RF Electron Gun

Lecture No. 3:
Operation and Applications of RF Gun

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Lecture No. 3

Operation of RF Electron Gun

- Cathode preparation
- Operation conditions
- Measurements of electron beam properties

Applications of Electron Sources

- Electron sources for high energy physics accelerator
- Electron sources for light sources
- Electron sources for direct applications

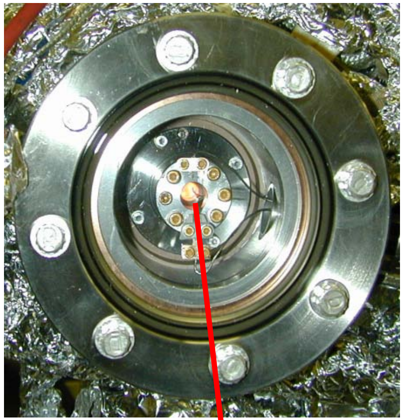
Generation and Applications of Ultra Short Electron Bunches Produced by RF Gun

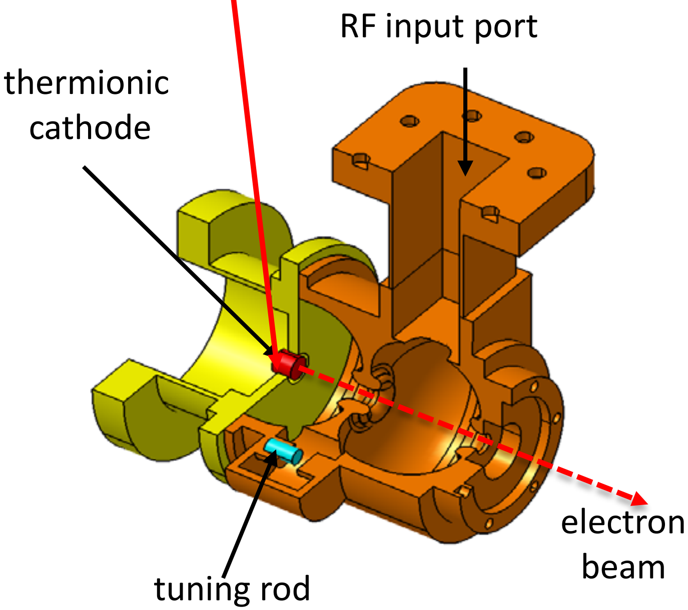
- Generation and applications of ultra short electron bunches at Chiang Mai University

Thermionic Cathode Assembly (1)

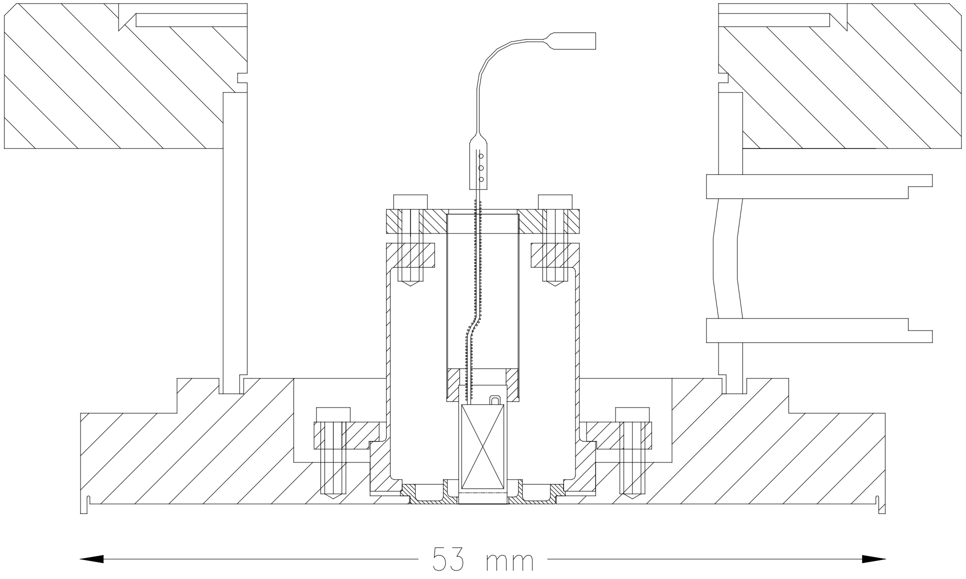
Cathode assembly

- Cylindrical SST cathode holder with screws for adjusting cathode position.
- Cathode with flat circular emitting surface of 3 mm is heated via filament connected to an external power supply.

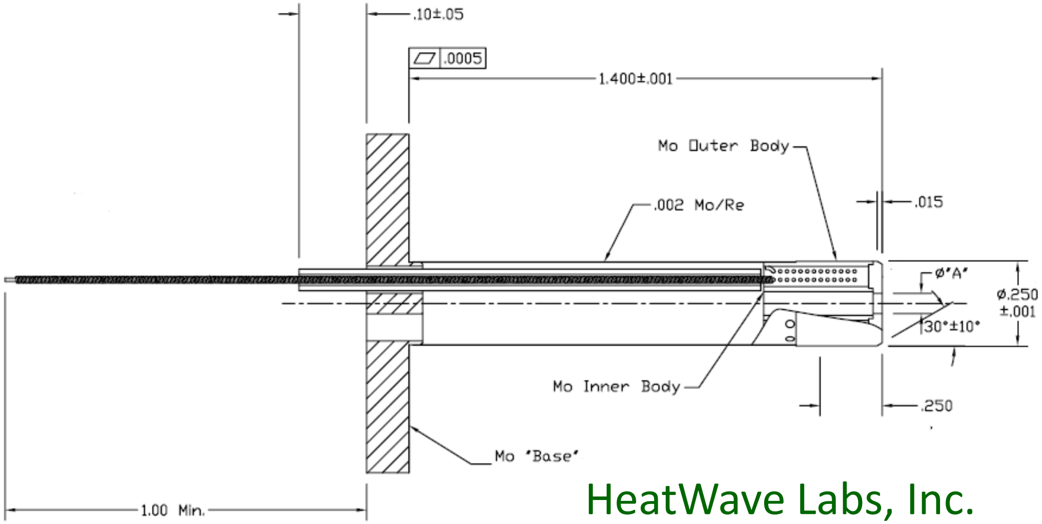




Thermionic Cathode Assembly (2)

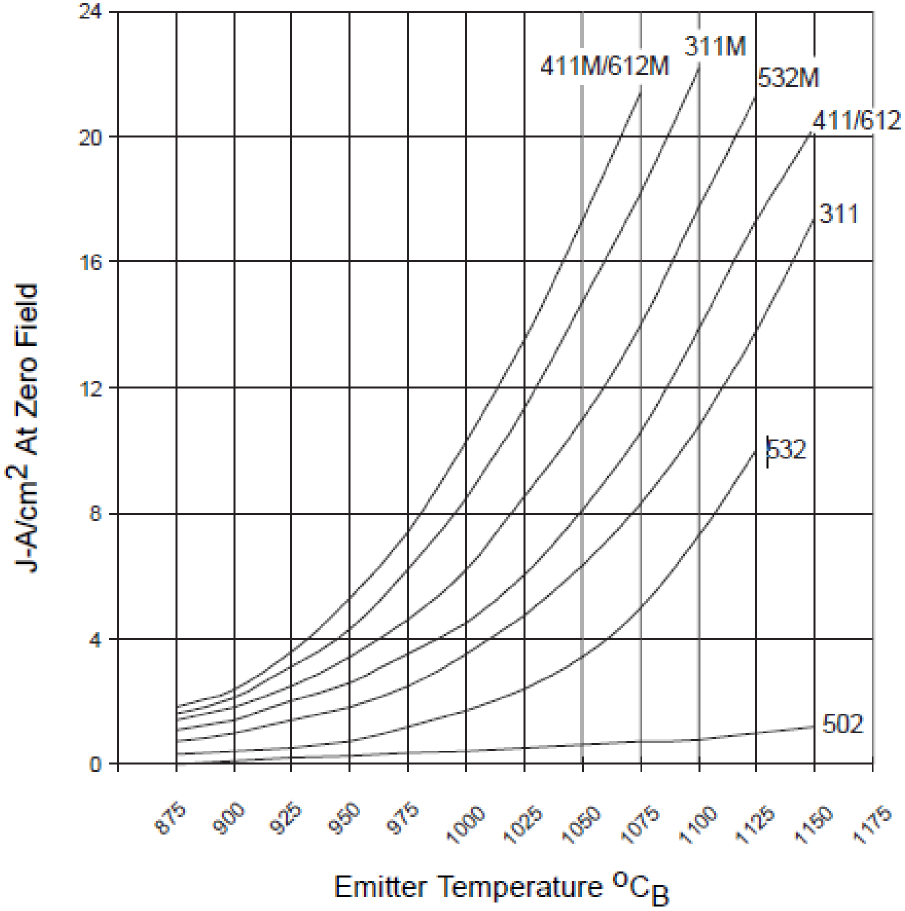


Thermionic cathode is an impregnated dispenser tungsten cathode coated with Os/Ru.
→ Flat circular emitting surface of 3 mm radius.



HeatWave Labs, Inc.

Emission Characteristics of Dispenser Cathodes



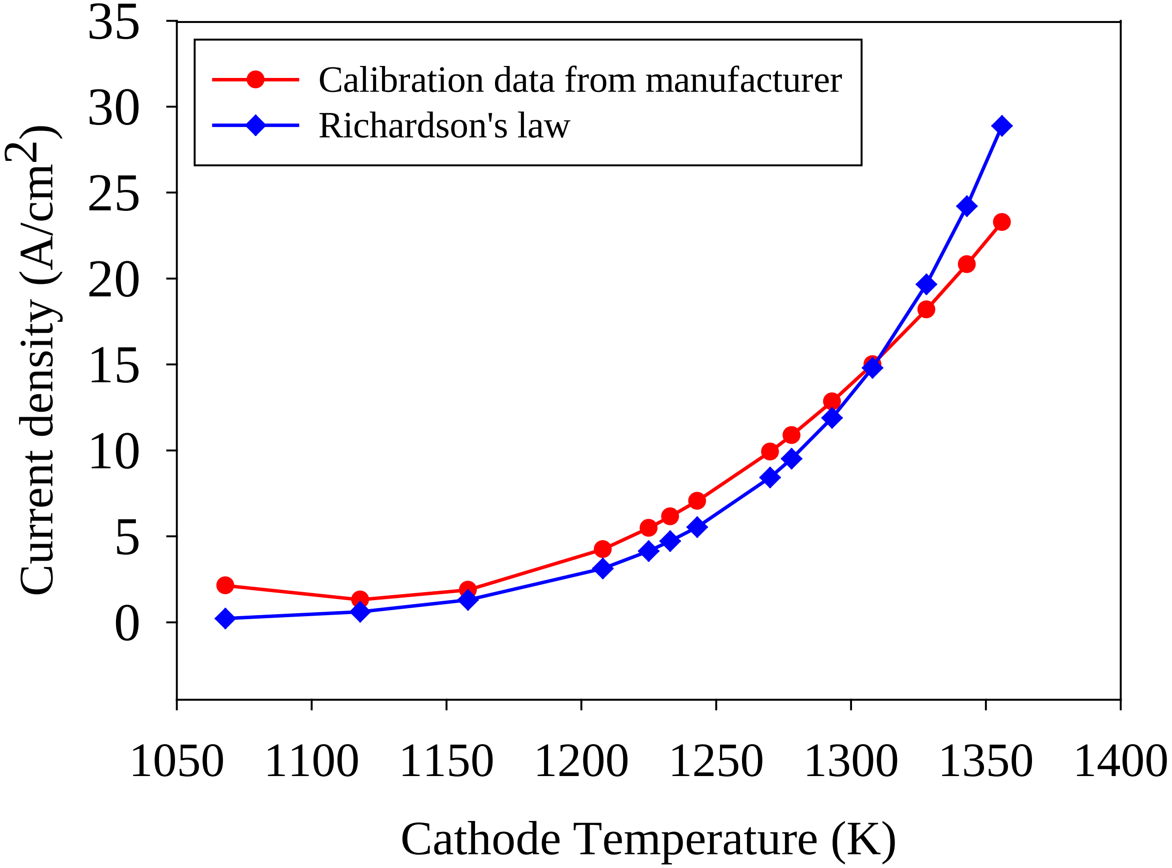
HeatWave Labs, Inc.

"Type M cathode" is an improved version of the impregnated cathode, which coated with an alloy of platinum group metals on the emissive surface to lower the work function.

→ It can be operated at lower temperatures than the standard dispenser cathode for the same current density, which results in longer operating lifetime.

Cathode Calibration vs. Theory

Comparison of current density as a function of cathode temperature from manufacturer’s calibration data and Richardson’s law.



Thermionic Cathode Preparation

The cathode needs to be heated to a high temperature (~900-1000^{o}*C)* for electron emission.

→ If the heat leakage is too high, the cathode might not reach the electron emission temperature.

→Thermal radiation from hot cathode can heat up the cavity wall near the cathode to expand due to thermal expansion. This may results in a resonant frequency shift of the gun.

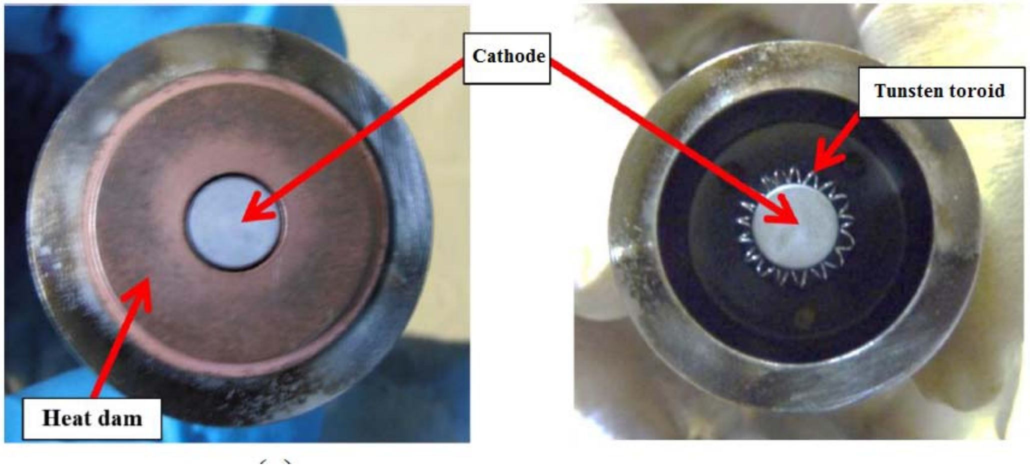
To prevent heat lost to the surrounding area, the cathode must be insulated from material.

→ A flat heat-dam made of Hastelloy C-276 with copper electroplating is used.

→ A narrow gap was made between the cathode stem and the heat-dam to function as a thermal insulator.

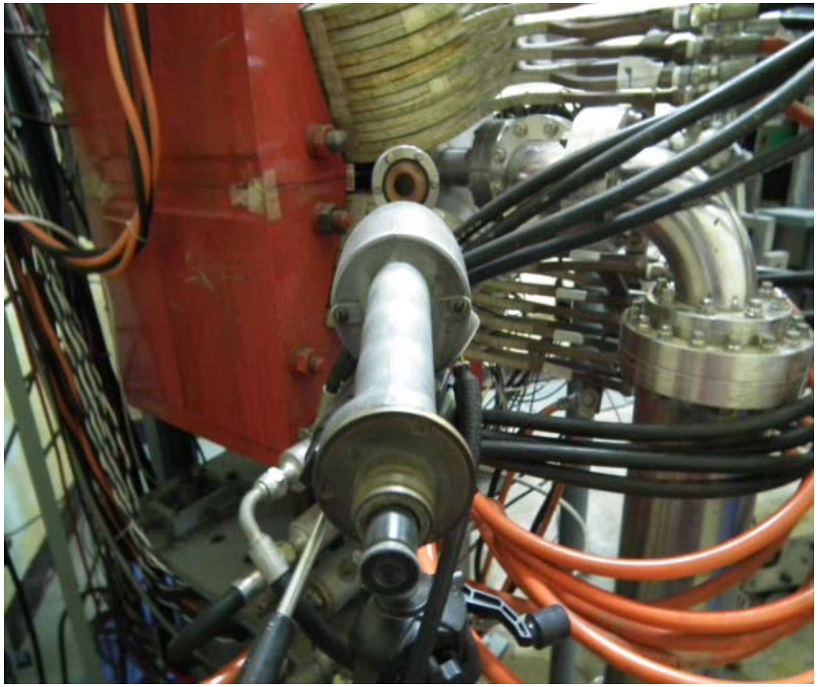
→ A toroidal- tungsten-spring is placed around the cathode stem to minimize heat leakage.

→ The cathode temperature depends greatly on the number of turns of the spring.



Cathode Processing Setup

Pyrometric measurement after cleaning and baking

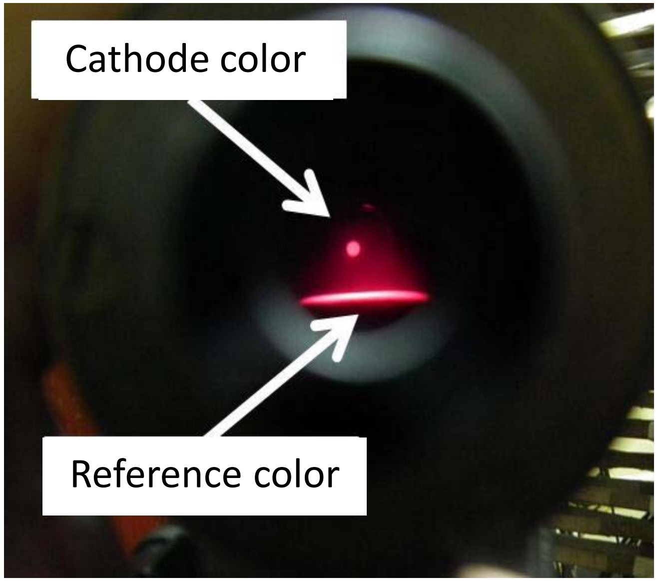


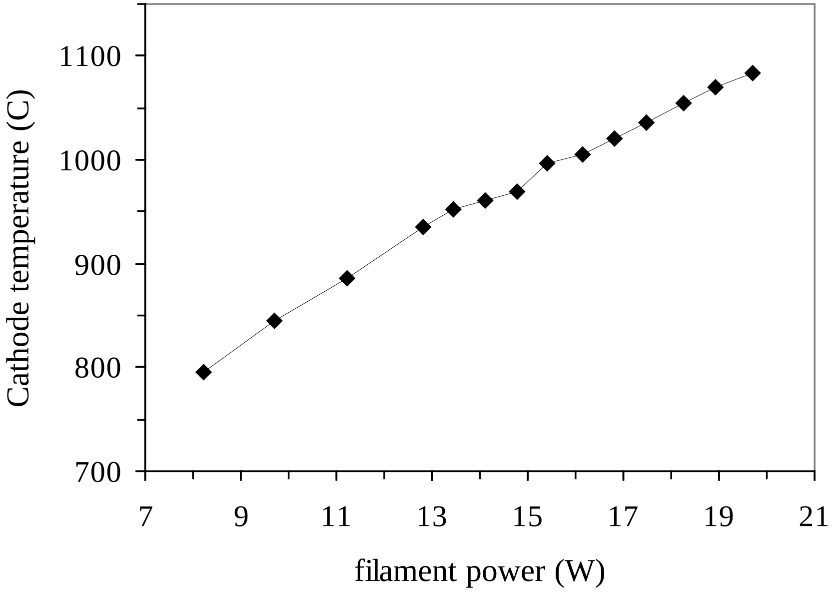
Pyrometric measurement for the gun, which installed in the beam line.

Temperature Measurements

Cathode tests (Pyrometric measurements)

- To activate the cathode to temperature > 1050 °C
- Measure the cathode temperature by using an 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)

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RF Power vs. Electric Field Gradient (1)

Input (forward) RF power given to the RF-gun is

$$P_{forward} = P_{cacity} + P_{beam} + P_{reflected}$$

Beam power is related to the kinetic energy of electron beam as

$$P_{beam} \approx (< KE >) I_{beam}$$

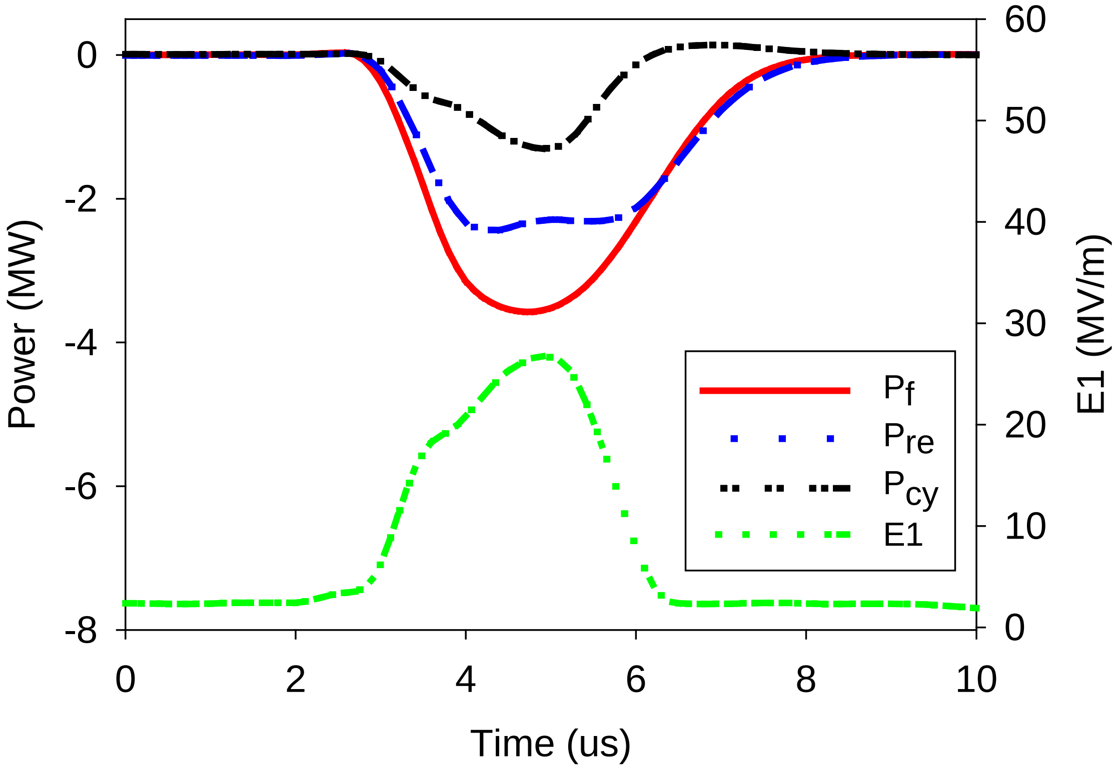
In of no electron emission from the cathode, the cavity wall losses is

$$P_{cavity} = P_f - \mathrm{P}_{\mathrm{r}\, eflected}$$

Compare with theoretical cavity wall losses (which can get from simulation)
→ Then, the average electric field gradient (E_o) can be calculated:

$$P_{cavity} = \frac{V_{acc}^2}{r_s d} = \frac{E_1^2 d}{r_s} \quad \Rightarrow \quad E_1^2 = \frac{P_{cavity}\ r_s}{d}$$

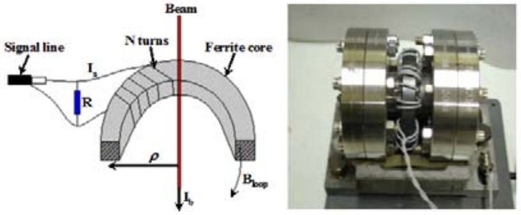
RF Power vs. Electric Field Gradient (2)



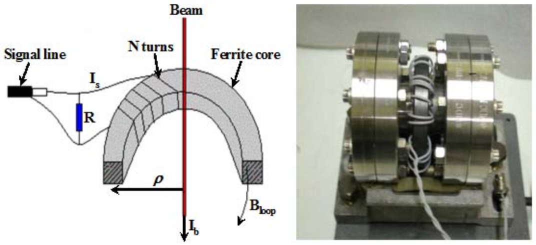
Measured RF powers and calculated average electric field gradient

Beam Power and Beam Current

Current Monitor

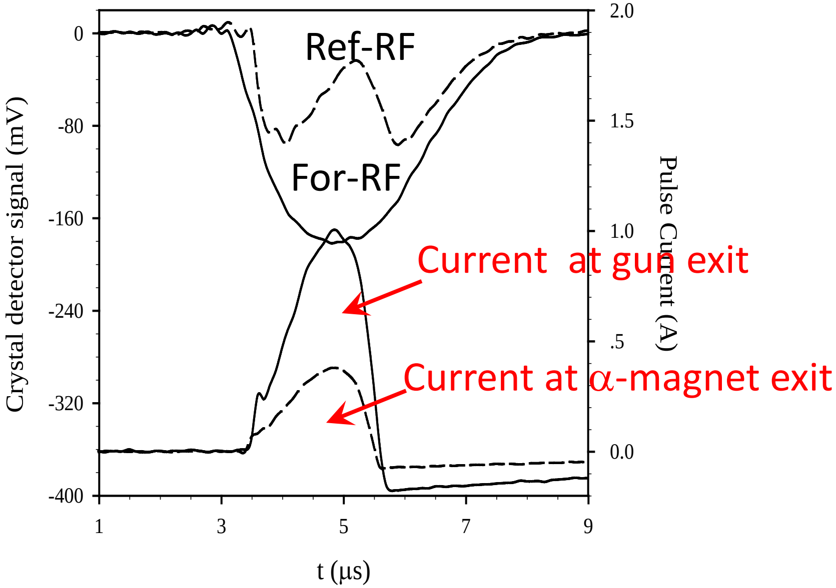


Schematic model of current transformer



Actual current transformer

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



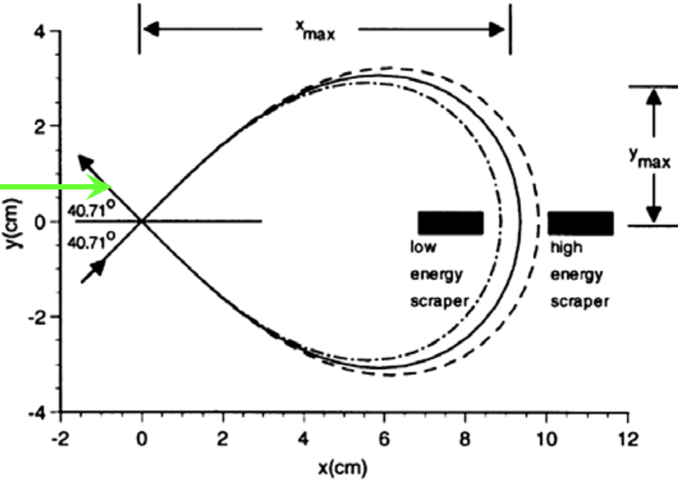
Peak current of ~ 1 A at ~2 MeV from RF-gun

- 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

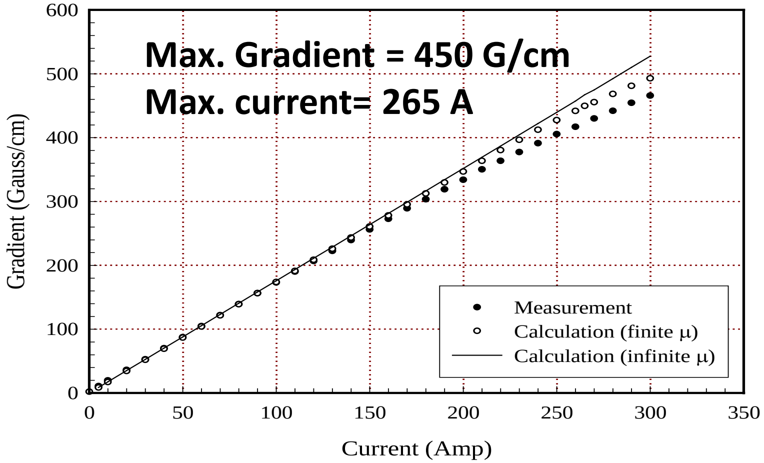
Peak current of 0.4-0.5 A at α- magnet exit (50-60% is filtered out by the energy slits).

Beam Energy Measurements after RF Gun

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



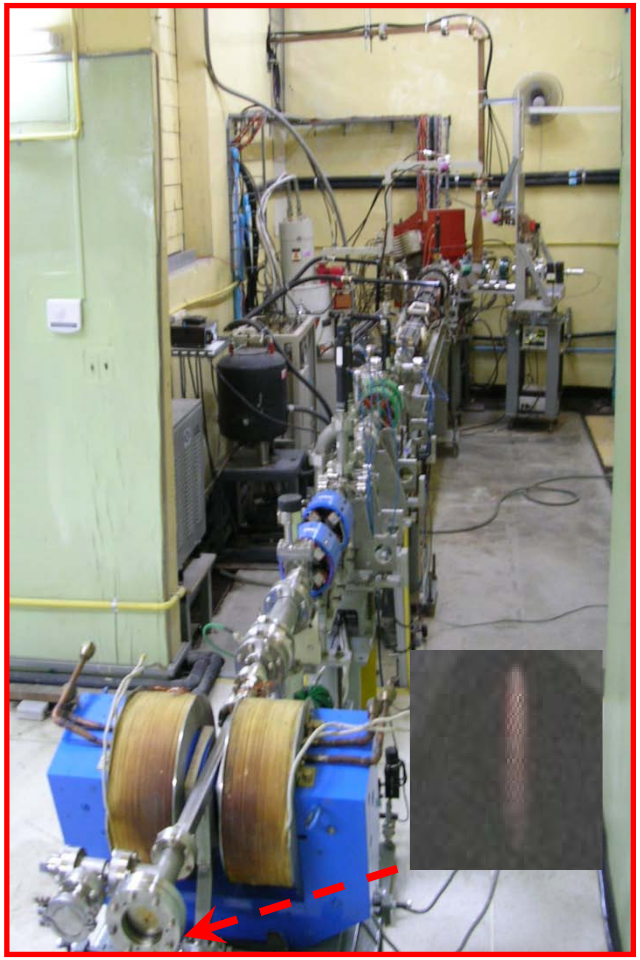
$$x_{\max} = 75.05\sqrt{\frac{cp}{mc^2 g}}$$



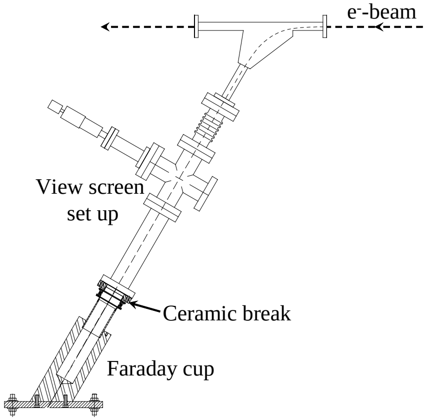
Max. Gradient = 450 G/cm
Max. current= 265 A

Energy Measurements (after Linac)

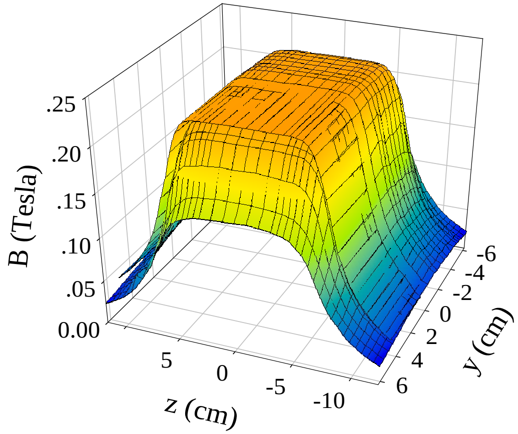
Dipole magnet is used as electron beam dump + energy spectrometer.



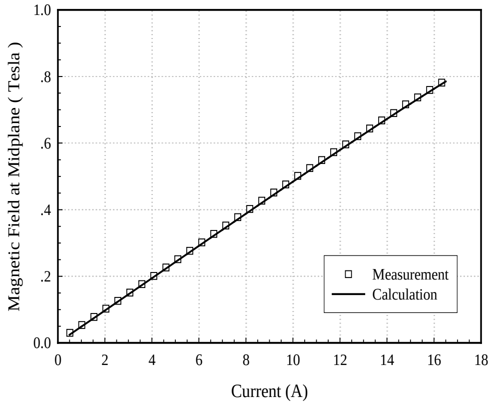
10-15 MeV electron beam



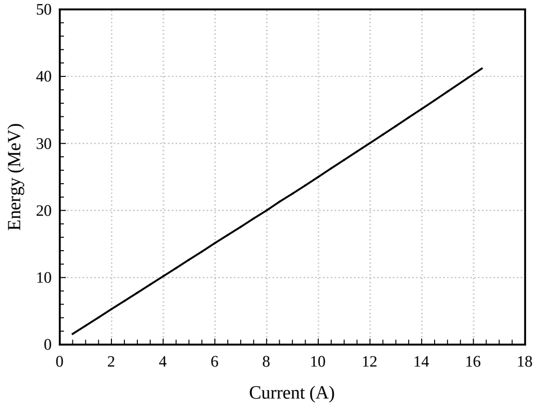
Deflect electron beam 60° respect to beam axis



Actual 3D-field distribution of dipole magnet

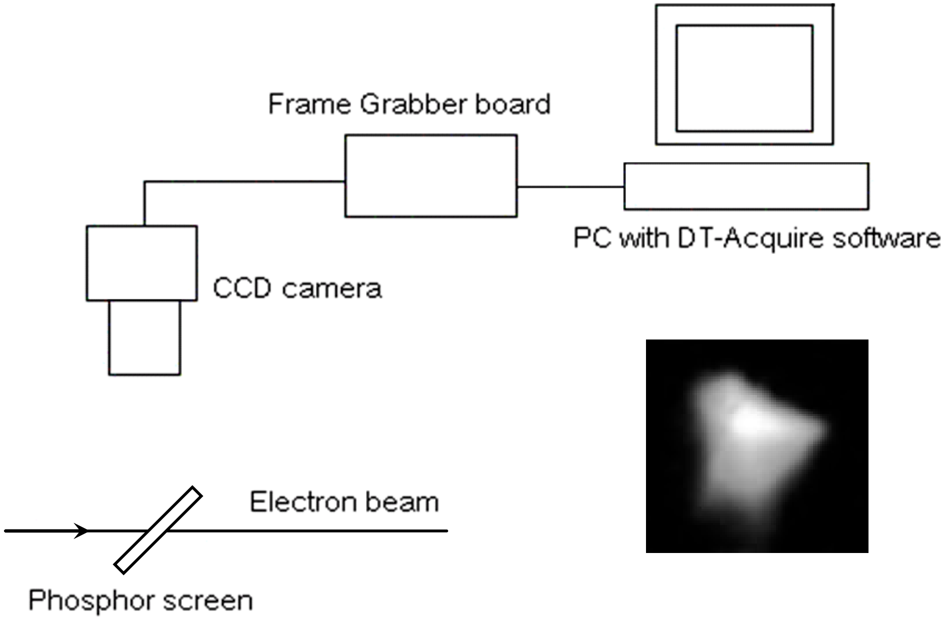


B~0.8 Tesla at current of 16 A



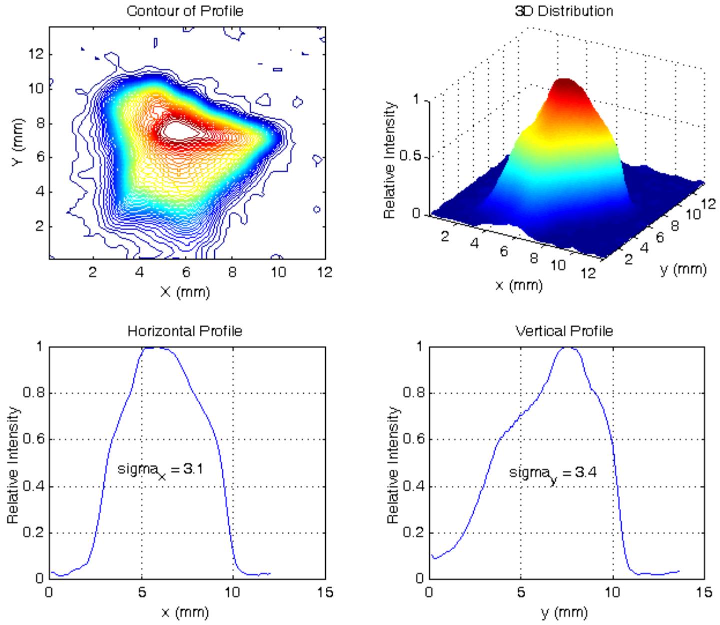
$$E(GeV)=\frac{0.2998\int B_y dz}{\beta\alpha}$$

Beam Profile Measurements



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

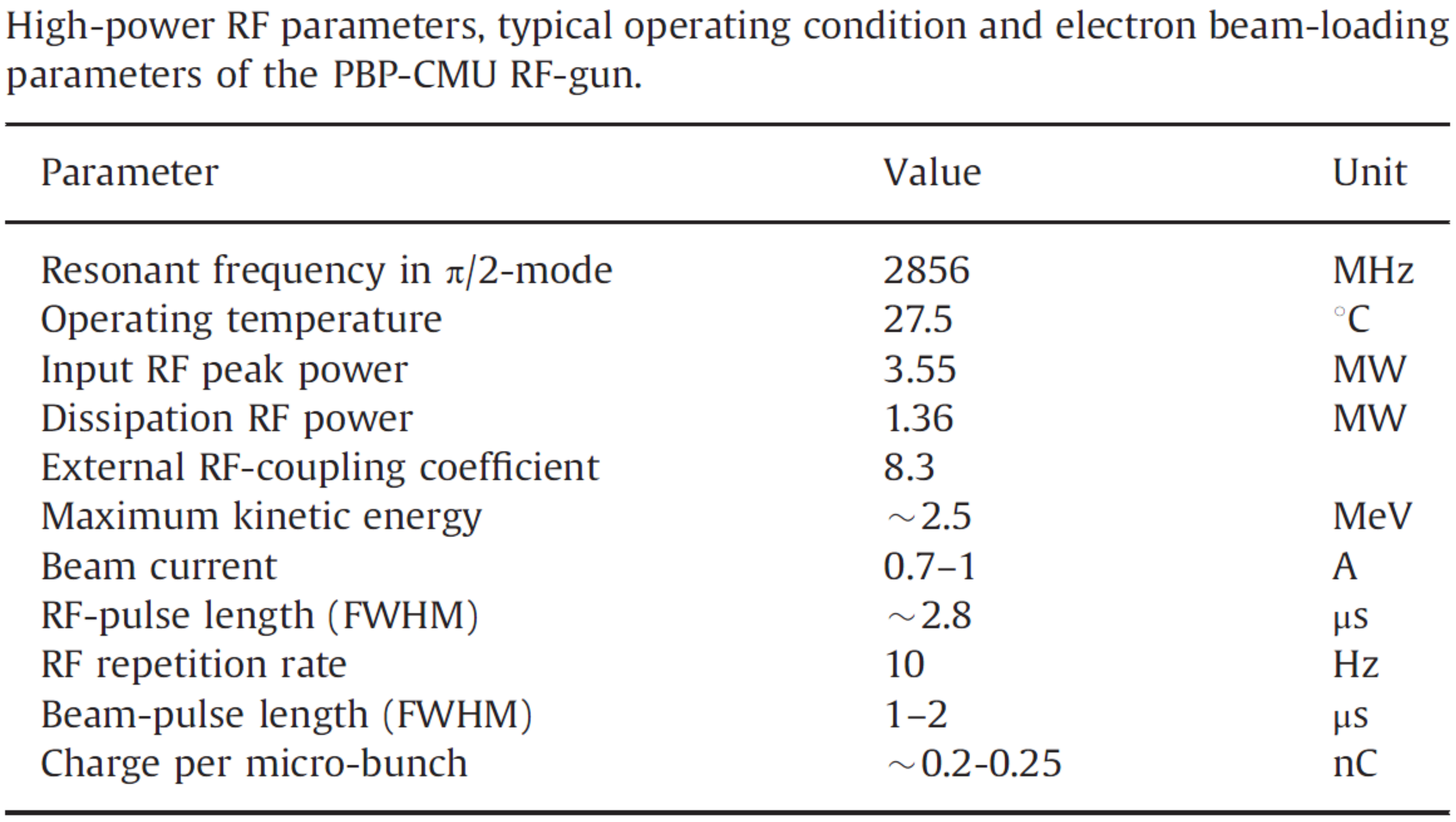
- -Phosphor screen (Gd_2O_2:Tb deposited on Al-plate)
- -CCD camera
- -Frame grabber broad (DT3315 Data-Translation)
- -PC with DT-Acquire software



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

(MATLAB code BAP, S. Chumphongphan)

Operation Conditions & Beam Measurements



High-power RF parameters, typical operating condition and electron beam-loading parameters of the PBP-CMU RF-gun.

Parameter	Value	Unit
Resonant frequency in π/2-mode	2856	MHz
Operating temperature	27.5	°C
Input RF peak power	3.55	MW
Dissipation RF power	1.36	MW
External RF-coupling coefficient	8.3	
Maximum kinetic energy	~2.5	MeV
Beam current	0.7–1	A
RF-pulse length (FWHM)	~2.8	μs
RF repetition rate	10	Hz
Beam-pulse length (FWHM)	1–2	μs
Charge per micro-bunch	~0.2-0.25	nC

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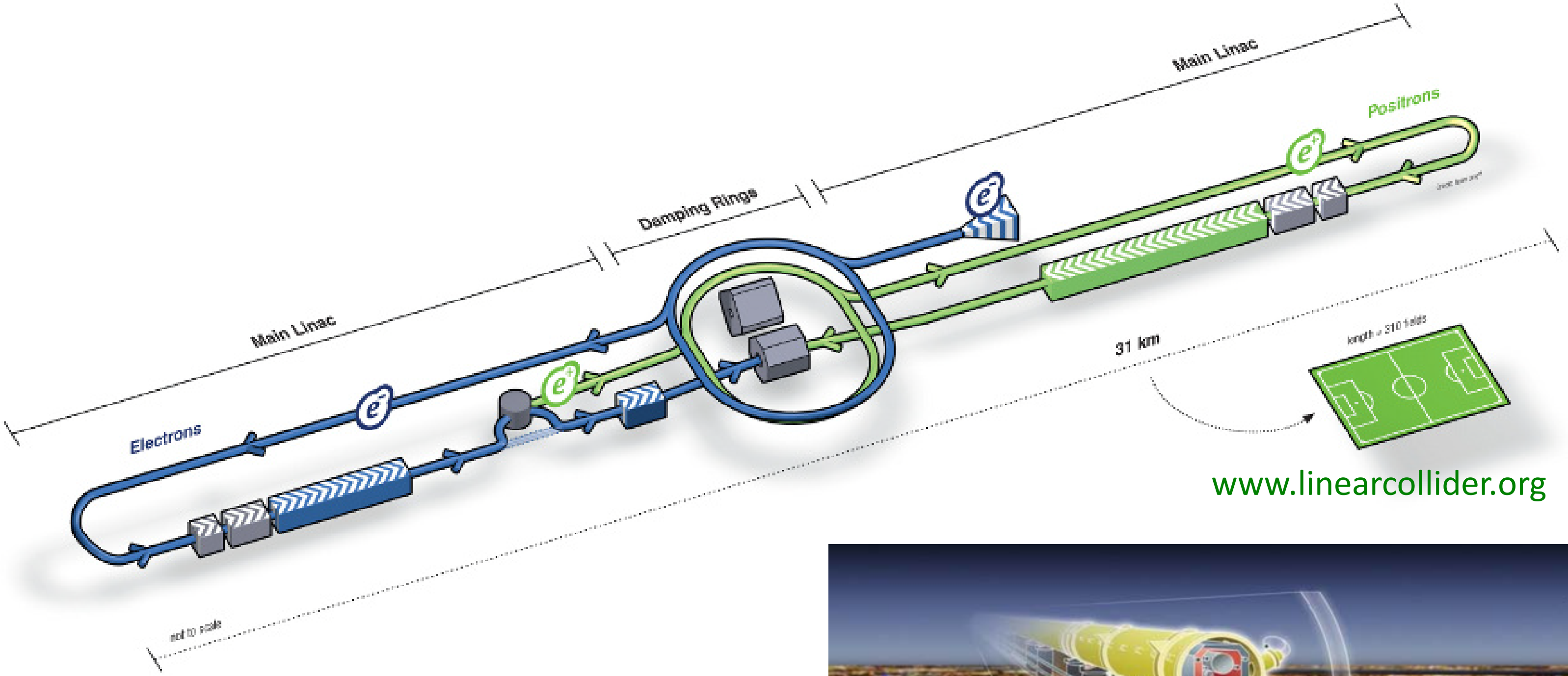
Electron Source for High Energy Physics

Example: Stanford Linear Accelerator Laboratory (SLAC)

3-miles linear accelerator at SLAC can accelerate electron beam to 10 GeV.

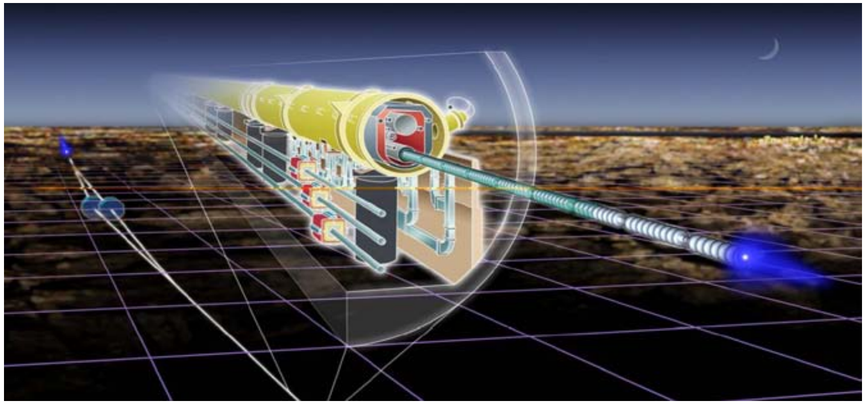
Electron Source for High Energy Physics

Example: **the International e^- - e^+ Linear Collider (ILC)**



www.linearcollider.org

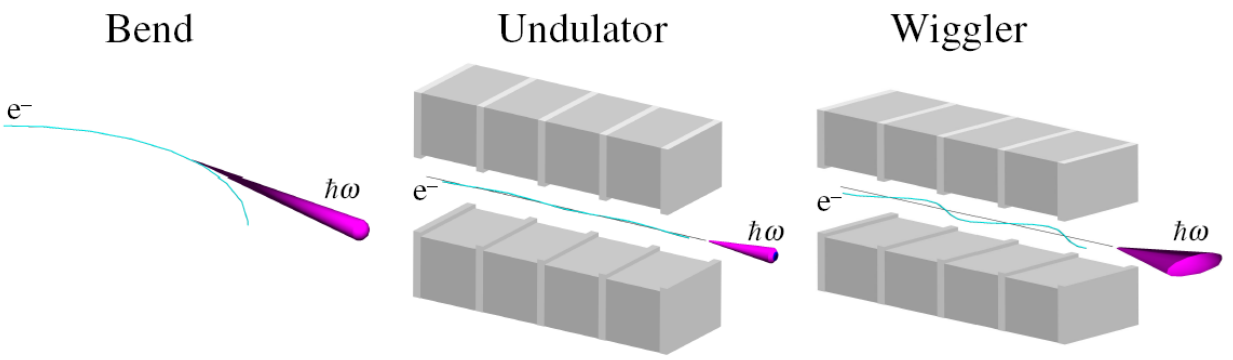
It is initially planned to have a collision energy of 500 GeV, with the possibility for a later upgrade to 1000 GeV (1 TeV).

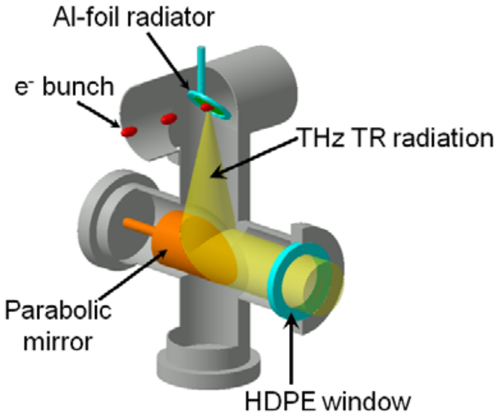


(A. Sessler and E. Wilson, Engines of Discovery: A Century of Particle Accelerators)

Electron source for light sources

Accelerating charges emit electromagnetic radiation





Radiation brightness

- In geometric optics, spectral brightness is defined as photon flux density in phase space about a certain frequency (number of photons per unit time per unit area per unit solid angle):

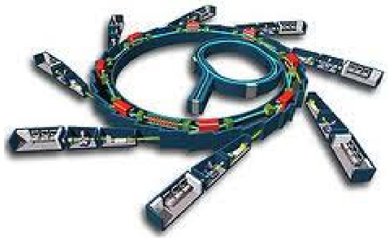
$$\boxed{B = \frac{d^2 I}{dA\,d\Omega} = \frac{d^2 I}{dx\,dx'\,dy\,dy'} \propto \frac{2I_p}{\varepsilon_x \varepsilon_y}}$$

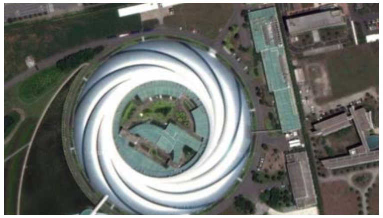
I - electron beam current
A - transverse area
Ω - the divergence
x, y – transverse coordinates
x', y' - indicate derivatives with respect to *z*

$\therefore$ We need electron beams with small emittance and high peak current.

Synchrotron Light Sources

Thermionic DC guns
Thermionic RF guns





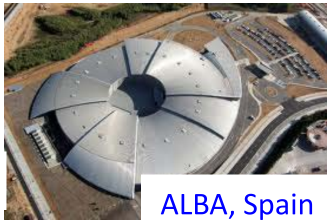
Shanghai light source (China)

Spring 8 (Japan)

Siam Photon (Thailand)

PETRAIII @ DESY (Germany)

Diamond (UK)

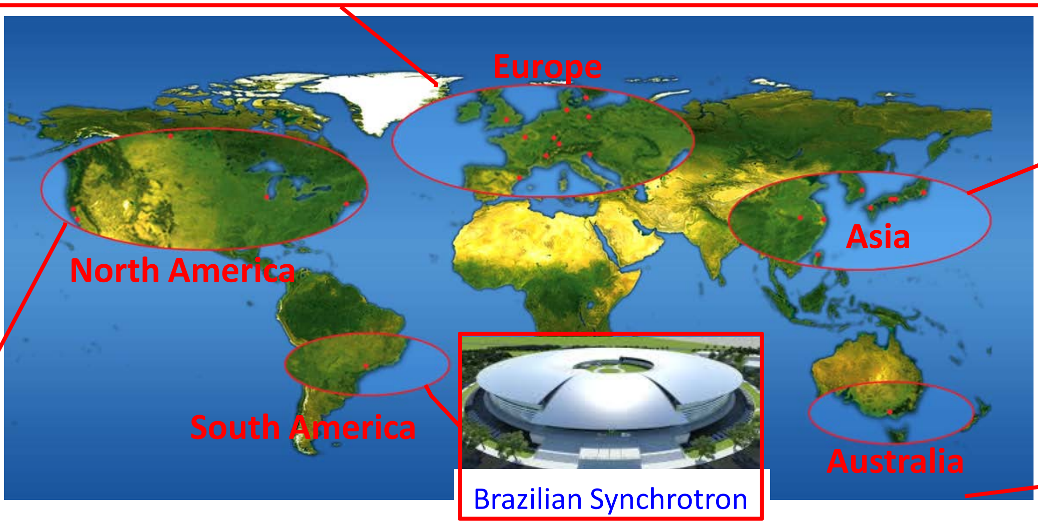


ALBA, Spain

ESRF, France

NSLS (USA)

APS (USA)

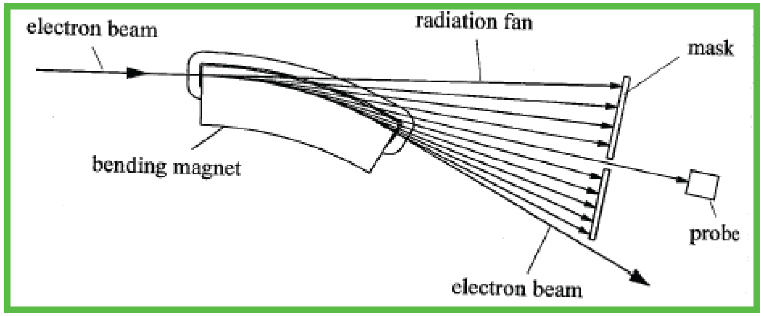


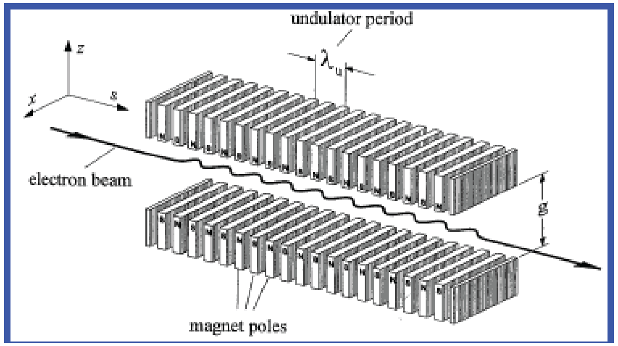
Brazilian Synchrotron

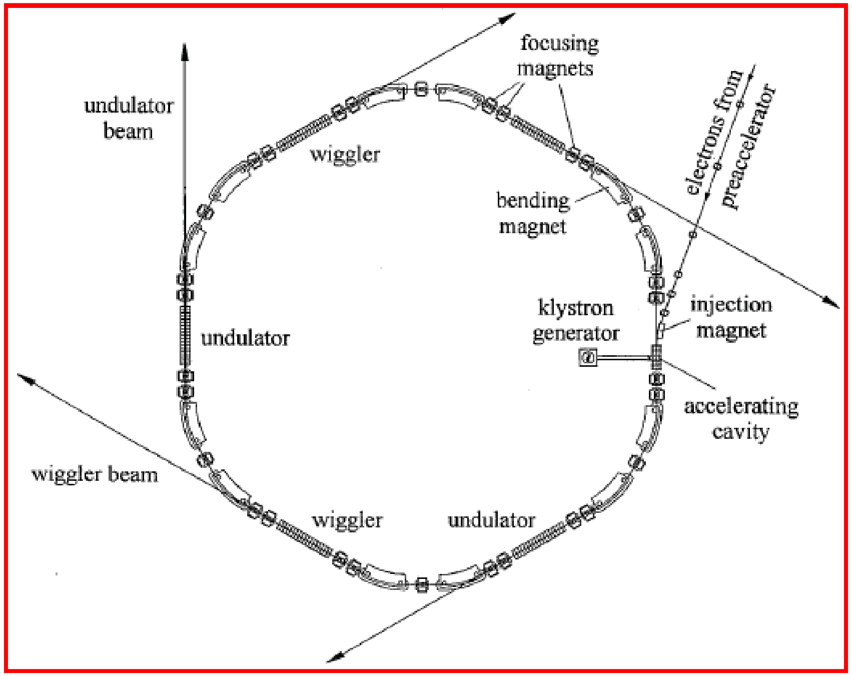
Australia light source (Australia)

Evaluation of Light Sources

- 1st Generation (1970s): Many HEP rings are parasitically used for X-ray production
- 2nd Generation (1980s): Many dedicated X-ray sources (light sources)
- 3rd Generation (1990s): Several rings with dedicated radiation devices (wigglers and undulators)
- 4th Generation (Present): Free Electron Lasers (FELs) driven by linear accelerators

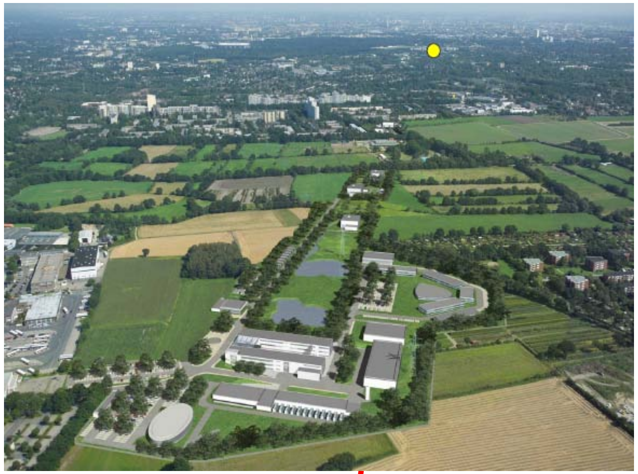




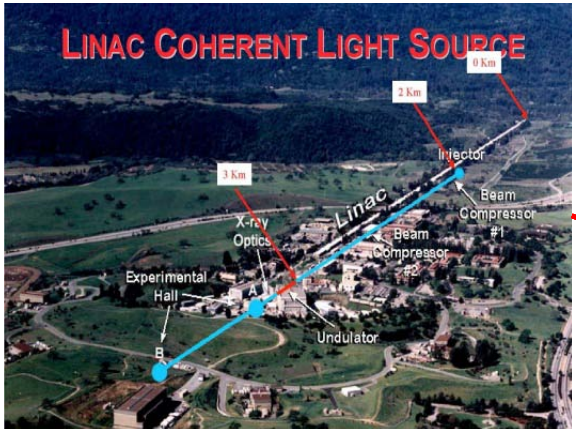


K. Wille, *The Physics of Particle Accelerators: An Introduction*, Oxford University Press, 2000.

4th Generation Light Sources (XFELs)



- European XFEL. Germany ($\lambda\sim$ 0.1-1.6 nm)
- FLASH @ DESY, Germany ($\lambda\sim$0.1-7 nm)
- SPARC, Italy ($\lambda\sim$ 0.6-40 nm)
- FERMI @ Elettra, Italy ($\lambda\sim$ 10-100 nm)
- SwissFEL, Switzerland (λ ~0.1-7 nm)



- LCLS FEL @ SLAC, USA ($\lambda\sim$ 0.15-1.5 nm)
- HGHG FEL @ NSLS, BNL, USA ($\lambda\sim$193 nm)

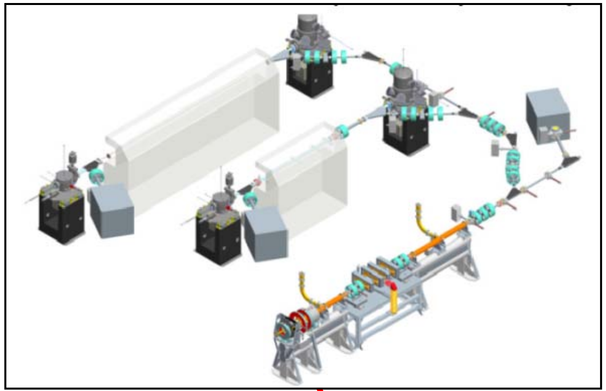
- SACLA XFEL @ Spring-8, Japan (λ > 0.1 nm)
- Shanghai FEL
- Pohang XFEL

Photocathode RF guns
(SACLA XFEL uses DC gun)

RF Electron Gun
S. Rimjaem

4th Generation Light Sources (IR-FELs)

Fritz Haber Institute THz FEL
Max Planck Institute
Berlin, Germany



ELBE @ HZDR
Germany

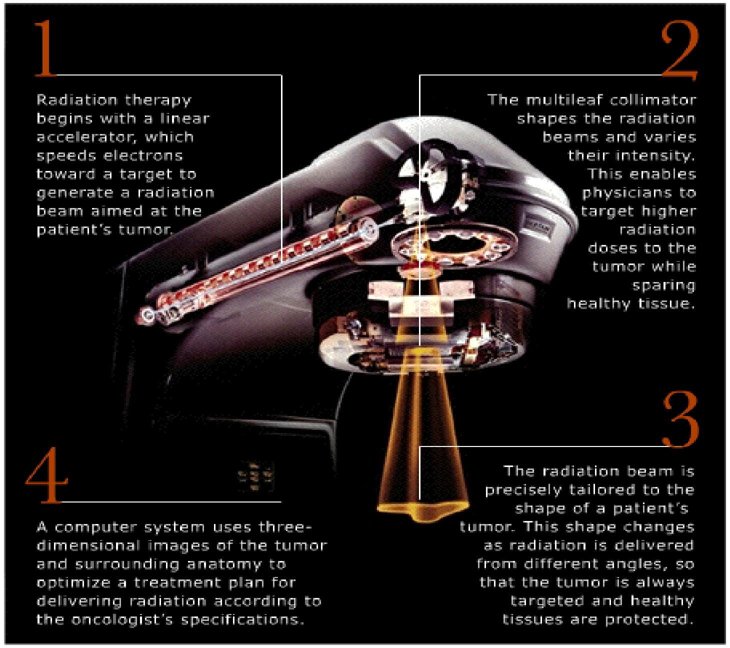
UCSB FEL, Santa Barbara, USA

KU-FEL, Kyoto University, Japan

Thermionic DC guns
Thermionic RF guns
Photocathode RF guns

Compact Linacs: e.g. Medical Linacs

Thermionic DC guns



1 Radiation therapy begins with a linear accelerator, which speeds electrons toward a target to generate a radiation beam aimed at the patient's tumor.

2 The multileaf collimator shapes the radiation beams and varies their intensity. This enables physicians to target higher radiation doses to the tumor while sparing healthy tissue.

3 The radiation beam is precisely tailored to the shape of a patient's tumor. This shape changes as radiation is delivered from different angles, so that the tumor is always targeted and healthy tissues are protected.

4 A computer system uses three-dimensional images of the tumor and surrounding anatomy to optimize a treatment plan for delivering radiation according to the oncologist's specifications.

- A modern system for treating a patient with x-rays produced by a high energy electron beam.
- The whole device is mounted on a gantry. As the gantry is rotated, so is the accelerator and the resulting x-rays.
- Then the radiation can be delivered to the tumor from all directions with precise control for positioning.

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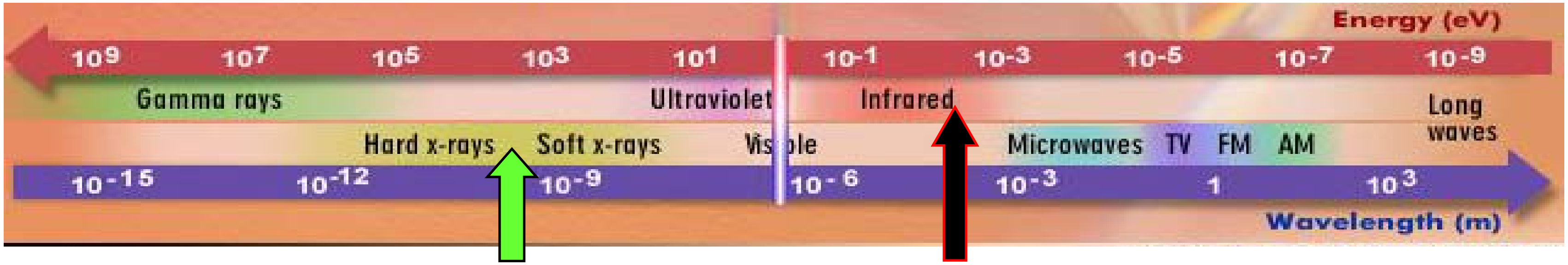
Applications of Ultra Short Electron Bunches

Direct Applications:

- Ultrafast time-resolved electron diffraction for studying dynamic of chemical reaction (A. Zeweil Noble Price Winner 2002)
- Ultrafast electron pulse radiolysis (K. Ka et al., Rev. of Sci. Instr., 2012)

Production of short (femtosecond) photon pulses:



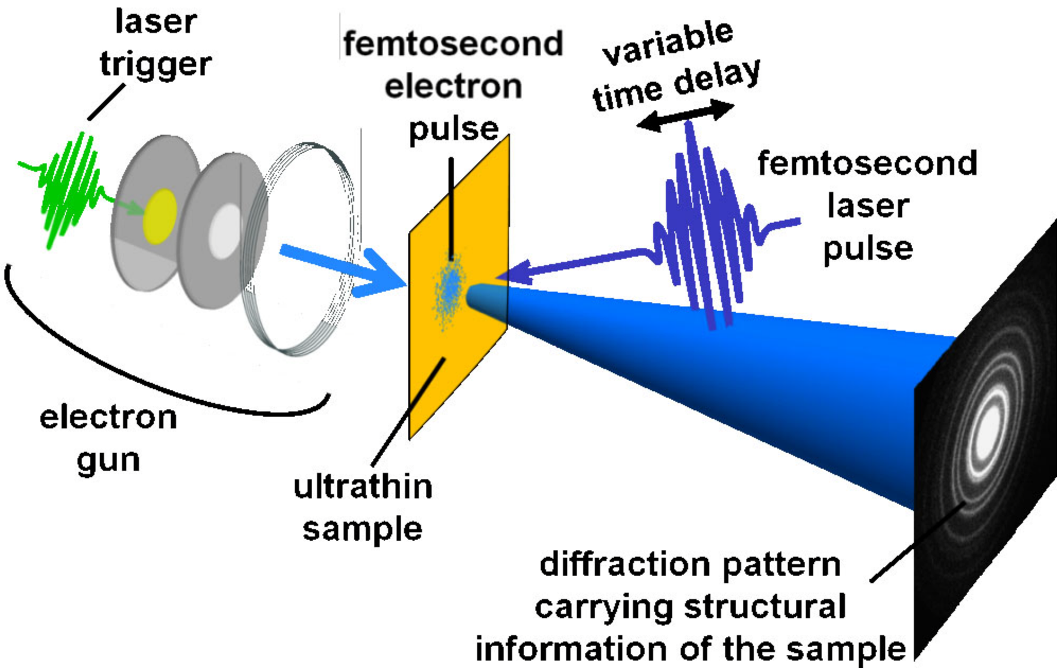
Femtosecond X-ray pulses for dynamic study at atomic scale

Intense far-infrared/THz radiation at frequencies of 100 GHz - 10 THz (λ: 3 – 0.03 mm) via, e.g.,
- Transition radiation
- Undulator radiation
- Free-electron lasers (FELs)

Direct Applications (1)

Examples: Photocathode RF guns

- Ultrafast time-resolved electron diffraction for studying dynamic of chemical reaction

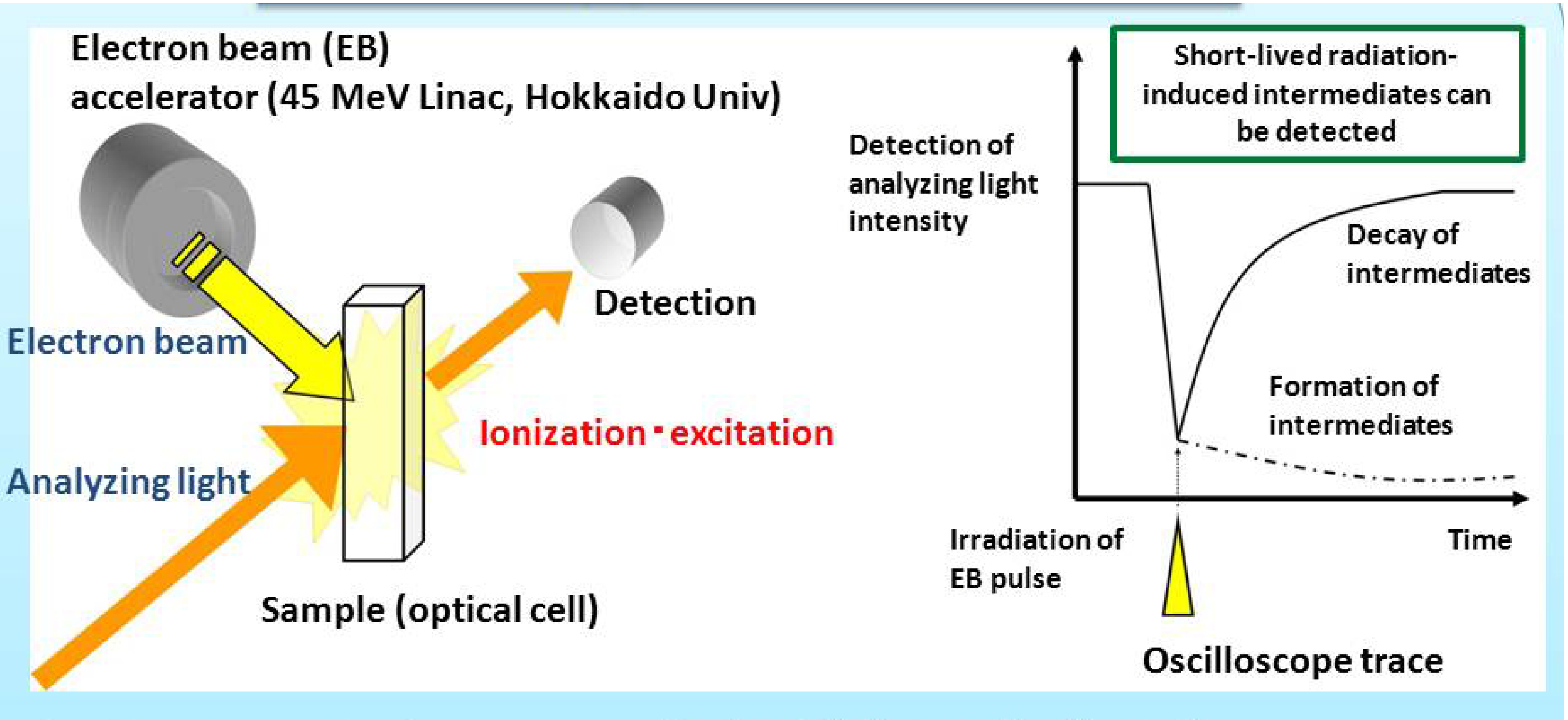


http://www.fhi-berlin.mpg.de/pc/PCres_methods.html

Direct Applications (2)

Examples:

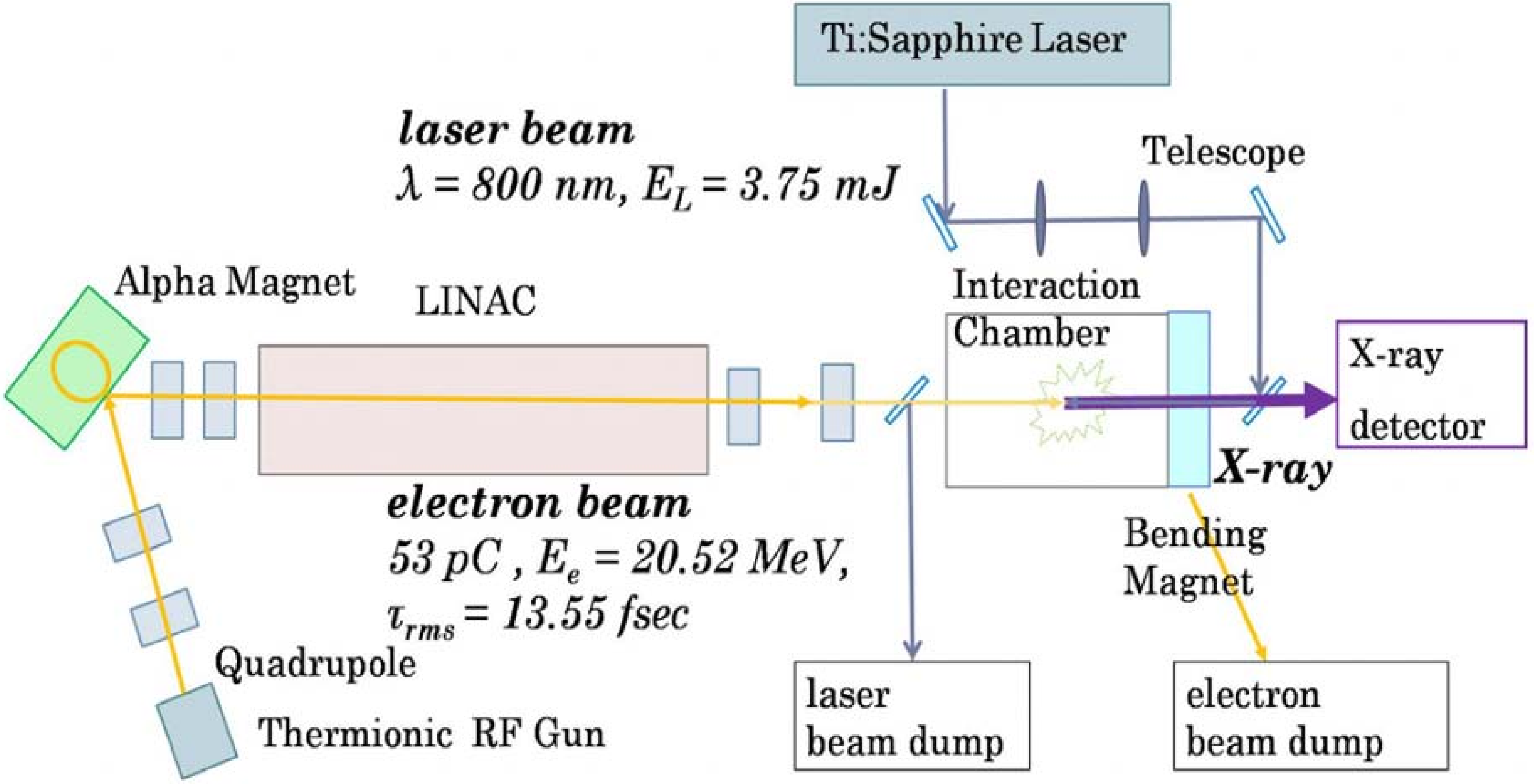
- Ultrafast electron pulse radiolysis



http://labs.eng.hokudai.ac.jp/labo/qsre/field/summary/semiconductor/

Production of Femtosecond X-ray pulses (1)

Examples: Head-on Inverse Compton scattering (ICS)

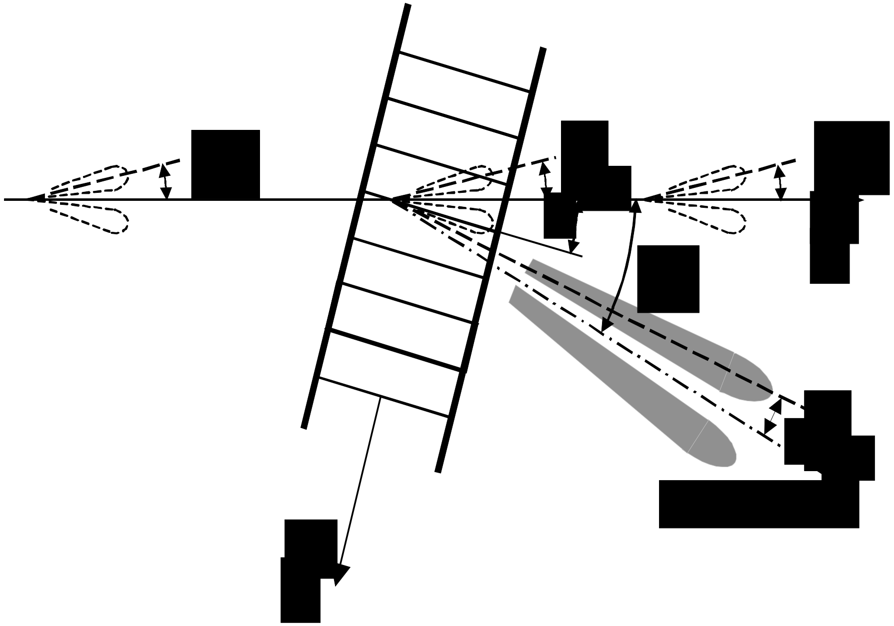


N.Y. Huang et al., Proceedings of PAC09, Vancouver, BC, Canada

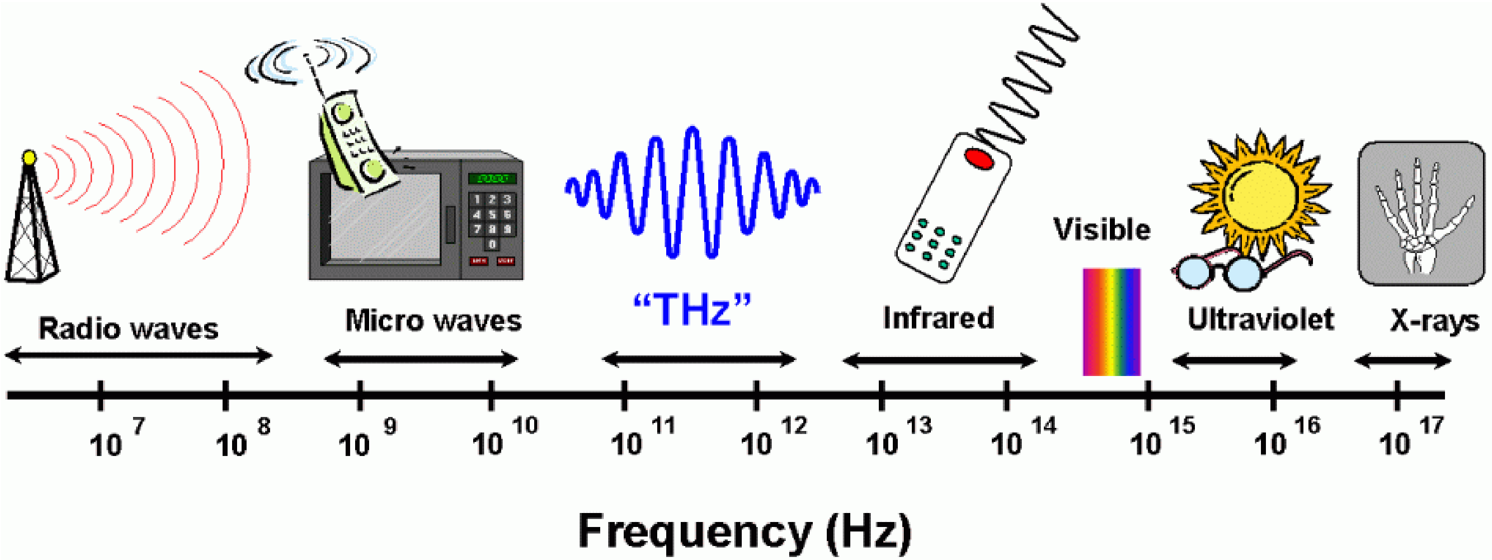
Production of Femtosecond X-ray pulses (2)

Examples: Parametric X-rays

PXR as diffraction of virtual photons associated with relativistic charged particles



THz Radiation (or THz waves)



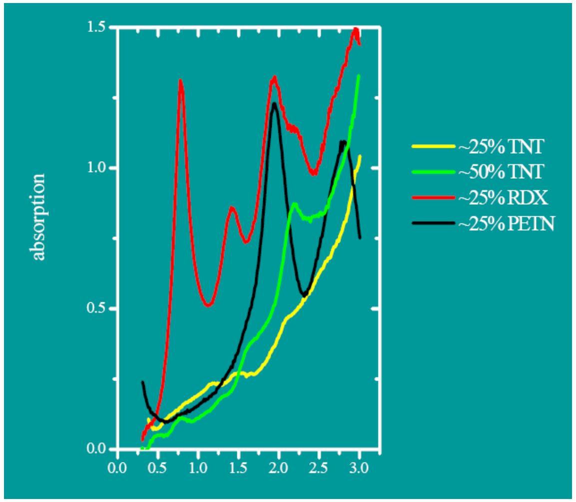
(http://www.sp.phy.cam.ac.uk/SPWeb/research/thzcamera/WhatIsTHzImaging.htm)

- gap between Microwaves and Infrared
- frequency from 100 GHz to 10 THz
- wave length from 30 mm – 0.3 cm
- In last 10-15 years, this area is unexplored region
  - lack of source and applications
- Now, THz technology is growing rapidly.

THz vs. Matters

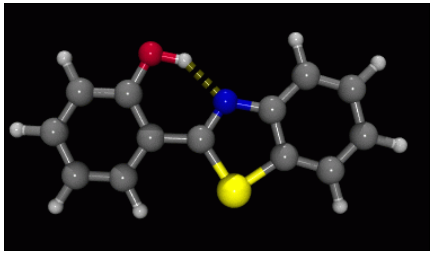
- Penetrate non-conducting material -
  e.g. clothes, wood, plastic, ceramic, paper

- Blocked by metals, water



- Chemical sensitive
  'finger print' absorption spectra

- Corresponds to intermolecular vibration and rotation



Weak hydrogen bond

THz Imaging : Advantages

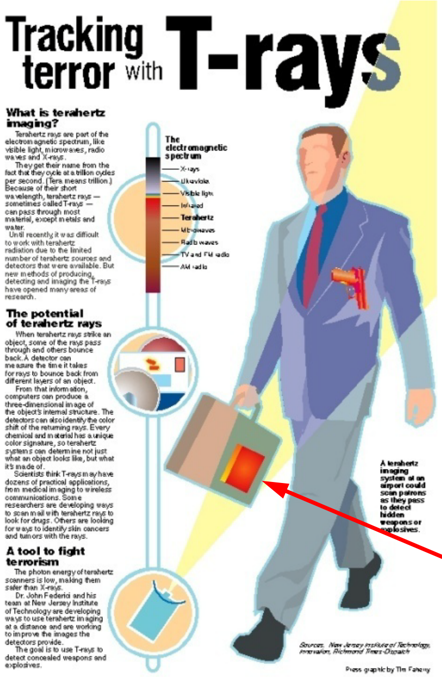
- **Safer**: low photon energies
- **Signature**: specific fingerprinting
- **More selective in soft materials**

e.g.,

- Security screening of hidden weapons or explosives
- Narcotics smuggling, suspicious packages
- Food quality control in frozen product
- Agriculture water-content check
- Medical diagnostic for cancerous cell
- Semiconductor wafer inspection

THz Imaging Applications (1)

Defense applications



Tracking terror with T-rays

What is terahertz imaging?

Terahertz rays are part of the electromagnetic spectrum, like visible light, microwaves, radio waves and X-rays.

They get their name from the fact that they cycle at a trillion cycles per second. (Tera means trillion.) Because of their short wavelength, terahertz rays — sometimes called T-rays — can pass through most material, except metals and water.

Until recently it was difficult to work with terahertz radiation due to the limited number of terahertz sources and detectors that were available. But new methods of producing, detecting and imaging the T-rays have opened many areas of research.

The potential of terahertz rays

When terahertz rays strike an object, some of the rays pass through and others bounce back. A detector can measure the time it takes for rays to bounce back from different layers of an object.

From that information, computers can produce a three-dimensional image of the object's internal structure. The detectors can also identify the color shift of the returning rays. Every chemical and material has a unique color signature, so terahertz systems can determine not just what an object looks like, but what it's made of.

Scientists think T-rays may have dozens of practical applications, from medical imaging to wireless communications. Some researchers are developing ways to scan mail with terahertz rays to look for drugs. Others are looking for ways to identify skin cancers and tumors with the rays.

A tool to fight terrorism

The photon energy of terahertz scanners is low, making them safer than X-rays.

Dr. John Federici and his team at New Jersey Institute of Technology are developing ways to use terahertz imaging at a distance and are working to improve the images the detectors provide.

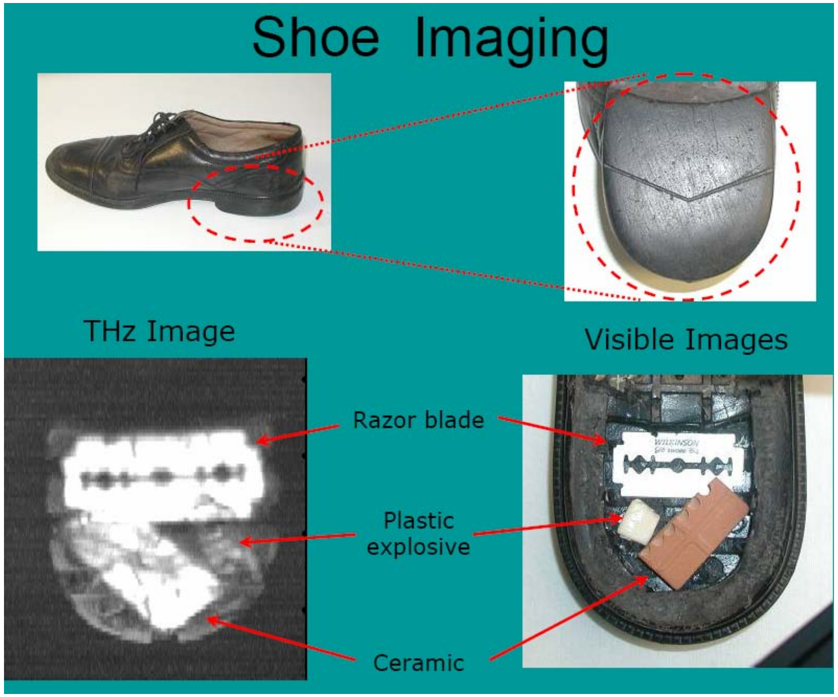
The goal is to use T-rays to detect concealed weapons and explosives.

A terahertz imaging system at an airport could scan patrons as they pass to detect hidden weapons or explosives.

Sources: New Jersey Institute of Technology, Innovation, Richmond Times-Dispatch

Press graphic by Tim Fahey

Standoff distance detection of weapon and explosives



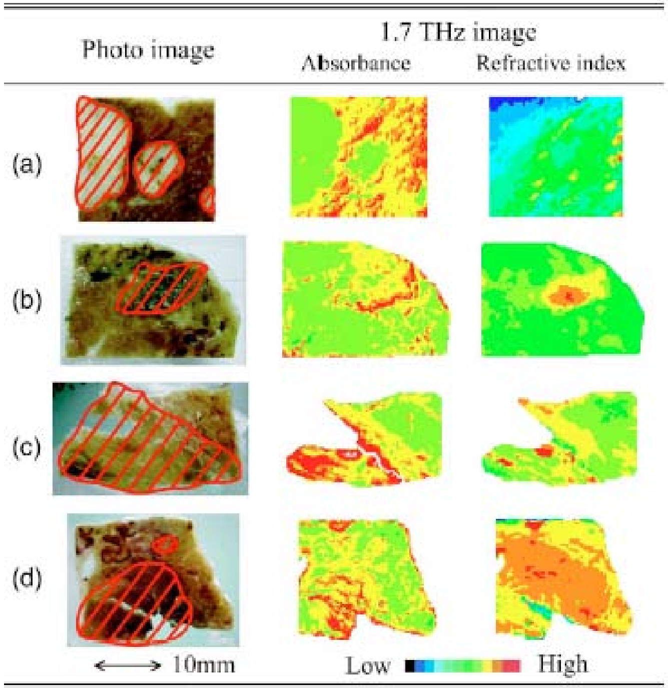
(http://www.thznetwork.org/wordpress/index.php/thz-images)

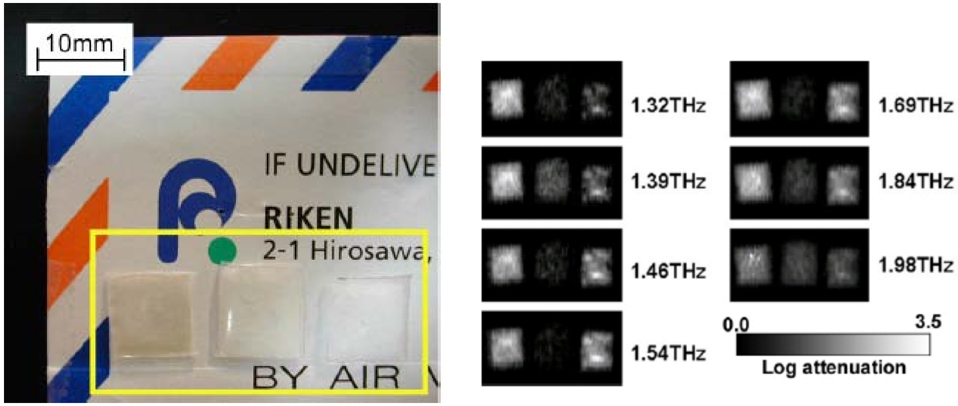
THz Imaging Applications (2)

Medical applications

THz imaging diagnostic of cancer tissues

Nakagima et al. [Appl. Phy Let. 90 041102(2007)]





(http://www.thznetwork.org/wordpress/index.php/thz-images)

Inspection

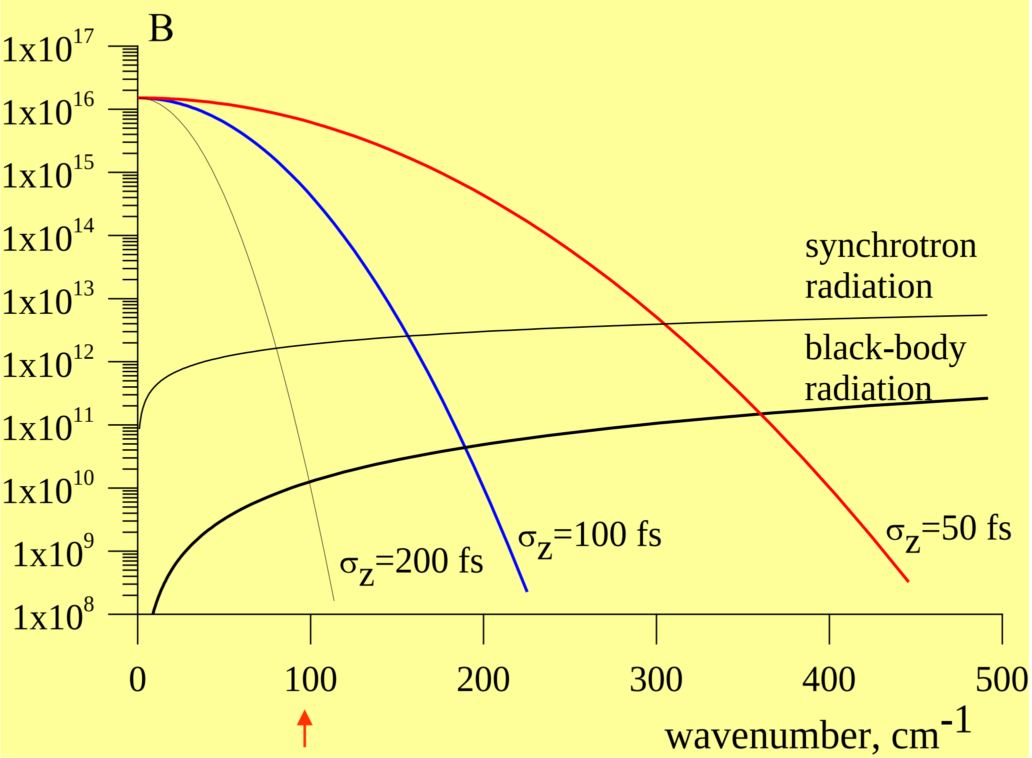
Non-destructive THz imaging of drugs in an envelop

Kodo Kawase et al (RIKEN, Japan)

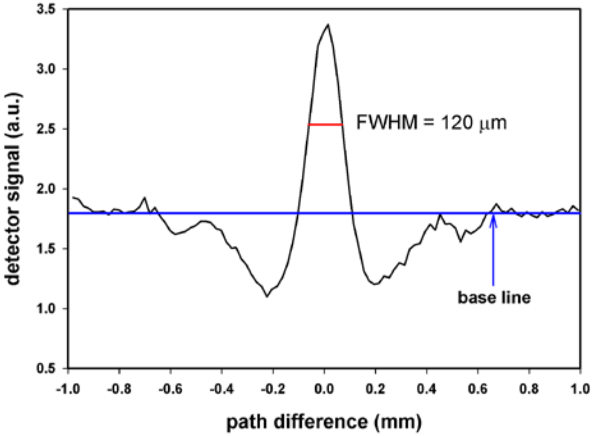
How to Produce Intense THz Radiation

Fourier transform of the short electron bunch provides broad radiation spectrum

$$\left|\tilde{E}_0(\omega)\right|^2 = \tilde{E}_0(\omega)\tilde{E}_0^*(\omega)\alpha\int_{-\alpha}^{+\alpha} I_0(\delta)e^{i\omega\delta/c}d\delta = FT\{I_0(\delta)\}$$



3 THz

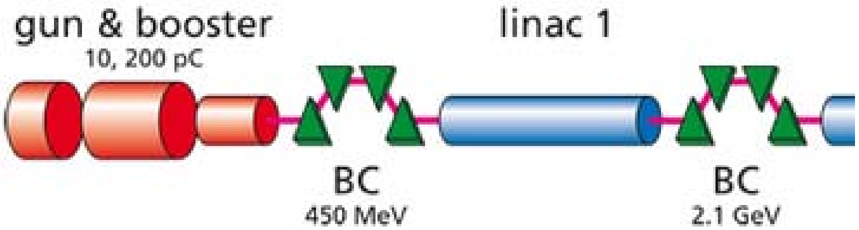


Calculated radiation brightness B(ph/s/mm^2/100%BW) vs. wave number for CTR, SR and black body radiation.

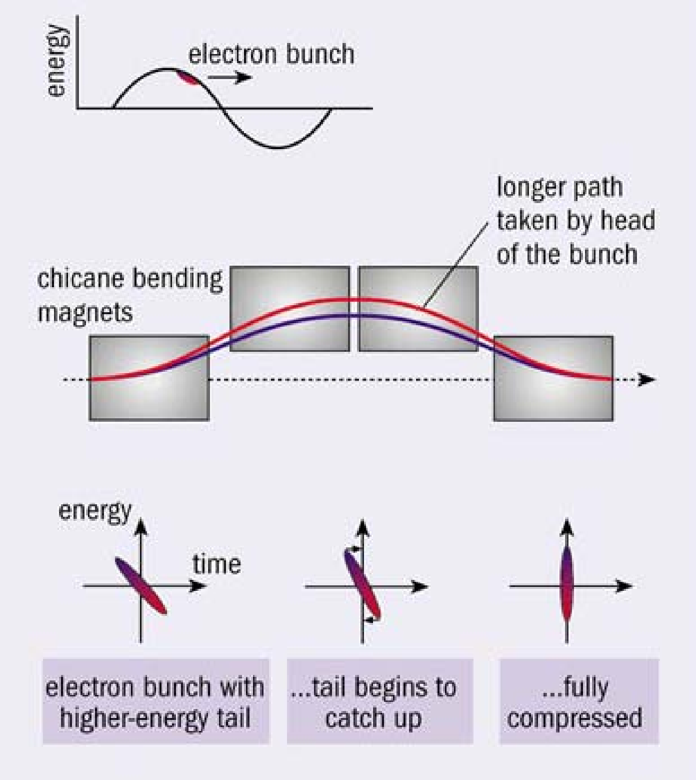
Generation of Short Electron Bunches (1)

Short electron bunches in the order of femtosecond scale can be generated by using an **RF gun** and a **magnetic bunch compressor**.

- ➢ High energy electron bunches with inversely linear correlation between energy-time distribution are normally compressed with **chicane**.



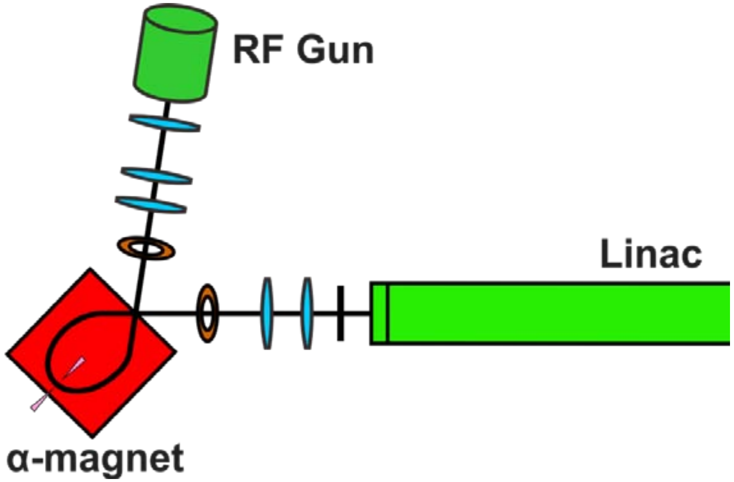
http:// www.psi.ch/swissfel/swissfel-accelerator



http://cerncourier.com/cws/article/cern/28925

Generation of Short Electron Bunches (2)

- Low energy electron bunches with linear correlation between energy-time distribution can be compressed with **α-magnet**.

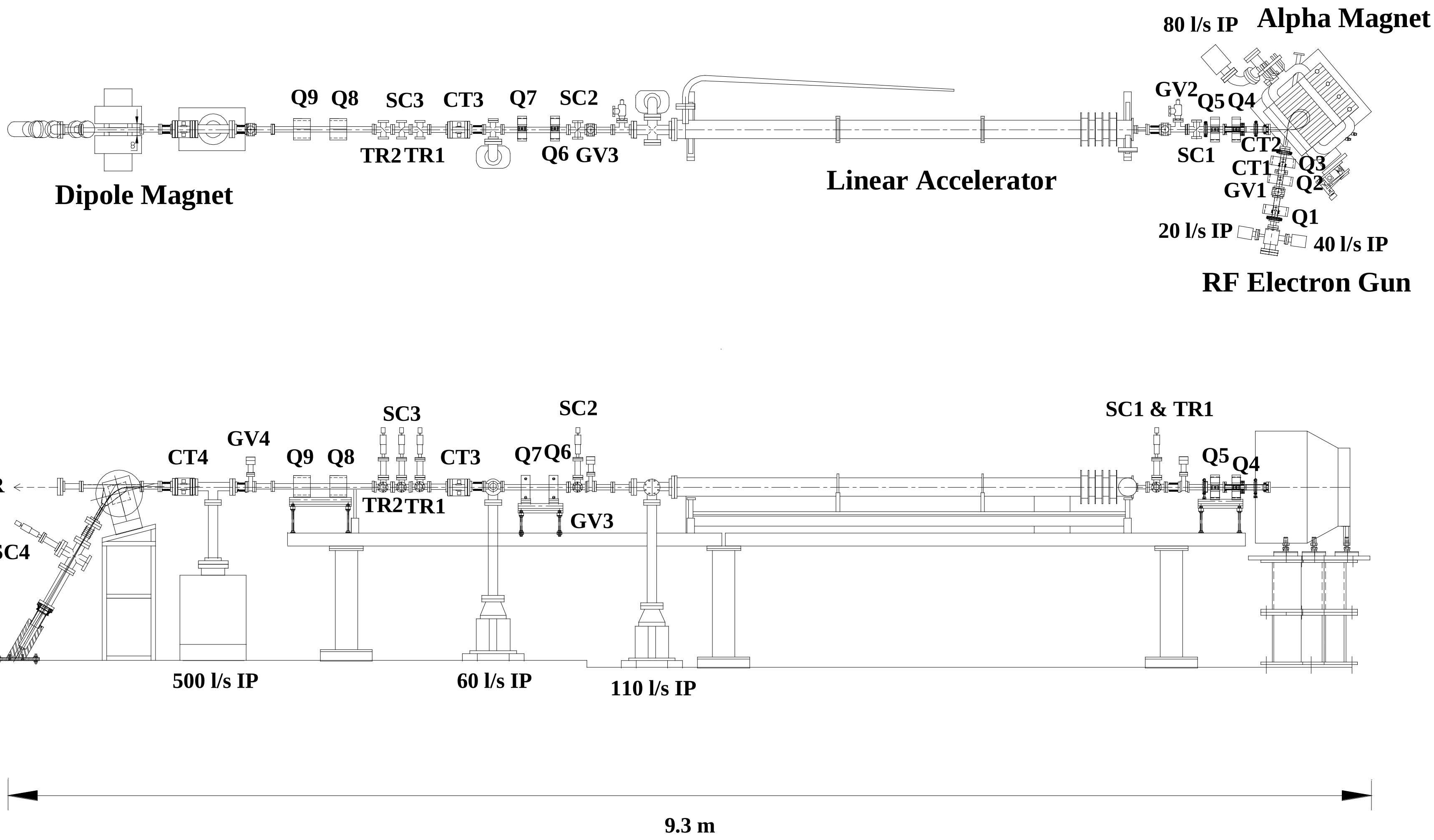


- Electrons with different momenta have different path lengths inside the α-magnet field.
- Energy slits are placed in a magnetic vacuum chamber to select only the core of the beam.

→ Emittance and energy spread are reduced.

→ The peak current is increased.

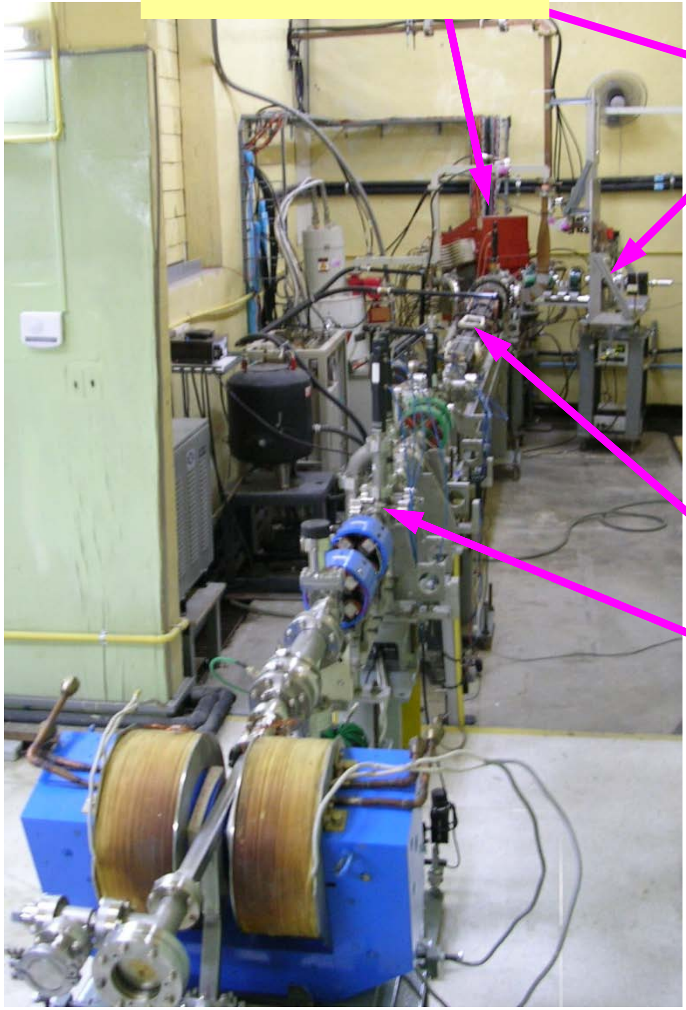
Linac System @ CMU

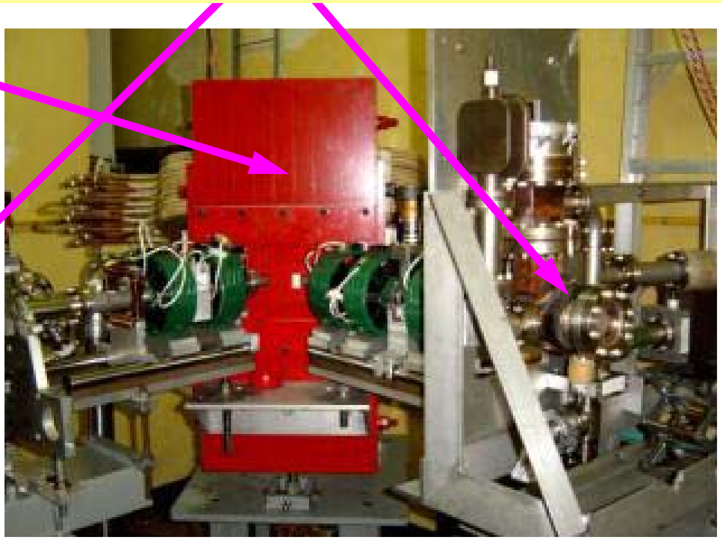


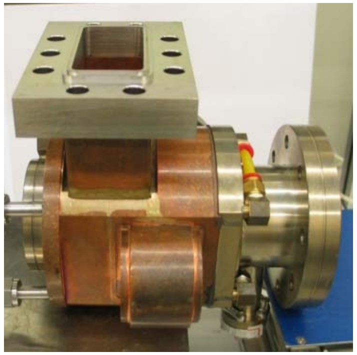
Generation of Short Electron Source at CMU

Alpha magnet
(bunch compressor)

S-band thermionic RF-gun (2-2.5 MeV (30 MV/m @ cathode)

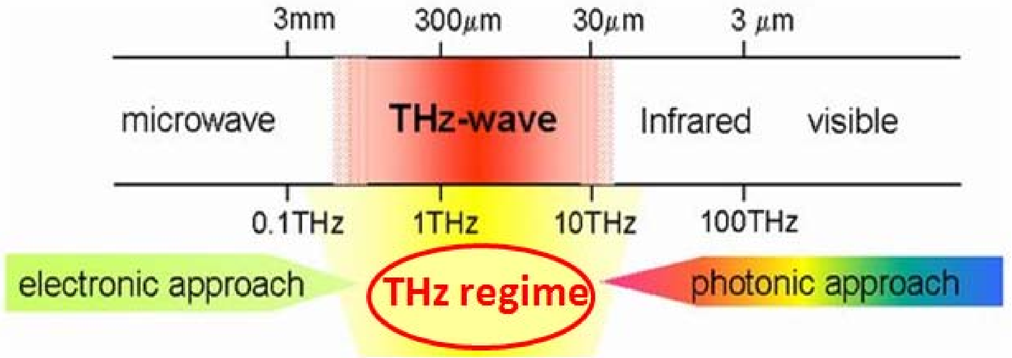




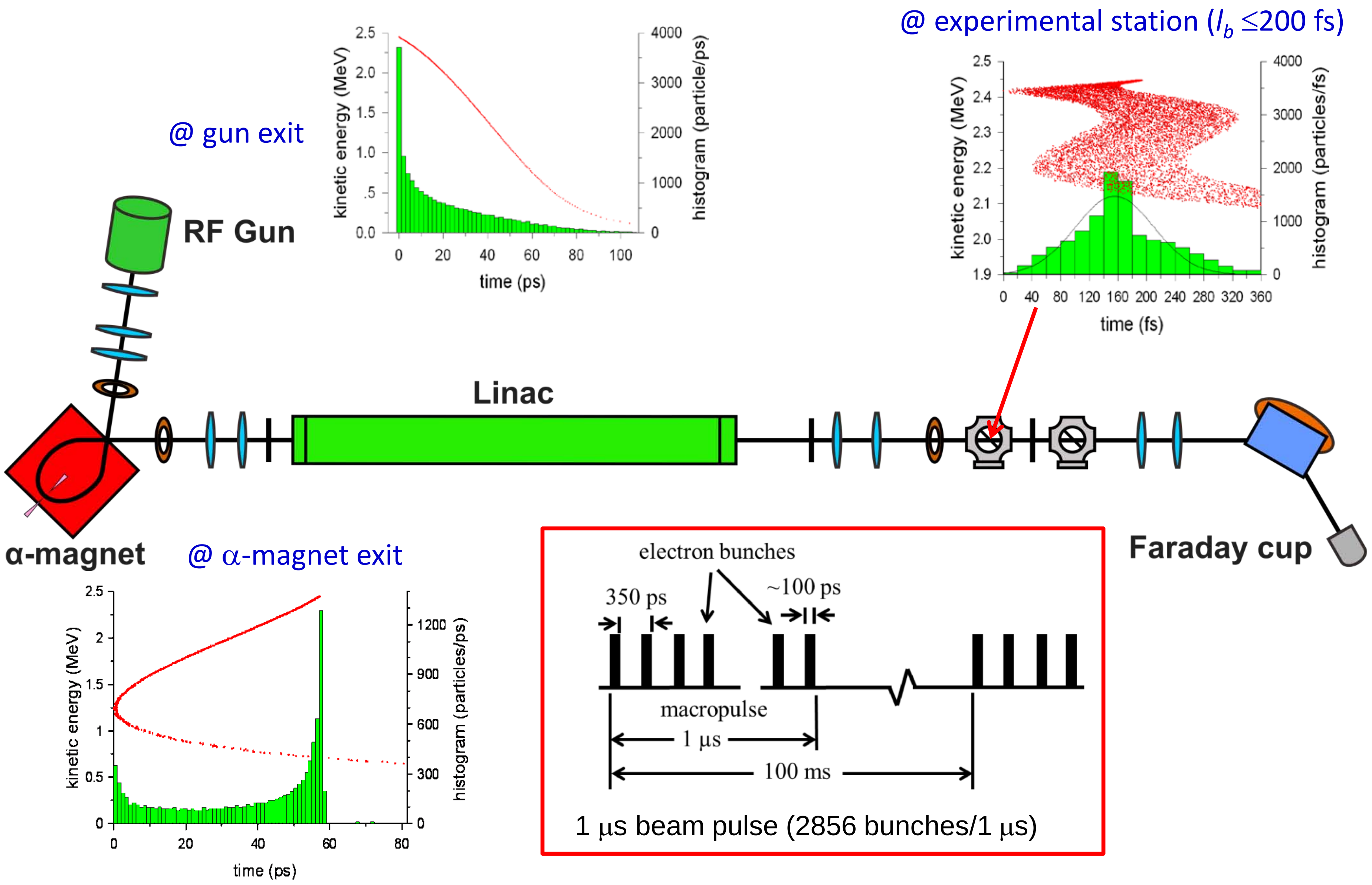


Linac (10-15 MeV (up to 30 MeV with higher RF power)

Transition radiation stations (0.23 nC/bunch, ≤ 200 fs)



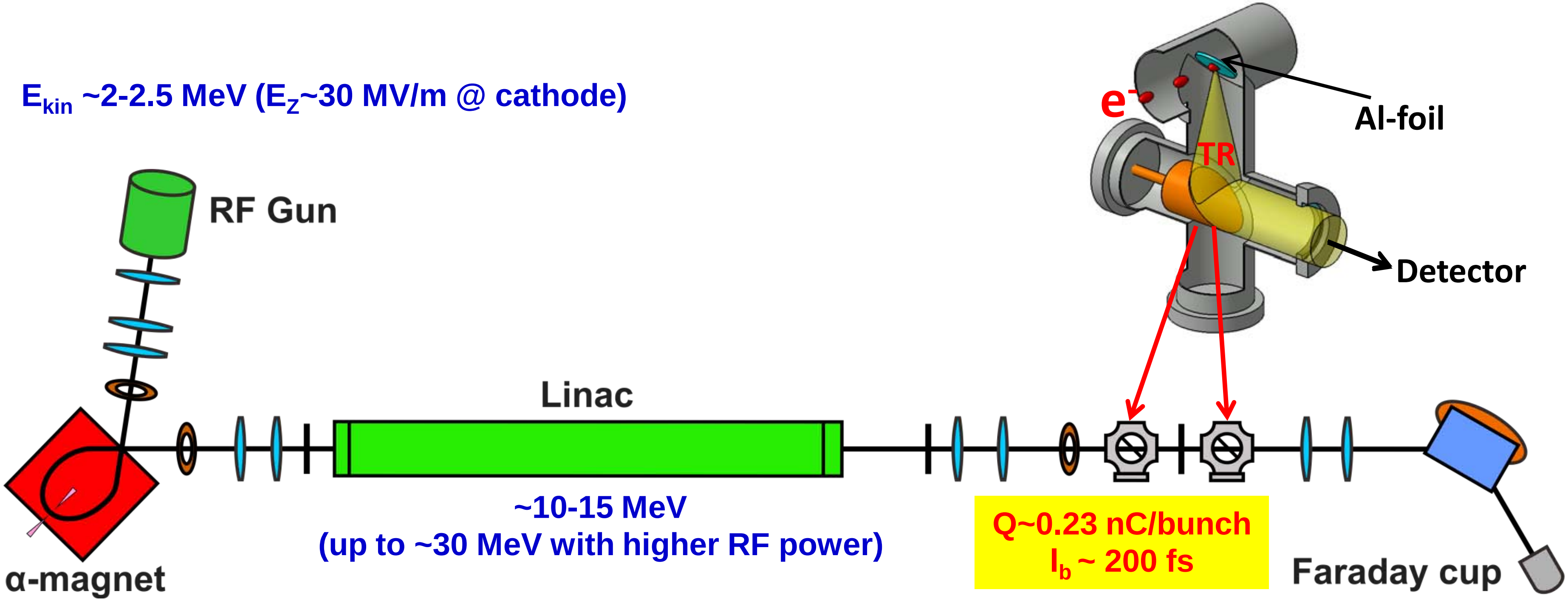
Generation of Short Electron Bunches (3)



1 μs beam pulse (2856 bunches/1 μs)

Generation of Transition Radiation

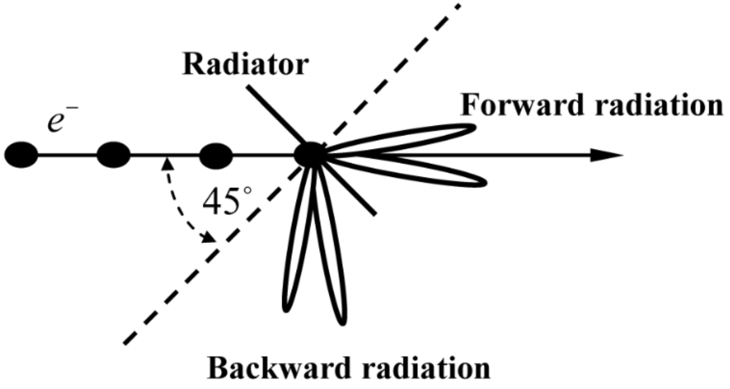
E_{kin} ~2-2.5 MeV (E_Z~30 MV/m @ cathode)



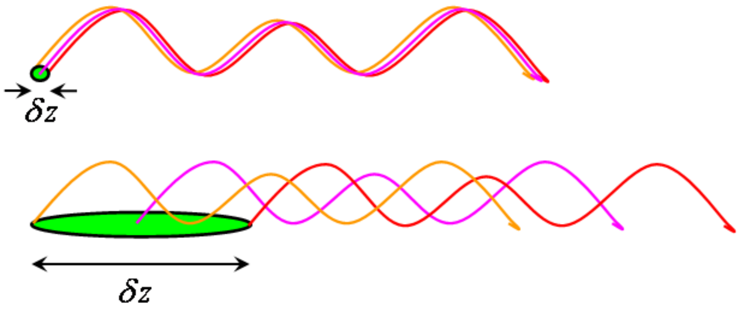
~10-15 MeV
(up to ~30 MeV with higher RF power)

Q~0.23 nC/bunch
l_b ~ 200 fs

~1.8-2.5 MeV, l_b ~ 10-20 ps



Coherent Transition Radiation



At wavelengths about or longer than the bunch length

↓

Radiation field add up coherently

↓

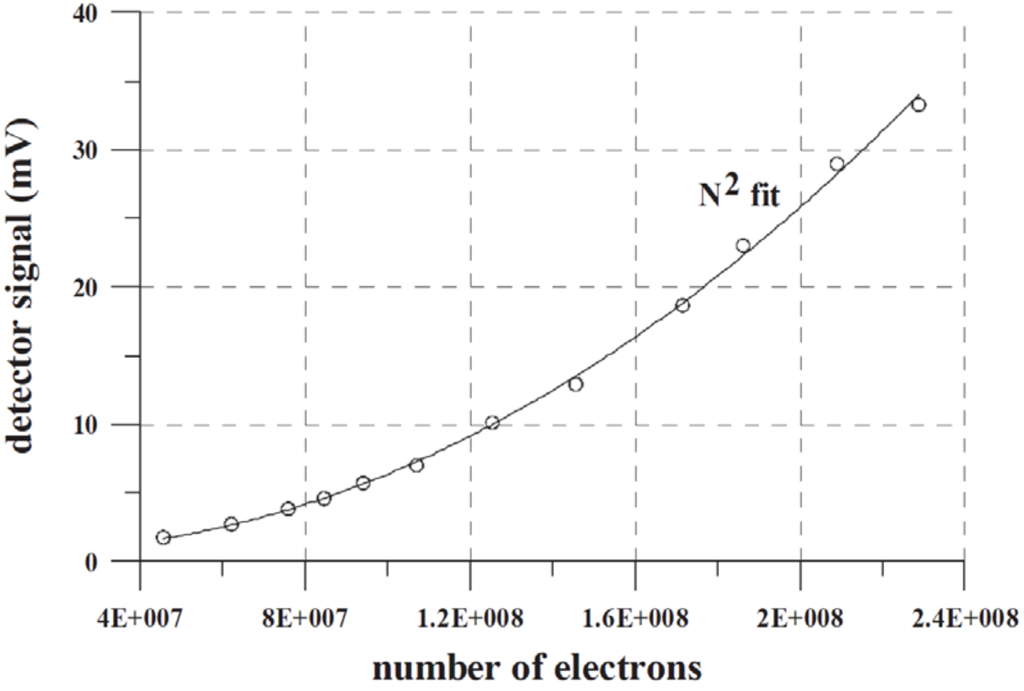
Electron short bunches is desired to produce coherent radiation

↓

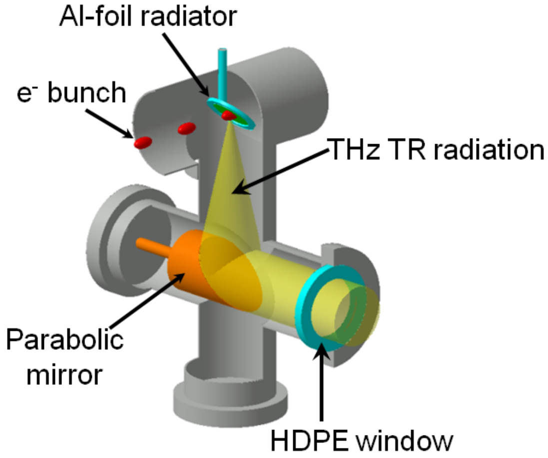
Radiation intensity α N^2

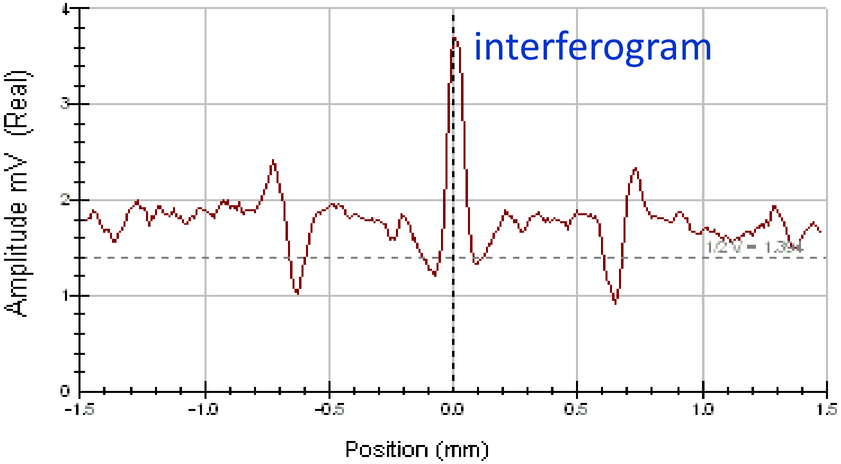
$$\frac{d^2I}{d\omega\, d\Omega} = [\overset{ISR}{N[1-f(\omega)]} + \overset{CSR}{N^2 f(\omega)}]$$

Detector signal of coherent transition radiation intensity vs. number of electrons.

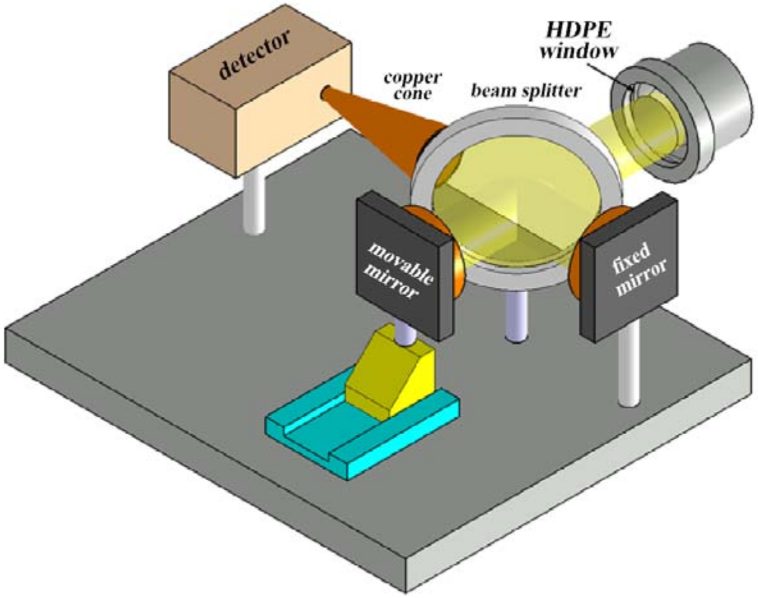


Bunch Length Measurement





Measured electron bunch ~ 200 fs (120 μm)

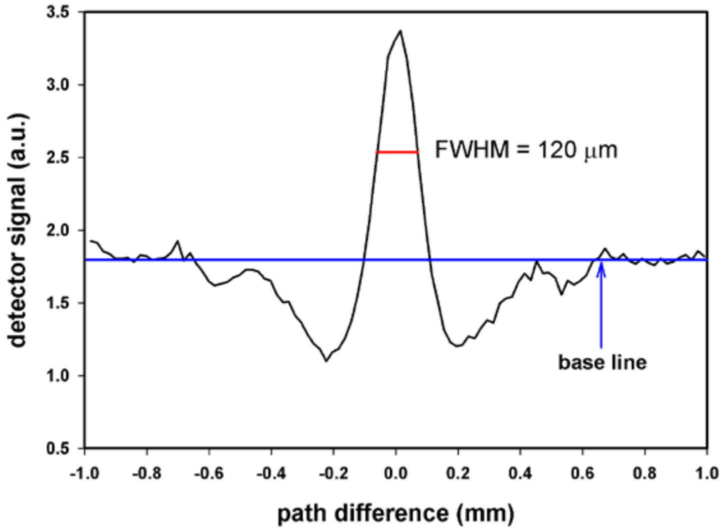


Michelson Interferometer

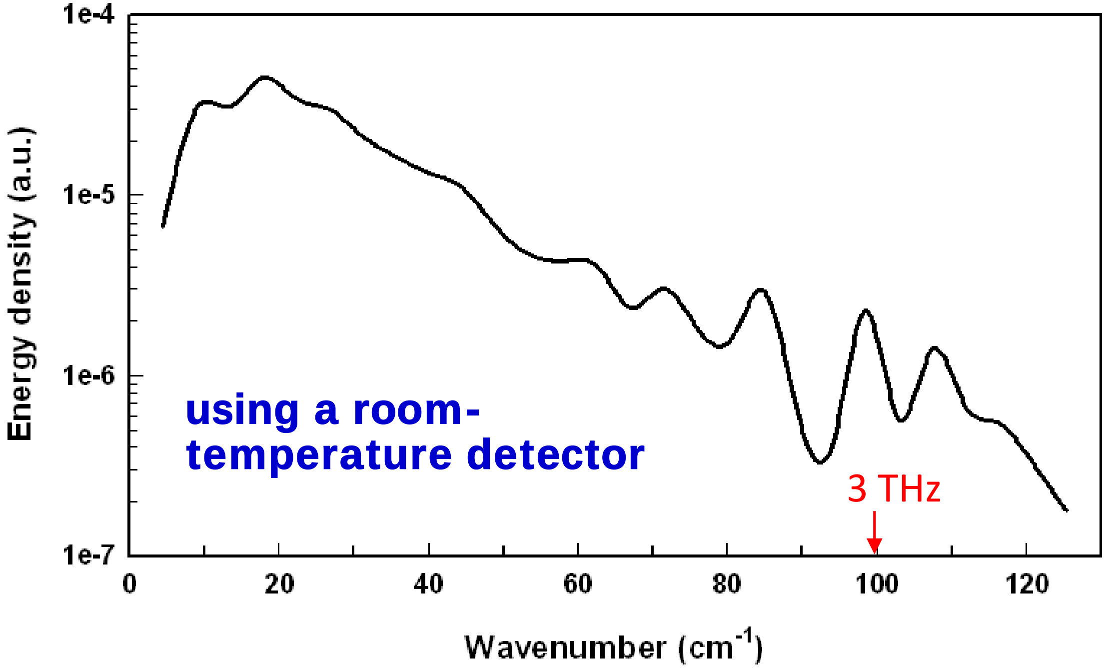
High Brightness THz Radiation with Broad Spectrum

Fourier transform of the short bunch provides broad radiation spectrum

$$\left|\tilde{E}_0(\omega)\right|^2 = \tilde{E}_0(\omega)\tilde{E}_0^*(\omega)\alpha\int_{-\alpha}^{+\alpha} I_0(\delta)e^{i\omega\delta/c}\,d\delta = FT\left\{I_0(\delta)\right\}$$



Measured electron bunch
~ 200 fs (120 μm)

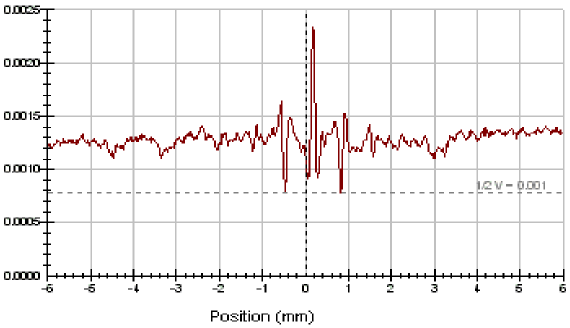


using a room-temperature detector

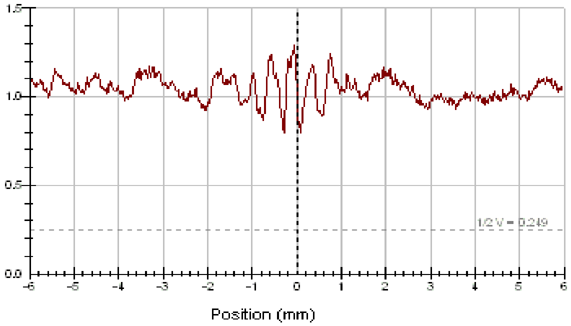
Measured THz radiation covers wave number of 5-80 cm^{-1} (frequency range of 0.3 – 2.4 THz)

Examples of THz Spectroscopy

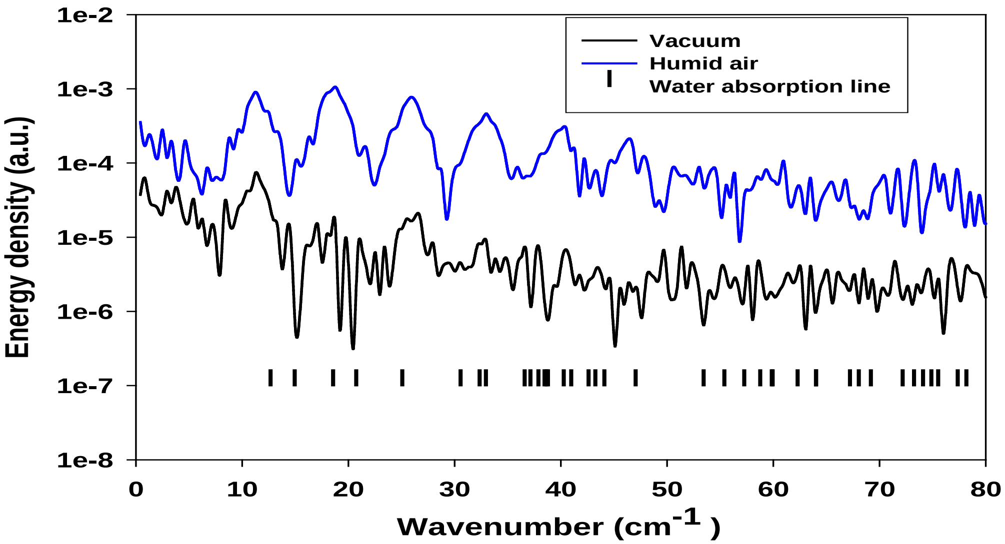
Water vapor spectrum & absorption lines



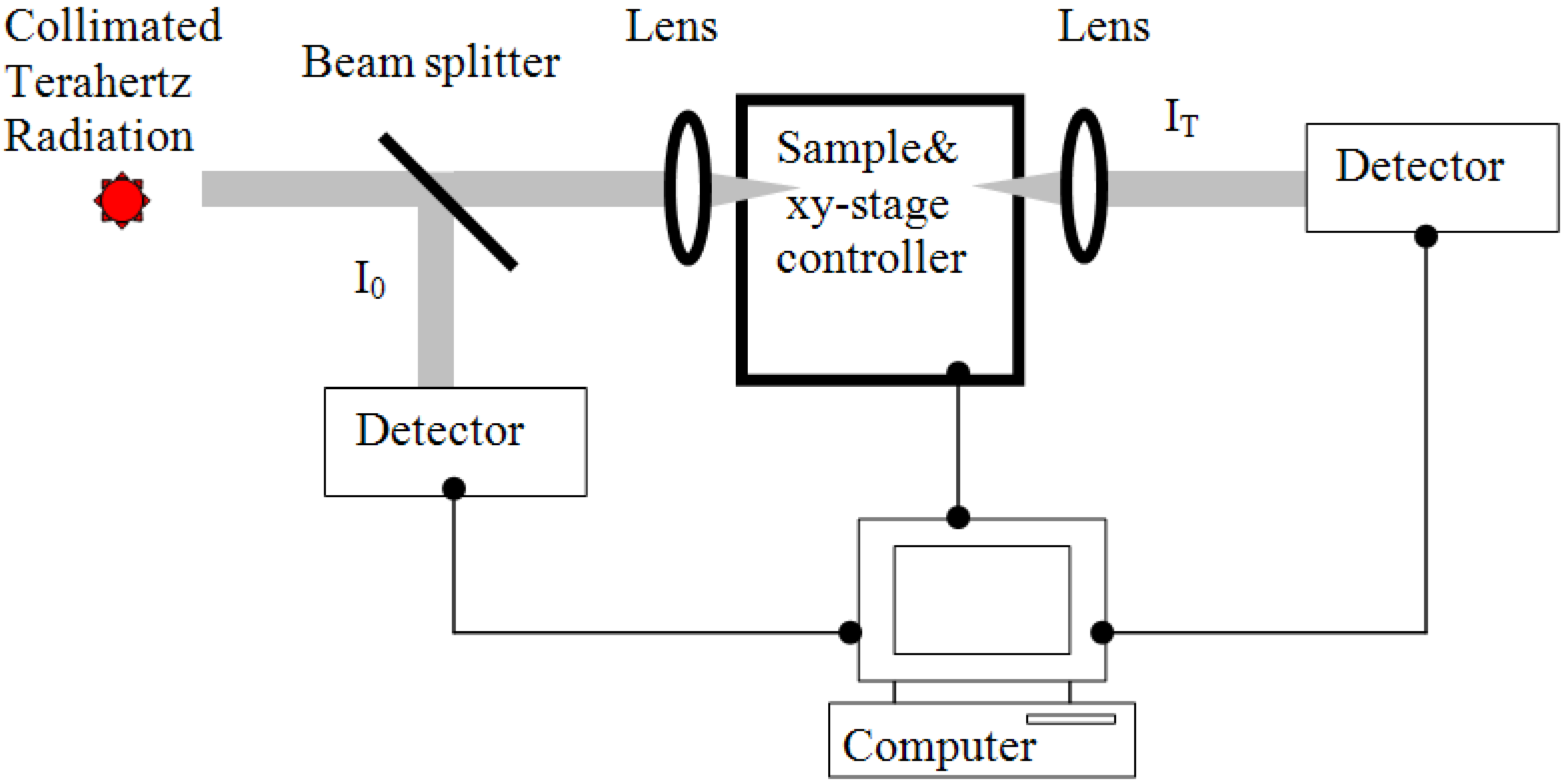
interferogram in vacuum



interferogram in humid air

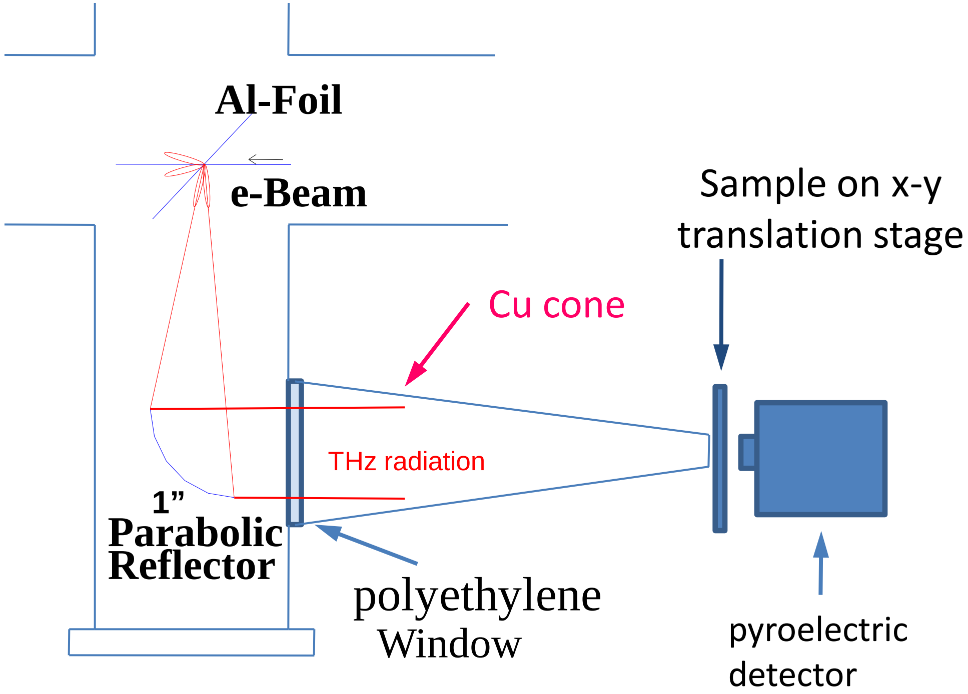


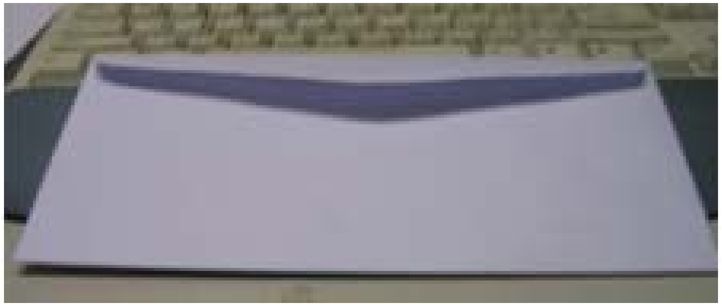
THz Imaging

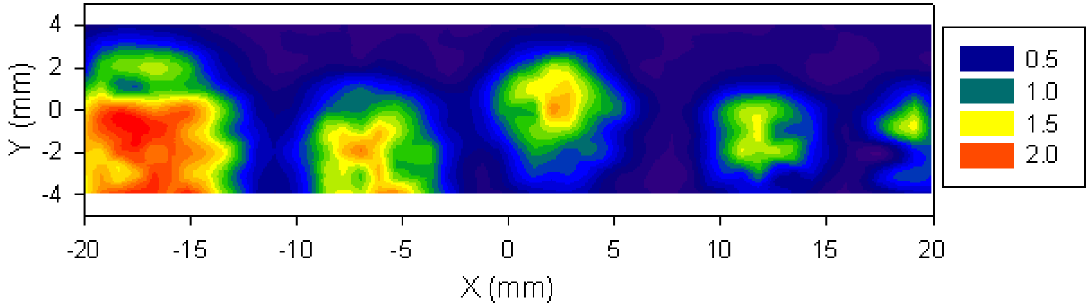


Design of THz imaging system at PBP, Chiang Mai University

THz Imaging of Sample in Envelop



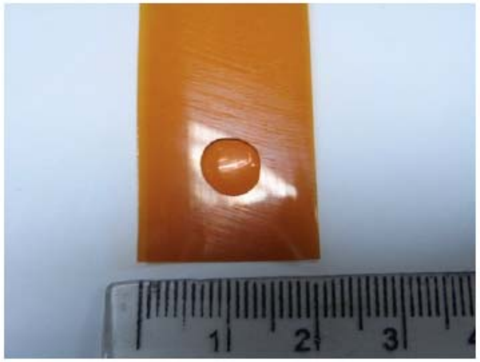


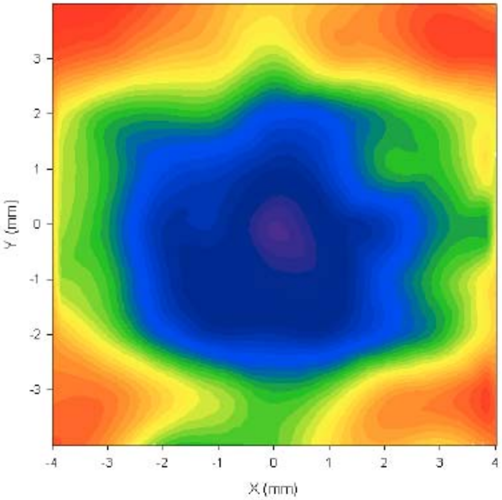


THz image of holes on Al-foil in an envelope

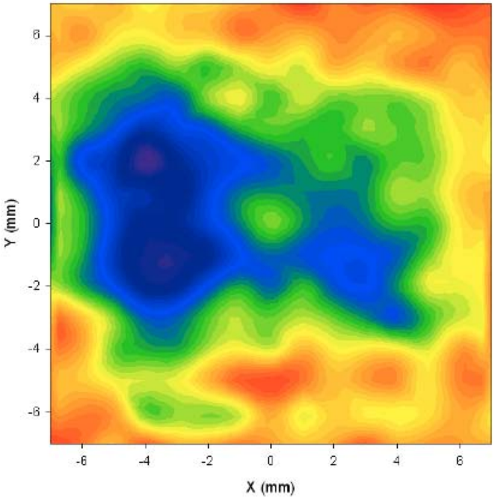
THz Imaging W/O Mesh Filter

Water drop





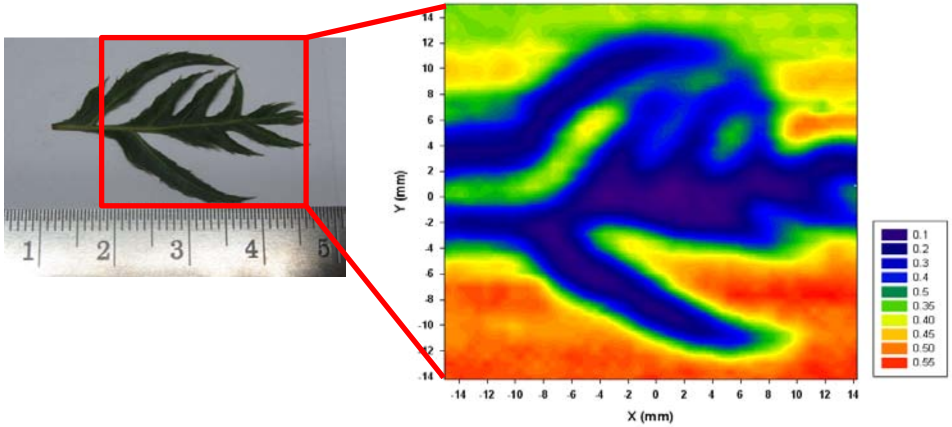
Cooked vs. Un-cooked Rice

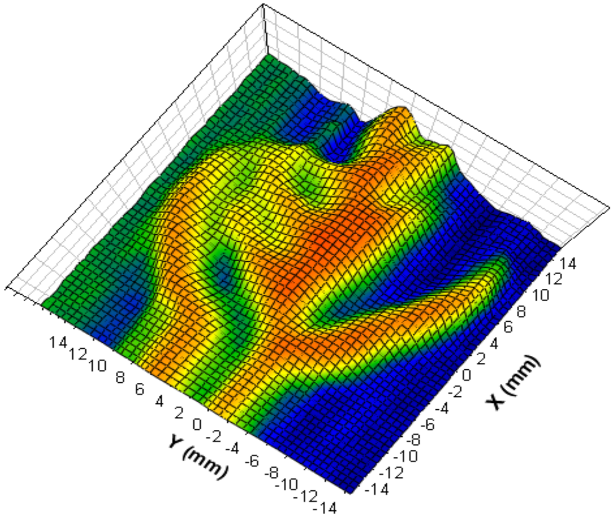


THz Imaging W/ Mesh Filter

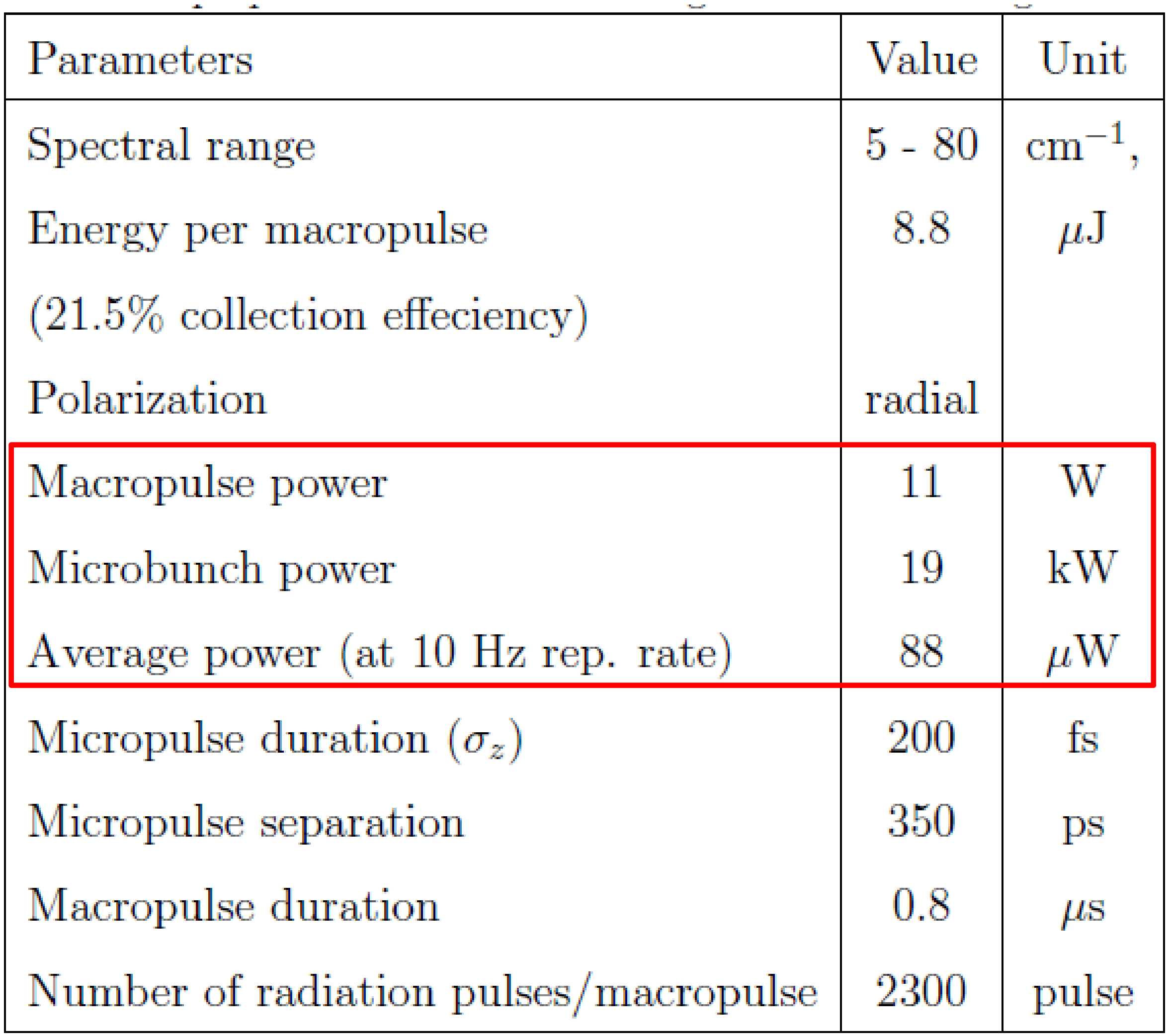
THz image of live leaves (better resolution)

with 180x180 μm copper mesh filter (20–40 cm^{-1} transmission band)





Properties of Coherent THz Radiation @ CMU



Parameters	Value	Unit
Spectral range	5 - 80	cm^{-1},
Energy per macropulse	8.8	μJ
(21.5% collection effeciency)		
Polarization	radial	
Macropulse power	11	W
Microbunch power	19	kW
Average power (at 10 Hz rep. rate)	88	μW
Micropulse duration (σ_z)	200	fs
Micropulse separation	350	ps
Macropulse duration	0.8	μs
Number of radiation pulses/macropulse	2300	pulse

Electron beam parameters	
Resonant frequency	2856 MHz
Beam energy	10 MeV
Electron bunch length	200 fs
Bunch charge	230 pC
Macropulse length	1 μs
Repetition rate	10 Hz

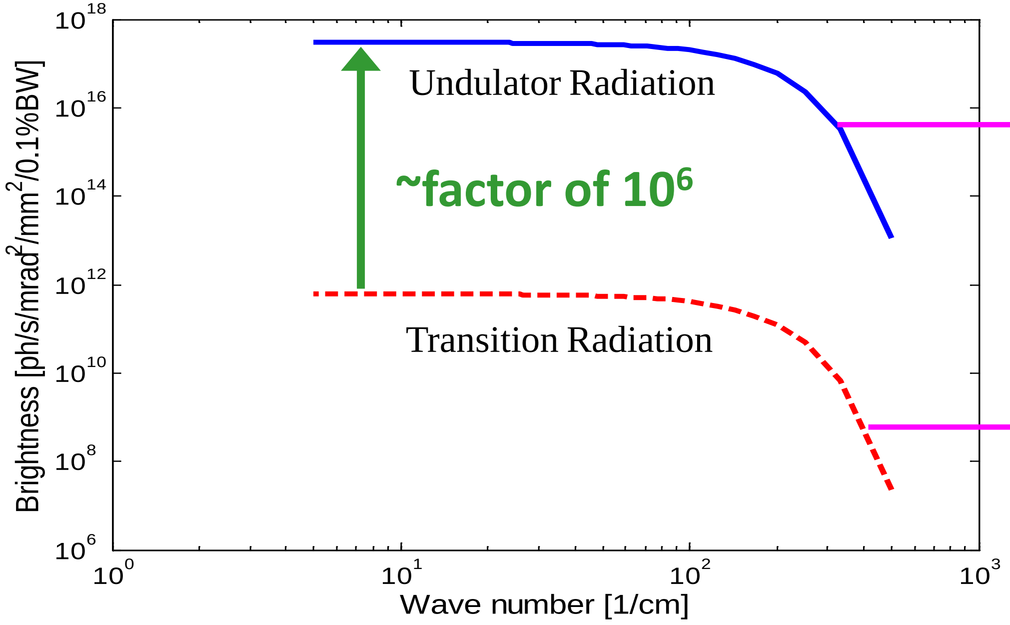
How to obtain brighter radiation?

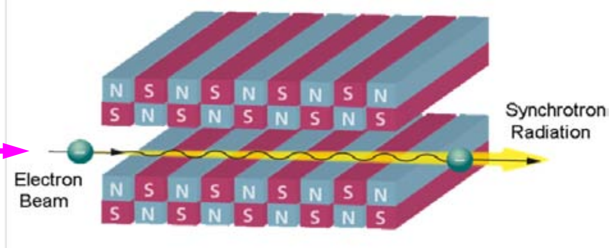
How to obtain brighter radiation?

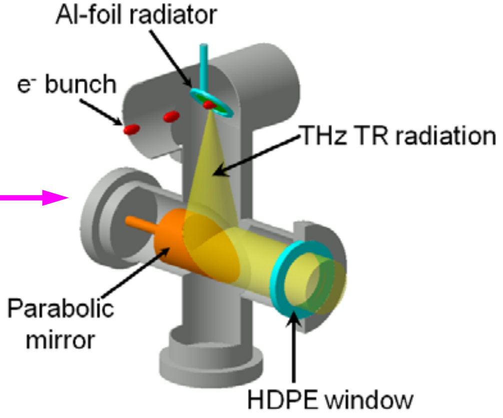
The greater the brightness, the more photons that can be concentrated on a spot.

Improvement of electron beam	
Resonant frequency	2856 MHz
Beam energy	10 MeV
Electron bunch length	**100 fs**
Bunch charge	**~100-200 pC**
Macropulse length	1 μs
Repetition rate	10 Hz

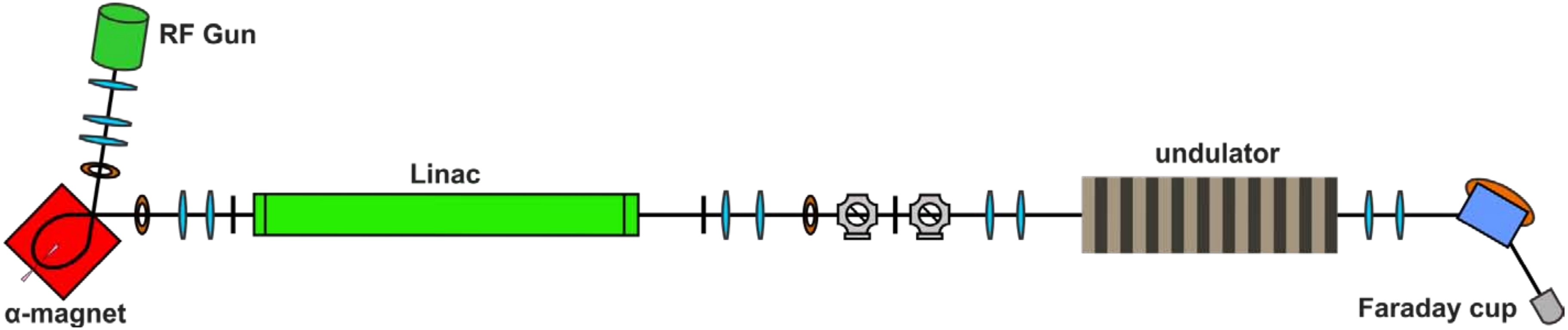
Brightness: number of photons produced per second, angular divergence of photons, cross-sectional area of beam, photons falling within a bandwidth (BW) of 0.1% of central wavelength.







Coherent THz Undulator Radiation @ CMU



Planar Electromagnet Undulator (EMU)

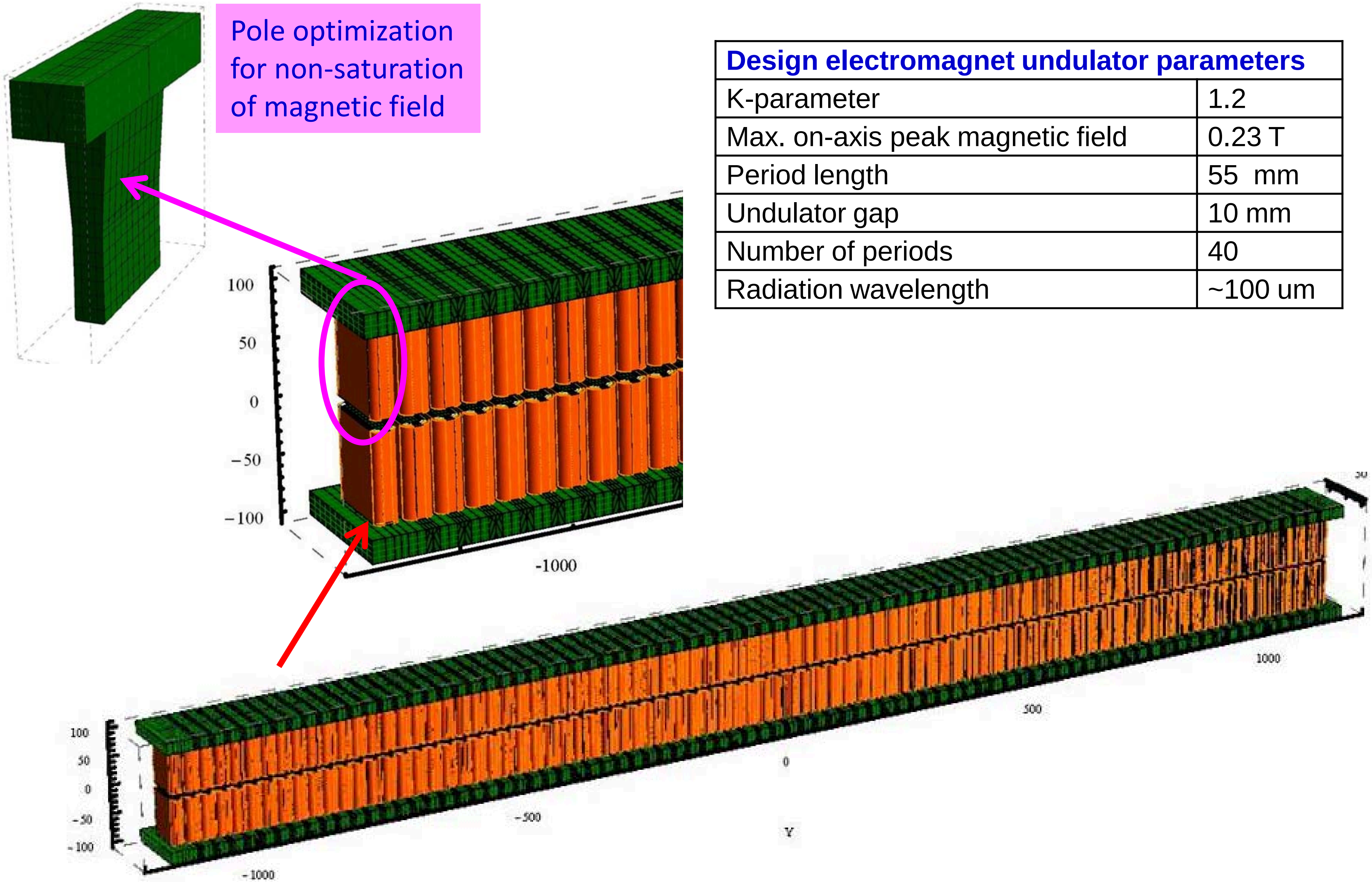
- Economical & simple choice
- Based on some experience of electromagnet dipoles and quadrupoles development in house
- Magnetic field strength is adjusted by varying the applied current

→ To avoid difficulty of mechanics for adjusting the gap

Preliminary parameters for CMU EMU	
K-parameter	1- 1.2
Max. on-axis peak magnetic field	~0.2 T
Period length	55 mm
Undulator gap	10 mm
Number of periods	40
Radiation wavelength	~100 um

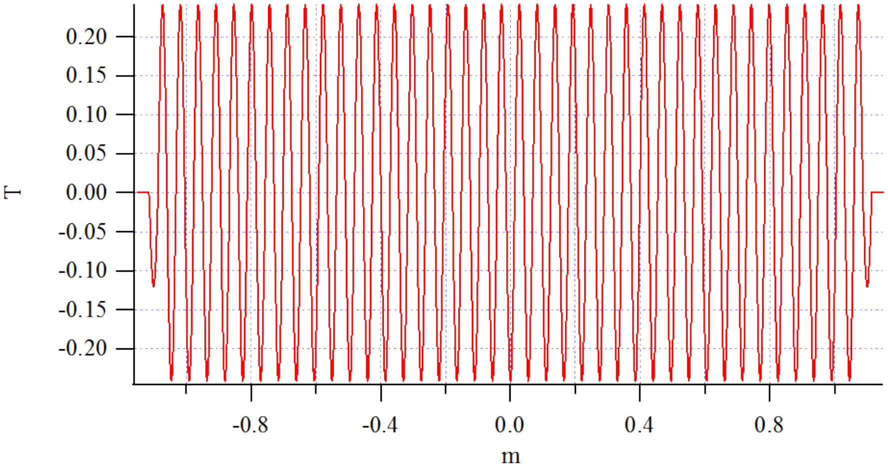
Electromagnet Undulator with 40 Periods (1)

Design electromagnet undulator parameters	
K-parameter	1.2
Max. on-axis peak magnetic field	0.23 T
Period length	55 mm
Undulator gap	10 mm
Number of periods	40
Radiation wavelength	~100 um



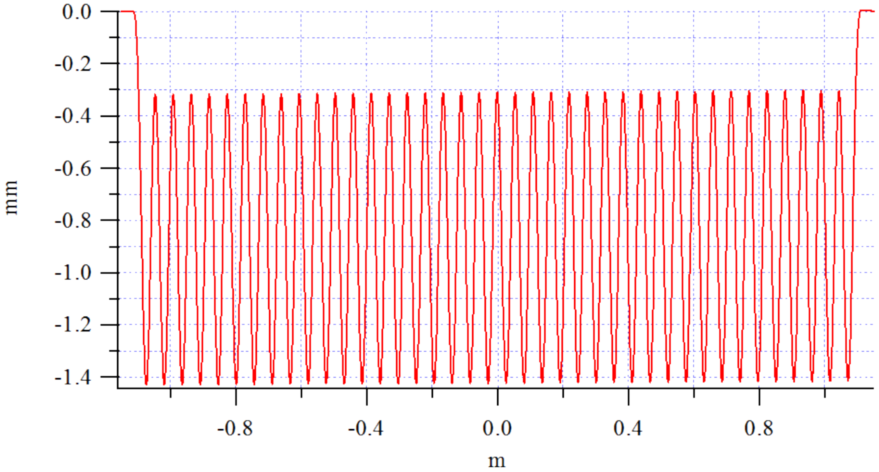
Pole optimization for non-saturation of magnetic field

Electromagnet Undulator with 40 Periods (2)



B_y along distance in undulator (z)

$$B_0[T]=(2\pi mcK)/(e\lambda_u)=K/(0.934\lambda_u[cm])$$

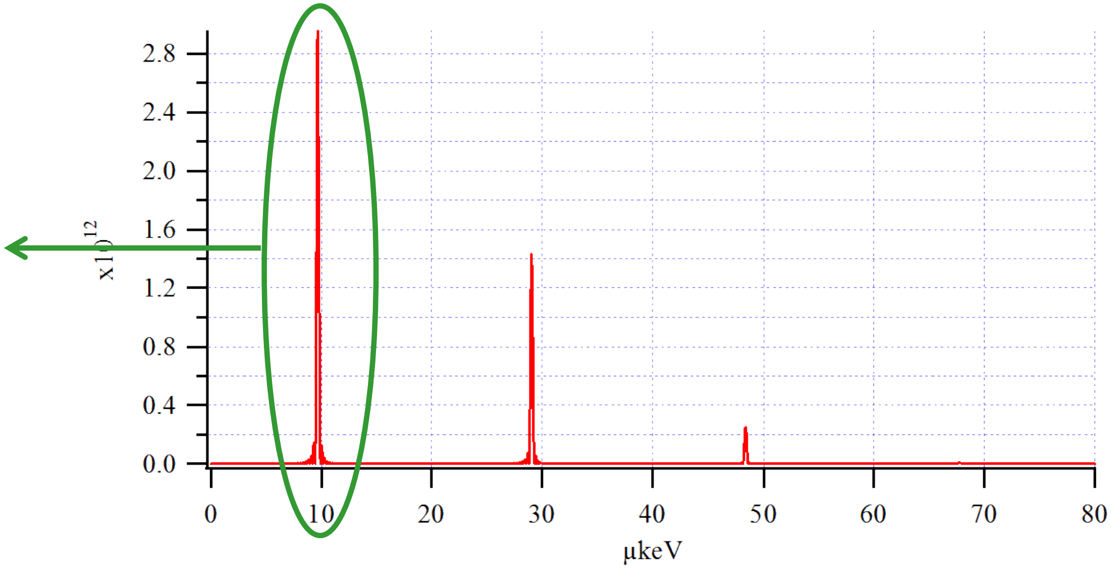


Transverse trajectory of electron along z

$$x=[K\lambda_u\sin(2\pi z/\lambda_u)]/[2\pi\beta\gamma]$$

Fundamental frequency ~ 2.4 THz

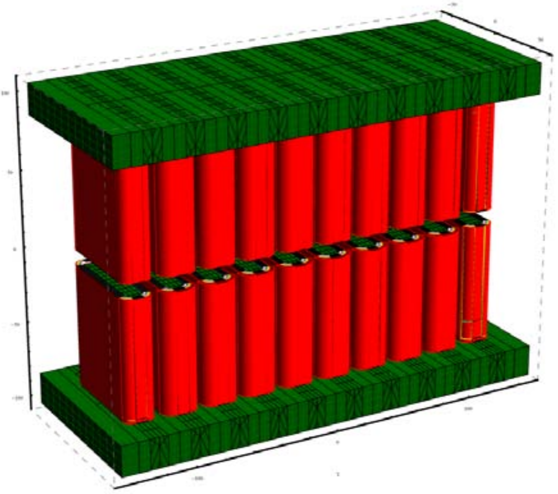
$$\lambda=\frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}+\theta^2\gamma^2\right)$$

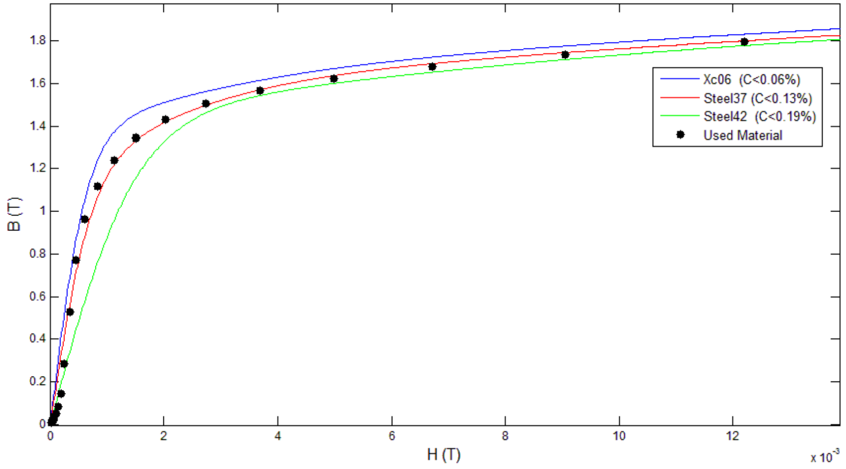


B2E simulated undulator spectrum

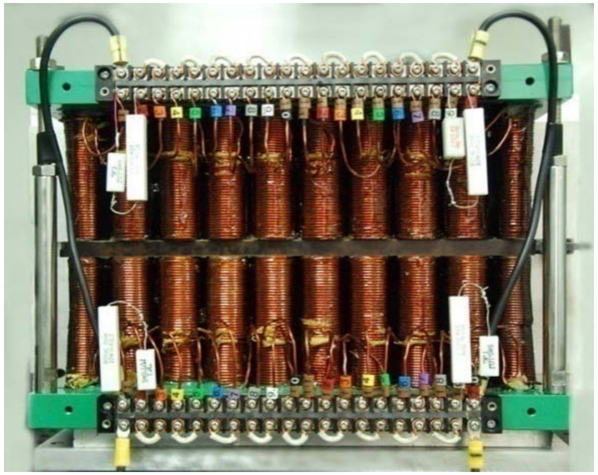
Design and Construction of EMU Prototype

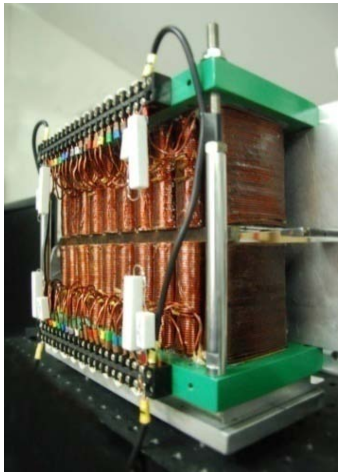
RADIA model (8 main poles + 2 end poles)

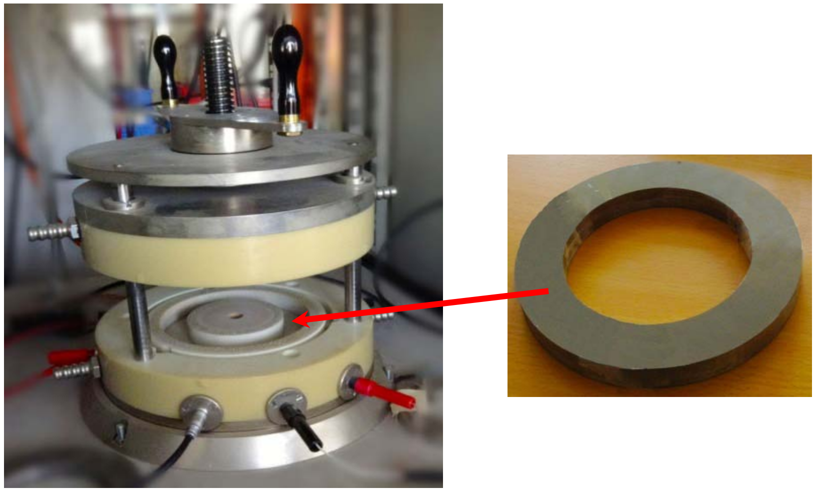




B-H curve of the material used to construct the undulator was measured by using **Split-coil permeameter** @ DESY







Final Remarks

Characteristics of particle beams and reliability in operation of an accelerator facility strongly depend on properties of the source.

- ➢ Development of high-brightness electron beams is a key and a critical issue in the success of most electron accelerator projects.
- ➢ RF electron guns are the powerful source with specifications depending on types of accelerators and applications.
- ➢ RF gun technology is one of main streams in the development of particle accelerators.

End of Lecture No. 3

Thank you for your attention!

Questions & Discussion