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R&D of rf structure and its applications in Tsinghua university

Accelerator Lab., Dept. of Engineering Physics，

Tsinghua University Beijing 100084

Outline

1. Introduction of Accelerator Laboratory
2. Low Energy Linacs and Their Applications
3. Research on RF Structure
4. Summary

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Accelerator Lab of Tsinghua University

Accelerator Lab

Department of Engineering Physics

- Institute of Nuclear Technology Application
- Institute of Technical Physics
- Institute of Nuclear Energy Science and Engineering Management (INESEM)
- Institute of Safety Science and Technology Research
- Medical Physics and Engineering
- Center for High Energy Physics, Tsinghua University

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Accelerator Lab of Tsinghua University

- Faculty
  - 13 faculties and more employee
  - About 15 graduate students
- Activities
  - Education (undergraduate and graduate)
  - Low Energy Linear Accelerators and Their Applications
  - Fundamental Accelerator Physic and technology
    - Accelerating Structures
    - High brightness electron injectors
    - Electron beam and laser beam interaction
    - Beam dynamics

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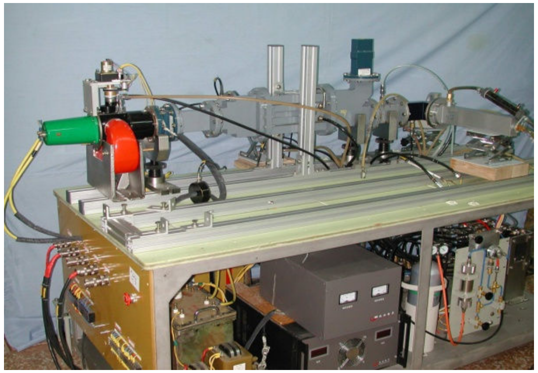
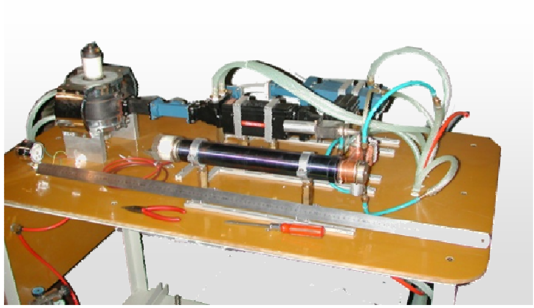
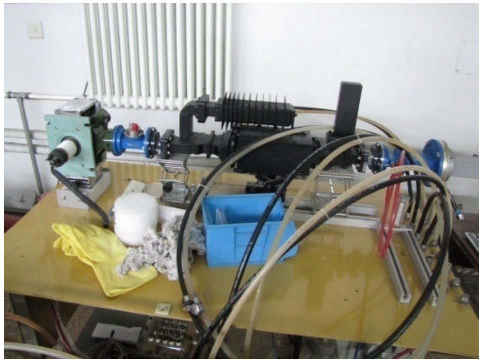
High power test stands

- Based on magnetron :

RF Power source	S-band	X-band	C-band	
Operation frequency	2992-3001	9300±20	5712±20	MHz
Output power	1- ~ 3.1	1.5	2.5	MW
Average power	4(MAX)	1(MAX)	2(MAX)	kW
Pulse width	1 ~ 4.	~3.5	4	μs
Repetition rate	325	~200	200	Hz
Cooling water temperature				°C
High Temp. Limit	87	50	50	°C
Temp. Stability	+/- 0.28	+/- 0.5	+/- 0.5	°C

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High power test stands

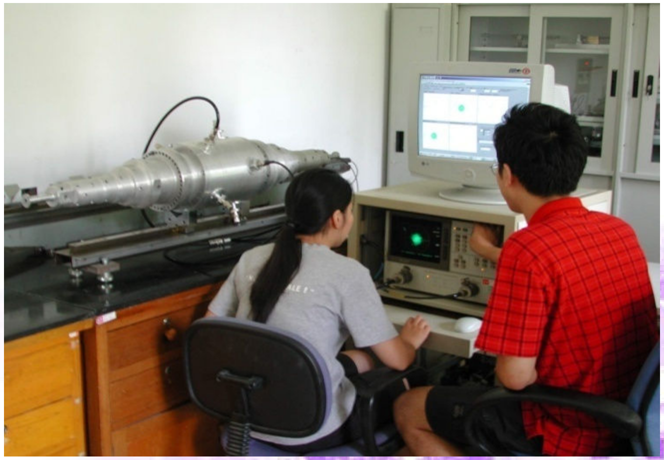
- Based on klystron :



RF Power source	Toshiba E3730A	Thales TH2163	
Operation frequency	2856	2856	MHz
Output power	50	5.5	MW
Average power	10	10	kW
Pulse width	4-6	4-6	µs
Repetition rate	50	250	Hz
Cooling water temperature	5-55	5-55	°C
High Temp. Limit	55	55	°C
Temp. Stability	+/- 0.3	+/- 0.3	°C

Microwave measurement for RF structure



Two based on SNA, two based on VNA

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Machining Workshop

high-precision machine tools
and CNC Machine

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Facility for brazing and baking

High-T hydrogen furnace

Medium-T hydrogen furnace

Laser welding machine

Leak detector

Annealing furnace

Vacuum furnace

Baking oven

Tool microscope

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Low Energy Linacs and Their Applications

- Cargo Inspection
- Medical Applications

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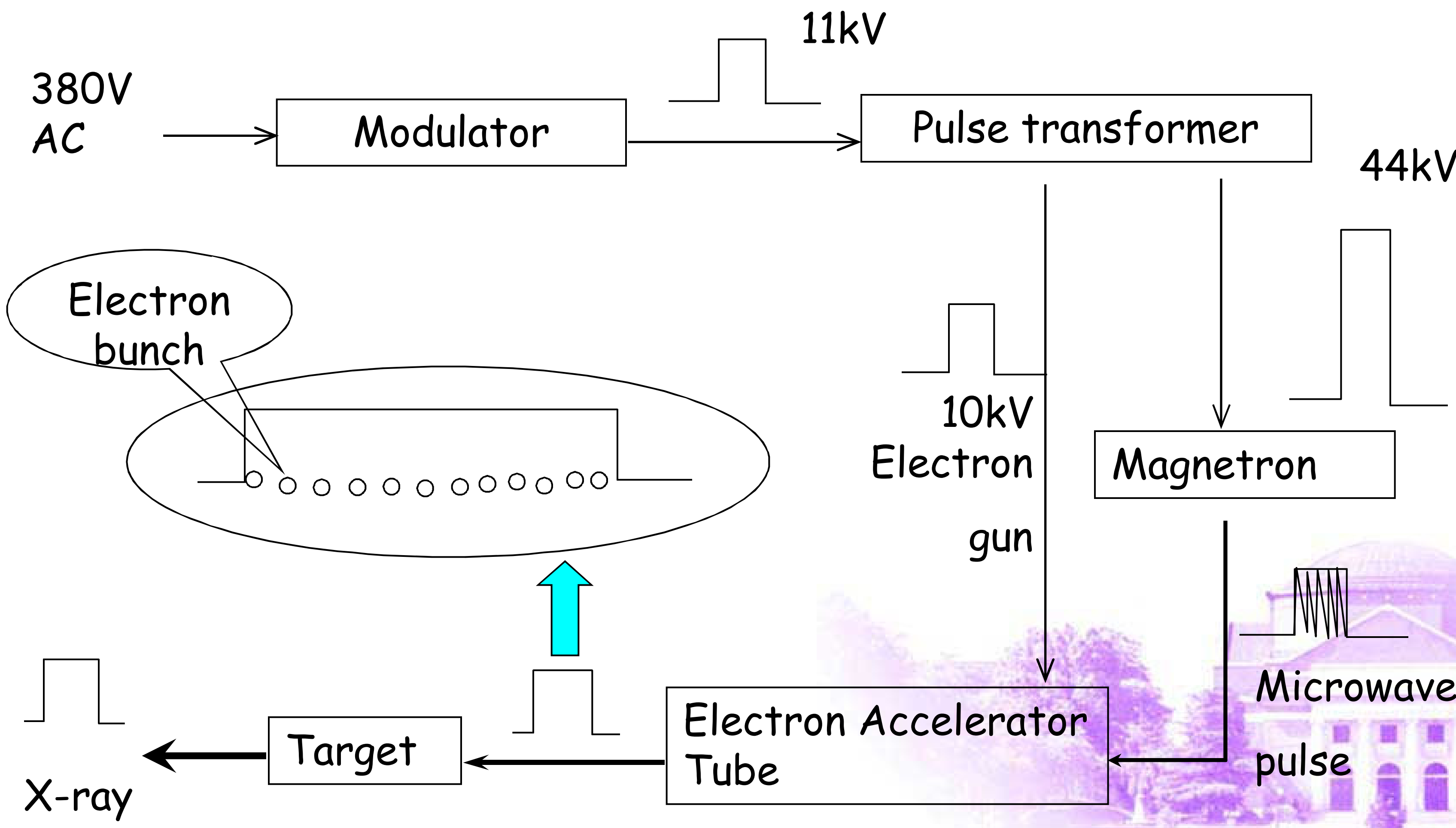
A Compact Linac system



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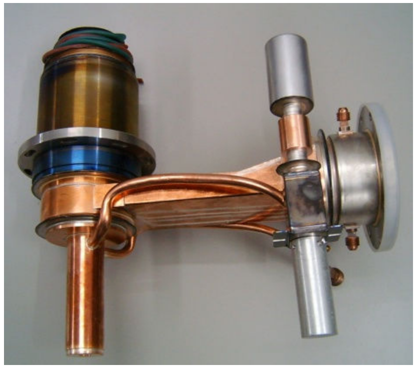
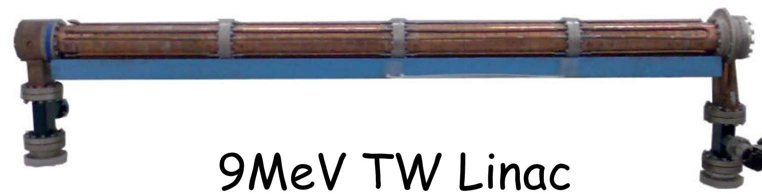
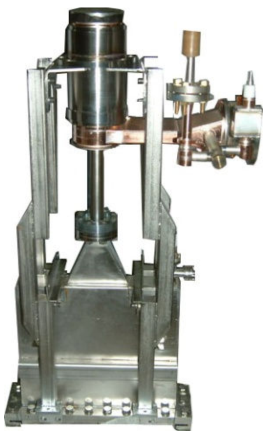

1.5MeV SW Linac

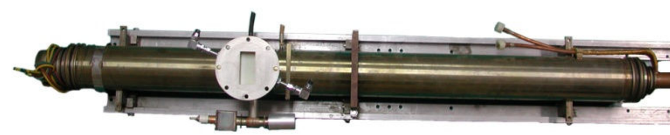

2MeV SW Linac


9MeV SW Linac


9MeV TW Linac


2MeV SW Linac


4MeV SW Linac


15MeV SW Linac


6MeV SW Linac

More than 300 accelerating tubes has been produced by Tsinghua U. for medical therapy and Non Destructive Testing.

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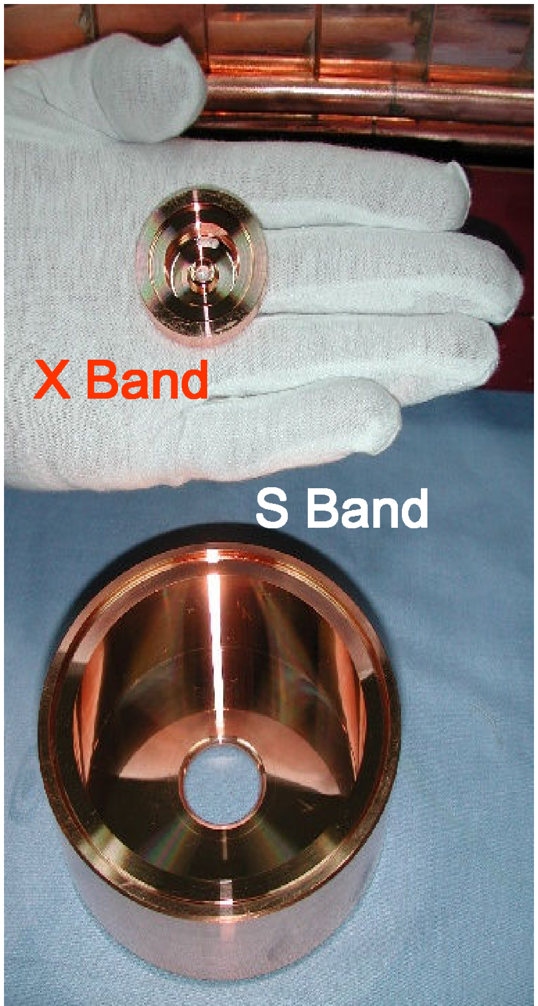
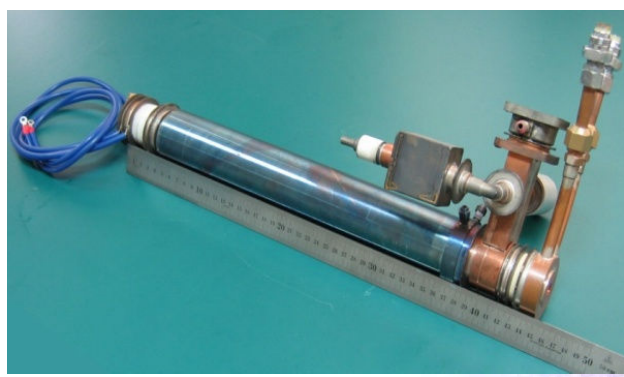
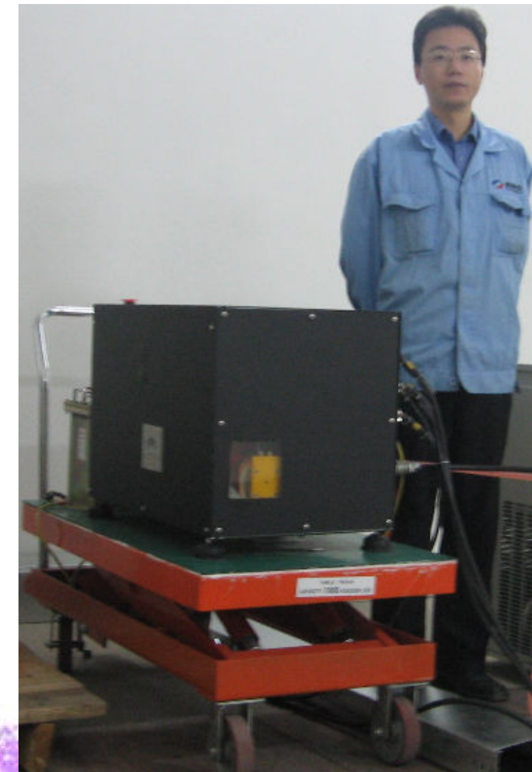
X-band Technology in Tsinghua U.



2.5MeV Accelerating tube



6 MeV Accelerating tube



X-band 2.5MeV Linac

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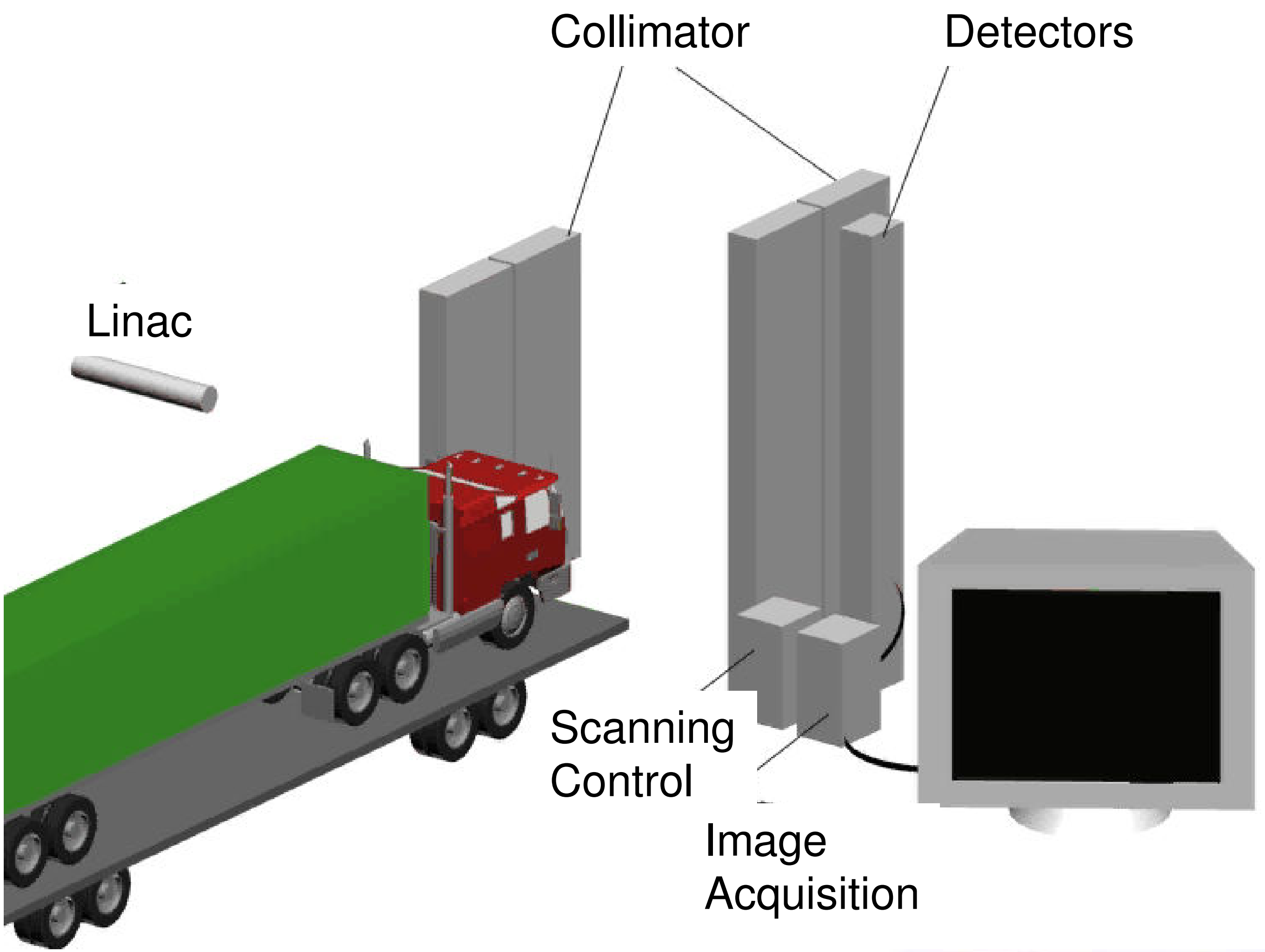
Cargo Inspection



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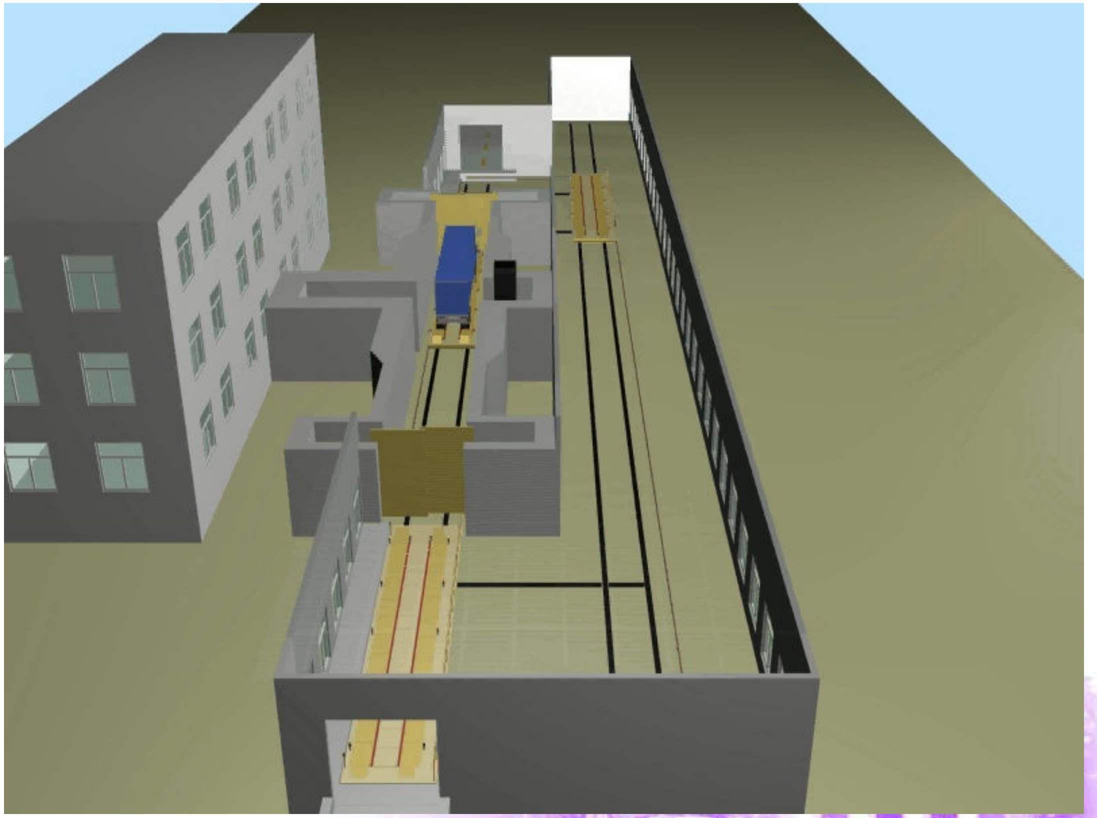
Fixed Container Inspection Systems

A 9 MeV TW linac as radiation source



RF source: 5MW klystron

Electron Energy: 9MeV

Dose Rate: 30 Gy/min-m

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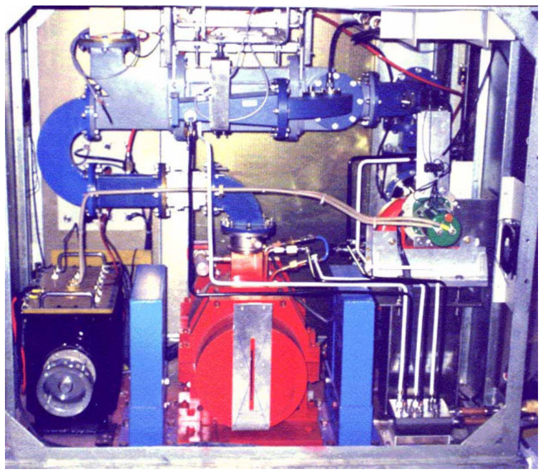
Relocatable Cargo Inspection System

A S-band 6~9MeV SW linac as radiation source



Electron energy 6MeV

Dose rate ~12cGy/min

RF Source: 2.6MW Magnetron

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Mobile Cargo Inspection System

S-band 2.5MeV SW Tube

Powered by a MG5125 magnetron

X-band 2.5MeV SW Tube

Powered by a 1MW 9300MHz magnetron

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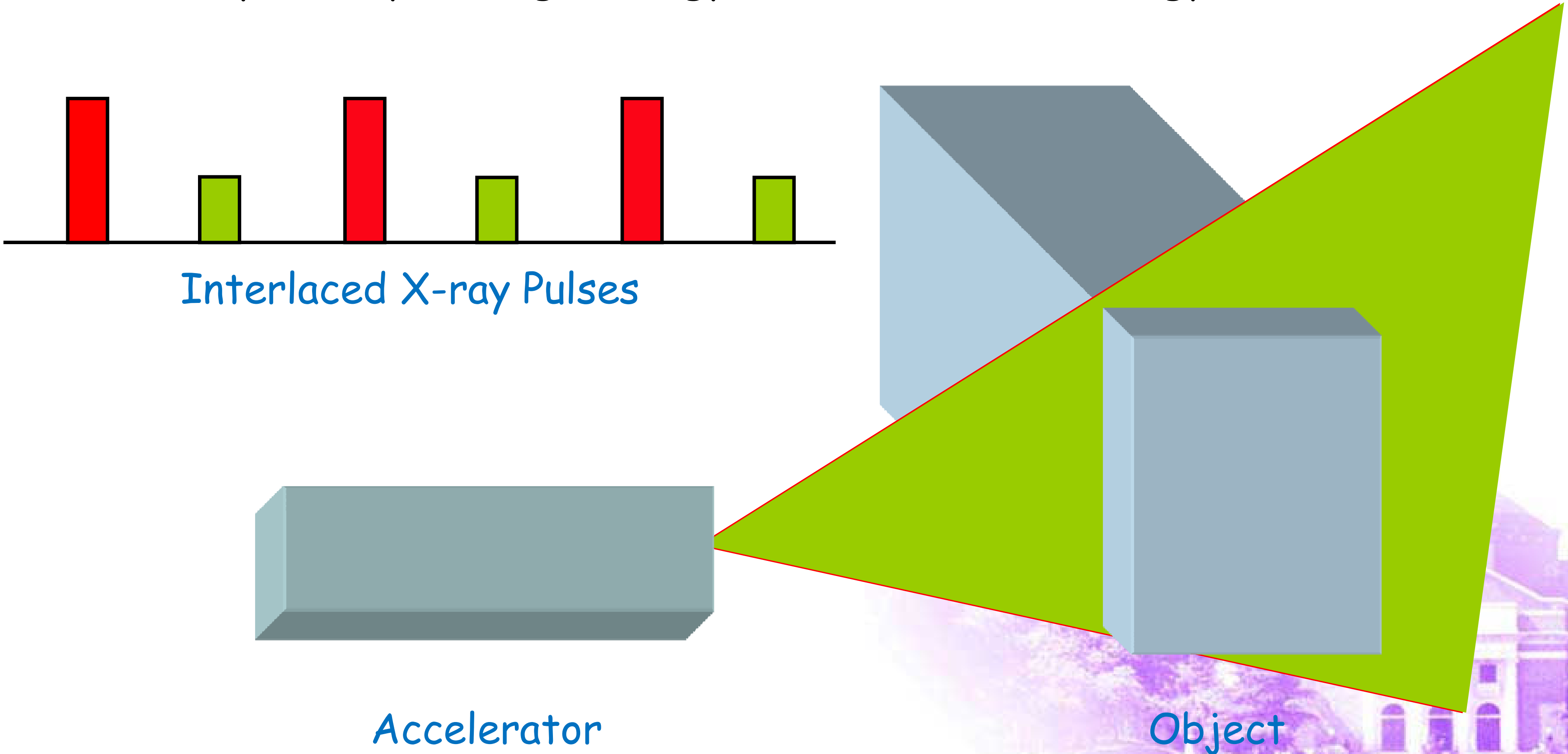
Dual-Energy accelerator

The Dual-Energy accelerator emits the pulsed interlaced X-rays composed by the high-energy ones and the low-energy ones



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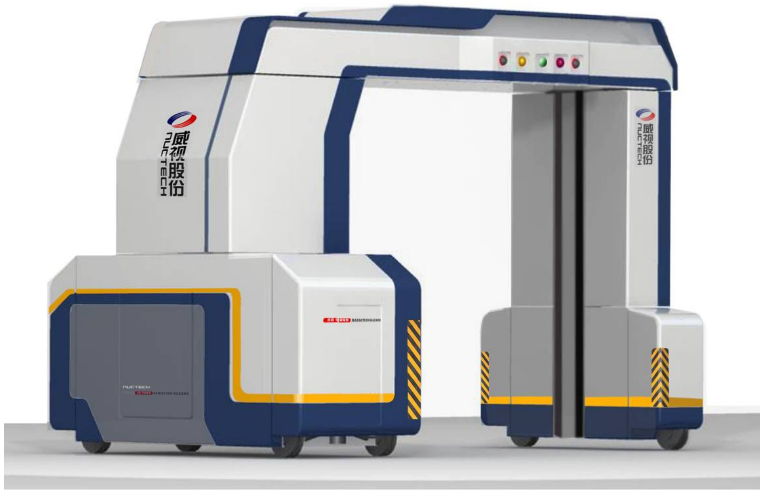
The Dual Energy Linac

- Magnetron MG5193: 2.6MW, 2998MHz, 4~5ms, 300pps
- Low-energy: 6-7MV and High-energy:9-10MV
- Maximum doserate(un-filter):
  - 6MV non-interlaced: 1000cGy/min@1m
  - 9MV non-interlaced: 3000cGy/min@1m
  - 6/9MV interlaced: 1500cGy/min@1m(500 of 6MV & 1000 of 9MV)
- 300pps in non-interlaced mode, and 150pps+150pps in interlaced mode
- X-ray focal spot size: smaller than 2 mm diameter at FWHM



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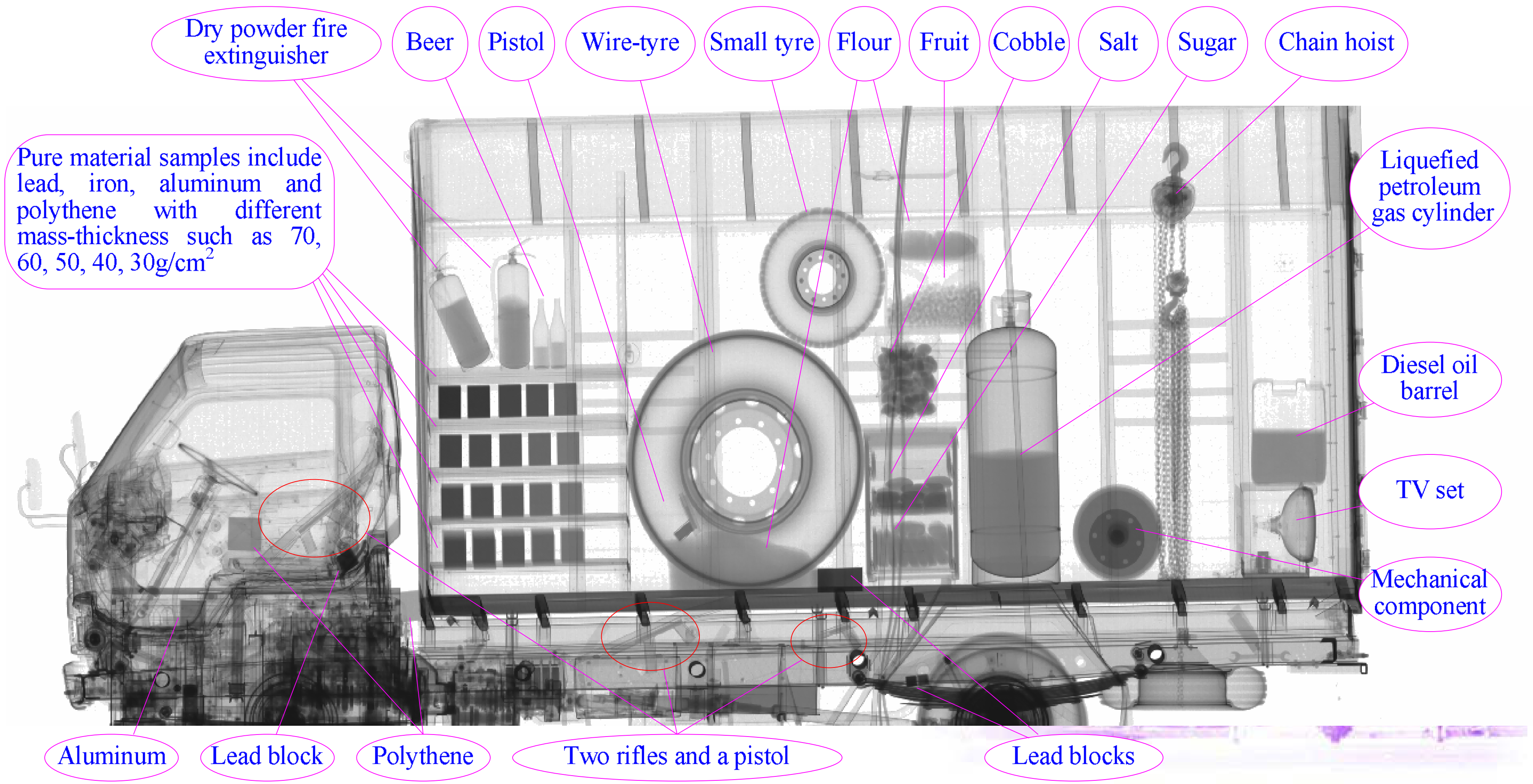
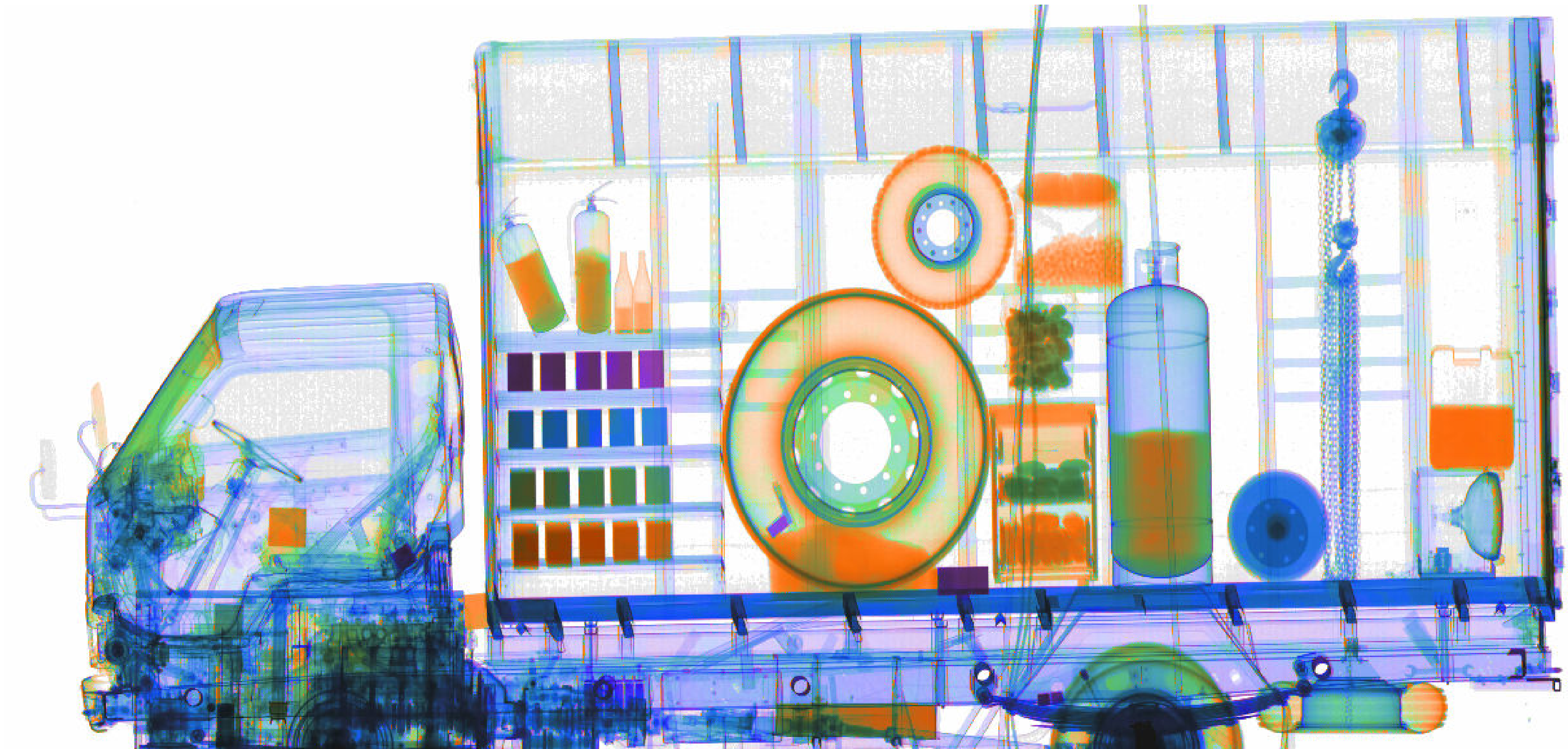
Grey Image of a Van with Different Tested Samples



Dual-Energy Color Image of a Van with Different Tested Samples



Dual-Energy Color Image: obtained by processing of dual-energy material discrimination algorithm according to effective atomic number

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Some of the Systems

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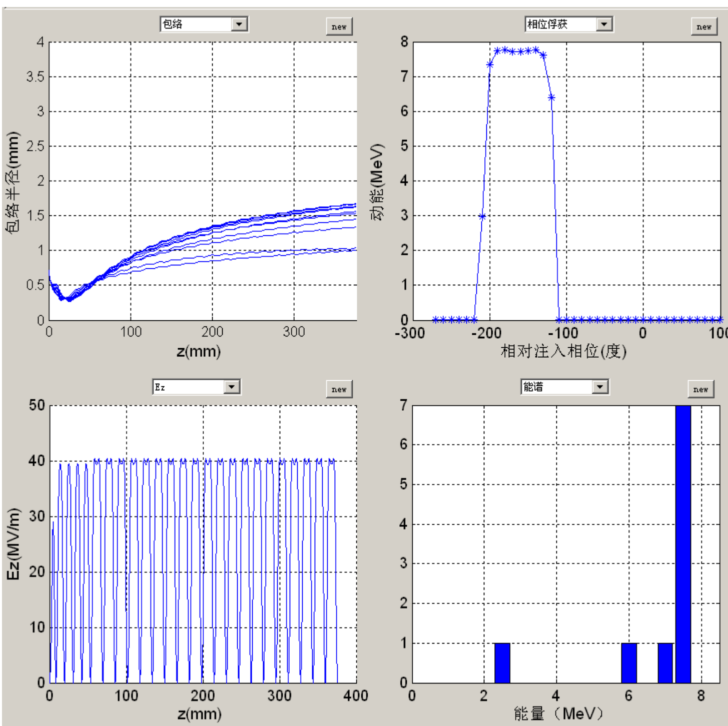
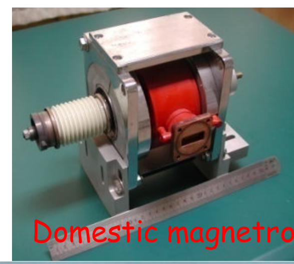
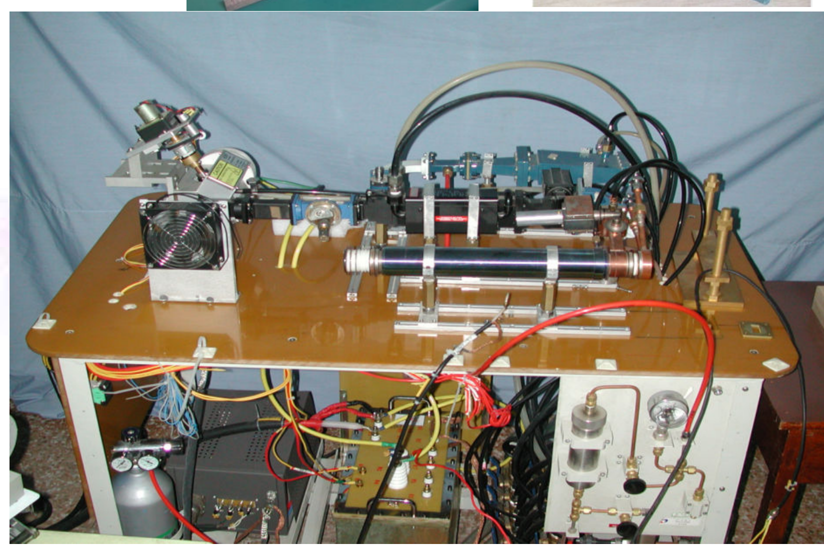
X-band SW 6MeV accelerating tube with axis coupling

P_0(MW)	1.40
I(μ A)	11.35
I_M(mA)	43.00
We(MeV)	**6.09**







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Double beam SW accelerating tube

- Vertical layout, compact, length of tube~0.4m
- 6MV X-ray, 6,9MeV electron beam
- Same magnetron, 2.6MW

	P(MW)	We(MeV)	I(mA)
X-ray	1.8	6	100
Electron beam	2.2	9	2
	1.5	7	2
	0.8	5	2

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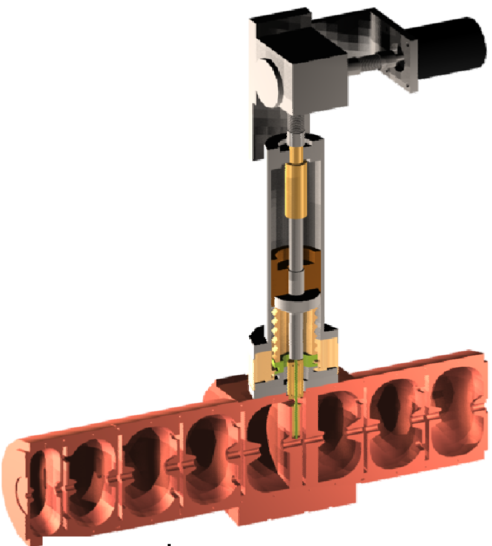
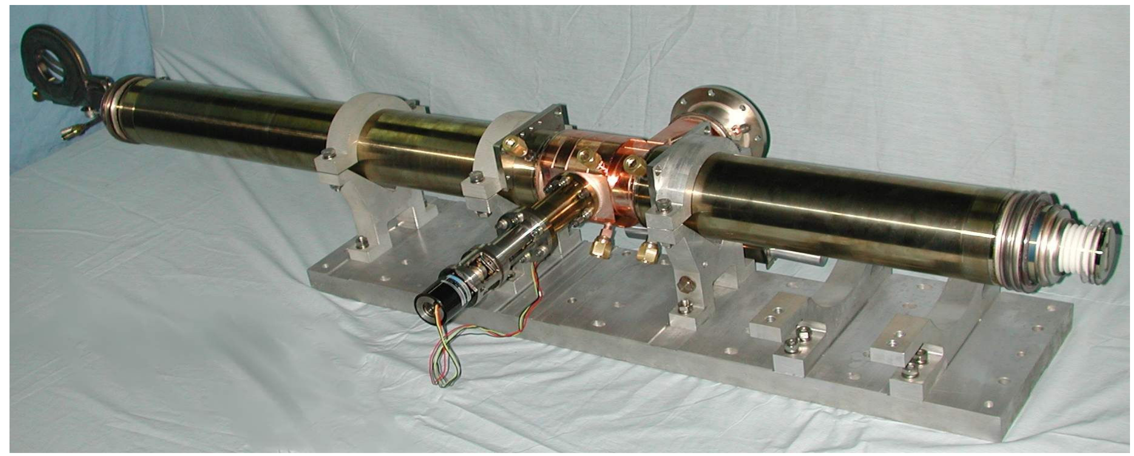
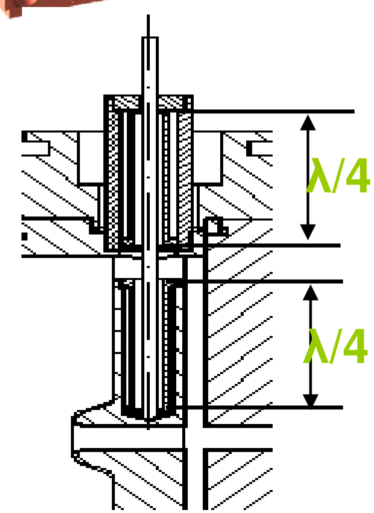
Medical SW accelerating tube with power switches

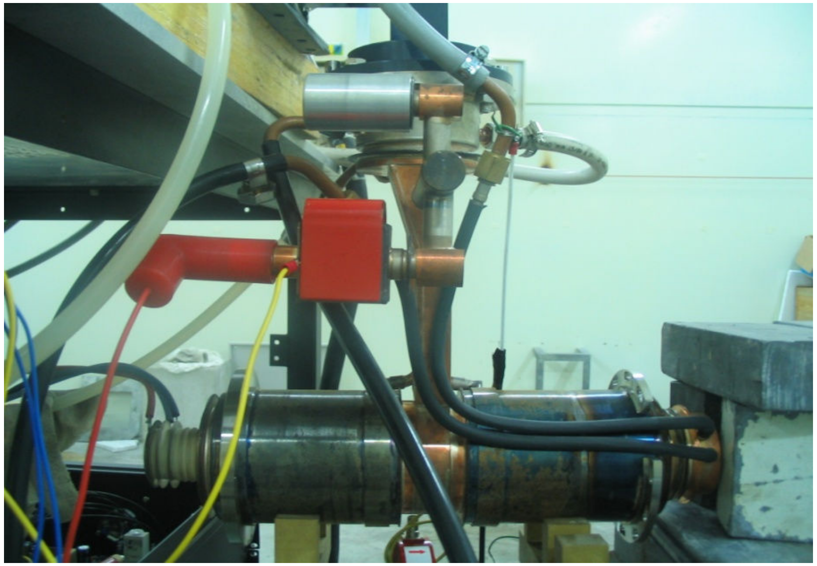






Beam energy (MeV)		Peak current (mA)		Power switch
Measured	Designed	Measured	Designed	
6.6	6.0	100	90	off
18.09	18.0	20	15	on
20.4	20.0	6.7	2	on

KV/MV Homologous double-beam accelerating tube



	Designed	Measured
Beam energy	100KV~900KV 6MV	700KV 6MV
Source Axis Distance	85cm	100cm
Dose of X-ray	80Gy/min	84Gy/min
Length of tube	40cm	40cm
Spot size	<Φ2mm	Φ1.65mm
Maximum radiation field	40cm×30cm	40cm×40cm
Minimum radiation field	5mm×5mm	5mm×5mm

Research on RF Structure

- ✓ Photocathode RF gun
- ✓ X-band DAW injector
- ✓ Multipactor Electron Gun

- ✓ Deflecting cavity
- ✓ Backward Traveling Wave Structure
- ✓ X-band PBG structure
- ✓ C-band choke mode cavity

- ✓ Measurement of ICHIRO copper model cavity
- ✓ Breakdown experiment of S-band structure

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Photocathode rf gun

- 1.6Cell 2.856GHz
  - ✓ **The tuner at the full cell is canceled to lower the risk of RF breakdown**
  - ✓ **the coupling hole between full cell and waveguide is lengthened to realize critical coupling without inserting an inductive or capacitive plug into the waveguide**
- ~100MV/m
- Coupling Hole (symmetrical design)
  - ✓ **The emittance growth due to dipole modes decreases to ~0.1μm**
- Metal Cathode (Copper or Magnesium)
  - ✓ **Low quantum factor~10^{-5}-10^{-4}**
  - ✓ **Easy to manufacture and not too much strict requirement to Vacuum**
- Inner Cooling Tubes
  - ✓ **50Hz@4μs**

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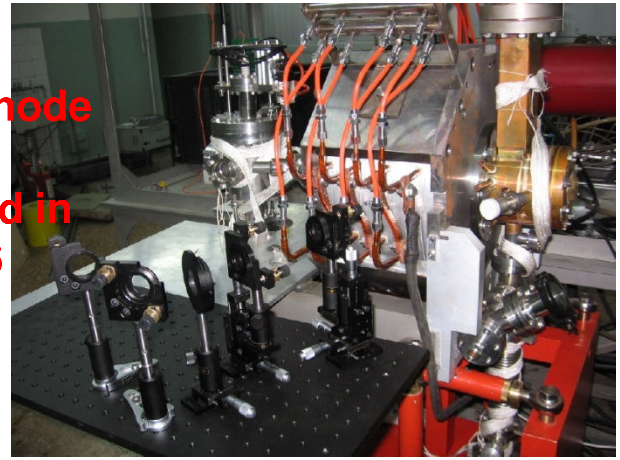
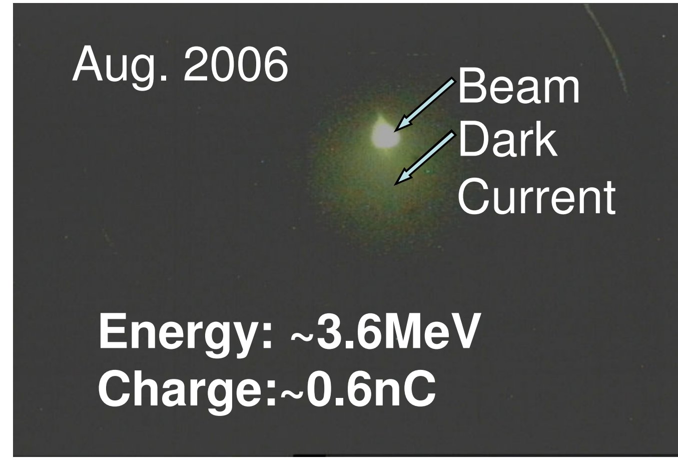
The 1st Photocathode RF Gun Developed in THU,2006





The 2nd Photocathode RF Gun Developed in THU, for SSRF 2006

The 3rd Photocathode RF Gun Developed in THU, for BNL 2007

The 4th Photocathode RF Gun Developed in THU, for NSRL 2008

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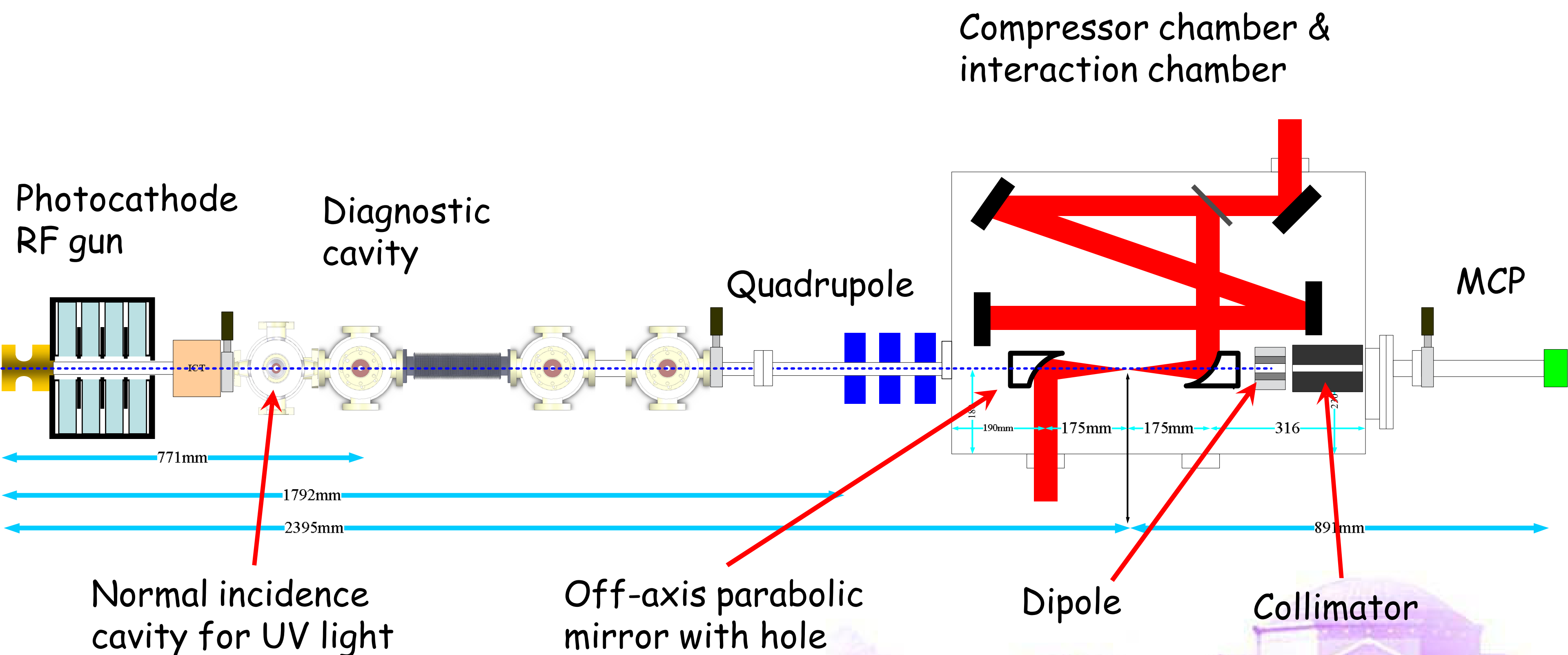
Thomson scattering experiment with rf gun



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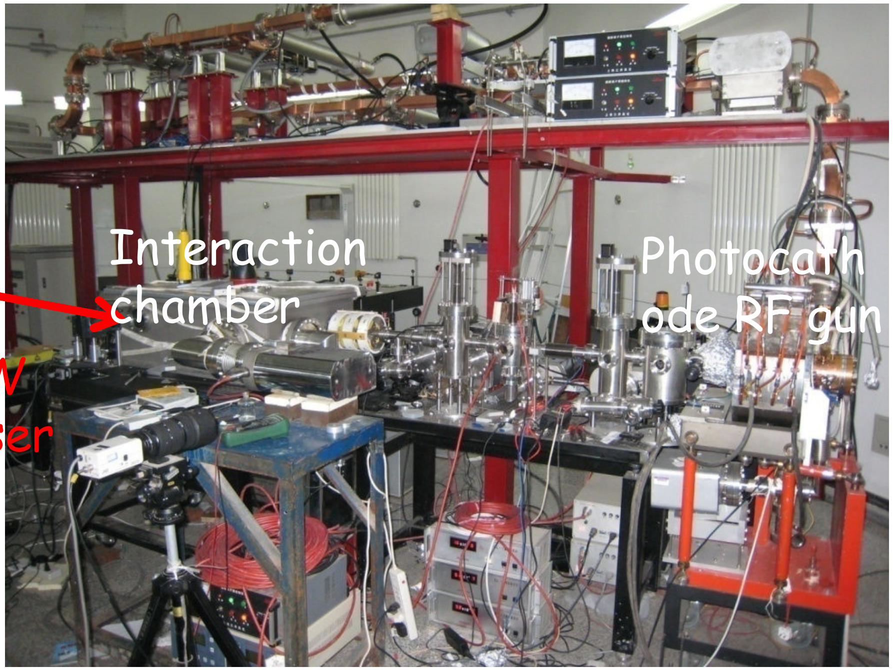

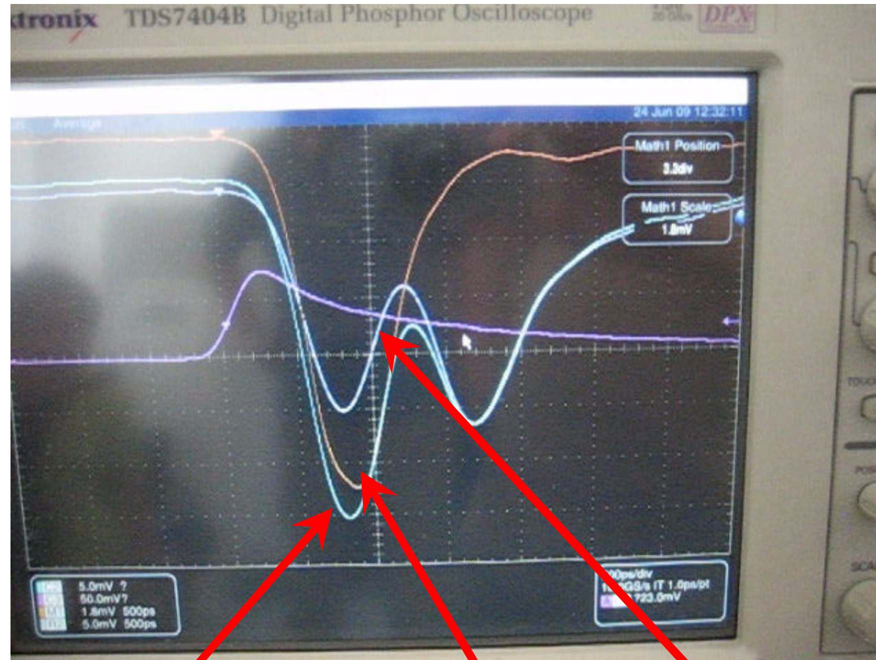

Thomson scattering experiment with photocathode RF gun and TW laser

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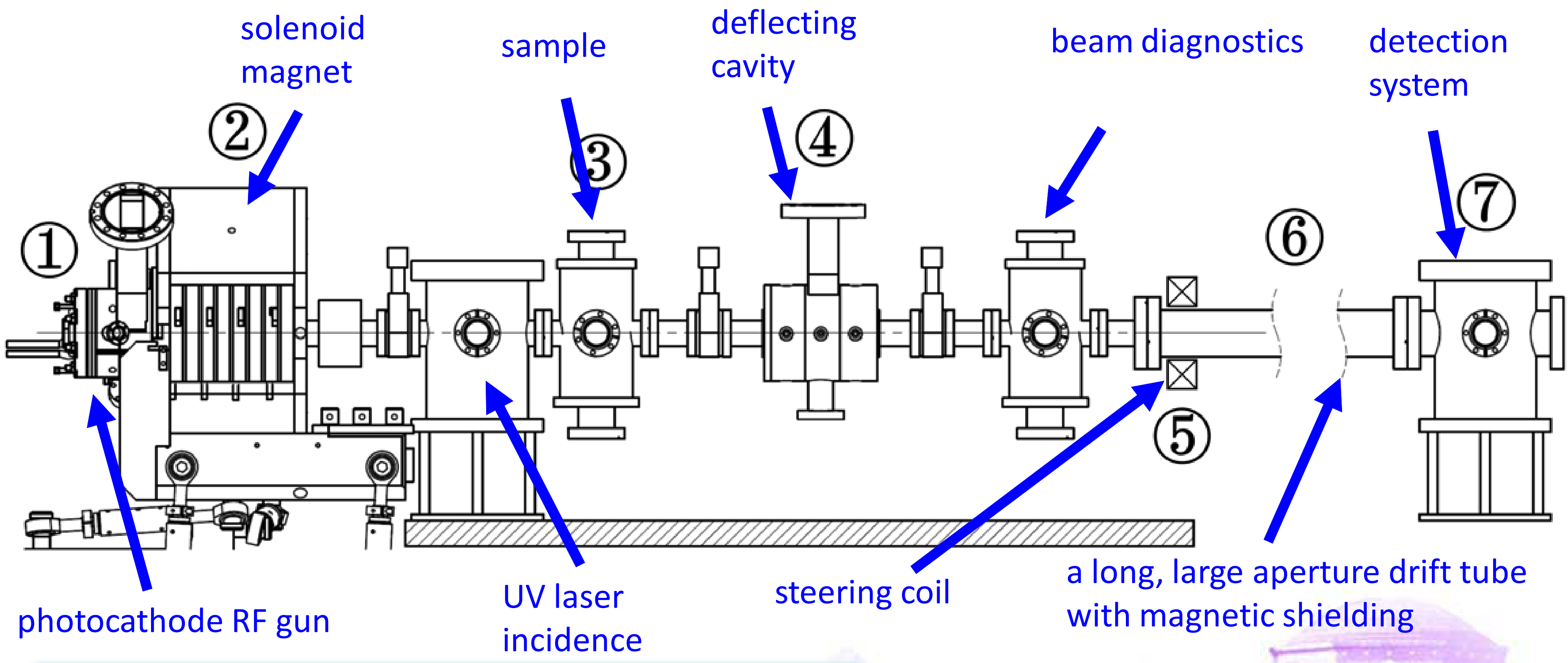
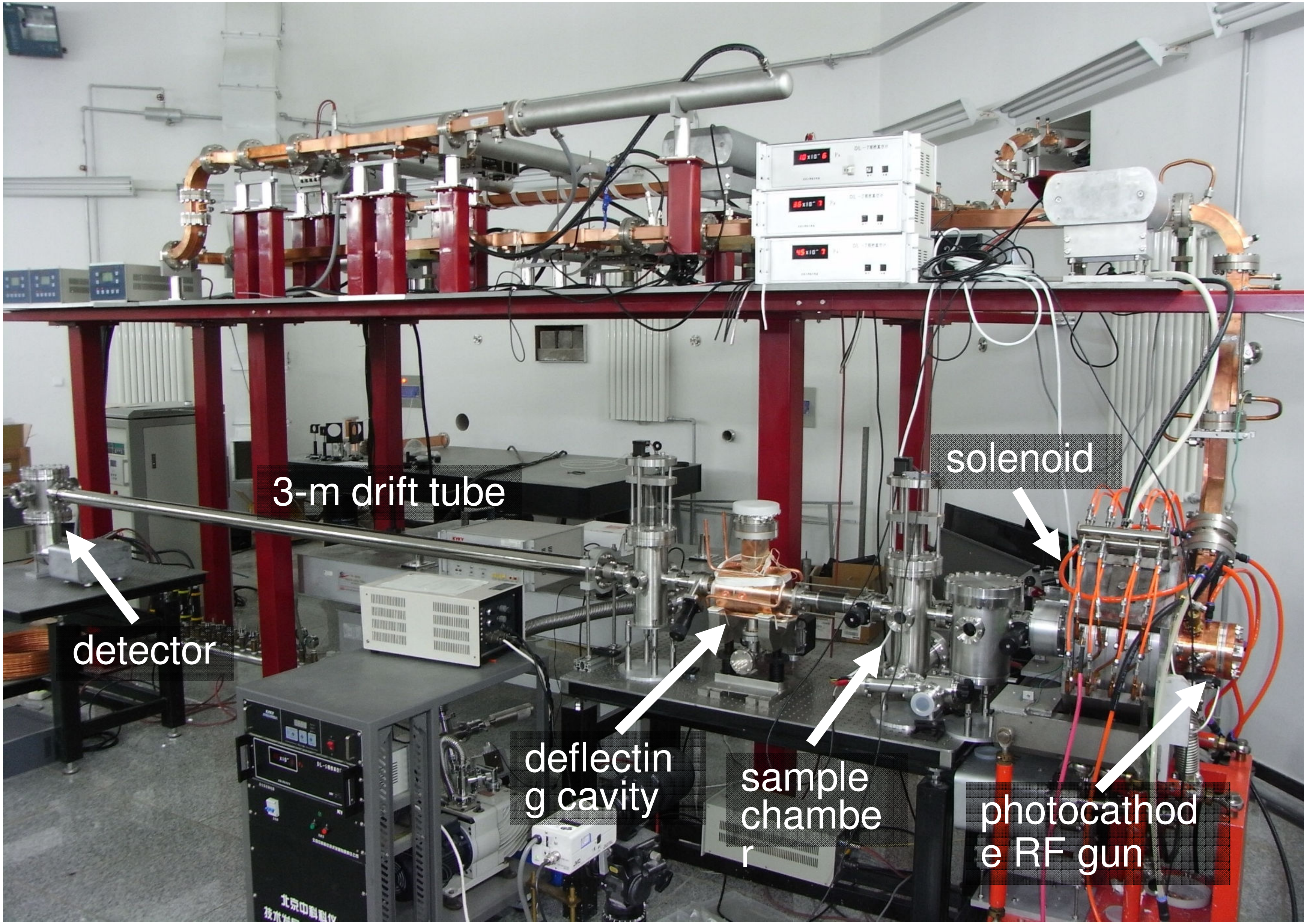
MeV UED experiments with RF gun



Laser, RF power system not shown

Layout of a MeV UED system

Experiment Setup



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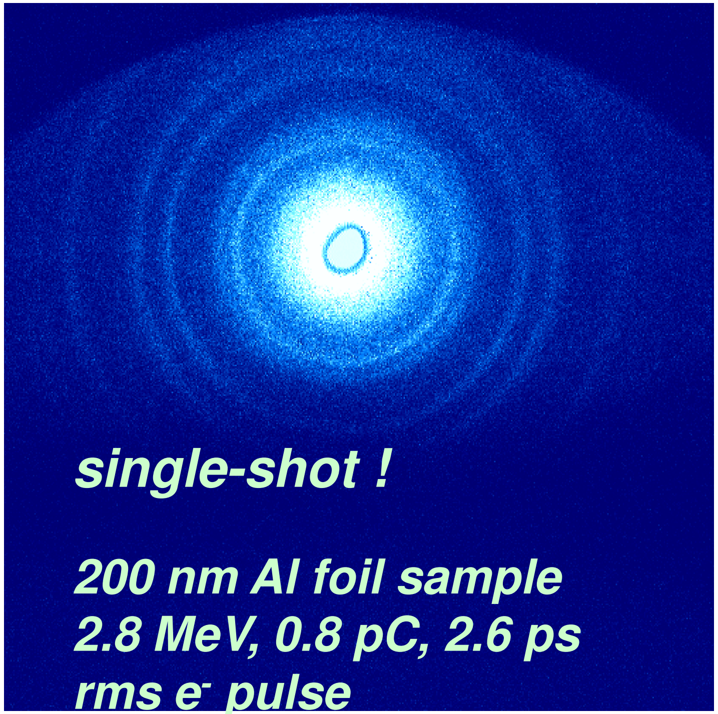
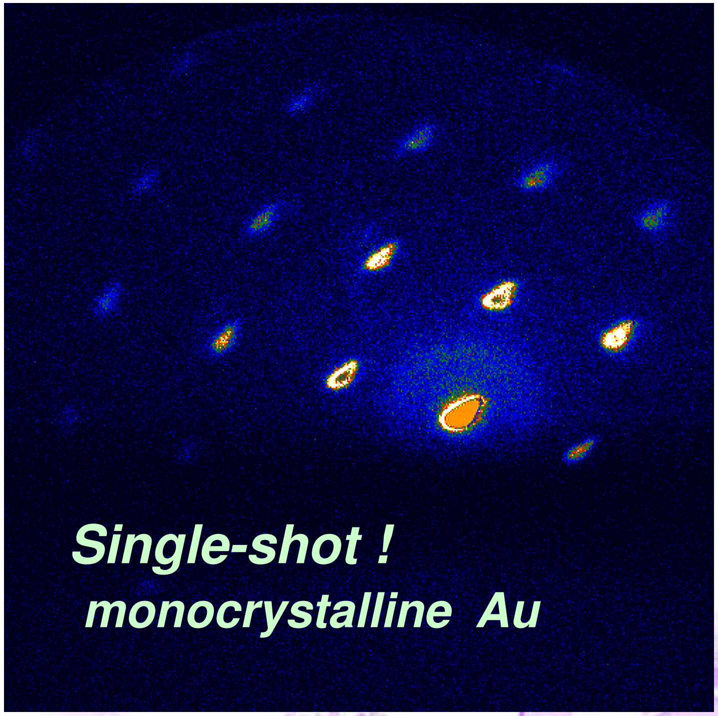
2nd round experiment – Oct, 2009

A long list of technical improvements: collimator, sample, steering coils, magnetic shielding, phosphor, mirror





Next step, to improve the detection efficiency by 100 times, using a MCP based electron multiplier.

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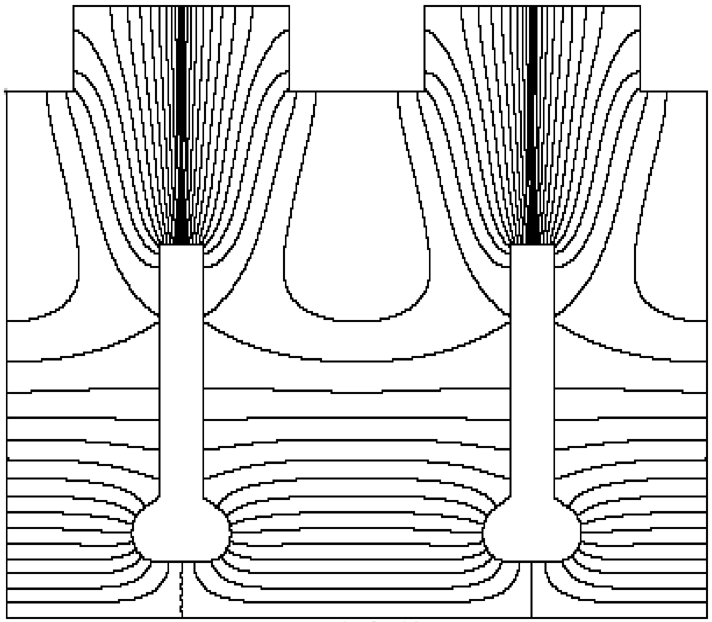
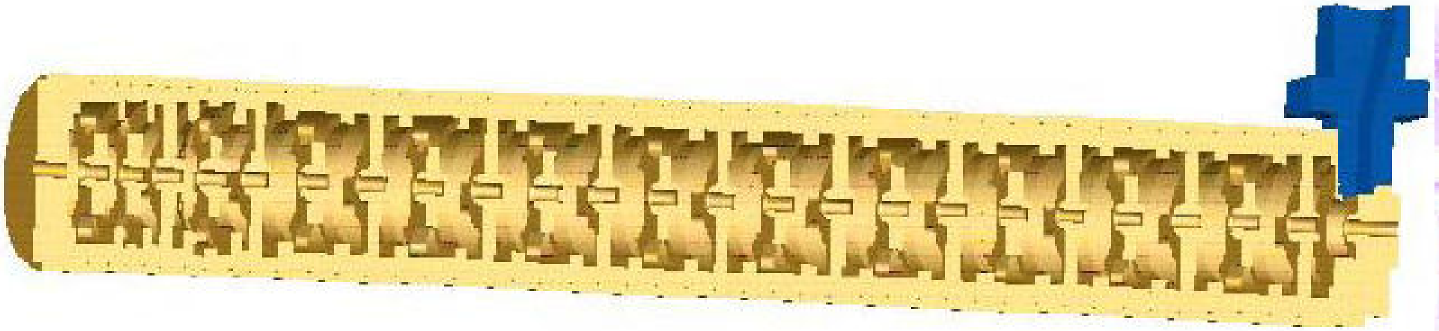
X-band DAW Accelerating Structure





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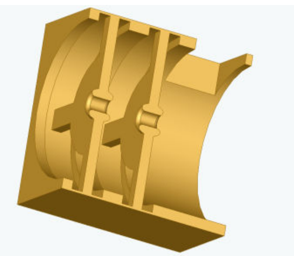
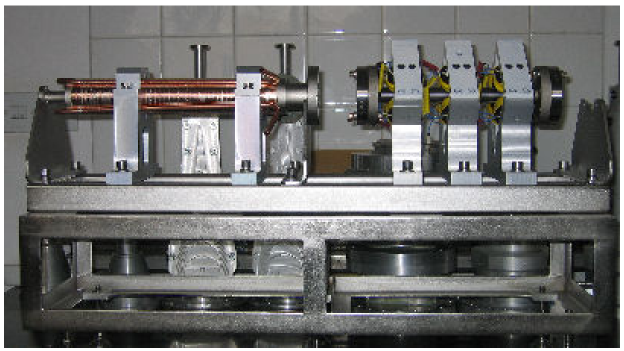
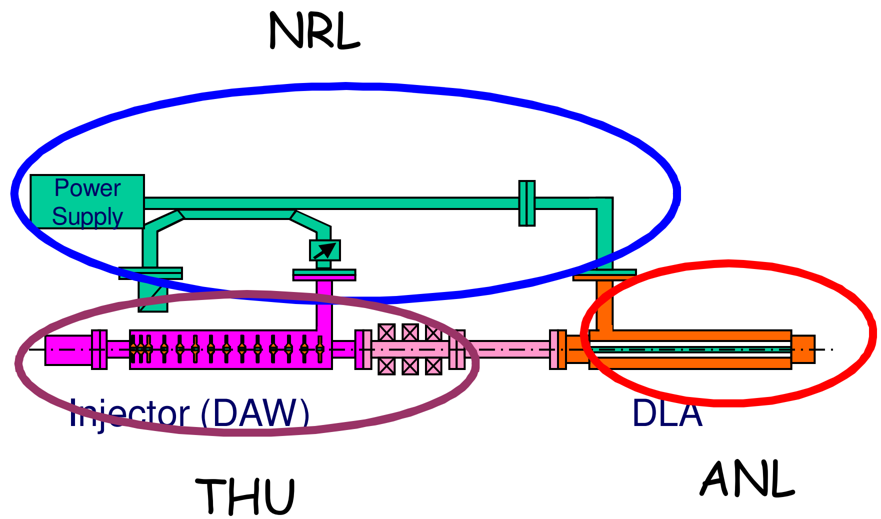
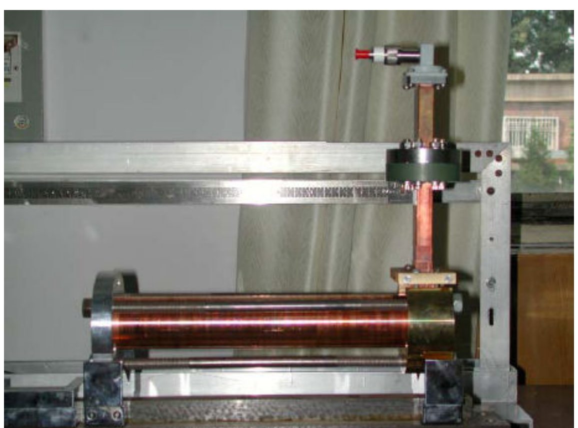
11.424GHz DAW Thermionic RF Gun for ANL

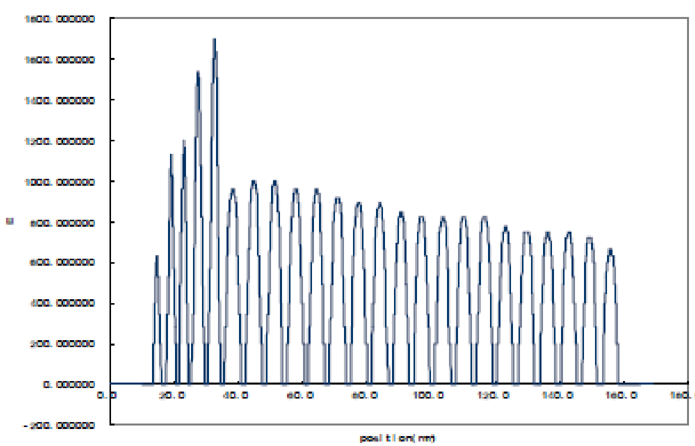
It's a cooperation project between ANL,NRL and THU

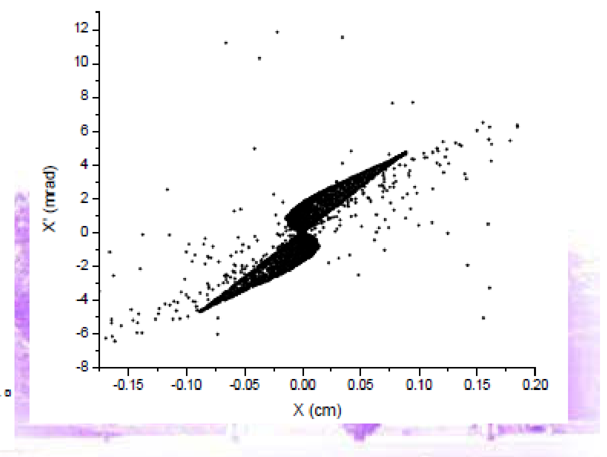












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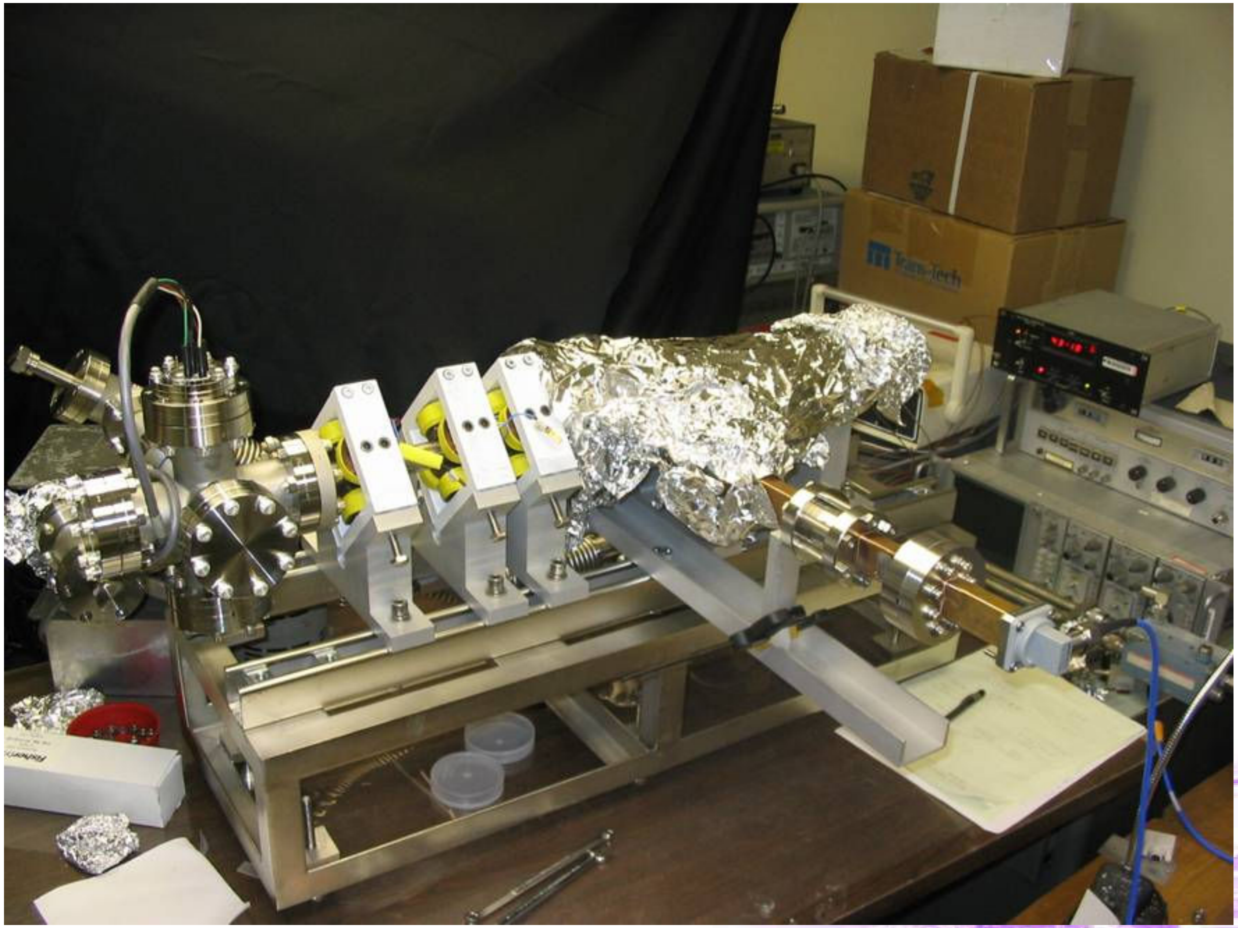
The X-band DAW Thermionic RF Gun in ANL



Shipped to ANL at 2005, and began experiment at the end of 2005.

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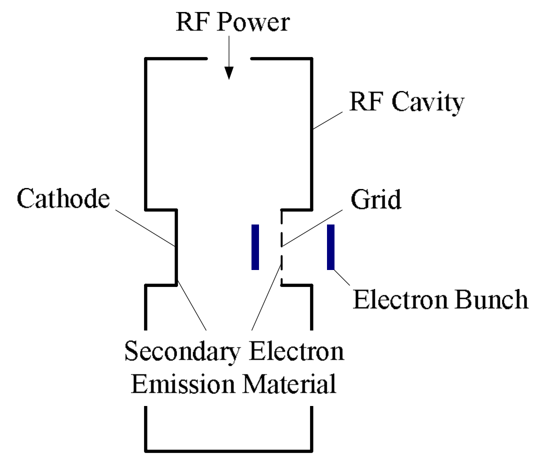
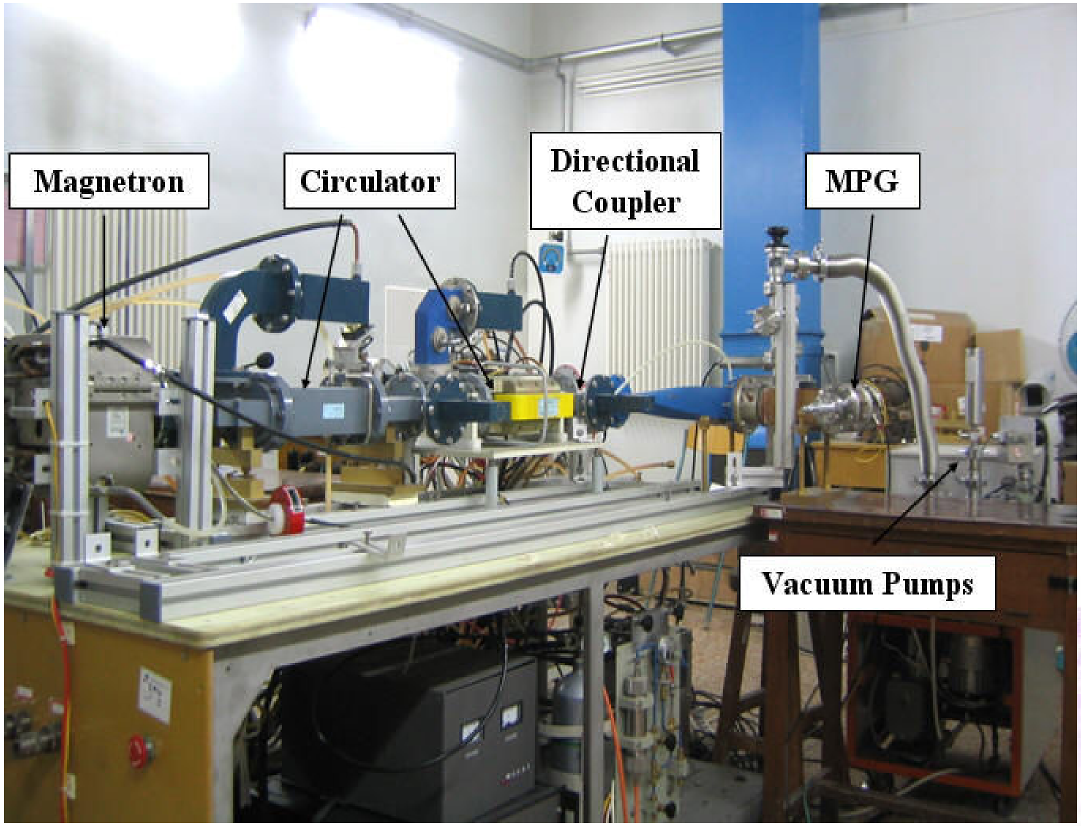
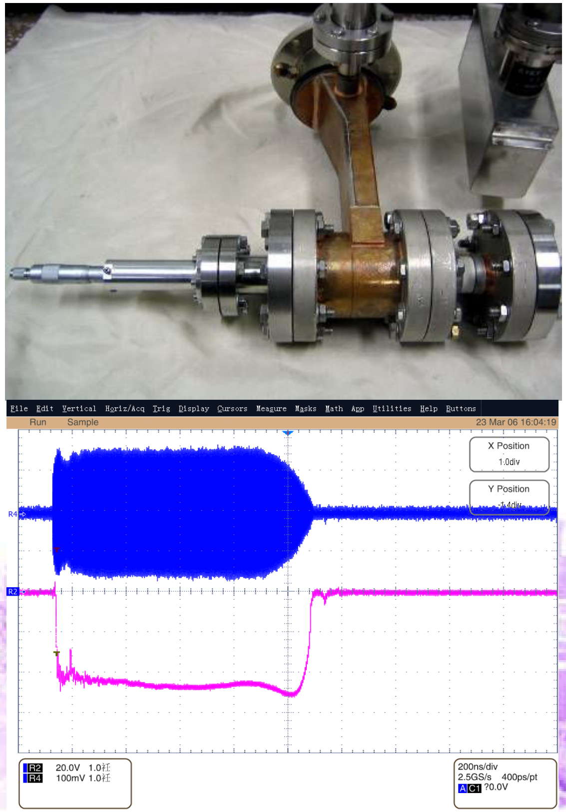
Multipactor Electron Gun

The beam current is 920mA







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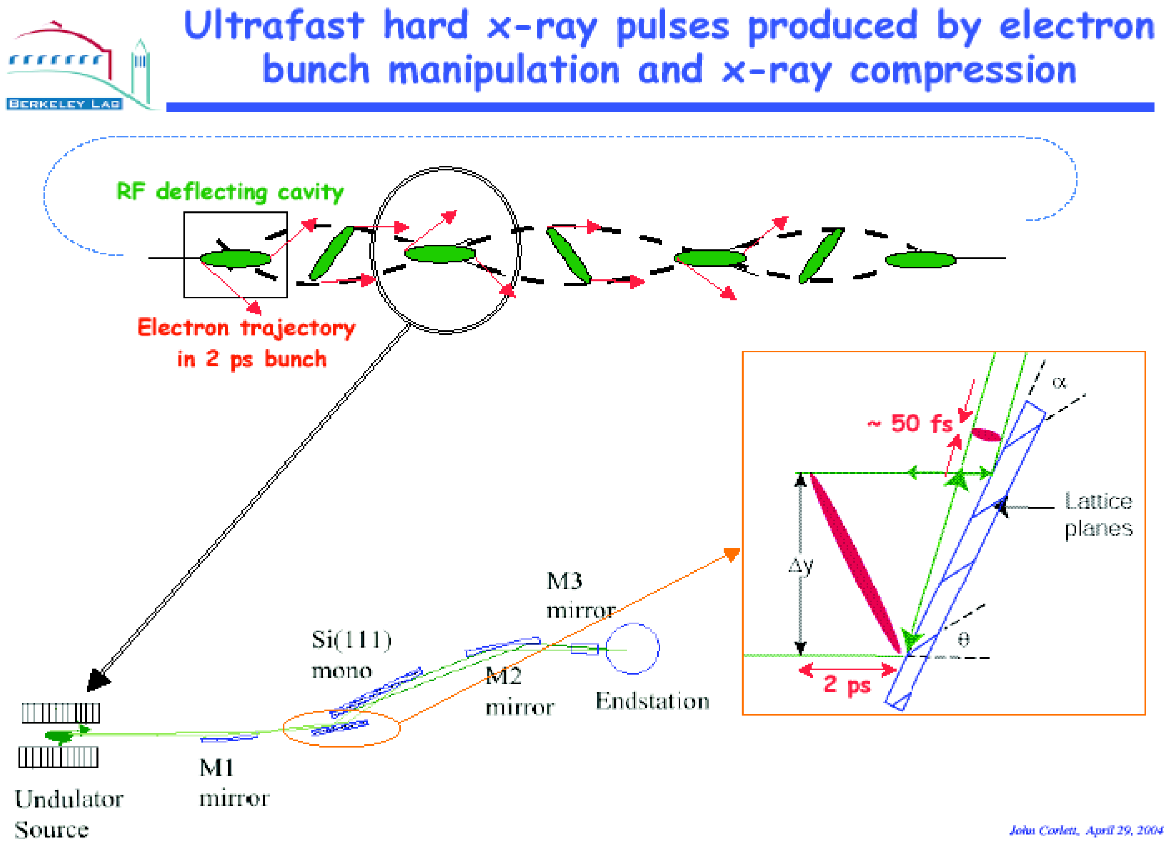
Superconducting Deflecting Cavity Design



- ALS (Advanced Light Source), LBNL
  - 1.5GHz, 2MV
  - Superconducting
- APS (Advanced Photon Source), Argonne
  - 2.8GHz, 6MV
  - Superconducting

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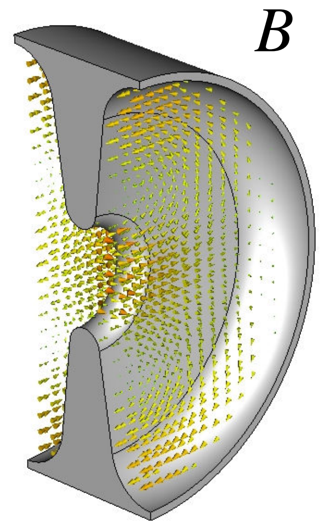
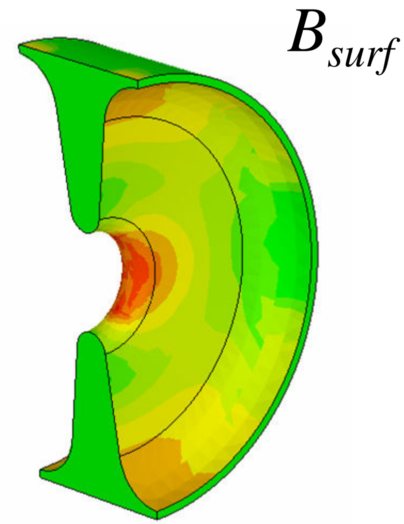
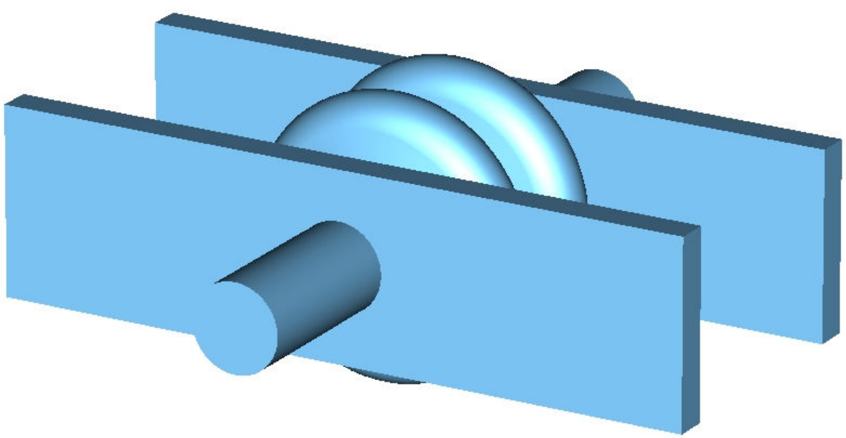
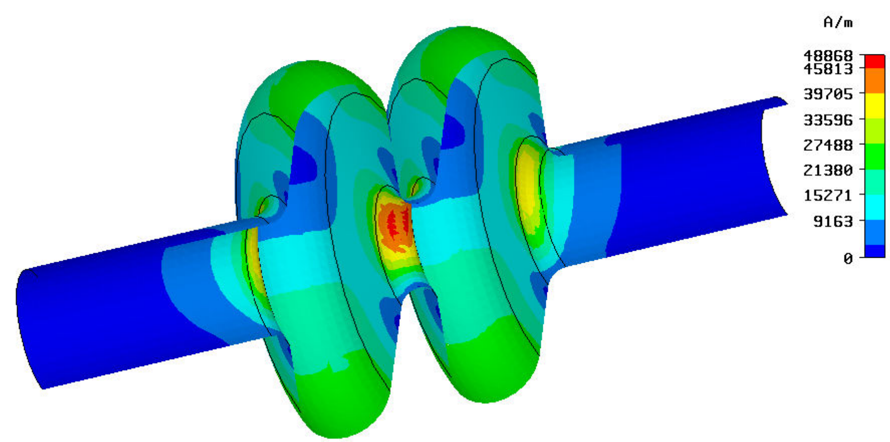
Superconducting Deflecting Cavity Design for ALS at LBNL

- Required Parameters:
  - Frequency: 1.5 GHz
  - Deflecting Voltage: 2 MV
  - Low impedance for storage ring
- Simulation
  - Cavity Geometry Optimization
  - LOM, HOM damper









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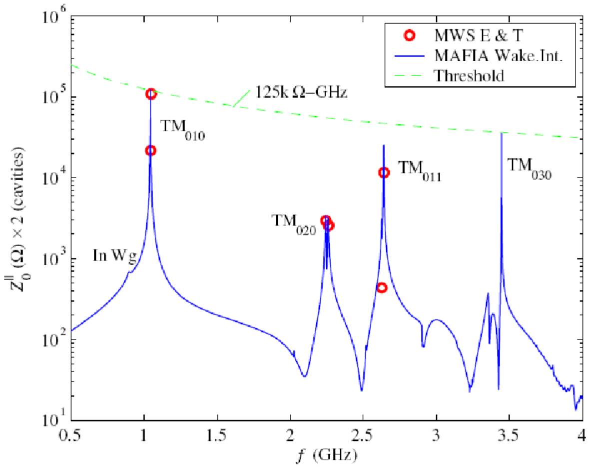
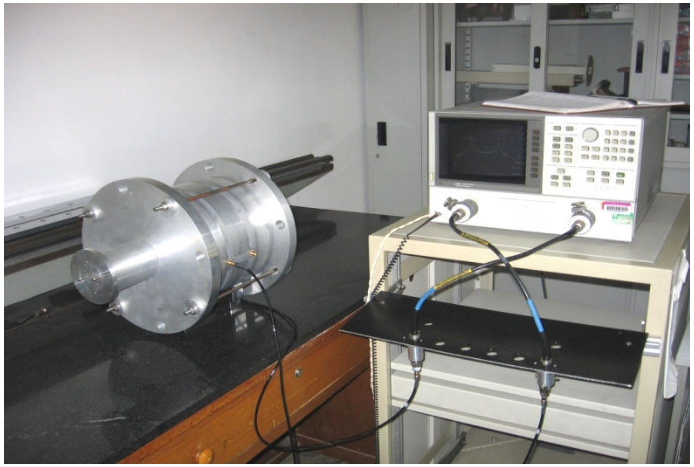
- Cold Test Model
  - Network Analyzer
  - With/without damping waveguide
  - Good agreement with simulation



mode		测量结果				CST-MWS T模块	
		f_{loaded} (MHz)	Q_0	Q_{load}	Q_{ext}	f (MHz)	Q_{ext}
LOM	TM_{010}, 0	1040.1	10843	2030	2498	1040.0	2286
	π	1043.5	10787	1709	2031	1043.8	1686
Working	TM_{110}, π, y	1492.8	11514	10983	–	1489.4	–
	0, y	1503.7	11903	12107	–	1501.3	–
SOM	TM_{110}, π, x	1495.1	11233	673	716	1491.7	686
	0, x	1504.5	11547	844	911	1502.5	930
HOM	TE_{111}, 0, x	1852.9	7757	202	207	1846.5	196
	0, y	1858.7	7898	159	163	1853.9	174
	π, x	1926.0	6103	356	378	1924.3	338
	π, y	1929.3	6045	252	263	1927.8	260



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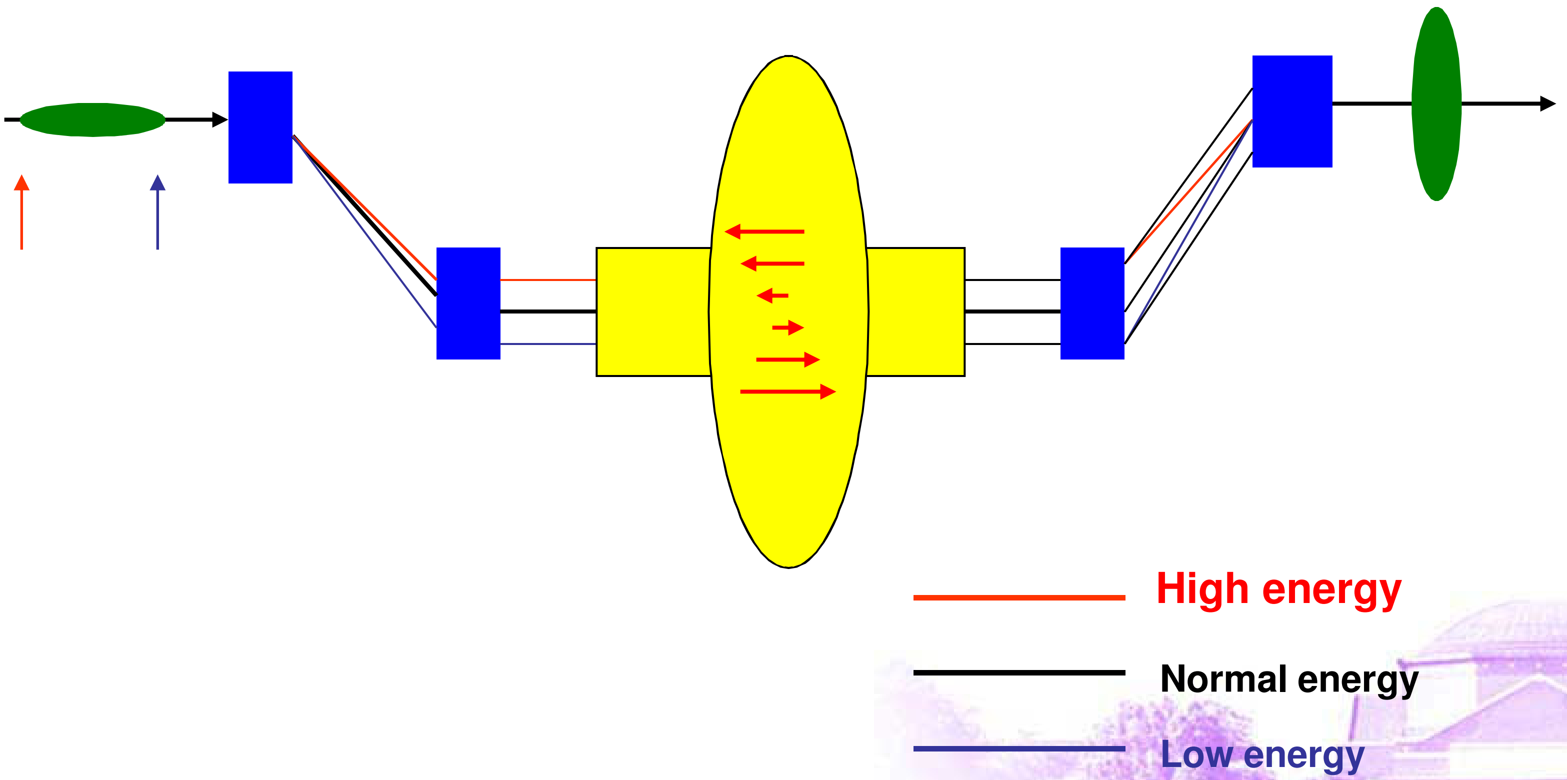
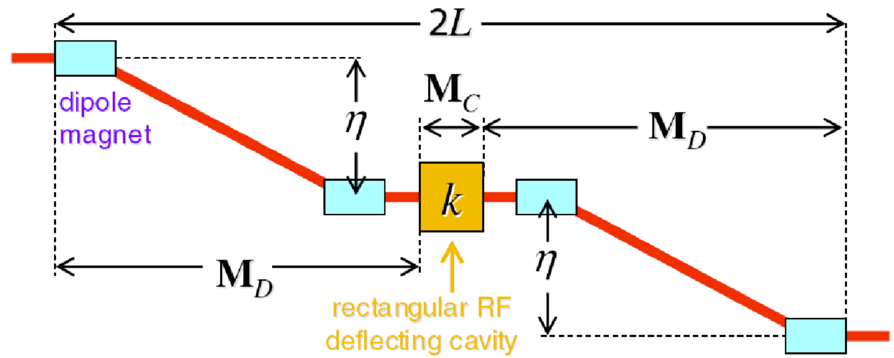
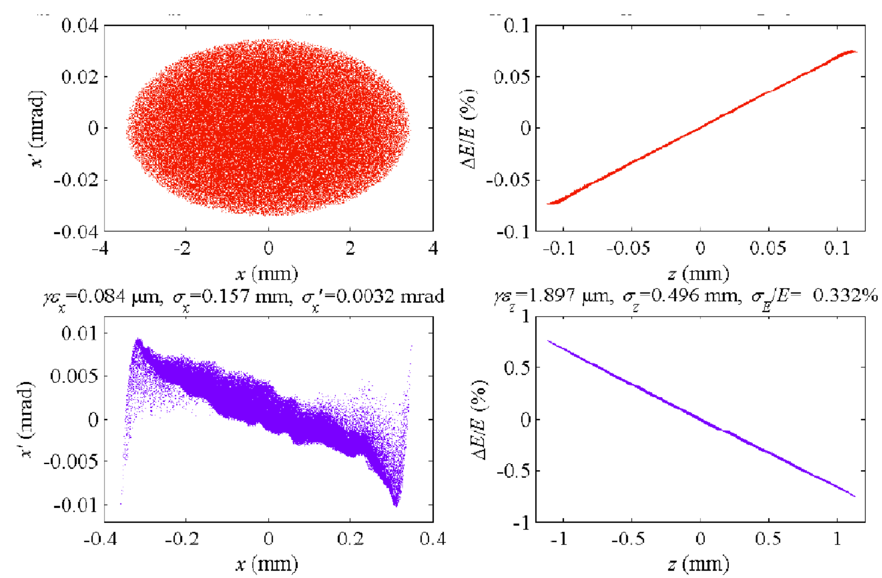
Deflecting Cavity for emittance exchange



L-band deflecting Cavity for emittance exchange at ANL

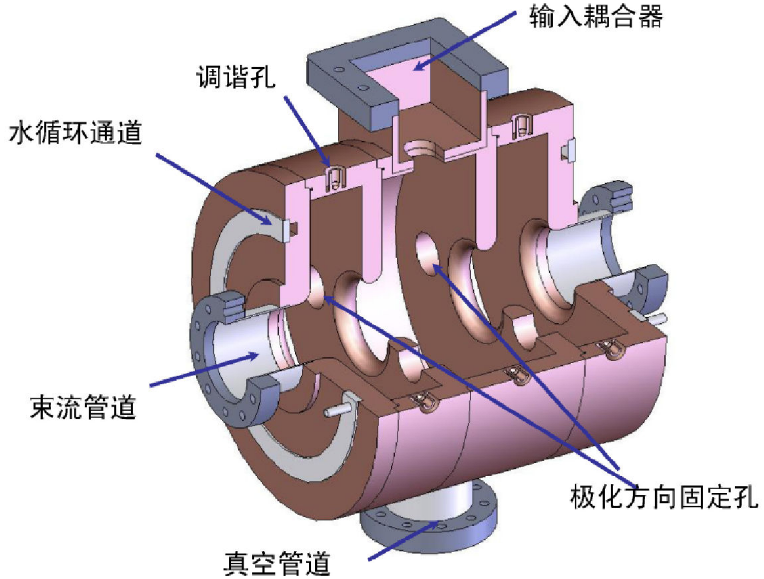
- collaborate with ANL, develop 3-cell L-band deflecting cavity
  - 1300-MHz
  - Input power: 2 MW
  - Deflecting voltage : 2.3 MV





Simulation by ANL

L-band deflecting Cavity for emittance exchange at ANL



Dimension 420x310x420 (mm)

	f / MHz	Q_0	Q_{ext}
模拟计算	1300.00	17000 ①	17700
精加工后测量	1300.91	13491	20500
Q_{ext} 调节②	– –	13185	16877
频率调谐	1299.78	15842	16318
焊接	1299.88	19567	16158
焊后调谐	1299.91		

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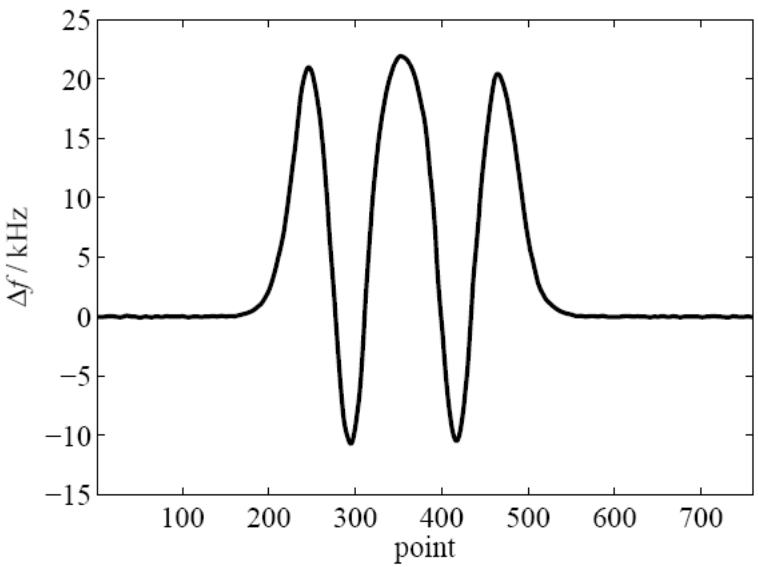
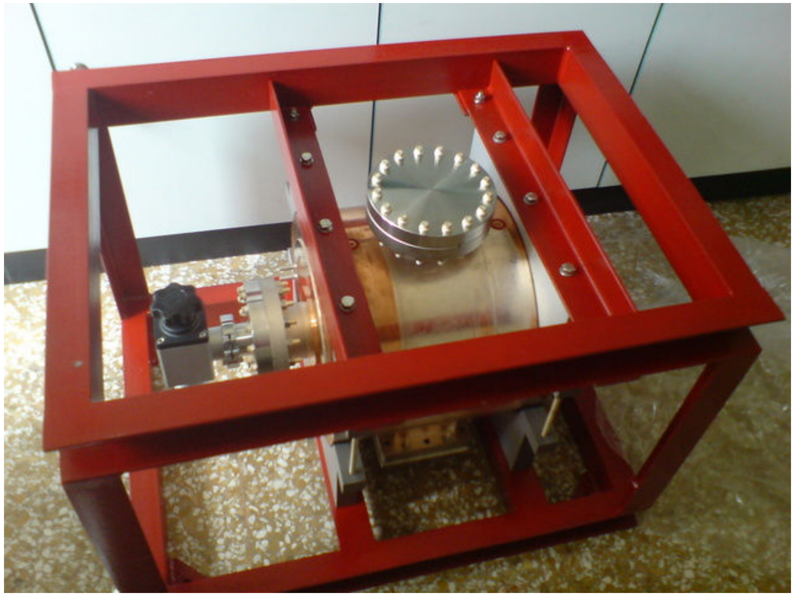
Measurement of field profile





	#1	#2	#3
Δf_{max}	$21.0^{\pm 0.2}$	$21.9^{\pm 0.2}$	$20.4^{\pm 0.2}$
$B_{max}/B_{2,max}$	$0.979^{\pm 0.01}$	1	$0.965^{\pm 0.01}$

The flatness of field profile is better than 96%

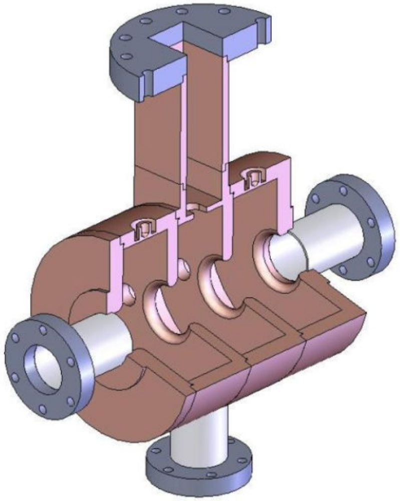
Measurement of bunch length with deflecting cavity

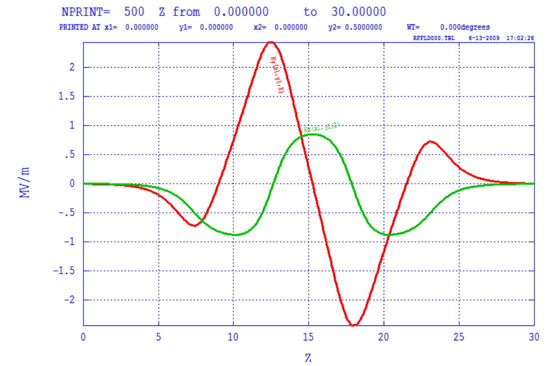
1. Exit of photocathode gun: 3.5MeV, 3ps
2. Exit of linac: 50MeV, 3ps
3. Exit of chicane:50MeV, 1ps

电子束动能	E_0	3.5	50	50	MeV
电子束团长度	σ_s	1	1	0.3	mm
归一化发射度	ε_N	3	3	3	mm · mrad
非归一化发射度	ε	0.39	0.03	0.03	mm · mrad
偏转腔工作频率	f_0	2856	2856	2856	MHz
偏转腔工作电压	V_{def}	1.0	1.3	3.4	MV
（等效）漂移长度	$D\ (R_{34})$	0.4	2.0	2.5	m
无偏转腔时屏幕束斑	$\sigma_{y,0}$	1.0	0.3	0.3	mm
纵向分辨长度	Δ_s	0.10	0.10	0.03	mm
偏转腔后屏幕束斑	σ_y	10	3.1	3.1	mm
横向分流阻抗	$R_\perp$	2.85	2.85	2.85	MΩ
输入功率	P_0	0.4	0.51	4.0	MW
表面最大电场	E_{peak}			~ 75	MV/m

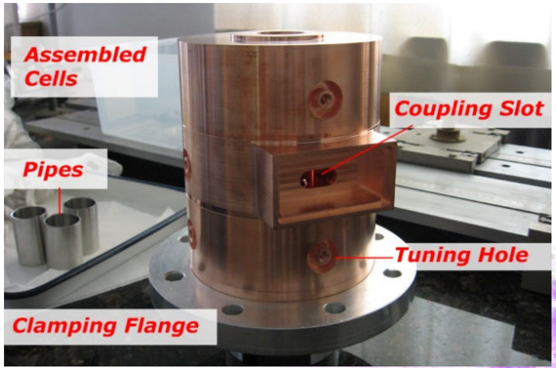
Structure design

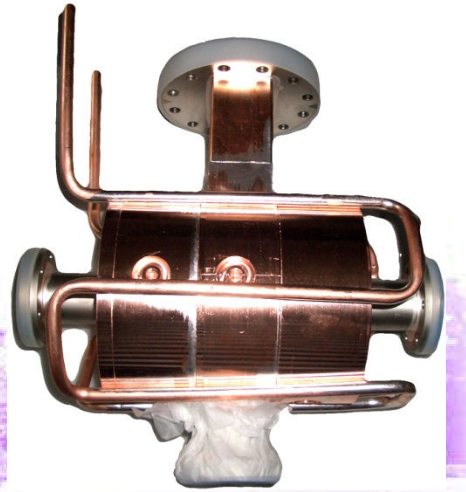
- feature
  - 2856 MHz
  - PI-mode
  - 3-cell
  - standing-wave
  - Water cooling



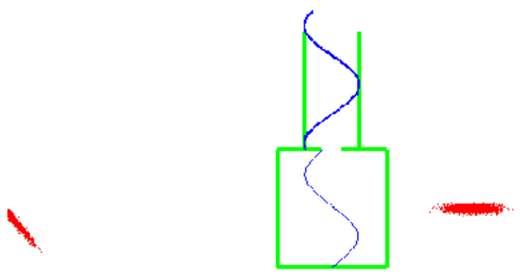


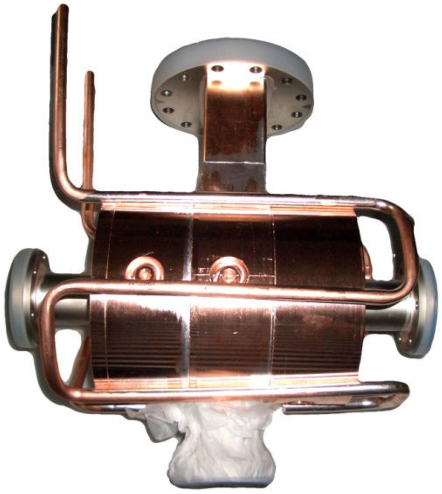
	THU	LOLA
	SW	TW
N-cell	3	104
L (m)	0.158	3.64
$r_\perp$ (MΩ/m)	20	15.3
P_0 (MW)	4	22
V_{def} (MV)	3.4	35

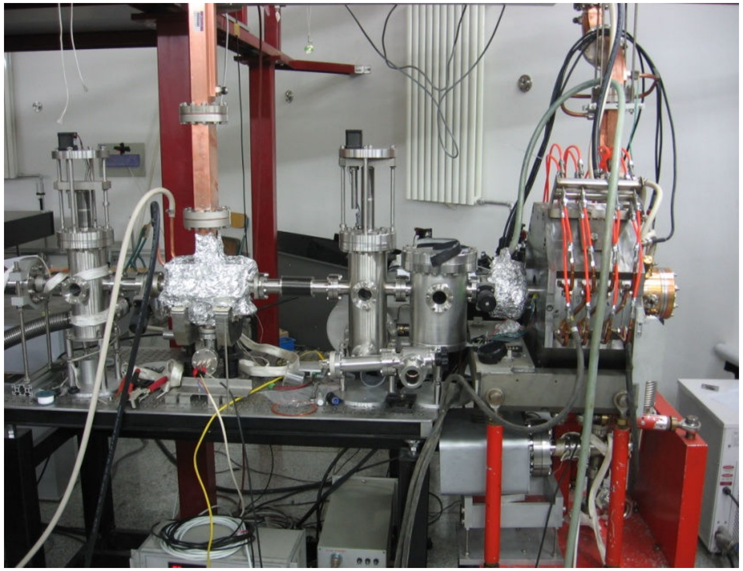


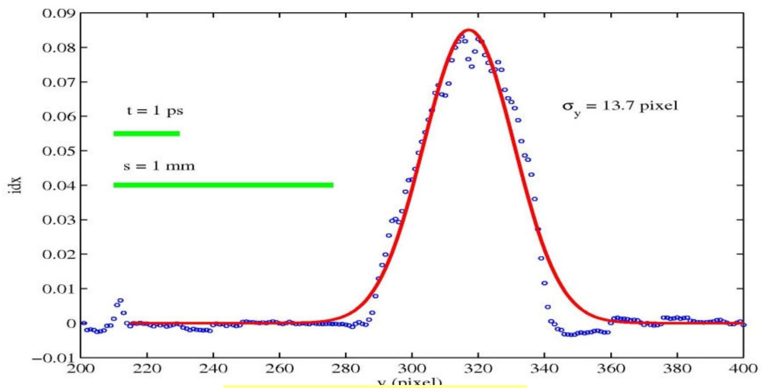


Bunch Length Measurement by RF Deflecting Cavity

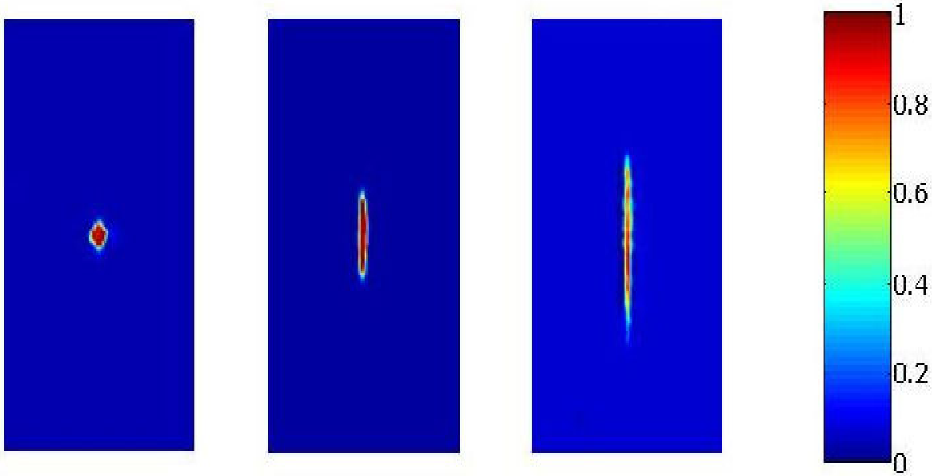








$\sigma_t = 0.64$ ps



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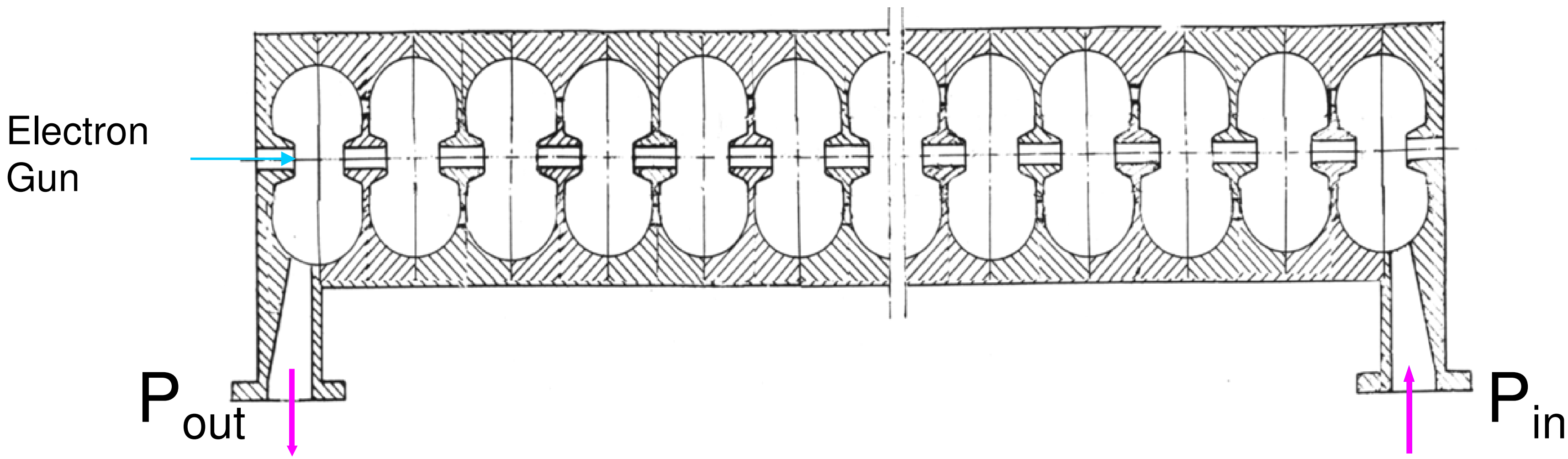
BTW (Backward Traveling Wave) Structure



16MeV BTW Accelerating Tube

10MeV BWT Accelerating Tube

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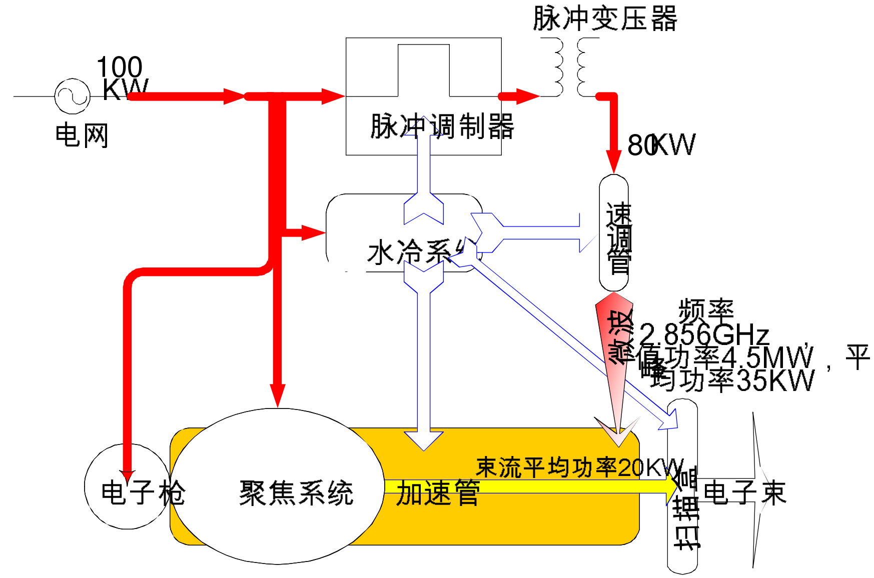
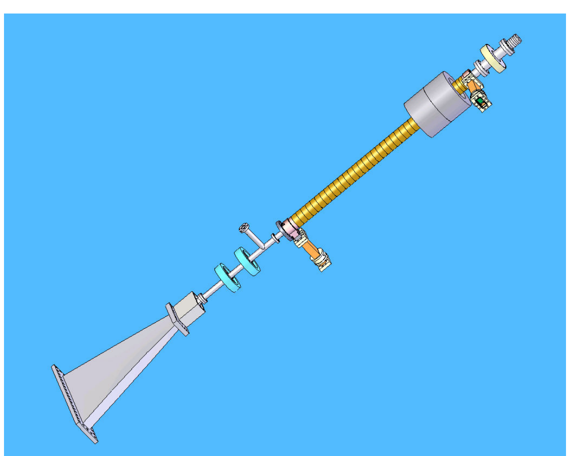
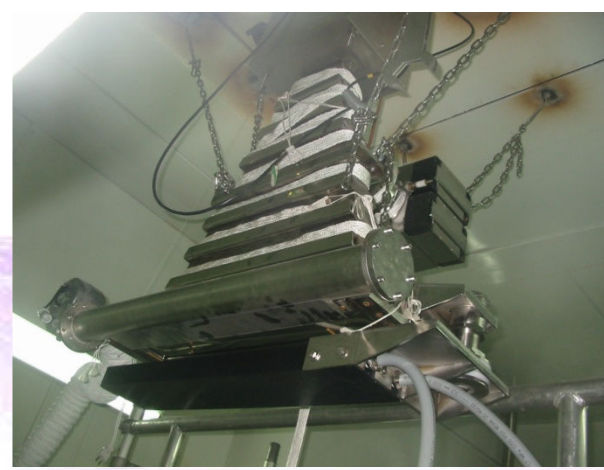
High average power Irradiation

10MeV， 20kW
S band BTW linac

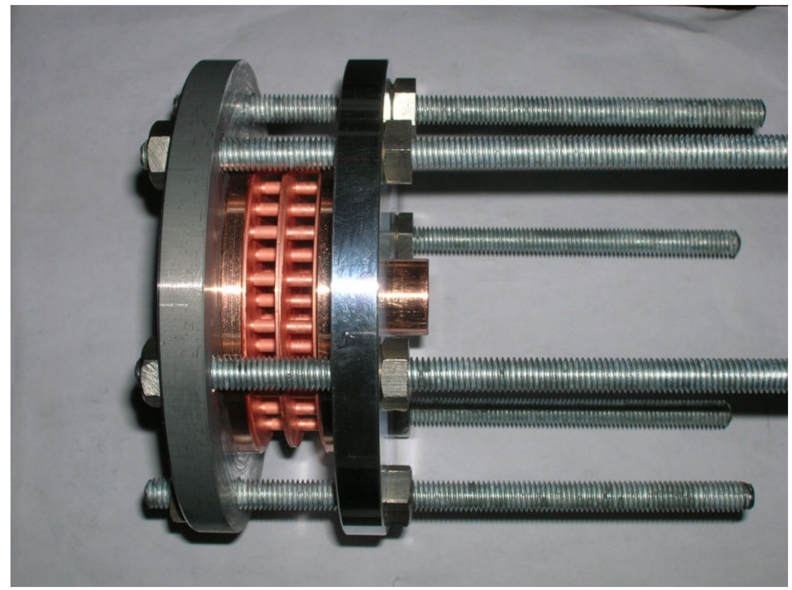


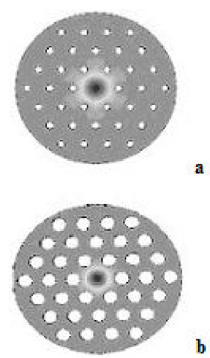


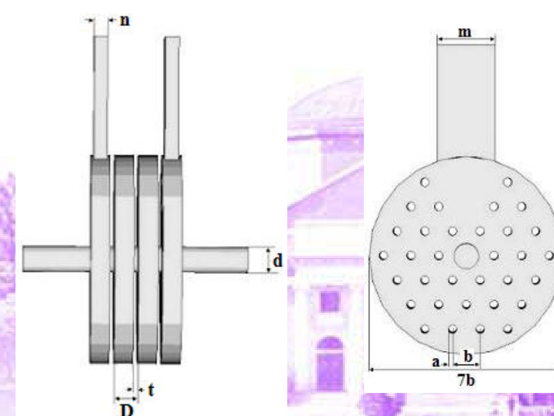


X-band PBG structure

Rod radius a/mm	1.64
Distance between the rods b/mm	10.96
Iris diameter d/mm	9.61
Iris thickness t/mm	1.71
The length of single period D/mm	8.75
Operating frequency f/GHz	11.42
Phase shift per cell θ	$2\pi/3$
Coupling coefficient between two cavities k	0.0556
Group velocity v_g	0.050c
Quality factor Q	5461
r/Q/ $k\Omega m^{-1}$	10.5
Accelerating gradient G/MVm^{-1}	$7.1\sqrt{P(MW)}$







C-band choke mode cavity

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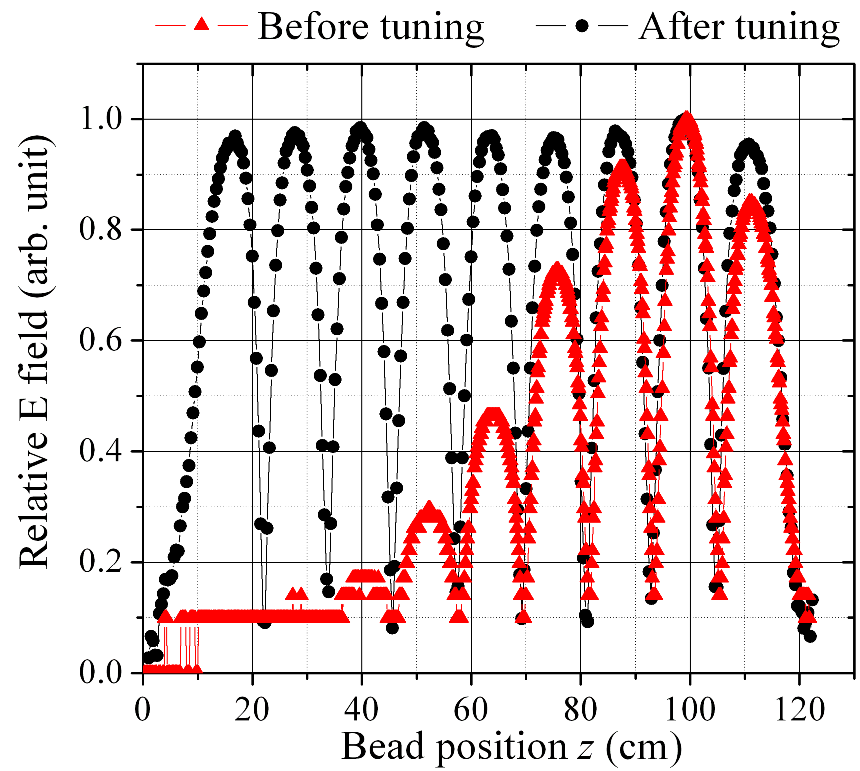
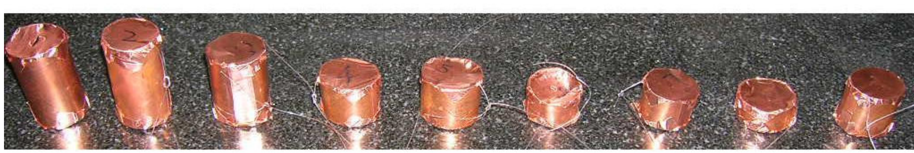
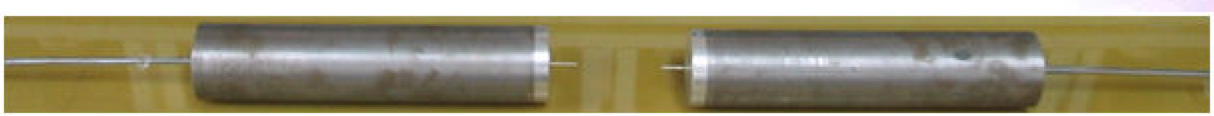
Field tuning and HOMs measurement of 9-cell ICHIRO copper model cavity

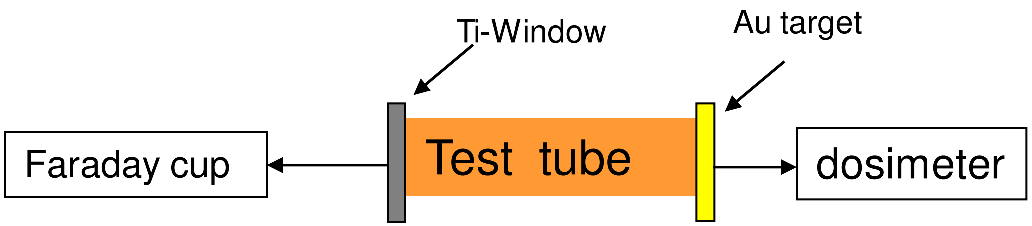


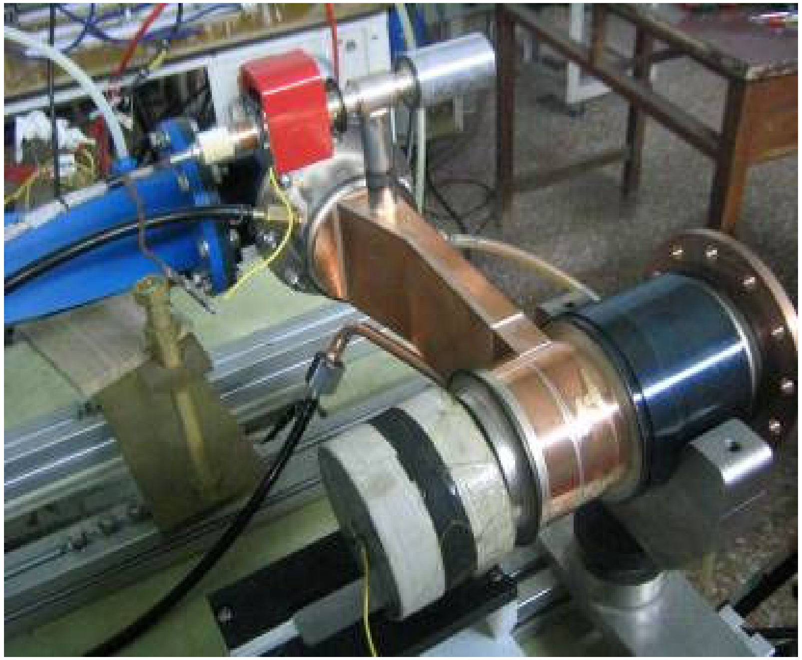


steel balls with different sizes



Breakdown experiment of S-band structure





- 3 pairs of cavities
- Coupler is in the middle
- Ti foil is used on the left side for the measurement of dark current
- Au target is on the right side for dose measurement due to dark current

- Breakdown occurs:

$$E_P = 390 MV/m$$

- The dark current is 2.6 mA
- Dose rate is 3.2R/min@1m

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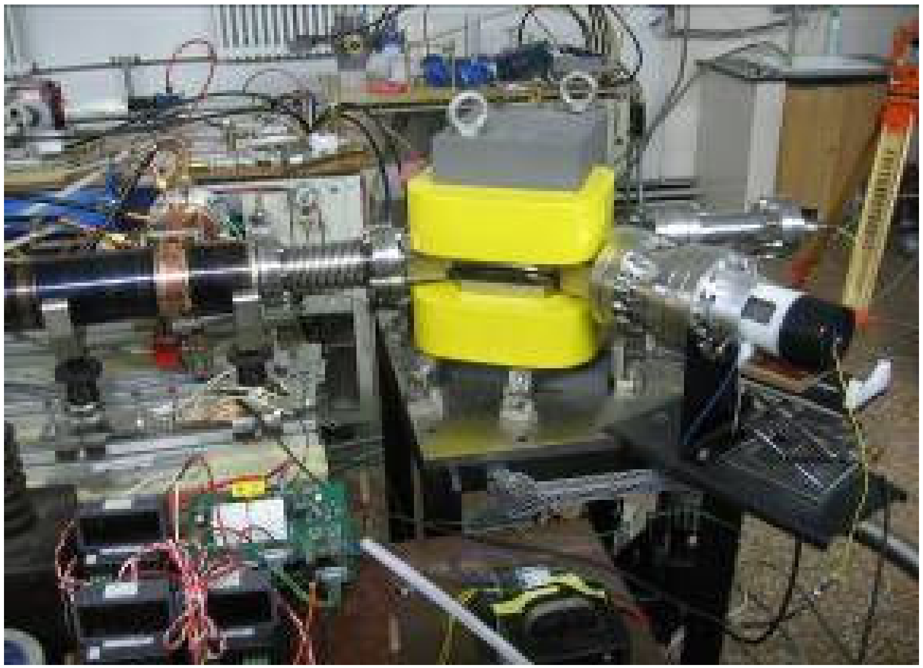
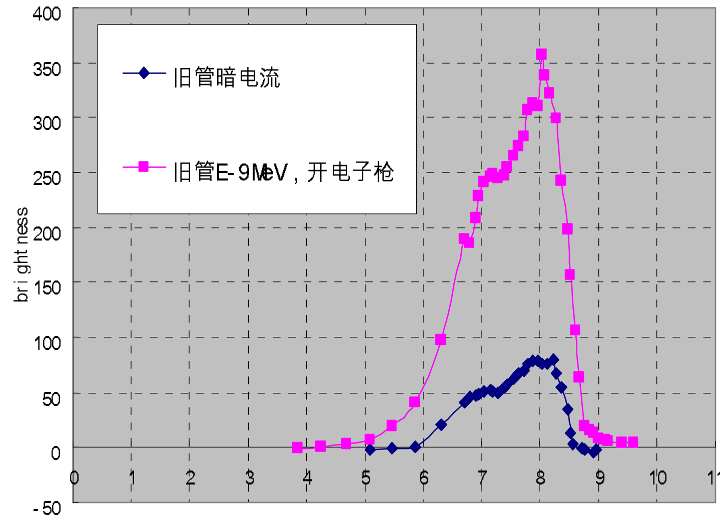
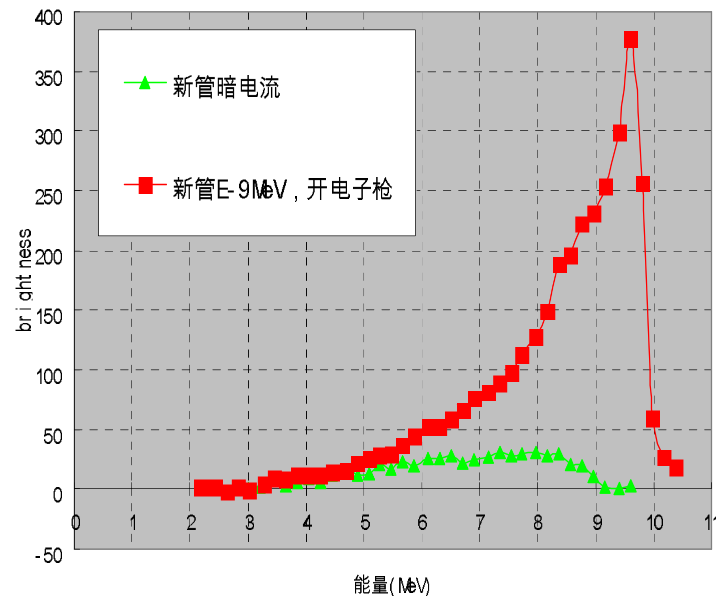
Measurement of energy spread before breakdown







Research the breakdown mechanism, optimize the design and improve the manufacturing technology

Summary

- More than 300 accelerating tubes has been produced by Tsinghua U. for medical therapy and NDT
- Some rf structures are developed succesfully
- We have good background on designing, manufacturing, testing and applying the new rf structure, especially x-band structure collaborated with CERN, KEK, SLAC

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Thanks for Your Attention！