國家同步輻射研究中心
National Synchrotron Radiation Research Center

Current Status of Taiwan Photon Source Operations

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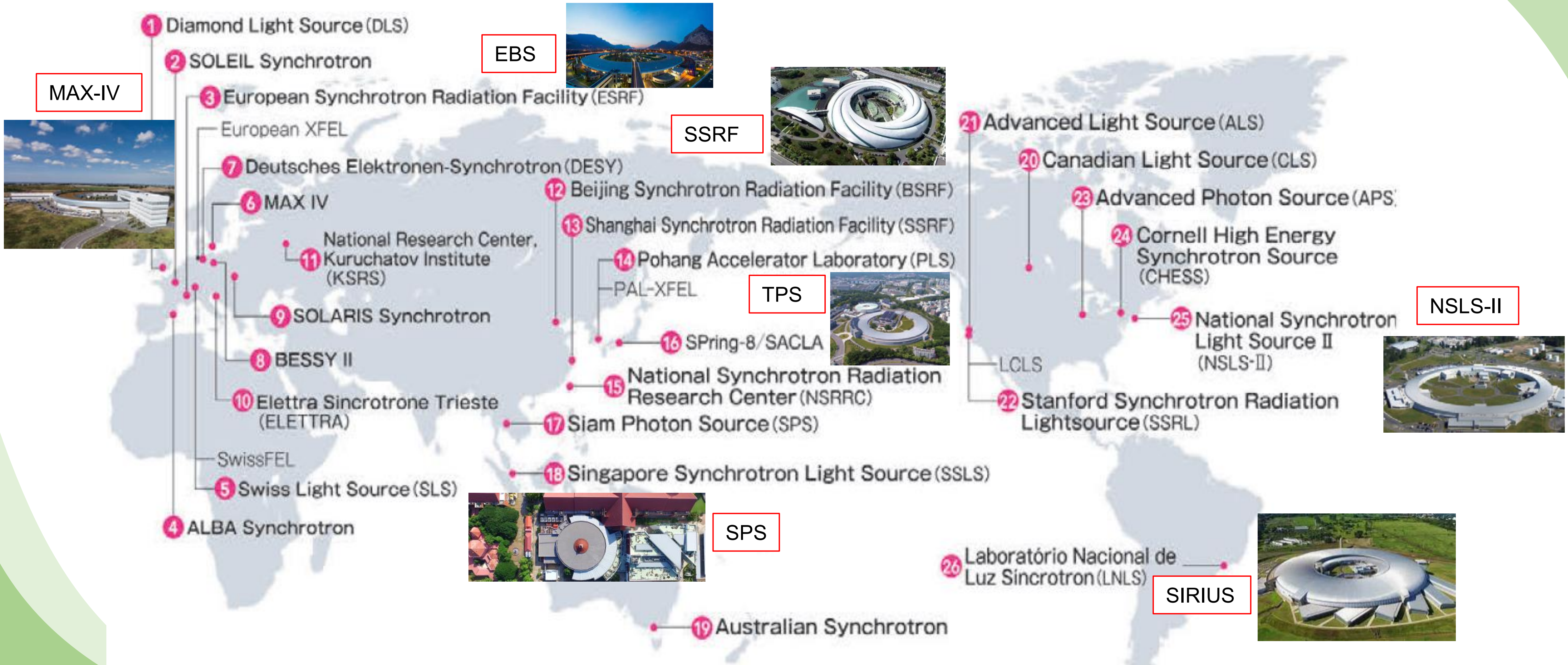
National Synchrotron Radiation Research Center (NSRRC)

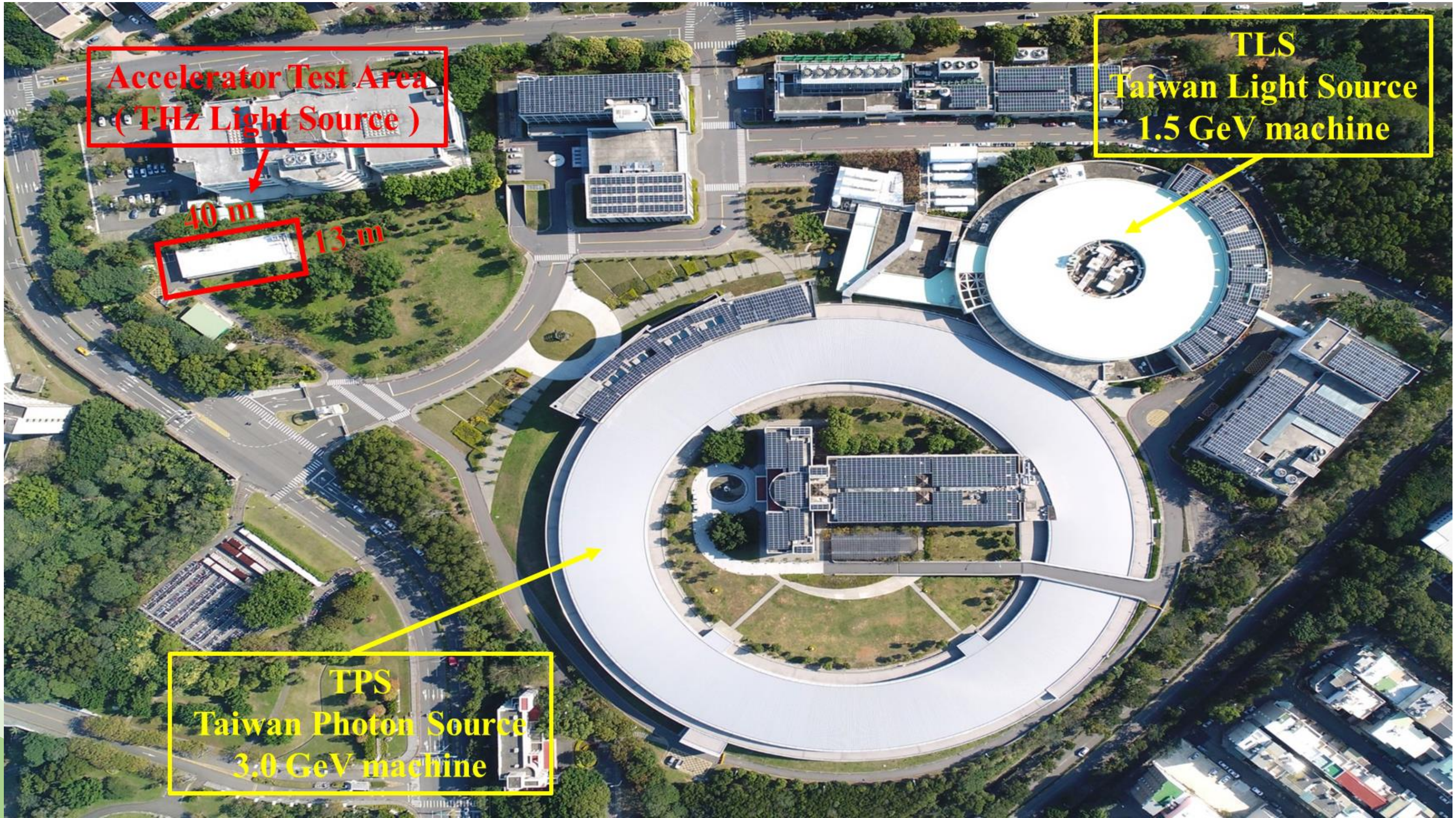
OCPA 2025, August 5, 2025

World’s Synchrotron Ring Facilities



Introduction of NSRRC Light Sources

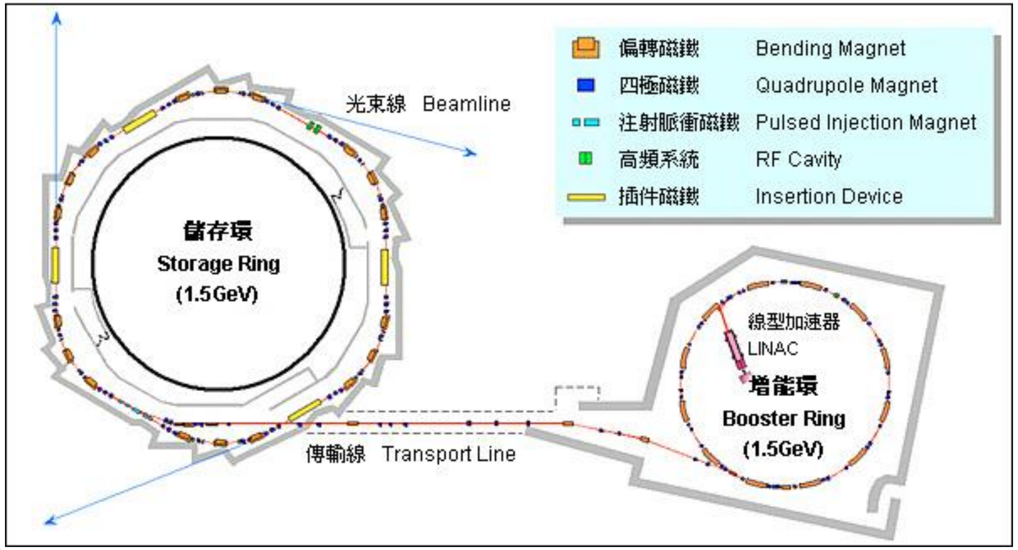
Light Sources at NSRRC

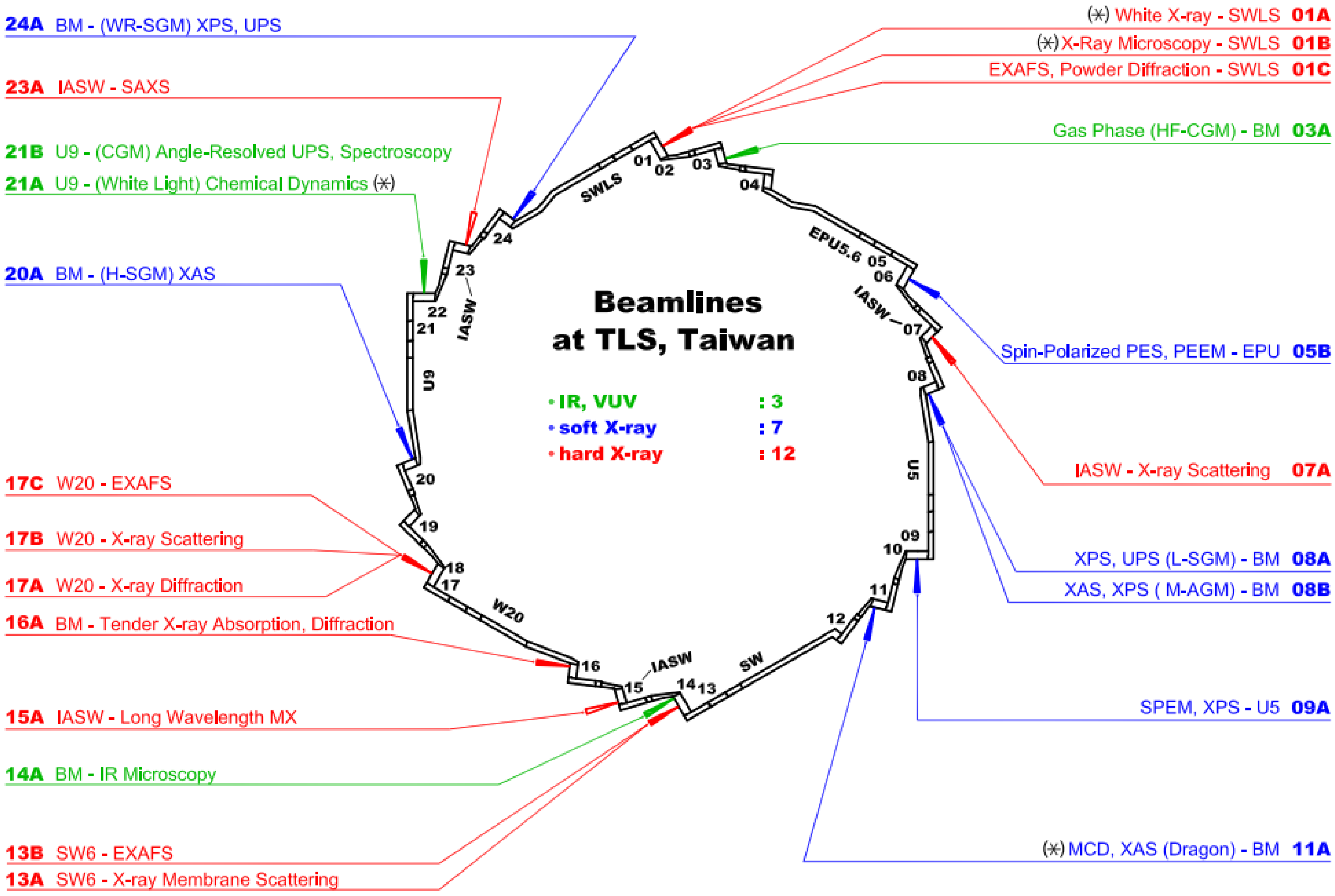


Current Machine Parameters

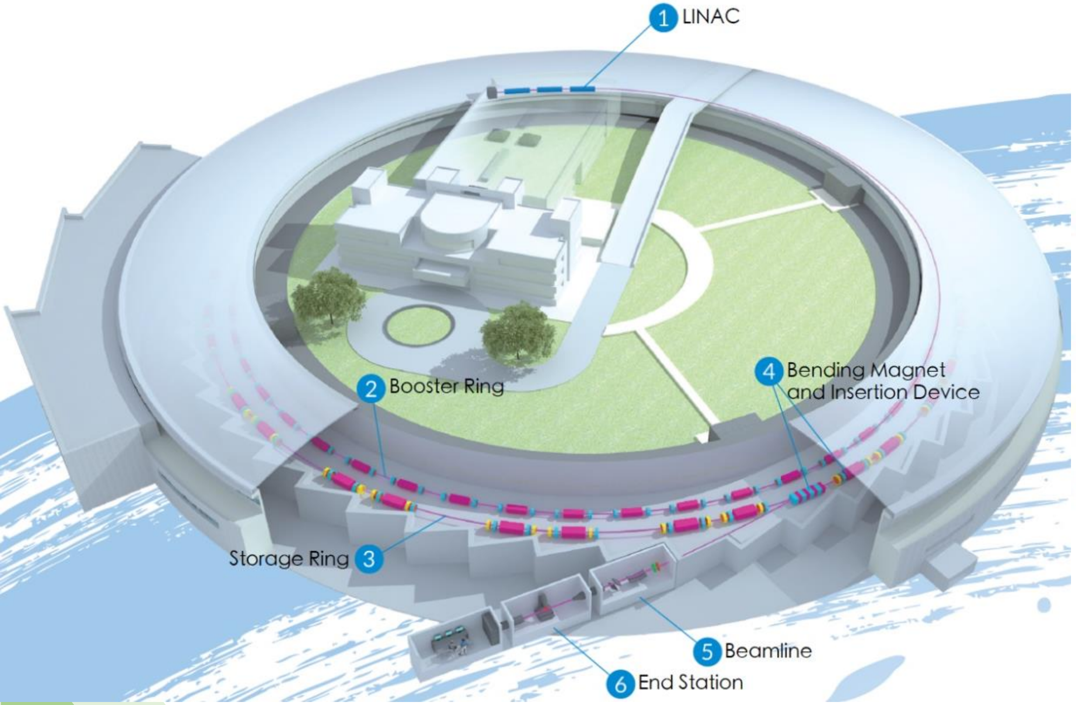
Main parameters	TLS	TPS
Energy [GeV]	1.5	3
LINAC [MeV]	50	150
Circumference of SR [m]	120	518.4
Operation Current [mA]	360	500
Emittance [nm-rad]	22 / 0.088	1.6 / 0.016
RF voltage [MV]	1.3	3.0
Straight Sections	6× 6m	6× 12m 18× 7m

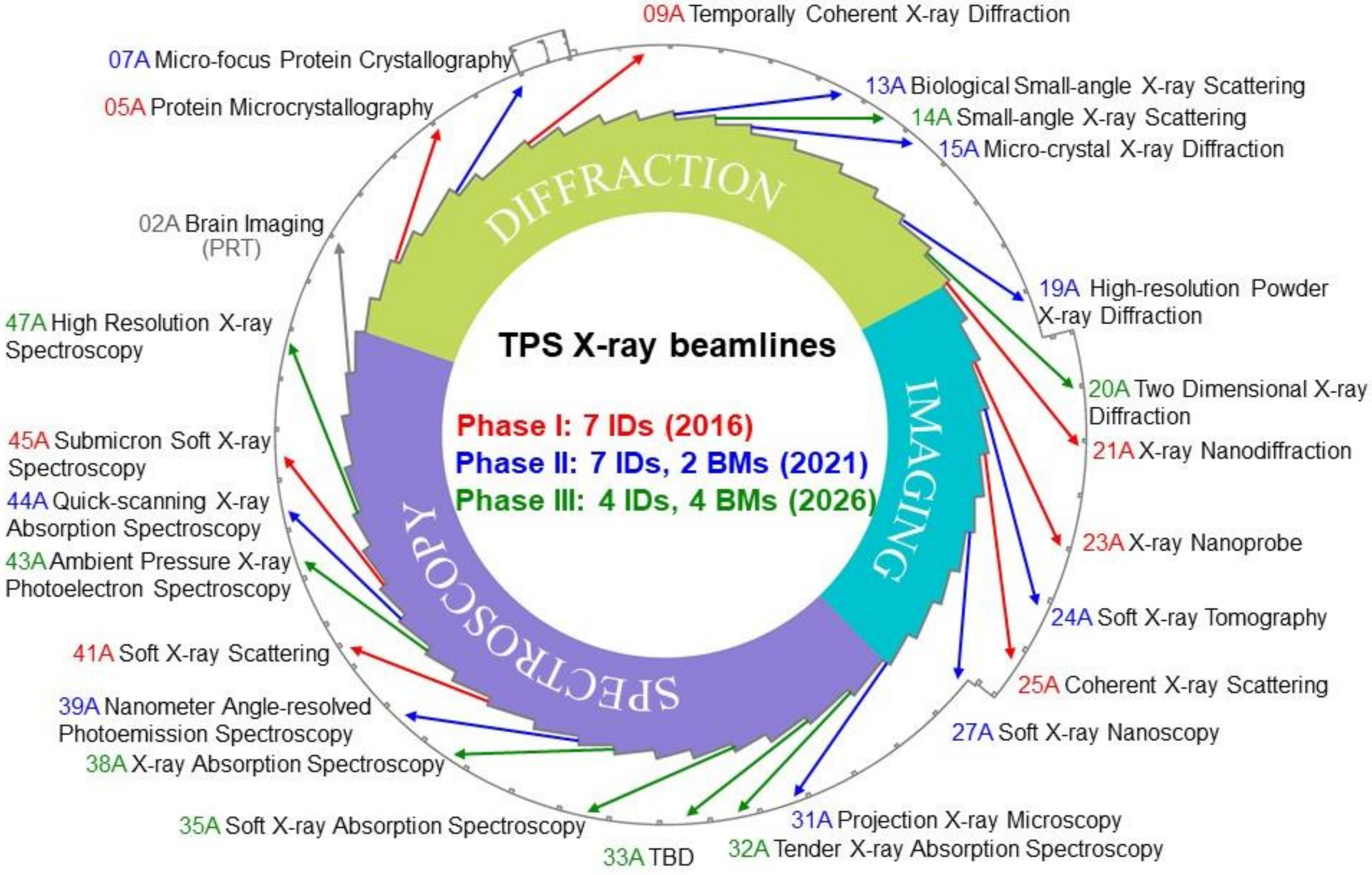
TLS Beamlines to End-Stations





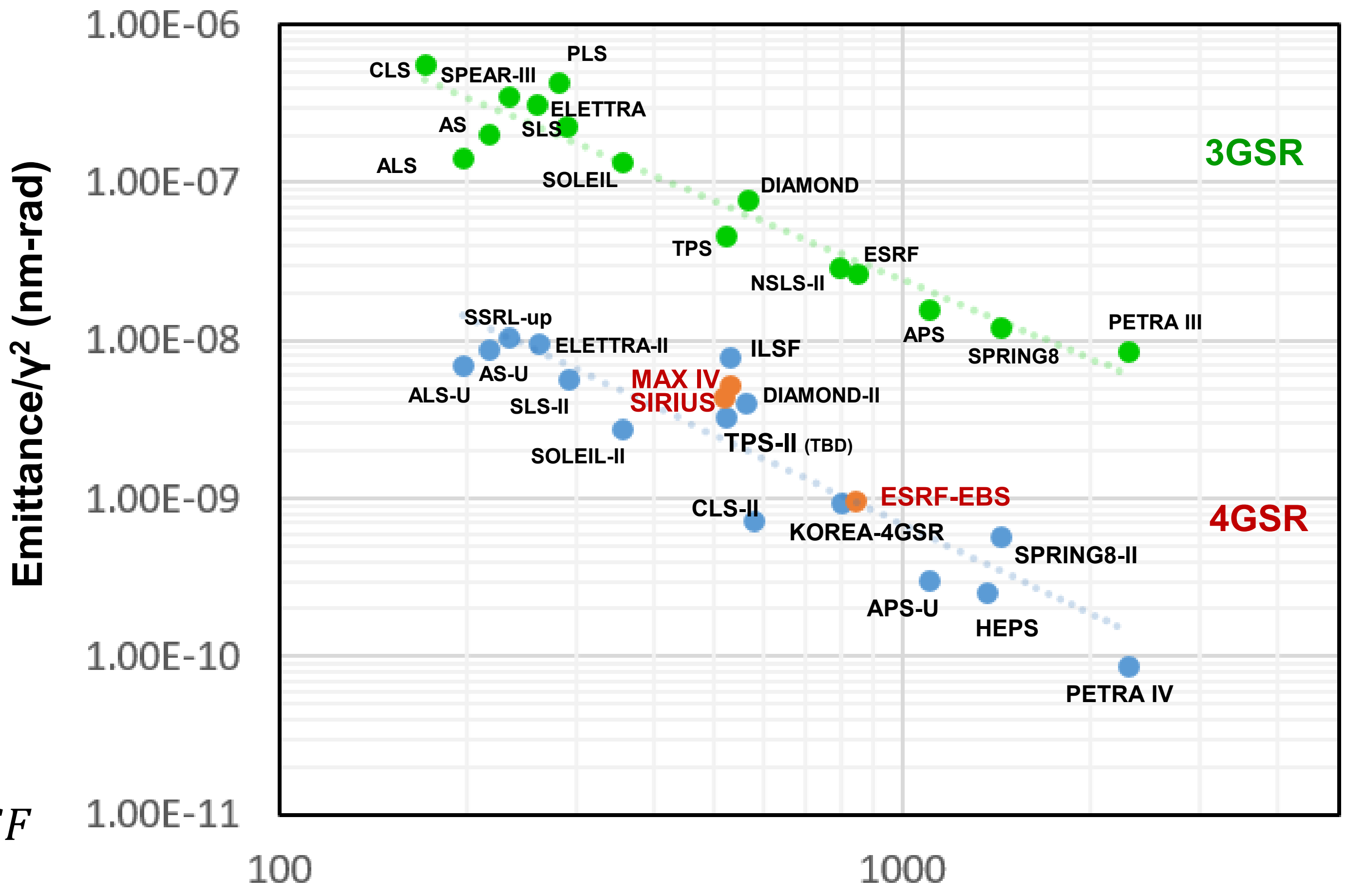
TPS Beamlines to End-Stations



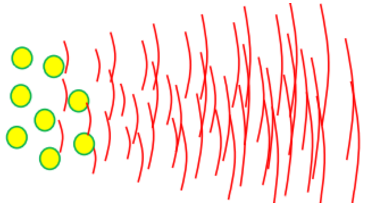


Toward diffraction-limited Storage ring light sources

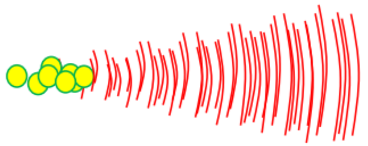
➢ Toward smaller electron beam emittance ring to increase the light brightness, spatial coherent flux, and coherent fraction.



Spatially incoherent



Spatially coherent



Coherent Fraction (CF)

$$CF = \frac{(\sigma_r \sigma_{r'})^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

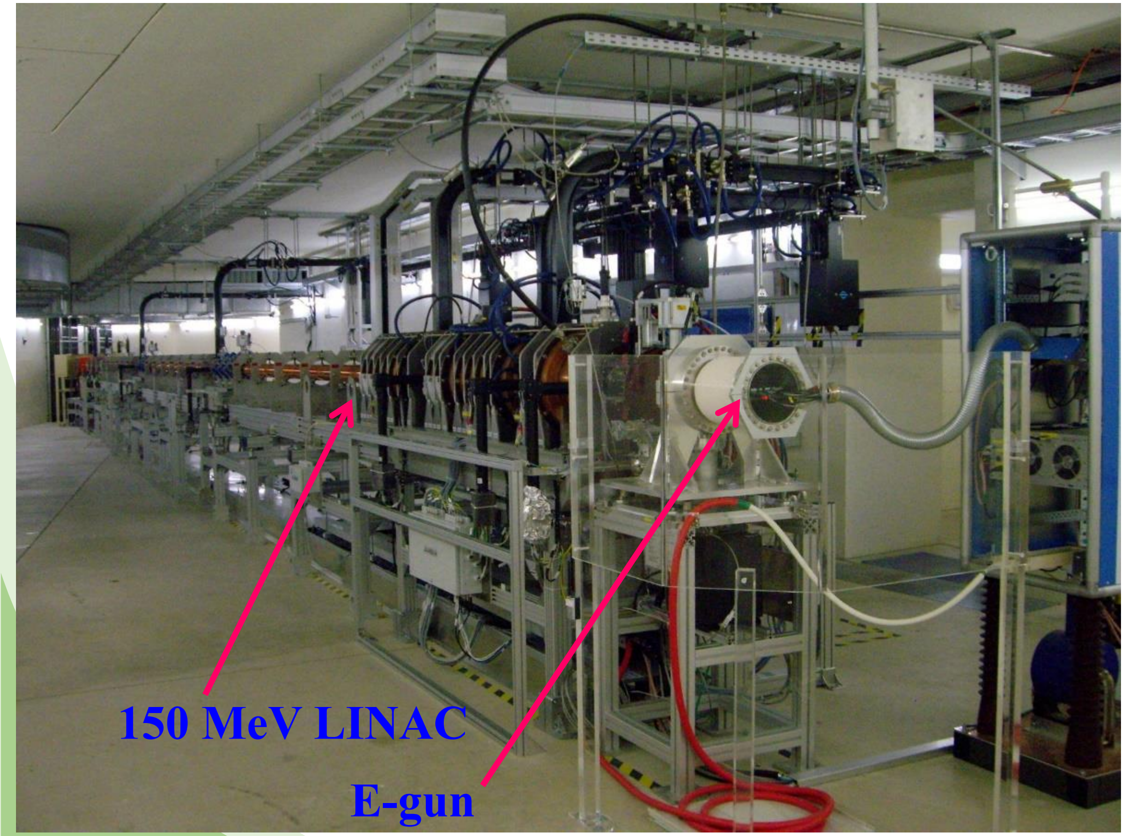
Spatial coherent flux

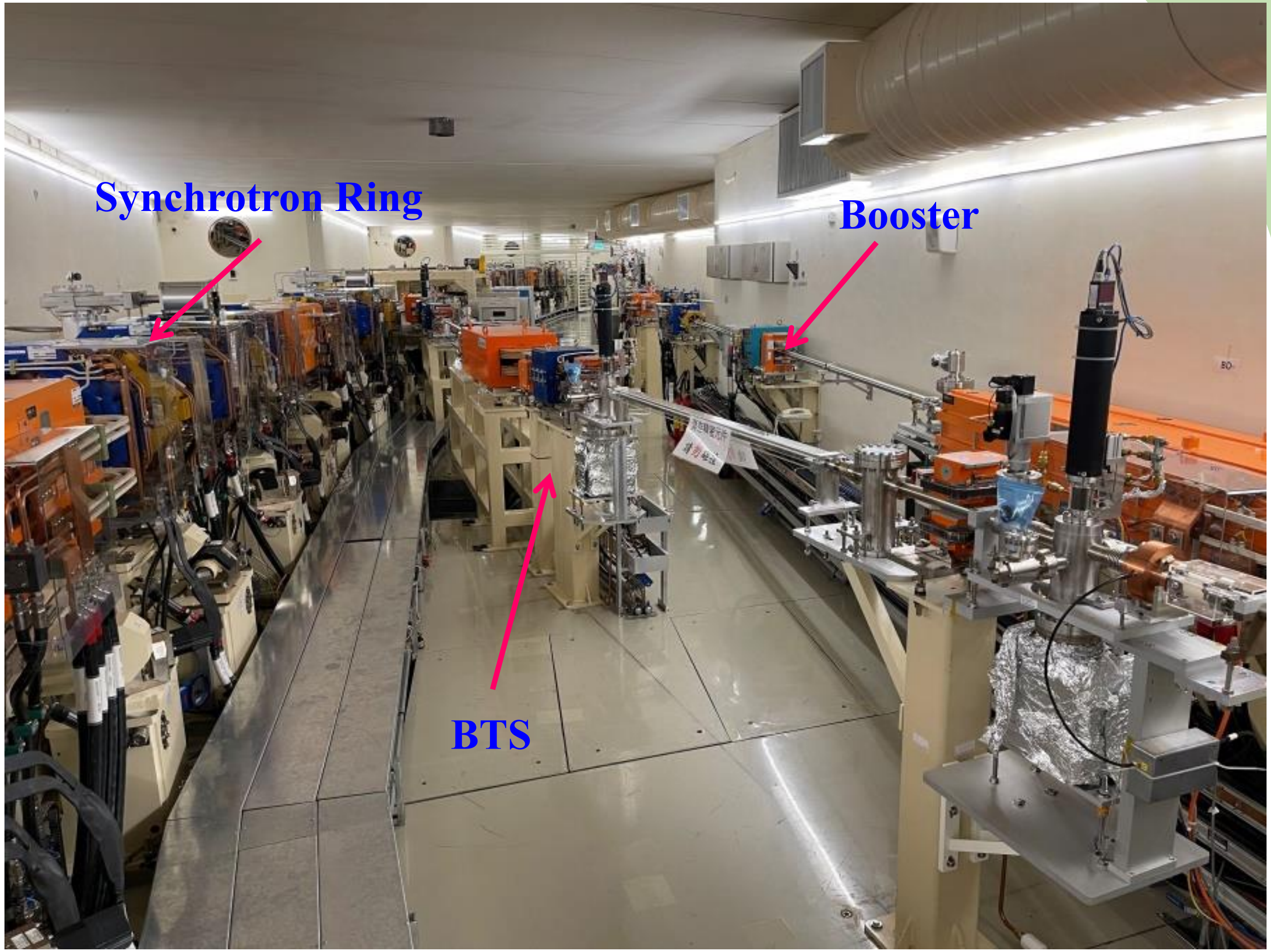
$$F_{coh,\ transverse} = flux * CF$$

The data of TPS-II (TBD) here is ε = ~~115~~ pm-rad, striving toward a goal that is ten times smaller than the current specification.

[Ref] #1 Multi-Bend Achromat Lattice Design for the Future of TPS Upgrade, M.S. Chiu et al., Journal of Physics: Conference Series, 1350, 2019, 012033.
#2 Masahiro Katoh, Lecture notes of "Synchrotron Light Source", KEK IINAS 5th International School on Beam Dynamics and Accelerator Technology, 2022/11/23.

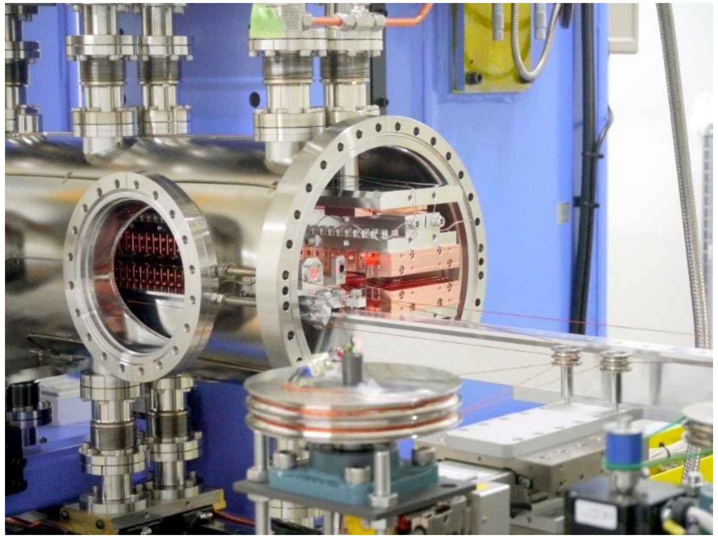
Inside the TPS tunnel

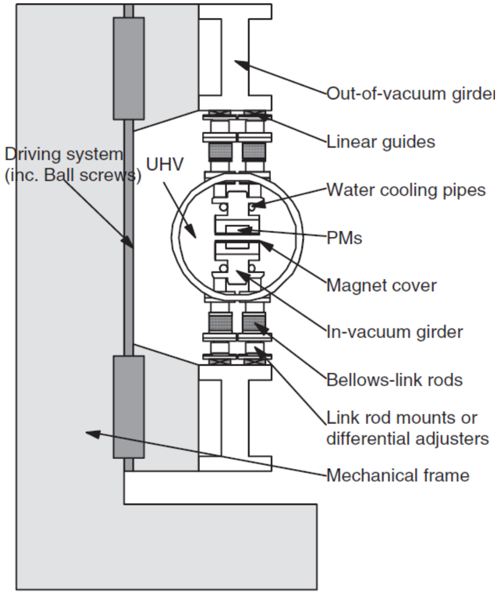




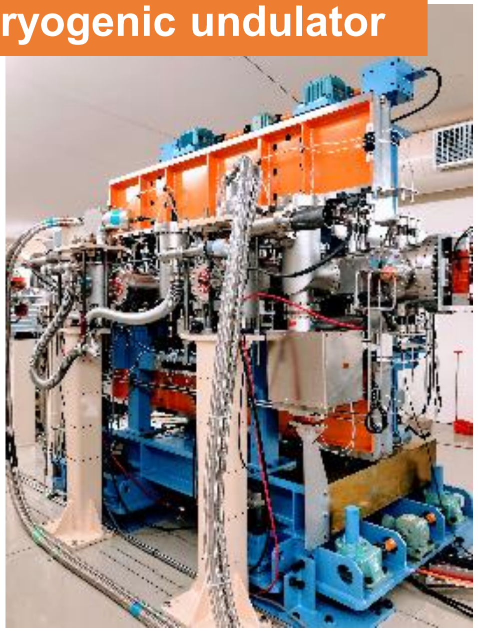
TPS Undulator Magnet

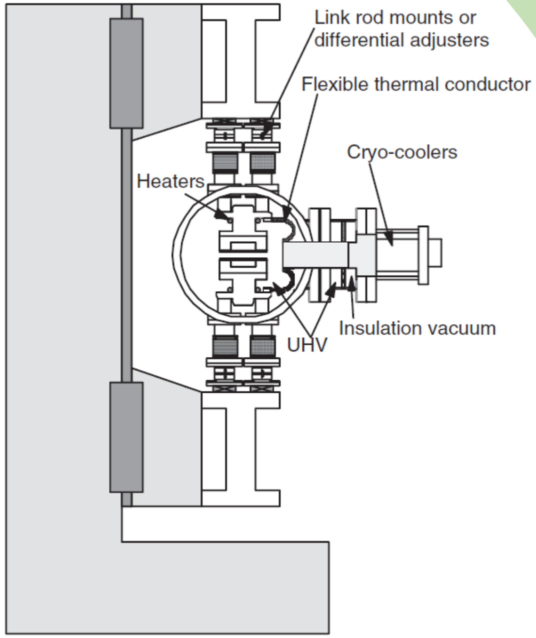
In-vacuum undulator





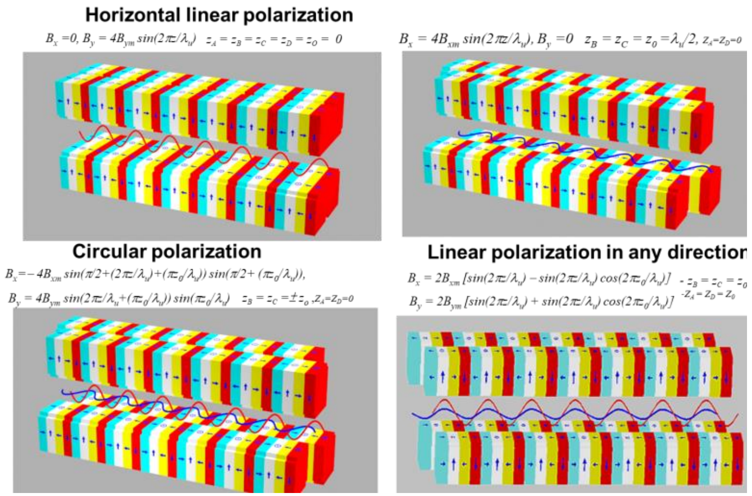
Cryogenic undulator





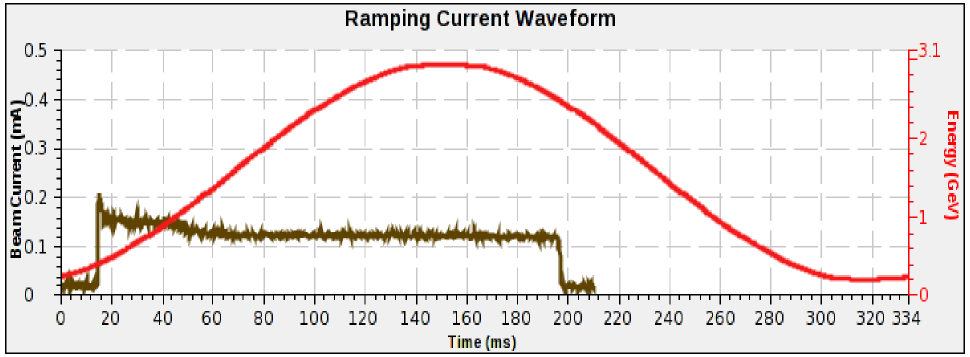
EPU 46

EPU 48

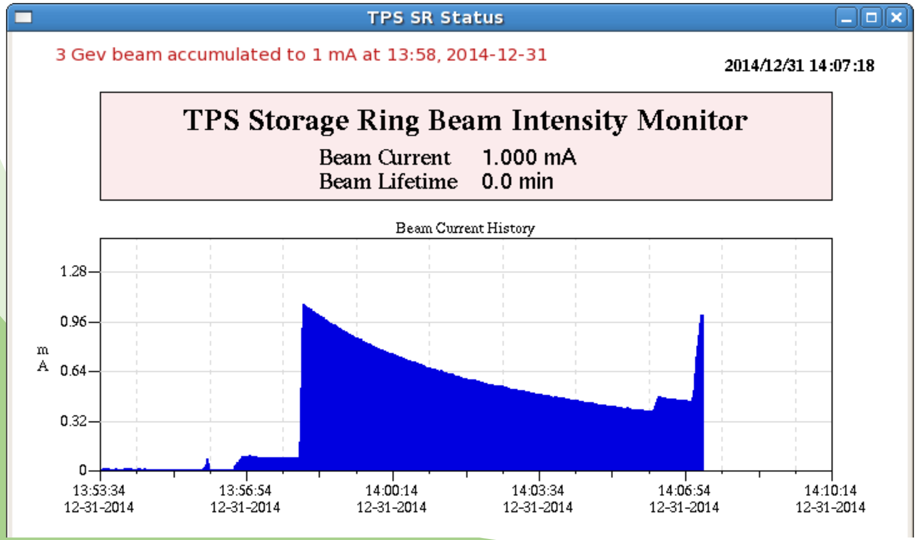


Control Room

Booster beam energy ramps to 3 GeV at 0.16 mA 2014-12-16



Storage ring beam current achieves 1 mA 2014-12-31

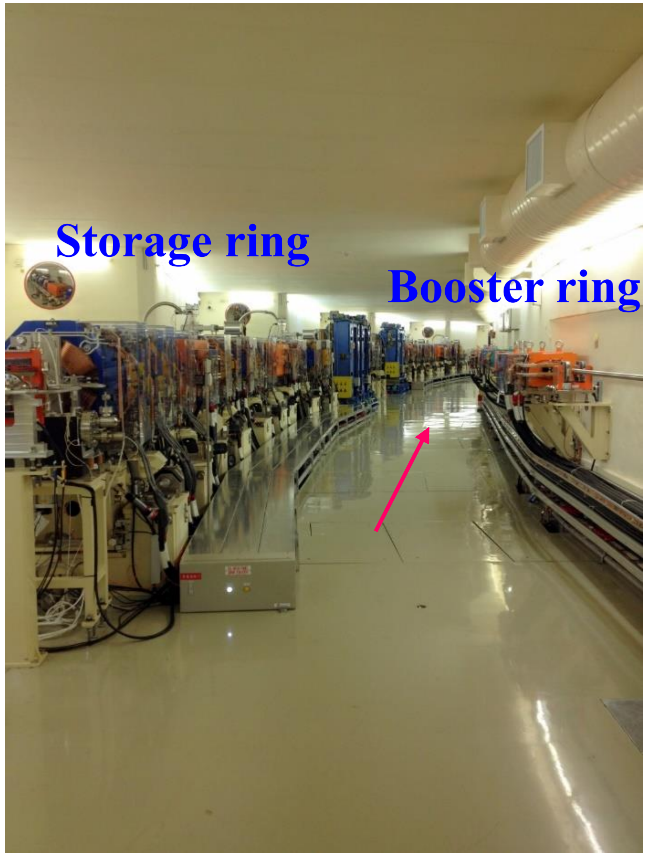


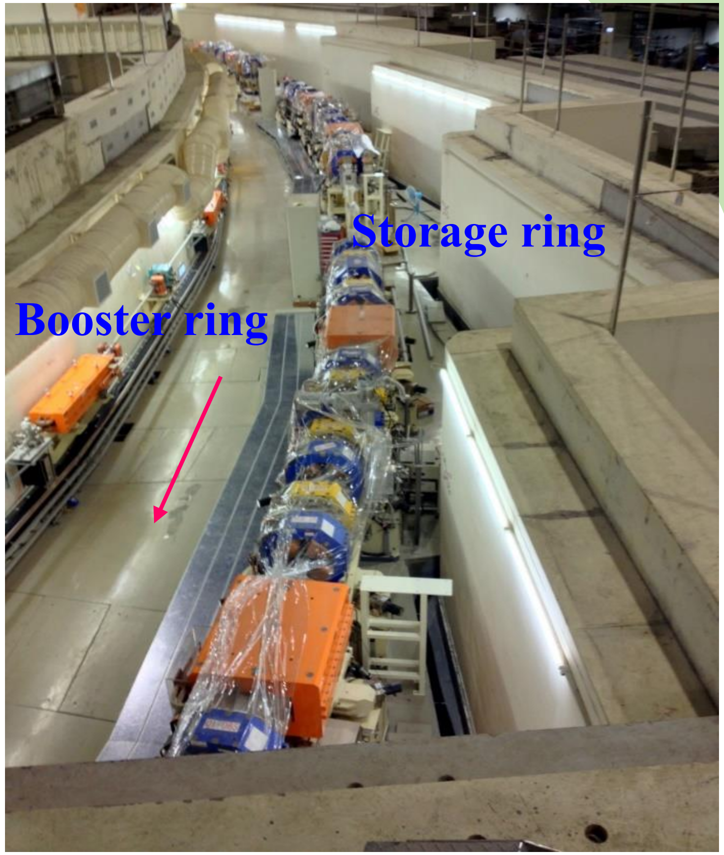
Taiwan Photon Source (TPS): From Design to Mature Operation

From Accelerator Design to Successful Commissioning

Design Objectives:
Enhance light source brightness
→ Requires reducing the electron beam emittance and increasing the stored current
Energy-efficient design
→ Aims to reduce the power consumption during routine operation

Practical Constraints:
Reducing electron beam emittance
→ A larger accelerator circumference is preferable (but limited by geographical conditions)

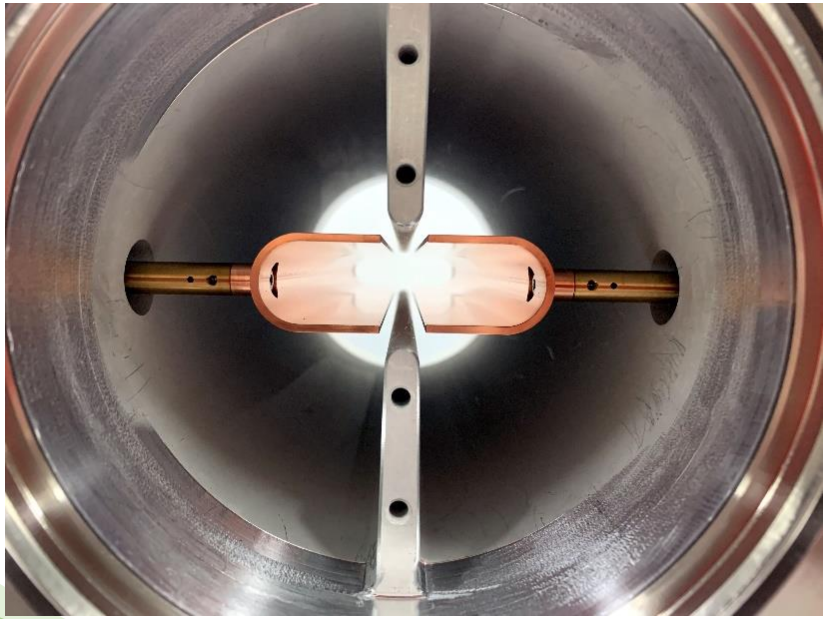




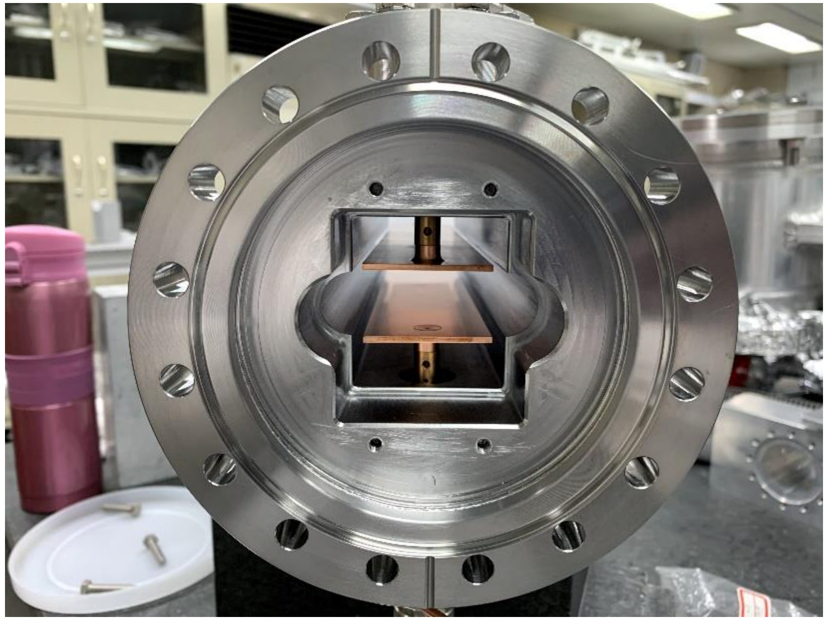
- On **December 31, 2014**, the electron beam was injected into the storage ring for the first time and accumulated to **1 mA**.
- On **January 15, 2015**, the storage ring current was increased to **30 mA**.

Optimization of Accelerator Parameters and Stable Operation

- Optimization of accelerator subsystem parameters → **Injection efficiency into the storage ring reaches 85%–90%**
- Monthly calibration of the storage ring's magnetic lattice functions → **Improves the stability and reproducibility of various beam properties**
- Continuous optimization of the fast orbit feedback system → **Maintains the stability of the electron beam orbit**
- Establishment of a feedback mechanism for the accelerator′ s working point (betatron tune) → **Ensures stability of the transverse beam size**
- Improvement of vacuum component design to reduce accelerator impedance → **Enables the storage ring current to reach 500 mA**

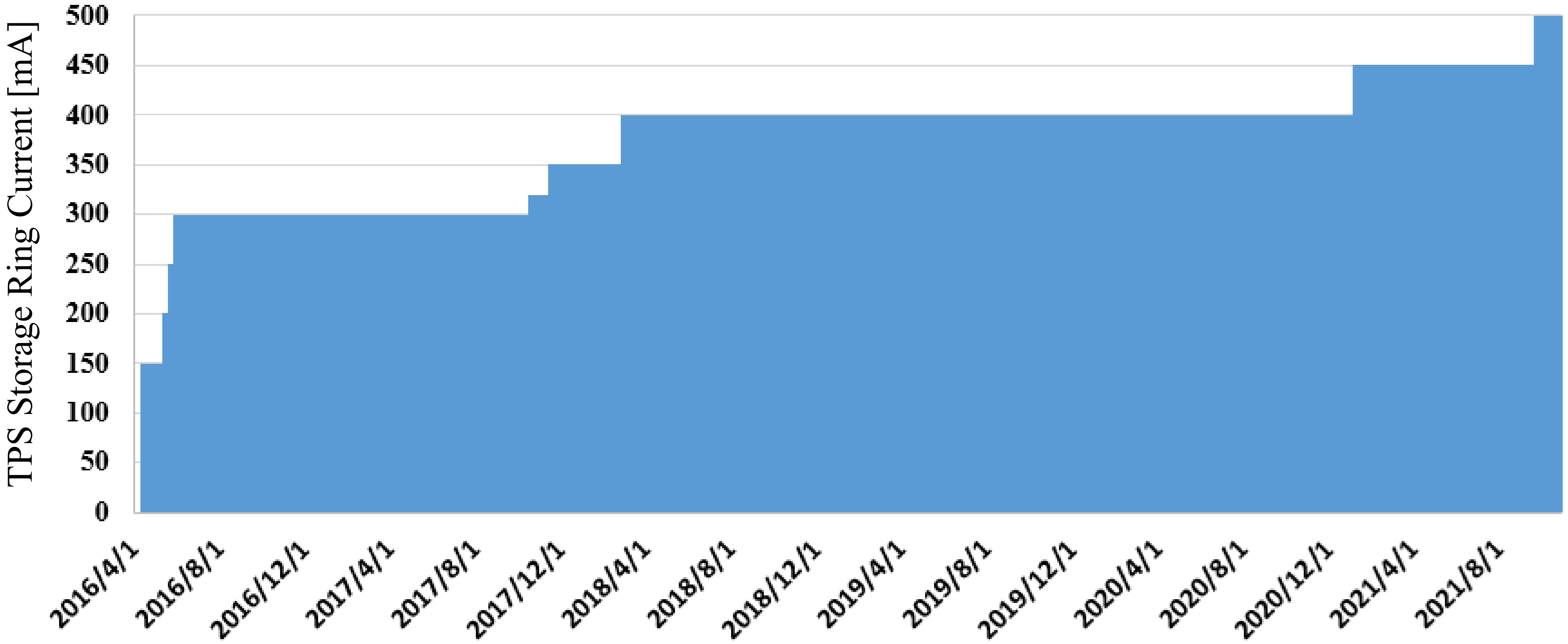


Horizontal BBF (Kicker)



Vertical BBF System (Kicker)

Taiwan Photon Source Operating Current



The highest photon flux among the new-generation synchrotron light sources:

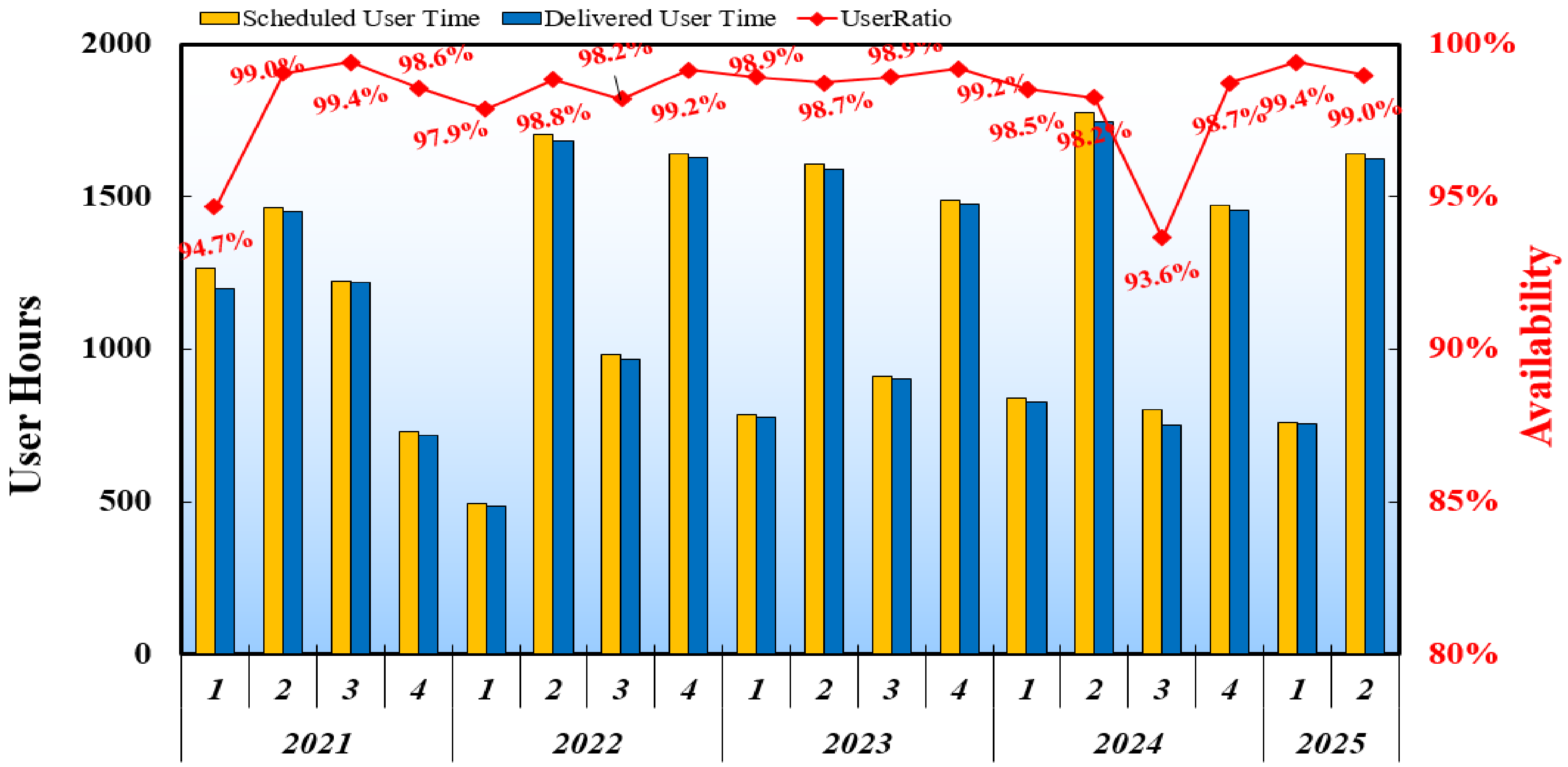
- Taiwan TPS (commissioned in 2015): routine operating current of 500 mA
- U.S. NSLS-II (commissioned in 2015): routine operating current of 400 mA
- Sweden MAX IV (commissioned in 2016): routine operating current of 300 mA

Operation Status of Taiwan Photon Source (TPS)

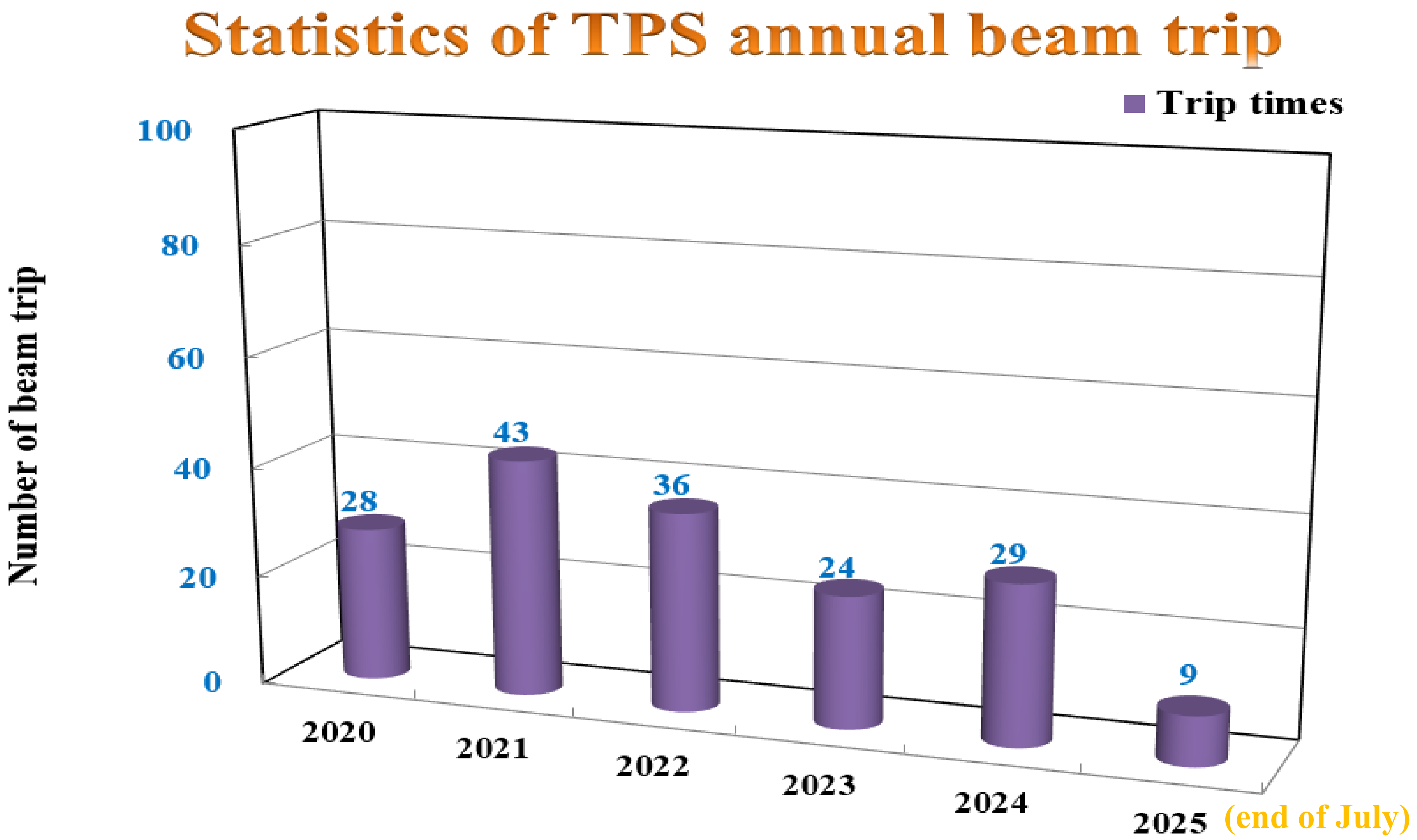
TPS - User Time and Availability

Scheduled user time 2024: 4,890 hrs, 2025: 2,399 hrs((end of July)

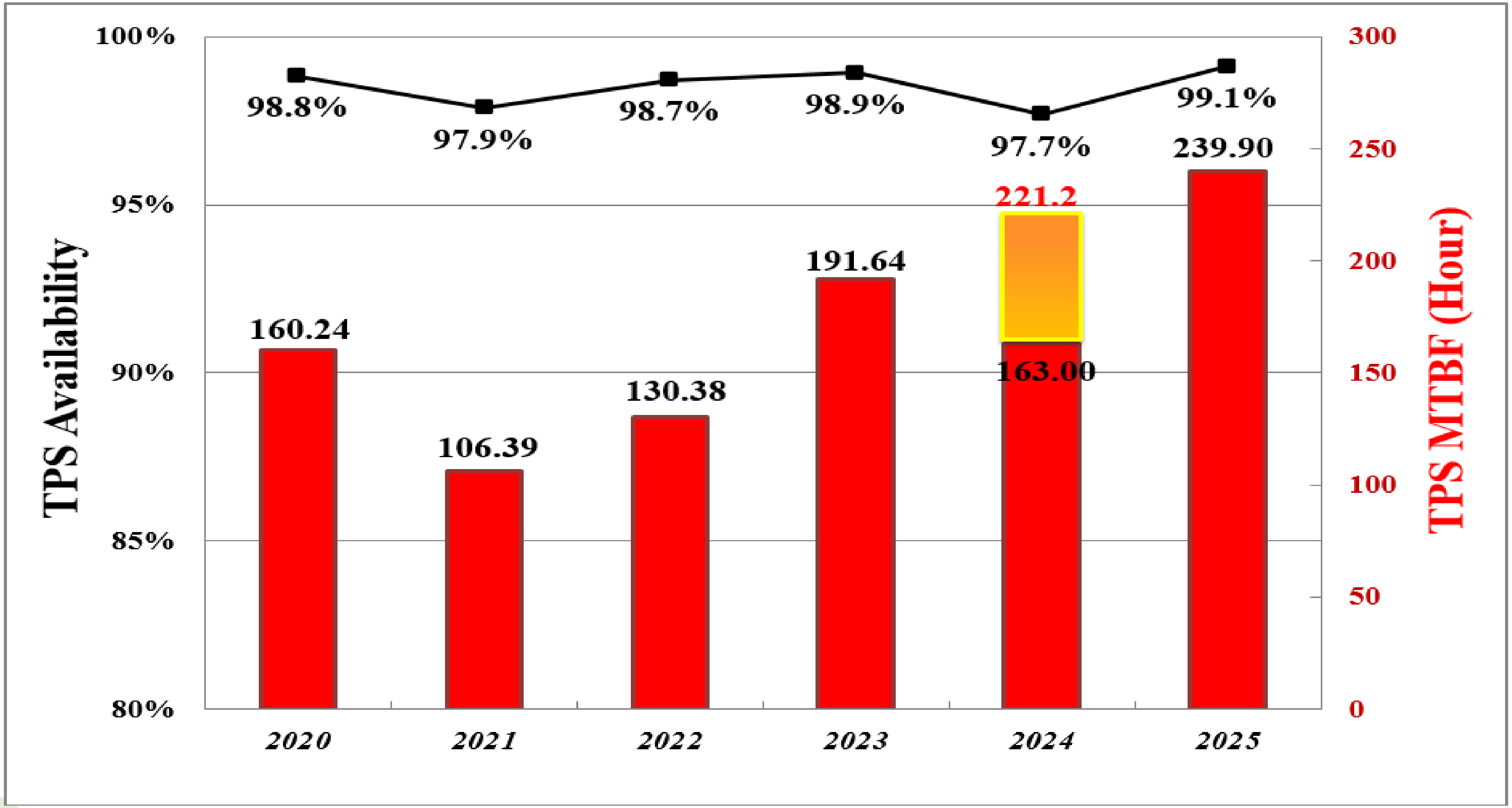
Availability 2024: 97.7%, 2025: 99.12%



TPS – Beam Trip Number



TPS - MTBF

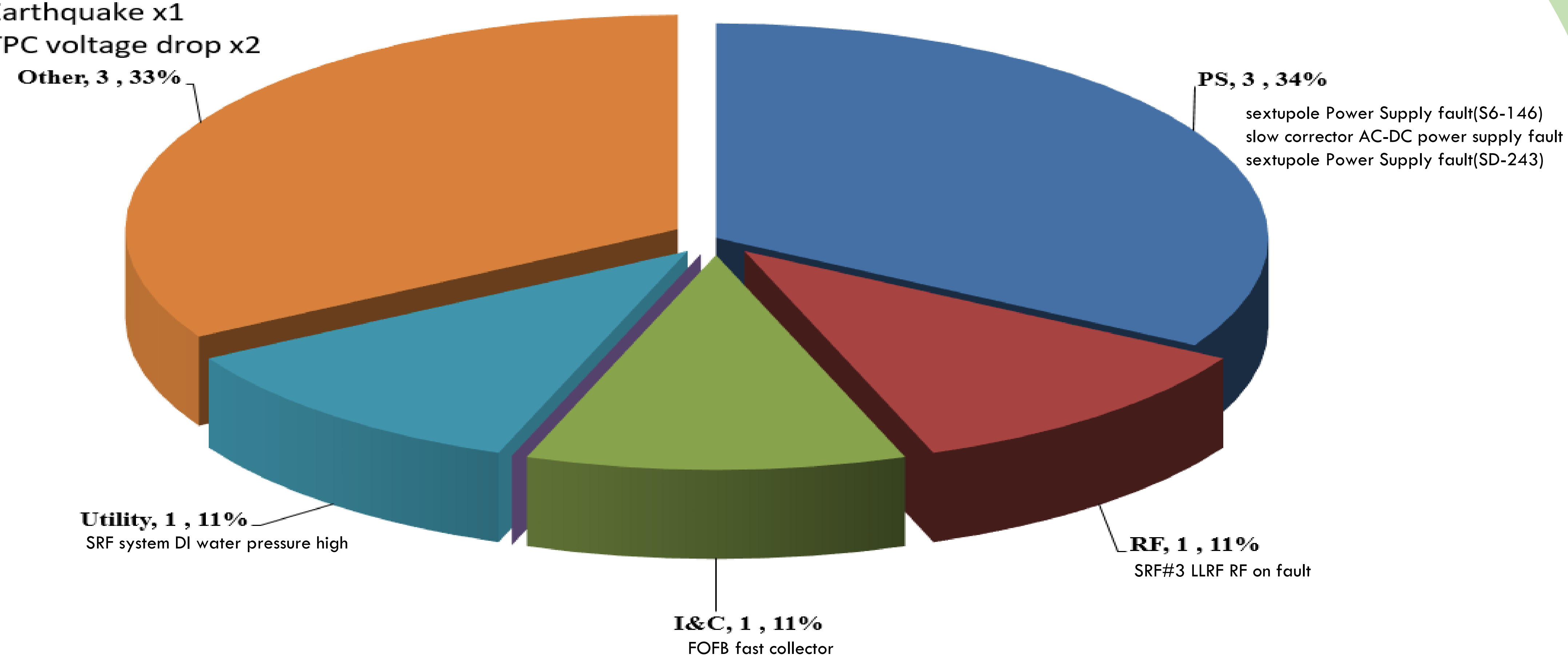


In 2024,

TPS – Trip Analysis

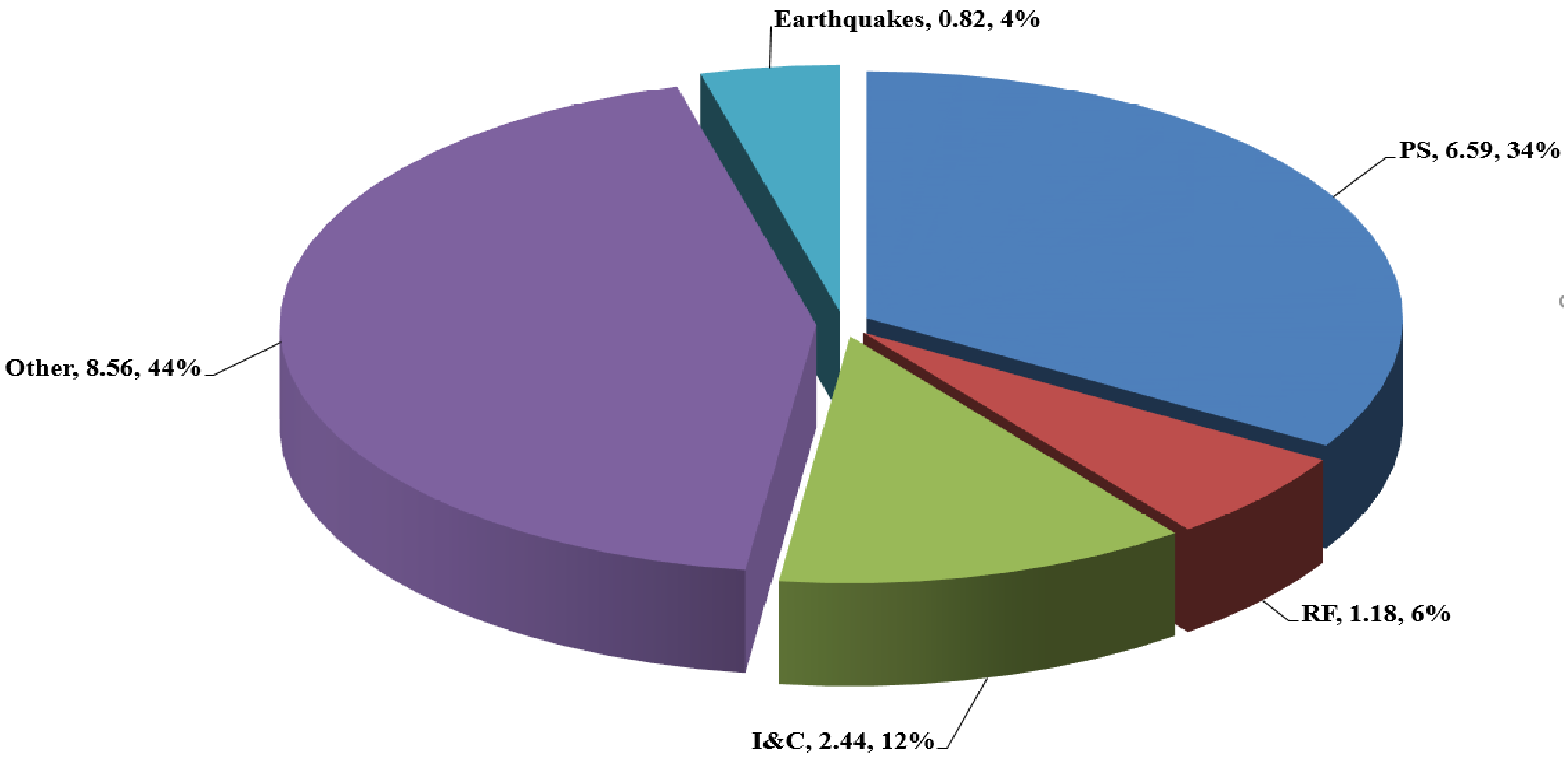
TPS 2025: 9 trip events in total by the end of July.

Other include:
- Earthquake x1
- TPC voltage drop x2



TPS – Downtime Analysis

TPS 2024/01-07
Downtime: 21.04 hours in total



Synchrotron Facility Operation Status Comparison

	年度	台灣光源 TLS	台灣光子源 TPS	美國光源 NSLS II	瑞士光源 SLS	英國光源 DLS	法國光源 SOLEIL	西班牙光源 ALBA	澳洲光源 AS	韓國光源 PLS II
Energy[GeV]		1.5	3	3	2.4	3	2.75	3	3	3
Schedule User Time[hours]	2019	5187	4635	5000	5056	4992	5082	4680	5048	4560
	2020	5112	4647	5130	4672	3445	4096	3584	3707	4560
	2021	5031	4681		5010	4532	4935	4646		
	2022	5040	4824		4960	5145	4015			
	2023	4791	4791		3500		4257			3264*
Beam Available [%]	2019	97.7%	98.4%	97.1%	99.2%	98.1%	98.9%	98%	98.9%	89.8%
	2020	93.3% (97.6%)	98.8%	97.0%	98.0%	96.2%	98.8%	98.2%	98.5%	82.7%
	2021	97.4%	97.9%		99.3%	97.4%	98.4%	96.4%		
	2022	98.9%	98.7%		97.4%	97.3%	99.0%	97.8%		
	2023	99.0%	98.9%		92.3%		97.3%			99.2%
Mean Time Between Value[hours]	2019	192.1	110.4	48.1	153.2	104.7	95.5	90	103	105.8
	2020	232.4	160.2	65.5	116.3	132	105.0	52.1	90	145.0
	2021	114.5	106.4		167	107.9	109	76.3		
	2022	168	130		97	112	139			
	2023	199.6	191.6		95		146			120*

*Jan 1, 2023-Aug. 1, 2023

**每周跳機一次的MTBF是128小時。

New Progress and Future Works on TPS Accelerator

Progress on TPS Accelerator

2021

– **500-mA routine operation at the last quarter, top-up + hybrid mode.**

2022

– **Upgrade on TPS FOFB system, greater bandwidth**

2023

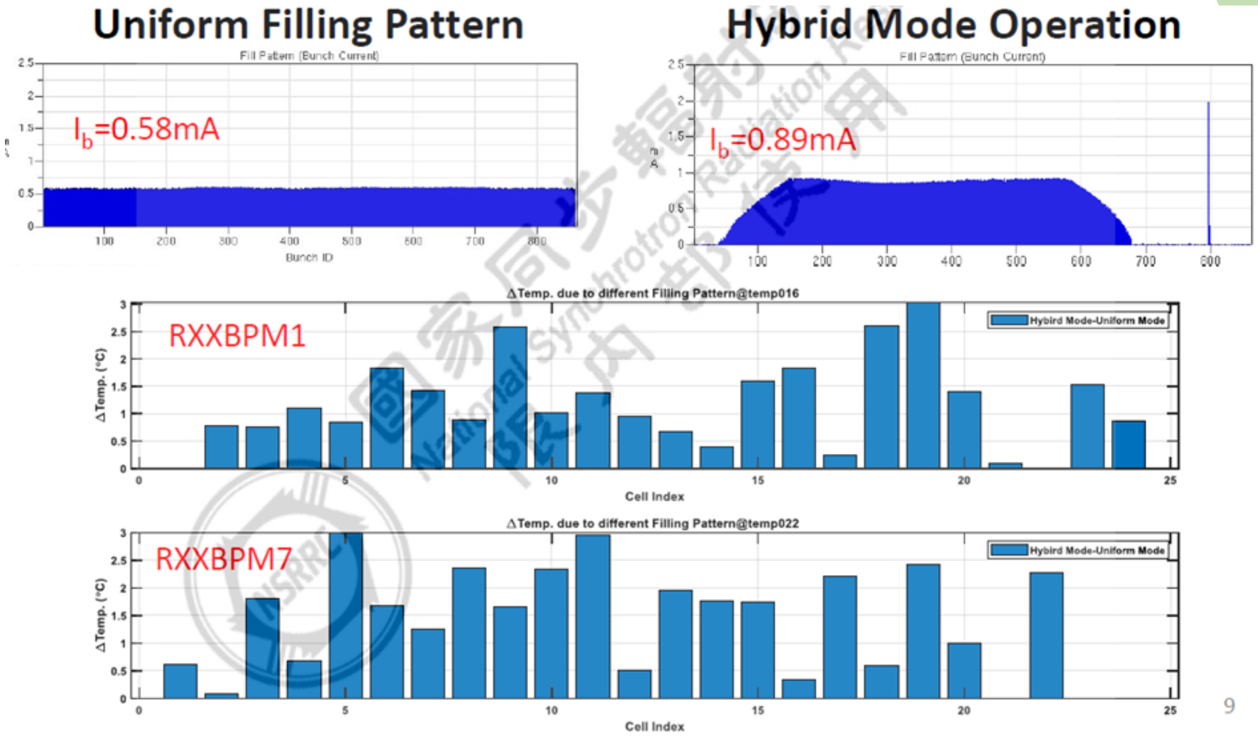
– **Three insertion devices (CUT18, EPU66, EPU168) are finished for remote beamline control.**

– **Routine operation of a homemade 320-kW solid state power amplifier (SSPA) for a superconducting RF module.**

2024

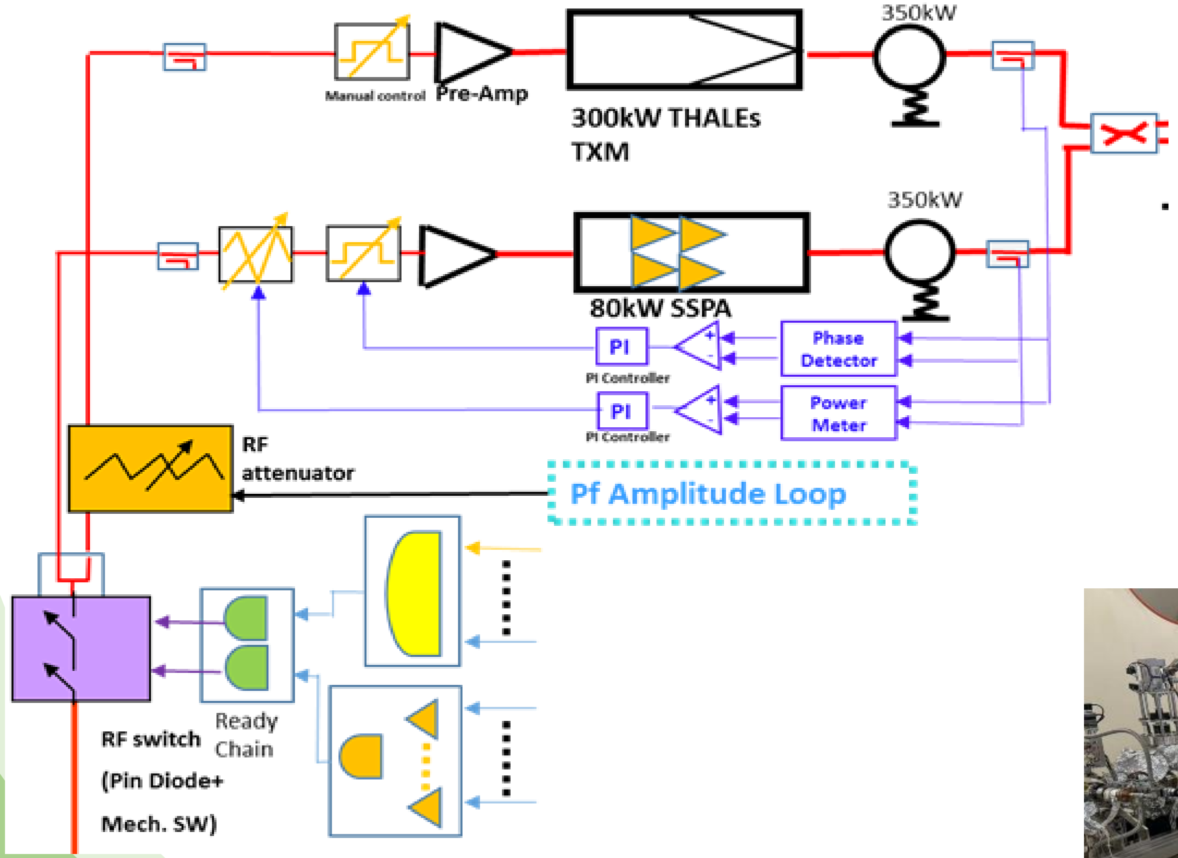
– **Successful uniform top-up mode operation reduces storage ring component heat loss.**

Uniform top-up mode operation

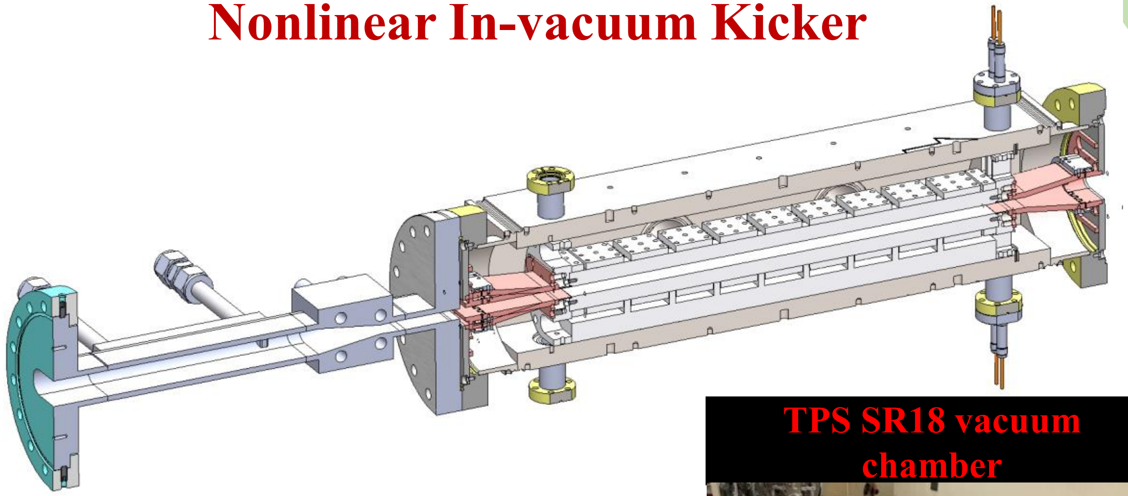


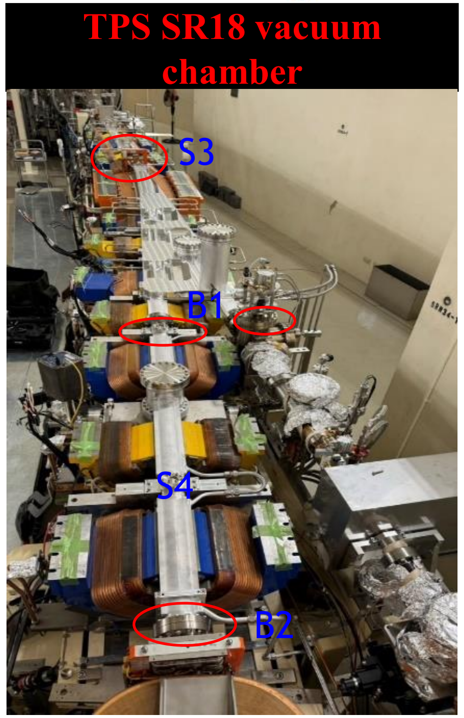
Progress on TPS Accelerator

1:4 RF power combine test



Nonlinear In-vacuum Kicker

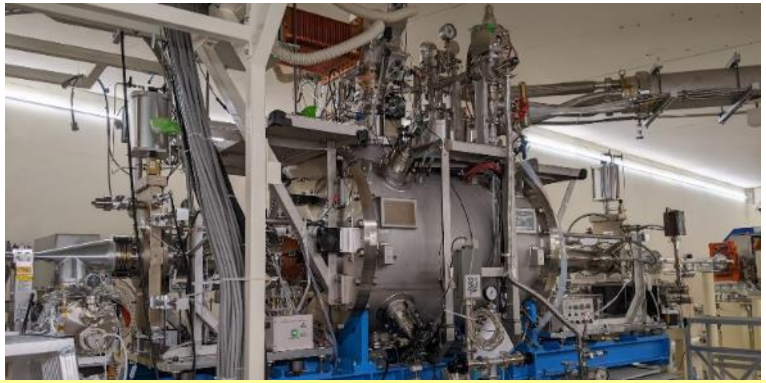




Accelerator Performance Enhancement and Indigenous Technology Development

MIT CU18 – Under Construction

中心設計 90%、台灣自製率 70%



500 MHz，4.5 KSuperconducting RF Resonator Assembly

日本設計，機構製造。台灣組裝，元件測試，性能試車。

Digital Fast RF Feedback Control System

中心設計與製造。射頻前端
模組參考美國NSLS-II設計。

320 kW 500 MHz High-Power Solid-State RF Source (NSRRC)

中心設計與製造

Large Aluminum Alloy Vacuum Chamber with Ultra-Low Outgassing Rate (NSRRC)

中心設計與製造

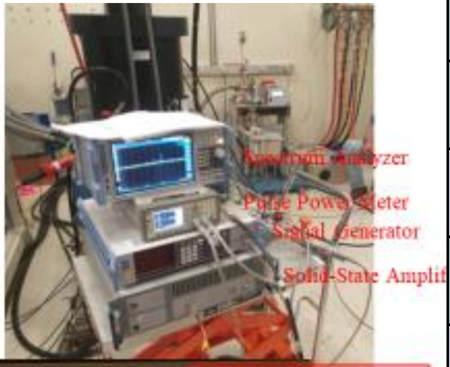
Testing and Improvement of the THALES TH2100 Klystron

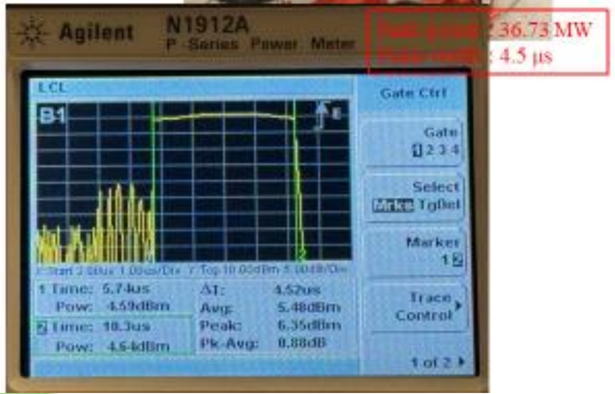



Operating klystron	Spares
TH2100A #113 (TPS)	2 #18 #108
TH2100A #109 (TPS)	
TH2100A #105 (TPS)	

Final Test of TH2100-109 Klystron

- The modulator used for the hot test was developed in-house by the LINAC team, with a voltage output pulse width of up to 4.5 microseconds. The LLRF system used was also a self-assembled system.
- The final test meets the specifications, the output power can reach 35 MW, and the waveform pulse width is 4.5 µs. The microwave output power measurement line attenuation is 99.3 dB, the peak measurement power is 6.35 dBm, and the actual output power is 36.73 MW





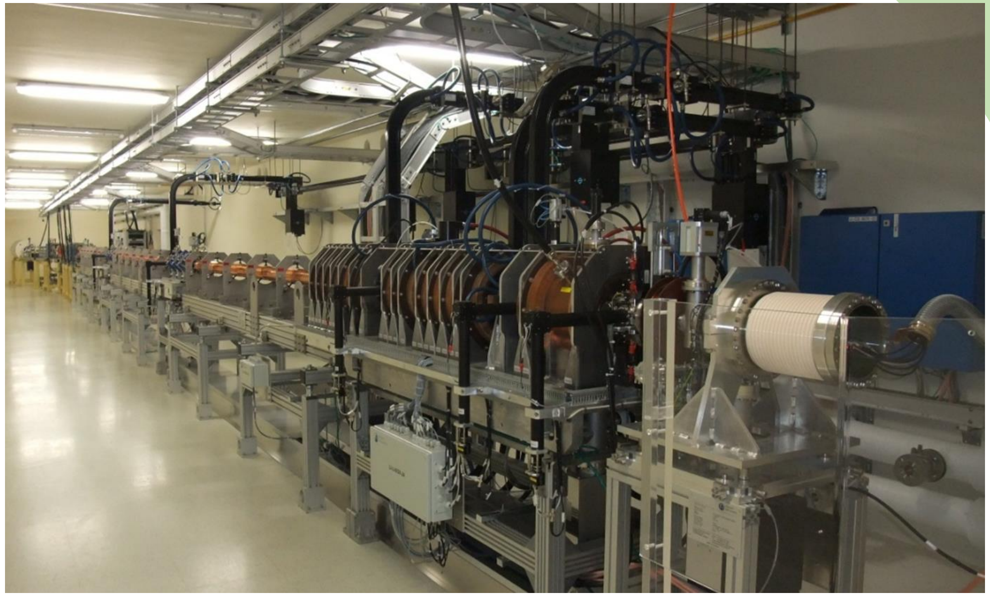
Faulty Klystron	Life Time (year)	Problem
TH2100A #21 (TLS)	N/A	Filament fail
TH2100A #48 (TLS)	9.6	Klystron arc
TH2100A #69 (TPS)	7.9	Filament fail
TH2100A #70 (TPS)	7.3	Klystron arc
TH2100A #72 (TPS)	7.9	Filament fail
TH2100A #86 (TPS)	2	Filament fail
TH2100A #100 (TPS)	4.2	Filament fail
TH2100A #104 (TLS)	2.6	Filament fail
TH2100A #106 (TPS)	3.8	Filament fail

Future Work of TPS

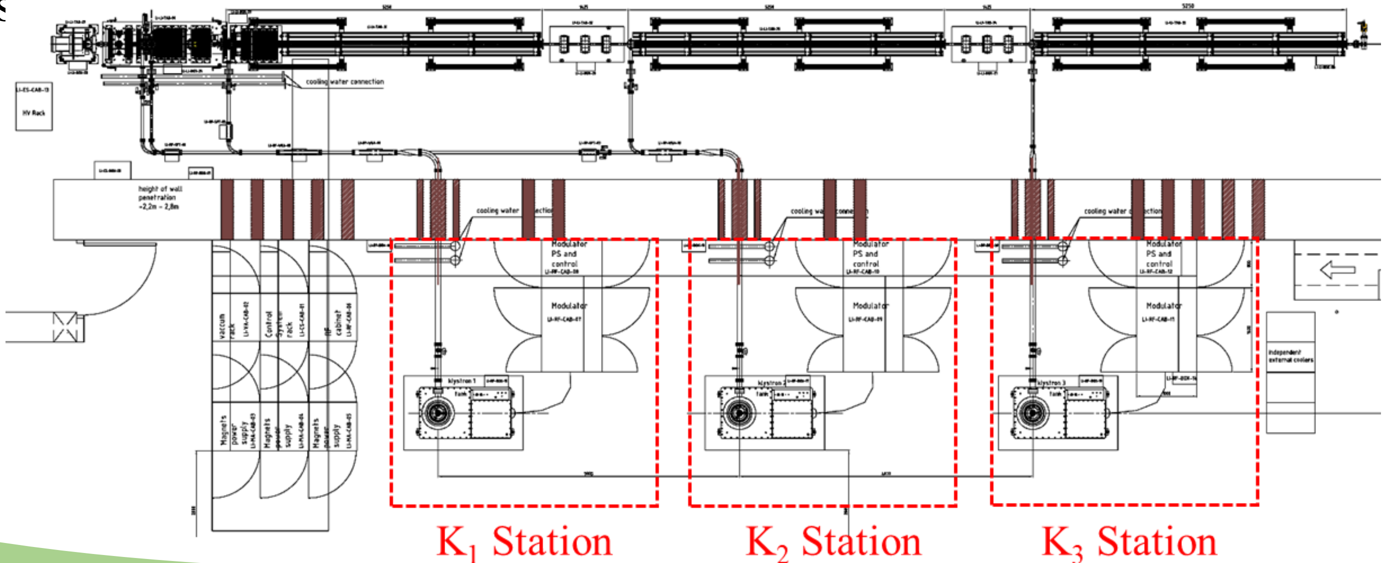
- The TPS-2 upgrade project is currently being actively planned by the NSRRC BD team.
- According to current decisions, the LINAC system and Booster ring system will remain unchanged in the TPS-2 upgrade project.
- The TPS LINAC Klystron upgrade will be carried out in two phases: the first during the summer long shutdown in 2025 and the second during the winter long shutdown in 2026.
- Design of a complete rescue mode for the TPS LINAC RF system is underway.
- A feasibility study is being conducted to evaluate increasing the TPS LINAC beam energy to 200 MeV.
- The construction of the third-phase beamline will also continue to be completed.

LINAC - TPS Pre-Injector RF Distribution

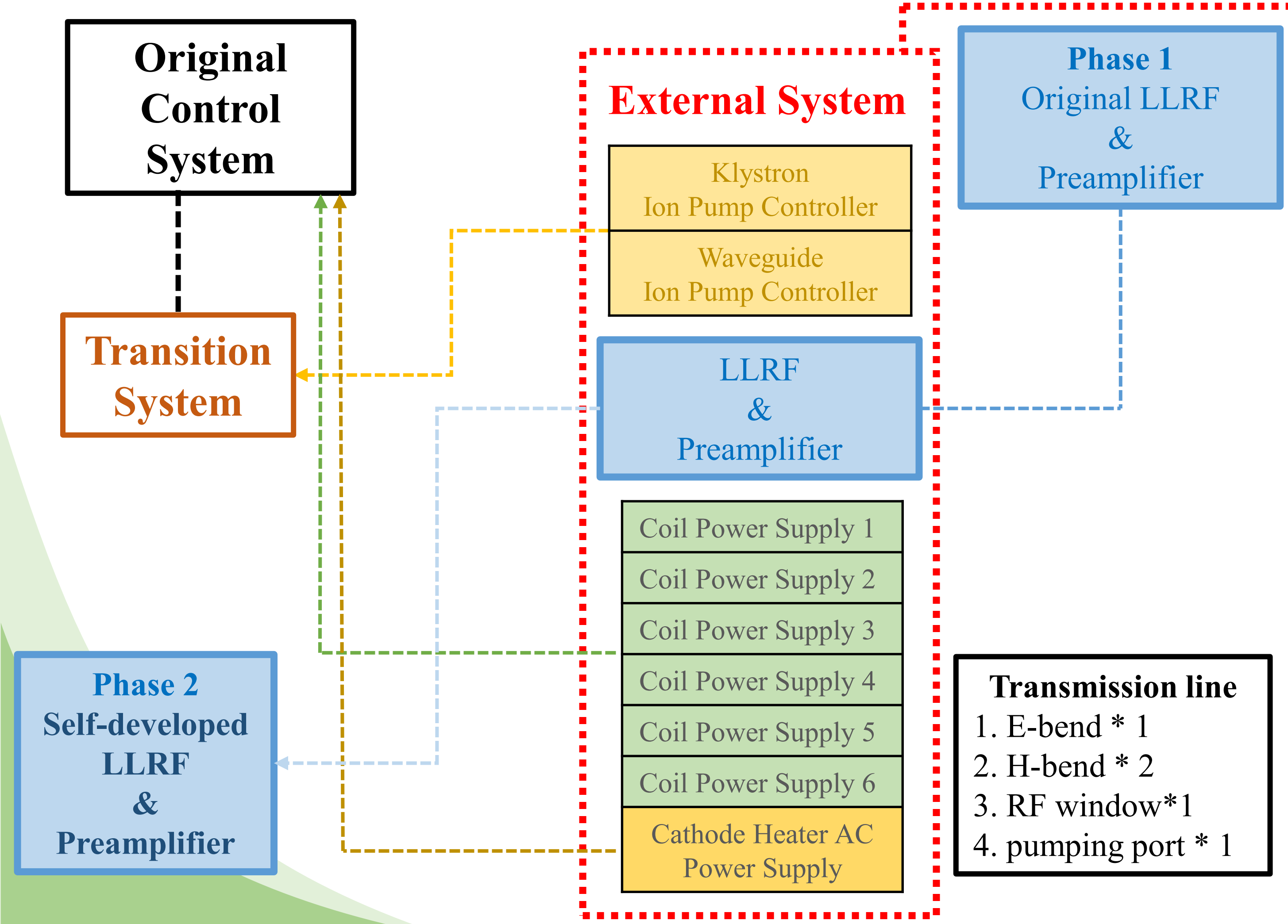
TPS pre-injector : 3 GHz, 3Hz, 150MeV (RI turn-key system)

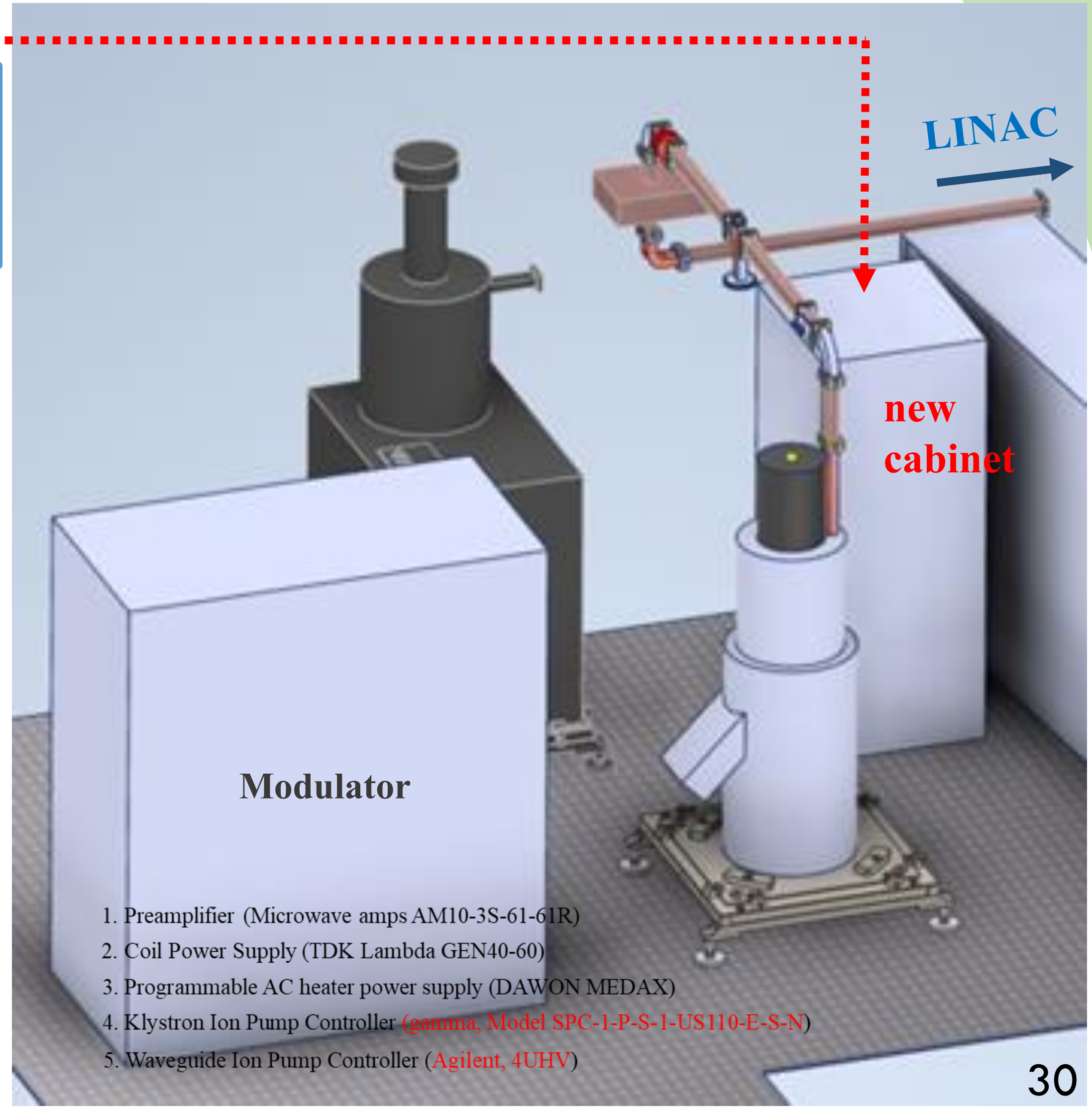


- 90 keV DC electron gun (Thermionic Cathodes)
- Sub harmonic pre-buncher SPB (500MHz)
- Primary buncher PBU (3 GHz)
- Final buncher FBU (3 GHz)
- Three 5.2 m linacs (3 GHz)
- Three Klystrons stations

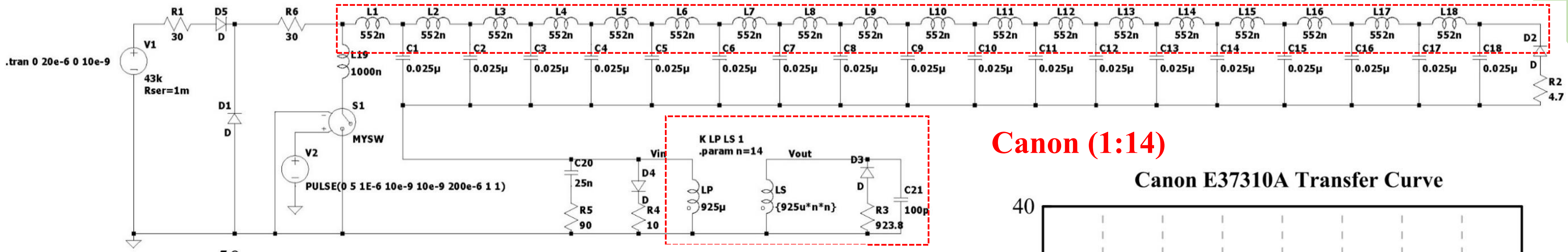


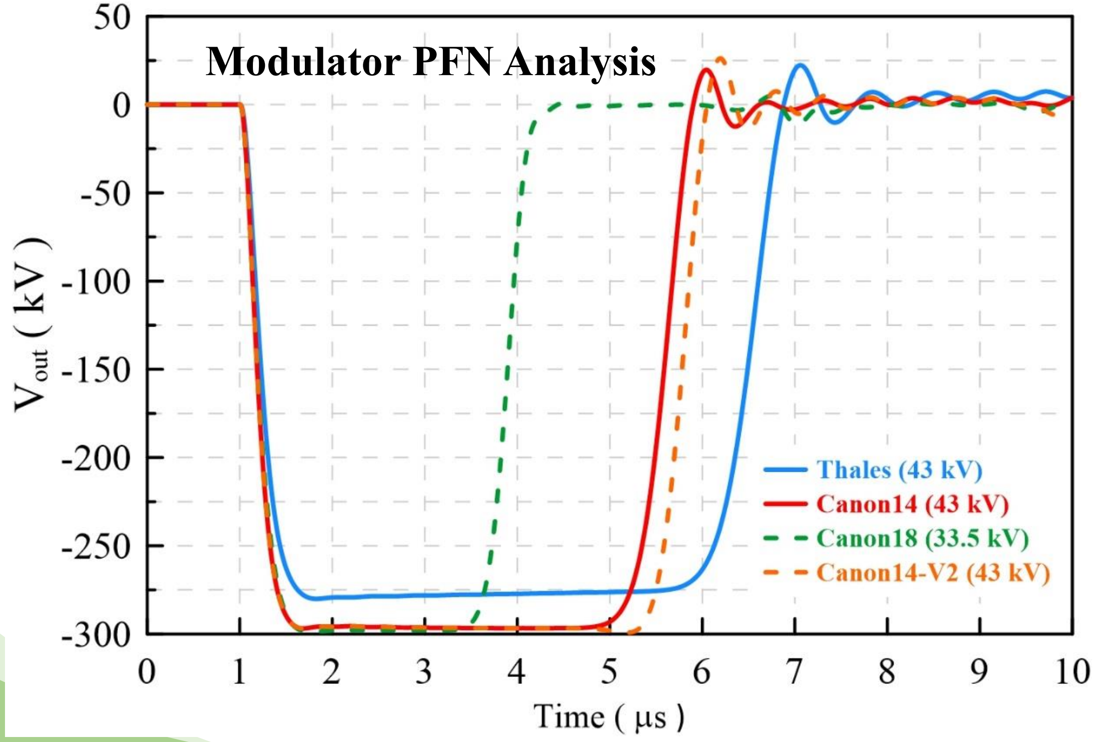
TLS LINAC Klystron Upgrade Project



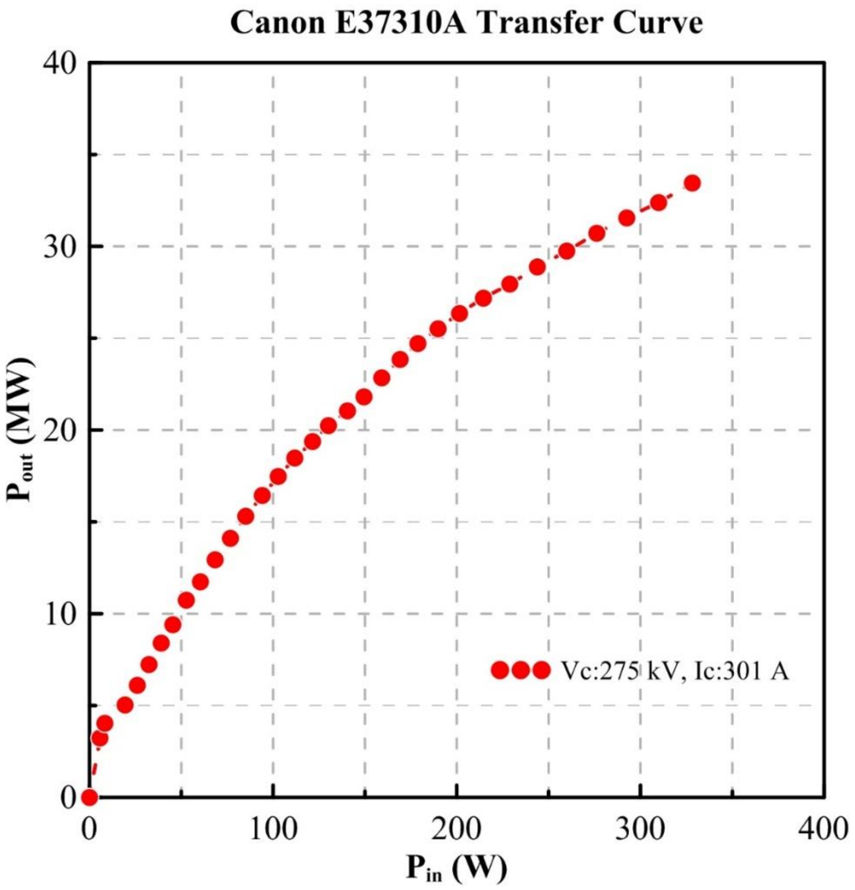


TLS LINAC Klystron Upgrade Project





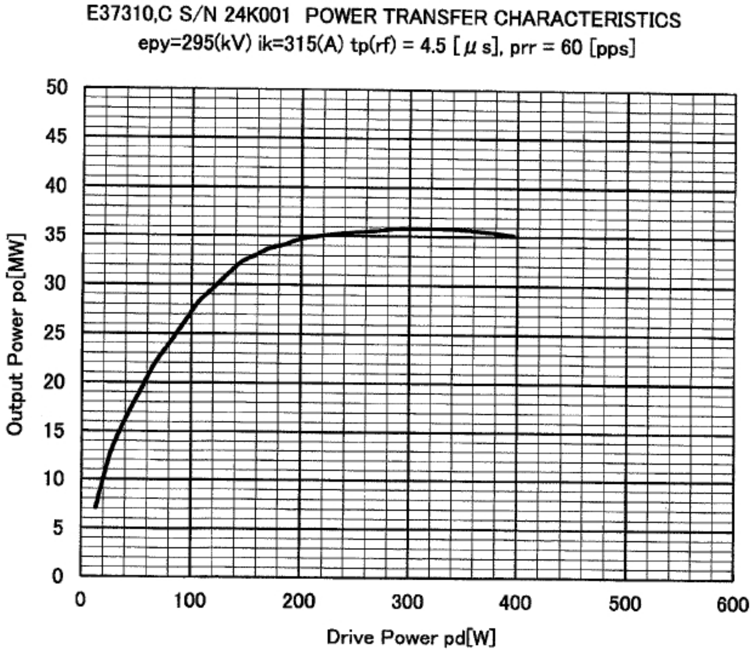
Canon (1:14)

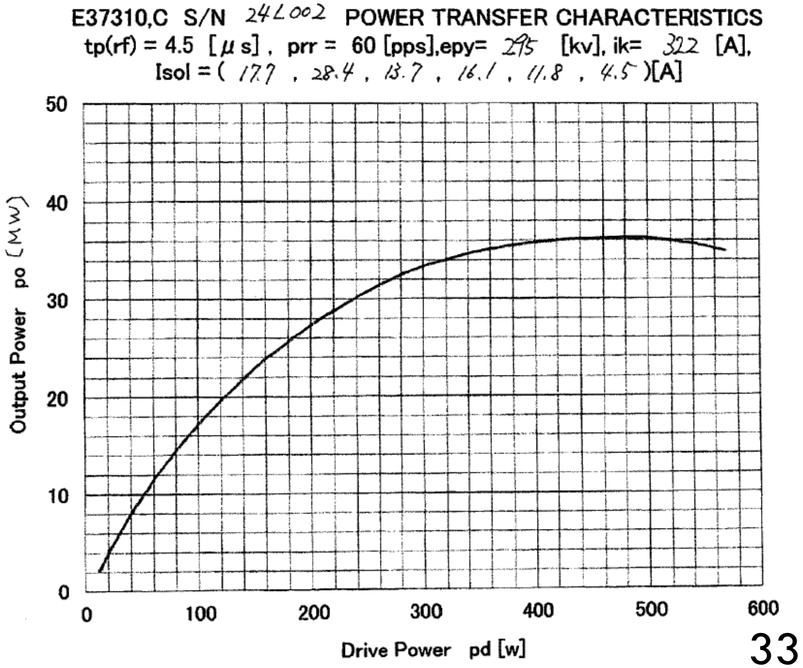


TLS LINAC Klystron Upgrade Project

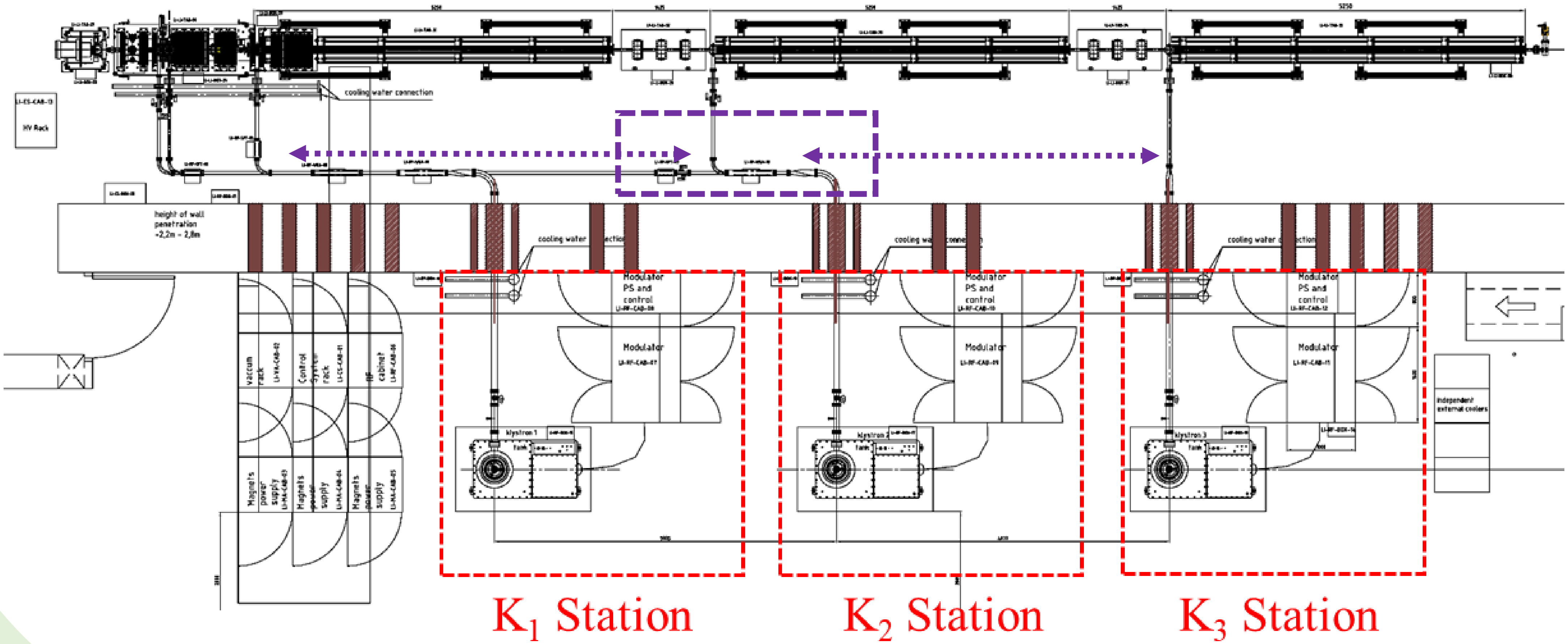
Test condition	
Inductance of one section of the new inductor [μH]	~1.3
Resistance of the dummy load [Ω]	5.2
CCPS output voltage [kV]	10
Measured voltage V_m (1 : 1000) [V]	5.18
Flat top width [μs]:	~2.8
FWHM [μs]:	~5

TLS LINAC Klystron Upgrade Project





Build a complete rescue mode for the TPS LINAC RF system

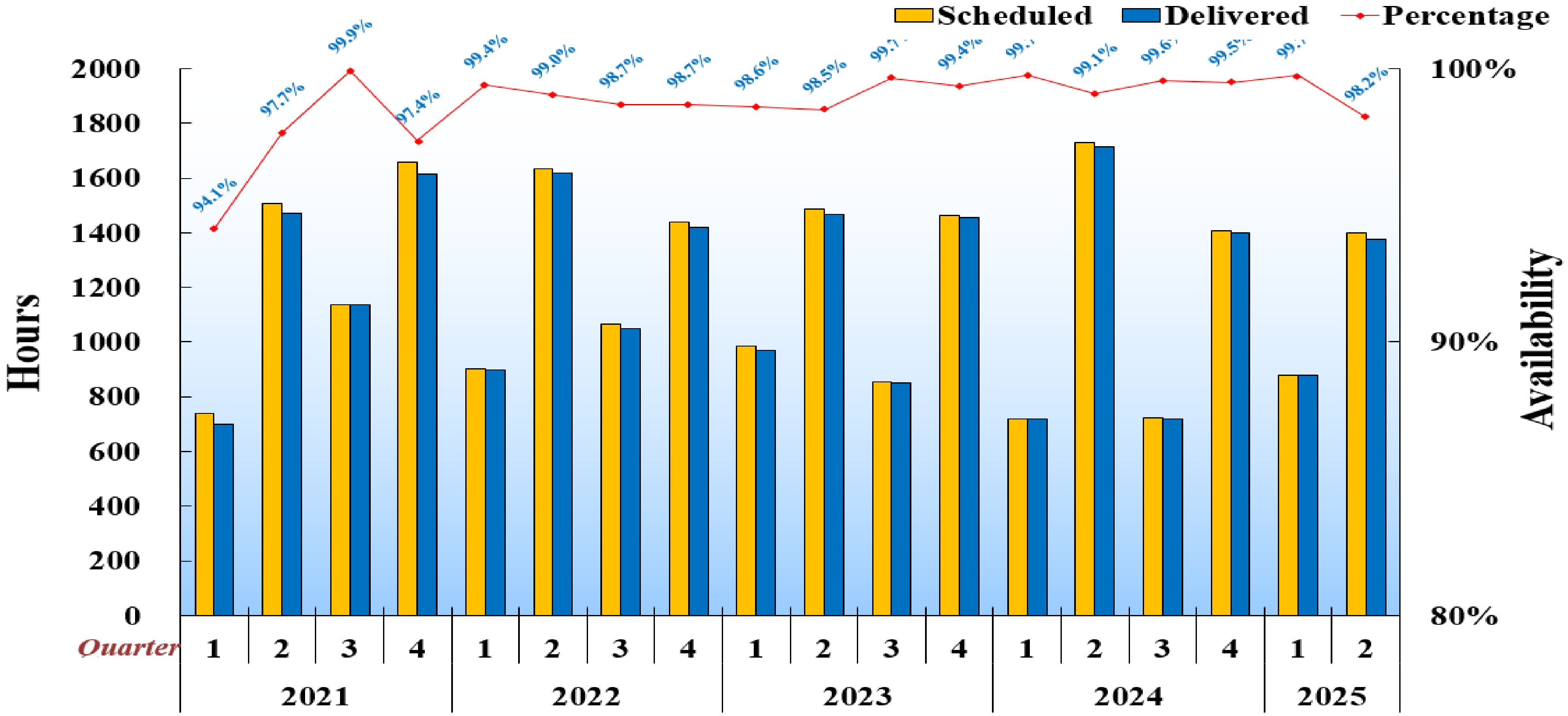


Operation Status of Taiwan Light Source (TLS)

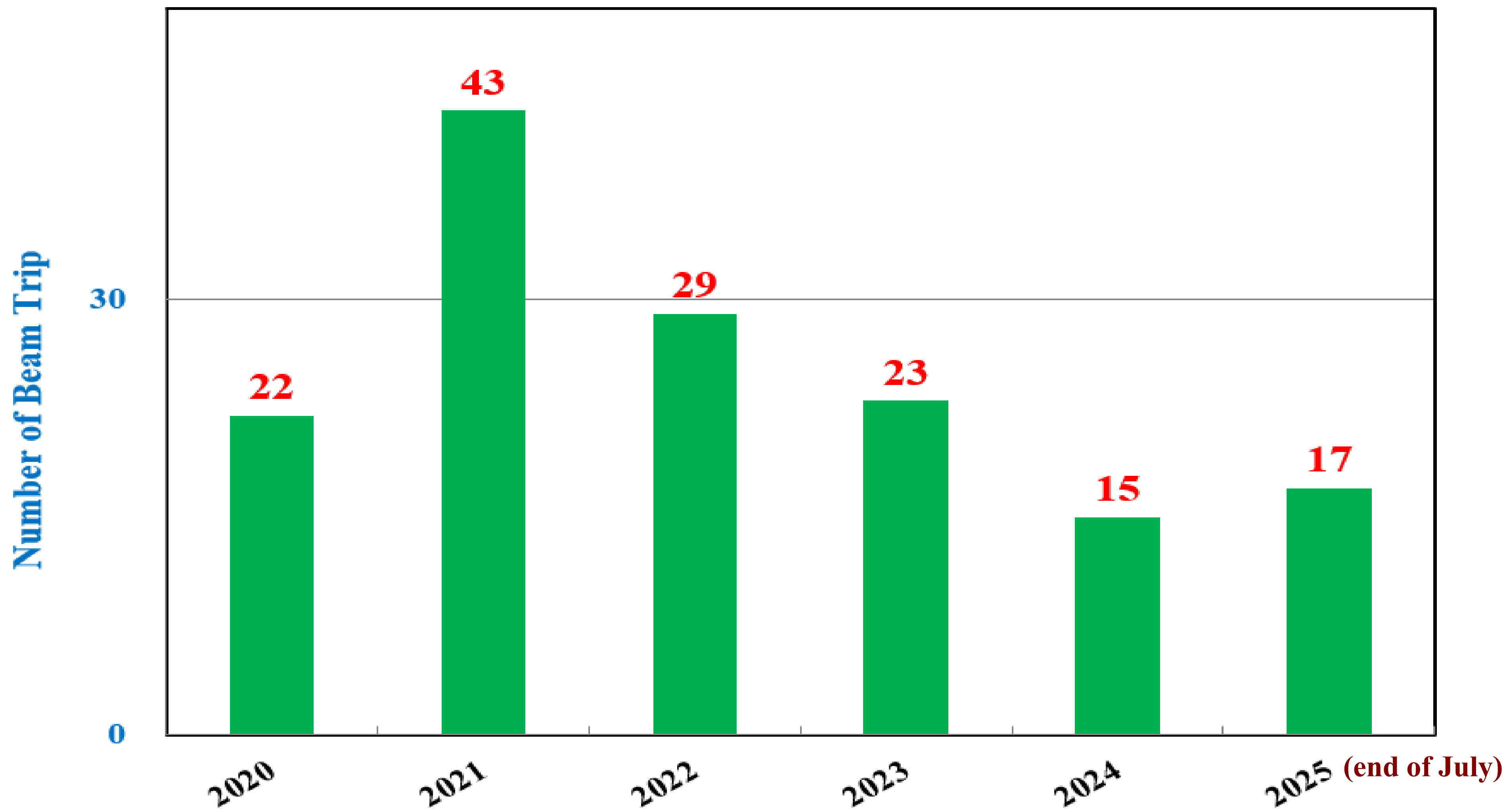
TLS Operation Statistics

Scheduled user time 2024: 4,578 hrs 2025: 2,280hrs (end of July)

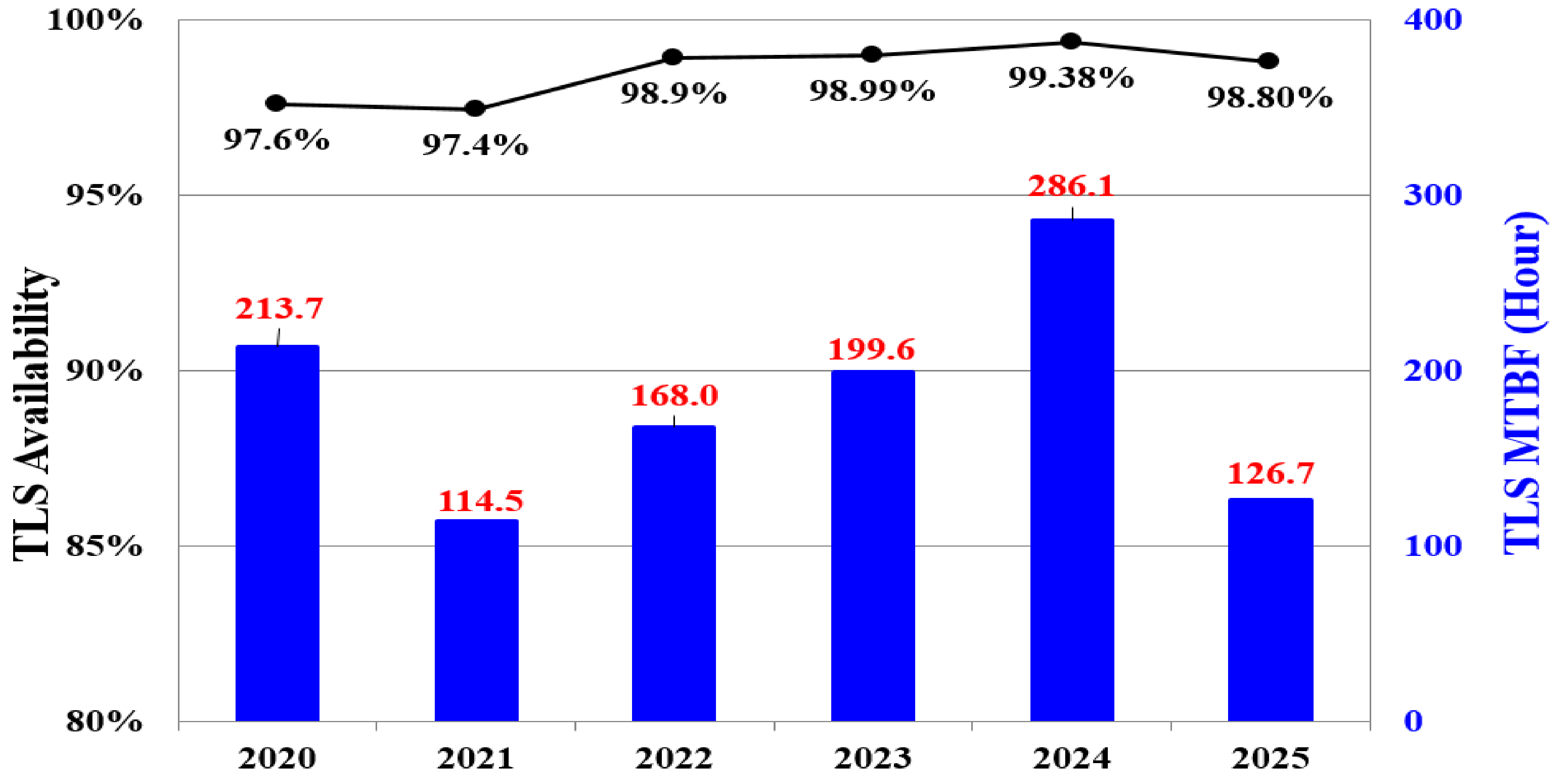
Availability 2024: 99.4% 2025: 98.8%



TLS – Beam Trip Number

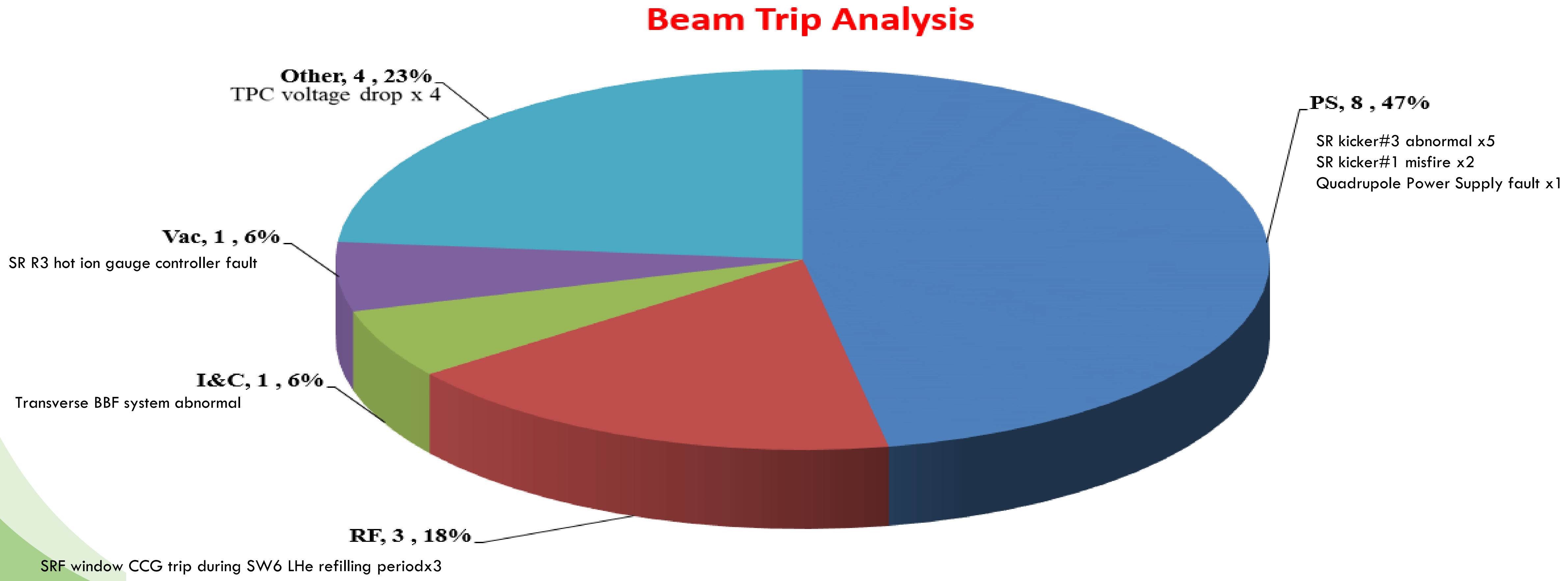


TLS - MTBF


100%
95%
90%
85%
80%
TLS Availability
97.6%
97.4%
98.9%
98.99%
99.38%
98.80%
213.7
114.5
168.0
199.6
286.1
126.7
2020
2021
2022
2023
2024
2025
400
300
200
100
0
TLS MTBF (Hour)

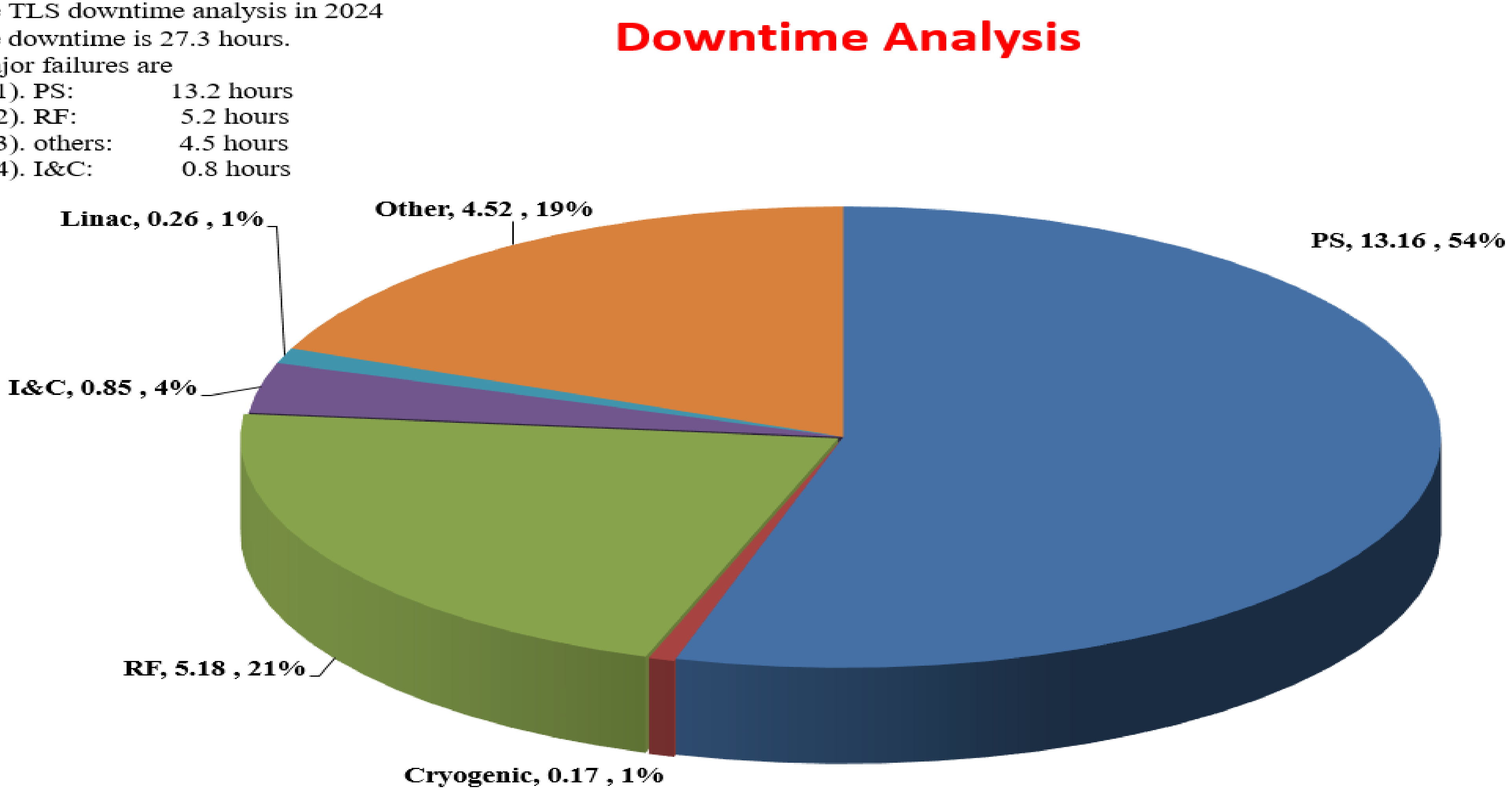
TLS – Trip Analysis

TLS 2025: 17 trip events in total by the end of July.



TLS – Downtime Analysis

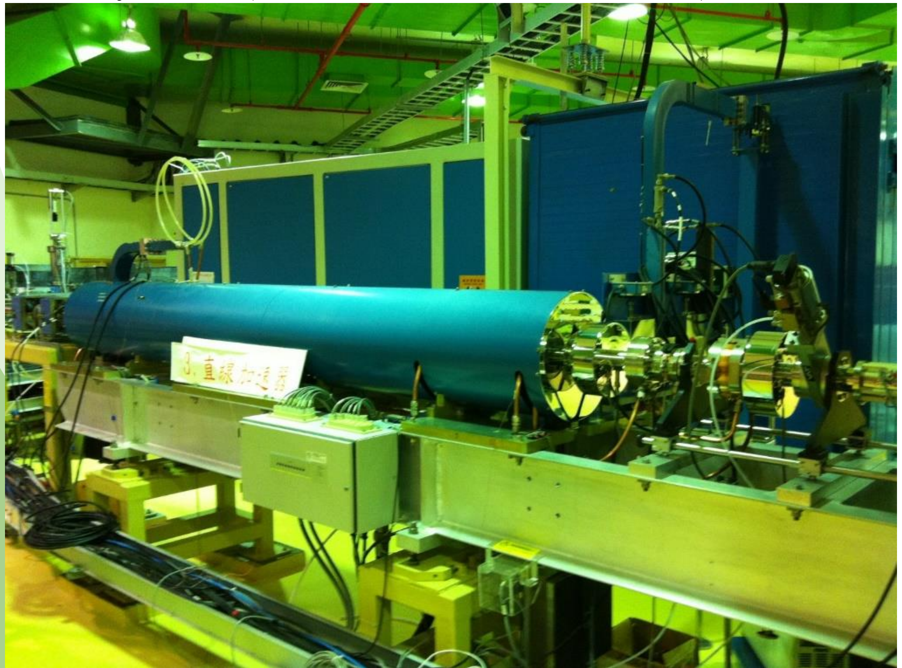
The TLS downtime analysis in 2024
The downtime is 27.3 hours.
Major failures are
- (1). PS: 13.2 hours
- (2). RF: 5.2 hours
- (3). others: 4.5 hours
- (4). I&C: 0.8 hours

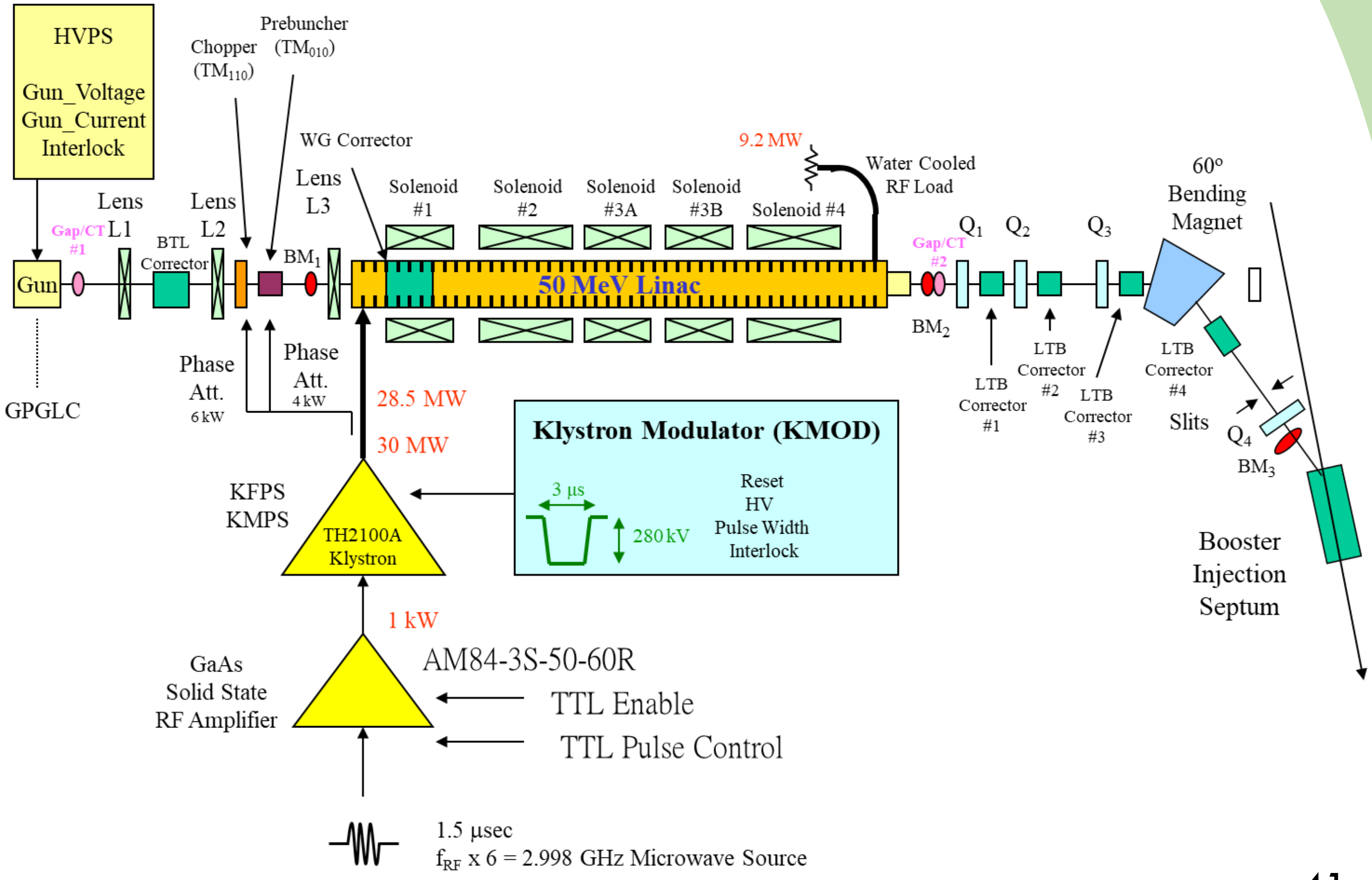


LINAC - TLS Pre-Injector Systems

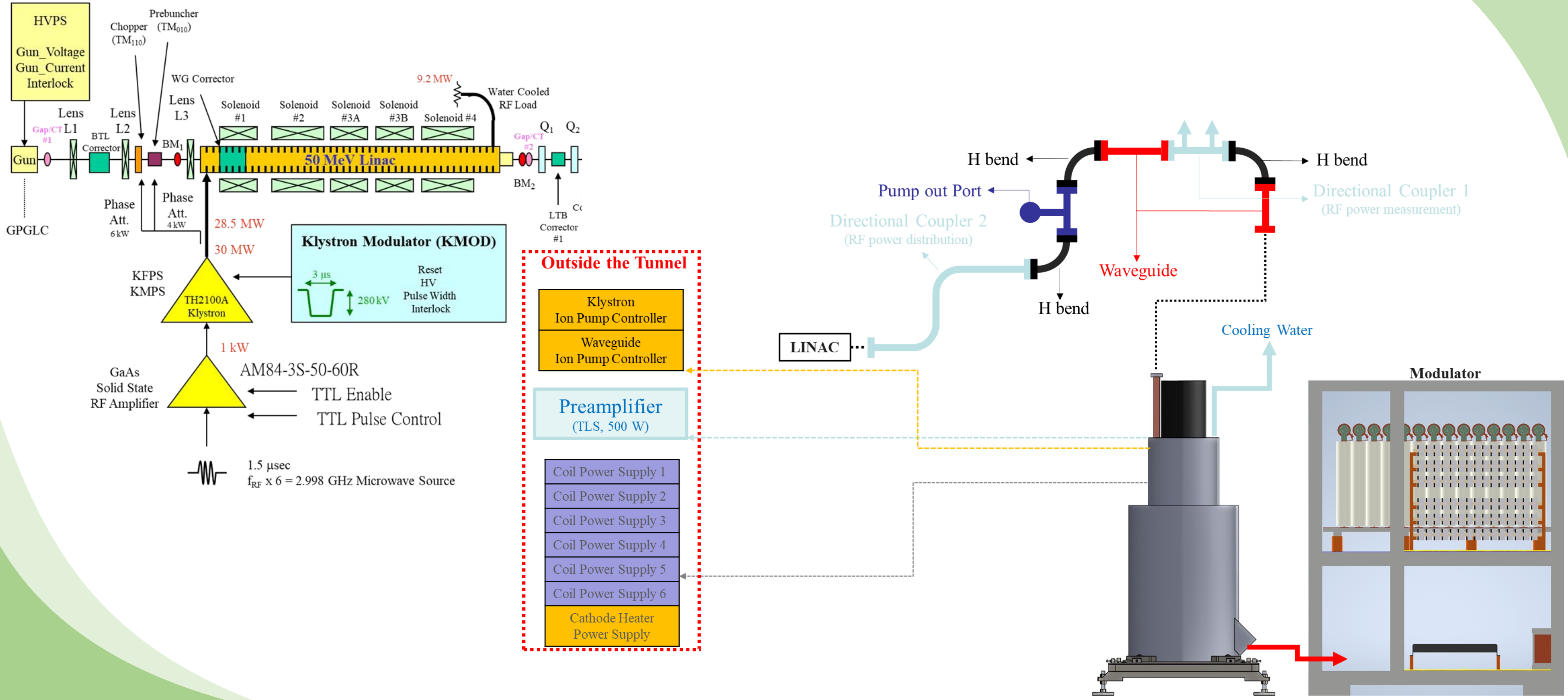
TLS pre-injector : 3 GHz, 10Hz, 50MeV (Scanditronix turn-key system)

- 140 keV DC electron gun (Thermionic Cathodes)
- Chopper (3GHz)
- Prebuncher (3GHz)
- LINAC (3GHz, 3m, SLAC type)
- Klystron (3 GHz, Canon E37310A)

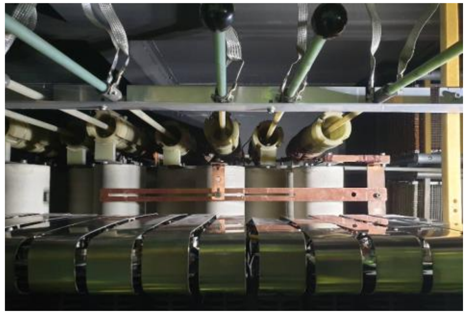


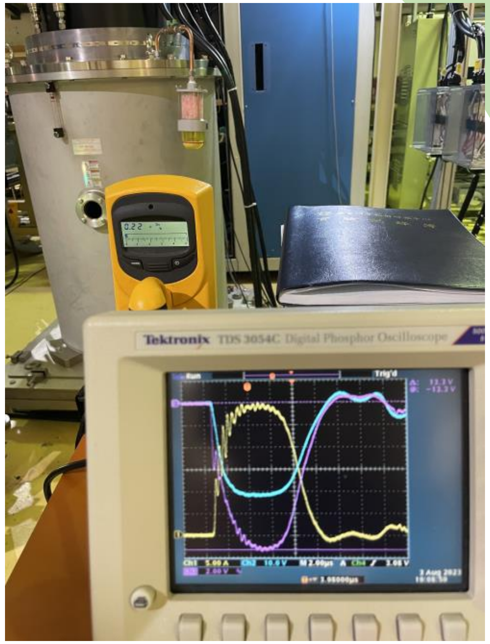


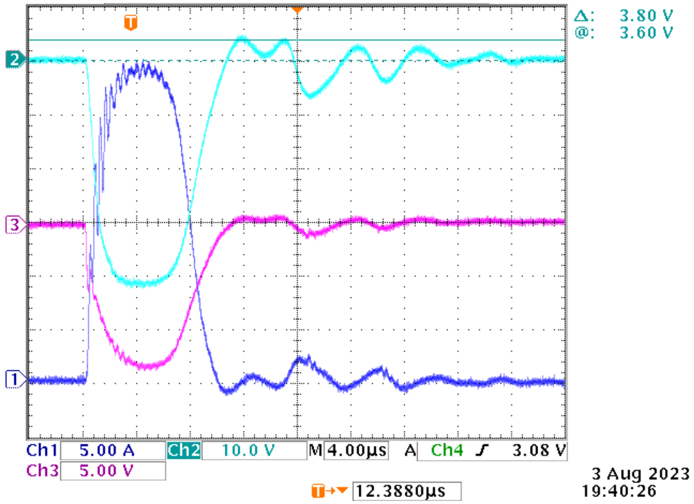
TLS LINAC Klystron Upgrade Project



TLS LINAC Klystron Upgrade Project



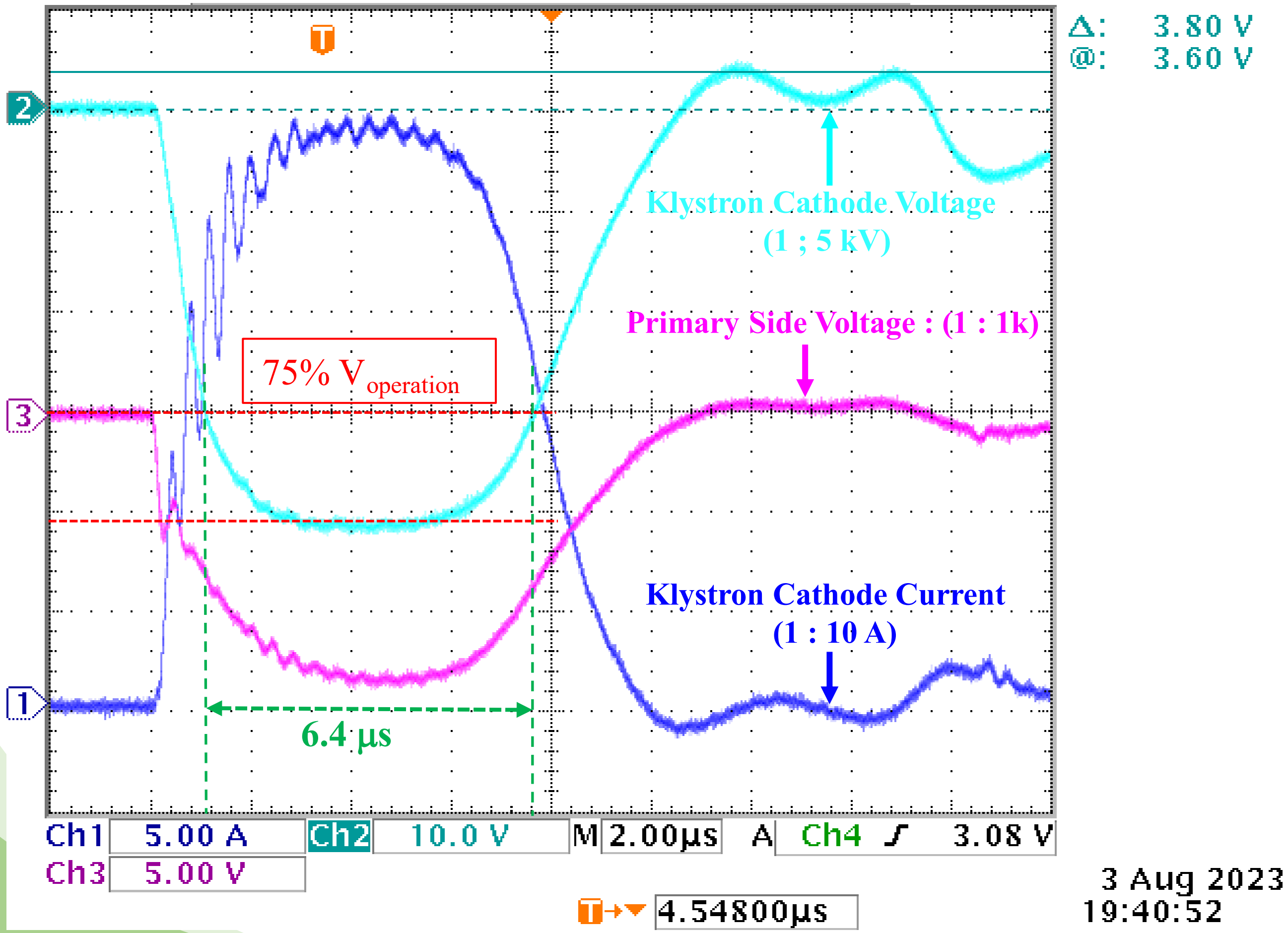


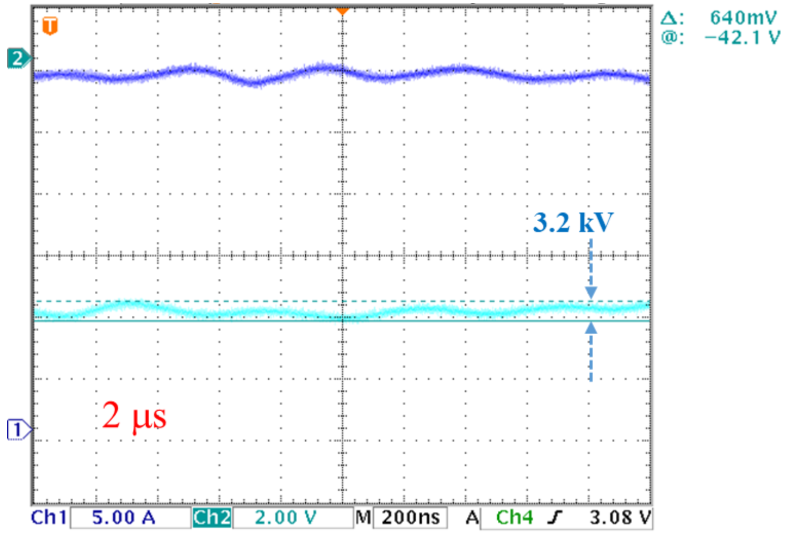


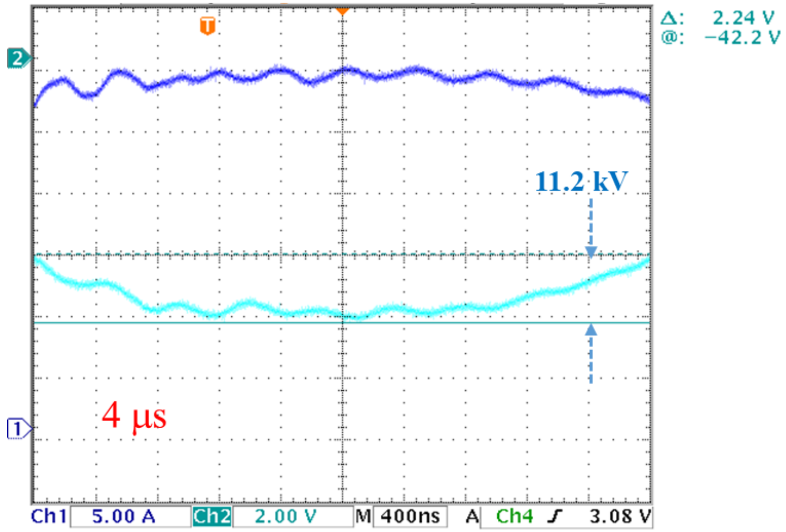
TLS LINAC Klystron Upgrade Project

TLS - Canon RF System – Modulator Tuning

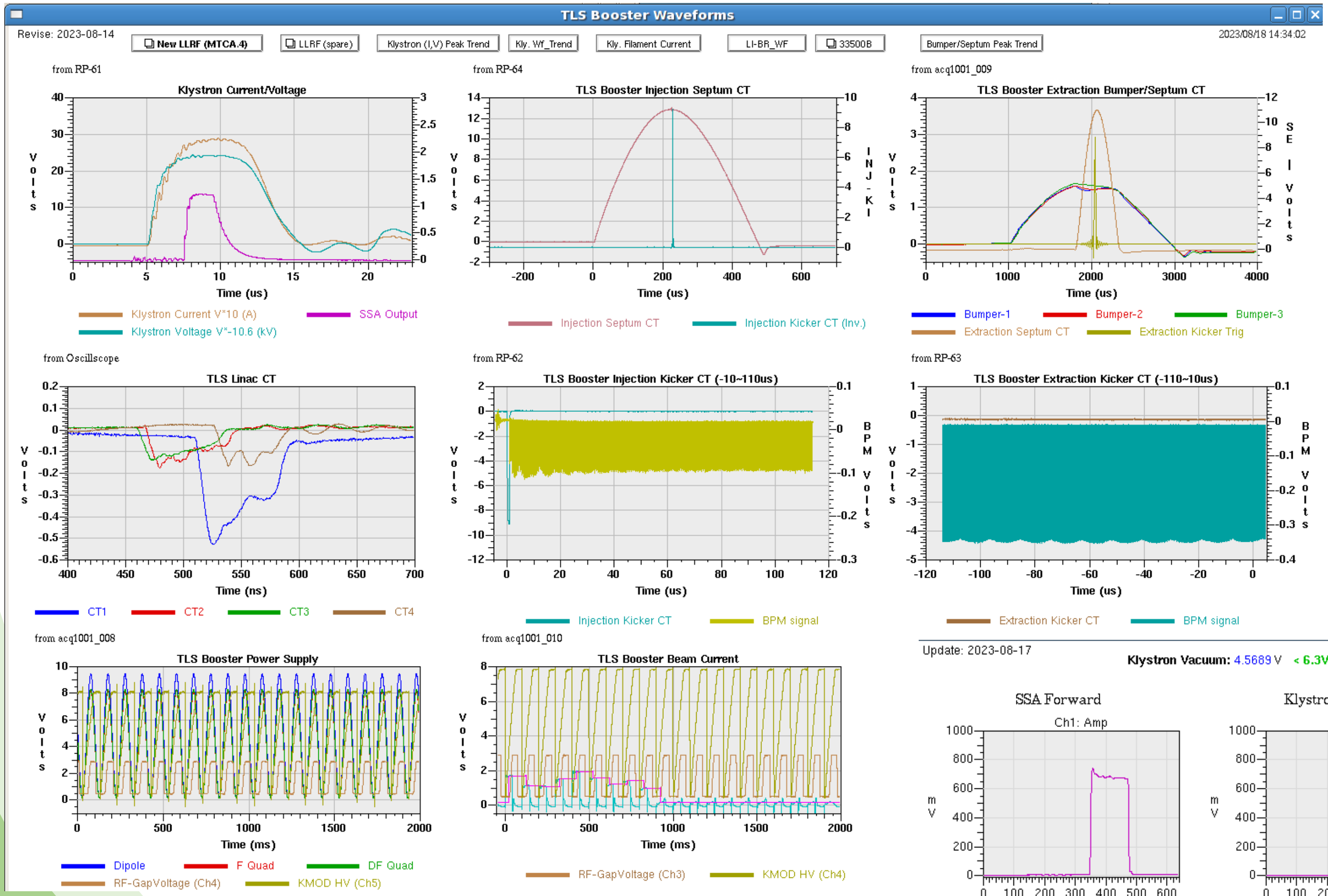
10 sections PFN

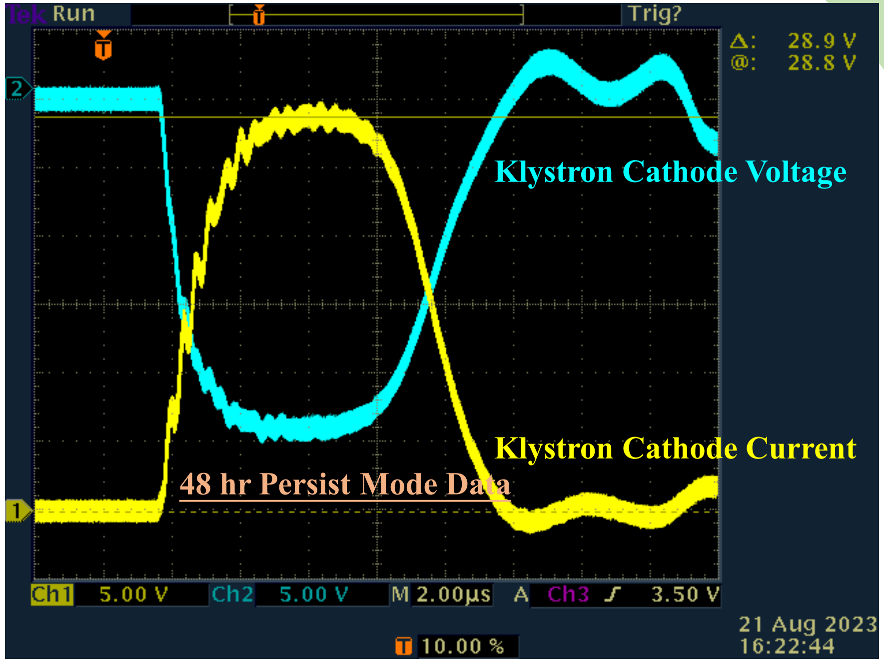


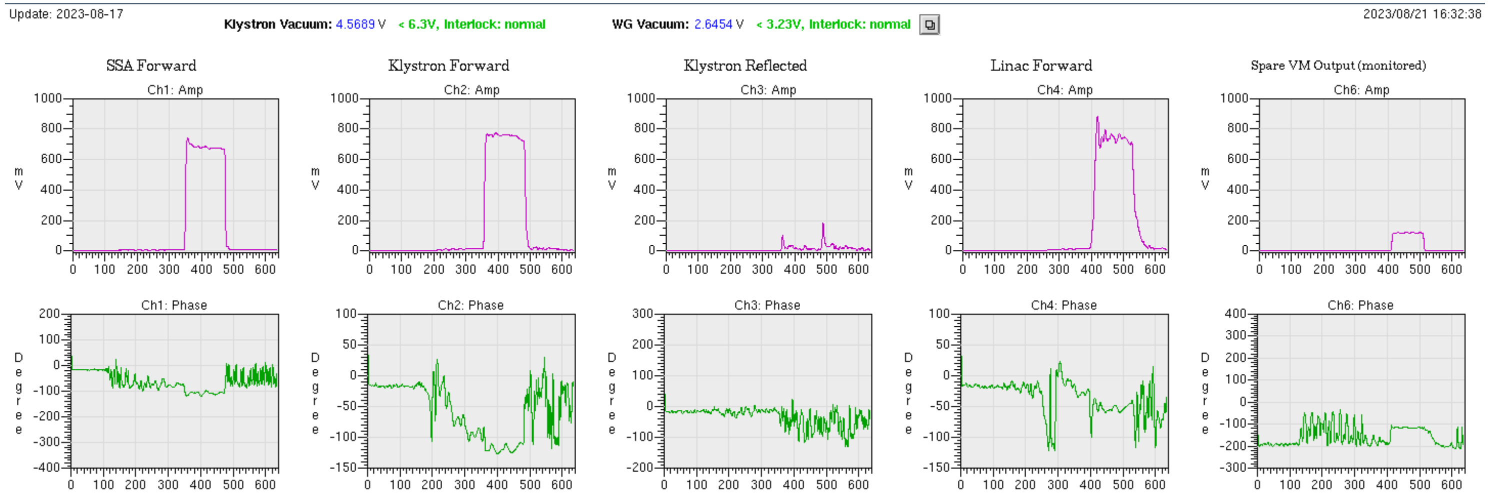




TLS LINAC Klystron Upgrade Project



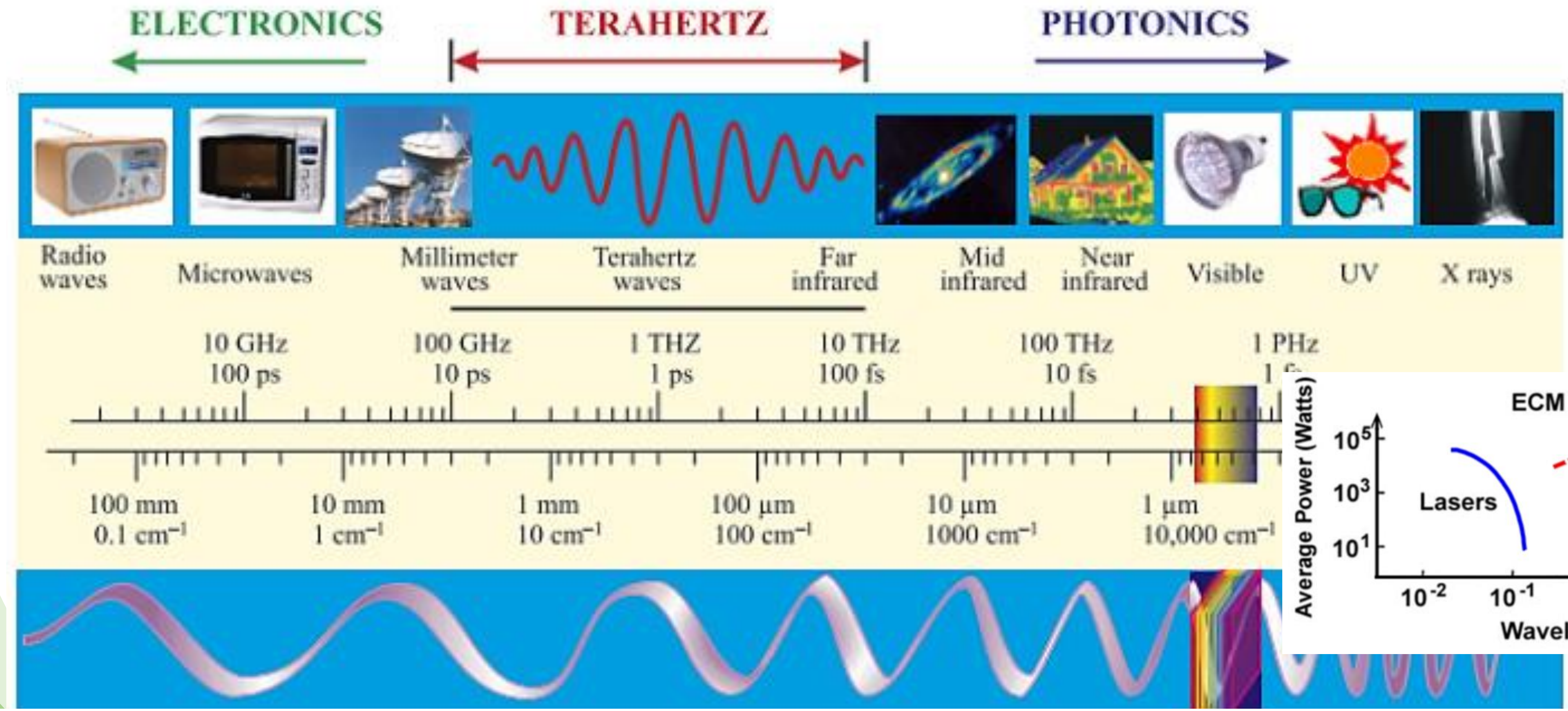


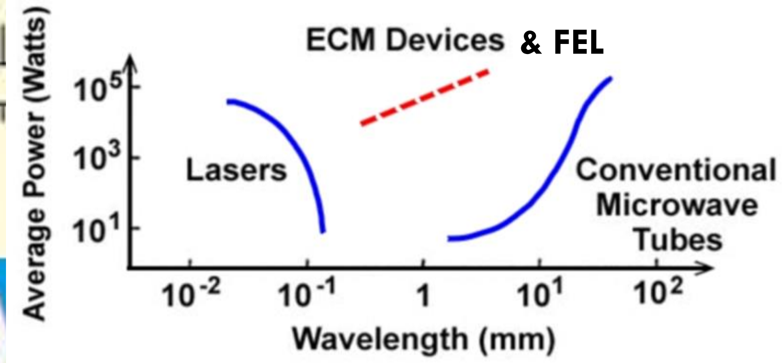


It has been operating stably for 2 years, with a maximum injection efficiency of up to 40%.

Superradiant Terahertz Light based on Linear Accelerator (STELLA)

What is the Terahertz (THz) Wave?





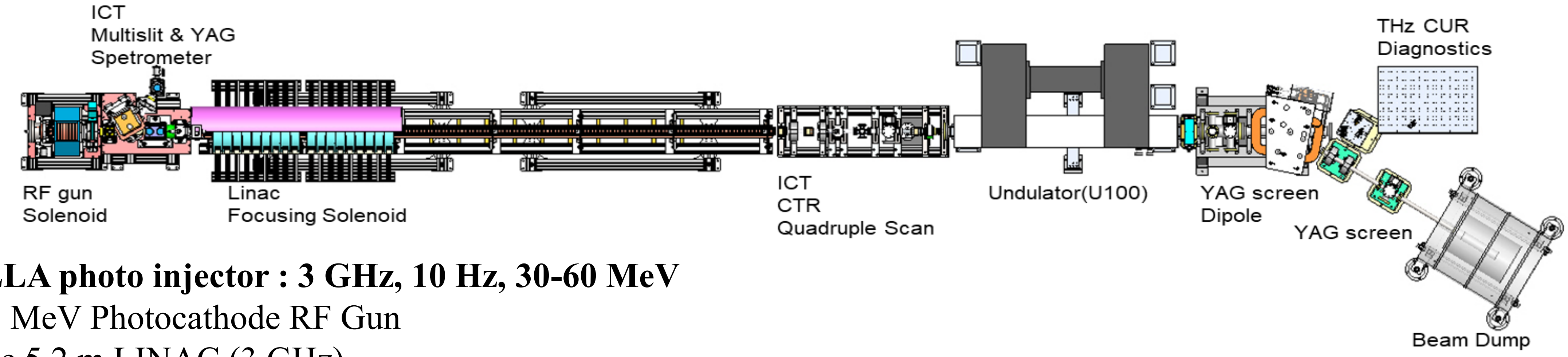
Terahertz wave (THz or T-ray), which is electromagnetic radiation in a frequency interval from 0.1 to 10 THz (3 mm to 30 µm), lies a frequency range with rich science but limited technology.

1 THz = 300 µm = 1 ps = 33 cm^{-1}

Superradiant Terahertz Light based on Linear Accelerator (STELLA)

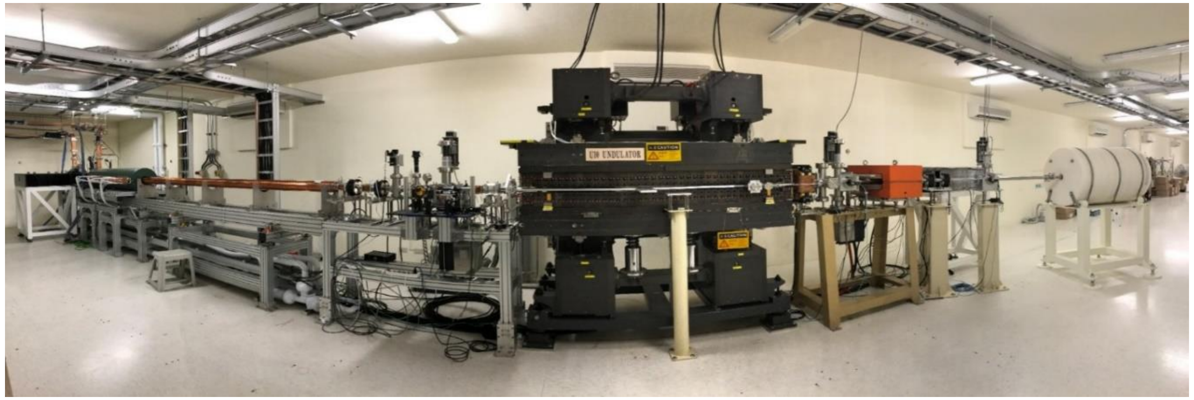
LINAC-based Coherent THz sources :

- Coherent undulator radiation (CUR) : Radiation produced by passing through an undulator
- Coherent transition radiation (CTR) : Radiation produced by hitting a metal foil

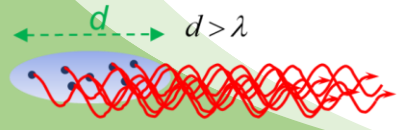


STELLA photo injector : 3 GHz, 10 Hz, 30-60 MeV

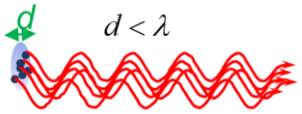
- 2.5 MeV Photocathode RF Gun
- One 5.2 m LINAC (3 GHz)
- One Undulator (U100, 18 periods)
- One klystrons station(Canon E37310A, Homemade modulator)



Superradiant Radiation



electrons radiate incoherently



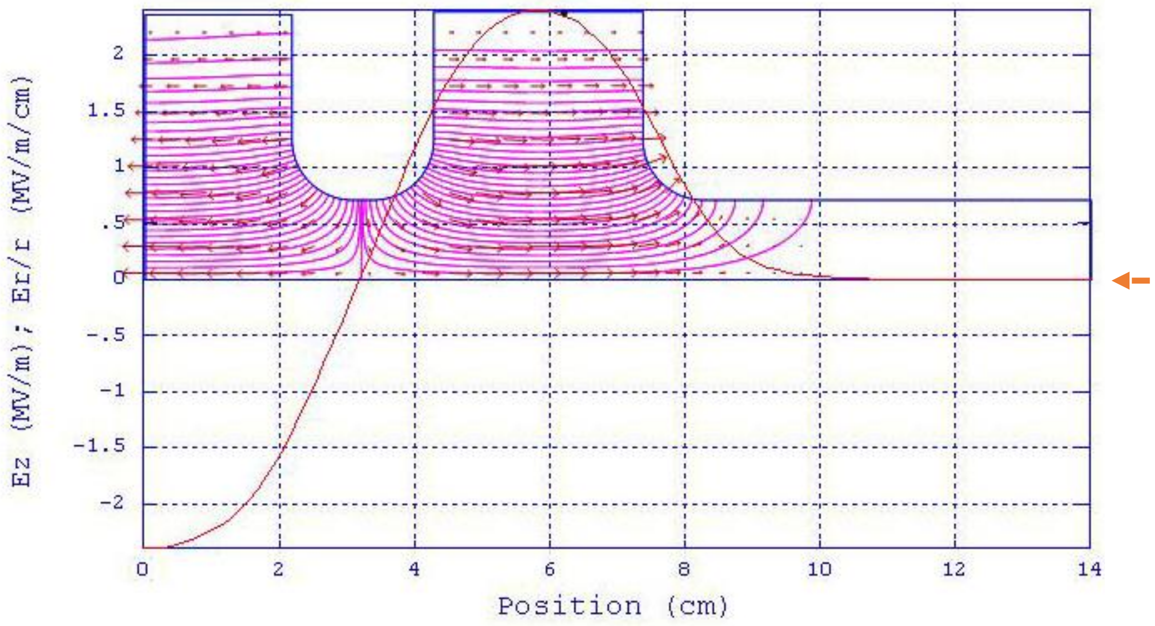
electrons radiate coherently

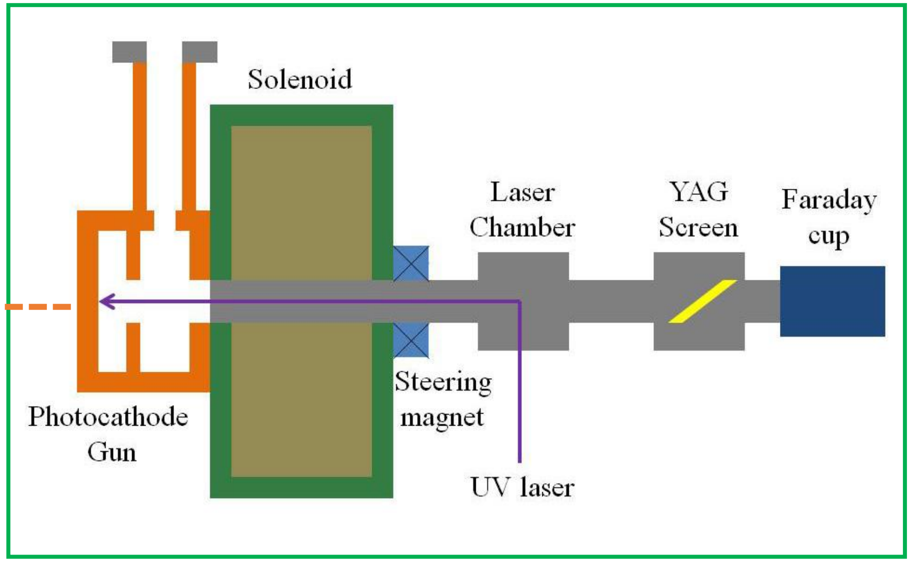
STELLA System Parameters (Latest Information)

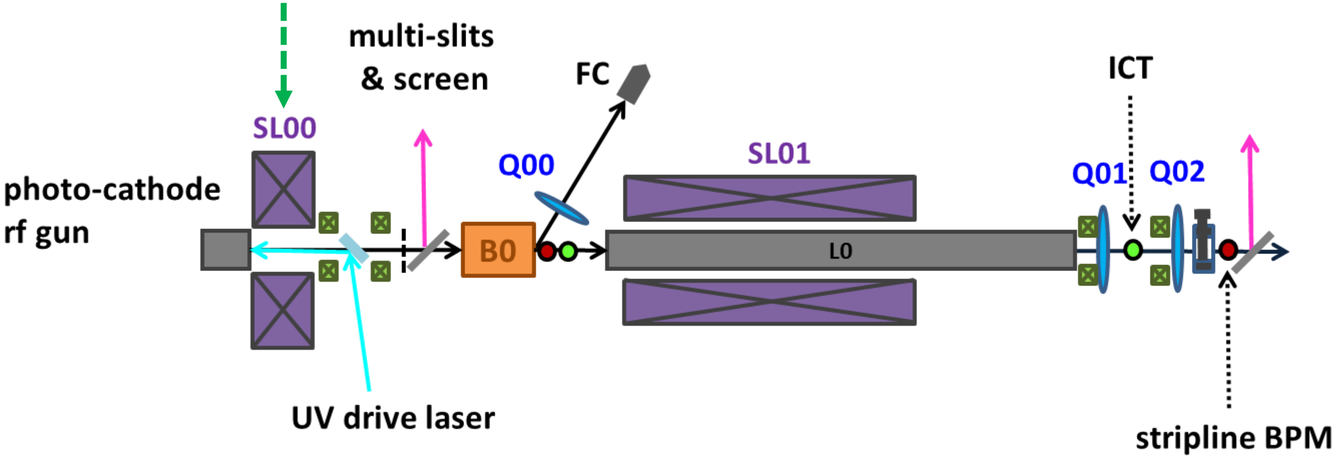
Photo-injector Parameters		
RF Gun	Peak field	50 MV/m
	Electron energy	2.5 MeV
UV Laser	Laser pulse length (FWHM)	3 ps
	Laser energy (@cathode)	Up to 120 μJ
Linac	E field gradient	12.5 MV/m
Electron beam	Electron energy	27 MeV
	Bunch length (rms)	240 fs
	Bunch charge	Up to 600 pC
	Repetition rate	10 Hz

THz parameters	CTR	Superradiant THz FEL
frequency (THz)	--	0.6 ~ 1.4 (tunable)
pulse duration	300 fs	18 ps
bandwidth	--	15%
THz energy (μJ)	2	20
THz peak power (MW)	6.6	1.1
Assumed focus spot size diameter (mm)	2	
THz peak field (kV/cm)	400	163
Repetition rate (Hz)	10	

Introduction of Photo-injector



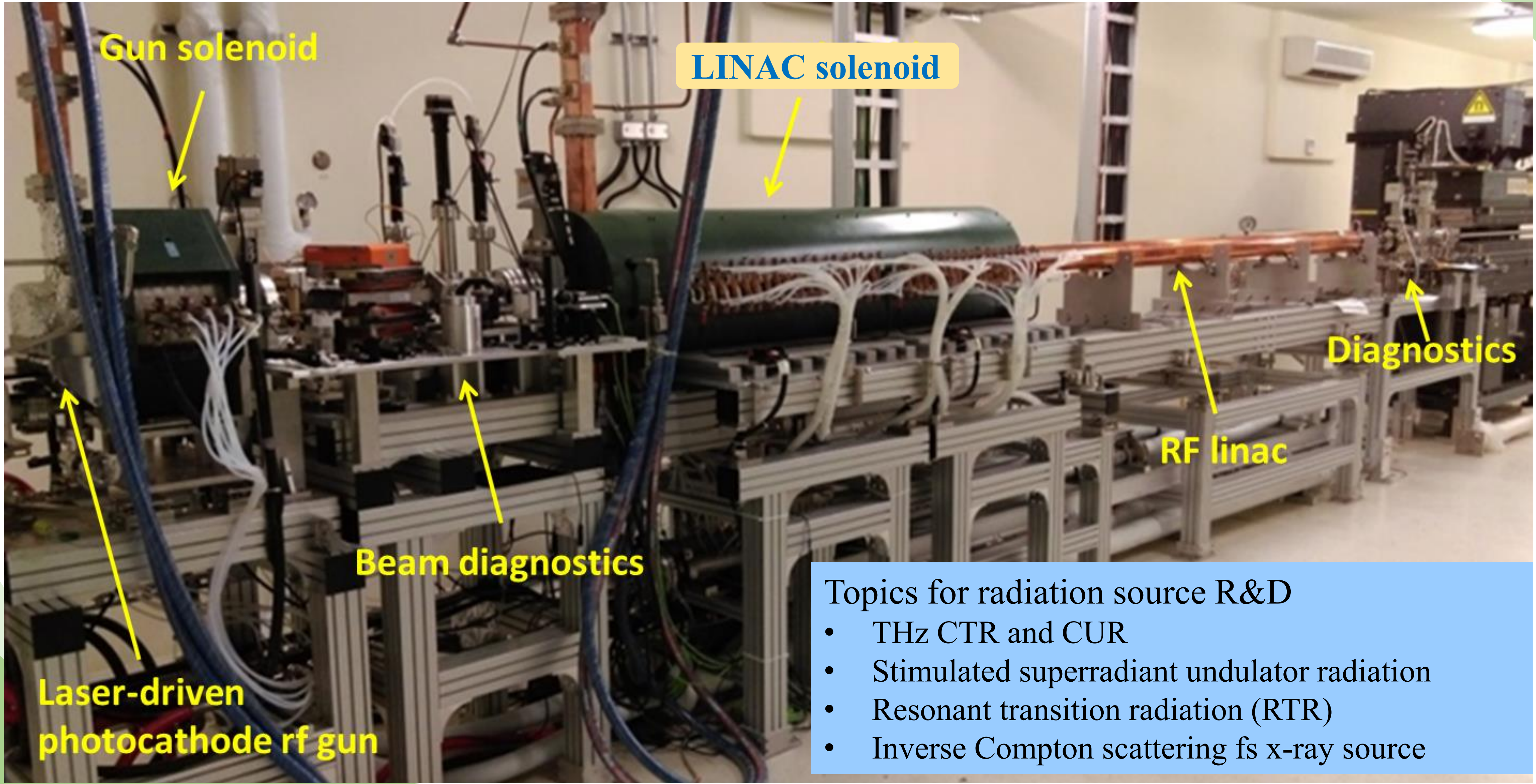




Main components

1. Photocathode RF Gun
2. Linear Accelerator (LINAC)
3. Pulsed RF System

The NSRRC Photo-injector LINAC System – a Test Accelerator for Light Source Development



Topics for radiation source R&D

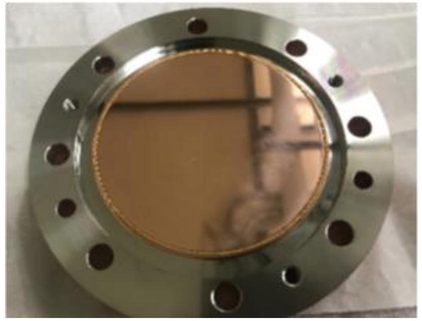
- THz CTR and CUR
- Stimulated superradiant undulator radiation
- Resonant transition radiation (RTR)
- Inverse Compton scattering fs x-ray source

Photo-cathode RF Gun

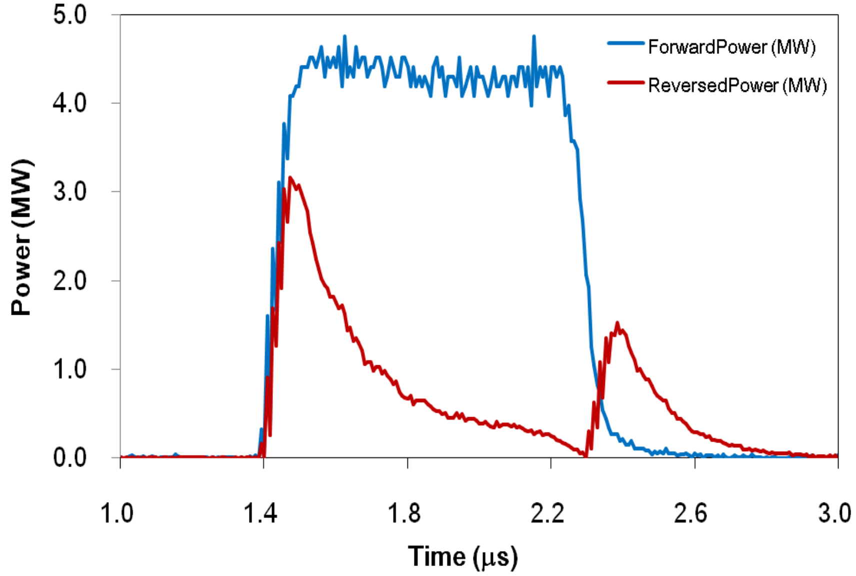
- Design is based on the 1.6 cell s-band RF gun developed at BNL DUV FEL.
- Copper (Cu) photo-cathode
- Operating at temperature 55°C , vacuum < 5 x 10^{-8} mbar

Parameter	Value
Frequency	2.99822 GHz (@55°C)
Q_0	~8000
Coupling coefficient	0.7
Peak field at the cathode	50 MV/m
Beam energy after gun	2.5 MeV
UV laser pulse duration (FWHM)	3 ps
Cathode quantum efficiency	~1 x 10^{-5}

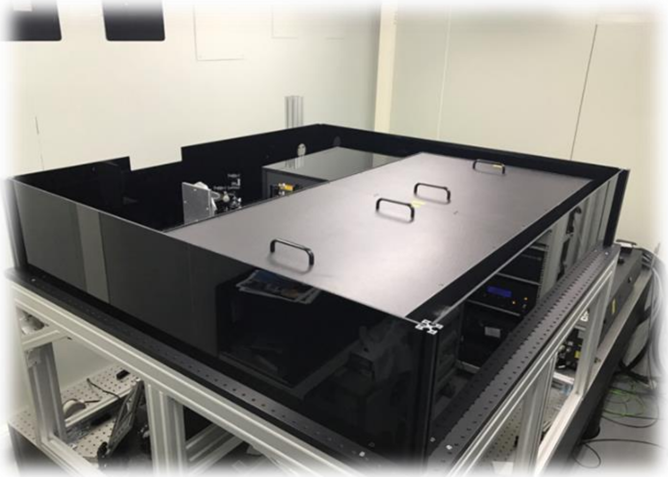
Cu cathode

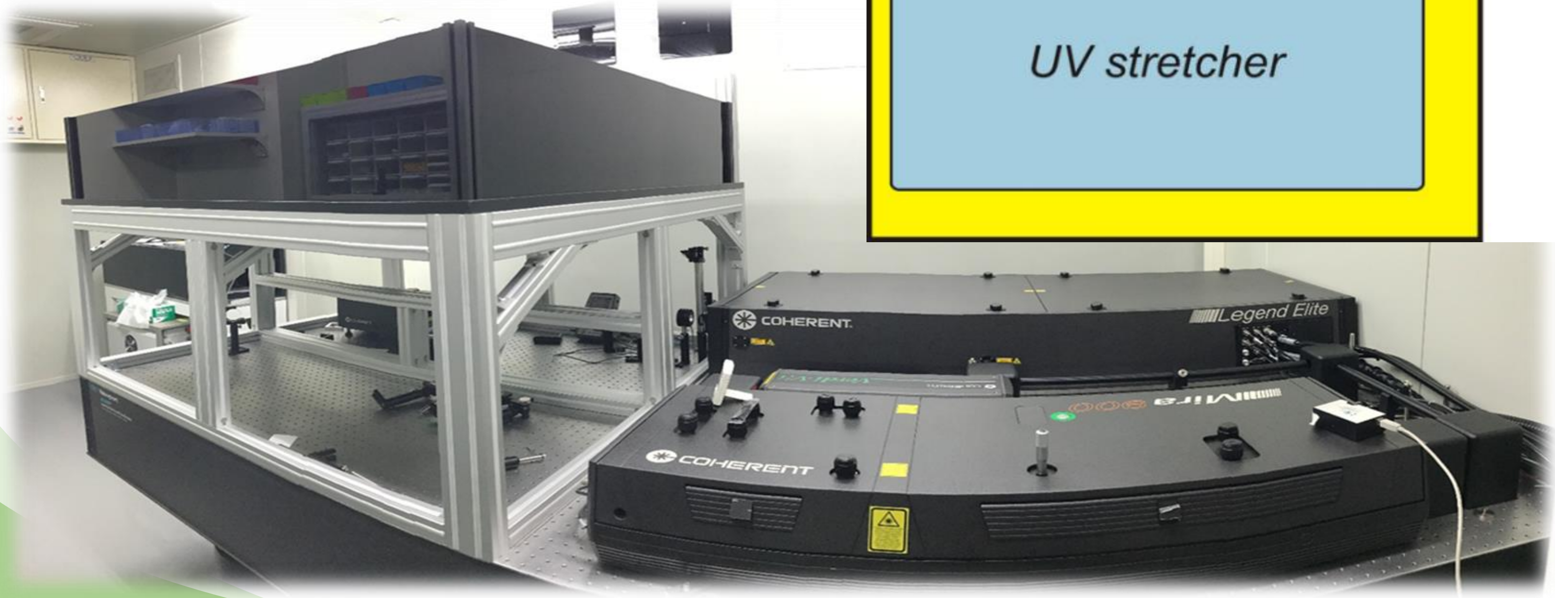


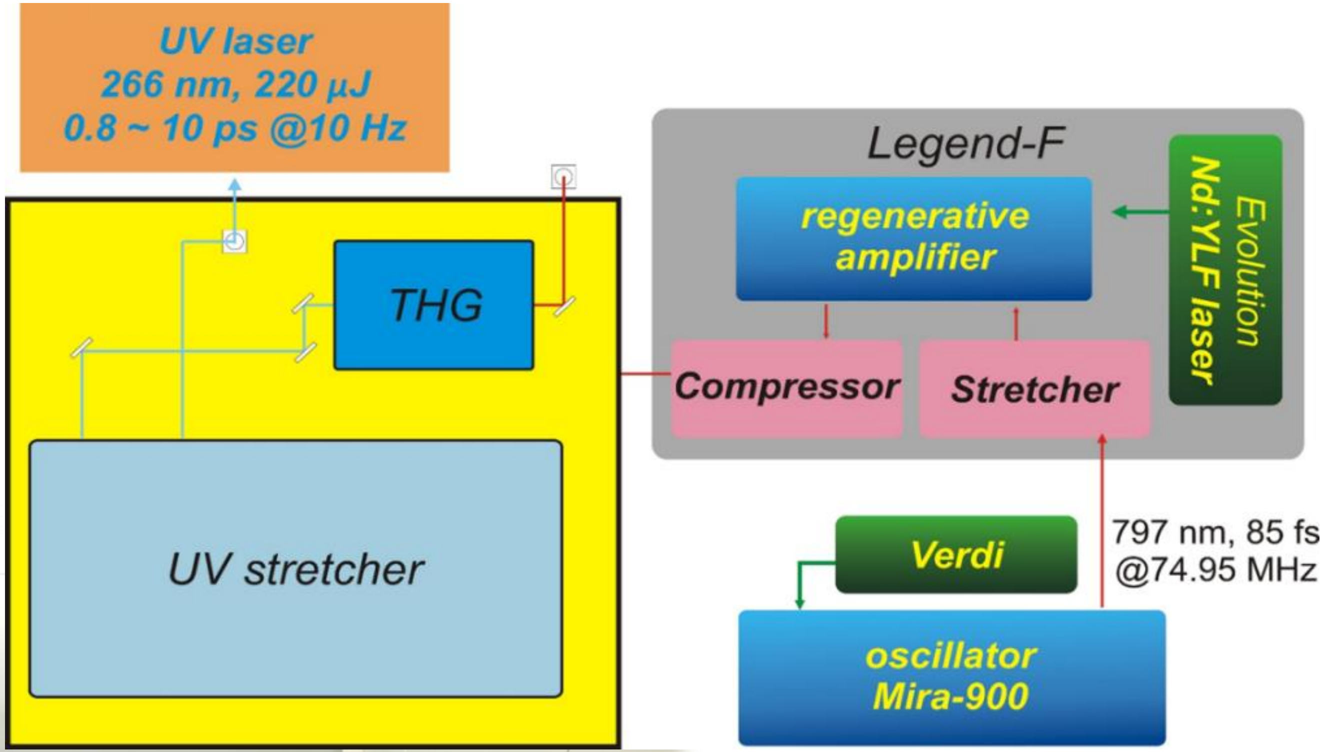
Forward and reverse power of the Gun



Drive Laser System for the Photo-cathode RF Gun



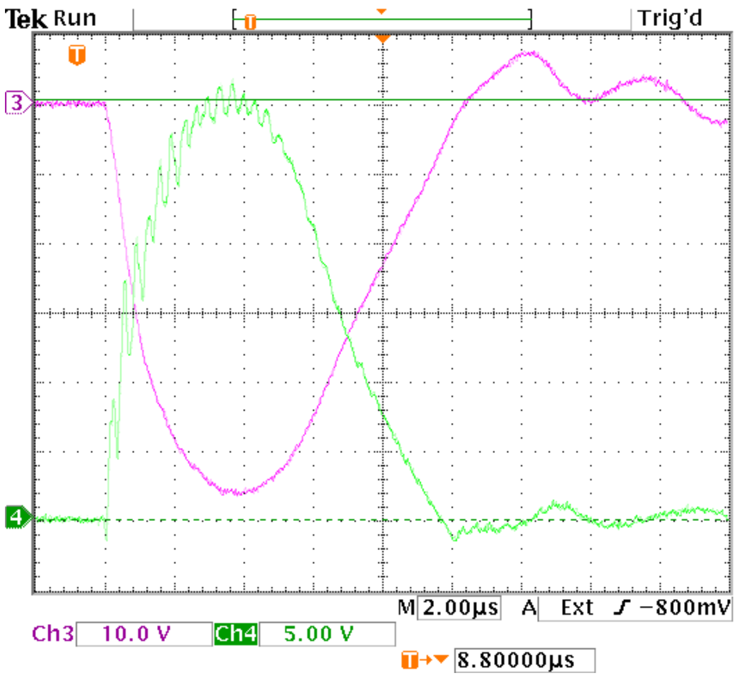




Pulsed Klystron System for the Photo-injector

Canon E37310A Klystron

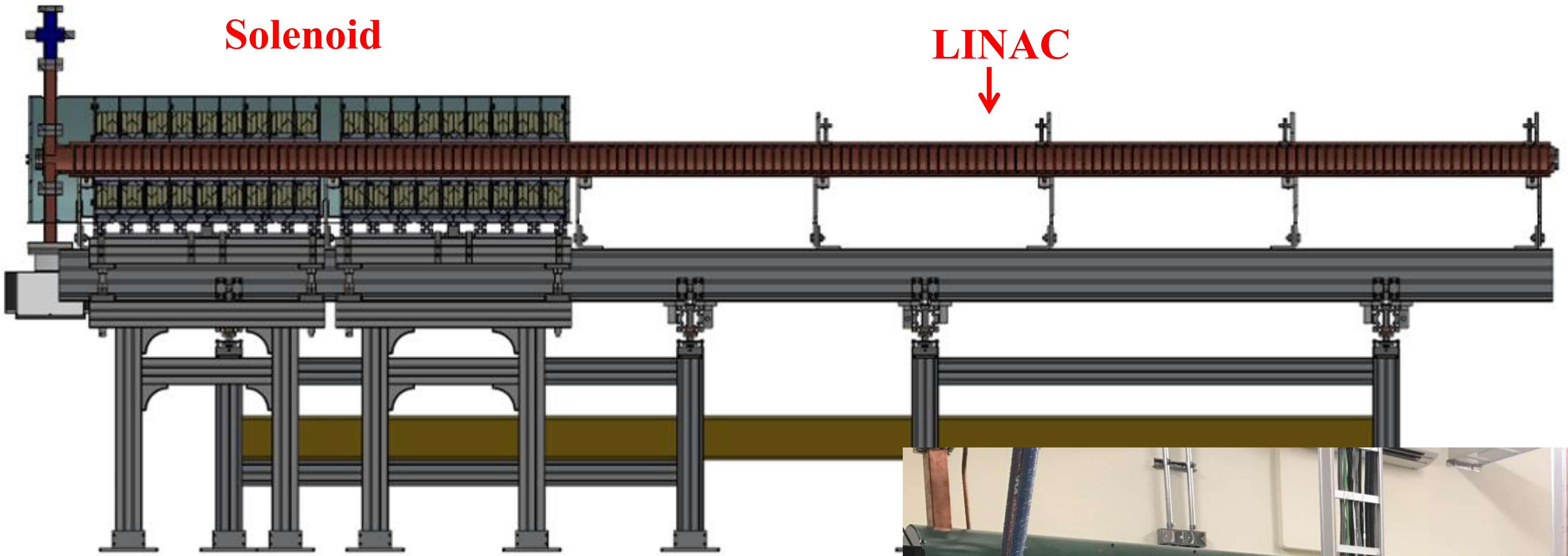
Canon Klystron	
Klystron voltage (kV)	281
Klystron current (A)	307
Output power (MW)	35
Pulse width (μs)	2



Homemade line-type Modulator	
9 sections PFN network	
PFN voltage, max (kV)	40
PFN character impedance (Ω)	2.8
PFN capacitance (μF)	0.1 x 9
Pulse width @ 50 % (μs)	6.5
Repetition rate (Hz)	10

Homemade Modulator

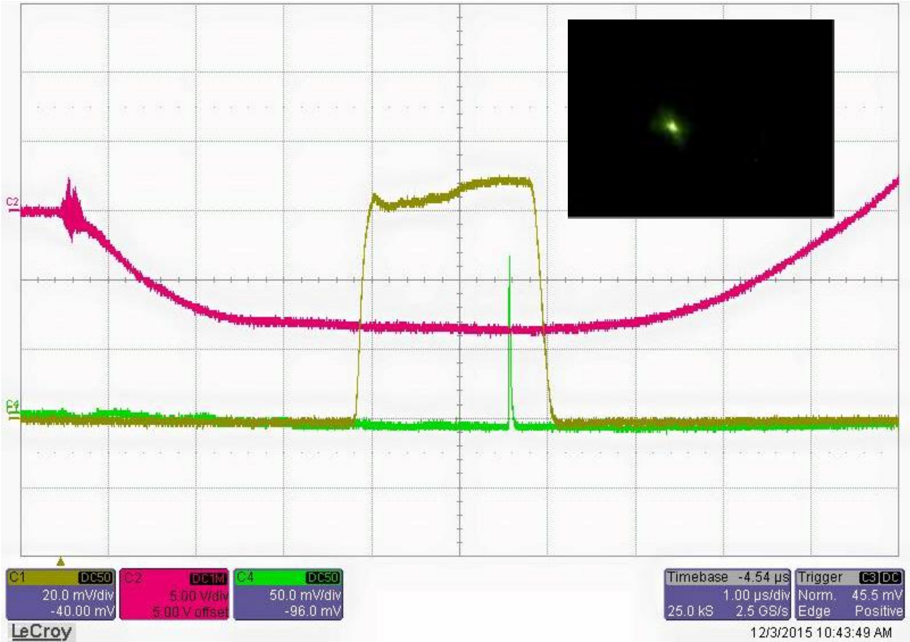
Photo-injector LINAC and Focusing Solenoid



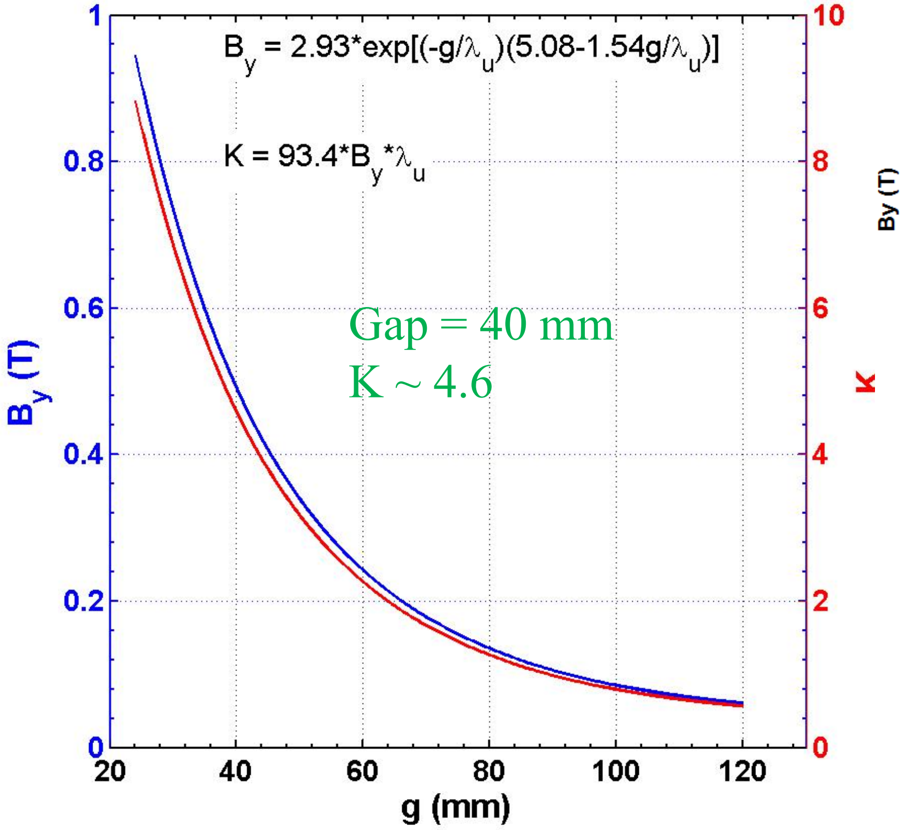
- 2998 MHz, DESY-type 156-cell copper, constant gradient.
- accelerating gradient >11 MV/m, total length: 5.2 m.
- Linac solenoid for more beam size and emittance control.

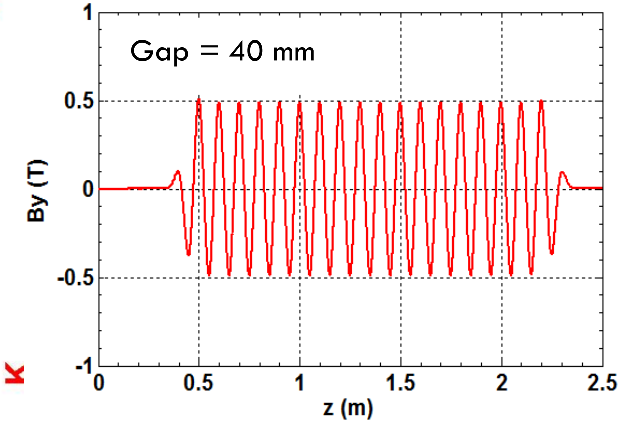
Commissioning of the NSRRC Photo-injector System

Parameters of the photo-injector system	
Laser pulse width (ps)	3
Laser energy (μJ)	up to 120
Power to RF gun (MW)	2.8
Power to Linac (MW)	24
Beam energy (MeV)	60
Beam charge (pC)	up to 600
Repetition rate (Hz)	10



NSRRC U100 Undulator

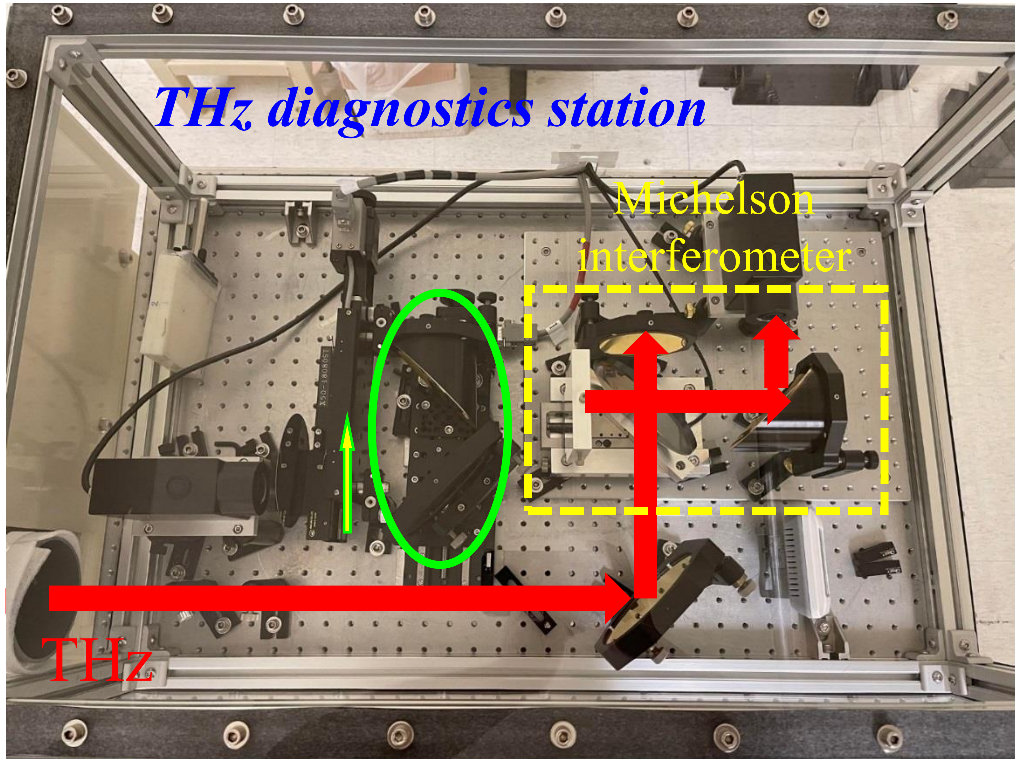




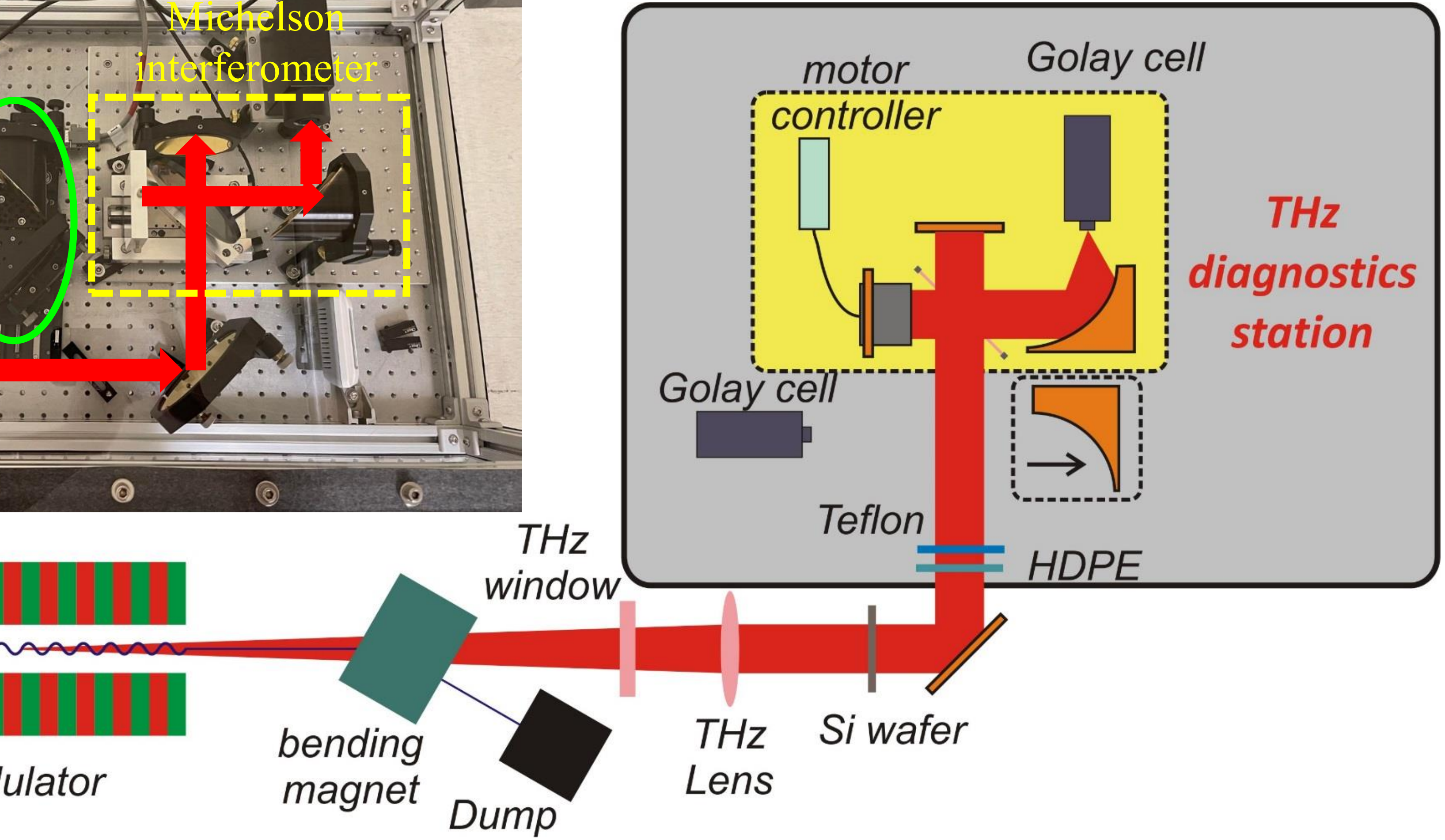
	U100
λ (mm)	100
N_{period}	18
L (m)	2.2
a_w	1.02
gap (mm)	24
B_y (T)	0.945
Ky_{max}	8.8

The U100 undulator built by the NSRRC magnet group more than 30 years ago is used for the superradiant THz FEL (pre-bunched THz FEL).

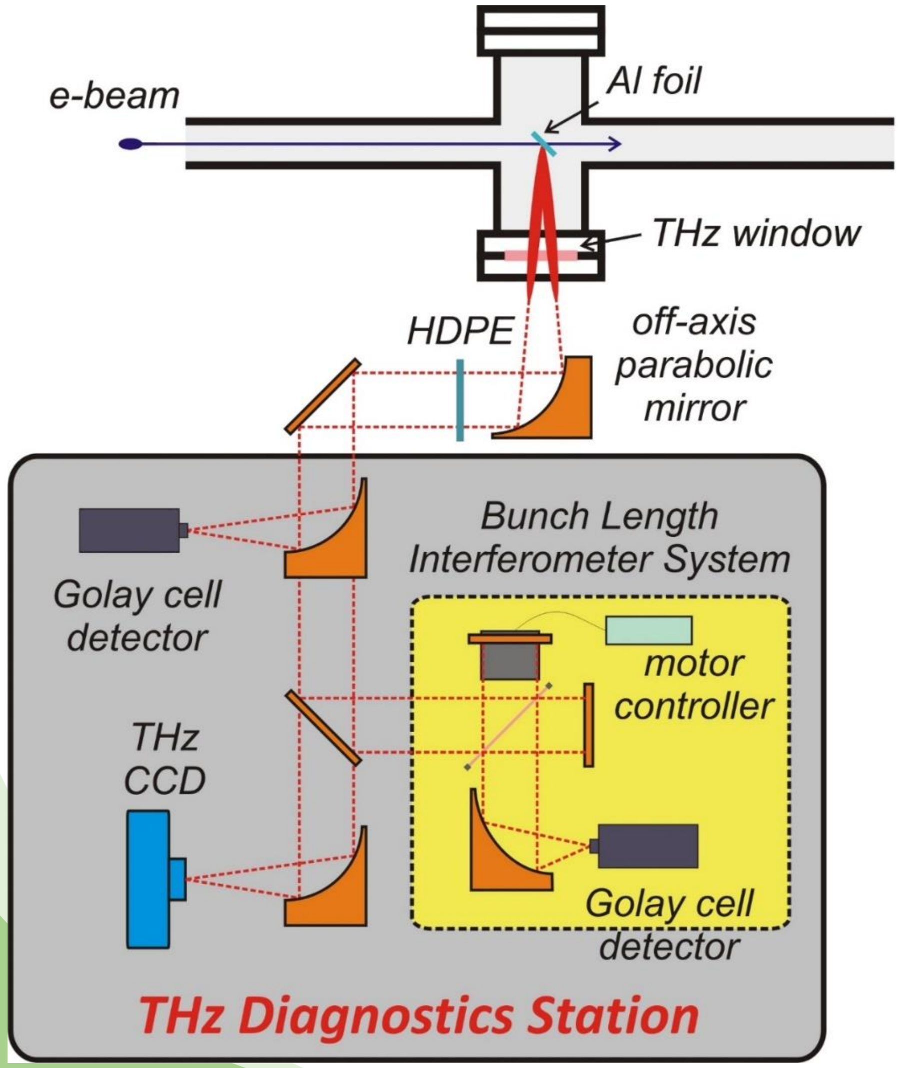
Output Diagnostics for Superradiant THz FEL

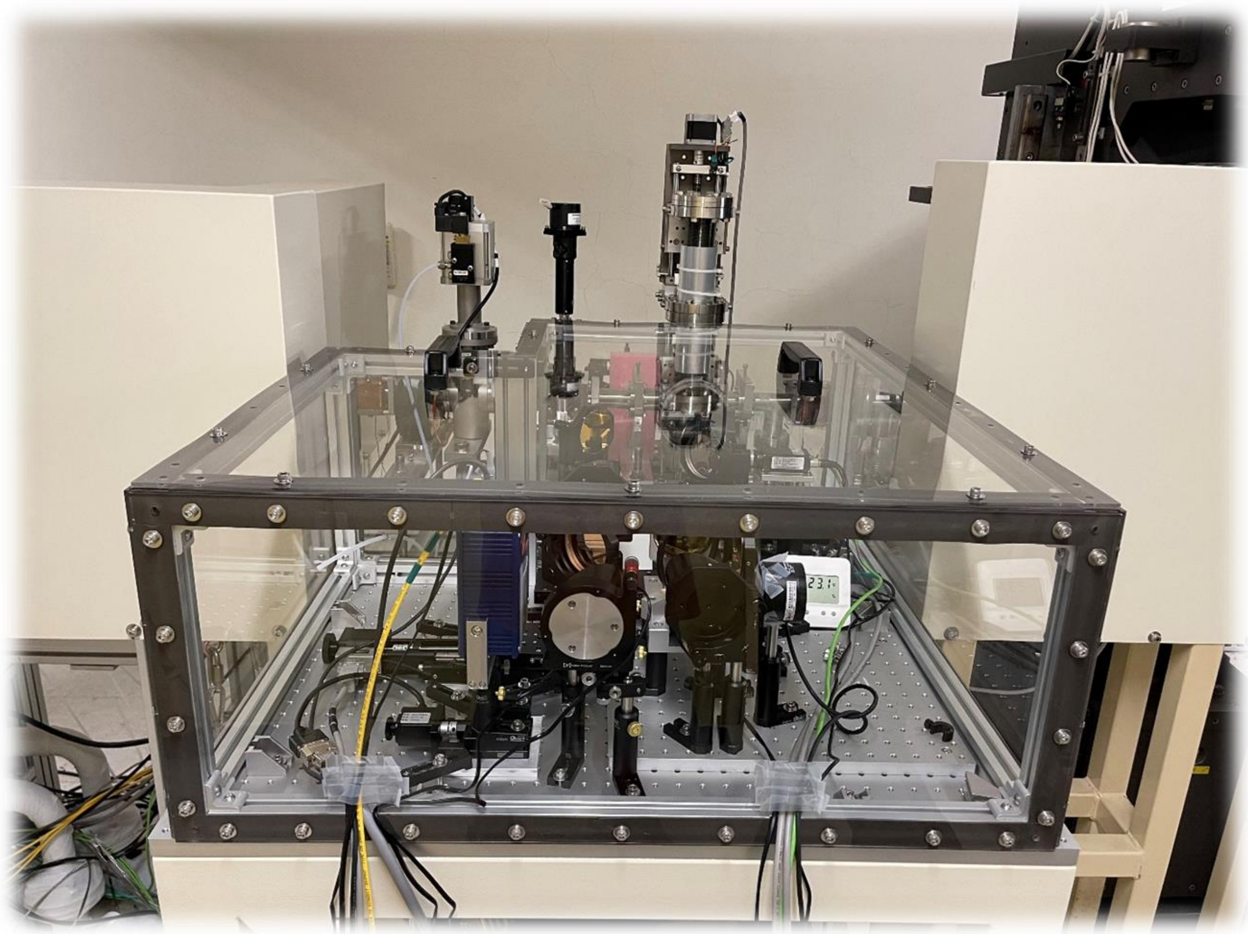


THz spectrum



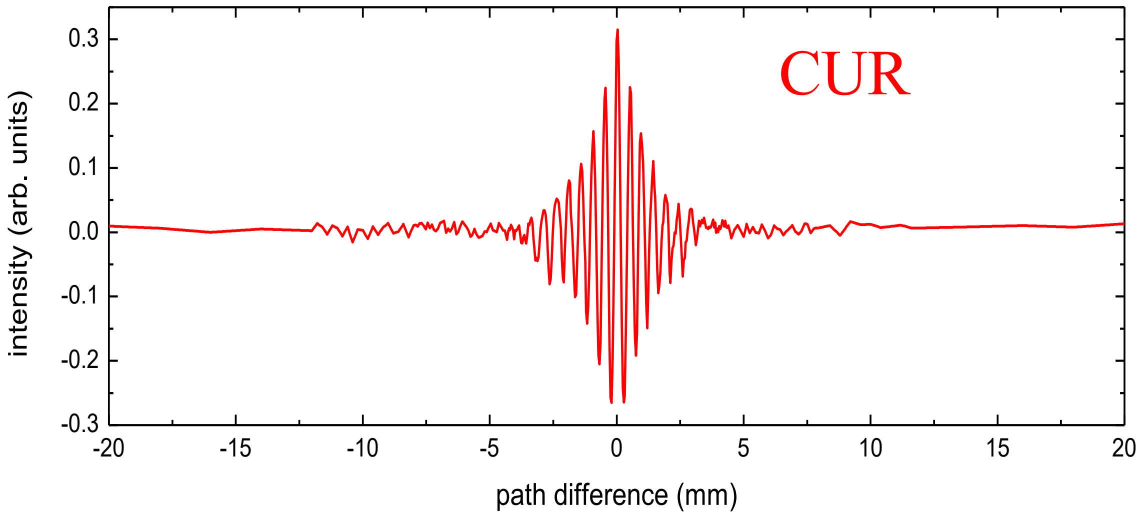
Setup of THz CTR Measurement

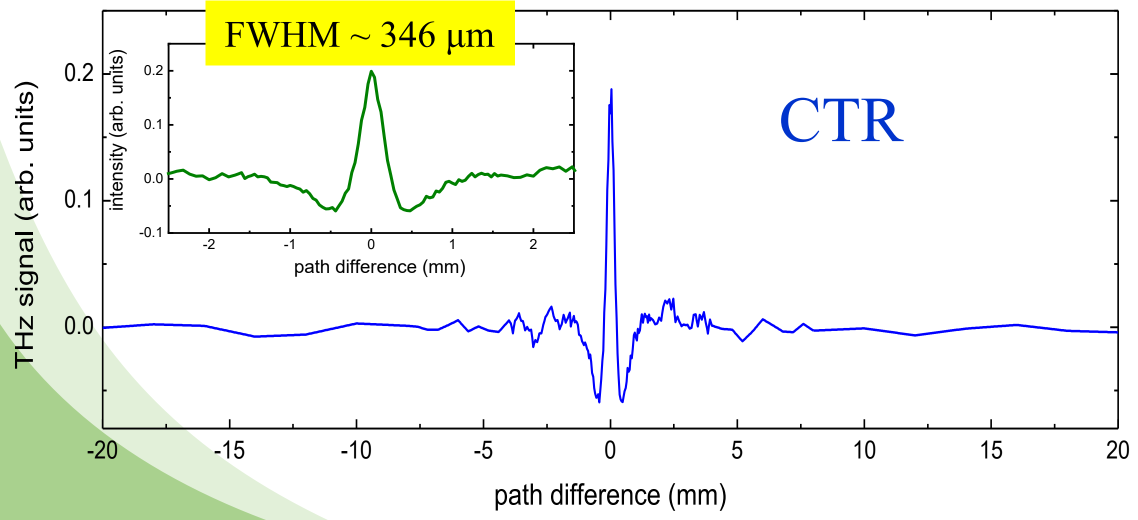


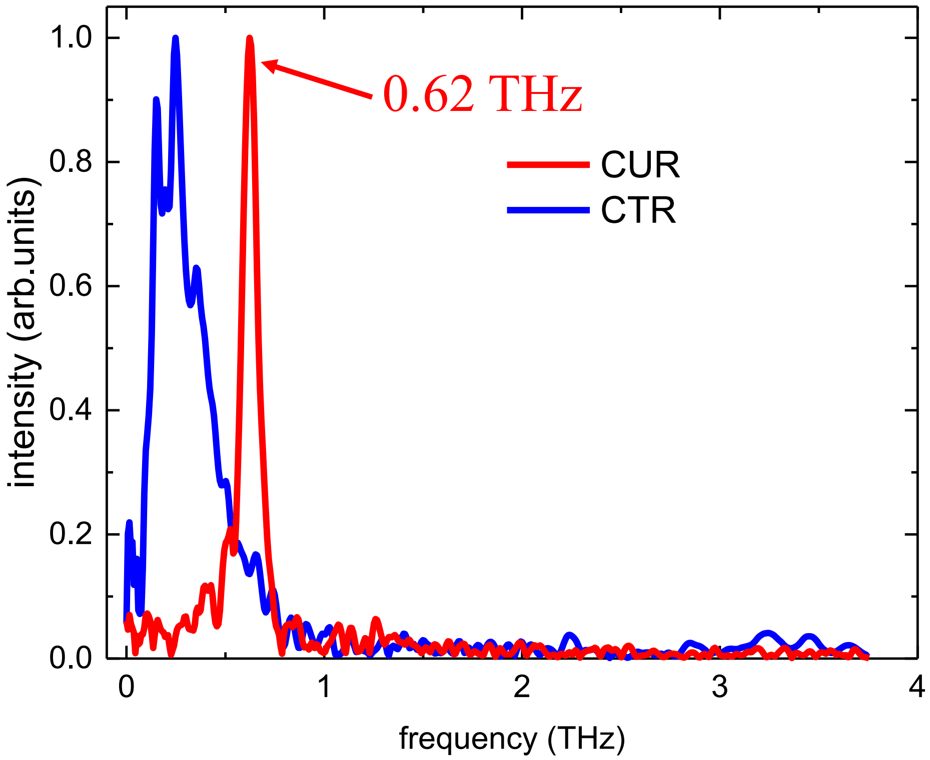


Measurements of the CTR spectrum give the information about the bunch length.

Interferograms of Superradiant THz FEL and CTR



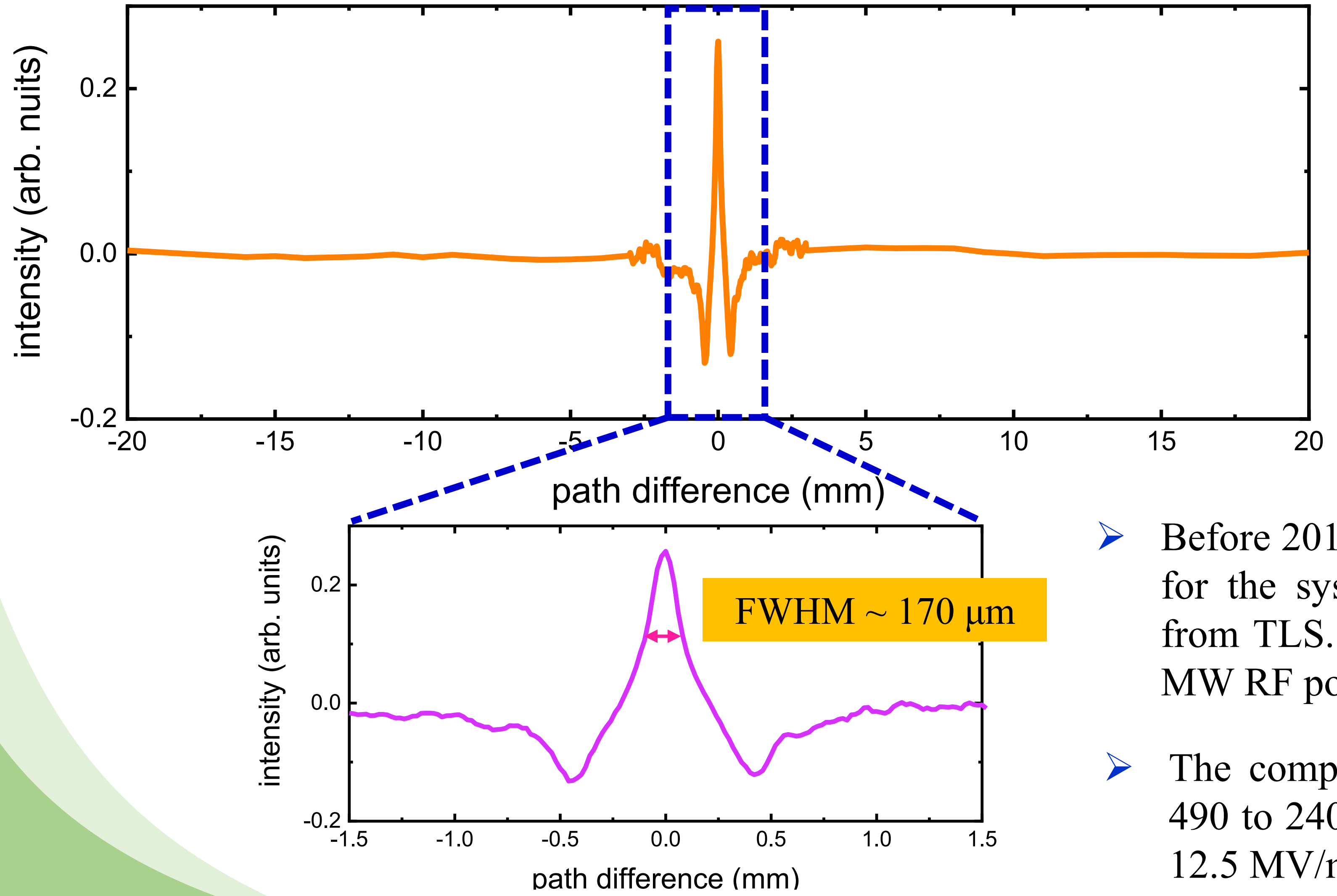




- In 2018, the central frequency of superradiant THz FEL is measured to be 0.62 THz, corresponding to the electron beam energy of 17.7 MeV.
- Assume Gaussian distribution, bunch length σ_z~ 147 μm = 490 fs.

$$\text{FWHM} = 2\sqrt{2ln2}\sigma_z$$

Shorter Bunch Length obtained with Higher Linac Field



- assume Gaussian distribution

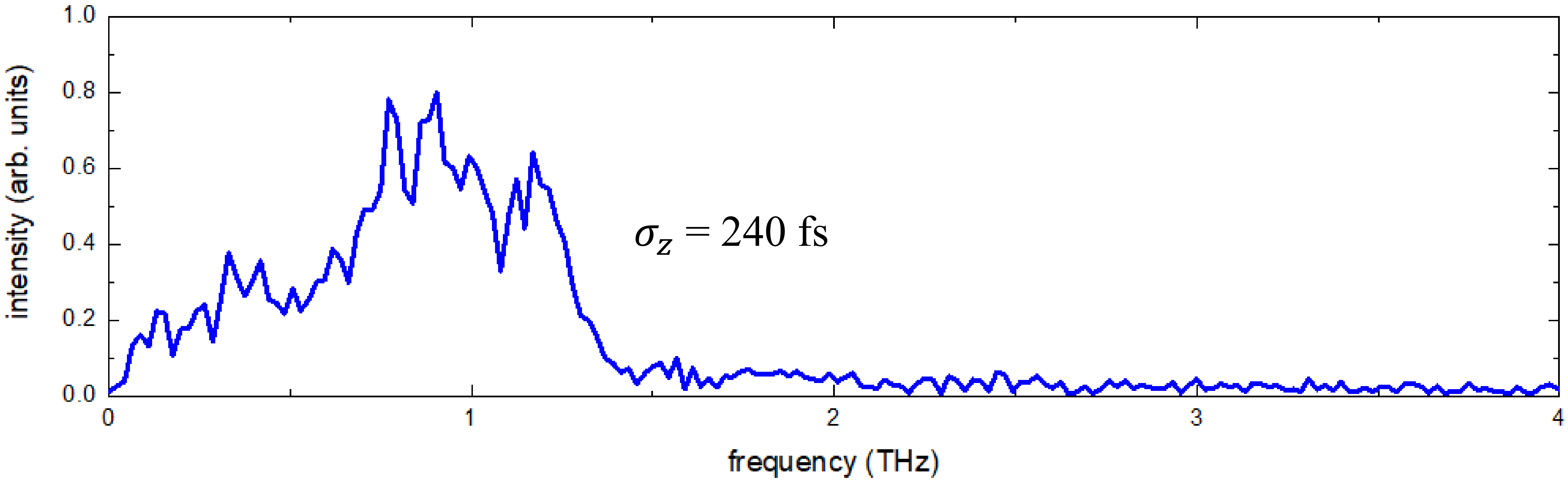
  FWHM = $2\sqrt{2ln2}\sigma_z$

  bunch length σ_z ~ 72 μm = 240 fs

- Before 2019, the Klystron with 14 MW RF power used for the system was Thales klystron which is retired from TLS. From 2020, a new Canon klystron with 30 MW RF power was used for the system.

- The compressed bunch length becomes shorter from 490 to 240 fs when the linac field increased from 8 to 12.5 MV/m.

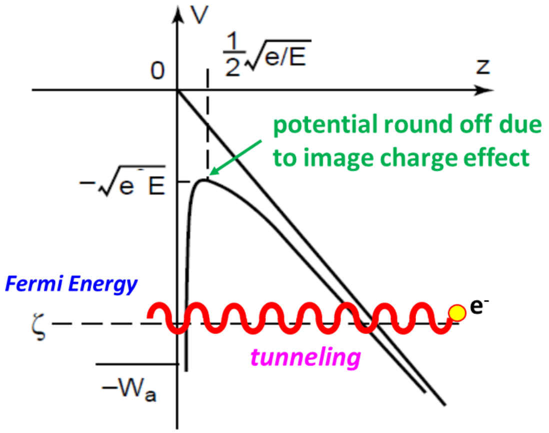
Superradiant THz FEL after upgrade



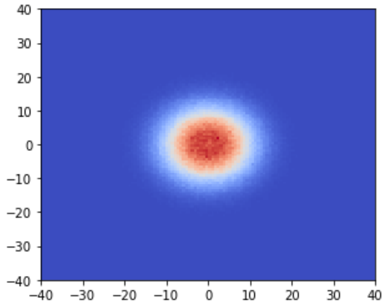
- After the RF system upgraded (Thales Klystron replaced by Canon Klystron) in 2020, the electron energy is increased to 27 MeV.
- The central frequency of the superradiant THz FEL with 20 μJ/pulse energy is shifted to around 1 THz when the bunch length is further compressed to 240 fs.

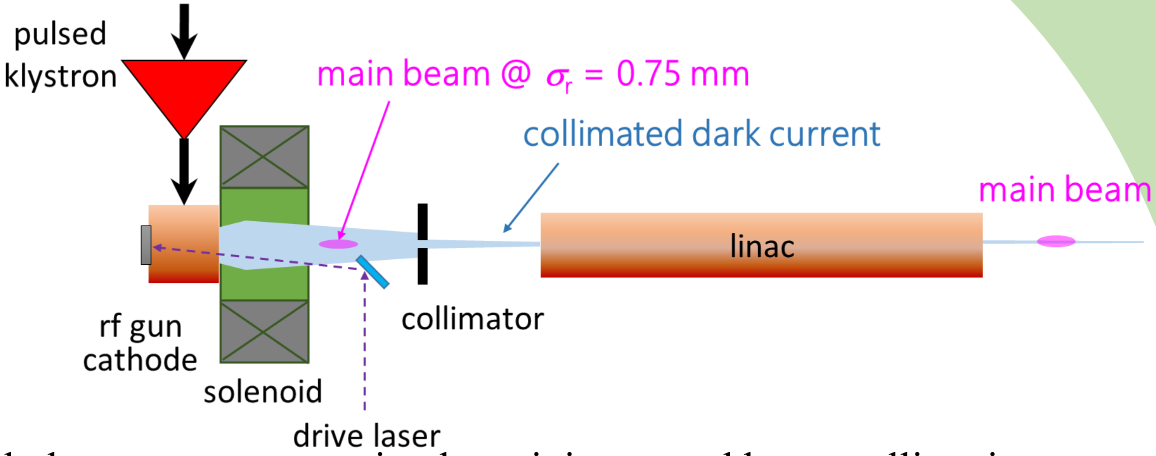
Future Work of STELLA

Simulation of Dark Current Transport in Photoinjector

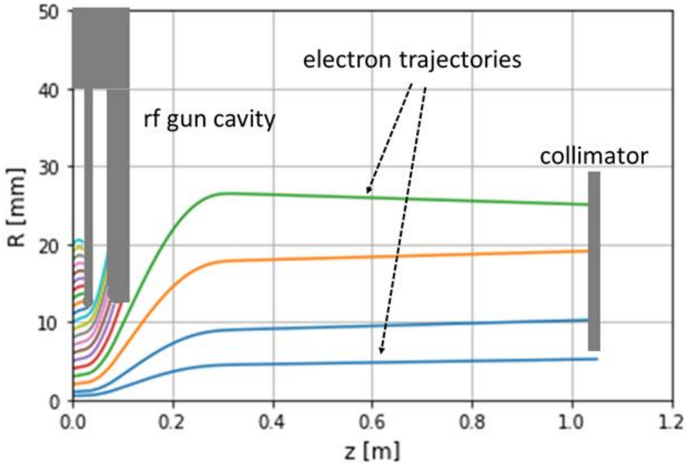


electron field emission (FE) from metallic surface

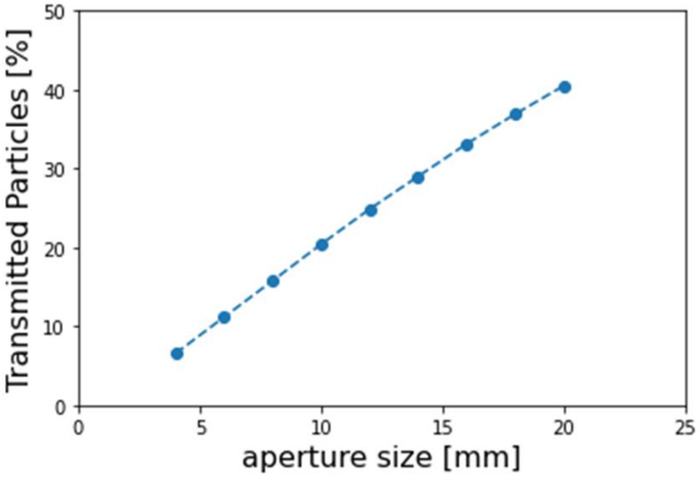




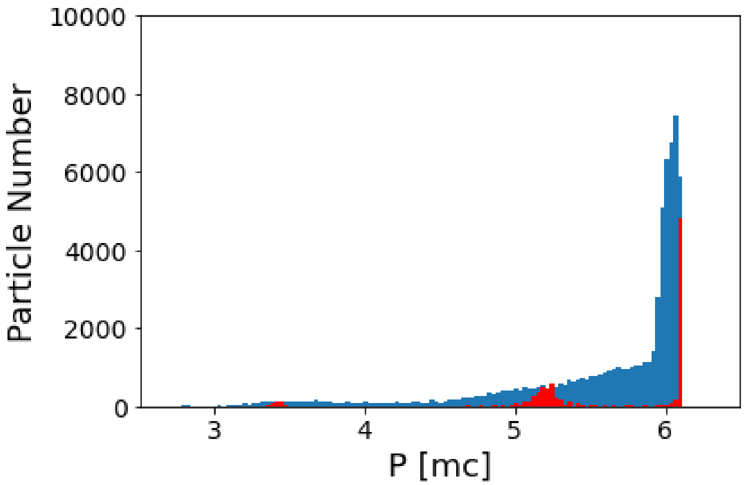
schematic of dark current transport in photo-injector and beam collimation



beam collimator selectively stops electrons emitted at different radial position

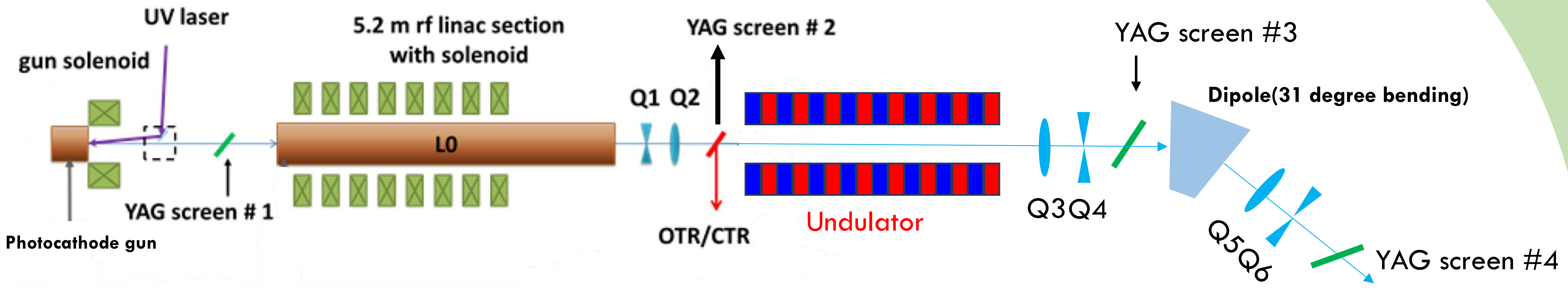


% of particles transmitted through collimator at different aperture sizes



beam momentum spectra with (red) and without (blue) 6-mm collimator

Design Beam Energy Spread Measurement



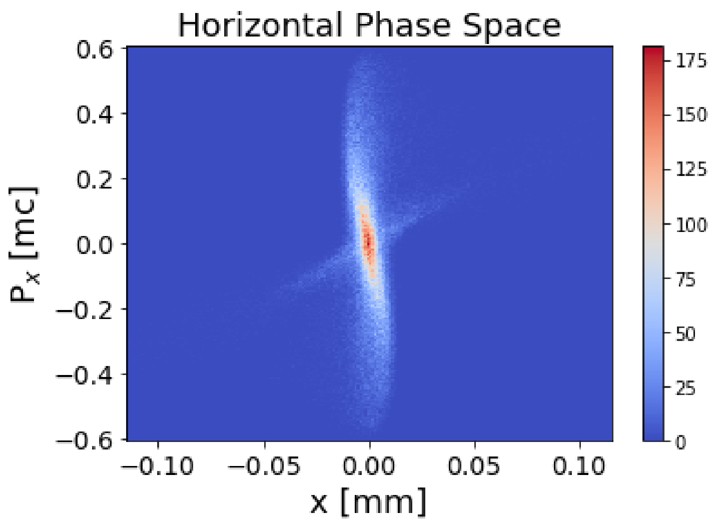
Measurement Criteria

$$\delta_{\min} = \frac{\delta p}{p_0} \geq \frac{2E_b}{D} = 2\frac{\sqrt{\epsilon\beta}}{D},$$

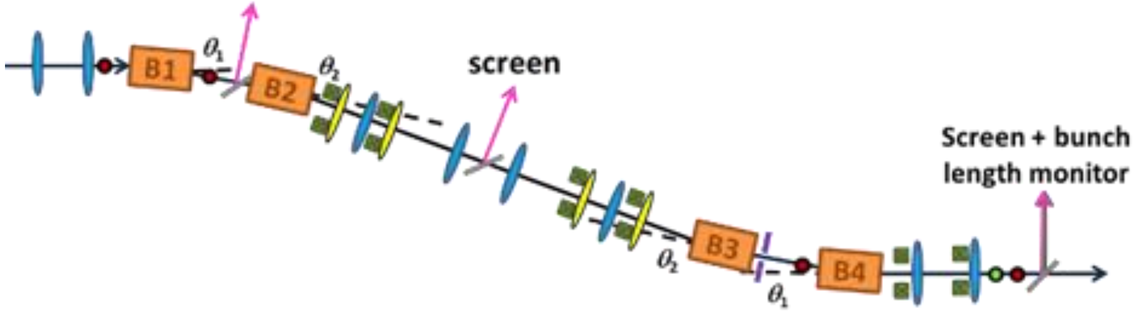
$\delta_{\min}$: minimum resolution for energy spread measurement
E_b : beam size
D : dispersion function

For good resolution
- Small emittance
- High dispersion

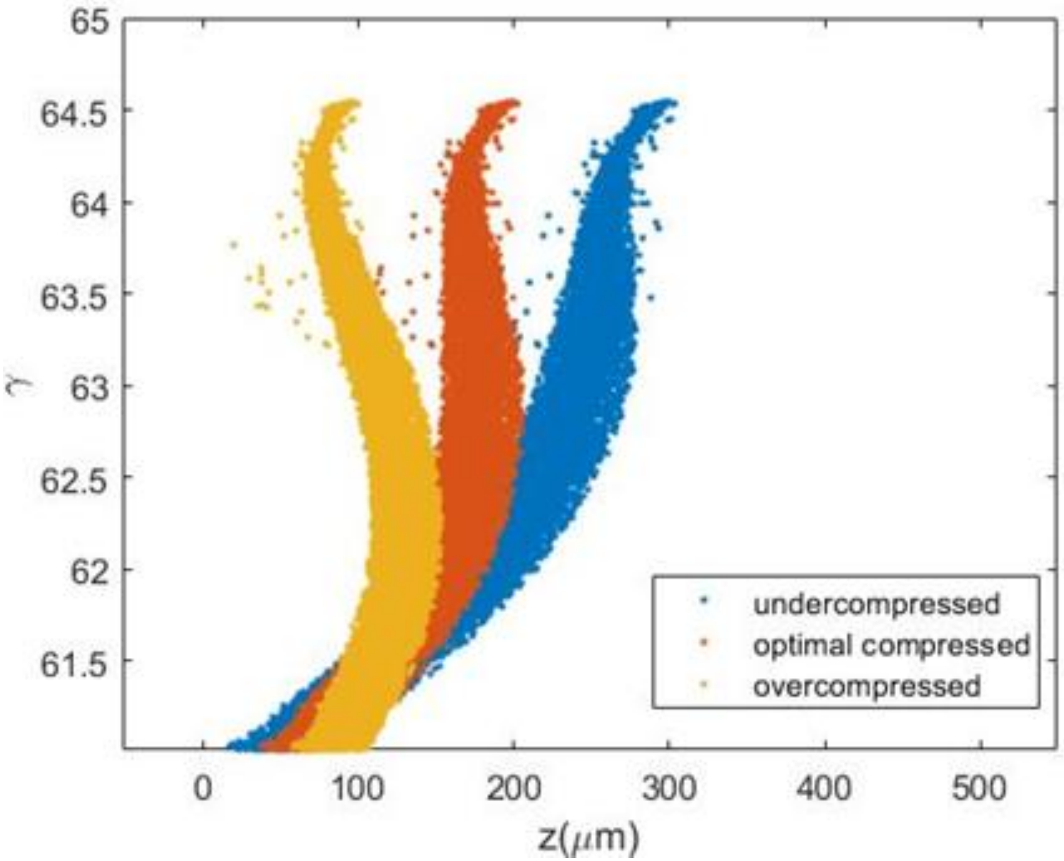
Impact-T Optimization



Further Bunch Length Reduction by Nonlinear Magnetic Bunch Compressor

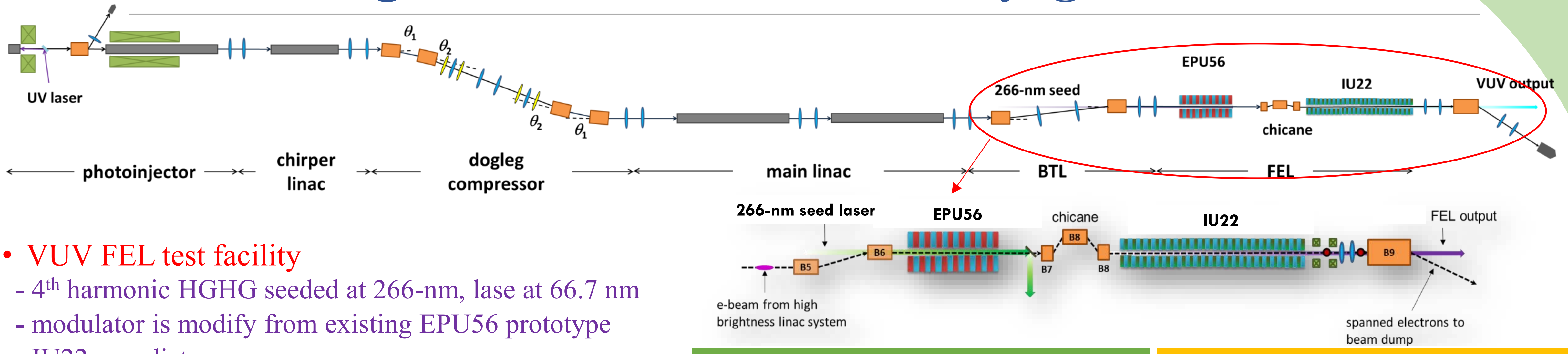


Layout of the double dogleg bunch compressor for the simulation of NSRRC THz FEL LINAC system.



Electron distributions under three different bunch compression conditions: (1) the optimal compression case where compression ratio is very large (red dots), (2) under compression case with compression ratio of about 20 (blue dots) and (3) over compression case with compression ratio of about 30 (yellow dots). Compressed bunch length is about 140 fs in the optimal compression case (i.e. an up-stood beam in longitudinal phase space).

Design of VUV FEL Test facility @NSRRC



- VUV FEL test facility
  - 4^{th} harmonic HGHG seeded at 266-nm, lase at 66.7 nm
  - modulator is modify from existing EPU56 prototype
  - IU22 as radiator
  - Start-to-end simulation in progress
  - short-term goal: CDR, including
    - Seed laser design
    - Magnets design
    - Vacuum system
    - RF & timing system design
    - VUV pulse diagnostics

Beam Parameters	
Energy	263 MeV
Peak current	800 A
emittance	3 µm
Energy spread	0.08 %

Modulator Parameters	
Type	Helical
Period length	56 mm
Undulator length	0.448 m
Undulator parameter, K	1.23
Peak magnetic field, B_0	0.2354 T
Seed laser wavelength	266 nm
Seed power	300 MW
Energy modulation	0.302 %

Radiator Parameters	
Undulator type	planar
Period length	22 mm
Undulator parameter, K	1.16
Peak magnetic field, B_0	0.538
Radiation wavelength	66.7 nm
Saturated power	372.5 MW
Pierce parameter	0.00203
Gain length	0.65

Unfortunately, the VUV FEL project has been temporarily suspended due to funding and space constraints.

Summary of STELLA

- Ultrashort few tens MeV electron bunches as short as 240 fsec can be generated from the photoinjector by means of RF bunch compression (i.e. velocity bunching).
- Accelerator-based coherent THz sources has been studied to demonstrate the capability of the NSRRC high brightness photo-injector. Generation of intense superradiation THz FEL as high as 20 μJ/pulse has been obtained at 0.6 ~ 1.4 THz which could be a useful tool for applications such as material science and biomedical imaging.
- The accelerator test facility will be transformed as a THz user facility. The THz beamline is under designed and the facility expects to open for users by the end of 2025.
- Continue with the numerical analysis of the dark current in the photoinjector and the design of a new RF electron gun. Improving pulse repetition rate by enhancing the performance of the RF photocathode gun.
- Increasing the frequency of THz source to 3 THz by shortening the bunch length with a dogleg bunch compressor.