Introduction to the Electron/Positron Injector LINAC

Kazuro Furukawa for Injector LINAC

<http://www-linac.kek.jp/linac-paper/general/>

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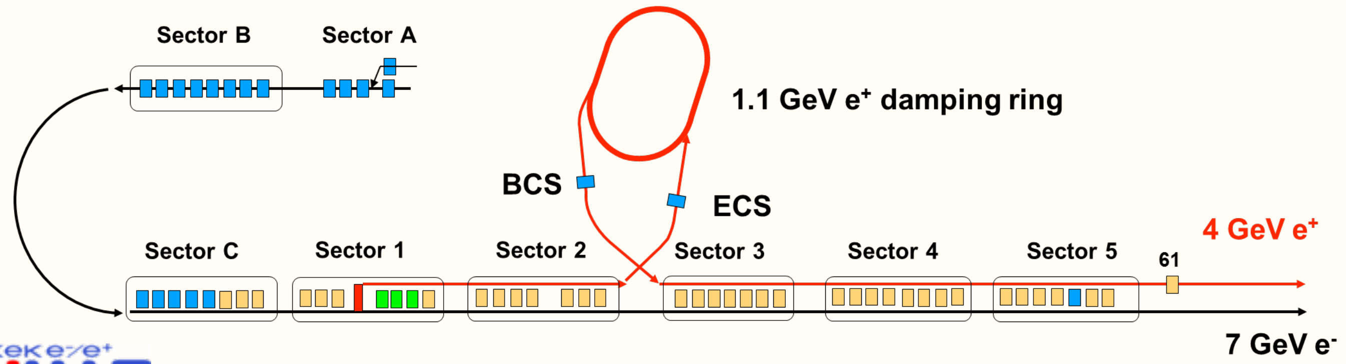
- History
- KEKB
- SuperKEKB
- Components
- Upgrade

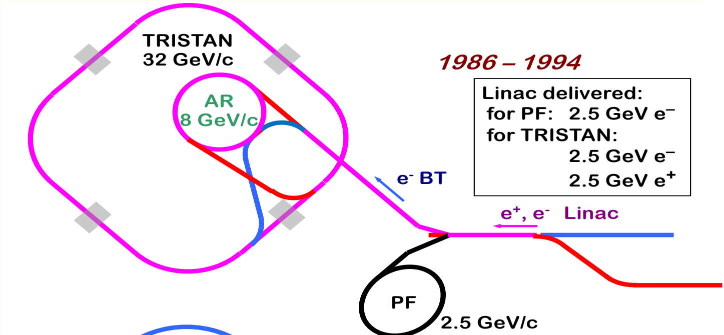
42-year History

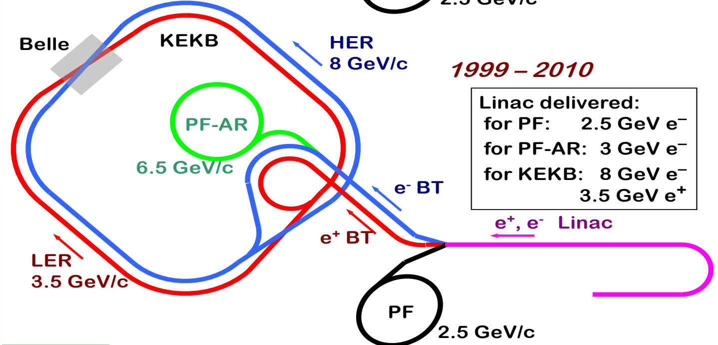
Injector Linac Project History

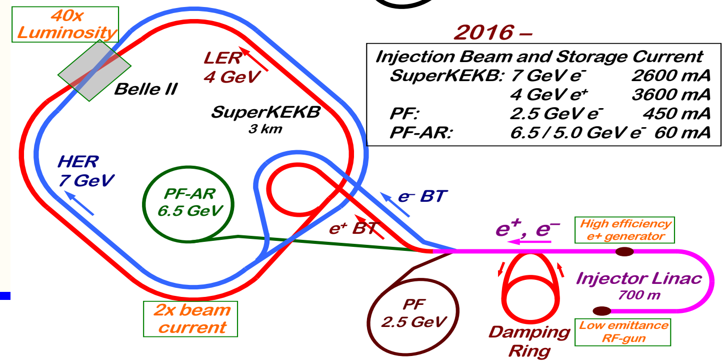
Project	Injection Energy	Exp. Energy	JFY 1970–2023
Photon Factory	2.5 GeV	2.5 GeV	Construct. / Injection Operation
TRISTAN	2.5 GeV	32 GeV	Construct. / Injection Operation
Slow Positron	2.5 GeV - 55 MeV	0.1 - 35 keV	Operation / Operation
KEKB	8 / 3.5 GeV	8 / 3.5 GeV	Construct. / Injection Operation
PF-AR	2.5 GeV - 6.5 GeV	5 - 6.5 GeV	Injection Operation
SuperKEKB	7 / 4 GeV	7 / 4 GeV	Construction / Injection

- **42 years of operation**
  - **for particle physics and photon science**
    - **Started with one of first dedicated light sources, PF**
    - **and the highest energy collider, TRISTAN with SRF**
  - **Long-term multiple disciplinary operations**
  - **Still many devices from the first generation**





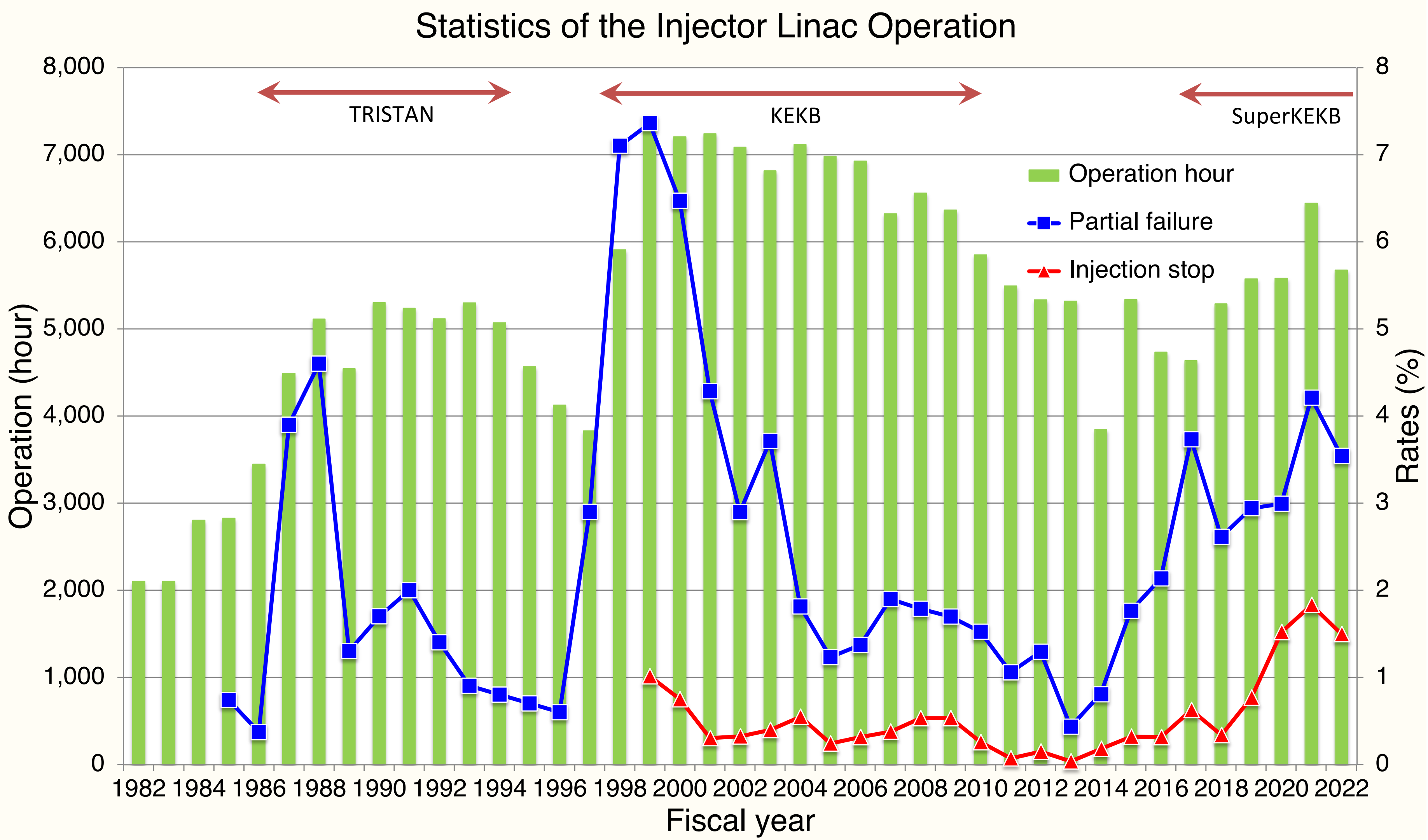




Operation Hours

◆ Yearly operation hours

¤ 200,000 hours accumulated on May.7.2020



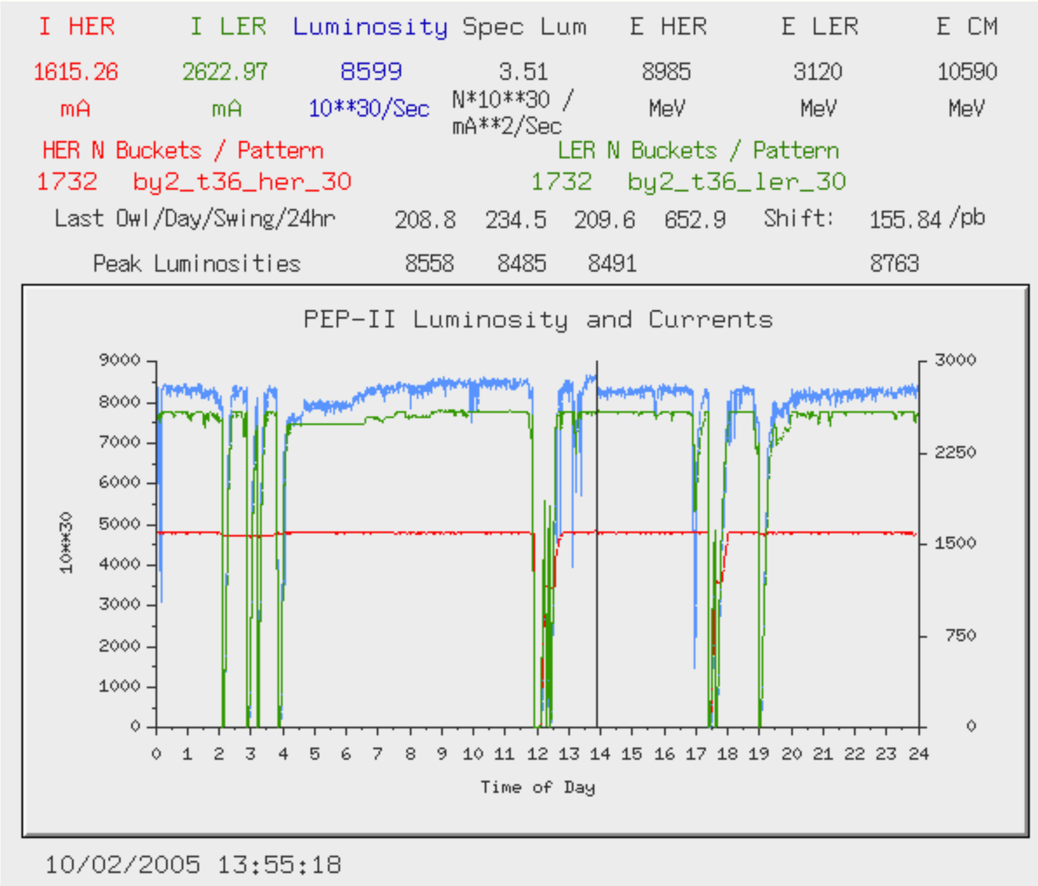
KEKB and Linac

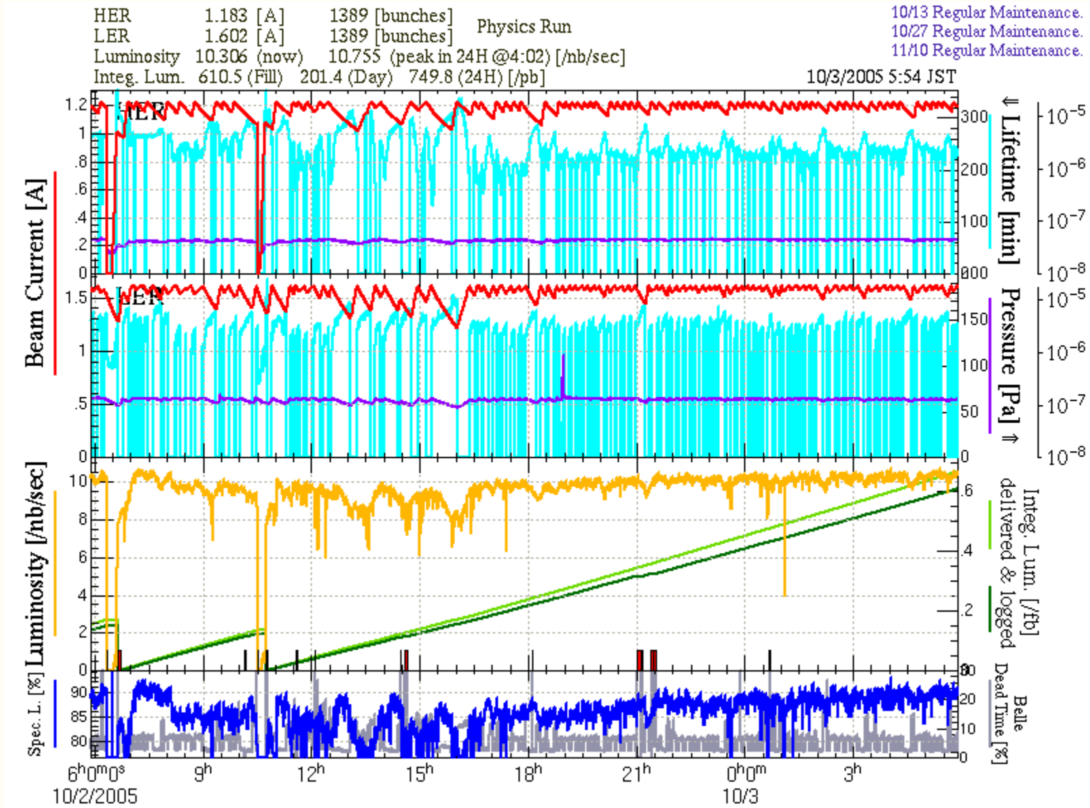
Some of KEKB Designs

- **Maximum reuse of TRISTAN inheritance**
- **However, still many improvements applied, ex.**
  - **Many bunch collisions with dual ring collider**
    - **Energy asymmetry for the boost of center of mass of Bs**
  - **Full energy injection**
    - **Energy upgrade with SLED RF pulse compressor at Linac**
      - **from 2.5 GeV (400 m) → 8 GeV (600 m)**
  - **Injection timing aperture of 30 ps**
    - **Slight RF frequency modification to have an integer relation**
      - **Linac 2856 MHz : 10.386 MHz x 275**
      - **Ring (508.5 MHz →) 508.9 MHz : 10.386 MHz x 49**

PEP-II/SLAC and KEKB

- **We exchanged ideas for PEP-II and KEKB**
  - **Viewed each other from control rooms**





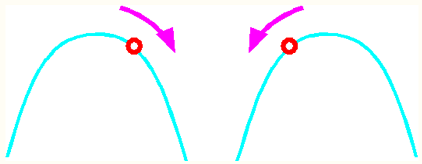
Plots as of Oct.2005

- **Friendly competition**

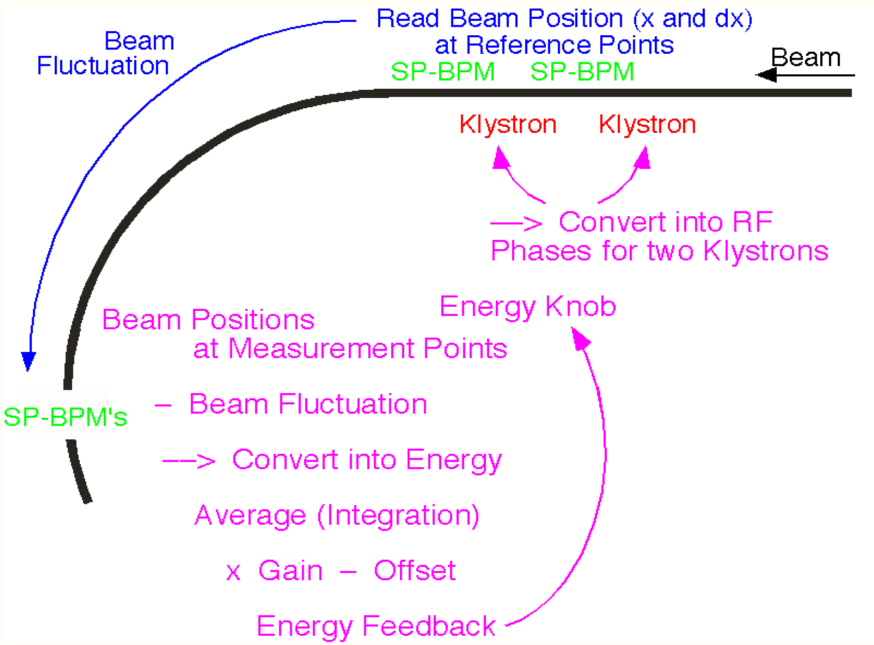
Energy and Orbit Stabilization Loops

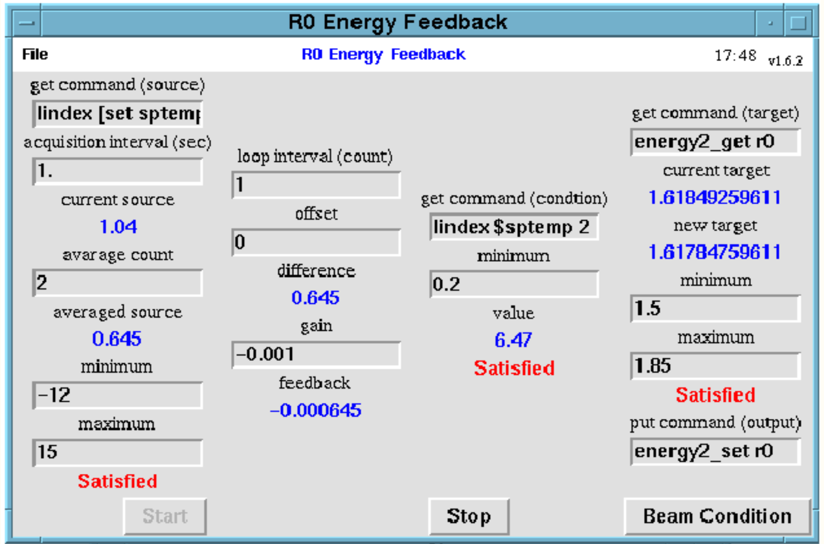
◆ BPMs - Energy knob

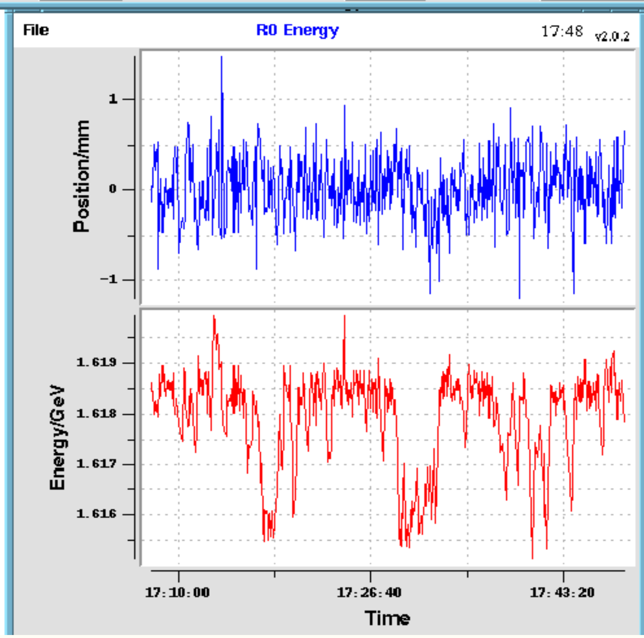
❖ **Energy knob, free from energy spread**



❖ **Simple P.I. Loop**







Many feedback loops along Linac depending on the beam modes

Feedback loop monitor

- **Robust operation is essential**
  - Remote monitoring in summary panel
  - Several conditions, limits in loop variables
  - Beam-mode dependent operation
  - Status and variable logging, and their viewers

File Checktime — Linac Feedback Status — 18:31 v1.3.0

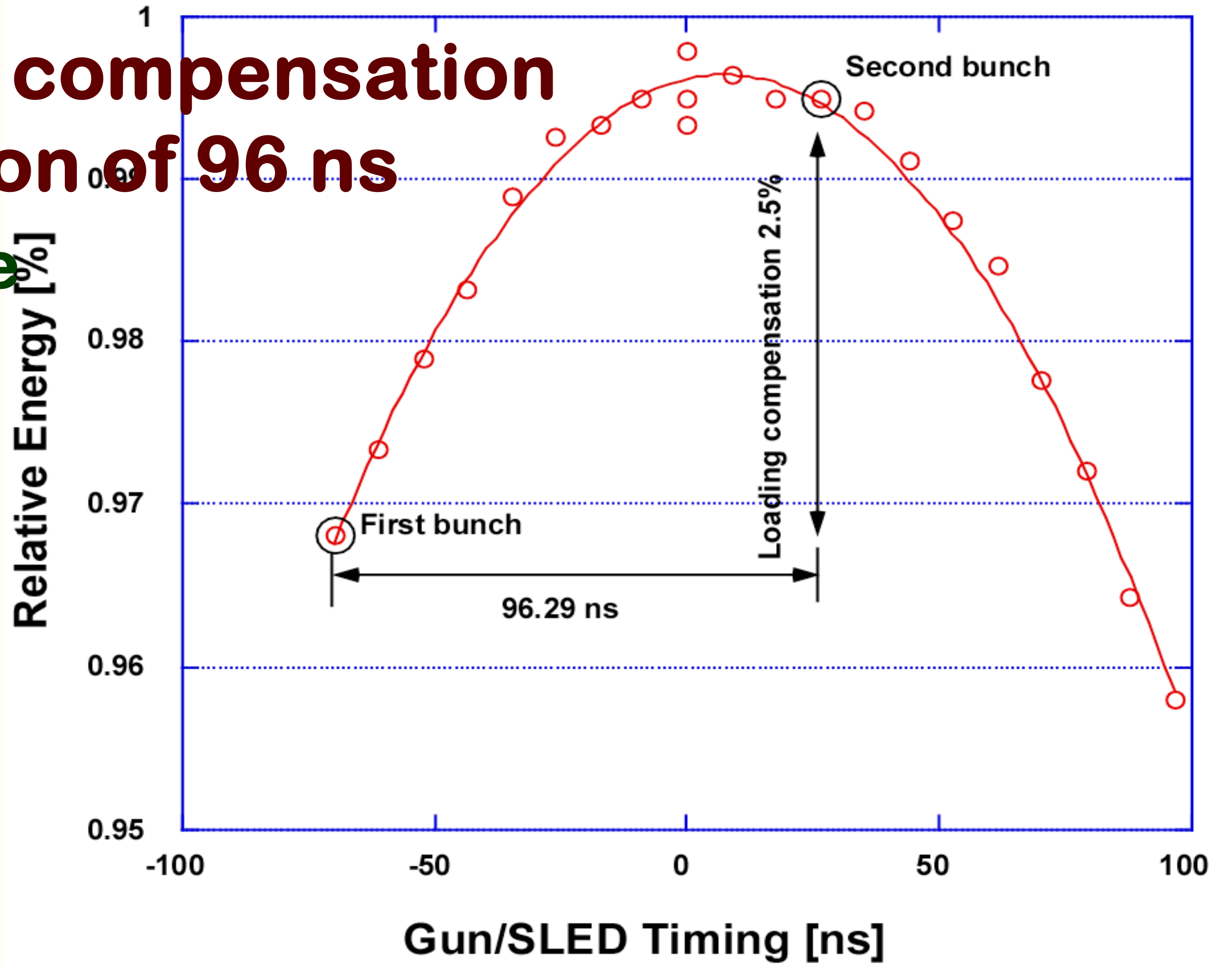
summay — Thu Jan 31 18:29:34 2002

Title	Name	Display	Hostname	Start	Status1	Status2	Status3	LastGet	LastPut		
	tkfb-arc.tcl	xp400g:0	lychee.kek.jp	Run	Beam on1 Denied	Denied		17:28:34	17:26:05	start	stop
Energy AR	tkfb-are	xp400c:0	lychee.kek.jp	Run	Beam on1 Denied	---		17:28:35	17:28:29	start	stop
GU_A1_G HV	tkfb-guna1	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:07	18:29:42	start	stop
GU_A1_G Delay e-	tkfb-guna1dle #2	xp400d:0	plum.kek.jp	Run	Beam elepos Denied	Satisfied		18:15:23	18:15:23	start	stop
GU_A1_G Delay e+	tkfb-guna1dlp	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:18	18:29:19	start	stop
GU_CT_G HV	tkfb-gunct	xp400d:0	plum.kek.jp	Run	Satisfied	---		18:29:39	---	start	stop
Energy KEKB e- 58	tkfb-kbe	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		17:06:36	17:06:29	start	stop
Energy KEKB e- BT	tkfb-kbebt	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		18:15:38	17:46:01	start	stop
Energy KEKB e+ 61	tkfb-kbp	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:46	18:29:48	start	stop
Energy KEKB e+ BT	tkfb-kbpbt	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:47	18:29:46	start	stop
Orbit 1XY KEKB e+	tkfb-orbit1XYpk	xp400g:0	poplar	Run	Satisfied	Satisfied		18:29:47	18:29:46	start	stop
Orbit 2XY KEKB e-	tkfb-orbit2XYek	xp400g:0	poplar	Run	Beam elepos Denied	---		18:15:35	18:15:27	start	stop
Orbit 5X KEKB e-	tkfb-orbit5Xek	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	Satisfied		18:15:31	18:15:31	start	stop
Orbit 5X KEKB e+	tkfb-orbit5Xpk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:42	18:29:42	start	stop
Orbit 5Y KEKB e-	tkfb-orbit5Yek #2	xp400c:0	lychee.kek.jp	Run	Beam elepos Denied	---		18:15:36	18:15:27	start	stop
Orbit 5Y PF/AR	tkfb-orbit5Ypa	xp400d:0	poplar	Run	Beam on1 Denied	---		17:28:30	17:26:02	start	stop
Orbit 5X PF/AR	tkfb-orbit5pfar	xp400d:0	poplar	Run	Beam on1 Denied	---		17:28:23	17:28:10	start	stop
Orbit 6X KEKB e+	tkfb-orbit6Xpk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:47	18:29:45	start	stop
Orbit 6Y KEKB e+	tkfb-orbit6Ypk #2	xp400c:0	lychee.kek.jp	Run	Satisfied	Denied		18:29:45	18:29:44	start	stop
Orbit A0X KEKB e+	tkfb-orbitA0Xpk	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit A0Y KEKB e+	tkfb-orbitA0Ypk	xp400d:0	poplar	Stop	---	---		Jan 29	Jan 29	start	stop
Orbit A1X KEKB e+	tkfb-orbitA1Xpk	xp400d:0	poplar	Stop	---	---		Jan 29	Jan 29	start	stop
Orbit A1Y KEKB e+	tkfb-orbitA1Ypk	xp400d:0	poplar	Stop	Satisfied	---		Jan 29	Jan 29	start	stop
Orbit BX KEKB	tkfb-orbitBX	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit BY KEKB	tkfb-orbitBY	xp400d:0	poplar	Stop	---	Satisfied		Jan 29	Jan 29	start	stop
Orbit RX KEKB	tkfb-orbitRX	xp400g:0	poplar	Run	Satisfied	Satisfied		18:29:48	18:29:48	start	stop
Orbit RY KEKB	tkfb-orbitRY	xp400g:0	poplar	Run	Satisfied	---		18:29:44	18:29:43	start	stop
Orbit 57-61 PF	tkfb-orbitpf #2	xp400g:0	lychee.kek.jp	Run	Beam on1 Denied	---		16:59:35	16:48:41	start	stop
Energy PF BT	tkfb-pfe #2	xp400c:0	lychee.kek.jp	Run	Beam on1 Denied	---		16:59:36	09:12:22	start	stop
Energy R0 e-	tkfb-r0	xp400g:0	lychee.kek.jp	Run	Satisfied	Satisfied		18:29:49	18:29:48	start	stop
SH_A1_S1 Power	tkfb-shb1 #2	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:40	18:29:29	start	stop
SH_A1_S1 Phase e-	tkfb-shb1phe	xp400d:0	plum.kek.jp	Stop				---	---	start	stop
SH_A1_S1 Phase e+	tkfb-shb1php	xp400d:0	plum.kek.jp	Stop				---	---	start	stop
SH_A1_S8 Power	tkfb-shb2 #2	xp400d:0	plum.kek.jp	Run	Satisfied	Satisfied		18:29:43	18:29:33	start	stop
SH_A1_S8 Phase e+	tkfb-shb2php	xp400d:0	plum.kek.jp	Stop				---	---	start	stop

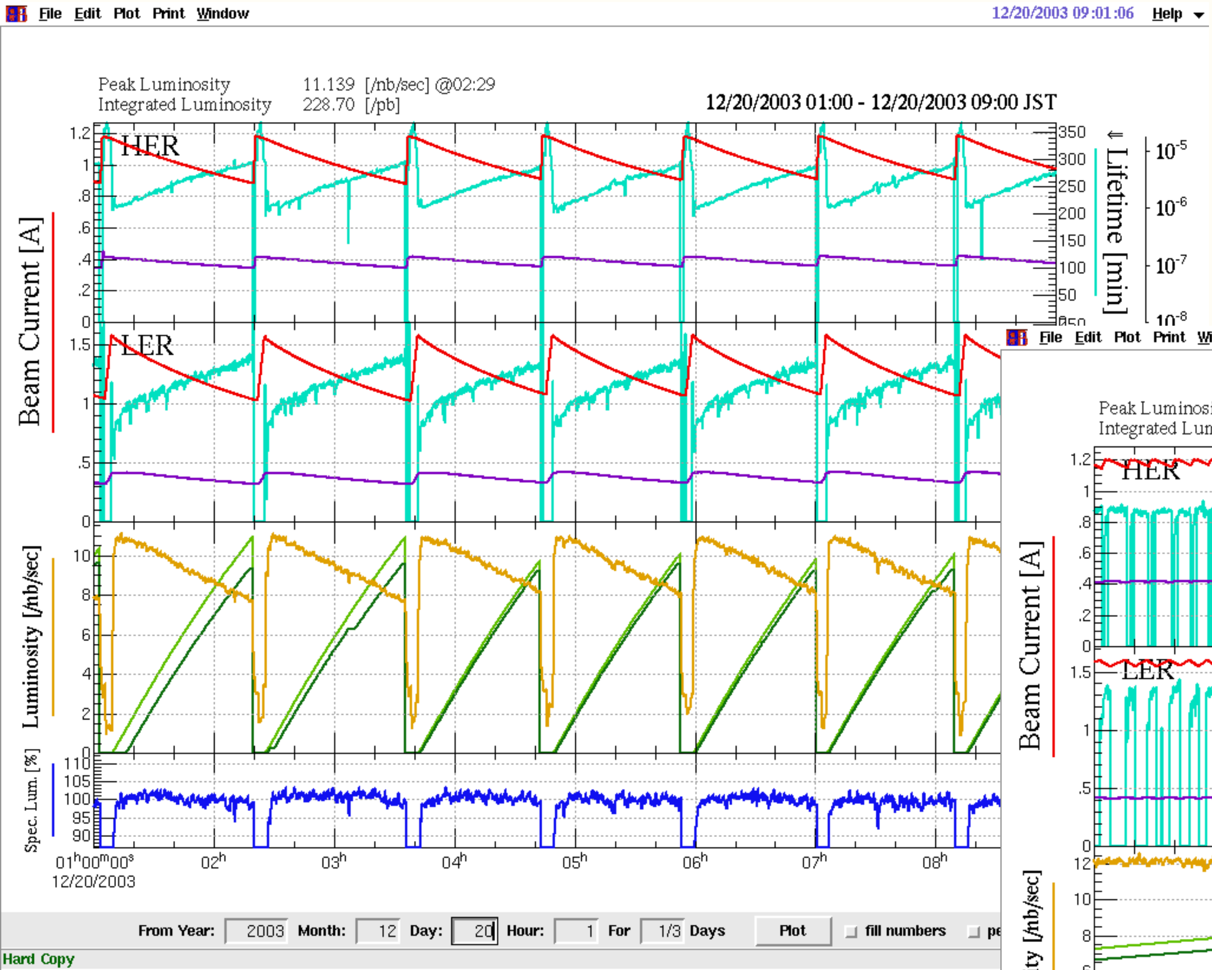
Last Update: Jan 31 18:29:49 — Update

Two Bunches in a Pulse

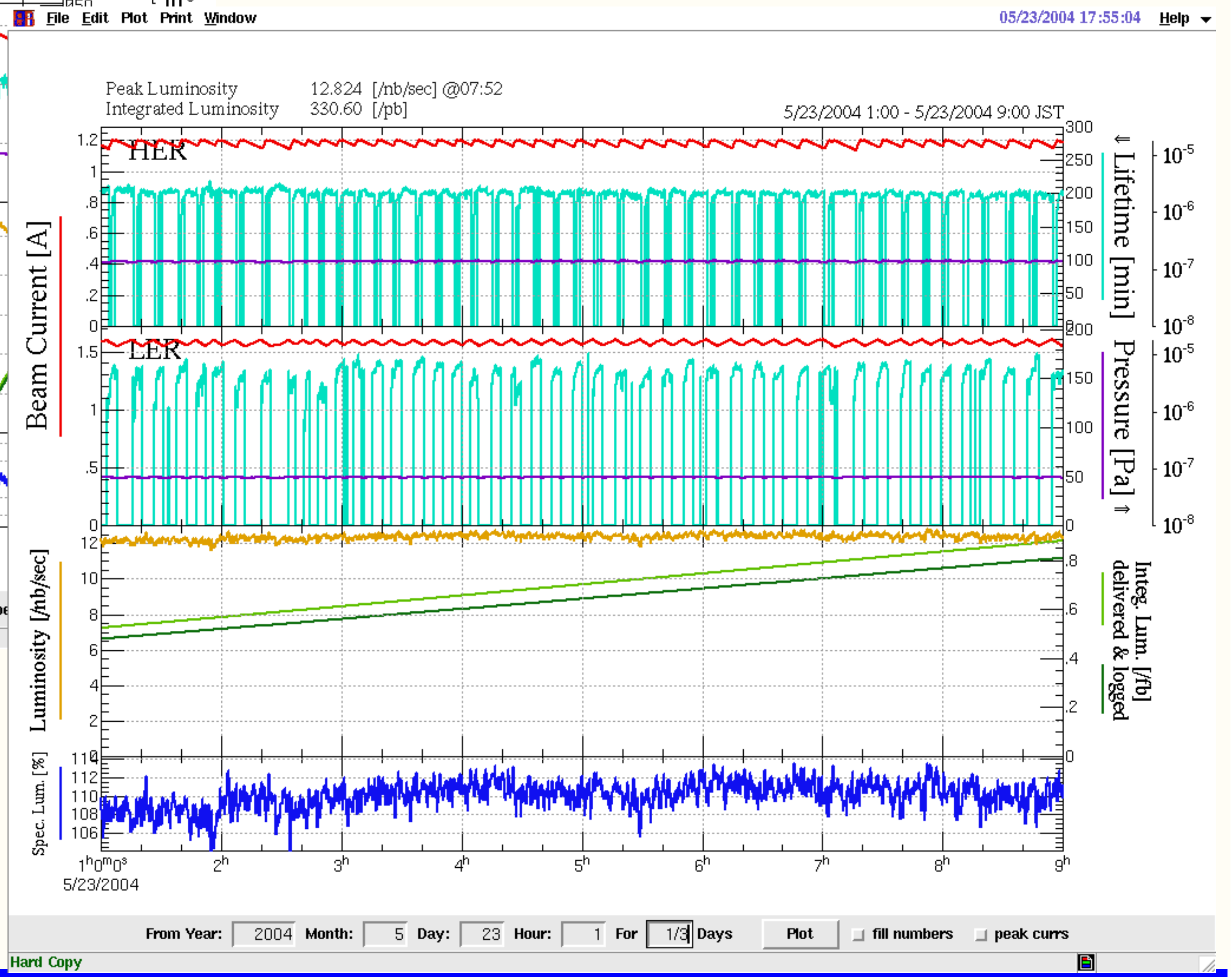
- **In order to double the injection beam**
- **Energy equalization**
  - **with beam loading compensation for bunch separation of 96 ns**
    - **We sometimes utilize energy difference in order to equalize the beam orbits**



Continuous injection



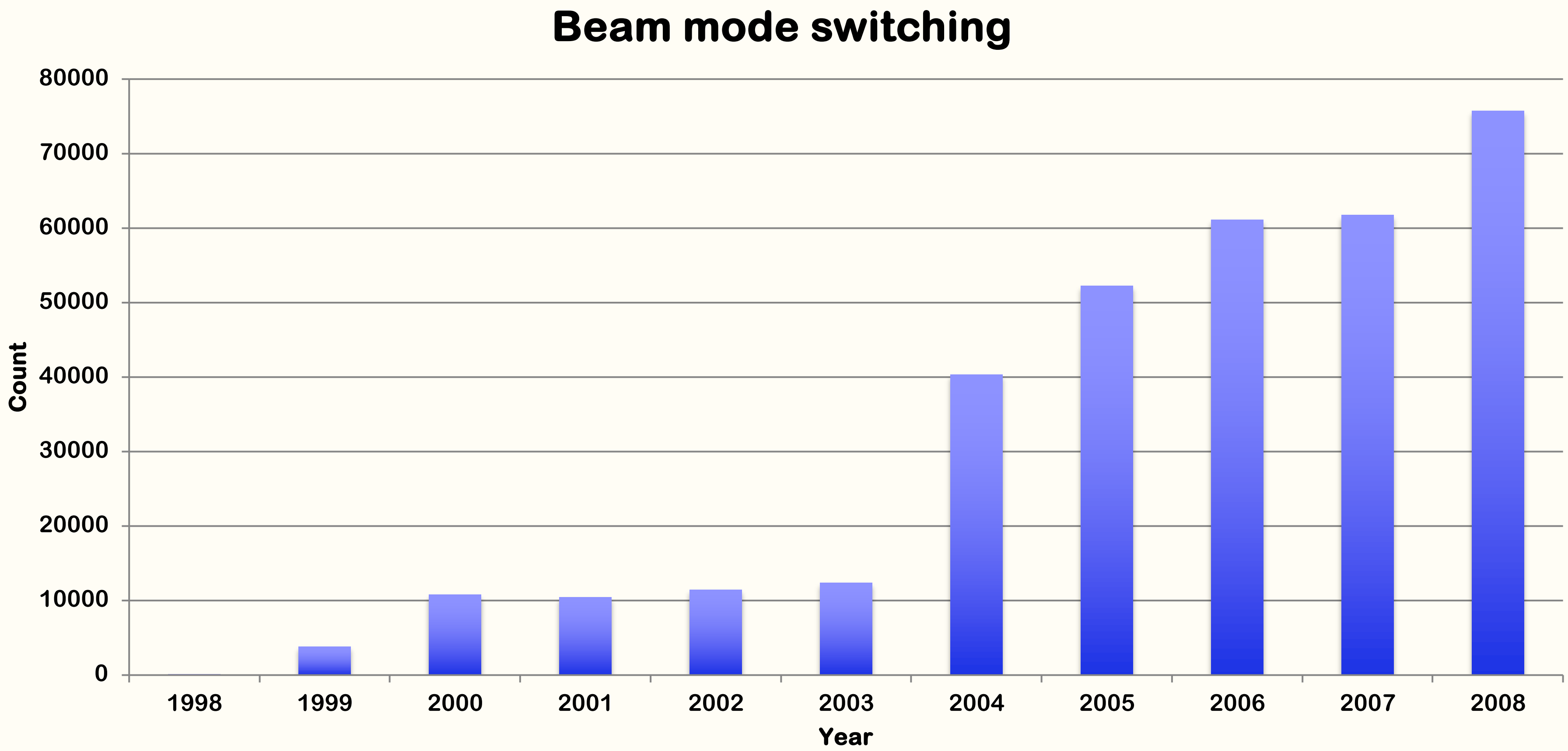
2004, after continuous injection was applied
Data acquisition continued during injection
(8-hour history of beam current, luminosity, etc.)



2003, before continuous injection was applied
Data acquisition stopped during injection
(8-hour history of beam current, luminosity, etc.)

Beam mode switching improvements

- Continuous injection was applied in 2004



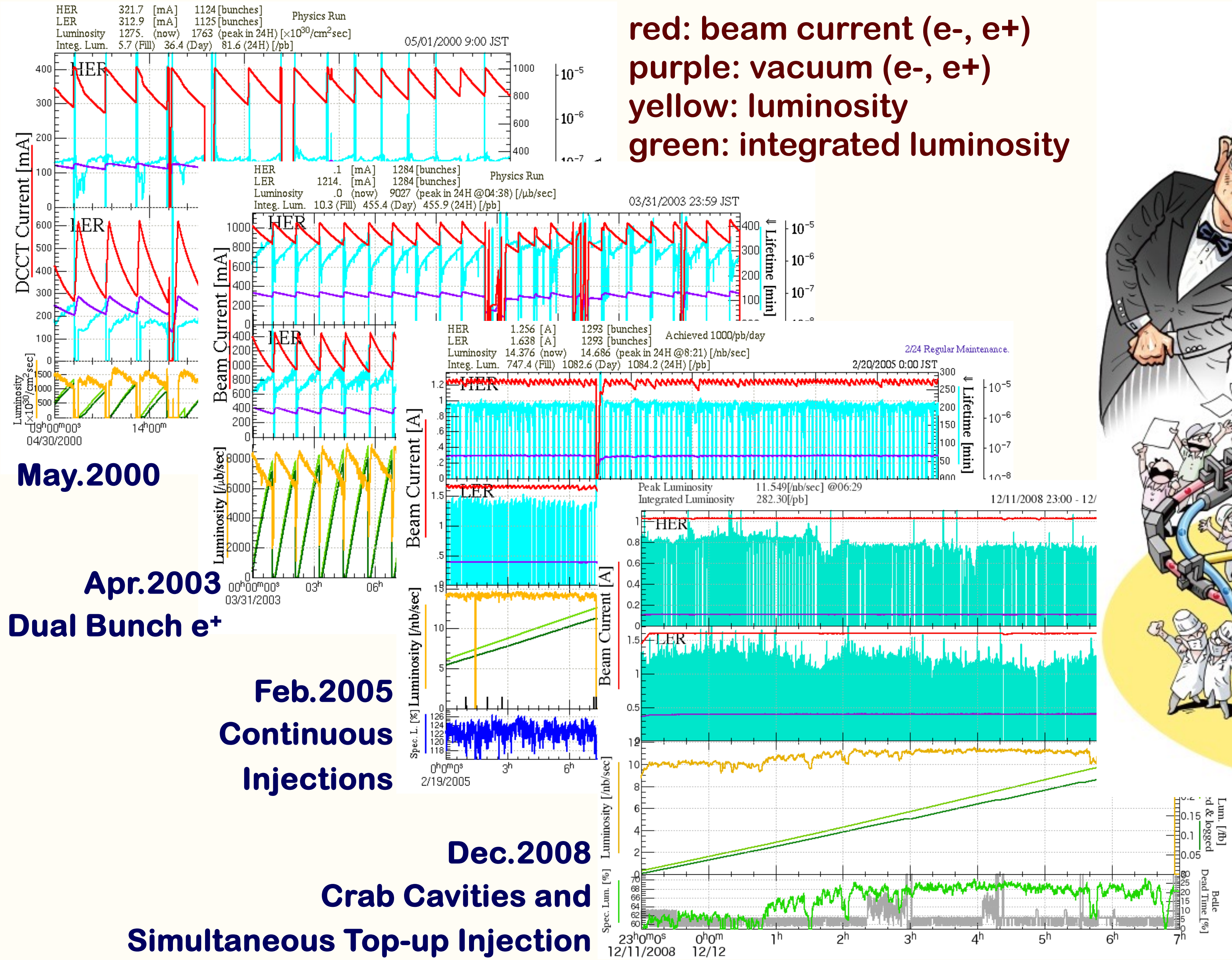
- Switched 360 times / day in 2008 (every 4 minute)
- Simultaneous top-up injection was applied in 2009

Main features of controls at KEKB

- EPICS as Main control Software Toolkit
  - Provided a robust basis of equipment controls
  - Reduced software design efforts
- Scripting Languages for Operational Software
  - SADscript/Tk, Python/Tk, Tcl/Tk, etc.
    - Especially, SADscript as a bridge btw. Accelerator simulation, Numeric manipulation, Graphic interface and EPICS controls
  - Bright new idea in the morning meeting could make the operation much advanced in the evening
    - Great tool to optimize the operation by rapid prototyping

KEKB Operation Improvement (base of SuperKEKB)

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



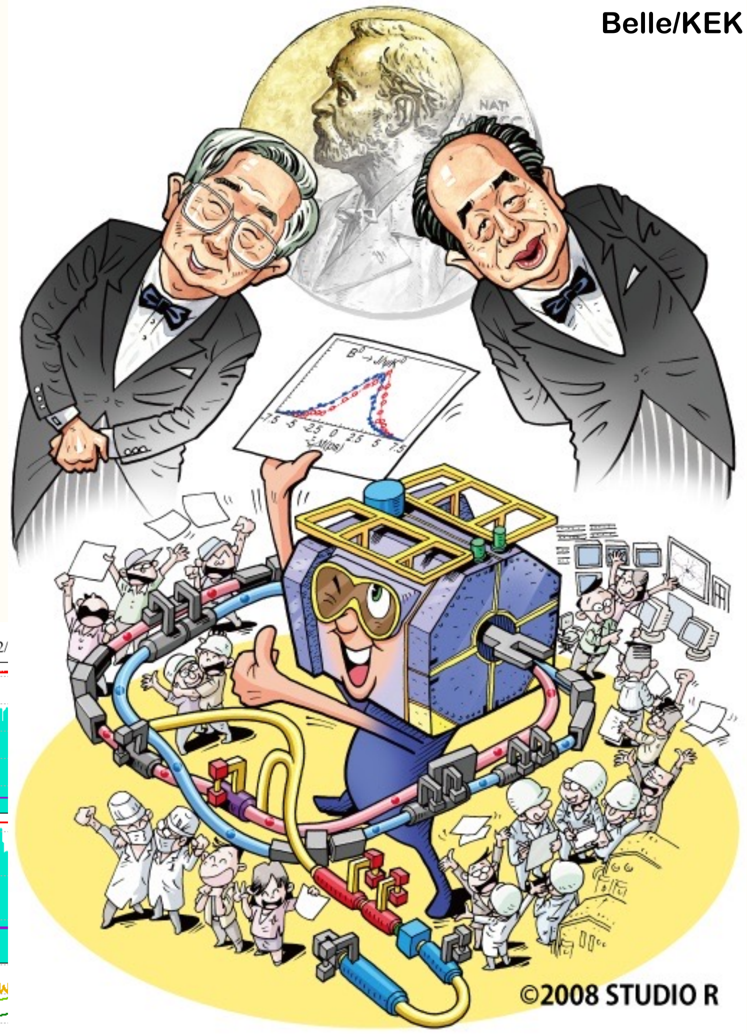
May.2000

Apr.2003
Dual Bunch e+

Feb.2005
Continuous
Injections

Dec.2008
Crab Cavities and
Simultaneous Top-up Injection

Belle/KEK



Keeps world luminosity record

Linac Design for SuperKEKB

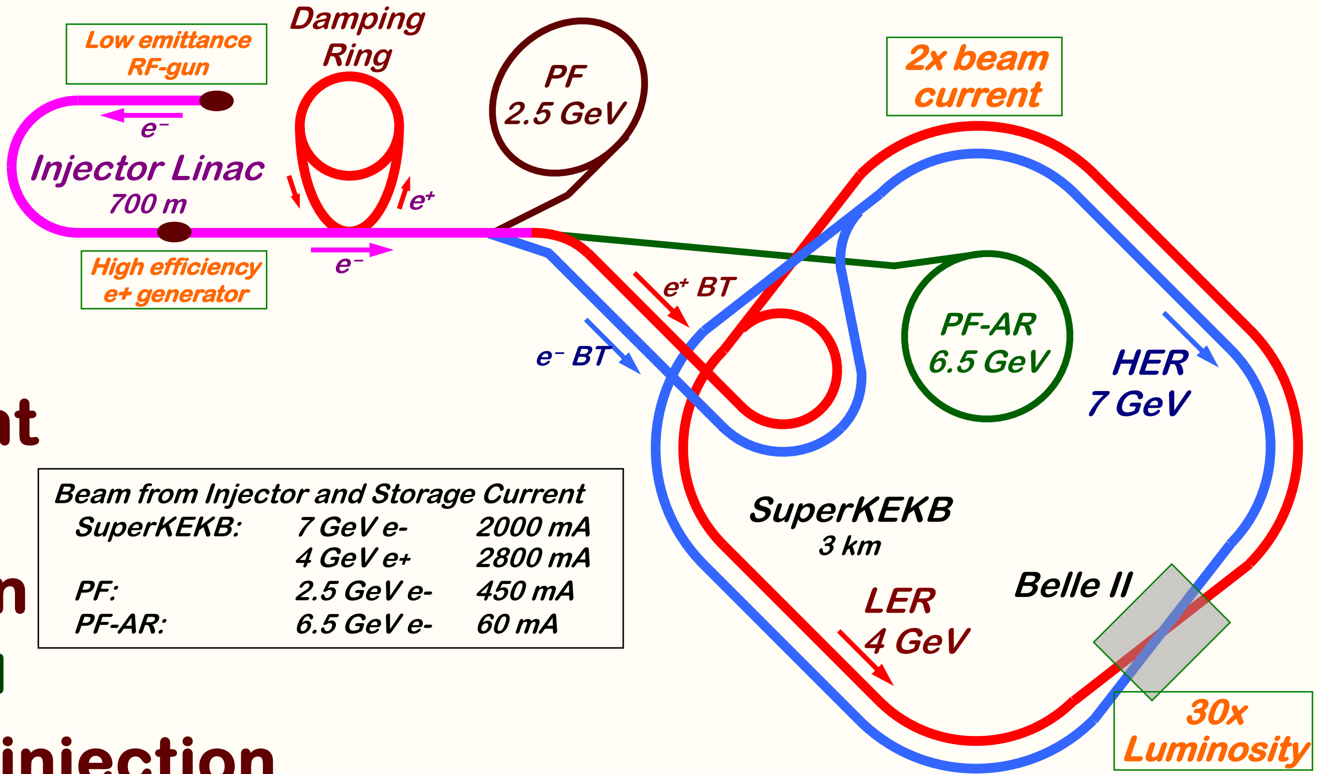
Mission of electron/positron Injector in SuperKEKB

◆ 30-times higher Luminosity

- 15-times higher collision rate with nano-beam scheme
  - → Low-emittance even at first turn → Low-emittance beam from Linac
- Twice larger storage beam
  - → Shorter storage lifetime → Higher beam current from Linac

◆ Linac challenges

- Low emittance e-
  - with high-charge RF-gun
- Low emittance e+
  - with damping ring
- Higher e+ beam current
  - with new capture section
- Emittance preservation
  - with precise beam control
- 4+1 ring simultaneous injection



Beam from Injector and Storage Current

SuperKEKB:	7 GeV e-	2000 mA
	4 GeV e+	2800 mA
PF:	2.5 GeV e-	450 mA
PF-AR:	6.5 GeV e-	60 mA

Linac Beam Parameters for KEKB/SuperKEKB

Stage	KEKB (final)		Phase-I (achieved)		Phase-II (achieved)		Phase-III (interim)		Phase-III (final)	
Beam	e+	e–	e+	e–	e+	e–	e+	e–	e+	e–
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Stored current	1.6 A	1.1 A	1.0 A	1.0 A	–	–	1.8 A	1.3 A	2.8 A	2.0 A
Life time (min.)	150	200	100	100	–	–	–	–	6	6
Bunch charge (nC)	primary e- 10 → 1	1	primary e- 8 → 0.4	1	0.5	1	2	2	primary e- 10 → 4	4
Norm. Emittance (γβε) (mrad)	1400	310	1000	130	200/40 (Hor./Ver.)	150	150/30 (Hor./Ver.)	100/40 (Hor./Ver.)	<u>100/15</u> (Hor./Ver.)	<u>40/20</u> (Hor./Ver.)
Energy spread	0.13%	0.13%	0.50%	0.50%	0.16%	0.10%	0.16%	0.10%	<u>0.16%</u>	<u>0.07%</u>
Bunch / Pulse	2	2	2	2	2	2	2	2	2	2
Repetition rate	50 Hz		25 Hz		25 Hz		50 Hz		50 Hz	
Simultaneous top-up injection (PPM)	3 rings (LER, HER, PF)		No top-up		Partially		4+1 rings (LER, HER, DR, PF, PF-AR)		4+1 rings (LER, HER, DR, PF, PF-AR)	

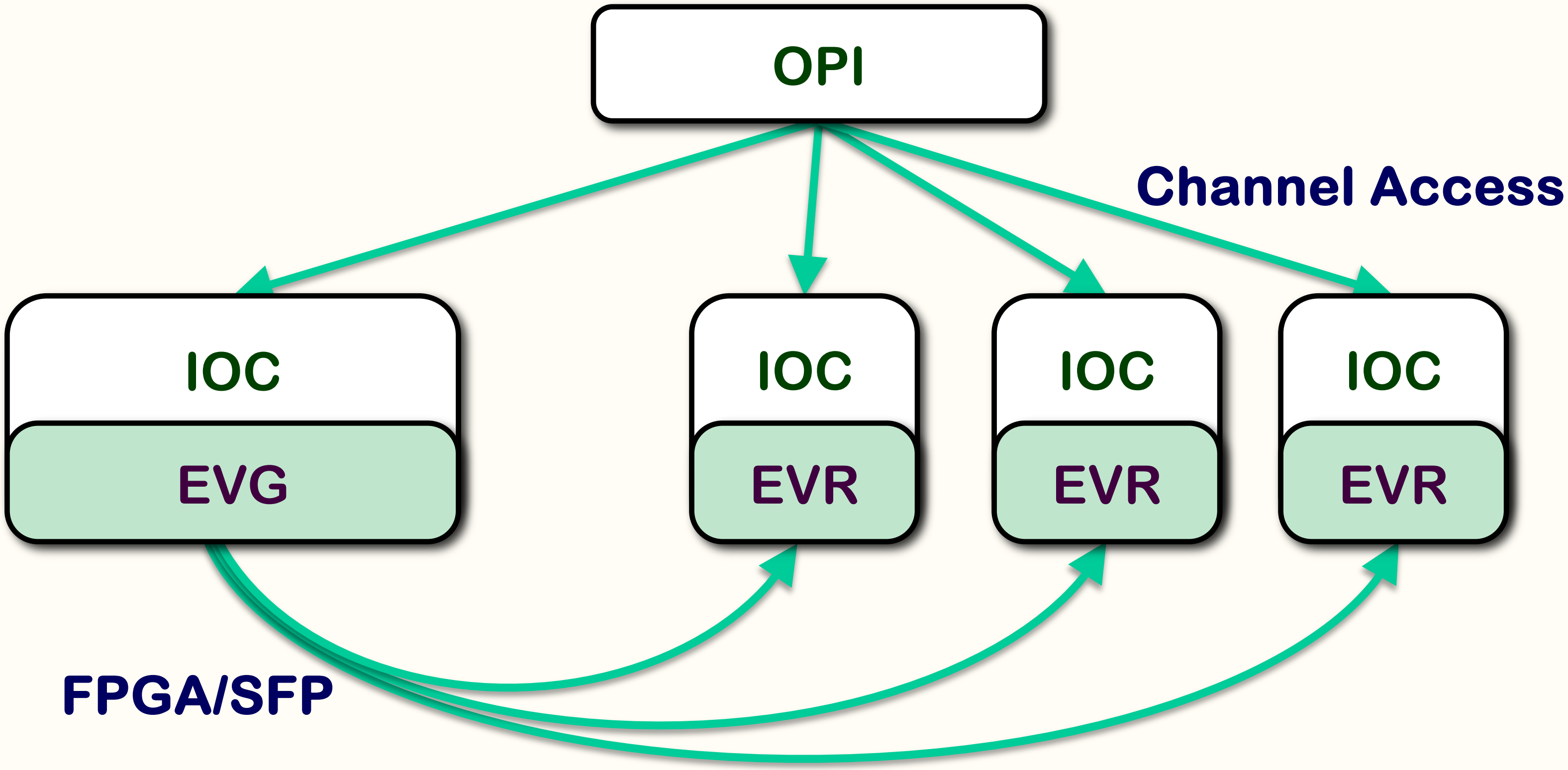
- **Gradual improvements keeping light source injections**

SuperKEKB Controls

- **Inherit Good part of KEKB Controls**
  - EPICS
  - Scripting languages
- **EPICS Channel Access (CA) Everywhere**
  - Embed EPICS control software (IOC) everywhere possible
  - Reduce efforts on protocol design, testing, etc
- **Dual Tier: Another layer in addition to EPICS/CA**
  - Event system helps EPICS with another channel/layer
  - Additional functionality, synchronization and speed

Dual-tier Controls

- **IOC controls via Conventional EPICS CA**
  - Above 1ms, ordered controls
- **Fast FPGA controls via SFP/Fiber (MRF)**
  - 10ps ~ 100ms, 114MHz synchronous controls



Some of Important Components

RF gun

https://www-linac.kek.jp/linac-com/rf-gun/

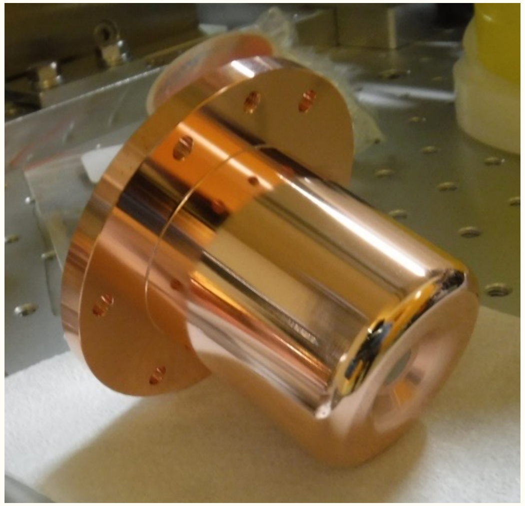
Photo cathode RF gun development

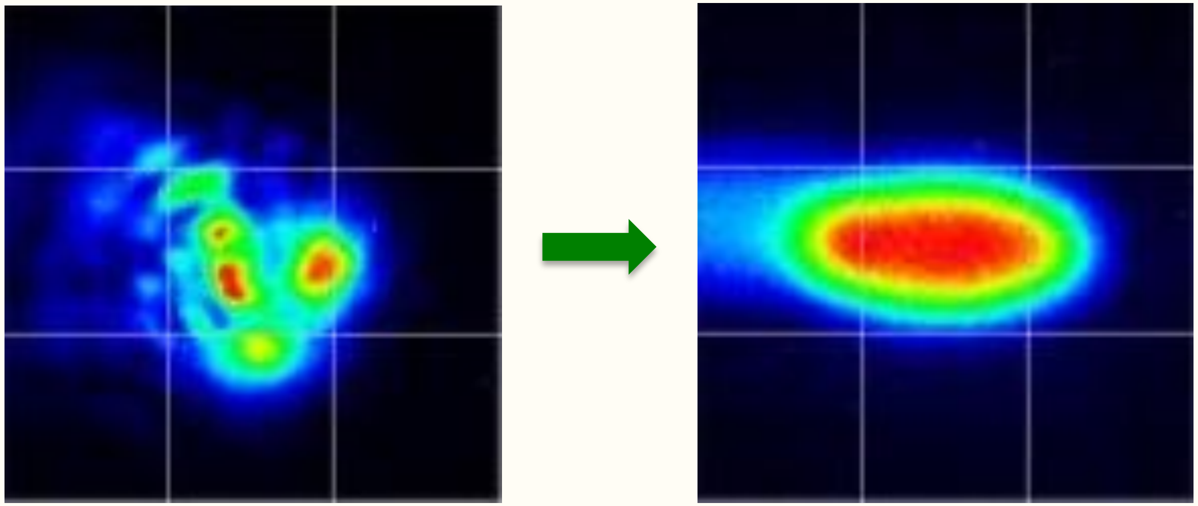
- Crucial for high-current low-emmittance beam
- New Ir5Ce cathode and new cavity QTWSC were successful
- Basic features were confirmed
- Cavity: DAW (disk and washer) → QTWSC (high space charge)
- Cathode: LaB6 → Ir5Ce (long life, medium q.e. >10^{-4})
- Laser: Nd:YAG → Yb:YAG thin disk and fiber → stay at Nd:YAG
  Regenerative amp. → Multi-pass amp. w/ cooling
- Staged laser system improvements with beam measurements
  - Aimed at 5-nC low-emittance stable beam for electron injection
  - 50Hz generation with heat dissipation (several possible plans)
  - Stability improvement, with precise synchronization (commercial oscillator)
  - Temporal manipulation for lower energy spread (was given up for now)
- More stability, more charge, and energy spread mitigation

RF Gun

- DOE diffraction optical element
- 2nd Laser system
- Stability feedback systems
- Yearly replacement of cathode

M. Yoshida





- Beam stability improved, but
- Further improvement necessary

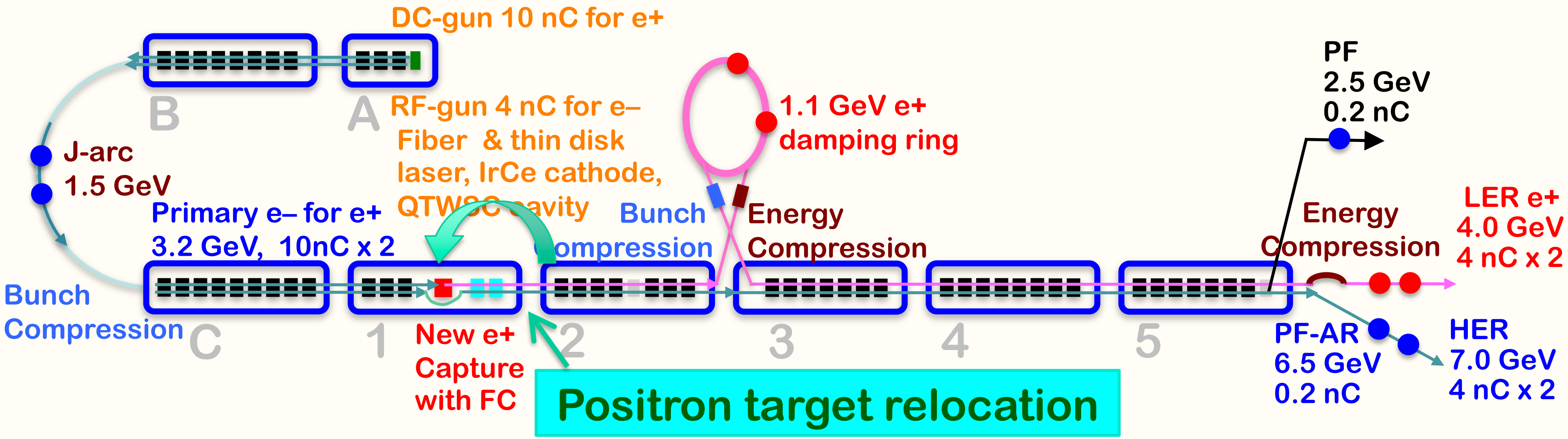
Electron Beam

- Transverse and longitudinal emittance blow-up mitigation should be solved
- High-power square-shaped laser is not stable yet, ECS is needed
  - Plan to construct in 2024-2026
- Transverse emittance should be controlled with more orbit stabilization and residual dispersion function hunting
- 1.5 nC is acceptable, but still 4 nC - 0.07%(ΔE) was not confirmed, hope to be investigated
- Emittance blowup in beam transport line by ISR, CSR, and others is being attacked beforehand

Positron Generation

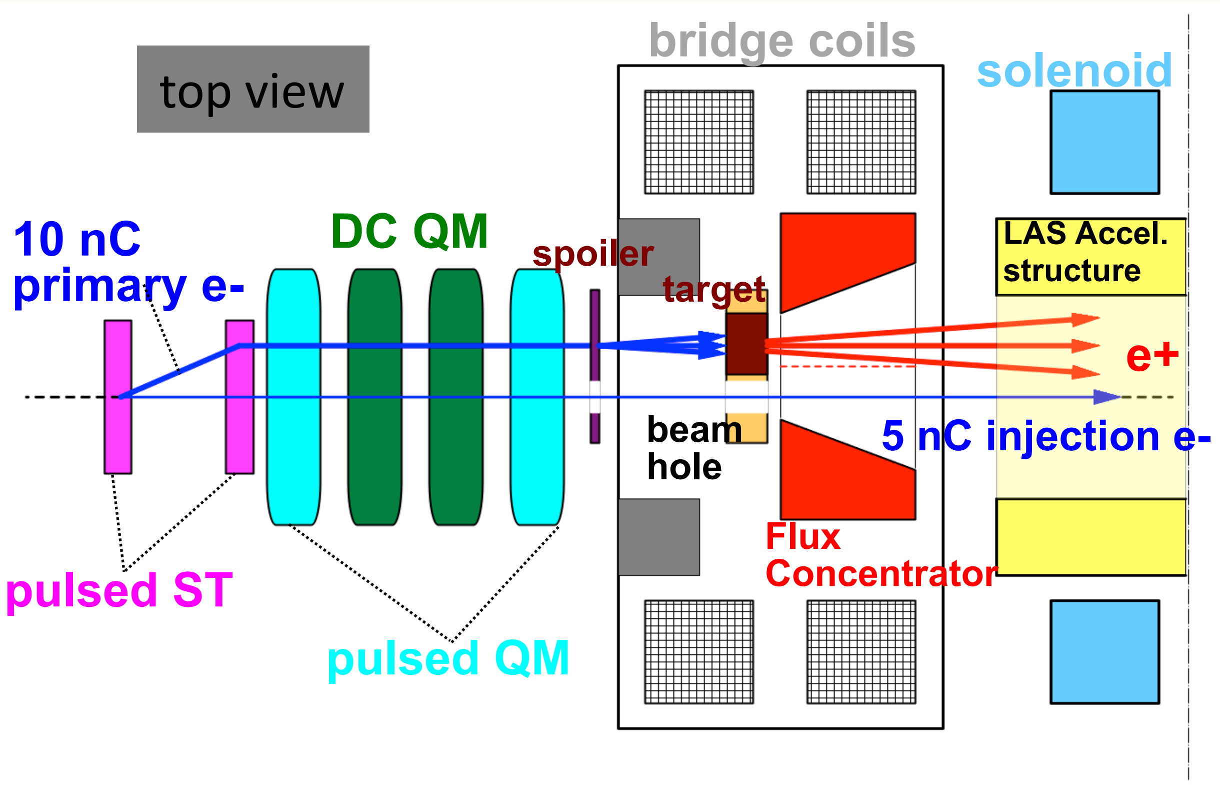
https://www-linac.kek.jp/linac-com/positron/

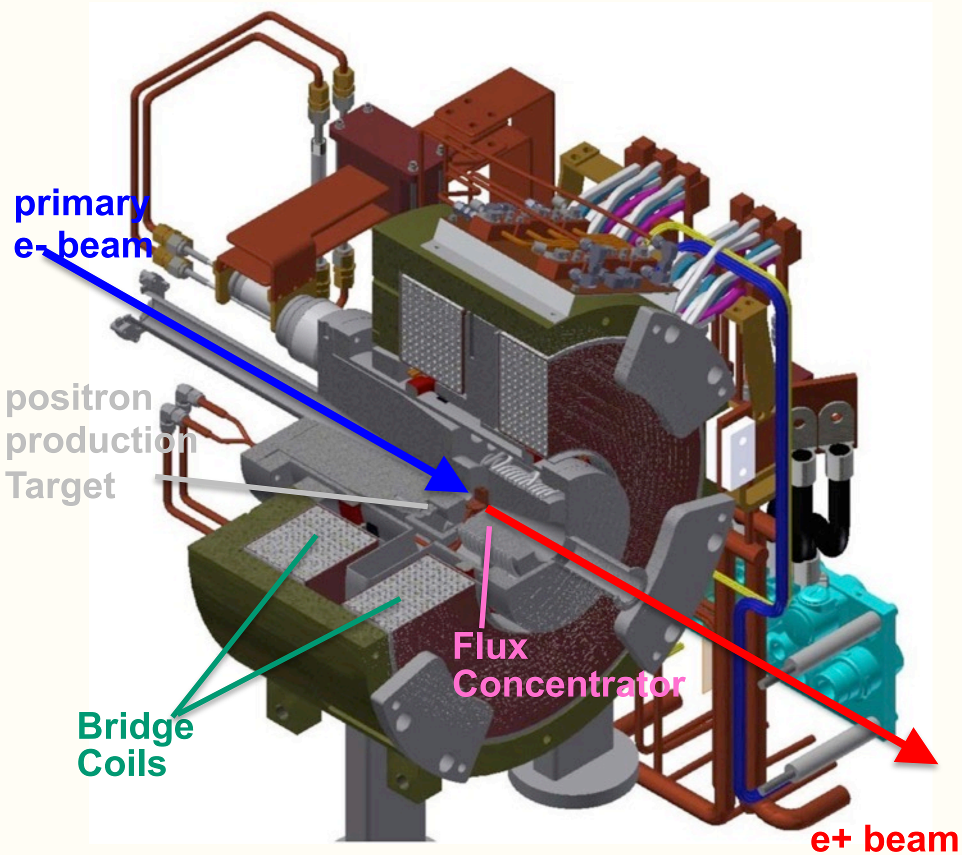
Positron Generator



- **Positron energy from 3.5 GeV to 4.0 GeV**
  - Relocation of target by 40 m with many heavy devices in the capture section
- **Installation of flux concentrator (4 T)**
- **1.5 times longer DC solenoid section (0.5 T)**
- **100 quad magnets surrounding accelerating structures**
- **Large aperture S-band structures (LAS) instead of L-band**
  - L-band structure (5/11 freq. for ILC synergy) and coaxial dummy load were developed as a backup

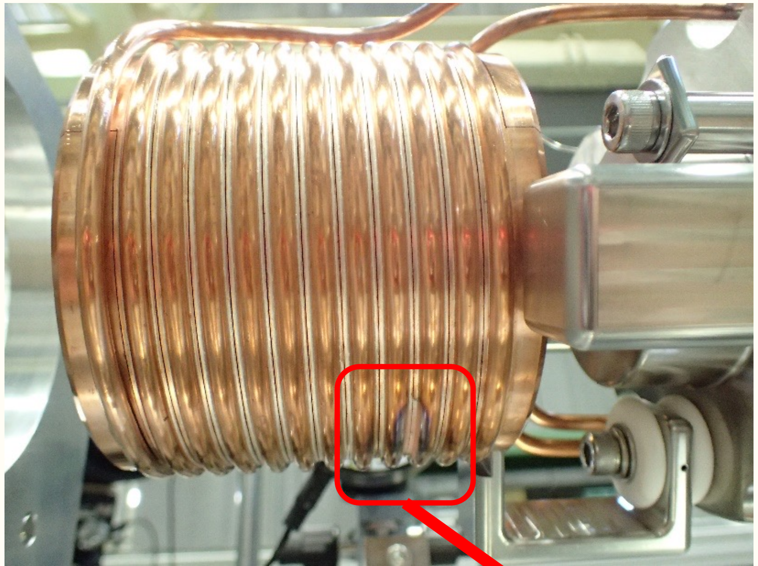
Positron generation for SuperKEKB



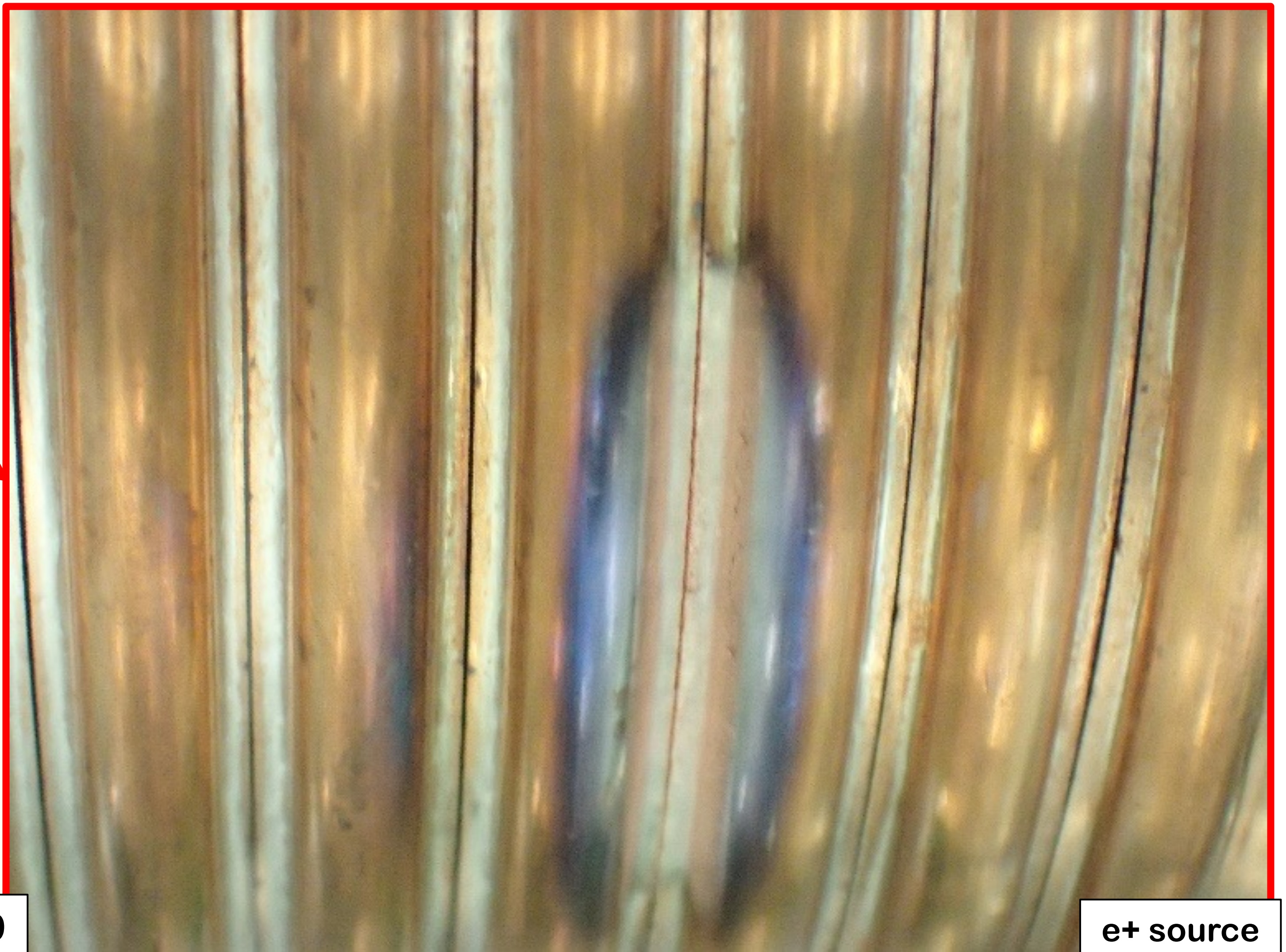


New positron capture section after target with
Flux concentrator (FC) and large-aperture S-band structure (LAS)
Satellite bunch (beam loss) elimination with velocity bunching
Pinhole (2mm) for electrons beside target (3.5mm)

After large discharge...



After large discharge



Slit gap got narrow. Not possible to apply high voltage unless the gap will be expanded.

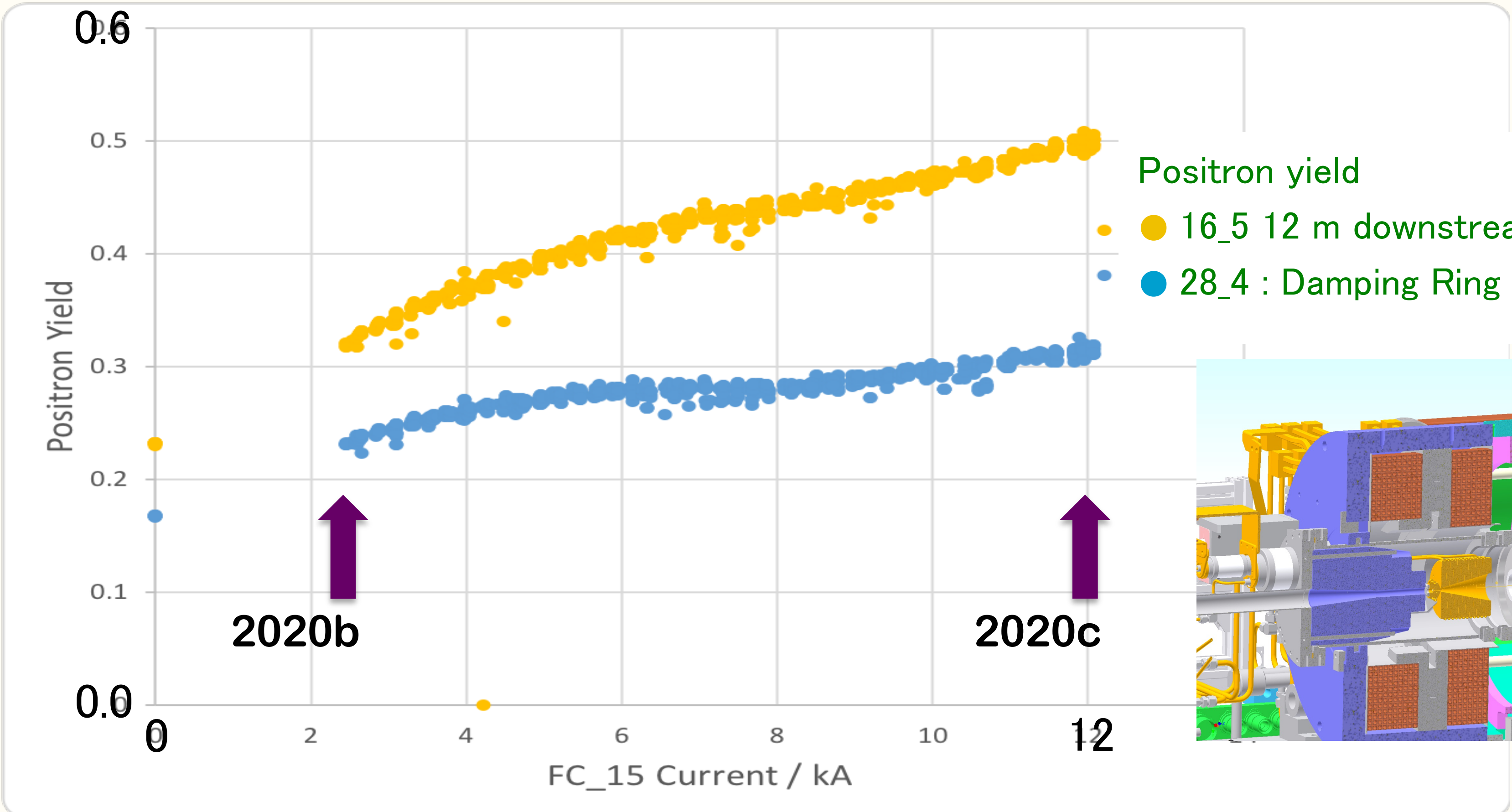
Y. Enomoto, SuperKEKB review, 2019

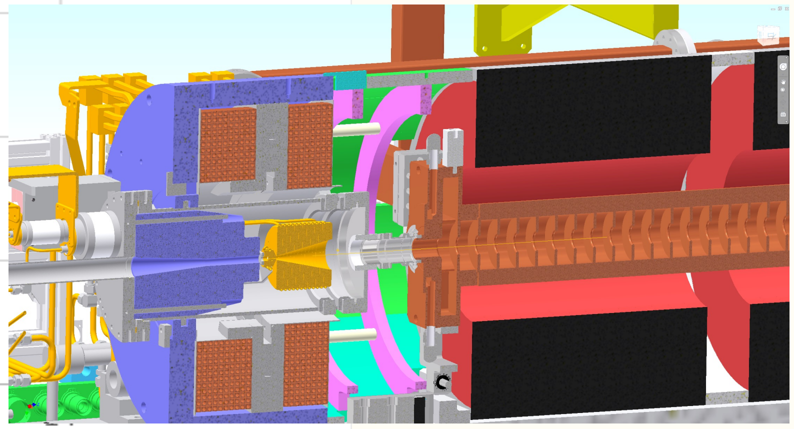
e+ source

Capturing improvement

- Cu Ni Alloy was applied for flux concentrator for stable 12 kA
- More beam monitors, more steering magnets are added

Y. Enomoto





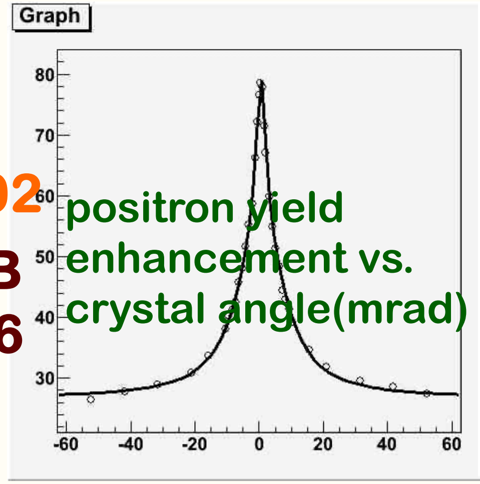
- 5 nC is available before damping ring now

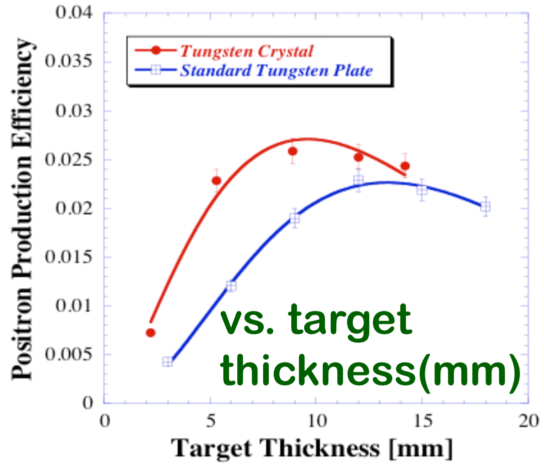
Positron Beam

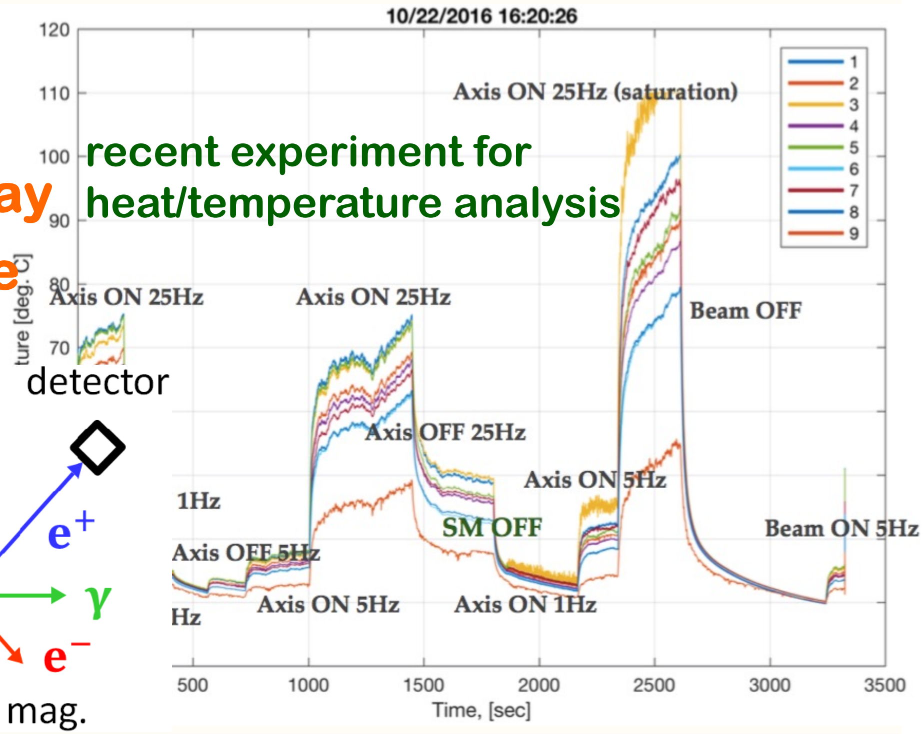
- Thermionic gun system is kept for large charge
- FC discharge issue was resolved
- Because of the complicated structure at the capture section installation of beam monitors and correctors were avoided until recently
- Some more beam optimization in the DC solenoid could be applied, even with more correctors and beam monitors
- 10 – 20% improvement could be achieved with higher gradient of LAS structures
- Primary electron beam could be increased as in initial plan of more than 10 nC (with thermionic gun)
- As the present off-center target design is a bit conservative, it could be optimized more
- >4 nC per bunch can be stably achieved

Crystal-assisted Positron Generation

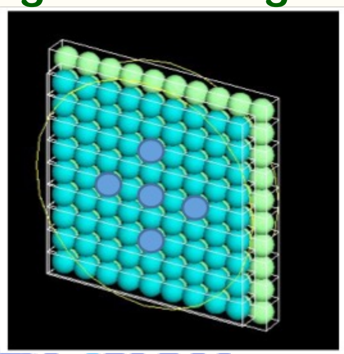
- **Application of electron channeling effect to enhance positron generation**
  - Experiments at KEK since 2000
  - Collaboration with LAL/Orsay since 2002
  - Employed the scheme to enhance KEKB positron injection 30% for a year in 2006
  - Experiments with hybrid crystal and amorphous targets to reduce heat deposit for linear collider
  - Further experiments with granular target for cooling efficiency proposed by LAL/Orsay
  - Planned to be employed in CLIC and FCC-ee

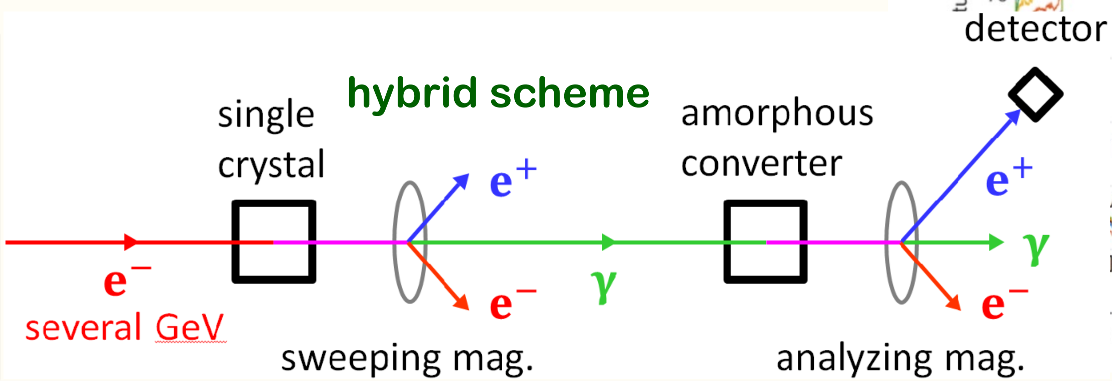






granular target



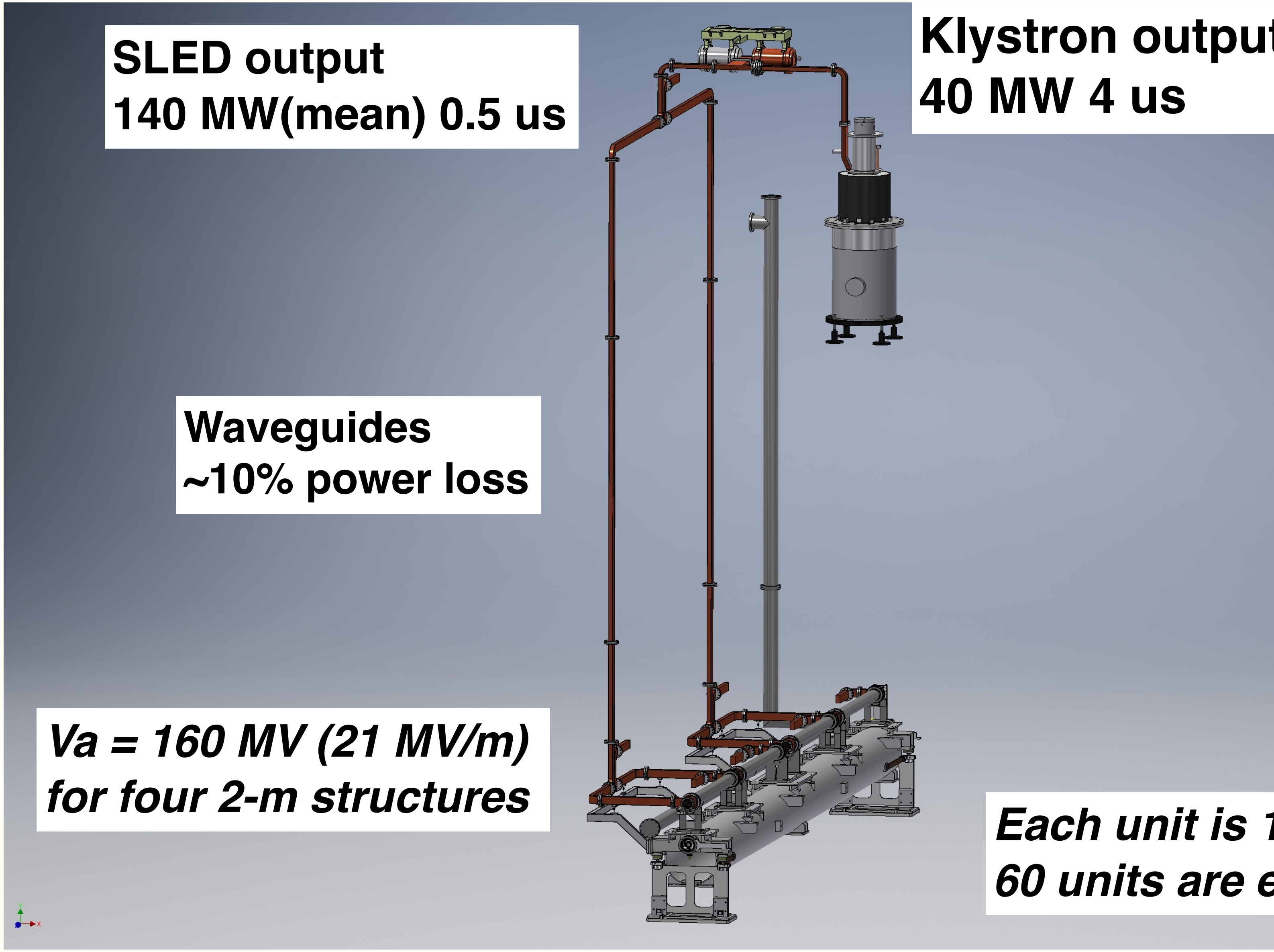


Accelerating Structures

https://www-linac.kek.jp/linac-com/6s/

Acceleration Unit Configuration

Designed performance of the accelerating unit

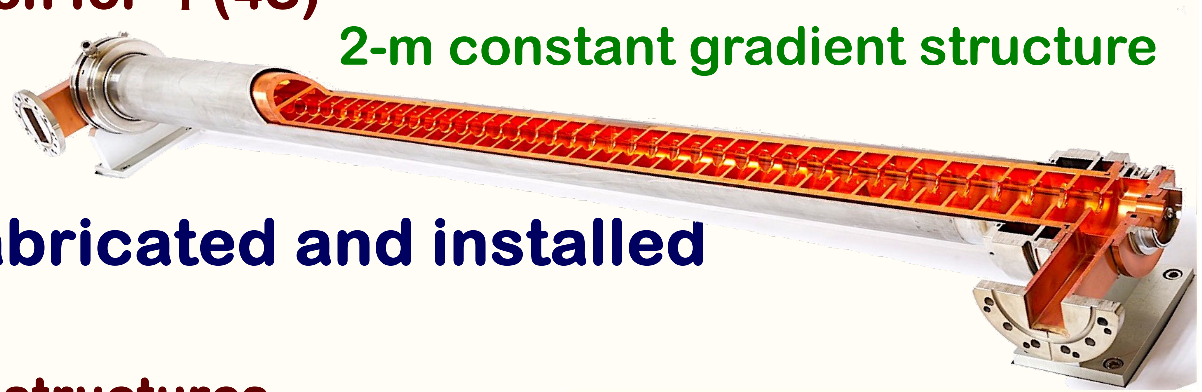


Each unit is 10-m long
60 units are employed

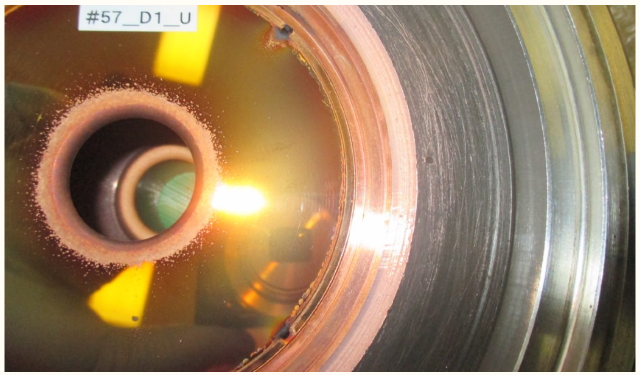
Accelerator Structure

- **Approx. 230 S-band accelerating structures employed**
- **Many aged (>40 years-old) structures are degraded**
  - Originally designed for 8 MeV/m and being used for 20 MeV/m
  - More than 19 structures have discharge issues
  - 6 structures had cooling water leakages
  - Risk of 7 GeV / 4 GeV acceleration for ϒ(4S)
  - ϒ(6S) resonance questionable

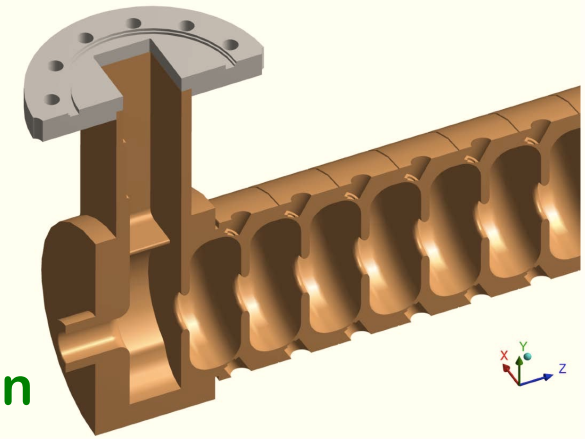
2-m constant gradient structure



- **New structures are being fabricated and installed**
  - Can reach 30 MeV/m
  - Since FY2019 as a 5 year plan, 16 structures
  - 12 more planned
  - ϒ(6S) reachable
  - But continuous degradation



Damaged structures



New design

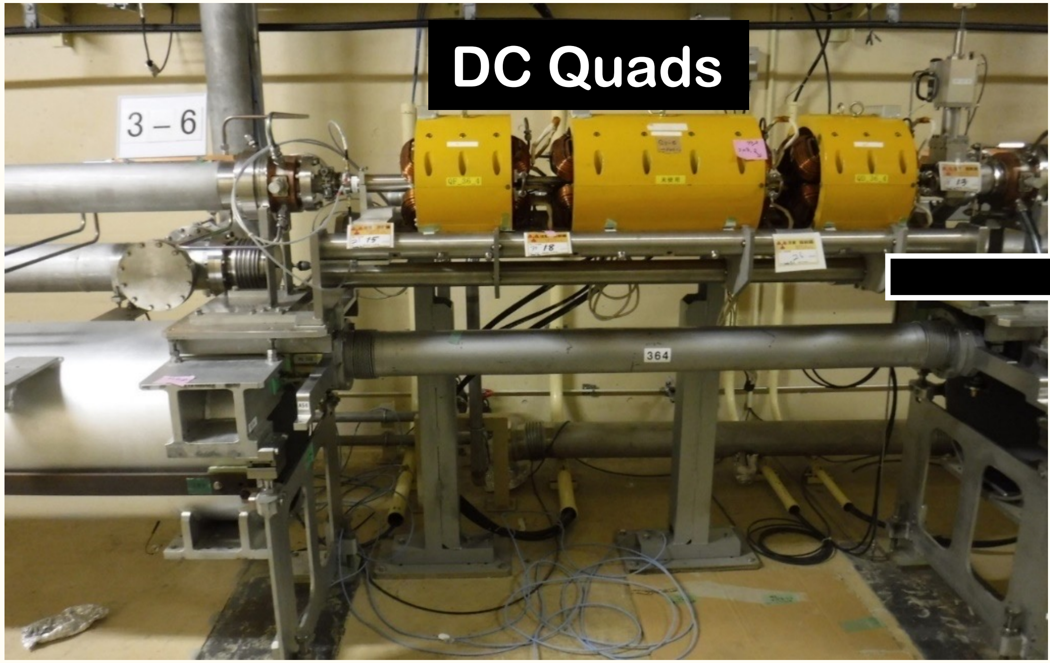
Pulsed Magnets / Kickers

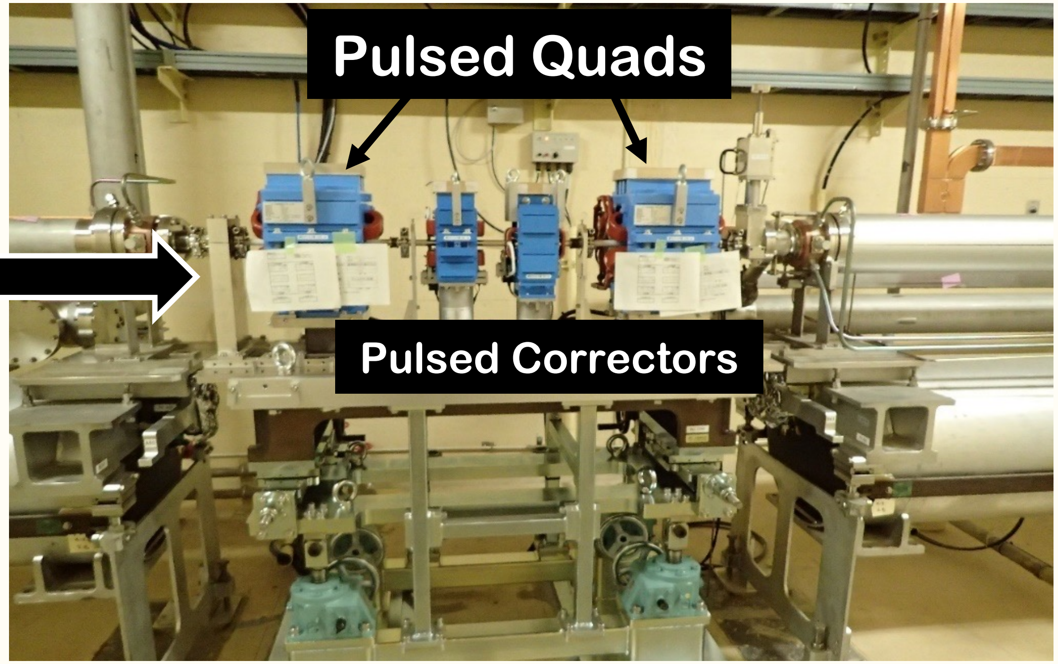
https://www-linac.kek.jp/linac-com/pulsed-magnet/

Pulsed Magnets and Power Supplies for PPM

Y. Enomoto
T. Kamitani

Pulsed Magnets



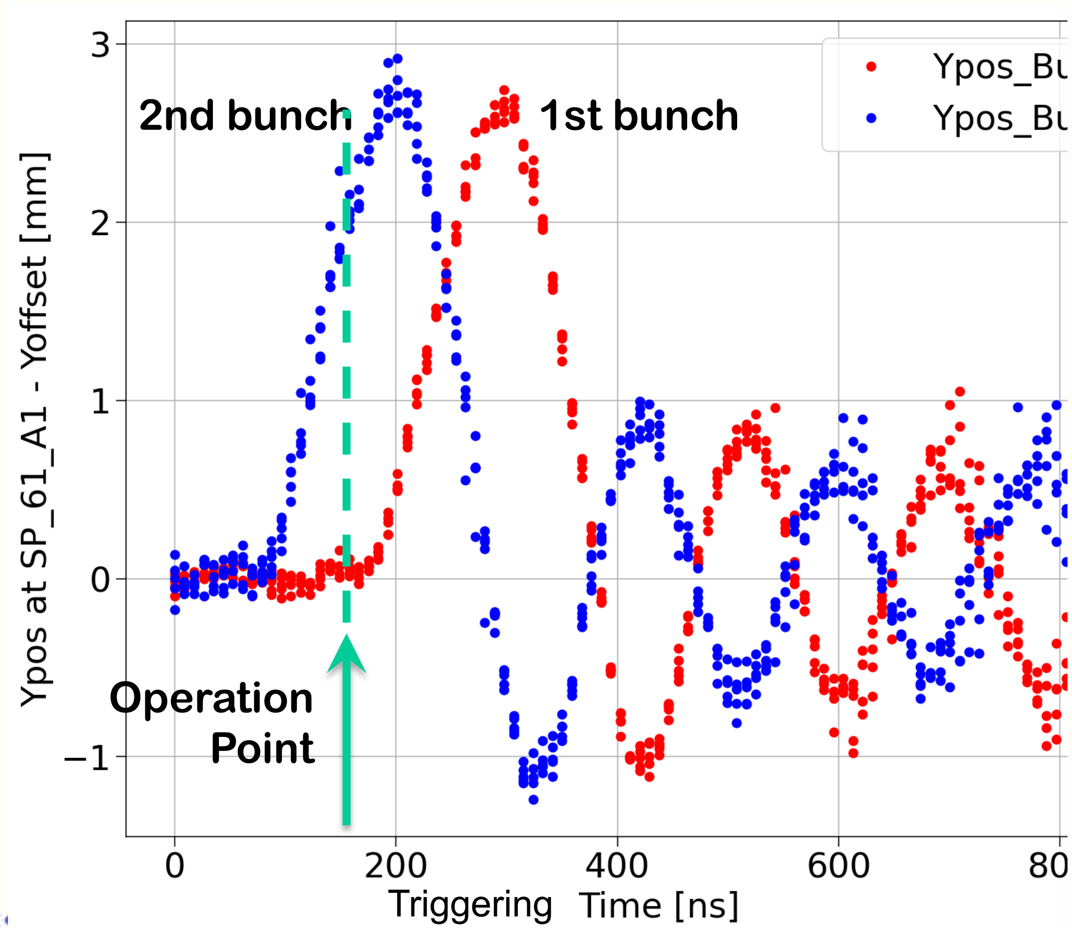


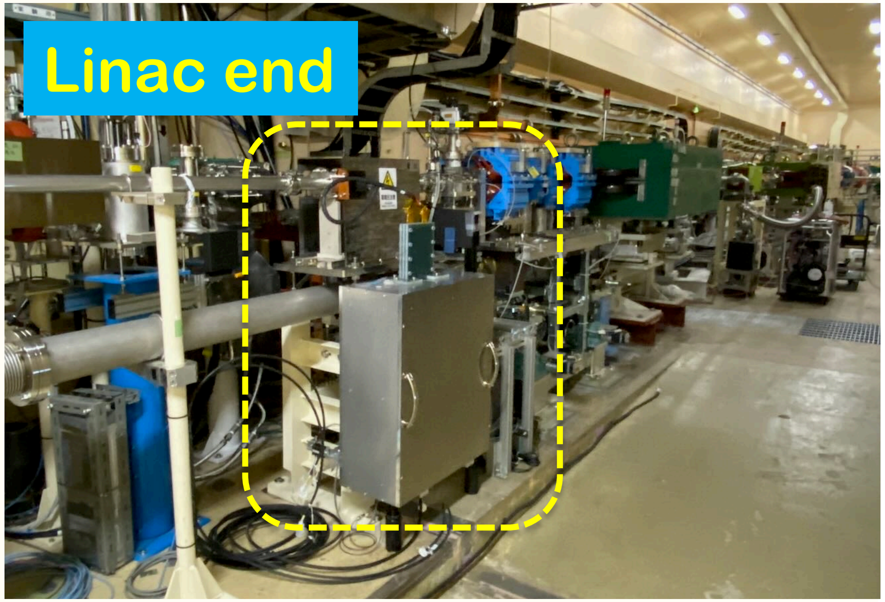
- **Pulsed quad x28 and pulsed corrector x 36 installed in 2017**
- **Many more pulsed magnets are being added** Now about 100 pulsed magnets
- **Good power supply stability of 0.01% (24 hours)**
- **PXI bus, PXI-EVR, cRIO, 50 Hz controls under MRF event and EPICS**
  - **At first with EPICS/Windows and LabVIEW, and now with EPICS/Linux**
- **Even with 69% power recovery from coils**

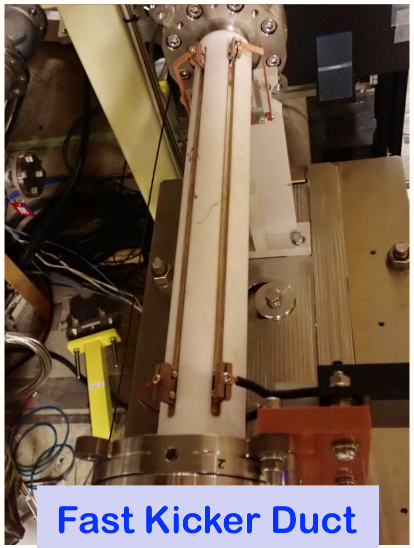
Fast corrector/kicker development

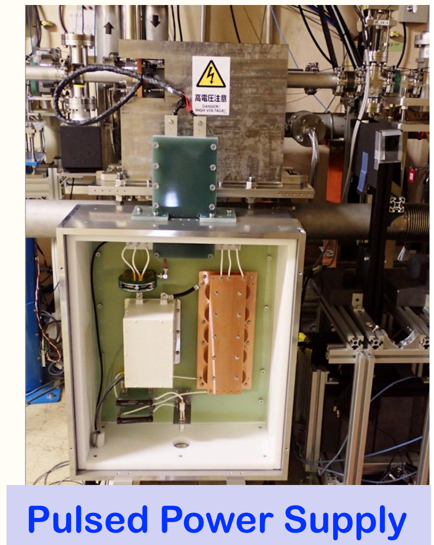
T. Kamitani et. al.

- **2-bunch independent corrector**
  - At the end of Linac (2023) and in BT
- **Ceramic embedded coils**
  - 2nd bunch can be independently kicked







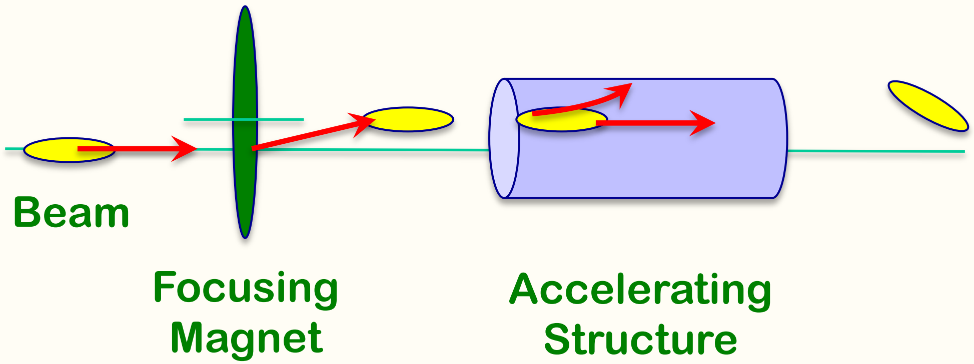


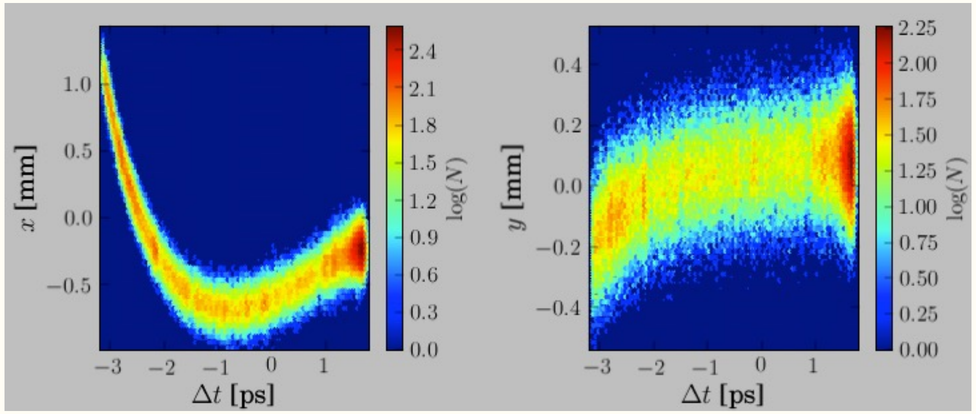
Emittance Preservation

Emittance Preservation and Alignment

- **If Device is off center of the beam**
  - **Focusing magnet (quad) kicks the beam bunch**
  - **Accelerating structure (cavity) excites wakefield, to bend the tail**
- **Distorted bunch in banana shape**
  - **Emittance dilution or blow-up, even 100 times larger**
    - **Depending on the beam optics and the beam charge**
- **Alignment and orbit correction is crucial to preserve the emittance**

Sugimoto et al.



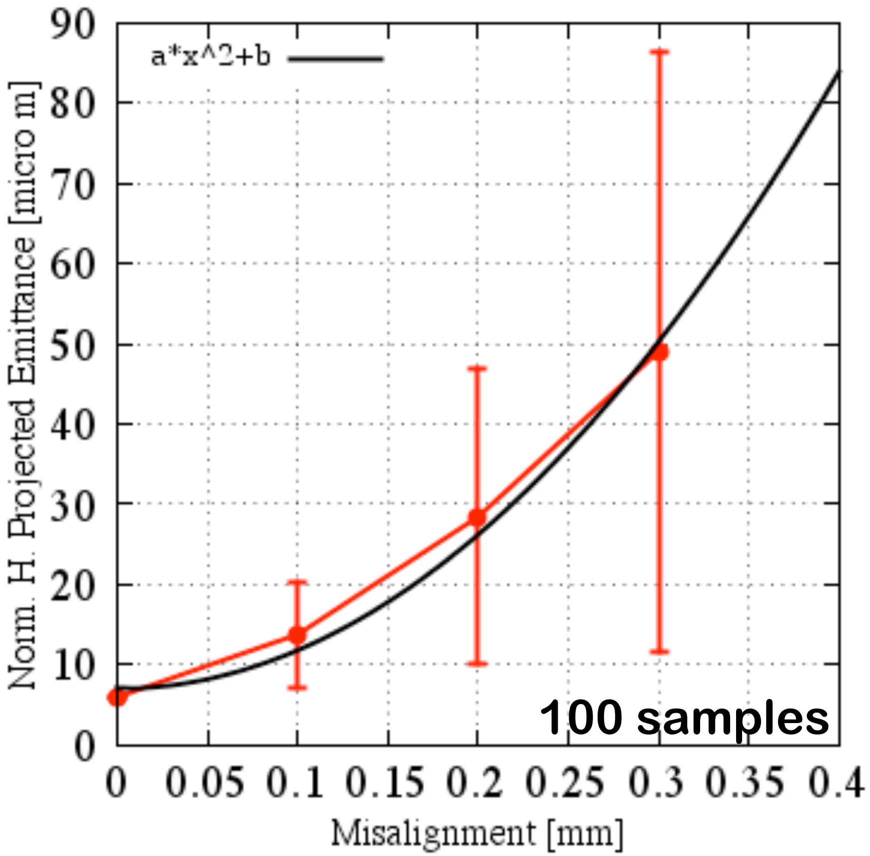


Transverse beam distribution in time direction

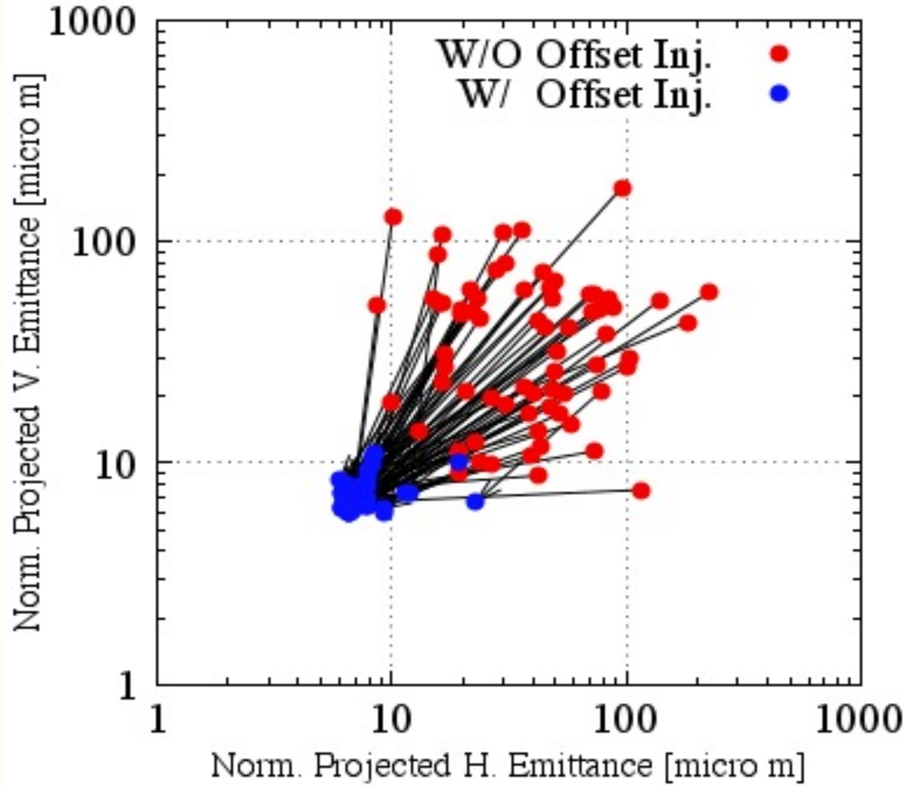
Emittance Preservation

- **Offset injection may solve the issue**
- **Orbit have to be maintained precisely**
- **Mis-alignment should be <0.1mm locally, <0.3mm globally**

Mis-alignment leads to Emittance blow-up



Orbit manipulation compensates it

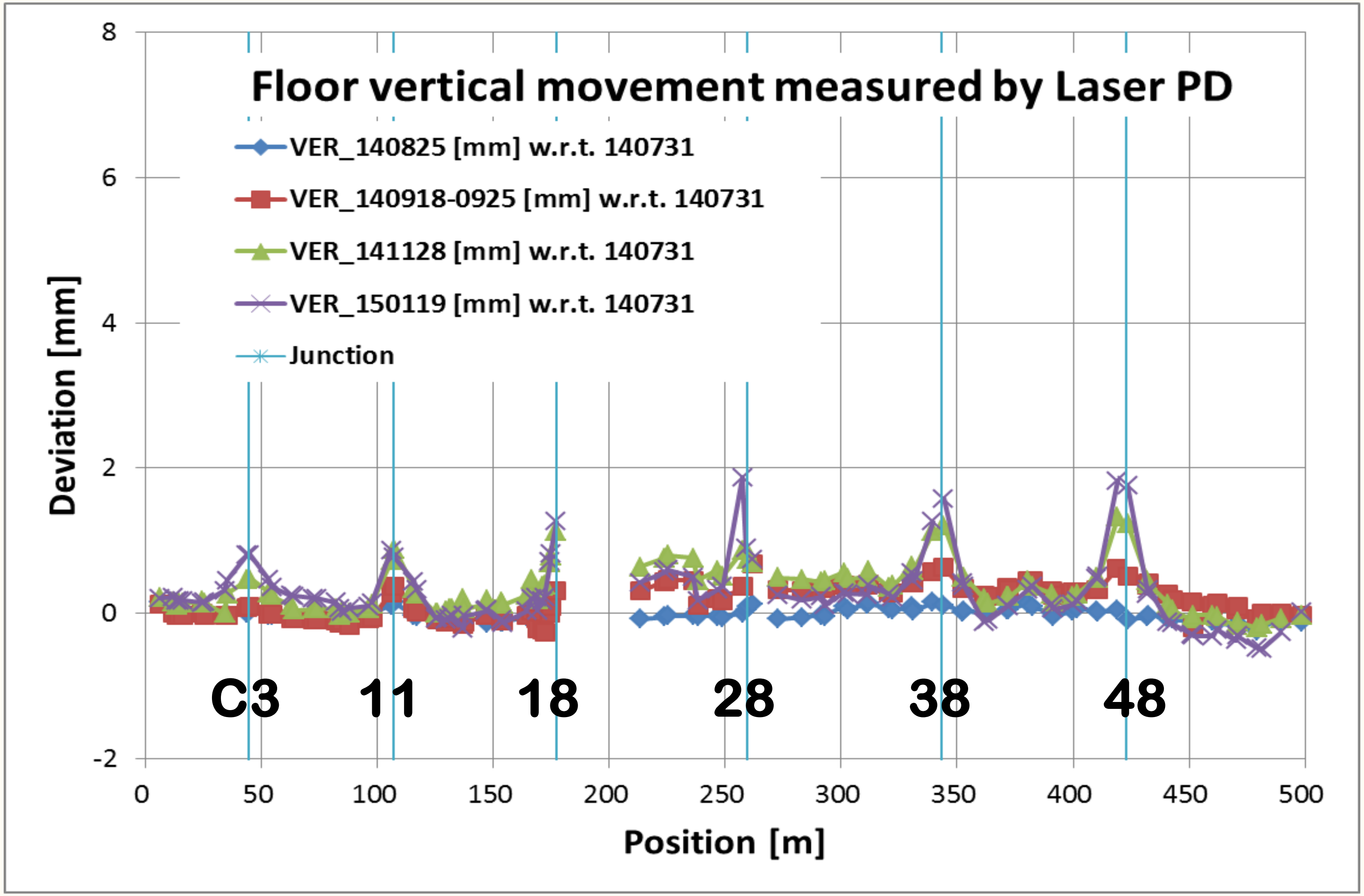


Sugimoto et al.

Floor vertical movement

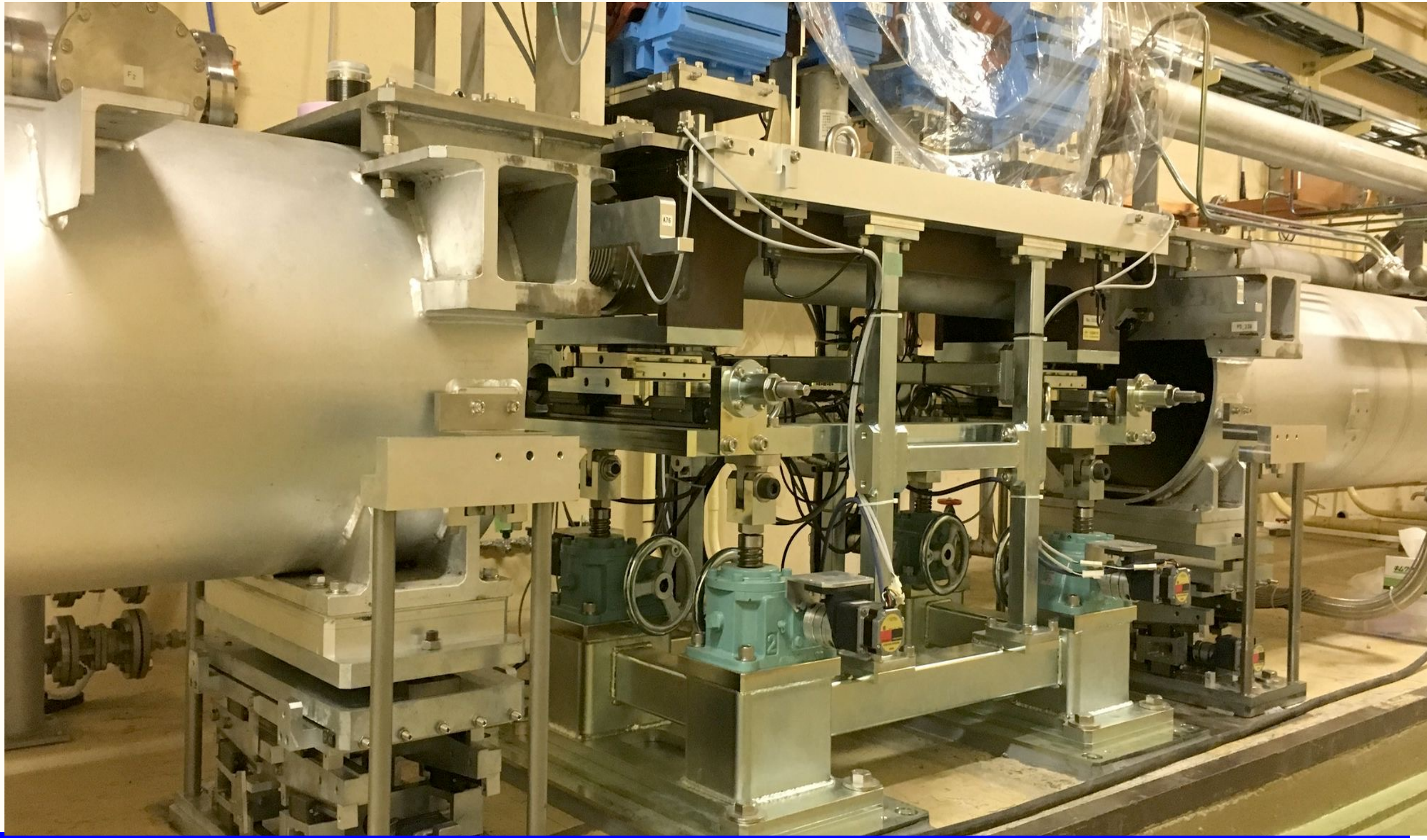
in a half year from summer to winter

Higo et al.



Girder mover for structures and magnets, with 1-10 μm precision

- The girder was already developed
- The alignment is not a big issue yet at present charge and with BT blowup

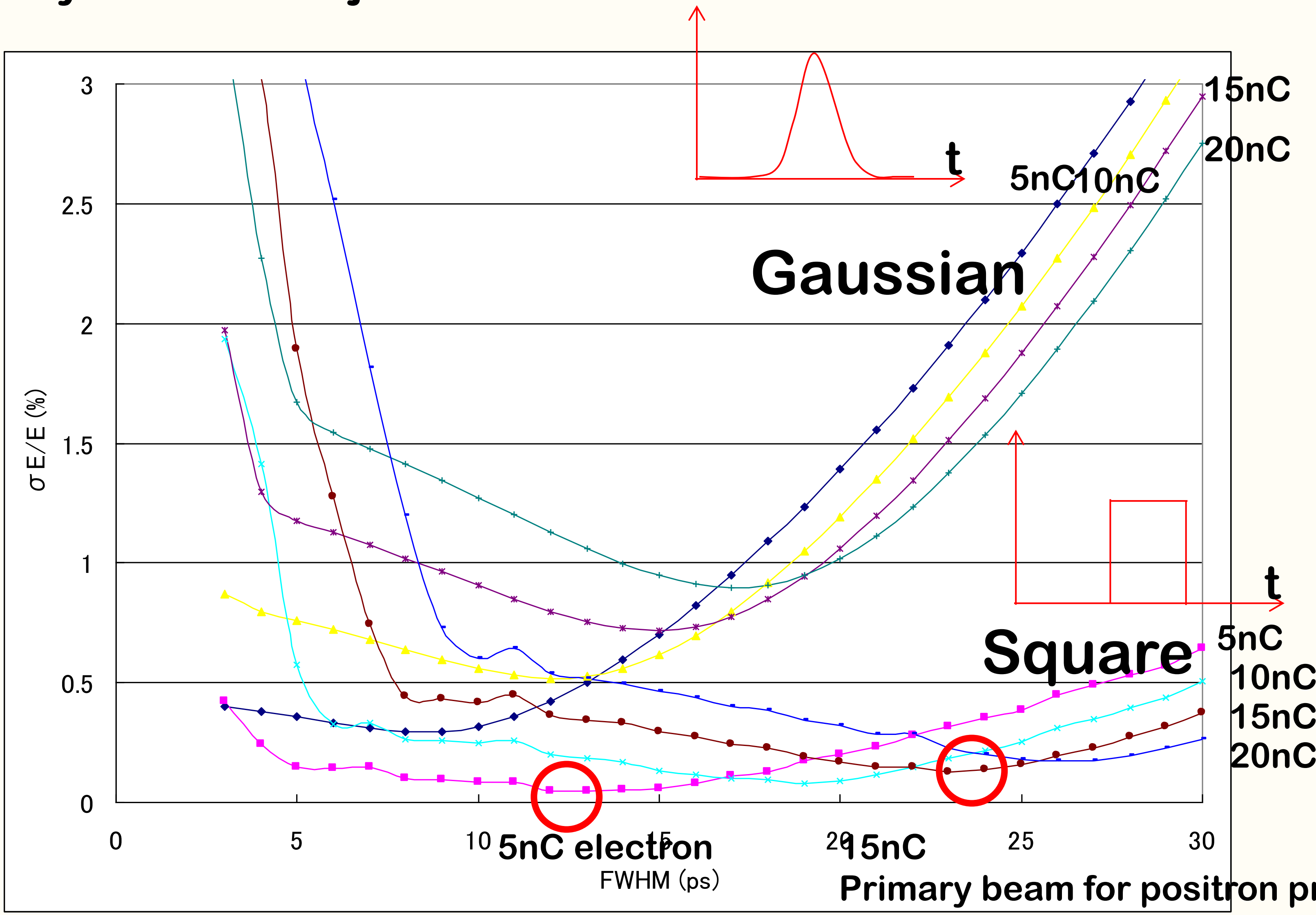


Energy Spread Management

Energy spread reduction using temporal manipulation

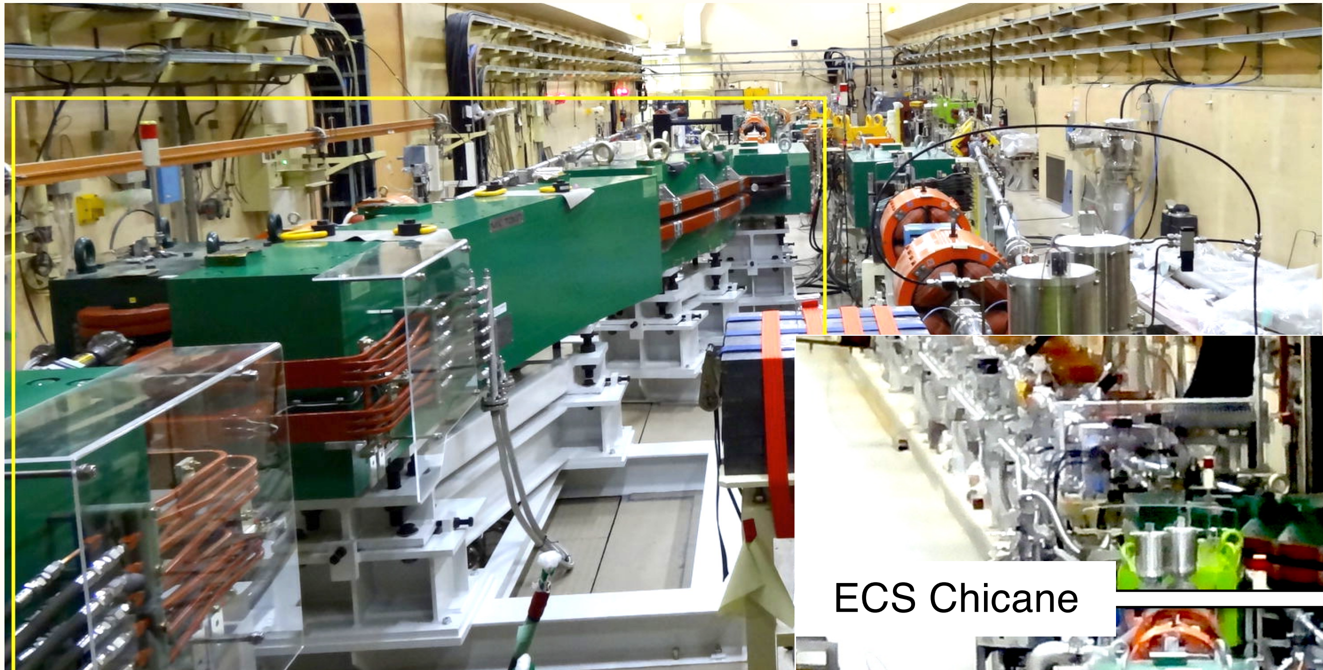
M. Yoshida

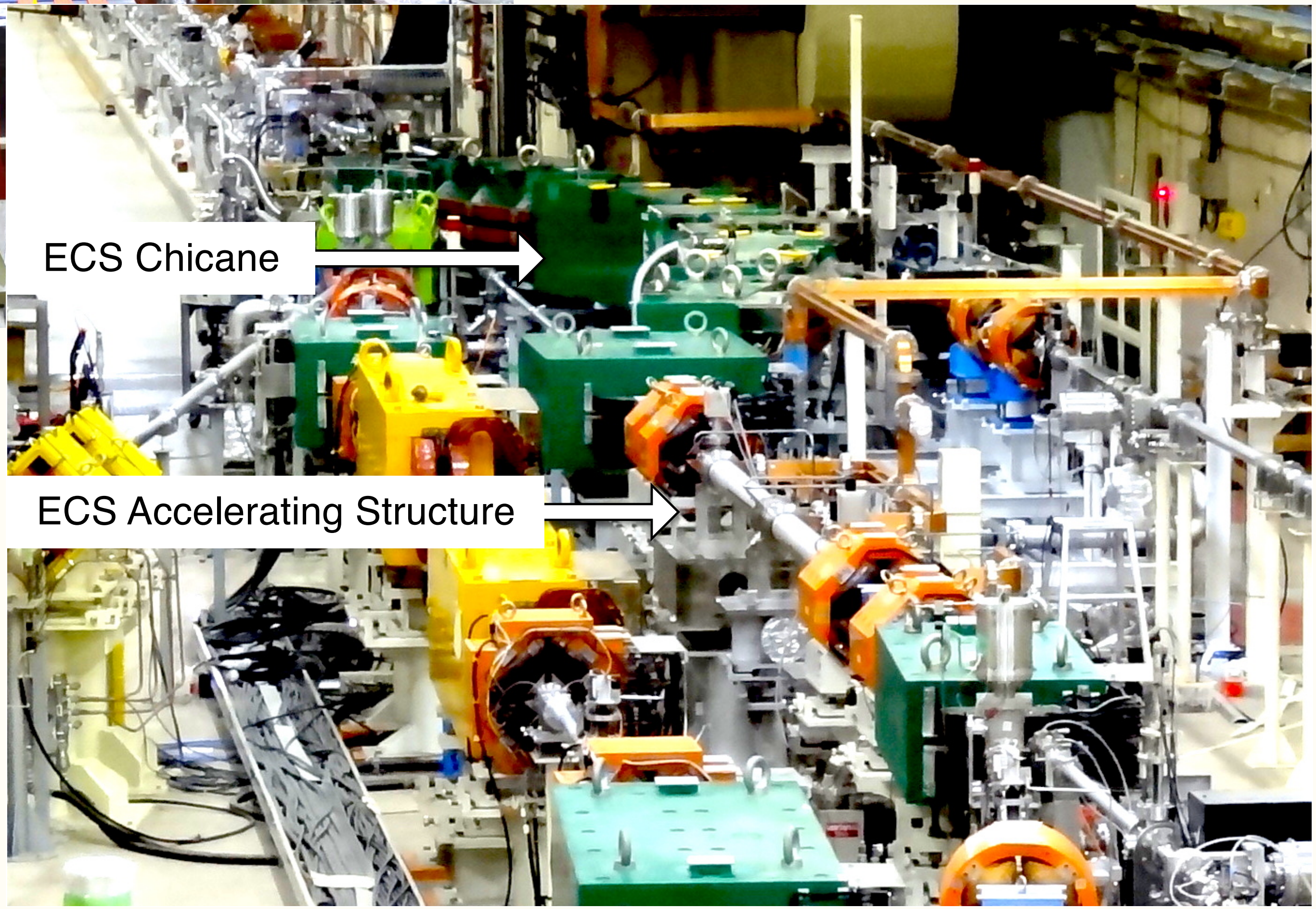
Energy spread of 0.1% is required for SuperKEKB synchrotron injection.



- If the laser shaping is not enough we may need to depend on ECS
- Especially additional requirement of 0.07%(ΔE) is rather difficult

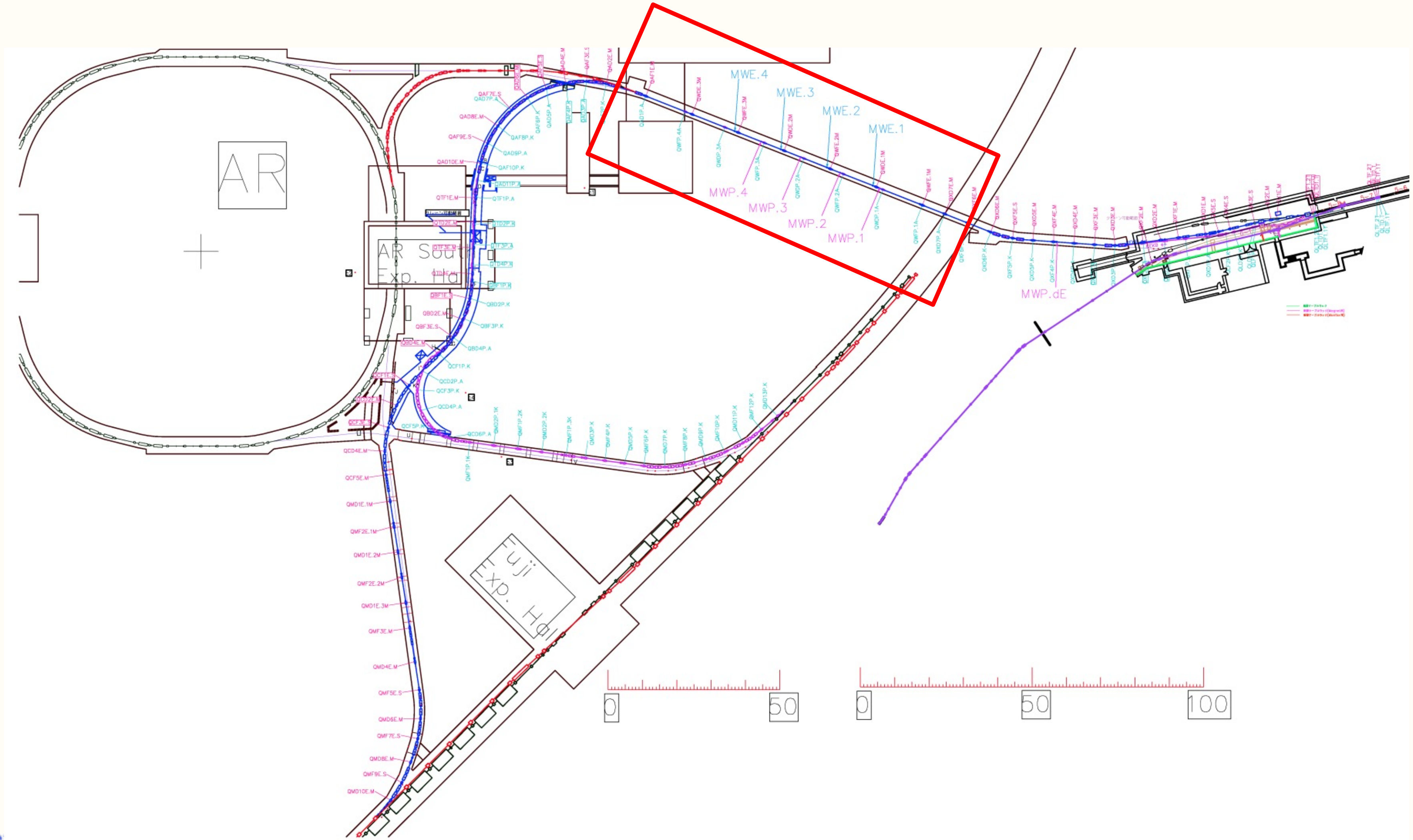
Positron energy compression system





ECS at MR-BTe

- It will be constructed on the BT in 2024-2025.

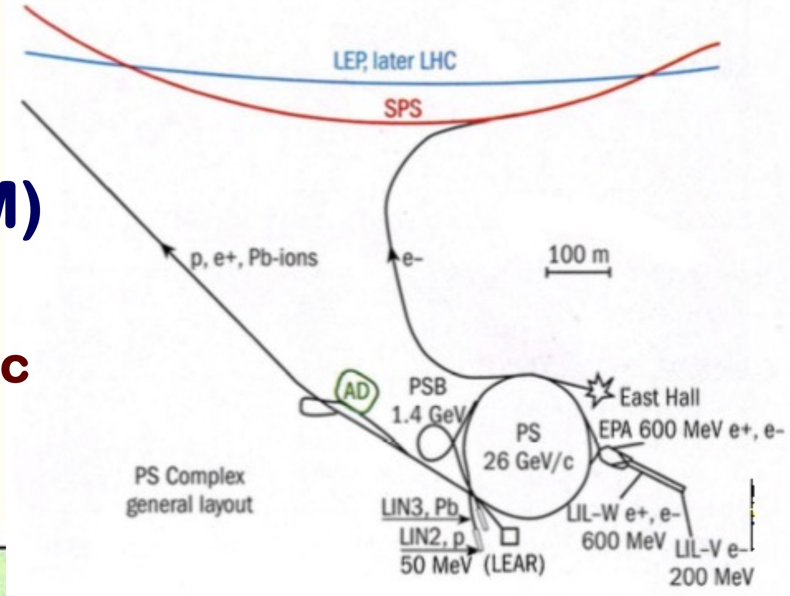


Virtual Accelerator
or Pulese-to-pulse Modulation

https://www-linac.kek.jp/cont/epics/event/

My dream of PPM

- **CERN PS Pulse-to-pulse modulation (PPM)**
  - **Visit to CERN 1994-1995**
  - **Variety of beams (e-, e+, p, ṕ, HI) every 1.2 (2.4) sec**



The CERN PS Complex today: eight accelerators and storage rings, with their interconnecting beam and transfer lines to the neighbouring SPS synchrotron.

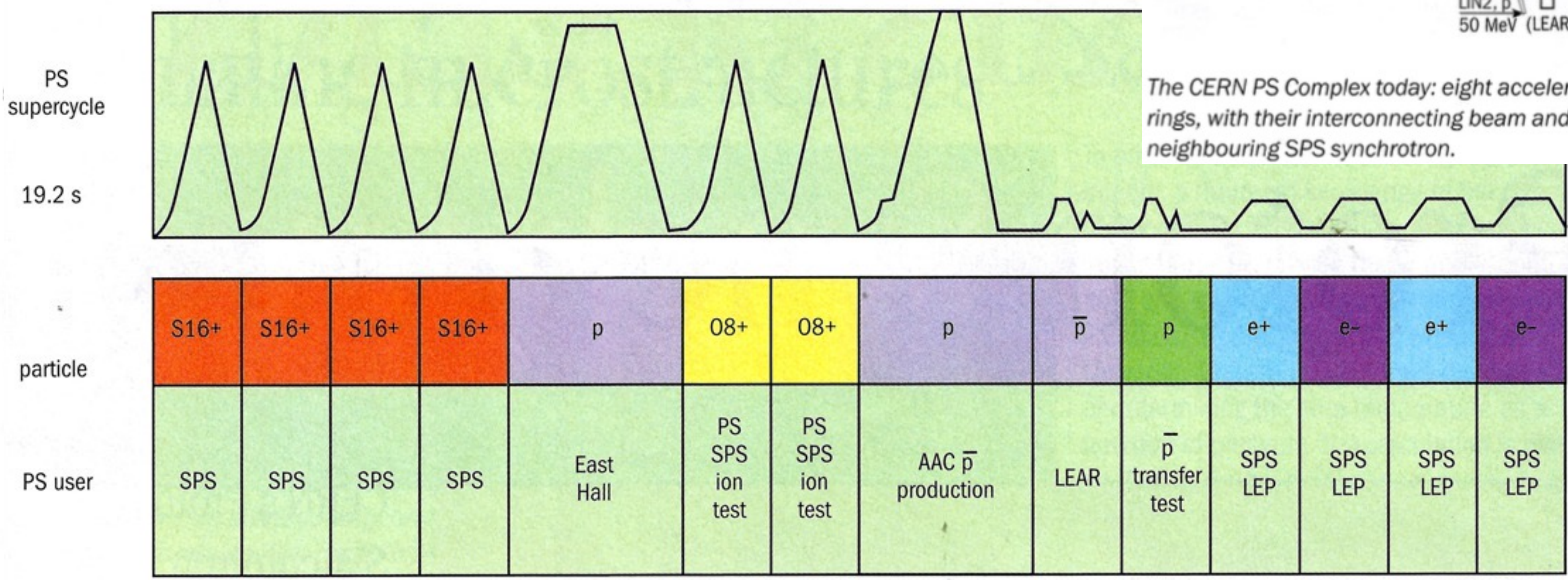


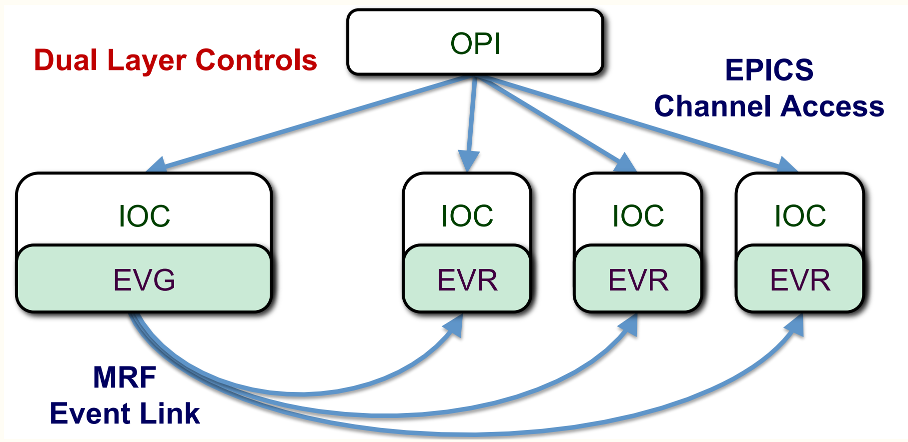
Fig. 1: A great variety of PS cycles are composed into a "supercycle", in which one user after another is served. In a particularly rich case, from August 1990, no less than six different kinds of particle (sulphur ions, protons, oxygen ions, antiprotons, electrons and positrons) were sequentially served to seven different destinations.

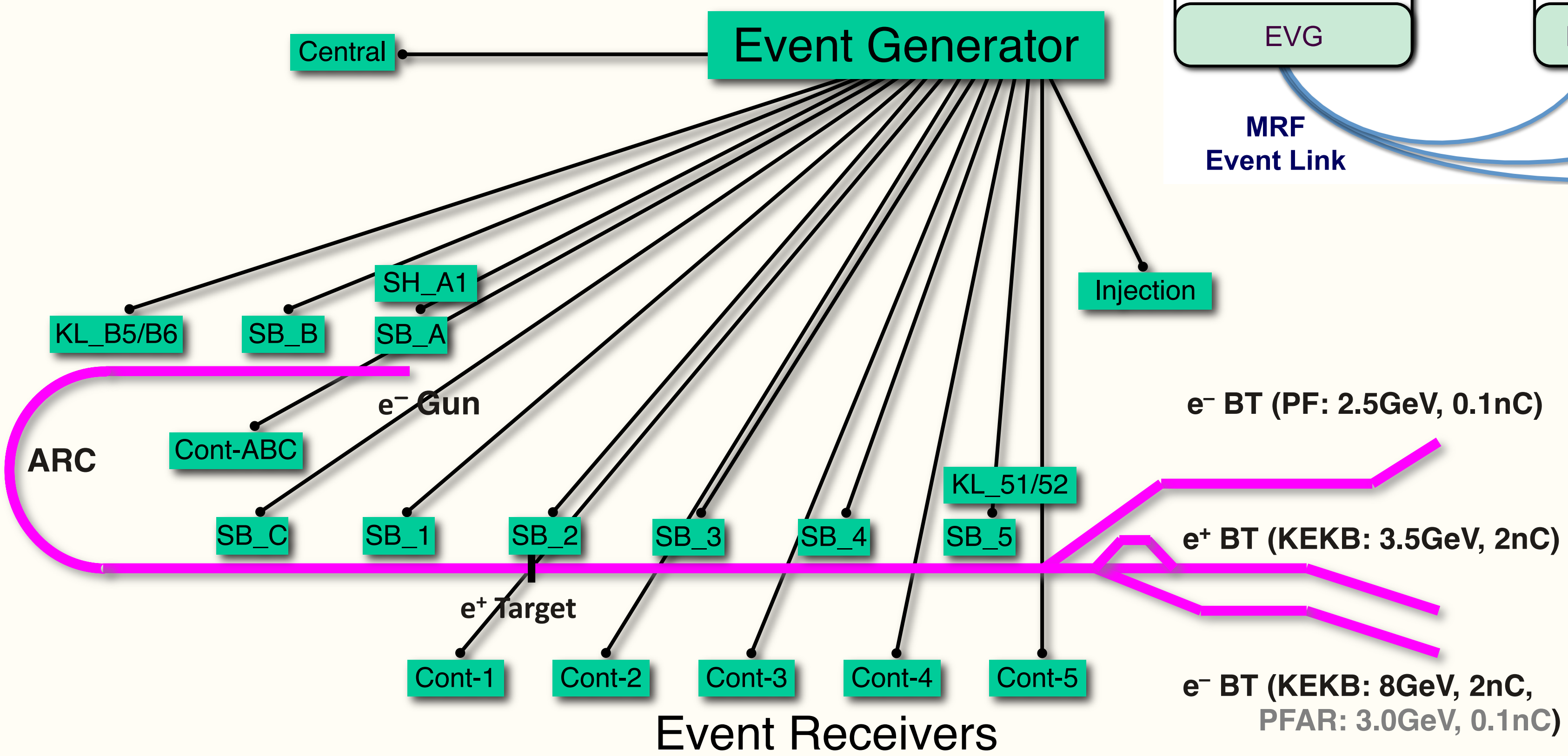
CERN Courier 1999

Fast Global Synchronous Controls

- Event-based controls (MRF)
- 114.24MHz event rate, 50Hz fiducials
- Timing precision < 10ps

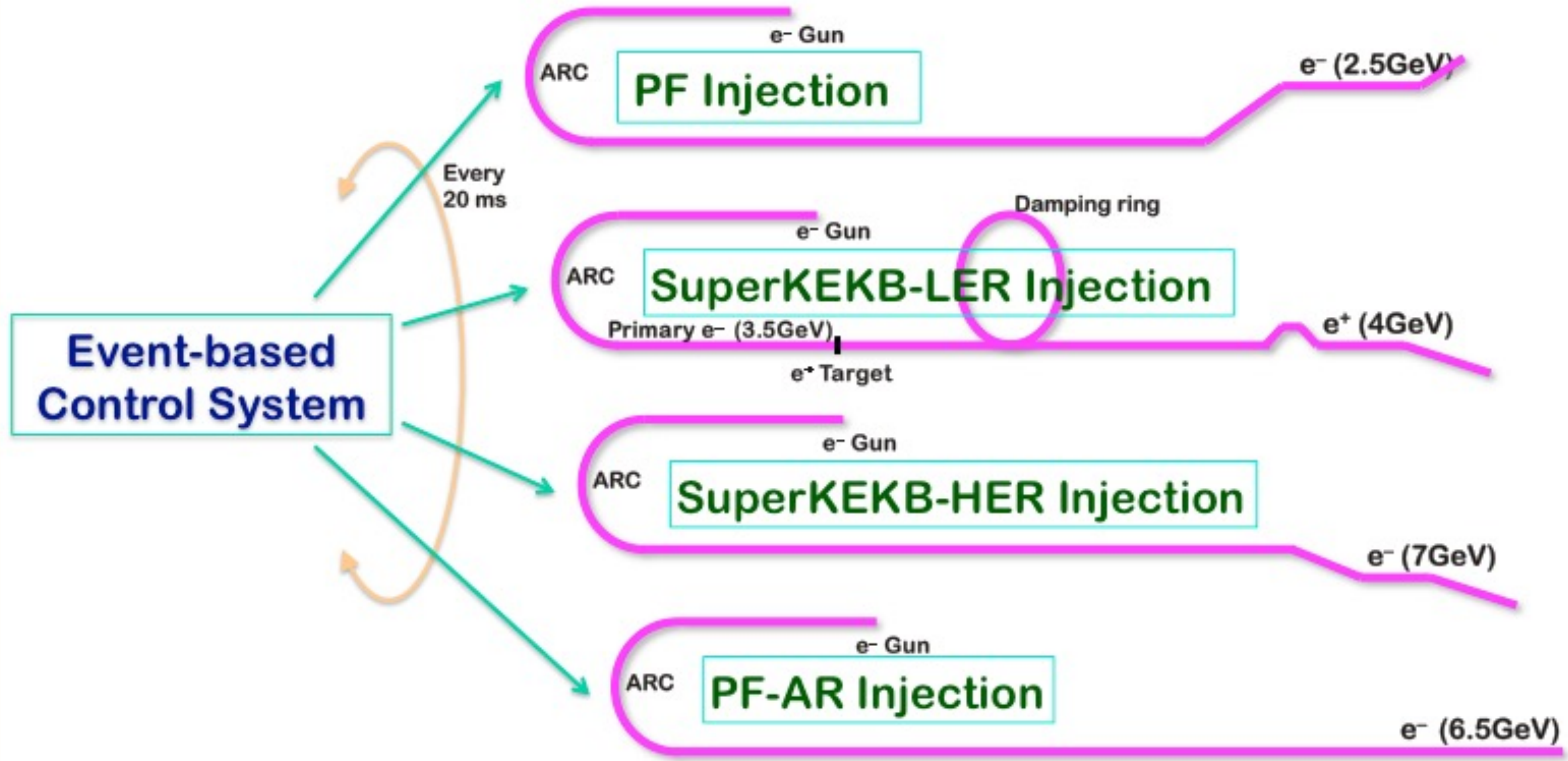
Dual layer control concept





One Machine, Multiple Virtual Accelerators (VAs)

- **Control/Monitor are carried dependent on a VA**
  - **Mostly independent between VAs**
- **Independent parameter set for each VA, one of the VAs is controlled at a time**
  - **VAs for Injections (HER (e-), LER (e+), PF, PF-AR) and Linac-only in SuperKEKB project**



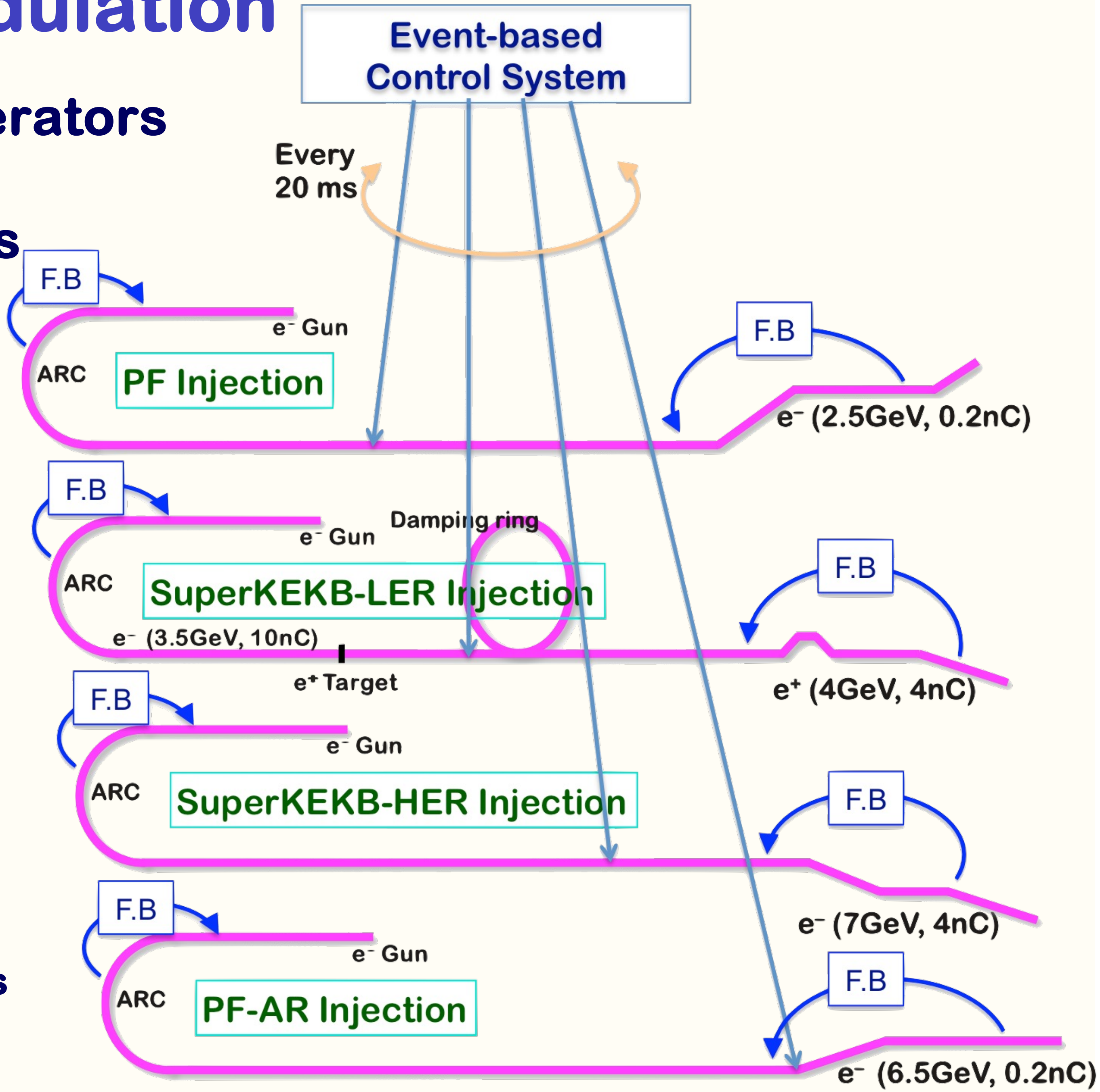
Pulse-to-pulse modulation

- **Four PPM virtual accelerators for SuperKEKB and photon science projects**
- **Multiple closed loops overlapped**
- **Since May.2019**

Based on
Dual-tier controls with
EPICS and event-system

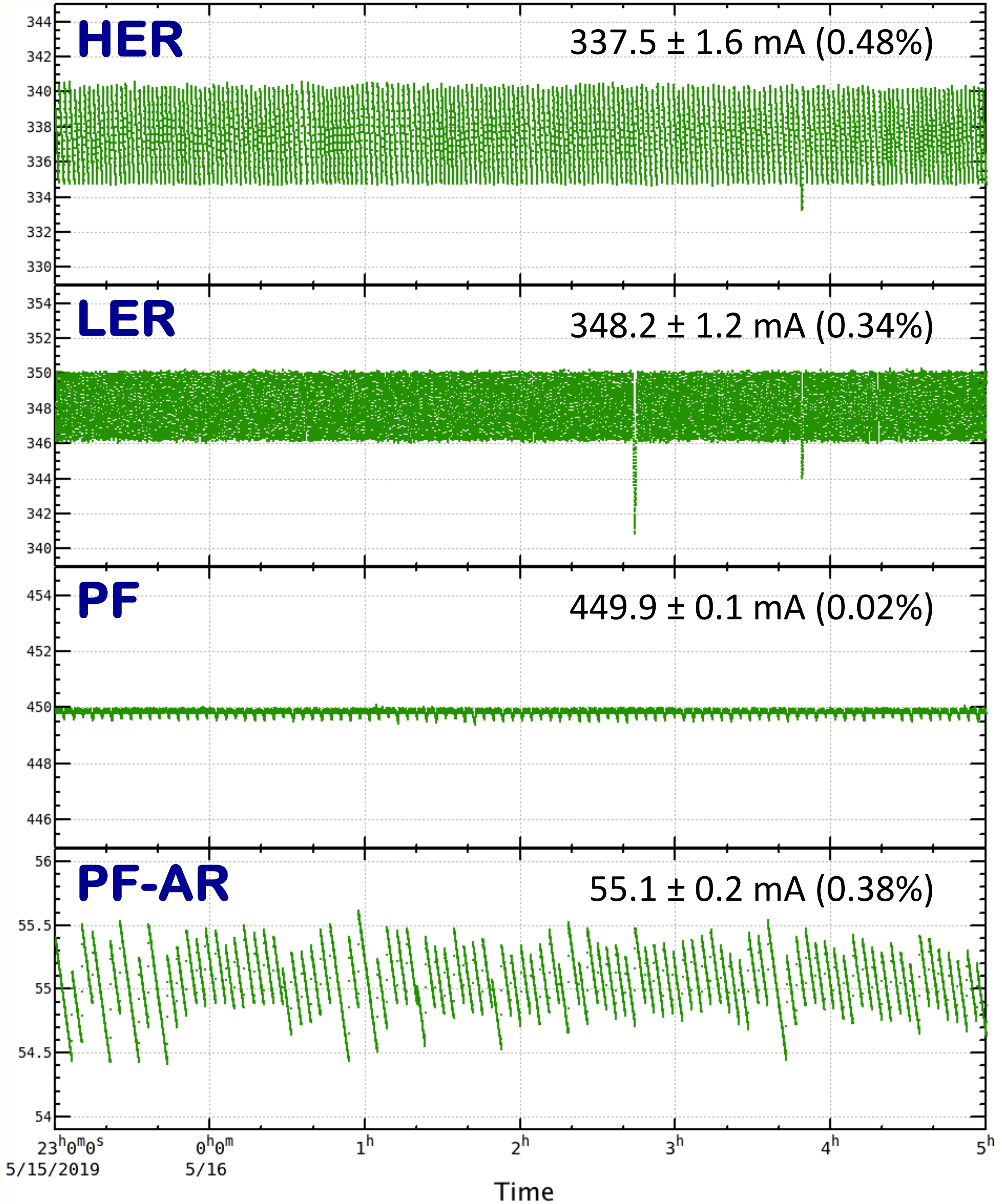
Independent parameter sets
for each VA (every 20ms)

additional PPM VAs
for stealth beam measurements
in the future



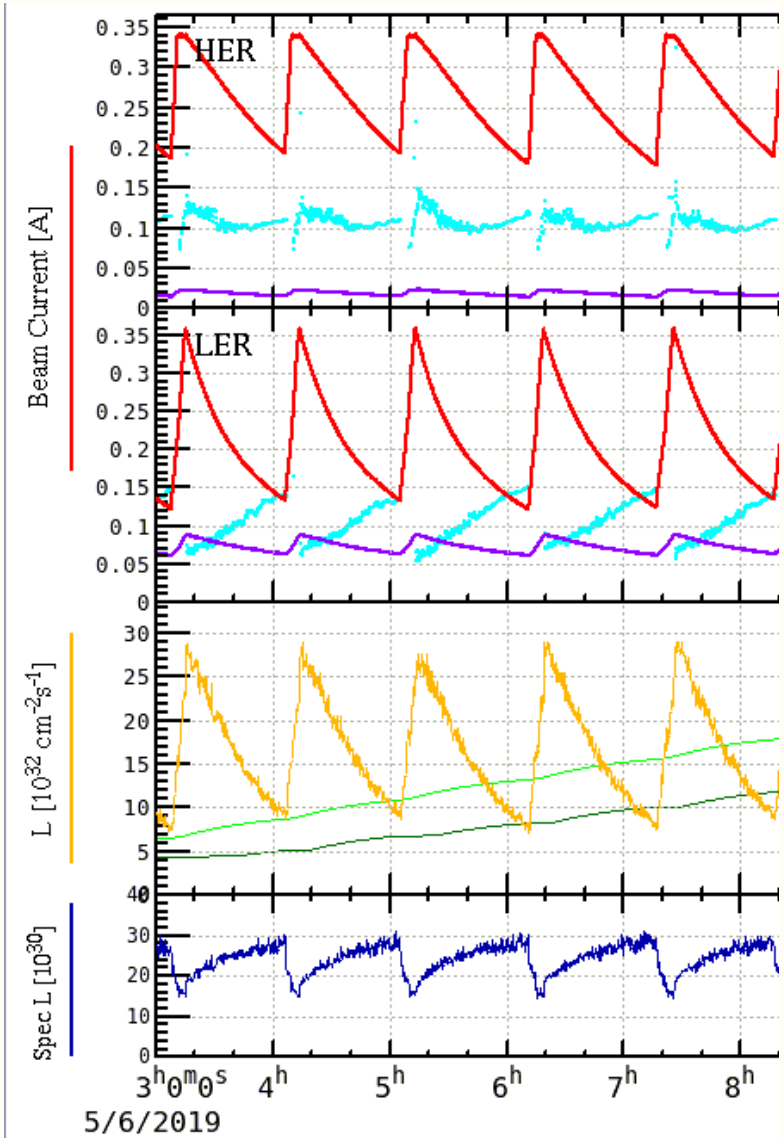
Simultaneous 4 + 1 Ring Top-up Injection

- **Realized for the first time**
  - SuperKEKB HER 7 GeV e–
  - SuperKEKB DR and LER 4 GeV e+
  - Photon Factory 2.5 GeV e–
  - PF-AR 5.0 / 6.5 GeV e–
- **4 beams are modulated at 20 ms PPM**
- **More than 200 pulsed devices were constructed for SuperKEKB, as well as beam and RF monitors**
- **Injection noise (background) were well studied from the 2nd week of May**



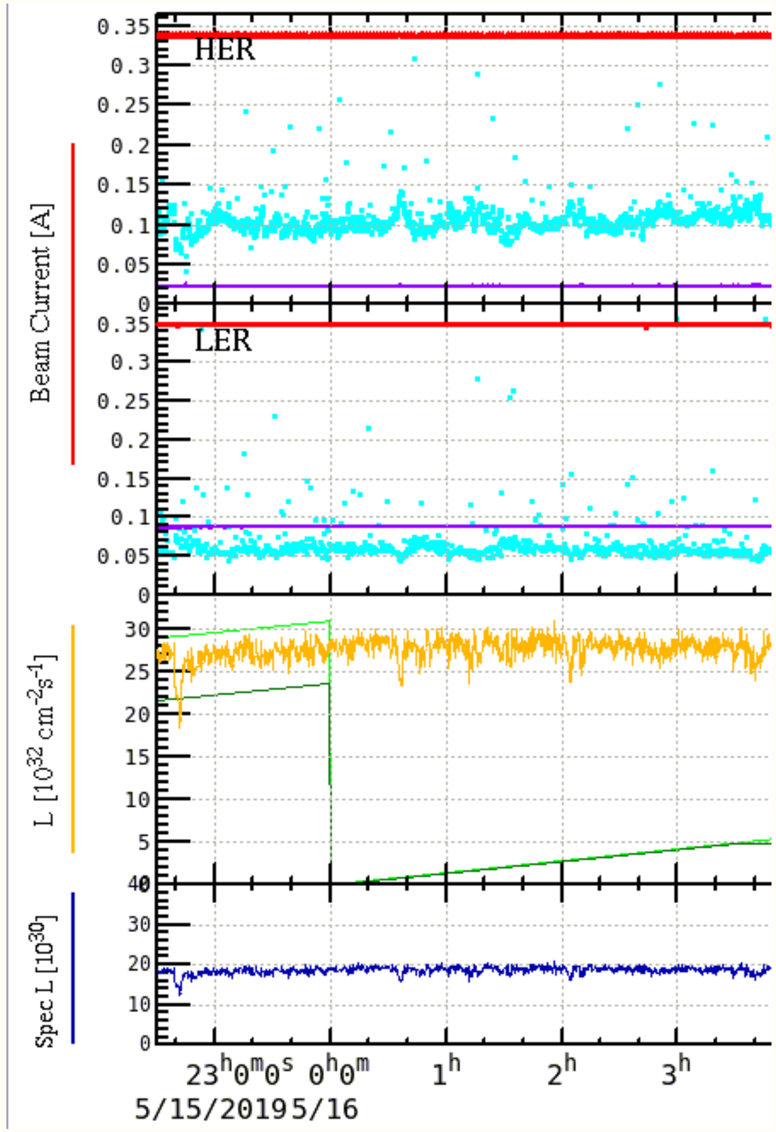
Simultaneous Top-up Injections

◆Integrated luminosity improvement (example)



17.54 /pb in 5.15 hr (5 fills) on May.6

41.64 /pb in 5.15 hr (top-up) on May.16

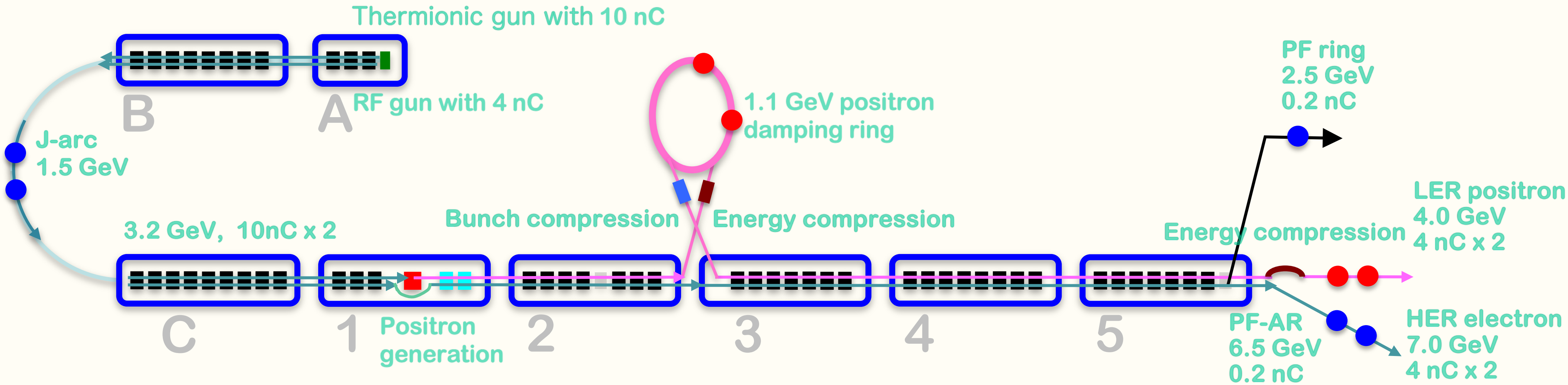


237% improvement

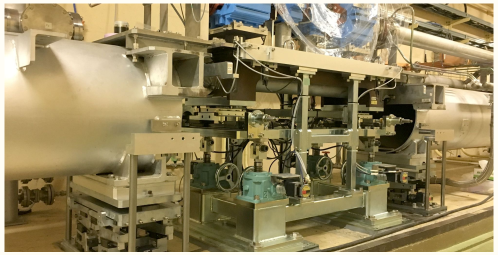
Heavy work in April was rewarded

Upgrade plan

Injector Linac Upgrade Items 2022 - 2026

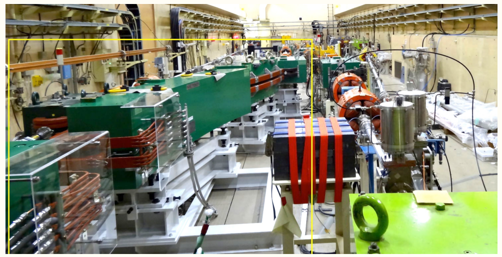


Pulsed magnets/kickers

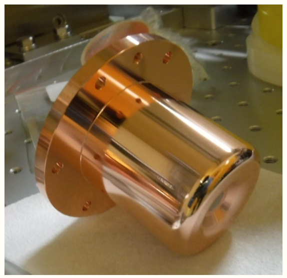


High precision movers

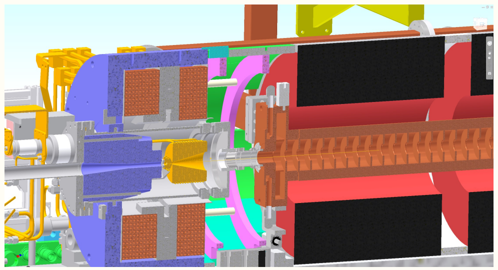
PCB capacitor renewal



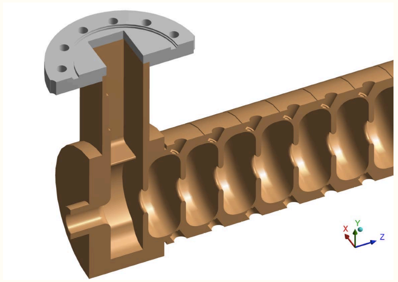
New energy compressor



RF gun



Positron capture section



Accelerating structure

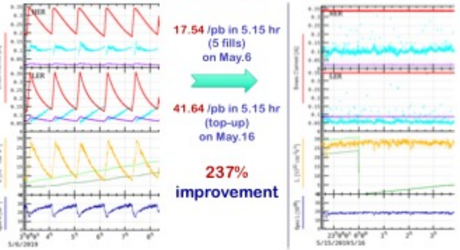
Challenges in Linac upgrade

- Achieving the both of higher injection beam charge and lower transverse/longitudinal emittance
- Maintaining higher availability and stability
- Establishing injection energy for higher resonances
- Solutions with upgraded hardware
  - Precise pulsed magnets and fast kickers
  - Energy compression system (ECS)
  - Accelerating structures to replace aged ones
  - Stable and high charge RF gun
  - Replacement of a lot of capacitors with PCB in power modulators
  - Movable girders for quads and structures in case
- With some Phronesis we can enjoy accelerators
  - Phronesis [Greek]: Practical wisdom, Ability to understand the Universal Truth

Carbon Neutral Activities at Injector LINAC

High Performance Simultaneous Top-up Injections

700 メートルの長さを持つ電子陽電子入射器は、電子ビームや電子の反物質の陽電子ビームを作り出して、高いエネルギーまで加速します。そのビームを素粒子物理実験や放射光科学実験に使われる 4 つのリング型加速器にむけて送り出します。連続してビームを作ると大きな電力が必要になるので、ビームを 100 万分の 1 秒だけパルス加速することによって電力を節約します。
さらに入射器は、1 秒間に 50 回もカメレオンのような変わり身をすることができます。一つの入射器なのに、あたかも 4 つの入射器が、同時に 4 つのリング加速器に電子・陽電子ビームを送り出すように振る舞うことができます。




ひとつの電子陽電子入射器が変わり身を繰り返しながら、4 つのリング型加速器に向けて電子や陽電子を送り出します。

ひとつの入射器を 4 つの入射器のように高速に切り替えて、電力を節約します。

入射器は 4 千キロワット以上の電力を必要としますので、この変わり身によって、3 台分 1 万キロワット以上の電力を節約していることになります。
高速の変わり身を始めた前後で SuperKEKB 素粒子衝突実験の成果を比較してみると、上の図のように 2.37 倍も実験効率が向上したことがわかります。衝突リングの電力は 4 万キロワットにもなりますから、ここでも電力の節約ができたことになります。

69% Power Recovery from Pulsed Magnet Coils

電子陽電子入射器は、エネルギー特性の異なる電子ビームや陽電子ビームを作り出して、素粒子物理実験や放射光科学実験に使われる 4 つのリング型加速器に向けて入射します。実験成果を最大にするために、入射器は 1 秒間に 50 回もカメレオンのような変わり身を行う 4 リング同時トップアップ入射機構を実現しました。
4 つのリングへの入射エネルギーが大きく異なるために、それぞれに対応した適切なビーム光学条件を整える必要があります。そこで 99 台のパルス電磁石を設置して入射毎に磁場強度を変更します。このため専用のパルス電源を開発して、電力の大きい収束電磁石には 200 V、300 A ほどの電力を供給します。この電源は電磁石のコイルとの組み合わせによって電力を回収できるように設計されました。


入射器に 99 台以上設置されているパルス電磁石。

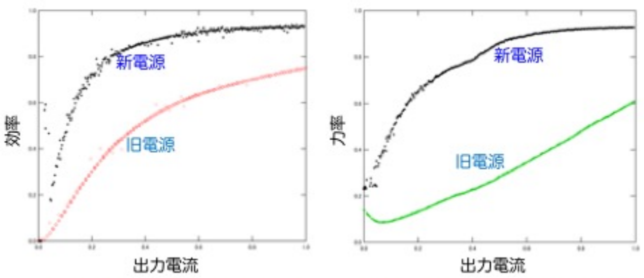

ひとつの電子陽電子入射器が変わり身をして 4 つのリング型加速器に向けて電子や陽電子を送り出します。


新しく開発されたパルス電源装置。

パルス電力が電磁石のコイルに供給されると、電磁石が磁場を発生し適切な特性を持つビームを導きます。コイルが一度パルス電力を受け取ると、今度は逆に電力を返そうとします。以前の電源ではこの戻ってきた電力は熱として捨てられていましたが、この電力を電源のコンデンサで受け取り、20 ミリ秒後の次のパルスで再利用することを可能にしました。測定するとその節約割合は 69% に達します。1 台あたりの電力は約 2.5 キロワットなので、全体で約 100 キロワットの電力の節約ができたことになります。

High Power Conversion Efficiency at Magnet Power Supplies

電子陽電子入射器では、大小さまざまな電磁石電源が390台ほど使われていますが、そのうちの15台ほどにおいては100kW前後の比較的大きな電力が消費されています。さらにそのうちの6台が2000年以前の古い設計の電源であるため、更新することにより効率が改善し、20%から30%の消費電力低減が期待できます。同時に電源の精度・安定度も一桁以上向上させることが可能となり、ビームの安定化に繋がるとともに、不安定であった場合に必要となる安定化機構の計算機等の付加設備が不要となるために、より環境負荷を下げることが可能になります。さらに電源の力率も大幅に向上するため、伝送路などで無駄に消費される電力も低減させることができます。



直流電磁石電源の電力効率を大きく改善することができます

力率も大幅に改善することが可能となるため、伝送路などで電力が無駄になりません


入射器に6台残っている20年以上使用された電磁石電源

旧型の電磁石電源は年々保守が難しくなっており、安定度も低下しているため、加速器運転に影響する場合も増えており、更新が必至となっています。更新の費用としては、1台あたり1000万円程度となり、6台で6000万円程度を必要とします。しかし、更新により1台あたり20kWから30kWを節約することができますので、電気料金を18円/kWhとすると、保守作業を含めて年間8ヶ月運転で260万円の節約となります。従って約4年で償却できることになります。

High Efficiency RF Power Distribution

電子陽電子入射器はA～C、1～5の８つのセクタで構成されています。一つのセクタには8台の大電力パルス・クライストロン配置されており、KEKB計画向けに開発された60kWパルス・クライストロン（サブブースタ）からマイクロ波が分配されて駆動されてきました。しかし、製造会社の都合によりサブブースタ・クライストロンの製造が不可能となったため、小型半導体増幅器を用いた分散駆動方式の開発を進めてきました。そして、その安定動作に成功したため、半導体増幅器の導入を進めています。下の図のような構成変更を行うことによって、多様なビーム加速モードに対応する自由度も向上しています。

一つのセクタを駆動するサブブースタ・クライストロン（上の赤枠）を、新しく開発された小型半導体増幅器（下の赤枠）による分散駆動方式に置き換えることが可能となりました。


旧型で大型のサブブースタ・クライストロン（右）と電源。

以前は１セクター当たりの平均消費電力が2kWでしたが、この構成変更によって電力を60%以上節約して、0.6 - 0.8kWに削減できることがわかりました。残っている４つのセクターを半導体増幅器を用いた分散駆動に変更することにより、さらなる節電を見込むことができます。１セクタの改造に1560万円がの費用が必要と見積もられていますので、４セクタでは6240万円の費用により約2.8kW分の節約が図られることになります。（納期については別途調査が必要です。）

Summary

- Injector LINAC continues multiple discipline injections in simultaneous top-up injection mode (PPM).

- Emittance blow-up at the 2nd half of beam transport line is still under investigation.

- The injector upgrade is implemented in 7 categories for the final beam parameters with higher bunch charges and lower transverse and longitudinal emittances. Further upgrade is also investigated.

Thank you

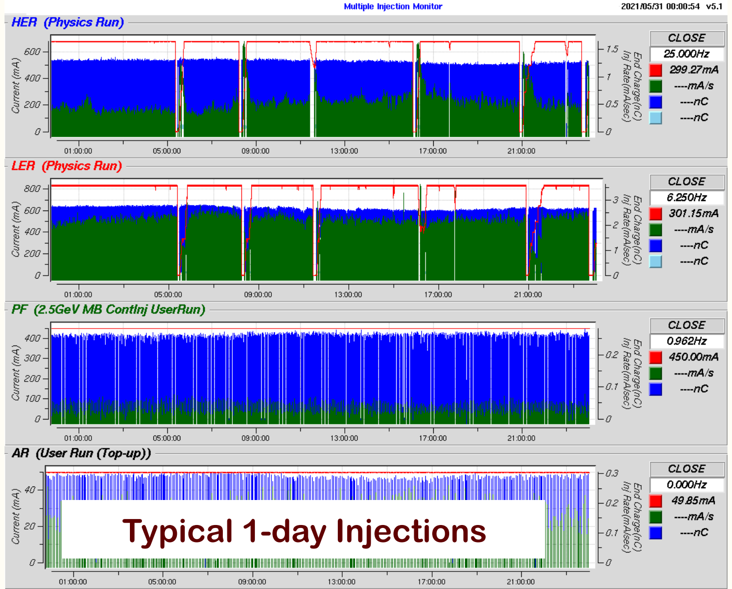
Papers and documents at <http://www-linac.kek.jp/linac-paper/general/>

Backup

Further Injector Improvement Possibilities

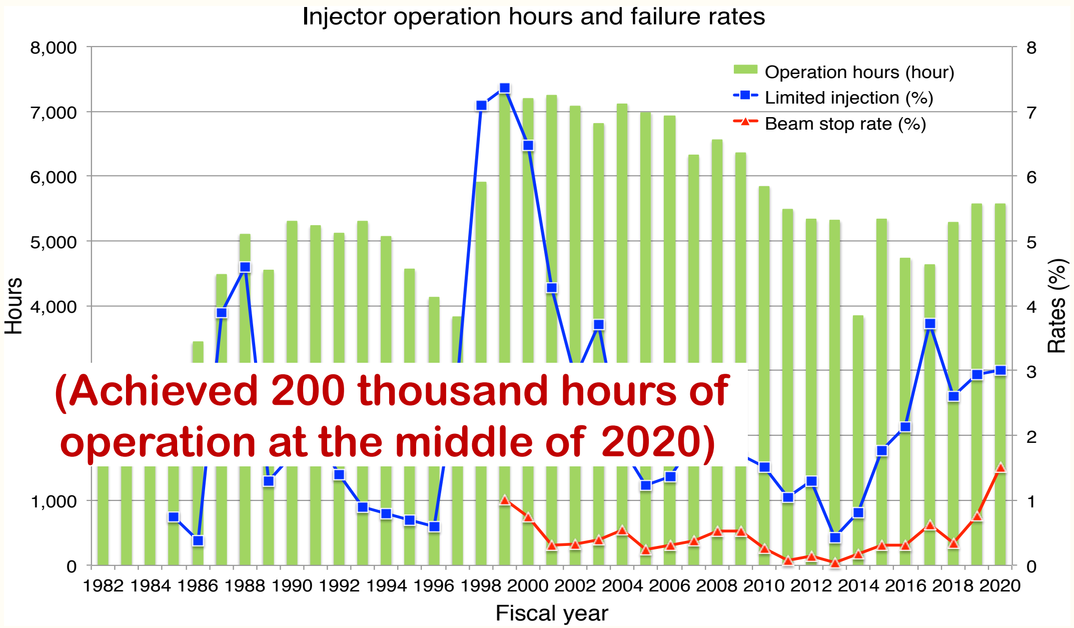
- **After injector upgrade in 7 categories**
  - Difficult to foresee now which parameters to improve further
- **Under consideration**
  - Further increase in positron bunch charge
    - LER stored current is higher and beam lifetime is shorter
    - Several possible plans exist
  - Beam transport line thru the direct tunnel
    - May relax CSR, etc
    - May interfere with PF-AR operation, may require huge radiation shield
  - Even higher energy
    - Not difficult in ring hardware up to 12 GeV with different energy ratio
    - Collision optics design should be investigated
    - However, quite expensive modification at LINAC and beam transport line
  - Polarization
    - Physics demand
    - R&D for resources, space, meaningful bunch charge
  - ...

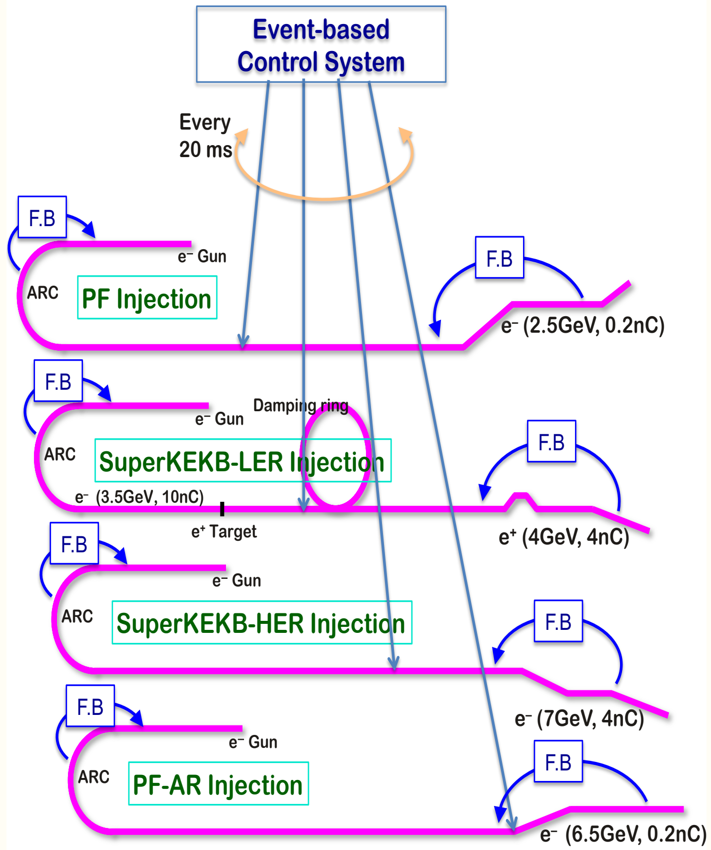
Improved Precision/Flexibility Injections



HER: 800mA, 12.5 – 25 Hz, 1.4 nC, 1 bunch
LER: 1000mA, 12.5 – 25 Hz, 3.0 nC, 1-2 bunch
PF ring: 450mA, <1 Hz, 0.25 nC
PF-AR: 50mA, <1 Hz, 0.3 nC

- **red: Ring current (mA)**
- **blue: Bunch charge (nC)**
- **green: Injection rate (mA/s)**





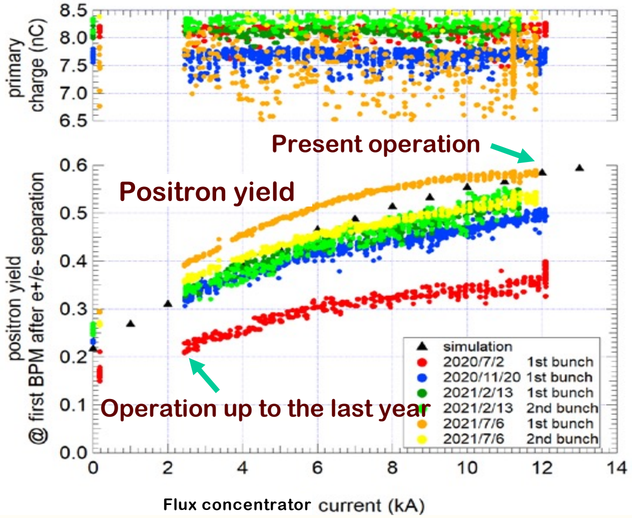
Four virtual injectors have enabled high efficiency simultaneous top-up injections

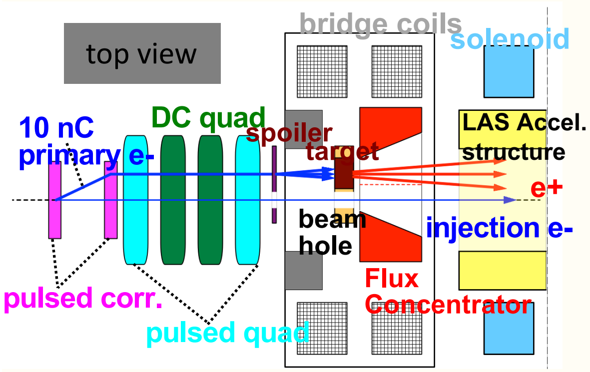
- **The injector provide high availability with advanced high-current and low-emittance injections for SuperKEKB as well as light source rings**

Recent LINAC Development and Progress

Positron production yield reaching designed value

- Copper-Nickel alloy was applied to flux-concentrator and resolved the discharge issues
- Optimized with newly installed correctors and monitors
- 3 nC/bunch enough for present SuperKEKB operation



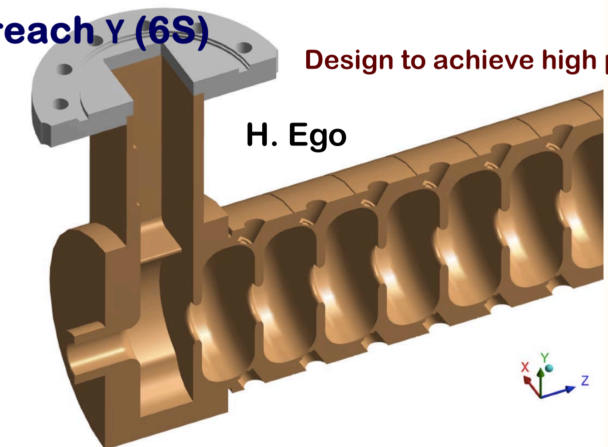


Y. Enomoto

New accelerating structures were designed and are being fabricated

- Planning to replace damaged 40 year-old 7% in 230 accelerating structures
- Succeeded to achieve high acceleration field and low discharge rate with the first 4 structures
- Will install 12 more structures in 2023
- Can reach Υ (6S)

Design to achieve high performance



Steady progress of positron beam