Design of Electron Gun

Abhay Deshpande
Scientist, Medical Electronics Division
Society for Applied Microwave Electronics Engineering and Research
SAMEER, IIT-B Campus, Powai
Mumbai 400 076

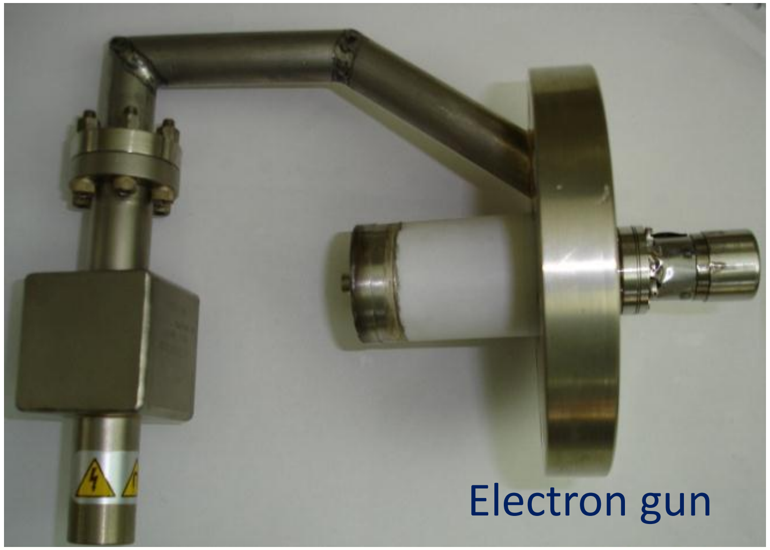
abhay@sameer.gov.in

Introduction of SAMEER

- SAMEER stands for 'Society for Applied Microwave Electronics Engineering and Research' and is an off shoot of TIFR.
- SAMEER is a R&D laboratory of Ministry of Communication and Information Technology (formerly Department of Electronics) of Govt of India.
- We have 3 centers: Mumbai (head office), Chennai and Kolkata and 2 upcoming centers at Vishakhapatnam and Guwahati.
- Successfully established Linac Development for 6 and 15 MeV electron linac.
- We have made $\pi/2$ mode, Standing Wave Side Coupled Linac and developed a Radiation Oncology Unit using this Linac.

Linac parts

Resonant Cavities



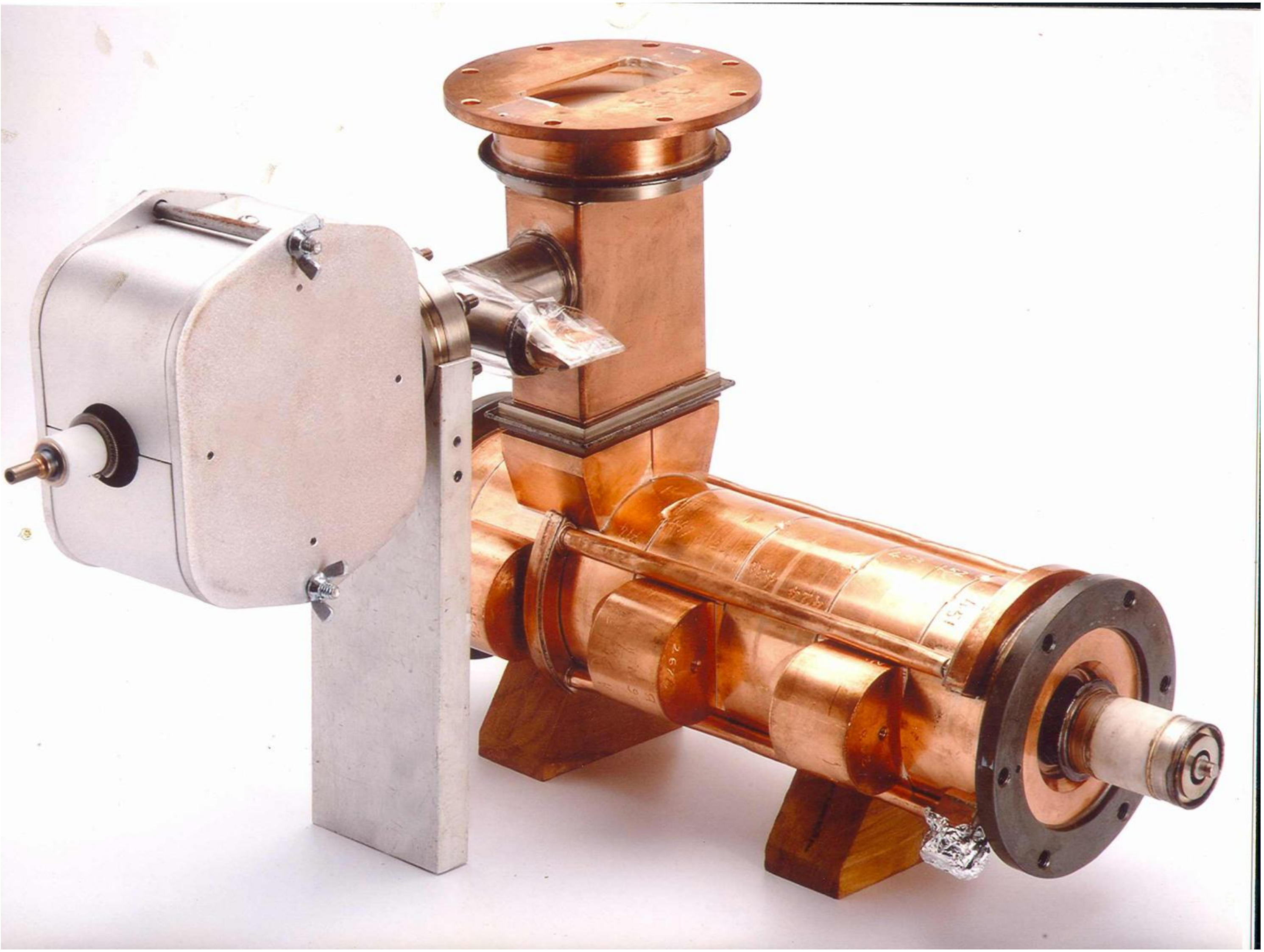
Electron gun

Target

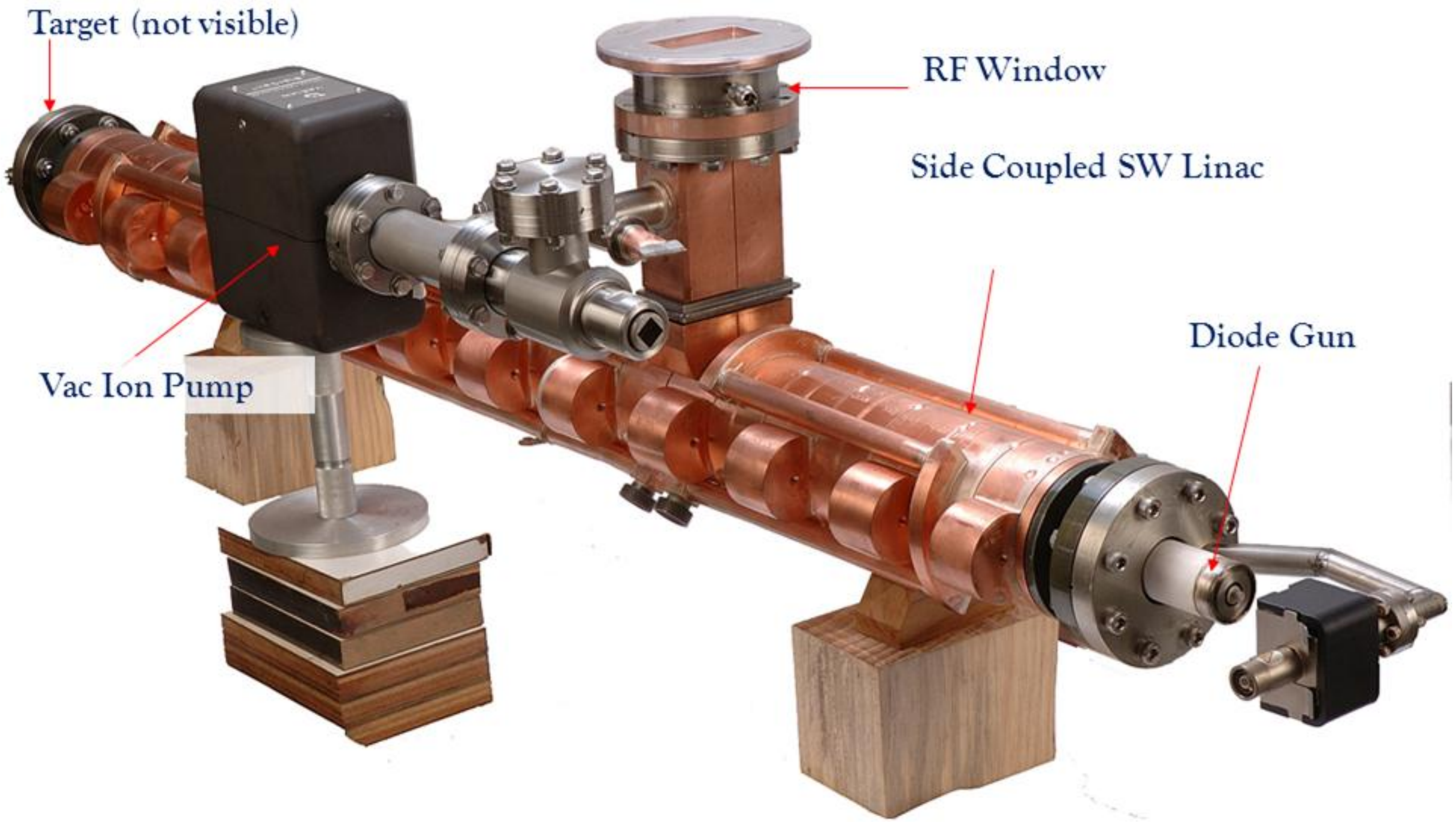
RF Window

Linac cavity

6 MeV Linac



15 MeV Linac

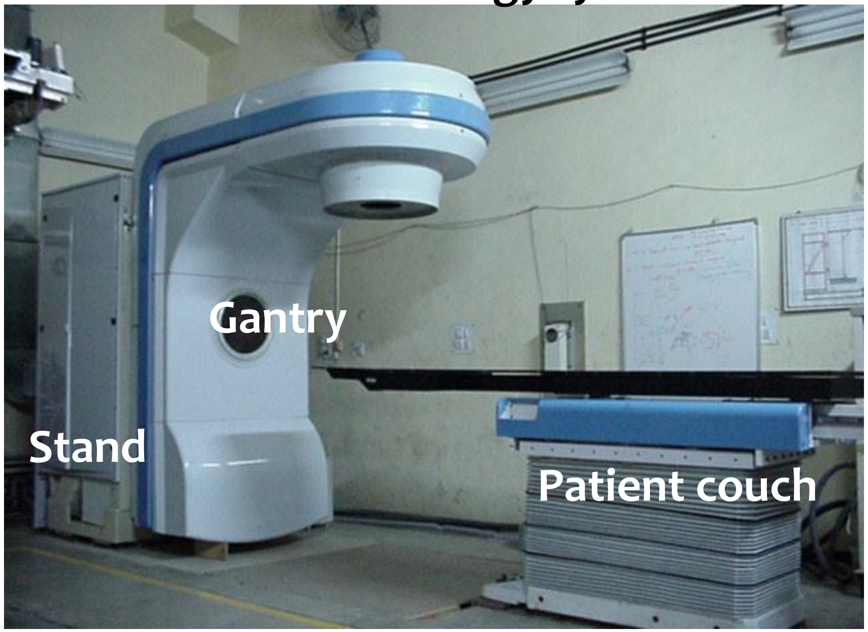

Target (not visible)
RF Window
Side Coupled SW Linac
Vac Ion Pump
Diode Gun

SAMEER Linac

- Standing Wave, side coupled structure operating at $\pi/2$ mode
- Stable operation at various locations
- Proven technology with most things done at SAMEER

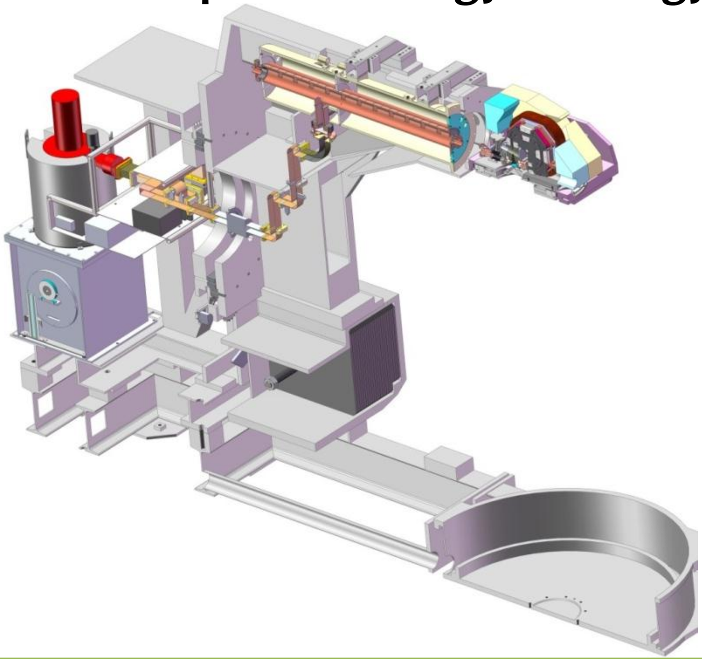
Parameter	Measured
Frequency, MHz	2997.65
Coupling, %	0.0278
Shunt Impedance, MΩ/m	87
Q (unloaded)	15000
VSWR	1.78
Energy, MeV	15
Input power, MW	6
Pulse width, μs	6

6 MeV Oncology system



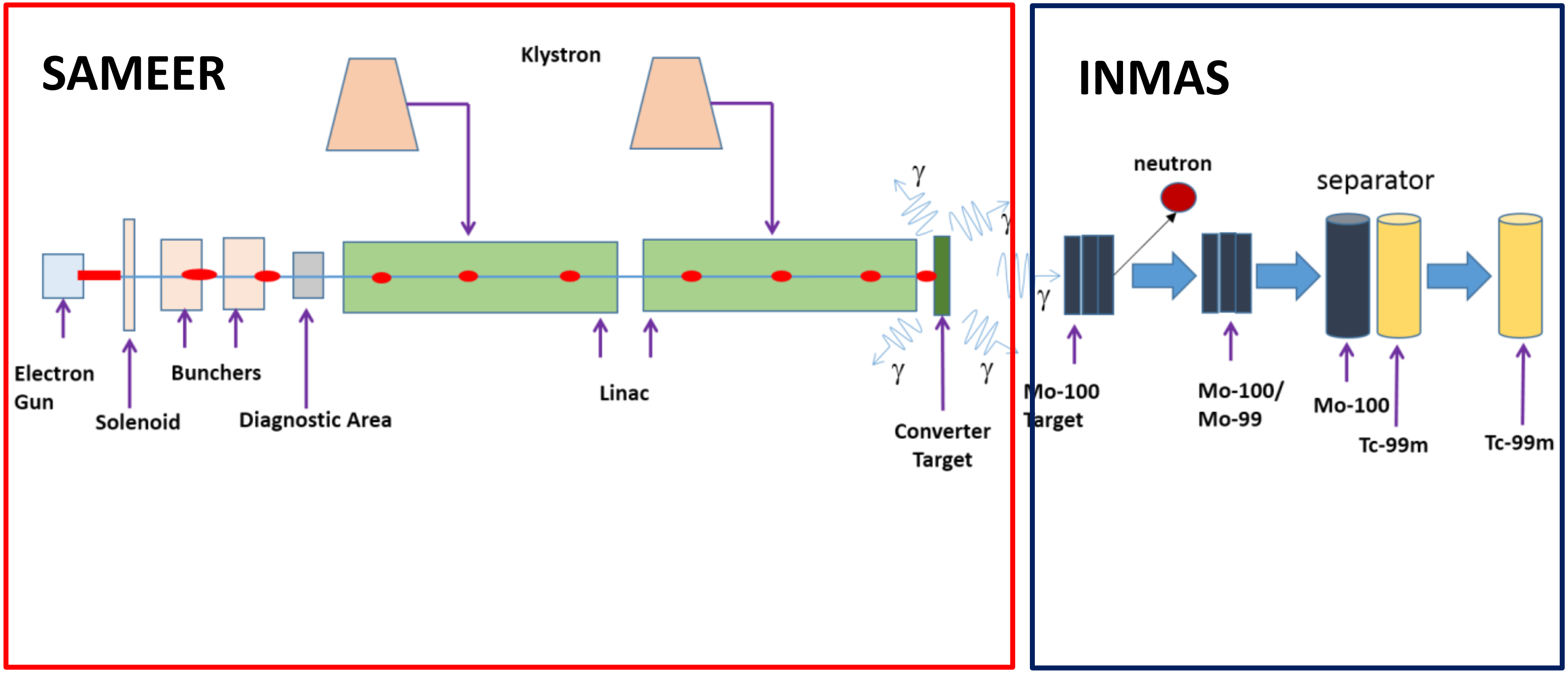
Energy, MeV	6
Dose Rate, RMM	240 (flattened)
Beam current average	120 μA
R F Power	Magnetron 2.6 MW
Flatness	2%
Symmetry	±3%
Field size, cm^2	Medical 0x0 cm to 35x35 cm

Dual mode dual photon energy Oncology system



Modes	Photon	Electron
Energy	6, 15 MV	6,9,12,15,18 MeV
Dose rate	500 RMM	500 RMM
RF Power	Klystron 6 MW	
Flatness	< 3%	
Symmetry	± 3%	
Field size	Variable from 0x0 cm to 35x35 cm	
Source to iso-center distance	100 ± 0.5 cm	

30 MeV, 8-10 kW Linac



- 30 MeV, 8-10 kW electrons hit the Convertor target to produce X-rays
- The X-rays hit an enriched Mo-100 target and by (γ,n) reaction Mo-100 converts to Mo-99 which has 66 hrs half life
- We elute Tc-99m from Mo-99. Tc-99m has 6.6 hrs half life

Design of RF Gun

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

- Basics of Electron Source
- RF Gun basics
- Details of RF photo cathode gun
- Cavity design for RF gun
- Fabrication of RF gun at KEK
- Experimental results of KEK gun
- Plan for IUAC RF gun
- Applications of RF Gun
- Beam dynamics for RF gun

Basics of Electron Source

- Electron source or electron gun is a device which provides electrons for accelerators
- It essentially needs an electron generation mechanism and an extraction mechanism
- The generation could be thermionic, field emission or photo emission
- Extraction mechanism could be DC or RF

Electron Emission Mechanisms

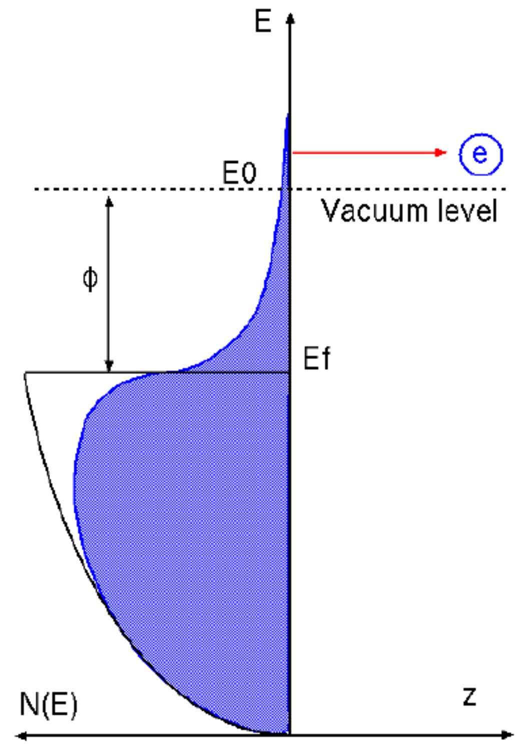
Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

- **Thermal emission:** When heated to high temperatures (1000 to 3000 ^{o}C), materials may emit electrons
- **Field emission:** Electron emission due to high fields on surface
- **Photo electric emission:** Electron emission from photo emitters when photons hit the surface

Thermionic Emission

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

- An emitter like Tungsten is heated using a dc / ac voltage
- At T=0; electrons occupy states up to Fermi Energy E_f
- For T>0, electron distributions extends to higher energy
- If the temperature is increased to say 1000 ^{o}C or above, electron acquire sufficient energy and escape outside.



Thermionic Emission

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

- Richardson- Dushmann Equation governs the emission process

$$J = AT^2 e^{-\frac{\varphi}{kT}}$$

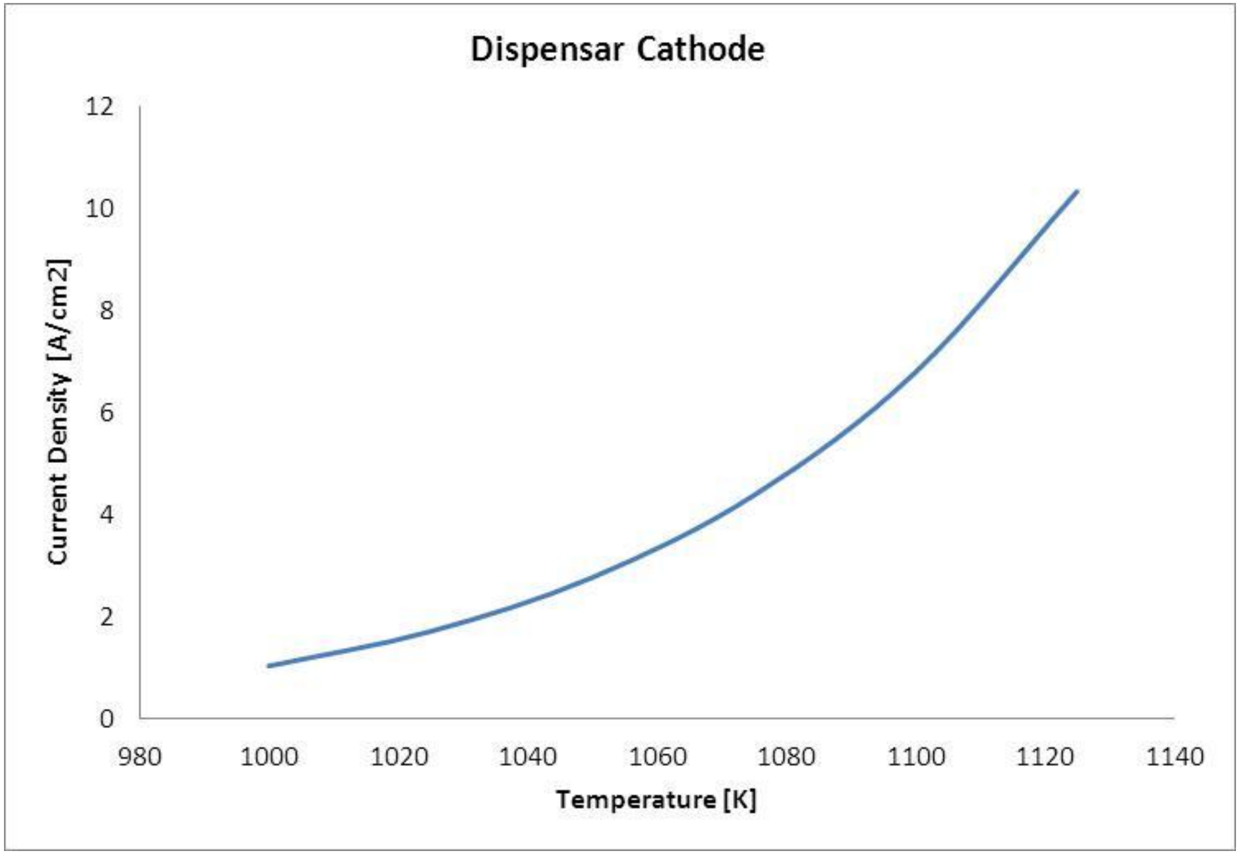
$$A = \frac{4\pi emk^2}{h^3} = 1.2 \times 10^6 [A/m^2 K^2]$$

where,
A is thermionic emission constant
T is temperature in ^oK
e is electronic charge $=1.6\text{x}10^{-19}$ C
m is electron mass $=9.11\text{x}10^{-31}$ kg
k_B is Boltzmann constant = $1.38 \text{ x } 10^{-23}$ (J/K)=$8.6175\text{x}10^{-5}$ (eV/K)
h is Planck's constant = $6.63 \text{ x } 10^{-34}$ (Js)

Thermionic Emission

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

- Example:
  - Pure Tungsten cathode
  - Dispenser cathode: These are of porous tungsten impregnated with Barium Oxide.



Field Emission

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

- If large RF field is applied, then the potential barrier becomes thin
- Electrons may tunnel out and emit from the surface
- Since there is no external heating is applied, hence it is many times referred as Cold Emission

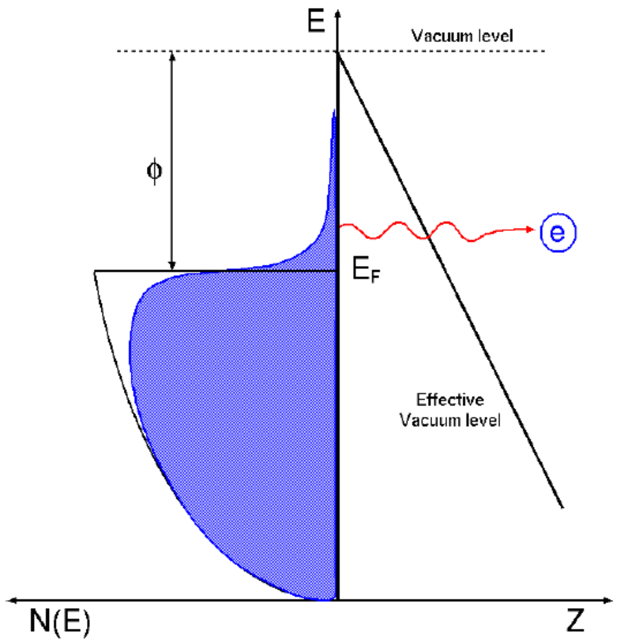
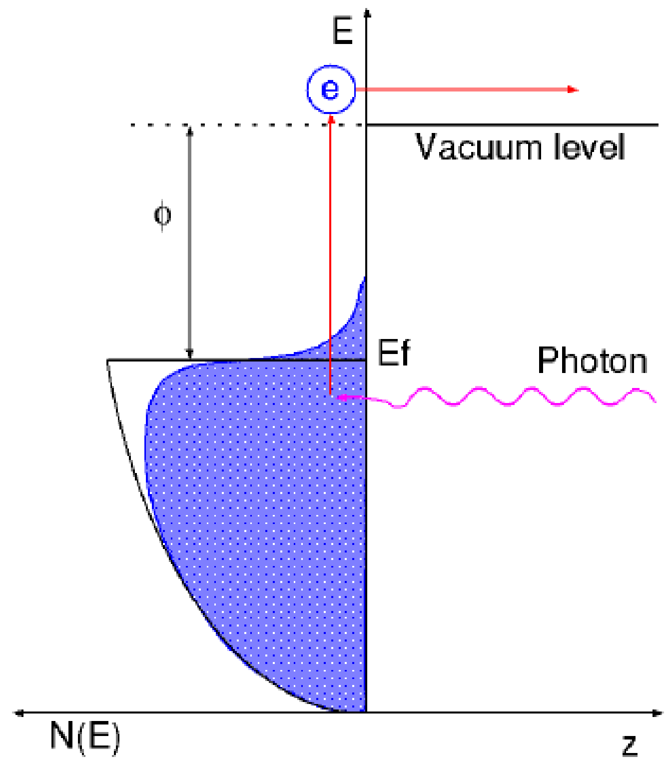


Photo electron emission

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

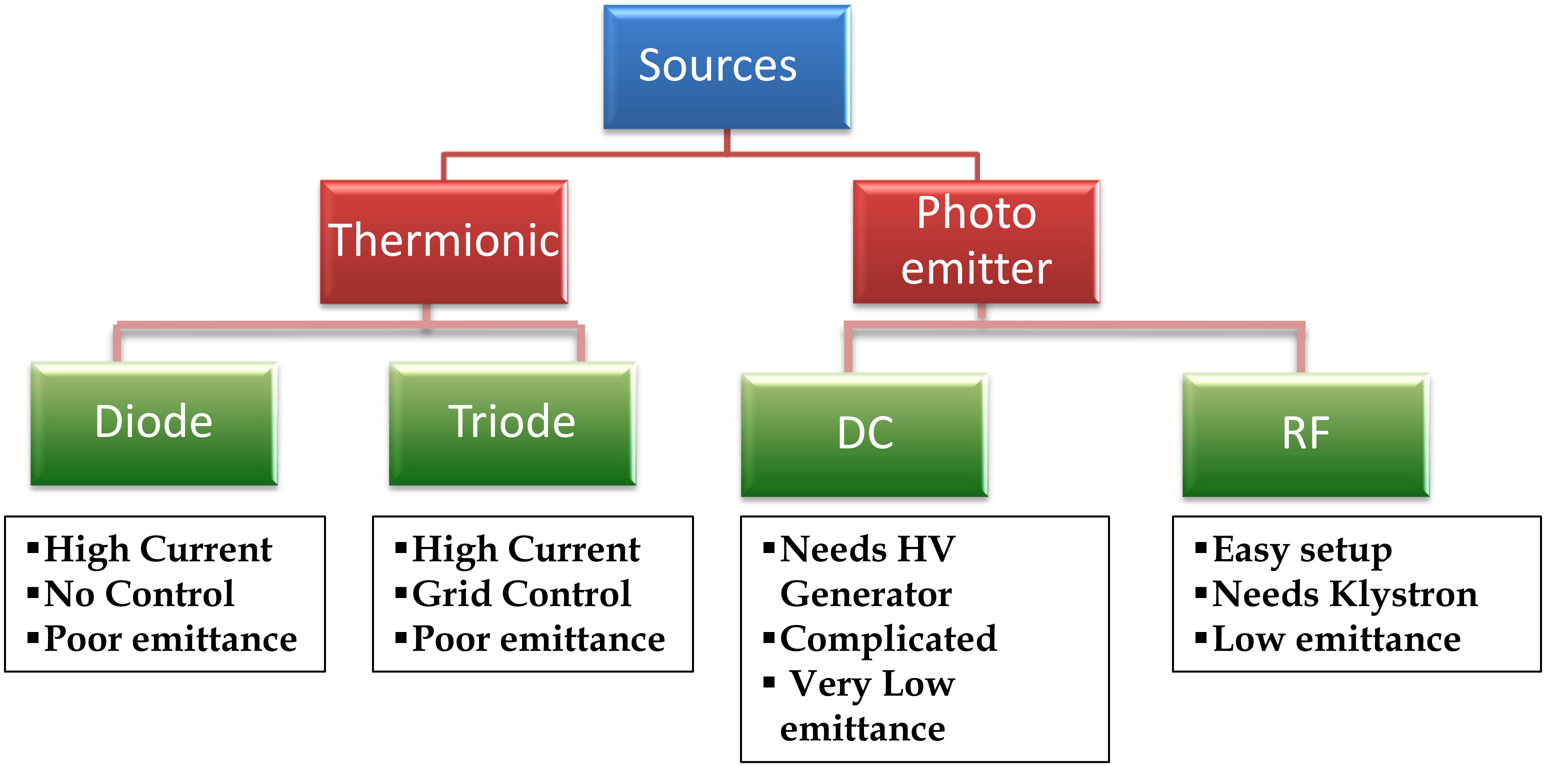
- A photon strikes the surface of an emitter
- The photon excites the electrons to higher energy states
- If the excited energy is sufficiently high, the electrons can escape outside
- The resultant current is photo emission current
- Condition for emission

$h\nu > \phi$



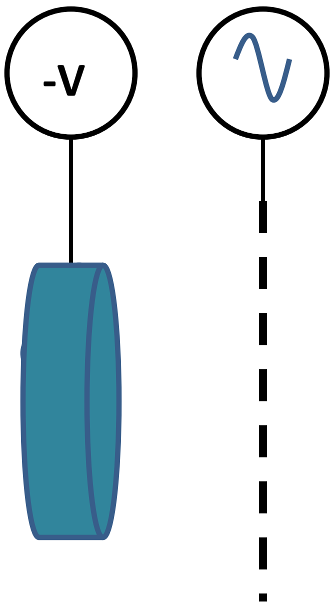
Extraction mechanism

- Once the electrons are generated using any of above methods, these can be extracted by DC or RF mechanism.
- Accordingly, we classify as DC or RF gun
- Next slide displays details of functioning of Thermionic Gun



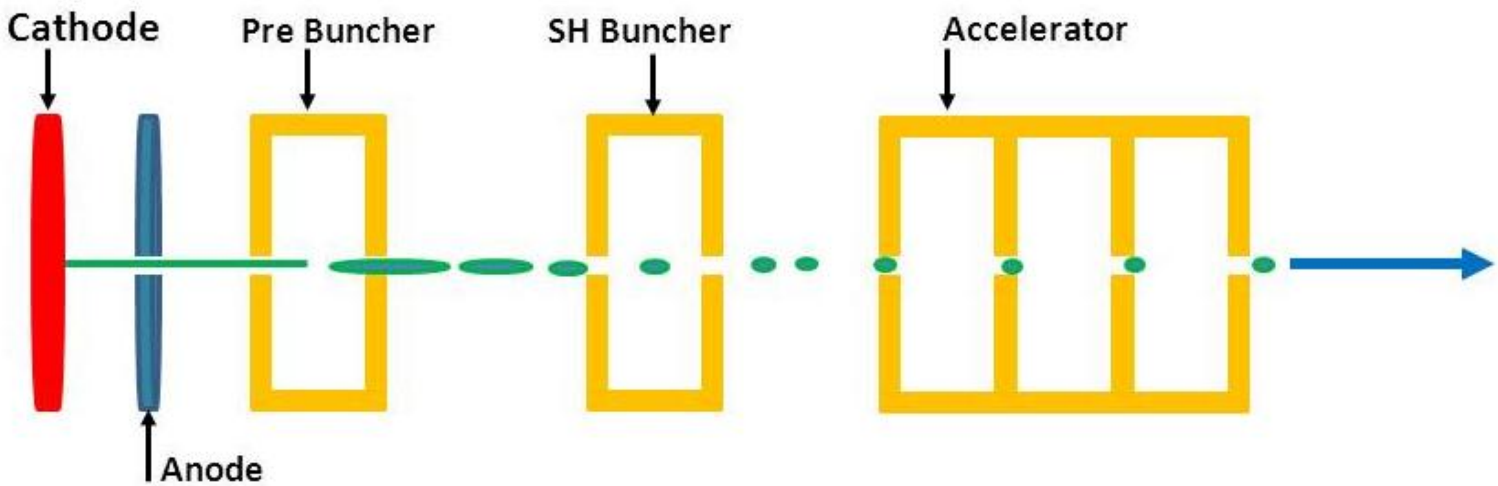
DC Thermionic Gun

- Emission is thermionic and hence continuous
- Extraction is by DC field
- A Grid can be used to control the emission



Configuration of thermionic gun

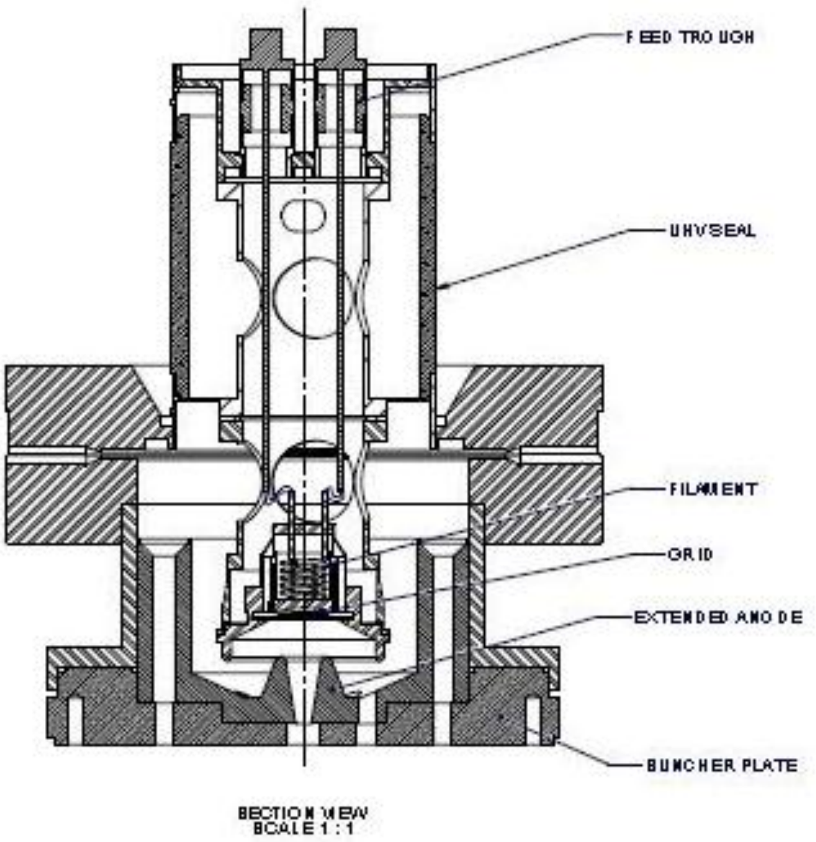
- Since the emission from thermionic gun is continous, we need to bunch the electrons using buncher cavities
- A typical configuration for thermionic gun looks like:



SAMEER Triode Gun

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

As an example…SAMEER triode gun is shown below



Cathodes

- Electron Source
- RF Gun Basics
- Details of RF Gun
- Cavity for RF Gun
- KEK RF Gun
- Results of KEK Gun
- Plan for IUAC Gun

Material	ϕ (ev)	T_e (K)
W	4.5	2860
Ta	4.1	2680
Mo	4.2	2230
Cs	1.9	320
Th-W	2.6	1800
BaO	1.0	1400
CeB_6	2.5	1720
LaB_6	2.5	1400
Dispenser	1.6	1100

Should be low

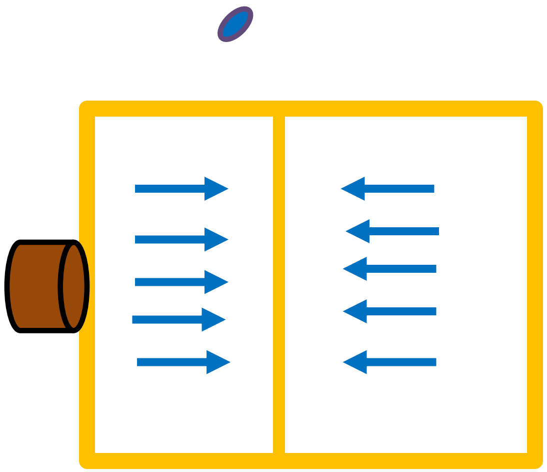
Higher is good

Photo cathode gun

- Uses the principle of Photo emission
- A laser of suitable wavelength hits a photo cathode and generates electron bunch
- The electrons are extracted using
  - DC potential: in case of DC photo cathode gun
  - High gradient RF field: in case of RF photo cathode gun

RF Photo cathode gun

- A photo cathode is placed at the entrance of RF cavity.
- The laser hits the photo cathode and generates electron bunch, which is quickly accelerated using high gradient fields near the cathode.
- Such a electron bunch has very high space charge and the beam diverges quickly
- If high gradient, of say 120 MV/m is made at cathode, then bunch accelerates very fast and exits from RF gun at around 6 MeV energy with low emittance of around 2π-mm-mrad



Comparison between Thermionic and RF Gun

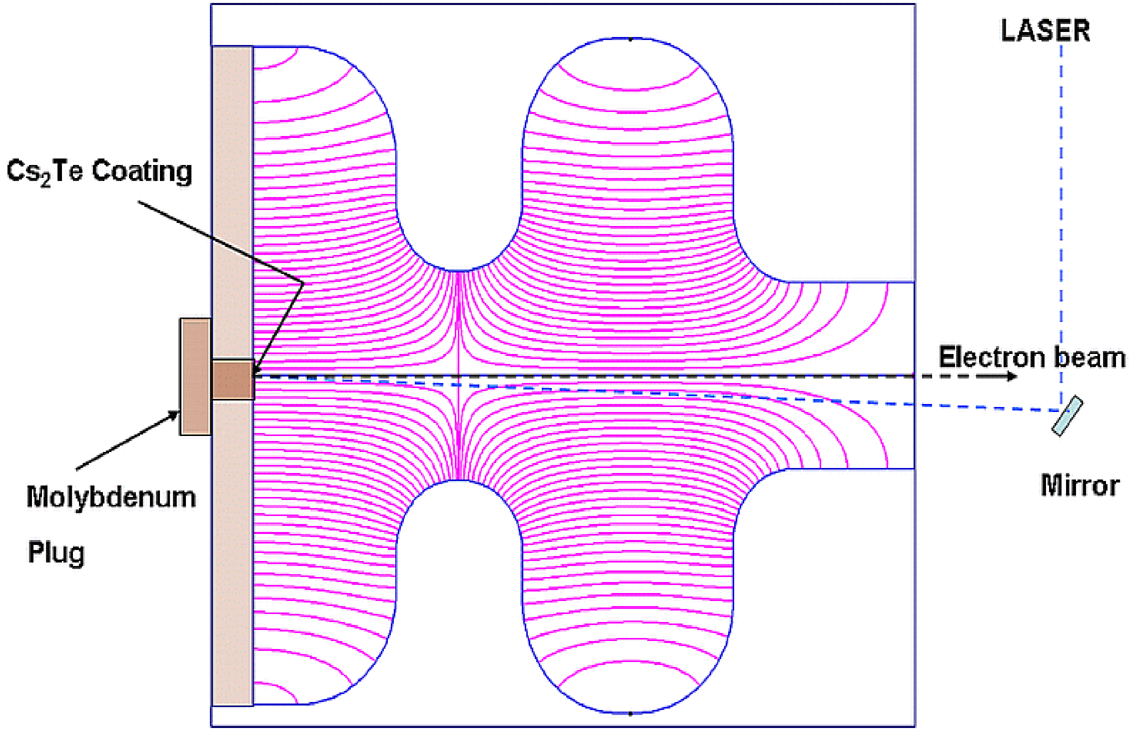
- Electron Source
- RF Gun Basics
- Details of RF Gun
- Cavity for RF Gun
- KEK RF Gun
- Results of KEK Gun
- Plan for IUAC Gun

	Thermionic Gun	RF Gun
Type of emission	DC	Pulse
Current	High average current possible	High peak current possible
Post Buncher	Mandatory	Not needed
Output energy	few tens of KeV	MeV
Emittance per nC	~ 10 -12 π-mm-mrad	<2 π-mm-mrad
Main usage	High current industrial, medical	Research accelerators

Operation of RF Photo cathode gun

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

- The **electron bunch charge** depends on the laser power and the quantum efficiency of the photo cathode material.
- The **bunch length** depends on the temporal laser profile.



RF Gun Cavity

RF Gun Details

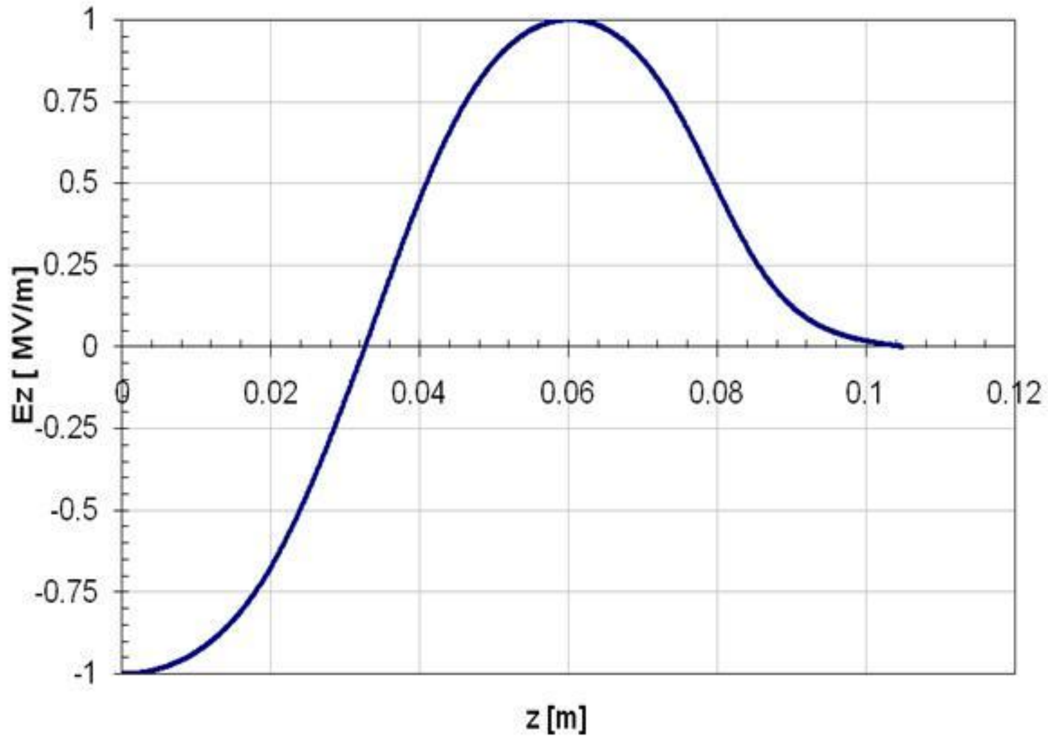
Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

- The RF gun usually operates at π-mode.
- An incident laser pulse hits the photo cathode to produce an electron bunch.
- If a 266 nm laser shines the surface of say Cs2Te photo cathode, electrons with ~ 4.66 eV energy are produced.
- Lets say, we get 1 nC charge with a bunch length of 5 ps and σ_x and σ_y is nearly 300 μm.
- Due to space charge forces, the emittance of bunch degrades immediately as it enters inside the first cell.
- The emittance is controlled by maintaining a very high gradient at the cathode plate. At KEK, we maintained 120 MV/m gradient at cathode.

RF Gun Details

- **Electron Source**
- **RF Gun Basics**
- **Details of RF Gun**
- **Cavity for RF Gun**
- **KEK RF Gun**
- **Results of KEK Gun**
- **Plan for IUAC Gun**

LUCX RF gun operating at π-mode.



Field distribution at π-mode

Brief summary of parameters of KEK RF Gun

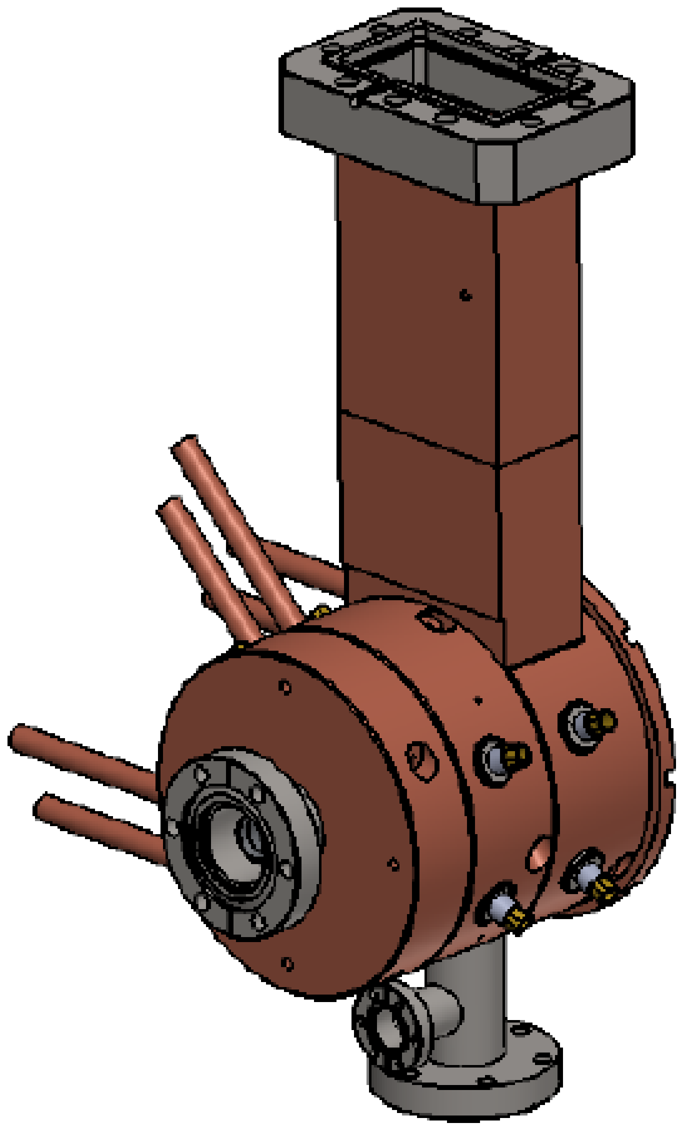
Operating Frequency	2856	MHz
Mode of Operation	π	
Mode Separation	8.6	MHz
Field Balance	1.0	
Iris Diameter	28	mm

Ref: Abhay Deshpande, Junji Urakawa et al. NIM-A 600 (2009) 361-366

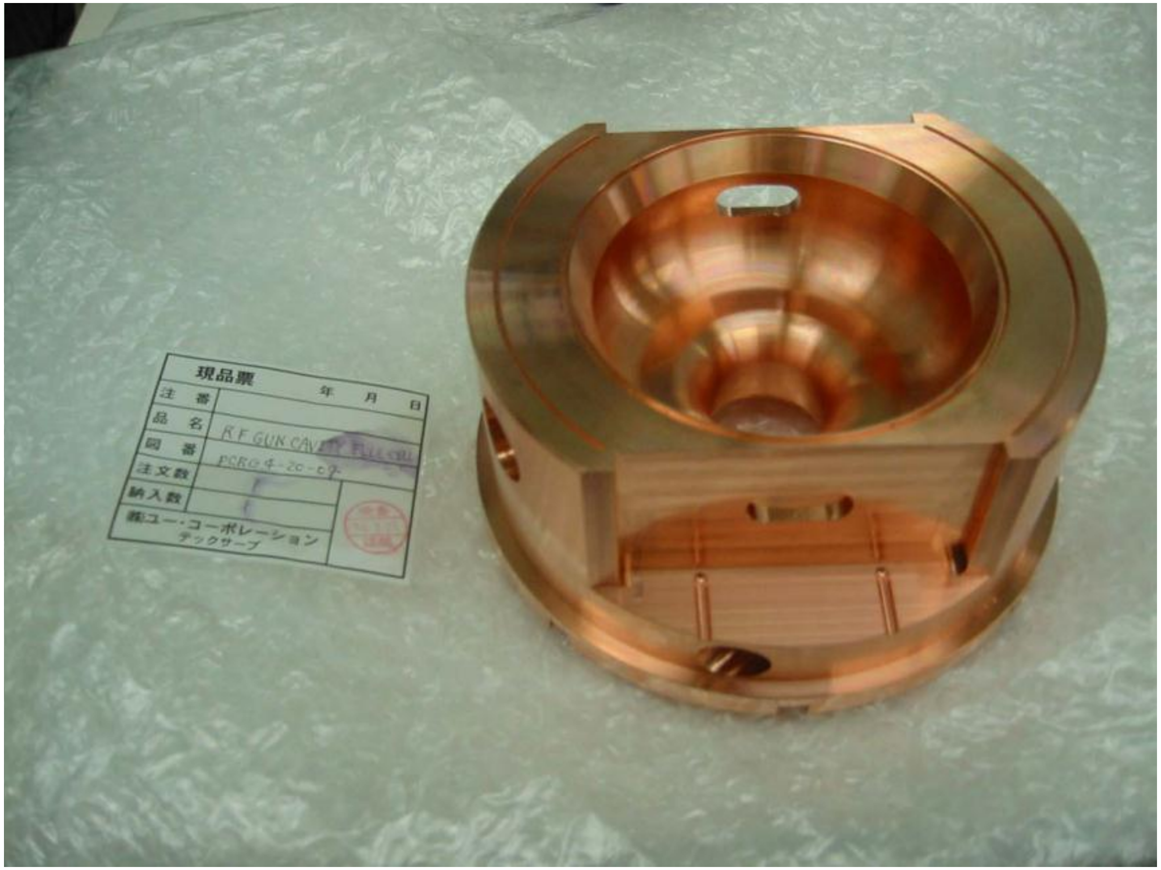
Brief summary of parameters

- Electron Source
- RF Gun Basics
- **Details of RF Gun**
- Cavity for RF Gun
- KEK RF Gun
- Results of KEK Gun
- Plan for IUAC Gun

- Followi ... ped to maximize the shunt ir
- The sep ... ncreased up to 9 MHz
- The stru ... sh code
- CAD dı ... ulations

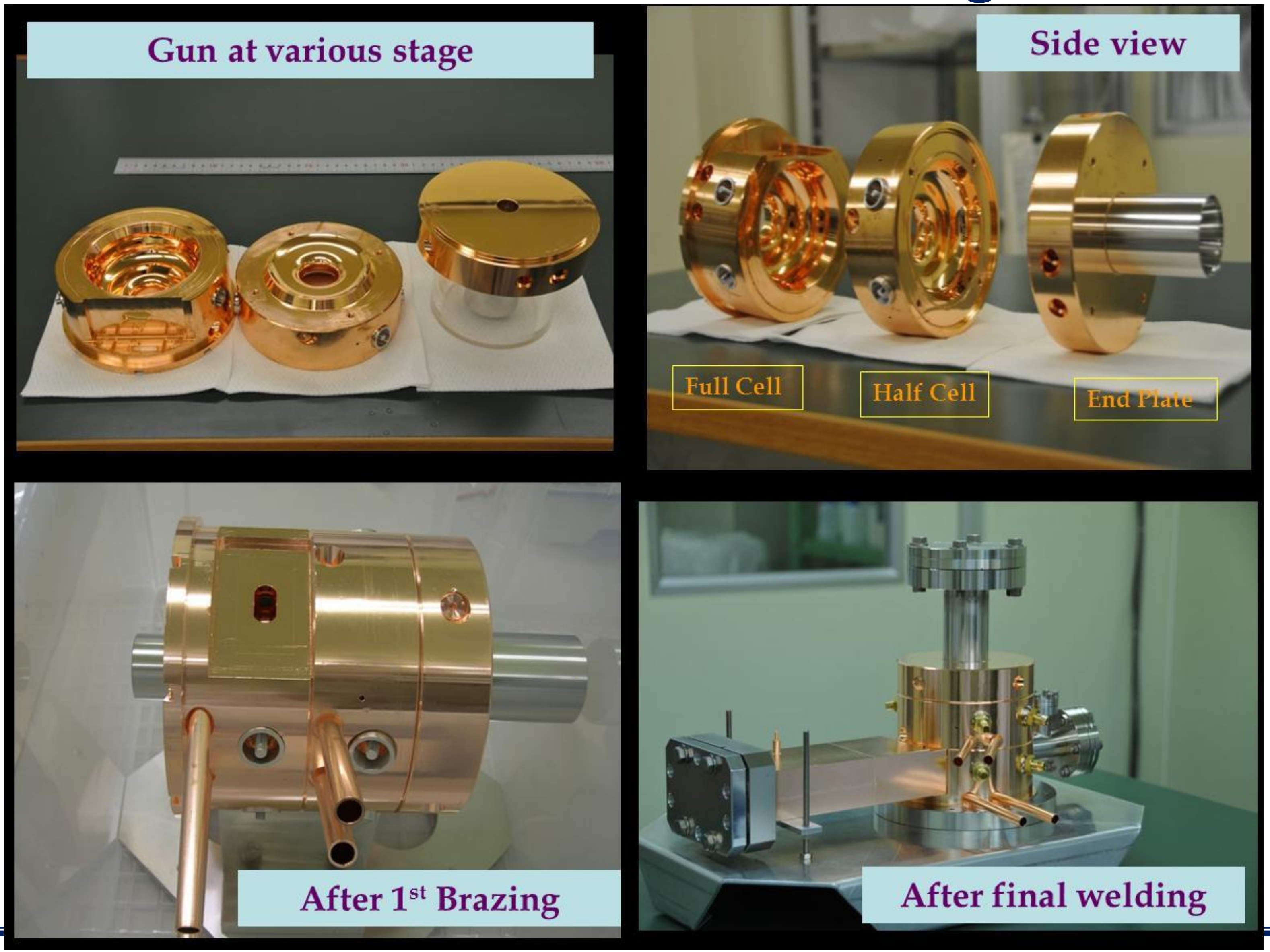


Rough Machining



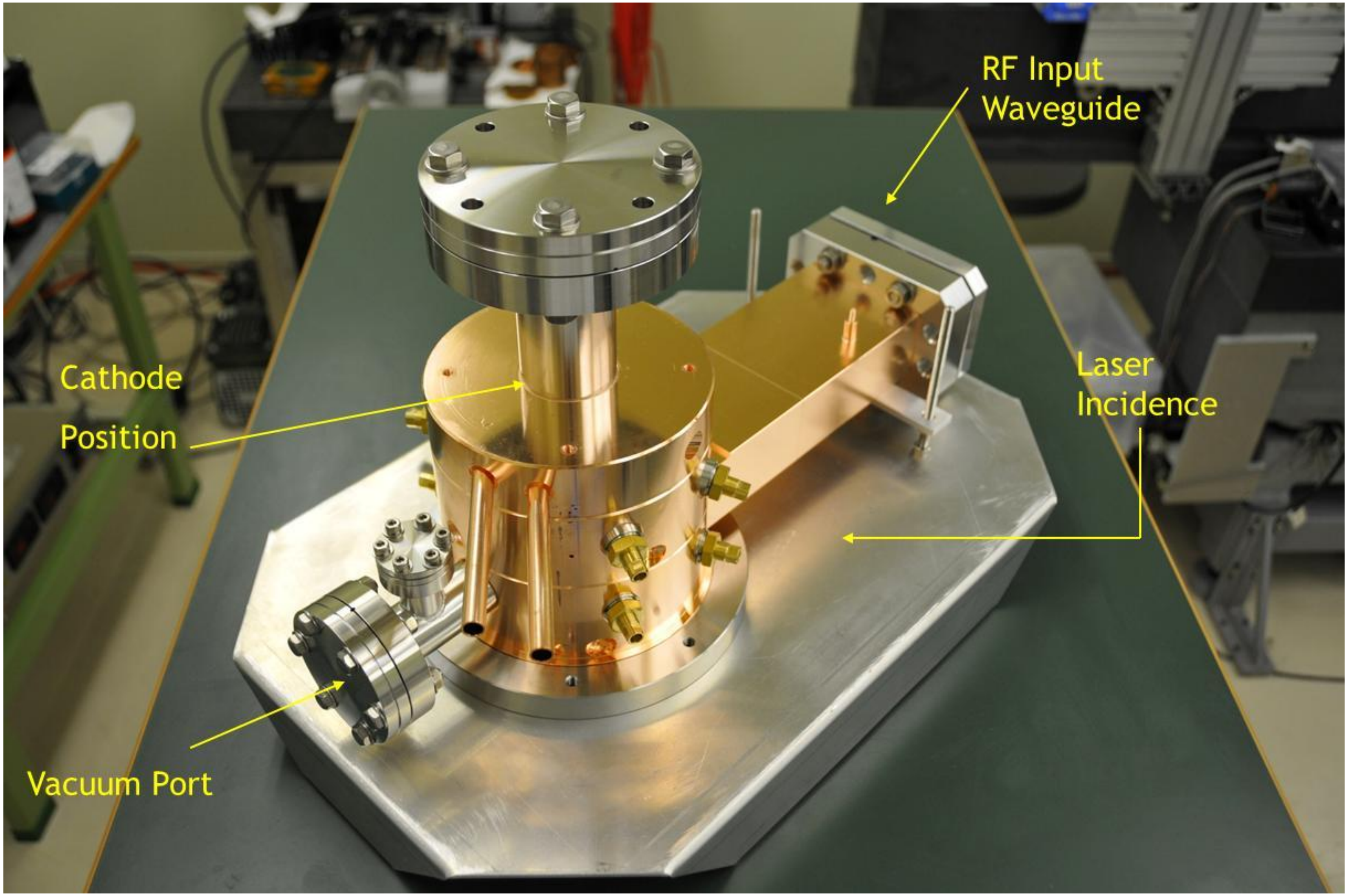
Fabrication at various stages

- Electron Source
- RF Gun Basics
- Details of RF Gun
- Cavity for RF Gun
- KEK RF Gun
- Results of KEK Gun
- Plan for IUAC Gun



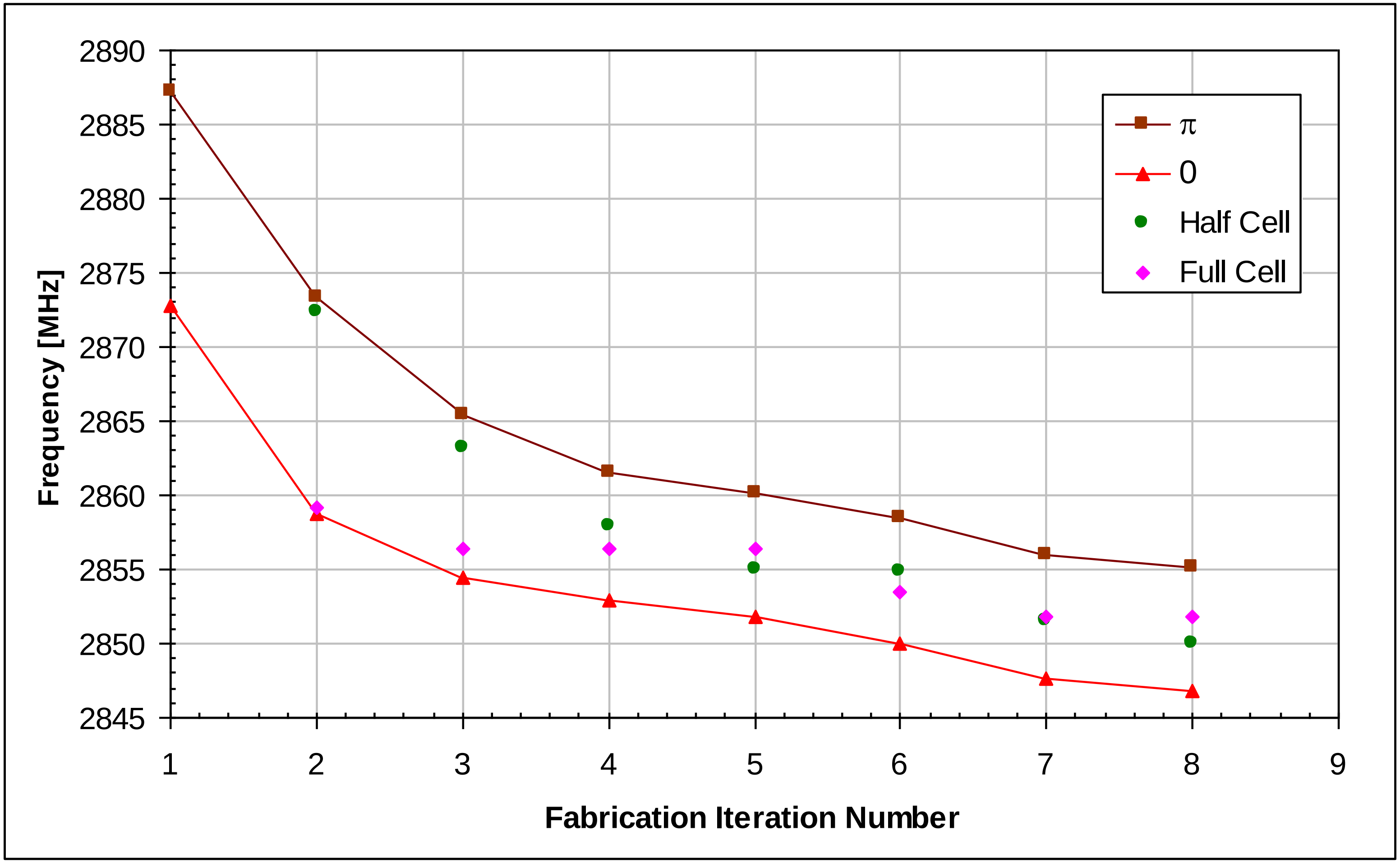
Complete RF Gun

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

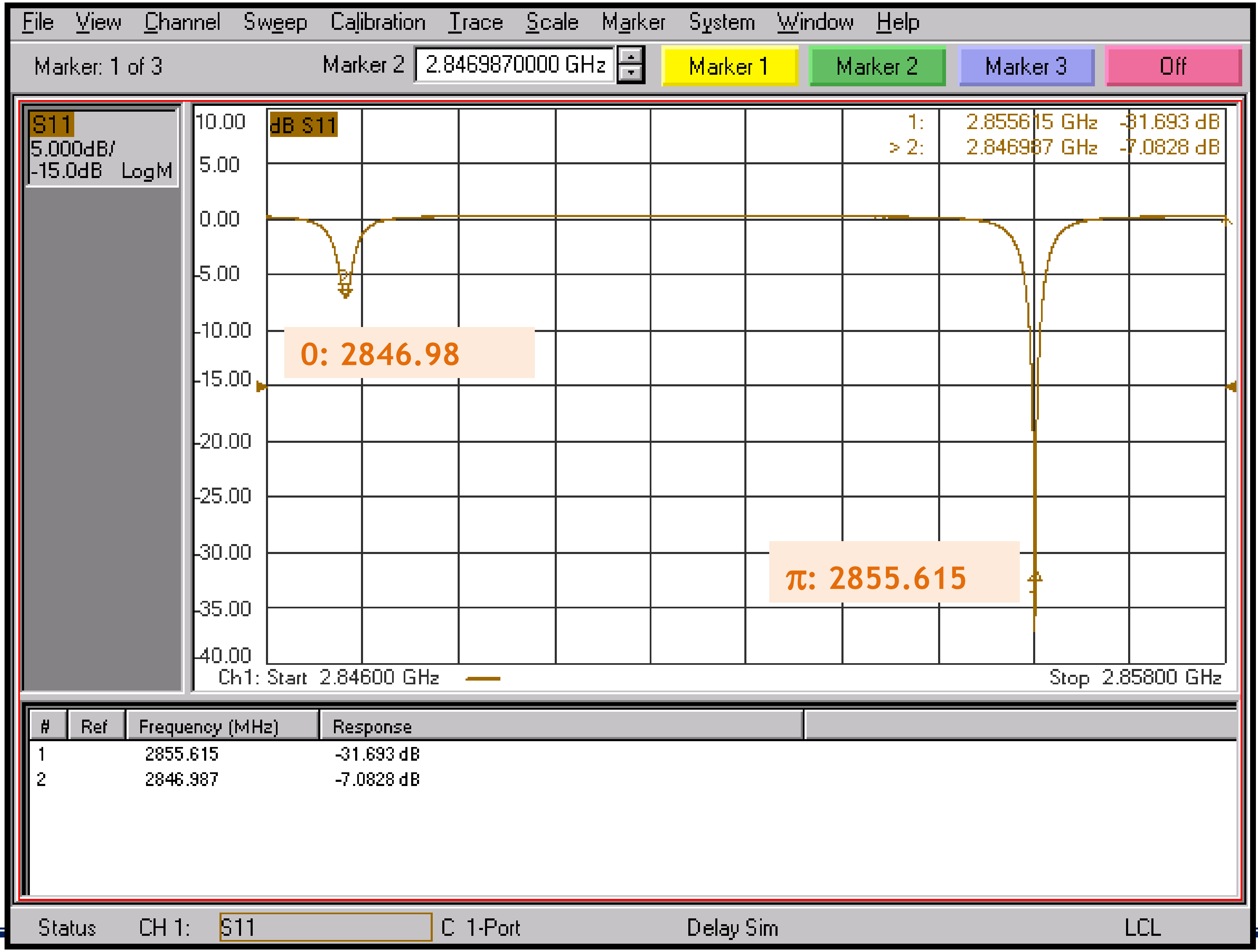


Fabrication history

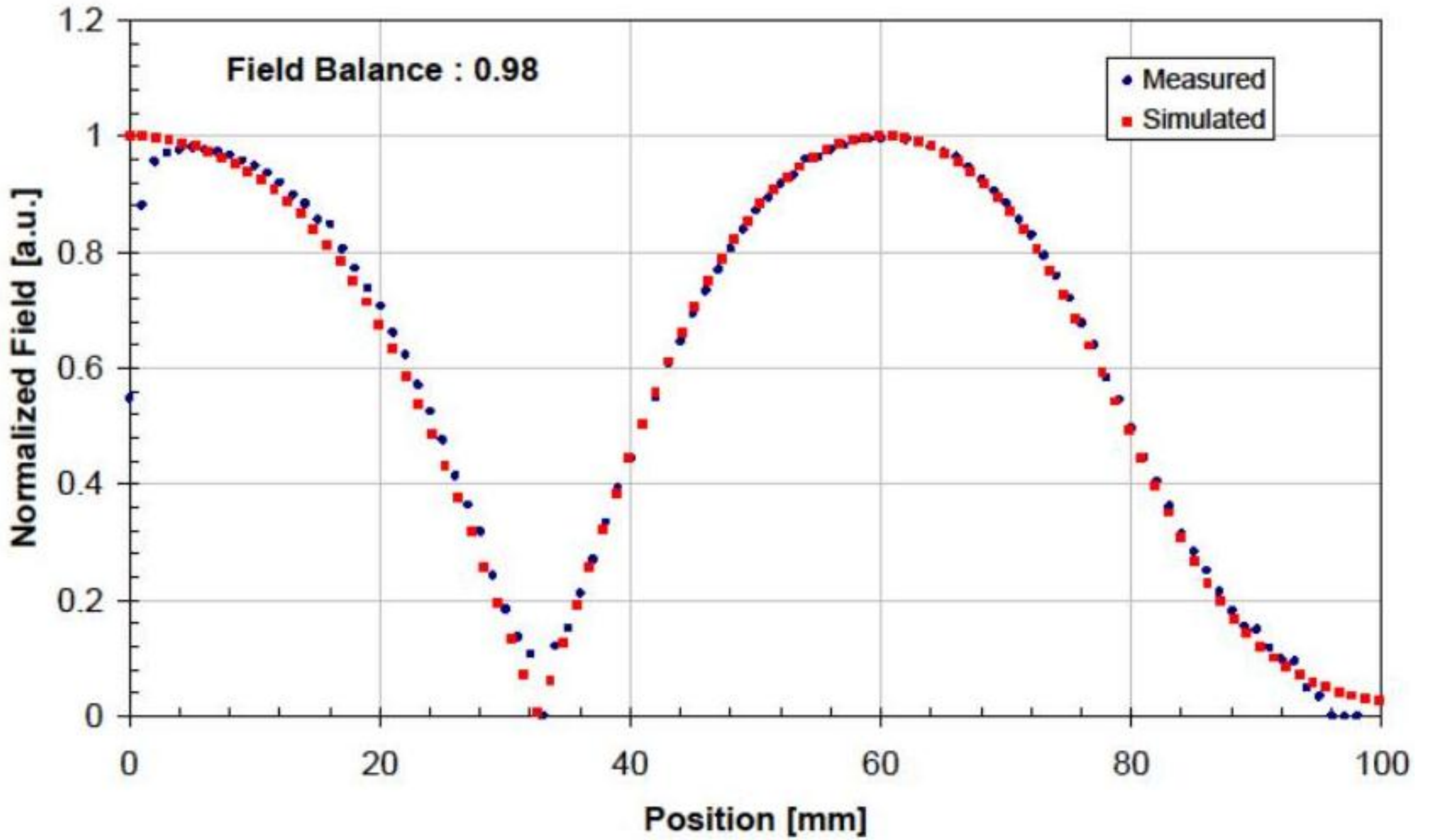
- **Electron Source**
- **RF Gun Basics**
- **Details of RF Gun**
- **Cavity for RF Gun**
- **KEK RF Gun**
- **Results of KEK Gun**
- **Plan for IUAC Gun**



Mode Frequency Measurements



Field Measurements



Low Power Measurements

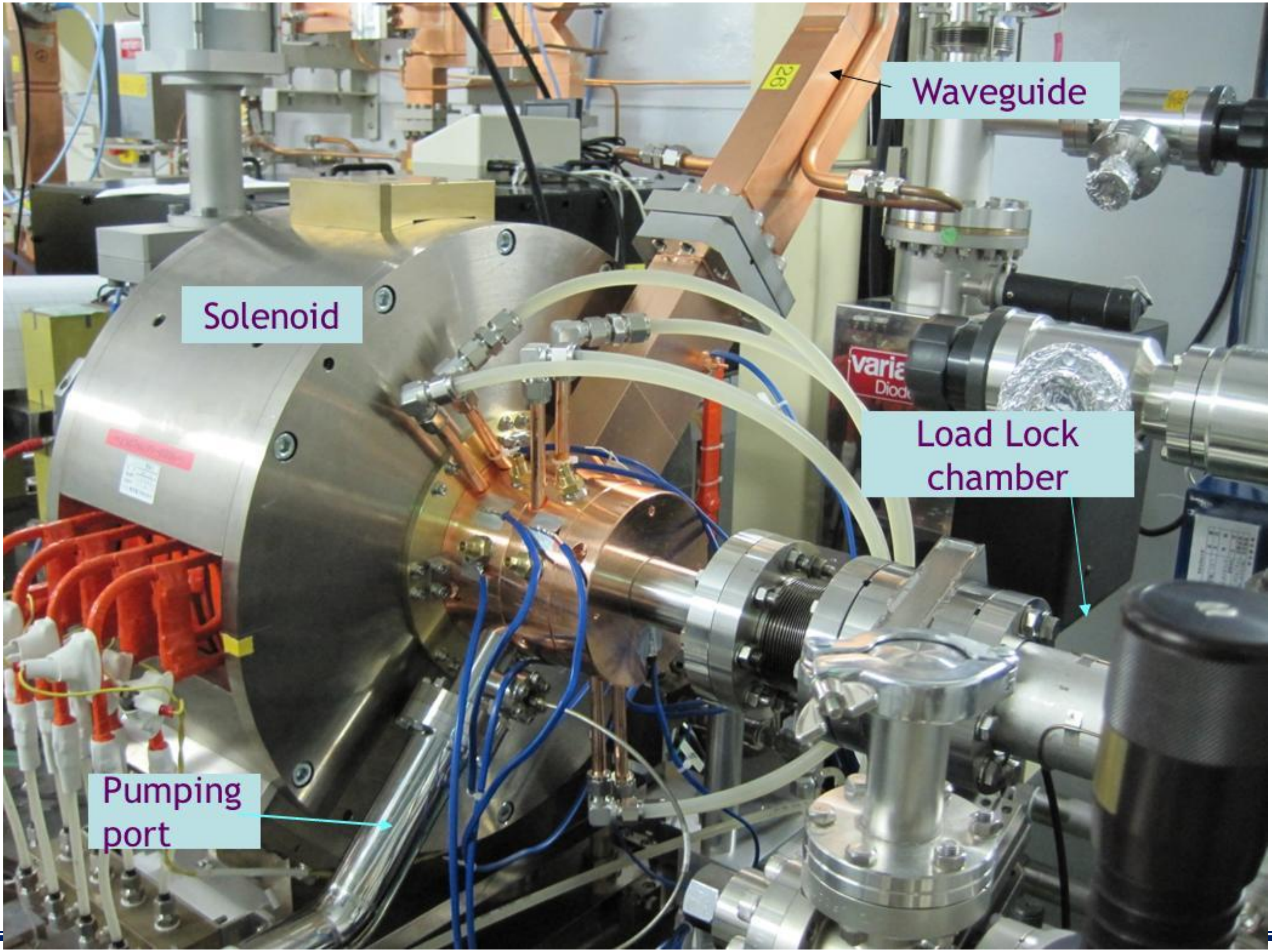
Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

	Simulated	Measured
Frequency MHz	2855.64	2855.61
Mode Separation MHz	8.67	8.63
Field Balance	1.0	0.98
Q	18000	14,700
Coupling β	1.0	1.03

RF Gun	Q
BNL (original)	7900
LUCX (Old)	7900
ATF (modified)	12600
BNL (modified)	12780
LUCX (modified)	14,700
LCLS (modified)	13,900

RF Processing

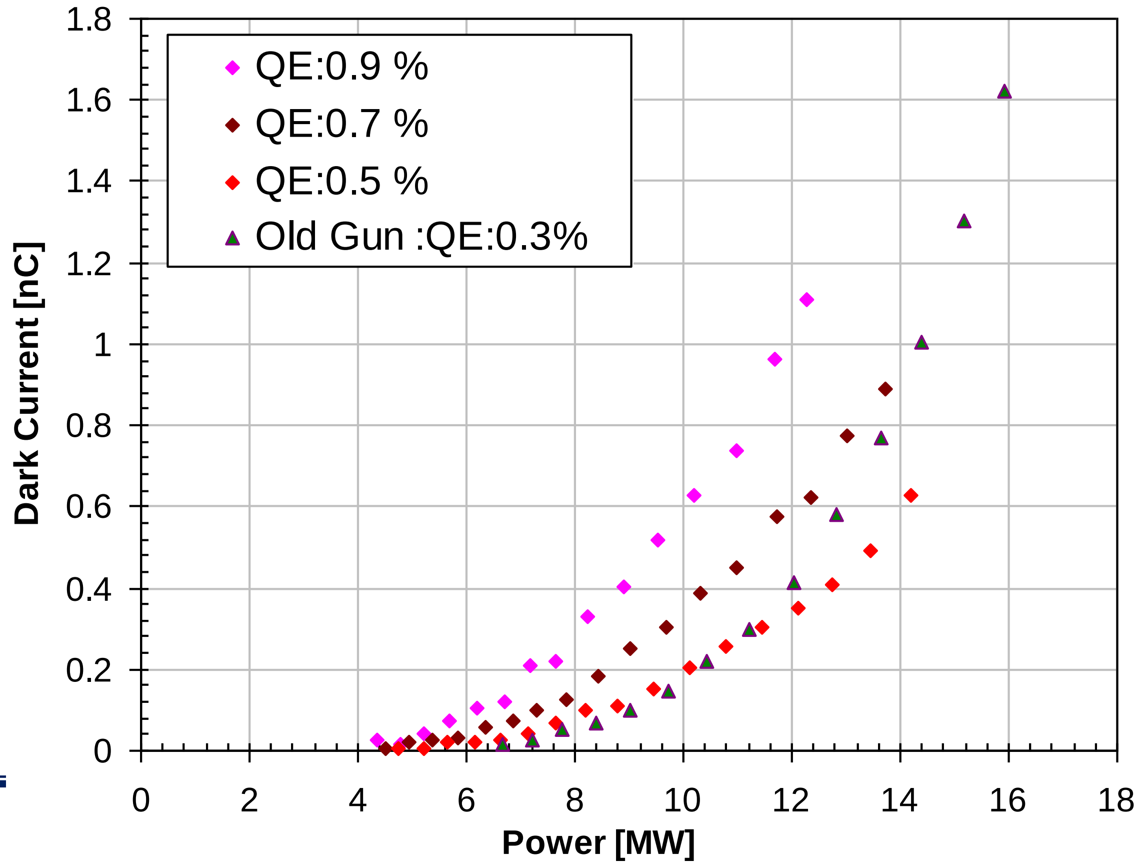
Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun



RF Processing

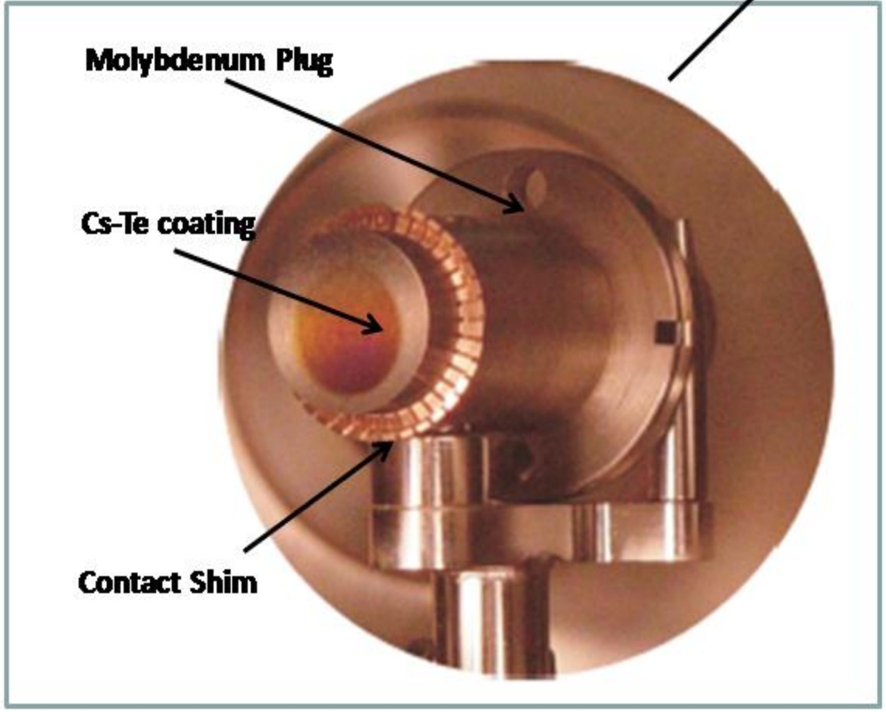
- Electron Source
- RF Gun Basics
- Details of RF Gun
- Cavity for RF Gun
- KEK RF Gun
- Results of KEK Gun
- Plan for IUAC Gun

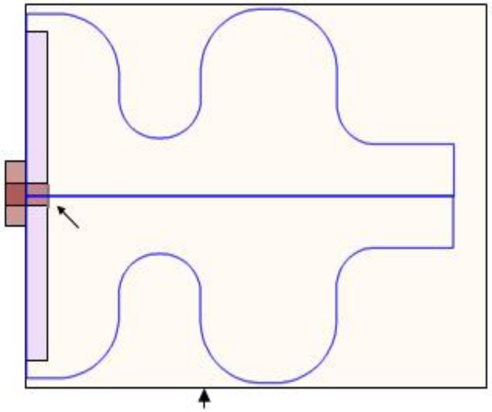
- The RF processing was carried out for 150 hrs at a pulse width of 2 μs and power of about 10 MW.
- Next, we coated the cathode with Cesium-Telluride (Cs_2Te) and conditioned the gun by operation for another 100 hrs.
- At 30 days after the coating, the quantum efficiency was found to be around 0.5% and the dark currents were substantially low.



Components for RF gun: Photocathode

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun





Choice of Photocathode

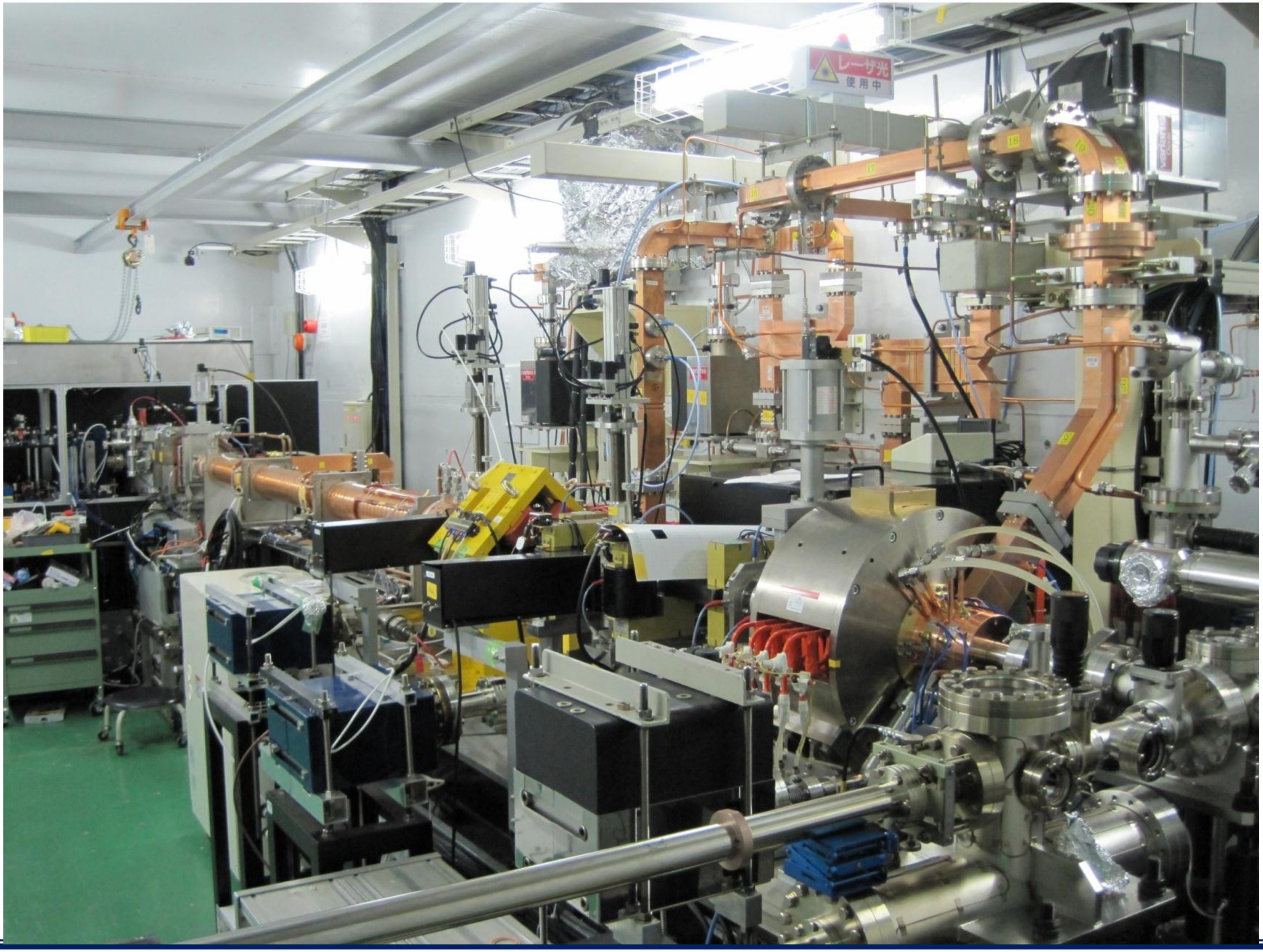
Thermionic	Temperature (K) k_BT (eV)	Radius (mm)	Current Density (A/cm^2)	Work Function(eV)	Thermal Emittance/beam size (μ/mm (rms))
CeB_6	1723 0.1486	1.5	42	2.3	0.539

Metal	λ (nm) E (eV)	QE	Vacuum (torr)	Work Function (eV)	Thermal Emittance/beam size (μ/mm (rms))	
					Calculated	**Measured**
Copper	250 , 4.96	1.4 x 10^{-4}	10^{-9}	4.6	0.5	**1.0 ± 0.1**
Mg	266, 4.66	6.4 x 10^{-4}	10^{-10}	3.6	0.8	**0.4 ± 0.1**
Cs_2Te	211, 5.88	~ 0.1	10^{-9}	3.5	1.2	**0.5 ± 0.1**
	264, 4.7				0.9	**0.7 ± 0.1**
	262, 4.73				0.9	**1.2 ± 0.1**
GaAs	**532, 2.33**	**~ 0.1**	**?**	**1.4±0.1**	**0.8**	**0.44±0.01**

Ref: D.H. Dowell et al., Nucl. Instr. and Methods in Phy. Res. A 528 (2004) 316.

Old LUCX

- **Electron Source**
- **RF Gun Basics**
- **Details of RF Gun**
- **Cavity for RF Gun**
- **KEK RF Gun**
- **Results of KEK Gun**
- **Plan for IUAC Gun**



LUCX parameters

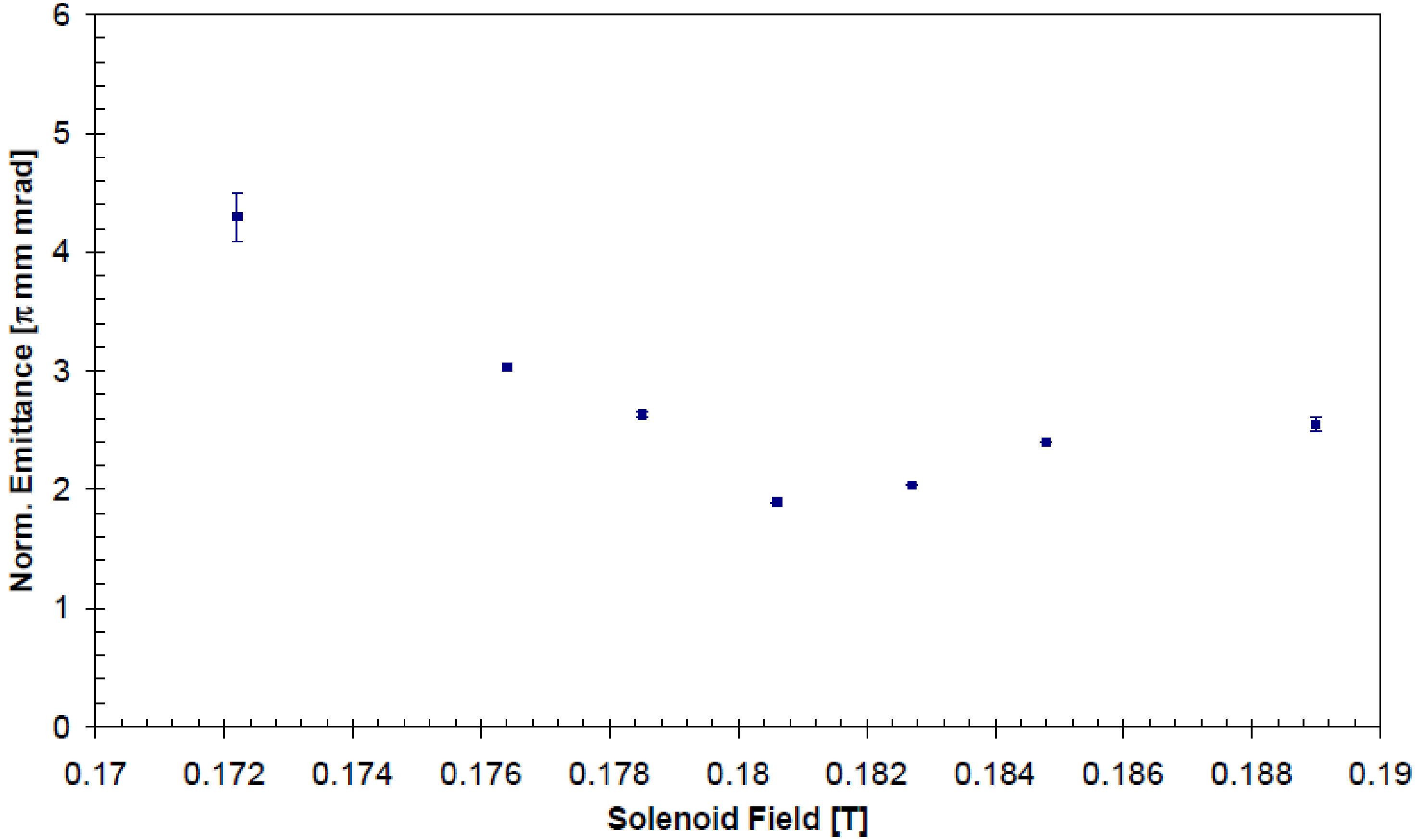
Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

Energy	50 5	MeV (High) MeV (Low)
Bunch Charge	0.5	nC (charge is variable)
Bunch Length	5.5	ps (rms)
Bunch spacing	2.8	ns
Number of bunches	100 (High Energy) 300 (Low Energy)	
Repetition rate	3.13 to 12.5	Hz
Normalized emittance	1.89± 0.1	π-mm-mrad (vertical)
Minimum beam size	50	μm (vertical)

Emittance measurement

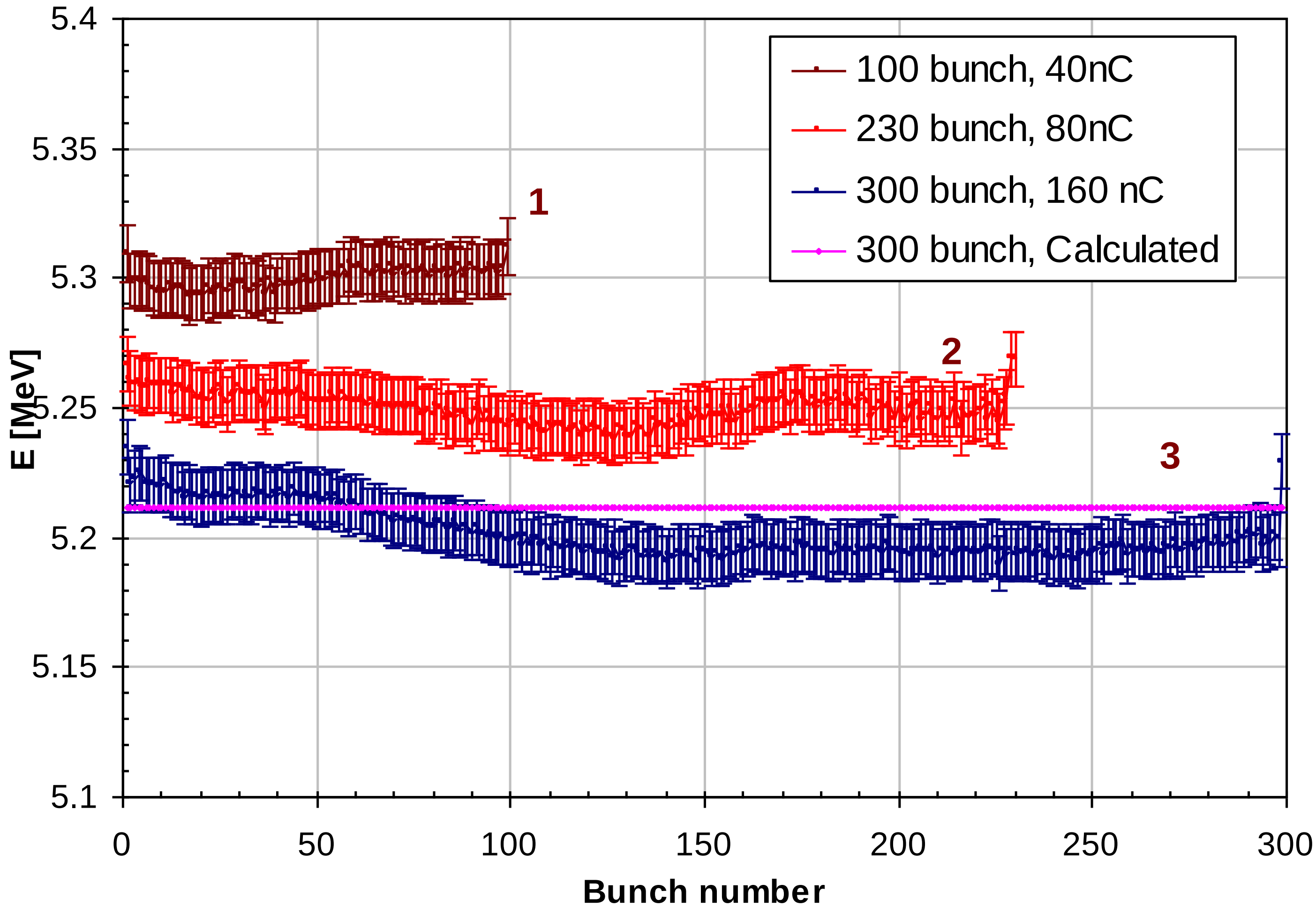
- Electron Source
- RF Gun Basics
- Details of RF Gun
- Cavity for RF Gun
- KEK RF Gun
- Results of KEK Gun
- Plan for IUAC Gun

- Charge : 1nC; Two bunch mode
- Normalized emittance is 1.89 ± 0.10 π-mm-mrad



Multi Bunch Beam

- **Electron Source**
- **RF Gun Basics**
- **Details of RF Gun**
- **Cavity for RF Gun**
- **KEK RF Gun**
- **Results of KEK Gun**
- **Plan for IUAC Gun**

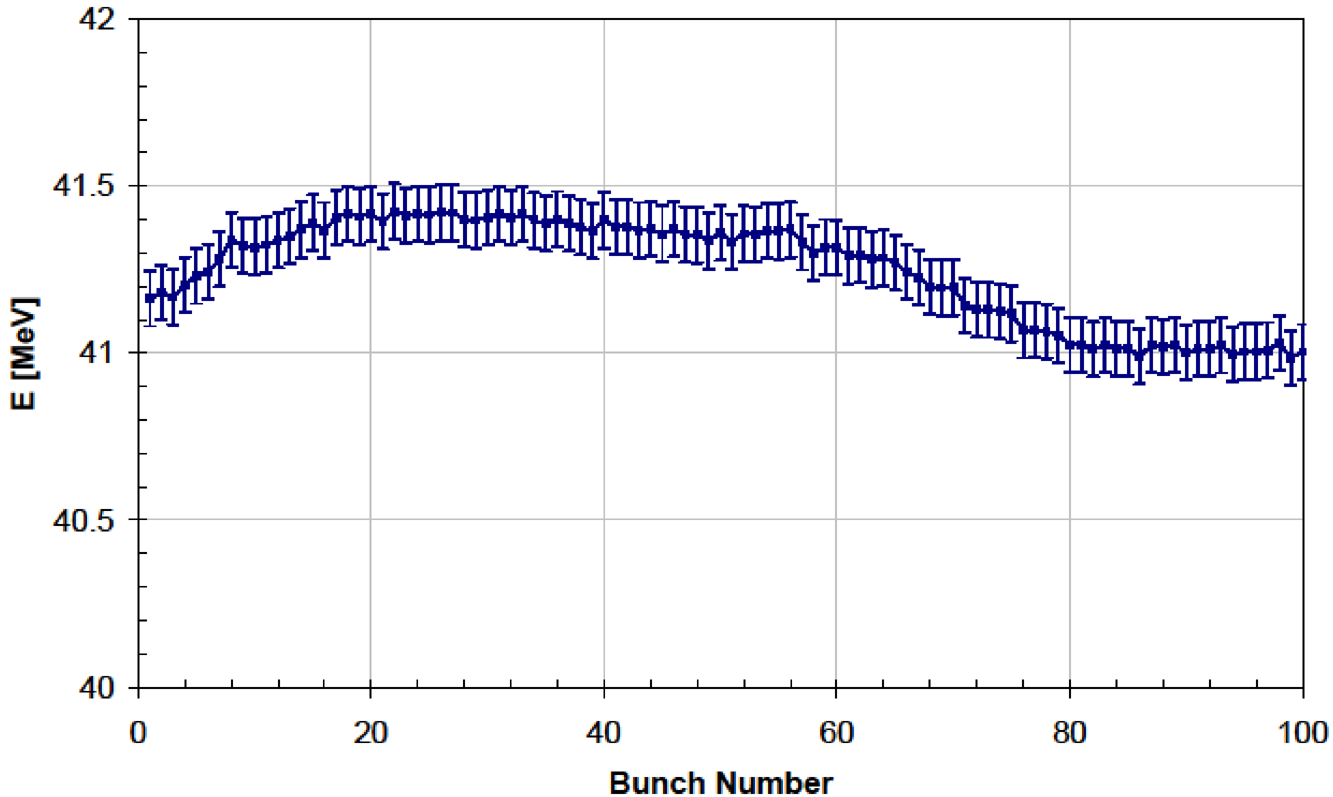


Peak-to-peak Energy Difference:

100 bunch: 0.36 % **230 bunch: 0.58%** **300 bunch: 0.85%**

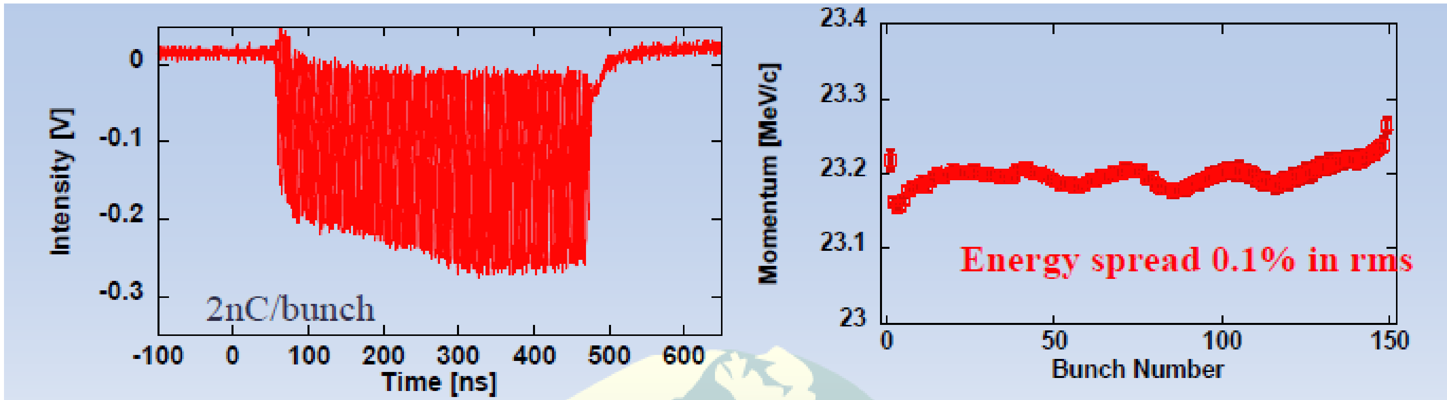
Multi Bunch Beam

- Electron Source
- RF Gun Basics
- Details of RF Gun
- Cavity for RF Gun
- KEK RF Gun
- **Results of KEK Gun**
- Plan for IUAC Gun

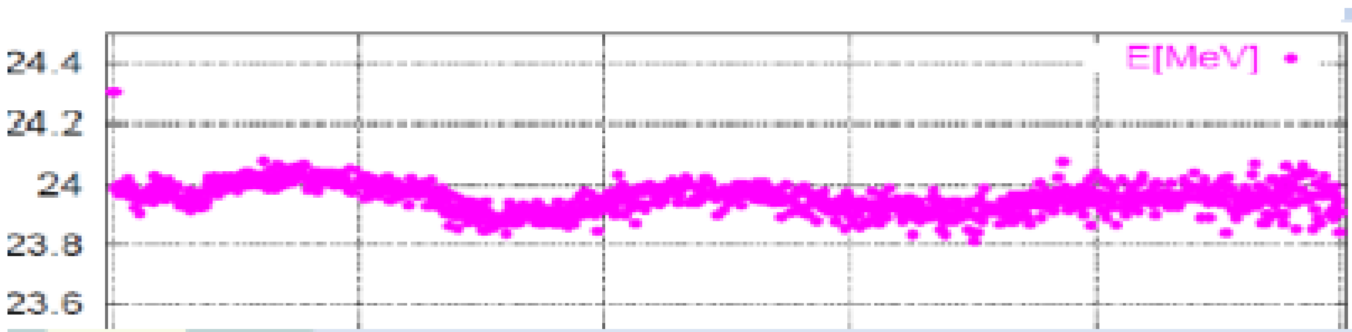


Power [MW]	Charge [nC]	% Energy Difference
39.2	40	0.7
40.6	42	1.4
42.1	42.5	0.9

Multi Bunch Beam

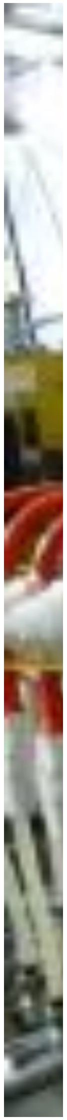


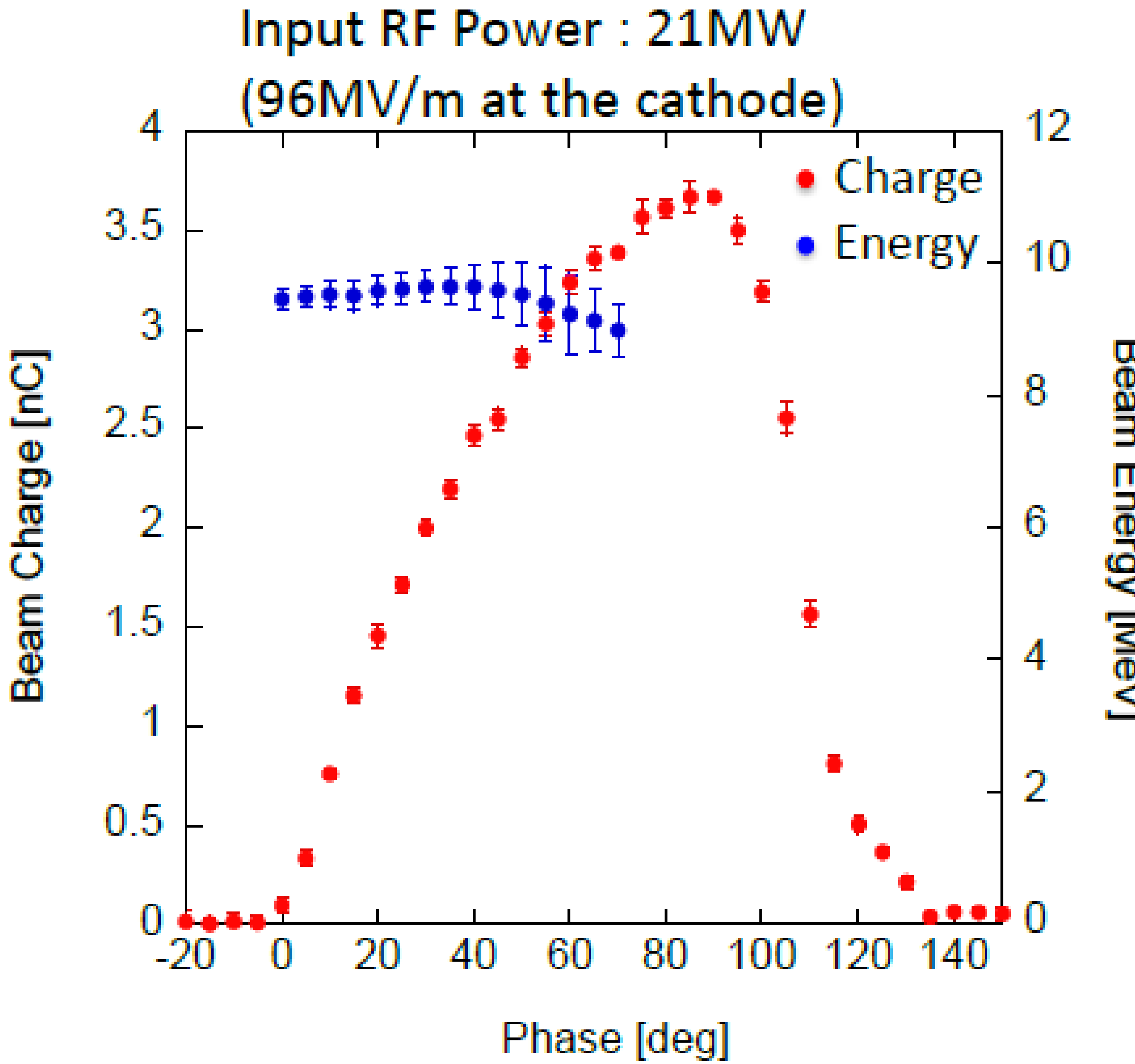
Number of bunches	Charge [nC]	Energy [MeV]
150	300	23



Number of bunches	Charge [μC]	Energy [MeV]
1000	0.5	24

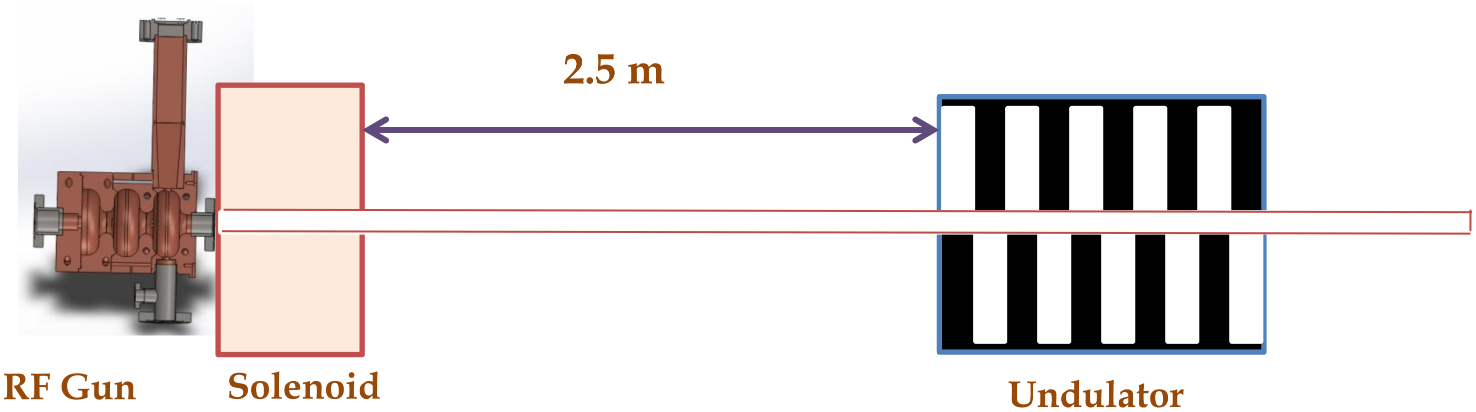
3.5 cell RF gun





Plan for IUAC- Phase 1

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

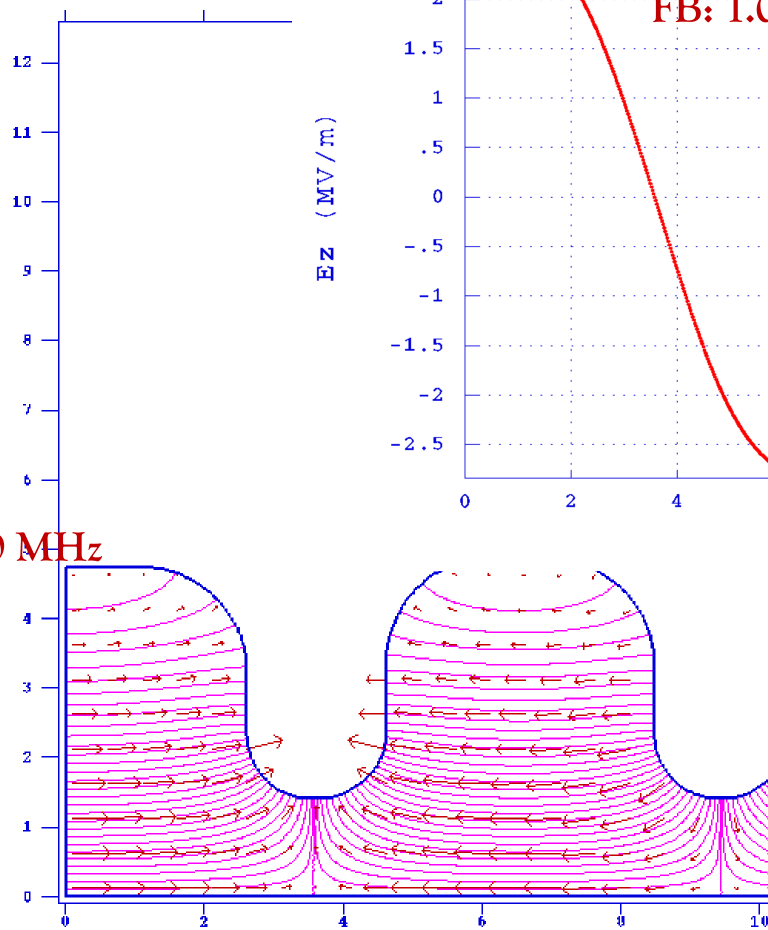


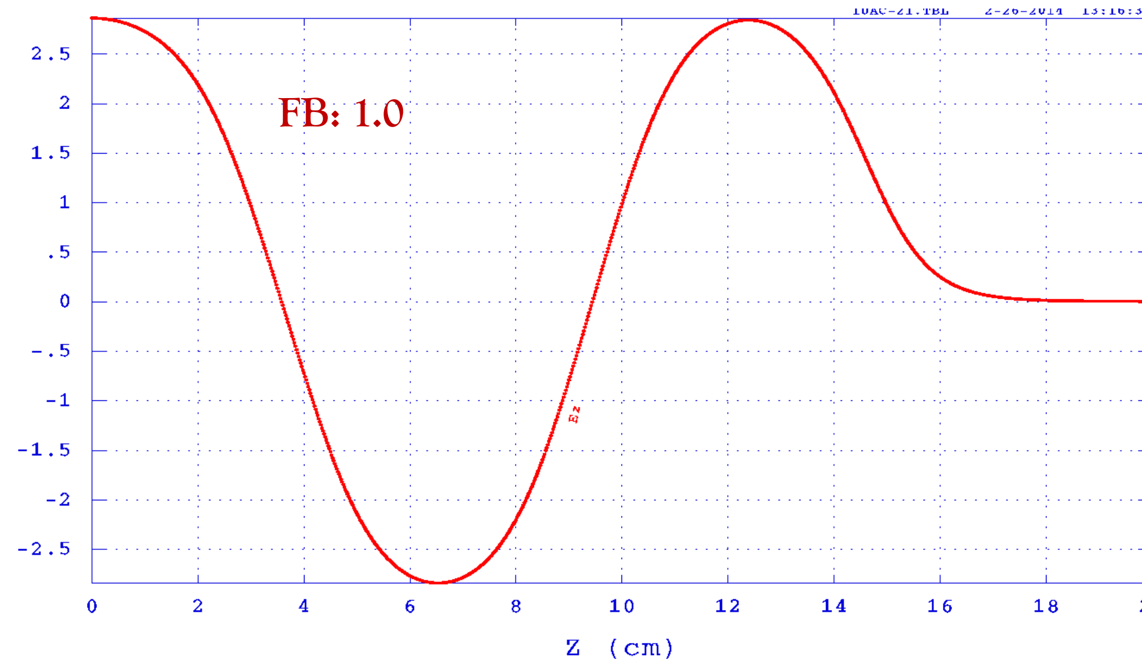
Parameter	Value	Unit
Frequency	2860	MHz
Bunch Charge	50	pC/pulse
No. of micro bunches	4 -16	
Energy	8	MeV

IUAC RF Gun

- Electron Source
- RF Gun Basics
- Details of RF Gun
- Cavity for RF Gun
- KEK RF Gun
- Results of KEK Gun
- **Plan for IUAC Gun**

RF Gun

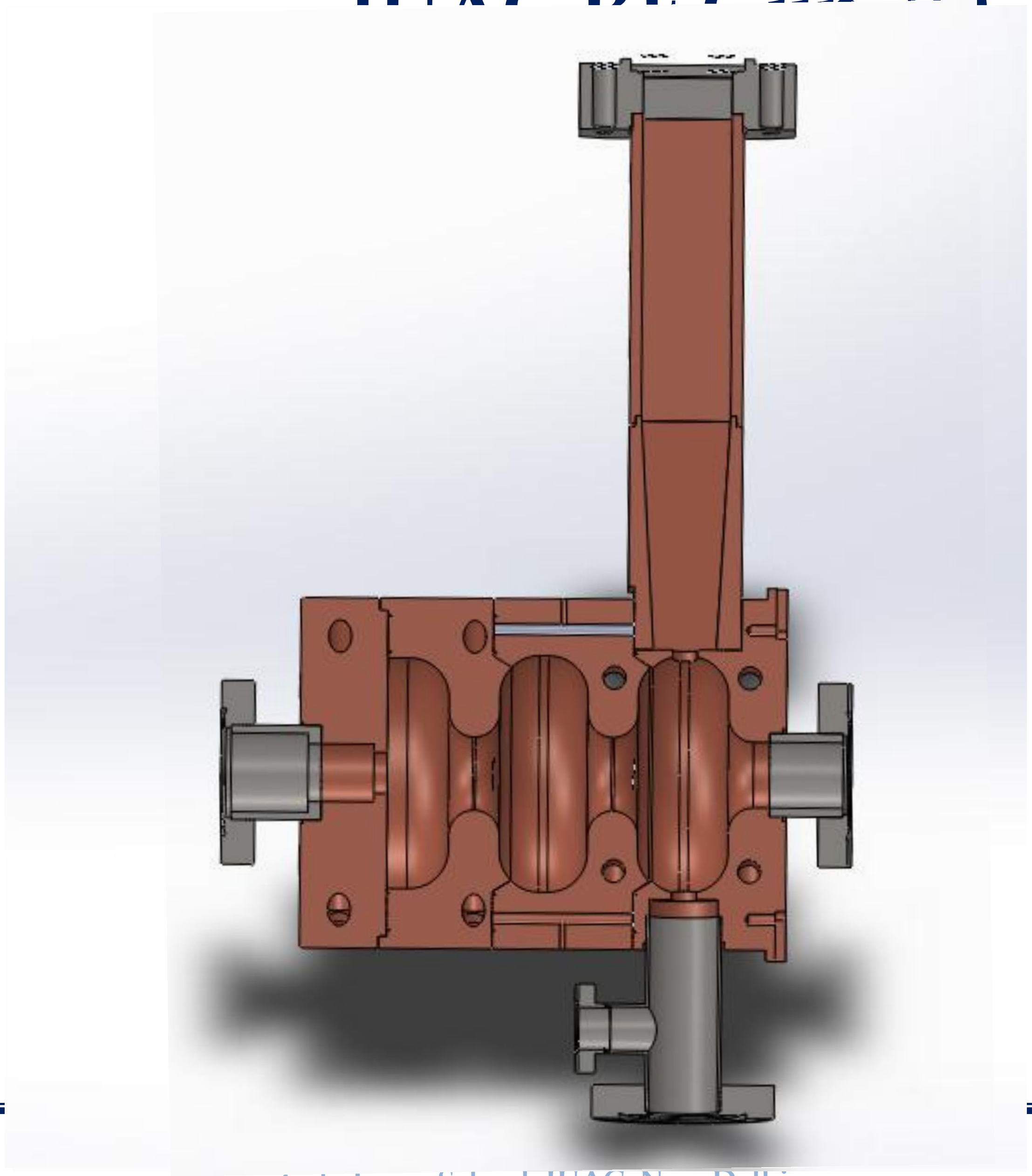




Mode	F in MHz
π	2859.76
$\pi/2$	2551.96
0	2549.15

IUAC RF Gun 3D

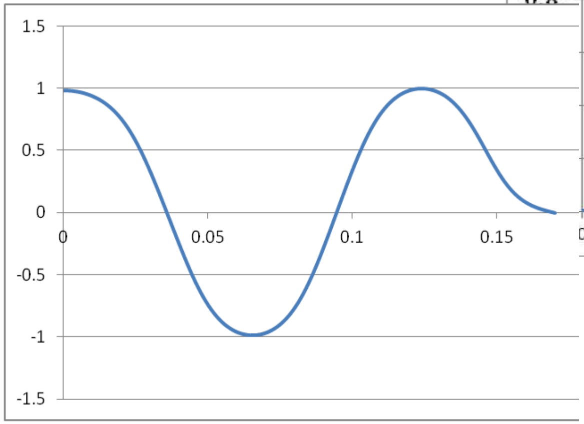
Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun

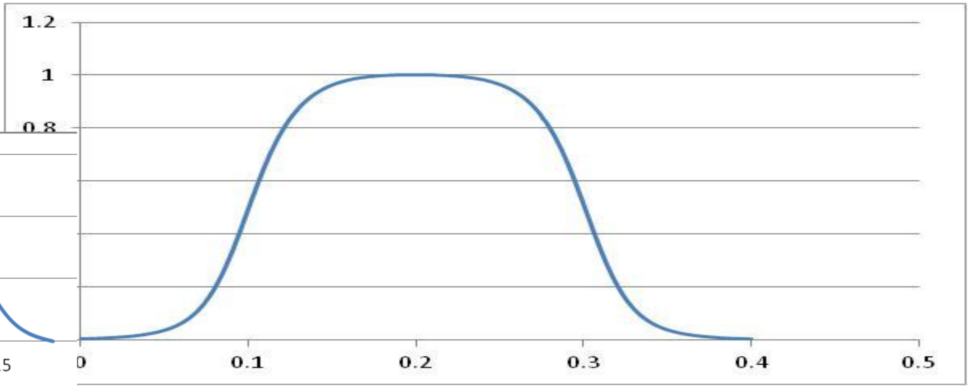


Beam simulations: Single Bunch

- **Electron Source**
- **RF Gun Basics**
- **Details of RF Gun**
- **Cavity for RF Gun**
- **KEK RF Gun**
- **Results of KEK Gun**
- **Plan for IUAC Gun**

Normalized π-mode field in RF gun





Normalized Solenoid field in RF gun

Transverse Size

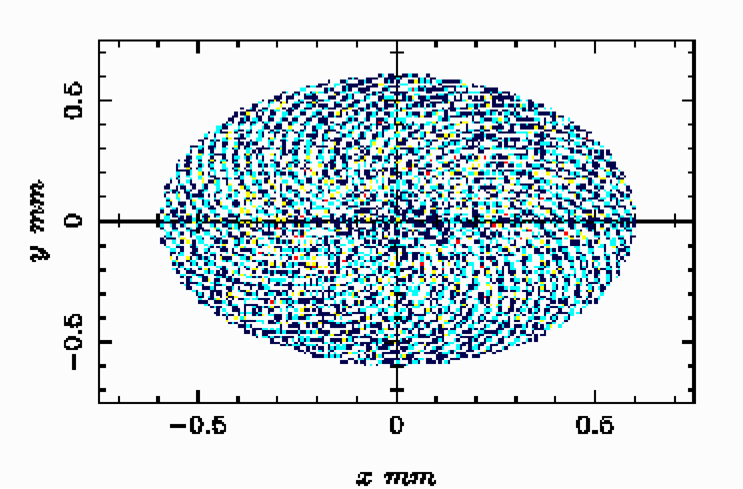
- $\sigma_x = \sigma_y = 0.3$ mm (Radial Profile)
- Radius is $2\sigma_x = 0.6$ mm
- FWHM = $\sqrt{3} * r = 1.039$ mm

Longitudinal Size

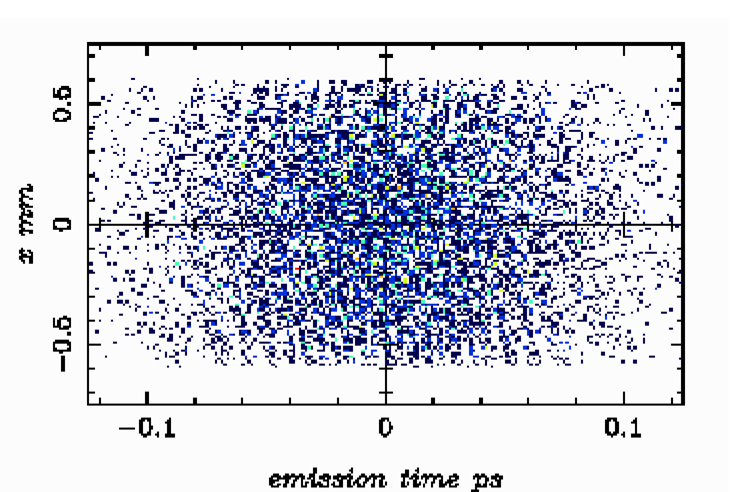
$\sigma_z = 50$ fs = 14.99e-6m= 15 μm

Laser profile at Cathode

Input		
Initial Energy	4.6	eV
Transverse Beam size (rms)	0.3	mm
Bunch length (rms)	50	fs
Charge	50	pC
Axial Field	120	MV/m
Solenoid Field	0.275	T



Transverse



Longitudinal

Beam size variation using ASTRA

Electron Source

RF Gun Basics

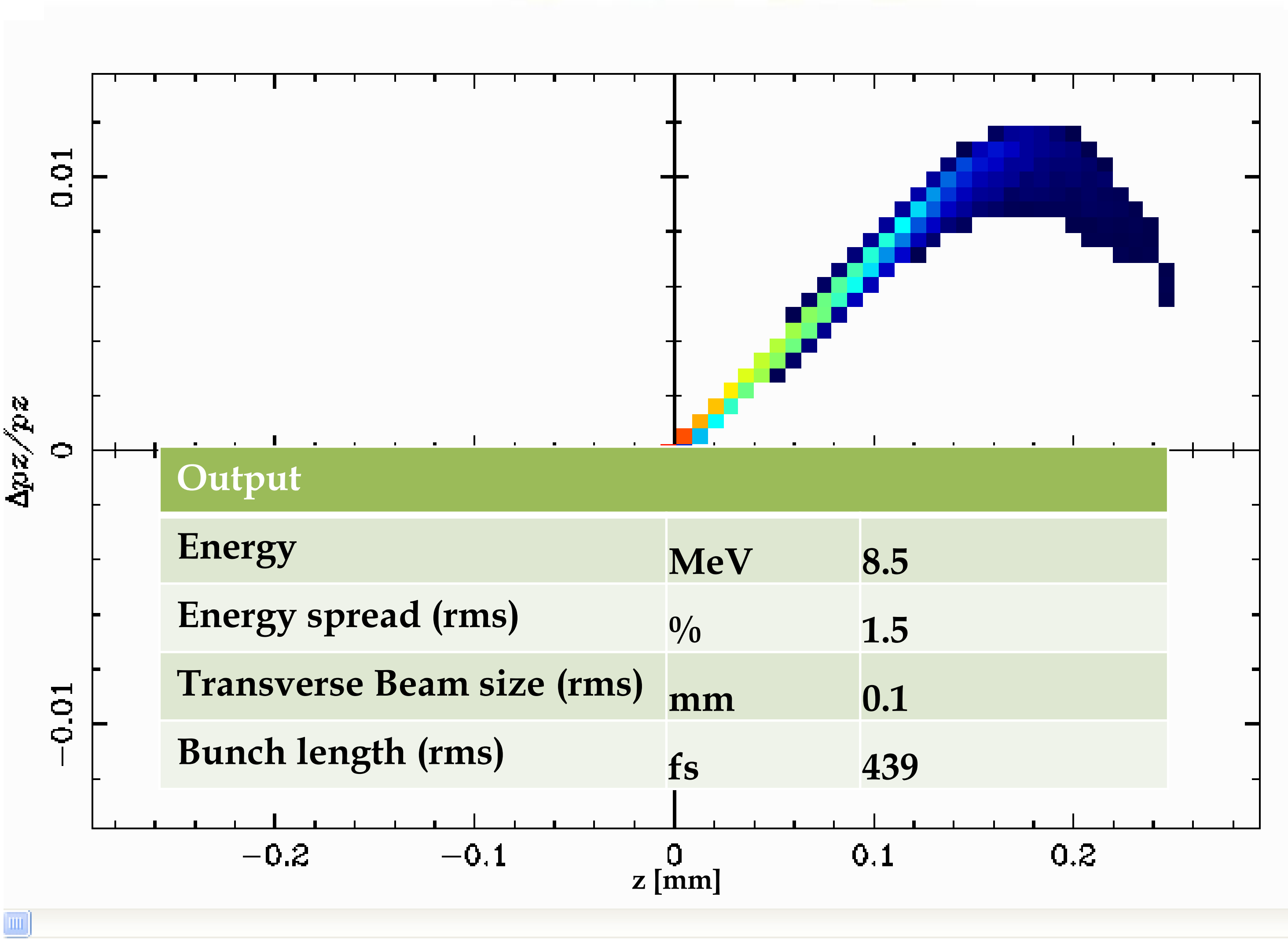
Details of RF Gun

Cavity for RF Gun

KEK RF Gun

Results of KEK Gun

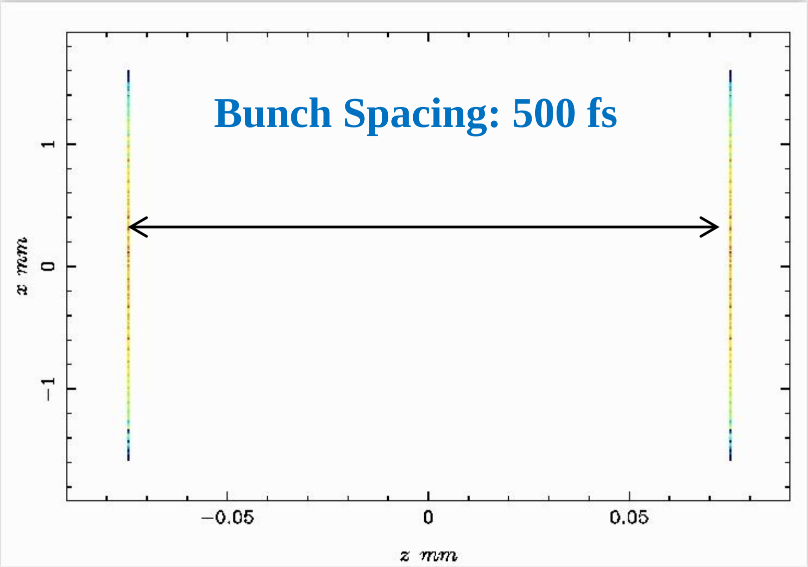
Plan for IUAC Gun

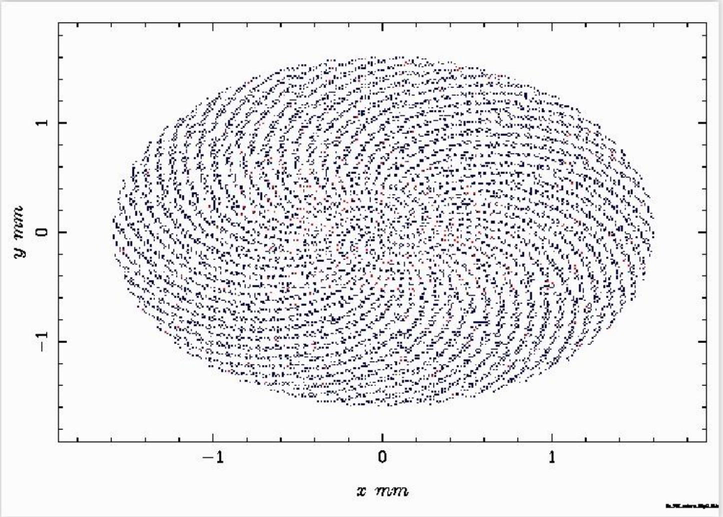


Output		
Energy	MeV	8.5
Energy spread (rms)	%	1.5
Transverse Beam size (rms)	mm	0.1
Bunch length (rms)	fs	439

Laser profile: Two bunch mode

Input		
Initial Energy	4.6	eV
Transverse Beam size (rms)	0.8	mm
Bunch length (rms)	50	fs
Charge	25	pC



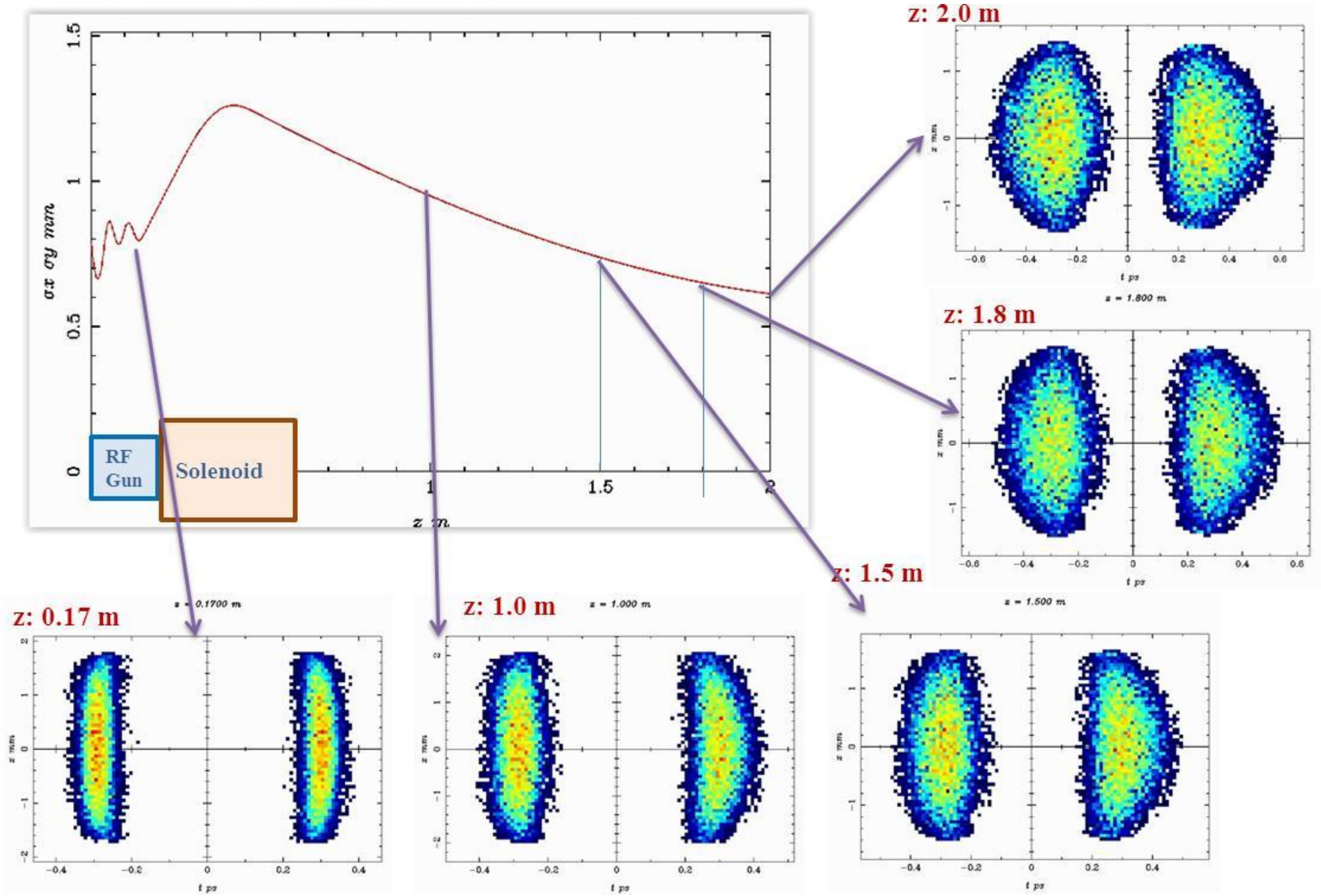


Transverse size: 0.8 mm

Beam profile: Two bunch mode

- Electron Source
- RF Gun Basics
- Details of RF Gun
- Cavity for RF Gun
- KEK RF Gun
- Results of KEK Gun
- Plan for IUAC Gun

Beam Size minimum: 0.6120 mm at 2 m; Beam Energy: 8.67 MeV
Normalized Emittance: 0.629 π-mm-mrad



Beam profile: Two bunch mode

- Energy : 8.67 MeV
- Total charge: 50 pC
- Micro bunches: 02
- Bunch spacing: 500 fs
- Energy Spread: 0.89 % (σ)
- Bunch length: 320 fs
- Transverse Beam size: 0.61 mm (σ)
- Normalized emittance: 0.629 π-mm-mrad

Status of RF gun work

- The base design is ready
- OFHC Copper shipment will come by May
- Alloys and other material purchased
- Jigs, Fixture design is on-going
- Trial machining will start very soon
- Plan to make one proto type gun this year
- Plan to initiate R&D for 1.3 GHz RF gun for IUAC Phase 2

Summary

- RF gun is a very popular choice for low emittance beams
- With ease in machining and simple fabrication technique RF gun technology is adapted at many places
- Laser technology is getting advanced much faster. This gives many choices available to RF gun designers

Thank you

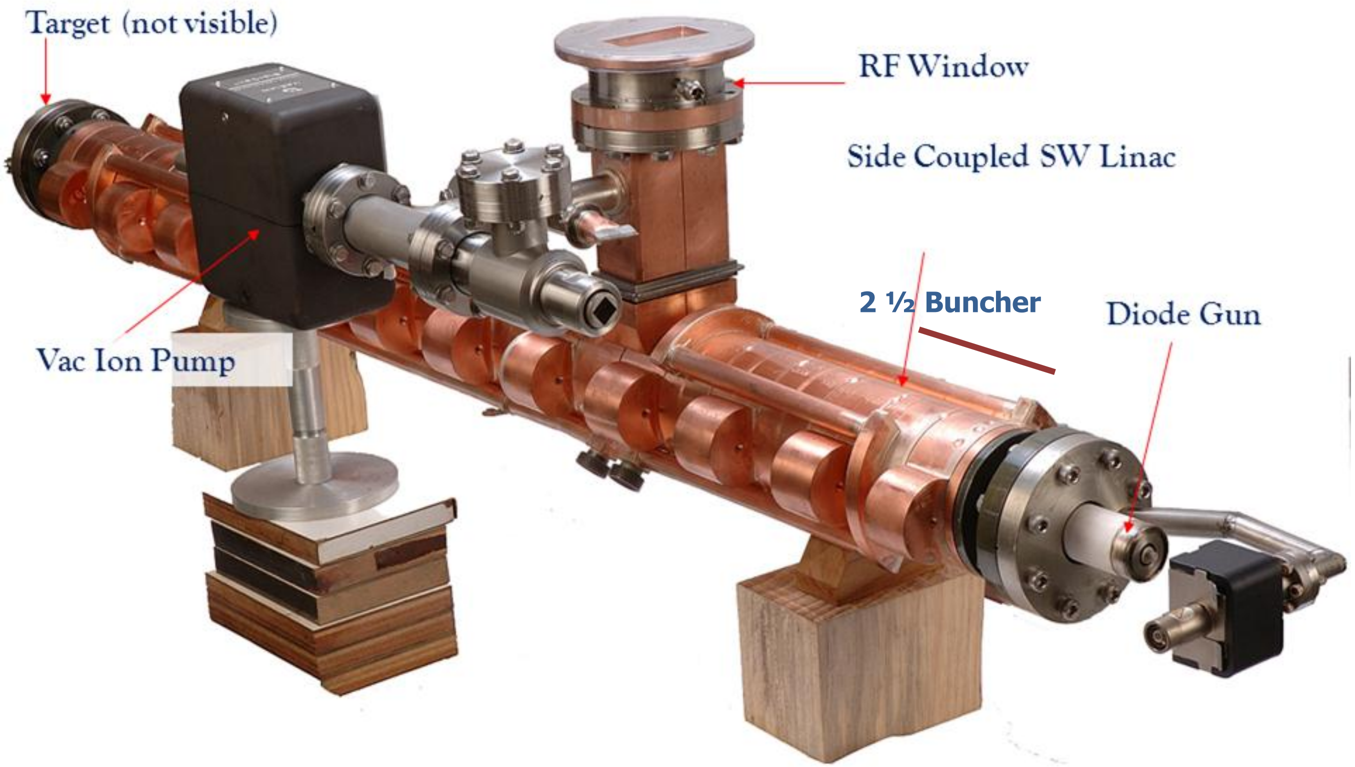
धन्यवाद !

ありがとうございます

Dr. Abhay Deshpande
MED1, SAMEER
IIT Campus, Powai
Mumbai 400 076
Tel: 022-2572-7226
Email: abhay@sameer.gov.in

SAMEER Linac

Electron Source
RF Gun Basics
Details of RF Gun
Cavity for RF Gun
KEK RF Gun
Results of KEK Gun
Plan for IUAC Gun
Use of RF Gun



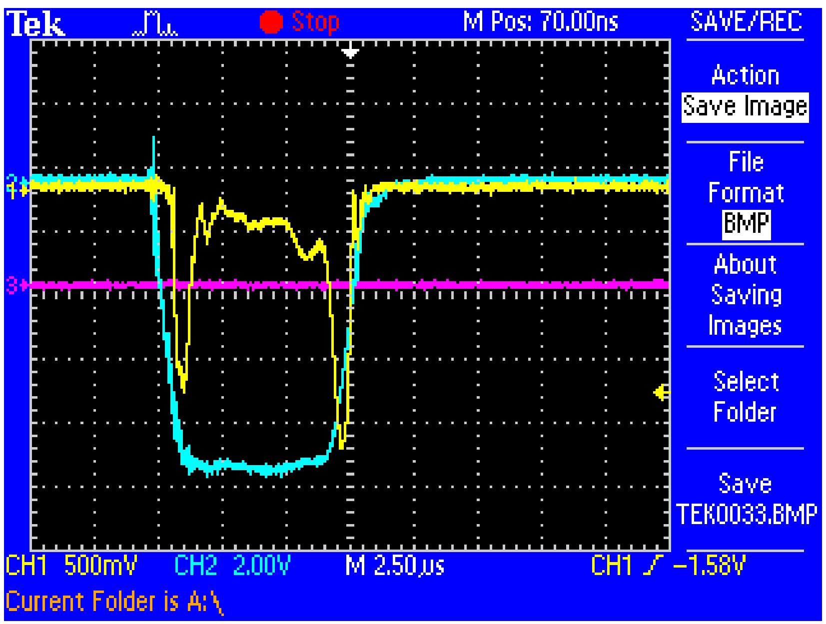
Accelerating Structure at SAMEER

Linac Designed at SAMEER

Parameter	Value		Unit
Energy	6	15	MeV
Frequency	2998	2998	MHz
Peak current	140	78	mA
Input Power	2.4	6	MW
Length of Tube	32	112	cms

Measured parameters for 15 MeV Linac

Parameter	Simulated	Measured
π/2 frequency, MHz	2998	2999
Side to main coupling %	0.03	0.0267
Shunt impedance, MΩ/m	100	87
Q (unloaded)	16000	15000
VSWR	1.5	2.02



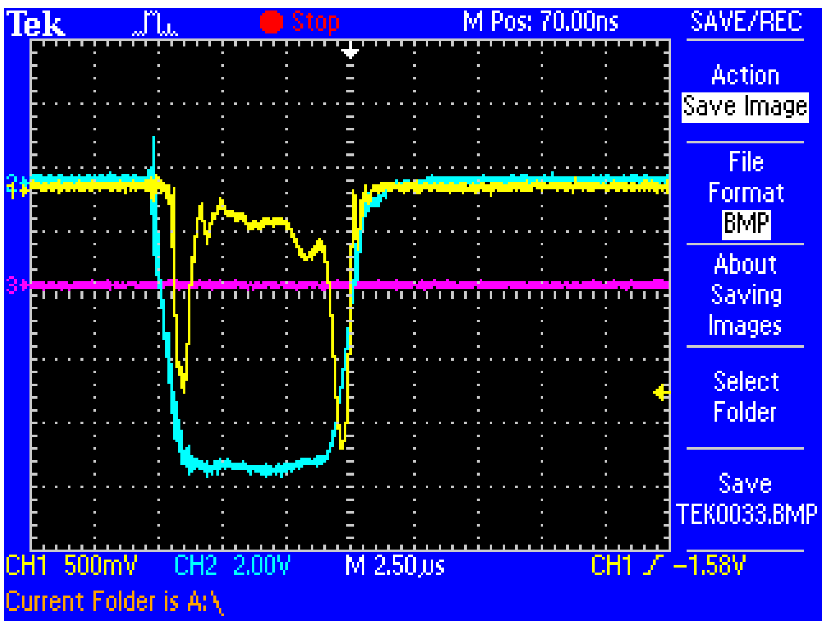
Experimental results

Linac Designed at SAMEER

Parameter	Value		Unit
Energy	6	15	MeV
Frequency	2998	2998	MHz
Peak current	140	78	mA
Input Power	2.4	6	MW
Length of Tube	32	112	cms

Measured parameters for 15 MeV Linac

Parameter	Simulated	Measured
π/2 frequency, MHz	2998	2999
Side to main coupling %	0.03	0.0267
Shunt impedance, MΩ/m	100	87
Q (unloaded)	16000	15000
VSWR	1.5	2.02



Parameter	Low	High
Energy (MeV)	6 MeV	16 MeV
Dose rate (Rads/min at 1 m)	300	4500
Peak current (mA)	120	80
Average current (μA)	120	80
Rep. rate (Hz)	250	166

Field Emission

- Fowler – Nordheim Equation governs the emission process and is given as:

$$J = \frac{e^3 F^2}{8\pi h \phi} \exp\left(\frac{4\sqrt{2m}}{3heF} \phi^{3/2} \right)$$

where,

F is the Surface field

e is electronic charge =$1.6\text{x}10^{-19}$ C

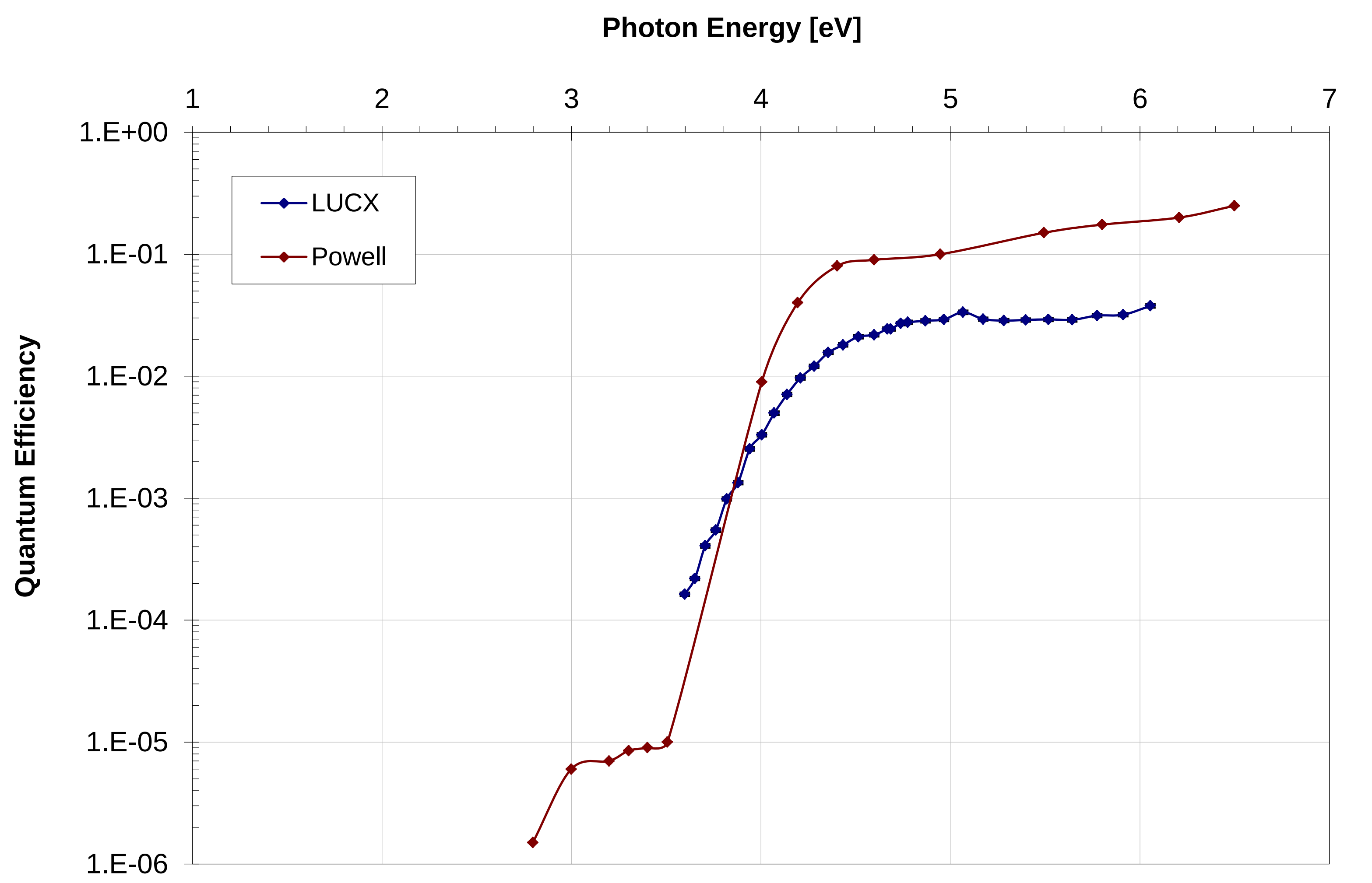
m is electron mass =$9.11\text{x}10^{-31}$ kg

k_B is Boltzmann constant = 1.38 x 10^{-23} (J/K)=$8.6175\text{x}10^{-5}$ (eV/K)

h is Planck's constant = 6.63 x 10^{-34} (Js)

Components for RF gun: Photocathode

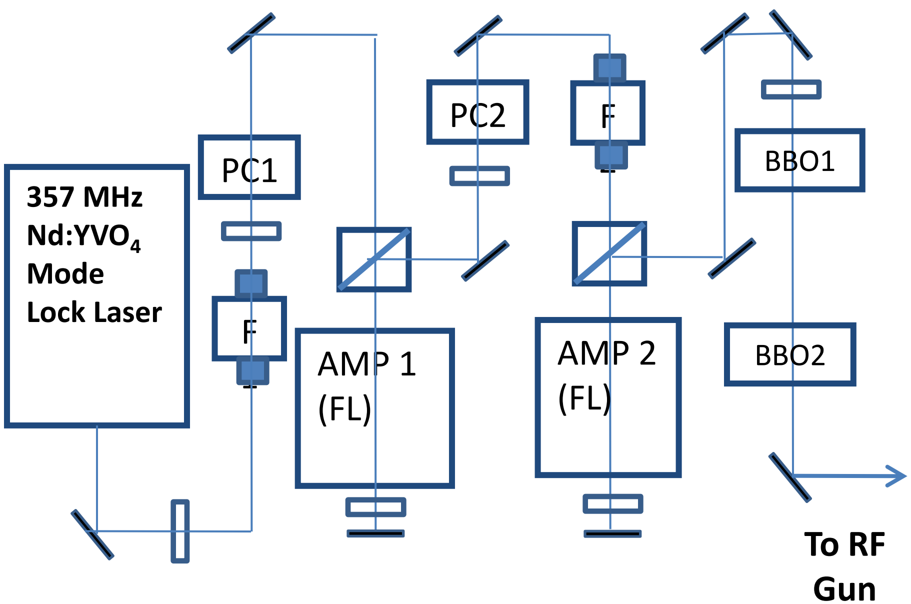
- **Electron Source**
- **RF Gun Basics**
- **Details of RF Gun**
- **Cavity for RF Gun**
- **KEK RF Gun**
- **Results of KEK Gun**
- **Plan for IUAC Gun**
- **Use of RF Gun**



Ref: R. A. Powell et al. Phys. Rev. B, Vol. 8, Number 8 (Oct 1973)

Components for RF gun: Laser System

- **$Nd:YVO_4$ laser will be used for RF photo cathode gun to generate electron bunches.**



Seed Laser	$Nd:YVO_4$ mode locked
Rep. rate	357MHz
Average Power	10 W
Wavelength of seed laser	1064 nm
Wavelength on photo cathode	266 nm
Pulse width	7 ps (rms)
Profile	Gaussian

PC: Pockels Cell
AMP: Flash Lamp Amplifier
FI: Faraday Isolator
BBO: Non linear optical crystal

Parameters of RF gun Laser

Parameter	Value	Unit	Remark
Laser Pulse width	7.0	ps	rms
Wavelength	1064	nm	
Peak Power	10	W	Average
Repetition Rate	357	MHz	
Power per pulse before amplification	28	nJ per pulse	
Power after IR to UV conversion	2.8	nJ per pulse	10 % efficiency
Amplification	2000		
Power per pulse after amplification	5.6	mJ per pulse	
Wavelength after down conversion	266	nm	
Quantum efficiency of photo cathode	0.1	%	
Charger per bunch	1.2	nC	Full Shutter

Modulator

Klystron Parameters

Parameter	Value
Peak output power	6 MW
Drive power	200 W (max)
Voltage	132 kV
Current	93.6 A
Pulse width	8.5 μs (max)
Duty	0.00126 (max)

Modulator Parameters

Parameter	Design	Measured
Peak Voltage	14 kV	13.5 kV
Peak current	1100A	1140A
Pulse width	6.5 μs (max)	6.5 μs (max)
PRF	200 Hz	200 Hz
Pulse rise time	1 μs	1 μs