National Synchrotron Radiation Research Center

Computational Challenges in the Development of THz FELs at National Synchrotron Radiation Research Center

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On behalf of NSRRC LINAC Group

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Outline

- Introduction of NSRRC Light Sources
- Simulation of Photo-injector Beam Dynamics with IMPACT-T
- Simulation of Superradiant THz Free Electron Laser with PUFFIN
- Facility Introduction : NSRRC THz FEL
- Future Work of STELLA
- Summary

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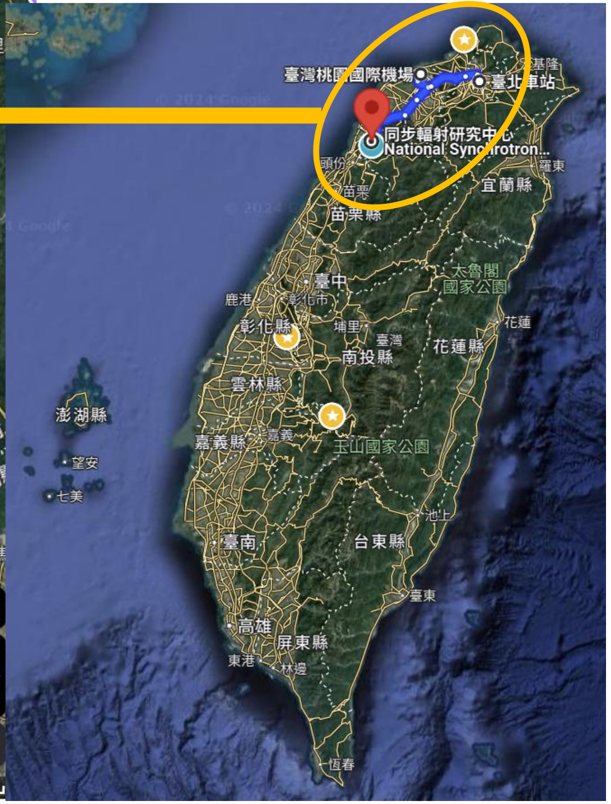
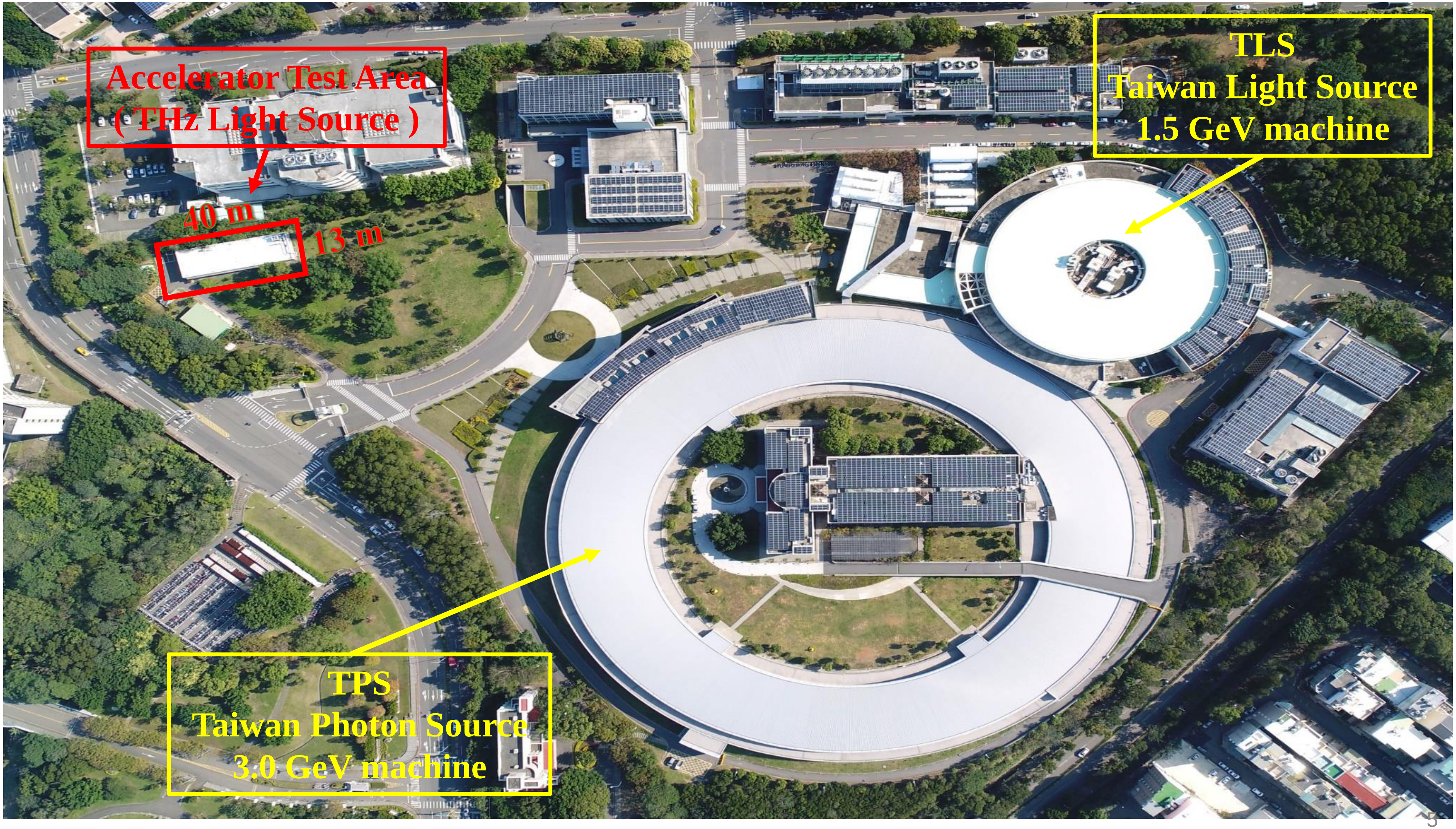
Introduction of NSRRC Light Sources

Introduction to the location of NSRRC



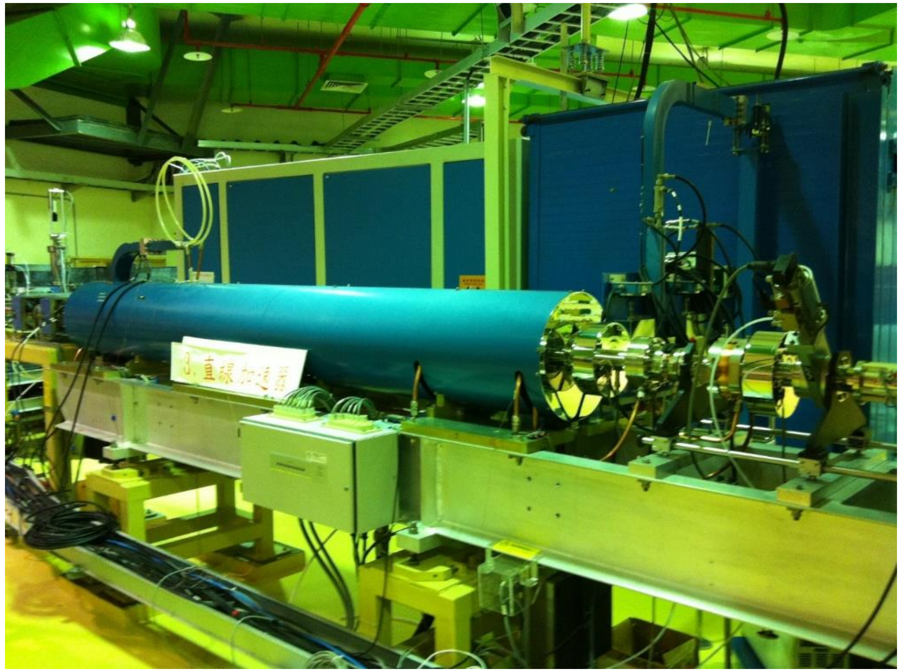
Light Sources at NSRRC

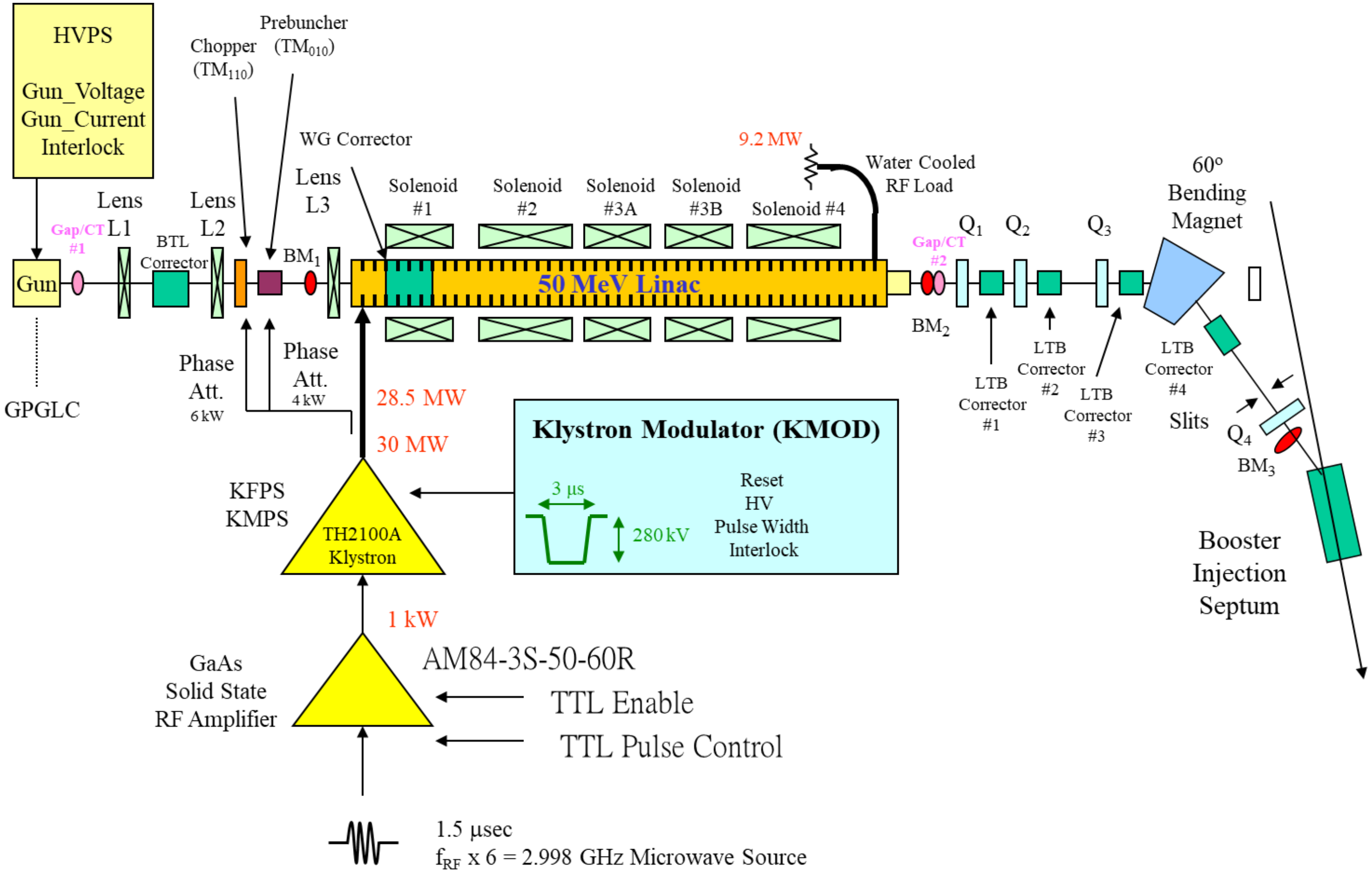


LINAC - TLS Pre-Injector Systems

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)

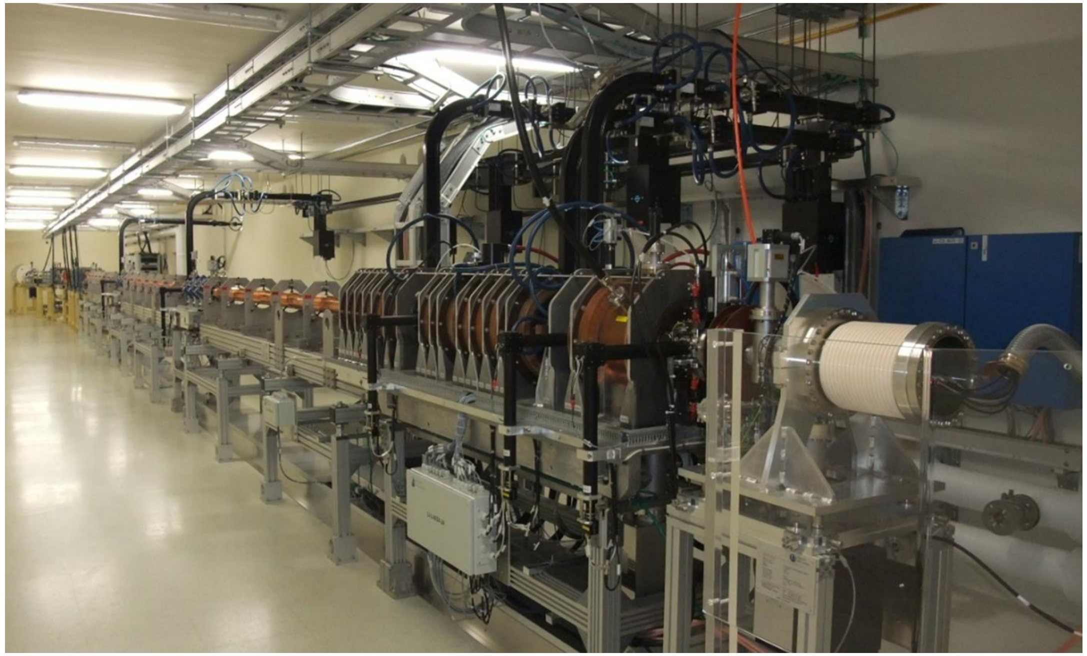


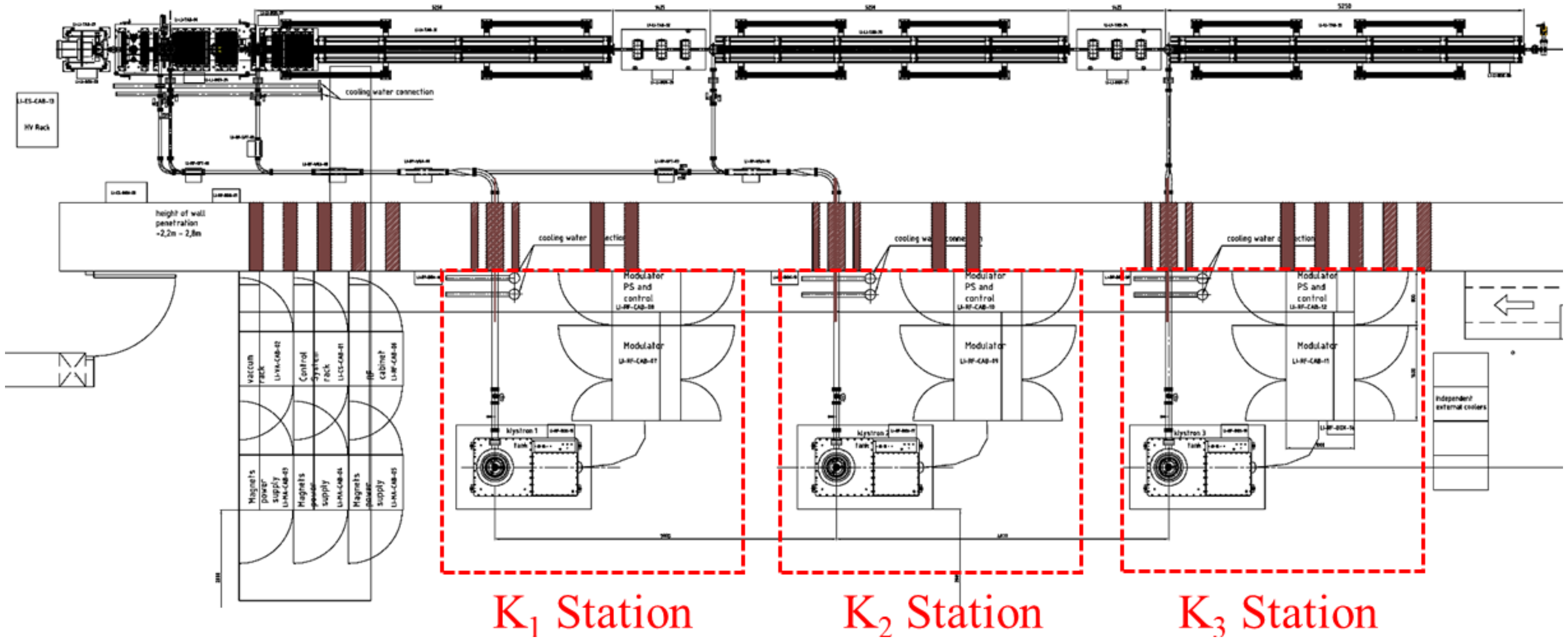


LINAC - TPS Pre-Injector RF Distribution

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

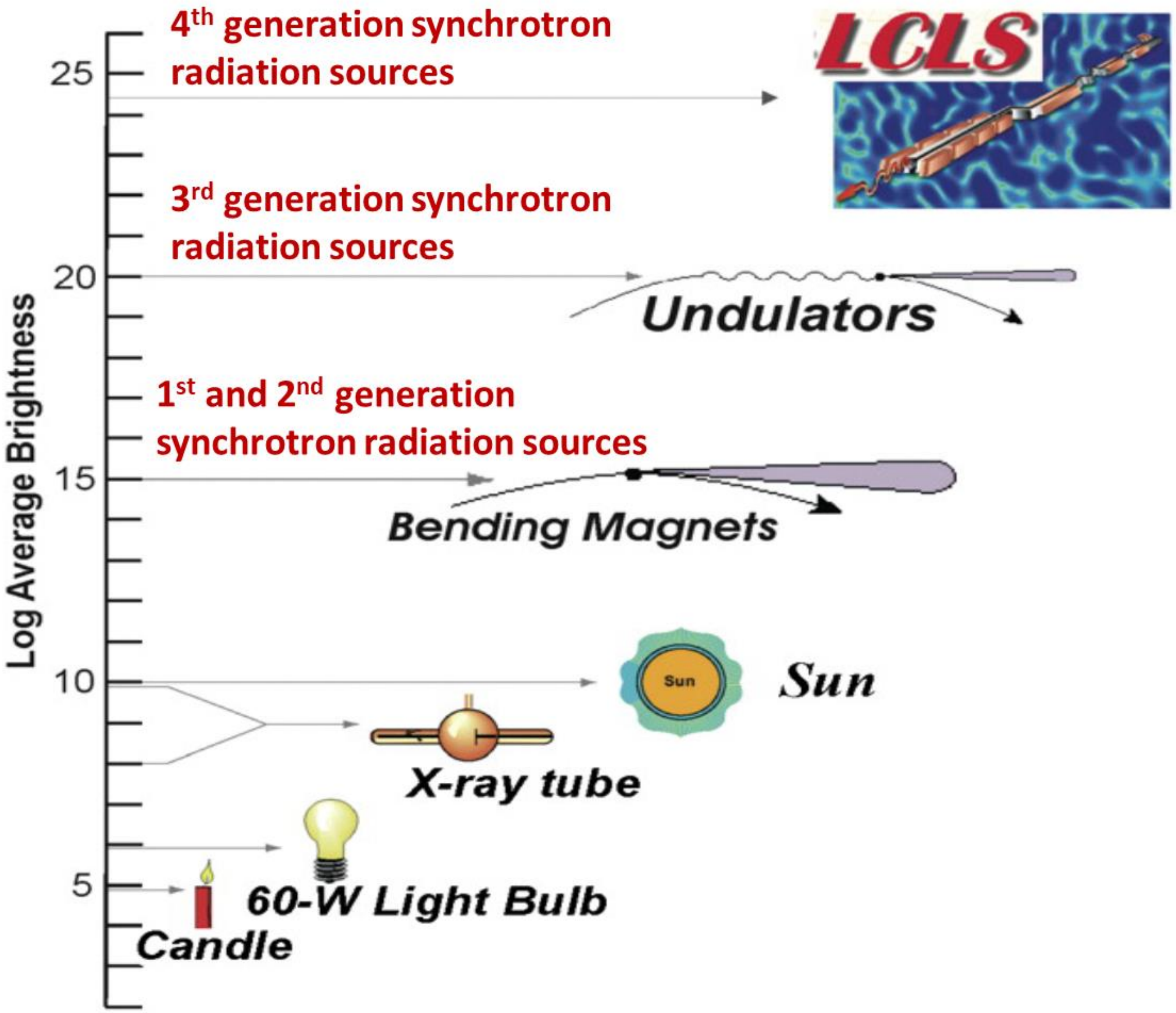
- 90 keV DC electron gun (Thermionic Cathodes)
- Sub harmonic pre-buncher SPB (500MHz)
- Primary buncher PBU (3 GHz)
- Final buncher FBU (3 GHz)
- Three 5.2 m linacs (3 GHz)
- Three Klystrons stations

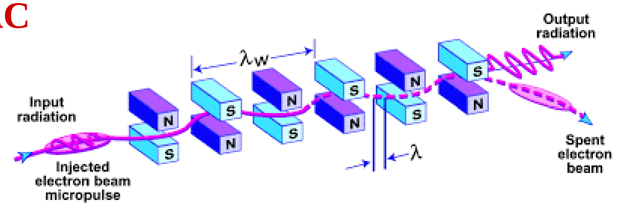




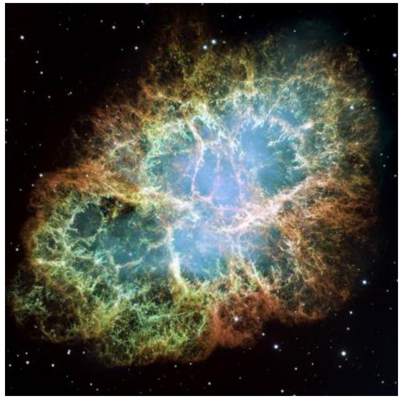
Introduction – Brightness of Synchrotron Light

LINAC Coherent Light Source at SLAC





free electron lasers

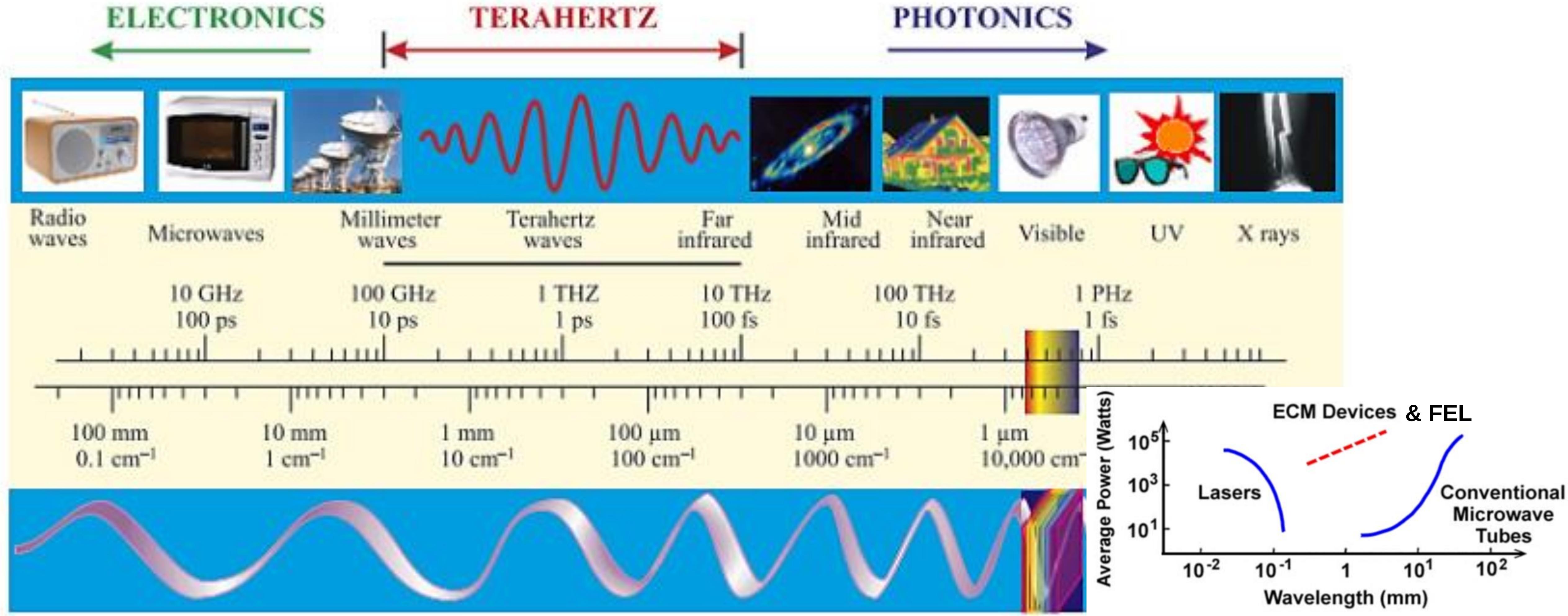


synchrotron light in the sky: crab nebula (near Taurus ζ) observed by Hubble telescope

Brightness = # of photons/seconds/unit solid angle/0.1% BW

$$B = \frac{\dot{N}_{ph}}{4\pi^2 \sigma_x \sigma_y \sigma_{x'} \sigma_{y'} \frac{d\omega}{\omega}}$$

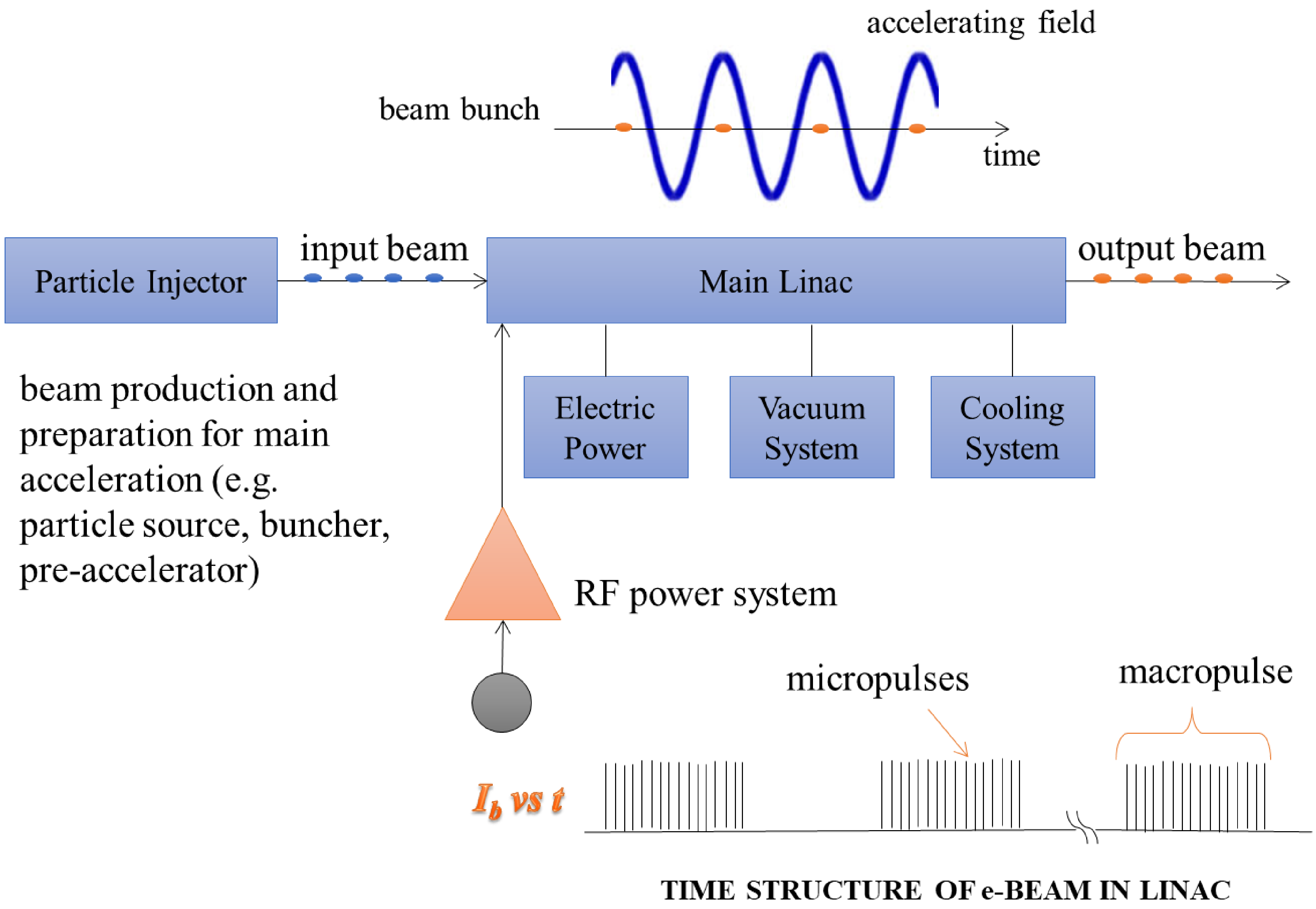
What is the Terahertz (THz) Wave?



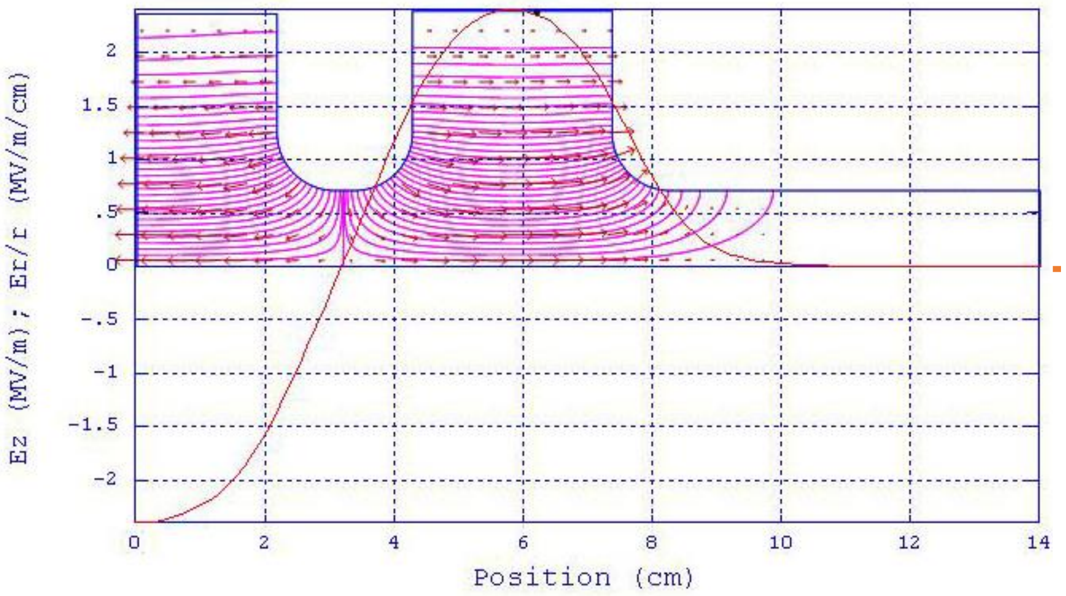
Terahertz wave (THz or T-ray), which is electromagnetic radiation in a frequency interval from 0.1 to 10 THz (3 mm to 30 μm), lies a frequency range with rich science but limited technology.

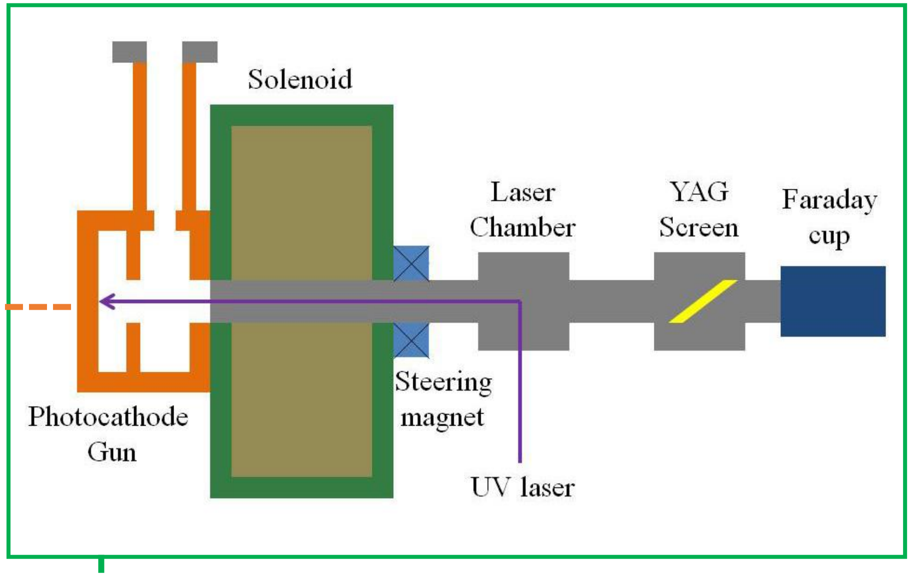
1 THz = 300 μm = 1 ps = 33 cm^{-1}

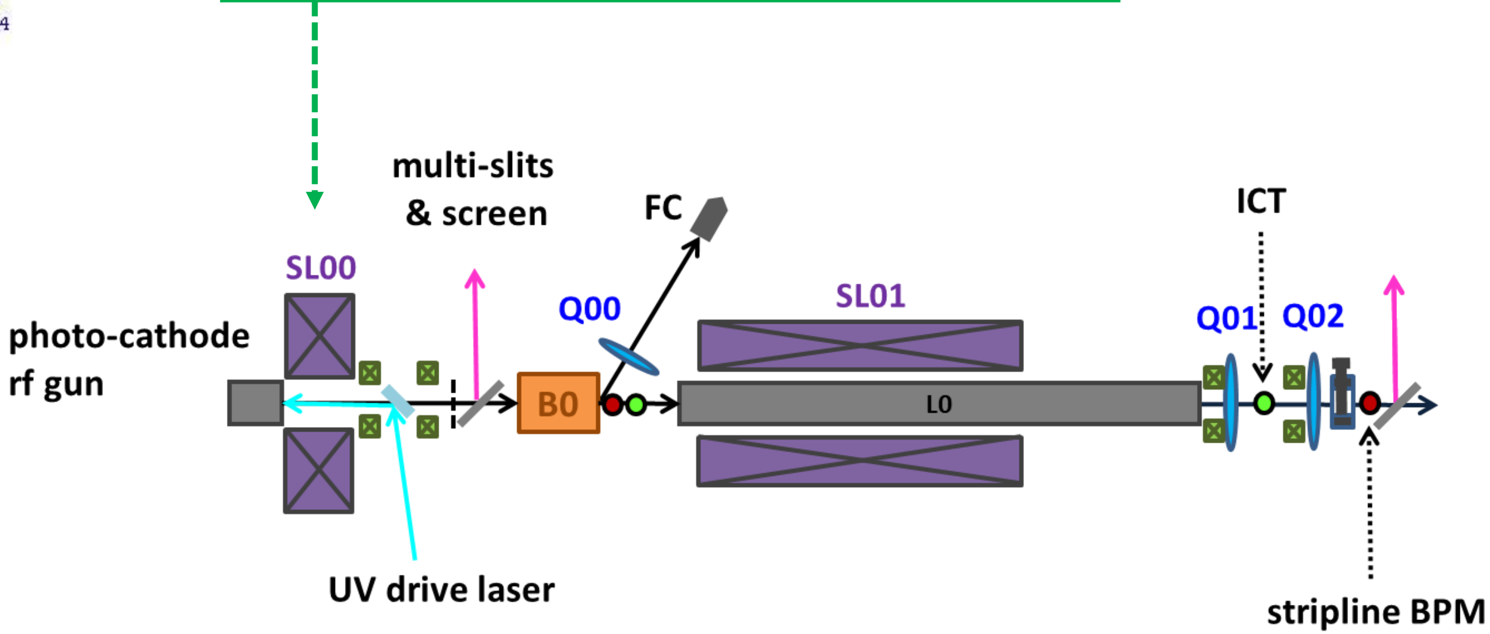
A Typical Electron LINAC System



Introduction of Photo-injector







Main components

1. Photocathode RF Gun

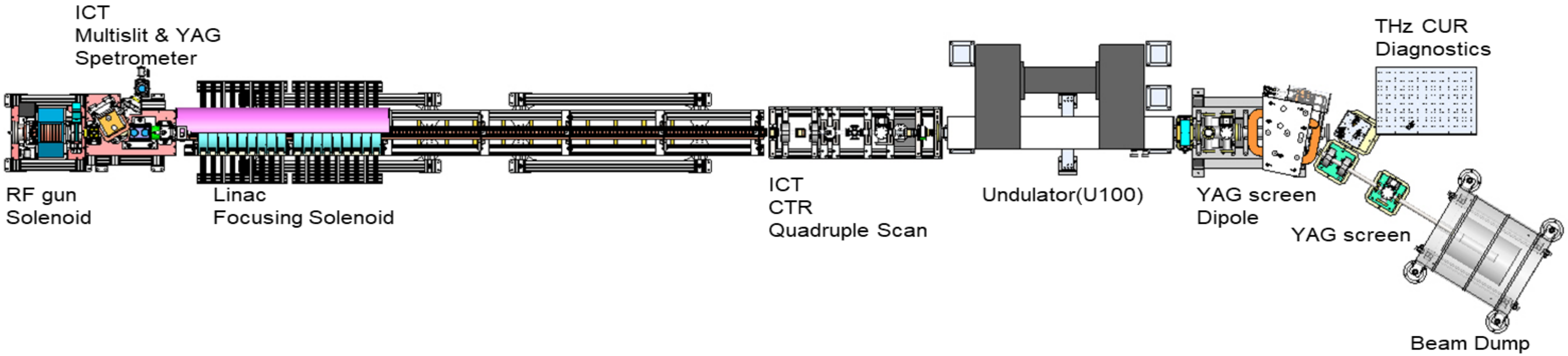
2. Linear Accelerator (LINAC)

3. Pulsed RF System

Superradiant Terahertz Light based on Linear Accelerator (STELLA) Technology

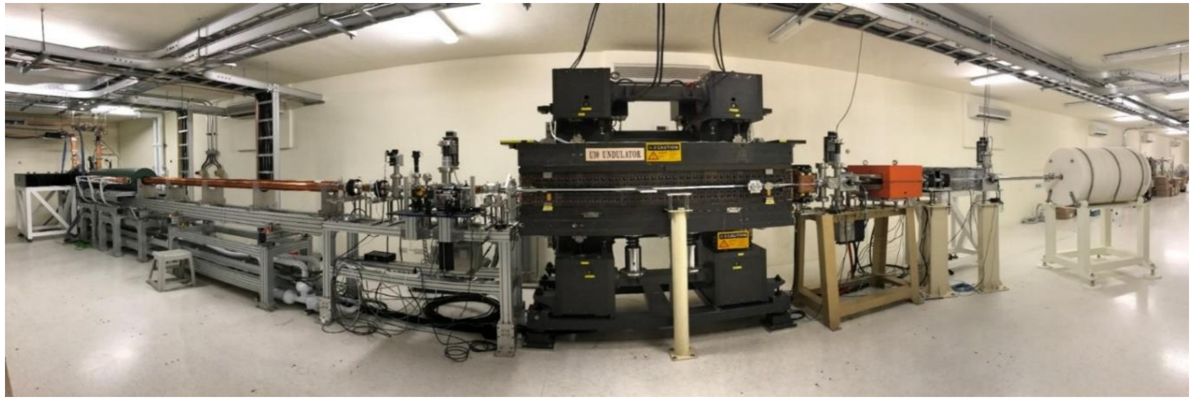
LINAC-based Coherent THz sources :

- 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)



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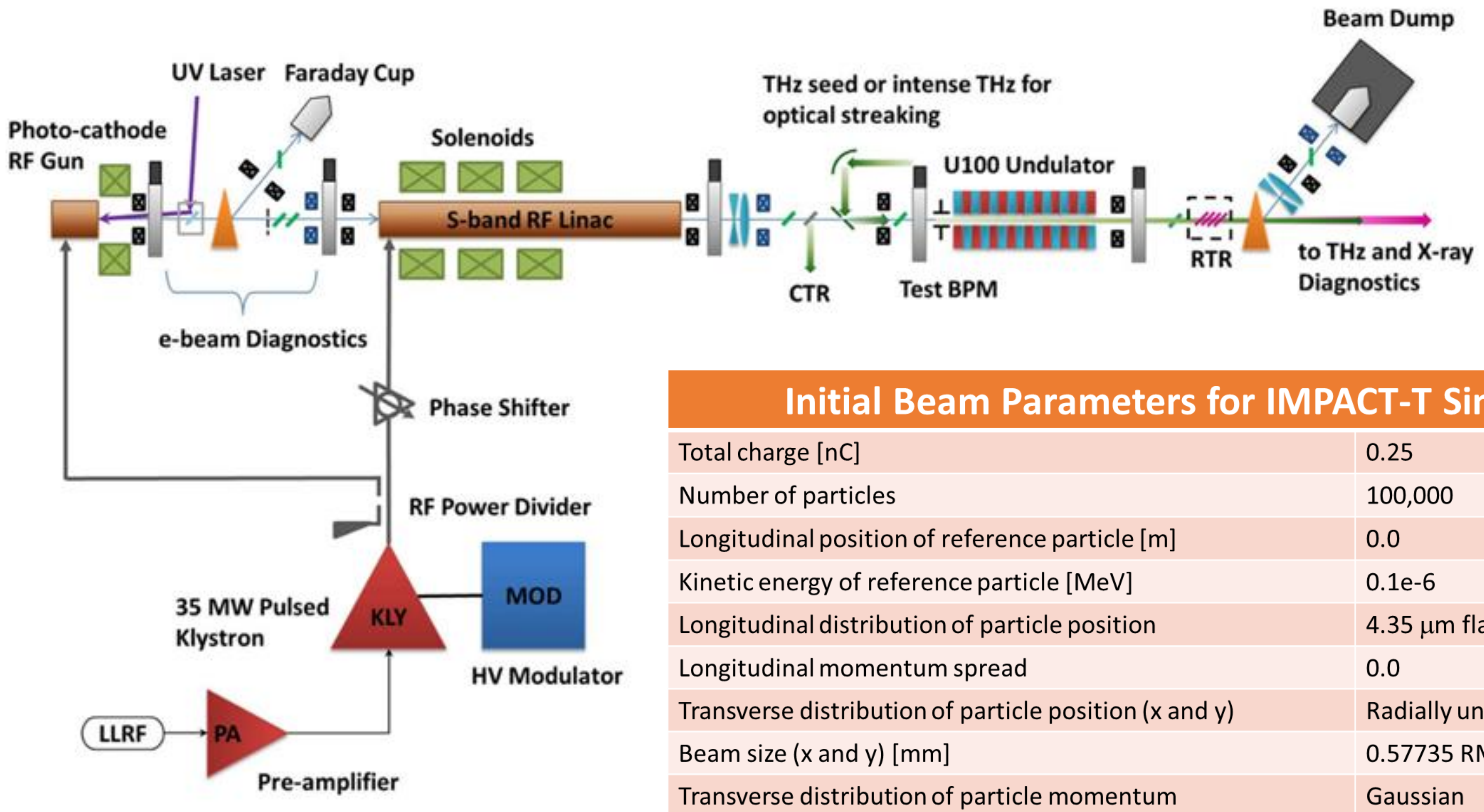
Simulation of Photo-injector Beam Dynamics with IMPACT-T

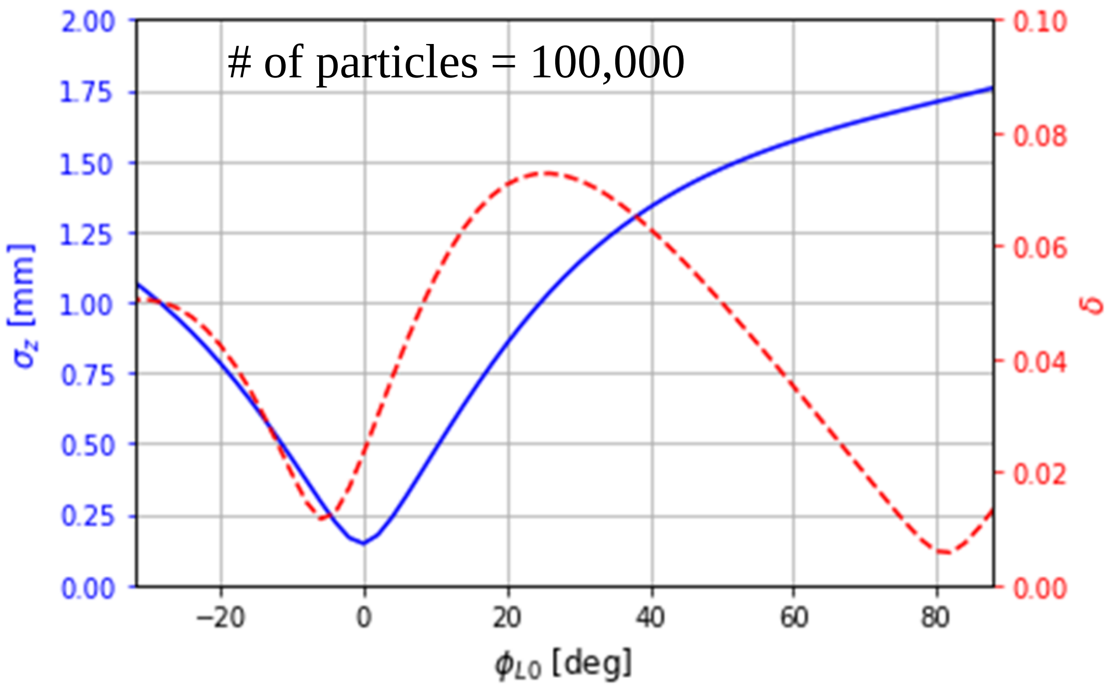
NSRRC Photoinjector and THz FEL Facility Schematic



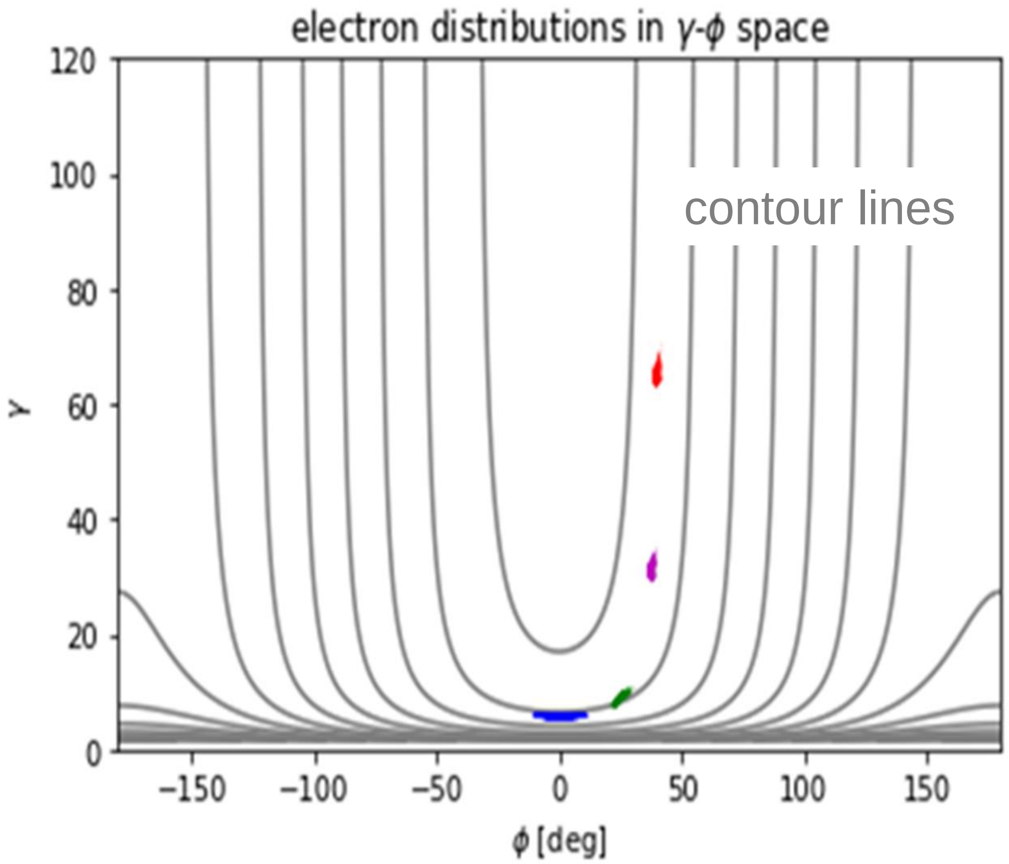
Initial Beam Parameters for IMPACT-T Simulation	
Total charge [nC]	0.25
Number of particles	100,000
Longitudinal position of reference particle [m]	0.0
Kinetic energy of reference particle [MeV]	0.1e-6
Longitudinal distribution of particle position	4.35 μm flat-top / 0.5 μm ramp
Longitudinal momentum spread	0.0
Transverse distribution of particle position (x and y)	Radially uniform
Beam size (x and y) [mm]	0.57735 RMS
Transverse distribution of particle momentum	Gaussian
Normalized initial emittance (x and y) [mm-mrad]	0.5 RMS

Simulation of Photoinjector Beam Dynamics

- Beam dynamics in photoinjector when operating in "short-bunch mode" is simulated with IMPACT-T code.
- IMPACT-T is a parallelized full 3D space charge tracking program which take short-range wakefields and CSR into account (https://github.com/impact-lbl/IMPACT-T).



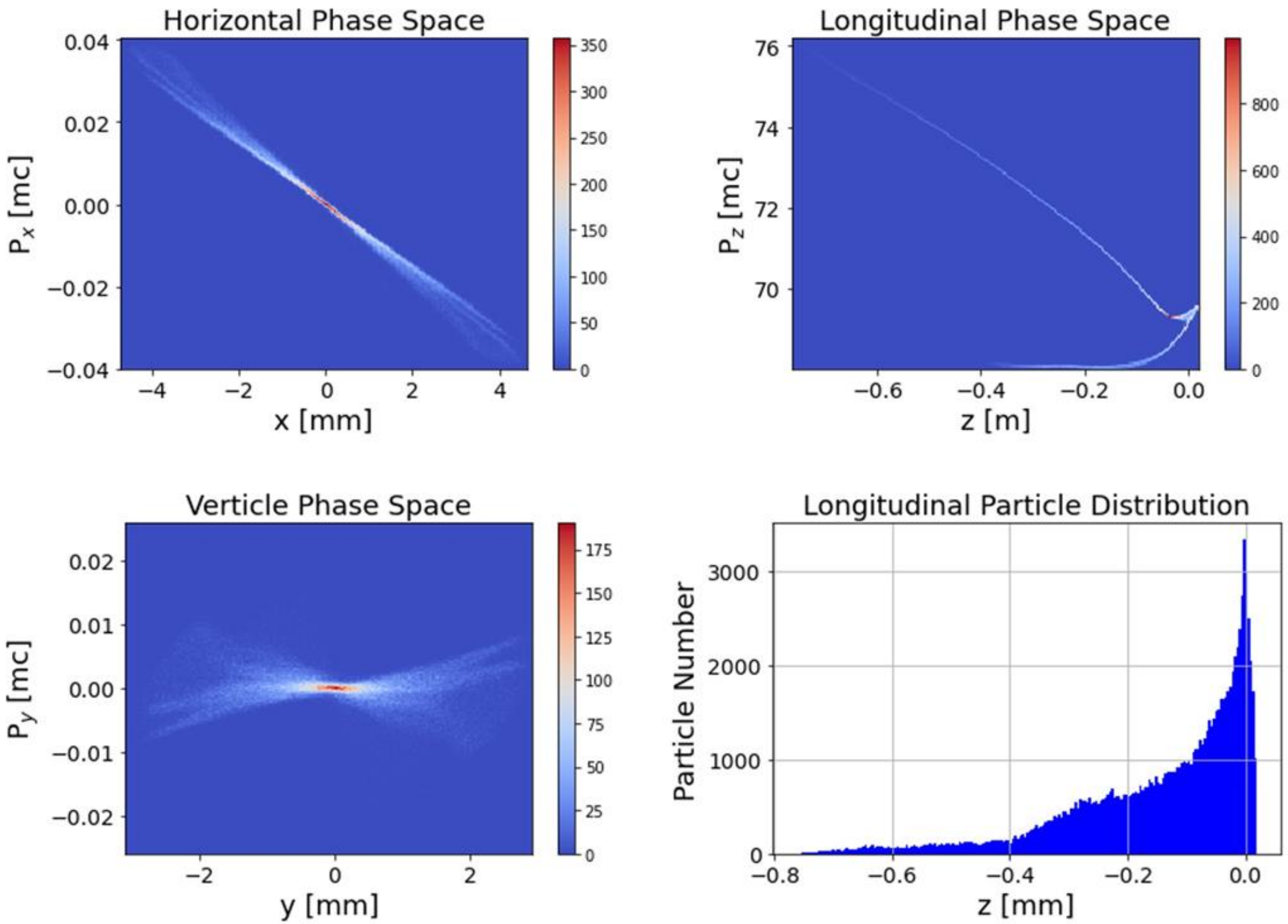
Bunch length (blue) and energy spread (red) versus linac phase with linac solenoid field @ 0.0 T. Minimum bunch length of ~200 μm (i.e. 667 fs in duration) can be obtained.



- **Beam injection near LINAC zero-crossing RF phase**
- **Phase slippage due to velocity difference between beam and RF field**
- **Bunch compression and acceleration simultaneously in RF LINAC (i.e. velocity bunching)**

Simulation of Photoinjector Beam Dynamics (cont'd)

100,000 particles



Particle distributions in horizontal (upper left), vertical (lower left), longitudinal (upper right) phase spaces and histogram of particle dist. (lower right).

- Beam injection near LINAC zero-crossing RF phase for minimum bunch length at photoinjector exit.
- Solenoid field is set at 0.045 T to aid beam focusing near LINAC entrance.
- Although shortest RMS bunch duration relatively long for generation of superradiant THz radiation, longitudinal particle distribution in real space showing that significant amount of particles are concentrated at the 'bunch head'. This contributes to the bunch form factor at THz frequencies.

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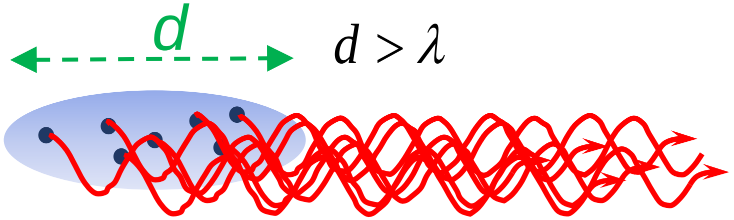
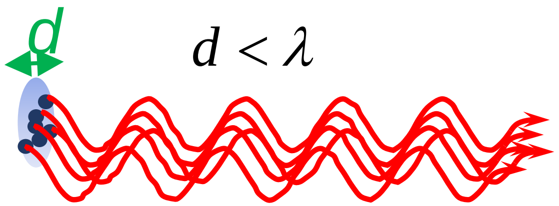
Simulation of Superradiant THz Free Electron Laser with PUFFIN

Superradiant Undulator Radiation



electrons radiate incoherently



electrons radiate coherently

- Coherent radiation power depends strongly on longitudinal particle distribution
- Due to the undulator R_{56}, bunch length and longitudinal particle distribution does not remain unchanged as the bunch traverses the undulator in a superradiant FEL

Radiation field from a single electron

$$\vec{E}_k(\omega) = \vec{E}_0 e^{i(\omega t + \varphi_k)}$$

Radiation power from a bunch of electrons

$$P(\omega) \propto \left(\sum_k^{N_e} \vec{E}_k \right) \cdot \left(\sum_j^{N_e} \vec{E}_j^* \right) \propto \sum_{k,j}^{N_e} e^{i(\omega t + \varphi_k)} e^{-i(\omega t + \varphi_j)}$$

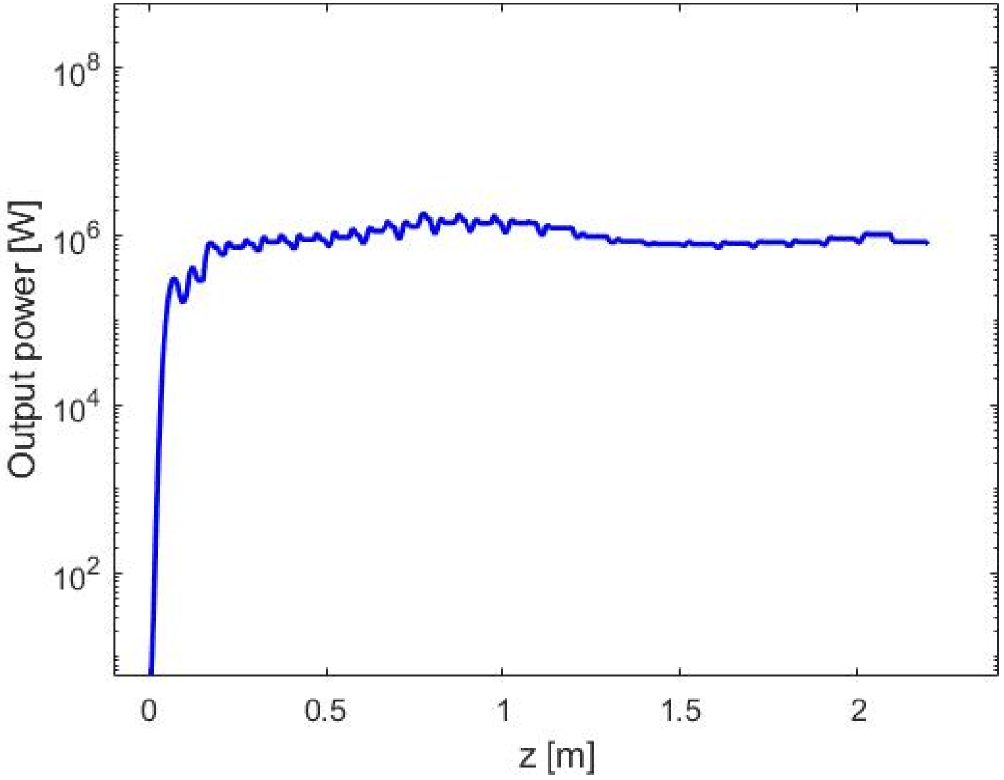
$$= \sum_{k,j}^{N_e} e^{i(\varphi_k - \varphi_j)} = N_e + \sum_{k \neq j}^{N_e} e^{i(\varphi_k - \varphi_j)} = N_e + N_e(N_e - 1) \left| \langle e^{i\varphi} \rangle \right|^2$$

$$P(\omega) = \left[N_e + N_e(N_e - 1) f(\omega)^2 \right] P_0(\omega)$$

where $P_0(\omega)$ is the single electron radiation power and

$f(\omega) = \left| \langle e^{i\varphi} \rangle \right|$ is the **bunch form factor**.

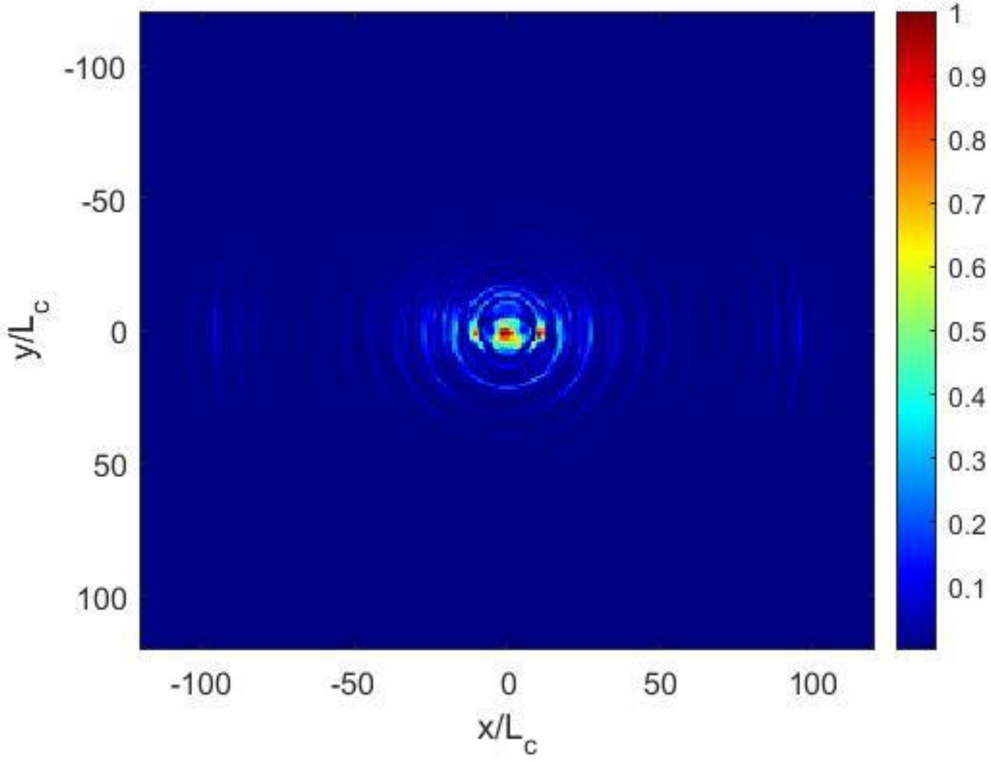
Simulation of Superradiant THz FEL



The radiation is immediately established in the U100 undulator and quickly achieves to its maximum value as we expected for super-radiant emission from an ultrashort drive bunch. In this simulation, the parameter K of the U100 undulator is set at 4.6 and the radiation frequency is 2.6 THz.

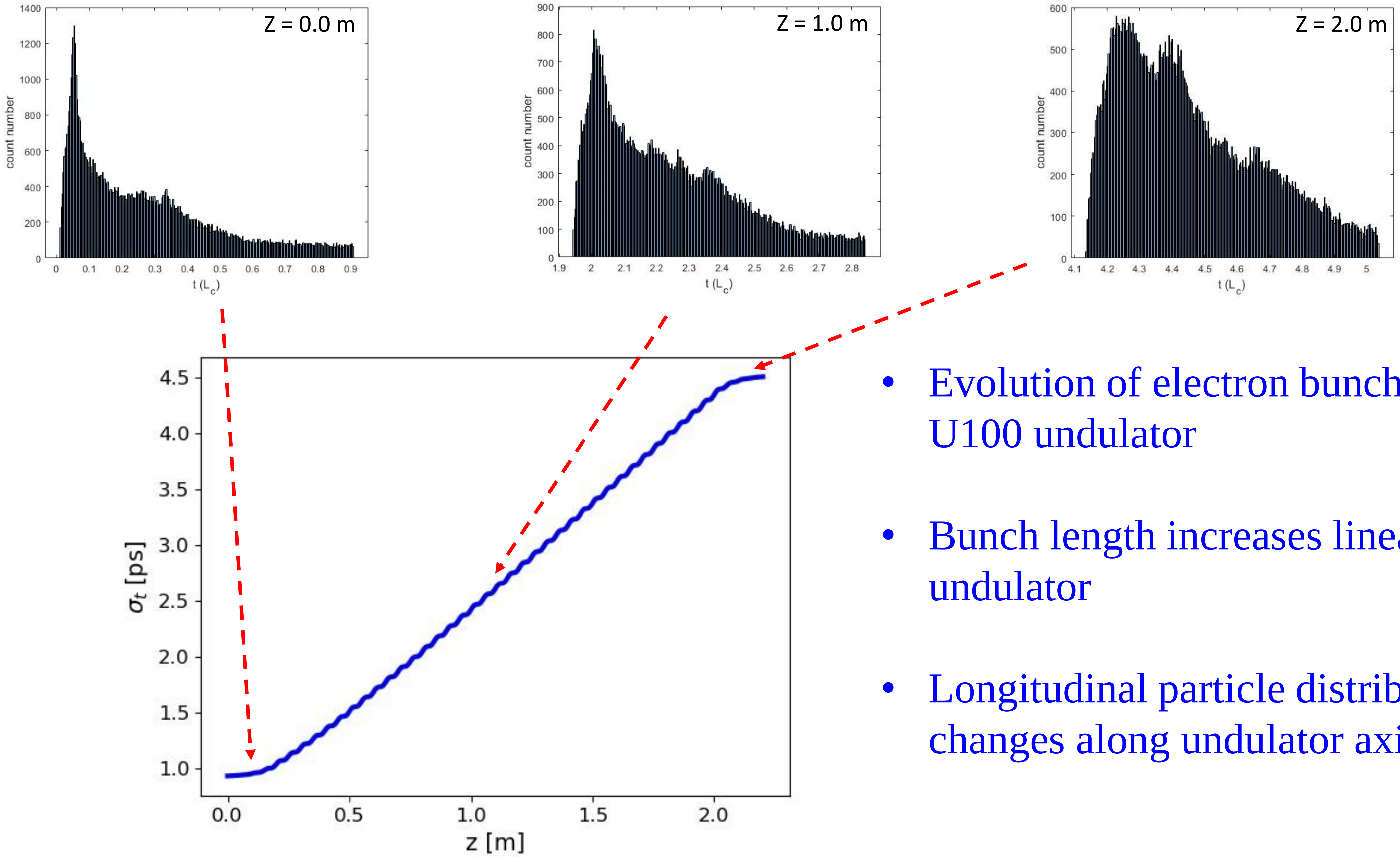
Limitations of GENESIS FEL simulation code
(ex. at 1 THz, the bunch length must be greater than 1 ps).

- Since the bunch is short w.r.t. radiation length, simulation is done by unaveraged 3D FEL code – PUFFIN
- For start-to-end simulation, we use the RF compressed beam simulated by IMPACT-T as input for PUFFIN simulation



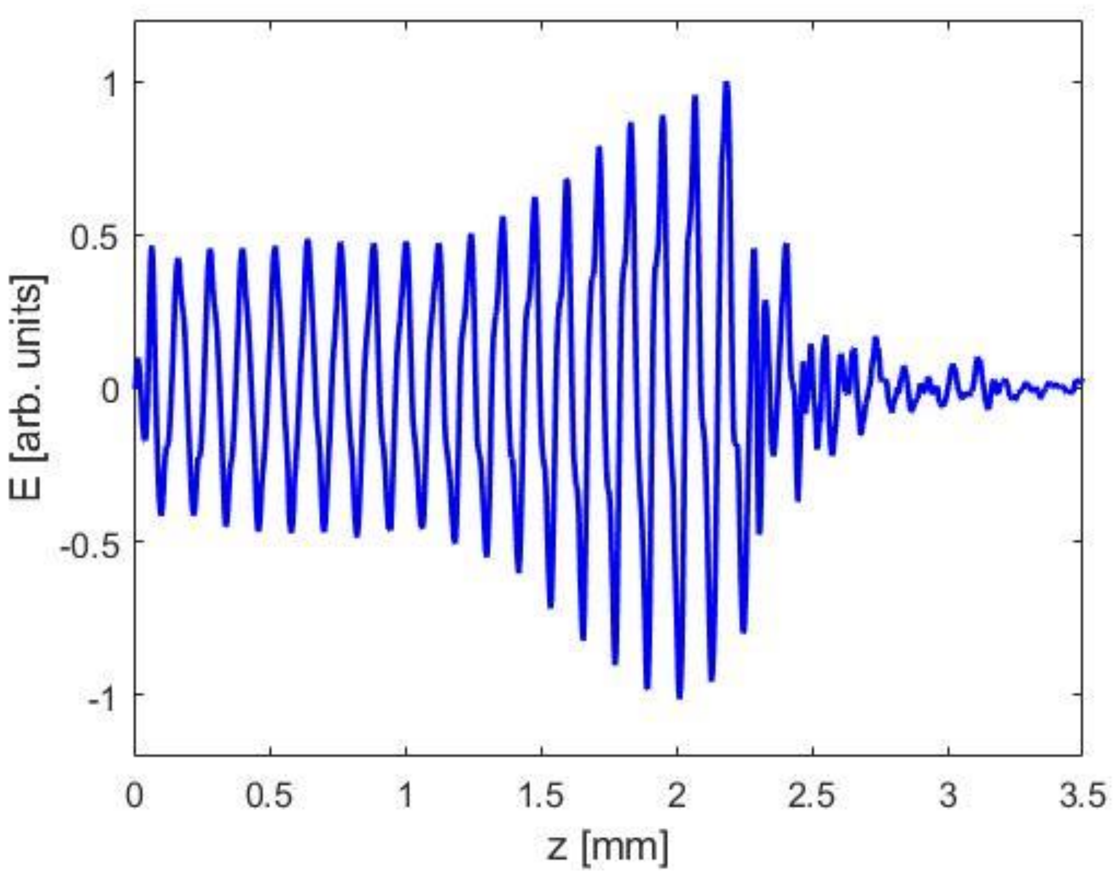
Spatial distribution of the THz radiation (c.f. L_c = 0.556 mm)

Simulation of Superradiant THz FEL (cont'd)

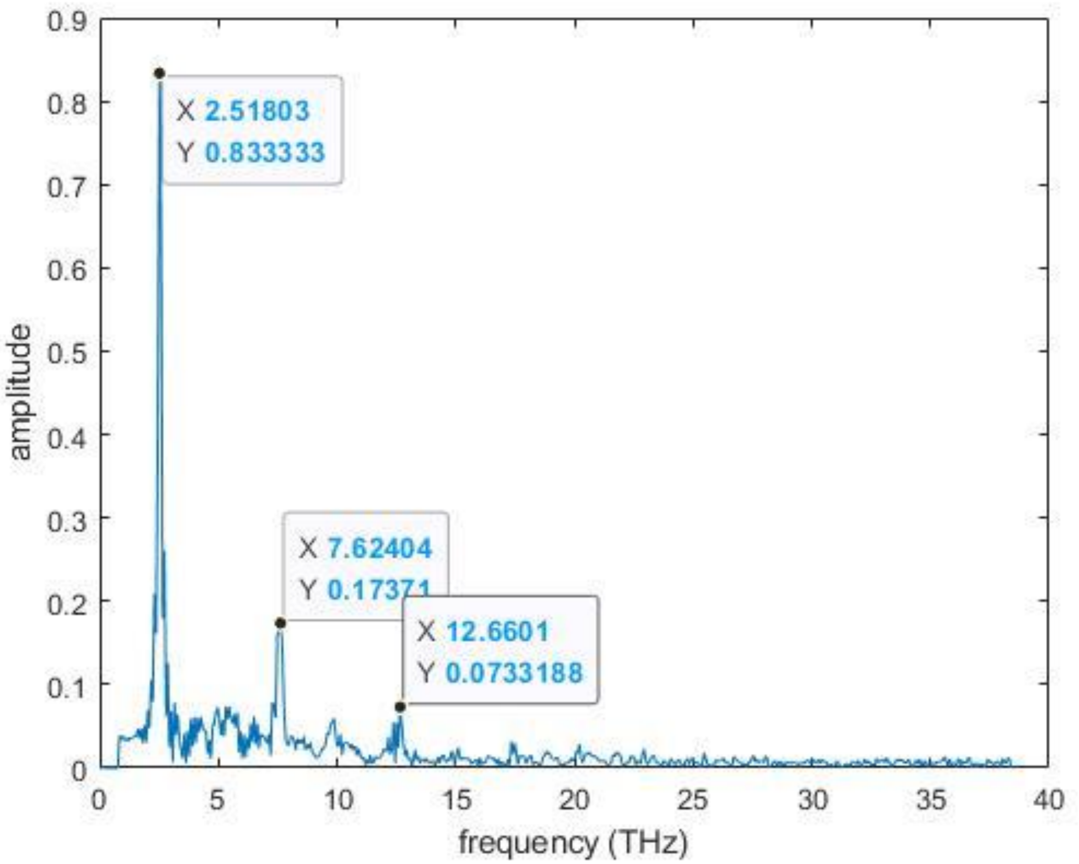


- Evolution of electron bunch length in U100 undulator
- Bunch length increases linearly in the undulator
- Longitudinal particle distribution changes along undulator axis

Simulation of Superradiant THz FEL (cont'd)



Snap-shot of superradiant radiation field at the 1.8 m U100 exit @ K = 4.6



Output radiation spectrum of superradiant THz FEL @ K = 4.6

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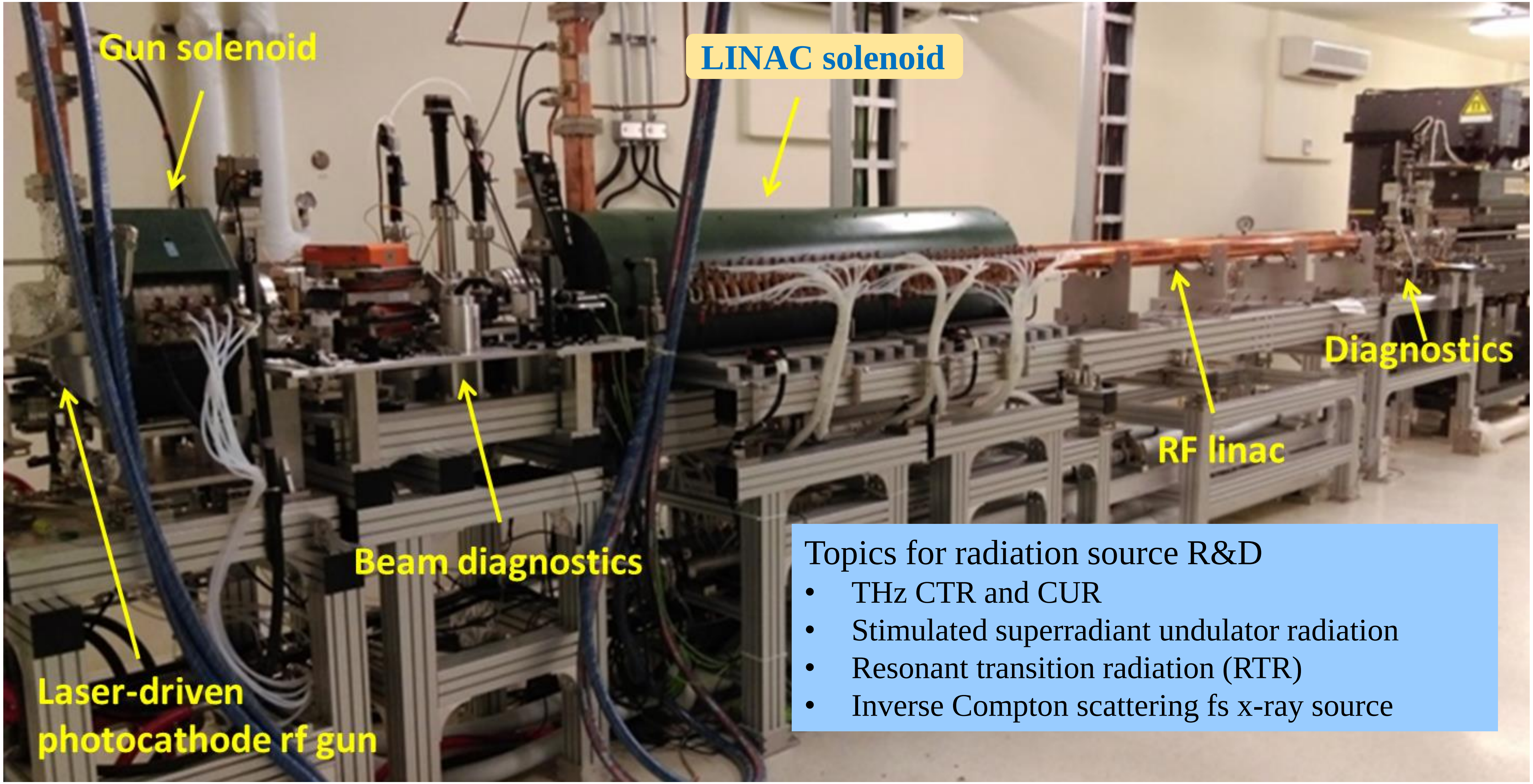
Facility Introduction : NSRRC THz FEL

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



Topics for radiation source R&D

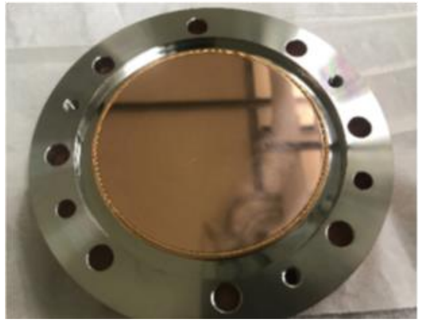
- THz CTR and CUR
- Stimulated superradiant undulator radiation
- Resonant transition radiation (RTR)
- Inverse Compton scattering fs x-ray source

Photocathode RF Gun

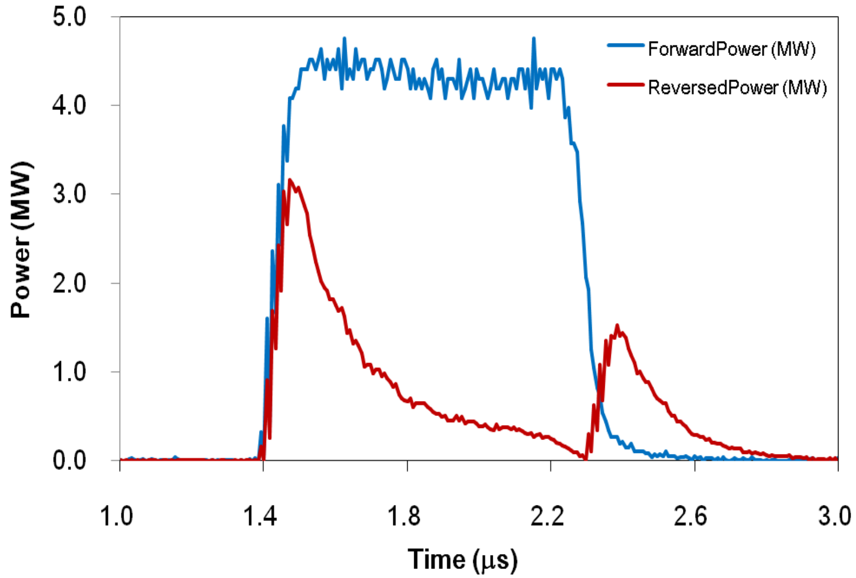
- Design is based on the 1.6 cell s-band rf gun developed at BNL DUV FEL.
- Copper (Cu) photo-cathode
- Operating at temperature 55°C , vacuum < 5 x 10^{-8} mbar

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}

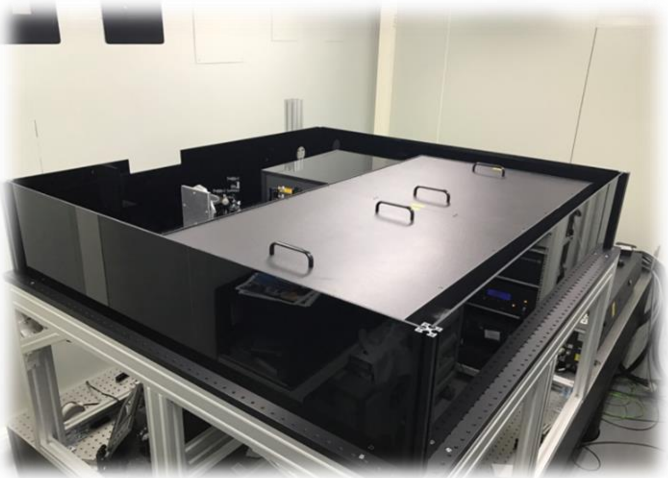
Cu cathode

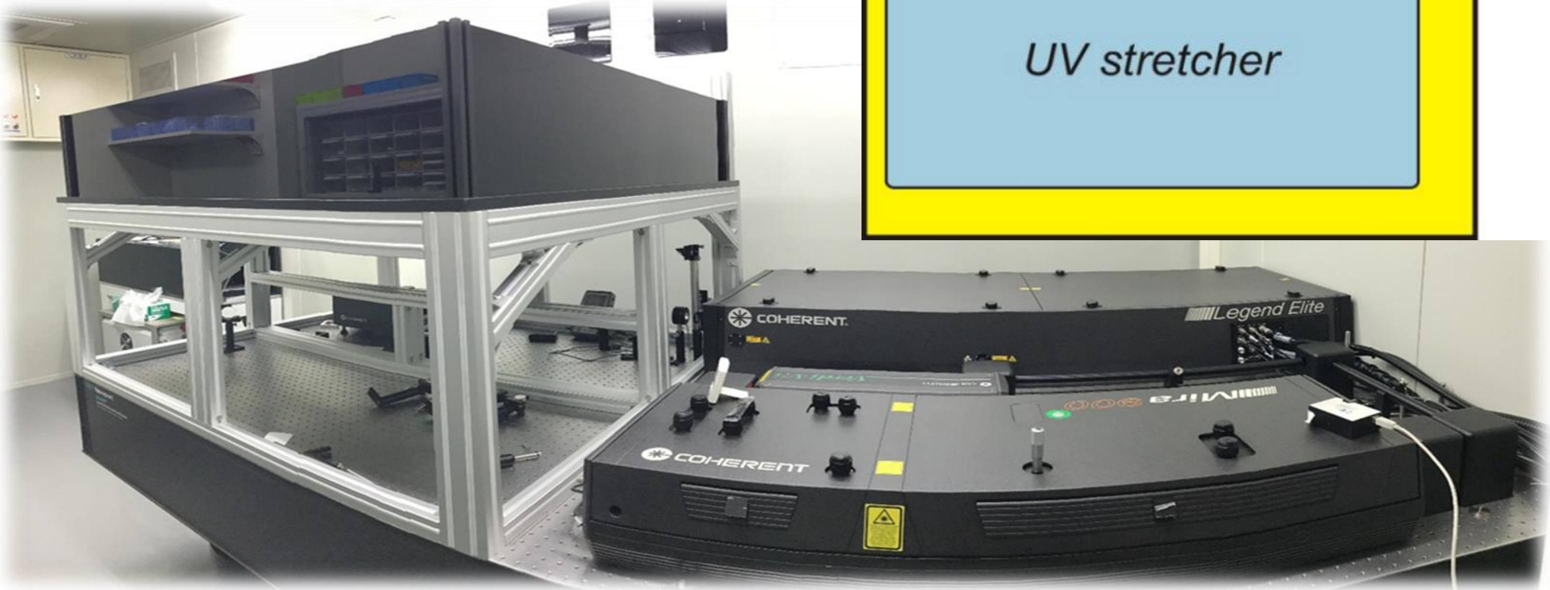


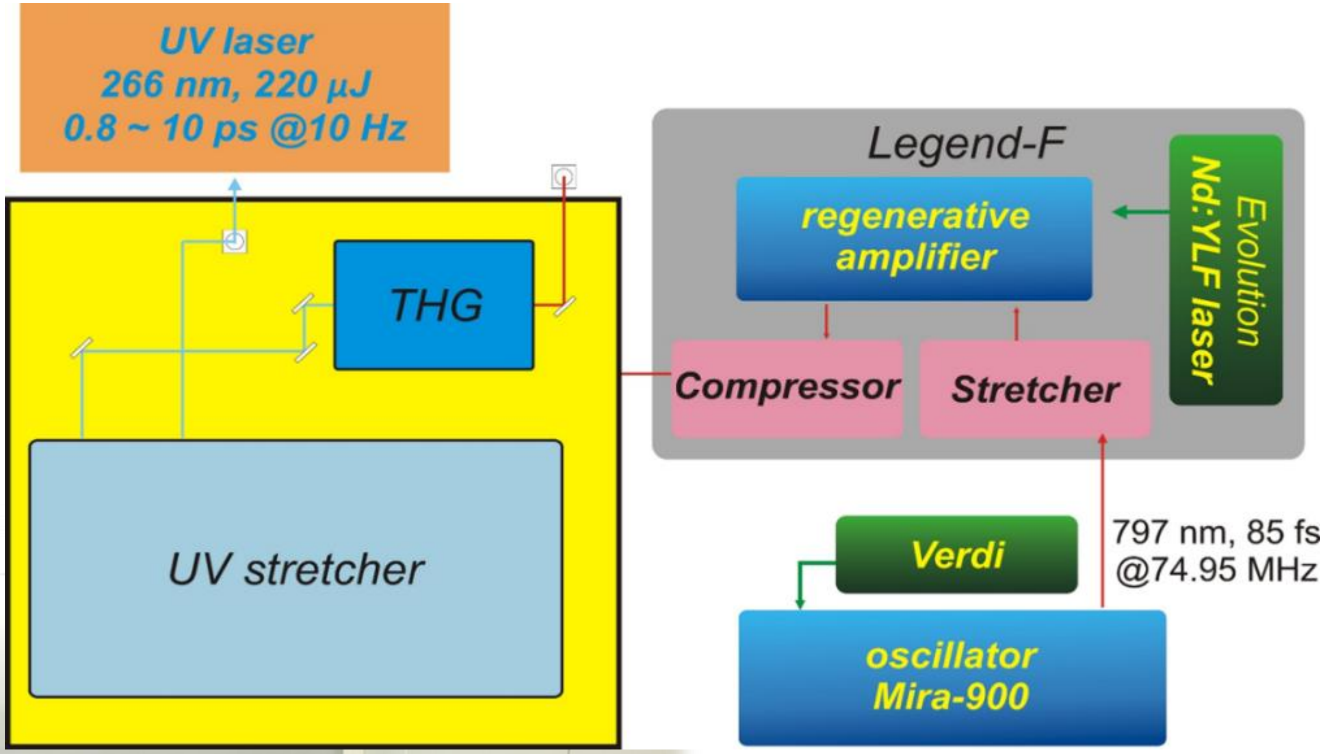
Forward and reverse power of the Gun



Drive Laser System for the Photocathode RF Gun



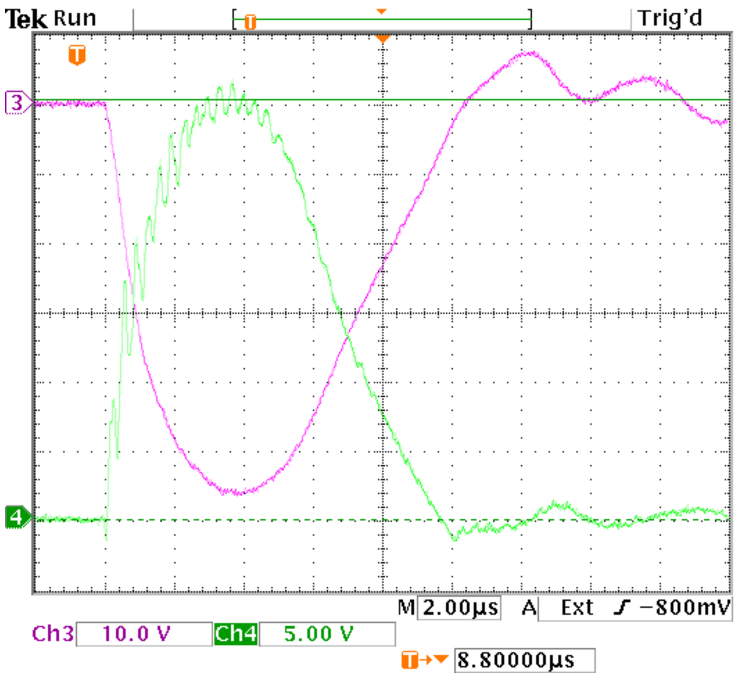




Pulsed Klystron System for the Photo-injector

Canon E37310A Klystron

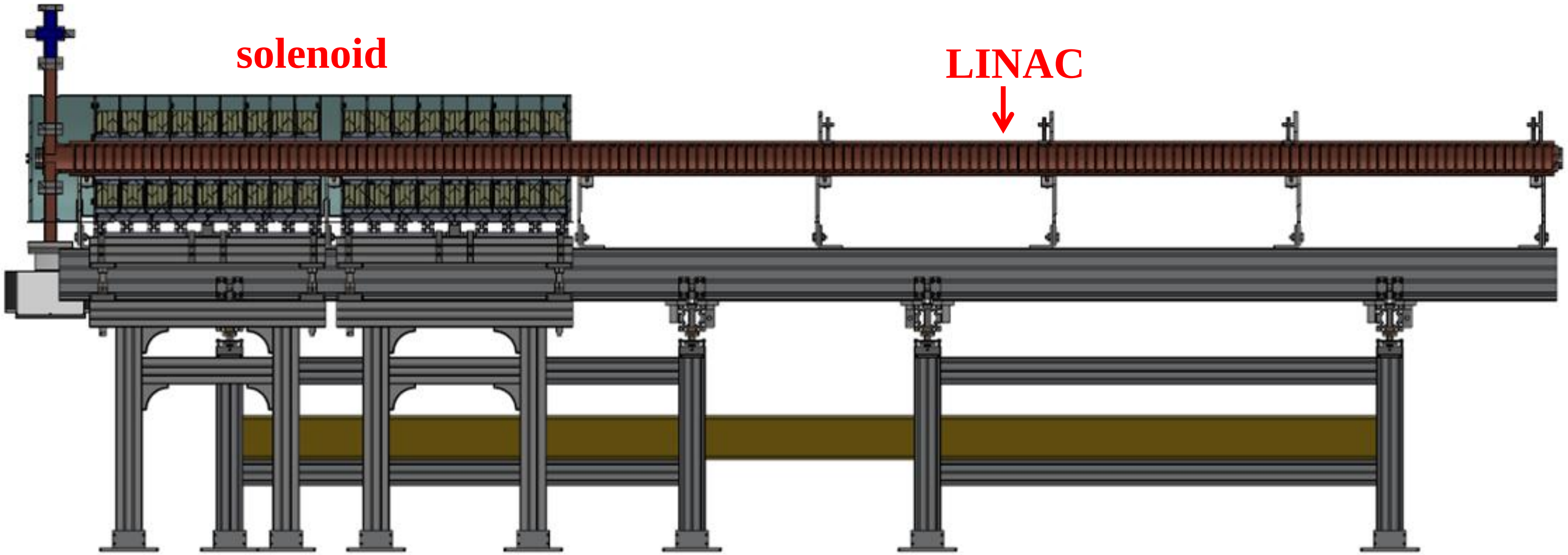
Canon Klystron	
Klystron voltage (kV)	281
Klystron current (A)	307
Output power (MW)	35
Pulse width (μs)	2



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

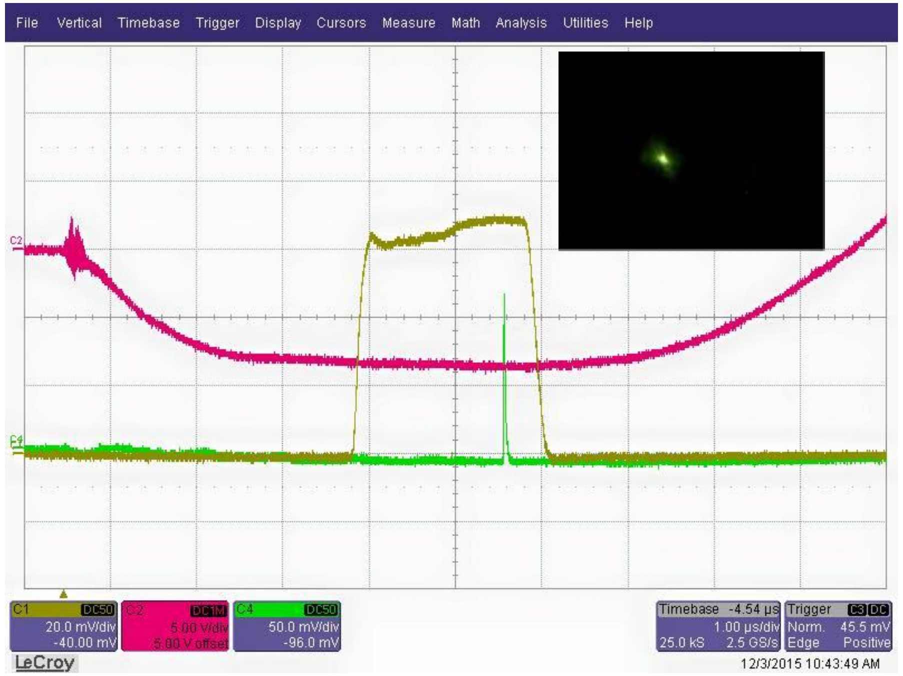
Photo-injector Linac and Focusing Solenoid



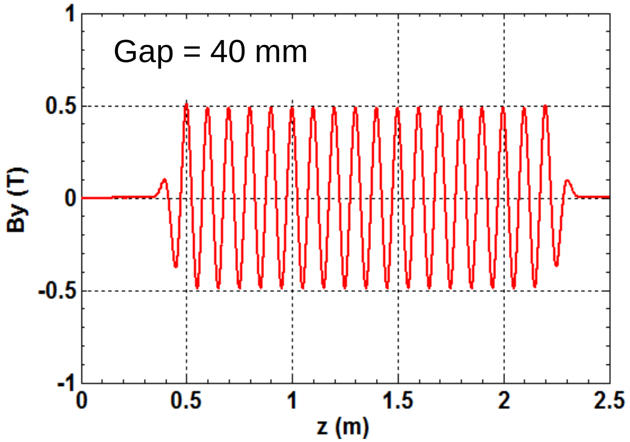
- 2998 MHz, DESY-type 156-cell copper, constant gradient.
- accelerating gradient >11 MV/m, total length: 5.2 m.
- Linac solenoid for more beam size and emittance control.

Commissioning of the NSRRC Photo-injector System

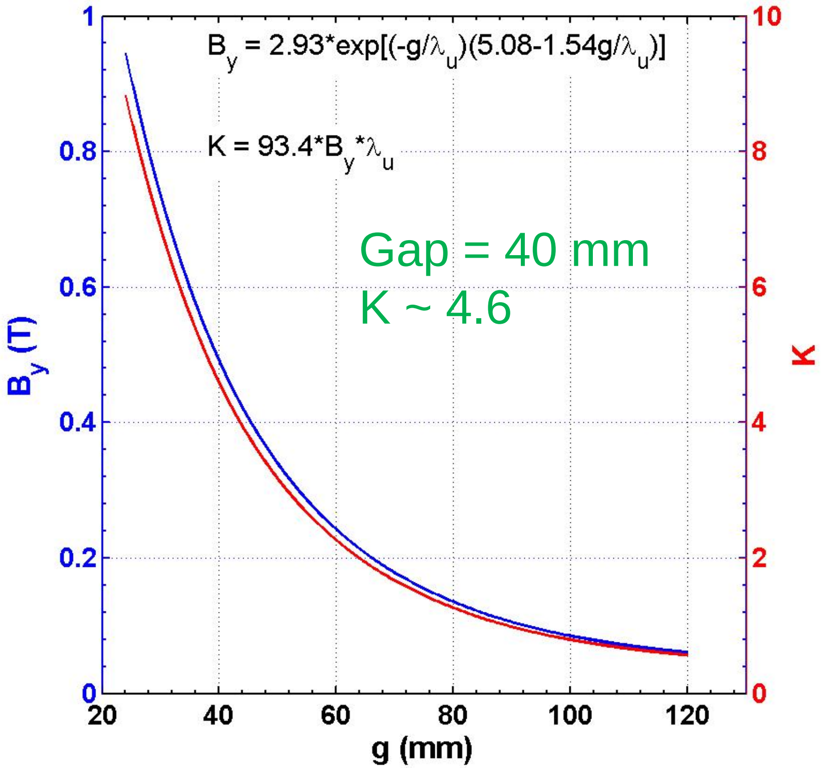
Parameters of the photo-injector system	
Laser pulse width (ps)	3
Laser energy (μJ)	up to 120
Power to RF gun (MW)	2.8
Power to Linac (MW)	24
Beam energy (MeV)	60
Beam charge (pC)	up to 600
Repetition rate (Hz)	10



NSRRC U100 undulator

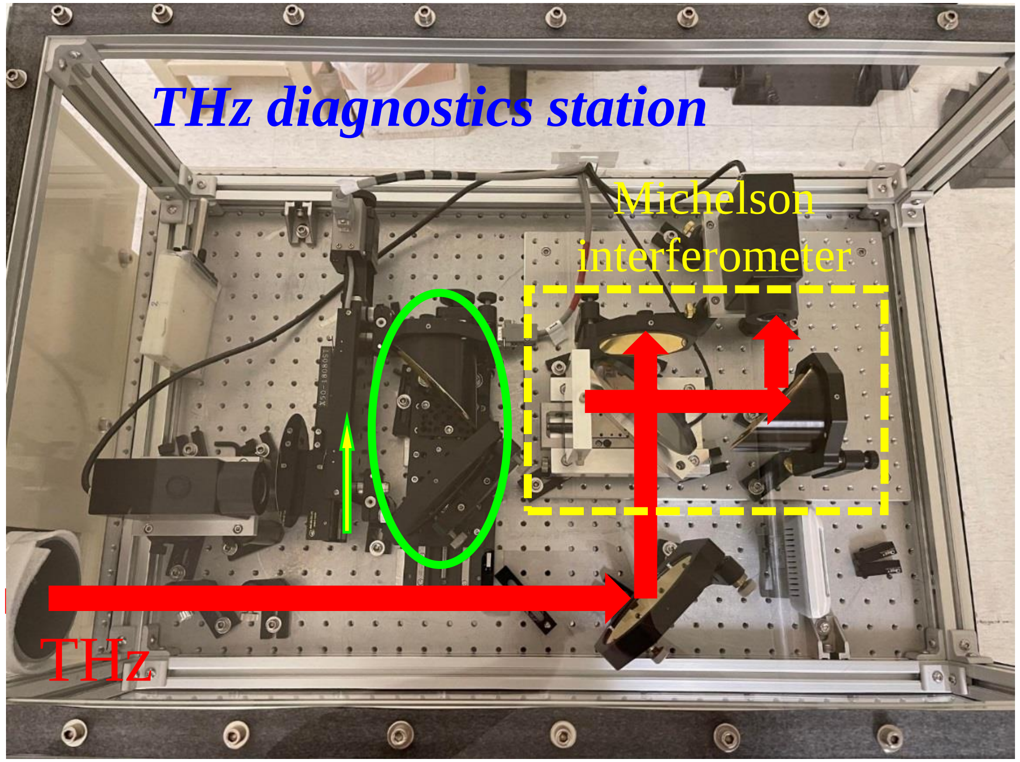


	U100
λ (mm)	100
N_{period}	18
L (m)	2.2
a_w	1.02
gap (mm)	24
B_y (T)	0.945
Ky_{max}	8.8

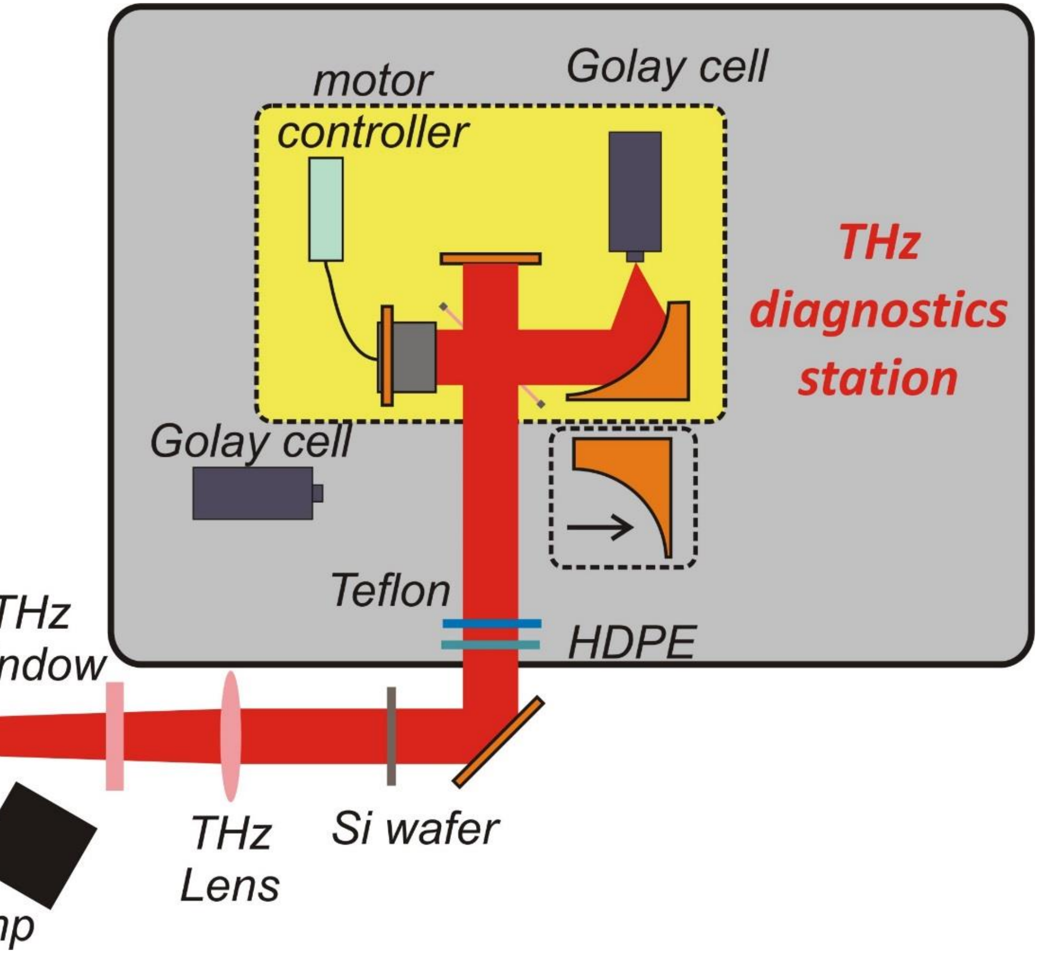


The U100 undulator built by the NSRRC magnet group more than 30 years ago is used for the superradiant THz FEL (pre-bunched THz FEL).

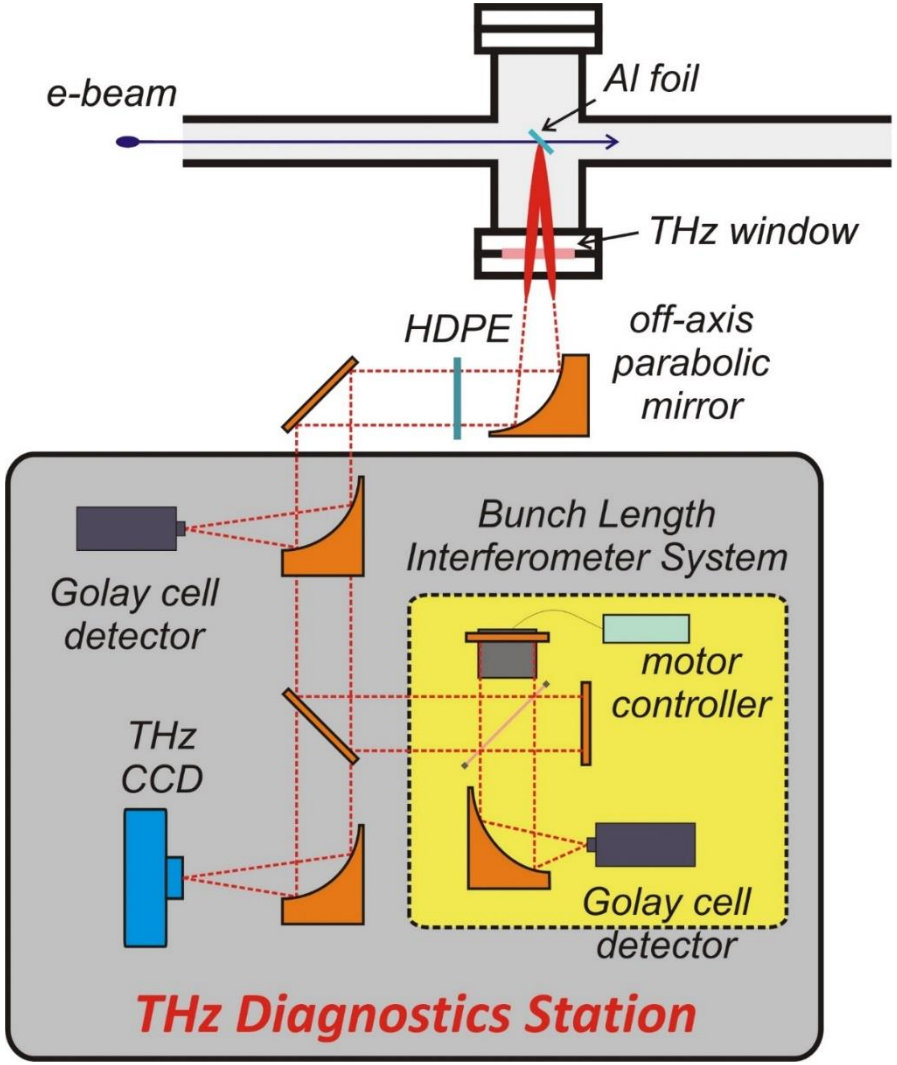
Output Diagnostics for Superradiant THz FEL

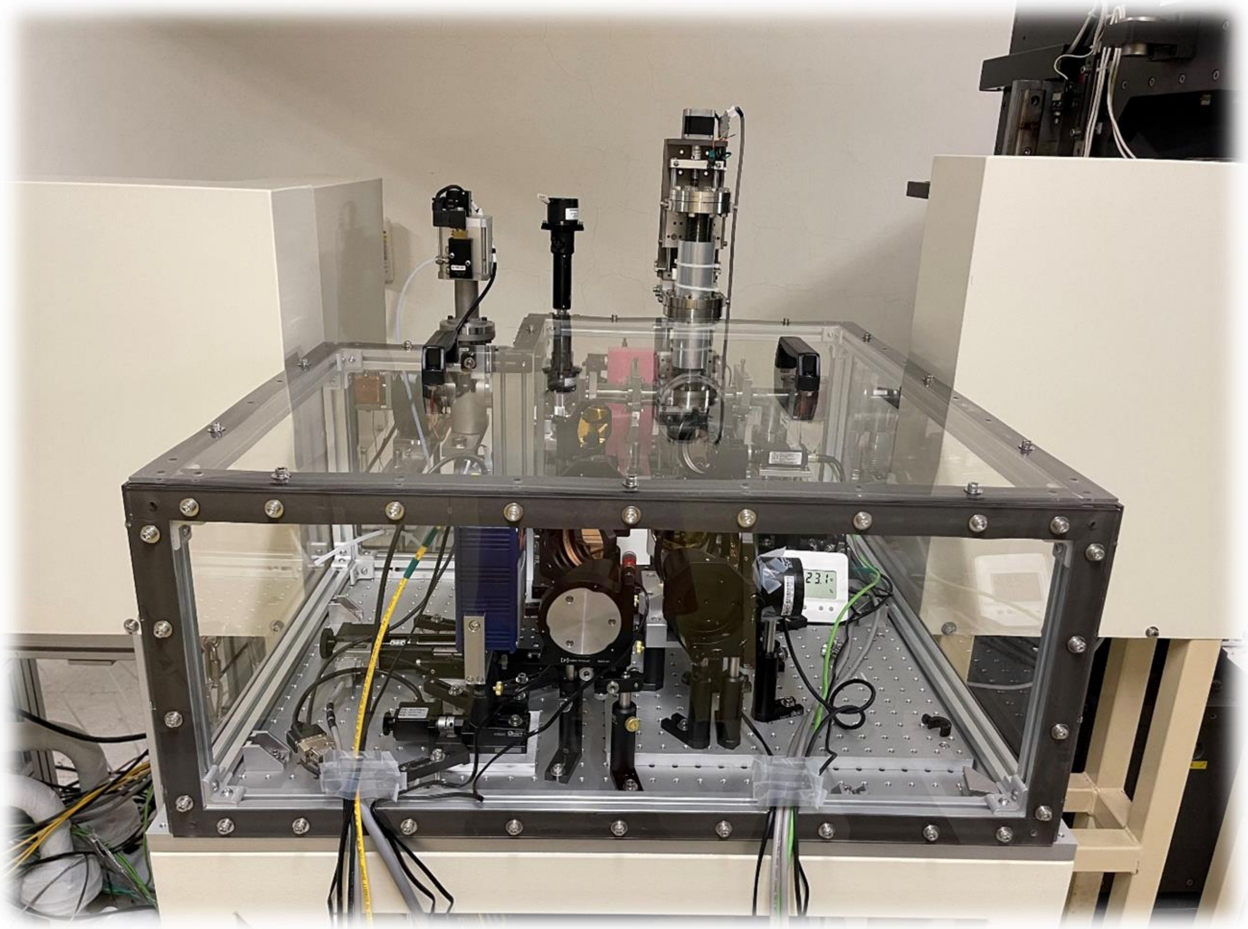


THz spectrum



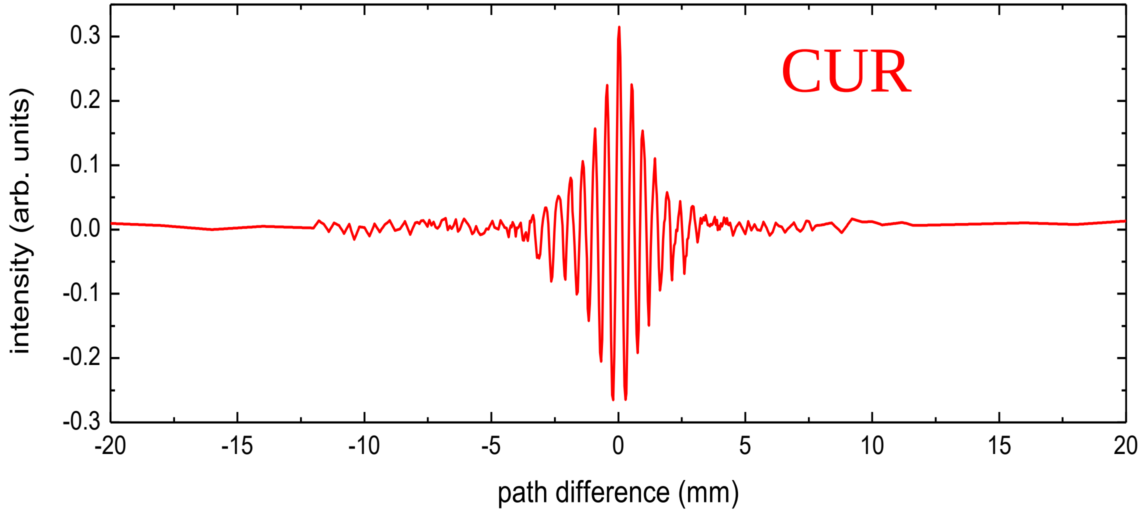
Setup of THz CTR Measurement

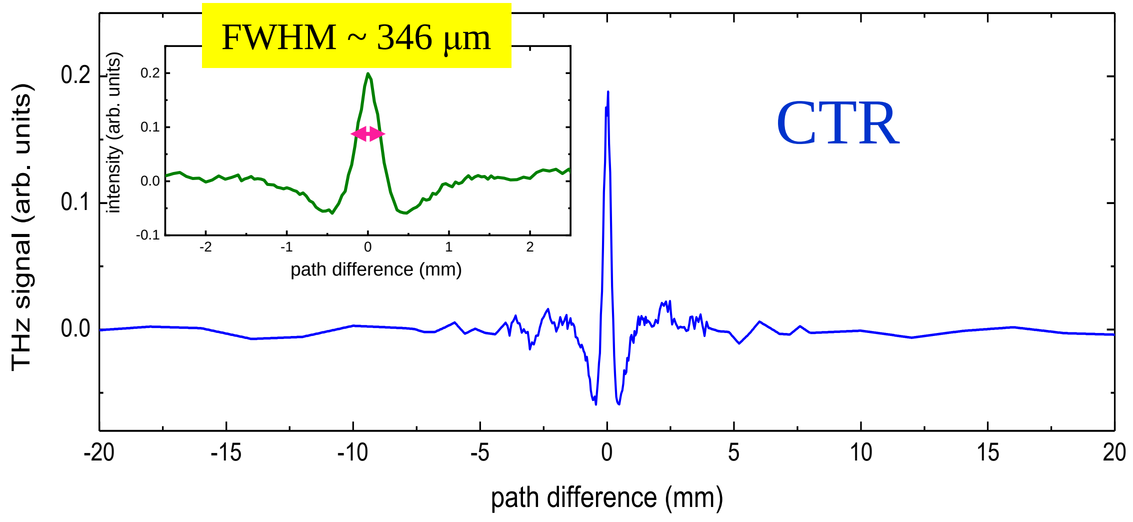


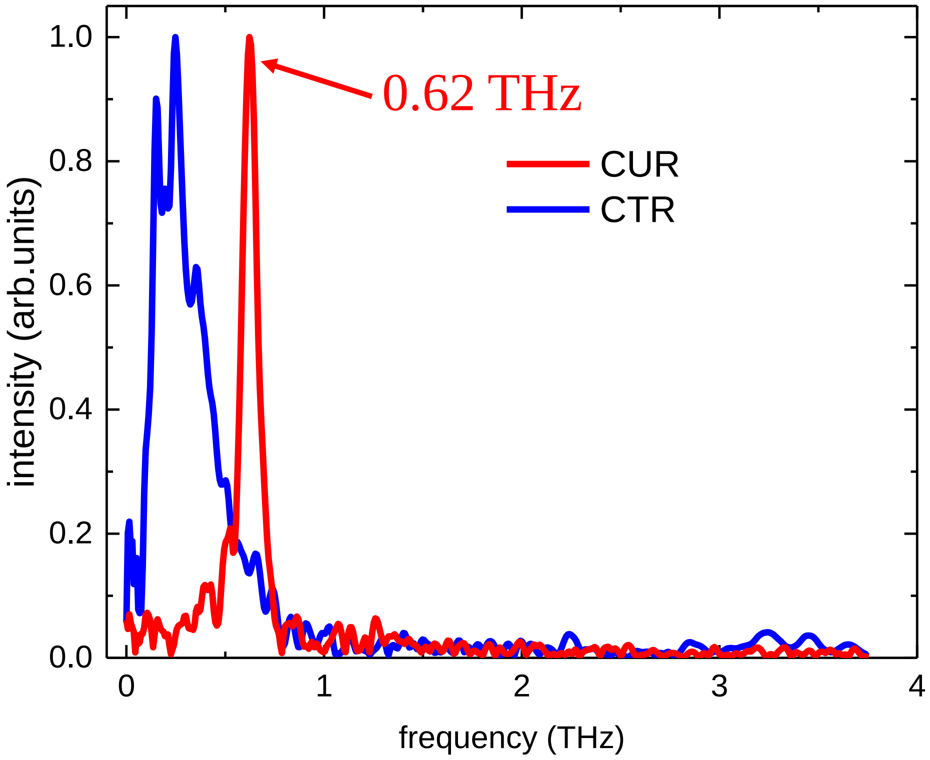


Measurements of the CTR spectrum give the information about the bunch length.

Interferograms of Superradiant THz FEL and CTR



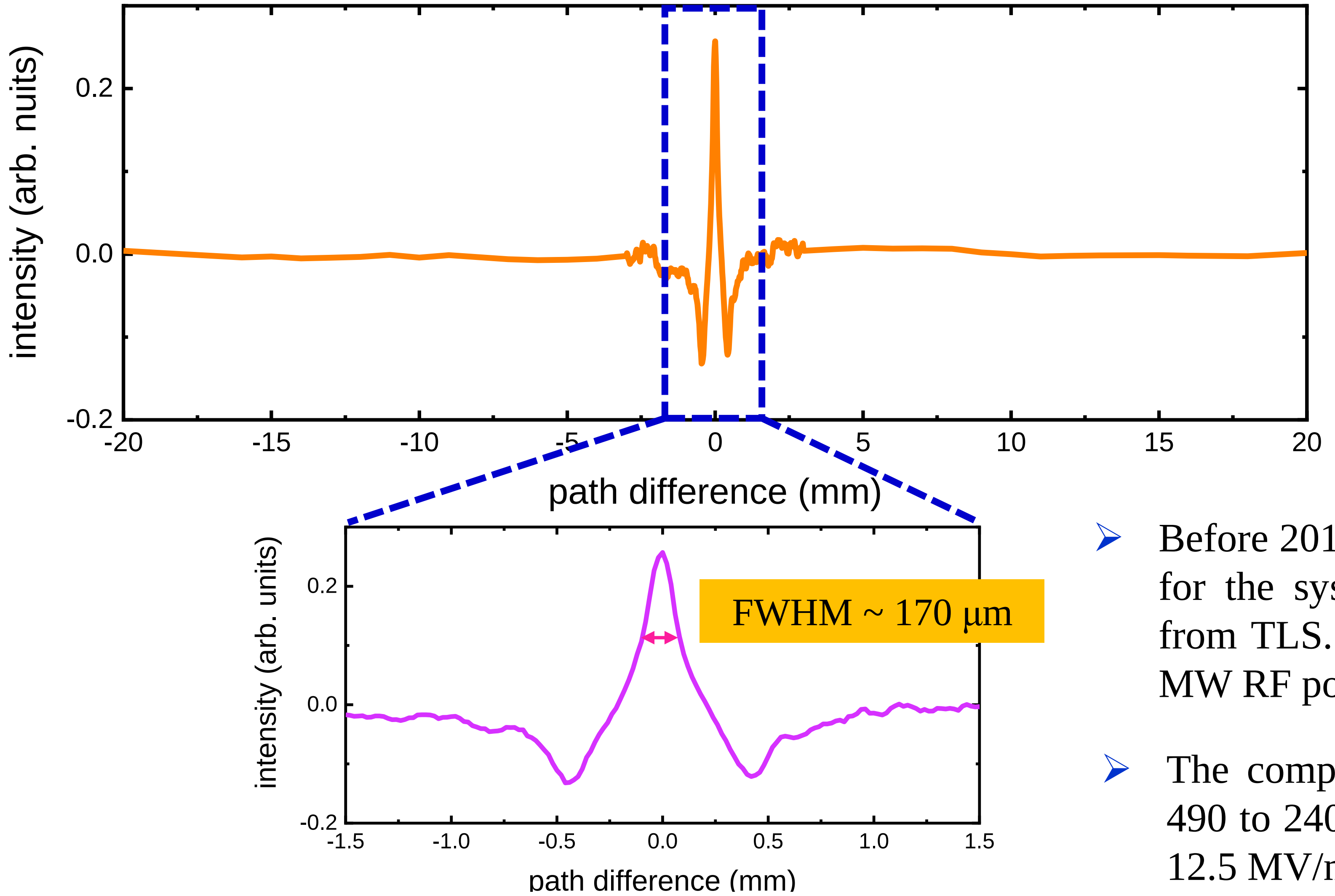




- In 2018, the central frequency of superradiant THz FEL is measured to be 0.62 THz, corresponding to the electron beam energy of 17.7 MeV.
- Assume Gaussian distribution, bunch length σ_z~ 147 μm = 490 fs.

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

Shorter Bunch Length obtained with Higher Linac Field



- assume Gaussian distribution

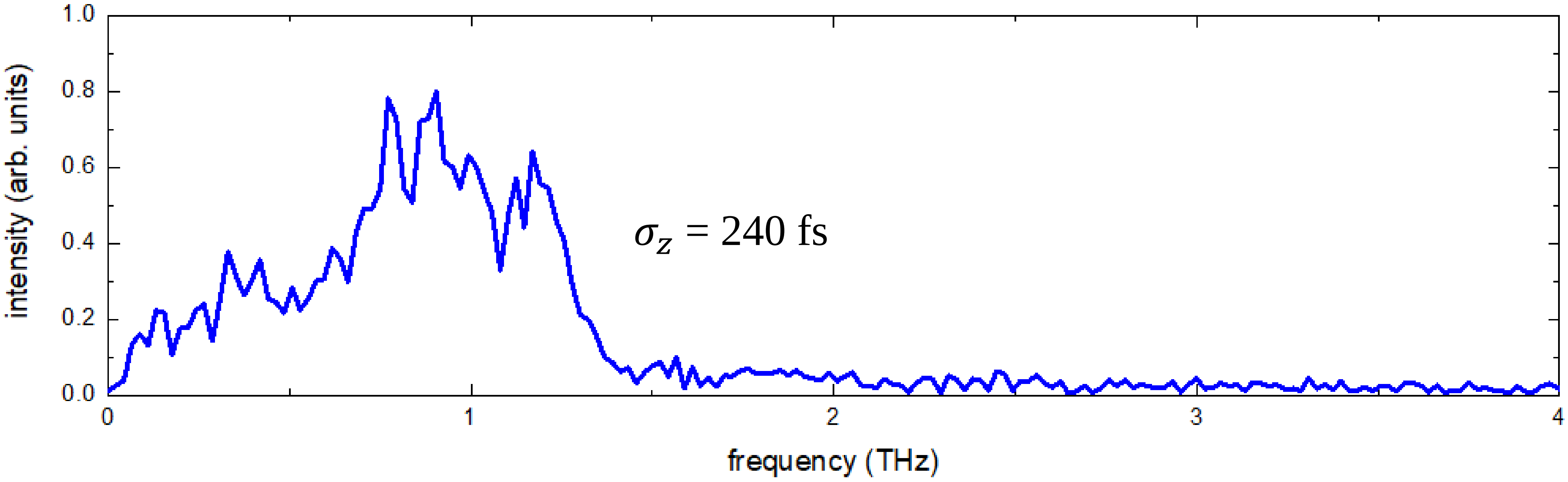
  FWHM = $2\sqrt{2ln2}\sigma_z$

  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.

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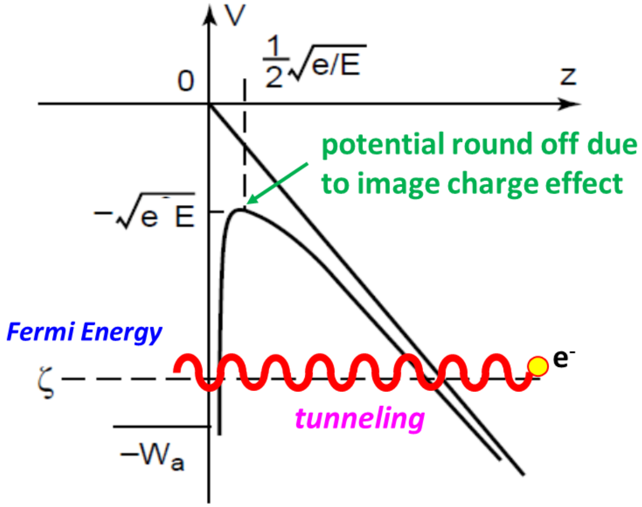
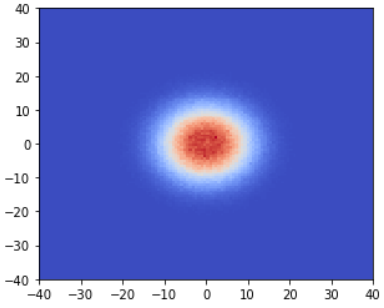
Future Work of STELLA

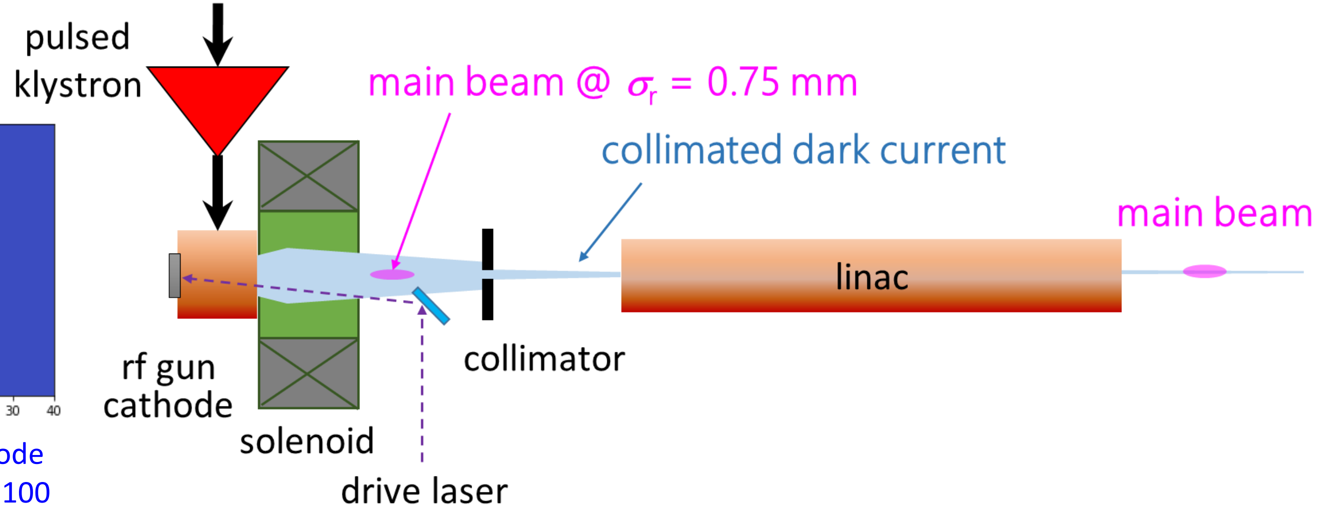
Future Works - Simulation of Dark Current Transport in Photoinjector



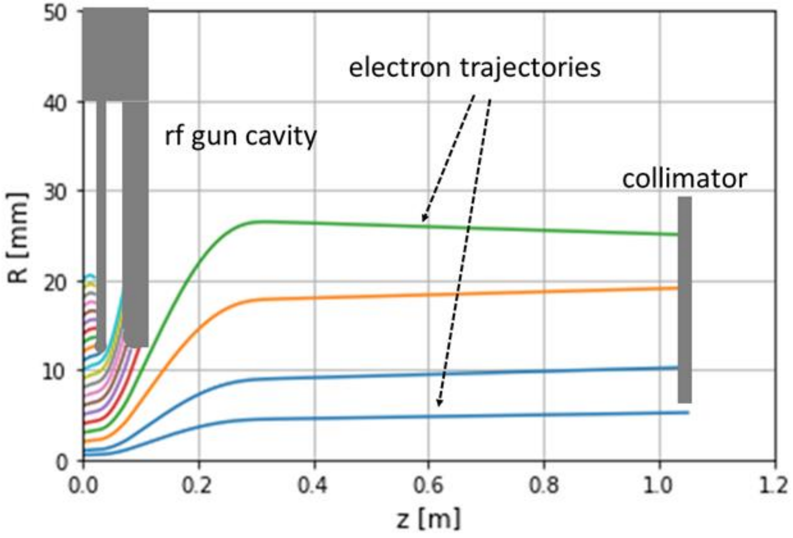
electron field emission (FE) from metallic surface



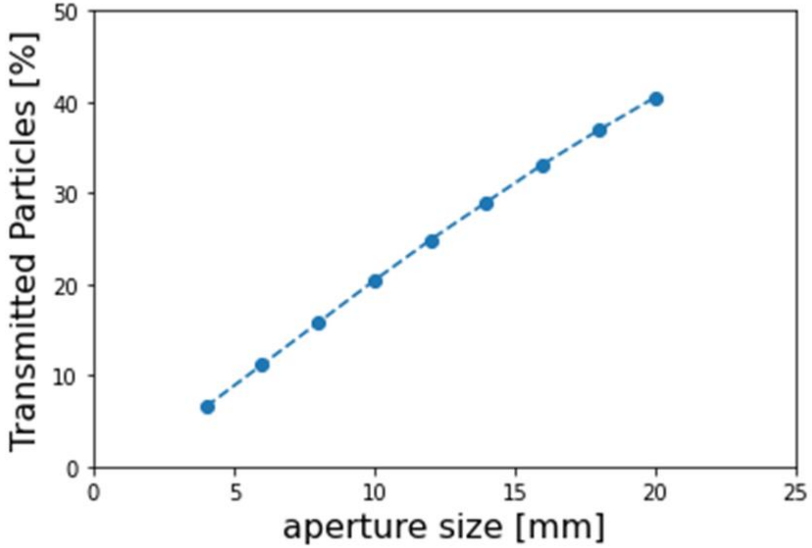
dist. of FE e-s on cathode
@ E_0 = 60 MV/m ; β = 100



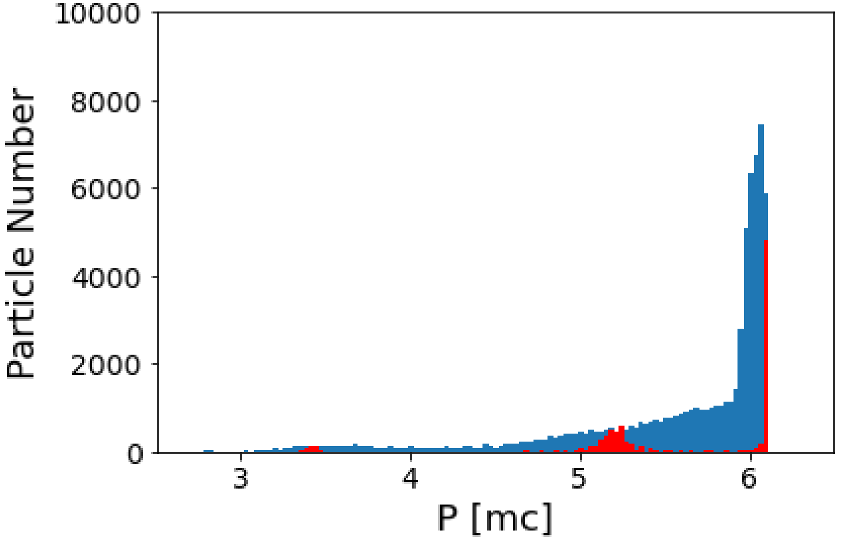
schematic of dark current transport in photo-injector and beam collimation



beam collimator selectively stops electrons
emitted at different radial position

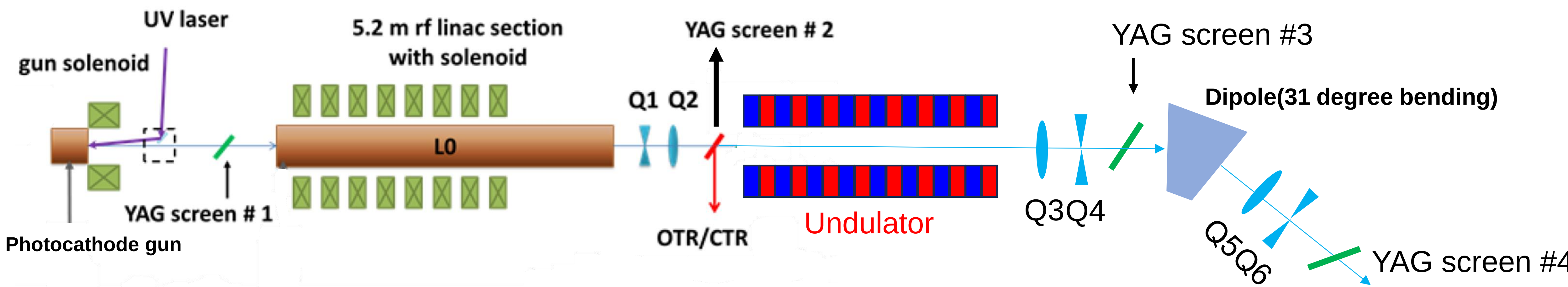


% of particles transmitted through
collimator at different aperture sizes



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

Future Works - Using IMPAC-T to design Beam Energy Spread Measurement



Measurement Criteria

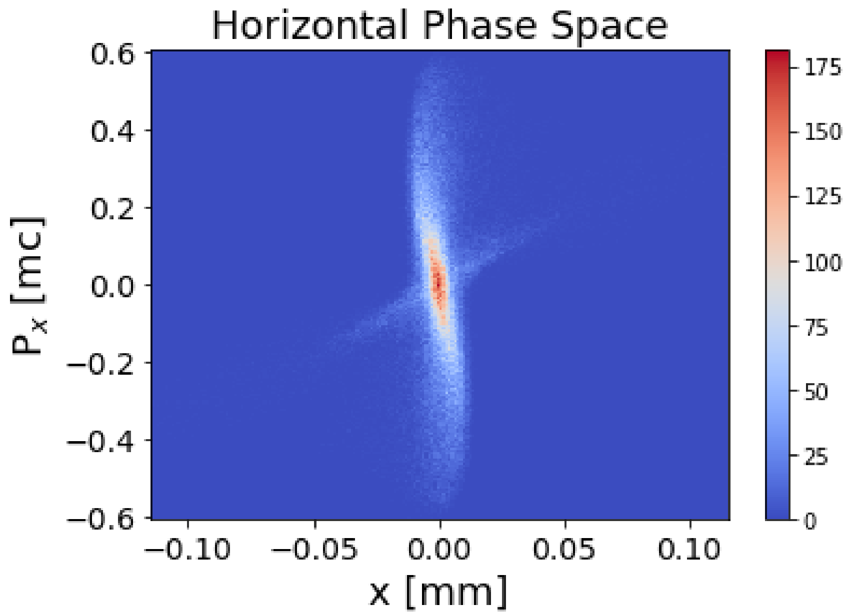
$$\delta_{\min} = \frac{\delta p}{p_0} \geq \frac{2E_b}{D} = 2\frac{\sqrt{\epsilon\beta}}{D},$$

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

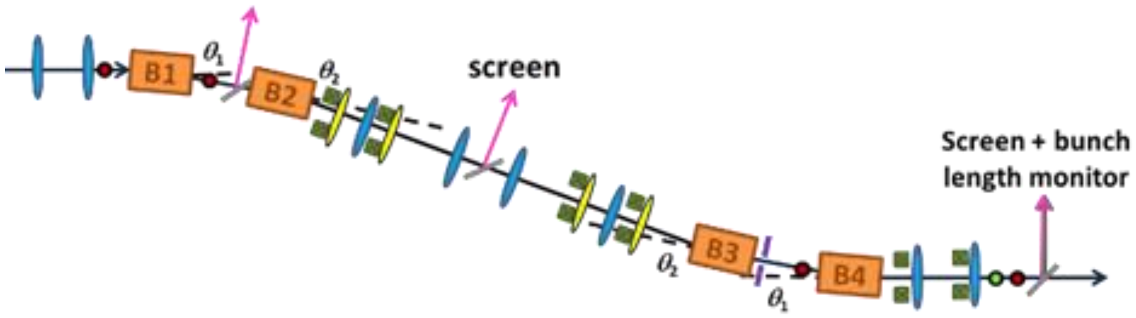
For good resolution

- Small emittance
- High dispersion

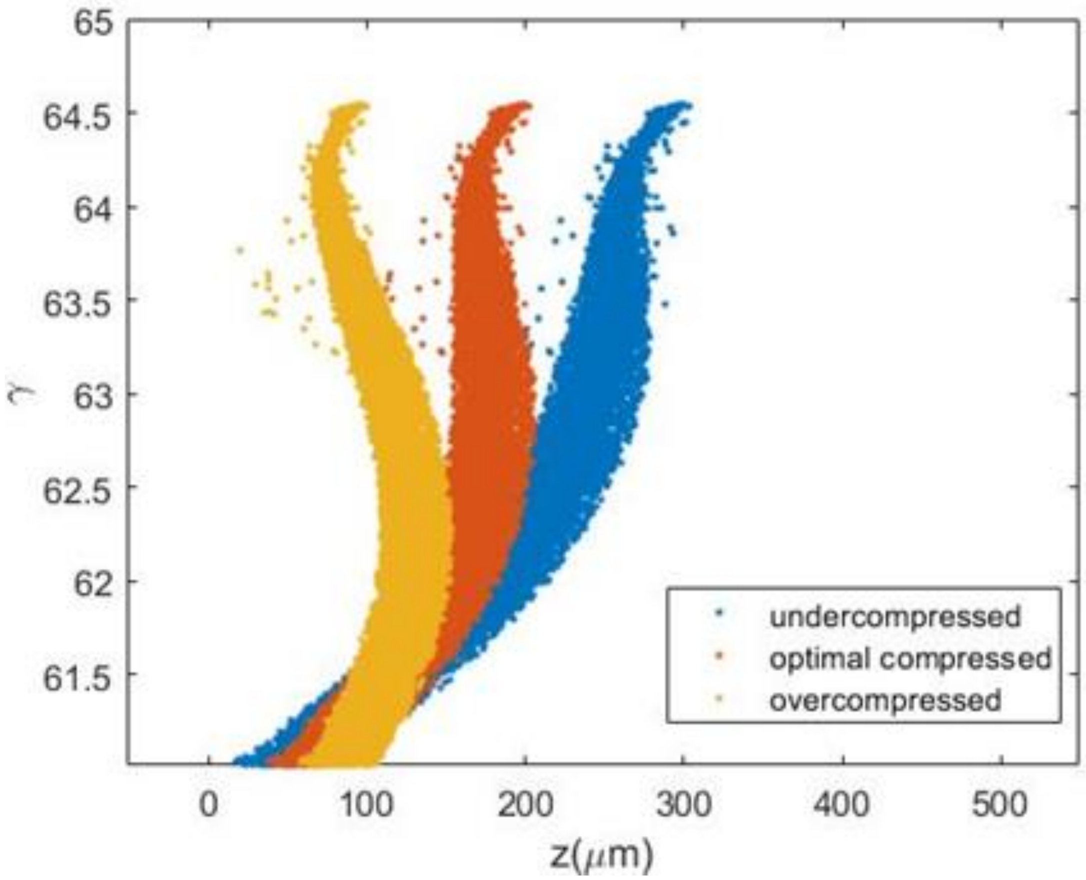
Impact-T Optimization



Future Works - Further Bunch Length Reduction by Nonlinear Magnetic Bunch Compressor

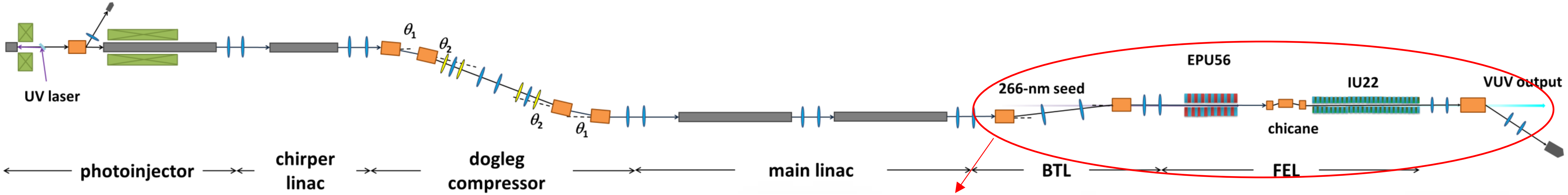


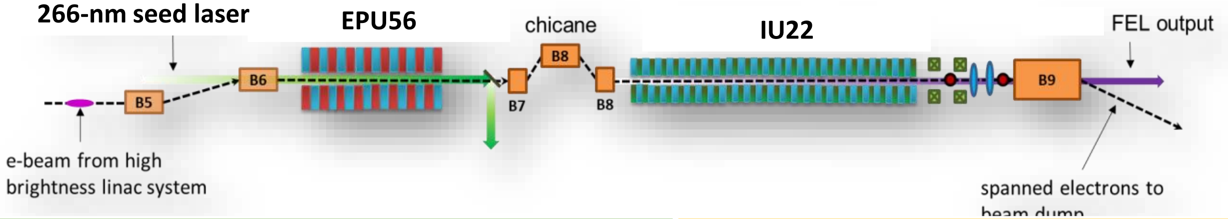
Layout of the double dogleg bunch compressor for the simulation of NSRRC THz FEL LINAC system.



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).

Future Works - Design of VUV FEL Test facility @NSRRC





- VUV FEL test facility
  - 4th 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.

NSRRC LINAC Group – STELLA Team members

Team members

1. Hiroshi Matsumoto (consultant)
2. W.K. Lau
3. A.P. Lee
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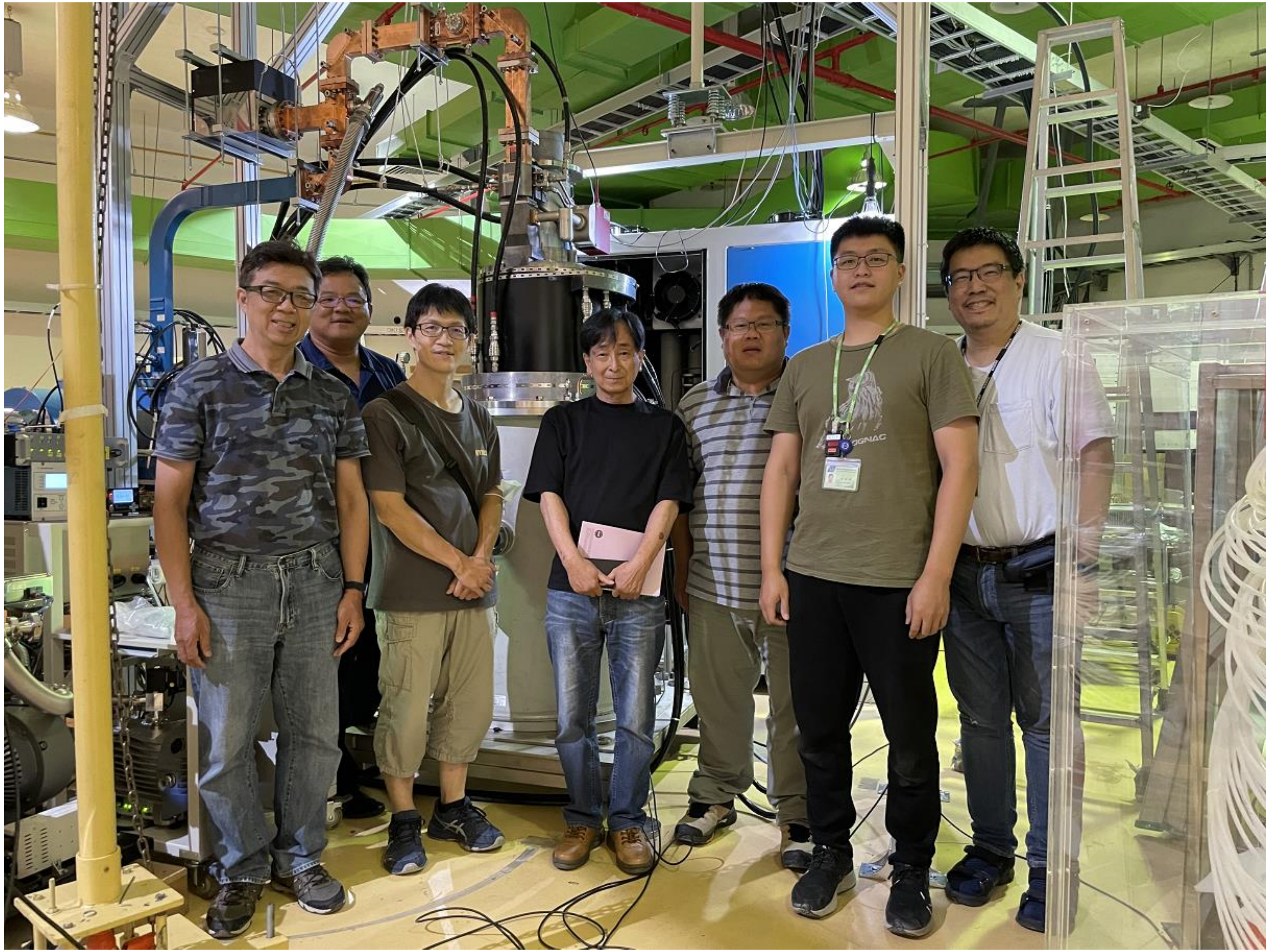
5. M.C. Chou
6. H.P. Hsueh
7. Y. J. Chang



Summary

- 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.
- Using IMPACT-T simulation to assist in the design of an electron beam characteristic measurement system.
- Develop numerical analysis capabilities for other related studies (The research topics in collaboration with teams outside of NSRRC), such as laser plasma accelerators and laser-trigger proton-boron fusion.

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

Thanks for your attention!

Welcome to Taiwan to attend the IPAC25