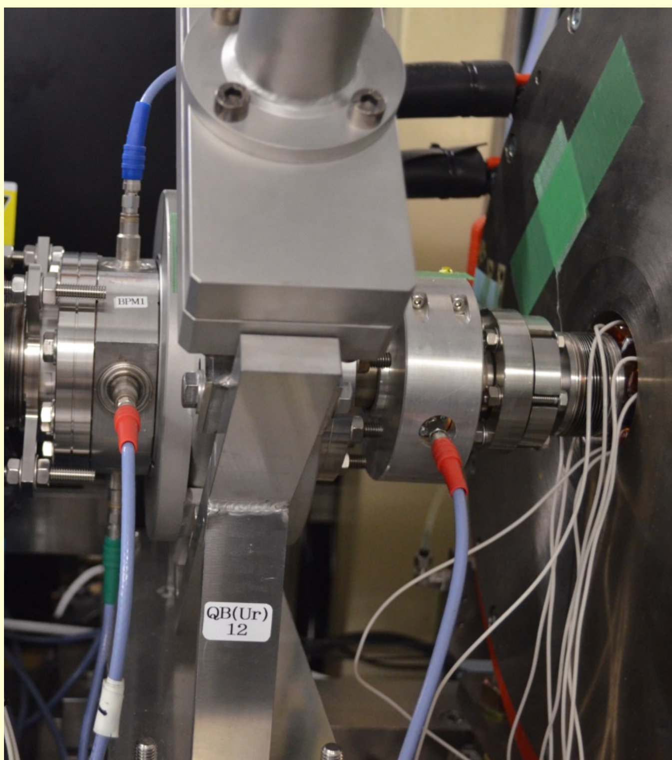


Electrons radiate spontaneously, now coherence is to be established

# Beam transport device – Solenoid (NC)

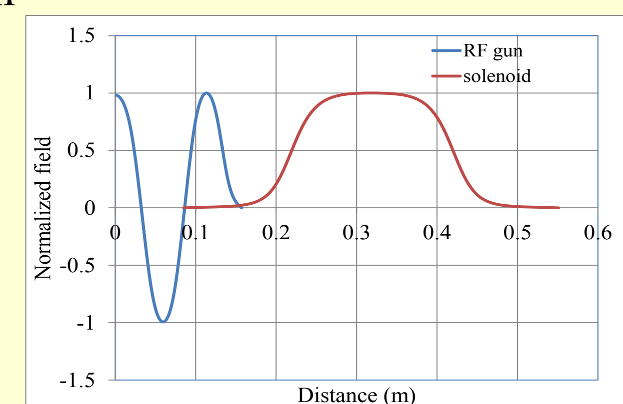







Specification for the solenoid magnet :

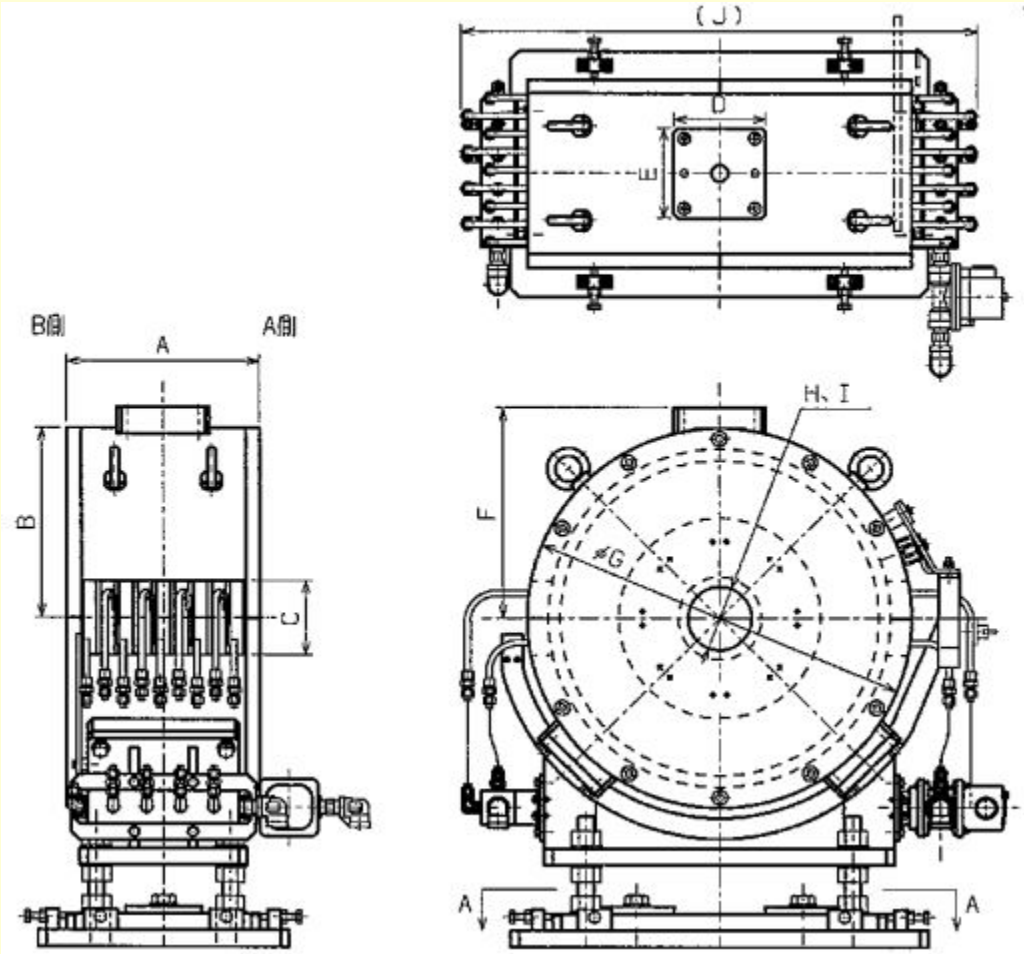
- Beam optics calculation demands ~ 0.27 T (max)
- Measured fields should be ~ 0.32 T (Max)
- Through bore dia ~ 75 mm
- Return Yoke is necessary
- IDX-Japan supplied the solenoid to KEK



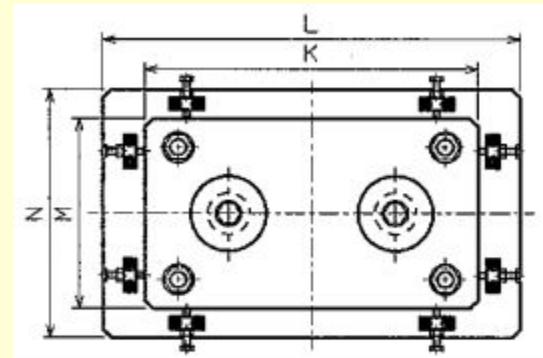
# Specification list of the Solenoid

| Parameters | Values |
|---|---|
| Maximum magnetic Field at the Centre of the solenoid | 0.35 T |
| Physical Length including mirror plate | ≤ 240 mm |
| Overall Diameter | ≤ 480 mm |
| Effective Length | ~ 200 mm |
| Bore Diameter | 76 mm, It should fit over 2.75” flange |
| Alignment mechanism/marks | Yes |
| Alignment Tolerances, both X and Y | ≤ 0.1 mm |
| Axial Field at a distance of 200mm from the centre of the solenoid magnet | < 30 Gauss |
| Inlet Water Pressure available at customer’s site | ~ 5 bar |
| Field Homogeneity | ~ 5 x $10^{-3}$ within ± 20 mm around the middle of the solenoid along the transverse and longitudinal direction |
| Stainless steel (Non-magnetic) support stand to be provided with ± 20 mm in X,Y and Z plane adjustments. The axis of the solenoid magnet (the height of the beam line) is 1.1 m. | |
| On the entrance side of the mirror plate, 16 tapped blind holes should be provided about the centre of the solenoid Pitch circle diameter (PCD) = 188 mm, Thread size = M4 , Depth of the blind tapped hole ≤ 8 mm | |
| Alignment marks on both sides (entrance and exit) of solenoid magnet to be provided for both X and Y axes | |
| Offset between Physical and magnetic axis of solenoid should be ≤ 0.1 mm. | |
| Matching power supply for solenoid magnet to be provided with remote polarity reversal option. | |
| All the current leads and all the water connections should terminate on the same side of the solenoid magnet | |
| Tolerance for Effective length: ± 2% of the specified value in above table. | |
| Yoke material: Solid XC 06 or equivalent. (The composition of the material should be mentioned and the test certificate should be provided. Material should be tested for porosity). | |

# Beam transport device – Solenoid (NC)




**Mechanical design & tolerances of LUCX's solenoid**




| Measuring | Reference value | Tolerance | Measured Value | Measuring | Reference value | Tolerance | Measured Value | |
|---|---|---|---|---|---|---|---|---|
| A | 230 | ±0.3 | 230.0 | H | 76 | ±0.2 | 76.0 | A side |
| B | 230 | ±0.3 | 230.0 | I | 76 | ±0.2 | 76.1 | B side |
| C | 90 | ±0.5 | 90.0 | J | (620) | | 630 | |
| D | 110 | ±0.3 | 110.0 | K | 400 | ±0.6 | 400.0 | |
| E | 110 | ±0.3 | 110.0 | L | 500 | ±0.6 | 500.1 | |
| F | 255 | ±0.1 | 254.93 | M | 230 | ±0.3 | 229.8 | |
| G | 460 | ±0.5 | 460.1 | N | 300 | ±0.3 | 300.0 | [Unit:mm] |

# Beam transport device – Solenoid (NC)

## Decision to be taken on:

### Laser device:

- KEK's offer – buy the components & assemble the complete device by laser experts ($200K)
  - To be developed in collaboration with KEK, addendum on MoU is initiated
  - Less expensive, to be tested with KEK's RF gun to produce e-beam
  - Much better hands on training (~ 1.5 months) during the assembly of different parts
- About 50% (100K) - unspent - collaborative project with KEK to fabricate Cu cavity
- If committee agrees - amount may be utilized for Laser, remaining $100K to be funded - IUAC

### Photocathode Deposition Device:

- Decision in last meetings – Global tendering after finalization of all the design parameters
- Design is frozen now, like to contact a few companies informally for their feedback e.g.
  - Kurt J. Lesker Inc., USA
  - VACOM Vakuum Komponenten & Messtechnik GmbH, Germany
  - Mewasa AG, Switzerland
  - Toyama, Japan – already contacted for their feedback about the feasibility of the PC device

EMD waiver

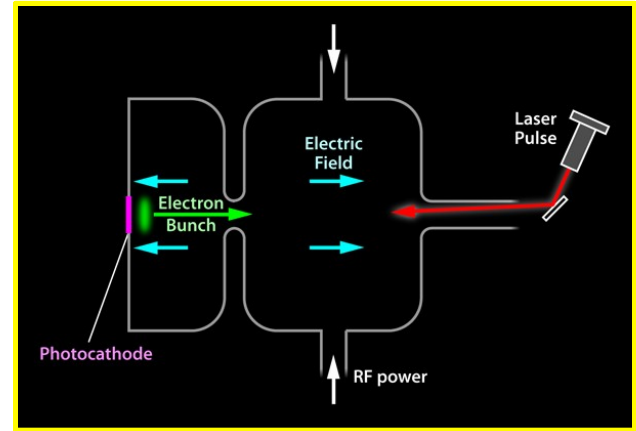
### Solenoid Magnet:

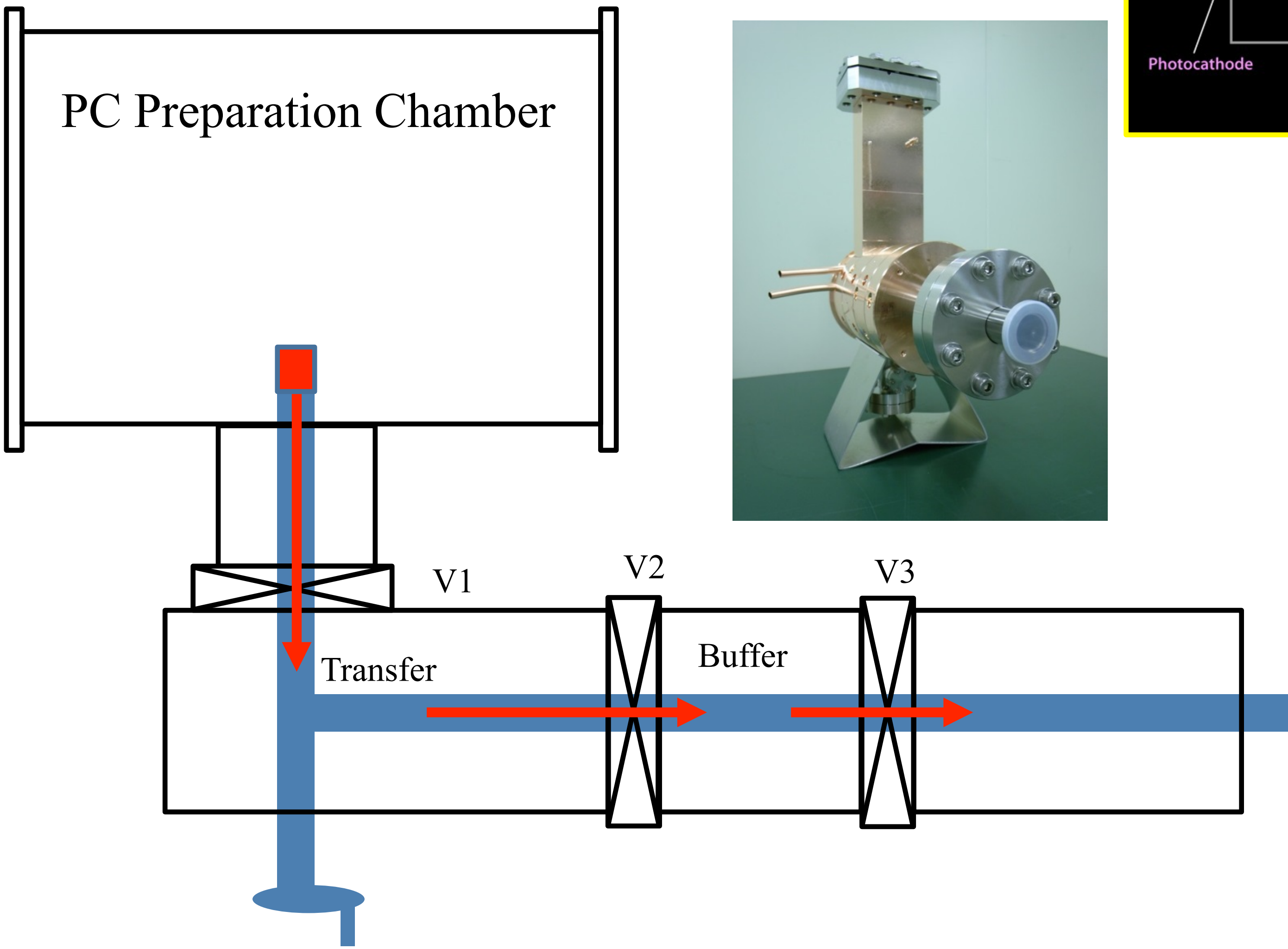
EMD waiver

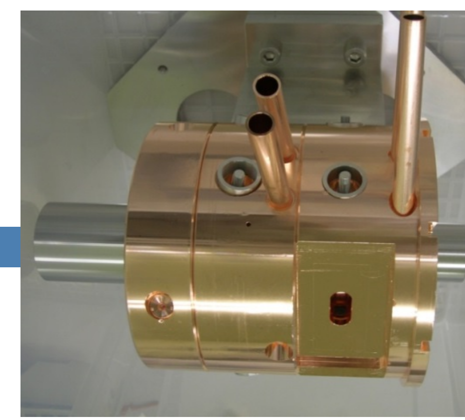
- Decision in last meeting – limited tendering after finalization its parameters
- Tender document is ready. Companies chosen to be contacted for limited tendering –

1. Danfysik, Denmark, 2. SigmaPhi, France, 3. IDX, Japan

# Photocathode insertion in to the cavity



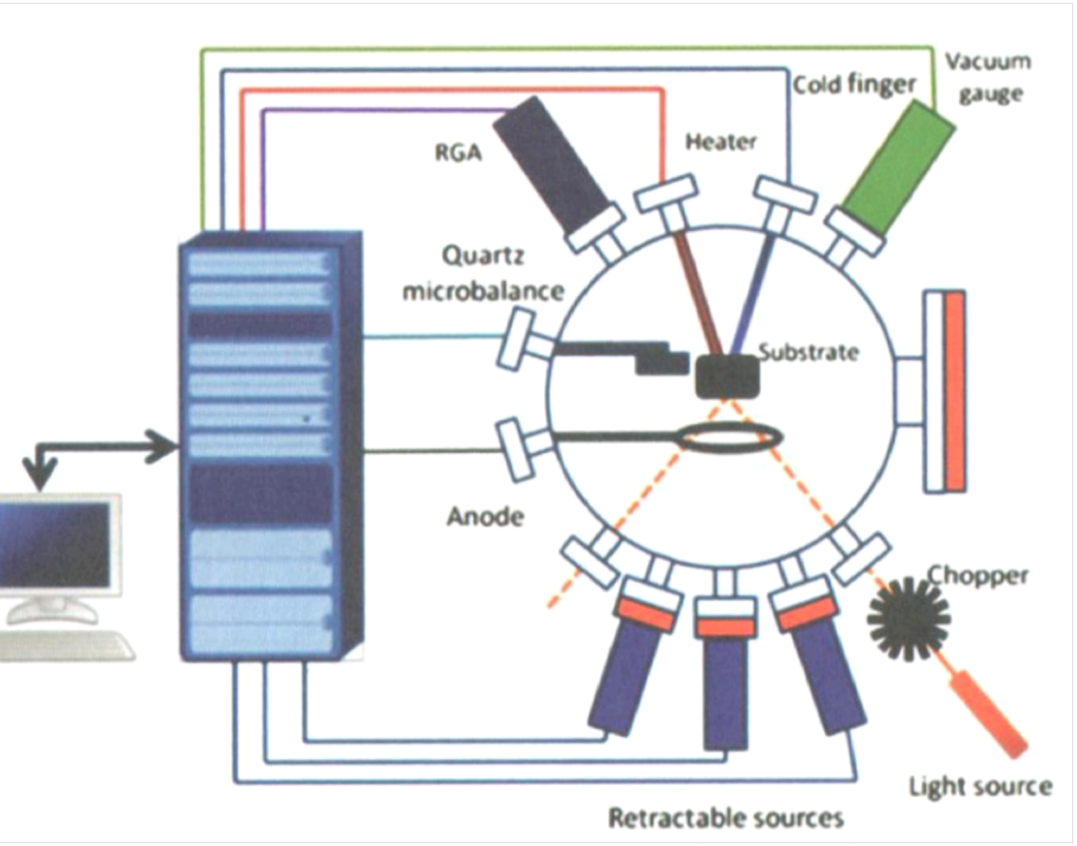



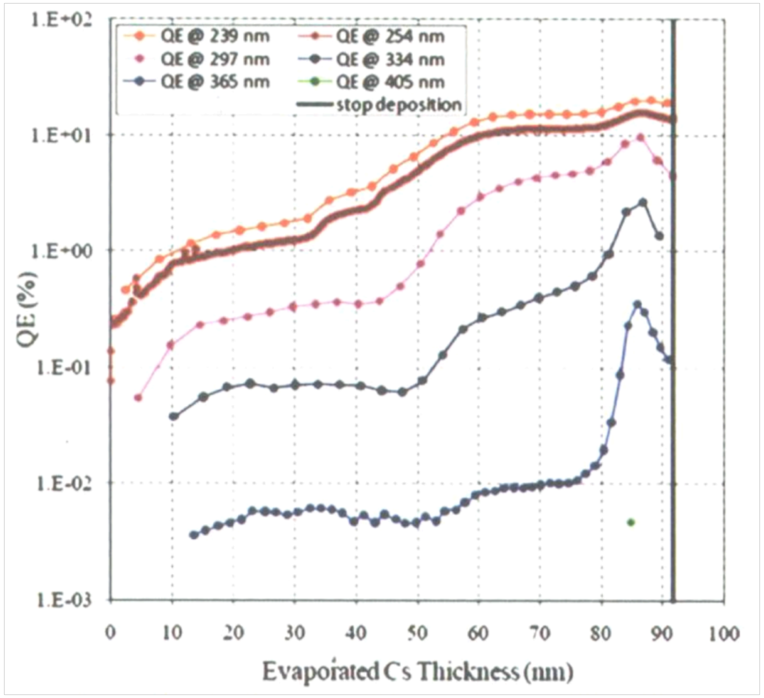



# Details of Photocathode

## Main Steps to produce $Cs_2Te$ photocathode

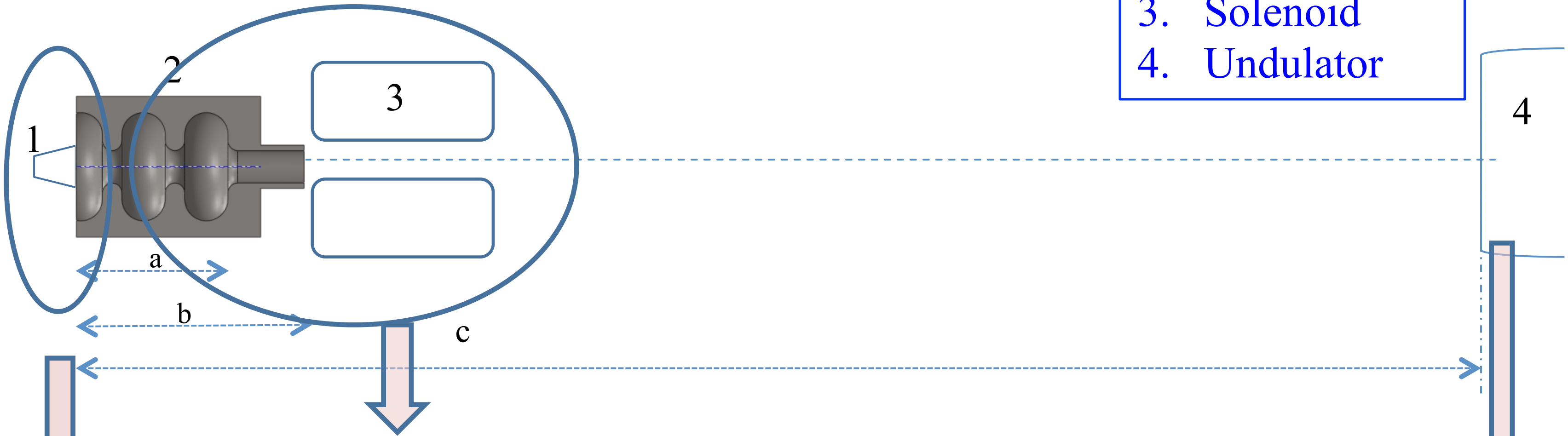
- Substrate – Mo – to be held at 120 C, while ~10 nm Te is deposited @ 1nm/m
- Film illuminated by UV light, Cs evaporated-same rate, Photocurrent monitored
- Max QE, source, substrate heater put off to be cooled naturally / rapidly cold finger
- Maximum QE is recorded around ~ 100 nm, Vacuum ~ $10^{-11}$ mbar



# Design of Solenoid - Beam optics simulation by ASTRA

1. Photocathode
2. Cavity
3. Solenoid
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

# Development of Phase-I of DLS

Physics Design

## Choice of Accelerator Components

Elect. & Cont.

- RF cavity – Copper (NC), S-band, 2.6 cell, water cooled, ? 0.1 C
- Frequency – 2860 MHz unlike 2856, SC PI/cavity : 130/1300 MHz
- **Photocathodes – Copper to start – easy, rugged, less sensitive vac - $Cs_2Te$ – Design frozen, Detail dwg. goes on**
- Laser – Conventional vs Fiber – Most probably Fiber laser - Choice - single pulse will be split in to many
- Klystron, Modulator – specification are frozen, tender floating soon
- **Solenoid,** other magnet – **Solenoid design frozen**, place order soon
- Undulator – preliminary design – detail design starts soon

# Procurement of Photocathode preparation equipment

Toyama Japan – Supplies various instruments which require UHV and precision m/c technology
- Supplies many PC deposition mechanism to KEK – LUCX, ATF, Photon factory

**TOYAMA**
*Pioneering New Horizons in Science*

Address: 3816-1, kishi, Yamakita-machi, Ashigarakami-gun, Kanagawa 258-0112, JAPAN
Phone: +81-465-79-1411
Fax: +81-465-79-1412
URL: http://www.toyama-en.com

15Z00564-BT-01-0
November 20, 2015

To: Dr. Subhendu Ghosh
Scientist "G",
Inter University Accelerator Center,
Aruna Asaf Ali Marg,
New Delhi - 110067,India.

**Budgetary Quotation for**
**Photocathode Preparation Chamber**

We are pleased to submit herein the budgetary quotation of Photocathode Preparation Chamber in response to your inquiry as follows:

| No. | Components | Q'ty | Price (JPY) |
|---|---|---|---|
| 1 | Photocathode Preparation Chamber | 1set | ¥14,600,000.- |
| 2 | Packing and FCA cost | 1set | ¥400,000.- |
| | Total Offer Price | | ¥15,000,000.- |

Option

| | | | |
|---|---|---|---|
| OP-1 | Vacuum components | 1set | ¥9,800,000.- |
| OP-2 | Installation work at site | 1set | ¥1,800,000.- |

**TOYAMA**
*Pioneering New Horizons in Science*

Address: 3816-1, kishi, Yamakita-machi, Ashigarakami-gun, Kanagawa 258-0112, JAPAN
Phone: +81-465-79-1411
Fax: +81-465-79-1412
URL: http://www.toyama-en.com

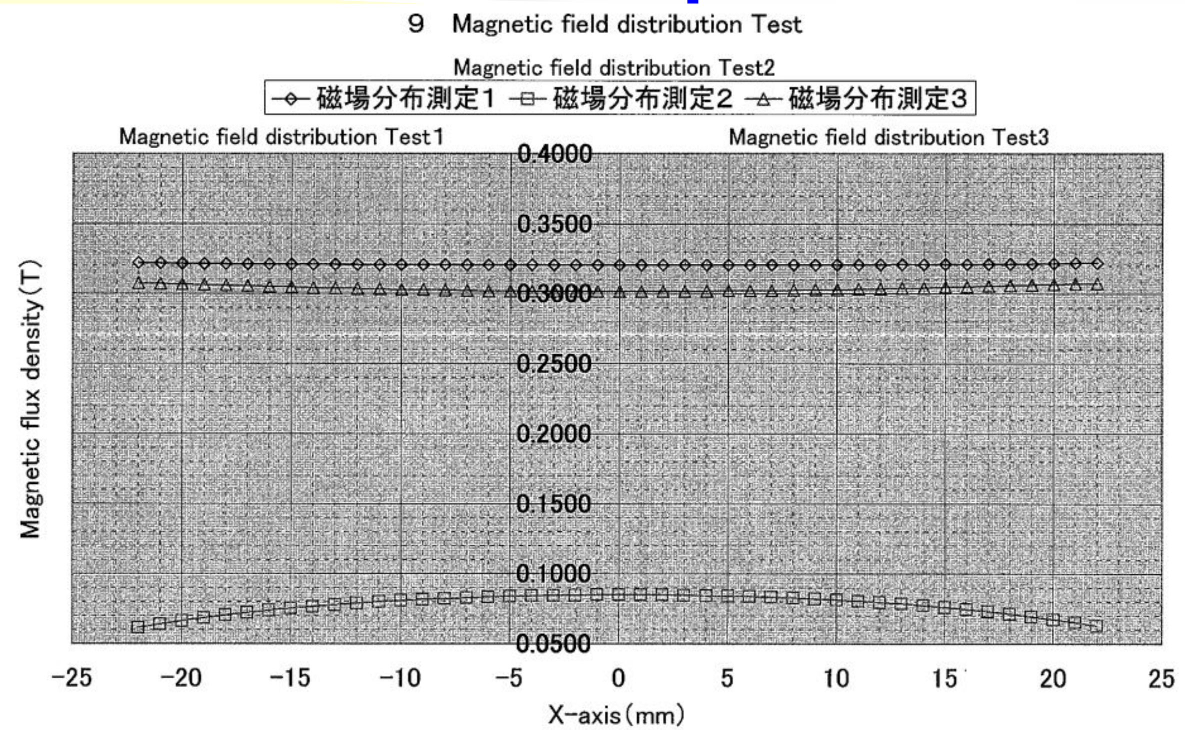
(Attachment sheet)

**Detail Scope of Supply**

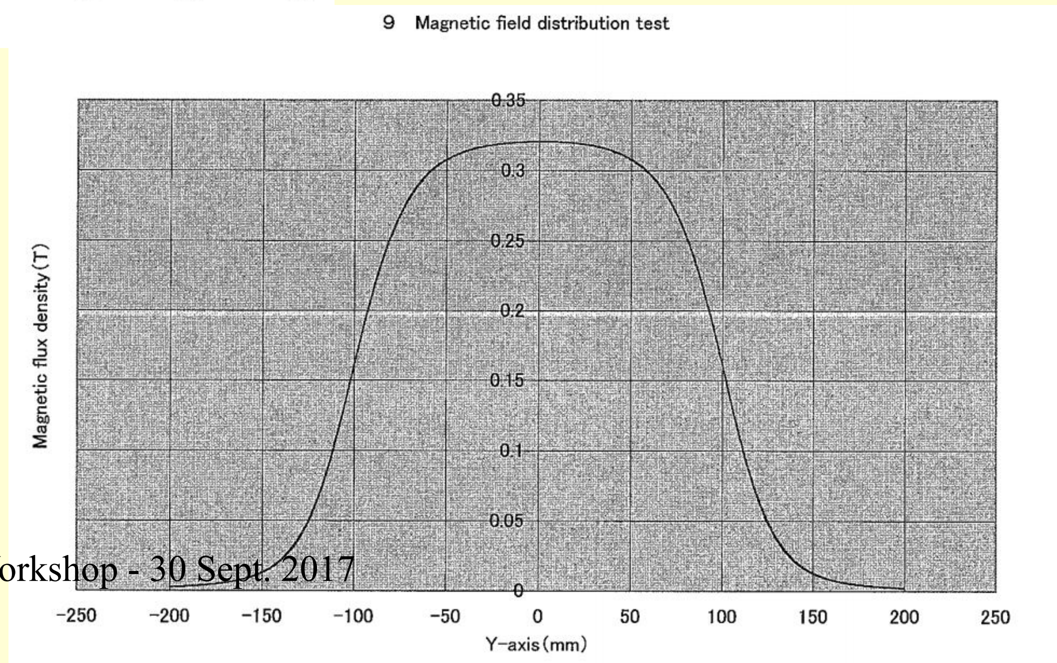
| No. | Description | QTY | Remarks |
|---|---|---|---|
| 1. | Photocathode Preparation Chamber | | |
| | 1) Vacuum chamber | 1 set | |
| | 2) Rotary motion feedthrough | 1 set | UHV compatible |
| | 3) Stepper Motor and cable | 1 set | |
| | 4) Magnet coupling for cathode transfer | 8 set | UHV compatible |
| | 5) Cathode (made of Mo) | 1 pc | |
| | 6) Cathode transfer fittings | 1 set | |
| | 7) Load Lock Adjuster | 1 set | |
| | 8) Support stands | 1 set | |
| | 9) Engineering | 1set | |
| | 10) Test and Documentation | 1 set | |
| 2. | Packing and FCA cost | | |
| | 1) Safety packing by wooden cases | 1set | |
| | 2) Export customs fee in Japan | 1set | |
| OP-1 | Vacuum components | | |
| | 1) Gate valves (manual operation) | 5 sets | ICF152 3sets<br>ICF203 2 sets |
| | 2) Ion Pumps (300L/s) with controllers and HV cables | 2 sets | |
| | 3) TMP (300L/s) with controllers and cables | 3 sets | |
| | 4) Baking heater and thermocouples | 1set | |
| | 5) Baking heater controller | 1 sets | |
| OP-2 | Installation work at site | | |
| | 1) Travel and accommodation expense | 1 set | |
| | 2) Working fee | 1 set | |

Yen 15,000,000 = Rs 80,66,432/
Yen 11,600,000 = Rs 62,38,040/

# Beam transport device – Solenoid (NC)




**Test report of LUCX's solenoid by IDX Japan**



# Specification offered for the Solenoid

## Danfysik

**SOLENOID MAGNET SPECIFICATION SHEET**

**QUOTATION: IND502989**
**PREPARED FOR: IUAC**
**DESCRIPTION: Solenoid magnet for FEL**
**DATE: 5 Feb. 2016**

**MAIN SPECIFICATION:**

| | | |
|---|---|---|
| Maximum field, B: | 0.35 | [T] |
| Length: | 200 | [mm] |
| Free aperture diameter, Di: | 76 | [mm] |
| Outer diameter yoke, Do: | $\leq$ 480 | [mm] |
| Yoke material: | XC06 | [-] |

**MAGNETIC FIELD QUALITY:**

| | | |
|---|---|---|
| Good field radius, GFR | 20 | [mm] |
| Integrated field homogeneity, GFR: $\Delta\int B_z dz(r)/\int B_z dz(0)$ | $<5\times10^{-3}$ | |

**COIL DATA:**

| | | |
|---|---|---|
| Conductor type: | Hollow conductor | [-] |
| Impregnation system: | DF3C | [-] |
| Conductor dimensions: | 7.0*7.0 / bore ø 4.0 | [mm] |
| Number of conductor layers: | 12 | [-] |
| Number of conductor turns per layer: | 25 | [-] |
| Total number of turns in solenoid $N_{tot.}$: | 300 | [-] |
| Cooling type: | Water cooled | [-] |
| Cooling water pressure drop: | 5 | [bar] |
| Cooling water flow: | 4.2 | [l/min.] |
| Cooling water inlet temperature: | 25 | [°C] |
| Cooling water temperature rise: | 13.3 | [°C] |

**INTERFACE DATA:**

| | | |
|---|---|---|
| Current, I: | 192.2 | [A] |
| Voltage complete magnet, U: | 20.2 | [V] |
| Power, complete magnet, P: | 3.9 | [kW] |
| Proposed power supply, output current, $I_{PS}$: | 200 | [A] |
| Proposed power supply, output voltage, $U_{PS}$: | 60 | [V] |
| Proposed power supply, output power, $P_{PS}$: | 12 | [kW] |

**GENERAL DATA:**

| | | |
|---|---|---|
| Total magnet weight, $W_{tot}$: | 120 | [kg] |

**VACUUM CHAMBER:**

| | | |
|---|---|---|
| Included/excluded: | Optional | [-] |

**MAGNET SUPPORT:**

| | | |
|---|---|---|
| Aluminium alloy support plate attached underneath the magnet with 3 tapped holes M24*1.5mm pitch for adjustment screw | Optional | [-] |

**ALIGNMENT FACILITIES:**

| | | |
|---|---|---|
| Alignment facilities included/excluded: | Included | [-] |
| Type: | To be agreed upon | [-] |

**OTHER ASCESSORIES:**

| | | |
|---|---|---|
| Flow switch included/excluded: | To be discussed | [-] |

# Beam transport device – Solenoid (NC)

**Budgetary estimate obtained for the solenoid**

IDX co.,Ltd.
Tel: +81-283-85-7200
Fax: +81-283-85-7272
E-mail: info@idx-net.co.jp
URL: www.idx-net.co.jp/

iDX

**Quotation No: 00013030** **Date: 11 November 2015**
**To : Inter-University Accelerator Center**
Aruna Asaf Ali Marg Near Vasant Kunj New Delhi, 110067 INDIA

## Quotation

| Item | Description | Quantity | Unit Price (US$) | Total Price (US$) |
|---|---|---|---|---|
| 1 | Solenoid electromagnet (MODEL No : ISM-51.3kk) | 1 | $29,280.00 | $29,280.00 |
| 2 | Packing costs, Transport costs | 1 | $4,067.00 | $4,067.00 |
| 3 | Insurance | 1 | $342.00 | $342.00 |
| | **Total** | | | **$33,689.00** |

Terms:
1. Payment Terms : A/P(Advance Payment) or through discussion.
2. This quotation is valid for 30 days.
3. Delivery time : 5.5months after order.
4. If currency exchange rates fluctuates by ±3 %, the rate will be re-negotiated and determined separately.
5. The total price excludes customs duties.
6. No warranty for this product.

Shigeo Kowada

Registered Address
IDX co.,Ltd
2946 Machiya-cho,Sano-shi Tochigi 327-0812 Japan