Review of ERL Projects at KEK and around the World

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for the ERL collaboration team

High Energy Accelerator Research Organization (KEK)

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Outline

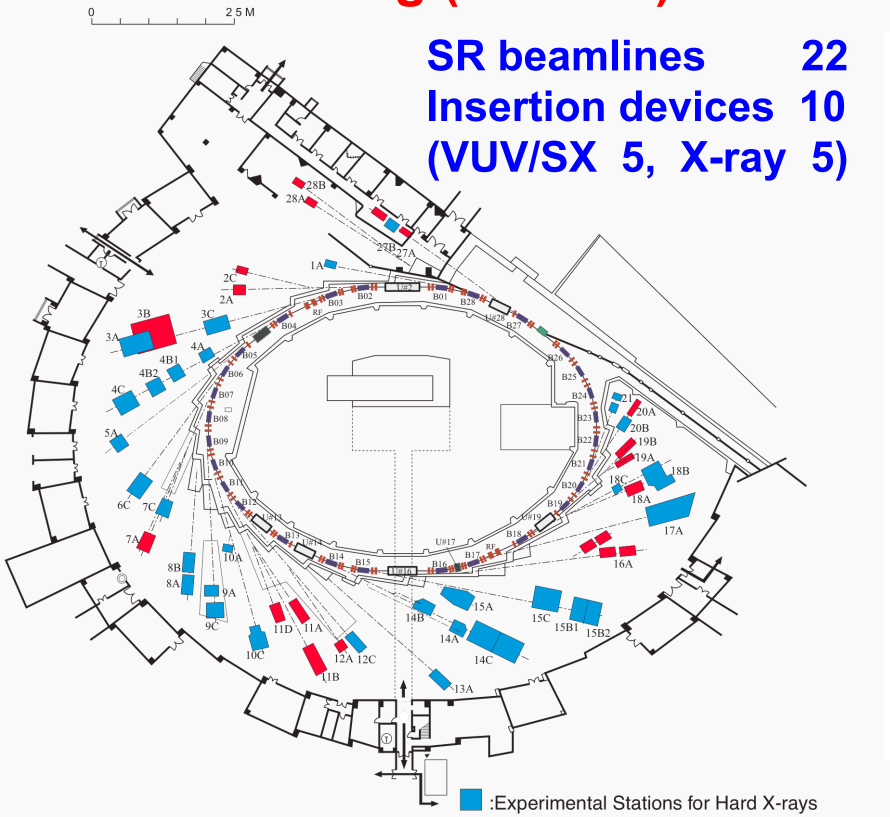
1. 3-GeV ERL Light Source Project at KEK
2. The Compact ERL (cERL) Project at KEK
3. Review of ERL Projects around the World
4. Summary and Outlook

3-GeV ERL Light Source Project at KEK

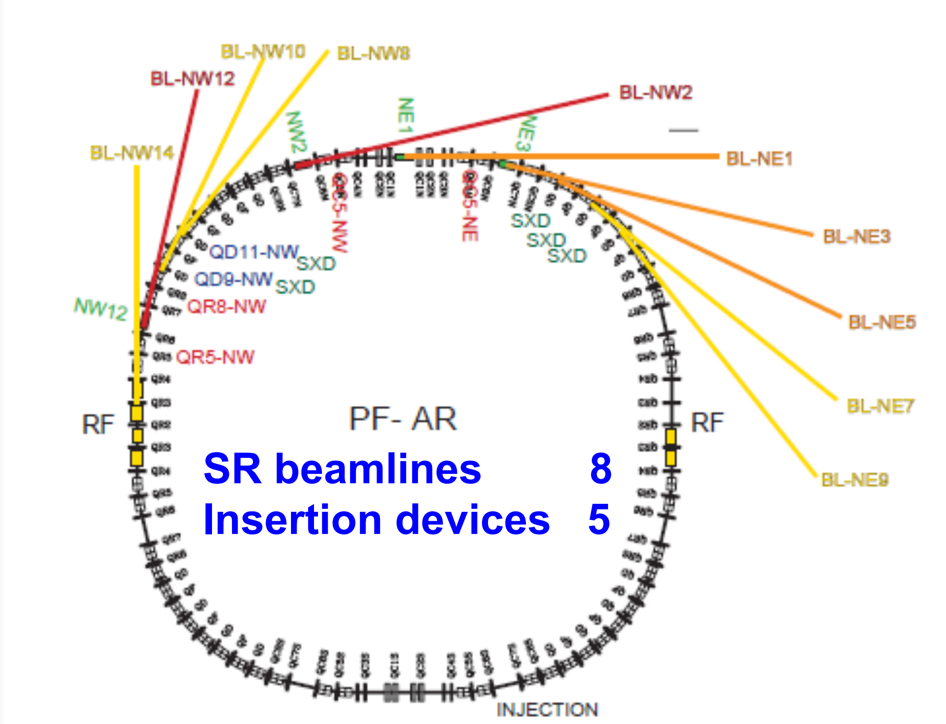
KEK Photon Factory (KEK-PF)

PF ring (2.5 GeV)

SR beamlines 22
Insertion devices 10
(VUV/SX 5, X-ray 5)



PF-AR (6.5 GeV)



SR beamlines 8
Insertion devices 5

- E = 2.5 GeV, C = 187 m
- Beam emittance : 34.6 nm·rad
- Top-up operation, I_0 = 450 mA

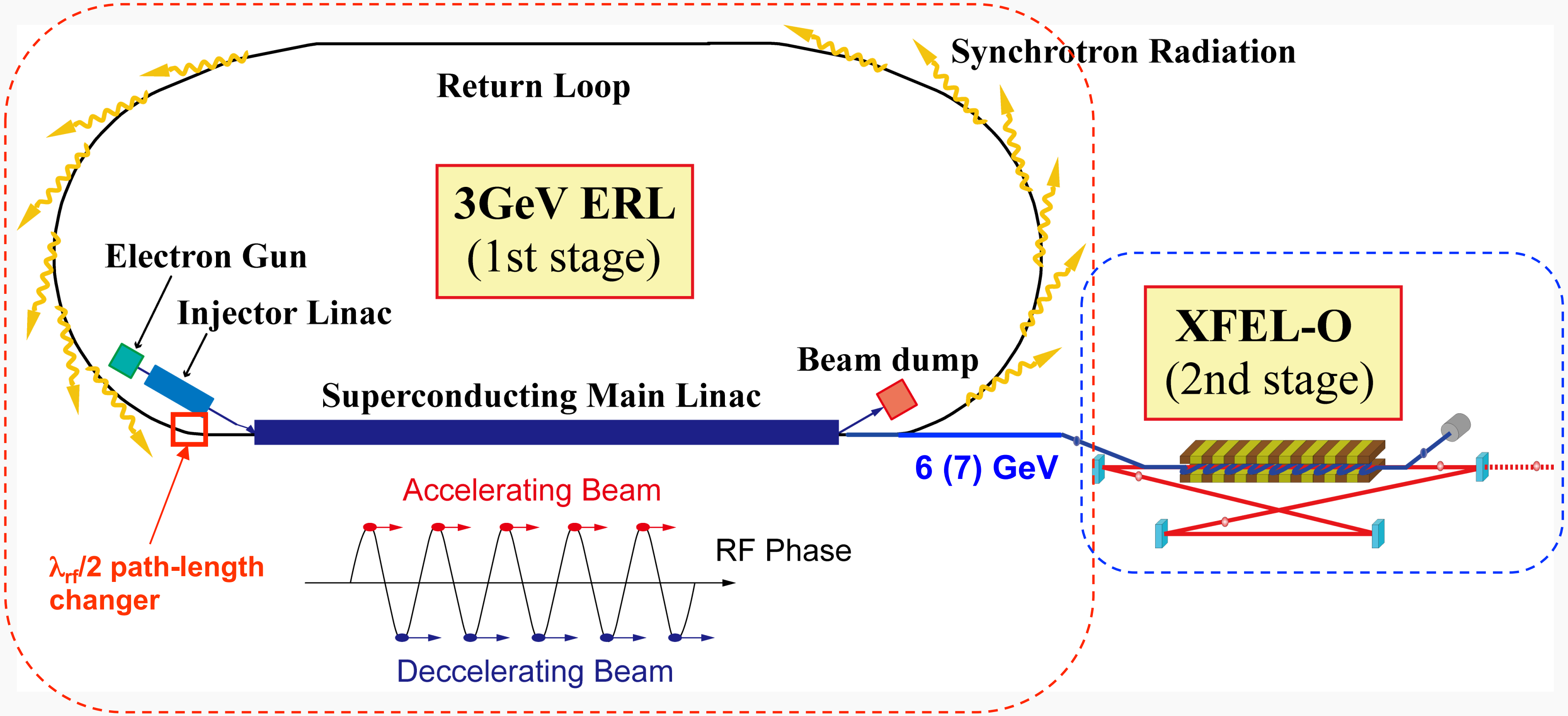
- E = 6.5 GeV, C = 377 m
- Beam emittance: 293 nm·rad
- Single bunch, I_0 = 60 mA

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

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**



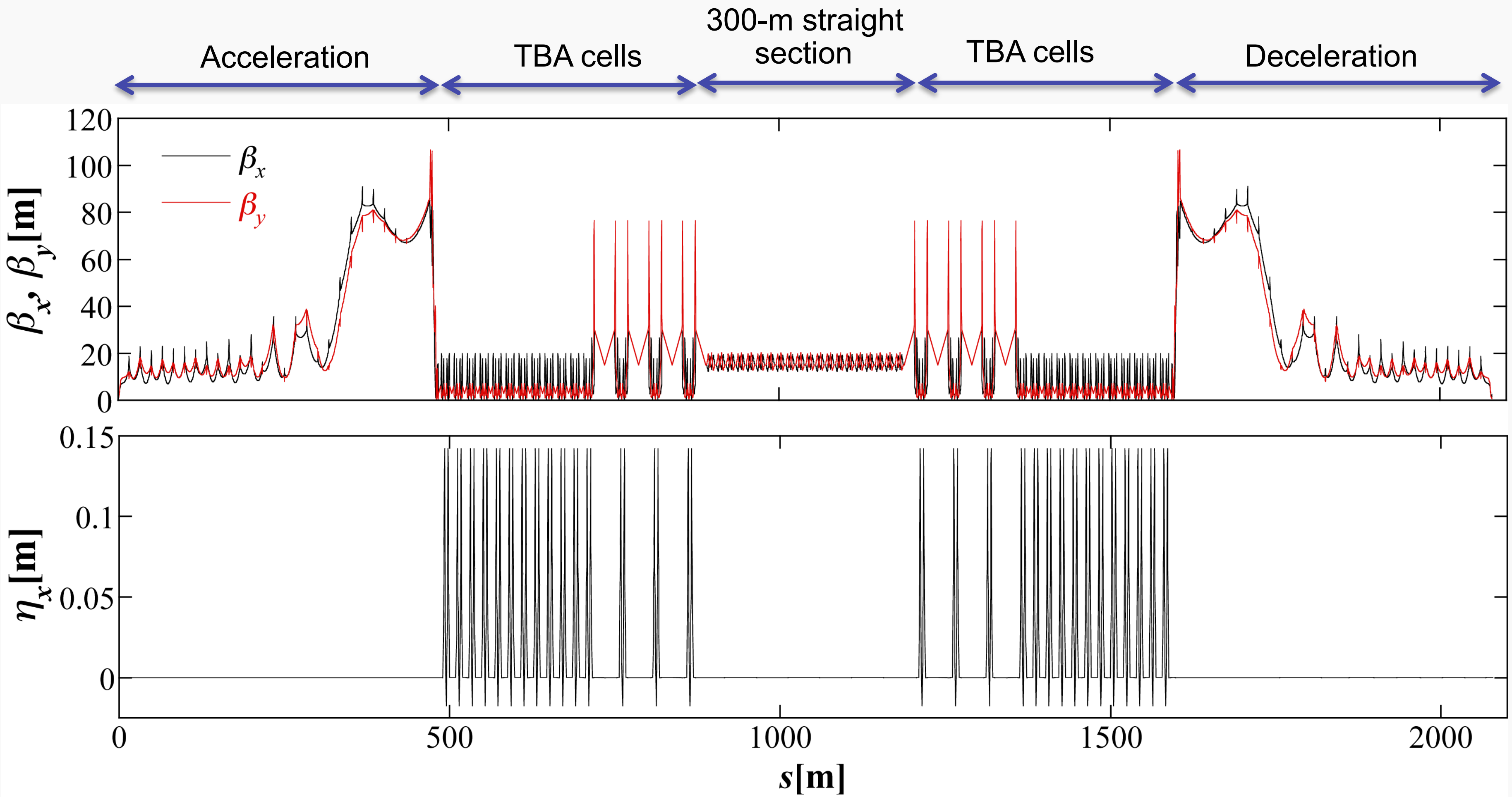
Schematic view of the ERL light source project at KEK

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	XFELO mode
Beam Energy	3 GeV				6 - 7 GeV
Beam Current	10 mA	100 mA	100 mA	77 μA (typ.)	10 μA
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)



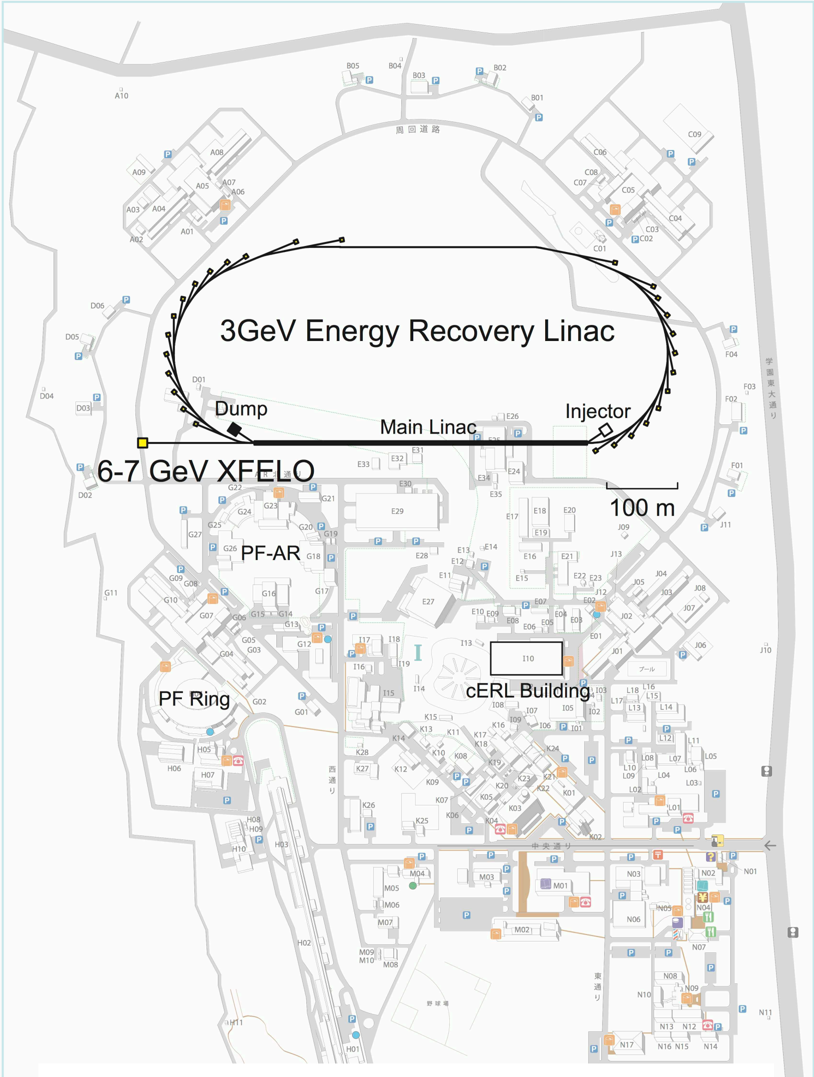
Emittance growth & energy spread increase due to ISR & CSR effects are negligible for both Ultimate and XFEL-O modes.

M. Shimada et al., MOPP019

Tentative Layout of 3-GeV ERL

Assumptions:

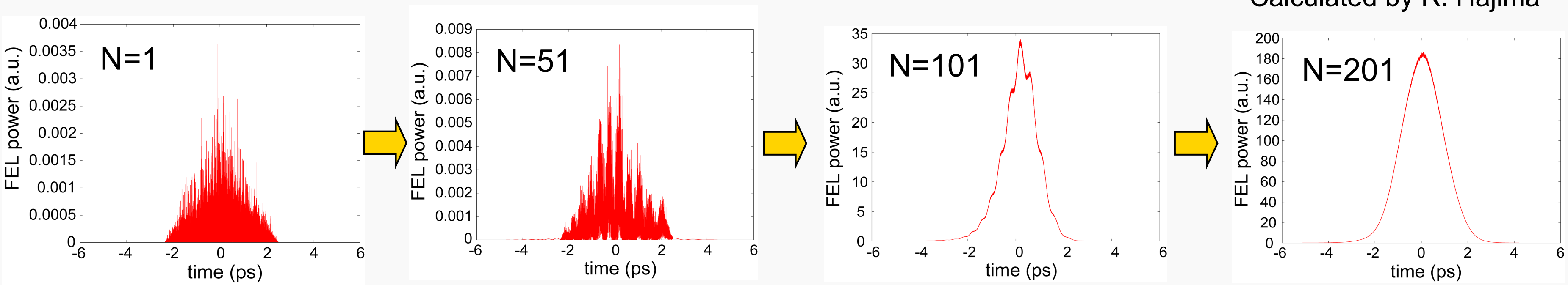
- Beam energy
  - Full energy: 3 GeV
  - Injection and dump :10 MeV
  - XFEL-O: 6-7 GeV
- Circumference : ~ 1600 m
- Main linac
  - Eight 9-cell cavities in a cryomodule
  - 28 cryomodules (224 cavities)
  - Cavity acc. gradient : 13.4 MV/m
  - Triplet QMs between cryomodules
  - Total length : ~ 470 m
    (average acc. gardient : 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



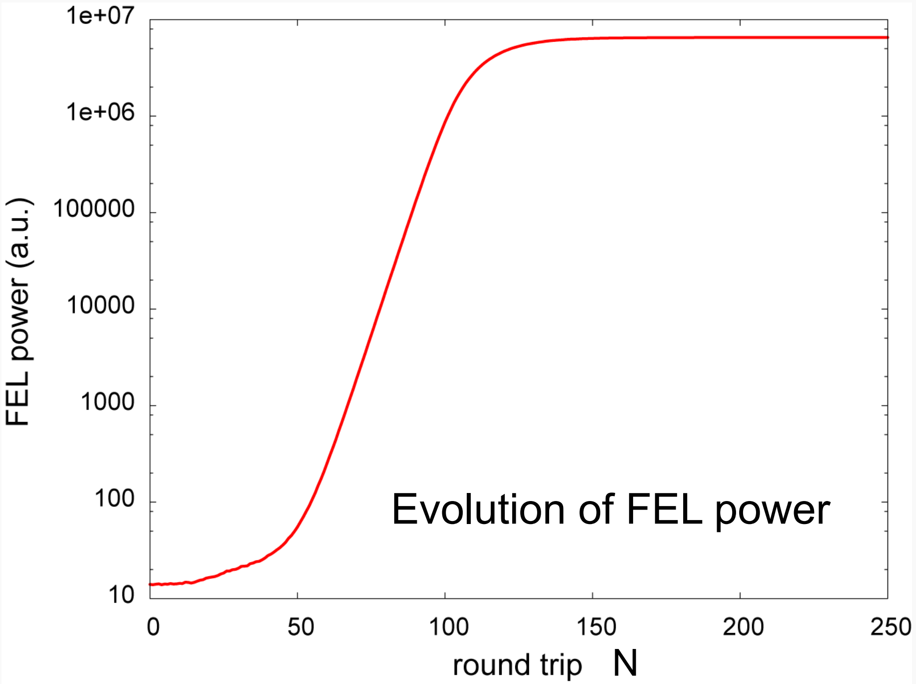
Layout at KEK Tsukuba Campus

Simulation of XFEL-O (6 GeV)

Calculated by R. Hajima



Evolution of temporal pulse profile



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 %

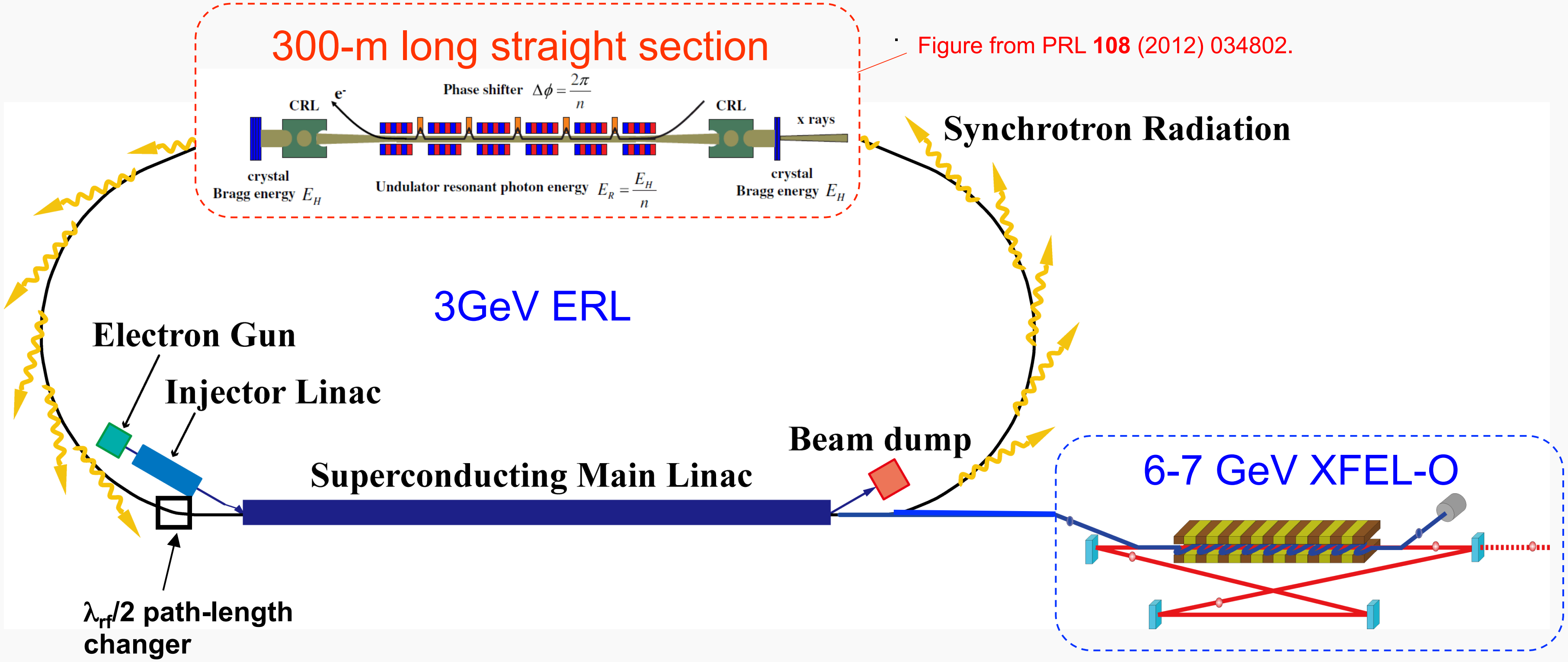
Potential of 300m Long Straight Section

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

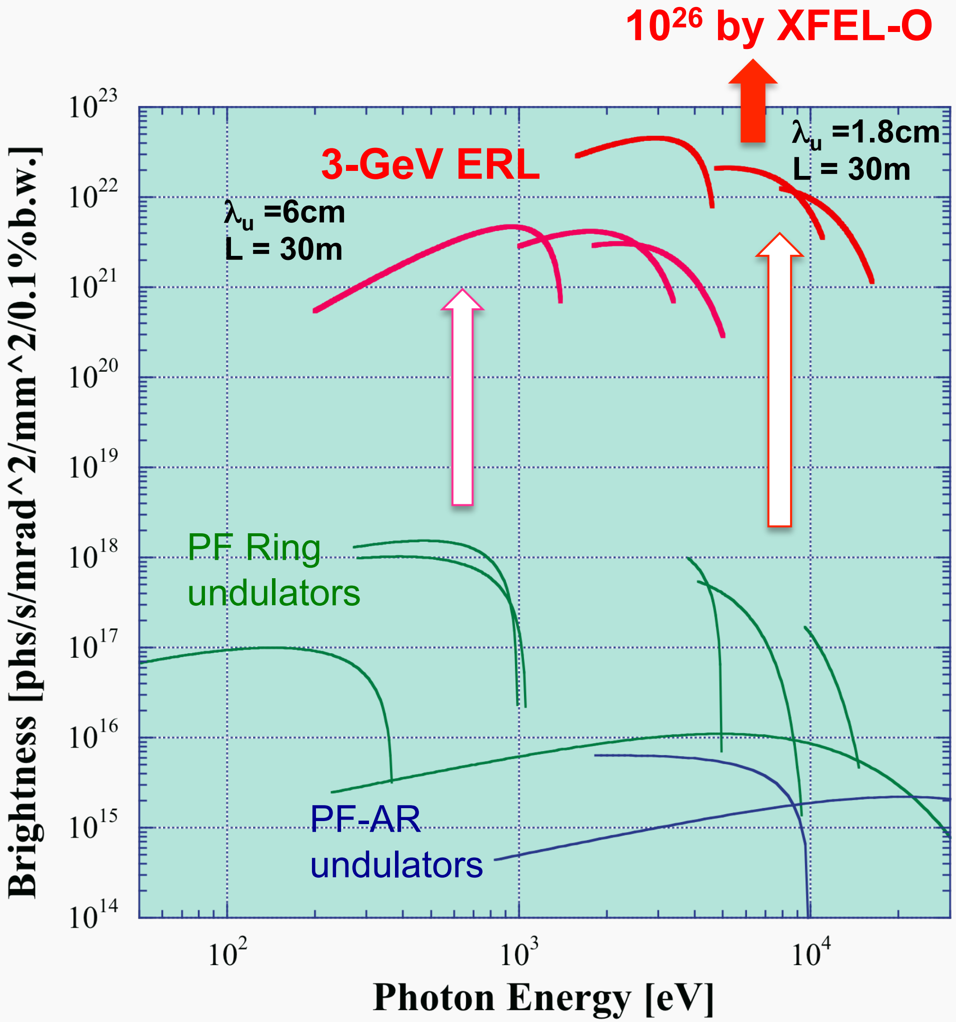
(3) Harmonic Lasing of XFEL-O



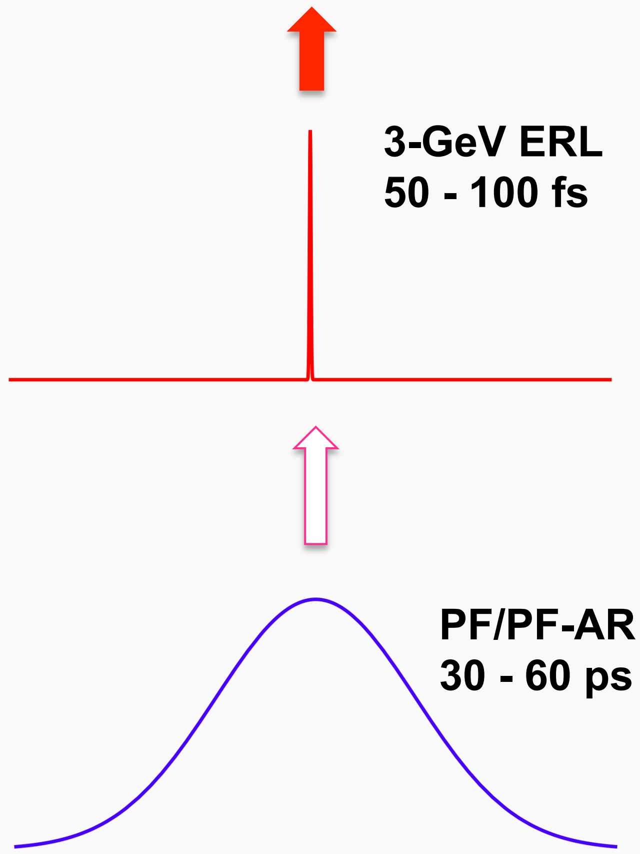
Norio Nakamura, IPAC12, May 22, 2012

Light Source Performance

Spectral Brightness



SR Pulse length



Calculated by K. Tsuchiya

The Compact ERL (cERL) Project at KEK

Compact ERL (cERL) Project

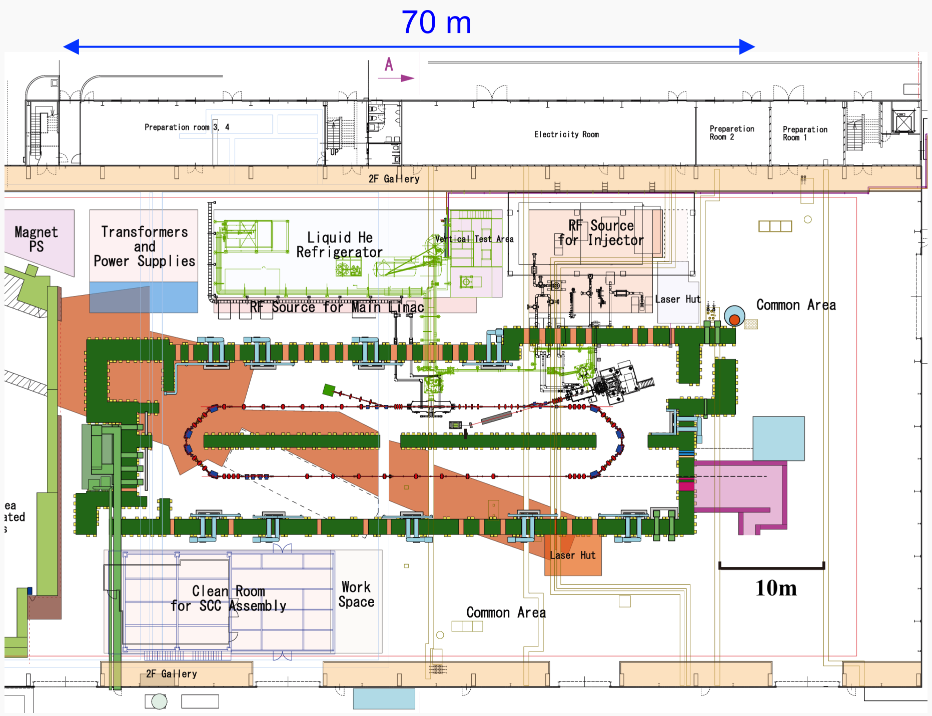
Purposes of the compact ERL

- 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

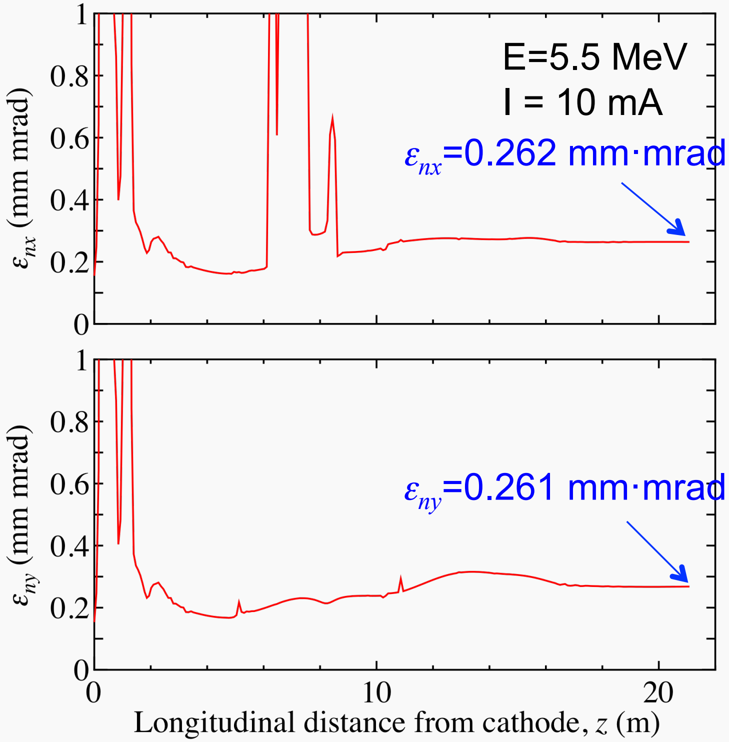
	Parameters
Beam energy (upgradability)	35 MeV 125 MeV (single loop) 245 MeV (double loops)
Injection energy	5 MeV (10 MeV in future)
Average current	10 mA (100 mA in future)
Acc. gradient (main linac)	15 MV/m
Normalized emittance	0.1 mm·mrad (7.7 pC) 1 mm·mrad (77 pC)
Bunch length (rms)	1 - 3 ps (usual)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

Commissioning is scheduled to start in 2013.



S. Sakanaka et al., MOPPP018

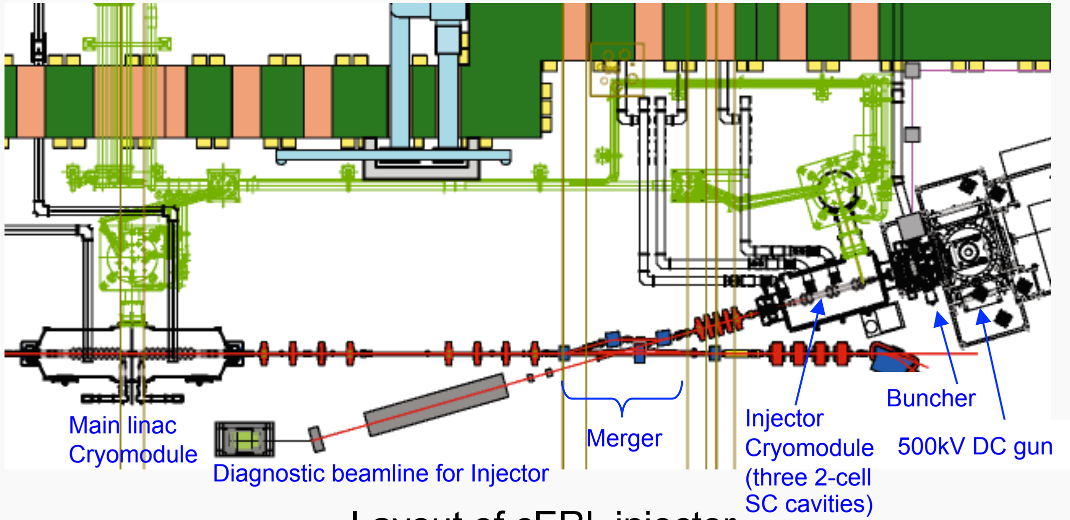
Injector Design



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

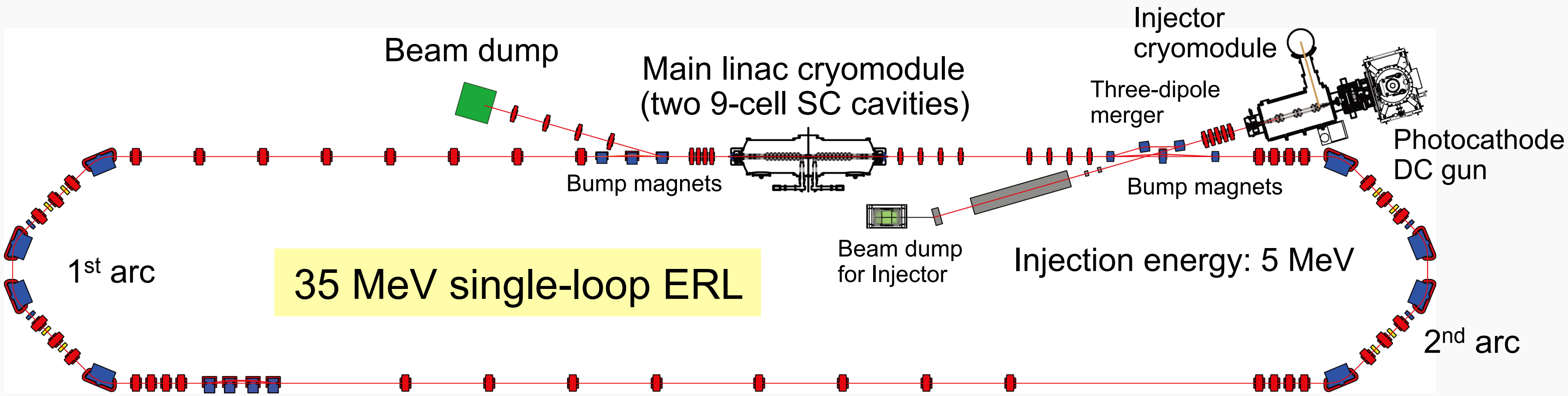


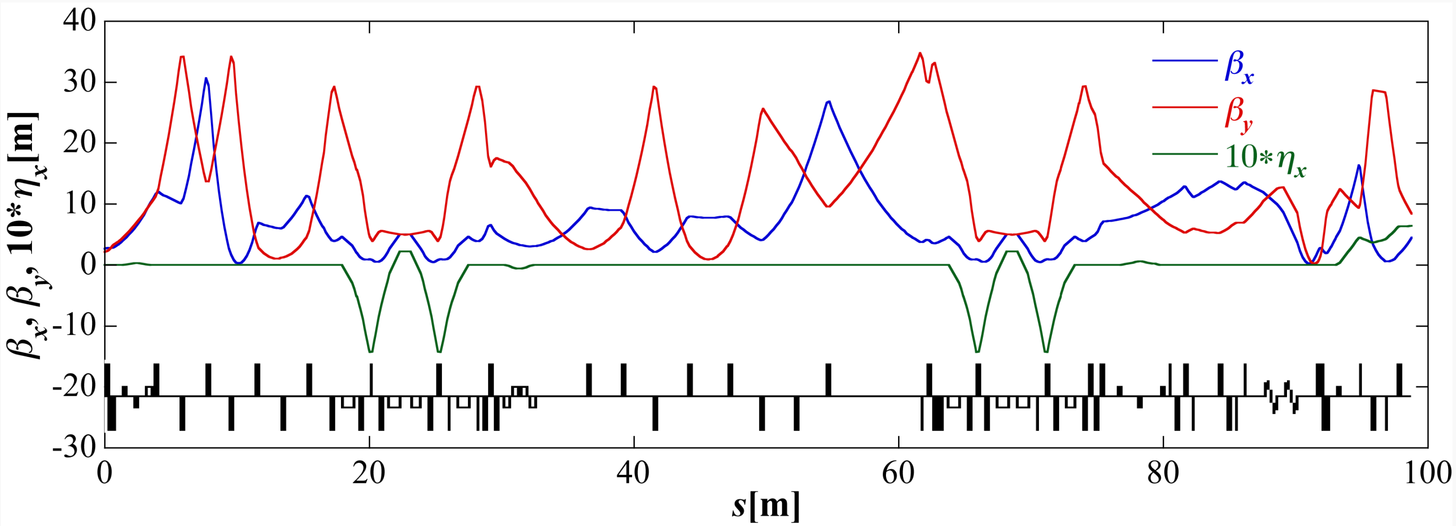
Layout of cERL injector.

Injector parameters

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)

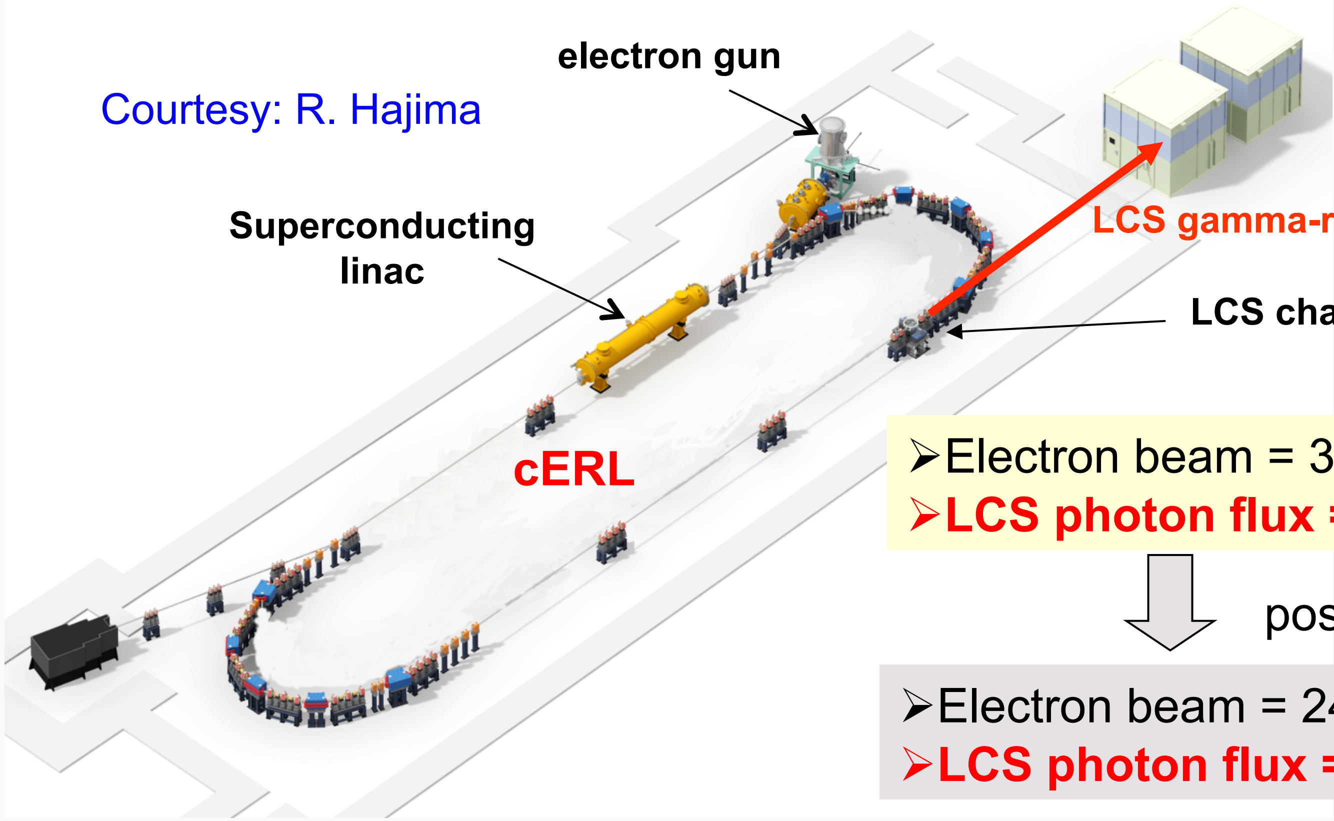
M. Shimada et al., MOPP019

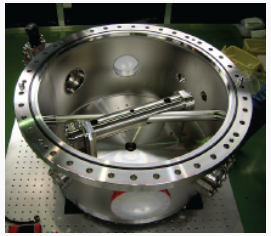
Laser Compton Scattering Experiment

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





- Electron beam = 35 MeV, 10 mA
- **LCS photon flux = $5x10^{11}$ ph/s @22keV**

⇩ possible upgrade in future

- Electron beam = 245 MeV, 10 mA
- **LCS photon flux = $1x10^{13}$ ph/s @1.1MeV**

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

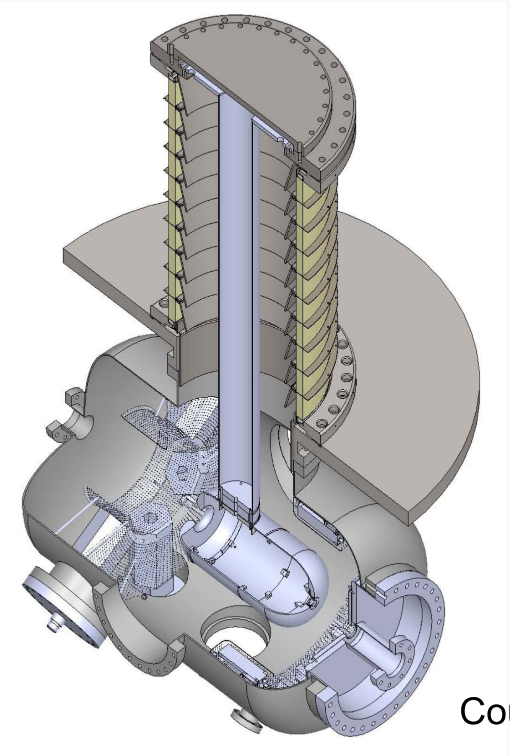
Photocathode DC Gun #1 at JAEA

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

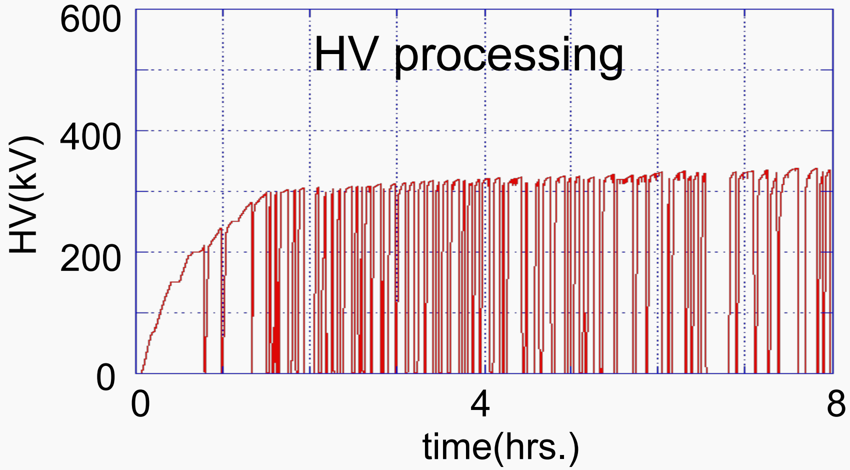
R. Nagai et al., Rev. Sci. Instrum. **81** (2009) 033304

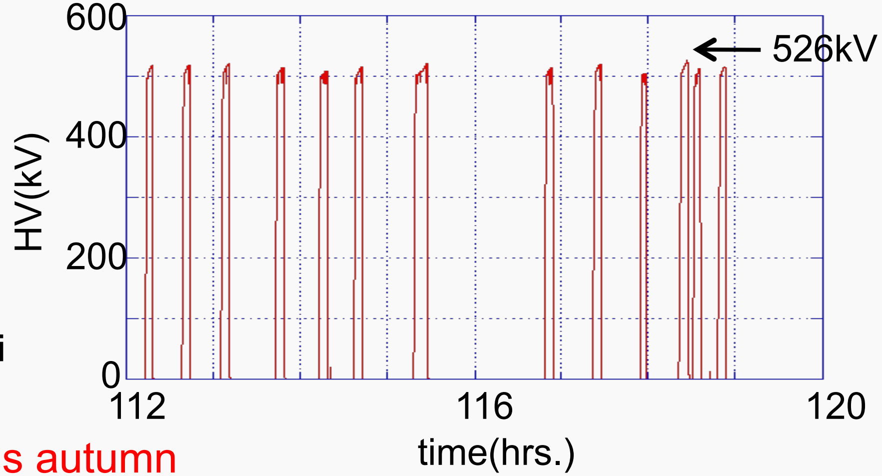
HV processing with cathode electrode and NEG pumps in place

- 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

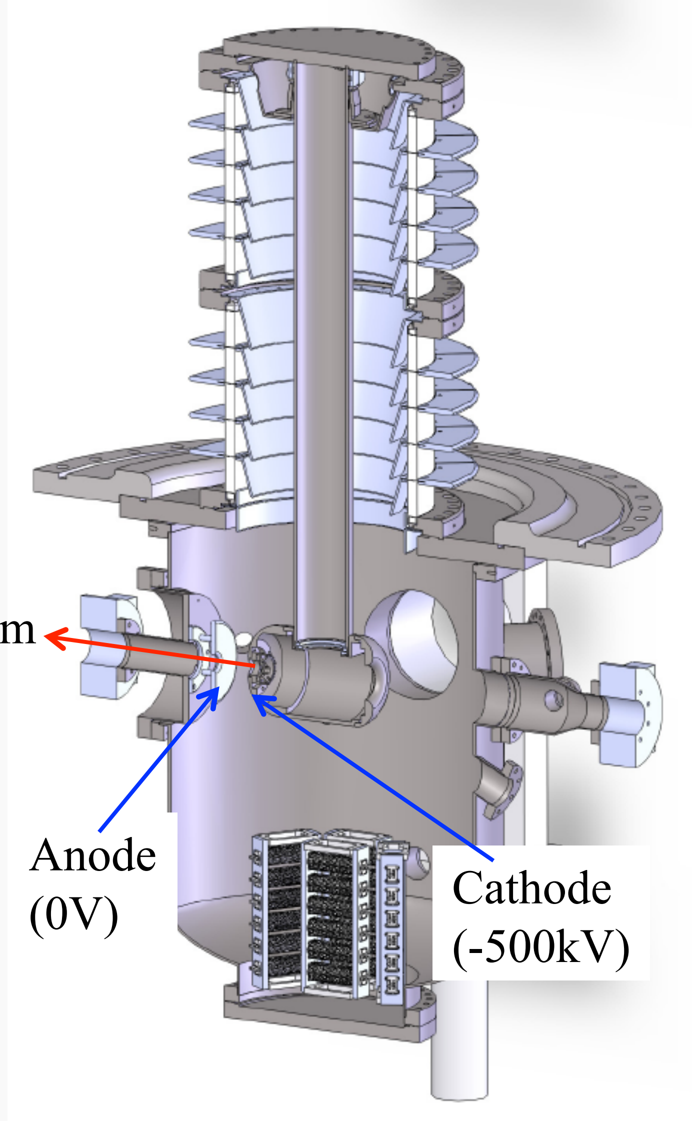
Photocathode DC Gun #2 at KEK

Courtesy: M. Yamamoto

Target pressure : 1x10^{-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: ~1x10^{-10} Pa·m^3/s (actual measurement)
- Main vacuum pump system
  - 4K Bakeable cryopump
    > 1000 L/s, for CH_4, N_2, CO, CO_2 @1x10^{-9} Pa (actual measurement)
  - NEG pump
    > 1x10^4 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

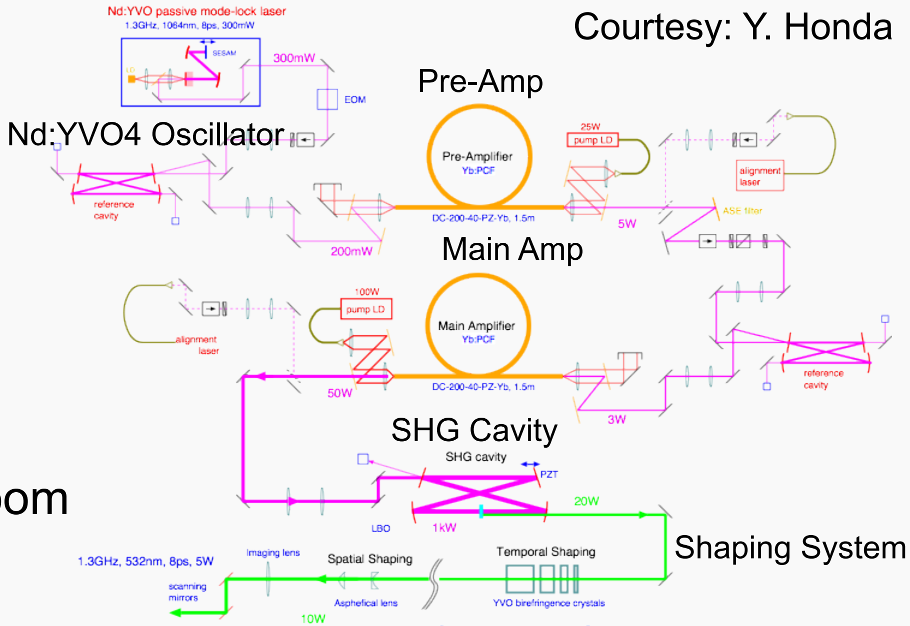
Achievements

- 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

Courtesy: Y. Honda



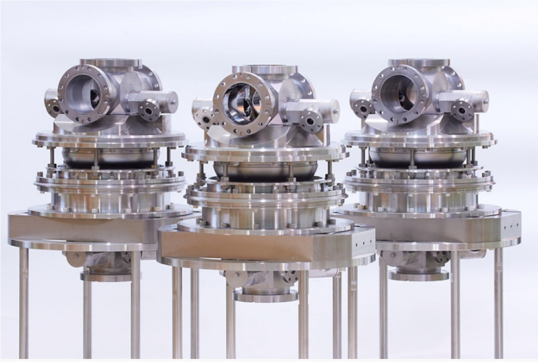
Layout of Laser System

Yb Fiber Amplifier System

SC Cavities for Injector (1)

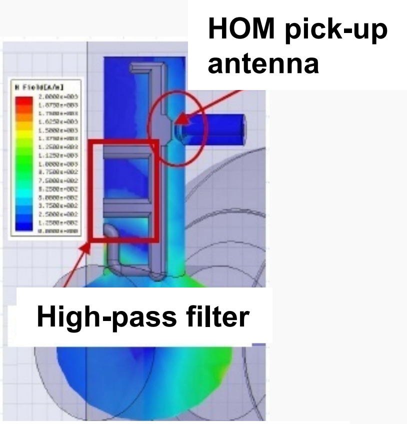
Courtesy: E. Kako, K. Watanabe

2-cell cavity



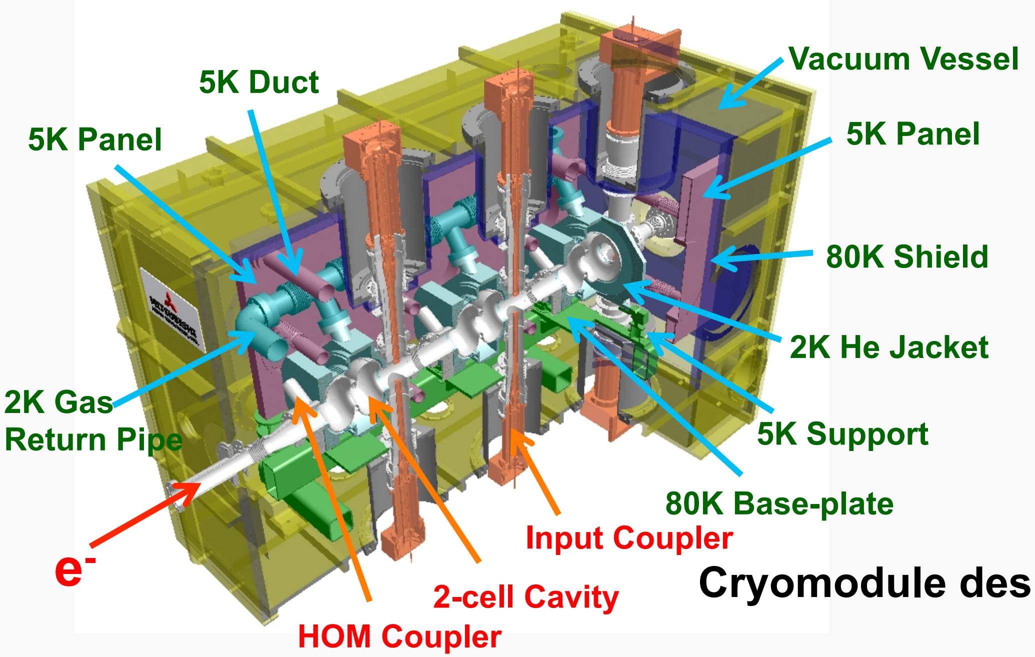
Cavities for cryomodule

All HOM couplers are loop-type



HOM-couplers and their structure

Input couplers

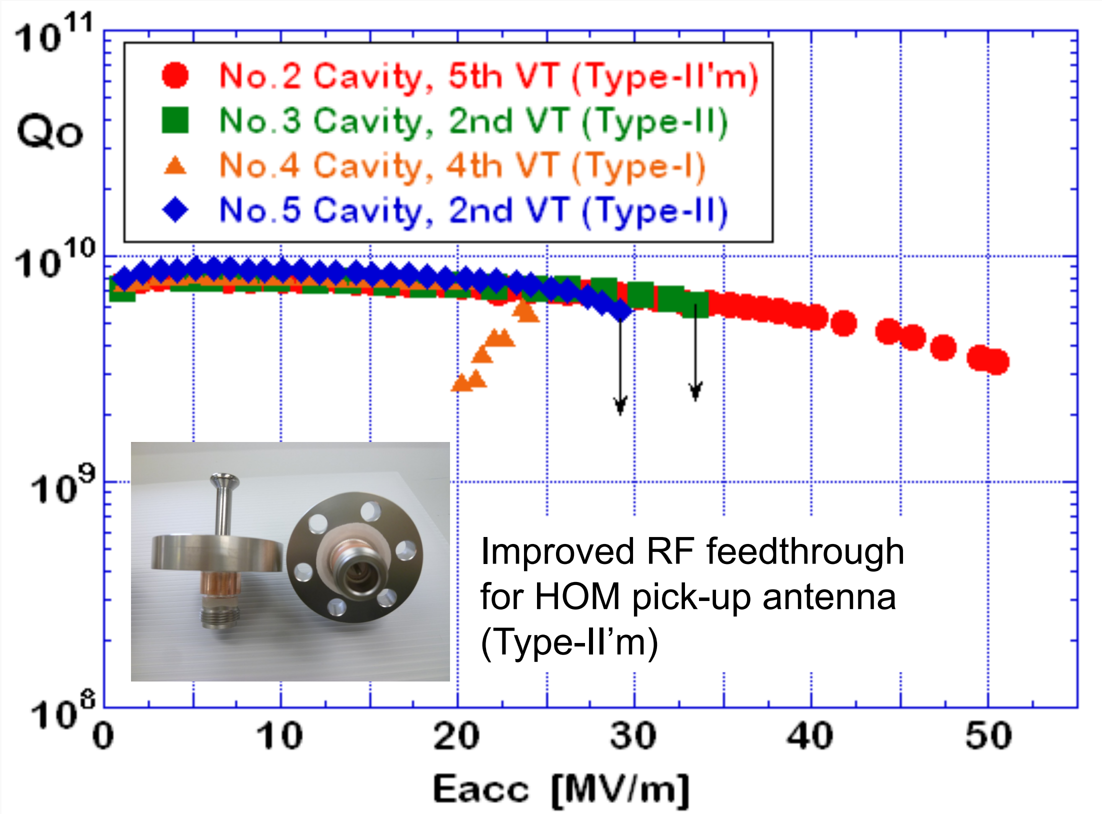


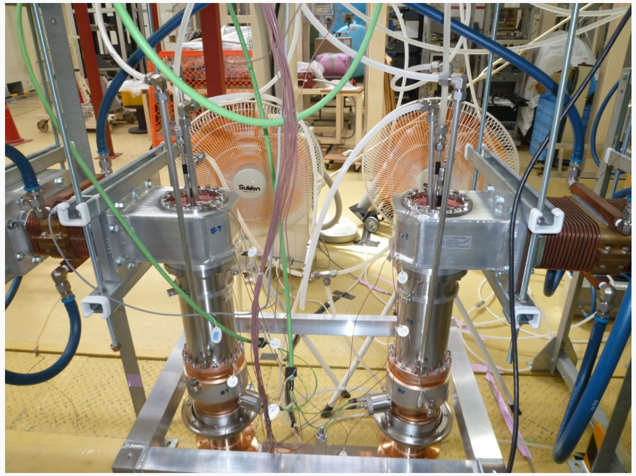
Cryomodule design

SC Cavities for Injector (2)

Courtesy: E. Kako

Results of Final Vertical Tests





RF conditioning of input couplers

Assembly of cryomodule

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

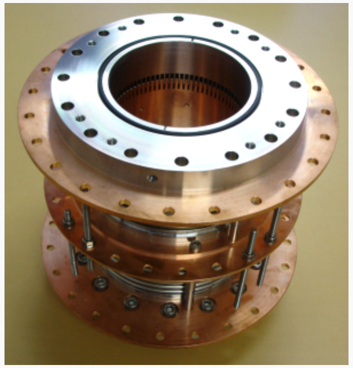
All the RF feedthroughs were replaced by Type-II'm.

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

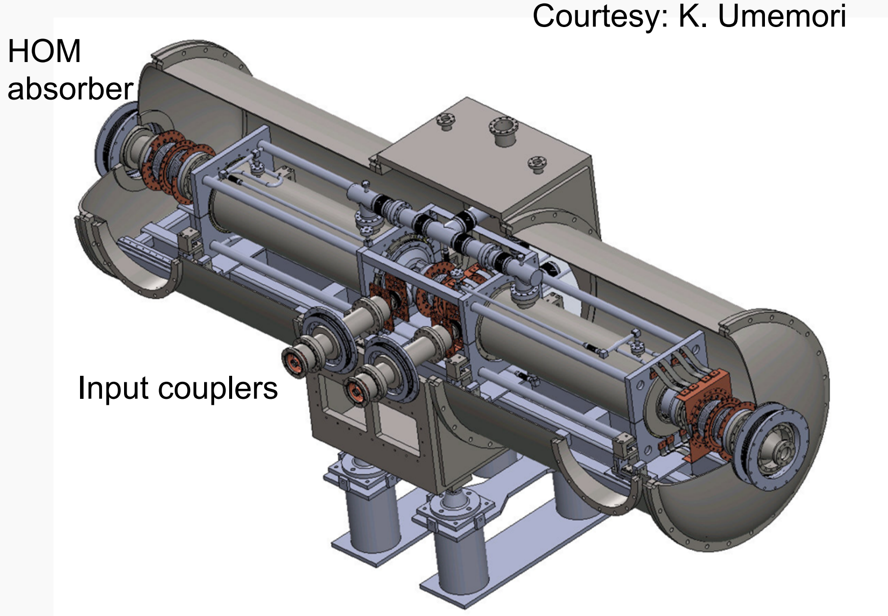
SC Cavities for Main Linac (1)

Courtesy: K. Umemori

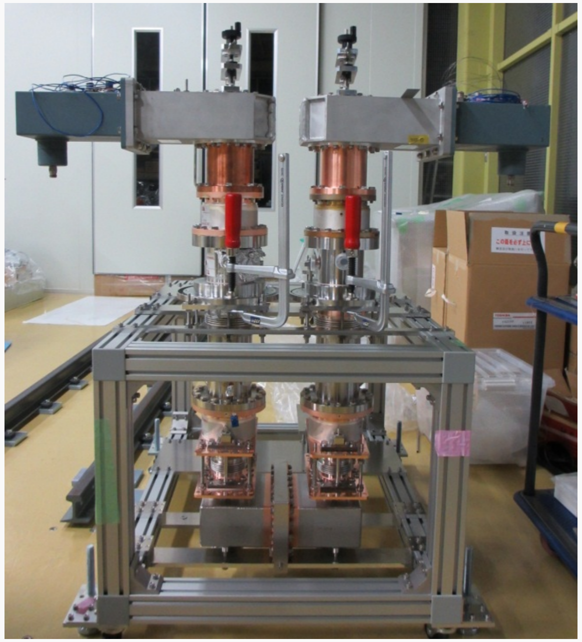
9-cell Cavities



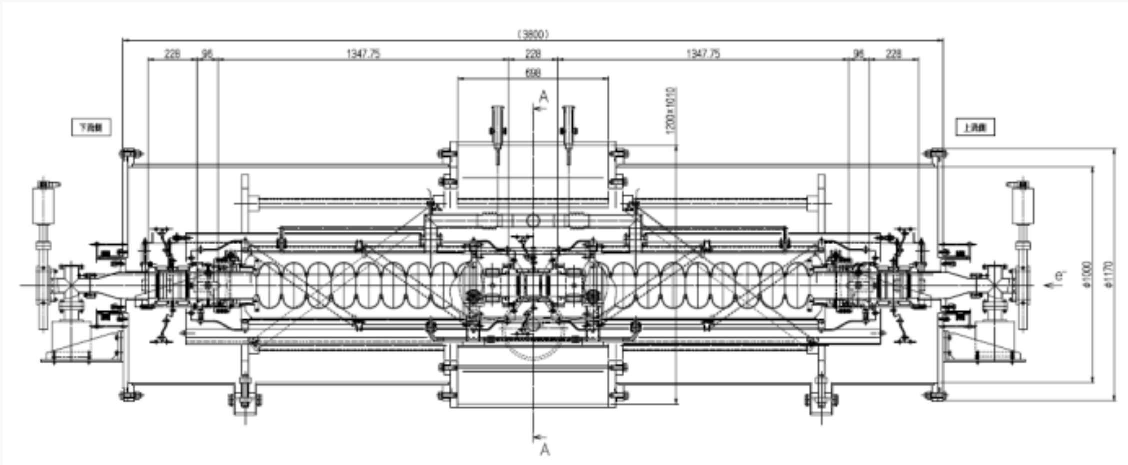
HOM Absorber



Cryomodule design



Input coupler



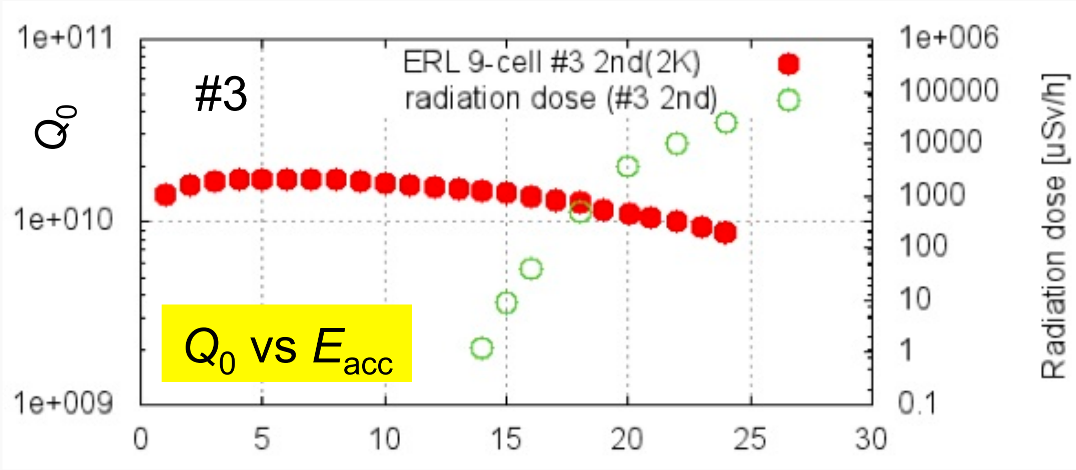
Cryomodule design (side view)

SC Cavities for Main Linac (2)

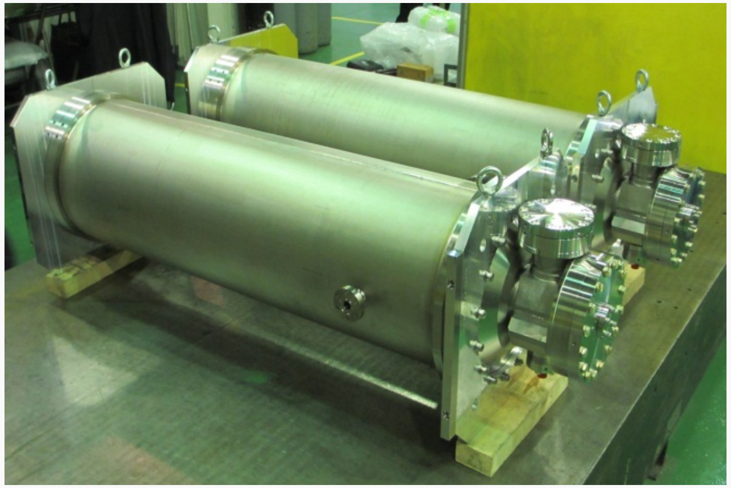
Courtesy: K. Umemori

Results of final vertical tests

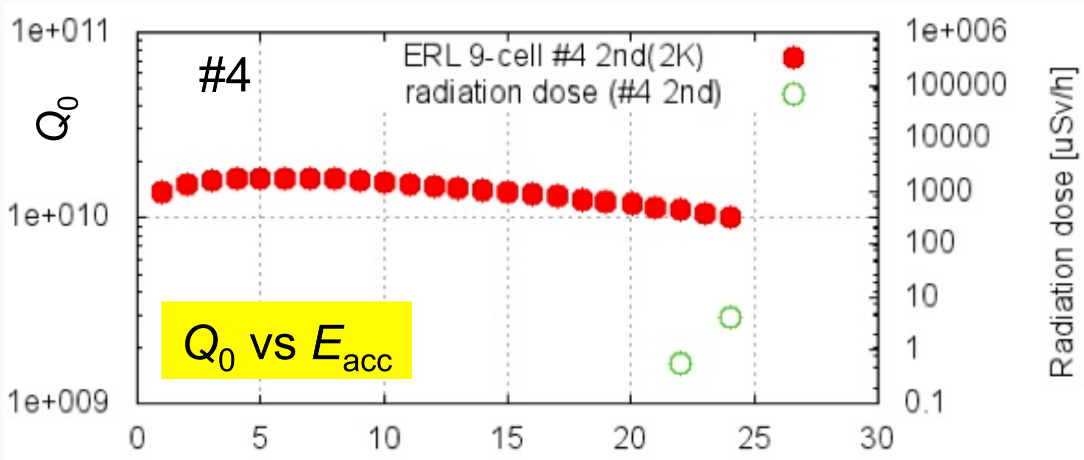
- E_{acc} of higher than 25 MV/m could be achieved in both cavities.
- Cavities satisfied cERL specification ($Q_0 > 10^{10}$ at 15 MV/m)
- Onsets of X-ray were 14 MV/m and 22 MV/m for the cavities #3 and #4, respectively.



E_{acc} (MV/m)



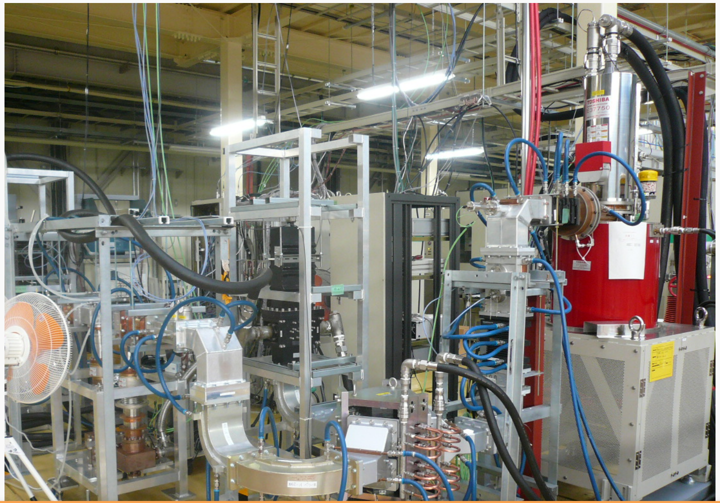
- Cavities are dressed with Helium jackets and waiting for installation into cryomodule.



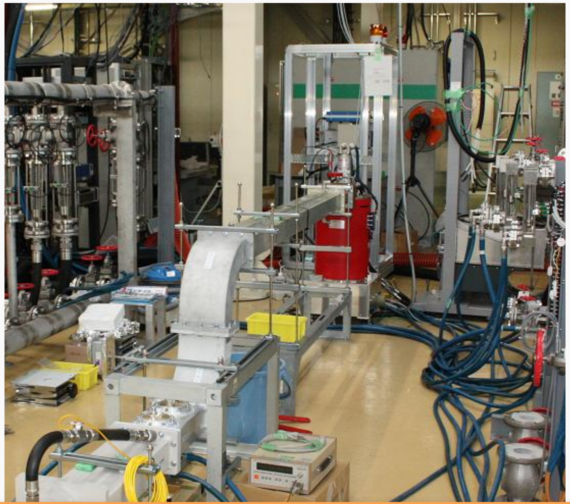
E_{acc} (MV/m)

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

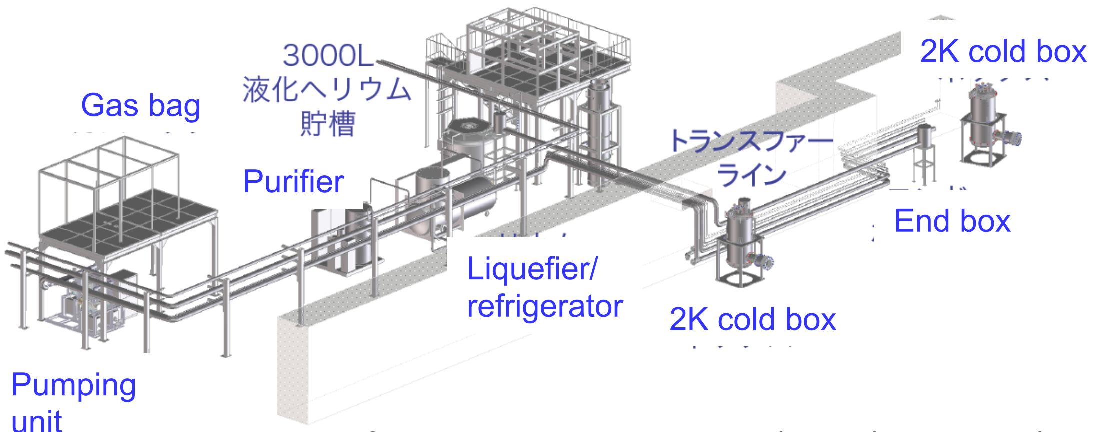
Courtesy: T. Miura

20kW CW IOT for buncher

Liquid-Helium Refrigerator

Overview of the system

Courtesy: H. Nakai



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

3000L liquefied helium storage vessel

2K cold box and end box

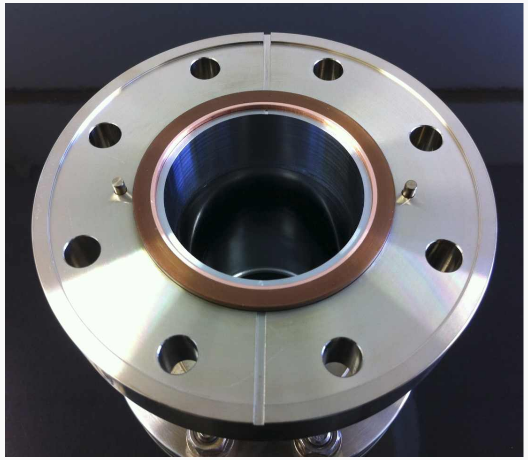
TCF200 helium liquefier/refrigerator

Magnet/Vacuum/Monitor

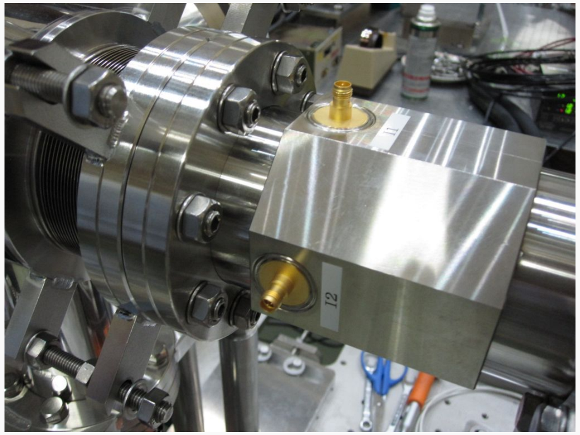
Courtesy: K. Harada, Y. Tanimoto, T. Honda, T. Obina, R. Takai

Bending magnet

Quadrupole magnet



Zero-gap Flange



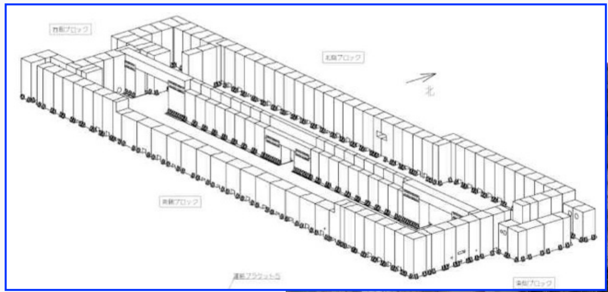
Stripline BPM with glass-type feedthrough

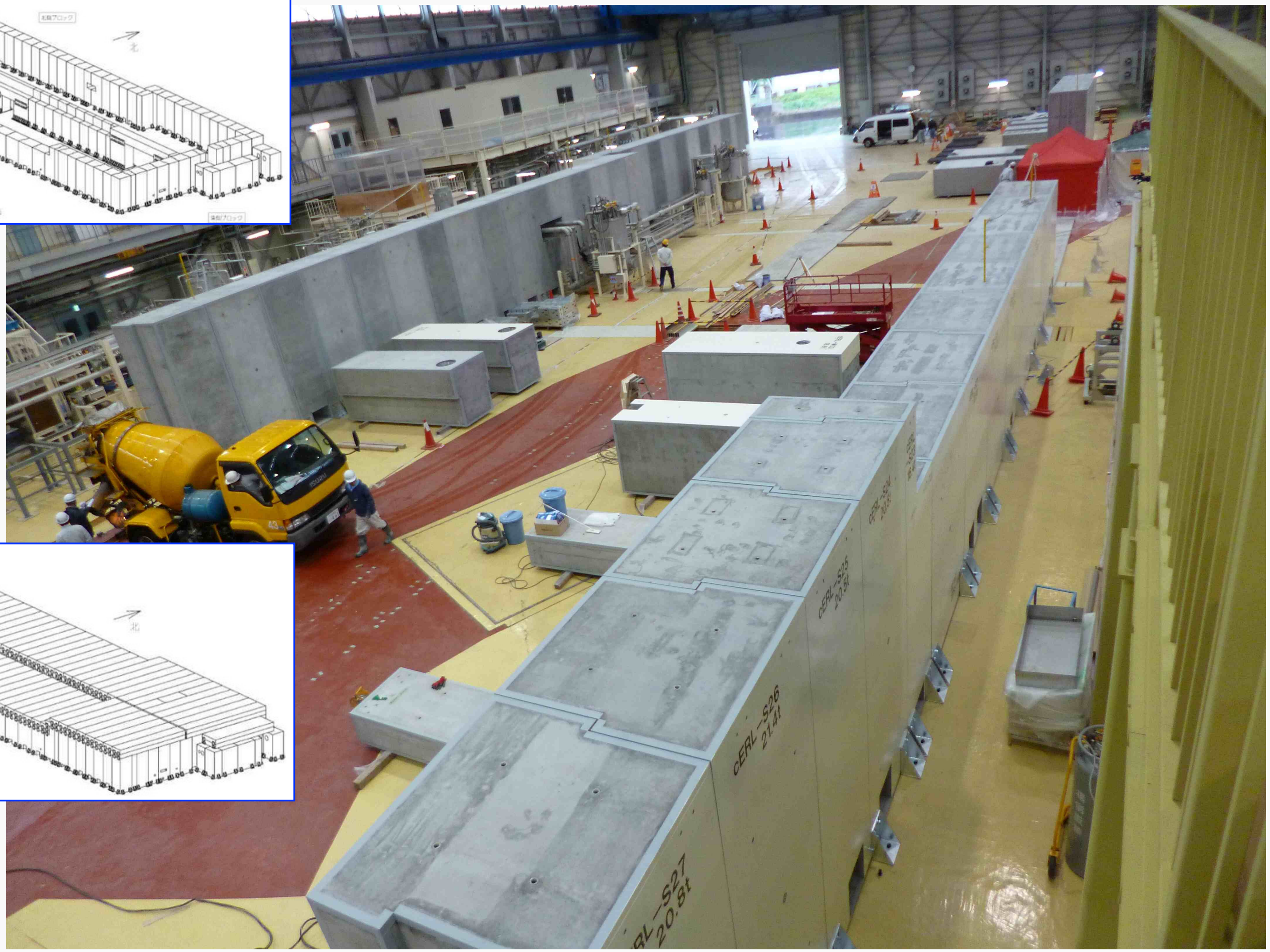
Screen monitor

Slit for emittance measurement

Radiation Shield for cERL

Courtesy: K. Haga

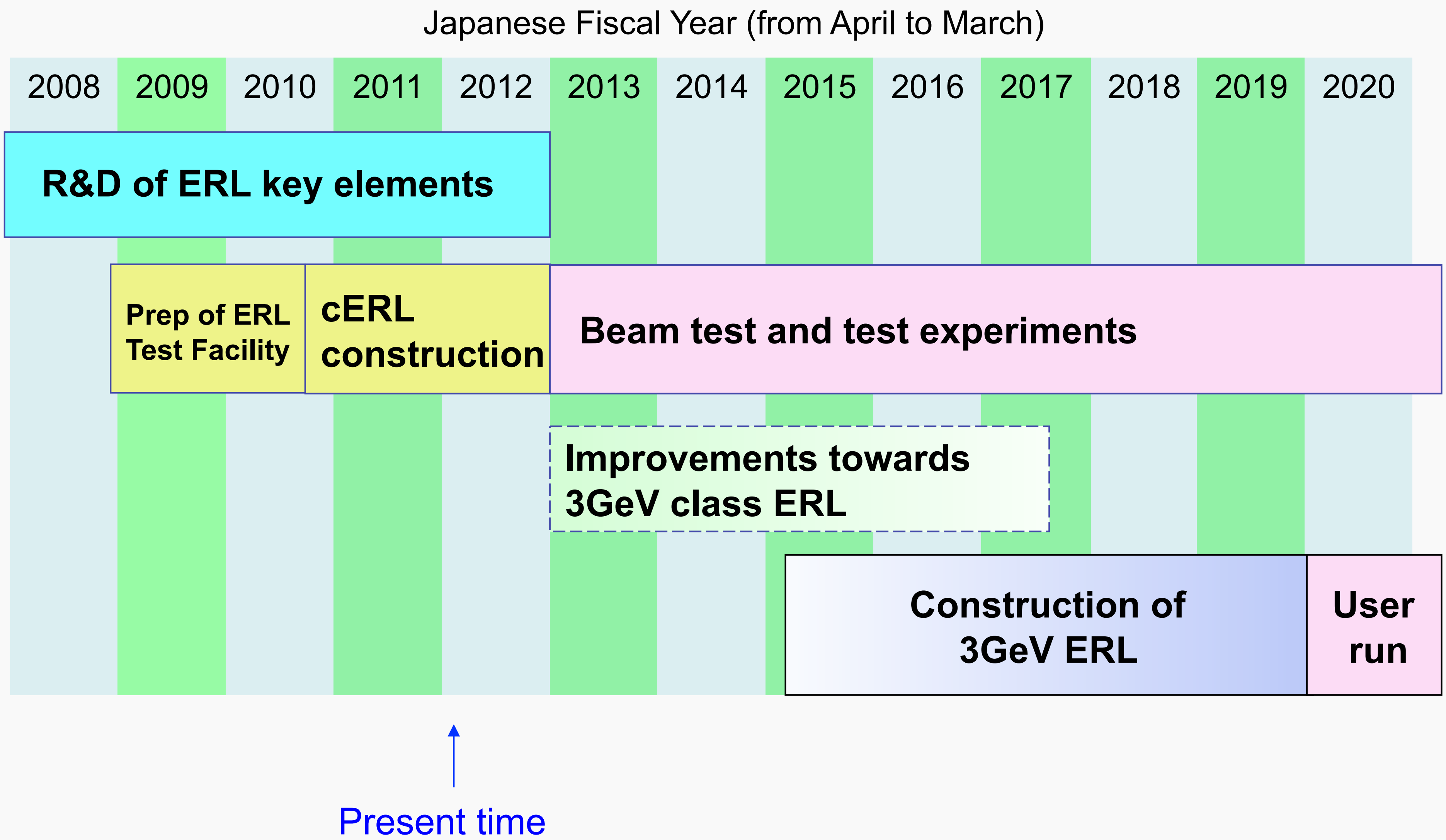




Construction of the radiation shield is on going and will be completed this autumn.

Road Map of ERL Projects

Courtesy: H. Kawata

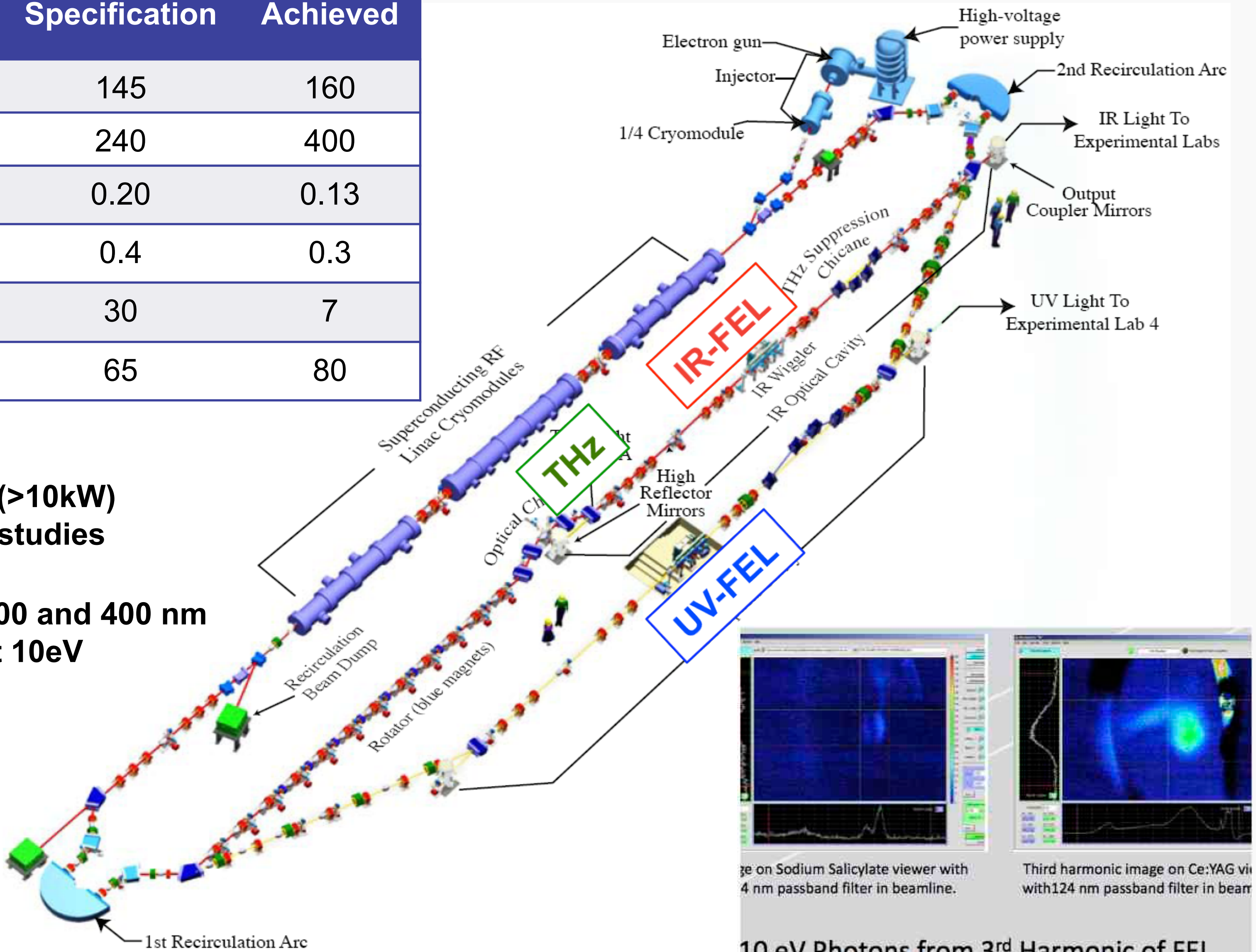


ERL Projects around the World

Jefferson Lab

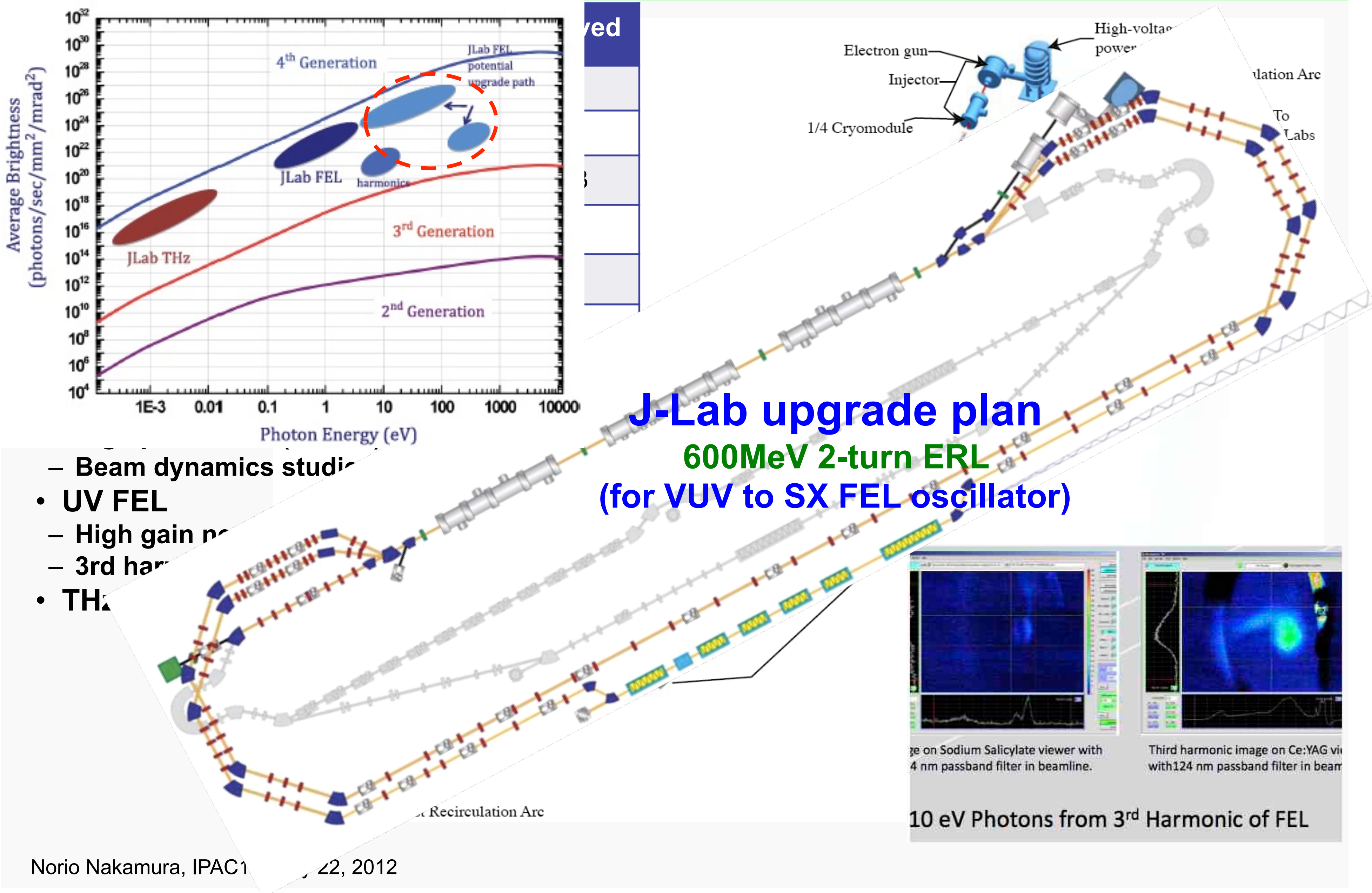
Beam Parameters	Specification	Achieved
Energy [MeV]	145	160
Peak Current [A]	240	400
σ_t [ps] at wiggler	0.20	0.13
$\sigma_{\Delta E}$ [%] at wiggler	0.4	0.3
$\varepsilon_{x,y}$ (rms) [mm-mrad]	30	7
ε_z (rms) [keV-ps]	65	80

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



10 eV Photons from 3^{rd} Harmonic of FEL

Jefferson Lab



– Beam dynamics studi

• UV FEL

– High gain n

– 3rd har

• TH

J-Lab upgrade plan

600MeV 2-turn ERL

(for VUV to SX FEL oscillator)

ge on Sodium Salicylate viewer with 4 nm passband filter in beamline.

Third harmonic image on Ce:YAG vi with124 nm passband filter in bea

10 eV Photons from 3rd Harmonic of FEL

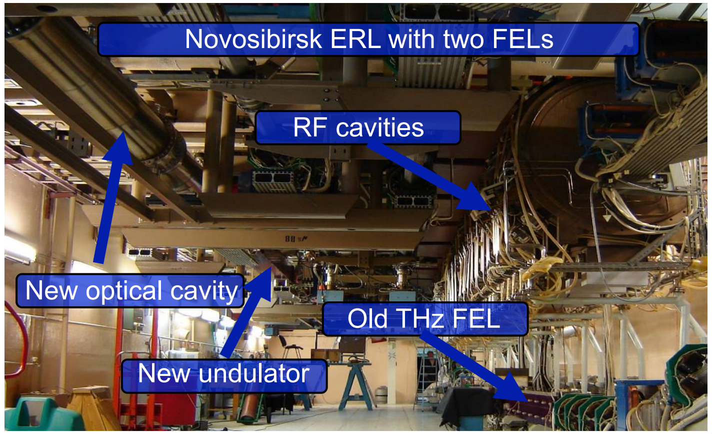
BINP

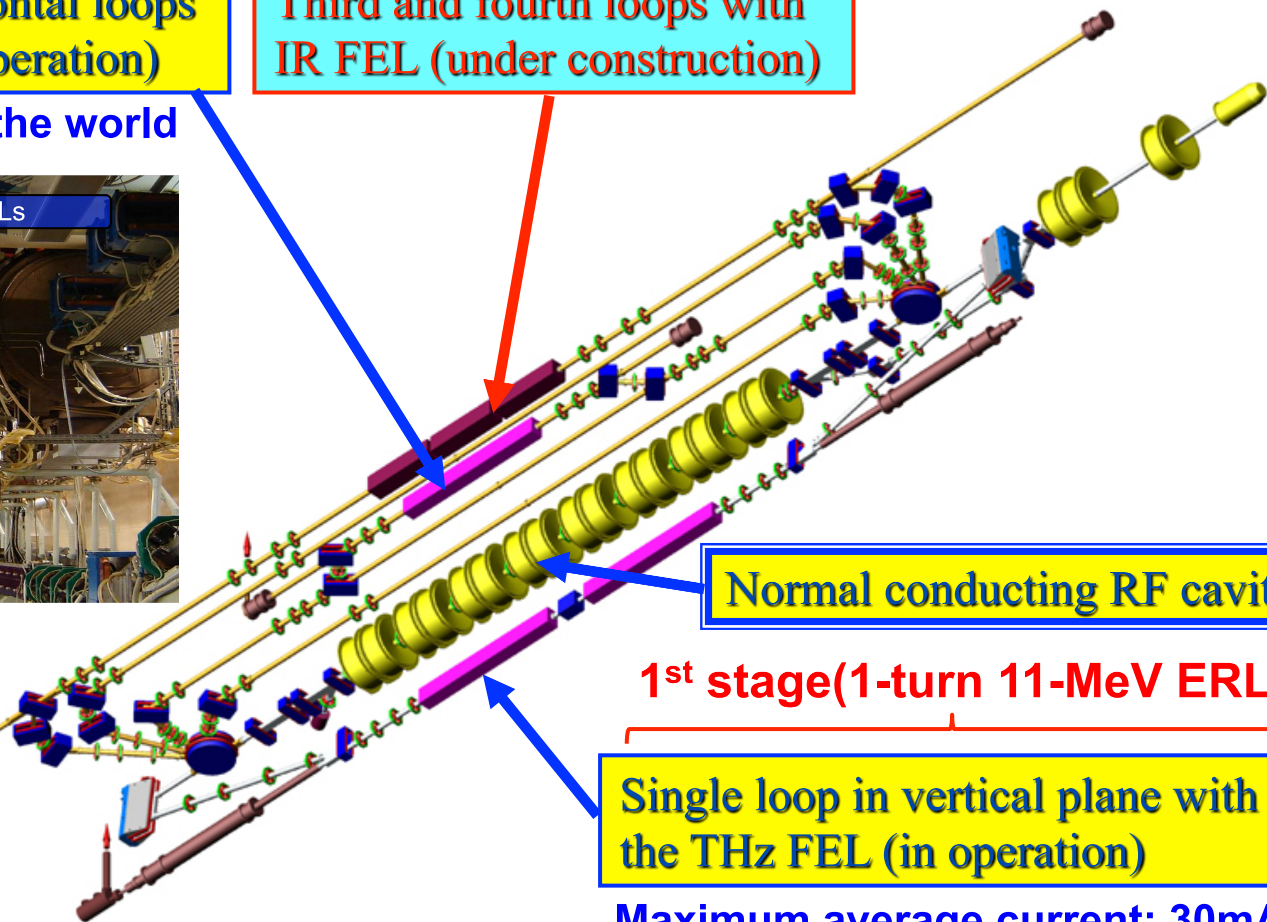
2nd stage(4-turn 40-MeV ERL)

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)





Normal conducting RF cavities

1st stage(1-turn 11-MeV ERL)

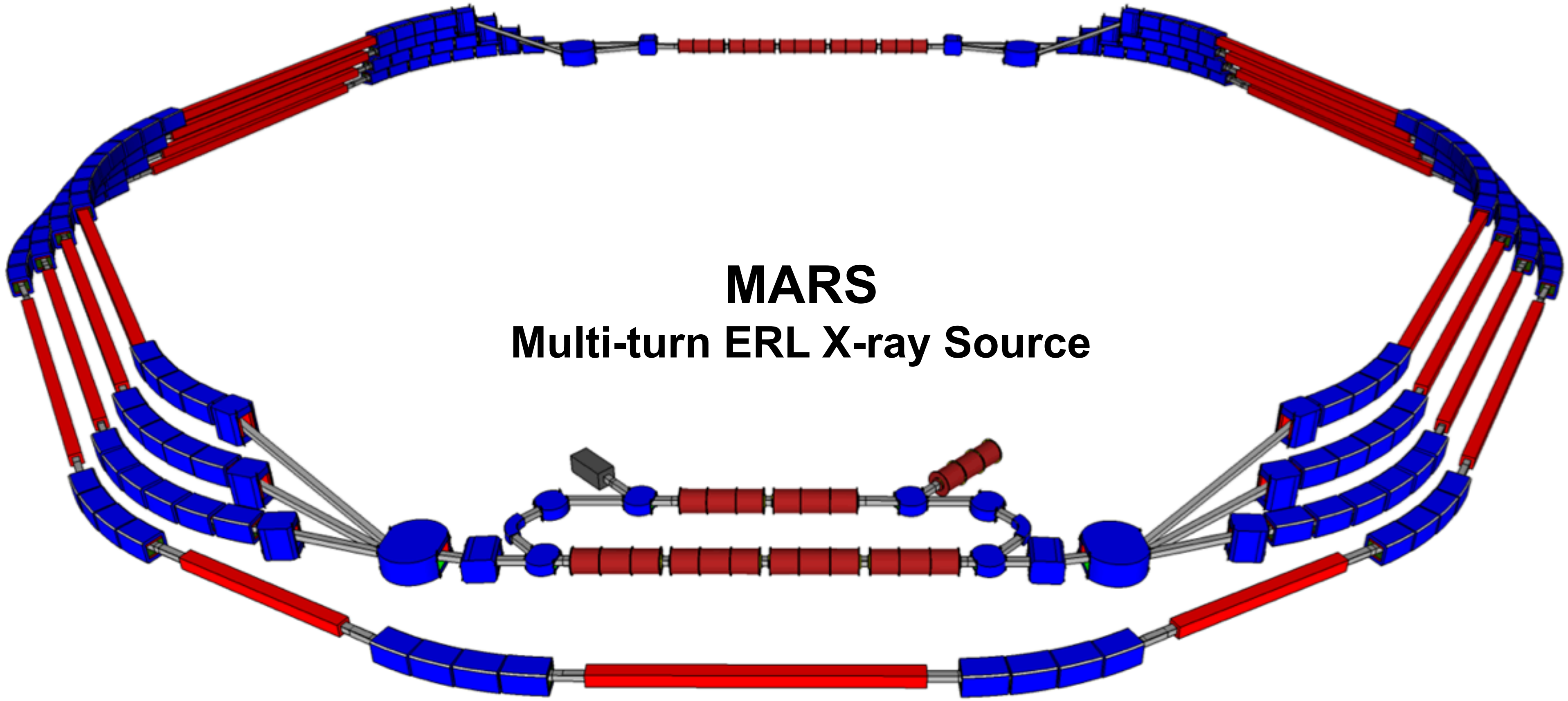
Single loop in vertical plane with the THz FEL (in operation)

Maximum average current: 30mA (world record for ERLs)

Full-scale ERL with 3 FELs at Novosibirsk

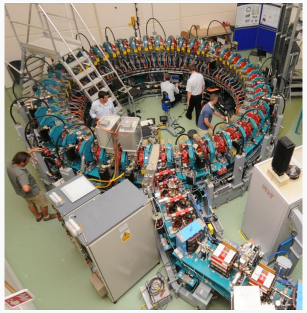
Norio Nakamura, IPAC12, May 22, 2012

BINP

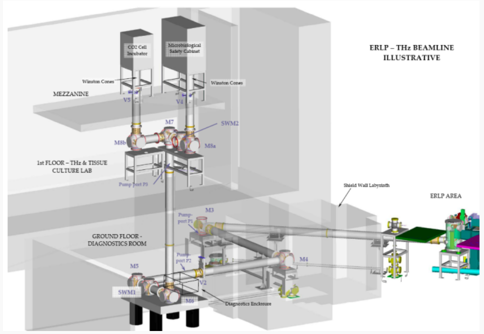


MARS
Multi-turn ERL X-ray Source

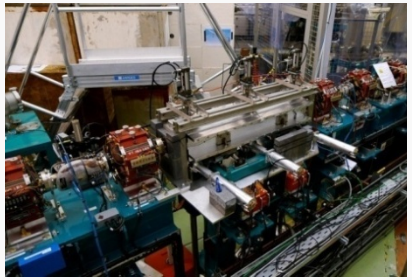
ALICE @ Daresbury Laboratory

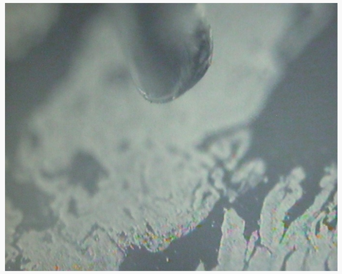


EMMA(first NS-FFAG)

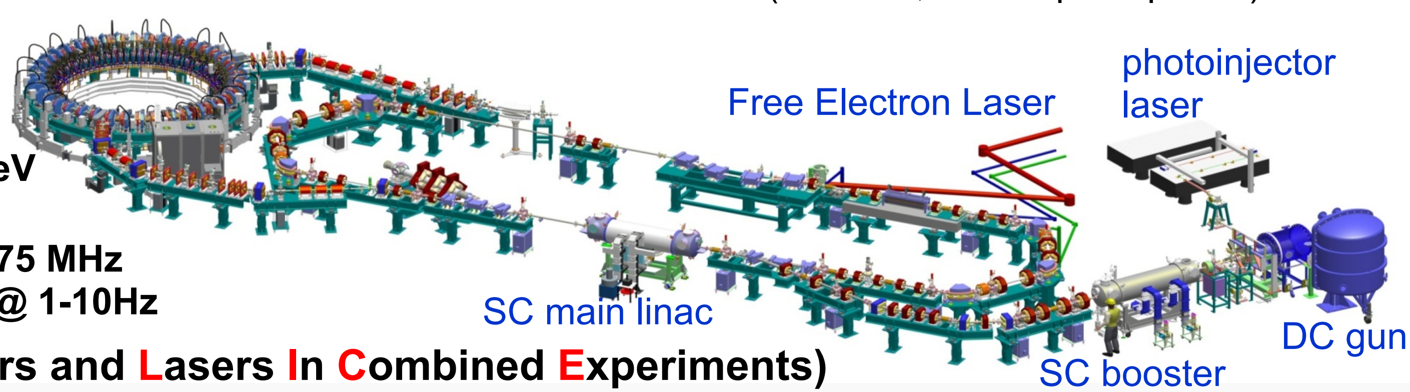


THz for biology



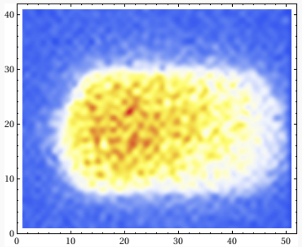


IR FEL & SNOM experiment
(5.7-8um, ~3MW peak power)

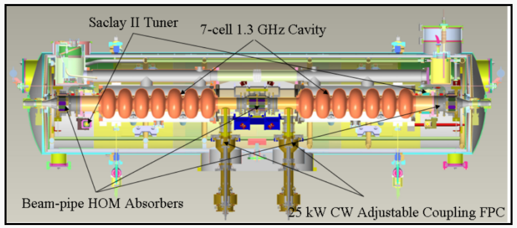


Energy: up to 27.5 MeV
Bunch : up to 100 pC
Repetition : up to 81.75 MHz
Bunch train : 100 μs @ 1-10Hz

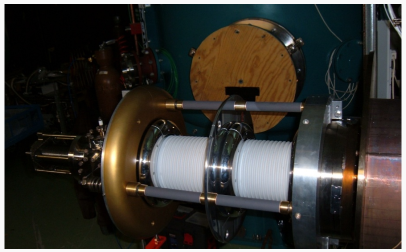
ALICE (Accelerators and Lasers In Combined Experiments)

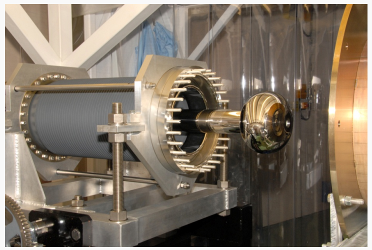


Compton Scattering
X-ray generation



Development of SRF module



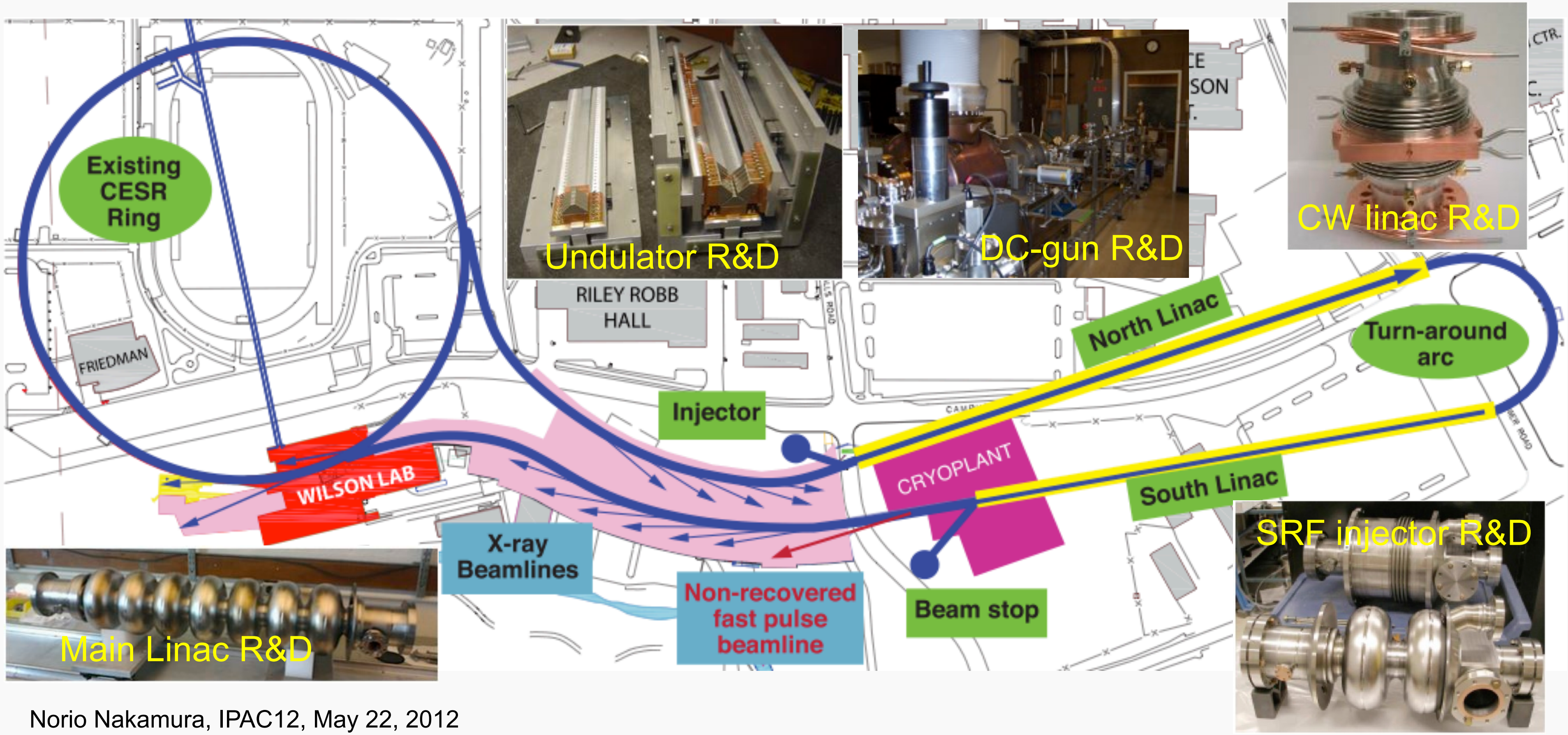


Gun Ceramic Change(230→325kV)

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

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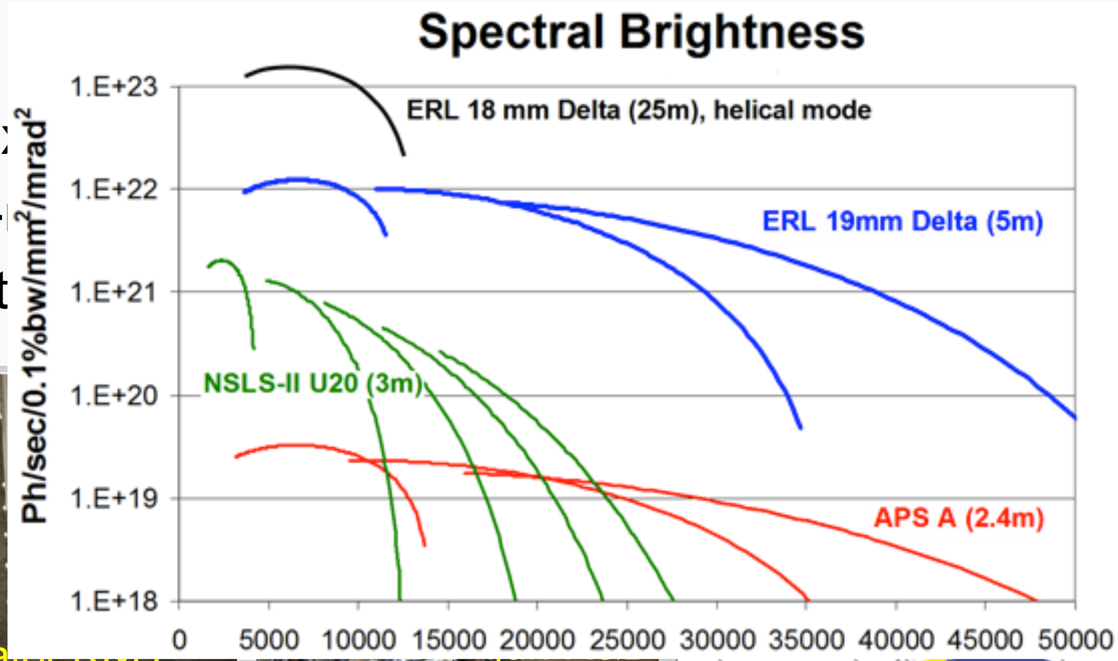
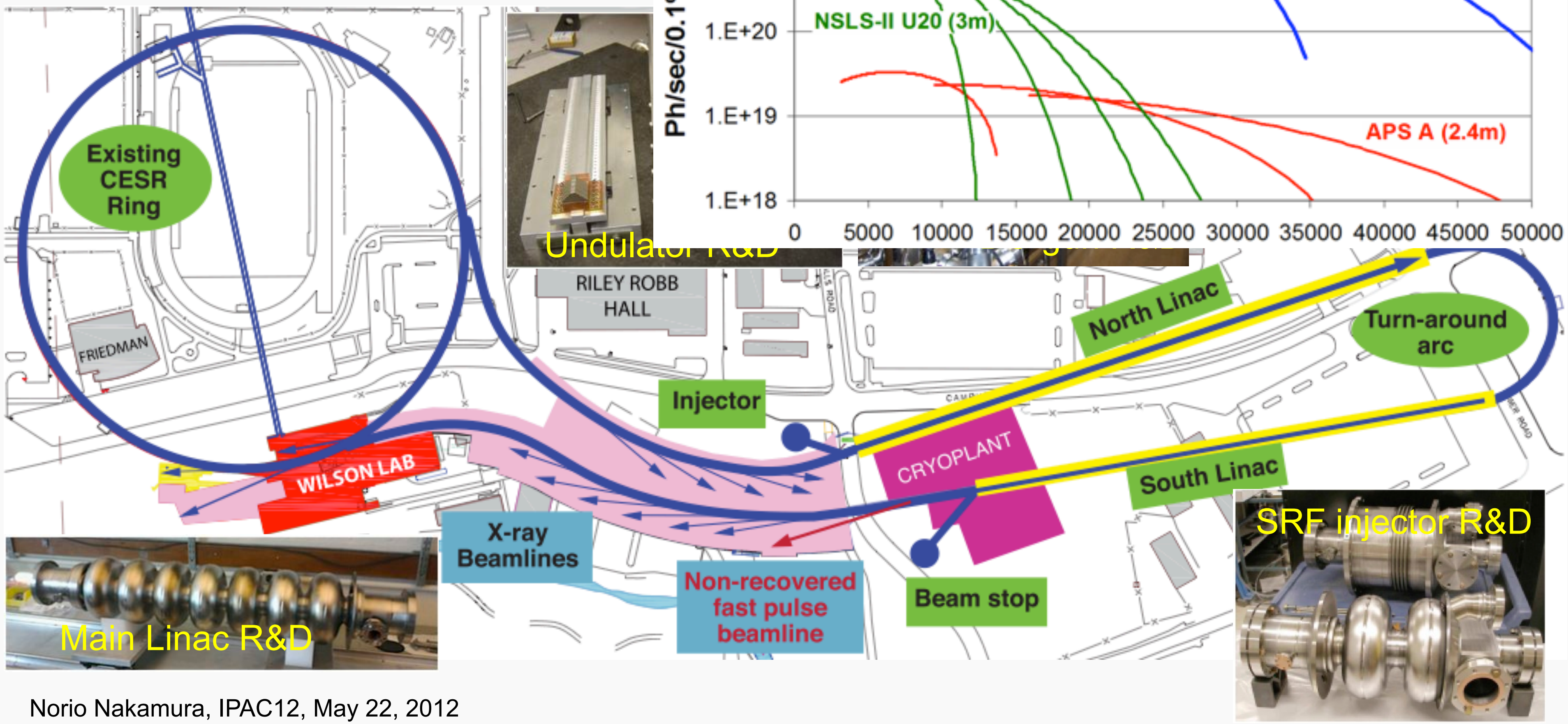
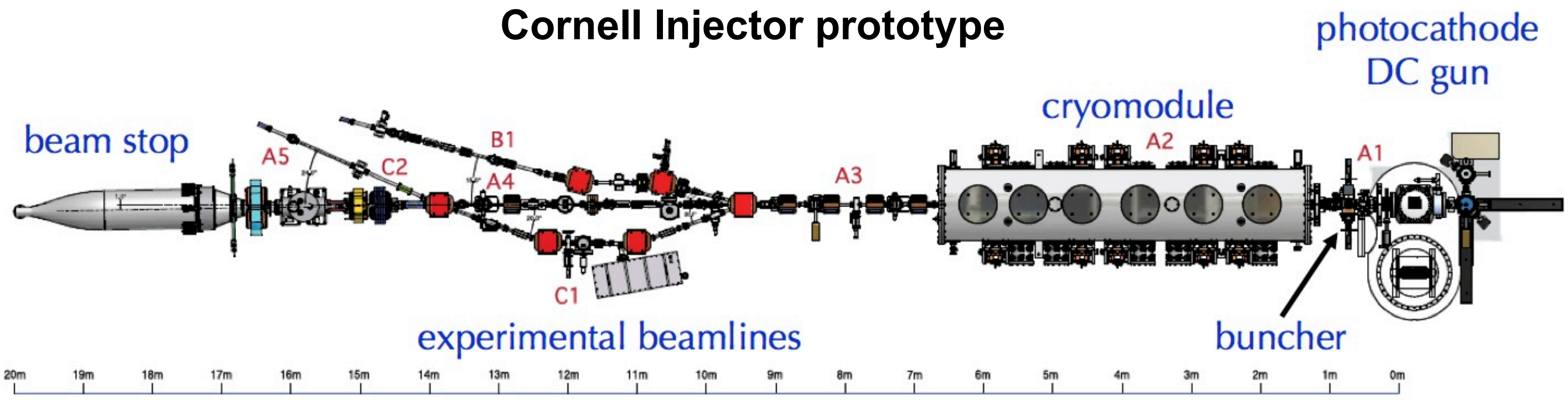
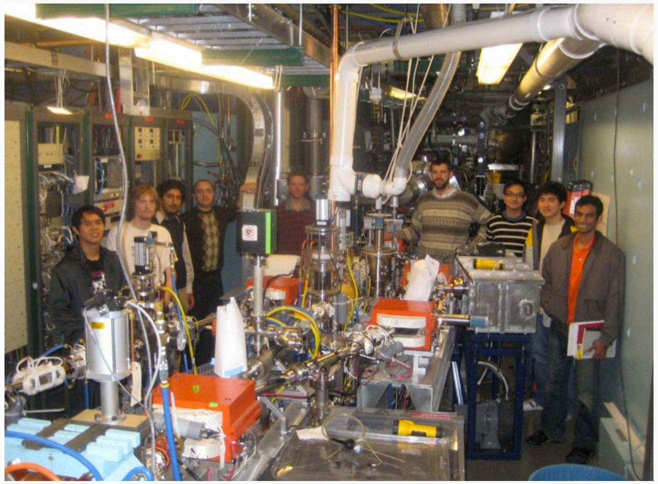




Injector Prototype @ Cornell University





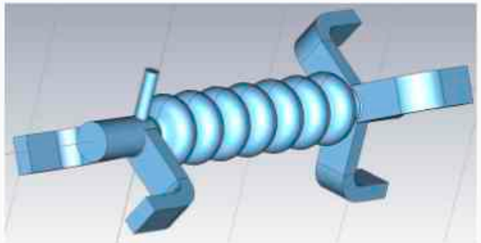
Achievements:

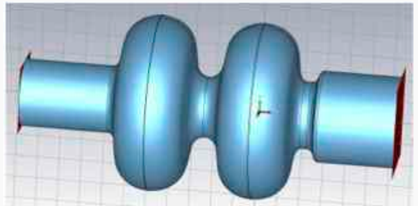
1) Max. DC-gun voltage: 440kV
2) Max. beam current: 52mA with GaAs
   (world record for photocathode guns)
3) 8-hour operation at 20mA with CsK_2Sb
4) Min. norm. emittance at 80pC: 0.7 mm·mrad
   with core norm. emittance : 0.3 mm·mrad
5) Largest injector-coupler power: 60kW
6) Largest SRF-cavity voltage: 13MV/m

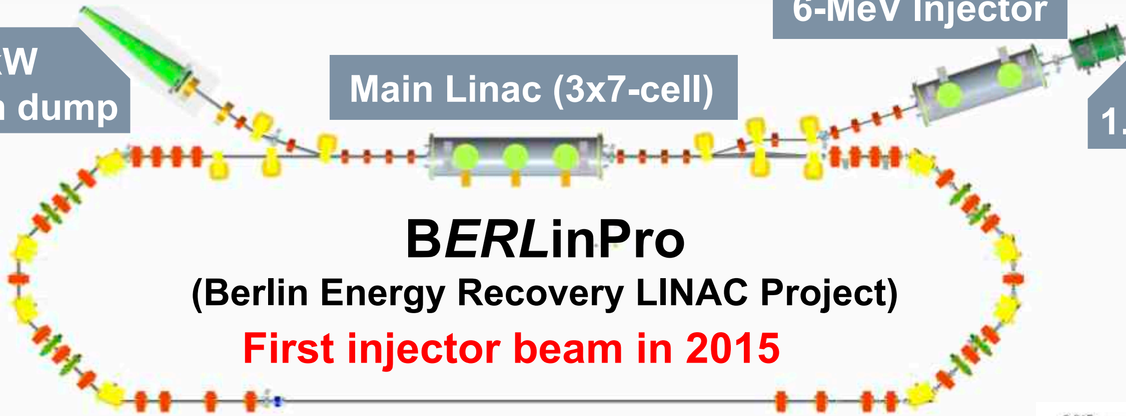
Achieved beam sufficient for an ultra-bright X-Ray ERL

B*ERL*inPro @ HZB

B*ERL*inPro: 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

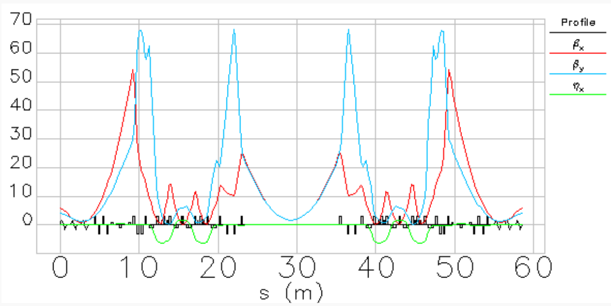

SC cavity for Injector



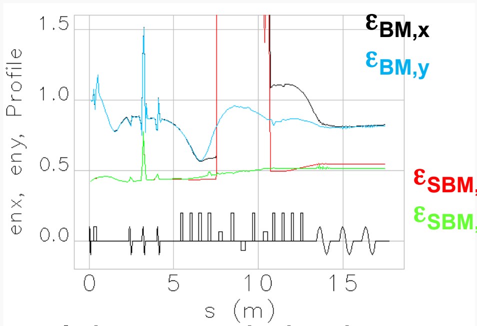
B*ERL*inPro

(Berlin Energy Recovery LINAC Project)

First injector beam in 2015

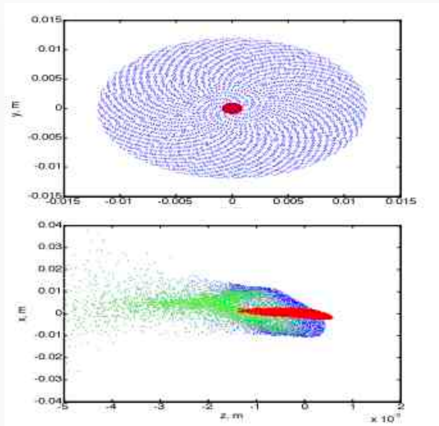


Optics for recirculation path



Injector optimization

Halo simulation



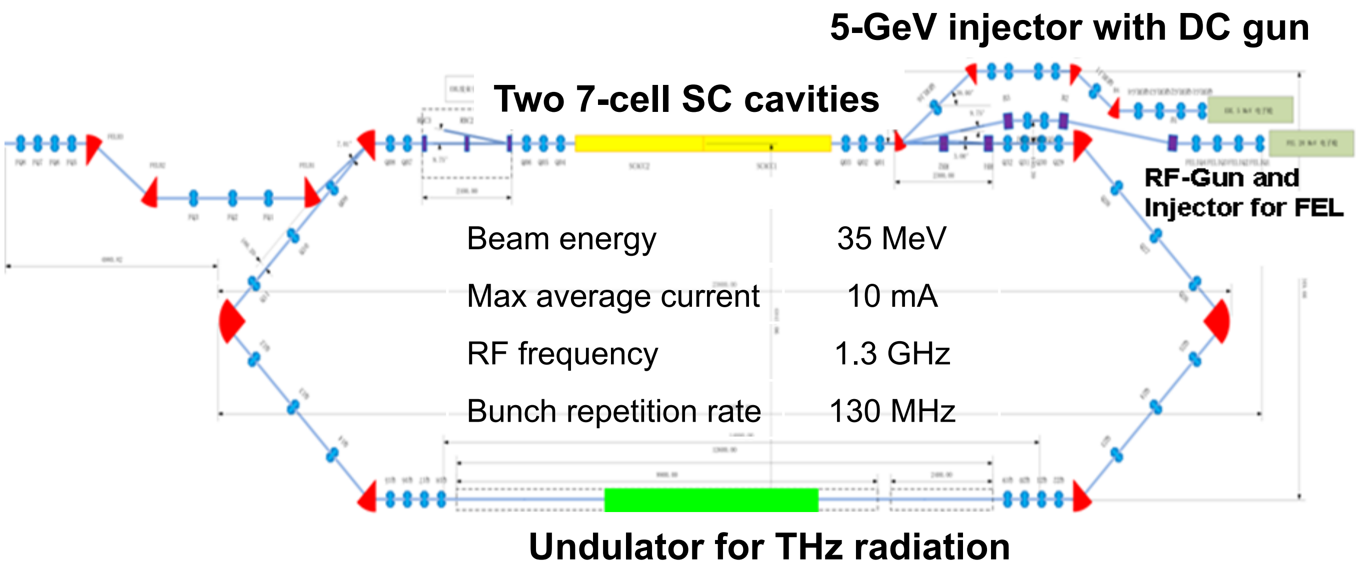
Norio Nakamura, IPAC12, May 22, 2012

IHEP-Beijing

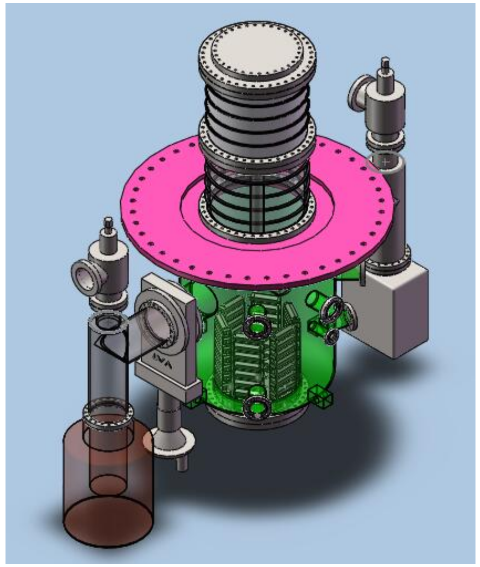
■ 500 kV DC-gun (with GaAs cathode as the 1st test) design is completed, and is funded by IHEP's innovation program, its construction is started.

■ 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

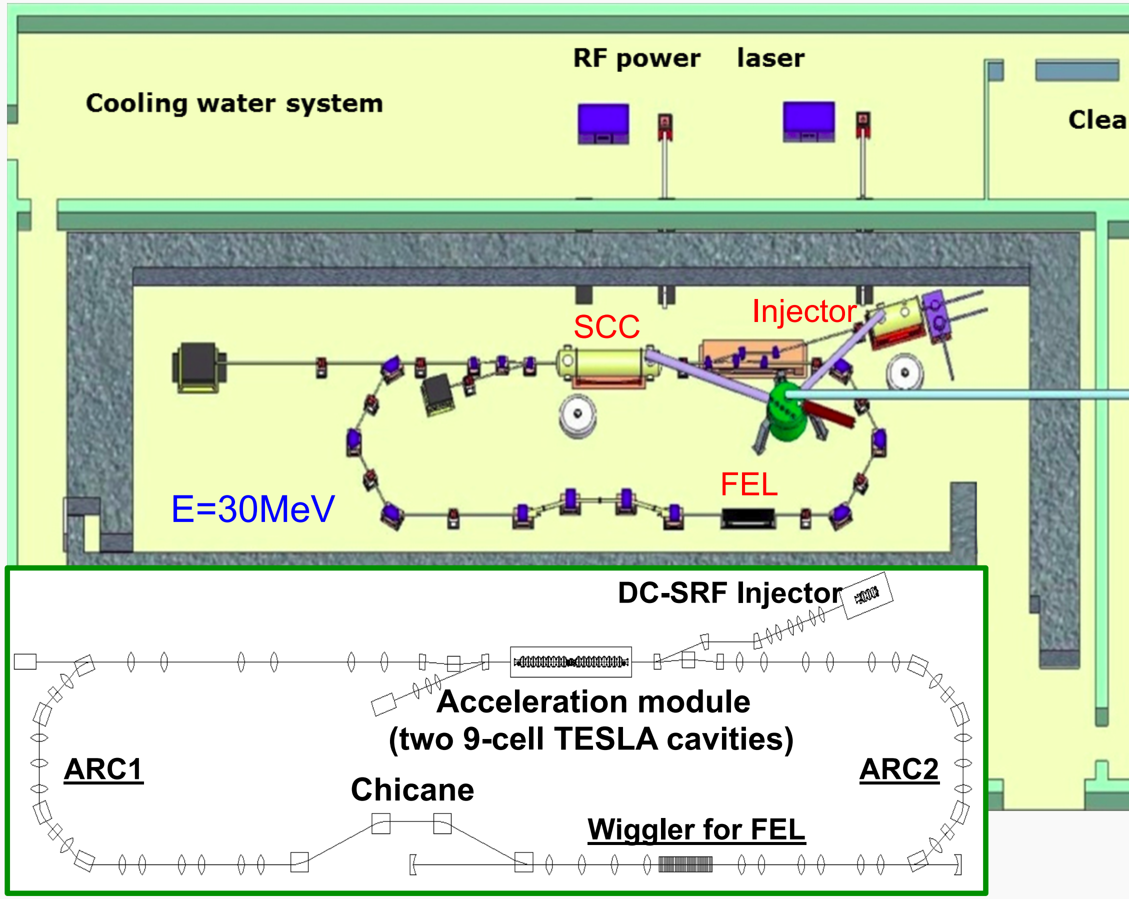


DC photocathode gun

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)



Lattice and optics design updated

DC SRF photo-injector
E_{acc}~11 MV/m,
Beam energy~2.5 MeV

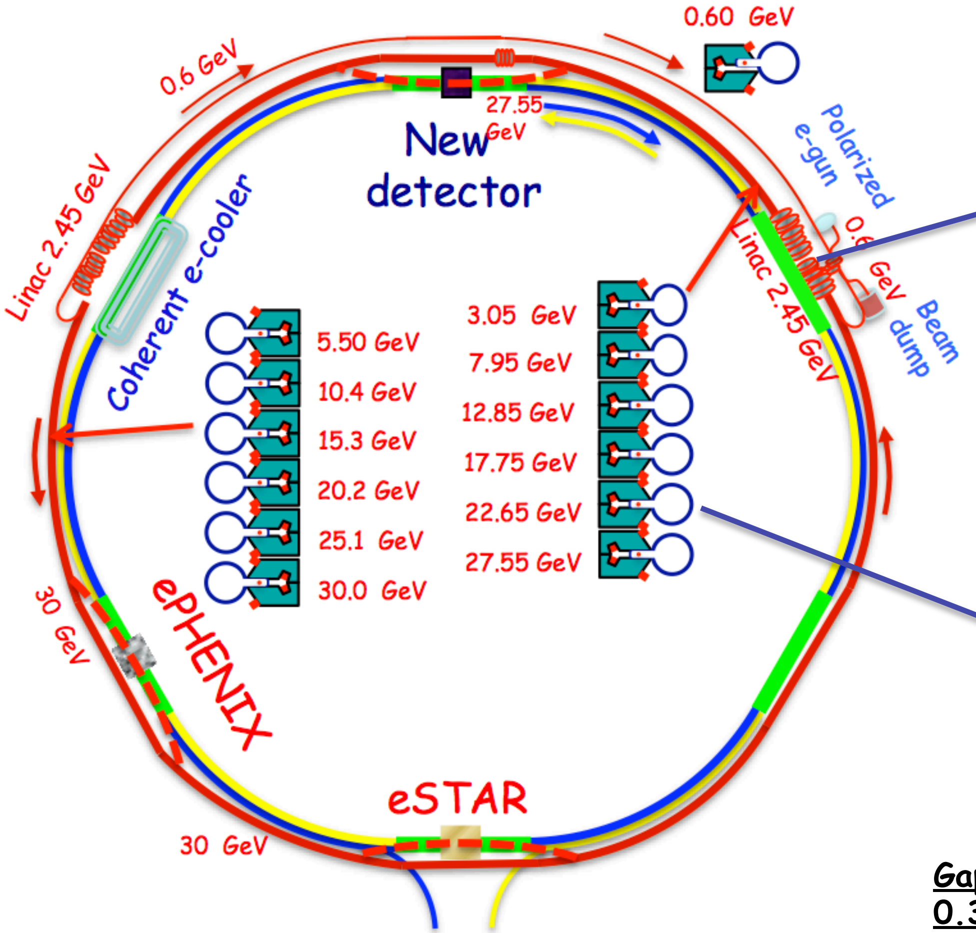
2K cryogenic system since 2010
(cooling capacity: 58W @2K)

eRHIC @ BNL

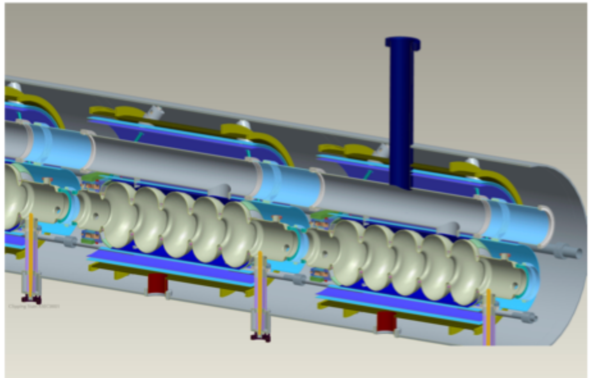
eRHIC (furure electron-hadron collider at RHIC)

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

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

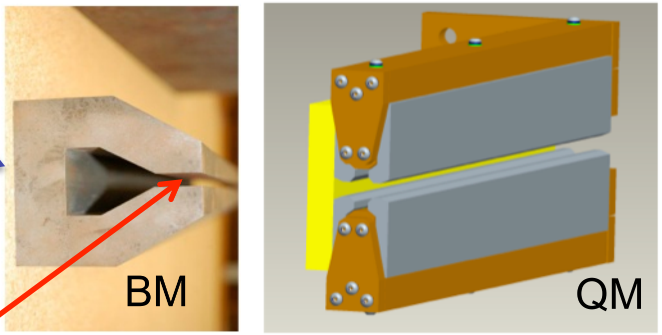


Total linac length : 200 m
Max. energy gain per pass : 2.45 GeV
Accelerating gradient : 19.2 MV/m



SRF Linac

More than 14000 magnets



Gap 5 mm total
0.3 T for 30 GeV

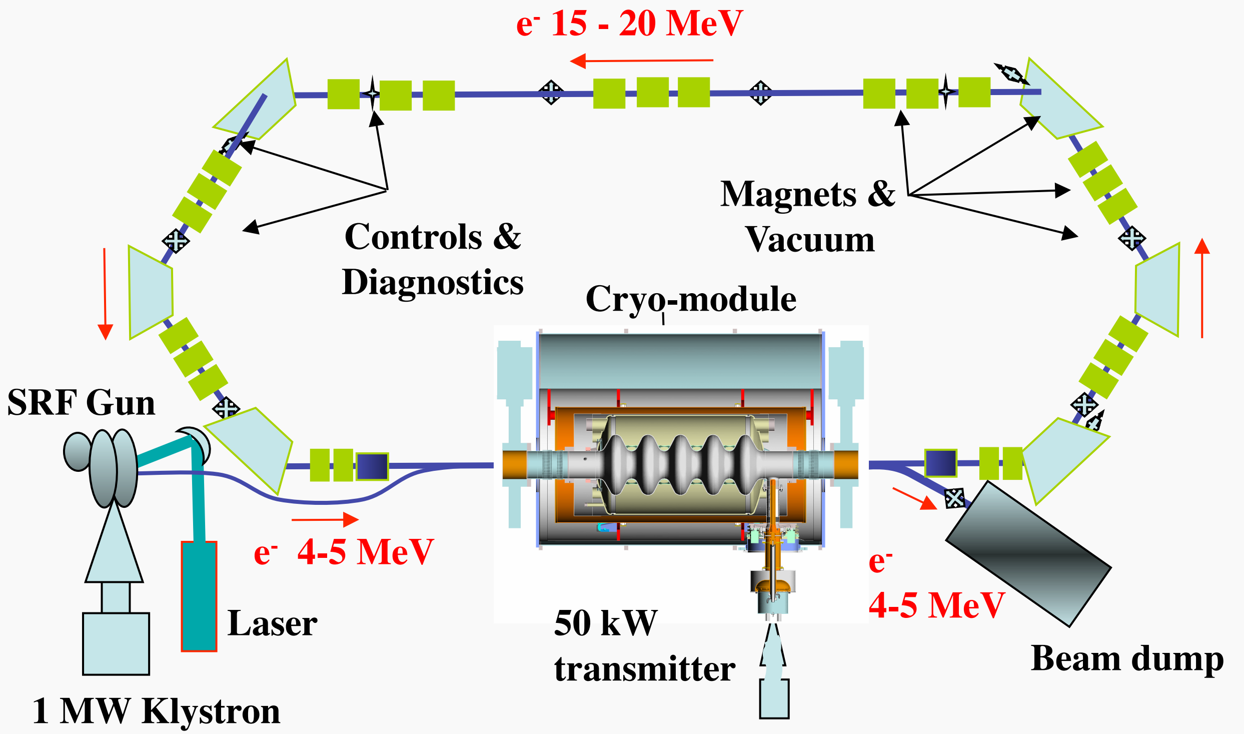
Compact magnets

Norio Nakamura, IPAC12, May 22, 2012

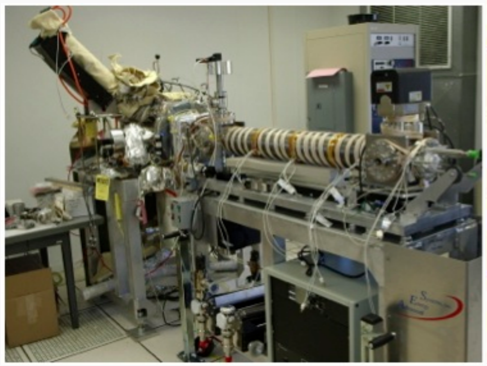
ERL Test Facility @ BNL

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



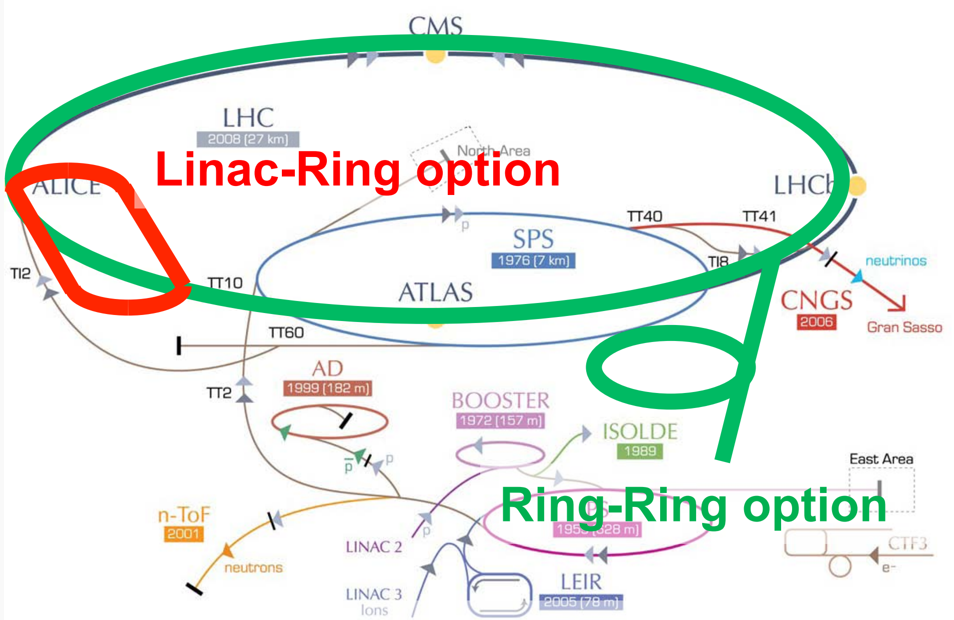
SRF gun



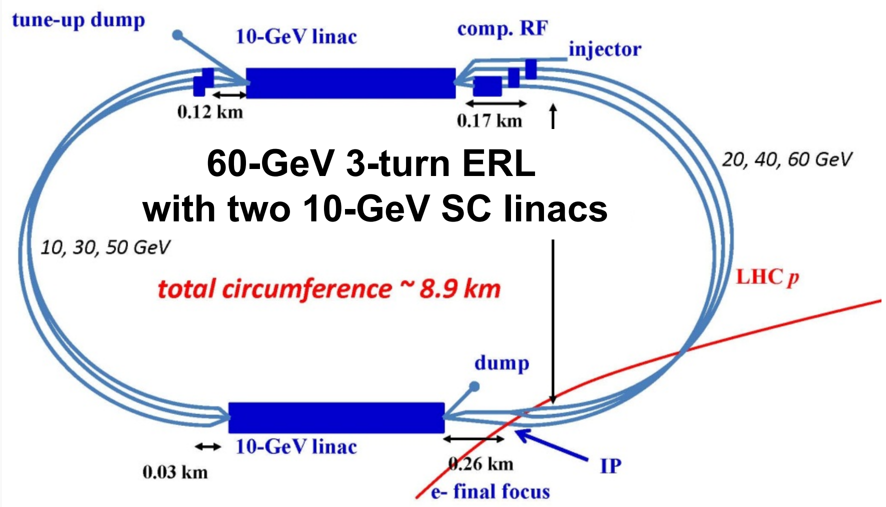
SRF gun
In cryomodule

Cryomodule
for SC cavity

LHeC @ CERN

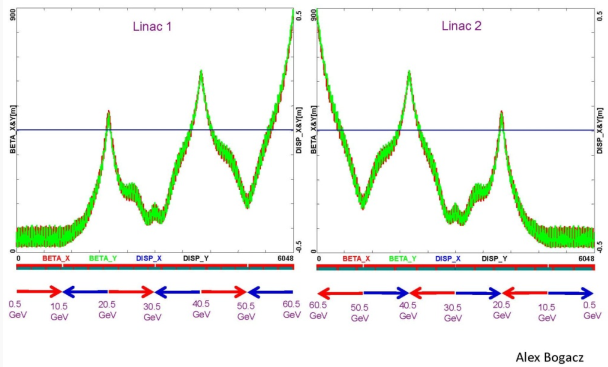


Large Hadron electron Collider (LHeC)



ERL configuration for Linac-Ring option

Linac beam optics



Advantages of Linac-Ring option :

(1) Higher luminosity potential up to 10^{34} cm^{-2} 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

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

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- 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.