My introduction and research activities

Shankar Lal

Free Electron Laser and Utilization Section

Materials Sciences Group

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Outline :

- Introduction: education and research experience
- Ph.D. work
- Design and development of RF accelerating structures at RRCAT
- Installation and commissioning of IR-FEL at RRCAT
- Summary

Educational and professional qualifications

- M.Sc. Physics (Micro-Wave electronics)-1999, Rajasthan university, Jaipur, Rajasthan, India

- One year orientation course on Lasers and Accelerators 2001-02, RRCAT, Indore

- Joined Free Electron Laser Lab at RRCAT in 2002 as staff member

- Ph. D.(Physics) -2015: Design & Development of S-band photocathode RF gun

Professional skills and experience

- RF design of accelerating structures: SUPERFISH and CST MWS
- Design and development of RF power couplers
- Development, tuning and RF characterization of accelerating structures
- High power testing of accelerating structures
- Study of beam loading and compensation in RF accelerating structures
- Other to making accelerators to work:
    - Development of high power microwave lines
    - Vacuum system development
    - Handling beam transport systems with electron beam diagnostics

Ph.D. dissertation

'Design, Construction and Experimental Studies with an S-band Photoinjector'

Aim of dissertation

Development of a 1.6 cell BNL/SLAC/UCLA type photocathode RF gun

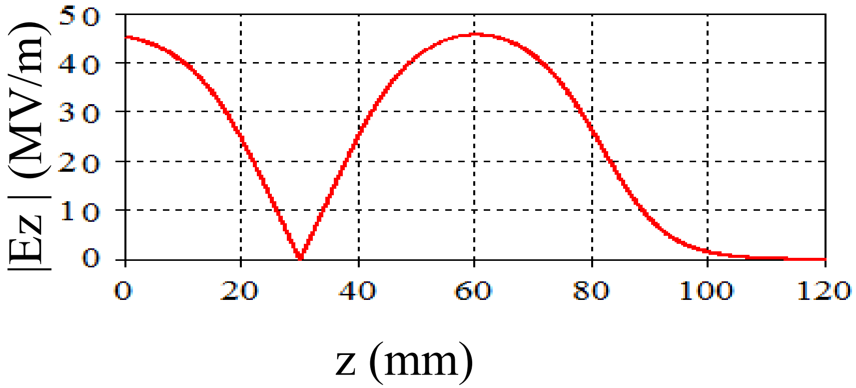
(i)To study and understand RF design & beam dynamics related issues

(ii) To identify critical issues related to the development and tuning of photocathode RF guns, and to perform analytical/experimental studies to address these issues

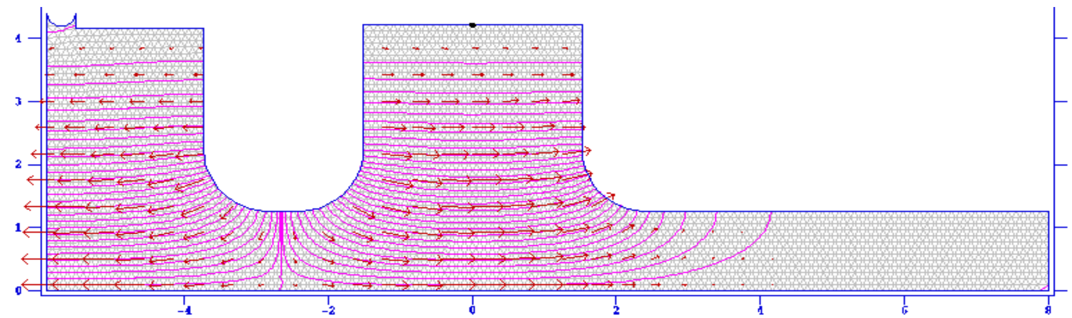
(iii) In-house development, tuning and characterization of a photocathode RF gun for possible future use as an injector for a light source

RF Design Study

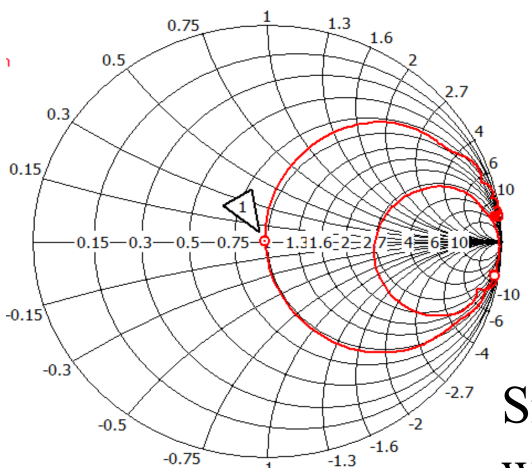
Basic geometry: **SUPERFISH**
Final geometry with ports for RF, Vacuum, laser and tuning: **CSTMWS**



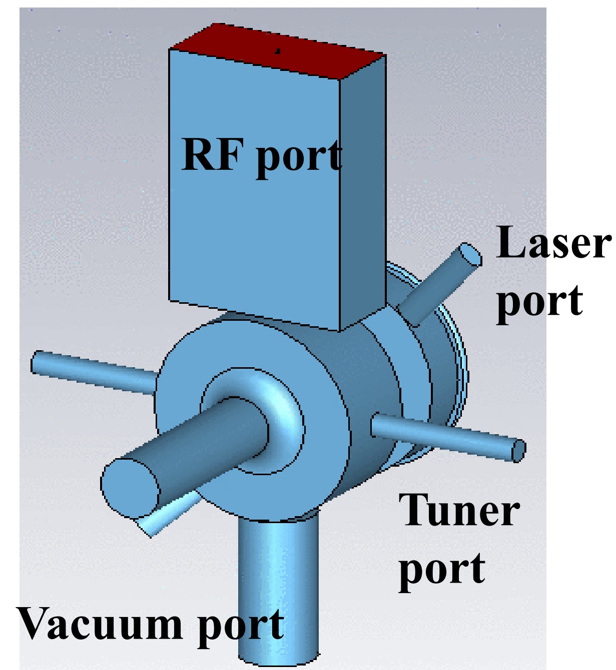
Variation of on-axis Ez along length



Field array plot predicted by SUPERFISH



Smith Chart showing waveguide to cavity coupling



3D view of photocathode RF gun

Beam dynamics study

Using beam dynamics code PARMELA

Parameters

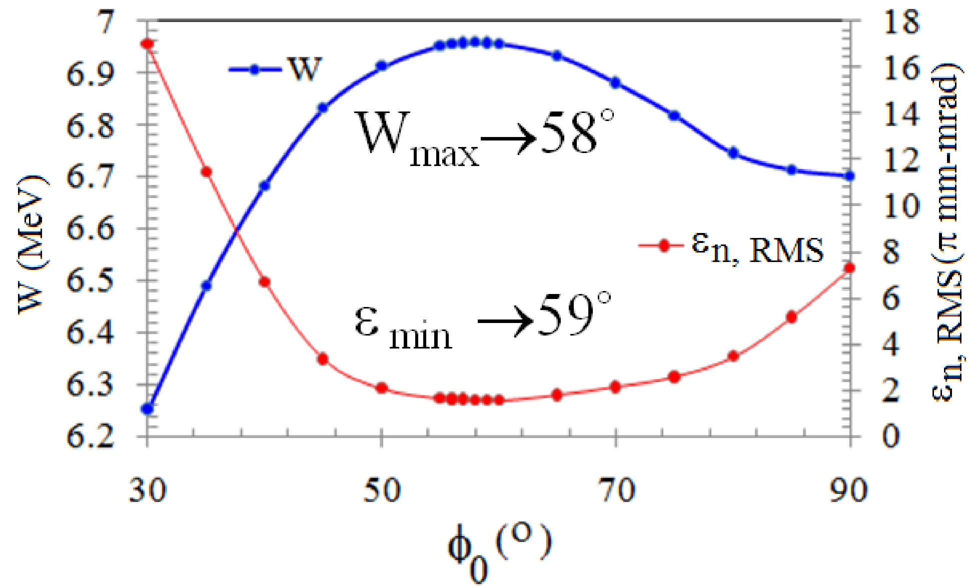
Peak charge = 1 nC

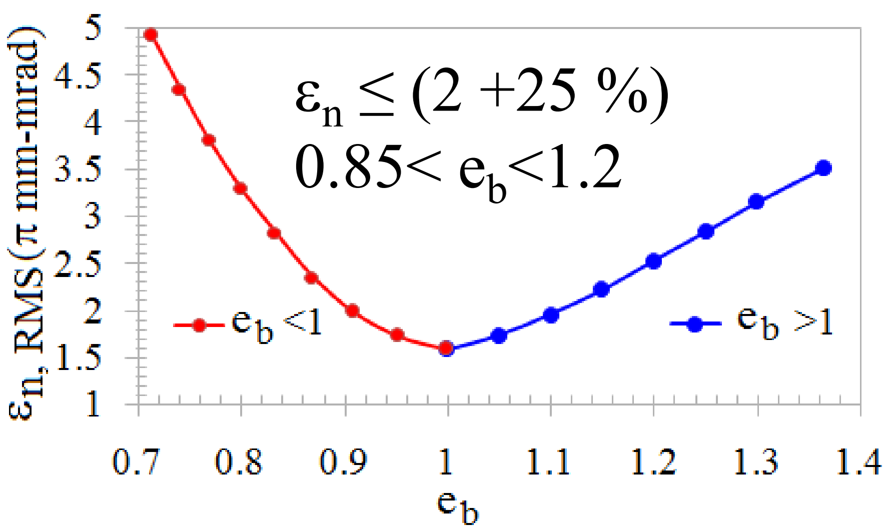
Bunch length = 10 ps

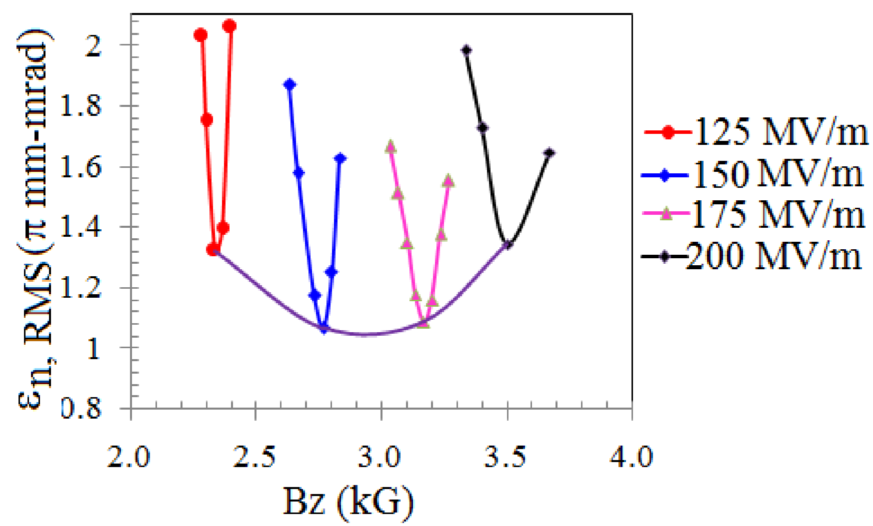
Accelerating field = vary

Solenoid field = vary

Laser injection phase = vary





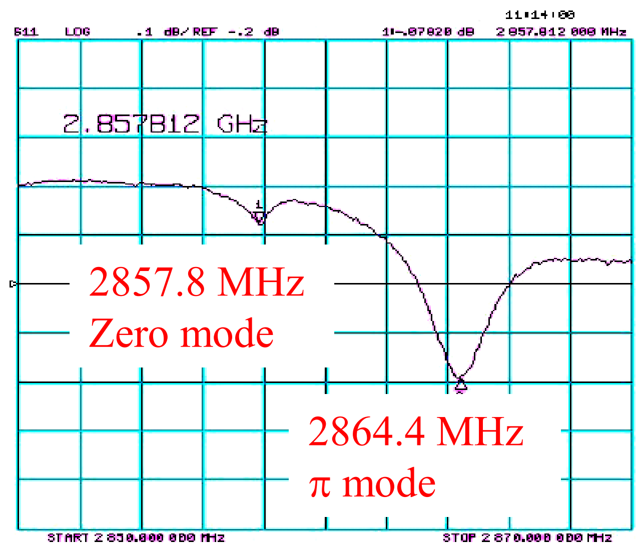


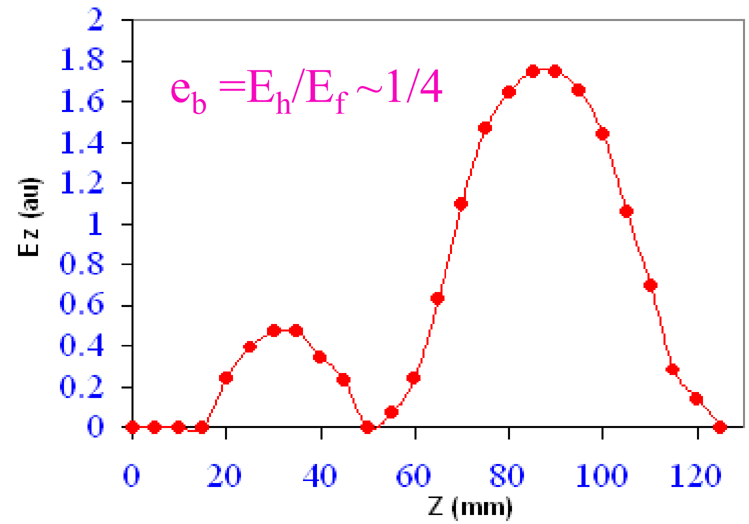
Photocathode RF gun development

- Prototyping: To qualify simulations and understand tuning and establish a machining procedure

Aluminum prototype (AGUN)

- To save material and machining cost.
- To understand agreement of experimental results with simulations.





AGUN components, frequency spectrum and bead-pull for the un-tuned photocathode gun

RF parameters far from final parameters: Require tuning

Aluminum prototype (AGUN)

Aluminum prototype is tuned by iterative cut-measure technique

Experimental observations:

RF parameters of gun (f_π, e_b and β_π) are

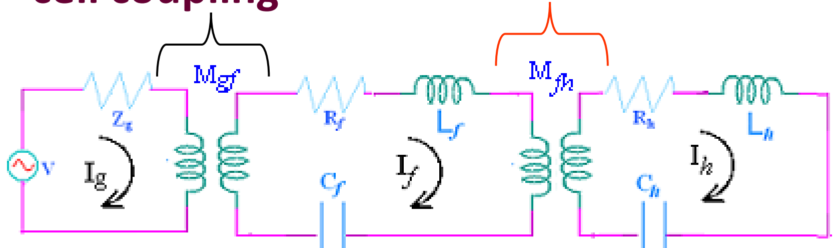
1) Interdependent: hence need to be tuned simultaneously.

2) Dependent on independent cell RF parameters (f_h, f_f , β_f)

An understanding of **interdependence** of RF parameters **(f_π, e_b, β_π)** and their **dependence** on independent cell RF parameters **(f_h, f_f , β_f)** can simply the tuning by enabling to predict independent cell RF parameters for desired gun RF parameters

Analytical study of PC gun

LCR equivalent model: Two step tuning procedure



$$\omega_\pi = \left[\frac{(\omega_f^2 + \omega_h^2)}{2(1-k_{fh}^2)} + \frac{\sqrt{(\omega_f^2+\omega_h^2)^2 - 4\omega_f^2\omega_h^2(1-k_{fh}^2)}}{2(1-k_{fh}^2)} \right]^{1/2}$$

$$e_b = \frac{|I_h|}{|I_f|} = \frac{R_h[1 + \frac{Q_h^2}{\omega^2 \times \omega_h^2}(\omega^2 - \omega_h^2)^2]^{1/2}}{\omega k_{fh} \sqrt{\frac{Q_h R_h}{\omega_h}} \sqrt{\frac{Q_f R_f}{\omega_f}}}$$

$$\beta = (\omega/\omega_f)^2 \beta_f R_f / \mathrm{Re}\left[Z_f + \frac{\bar{Z}_h}{e_b^2} \right]$$

Two Step tuning procedure

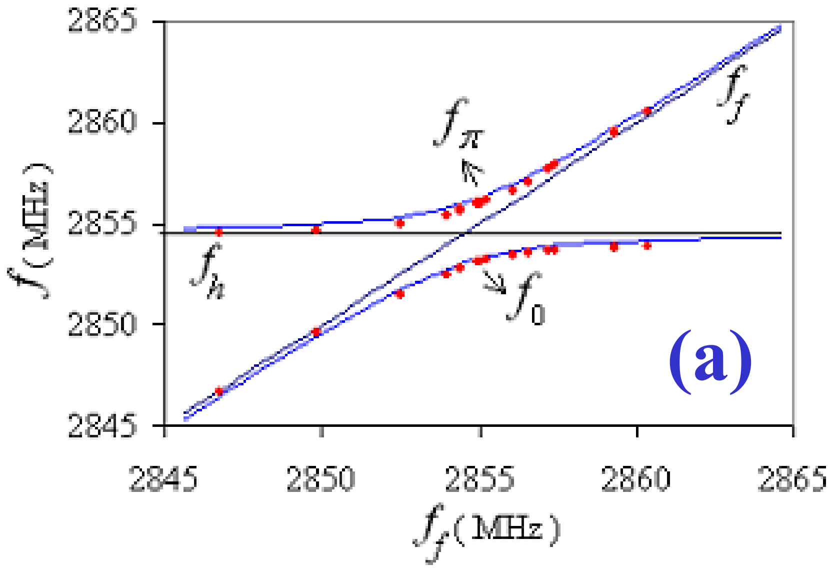
1. Tune f_h to predicted value
2. Tune f_f and β_f to desired values

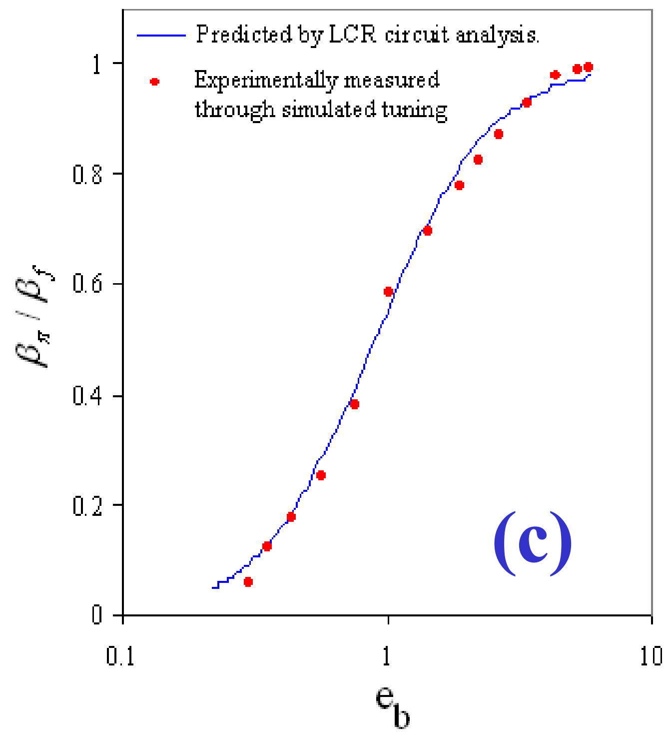
Coupled gun gives desired f_π, e_b and β_π

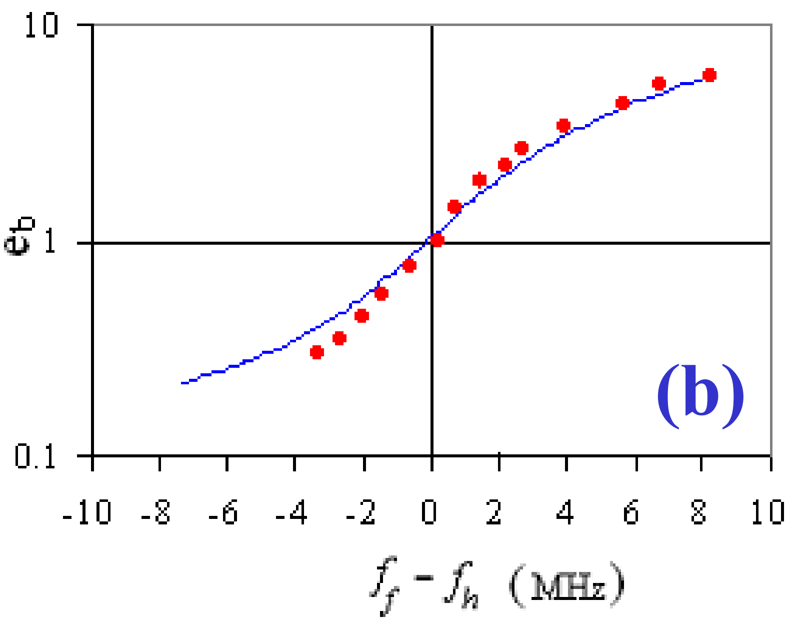
Only one cell needs to be tuned at time

Ref: A new two-step tuning procedure for a photocathode gun
Shankar Lal, K.K.Pant, S. Krishnagopal**, NIM A 592 (2008)**

Verification of tuning procedure through experiments







(a) $f_\pi - f_0$ is minimum when $f_f \sim f_h$.

(b) e_b is ~1 when f_f - f_h is minimum

(c) $\beta_\pi / \beta_f \sim 0.6$ when $e_b \sim 1$

Experimental results agree very well with predictions

Scaling law to predict geometrical dimensions of gun

$$f_h = \left(\frac{a_h}{R_h^{b_h}}\right)^2 \{1 - 2\Delta f_{laser}\}^{1/2}$$

$$f_f = \left(\frac{a_f}{R_f^{b_f}}\right)^2 \{1 - \Delta f_{RF} - \Delta f_{vacuum} - 2\Delta f_{tuner}\}^{1/2}$$

$$\beta_f = C\, l_0^6\, e^{-2\alpha_0 d}\, \frac{H_1^2}{P_c}$$

Predict : R_h, R_f and L_{RF}

for

Desired f_h, f_f and β_f

Effect of vacuum
f (vacuum) = f (air) + 0.8 MHz

Effect of brazing
f_f (brazed) = f_f (un-brazed) + 13kHz/B(μm)
β_f (brazed) =1.17×β_f (un-brazed)

Two photocathode guns successfully tuned

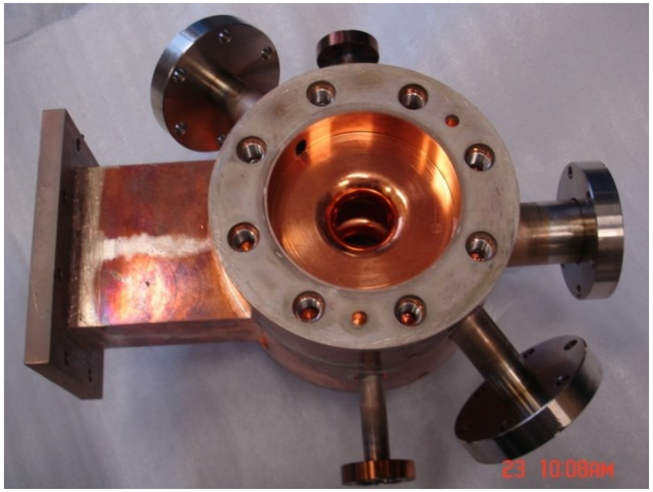
Ref : A novel scaling law relating the geometrical dimensions of a photocathode RF gun to its RF properties, **Shankar Lal**, K. K. Pant and S. Krishnagopal, **RSI 82, 123304 (2011).**

Photocathode RF gun development

- Machining
- Brazing
- RF tuning and characterization
- Vacuum testing

Gun components

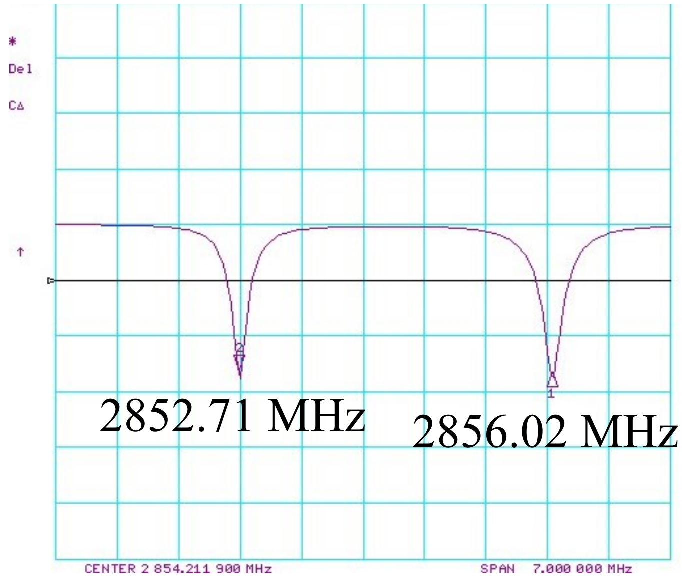
Brazed gun



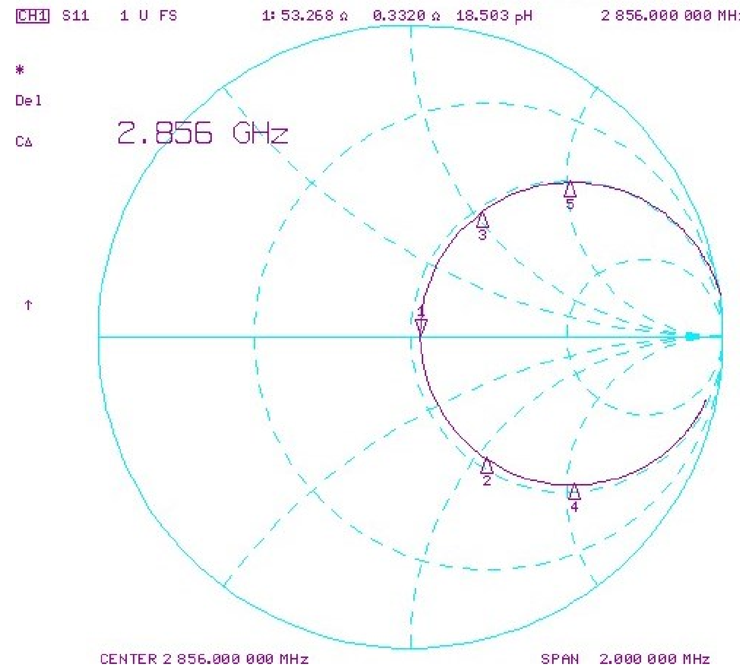
Gun structure

Ref: Ajay Kak, P.K. Kulshreshtha, **Shankar Lal** in Proceedings of InPAC 09.
Ajay Kak… **Shankar Lal** et al, Journal of Physics: Conference Series 390 (2012) 012025.

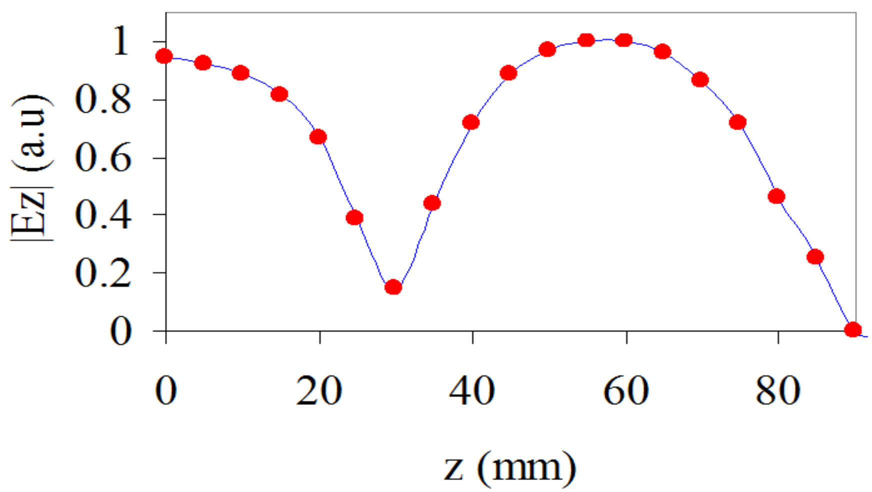
RF characterization: Cold test measurements



Frequency spectrum of tuned gun



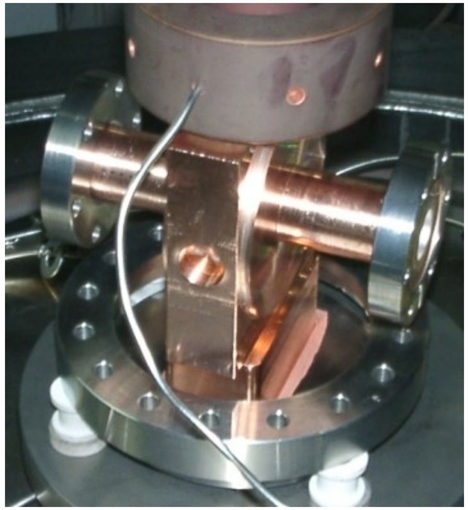
Smith chart of tuned gun



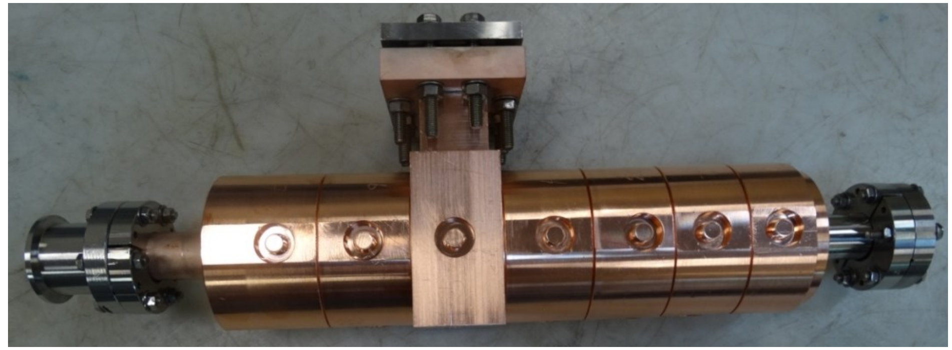
On-axis accelerating field profile

Design and development of other accelerating structures

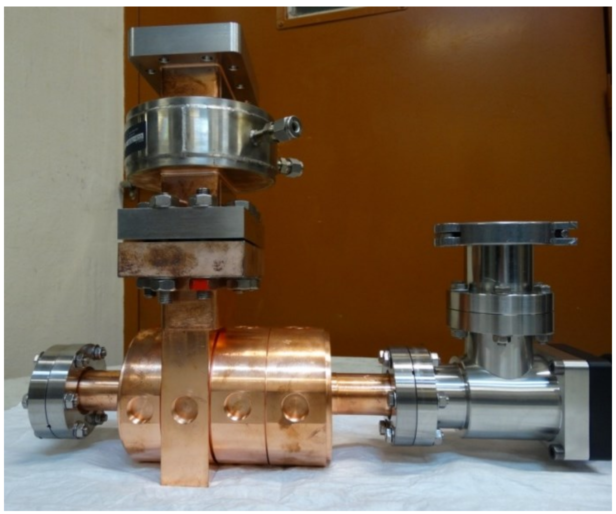
476 MHz SHPB



S-band pre-buncher



7-cell S-band accelerating buncher



4-cell S-band accelerating buncher

PWT linac

PWT disk array

Plan Wave Transformer (PWT) linac: 4, 8, 12 and 20-cell

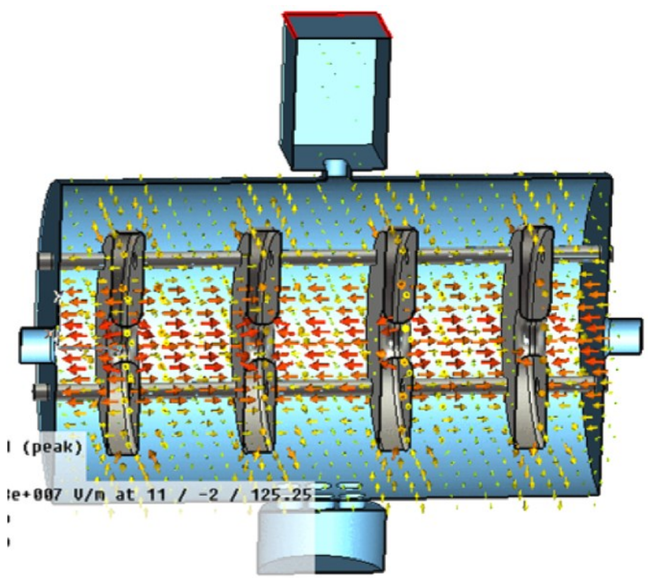
Disk washer loaded

SW wave π mode

High inter-cell coupling

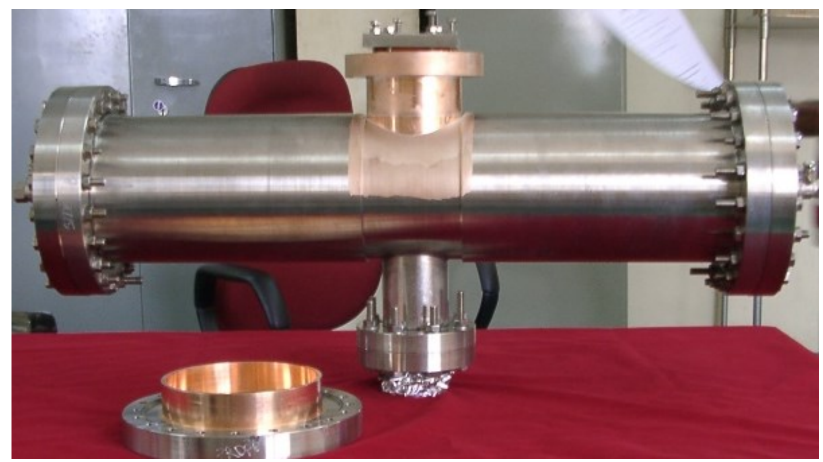
RF parameters	
f_π (MHz)	2856
Q_0	~ 20000
R (MΩ/m)	65

RF design: CST



Field array plot in 4-cell PWT linac

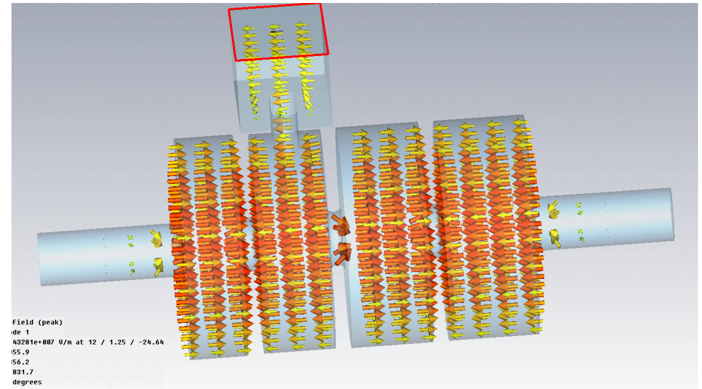
PWT disk array



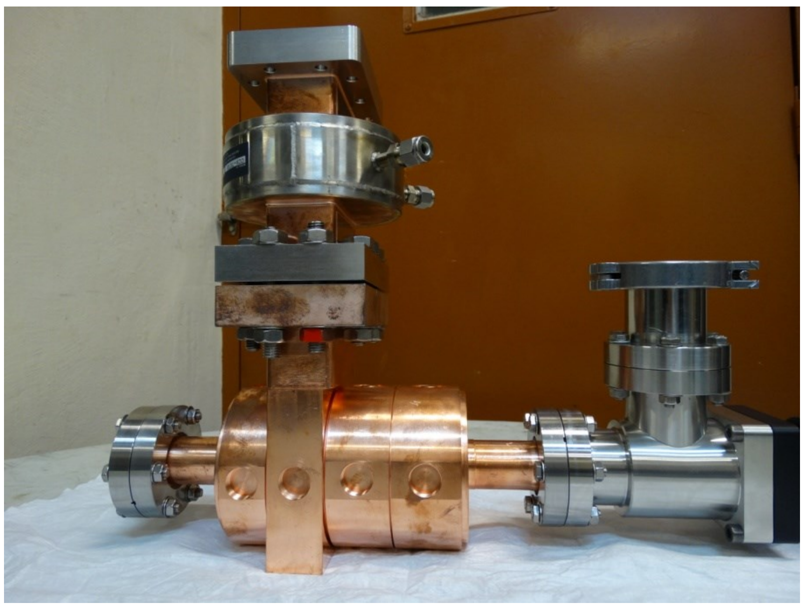
PWT linac tank and reservoir

4 -and 7-cell S- band accelerating Buncher

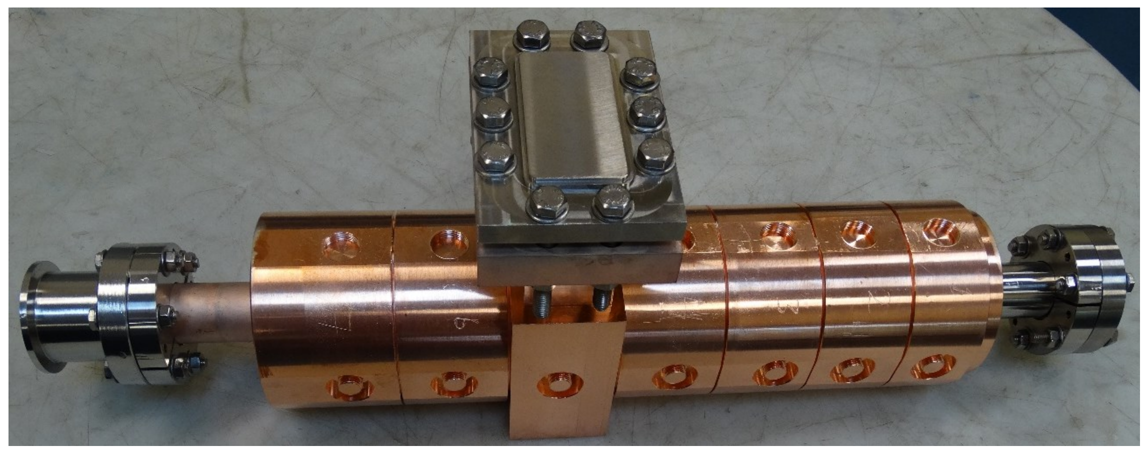
- Disk loaded structure
- First 4-cells of variable length
- Last three cells of fix length



Field array plot in 4-cell S-band accelerating buncher



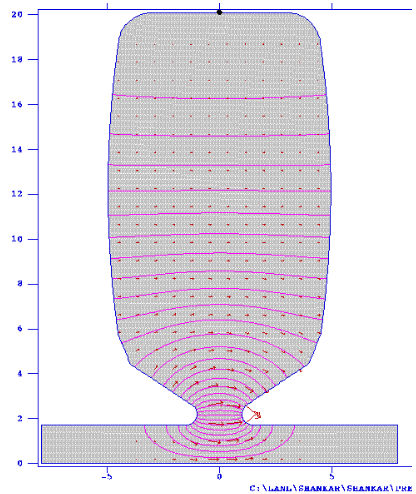
4-cell accelerating buncher during vacuum testing

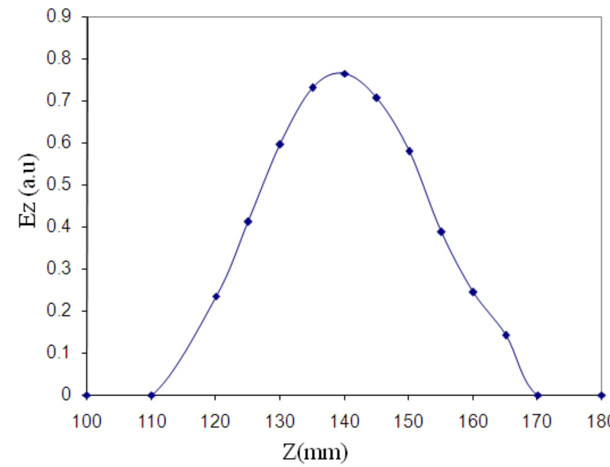


7-cell accelerating buncher during vacuum testing

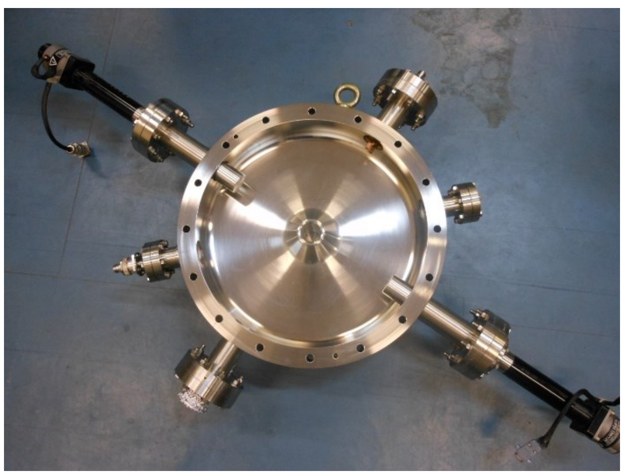
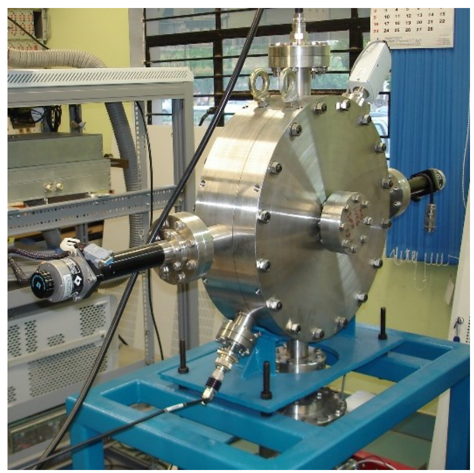
476 MHz Sub-Harmonic Pre-Buncher (SHPB)

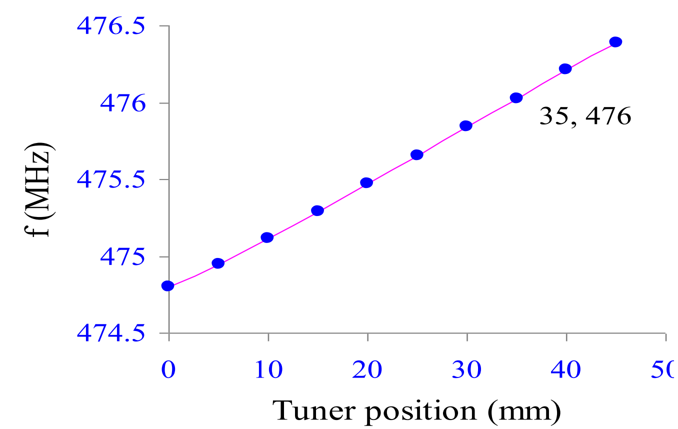
- Re-entrant design
- SS (low Q ~ 2000)
- R/Q ~ 170


2D model of pre-buncher cavity



On axis accelerating field profile



View of one half of pre-buncher and full assembly



Resonant frequency v/s tuner positions

Tuning and RF characterization of RF accelerating structures

Frequency tuning

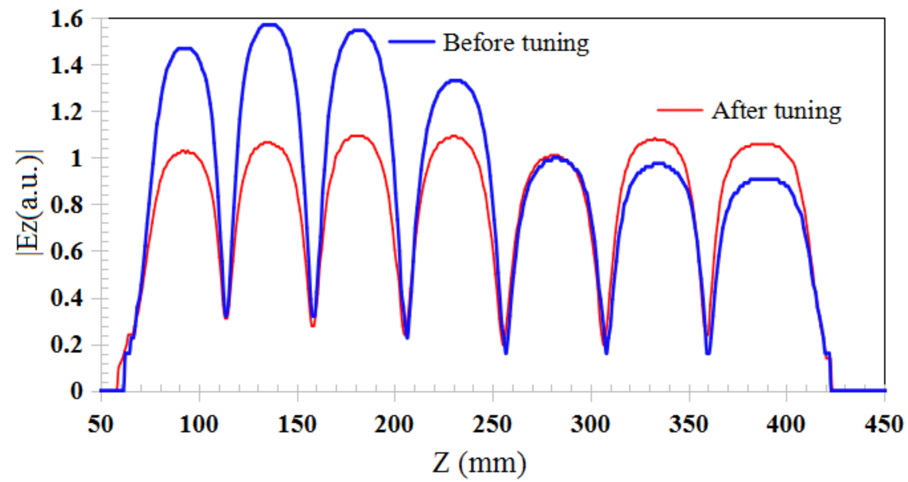
- 476 MHz SHPB: cut-measure technique & tuners
- S-band bunchers: plastic deformation (push & pull)
- Plan Wave Transformer (PWT) linac : vary structure length using gaskets of different thickness

Tuning of transmission line to cavity coupling

- 476 MHz SHPB: Loop size and rotation
- S-band bunchers & PWT: varying RF coupling slot length

RF characterization : VNA in reflection mode

- Smith Chart: Frequency, quality factor, β
- Bead-pull: on-axis electric field profile, R_{sh}/Q



On-axis field profile in 7-cell S-band buncher before and after tuning ;

Ref: **Shankar Lal** et al. in proceedings of IPAC10, Kyoto, Japan, p. 1713.
Shankar Lal and K.K.Pant, NIMA 889 (2018), 57-62

Design and development of RF power couplers

Hole/Slot coupling

- Applied Gao's scaling law to predict slot sizes for different structures
- Good agreement observed for PWT linac (good inter-cell coupling
- Modified for 1.6 cell photocathode gun and 4-cell/7-cell buncher structures with poor inter-cell coupling

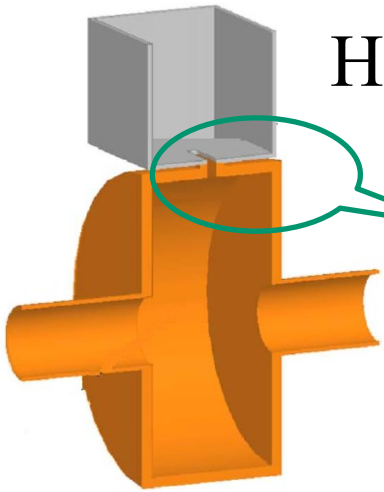
Ref: S. Krishnagopal, **Shankar Lal** et al. EPAC08, p.2734
Shankar Lal, et al., IPAC 10, 1713.

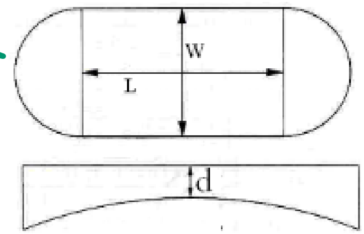
Loop coupling

- Modified Faraday's law for predicting loop size for desired value of $\beta > 1$ with good accuracy
- Included effect of loop inductance
- Coupler loops developed for a 476 MHz sub-harmonic pre-buncher and successfully tested at high powers

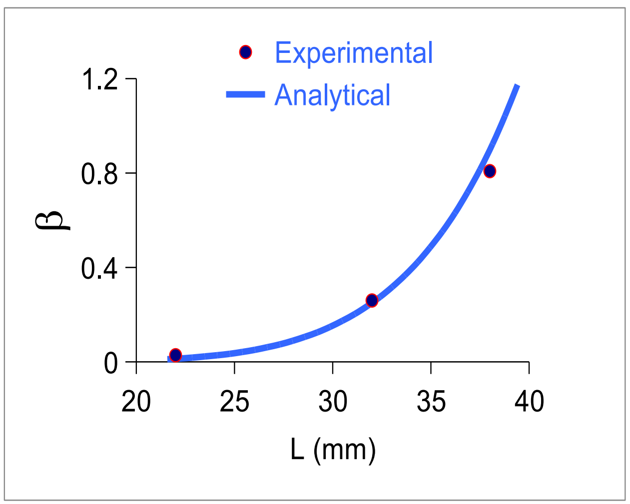
Ref : **Shankar Lal** and K.K.Pant, "Study of the effect of loop inductance on the RF transmission line to cavity coupling coefficient", **RSI 87, 083308 (2016)**

Hole/Slot coupling



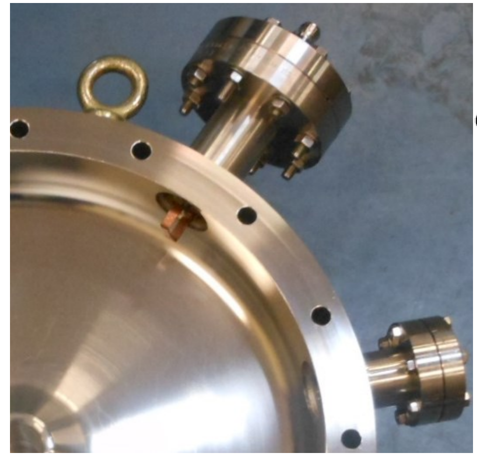


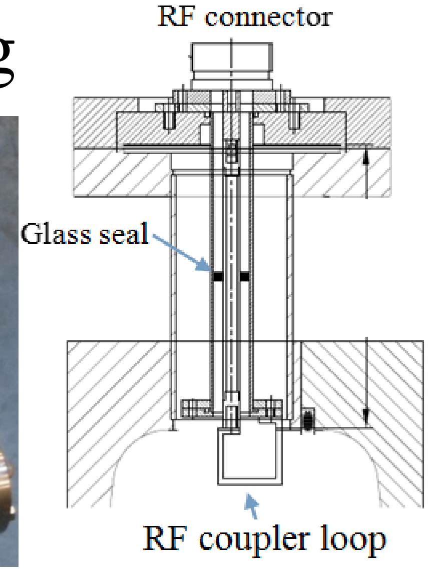
$$\beta = \frac{\pi Z_0 \kappa_0 \Gamma_{10} e_0^4 l_1^6 \exp(-2\alpha_0 d)}{9ab(K(e_0)-E(e_0))^2} \frac{H_1^2}{P_c}$$



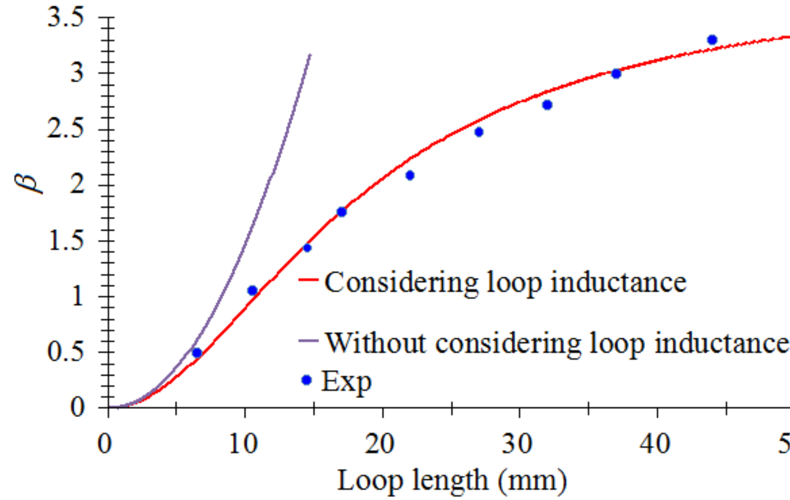
β with slot length for 4-cell PWT linac

Loop coupling





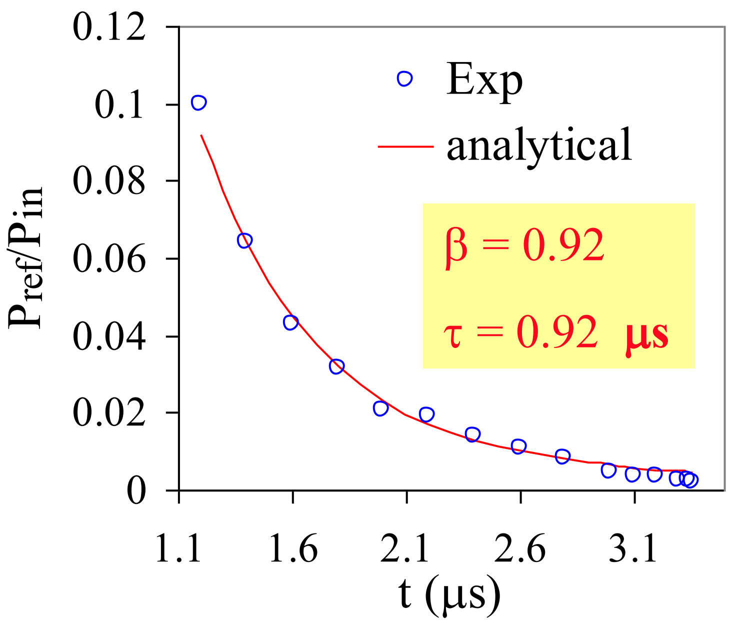
$$\beta = \frac{(\omega_0 \mu_0 A \cos\theta)^2}{2} \frac{Z_W}{Z_W^2 + (\omega L_L)^2} \frac{H_\phi^2}{P_c}$$



β with length of loop for 476 MHz SHPB

PWT linac: High power RF testing

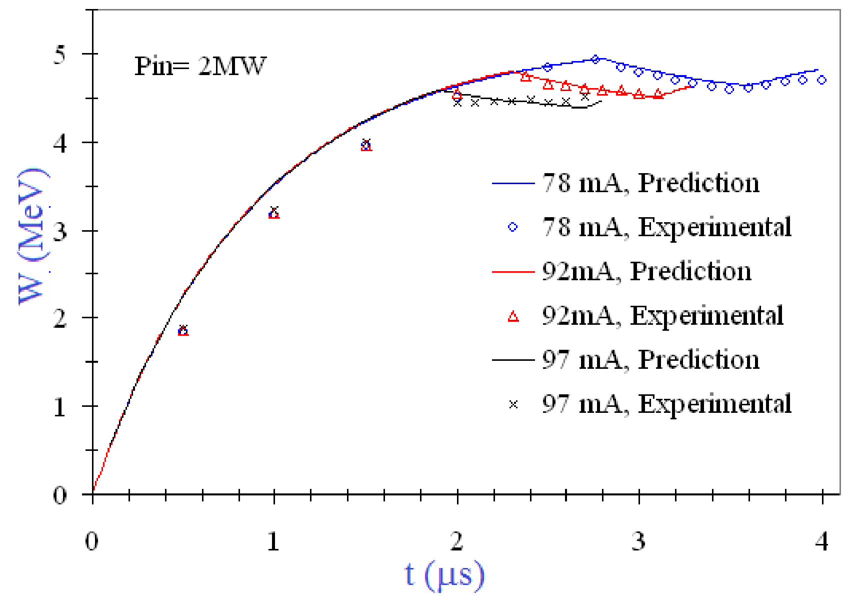
- High power RF conditioning
- High power RF characterization: by analyzing transient response of reflected RF power



$$\frac{P_{ref}}{P_{in}} = \left[\frac{2\beta}{1+\beta}\left(1 - e^{-t/\tau}\right) - 1\right]^2$$

Ref: **Shankar Lal** et.al, IPAC 10, 1713.

Study of beam loading and scheme for compensation



$$\frac{t_1(optimum)}{\tau} = log_e\left(2\sqrt{\frac{\beta P_{in}}{R_{sh}}}\right) + log_e\left(\frac{t_b}{q}\right)$$

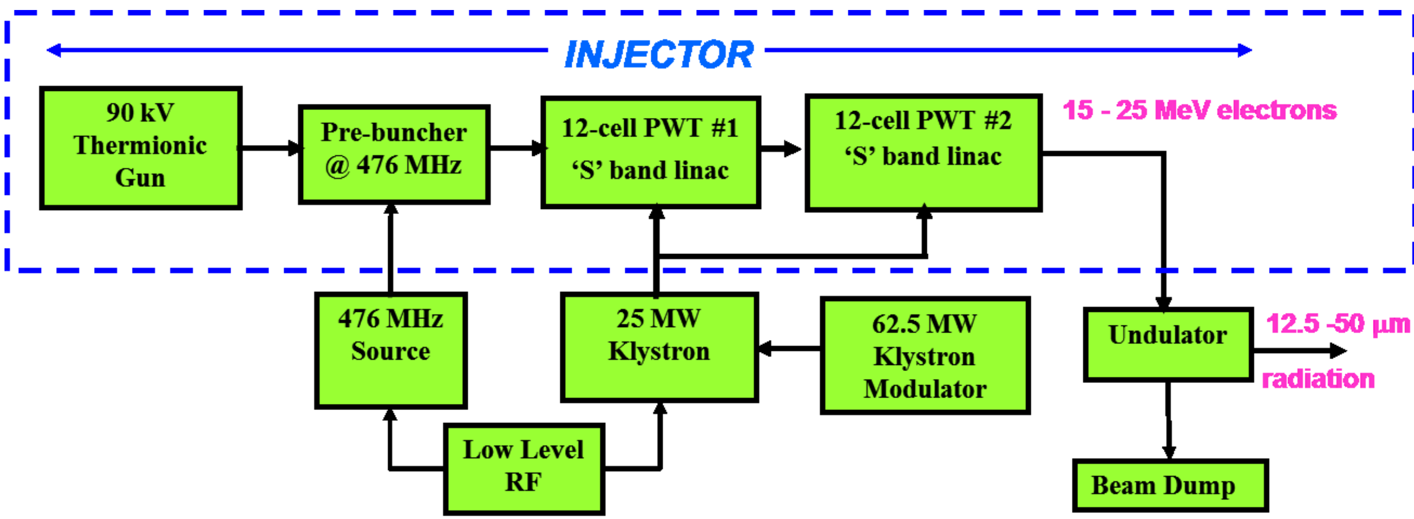
$$V_{eff} = 2\sqrt{\frac{\beta R_{sh} P_{in}}{1+\beta}}\left(1 - e^{-\frac{t_1(optimum)}{\tau}}\right) + \frac{1}{2}V_0$$

Ref : **Shankar Lal**, K. K. Pant, **RSI 85, 123302 (2014)**

Participation in installation, commissioning and regular operation of injector system for FEL at RRCAT

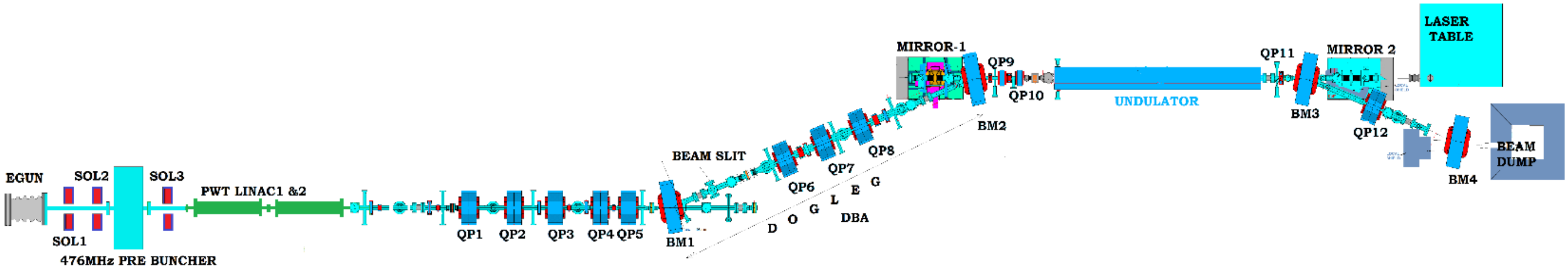
IR-FEL Design parameters	
Wavelength	12.5-50μm
Pulse structure	10 ps @ 29.75 MHz for 10 μs @ 1-10 Hz
IR power	2 MW (10 ps)/ 30 mW

Electron beam & undulator design parameters	
Electron beam	15-25 MeV, < 0.5%, >30 A, 30 mm mrad
Undulator	NdFeb, 50mm, 2.5 m gap =25-40mm, K =1.2-0.5



Schematic of IR-FEL at RRCAT

IR-FEL at RRCAT

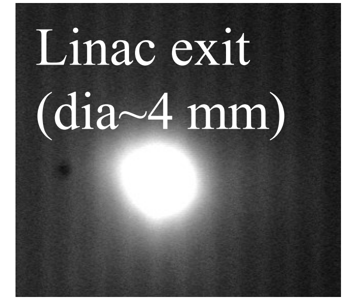


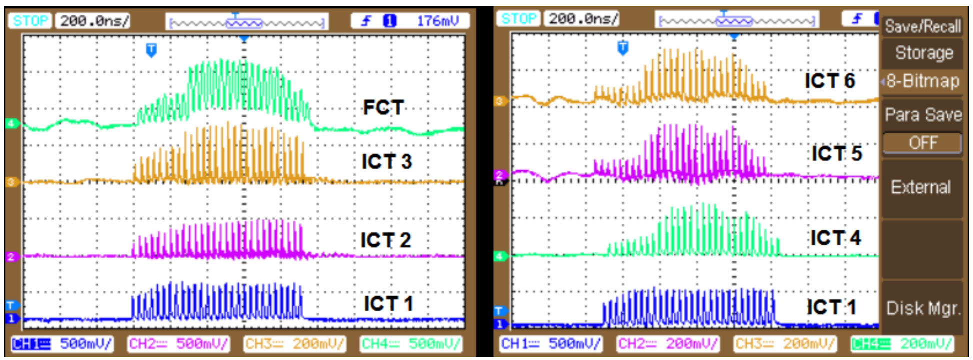
Layout of IR-FEL beam line

IR-FEL tunnel (5 m x 3.5 m x 60 m long) with components installed inside in tunnel

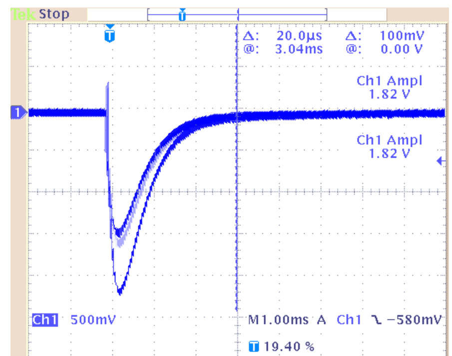
IR-FEL commissioning Experiments: Stage 1

- Initial trials started: Jan 2016
- Electron beam pulse:1 μs
- Without down stream mirror
- First light observed : Feb 2016

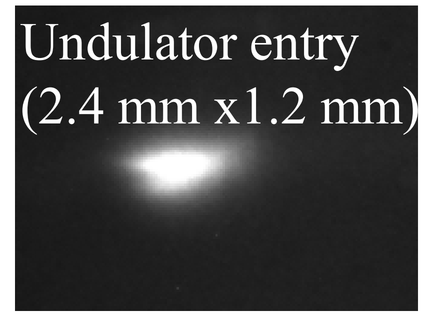




Electron beam signals at different locations



Bolometer signals

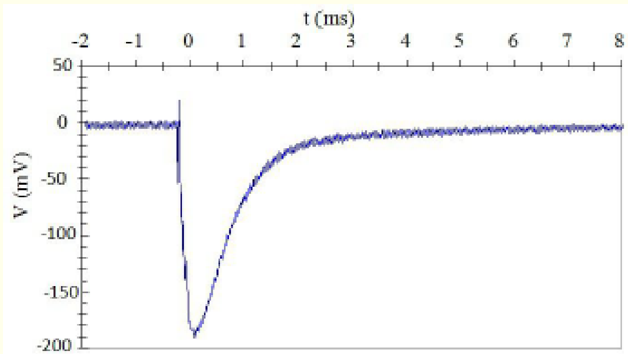


Electron beam parameters	
W(MeV)	~17
I (A)	~22 peak

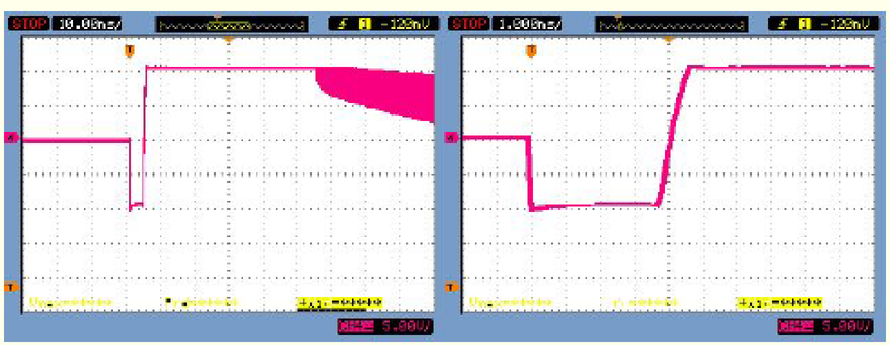
IR parameters	
wavelength	37 μm
IR power	~3mW (avg. 1 μs) 10W (peak)

IR-FEL commissioning Experiments: Stage 2

- Electron beam pulse width :5μs pulse
- Optical cavity (down stream mirror) installed
- First signature of lasing observed : Nov. 2016
- Enhancement over spontaneous power: ~ 10^5



Typical bolometer signal with optical cavity length detuned



Typical bolometer signals showing a high degree of saturation with optical cavity tuned to design length

Electron beam parameters	
W(MeV)	~18
I (A)	~26 peak
Emittance	~ 40 mm mrad

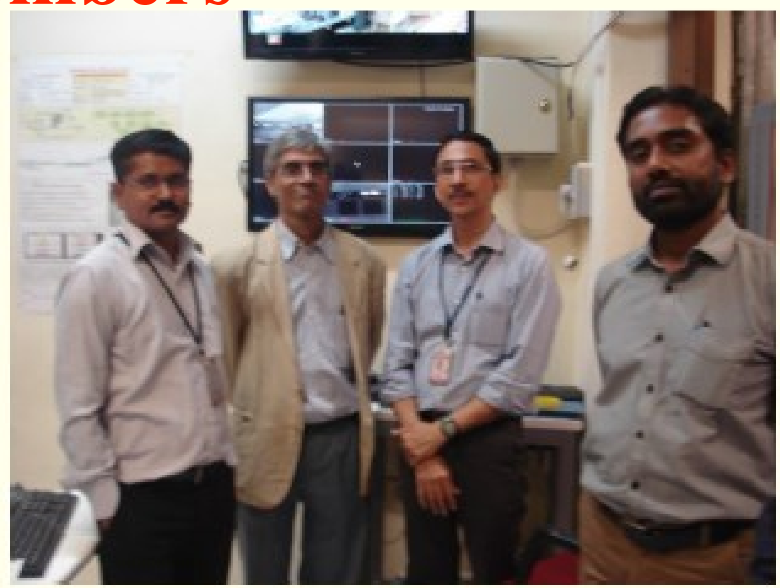
IR parameters	
wavelength	34μm (calculated)
IR power	~500 mW (avg. 5μs) ~2 kW (peak 10ps)

Improvement in stability & flatness of RF is underway

Ref: K.K. Pant et. al, Current Science, Jan 2018

IR-FEL Commissioning Experiments: lasing day

Team members

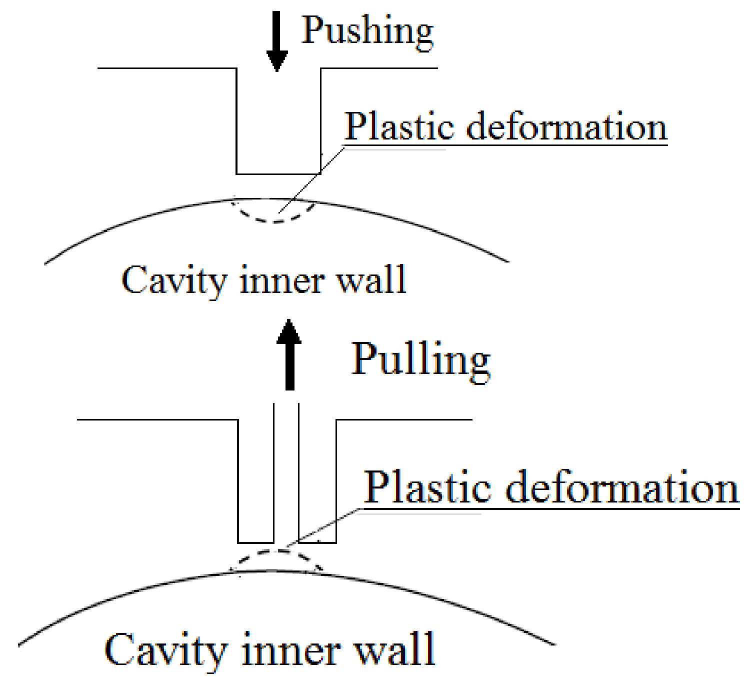


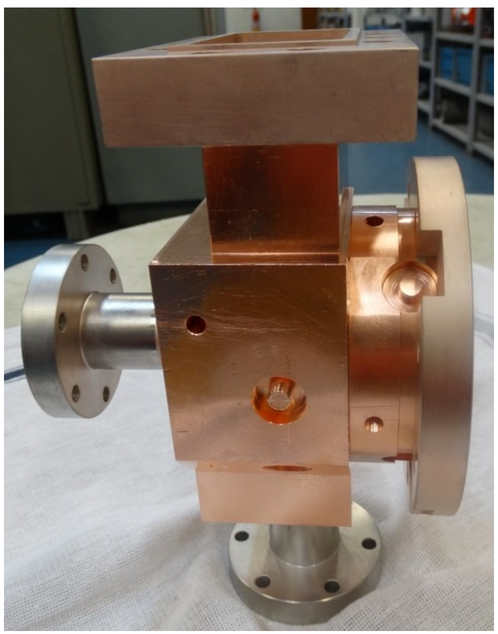
New photocathode RF gun design and development

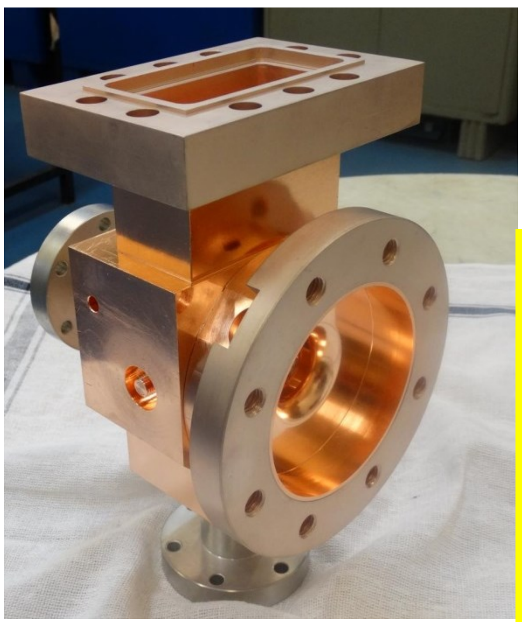
Photocathode RF gun: 1.6 cell BNL/SLAC/UCLA type -III without physical tuners

Tuning by Plastic deformation

- Deform cavity wall locally
- Both direction (pull and push)







Status

- Tuned for pi mode 2856 MHz, FB ~1 and β_{RF}~1.5
- RF conditioned @ 6.5 MW, 4μs $E_{cathode}$ =~110 MV/m

Summary

I have some experience in :

- RF design, development and high power testing of RF accelerating structures.
- Tuning of RF accelerating structures (resonance frequency, field uniformity and RF power coupling).
- Beam loading effect and its compensation.
- Installation and commissioning of FEL injector system at RRCAT (high power RF transport line, vacuum testing, RF conditioning etc.)
- Hope my experience may be useful at PITZ (design RF accelerating structures and experiments)

Thanks