Operation of Superconducting Linear Accelerator and design of proposed Light Source at Delhi (LSD)

Subhendu Ghosh
Inter University Accelerator Centre,
New Delhi

Presentation at DESY – 09 Sept. 2014

Outline

1. Superconducting Linac
   - Quarter Wave Resonators, cryostats etc.
   - Linac operation and latest results
   - A few interesting challenges in linac operation

2. Existing SRF Technology
   - Infrastructures and fabrication of QWRs at IUAC
   - Fabrication of 325 MHz Single Spoke resonators for Project-X
   - Tesla type 1.3 GHz cavities

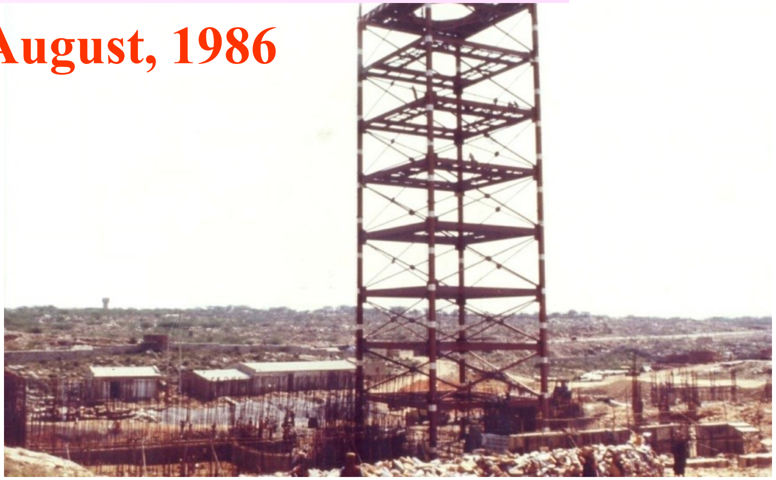
3. Delhi Light Source (DLS)
   - Phase-I – Resonator, Laser system, Photocathode, Klystron – status and parameter finalization
   - Phase-II – Exploring stage, literature survey, Collaboration

History of IUAC

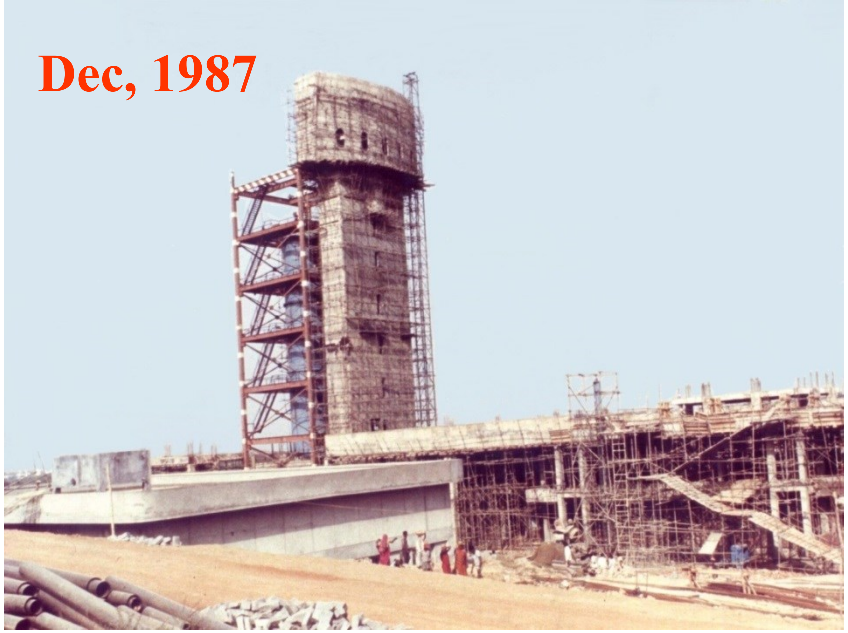
Formerly (Nuclear Science Centre)

Before July, 1986

August, 1986



Dec, 1987



Nov, 1989

Inter University Accelerator Centre

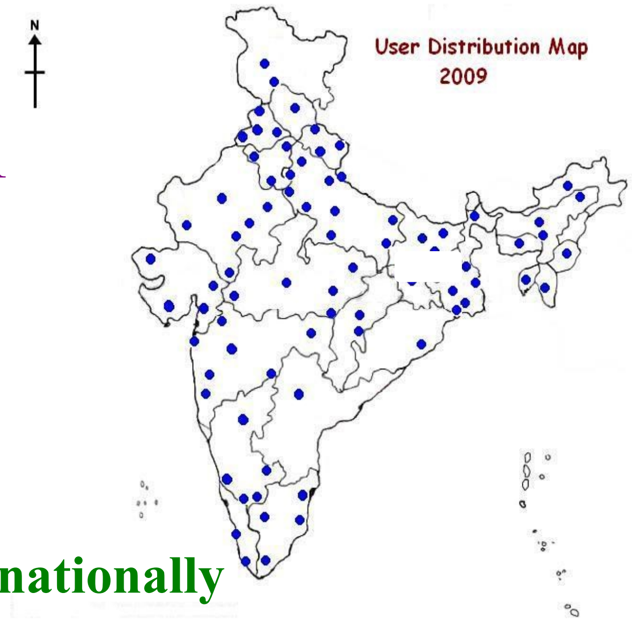
(The first Inter-University Centre of UGC)

- **Established in 1984 as an autonomous institution funded by Indian Government**
- **Accelerator facility operational by 1991**
- **Objectives:**

To provide world class accelerator system along with experimental facilities

To create basic infrastructure to facilitate internationally competitive research

Anybody from any university, IIT, NIT, or any other institutes, in India or abroad can be user



Users : 400

Universities : 83

Colleges : 54

Other Institutes : 63

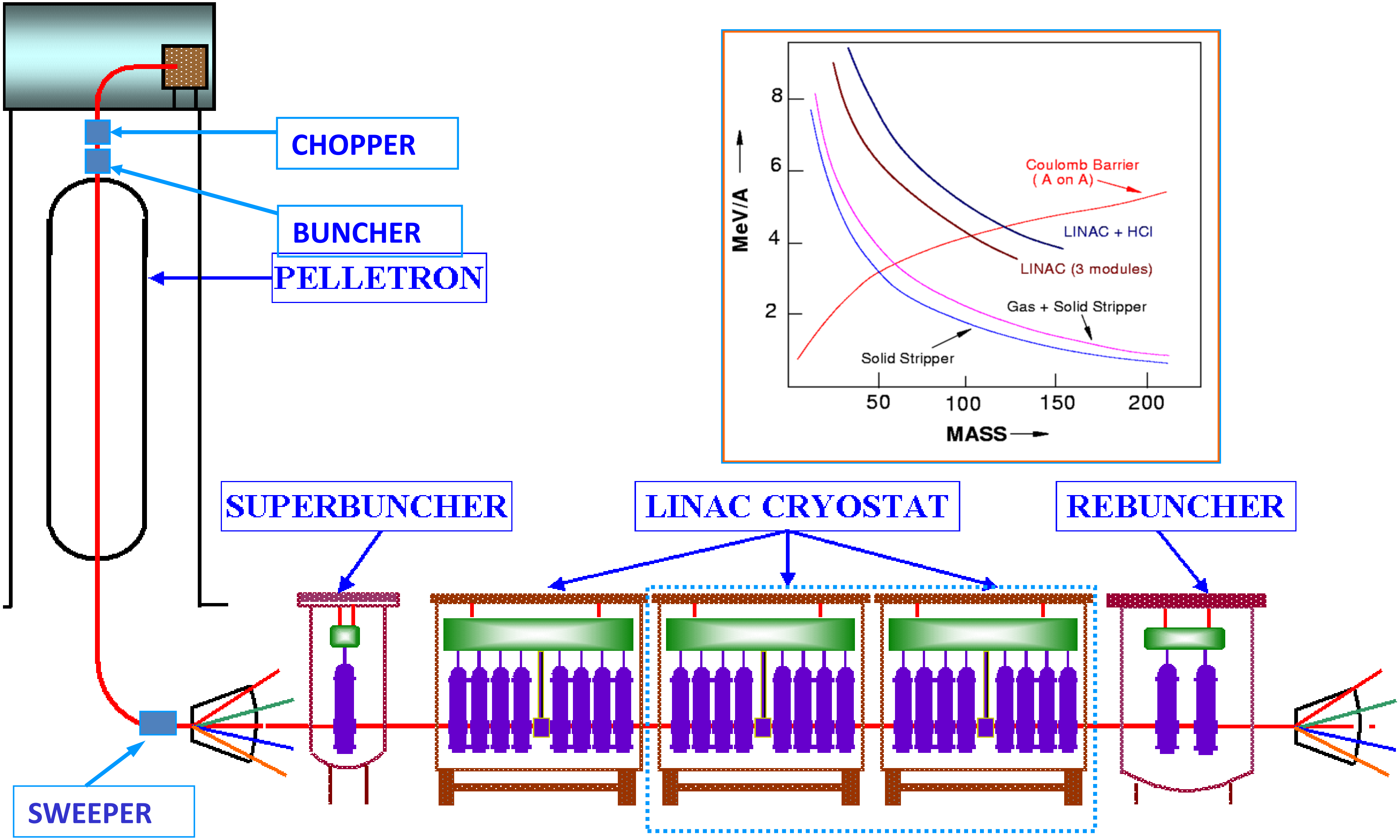
Activities of the Centre

- Development & Operation of Accelerator
  - 15 UD Pelletron Accelerator & Superconducting Linac
  - Low Energy Ion Beam facility
  - 1.7 MV Pelletron Accelerator

  Ion beam accelerators – presently operational

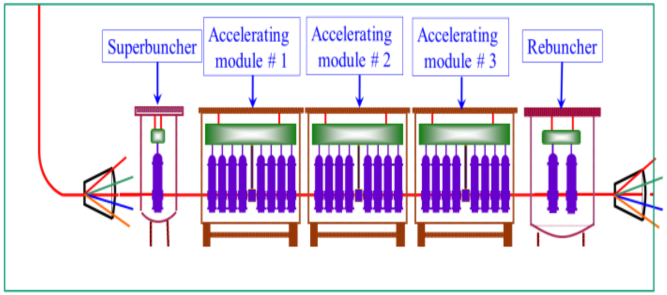
  - High current Injector – Under Construction
  - Free Electron Laser – a light source – Planning stage
- Research using Ion Beams
  - Nuclear Physics, Material Science, Atomic Physics, Radiation Biology, Accelerator Mass Spectrometry
- Programs at under/post graduate and Ph.D. levels
  - 5-6 weeks Summer project (B.Sc.), 3 weeks M.Sc. Orientation Programme
  - Recruitment of Ph.D. students and fresh M.Sc. as employee
  - Local guidance for the Ph.D. students registered elsewhere

Layout of the Accelerator system of IUAC

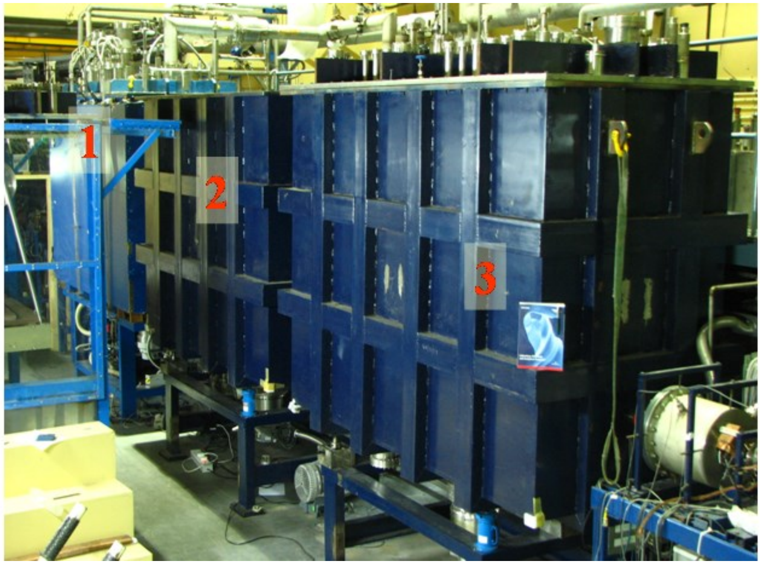


Major components of Linac

- Niobium Quarter Wave Resonator (QWR)
- Cryostats and cryogenics (LHe and LN_2)
- RF electronics (to power, phase and amplitude locking etc.)
- Beam transport elements

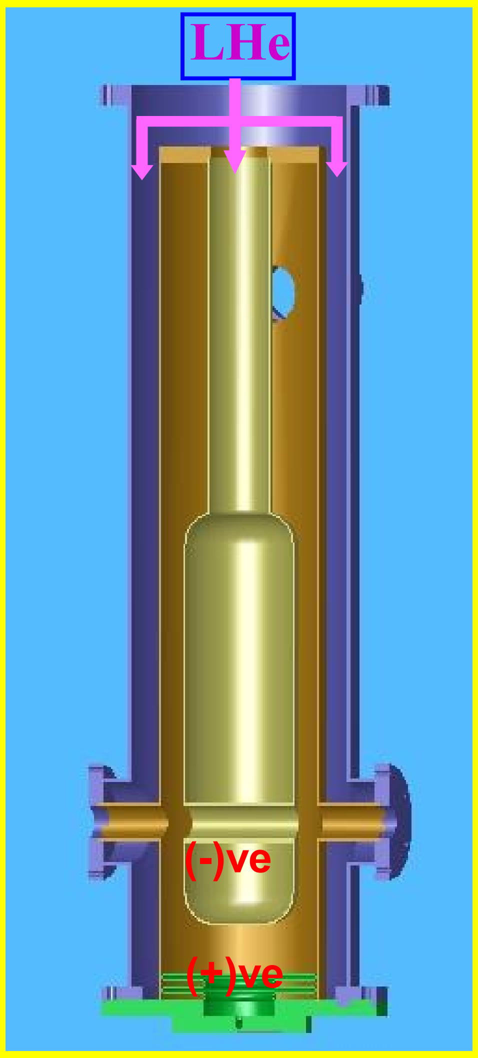


Niobium Resonators

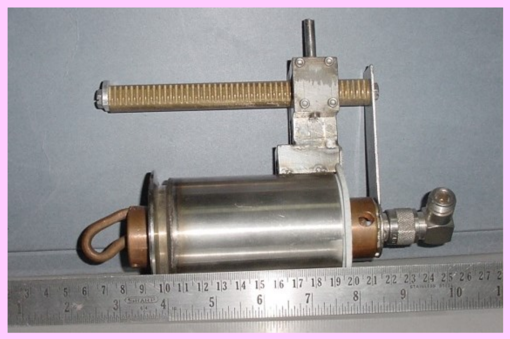


Linac Cryostats

Niobium Quarter Wave Resonator (QWR)



QWR schematic



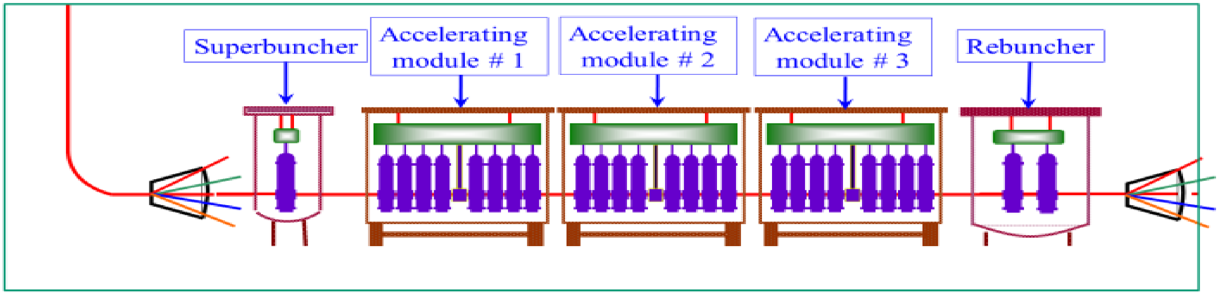
Drive Coupler

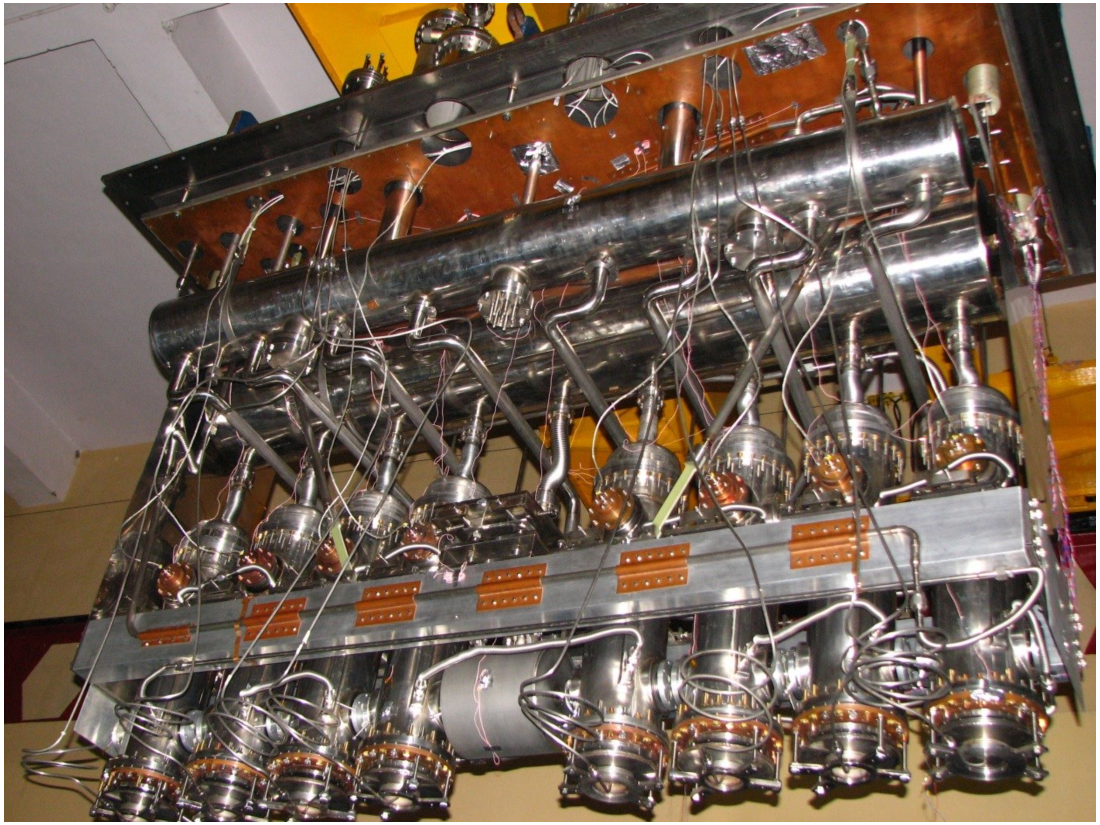
Pickup loop

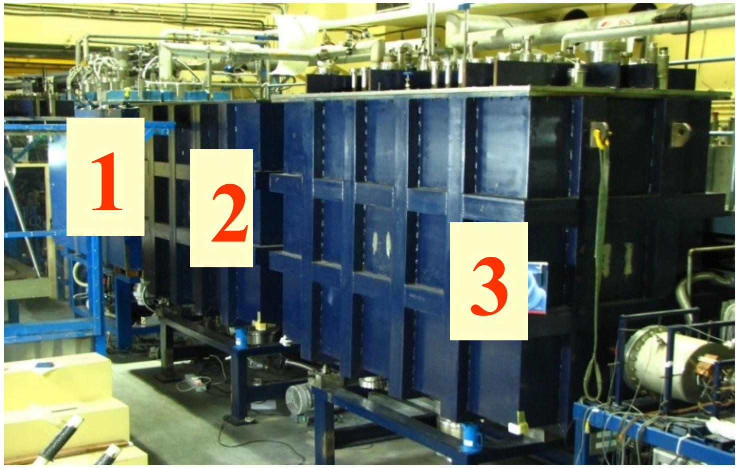
Mechanical Tuner (Nb)

SS-jacketed Nb QWR

Cryostats and Cryogenics

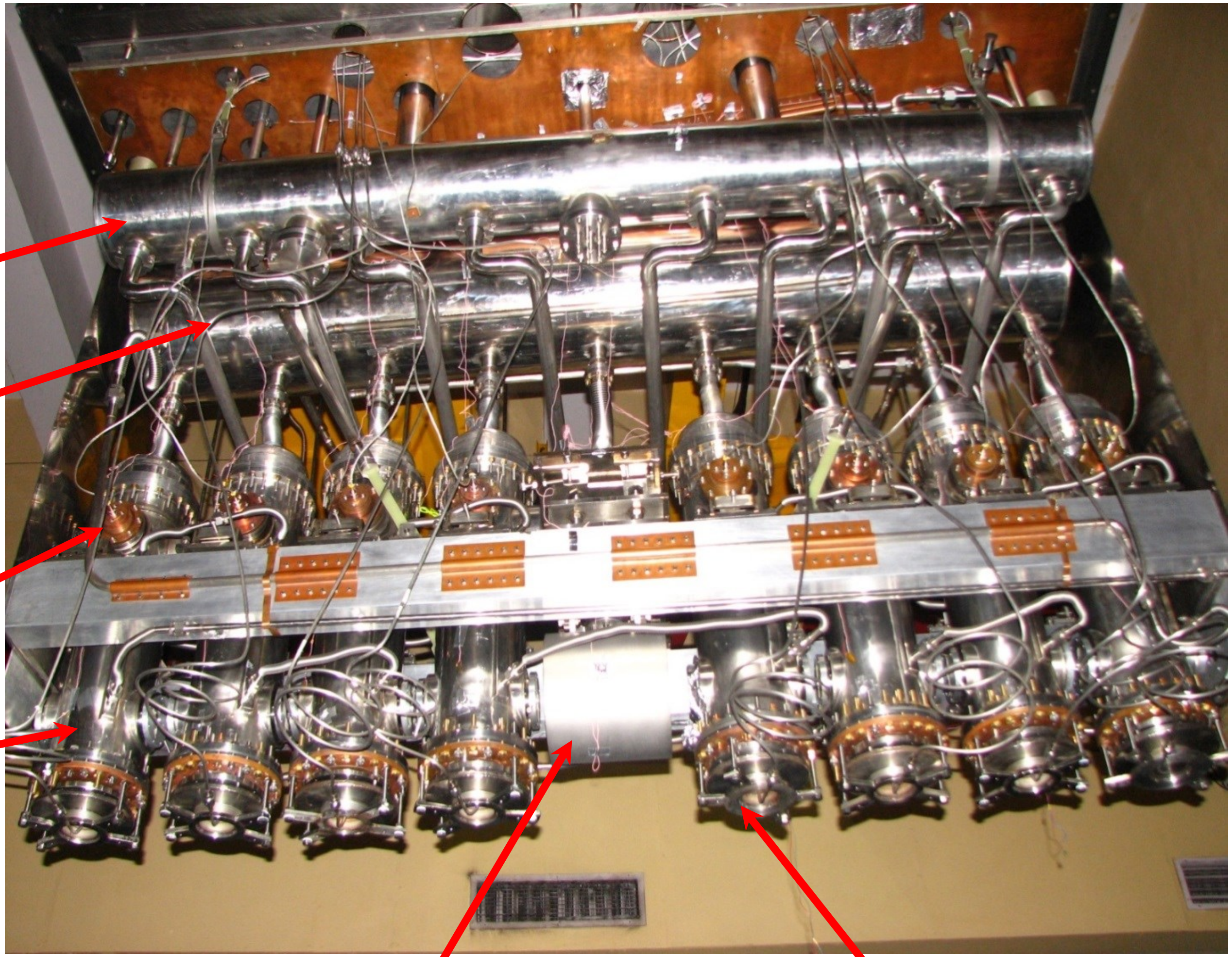






Cryostats and Cryogenics

A Linac cryostat with 8 resonators and a solenoid magnet



Liquid Nitrogen vessel

Liquid He-vessel

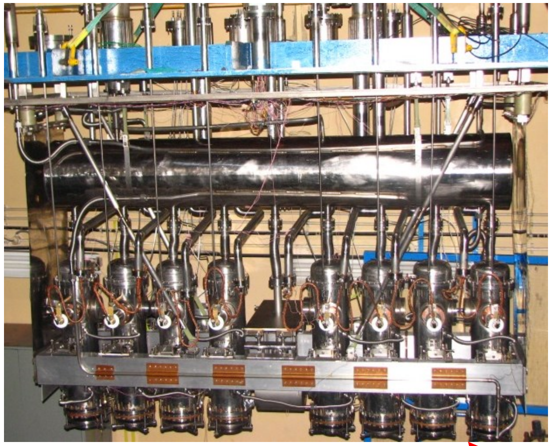
Drive coupler

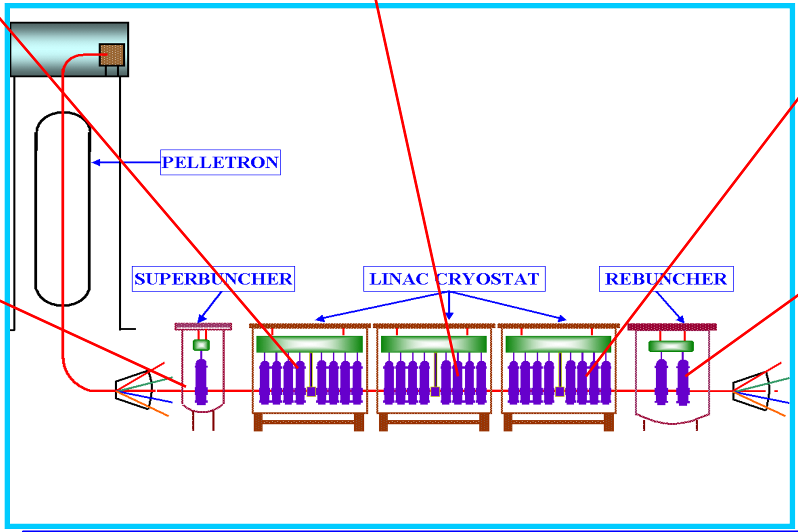
Resonators

SC Solenoid

Mechanical Tuner

Linear accelerator systems



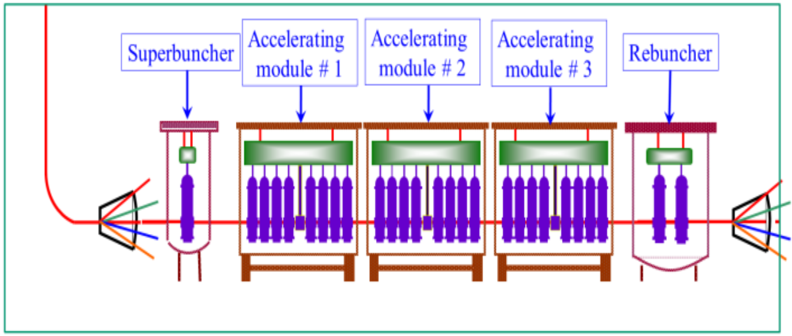


Consists of 27 identical Quarter Wave resonators, $\beta_0 = 0.08$, $f_0 = 97$ MHz

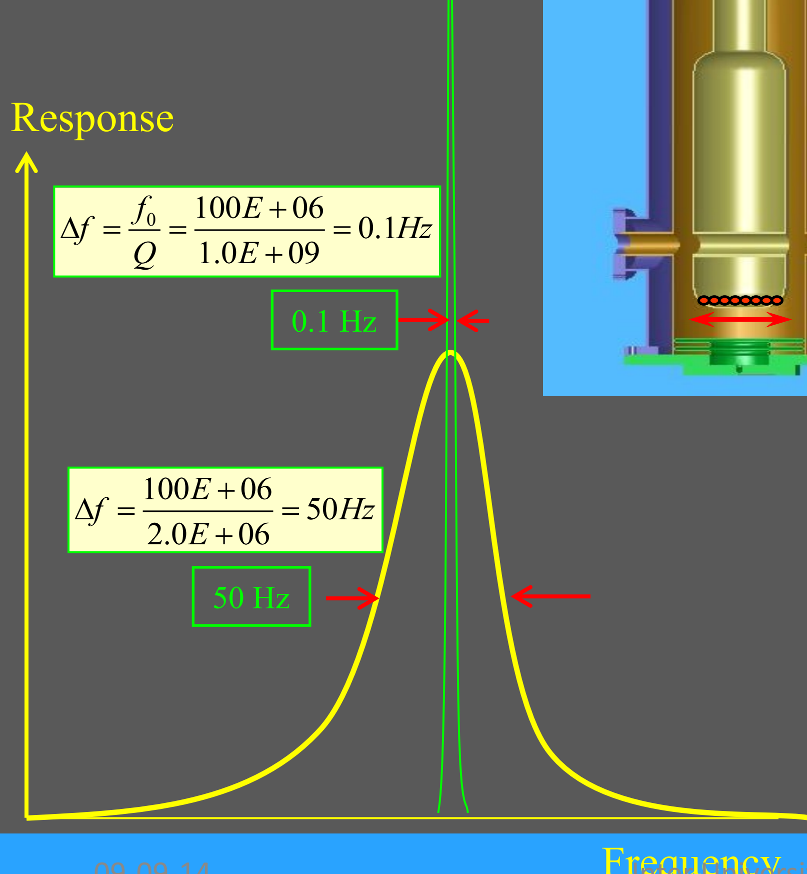
SC Linac operation & Beam Acceleration

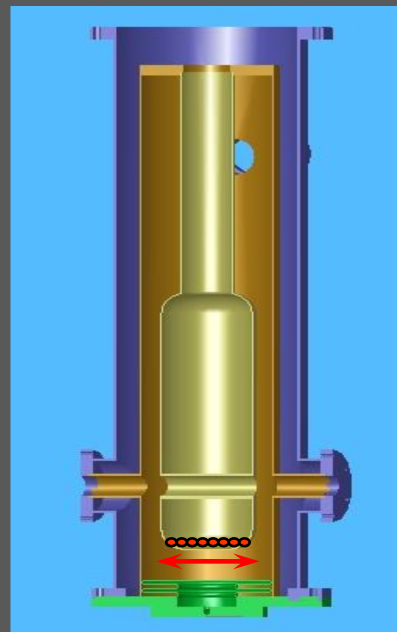
- All 5 cryostats (SB, 3 Accelerating and RB) are operational
- 1st. and 2nd. accelerating modules are having all 8 QWRs
- Third accelerating mod. - 6 QWRs, 2 will be installed soon
- Cold test and beam acceleration with all five cryostats took place during April - June 2014.

Beam species	Pelletron energy (MeV)	ΔT obtained by SB (ps)	Egain from LINAC (MeV)	Total energy (MeV)	ΔT obtained by RB (ps)
$^{48}Ti^{14+}$	162	160	113	275	185
$^{31}Si^{12+}$	130	117	91	221	RB not operated



Challenges in Superconducting Linac operation





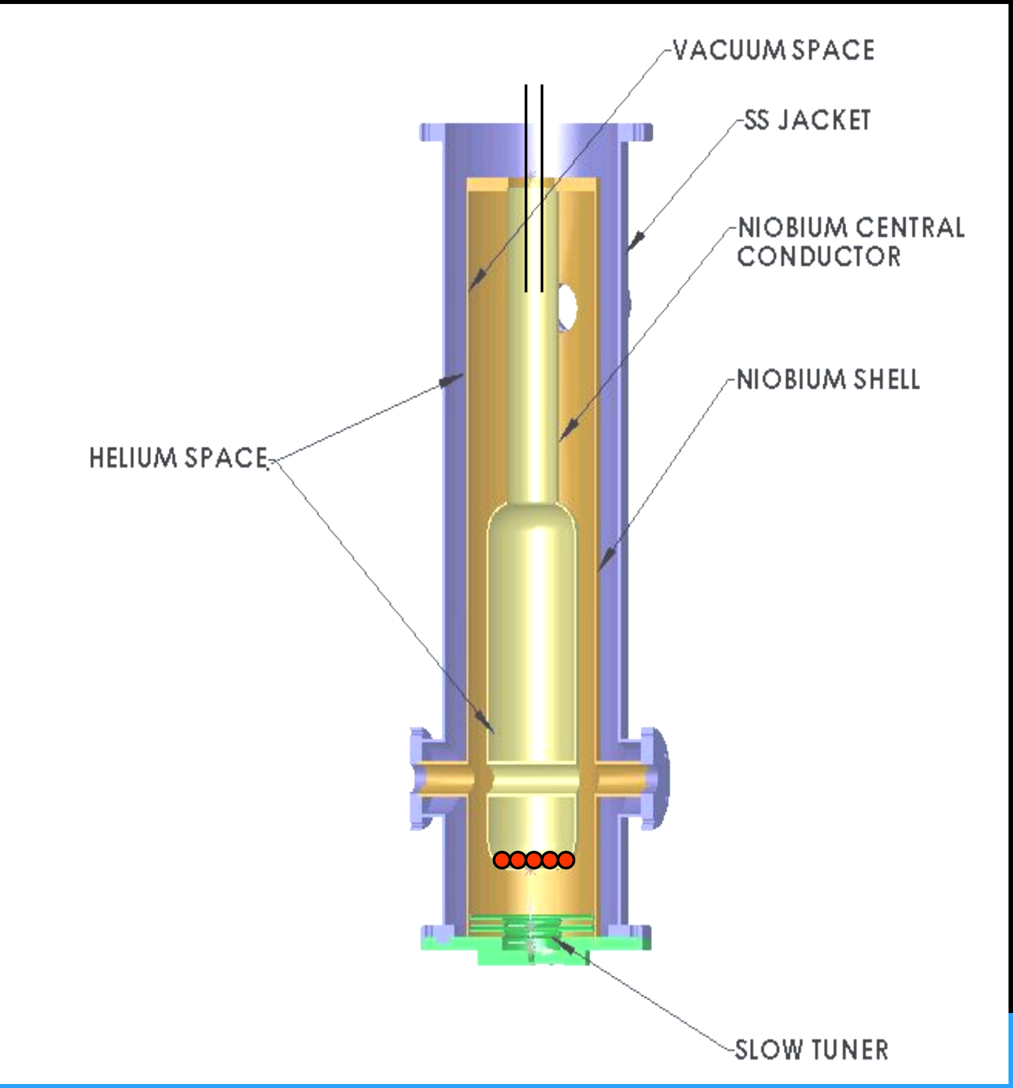
Source of frequency jitter around central freq.

- Central conductor – acting as a pendulum vibrate at natural freq. ~ 60 Hz
- Tuner bellows vibrate around ~ 30 Hz
- Thin Nb sheet vibrate ~ few Hz due to He pressure fluctuation
- Higher order cryogenic excitation modes may be present

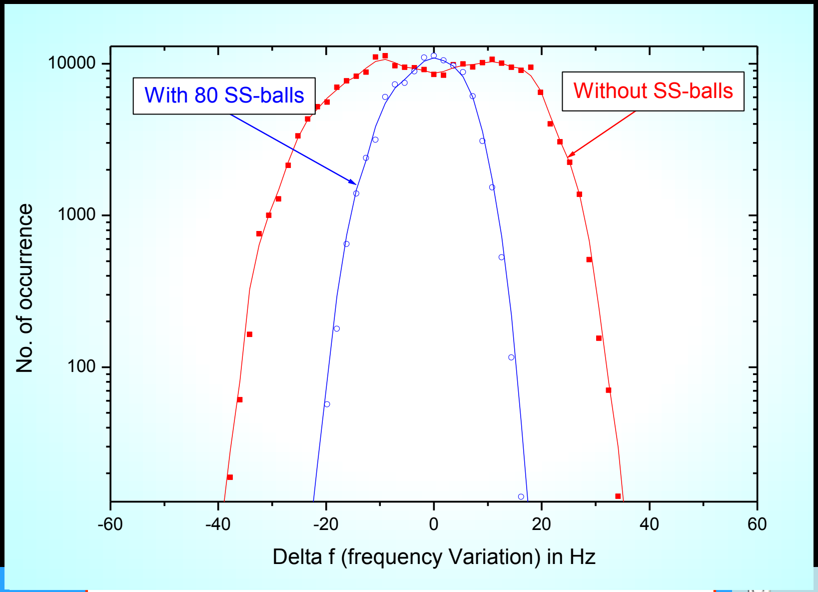
As a result, more RF power is required
To maintain stable phase/amplitude lock

Challenges in Linac operation

• Experiments of vibrational damping on Quarter Wave Resonators

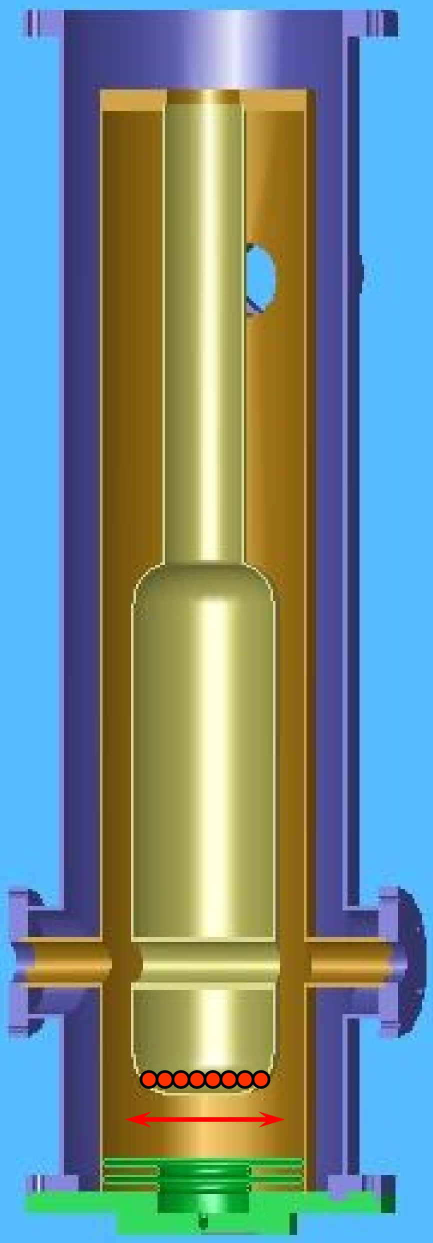


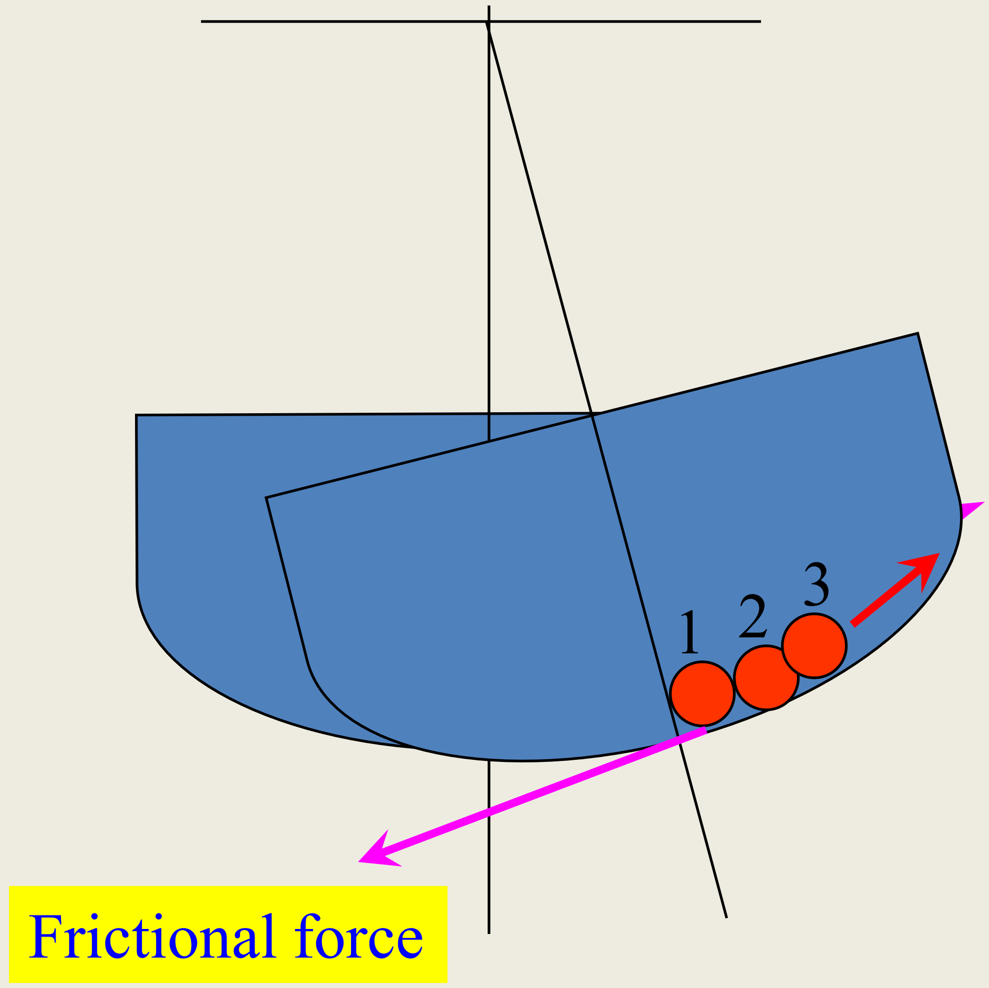
Frequency excursion (Δf) of a niobium resonator at room temperature without and with few tens of SS-balls.



❖ At LHe temperature

Physical explanation behind Damping





Challenges in Linac operation

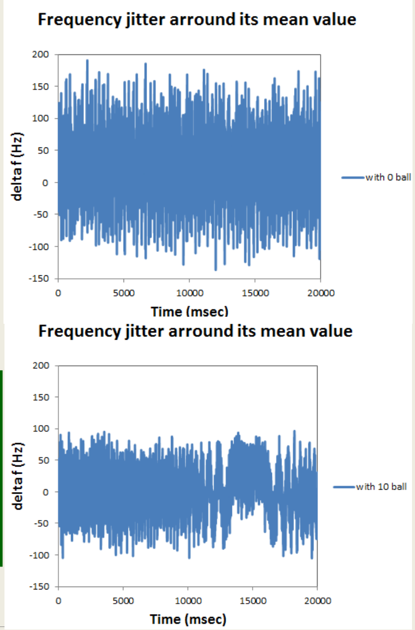
- Experiments of vibrational damping on Quarter Wave Resonators

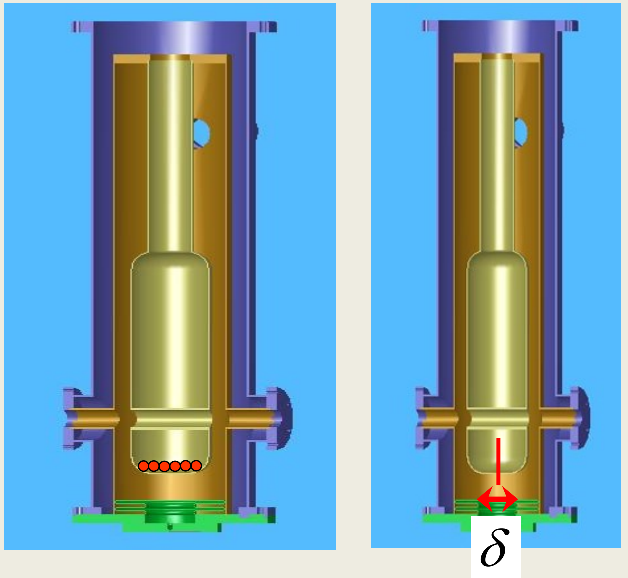
Power required during phase locking is reduced

$P_{amp} = \Delta\omega_{shake} \times U$

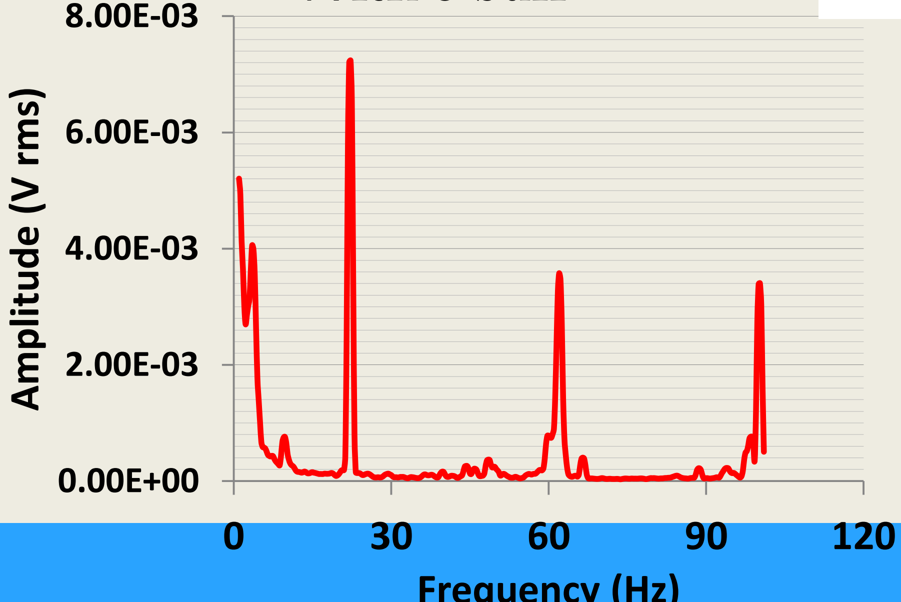
Without vibration damper:
Ea ~ 3 MV/m, P_f = 50 W, P.E. ~ 200 mv

With vibration damper (35 nos, 8 mm dia)
Ea ~ 3 MV/m, P_f = 23 W, P.E. ~ 200 mv
54% reduction in power

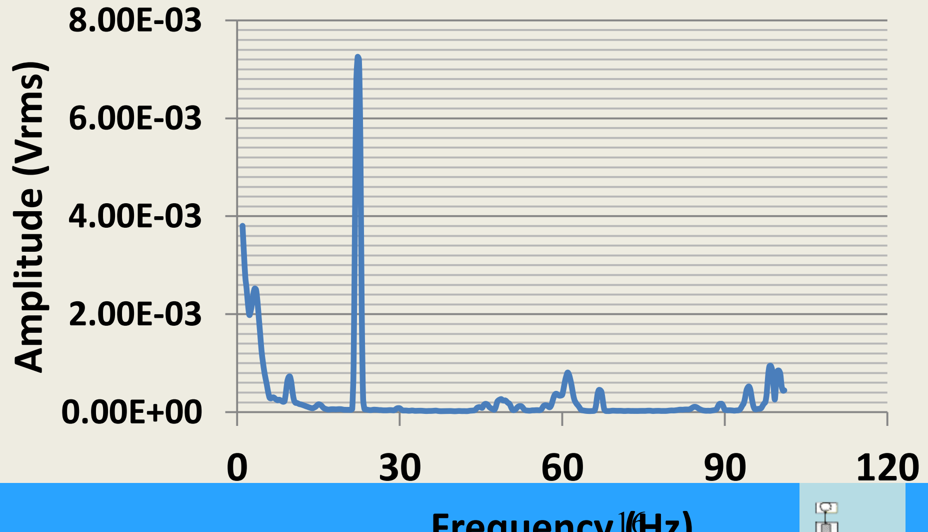




With 0 ball



With 35 balls



Challenges in superconducting Linac operation

Resonator frequency will drift

Slow drift (tens of sec)
± 250 Hz or so

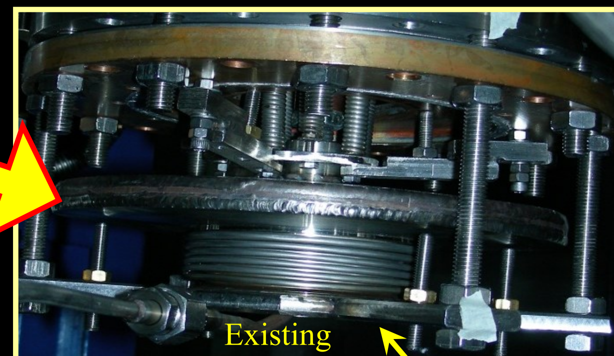
Controlled by mechanical tuner

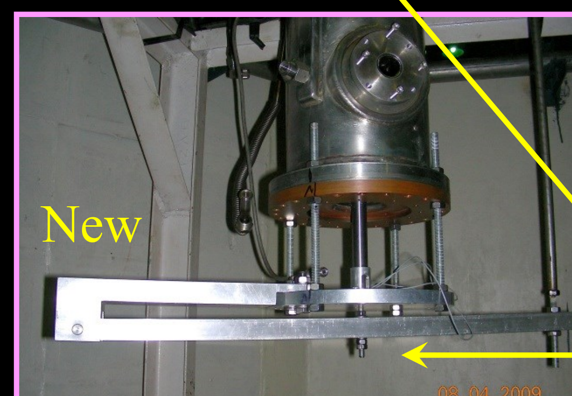
Fast drift (tens of ms)
± 25 Hz or so

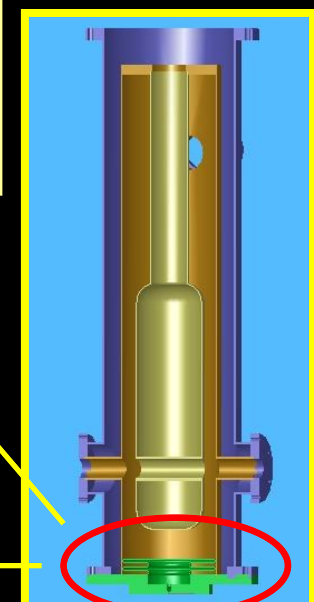
Controlled electronically by res. controller

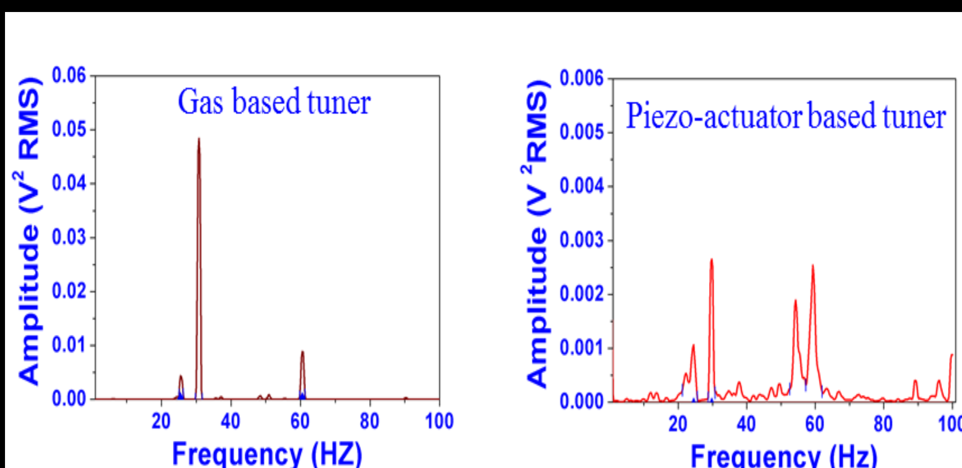
Why alternative frequency tuning mechanism

- Average RF power will be reduced
- Improved dynamics for the phase/freq control
- Acts as vibrational damper for mech. Tuner (~30 Hz)
- Flexing the tuner bellow by helium gas
  - Expensive & Not so simple method





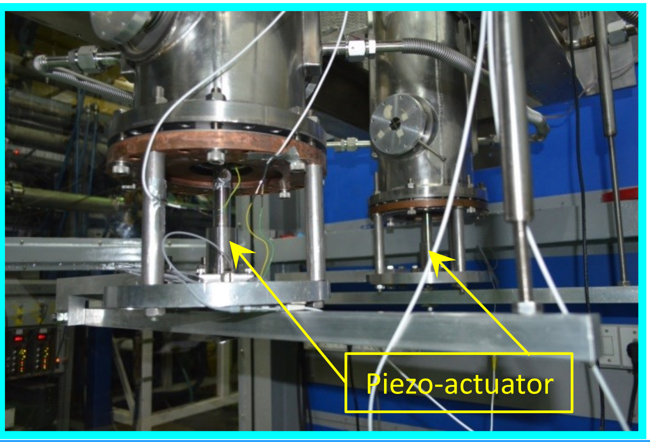




Challenges in superconducting Linac operation

- All gas based tuner of cryostats - 2/3 being replaced by Piezo based tuner

Cavities	With Gas based tuner (2012-13)				With Piezoelectric actuator based tuner (2014)			
	Locking Field @ 4-6W	Phase stability	Amplitude stability	RF Power (Maximum)	Locking Field @ 4-6W	Phase stability	Amplitude stability	RF Power (Maximum)
R22	2.3	$\pm 0.2^0$	0.7%	120 W	2.98	$\pm 0.1^0$	0.03%	90 W
R24	2.57	$\pm 0.5^0$	0.7%	120 W	3.17	$\pm 0.1^0$	0.015%	100 W
R25	2.22	$\pm 0.1^0$	0.16 %	130 W	2.30	$\pm 0.03^0$	0.01%	100 W
R28	2.9	$\pm 0.1^0$	0.1%	100 W	2.9	$\pm 0.05^0$	0.03%	80 W
R33	2.42	$\pm 0.3^0$	0.1%	120 W	2.73	$\pm 0.05^0$	0.02%	90 W



Strengths Available

(existing facilities, expert manpower and infrastructure setup)

EBW

60kV, 250mA, 2x1x1 metre

SPL

EP, DI water plant, US bath, HPR

All mechanical works, e.g. forming machining etc. are performed by a commercial vendor, with whom we closely work.

Test Cryostat

HVF

HVF

SRF infrastructure at IUAC – Cryogenic resources

OLD REFRIGERATOR
Capacity ; 500 W at 4.2 K

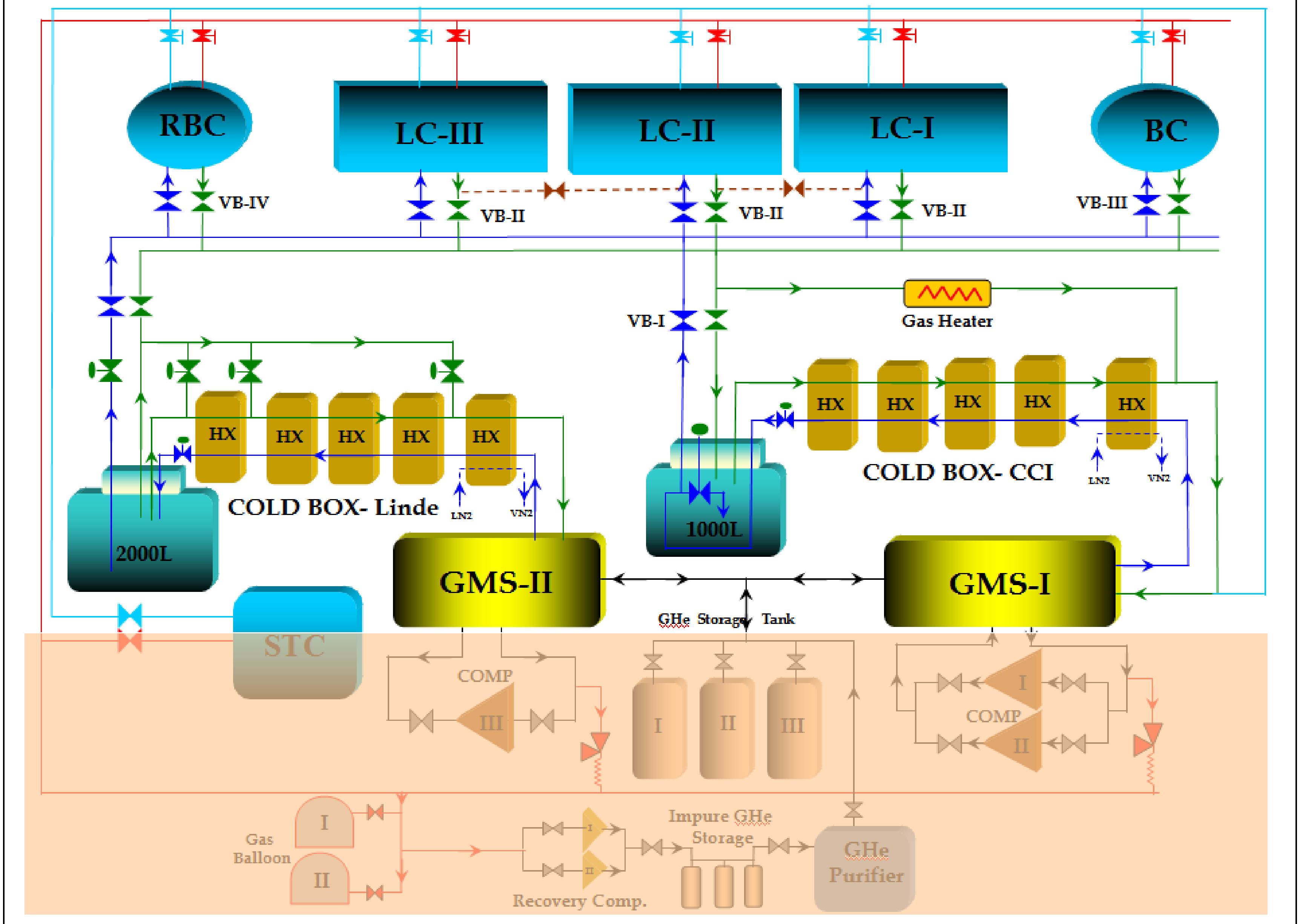
NEW REFRIGERATOR
CAPACITY : 1 KW at 4.2 K

CRYOGENIC CONTROL ROOM

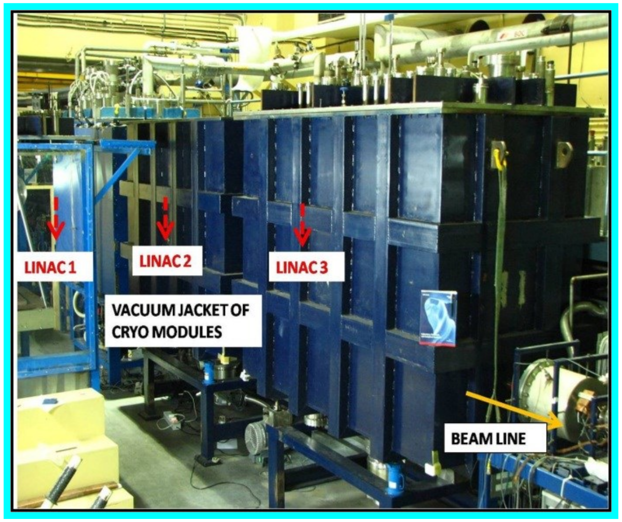
HELIUM PURIFIER

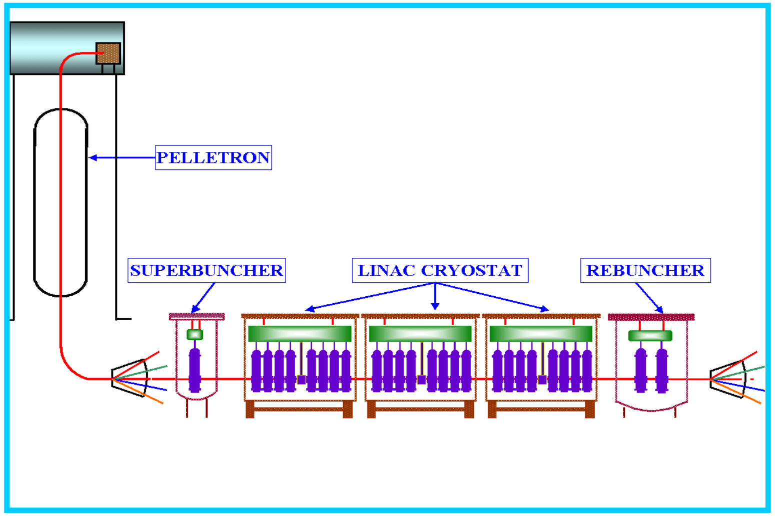
HELIUM GAS STORAGE

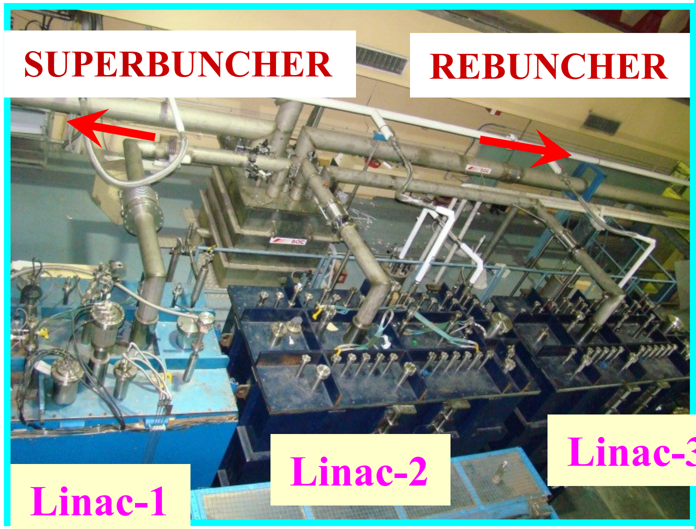
Schematic of Helium Cryo - Network of Superconducting LINAC



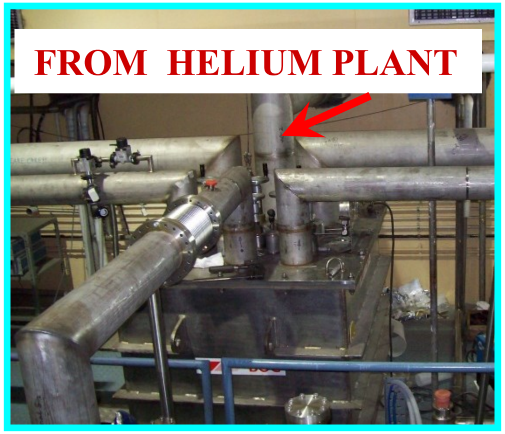
Liquid Helium Distribution Line







REBUNCHER



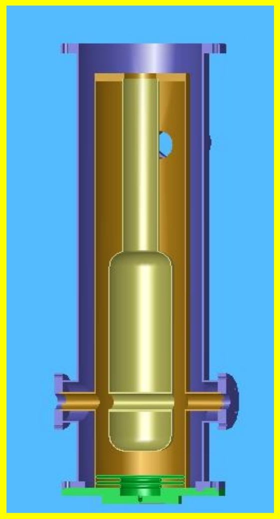
VALVE BOX

Fabrication and testing of QWR at IUAC

Central Conductor

Electropolished Niobium
Central Conductors

Top Flange



Central Conductor & Housing

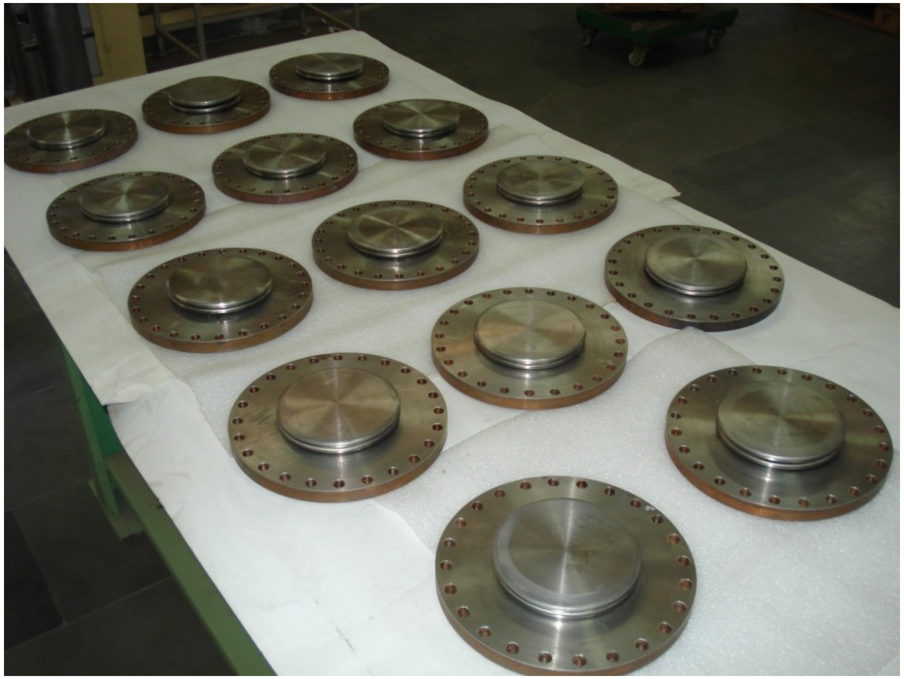
Mechanical Tuner

Electropolished niobium Top Flanges (top middle), major Assemblies of the QWRs (above) and Slow Tuner bellows (left).

Fabrication and Testing of QWR at IUAC

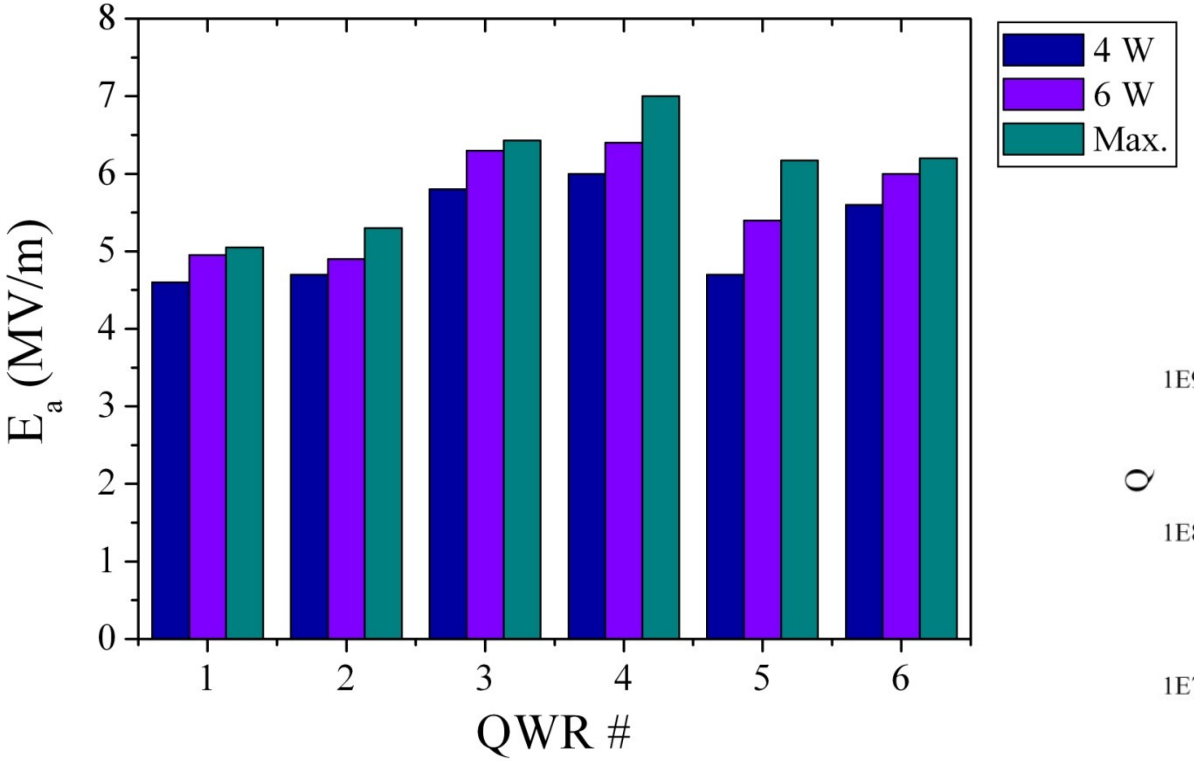
Resonators

Mechanical Tuner

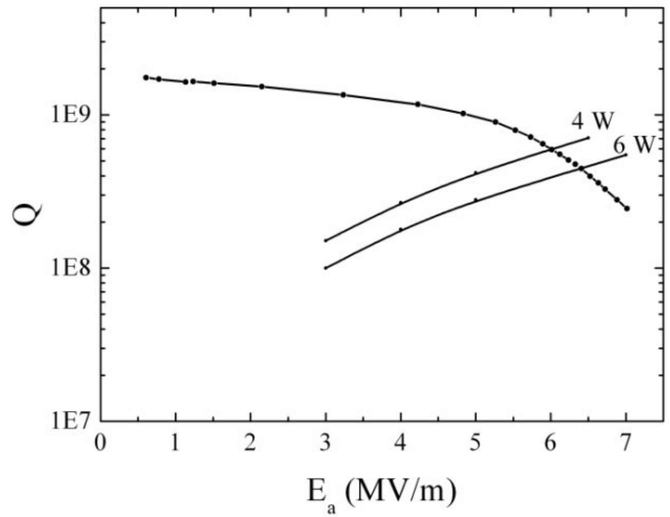


Superconducting Niobium Quarter Wave Resonators (left) and Nb Slow Tuner bellows (above), built at IUAC for the Superconducting Linac.

Fabrication and Testing of QWR at IUAC



Best performance of an indigenously built QWR



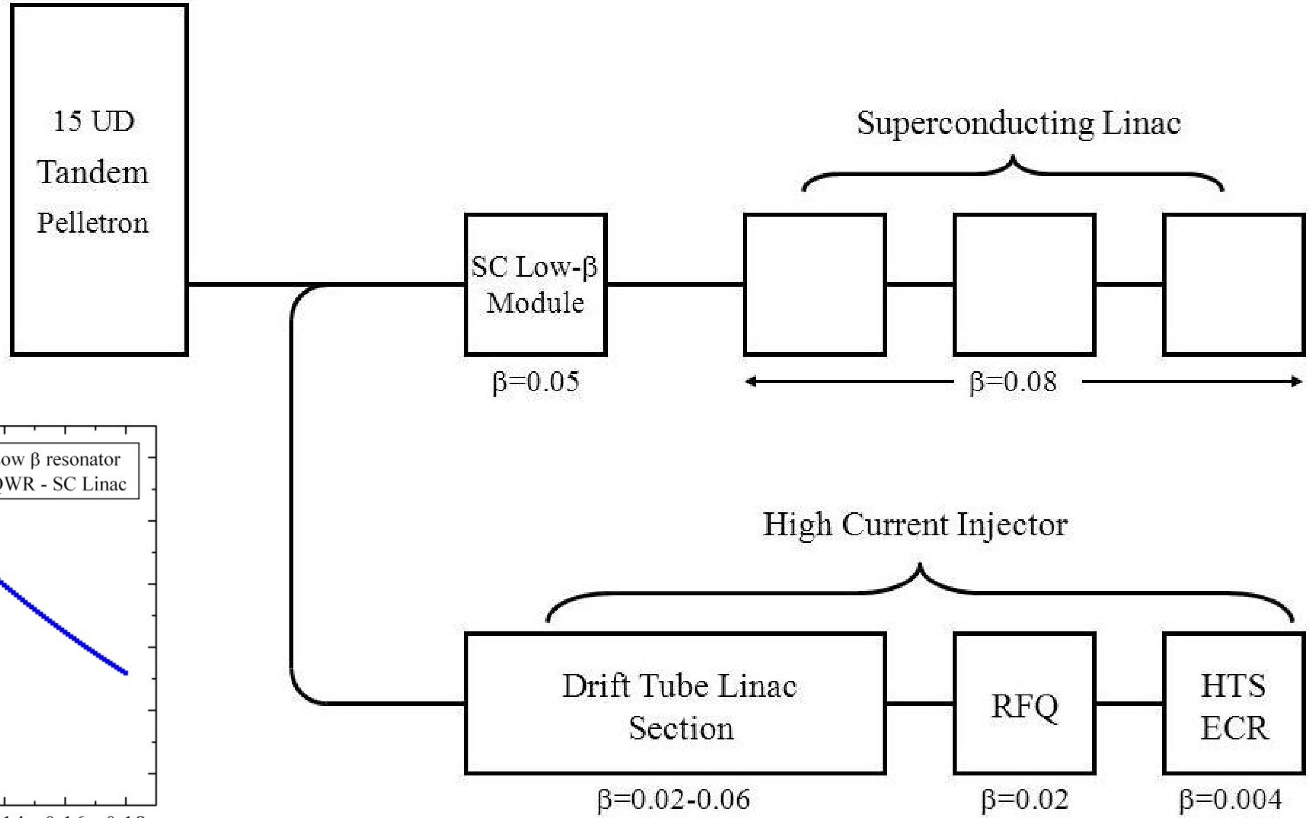
Accelerating gradient E_a at 4.2 K achieved in different QWRs indigenously built at IUAC, for the Superconducting Linac.

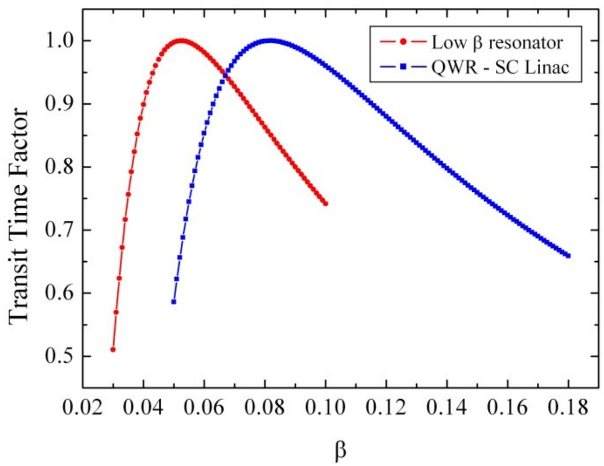
Resonator Q as a function of the accelerating gradient E_a at 4.2 K (for QWR # 4).

Design and development of Low beta Resonator

High Current Injector - HCI

SC low β module to be located so that it can accelerate beams from HCI as well as Pelletron accelerator.

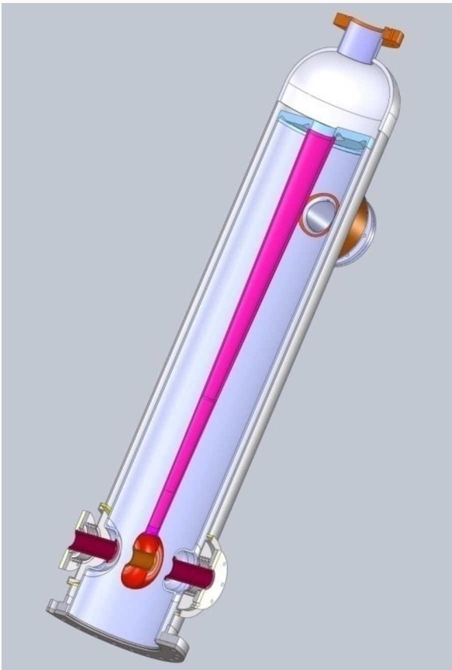




TTF - LBR+QWR

Proposed High Current Injector (HCI) at IUAC

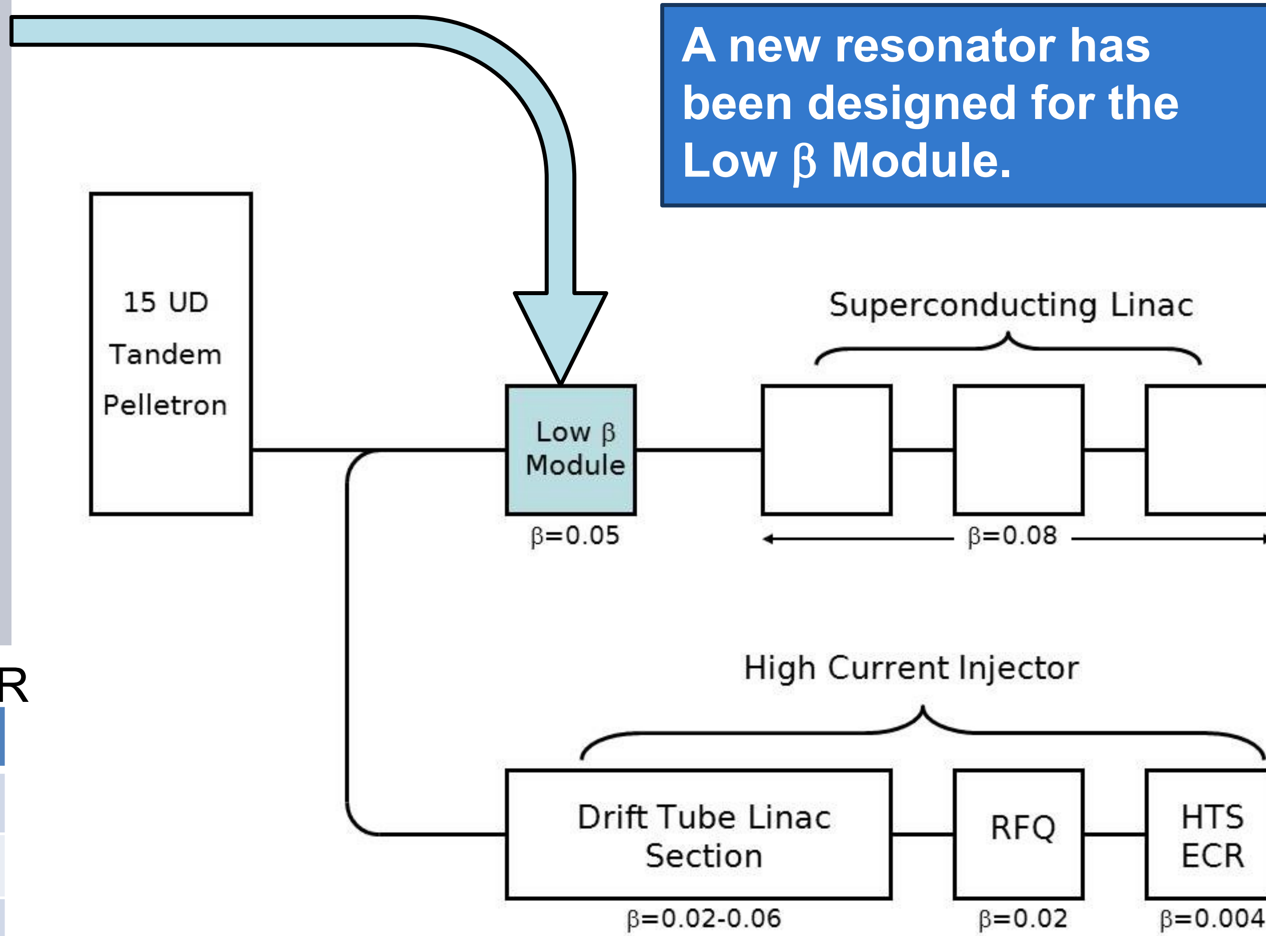
Design and development of Low Beta Resonator



Cut away 3D view of LBR

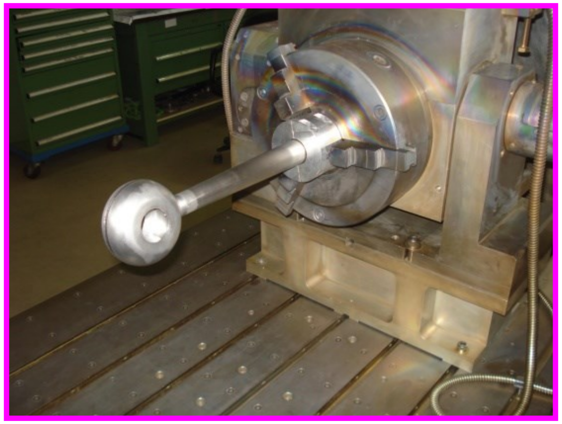
Parameter	Value
β	0.05
f	97 MHz
L_{eff}	~11 cm
U_0	26 mJ
B_{peak}	64 G

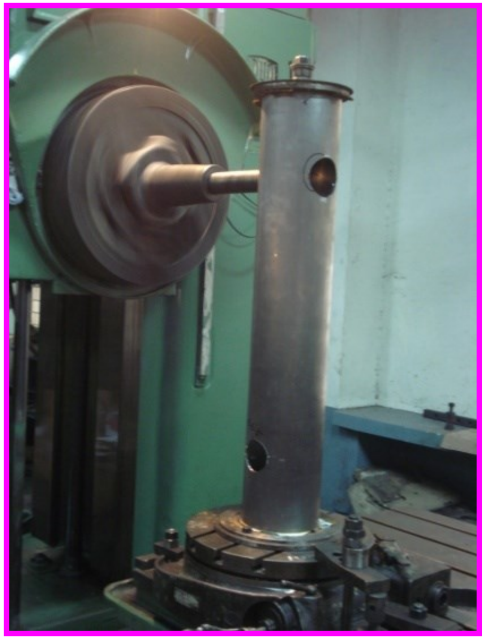
A new resonator has been designed for the Low β Module.

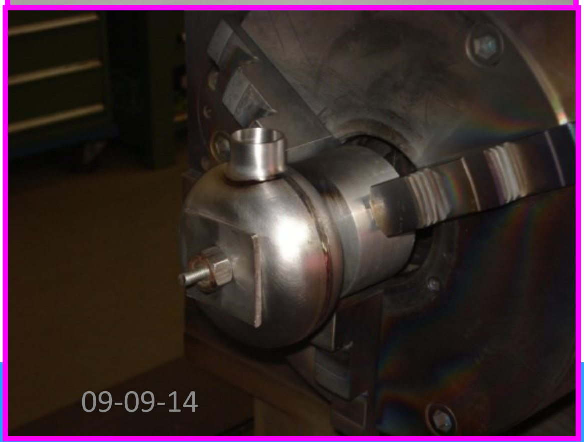


High Current Injector

Design and development of Low beta Resonator



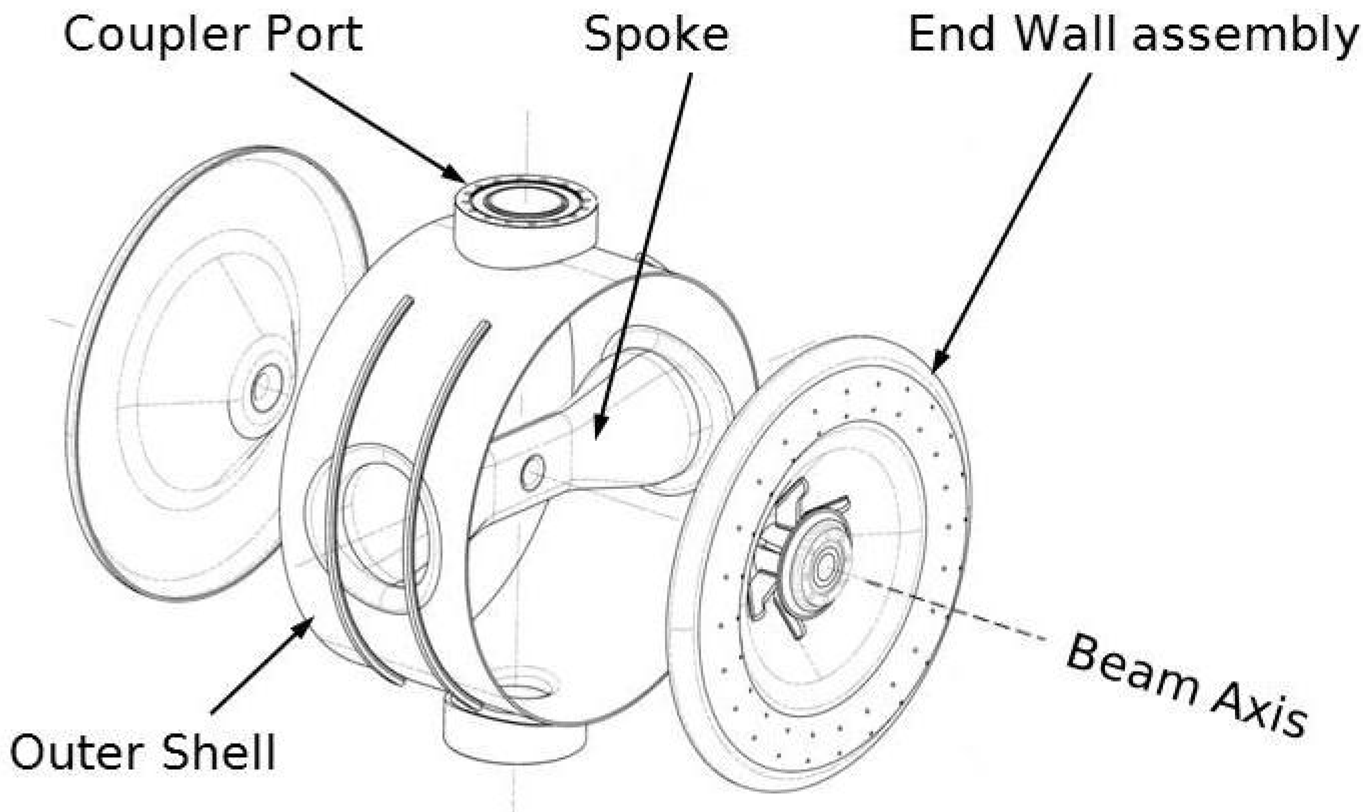




Prototype low beta resonator to be tested soon

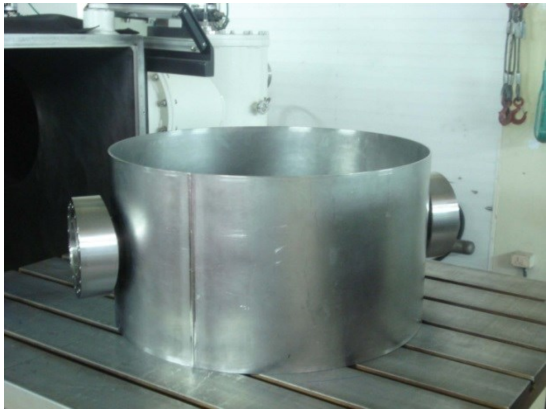
Fabrication of Single Spoke resonator for Project-X

IUAC is presently constructing two SSR1 niobium resonators.



SSR1 - β=0.22, 325 MHz, Niobium Assembly

Fabrication of Single Spoke resonator for Project-X



Shell with Coupler Ports

End Wall assembly

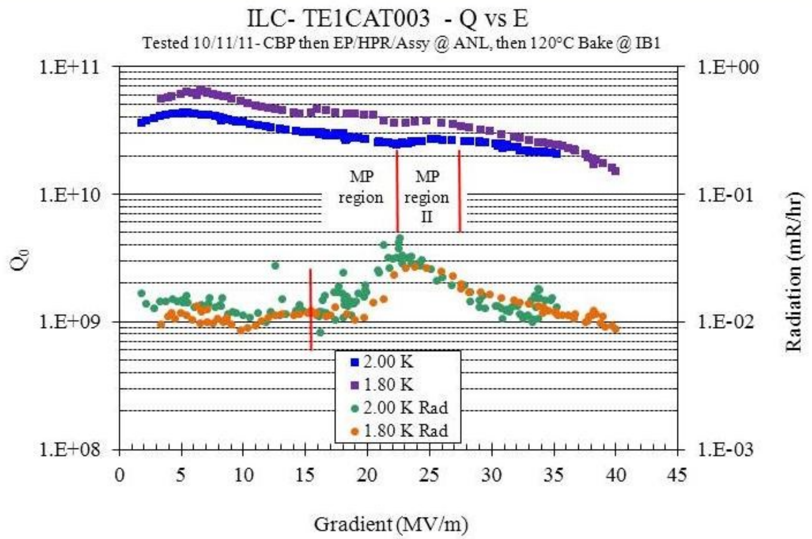
Electropolished End Wall

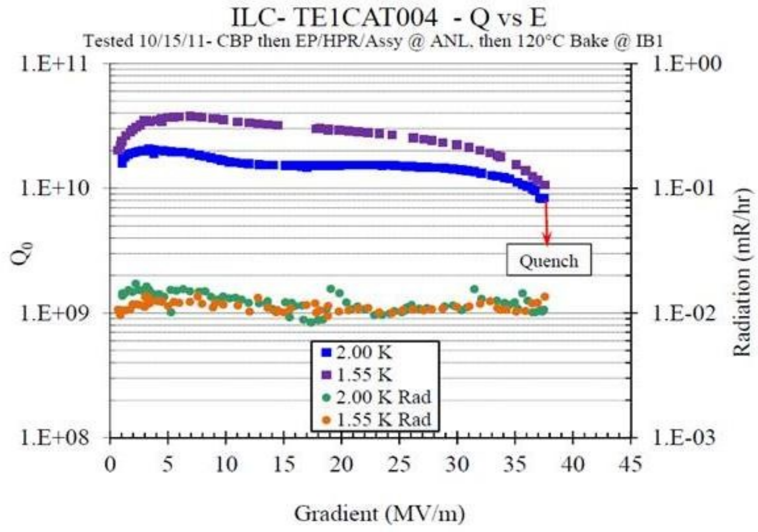
Spoke assembly after electropolishing.

Present status

- Two outer shell assemblies and the end walls are electropolished
- Spoke to shell collar transition EBW is done
- End walls to be welded with shell

Tesla Type 1.3 GHz Single cell cavity





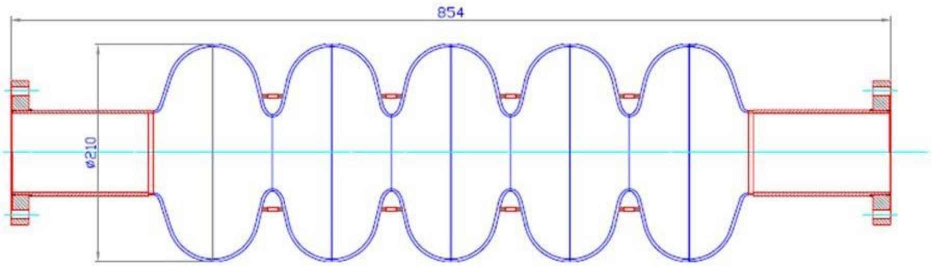
Accelerating gradient achieved in Cavity # 3 & 4

- Formed and machined at RRCAT
- Electron beam welded at IUAC
- EPed and surface treatment at ANL/Fermilab
- Tested at Fermilab

A niobium Single cell Cavity

Tesla Type 1.3 GHz multi cell cavity

Near Future

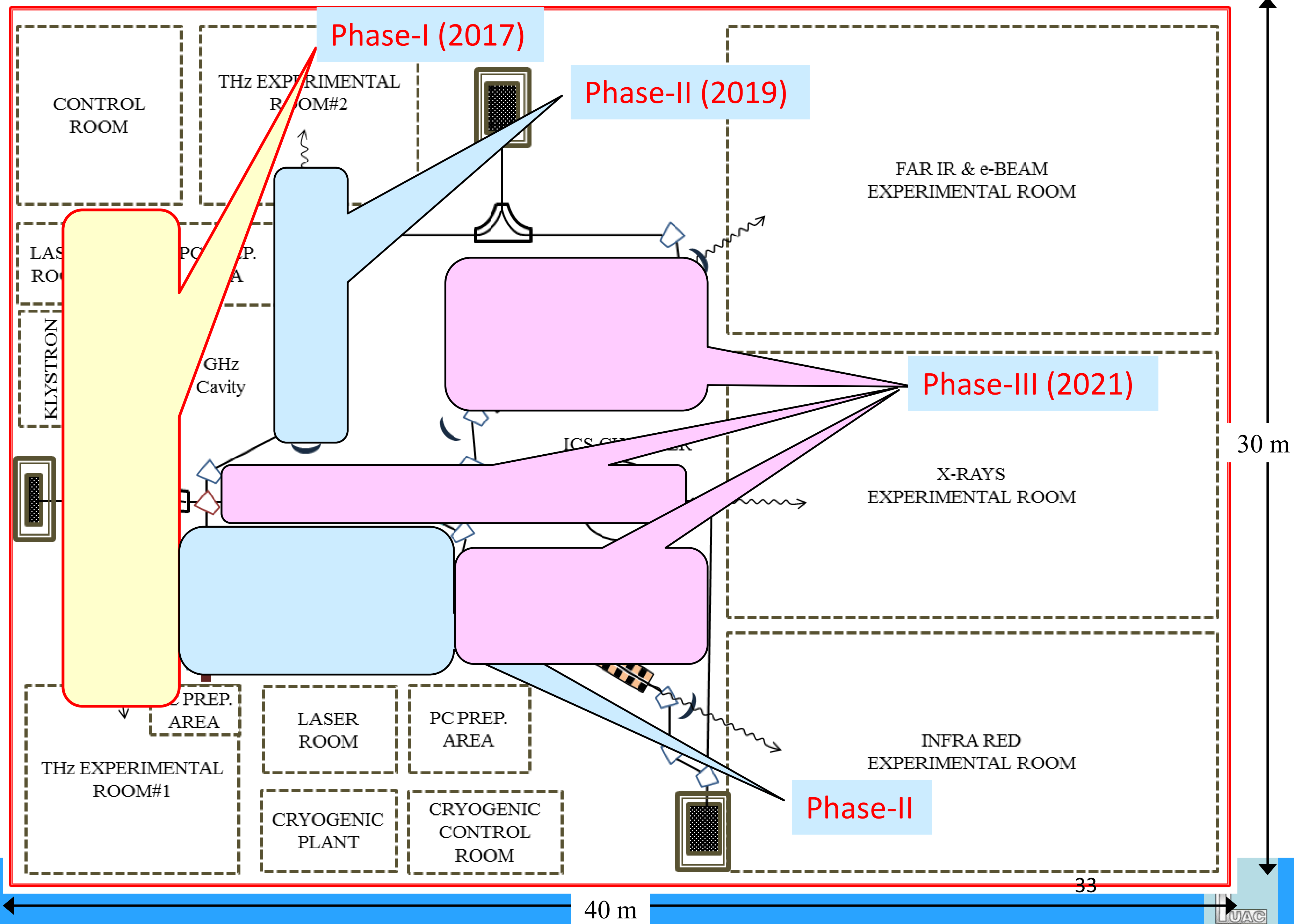


- Will be formed/machined RRCAT
- To be beam welded at IUAC
- To be EP'ed and surface treatment at ANL/Fermilab
- To be tested at Fermilab

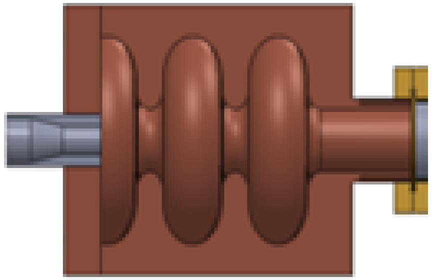
Fabrication of 650 MHz Single cell cavities for Project-X - Future

- Will be formed/machined at RRCAT
- To be beam welded at IUAC
- To be EP'ed and surface treatment at ANL/Fermilab
- To be tested at Fermilab

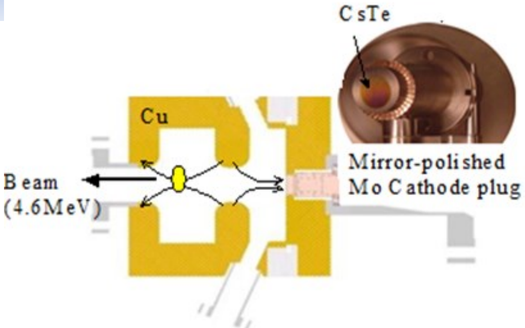
Layout of Delhi Light Source (DLS)

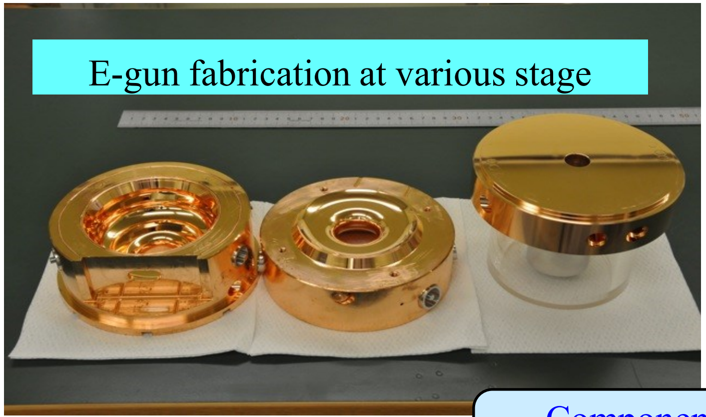


Phase-I: RT e-gun

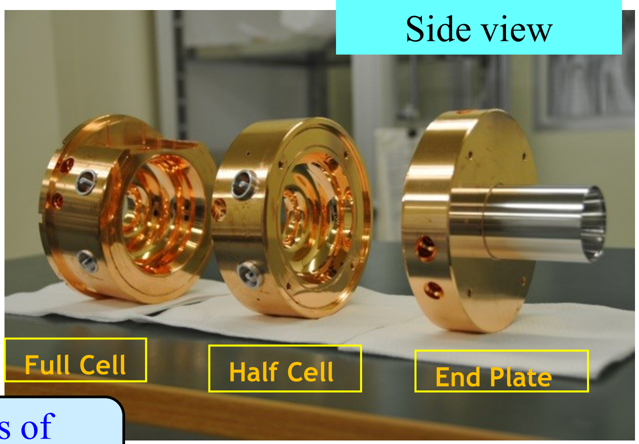


2.6 cell, S-band resonator
Frequency = 2860 MHz
Q-value (expected) ~ 15000

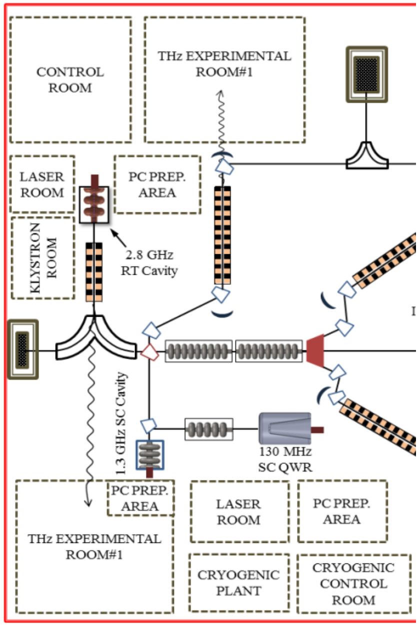




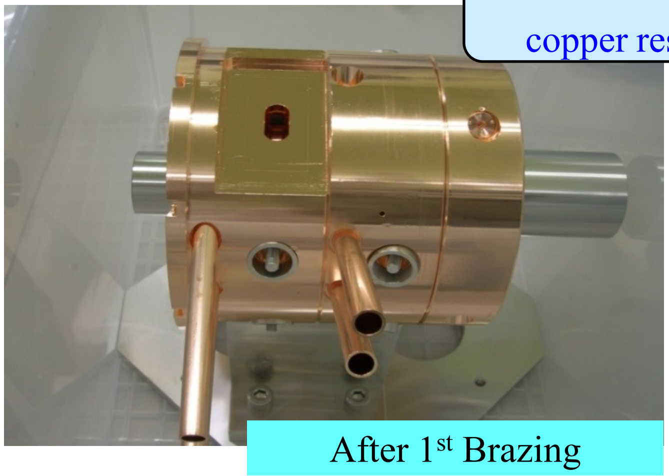
E-gun fabrication at various stage



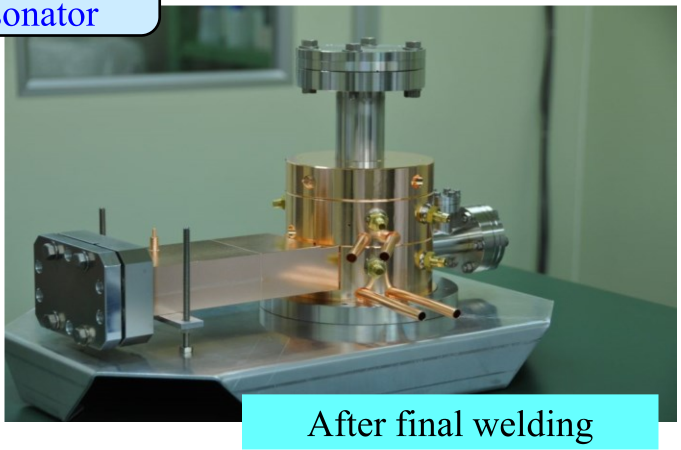
Side view



Components of copper resonator



After 1st Brazing

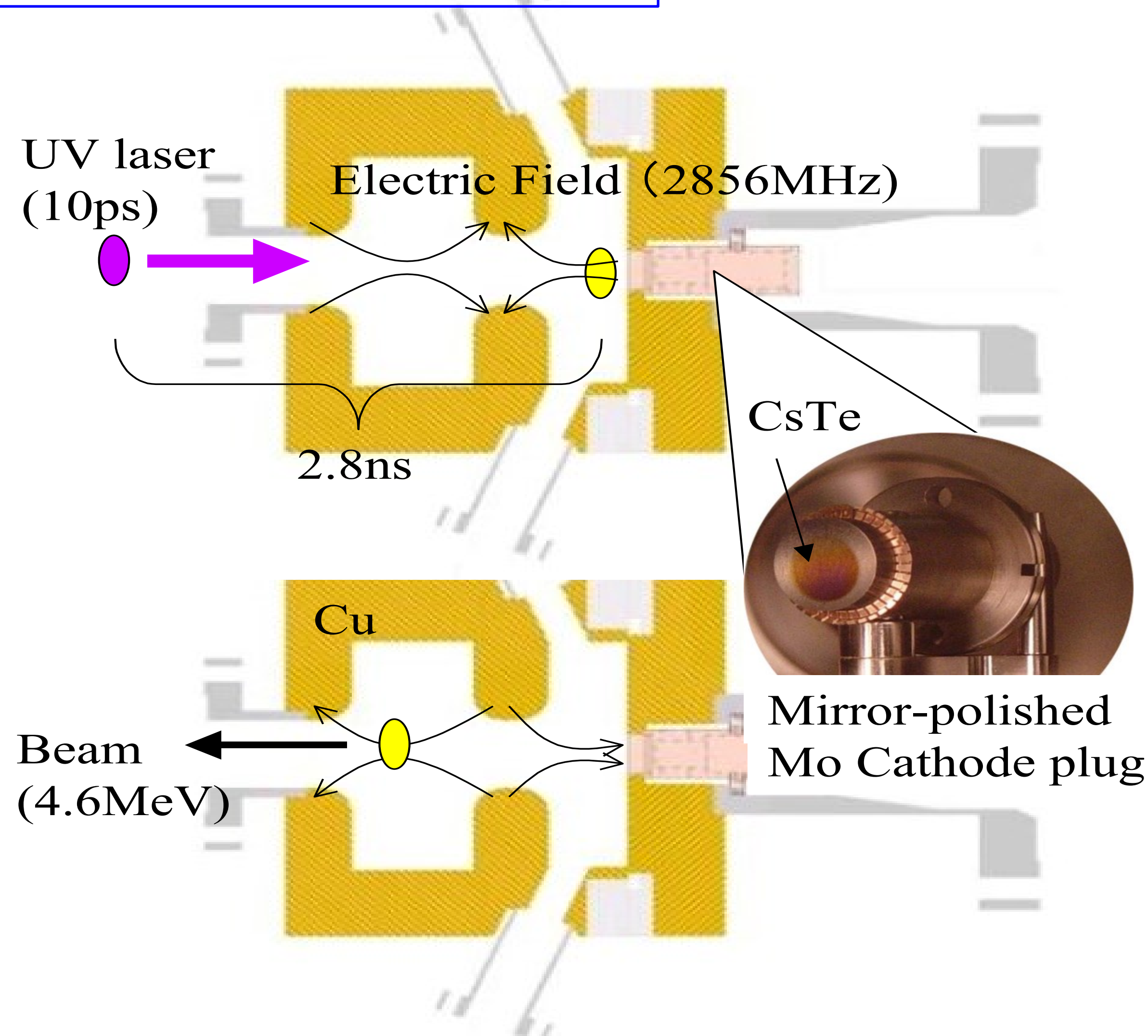


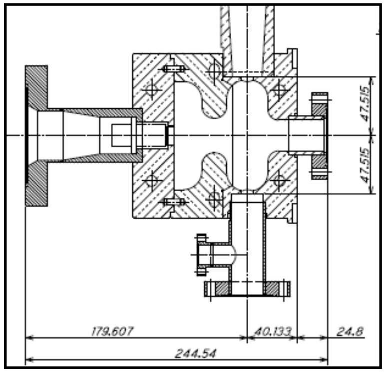
After final welding

Courtsey:
Prof. Junji Urakawa

Phase-I: RT e-gun

Details of Photocathode





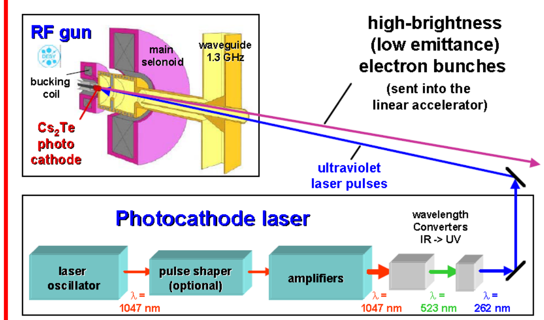


Figure 1: General setup of a photoinjector
(picture of the gun by courtesy of K. Floettmann, DESY Hamburg)

Courtsey:
Prof. Junji Urakawa

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 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

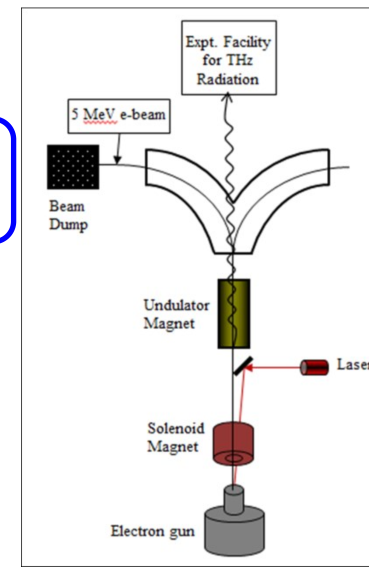
Details of Photocathode

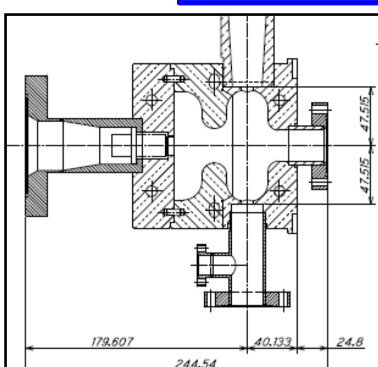
- Preparation of Semiconductor photocathode e.g. Cs_2Te
- Preparation / Procurement of GaN (?)

To be developed at IUAC

Photocathode preparation chamber & load lock mechanism to transfer in to accelerating resonator

Cathode Preparation Chamber ⟷ **Cathode Transport System (under vac)** → **Accelerating Resonator** → 8 MeV e-beam





Courtsey:
Prof. Junji Urakawa, KEK

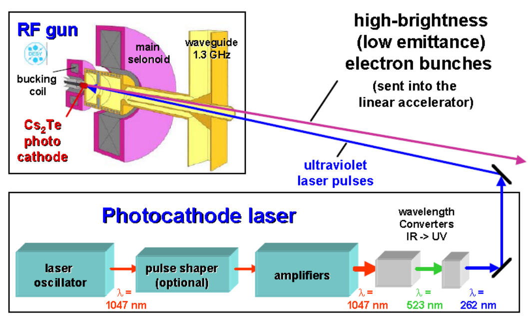
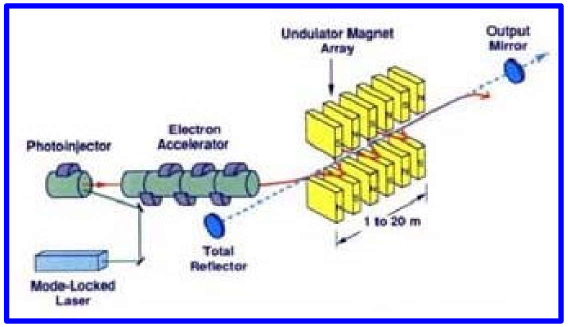
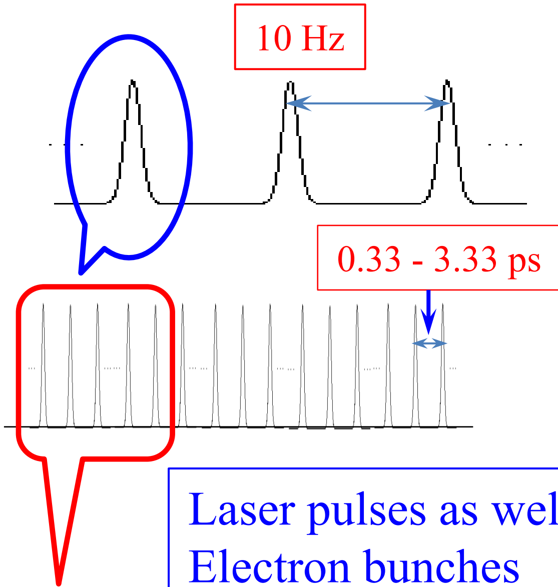
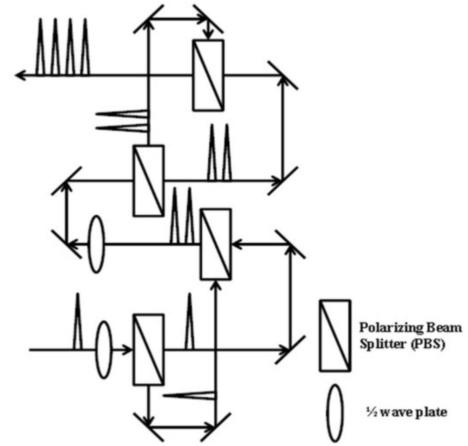


Figure 1: General setup of a photoinjector
(picture of the gun by courtesy of K. Floettmann, DESY Hamburg)

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





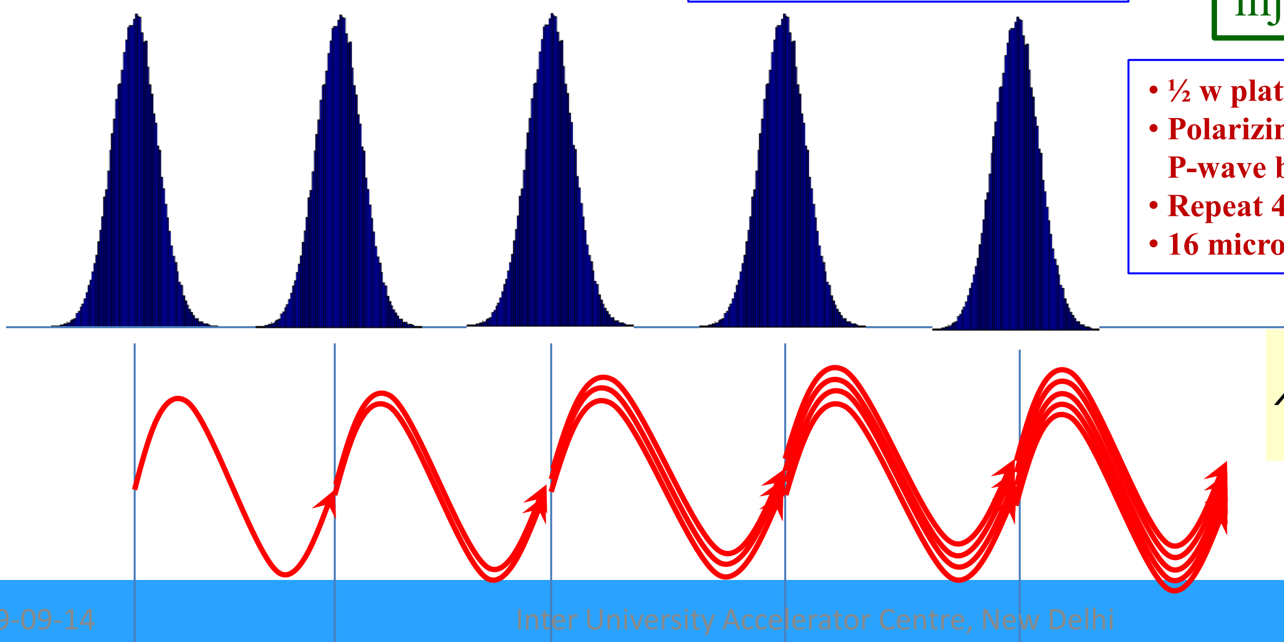


f = 3 – 0.3 THz
T = 0.33 ps to 3.3 ps
λ = 30 μm to 1 mm

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 45°.
- 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 – tentative specifications

Aim is to produce 0.1 nC e-charge /laser pulse @ 266 nm, Pulse width ~ 100-200 fs

- 100 pC/micro-pulse means = $100 \times 10^{-12} / 1.6 \times 10^{-19} = 6.25 \times 10^{8}$ electrons
- If QE = 0.5% (worst case), $1.56\times10^{11(b)}$ photons are necessary to produce 6.25×10^{8} electrons
- Energy of a photon, $E = h\nu$, $7.5\times10^{-19(a)}$, Total energy per pulse = (a) x (b) ~ 116 nJ/pulse
- Single laser splitting into 16 pulses, so energy per pulse (minimum) = 0.116 x 16 ~ 2 µJ/pulse
  - With a safety factor of 5, energy per pulse = 10 µJ/pulse
- Conversion from IR (800 nm) to UV (266 nm) – power down-conversion is 5%
- **Minimum Laser power (800 nm) ~ 200 µJ/pulse**
- If the frequency of the rep rate is 10 Hz/10 KHz, power required @ 1066 nm = 2 mW / 2 W

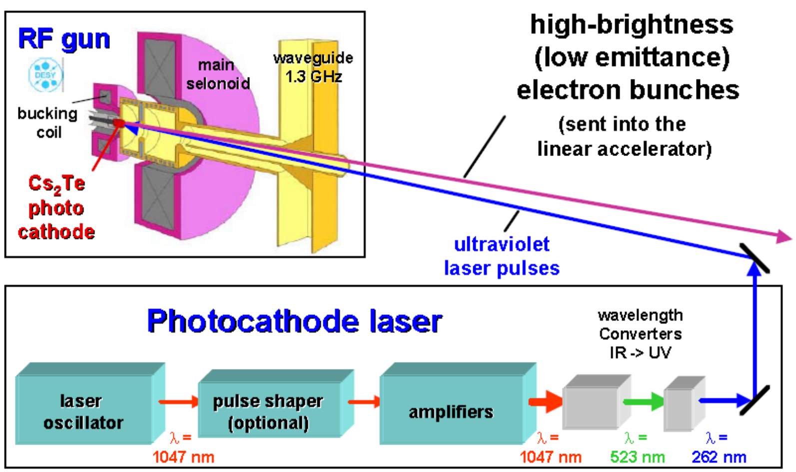
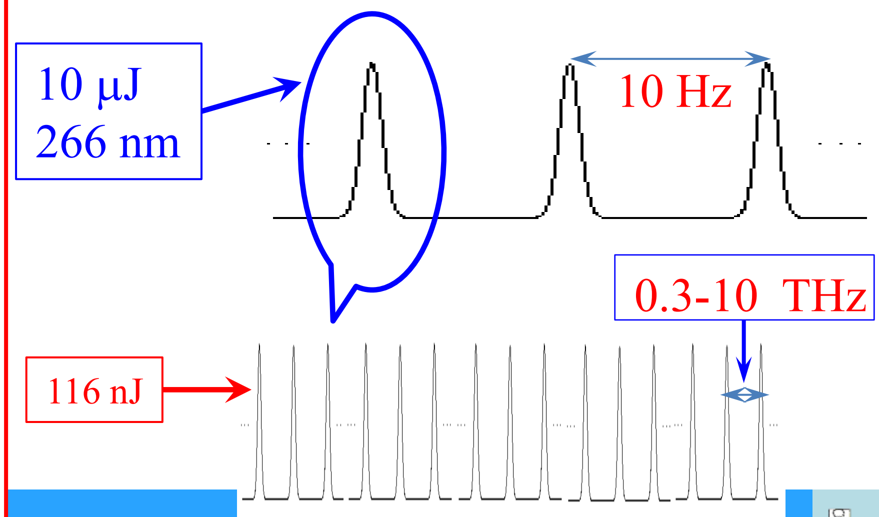


Figure 1: General setup of a photoinjector
(picture of the gun by courtesy of K. Floettmann, DESY Hamburg)



Recommended Laser system for FEL (RT PI)

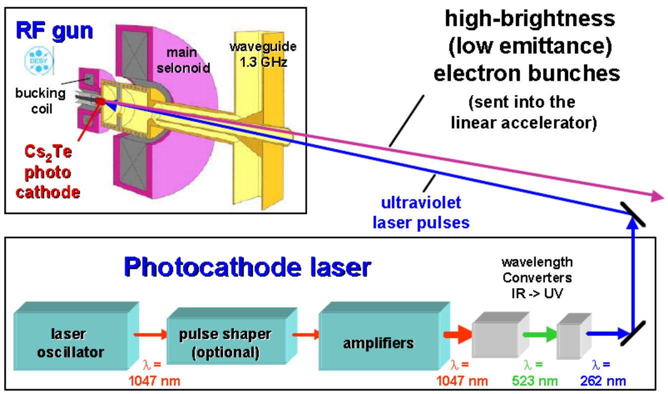


Figure 1: General setup of a photoinjector
(picture of the gun by courtesy of K. Floettmann, DESY Hamburg)

The Laser system of AT is based on Ti:Sa Oscillator			
Wavelength	800 nm		
Reference Frequency	130 MHz		
Oscillator Frequency	130 MHz		
Pulse duration	< 20 femto-sec		
Model Name	Trident - X	Trident - C	Trident - M
Repetition rate	10 Hz	100 Hz	Multi KHz
Energy per pulse	≤ 25 mJ	≤ 10 mJ	≤ 3 mJ
Stability	<1.5% rms	< 1.2% rms	< 0.8% rms
ASE contrast	$>10^5.1$		

Laser Osc. (130 MHz, 7.69 ns, 100 fs, λ = 1 – 0.78 μm

Shutter (Width < 4 ns, f = 10, 100 Hz

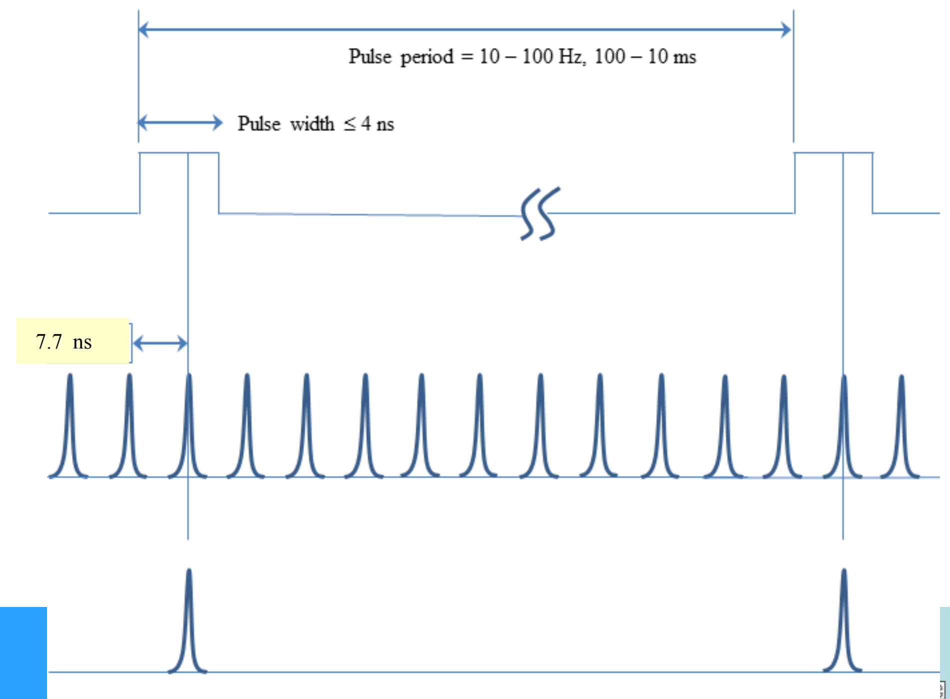
Amplifier

Freq converter (IR to UV)

e-Gun

Single pass e-beam, low frequency (10 Hz)

Suitable for RT e-gun



Tentative parameters for the THz facility at IUAC (modified)

Beam Parameters:

Electron Energy (MeV)	7
Charge / Pulse (pC)	100
E-beam bunch length (fs)	300
No. of micro-bunches (300fs each)	16
Frequency of micro-bunch trains (Hz)	10
Peak current (Amp) [1]	333
Peak beam power (GWatts) [2]	2.3
Average beam current (nA) [3]	16
Average beam power (watts) [4]	0.112

Radiation & Undulator Parameters:

Radiation wavelength (μm)	150
K-parameter	0.8
Undulator period (cm) [5]	3.4
RMS strength (Tesla) [6]	0.25
Number of periods (N) w 1m undultr	30
Peak radiation power (MW) [7]	15
Average radiation power (mW) [8]	0.75
Peak no. of photons [9] / 200 fs	10^{28}
Average no. of photons / sec [10]	10^{17}

[1] $\frac{100pC}{300\times10^{-15}} = 333A$

[2] 333A x 7 -MV = 2.3 GW

[3] 100pC x 16 x 10 Hz = 16 nA

[4] 16 nA x 7 ~~5~~ MV = 112 mWatts

[5] $150\times10^{-6} = \frac{\lambda_u}{2\gamma^2}[1+K^2] \Rightarrow \lambda_u \approx 34mm$

[6] $0.8 = \frac{e\times B_u\times\lambda_u}{2\times\pi\times m\times c} \Rightarrow B_u = 0.25T$

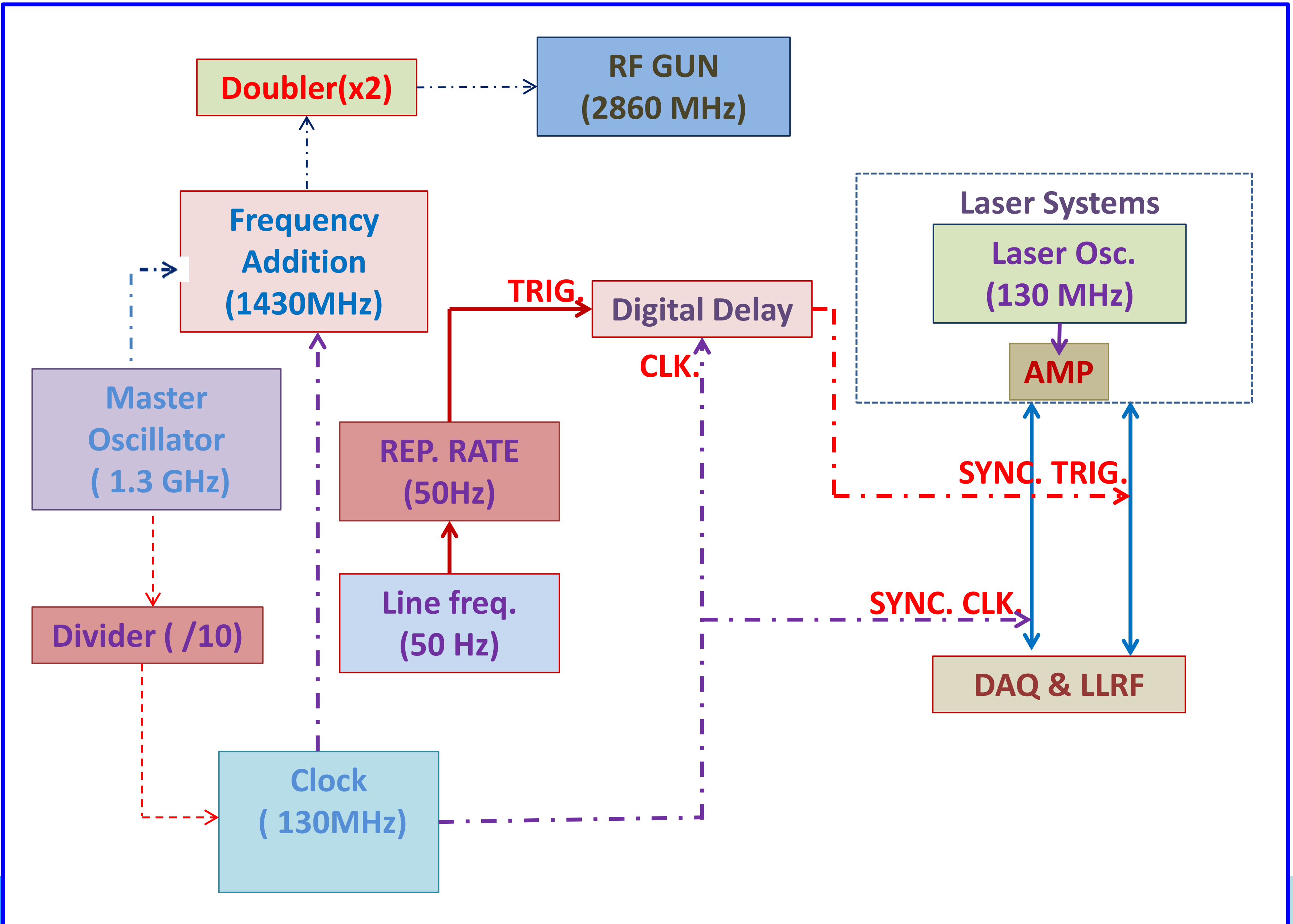
[7] $P_{out} \approx \frac{1}{5N}P_{beam} = \frac{1}{150}\times2.3\times10^9 \approx 15MW$

[8] $P_{out} \approx \frac{1}{5N}P_{beam} = \frac{1}{150}\times0.112 = 0.75mW$

[9] $\frac{23.3\times10^6}{h\nu} = 1.76\times10^{28}$

[10] $\frac{0.75\times10^{-3}}{h\nu} = 5.68\times10^{17}$

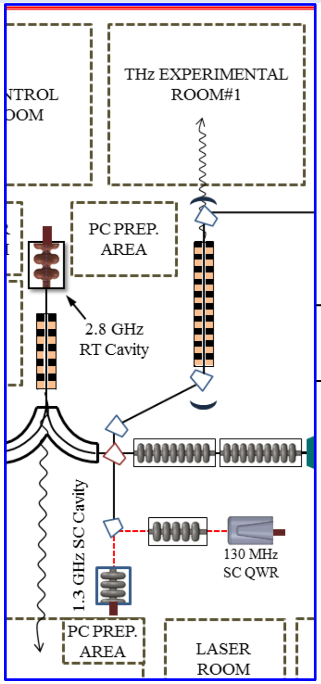
Reference clock distribution system of FEL



Superconducting electron gun (DST & IUAC funded)

1 **3.6 cell 1.3 GHz SC gun**
Final Energy ~ 8 Mev

2 **QWR (130 MHz) SC RF gun + 5 cell 1.3 GHz**
Final Energy ~ 10 MeV

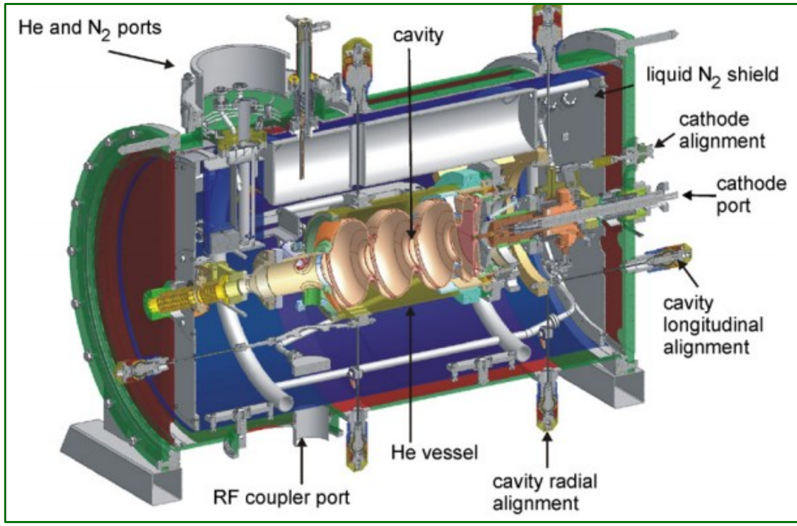


Advantage of 1.3 GHz resonator over 130 MHz QWR

- Much more matured technology
- Already in operation
- Technical knowhow exists
- Acquired knowledge will be useful for making 9 cell resonator, has to be made anyway

To develop knowledge on:

- Cavity (3.5 cell) and cryostat fabrication
- Handling of 2K LHe and other cryogenics details
- Indep. tuning mechanism of gun and accel. cells
- Design of the choke filter
- Design of HOM and input couplers

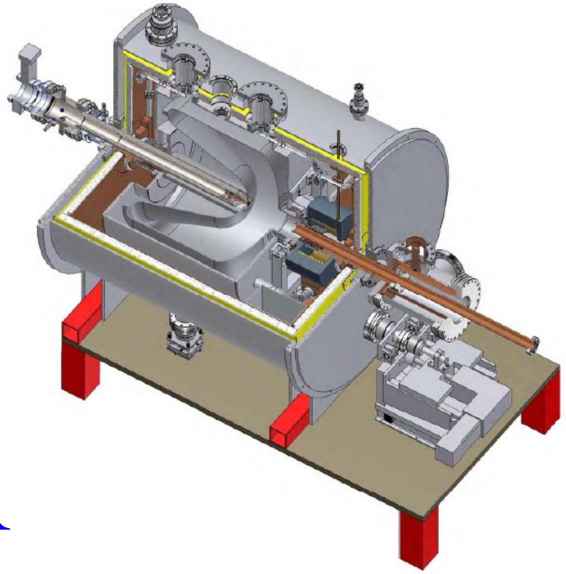


Courtsey: A.Arnold et. al, NIM A 577 (2007) p. 440

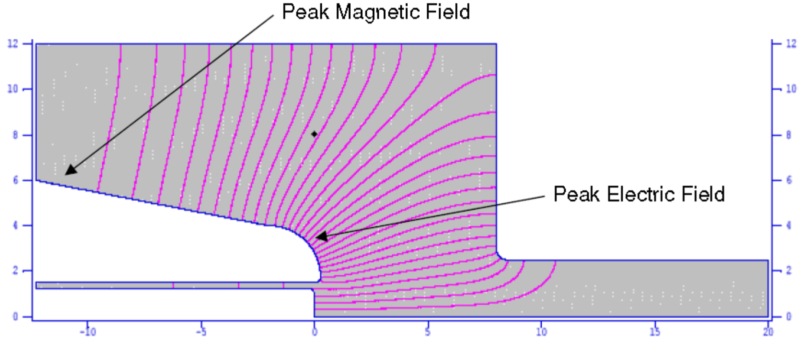
Superconducting electron gun (DST & IUAC funded)

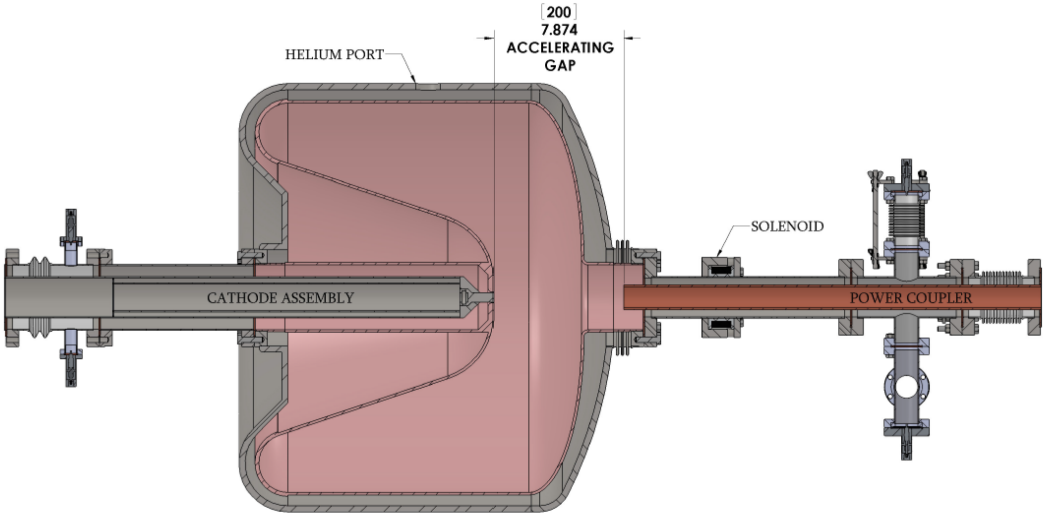
2

QWR RF gun followed by 5 cell 1.3 GHz
Energy from QWR ~ 2 MeV



- Frequency of the resonator ~ 130 MHz
- Structure – Double walled Niobium QWR
- Energy obtained ~ 2 MeV
- To be followed by 1.3 GHz ~5 cell, Final energy ~ 10 MeV

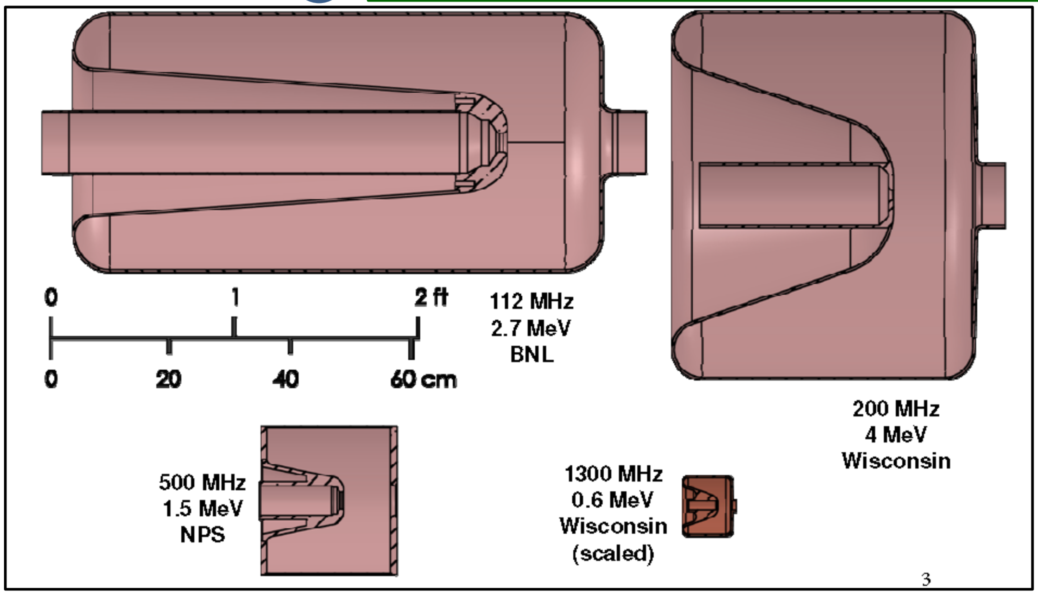


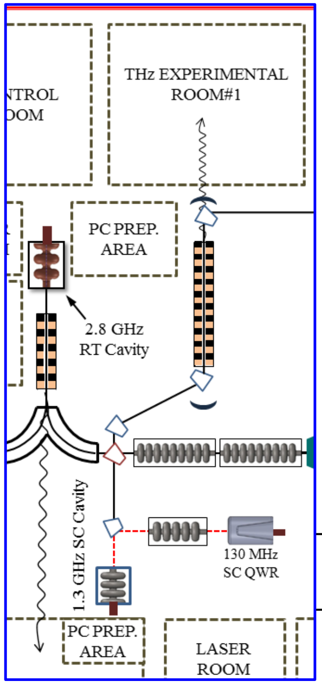


Superconducting electron gun (To be funded by DST & IUAC)

2

QWR (130 MHz) RF gun + 5 cell 1.3 GHz
Final Energy ~ 10 MeV





SC RF gun

Advantage of low frequency resonator over higher frequency resonator

- Cryoplant operation at 4.2 K
- Small accelerating gap in comparison to the λ_{RF} so electric field is practically dc ($T_{130} \sim 7.69$ns, $T_{1300} \sim 0.769$ns)
- Reduced RF losses @ PC (dielectric loss ~ f, skin effect ~ sqrt(f)
- High power, inexpensive CW source and RF couplers available
- Improved photocathode lifetime & less MP

Disadvantage:

- Still not used for operation
- Chances of failure ???

Collaboration, MoU etc.

Strategy:

- Collaborative institute should have their individual benefit
  - Should identify areas with common interests
  - Clarify each other's requirement/expectation

IUAC's requirement:

- Develop SC 1.3 GHz, accelerate e-beam
  - Fabrication of cavity, Surface preparation, vertical test, fabrication of cryostat and final testing
  - Production of high quality e-beam, different diagnostic
- Develop undulator and produce e.m. radiation
  - Design, Fabrication/procurement of Undulator
  - Production of em radiation & diagnostic/measurement
  - Transport and delivery of the beam for experiment
- Start developing an user base (presently for THz)

Collaboration, MoU etc.

What IUAC can offer:

- In Accelerator development:
  - Provide manpower to work in Host Institute's accelerator project
  - Gain experience while working and apply that at DLS
  - IUAC can develop multiple components, for host/guest institutes

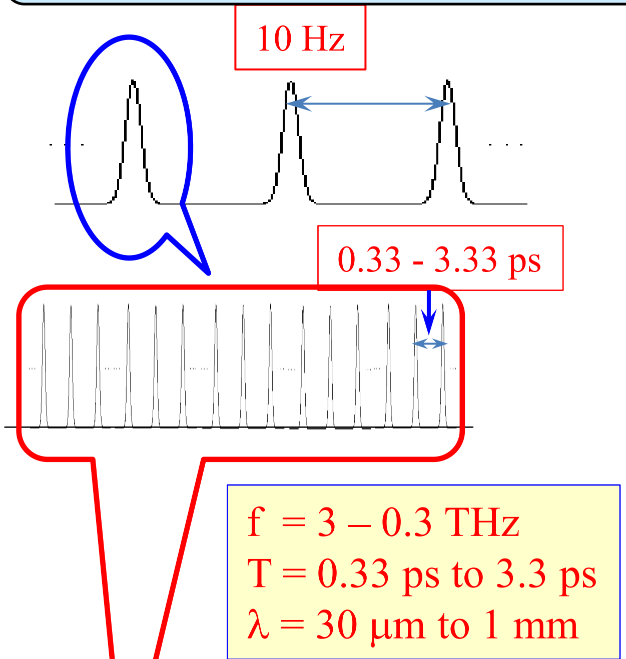
- In the field of Experiments etc.:
  - IUAC can form a researcher's group in India. They jointly propose some experiments in host institutes. Indian researcher/students can work in developing beam line, expt. setup etc.
  - Researcher from host institutes can participate in expts at IUAC

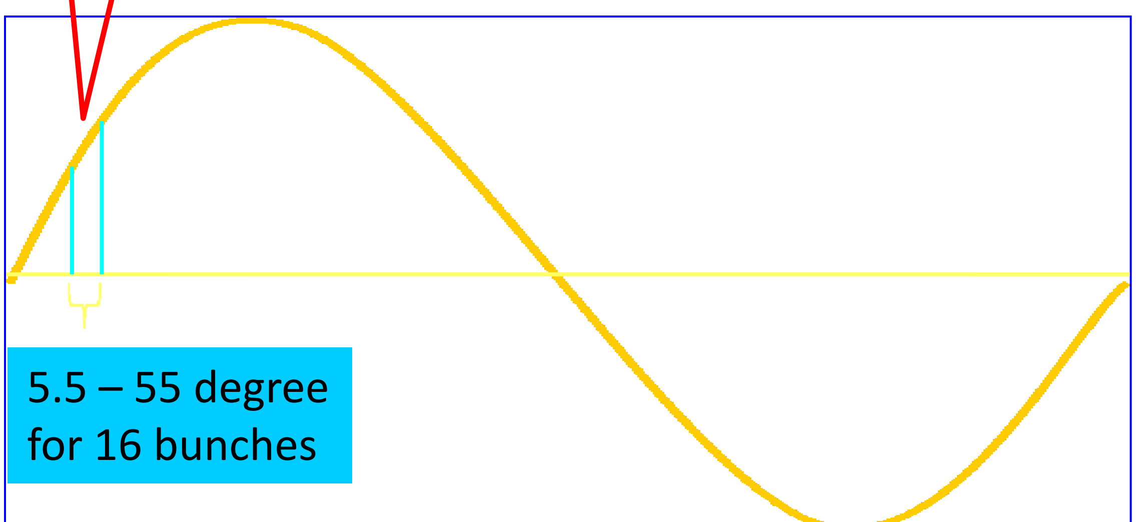
Conclusion

- IUAC has taken up a project to develop a compact Light source
- Project has got three parts -
  - Development of RT e-gun and produce THz
  - Development of SC e-gun and produce high power THz
  - Development of 1.3 GHz 9 cell cavity, increase the e-energy & produce IR and X-rays (ICS)
- For development of SC RF gun and 1.3 GHz 9 cell cavity, IUAC wants to collaborate. SRF technology exists at IUAC.
- For development of user base, IUAC wants to train Indian researcher in the field of photon science


Thank you for your kind attention

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
- 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

Beam optics design for the RT e-Gun

Requirements for the first phase of the project:

Beam energy(E): 8 MeV

Spread (ΔE)~1% (~80keV)

Bunch charge : 0.2 nC

Bunch width: 0.2ps

Normalized transverse emittance: ~1π mm-mrad

Tranverse beam size at the undulator ~250μm

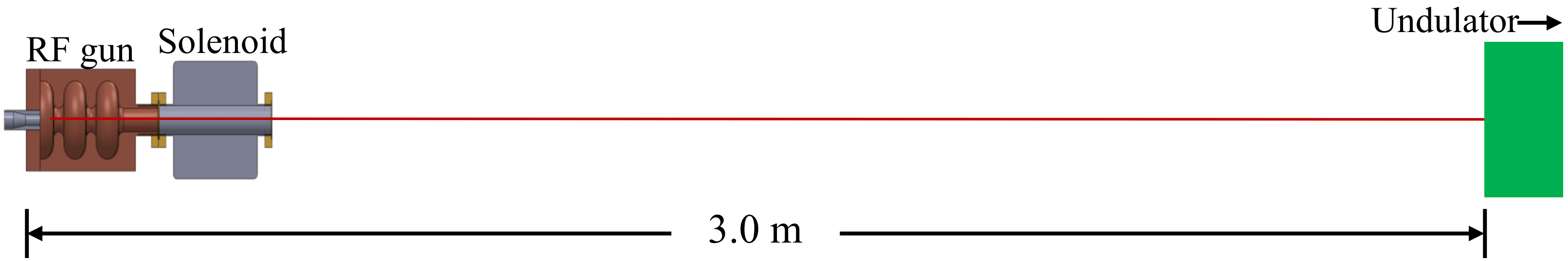
Initial design calculations being done using ASTRA (**A** **S**pace **C**harge **T**racking **A**lgorithm).

A tentative list of the essential beam line components with their approximate positioning are being prepared.

Beam optics design for the proposed light source facility (RT e-Gun)

Preliminary trial runs with ASTRA (to understand the working of the code)

Beam line configuration used in trials



Beam optics design for the RT e-Gun

Optimizations:

Laser Injection phase= 21°
Accelerating field in 2.6 cell RF cavity= 120 MV/m
Solenoid field=0.238 T
Solenoid position=0.16 m
Solenoid field profile

Results:

Output beam energy=8.56 MeV
Energy spread (ΔE)=41.5 keV
Horizontal beam size (σx)=0.1 mm
Vertical beam size (σy)=0.1 mm
Normalized transverse emittance case 1 (εx, εy) ~ 1.05/1.04 π mm mrad radial
Normalized transverse emittance case 2 (εx, εy)=1.49 / 1.37 π mm mrad gaussian
Longitudinal beam emittance case 1 (εz)= 3.348 π keV mm (mm @ 8.56 MeV = 3.3 ps)
Longitudinal beam emittance case 2 (εz)= 10.6π keV mm

Klystron and modulator – purchase, installation, testing

Klystron

Sl.	Parameter	Value	Remarks
1.	Rated Peak Output power	≥ 25 MW	
2.	Rated average Output power	≥ 20 KW	
3.	Central operating frequency	2860 MHz	2856 MHz klystron easily converted to 2860 MHz
4.	Bandwidth (-1 dB)	A few MHz	To be specified
5.	Maximum operating output RF pulse duration measured at 3dB points	4 μs	
6.	Operating Pulse repetition rate	Up to 200 Hz	To be confirmed by expert

Modulator

	Parameter	Value	Remarks
1.	Modulator Power peak	≥ 75 MW	
2.	Modulator Power average	≥ 20 kW	Decided by Pul Rep Freq (PRF)
3.	Pulse voltage	≥ 280 kV	
4.	Pulse Current	≥ 280 A	
5.	Operating Pulse repetition rate	up to 200 Hz	PRF To be checked
6.	**Pulse length (top)**	**~ 4 μs**	

Challenges in superconducting Linac operation

Resonator frequency will drift

Slow drift (tens of sec)
± 250 Hz or so

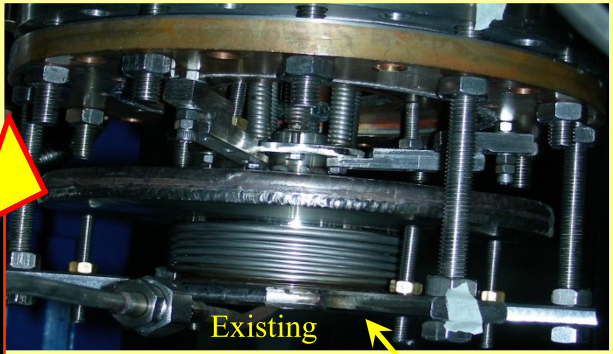
Controlled by mechanical tuner

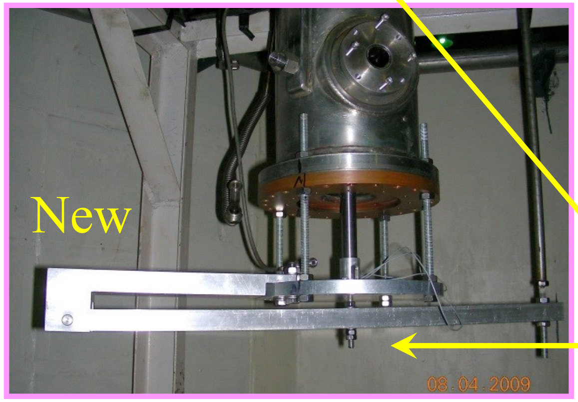
Fast drift (tens of ms)
± 25 Hz or so

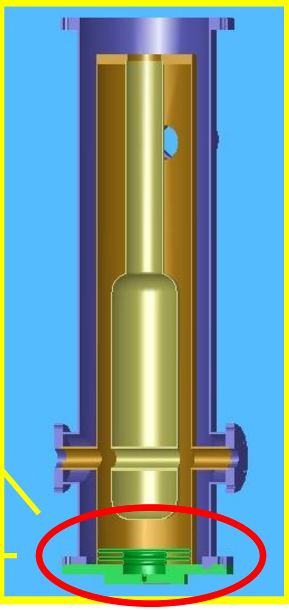
Controlled electronically by res. controller

Why alternative frequency tuning mechanism

- Average RF power will be reduced
- Improved dynamics for the phase/freq control
- Acts as vibrational damper for mech. Tuner (~30 Hz)
- Flexing the tuner bellow by helium gas
  - Expensive & Not so simple method







Gas controlled tuner (Present)			Piezo-crystal tuner (new)		
Resp. Time	Freq Varia-tions	Amp. Power (Max)	Resp. Time	Freq Varia-tions	Amp. Power (Max)
Second	97,000, 000 ± 25 Hz	275 watts	~ 50 msec	97,000, 000 ± 1.25 Hz	113 watts

Research with THz, IR and X-rays from FEL

Biological research:

Tera Hertz : 1. Oncology – skin cancer, [British J. Dermatology, 151:424-432, 2004]

2. Molecular structure determination in drug research [Journal of Biological Physics, 29, 89–100 (2003)]
3. Dentistry, Oral healthcare, Tissue ablation, Security surveilance
4. Chemical and bioagent detection through THz spectroscopy
5. Time resolved THz spectroscopy of protein folding, Expt. with Biochips, Food processing

Infra-red : 1. Ablation – Tissue, Bone, Fat, Cholesterol ester etc.

2. Application in Neurosurgery

X-rays : 1. Artificial leaf – to produce Oxygen, proton, will provide a source of alternate fuel in future

[Jan Kern et al. Science Express, published on line on 14 Feb 2013, DOI: 10.1126/science 1234273]

2. Research in structural biology with single protein crystal – 3D images from 2D [Nov. 2012, Science]

Research in Physical Sciences: [terahertz]

Tera Hertz : 1. Research in Electro-optics - building block of modern comm. & information processing

2. Coherent quantum control - control the quantum mech state of electron – future quantum computing - qubits
3. Terahertz Rabi Oscillations
4. THz – time domain spectroscopy (TDS) and THz tomography started obtaining images
5. Electron paramagnetic resonance (EPR) or Electron spin resonance (ESR) – a technique to study material with the unpaired electron – successfully done with T-rays
7. Terahertz dynamics in materials especially dynamics driven far from equillibrium
8. Photon assisted transport
9. Material Physics, Device Physics, High altitude communication

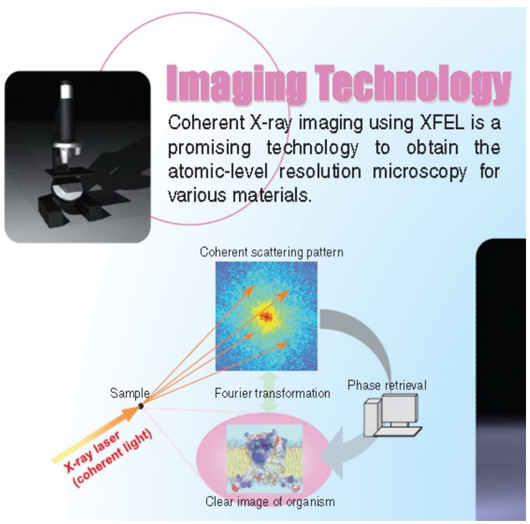
Research with THz, IR and X-rays from FEL

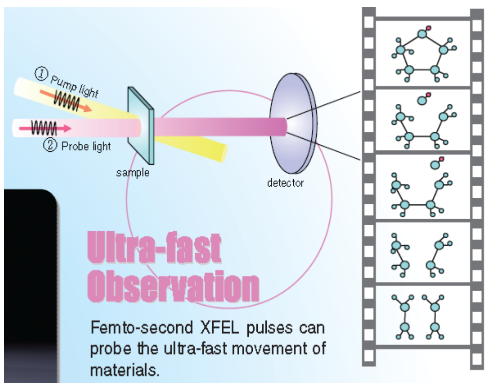
Research in Physical Sciences:

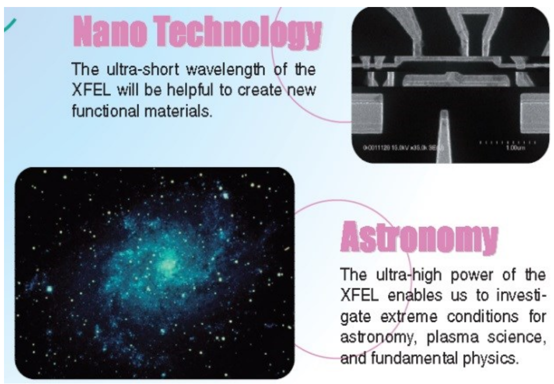
Infra-red :

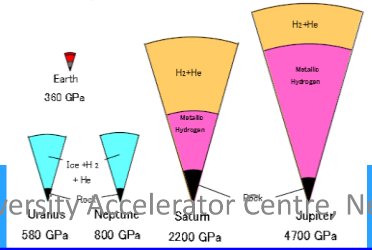
1. Nonlinear Vibrational Spectroscopy in the condensed phase [PRL, **70**, (1993), 2718]
   (a) Vibrational photon echoes (b) Pump probe Experiment
2. Condensed matter research in vibrational relaxation phenomena[Infrared Phys. **89**, (199**6**), 297]
   (a) Amorphous material (b) Nanostructures (c) Spintronics (d) Biomolecules
3. Gas Phase IR spectr. – IR resonance enhanced multi-photon ionization (IR-REMPI) [Infrared Phys. **89**, (199**6**), 297]
   (a) Fullerenes (b) Nanocrystals (c) Clusters and complexes (d) Biomolecules
4. Materials analysis and processing [Ref. Photochemistry and Photobiology, 2005, 81, 711-735]
   (a) 2-colour matrix-assisted laser desorption and ionization
   (b) Mass spectrometry of complex environmental materials
   (c) IR matrix-assisted pulsed laser evaporation of nucleotides

X-rays :







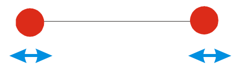


Metallic Hydrogen – predicted to be a room temperature Superconductor

Structural and magnetic property of Hydrogen under ultra high pressure are imp.

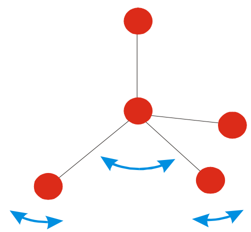
Problem I: Investigations on topology and internal motions in bio molecules(DNA, RNA, Protein).

Bonds



$>700\ cm^{-1}$

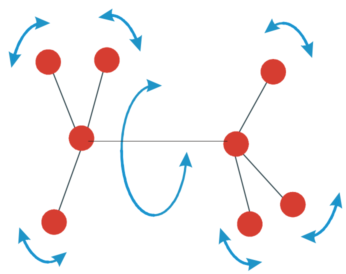
Bond angles



$300\text{-}900\ cm^{-1}$

can be investigated by IR spectroscopy

Torsion angles



$<300\ cm^{-1}$

cannot be investigated by IR spectroscopy…..one Requires Thz spectroscopy

Important for DNA, RNA and Protein

- The far-infrared region of DNA and RNA **absorption spectra (2 - 300 cm^{-1})** reflects **low-frequency molecular internal motions.**
- Resonant frequencies of such motions called **phonon modes**- strongly dependent on:
  - the **weak hydrogen bonds** of the double-helix base-pairs and **non-bonded interactions** between different functional groups.

Problem II: Carrier Mobility in Disordered Systems

In disordered Systems, such as amorphous semiconductor, organic semiconductors, polymer:
Carrier mobility cannot be measured by conventional techniques, such as Hall effect, thermoelectric effect and time of flight.

THz Measurement is non-contact, all optical measurement, providing carrier concentration and frequency dependant mobility. The THZ signal can be correlated to carrier mobility as per the equation below

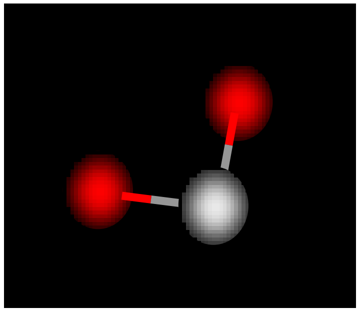
$$\mu = \frac{(\Delta T / T_o) h\nu (1+n)}{\eta e F (1-e^{-\alpha d}) Z_o}$$

μ	*= Mobility*
$\Delta T / To$	*= Differential transmission*
η	*= Photogeneration efficiency*
h	*= Planck's constant*
ν	*= THz frequency*
n	*=Refractive index of substrate*
e	*=Electric charge*
F	*=Fluence*
Z_0	*= Free space impedance*

Phenomena at Terahertz (THz) Frequencies:

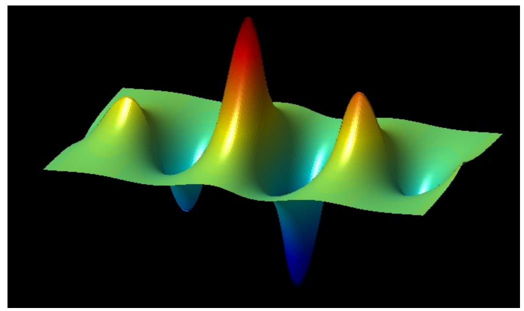
1 THz = 10^{12} Hz =1 ps = 300 μm = 0.004 eV = 33.3 cm^{-1}

Molecular Physics



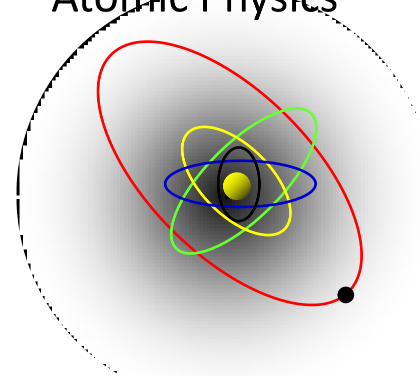
molecules

Plasma Physics



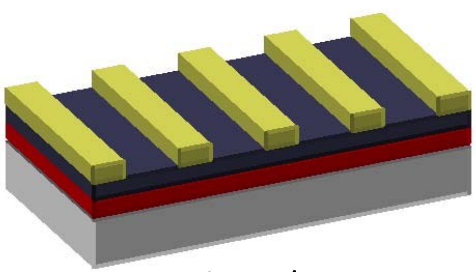
Gaseous and solid-state plasmas

Atomic Physics



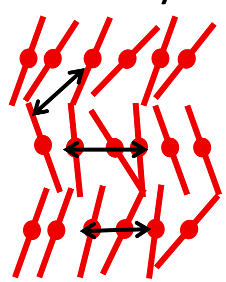
Rydberg atoms

Solid State Physics



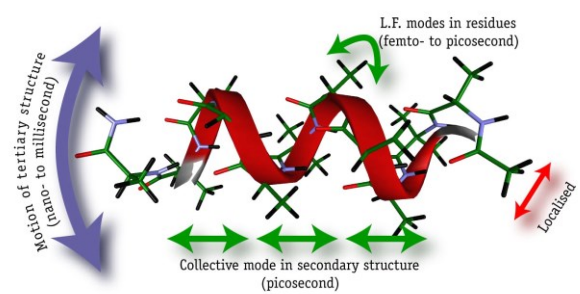
Semiconductor nanostructures

Solid State Physics

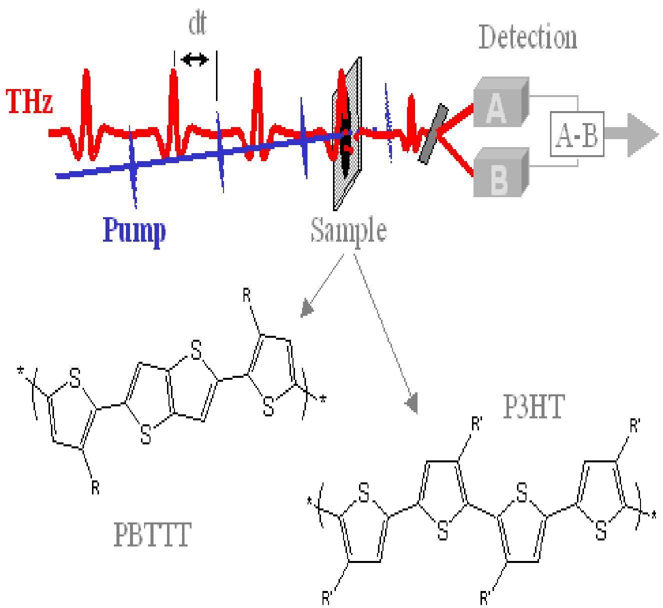


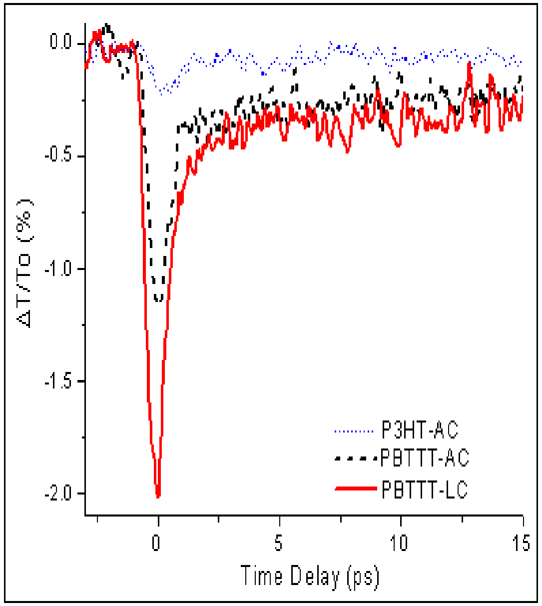
Mobility in Disorder System

BioPhysics



Biomolecules & proteins


dt
THz
Detection
A
B
A-B
Pump
Sample
P3HT
PBTTT

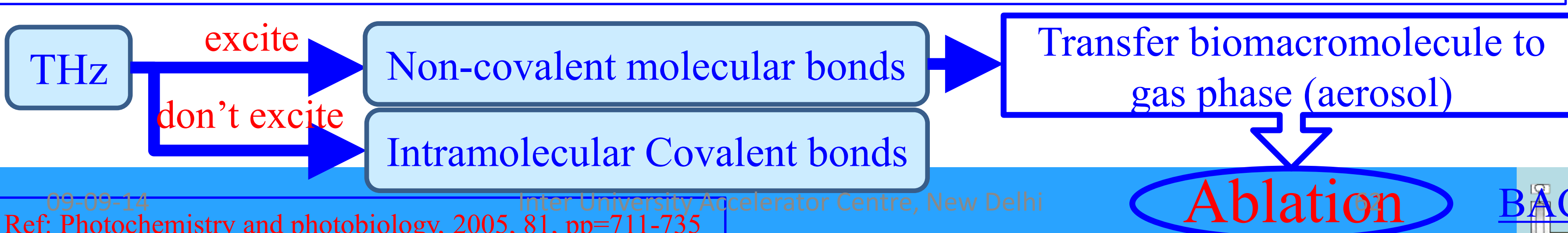

ΔT/To (%)
Time Delay (ps)
P3HT-AC
PBTTT-AC
PBTTT-LC

Research opportunities with different radiations from Free Electron Laser

Tera Hertz range - sub-millimeter radiation – 0.3 to 3 THz (10^{-12} Hz)

Ablation of biological macromolecules under the action of THz irradiation

- Ablation is defined as the removal of material from the surface of object due to vaporization, chipping, or other erosive processes. Ablation can be the transfer of biomacromolecules from solid surface to the aerosol phase under FEL THz irradiation.
- Terahertz irradiation excites non-covalent molecular bonds (including hydrogen bonds).
- Mild, non-destructive ablation has been demonstrated for various nucleic acids (phage DNA and plasmids), proteins, and enzymes.
- Radiation of wavelength from 110 μm to 240 μm can be used, while it is well-known that radiation about 150 μm is capable to excite out-of-the-plane deformation vibrations in intermolecular hydrogen bonds O-H...O and O-H...N.
- Selective dissociation of these bonds by means of FEL radiation makes it possible to transfer a biomacromolecule to the gas phase (aerosol) with the retention of intramolecular covalent bonds.
- This allowed development of a new method of mild and non-destructive ablation.



Ref: Photochemistry and photobiology, 2005, 81, pp=711-735

Research opportunities (Bioscience) with Free Electron Laser beam

A few interesting examples:

3. Research on Biomedical science – to study life forms on different levels – from biomolecules and subcellular structures up to whole organism, Ref [1]

- Advantage of FEL over biomedical laser technique:
  - Superior to regularly used classical laser sources in optimizing wavelength-dose-pulse structure pattern to various types of tissue ablation
  - Minimizing the adverse effects in photo-ablative surgical techniques. Ref [5]

Characteristic absorption bands of a few molecule (mid IR range)

Molecule	Optimal ablation wavelength
Water (OH stretch mode)	2.94 µm
Protein (amide II band)	6.45 µm
Protein (amide I band)	6.10 - 6.12 µm
Stretch of Protein (C = O)	8.525 µm

- Techniques
  - Selection of optimal wavelength at which FEL radiation ablates a tissue → relative absorption of main tissue components, water, the mineral components and the specific proteins
  - FEL laser irradiation can superheat tissue water, driving thermal vapor bubbles confined by tissue matrix and leading to tissue ablation, Ref [6,7,8]
  - Absorption band of many tissues may not be strongest in mid-IR, however FEL ablation is efficient while minimizing collateral damage.
  - Knowing the absorption spectra of a tissue, λ can be guessed to be suitable for optimal ablation
  - Verification of test experiment on the sample needs to be conducted before final application

Research opportunities (Bioscience) with Free Electron Laser beam

A few interesting examples:

3. Research on Biomedical science – to study life forms on different levels – from biomolecules and subcellular structures up to whole organism

- Successful experiments being done
  - Experiments are mostly done with mid IR range of wavelength (1-10 μm)
  - Cortical bone ablation – highest mass removal occurred at 6.1μm, with least thermal injury, Ref [5,9]
  - Selective removal cholesterol ester in Carotid artery with 5.75 μm of radiation, Ref [10]
  - Exploiting the wavelength range between 1.21 to 1.72 m, fat absorbs radiation more than water, selective damage of fat without damage to overlying epidermis and dermis. Ref [11]
  - Surgery in Opthalmology, Oncology, Neurosurgery

  - In Neurosurgery –
    - Brain tumors infiltrate vast operative brain regions, not possible to remove it in conven method
    - Optical laser affect surrounding structures and reacts differently with denser (cortex) and thinner (white matter) portion of brain
    - FEL is expected to do the job efficiently to control damage / ablation mechansim by adjusting radiation parameters like wavelength, fluence and pulse time structure.
    - Researches are in full swing to develop new optimized techniques and devices

Research opportunities with different radiations from Free Electron Laser

Tera Hertz range - sub-millimeter radiation – 0.3 to 3 THz (10^{-12} Hz)

Terahertz electro-optics

- Control of light propagation in materials and material structure by applying a DC or slowly varying AC fields
  - A powerful probe to understand the properties of materials – being used as fundamental building block of modern communication and information processing.
- In place of dc or slowly varying electric fields, THz frequencies are applied
- THz frequencies exceed the relaxation rates of most of the interesting materials systems and THz radiation resonates with internal quantum mechanical transitions
- Results to enhanced modulation of incident light due to its variable absorption

Ref:

1. Photochemistry and photobiology, 2005, 81, page, 711-735.
2. Nordstrom, et al. (1998) Excitonic dynamical Franz-Keldysh effect. Phys. Rev. Lett. 81, 457–460.
3. Carter, S. et. al. (2004) Terahertz electro-optic wavelength conversion in GaAs quantum wells: improved efficiency and room-temperature operation. Appl. Phys. Lett. 84, 840–842.

Research opportunities with different radiations from Free Electron Laser

Tera Hertz range - sub-millimeter radiation – 0.3 to 3 THz (10^{-12} Hz)

Control of quantum mechanical states in solids – utility of quantum computing and IT

- In quantum structure of the semiconductor, the electron motion follows the oscillations of the THz fields for many cycles before it relaxes or is scattered
- "Quantum computing" relies on the control of the quantum mechanical states before they relax or loose their phase coherence.
- In the anticipated "quantum computer", information is stored as 'qubits'.
  - Classical computer has memory made up of bits, where each bit represents either a one or a zero.
  - Quantum computer maintains a sequence of qubits.
  - 1 qubit can represent a one, a zero, or, crucially, any quantum superposition of these two qubit states;
  - 2 qubits can be in any quantum superposition of 4 states, 3 qubits can be in any superposition of 8.
  - A quantum computer with qubits can be in an arbitrary superposition of up to different states simultaneously whereas a normal computer that can only be in one of these states at any one time.
  - A quantum computer operates by setting the qubits in a controlled initial state that represents the problem at hand and by manipulating those qubits with a fixed sequence of quantum logic gates.
  - The sequence of gates to be applied is called a quantum algorithm.
  - The calculation ends with measurement of all the states, collapsing each qubit into one of the two pure states, so the outcome can be at most classical bits of information.

Ref: 1. Photochemistry and photobiology, 2005, 81, pp=711-735, 2. C. H. Bennett. and D. P. DiVincenzo, Nature (London)404,247(2000)
3. J. I. Cirac and P. Zoller, Nature (London)404,579(2000), 4. D.P. DiVincenzo, Science, New Series, Vol. 270, No. 5234 (Oct. 13, 1995), 255-261 – (very good for basic understanding)

Research opportunities with different radiations from Free Electron Laser

Tera Hertz range - sub-millimeter radiation – 0.3 to 3 THz (10^{-12} Hz)

THz Rabi Oscillations in isolated donors

- A 2-level system undergoes Rabi Oscillations when a high frequency field is sufficiently intense that it drives the system from the ground to the excited state and back down again before it loses quantum mechanical phase memory.
- These experiments showed that hydrogen atom like motional states of electrons, bound to donor impurities, can serve as model 'qubits'

References for THz Rabi Oscillation:
1. Hegmann, F. A., et al. Appl. Phys. Lett. 76, 262–264.
2. Keay, B. J., et al. Semiconductor Sci. Technol. 11, 1596–1600.
3. Keay, B. J., et al. Phys. Rev. Lett. 75, 4102–4105.