Pulse-to-pulse beam modulation for 4 storage rings with 64 pulsed magnets

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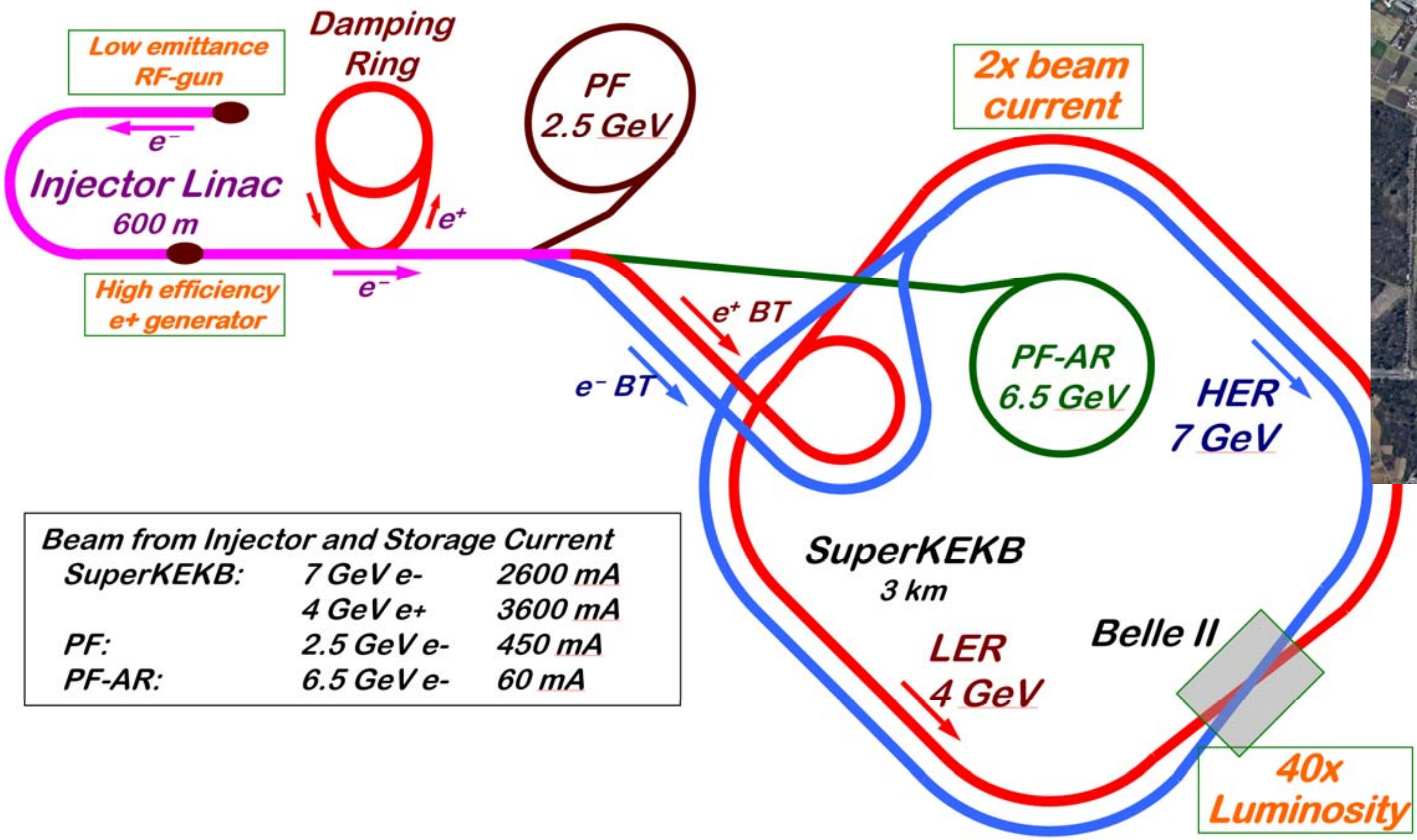
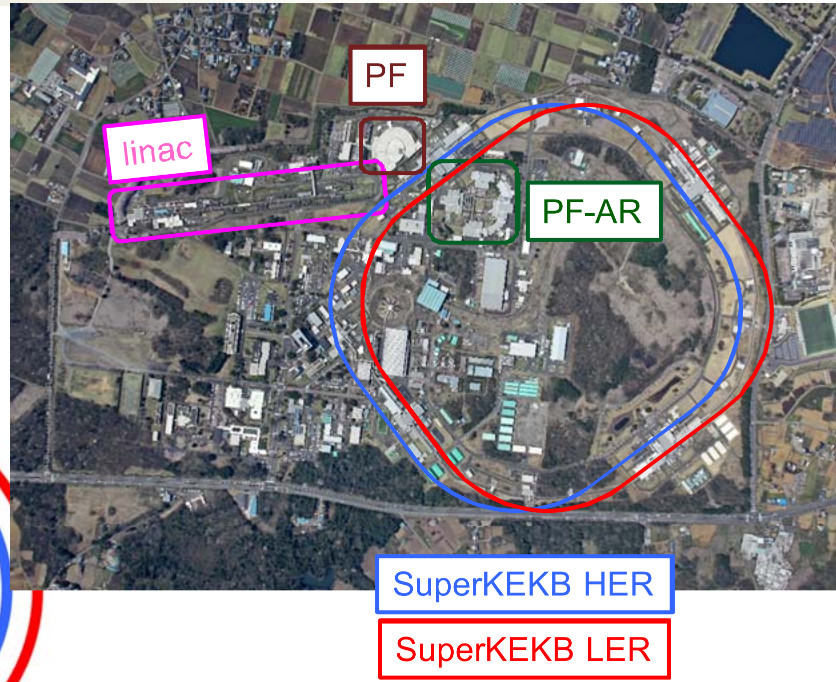
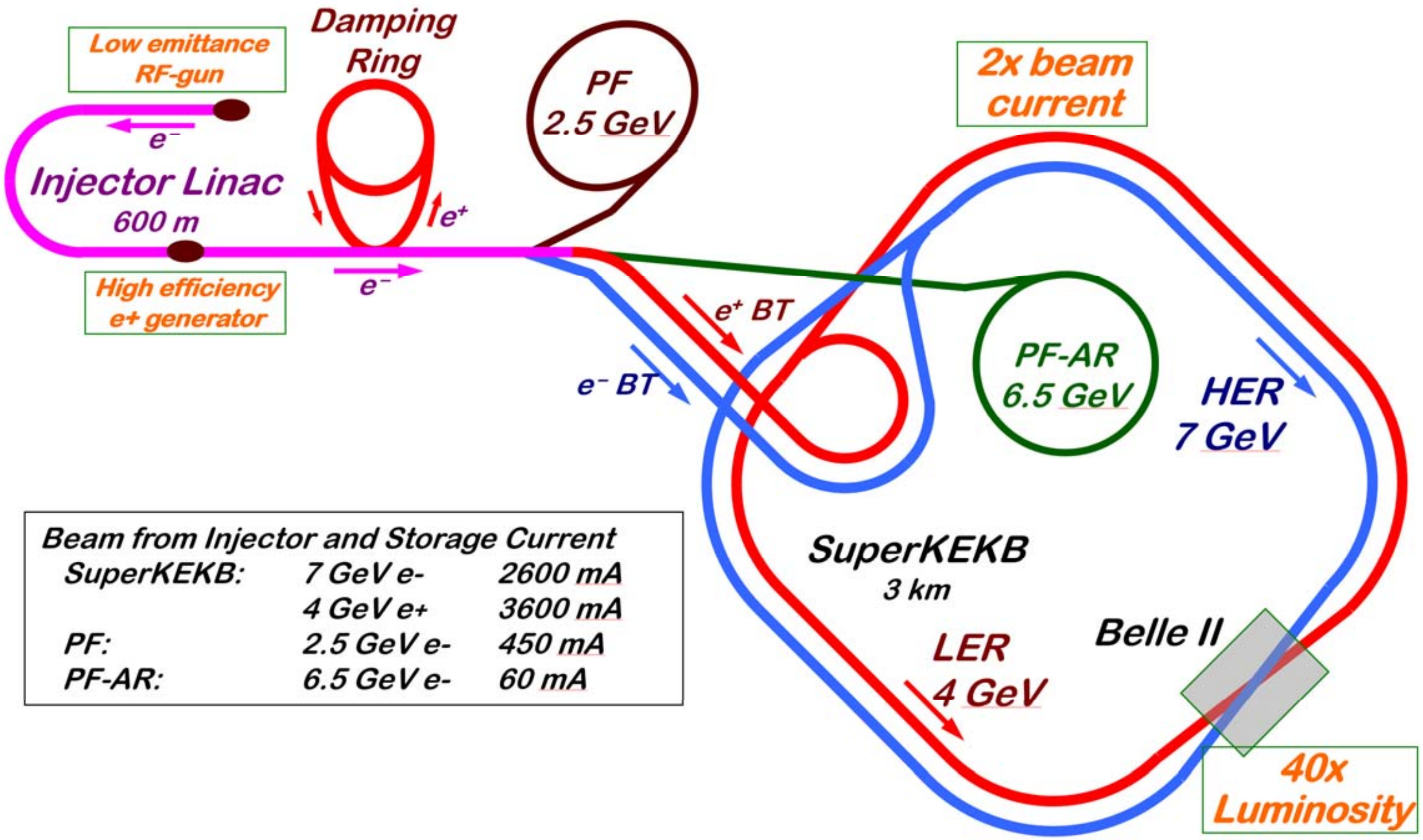
Accelerator complex in KEK Tsukuba



Beam from Injector and Storage Current		
SuperKEKB:	7 GeV e-	2600 mA
	4 GeV e+	3600 mA
PF:	2.5 GeV e-	450 mA
PF-AR:	6.5 GeV e-	60 mA



Accelerator complex in KEK Tsukuba



Beam from Injector and Storage Current

SuperKEKB:	7 GeV e-	2600 mA
	4 GeV e+	3600 mA
PF:	2.5 GeV e-	450 mA
PF-AR:	6.5 GeV e-	60 mA

- 4 rings and 1 linac
  - Two light source rings
    - PF, PF-AR
  - Two collider rings
    - SuperKEKB LER, HER
- Parallel configuration
  - No booster ring
- All storage rings
  - Full energy injection
- Top-up injection
  - Keep intensity of photon constant
  - Compensate short life time (360sec.)
- Two electron guns
  - RF gun for low emittance injection to SuperKEKB HER
  - Thermionic gun for high charge (10 nC) to produce large number of positrons
- Positron injection to LER

Our linac is an all-in-one injector

Requirements and progress on pulse-to-pulse operation

- Slow switch operation (-2009)

PF	PF-AR	KEB HER/LER	PF	PF-AR	KEKB HER/LER
20 min.	10 min.	7.5 hours	20 min.	10 min.	7.5 hours

- 3 ring injection with ***DC magnets (2010)***
  - PF pulsed bending magnet (switching magnet) was installed at the end of the linac.

PF-AR	PF, KEB HER/LER	PF-AR	PF, KEKB HER/LER
10 min.	7.8 hours	10 min.	7.8 hours

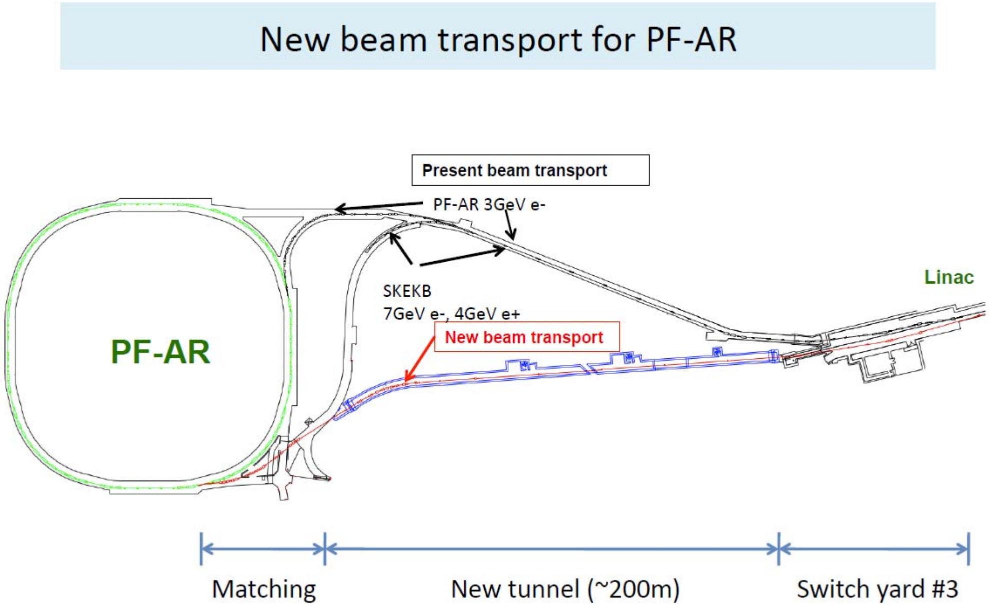
PF pulsed bending magnet

- Toward SuperKEKB (2018-)
  - Very short beam life time in the SuperKEKB rings (360 sec.).
    - 10 min. Interruption is not acceptable.
    - PF-AR direct injection line was constructed.
  - Small dynamic aperture
    - Low emittance beam is required for injection.
    - RF gun and positron dumping ring were installed.
    - For emittance preservation, optimization of the optics for each ring is required.

PF, PF-AR, SuperKEB HER/LER
always

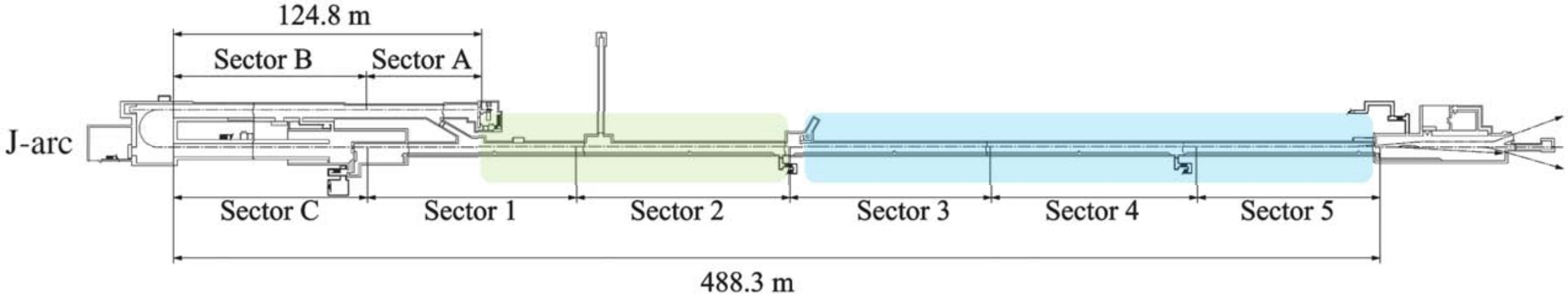
Replace DC magnets with pulsed magnets

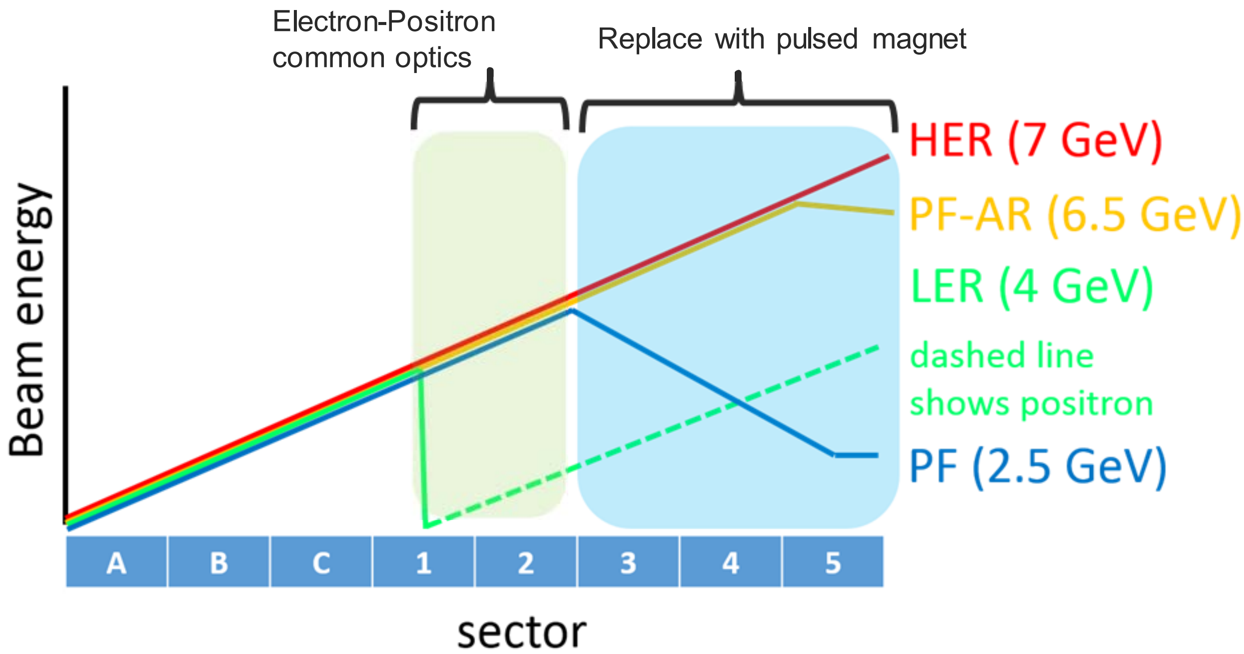
Requirements and progress on pulse-to-pulse operation



	KEKB		SuperKEKB	
	Charge	Emittance	Charge	Emittance
electron	1 nC	300 mm･mrad	5 nC	50 (H) / 20 (V) mm･mrad
positron	1 nC	1500 mm･mrad	4 nC	100 (H) / 20 (V) mm･mrad

Beam energy and structure of our linac

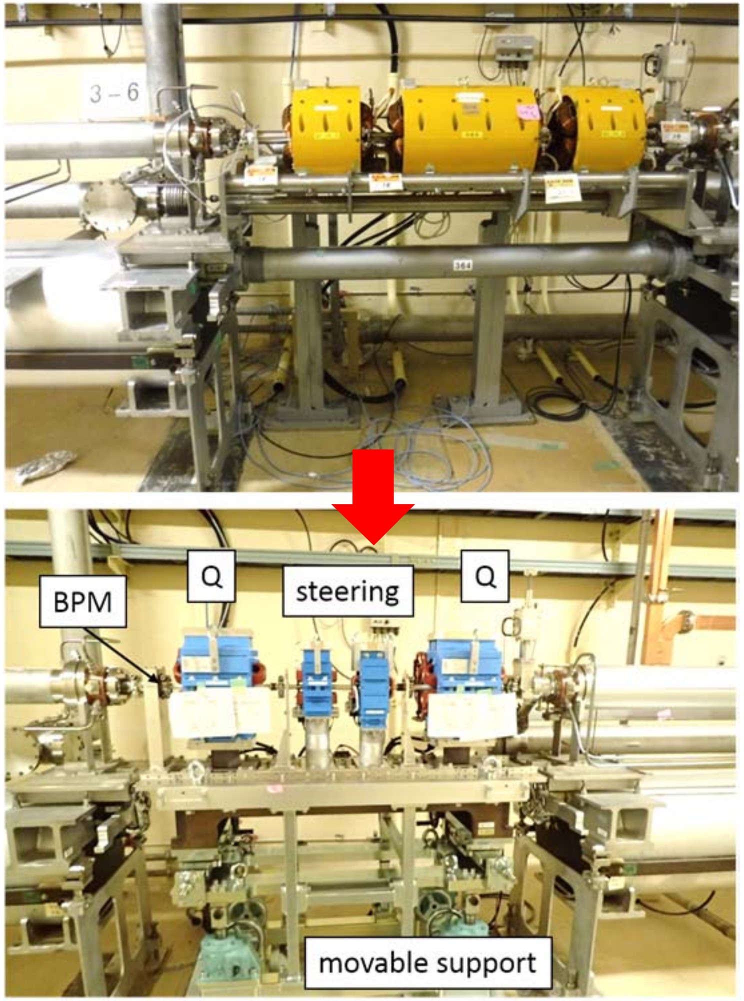




- 600 m long, 8 sectors
- Maximize common energy section to use DC magnets as much as possible
- Install pulsed magnets mainly in sector 3 to sector 5

26 quads and 26 steerings @ sector 3-5
10 steerings @ sector 1,2
2 quads @ positron production target

Replacement of magnets



type	L@1 kHz	R	max current	magnetic field	gap	Installed Num.
PX_16_5	2.4 mH	71 mohm	40 A	1040 AT	72 mm	1
PY_16_5	2.4 mH	71 mohm	40 A	1040 AT	72 mm	1
PX_17_2	2.6 mH	127 mohm	40 A	1440 AT	39 mm	4
PY_17_2	2.6 mH	126 mohm	40 A	1440 AT	39 mm	4
PX_32_4	2.9 mH	115 mohm	40 A	1440 AT	20 mm	13
PX_32_4	2.9 mH	115 mohm	40 A	1440 AT	20 mm	13
PM_32_4	1.0 mH	8 mohm	330 A	60 T/m	ϕ 20 mm	28

Maximum design current of steering magnets are 40 A but operated at 10 A

- 64 magnets were installed in 2017.
  - Several types of steering magnets
  - One type of quad magnet
- 52 magnets of them were installed as a common unit.
  - 2 x quad magnets.
  - horizontal and vertical steering magnets
  - BPM
  - Movable support

Requirements for power supply

PF pulsed bending magnet and pulsed power supply

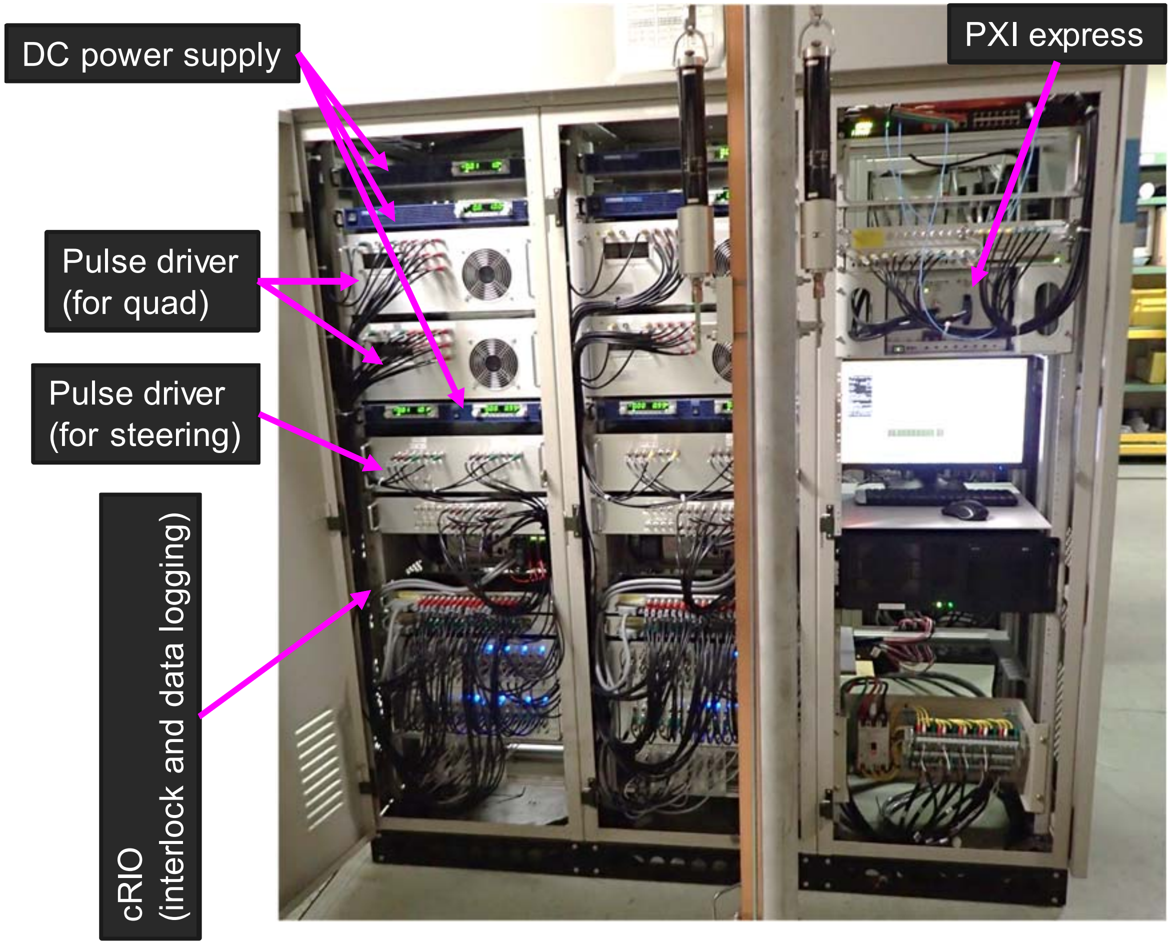
- Install pulsed power supplies for 28 quads and 36 steerings.
  - budget is limited
  - Installation space is limited
  - Commercial power is limited
- Off / On control is not satisfactory.
  - Output setting should be changed pulse-to-pulse
- Compatible with MRF event timing system.
- Compatible with EPICS control system.

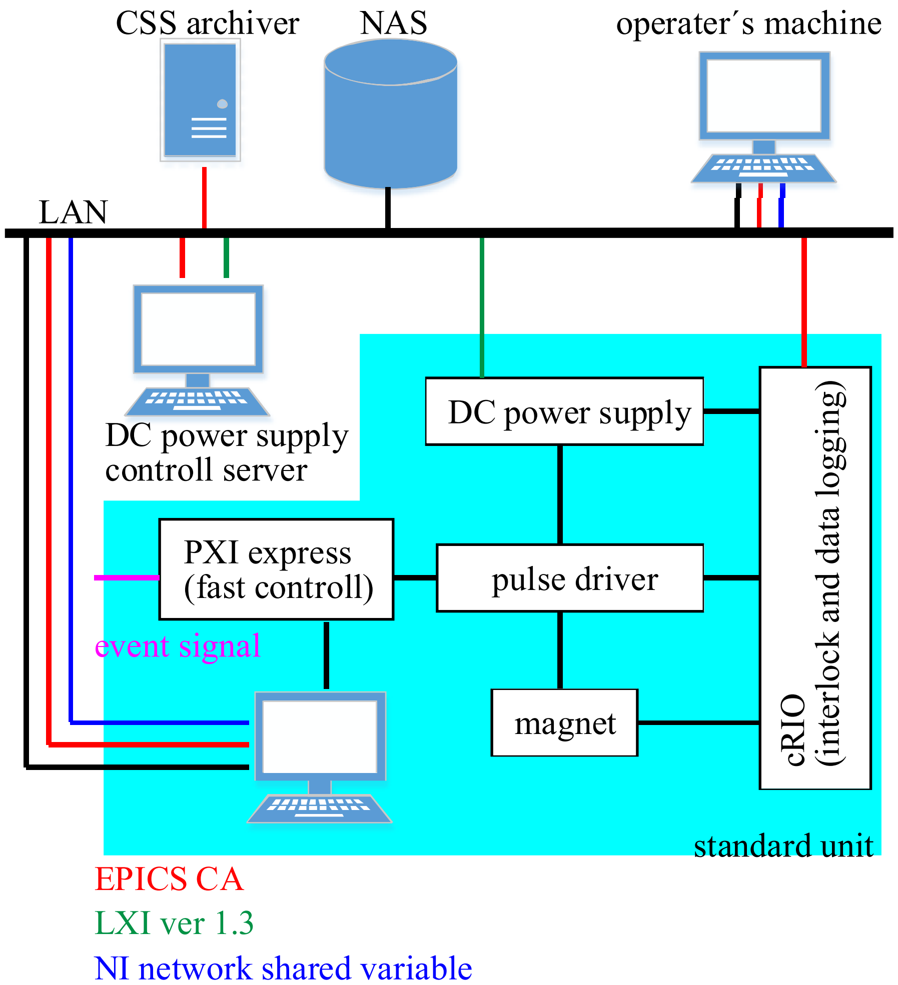
・PF pulsed bending magnet
・Klystron
・Electron gun
etc. are compatible with pulsed operation.
But most of them are off / on or on timing / off timing control.

Decided to develop pulsed power supplies by ourselves.

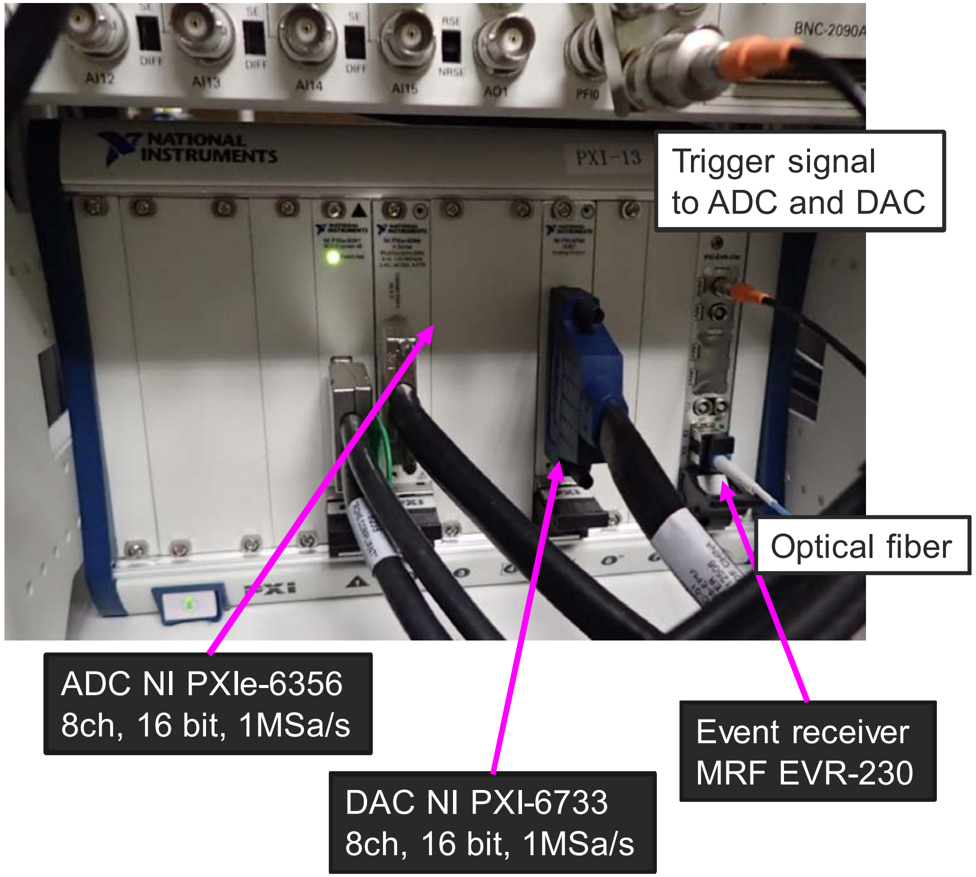
System configuration of the pulsed power supplies

Standard power supply unit (4 x quad + 4 x steering)





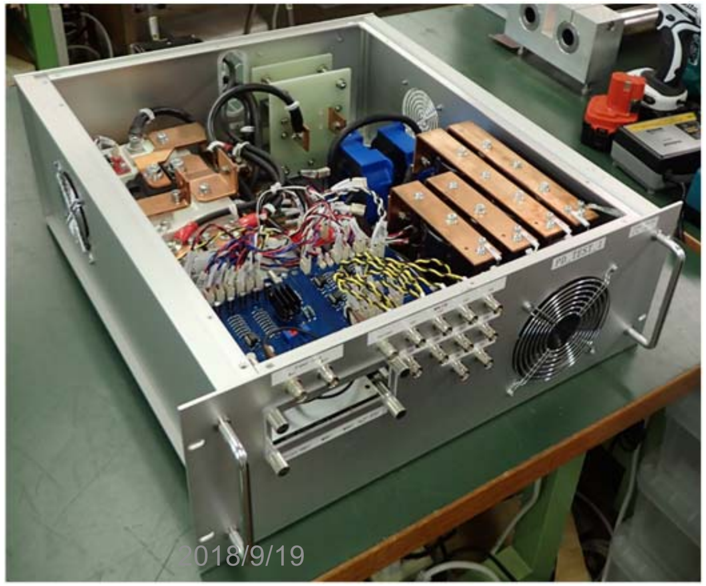
Timing and fast control



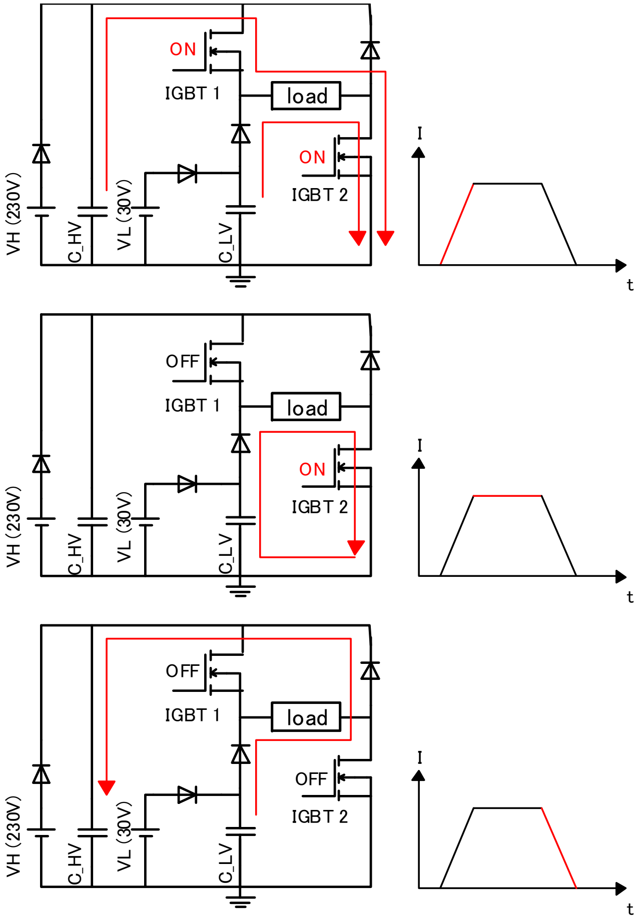
- PXI express system is adopted for fast control of the power supplies.
- All of the intelligent functions are processed by PXI express unit
  - Pulse driver works as a kind of power amplifier
  - Separation of control and power section makes it possible for us to flexible installation of different capacity of power supplies in the future.
- MRF(Micro-Research Finland) event receiver with PXI form factor is used for timing control
  - MRF event timing system is used as a master timing system of our linac.
- Mode and shot ID information are sent to the event receiver via optical fiber
  - Mode determine the destination of the beam.
  - Shot ID is used for tagging the data.

Energy recovery pulse driver for Q magnet

parameter	value
max current	330 A
max voltage	230 V
stability	0.1%
cooling	water cooled
power consumption	1500 W
repetition	50 Hz



Operation principle of the circuit



- Turn on both IGBTs and current flow from both of capacitors.
- Turn off IGBT 1 and control gate voltage of IGBT 2 to keep constant current
- Turn off both IGBTs and stored energy is recovered to the capacitor (C_HV).

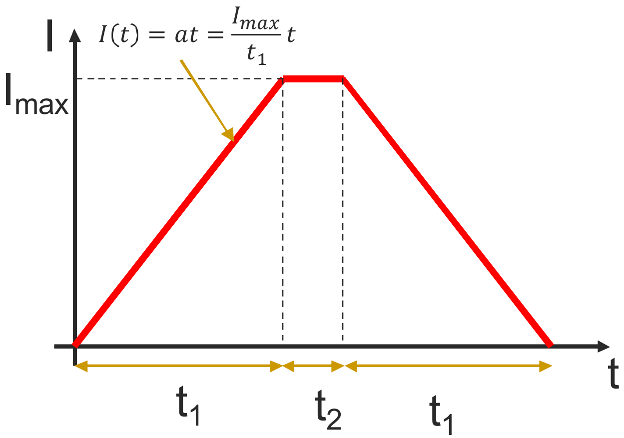
Energy recovery
+
Water cooling
⇩
19 inch width
3U height

Energy consumption balance

Stored energy in inductance

$$P_L = \frac{1}{2} L I_{max}^2$$

Ohmic loss per cycle



$$P_{joule} = \int_0^{2t_1+t_2} R I(t)^2 dt$$

$$= R\left\{2a^2 \int_0^{t_1} t^2\, dt + I_{max}^2 t_2\right\}$$

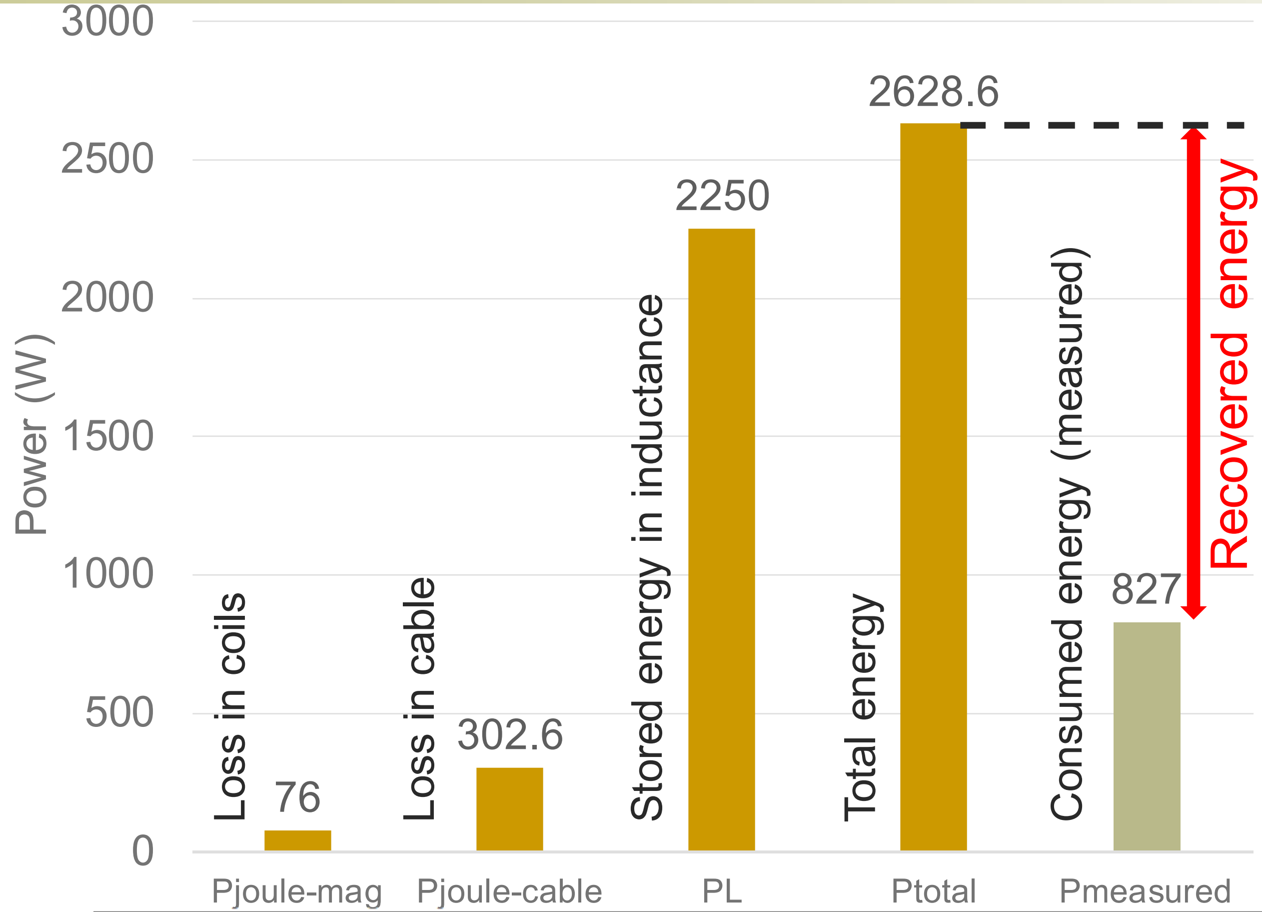
$$= R\left(2\frac{I_{max}^2}{t_1^2}\frac{1}{3}t_1^3 + I_{max}^2 t_2\right)$$

$$= R I_{max}^2\left(\frac{2}{3}t_1 + t_2\right)$$

	Q (PM_32_4)	ST (PX_32_4)
t_1 (s)	2.5 m	←
t_2 (s)	0.5 m	←
I_{max} (A)	300	8
L (H)	1 m	3 m
R_{mag} (Ω)	7.8 m	115 m
R_{total} (Ω) incl. cable	38.83 m	298.85 m
$P_{joule\text{-}mag}$ (W) @ 50 Hz	76	0.797
$P_{joule\text{-}cable}$ (W) @ 50 Hz	302.6	1.275
$P_{joule\text{-}total}$ (W) @ 50 Hz	378.6	2.072
P_L (W) @ 50 Hz	2250	4.8
P_{total} (W) @ 50 Hz	2628.6	6.872

- Consumed energy by one quad magnet @ 300 A, 50H z without energy recovery is 2628.6 W.
- Consumed energy by one steering magnet @ 8 A, 50H z without energy recovery is 6.872 W.
- Consumed energy by steering magnet is negligibly small.

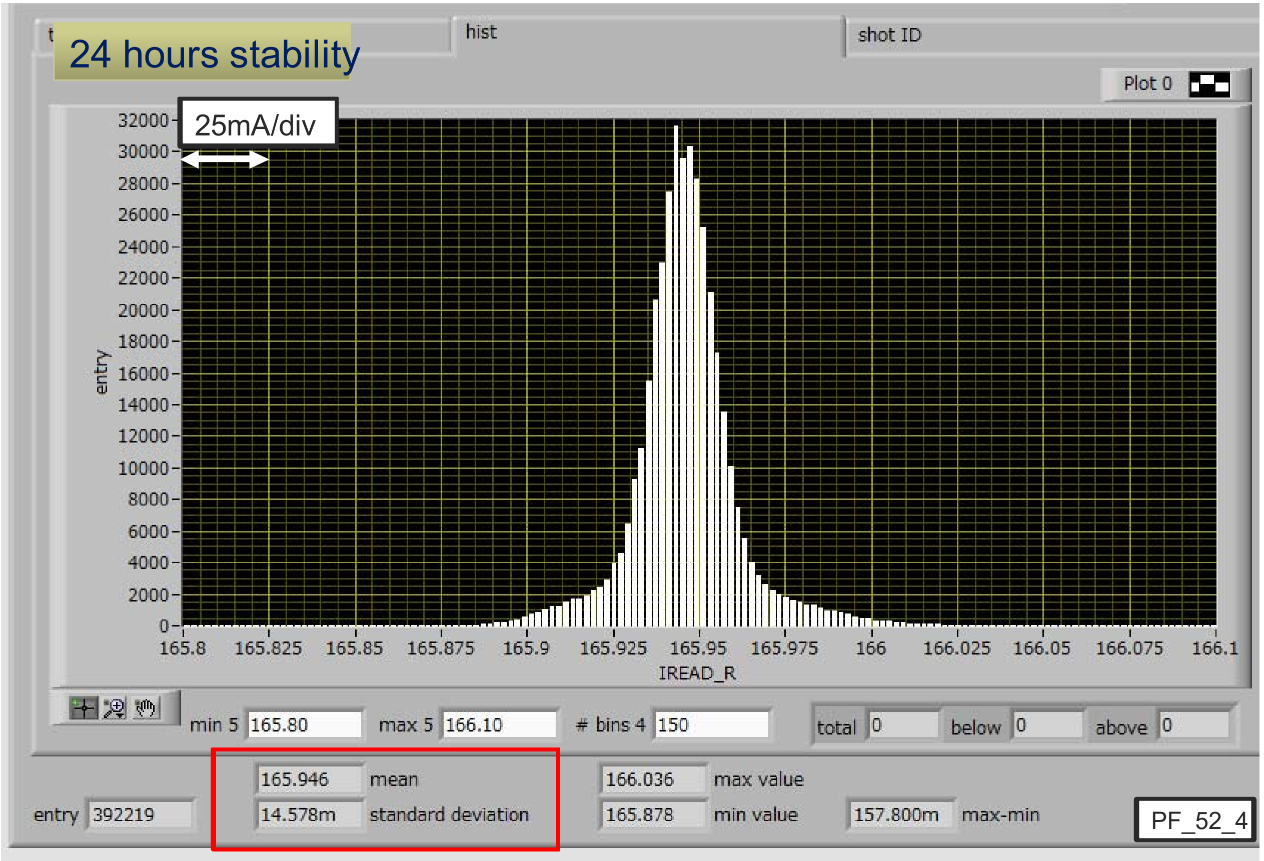
Energy consumption balance



Total energy recovery efficiency = 100 x (1 - $P_{measured}$ / P_{total}) = 68.5%
L energy recovery efficiency = 100 x (1- $P_{measured}$ / P_L) = 80.1%

- Measured consumed energy includes loss in puled driver circuit and DC power supplies to charge capacitors
  - True energy recovery efficiency (ratio of recovered energy and stored energy in inductance is better than 80.1%

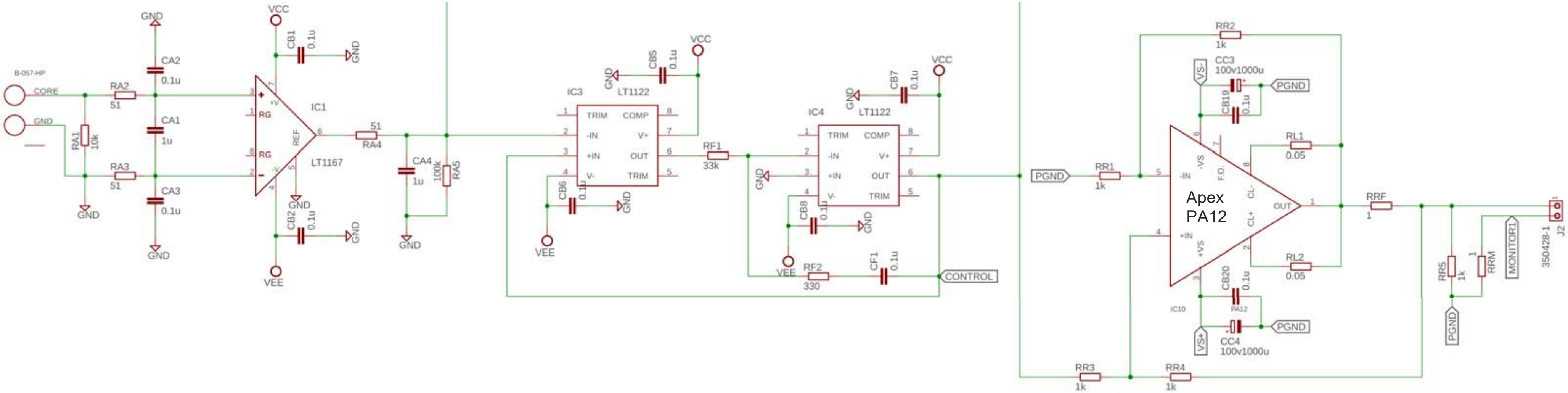
Stability measurement



0.014578 / 165.946 = 0.0088% (requirement 0.1 % @ 330 A)

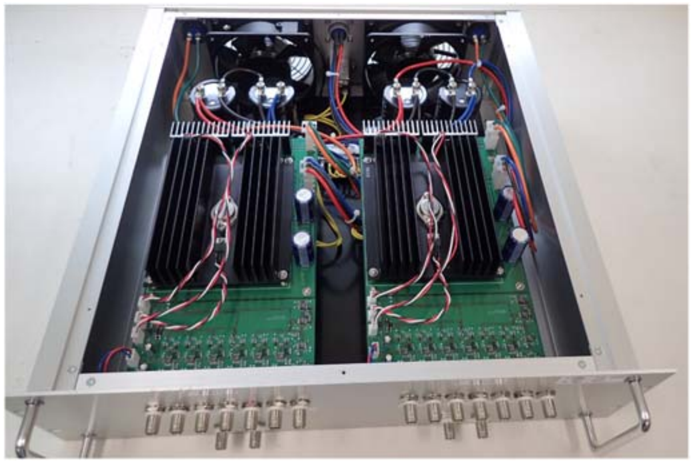
- Stability measurement for 24 hours
- Output 166 A and 0 A alternately
- Output current was monitored built-in DCCT and PXIe ADC.

Pulse driver for steering magnet



Input buffer　　Slew rate limiter　　Power amplifier

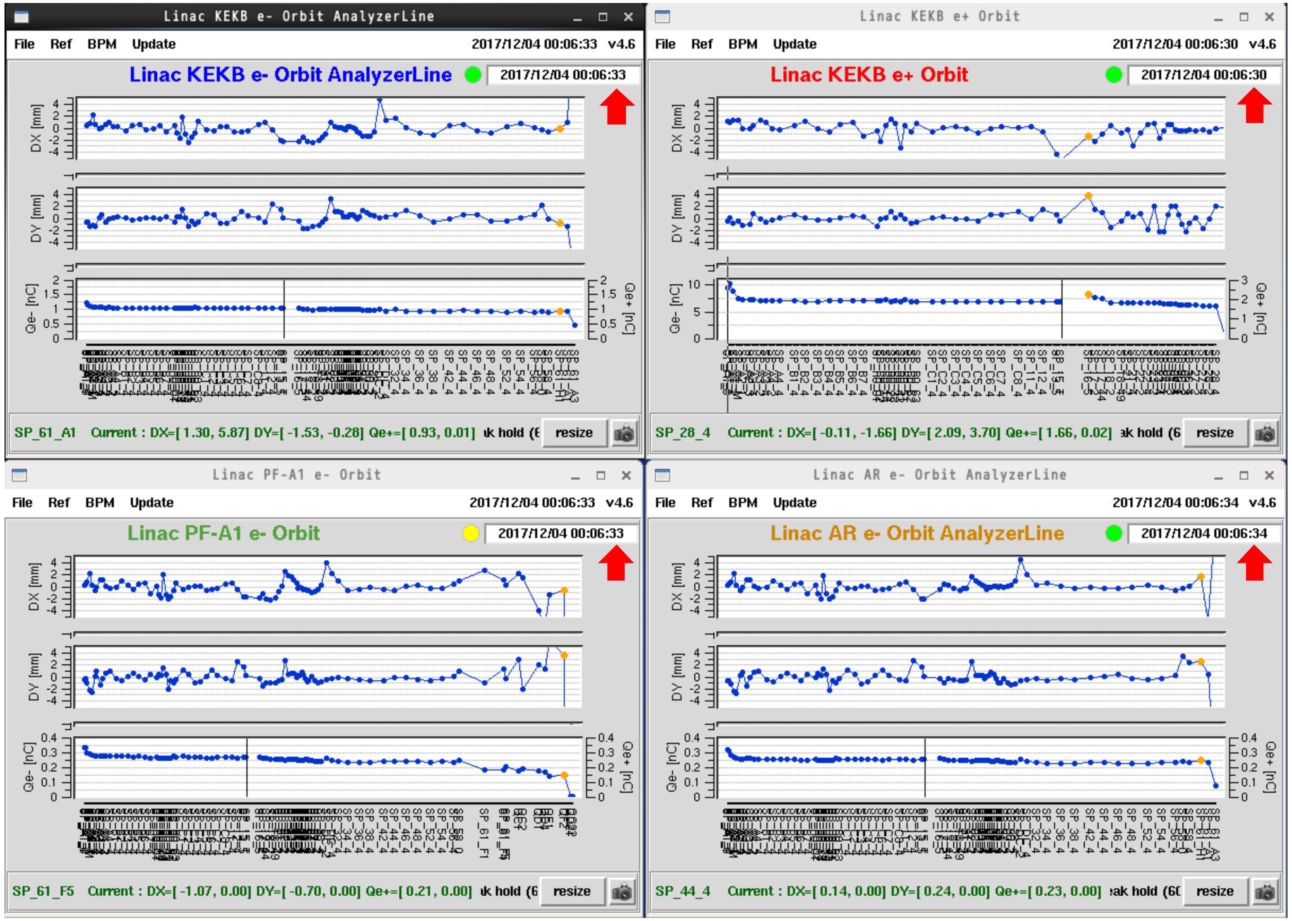
parameter	value
max current	± 10 A
max voltage	± 40 V
stability	0.01%
cooling	air cooled
power consumption	750 W
repetition	50 Hz



- Bipolar power supply by power Op amp (Apex PA12)
  - Low efficiency but Simple circuit
- Air cooled
- 2ch / case
- Built-in slew rate limiter

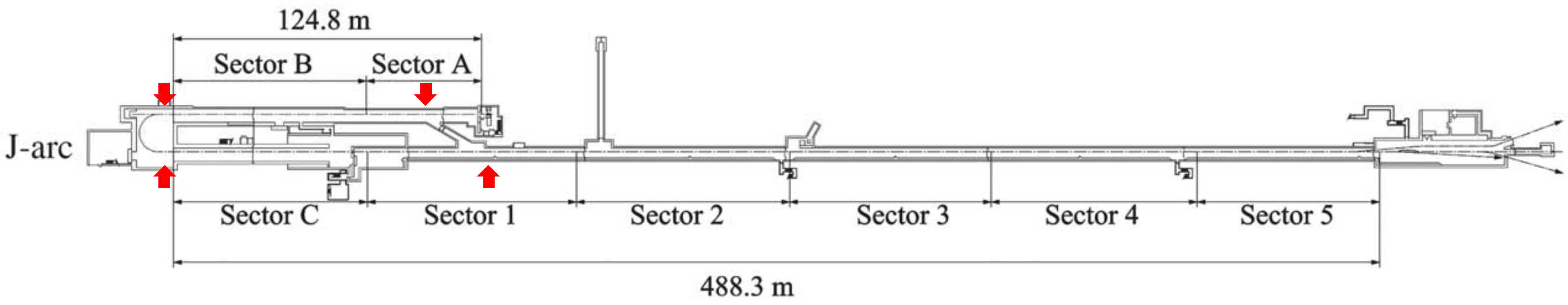
Pulse-to-pulse injection

BPM data (orbit and charge) for 4 different rings



- After the installation, comprehensive test was done in September 2017.
- Pulse-to-pulse operation was demonstrated successfully.
- For one year (Sept. 2017 – Sept. 2018), the system has been working very stably. No severe problem happened.

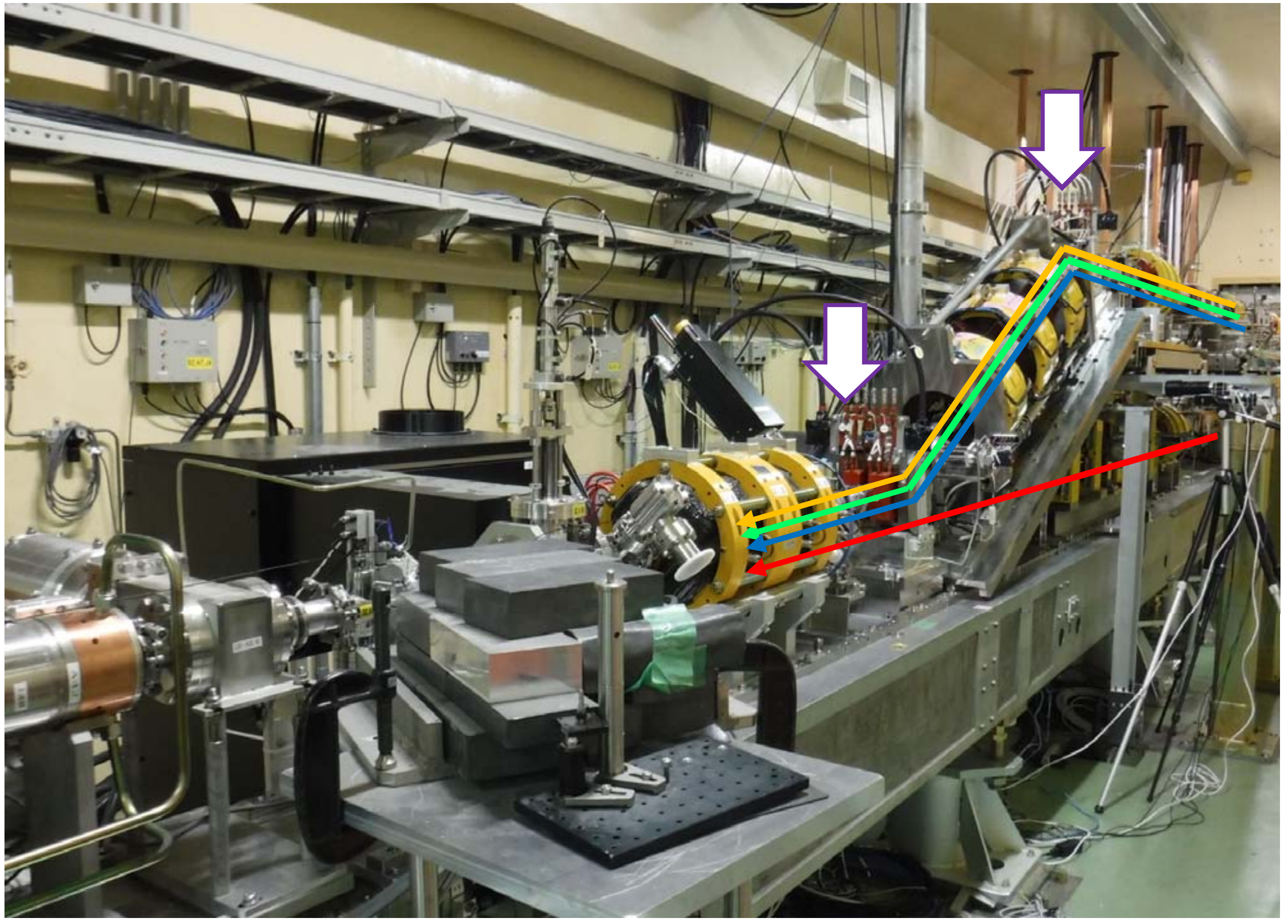
Plan in FY2018



- 2 bend magnets @ merging line.
  - Shot by shot switch of the RF / thermionic e⁻ gun.
- 4 quad and 4 steering magnets @ sector A.
  - To match the beam from the RF/ thermionic e⁻ gun.
- 8 steering magnets @ inlet and outlet of the arc section.
- 1 steering magnet @ sector 1 (before the positron production target)
- Replace power supply and control system of old 11 steering magnets

19 magnets,30 power supplies will be installed in FY2018

Plan in FY2018



2 bend magnet at merging line

Thermionic e^- gun

PF-AR
LER(for e^+ production)
PF

HER

RF e^- gun

Summary

- In 2017, 64 pulsed magnets (28 quad, 36 steering) were installed.
- New pulsed power supply with energy recovery function was developed.
- Pulse-to-pulse injection to 4 rings were demonstrated.
- The system has been working very stably for one year.
- Further 19 magnets and 30 power supplies are plan to be installed in 2018.

members

- K. Furukawa
  - Adviser, management of the project, timing system
- T. Kamitani
  - Magnet design
- F. Miyahara
  - Timing system
- T. Natsui
  - Energy recovery pulse driver
- M. Satoh
  - Timing and control system, software
- K. Yokoyama
  - Magnet design
- M. Yoshida
  - Energy recovery pulse driver
- S. Ushimoto
  - cRIO interlock and data acquisition system
- H. Satome
  - Device driver for event receiver

Thank you
for your attention!