FRXBB201

Beam Commissioning of Energy Recovery Linacs

9:30-10:00, May 17, 2013

IPAC2013

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[2] KEK, High Energy Accelerator Research Organization

Outline

- Introduction
  - Energy Recovery Linac
- ERL projects in the world
- 3 GeV ERL project at KEK
- Construction of Compact ERL (cERL)
- Beam commissioning of cERL injector
- Summary

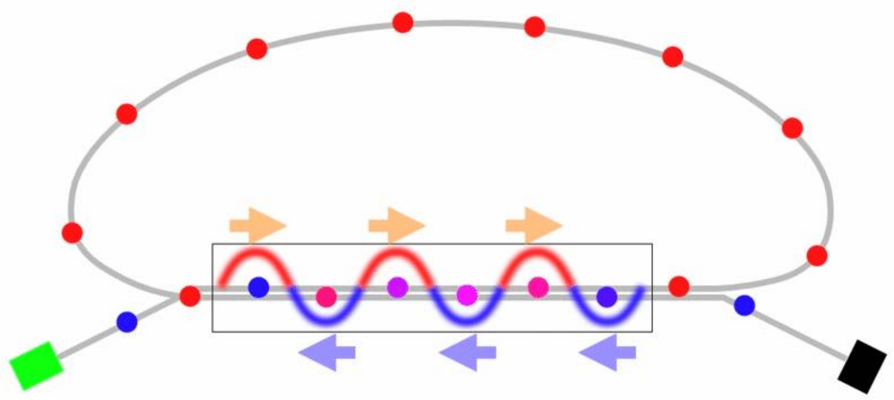
I apologize to you that I can not attend the IPAC2013 by my family emergency.
Tsukasa Miyajima

Introduction

- Energy Recovery Linac

Energy Recovery Linac for synchrotron light source

- Energy Recovery Linac
  - Fresh electron beam is always generated by electron gun.
  - Injected beam is accelerated by main linac.
  - After recirculation, the beam is decelerated and energy is recovered by main linac.



Advantage:

- Low emittance and short bunch, as linac based feature.
- High average current, thanks to energy recovery

Difficulties to be overcome:

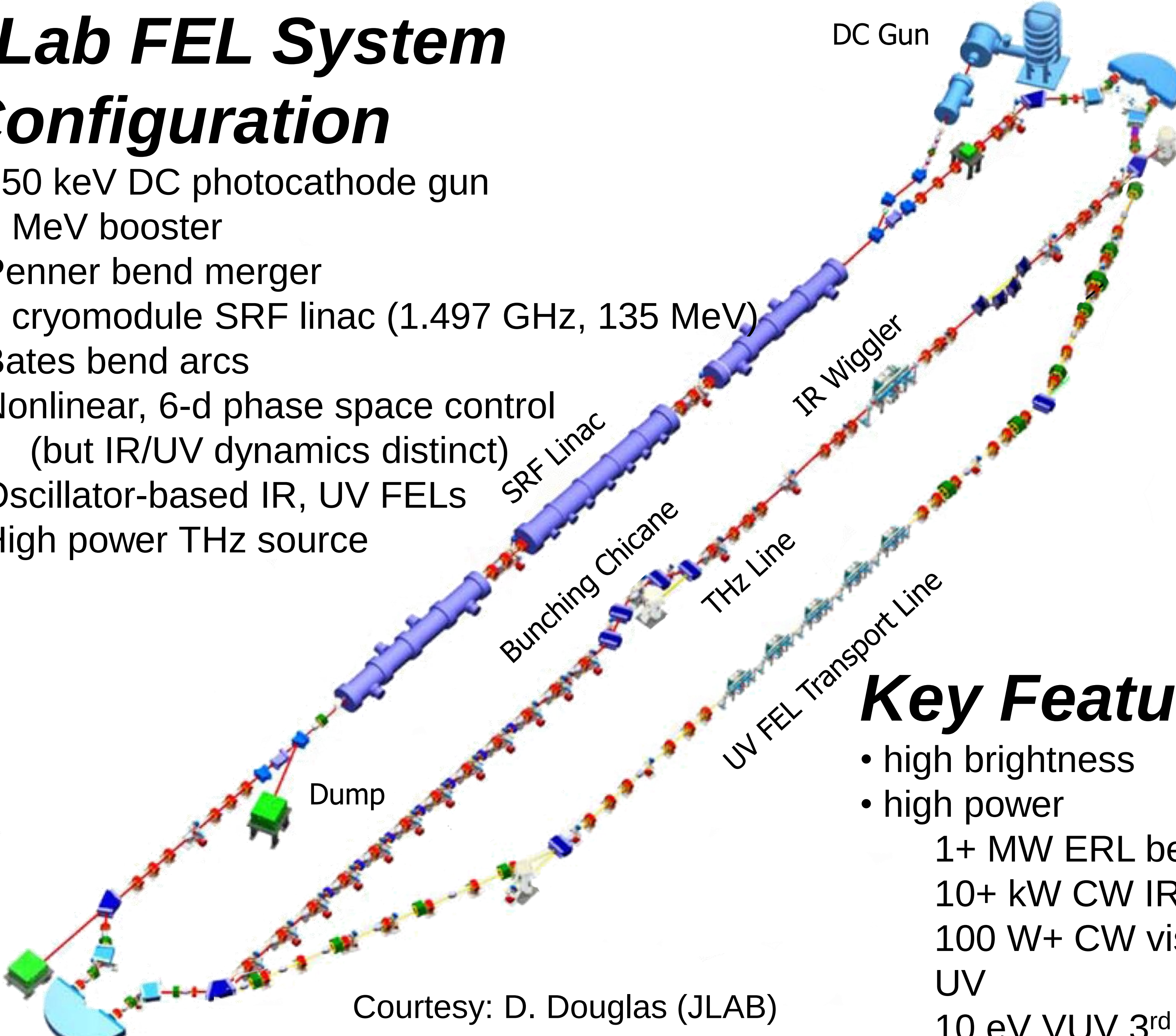
- Generation of a low-emittance beam from an injector
- Stable acceleration of a high-average current beam.

ERL projects in the world

- ERL projects in the world

JLab FEL System Configuration

- 350 keV DC photocathode gun
- 9 MeV booster
- Penner bend merger
- 3 cryomodule SRF linac (1.497 GHz, 135 MeV)
- Bates bend arcs
- Nonlinear, 6-d phase space control
  (but IR/UV dynamics distinct)
- Oscillator-based IR, UV FELs
- High power THz source



Courtesy: D. Douglas (JLAB)

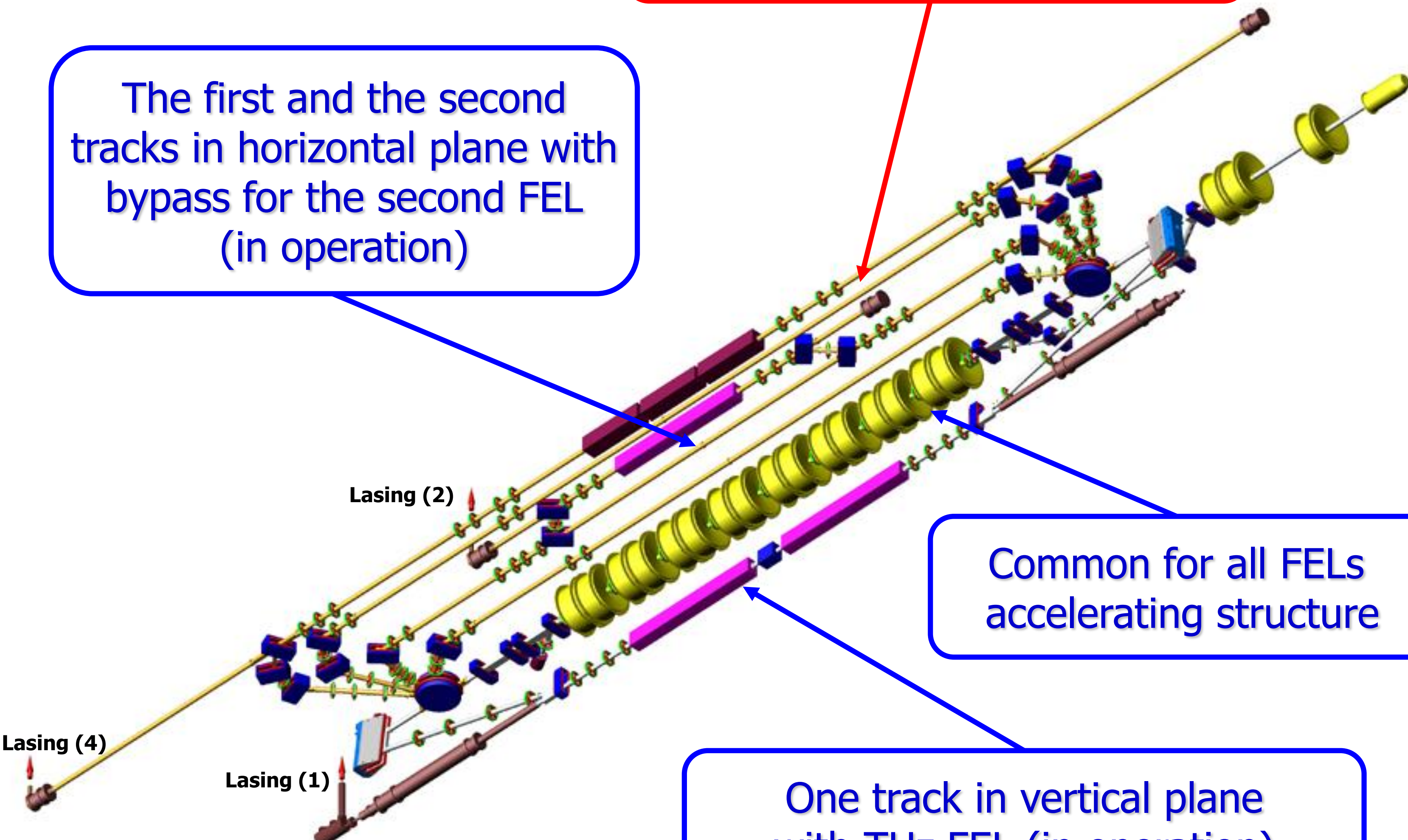
Key Features

- high brightness
- high power
  - 1+ MW ERL beam power
  - 10+ kW CW IR
  - 100 W+ CW visible/near UV
  - 10 eV VUV 3rd harmonic
- operational flexibility

BINP

The third and the fourth tracks with IR FEL (commissioning)

The first and the second tracks in horizontal plane with bypass for the second FEL (in operation)



Common for all FELs accelerating structure

One track in vertical plane with THz FEL (in operation)

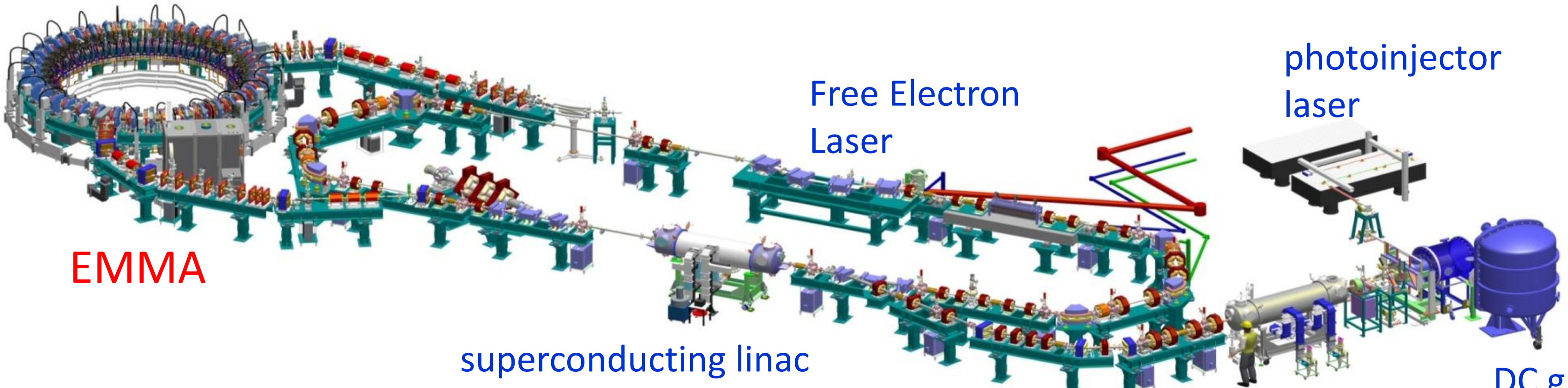
Courtesy: N. Vinokurov(BINP)

The ALICE Facility @ Daresbury Laboratory

Accelerators and Lasers In Combined Experiments

Alice
Accelerators and Lasers
In Combined Experiments

An accelerator R&D facility based on a superconducting energy recovery linac

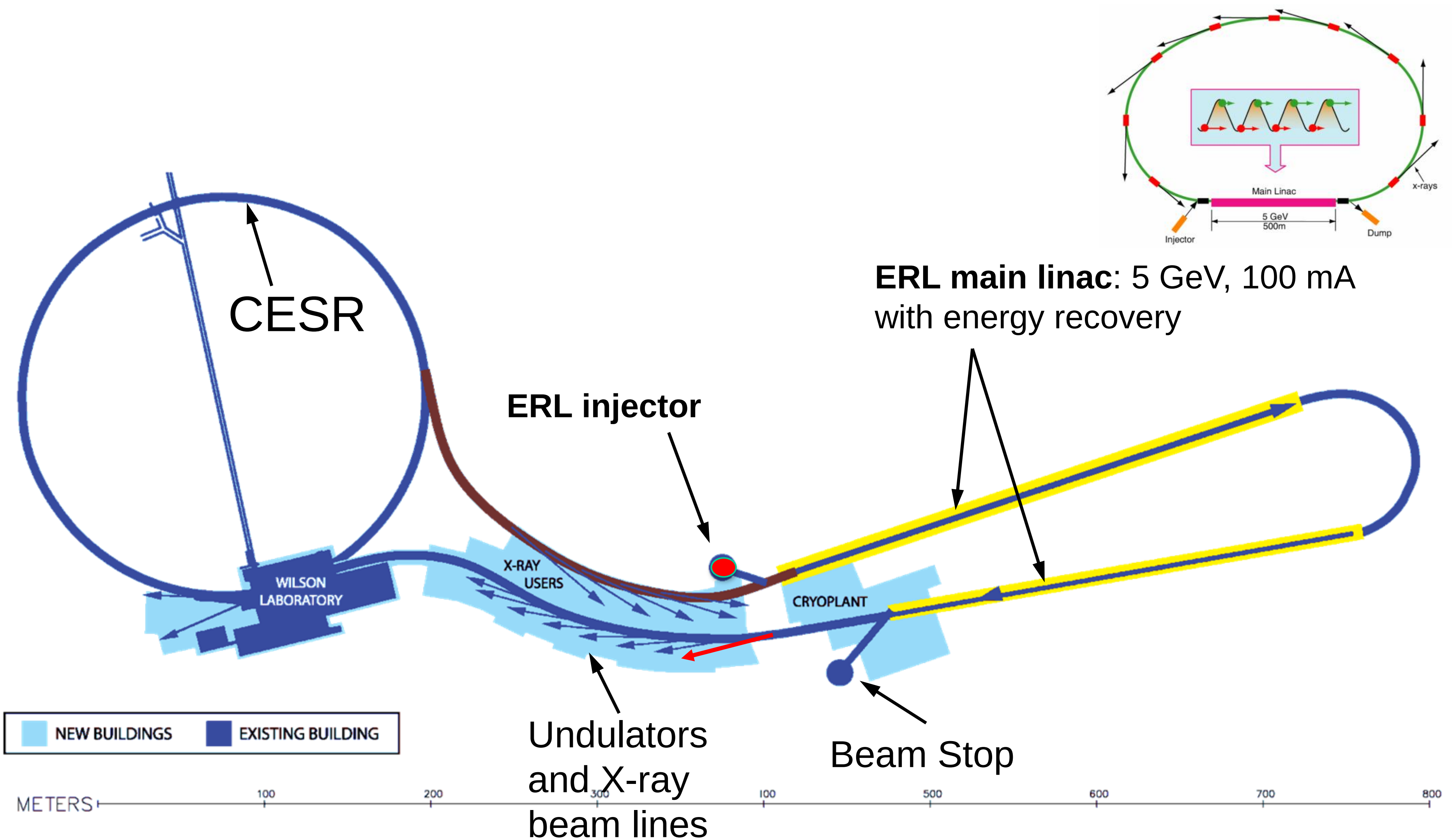


SRF: 1.3 GHz
Injector: 6.5 MeV
Loop: 12.0 – 26.0 (27.5) MeV

Bunch charge: 40-60 pC
Bunch rep: up to 81.25 MHz (variable)
Bunch train: 0 - 100 μs x 1-10 Hz

Courtesy: S. Smith (Daresbury)

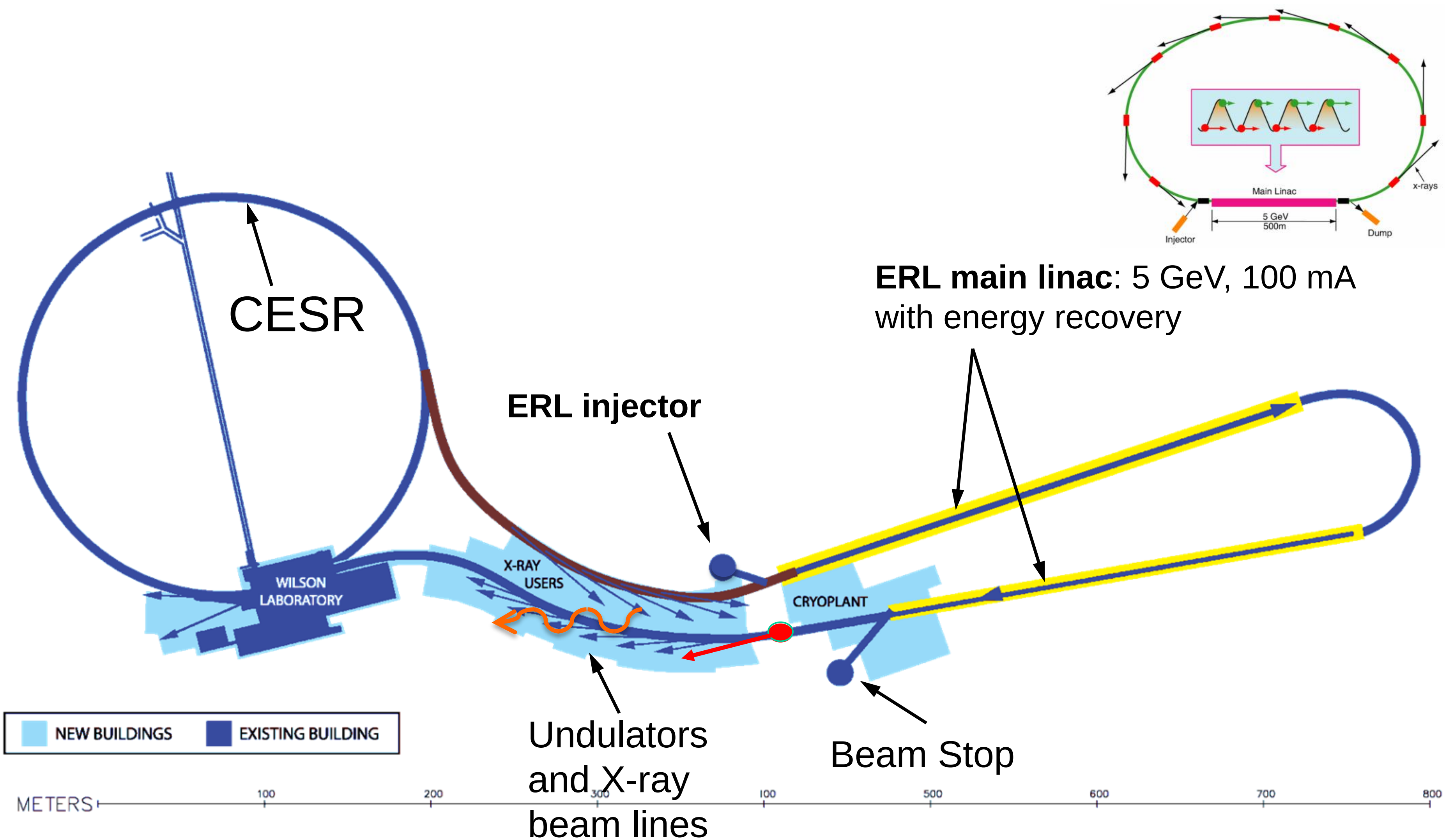
Cornell University



Courtesy: I. Bazarov (Cornell University)

slide credit: M. Liepe

Cornell University



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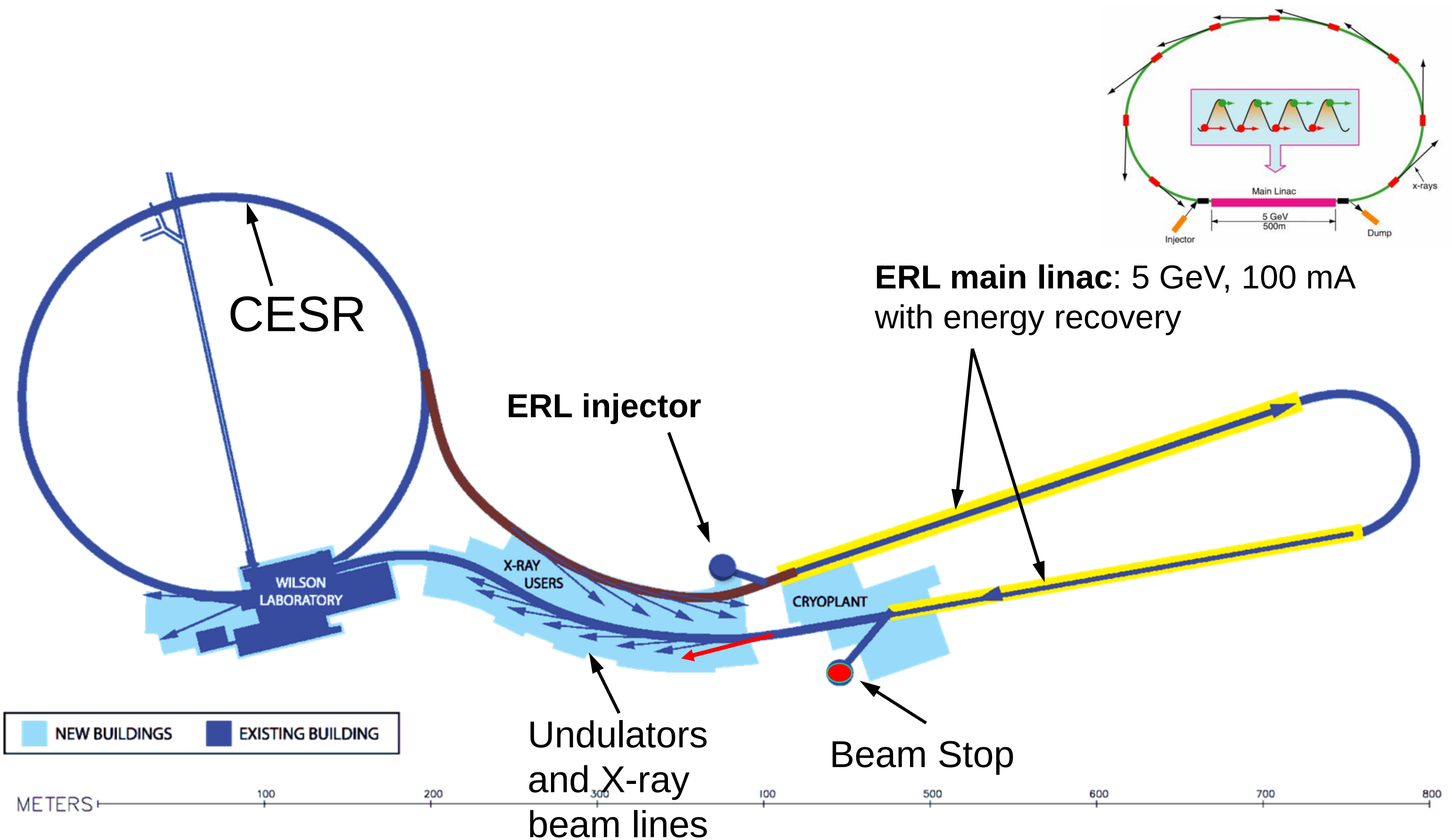
Cornell University

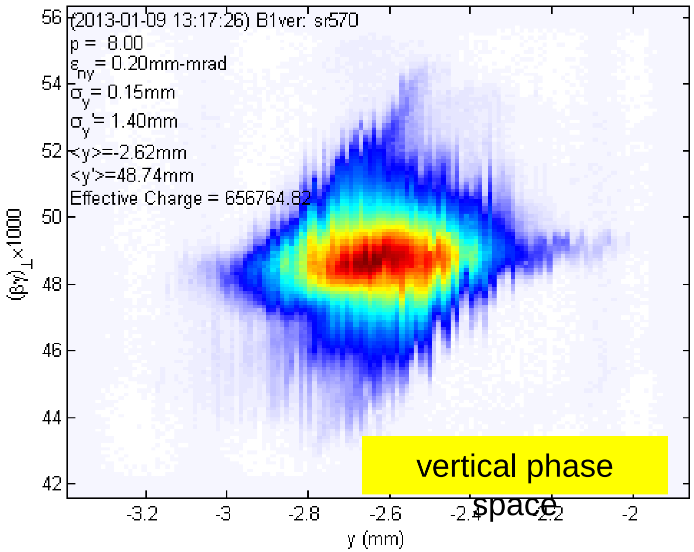


Courtesy: I. Bazarov (Cornell University)

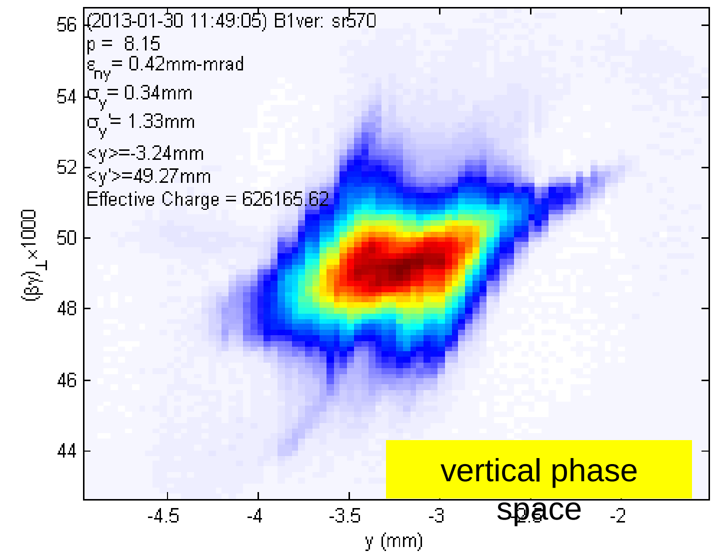
slide credit: M. Liepe

ultra-low emittance beam at the Cornell injector

20 pC/bunch



80 pC/bunch



Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps rms

0.22/0.15 mm-mrad **0.49/0.29 mm-mrad**

Normalized rms core* emittance (horizontal/vertical) @ core fraction (%)

0.14/0.09 mm-mrad @ 68% **0.24/0.18 mm-mrad @ 61%**

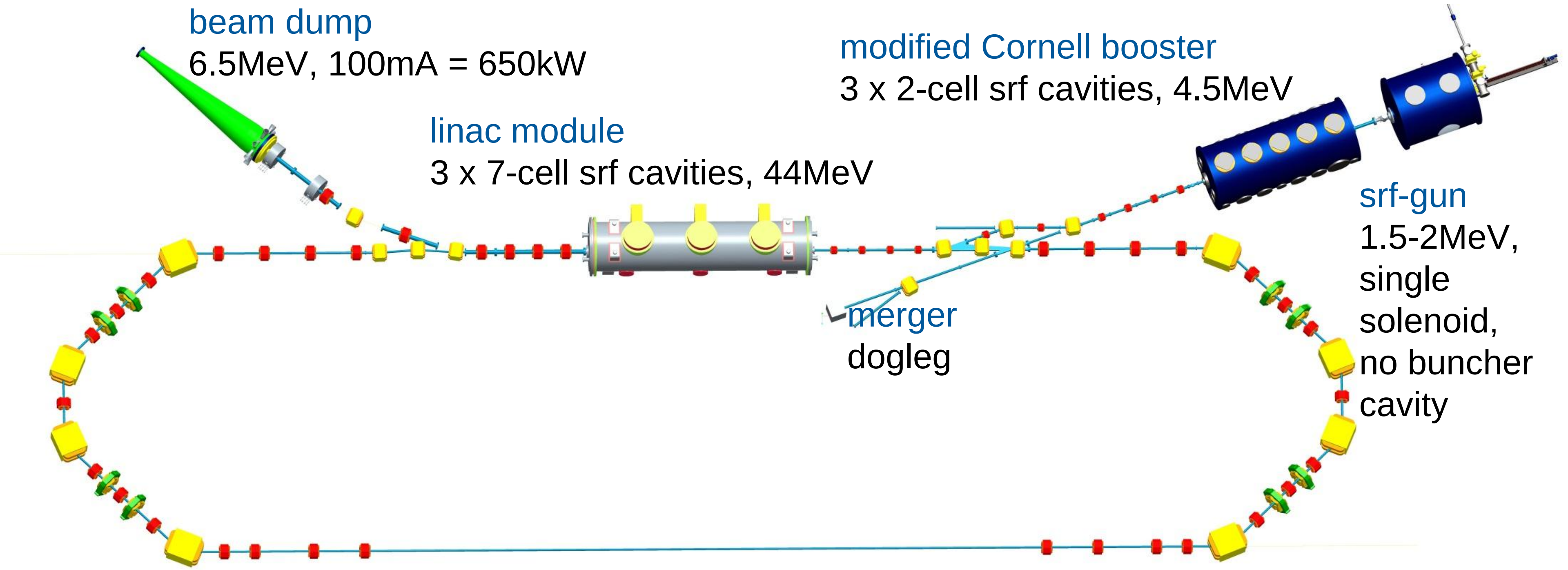
20x the brightness at 5 GeV of the best storage ring (1nm-rad hor. emittance 100 mA)!
Similar to the best NCRF guns emittance but with > 10^6 repetition rate (duty factor = 1)

Courtesy: I. Bazarov (Cornell University) ***Phys. Rev. ST-AB 15 (2012) 050703**

BERLinPro at Helmholtz-Zentrum Berlin (HZB)

B*ERL*inPro = Berlin Energy Recovery Linac Project

100mA / low emittance technology demonstrator (covering key aspects of large scale ERL)



Project start 2011,
fully funded (36.5 M€)

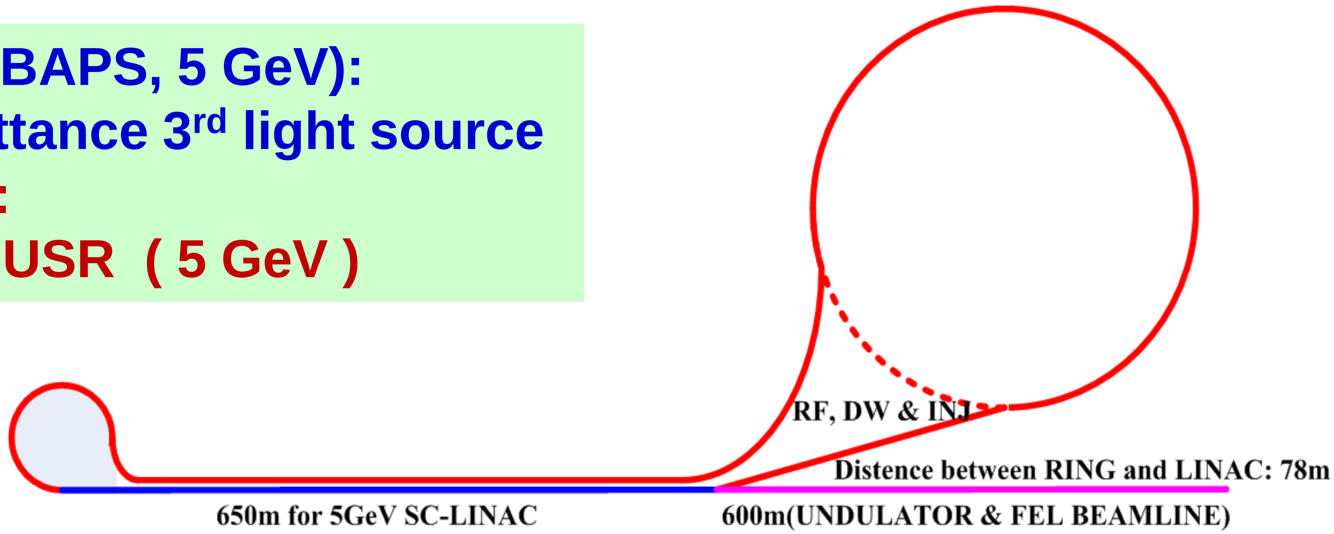
	Basic Parameter
max. beam energy	**50MeV**
max. current	**100mA (77pC/bunch)**
normalized emittance	**1 π mm mrad**
bunch length (straight)	**2 ps or smaller**
rep. rate	**1.3GHz**
losses	**< 10^{-5}**

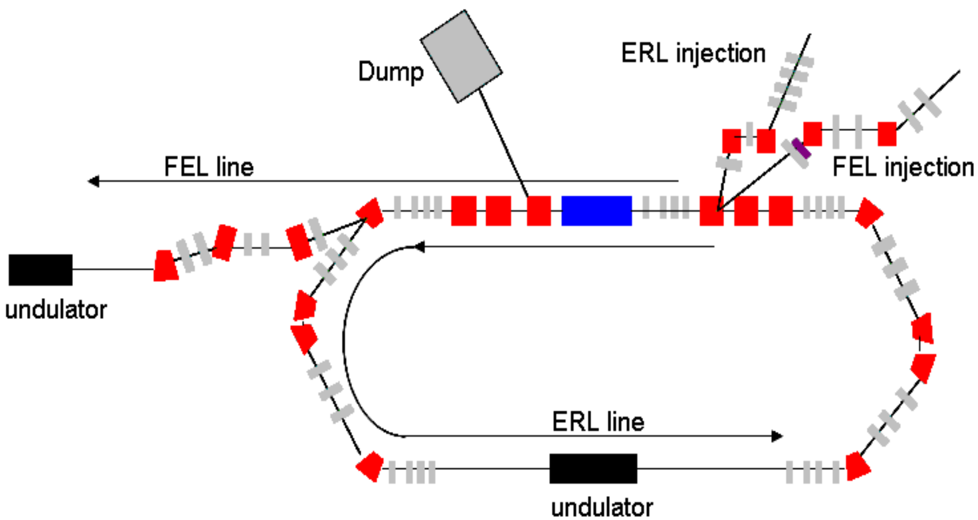
Courtesy: A. Jankowiak (HZB)

Beijing Advanced Photon Source at IHEP

(BAPS and Future Plan)

1st Phase (BAPS, 5 GeV):
Low emittance 3rd light source
2nd Phase :
XERL or USR (5 GeV)





IHEP-ERL Test Facility

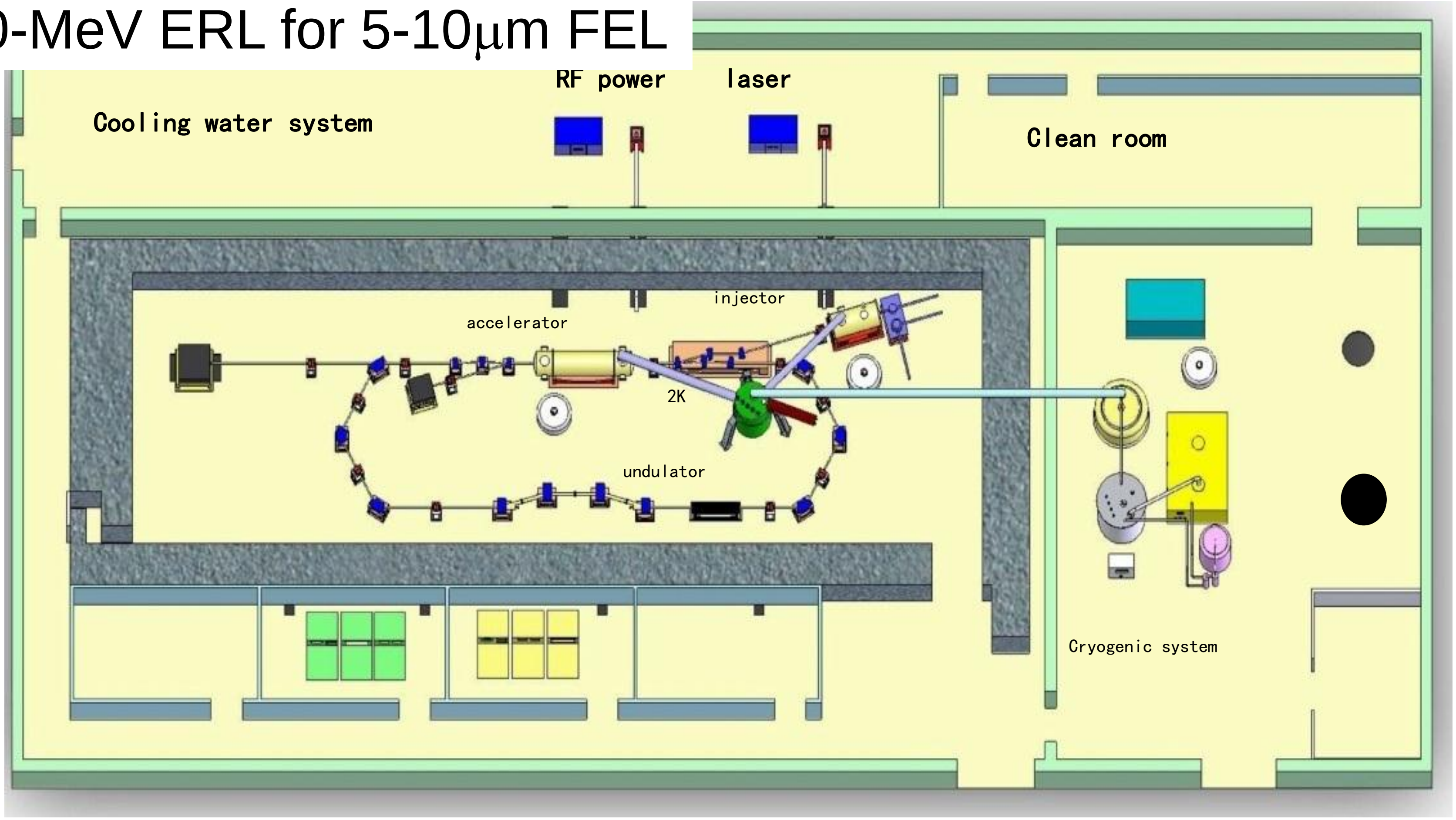
(35 MeV- 10 mA)

Conceptual design and gun construction are in progress

Courtesy: S. H. Wang, J. Q. Wang (IHEP)

PKU-ERL (Peking University)

30-MeV ERL for 5-10μm FEL



PKU-ERL consists of DC-SRF photocathode injector, main superconducting accelerator, beam transport loop, undulater and beam dump

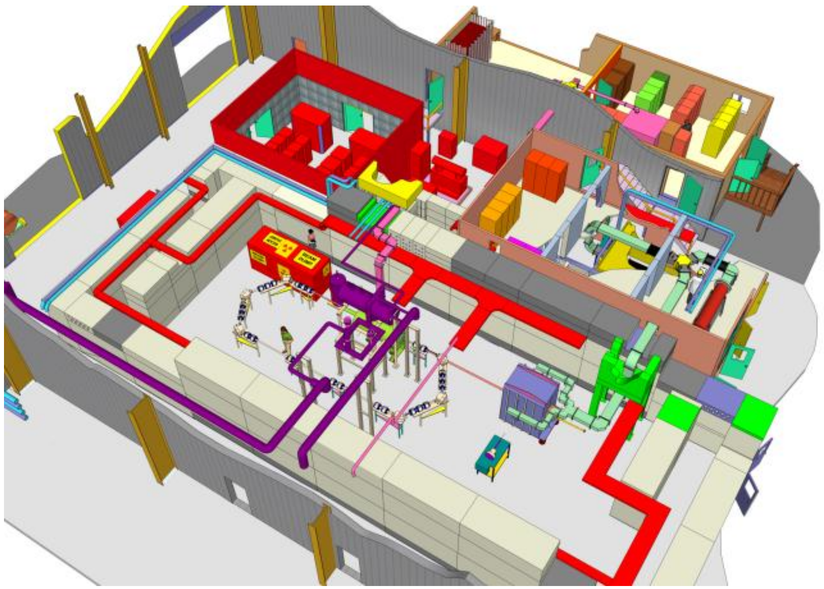
Courtesy: L. X. Liu (Peking U.)

IHIP, Peking University, China

The R&D Energy Recovery Linac at BNL

BROOKHAVEN NATIONAL LABORATORY

A test facility for high energy electron cooling and electron ion colliders.



	High Current	High charge
Charge per bunch, nC	0.5	5
Numbers of passes	1	1
Energy maximum/injection, MeV	20/2.5	20/3.0
Bunch rep-rate, MHz	700	9.383
Average current, mA	350	50
Injected/ejected beam power, kW	750	15
R.m.s. Normalized emittances ex/ey, mm*mrad	1.4/1.4	4.8/5.3
R.m.s. Energy spread, $\delta E/E$	$3.5 \text{x} 10^{-3}$	$1 \text{x} 10^{-2}$
R.m.s. Bunch length, ps	18	31

SRF Linac CET (done 2009)

SRF Gun CET (done 2012)

First beam test: Summer of 2013

Courtesy: D. Kayran (BNL)

3 GeV ERL project at KEK

3GeV ERL Light Source Plan at KEK

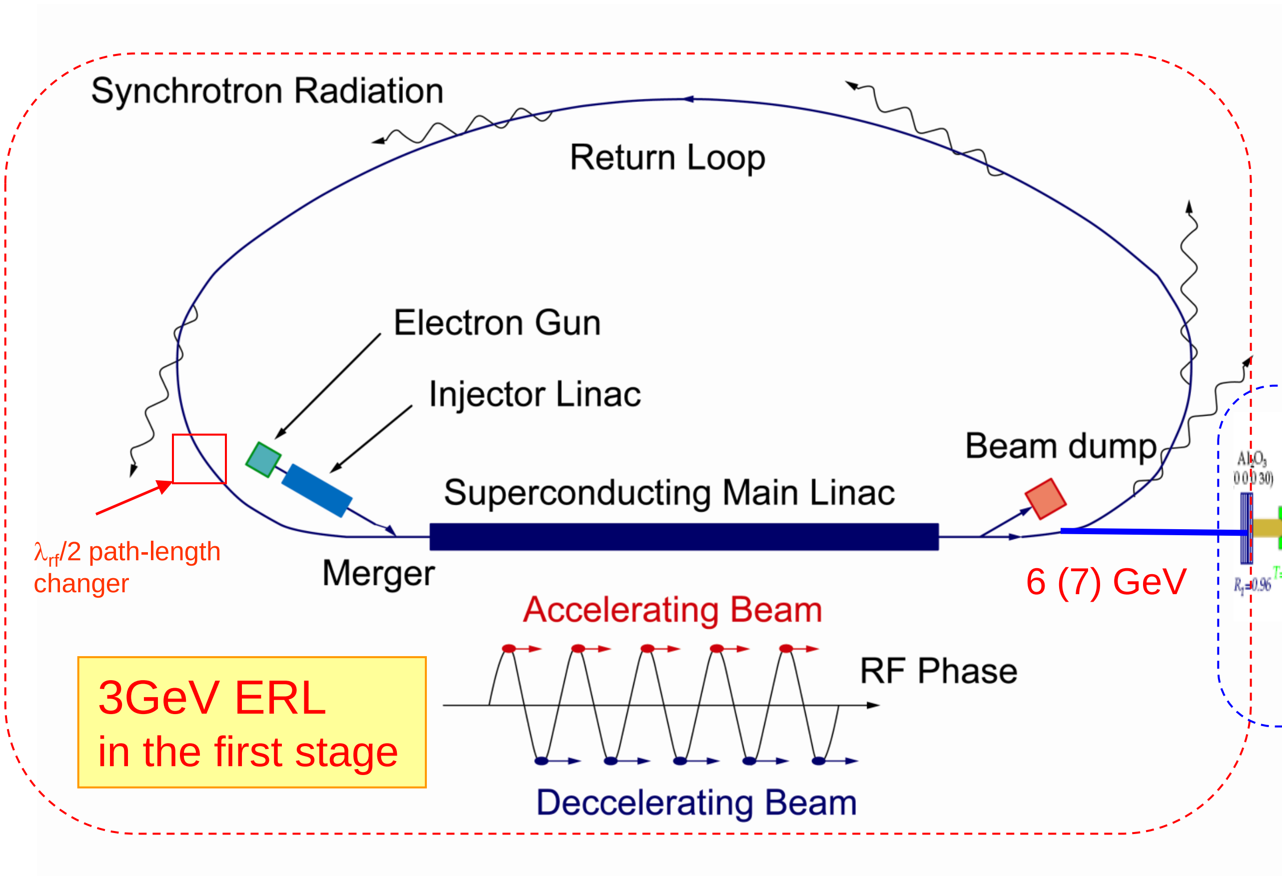
Shogo Sakanaka
FLS2012

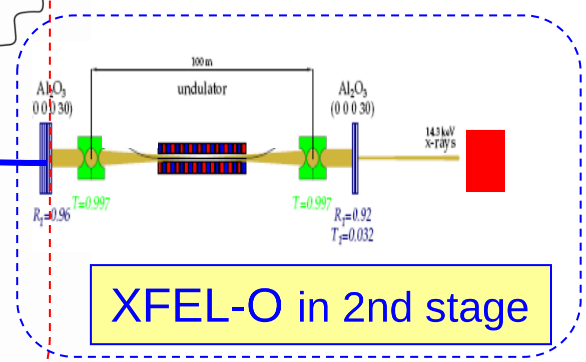
Needs for future light source at KEK

- Driving cutting-edge science
- Succeeding research at the Photon Factory (2.5 GeV and 6.5 GeV rings)

3-GeV ERL that is upgradable to an XFEL oscillator

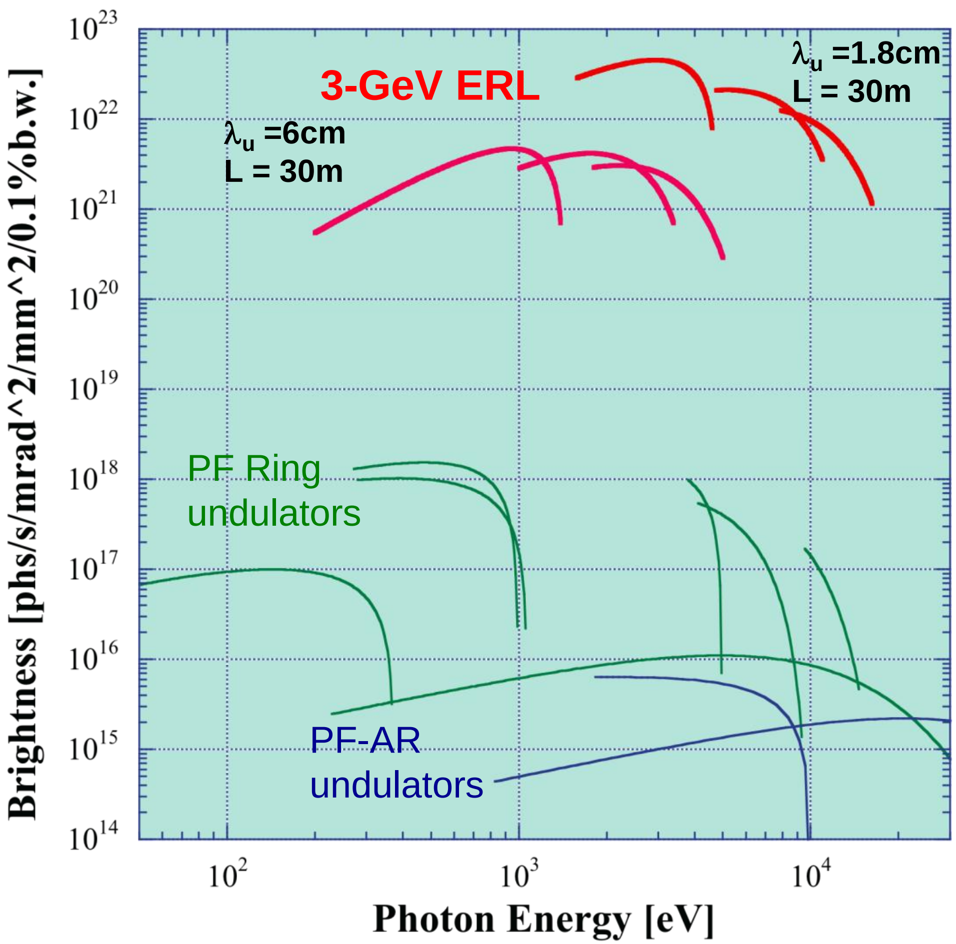
Layout and beam optics are under design.





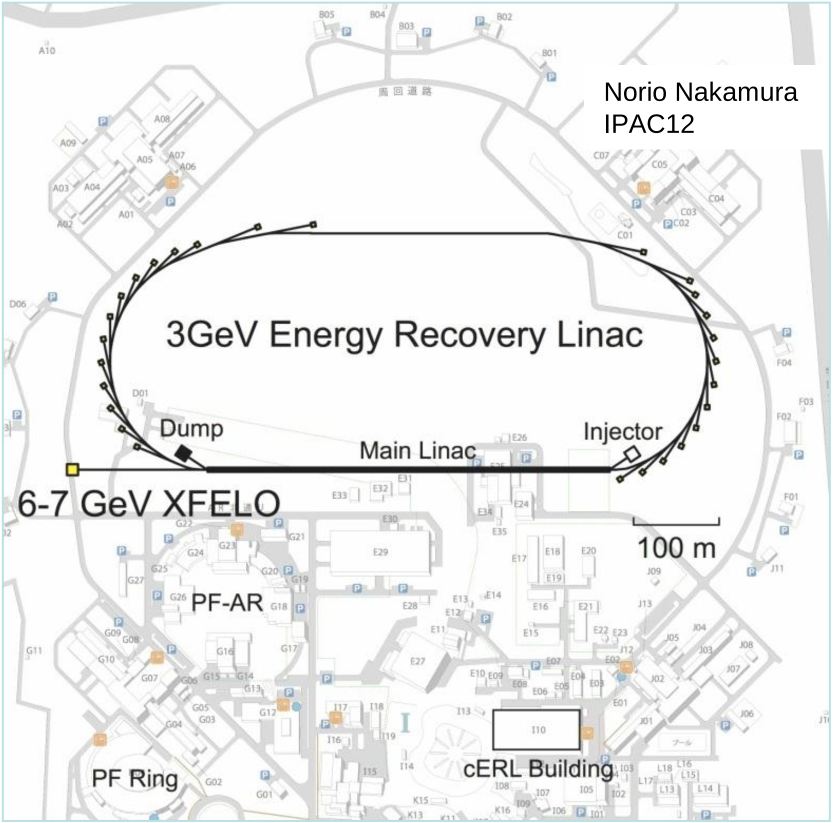
Expected Performance of the 3-GeV ERL

Spectral Brightness



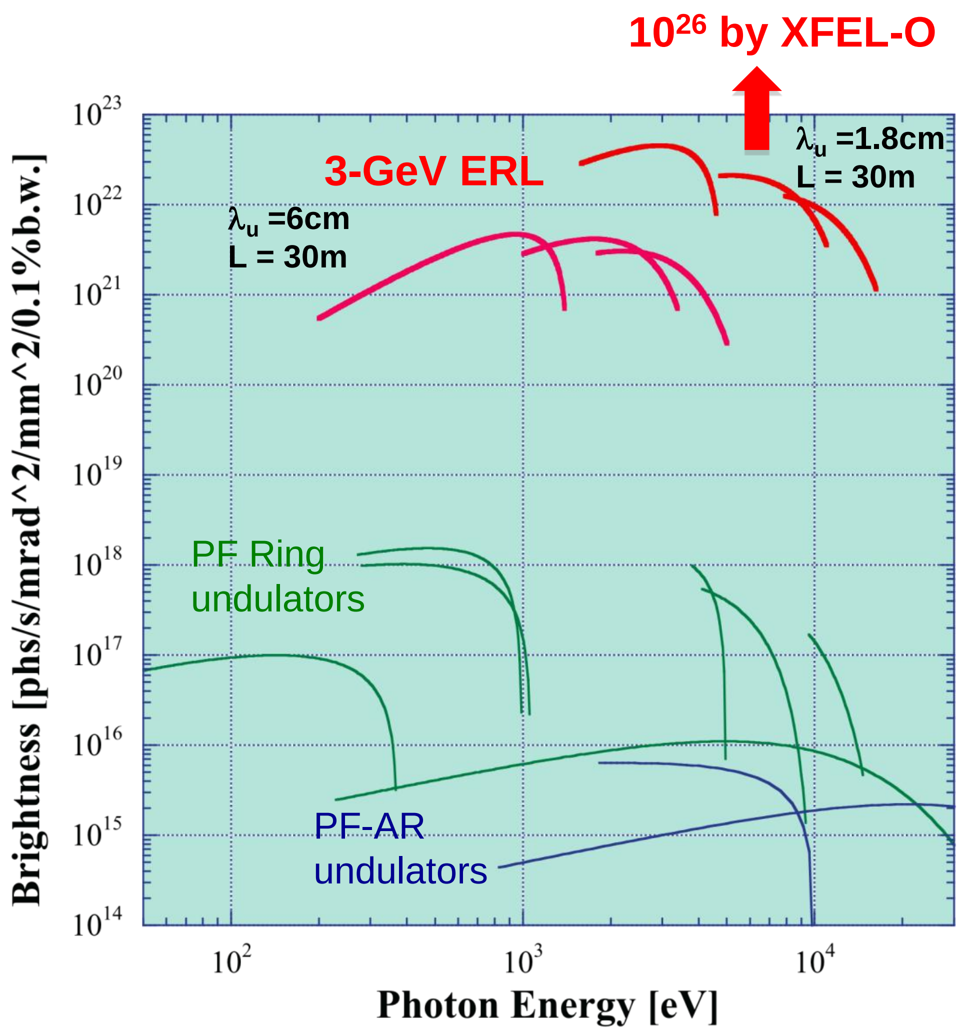
Calculated by K. Tsuchiya

Tentative layout



Expected Performance of the 3-GeV ERL

Spectral Brightness



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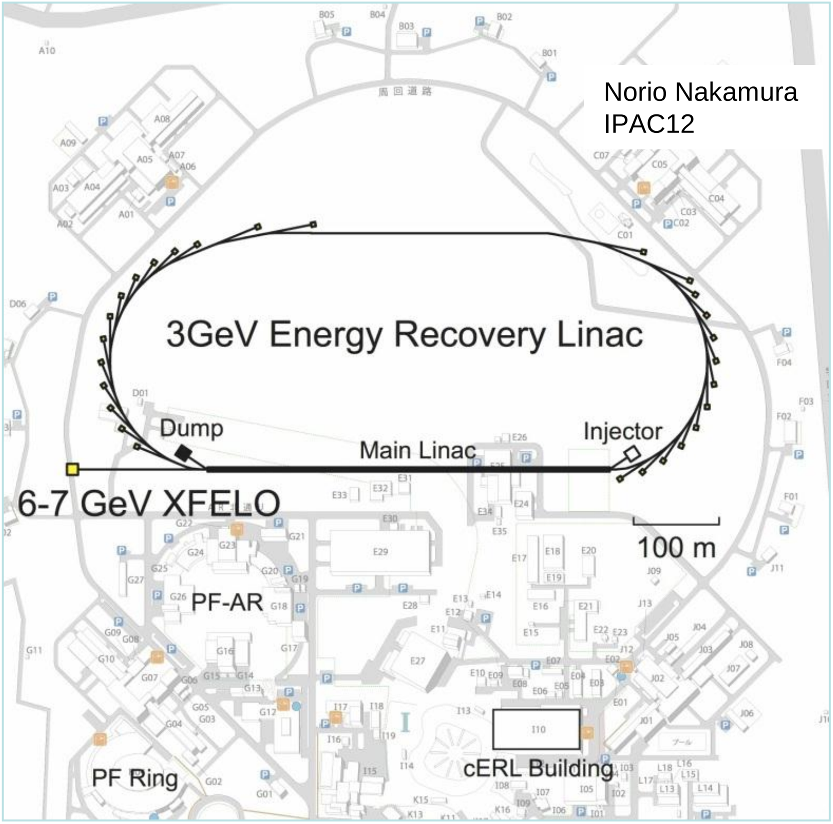
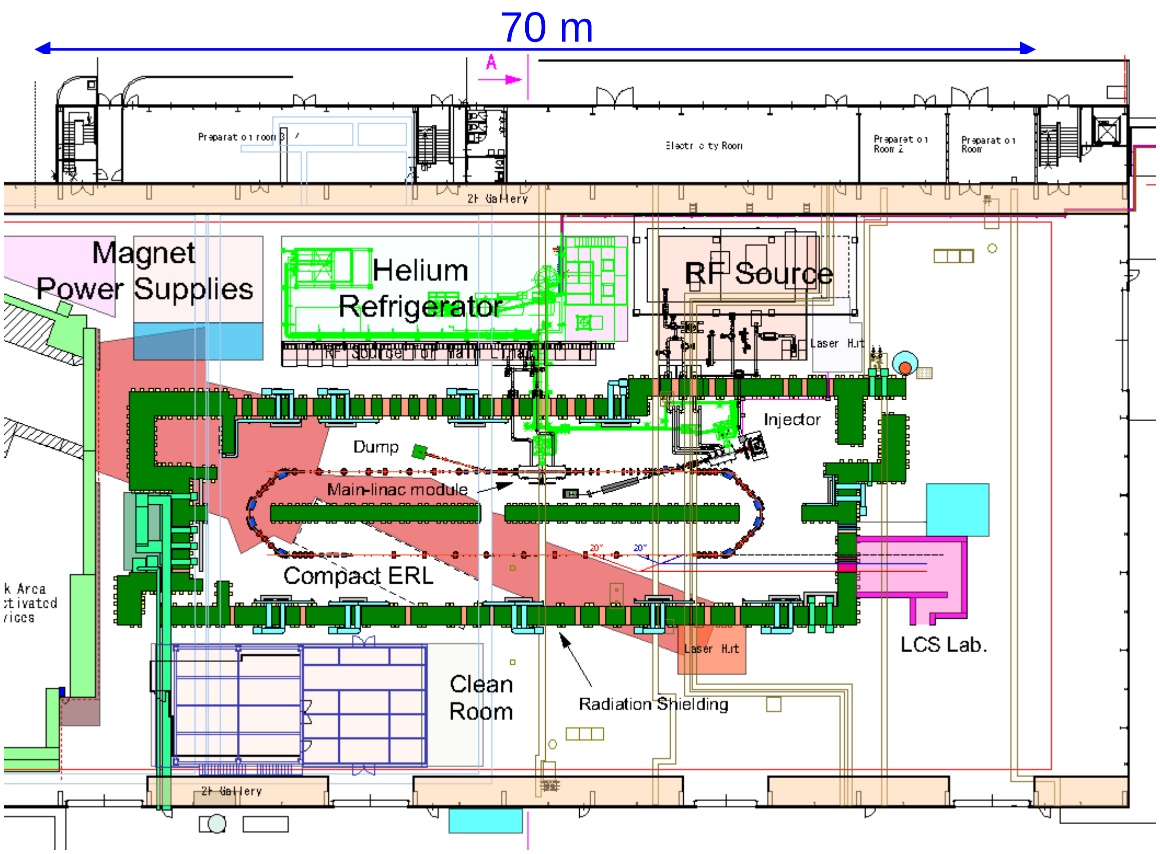


Compact ERL (cERL)

Construction and Commissioning

Goals of the Compact ERL

- Demonstrate reliable operations of our R&D products (guns, SRF, ...)
- Demonstrate the generation and recirculation of ultra-low emittance beams

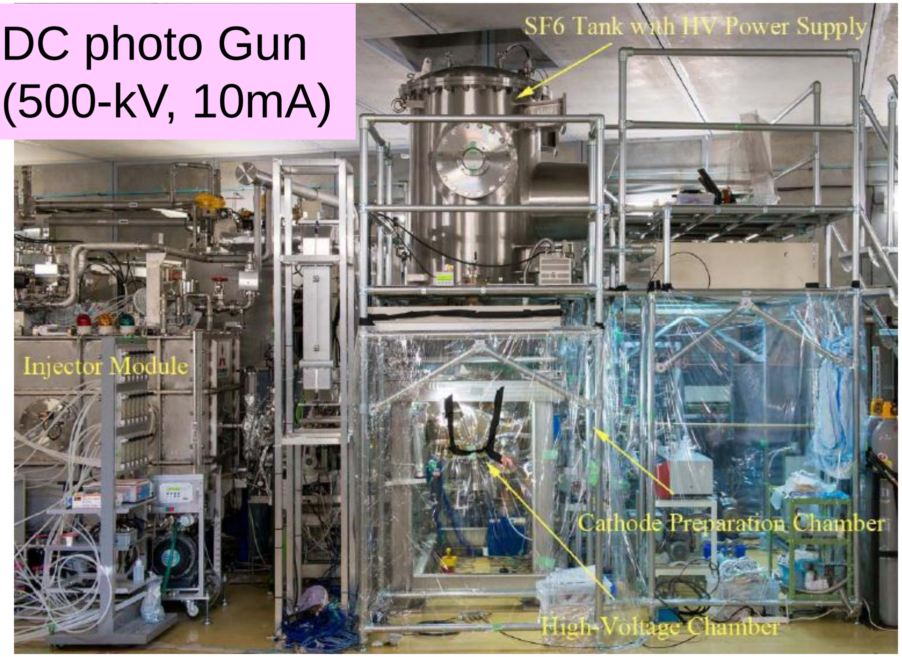


Parameters of the Compact ERL

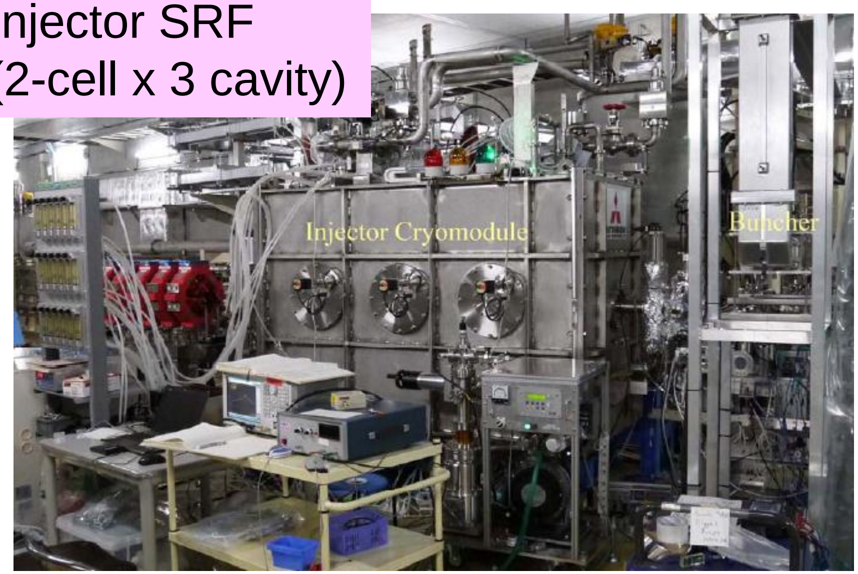
	Parameters
Beam energy (upgradability)	35 MeV 125 MeV (single loop) 245 MeV (double loops)
Injection energy	5 MeV
Average current	10 mA (100 mA in future)
Acc. gradient (main linac)	15 MV/m
Normalized emittance	0.1 mm·mrad (7.7 pC) 1 mm·mrad (77 pC)
Bunch length (rms)	1 - 3 ps (usual) ~ 100 fs (with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

Major Components for the cERL

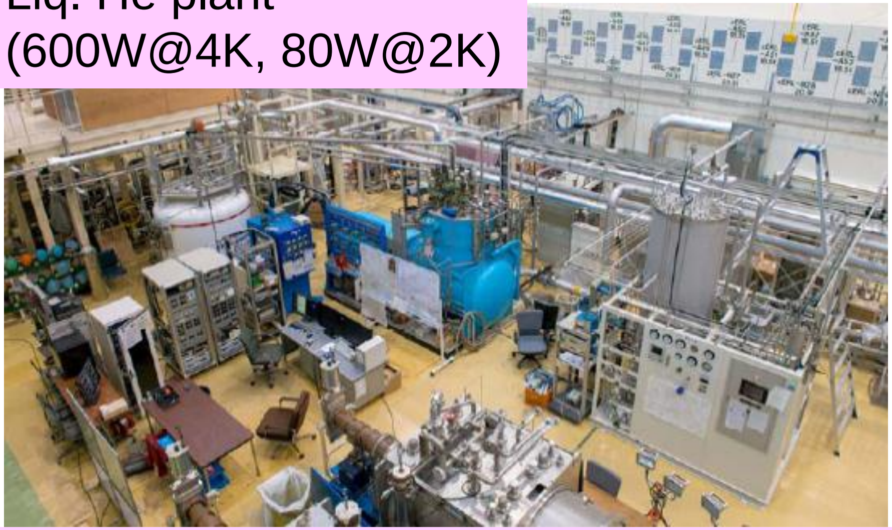
DC photo Gun
(500-kV, 10mA)



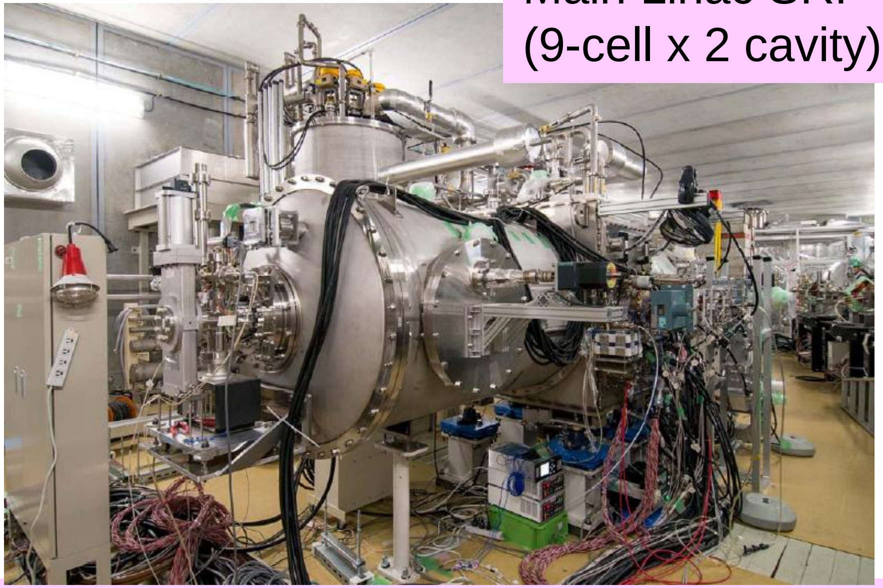
Injector SRF
(2-cell x 3 cavity)



Liq. He plant
(600W@4K, 80W@2K)



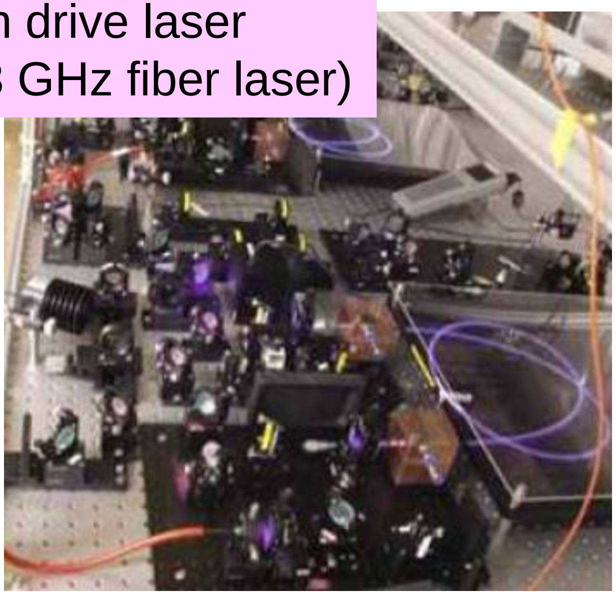
Main Linac SRF
(9-cell x 2 cavity)



Major Components for the cERL

300 kW, 30 kW Kly.
20 kW IOT
FPGA-based LLRF

Gun drive laser
(1.3 GHz fiber laser)



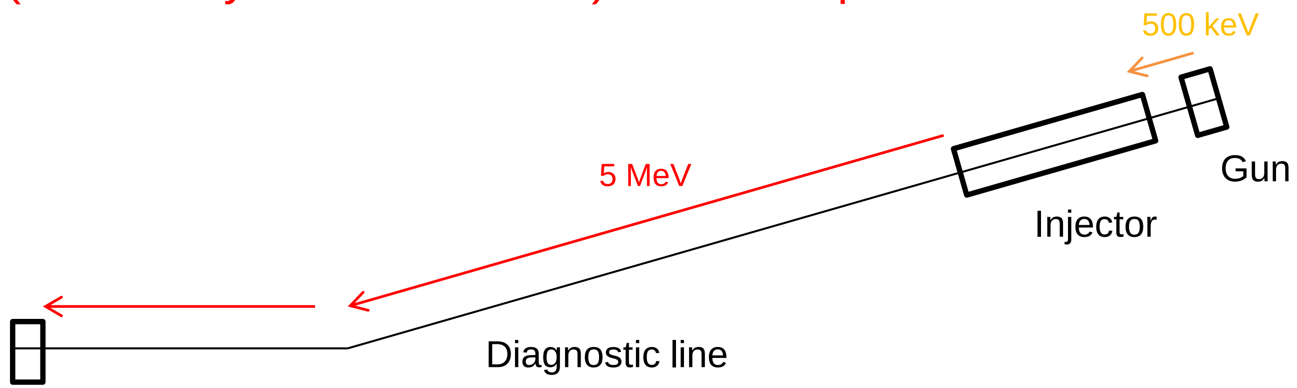
Radiation shield
(1.5-m thick side, 1-m thick top)

See for detail
WEPWA015 (Sakanaka et al.)
and references therein

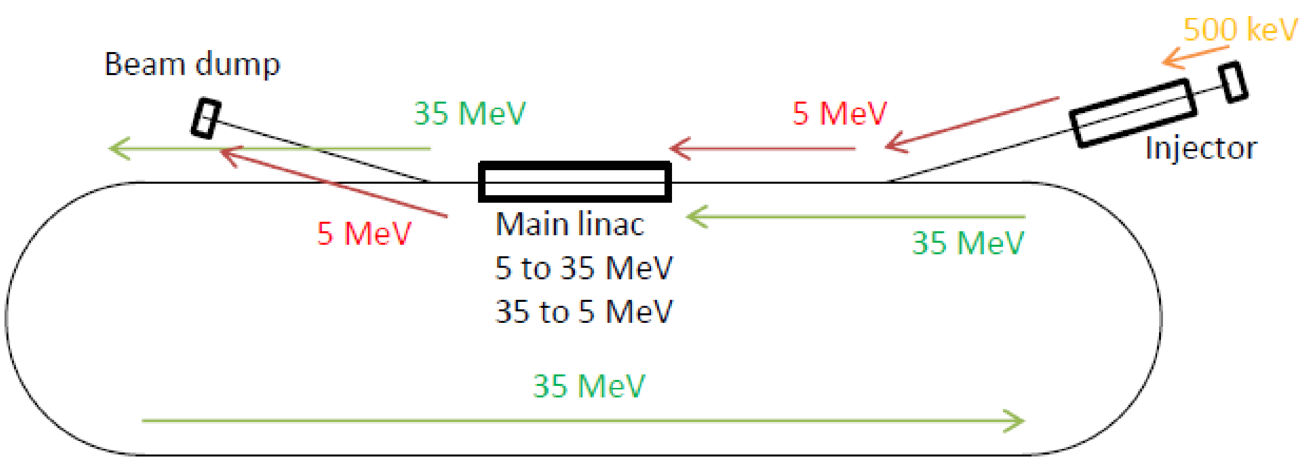
2 Stage Commissioning of cERL

Phase 1 : from April to June 2013

Max beam power (allowed by radiation center): 6MeV x 1μA

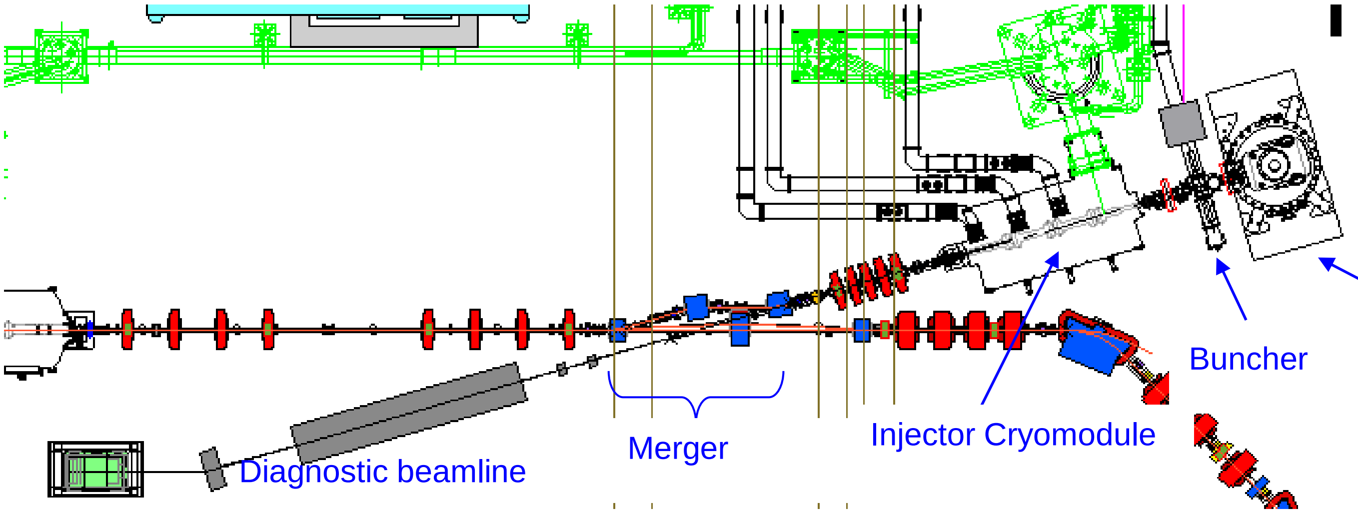


Phase 2 : from autumn 2013



1^{st} beam operation of cERL injector

- 1^{st} beam operation of cERL : April 2013



Parameters of the Compact ERL Injector

Gun voltage	500 kV
Beam energy	5 – 10 MeV
Beam current	10 – 100 mA
Normalized rms emittance $\varepsilon_n = \varepsilon(\gamma\beta)$	1 mm·mrad (77 pC/bunch) 0.1 mm·mrad (7.7 pC/bunch)
Bunch length (rms)	1 – 3 ps (0.3 – 0.9 mm)

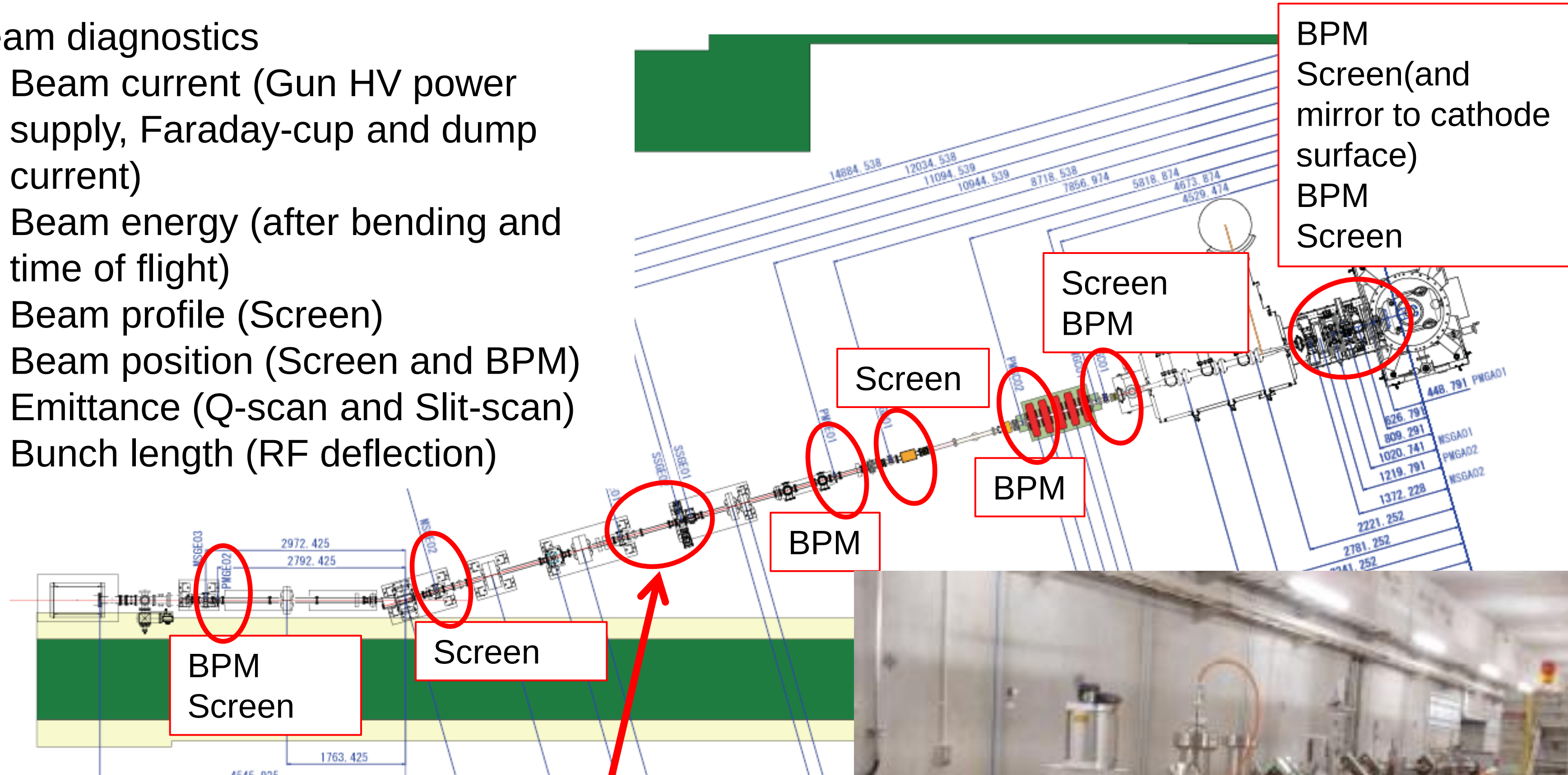
At the 1^{st} beam operation

Beam current < 1μA

(Gun drive laser with macro pulse mode)

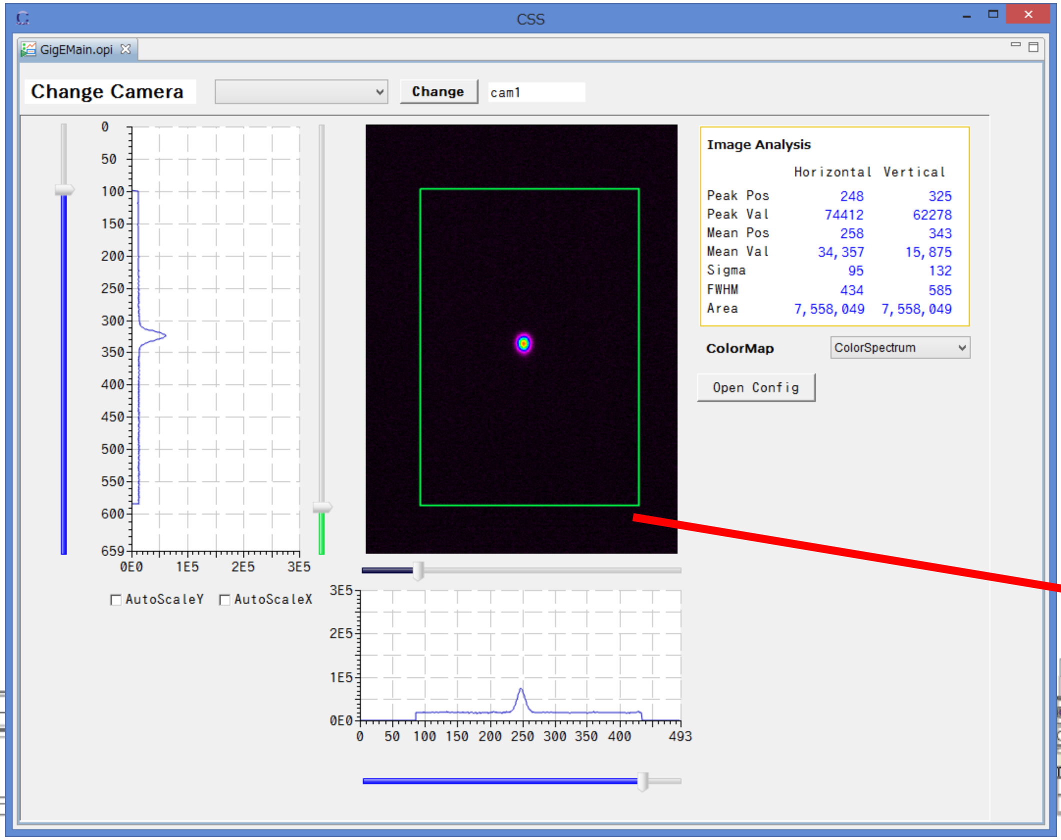
Monitors in the cERL injector beamline

Beam diagnostics
- Beam current (Gun HV power supply, Faraday-cup and dump current)
- Beam energy (after bending and time of flight)
- Beam profile (Screen)
- Beam position (Screen and BPM)
- Emittance (Q-scan and Slit-scan)
- Bunch length (RF deflection)

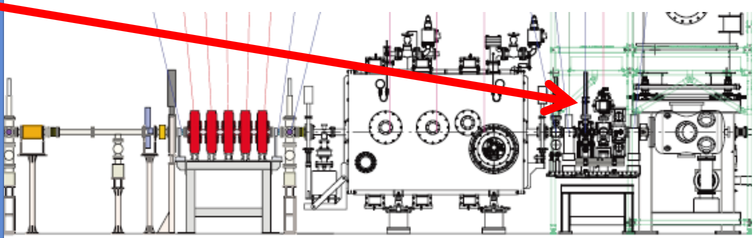


Beam Generation from the Gun (22, April)

- Gun voltage : 390 kV
- Beam current: 150 pA (pulse train = 1.3 GHz x 1 μs x 5 Hz)
  - We generated a 390-keV beam from the DC photo cathode gun.
  - The electron beam with 390 keV passed through the center of screens

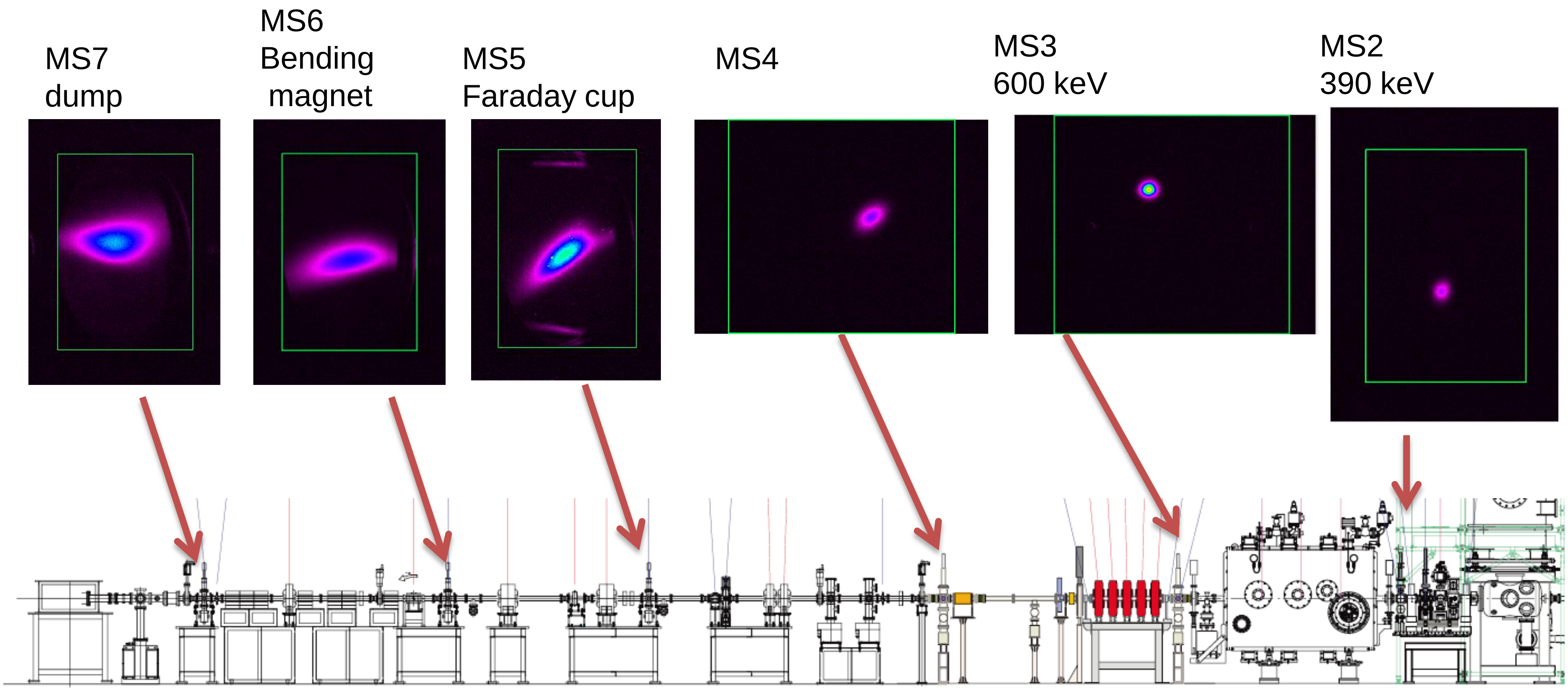


Beam profile on screen 1



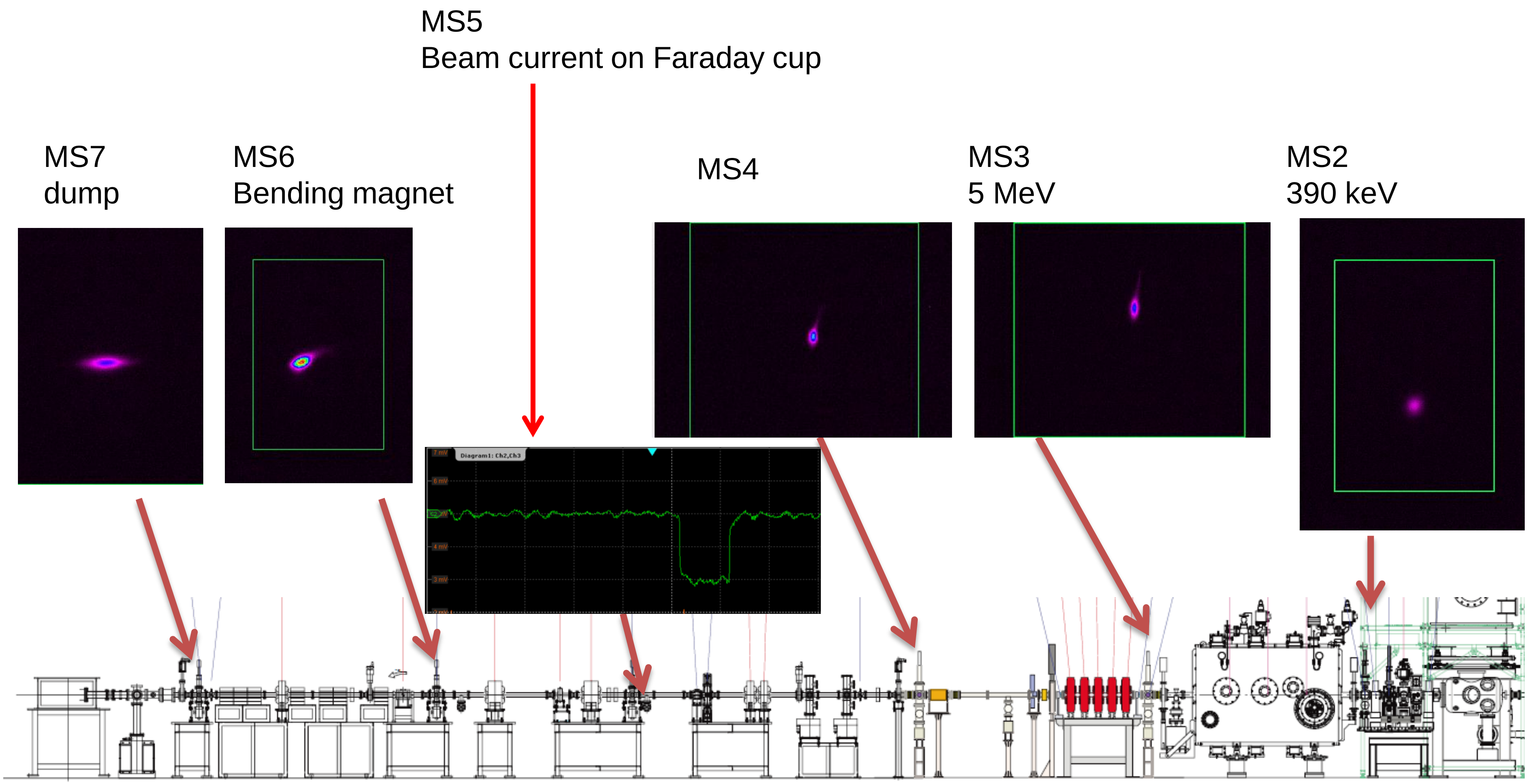
Turned on #1 cavity (24, April)

- The electron beam was accelerated by #1 cavity with Eacc = 1.6 MV/m.
- The accelerated beam was observed on screen 3 (MS3).
- We succeeded in acceleration from 390 keV to 600 keV.
- We succeeded in transporting the beam to dump without any beam loss.



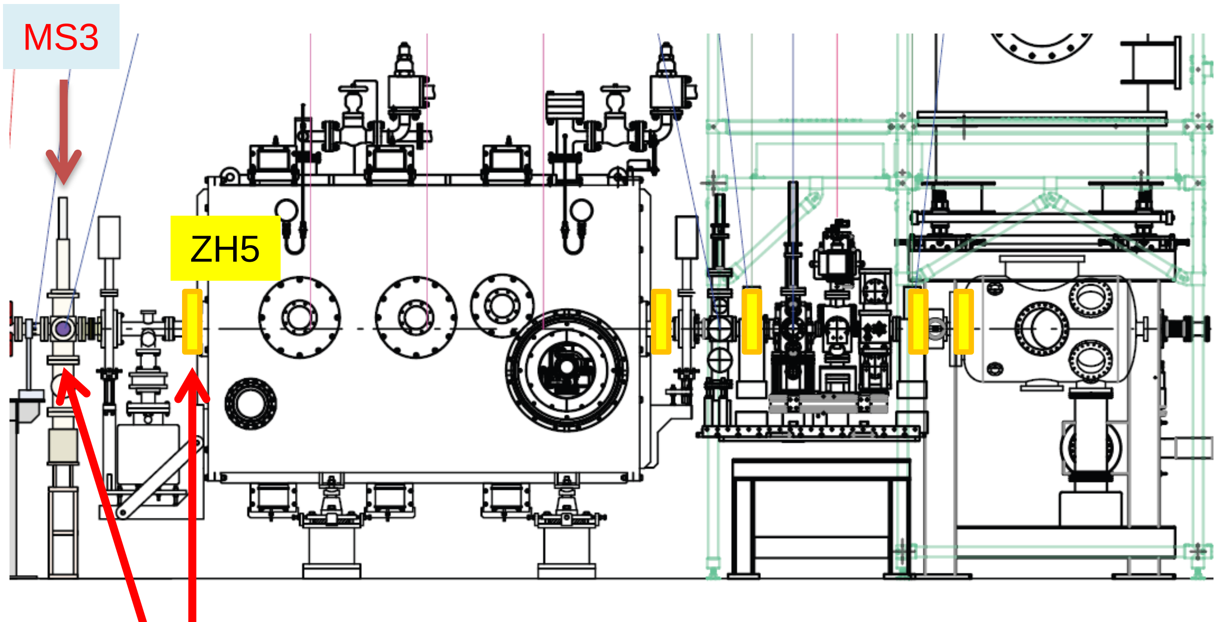
Beam Acceleration by Injector SRF (25, April)

- The electron beam was accelerated by #1,2,3 cavities.
- Successful acceleration to 5 MeV with Eacc of 7.1 MV/m.

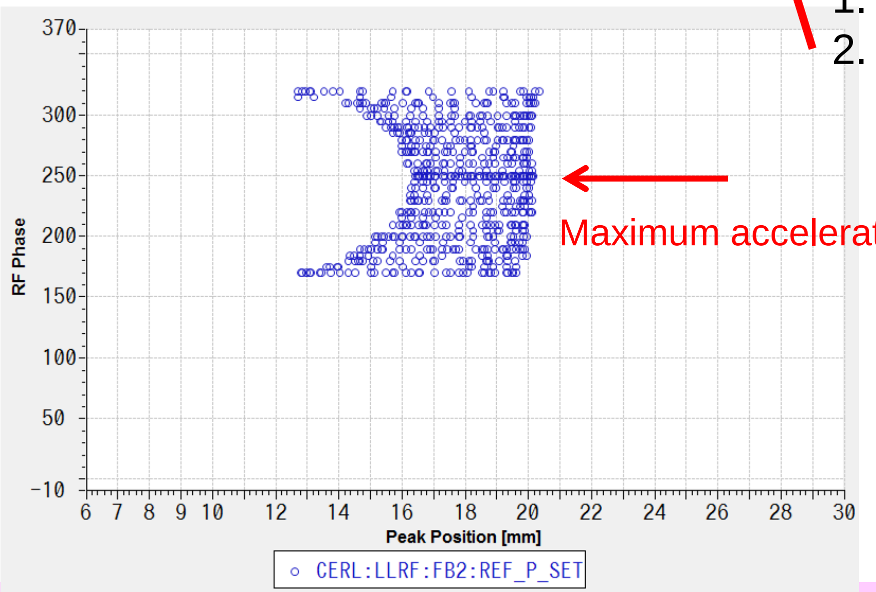


How to adjust cavity phase

- Response of steering magnet on the screen 3 (MS3) was measured varying the cavity phase.
- Difference of the position on MS3: minimum ⇒ maximum acceleration phase



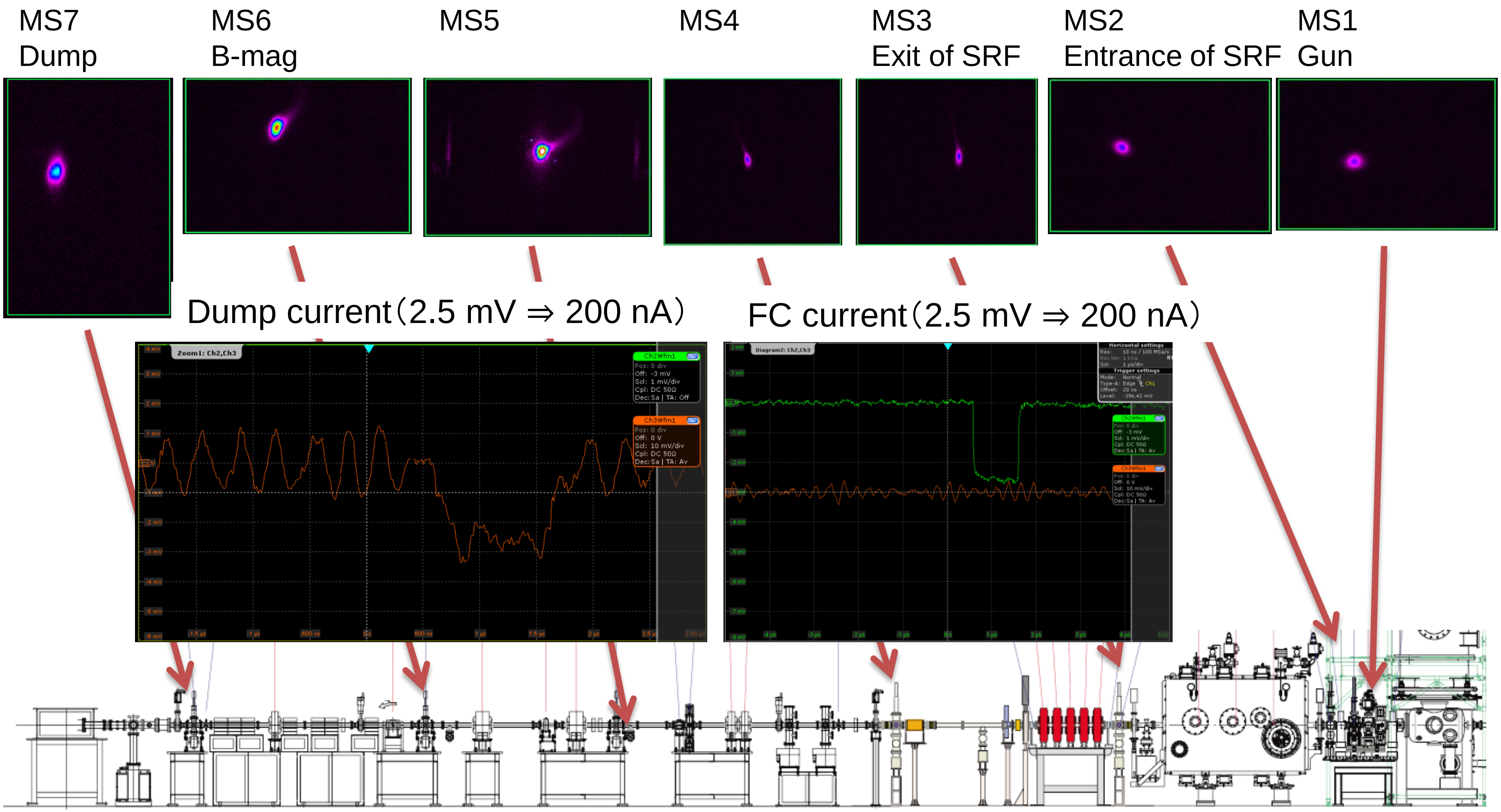
1. Drive a steering coil with sinusoidal current
2. Measure beam deflection on the screen with varying the cavity phase.



<u>Example of phase tuning</u>
Horizontal axis: beam position
Vertical axis: phase of cavity

Increasing the Beam Current (26, April)

- Beam current increased from 150 pA to 200 nA (macropulse 1 μs → 1.6 ms)
- Successful beam transport to the dump without any beam loss.



Summary

- 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

- Beam commissioning of cERL phase 1 in KEK
  - 390 keV beam generation from the photo cathode DC gun
  - Acceleration by injector SRF cavities to 5 MeV
  - 200 nA operation for the radiation safety inspection.
  - In this summer, we are going to construct a return loop, and start the beam commissioning phase 2 for the whole cERL.

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- S. H. Wang, J. Q. Wang (IHEP) and their colleagues
- L. X. Liu (Peking U.) and his colleagues
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