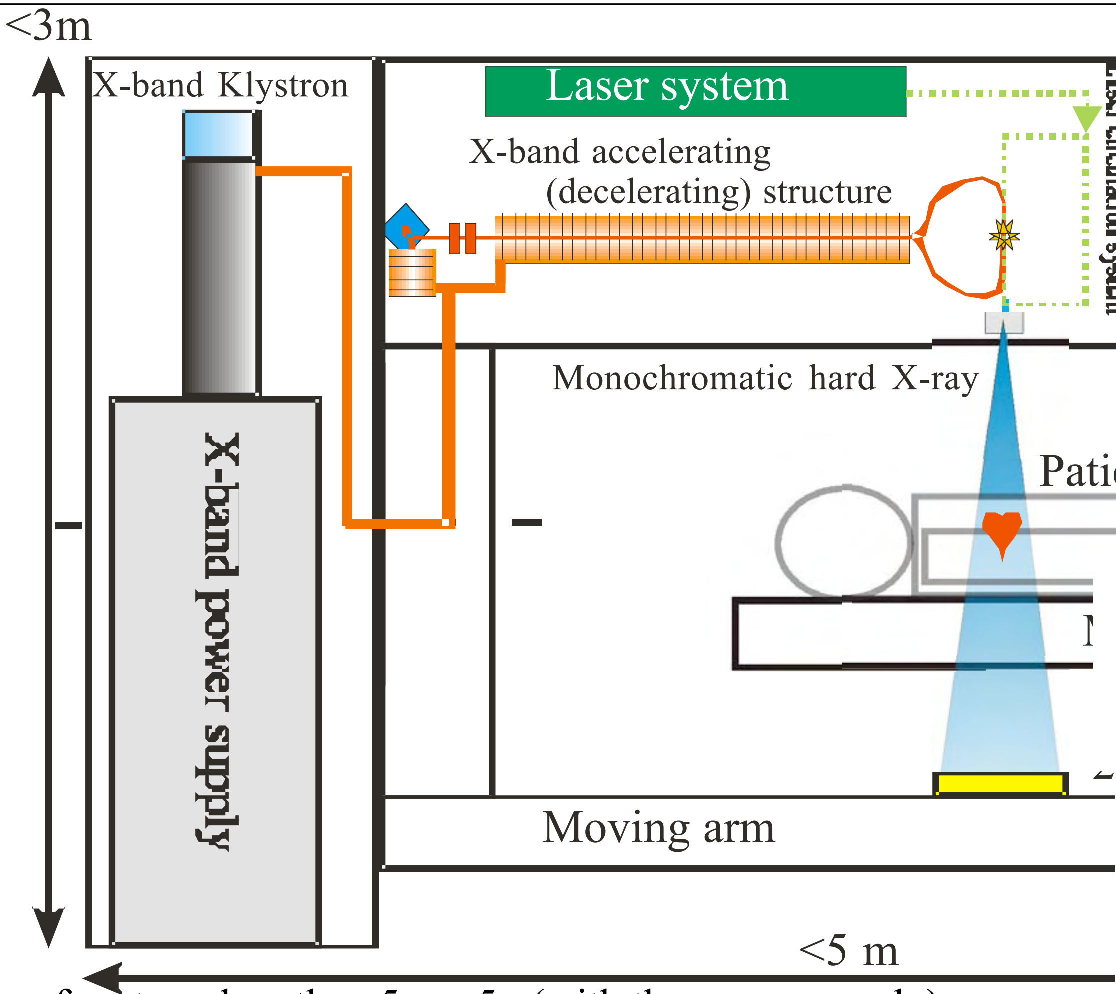
October 11, 2005
ICFA Workshop on
The Physics and Applications of High Brightness Beams

“High Brightness Beam Applications: Inverse Compton Scattering”

Nuclear Professional School
University of Tokyo

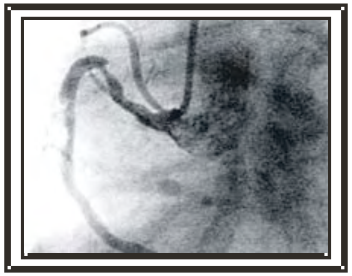
Mitsuru Uesaka

Monochromatic Tunable Hard X-ray Source by X-band-linac/YAG-laser Compton Scattering

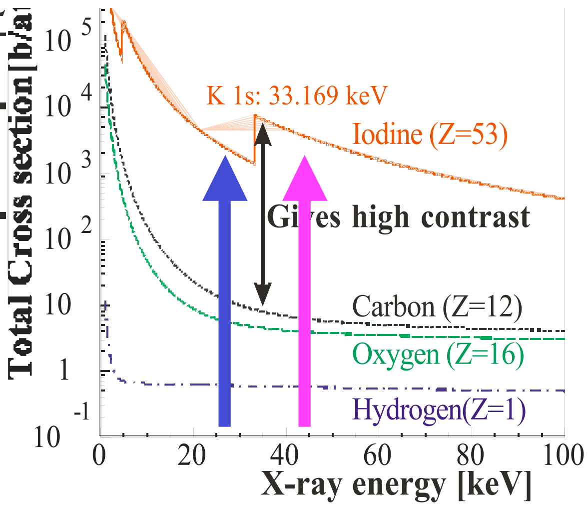


Intravenous injection of contrast agent

Dynamic image of coronary artery



Total Cross Section of X-ray attenuation for various elements



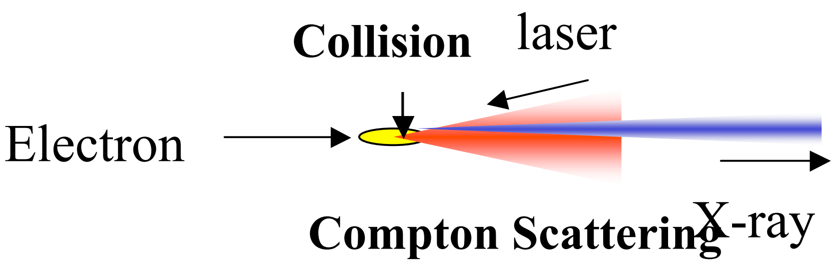
Scale of system: less than 5m x 5m(with the power supply)

Price: ~4 million dollars

X-ray energy(max.): 10~50 keV

X-ray intensity: $>10^9$photons/s(total)

Monochromatic Hard X-ray by Compton Scattering



Collision
laser
Electron
Compton Scattering
X-ray

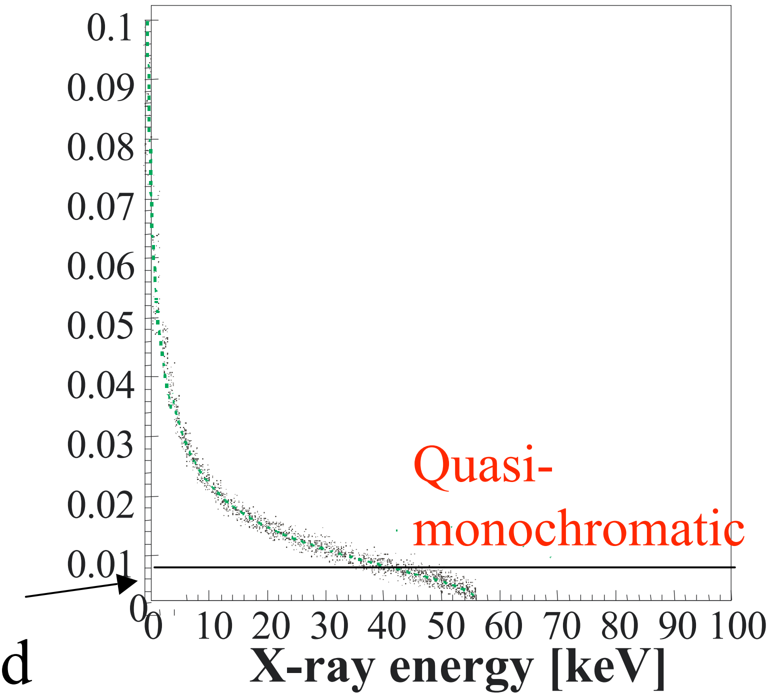
$$\lambda_r = \frac{\lambda_L}{2\gamma^2}\left(1 + \frac{1}{2}K^2\right)$$

(K: Wiggling angle of electron)

$\lambda_L \approx 1\mu m$ (laser wavelength)

$\gamma \leq 10^2$ $(50MeV)$

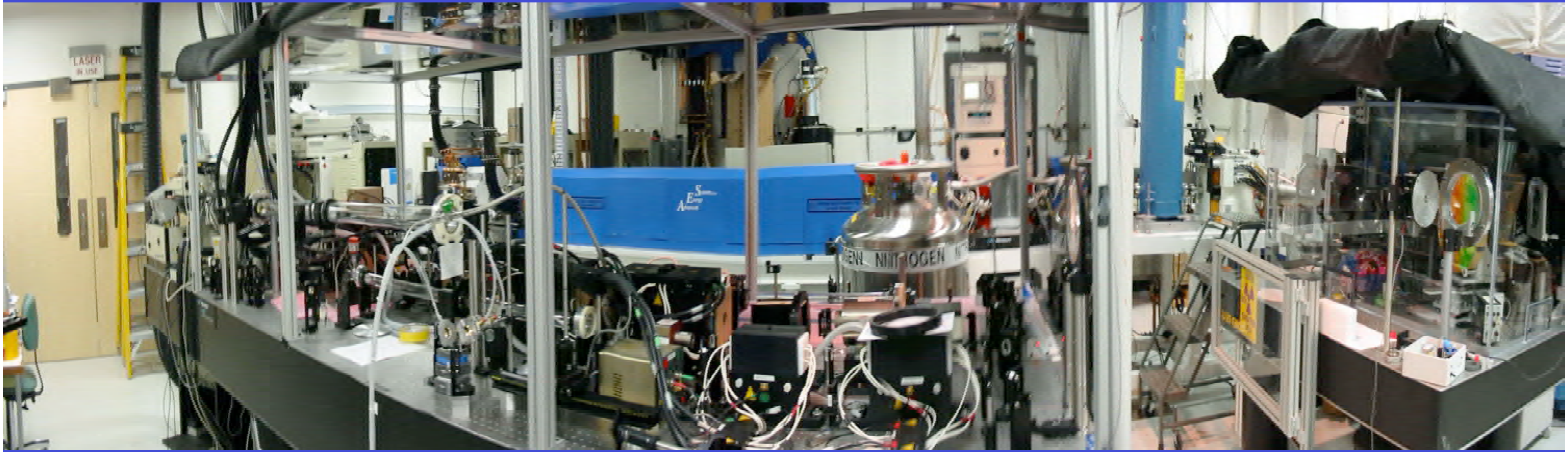
$\lambda_\gamma \leq 1\overset{\circ}{A}$ (X-ray)



5mrad

X-ray energy vs Angle

Pulsed, tunable, monochromatic X-ray machine at MXI Sys./Vanderbilt's W.M. Keck Free-Electron Laser Facility



Machine Specifications:

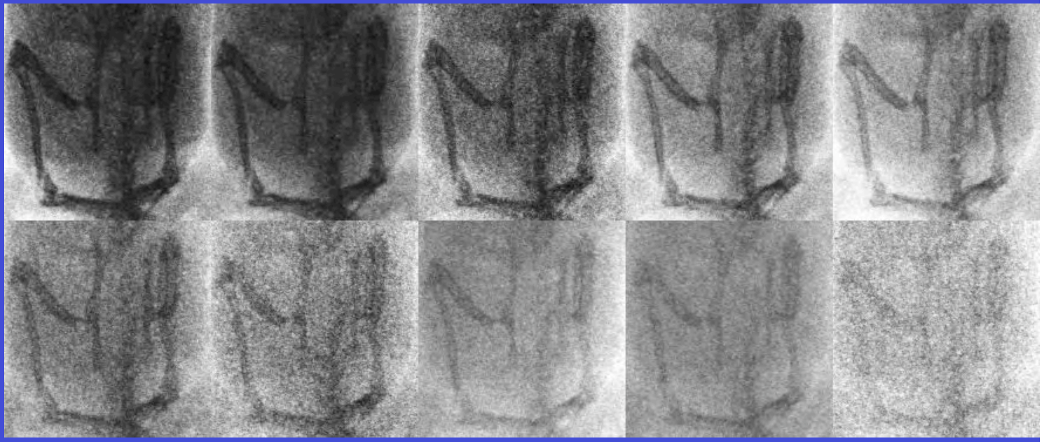
E-beam:	**50 Mev Linac running in "single pulse" mode**
	1 nanocoulomb/pulse
Laser:	**Nd:Glass**
	1052 nm
	20J – (10J compressed to 10 ps)
	.003 Hz
X-ray beam:	**10^{8} photons/shot**
	tunable from 12 to 50 keV
	1-10% bandwidth

Energy differences in a finger

19 keV

29 keV

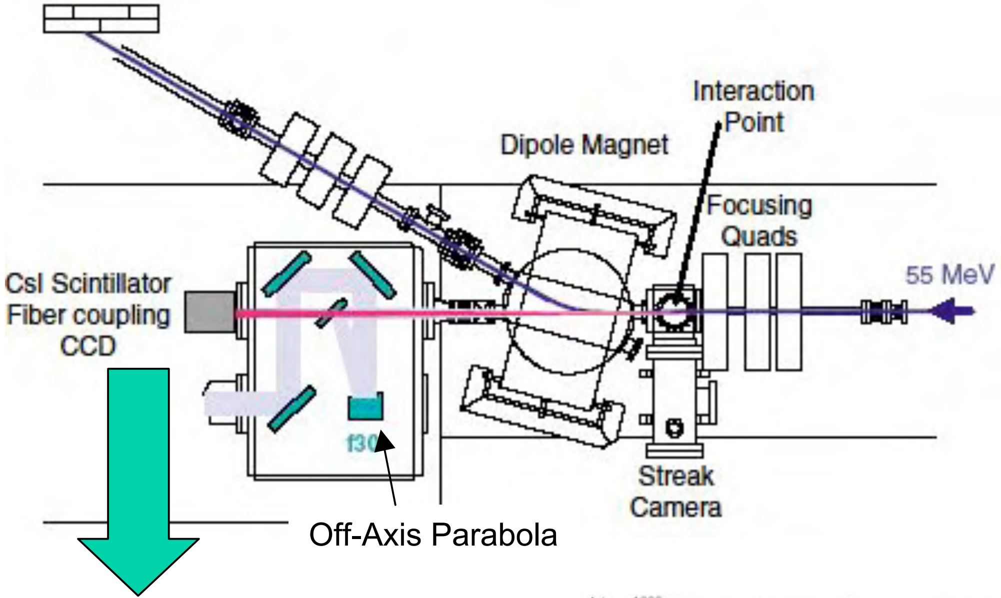
or in a body, such as a mouse

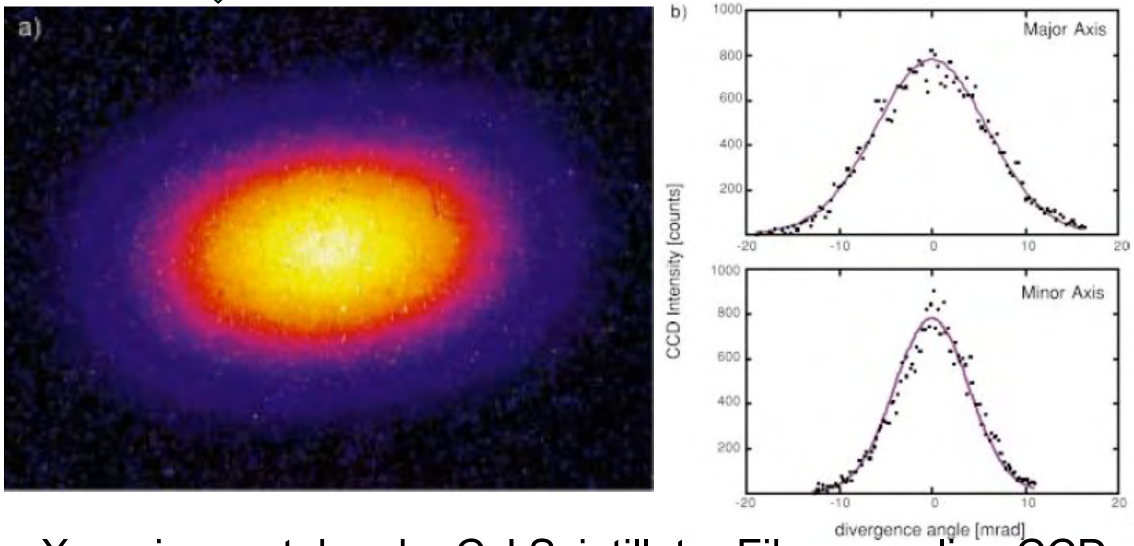


Energy movie from 15 keV to 33 keV

We have the ability to specifically tune the X-rays to the imaging task at hand.

Inverse Compton scattering experiment by 70MeV linac and Ti:Sapp laser at PLEIADES, LLNL





X-ray image taken by CsI Scintillator Fiber coupling CCD

Alignment

Spatial Alignment
aluminum cube at collision point

Temporal Alignment
streak camera

Future works

- Permanent quadrupole magnet for electron beam focusing
→beam size:15 μm
- 540 mJ Laser pulse for interaction
- Tuning up of the UV Laser for photo injector

Goal

Total flux: 10^8 photons/sec
Peak brightness:
10^{20} photons/mm^2
/s/mrad^2/0.1 % band width

LOA(France), etc.

Hard- X-ray on the Thompson scattering

Hard X-rays (~10-20 keV) in a 1-2^{o} cone can be produced with 12TW Laser

Normalized Intensity

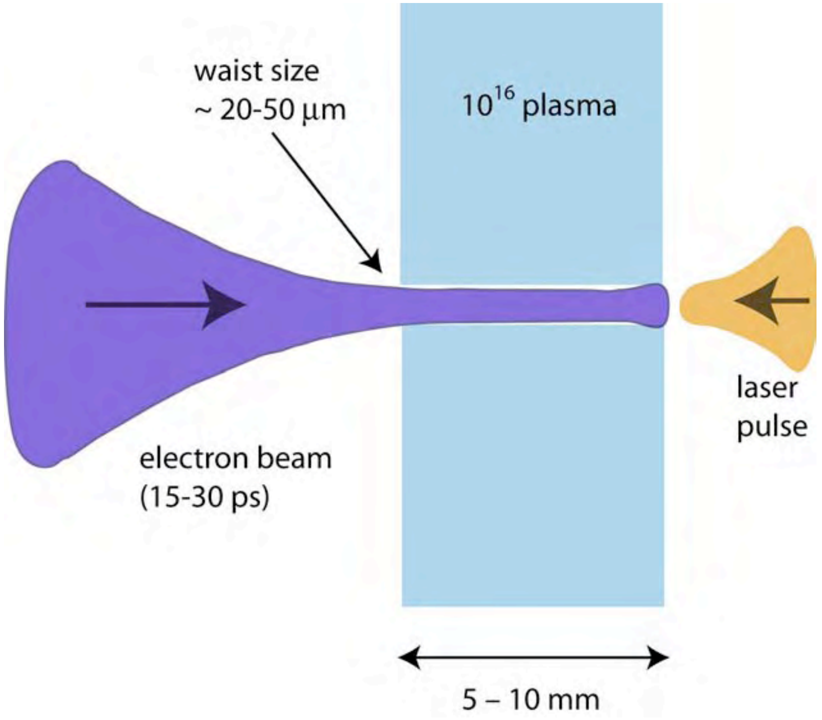
Normalized Intensity

Laser pulse and electron
bunch encounter can be
produced with use of
the laser self-focusing

F.He, Y.Lau, D. Umstadter, R.Kowalczyk
PRL, 90,055002 (2003)

$$\omega \sim m\omega_0 8\gamma_0^2/(1+a_0^2)$$

Beam-driven channel scenario



- long electron beam (3–4 mm), high charge (~10-100 nC)
- laser pulse arrives when beam head exits plasma
- laser guiding over 5–10 Z_R through plasma-formed channel

R.Yoder and J.Rosenzweig

First and Second Generation
Inverse Compton Scattering X-ray Sources

First Generation

MXI Sys/Vandervilt, PLEIADES, U.Tokyo/KEK/JAERI, Sumitomo etc.

-Single-electron-single-laser Compton scattering

-First demonstration and application

-Intensity up to 10^8 photons/s

-Intensity fluctuation due to the time-jitter between electron and laser puls

Second Generation

U.Tokyo, Lyncean Tech.(R.Ruth), Sumitomo/AIST/KEK, etc.

-Multi-scattering of electron- and laser-pulses

-Intensity of more than 10^9 photons/s

-A variety of applications for medicine, protein structural analysis, nondestructive evaluation and nuclear engineering

Laser circulation system

RF pulse length: ζ 10000 bunches

Laser pulse length: 10 ns(FWHM)

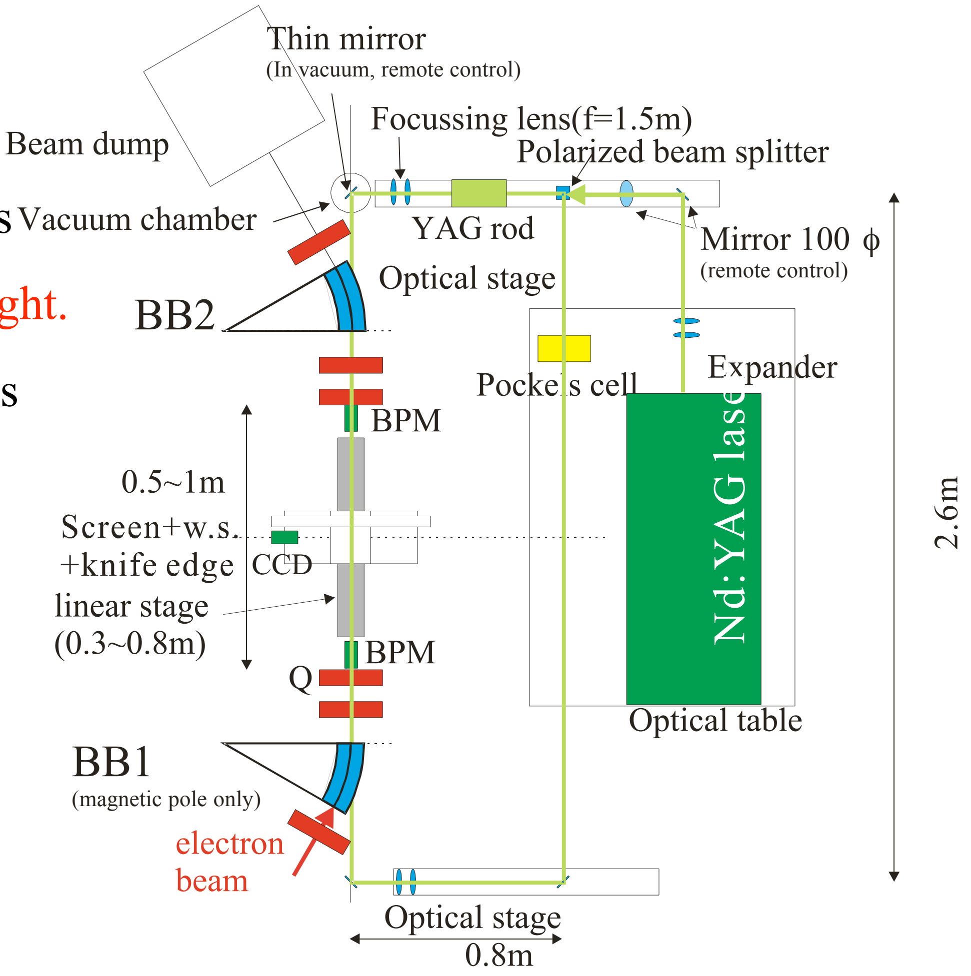
ζ collide with 110 bunches

Increase X-ray yield by re-incident the laser light.

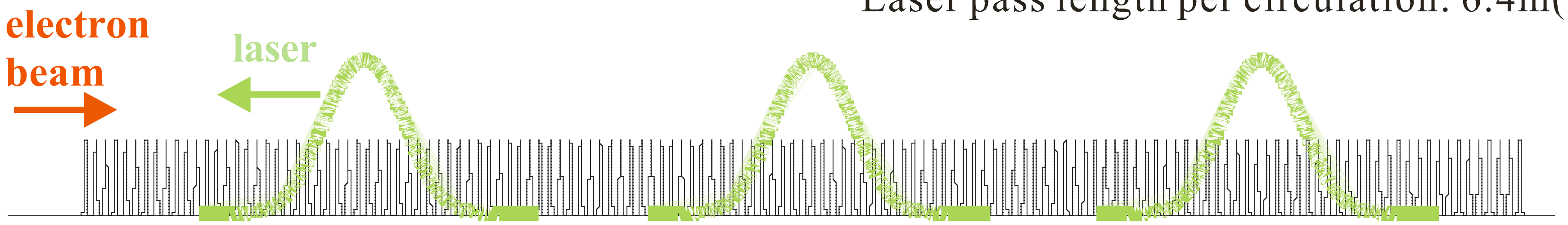
21 ns per a revolution ζ 47 revolutions per 1ms

Enhancement:

- 10 times(max.) with 90% transmission per revolution: 10^9photons/s
- 100 times with 5J pulse and laser power compensation by Nd:YAG rod: 10^{10}photons/s



Laser pass length per circulation: 6.4m(21ns)



Performance of Linac/Laser Inverse Compton X-ray Source

Laboratory	Electron Energy	Charge	Wavelength & Power of Laser	X-ray Energy & Intensity	Fluctuation of X-ray Intensity
SHI[1]	14 MeV (S-band)	400 pC Single Bunch	800nm, 300 mJ, (Ti:Sapphire, 300 ps)	3.5 keV < 1.0E+4 photons/shot	50%
MXI Systems Inc[2]	25 MeV (S-band)	500 pC Single Bunch	1 μm, 20 J (Nd:Glass)	12～50 keV 1.0E+8 photons/sec	50%
LLNL[3]	57 MeV (S-band)	250 pC Single Bunch	780 nm, 400 mJ (Ti:Sapphire, fs)	40～80 keV 1.0E+8 photon/ssec	tens%
SLAC	60 MeV (S-band)	500 pC Single Bunch	800 nm, 300 mJ (Ti:Sapphire, fs)	20～85 keV 1.0E+8 photons/s	80%
Univ. of Tokyo /NIRS/KEK[4]	35 MeV (X-band)	20 pC×10000 Multi Bunches	1 μm, 2 J, (Nd:YAG, 10 nsec)	33 keV 1.0E+8 photons/s	<10%

[1] :M.Yorozu *et al.* Jpn.J.Appl.Phys., Vol.40 (2001) pp. 4228-4232
[2] :F.E.Carroll *et al.* Am.J.Rentgenol. 181 (2003) 1197
[3] :W.J.Brown *et al.* Phys.Rev.Lett.Vol.7 060702 (2004)
[4] :K.Dobashi *et al.* Jpn.J.Appl.Phys., Vol.44 (2005) pp. 1999-2005

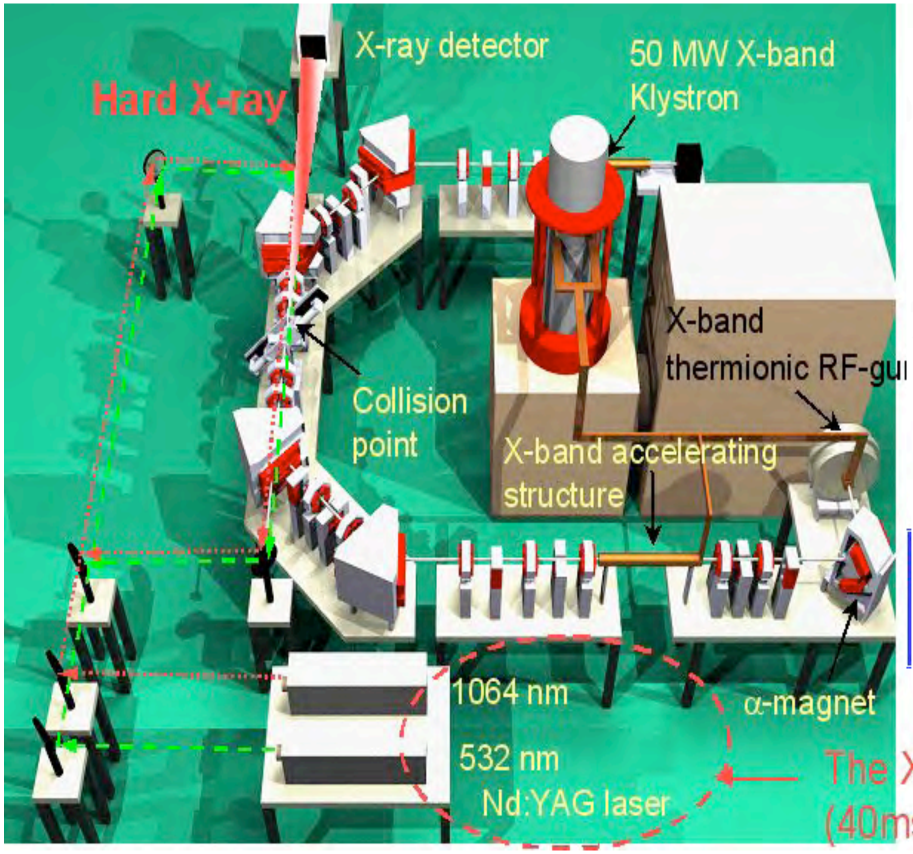
Performance of Typical Monochromatic Tunable Hard X-ray Source

Laboratory	Source of X-ray	Changing method of X-ray Energy	X-ray Intensity	Changing time	Intensity Fluctuation
KEK, SPring-8, etc	SR	Diffraction grating	10^{11} photons/sec	~ 10 min.	< 10 %
Iwate Med. Univ ,etc[5]	Discharged Plasma	Electrode	~ 10^{6} photons/sec	~ hours	? (Unknown)
Univ. of Tokyo /NIRS/KEK	Compton Scattering	Wavelength of Laser	10^{8} photons/sec	~ 40 msec (@ 25 Hz)	< 10 %

[5] :M. Sagae *et al.* Jpn.J.Appl.Phys., Vol.44 (2005) pp. 446-449

Compton scattering hard X-ray source

Compact hard X-ray source based on Compton Scattering



Properties of the generated X-ray

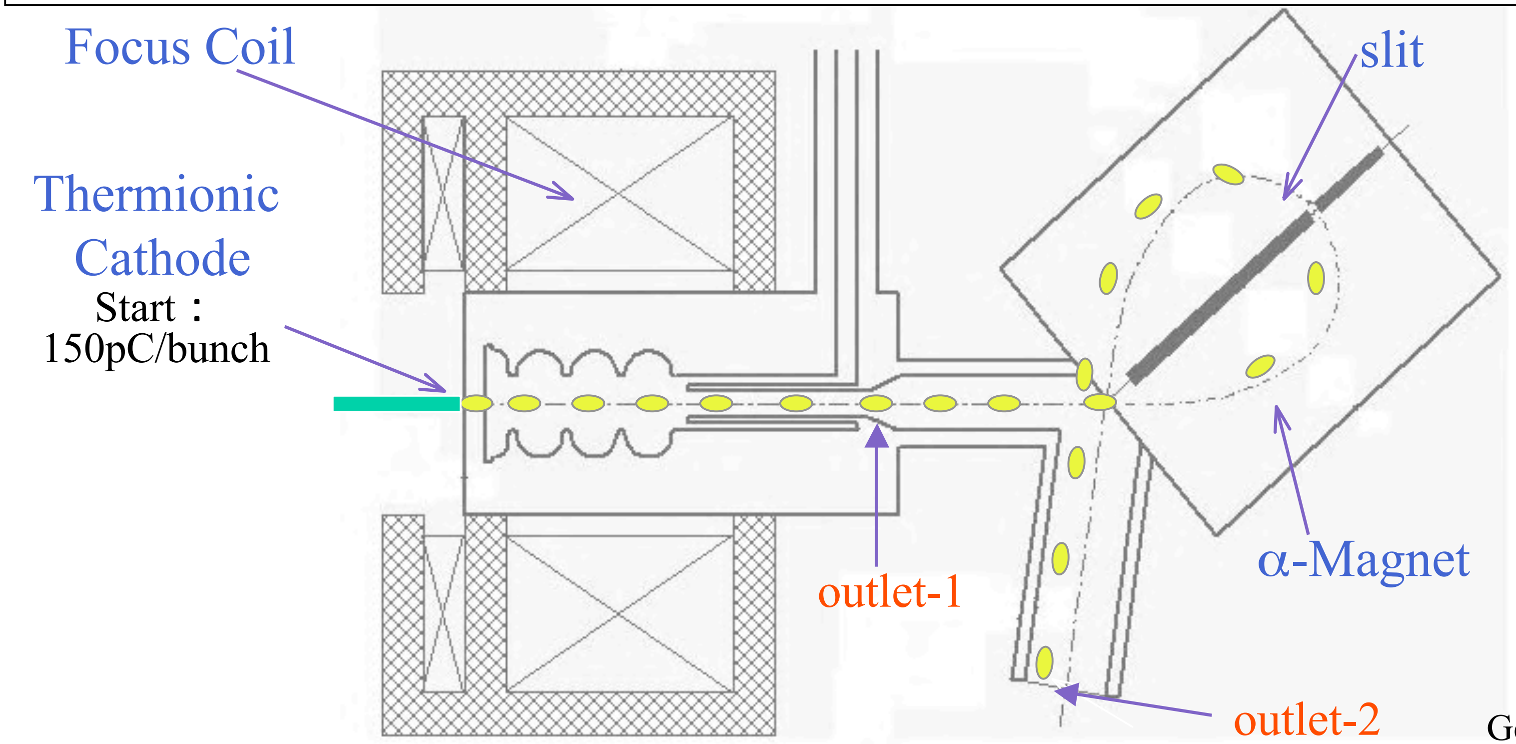
Electron beam energy : 35 MeV, Charge : 20 pC/bunch

Laser wavelenght (nm)	1064	532
Pulse energy (J/pulse)	2.5	1.4
X-ray yield (photons/pulse)	9.9×10^{6} (10^{8})	4.4×10^{6} (10^{8})
Maximum X-ray energy (keV)	21.9	43.8
Energy spread (%) rms	1-10	

10 pps with laser circulation

The X-ray energy can be changed quickly (40ms) by introducing two lasers

X-band 3.5MeV axisymmetric thermionic RF gun under collaboration with Prof. Marnix van der Wiel, et al., of Eindhoven U. Tech.

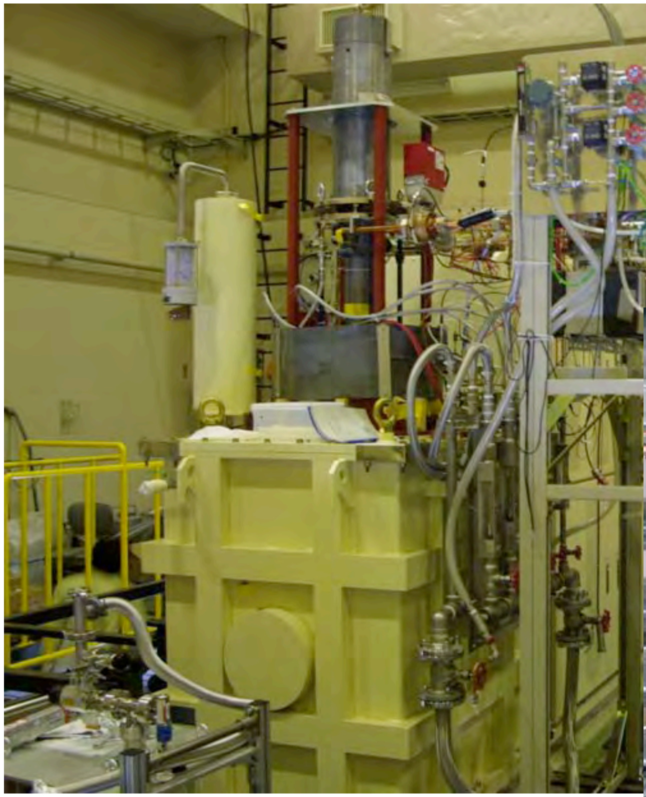


*Using Code GPT: General Particle Tracer

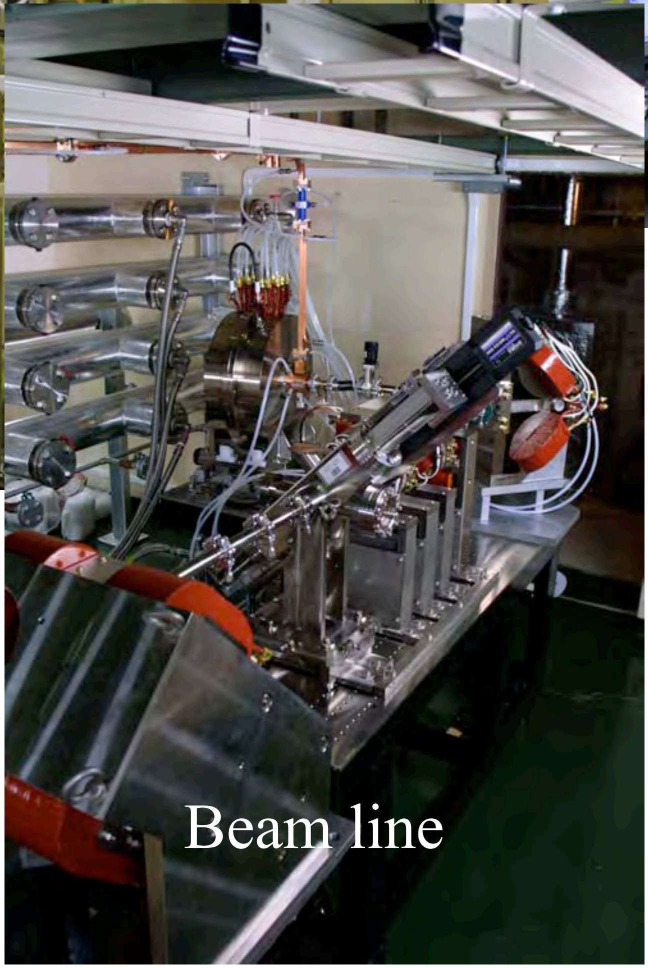
Beam Parameter Simulated by GPT*

Beam Characteristics	unit	@outlet of RF-Gun	@outlet of α-Magnet
Energy	MeV	0.12～3.58	3.46～3.58
Emittance	mm mrad	196π	16.6π
Charge	pC/bunch	78.4	25.8
Bunch length σz	psec	-	0.67

X-band Linac Facility at Univ.Tokyo



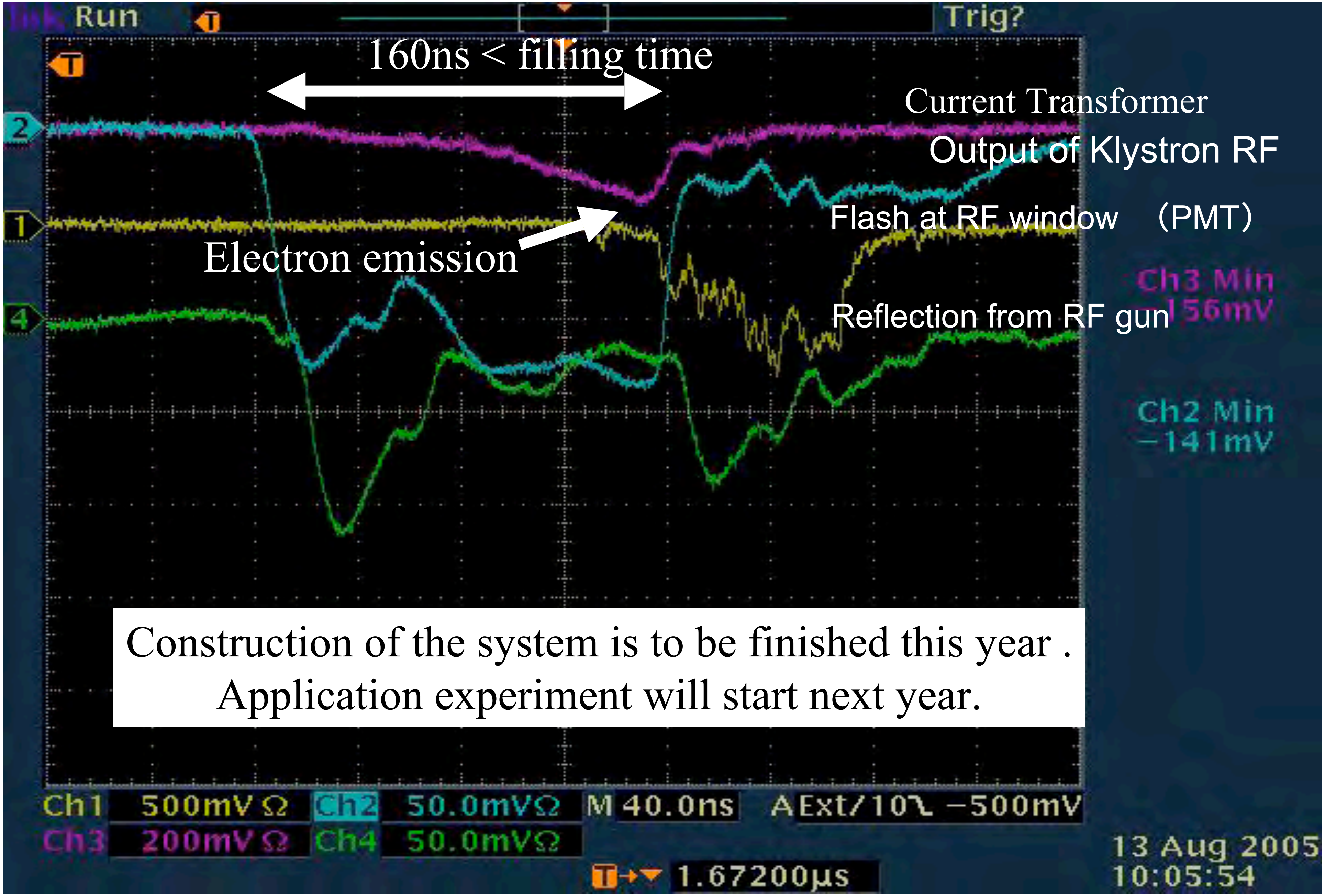
RF source



Beam line

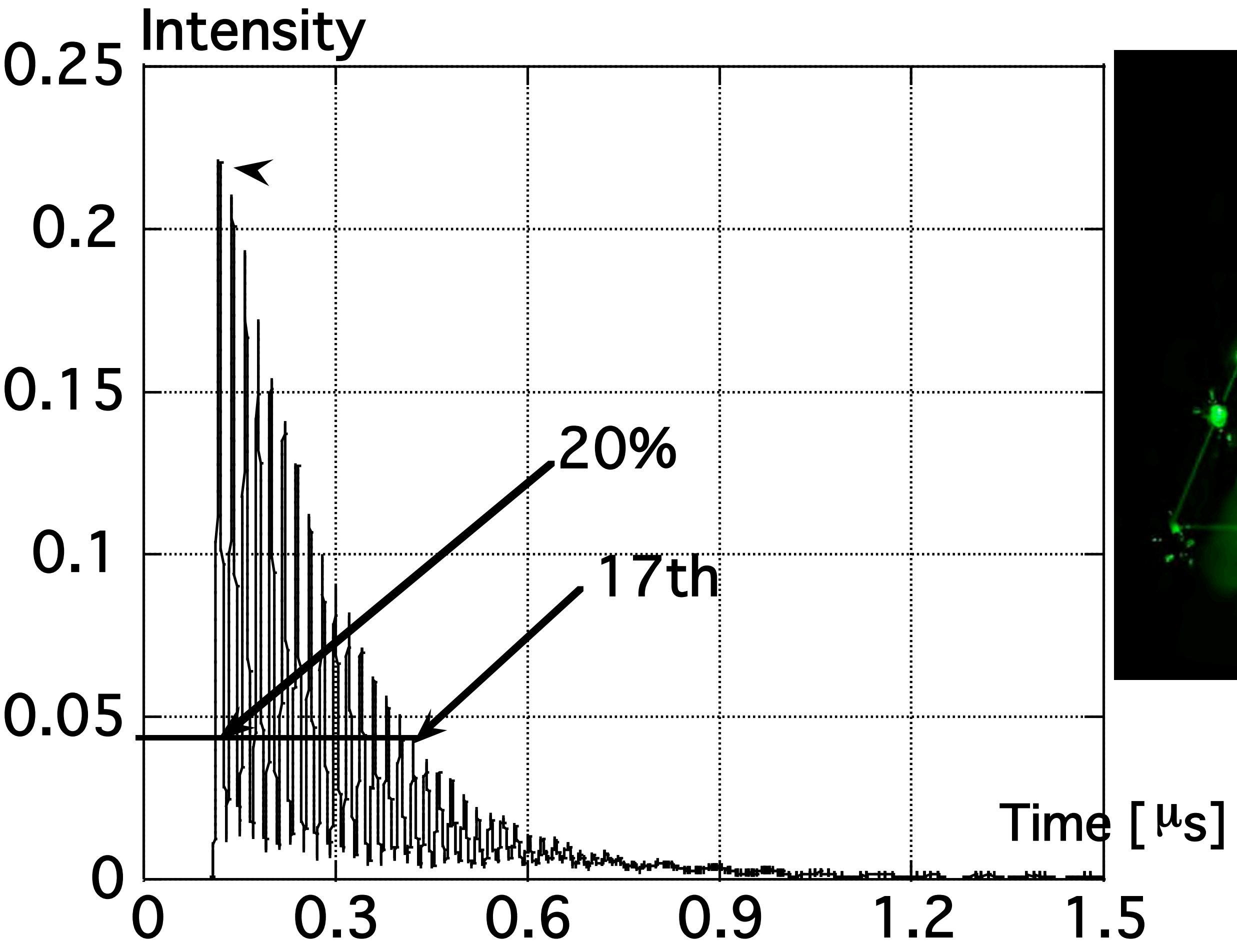
Control room

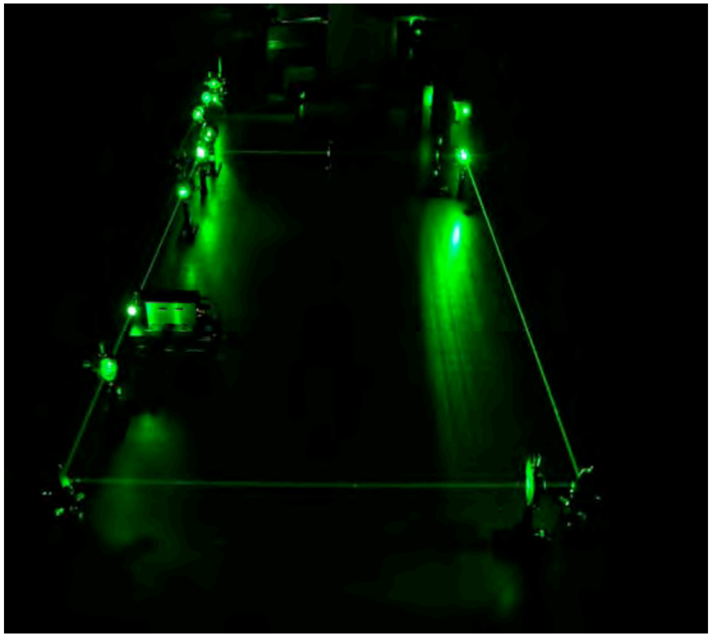
Now RF aging of the gun is under way



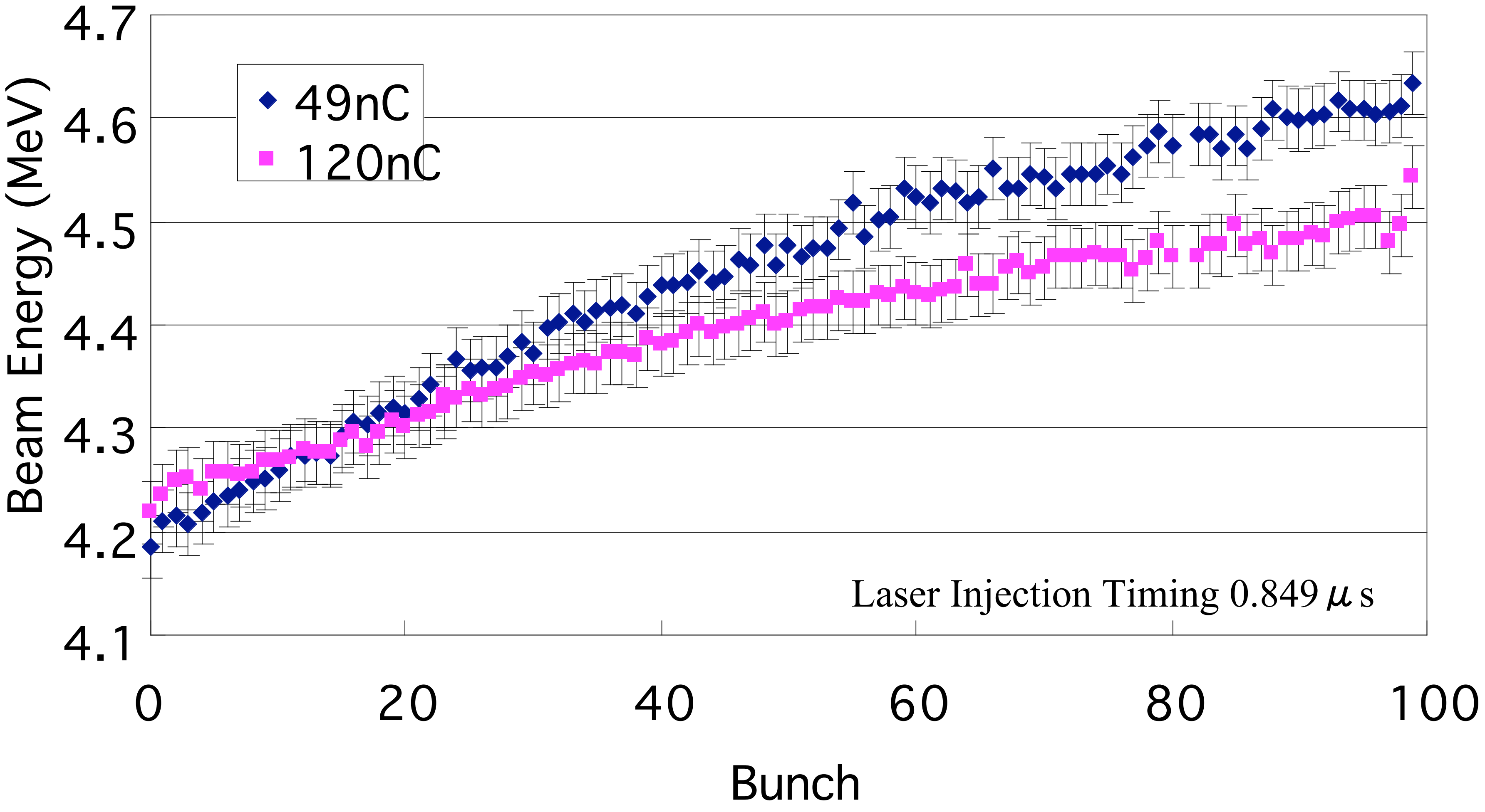
Construction of the system is to be finished this year .
Application experiment will start next year.

Circulation at 2nd Harmonics to get 10 times increase of X-ray yield





Bunch-by-bunch Beam Energy

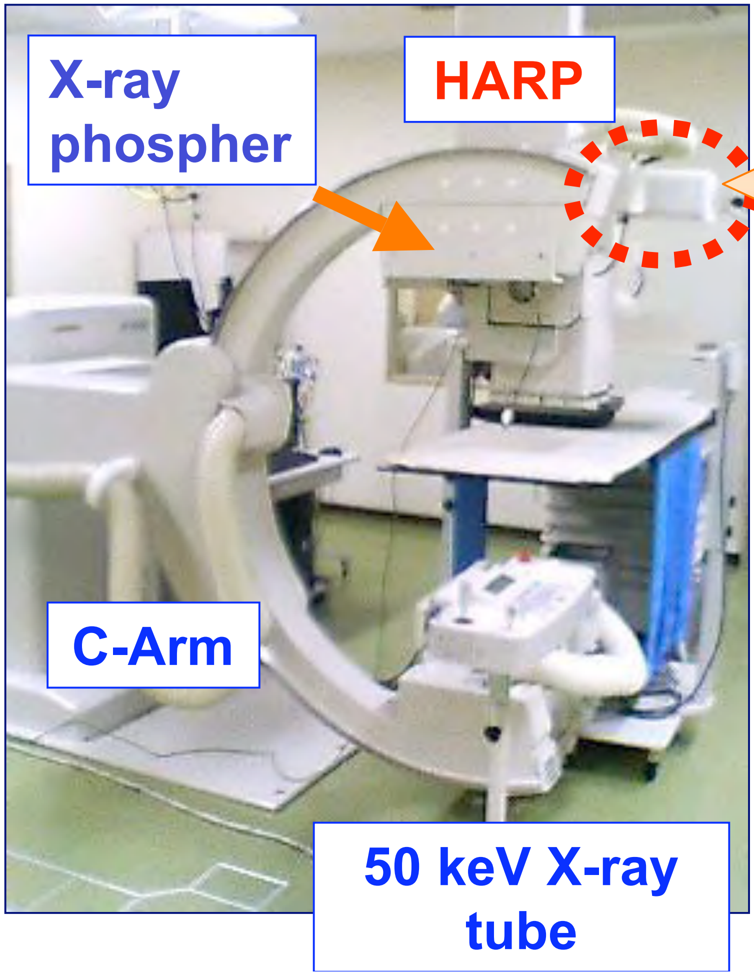


Applications

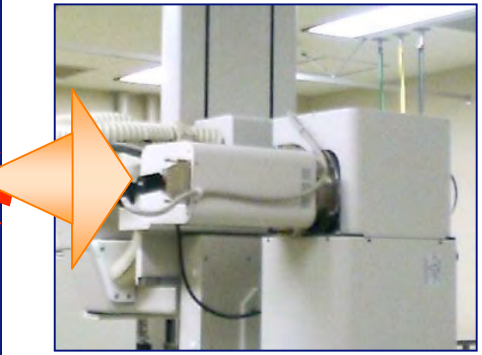
- Static/dynamic imaging for medical and industrial uses
- Dual energy X-ray CT to get 3D distributions of atomic-number- and electron-densities for light atoms up to ^{43}Tc
- Subtraction CT across the K-edge to get 3D distribution of specified heavy atoms
- Protein structural analysis

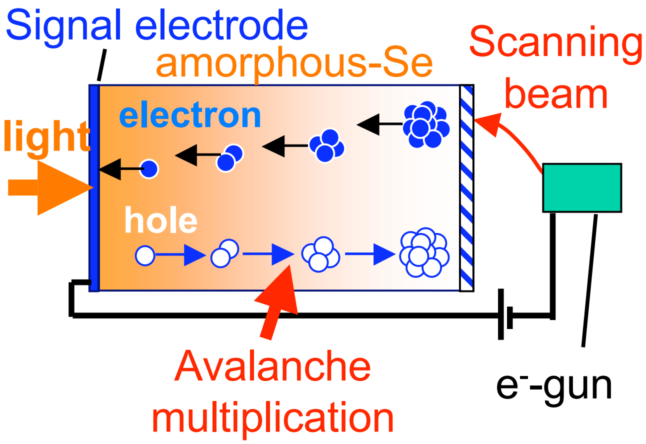
Ultra Micro-vessel Angiography for Diabetic Femur and Thrombus @ NCVC (National CardioVascular Center)

X-ray tube (50kVp) with high-sensitivity HARP camera



HARP (High-gain Avalanche Rushing amorphous Photoconductor) camera





Micro-vessels visualized by contrast agent

Imaging area:
20cm × 20cm
Space resolution:
25 μm

Ultra Micro-vessel Angiography by Compact Monochromatic Hard X-ray Source

Ultra Mico-vessel angiography by polychromatic hard X-ray

- 30 images/s
- Space resolution: 25 μm

Required photon intensity

4.8×10^{10} photons/mm^2/s @33-35keV 4.8×10^{9} photons/mm^2/s @51-54keV

Compact hard X-ray source based on electron-laser collision

- 10 times circulated laser colliding with electron

Expected photon intensity

2×10^{7} photons/mm^2/s @33-35keV 1×10^{7} photons/mm^2/s @51-54keV

Angiography by the compact hard X-ray source

- High-sensitivity HARP camera
- 10 images/s
- Pixel size (100 μm ×100μm)

Photon intensity is reduced

Angiography can be performed!
(Space resolution: 100 μm)

Future plan to perform ultra micro-vessel angiograpphy

High power laser (7J/pulse), 40 times circulated laser, Wide length of electron macro pulse and Small light spot (25 μm diameter) etc… → Space resolution: 25 μm

Dual Energy CT for 3D Distribution of Atomic-Number- and Electron Densitis for Lighter Atoms up to ^{43}Tc

Linear attenuation coefficient is approximately written as a function of *Z* and *E*

$$\mu \cong \boxed{\rho\frac{N_A}{A}Z}\left(4\sqrt{2}Z^4\alpha^4\left(\frac{mc^2}{E}\right)\phi_0\sum_{nll'}f_{nll'}+\sigma_{KN}+\frac{Z\left(1-Z^{b-1}\right)}{Z'^2}\sigma_{SC}^{coh}(Z',E')\right)$$

$$=\rho_e\left(Z^4F(Z,E)+G(Z,E)\right)$$

ρ: mass density

N_A: Avogadro's number

σ_{KN}: Klein-Nishina cross section

σ_{SC}: Coherent scattering cross section of standard element Z'

$Z'=8$ (Oxgen) and $E'=(Z'/Z)^{1/3}E$

Effective atomic number and electron density are derived from linear attenuation coefficients for two energies

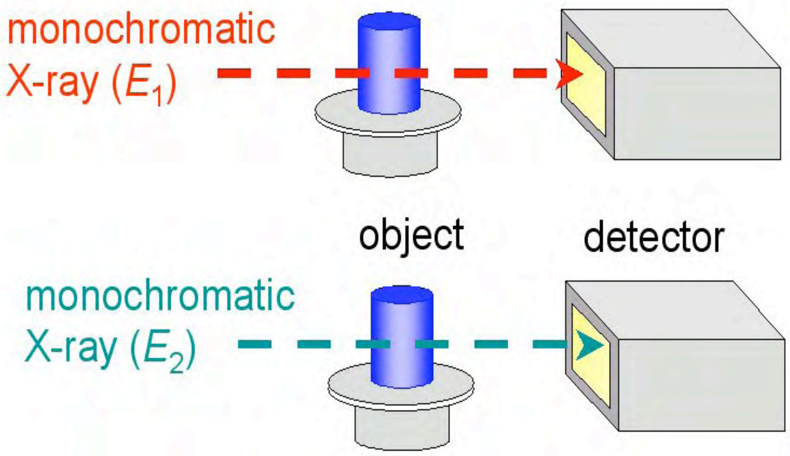
$$\mu(E_1)=\rho_e\left(Z^4F(Z,E_1)+G(Z,E_1)\right)$$

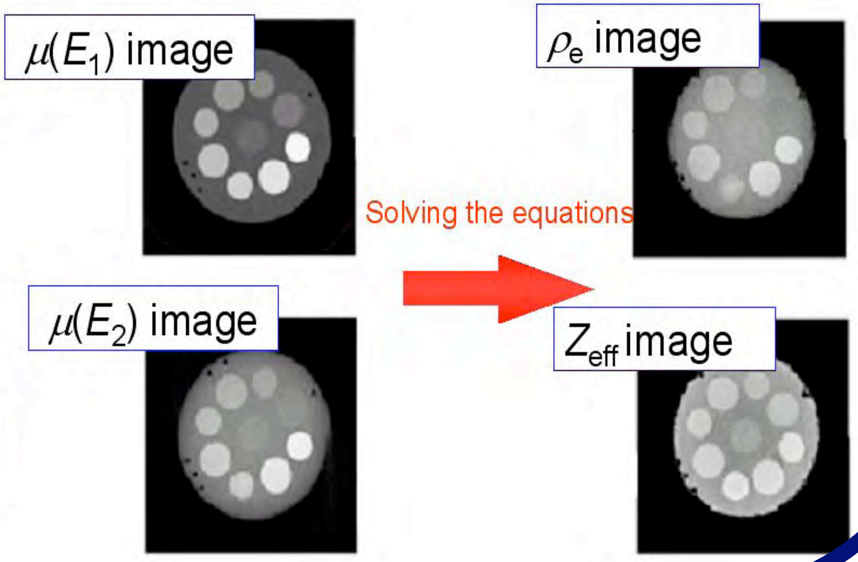
$$\mu(E_2)=\rho_e\left(Z^4F(Z,E_2)+G(Z,E_2)\right)$$

Effective atomic number
$$Z^4=\frac{\mu(E_2)G(Z,E_1)-\mu(E_1)G(Z,E_2)}{\mu(E_1)F(Z,E_2)-\mu(E_2)F(Z,E_1)}$$

Electron density
$$\rho_e=\frac{\mu(E_1)F(Z,E_2)-\mu(E_2)F(Z,E_1)}{F(Z,E_2)G(Z,E_1)-F(Z,E_1)G(Z,E_2)}$$

Dual-energy X-ray CT experiment



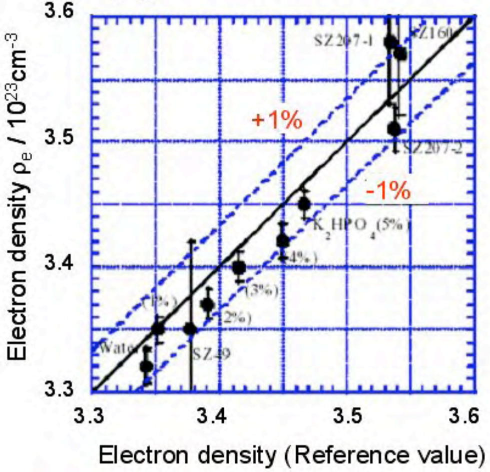


Torikoshi(NIRS), et al.

Dual-energy X-ray CT by SR light sources

Electron density and atomic number have been measured for
biological materials consist of light elements ($Z \leq 20$) [1,2]

ρ_e measurement



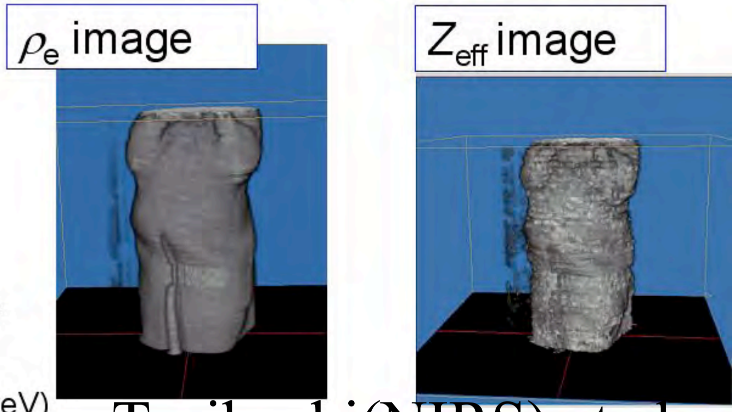
Precise electron density can be measured in agreement with 1 % of the theoretical values

(X-ray energy : 40 keV, 70 keV)

Volume data of a rat are constructed

(X-ray energy : 40 keV, 70 keV)

Volume rendering of a rat



Torikoshi(NIRS) et al.

Dual-energy CT for atomic number identification in a material

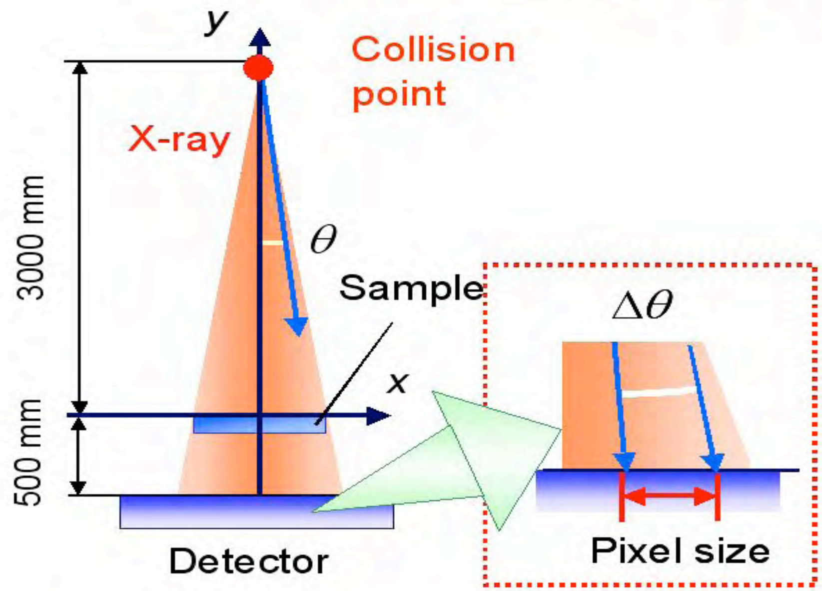
Can we apply the method to medium *Z* elements?

- The dual-energy analysis cannot be used below K-edge energy of a atom
- When maximum X-ray energies are 21.9 keV and 43.8 keV, elements up to Z = 38 should be identified
- Energy spread $\Delta E/E$ of the monochromatic X-ray

  SR light :10^{-1} – 10^{-2} % (negligible), Compact X-ray source : 1 to 10%

Numerical simulation to examine applicability

Applicability of the dual-energy analysis



Assuming a point light source
Pixel size : 0.1 to 1.0 mm
Electron beam energy : 35MeV
Laser wavelength: 1064nm, 532nm
Maximum X-ray energy: 21.9keV, 43.8keV

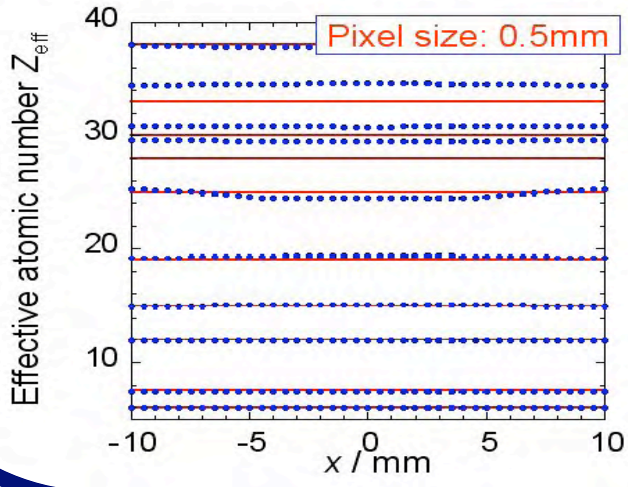
Energy spread $\Delta E/E$: 1 to 10%

X-ray energy depends on the position on the detector

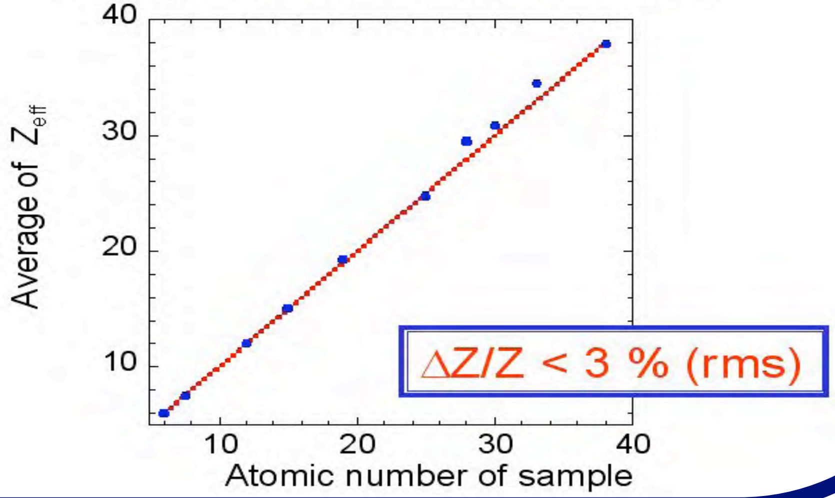
Pixel size : 0.5mm
$\Delta\theta$: less than 0.2 mrad
$\Delta E/E$ in a pixel: 0.1 %

Effective atomic number simulated by considering the X-ray energy profile

Effective atomic number calculated at each pixel



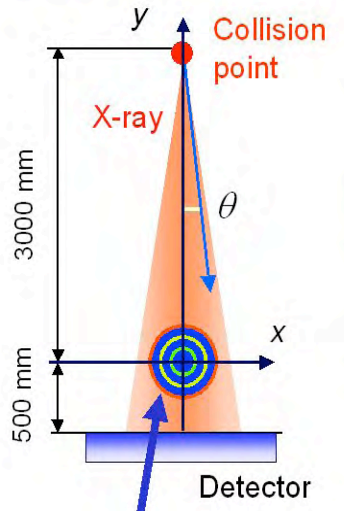
Average of the effective atomic numbers

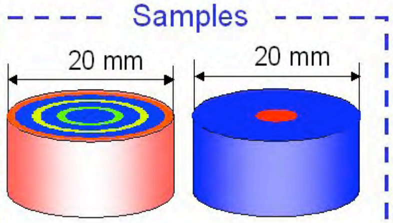


$\Delta Z/Z < 3\ \%$ (rms)

CT simulation for low to medium *Z* elements

Geometry of the CT system

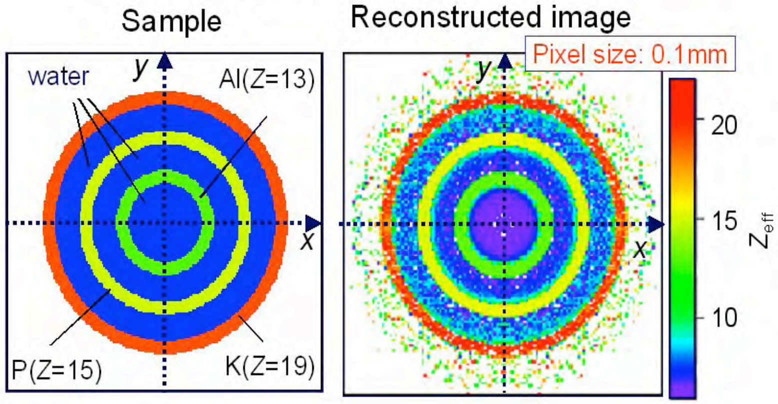




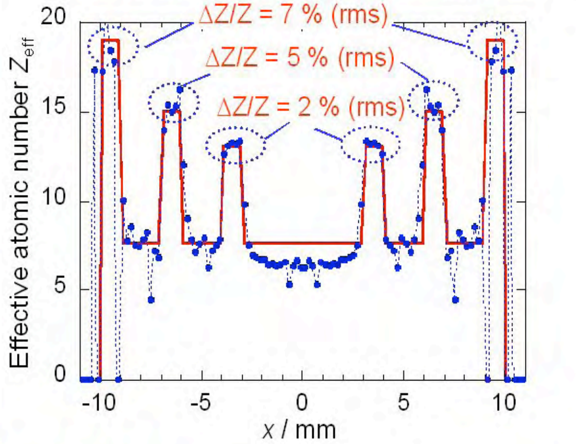
Cylindrical sample contains low to medium *Z* elements is simulated

Sample 1 (low *Z* elements)

Atomic number distribution

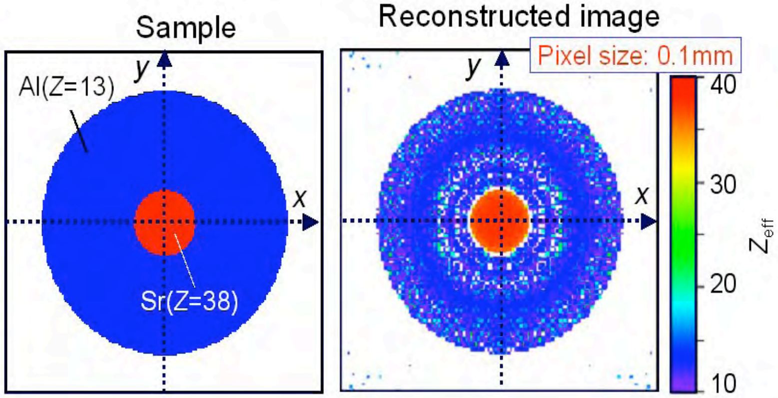


Atomic number distribution at y=0mm

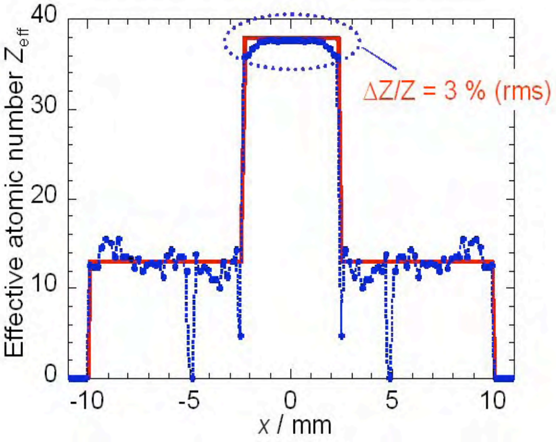


Sample 2 (medium *Z* elements)

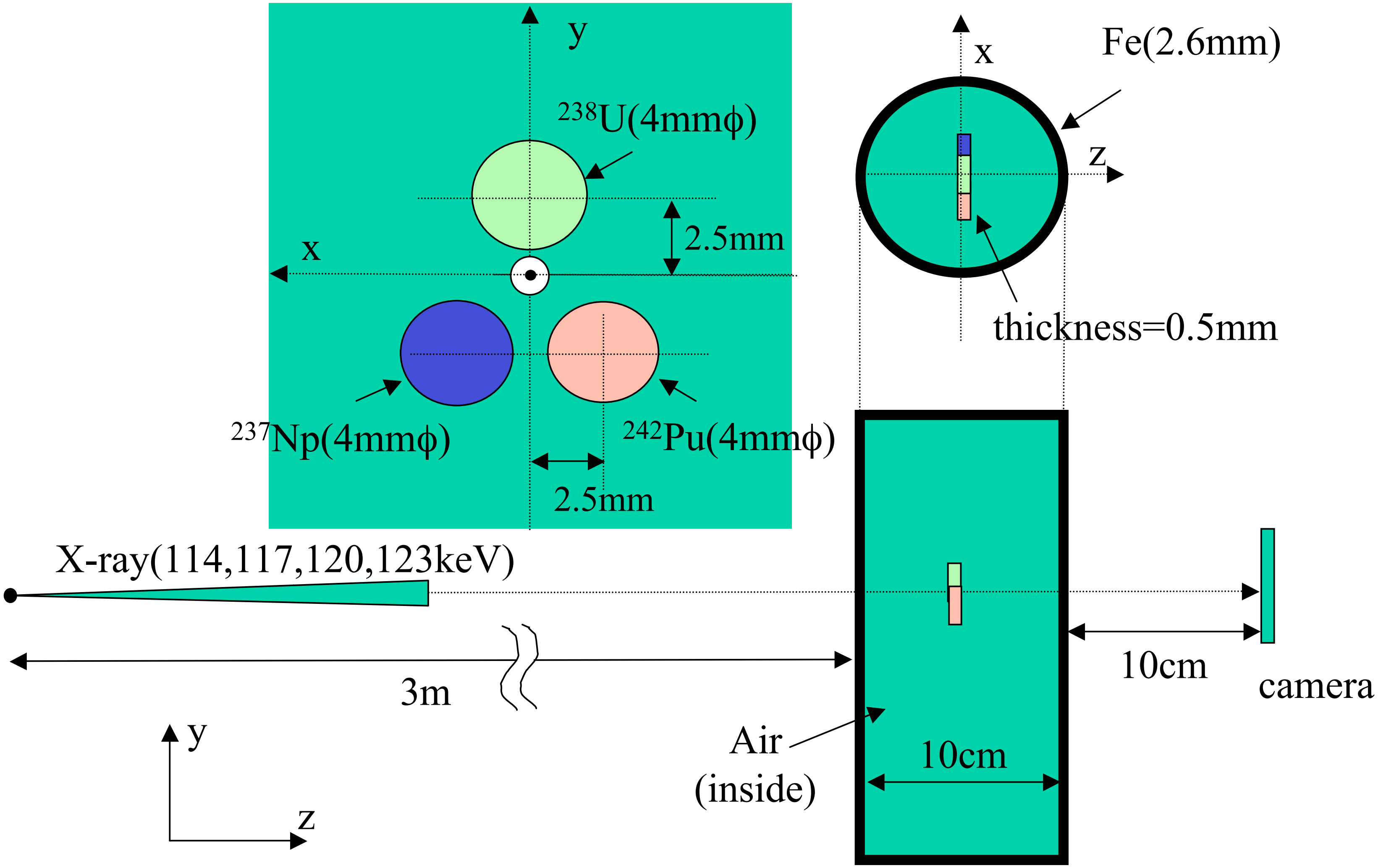
Atomic number distribution



Atomic number distribution at y=0mm

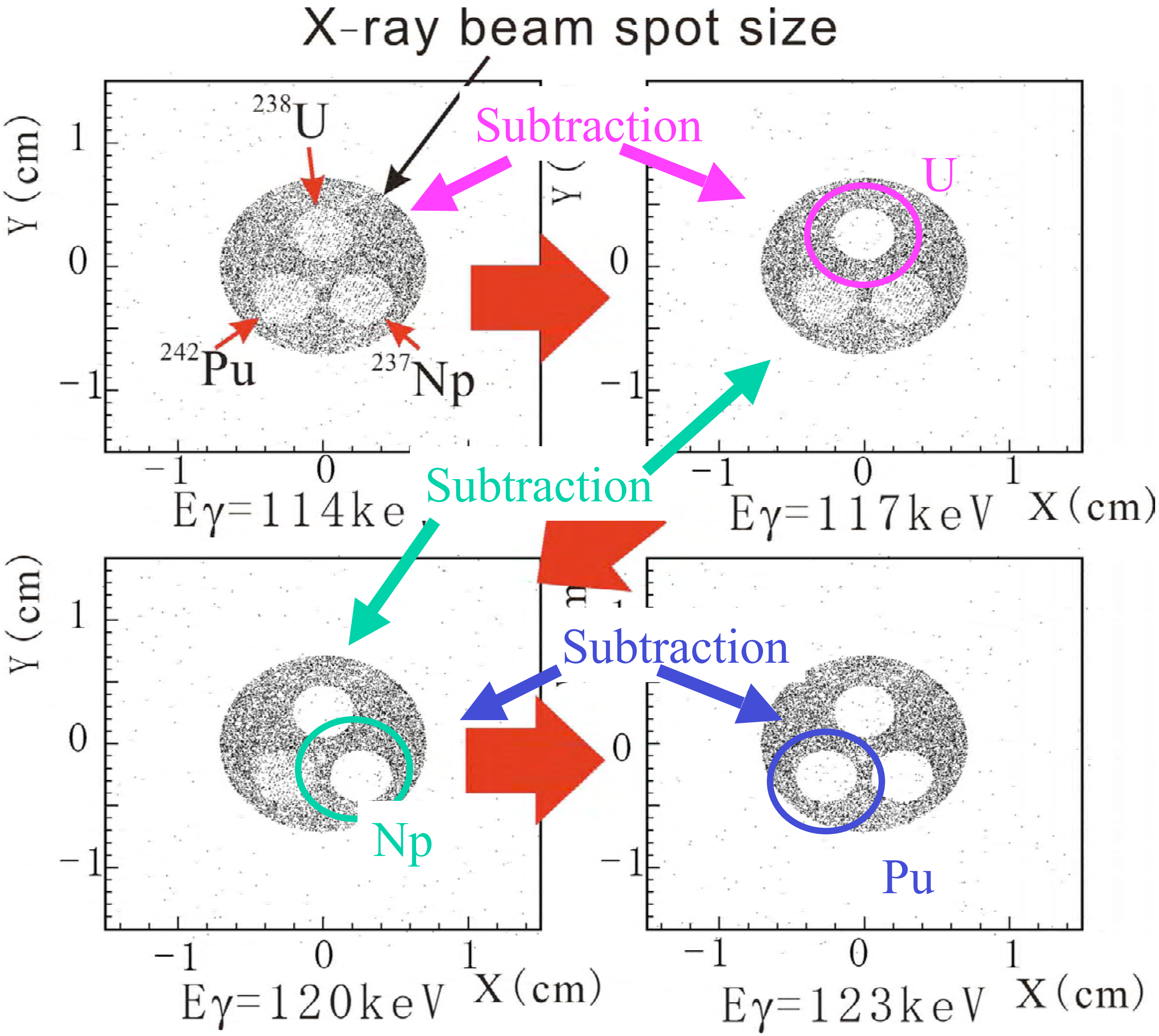


Subtraction CT across the K-edge to get 3D distribution of specified heavy atoms.



Atomic number identification for material inside iron can
(EGS4 test geometry) (**** **Radiography** ****)

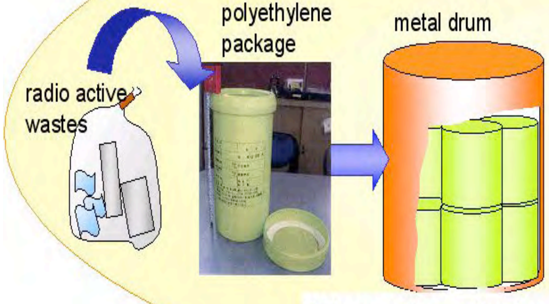
X-ray distribution at CCD camera (just a plot. Pixel size is not considered)



Application plans of the compact hard X-ray source

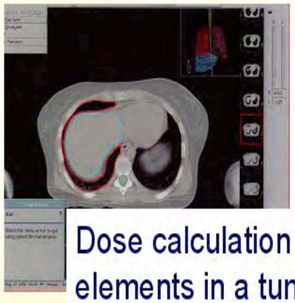
Atomic number identification by dual-energy X-ray CT

Nondestructive test



Element analysis inside a package

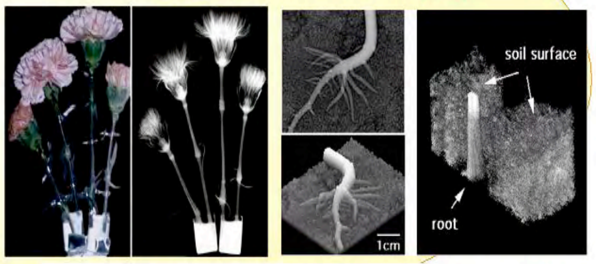
Radiation Treatment Planning



Dose calculation by considering elements in a tumor for advanced radiation therapy

Neutron radiography with X-ray CT

Imaging of water in a plant [3,4]



Movement of a element in a living plant

Compact monochromatic hard X-ray source

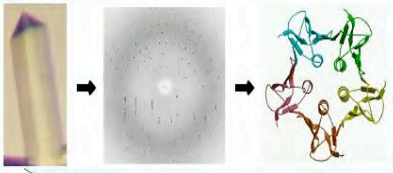
Micro vessel angiography

Image of coronary [5]

Diameter of micro vessel is less than 100μm

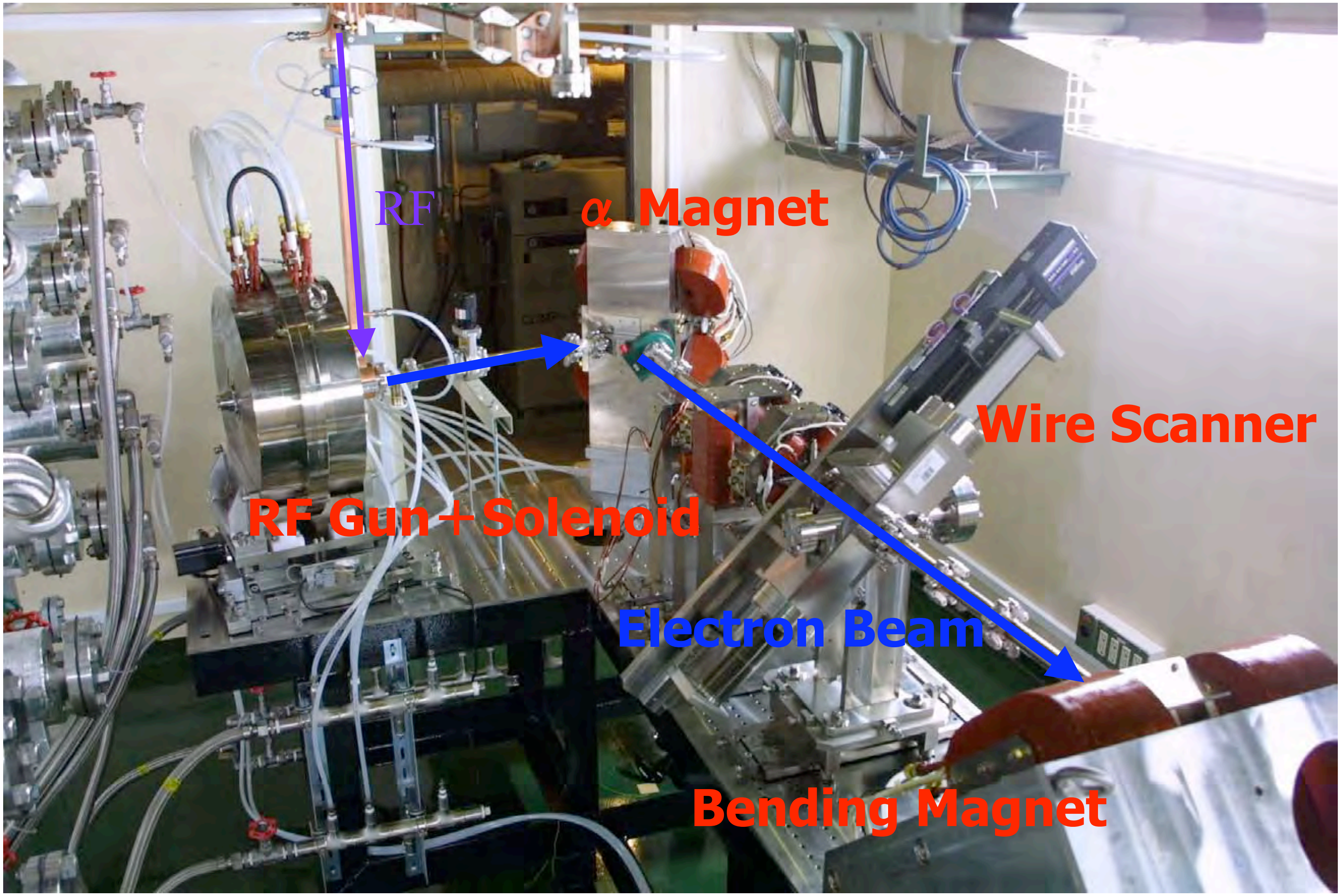
Micro vessel angiography will be tested with spatial resolution of 100μm

Protein structural analysis

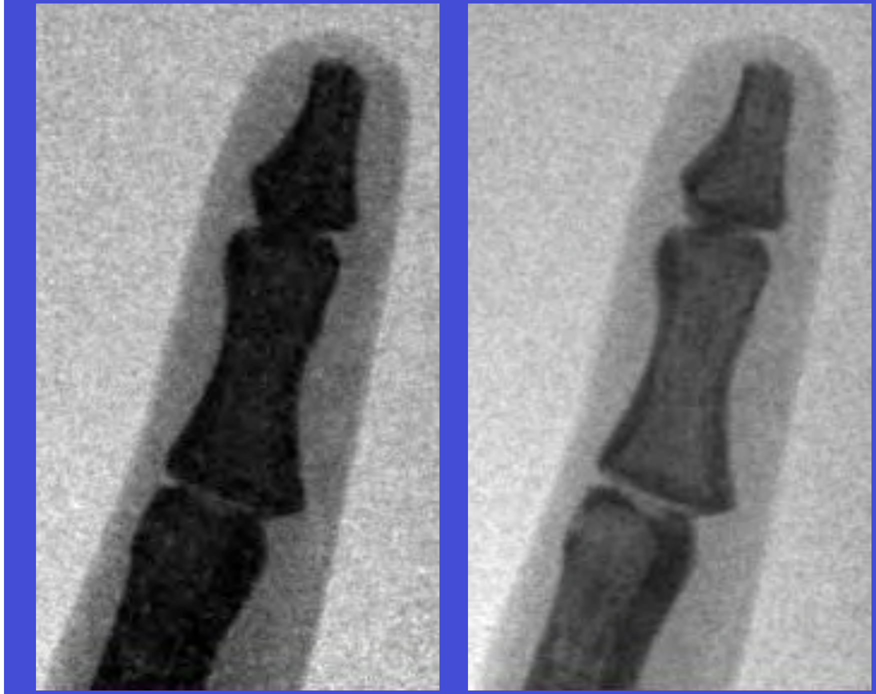


Structure analysis in a small laboratory

System of Beam-Experiment



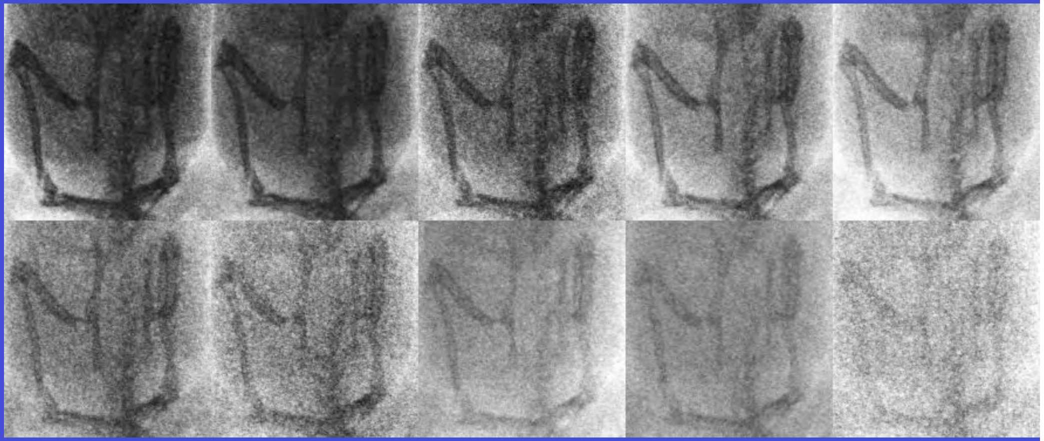
Energy differences in a finger



19 keV

29 keV

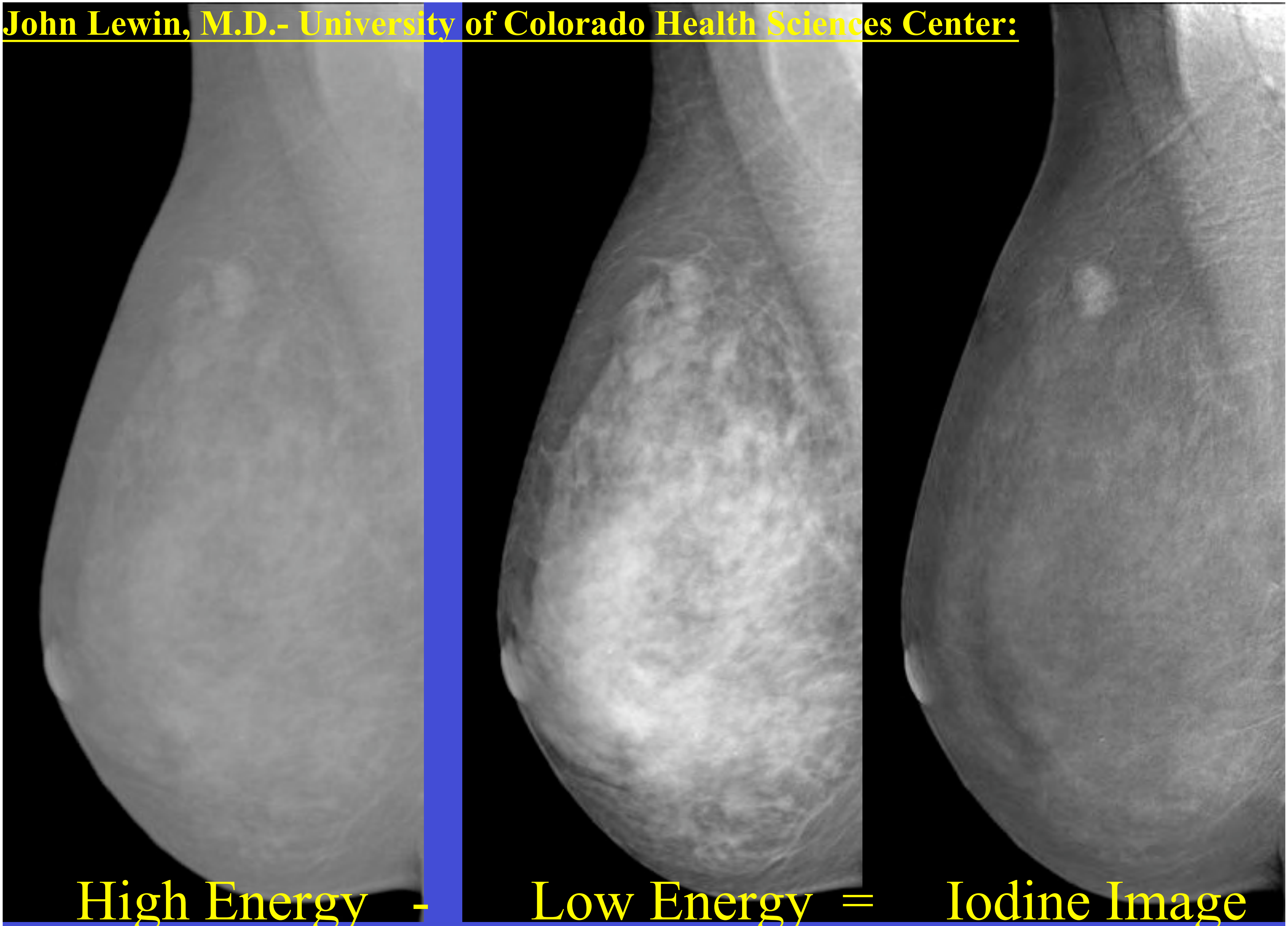
or in a body, such as a mouse



Energy movie from 15 keV to 33 keV

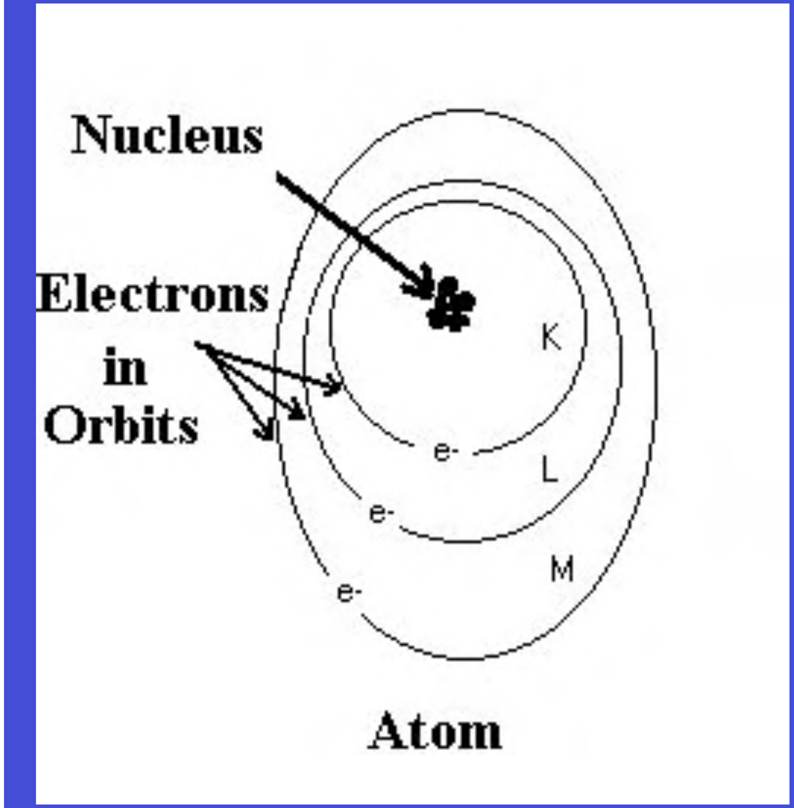
We have the ability to specifically tune the X-rays to the imaging task at hand.

John Lewin, M.D.- University of Colorado Health Sciences Center:



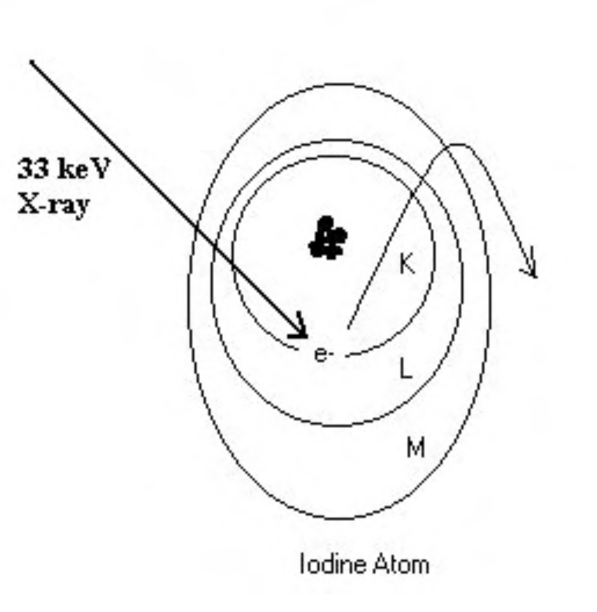
High Energy - Low Energy = Iodine Image

Stylized diagram of an atom:



Each electron is bound in its orbit by a characteristic energy for that particular atom/ orbit. This is called its binding energy. The binding energy is different for each atom in the periodic chart.

Our beam can be tuned to just the right energy to knock the k-shell electron out of its orbit. For the Iodine atom that energy is 33.2 keV.



3D Evaluation of Atomic Number Distribution

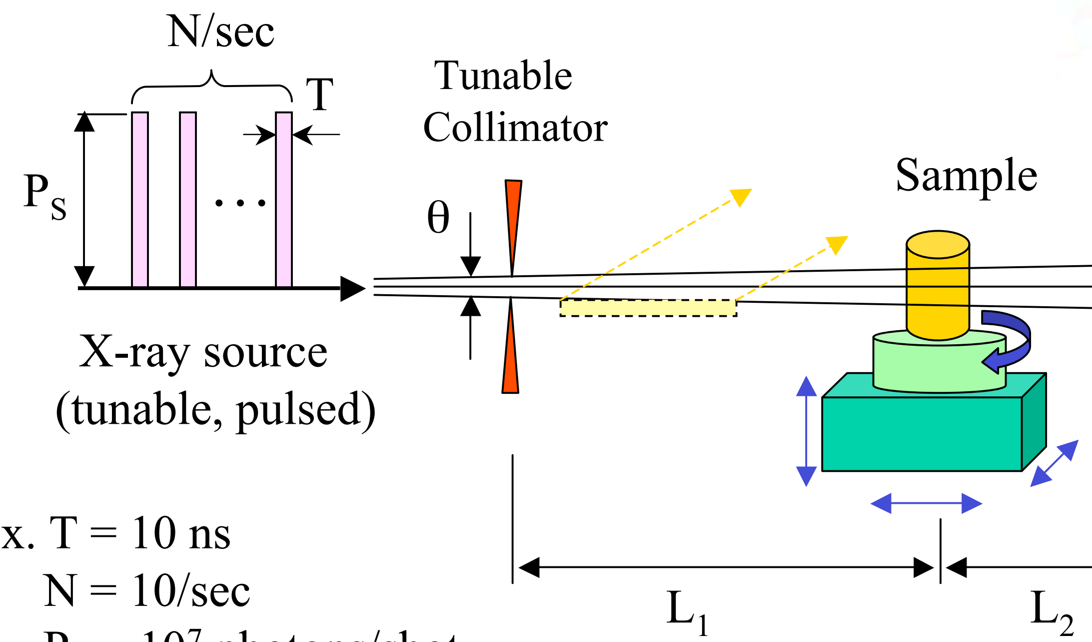
1. Light Atoms up to ^{43}Tc
- Interpolation of the X-ray attenuation constant between charateristic edges is available.
- 3D distributions of the atomic number density and electron density can be obtained
- Their spatial resolution is determined by the X-ray source size.

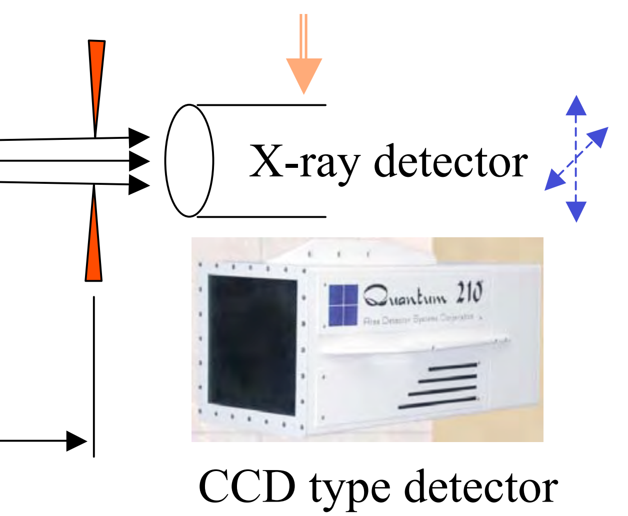
2. Heavy Atoms
- The interpolation does not work.
- Subtraction CT gives 3D distribution of specified atoms.

Scheme of CCB X-Ray Testing System

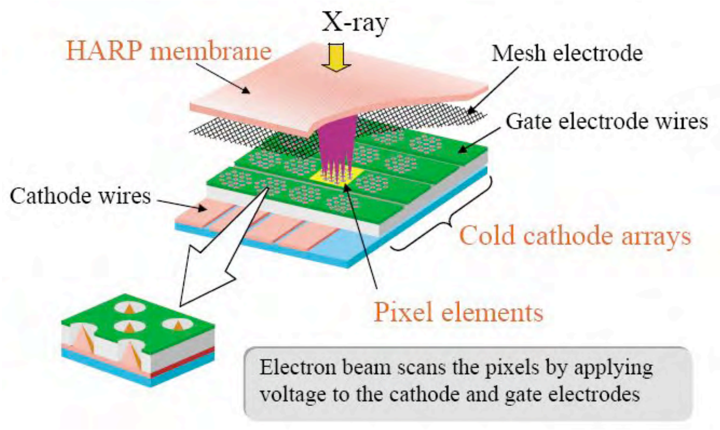
Compact Compton Backscattering
Hard X-ray Source (UTNL)

Photon energy:
10 ~ 50 keV





HARP-based detector (NHK)



Ex. T = 10 ns
N = 10/sec
$P_S = 10^7$ photons/shot
$P_F = 10^8$ photons/s
~ 10^9 photons/s; laser circulation

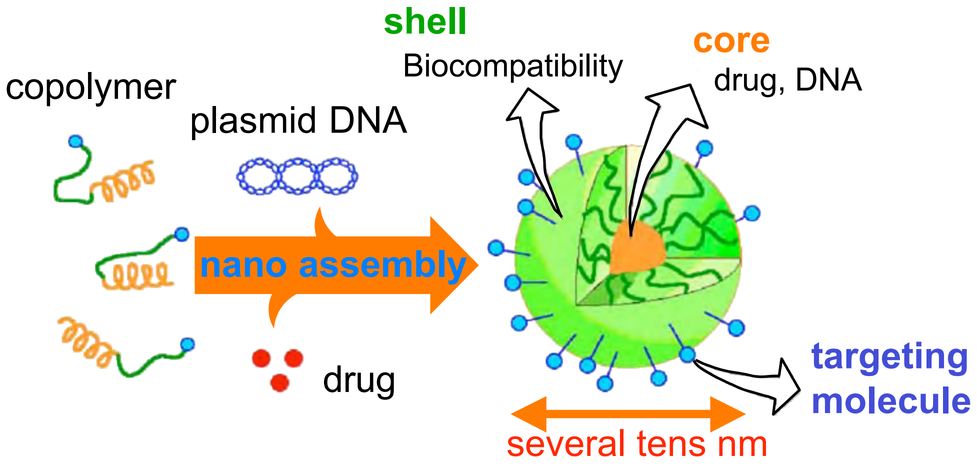
Periodic Motion of Sample (< 200 Hz)

CCD type detector
Active area: 21cm x 21cm
Spatial resolution: 90 μm
(~ 0.5 MUSD)

Applications of Hard X-ray and Nano Particles for Cancer Therapy and Diagnosis

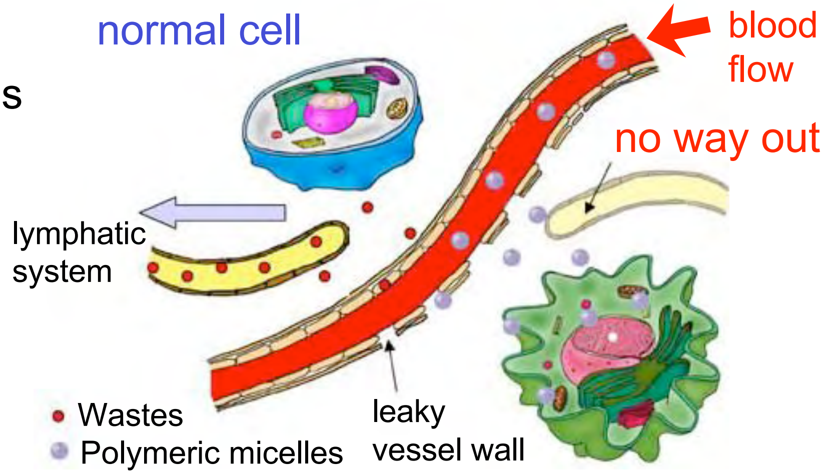
Polymeric micelles for drug delivery

- Application for cancer therapy
- Site-specific targeting and accumulation by micelles



shell
Biocompatibility
core
drug, DNA
copolymer
plasmid DNA
nano assembly
drug
targeting molecule
several tens nm

Tumor targeting



normal cell
blood flow
no way out
lymphatic system
● Wastes
● Polymeric micelles
leaky vessel wall
cancerous cell

Ref.
K. Kataoka *et. al.* Adv. Drug Del. Rev. **47** (2001) 113.
K. Kataoka lab. http://bmw.mm.t.u-tokyo.ac.jp

X-ray application for cancer therapy and diagnosis with micelles

Diagnosis

- X-ray imaging of tumors
- Contrast agent including Iodine delivered and accumulated by micelles

Therapy

- Enhanced radiation damage to cancer cells targeted and stimulated by micelles with specific agents
- X-ray irradiation to micelles for nuclei acid and protein delivery to cancer cells

4D(space and time) control of Chemo-radiology

M.Uesaka(Nuclear Engineering Research Laboratory, Univ.Tokyo)
K.Nakagawa(Department of radiology, Univ.Tokyo Hospital)

1. Advanced compact accelerators available at hospital

- **higher RF(C,X,Ka,Ku,W-bands)**
- **Compton scattering hard X-rays**
- **compact ion accelerator**
- **Table-top TW laser**

2. Spatial control

(i)X-ray and electron

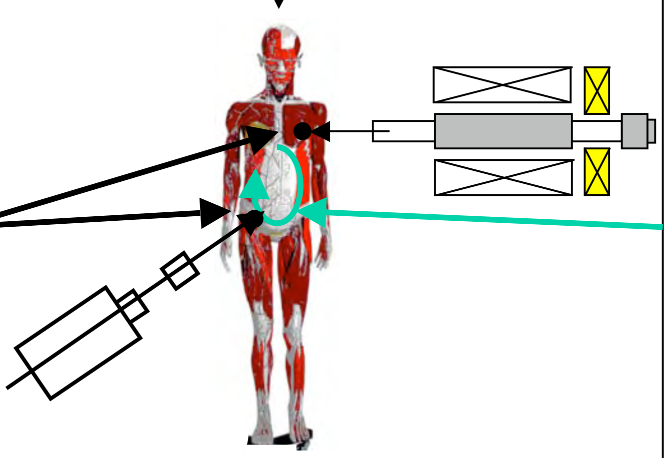
- **IMRT**

(ii)Compton scattering hard X-rays

- **Intravenous angiography**
- **Auger electron therapy**

(iii)Precise spatial dosimetry

- **new material and phantom**

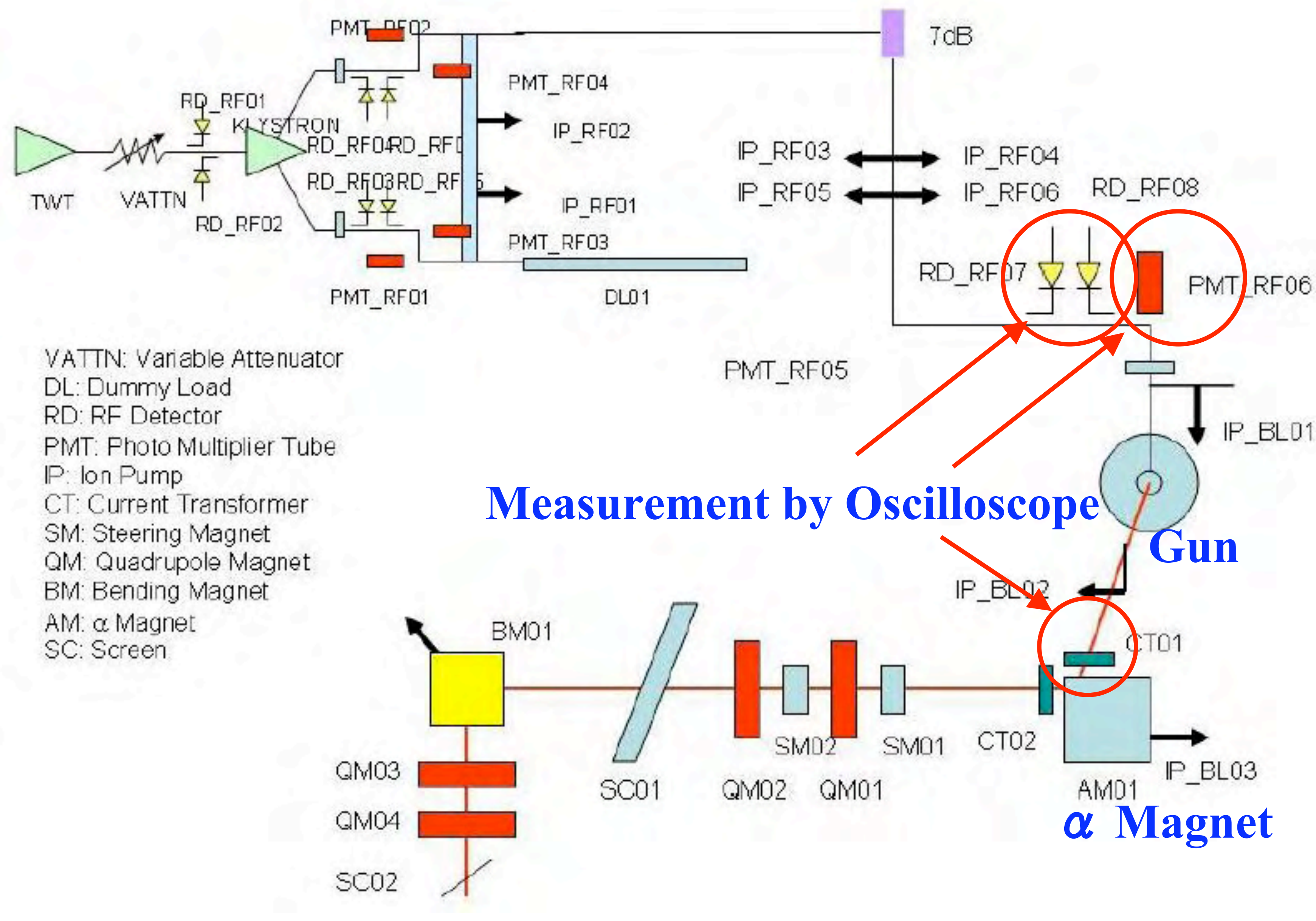


3.Temporal control

- **simulation and diagnosis for circulatory system(medicine, contrast agent, Au powder)**
- **Timing control of irradiation**
- **detection and control of oxygen content**
- **radiation chemistry of bio-water and control of OH radical content**
- **simulation and diagnosis of blood flow in capillary**
- **PET analysis**

4. Upgrading and optimization by integrated treatment program

System of RF Gun Aging



VATTN: Variable Attenuator
DL: Dummy Load
RD: RF Detector
PMT: Photo Multiplier Tube
IP: Ion Pump
CT: Current Transformer
SM: Steering Magnet
QM: Quadrupole Magnet
BM: Bending Magnet
AM: α Magnet
SC: Screen

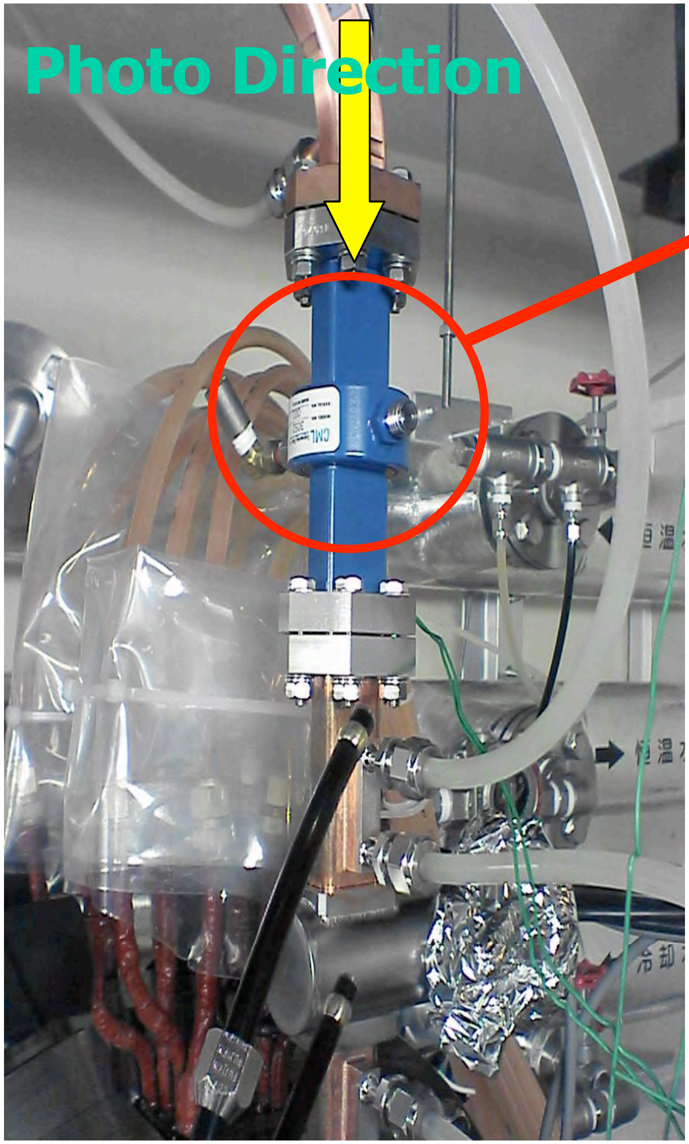
Measurement by Oscilloscope

Gun

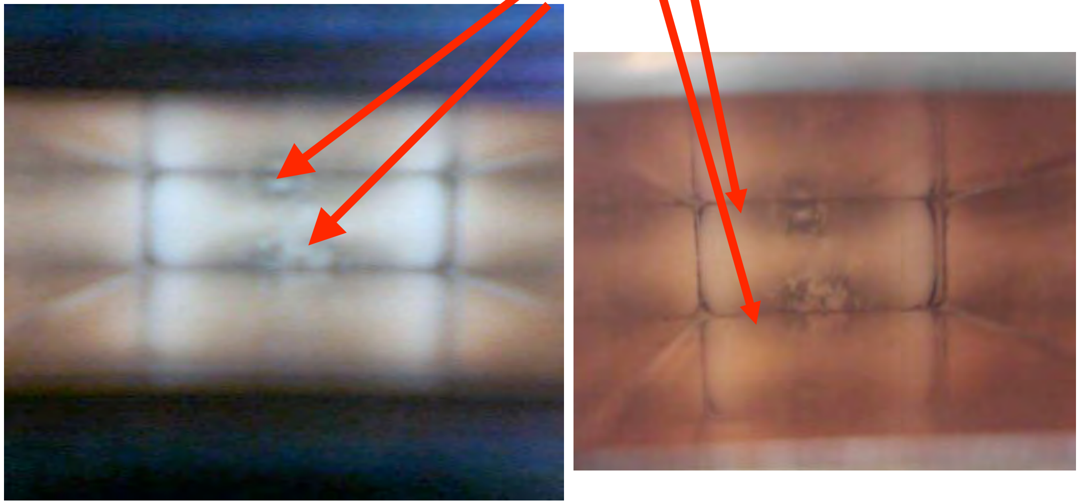
α Magnet

Trouble Point

Discharge @ RF Window（12MW）



Discharged Signatures



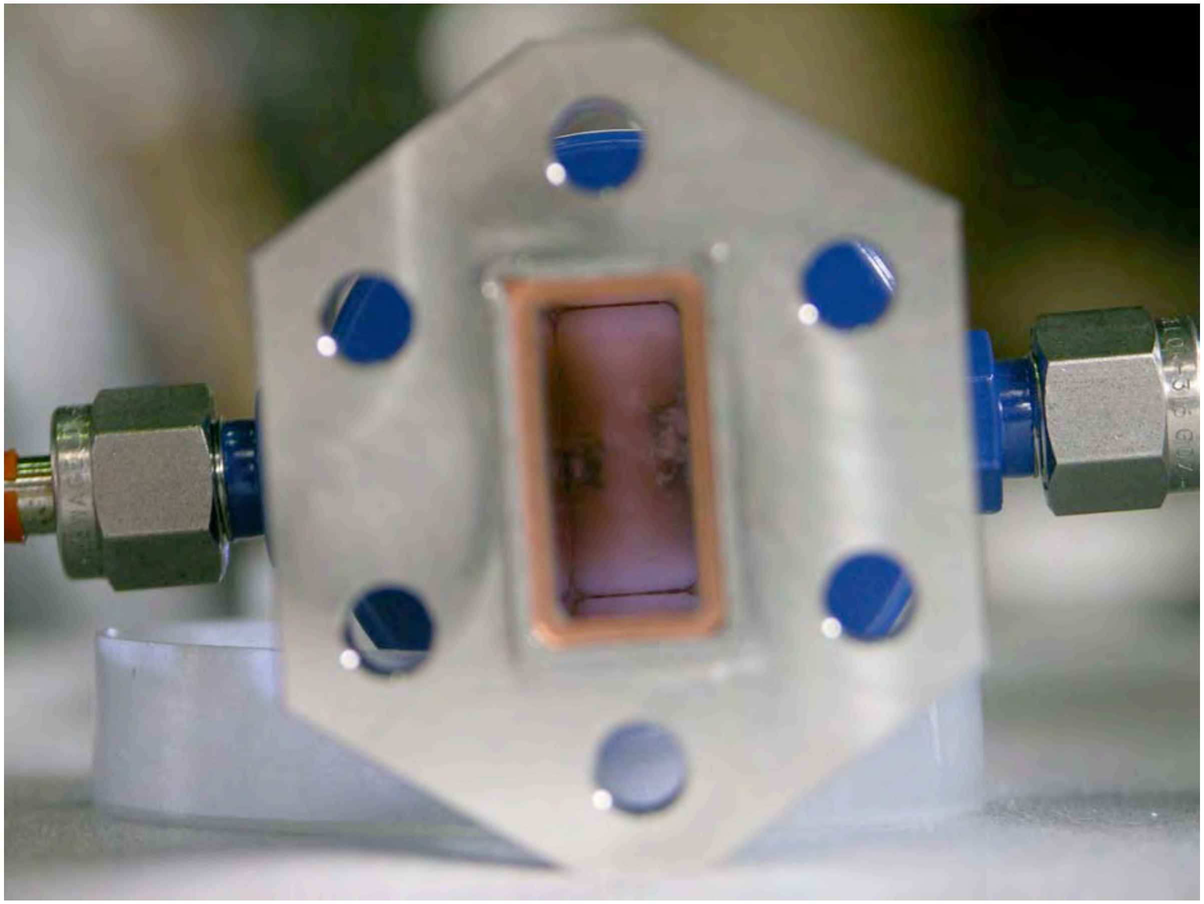
- **Discharge of multi-pactaring**

In addition, We could not see discharged signature at Gun side.

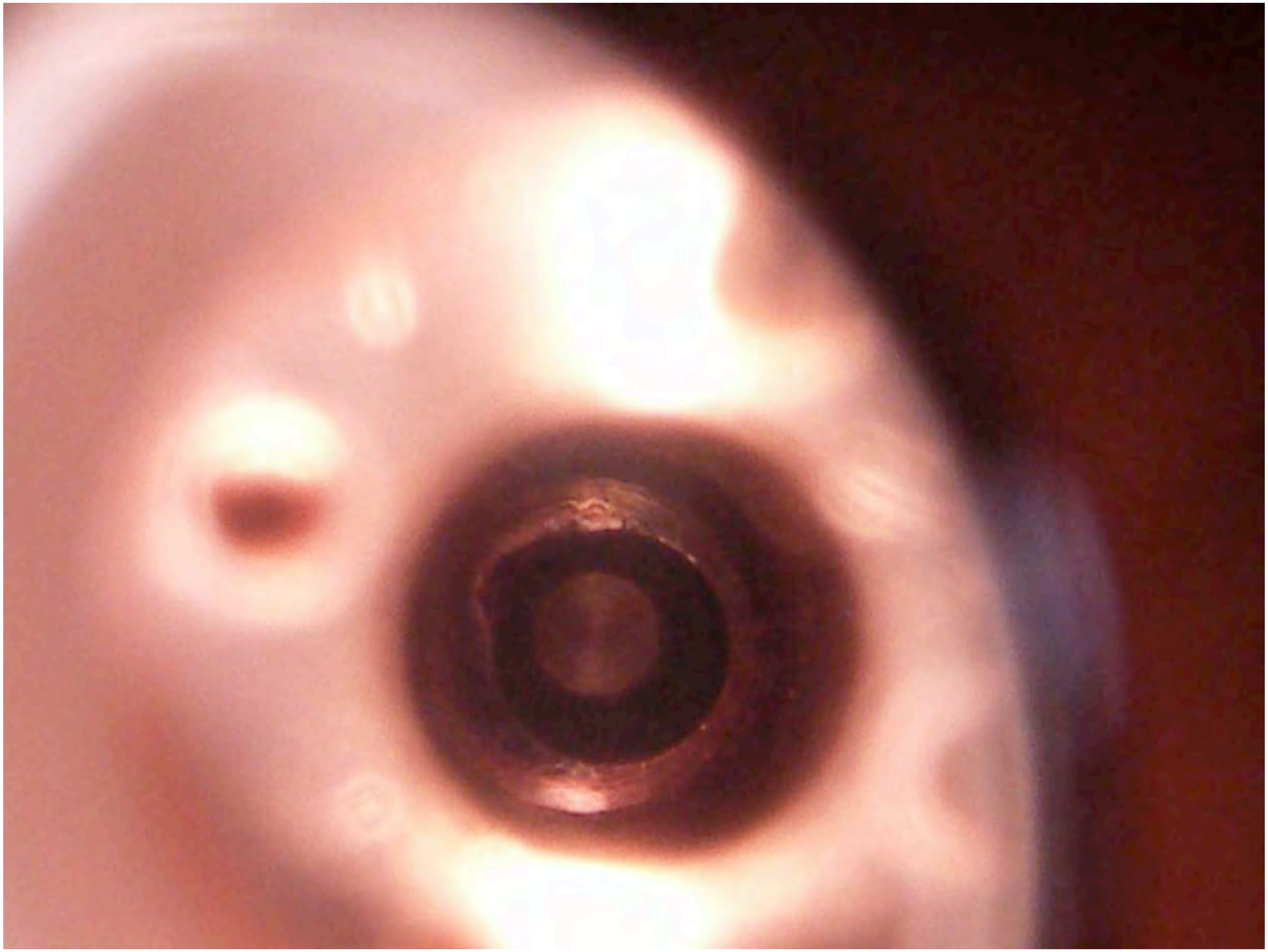
Worse vacuum at upstream

Amplified discharge

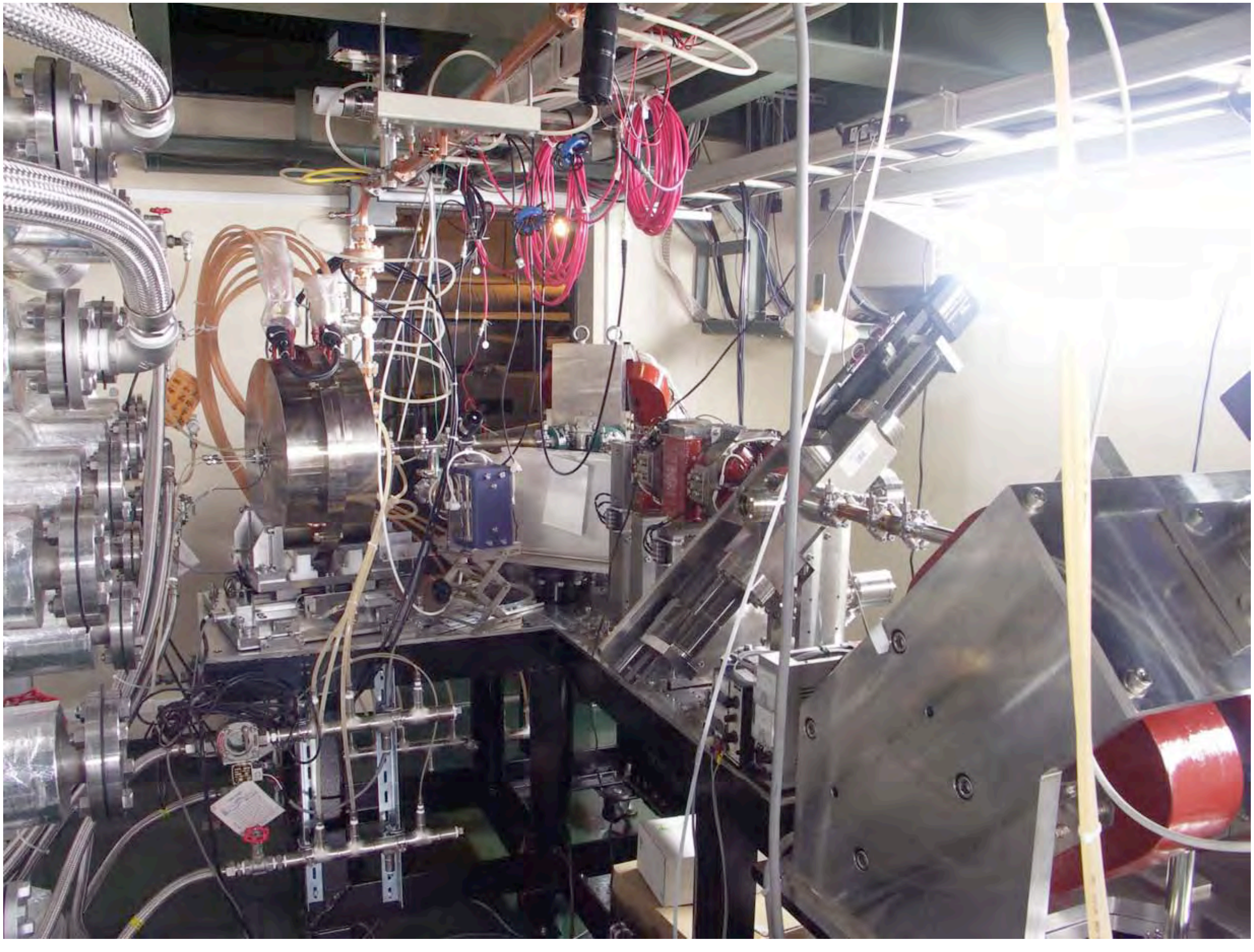
Discharged Signatures



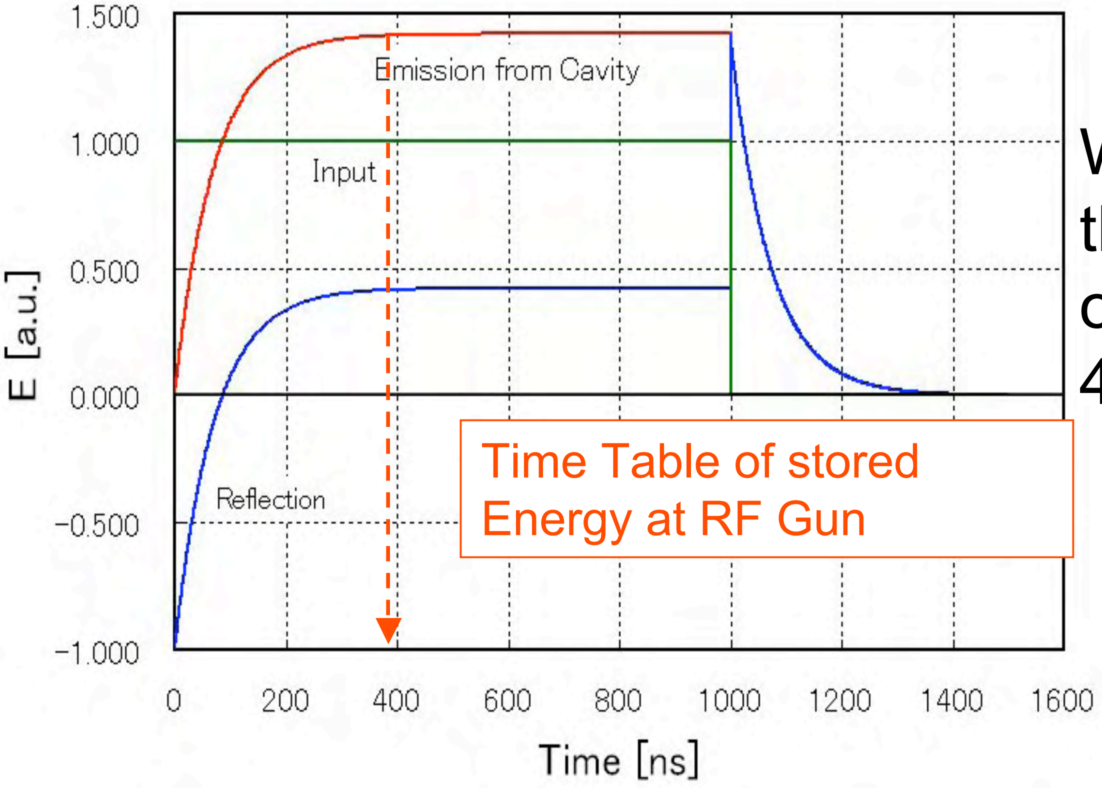
Cathode



New Beam Line



Stored Energy & Reflection

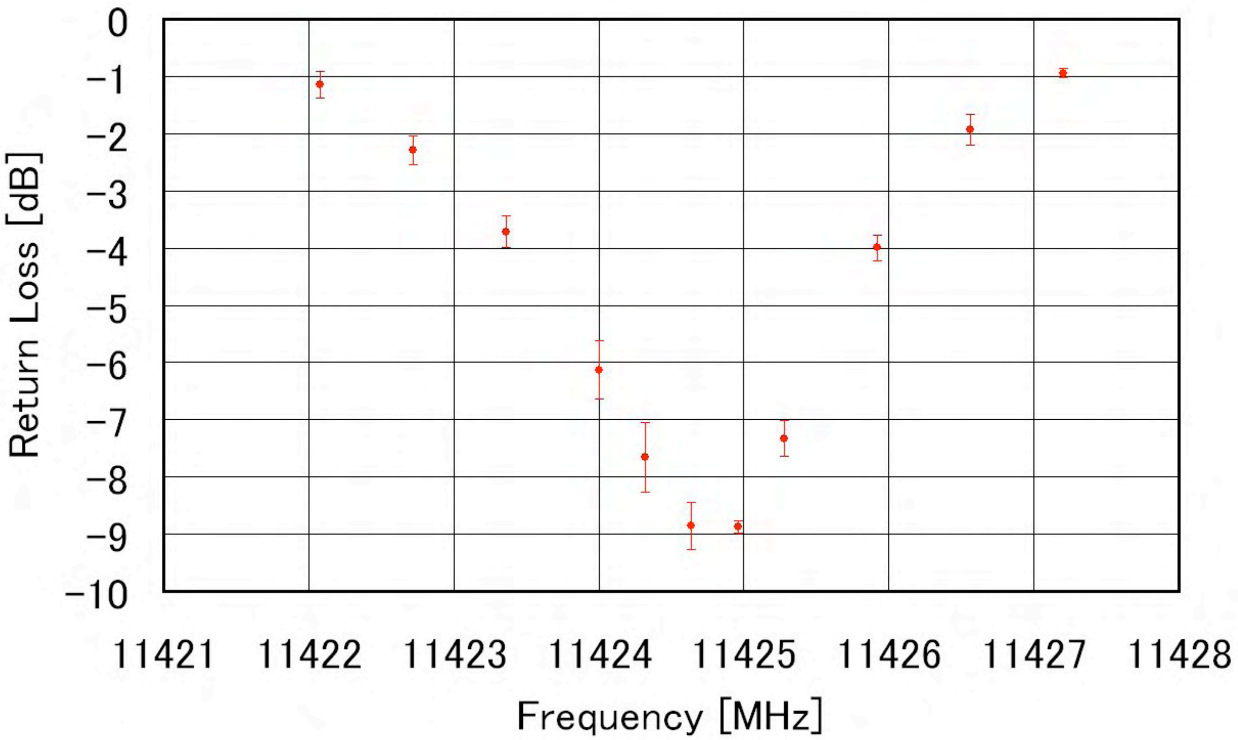


Time Table of stored Energy at RF Gun

We can evaluate the characteristics of the gun with 400ns pulse.

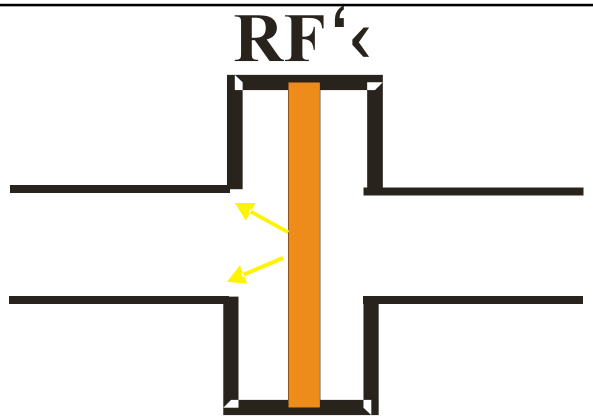
Flat → Cavity has been filled

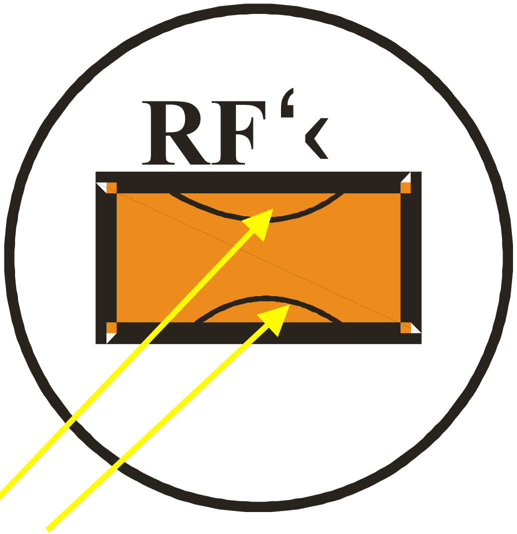
Return loss at the gun



Discharged signatures remain like shape of 8.

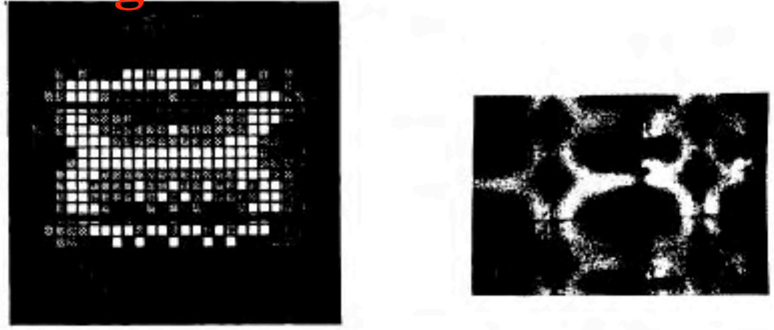
Discharge of multi-pactaring





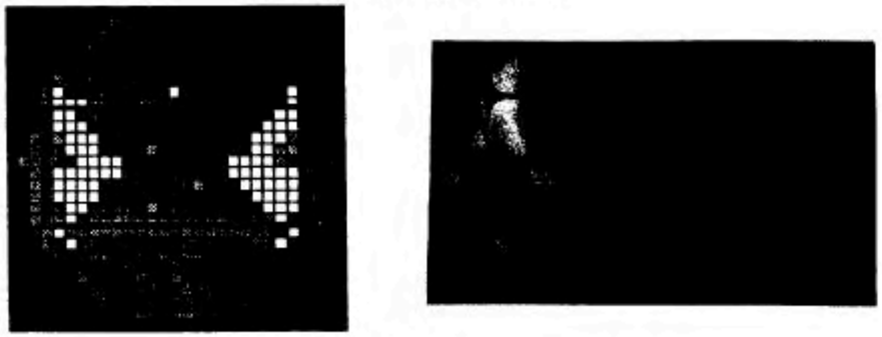
Discharged Signatures

Development of an S-band RF Window
for Linear Colliders
A.MIURA and H.MATSUMOTO
KEK Preprint 92-215 March 1993 A



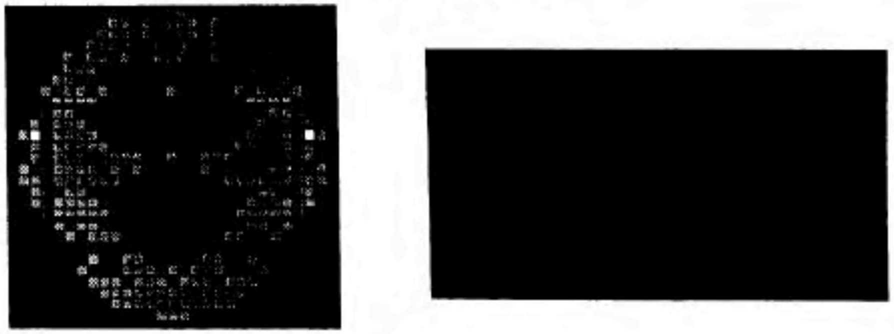
(a1) (b1)

Transmission power of 4MW



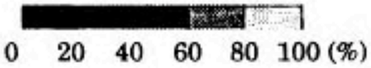
(a2) (b2)

Transmission power of 10MW

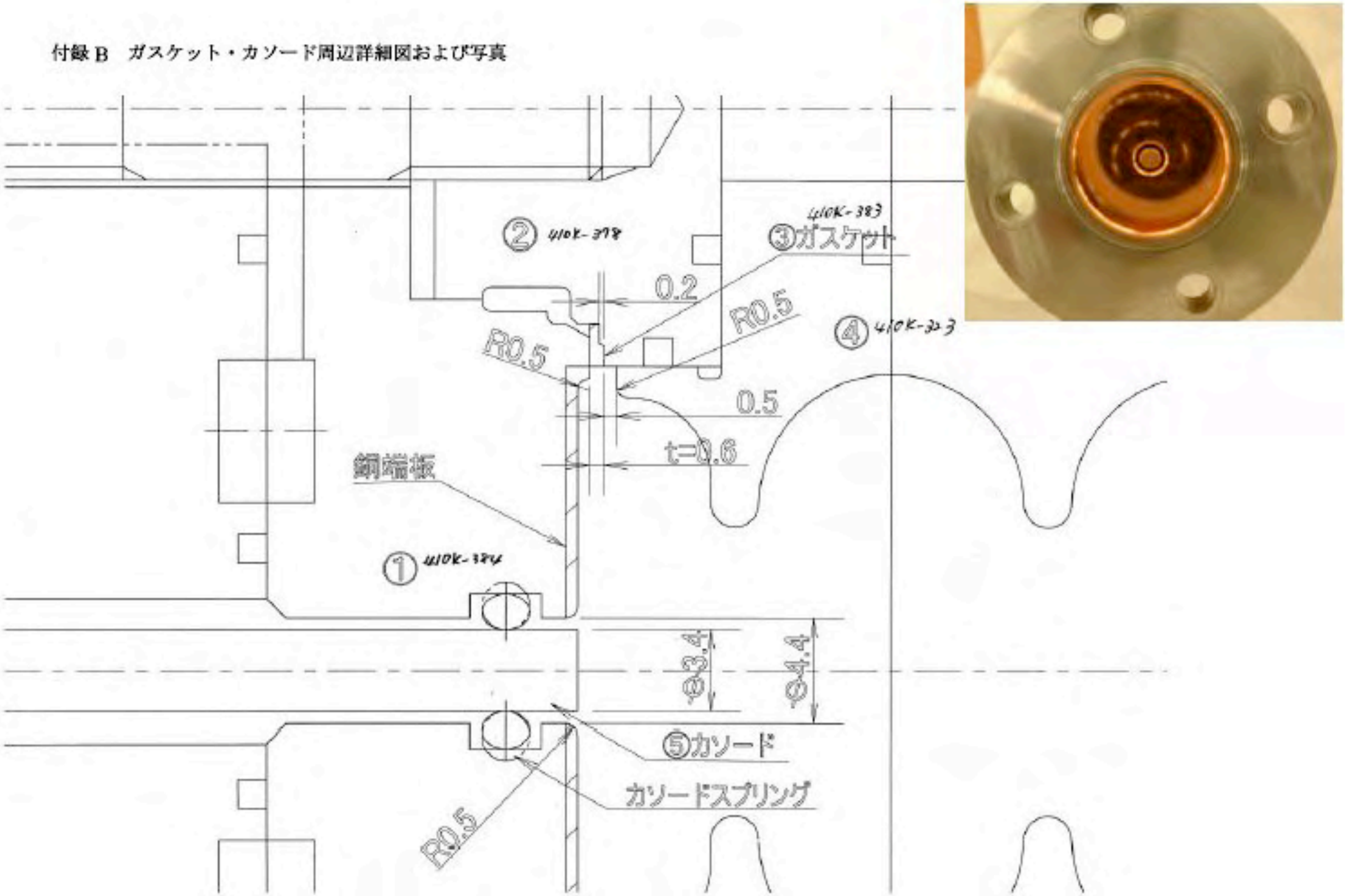


(a3) (b3)

Transmission power of 50MW



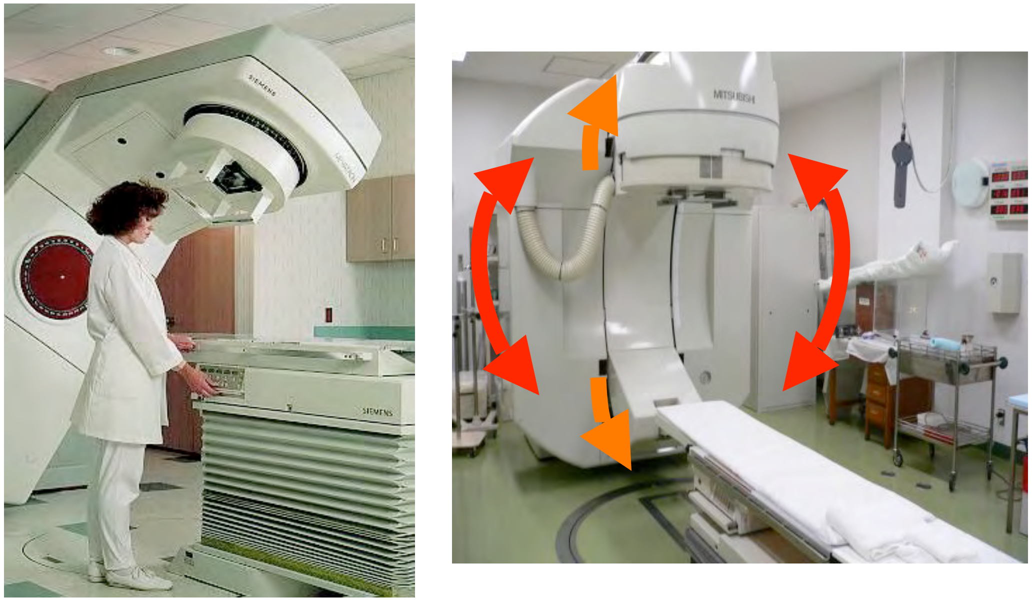
付録 B　ガスケット・カソード周辺詳細図および写真



Design of New Compact Stereotactic X-band Therapy Machine

Stable and high-current commercial S-band machine, but large

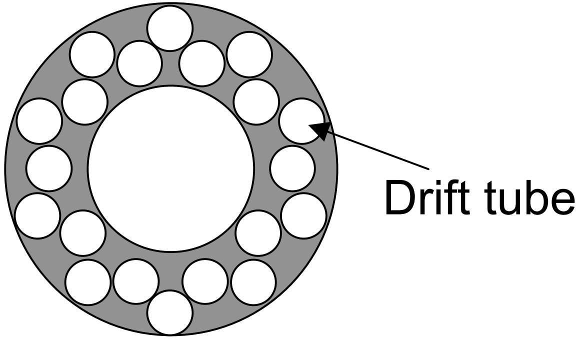
Compact X-band(9.3GHz) machine, but unstable and low-current



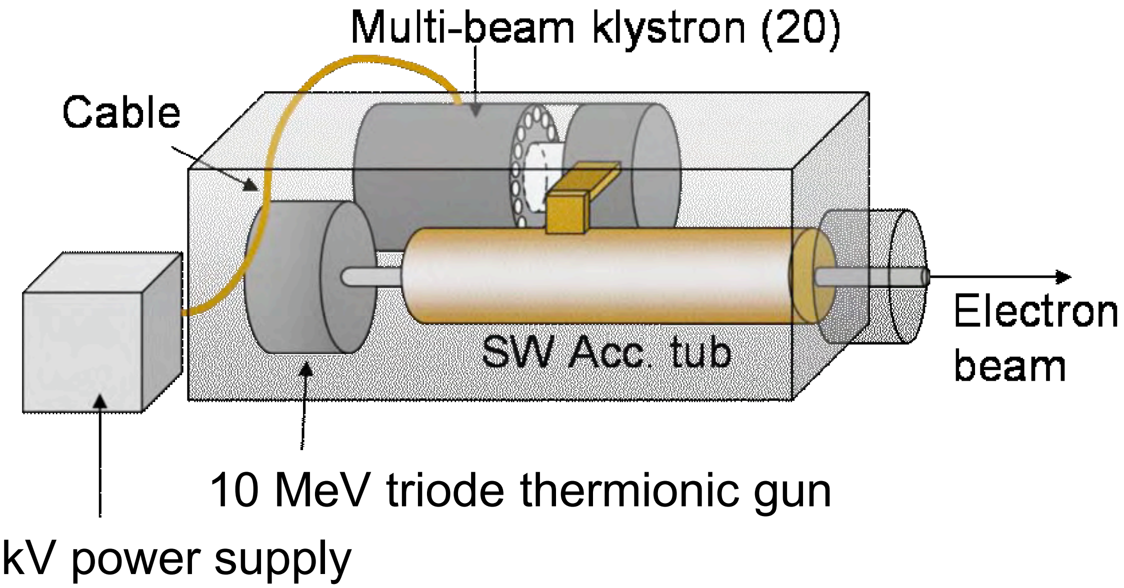
This stability and high-currents

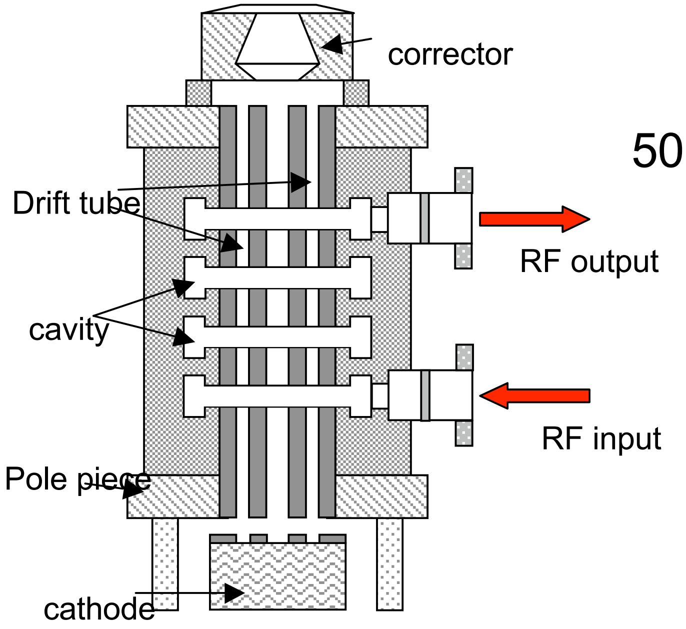
This size

Schematic layout of compact accelerator using multi-beam klystron (Type 1)

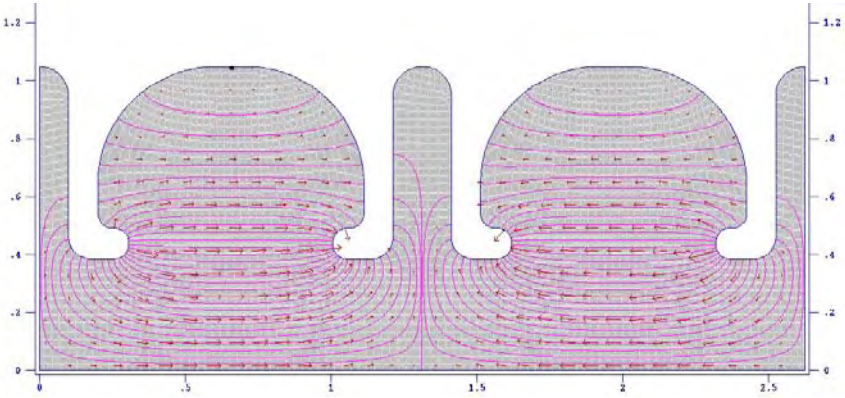


Top view



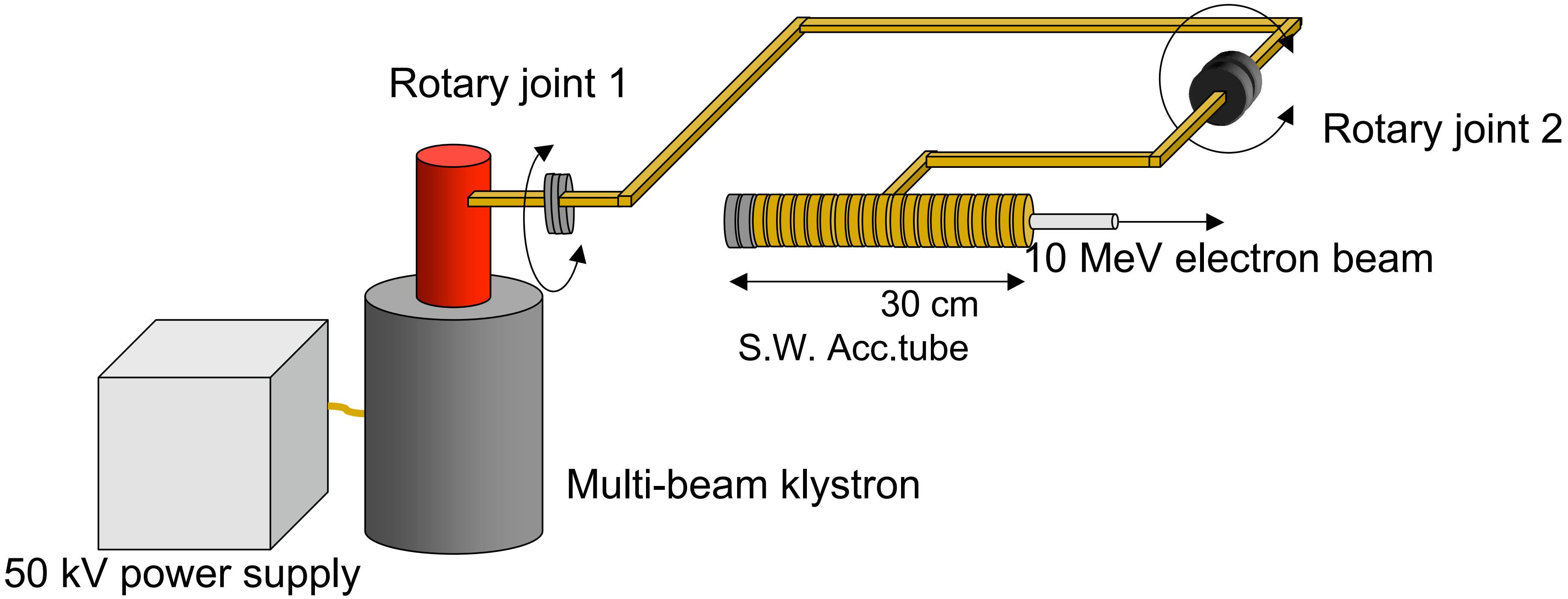


Side view



Structure of standing wave acc. tube

Schematic layout of compact accelerator using multi-beam klystron (Type 2)



Hard X-ray Sources by Thomson Scattering

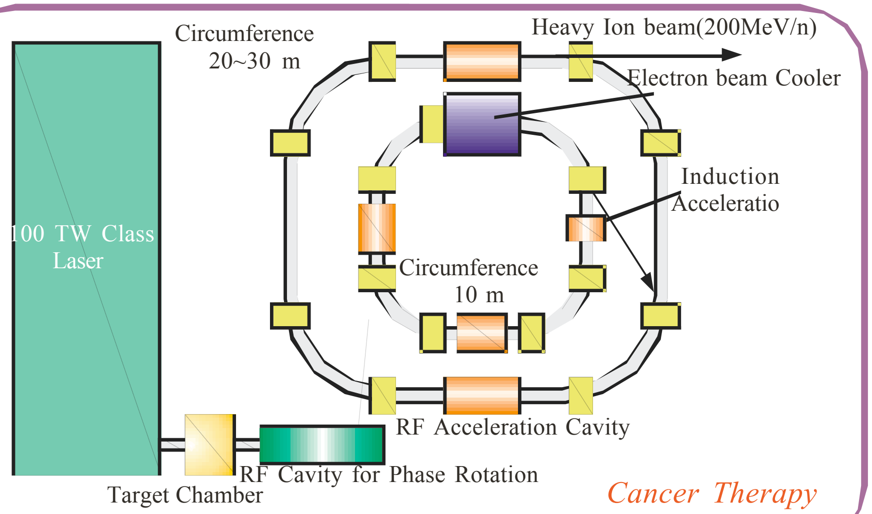
	Electron energy	Electron Charge	Laser wave length Laser Power	X-ray energy Photon number
Sumitomo [1] Heavy Industry	14 MeV (S-band)	400pC Single bunch	800nm, 300mJ (Ti:Sapphire, 300ps)	3.5keV <1.0E+4 photon/shot
[2] MXI Systems Inc	25MeV (S-band)	500pC Single bunch	1μm, 20J (Nd:Glass)	12, 50keV <1.0E+8 photon/sec
[3] **Univ.Tokyo/NIRS / KEK**	**35MeV (X-band)**	**20pCx10000 Multi bunch**	**1μm, 2J (Nd:YAG, 10ns)**	**33keV <1.0E+8 photon/sec**
Univ.Tokyo /NIRS	**~10MeV (Laser Plasma Acc.)**	**>10pC Single bunch**	**800nm, 300mJ (Ti:Sapphire, 40fs)**	**10-20keV ~2.0E+7photon/sec**

[1] :M.Yorozu *et al.* Jpn.J.Appl.Phys., Vol.40 (2001) pp. 4228-4232
[2] :F.E.Carroll *et al.* Am.J Rentgenol. 181 (2003) 1197
[3] :K.Dobashi *et al.* Jpn Appl.Phys., Vol.44 (2005) pp. 1999-2005

Therapy Accelerator

	Average Current	Peak Current	Repetition rate
Present Medical Linac Acc.	~30mA	~500 mA (3μs)	300Hz
Laser Plasma Acc.	~100 pA	~200 A (~50fs)	10Hz

Development of Advanced Compact Accelerators



Circumference
20~30 m

Heavy Ion beam(200MeV/n)

Electron beam Cooler

Induction
Acceleratio

100 TW Class
Laser

Circumference
10 m

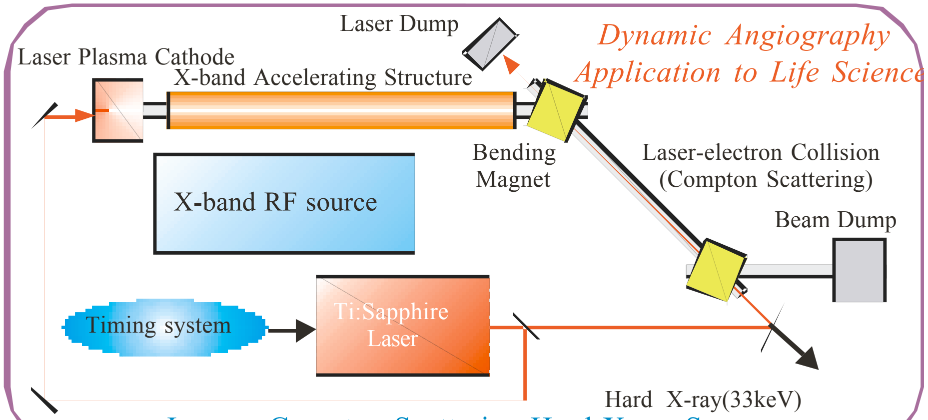
RF Acceleration Cavity

RF Cavity for Phase Rotation

Target Chamber

Cancer Therapy

Heavy Ion Synchrotron



Laser Dump

Laser Plasma Cathode

X-band Accelerating Structure

Dynamic Angiography
Application to Life Science

Bending
Magnet

Laser-electron Collision
(Compton Scattering)

X-band RF source

Beam Dump

Timing system

Ti:Sapphire
Laser

Hard X-ray(33keV)

Inverse Compton Scattering Hard X-ray Source

Virtual Laboratory

Japan Atomic Energy
Research Institute

National Institute of
Radiological Sciences

The University
of Tokyo

Hiroshima
University

Osaka
University

Kyoto
University

Advanced Industrial
Science and Technology

High Energy Accelerator
Research Organization

Japan Nuclear Cycle
Development Institute

Staged Development of Compact Accelerator at University of Tokyo

S-band Linear Accelerators

RF 2.856 GHz

Gradient 10 MV/m

User Facility

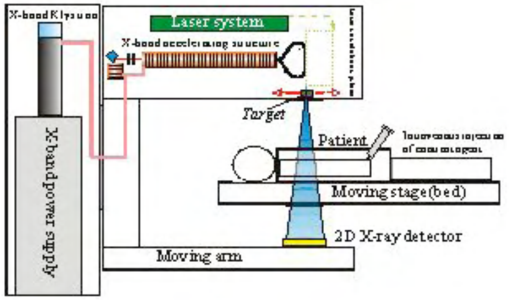
Application:Radiation Chemistry/Physics, Beam Physics

Size: Building

X-band Linear Accelerator

RF 11.424 GHz

Gradient 40 V/m



Proto-type Development

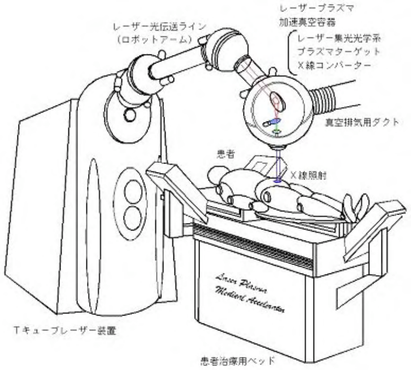
Application:Dual-Energy/Subtraction X-ray CT for Medical Use

Size: Room

Laser Plasma Accelerator

RF 10～100 THz

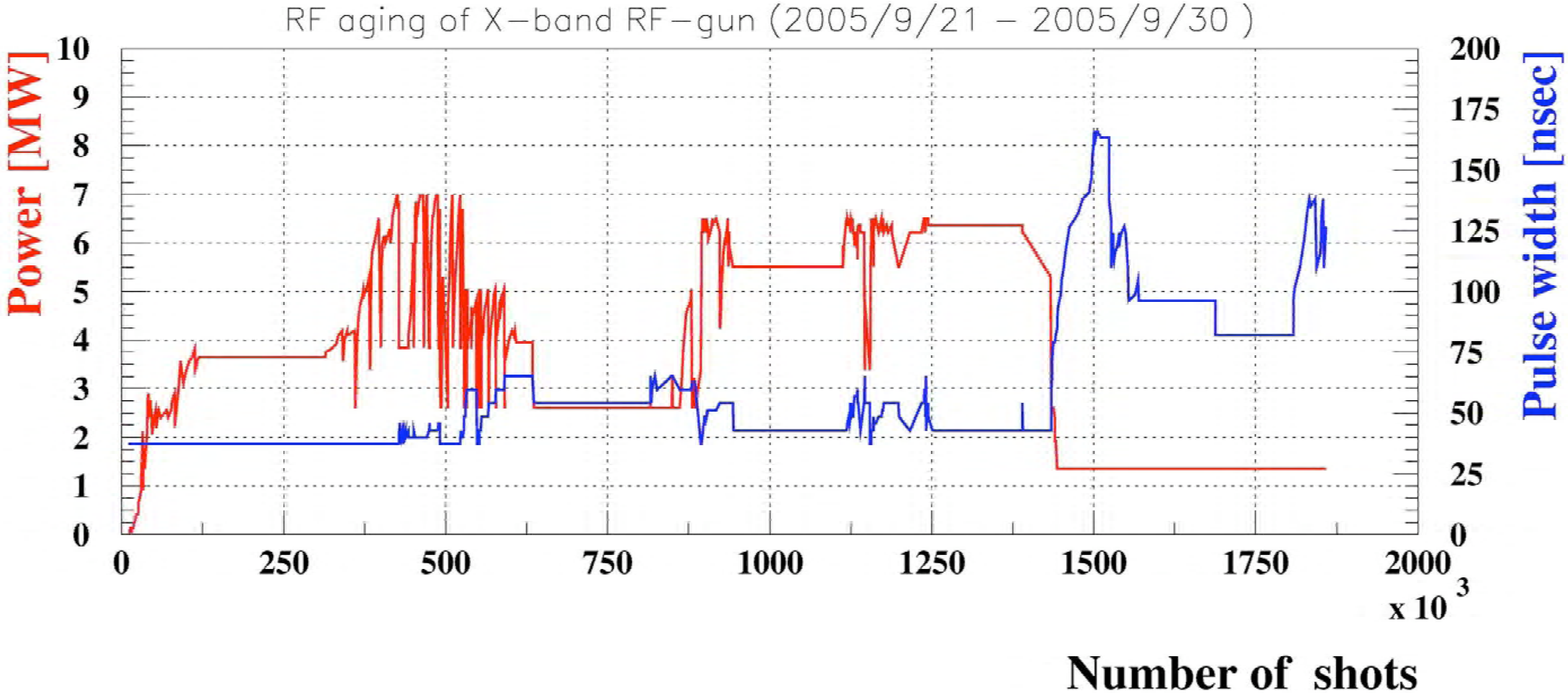
Gradient ～100GV/m



Beam Physics

Size: Table-top

History of RF aging of RF-gun



Development of an X-band Photoinjector at SLAC*

A. E. Vlieks, G. Caryotakis, R. Loewen, D. Martin, A. Menegat
SLAC, 2575 Sand Hill Rd, Menlo Park, CA 94025, USA
E. Landahl, C. DeStefano, B. Pelletier, and N.C. Luhmann, Jr.
3001 Engineering III, Dept. of Applied-Science
Davis, CA 95616, USA

Ｘバンドライナック・コンプトン散乱Ｘ線パラメータ

ＲＦガン	セル数	5.5
	電界強度（カソード面）	200ＭＶ/ｍ@16ＭＷ
	Filling time	65ns
	カソード材質	銅
	ＲＦパルス幅	200ns
	エネルギー	7MeV
	電荷	0.5nC/サブピコ秒
	エミッタンス	1π mm.mrad
ライナック	エネルギー	60MeV
	パワー	60MW
	クライストロン	
	繰り返し	60Hz
	加速管長	1.05m
レーザー		Ti:Sapp.
X線	エネルギー	20－85keV
	フラックス	～10^{8}光子/ s

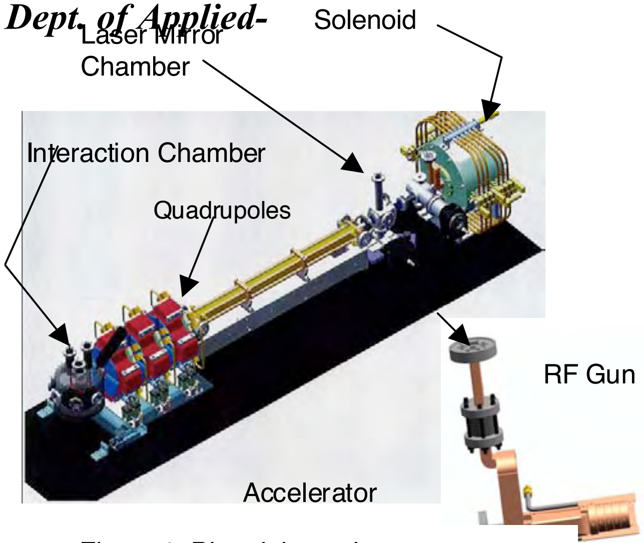
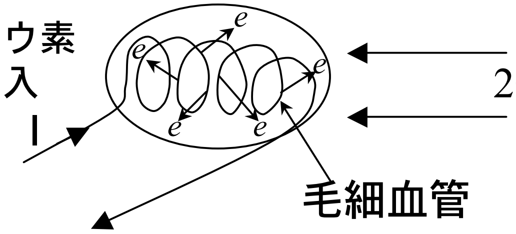


Figure 1. Photoinjector Layout

応用

Ｘ線照射2次電子ガン治療
ガン細胞



ヨウ素注入

20-85keVＸ線

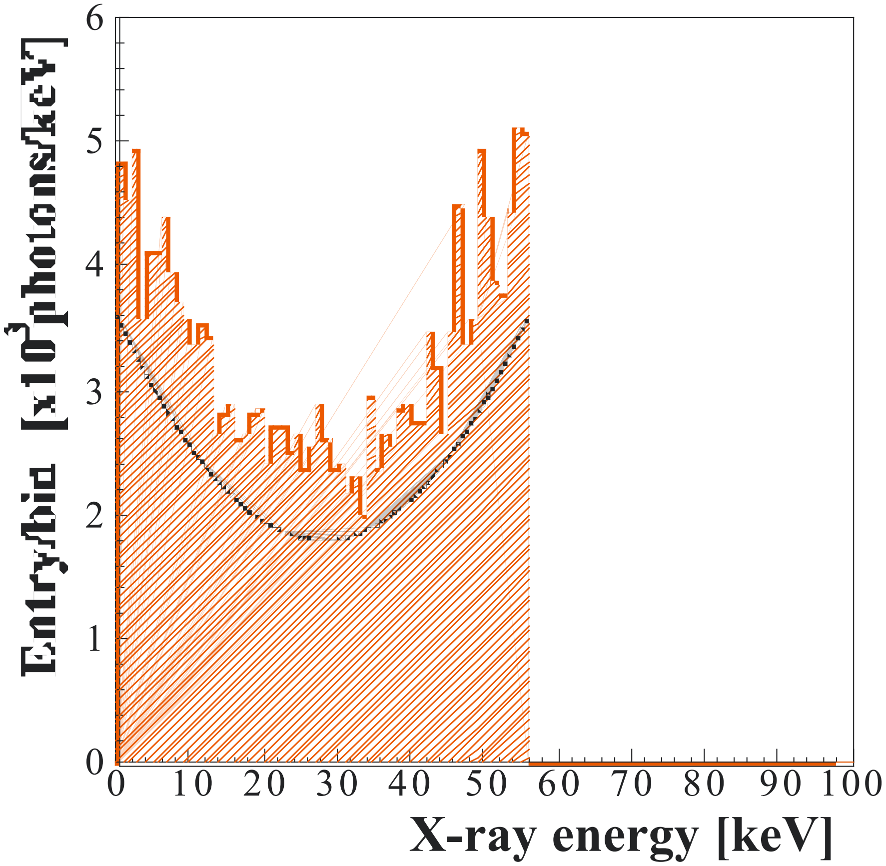
毛細血管

UCLA, Univ.Michigan 医学部と共同研究

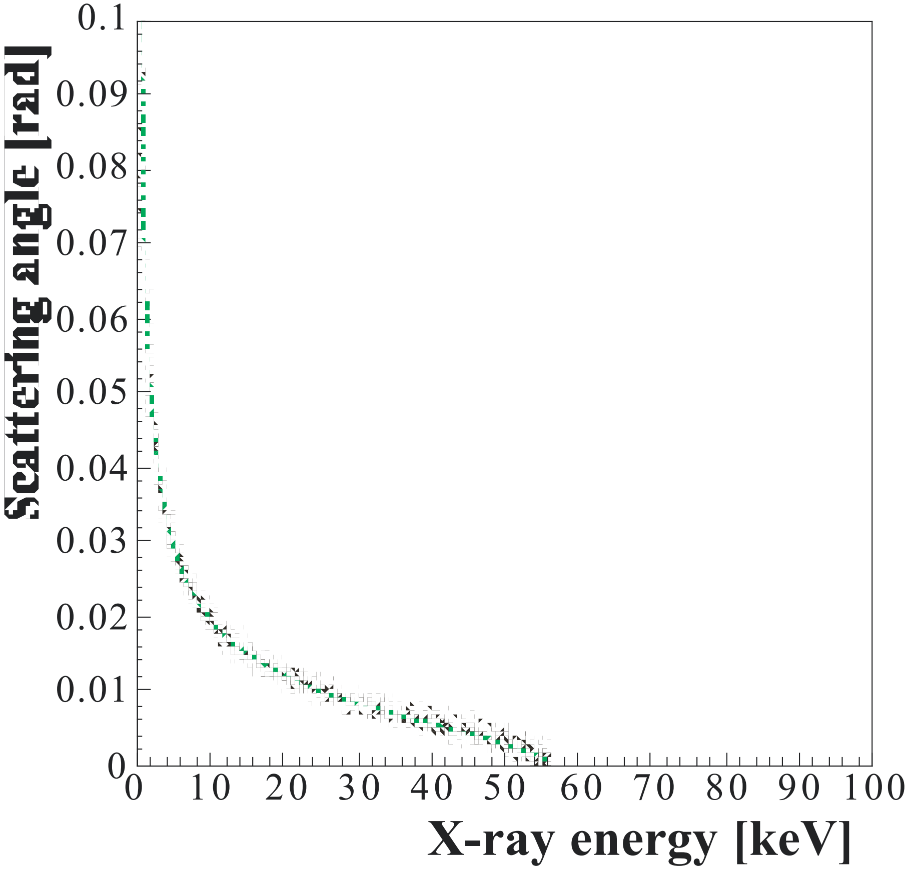
Result of beam-beam interaction Monte-Carlo Simulation code CAIN and Klein-Nishina's equation

(CAIN: K .Yokoya@KEK)

Energy spectrum



Angular distribution



X-ray Yield: $1.7\text{x}10^7$photons/laser-pulse x 10 circulation x 10 pps =$1.7\text{x}10^9$photons/s