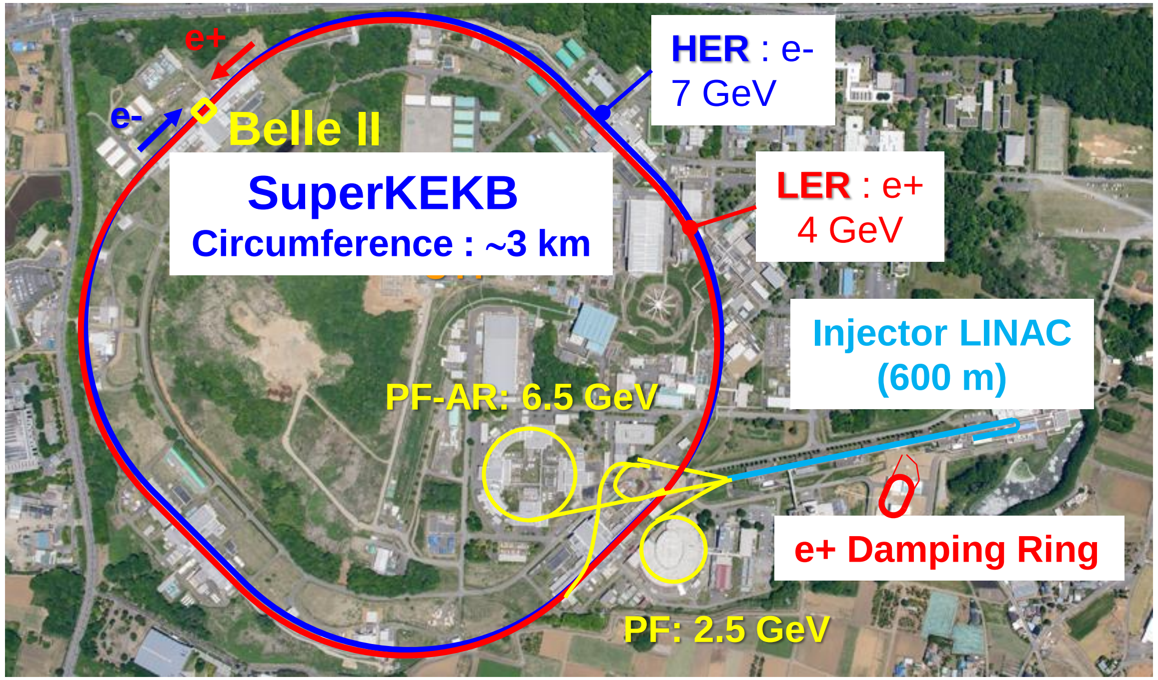
Simultaneous Top-Up Injection into four Storage Rings at SuperKEKB

Masanori Satoh (KEK)
on behalf of Injector Linac Group

KEK e-/e+ Injector Linac History

1978-1981: Construction of injector linac for Photon Factory (PF)
1982: Injector for PF (e-: 2.5 GeV)
1986-1994: Injector for PF, TRISTAN (e-: 2.5 GeV, e+: 2.5 GeV)
1987: PF-AR started
1993: Injector upgrade for KEKB project (e-: 2.5 GeV => 8 GeV, e+: 2.5 GeV => 3.5 GeV)
1998: KEKB commissioning started
2002: Two bunch injection to KEKB
2003 March: Achievement of 100,000 Hours of Operation
2004: Simultaneous top up project started
2005: PF new BT (decoupling from LER BT)
2009 Apr.: Simultaneous top up of 3 storage rings (KEKB HER/LER, PF)
2010 June 30: KEKB end of operation
2012: PF-AR direct beam transport (new BT) design started (decoupling from HER BT)
2016: SuperKEKB Phase1 (HER 7 GeV e-, LER 4 GeV e+)
2017: PF-AR full energy (6.5 GeV) injection with new BT
2018: SuperKEKB Phase2
2019: SuperKEKB Phase3
2019 May: Simultaneous top up of 4 storage rings (SuperKEKB HER/LER, PF, PF-AR) WEPAB037
2020 May: Achievement of 200,000 Hours of Operation WEPAB036

Electron Accelerator Complex in KEK Tsukuba Campus :one injector, four storage rings (and e+ DR)



Each ring requires much different beam quality

Bunch charge: 0.1 nC – 4 nC (10 nC for e+ production)
Beam energy: 2.5 GeV – 7 GeV
Beam energy spread: 0.07% –
Emittance: 15 – 150 mm·mrad (normalized)

Injector Linac provides the beams to 4 (+1) different rings up to 50 Hz

- **Photon Factory**
- **PF-AR**

} Light Source

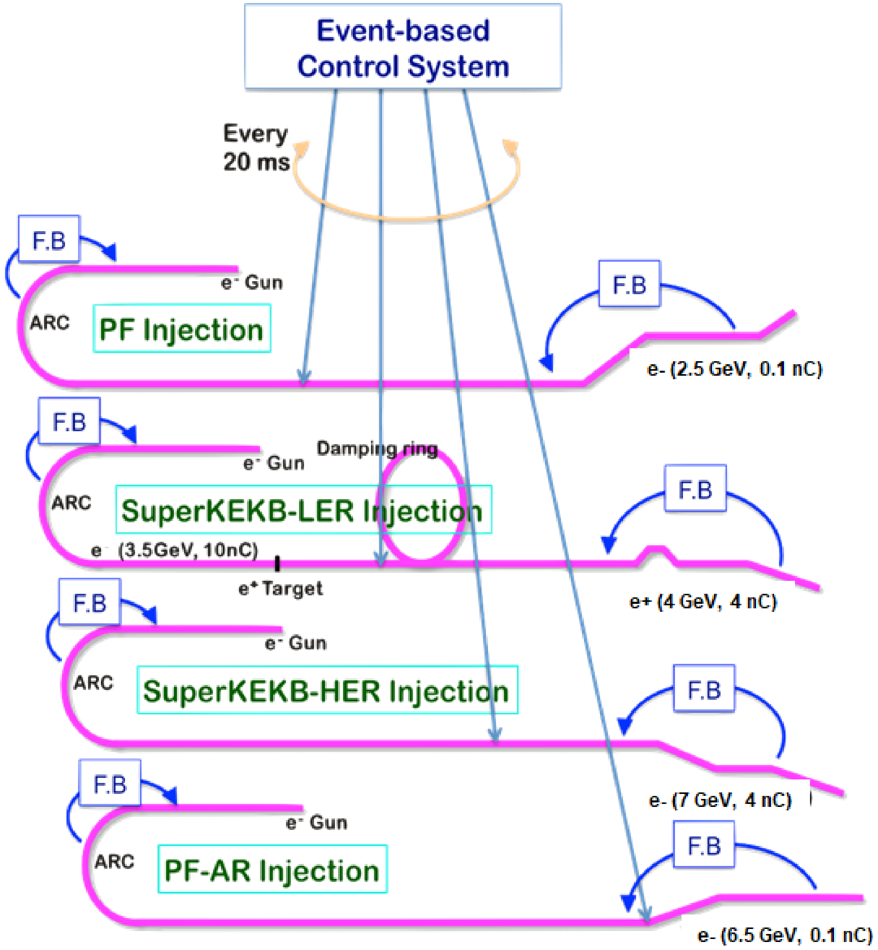
- **SuperKEKB High Energy Ring (HER)**
- **SuperKEKB Low Energy Ring (LER) + Damping Ring**

} Belle II experiment

Injector Goal

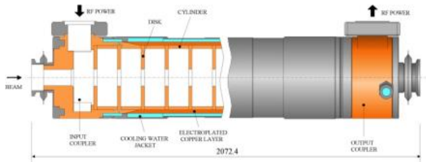
- **High quality beam for SuperKEKB (high bunch charge, low emittance, small energy spread)**
  - **Low emittance rf e- gun, DR ring for e+, good alignment, etc.**
- **Simultaneous top-up for 4 rings (short beam life time of SuperKEKB MR ～ 6 min.)**
  - **Event based timing system, pulsed magnet, fast rf phase/timing, fast monitors (up to 50 Hz)**

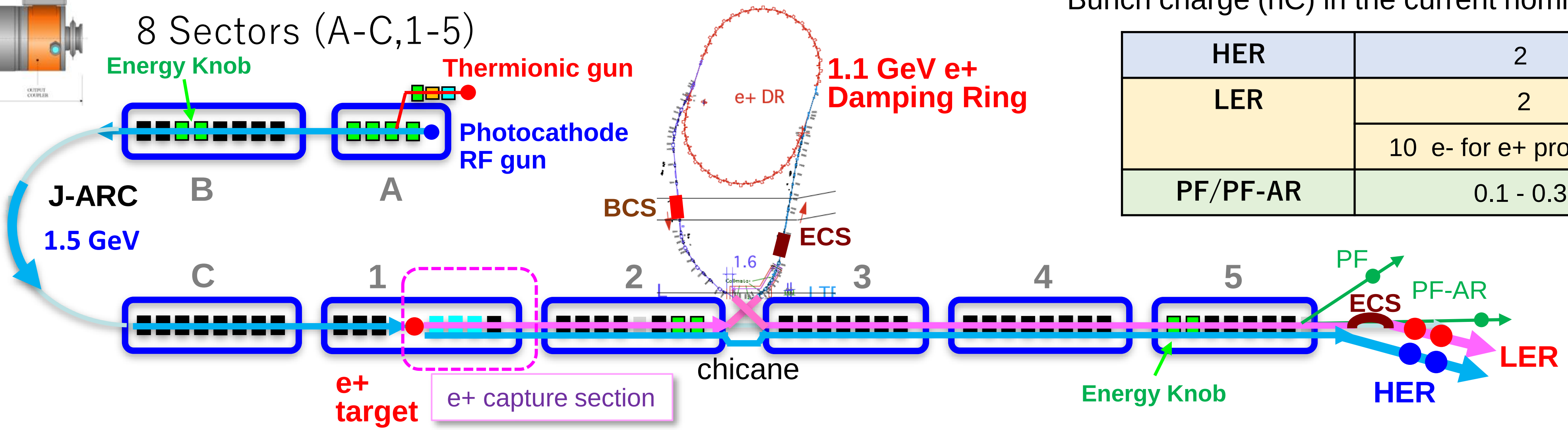
	PF/PF-AR injection	KEKB injection (archived)		SuperKEKB injection (final)	
		LER	HER	LER (w/ DR)	HER
Bunch charge (nC)	0.1 - 0.3	1	1	**4** **2 (achieved)**	**4** **2 (achieved)**
Normalized emittance (H/V) (μm)	150	1400	310	**100/15**	**40/20**
Energy spread (%)	n.d.	0.15	0.05	**0.16**	**0.07**
Beam energy (GeV)	2.5/6.5 or 5	3.5	8	4	7



Injector Linac Operation Outline

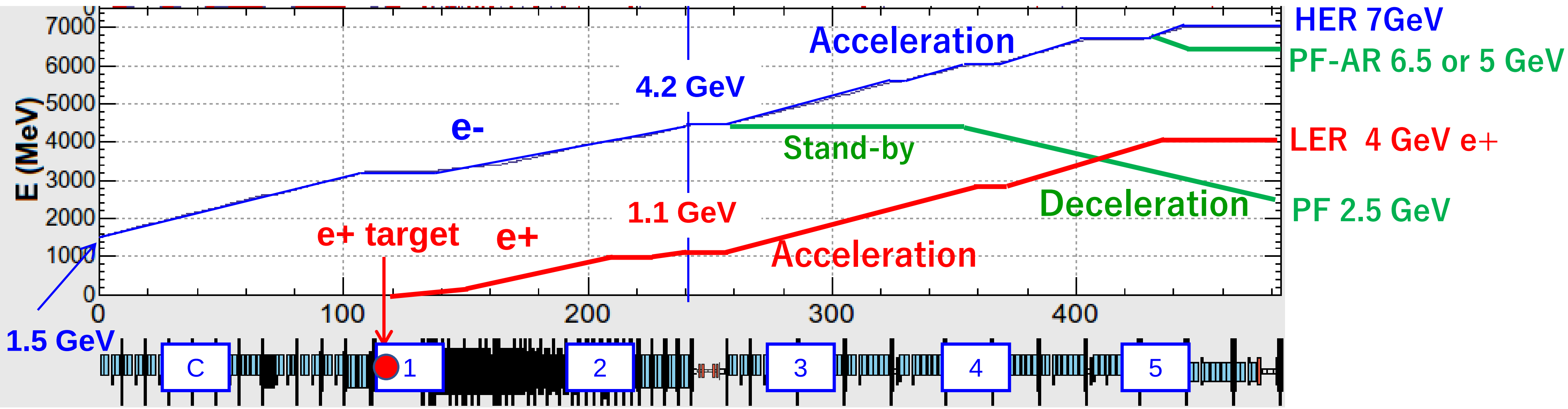
60 klystron units
240 accelerating structures (S-band 2-m-long)





Bunch charge (nC) in the current nominal operation

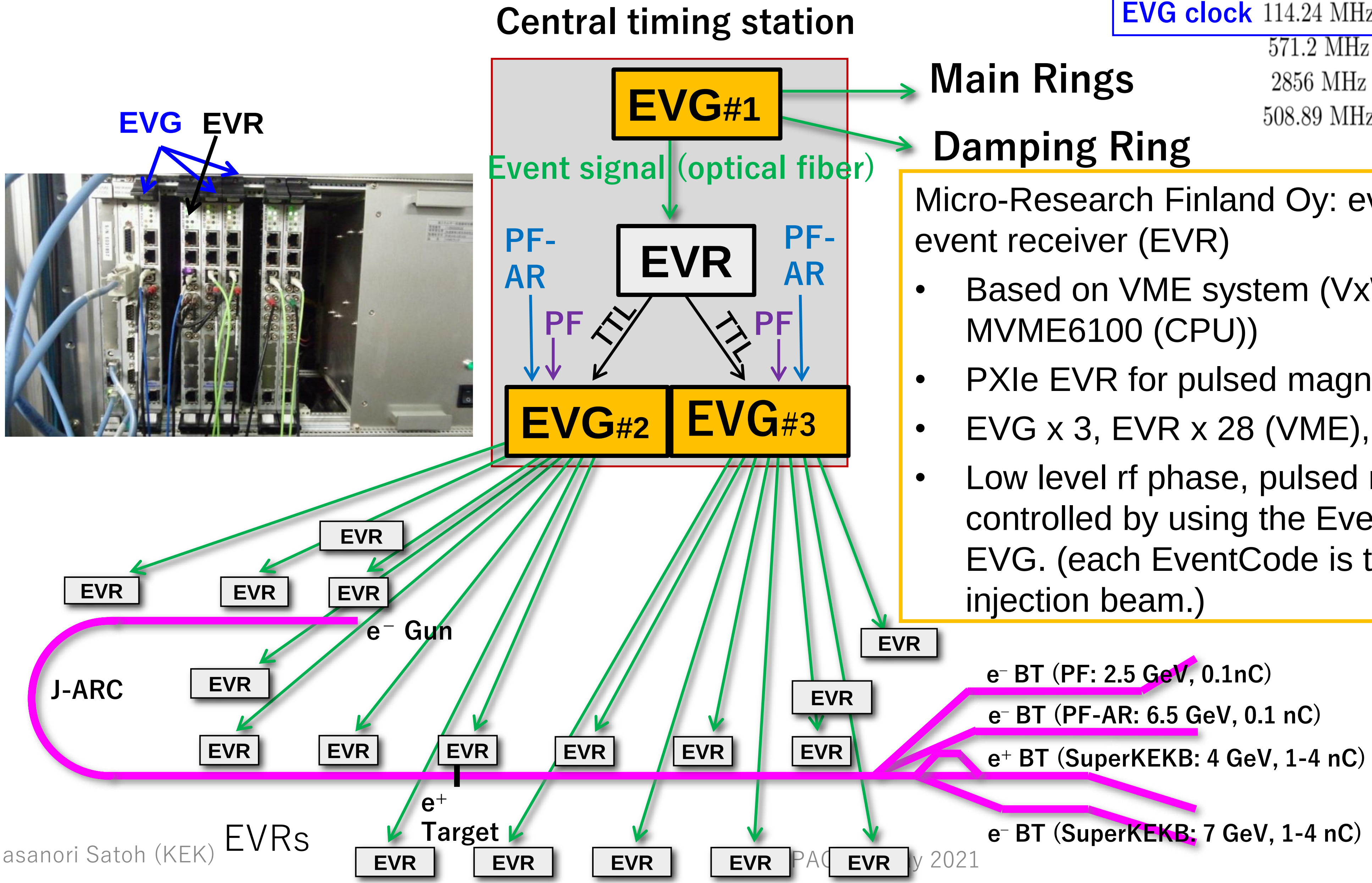
HER	2
LER	2
	10 e- for e+ production
PF/PF-AR	0.1 - 0.3



Beam energy for each beam mode along the beam line after the J-ARC.

Event Based Timing System

Frequency	Ratio	Purpose
10.385 MHz	-	RF Gun
EVG clock 114.24 MHz	x11	Linac SHB1 & RF Gun
571.2 MHz	x55	Linac SHB2
2856 MHz	x275	Linac Main RF & RF Gun
508.89 MHz	x49	DR & MR RF

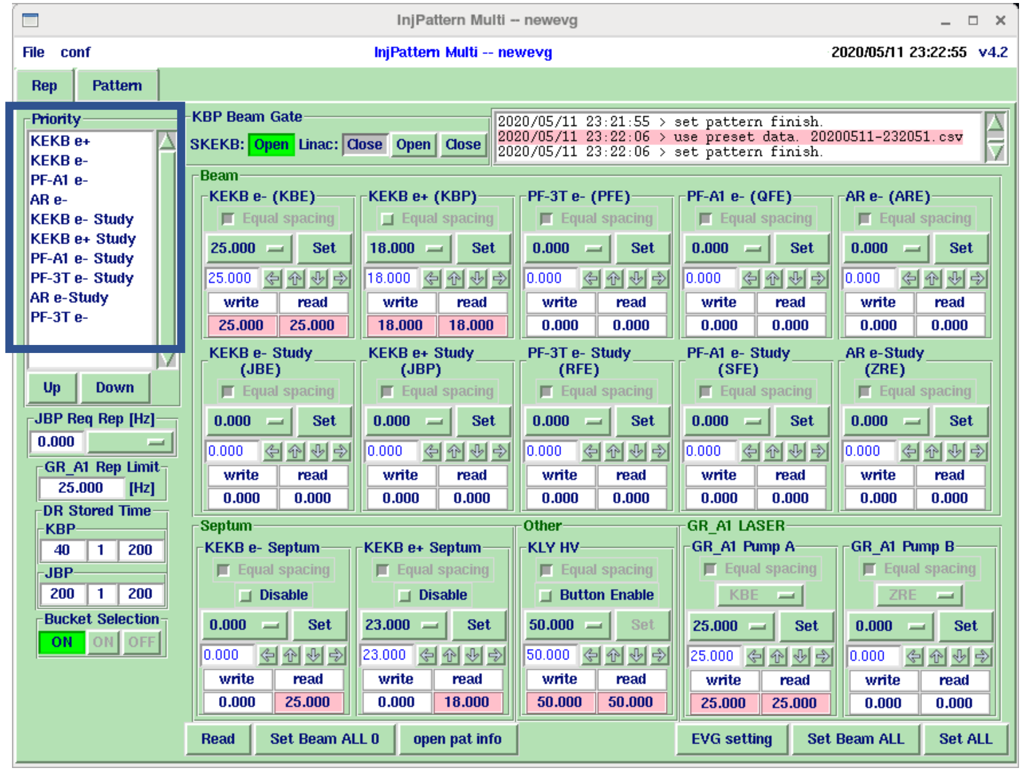


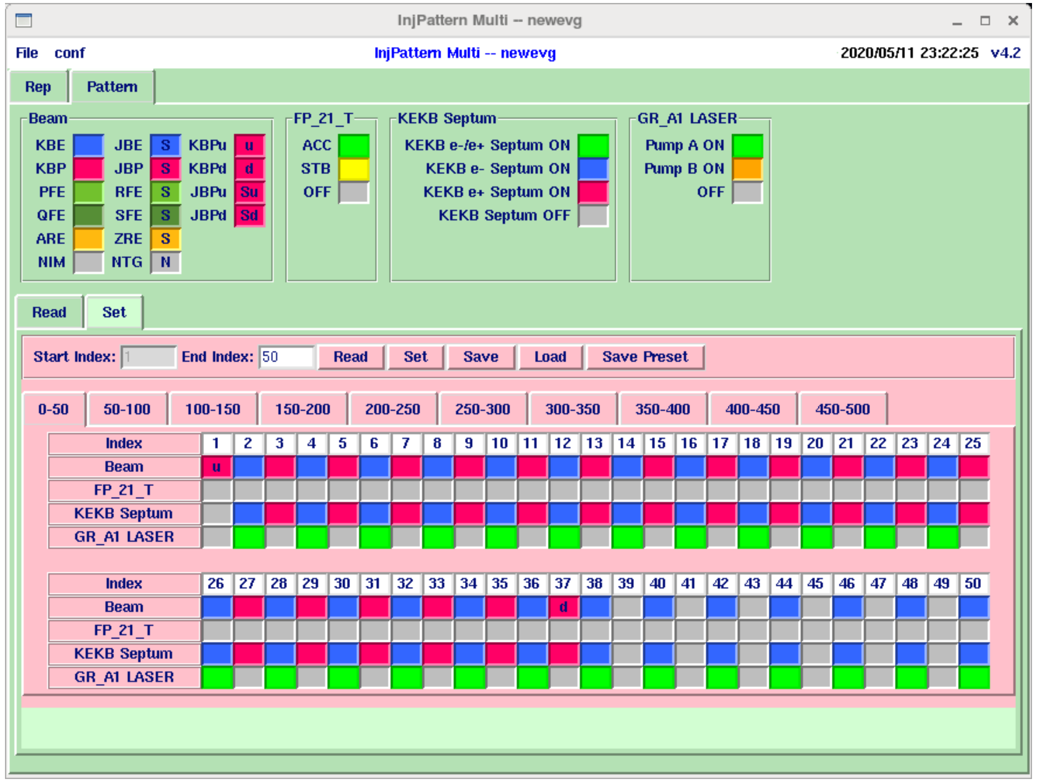
Micro-Research Finland Oy: event generator (EVG), event receiver (EVR)

- Based on VME system (VxWorks6.8 (RTOS), MVME6100 (CPU))
- PXIe EVR for pulsed magnet control
- EVG x 3, EVR x 28 (VME), x17 (PXIe)
- Low level rf phase, pulsed magnet, etc are controlled by using the EventCode distributed from EVG. (each EventCode is tagged to each ring injection beam.)

Beam Injection Pattern Generation

- Beam repetition rate is determined by demand from each ring.
- Priority can be defined.





Beam repetition rate management for each beam injection mode.

Beam mode

KBE: SuperKEKB e- (HER)

KBP: SuperKEKB e+ (LER)

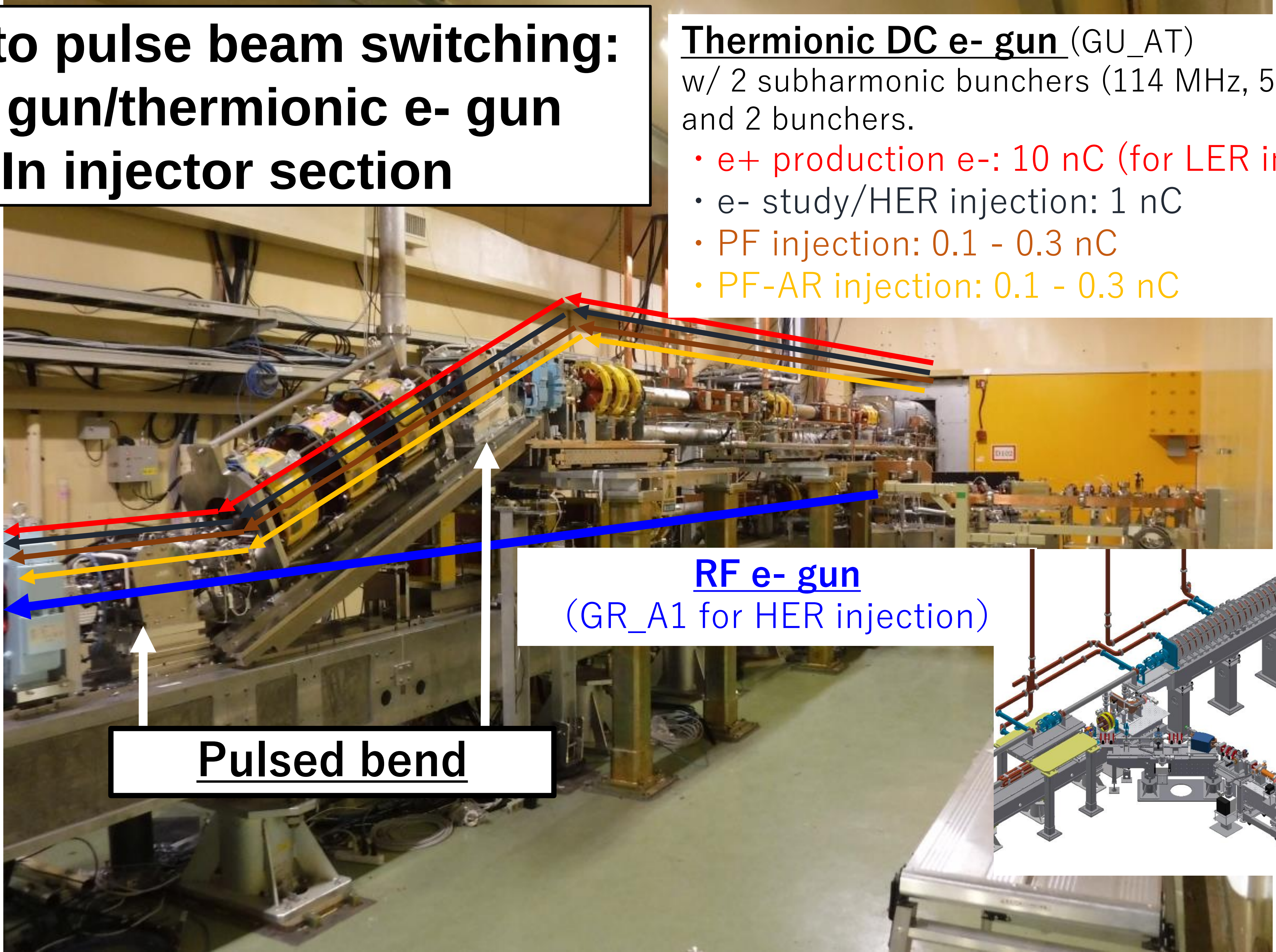
QFE: PF

ARE: PF-AR

Pulse to pulse beam switching: rf e- gun/thermionic e- gun In injector section

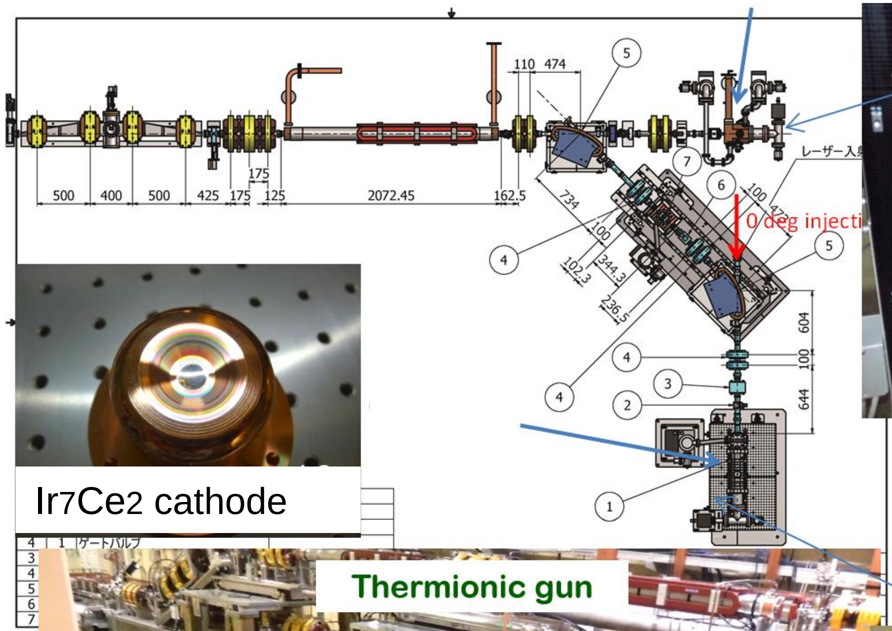
Thermionic DC e- gun (GU_AT)
w/ 2 subharmonic bunchers (114 MHz, 571 MHz) and 2 bunchers.

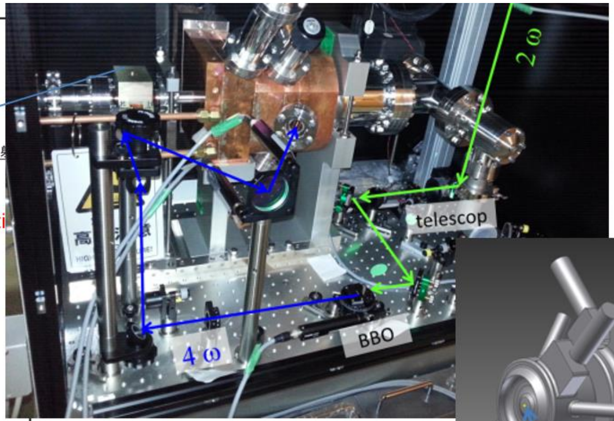
- e+ production e-: 10 nC (for LER injection)
- e- study/HER injection: 1 nC
- PF injection: 0.1 - 0.3 nC
- PF-AR injection: 0.1 - 0.3 nC

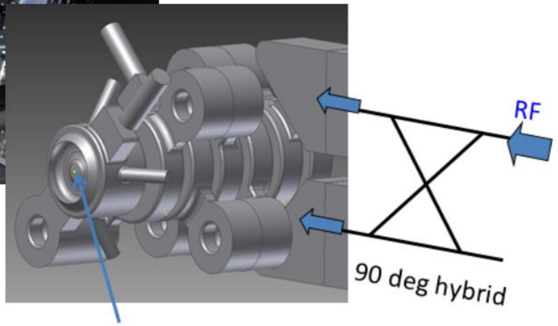


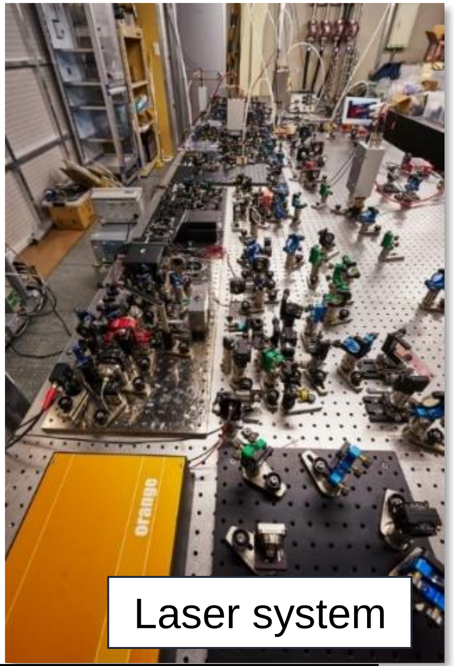
RF e- gun
(GR_A1 for HER injection)

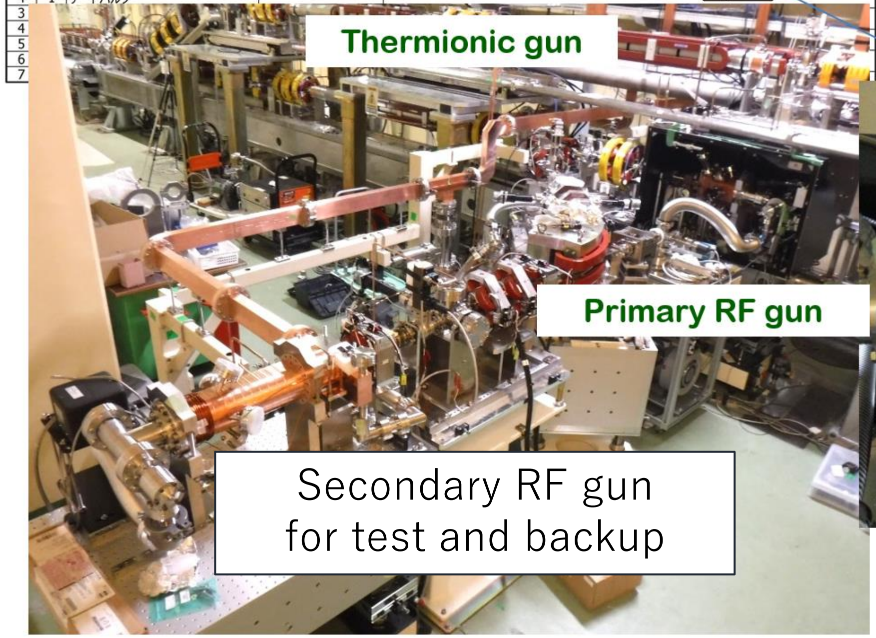
Low emittance photocathode rf e- gun



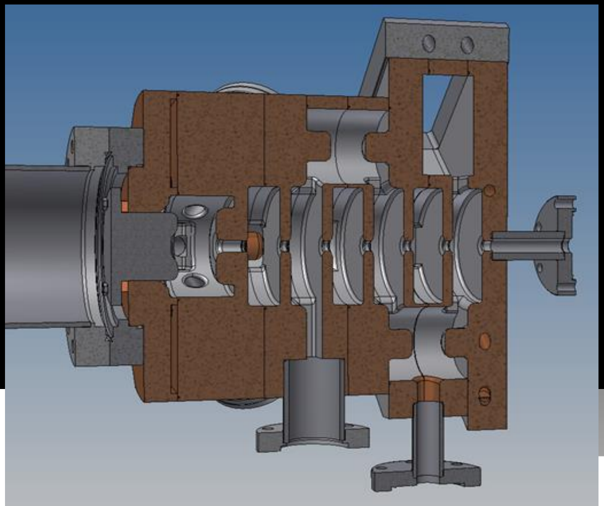


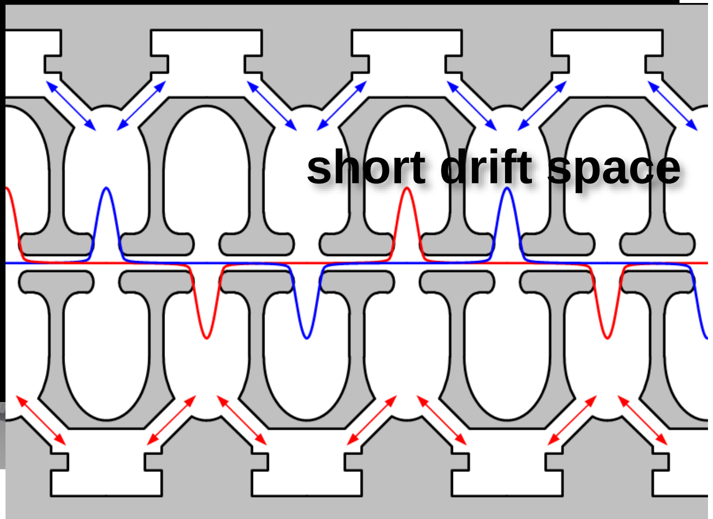






- Photocathode: Ir_7Ce_2
- Cavity: QTWSC (Quasi Travelling Wave Side Coupler)
  - Strong focusing electric field





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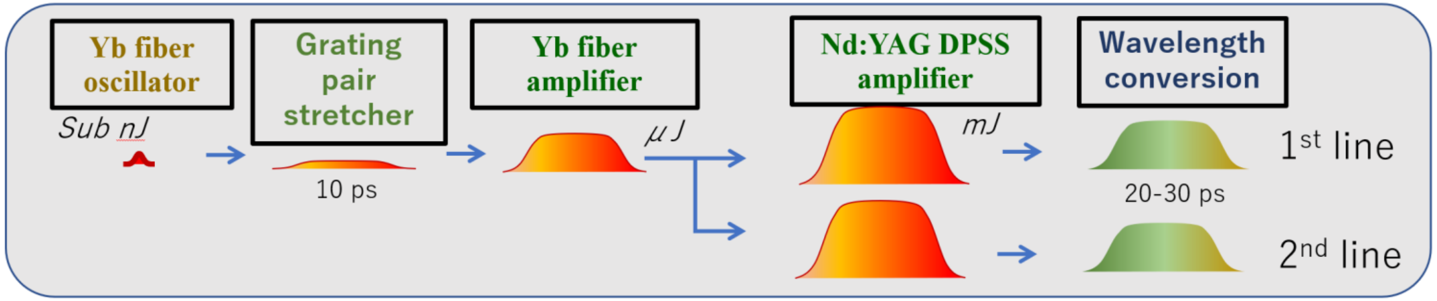
Hybrid laser system for rf e- gun

- Yb doped fiber and Nd:YAG DPSS module Amplifier



- **Output Power in 1st line:**
- *ω (1064 nm): 32 mJ*
- *2ω (532 nm): 11 mJ*
- *4ω (266 nm): 1.2 mJ*

emittance

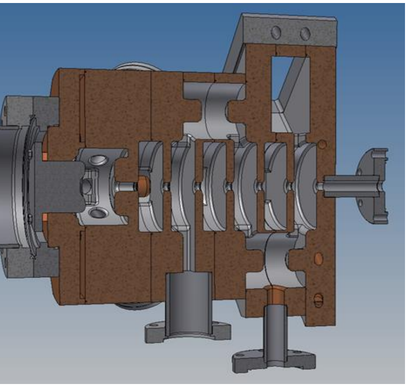
$\varepsilon_{nx,nxy}$ (2 nC) ~20 μm (BT)

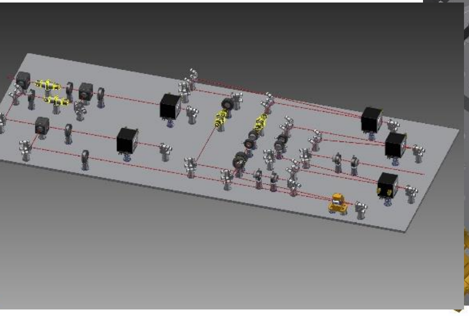
Results of measurement

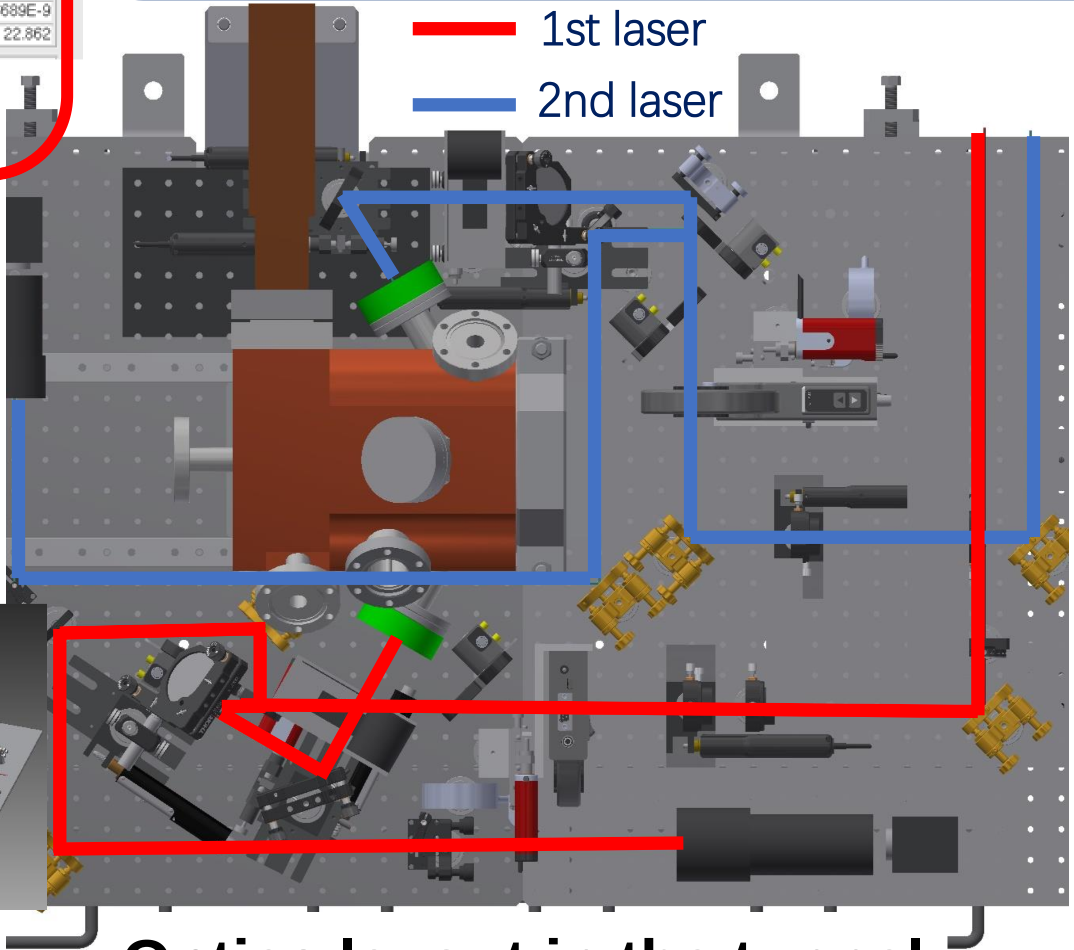
β_x @MW.1 [m] :	3.220	β_y @MW.1 [m] :	56.115
α_x @MW.1 :	.292	α_y @MW.1 :	2.507
ε_x [m] :	1.4328E-9	ε_y [m] :	1.5402E-9
$\Delta\varepsilon_x$ [m] :	3.887E-10	$\Delta\varepsilon_y$ [m] :	5.398E-10
$\gamma\varepsilon_x$ [μm] :	19.628	$\gamma\varepsilon_y$ [μm] :	21.099
$\Delta\gamma\varepsilon_x$ [μm] :	5.324	$\Delta\gamma\varepsilon_y$ [μm] :	7.395
Goodness x :	.437	Goodness y :	.256
Bmag x :	1.986	Bmag y :	1.084
ε Bmag x :	2.8450E-9	ε Bmag y :	1.6689E-9
γε Bmag x :	38.972	γε Bmag y :	22.862

Optics plot

Goal: $\varepsilon_{nx,nxy}$ (4 nC) ~40/20 (H/V) μm)

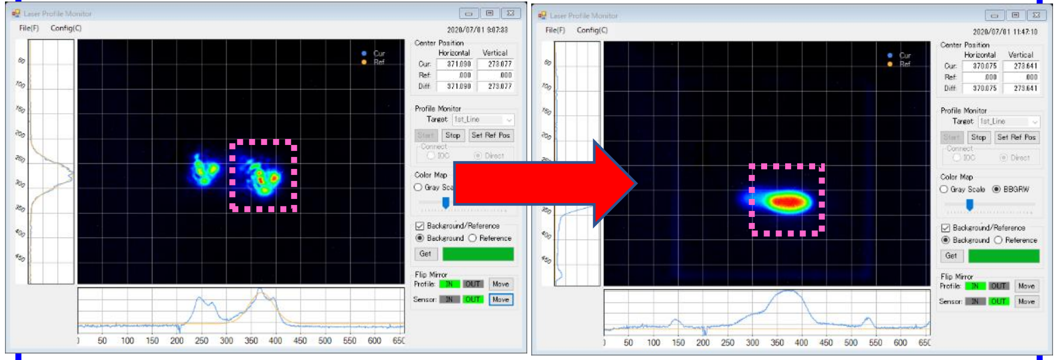




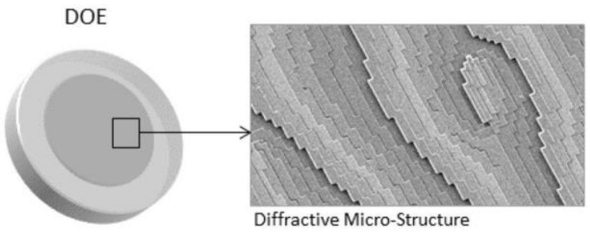


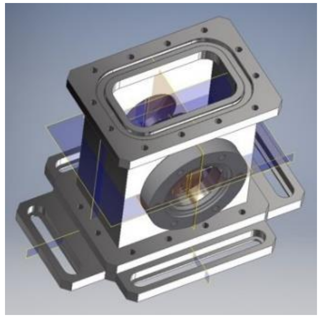
Optics layout in the tunnel

DOE (diffractive optical element) in 1st laser line: Laser beam homogenizer for low emittance beam w/ high intensity bunch charge.



world first DOE application in UV laser





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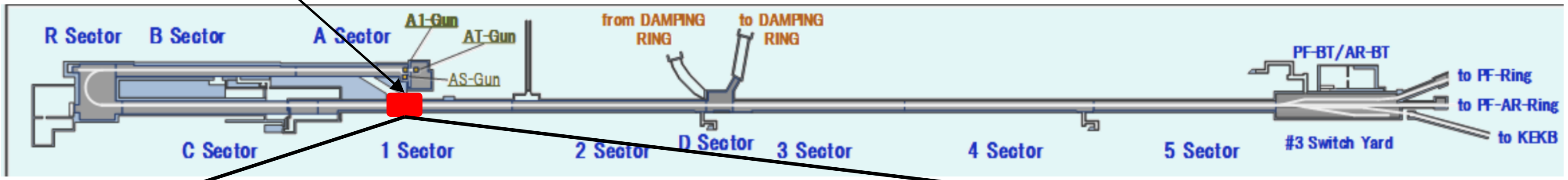
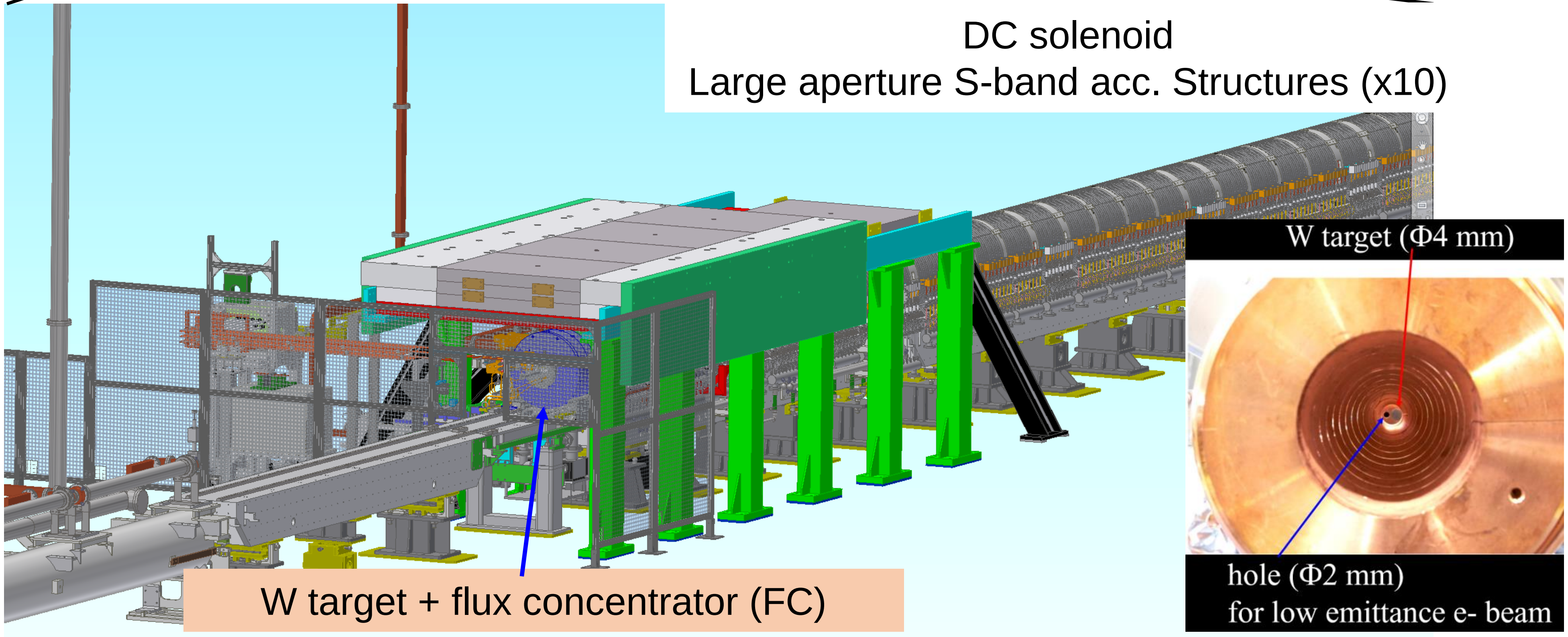
Positron source setup at Sector1

Positron target and capture section





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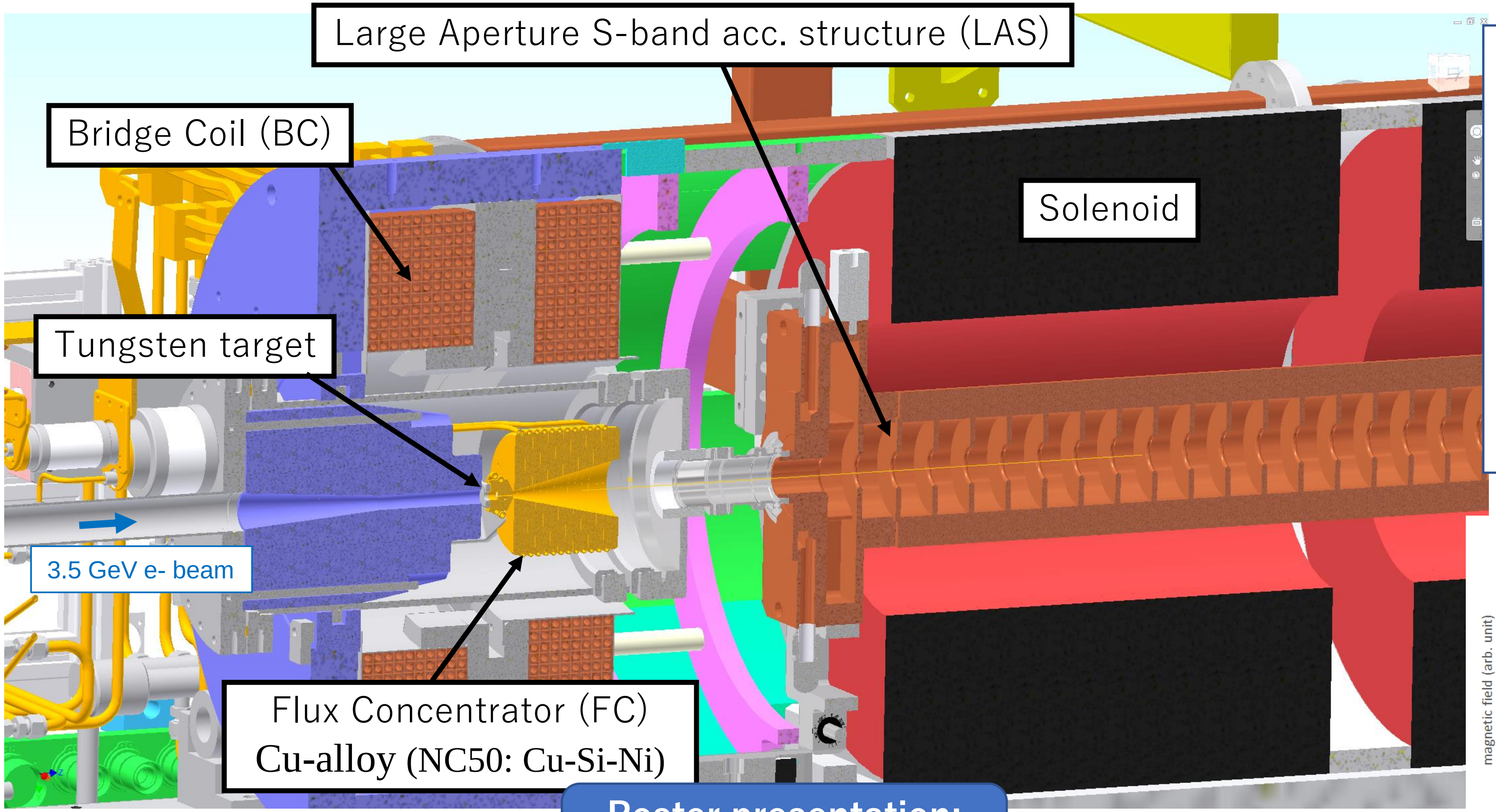
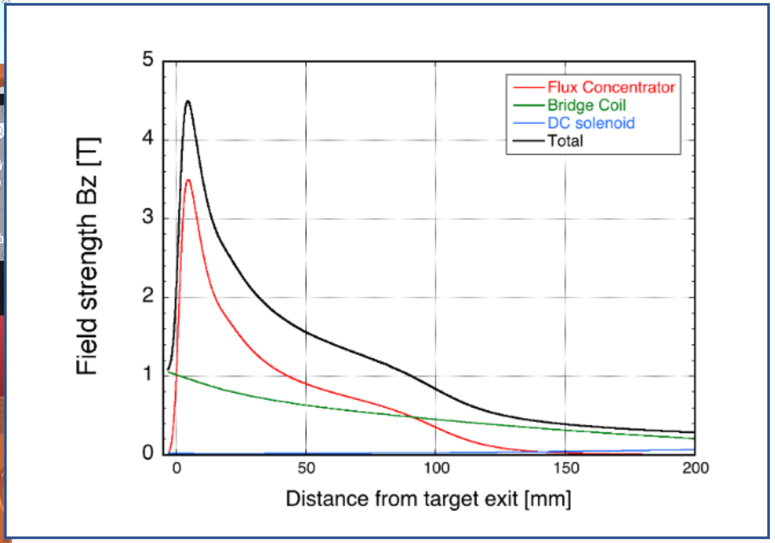
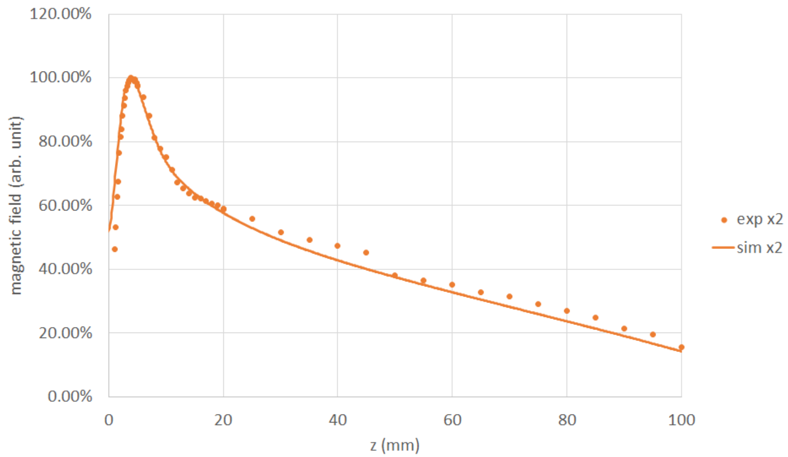
Positron Capture Section: Flux concentrator, bridge coil, solenoid







Poster presentation: [WEPAB144]

I_{FC}= 12 kA

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emittance

$\varepsilon_{nx,nxy}$ (2.3 nC)
～99.7/3.2 μm (BT)

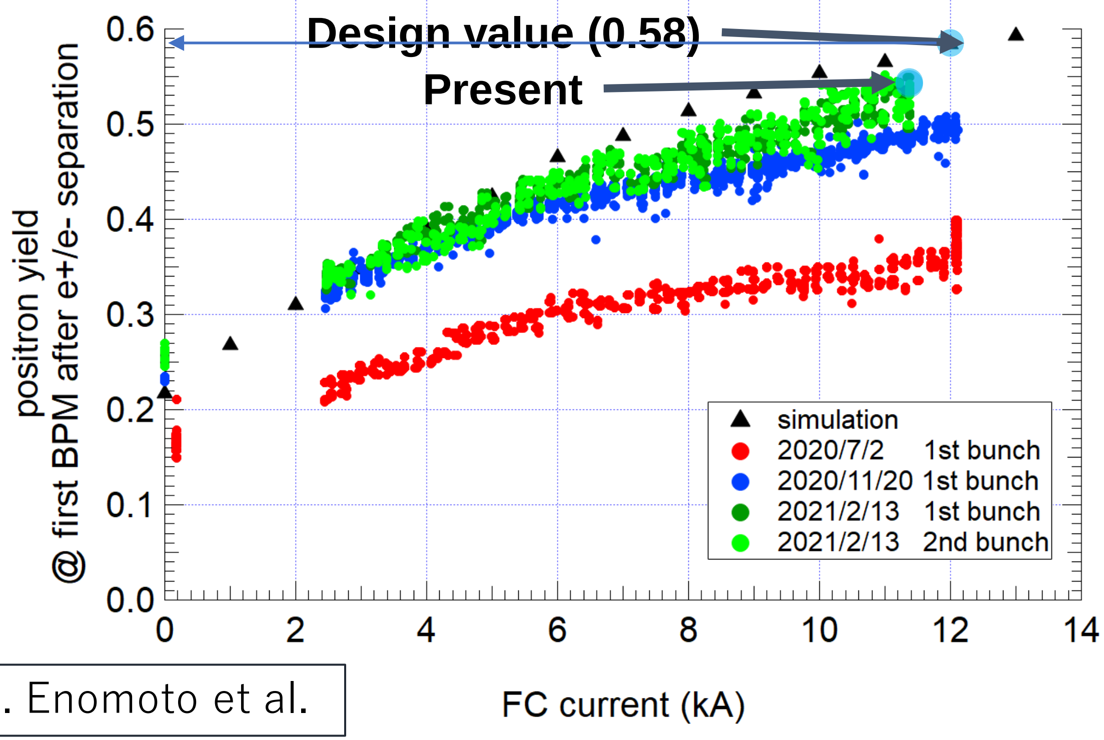
Results of measurement

β_x @MWP.1 [m] :	9.504	β_y @MWP.1 [m] :	20.183
α_x @MWP.1 :	-.251	α_y @MWP.1 :	1.737
ε_x [m] :	1.3258E-8	ε_y [m] :	4.193E-10
$\Delta\varepsilon_x$ [m] :	3.5336E-9	$\Delta\varepsilon_y$ [m] :	1.498E-10
$\gamma\varepsilon_x$ [μm] :	99.667	$\gamma\varepsilon_y$ [μm] :	3.152
$\Delta\gamma\varepsilon_x$ [μm] :	26.563	$\Delta\gamma\varepsilon_y$ [μm] :	1.126
Goodness x :	.827	Goodness y :	.982
Bmag x :	1.089	Bmag y :	1.458
ε Bmag x :	1.4436E-8	ε Bmag y :	6.112E-10
γε Bmag x :	108.522	γε Bmag y :	4.594

Goal: $\varepsilon_{nx,nxy}$ (4 nC)
～100/15 (H/V) μm)

Positron yield

- 5 nC at BPM<SP_16_5> (1st BPM after e+ target)
- ～ 3 nC LTR (Linac To damping Ring) and downstream
- For obtaining 4 nC at BT:
  - Some more steering/Q magnets will be installed after target in 2021 (this summer).
  - Increase gradient: 7.3 MV/m to 14.0 MV/m (design) for two structures (AC_15_1[2] situated at downstream e+ target)
  - Increase FC field and DC solenoid field. (power supply should be improved)



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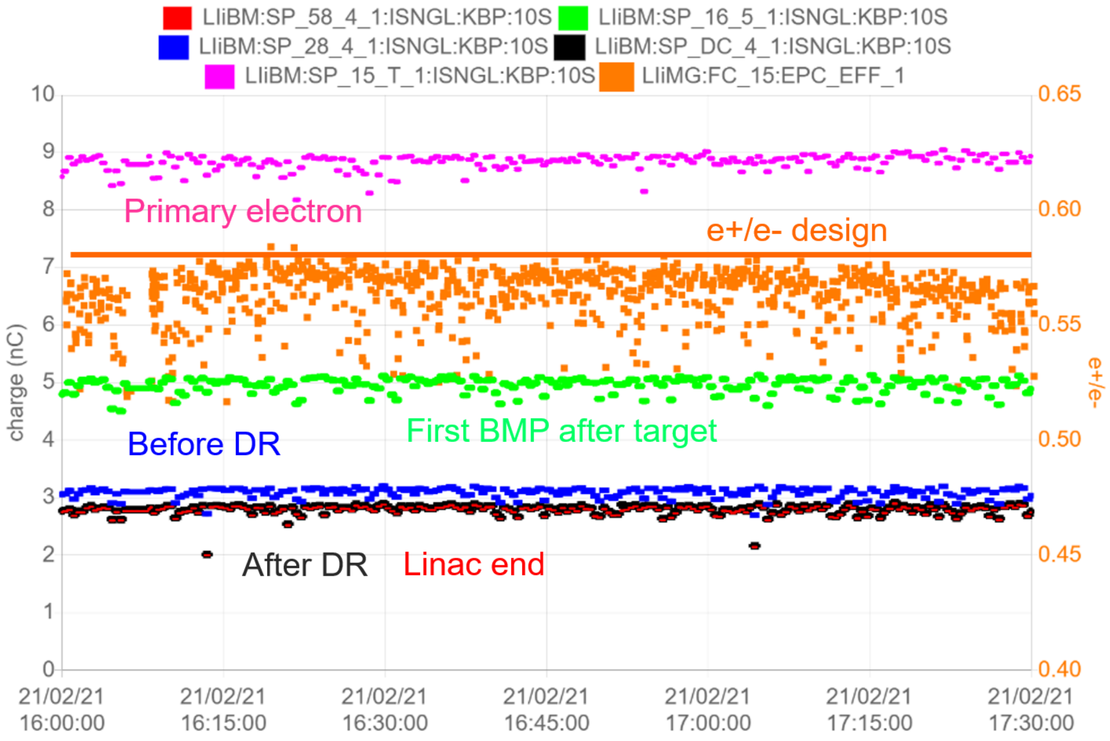


Pulsed magnet system

- Pulsed quad (x 32) (w/ ceramic duct), steering (x 65) and bend (x 2) are used (mainly in sector 3 to sector 5) since 2017
- PXIe based control system (Windows, LabVIEW, EPICS, MRF event receiver) (x 16) have worked fine.
- **Power supply stability: 0.01%** (24 hours) ⇔ requirement : 0.1%
- Stored energy in an inductance of the magnet are recovered to capacitors.
- **Total energy recovery efficiency 68.5% (measured).**

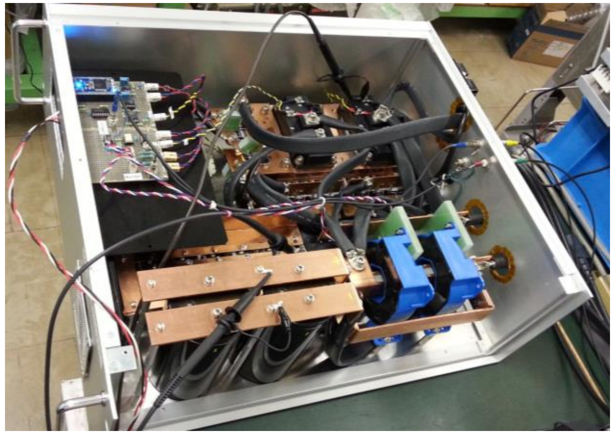
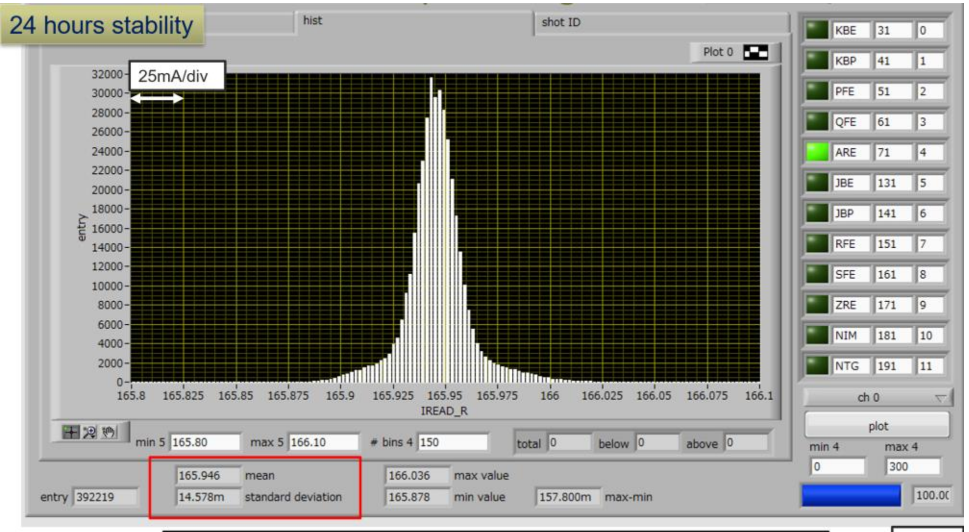
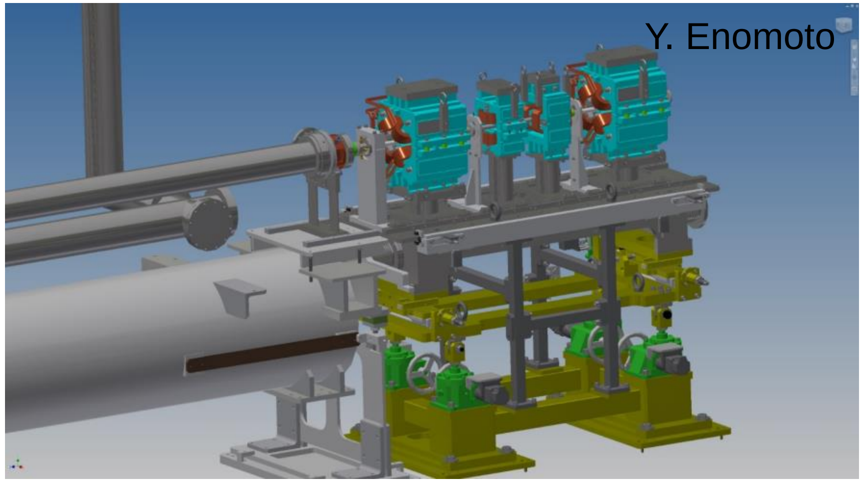


Photo of a prototype pulsed Q driver designed by T. Natsui



0.014578 / 165.946 = 0.01 % (requirement 0.1 % @ 330 A)

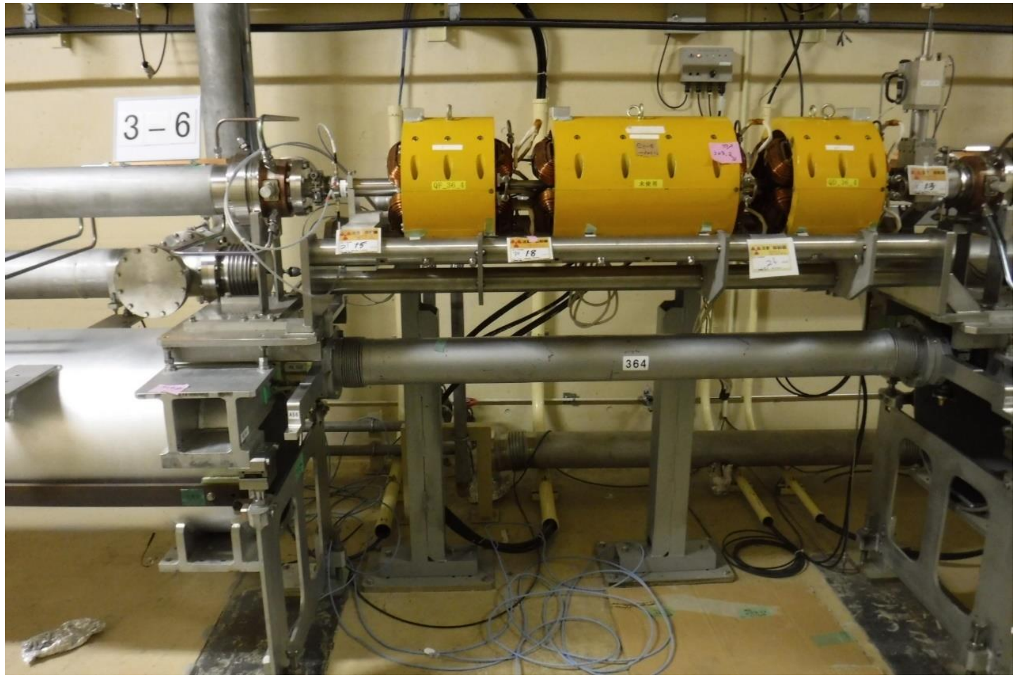
Current statistics in 24 hours



Movable girder for pulsed magnet (remote controllable, 10 μm step)

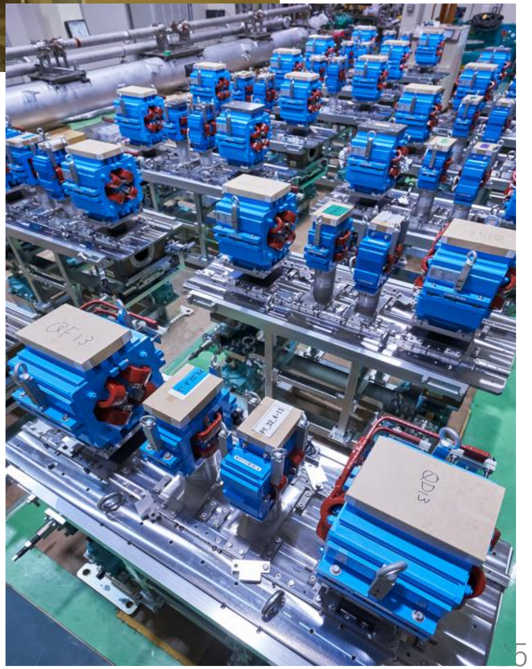
Photo of control unit and power supply

All magnets in Sector3-5 were replaced by pulsed one in 2017



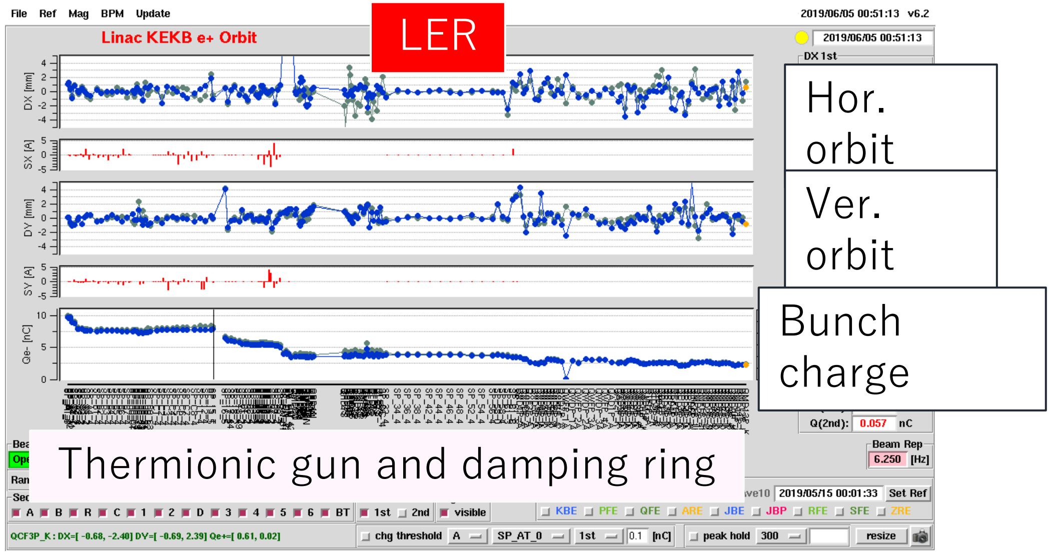
Old DC magnets
Q triplet

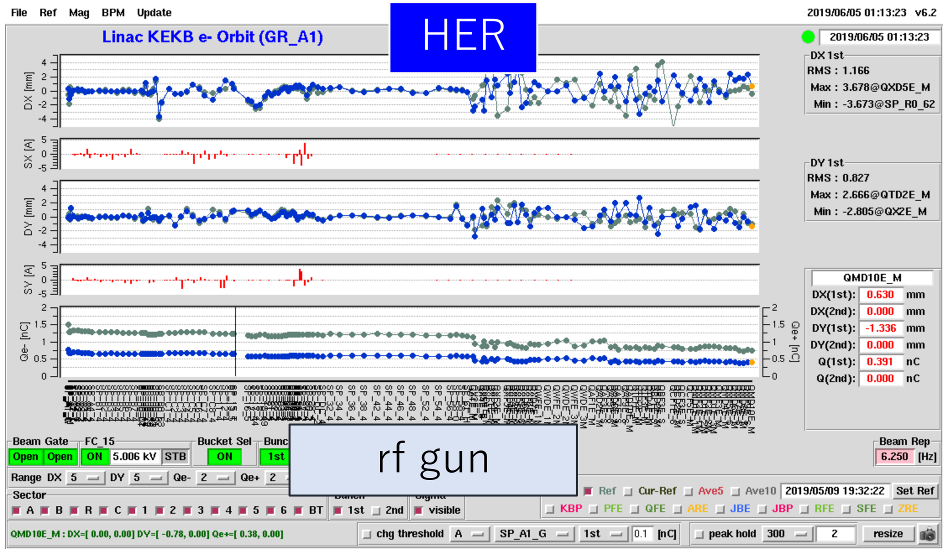
New pulsed magnets
QF
Horizontal steering
Vertical steering
QD

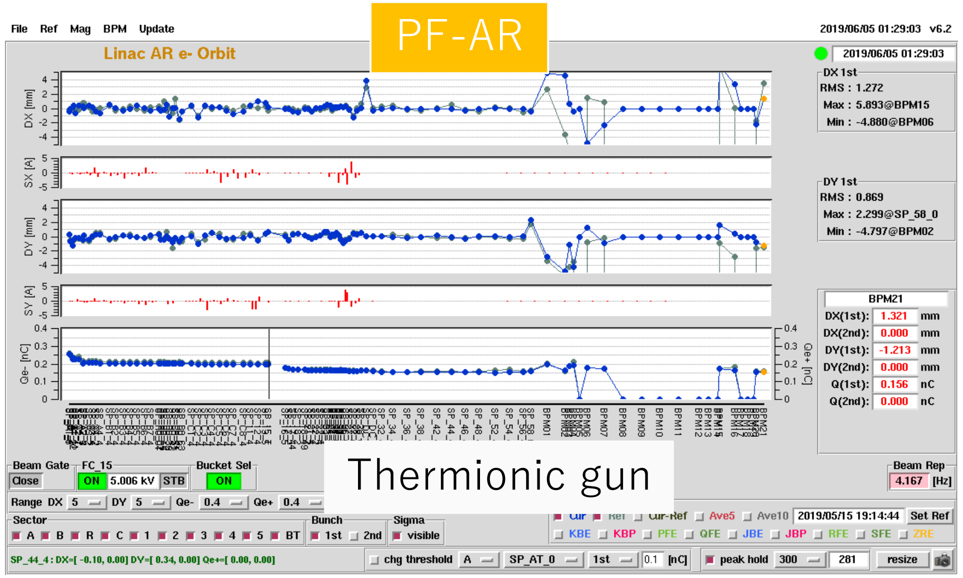


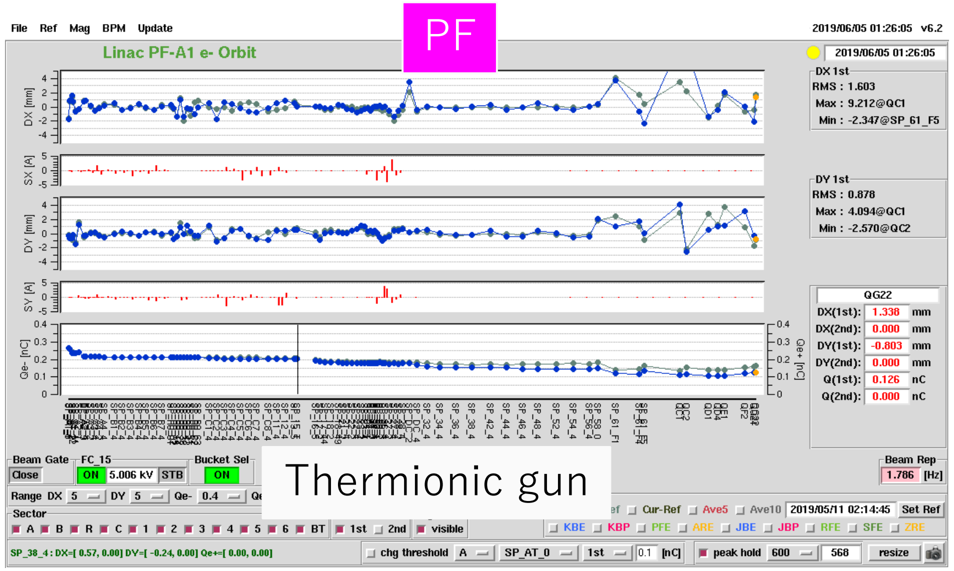
We renewed power supply, cooling water, cabling, support, control system, software, etc in 99 working days.

Beam orbit snapshot during simultaneous top up injection

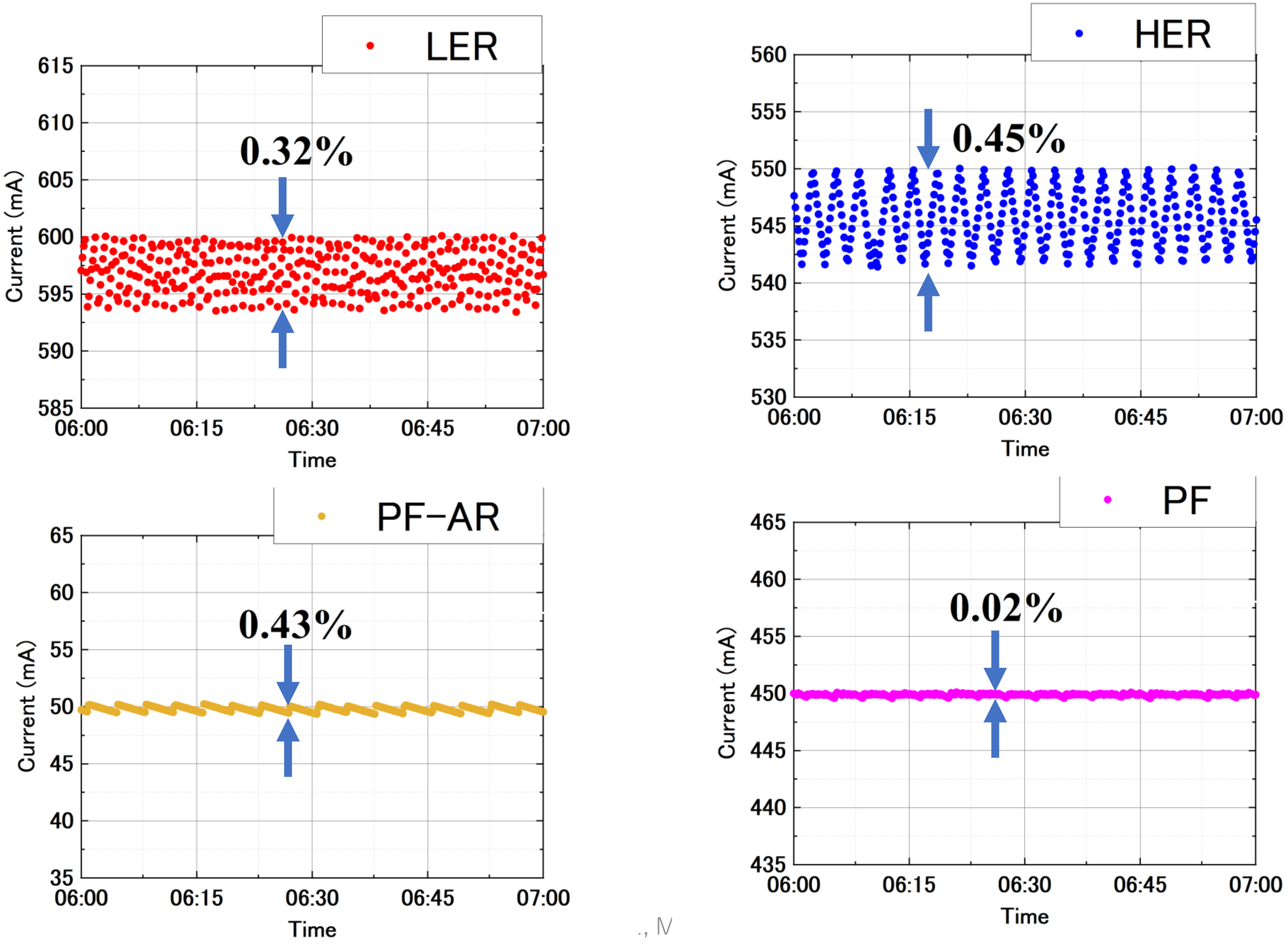




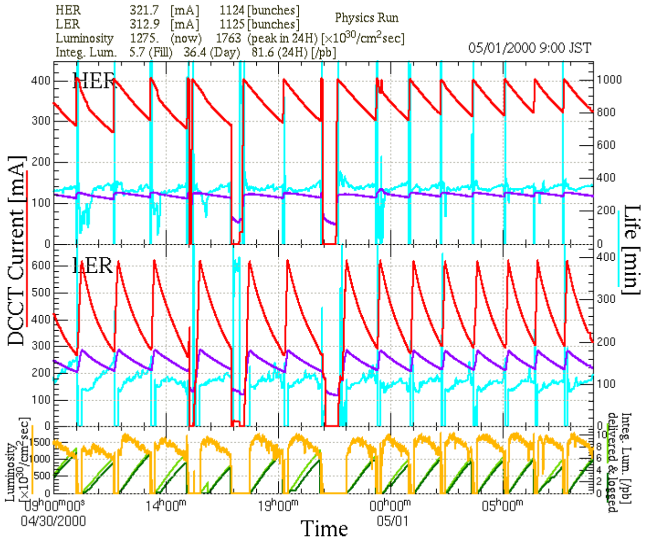




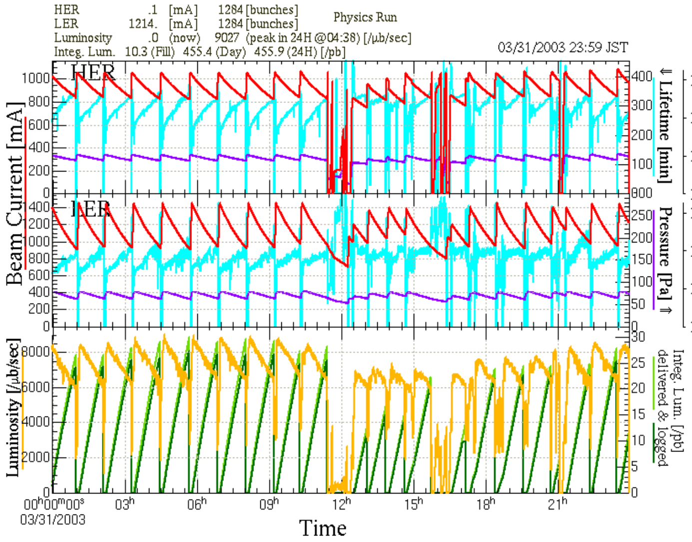
Stored current stability during simultaneous top up injection



Long way to simultaneous top-up injection into 4 rings (1)

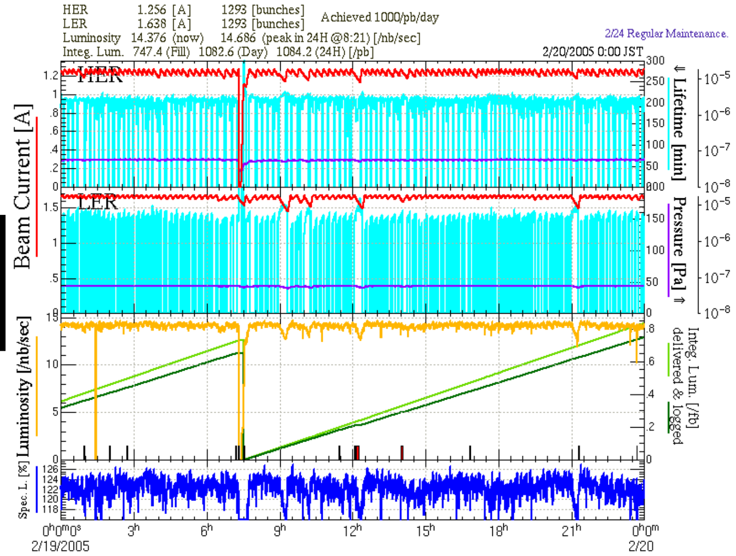


May.2000



Apr.2003, Dual Bunch injection

New PF-BT in 2005

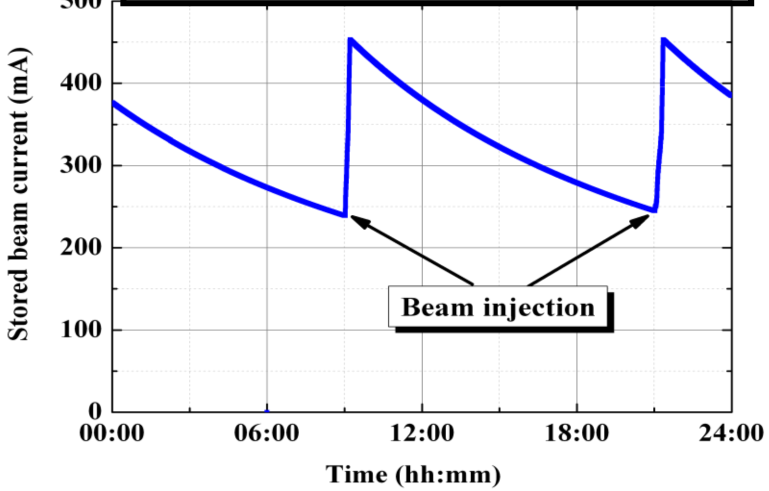


Feb.2005, Continuous Injections

red: beam current (e-, e+)
purple: vacuum (e-, e+)
yellow: luminosity
green: integrated luminosity

However, still PF, PF-AR injection 2-3 times daily

PF

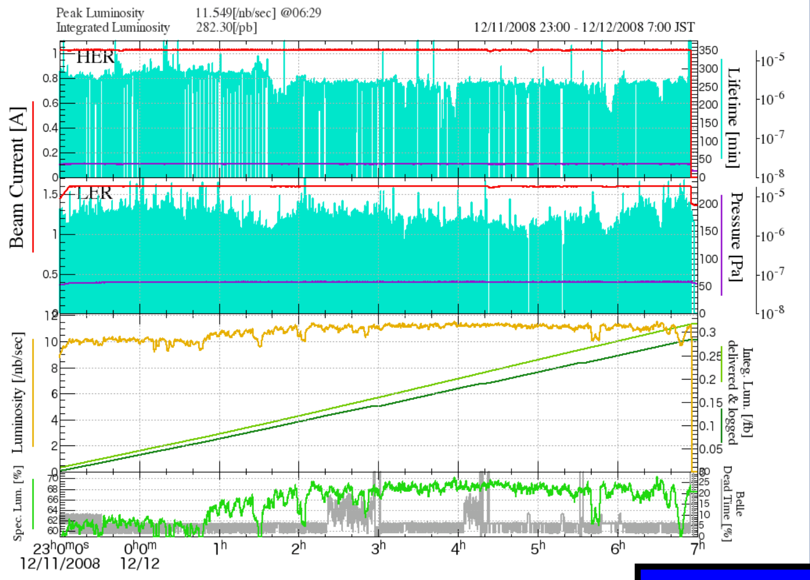


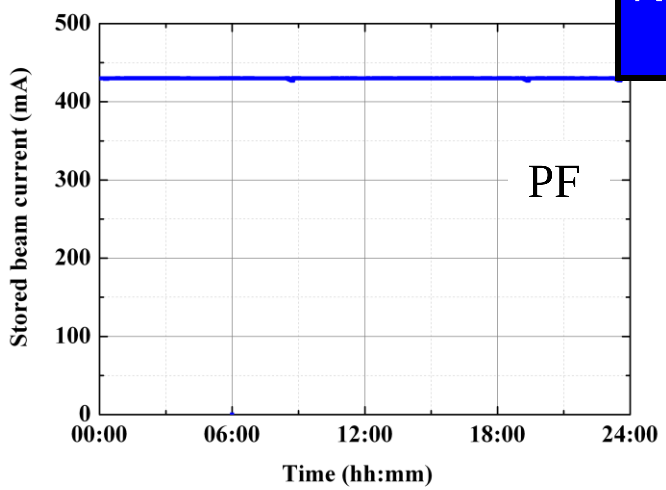
2004: Simultaneous top up injection project started

2005: New PF BT (decoupling from LER BT)

2017: New PF-AR BT (decoupling from HER BT)

Long way to simultaneous top-up injection into 4 rings (2)





New PF-AR BT
in 2017

2009, simultaneous top-up
for 3 rings (KEKB HER/LER, PF)

2019, simultaneous top-up
for 4 rings ! (SuperKEKB HER/LER, PF, PF-AR)

Summary

Simultaneous top up injection operation of 4 storage rings (SuperKEKB HER/LER, PF, PF-AR) has successfully established.

- **Pulse to pulse beam control based on the event based timing system, low level rf phase control, pulsed magnet (Quad, Steering, Bend)**
- **50 Hz monitoring (BPM, rf, pulsed magnet PS, FC) and analysis tools**
- **Many People's Continuous Contributions and Efforts over 15 years**

Future improvements:

- **Improvement of reproducibility beam quality (emittance, energy spread)**
- **Achievement of the final parameter required for SuperKEKB (high bunch charge, low emittance)**
- **Deteriorated subsystem will be replaced (damaged acc. Structures, old magnet power supply and controller, and so on)**

Thank you for your attention!