Generation of Femtosecond Electron Pulses and Far Infrared Radiation in Thailand

Fast Neutron Research Facility (FNRF)
Physics Department, Chiang Mai University (CMU)
Chiang Mai, Thailand

PIZT Physics Seminar (September 26, 2006)

Sakhorn Rimjaem

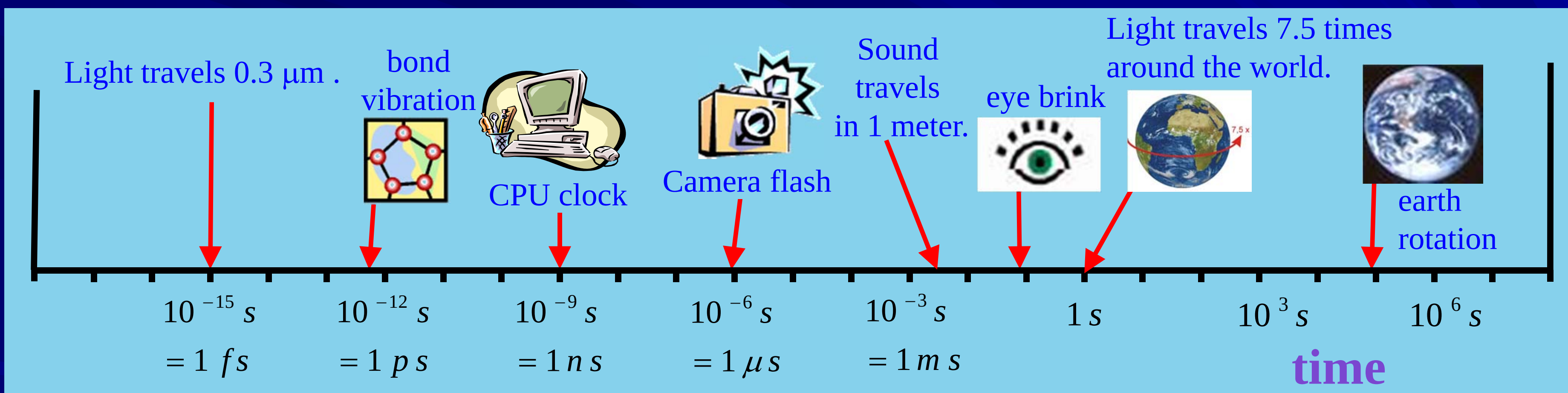
Outline

- Motivation, research objective and applications
- SURIYA project at Chiang Mai University
- Design of electron source and beam dynamic studies of electrons and bunch compression
- Construction and RF-measurements of thermionic RF-gun
- SURIYA components and whole system
- Electron beam production and characterizations
- Coherent FIR radiation and bunch length measurements

Motivation and Research Objective

⟹ Research Objective:

to investigate the generation of femtosecond electron bunches as a source of coherent far infrared radiation

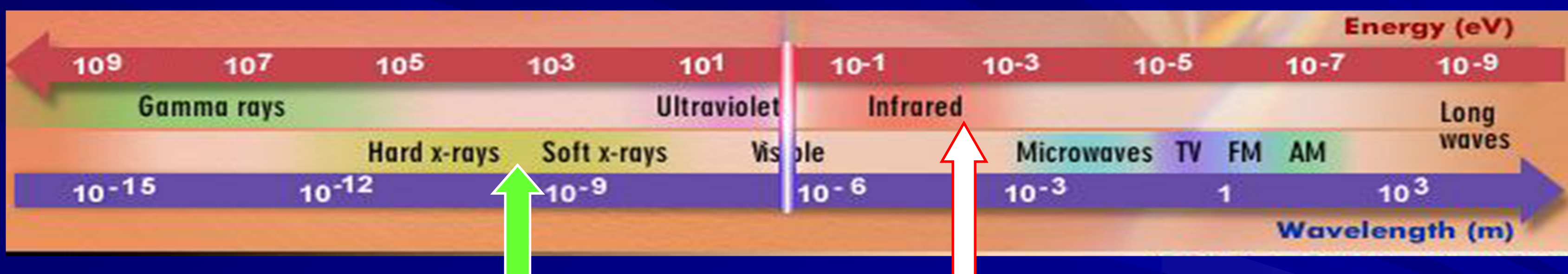


Applications of Femtosecond Electron Bunches

- **Direct Application**

  Ultrafast Radiolysis (A. Zeweil Noble Price Winner 2002)
  To study dynamic of chemical reaction by electron diffraction

- **Production of femtosecond photon pulses**



Femtosecond X-ray pulses for dynamic study at atomic scale

Intense far-infrared radiation (THz radiation) at 50-1000 μm

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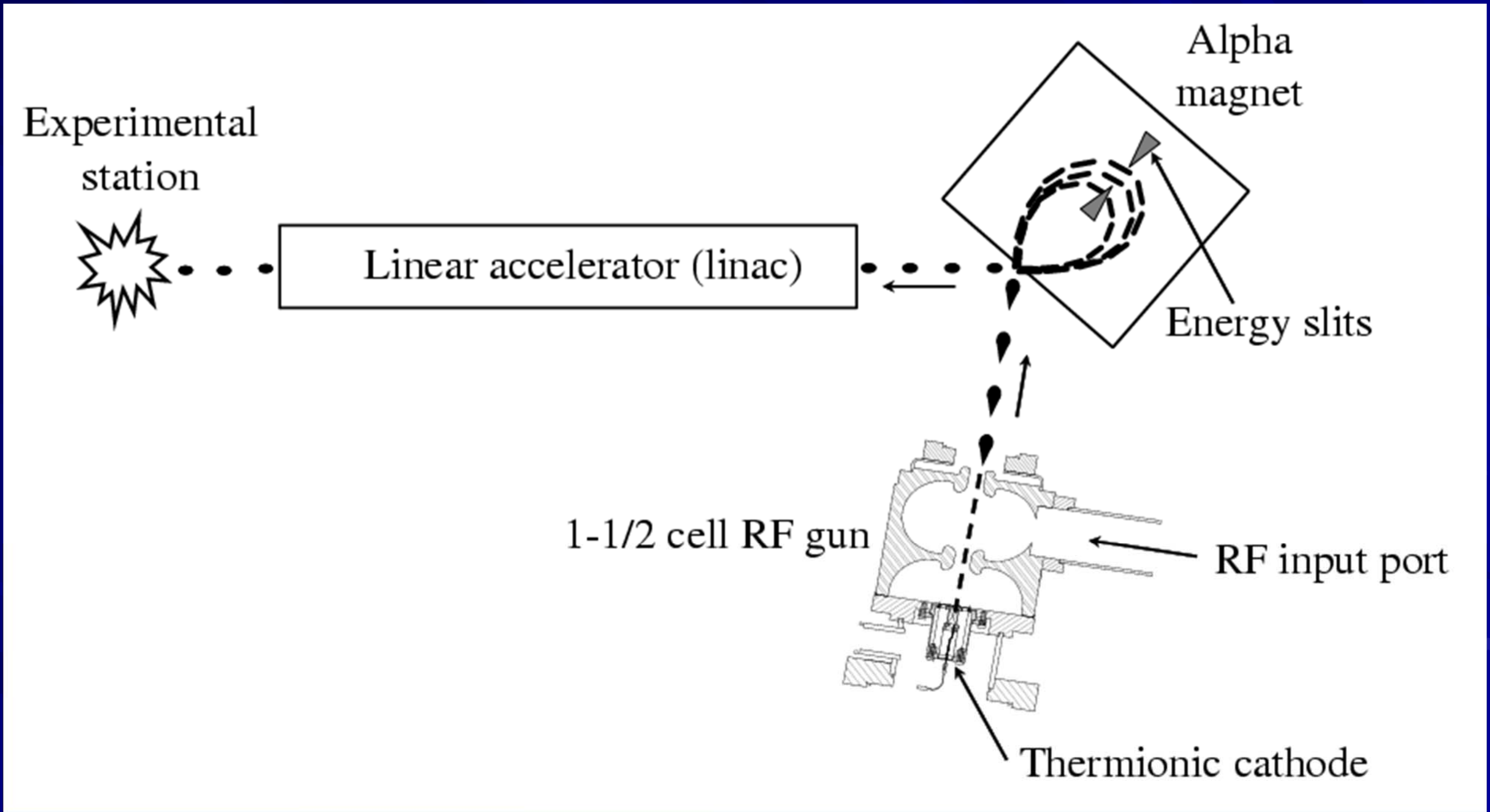
SURIYA

Femtosecond Electron and Photon Facility



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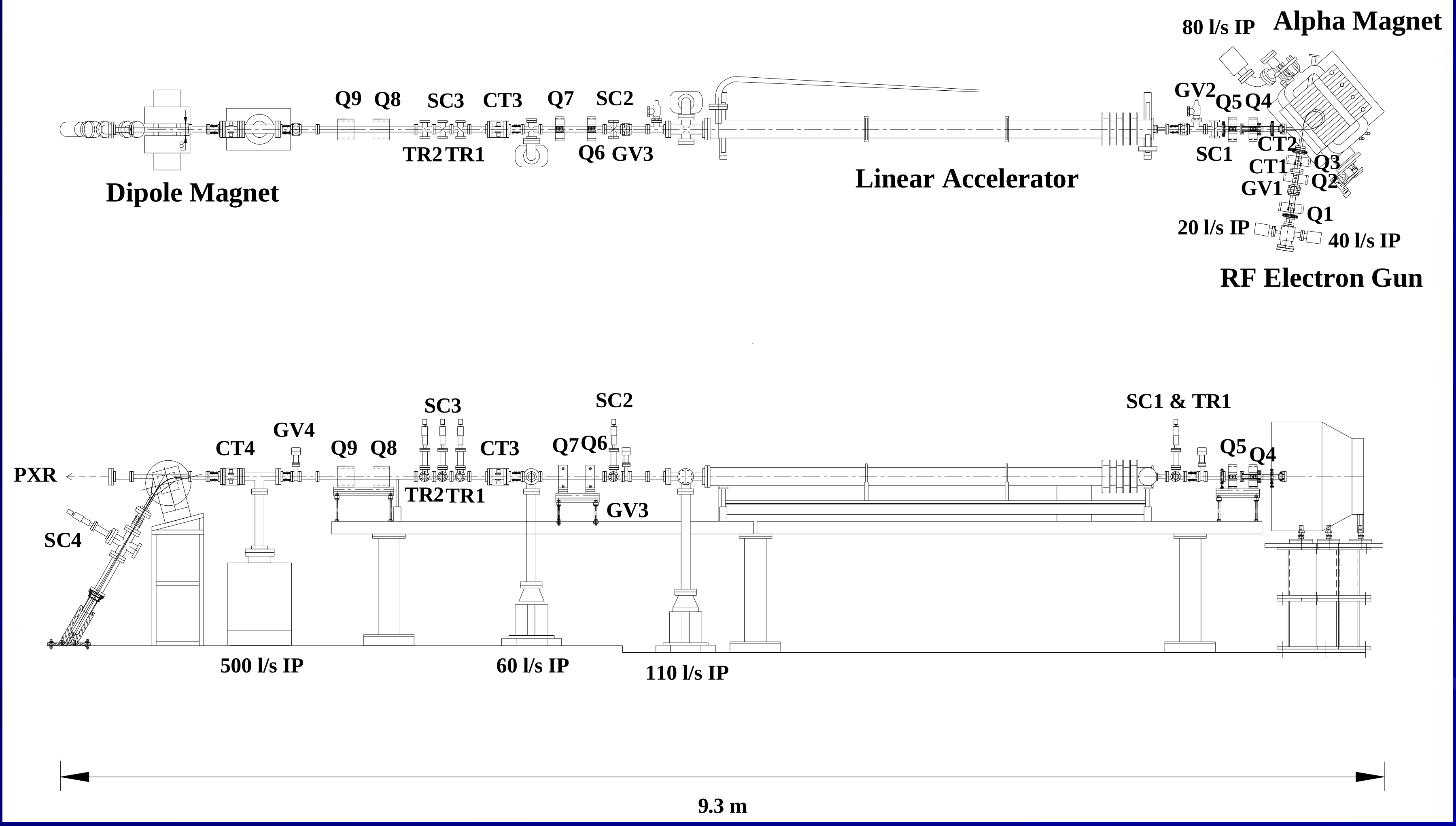
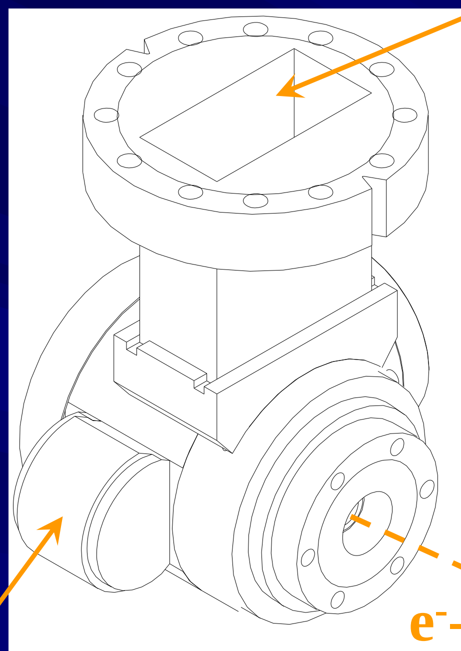
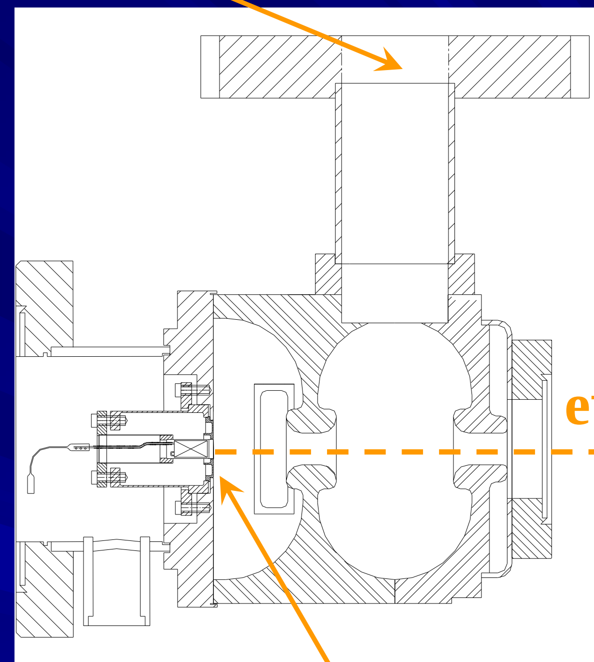
SURIYA Beam Transport Line



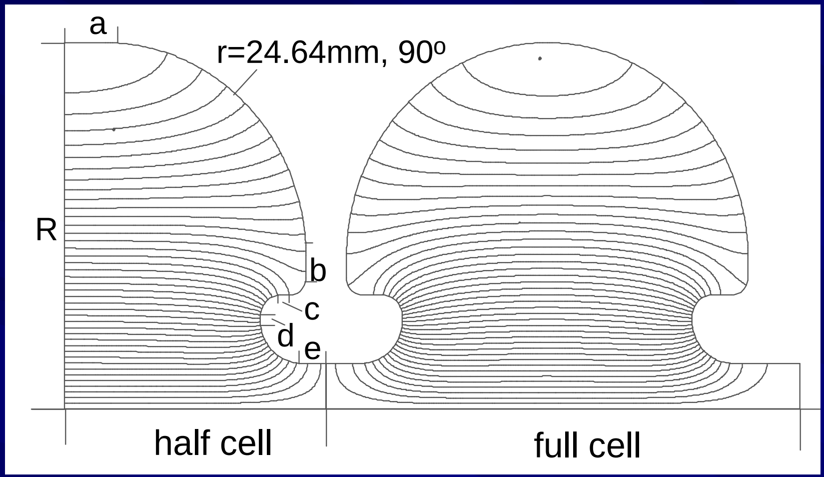
Electron Source : Thermionic RF-gun

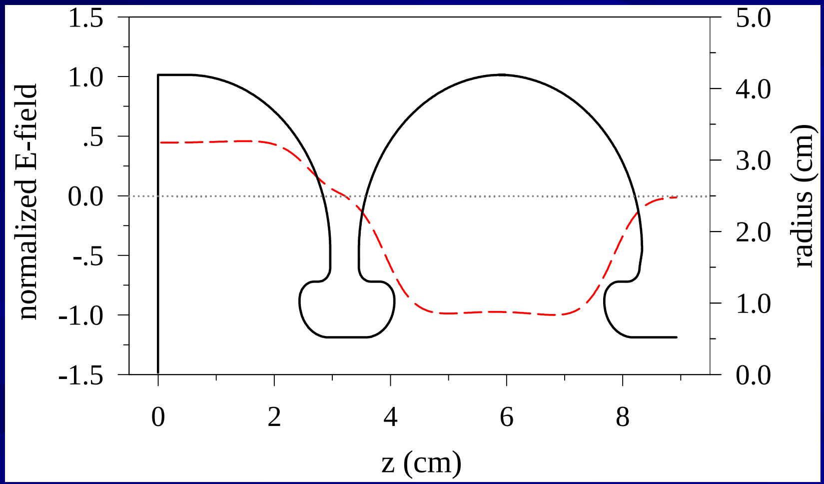




half-cell and full-cell are π excitation mode
side-coupling cavity leads the whole RF-gun to π/2 excitation mode

RF Simulations of Electron Source





Overall length = 90.1 mm
Maximum inner radius = 41.9 mm

- **SUPERFISH** (LANL) **was used to study**
  - **Shape optimization**
  - **RF-parameters**
  - **Accelerating field distribution**

Parameters for the initial design RF-gun

Parameter	HC	FC
Cavity length (mm)	32.1	58.1
Effective length (mm)	25.1	38.7

Beam Dynamic Study

★ **PARMELA** (LANL)

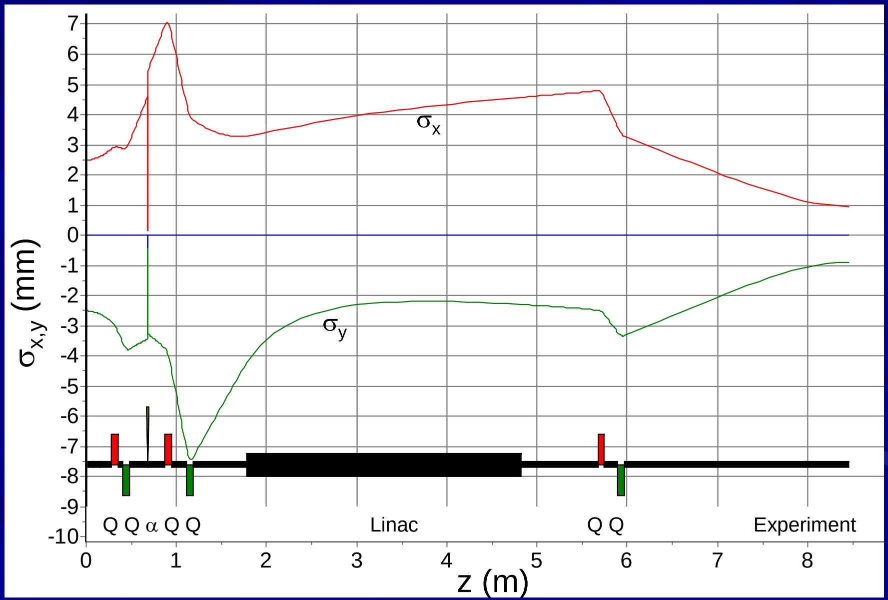
- Track particles through RF-fields obtained from SUPERFISH
- Solve Maxwell's equations for EM field including space charge effect
- Results show both longitudinal and transverse distributions

★ **Beam Optics** (H. Wiedemann)

- Simulate beam optics in the alpha magnet, linac and other components
- Used to optimize the electron beam size through the beam line

★ **BCompress** (H. Wiedemann)

- Study beam dynamics from gun exit to experimental stations
- Determine locations of experimental stations, electron bunch length, bunch charge, peak current



(S. Rimjaem et al., NIM A 533, 2004)

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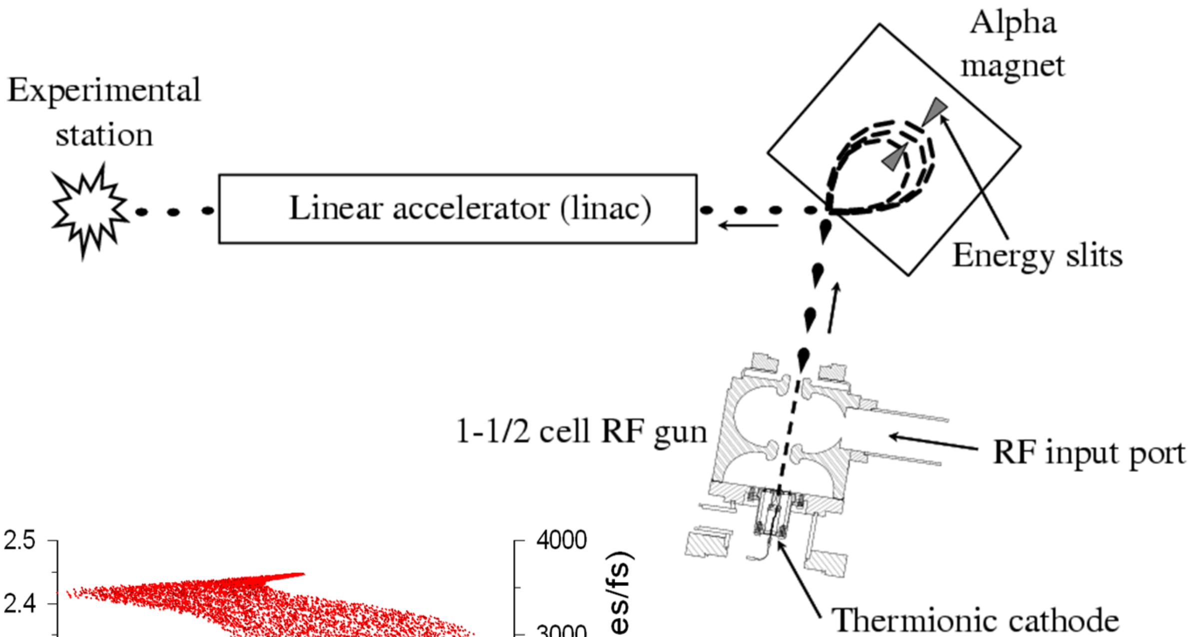
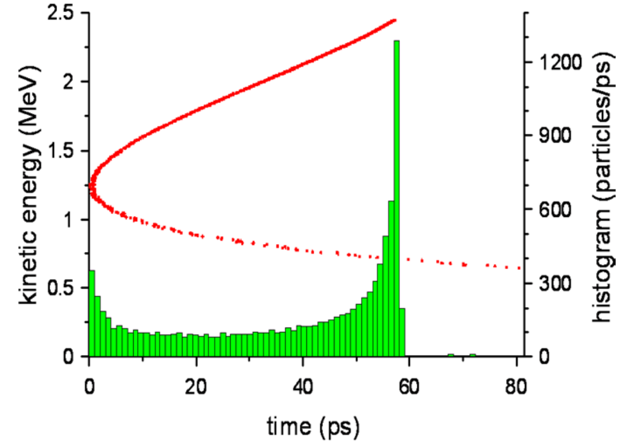
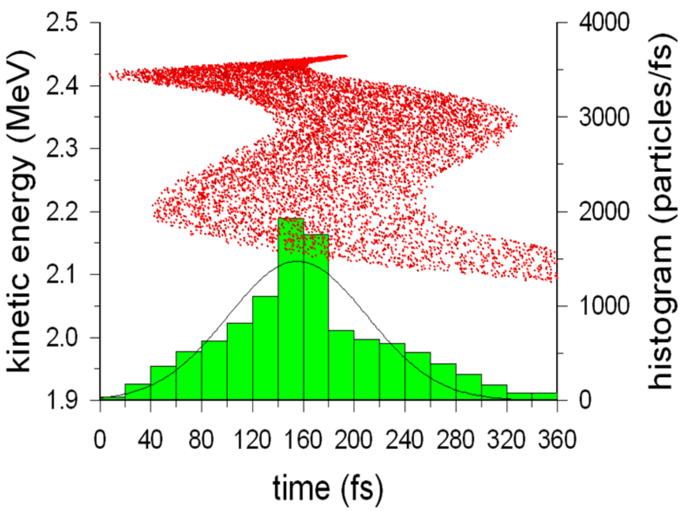
Beam Dynamic Study Results



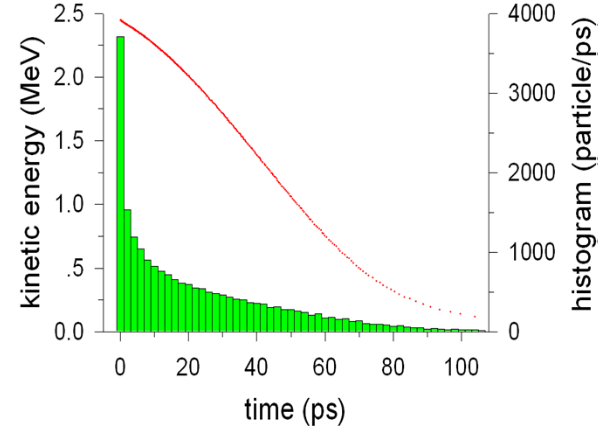


at α-magnet exit



at experimental station (l_b~53 fs)

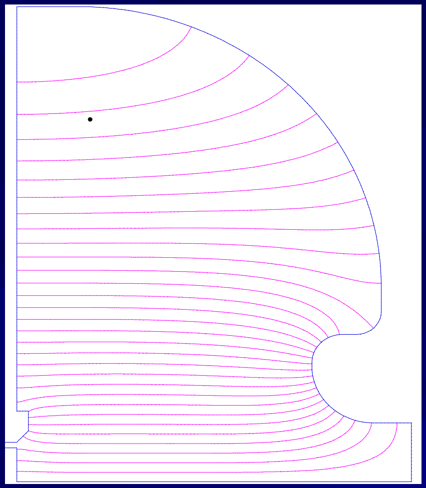
100,000 simulated macroparticles per bunch with cathode current of 2.9 A and each macroparticle represents a charge of 10.15 fCb or 6.34×10^4 electrons

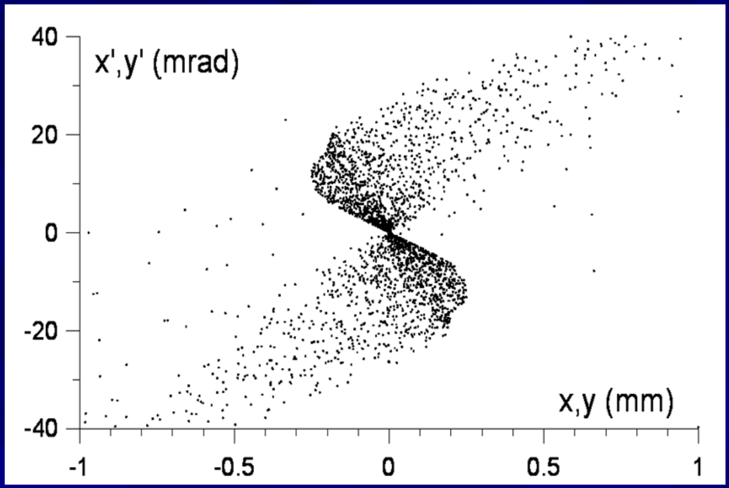


at RF-gun exit (l_b~10 ps)

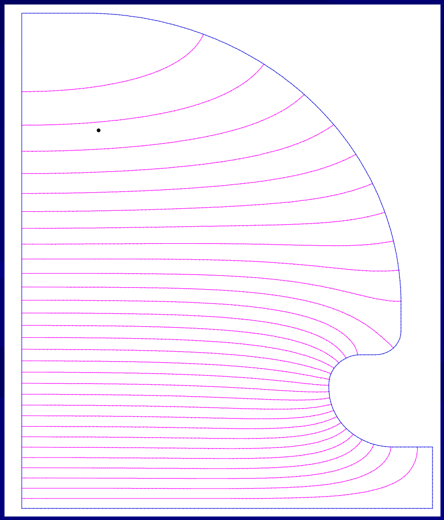
(S. Rimjaem et al., NIM A 533, 2004)

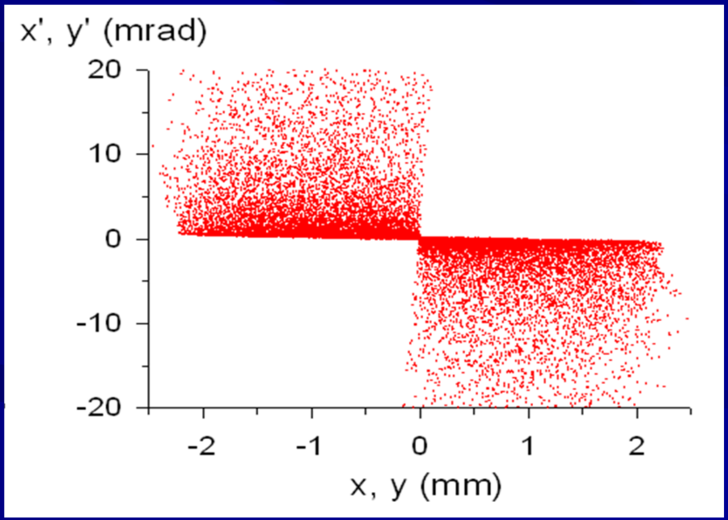
Transverse Beam Dynamics





Transverse phase-space distribution at SUNSHINE RF-gun exit
- nose cone cathode
- divergence ~10 mrad
- limit bunch length ~120 fs





Transverse phase-space distribution at SURIYA RF-gun exit
- flat cathode
- bigger iris radius
- divergence ~1 mrad
- $\varepsilon_{n,rms}$~3.8 mm-mrad
- bunch length ~53 fs

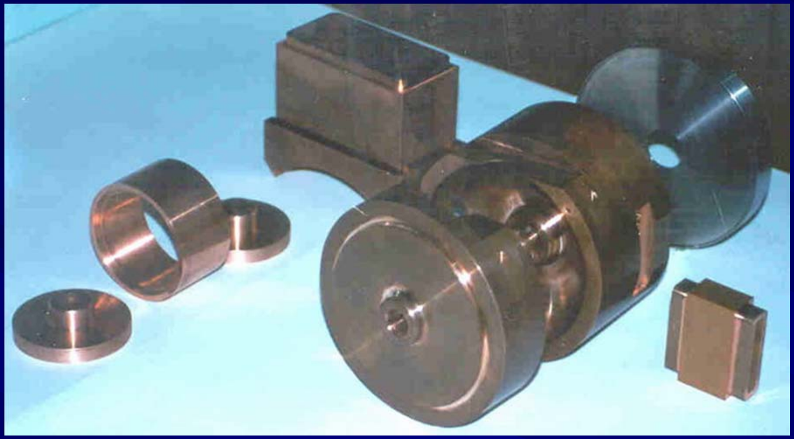
(S. Rimjaem et al., NIM A 533, 2004)

Initial Design & Actual RF-gun Simulation Results

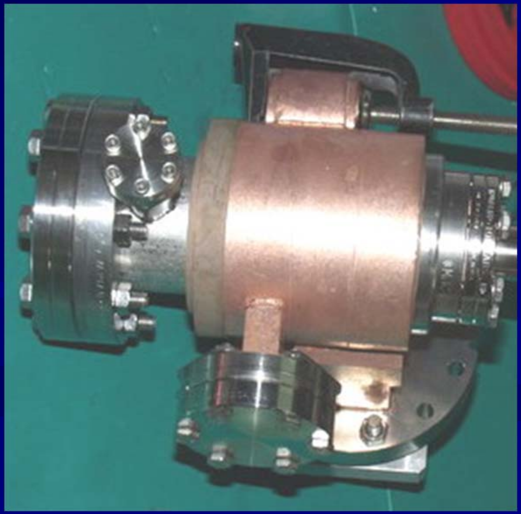
Parameter	Design RF-gun	Actual RF-gun
Cavity length of HC/FC (mm)	32.1 / 58.1	31.6 / 57.2
Effective length of HC/FC (mm)	25.1 / 38.7	24.9 / 39.2
f_{rf} of HC/FC (MHz)	2863.6 / 2825.0	2880.6 / 2868.8
Q_0 of HC/FC	15263 / 13022	15692/ 13343
β= v/c at gun exit	0.9851	0.9849
Max. kinetic energy (MeV)	2.45	2.44
Ave./max. field in HC (MV/m)	23.9 / 29.9	22.7 / 28.7
Ave./max. field in FC (MV/m)	45.0 / 67.6	46.9 / 68.5
Ave. field ratio	1.88	2.07
Max. field ratio	2.26	2.39
Cathode radius (mm)	3	3
Cathode emission current (A)	2.9	2.9
Cathode current density (A/cm^2)	10	10
Charge per bunch (pCb)	94	94
Peak current (A)	707	682
Bunch length, rms (fs)	53	55

★ Actual RF-gun + SURIYA beamline: bunch length = 62 fs, bunch charge = 94 pCb, peak current = 604 A

RF-gun Construction



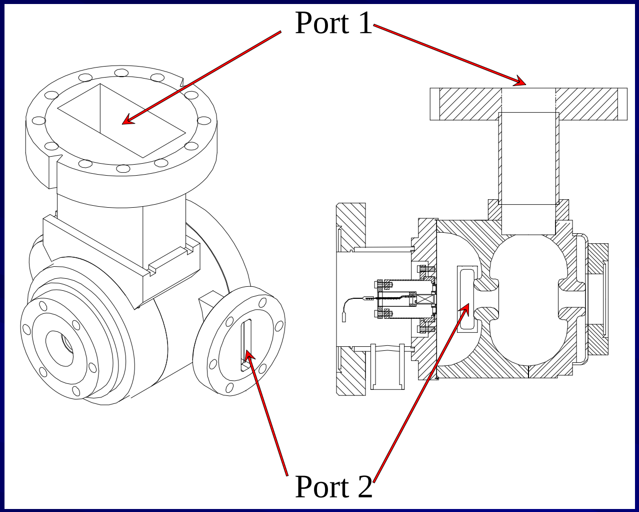
Cavities and related components fabrication
- Oxygen Free High Conductivity copper (OFHC copper)
- CNC machining (Thai-German Institute)



RF-gun components forming
- Welding (SST components)
- High temperature brazing in free-O_2 environments (NSRRC, Taiwan)

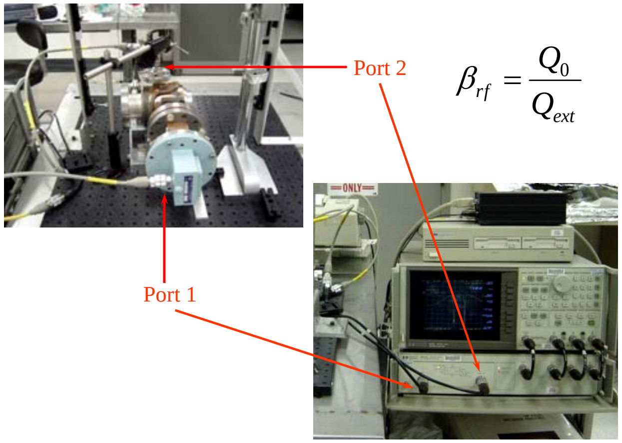
completed RF gun

Low Power RF Measurements



RF-measurements

- Before and after the RF-gun brazing process
- Using network analyzer
- Input RF-power level = 1 dB (10 mW)
- RF-power input port → waveguide at FC
- Output pick up port → vacuum port at HC

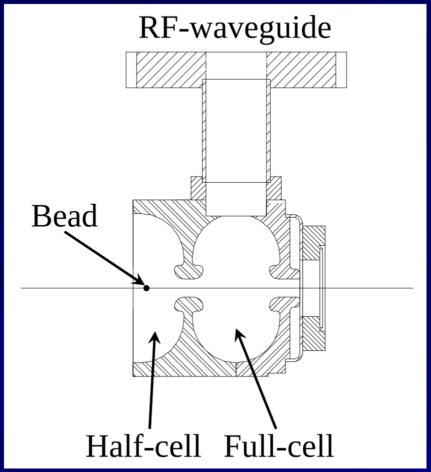


$$\beta_{rf} = \frac{Q_0}{Q_{ext}}$$

Parameter	Value
Resonant frequency HC/FC (MHz)	2854.6 / 2858.3
Resonant frequency of whole gun (MHz)	2855.3
T_{gun} for operating at 2856 MHz (^oC)	27.5
Unloaded quality factor (Q_0)	12979
Loaded quality factor (Q_L)	1741
External quality factor (Q_{ext})	1568
RF-coupling coefficient	7.45
Peak field ratio	2.07

(S. Rimjaem et al., Solid State Phenomena 107 , 2005)

On-axis Field Profile Measurements

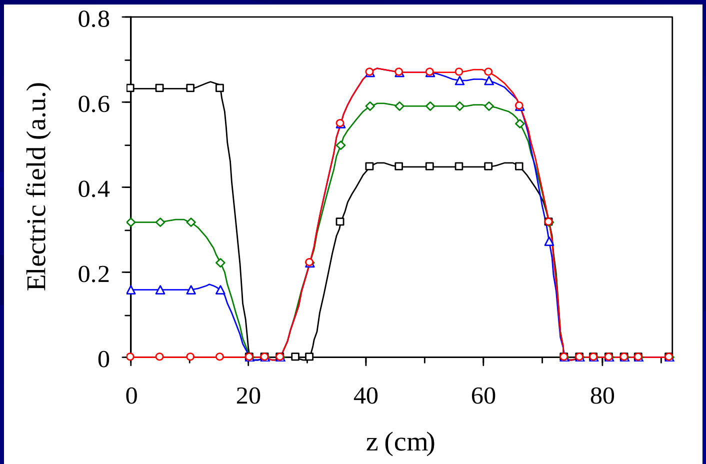


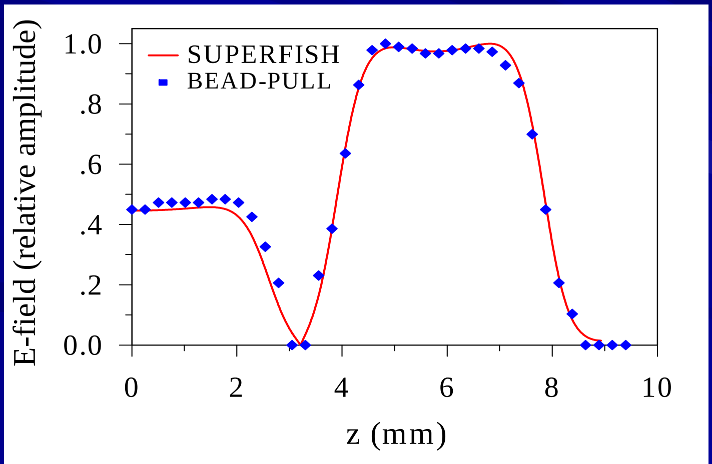
Slater's Perturbation

$$\frac{\Delta\omega}{\omega} = \frac{\Delta U_M - \Delta U_E}{U} = \frac{\int_{\Delta V} (\mu H^2 - \varepsilon E^2) dV}{\int_V (\mu H^2 + \varepsilon E^2) dV}$$

Bead-pull measurement

- 2.36 mm diameter dielectric bead
- Resonant frequency shift $\rightarrow$ $E_z \; \alpha \; \sqrt{\Delta\omega} = \sqrt{f - f_0}$



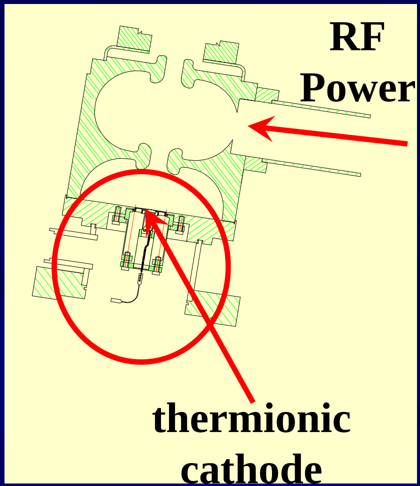


$$\frac{E_{p2}}{E_{p1}} = 2.07$$

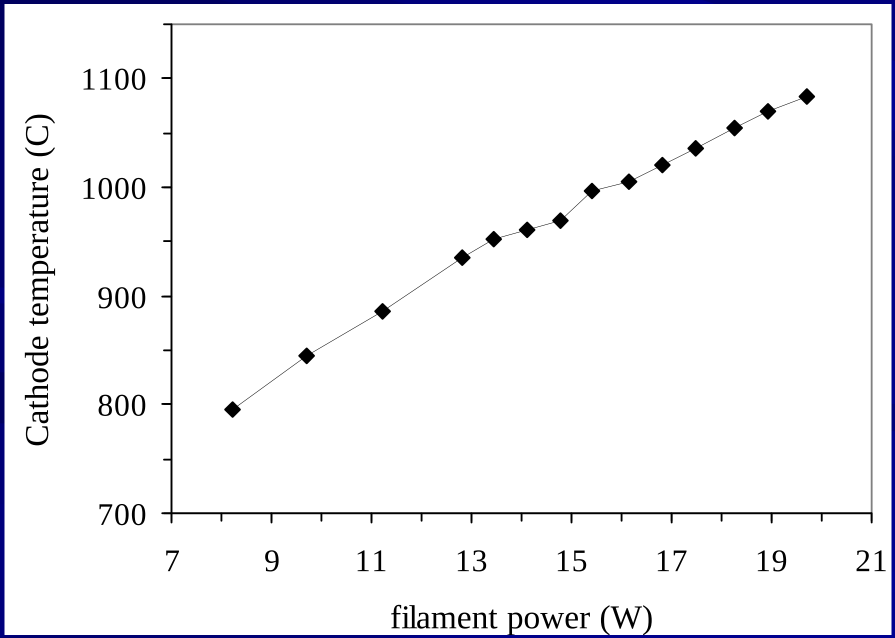
$$\frac{E_{ave,2}}{E_{ave,1}} = 1.85$$

(S. Rimjaem et al, EPAC2004)

Cathode Installation and Tests



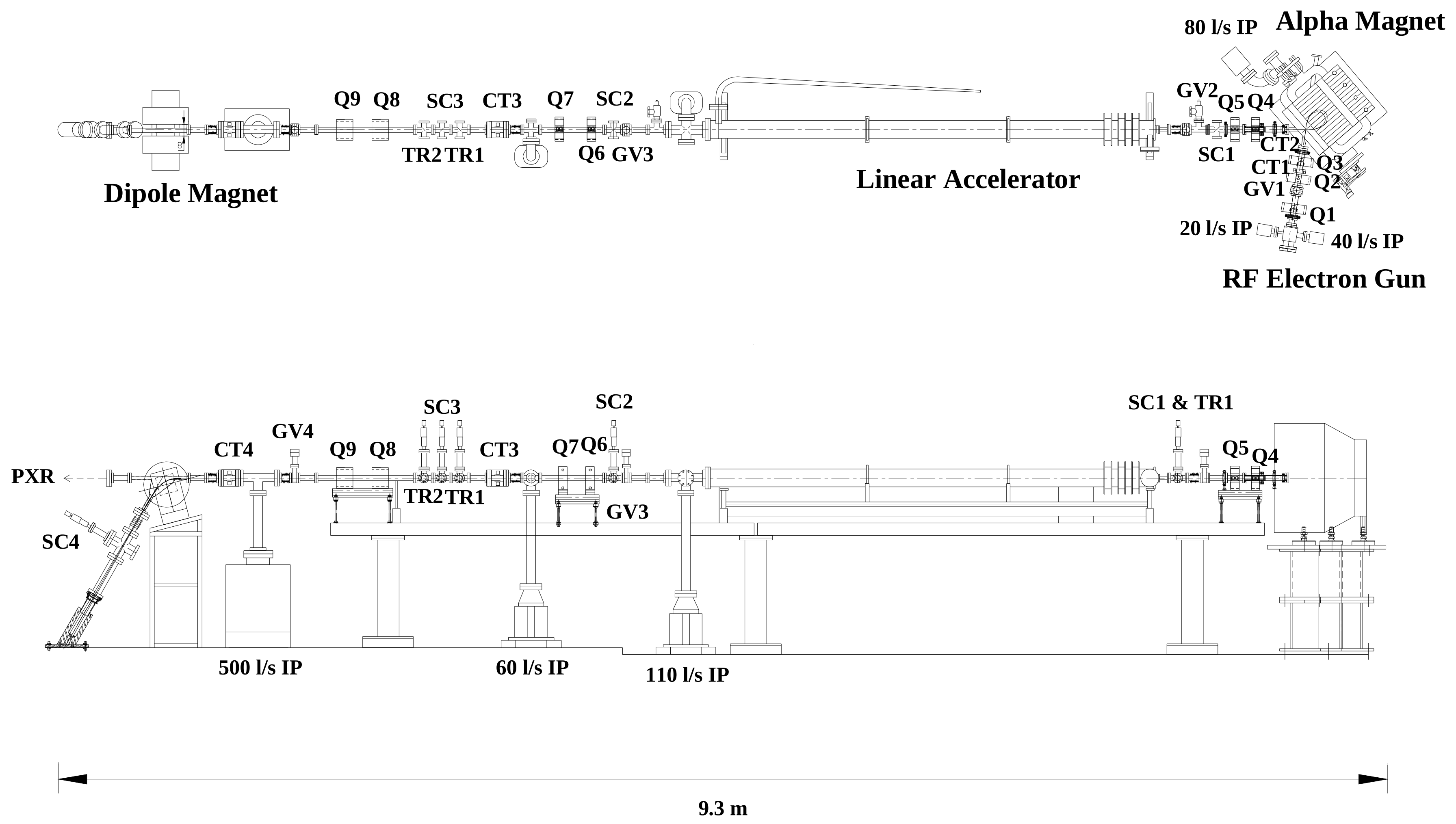
★ **Thermionic cathode**
- Dispenser tungsten cathode coated with barium oxide
- Flat circular emitting surface of 3 mm radius



★ **Cathode tests (Pyrometric measurements)**
- To activate the cathode to temperature > 1050 °C
- Measure the cathode temperature by using optical Pyrometer
- Required for new cathode or when cathode experiences poor vacuum or chemical contamination

★ **Operating temperature ~900-1000°C**
(cathode heating power ~ 13-17 W)

SURIYA Beam Transport Line



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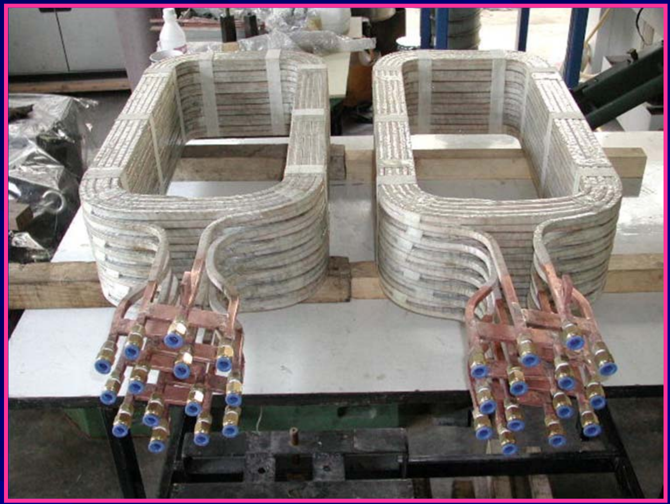
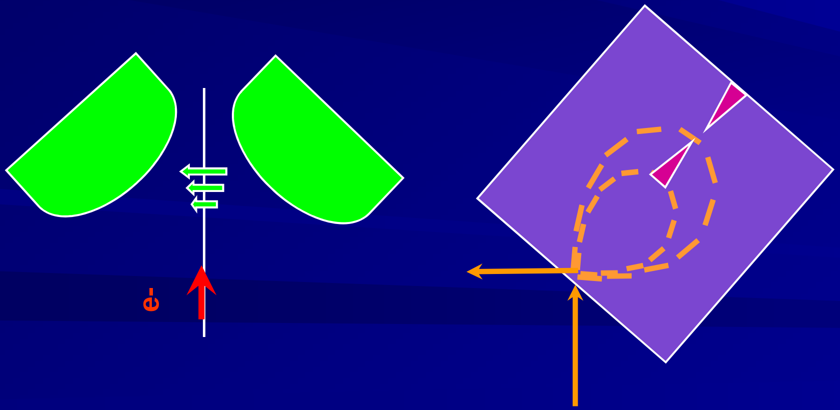
Magnetic Bunch Compressor : α-Magnet

alpha magnet poles

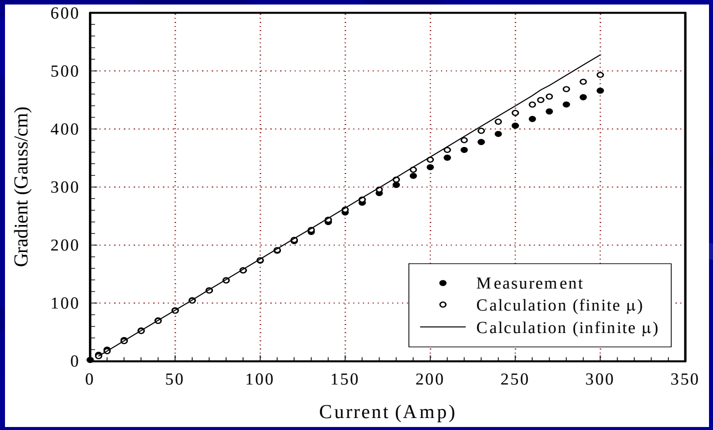


alpha magnet coils

completed alpha magnet



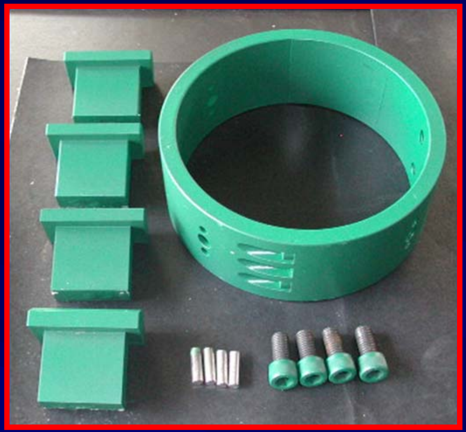
alpha magnet design: code Poisson



Max. Gradient = 450 G/cm Max. current= 265 A

(J. Saisut, M.S. Thesis, Chiang Mai University, 2003)

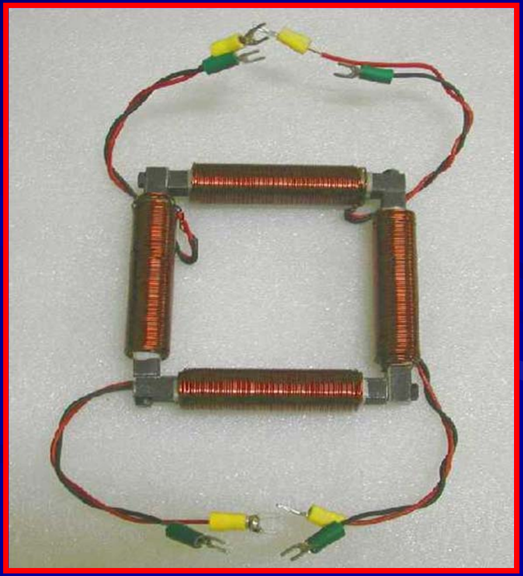
Quadrupole and Steering Magnets



quadrupole magnet poles & coils & frame

steering coils

completed quadrupole magnet



completed steering magnet

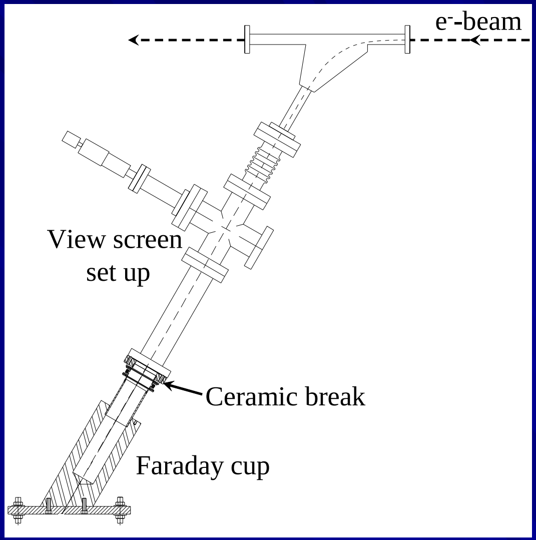
Dipole Magnet and Charge Collector

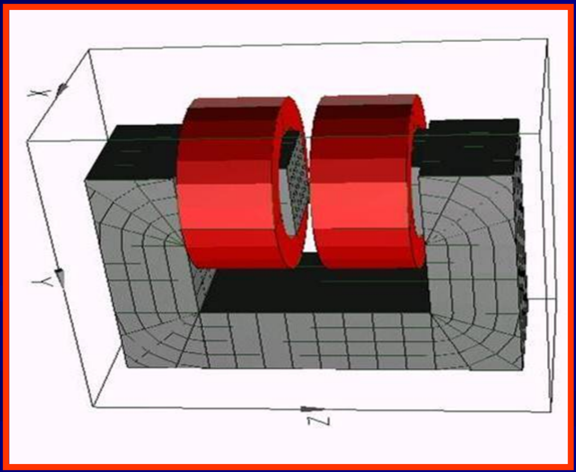
Deflect electron beam 60° respect to beam axis

Electron beam dump

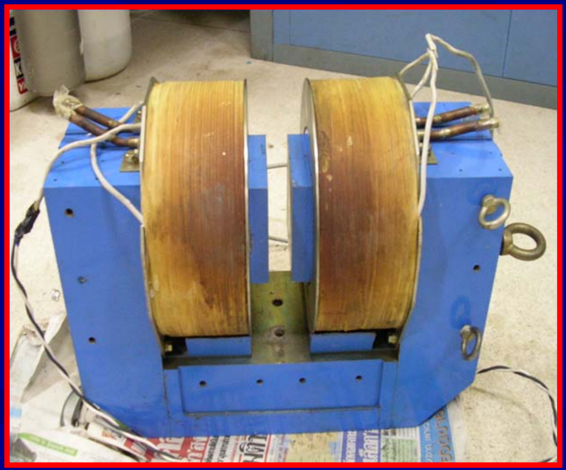
&

energy spectrometer

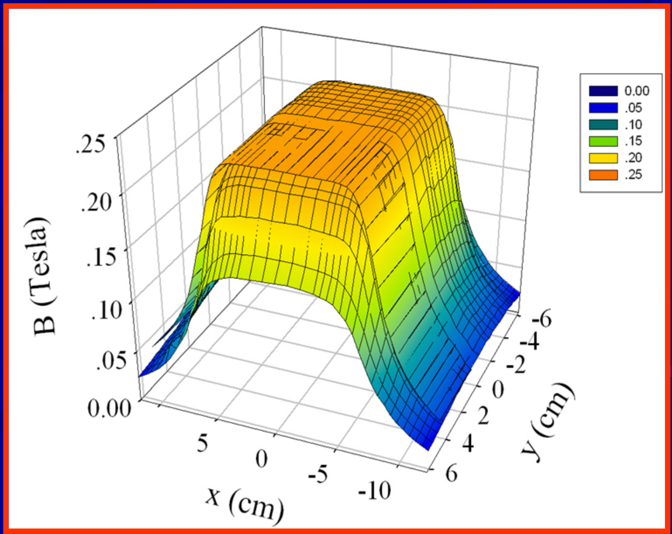




design & simulation (Radia)



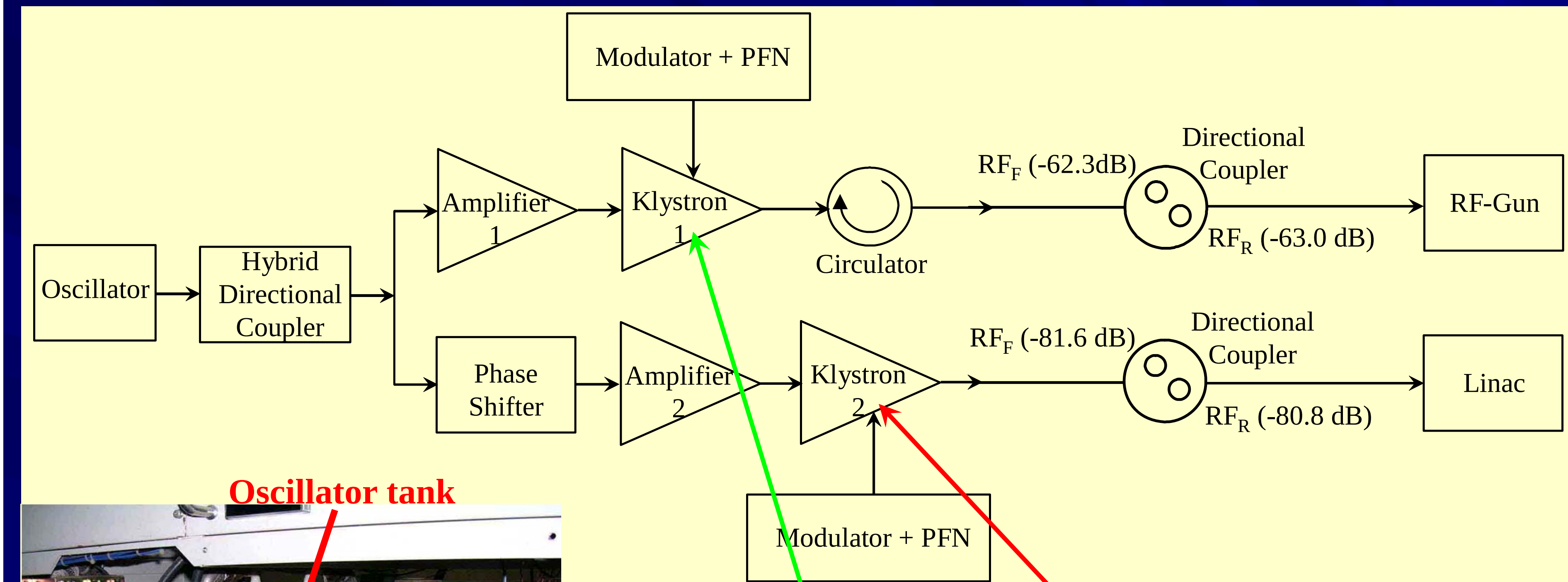
completed magnet



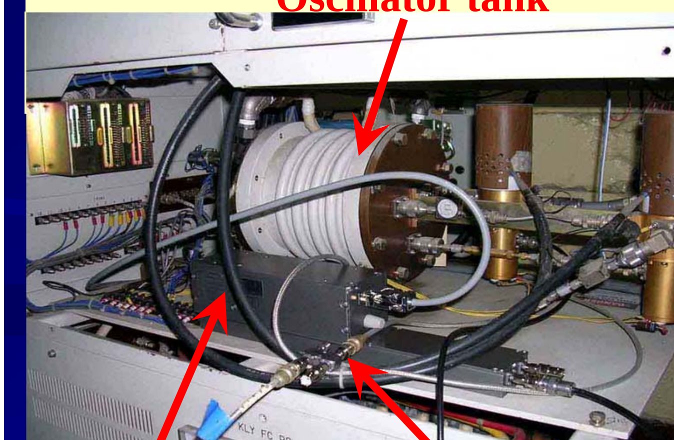
B-field distribution

(S. Rimjaem et al., Solid State Phenomena 107, 2005)

RF System



Oscillator tank



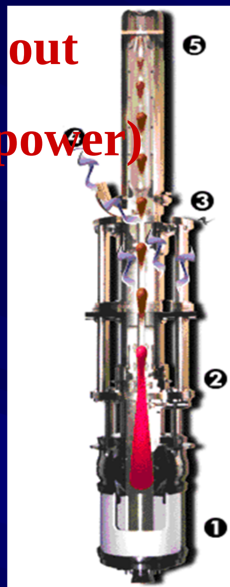
Phase shifter

90^o hybrid directional coupler

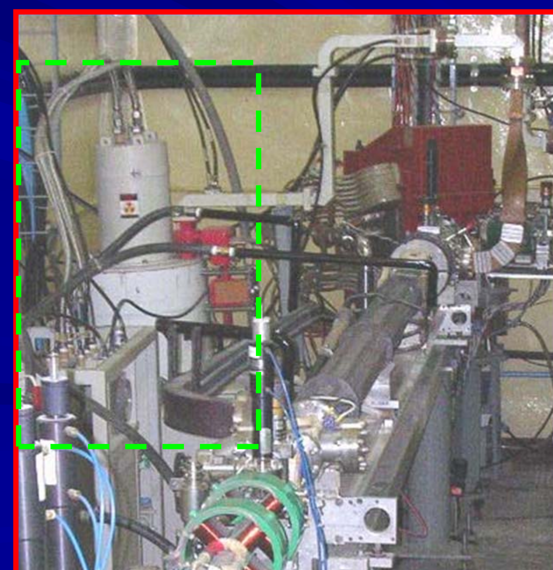
RF-output pulse of 5 MW peak power for ~2 μs

5 MW peak power
250-300W average power for 5-6 μs

Electrical and RF-system



www2.slac.stanford.edu/vvc/accelerators/klystron.html



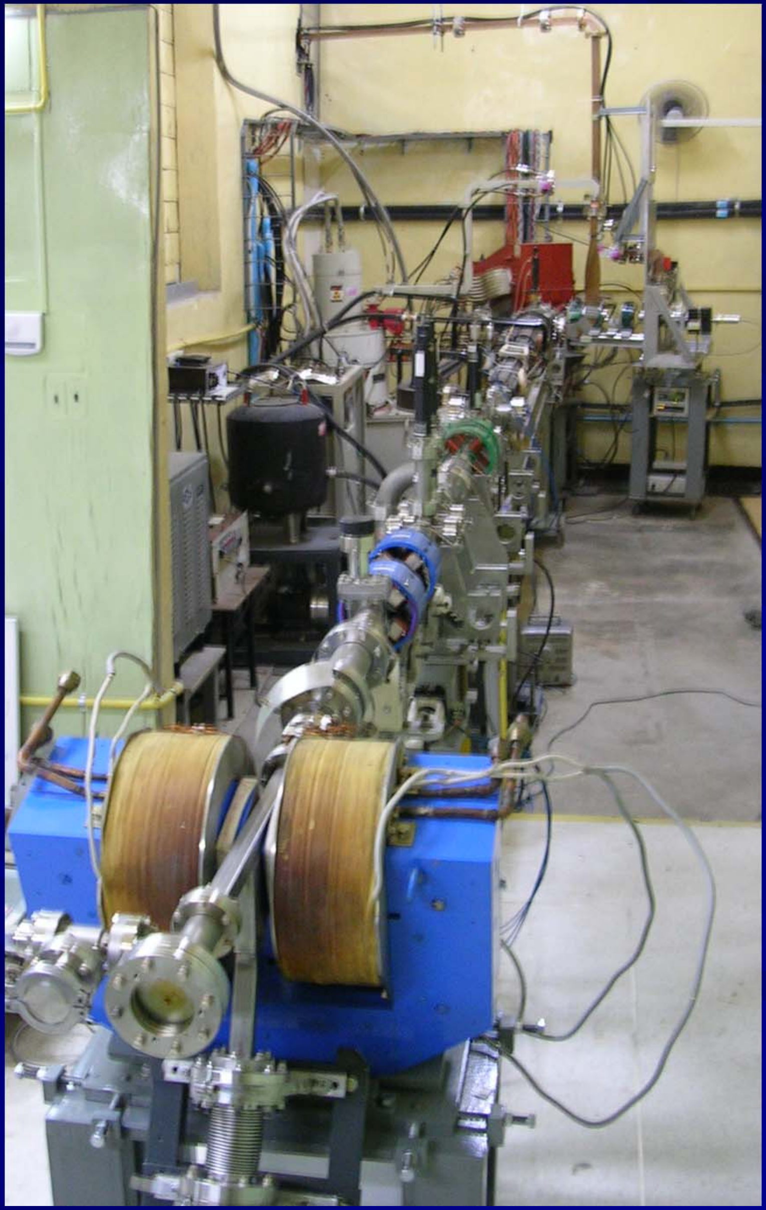
Beamline Installation

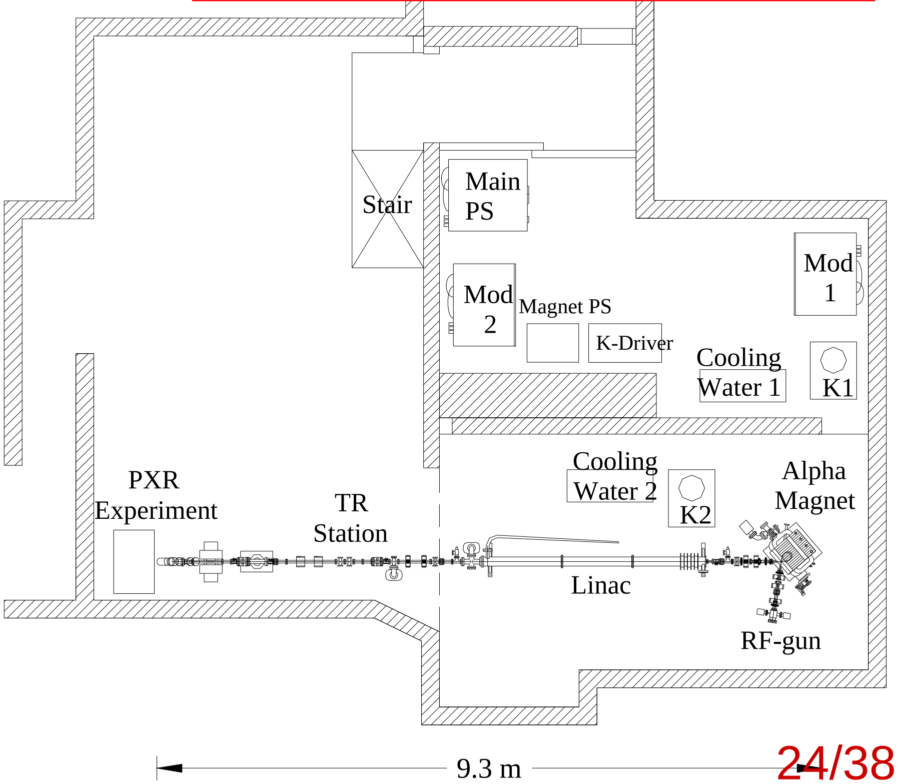




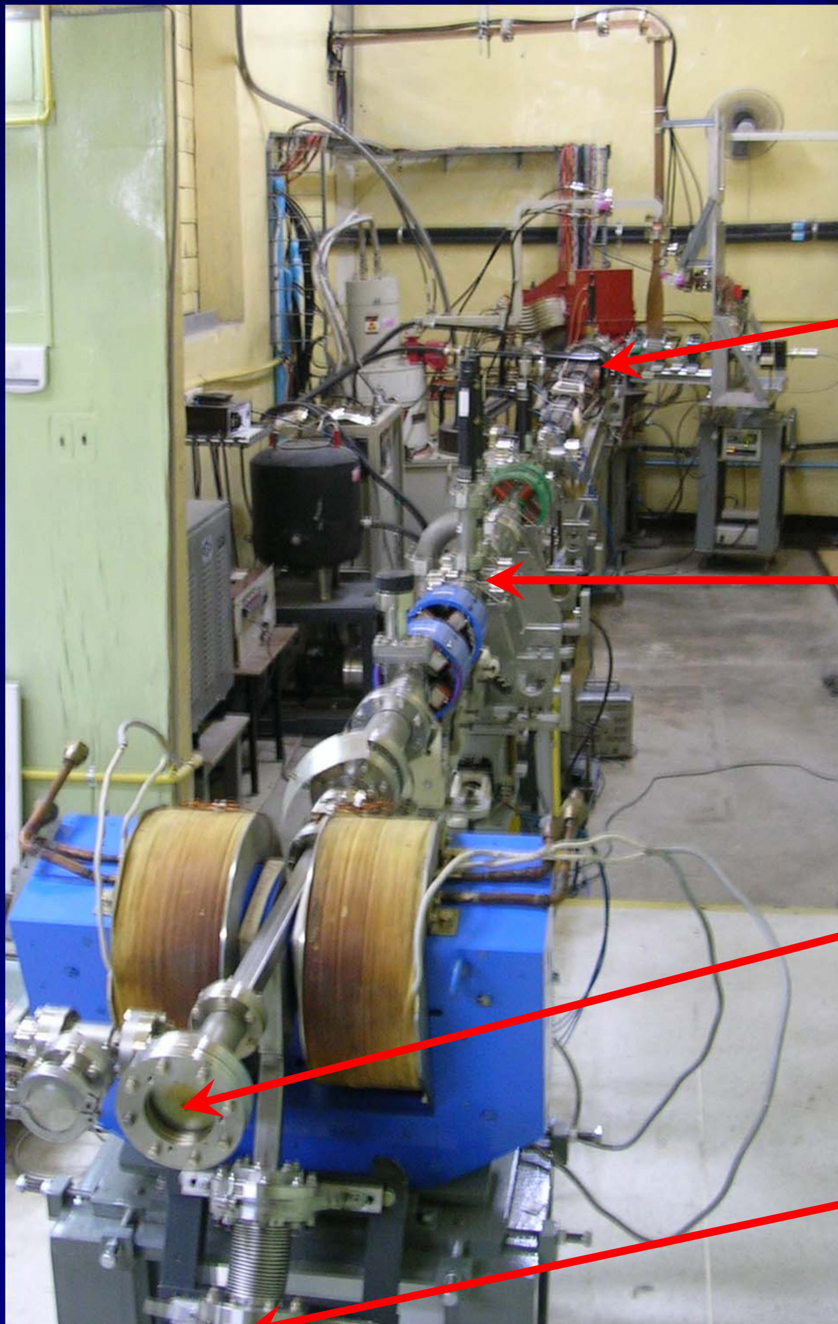


SURIYA Lay Out





Beam Diagnostics



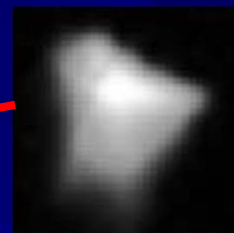


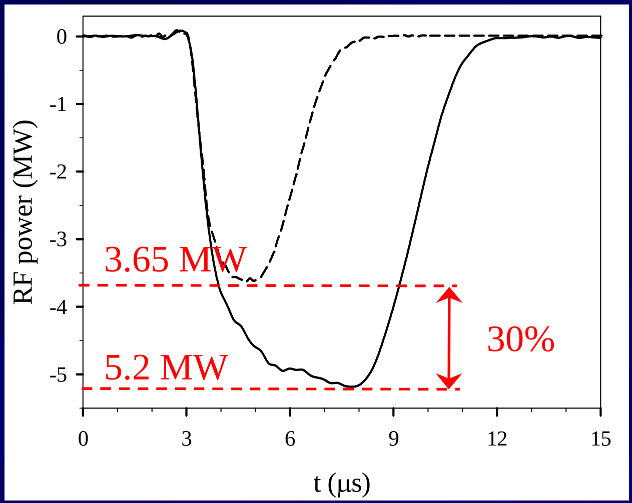
Image of electron beam with max. kinetic energy of 2.4 MeV

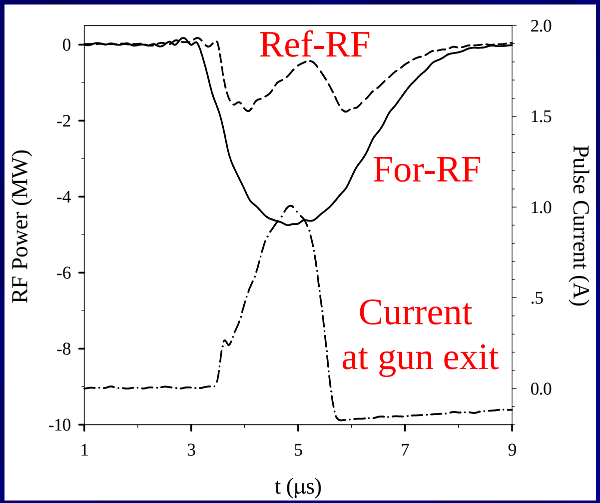
Image of electron beam at transition radiation station

Image of electron beam at the end of beamline

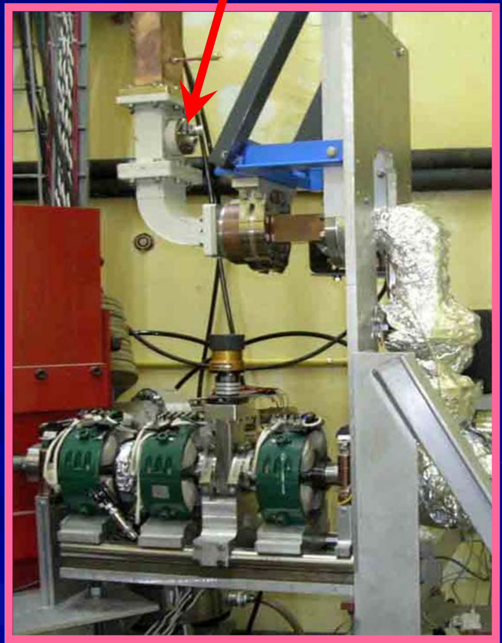
Image of electron beam at view screen downstream of dipole magnet

High RF-power Operation

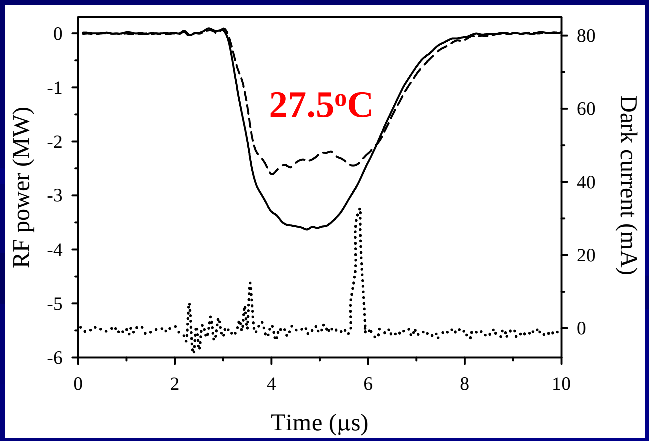


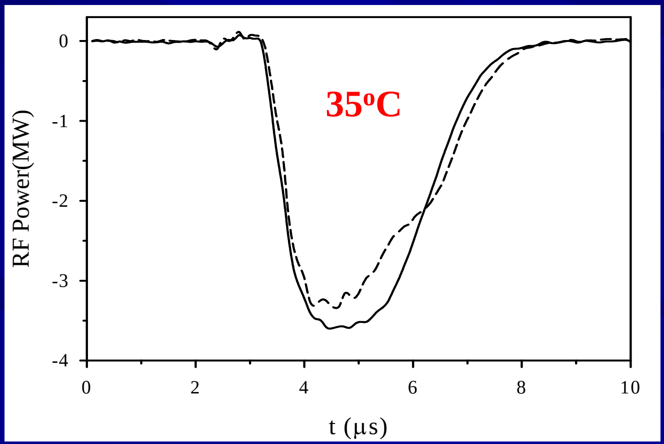


Directional coupler
Crystal Detector



RF-gun Temperature and Thermal expansion





$$\frac{\Delta f}{\Delta T} \approx -\frac{2.405c}{2\pi a}\alpha$$

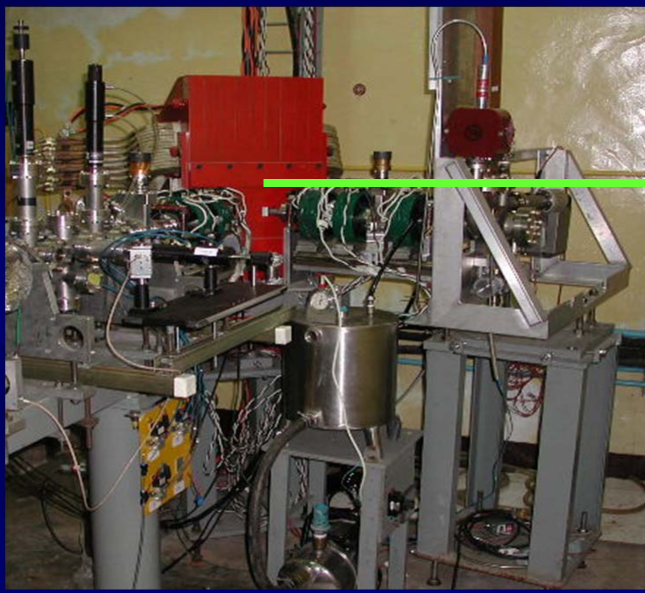
$$\approx -48.3\, kHz/{}^{o}C$$

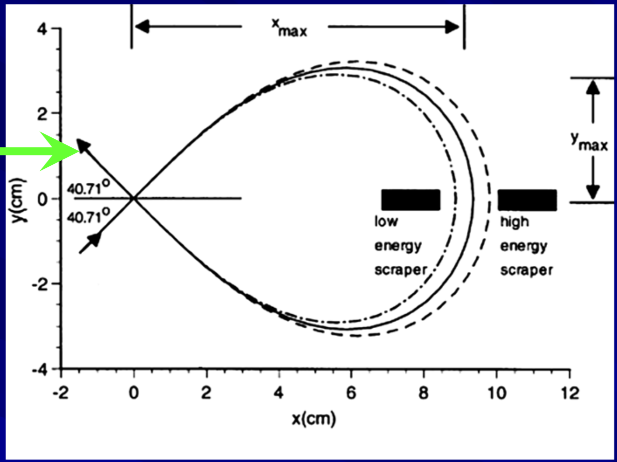
Cavity absorption power ~ 1.46 MW

Frequency de-tuned of 362 kHz (little cavity absorption)

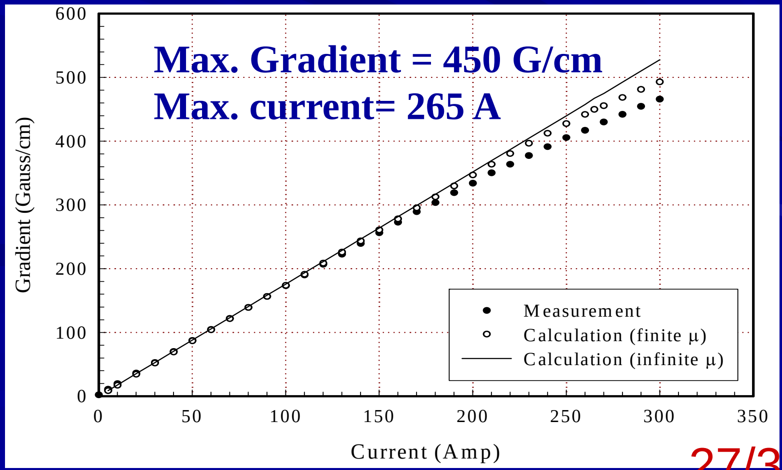
Beam Energy Measurements (RF-gun)

Using energy slit inside alpha magnet vacuum chamber: E_{max}=2-2.4 MeV



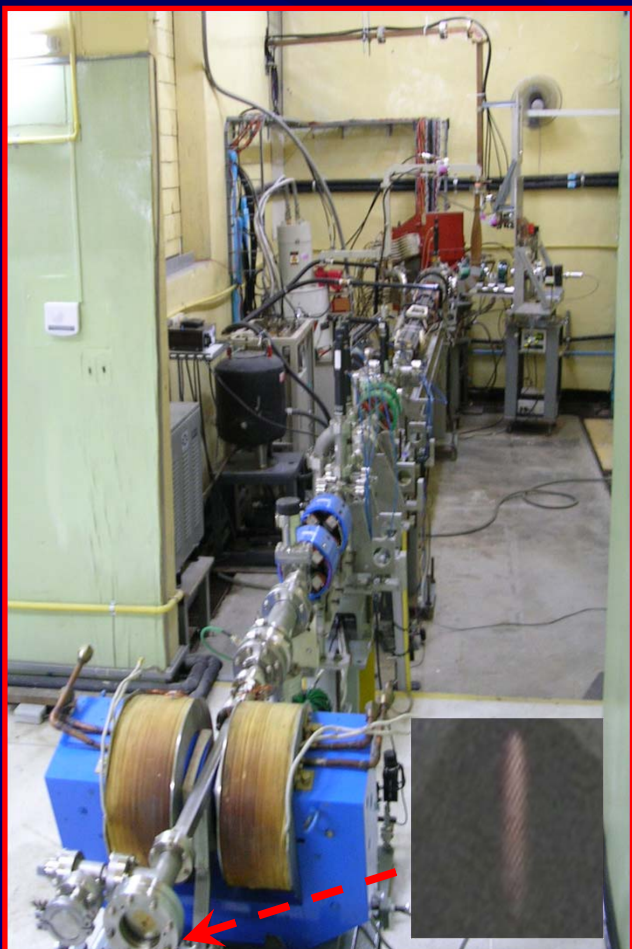


$$x_{max} = 75.05\sqrt{\frac{cp}{mc^2 g}}$$

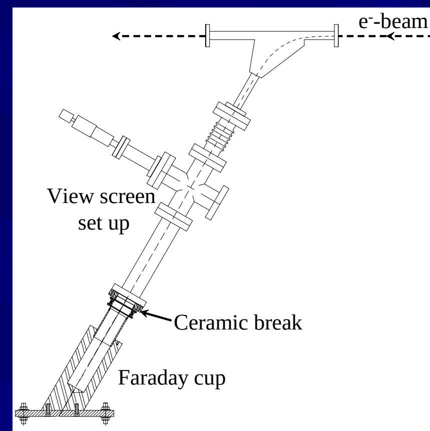


Beam Energy Measurements (after post linac acceleration)

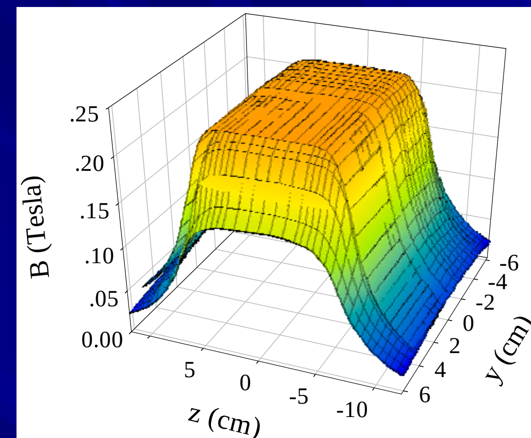
Dipole magnet as electron beam dump + energy spectrometer



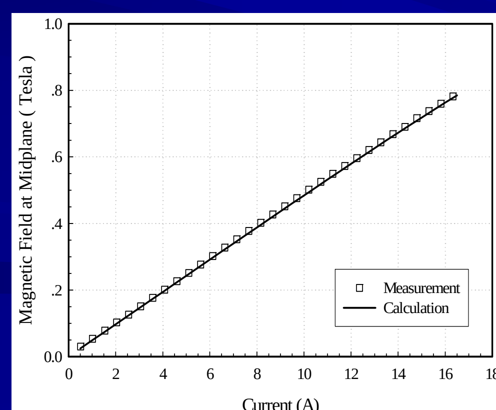
13 MeV electron beam (< 20 MeV)



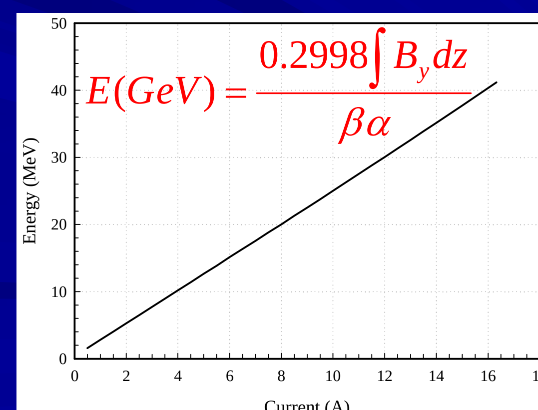
Deflect electron beam 60º respect to beam axis



Actual 3D-field distribution of dipole magnet



B~0.8 Tesla at current of 16 A



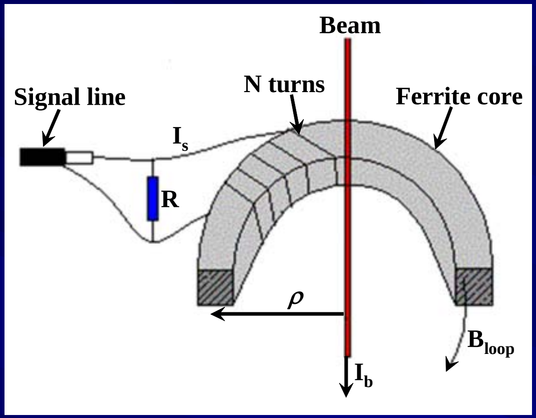
Trajectory Simulator

(K. Kusoljariyakul)

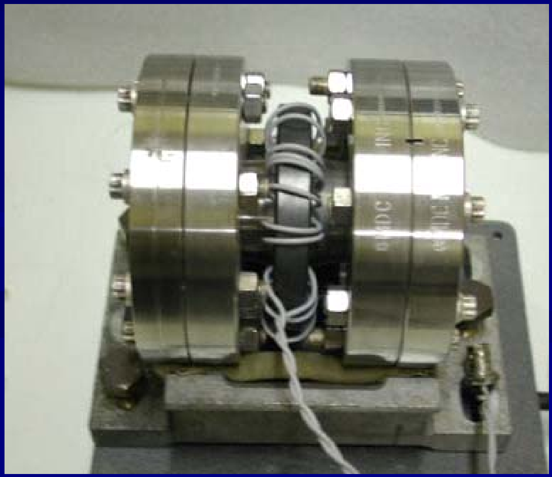
Beam Current and Beam Power

Current Monitor

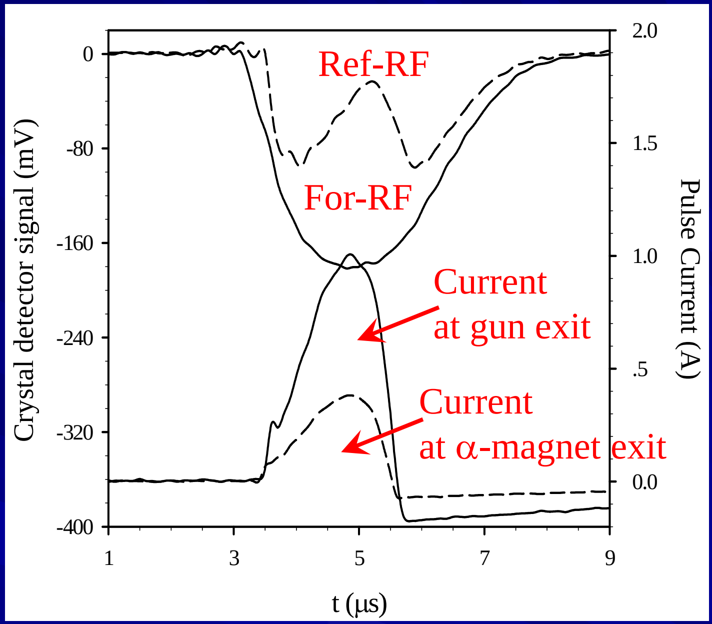
$$I_b = N_s I_s = \frac{N_s}{R} V_s = \frac{8}{50} V_s = 0.16\, V_s$$



Schematic model of current transformer



Actual current transformer



Peak current of ~ 1 A at about 2 MeV from RF-gun

Beam power $P_b \sim I_b \times E_{kin}$ = 2 MW

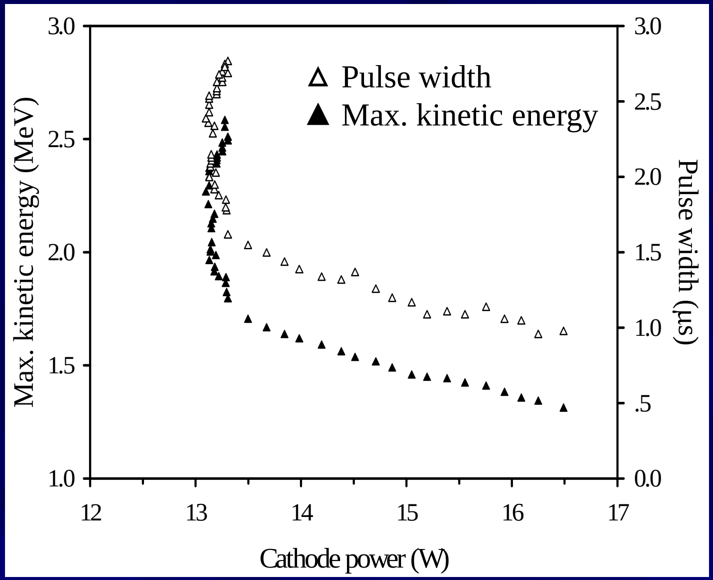
Cavity wall losses P_{cy} ~ 1.46 MW

$P_{cy} + P_b$ = 3.46 MW

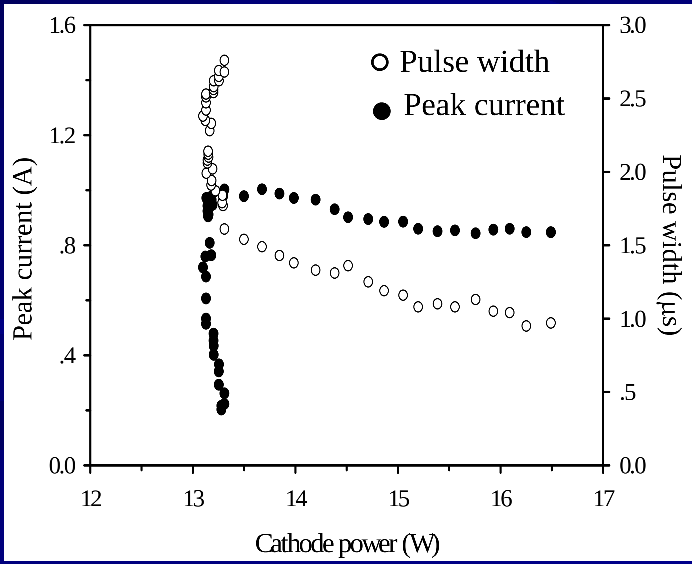
Peak current of 0.4-0.5 A at α- magnet exit
(50-60% is filtered out by the energy slit)

Electron Beam Loading in RF-gun

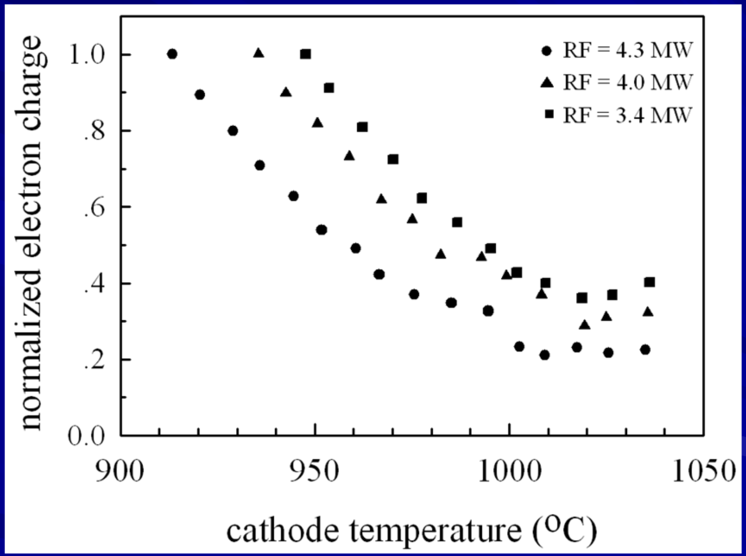
- Cathode operating temperature: 950-1000°C
- Filament heating power: 13-16 W
- Maximum beam peak current: 1 A
- Beam current pulse width: 1-2.5 μs
- Number of microbunches/macropulse: 3000-7000
- Maximum kinetic energy: 2-2.6 MeV



Maximum kinetic energy and beam pulse width as a function of cathode heating power



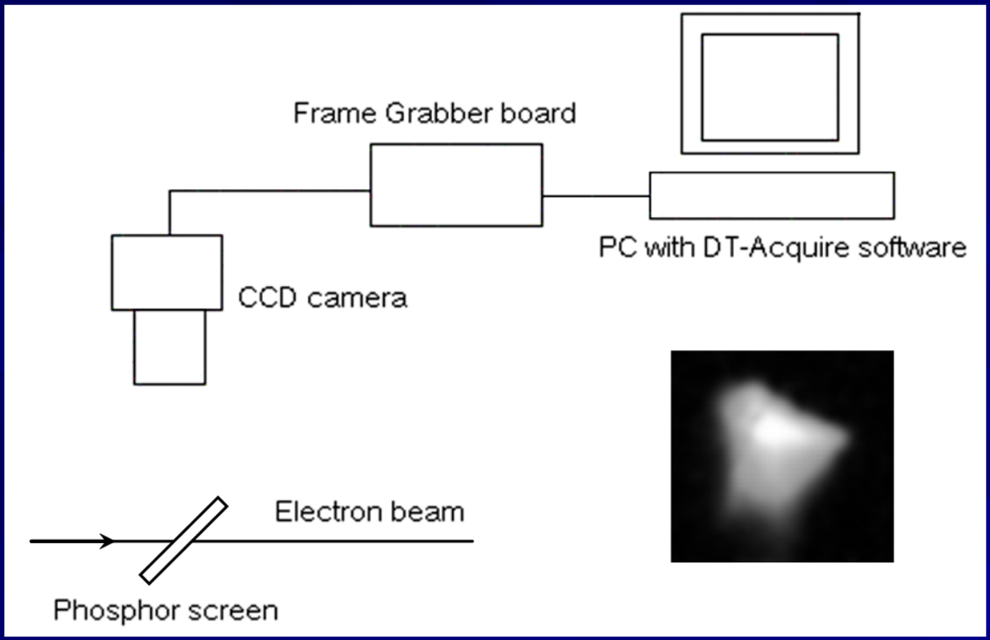
Beam peak current and beam pulse width as a function of cathode heating power



Normalized electron charge from RF-gun as a function of cathode temperature

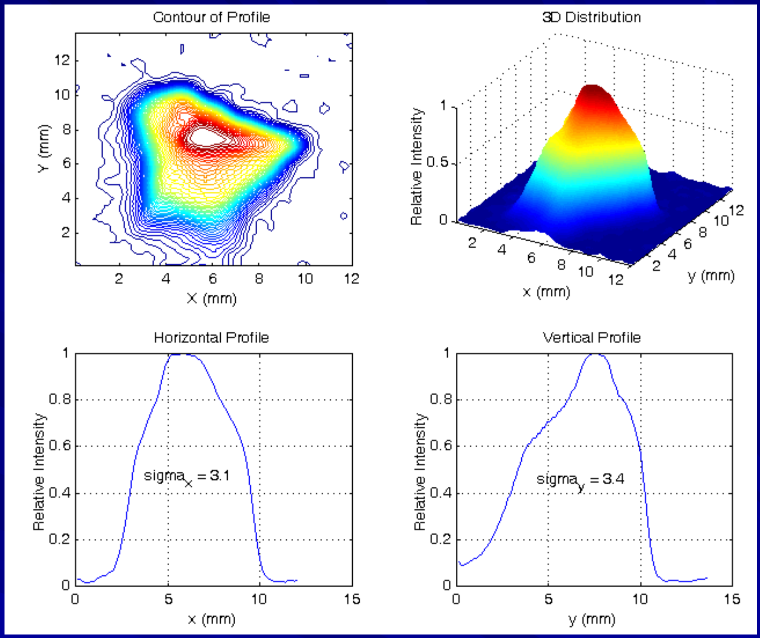
(S. Rimjaem et al, PAC2005)

Beam Profile Measurements



Schematic layout of beam profile measurement setup and a 2.4 MeV electron beam image (SC2)

-Phosphor screen (Gd_2O_2:Tb deposited on Al-plate)
-CCD camera
-Frame grabber broad (DT3315 Data-Translation)
-PC with DT-Acquire software



Relative intensity distribution of electron beam in 2D and 3D and the horizontal and vertical beam profiles

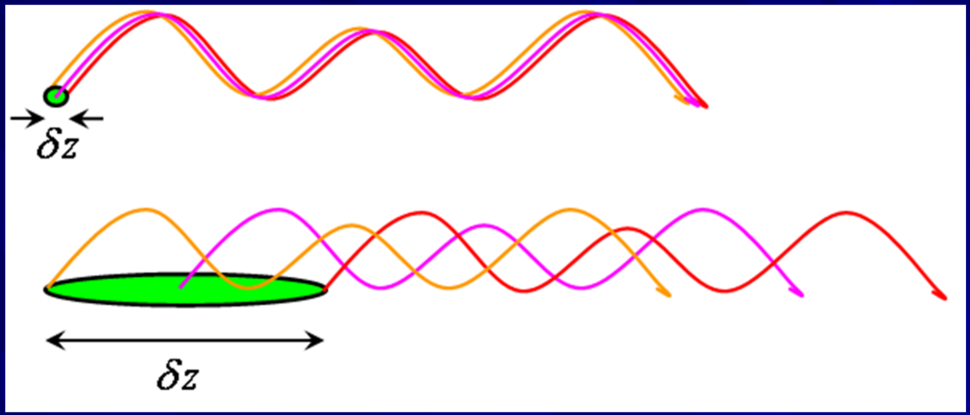
(MATLAB code BAP, S. Chumphongphan)

Typical operating parameters and electron beam characteristics at SURIYA

Parameter (July 4, 2006)	RF-gun	Linac
Resonant frequency (MHz)	2856	2856
Repetition rate (Hz)	10	10
Operating temperature at 2856 MHz (^{o}C)	27.5	54
Input RF-power (MW)	3.65	~ 5.1
Expected beam energy (MeV)	2.5-3.0	20
Max. measured beam energy (MeV)	2.7	10-13
Beam peak current (mA)	1000	110
Macropulse length (μs)	~2	~1
Number of bunches per macropulse	~5700	~2856
Number of electrons per bunch	1.4×10^9	2.4×10^8

★ The expected bunch length (from simulation) for SURIYA system with present operating parameters is 75 fs and a total charge of 93 pCb.

Radiation from Electron Bunches



At wavelengths about or longer than the bunch length

↓

Radiation field add up coherently

↓

Electron short bunches is desired to produce coherent radiation

↓

Radiation intensity α N^2

$$I(\omega) = NI_e(\omega) + N(N-1)I_e(\omega)f(\omega)$$

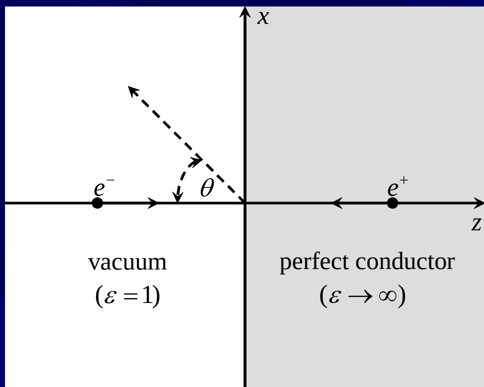
Bunch form factor

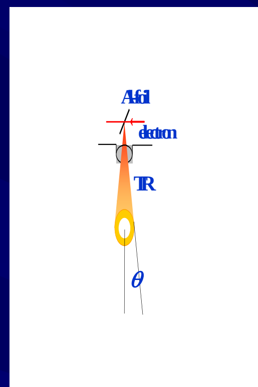
(Fourier transform of the normalized charge distribution)

For electron beam of 10^8-10^9 electrons/bunch

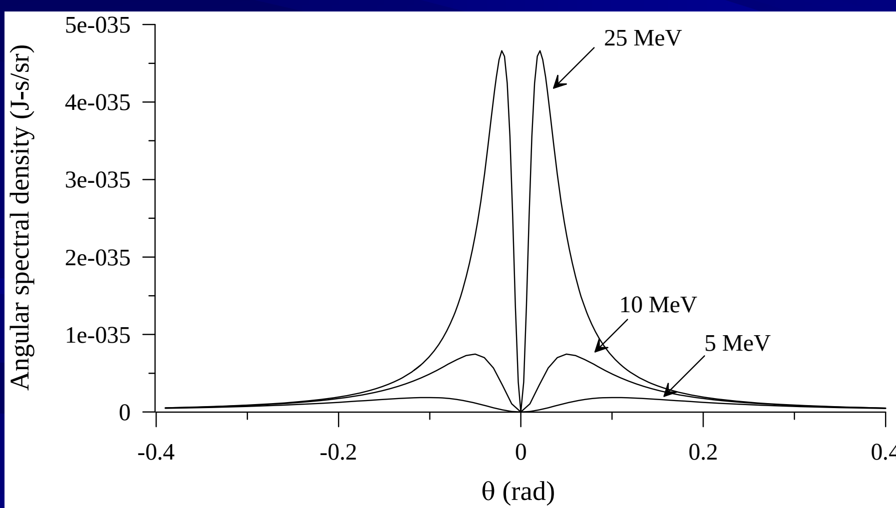
$$\frac{I_{coherent}}{I_{incoherent}} \approx 8-9 \ \ orders$$

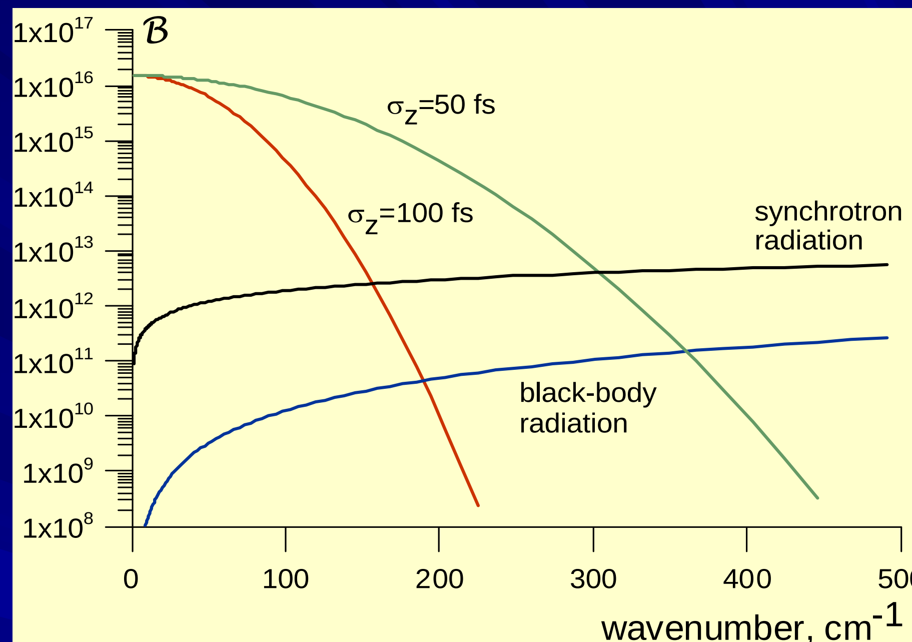
FIR Radiation from Transition Radiation





TR is generated while electron passes an interface between two dielectric material





Radiation brightness B (ph/s/mm²/100%BW) vs. wave number

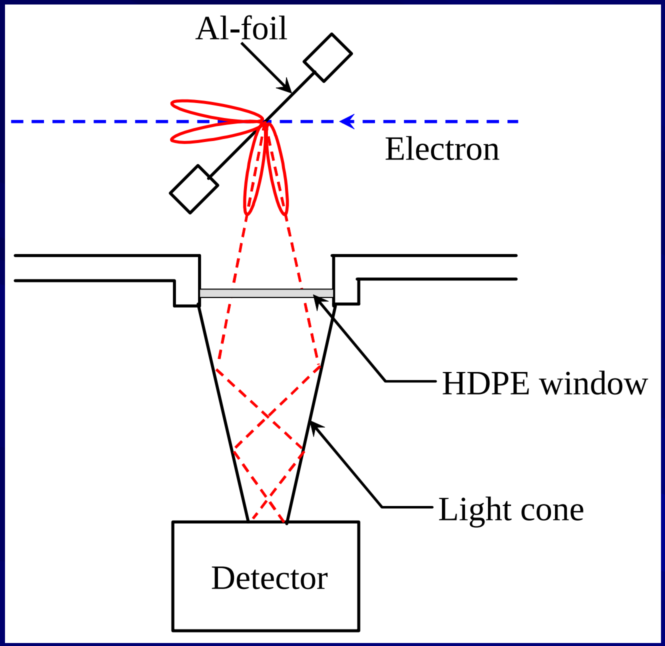
Form factor for Gaussian bunch $f(\omega) = e^{-(\omega\sigma_z / c^2)}$

The spectral angular distribution of TR from a vacuum-conductor interfaces

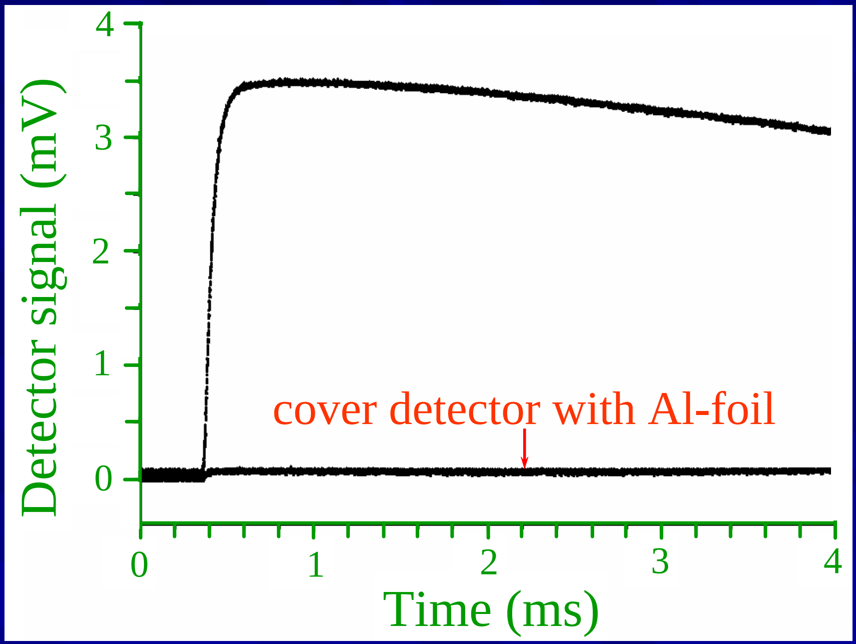
(C. Settakorn, Ph.D. Thesis, Stanford University, 2001 and S. Rimjaem et al, SRI2006)

$$\frac{dW}{d\Omega\, d\omega} \approx \frac{e^2 \beta^2 \sin^2\theta}{\pi^2 c \left(1 - \beta^2 \cos^2\theta\right)^2}$$

Transition Radiation Observation



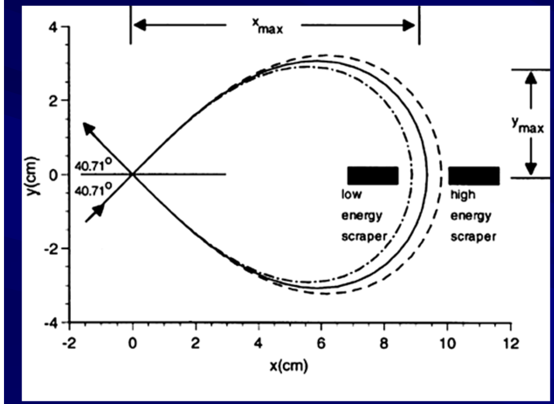
Transition radiation measurement setup

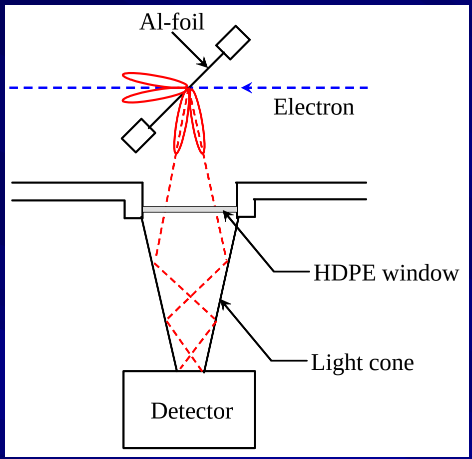


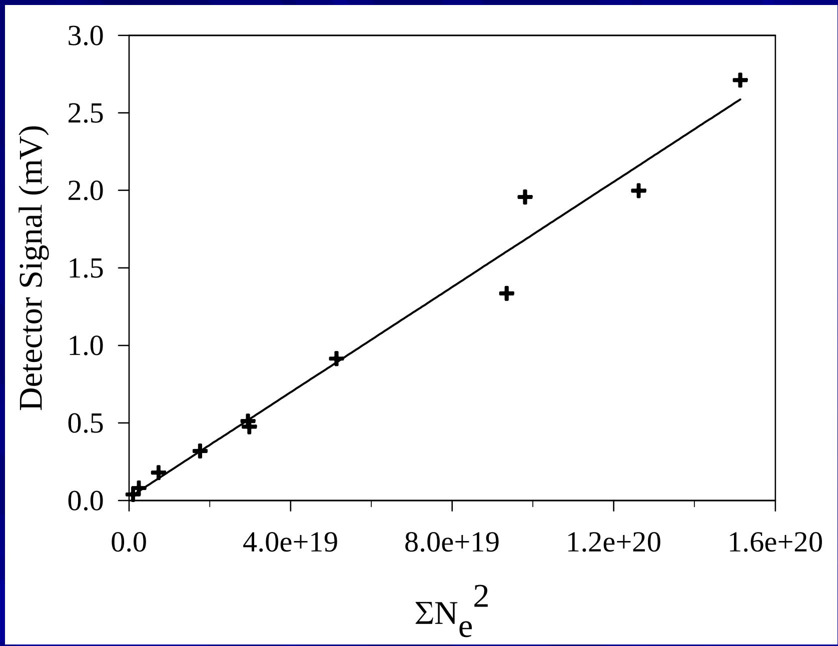
FIR radiation from transition radiation signal

Detector
↓
Pyroelectric detector + pre-amplifier

Coherent Transition Radiation







Coherent transition radiation measurement

Coherent FIR from transition radiation

Vary electron charge by moving low energy slit scraper

↓

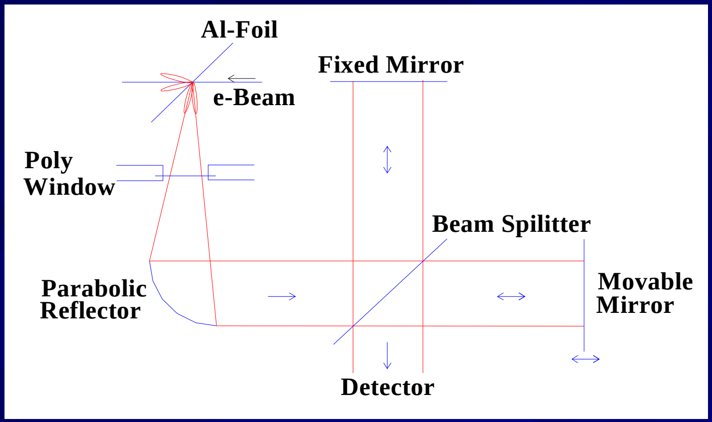
Pyroelectric detector + pre-amplifier

Radiation intensity α N^2

$$I_{cTR} \propto \sum_i N_i^2 f(\omega)$$

Bunch Length Measurements

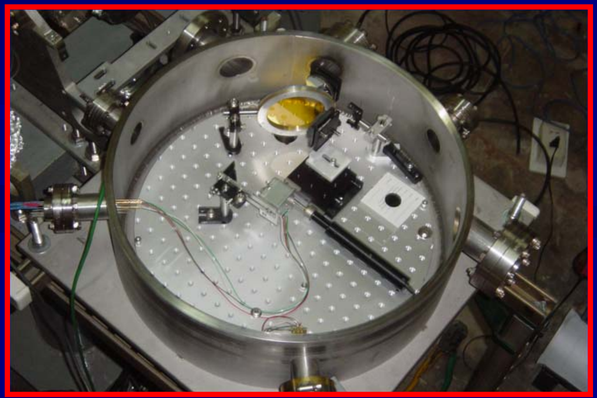
Bunch length measurement setup



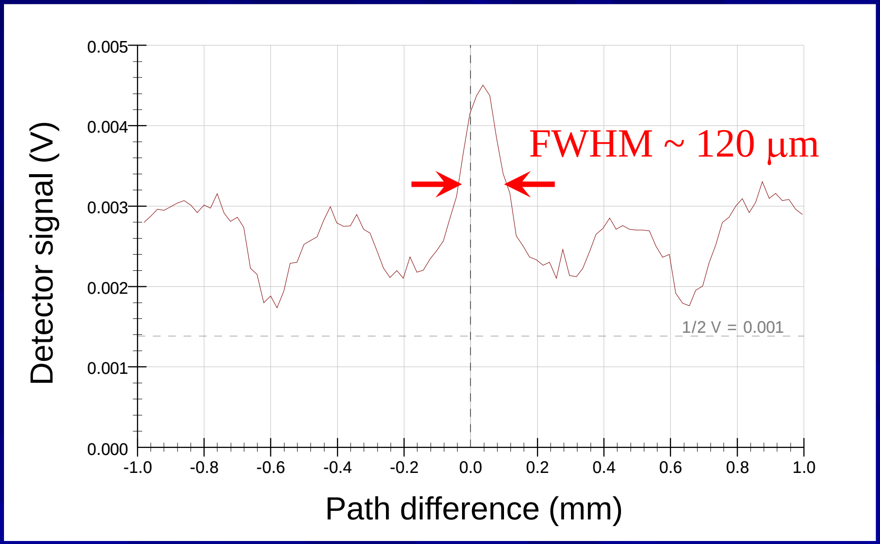
Michelson Interferometer

↓

Autocorrelation of coherent TR



Interferogram from the in-air Michelson interferometer



Bunch length measurement results for Gaussian pulse

↓

FWHM ~ 800 fs or σ_z ~ 240 fs

(C. Settakorn, Ph.D. Thesis, Stanford University, 2001)

Thank you!

SURIYA
Chiang Mai University