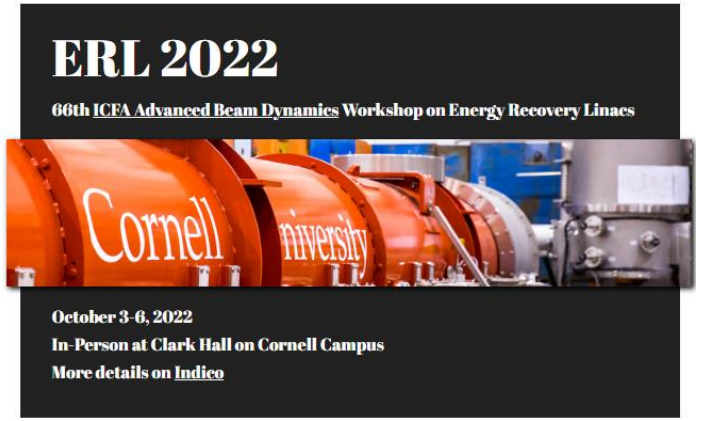

Beam tuning for IR-FEL and industrial application at the compact ERL

ERL2022

66th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

October 3-6, 2022

Clark Hall on Cornell campus

Miho Shimada, KEK

cERL collaboration team 2019-2022

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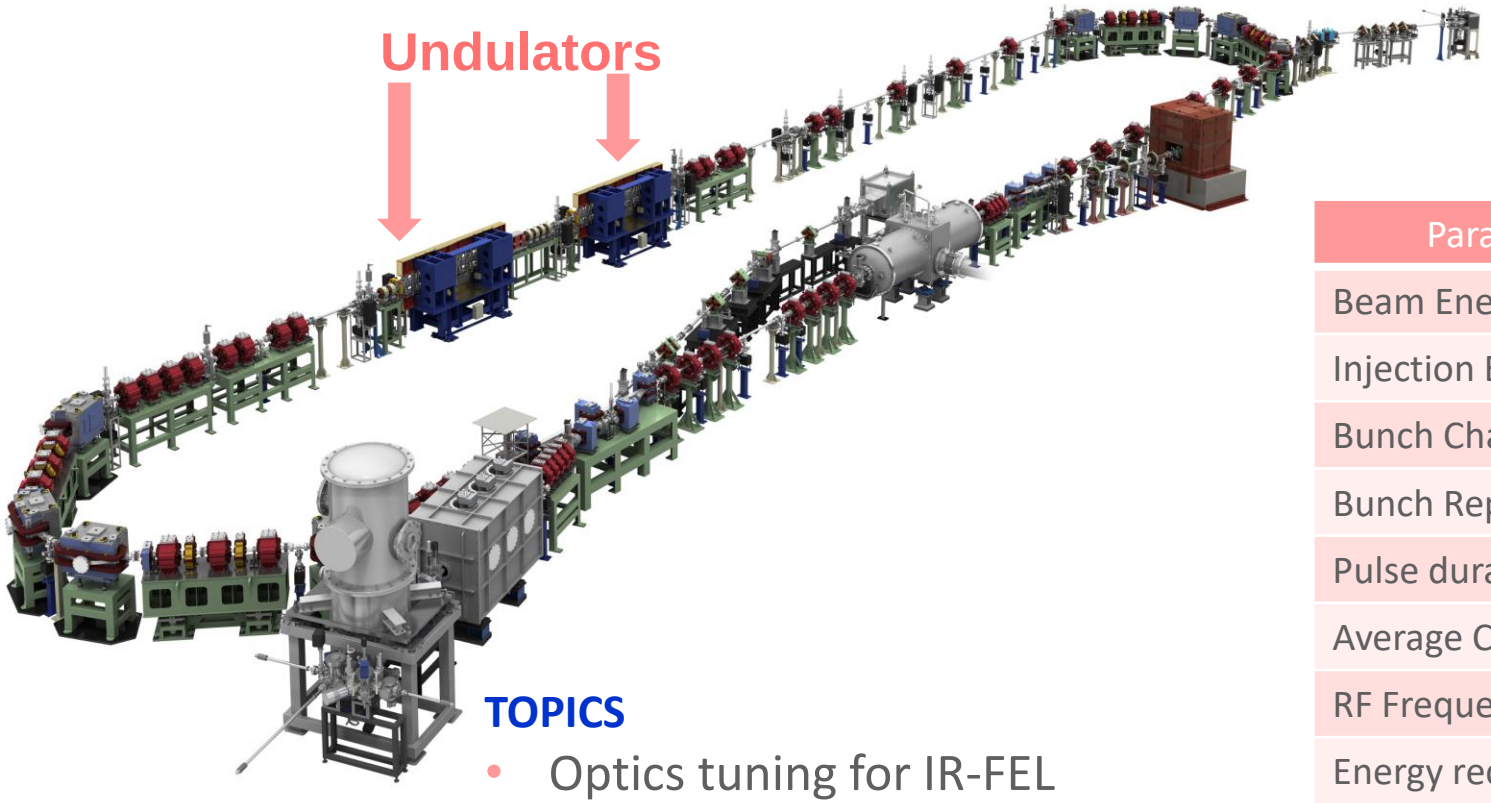
Institute of Modern Physics (IMP) CAS China Zong Yang

Compact ERL



Parameter	IR-FEL	CW operation
Beam Energy	17.5 MeV	17.5 MeV
Injection Energy	5 MeV	3.5 MeV
Bunch Charge	60 pC	0.2 pC
Bunch Repetition	81.25/1300 MHz	1300 MHz
Pulse duration	1 / 0.1 μs	CW
Average Current	24 / 39 nA	0.25 mA
RF Frequency	1.3 GHz	1.3 GHz
Energy recovery	no	yes

Parameters of cERL (2019-2022)

TOPICS

- Optics tuning for IR-FEL
  - 60 pC/bunch w/o energy recovery
  - Scan of energy chirp for bunch compression
  - AI tuning (bunch compression, matching to undulators, etc)
- High beam current operation with undulator
  - Low charge, CW 250uA
  - Optics matching, orbit correction
  - Mitigation of the radiation due to beam loss

OUTLINE

- Optics tuning for IR-FEL w/o energy recovery
- High beam current operation with undulator
- Summary

OUTLINE

- Optics tuning for IR-FEL w/o energy recovery
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Install of undulator for IR-FEL

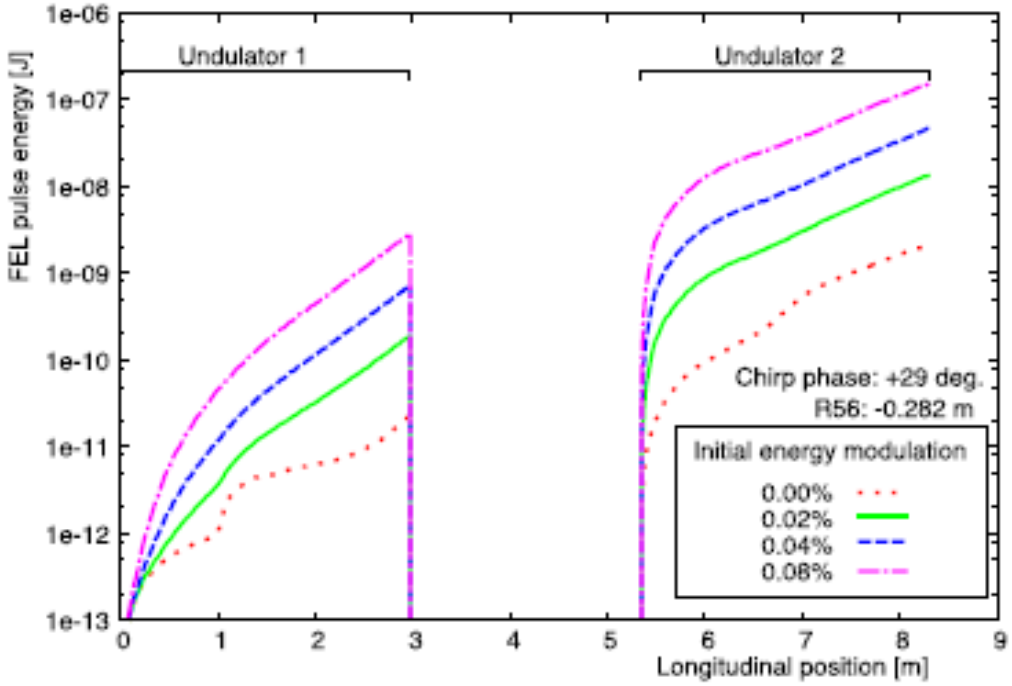


FIG. 1. Simulated FEL power development along the undulator based on the beam parameters determined in the experiment, chirp phase of +29° and R_{56} of −0.282 m. The initial energy modulation is an empirical parameter to adjust the absolute power using the start-up effect. The radiation wavelength was set to 20 μm.

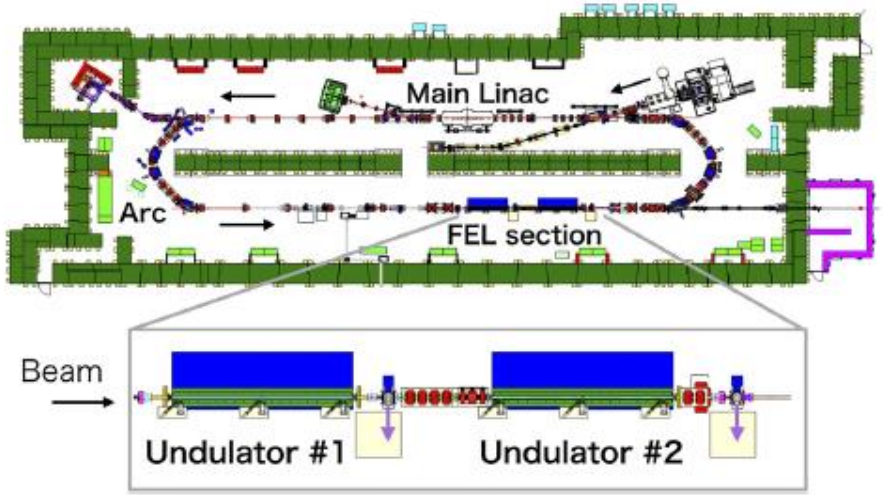


TABLE I. Parameters used in the simulation.

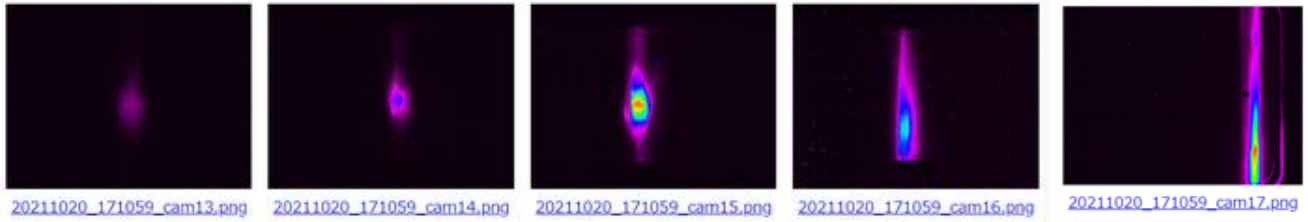
Initial distribution	
Bunch charge	60 pC
Norm. emittance (X)	1.63 μm
Norm. emittance (Y)	2.01 μm
Bunch length	1.85 ps (rms)
Energy spread $\Delta\gamma/\gamma$	2.23×10^{-3} (rms)
Transport	
Chirp phase	+29° (at 1.3 GHz)
R_{56}	−0.282 m
Entrance of undulator	
Energy γ	34.46
Norm. emittance (X)	4.45 μm
Norm. emittance (Y)	1.85 μm
Bunch length	1.94 ps (rms)
Energy spread $\Delta\gamma/\gamma$	6.22×10^{-3}
Energy modulation	0.02%
Undulator	
Strength a_w	0.97
Tapering coefficient	−0.048
Period λ_u	24 mm
Length	3 m × 2

Y. Honda et al., Rev. Sci. Instrum **92,** 113101 (2021)
H. Sakai in ERL2022 presentation

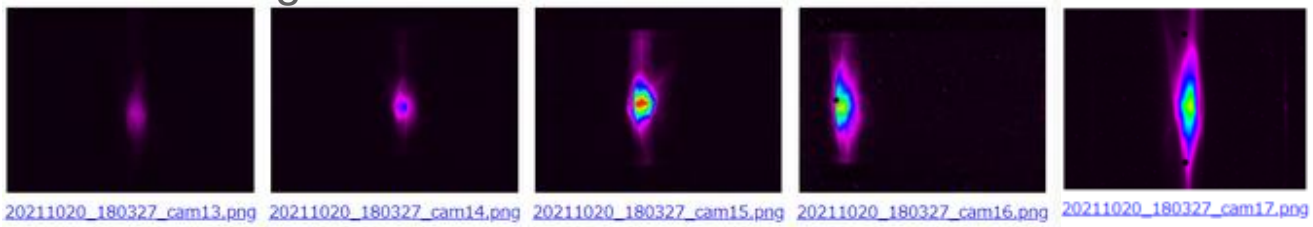
Beam profiles after matching

Arc of recirculation loop

Before matching

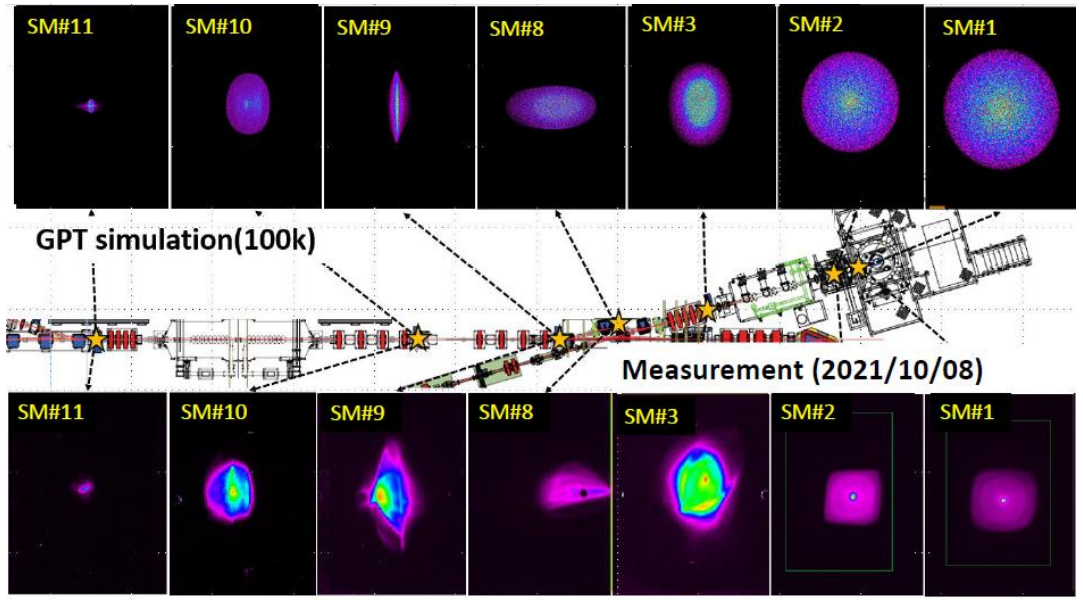


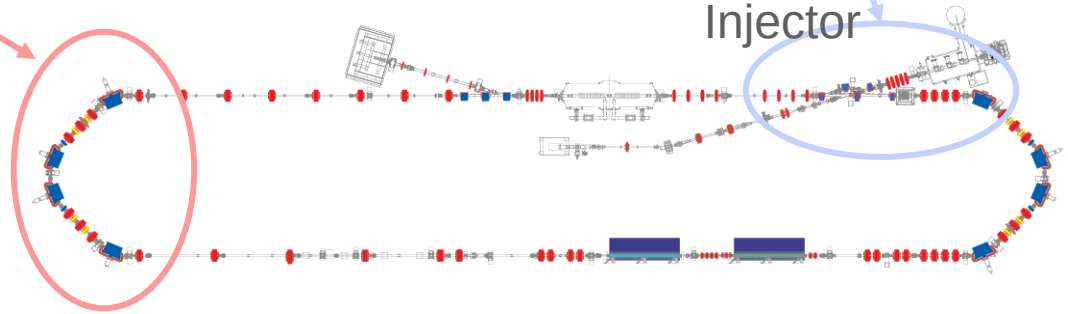
After matching



cam13 cam14 cam15 cam16 cam17

Injector





Arc of the recirculation loop

QMs in arc dedicates only to R56 and achromat tuning.
Transverse profiles are controlled with QMs in the straight section

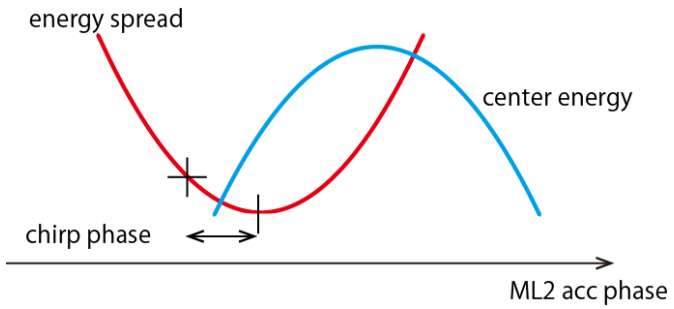
Injector

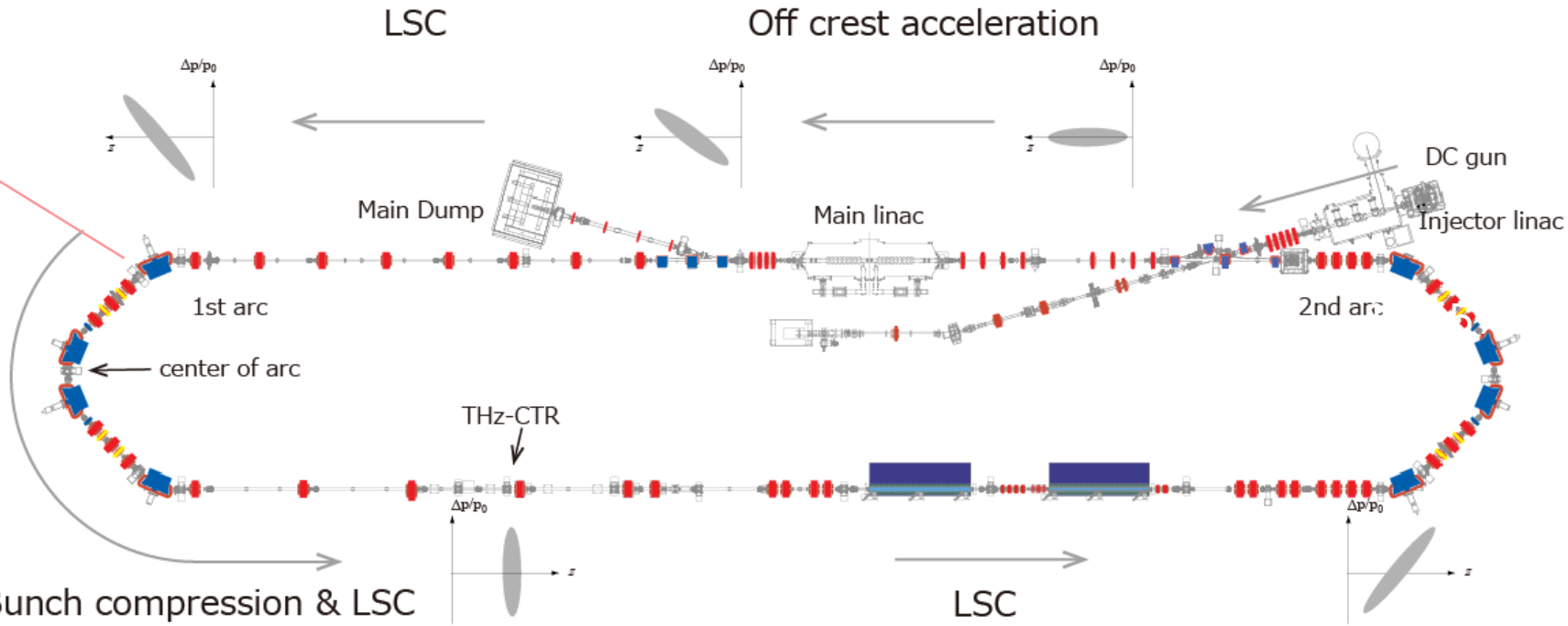
Q scan response is matched as well as the transverse profiles

Bunch compression with LSC at cERL

LSC : Longitudinal phase space

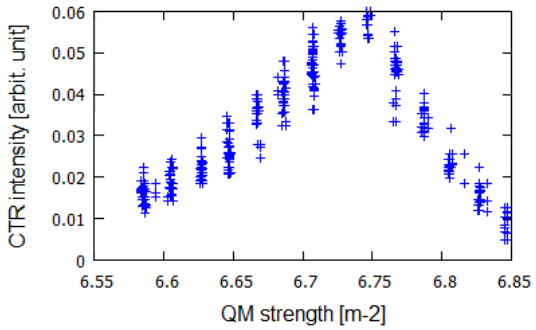
Minimum energy spread is defined as zero chirp phase



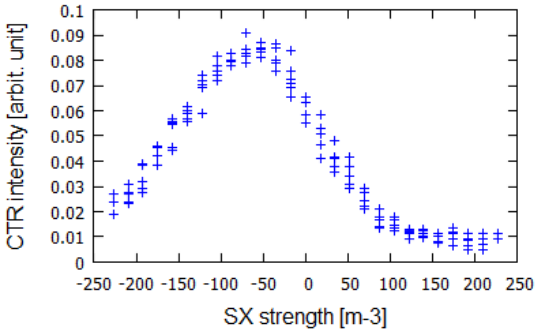


Intermediate energy beam at cERL feels the LSC effect
→ changing the longitudinal phase space distribution

Bunch compression tuning is demonstrated to maximize the THz-CTR or IR-FEL intensity.

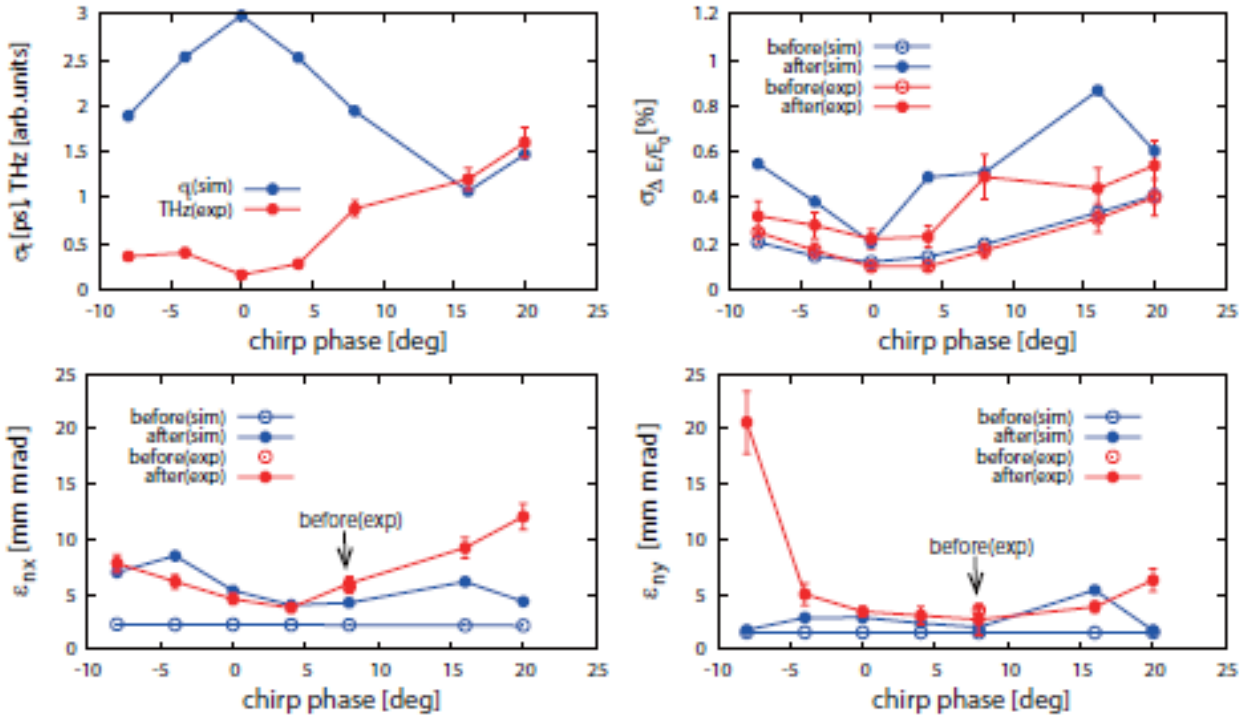


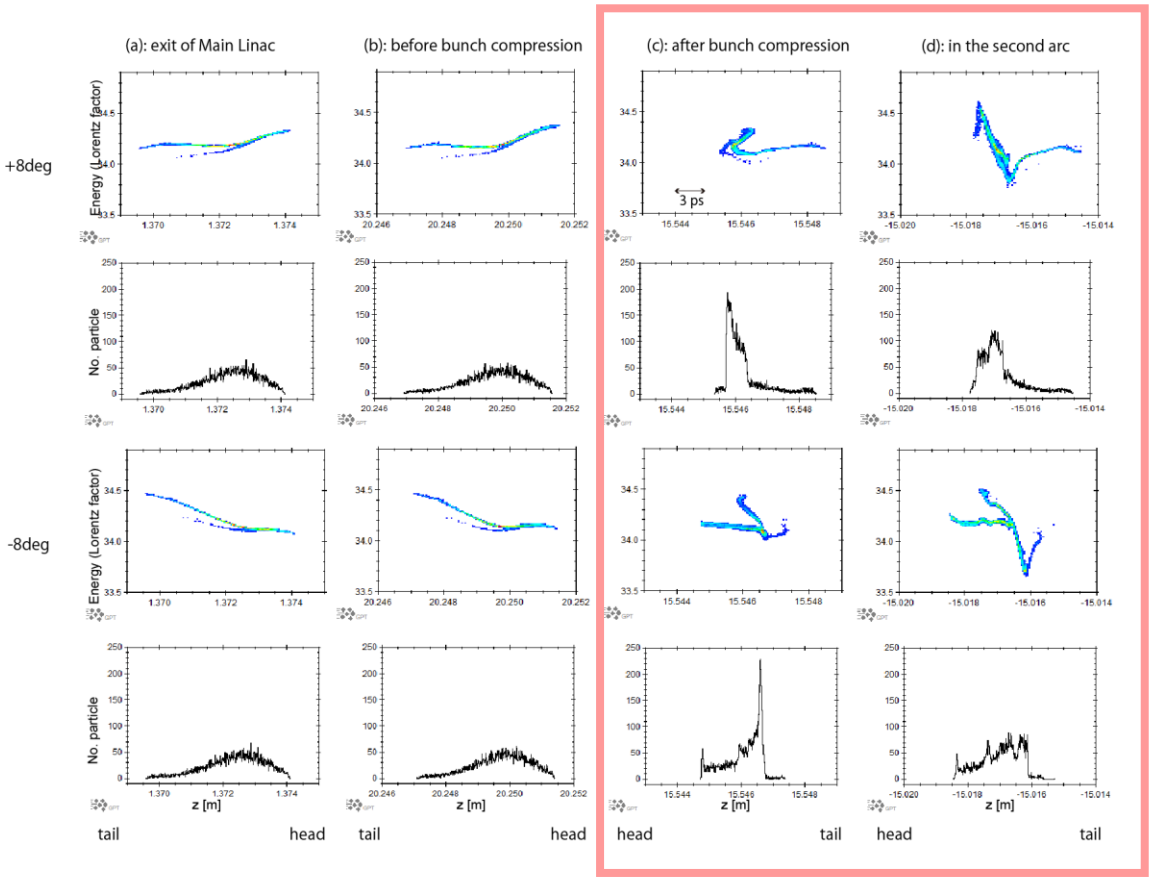
R56 survey

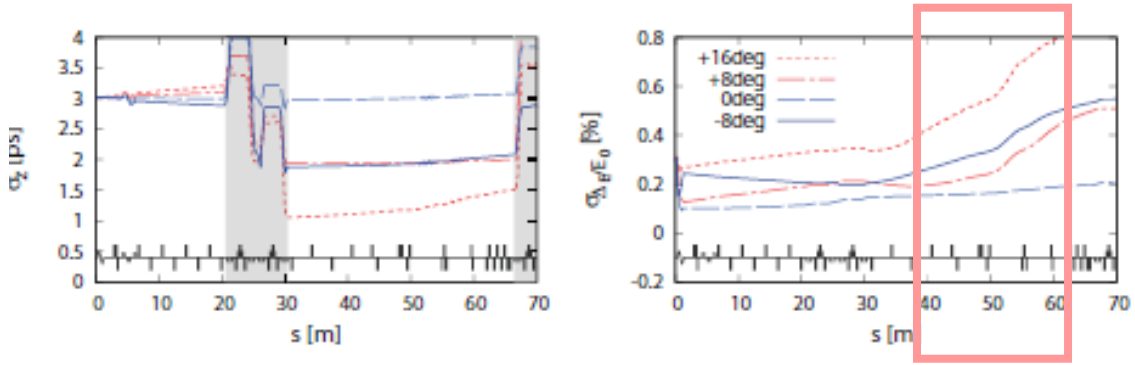


T566 survey

Chirp phase scan







Experimental results (2019.6)

chirp phase +8 deg is suitable for application such as IR-FEL (balance of short bunch length, small energy spread, …)

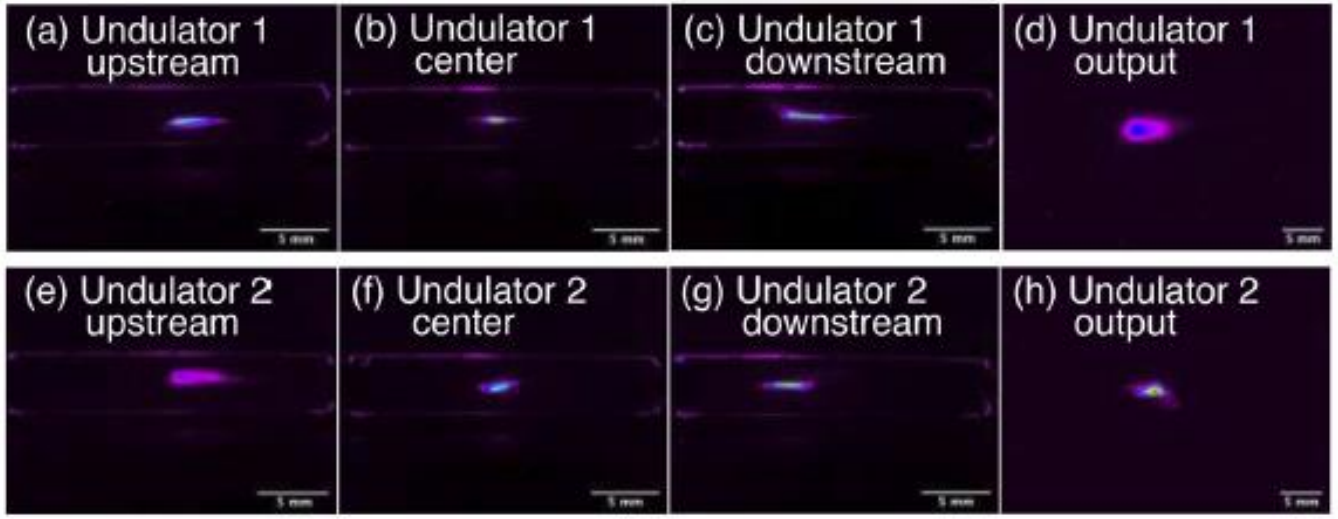
Tracking simulation

energy spread increases at the south straight section

→ LSC is dominant (compared with CSR wake)

M. Shimada et al., to be submitted

Undulator tuning



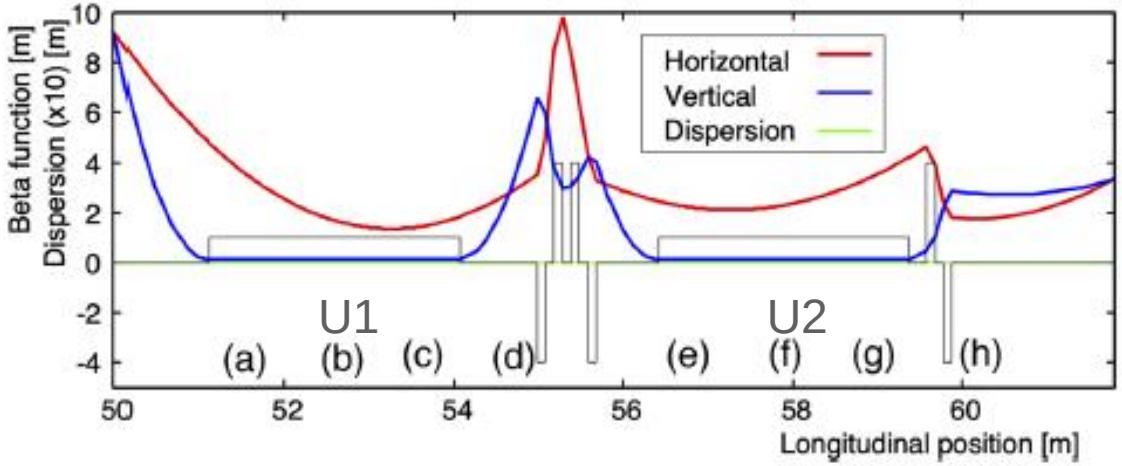


TABLE III. Measured beam parameters after FEL optimization.

Bunch charge		60 pC/bunch
Exit of main linac		
Norm. emittance (X)	ε_x	$3.27 \pm 0.17\ \mu$m
Norm. emittance (Y)	ε_y	$1.57 \pm 0.05\ \mu$m
Energy spread	$\Delta\gamma/\gamma$	0.6%
Total energy	σ_t	17.7 MeV
Transport		
Chirp phase		$+29^\circ$
R_{56}		-0.282 ± 0.046 m
Entrance of undulator		
Norm. emittance (X)	ε_x	$5.55 \pm 0.19\ \mu$m
Norm. emittance (Y)	ε_y	$5.11 \pm 0.16\ \mu$m
Bunch length (rms)	σ_t	~ps (0.6 ps structure)

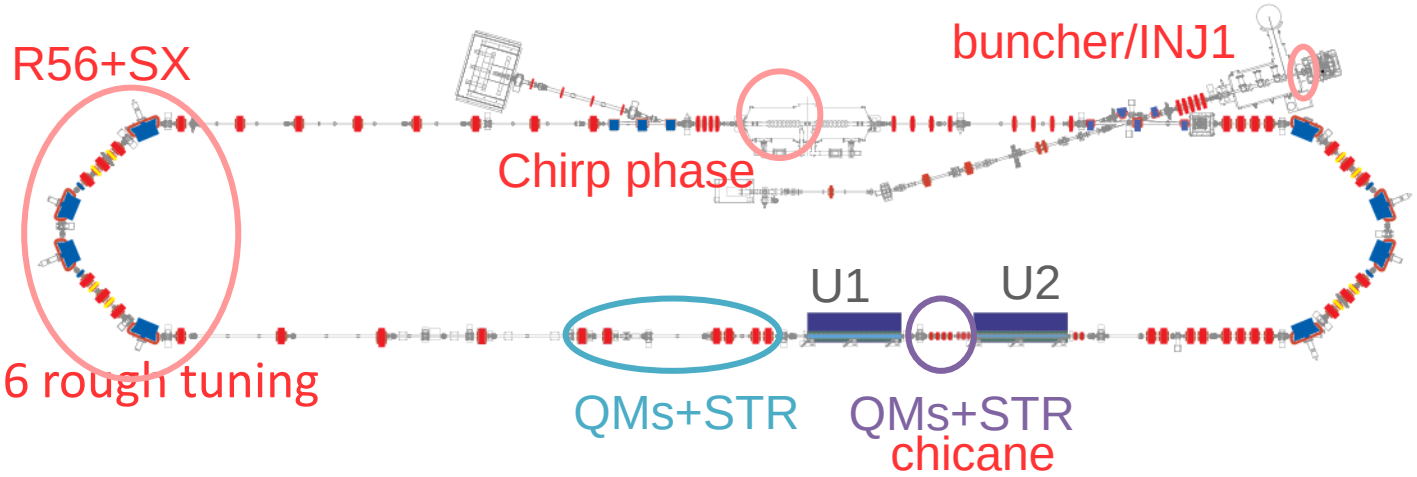
Best chirp phase depends on the operation season

Name	ratio	reference	diff	src
QMIS01	0	-0.743	0	-0.743
QMIS02	0	-2.207	0	-2.207
QMIS03	0	1.382	0	1.382
QMIS04	0	3.219	0	3.219
QMIS05	0	-6.552	0	-6.552
QMIS06	0	-0.296	0	-0.296
QMIS07	-8.68243	-35.46	0	-35.46
QMIS08	41.5856	44.587	0	44.587
QMIS09	-44.5416	-6.832	-0	-6.832
QMIS10	11.30896	-15.291	-0	-15.291

The screen monitor profiles are matched with the design optics by a combination quadrupoles. The matching points are at U1 and U2, respectively.

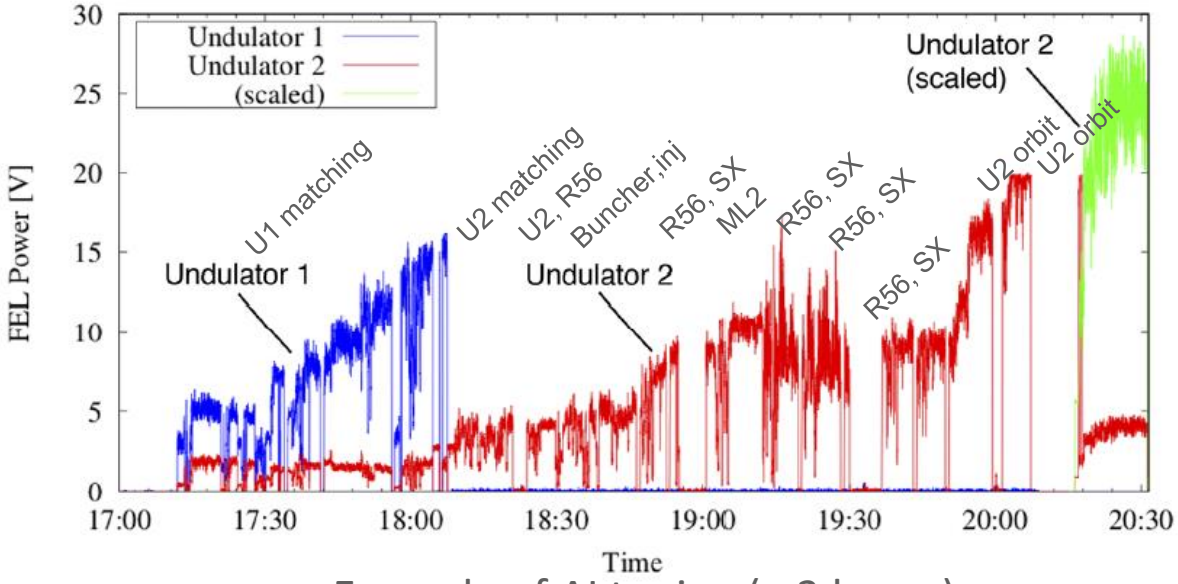
Y. Honda et al., Rev. Sci. Instrum **92,** 113101 (2021)

AI tuning at IR-FEL



Typical tuning recipe made by beam experience

1. Manual tuning
   Chirp phase setting, 17.7 MeV setting, and R56 rough tuning
2. AI tuning 1 (maximizing U1 signal)
   R56+SX → 4 Steering(H/V) → 6 QMs
3. AI tuning 2 (maximizing U2 signal)
   orbit between U1 and U2 → 4 QMs → R56+SX → 4 Sttering(H/V) → buncher/INJ1 cavity → R56+SX → chirp phase (ML2) → R56+SX → 4 Steering(H/V) → (chicane between U1 and U2)



Example of AI tuning (~ 3 hours)

Red: longitudinal profile tuning
Combination of RF and R56 tuning
R56 tuning almost does not change transverse profile
Blue and Purple: transverse profile and orbit tuning
Combination of QMs and orbit tuning
U2 tuning after U1 tuning

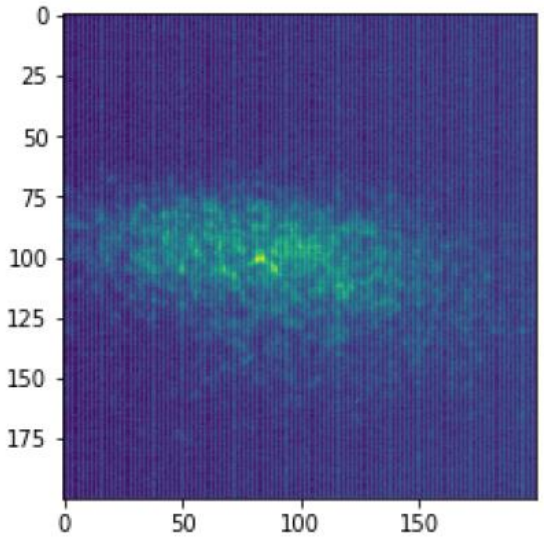
AI makes the beam tuning highly effective because 3~6 parameters are optimized at once

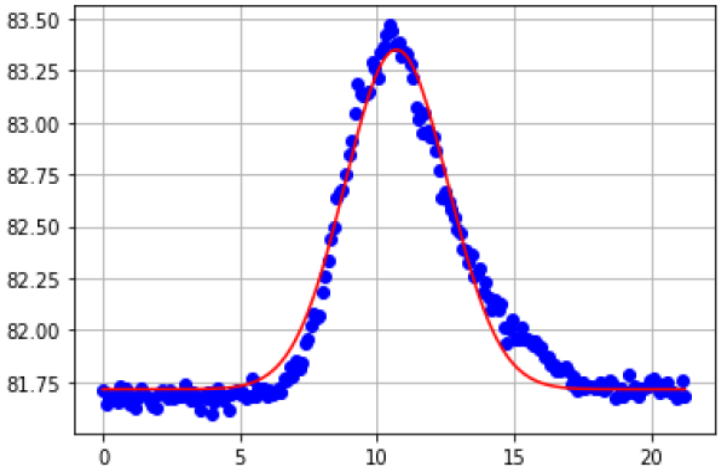
Bunch length measurement with streak camera

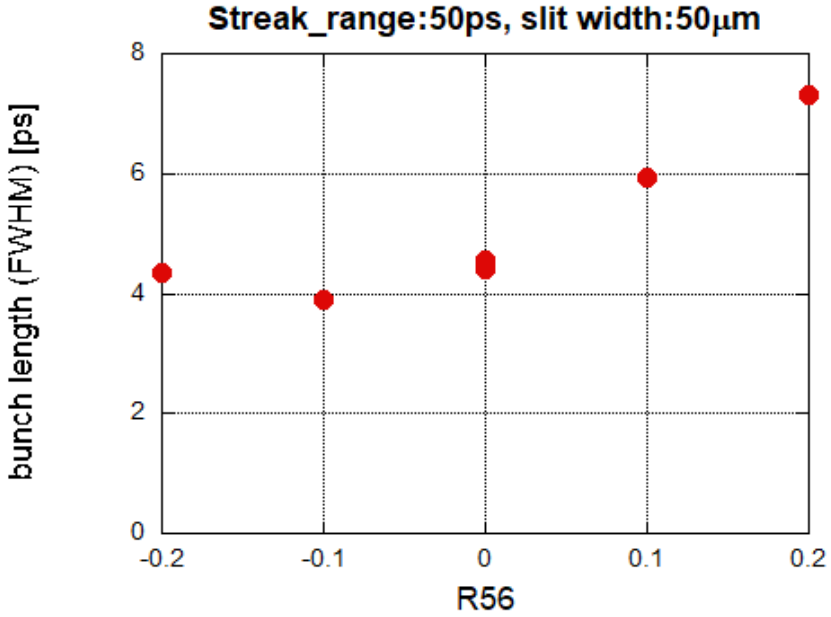
Streak camera: FESCA-200
OTR at the THz-CTR measurement location
Sequence 100 images are stacked

Results

Bunch length depends on R56
Minimum rms bunch length is 1.66 ps with 0.64 ps resolution







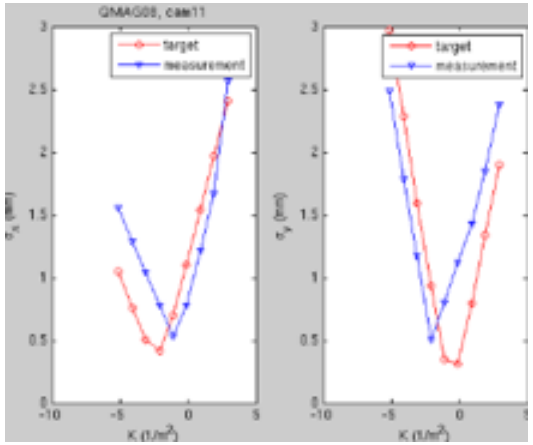
OUTLINE

- Optics tuning for IR-FEL w/o energy recovery
- High beam current operation with undulator
- Summary

Beam matching at low charge

Low energy region at the injector

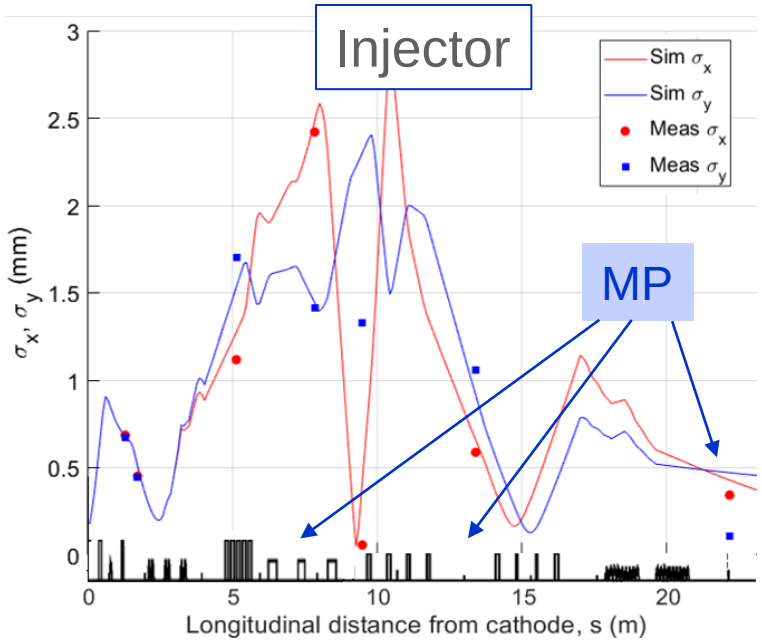
- Match the Q scan response measurement with the design
- Q scan measurement is iterated because it is difficult to estimate the optics development with liner optics (strong space charge effect)

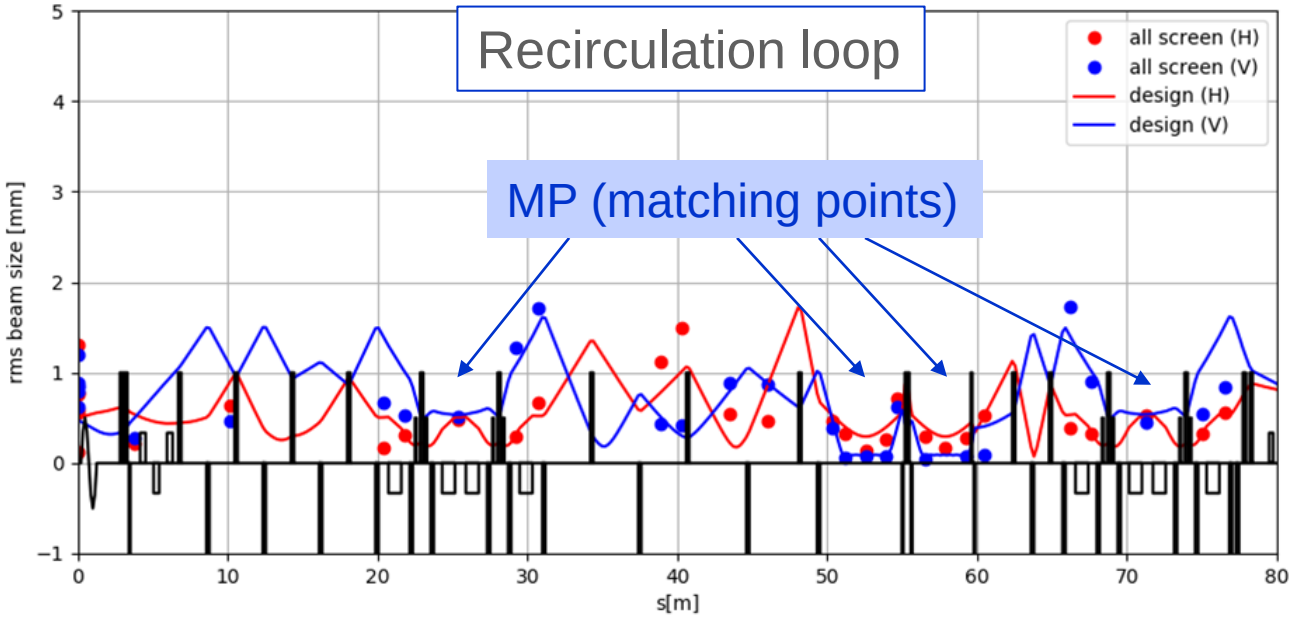


Example of injector matching

Intermediate energy region at the recirculation loop

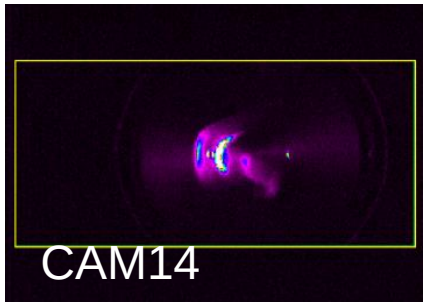
- Obtain the beta function at one Q scan measurement, matching the downstream optics with linear optics





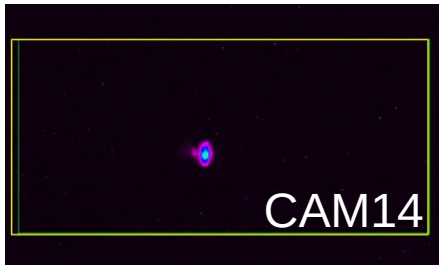
Beam tuning for high current CW operation (trials)

1st trial: Gun laser pulse 40ps → limited at 1μA



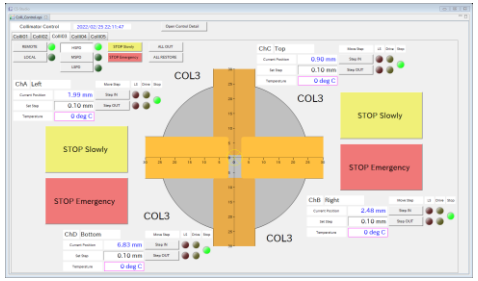
Radiation interlock at gun
(return beam hits the gun?)
Three peaks in the dispersion area

2nd trial: Gun laser pulse 3ps → limited at 100μA



Longitudinal profile is simple
High radiation level at the undulator

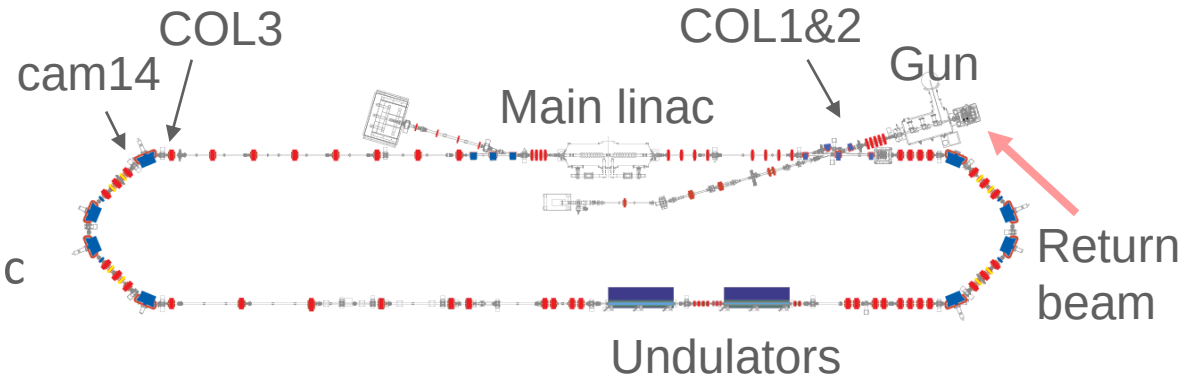
3rd trial : Insertion of COLs → go to 300μA



High radiation level out of the shield!
Collimator (COL3) at high energy is harmful.

4th trial : Remove COL3 → limited at 200μA

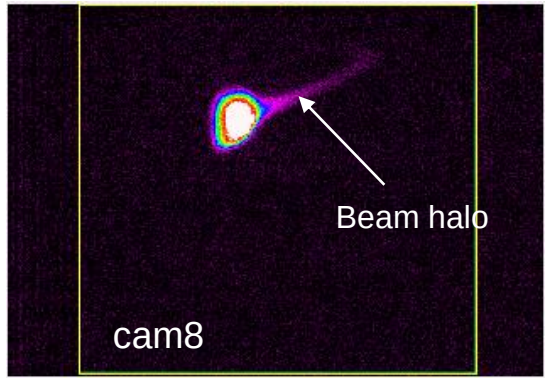
High radiation level at gun and exit of the main linac



Beam loss position is changed at every trial…

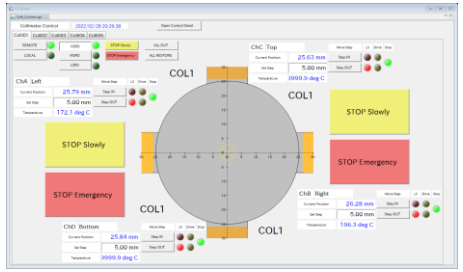
Halo and tail collimation at low energy

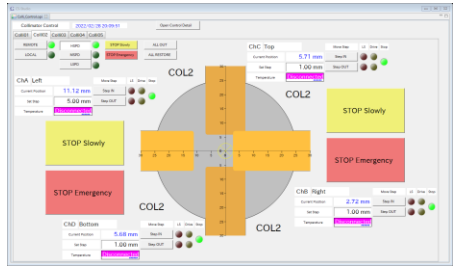
5th trial: Vertical off-center orbit at injector cavity → limit at 40μA



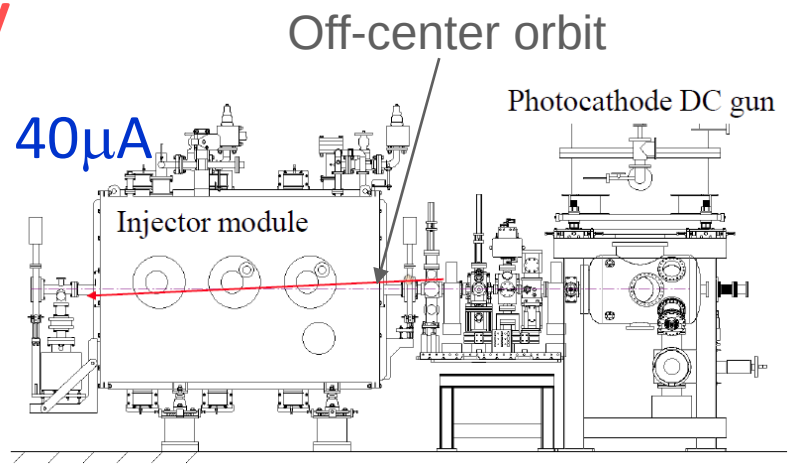
Off-center cavity orbit kicks the long tail

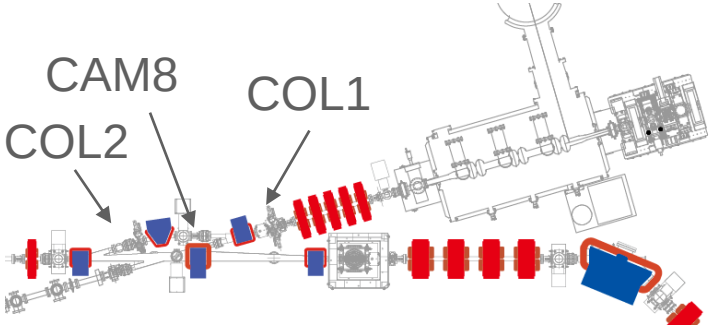
Collimator (COL2) for halo elimination





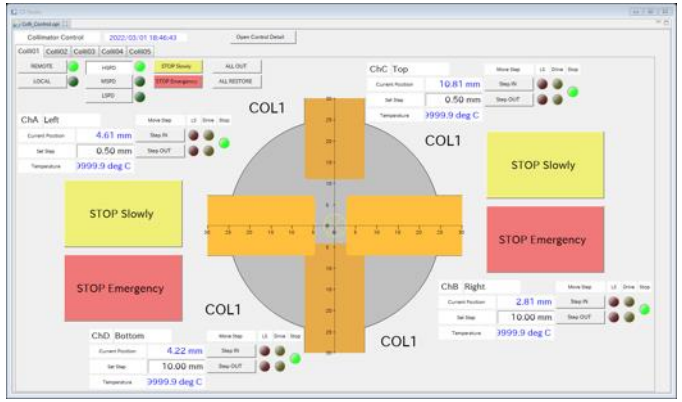
→ High radiation level around the main linac

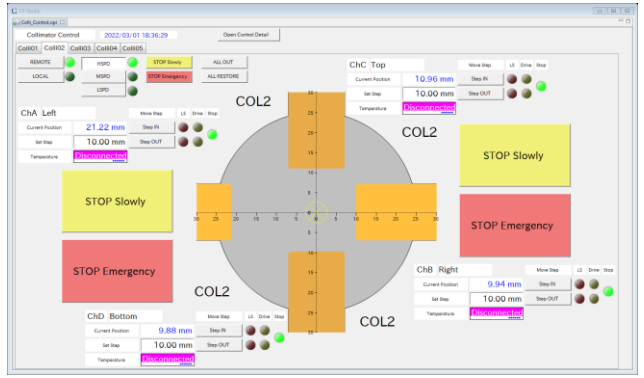


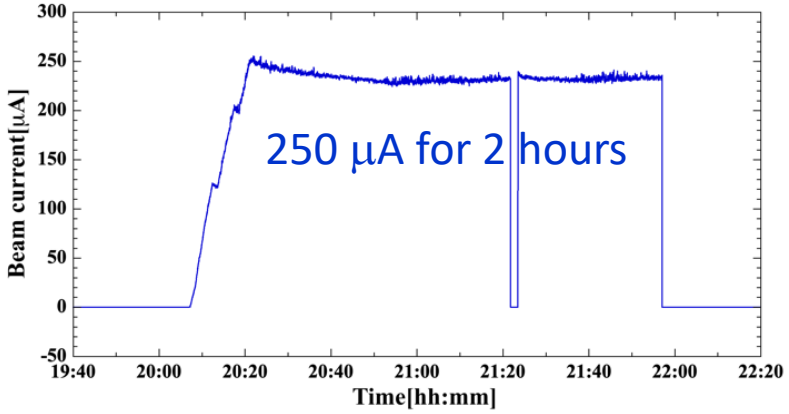


6th trial: off-center orbit + collimator tuning → go to 250μA

250μA is achieved with a low level (higher current terminated by time limit)



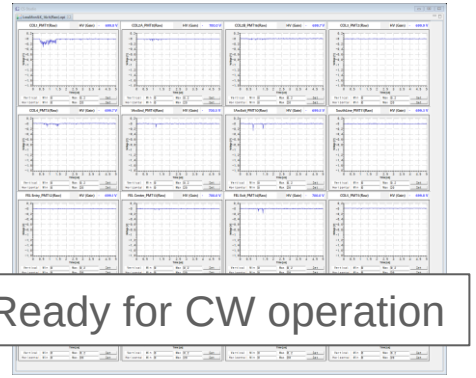




Measurement of radiation level due to beam loss

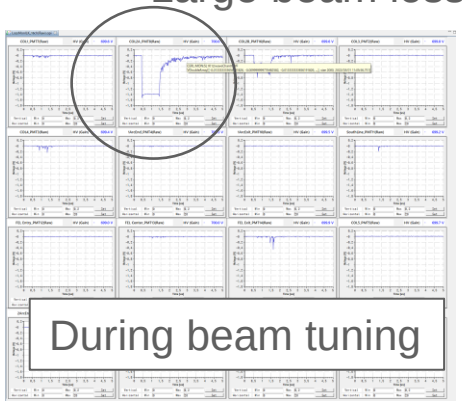
Before the high current operation

PMTs with CsI scintillators (16 + 4)
beam tuning with burst mode (extremely low average current)



Ready for CW operation

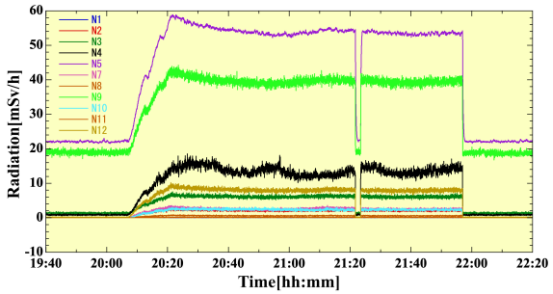
Large beam loss

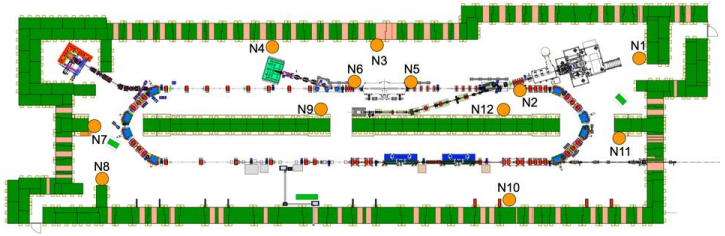


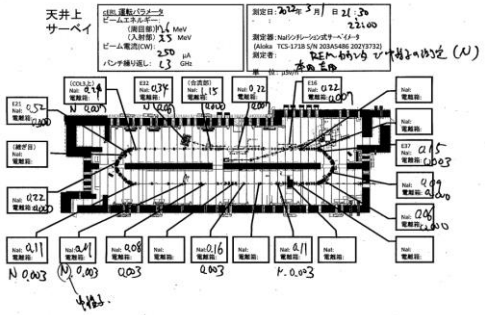
During beam tuning

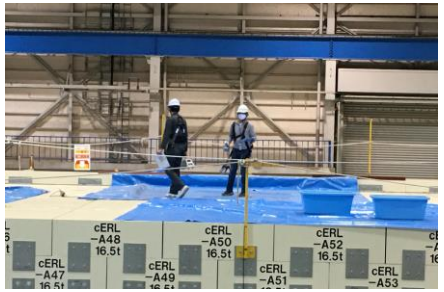
During the high current operation

12 ALOKA monitors, PMTs for fast Interlock, manual survey out of the shield



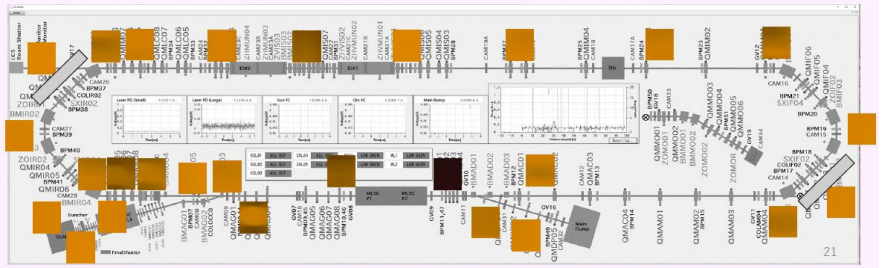




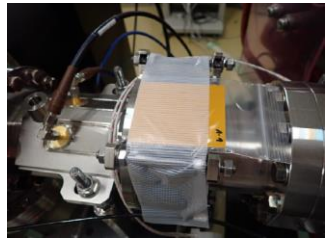


After the high current operation

Gafchromic film



Calibration



etc…

Compared with the previous operation

	Feb-Mar. 2022	Jun. 2018	Feb-Mar. 2016
Maximum beam current [uA]	250 (time limit of tuning)	900 (not to exceed 1mA by a fluctuation of a current monitor)	
Injection energy [MeV]	3.5 (increased for small emittance)	3.0	2.9
Recirculation energy [MeV]	17.6 (limited by FE of the main linac)	17.6	19.9
Momentum ratio	1:5 (limited by chamber aperture)	1:6	1:7
Gun laser pulse [ps]	3 (suitable for small bunch charge)	3	3
Bunch repetition [MHz]	1300	1300	162.5 / 1300
Bunch charge [pC/bunch]	0.2	0.7	5.5 / 0.7
Undulator	Yes (first trial)	No	No

Even after installing the undulator, the high current beam operation is successful!

Summary

Optics tuning for IR-FEL w/o energy recovery

- Beam size is matched at key locations; end of the main linac, in the arc, and two FELs.
- Chirp phase survey by manual
- AI beam tuning for maximizing the IR-FEL intensity

High beam current operation with undulator

- RMS beam size matches with the design optics at a small bunch charge
- Collimation at high energy causes harmful radiation
- Off-center orbit in the injector works for collimating the halo and tail at low energy
- Successful 250uA CW operation with the small radiation level