Free electron laser (FEL) and Delhi Light Source (DLS)

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New Delhi

Highlights of the presentation

1. Principle of Operation of FEL
   - Qualitative and pictorial representation

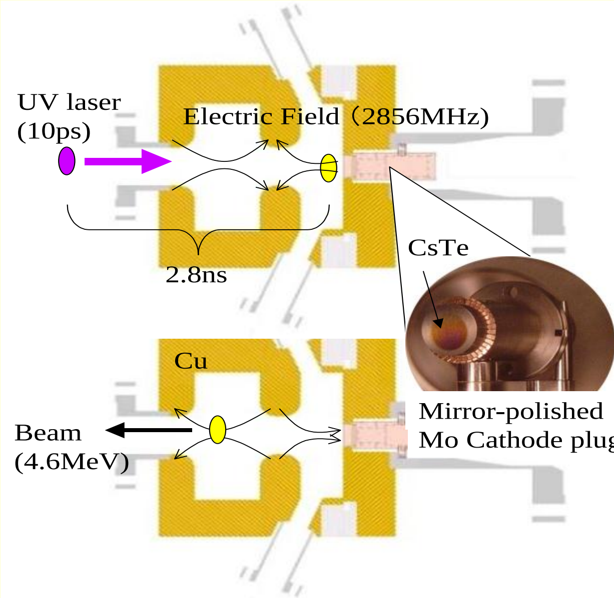
2. Outline of Delhi Light Source (DLS) at IUAC
   - Phase-I – Production of THz radiation by NC PC RF gun

3. Challenges in FEL

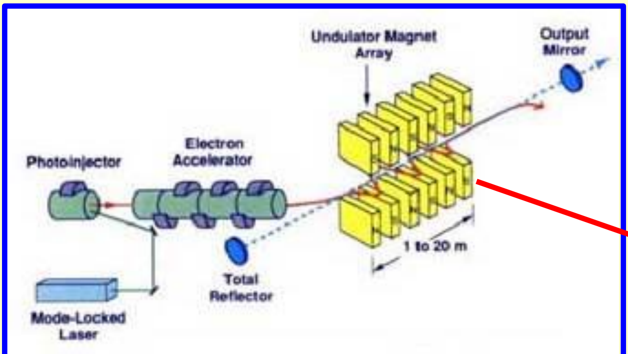
Principle of operation of FEL

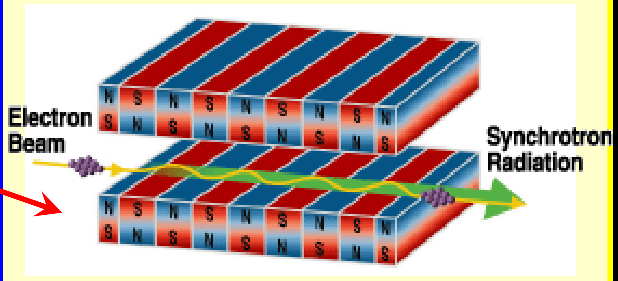
Major components:

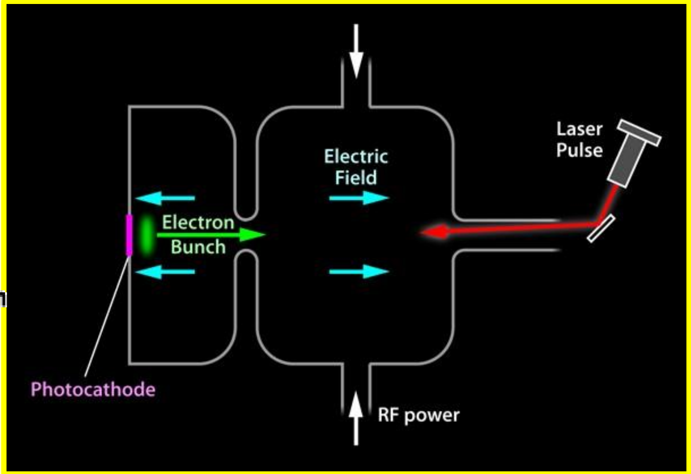
1. An electron gun – based on laser operated PC & a resonator powered by klystron/modulator
2. A laser system – produce the electron bunches
3. An Undulator magnet – to produce e.m. radn.
4. Bending and other magnets – transport the electron beam - electron gun to beam dump
5. Beam diagnostic and e.m radiation detector systems
6. Electronics, Control, Beam based tuning



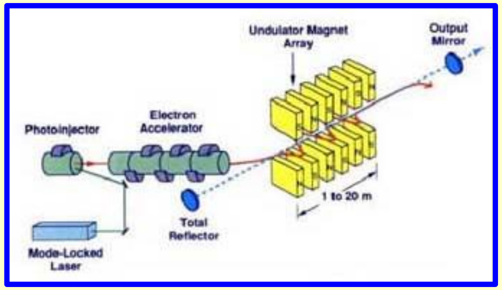
Courtesy:
Prof. Junji Urakawa

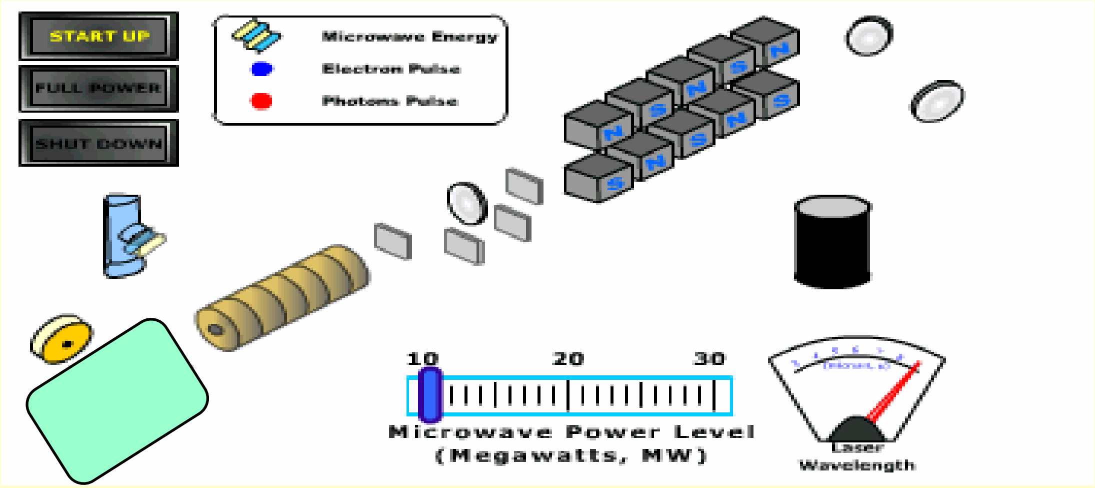






Principle of operation of FEL



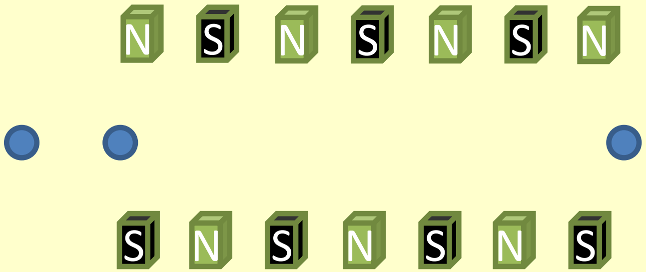


Relativistic effect on electron

- Energy > few hundreds of KeV
- Length of the moving object contracts

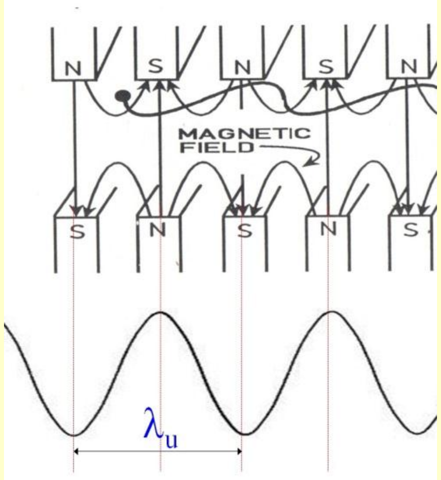
How the Photons are generated

- Undulator appears to move towards electron, length to be contracted and is determined by (1/γ).
  For electron accelerated to 5 MeV, $\gamma = \frac{E}{E_0} = \frac{5}{0.511} \approx 10$



- If λ_U = undulator period (~30 mm), then after length contraction $\lambda^* = \lambda_U/\gamma = 3$ mm

- The electron oscillate and emit a radiation of wavelength λ^*
- So λ^* observed by the stationery observer is reduced by (1/2γ) (relativistic doppler effect)
- The final wavelength $\lambda_R = \lambda^*/2\gamma = 150\ \mu m = 2$ THz



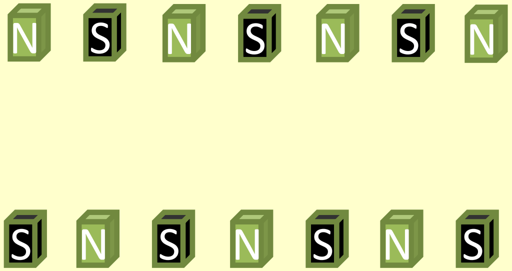
Upto now – Non-coh Radition produced by electron bunch

Principle of operation of FEL

Equation of the radiation produced by wiggling electrons

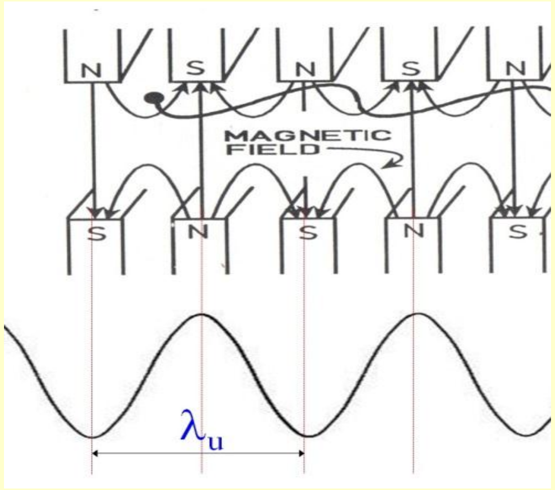
$$\lambda_R = \frac{\lambda_U}{2\gamma^2}[1+K^2]$$

$$K = \frac{eB_U\lambda_U}{2\pi mc}$$



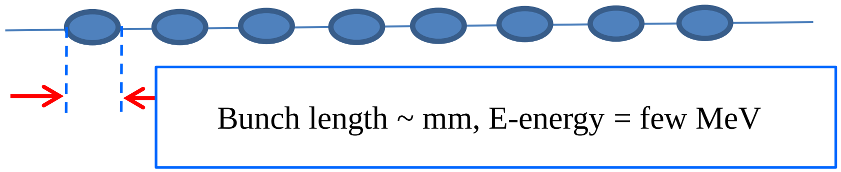
λ_U – Undulator wavelength
B_U – Undulator mag field

$$\gamma = \frac{E}{E_o} = \frac{5}{0.5} = 10$$



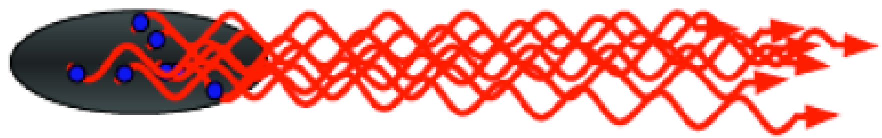
Principle of operation of FEL

Importance of Coherent radiation



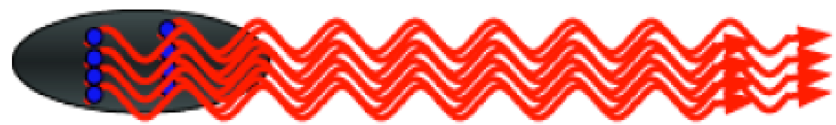
Spontaneous Radiation:

$$I_{\text{rad}} \propto N_e$$

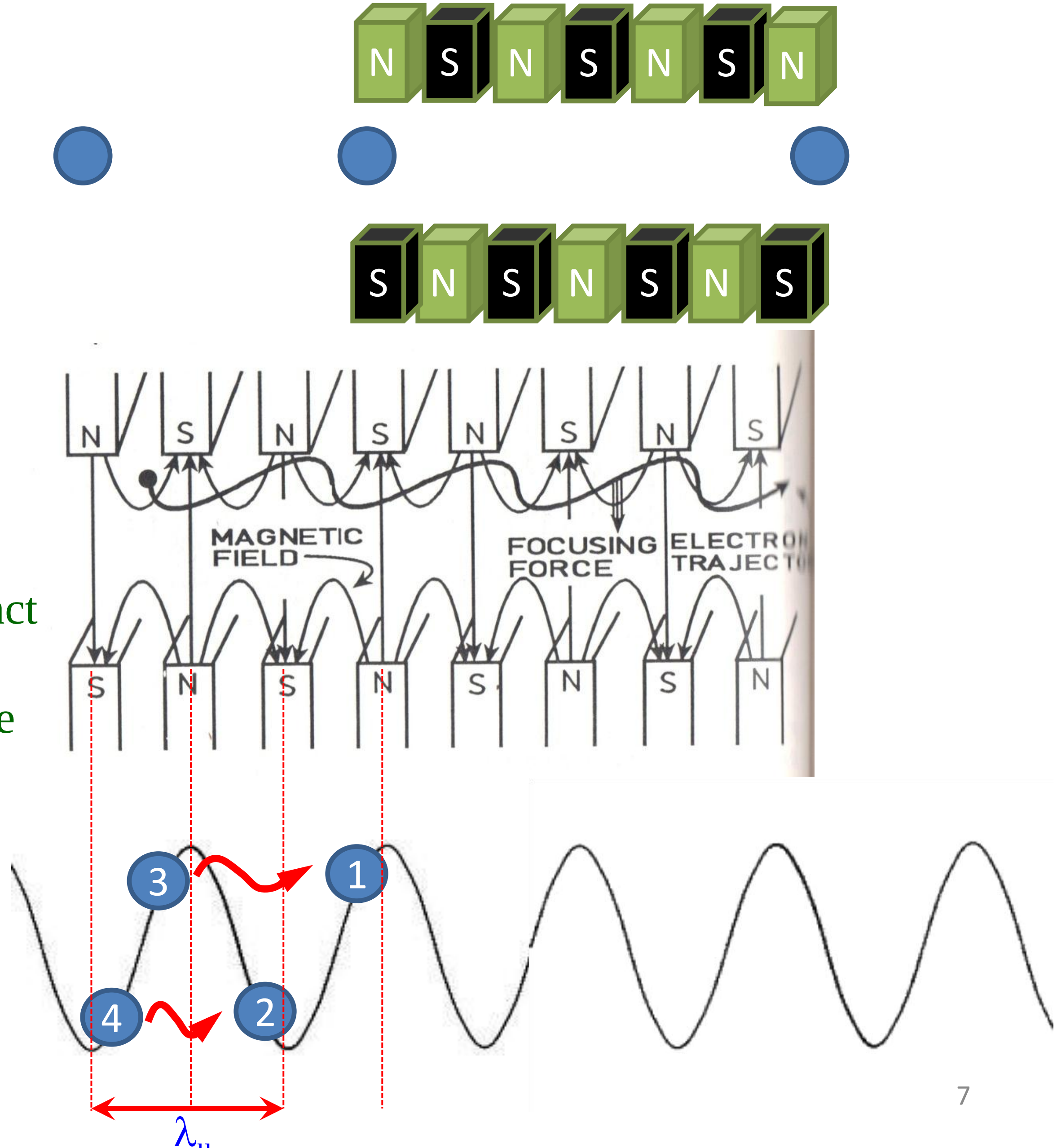


Coherent Radiation:

$$I_{\text{rad}} \propto N_e^2$$

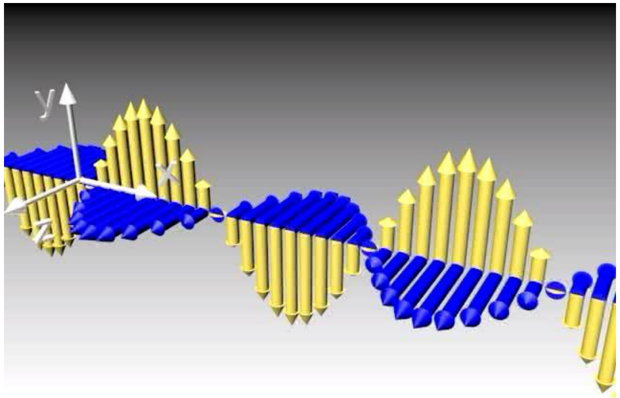


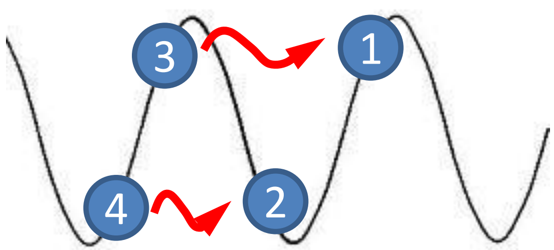
How Coherent radiation is produced in FEL



- Electron emits radiation of a distinct wavelength (photon),
- The photon moves in a straight line interacting with another electron

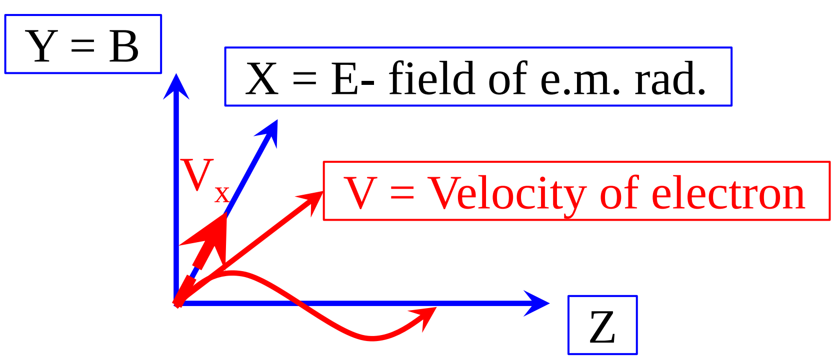
How Coherent radiation is produced in FEL

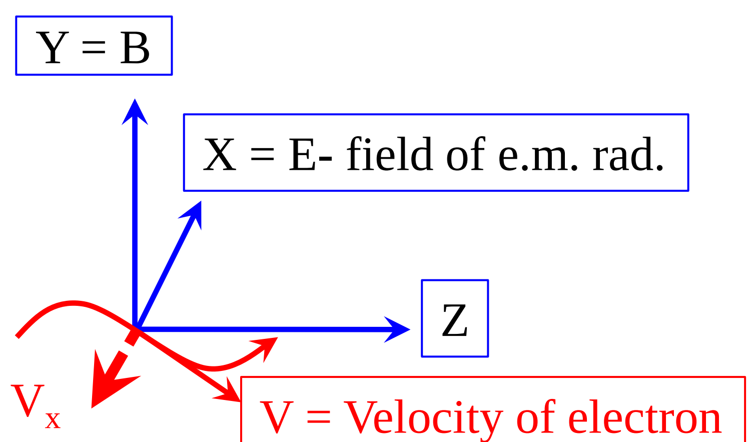




- **Electron emits radiation**
  - ⇨ a distinct wavelength ,
  - ⇨ interacts w 2nd electron

- **E-field component of radiation**
  - ⇨ interacts w X-comp of the wiggling motion of electron
  - ⇨ Results to accl / deccel of electron
  - ⇨ some electrons move faster some move slower - velocity modulation



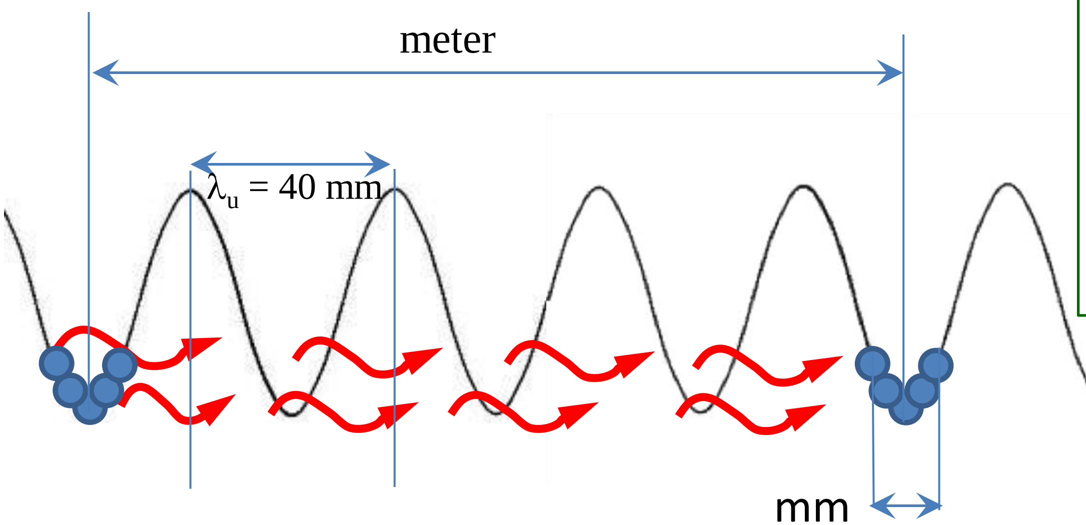


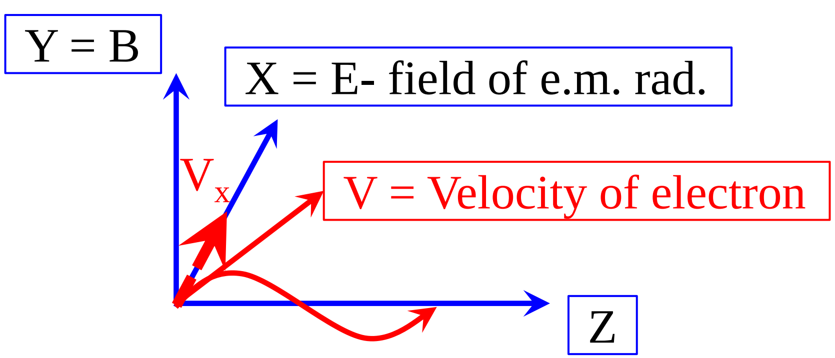
How Coherent radiation is produced in FEL

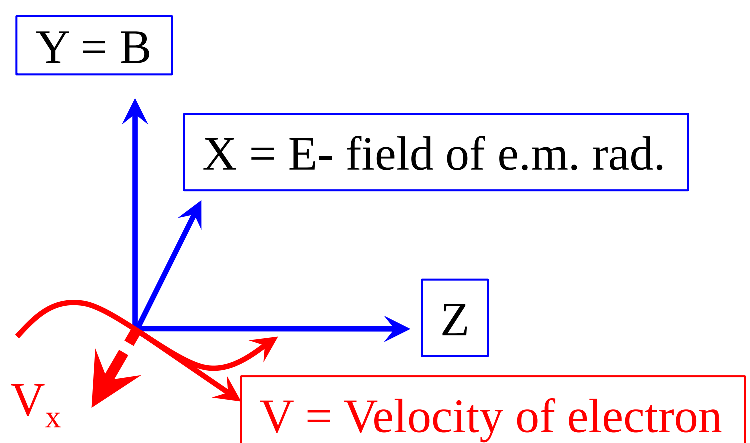
Electron velocity close to c
E-beam bunch length ~ mm (ps)
E-beam bunch separation ~ meter (MHz)

- 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

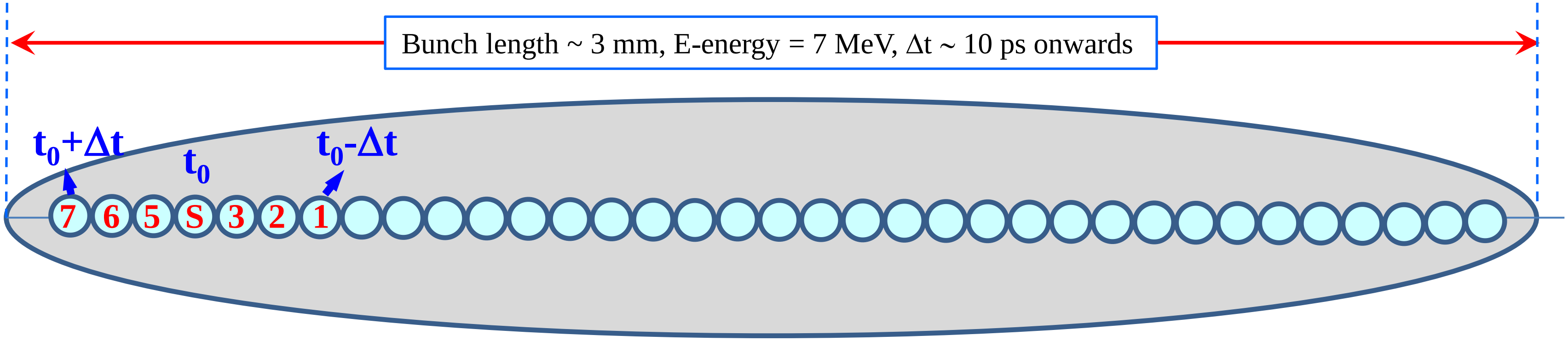






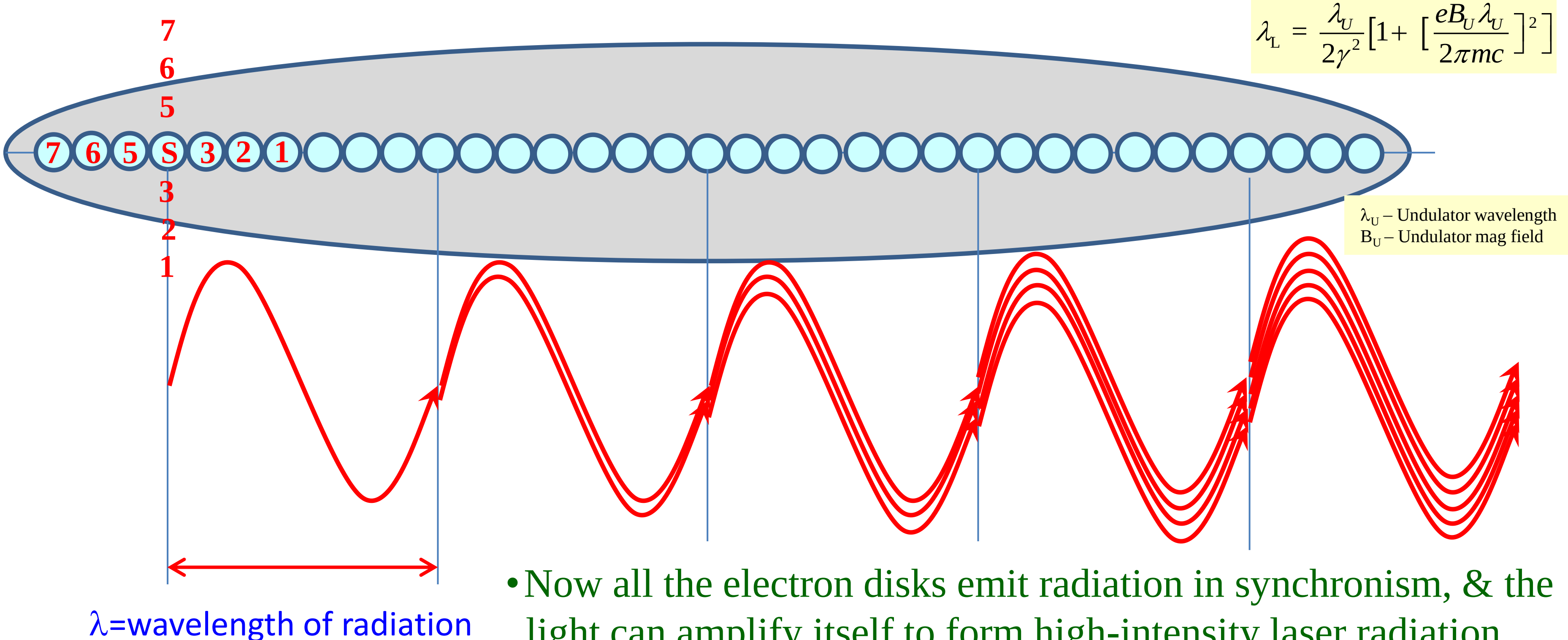
How Coherent radiation is produced in FEL

– Concept of Microbunching (followed in Phase-II/III, unlike Phase-I)



Interaction of Photon and wiggling electron inside undulator magnet

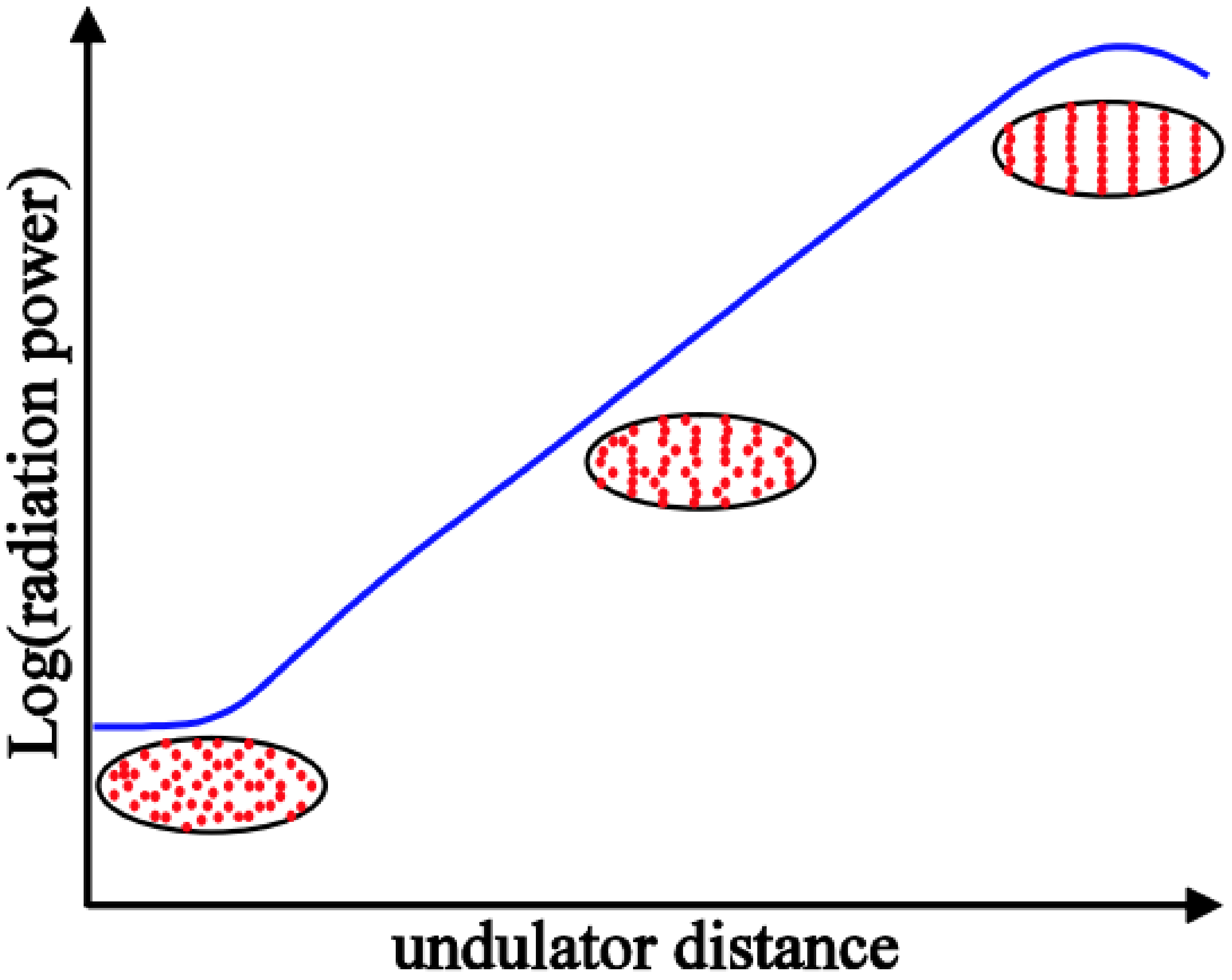
$$\lambda_L = \frac{\lambda_U}{2\gamma^2}\left[1 + \left[\frac{eB_U\lambda_U}{2\pi mc}\right]^2\right]$$



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

How Coherent radiation is produced in FEL

– Concept of Microbunching (followed in Phase-II/III, unlike Phase-I)



Injection energy of an Electron in to Undulator

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

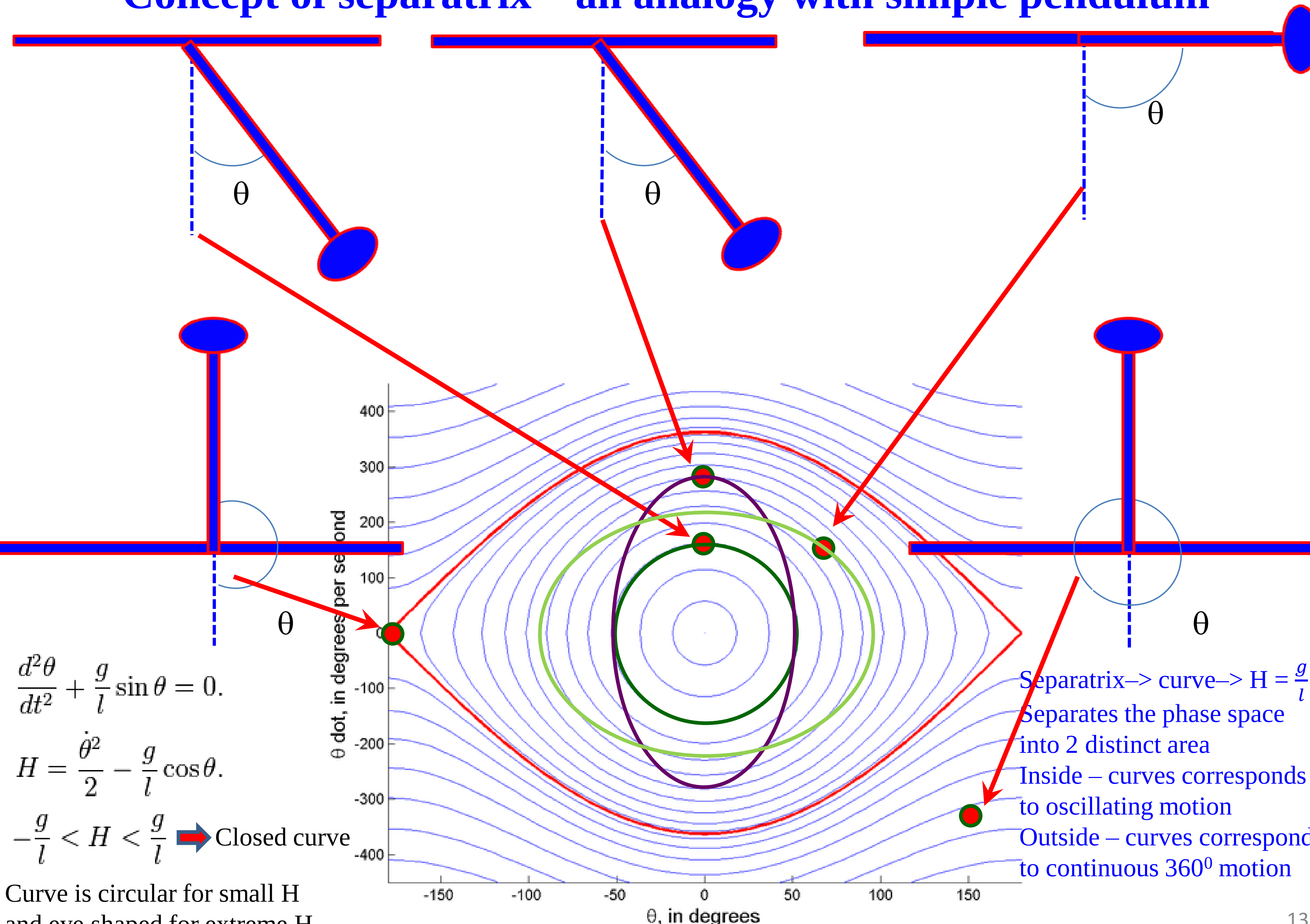
$$\gamma = \frac{E}{E_0} = \frac{5}{0.511} \approx 10$$

If the electron energy exactly meets the resonance

- Micro-bunching of the electron beam is taking place
- 50% electron will gain energy from photon & 50% will lose
- But there is no net energy transfer from electron to photon
- There is no net gain so the photon intensity doesn't grow

<u>But before that let us introduce the concept of separatrix</u>

Concept of separatrix – an analogy with simple pendulum



$$\frac{d^2\theta}{dt^2} + \frac{g}{l}\sin\theta = 0.$$

$$H = \frac{\dot{\theta}^2}{2} - \frac{g}{l}\cos\theta.$$

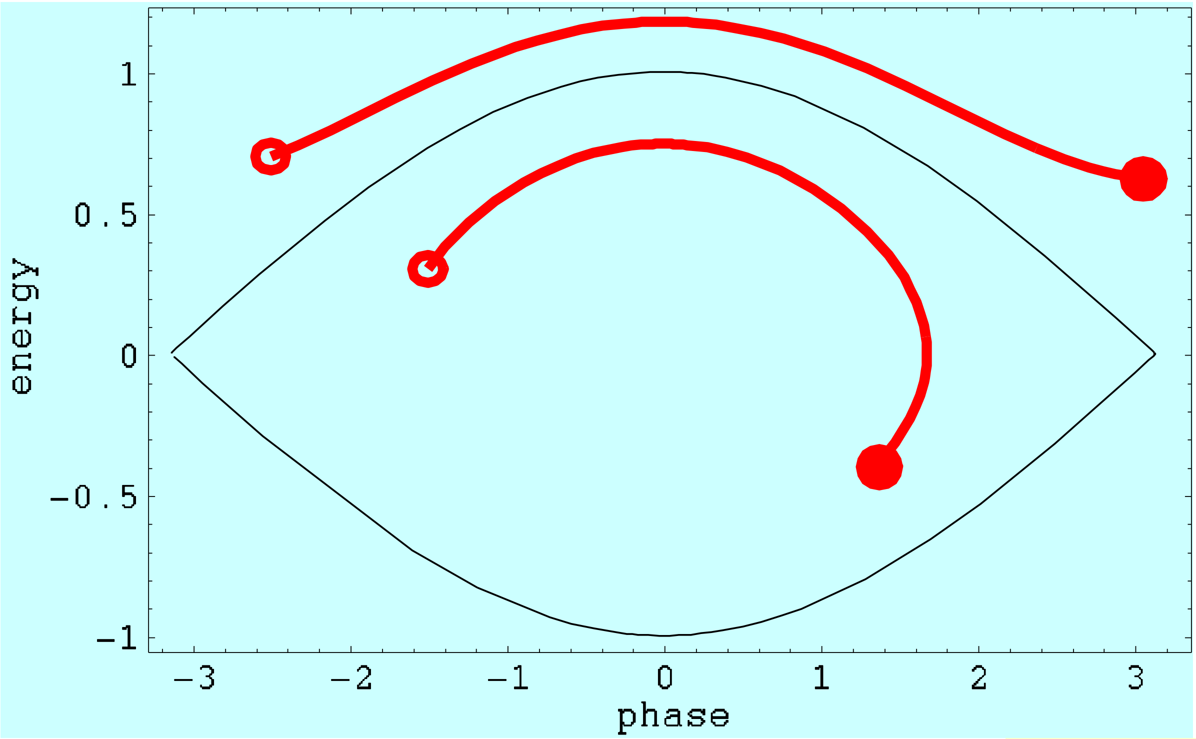
$-\frac{g}{l} < H < \frac{g}{l}$ ➡ Closed curve

Curve is circular for small H
and eye shaped for extreme H

Separatrix–> curve–> H = $\frac{g}{l}$
Separates the phase space into 2 distinct area
Inside – curves corresponds to oscillating motion
Outside – curves corresponds to continuous 360^0 motion

Injection energy of an Electron in to Undulator

Picture Courtsey: Dr. P.Michel, HZDR



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

Electron energy & its phase co-ordinate is outside

- won't be confined in oscillatory motion
- lost during the transit through accelerator
- Results to e-beam loss and hence radiation, $I \propto N^2$

$$\gamma = \frac{E}{E_0} = \frac{5}{0.511} \approx 10$$

Injection energy of an Electron in to Undulator

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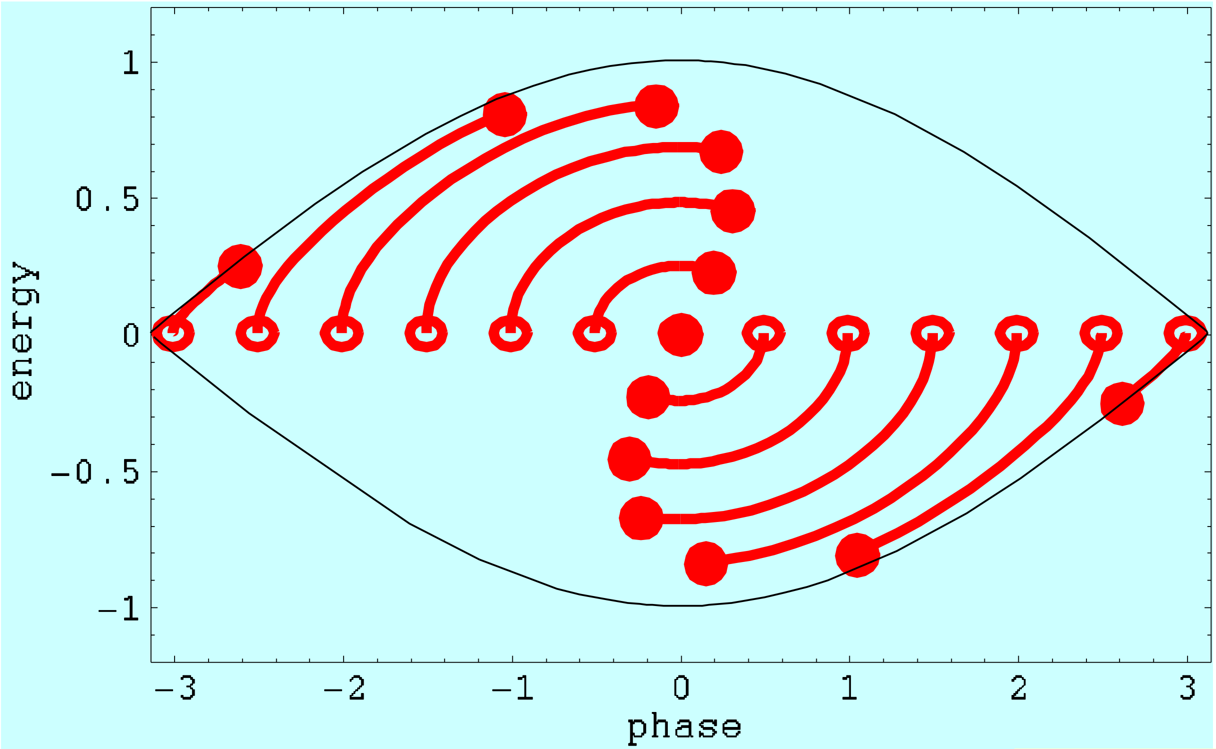

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Injection energy of an Electron in to Undulator

Electron's energy is to be slightly enhanced

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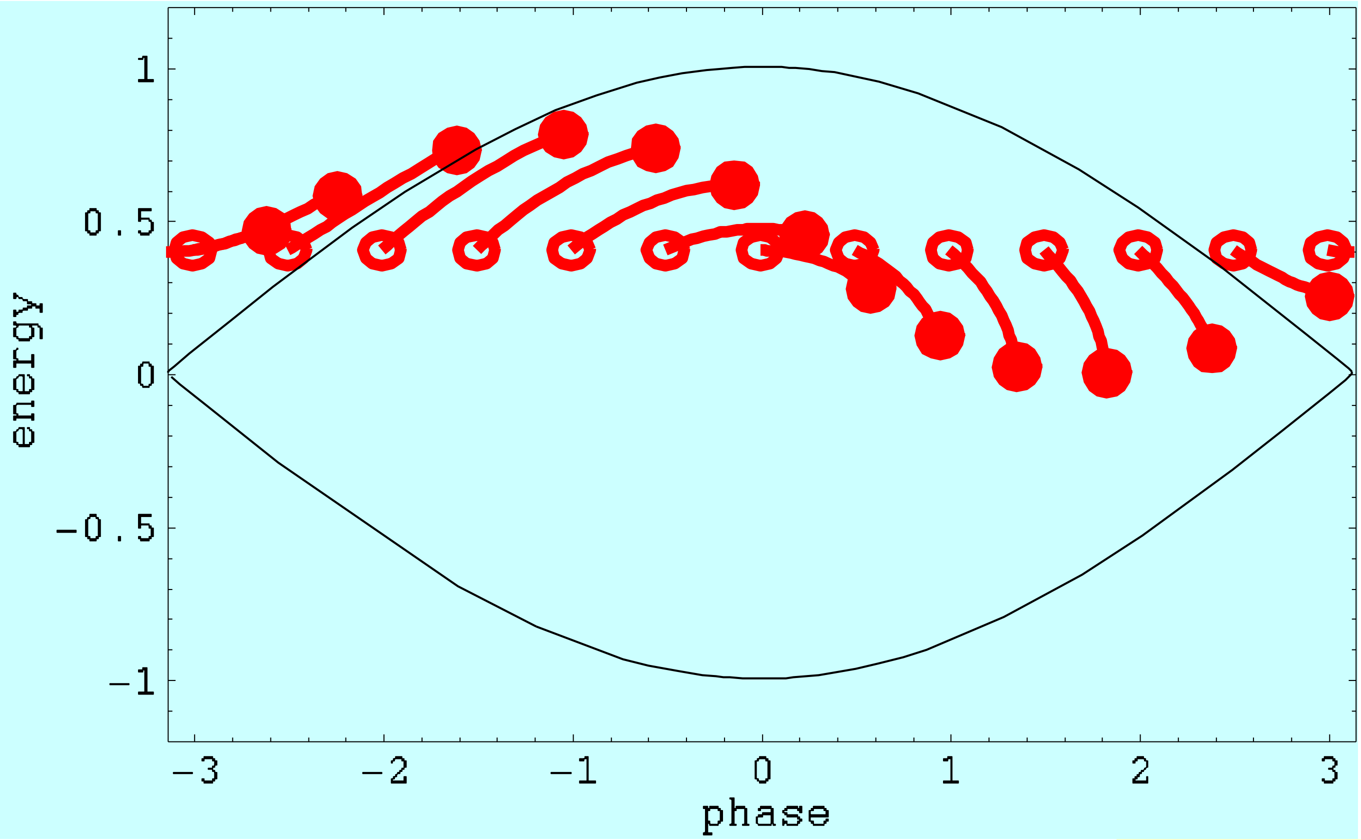

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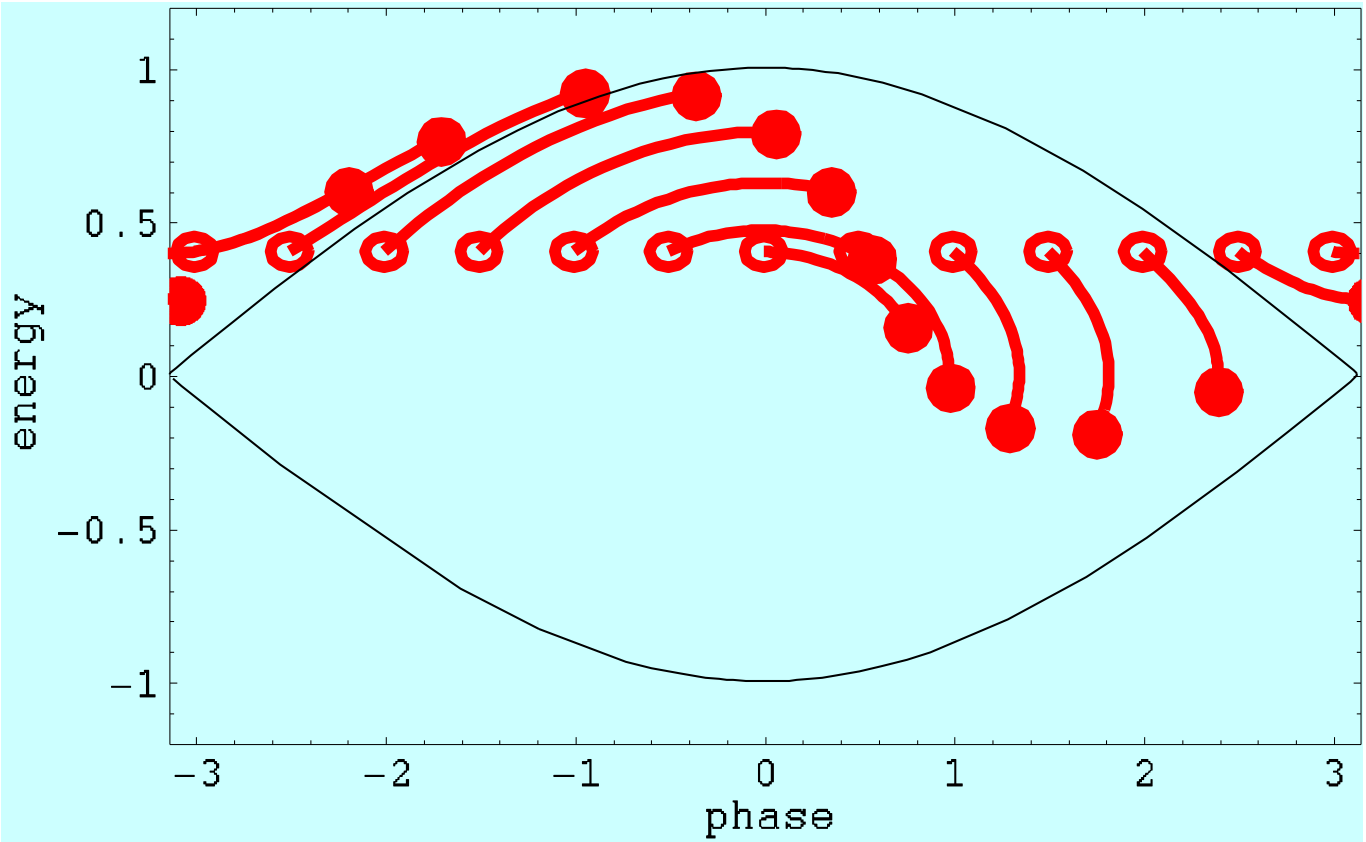

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Indo-Japan school on Advanced Accelerators for Ions and Electrons
16-18 February 2015

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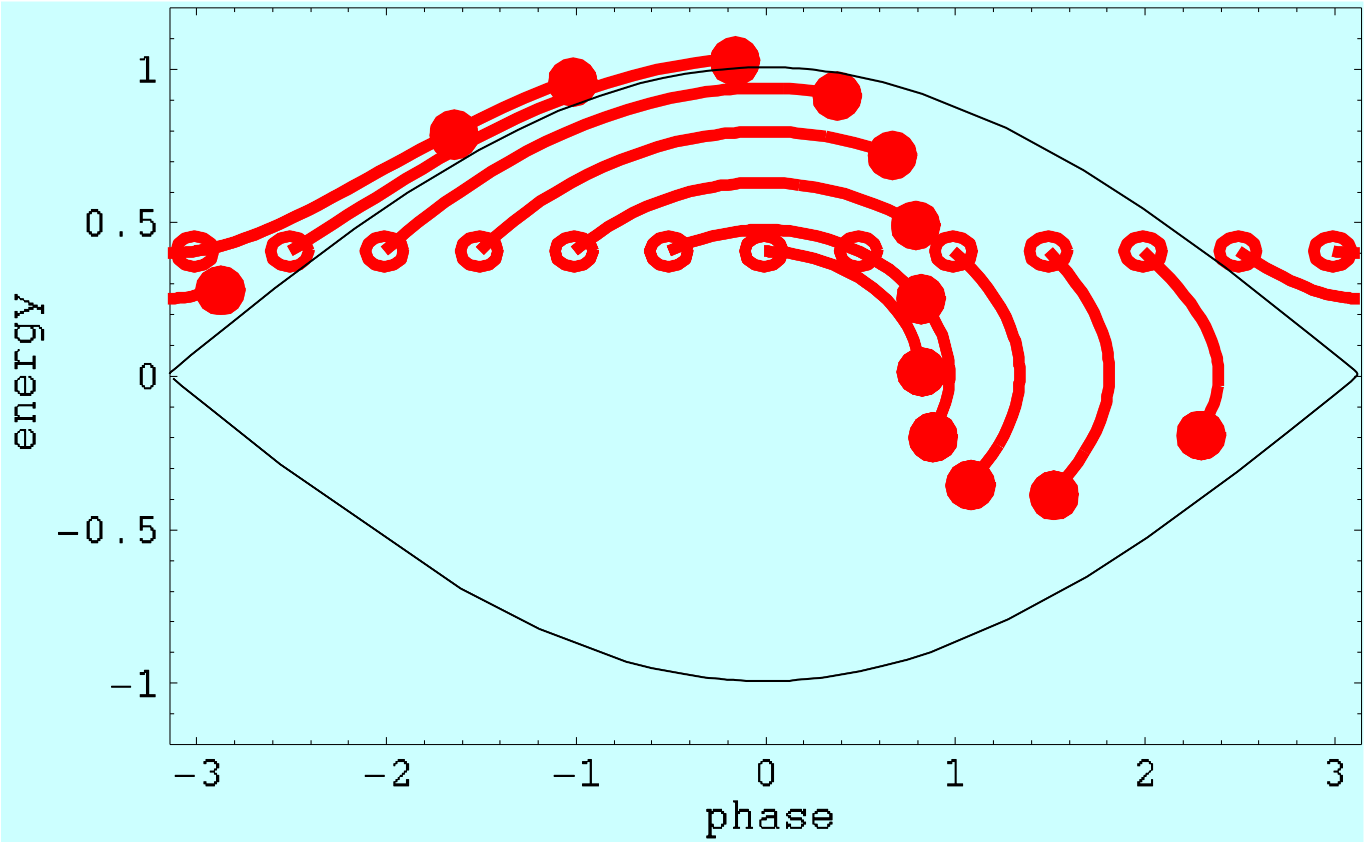

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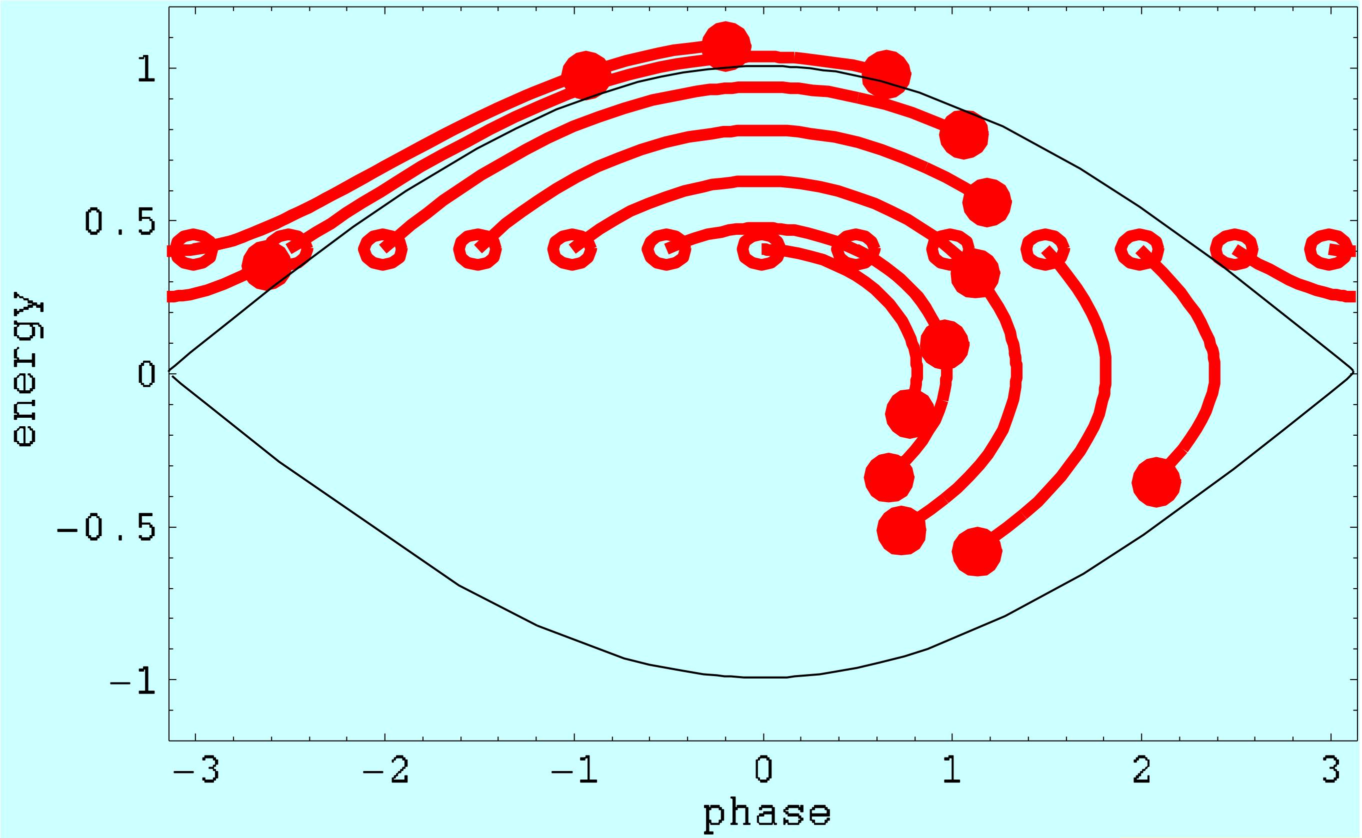

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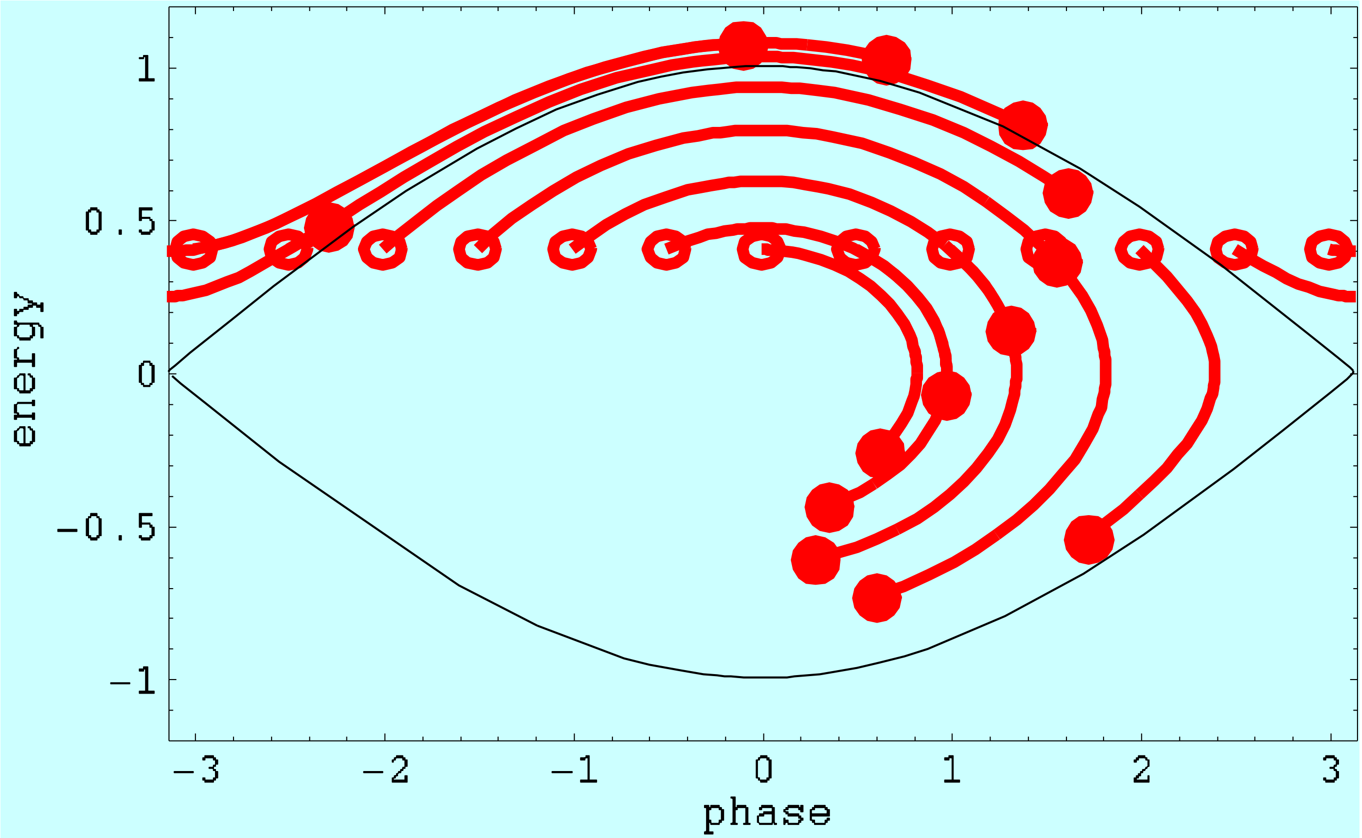

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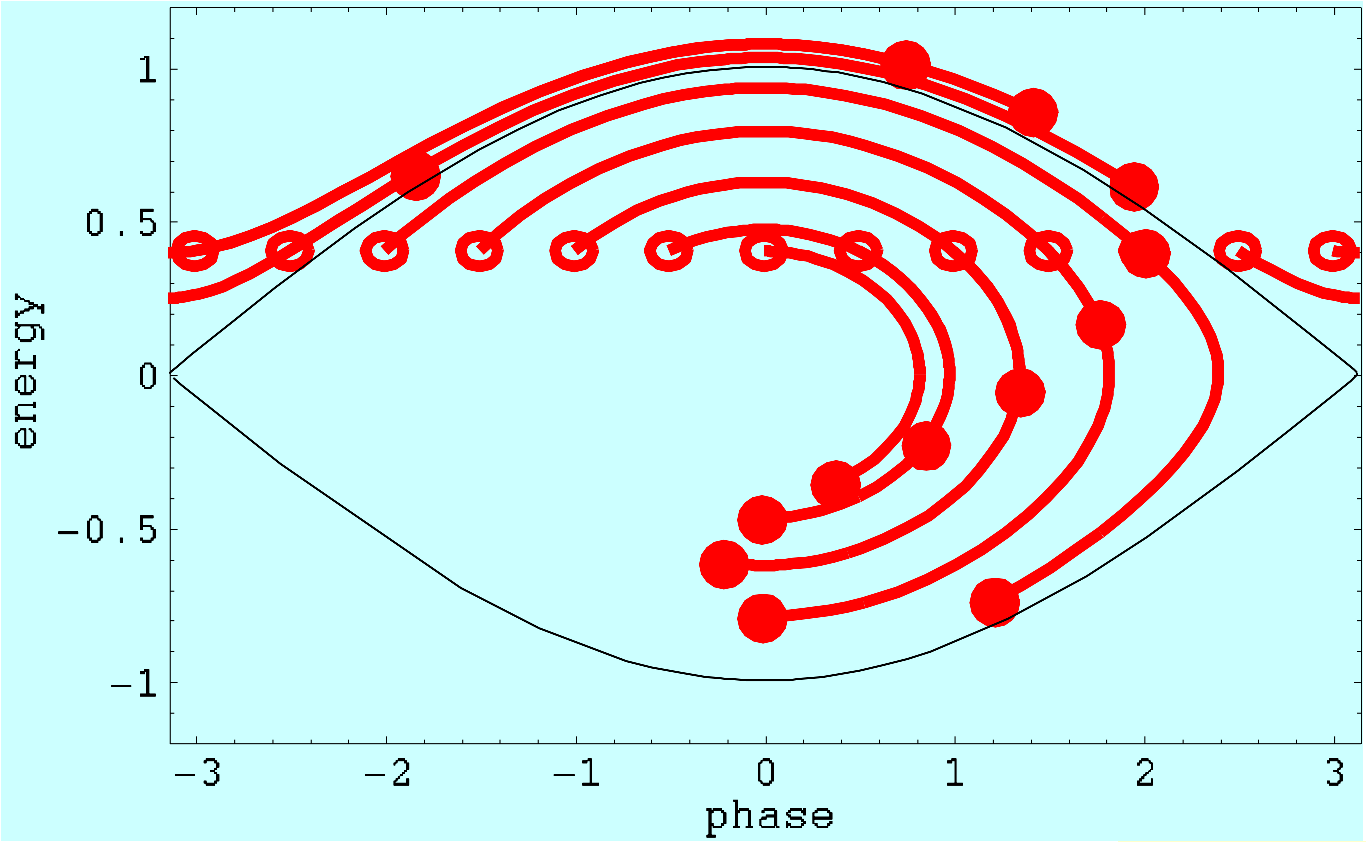

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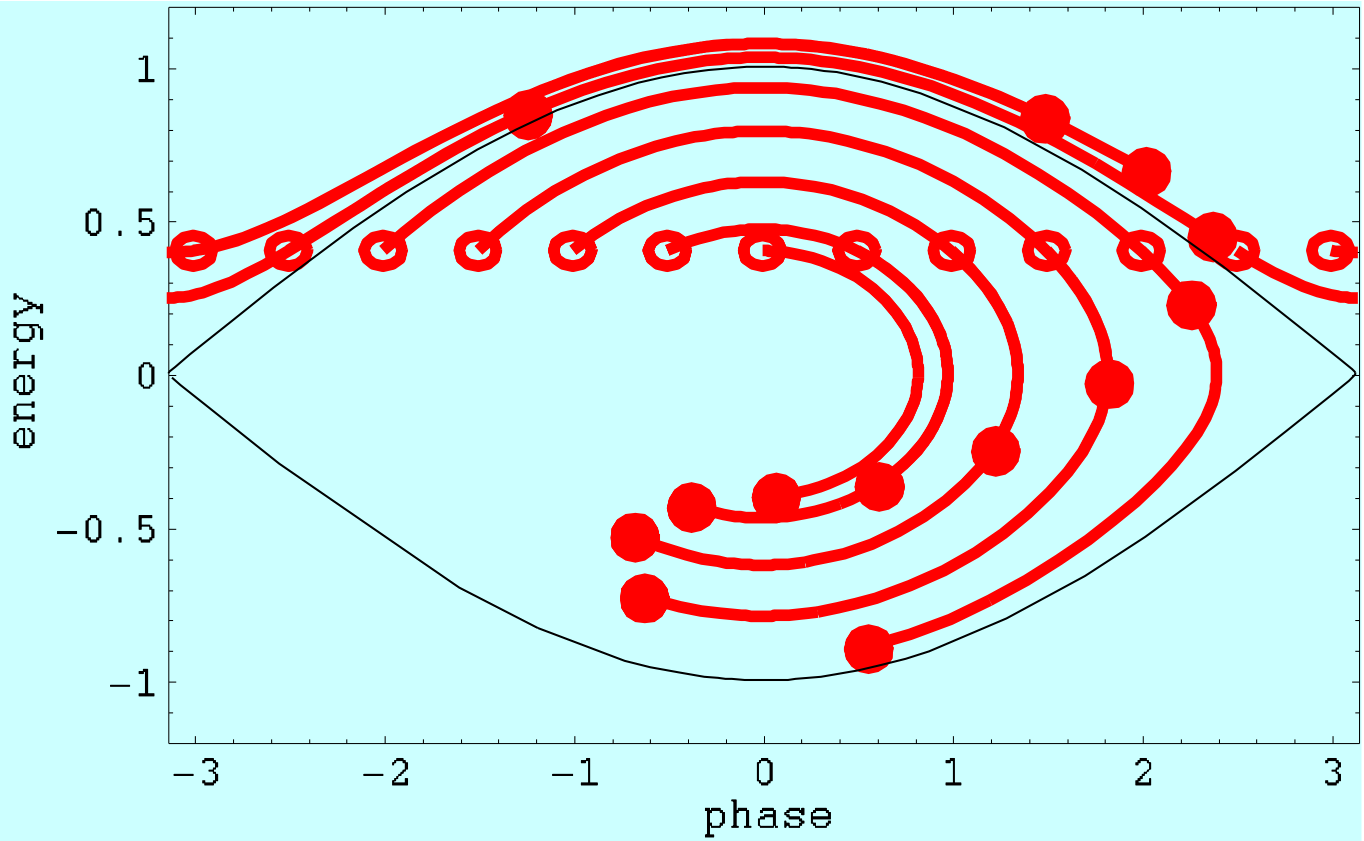

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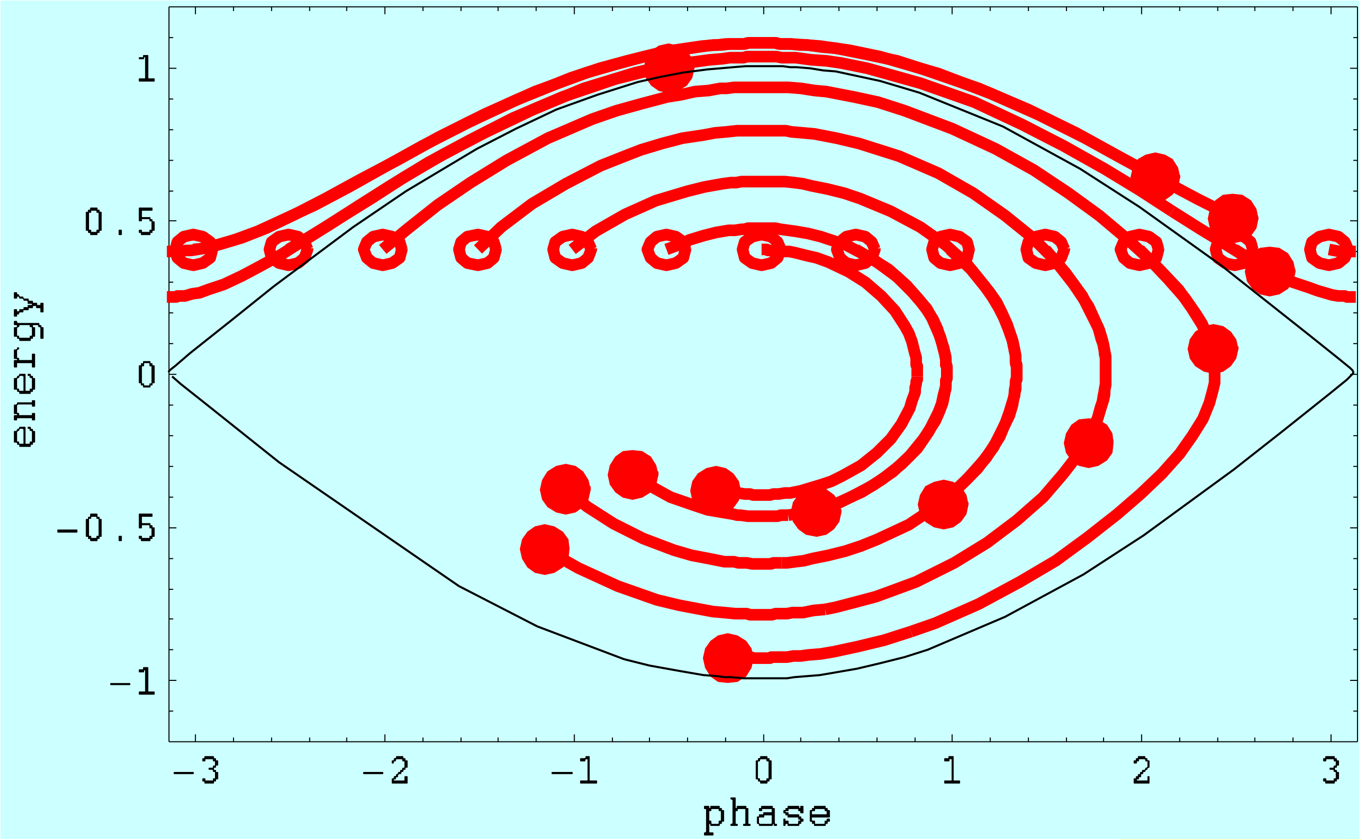

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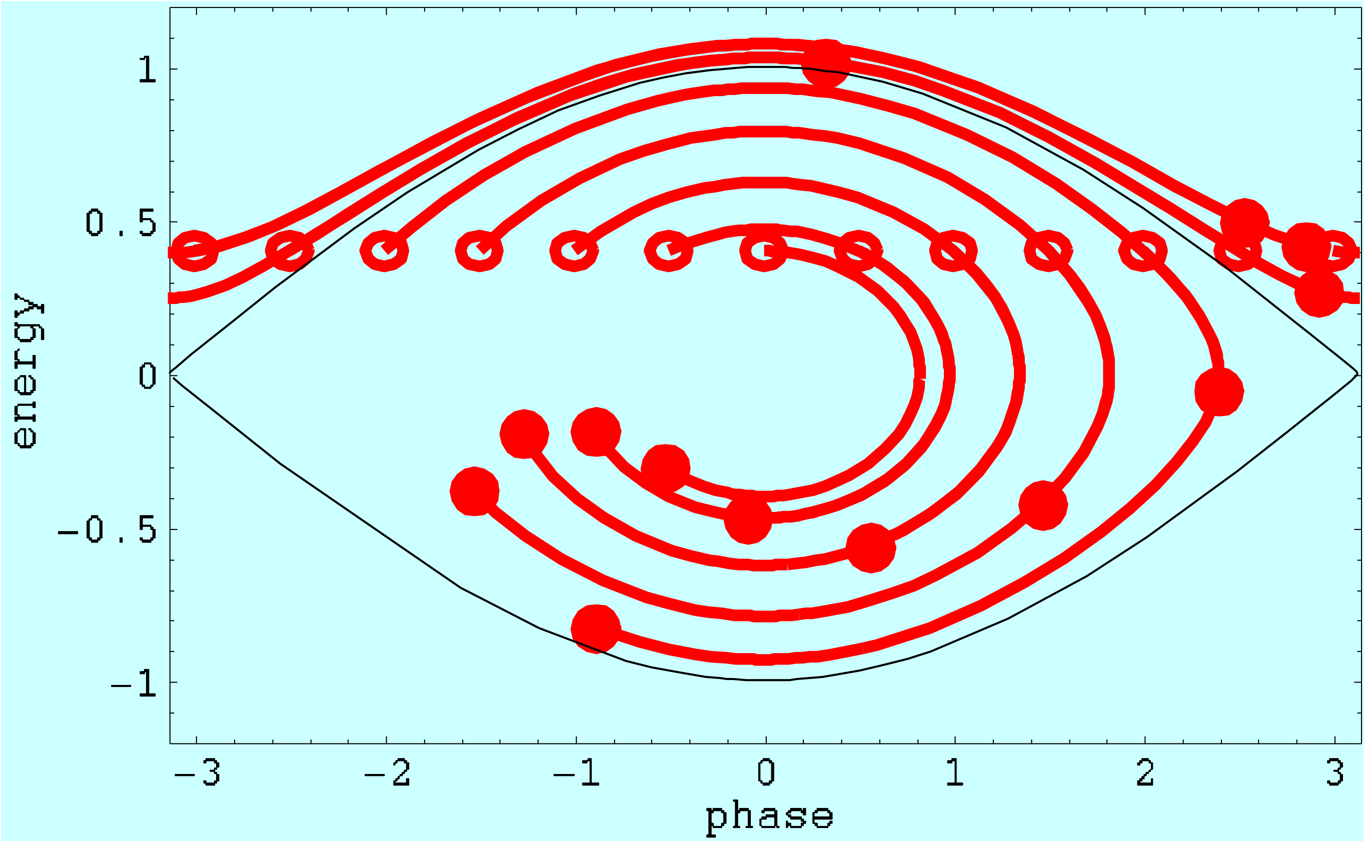


Electron losing energy > Electrons gaining energy

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

INTRODUCTION TO DELHI LIGHT SOURCE (DLS)

It is an Free Electron Laser machine & produces em radiation

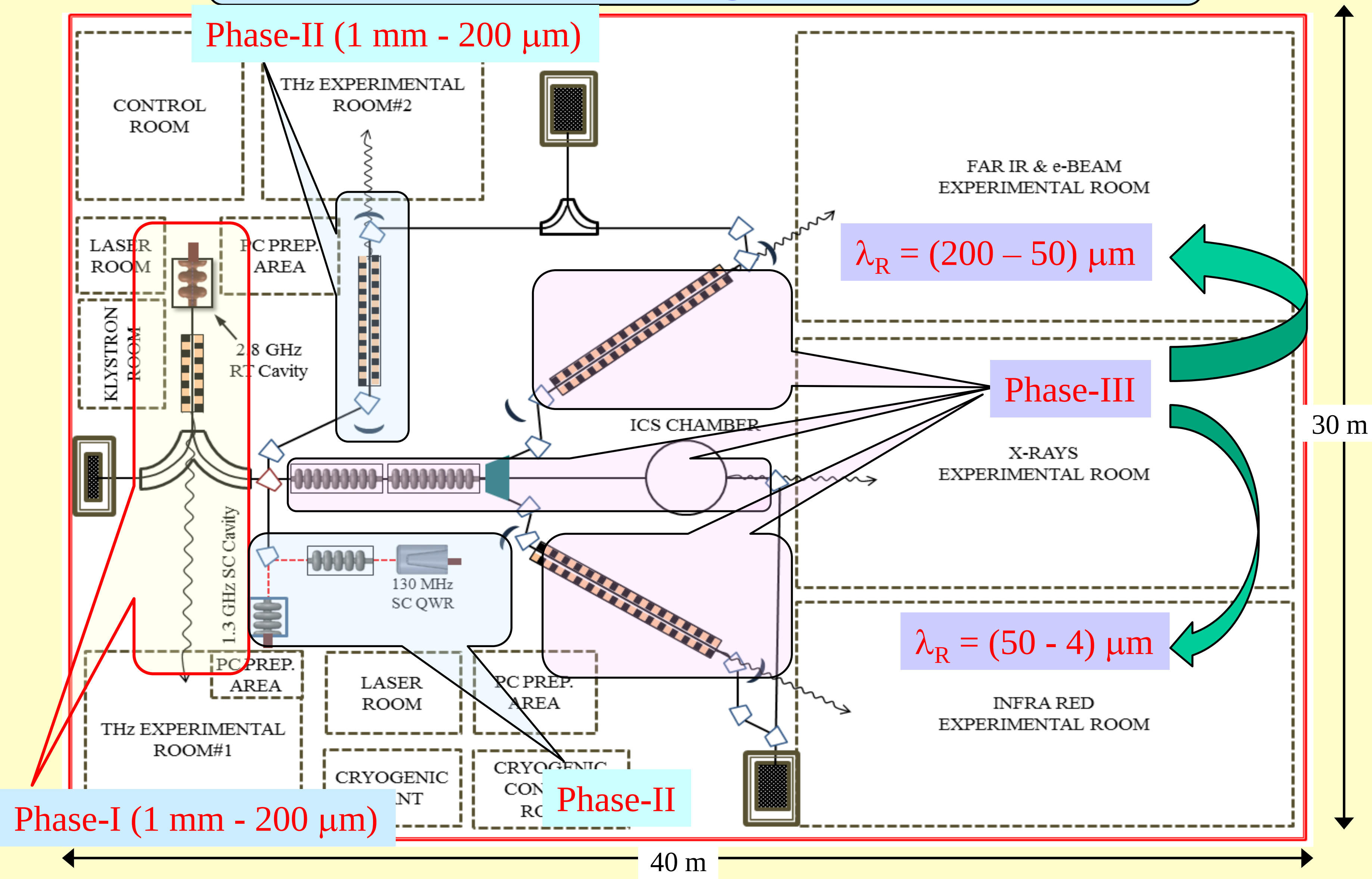
Motivation:

- IUAC – national research facility using ion beams from accelerators
- To extend the research activities using coherent photons in emerging areas of physical, chemical, biological and medical sciences

Plan:

- Development of a Photo injector based electron gun to produce electron beam of ~ 7 MeV suitable for a free electron laser (FEL)
- Develop a compact FEL to produce radiation up to THz (Phase-1)
- Develop SC RF-gun to produce THz with higher av. power (Ph - 2)
- Extend it to increase the radiation range to IR & X- rays (Phase-3)

Layout of Delhi Light Source (DLS)



Development of Phase-I with KEK Collaboration

DLS

Physics Design

- Wavelength based on Expt. requirement
- E-beam energy
- Available space
- Beam optics design

Choice of Accel. Components

- RF cavity, Frequency
- Photocathodes
- Laser
- Klystron, Modulator
- Undulator, other Mag

Electronics and Control

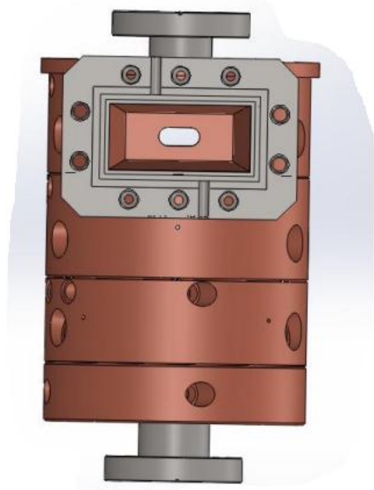
- For RF cavity & Time synchro syst
- For Diagnostics & Meas. System
- Control system

Help from KEK, also from BARC, RRCAT, SAMEER, VECC

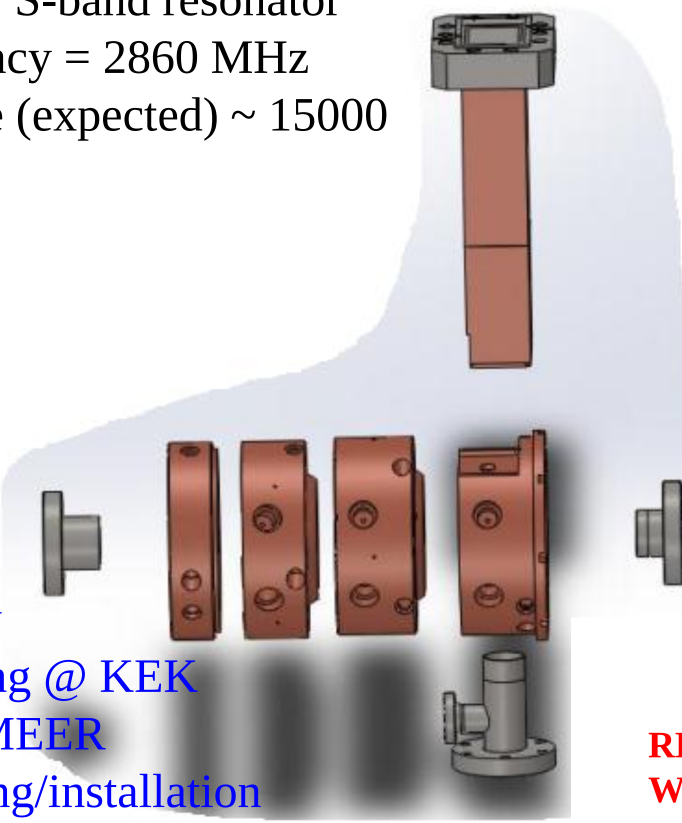
Major component of Phase-I of DLS

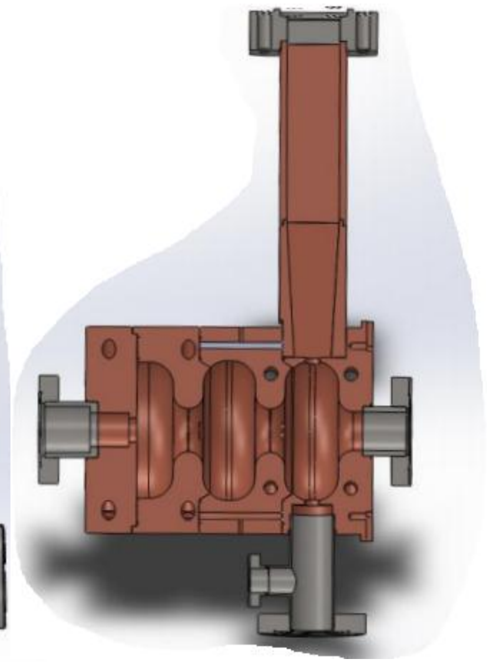
1. The electron gun –
   - Copper cavity
   - Photocathode
   - Laser system
   - RF system
2. Undulator magnets, other magnets
3. Beam diagnostics
4. Tentative parameters for the THz facility of Phase-I

2.6 cell, 2860 MHz, Copper cavity



2.6 cell, S-band resonator
Frequency = 2860 MHz
Q-value (expected) ~ 15000



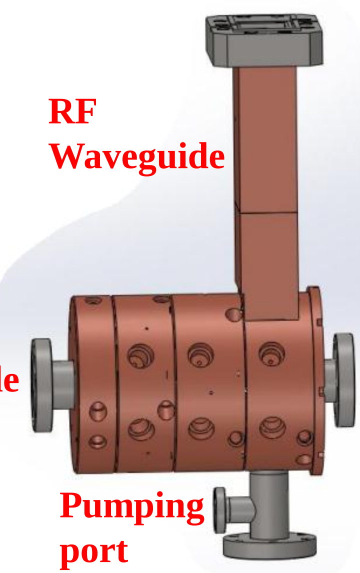


Activity at KEK:

Fabrication soon to be started at KEK
Rough machining at Japanese industry
Final m/c, frequency tuning and brazing @ KEK
along with personnel from IUAC/SAMEER
Shipped to IUAC for high power testing/installation

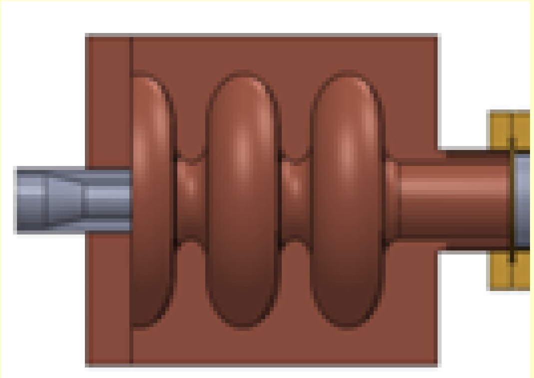
Activity at SAMEER/IUAC:

Fabrication will be started at SAMEER
High power test at IUAC



Picture Courtsey: Dr. A.Deshpande, SAMEER

Phase-I: RT e-gun



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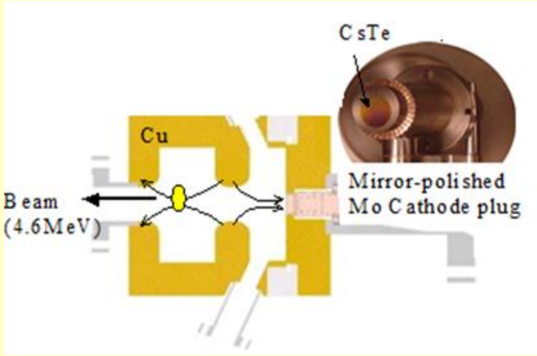
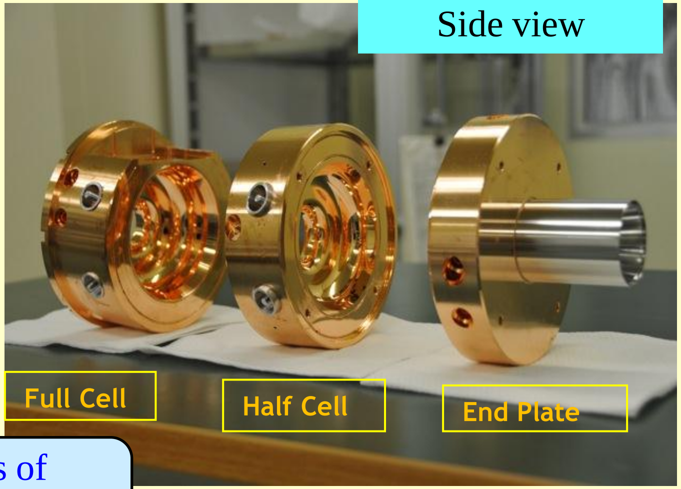
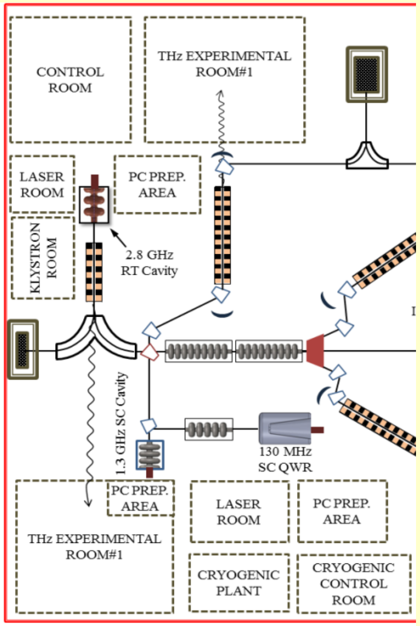


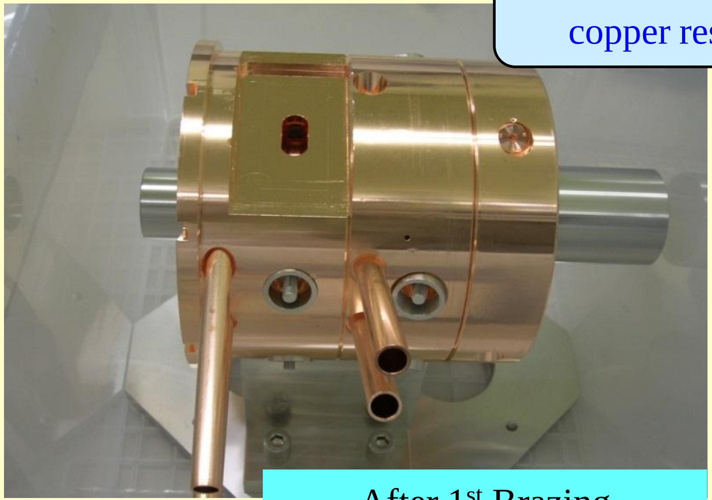
E-gun fabrication at various stage



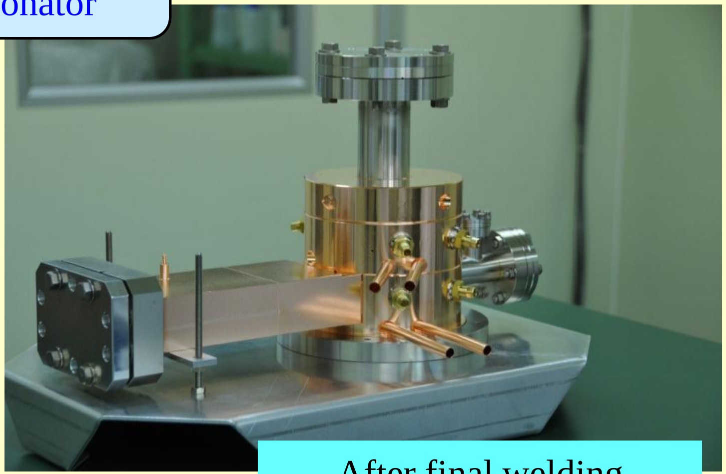
Side view



Components of copper resonator



After 1st Brazing



After final welding

Picture Courtesy:
Prof. Junji Urakawa

Photocathode and its development at IUAC

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 µJ
Magnesium	0.62	4.66 eV	266			9.2 µJ
Lead	0.016	5.8 eV	214			2.2 µJ
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

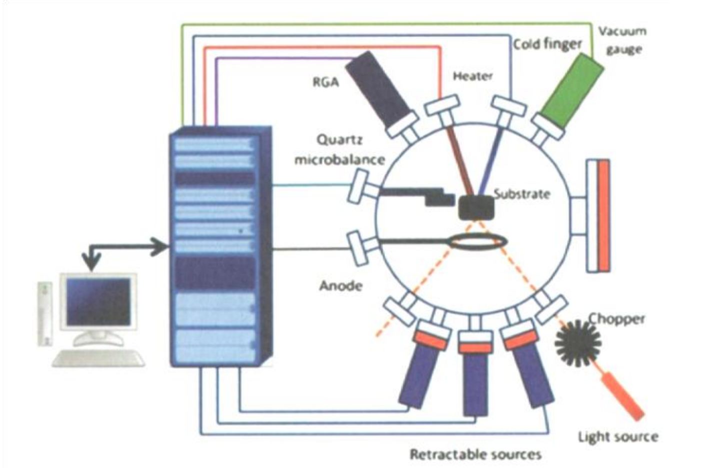
- Cathode thickness ~ 100 nm, surface roughness ≤ 10-20 nm

Phase-I: RT e-gun

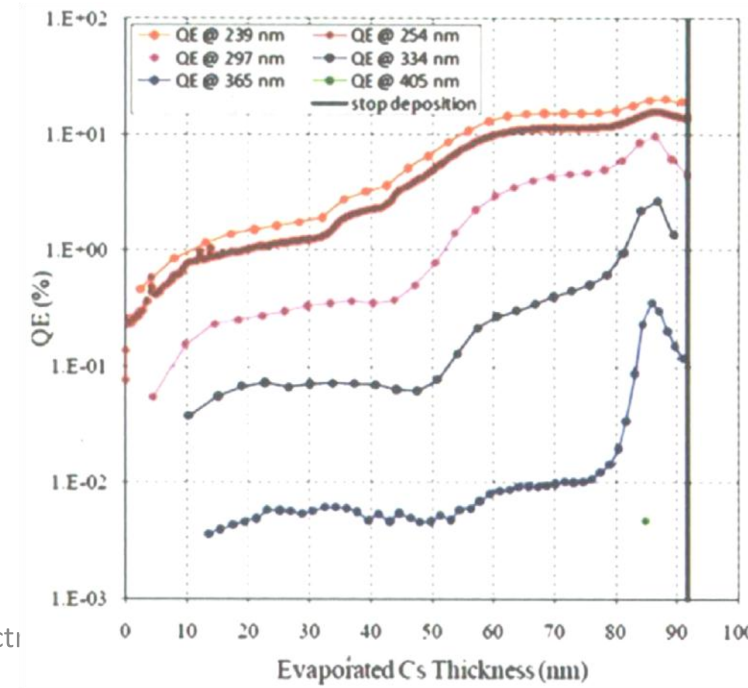
Details of Photocathode

Main Steps to produce Cs_2Te photocathode

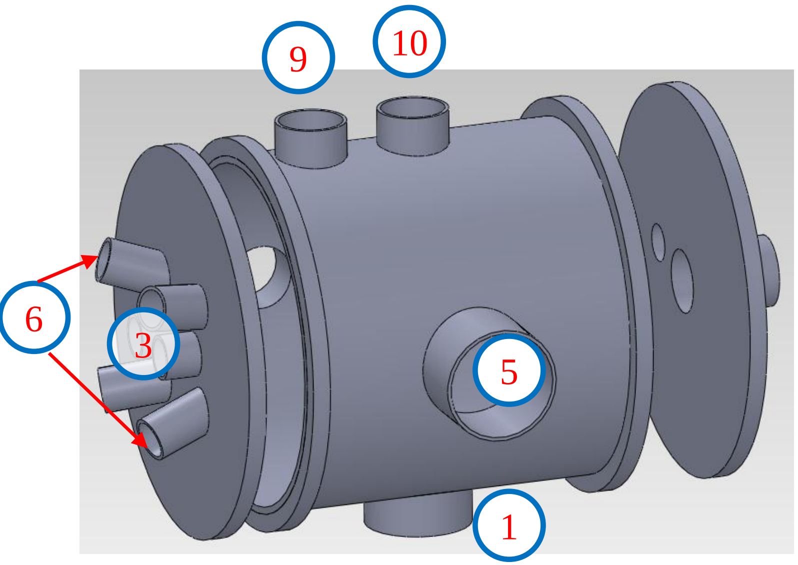
- Substrate – Mo – to be held at 120 C, while ~10 nm Te is deposited @ 1nm/m
- Film is then illuminated by UV light @ 365nm Cs is evaporated @ same rate, Photocurrent is constantly monitored
- At maximum QE, source and substrate heater are turned off simultaneously, to be cooled rapidly by a cold finger

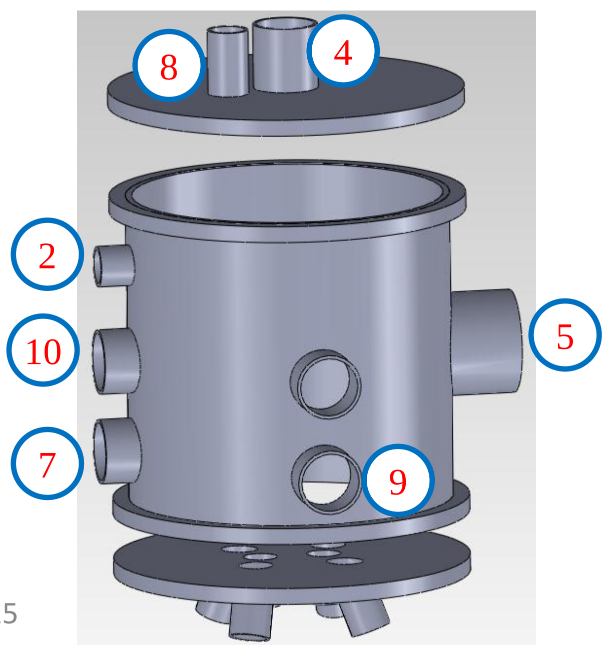


Picture Courtesy: Dr. Triveni Rao, BNL



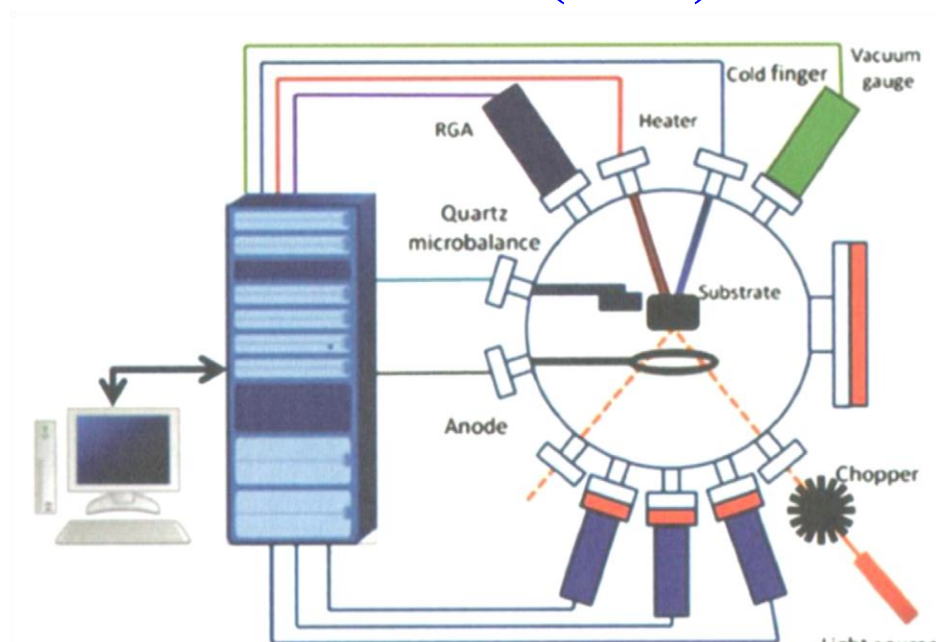
Photocathode Preparation Chamber





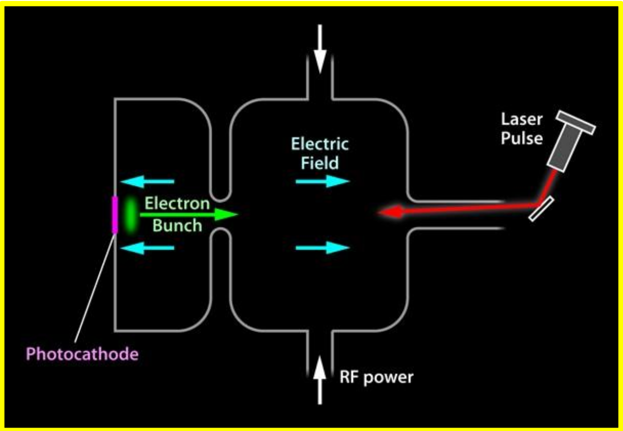
Ports

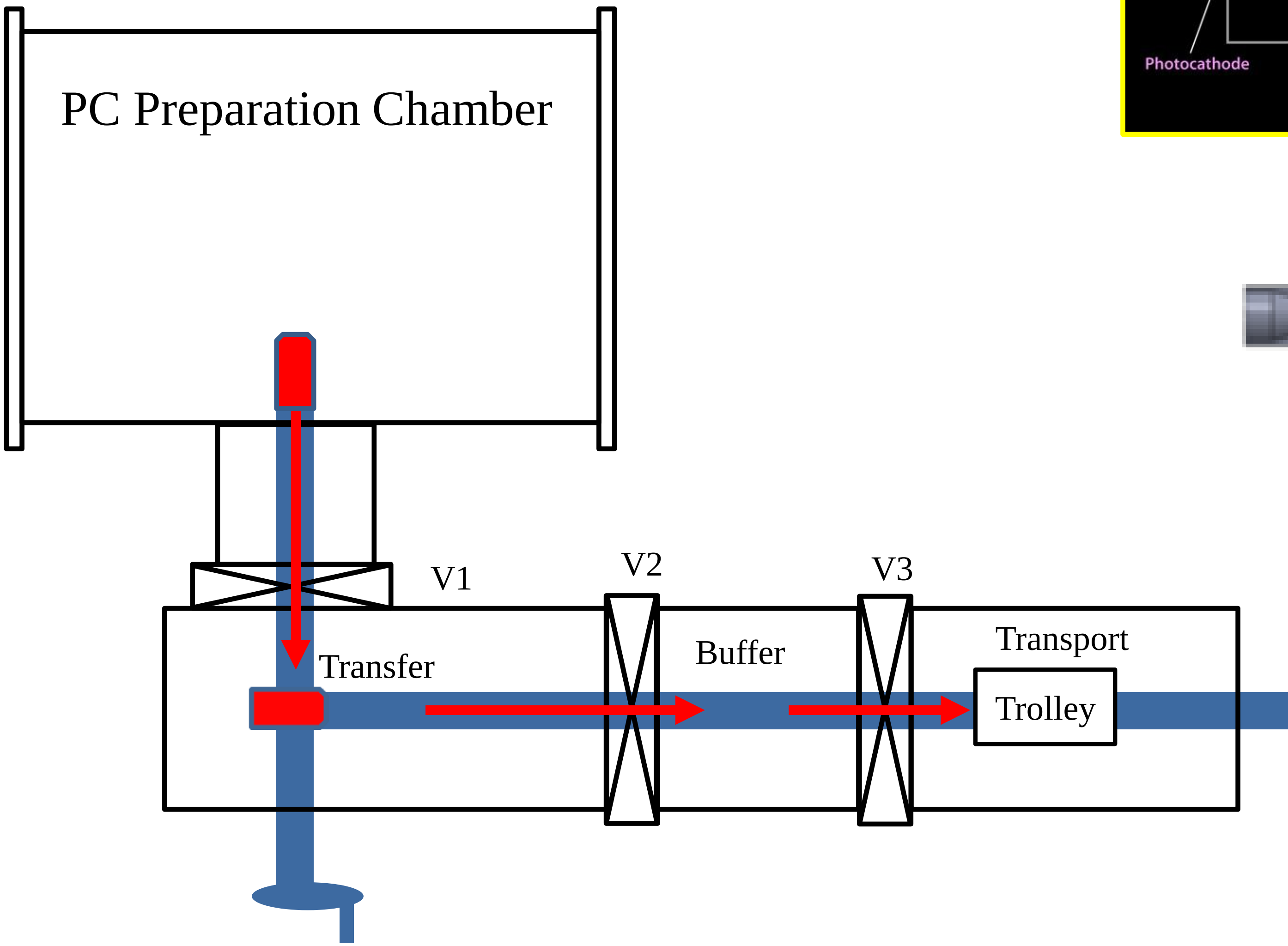
1. Pumping port (1 no.)
2. Vacuum gauge (1 no.)
3. Retractable Source (4 nos.)
4. Insertion for substrate.
5. PC transport after deposition
6. QE measurement (2 nos.)
7. Connections for heater (1 no.)
8. RGA (1 no.)
9. Thickness measurement
10. View Port (2 nos.)

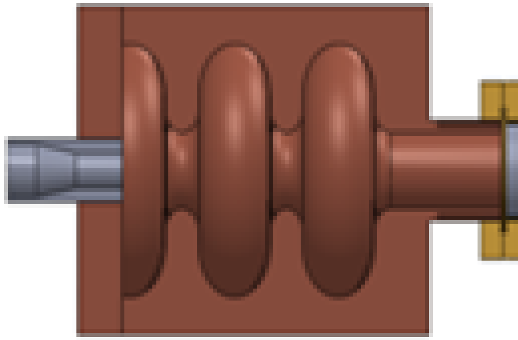


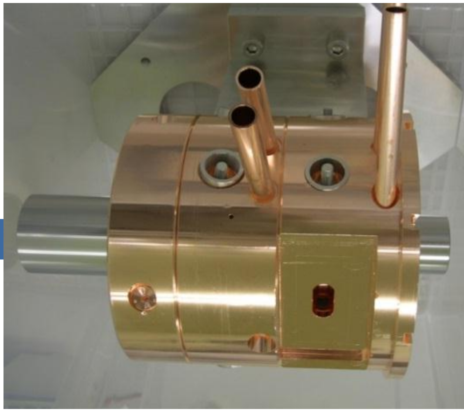
Picture Courtsey: Dr. Triveni Rao, BNL

PC insertion in to the cavity



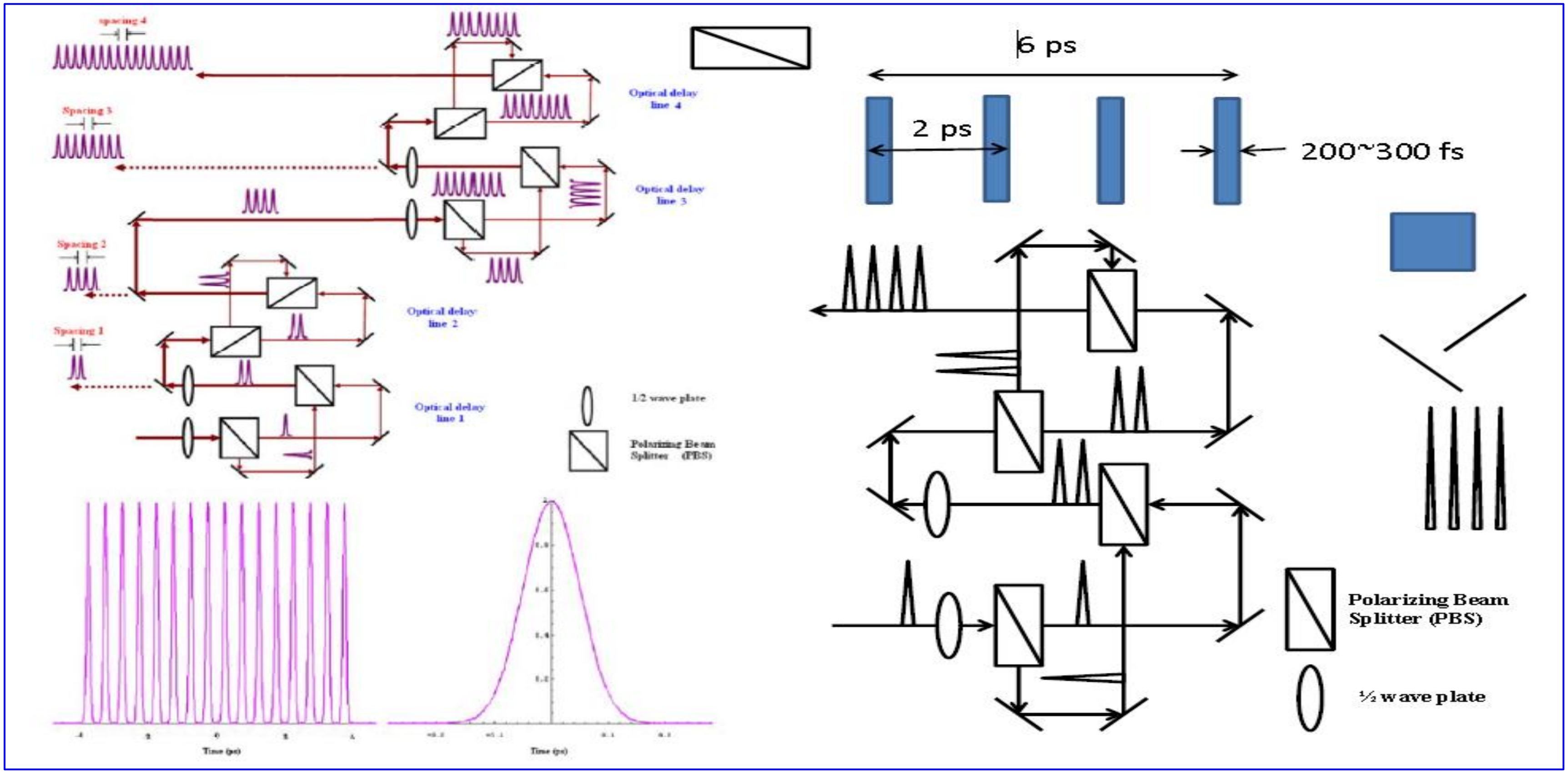






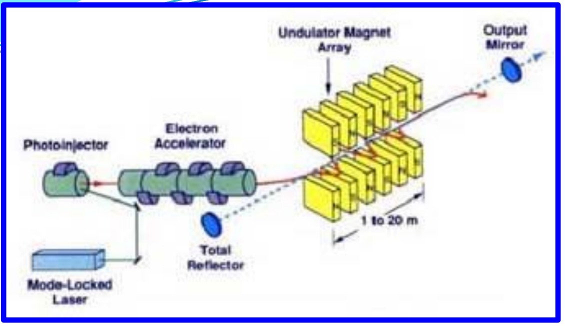
Phase-I: A pre-bunched FEL, microbunching before undulator

- This is different from the conventional FEL system. Pre-bunch the electron beam before undulator (@ PC – "comb beam".
- Single laser pulse will be split into 16
- The separation of the successive pulses will be varied from 3.33 ps (0.3 THz) to 800 fs (3.33 THz) to tune the FEL.

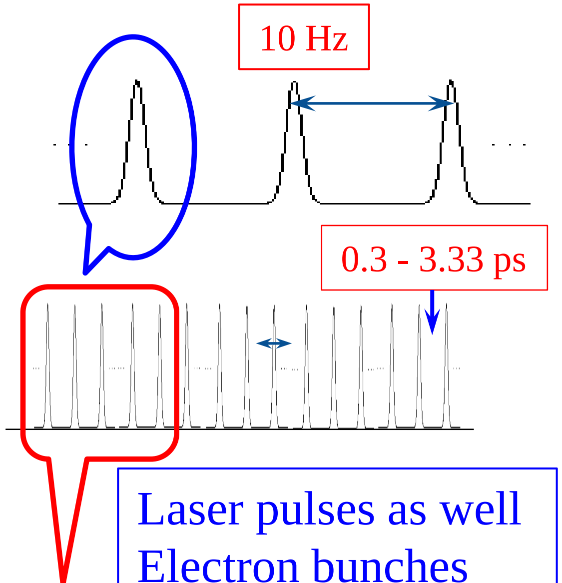


Courtesy: S. Liu & J.Urakawa, Proc. of FEL 2011, page-92

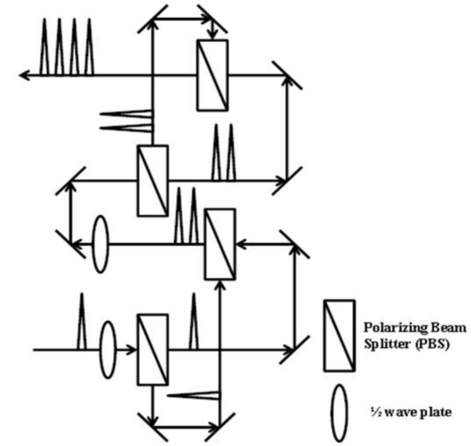
Phase-I: A pre-bunched FEL, microbunching before undulator



f = 1.25 – 0.3 THz
T = 0.8 ps to 3.3 ps
λ = 240 μm to 1 mm

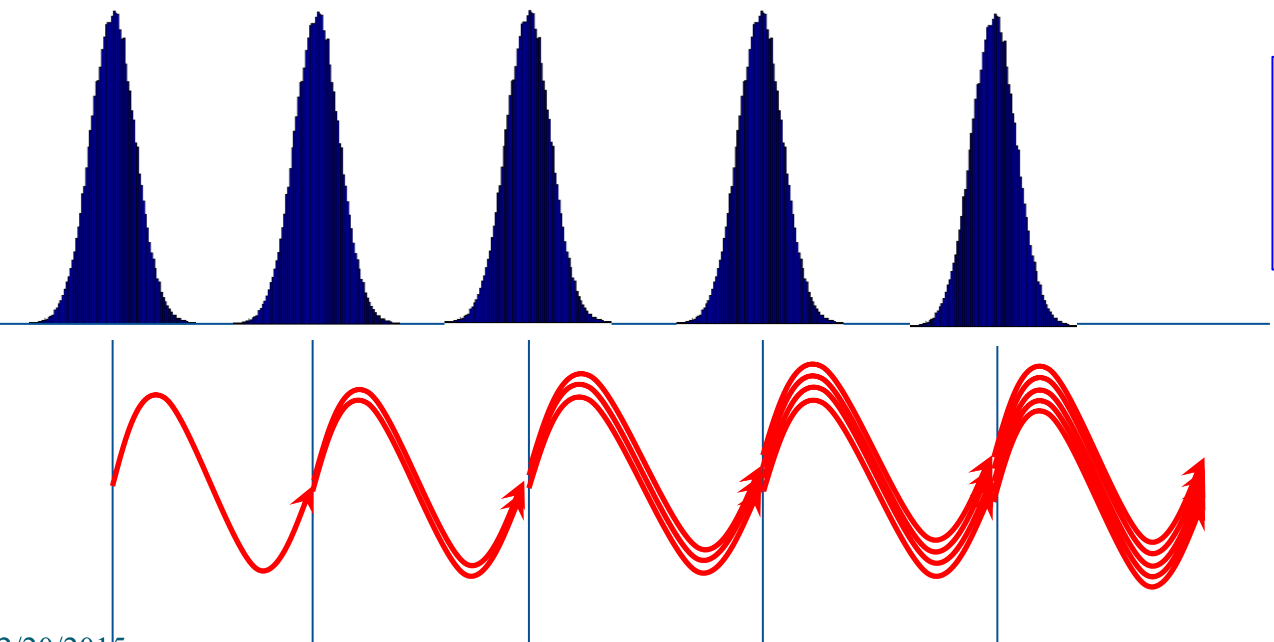


Laser pulses as well
Electron bunches



Pre-bunched beam with variable separation are injected in to the undulator

- **½ w plate rotates S-wave by 45º.**
- **Polarizing beam splitter makes S-wave & P-wave by reflection & transmission.**
- **Repeat 4 times with delay of about 333 fs.**
- **16 micro bunched laser within 5 psec.**



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

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

λ_U – Undulator wavelength
B_U – Undulator mag field

Laser – How to calculate required power to produce electrons

Example: Produce 12.5 pC e-charge / laser pulse @ 266 nm

- 12.5 pC/micro-pulse means = 8 x 10^7 electrons
- If QE = 0.5% (worst case), 10^7 electrons are produced by 10^{10} photons (UV)
- Total energy per micro-pulse ~ 12 nJ
- Single laser splitting into 16 pulses, so energy per macro-pulse ~ 200 nJ
    - With a safety factor of 5, energy per pulse = 1 μJ (UV)
- Conversion from IR (800 nm) to UV (266 nm) – power down-conversion is 5%
- **Minimum Laser power (800 nm) ~ 20 μJ/pulse**
- If the frequency of the rep rate is 10 Hz/10 KHz, power required @ 800 nm = 0.2 / 200 mW

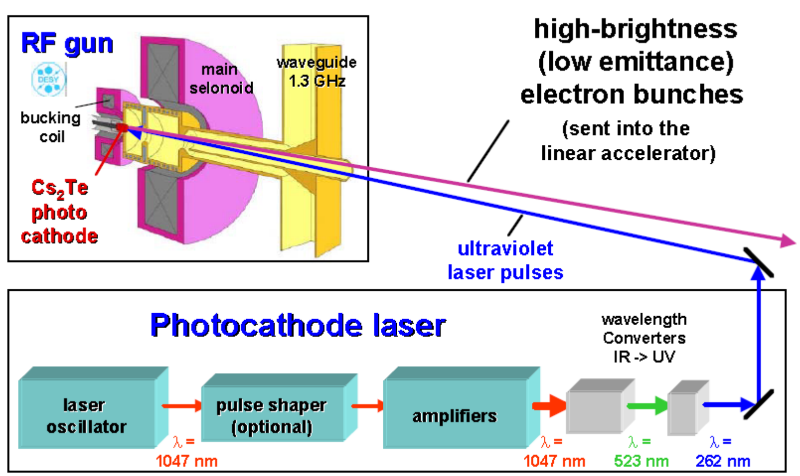
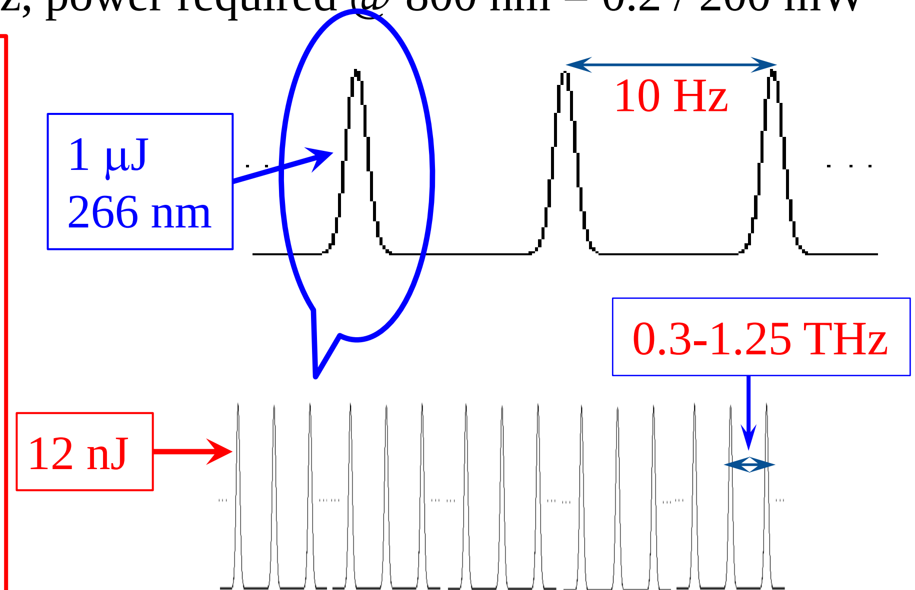
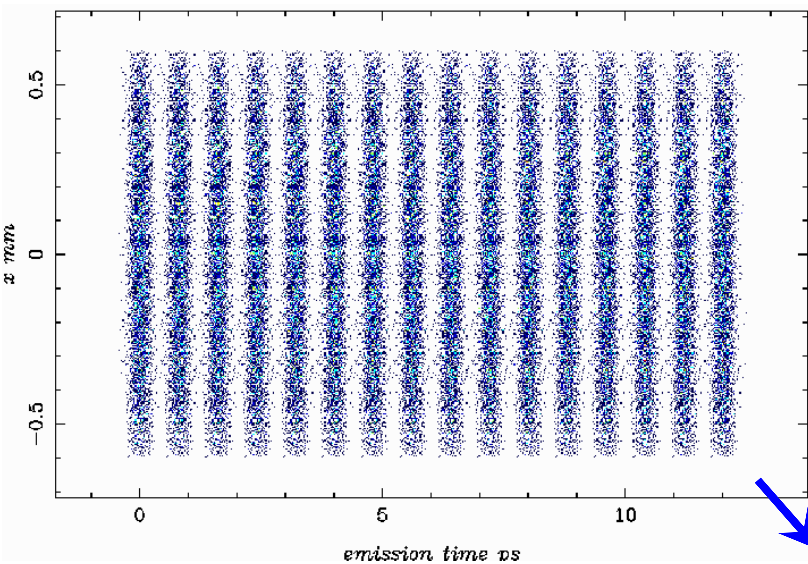


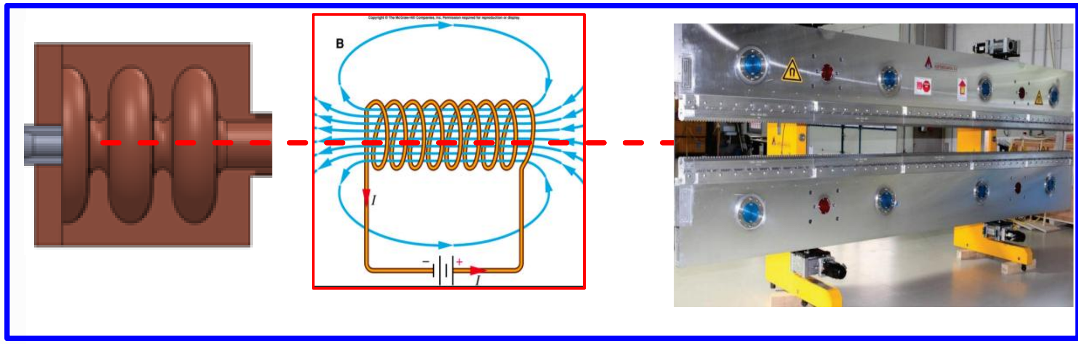
Figure 1: General setup of a photoinjector
(picture of the gun by courtesy of K. Floettmann, DESY Hamburg)

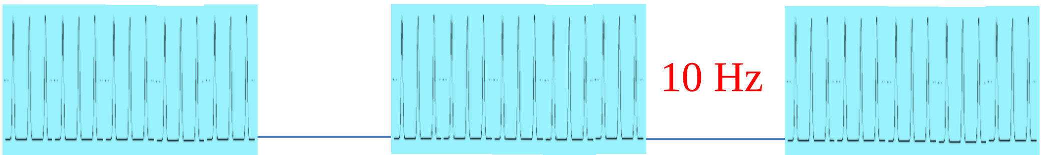


Quality of e-beam before producing THz - ASTRA calculation



At Photocathode location





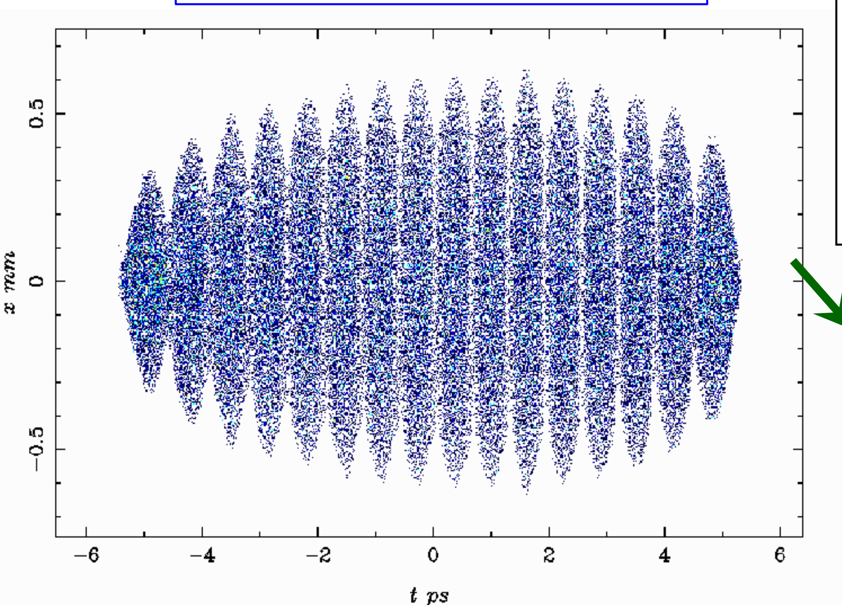
Input beam parameters:

Laser spot = 0.35mm, ε_x, ε_y = 0.27 π mm-mrad

No. of microbunch, macrobunch/sec = 16 & 10

Microbunch width ~ 300 fs, Separation ~ 800 fs

Charge per micro/macro bunch (pC) = 12.5 / 200



At Undulator entrance

Output Parameters: @ 2.0 m (Undulator)

E = 8.7 MeV, Accelerating Field = 120 MV/m

ΔE = 46 keV, Injection Phase = 26^{o}

σ_x, σ_y= 0.243 mm, ε_x, ε_y=0.49 π mm-mrad

Choice of laser system for Phase-I of DLS

Fibre Laser System:

Merits:

- Compact, Cheap, Easy to use
- High rep rate & high average power
- Better beam quality
- Futuristic

Demerits:

- Less Peak power & Energy/pulse
- Larger pulse width
- Subject still is evolving

Ti:Sa Laser System:

Merits:

- High peak power & Energy/pulse
- Smaller pulse width
- Matured technology

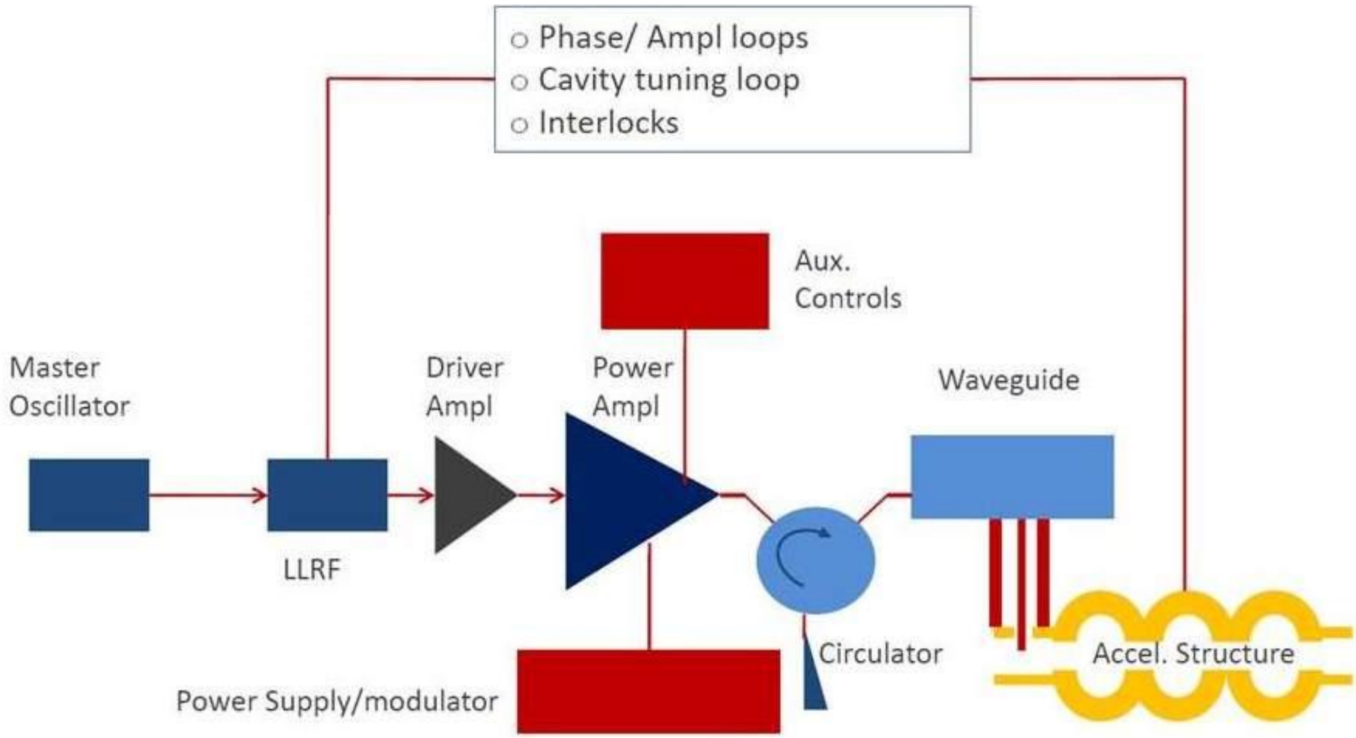
Demerits:

- Large, expensive, reasonably difficult
- Lower rep rate and lower average power
- Beam quality is worser than Fiber laser
- May be outdated in future

Possible plan for the laser system of DLS :

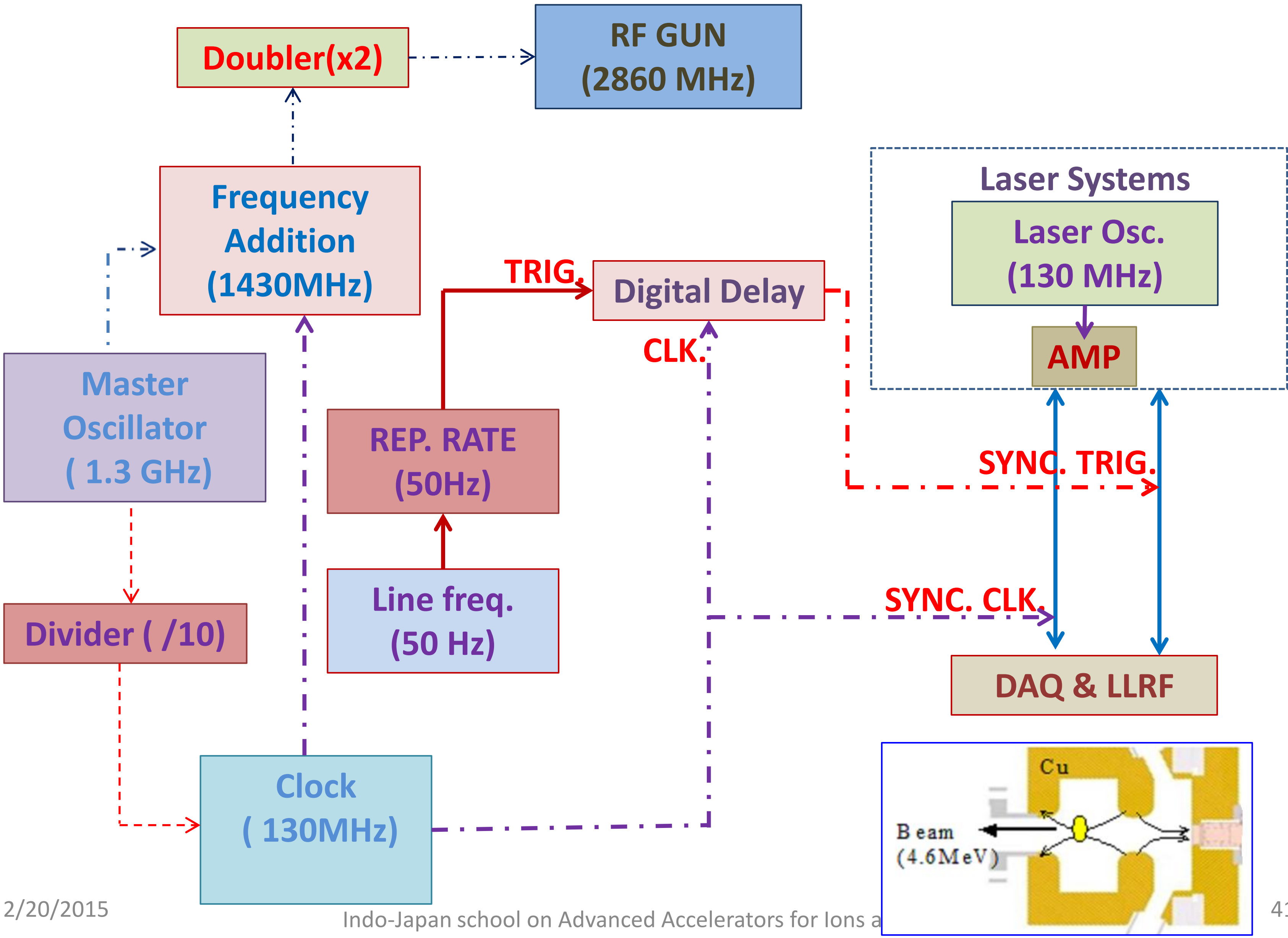
- First start with well proven Ti;Sa Laser system
- Start producing electron beam
- Then go for Fiber laser system

RF Requirements for Accel. Structures of FEL

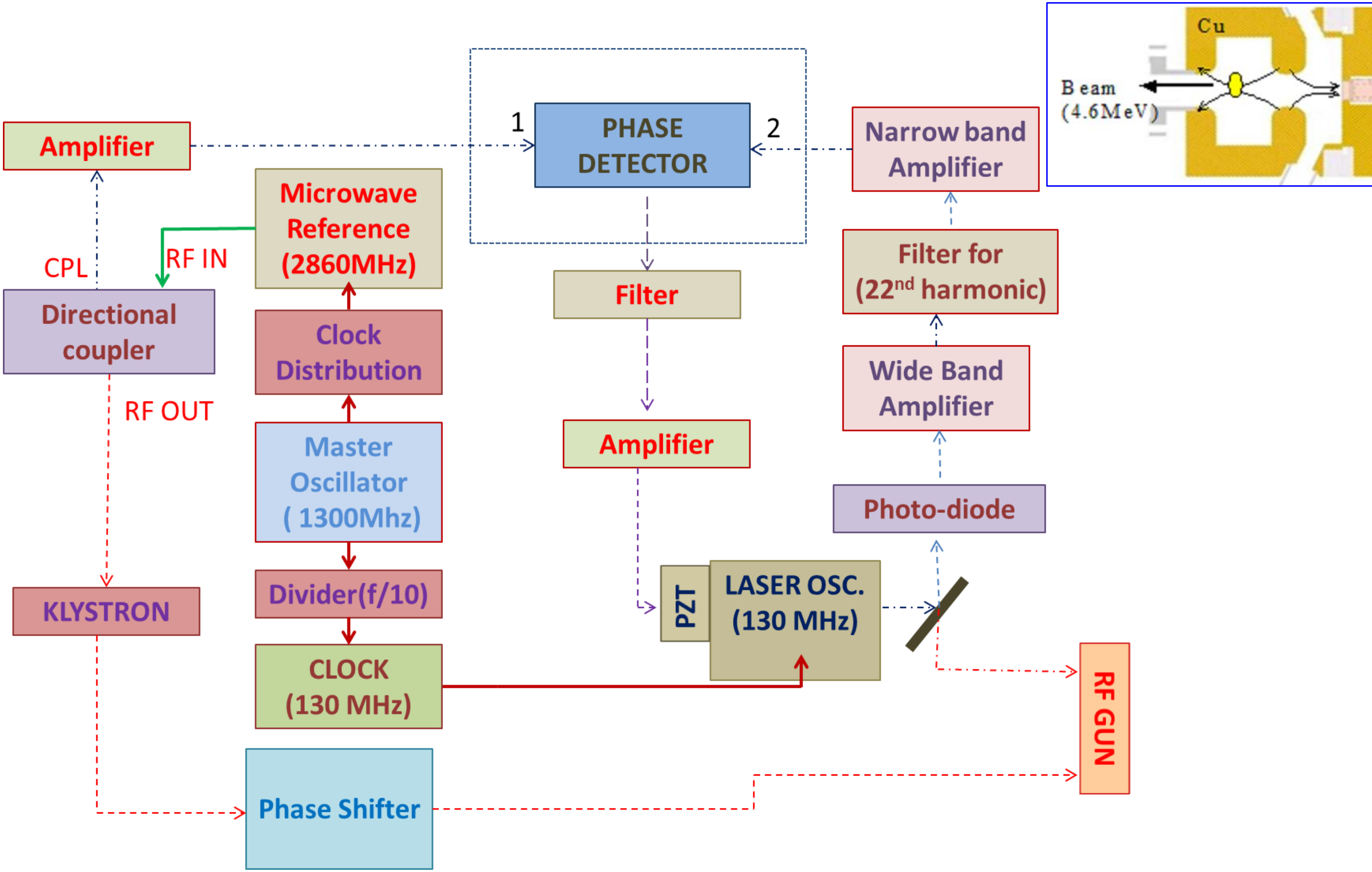


- **A Reference Clock distribution system (Master Oscillator)**
- **Low Level RF (LLRF) control modules for phase and amplitude stability**
- **High Power RF for generating field in Cavity**
- **Wave guides for RF power distribution**

Reference clock distribution system of FEL



Laser to RF Synchronisation in electron gun



Magnets for Delhi Light Source

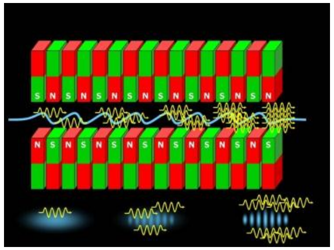
3. Undulator, solenoid, bending and quadrupole magnets

Undulator magnet:

- To be made from permanent magnet
- Arrangement to change the gap by μm
- Field homogeneity to be maintained

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

λ_U = Undulator period
γ = Electron relativistic factor = E/E_0
B_U = Magnetic field strength of undulator



Solenoid magnet:

- Electromagnet
- Field homogeneity to be maintained

Bending magnet:

- Electromagnet
- Field homogeneity to be maintained

Quadrupole magnet:

- Electromagnet
- Field homogeneity to be maintained

Tentative undulator parameters for THz and IR

Undulator	Wavelength of radiation λ_R	Beam Energy (MeV)	Wavelength of Undulator λ_U (m)	K-para	B_u from K-para (T)	Gap length (m)	B_u from gap length (T)
U1	1 mm	7	0.048	2.61	0.583	0.020	0.582
(Ph - I/II)	200 μm	7	0.048	0.75	0.168	0.039	0.164
U2	200 μm	15	0.048	2.49	0.555	0.021	0.538
(Ph – III)	50 μm	15	0.048	0.89	0.199	0.035	0.205
U3	50 μm	16	0.040	1.204	0.322	0.023	0.33
(Ph – III)	4 μm	40	0.040	0.474	0.127	0.037	0.125

Structure: Planer with PM

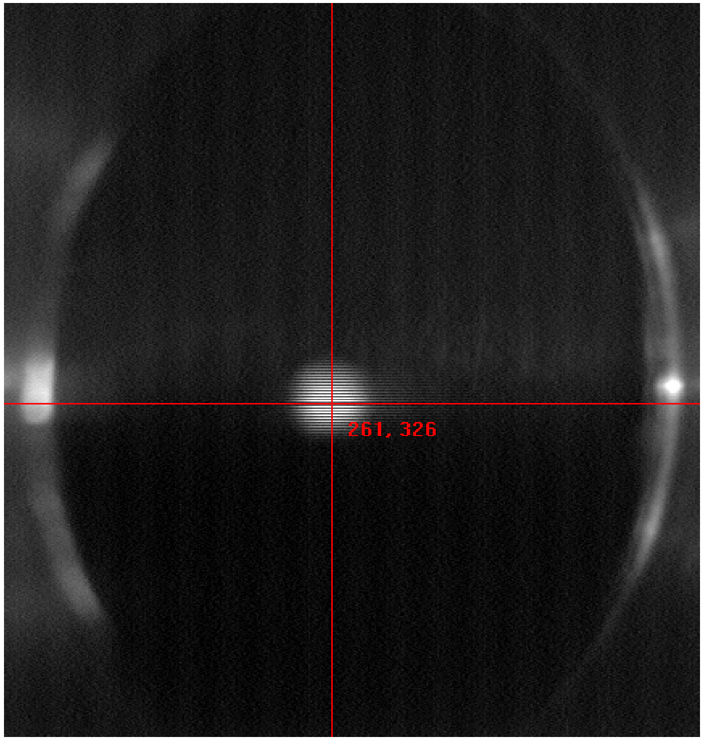
$$\lambda_R = \frac{\lambda_u}{2\gamma^2}[1 + K^2]$$

$$\gamma = \frac{E}{E_0}, \quad K = \frac{e \times Bu \times \lambda_u}{2\pi mc}$$

$$B_u = 3.694 \exp[-5.068 \frac{g}{\lambda_u} + 1.52 (\frac{g}{\lambda_u})^2]$$

For hybrid undulator made from NdFeB magnet with $0.1 < \frac{g}{\lambda_u} < 1.0$

Beam diagnostic



40 MeV x 1 mA = 40 kW

→ ***prevent damage***

Importance of Diagnostic

- Ensure good beam quality
- Measure E, Emittance, Current, Profile
- Trouble shoot in case of problem

Beam diagnostic

Diagnosis of the beam	Equipment
size/shape	Viewscreen with Camera
position	viewscreen, BPM
current	cathode current, BPM, ICT, dump current
energy	NMR, viewscreen, BPM
energy spread	viewscreen
bunch length	EOS, interferometer, etc.
bunch arrival time	BAM
beam loss	BLM

Tentative parameters for the THz facility at IUAC

Beam Parameters:

Electron Energy (MeV)	7
Charge in macro/micro Pulse (pC)	200/12.5
Time width of micro-bunch (fs)	300
Micro-bunches separation (fs)	800
Freq. of micro-bunch trains (Hz)	10
Peak current (Amp) [1]	42
Peak beam power (MW) [2]	294
Average beam current (nA) [3]	2
Average beam power (m-watts) [4]	14

Radiation & Undulator Parameters:

Radiation wavelength(μm), 1.25 THz	240
K-parameter	0.75
Undulator period (mm), λ_u [5]	48
RMS strength (Tesla), B_u [6]	0.17
No. of periods (N) ~ 1m undulator	20
Peak radiation power (MW) [7]	2.9
Average radiation power (mW) [8]	~ 1
Peak no. of photons [9] / 300 fs	10^{27}
Average no. of photons / sec [10]	10^{16}

[1] $\frac{12.5\ pC}{300\times10^{-15}} = 42\ A$

[2] 42A x 7 MV = 294 MW

[3] 12.5pC x 16 x 10 Hz = 2 nA

[4] 2 nA x 7 MV = 14 mWatts

[5] $200 \times 10\text{-}6 = \frac{\lambda_u}{2\gamma^2}[1 + K^2] \Rightarrow \lambda_u \approx 48\ mm$

[6] $0.75 = \frac{e\times Bu\times\lambda_u}{2\times\pi\times m\times c} \Rightarrow B_u = 0.168$ T

[7] $P_{out} \approx \frac{1}{5N}\times P_{beam} = \frac{1}{100}\times 294\times10^6$

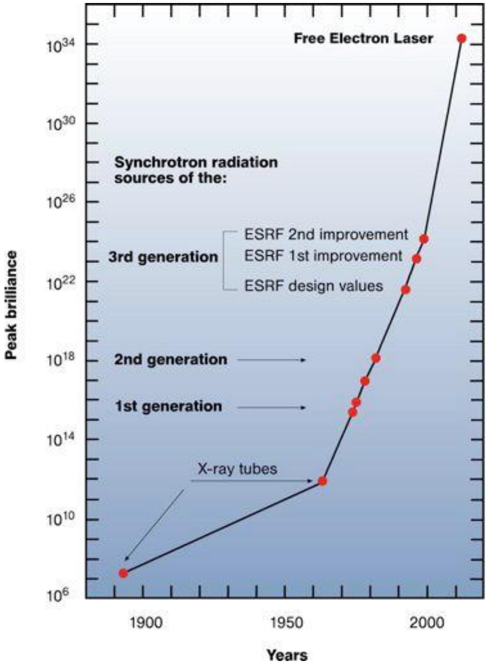
[8] $P_{out} \approx \frac{1}{5N}\times Pbeam = \frac{1}{100}\times 14 = 0.014\ mW$

[9] $\frac{2.94\times10^6}{h\nu} = 2.2\times10^{27}$

[10] $\frac{0.014\times10^{-3}}{h\nu} = 1.0\times10^{16}$

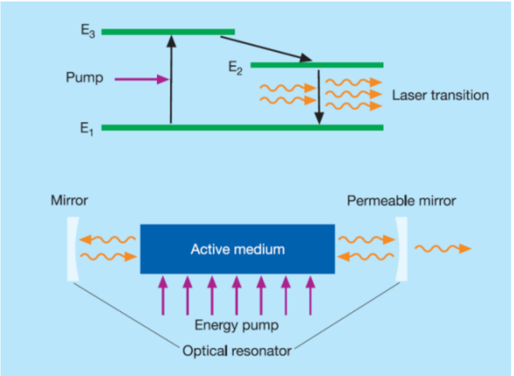
Challenges of Free Electron Laser

Different light sources available today



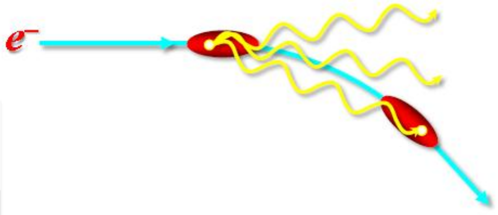
Conventional laser

- Peak intensity can be extremely high, however not tunable,
- Non availability of hard X-ray laser (> ~5 keV or so)



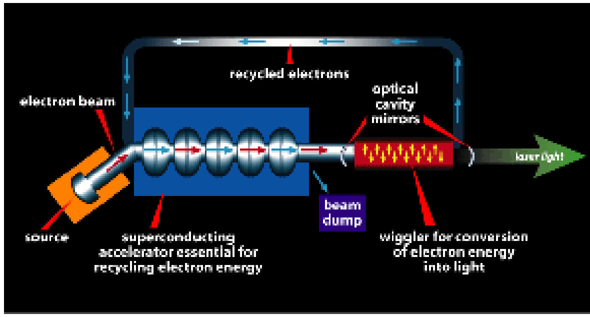
Synchrotron

- Produces incoherent radiation, so peak intensity is low
  No. of photons per pulse is less,
  Photon flux (ESRF) = 10^{13} photons /sec/0.1%BW



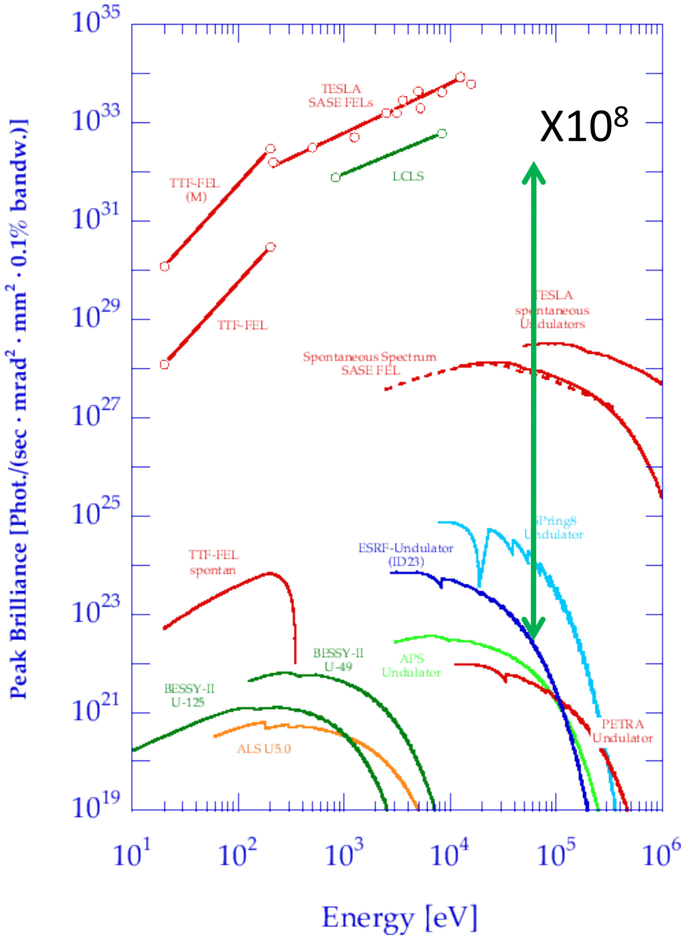
Free Electron Laser

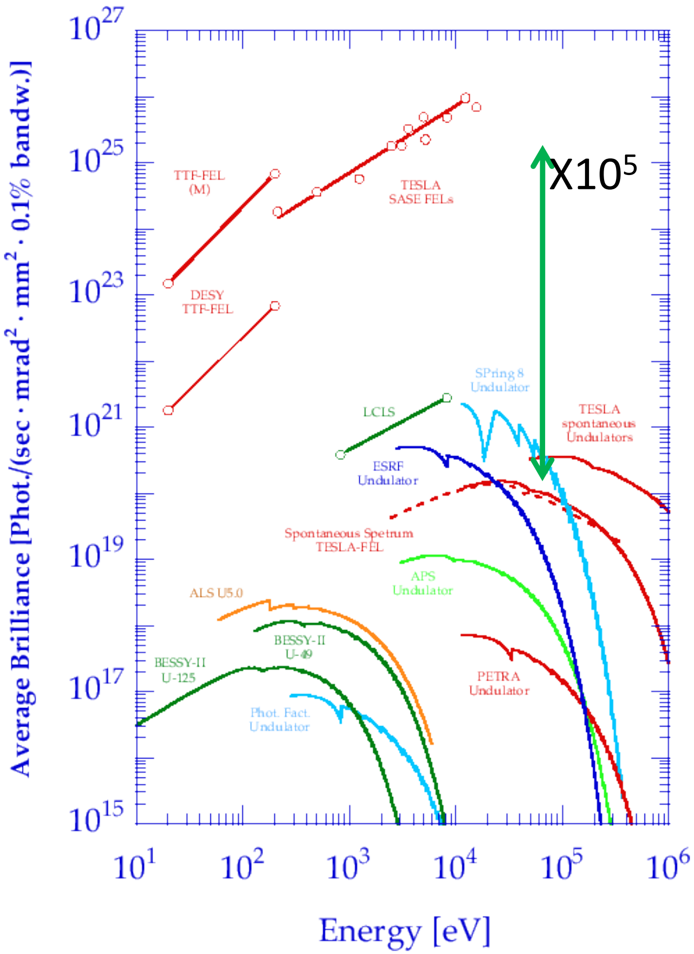
- Produces coherent radiation, so peak intensity is high
  No. of photons per pulse is more than SR
  Photon flux (XFEL) = 10^{19} photons/sec/0.1%BW
- Tunable (1 mm-1^0A), produce very narrow width radiation



Challenges of Free Electron Laser

Brilliance Comparison between spontaneous and coherent emission



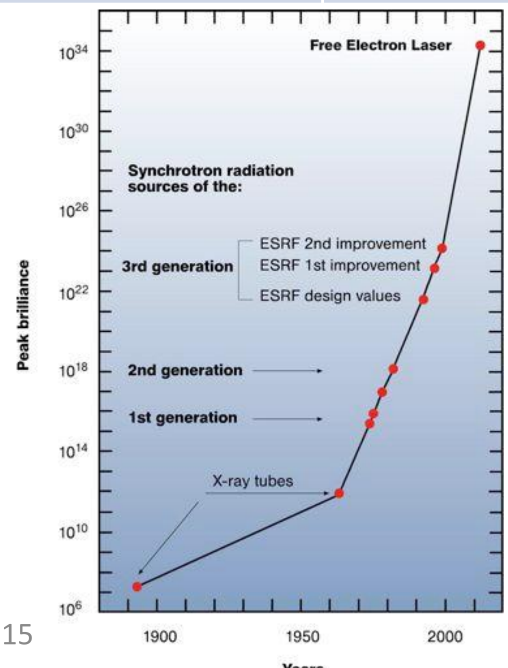


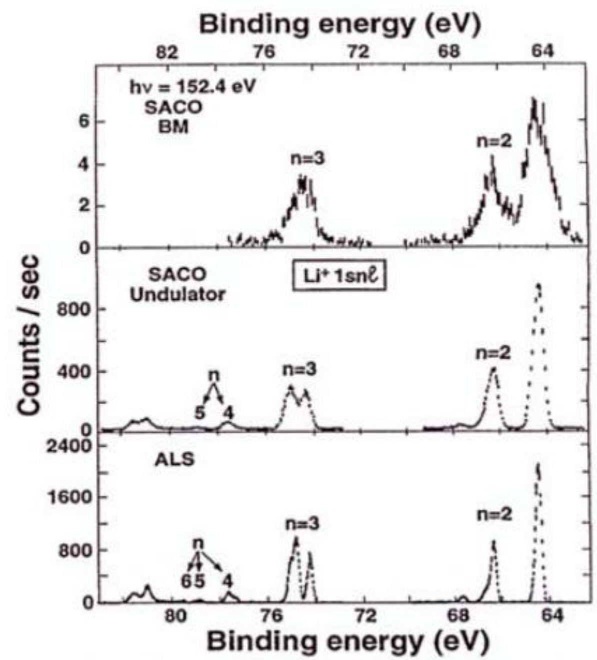
Brilliance depends on:

- No of photons produced/sec
- Ang. Div. of photons, how fast beam spreads out
- The cross-sectional area of the beam
- The photons falling within a bandwidth of 0.1% of the central wavelength or frequency

Challenges of Free Electron Laser

Parameters	Synchrotron Radiation	FEL – Radiation	Advantage of 4th Generation Light Sources
Wavelength	X-rays	THz – X-rays	Wide freq spec., Tunable
Brilliance (Peak)	~ 10^{25} (max)	~ 10^{34} (max)	Enhanced count rate Expt. w low cross-sec
Brilliance (average)	~ 10^{21} (max)	~ 10^{26} (max)	Same as above
Pulse Width	Tens to Hundreds of ps	Tens to hundreds of fs	Snapshot of an atom, fast dynamic process
Line-width, ΔE/E	≤ 10^{-3}, best case	10^{-3} to 10^{-4}	Focussed Expt, cohernt image





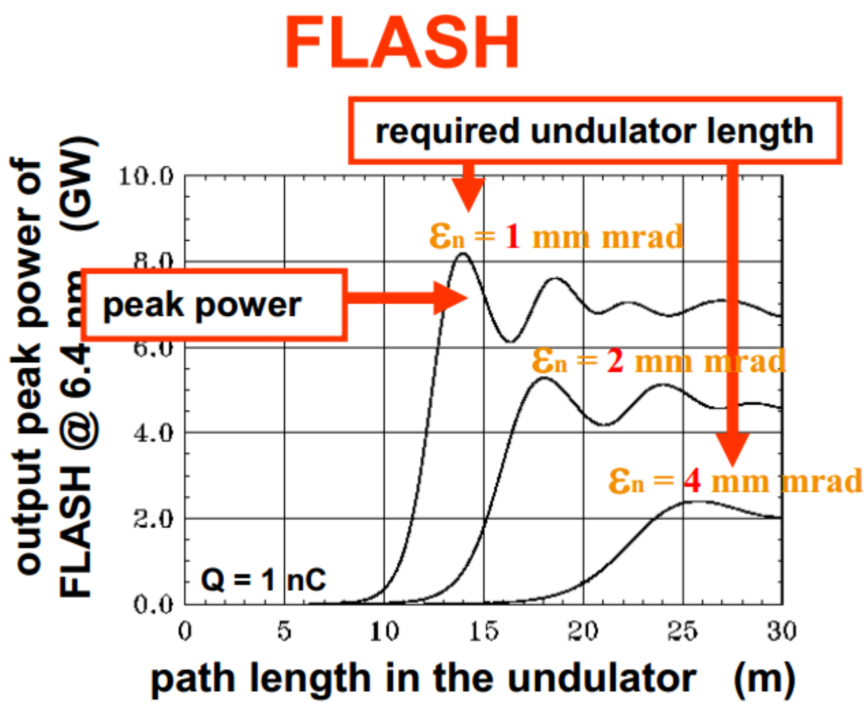
Excitation of hollow atom states of Li atom

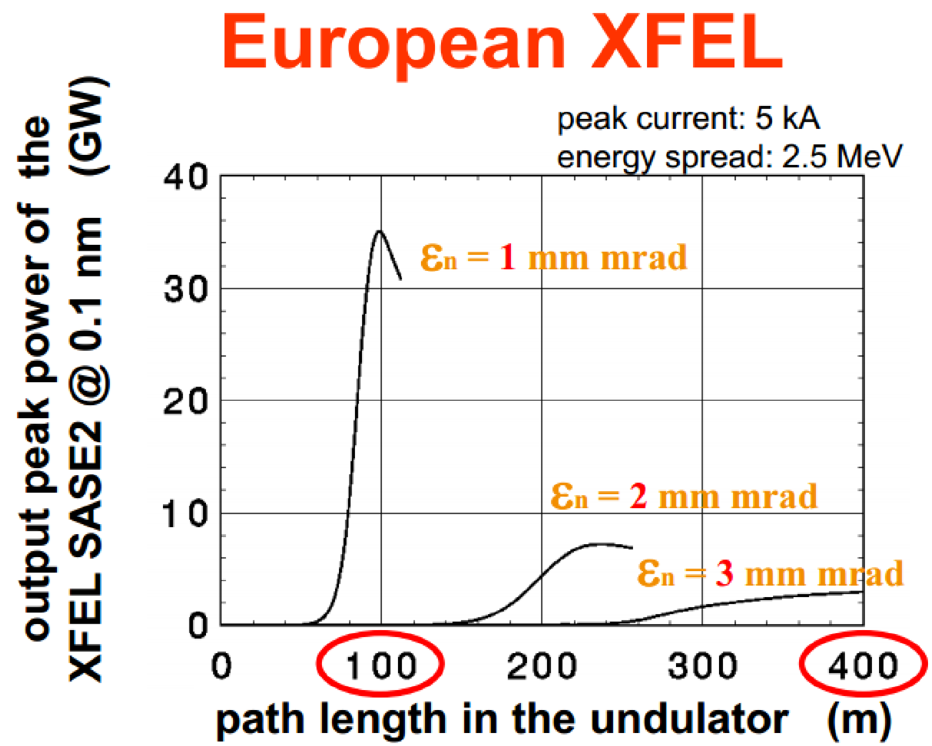
Challenges of Free Electron Laser

Advantage – FEL	Challenges
Peak/Average Power very high	• Ideally $I \propto N^2$, electron no. must be very high • High Power Laser – Expensive, delicate, chance of damage • Coherence to be preserved – less E-spread, Excellent beam optics design, Skilled beam tuning • Beam emittance should be extremely small
Short Pulsewidth (fs)	• High power density of laser – thermal lensing, non-linear effect, device damage • Electrons will be packed in a tiny packet –space charge effect, emmitance growth - reduction of radiation power, increase of undulator length
Source of tuneable wavelength	• THz to X-rays, large accelerator facility and beam line • Demand of huge skilled manpower • Very expensive, difficult for a single laboratory

An Important challenge – emittance control

1. Emittance should be very small
2. Energy spread should be below 0.1%





Example: XFEL goal: Slice Emittance (1 nC): 1.0 mm mrad@undulator

An Important challenge for an efficient FEL – control of transverse emittance

Transverse emittance: Main reasons to increase in PC RF gun

Tranv. Emitt. – product of beam size and beam divergence, $Brightness, B = \frac{1}{8\pi^2}\frac{I}{\varepsilon_x \varepsilon_y}$

$$\varepsilon_{total} = \varepsilon_{th} + \varepsilon_{RF} + \varepsilon_{sc}$$

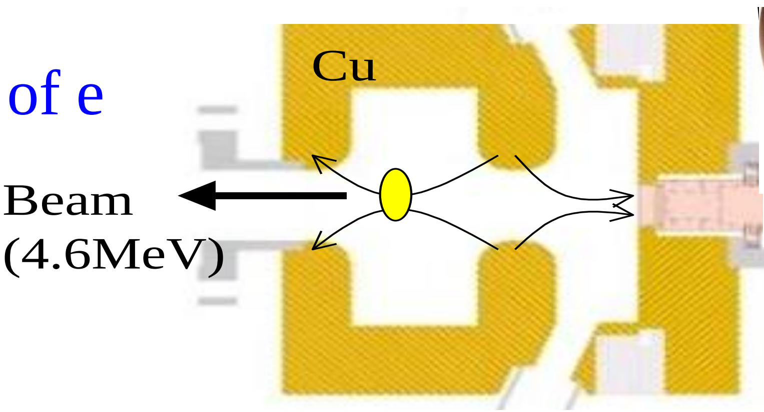
ε_{th} = Thermal emittance

$\propto \sigma_{x,y} * \sqrt{E_k}$,

$\sigma_{x,y}$: rms of laser spot @ PC, E_K : KE of e

ε_{RF} = Due to RF,

$\propto \sigma_{x,y} * \sigma_z$, σ_z : electron bunch length

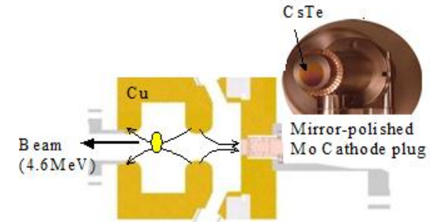


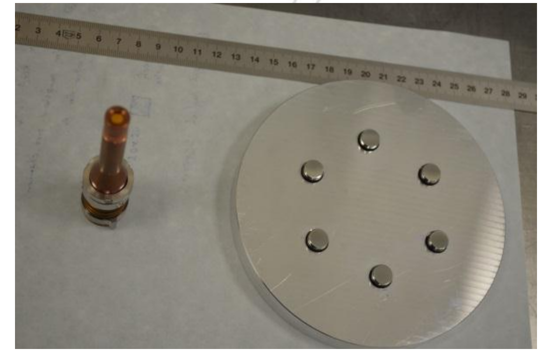
ε_{SC} = Space charge dependent,

$\propto$ electron's energy, q/e-bunch, time structure, laser pulse shape

Details of Photocathode

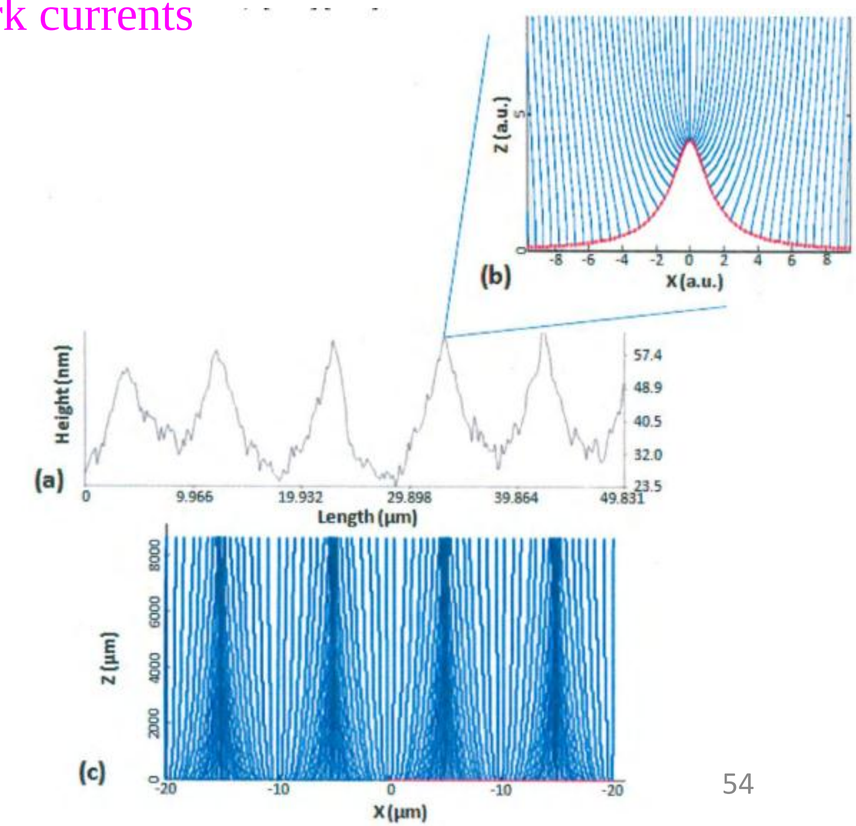
Fabrication of photocathode – Cs_2Te, thin film deposition





Substrate:

- Good thermal and electrical conductor, SS, Mo, doped Si
- Inertness of the substrate to avoid diffusion, Cu – bad choice
- Surface roughness causes – increase in intrinsic emittance
  increase in emittance – e-field
  enhanced e-emis., Dark currents
- Preparation (no contamination)
  - BCP
  - Polished w diamond polishing compd.
  - US rinse – acetone, ethanol
  - Bake @500C for 30 min before cath. fab.
    to evaporate O-species – H_2O, CO_2, CO



Vacuum chamber requirement:

- UHV chamber – 10^{-10} mbar
- Bakeable to ≥ 200C, water vapour
- Chamber design includes the interface system for transporting the cathode

Conclusion

- FEL – fourth generation light source, superior than Synch. source

  Tunable (THz-X-rays), high peak/av. power, short pulse-width
- DLS is to develop a compact light source based on FEL at IUAC
- Phase-I: 7 MeV e-beam, Production of THz by NC Cu based PI (IUAC and BRNS funded),
- THz production from Phase-I : by 2017 – Collaboration with KEK
- Phase-II: 7-10 MeV e-beam, Production of THz by SC Nb based PI
- Phase-III: 40 MeV e-beam, Production of IR by SC Nb resonator &

  Production of X-rays by ICS


Thank you for your
kind attention

An Important challenge for an efficient FEL – control of transverse emittance

Transverse emittance: Main reasons to increase in PC RF gun

$$\varepsilon_{total} = \varepsilon_{th} + \varepsilon_{RF} + \varepsilon_{sc}$$

Reduce

$\varepsilon_{th} \propto \sigma_{x,y} * \sqrt{E_k}$

- Reduce Laser spot size, less x/y
- Reduce K.E. of the emitted electrons

No. of photons will reduce,

can be avoided by increasing lux density – problem of thermal Lensing, non-linear effect, device damage,

A optimization is to be made

Electron when emitted from PC surf.

Emerges in a cone with an angle θ

$$\cos\theta = \sqrt{\left(\frac{E_T}{E - Ef}\right)}$$

E_T = Energy required to escape

E_f = Fermi energy level

E = Energy of the electron just escaped

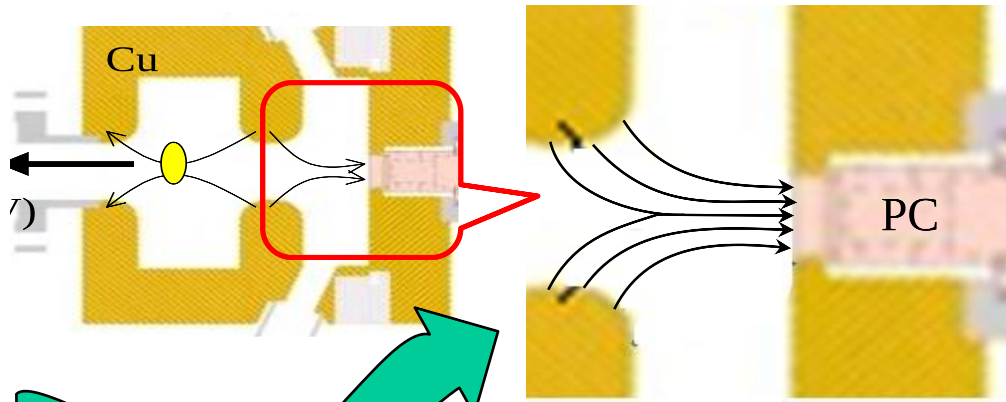
An Important challenge for an efficient FEL – control of transverse emittance

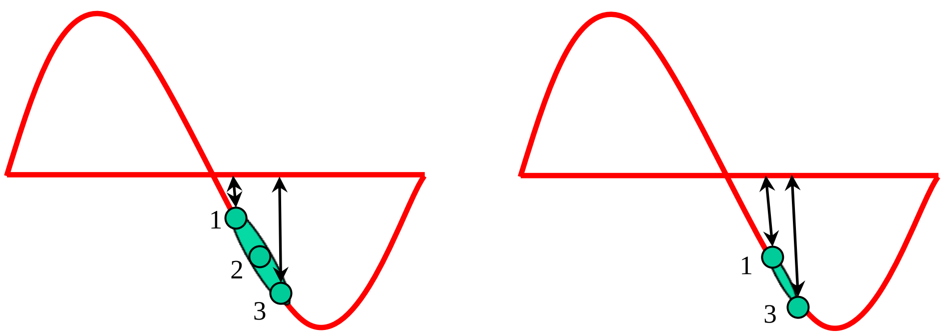
Transverse emittance: Main reasons to increase in PC RF gun

$$\varepsilon_{total} = \varepsilon_{th} + \varepsilon_{RF} + \varepsilon_{sc}$$

Reduce

- Reduce Laser spot size
- Reduce accelerating fields
- Reduce electron bunch length





An Important challenge for an efficient FEL – control of transverse emittance

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$$\varepsilon_{total} = \varepsilon_{th} + \varepsilon_{RF} + \varepsilon_{sc}$$

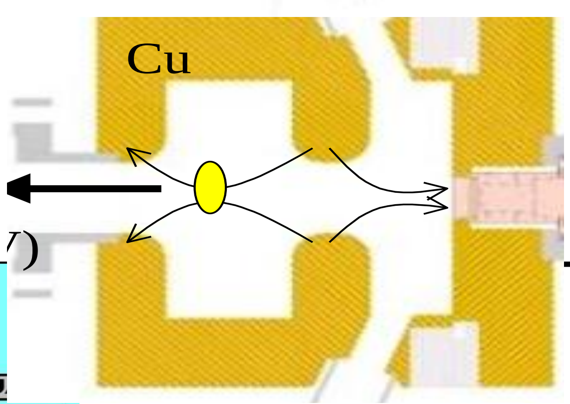
Reduce

- Reduce Laser spot size
- Reduce accelerating fields
- Reduce electron bunch length

No. of photons will reduce,
can be avoided by increasing lux density – problem of thermal Lensing, non-linear effect, device damage, Optimization is to be made

Not desired, make a compromise
less E_{gain}, electron takes longer to be relativistic, more SC effect

Powerful laser (ps or fs) with high power density,
Expensive, Thermal lensing, Stringent operating condition, High damage probability etc.



An Important challenge for an efficient FEL – control of transverse emittance

Transverse emittance: Main reasons to increase in PC RF gun

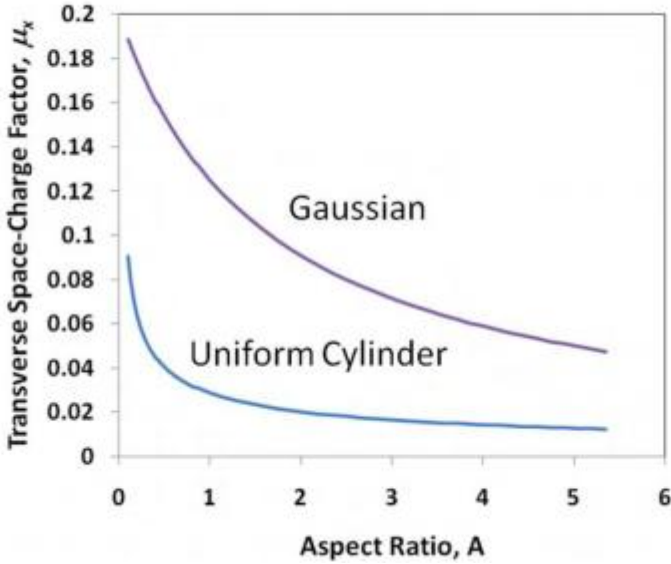
$$\varepsilon_{total} = \varepsilon_{th} + \varepsilon_{RF} + \varepsilon_{sc}$$

Higher Ea, less electrons per bunch reduce ε_{SC}

Reduce

Space charge emitt. depends on Bunch shape e.g.

- Overall radial expansion of the bunch– non-relativistic
- Transverse to longitudinal aspect ratio
  for Gaussian distri. (σ_x / σ_z), rotational symm. system
- Transverse to longitudinal aspect ratio
  for Cylindrical distri. (a/L), radius-a, length-L
- Functional form of charge distribution –
  Gaussian or Cylindrical or 3D ellipsoidal etc.

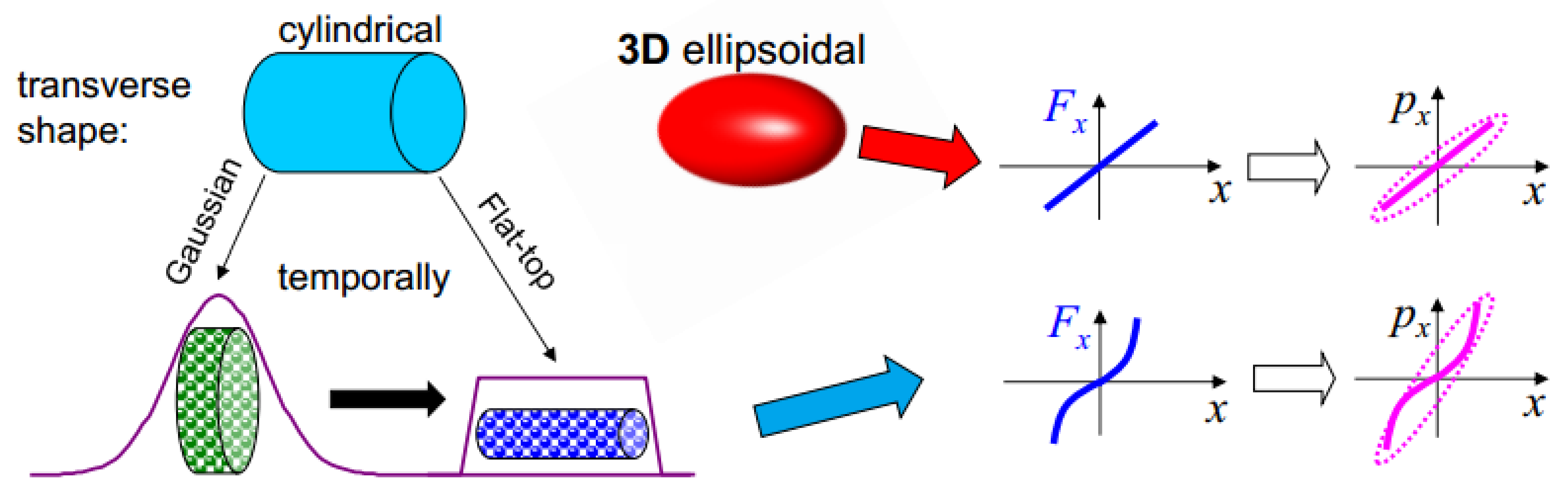


An Important challenge – emittance control

Photocathode Laser pulse shaping (in time and space) ------

Toward 3D ellipsoid

- Reduce requirement of cathode gradient, lot of additional flexibility
- Minimize the impact of the space charge on the transverse emittance

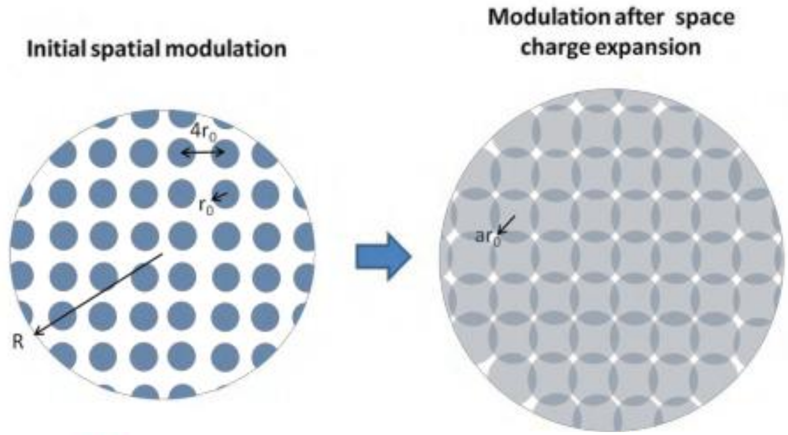


- 30-50% lower av. slice emittance
- Better long. compression, reduced beam halo, less sensitivity to machine setting
- German-Russian collaboration – Installation at PITZ, DESY – Autumn 2014

An Important challenge for an efficient FEL – control of transverse emittance

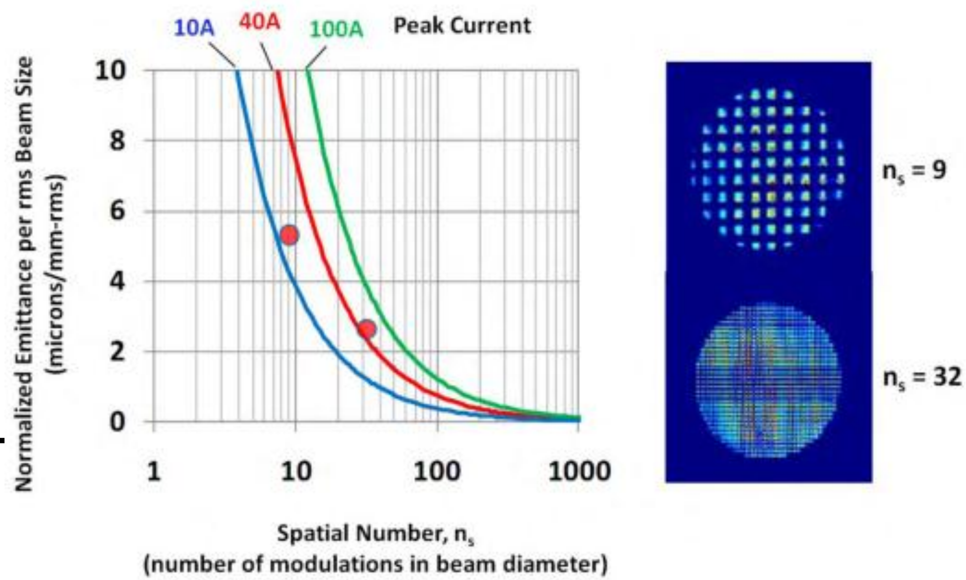
Transverse emittance: Main reasons to increase in PC RF gun

$$\varepsilon_{total} = \varepsilon_{th} + \varepsilon_{RF} + \varepsilon_{sc}$$



SC emit. depends – uniformity of transv. emision

- Decreases when the distribution is uniform when no. of beamlets are more
- Shorter expansion distance over which the beamlets can expand, undergoing transverse acceleration,
- So smaller final transverse velo, smaller the emittance



Different types of RF e-gun used in FEL worldwide

RF Gun

NC

High Grad

Merits

- Higher beam energy
- Less space charge
- Reduced beam emitt
- Strong solenoid can be put in the vicinity
- Extract higher q for fixed beam dimension

Demerits

- Cath roughness, dark current
- Reliability, heat load
- Large ε_{RF} for long bunches
- Large energy spread
- Low average power

SC

Merits

- CW or quasi-cw opn
- High average Power
- Less ε_{RF} & less energy spread
- Futuristic, performance will improve

Demerits

- Difficult, NC PC in SC environment
- Beam energy low
- Enhanced space charge effect, emitt
- Solenoid far off

Low frequency(100-500 MHz)

- Cryo operation at 4.2 K
- Small accelg gap w.r.t. λ_{RF} elec field is practically dc
  ($T_{130} \sim 7.69$ns, $T_{1300} \sim 0.769$ns)
- Less RF current on cathode
- Much less MP

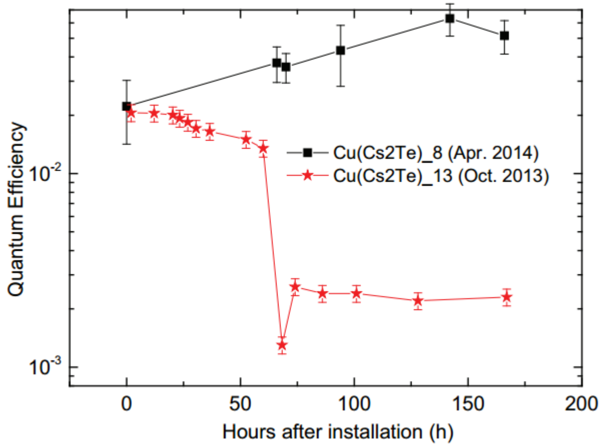
High freq (1300 MHz)

- Matured technology
- Routine operation
- Fab of 9 cell cavity will be easier

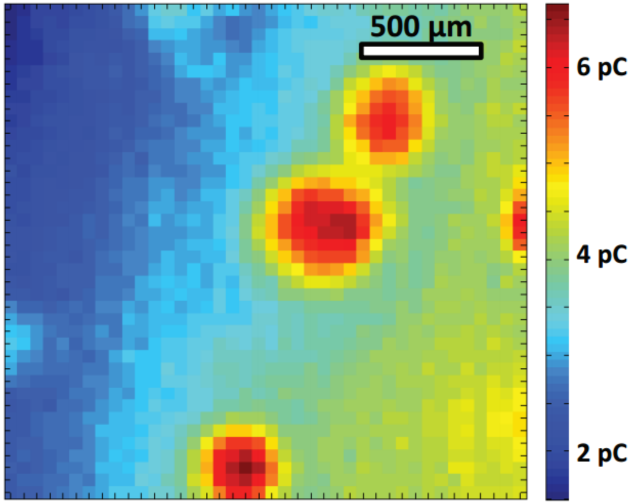
Recent results on Photocathode

SwissFEL – PSI Swiss FEL status, FEL-2014

Deposition process – identical to CERN recipe, 15 nm Te, 25 nm Cs evaporated on Cu
Cu substrate undergone the same process od annealing/cleaning like the copper PC
Aperture mask – deposition area ~ 1 cm diameter. PC transferred from eva chamber to the gun
Load lock via a vac suitcase
Initial pressure inside the evaporation chamber is ~ 3 x 10^{-10} mb
During evaporation deteriorates to ~ 1 x 10^{-8}mb
Base pressure in the gun with RF ON ~ 1 x 10^{-9} mb



Perfromance of Cs2Te PC
Improved vacuum during dep for better PC
(262 nm, 200 pC, $\sigma_{t,laser}$ = 4 ps, 10 Hz)



Nonuniformities of Cs_2Te PC
QE map Cu(Cs2Te)_13 measured in the gun
By scanning small laser spots with const. E.
Non-uniformities are not good and might be related to deposition procedure

Recent results on Photocathode

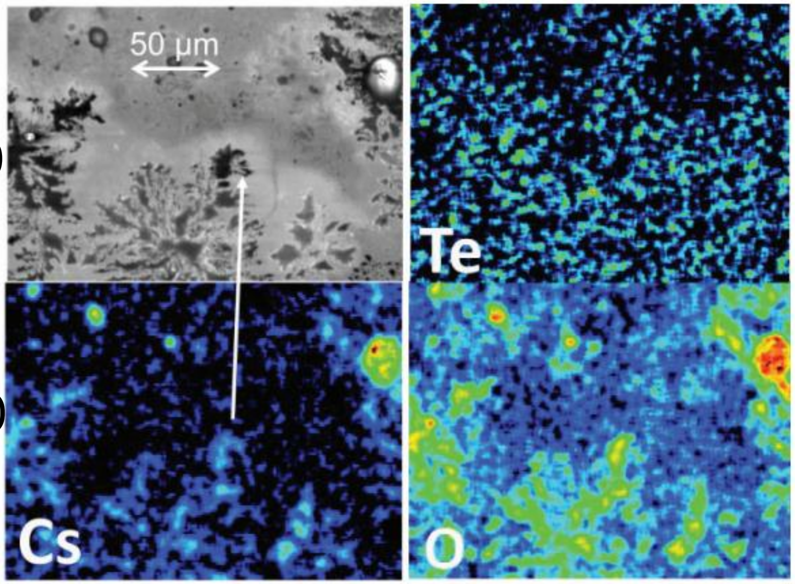
SwissFEL – PSI

Swiss FEL status, FEL-2014

Energy dispersive X-ray spectroscopy

Cu(Cs2Te)_13

(a) (b) (c) (d)

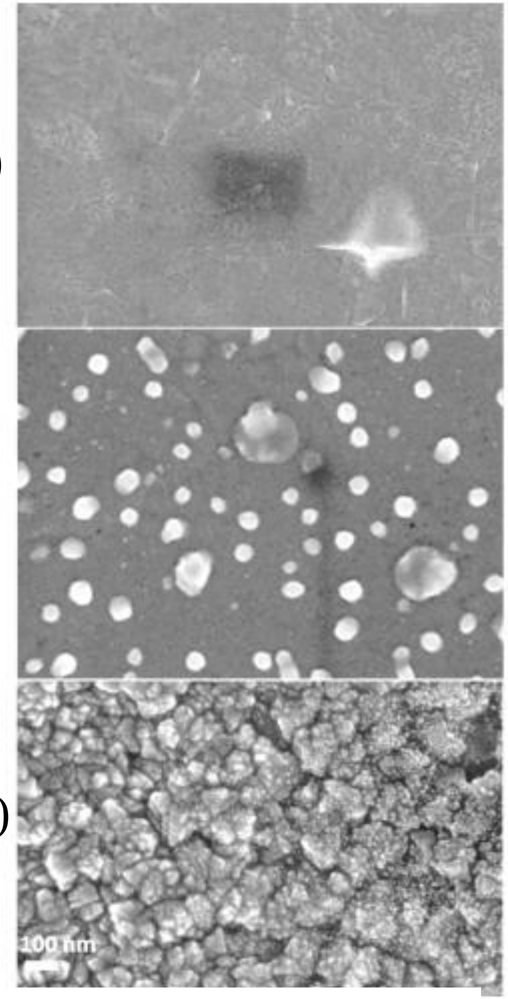


EDX analysis of Cu(Cs2Te)_13 cathode showing the distribution of Cs (caesium), O (oxygen) and Te (Tellurium). The SEM reference picture (with back scattered electrons) is in the upper left corner.

(b),(c),(d) Distribution of Cs, O & Te
(a) SEM ref pic w back scatt electron
High concentration of Cs and O which goes to Cs sites @ measurement (air exp)
Te is evenly distributed as supported in (e)

SEM Picture

(e) (f) (g)



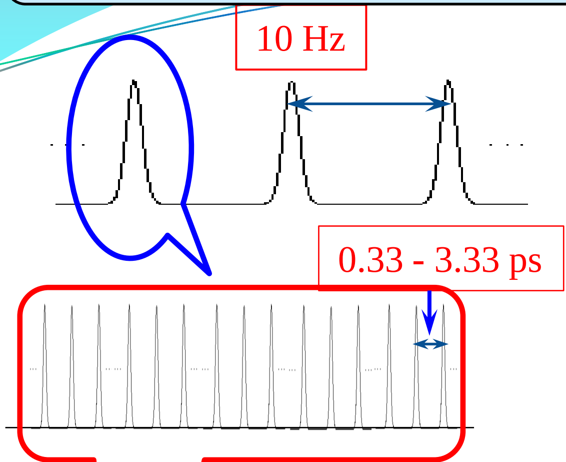
(e) 15 nm Te on Cu Uniformly Distributed with some granularity

(f) 25 nm Cs on Cu, Nonuniform distr Cs grows in islan on nucleation site

(g) 40 nm Cs_2Te compound on Cu Combination of island with granularity

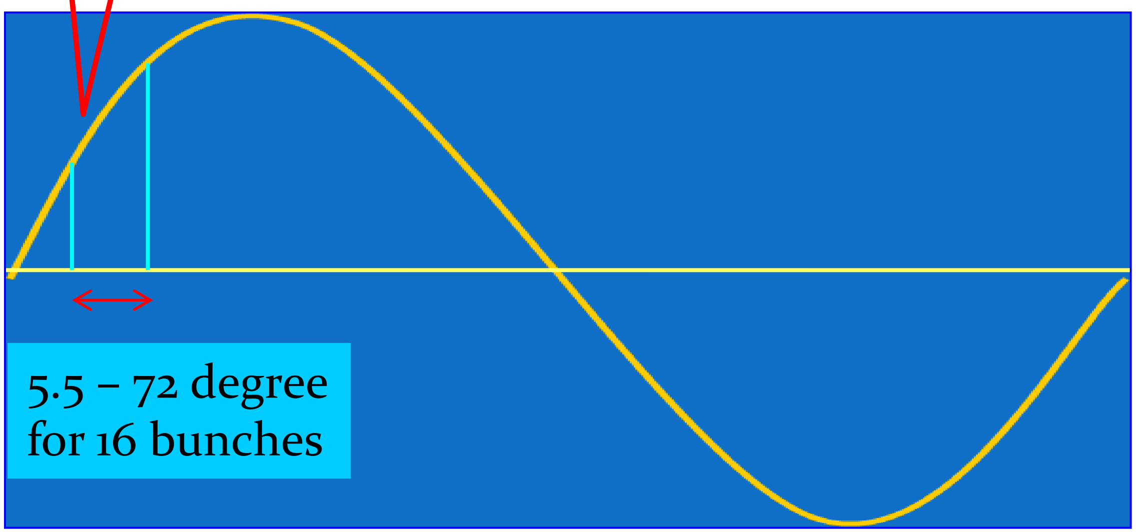
SEM pictures taken after air exposure, so it's not clear what comes from oxidation and what was the Cs non-uniformity after dep.
Av roughness went from 3 nm (virgin Cu) to 15 nm, not clear – from Oxidation or evap.

Phase-I: A pre-bunched FEL (BRNS/IUAC funded)



f = 3 – 0.3 THz
T = 0.33 ps to 3.3 ps
λ = 30 μm to 1 mm

- Head of micro-bunch train – min accel. field
- Tail of micro-bunch train - max accel. Field
- However difference in accel. gradient is not that large
  - Beam loading effect
  - Phase slippage
- Beam dynamic simulation and careful beam tuning
- Beam loading effect is very severe
  - For 100 pC/microbunch
  - For more than 10 microbunches/train
  - More careful simulation is necessary



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

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

λ_U – Undulator wavelength
B_U – Undulator mag field

An Important challenge for an efficient FEL – control of transverse emittance

Transverse emittance: Main reasons to increase in PC RF gun

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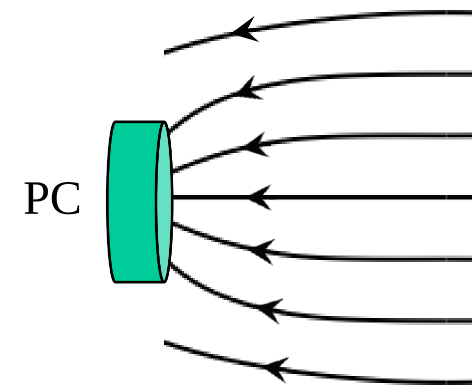
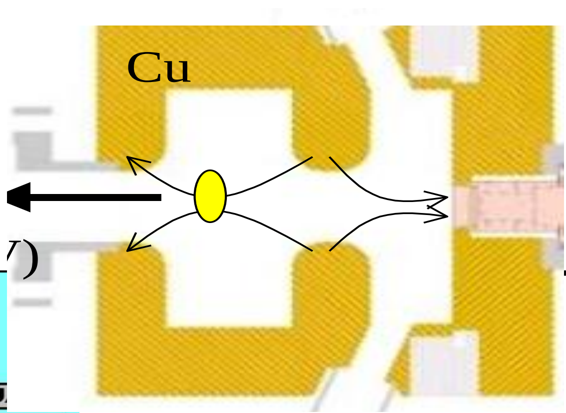
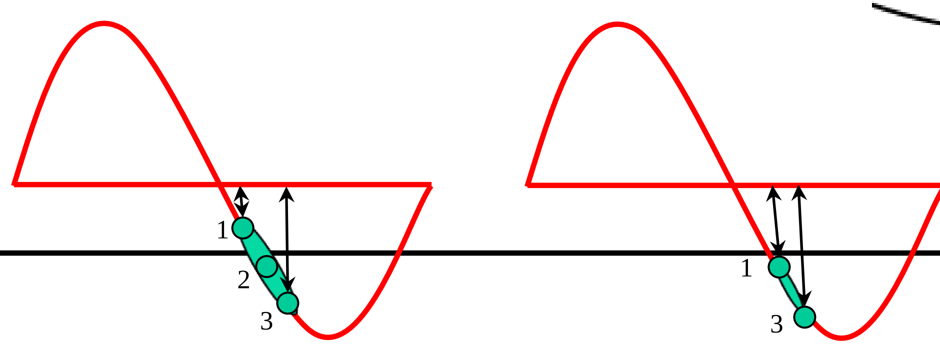
can be avoided by increasing lux density – problem of thermal Lensing, non-linear effect, device damage, Optimization is to be made

- Reduce Laser spot size
- Reduce accelerating fields
- Reduce electron bunch length





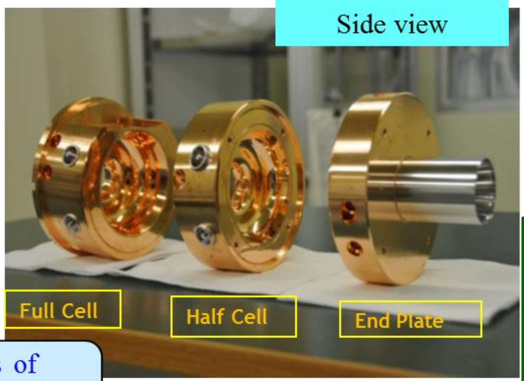


2

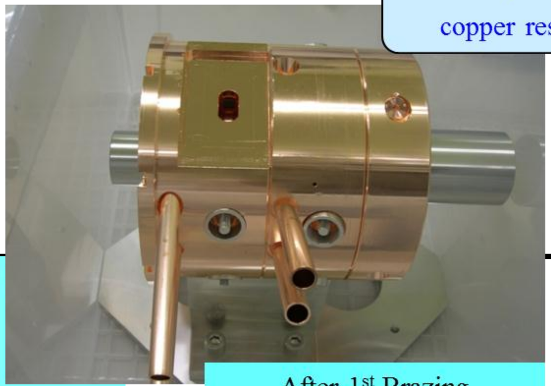
Jobs to be executed at KEK

Complete fabrication of 2860 MHz, 2.6 cell copper cavity at KEK

- Rough machining of the copper cavity
- Final machining of the copper cavity to a surface finish of less than 50 nm
- Frequency tuning of the cavity before brazing
- Frequency check of the cavity after brazing at different temperature of cooling water
- Field balancing between the different cells of the cavity by adjusting the plungers
- Bead pull test to validate different parameters of the cavity



Components of copper resonator



Involvement of IUAC

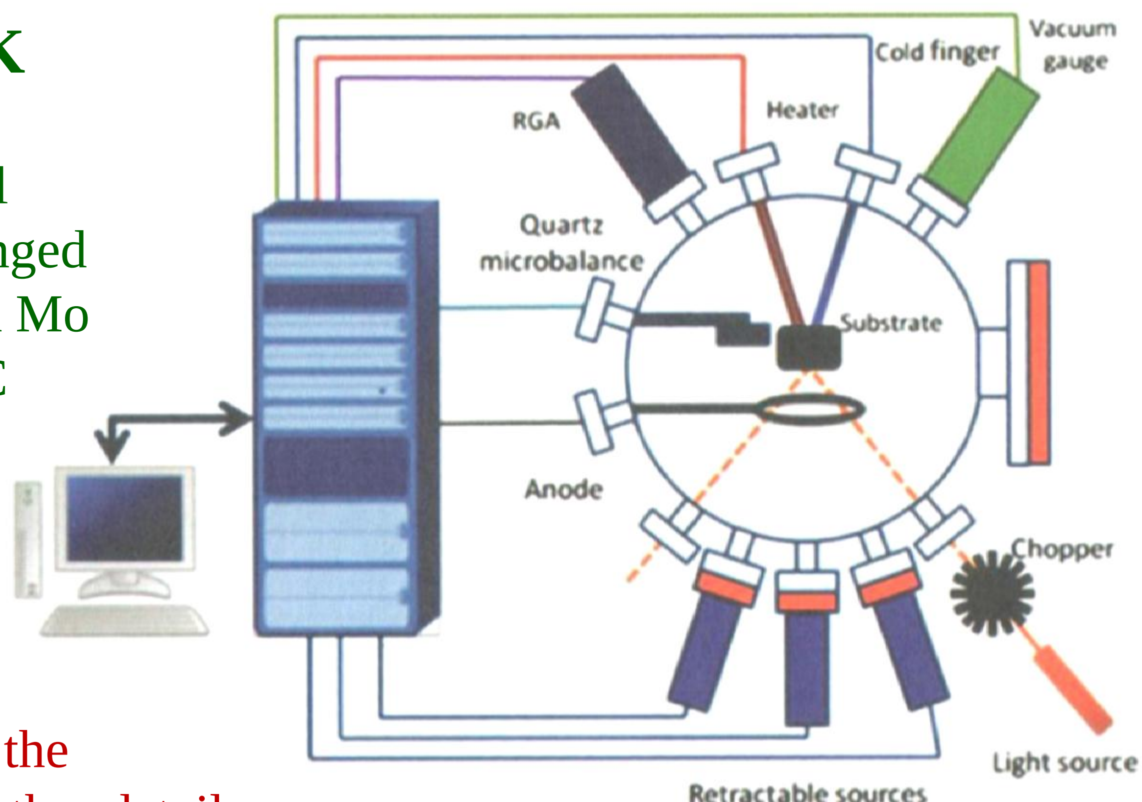
- IUAC personnel will participate in the fabrication of the cavity
- Learn freq. tuning, field balancing, beam pull meas of a Cu cavity
- Learn RF conditioning & Q-meas
- Learn other details of the Cu-cav

Preparation and insertion of photocathode in to the cavity

- Substrate – Mo – to be held at 120 C, ~10 nm Te is deposited @ 1nm/m
- Film is then illuminated by UV light @ 365nm Cs is evaporated @ same rate, Photocurrent is constantly monitored
- At maximum QE, source and substrate heater are turned off

Manpower Training at KEK

- PC preparation mechanism to be demonstrated to IUAC personnel
- Polished Mo substrate to be arranged
- IUAC personnel deposit CsTe on Mo
- Characterization of new CsTe PC
- To be inserted in to the existing copper cavity, generate e-beam



Setting up facility at IUAC

- Access to the drawing, design of the prep. chamber, load lock mech, other details
- Supervision of the development of IUAC's facility
- Advise/guidance about measurement, insertion of PC in to cavity

FEL light – What is so special ?

- Source of e.m. radiation in the range of THz - X-ray
- Frequency is tunable, can vary from λ = 1mm to $1\,^0A$
- Source with maximum Peak and Average brilliance
- Source with shortest wavelength of the radiation
- Source with shortest duration of radiation exposure (fs)

How Fast is a Femtosecond (10^{-15} s) **?**

light takes to travel the width of a human hair (~ 100 fs), electron takes 0.15 fs to complete a rev in lowest orbital, neurons takes 200 fs to transport electrochemical signals from retina to brain, C-C stretching vibration in a polymer has period of 23 fs.

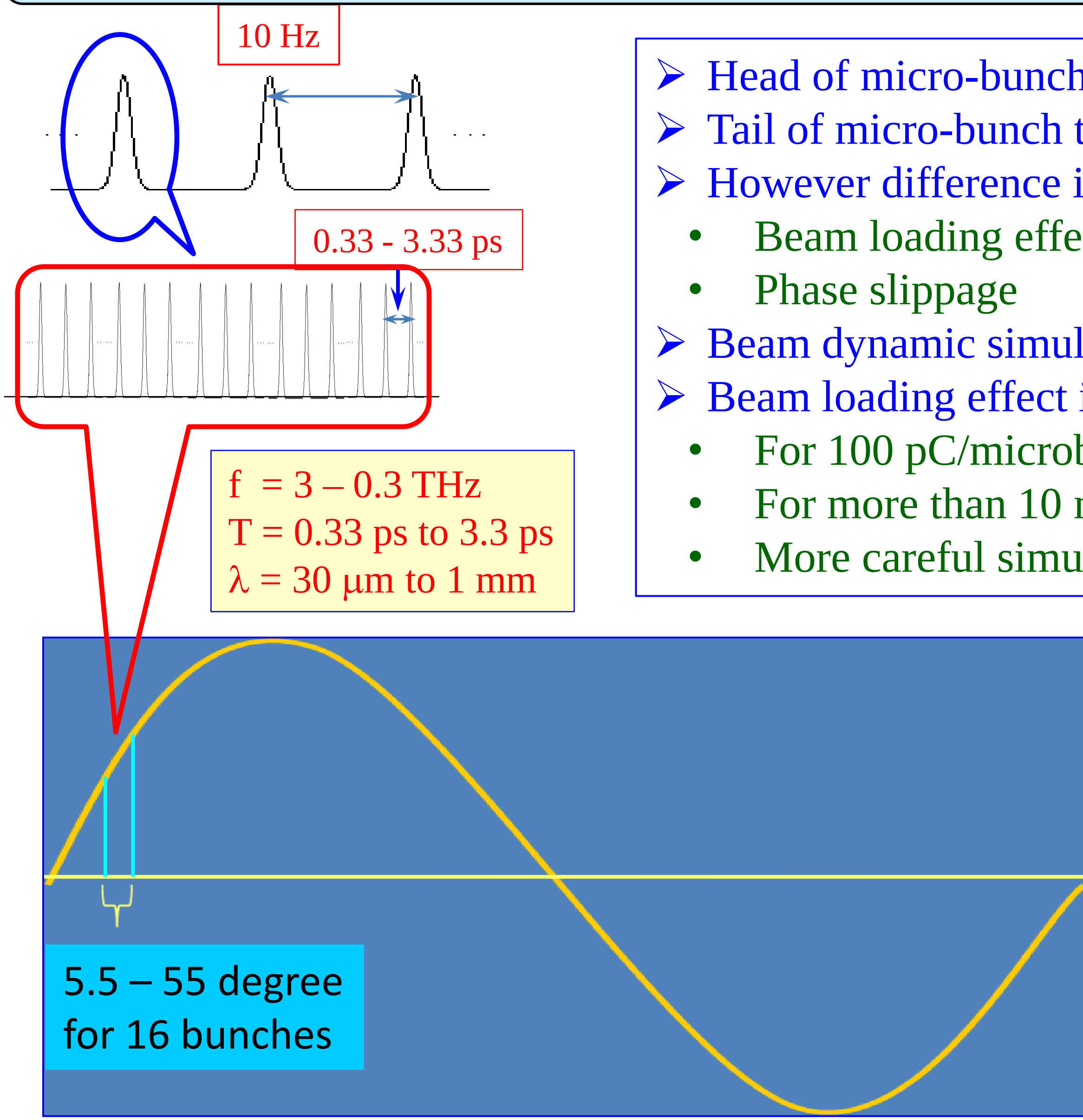
Capturing the Ultrafast

- The atom/molecule is pulsating with frenetic motion.
- FEL light captures images with a "shutter speed" of <100 femtoseconds (10^{-15} second).
- Snapshot of atom/molecule in motion is possible.
- Understanding fundamental processes in Physics, Chemistry, technology and life sciences.

Probing the Ultra-small

- Diameter of a human hair is about 1/1000 of an inch (25 μm)
- λ of visible light ~ 50 times smaller than this (400 – 700 nm). Ordinary microscopes can easily resolve a hair.
- A molecule, ~ 10,000 times smaller than a hair, is too small to be resolved with visible light. (2.5 nm, 25 ^0A)
- X-rays, with λ that are smaller than a molecule, are ideal for imaging at this scale. (Hard X-rays ≤ 0.1 nm, $1\,^0A$)

Phase-I: A pre-bunched FEL (BRNS/IUAC funded)



- ➢ Head of micro-bunch train – min accel. field
- ➢ Tail of micro-bunch train - max accel. Field
- ➢ However difference in accel. gradient is small
  - Beam loading effect
  - Phase slippage
- ➢ Beam dynamic simulation and careful beam tuning
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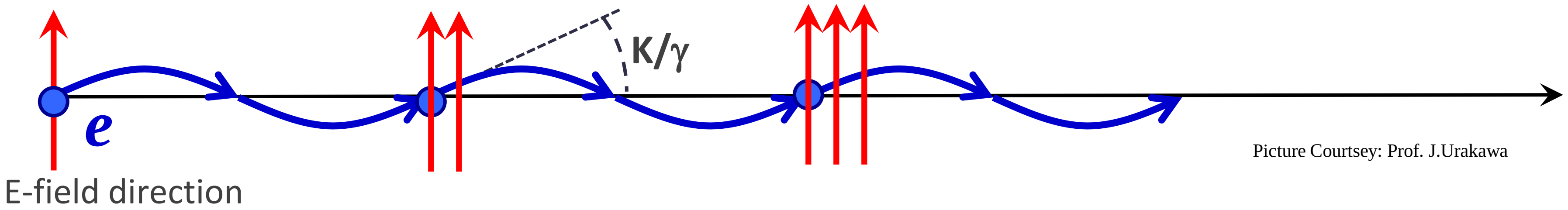
$$\lambda_L = \frac{\lambda_U}{2\gamma^2}\left[1 + \left[\frac{eB_U\lambda_U}{2\pi mc}\right]^2\right]$$

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

λ_U – Undulator wavelength
B_U – Undulator mag field

Injection energy of an Electron in to Undulator



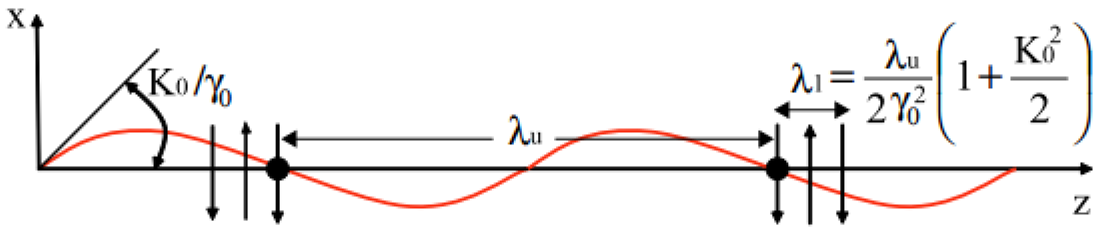


FIG. 2. (Color) After an electron (black dot) travels one undulator period λ_u of the sinusoidal trajectory (in red), a plane wave (represented by alternating vertical arrows) overtakes the electron by one resonant wavelength λ_1. Thus, the undulator radiation carrying this resonant wavelength can exchange energy with the electron over many undulator periods.