A Compact Gamma Ray Source Based on ICS

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Outline

- Brief Introduction to ICS gamma-ray sources
- Overview of the ICS gamma-ray sources in THU
- **V**ery compact **I**CS **GA**mma-ray **S**ource (VIGAS)
  - Motivation
  - Physics design
  - S-band photo-injector
  - X-band linac
- Summary

Inverse Compton Scattering X-ray Source

- Frequency of the Scattering Photon

$$\omega_x = \frac{2\gamma^2(1-\cos\psi)}{1+a_0^2/2}\omega_0$$

- Differential cross-section

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

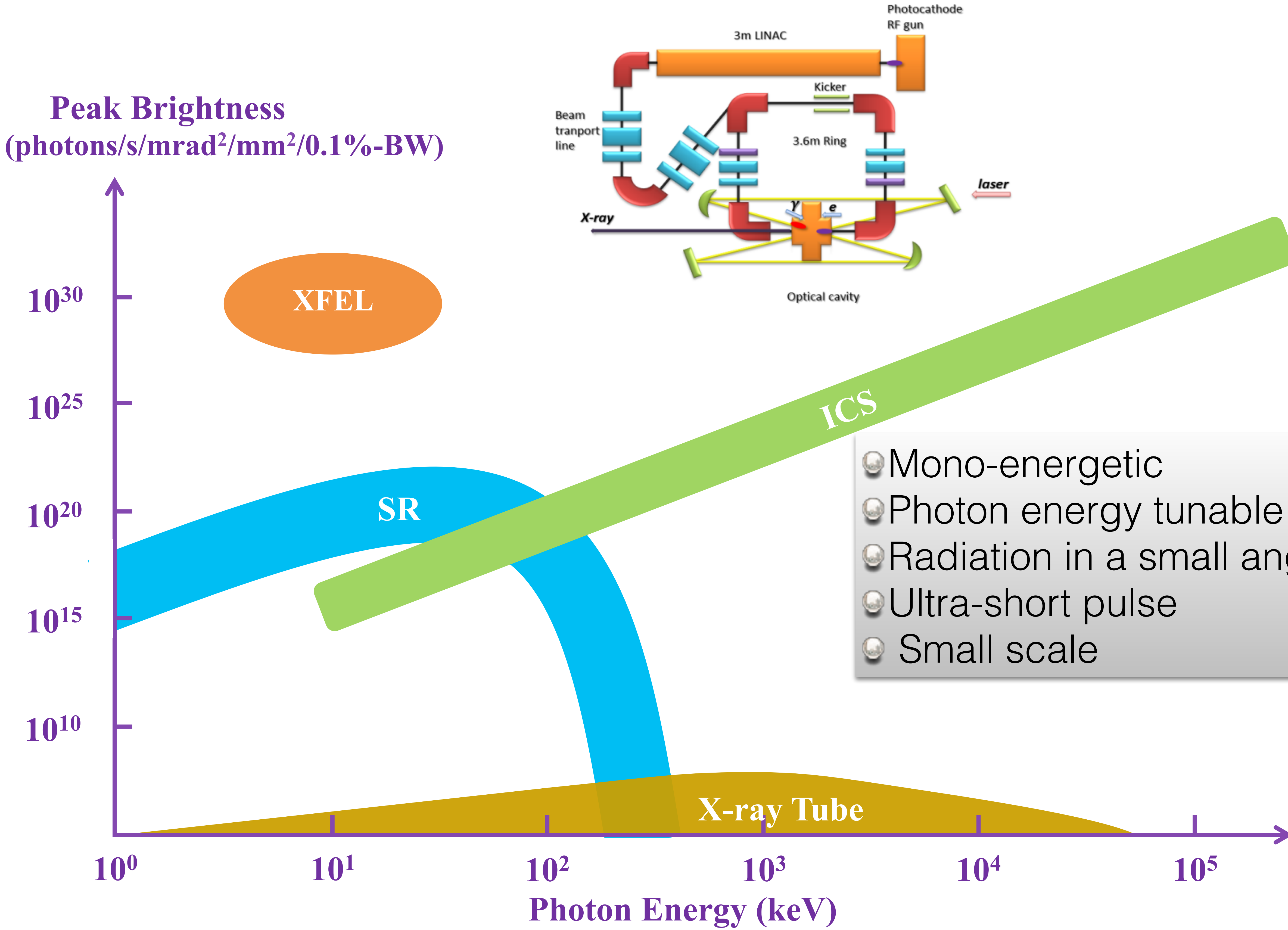
if the photon energy is much smaller than the rest energy of electron,

$$\varepsilon = \frac{h\nu}{m_0c^2} \ll 1 \quad \Rightarrow \quad F_{KN} \sim 1 \quad \Rightarrow \quad \left(\frac{d\sigma}{d\Omega}\right)_{KN} = \frac{r_e^2}{2}(1+\cos^2\theta)$$

- Total Cross-section

$$\sigma_{\mathrm{Th}} \equiv \frac{8\pi}{3}r_e^2 = 6.65\times10^{-29}\ \mathrm{m}^2 = 0.665\ \mathrm{barn}$$

TS/ICS Sources Compared with Other Light Sources



- Mono-energetic
- Photon energy tunable
- Radiation in a small angle
- Ultra-short pulse
- Small scale

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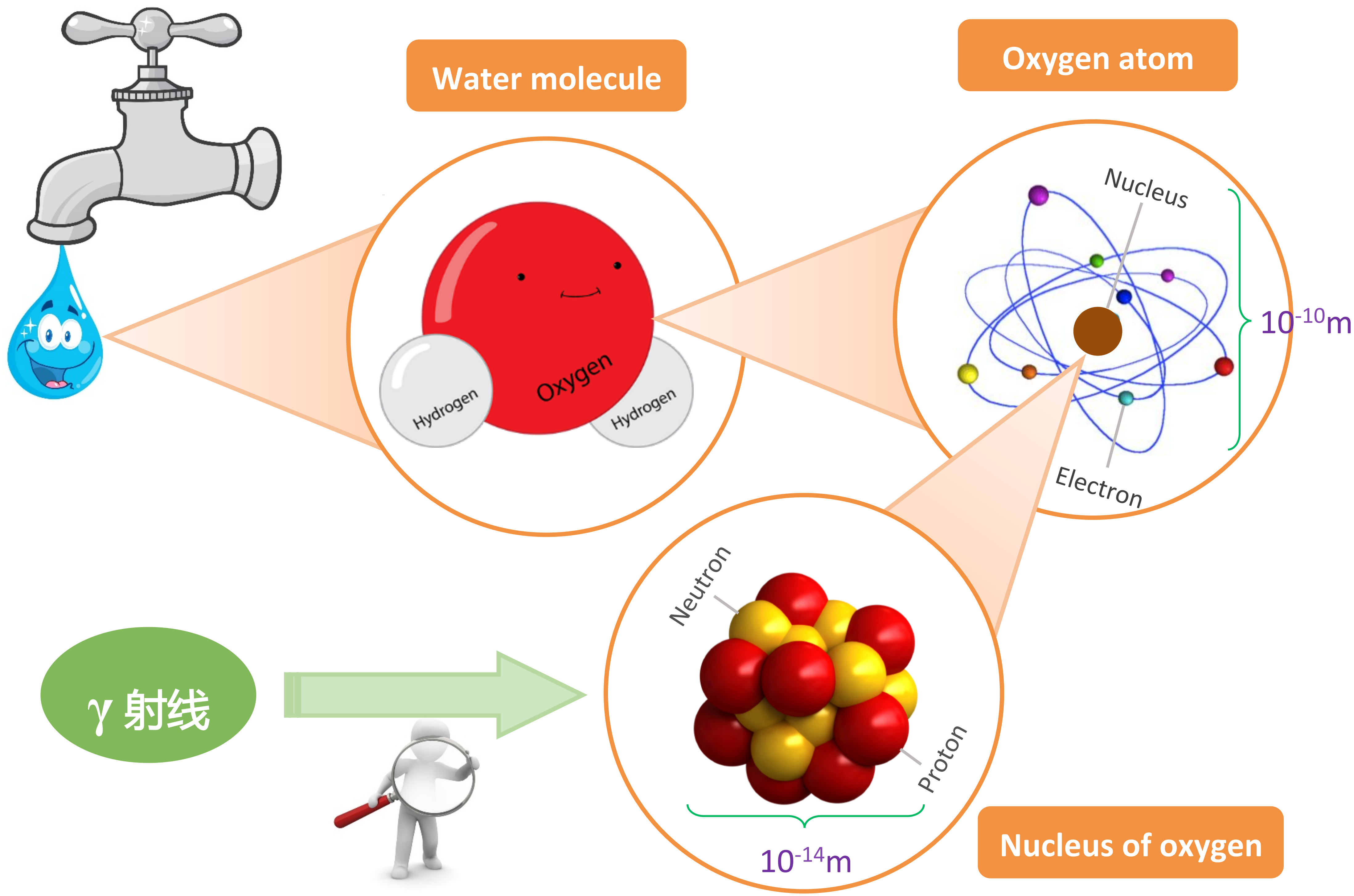
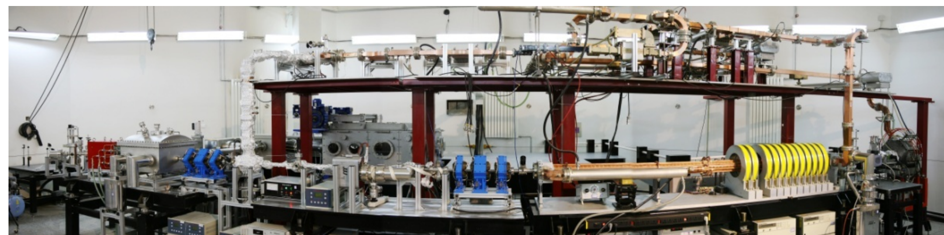
Probe for Nuclear Studies



ICS Studies at Tsinghua

Milestones on the Road from TTX to XGLS



2013-2018: XGLS-3MeV, 10^8/pulse

2001: Beginning of the TS studies in THU

2002: Collaboration on TS with CAEP

2006: The 1st scattering x-ray (4.6keV, 1.7×10^4) was got with a BWT linac of THU and YAG laser from CAEP

2009: Soft X-ray generation experiment using photocathode rf gun at the TTX， 290.4 eV, 1 ps, and 6.4×10^3.

2011: Generation of first hard X-ray pulse at TTX, 51.7 keV , 1.0×10^6

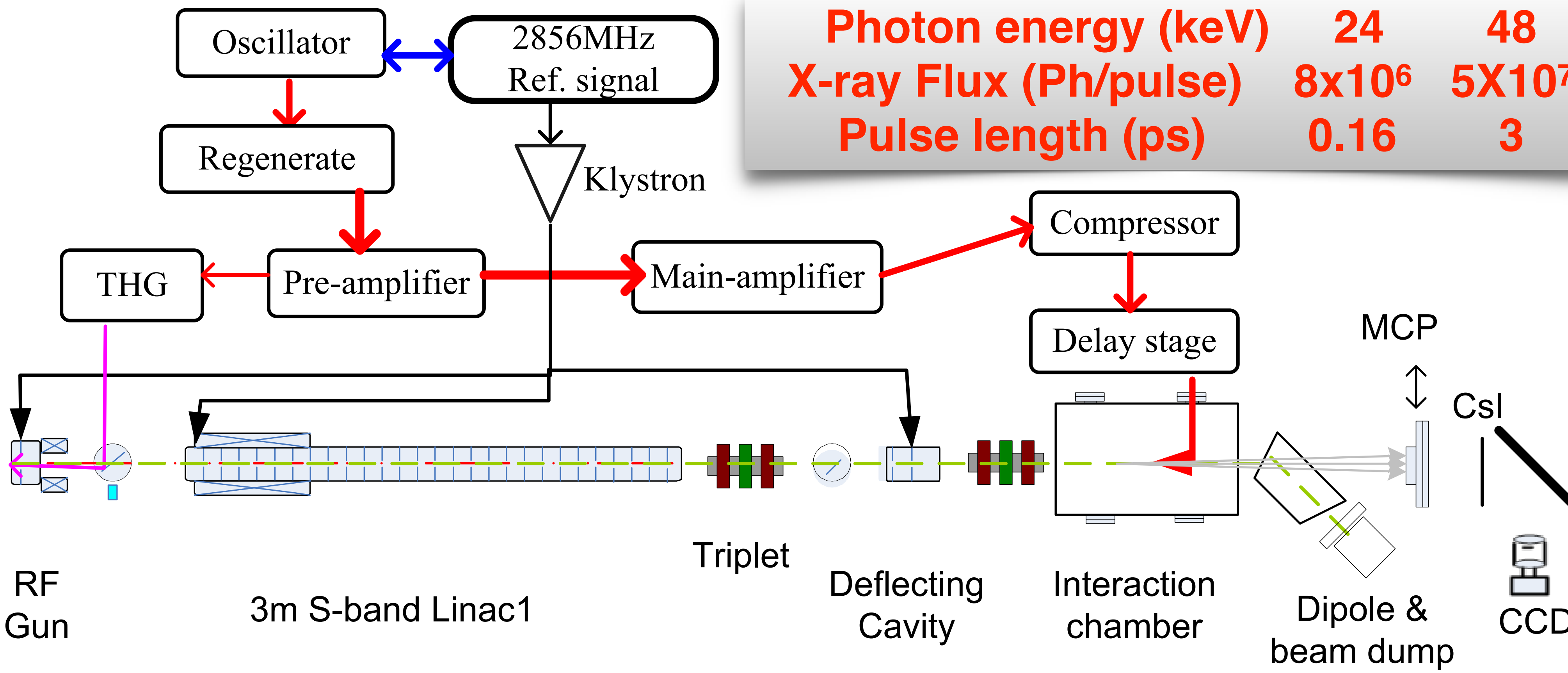
1. Chinese Physics C , Vol. 32, No. 1, Jan., 2008
2. NIM A 608 (2009) S70–S74
3. NIM A 637 (2011) S168–S171
4. REVIEW OF SCIENTIFIC INSTRUMENTS **84**, 053301 (2013)

Tsinghua Thomson scattering X-ray source (TTX):

TTX-I is operating, TTX-II is under technical design.

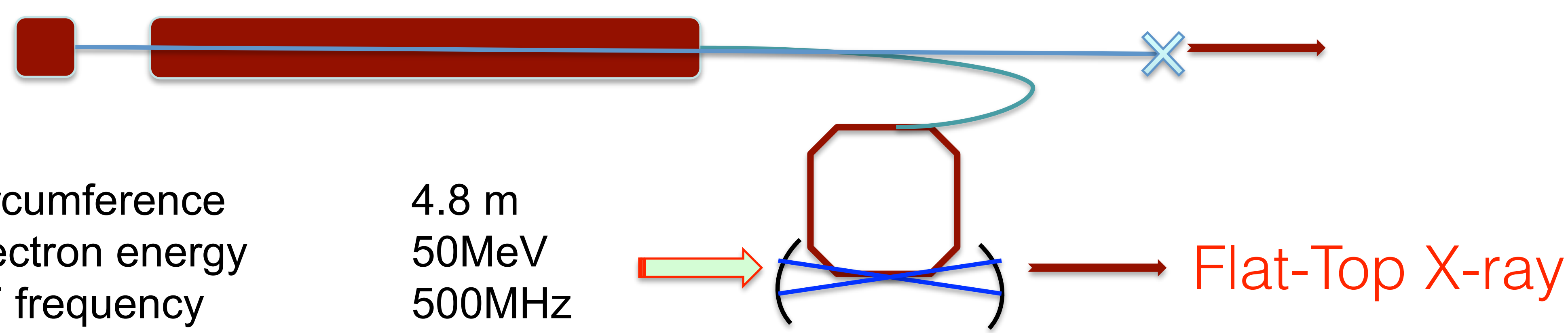
Photon energy (keV)	24	48
X-ray Flux (Ph/pulse)	8×10^{6}	$5\mathrm{X}10^{7}$
Pulse length (ps)	0.16	3

TTX-I



TTX-II

Circumference	4.8 m
Electron energy	50MeV
RF frequency	500MHz
X-ray Flux	~10^{10}ph/s



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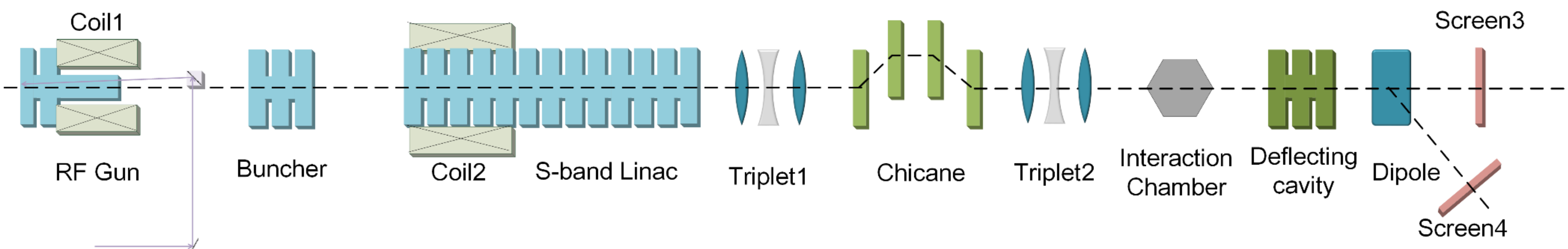
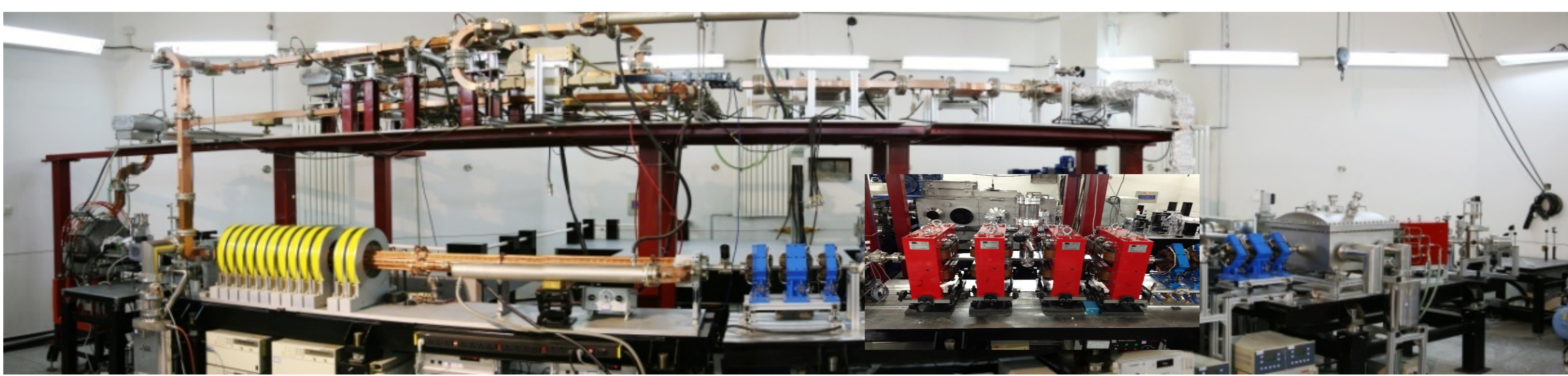
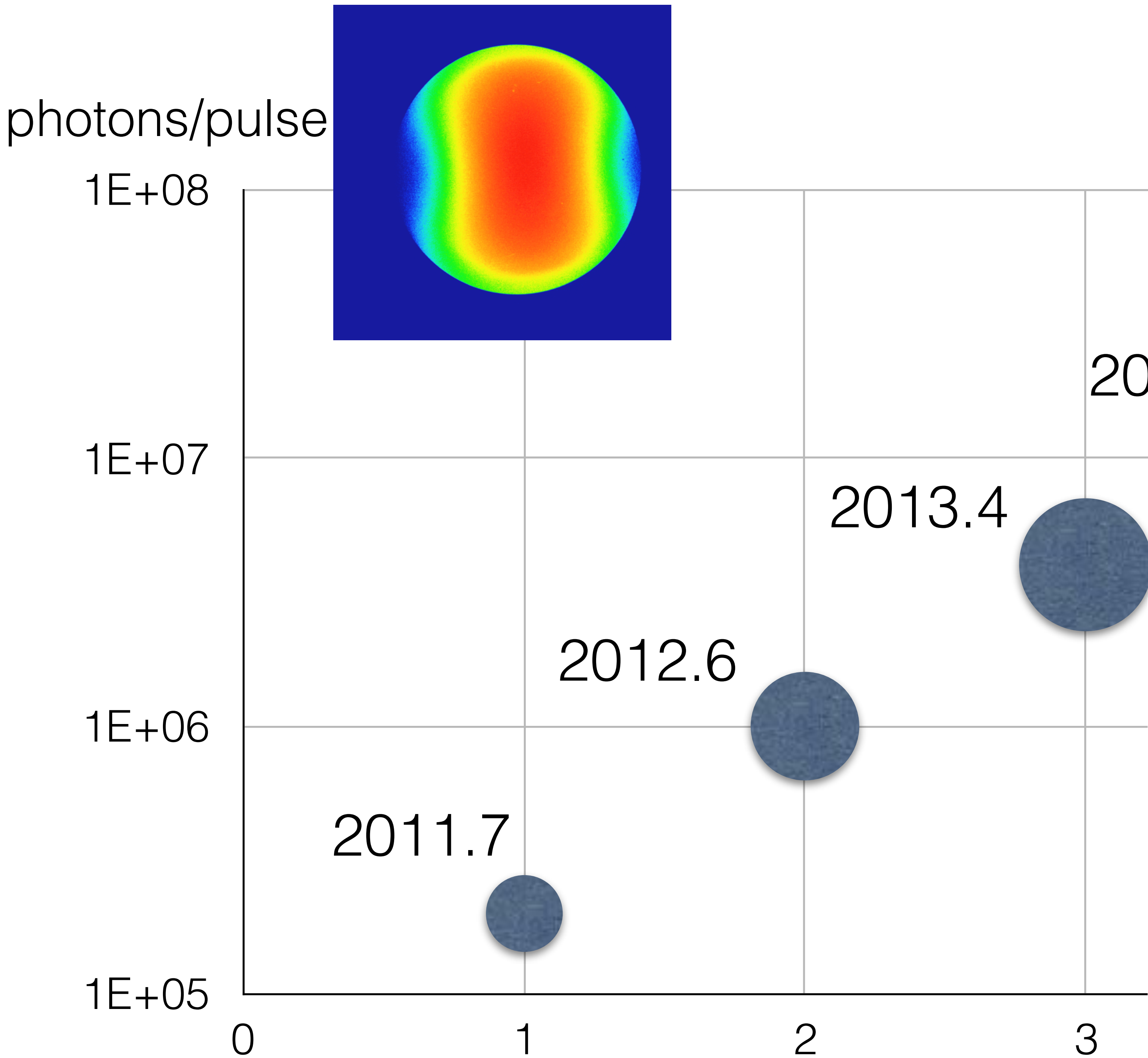
The 50MeV Electron linac beam line of TTX

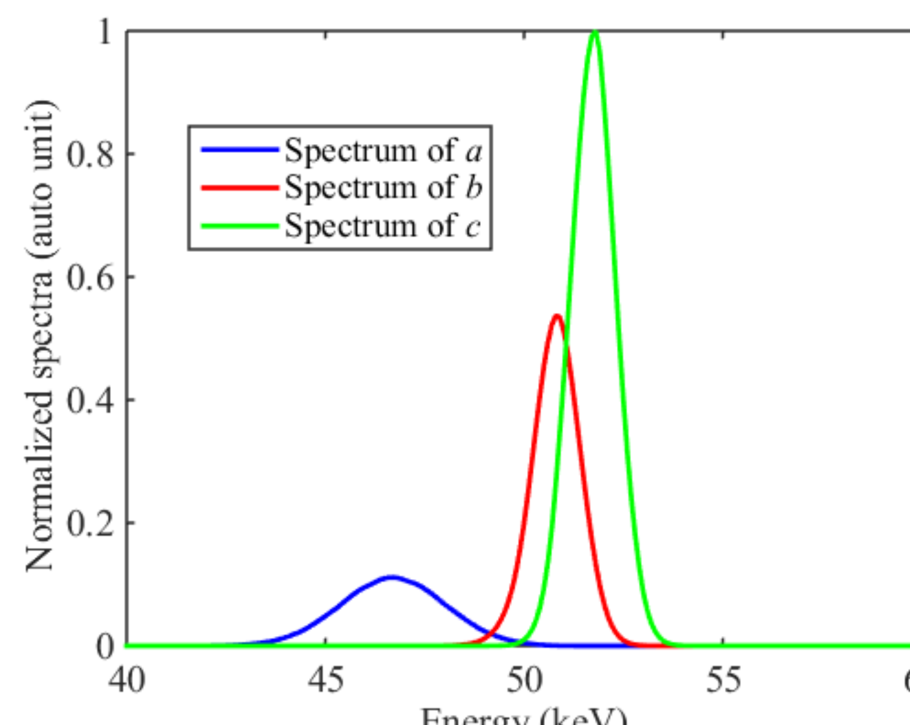


- The maximum gradient of the gun is ~110MV/m and the bunch charge from a few pC to ~1nC.
- An S-band TW cavity was installed for ballistic bunching before the acceleration.
  - The acceleration phase is set at ~-90° to introduce an energy chirp
  - Simulations show the emittance can be preserved when compression factor $C<3$
- A 4-dipole chicane has been installed after the linac
  - The bend angle can be varied up to ~15°.
- The combination of ballistic bunching and magnetic compression enable us to generate ultrashort (rms<20fs) and high-intensity (~10kA) electron beam.



Photon flux of TTX-I





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NIM A 608 (2009), NIM A637(2011), RSI 84, 053301(2013)

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Advanced Imaging with TTX-I

- Small spot size:
  - ☑ Phase Contrast Imaging (including PC CT)
- Tunable Energy:
  - ☑ Multi-Energy X-ray Imaging (Material Identification, K-edge Imaging…)
- Narrow Spectra:
  - ☑ Mono-Energetic X-ray CT
- Short Pulse Length:
  - ☑ Fast Process Imaging

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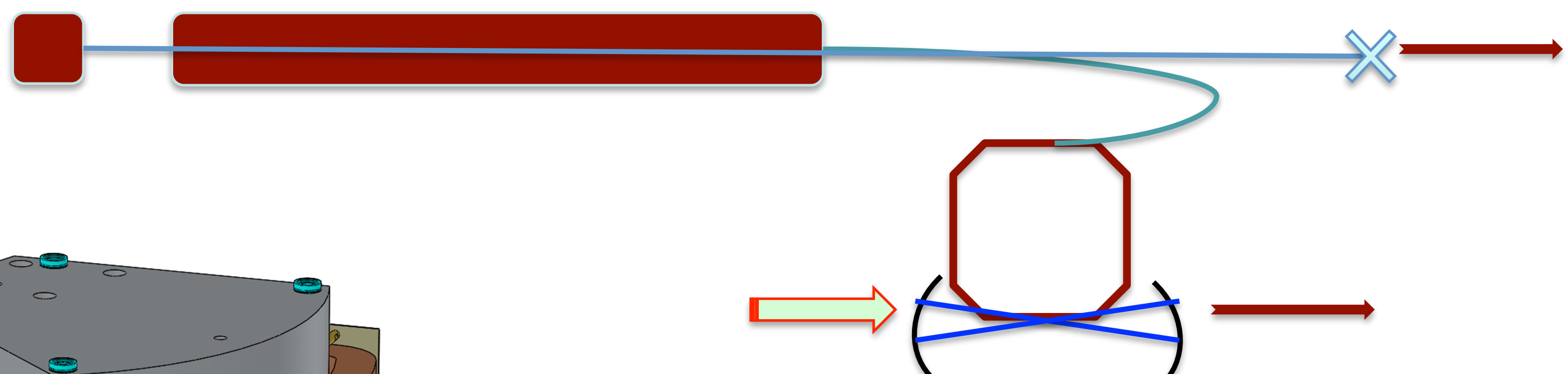
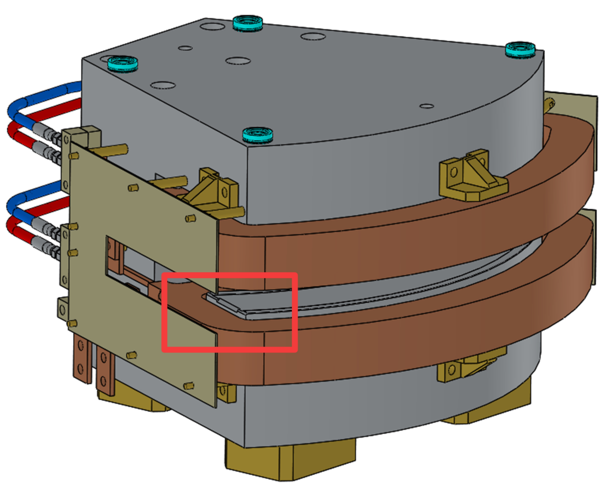
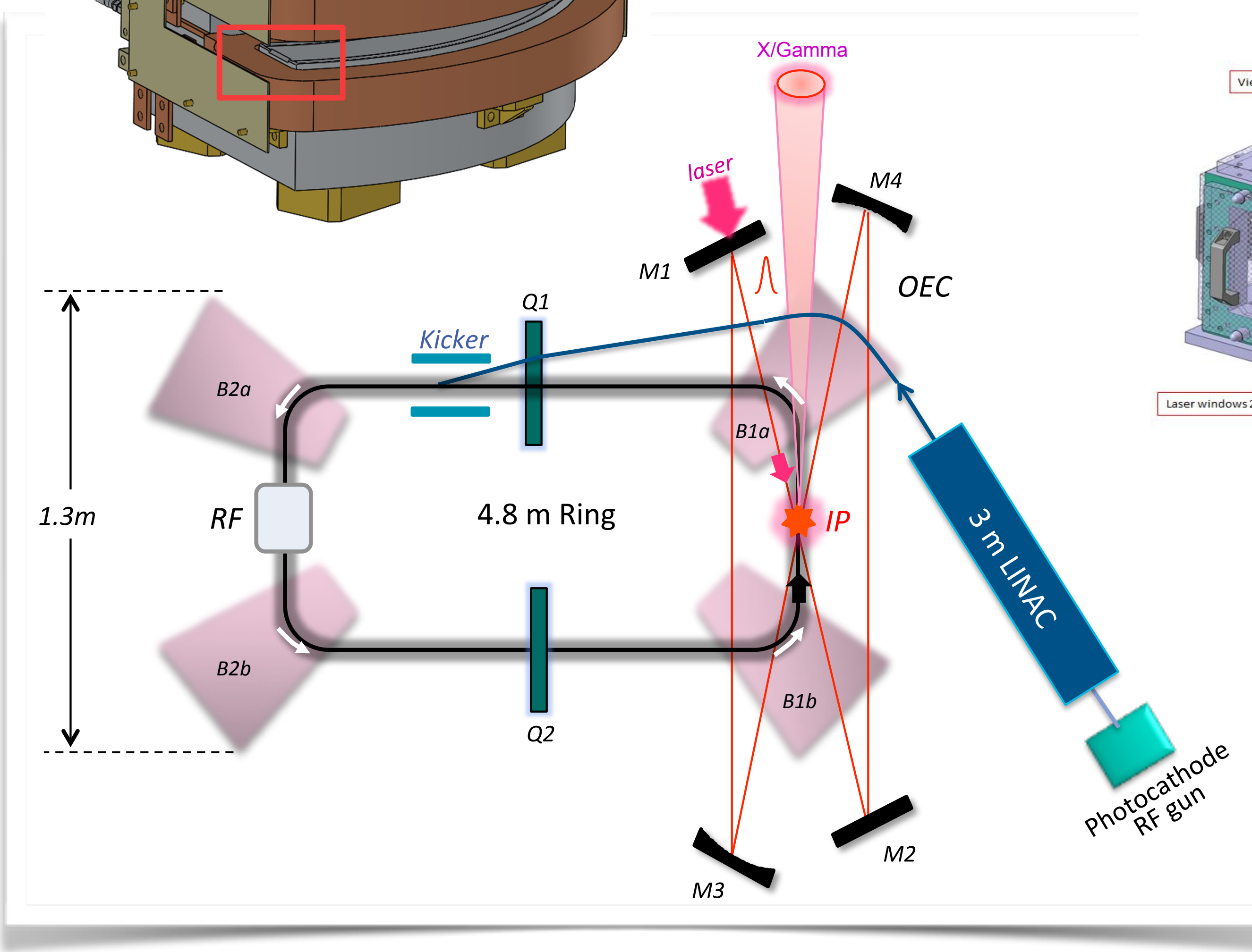
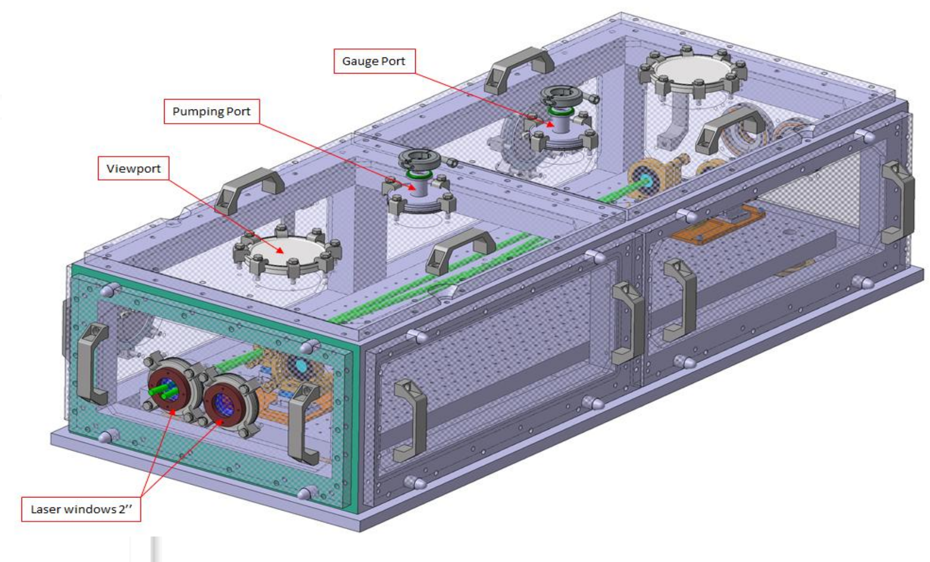
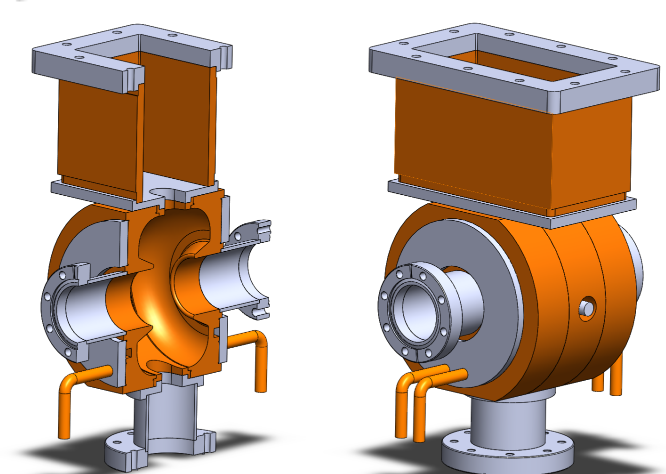
TTX-II with LESR and Optical Cavity











- XU H., RSI V85 No.3 033305 (2014)
- Y. You, PhD Thesis, Tsinghua University (2014)
- X.Liu, PhD Thesis, Tsinghua University (2018)

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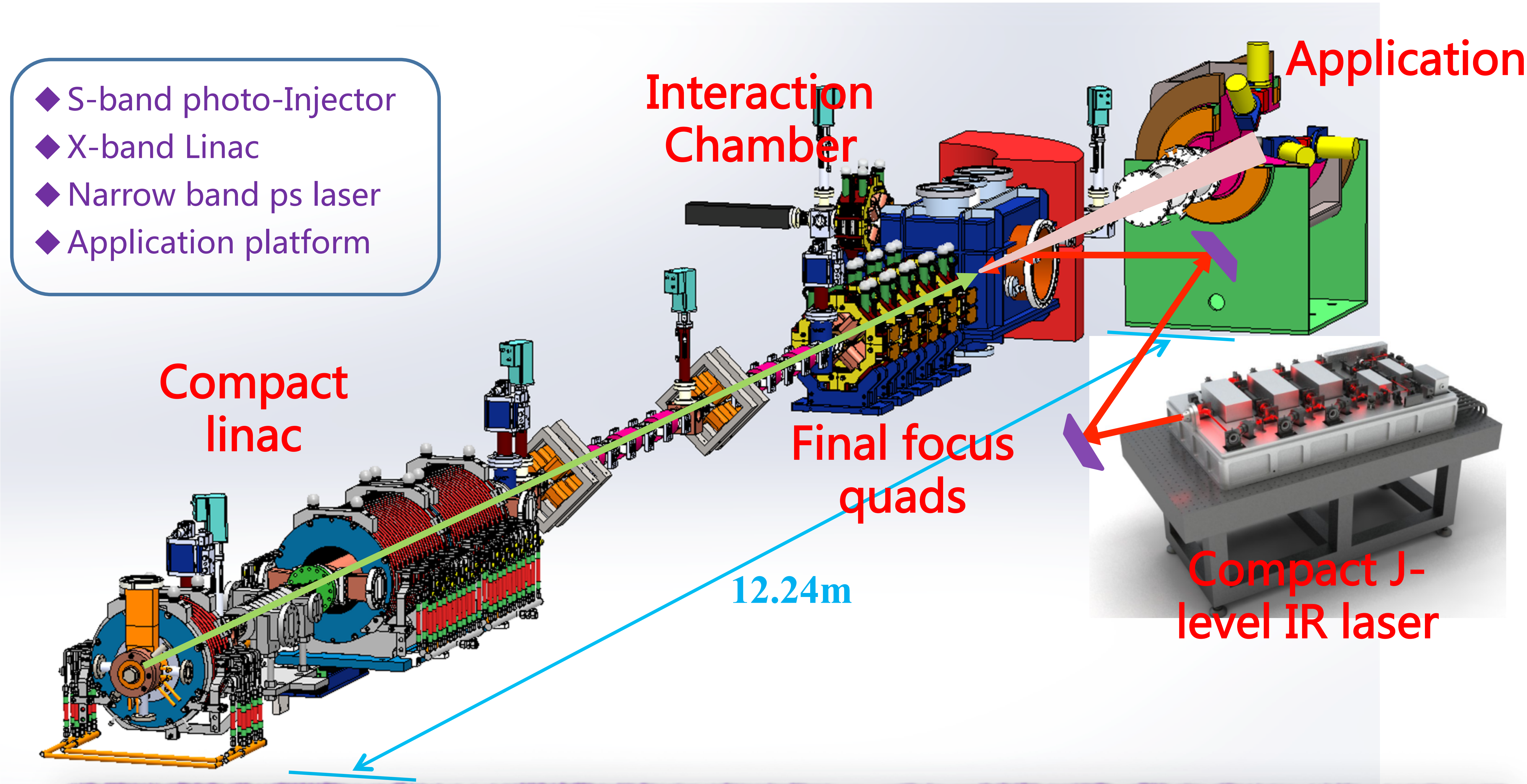
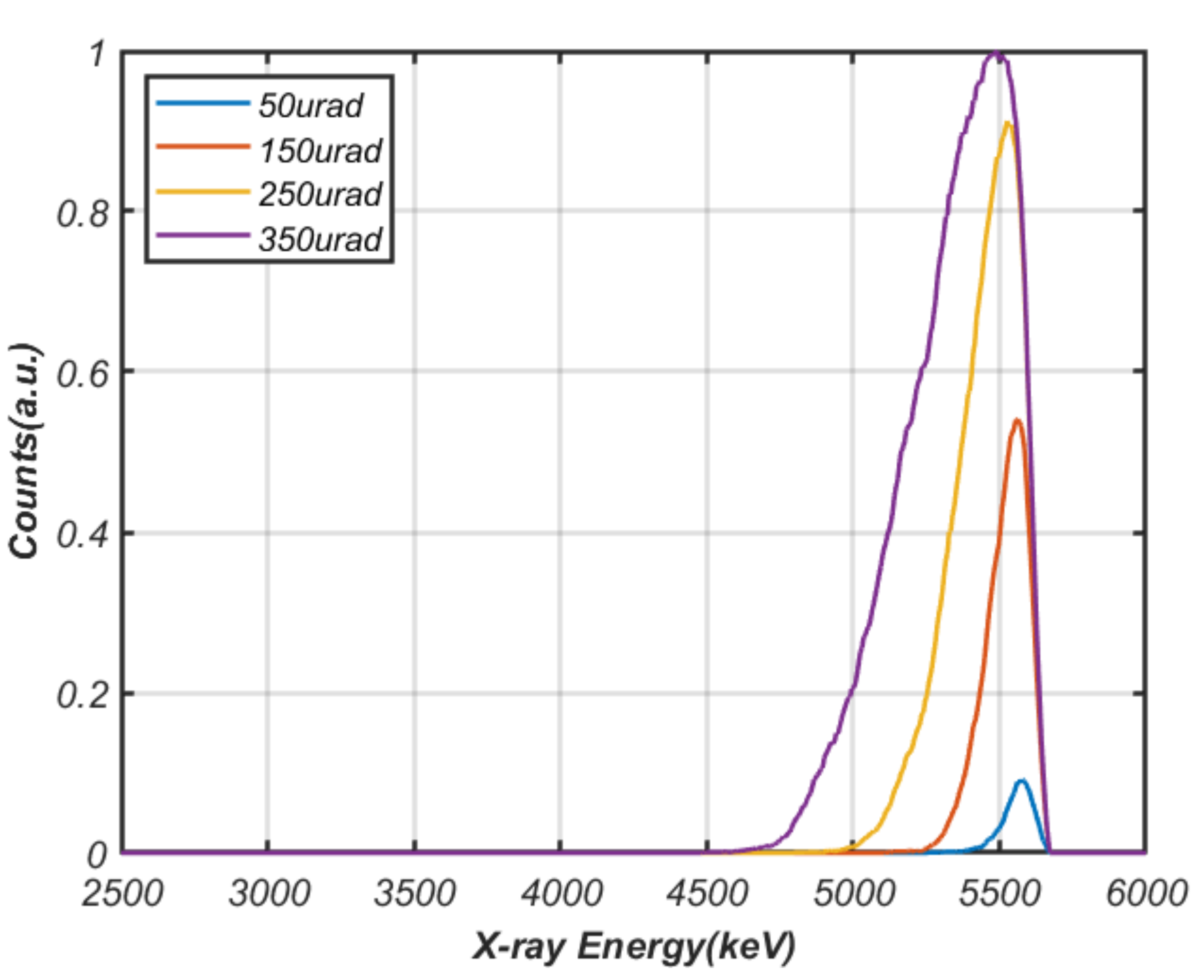
A Very Compact ICS Gamma Ray Source- VIGAS

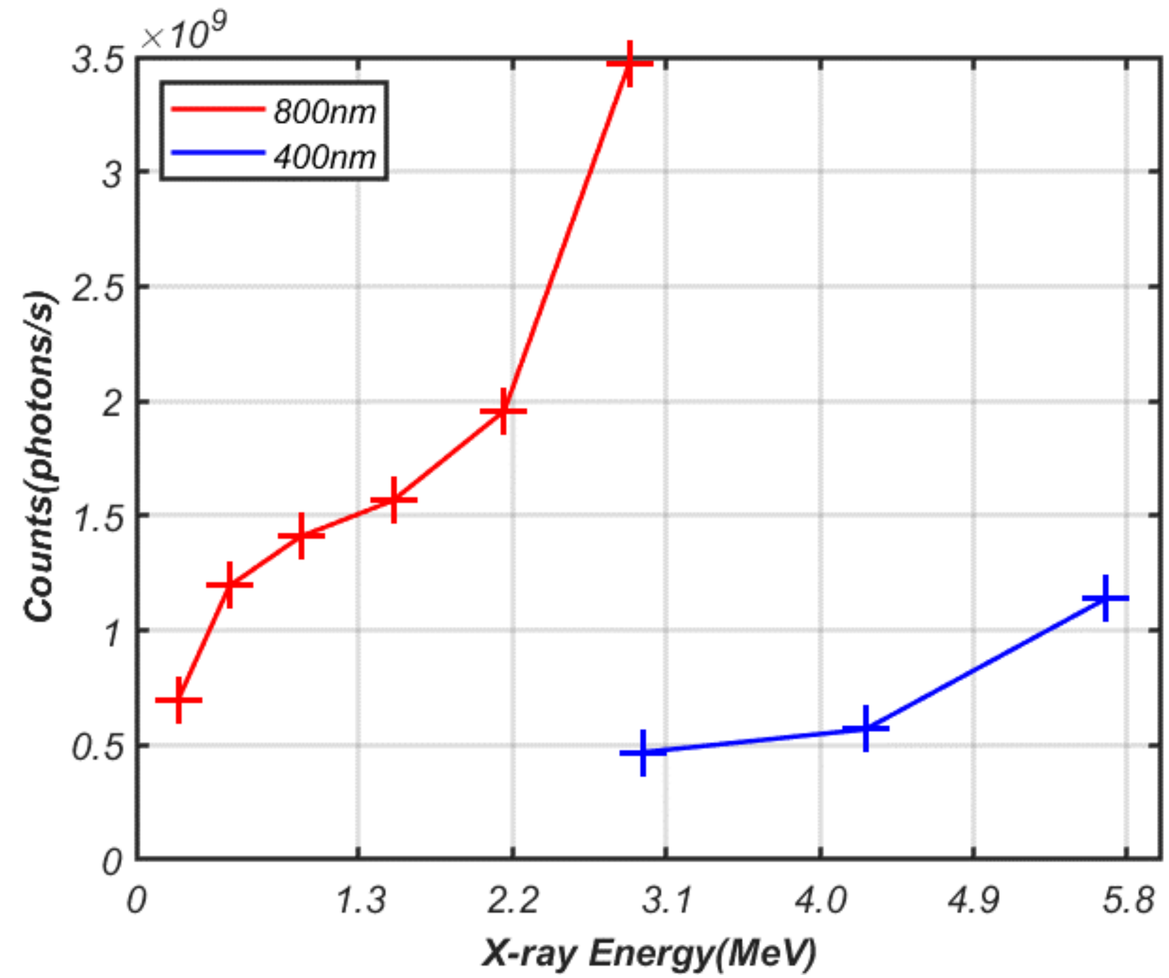
- S-band photo-Injector
- X-band Linac
- Narrow band ps laser
- Application platform



γ-ray energy: 0.2-4.8MeV
Bandwidth with collimator : <1.5%
Total photon flux(ph/s): $>4\times10^8$@0.2-2.4MeV; $>1\times10^8$@2.4-4.8MeV
Photon flux with 1.5% Bandwidth(ph/s): $>4\times10^6$@0.2-2.4MeV; $>1\times10^6$@2.4-4.8MeV
controllable polarization from linear to circular

Simulated Performance of the Compact ICS Gamma Ray Source





Laser: ~1.5J@800nm/0.8J@400nm, <10ps, <10um@IP

Gamma-ray energy is tunable in 0.06~5.82MeV with electron energy in 50~350MeV 。
photon flux:1.2×10^9ph/s@400nm; 3.5×10^9ph/s@800nm

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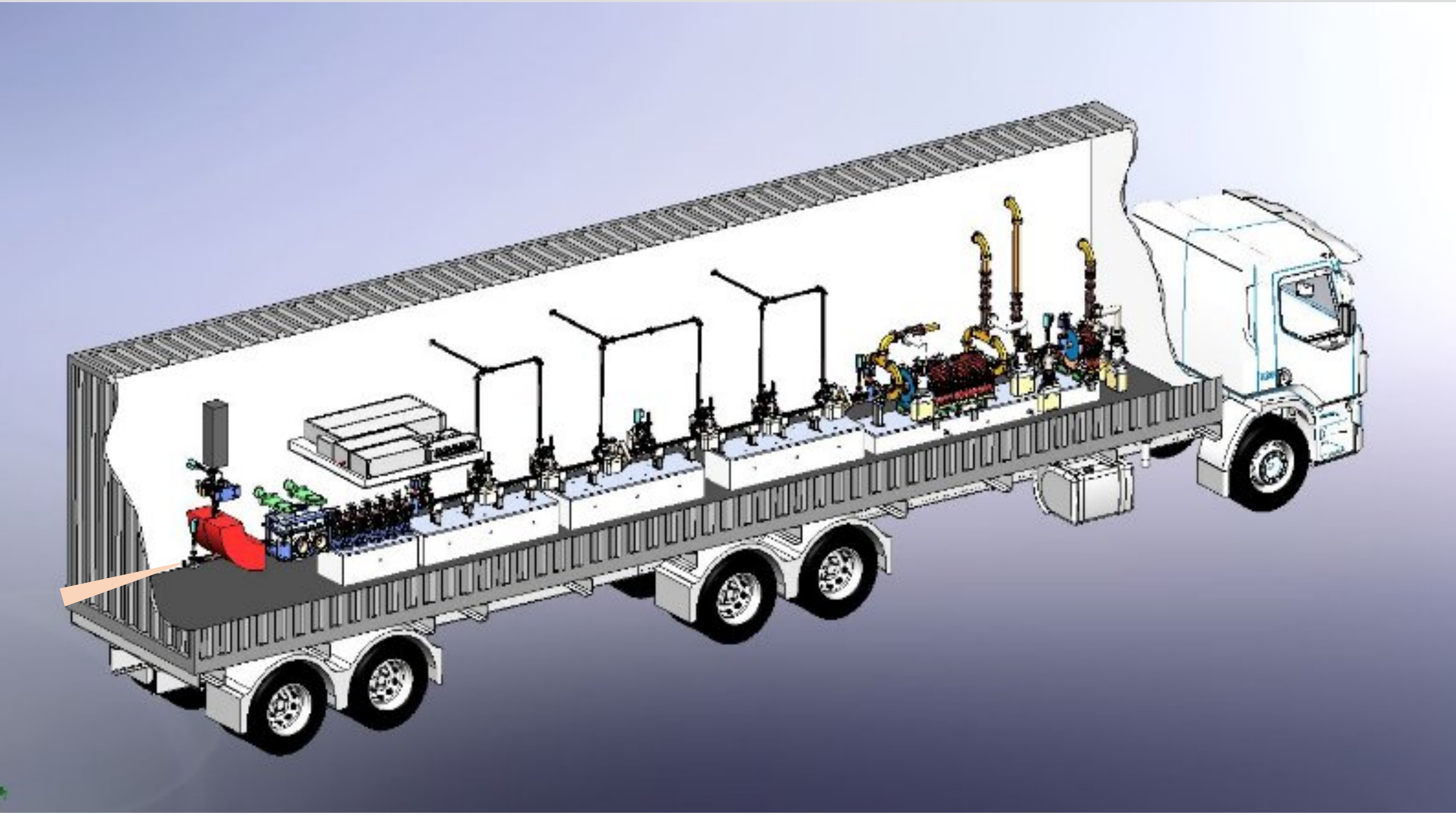
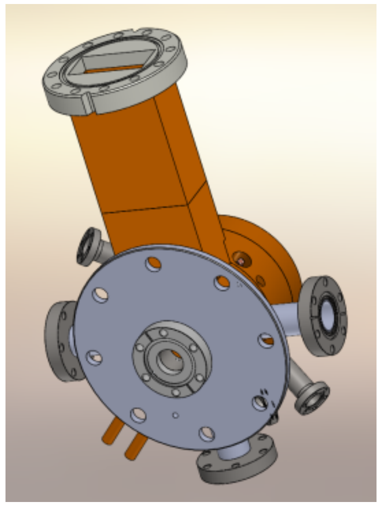
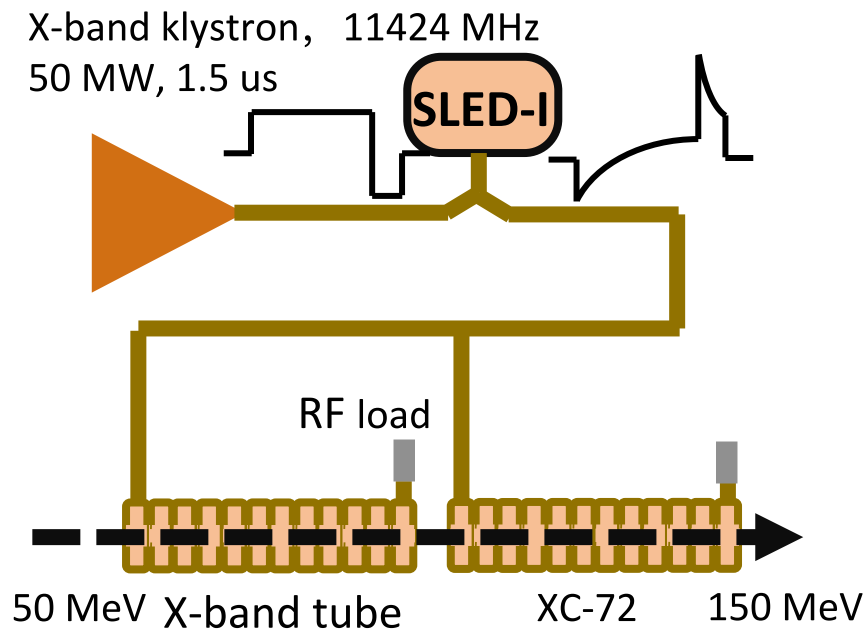
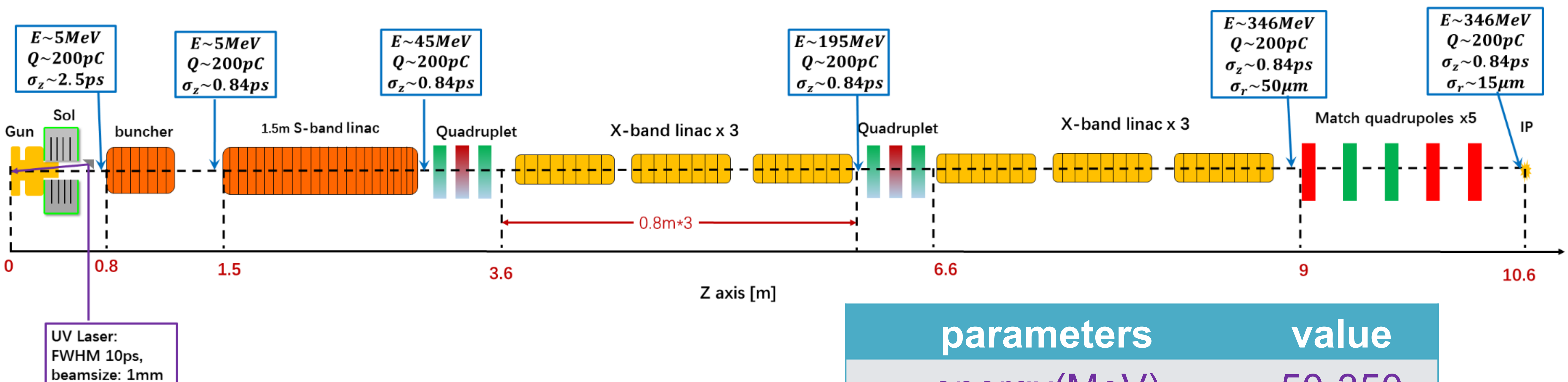
The Main Structure of VIGAS can be installed in a standard container

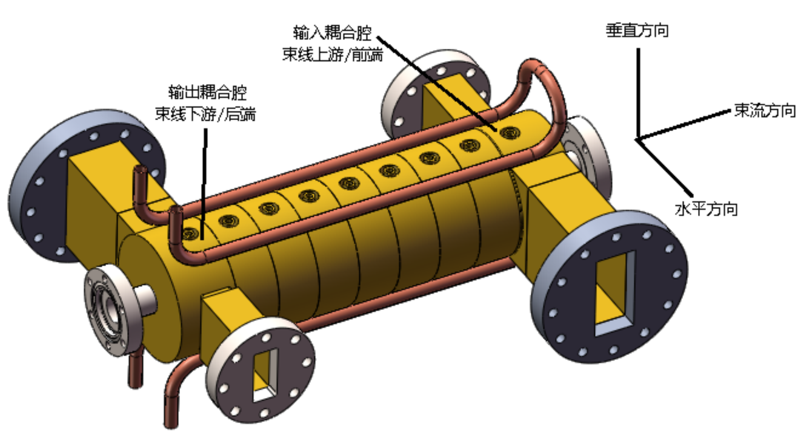


S&X band Linac









parameters	value
energy(MeV)	50-350
charge(pC)	>200
emittance(mm·mrad)	<0.6
Bunch length(ps)	<2
Energy spread(%,	<0.3
beam size(um, rms)	<20

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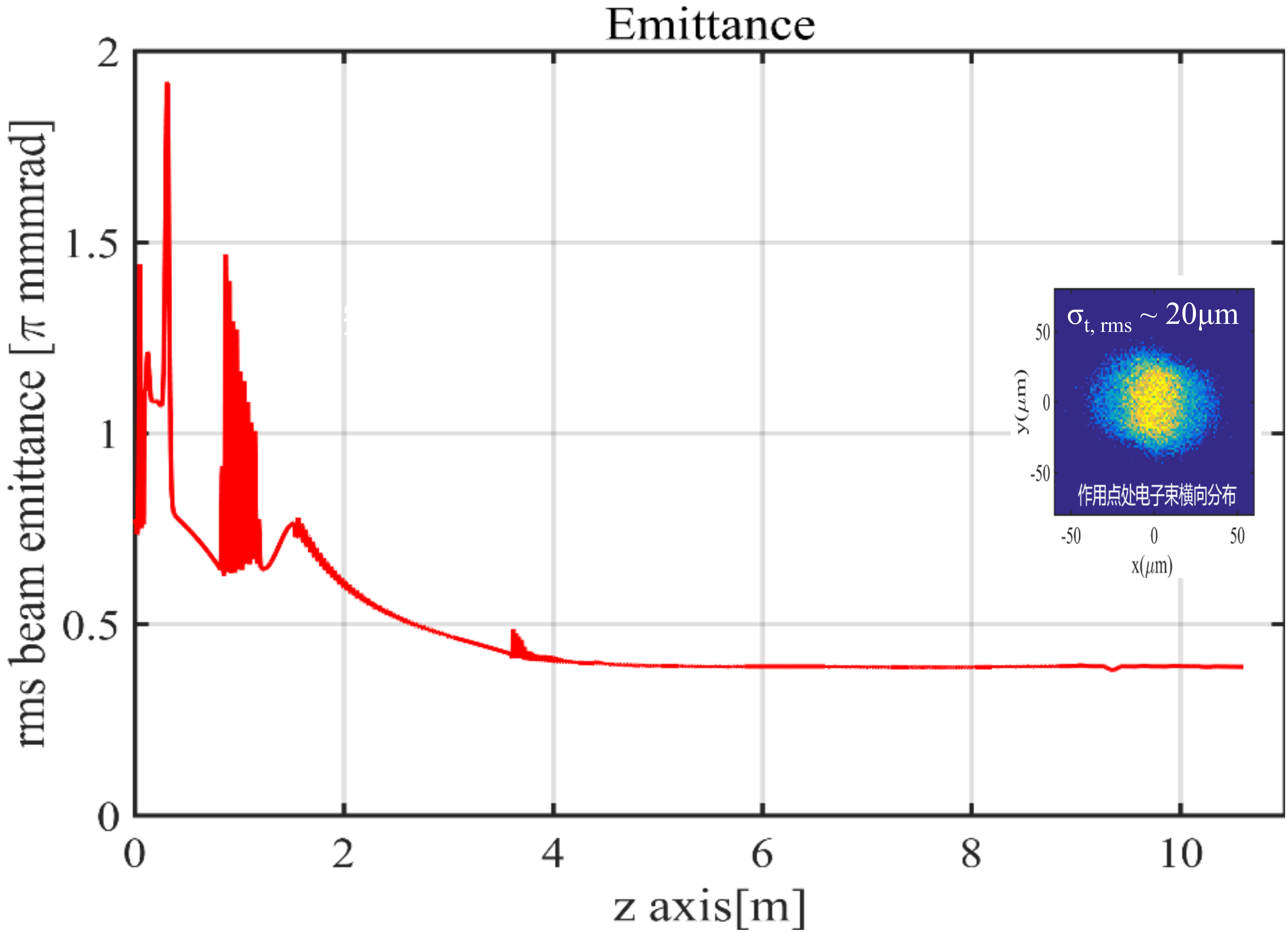

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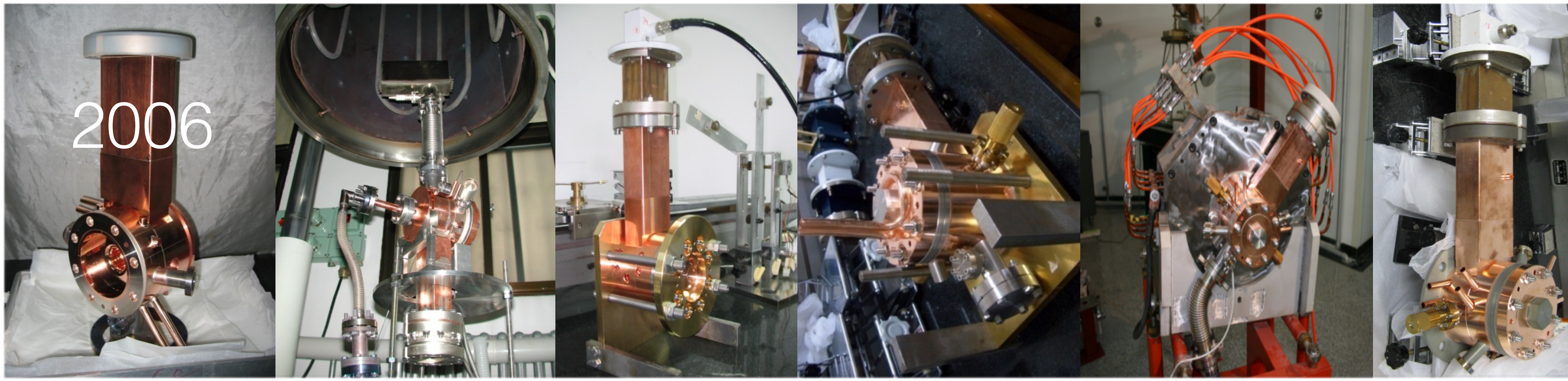
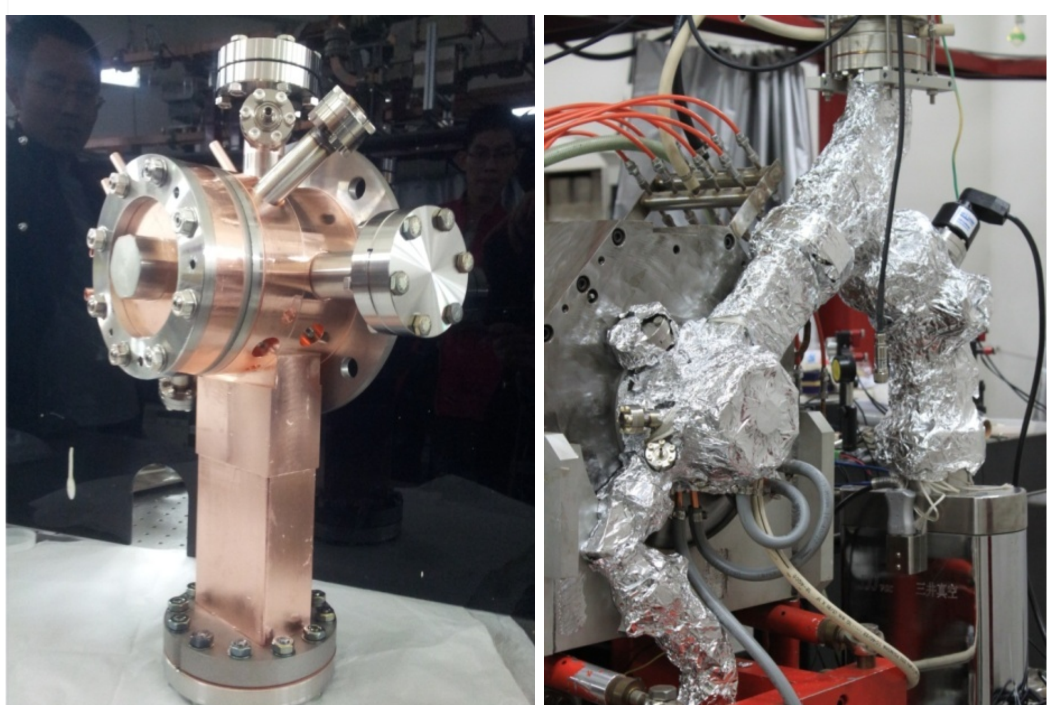
Photocathode RF Gun Development at THU



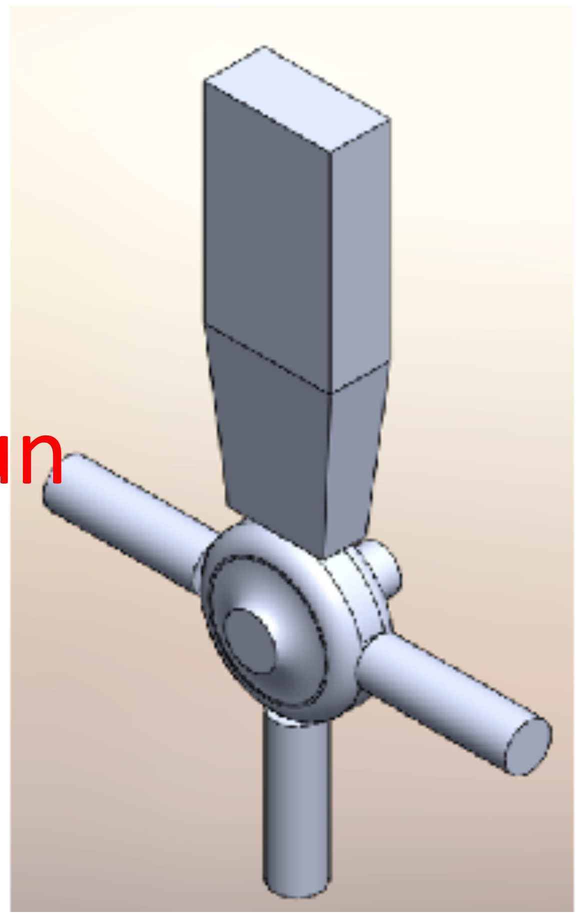
2011

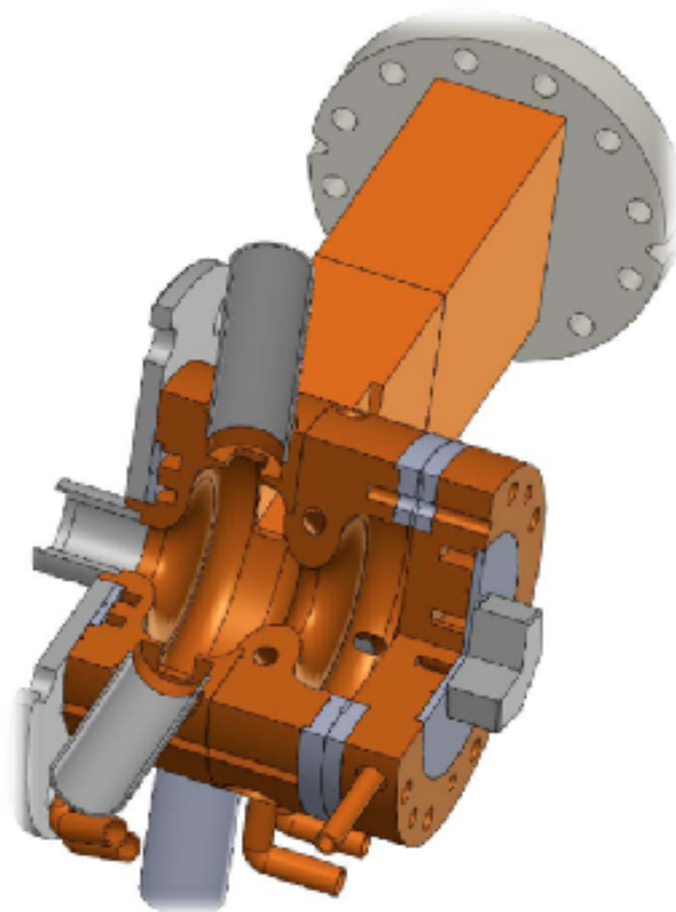


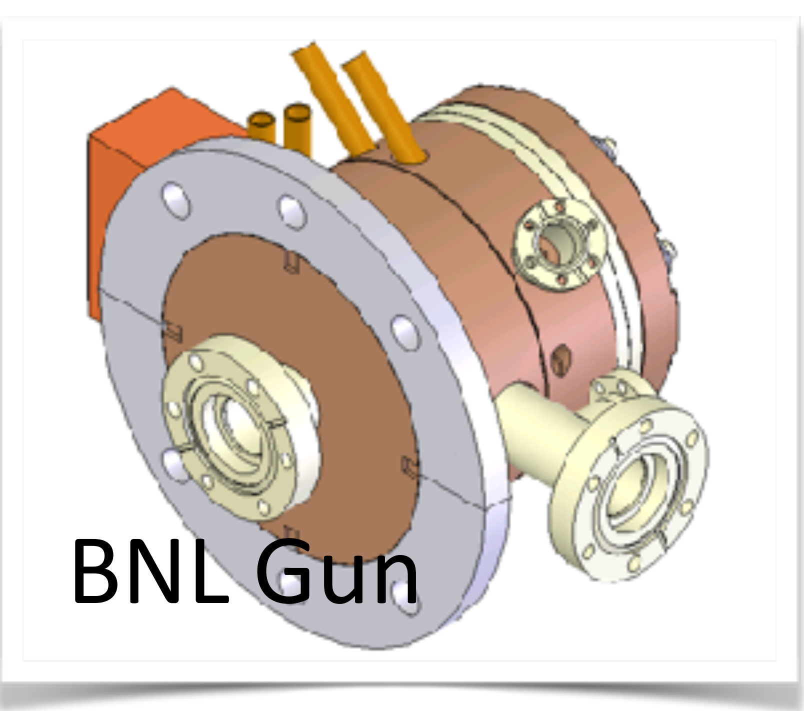
Parameters	*Value*	*Unit*
PI mode frequency	2856	MHz
Quality factor Q_0	14000	
Coupling factor β	1.3	
Electric field on cathode	120	MV/m
RF pulse width	1.7	μs
Repetition rate	10	Hz
Peak power of wall heat loss	9.4	MW
Input RF peak power	11.3	MW
Cathode material	Copper	
QE	4×10^{-5}	
dark current at 120 MV/m	< 250	pC/pulse

The gun designed to eliminate the multiple modes

THU Gun



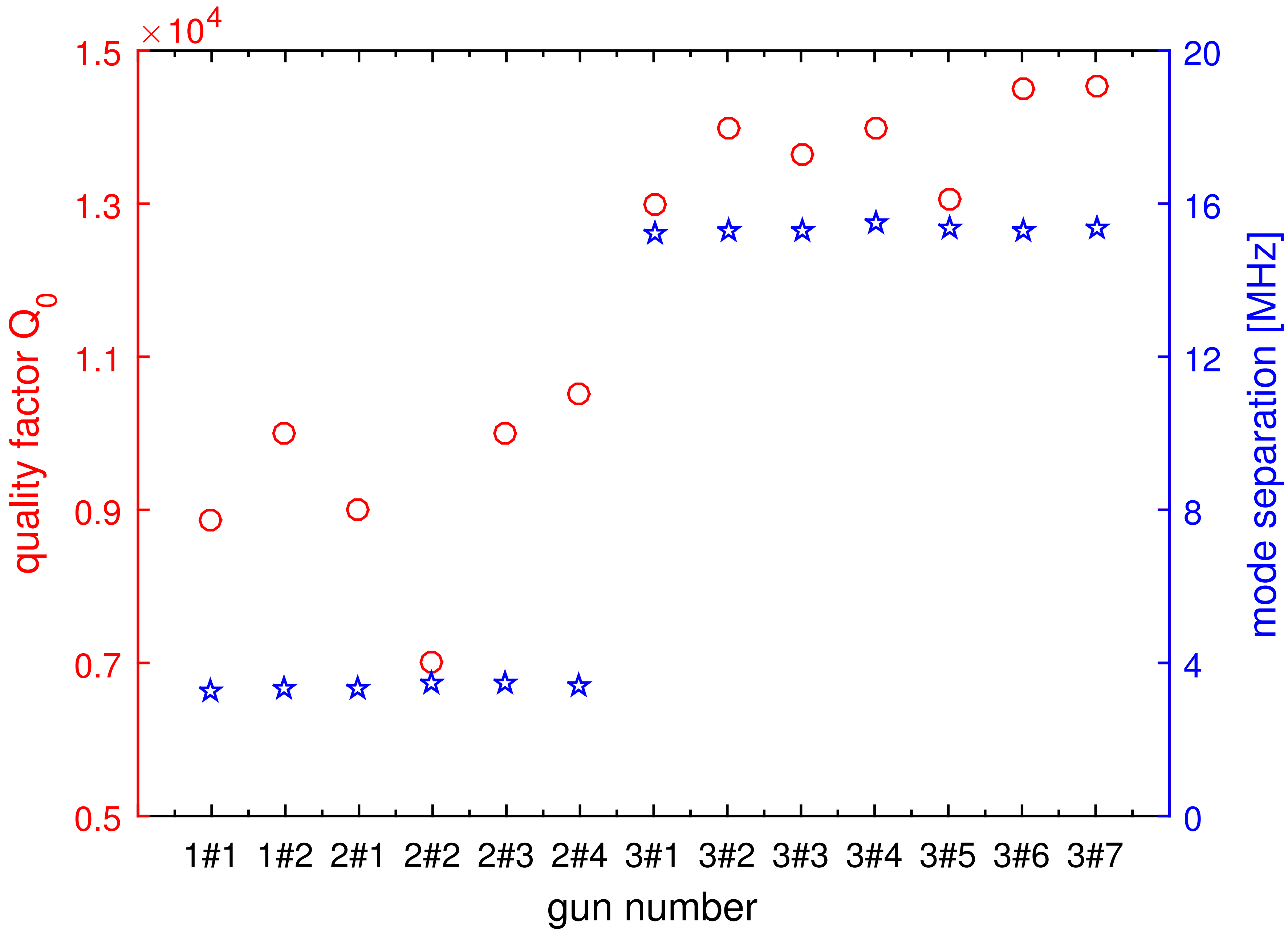




	Dipole	Quadruple
BNL	2E-03	2E-02
LCLS	9E-06	5E-05
THU	7E-05	1E-05

*CST simulation, H_ϕ analysis @ r=10mm

The unloaded quality factors and 0-pi mode separations of the three generations of the photocathode rf gun developed by THU



1st generation:

- silver copper brazing

2nd Generation:

- gold copper brazing
- Optimized vacuum pump hole

3rd Generation:

- gold copper brazing.
- optimized vacuum pump hole.
- added another two holes to eliminate quadruple.
- thin and ellipse iris.
- no Helico flex.
- dry ice cleaned cathode
- round corner.

…

L. M. Zheng *et al*., Nucl. Instrum. Methods Phys. Res Sect. A 834, 98-107 (2016)
H. Qian *et al*., in the proceedings of FEL 2012
H. Qian *et al*., in the proceedings of IPAC2011

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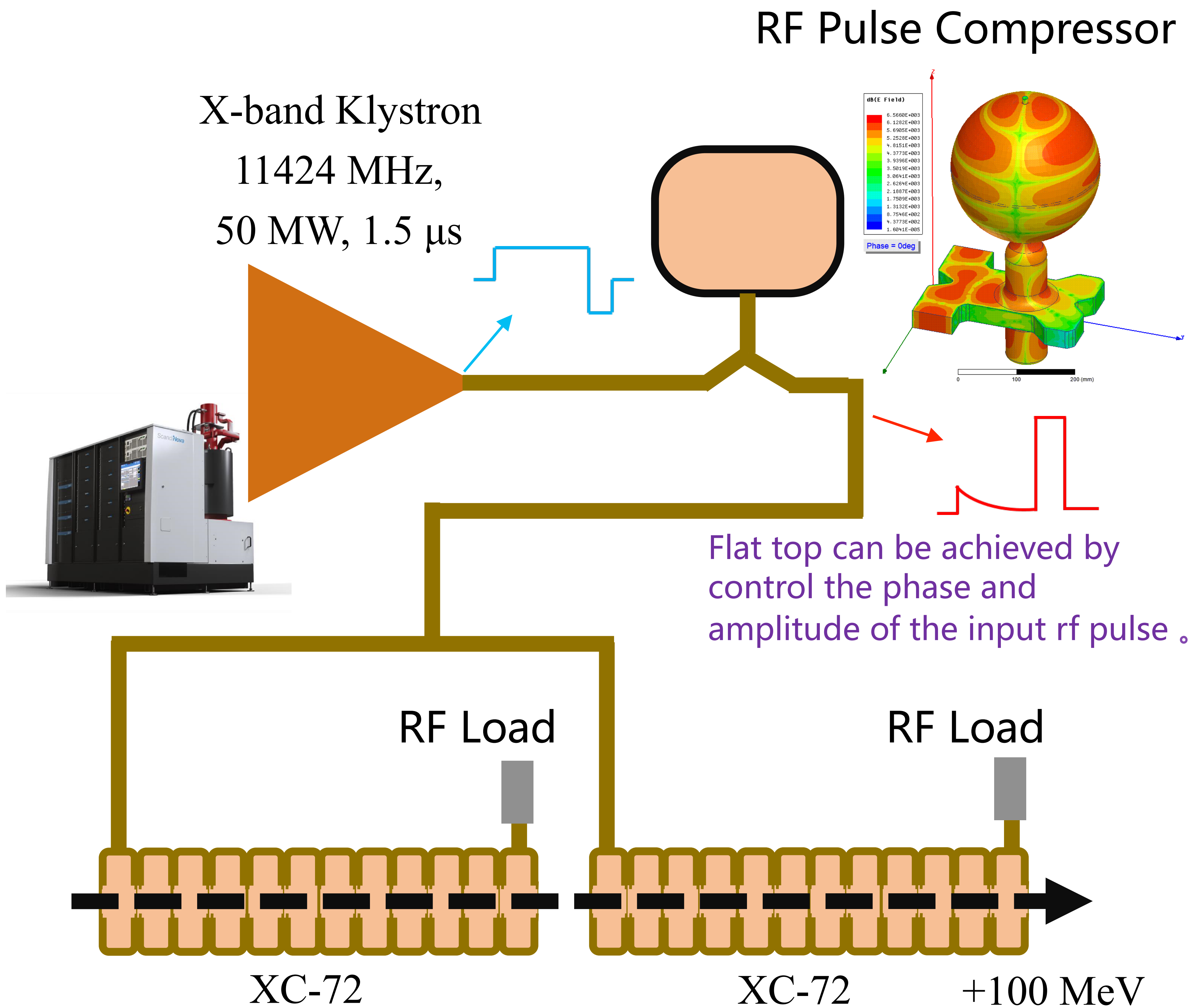
A Section of the X-band Linac



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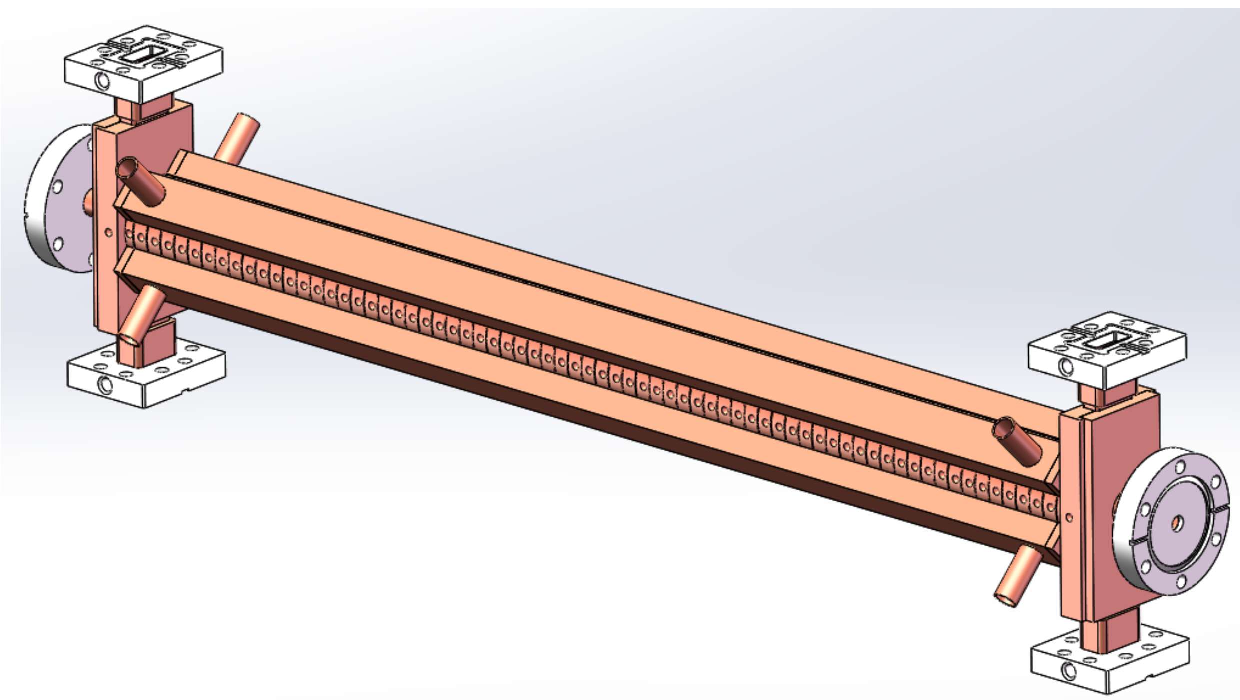
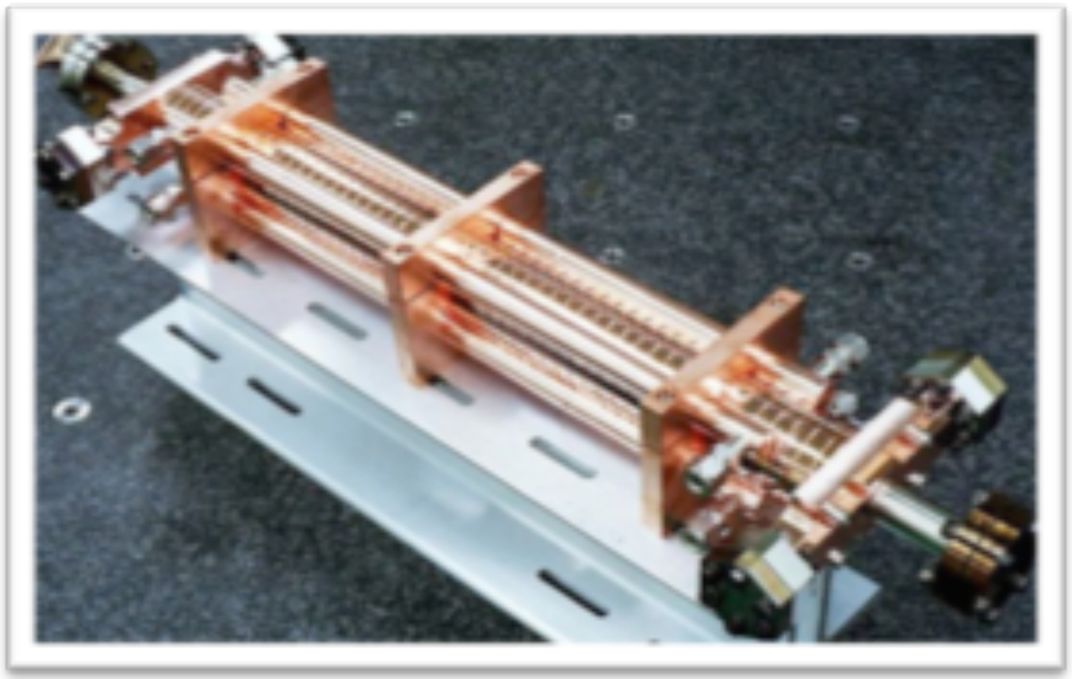
X-band High Gradient Structure

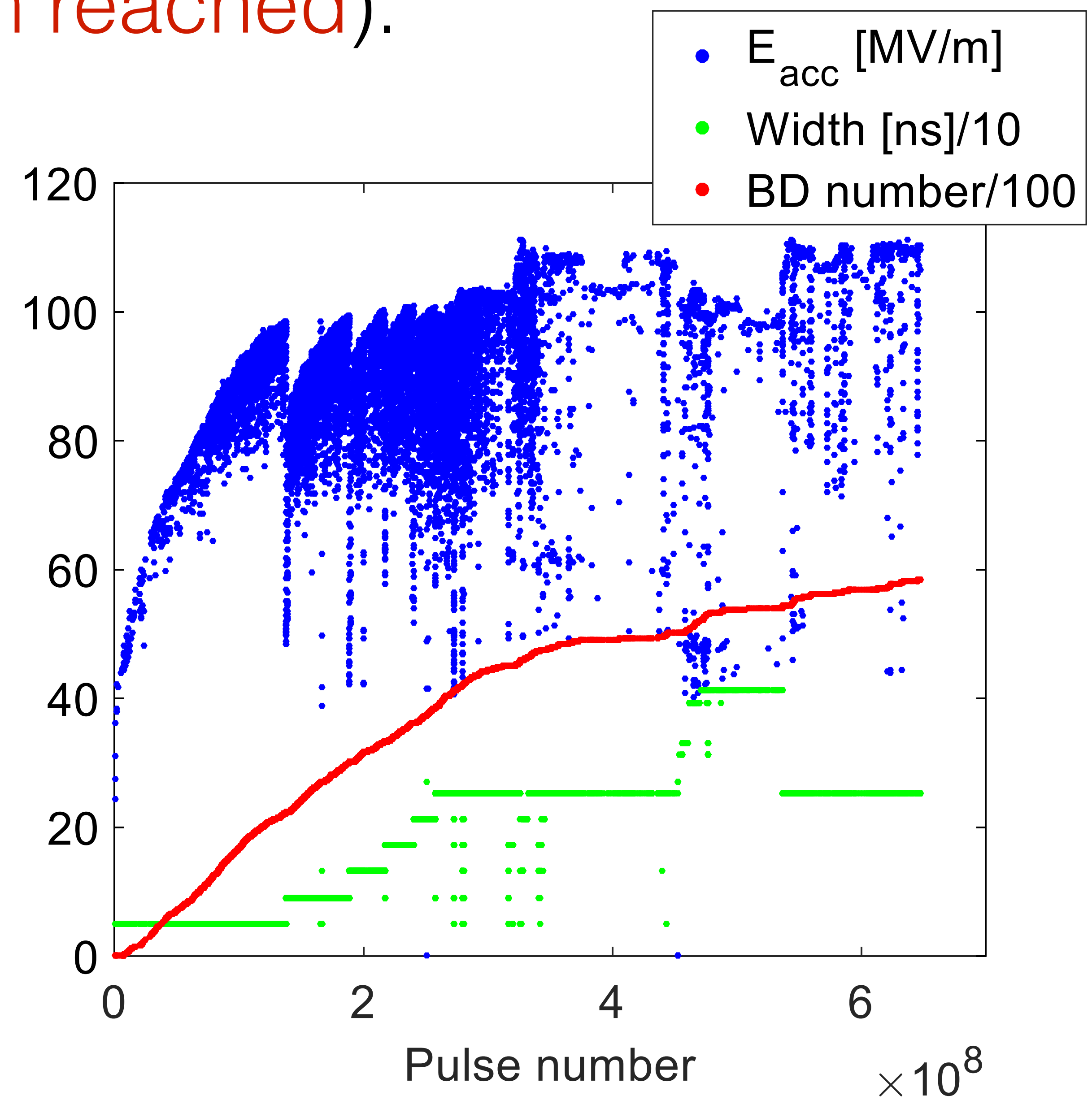


Parameters	Value
Freq. (GHz)	11.424
Phase Shift (degree)	120
Cells	72
Length (mm)	630
Filling Time (ns)	88
a (mm)	4, 3
v_g/(0.01c)	3.76, 1.38
R/Q (kOhm/m)	14.2, 16.3
Q	6900, 7100
Input Power(MW)	50
Gradient (MV/m)	80
S_{21} (dB)	-4.3

T24 design, assembled/tuned/baked/bonded at Tsinghua University in 2014, test at KEK in 2014-2015 (110 MV/m reached).

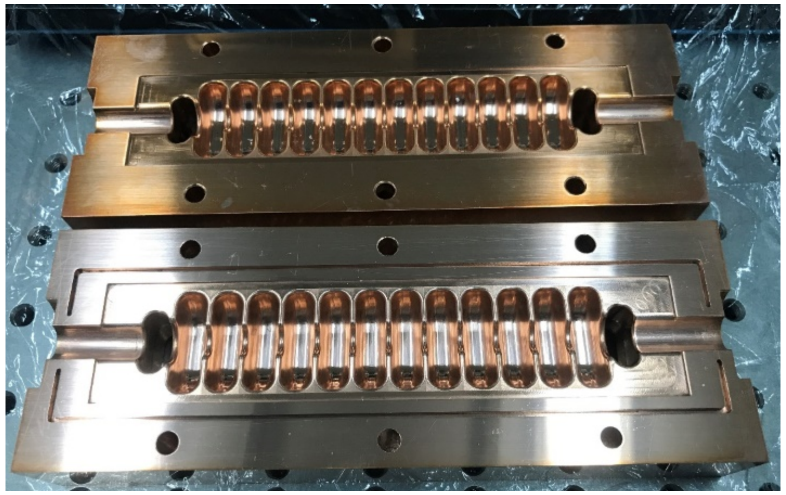


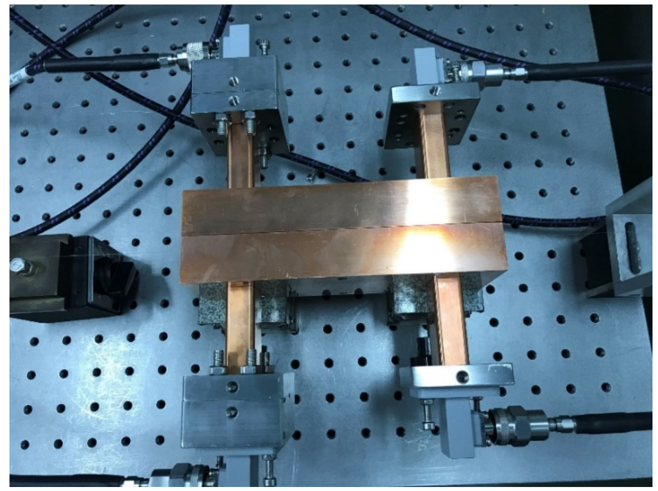
Input power	51.8 MW
Gradient	110.2 MV/m
BDR	1.26Ã—10^{-6} bpp
Pulse width	252 ns
Total RF pulse	6.5Ã—10^{8}
Total BD number	6000
Total RF-on time	3600 hours



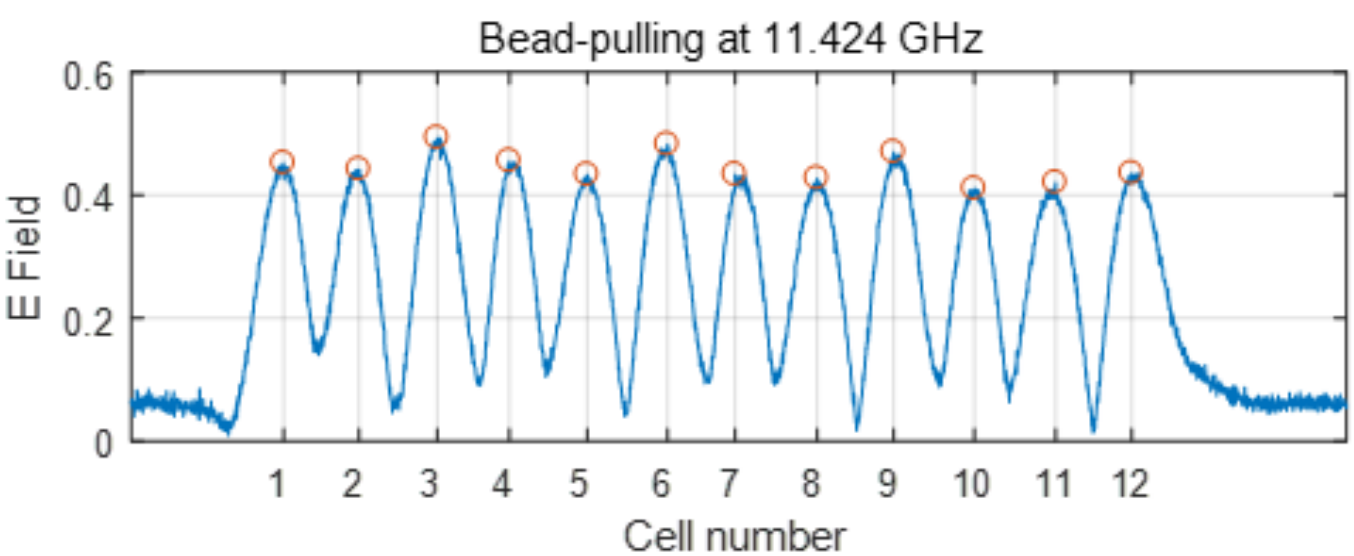
Parameters of high power tests of T24_THU#1 at KEK

Designed and manufactured a 12-cell open cell



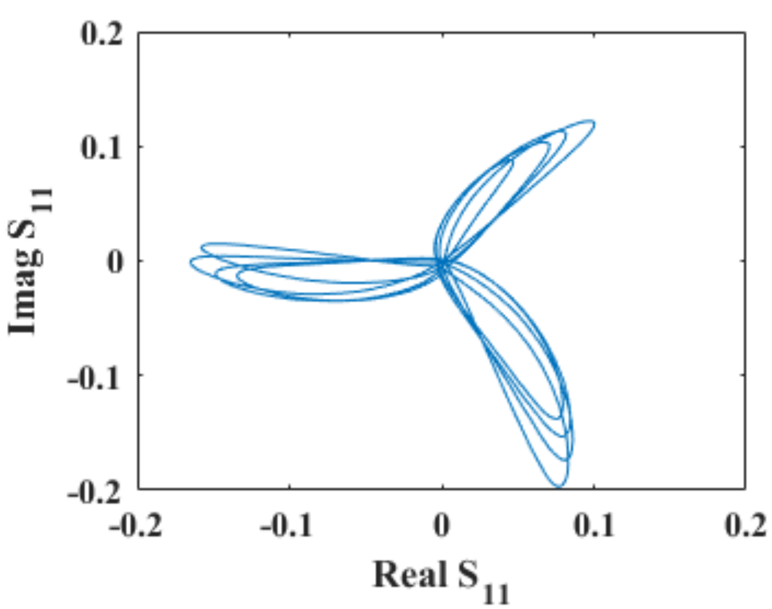


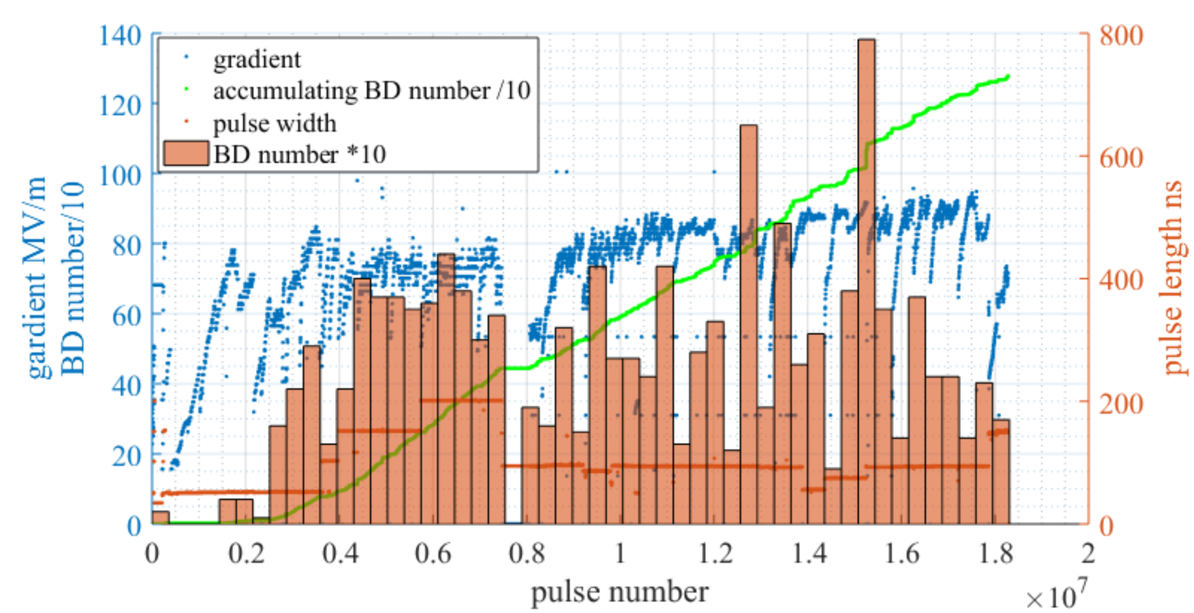
Parameters for 100 MV/m gradient		
	C12-	T24-
Input power [MW]	65.3	45.3
Output power [MW]	52.56	26.3
Filling time [ns]	14.7	48.2
Max surface E-field	255	264
Pulse temperature	30	23
Max surface *Sc*	**6.2**	**5.1**



High Power Test at TPoT-X:

Reached 87 MV/m with BDR= 7×10^{-5} / pulse and pulse width = 100 ns; now is still conditioning.





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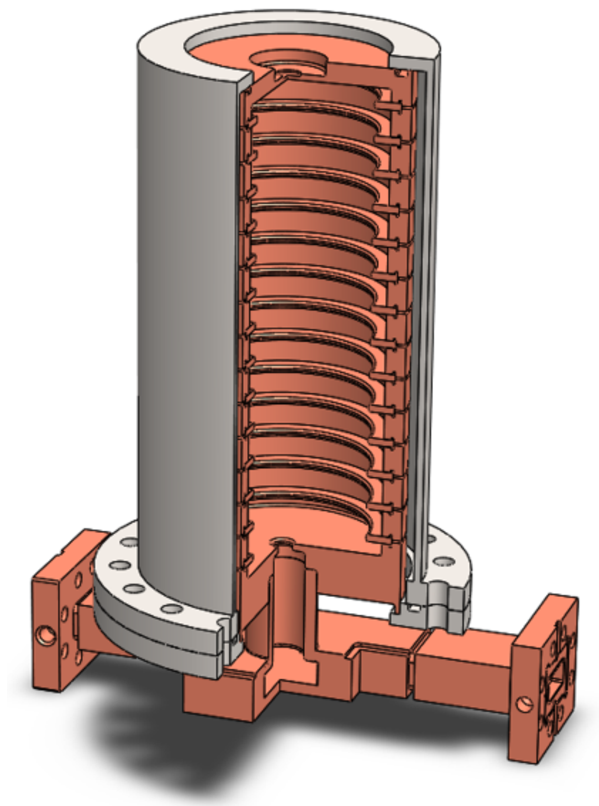
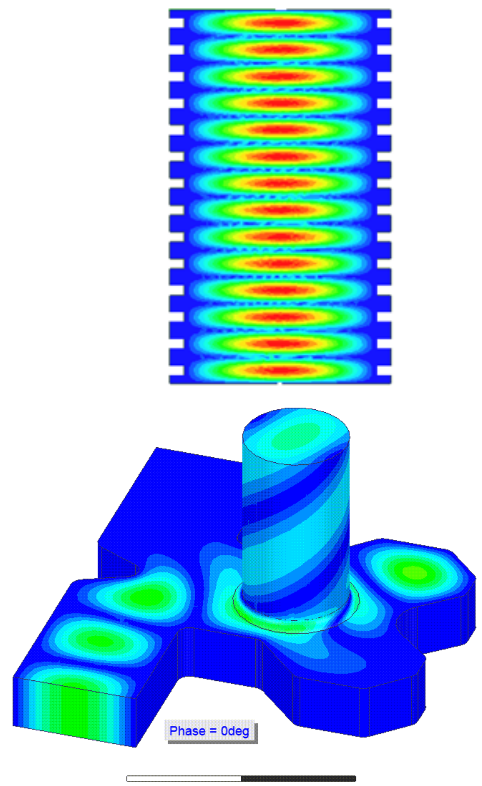
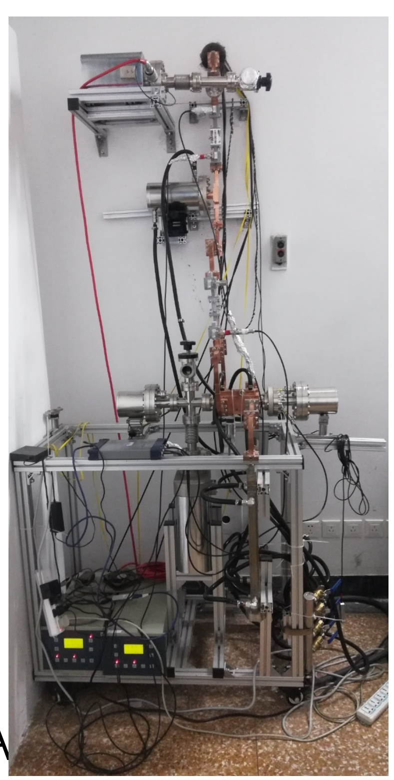
A compact SLED-I RF pulse compressor using a cylindrical corrugate cavity was designed and tested at TPoT-X : Peak power gain = 5 for 1.5 us -> 100 ns

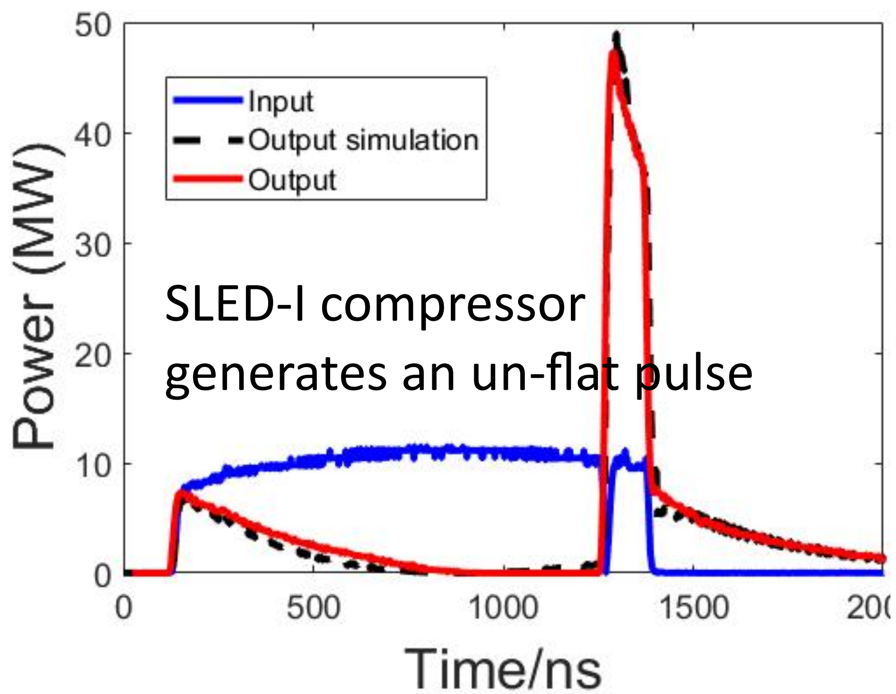


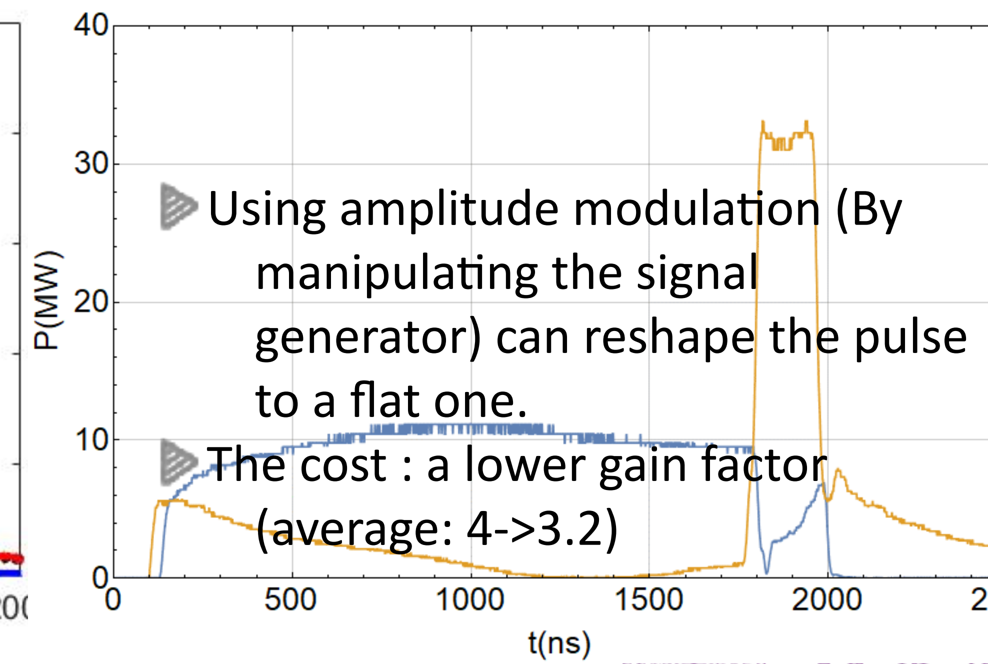


Operation frequency	11.424GHz
Mode	$HE_{1\text{-}1\text{-}14}$
Cavity diameter ($2a$)	69.60 mm
Cavity length	191.52 mm
Corrugation depth (d)	6.56 mm
Corrugation distance (h_1)	10.68 mm
Corrugation width (h_2)	3.00 mm
Quality factor (Q_0)	115,000
Iris diameter	8.18 mm
Coupling coefficient (β)	3.5

TPoT-X







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Summary

- Inverse Compton Scattering (**ICS**) between an electron bunch of hundreds of MeV and a laser pulse is one of the best ways to generate high brightness gamma-ray.
- Several projects of ICS source. **TTX-I**, **TTX-II** are operating or under construction.
- **VIGAS** (Very compact Ics GAmma-ray Source) whose main linac is based on high gradient x-band structures has been designed, and the key technologies of it is under R&D.