Delhi Light Source (DLS): A Compact FEL-THZ facility

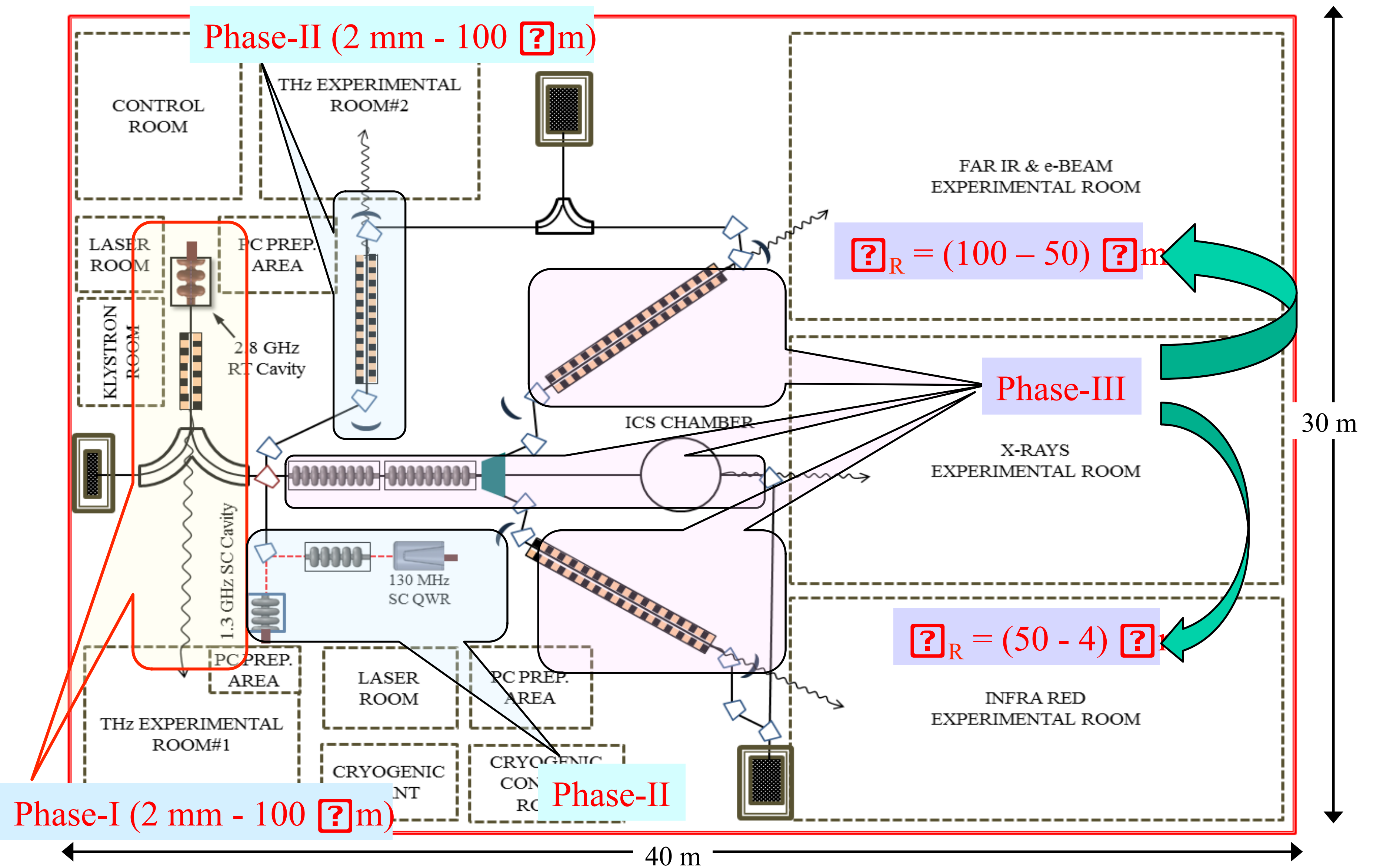
Subhendu Ghosh
Inter University Accelerator Centre, New Delhi, India
(A National Accelerator Centre for providing ion beam based research opportunity)

Plan of Presentation

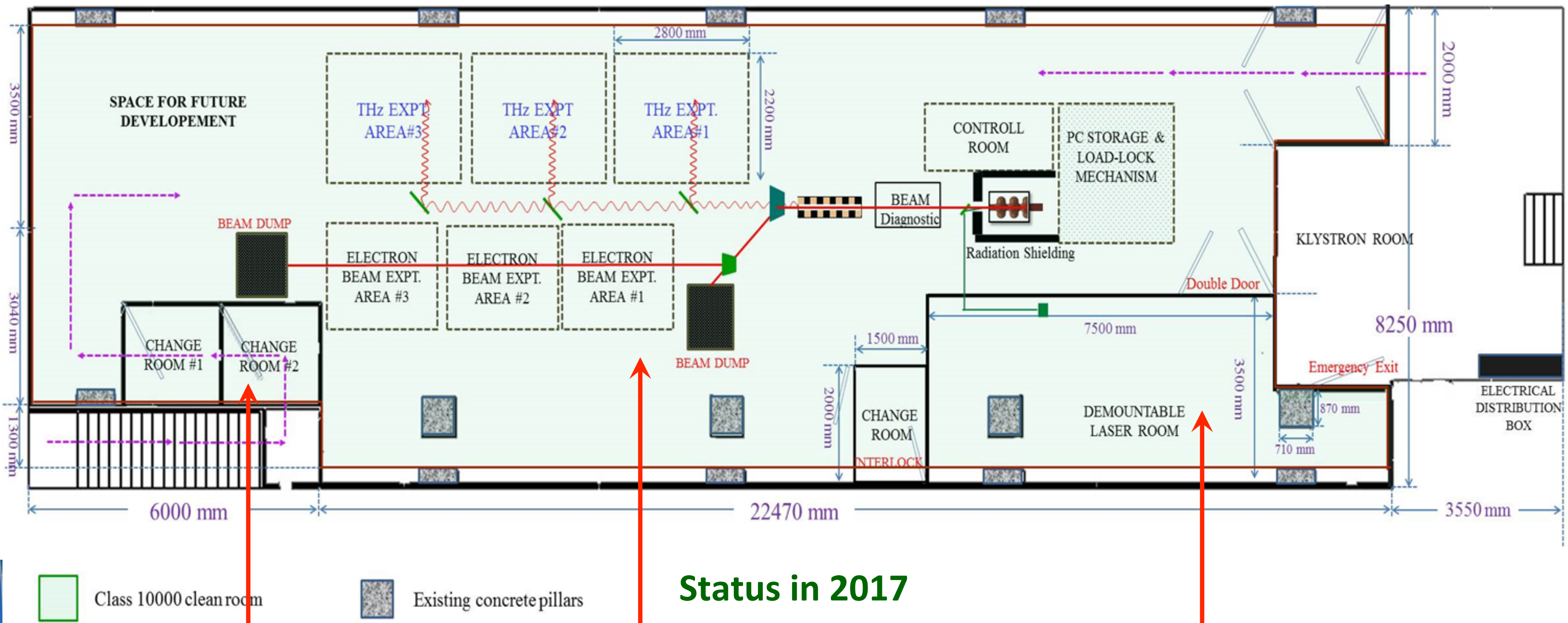
- Concept of DLS, how is it different from conventional FEL
- Major developments for different sub-systems
  - Beam optics calculation
  - Cavity fabrication and testing
  - Laser design and development
  - Photocathode deposition system - design, fabrication, testing
  - Undulator – design
- Deliverables
- Time chart
- Conclusion

INTRODUCTION TO DELHI LIGHT SOURCE (DLS)

Layout of Delhi Light Source (DLS)

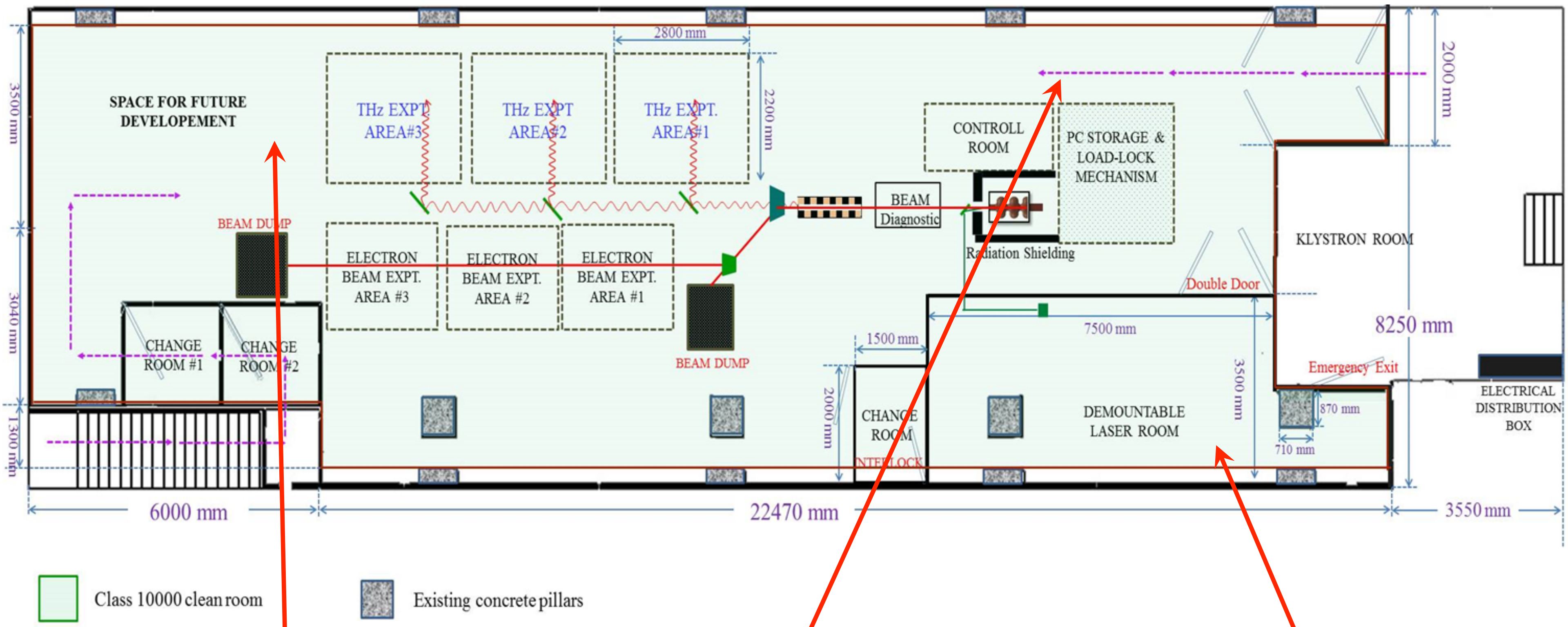


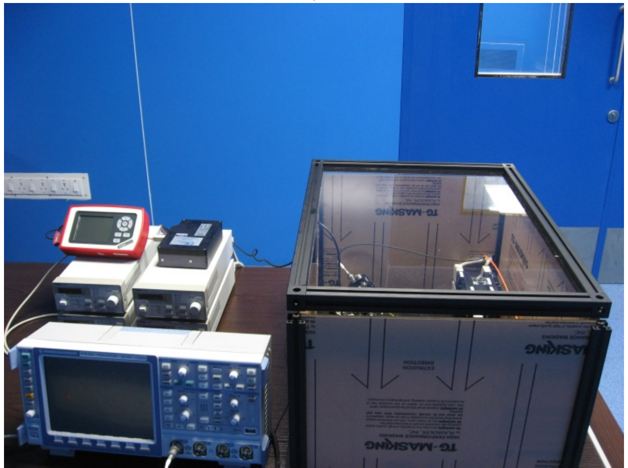
Class 10000 clean room to accommodate Phase-I of the facility



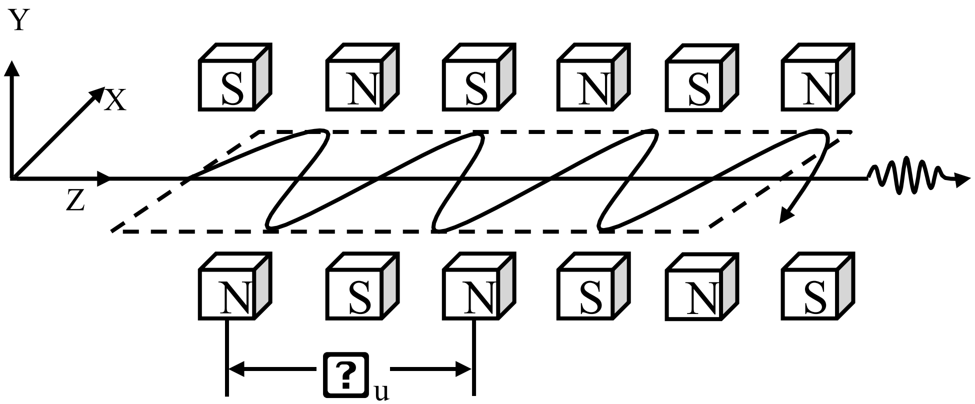
Status in 2017

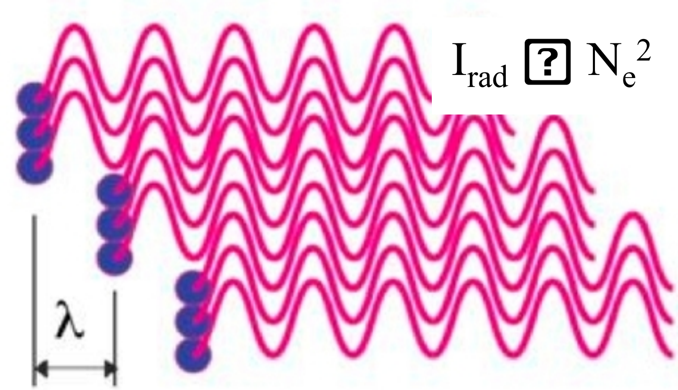
Class 10000 clean room to accommodate Phase-I of the facility





Conventional FEL – Oscillator, Seeded & SASE

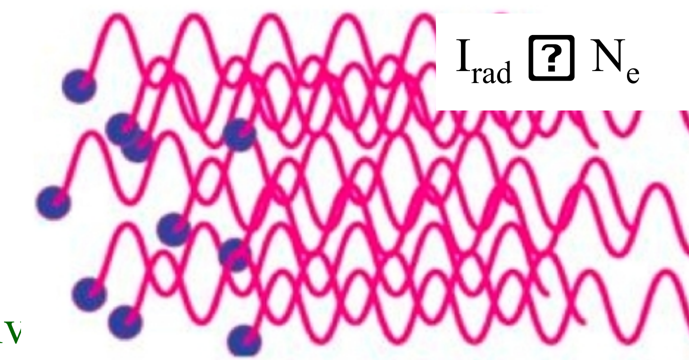




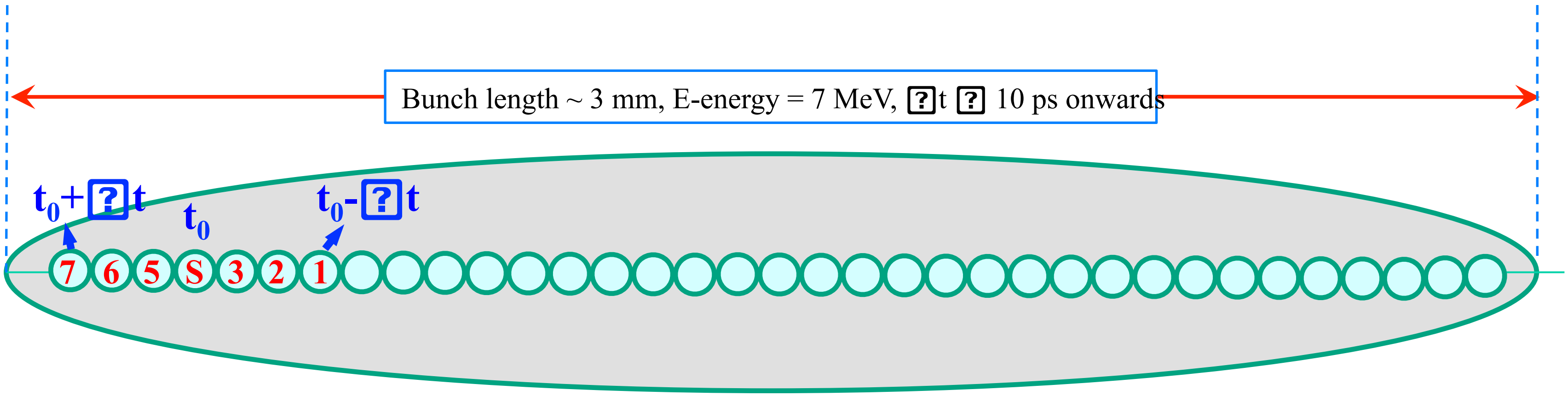
Major points:

- Relativistic electron
- Approaching Undulator magnet, $?_U$
- $?_U$ - length contracted to $?_U^* = ?_U/?$, $? = E/E_0$
- $?_U^*$ = Emitted wavelength from the electron
- Wavelength (lab fr.) = $?_R = ?_U^* /2? = ?_U /2?^2$, relativ Doppler effect
- Including the parameter of Undulator, wavelength measured will be

$$?R=?U/2?2\ [1+K2/2\ ]\ where\ K=0.934Bu(T)?U(\text{cm})$$

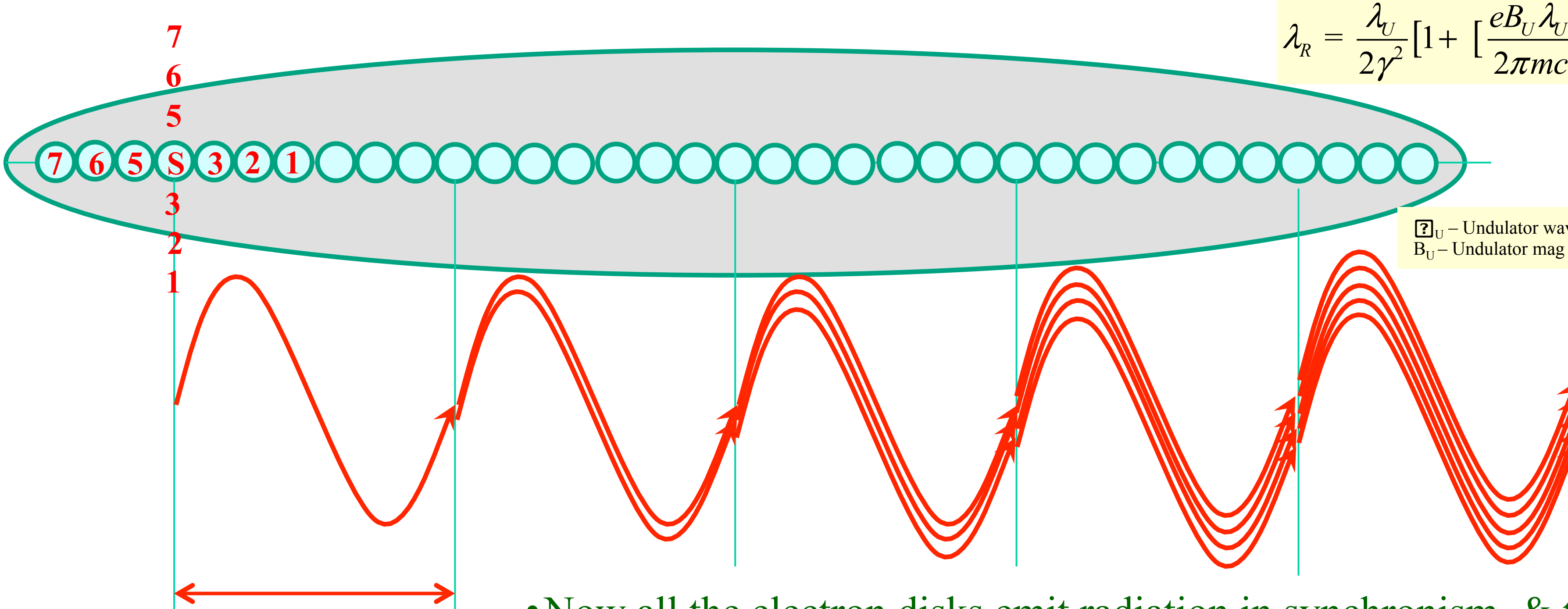


Microbunching in FEL (Osc., Seeded and SASE)



Interaction of Photon and wiggling electron inside undulator magnet

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

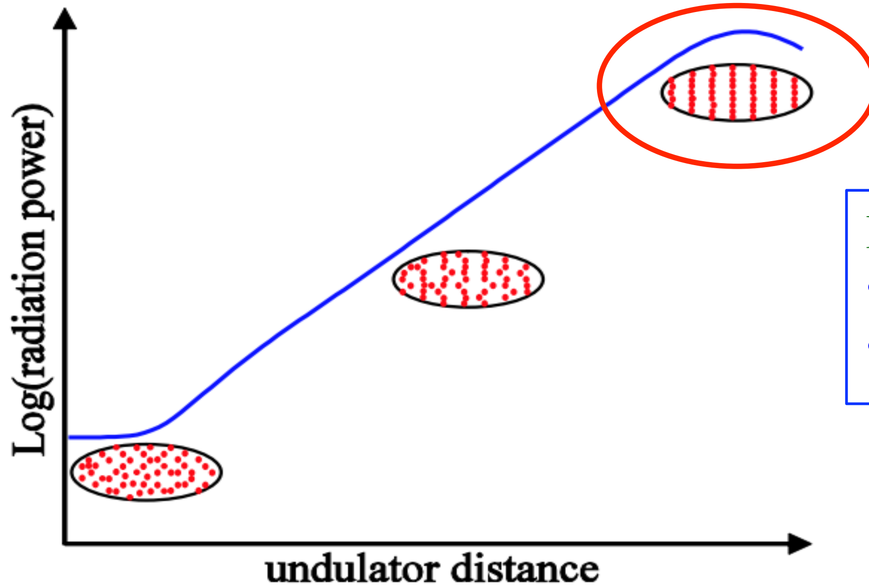


$?_U$ – Undulator wavelength
B_U – Undulator mag field

?=wavelength of radiation

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

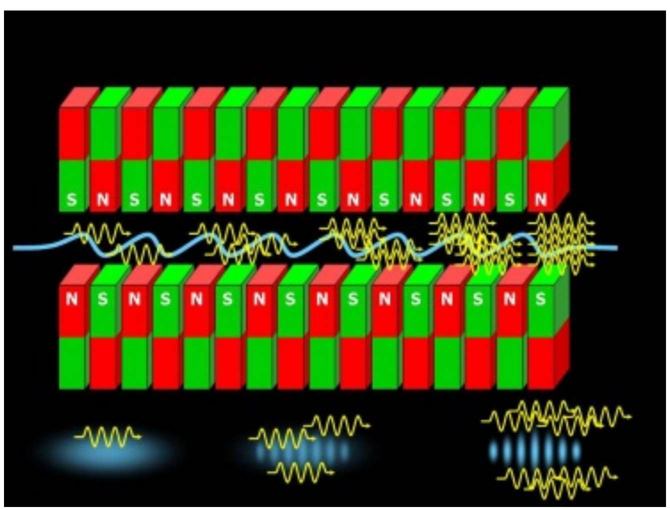
Pre-bunched FEL - How is it different from conventional FEL



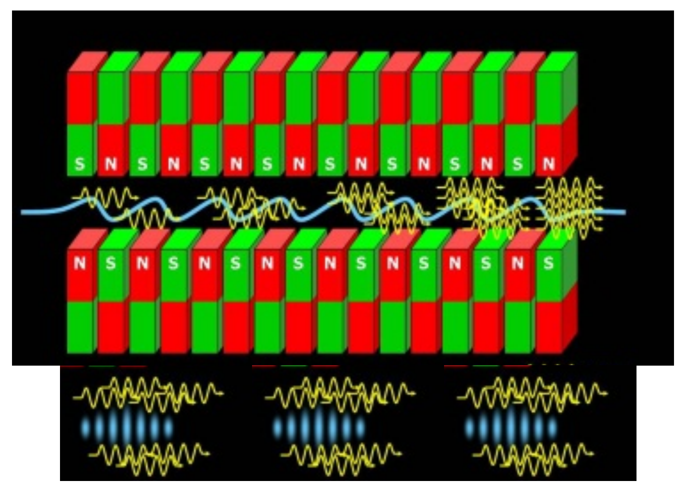
Starting point of Delhi Light Source

Requirement:
- **Electron disc formation**
- **Separation equal to $?_R$**

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



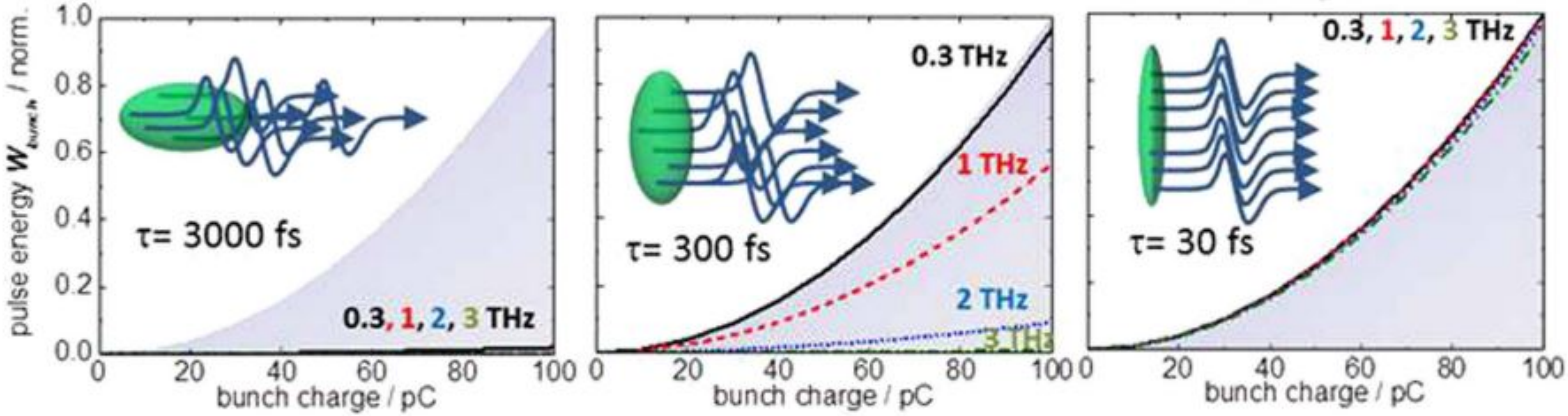
Conventional FEL



Prebunched FEL (Phase-I of DLS)

Super-radiant radiation from microbunch train

Super-radiant radiation



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

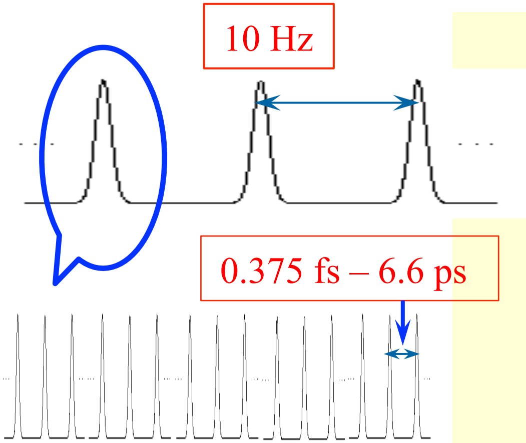
If the time width of the electron beam bunch is ~ 300 fs, then 1/? = 3.3 THz

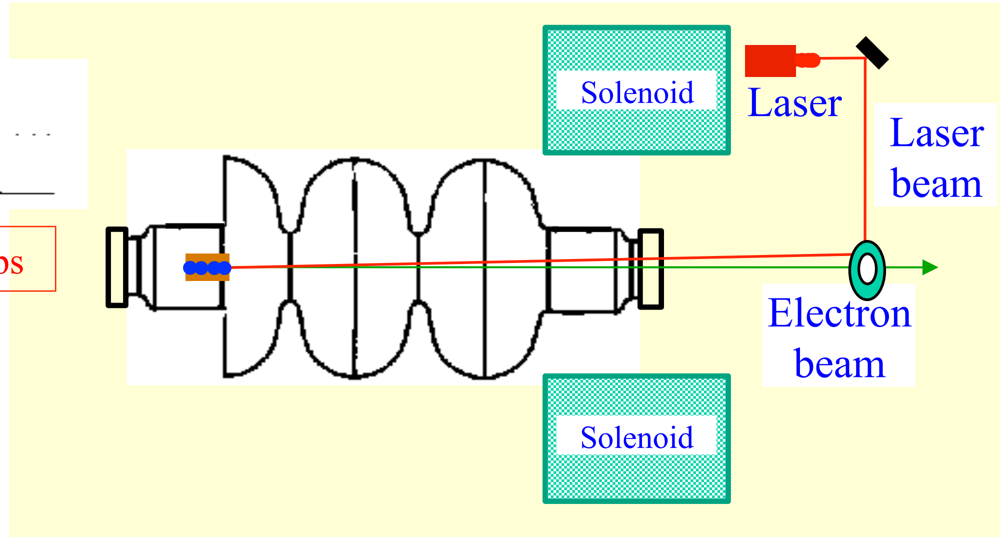
Delhi Light Source (DLS): Super-radiant with microbunch train

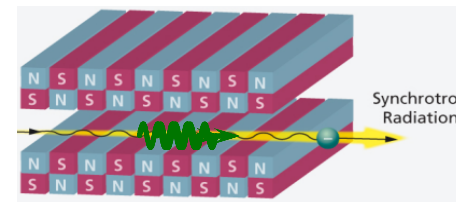
- **e-bunches which is few hundred of fs (200 fs) – superradiant (I ? N_1^2)**
- **In addition, train of microbunches (separation ~ 500 fs to a few ps) will be produced**
- **So I ? $(N_1 + N_2 + \ldots + N_{16})^2$**

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

Major components of FEL – Pre-bunched FEL







Undulator Magnet

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

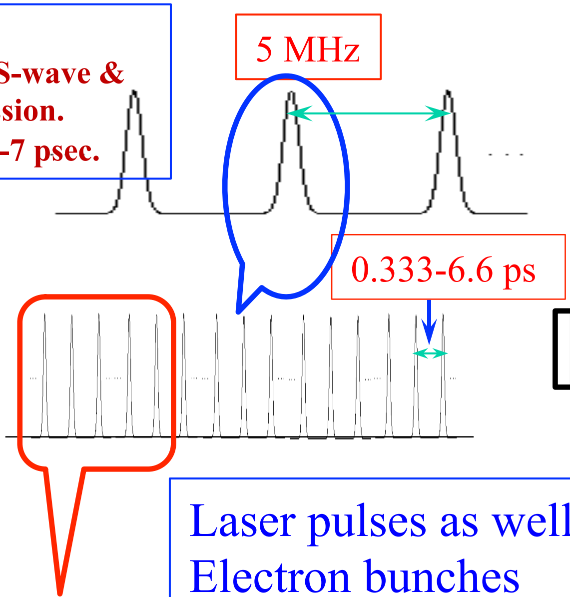
$$\lambda_R = \frac{\lambda_U}{2\gamma^2}\left[1 + \left[\frac{eB_U\lambda_U}{2\pi mc}\right]^2\right]$$

$\gamma = E/E_o = 8/0.5 = 16$

λ_U – Undulator wavelength
B_U – Undulator mag field

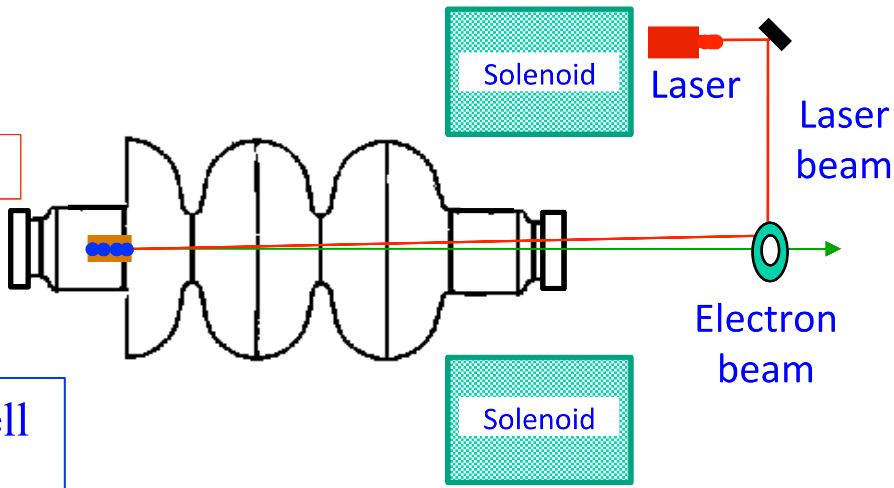
Laser system of DLS

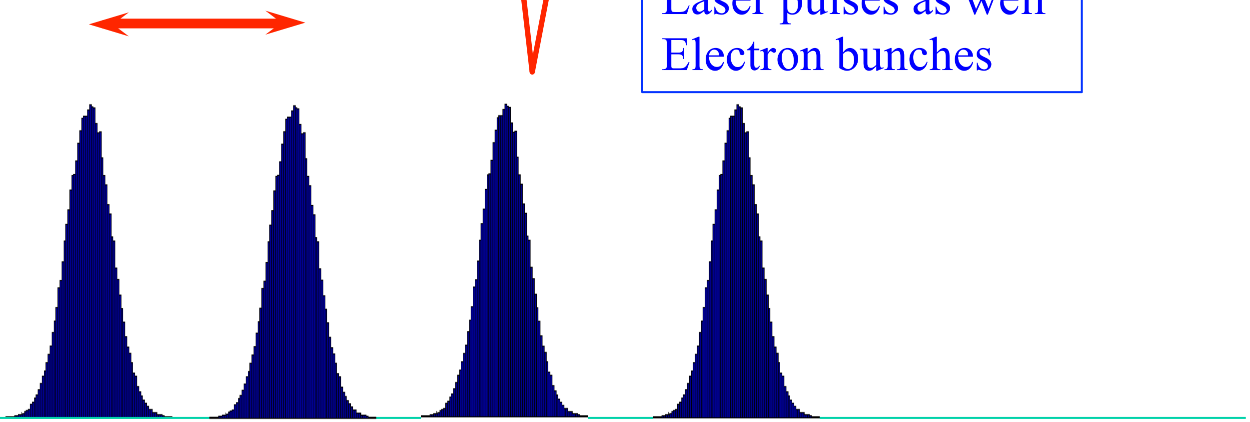
- ½ w plate rotates S-wave by 45°.
- Polarizing beam splitter makes S-wave & P-wave by reflection & transmission.
- 16 micro bunched laser within 6-7 psec.

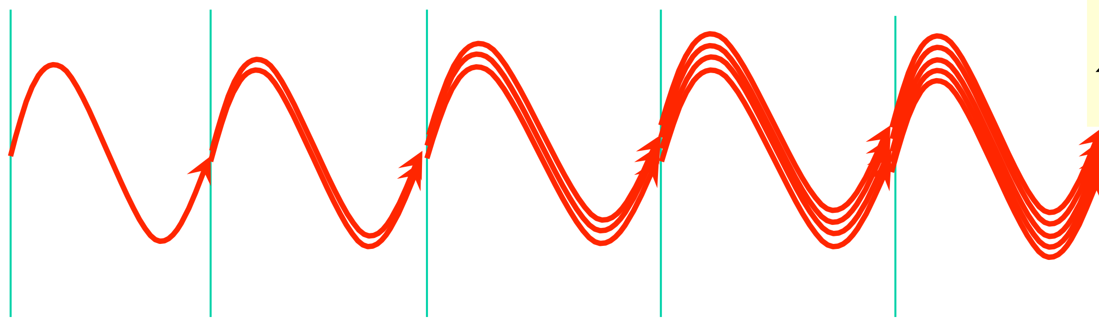


f ~ 3 – 0.18 THz
T = 333 fs to 6.6 ps
? = 100 ?m to 2 mm

Laser pulses as well
Electron bunches







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

$$\gamma = E/E\downarrow o = 8/0.5 = 16$$

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

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 design., Osc+PA+Amp (1st stage) done: IUAC+KEK (AA+JW+Waseda Univ.+others)
Klystron, Modulator - Order placed - Scandinova, delivery '18 Autumn
Solnd, Undulator, etc. – Delivered, Available – Summer 2019

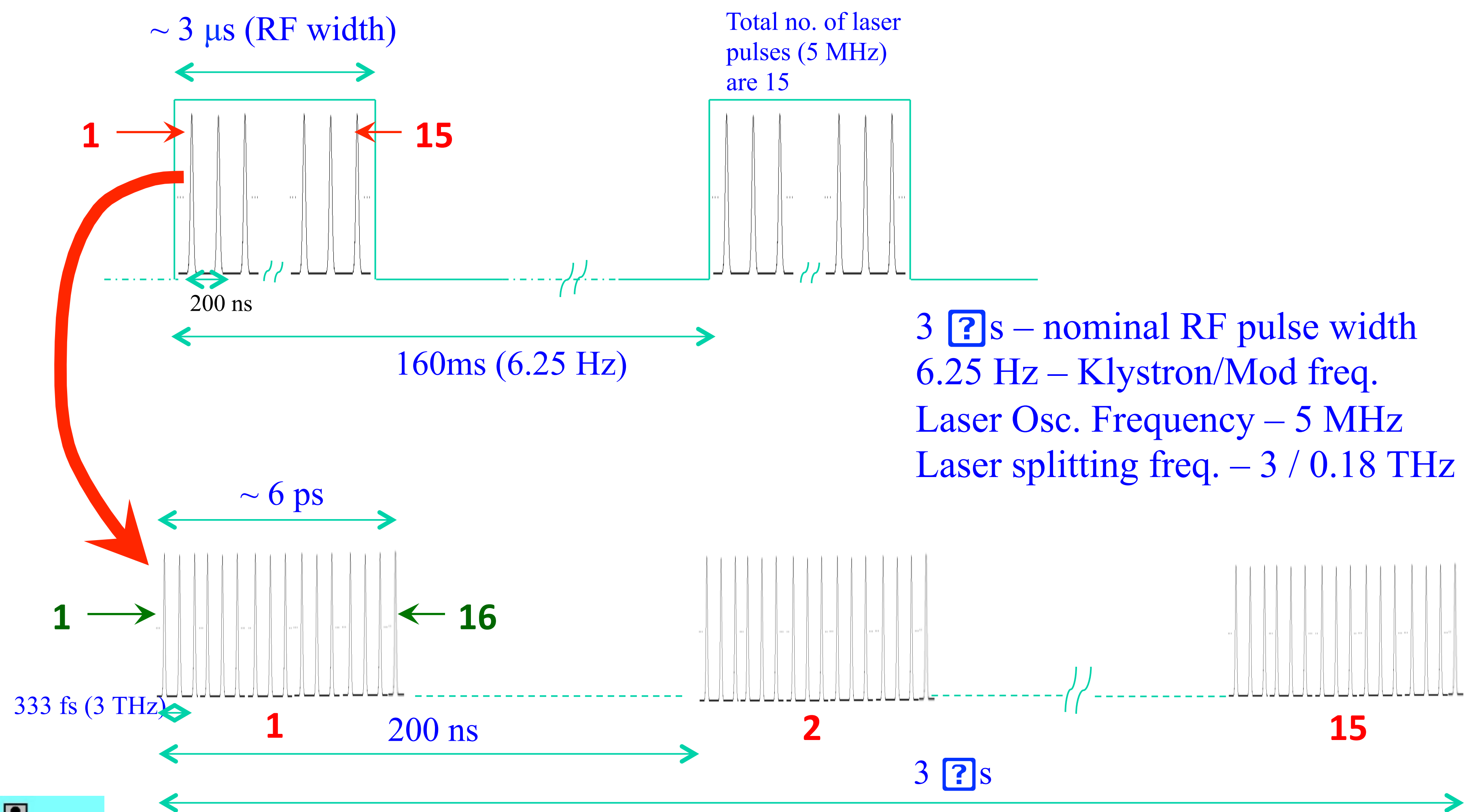
Electronics and Control

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

- Preliminary design
- Collaboration w BARC
- Components being procured

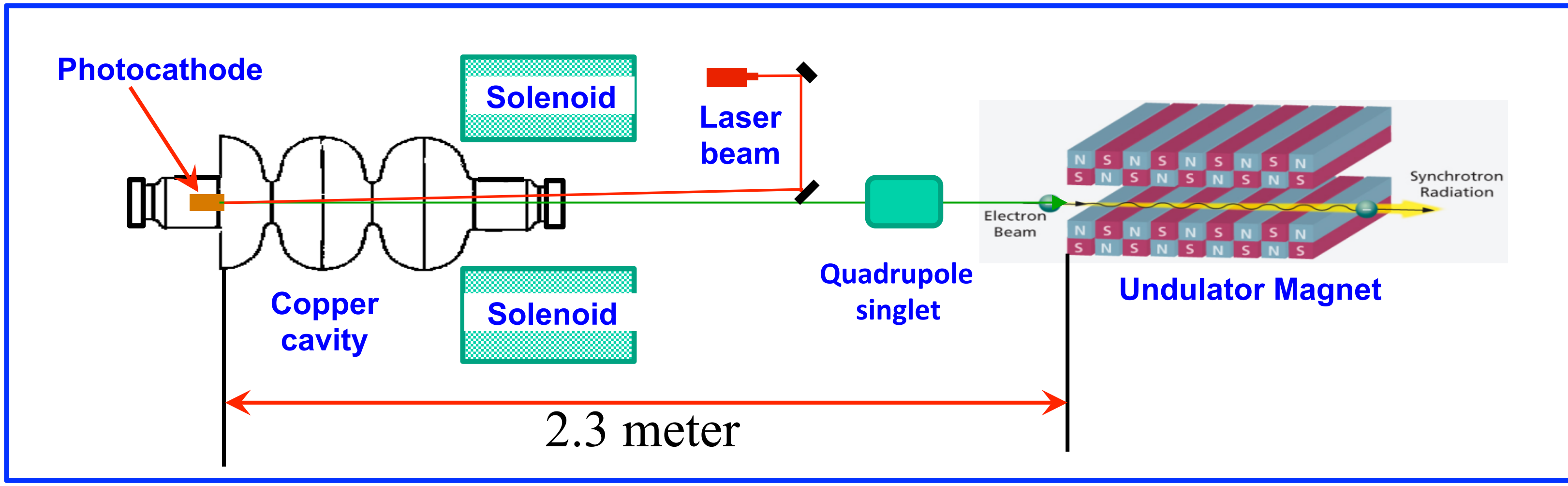
Scheme of production of Electron Beam Micro-bunches

Production of electron beam microbunches - multi-micro bunch train



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 cathode:

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

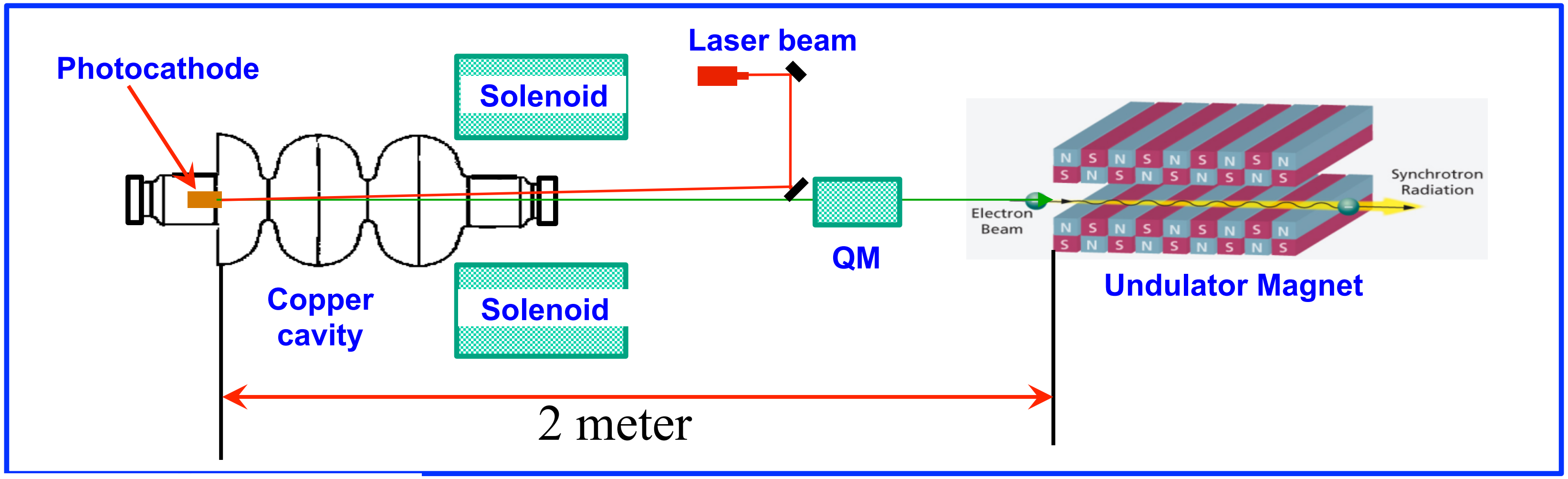
Parameters at rf gun and solenoid:

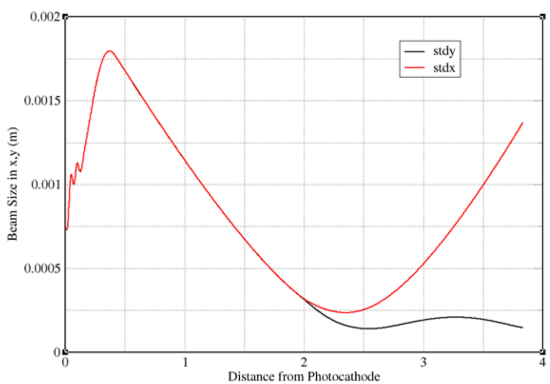
- Laser injection phase (RF phase what electron sees at the photocathode)
- Max possible E field of gun
- Optimize B field of Solenoid

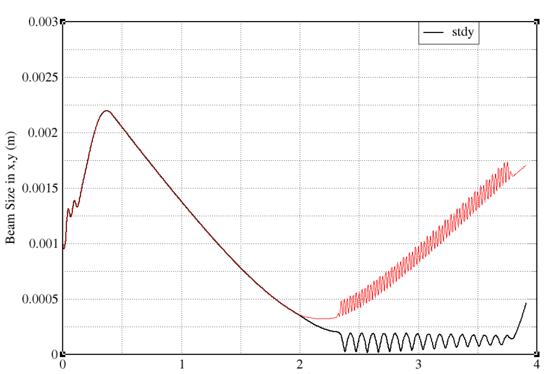
Results (important parameters):

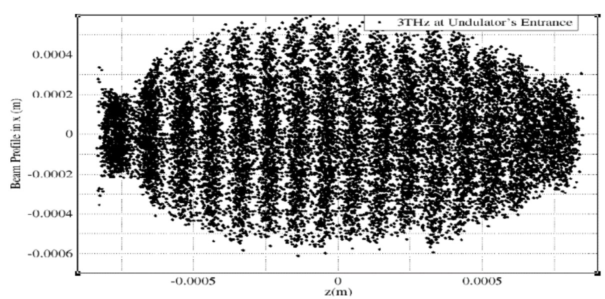
- Transverse emittance
- Spot size
- Bunch time spread
- Energy
- Energy spread

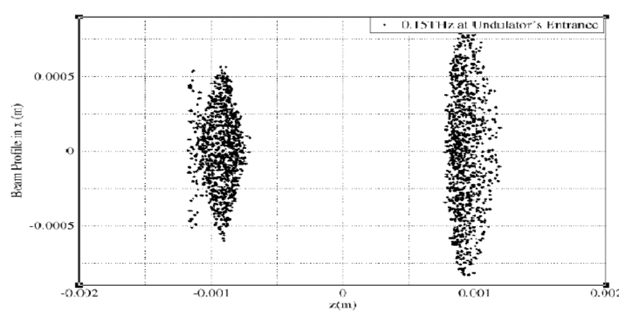
Beam optics calculation of Phase-I (GPT)





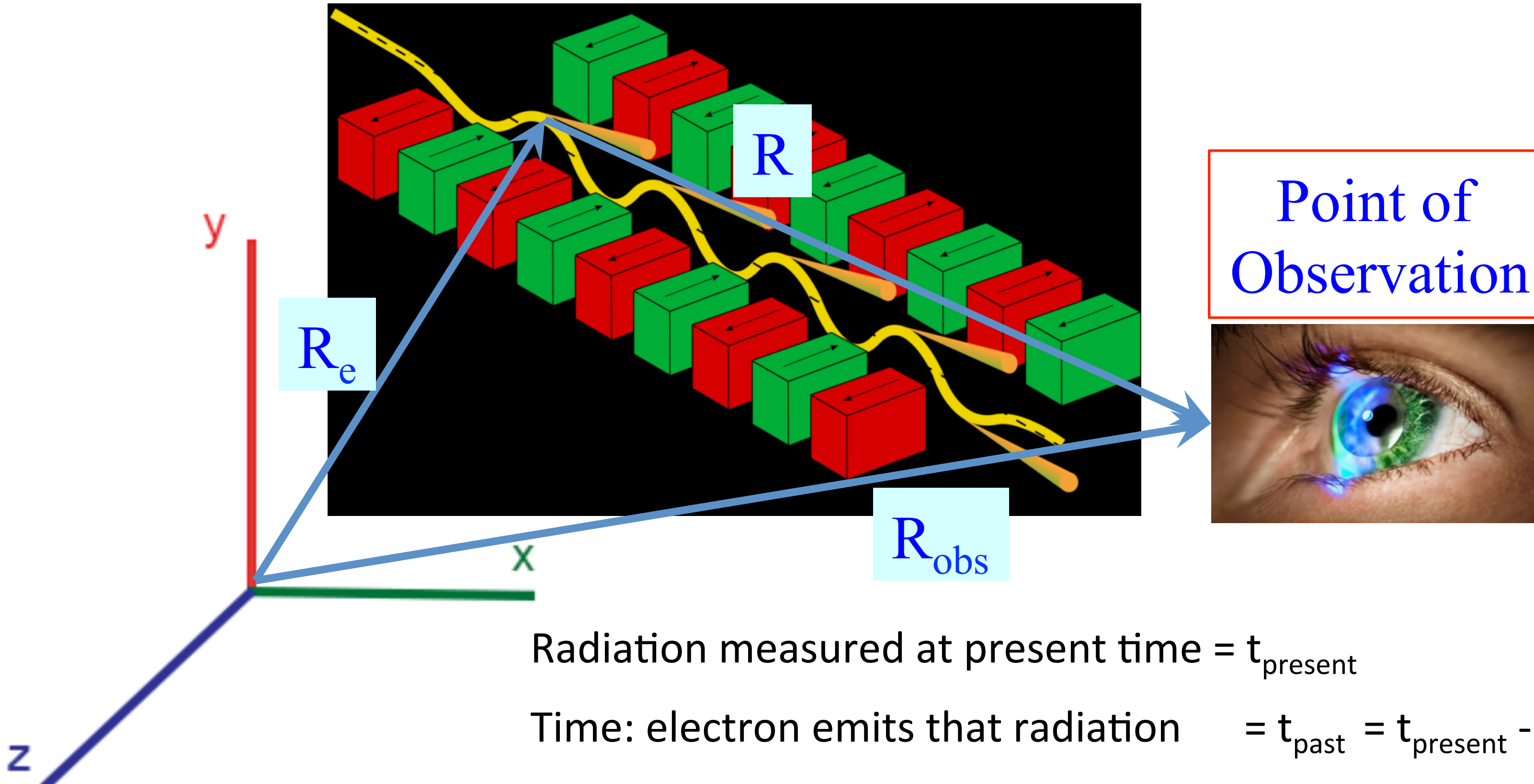






Radiation frequency range (THz)	0.18	3
Accelerating field (MV/m)	59	112
Launching phase (deg)	41	30
Electron Energy (MeV)	4.0	8.2
Energy spread (%)	1.1	0.68
e-beam FWHM @ cathode (fs)	200	200
Total charge (pC)/microbunch	15	15
Number of microbunches	2	16
Av. microbunch separation at undulator's entrance (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) ? mm-mrad at undulator's entrance	3.0, 3.2	4.2, 4.8

RADIATION FROM ACCELERATED CHARGES



Radiation measured at present time = $t_{present}$

Time: electron emits that radiation = t_{past} = $t_{present}$ - R/c

$$\boldsymbol{E}(r,t) = \frac{q}{4\pi\epsilon_0}\left(\frac{\boldsymbol{n}-\boldsymbol{\beta}}{\gamma^2 \kappa^3 |\boldsymbol{R}|^2} + \frac{\boldsymbol{n}\times((\boldsymbol{n}-\boldsymbol{\beta})\times\boldsymbol{\beta})}{c\kappa^3 |\boldsymbol{R}|}\right)_{t_r}$$

$$B(r,t) = n(t_r)/c \times E(r,t)$$

R = R_{obs} – R_e , distance of the observation point from the source of radiation

n = **R**/R, unit vector pointing from source of radiation to the observation point

?, $d?/dt$ are the velocity and acceleration of the particle

? = 1- n??

COMPUTATION OF RADIATION BY LIENARD-WIECHERT POTENTIAL

Create/Load Particle Phase Space (t,x,y,z,px,py,pz) from GPT, ASTRA

↓

Use Vay's Particle Pusher algorithm to evolve beam distribution (particle moves thru Undulator)

↓

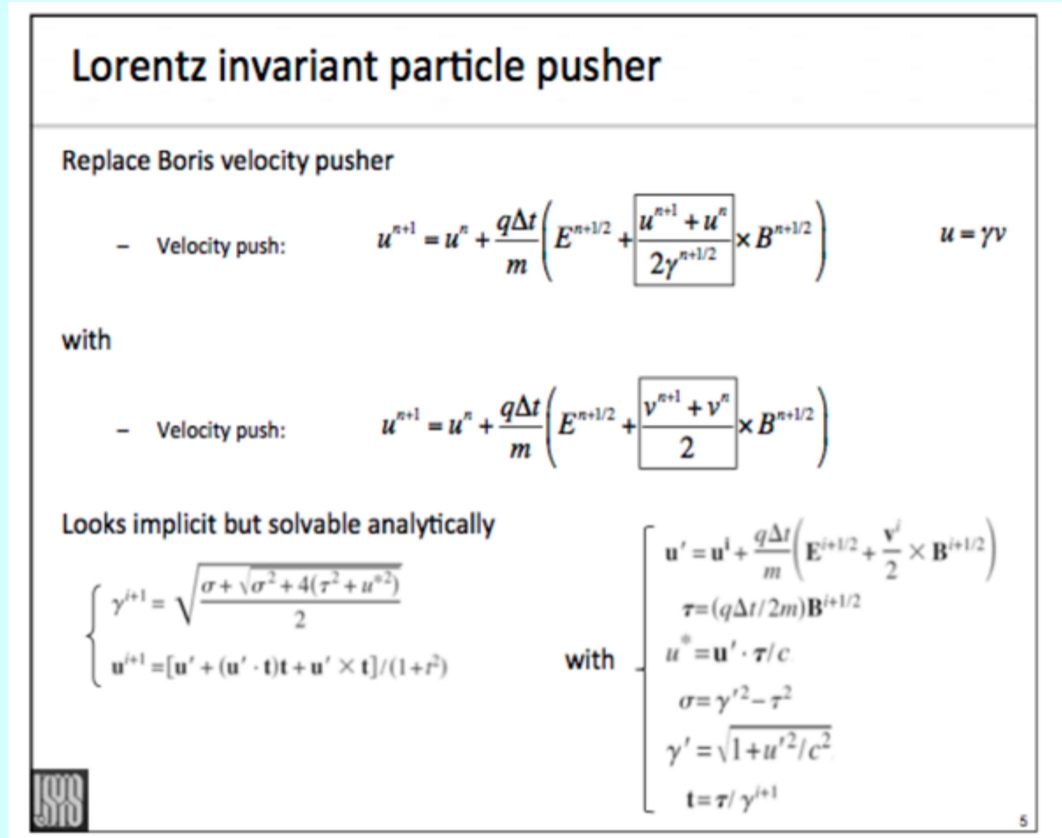
At a separation of ~mm; R, p, [?]-dot and t of all the electrons are computed

↓

Trajectories integrated to t + dt & stored in particle's memory

↓

These data are retarded Positions, Velo. Acceleration & time → **Compute e.m. radiation by Lienard Wiechert Fields**

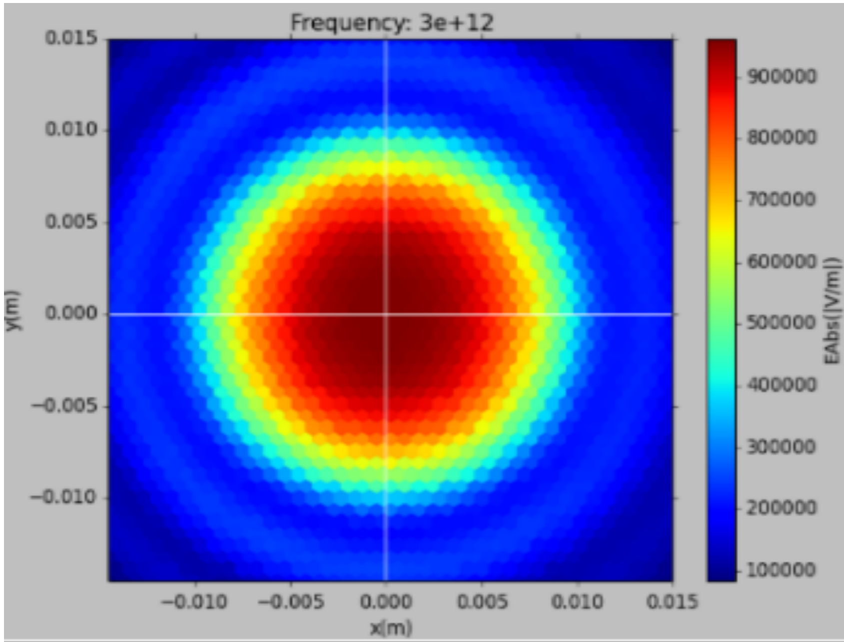


$E(r, t) = q/4\pi\epsilon\downarrow 0 \quad (n - \beta)/\gamma\uparrow 2 \ \kappa\uparrow 3 \ |R|\uparrow 2 + n\times((n-\beta)\times\dot\beta) / c\kappa\uparrow 3 \ |R|)\downarrow t\downarrow r$

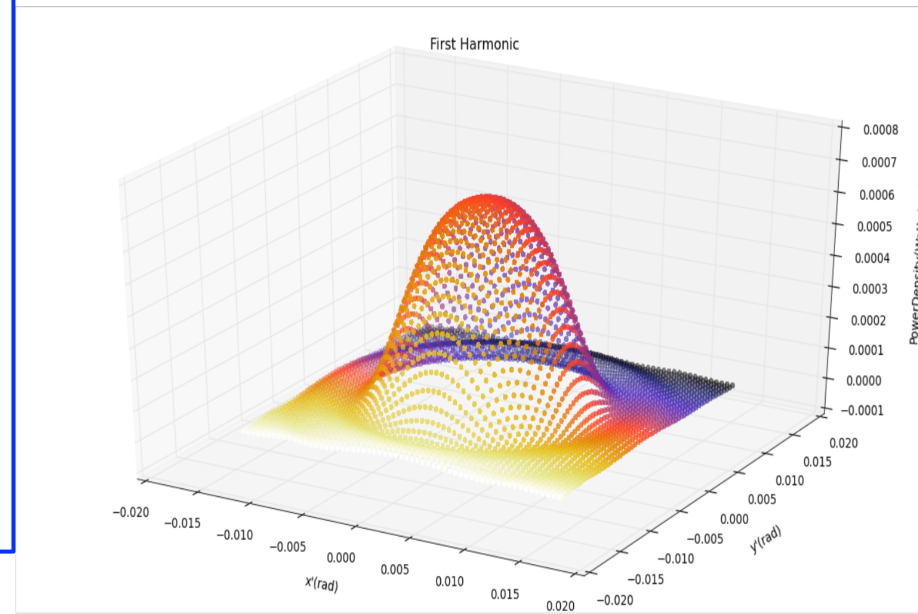
$B(r, t) = n(t\downarrow r)/c \times E(r, \ldots$

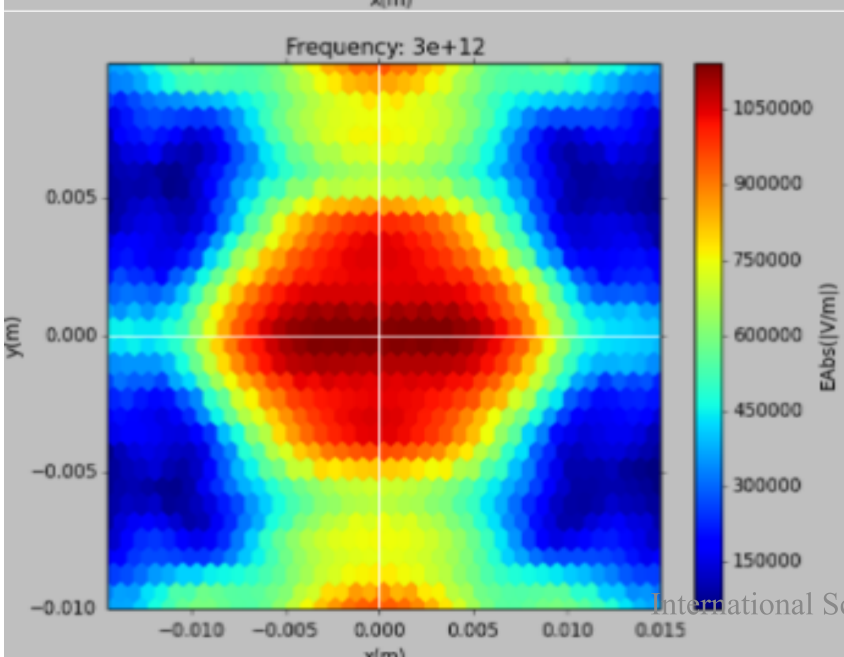
*J L Vay, Physics of Plasmas 15, 056701(2008)
''Boris, J.P. (November 1970). "Relativistic plasma simulation-optimization of a hybrid code". Proceedings of the 4th Conference on Numerical Simulation of Plasmas. Naval Res. Lab.,

Transverse profile of Radiation – 3 THz

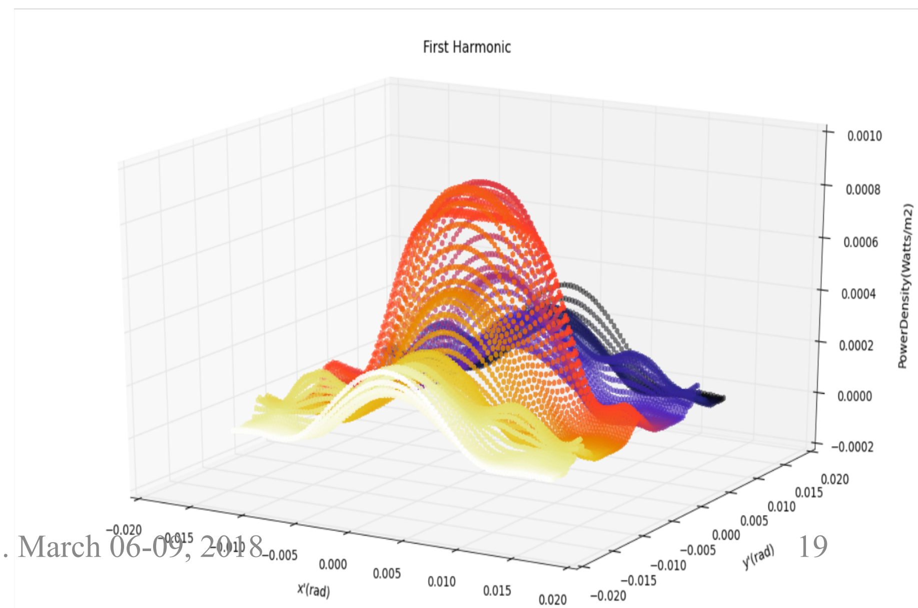


FREE SPACE

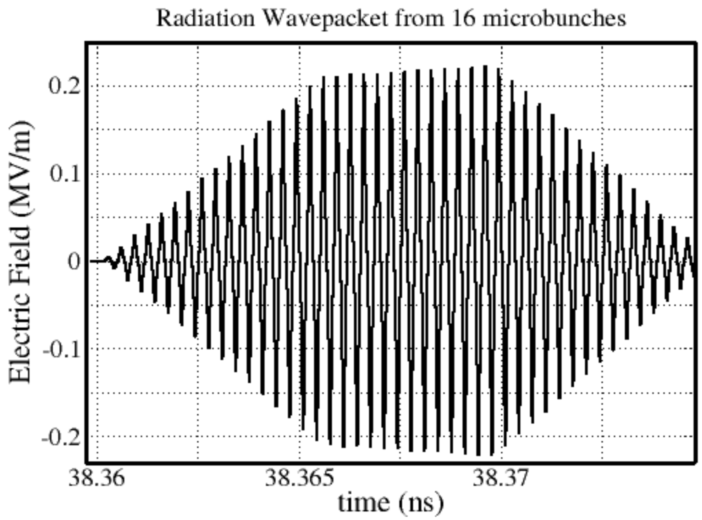


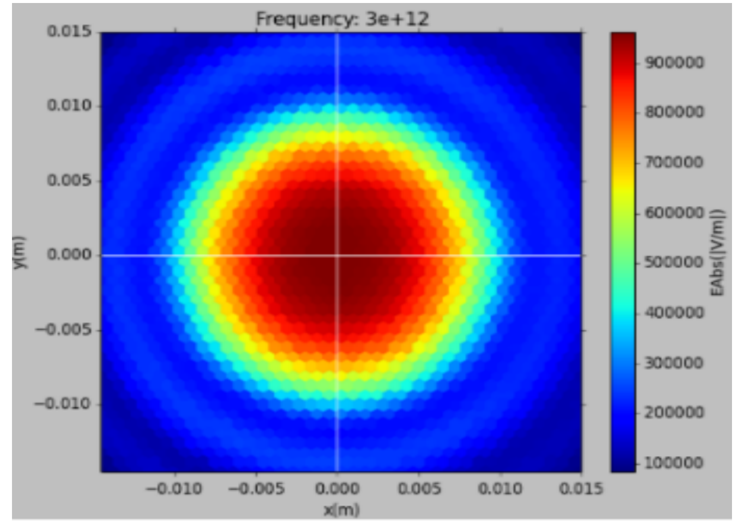


BEAM PIPE



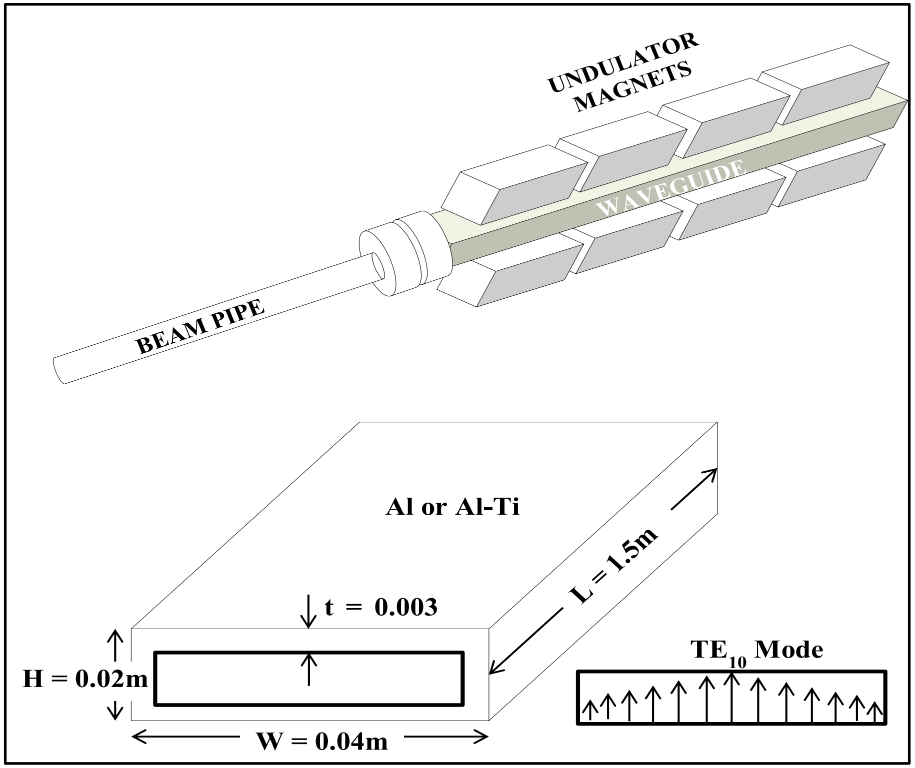
Radiation simulation

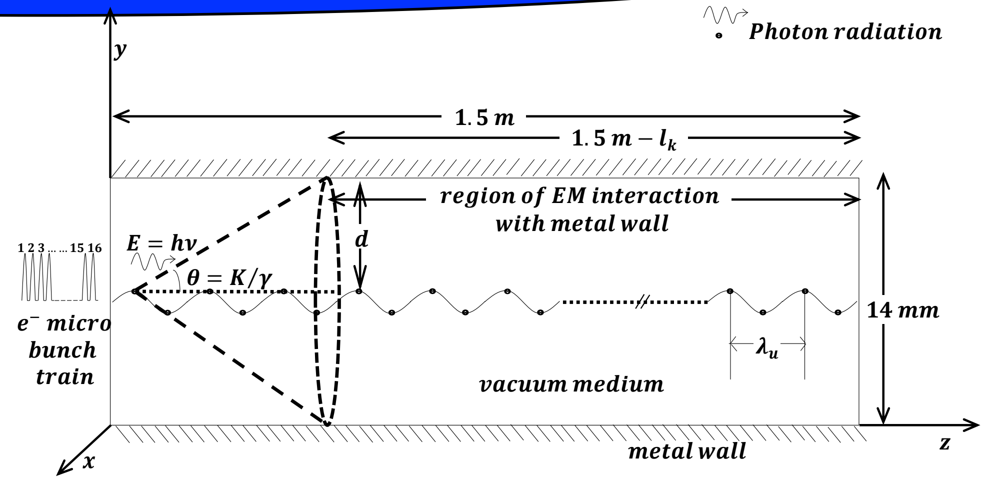




Time width	Number of electrons	Total electron current	Energy content of 3 THz (?J)	Remarks
~ 200 fs	9.3 ? 10^7	75 A	< ~ 1	Single e-bunch.
~ 6 ps	1.5 ? 10^9	40 A	~ 12	Train of 16 e-bunches.
~ 3 ?s	2.25 ? 10^{10}	1.2 mA	~ 180	Train of 15 no. of 16 e-bunches.
1 sec.	1.4 ? 10^{12}	22.5 nA	~ 1125	Train of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

Transportation & Attenuation of THz through beam pipe





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

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

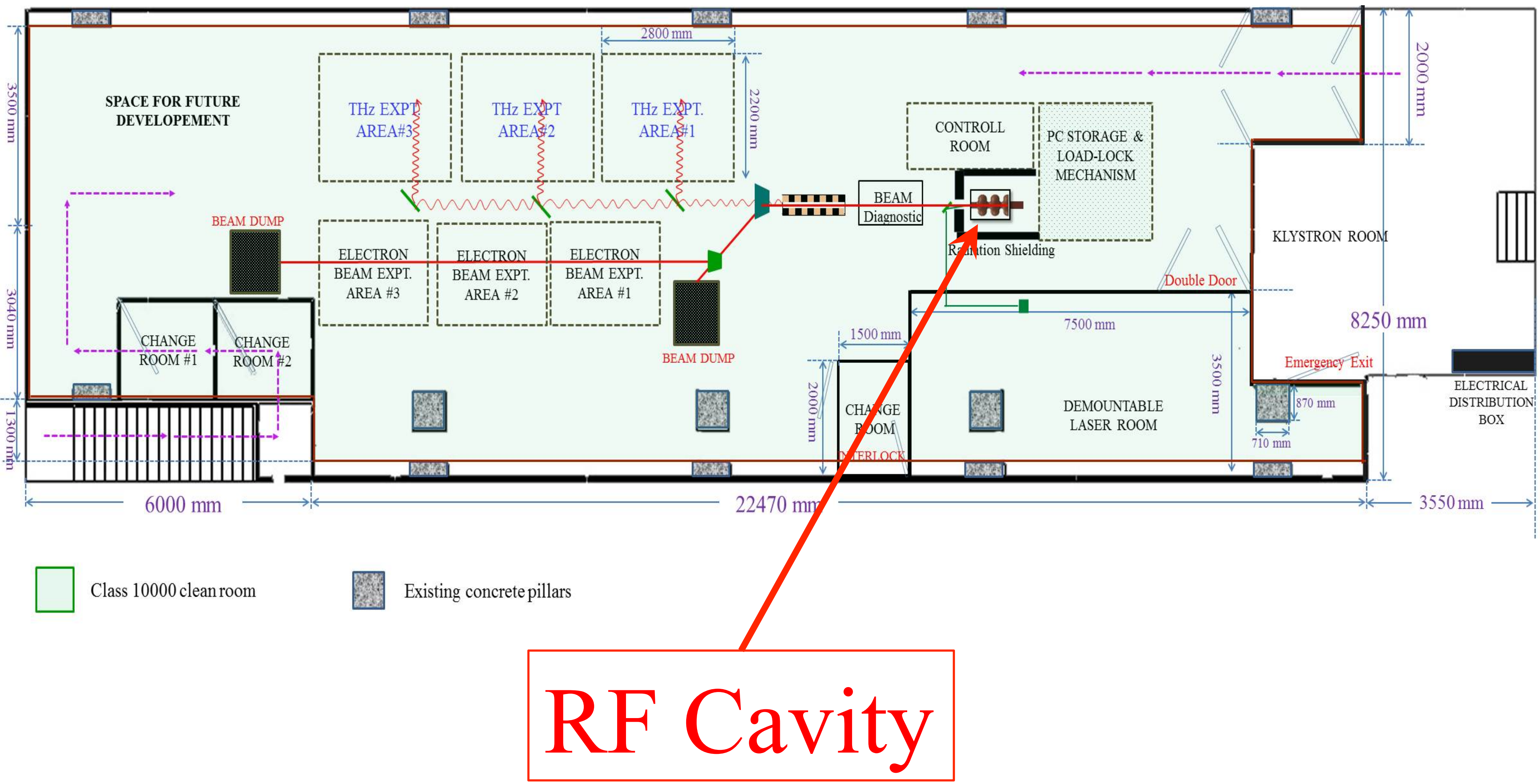
$$P_k = \begin{cases} (k^2).P_1, & 1 \le k \le N_b \\ (N_b^2).P_1, & N_b+1 \le k \le N_u \end{cases}$$

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

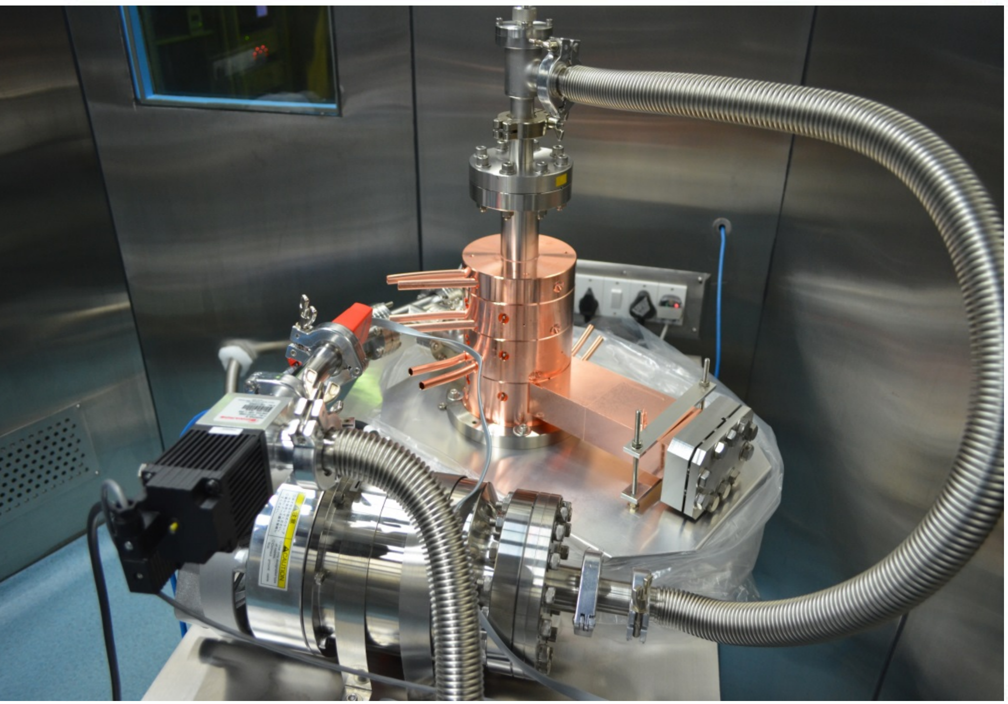
Material	Attenuation Constant (Np/m)	
	0.18 THz	3 THz
Al	0.1185	0.1618

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

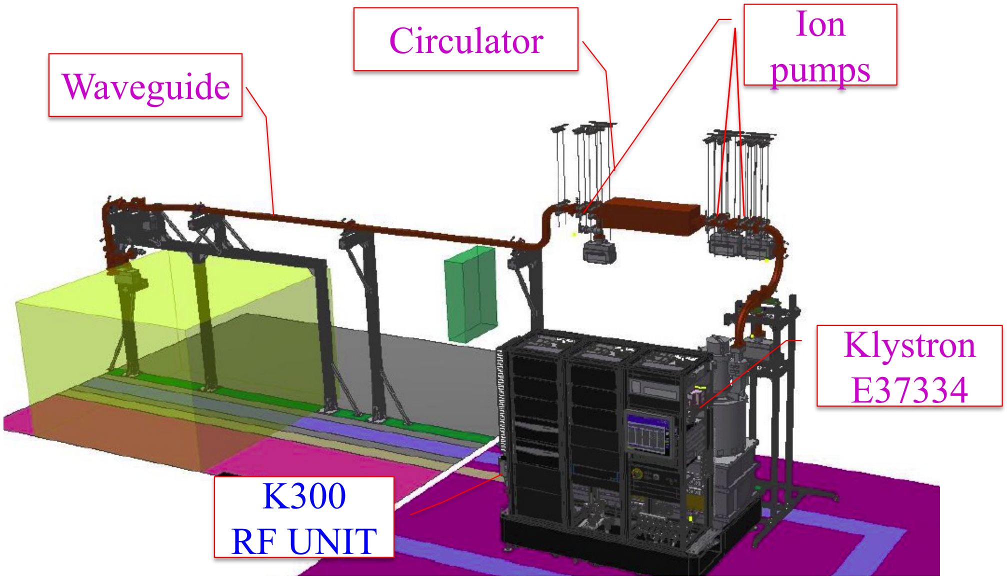
Phase-I of the project: complete layout with expt. stations



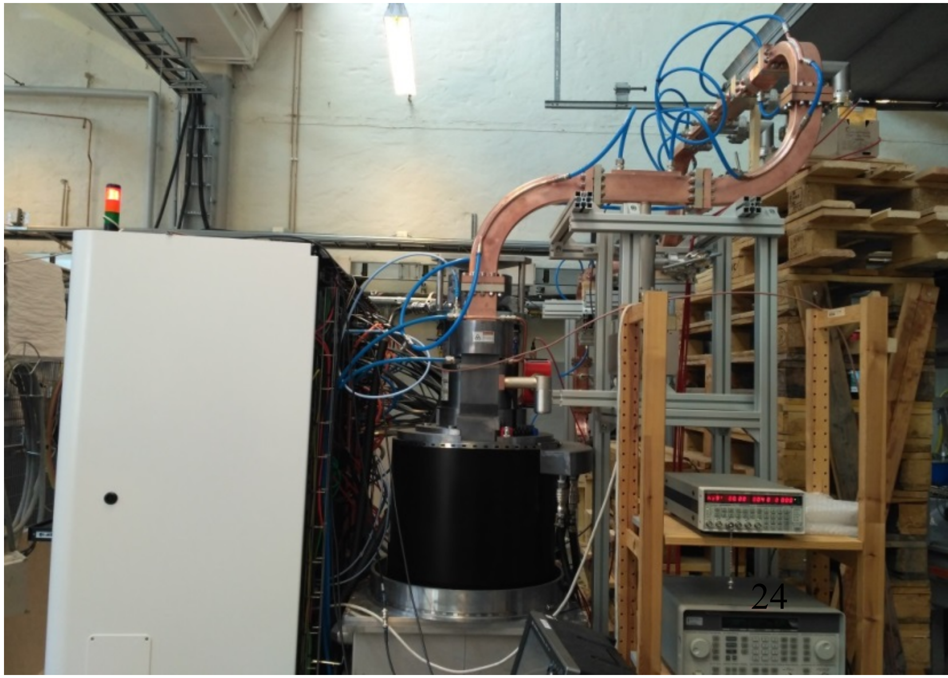
Electron Gun at IUAC



Layout of HP-RF System



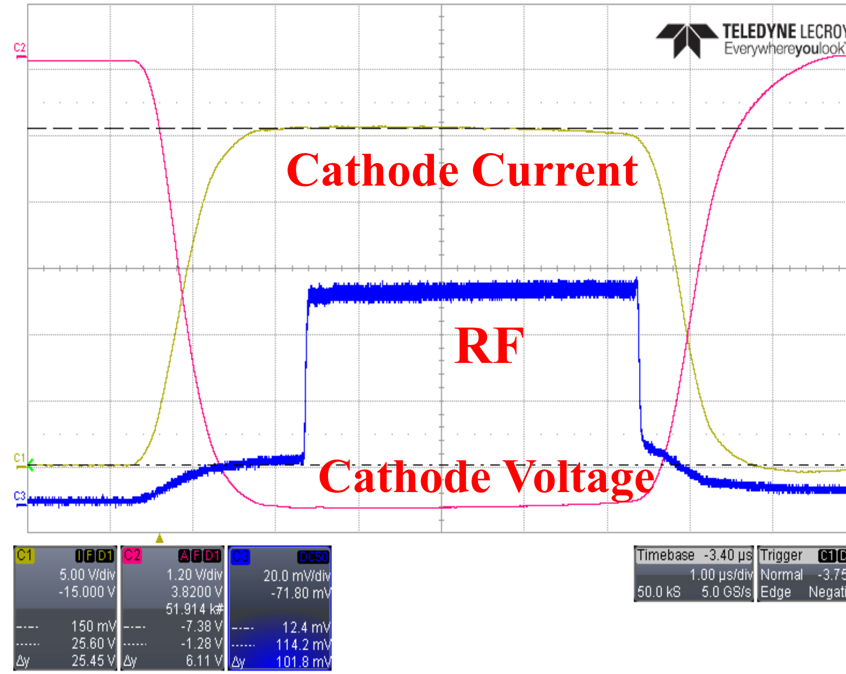
- Toshiba Klystron E37334 & Solenoid magnet
- Scandinova K300 Modulator
- Solenoid Power Supply & Ion Pump Power Supplies
- RF Drive amplifier
- Cooling of Klystron (Collector, Body, window), Solenoid
- Diagnostics and interlocks
- WR284 RF waveguide system (circulator, Loads, Directional couplers)

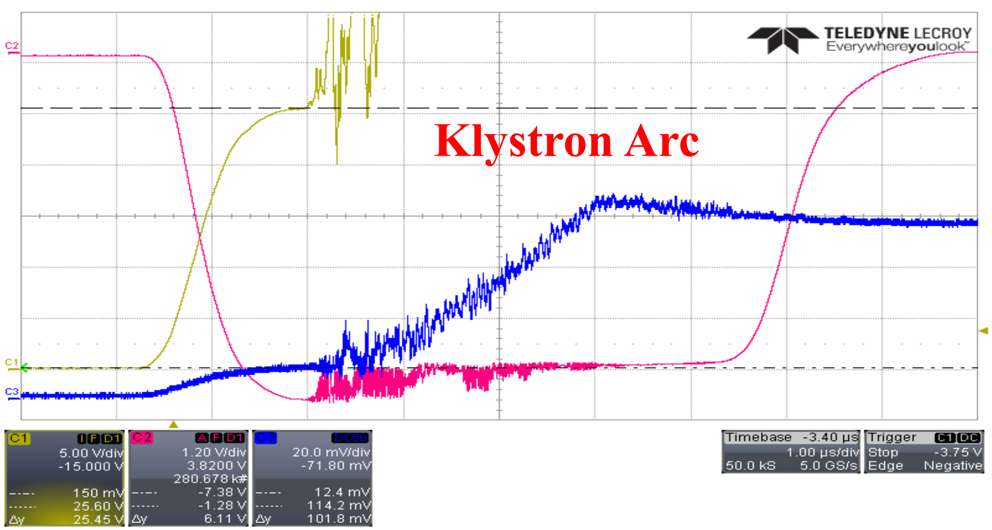


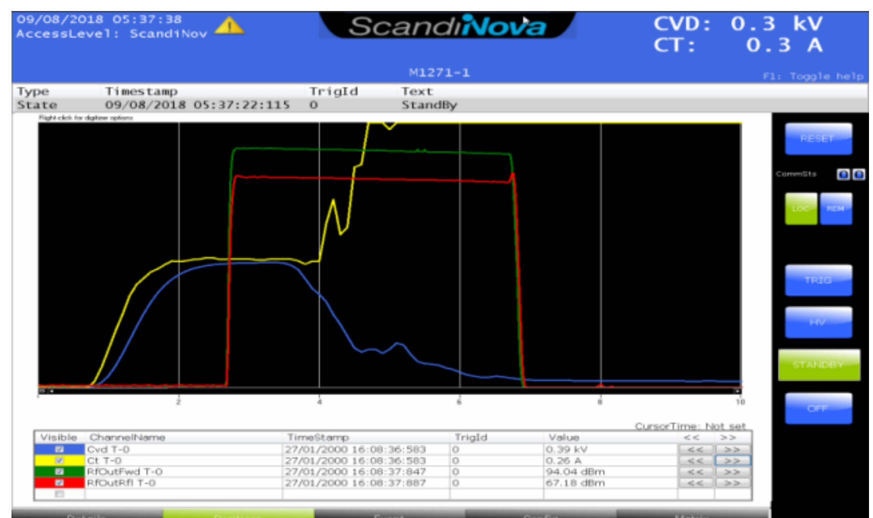
Factory Acceptance Results
(Important Klystron & Modulator Parameters)

Main Parameters	Tender Requirement	Factory Achieved Results
RF Peak Power	25 MW	~ 25 MW
RF Average Power	5 kW	~ 5 kW
RF Pulse width	≤ 4 μs	≤ 4 μs
Cathode Voltage	>245 kV	~ 251 kV
Cathode Current	255 A	~ 255 A
Pulse Flatness	≤ ± 0.3%	± 0.29 %
Pulse-to-Pulse Stability	≤ 50 ppm	~ 42 ppm
Pulse Repetition Rate	≤ 50 Hz	≤ 50 Hz
Rate of Rise	200-250 V/μs	~ 311 V/μs
Rate of Fall	200-250 V/μs	~ 243 V/μs

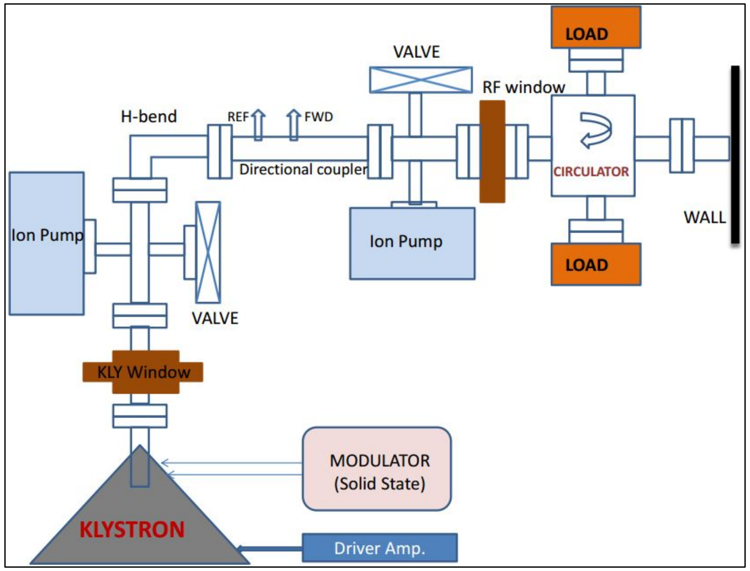
Klystron & Modulator Diagnostics

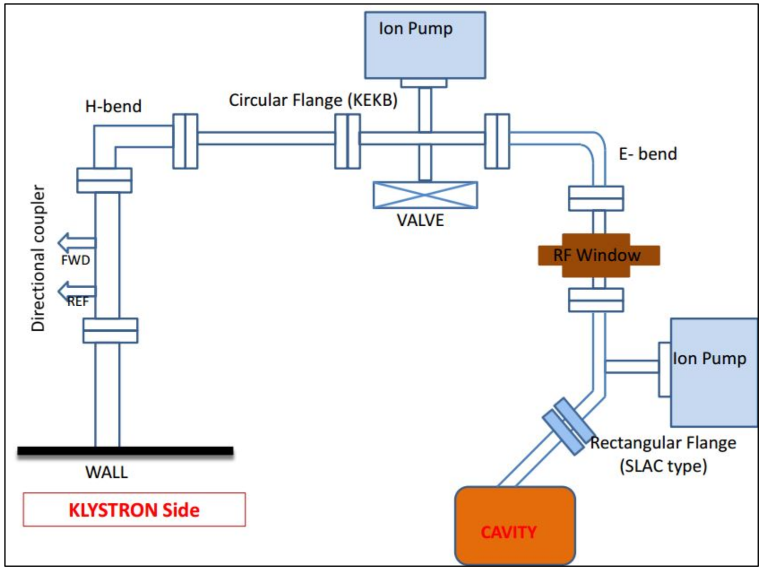




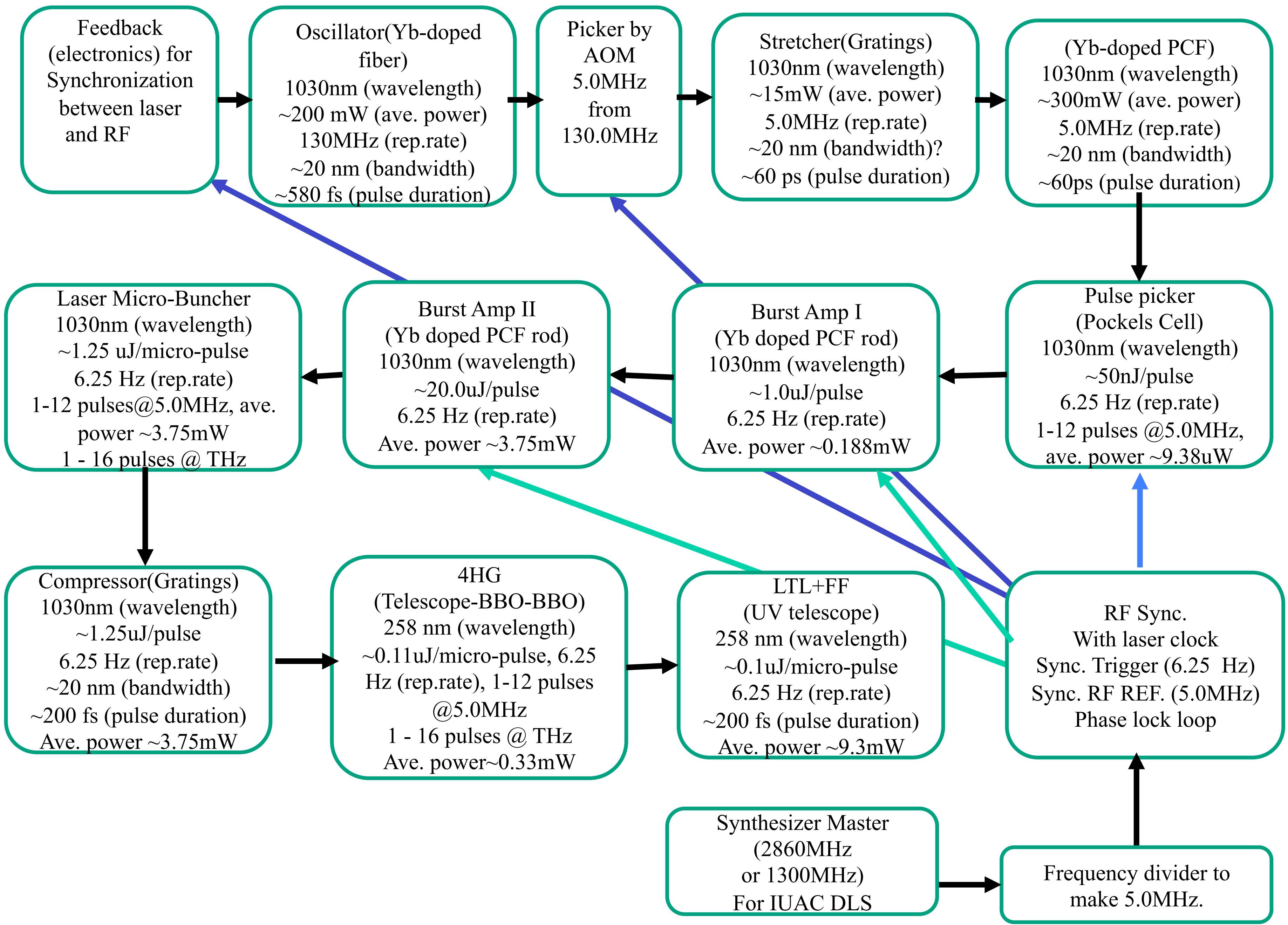


Klystron based high power RF source

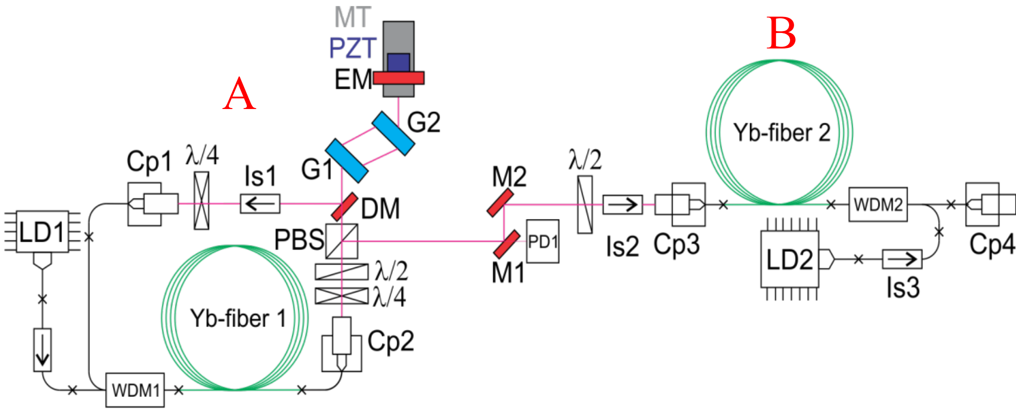




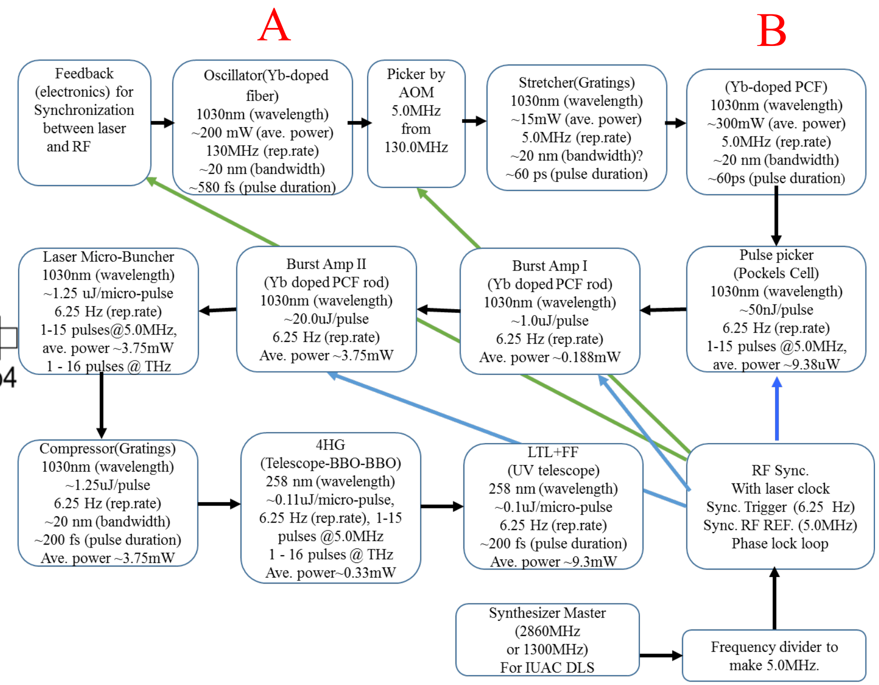
Block diagram of the fiber laser system

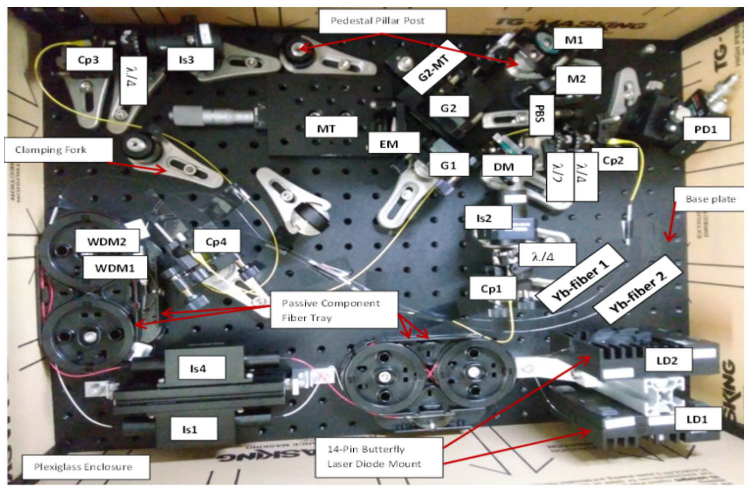


Testing and installation of Prototype Fiber oscillator + pre Amplifier



Schematic of Fiber Oscillator

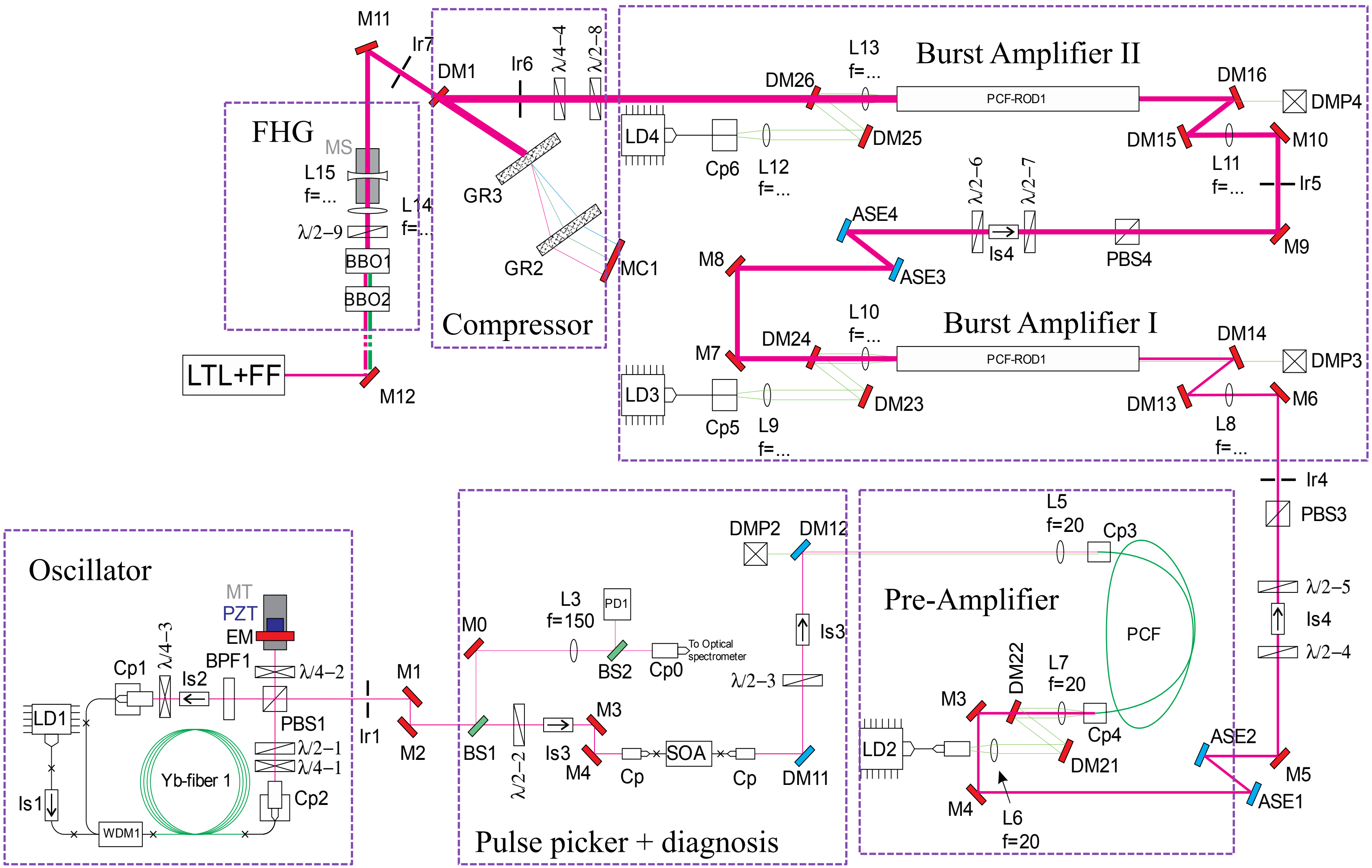




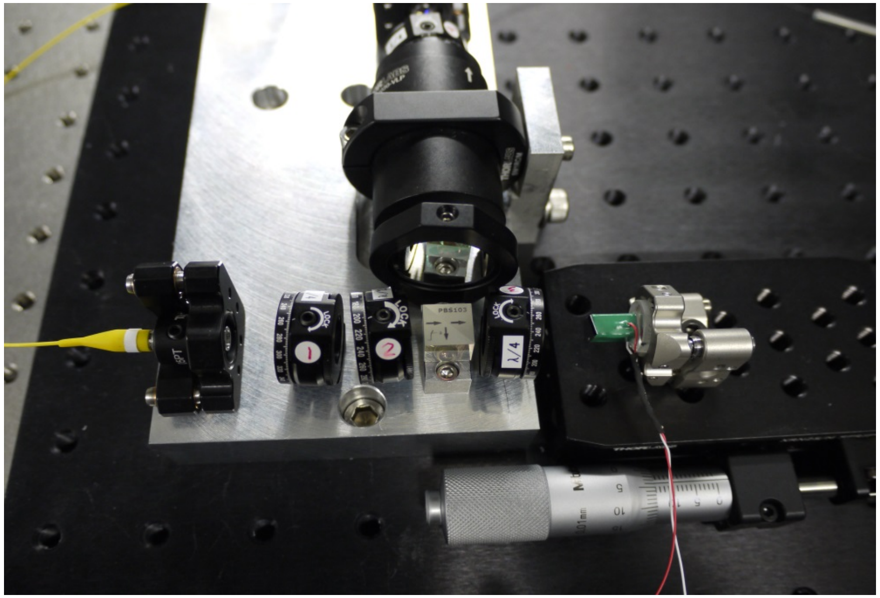
Oscillator + Pre amplifier

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

The latest design of the fiber laser



Oscillator



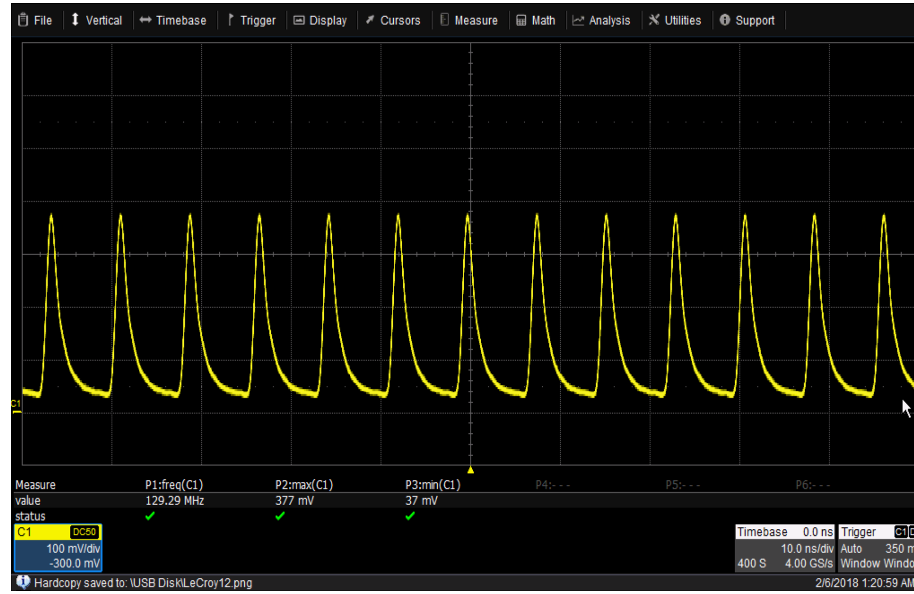
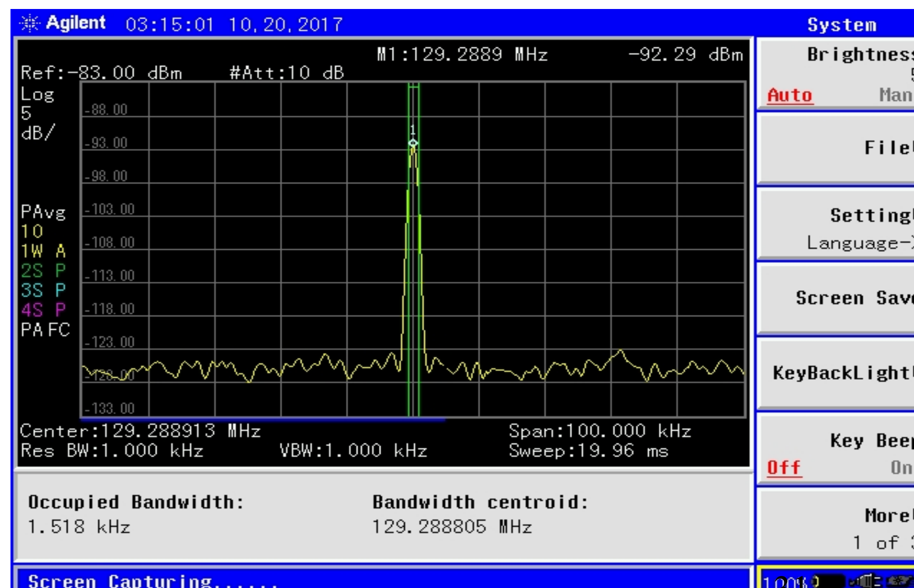


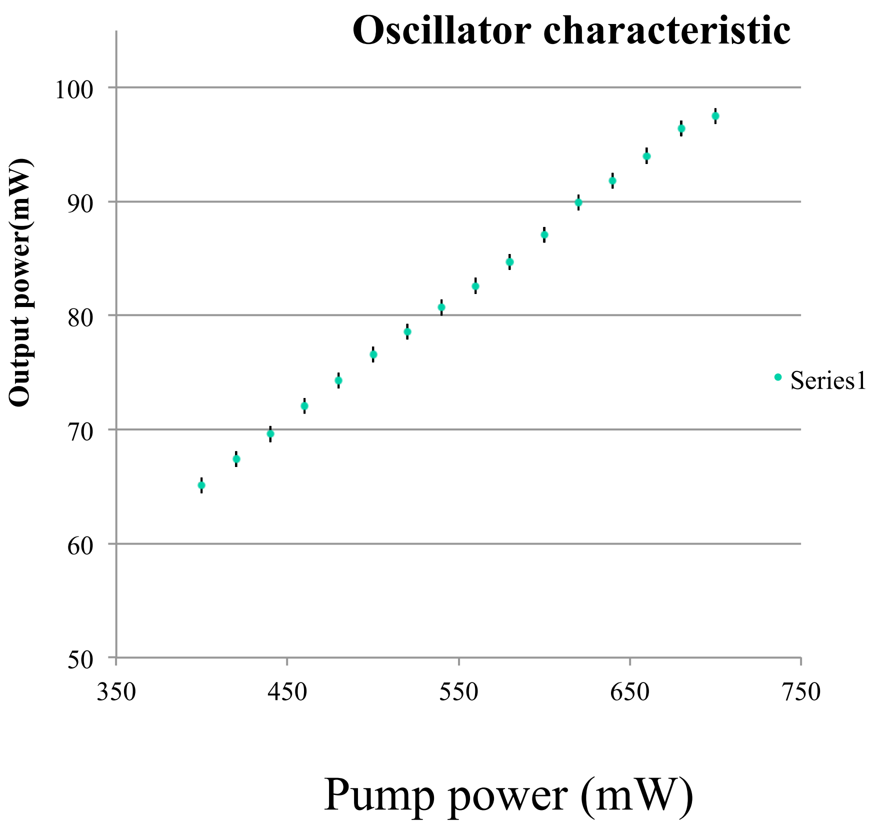
Photo diode signal

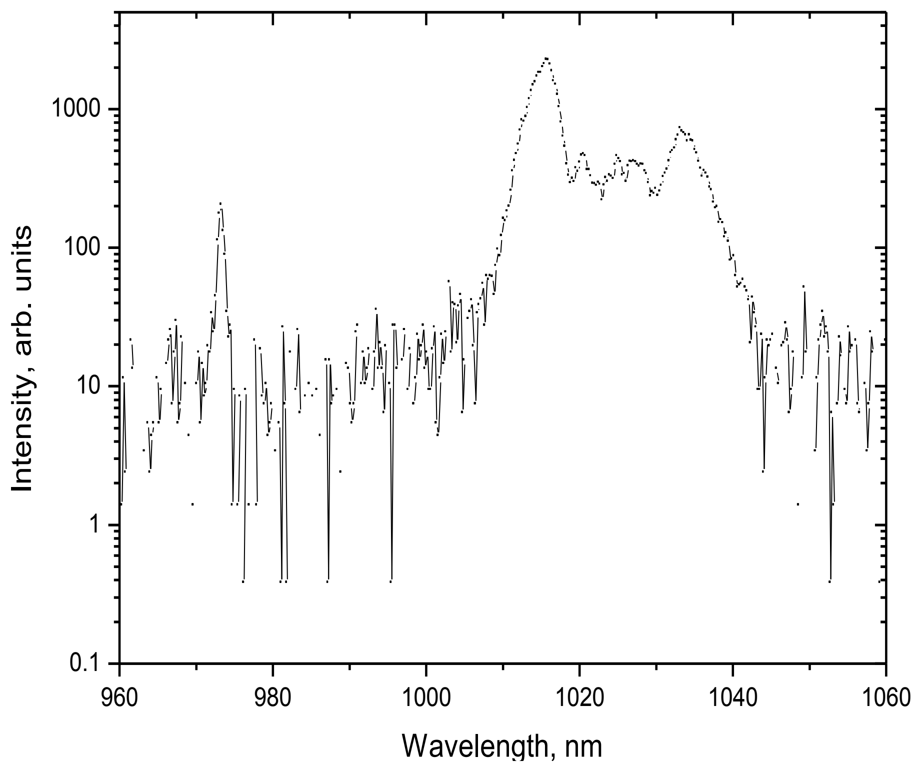
Pulse to pulse stability



Central frequency 130 MHz

Oscillator Characteristics



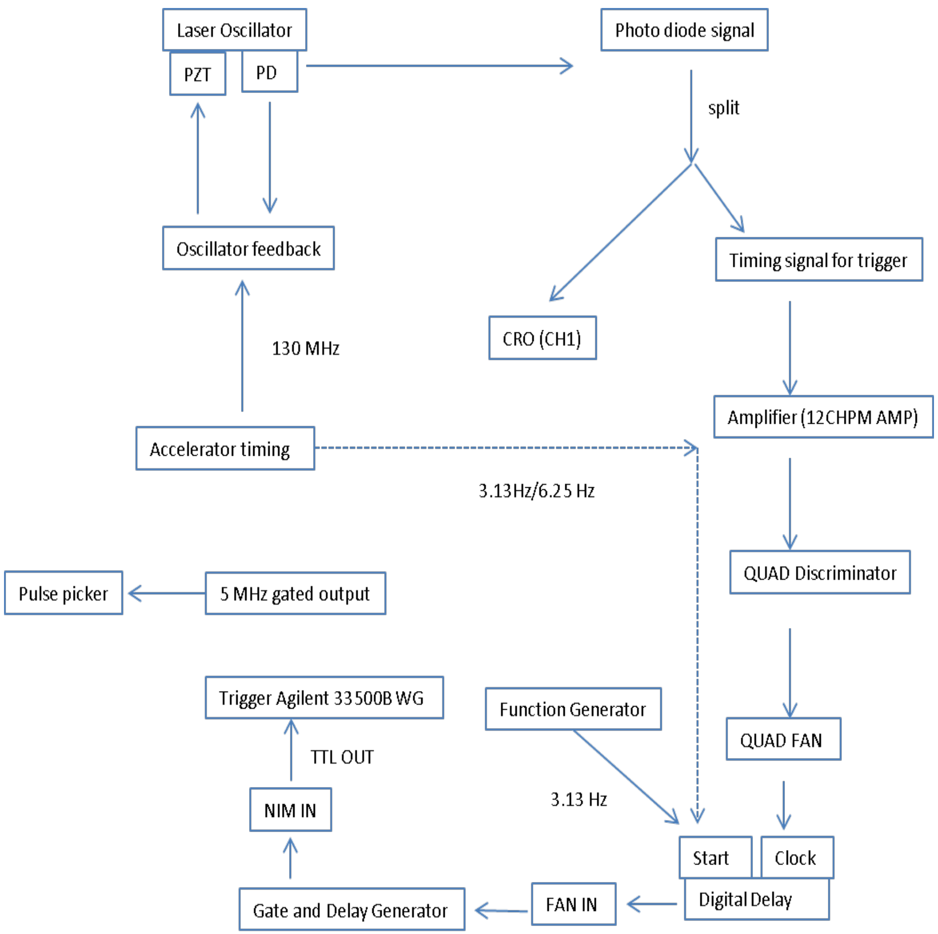


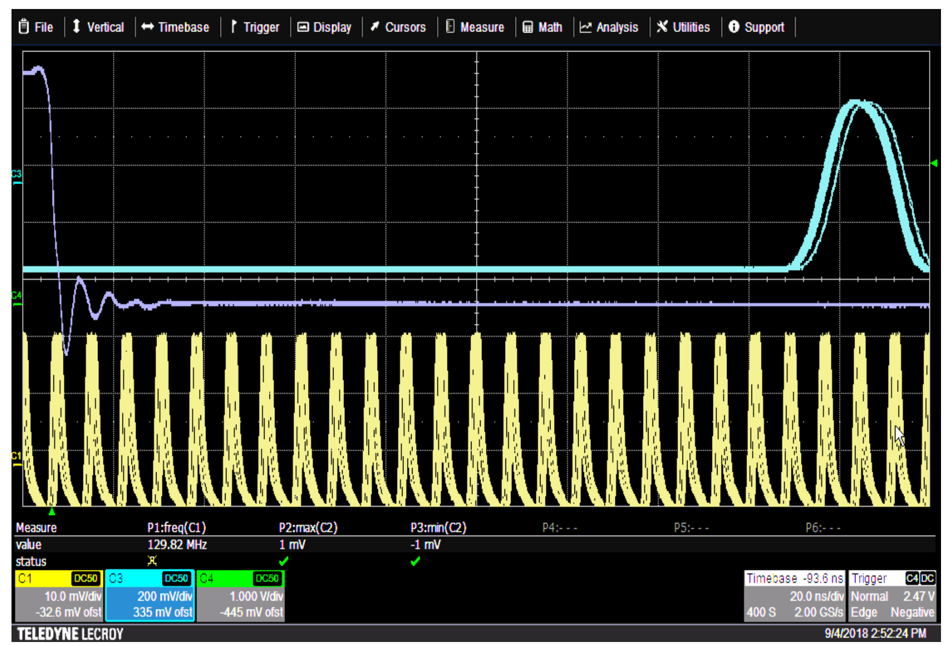
RMS stability < 0.3%

BW> 25 nm

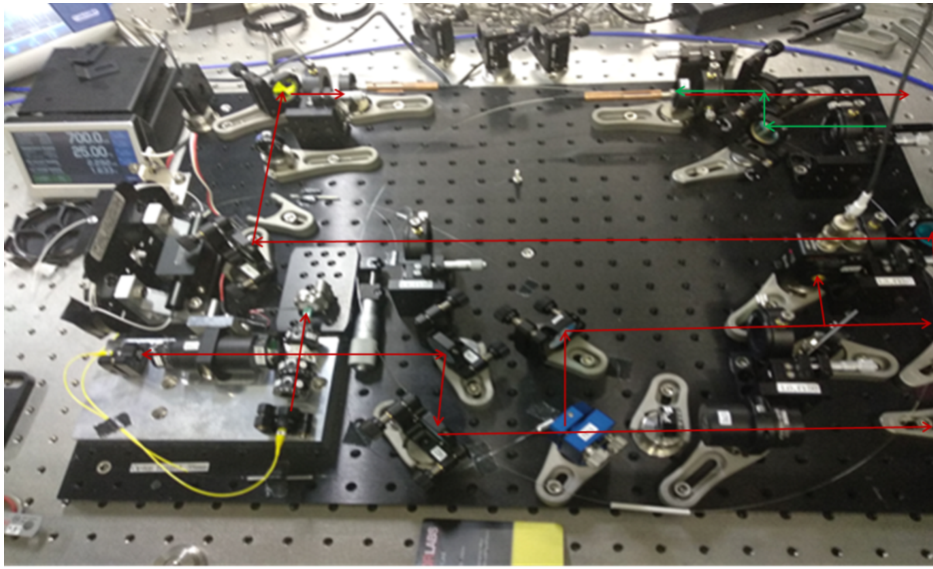
Pulse picker timing

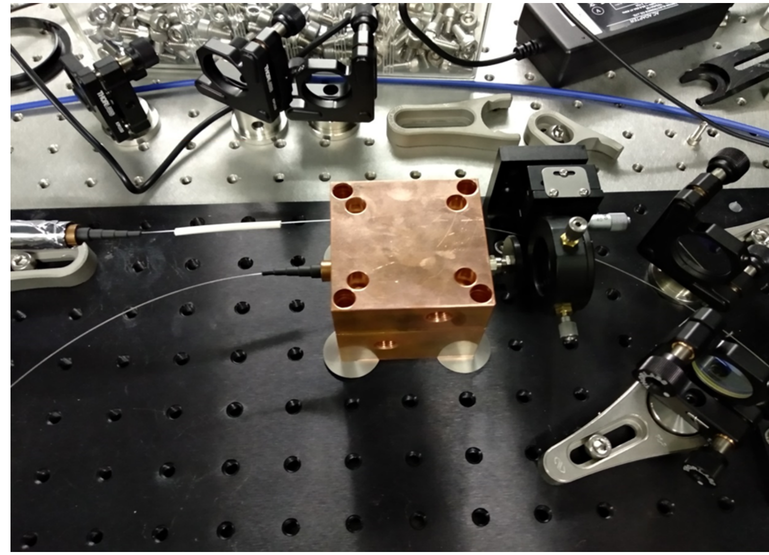
In order to make better precision
We need higher spec function generator



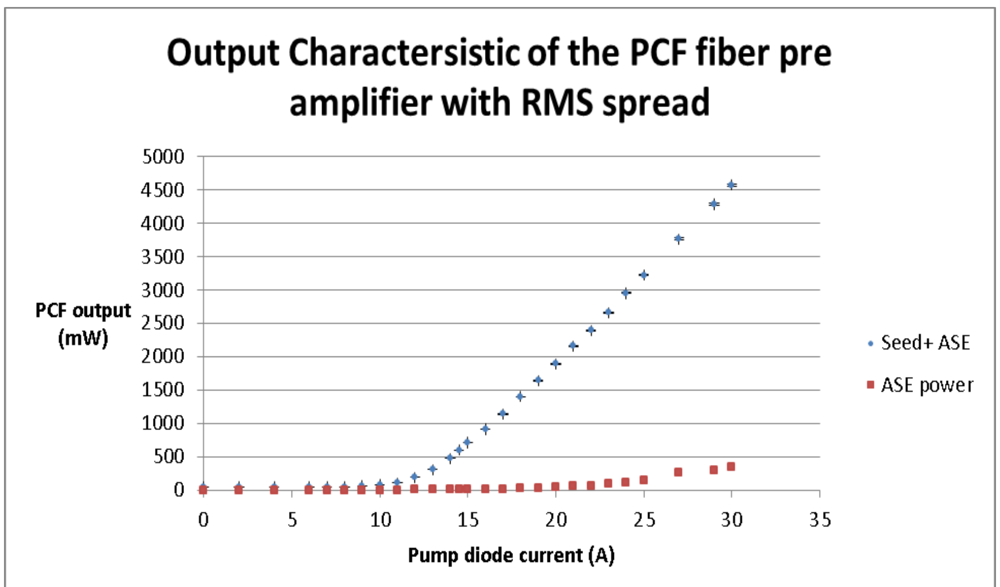


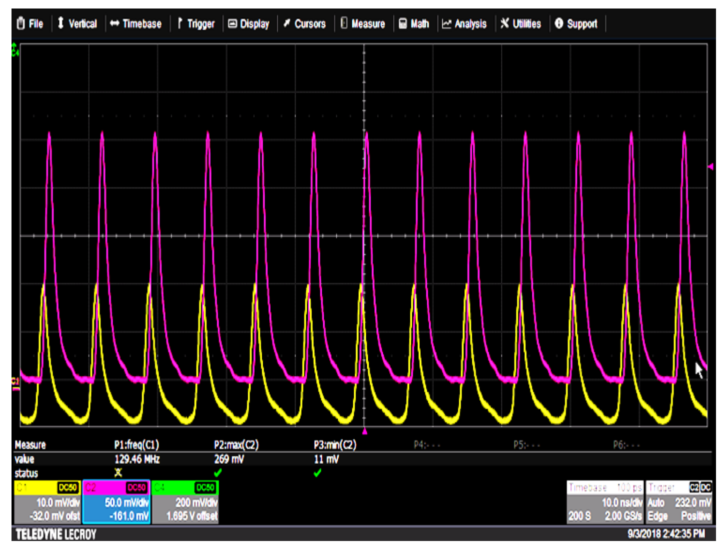
Oscillator + Pre amplifier





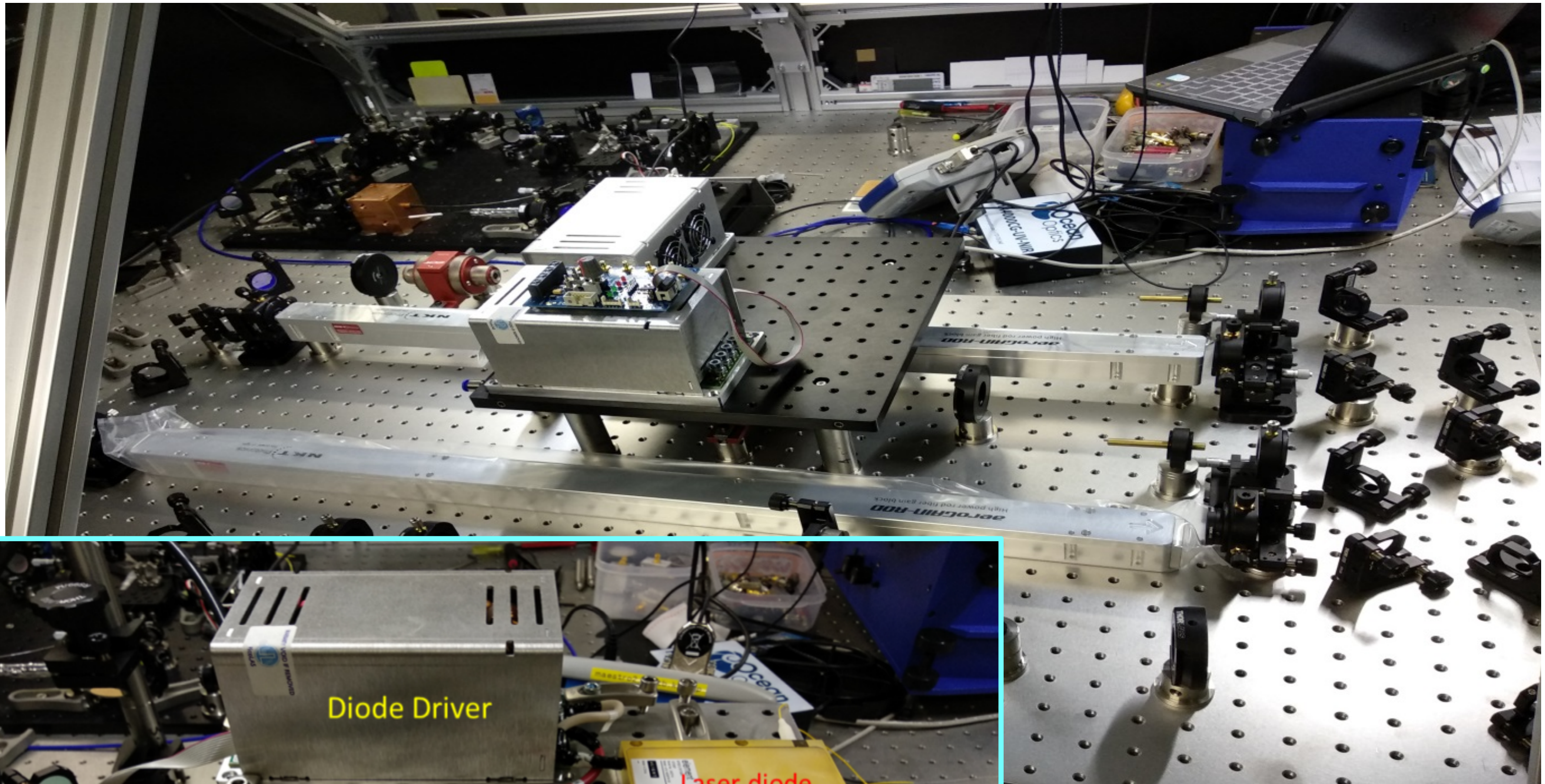
Pre amplifier cooling block

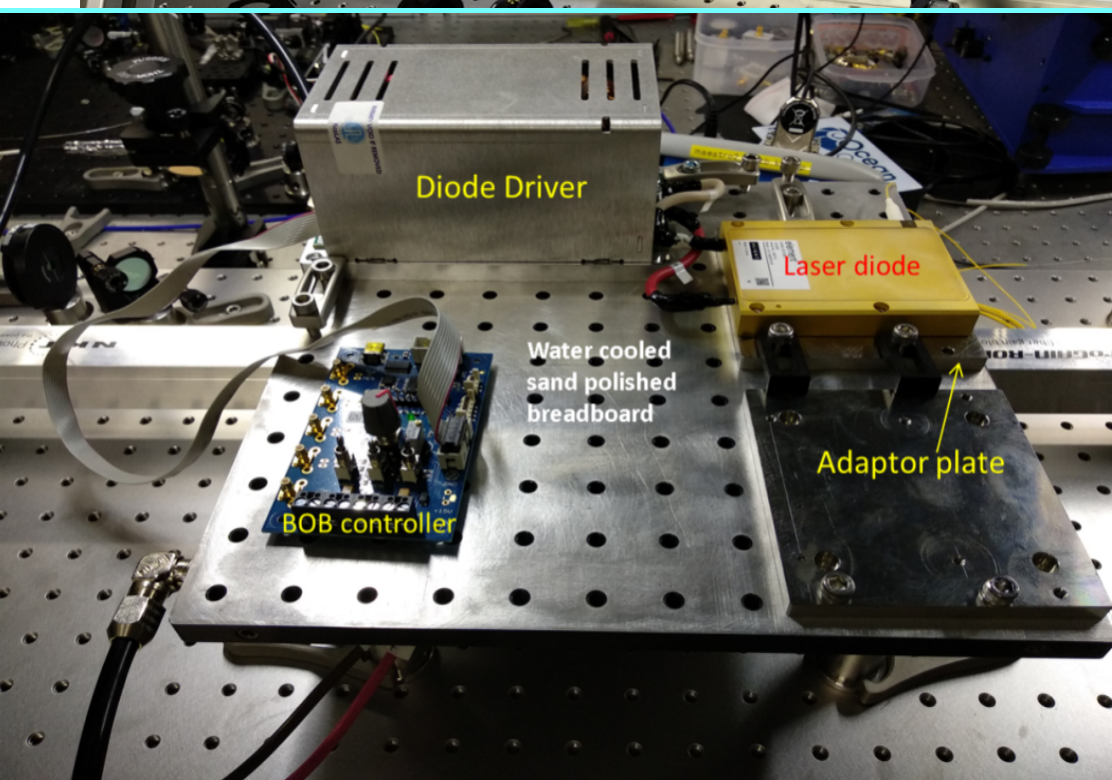


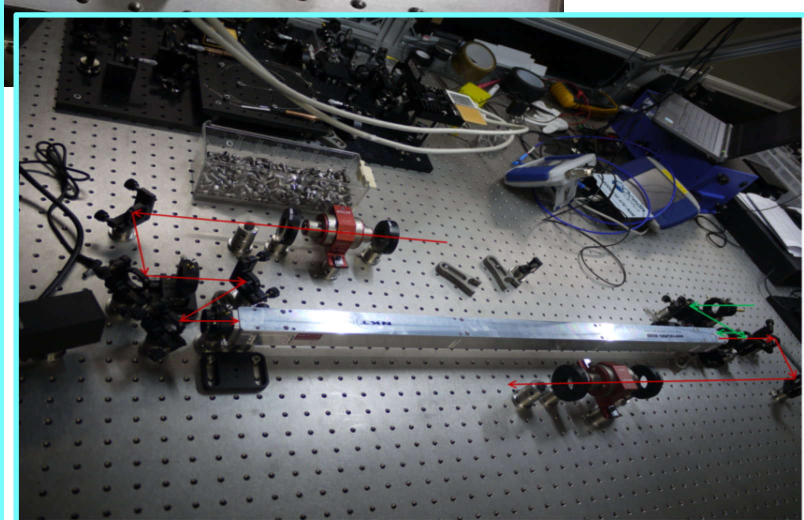


Oscillator (yellow) and pre amp (pink) photo diode signal

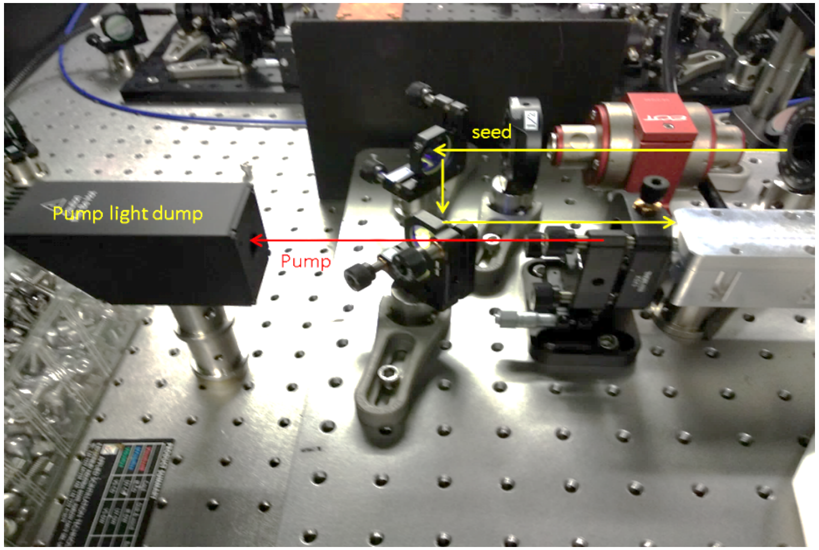
Main amplifier assembly



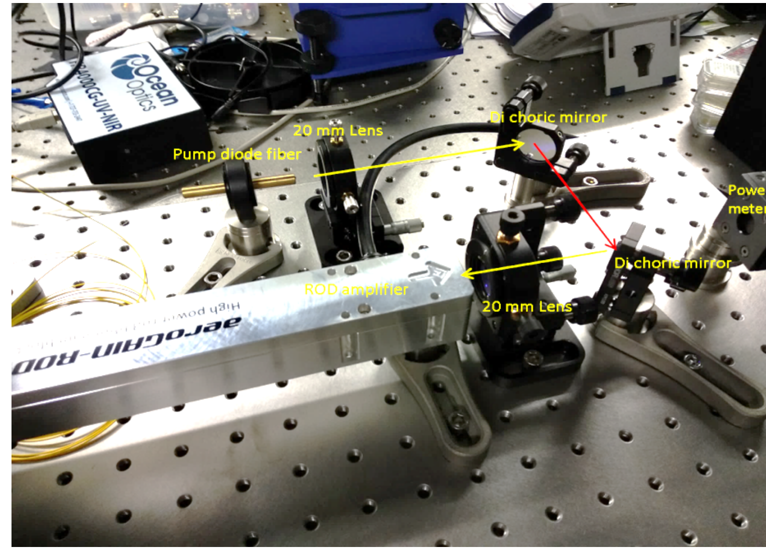




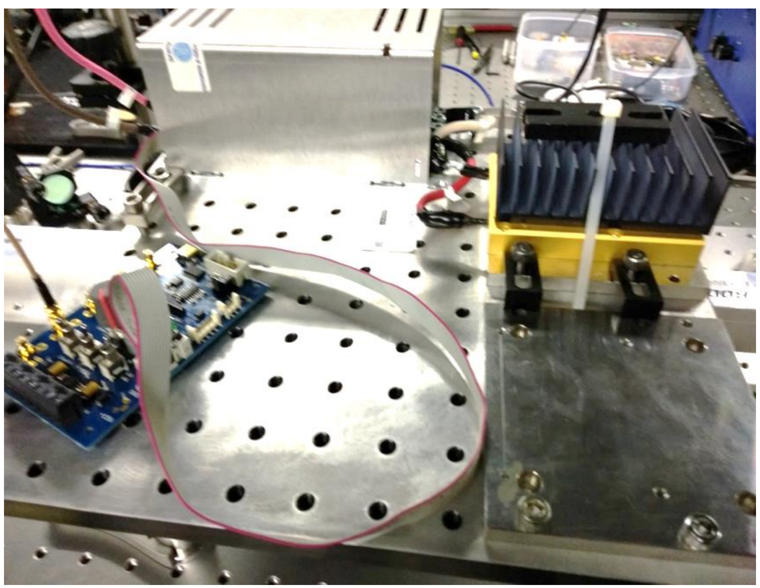
Main Amplifier CW testing



Seeding with Pre amplifier output

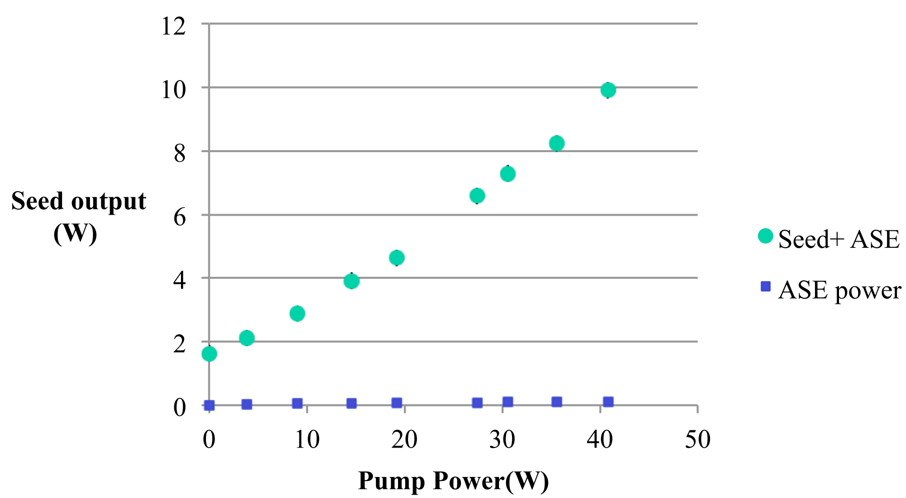


Pumping the main amplifier

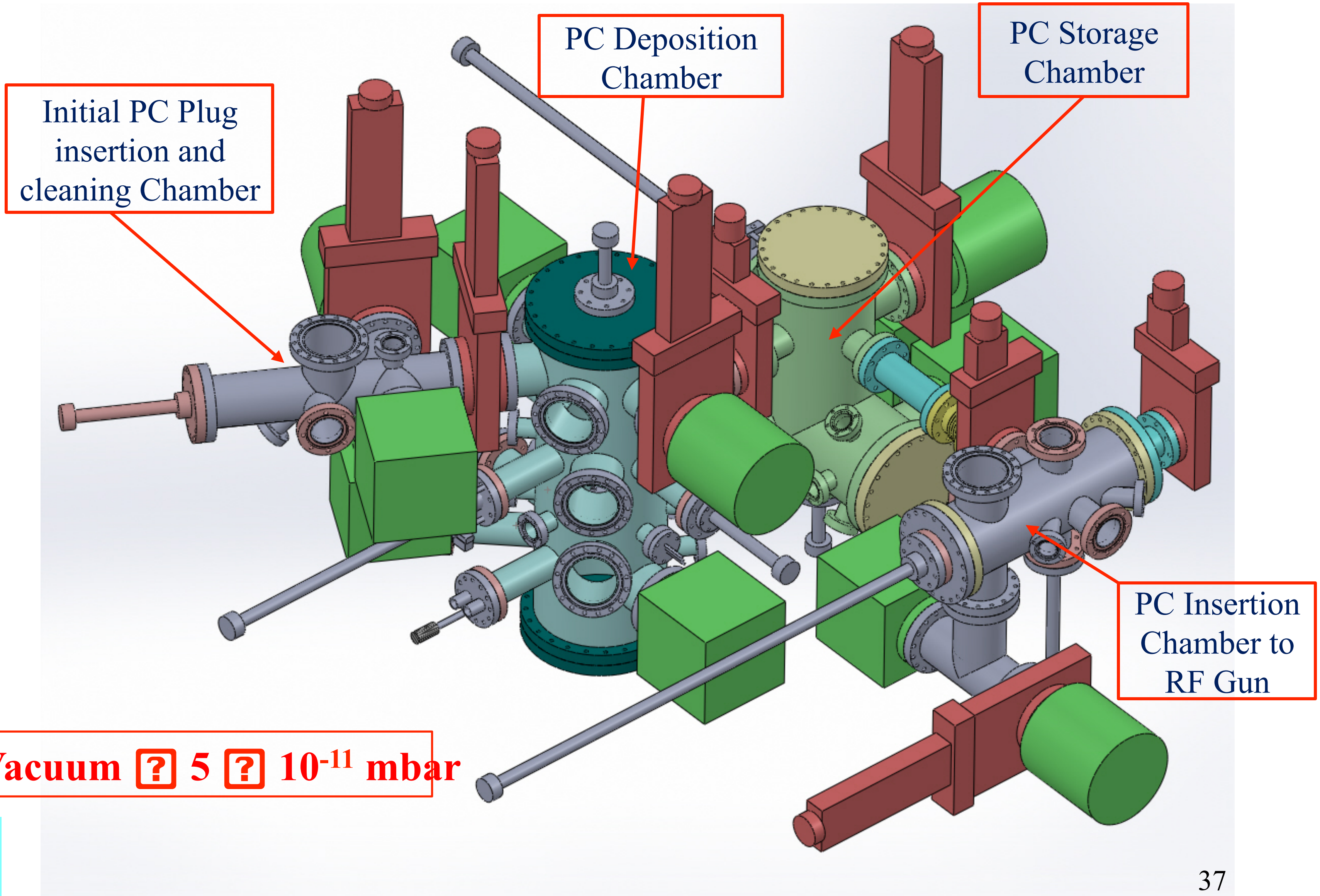


Cooling arrangements of diode

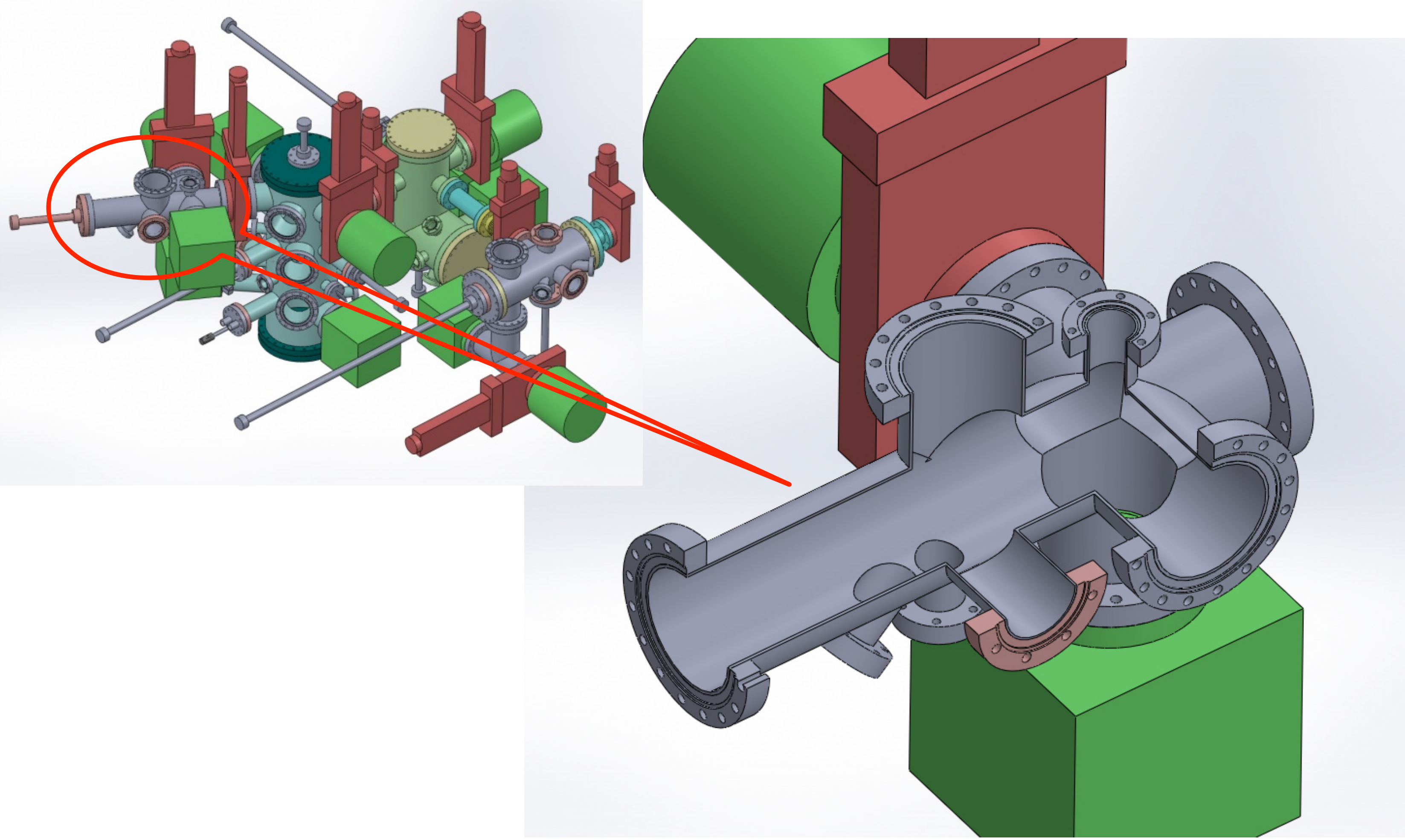
Output Charactersistic of the Burst Amplifier 1



Photocathode deposition and transportation system

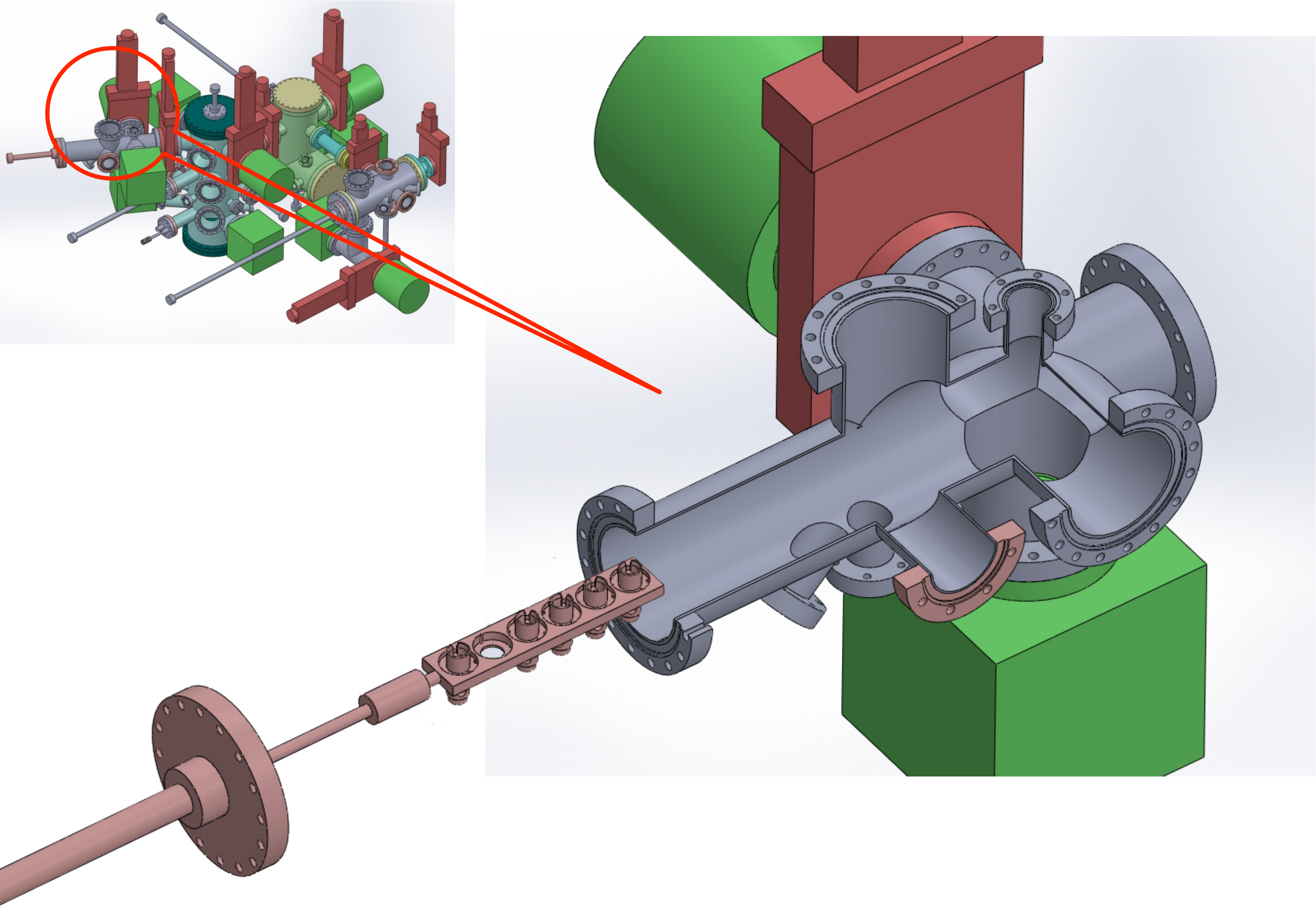


Base Vacuum [?] 5 [?] 10^{-11} mbar



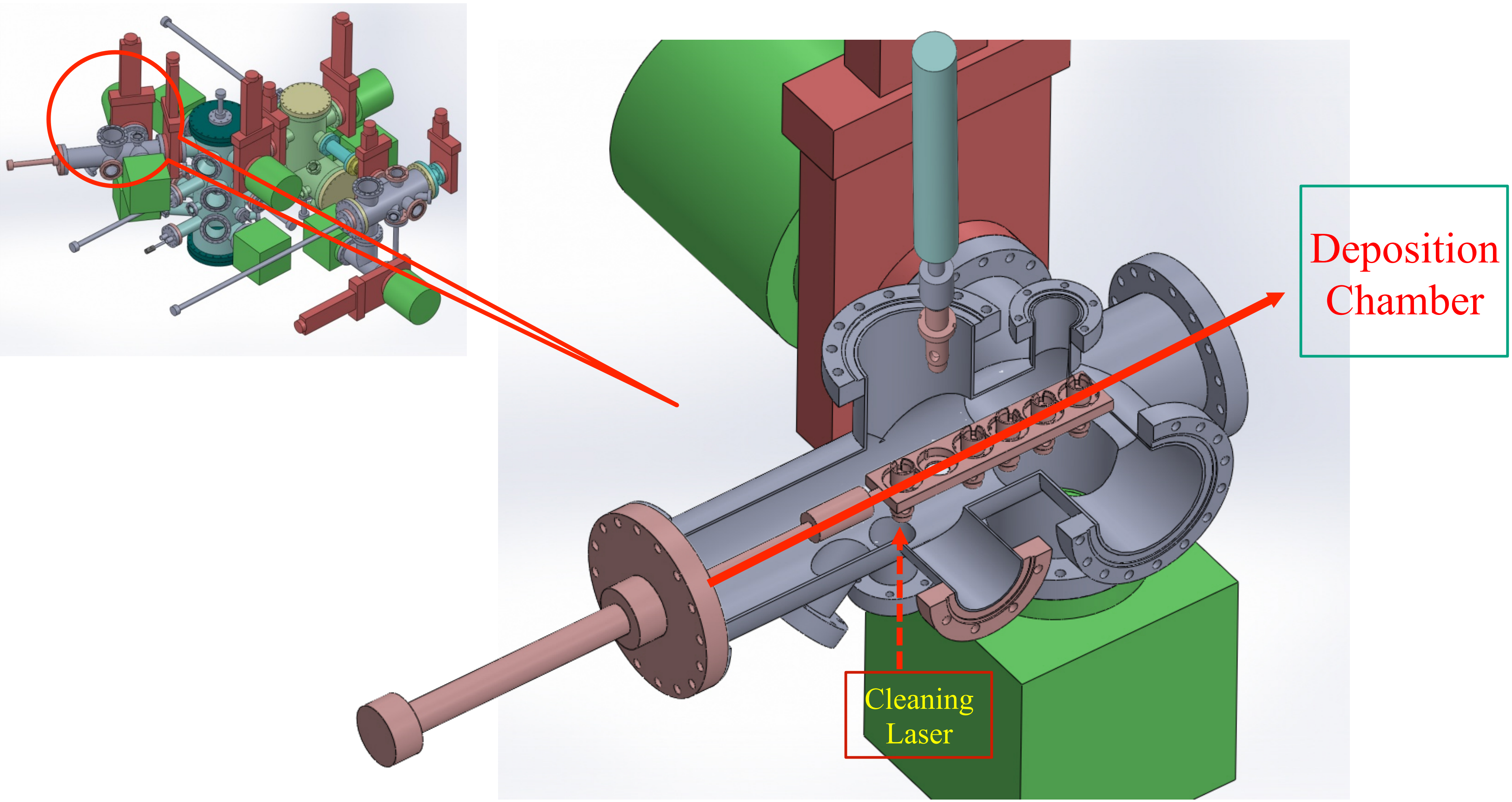
Base Vacuum ? 5 ? 10^{-11} mbar

Loading and cleaning chamber



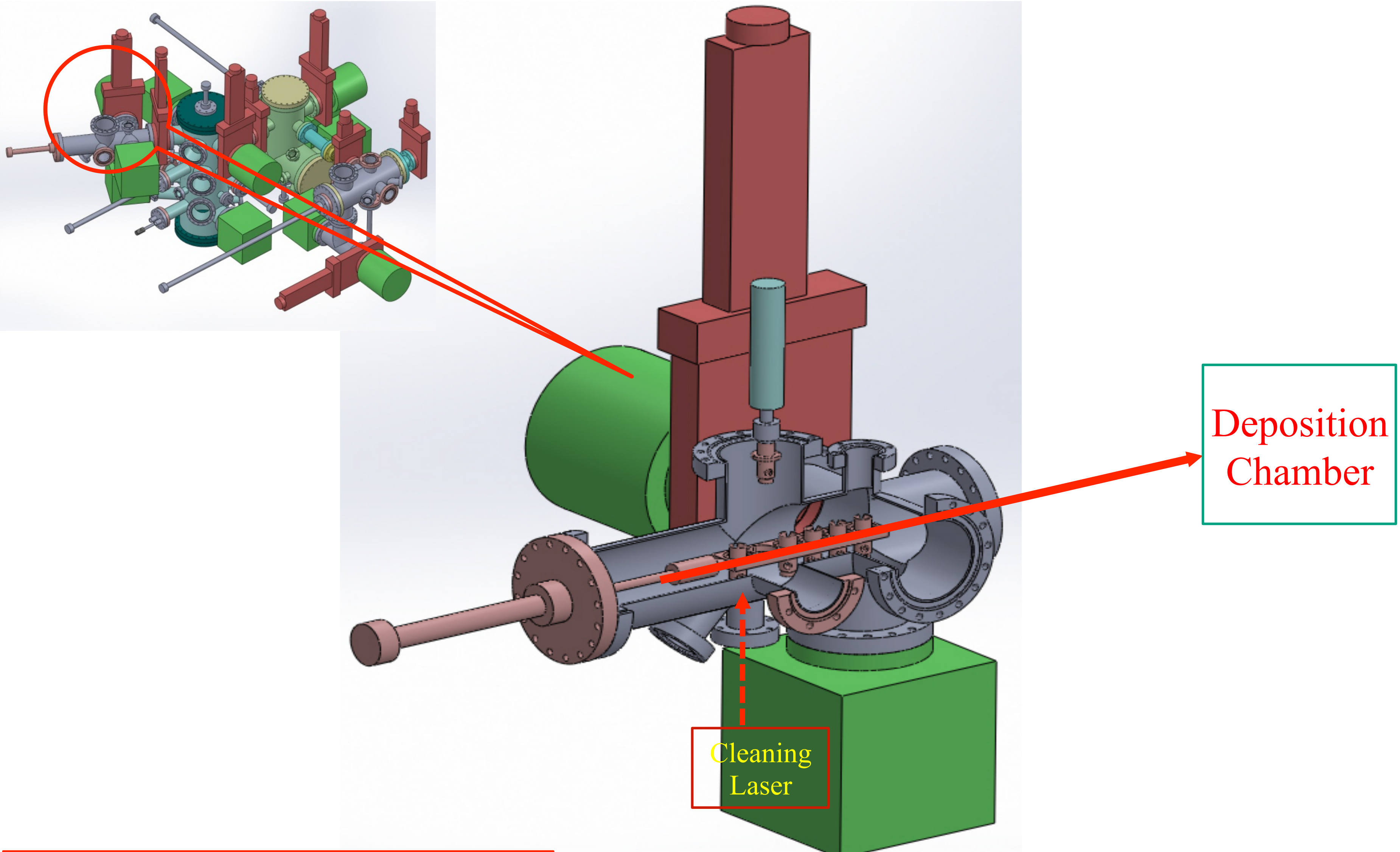
Base Vacuum ? 5 ? 10^{-11} mbar

Initial PC plug loading and cleaning chamber



Base Vacuum ? 5 ? 10^{-11} mbar

Initial PC plug loading and cleaning chamber

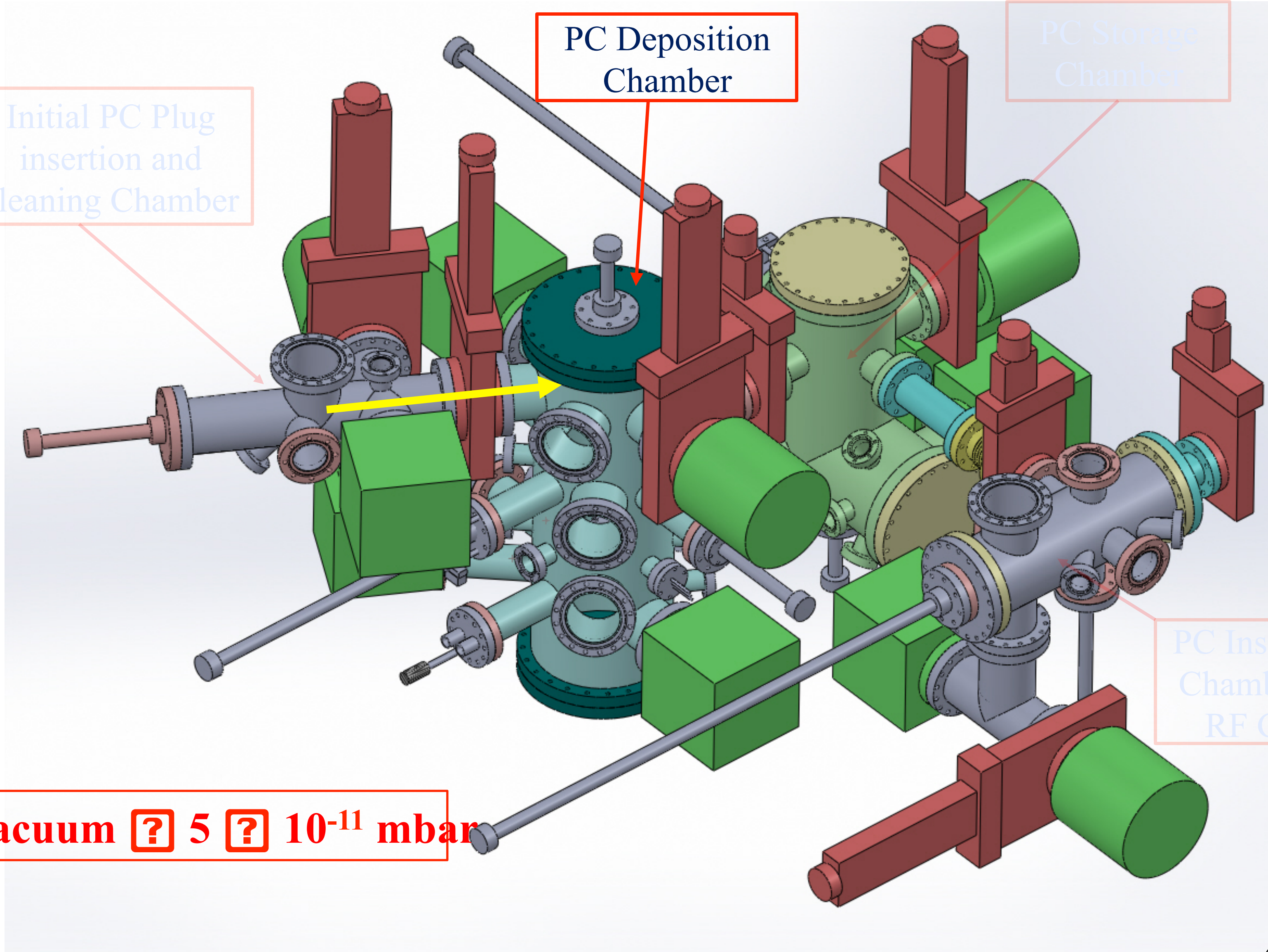


Base Vacuum ? 5 ? 10^{-11} mbar

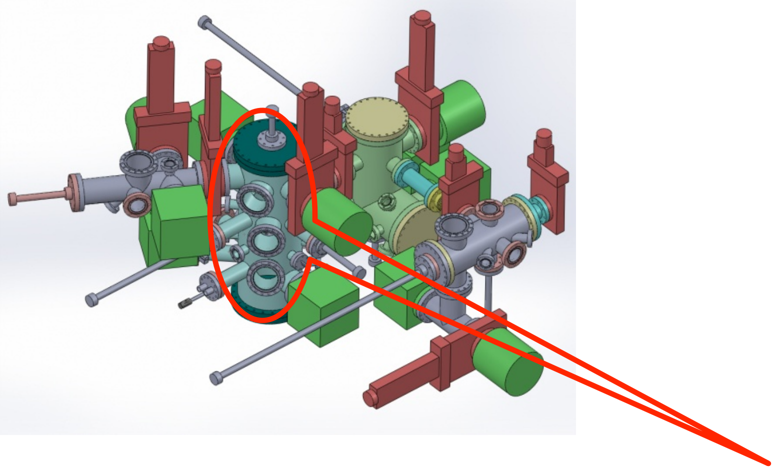
UAC

Initial PC plug loading and cleaning chamber

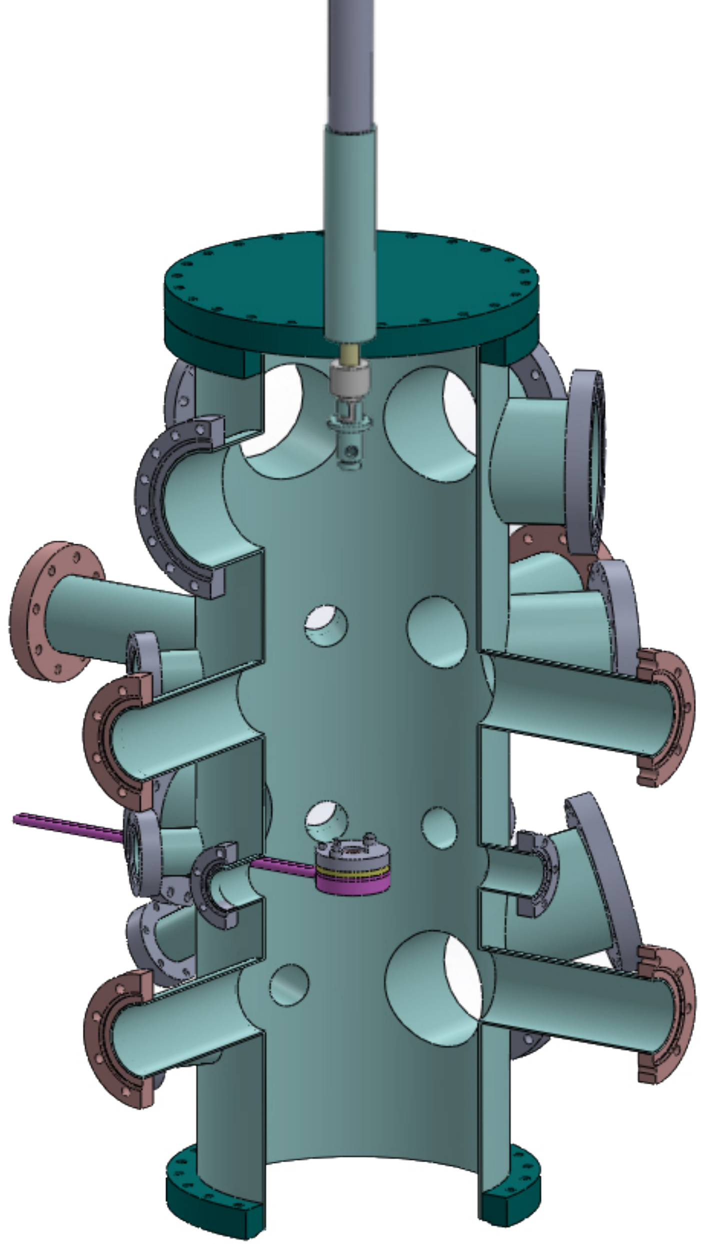
Photocathode deposition and transportation system

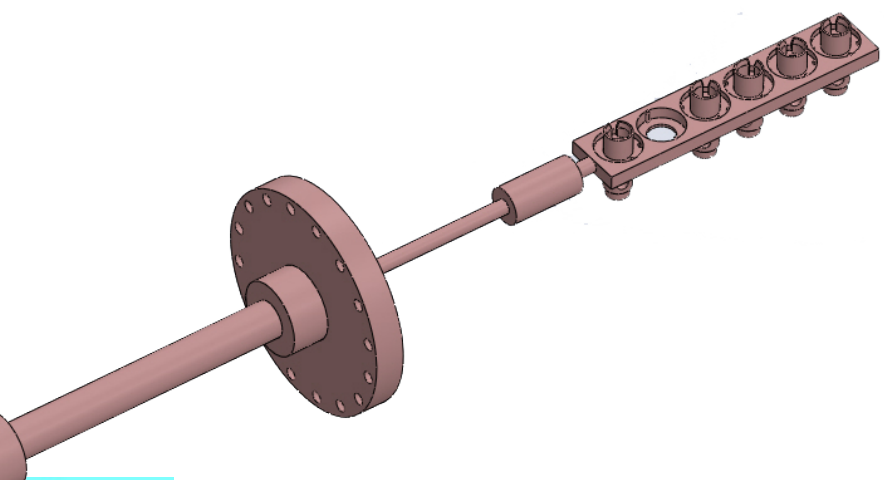


Base Vacuum ? 5 ? 10^{-11} mbar

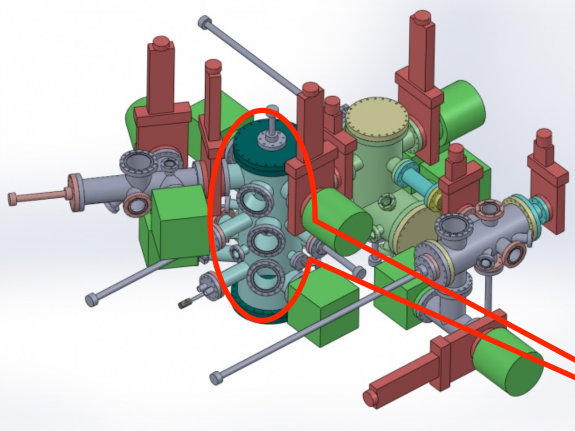


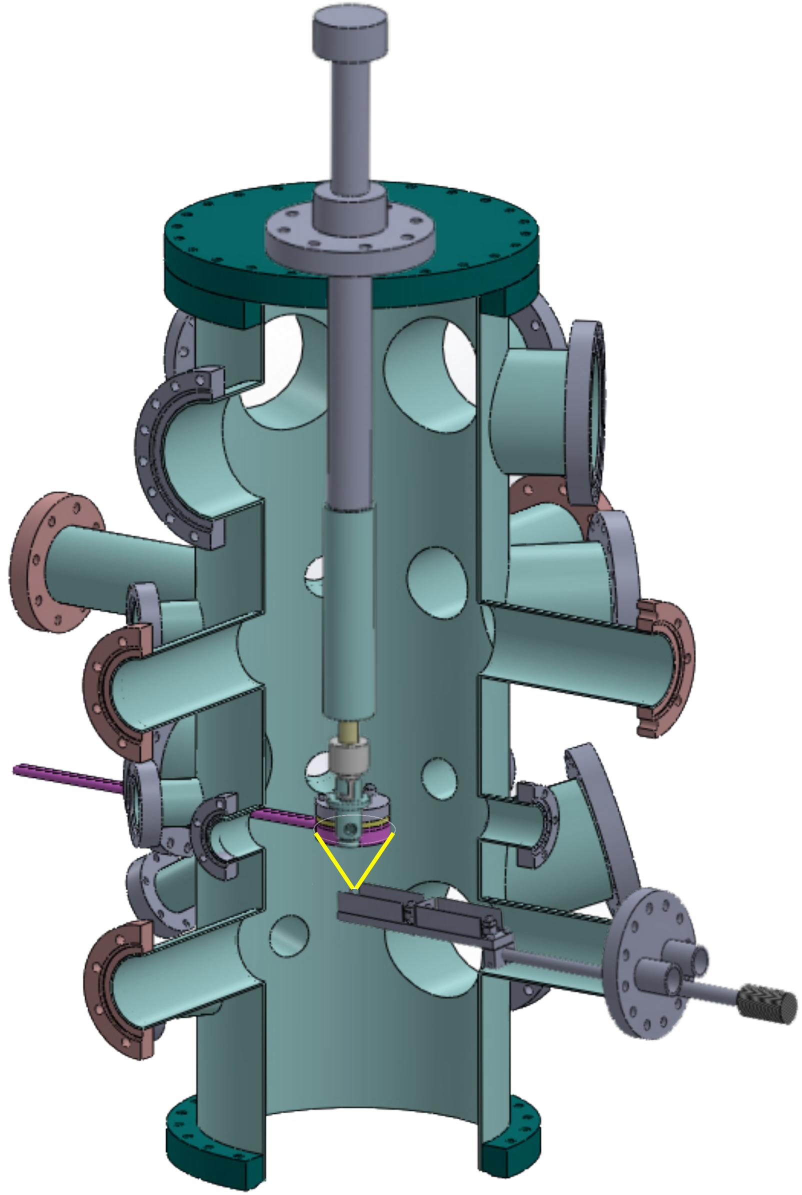
Base Vacuum ? 5 ? 10^{-11} mbar





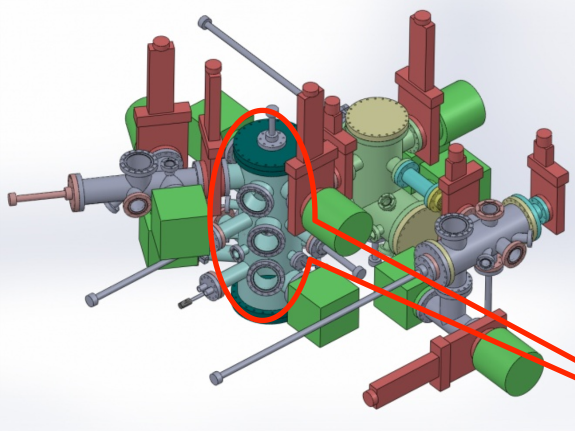
PC Deposition chamber

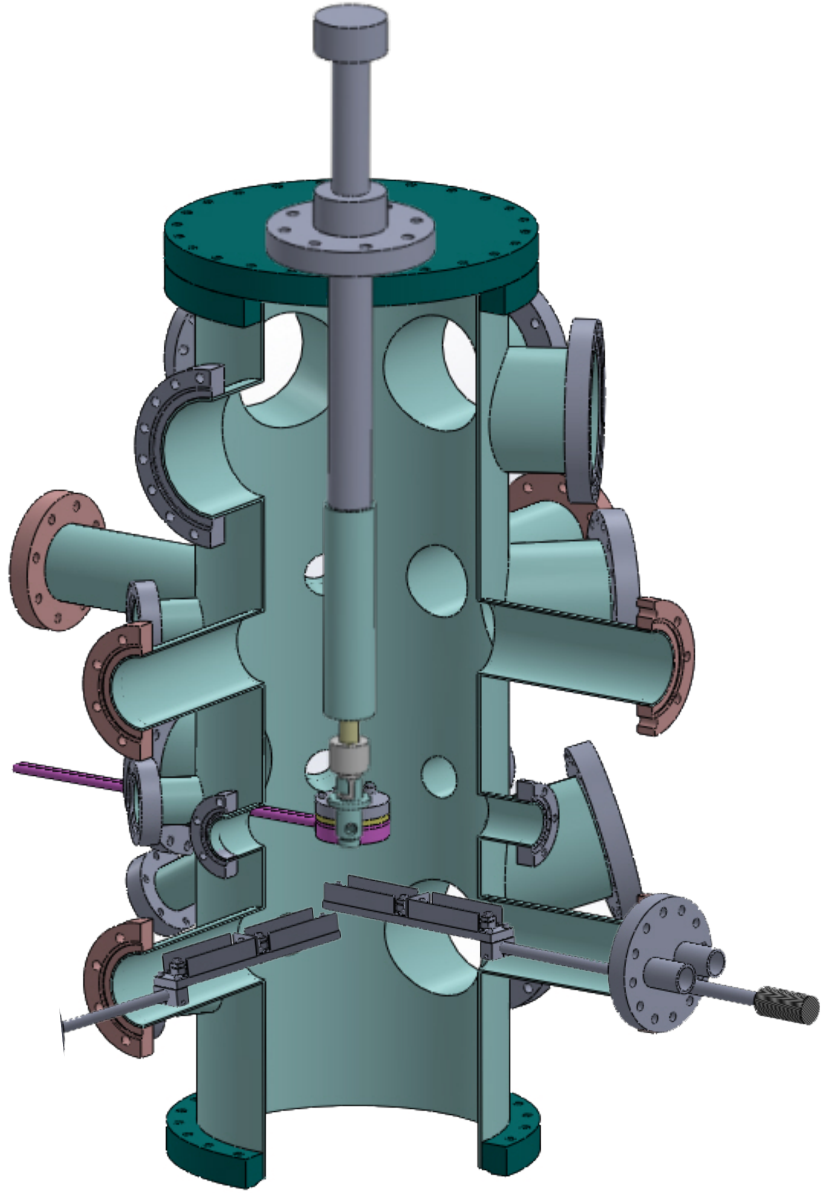




Base Vacuum ? 5 ? 10^{-11} mbar

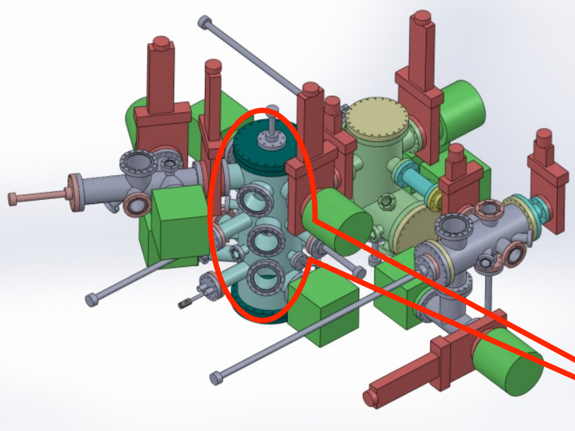
PC Deposition chamber

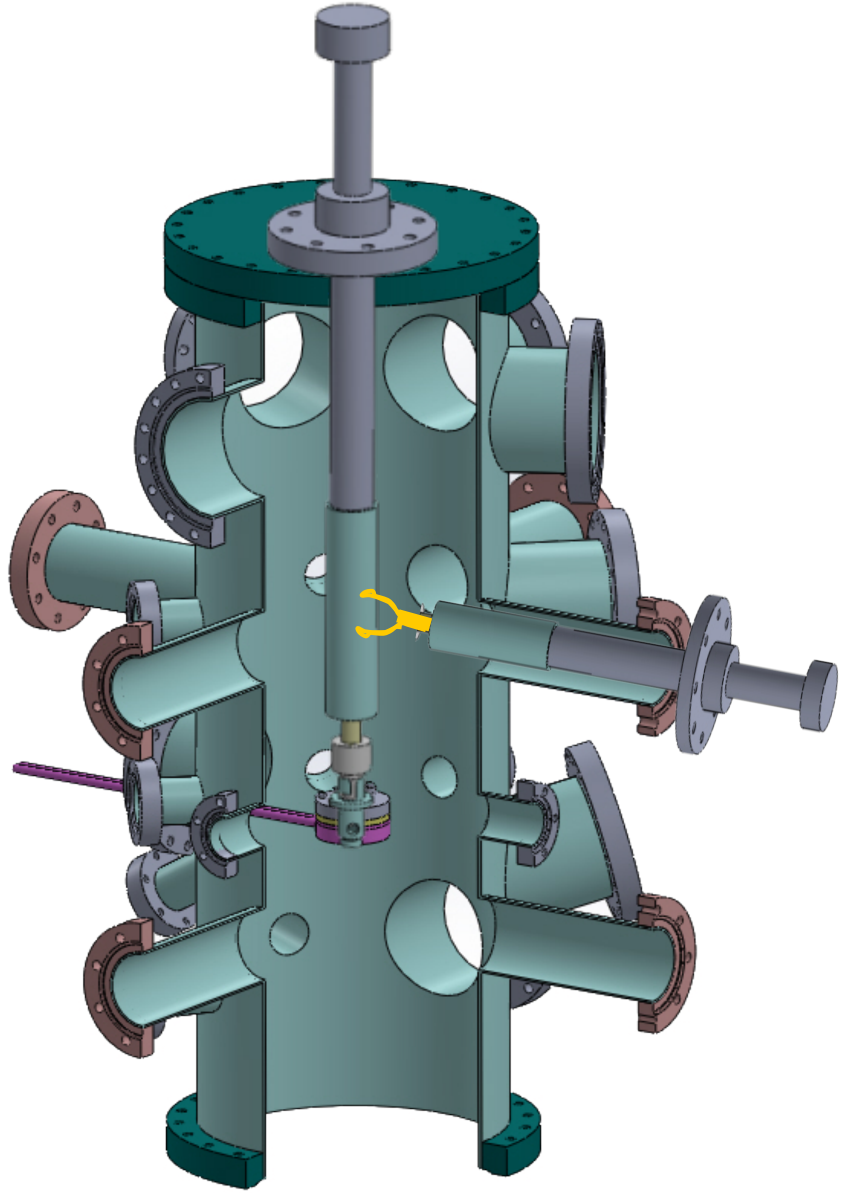




Base Vacuum ? 5 ? 10^{-11} mbar

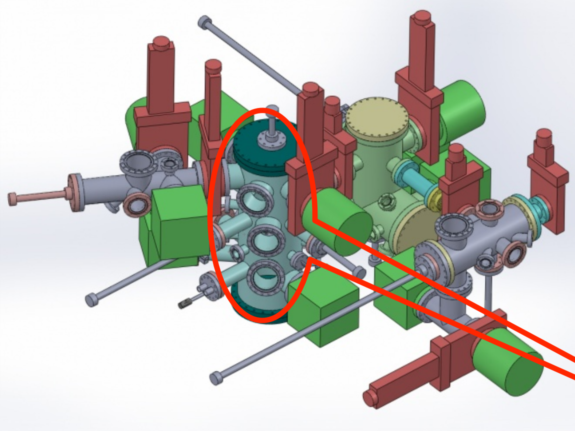
PC Deposition chamber

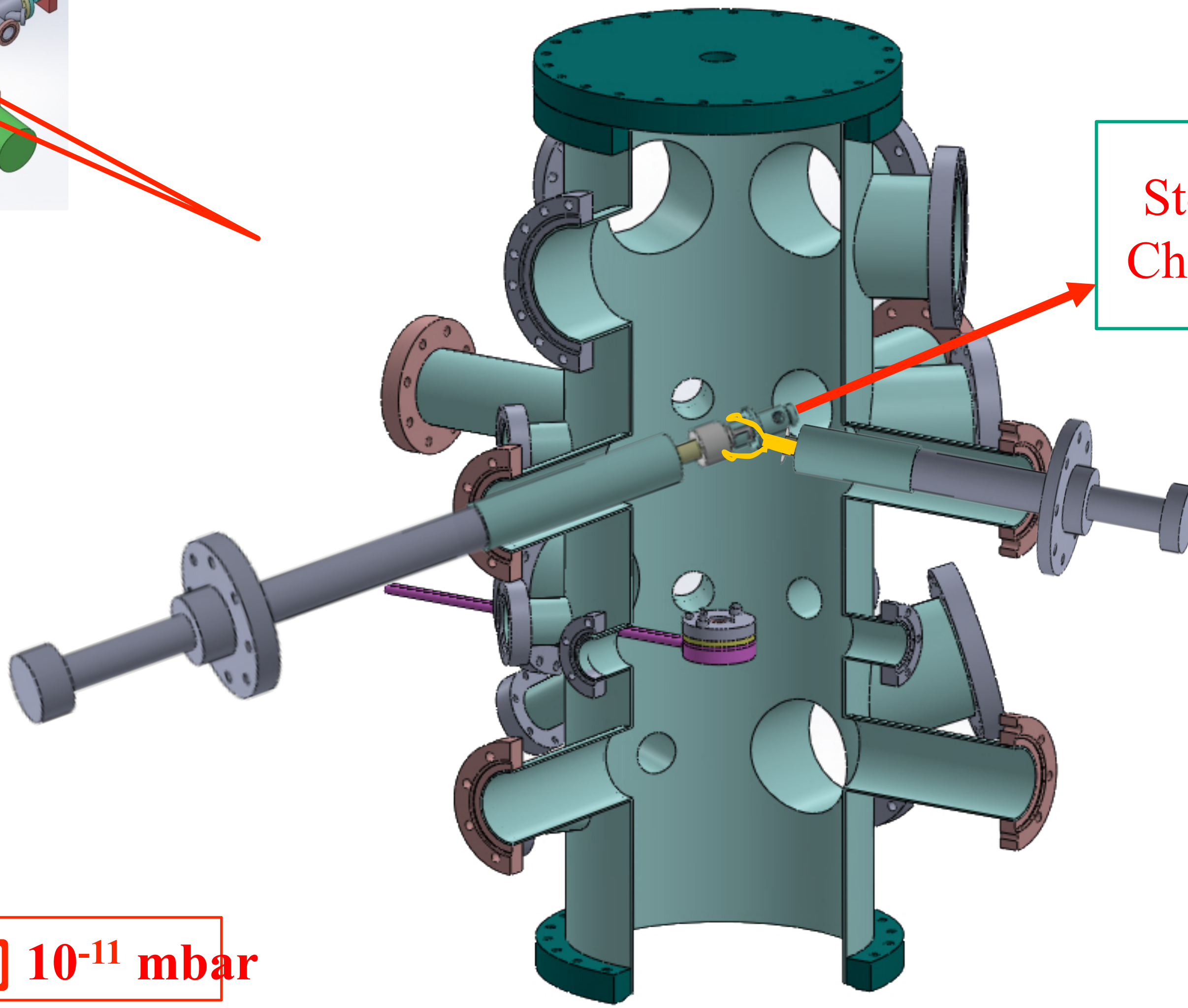




Base Vacuum ? 5 ? 10^{-11} mbar

PC Deposition chamber

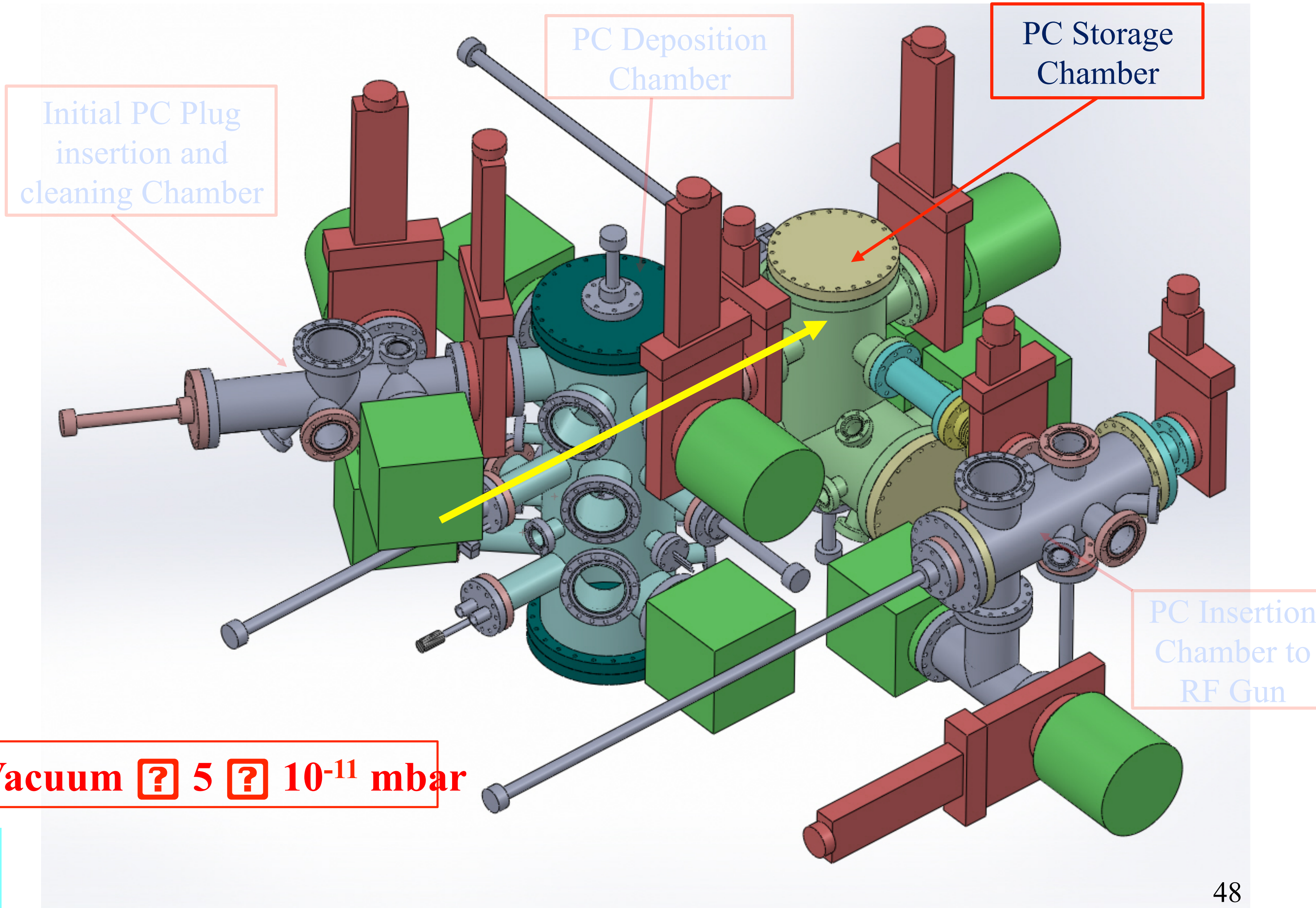




Base Vacuum ? 5 ? 10^{-11} mbar

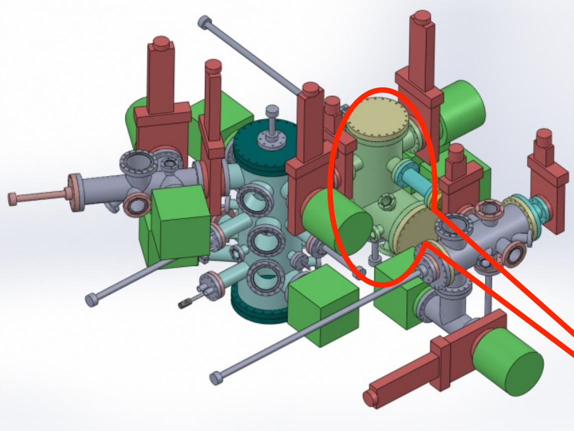
PC Deposition chamber

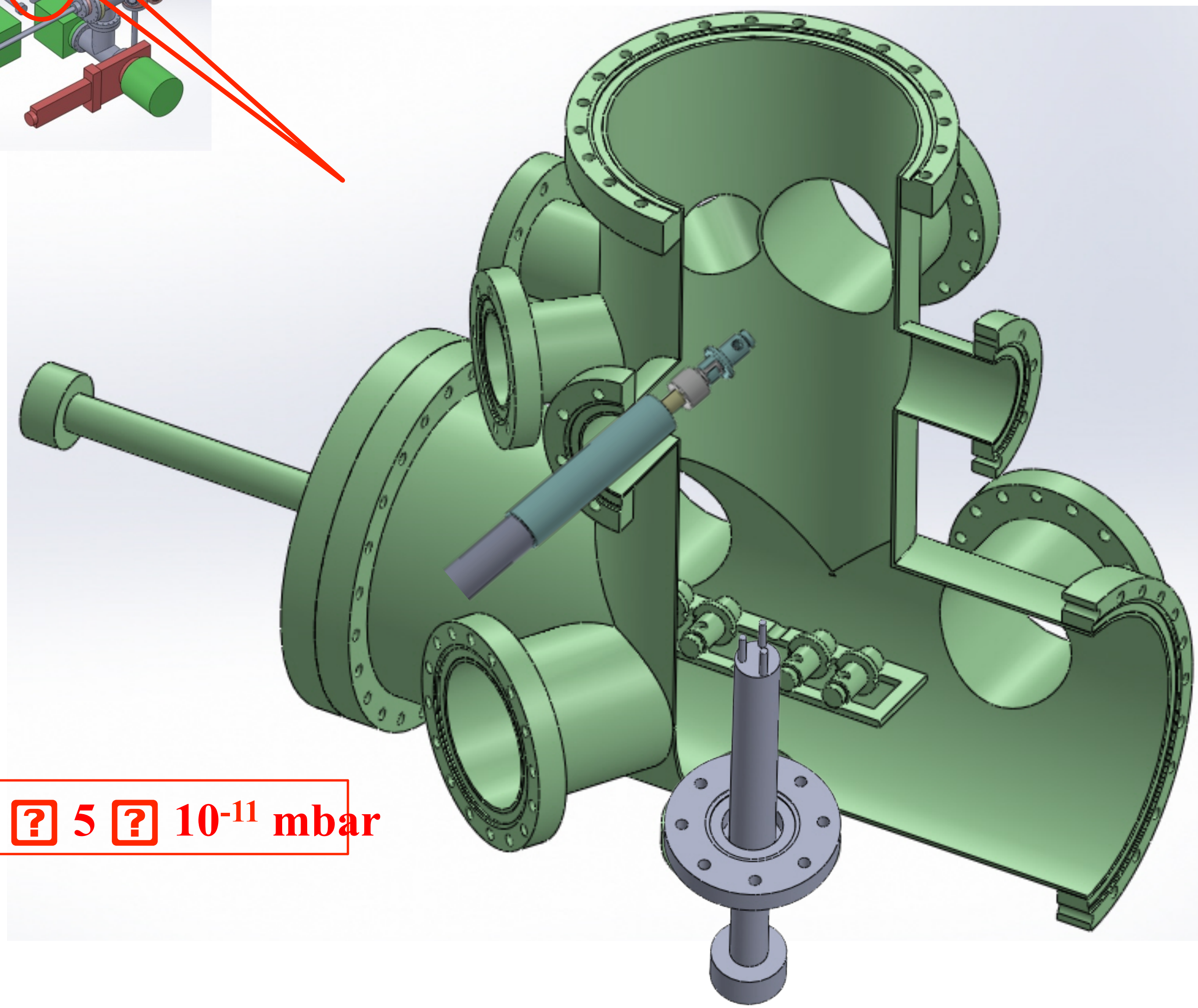
Photocathode deposition and transportation system



Base Vacuum ? 5 ? 10^{-11} mbar

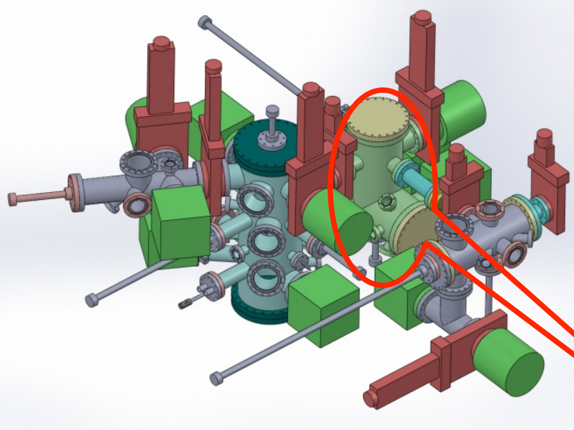
PC Storage chamber

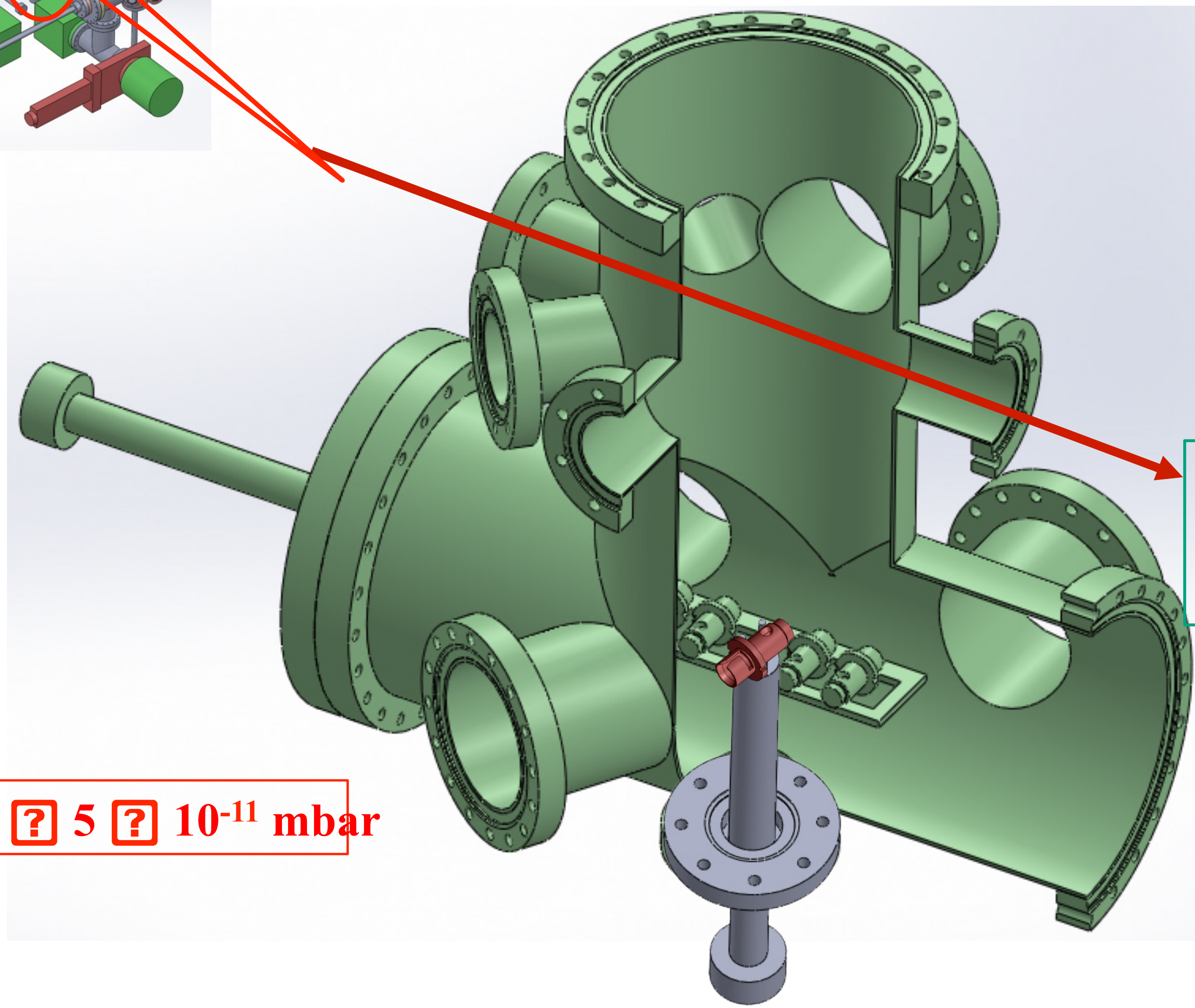




Base Vacuum ? 5 ? 10^{-11} mbar

PC Storage chamber

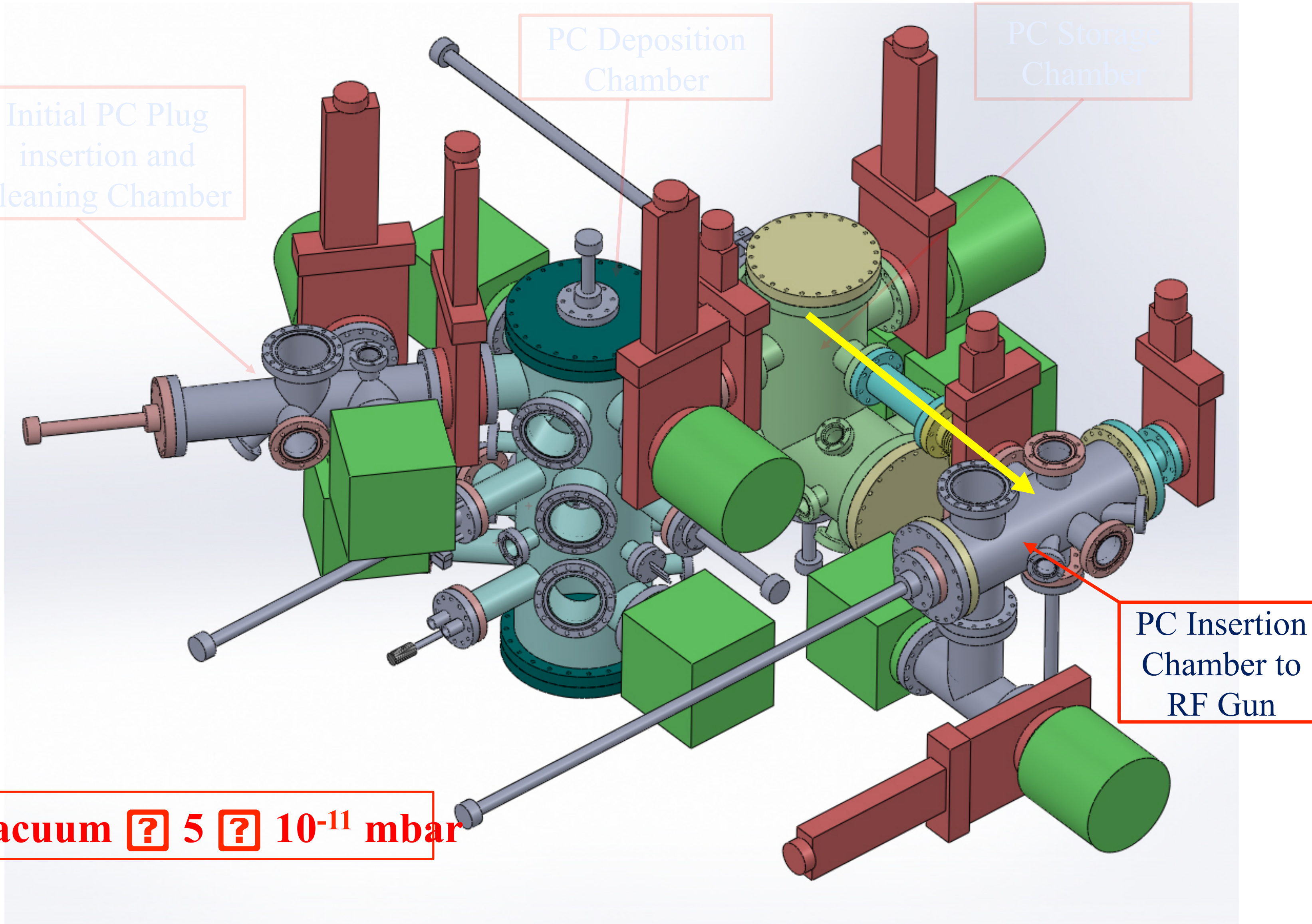




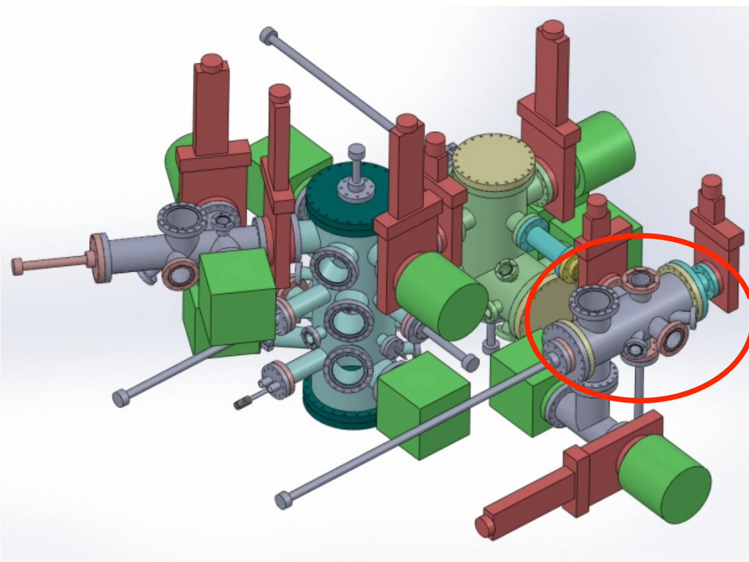
Final Insertion Chamber

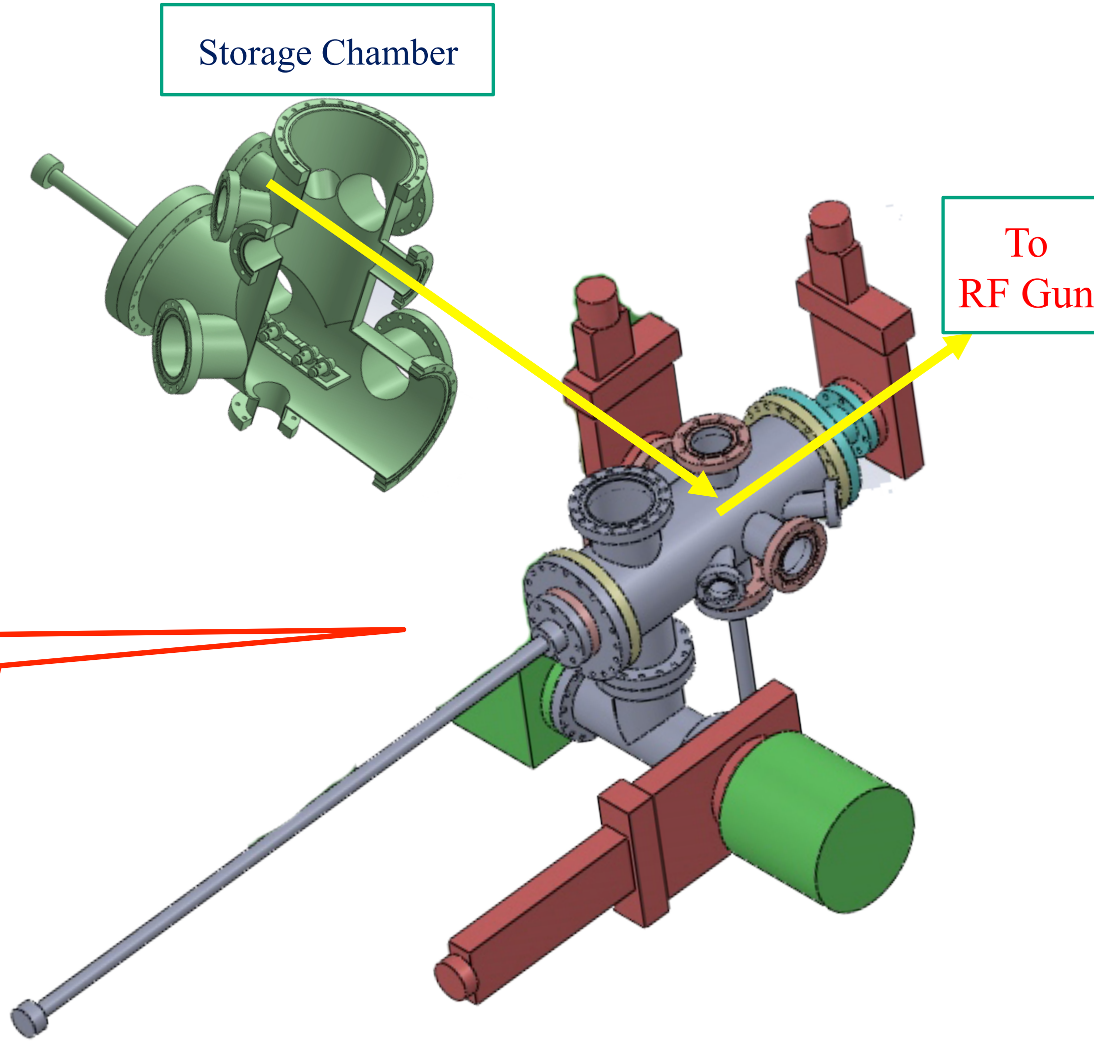
Base Vacuum ? 5 ? 10^{-11} mbar

Photocathode deposition and transportation system



Base Vacuum ? 5 ? 10^{-11} mbar

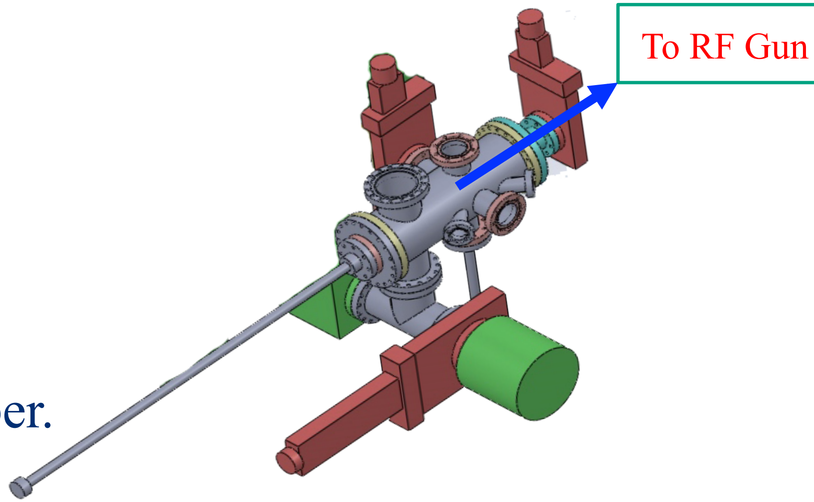




Base Vacuum ? 5 ? 10^{-11} mbar

Insertion chamber in to the RF gun

Insertion chamber in to the RF gun



Photocathode system.

- Vacuum testing of final PC insertion chamber.

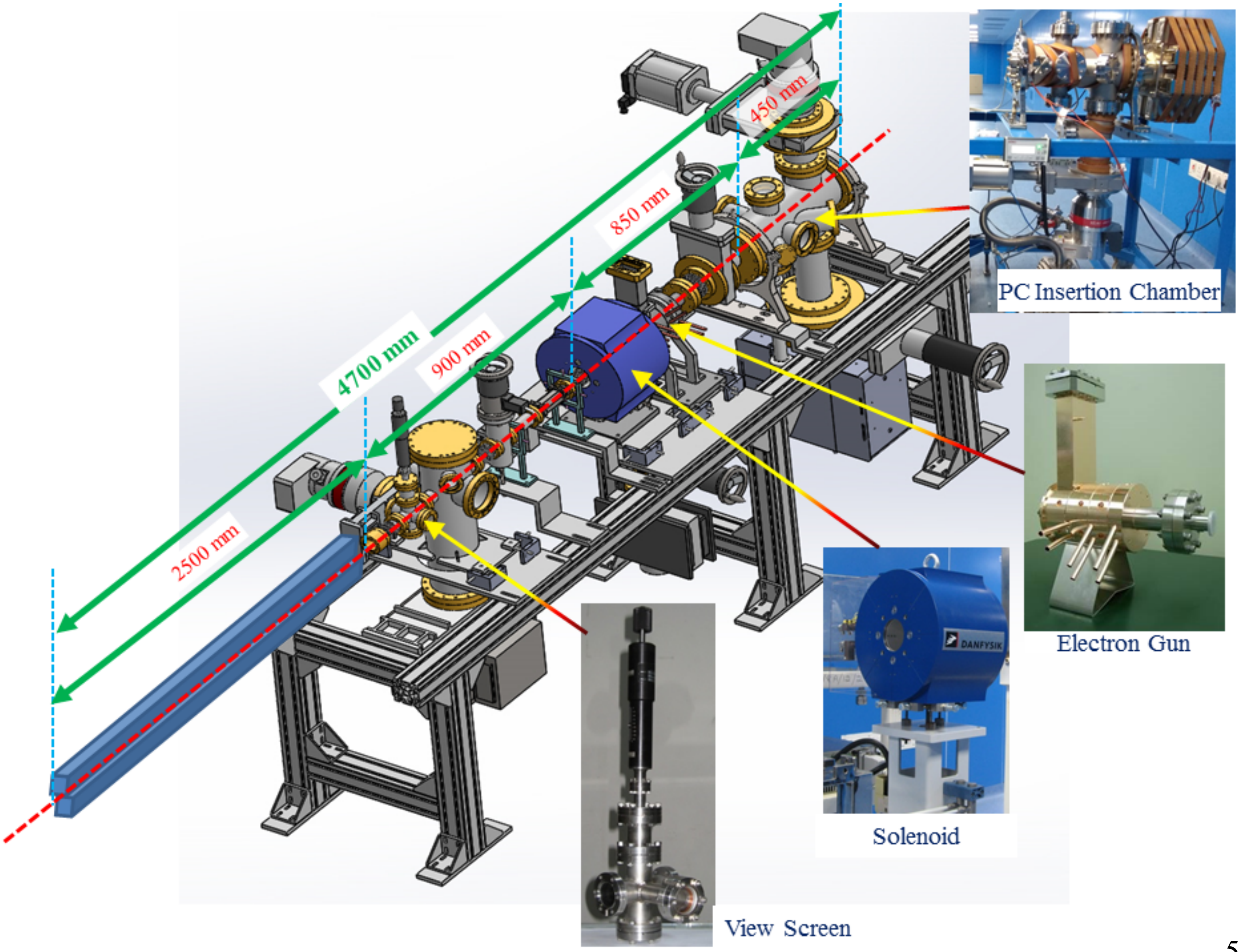
Evacuation and baking

Ion pump evacuation

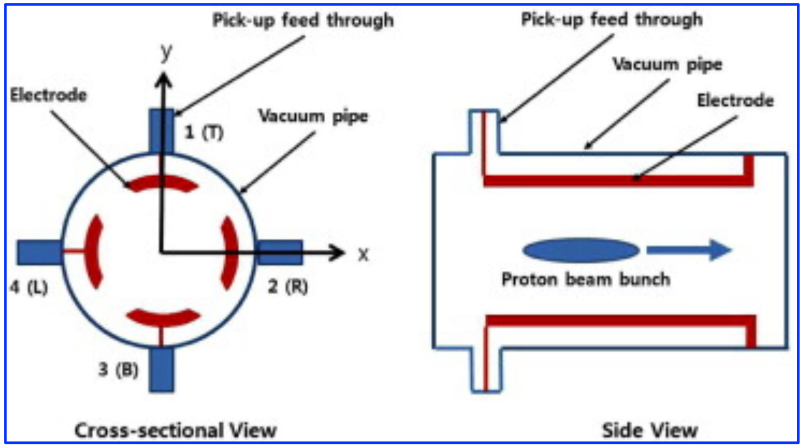
Ion pump Baking along with chamber

Ultimate vacuum: 1.7 X 10 $^{-10}$ mbar (Ext. Gauge)

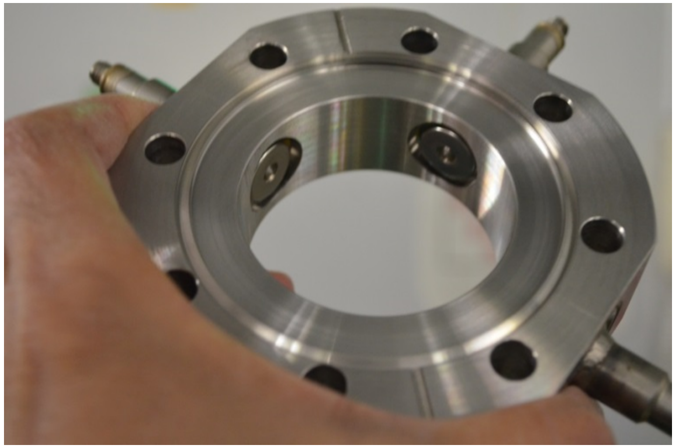
5.9 X 10 $^{-11}$ mbar (Ion Contrlr)


4700 mm
2500 mm
900 mm
850 mm
450 mm
PC Insertion Chamber
Electron Gun
Solenoid
View Screen

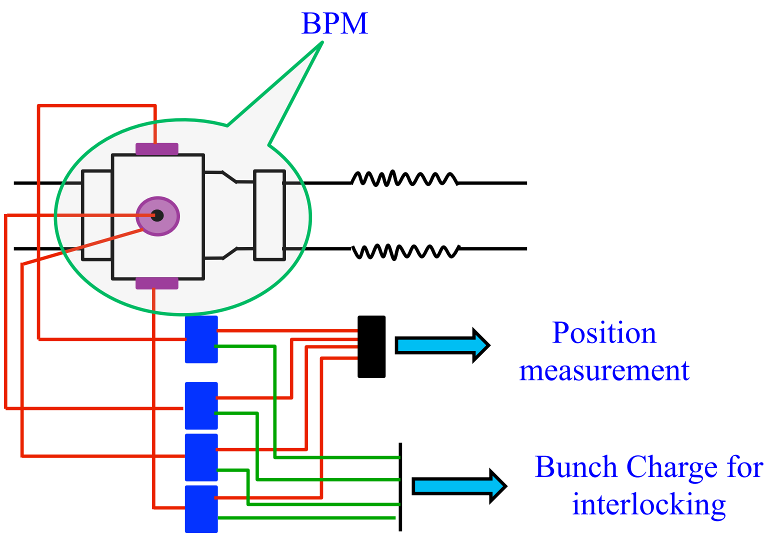
Strip-line or Button BPM



Stripline BPM



Button BPM



Schematic of the Beam position measurement layout.

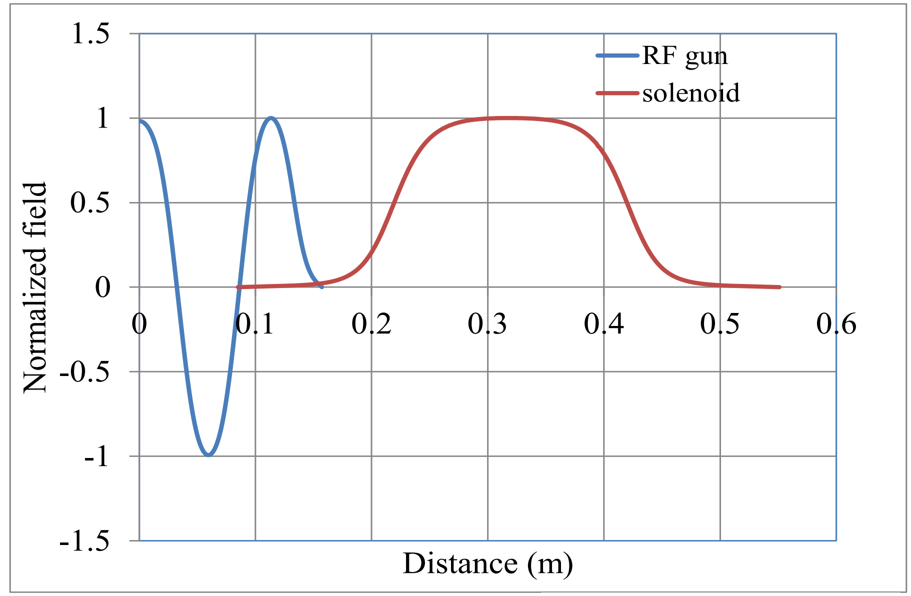
Stripline BPM

- 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

Parameters for BPM, FC & LLRF are finalized, Tender floated

Beam transport device – Solenoid (NC)

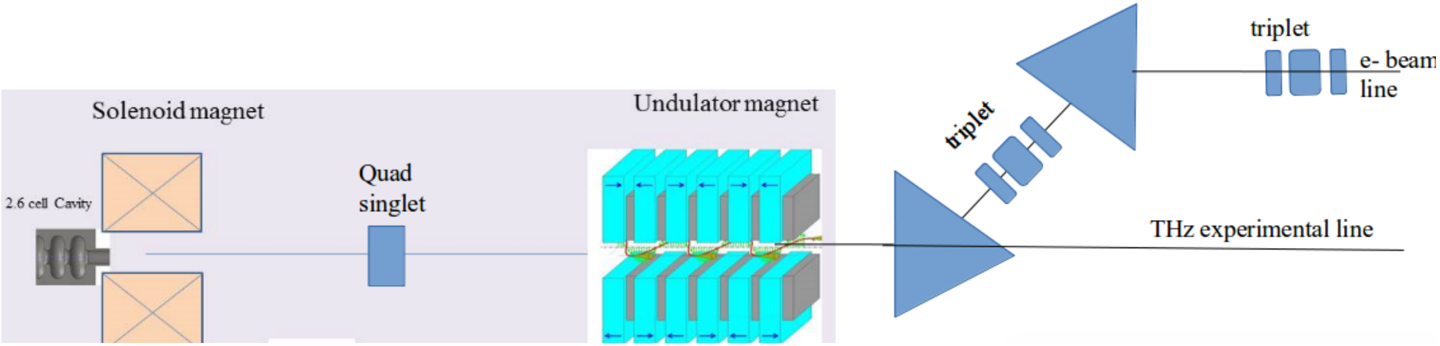
Parameters	Values
Maximum magnetic Field at the Centre of the solenoid magnet	0.35 T
Physical Length including return yoke	≤ 240 mm
Overall Diameter	≤ 480 mm
Effective Length	~ 200 mm
Bore Diameter	76 mm, fit over 2.75” flange
Alignment marks	Yes
Longitudinal alignment Tolerance	≤ 0.25 mm
Transverse 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 ± 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

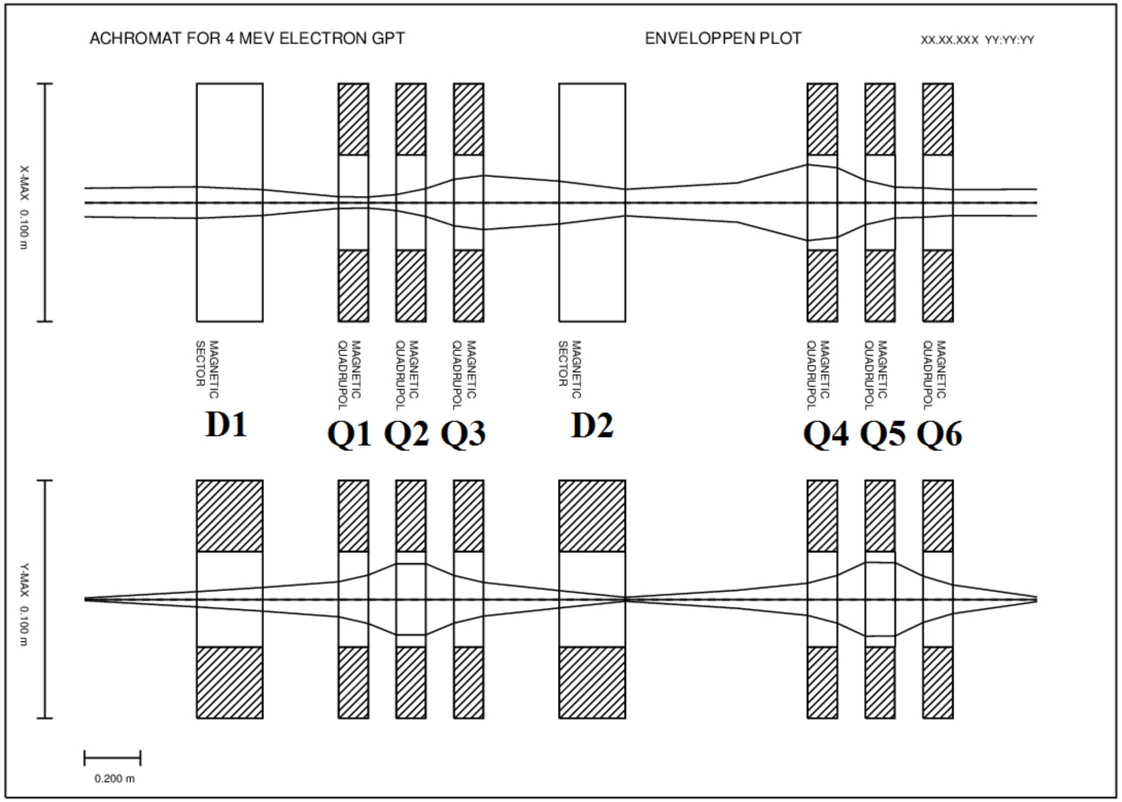


3D technical design of solenoid magnet (from Danfysik)

Installed at IUAC

Transverse Optics, Quadrupole and Dipoles

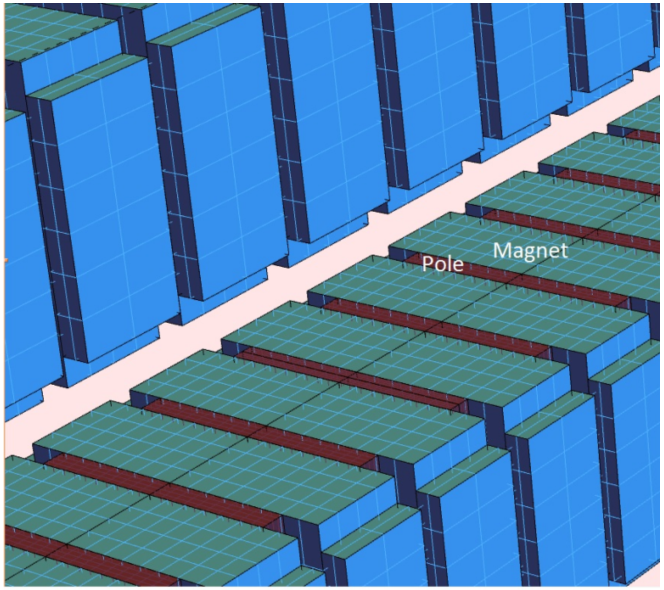




Field (G)	4 MeV	8 MeV
D1	497	944
Q1	131	185
Q2	121	171
Q3	171	241
D2	497	944
Q4	148	210
Q5	190	269
Q6	148	210

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

$?_R$ (~mm)	Freq. to be Produced (THz)	Electron Energy (MeV)	$?_U$ (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

Opportunity – to utilise an Unused Undulator magnet of Bessy

with the help of DESY (Dr. Markus Tischer)

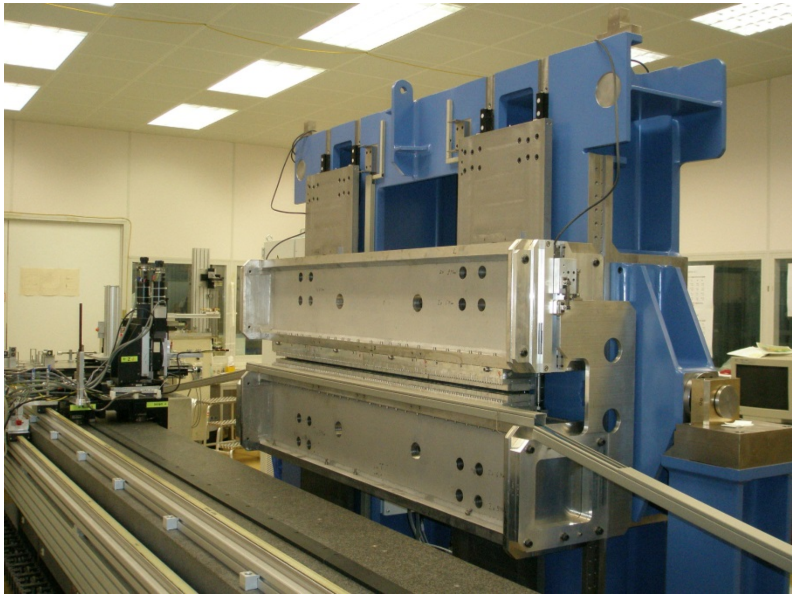
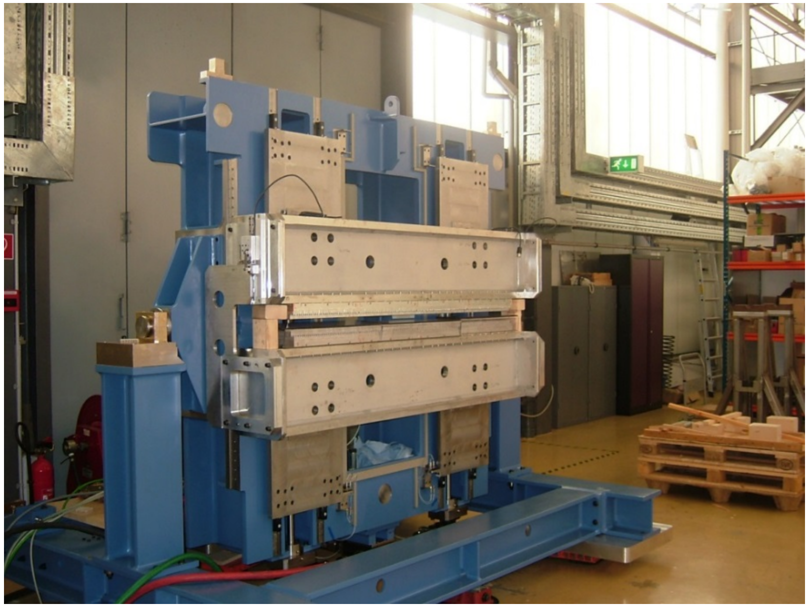
Comparison between designed Undulator for DLS and Undulator of Bessy

	Designed Undulator for DLS	Bessy's Undulator
Technology	Hybrid planar	Planar
Magnet	NdFeB magnet (B_r =1.21T)	NdFeB magnet
Pole	Vanadium permendur	Not Applicable
Period length	50 mm	48mm
No of Periods	28 (Full)	41
Device length	~1.5 m	~ 2 m
Magnetic gap	20 - 45 (mm)	17-42 (mm)
Magnetic field	0.62 - 0.11 (T)	0.62 - 0.11 (T)
Undulator parameter (K)	2.89 - 0.61	2.73 -0.52
Wavelength	0.18 - 3.0 (THz)	0.18 - 3.0 (THz)
gap reproducibility	0.01 mm	Should be similar
Beam Line Height	1.1 m	0.5 m

$$\lambda_R = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{K^2}{2}\right]$$

K = 0.934 ? B_u(T) ? ?$_u$(cm)

A few pictures of Bessy's Undulator

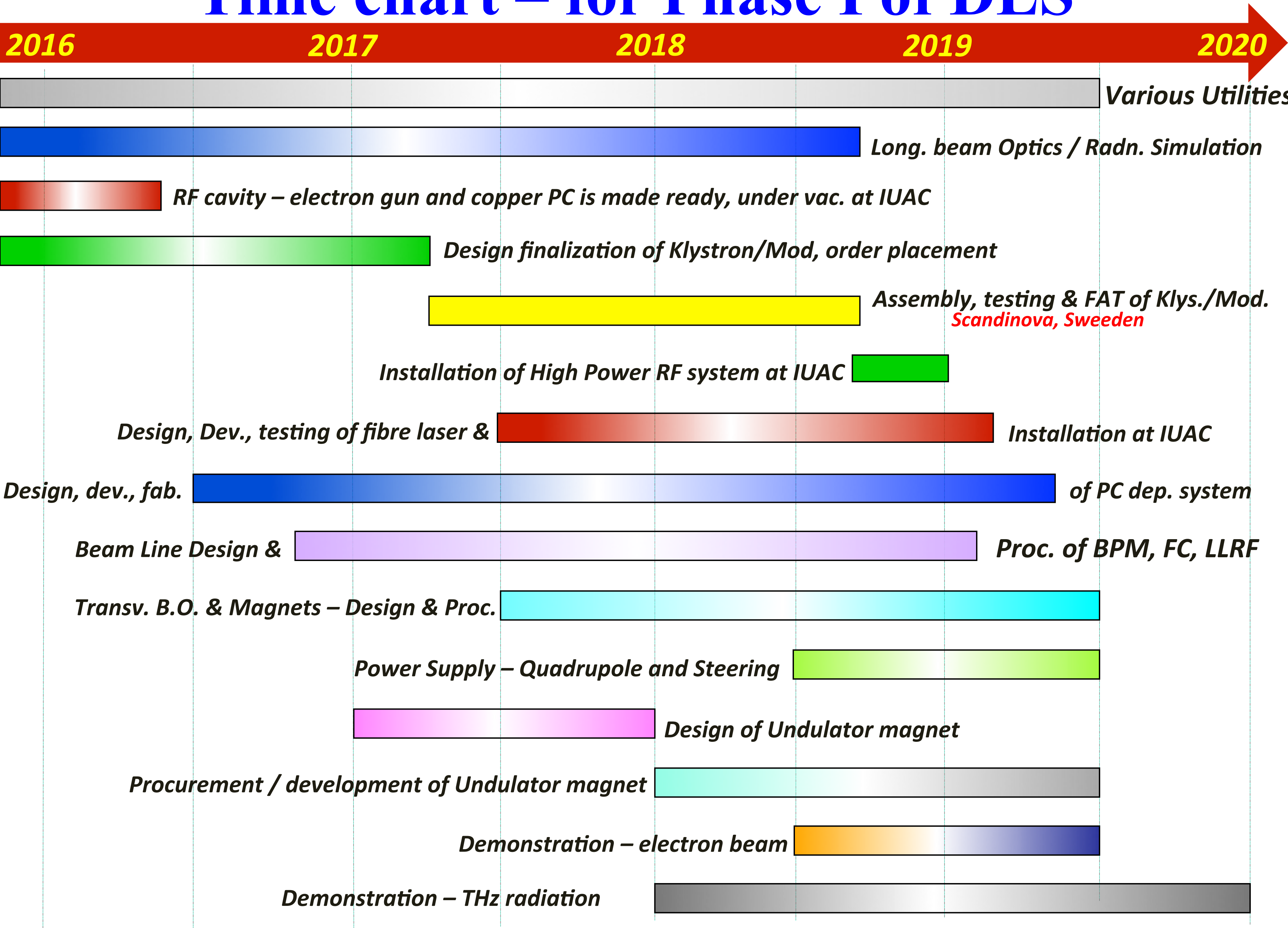

Expected Deliverables from Delhi Light Source

THz Frequency range : 0.18 to 3 THz

0.18 THz (1.7 mm, 6 cm^{-1}, 0.7 meV) to
3.0 THz (100 ?m, 100 cm^{-1}, 12 meV)

Time width	No. of electrons	Total electron current	Energy content of 3 THz (?J)	Electric field of 3 THz	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 ?s	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	? 100 kV/cm	Train of 15 no. of 16 e-bunches arriving 6.25 times in a sec.

Time chart – for Phase I of DLS



Conclusion

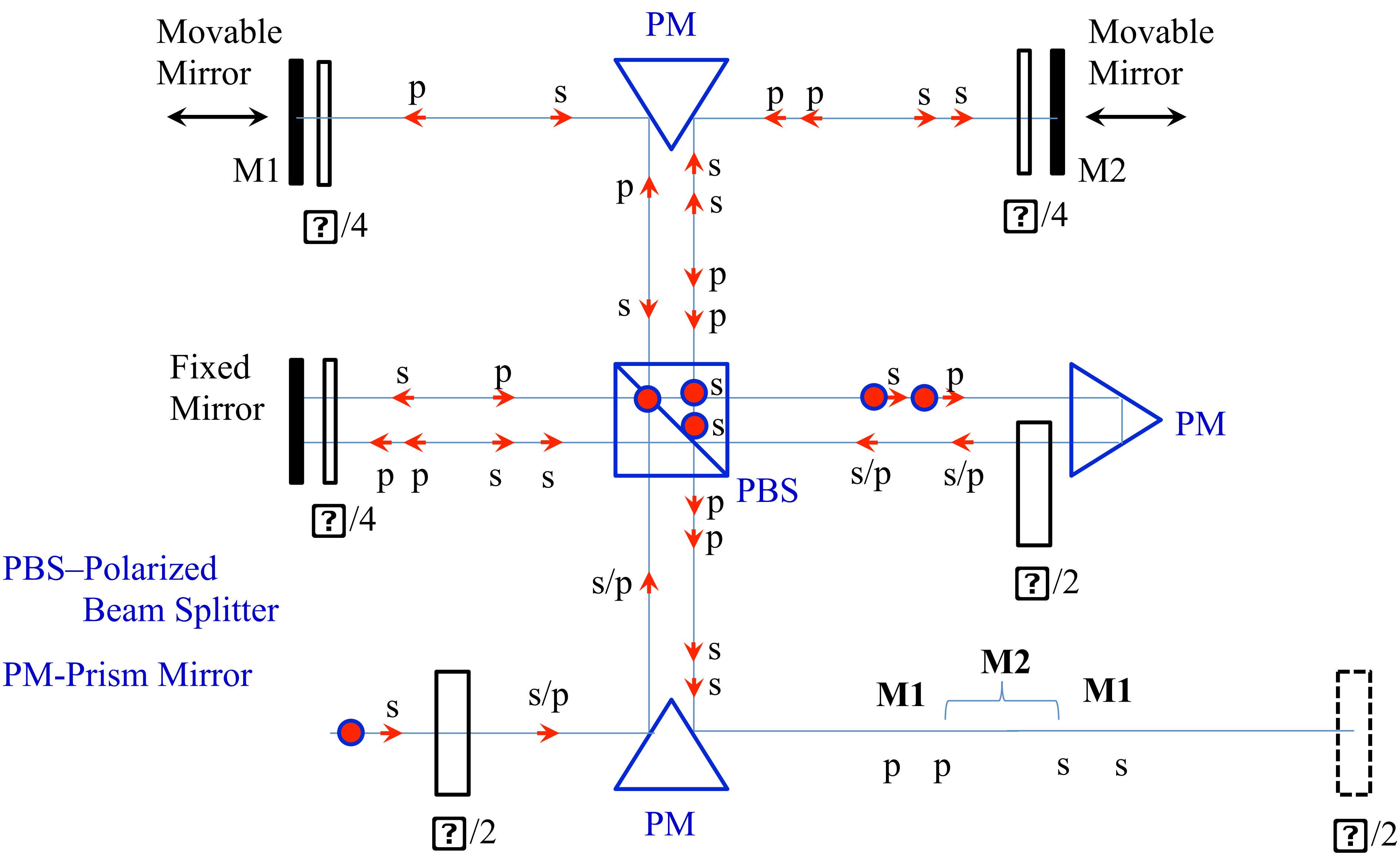
- IUAC – A national level Accelerator User Facility – providing Ion beam 24 × 7.
- IUAC – wants to increase user base by providing photon beam
- Delhi Light Source – A pre-bunched Free Electron Laser
- Photocathode RF electron gun will produce good quality of e-beam (~ 4 – 8 MeV)
- Electron beam to be injected in to a compact undulator to produce THz (3.0 to 0.18)
- Electron beam is to produced by the middle of 2019
- THz will be demonstrated by the end of 2019
- THz radiation & Electron beam to be used for experiments in multidisciplinary Sc. in fundamental and applied areas.

Thanks for your patience

Laser Device

Splitting a single laser pulse in to many and change their separation

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

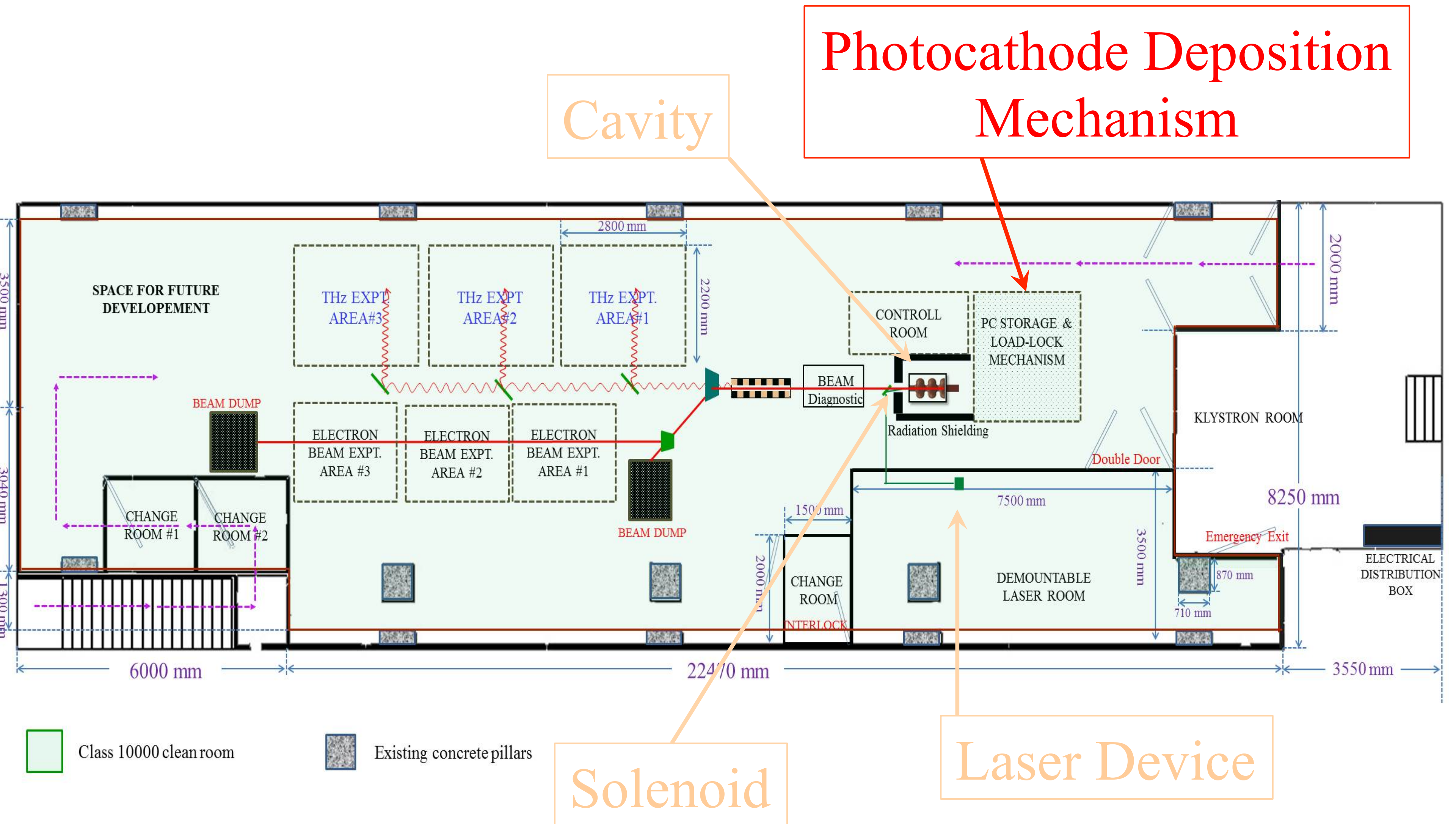


Courtesy: Dr. A. Aryshev

Available laser power vs. Beam optics requirement

Laser Specification						
System	Energy/ pulse (UV)	Cathode	No of Microbunches	Available charge/ pulse	Equipments to be supplied	Tentative Price
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:

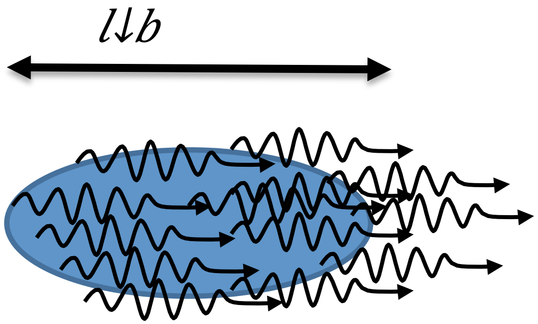
- Metal Photocathode e.g. Copper, Magnesium, Lead
- Semiconductor photocathode e.g. Cs_2Te, K_2CsSb, GaAs

To be developed at IUAC

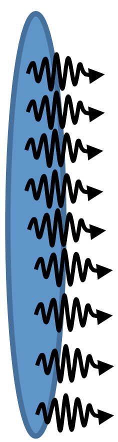
Cathode	Quantum Efficiency (%)	Photon Energy (eV)	Photon wavelength (nm)	Advantage	Disadvantage	Laser Energy for 1 nC/pulse (~ 10^9 e/pulse)
Copper	0.014	4.96 eV	250	Rugged, Long life, Less vac	Less QE, High Laser energy	35.4 ?J
Magnesium	0.62	4.66 eV	266			9.2 ?J
Lead	0.016	5.8 eV	214			2.2 ?J
Cs_2Te	~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 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

Bunching factor of a Single micro-bunch



$f(\omega)$ -> 0



$f(\omega)$ -> 1

Total Radiation Field is given by the sum of plane waves emitted by individual electrons:

$$E = E_0 \sum_{j=0}^{N} \exp\left(i\omega \, \mathbf{n}.\mathbf{r}_j / c\right)$$

Amplitude of the field is given by:

$$|E| = \sqrt{E^* E} = E_0 \sqrt{\sum_{j=0}^{N} \exp\left(i\omega \, \mathbf{n}.\mathbf{r}_j / c\right) \sum_{k=0}^{N} \exp\left(-i\omega \, \mathbf{n}.\mathbf{r}_k / c\right)}$$

The above equation in a more detailed fashion was solved in Hirschmugl's famous paper and the solution is given below:

$$|E| = \sqrt{N + N(N-1) f(\omega)} \, E_0(\omega)$$

where $f(\omega)$ is called the bunching factor of the bunch corresponding to frequency ω and is given by

$$f(\omega) = \frac{1}{N(N-1)} \sum_{j,k=1 \, (j \neq k)}^{N} \exp\left(i\omega \, \mathbf{n}.(\mathbf{r}_j - \mathbf{r}_k)/c\right)$$

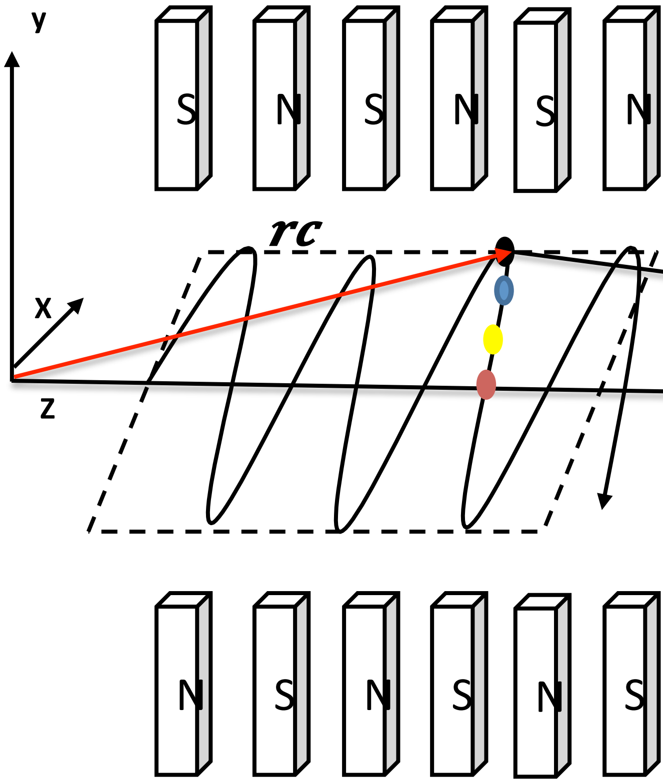
It is clear from above equation that the amplitude of radiation will be maximum along undulator's axis if $f(\omega) \rightarrow 1$. This condition is possible only if the bunch length ($l_b \sim z_{first} - z_{last}$) is extremely small as compared to the wavelength of the radiation i.e.

$$\omega (z_{first} - z_{last})/c \approx 2\pi (z_{first} - z_{last})/\lambda c \rightarrow 0$$

Such a bunch is called a **"Super-radiant bunch"**

C. J. Hirschmugl, M. Sagurton, and G. P. Williams, "Multiparticle coherence calculations for synchrotron-radiation emission," *Phys. Rev. A*, vol. 44, no. 2, pp. 1316–1320, 1991.

Bunching factor of a multi micro-bunch structure



$\boldsymbol{n} = \boldsymbol{R}/R \approx \boldsymbol{r}$

$\boldsymbol{rc}$ = position of centre of mass of a microbunch

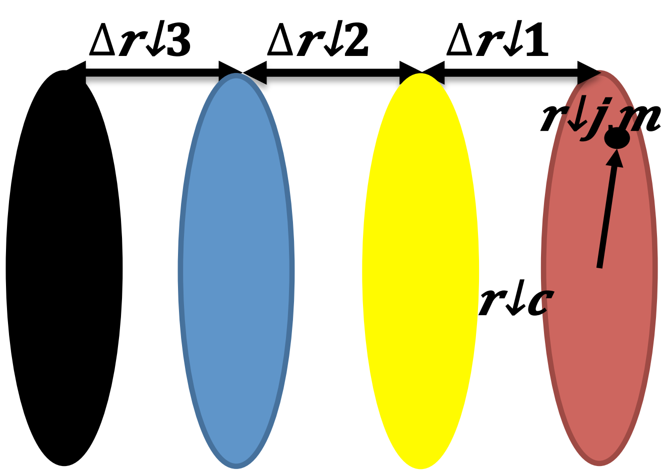
$\boldsymbol{rj,m}$ = position of j[th.] particle wrt to the m[th.] particle of the microbunch

The bunching factor of the comb beam is given:

$$f(\omega)=\sum_{m=0}^{N_m-1}\left(\sum_{j=1}^{N_e}\exp\left(i\omega\,\boldsymbol{n}.\boldsymbol{r}_{j,m}/c+i\omega\,\boldsymbol{n}.\Delta\boldsymbol{r}_m/c\right)\right)/N_m N_e$$

$f(\omega)\rightarrow 1$ only if

$\boldsymbol{n}.\boldsymbol{r}_{j,m}/c \ll \lambda$ & $\boldsymbol{n}.\Delta\boldsymbol{r}_m/c \approx \lambda$



$\boldsymbol{n}.\boldsymbol{r}_{j,m}$ = position of j[th] particle of m[th] microbunch from the centre of mass of that microbunch

$\boldsymbol{n}.\Delta\boldsymbol{r}_m$ = longitudinal separation between microbunches

$\boldsymbol{n}.\Delta\boldsymbol{r}_c$ = z component of centre of mass of the micro bunch