清華大學
Tsinghua University

A Very Compact Inverse Compton Scattering Gamma-ray Source (VIGAS) at Tsinghua University

Chuanxiang Tang

On behalf of the VIGAS team

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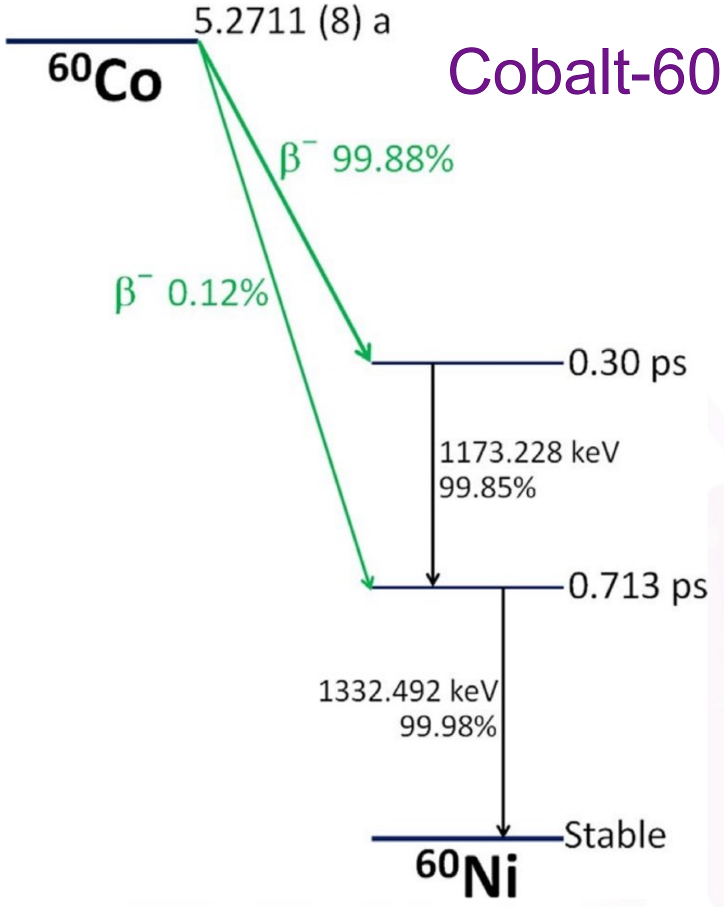
Outline

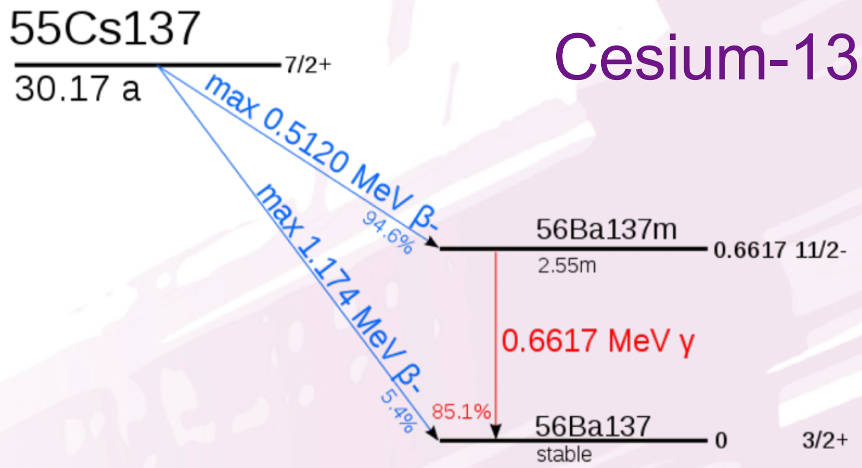
- Inverse Compton Scattering (ICS) X/γ Source
- An overview of VIGAS Gamma-ray Source
- Development of VIGAS
- Performance of VIGAS
- Summary

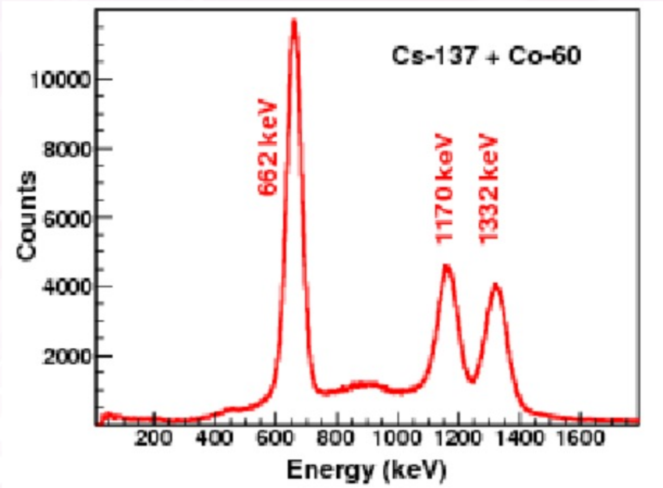
Gamma-ray normally from decay of nuclei

Cobalt-60



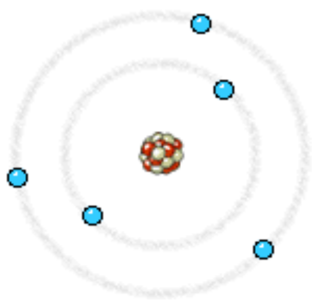
Cesium-137



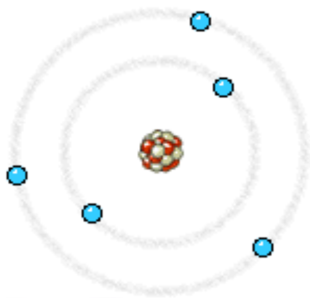


The spectra of the radiations of Cobalt-60 and Cesium-137

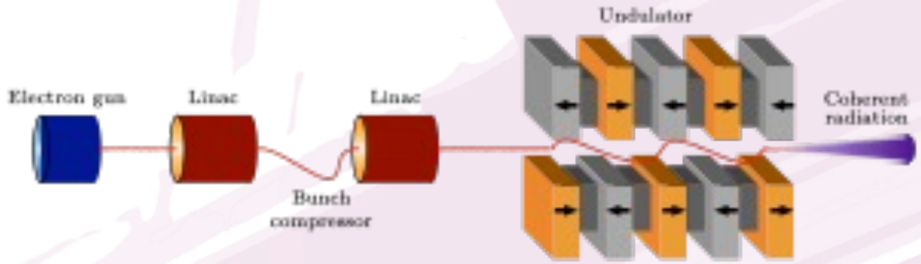
X-ray normally from free or bound electrons



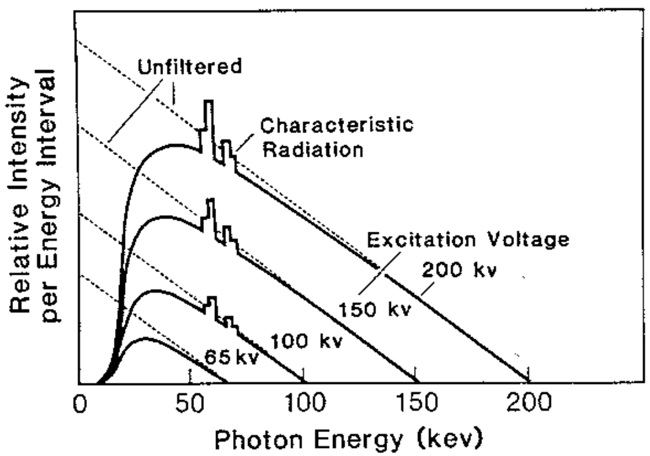
Bremsstrahlung



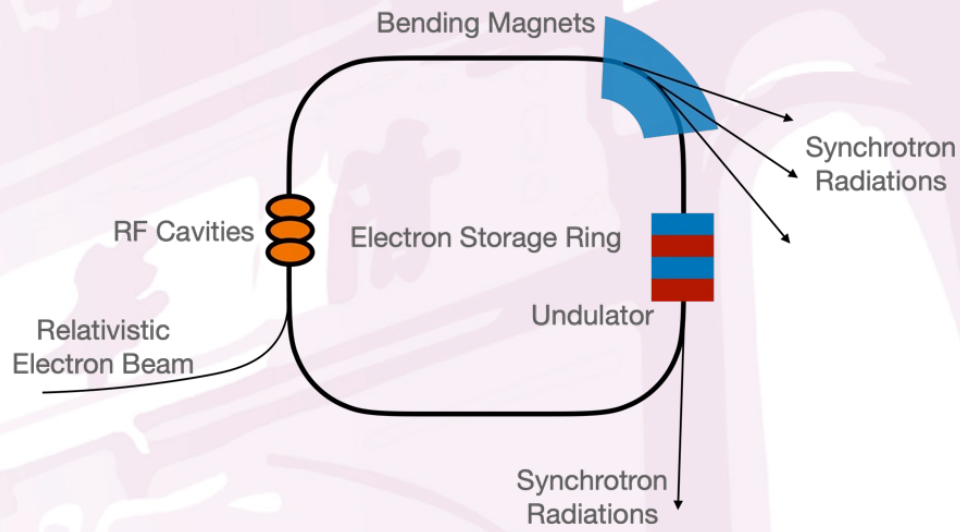
Characteristic radiation



Free Electron Laser

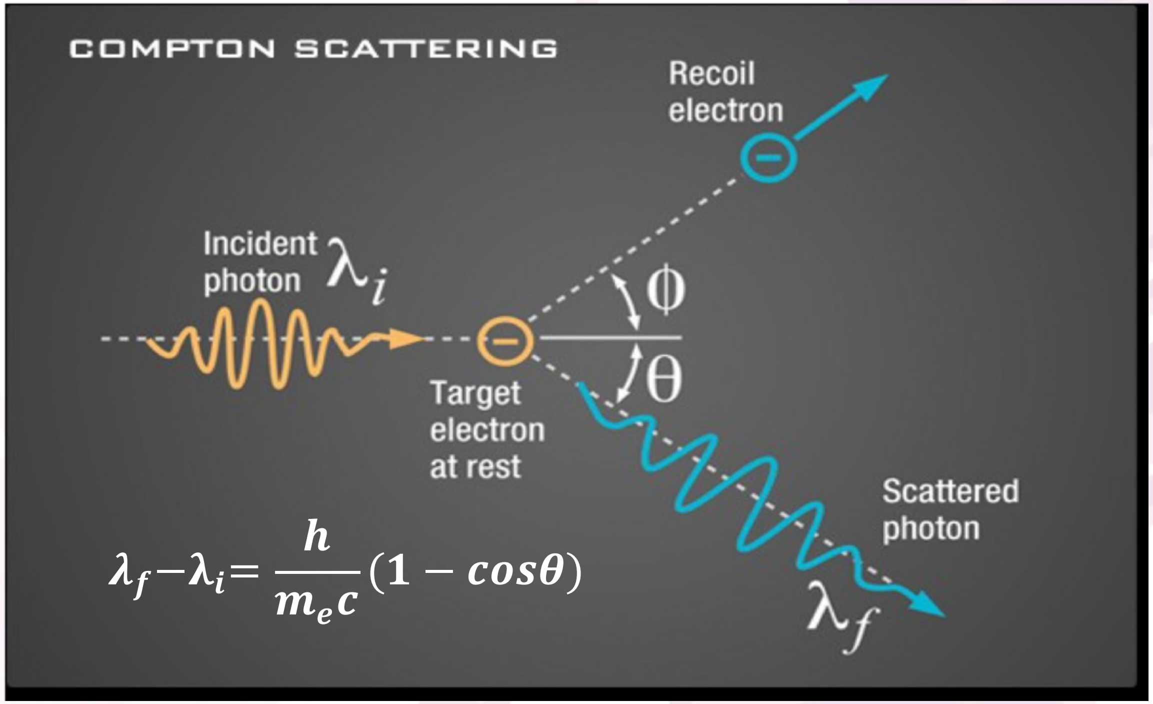


The X-ray spectra of x-ray tube with different voltages



Synchrotron Radiation Source

Inverse Compton Scattering(ICS)



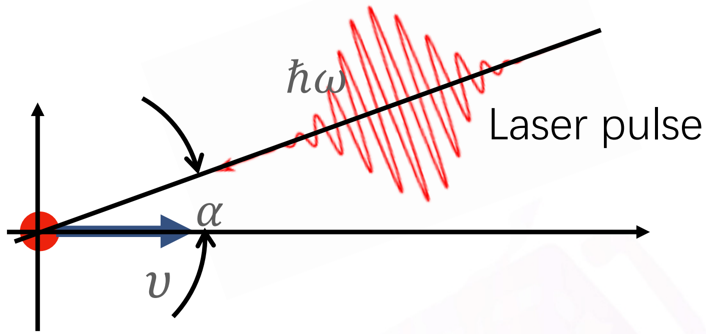
Arthur H. Compton
Discovery: 1923
Nobel Price in Physics: 1927

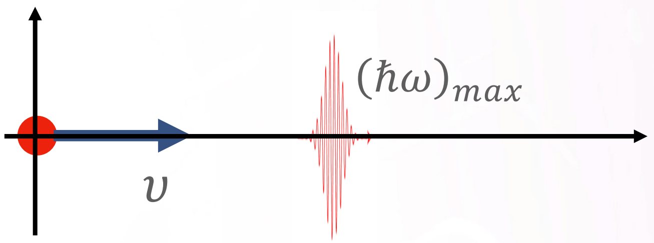
CS: Compton scattering is an inelastic scattering of a photon by a free charged particle, usually electron.

ICS: a charged particle transfers part of its energy to a photon.

A.H. Compton, Bull. Nat. Res. Council (US) 20 (1922) 19； Phys. Rev. 21 (1923) 483

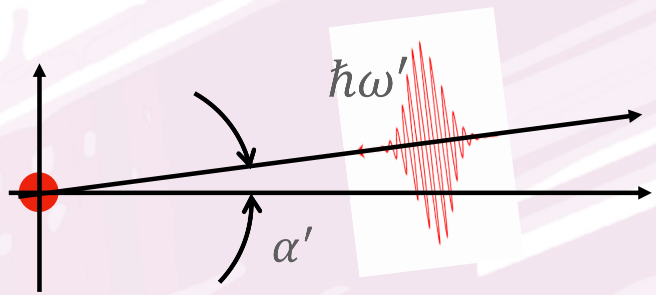
Classical model of ICS



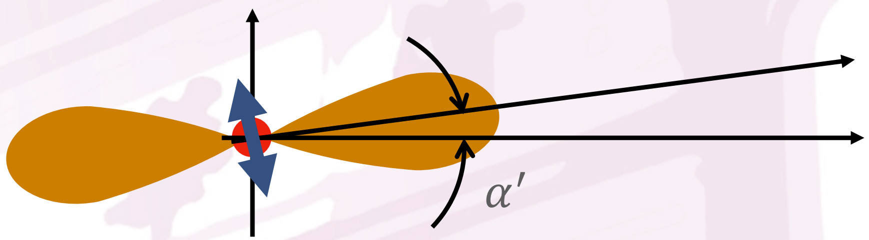


$$(\hbar\omega')_{\max} = \gamma^2\hbar\omega(1 + v/c)^2 \approx 4\gamma^2\hbar\omega$$

Laboratory Frame



$$\hbar\omega' = \gamma\hbar\omega[1 + (v/c)\cos\alpha]$$

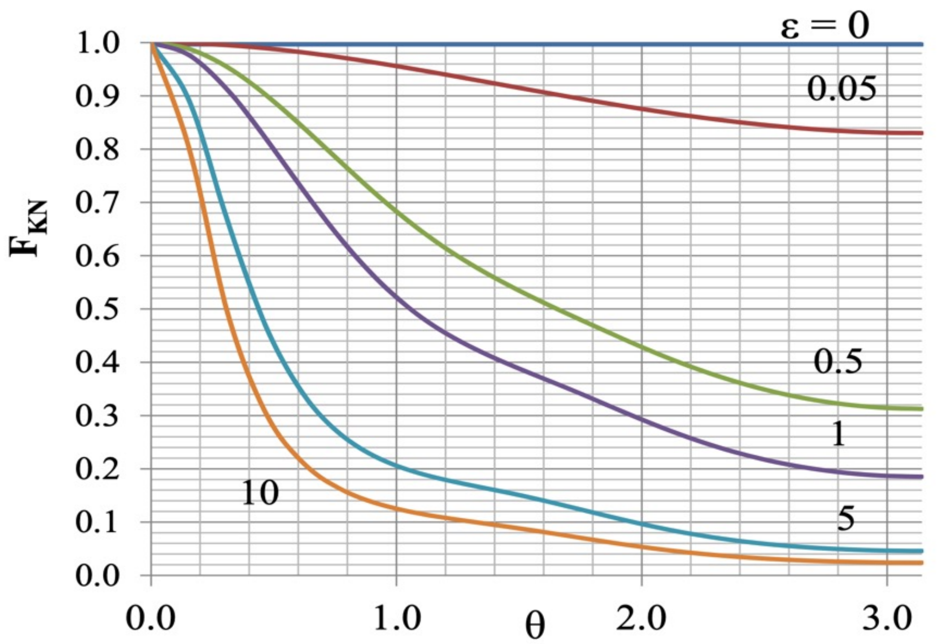


Electron Frame

QED: Klein-Nishina Formula, 1929

$$\left(\frac{d\sigma}{d\Omega}\right)_{KN} = \frac{r_e^2}{2}\left(\frac{v'}{v}\right)^2\left\{\frac{v'}{v}+\frac{v}{v'}-sin^2\theta\right\} = \frac{r_e^2}{2}(1+cos^2\theta)F_{KN}$$

$$F_{KN} = \frac{1}{[1+\varepsilon(1-cos\theta)]^2}\left\{1+\frac{\varepsilon^2(1-cos\theta)^2}{[1+\varepsilon(1-cos\theta)][1+cos^2\theta)}\right\}$$



$$\varepsilon = \frac{hv}{mc^2}$$

$$hv \ll mc^2$$

$$\varepsilon \to 0$$

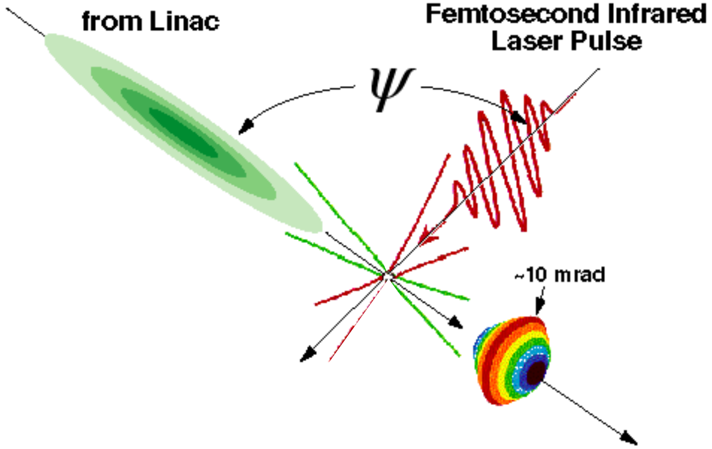
$$F_{KN} = 1$$

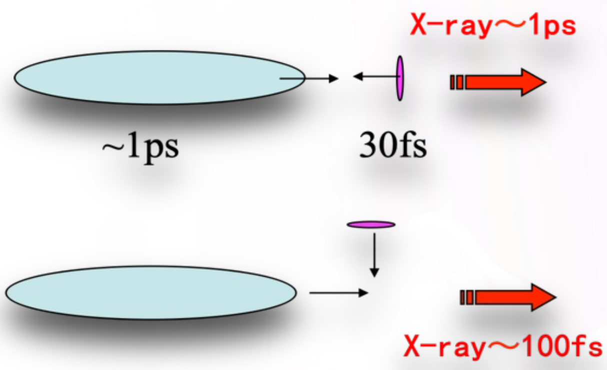
$$\left(\frac{d\sigma}{d\Omega}\right)_{KN} = \frac{r_e^2}{2}(1+cos^2\theta)$$

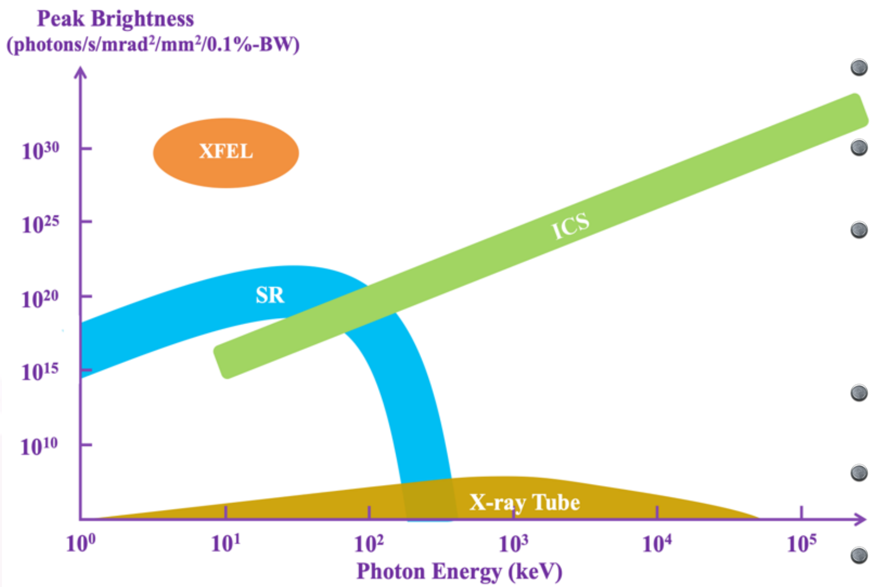
ICS

TS

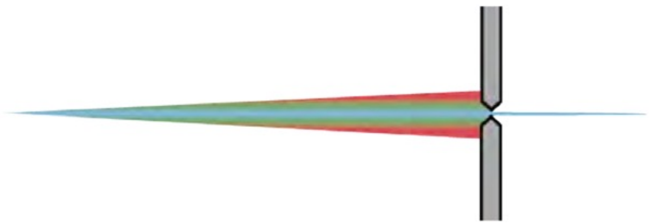
ICS X/γ ray source







- High Energy
- Mono-energetic
- Continuously Tunable
- Micro Focus Spot
- Untra-short Pulse
- Compact

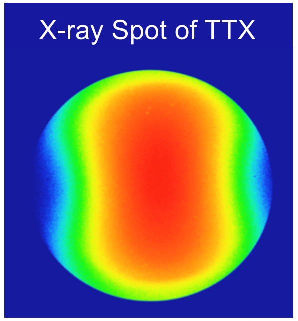


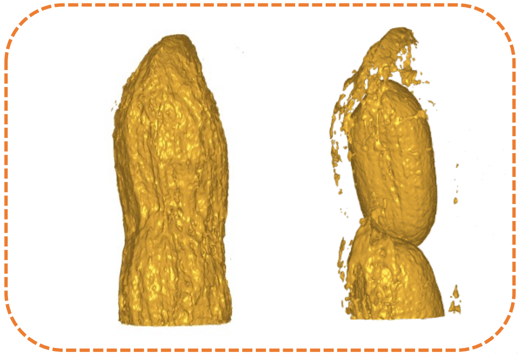
$$E_X = \frac{4\gamma^2}{1 + a_0^2/2 + \gamma^2\theta^2} E_l$$

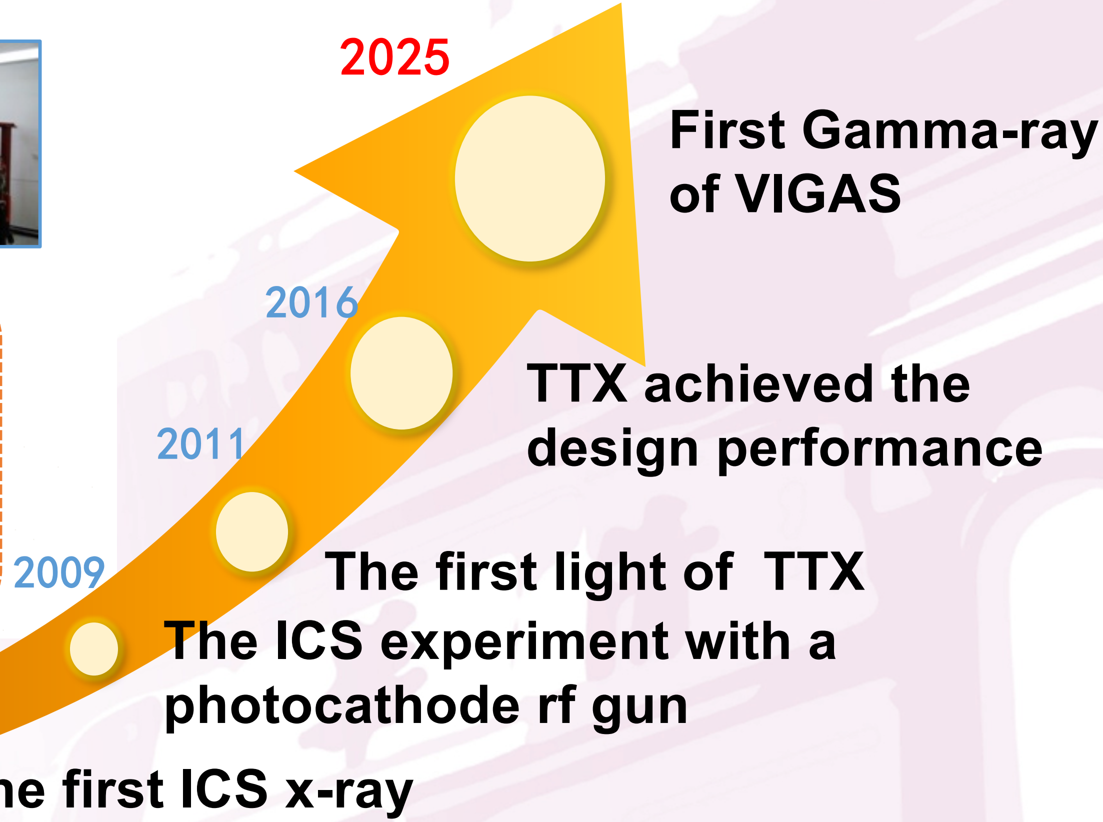
Tsinghua University

The ICS X/γ ray source studies at THU

TTX

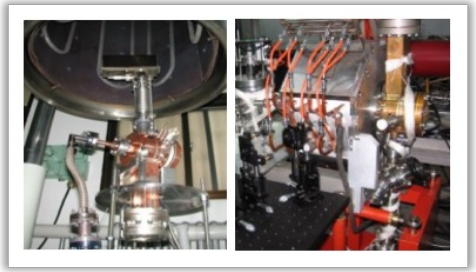


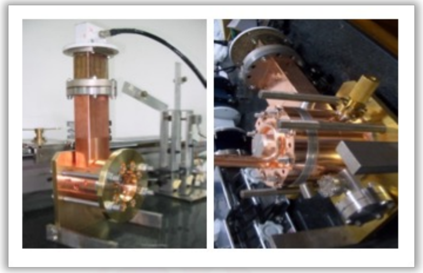


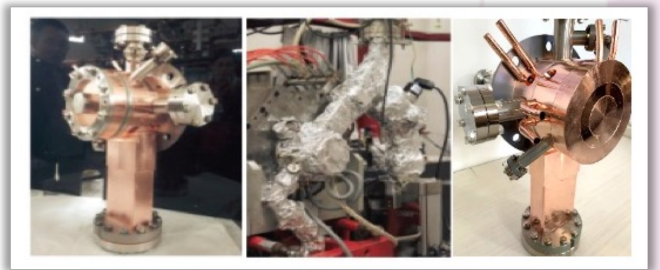


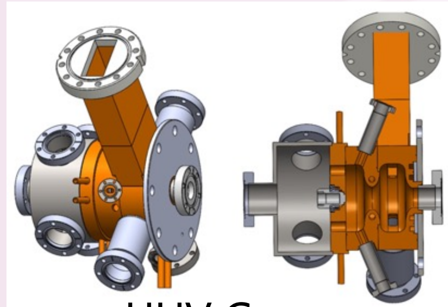
Photocathode RF gun studies at THU

1st Generation	2nd Generation	3rd Generation	4th Generation Semiconductor/ bialkali









UHV Gun

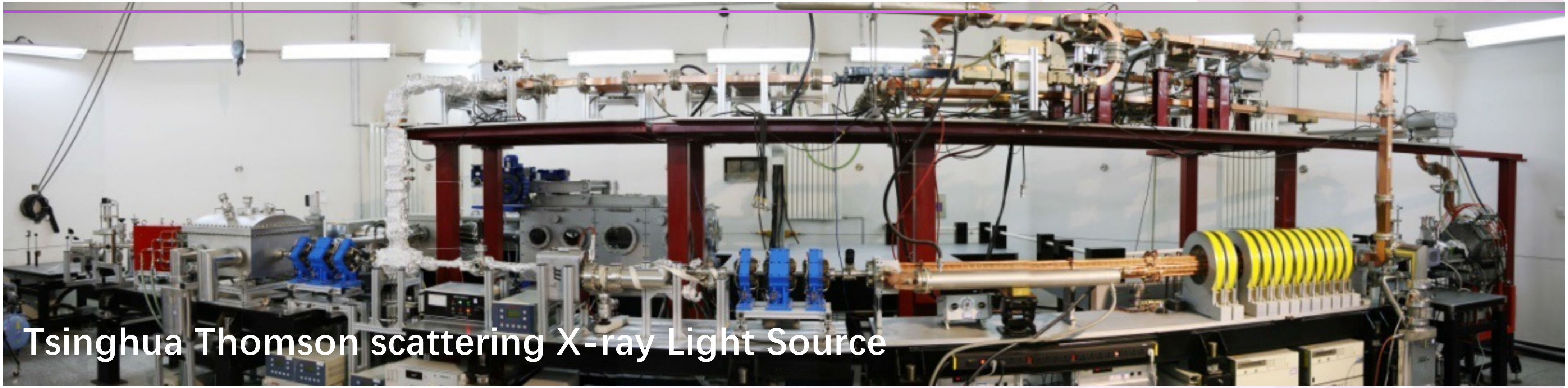
2002-2006 | 2006-2009 | 2009-2018

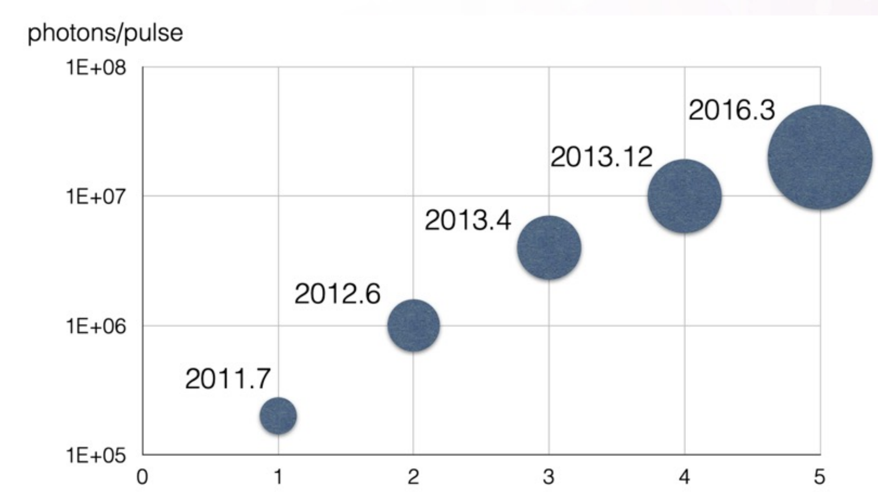
	1st Generation	2nd Generation	3rd Generation
Photocathode	**Copper**	**Copper**	**Copper**
Gradient	~80MV/m	80-100MV/m	100-120MV/m
Brazing	Silver-Copper	Gold-Copper	Gold-Copper
Dark Current	High	Low	Low
$0-\pi$ Mode separation	~3MHz	~3MHz	~15MHz

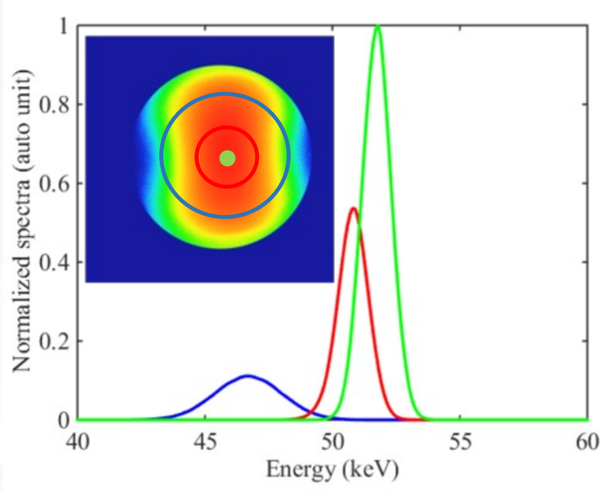
VHF Gun

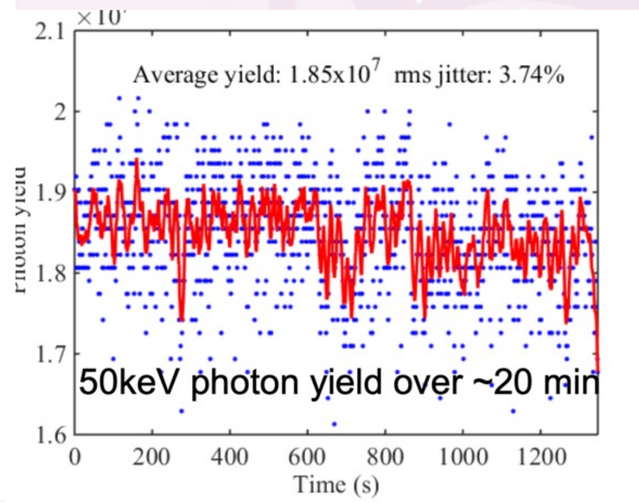
Zheng, Lianmin, et al. *NIMA* 834 (2016): 98-107.

TTX and its performance

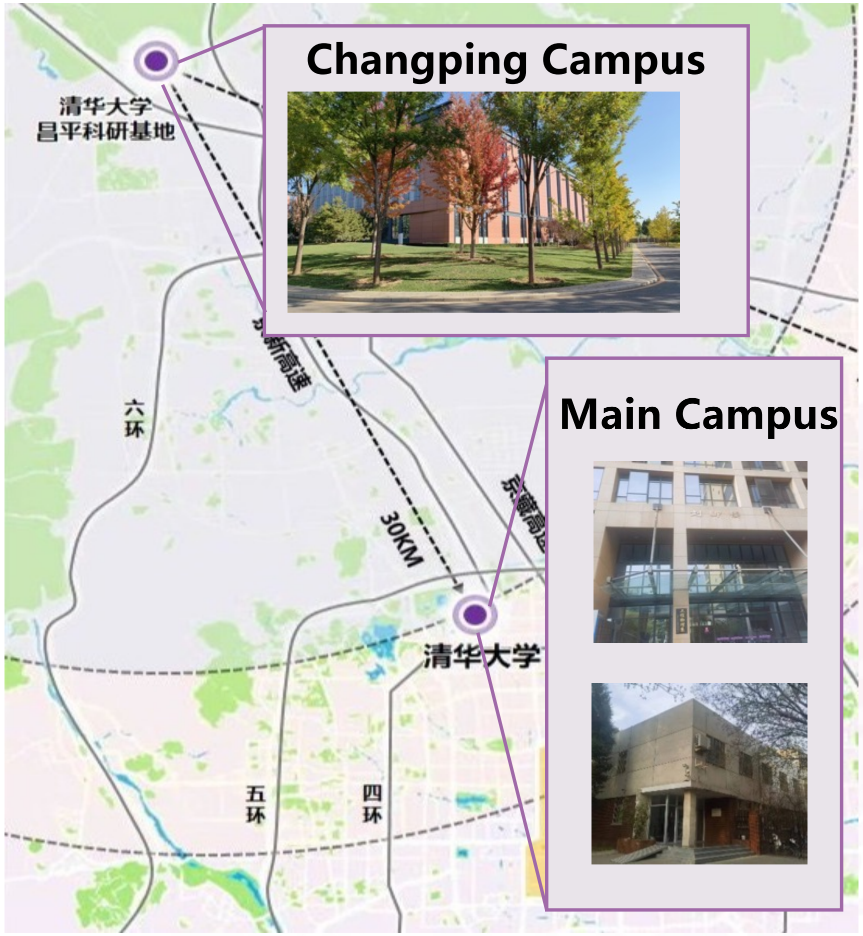






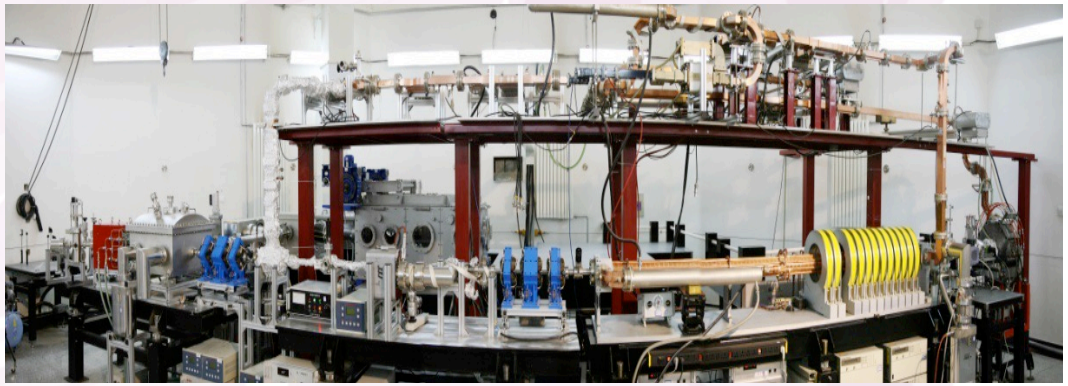


Tsinghua ICS light sources

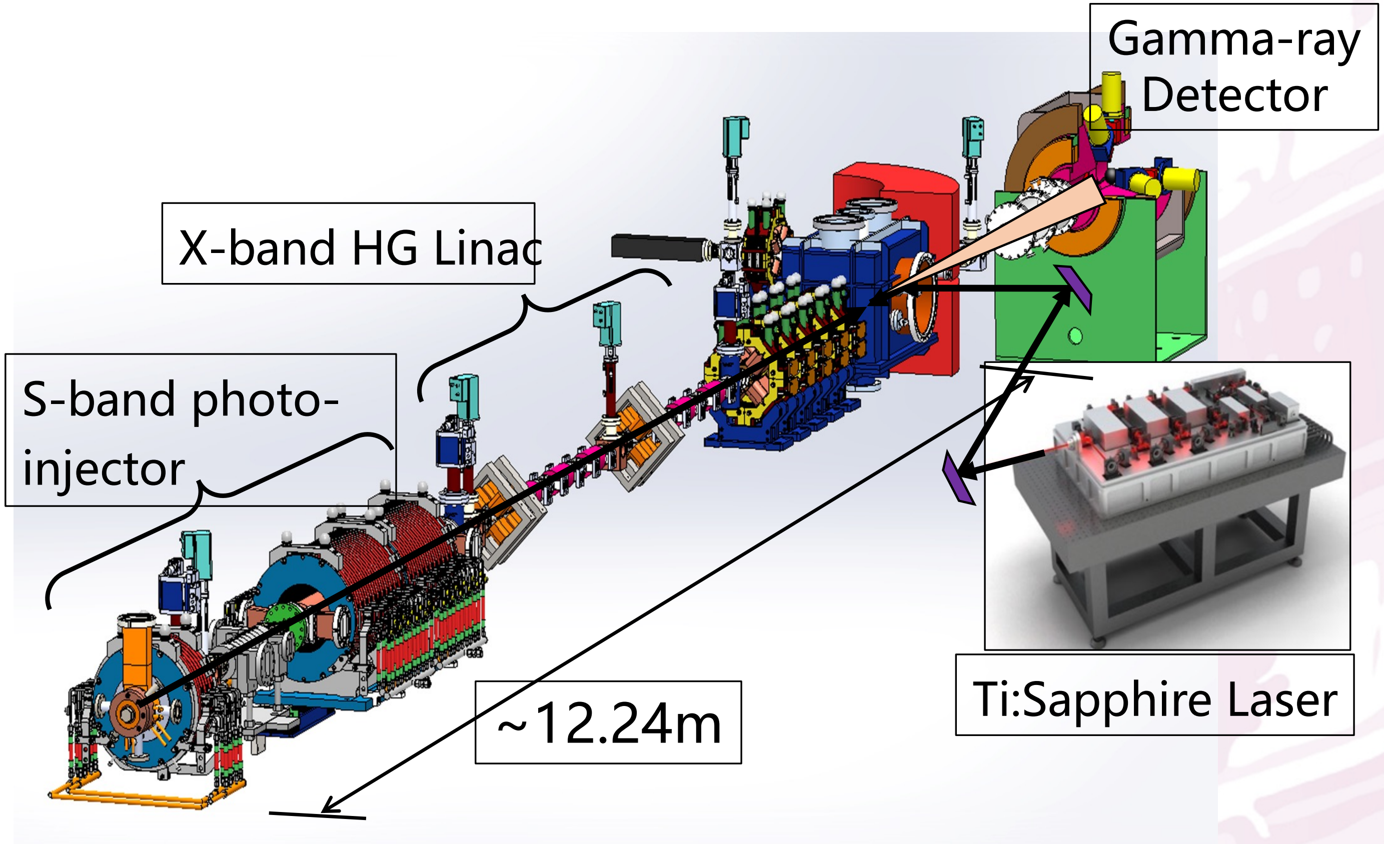


VIGAS (2025)

TTX (2016)

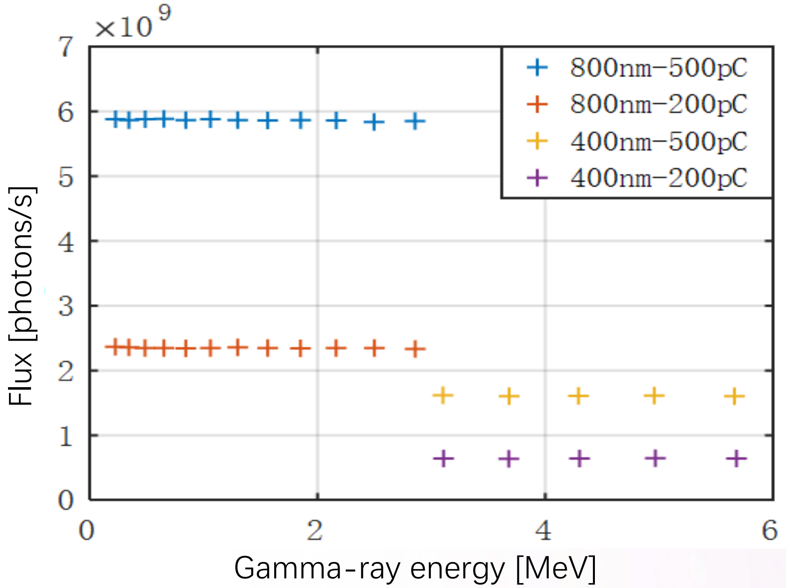


A Very Compact ICS Gamma-ray Source-VIGAS

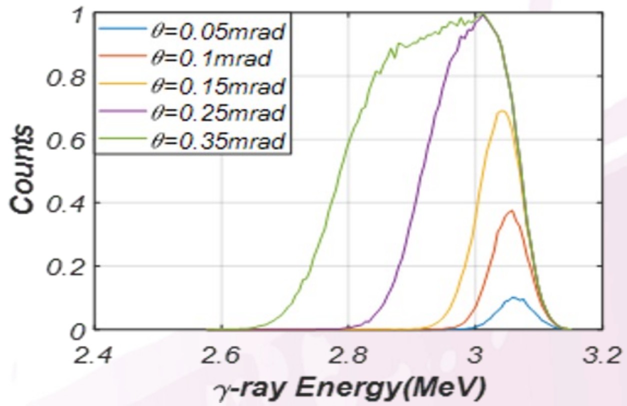


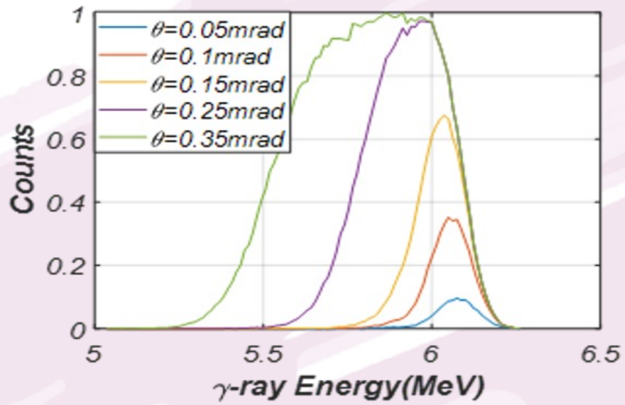
- Photo Energy: 0.2-4.8 MeV
- Photon Flux (photon/s):
  >4x10^8 @0.2-2.4 MeV
  >1x10^8 @2.4-4.8 MeV
- Flux within 1.5% band-width(photon/s):
  >4x10^6 @0.2-2.4 MeV
  >1x10^6 @2.4-4.8 MeV
- Polarization: linear to circular.

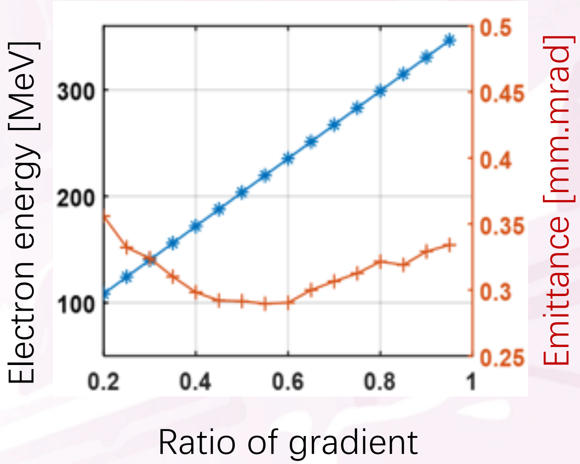
Simulated Performance of VIGAS

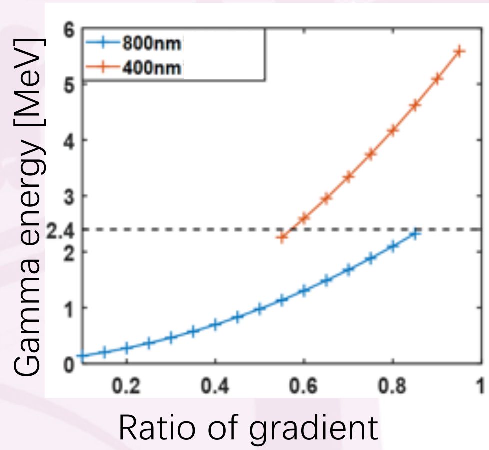


The scattering photon flux for electron bunch charge of 500 nC and 200 nC , colliding with 800 nm and 400 nm laser pulse

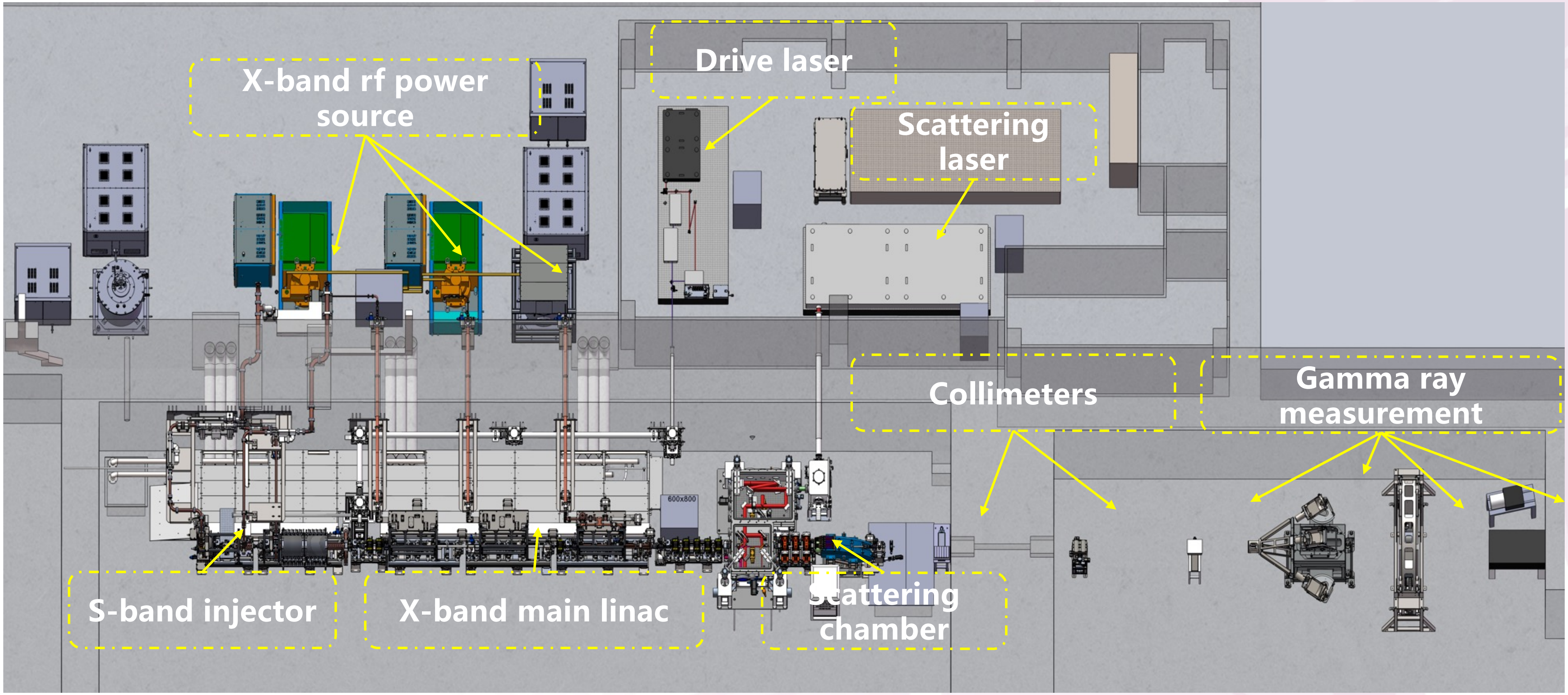








Layout of VIGAS



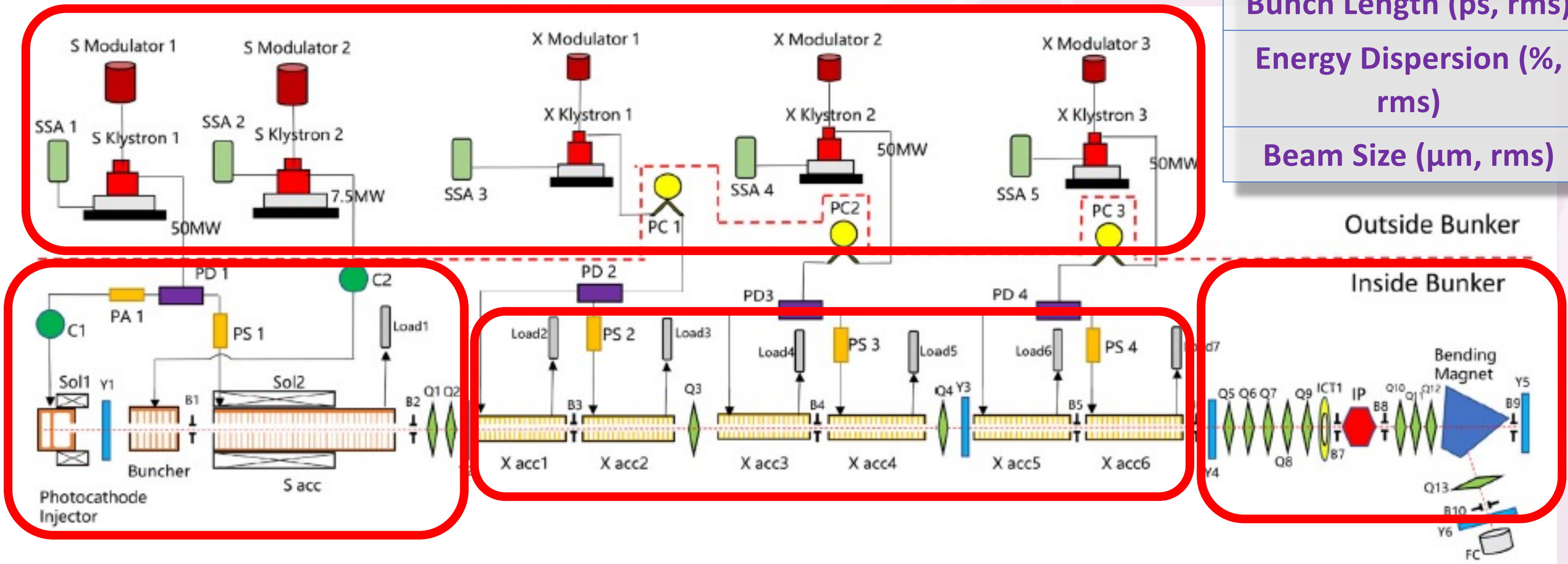
The electron linac of VIGAS

S-Band Injector + X-Band Main Linac → Compact Layout

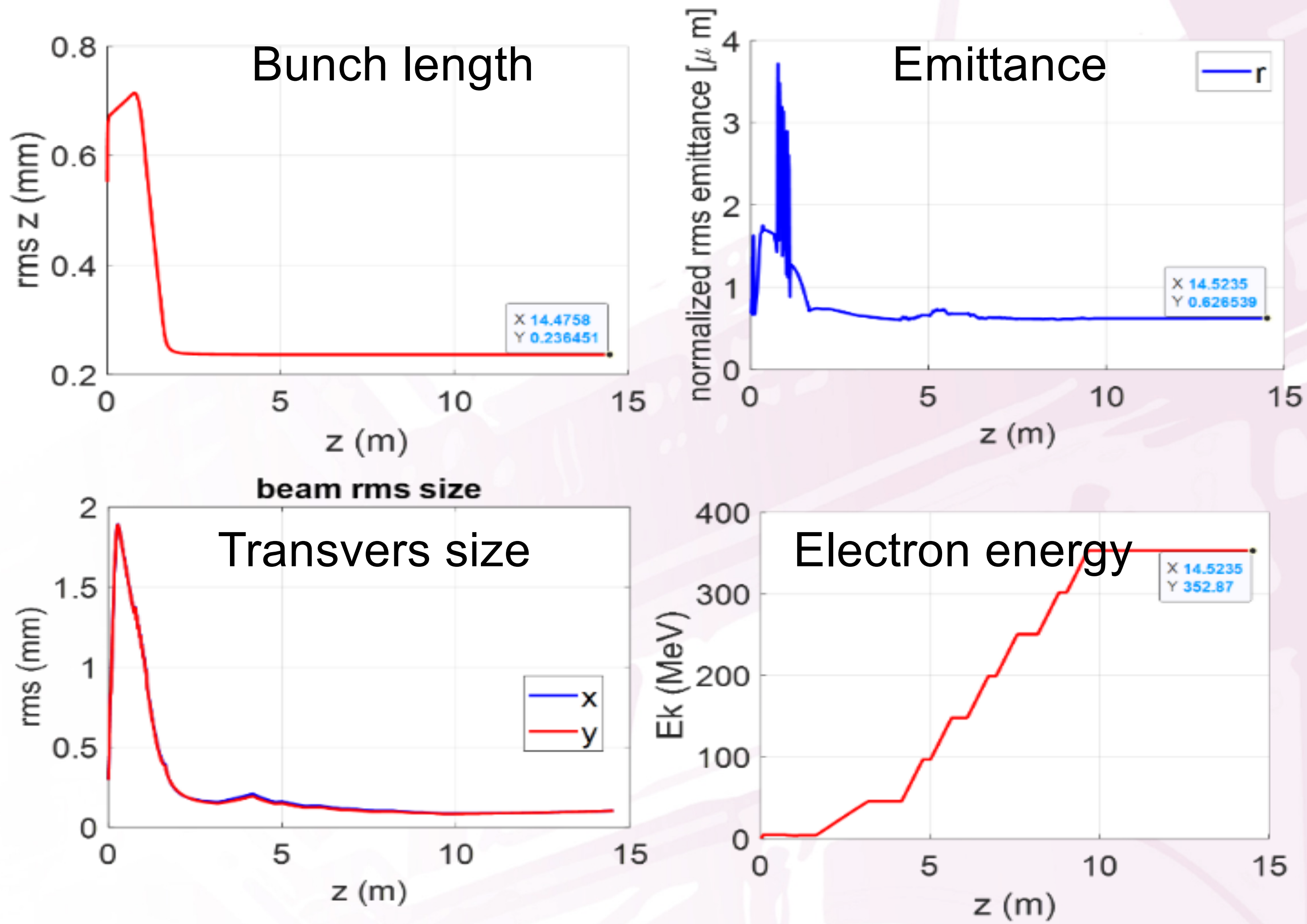
1.5 m x 30 MV/m

0.62 m x 80 MV/m (x6)

Parameters	Value
Beam Energy (MeV)	50-350
Bunch Charge (pC)	>200
Norm. Emittance (mm·mrad)	<0.6
Bunch Length (ps, rms)	<2
Energy Dispersion (%, rms)	<0.3
Beam Size (μm, rms)	<20

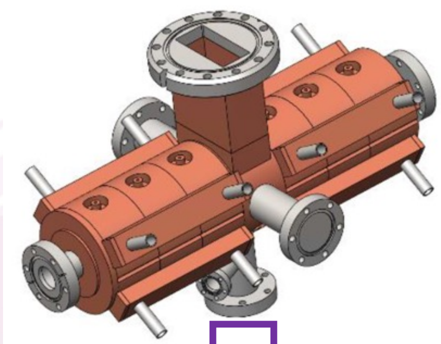


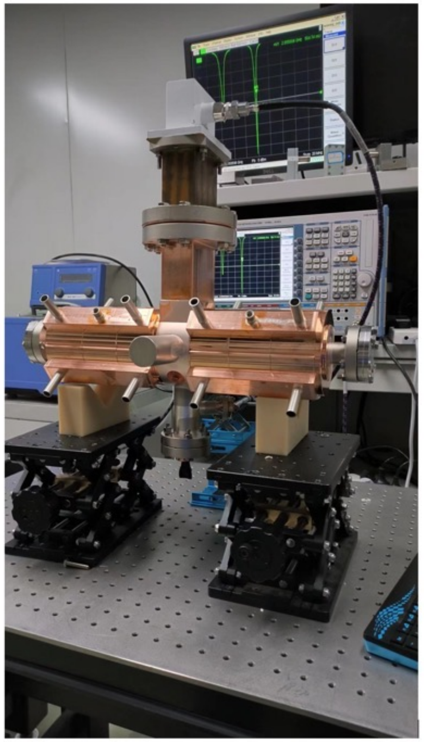
Beam dynamics of VIGAS Linac



S-band injector & buncher

Zheng, Lianmin, et al.
NIMA 834 (2016): 98-107.





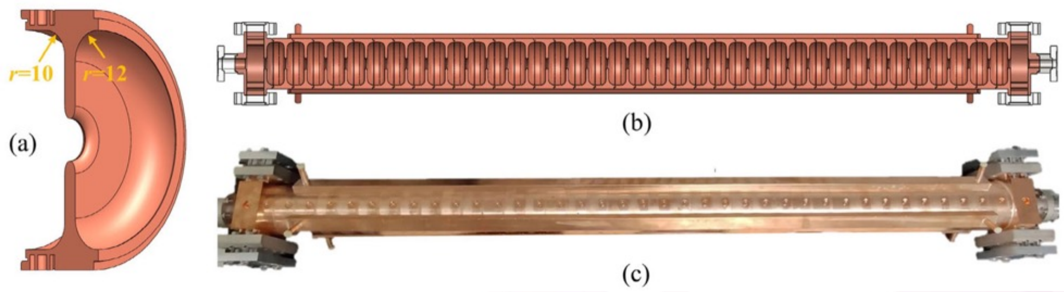
Parameters	Value	Unit
π mode frequency	2856	MHz
Q_0	14000	
Working field strength	100-120	MV/m
Emitting charge	>200	pC
Cathode material	Copper	
Quantum efficiency	3.5-4×10^{-5}	
Emittance	~0.6	um

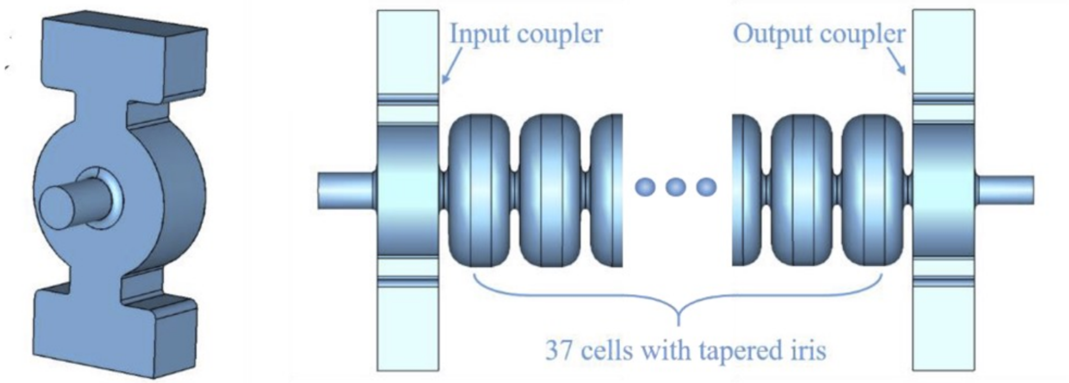
Parameters of S-band injector

Parameters	Value	Unit
π mode frequency	2856	MHz
Q_0	17000	
Coupling coefficient	1.2	
Shunt impedance	50	MΩ/m
Working field strength	23	MV/m

Parameters of S-band 7-cell buncher

S-band TW acc





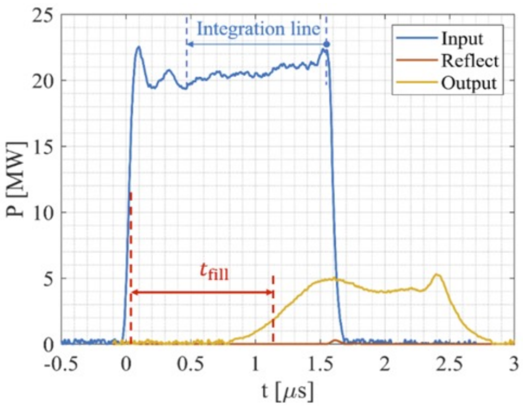
Design Parameters	Value	Unit
Frequency	2856	MHz
Phase advance	$3\pi/4$	
Length	1.535	m
Cell number	39	
Iris radius	10.22-8.13	mm
Iris thickness	5.7	mm
Iris elliptical ratio	1.8	
Filling time	1050	ns
Group velocity	0.72-0.30	%/c
Shunt Impedance	66-72	MΩ/m
Average Gradient	25.7@21MW	MV/m

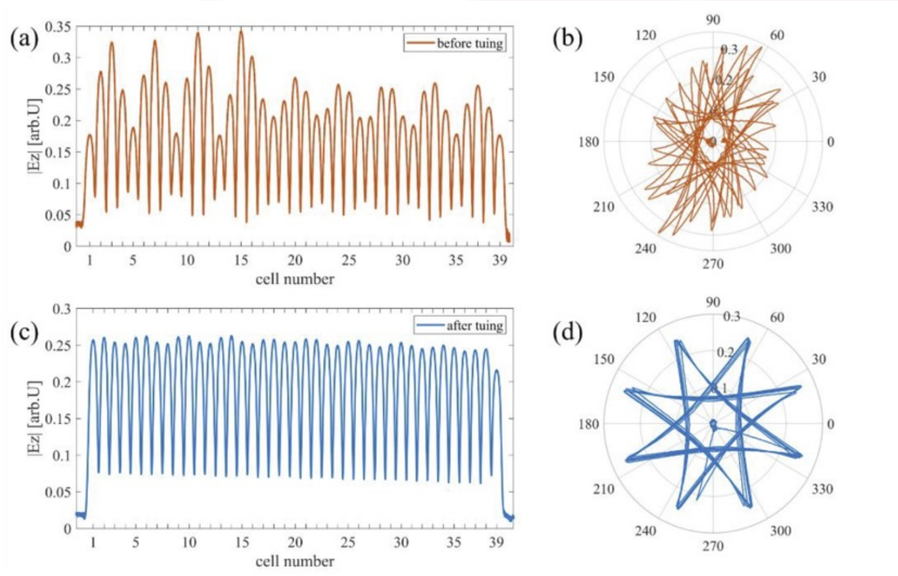
Lin, Xian-Cai, et al. *Nuclear Science and Techniques* 33.11 (2022): 147.

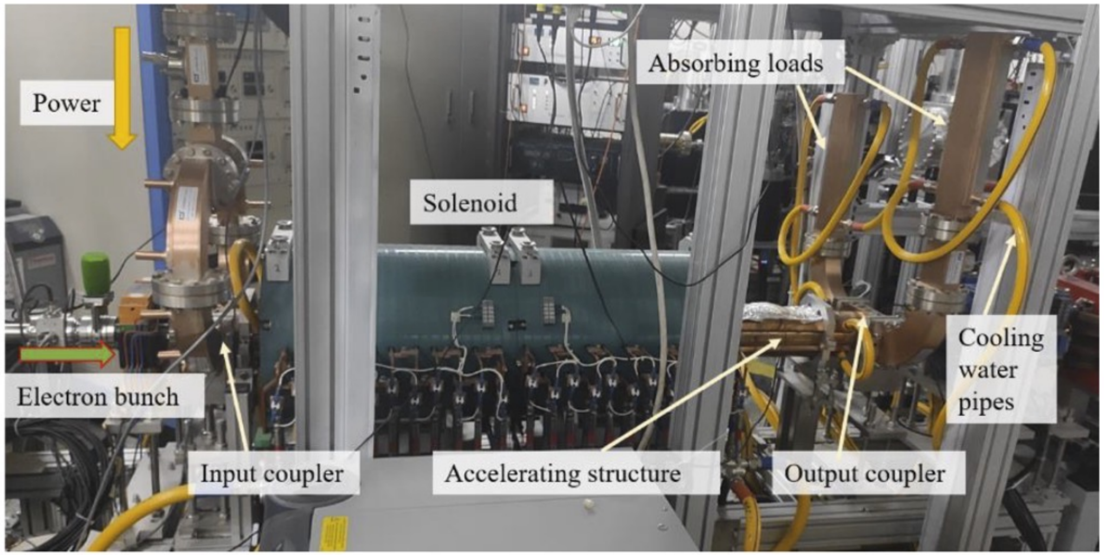
S-band TW acc

High power tested

- Conditioning:
  - 120 hours
  - 4 million pulses

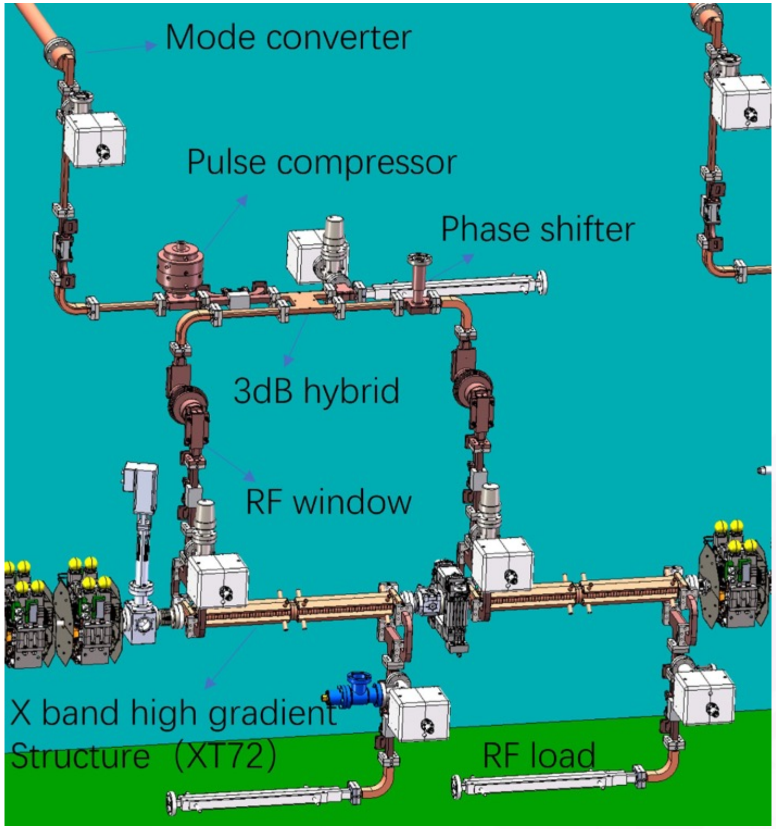






Parameters	Measurement	Simulation
Frequency	2.856 GHz	2.856 GHz
Phase advance	134.97°	135°
Gradient @20.7MW	24.2 MV/m	25.7 MV/m
Filling time	1090 ns	1050 ns

X-band waveguide system

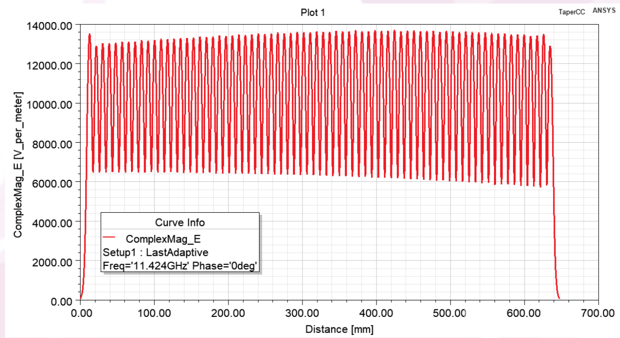


- One klystron
  - 50MW, 1.5us
- One pulse compressor (SLED I type)
- Maximum rf loss due to waveguides and rf components from klystron to Xacc is about 0.9dB
- Peak power at Xacc input is about 91 MW if power compressor gives gain factor as 4.5
- Two X band high gradient structures
  - Average gradient ≥ 80 MV/m
  - Energy gain per structure > 50 MeV
  - Filling time < 150ns

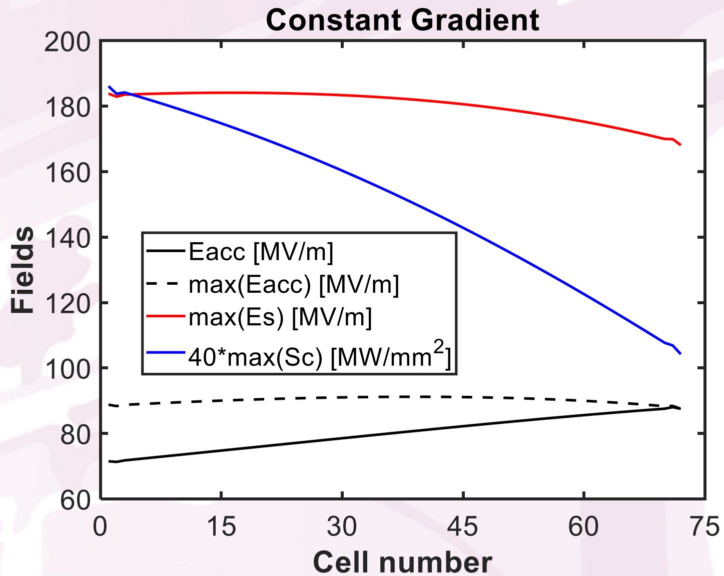
Deng, H., Zha, H., Shi, J. *et al.*"X-band high-gradient main linear accelerator for compact inverse-compton light source". *Eur. Phys. J. Spec. Top.* **234**, 8125–8136 (2026). https://doi.org/10.1140/epjs/s11734-025-01826-2;

X-band TW linac

- We switch to CG scheme with maximum surface field 20% lower than CI

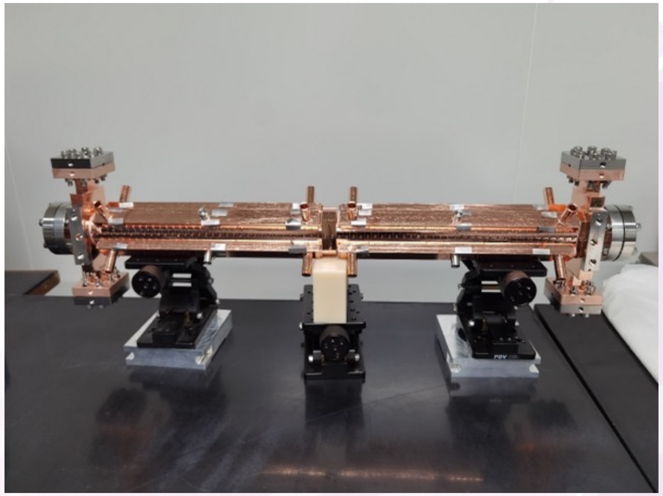


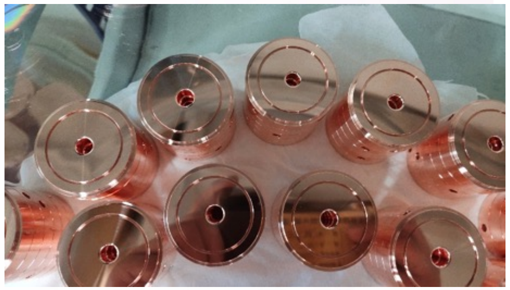
Parameters	CI	CG
Iris aperture a [mm]	3.5	3.92 ~ 3.12
Iris thickness d [mm]	1.8	1.8
Shunt imp. R [MΩ/m]	101	93 ~ 109
Group velocity v_g/c	2.20%	3.22% ~ 1.46%
Quality factor Q	6990	7020 ~6970
Filling time T_f [ns]	95	97
E_s [MV/m]	224	185
S_c [MW/mm^2]	5.65	4.50
β of pulse compressor	3.5	3.5
Pin @80MV/m with pc [MW]	81.3	80.1

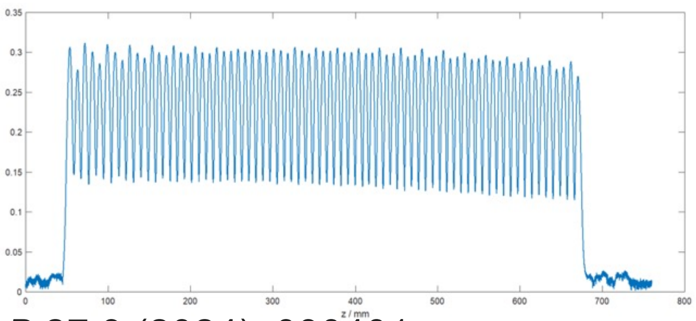


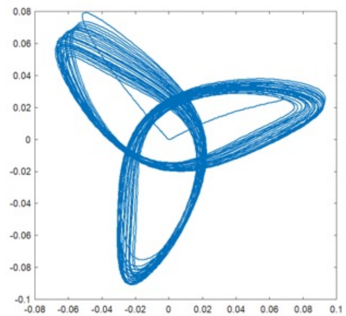
X-band TW linac

- XT72 (X-band Tapered structure with 72 cells)
- COST: CG 20% higher than CI
- Same Tuning procedure
- High power conditioning started from Oct. 20, 2023



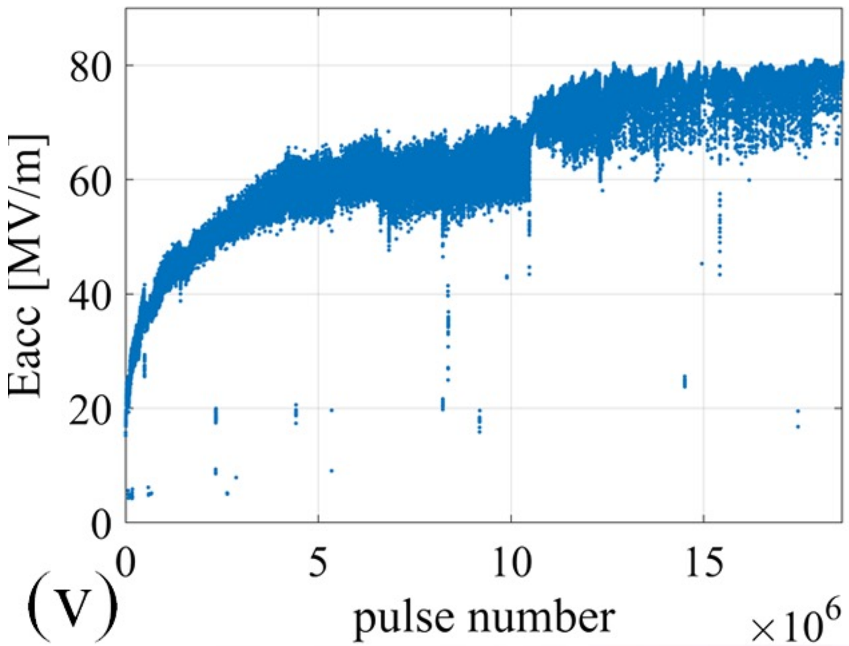






Gao, Qiang, et al. *PRAB* 27.9 (2024): 090401.

High-gradient performance of XT72 #1



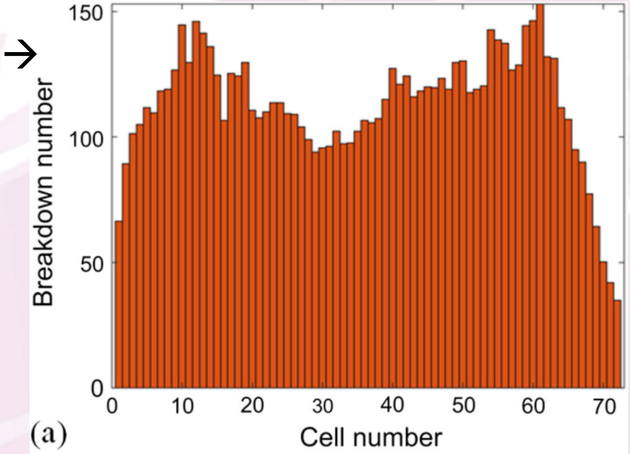
Gradient @ 80MV/m

BDR rate 1e-4

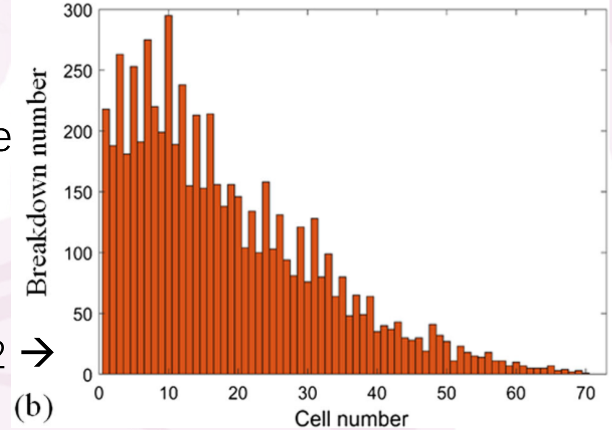
Breakdown event
evenly distributed
Compared with XC72 (CI)

XT72 has better performance

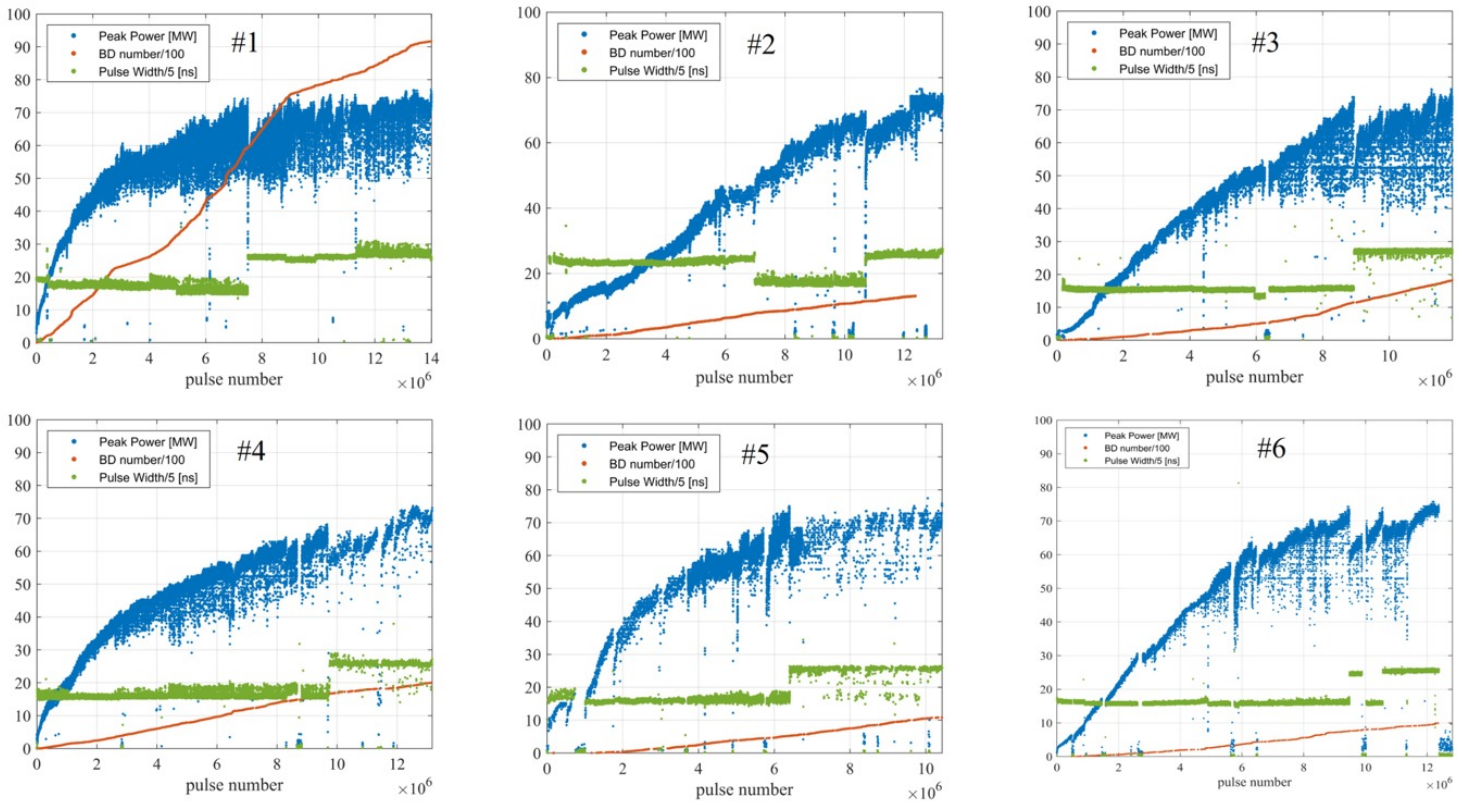
BD in XT72 →



BD in XC72 →



Conditioning results



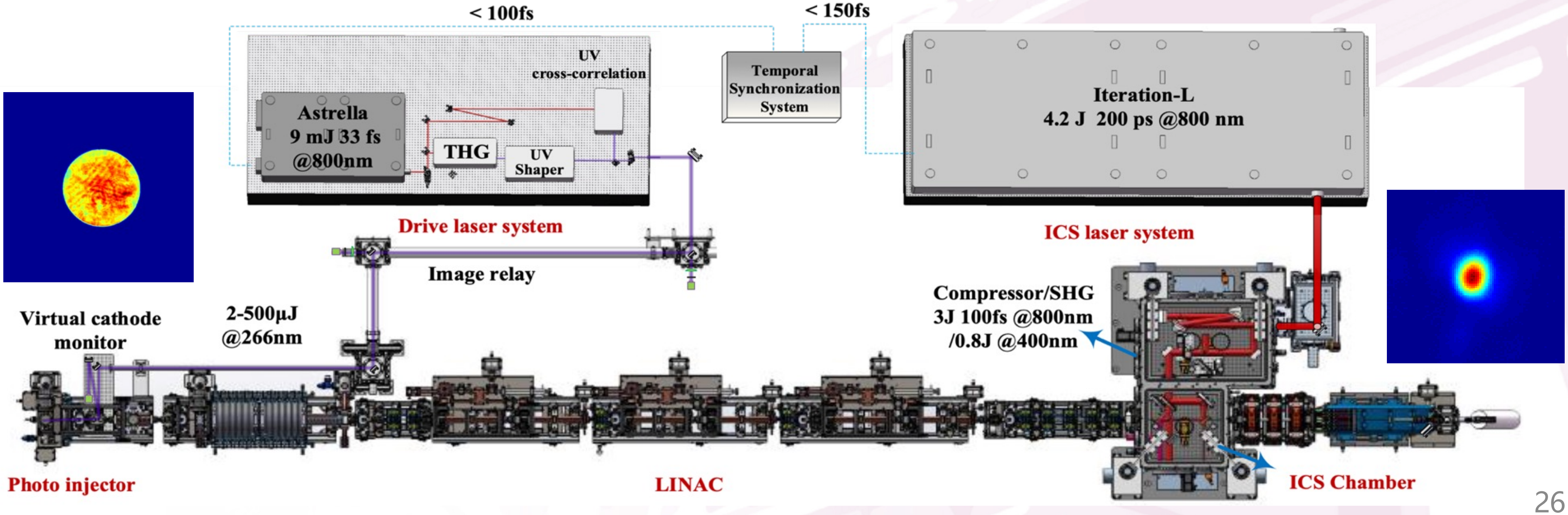
- Blue line: Input power/MW
- Green line: Pulse Width/5 ns
- Red line: BD number/100

- All 6 accelerating structures were conditioned
- To reach 80MV/m, ~15 million pulses, About 100 hours of conditioning at 40Hz

The laser systems of VIGAS

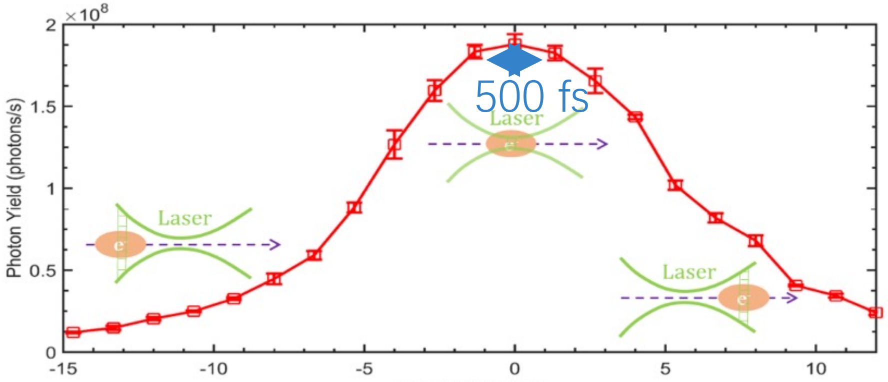
266nm drive laser for photocathode rf gun

800/400 nm scattering laser

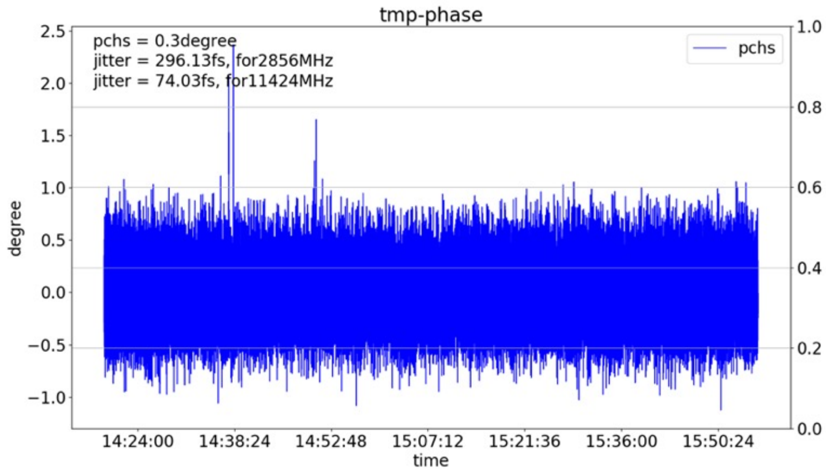


Tian, Qi-Li, et al. "Laser system of the very compact inverse Compton scattering γ-ray source at Tsinghua University". *Nuclear Science and Techniques* 37.10 (2026): 208.

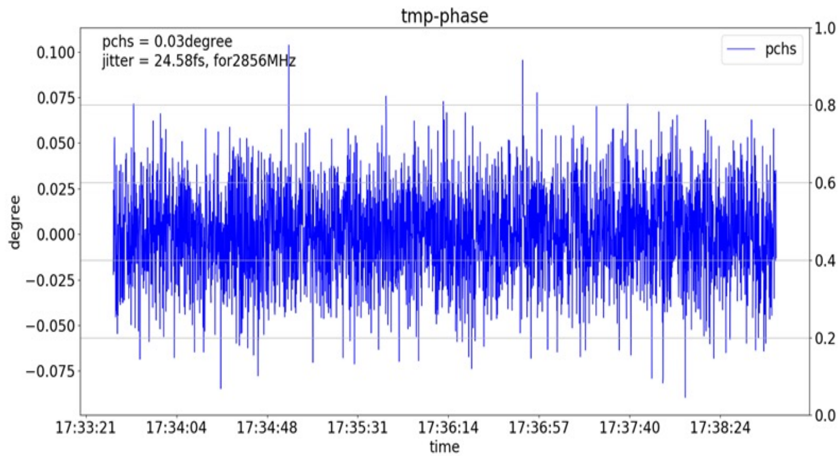
Synchronization and LLRF



According to the experimental results of TTX , the time jitter of the arrival times of electron bunch and laser pulse at the IP need to be less than 500fs.

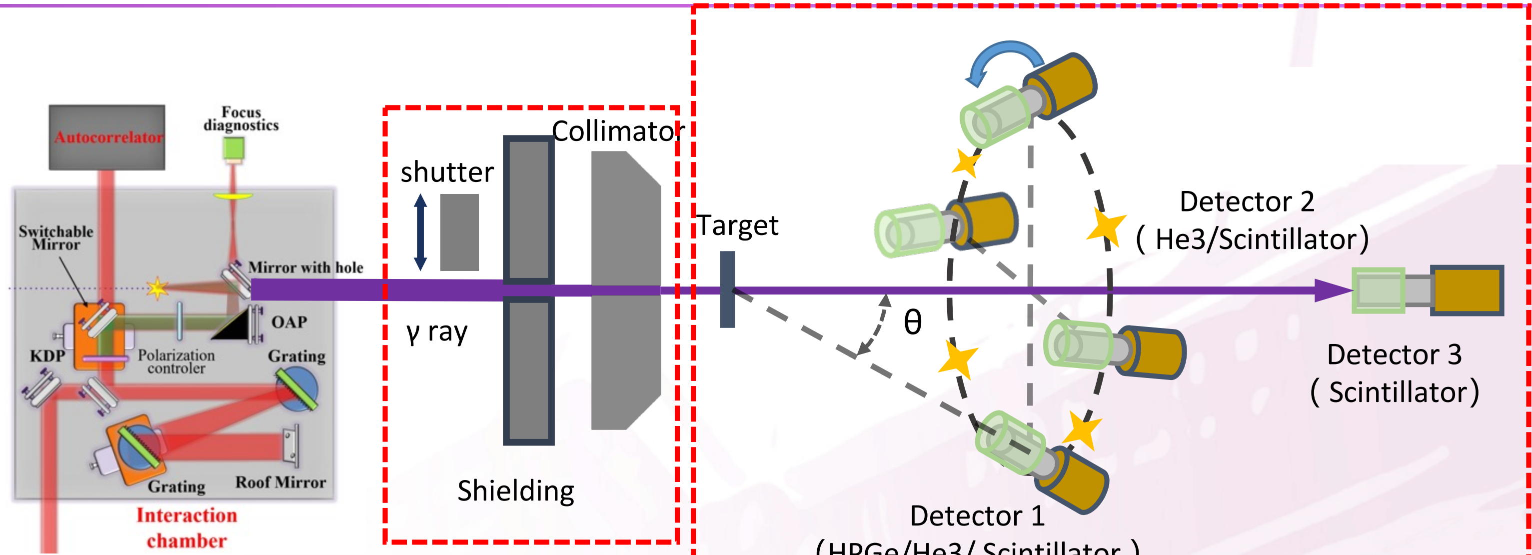


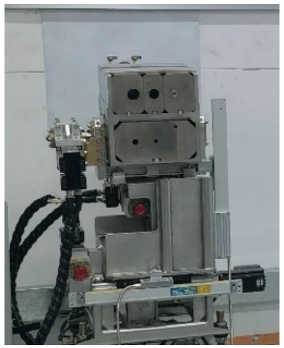
The jitter of LLRF of x-band rf system is less than 75fs

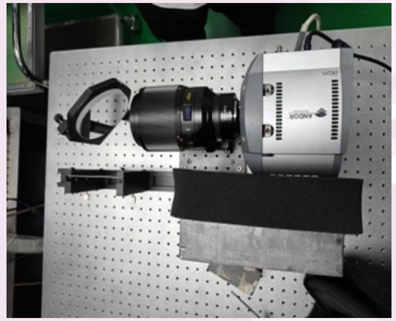


The jitter between drive laser pulse and s-band rf is less than 25fs

The gamma-ray detection system of VIGAS







Collimator

- ✓ Shutter
- ✓ Collimation

Gamma ray detection

- ✓ Energy detection
- ✓ Photon flux detection
- ✓ Polarization detection

Imaging

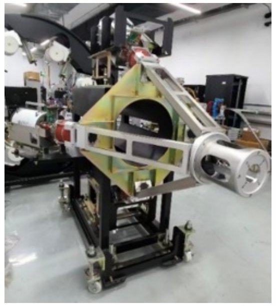
- ✓ High Resolution
- ✓ NRF

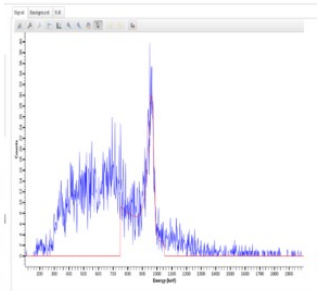
Xuanqi Zhang, Yulan Li, Zhi Zhang et al., "A Compton scattering-d energy spectrum measurement method for high flux gamma-ray of VIGAS facility", *Nucl. Instrum. Methods Phys. Res., Sect. A* **1085**, 171278 (2026).

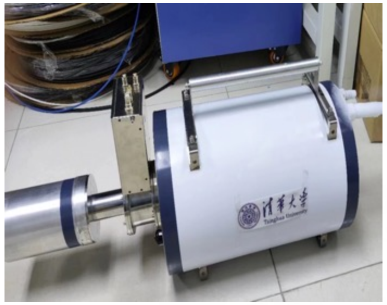
The energy, spectrum, flux and polarization measurement

Energy Spectrum:

- Compton Scattering method
- High Purity Germanium Detector (HPGe)







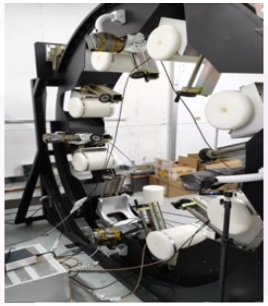
1.3 MeV

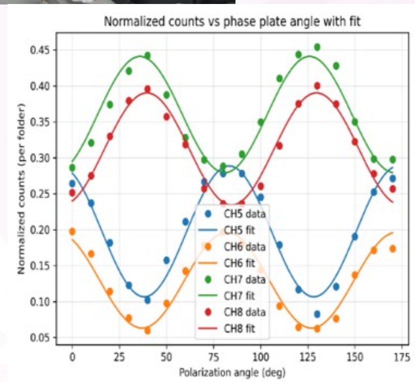
1.33%

Bandwidth

Polarization:

- Compton Scattering method
- NaI detector with change of laser polarization

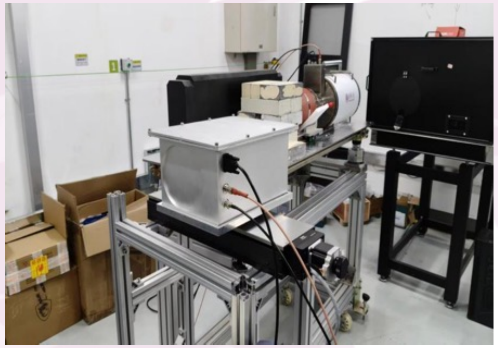




1.3 MeV Polarization Curve

Flux:

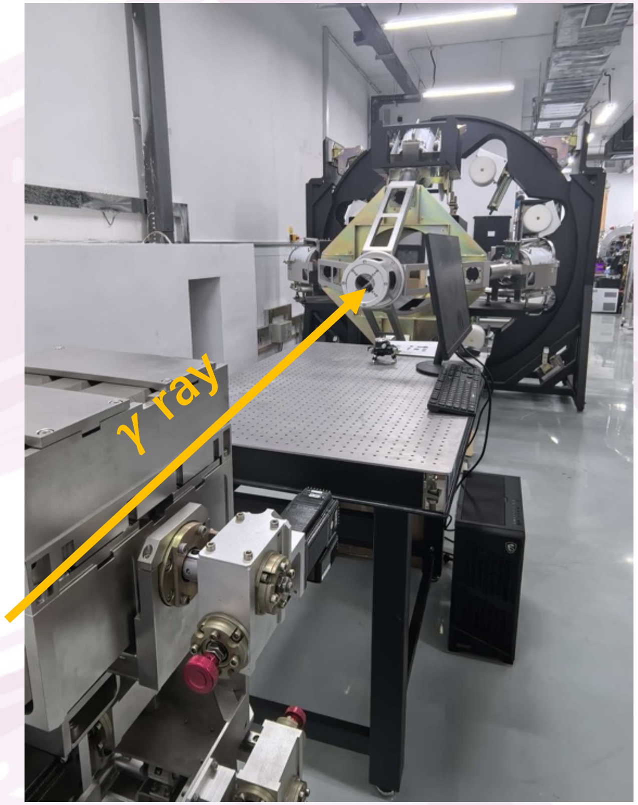
- Large NaI detector
- Flux is proportional to counts



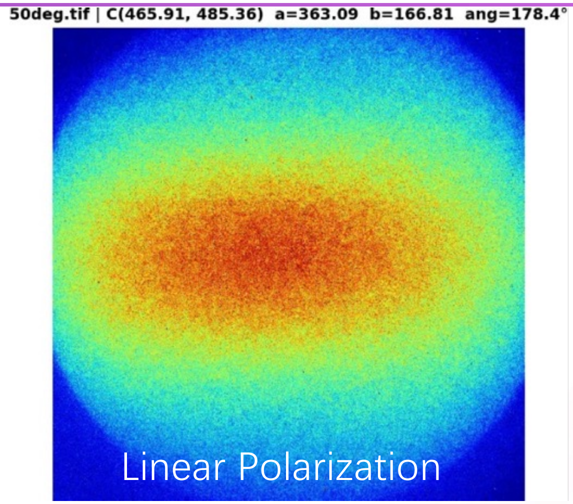
VIGAS got its 1st light on July 14, 2025 !

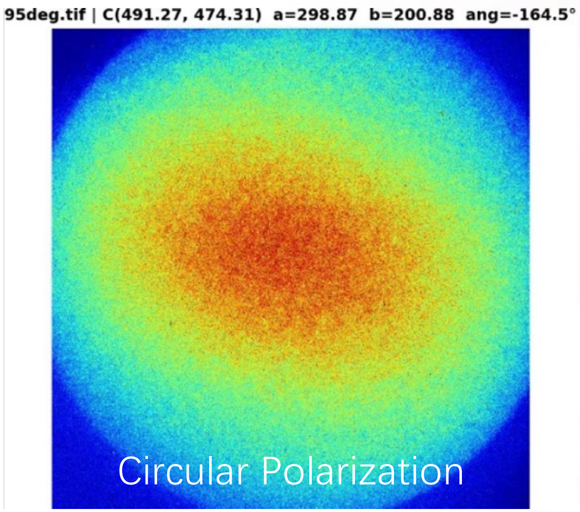
350MeV electron linac

γ-ray measurement



The performance of VIGAS

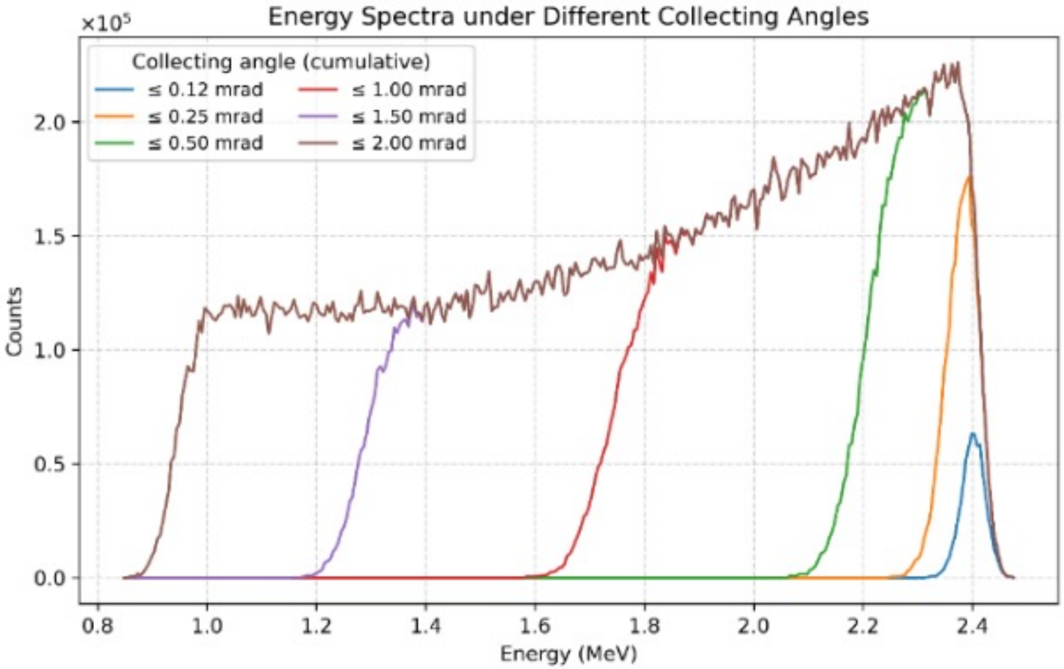




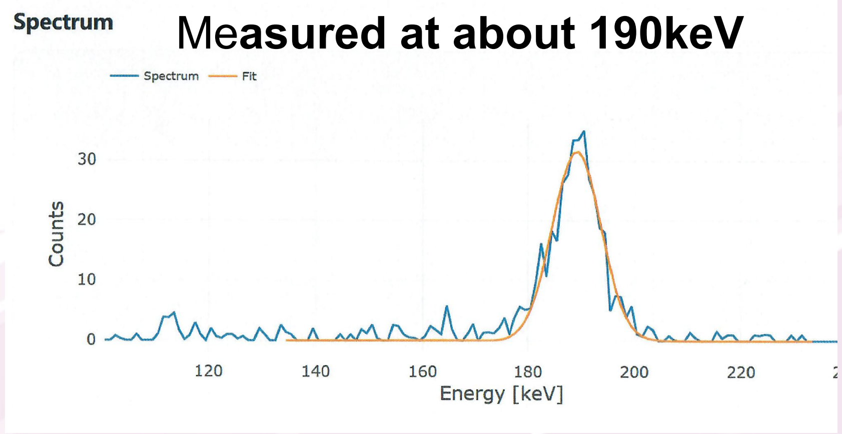
Parameters	Laser wavelength	Measured results
γ photon energy	800 nm	0.198 ±0.01 (MeV)
		1.35 ±0.01 (MeV)
	400 nm	2.67 +0.03 -0.05 (MeV)
		3.32±0.02 (MeV)
		5.05 +0.03 -0.02 (MeV)
Spectrum width	800 nm	1.21% @1.3MeV
	400 nm	1.36% @2.6MeV
1.5% bandwidth flux	800 nm	1.66x10^7 (ph/s)@1.3MeV
	400 nm	4.10x10^6 (ph/s) @2.6 MeV
Total flux	800 nm	9.19x10^8 (ph/s)@1.3MeV
	400 nm	2.28x10^8 (ph/s)@2.6MeV
Polarization	Tunable continuously from linear to circular	

清華大學 Tsinghua University

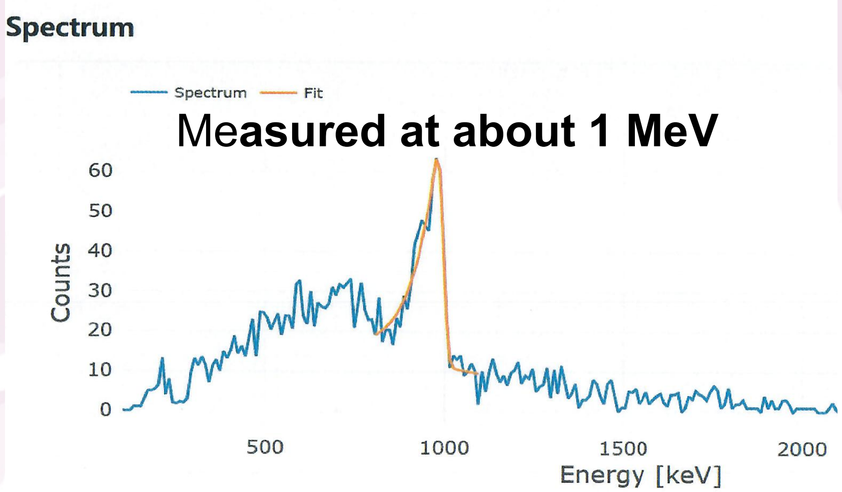
Spectra of VIGAS gamma ray



Simulation with CAIN

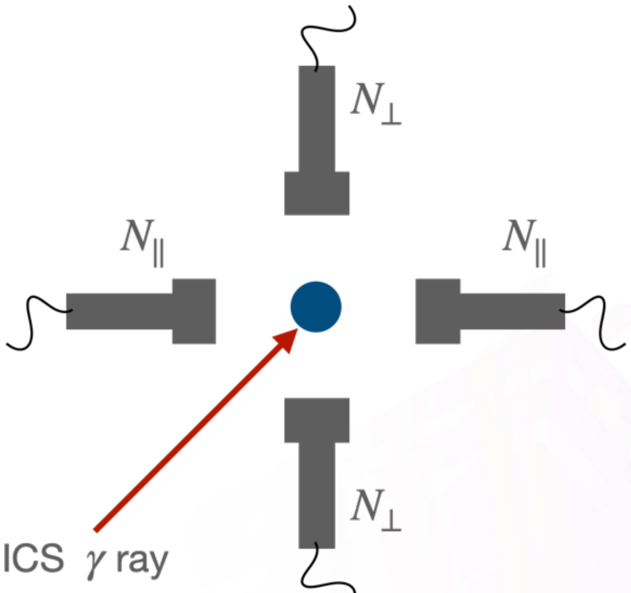


Measured at about 190keV



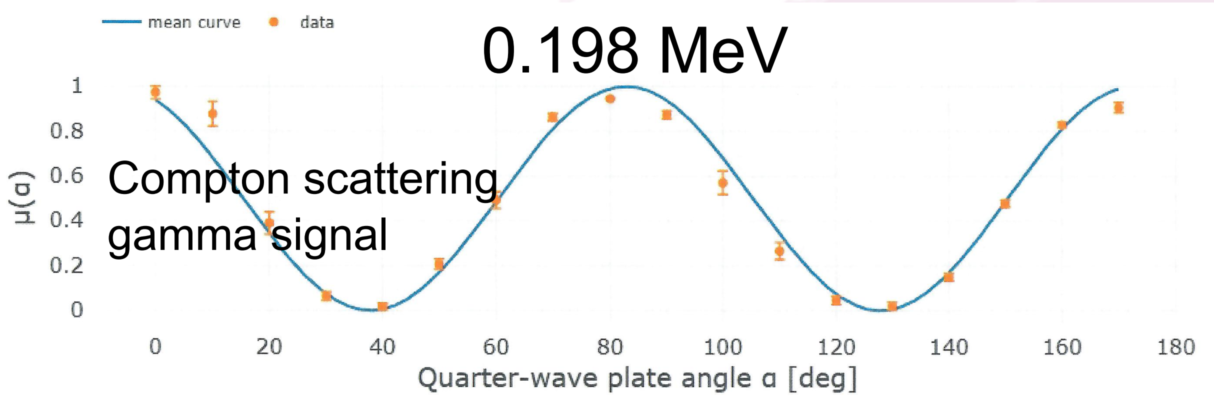
Measured at about 1 MeV

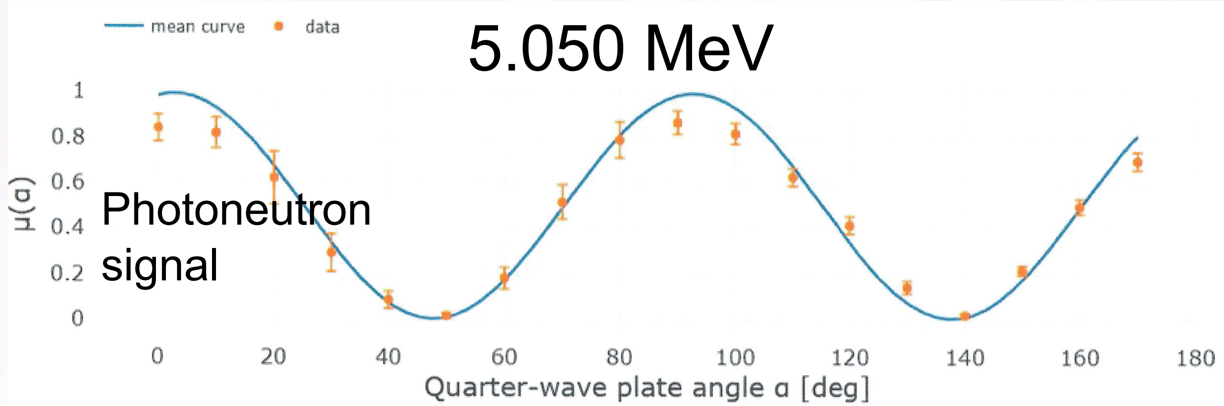
Polarization



$$N(\phi) = N_0[1 + u\cos(2\phi)]$$

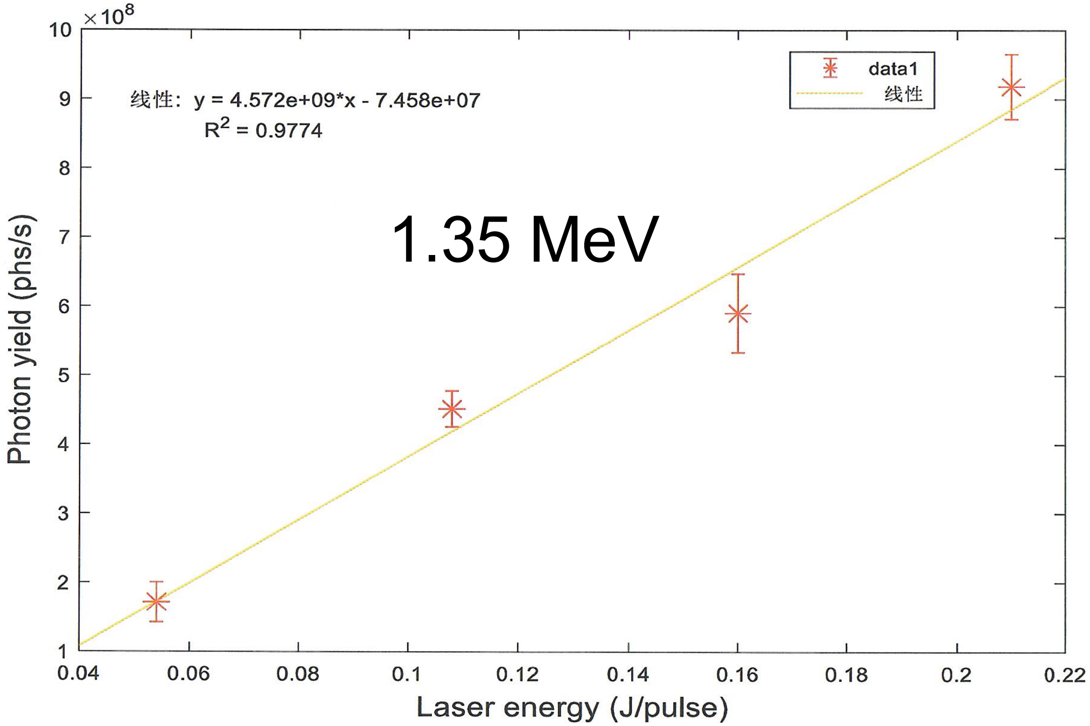
$$u = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}$$

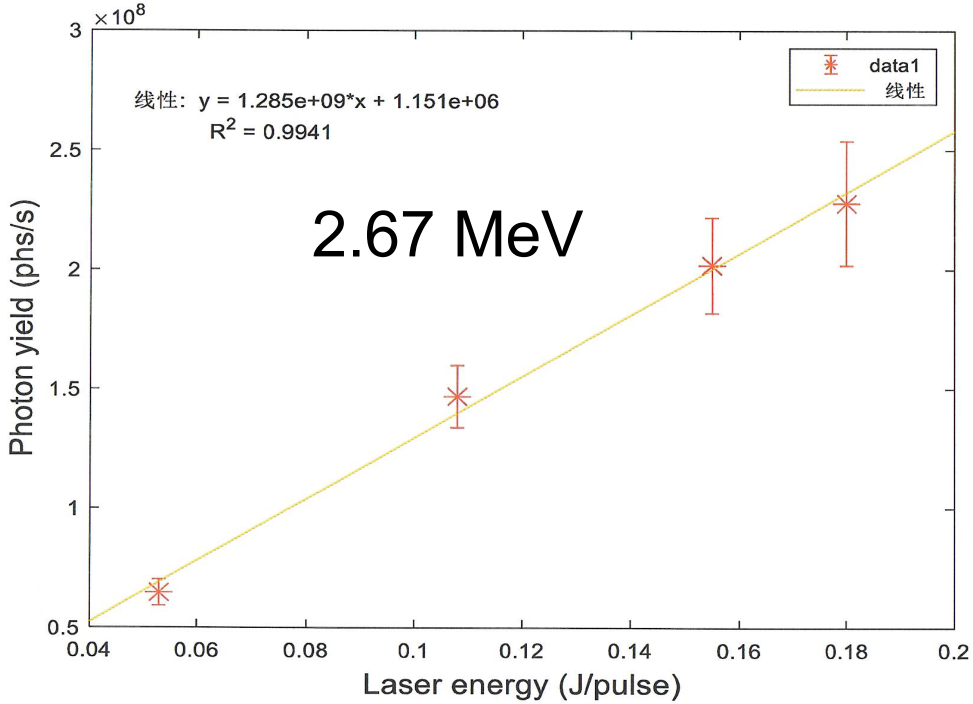




Hongze Zhang, Zhijun Chi, Yingchao Du et al., "Monte Carlo simulation code for polarized inverse Compton scattering sources", *Phys. Rev. Accel. Beams* **27(2024)**, 103401

Gamma-ray total flux





The gamma ray total flux is proportional to the energy of the scattering laser pulse.

Summary

- Inverse Compton Scattering x/γ-ray sources have very good properties for different applications, mono-energetic , tunable energy, small focus spot, polarized and compact…
- VIGAS is developed with 0.2-4.8MeV photon energy within 12 meters scale, adopting s-band injector and 6 HG x-band TW waveguides.
- VIGAS is now ready for users of advanced x/ γ ray imaging, nuclear physics, NRF and other fundamental researches with MeV photons.

Thanks for your attention!