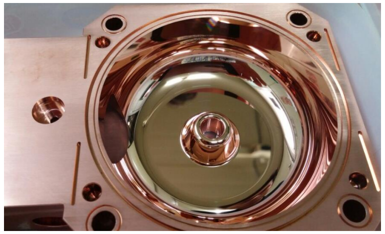
January 29th, 2018, Daejeon, Korea



KAERI 한국원자력연구원
Korea Atomic Energy Research Institute

KAERI's Developments of Various Electron Accelerators for Medical/Industrial/ Basic Scientific Applications

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- ☐ Short Introduction to KAERI
  - KAERI Facts and KAERI's Accelerators
  - KAERI's Roadmap for Developments of Electron Accelerators
- ☐ Introduction to Electron Linear Accelerators (Linacs)
  - Applications of MeV Range Electron Linacs
  - Main Components of Low Energy RF Linacs
- ☐ Electron Linear Accelerator (Linac) Developments at KAERI
  - 6 MeV & 15 MeV S-band Linacs for Medical, CIS, and NDT
  - 6 MeV X-band Linacs for CyberKnife
  - 10 MeV 10 kW Linac for Electron Beam Irradiation Facility
  - S-band RF Gun for Ultrafast Sciences
  - 20 MeV Superconducting Linac for neutron Time of Flight Facility
- ☐ Short Introduction to a New Korean Synchrotron Light Source
- ☐ Summary

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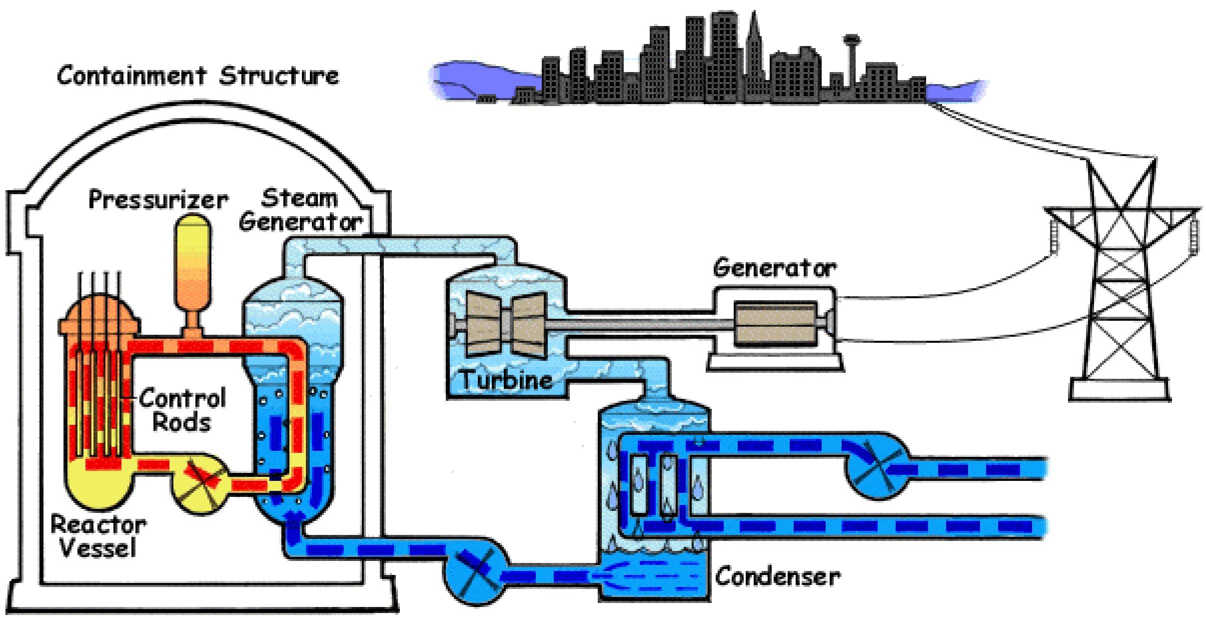
Introduction to KAERI

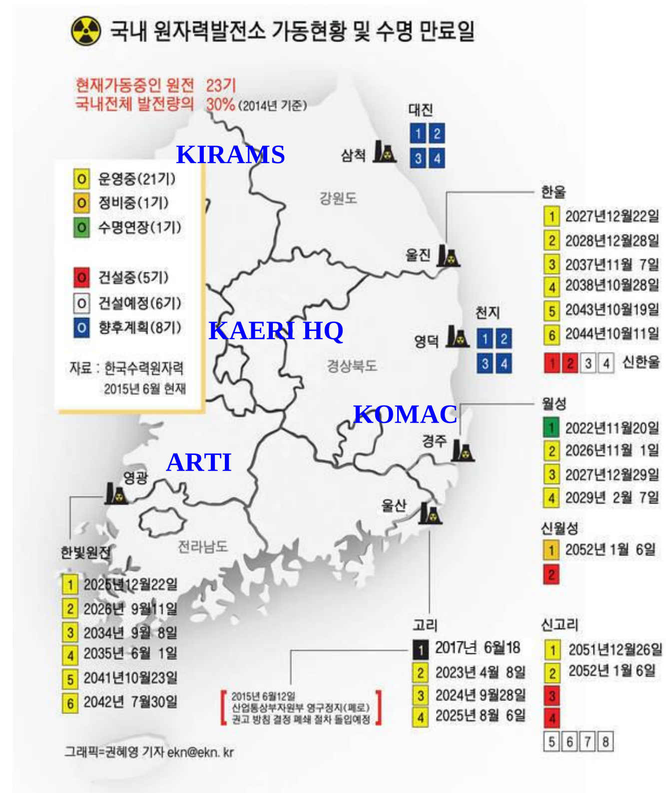
Korea Atomic Energy Research Institute (KAERI) for R&D Nuclear Energy

- □ **KAERI is the first national laboratory in Korea (established in 1959)**
- □ **Employees are about 3000 (2nd largest national lab. in Korea).**
- □ **Annual R&D funding is about 600 M$ (~ 6000 억원).**
- □ **In 2007, the Korea Institute of Radiological & Medical Sciences (KIRAMS, 한국원자력의학원, 원자력병원) was separated from KAERI.**



Introduction to KAERI

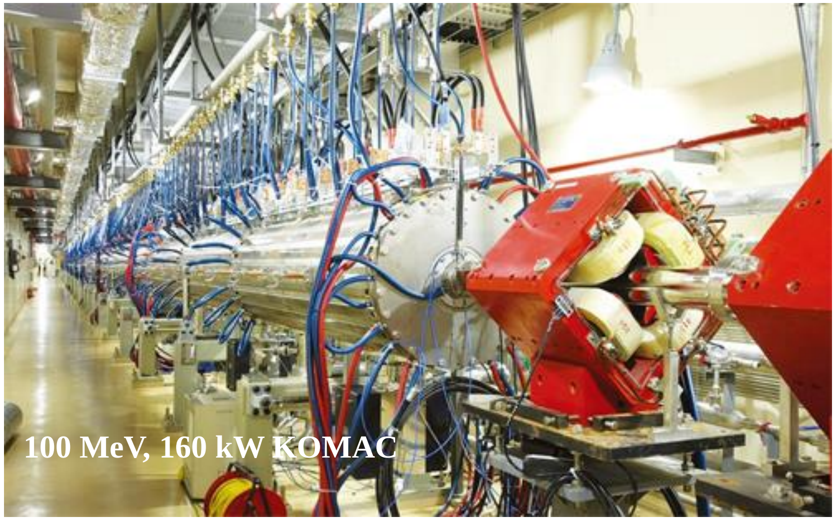
- ☐ **KAERI is an R&D leading institute to construct 24 nuclear reactors in Korea.**
- ☐ **KAERI has a multi-purpose 30 MW research reactor (HANARO) in 1995.**



- ☐ **KAERI established the Advanced Radiation Technology Institute (ARTI) at Jeongeup in 2006.**
- ☐ **KAERI established Protron Accelerator Complex (KOMAC) Kyeongju in 2013.**

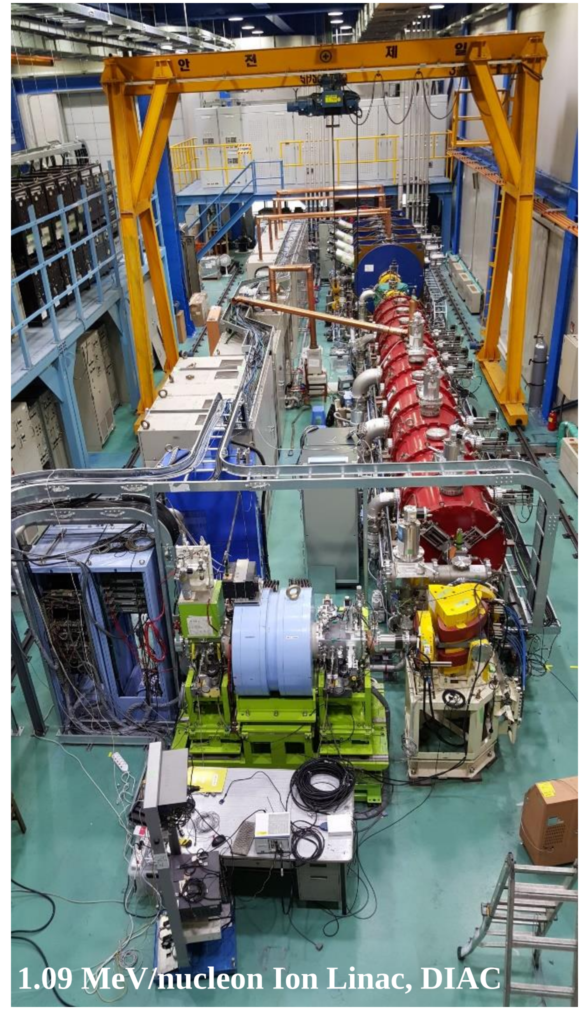
Introduction to KAERI

□ KOMAC: Protron, HANARO: Neutron, DIAC: Ion, ARTI: Electron Linacs


100 MeV, 160 kW KOMAC

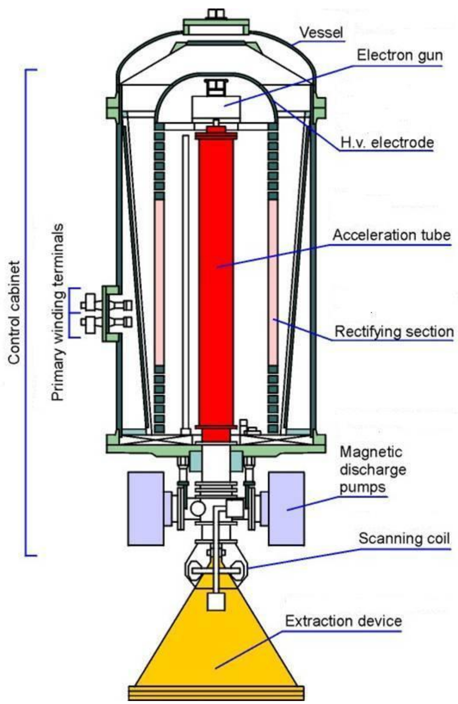

20 MeV, 100 kW Superconducting e-Linac


ARTI
10 MeV, 10 kW e-Linac


1.09 MeV/nucleon Ion Linac, DIAC

Introduction to KAERI

- ☐ ARTI has a 30 MeV, 500 μA (maximum $H^- \rightarrow H^+$ at Carbon) Cyclotron.
- ☐ A new 2.5 MeV 100 kW Electron Accelerator will be installed at ARTI by 2018.
- ☐ A new 10 MeV 30 kW Electron Accelerator will be installed at ARTI by 2018.



ELV-8, Height ~ 6.3 m

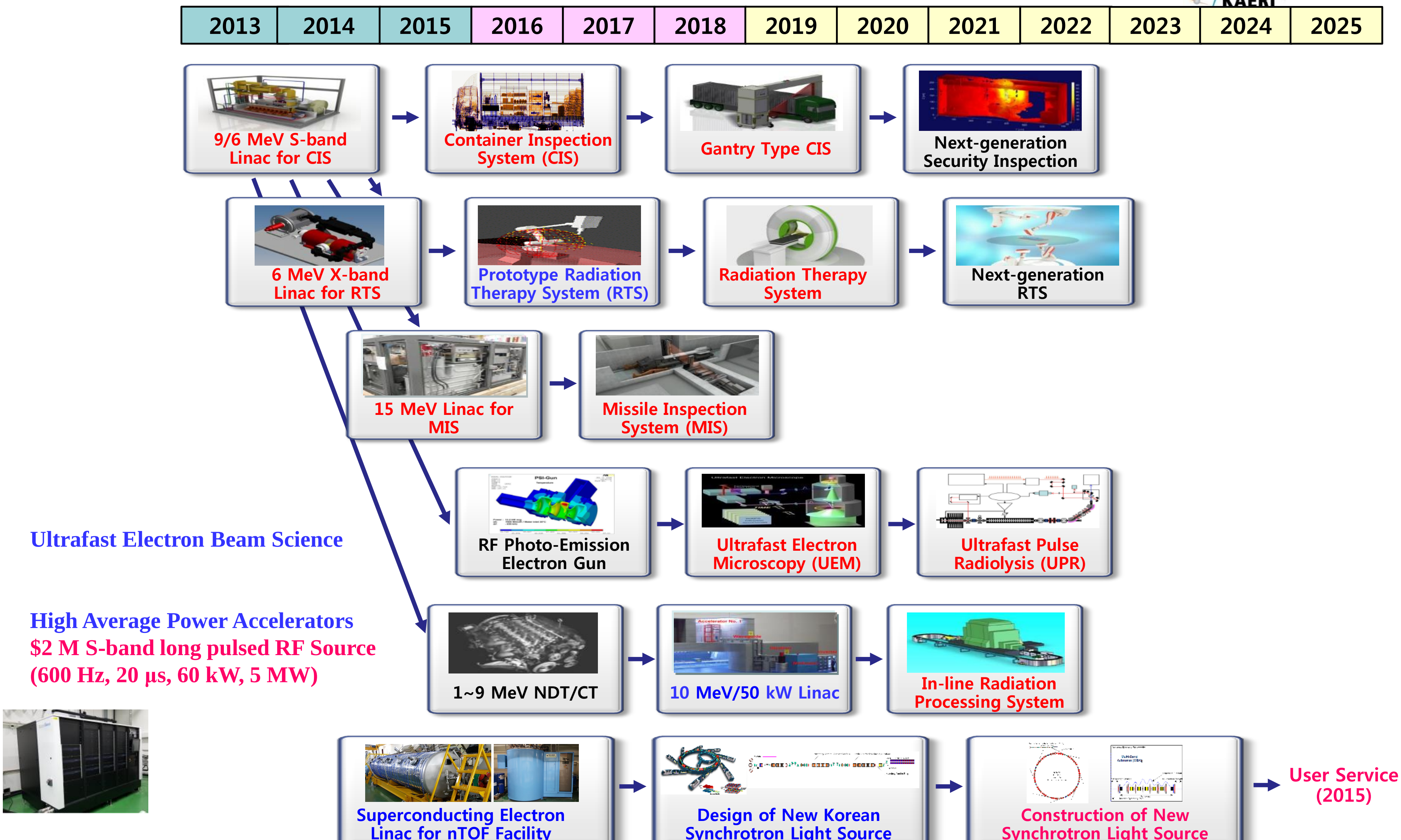
2.5 MeV, 100 kW Accelerator (EB-Tech)

30 MeV, 500 μA Cyclotron

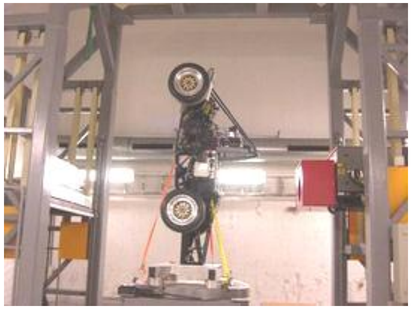
Machine parameter	Specification
Minimum beam energy	9 MeV
Nominal beam energy	10 MeV
Maximum Beam energy	11 MeV
Minimum average beam current	0.1 mA
Maximum average beam current	3 mA
Range of pulsed beam current	30 mA - 440 mA
Range of pulse repetition frequencies	30 Hz - 600 Hz
Length of electron window in scanning direction	3000 mm
Minimum scan width at electron window (power density)	150 mm
Maximum scan width at electron window (10% under-scan)	2700 mm
Maximum average beam power at 10MeV	30 kW

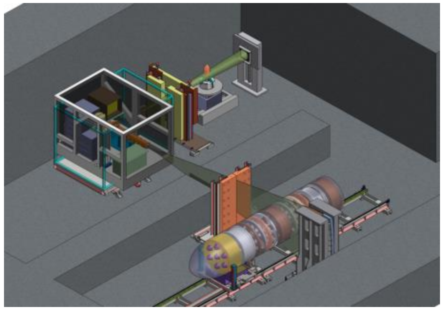
10 MeV, 30 kW e-Linac

KAERI's Roadmap for Electron Accelerators

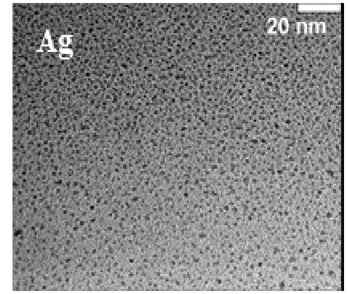


Applications of RF Electron Linacs





- ERP Market
- $200 M / Year
- 14% Growth / Year



- RTS & Diagnostic Market
- $3 B / Year
- 16% Growth / Year

- Security, CIS, & NDT Market
- $500 M / Year
- 30% Growth / Year

RF Electron LINACs

EBP Electron Beam Processing

CIS/NDT Container Inspection System

RTS Radiation Therapy System

ARF Advanced Research Facility

- Ultrafast Electron Diffraction (UED)
- Ultrafast Electron Microscopy (UEM)
- Ultrafast Pulse Radiolysis (UPR)
- Light Source Facility (Synchrotron, XFEL)

RF Accelerator

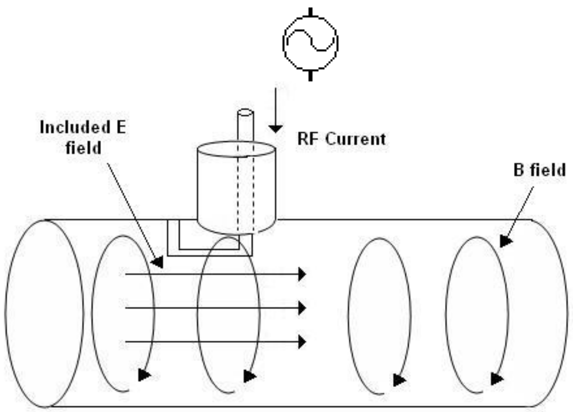
To avoid arcs and to get a higher gradient, RF accelerators are used.

RF electric field supplies an acceleration by Lorentz force:

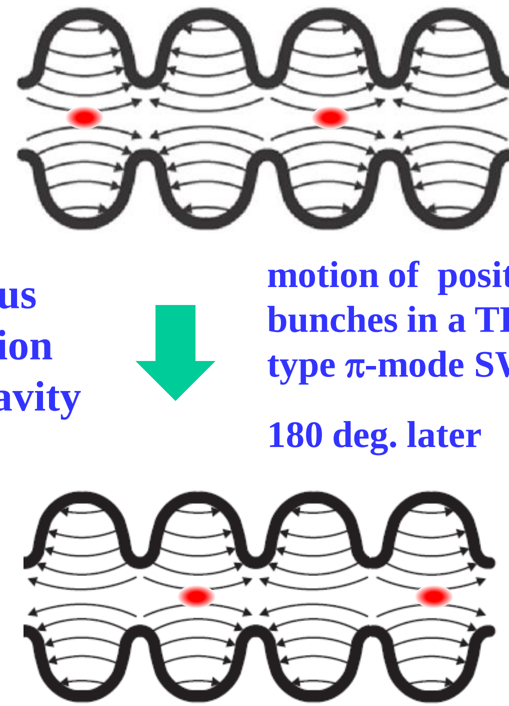
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

L-band: *f* ~ 1.5 GHz (l ~ 10 cm)
S-band: *f* ~ 3 GHz (l ~ 5 cm)
C-band: *f* ~ 5 GHz (l ~ 3 cm)
X-band: *f* ~ 9-12 GHz (l ~ 1.5 cm)

RF power source (ex, klystron, magnetron)



Courtesy of Fermilab



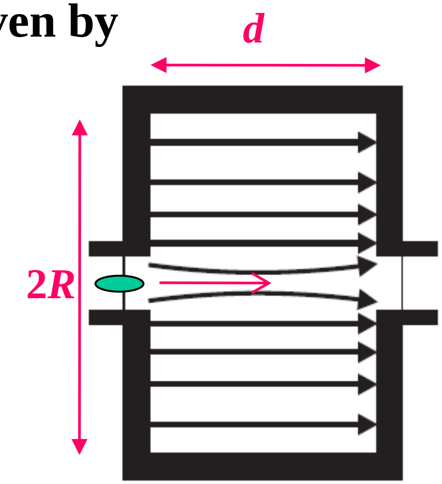
continuous acceleration in an RF cavity

motion of positive bunches in a TESLA type π-mode SW SRF cavity

180 deg. later

Resonance Frequency of an RF Cavity

If a charged beam crosses an RF cavity at t, then an acceleration by the RF cavity is $Gd\cos(2\pi f_{rf}t + \phi_0)$, where G is gradient of the cavity, d is length of the cavity, ϕ_0 is the initial RF phase, f_{rf} (~ f_{010}) is RF frequency. In this case, the longitudinal electric field E_z and resonance angular frequency ω_{mnp} of the TM$_{mnp}$ mode is given by



$$E_z(r,\varphi,z,t) = E_0 J_m(kr)\cos(m\varphi)\cos\left(p\pi\frac{z}{d}\right)\cos(\omega t)$$

$$\omega_{mnp} = \frac{1}{\sqrt{\epsilon\mu}}\sqrt{\frac{x_{mn}^2}{R^2} + \frac{p^2\pi^2}{d^2}} \qquad k^2 = \epsilon\mu\omega^2 - p^2\pi^2/d^2$$

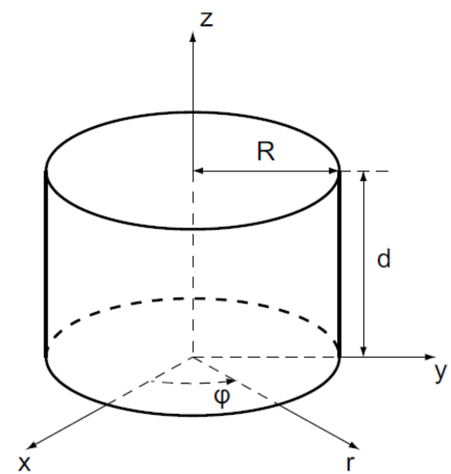
Here, x_{mn} is the nth solution of J_m, $J_m(x_{mn}) = 0$, and p is 0, 1, 2, ...

For the lowest TM$_{010}$ mode, the resonance frequency f_{010} and EM fields of the cavity is given by

$$f_{010} = \frac{c}{2\pi}\cdot\frac{2.405}{R} \equiv \frac{\omega_0}{2\pi}$$

$$E_z(r,z,t) = E_0 J_0\left(\frac{x_{01}r}{R}\right)\cos(\omega_0 t);$$

$$B_\varphi(r,\varphi,t) = \sqrt{\epsilon\mu}E_0 J_1\left(\frac{x_{01}r}{R}\right)\sin(\omega_0 t)$$

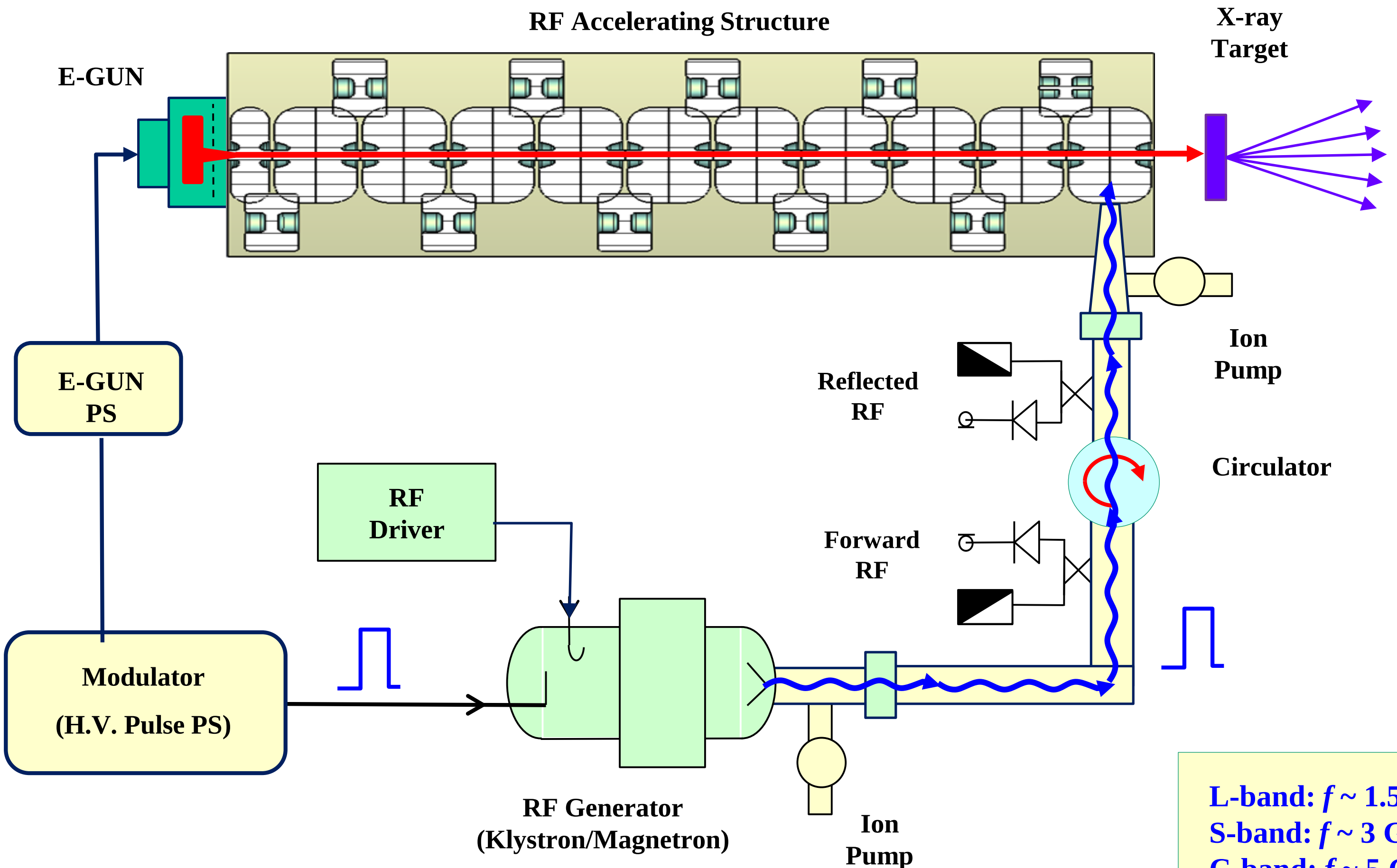


$$d \sim v\cdot\frac{\lambda_{rf}/2}{c} = \beta\cdot\lambda_{rf}/2 \text{ for } \pi \text{ mode SWRF cavity}$$

Note that m,n,p are the number of nodes of the mode in the φ, r, z direction.
See Resonant Cavities in J.D. Jackson's Classical Electrodynamics.

Main Components for RF Electron Linac

Whole 6 MeV Linac ~ $1 M & Structure Only ~ $0.1 M



L-band: *f* ~ 1.5 GHz (l ~ 10 cm)
S-band: *f* ~ 3 GHz (l ~ 5 cm)
C-band: *f* ~ 5 GHz (l ~ 3 cm)
X-band: *f* ~ 9-12 GHz (l ~ 1.5 cm)

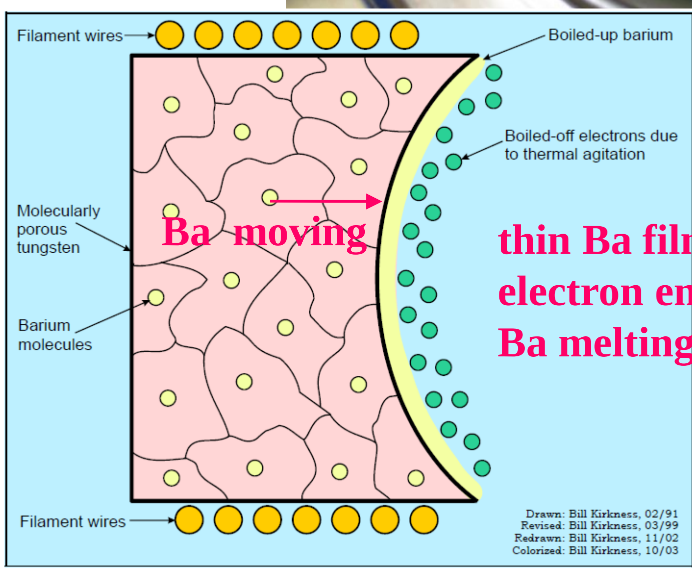
Ex. of Themionic Emission - 20 kV DC gun

DC Gun from Varian Medical Linac

RADPARTS.com KAERI

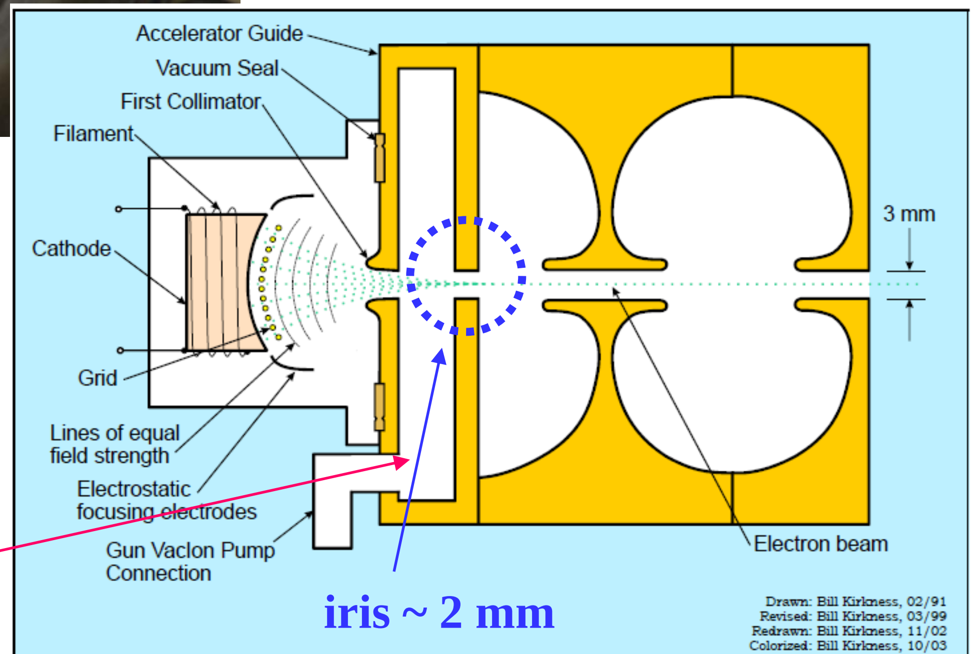
Gun for Varian Medical Lianc

- Cathode : W+Ba dispenser cathode
- Working Temperature : 600 - 700^{o}C
- Max DC Gap Voltage ~ 20 kV
- Max Gun Gradient ~ 1 MV/m
- Cathode Diameter : ~ 11 mm
- Beam Energy at Gun Exit ~ 20 keV
- Price ~ $14,000 (brand-new)



thin Ba film
electron emission before
Ba melting

pumping
to avoid Ba
escape

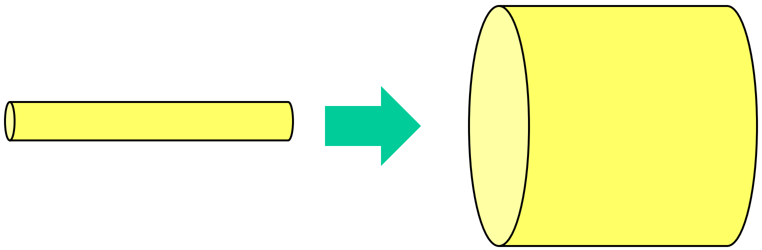


iris ~ 2 mm

Space Charge Force - Lengthening & Broadening

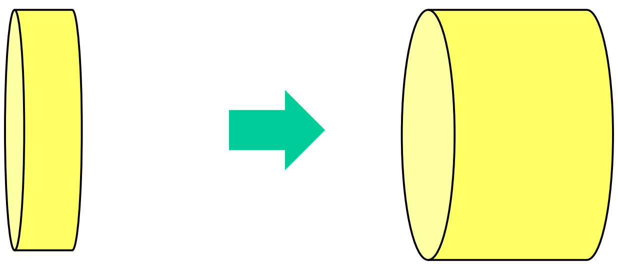
$$F(r) = \frac{Nq^2}{2\pi\epsilon_0 l \gamma^2} \frac{1 - \exp\left(-\frac{r^2}{2\sigma^2}\right)}{r}$$

$$F_{\parallel} = \frac{3}{\pi} g \frac{N_b q^2}{\epsilon_0 l_b^3 \gamma^2} z \qquad g = 1 + 2\ln\frac{b}{a}$$



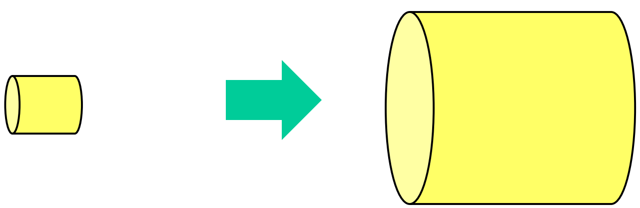
under a low energy, a high charge, a long bunch length and a small transverse beam size

transverse beam size broadening is generated due to the transverse space charge force.



under a low energy, a high charge, and a short bunch length but large transverse beamsize

bunch length lengthening is generated due to due to the longitudinal space charge force.



under a low energy, a high charge, a short bunch length and a small transverse beam size

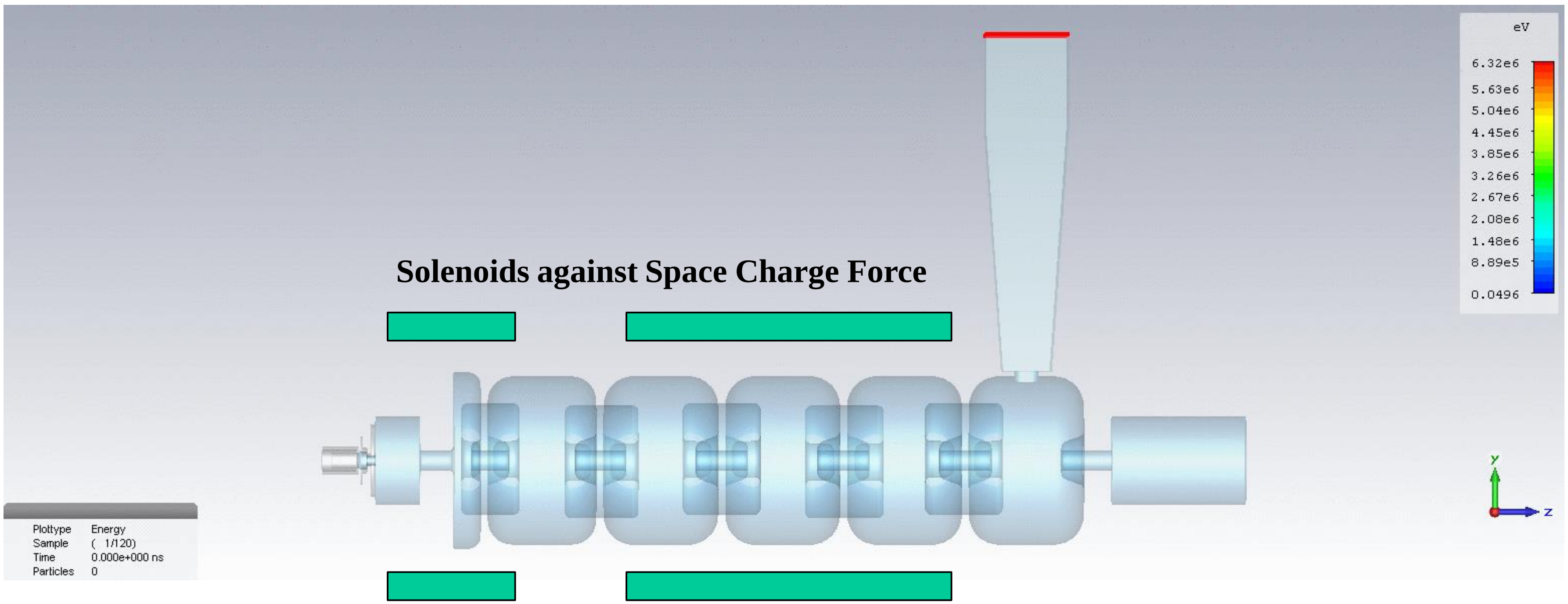
bunch length lengthening & transverse beam broadening are generated due to the longitudinal and transverse space charge forces.

Electron Beam Motion in RF Linac

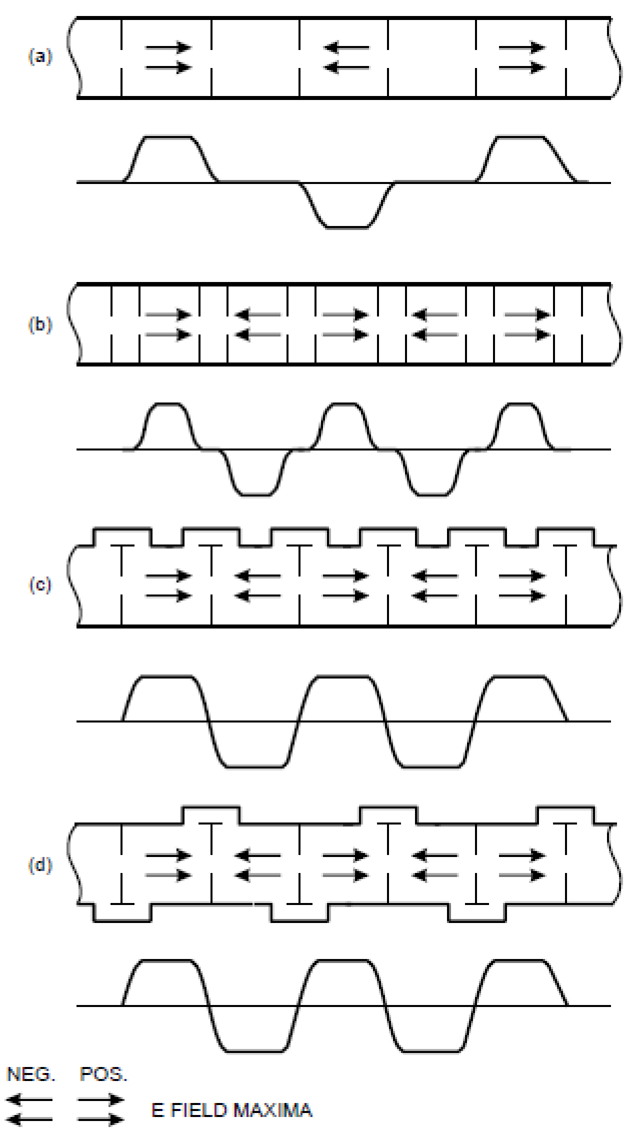
CST PS Simulation

Courtesy from Pikad Buaphad

6 MeV 2998 MHz Electron Linac



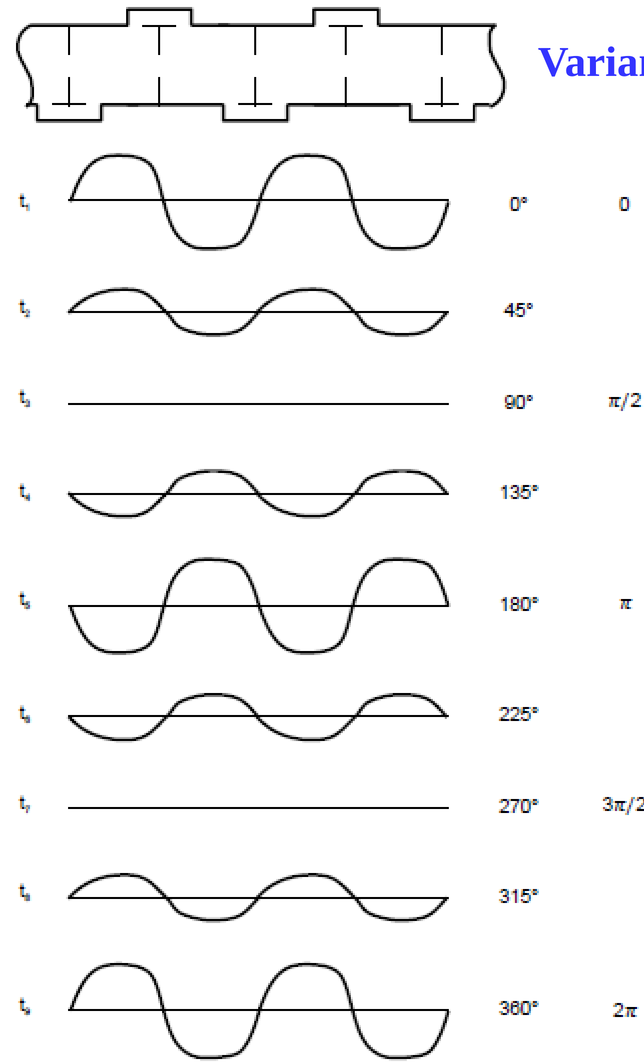
Coupling Cells in Standing Wave Accelerator



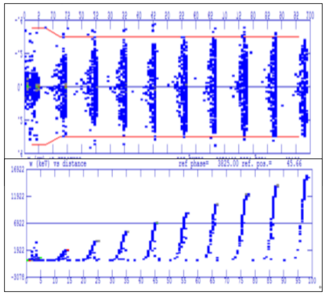
π/2

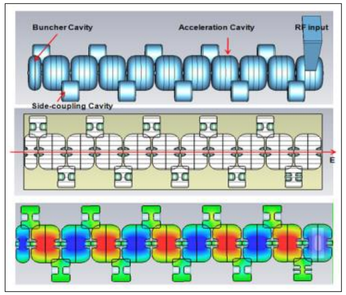
π

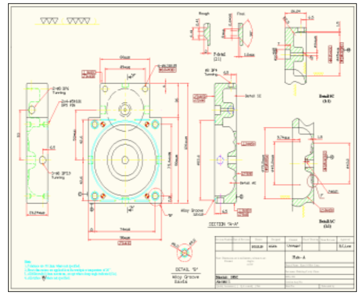
Varian Linac

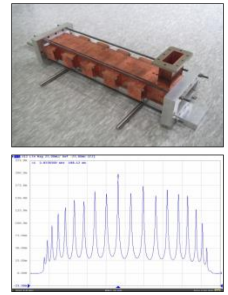


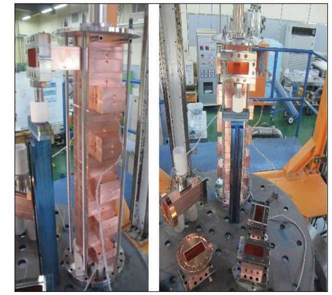
Fabrication Processes of S-band Linac Structure



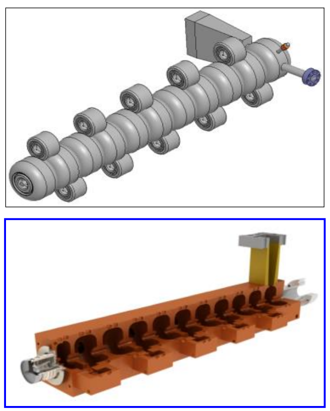


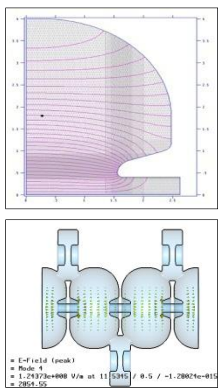


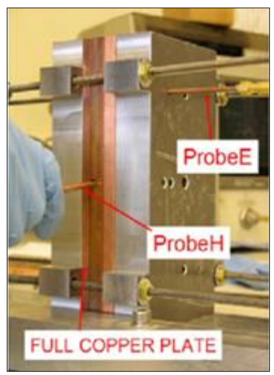


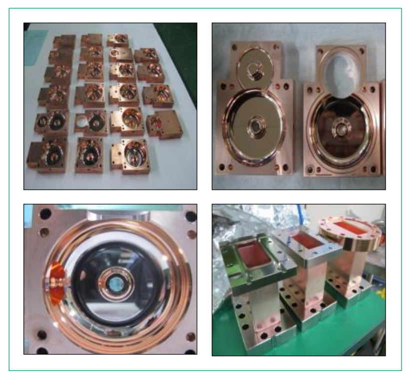


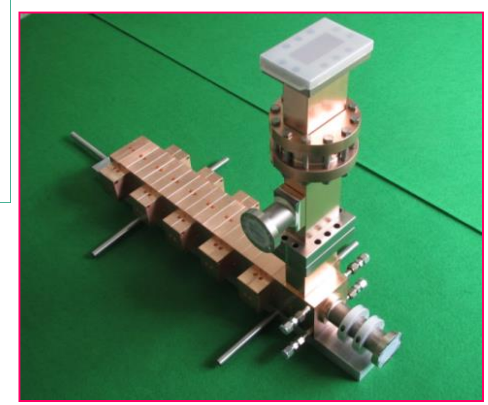
Conceptual Structure Design → Beam Dynamics Simulation → Detailed Structure Design (CST MS) → Crossing Beam Simulation (CST PS) → Model Design and Fabrication → Detailed Structure Drawing → Cell Fabrication → RF Measurement & Tuning → Celll Cleaning → Brazing → Vacuum Test & 2nd Tuning











S-band & X-band Cells with 10 nm Roughness

Diamind turning technology is used to obtain 10 nm range surface roughness!
KAERI & RTX are main customers.

Hadong Precision
Ultrafine Roughness with Diamond
하동정밀

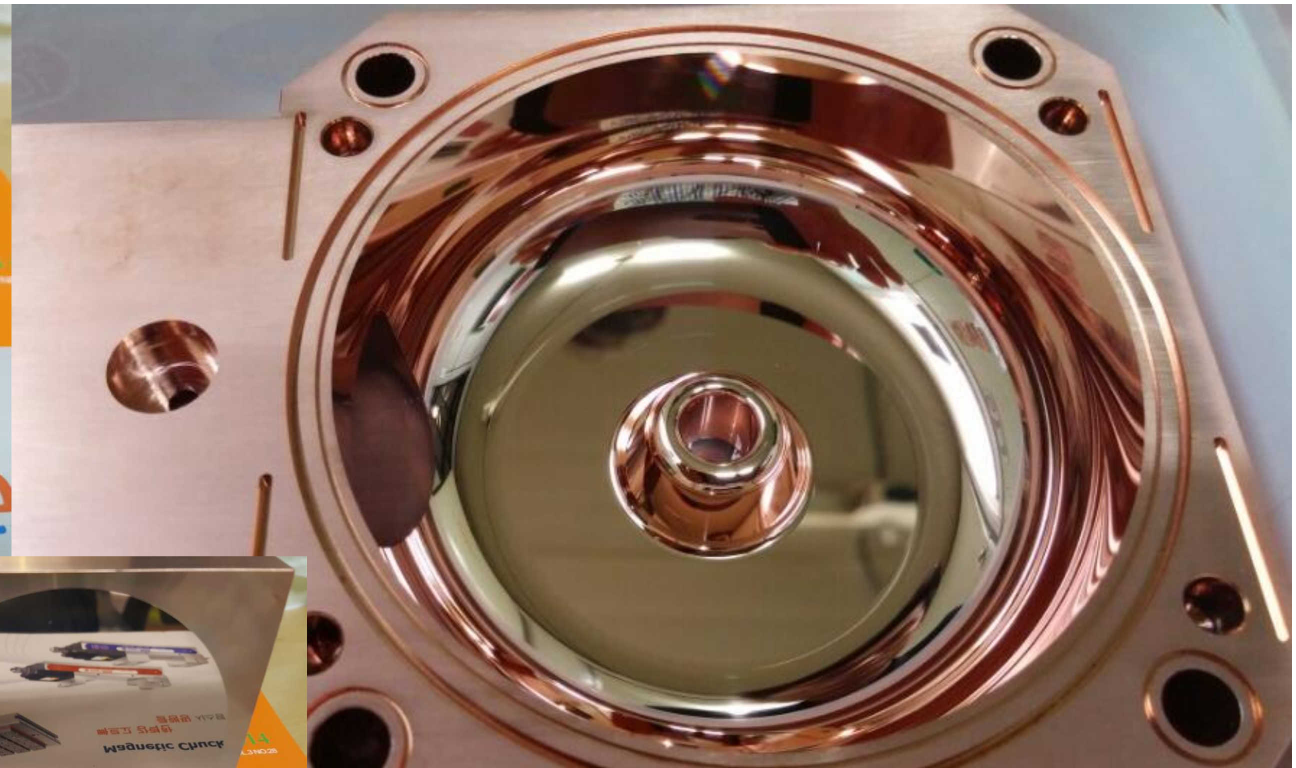
S-band & X-band Cells with 10 nm Roughness

KAERI

Diamind turning technology is used to obtain 10 nm range Surface Roughness!

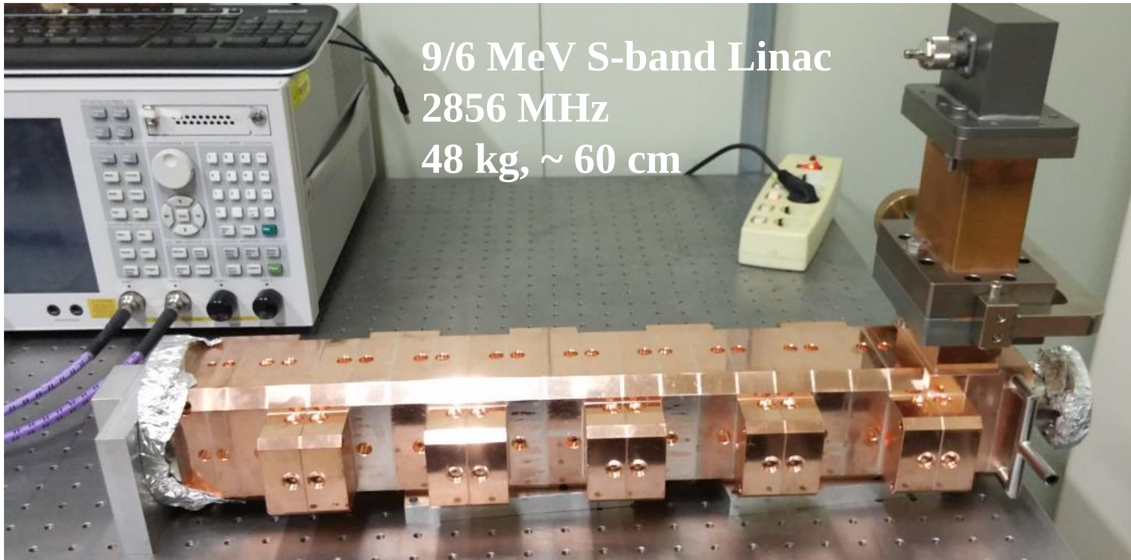
KAERI & RTX are main customers.

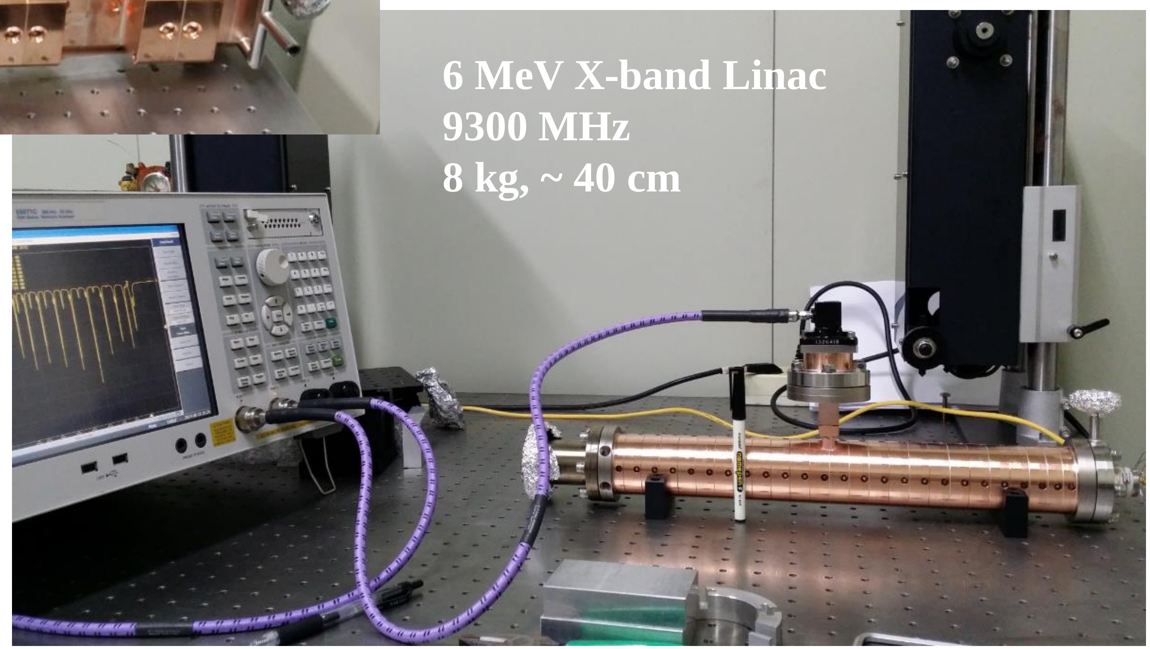
Mirror like surface!



Hadong Precision
Ultrafine Roughness with Diamond

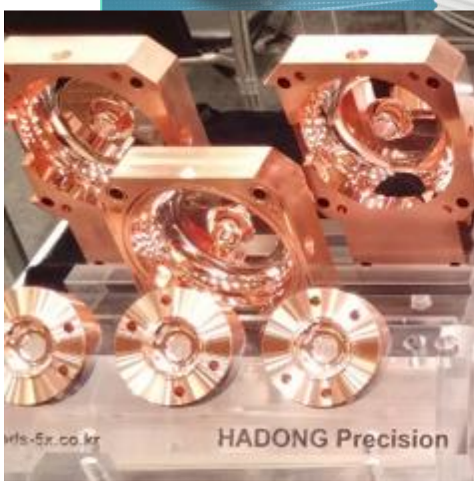
S-band & X-band Linac Structure after Brazing



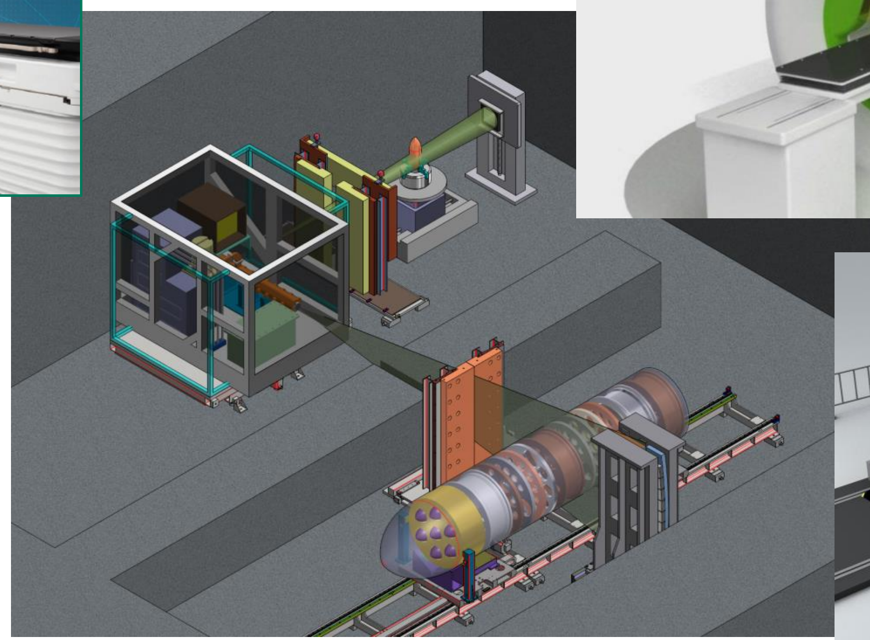


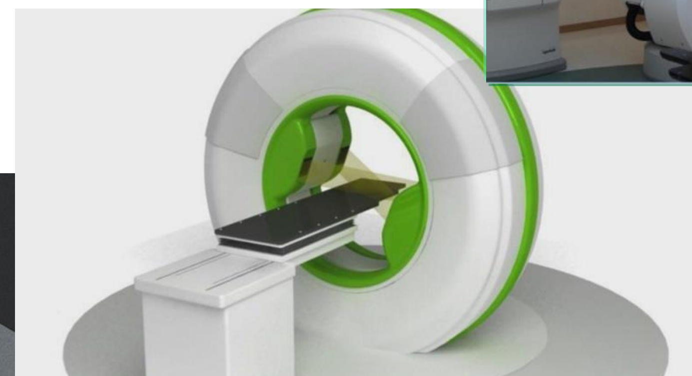
KAERI's RF Electron Linac Projects

- ☐ 9/6 MeV Dual Energy S-band (= 2856 MHz) Linac Project for Container Inspection.
- ☐ 15 MeV S-band Linac Project for Missile Inspection System
- ☐ 6 MeV S-band Conventional Radiation Therapy System
- ☐ 6 MeV X-band (= 9.3 GHz) Linac Project for CyberKnife
- ☐ 6 MeV X-band Higher Gradient Linac Project for Dual Head Gantry



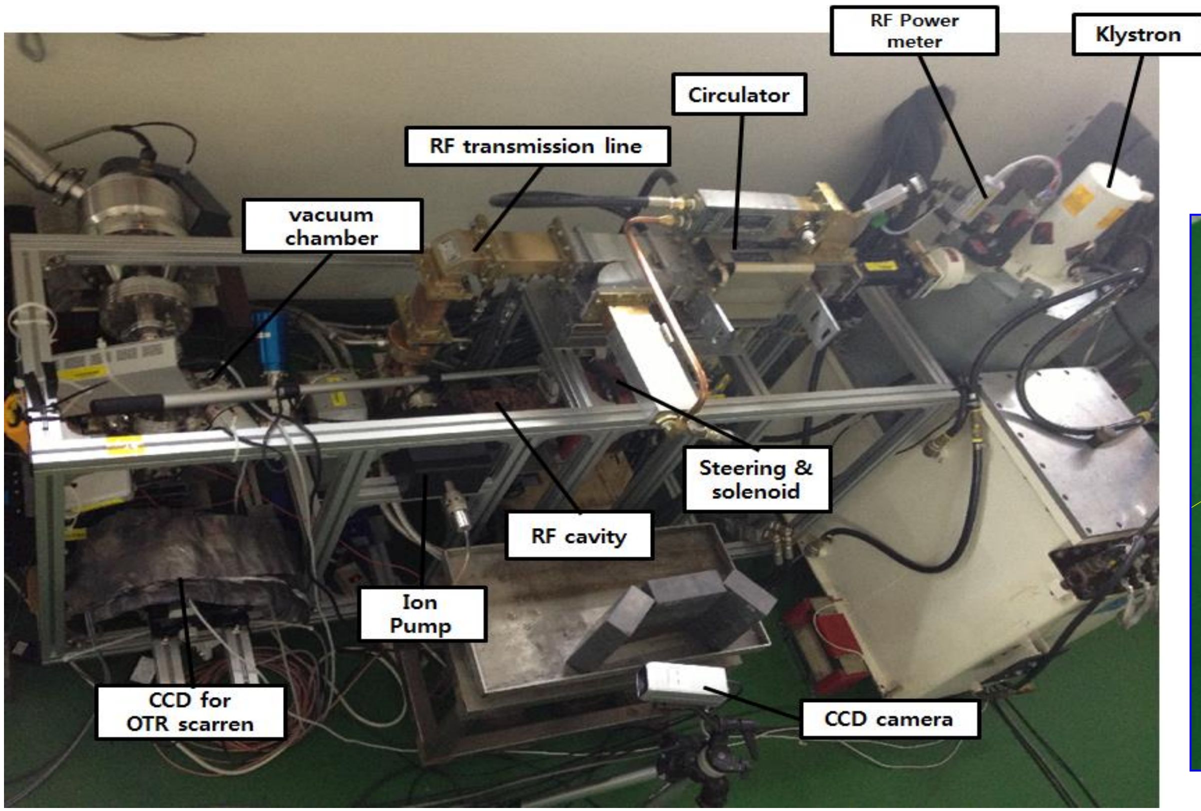
Cells for S & X-band Linacs

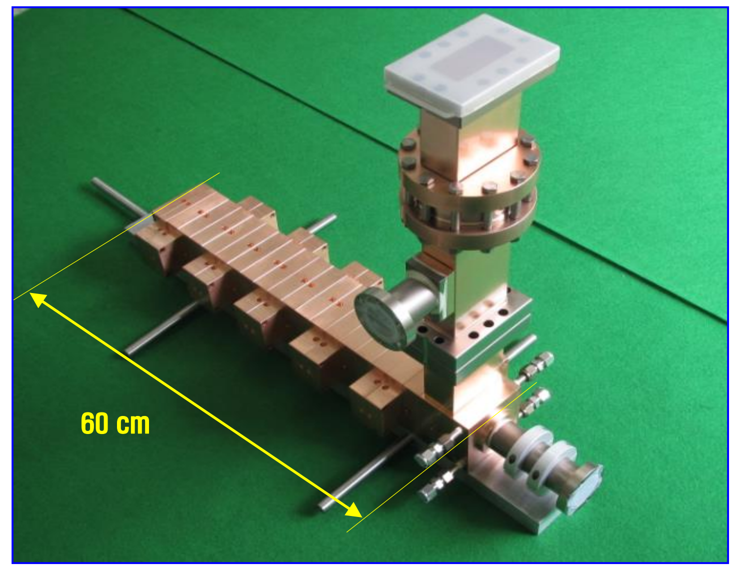




KAERI's 9/6 MeV S-band RF Electron Linac

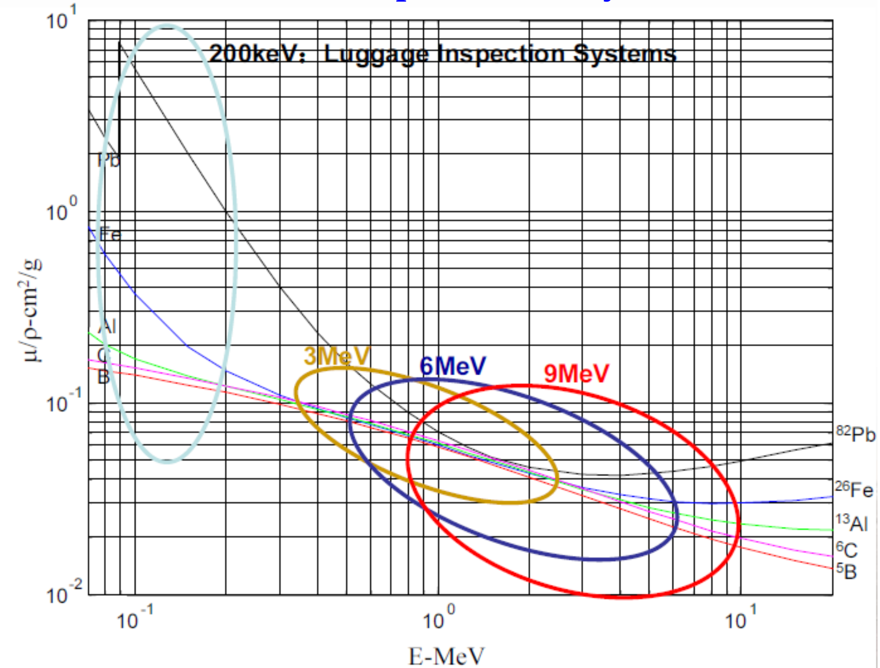
- E-beam energy : 9/6 MeV ⇨ Penetration Depth (steel 400 mm @ 9 MeV, 30 Gy/min @ 1 m)
- Spot size : < 2 mm ⇨ Resolution
- Average power: > 1 kW ⇨ Scan Speed (0.3 m/s, < 1-2 min @ 1 kW)
- **Dual-energy mode** ⇨ **Materials Discrimination**

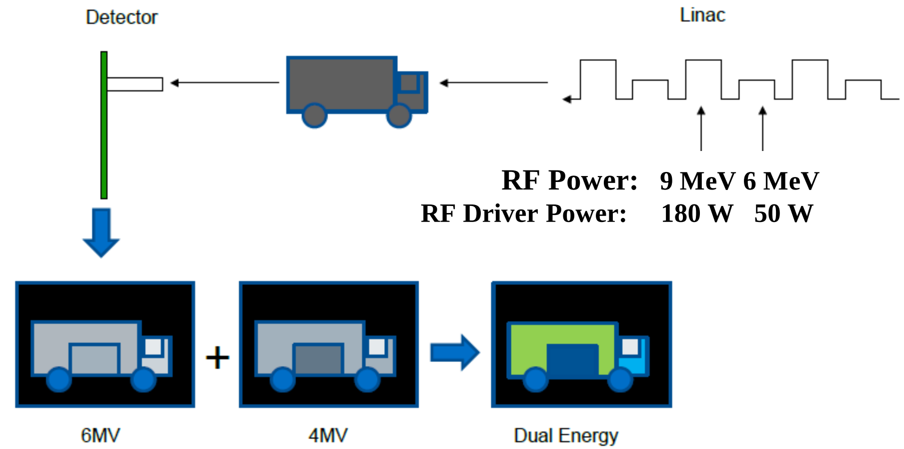


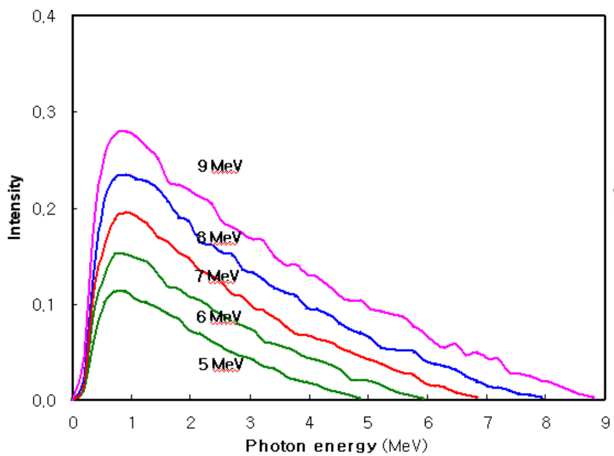


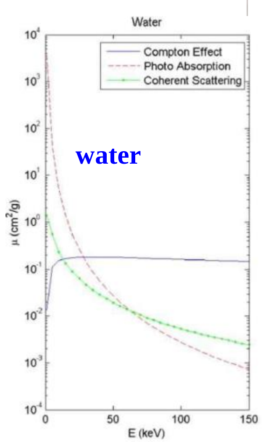
Dual Energy Screening

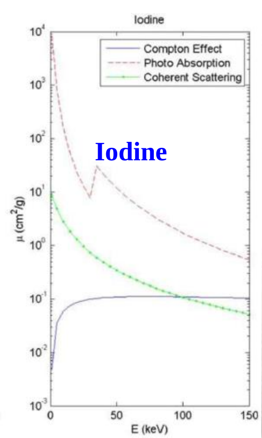
Photoelectric Absorption of X-ray in Matter: Different Absorptions for Different Matters & Energies



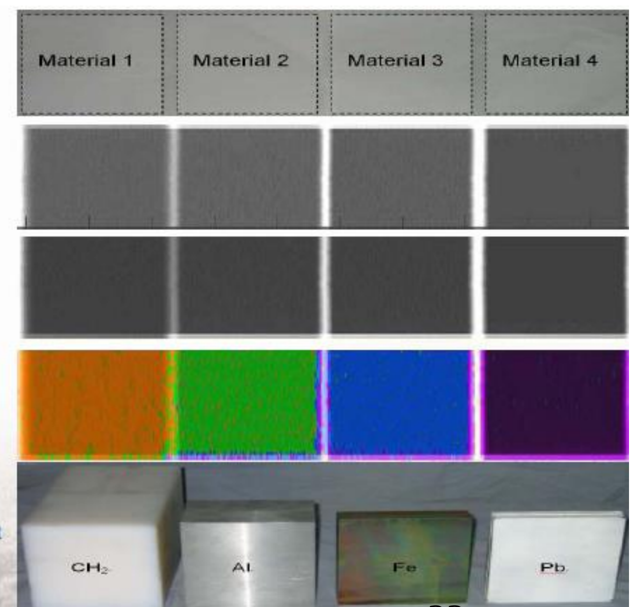








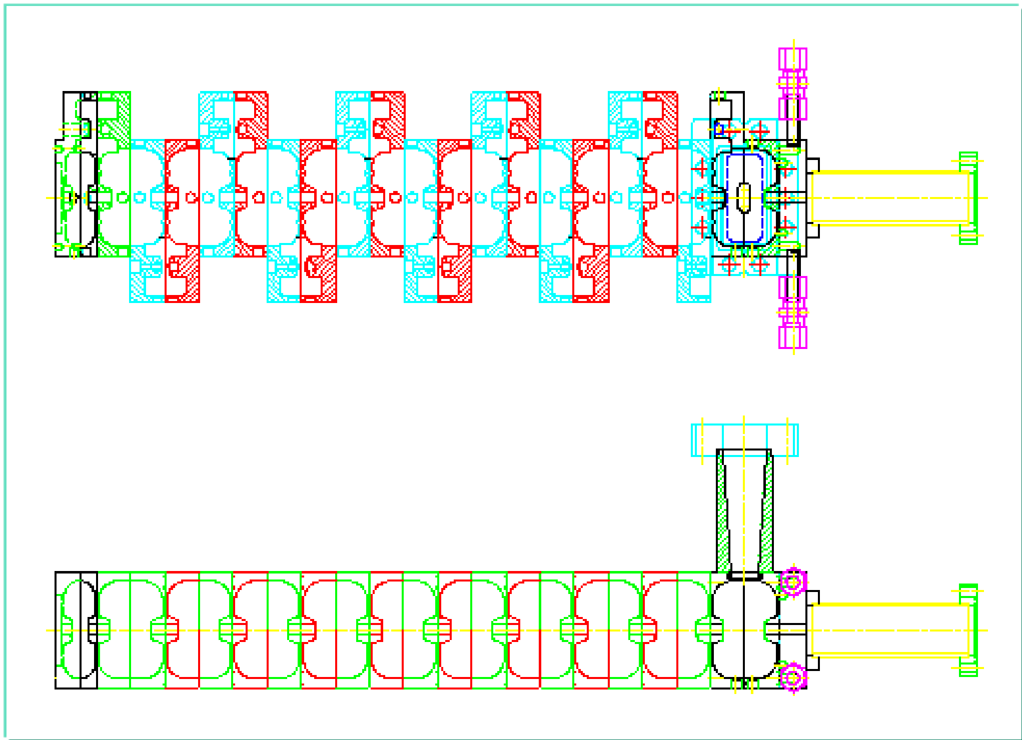
- Unknown material
- High-energy image
- Low-energy image
- Dual-energy image
- Unveil the scanned object

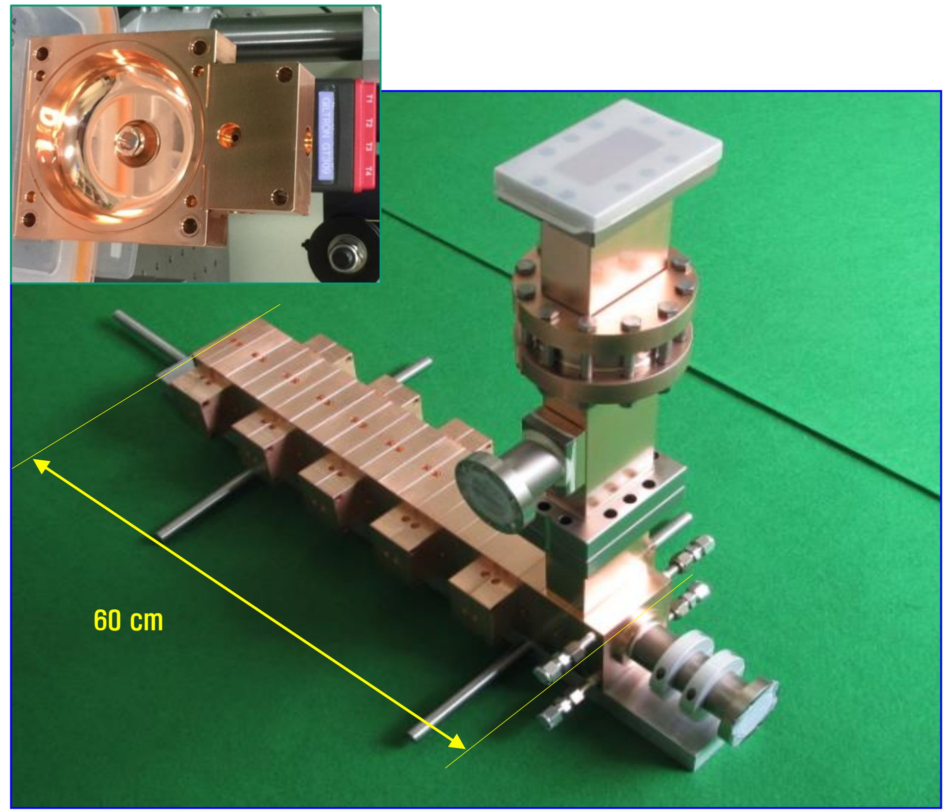


KAERI's 9/6 MeV S-band RF Electron Linac

Central Frequency ~ 2856 MHz
11 Cells for 9/6 MeV
One Bunching Cell
Length ~ 0.6 m
Nosecone for a high gradient (15 MV/m)
Weight ~ 48 kg

unload Q_0 ~ 16000
coupling beta ~ 2.1
RF power for 9 MeV ~ 5.5 MW

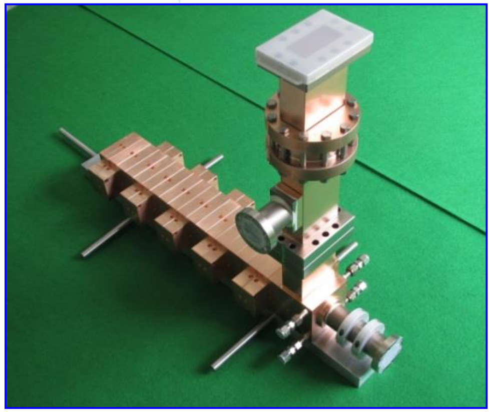


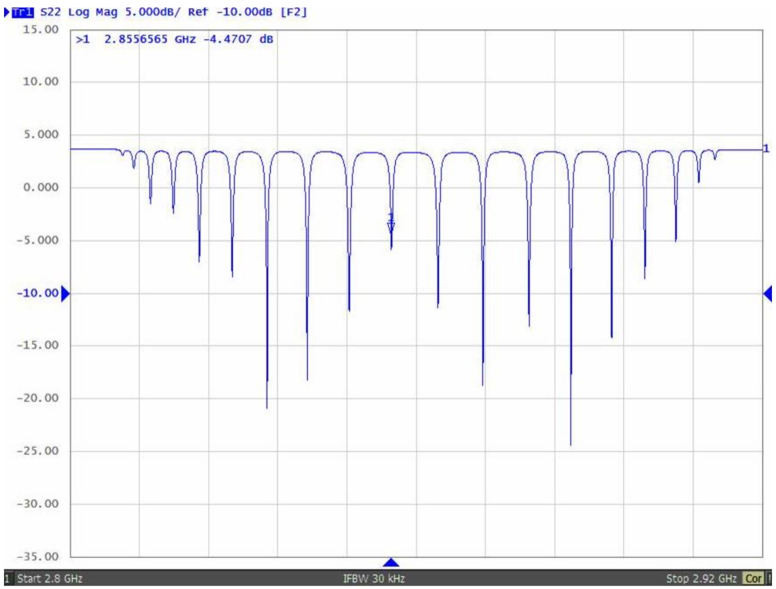


KAERI's 9/6 MeV S-band RF Electron Linac

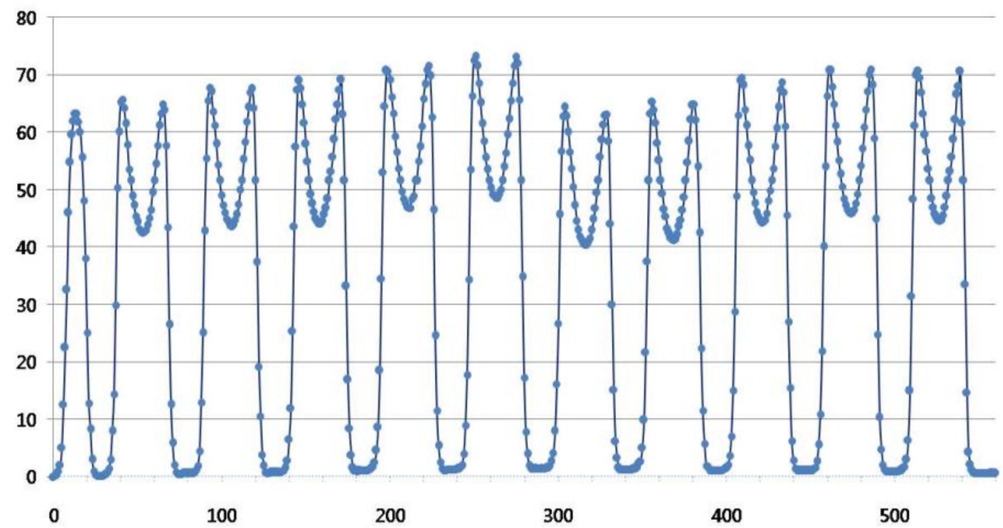
Central Frequency ~ 2856 MHz
11 Cells for 9/6 MeV
One Bunching Cell
Length ~ 0.6 m
Bore Radius ~ 4 mm
Cell Length ~ 26.24 mm
Nosecone for a high gradient (15 MV/m)
Weight ~ 48 kg

Unload Q_0 ~ 16175
External Q_{ext} ~ 7880.19
Coupling beta ~ 2.053
Shunt Impedance ~ 150 MΩ/m
RF power for 9 MeV ~ 5.5 MW



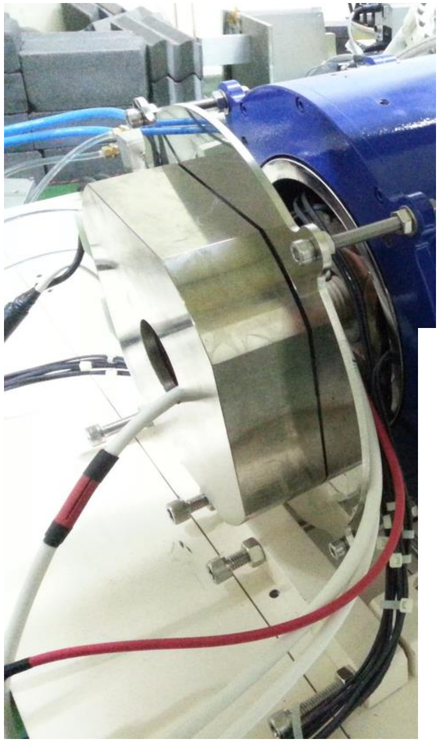


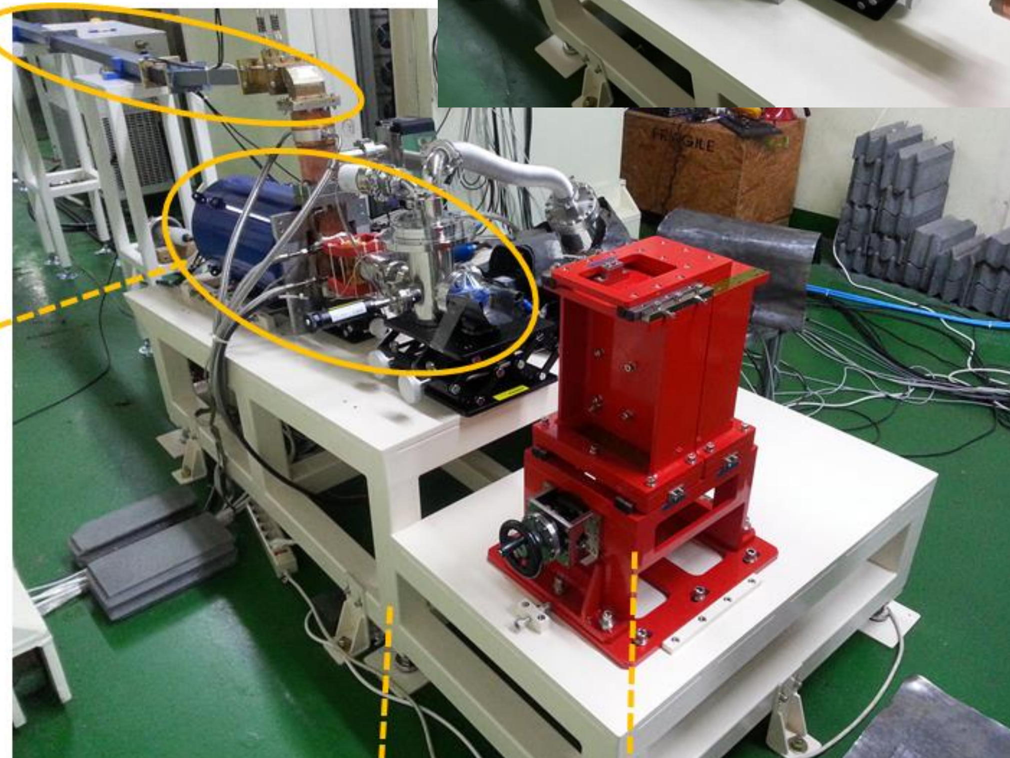
Measured S_{11} spectrum

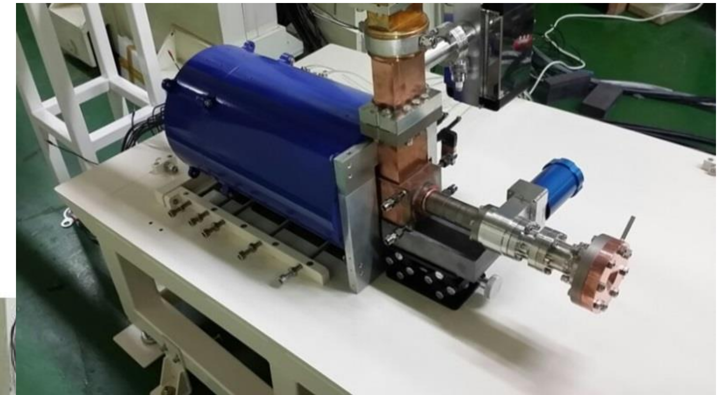


Measured E-Field distribution

Solenoids for S-band Linac - April 2014







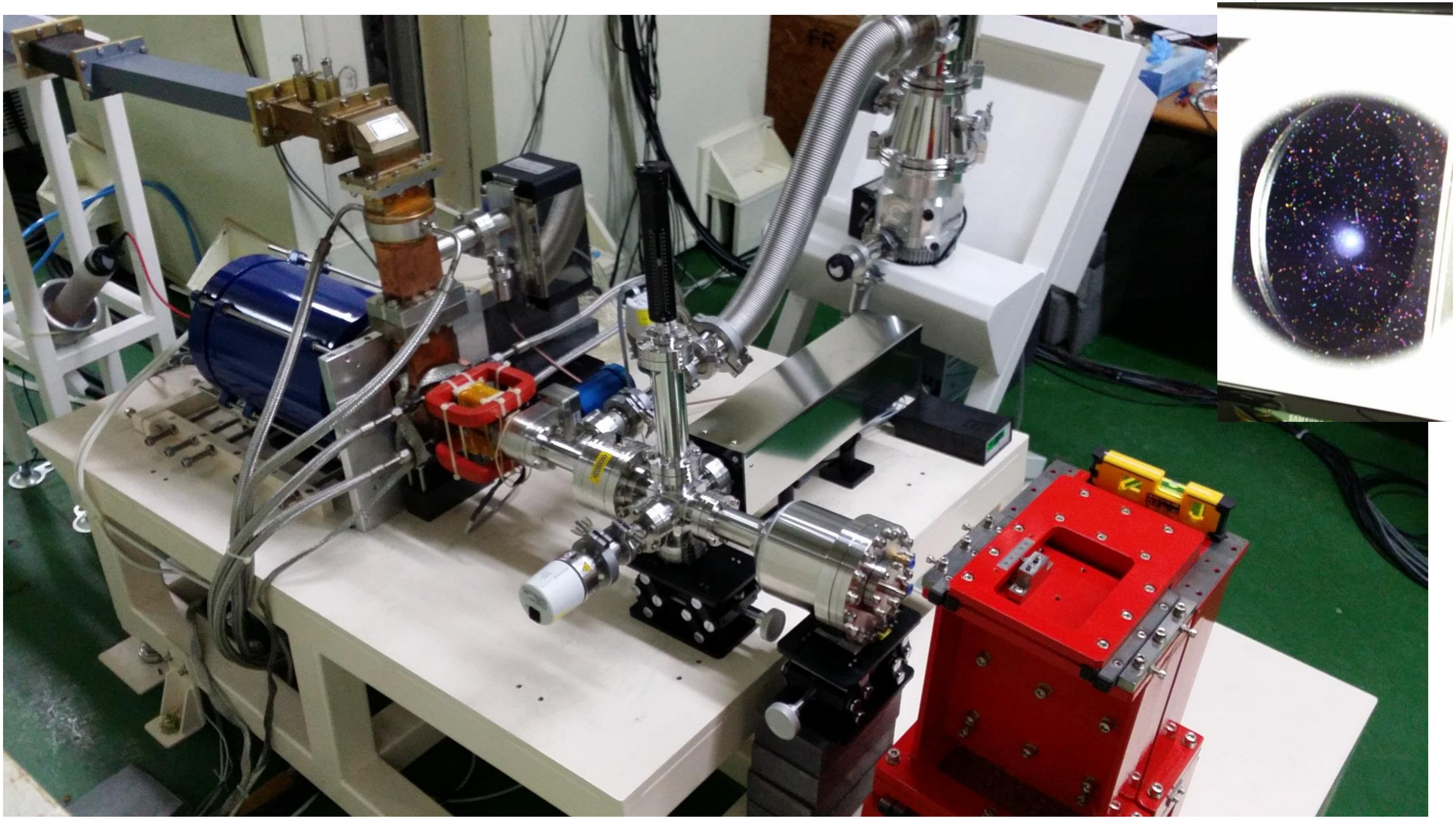
RF Waveguide

9/6 MeV RF
Electron Linac

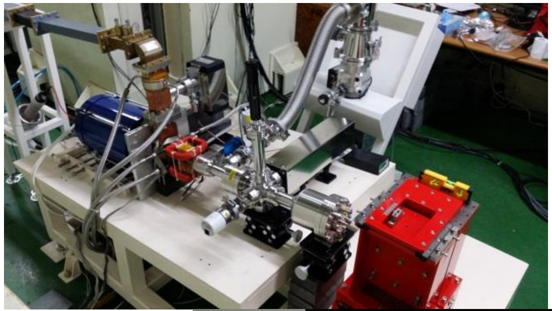
Linac Girder

Collimator

S-band Linac - February 2015

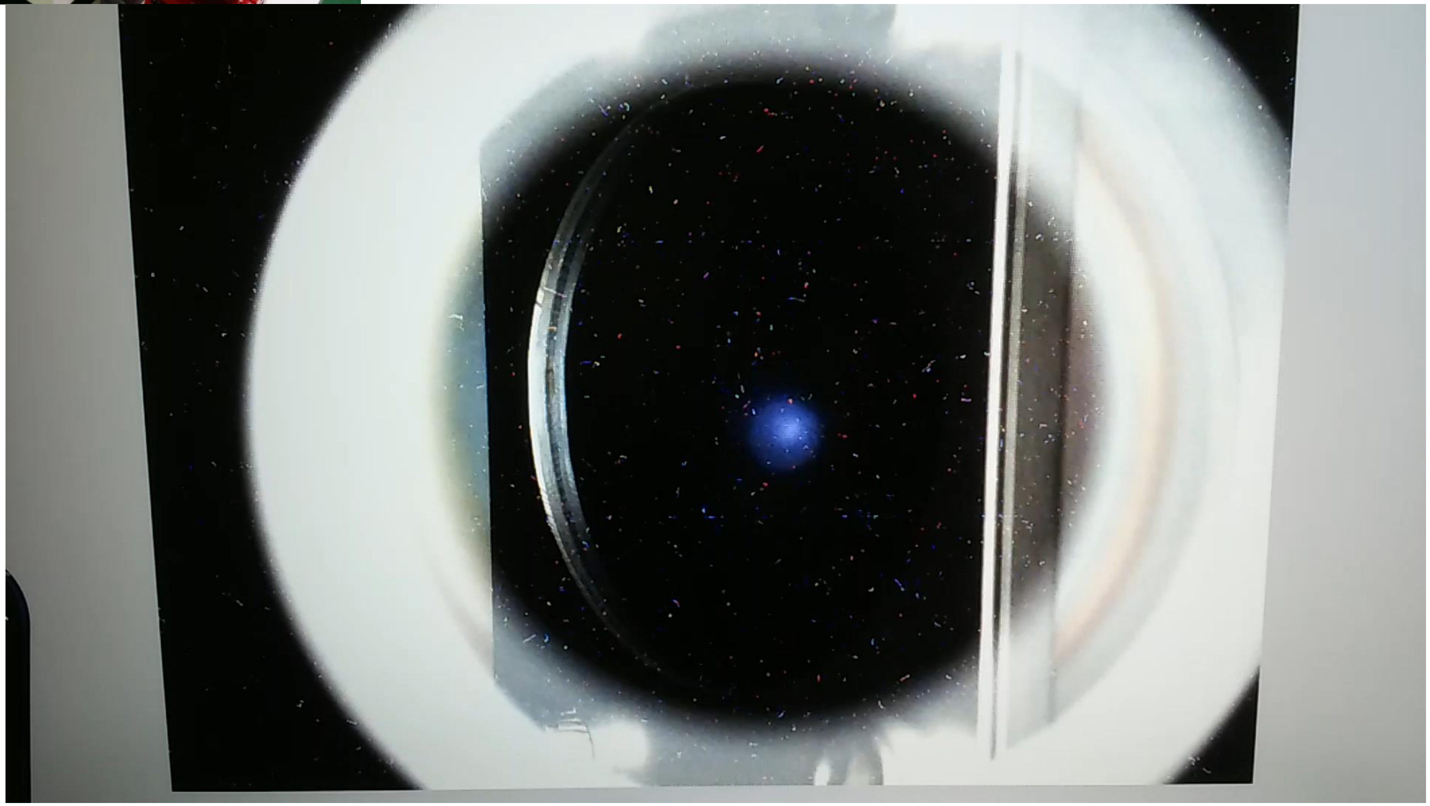


S-band Linac - February 2015

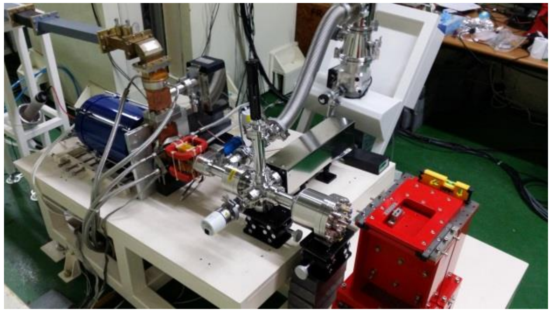


9 MeV, 125 mA
100 Hz, 5 MW
19 kV
P_{ave}: 450 W

Beam spotsize on OTR
FW: 2.3 mm
FWHM: 0.89 mm
rms: 0.38 mm

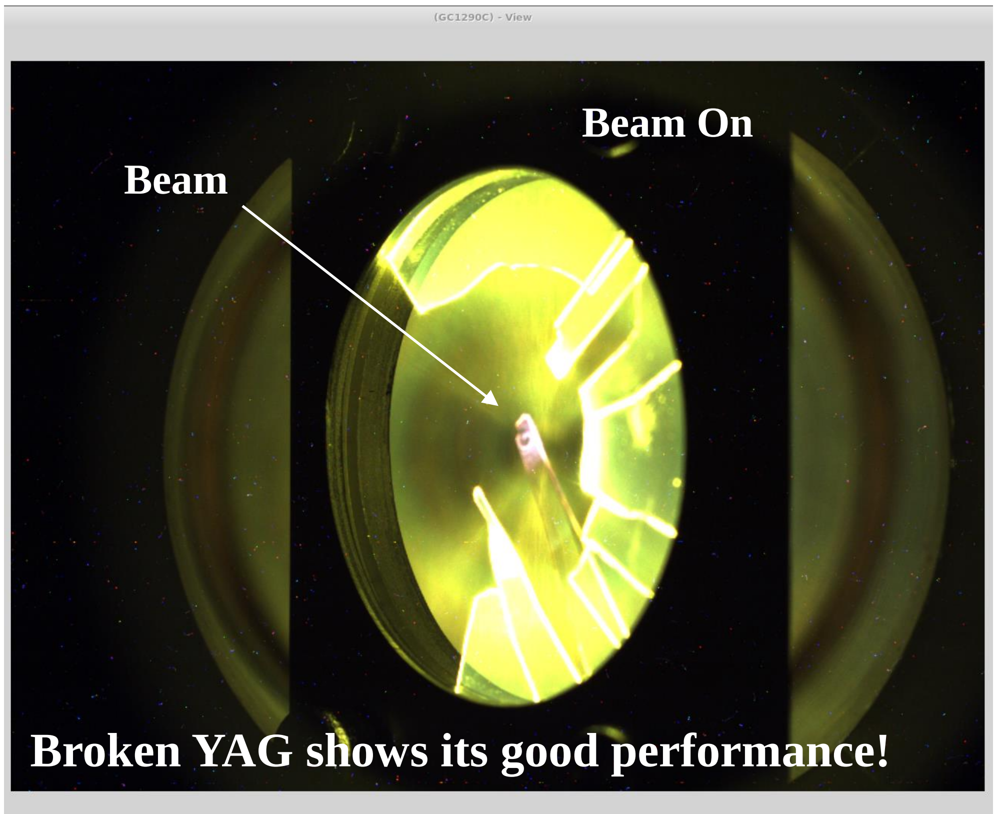


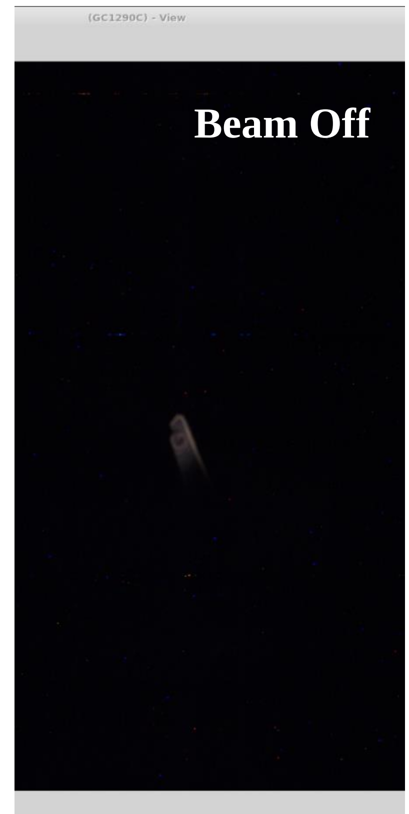
Powerful S-band Linac - February 2015



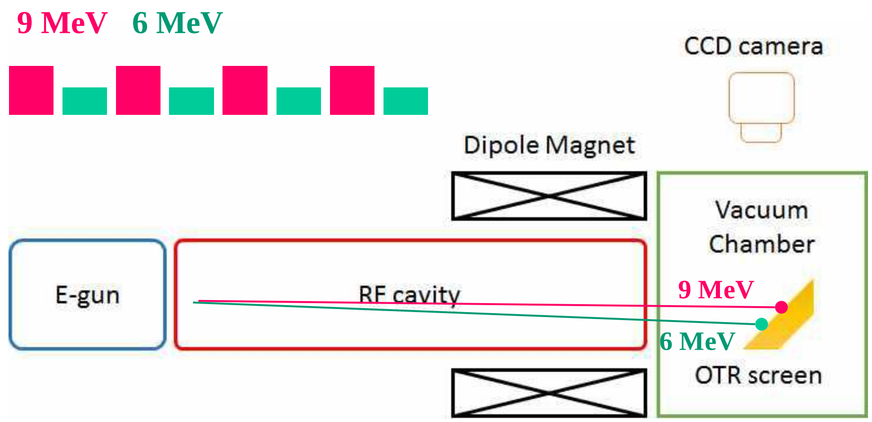
6 MeV, 175 mA
100 Hz, 3 MW
25 kV
P_{ave}: 420 W

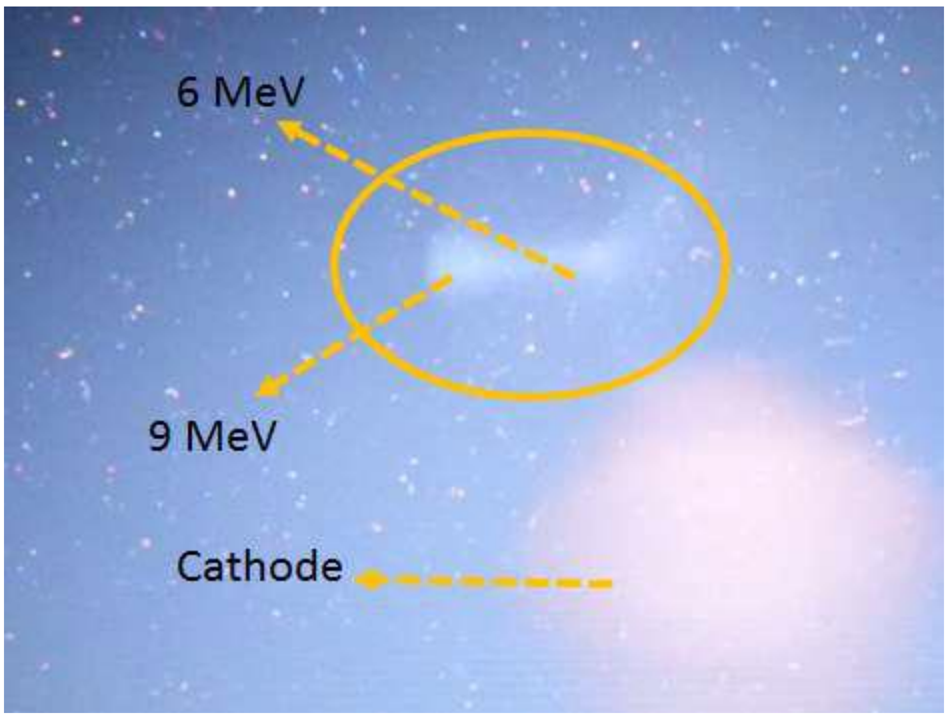
Beam spotsize on YAG
FW: 2.3 mm
FWHM: 0.89 mm
rms: 0.38 mm

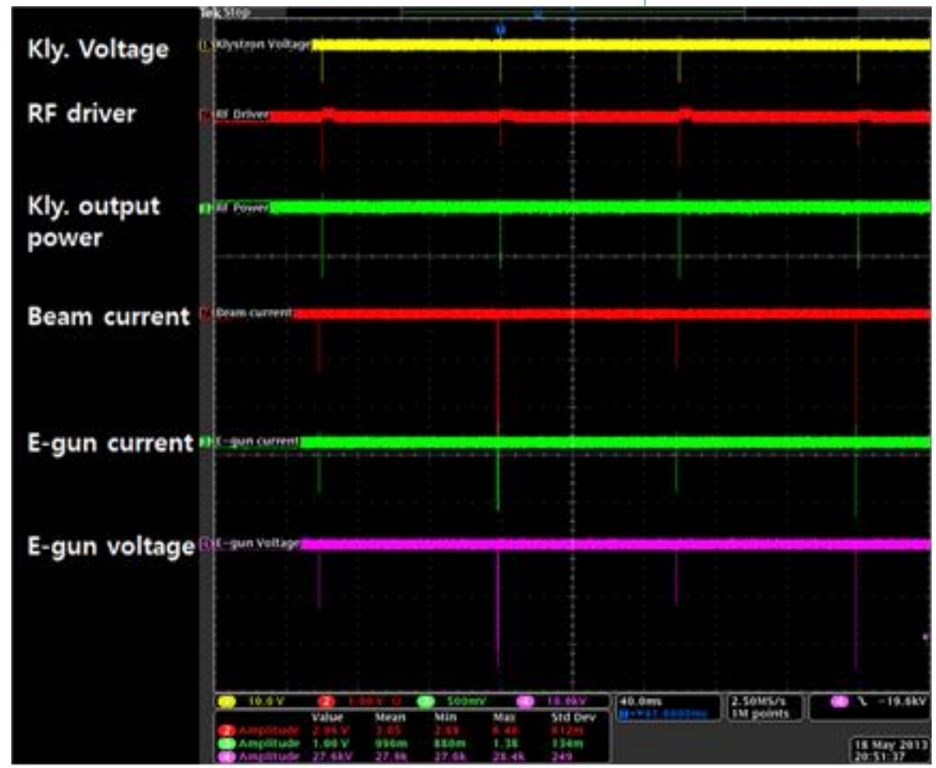


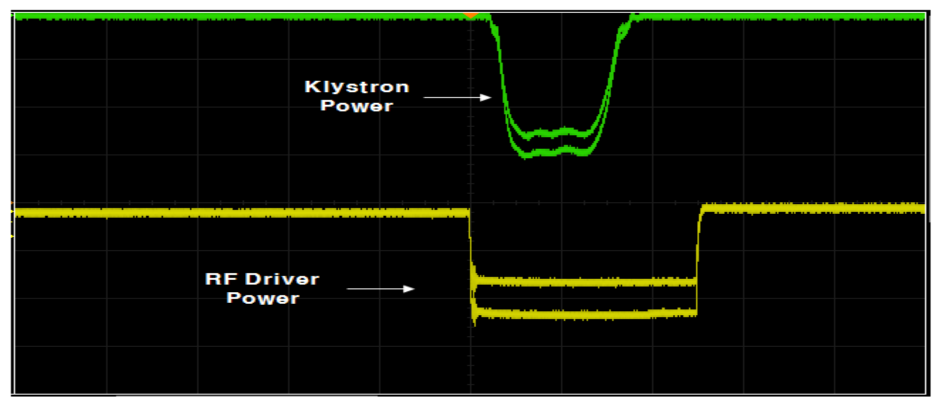


Pulse-to-Pulse 9/6 MeV Dual Energy Demo!

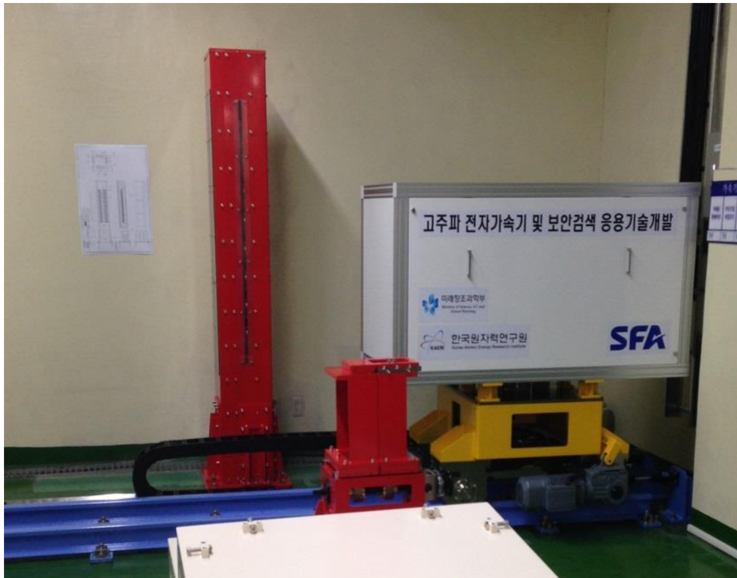








Moving System & Detector Array for CIS



Detection Technology X-scan LCS 4.6 detector: Scintillator + Photodiode

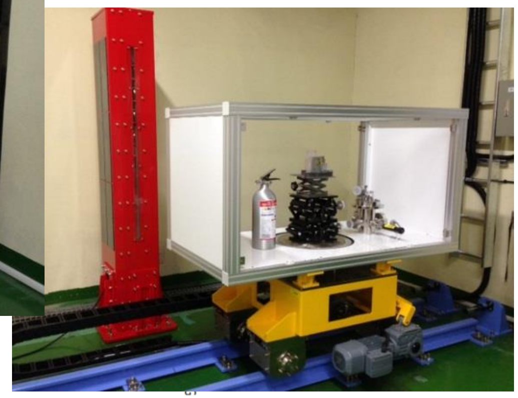
One pixel : Cadmium Tungsten (CdWO4) Scintillating Crystal + Photodiode

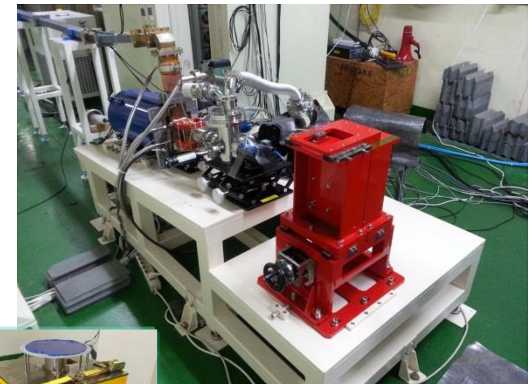
Pixel per Module: 32 pixels (total 256 pixels for 8 modules)

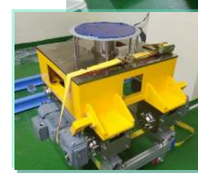
Pixel size: 4.0 mm (W) × 4.6 mm (L) × 7 mm (H)

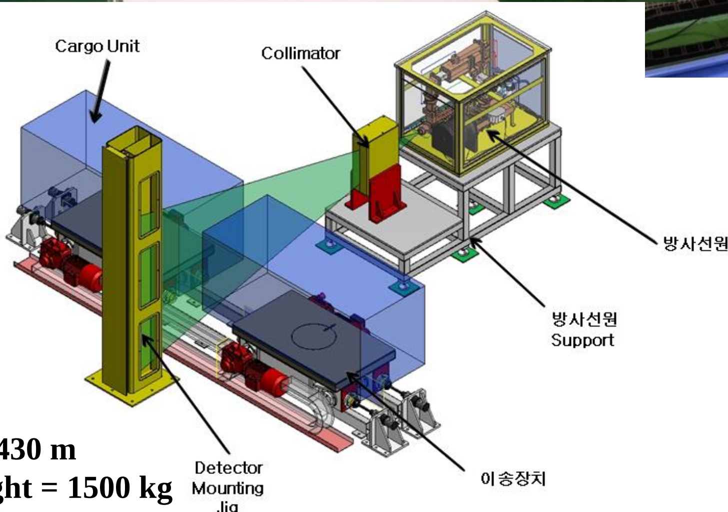
Max speed: 300 - 500 Hz

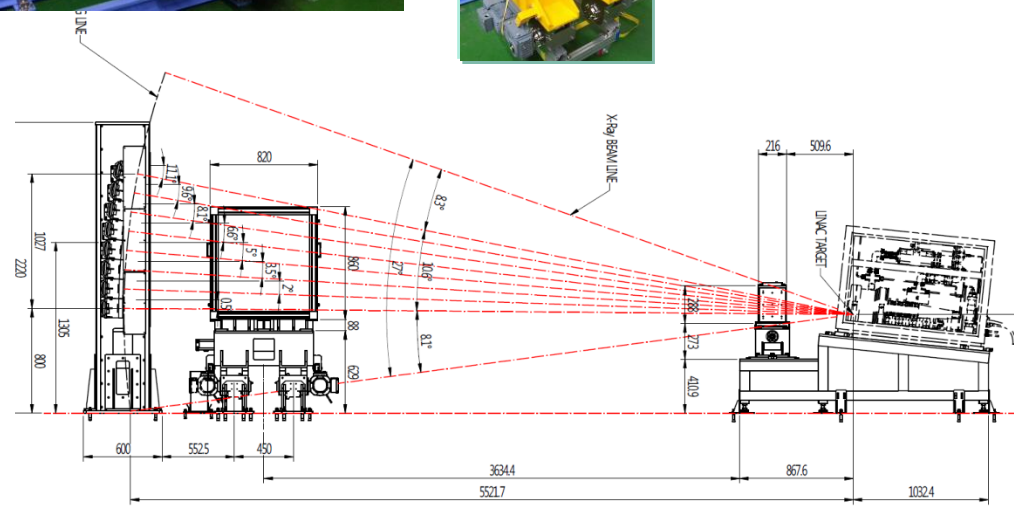
ADC: 18 bit









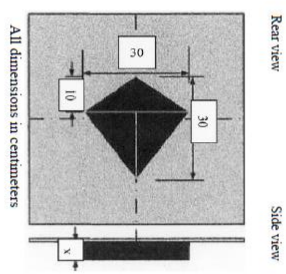


Length = 4.430 m
Whole Weight = 1500 kg
Speed = 0.1 - 1 m/sec
Turn Table Rotation Load = 200 kgf

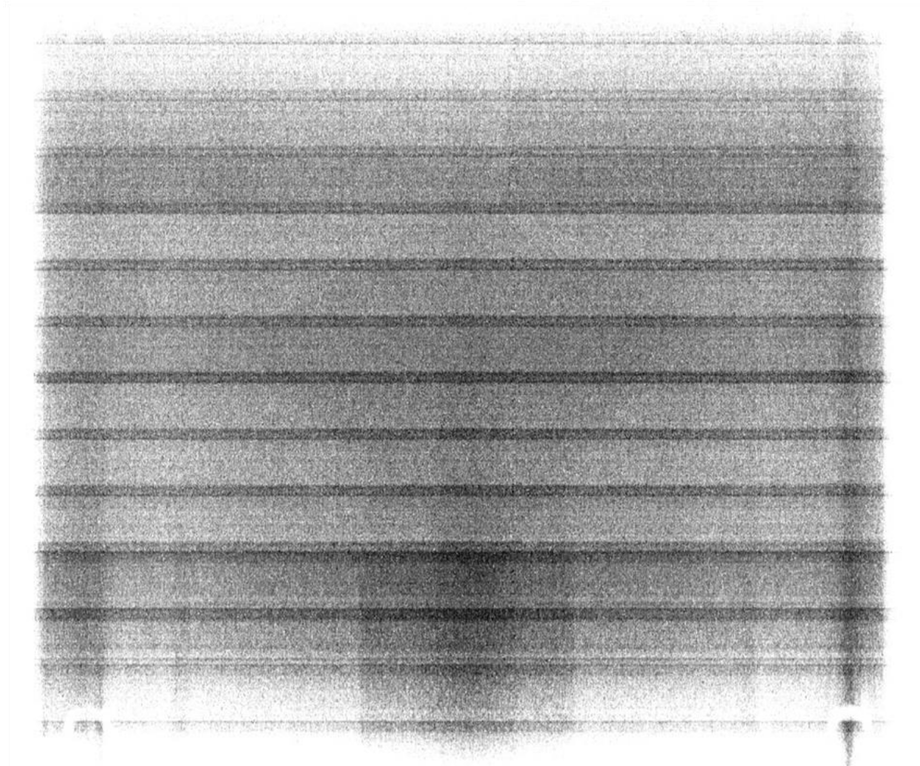
Penetration Test (June, 2015)

By using 380 mm steel plates with a 6 cm thickness diamond plate, we could find direction of the diamond shape (ANSI 42.46).

Real Objects (Steel 380 mm)



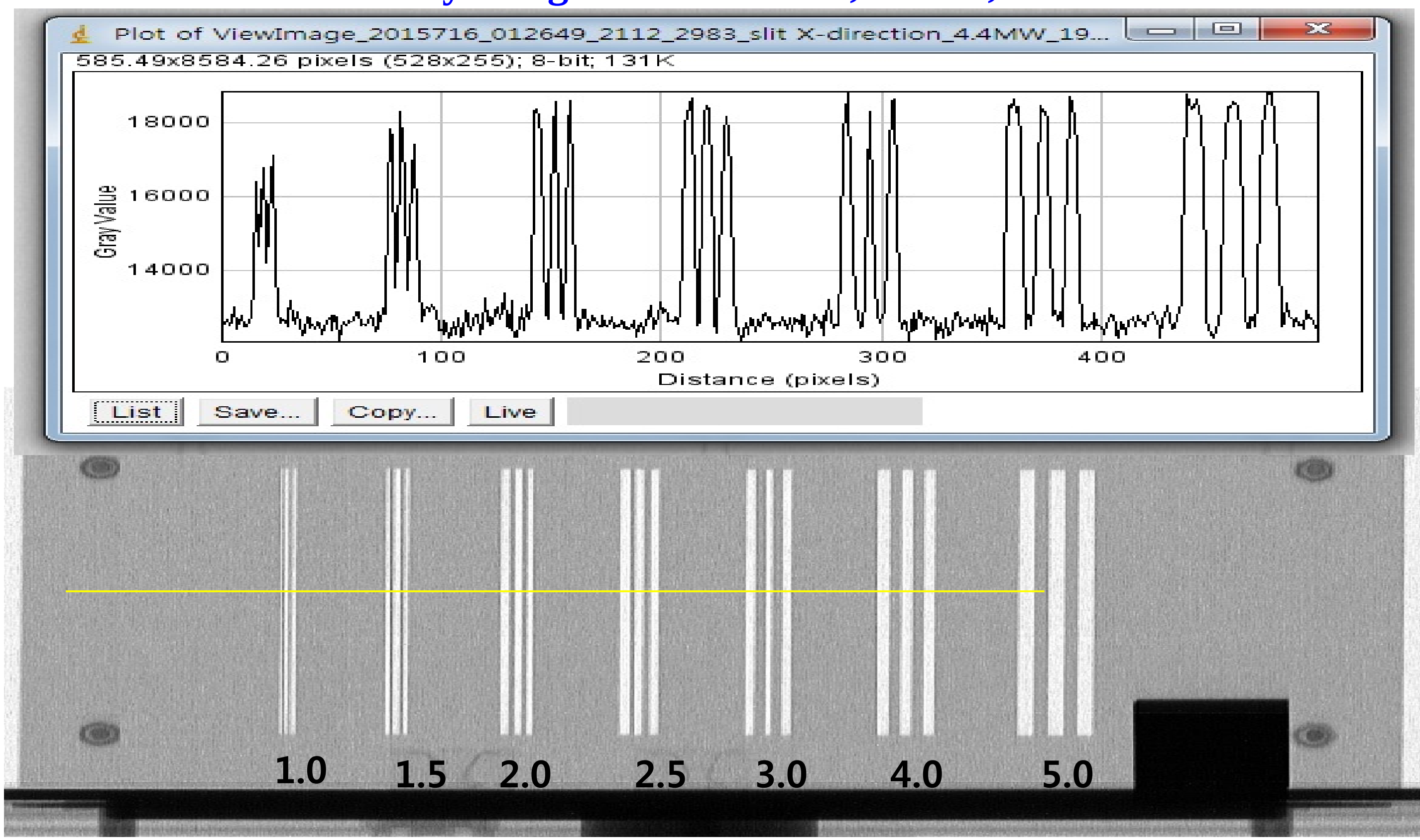
X-ray Image from Detector, 9 MeV, 100 Hz

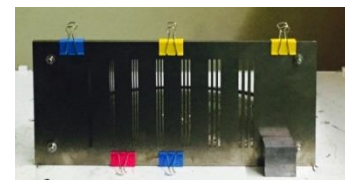


Spatial Resolution Test (June, 2015)

By using slits with various widths (1 - 5 mm) and a thickness of 10 mm, we could distinguish a slit with a width of 1 mm (ANSI 42.46).

X-ray Image from Detector, 9 MeV, 100 Hz





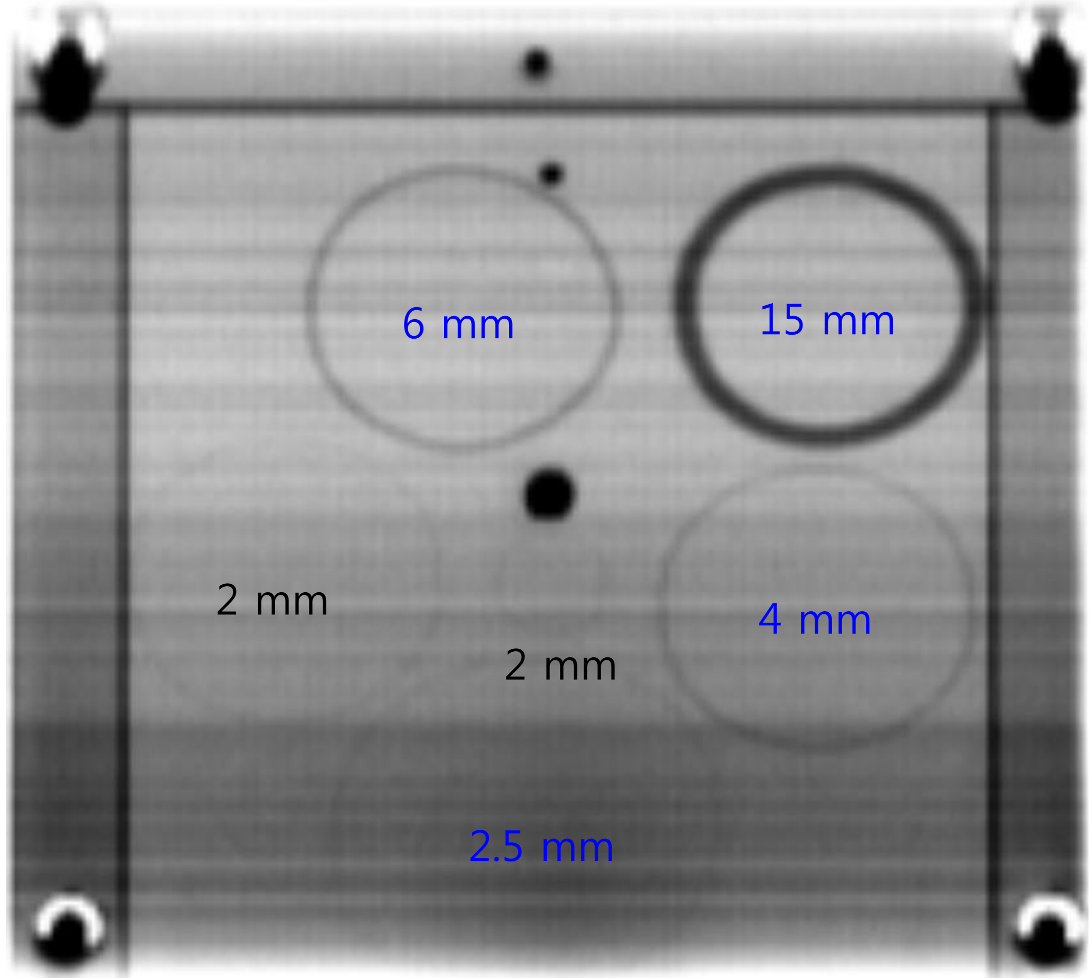
Real Object

Contrast Test (June, 2015)

By using 150 mm steel plates with various thickness rings, we could distinguish a ring with a thickness of 2 mm (ANSI 42.46)

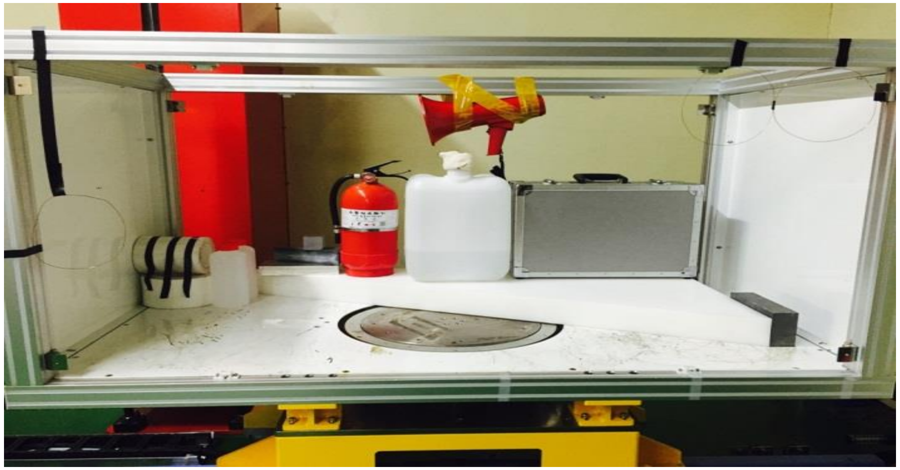
- **0.5 mm Ring (@ air)**
- **2 mm Ring (@ 100 mm steel)**
- **2.0 mm Ring (@ 150 mm steel)**
- **4 mm Ring (@ 200 mm steel)**
- **6 mm Ring (@ 250 mm steel)**
- **15 mm Ring (@ 300 mm steel)**

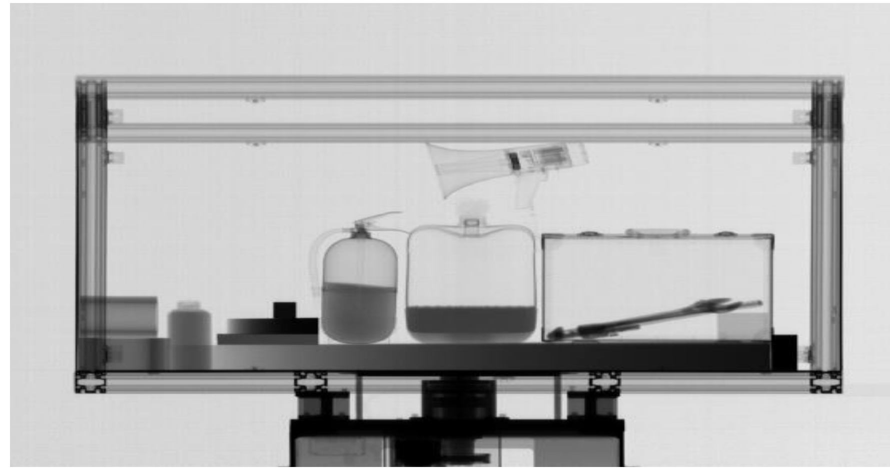
Contrast = 2/150 = 1.3%



X-ray Image from Detector Arrays (June, 2015)

Real Objects





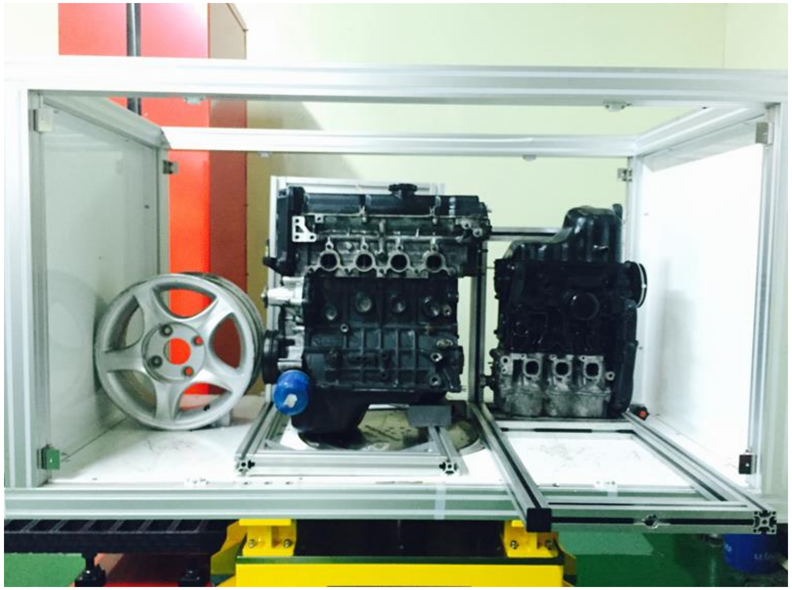
X-ray Image from Detector
9 MeV 19 kV @ gun, 100 Hz

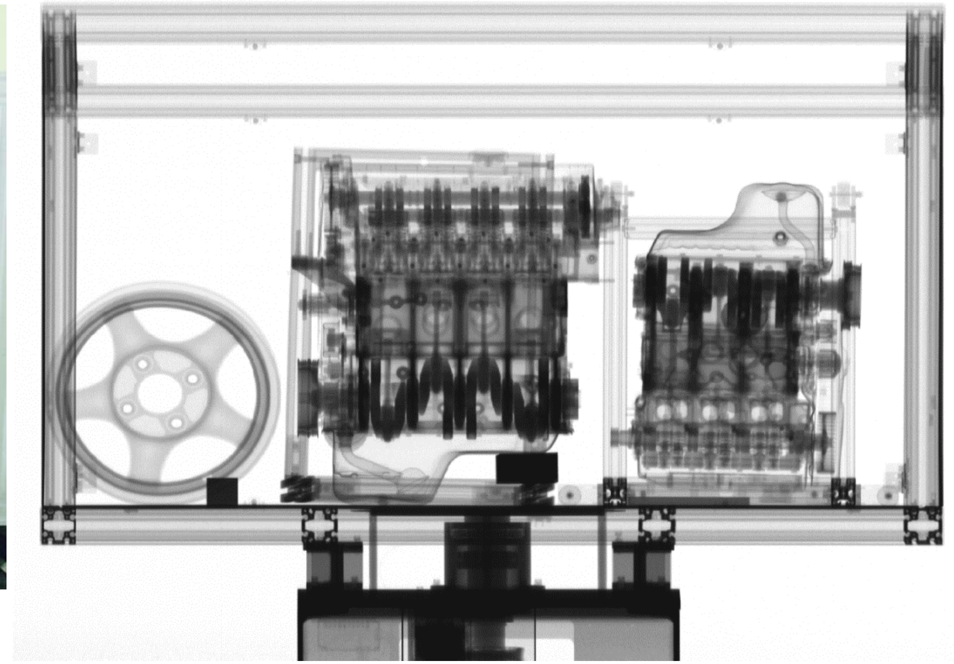
Our container inspection system was selected as one of Korean outstanding research 100 in 2016

컨테이너검색기 시제품 개발
2016년 국가연구개발 우수성과 100선에 선정

X-ray Image from Detector Arrays (June, 2015)

Car Engines and Wheel



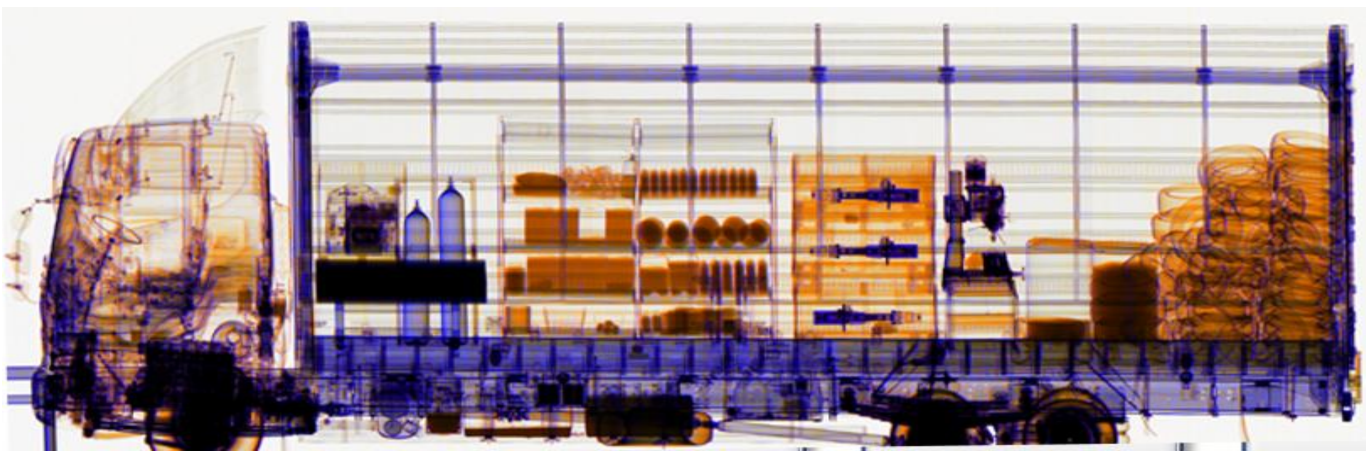


X-ray Image from Detector

Our container inspection system was selected as one of Korean outstanding research 100 in 2016

컨테이너검색기 시제품 개발
2016년 국가연구개발 우수성과 100선에 선정

Pseudo-Color Image with Developed SW (June, 2015)



Blue: Inorganic
Orange: Organic

국가연구개발 우수성과

귀하의 연구성과가 「2016년 국가연구개발 우수성과 100선」으로 선정되었기에 이 증서를 드립니다.

2016년 7월 7일

최 양 희

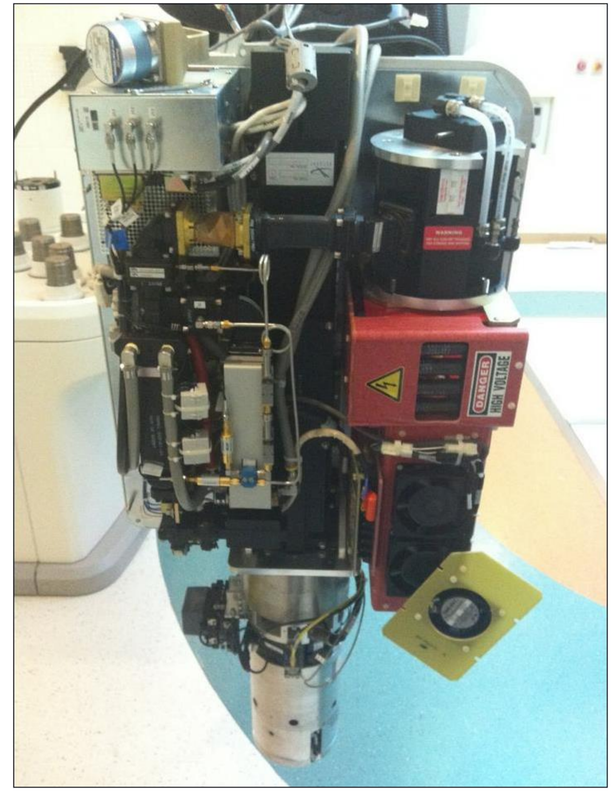
Our container inspection system was selected as one of Korean outstanding research 100 in 2016

Commercial CIS Vs. KAERI CIS

Parameters	Commercial CIS	KAERI CIS	Performance
Dual Beam Energy (MeV)	9/6	9/6	Same
Beam Spotsize (mm, FWHM)	2	0.9	Outstanding
Penetration Depth (mm, Steel)	380	380	Same
Spatial Resolution (mm)	-	1	Outstanding
Contrast (%)	1.7	1.3	Outstanding
Organic / Inorganic	○	○	Same

6 MeV X-band Linac for Medical

For the medical applications (CyberKnife & dual head gantry), we promised following parameters:



RF Frequency ~ 9.3 GHz
beam energy ≥ 6 MeV
dose rate ≥ 500 cGy/min
target spotsize ≤ 2 mm (FW)

To supply those parameters, we are developing new X-band electron linacs.

bunching cells: 10.5 cells with energy gains of 122 - 245 keV
accelerating cells: 14 cells with 16 MV/m (coupler @ 14th cell)
gun gap voltage ~ 20 kV
peak current at gun exit ~ 100 - 200 mA
peak energy at linac exit ~ 6 MeV
beam capturing coefficient ~ 50%
average beam power ~ 167 W for 500 cGy/min
peak / average current at linac exit ≥ 50 - 100 mA / 28 μA for 500 cGy/min
with a duty factor 0.0009
duty factor of L3 magnetron: ~ 0.0002 (2 MW) - 0.0008 (1.7 MW).
duty factor of CPI magnetron: ~ 0.0018 (1.5 MW)

Risks when we chose X-band RF Linac

Only several laboratories around world could fabricate working X-band linacs.

Over all fabrication error should be smaller than 2 μm → too challenging!

Up to now, no company or laboratory made a working X-band RF linac!

Many accelerator experts mentioned to us

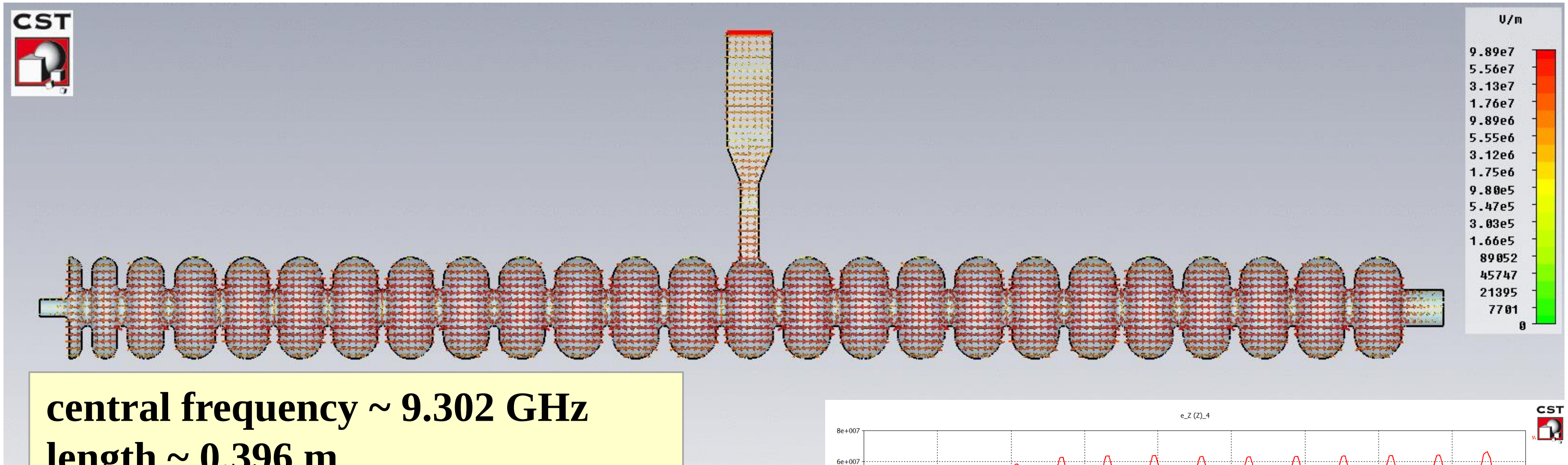
"Impossible with KAERI's skills and technologies!"

And recommended us to fabricate it at other foreign countries.

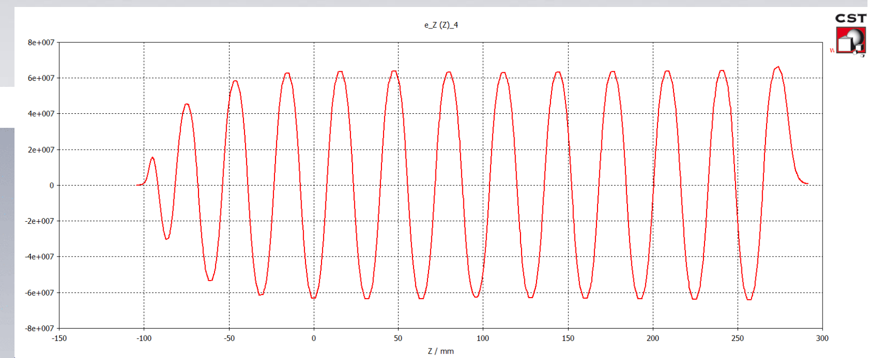
However, after considering many things, we chose X-band RF linac and started to fabricate in Korea!

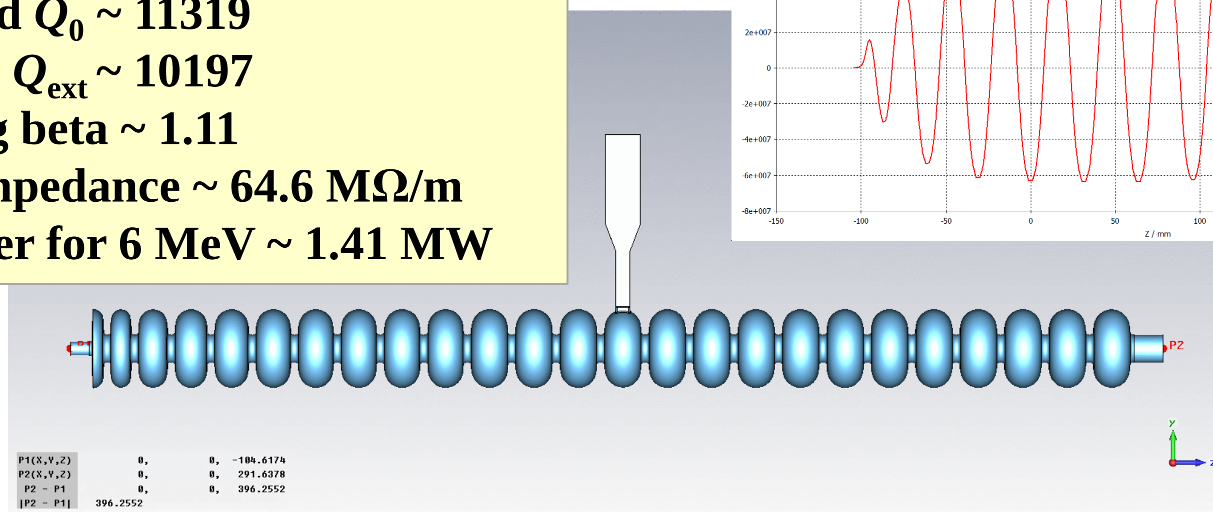
Current Status - 6 MeV X-band Linac

ISU & KAERI teams designed an X-band linac structure with 24.5 cells.



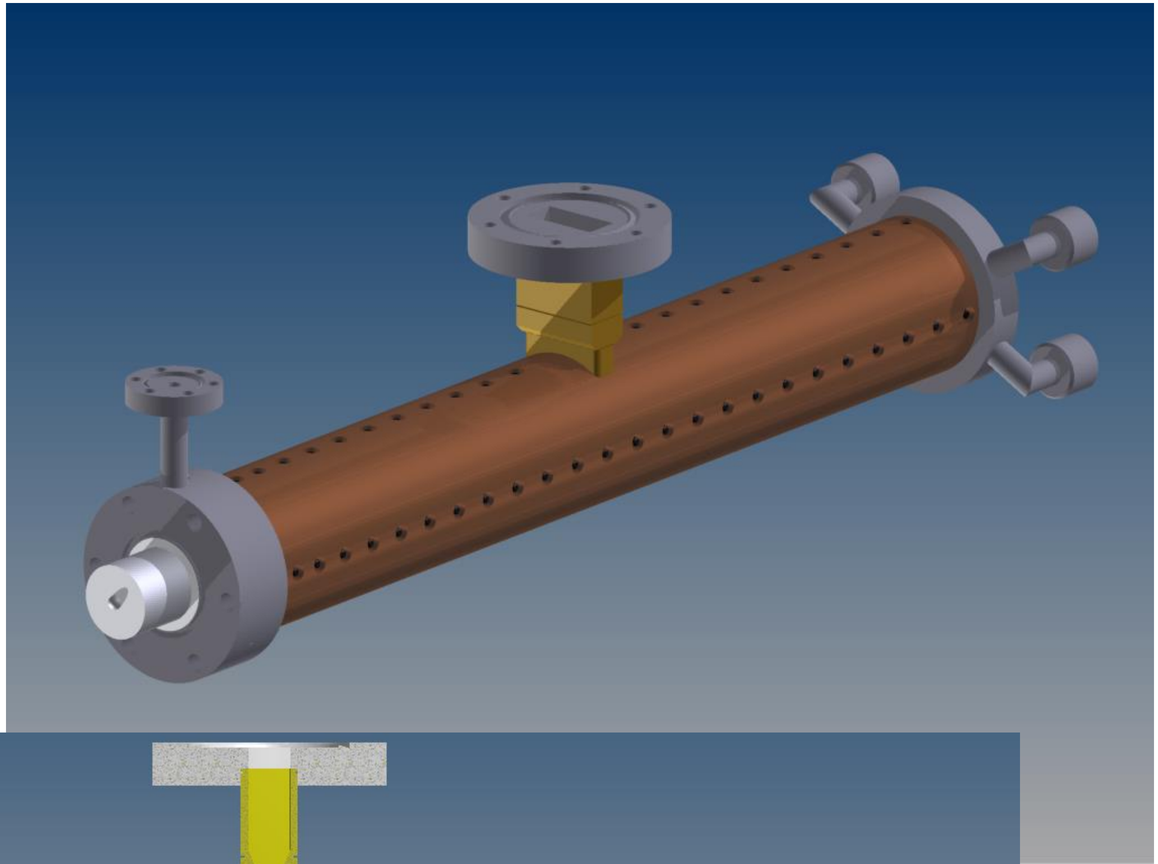
central frequency ~ 9.302 GHz
length ~ 0.396 m
unloaded Q_0 ~ 11319
external Q_{ext} ~ 10197
coupling beta ~ 1.11
shunt impedance ~ 64.6 MΩ/m
RF power for 6 MeV ~ 1.41 MW

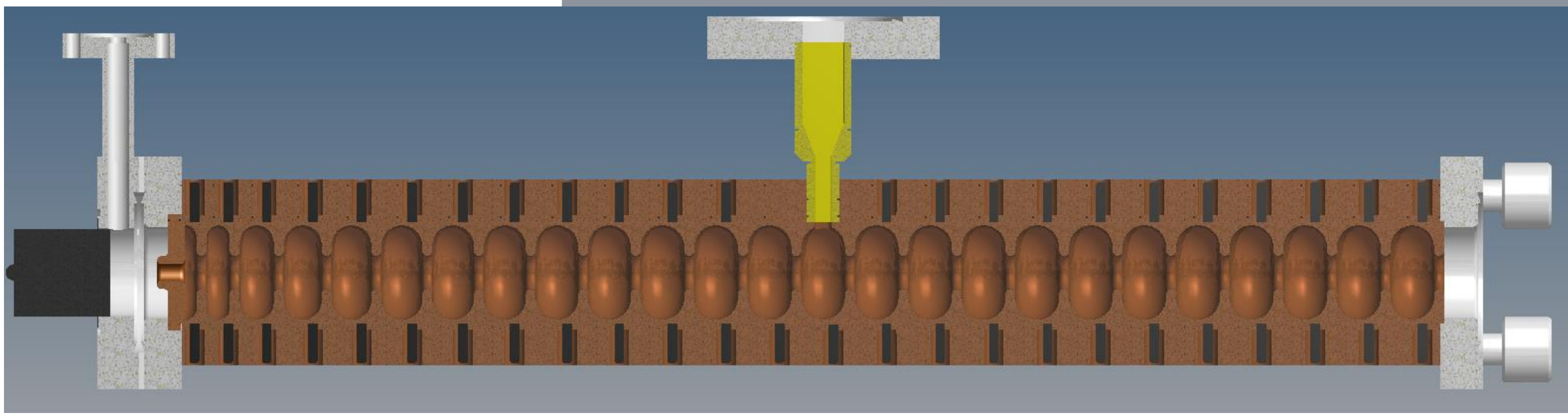




X-band Linac 3D Drawing

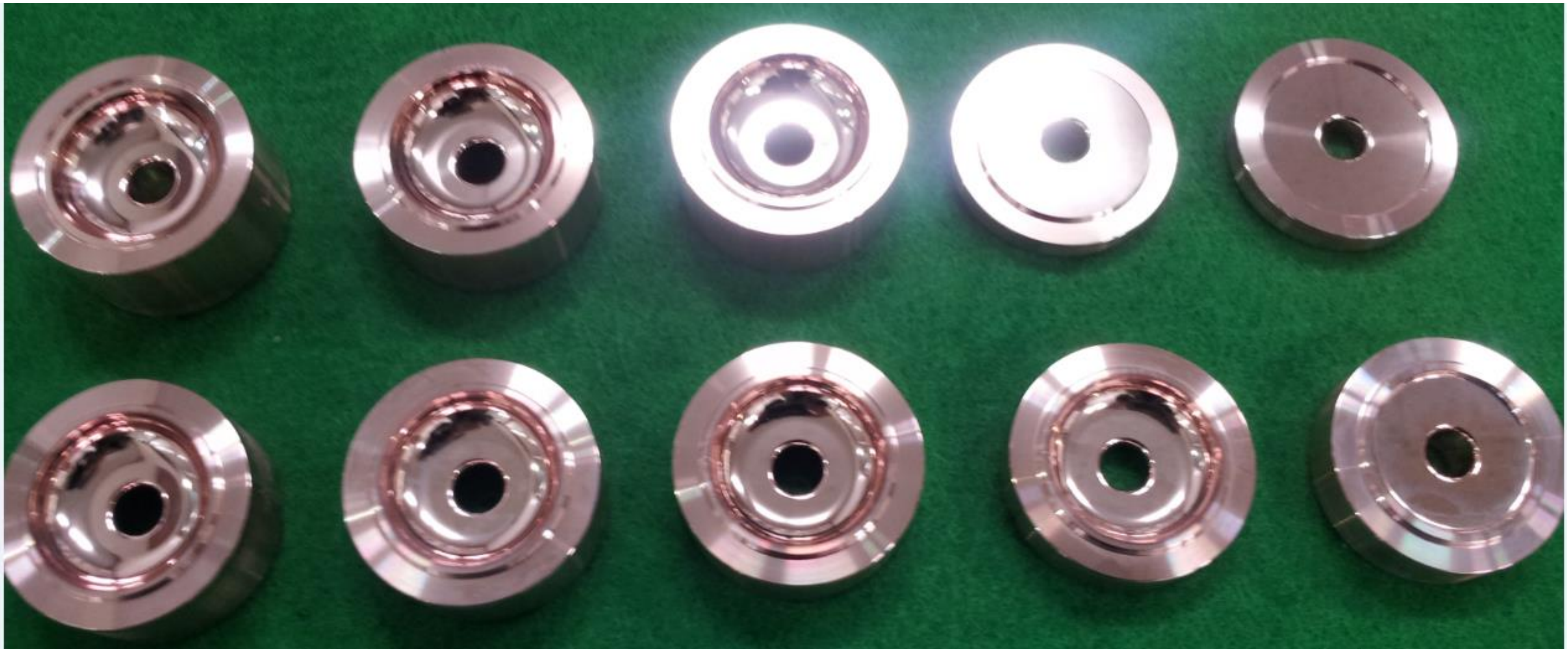
24.5 cells with 10 bunching cells
central frequency ~ 9.302 GHz
length ~ 0.396 m
unloaded *Q* ~ 11319
coupling beta ~ 1.11
R_{sh} ~ 64.6 MΩ/m
Power for 6 MeV ~ 1.41 MW
Cell length ~ 16.1 mm
Radius ~ 14.2 mm
Gradient ~ 17 MV/m
Weight ~ 8 kg





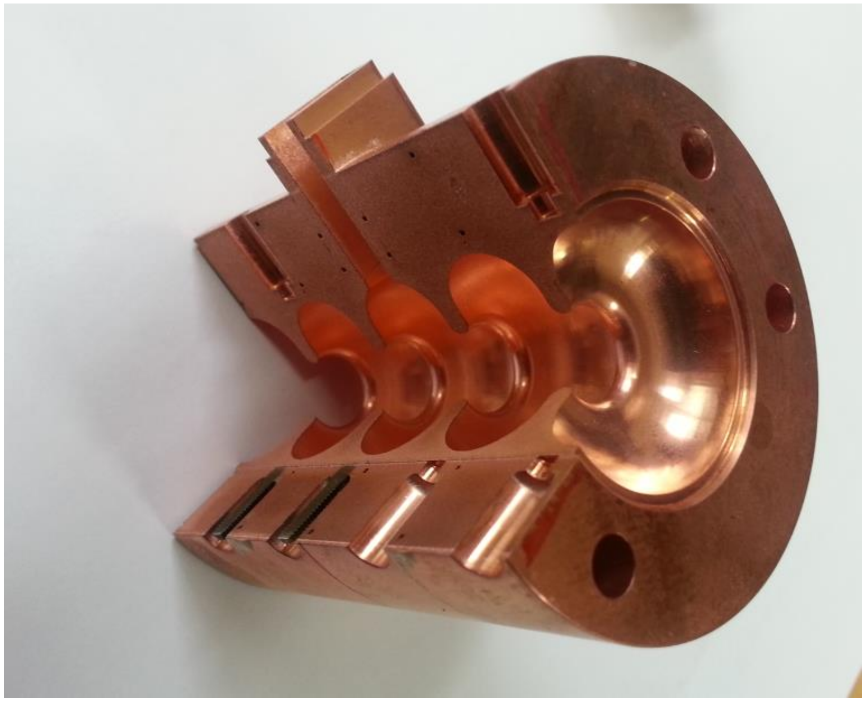
X-band Linac Fabrication - Cells

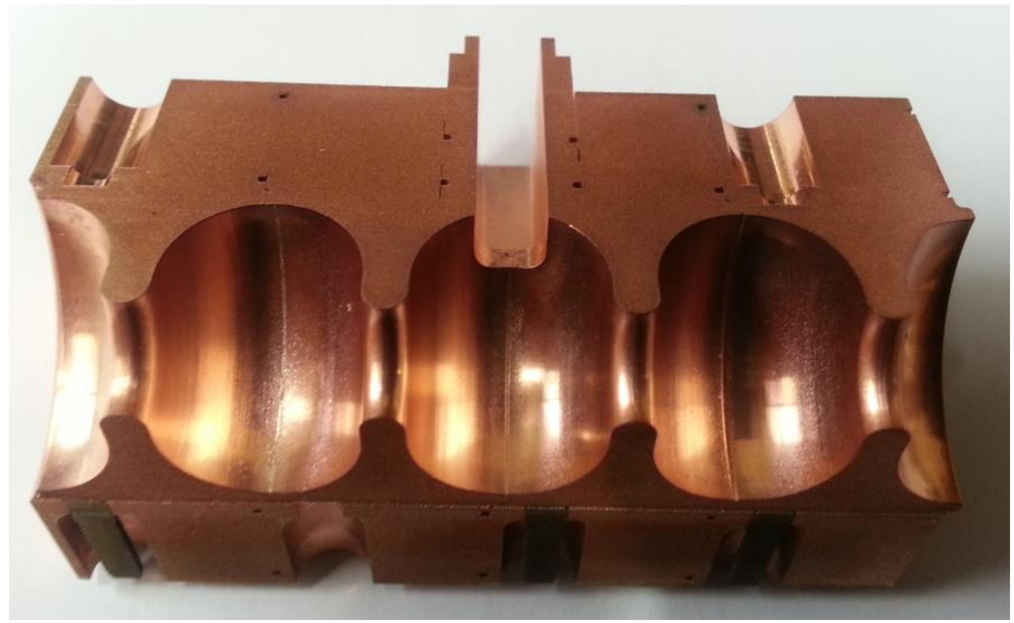
Cells for X-band linac



X-band Linac Fabrication - Brazing Test

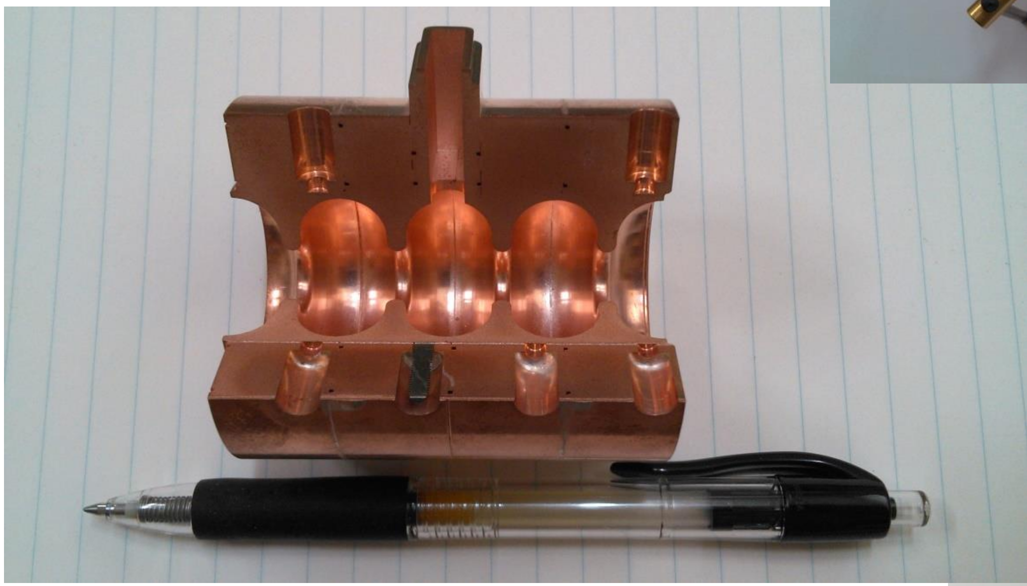
Brazed coupler cell for X-band linac

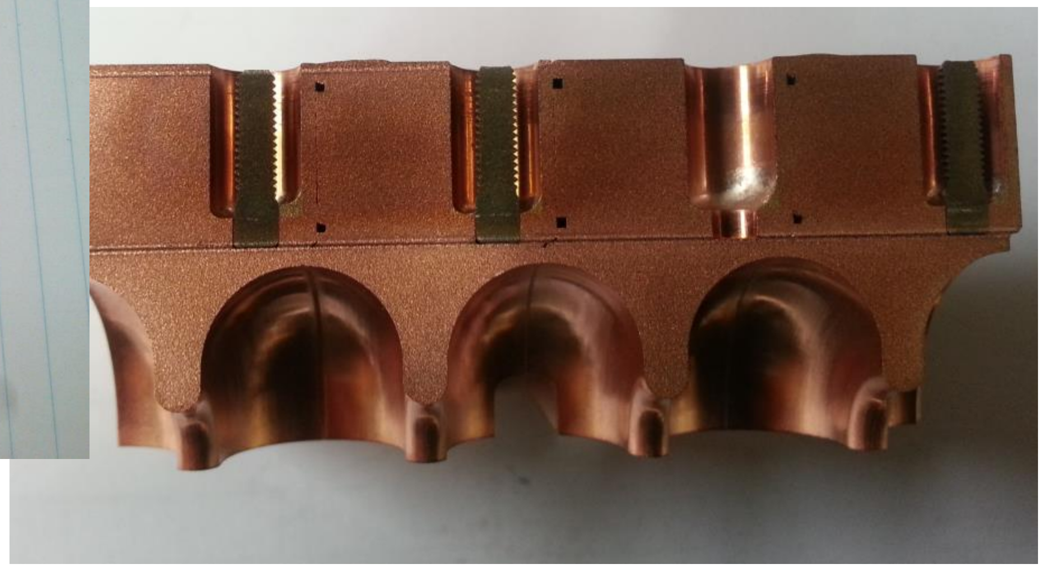




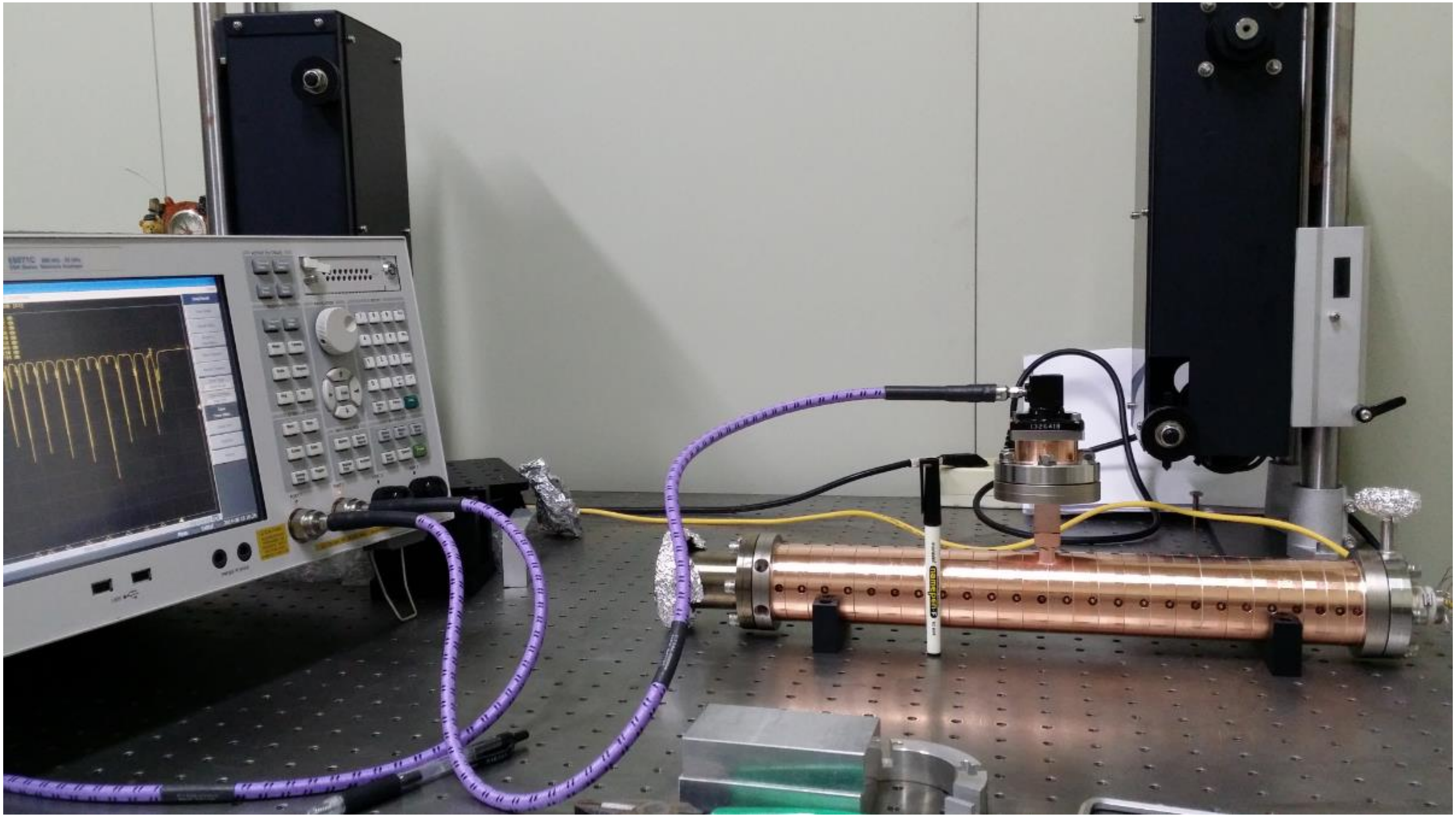
X-band Linac Fabrication - Tuners

Tuners for X-band linac

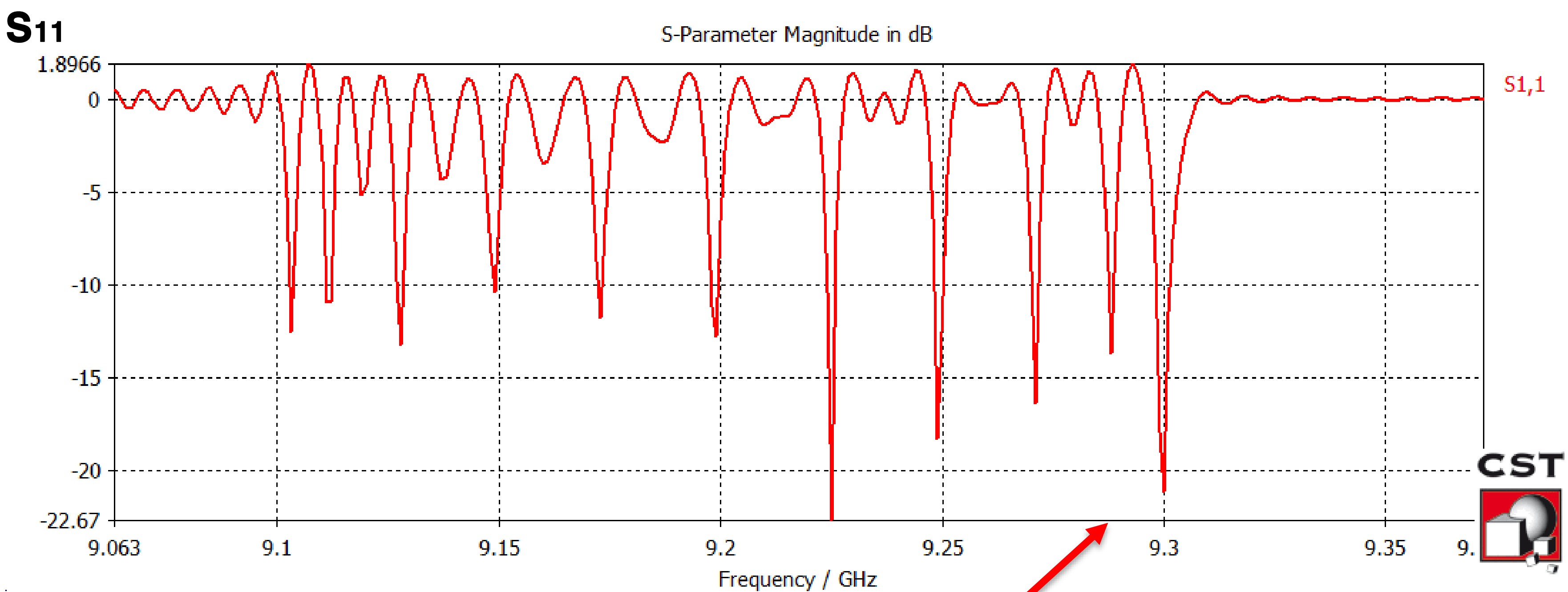




X-band Linac - Fabricated Linac



X-band Linac - CST Simulation

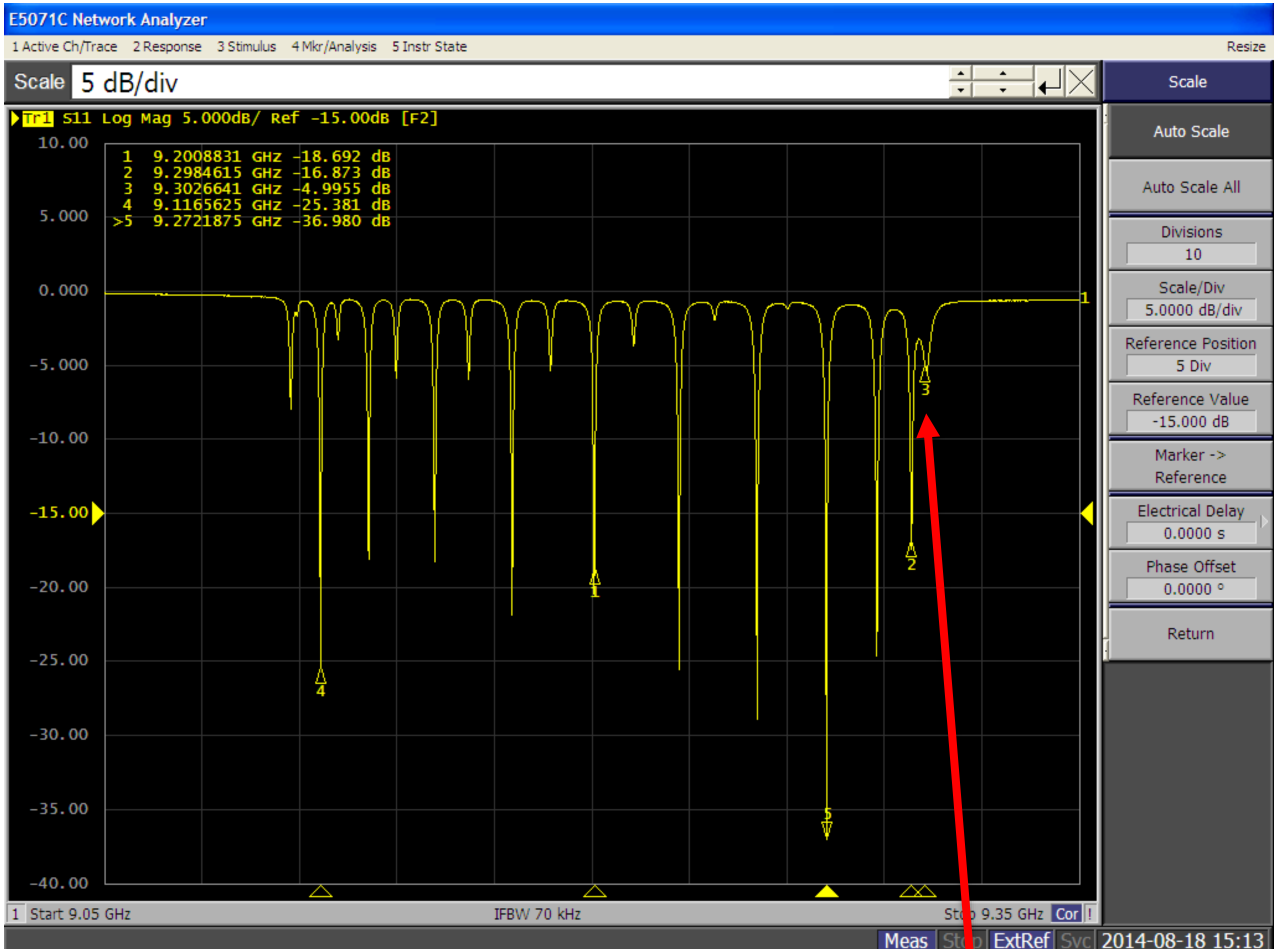


CST Simulation

π mode ~ 9.302 GHz

X-band Linac - Fabricated Linac

S11



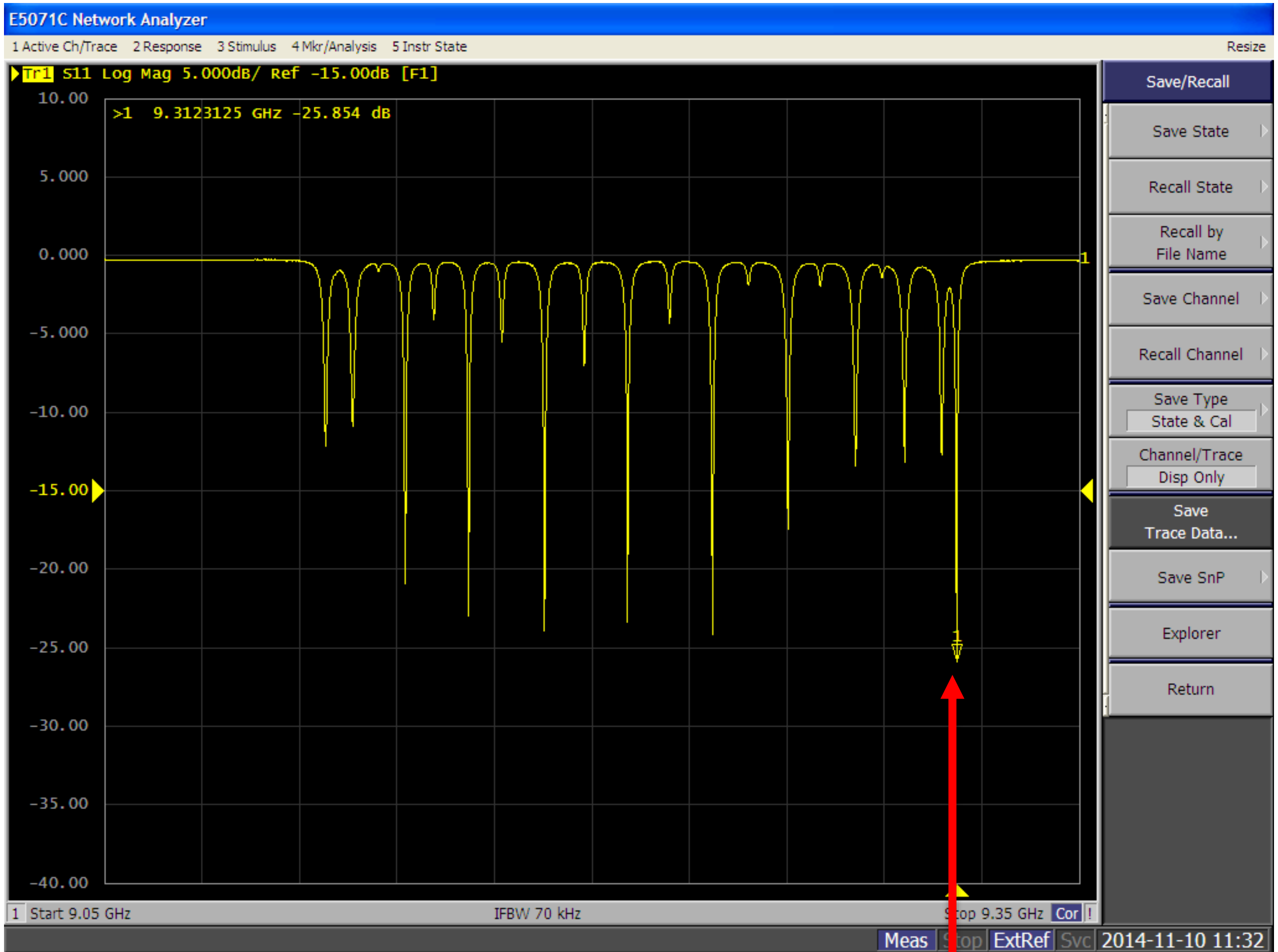
Right After Fabrication

π mode ~ 9.302 GHz with -5.0 dB

KAERI did Great Design & Fabrication!

X-band Linac - Fabricated Linac

S11



After Final Tuning @ Tempearture = 30 degree

KAERI did Great Tuning!

π mode ~ 9312.31 MHz with -27 dB

(0.2% reflection)

6 MeV X-band Linac RF Magnetron

Required beam current depends on duty factor.
Duty factor of L3 PM1110X 1.7 MW magnetron: 0.0008
Bandwidth of PM1110X Magnetron (3 dB) ~ 0.2 MHz
Tuning Range = +/- 25 MHz
Automatic Frequency Controller (AFC) was developed by KAERI.

Performance Characteristics

Frequency .... 9.300 GHz, +/- 25 MHz
Peak Pulse Power output .... 1,700 kW (min)
Average Power output .... 1,360 W (at .0008 duty)
Peak Anode Voltage .... 32-36 kV
Peak Anode Current .... 88 A
Average Anode Current .... 70 mA
Pulse Width .... 4.0 uSec
Duty Cycle .... 0.001 (typical operation at .0008)
Filament Voltage (standby) .... 10 V
Filament Current (standby) .... 15 A
Filament Voltage (oscillating) .... 2 V (back down required)
Warm-up time .... 300 Sec.
Load VSWR .... 1.2:1 (max)

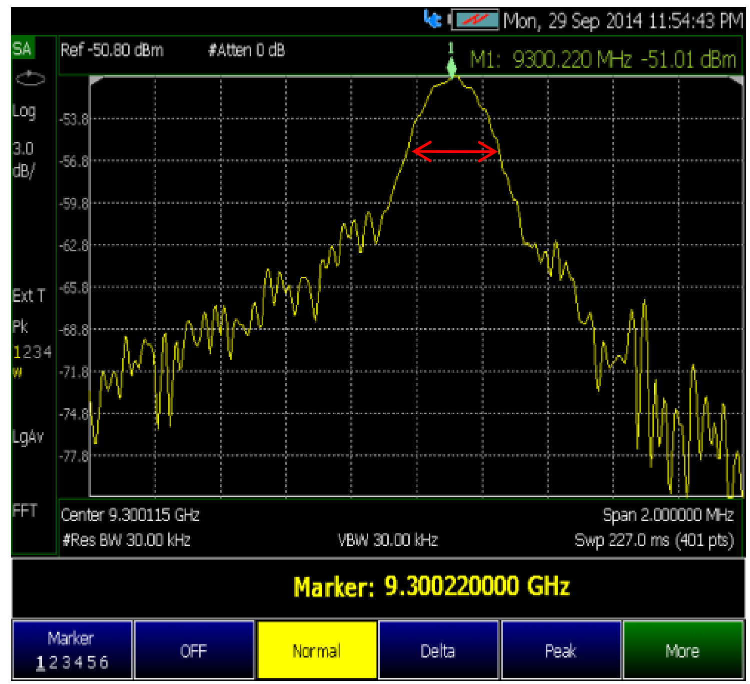
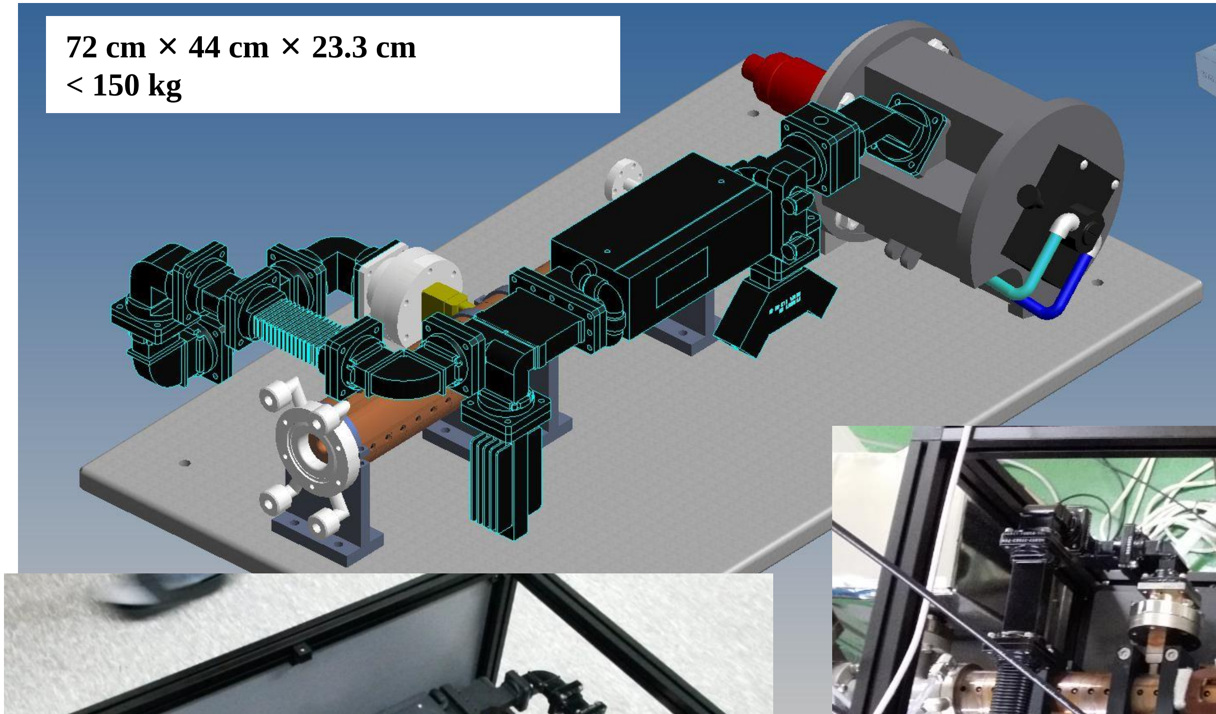
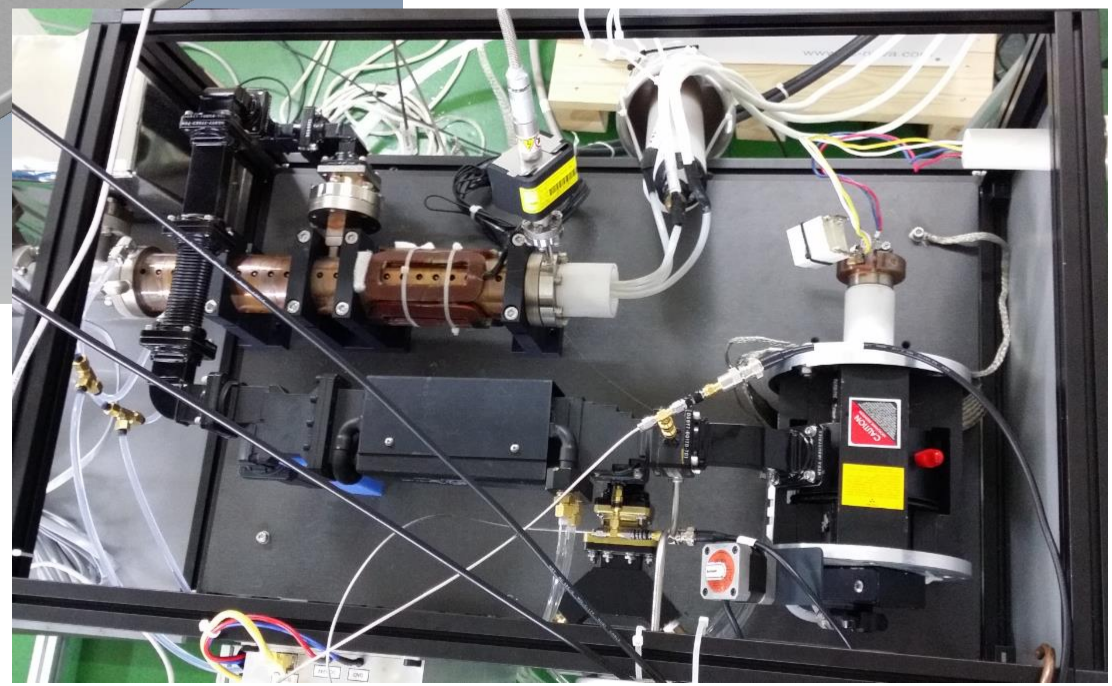


Photo of Assembled X-band Linac

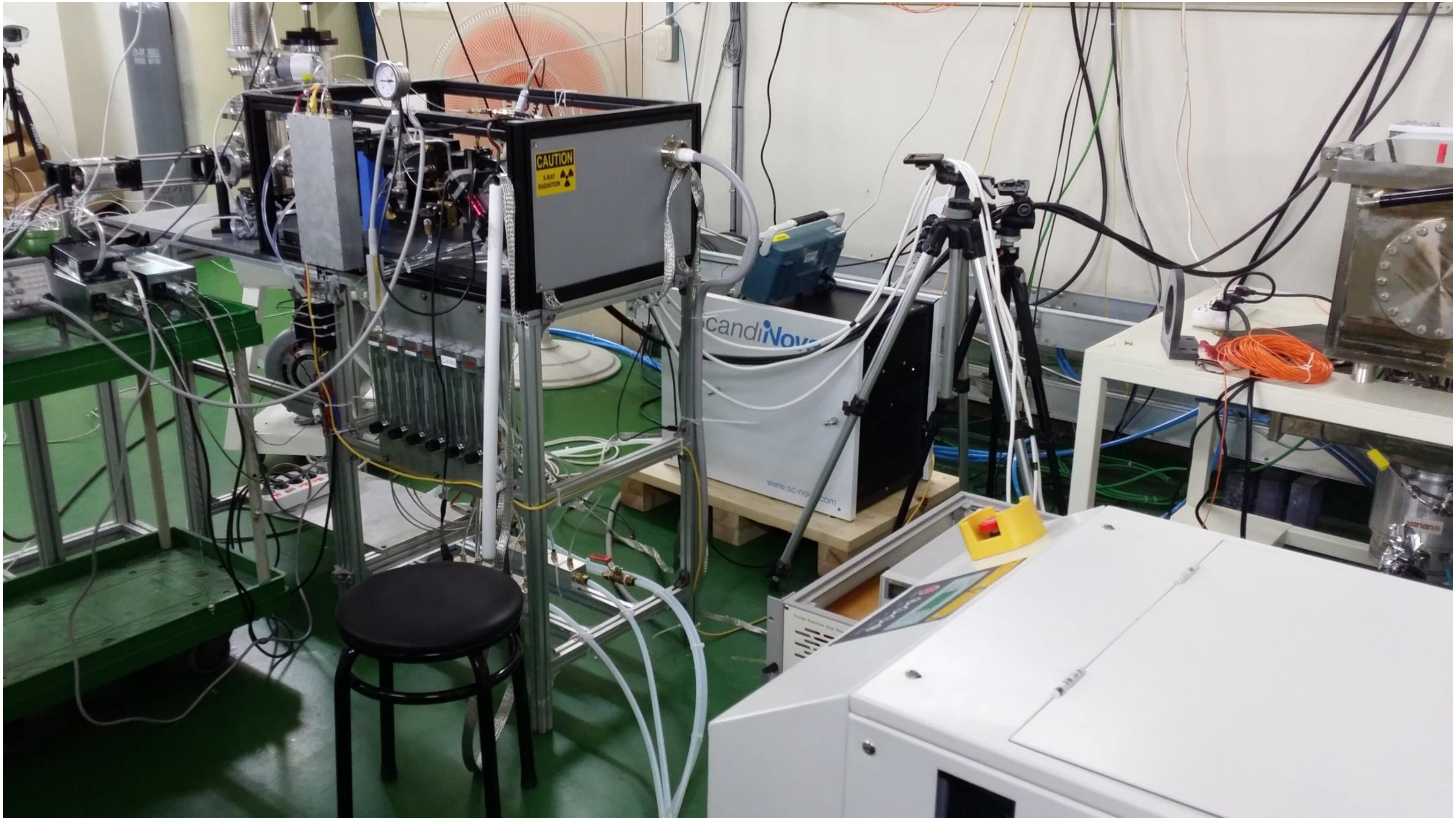


after baking ~ 1.0E-8 Torr



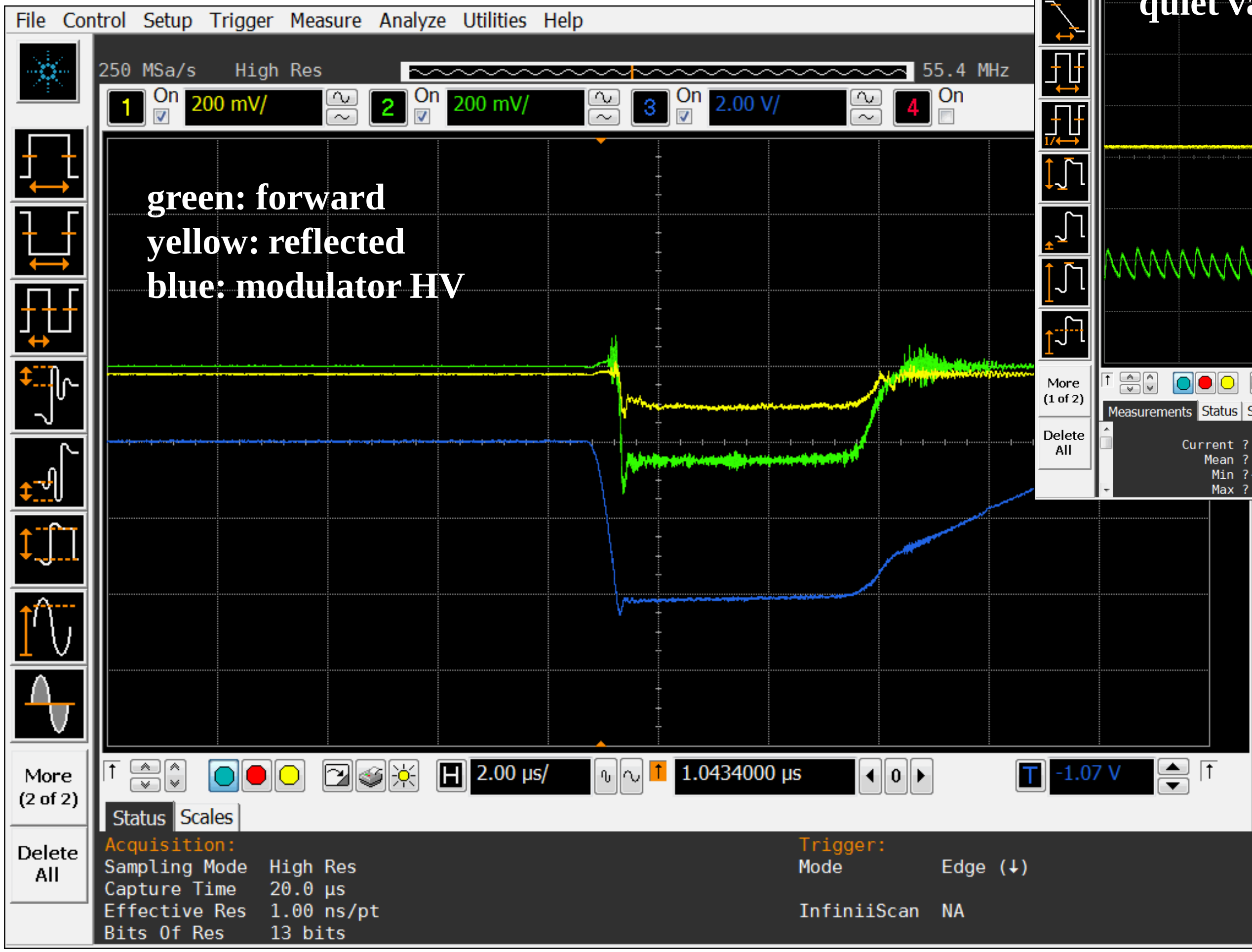
before baking

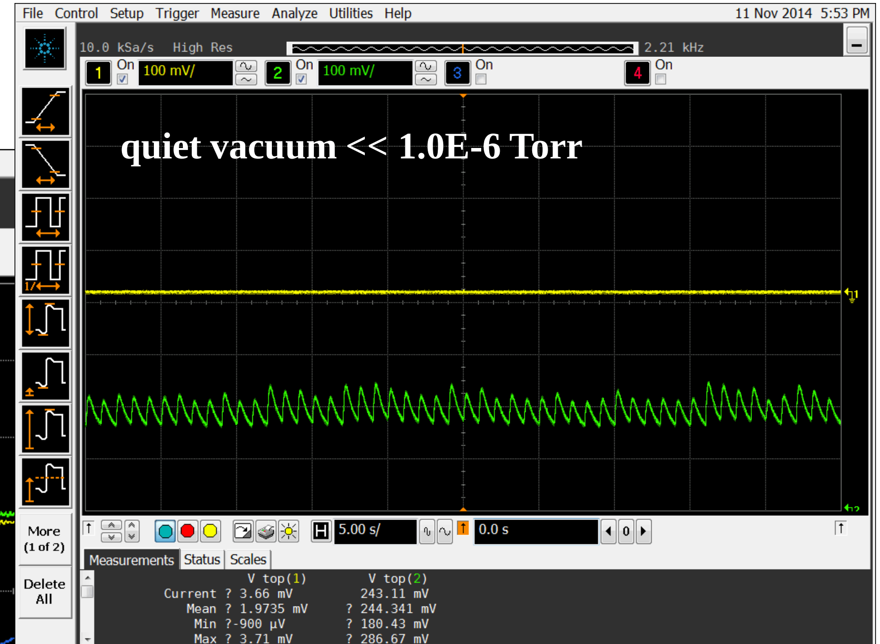
Photo of Assembled X-band Linac



RF Condition with 2.1 MW

We could finish RF condition only with one day!
2.1 MW full power, 4 μs, 2 Hz,
Vacuum ~ 1.0E-8 Torr
This is a good indication of our great jobs!





1st Beam from X-band Linac - Nov. 14th, 2014

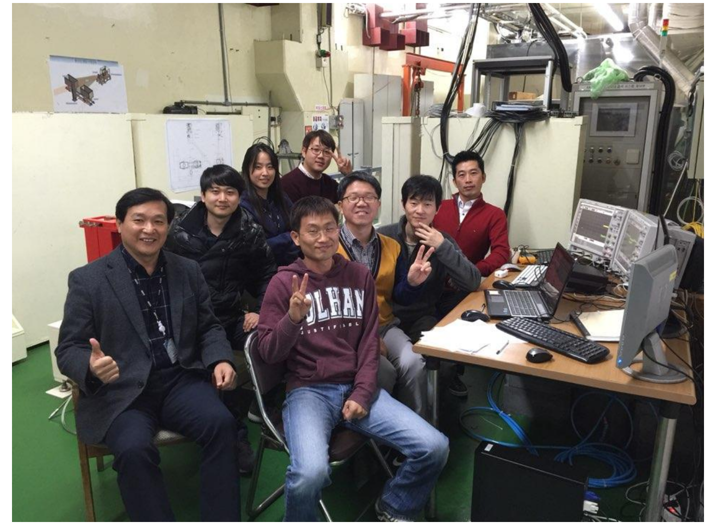
KAERI

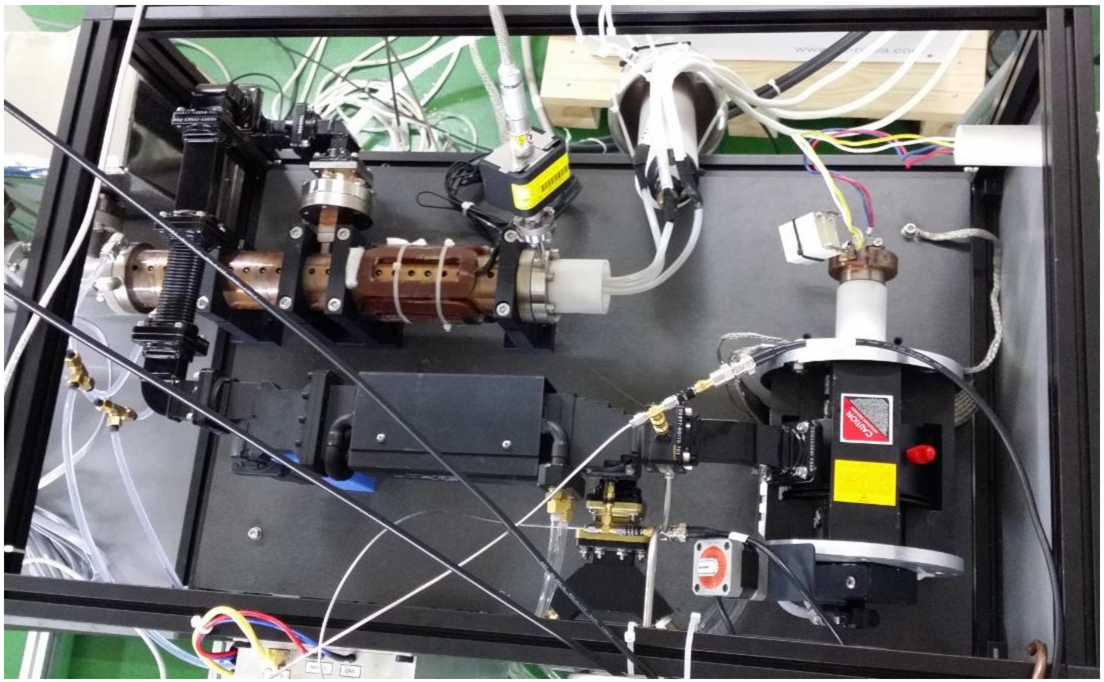
We could get the first beam from the 6 MeV X-band linac on November 14th, 2014!

2.1 MW full power, 4 μs, 2 Hz,

Vacuum ~ 1.0E-8 Torr

Our X-band design worked!





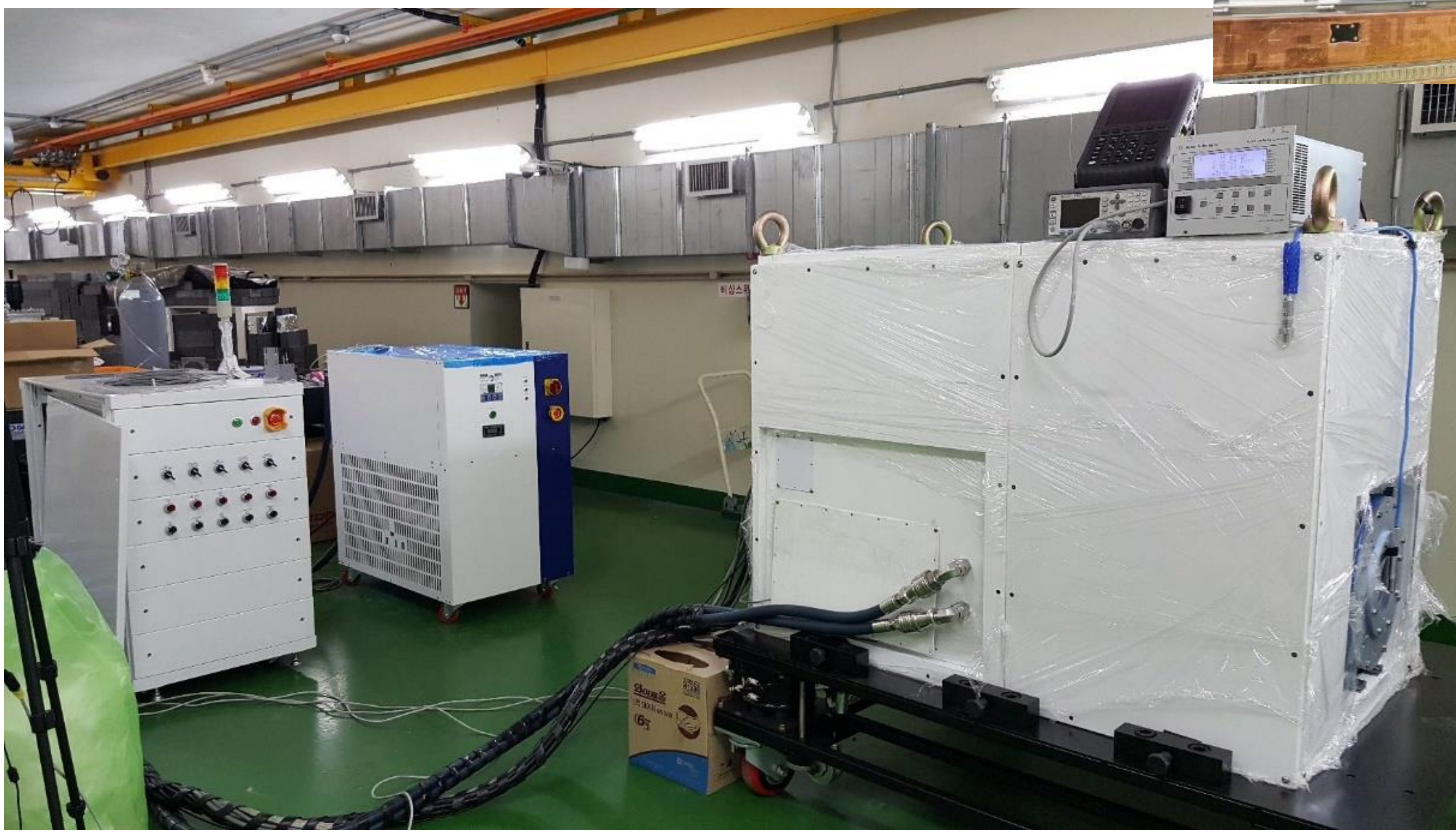
Our Technologies were transferred to RTX

RTX (http://www.irtx.co.kr) Radiation Technology eXcellence

Non-destructive Test (NDT) System for Missile (LAROEN)

2 Systems (9 MeV, 6 MeV 2856 MHz Linac) in 2015

1 System (6 MeV 2998 MHz Linac) in 2016

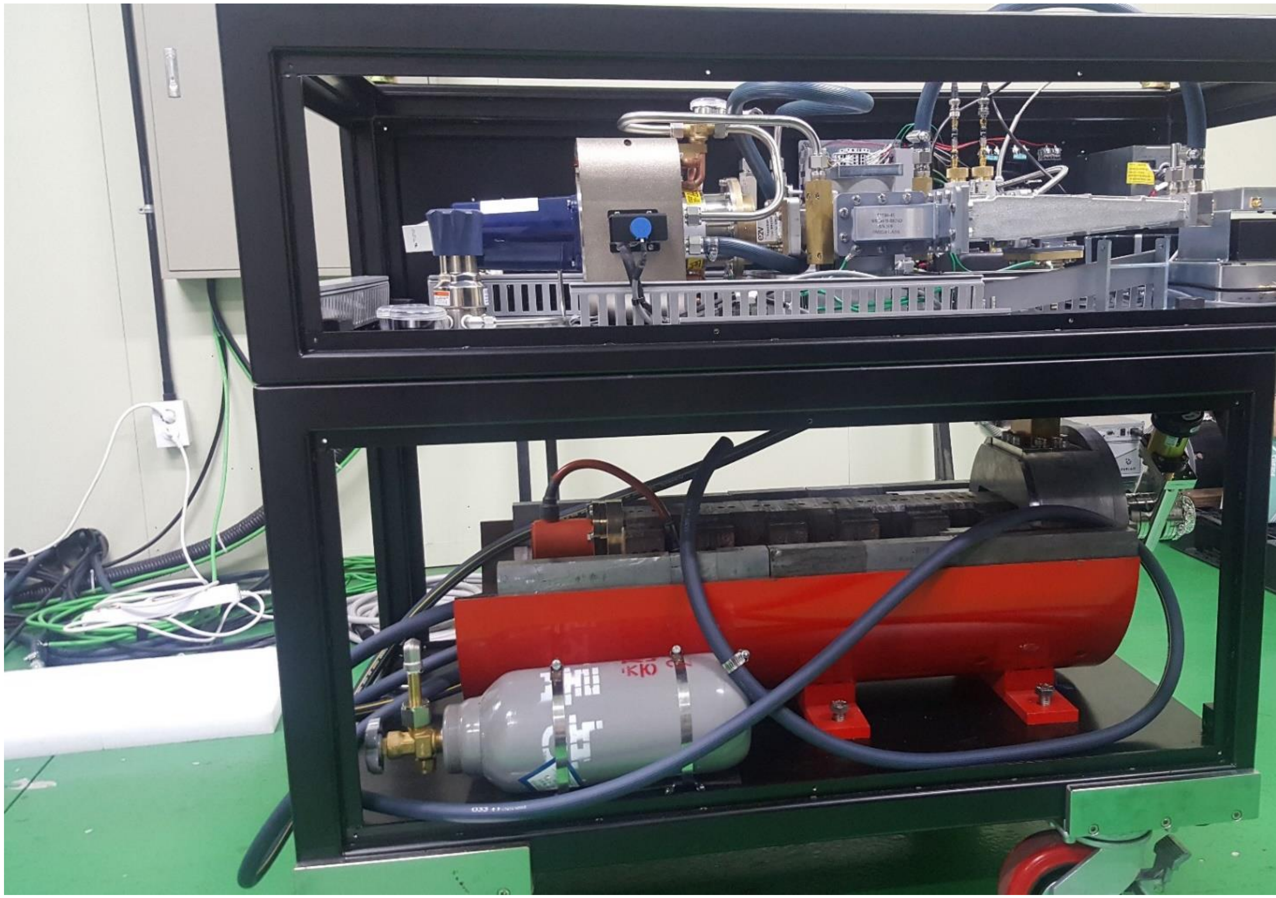


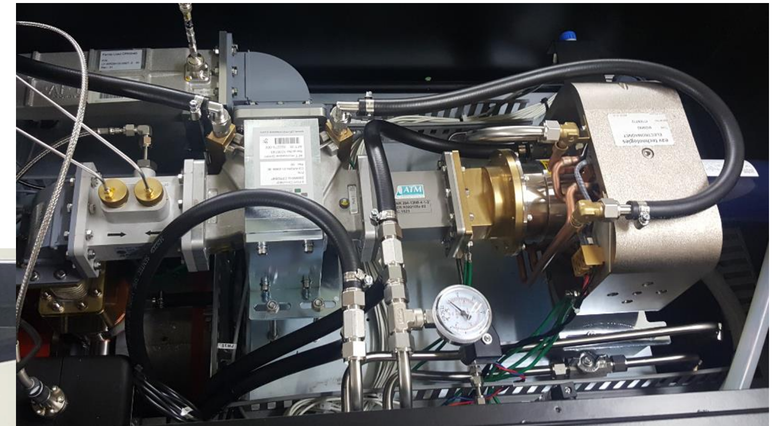
Our Technologies were transferred to RTX

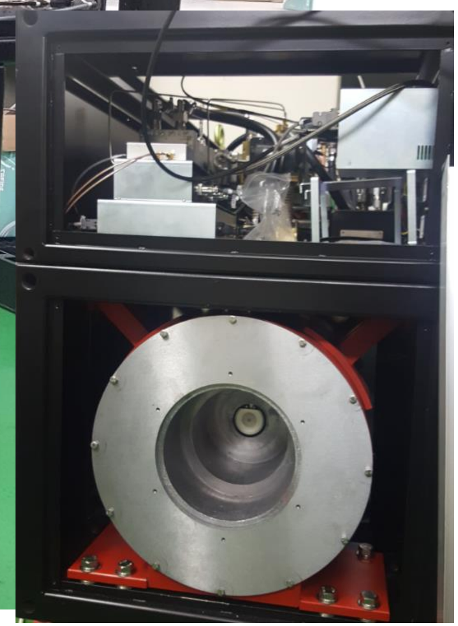
RTX (http://www.irtx.co.kr) Radiation Technology eXcellence

4 Systems for CIS, January 2018

(9/6 MeV 2998 MHz Linac with 13 cells)

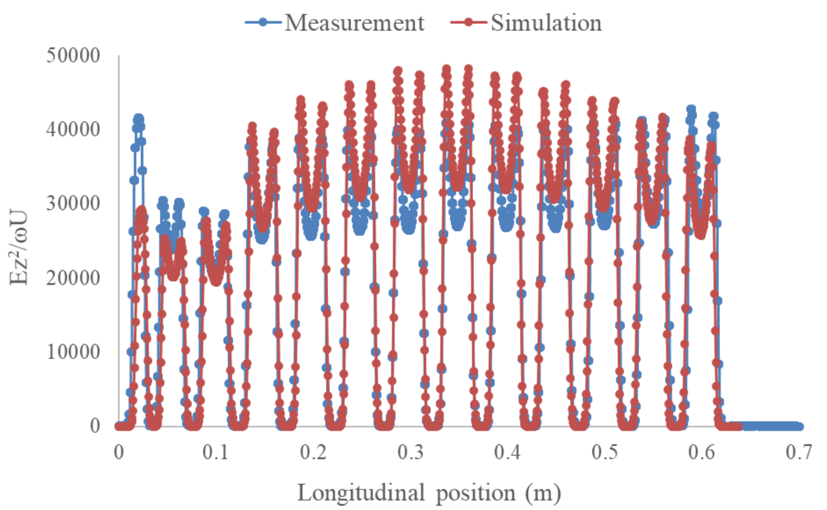




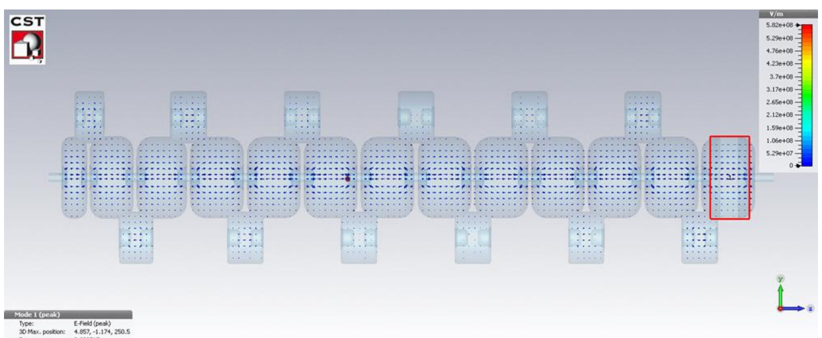


New 9/6 MeV European S-band Linac for CIS

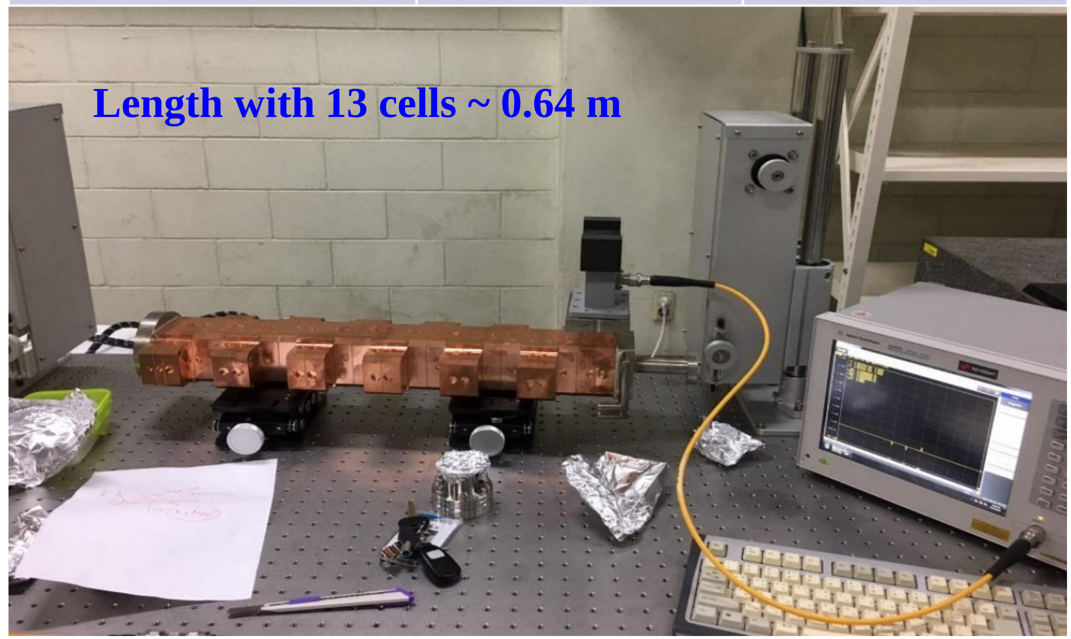
European S-band for a cheaper and low power magnetron (3.1 MW e2v MG6062)



Parameter	CST Simulation	Measurement
Frequency (MHz)	2998.72	2998.14
Shunt impedance (MΩ/m)	87	90
Unloaded Quality factor	16007	14095
Loaded Quality factor	5995	5201
Beta coupling	1.67	1.71



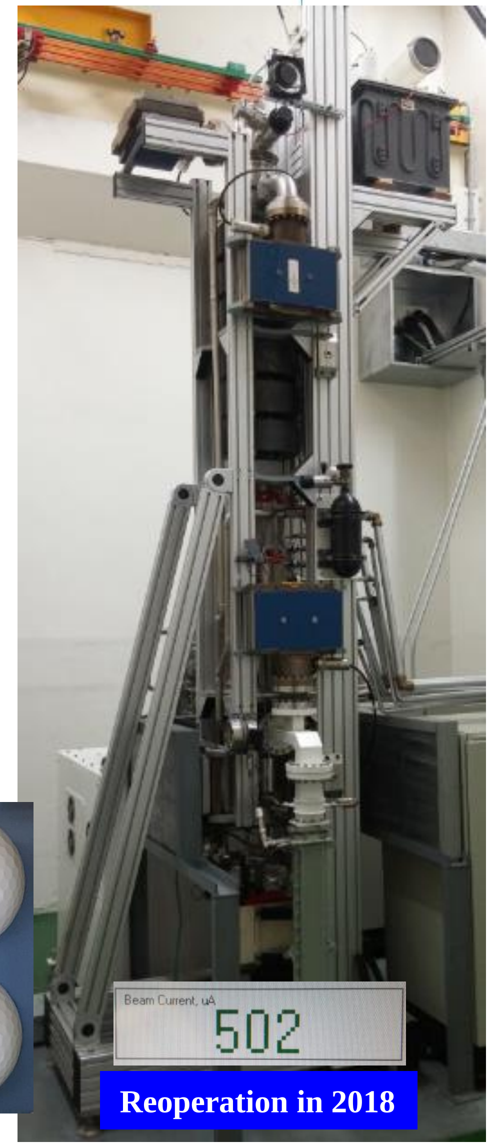
Radiation Technology eXcellence



KAERI - 10 MeV 10 kW Electron Irradiation Facility

Toriy KIU-147A Klystron for 10 MeV 10 kW Linac

Peak RF Power: 6 MW
Average RF Power: 25 kW
Pulse Width: 16 μs
Max Repetition: 300 Hz
Cathode Voltage: 57 kV
Cathode Current: 300 A
RF Frequency: 2856 MHz
Price ~ 0.3 M$

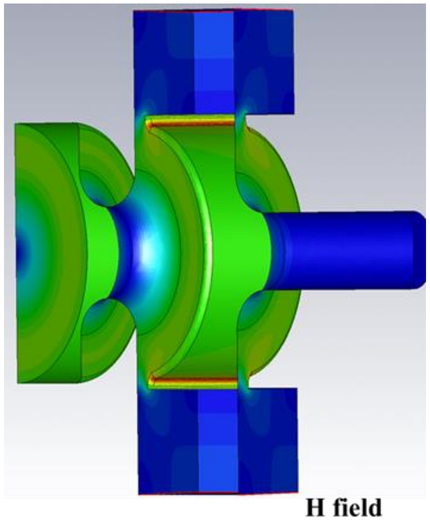


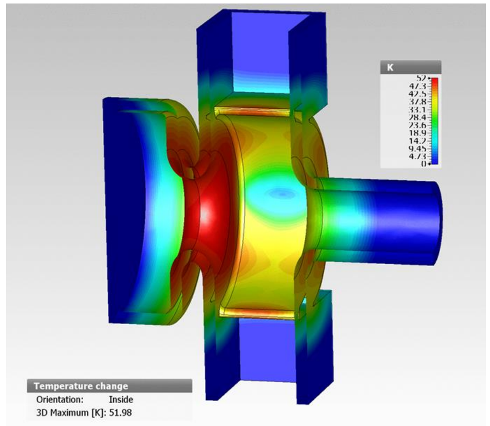
Reoperation in 2018

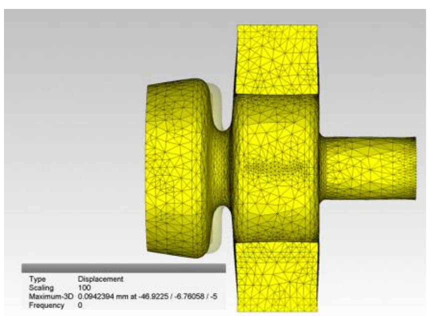
Operated Time: 4225 Hours (Lifetime: 3000 Hours)

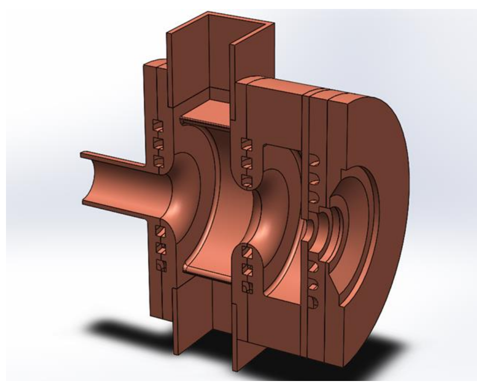
KAERI's Design of S-band RF Gun for UEM

- 1.6 Cell RF-gun with Operation Frequency 2856 MHz, π-mode
- Mode Separation of 15.5 MHz







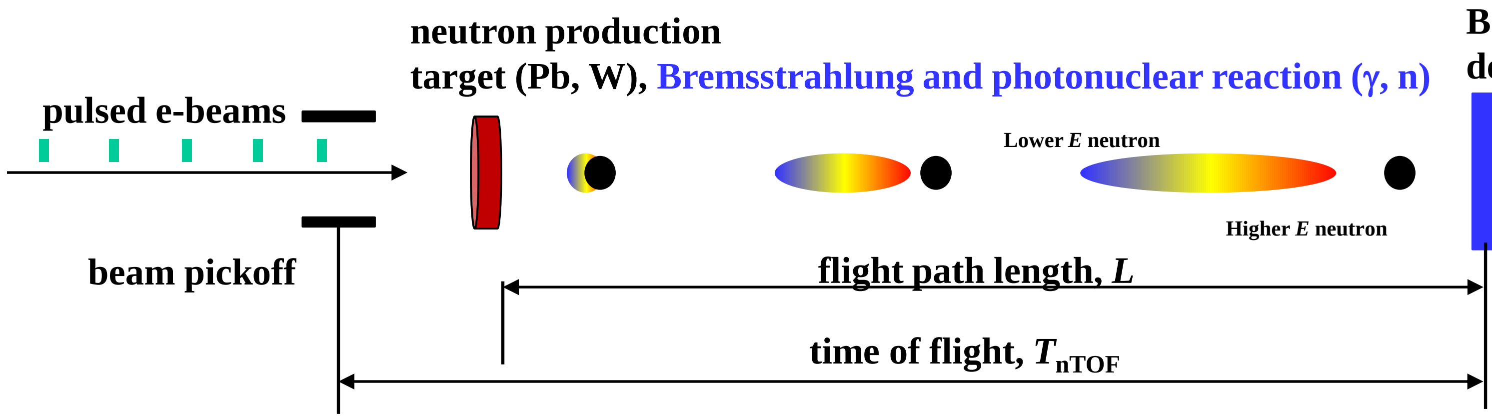


For Ultrafast Applications (UED, UEM)

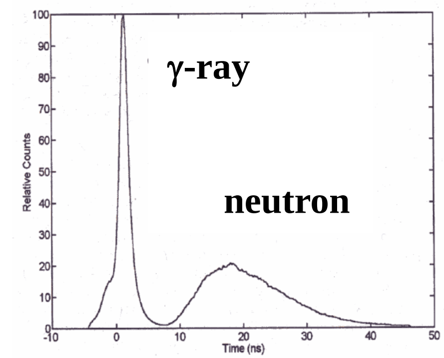
RF parameters	Value
Frequency at π-mode (MHz)	2856
$\Delta f = f_\pi - f_0$ (MHz)	15.5
Gun length (m)	0.14
Unloaded quality factor, Q_0	13837
External quality factor, Q_{ext}	12125
Shunt impedance, R_{sh} (MΩ/m)	21.3
External coupling coefficient, β_{ext}	1.14
RF pulse length, τ_{RF} (μs)	4
Peak electric field (MV/m)	120
RF input power (MW)	10
Repetition rate (Hz)	120

KAERI neutron Time Of Flight (nTOF)

To measure energy and energy-resolved neutron cross-sections for construction materials of fusion and fission reactors and to find handling processes of waste from reactors, we may use the nTOF technology.



BaF_2 Scintillation detector (resolution ~ 640 ps)



Neutron TOF $= \frac{72.3\,L}{\sqrt{E_n}}$ (non-relativistic) γ-ray TOF $= \frac{L}{c}$ c is velocity of light

Example: L = 20 m TOF_γ = 67 ns E_n = 1 MeV TOF_n = 1.5 μs

E_n = 100 MeV TOF_n = 150 ns

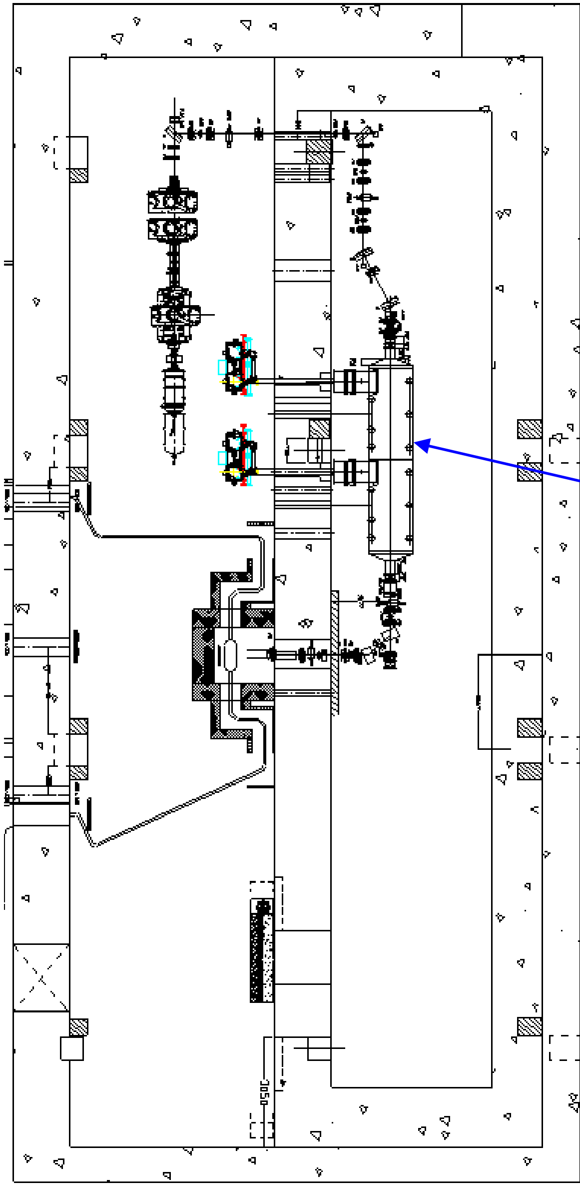
$$E = m_n c^2 \left(\frac{1}{\sqrt{1-(v/c)^2}} - 1 \right)$$

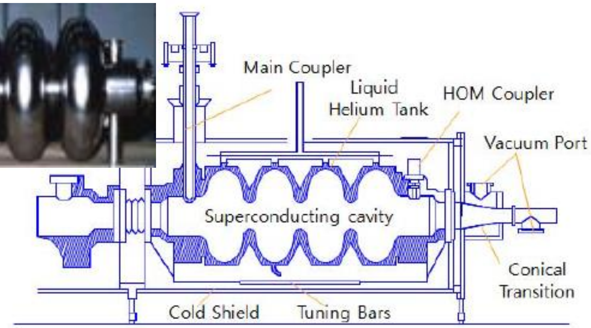
Flight Path Length (m)	Neutron Energy (MeV)	TOF−γ (ns)	TOF n (ns)	Wrap Around 1.8 μs (keV)	Wrap Around 3.6 μs (keV)	ΔE (keV)
10	1	33	722	161.34	40.33	3
	2		511			8
	10		230			87
	20		164			244

$\Delta E/E = \Delta T_{detector}/T_{nTOF}$

A longer path gives a longer T_{nTOF} and a better energy resolution if neutron intensity is sufficient.

Linac for KAERI nTOF Facility - SRF Linac Area





Fundamental resonant frequency	352 MHz
Cavity material	Nb-coated copper
Number of cell	4-cell per cavity
Q_0	3.4×10^{-9} at 6 MV/m, 4.5 K
R/Q	500
Freq. tuning range	50 kHz (maximum)
Active length	1.7 m

352 MHz CERN SPS Superconducting Linac

- Operated max gradient: 7.8 MV/m

→ 6 MV/m × 1.7 m × 2 Cavities = 20.4 MeV

E_{max} ~ 20 MeV

$P_{max,ave}$ ~ 100 kW for E = 20 MeV and I_{ave} = 5 mA

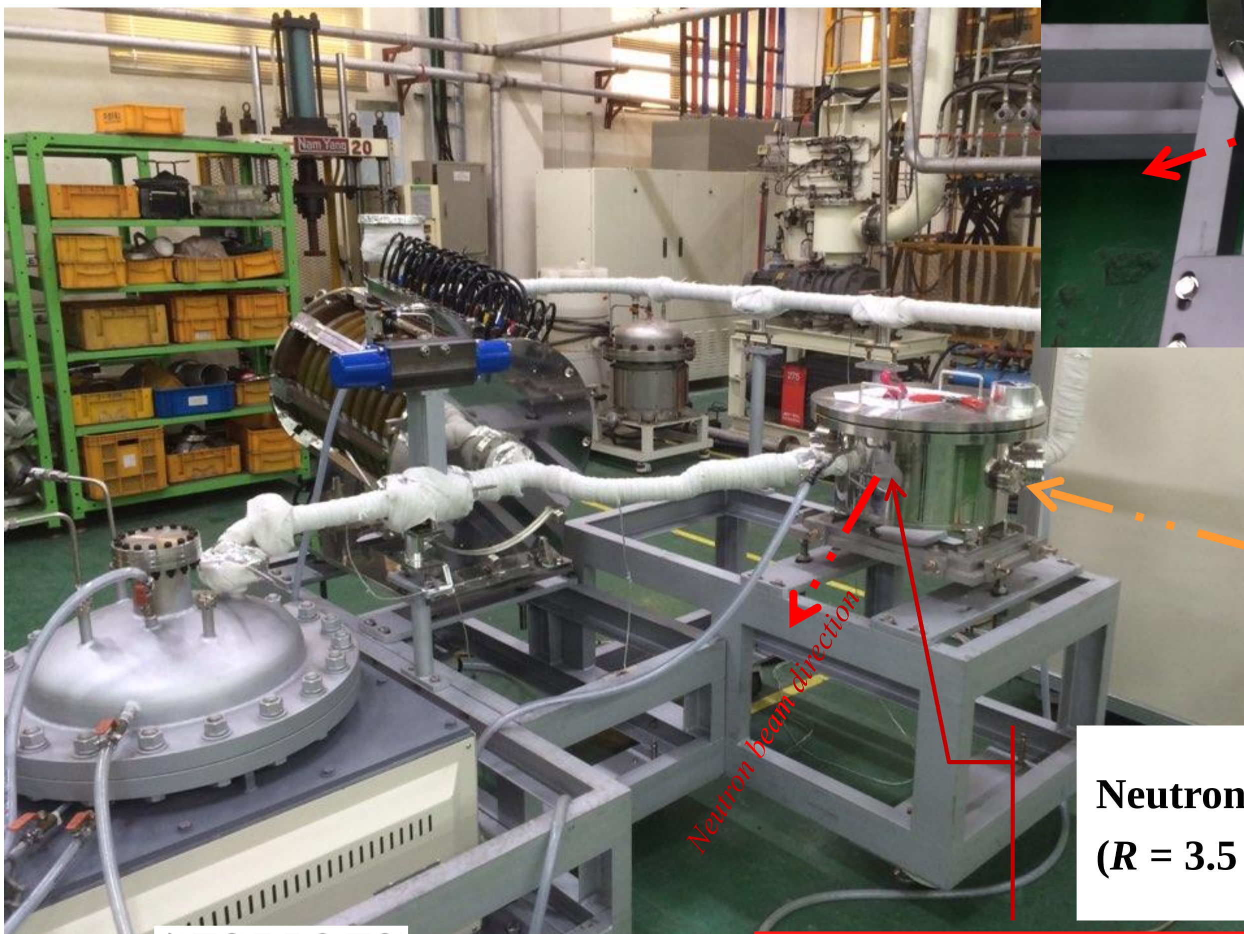
Q ~ 0.4 nC

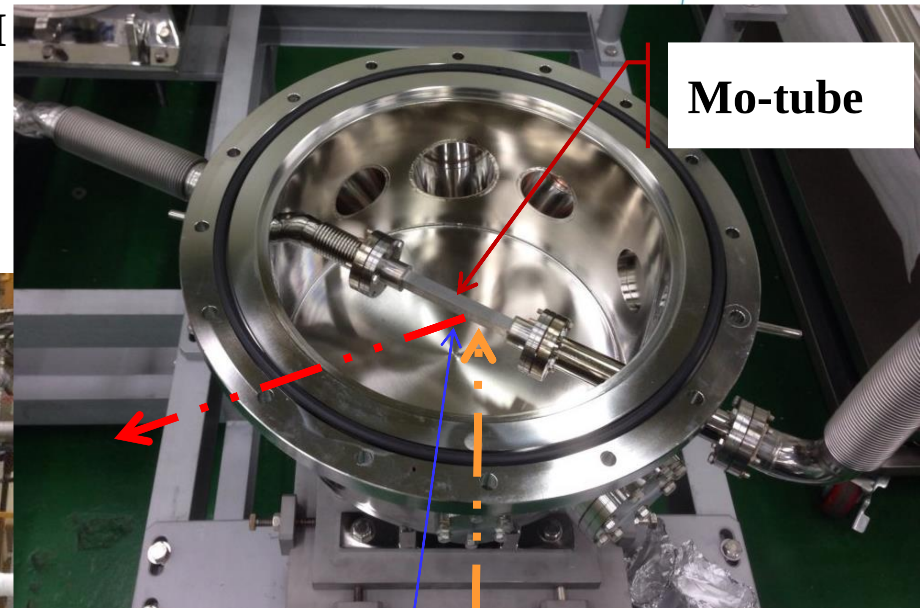
Bunch Length ~ 20 ps

Status of Liquid Lead Target

Fabricated & under testing at VITZRO TECH

VITZRO TECH
(주) 비츠로테크





Molybdenum(Mo)-tube
ID: 1.4 cm x 1.4 cm
thickness: 0.5 mm

e-beam size: 5 mm (FWHM)
Gaussian shape

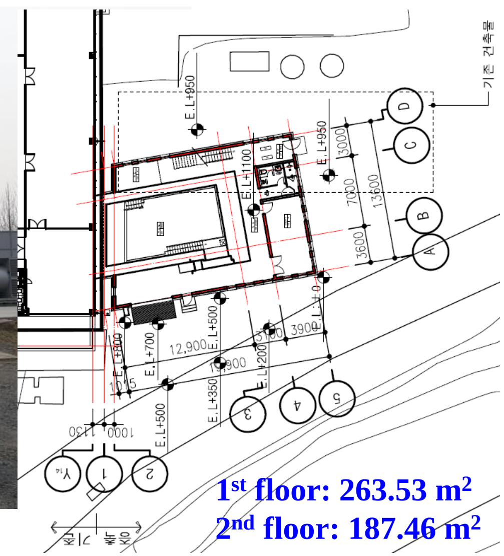
Neutron Beam Window
(*R* = 3.5 cm, 1 mm thick, SS316)

Location of KAERI nTOF Facility

Status of 2016 Spring

In 2018, construction of a new experimental building will be started

Status of 2017 Spring



1st floor: 263.53 m^2
2nd floor: 187.46 m^2

[Accelerator and Target]

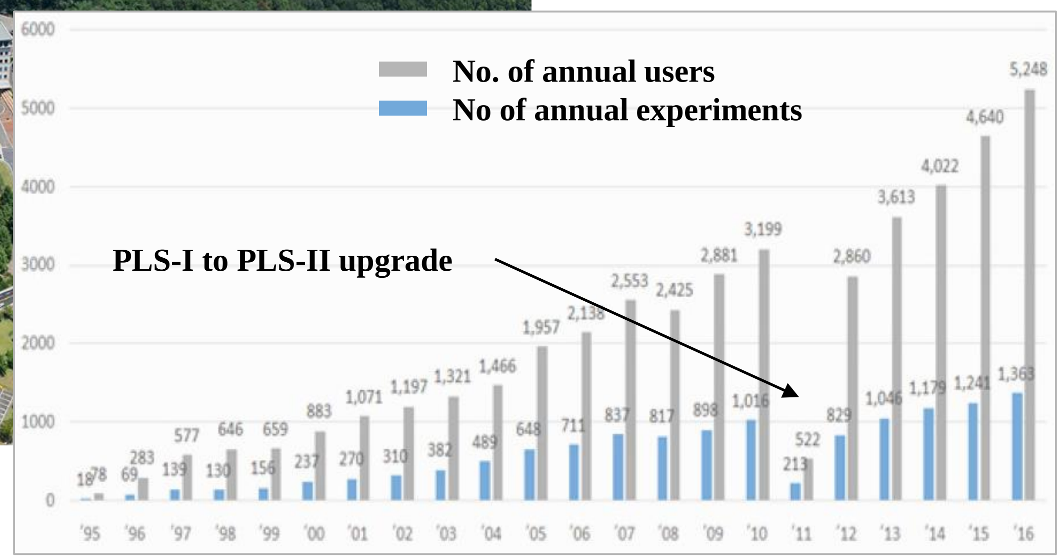
1st Floor and Basement of KAERI Engineering Building

[nTOF Experimental Hall]

a Temporary Building was removed in 2016.

Status of Korean 3rd Generation Source, PLS-II

Since the PLS-II storage ring (3 GeV, 281.82 m) is the only 3rd generation light source in Korea, Korean users are struggling to get its beamtime due to rapid user overflow (~ 6000 users in 2017). Therefore, we have been considering construction of a new advanced synchrotron light source facility.

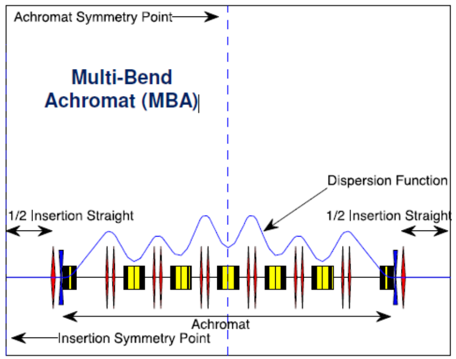


New Korean Synchrotron Light Source

We would like to use Ultimate Storage Ring (USR) concept for the new Korean advanced synchrotron light source facility. Its considering parameters and layout are followings (all things are not fixed yet).

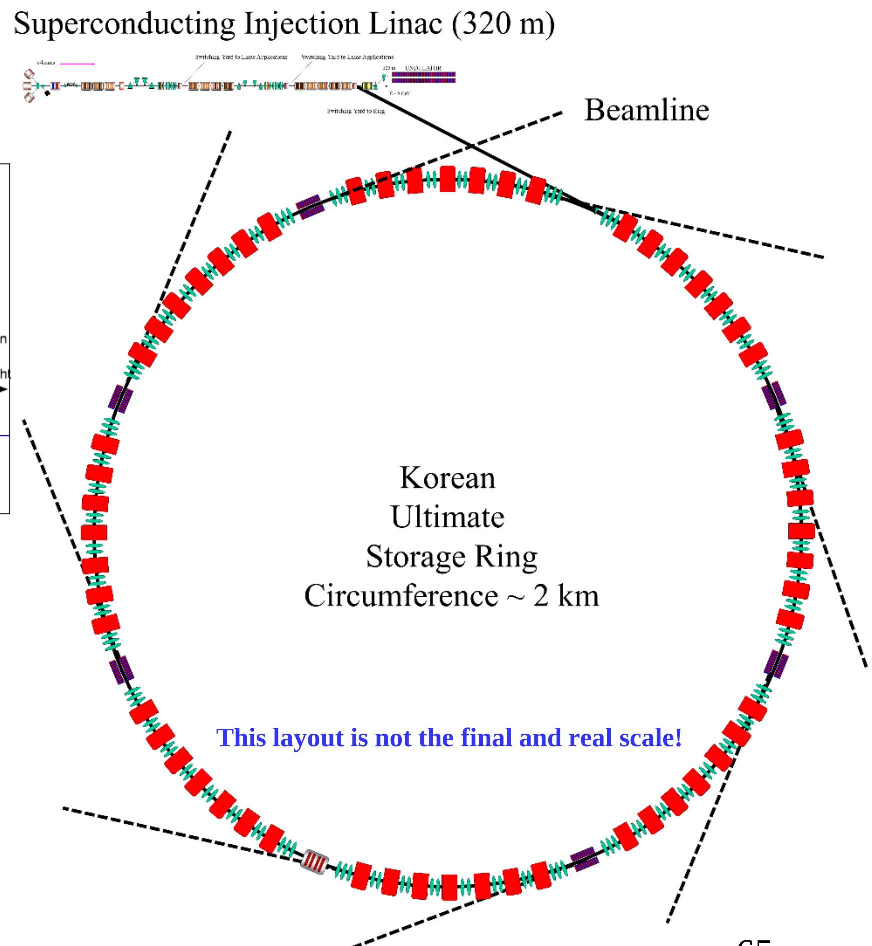
Storage Ring

Ring Concept: Ultimate Storage Ring
Lattice Type: Multi-Bend Acromat (MBA)
Beam Energy ~ 5 GeV
Beam Current ~ 300 mA
Circumference ~ 2 km
Ring Diameter ~ 637 m
Natural Emittance ~ 10 pmrad
RF Frequency ~ 325 MHz



Injection Linac

Linac Type: Superconducting CW Linac
Max Beam Energy ~ 5 GeV
Bunch Repetition Rate: 1 MHz - 100 MHz
Single Bunch Charge ~ 200 pC - 2 nC
Average Current ~ 0.1 mA - 100 mA
RF Frequency ~ 1300 MHz
Max Gradient ~ 25 MV/m
Linac Length ~ 320 m

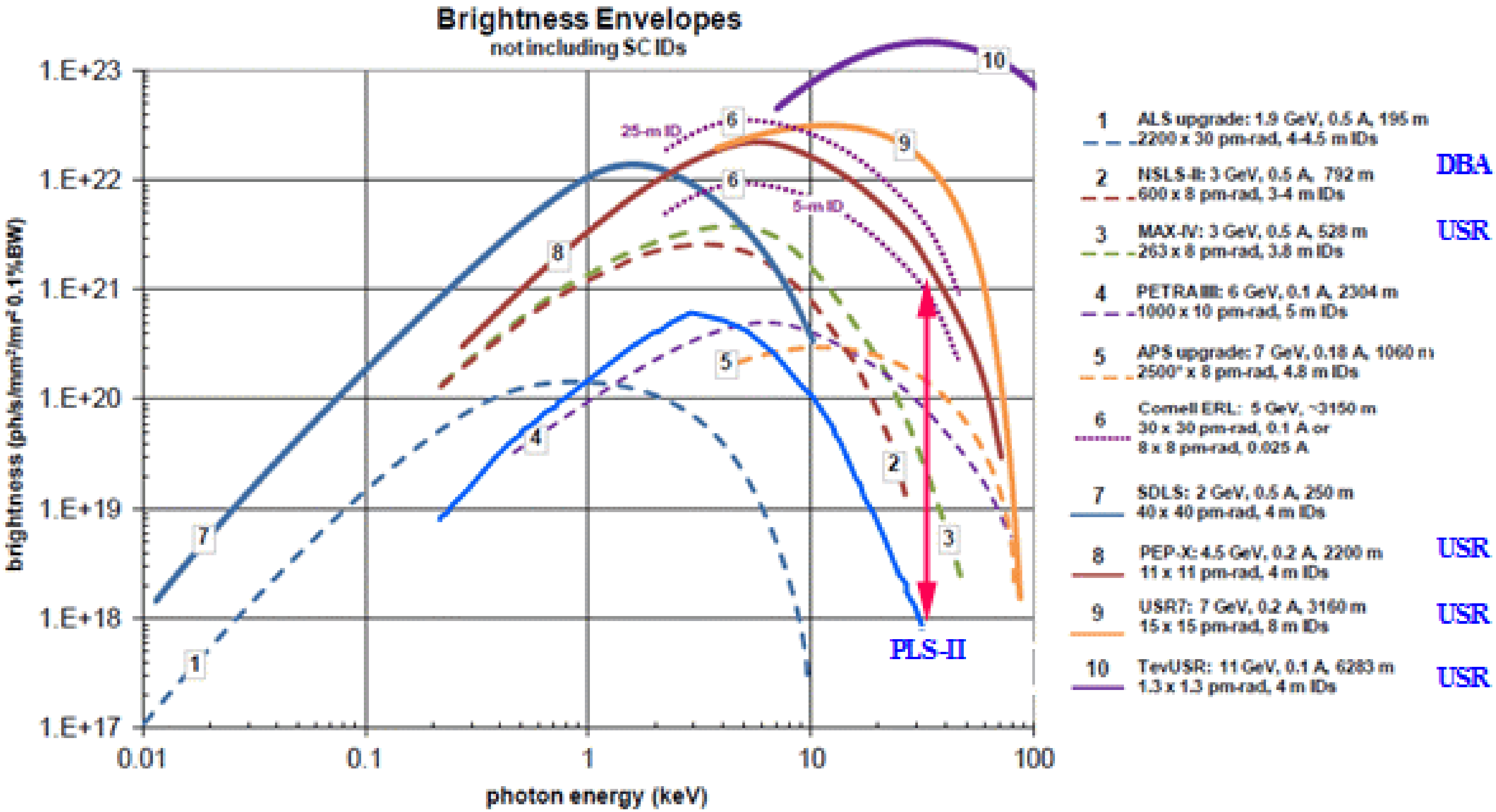


Facility Area ≥ 1 km × 1 km
Total Budget < 1 B$

Milestone of New Korean Synchrotron Light Source

2018 - 2020: Design
2021 - 2023: Construction
2024: Commissioning
2025: User Service

At hard X-rays, at least 100 - 1000 times brighter than PLS-II



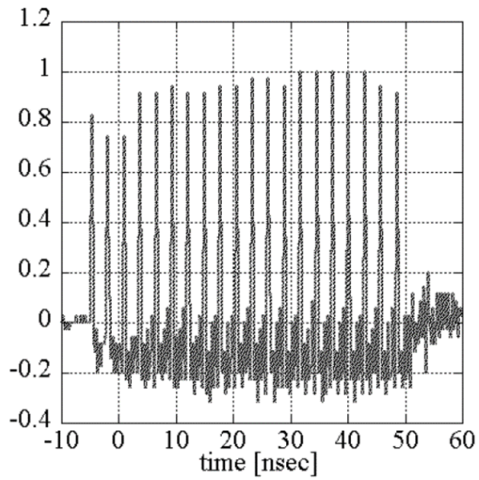
Courtesy of R. Hettel

5 GeV Superconducting Injection Linac

Since we would like to operate the 5 GeV superconducting injection linac with a high repetition bunch rate, we may use the linac for various linac applications as well as storage ring injection by using fast switching yard kickers and multi-electron guns with a high speed gun driving laser from Time-Bandwidth.

Injection Linac

Linac Type: Superconducting CW Linac
Max Beam Energy ~ 5 GeV
No. of Operating Gun: 1 - 5
Bunch Repetition Rate: 1 MHz - 100 MHz
Single Bunch Charge ~ 200 pC - 2 nC
Average Current ~ 0.1 mA - 100 mA
RMS Bunch Length: 50 fs - 50 ps
RF Frequency ~ 1300 MHz
Max Gradient ~ 25 MV/m
Linac Length ~ 320 m

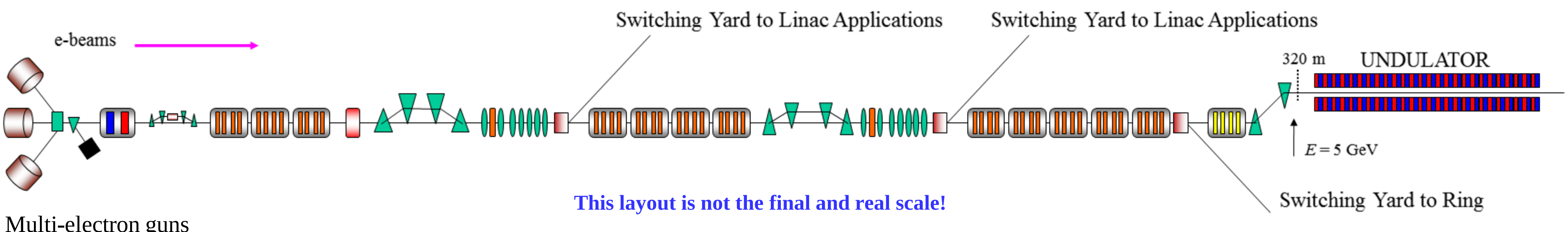


Structure of micro bunches , M. Kuriki *et al*., EPAC2004

KEK ATF Nd:YVO_4 laser from Time-Bandwidth

Max Repetition Rate = 357 MHz
Pulse Spacing = 2.8 ns
Energy per Pulse = several μJ
Laser Pulse ≈ 10 ps (FWHM)
Wavelength = 266 nm
Max Single Bunch Charge ≈ 5 nC
Cathode Material: Cs_2Te

DESY FLASH has a similar operating laser.
We can use a similar Time-bandwidth Argos laser for our CW injector.



This layout is not the final and real scale!

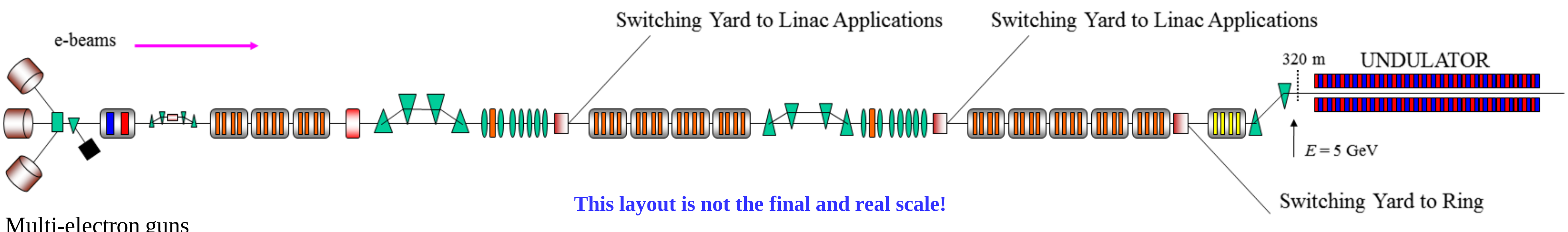
Our Experiences with Advanced Accelerators

- **Design and Operation of Various Storage Rings** at Pohang Accelerator Laboratory (PAL), Duke University, and Indiana University
- **Design and Operation of Longitudinal Beam Feedback Systems** for Storage Rings at PLS-I of PAL and OK-5 FEL of Duke University
- **R&D on Various Beam Instabilities and Lifetime in Storage Ring** at PLS-I of PAL, OK-5 FEL of Duke University, and Alpha Ring of Indiana University
- **Design and Operation of RF Photoinjectors and Bunch Compressors** at SCSS of SPring-8, FLASH and European XFEL of DESY, SwissFEL of PSI, and Mark-III FEL of Duke University
- **Design and Operation of Various Linacs for X-ray FEL Projects** at SCSS of SPring-8, FLASH and European XFEL of DESY, SwissFEL of PSI, and Mark-III & OK-5 FELs of Duke University
- **Production of High Intensity Gamma-Ray with Laser Compton Scattering** at Duke University HIGS Facility
- **Production of Femtosecond long Electron and X-ray FEL Photon Beams** at FLASH of DESY and Mark-III of Duke University

Possible Applications with 5 GeV Linac

After considering our experiences, we may choose following applications for our 5 GeV superconducting CW injection linac:

- ☐ **Medical Isotope Production Facility (^{99}Mo, ^{47}Sc, ^{67}Cu, ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{123}I)**
- ☐ **High Average Power Gamma-Ray Facility with Laser Compton Scattering (LCS)**
- ☐ **e-γ-n Complex for Science, Applications, and Nuclear Waste Transmutation**
- ☐ **High Average Power EUV and X-ray FEL Facility for Lithography and Basic Sciences**
- ☐ **Ultrafast Pulse Radiolysis Facility**



This layout is not the final and real scale!

e-γ-n Complex with 5 GeV Linac

- Phase-I (~ 2024)
- Phase-II (~ 2027)
- Phase-III (~ 2030)

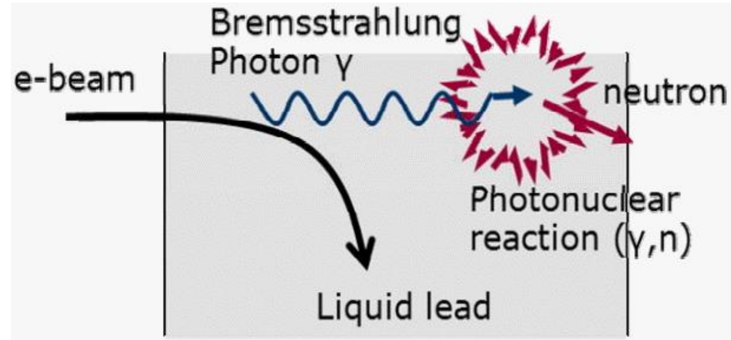


Photo-neutron TOF
Nucleer Infrastructure

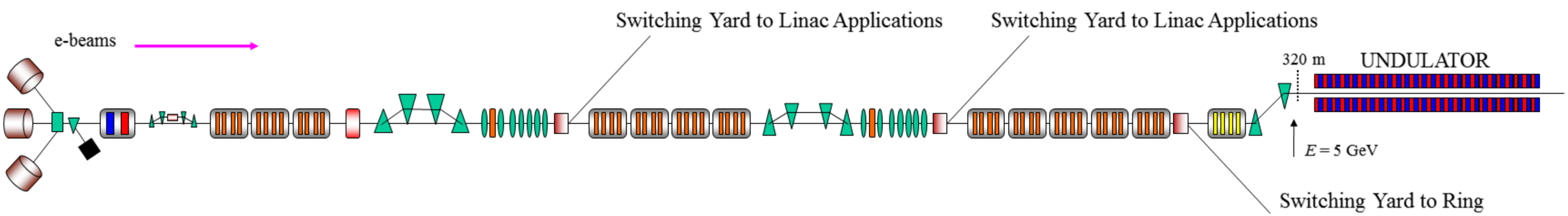
Photo-neutron for Science
Isotope, Medical …

e-ADS
Actinides Transmutation

LCS-γ LLFP Transmutation
Photonic Nuclear Physics

High Average Power
EUV & X-ray FEL

30 MeV **60 MeV** **100 MeV** **1 GeV** **5 GeV**



Summary

There are various growing user applications with MeV-range RF electron linacs.

KAERI has successfully developed various S-band electron linacs for CIS and NDT applications.

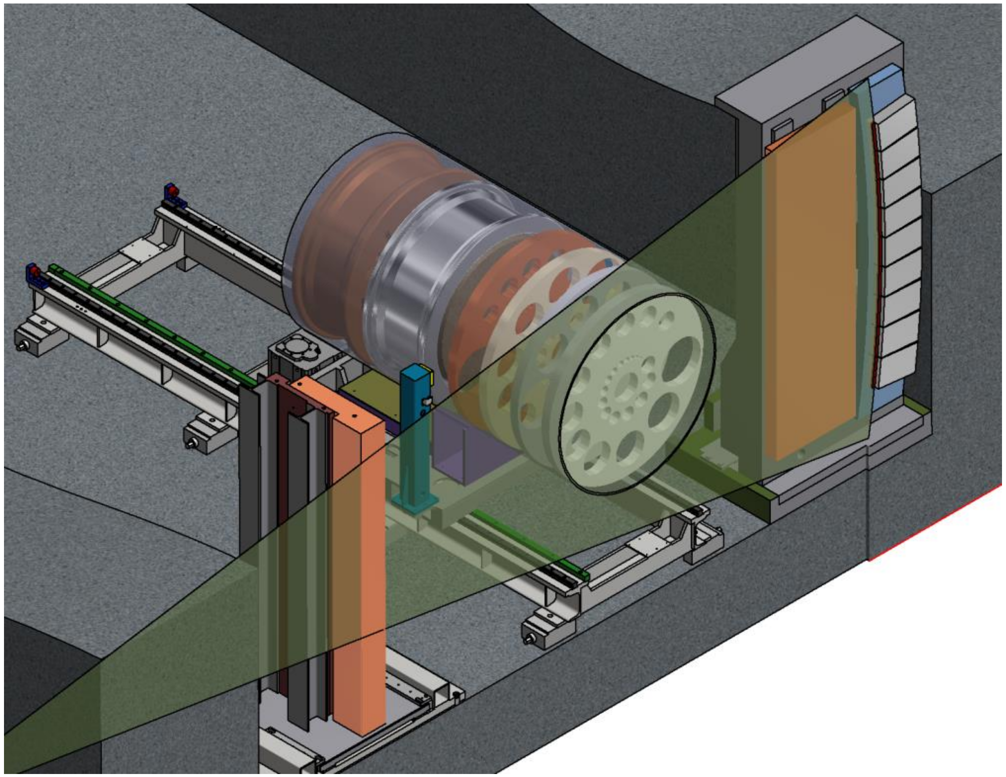
KAERI also has successfully developed a 6 MeV X-band electron linac for medical applications.

KAERI has transferred RF linac technologies to RTX and SEC.

In addition, KAERI has been working to construct a new nTOF facility with a 20 MeV superconducting electron linac.

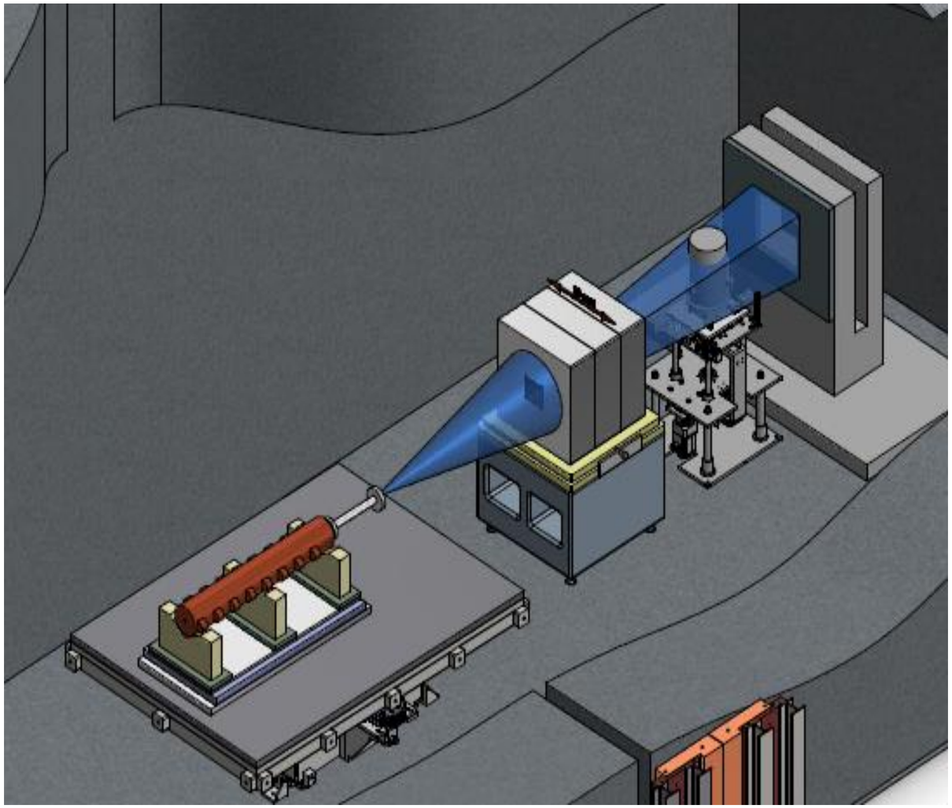
Now KAERI is ready to develop advanced accelerator facilities for neutron Time Of Flight (nTOF), ultrafast electron beam sciences, soil-treatment system, and a new synchrotron light source.

Appendix - LDA for 15 MeV MIS



Parameters	Values
Energy Range	Max. 15 MeV
Scintillator	$CdWO_4$
Scintillator Thickness	>10 (mm)
Resolution(Pitch)	0.8 x 1.2 (mm)
Pixel Number /Active area	2112 pixels/1689.6 ㎜ 192 pixels-153.6㎜/module X 11 module
Dynamic Range	> 75 dB
A/D Resolution	> 16 bit
Geometric Structure	Curved Shape
Anti Crosstalk	Curved Shape

Appendix - FPXD for 15 MeV MIS



Paramters	Value	ETC
Energy Range	Max. 15 MeV	
Scintillator	DRZ plus	
Resolution(Pitch)	0.2 (mm)	Binning 0.4 (mm)
Pixel Number/ Active area	2048 x 2048 pixels 406.4 x 406.4 (mm)	Binning 1024x1024
Dynamic Range	> 88 dB	
A/D Resolution	> 16 bit	
Frame rate	1 ~ 4 fps	Binning 4 fps

Appendix - Performance of KAERI nTOF Facility

Facility	CERN n_TOF	CERN n_TOF Phase-2	LANL NSC	ORNL SNS	FZK VdG	ORNL ORELA	IRMM GELINA	ELBE	ELBE with SRF	KAERI
Pulse charge / nC	ca. 10^3	ca. 10^3	$4 \cdot 10^3$	$3 \cdot 10^4$	0.01	ca. 100	ca. 100	0.08	1.8	0.4 nC
Power / kW	10	10	60	1000	0.4	8	7	5	40	1.36 kW
Pulse rate / s^{-1}	0.4	0.4	20	60	$2.5 \cdot 10^5$	500	800	$1.6 \cdot 10^6$	$5 \cdot 10^5$	0.2 MHz
Flight path / m	183	ca. 20	60	84	0.8	40	20	4	4	$\leq$ 12 m
n pulse length / ns	> 7	> 7	125	100-700	ca. 1	> 4	> 1	< 0.4	< 0.4	20 ps
E_{min} / eV	0.1	0.1	1	0.1	10^3	10	10	$2 \cdot 10^5$	$5 \cdot 10^4$	100 keV
E_{max} / eV	$3 \cdot 10^8$	$3 \cdot 10^8$	ca. 10^8	ca. 10^8	$2 \cdot 10^5$	$5 \cdot 10^6$	$4 \cdot 10^6$	$7 \cdot 10^6$	$1 \cdot 10^7$	7 MeV
Resol at 1 MeV / %	0.5	5	ca. 10	> 10	ca. 10	< 1	< 2	ca. 1	ca. 1	$\leq$ 1%
n flux dens / s^{-1} cm^{-2} (E decade)$^{-1}$	10^5	ca. 10^7	ca. 10^6	10^6-10^7	ca. 10^4	10^4	$4 \cdot 10^4$	$4 \cdot 10^5$	$3 \cdot 10^6$	$\leq 10^5$

Total number of outgoing neutrons through Mo-tube: 4.05503E+11 #/sec