



Review of ERL Projects at KEK and around the World

**Norio Nakamura
for the ERL collaboration team**

High Energy Accelerator Research Organization (KEK)

ERL Collaboration Team



High Energy Accelerator Research Organization (KEK)

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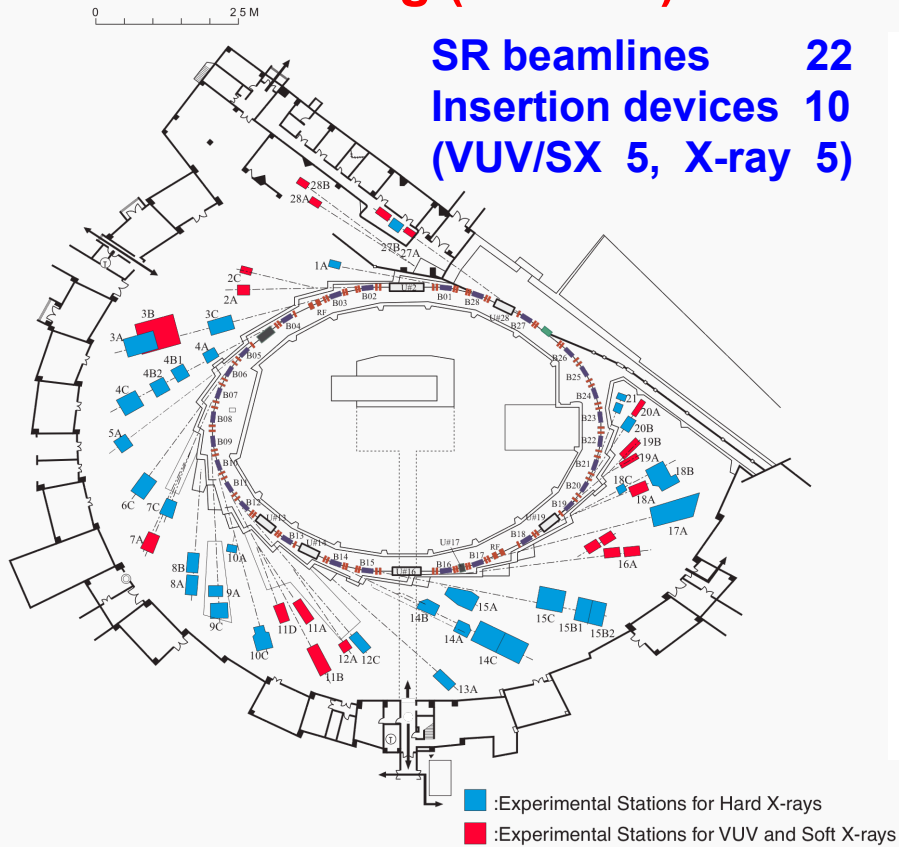
Outline

- 1. 3-GeV ERL Light Source Project at KEK**
- 2. The Compact ERL (cERL) Project at KEK**
- 3. Review of ERL Projects around the World**
- 4. Summary and Outlook**

3-GeV ERL Light Source Project at KEK

KEK Photon Factory (KEK-PF)

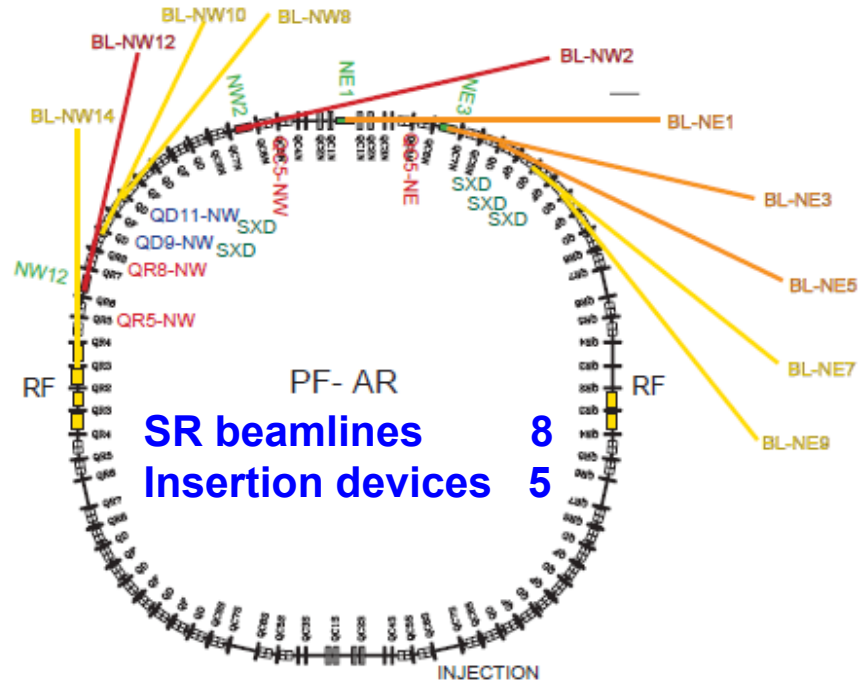
PF ring (2.5 GeV)



- $E = 2.5 \text{ GeV}$, $C = 187 \text{ m}$
- Beam emittance : $34.6 \text{ nm}\cdot\text{rad}$
- Top-up operation, $I_0 = 450 \text{ mA}$

More than 30 years have passed since construction of both rings.

PF-AR (6.5 GeV)

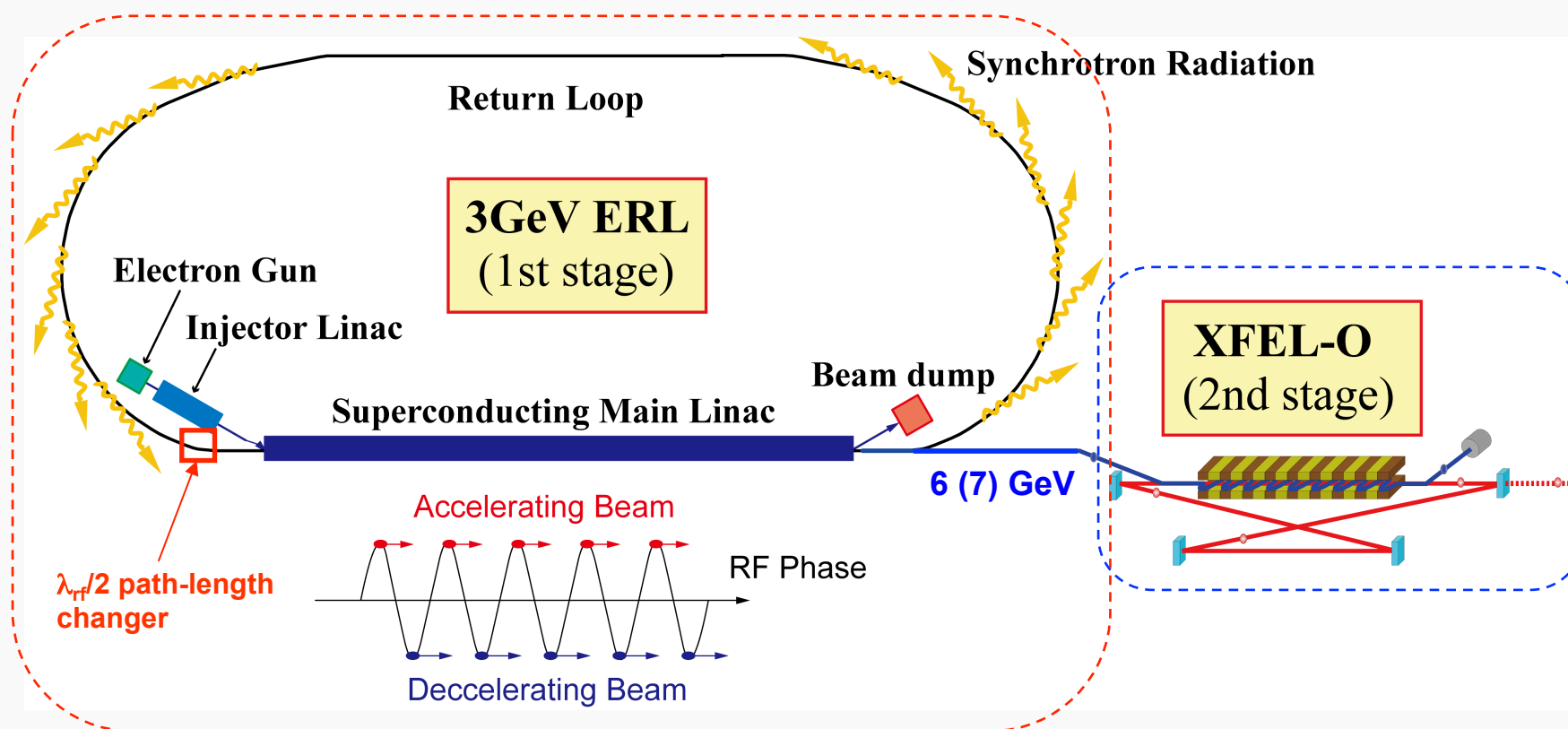


- $E = 6.5 \text{ GeV}$, $C = 377 \text{ m}$
- Beam emittance: $293 \text{ nm}\cdot\text{rad}$
- Single bunch, $I_0 = 60 \text{ mA}$

ERL Light Source Project at KEK

ERL-based Light Source Project at KEK (2 Stages)

1. **3-GeV ERL** as **VUV and X-ray SR source**
2. **6-7 GeV XFEL Oscillator**



Schematic view of the ERL light source project at KEK

Beam Parameters for Operational Modes

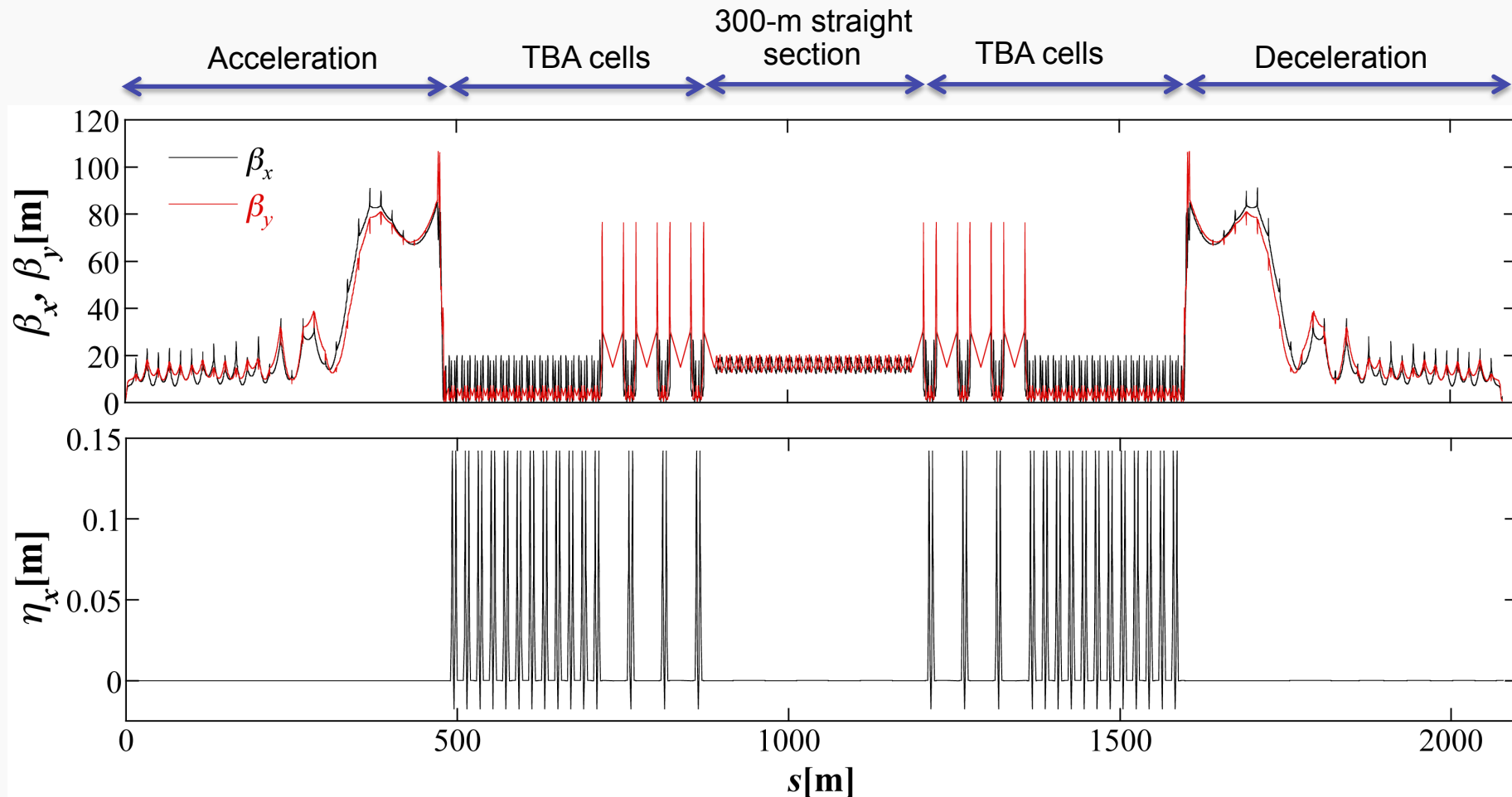
3 GeV ERL

XFEL-O

	High Coherence (HC) mode	High Flux (HF) mode	Ultimate (UL) mode	Ultra-Short Pulse (US) mode	XFEL-O mode
Beam Energy	3 GeV				6 - 7 GeV
Beam Current	10 mA	100 mA	100 mA	77 μ A (typ.)	10 μ A
Bunch Charge	7.7 pC	77 pC	77 pC	77 pC	10 pC
Repetition Rate	1.3 GHz	1.3 GHz	1.3 GHz	1 MHz	1 MHz
Norm. Emittance	0.1 mm·mrad	1 mm·mrad	0.1 mm·mrad	-	0.2 mm·mrad
Emittance	17 pm·rad	170 pm·rad	17 pm·rad	-	15 pm·rad
Energy Spread	2×10^{-4}	2×10^{-4}	2×10^{-4}	-	5×10^{-5}
Bunch Length	2 ps	2 ps	2 ps	≤ 100 fs	1 ps

Beam Optics of 3-GeV ERL

Preliminary Optics (from after merger to before dump line)



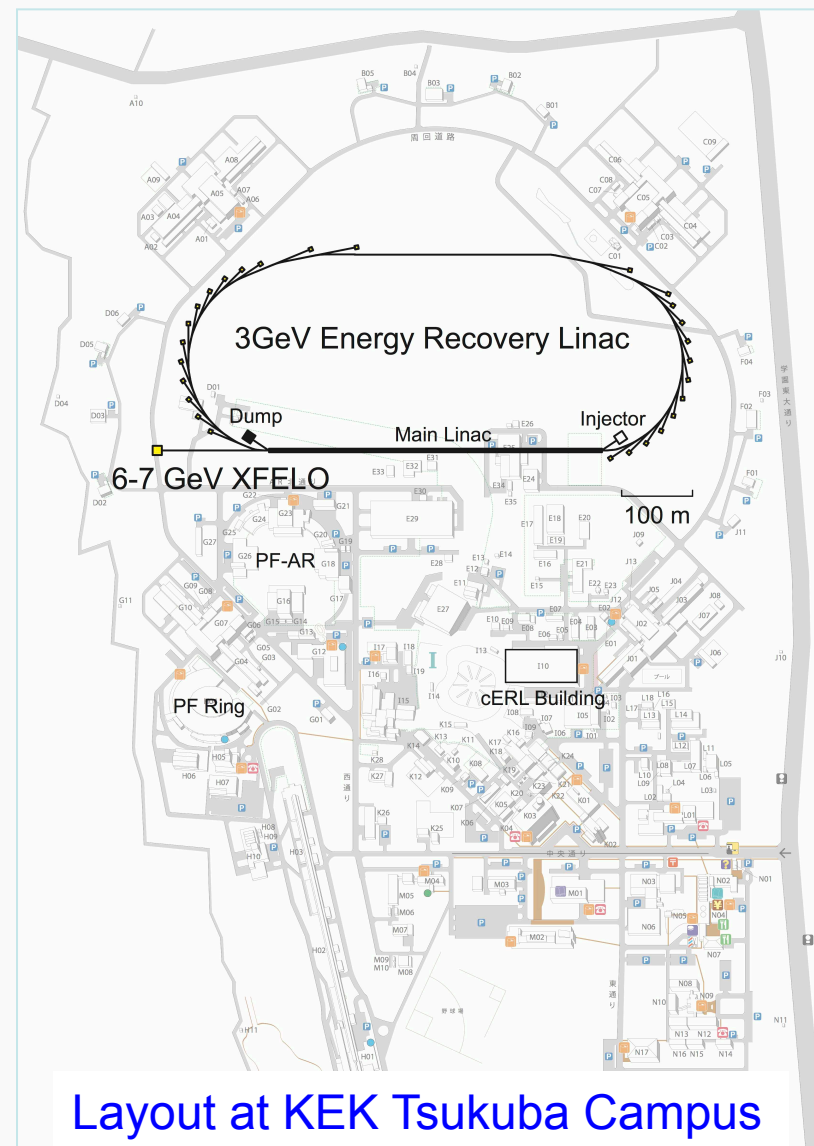
Emittance growth & energy spread increase due to ISR & CSR effects are negligible for both Ultimate and XFEL-O modes.

M. Shimada et al., MOPP019

Tentative Layout of 3-GeV ERL

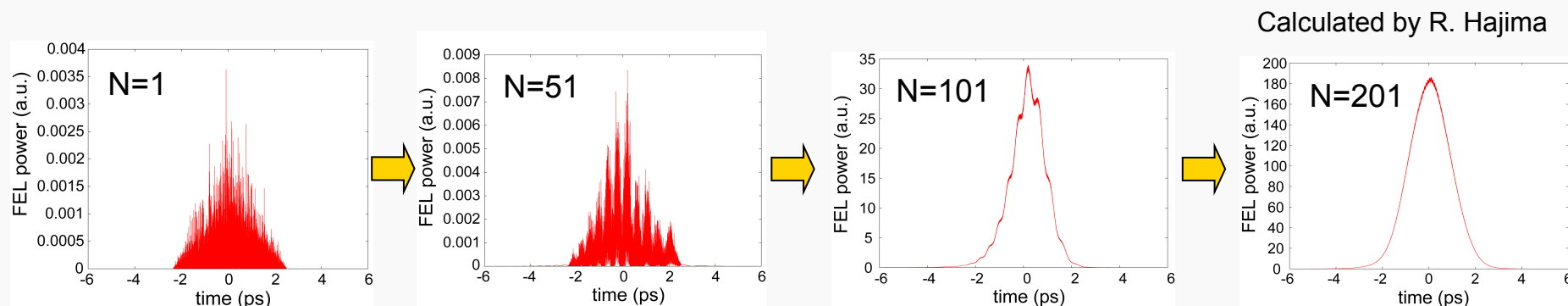
Assumptions:

- Beam energy
 - Full energy: 3 GeV
 - Injection and dump :10 MeV
 - XFEL-O: 6-7 GeV
- Circumference : ~ 1600 m
- Main linac
 - Eight 9-cell cavities in a cryomodule
 - 28 cryomodules (224 cavities)
 - Cavity acc. gradient : 13.4 MV/m
 - Triplet QMs between cryomodules
 - Total length : ~ 470 m
 - (average acc. gradient : 6.4 MV/m)
- TBA cells for ID's
 - 22 x 6 m short straight sections
 - 6 x 30 m long straight sections
- 300-m long straight section

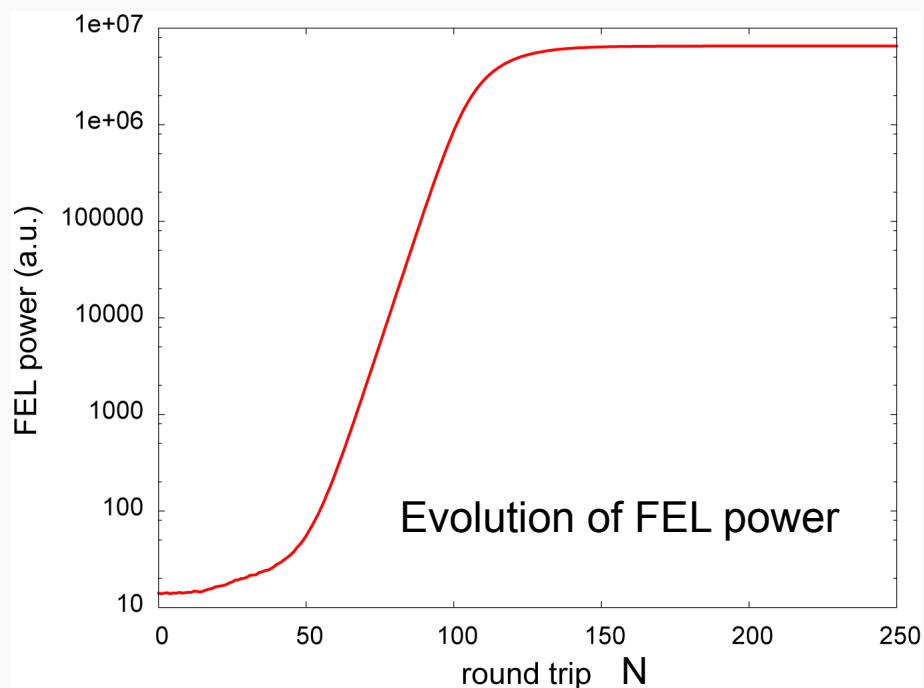


Layout at KEK Tsukuba Campus

Simulation of XFEL-O (6 GeV)



Evolution of temporal pulse profile



Evolution of FEL power

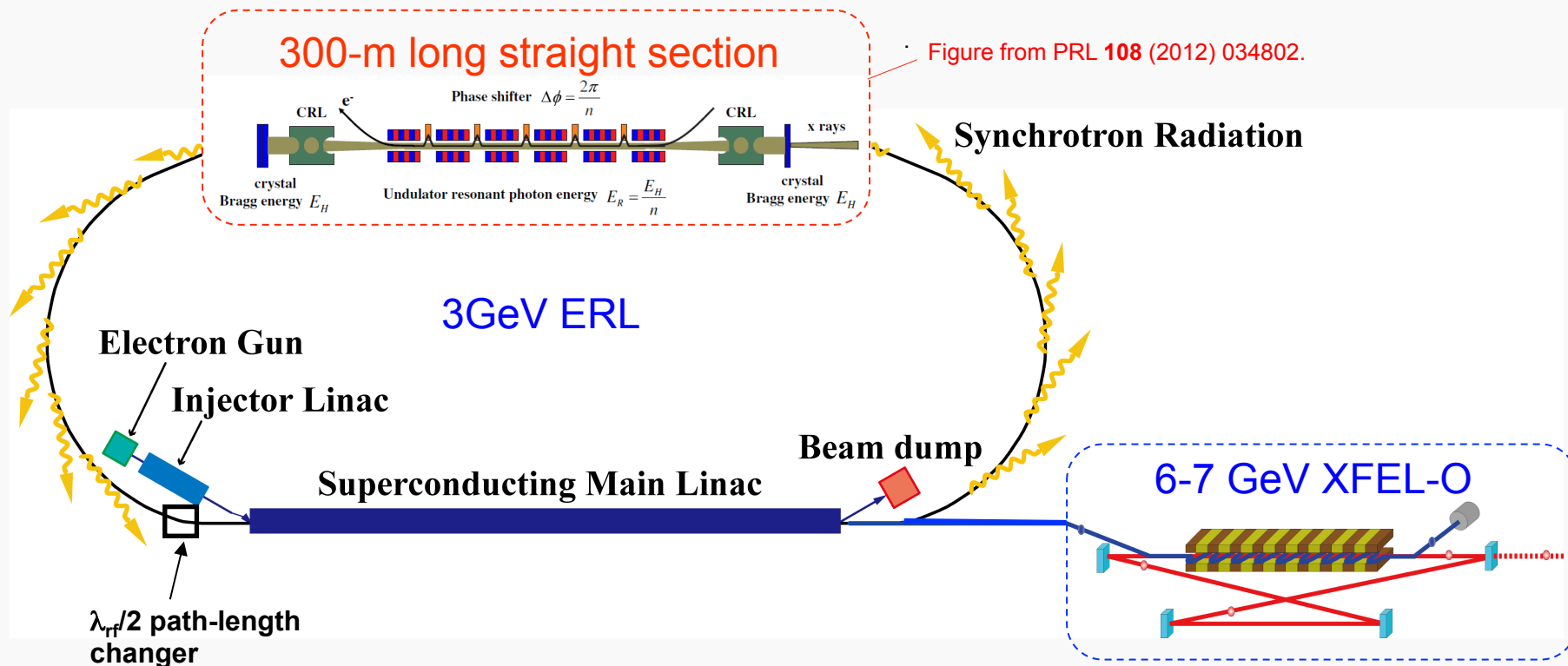
Example of parameters for XFEL-O

Parameter	Value
Beam energy	6 GeV
Bunch charge	10 pC
Bunch length	1 ps
Energy spread	5×10^{-5}
Norm. emittance	0.2 mm mrad
Photon energy	12 keV
Undulator length	58 m
Undulator period	19.4 mm
Gain	43 %

Potential of 300m Long Straight Section

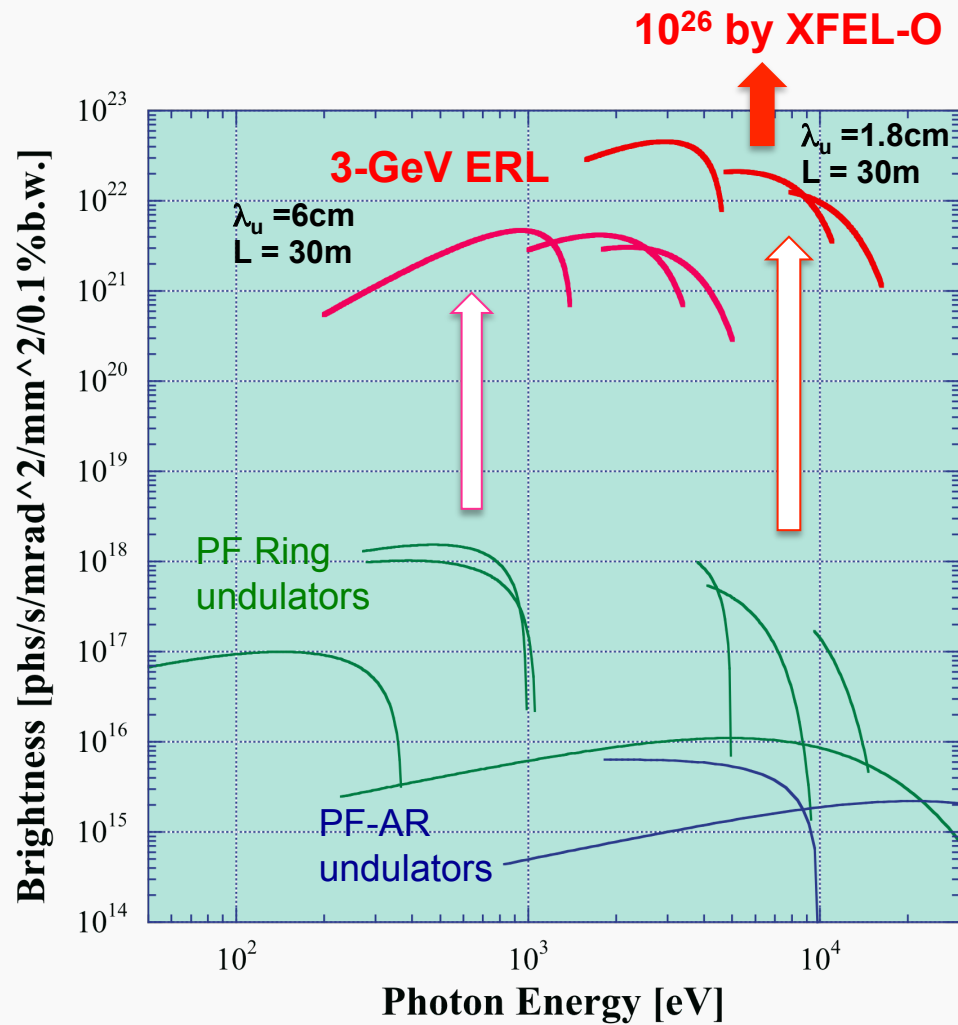
Potential of 300-m long straight section (E=3GeV) :

- (1) 300-m Undulator – Spectral Brightness $10^{23} - 10^{24}$
- (2) EEHG FEL including generation of attosecond VUV/X-ray pulses
- (3) Harmonic Lasing of XFEL-O

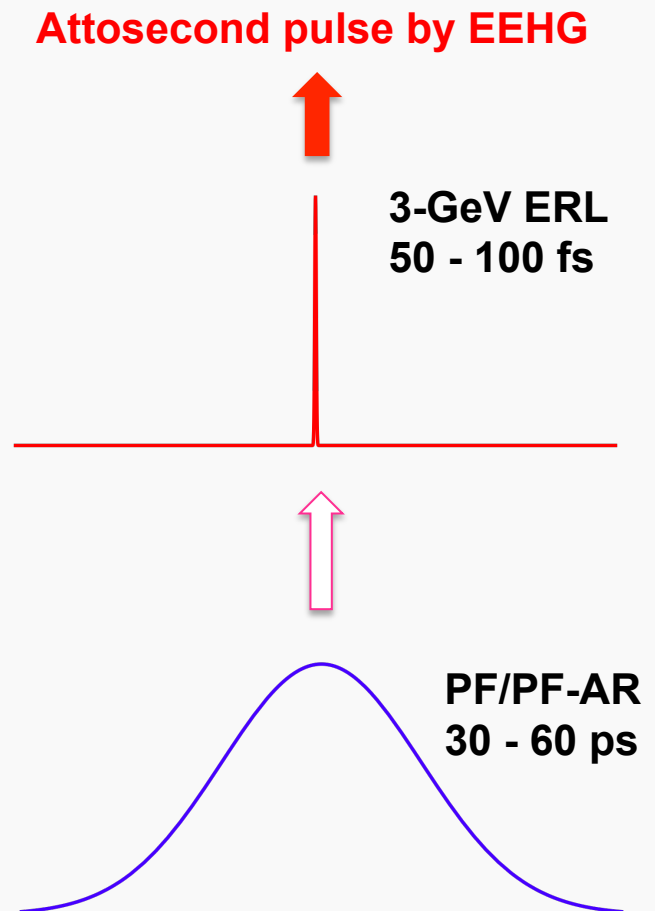


Light Source Performance

Spectral Brightness



SR Pulse length



Calculated by K. Tsuchiya

The Compact ERL (cERL) Project at KEK

Compact ERL (cERL) Project

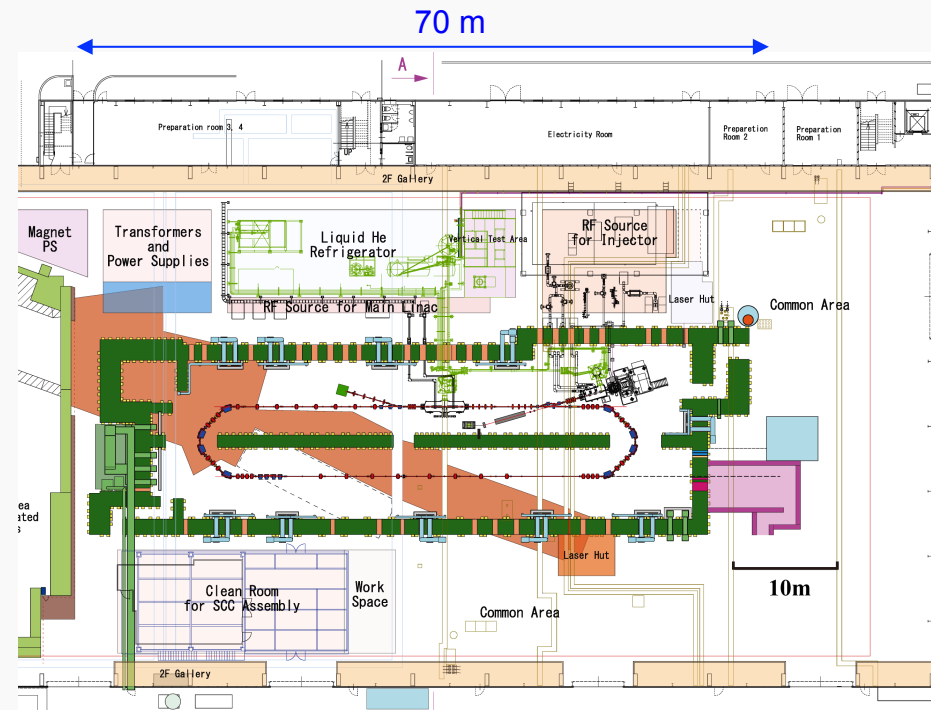
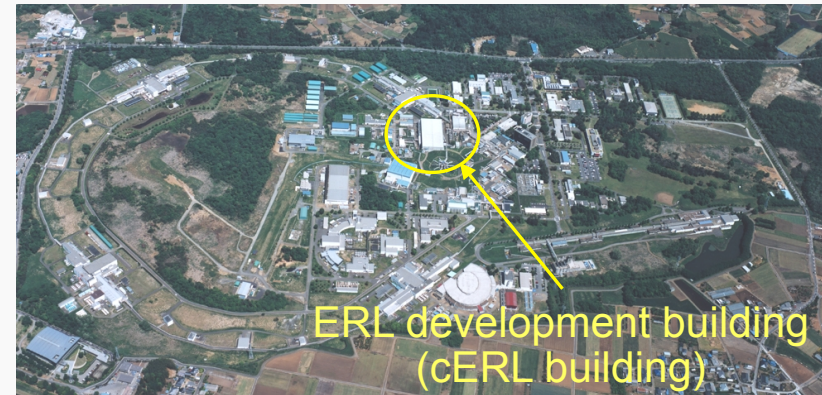
Purposes of the compact ERL

- Demonstrating reliable operations of our ERL components (guns, SC-cavities, ...)
- Demonstrating generation and recirculation of ultra-low emittance beams at high currents
- 1st target : 1 mm·mrad for 10mA @ 35 MeV

Parameters of the Compact ERL

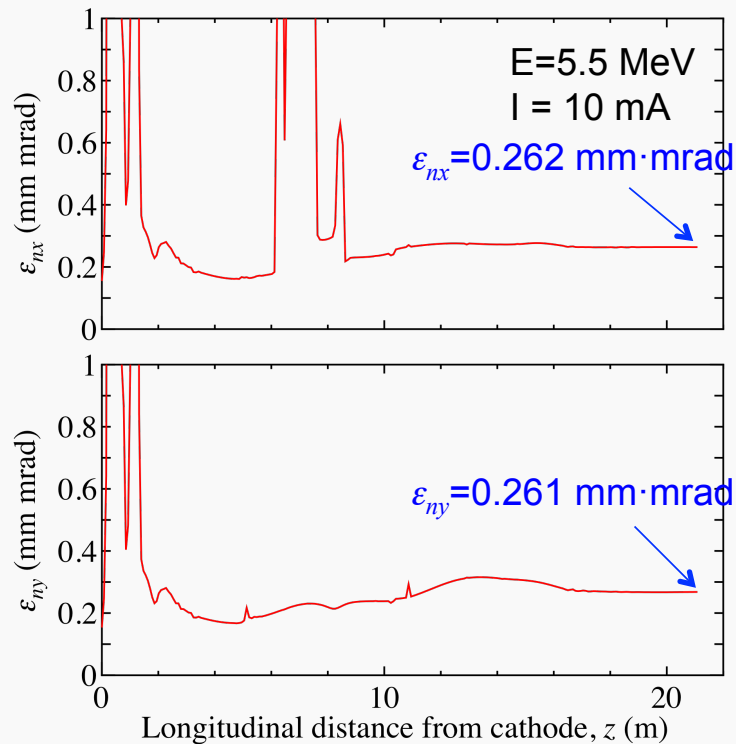
	Parameters
Beam energy (upgradability)	35 MeV 125 MeV (single loop) 245 MeV (double loops)
Injection energy	5 MeV (10 MeV in future)
Average current	10 mA (100 mA in future)
Acc. gradient (main linac)	15 MV/m
Normalized emittance	0.1 mm·mrad (7.7 pC) 1 mm·mrad (77 pC)
Bunch length (rms)	1 - 3 ps (usual) ~ 100 fs (with B.C.)
RF frequency	1.3 GHz

Commissioning is scheduled to start in 2013.



S. Sakanaka et al., MOPPP018

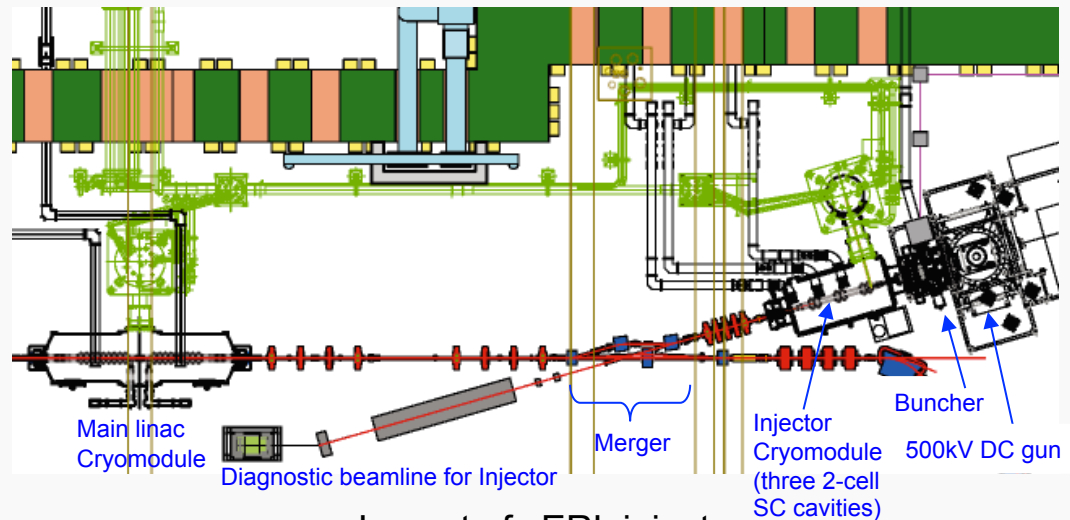
Injector Design



Simulation result from the gun to just after the main linac.

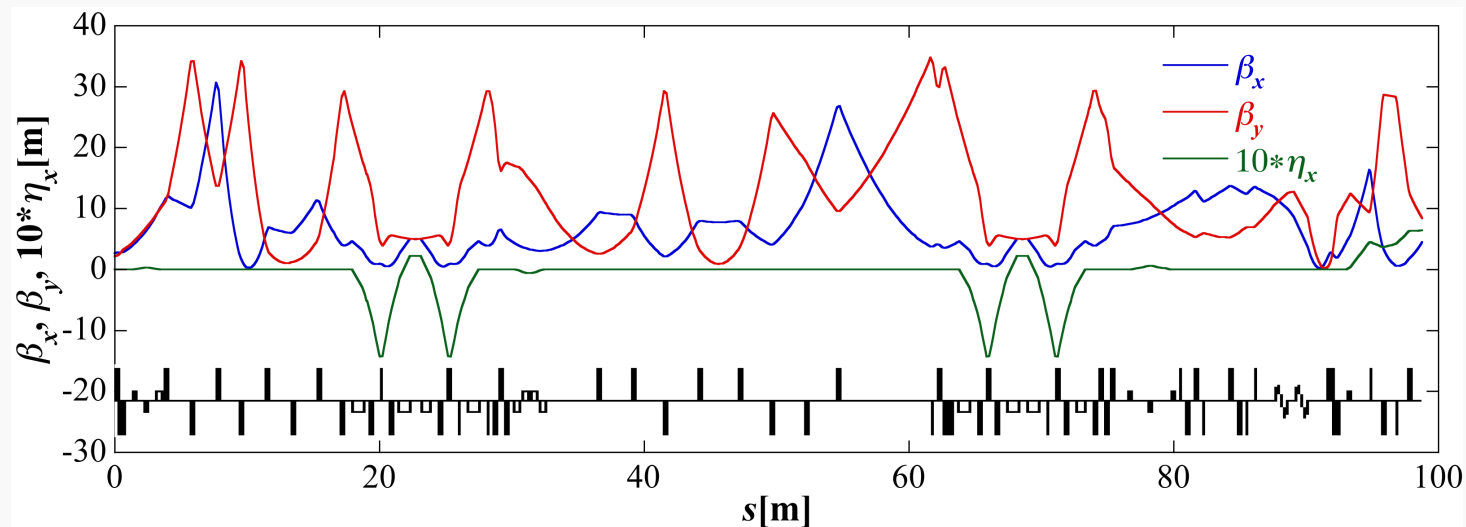
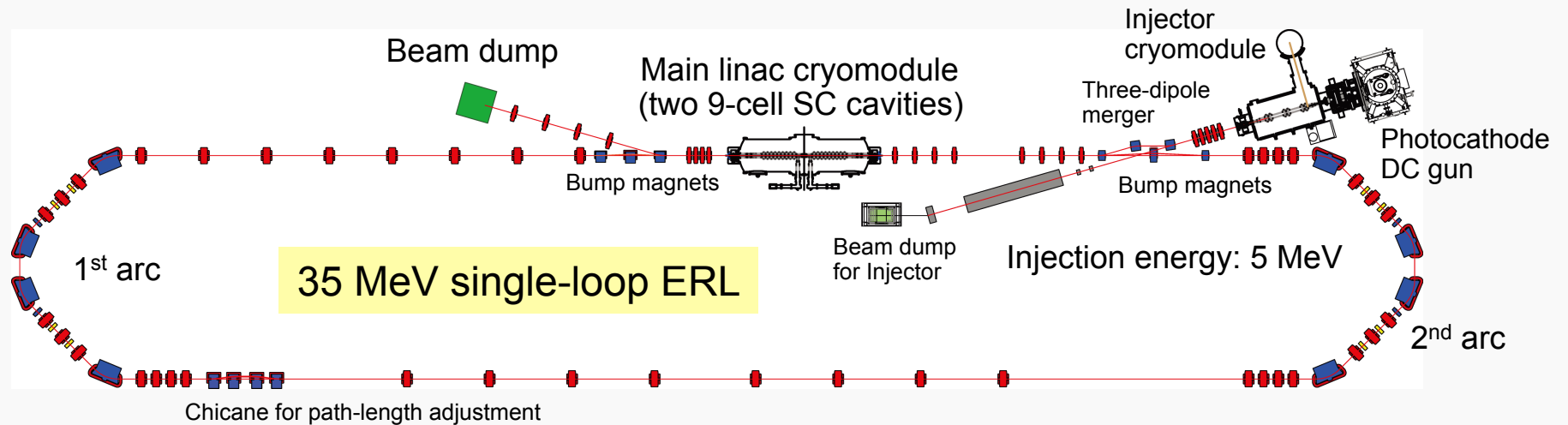
1st goal (1 mm·mrad for 10 mA) is achievable.

T. Miyajima et al., MOPPP017



Parameter	Value
Gun DC voltage	500 kV
Beam energy of injector	5 MeV
Charge/bunch (Current)	7.7 pC (10mA)
Full width of laser pulse	16 ps
Spot diameter of laser	0.52 mm
Magnetic fields of solenoids #1, #2	0.0364, 0.0146 T
Voltage of buncher cavity	105 kV
Eacc of 1st, 2nd, and 3rd SC cavity	6.84, 7.53, 7.07 MV/m
Offset phase of 1st, 2nd, and 3rd cavity	29.9, -9.8, -10.0 degrees

Lattice and Optics of cERL



Betatron and dispersion functions (from after main linac to beam dump)

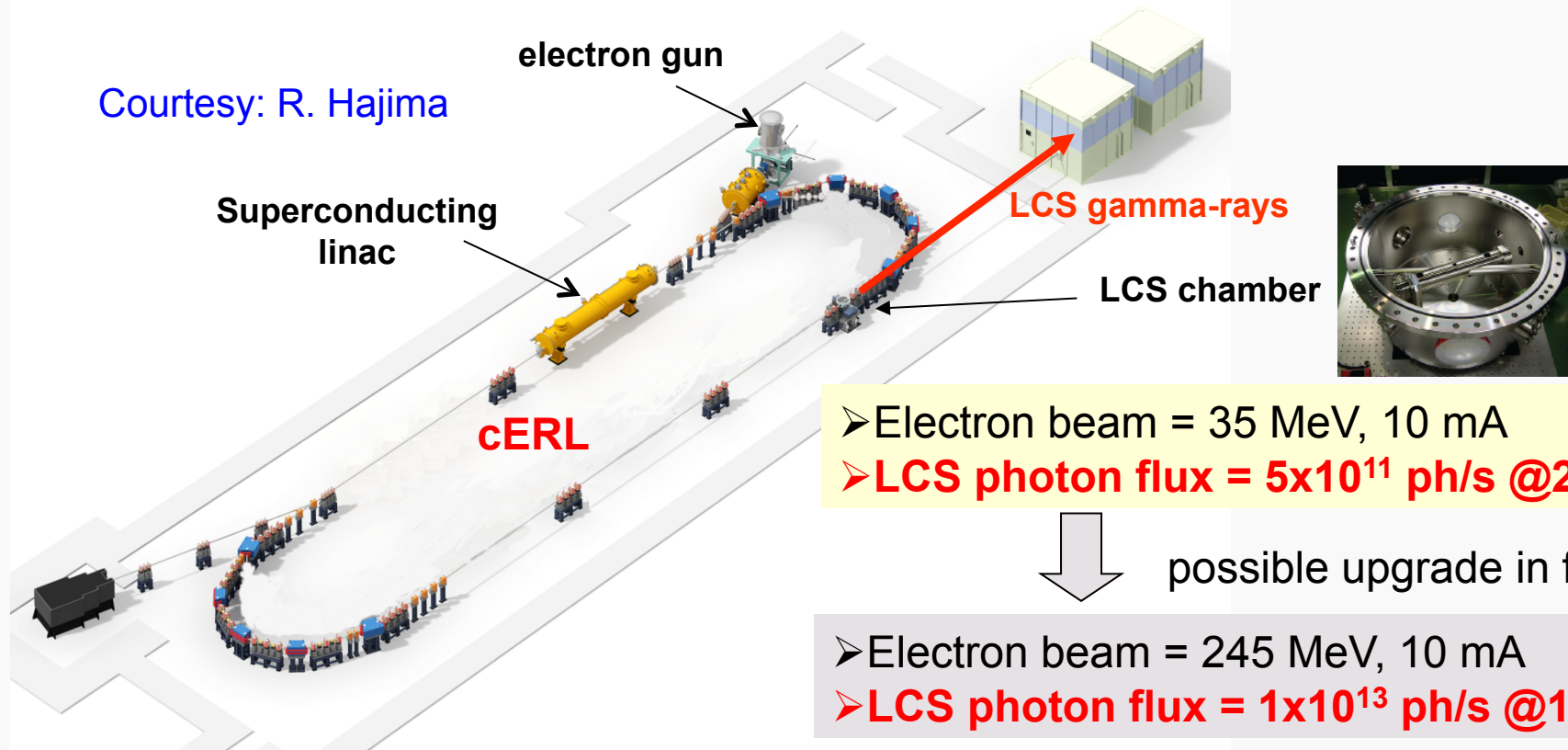
M. Shimada et al., MOPP019

Laser Compton Scattering Experiment

Nondestructive measurement of isotopes by LCS γ -rays at the cERL

3-year R&D program of JAEA was funded from MEXT (FY2011-2013).

Courtesy: R. Hajima



Lattice and optics of the LCS section is being designed.
A laser system including a laser cavity is being developed.

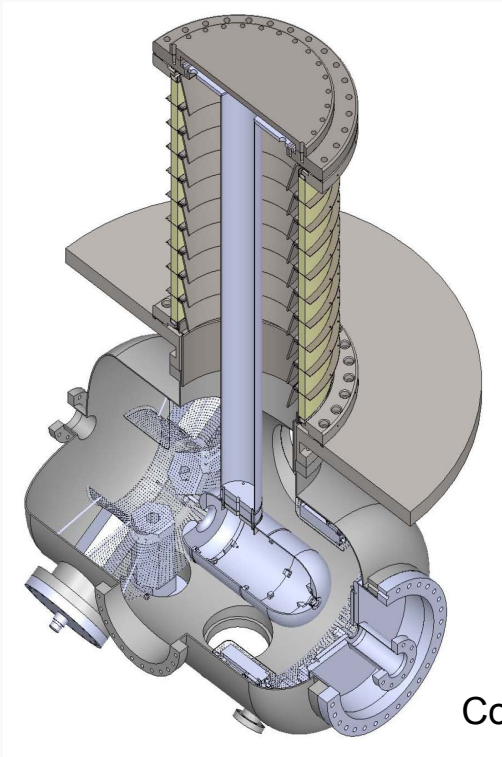
Photocathode DC Gun #1 at JAEA

8-hour operation at 510 kV with a segmented ceramic insulator

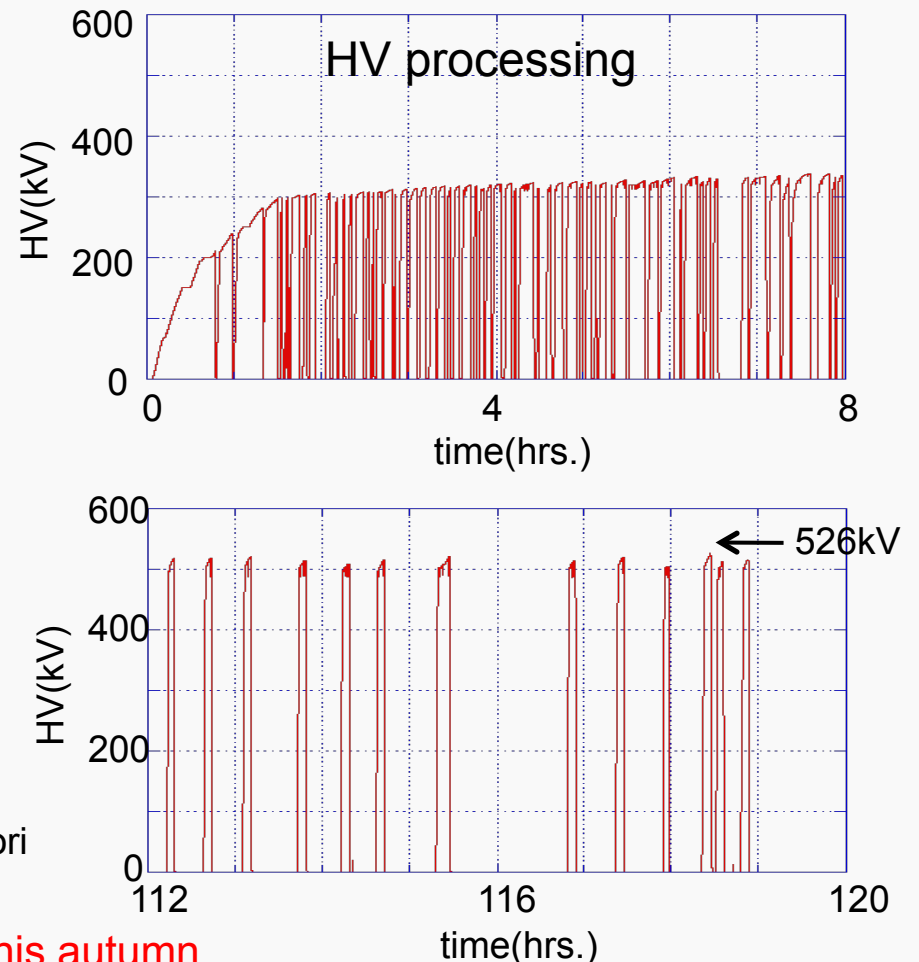
R. Nagai et al., Rev. Sci. Instrum. **81** (2009) 033304

HV processing with cathode electrode and NEG pumps in place

- HV processing up to 526 kV
- Local radiation problem needs to be solved



Courtesy: N. Nishimori



Scheduled to be installed in the cERL beamline this autumn

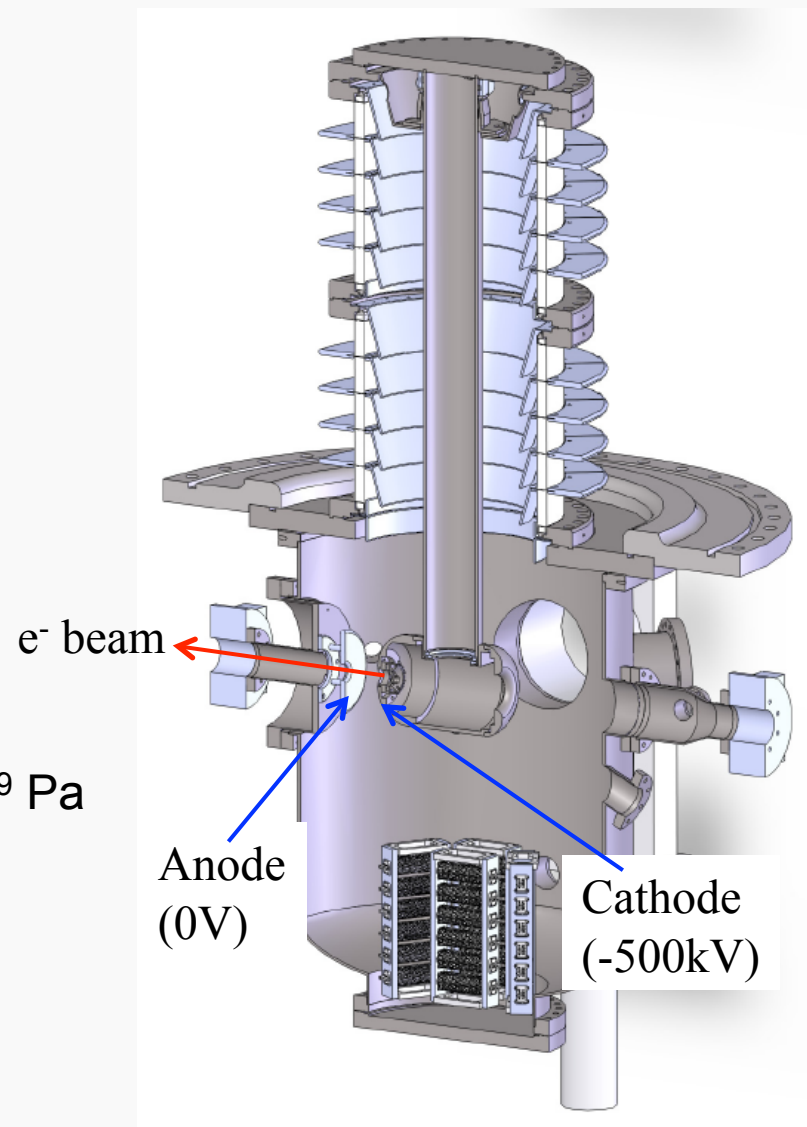
Photocathode DC Gun #2 at KEK

Courtesy: M. Yamamoto

Target pressure : 1×10^{-10} Pa

(to preserve the NEA state on the cathode)

- High voltage insulator
 - Segmented structure
 - Special Al_2O_3 material (TA010, Kyocera)
- Low outgassing system
 - Titanium chamber, electrode, guard rings
 - Total outgassing rate: $\sim 1 \times 10^{-10} \text{ Pa} \cdot \text{m}^3/\text{s}$
(actual measurement)
- Main vacuum pump system
 - 4K Bakeable cryopump
 - > 1000 L/s, for CH_4 , N_2 , CO , CO_2 @ 1×10^{-9} Pa
(actual measurement)
 - NEG pump
 - > 1×10^4 L/s, for H_2 (design value)
- 600-kV HV Power Supply system



Laser System

Laser system

- 1.3GHz Nd:YVO4 oscillator
- Yb photonic-crystal-fiber amplifier
- SHG with an external cavity
- Shaping system

Specifications

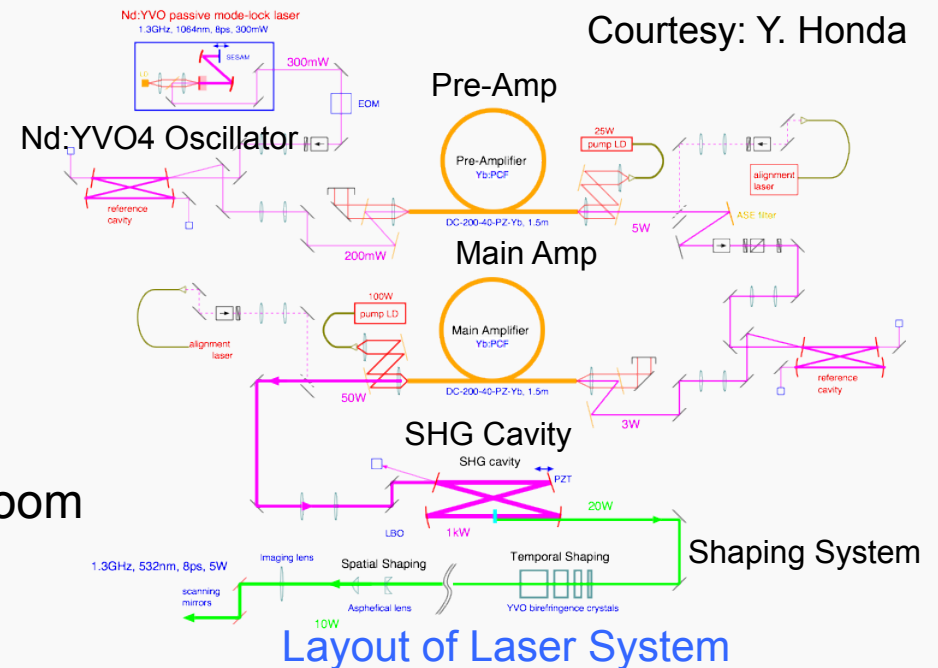
- 532 nm, 2.3 W on cathode for 10 mA
→ 5W(532nm), 25W(1064nm) at laser room
- 32 ps pulse duration
→ stacking of eight 8-ps pulses

Achievements

- 38 W(1064 nm) at 1.3 GHz
with a 1-stage fiber amplifier
- 70 W(1064 nm) at 1.3 GHz
with a 2-stage fiber amplifier
- SH generation and pulse stacking

Operation of 10 mA or more is promising.

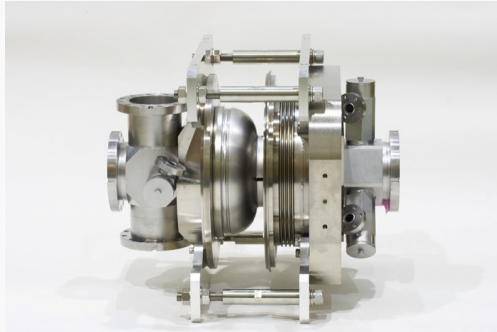
Y. Honda, TUPPD056



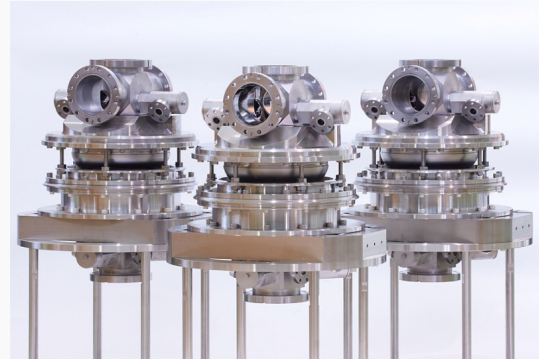
Yb Fiber Amplifier System

SC Cavities for Injector (1)

Courtesy: E. Kako, K. Watanabe



2-cell cavity

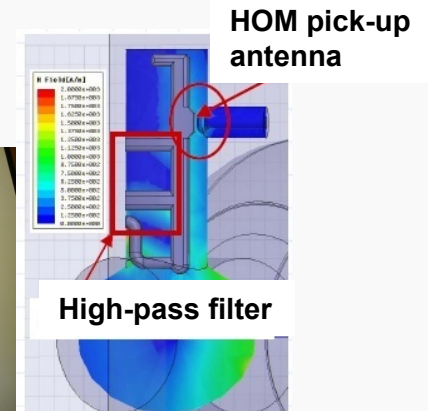


Cavities for cryomodule

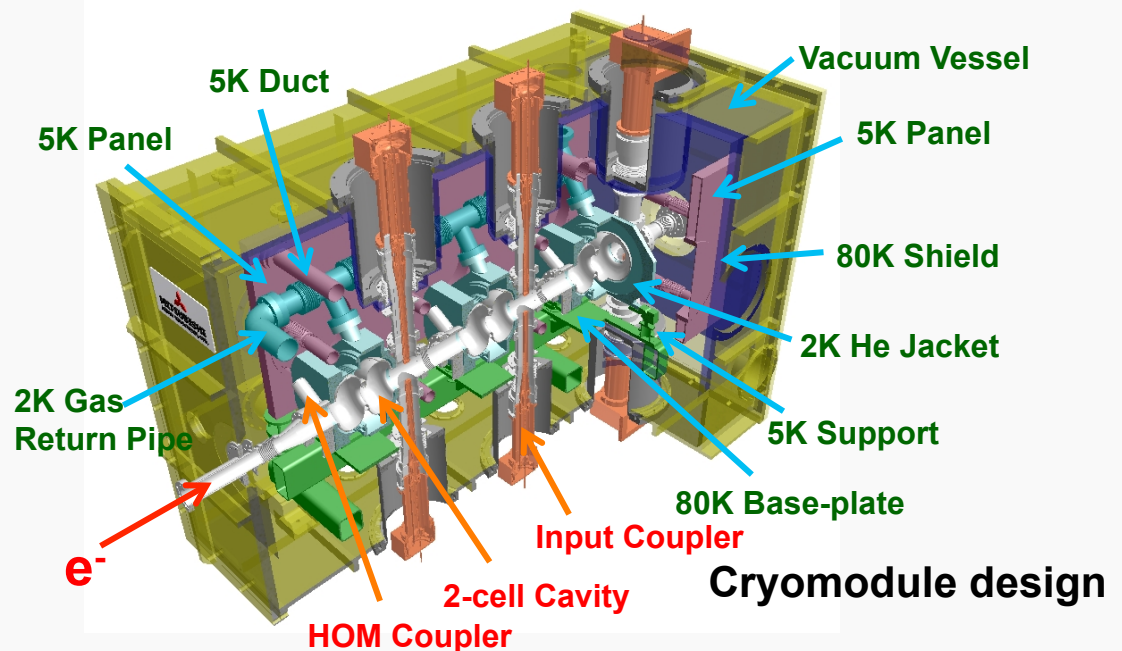
All HOM couplers are loop-type



HOM-couplers and their structure

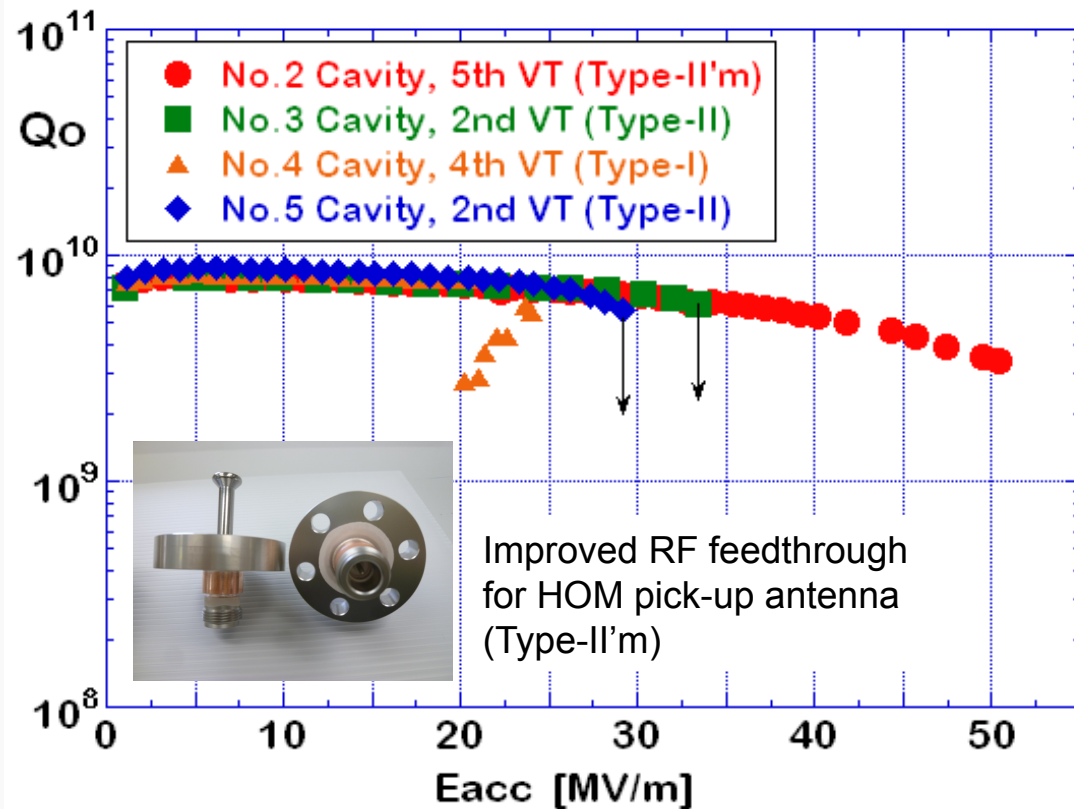


Input couplers



SC Cavities for Injector (2)

Results of Final Vertical Tests

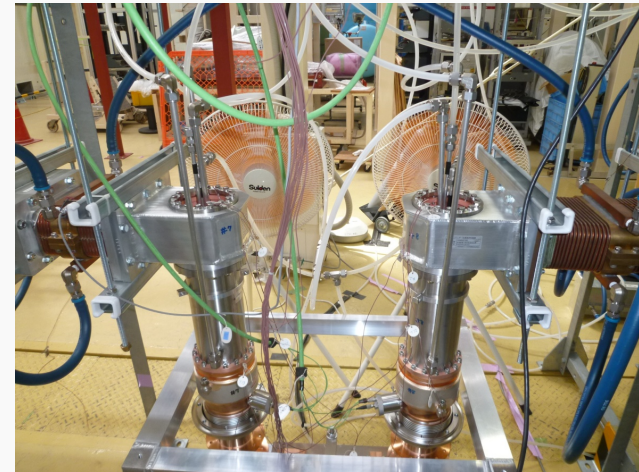


Improved RF feedthroughs in HOM couplers increased accelerating gradient (cERL specification: $E_{acc} > 11$ MV/m).

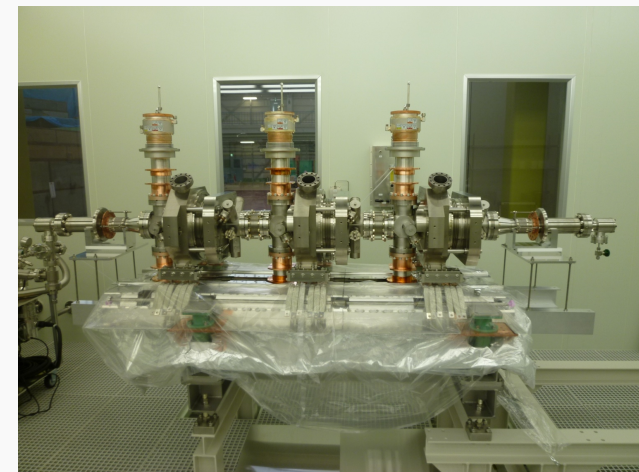
All the RF feedthroughs were replaced by Type-II'm.

Please see E. Kako et al., WEPPC012, WEPPC015 for details.

Courtesy: E. Kako



RF conditioning of input couplers

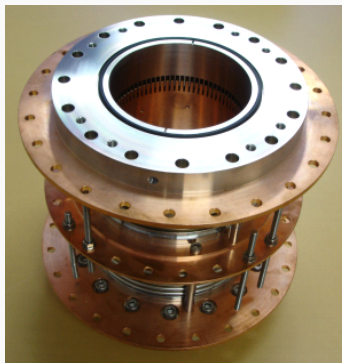


Assembly of cryomodule

SC Cavities for Main Linac (1)

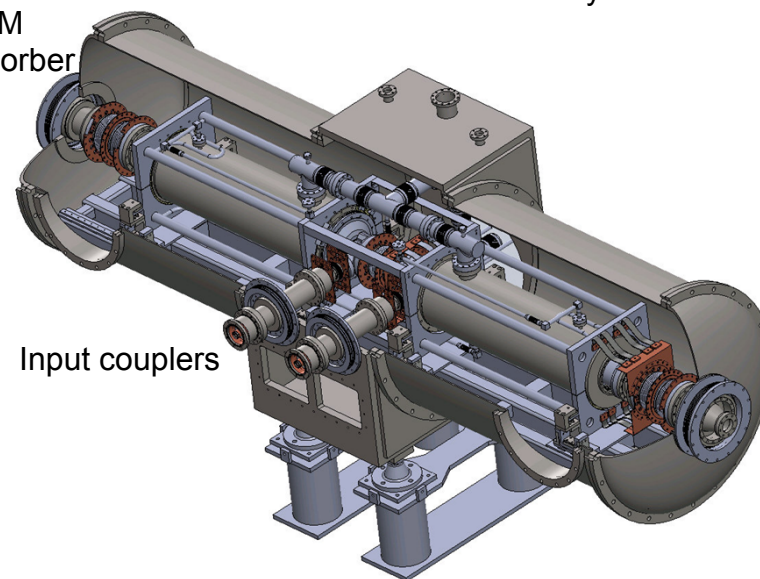


9-cell Cavities



HOM Absorber

HOM
absorber

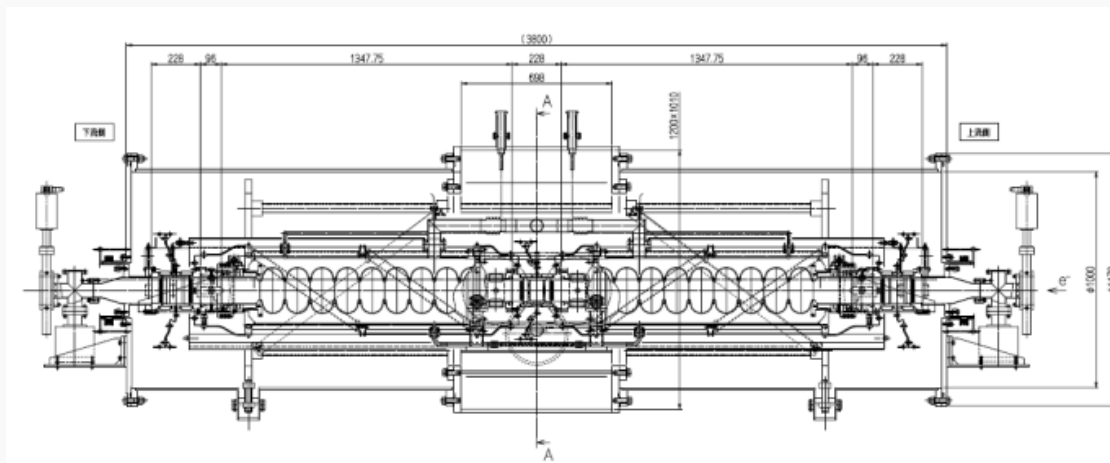


Input couplers

Cryomodule design



Input coupler



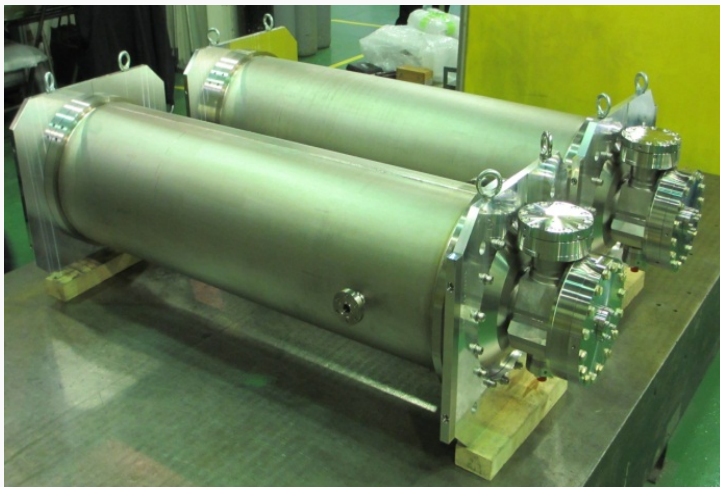
Cryomodule design (side view)

Courtesy: K. Umemori

SC Cavities for Main Linac (2)

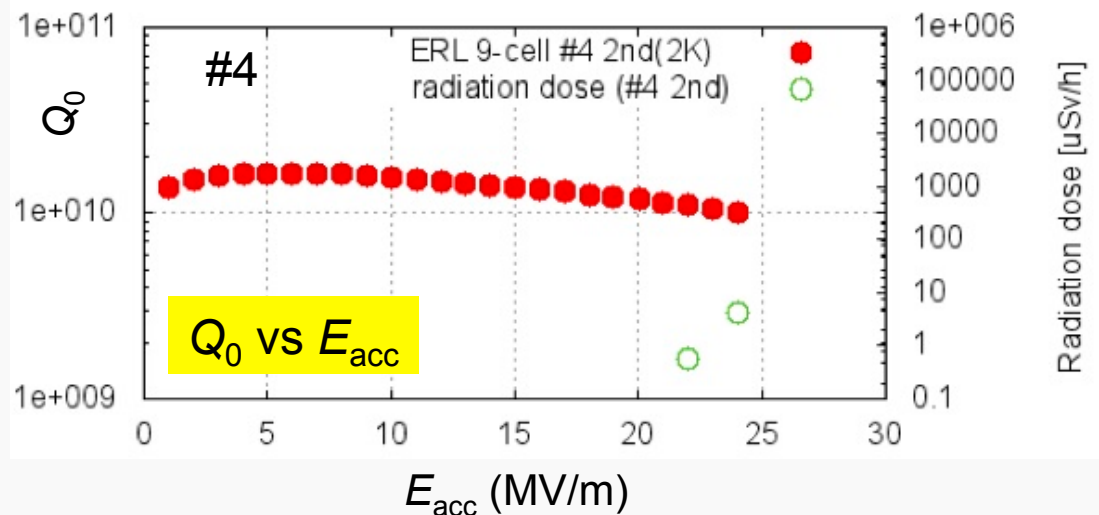
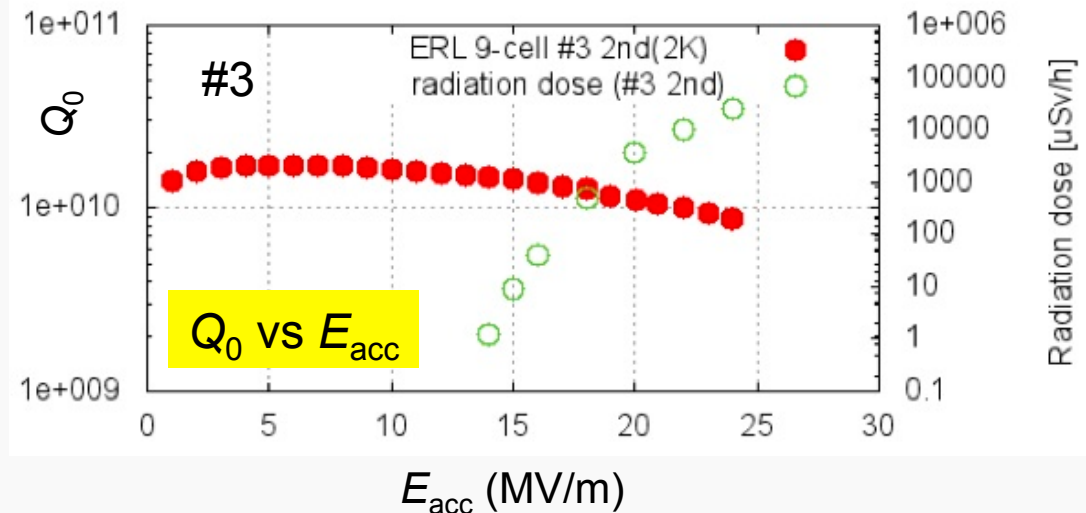
Results of final vertical tests

- E_{acc} of higher than 25 MV/m could be achieved in both cavities.
- Cavities satisfied cERL specification ($Q_0 > 10^{10}$ at 15 MV/m)
- Onsets of X-ray were 14 MV/m and 22 MV/m for the cavities #3 and #4, respectively.



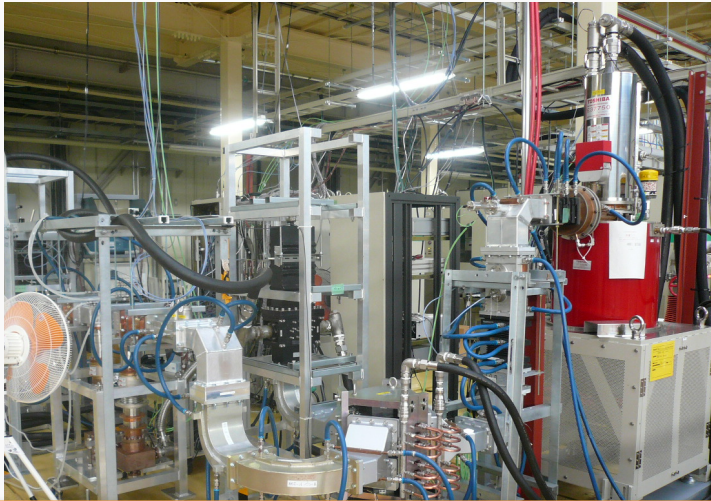
- Cavities are dressed with Helium jackets and waiting for installation into cryomodule.

Courtesy: K. Umemori

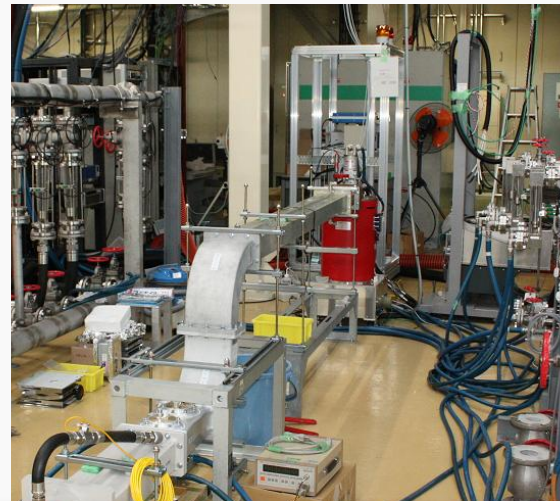


K. Umemori et al., MOOBC02, WEPPC011

1.3 GHz CW RF Sources



300kW CW Klystron for injector SCC



30kW CW Klystron for injector SCC



30kW CW IOT for main SCC

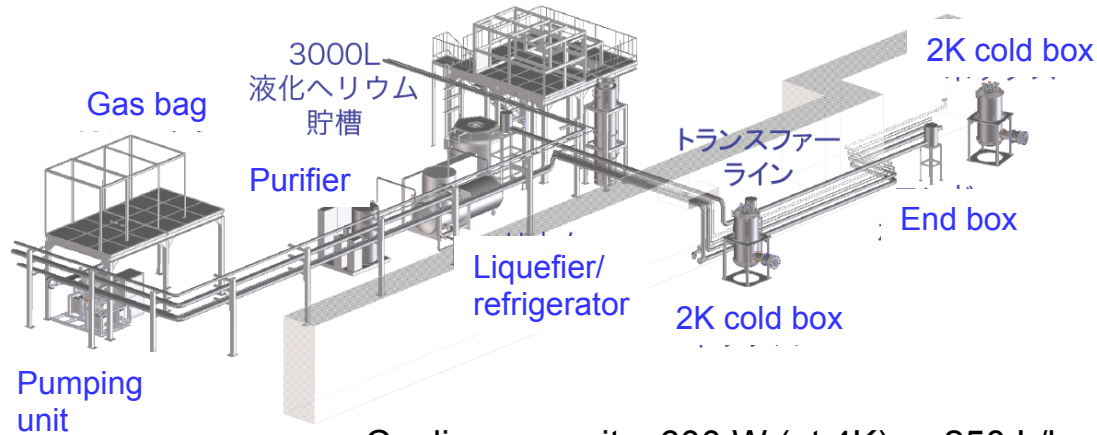
Courtesy: T. Miura



20kW CW IOT for buncher

Liquid-Helium Refrigerator

Overview of the system



Cooling capacity: 600 W (at 4K) or 250 L/h

Courtesy: H. Nakai



3000L liquefied helium storage vessel



2K cold box and end box



TCF200 helium liquefier/refrigerator

Magnet/Vacuum/Monitor

Courtesy: K. Harada, Y. Tanimoto, T. Honda, T. Obina, R. Takai



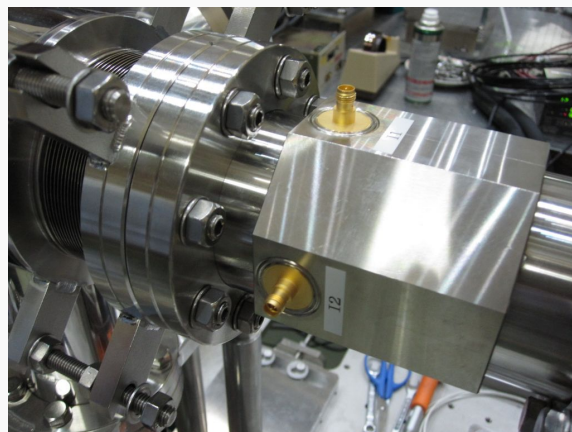
Bending magnet



Quadrupole magnet



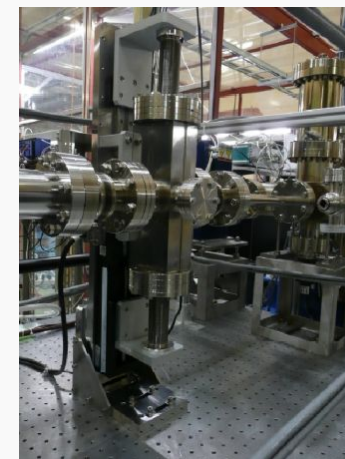
Zero-gap Flange



**Stripline BPM
with glass-type feedthrough**



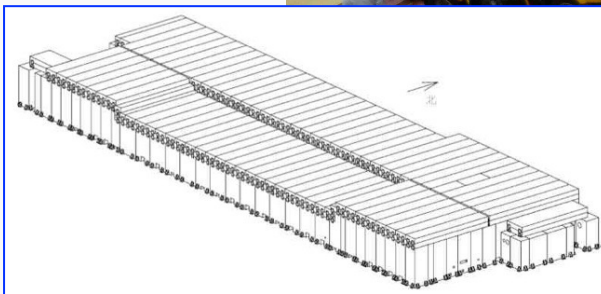
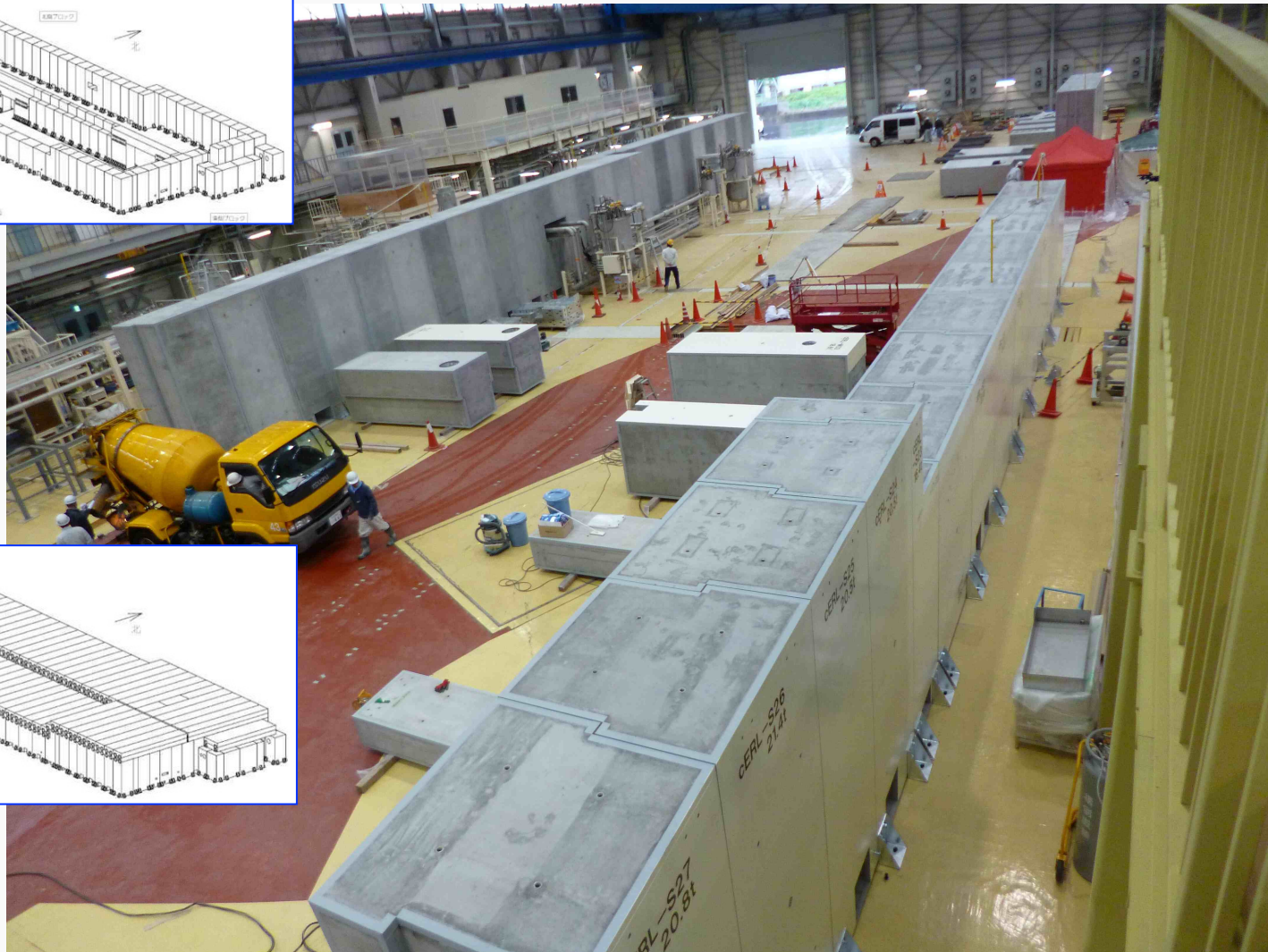
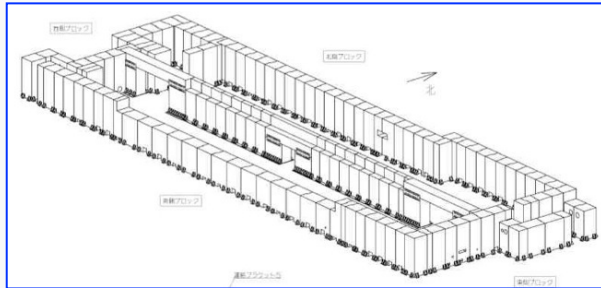
Screen monitor



**Slit for emittance
measurement**

Radiation Shield for cERL

Courtesy: K. Haga

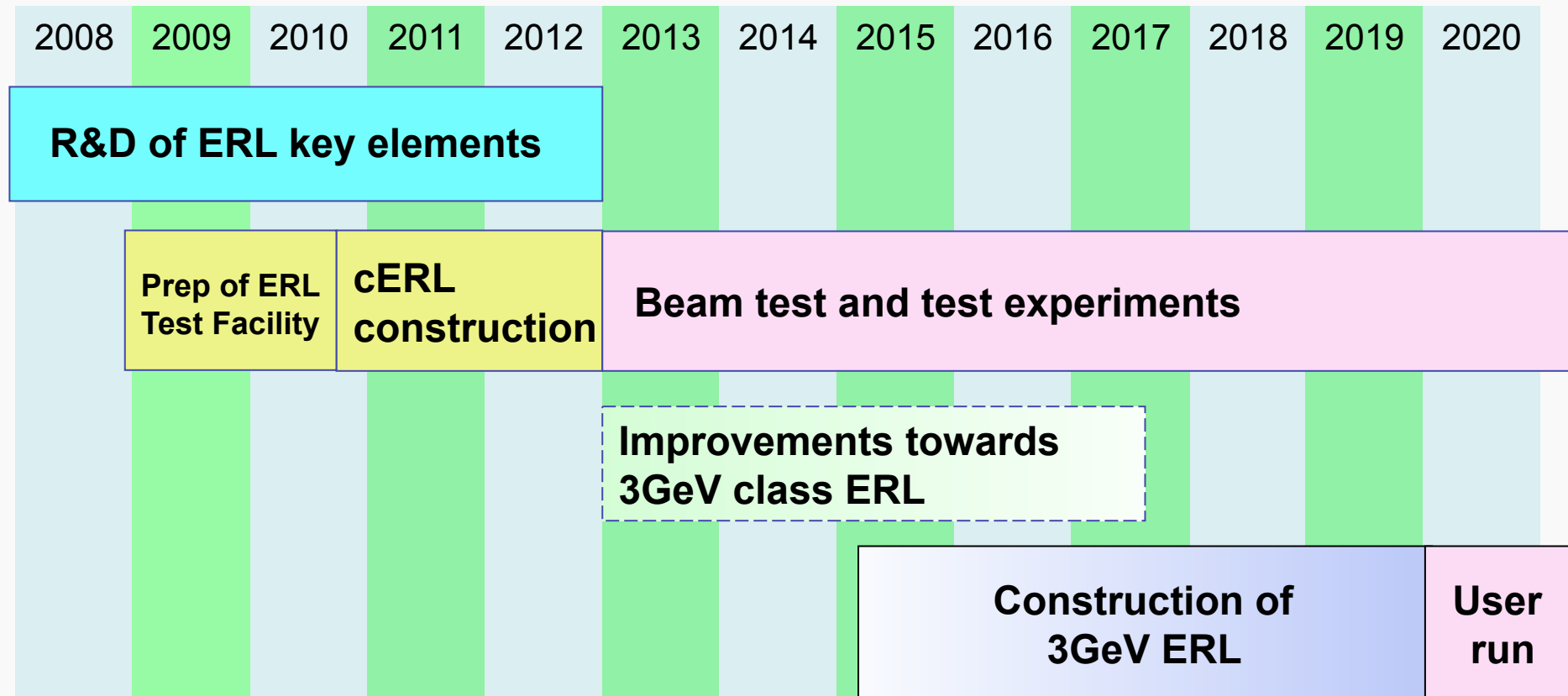


Construction of the radiation shield is on going and will be completed this autumn.

Road Map of ERL Projects

Courtesy: H. Kawata

Japanese Fiscal Year (from April to March)



↑
Present time

ERL Projects around the World

Jefferson Lab

Beam Parameters	Specification	Achieved
Energy [MeV]	145	160
Peak Current [A]	240	400
σ_t [ps] at wiggler	0.20	0.13
$\sigma_{\Delta E}$ [%] at wiggler	0.4	0.3
$\varepsilon_{x,y}$ (rms) [mm-mrad]	30	7
ε_z (rms) [keV-ps]	65	80

- **IR FEL**
 - High power FEL (>10kW)
 - Beam dynamics studies
- **UV FEL**
 - High gain near 700 and 400 nm
 - 3rd harmonics at 10eV
- **THz source**

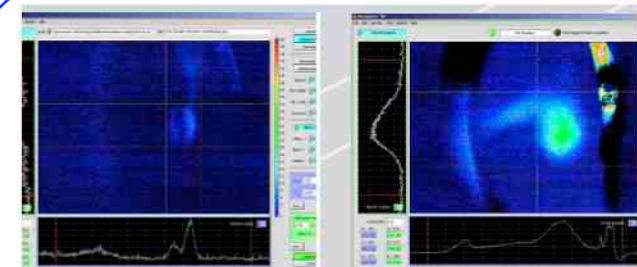
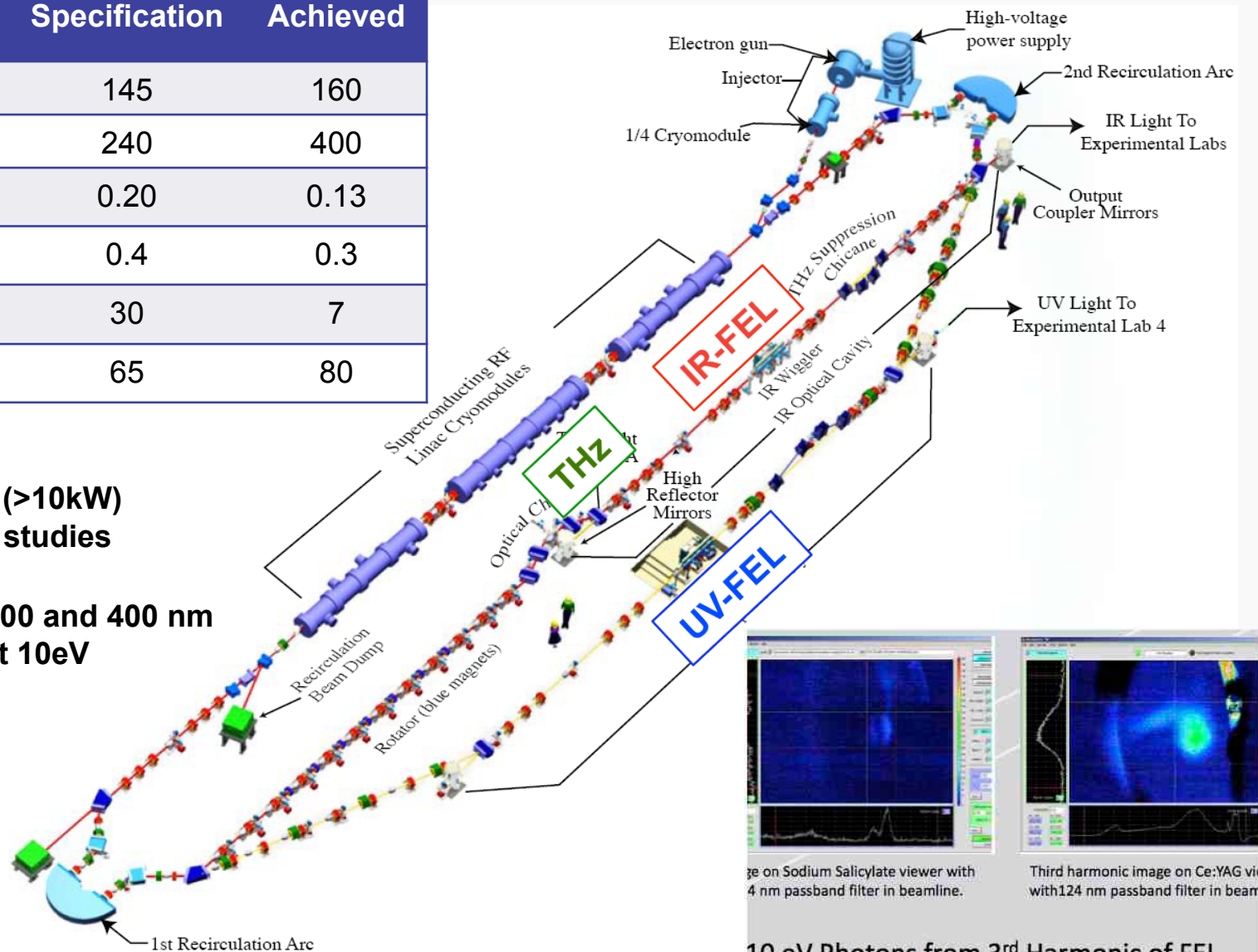
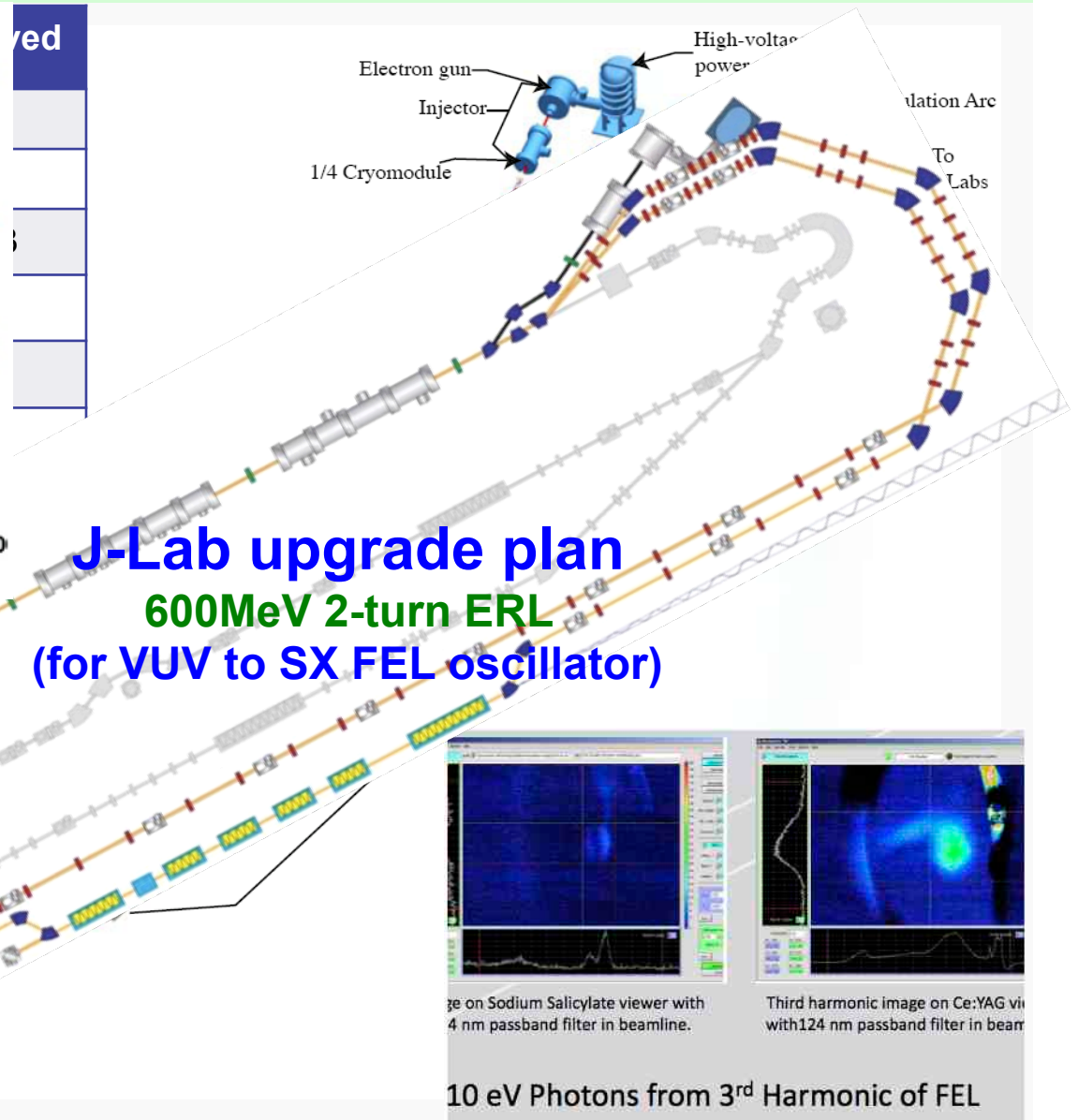
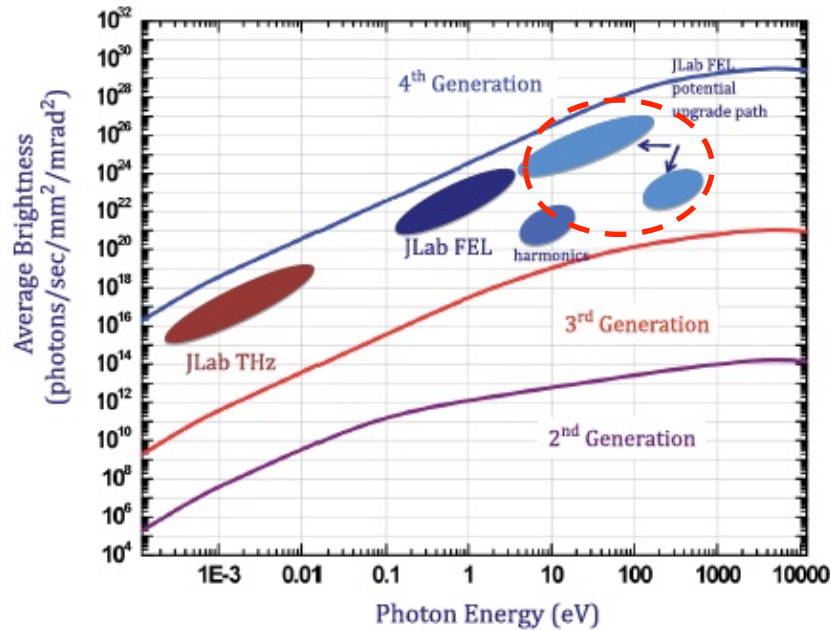


Image on Sodium Salicylate viewer with 4 nm passband filter in beamline. Third harmonic image on Ce:YAG viewer with 124 nm passband filter in beamline.

10 eV Photons from 3rd Harmonic of FEL

Jefferson Lab



- Beam dynamics studies
- UV FEL
- High gain n
- 3rd har
- THz

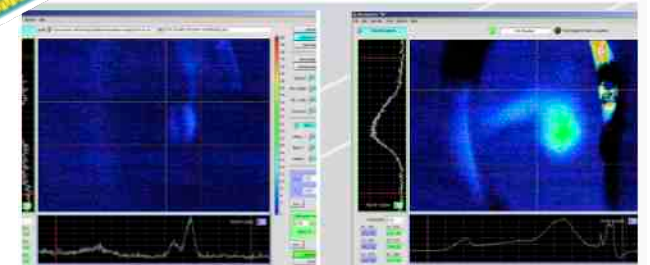


Image on Sodium Salicylate viewer with 4 nm passband filter in beamline. Third harmonic image on Ce:YAG viewer with 124 nm passband filter in beamline.

10 eV Photons from 3rd Harmonic of FEL

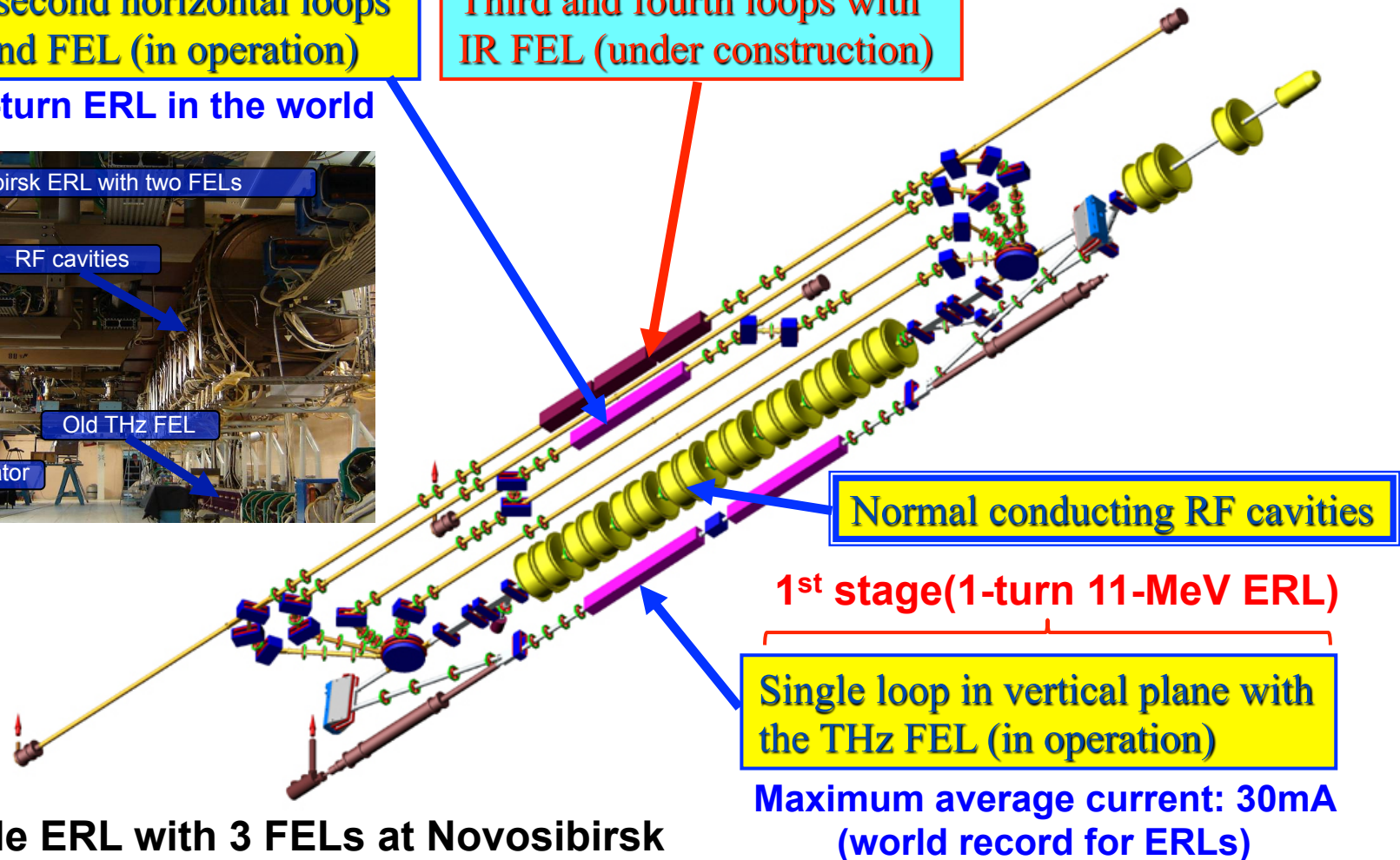
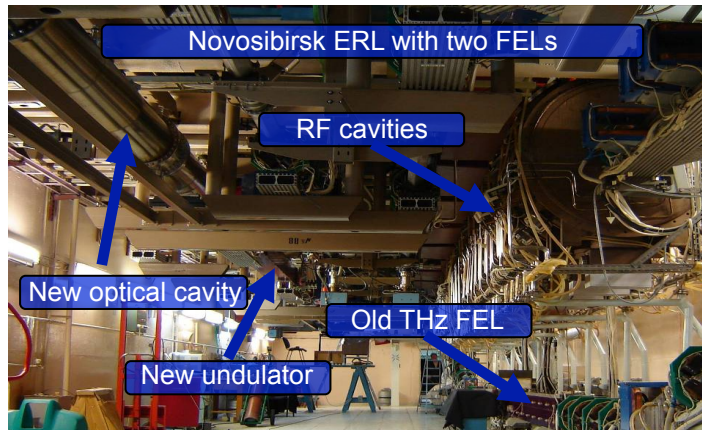
BINP

2nd stage(4-turn 40-MeV ERL)

First and second horizontal loops with second FEL (in operation)

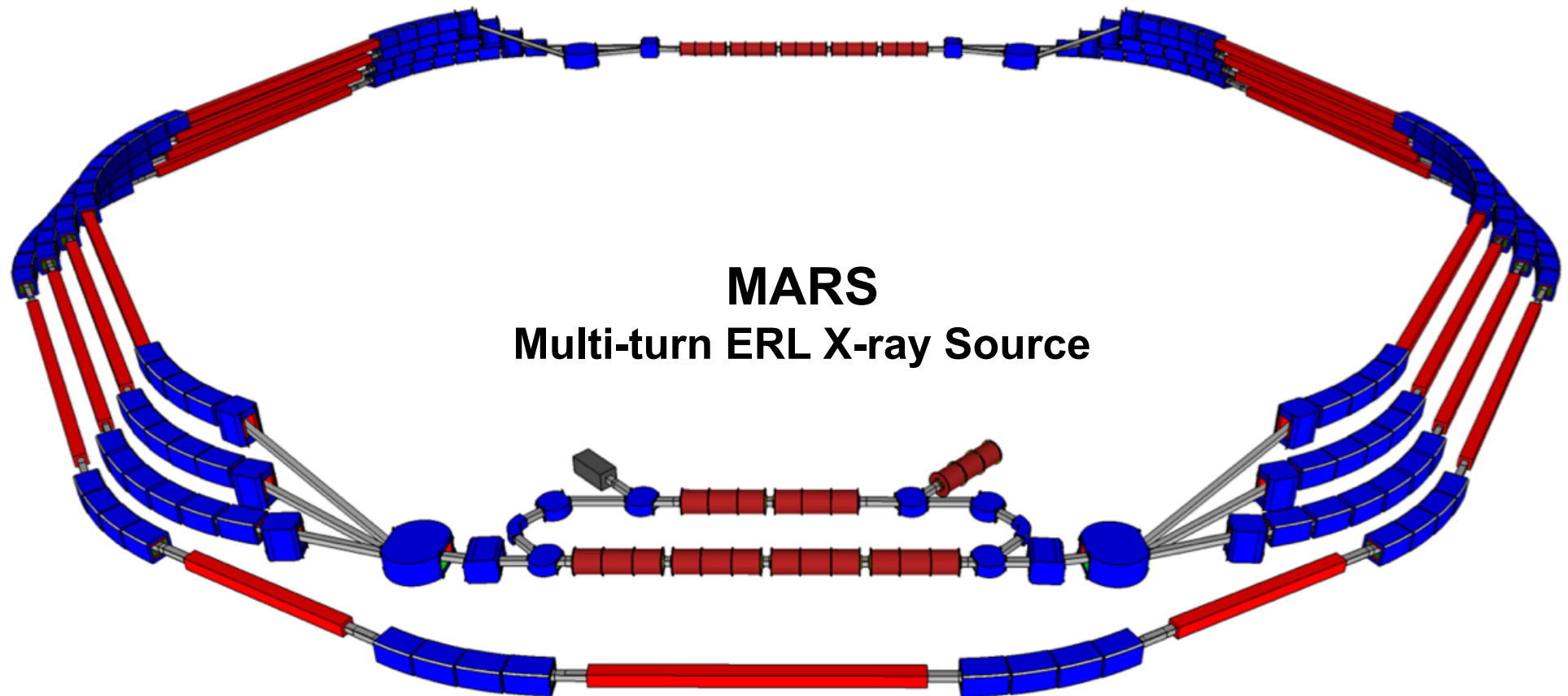
First multi-turn ERL in the world

Third and fourth loops with IR FEL (under construction)

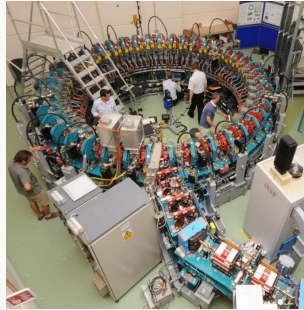


Full-scale ERL with 3 FELs at Novosibirsk

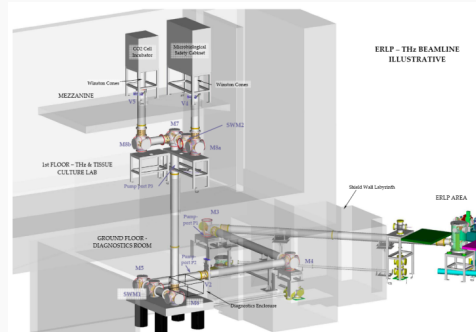
BINP



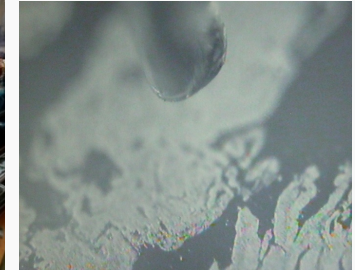
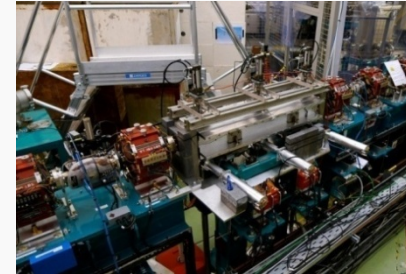
ALICE @ Daresbury Laboratory



EMMA(first NS-FFAG)



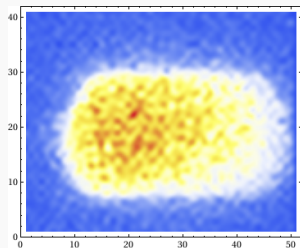
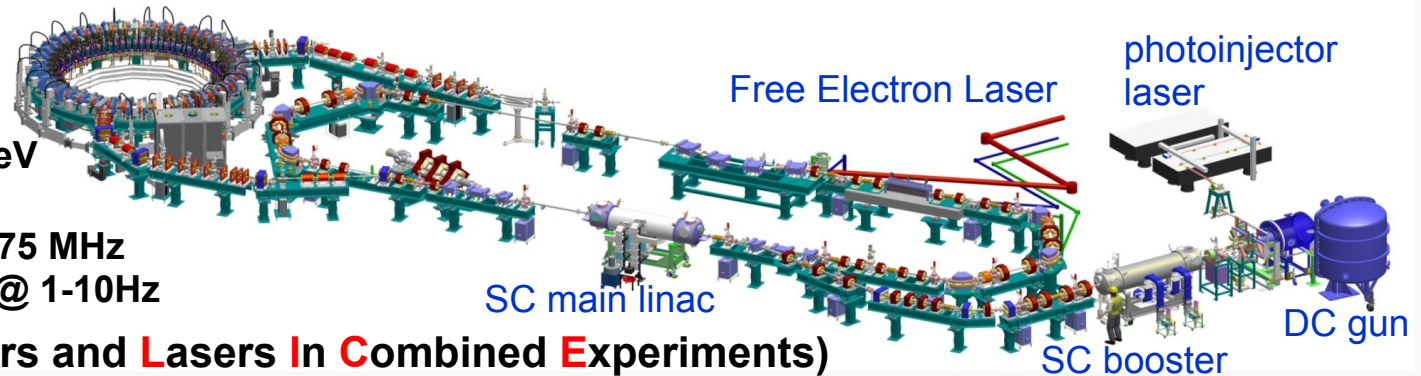
THz for biology



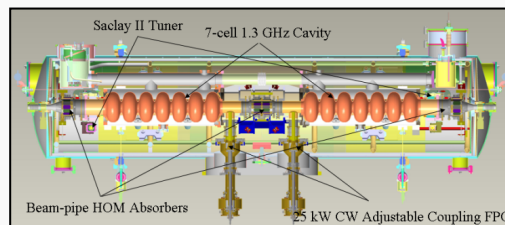
IR FEL & SNOM experiment
(5.7-8um, ~3MW peak power)

Energy: up to 27.5 MeV
Bunch : up to 100 pC
Repetition : up to 81.75 MHz
Bunch train : 100 μ s @ 1-10Hz

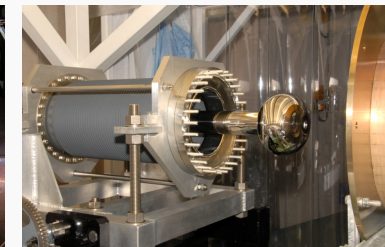
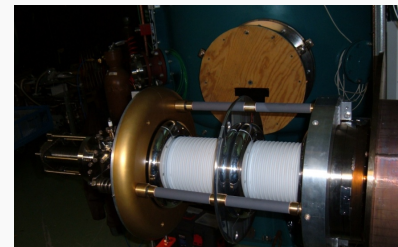
ALICE (Accelerators and Lasers In Combined Experiments)



Compton Scattering
X-ray generation



Development of SRF module

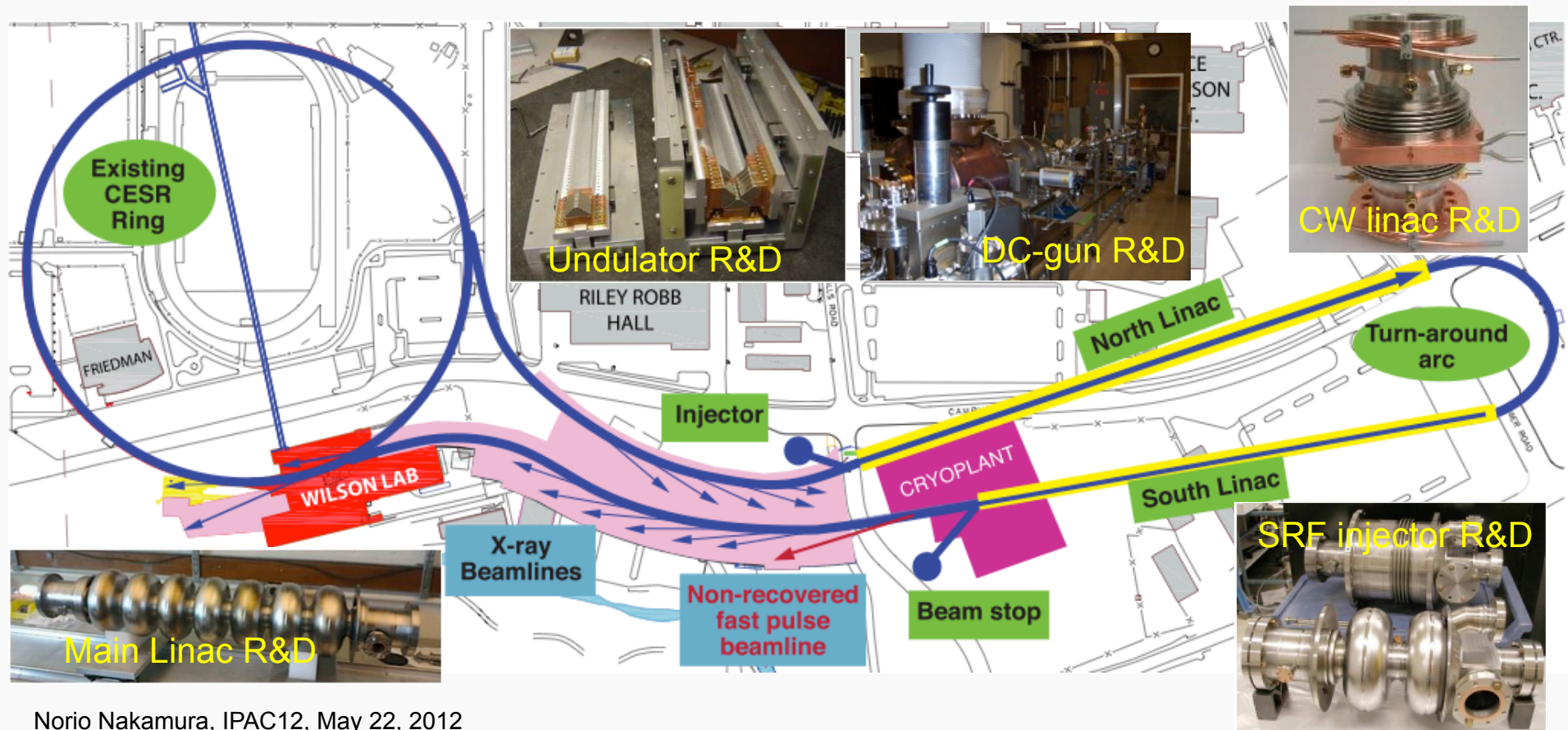


Gun Ceramic Change(230→325kV)

5-GeV ERL @ Cornell University

Cornell ERL Project

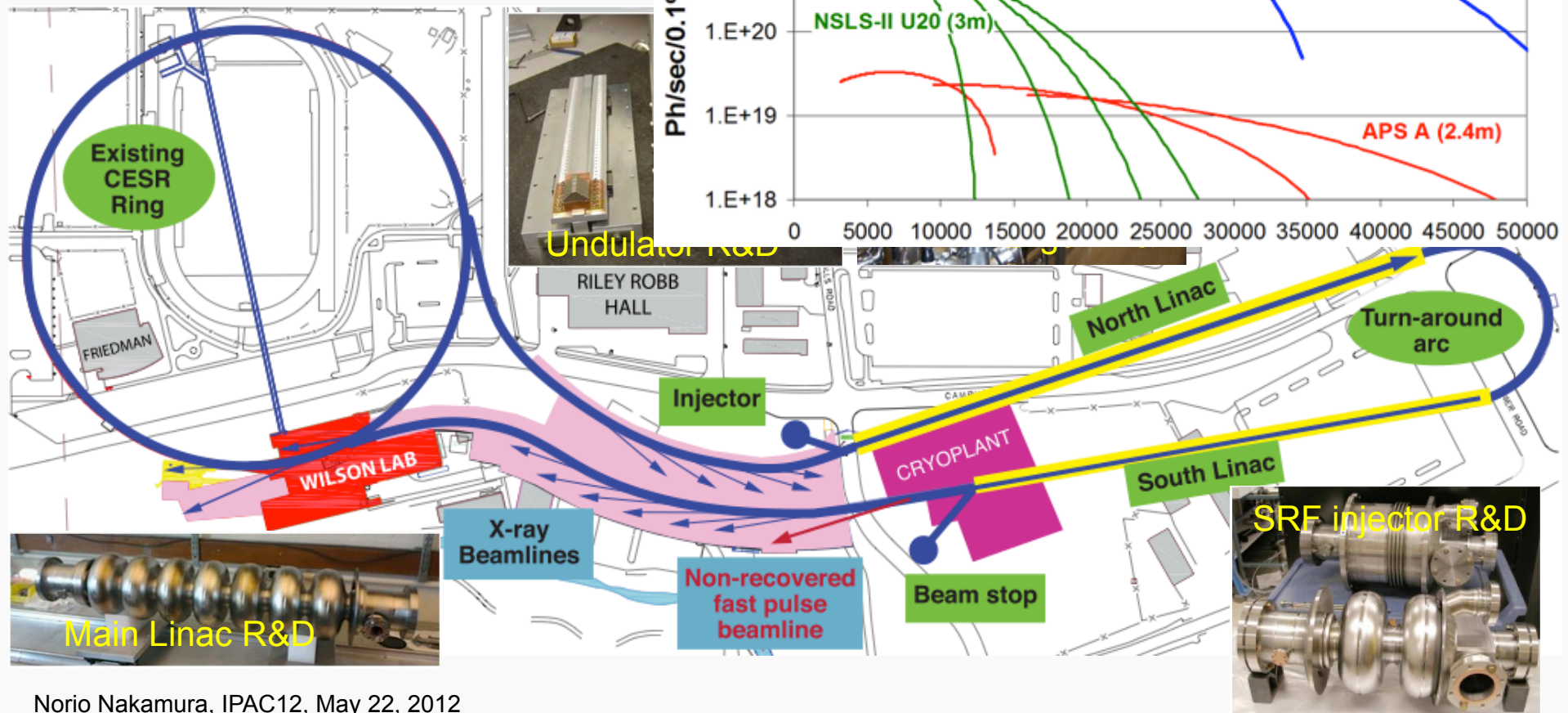
- 5-GeV ERL light source as extension of CHESS
- R&D for realizing the ERL X-ray source
- PDDR(Project Design Definition Report) ready for submission



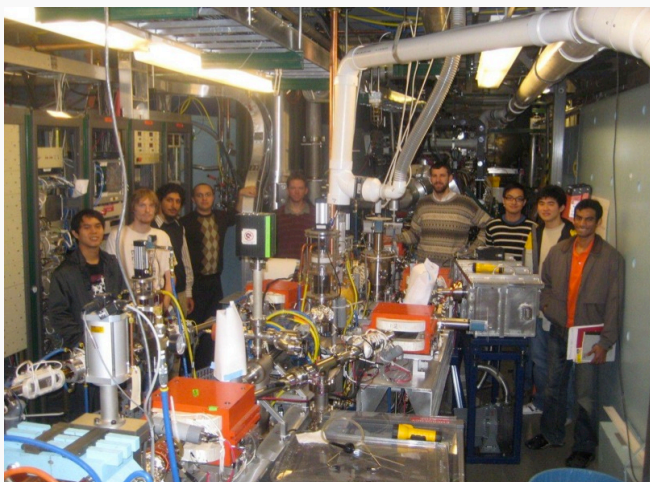
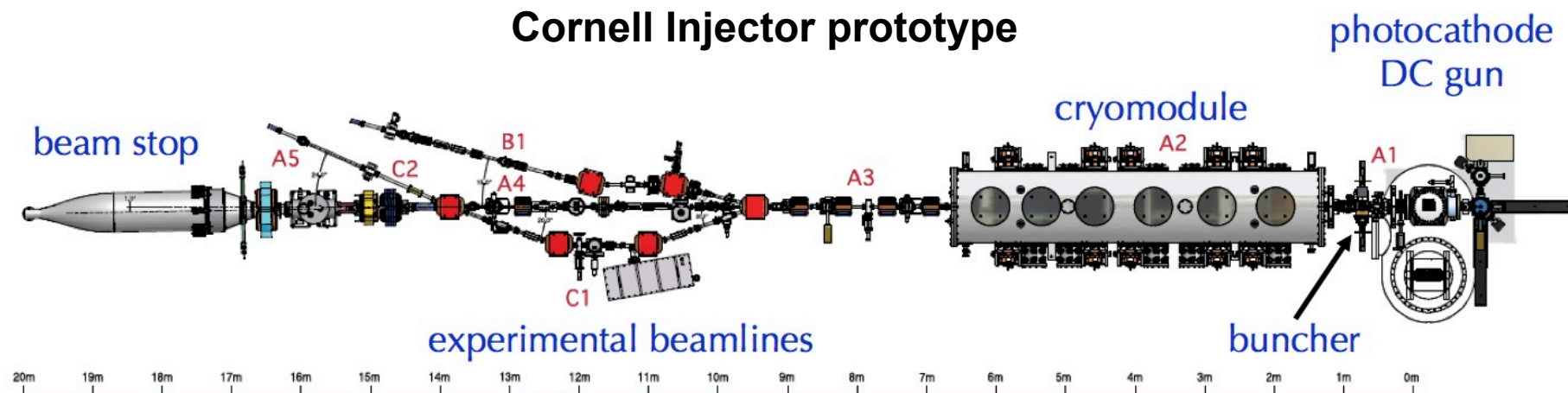
5-GeV ERL @ Cornell University

Cornell ERL Project

- 5-GeV ERL light source as e
- R&D for realizing the ERL X-
- PDDR(Project Design Definit



Injector Prototype @ Cornell University



Achievements:

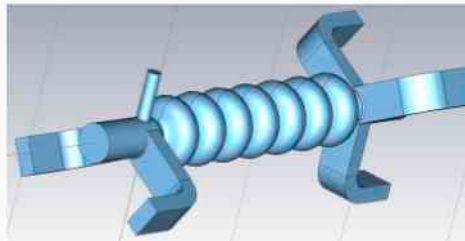
- 1) Max. DC-gun voltage: 440kV
- 2) Max. beam current: **52mA** with GaAs (world record for photocathode guns)
- 3) **8-hour** operation at **20mA** with CsK₂Sb
- 4) Min. norm. emittance at **80pC**: **0.7 mm·mrad** with core norm. emittance : **0.3 mm·mrad**
- 5) Largest injector-coupler power: 60kW
- 6) Largest SRF-cavity voltage: 13MV/m

Achieved beam sufficient for an ultra-bright X-Ray ERL

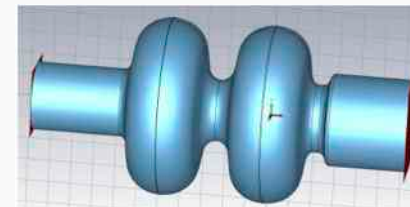
BERLinPro @ HZB

BERLinPro: Main Project Parameters

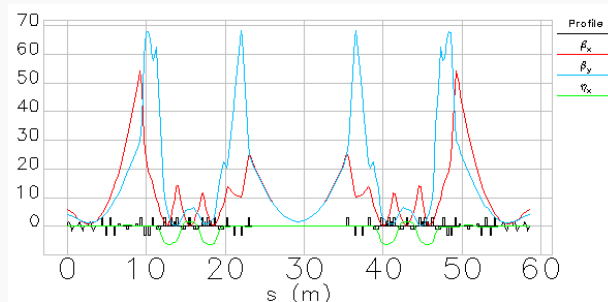
Beam kinetic energy	50 MeV
Max average current	100 mA
Bunch charge	77 pC
Emittance (norm.)	1.0 mm·mrad
Bunch repetition rate	1.3 GHz



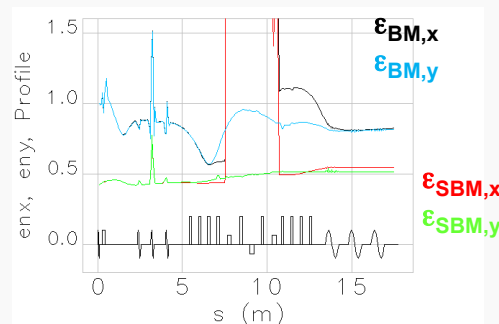
SC cavity for Main Linac



SC cavity for Injector

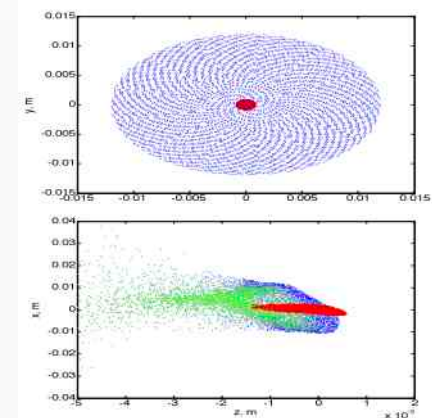


Optics for recirculation path



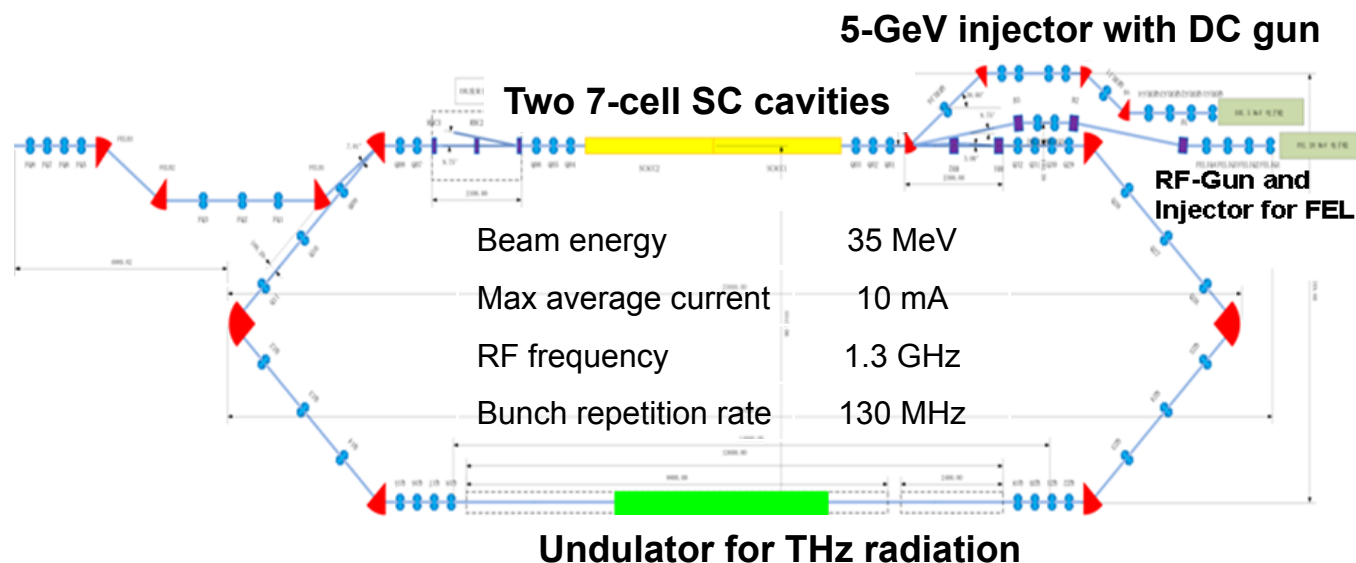
Injector optimization

Halo simulation

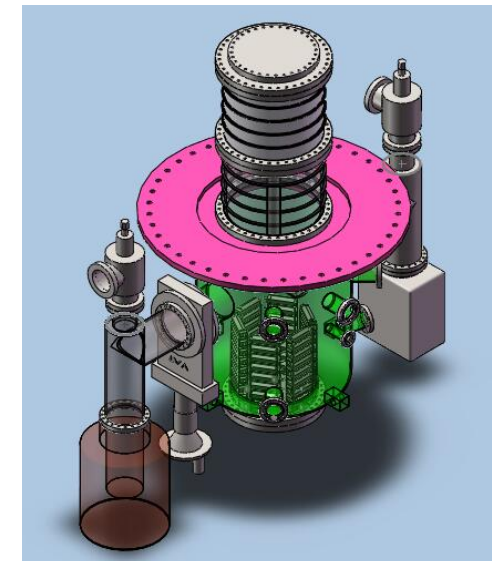


IHEP-Beijing

- 500 kV DC-gun (with GaAs cathode as the 1st test) design is completed, and is funded by IHEP's innovation program, its construction is started.
- The 1st 1.3 GHz 9-cell ILC type SC cavity (with large grain and low loss) has obtained 20 MV/m; the preliminary design of CW 7-cell cavity is done.
- The conceptual design of the 35MeV-10 mA TF is almost completed, and is in the further improvement.



Layout of the ERL-FEL Test Facility at IHEP

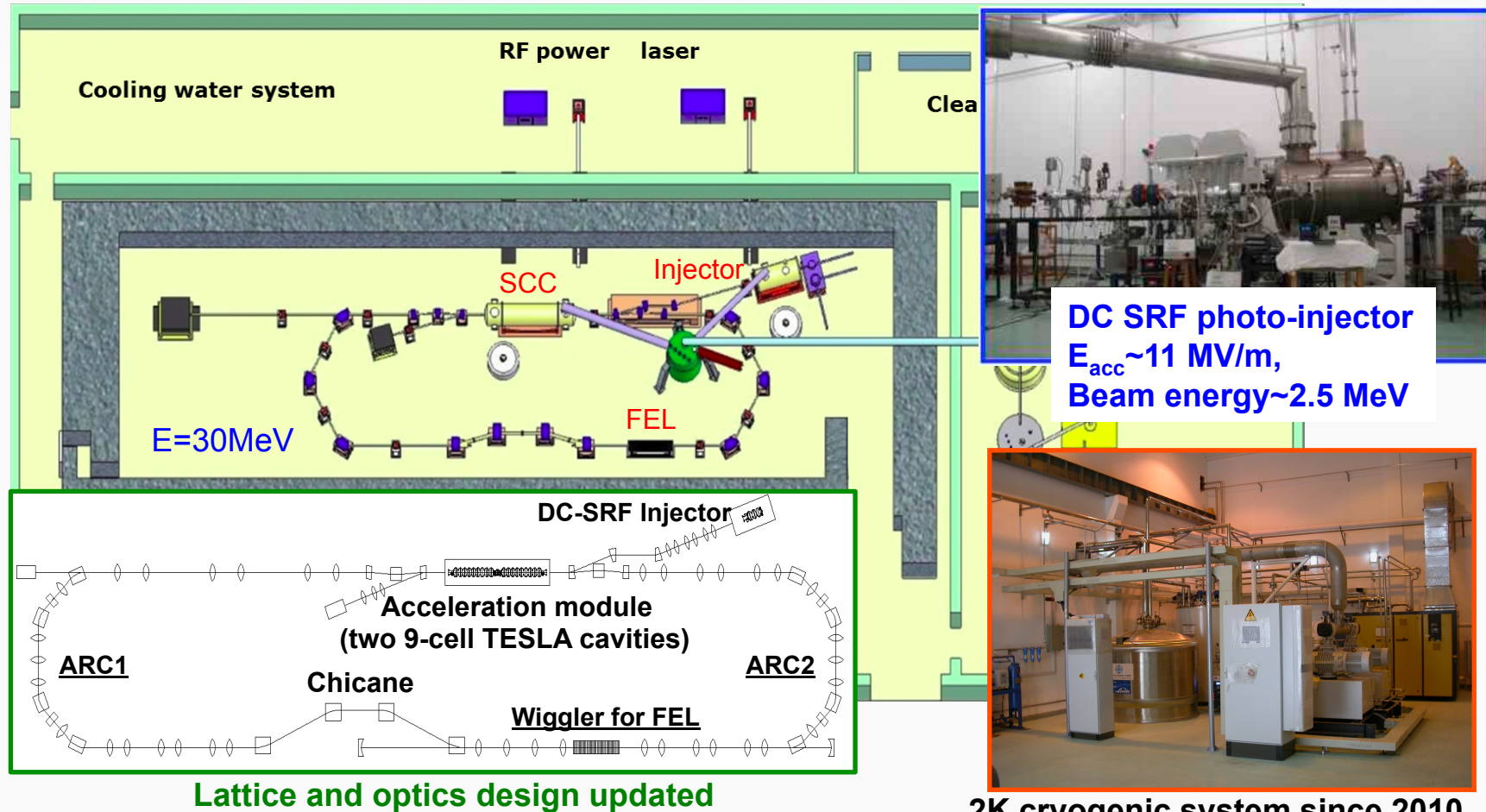


DC photocathode gun

Peking University

Plan view of Peking University Superconducting ERL Test Facility(PKU-SETF)

To demonstrate energy recovery, ERL-based FEL and radiation sources and ERL key technologies (DC SRF injector & Acceleration module)



eRHIC @ BNL

eRHIC (future electron-hadron collider at RHIC)

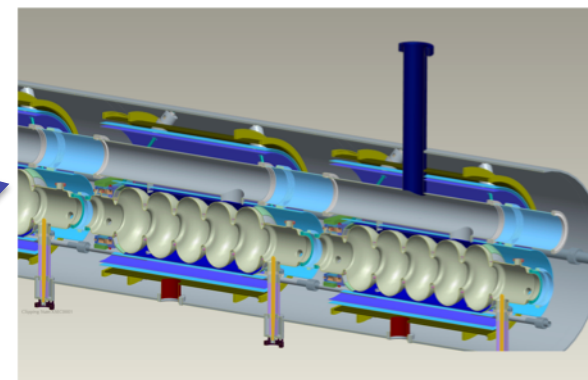
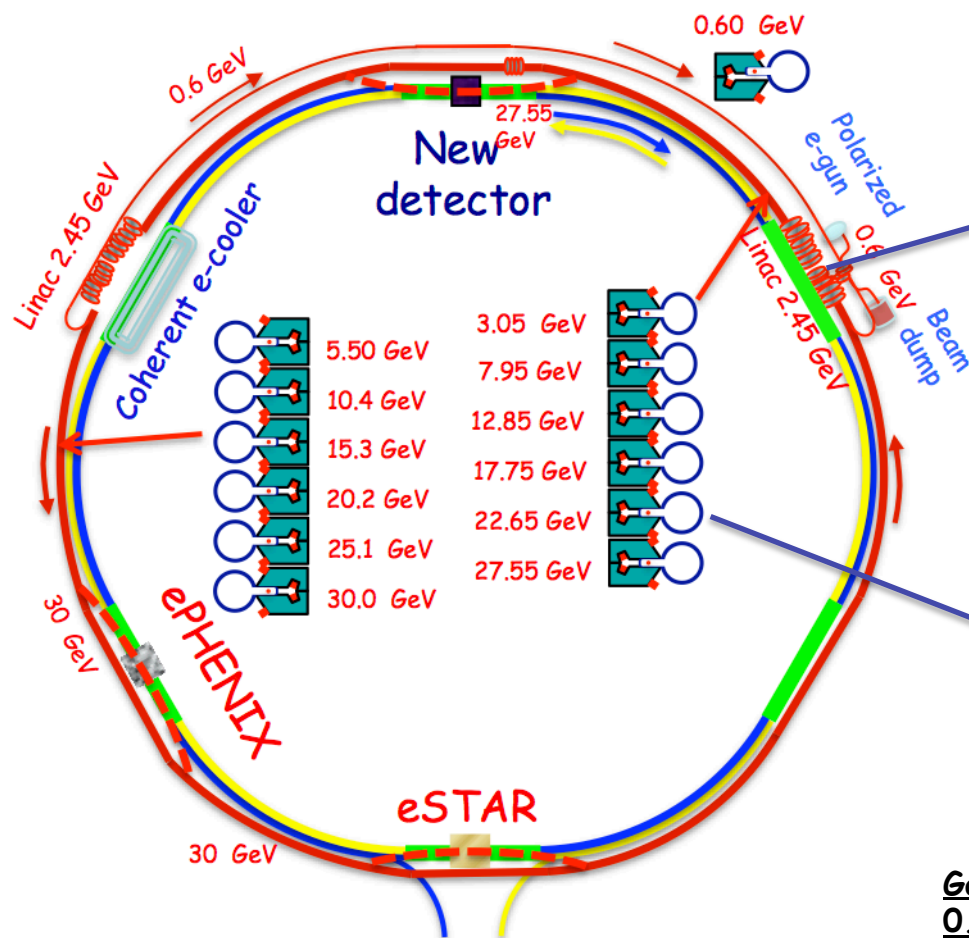
$E_{\text{max}} = 30 \text{ GeV}$ (electron), $L = 10^{33}\text{-}10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

6-turn ERL for acceleration/1-turn ERL for e-cooling

Total linac length : 200 m

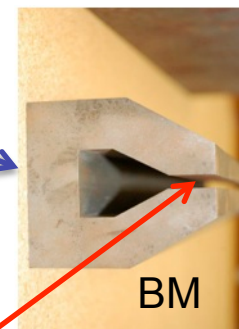
Max. energy gain per pass : 2.45 GeV

Accelerating gradient : 19.2 MV/m

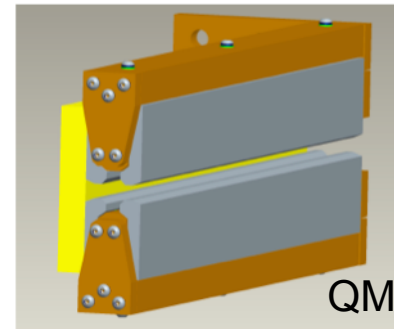


SRF Linac

More than 14000 magnets



BM



QM

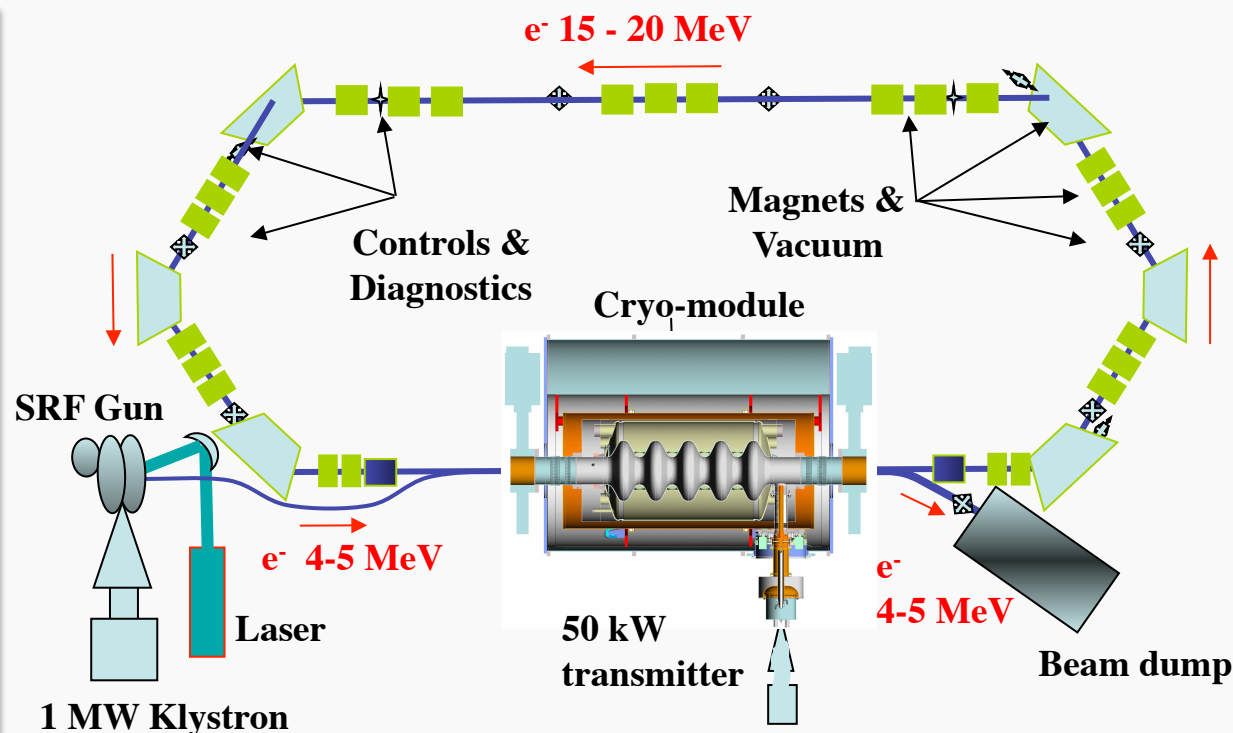
Gap 5 mm total
0.3 T for 30 GeV

Compact magnets

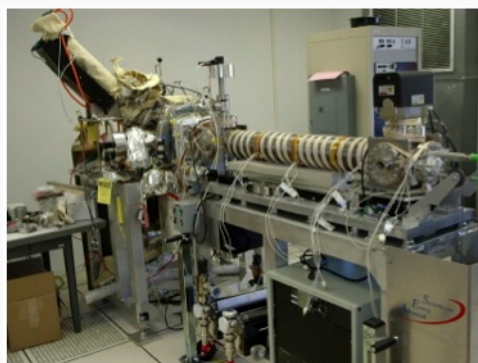
ERL Test Facility @ BNL

ERL Test Facility at BNL

- Max. energy : **20 MeV**
- Max. current : **0.5 A CW**
- 704 MHz **SRF gun**
- **704 MHz** 5-cell SC cavity
- Study items :
 - HOMs and BBU
 - Emittance growth
 - Halo
- First beam from **SRF gun** :
September 2012
- First **ERL** beam :
May 2013



SRF gun



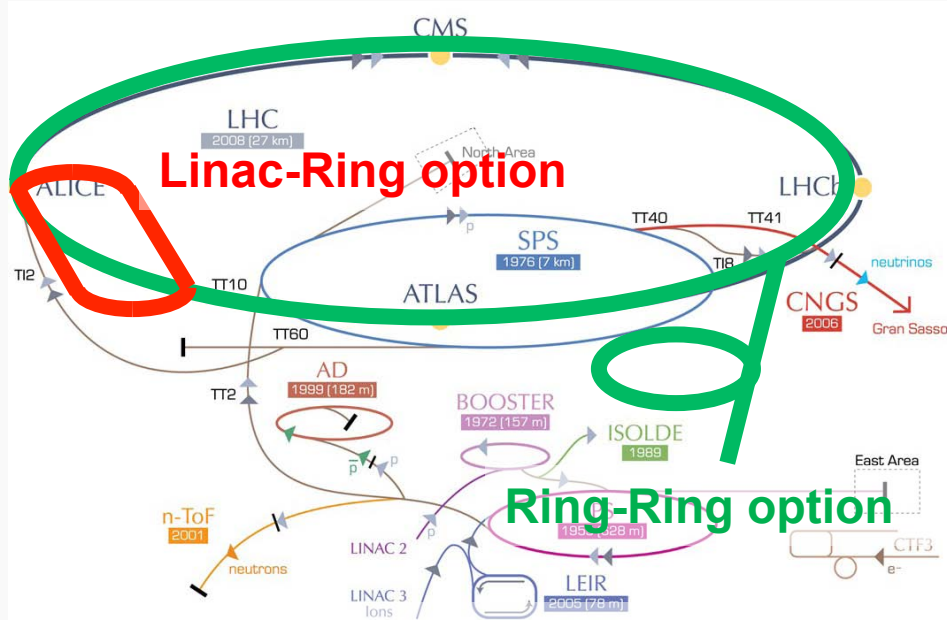
SRF gun
In cryomodule



Cryomodule
for SC cavity



LHeC @ CERN

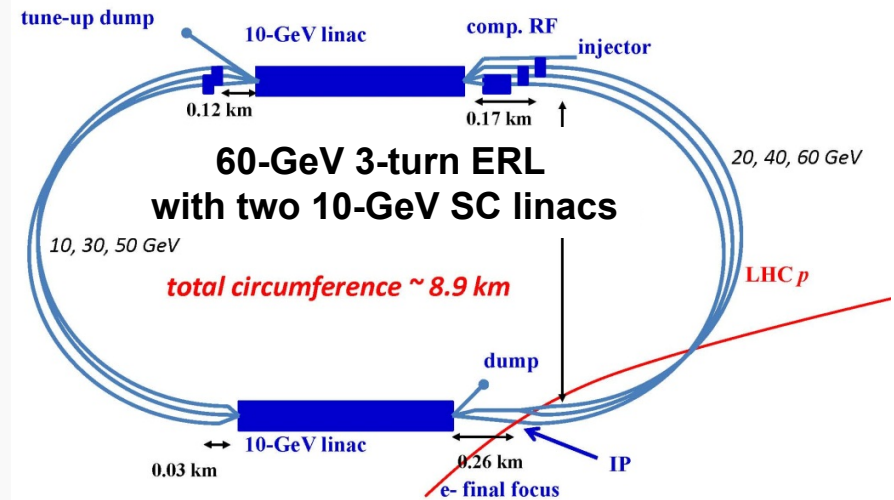


Large Hadron electron Collider (LHeC)

Advantages of Linac-Ring option :

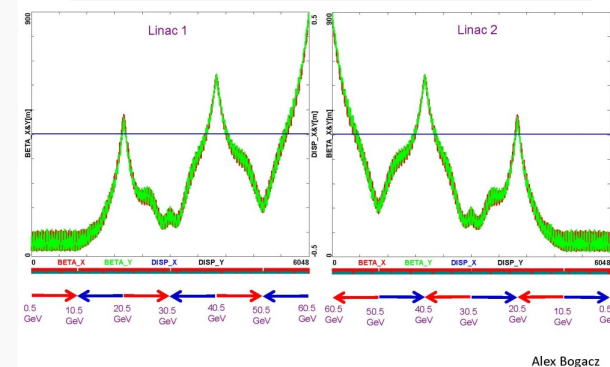
- (1) Higher luminosity potential up to $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- (2) Decoupling from LHC operation/infrastructure
- (3) Higher polarization degree of electrons
- (4) Reusable SC linacs for other projects

Draft CDR completed 2011, TDR by 2014, first beam by 2022



ERL configuration for Linac-Ring option

Linac beam optics



Summary and Outlook

ERL-based Light Source Project at KEK

- 3-GeV ERL with 6-7 GeV XFEL-O
- Possible further upgrades in 300-m straight section

Combination of a multi-GeV ERL and an FEL seems promising.

Compact ERL project at KEK

- 35 MeV single loop for 1st commissioning in 2013
- R&D and construction in progress

Target specifications of key components are being satisfied.

ERL Projects around the World

- 10 - 100 MeV ERLs established as high-power IR and THz sources
- R&D toward future VUV to X-ray light sources and colliders
- Significant progress in ERL technologies and operational experiences

Encouraging us to work on further development for future ERL projects.

ERL2011 Workshop at KEK

**Thank you for your attendance
in spite of the difficult situation
after the Great East Japan Earthquake.**

- The 50th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs
- Venue: KEK, Tsukuba, Japan
- Date: October 16 – 21, 2011
- Number of Participants : ~120



**KEK, Tsukuba, Japan
October 16-21, 2011**

<http://erl2011.kek.jp>

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Particle Accelerator Society of Japan / The Japanese Society for Synchrotron Radiation Research

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- N. Vinokurov, G. Kulipanov (BINP) and their colleagues
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- A. Jankowiak (HZB) and his colleagues
- S. H. Wang, J. Q. Wang (IHEP) and their colleagues
- L. X. Liu (Peking U.) and his colleagues
- V. Ptitsyn, I. Ben-Zvi (BNL) and their colleagues
- F. Zimmermann (CERN) and his colleagues

Thank you for providing material for my presentation.

Thank you for your attention.