A New Compact 3 GeV Light Source in Japan

Nobuyuki Nishimori

on behalf of the Japanese 3 GeV accelerator team

QST

Photo courtesy of PhoSIC

Photo courtesy of PhoSIC

NanoTerasu will form a Japanese photon science platform together with SPring-8, which has covered a wide spectral range from UV to hard X-rays.

Photo courtesy of PhoSIC

NanoTerasu focuses on brighter and more coherent soft to tender X-rays with superior stability and reliability.

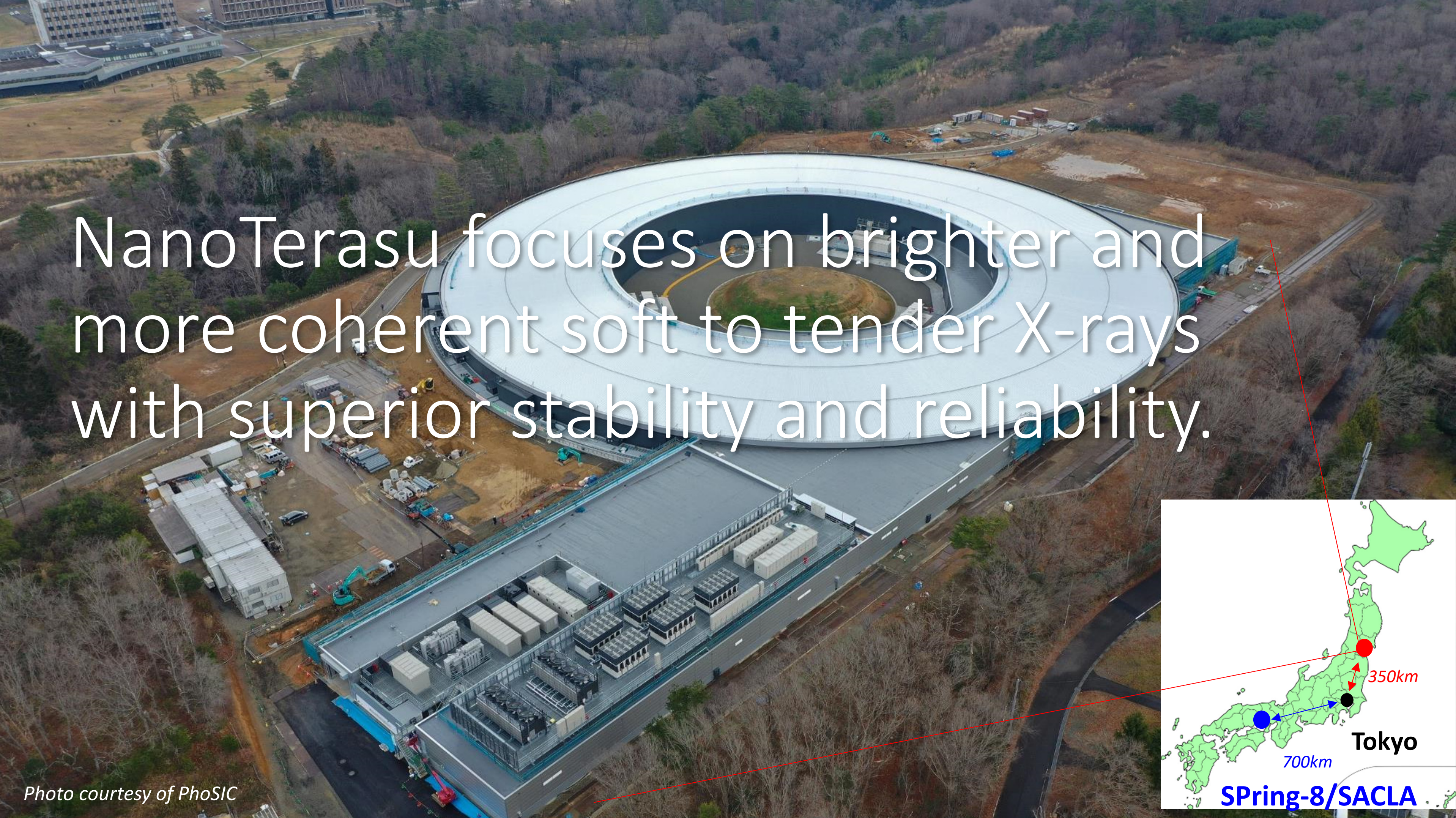

Photo courtesy of PhoSIC


Installation of the accelerator system
is in progress for the first light in 2023.
Photo courtesy of PhoSIC

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3GeV Linac

3GeV storage ring

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3GeV Linac

3GeV storage ring

Experimental hall

Outline

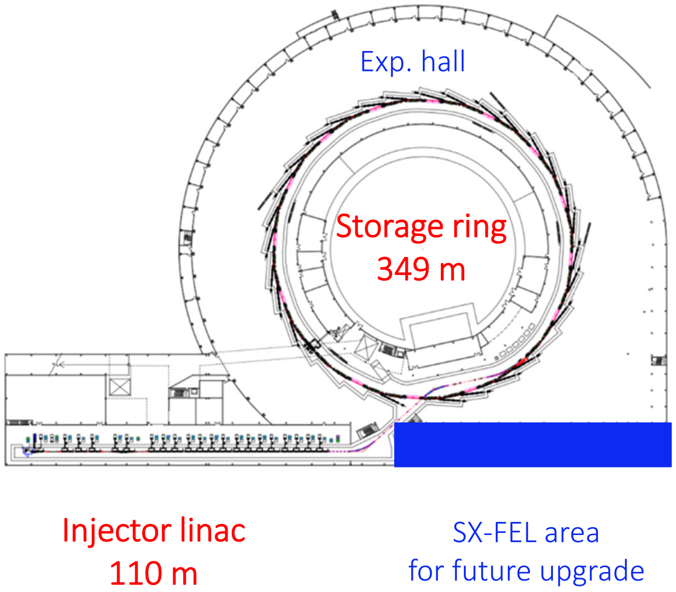
1. *Light source overview*
2. *Accelerator system*
   - *2-1. Storage ring*
     Lattice, Magnet, Vacuum, RF, Beam injection
   - *2-2. Injector Linac*
3. *Schedule & Status*
4. *Summary*

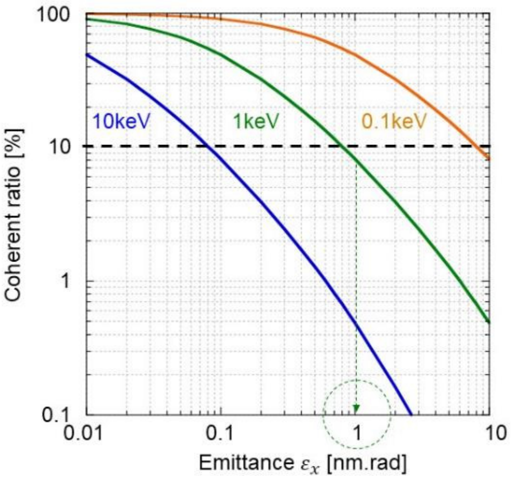
1. Light source overview

Accelerator system:

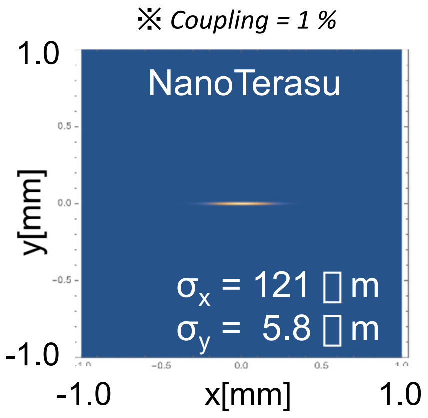
- *Storage ring target emittance set around 1 nm.rad providing a high coherence at SX wavelengths*
- *3-GeV C-band full-energy injector linac enabling a future extension to SX FEL (Free Electron Laser)*

Ring parameters	
Beam energy	*3 GeV*
Natural emittance	*1.14 nm.rad*
Stored current	*400 mA*
Max. number of undulators	*14*
Max. number of multi-pole wigglers (MPWs)	*14*



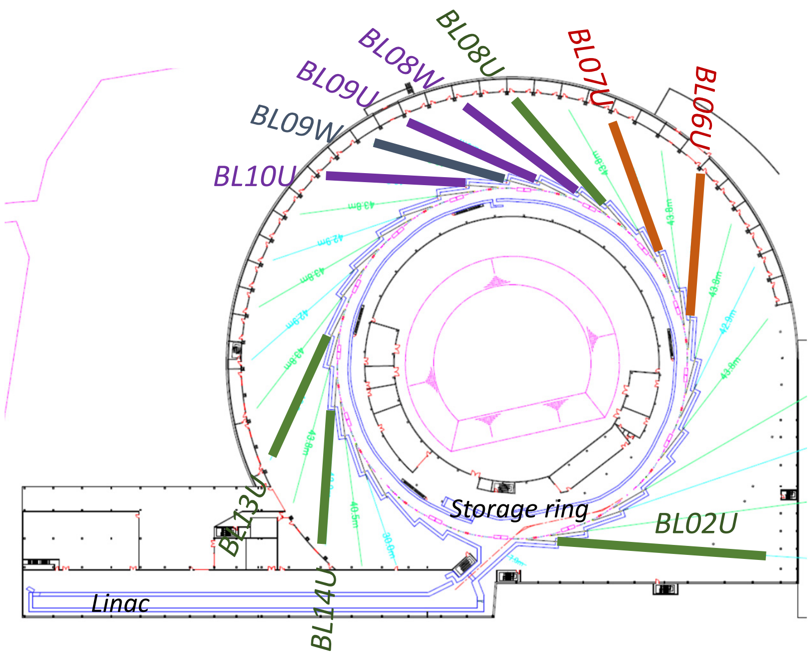


Beam size at undulator center

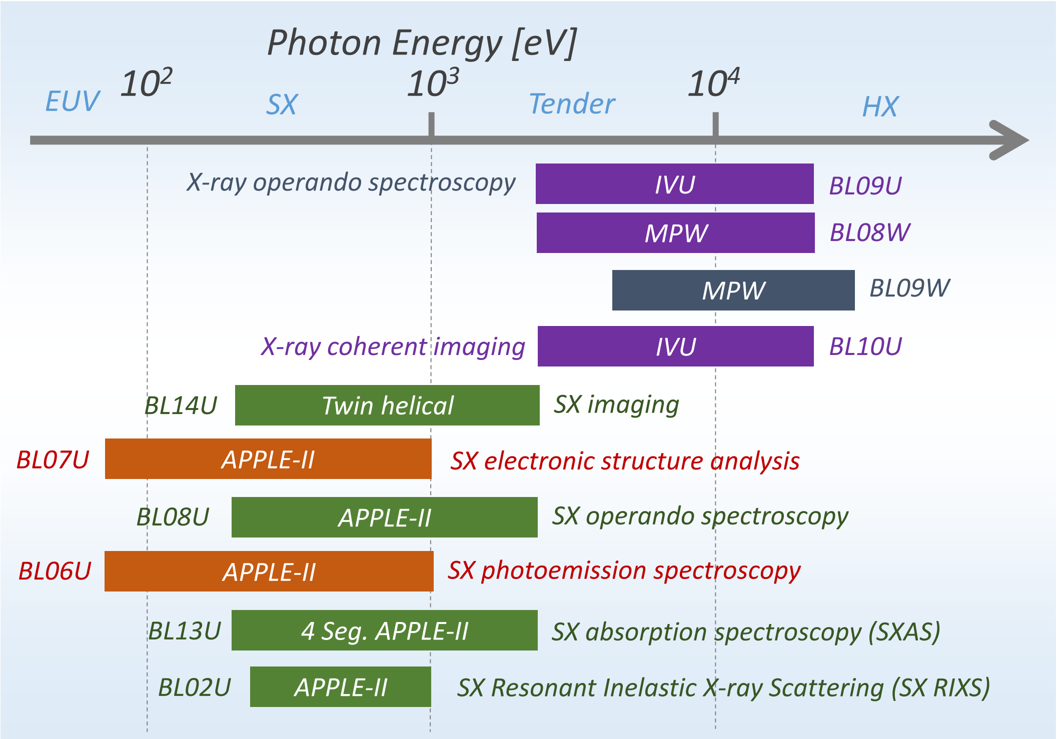


1. Light source overview

Undulators and MPWs in the first phase 10 beamlines

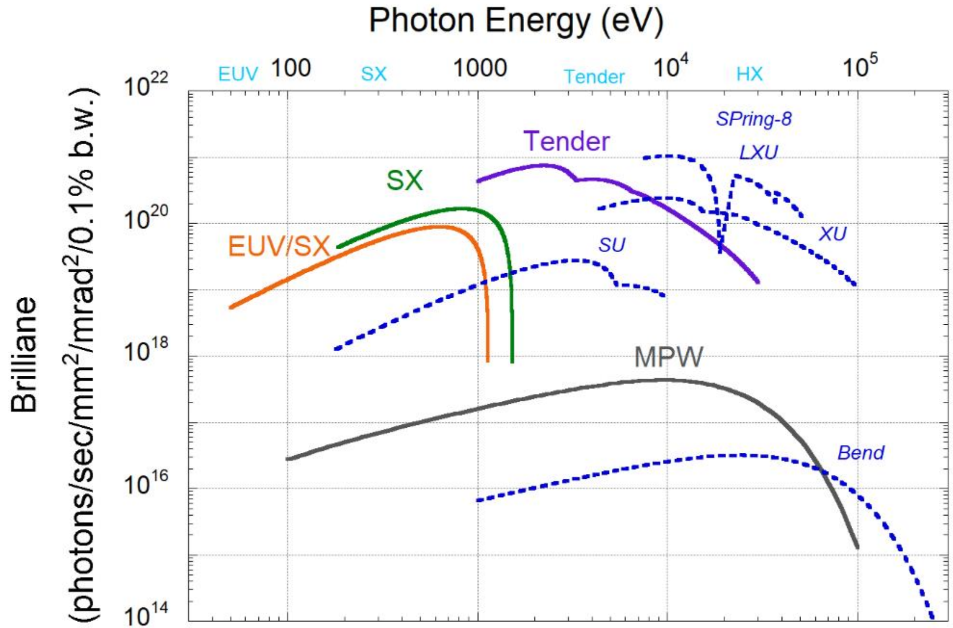


Typical beamline length is 60m from ID center

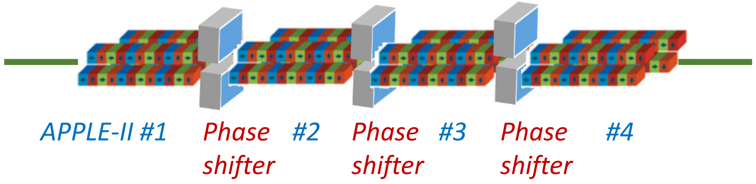


1. Light source overview

APPLE-II is the workhorse of the SX sources.

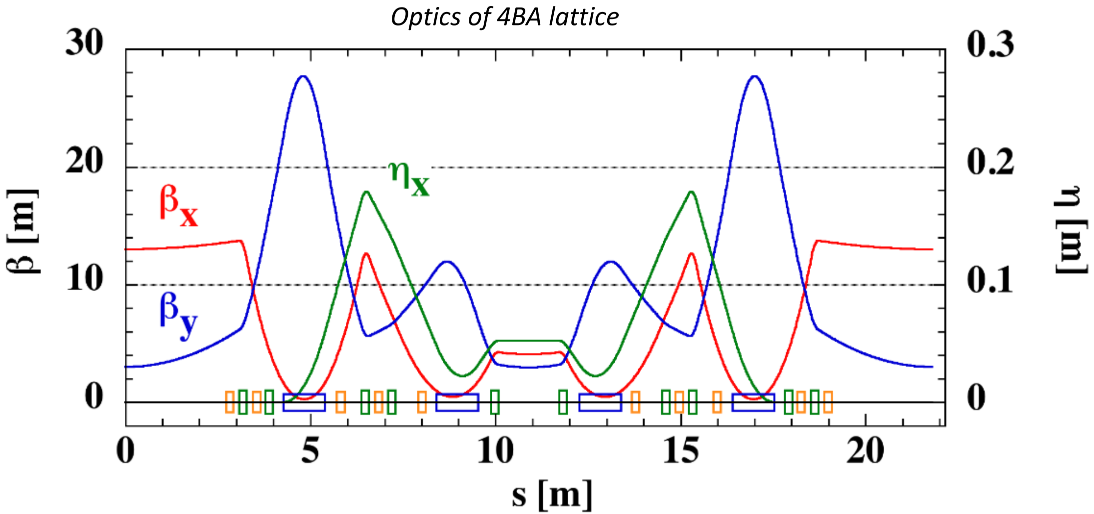


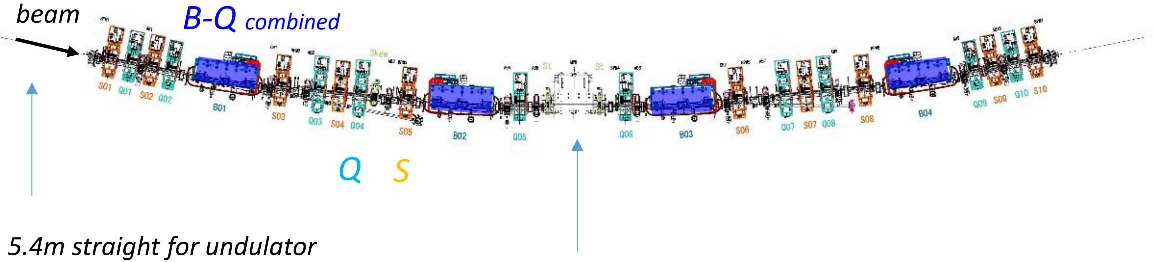
BL	ID	λ_w (mm)	N_w
02U *07U*	*APPLE-II*	*56*	*71*
06U *08U*	*APPLE-II*	*75*	*53*
13U	*4 Seg. APPLE-II*	*56*	*11 x 4*



- *Brilliance ~10^{21} photons/sec/mm^2/mrad^2/0.1% b.w. for 1-3 keV*
- *MPW Hard X-ray (HX) sources*

2-1. Storage ring (SR): 4BA lattice





Ring parameters	
Natural emittance	*1.14 nm.rad*
Energy spread	*0.084 %*
Betatron tune (□$_x$,□$_y$)	*(28.17, 9.23)*
Natural chromaticity (□$_x$,□$_y$)	*(-60.50, -40.99)*
Damping partition number (J_x,J_y,J_z)	*(1.389, 1.0, 1.611)*
RF accelerating frequency	*508.759 MHz*
Harmonic number	*592*
Natural bunch length	*2.92 mm (9.74 ps)*

Magnet	Max. fields	#/cell	#/ring
B-Q combined	*0.87 T* *-7.1 T/m*	*4*	*64*
Quadrupole	*49 T/m*	*10*	*160*
Sextupole	*1540 T/m^2*	*10*	*160*

H-focusing: 8 quads.
V-focusing: 4 B-Q combined bends + 2 quads.

2-1. SR: Electron beam dynamics

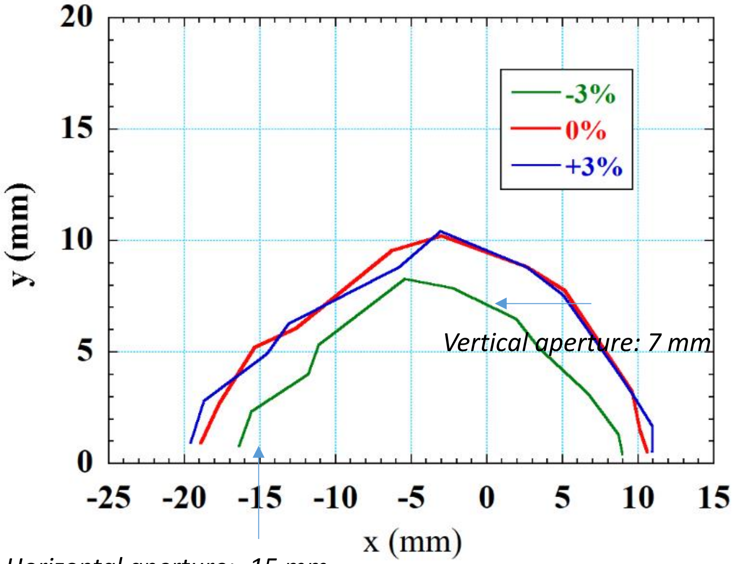
Optimization of sextupoles and dynamic aperture

- *Target chromaticity (+1, +1)*
- *Horizontal aperture: -15 mm for stable beam injection*
- *Vertical aperture: 7 mm larger than IVU min. gap*

Touschek lifetime and intrabeam scattering

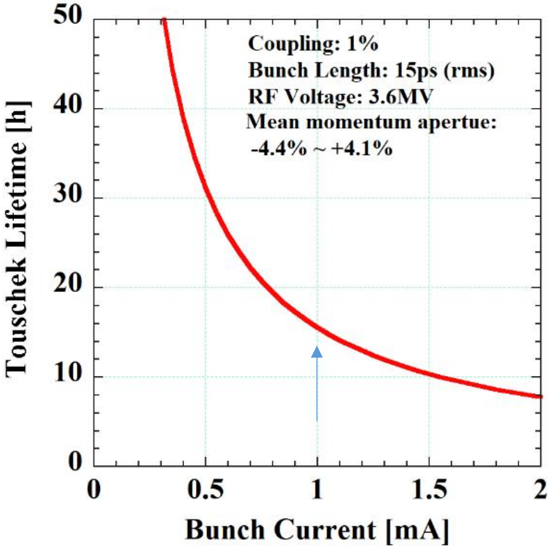
- *Touschek Lifetime of 15 hours*
- *Small emittance growth by intrabeam scattering*

Dynamic aperture

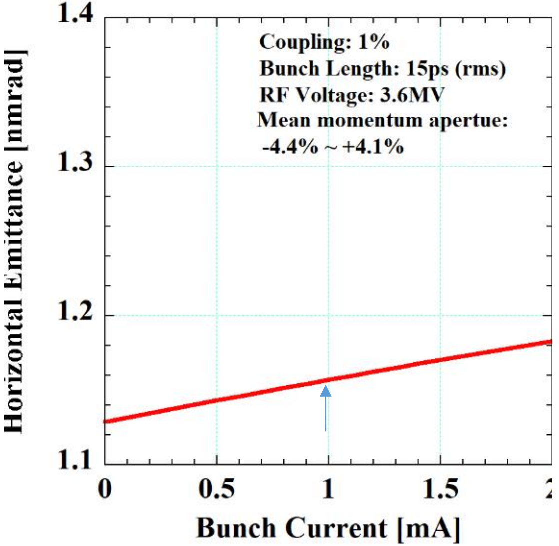


Horizontal aperture: -15 mm

Touschek lifetime



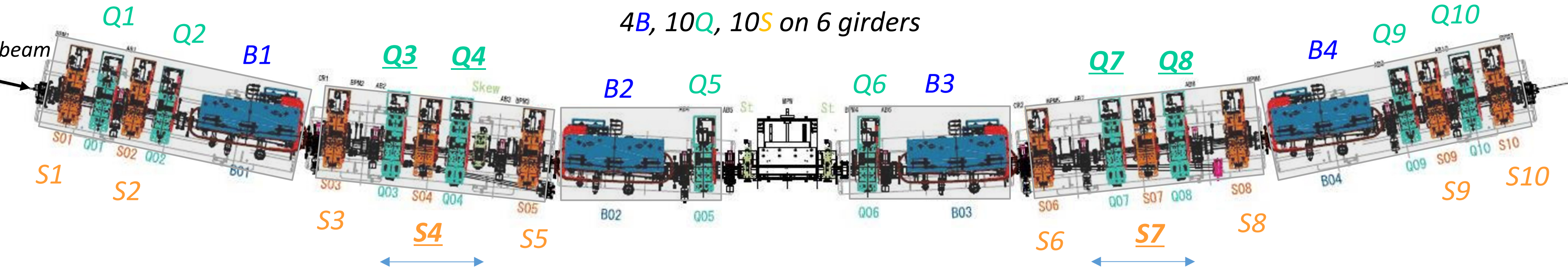
Emittance growth



2-1. SR: Magnet

Concept

Magnet system with small number of types and power supplies for low cost and easy maintenance



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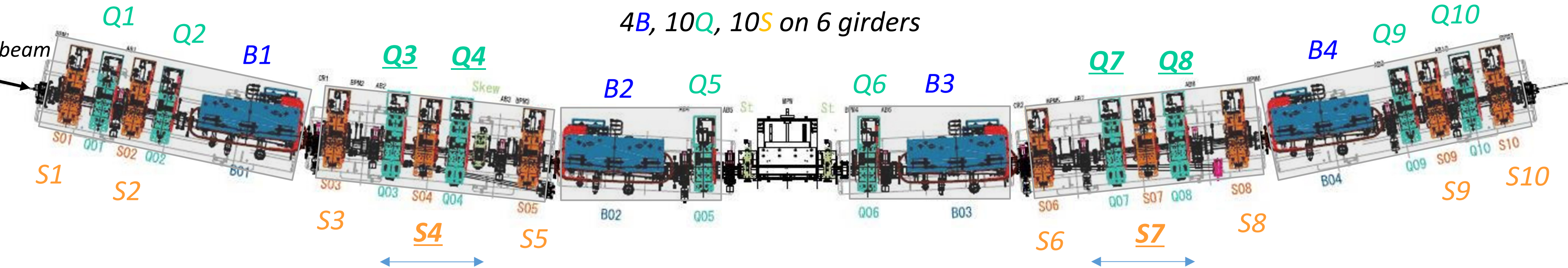
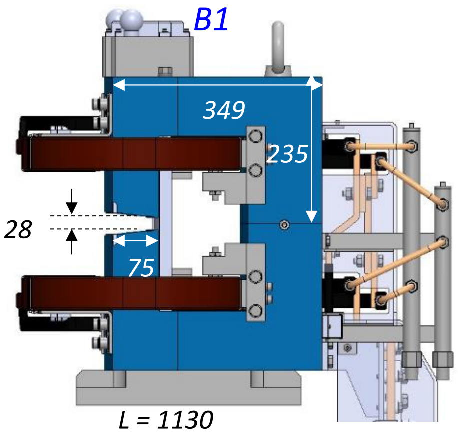


B-Q combined (massive steel)



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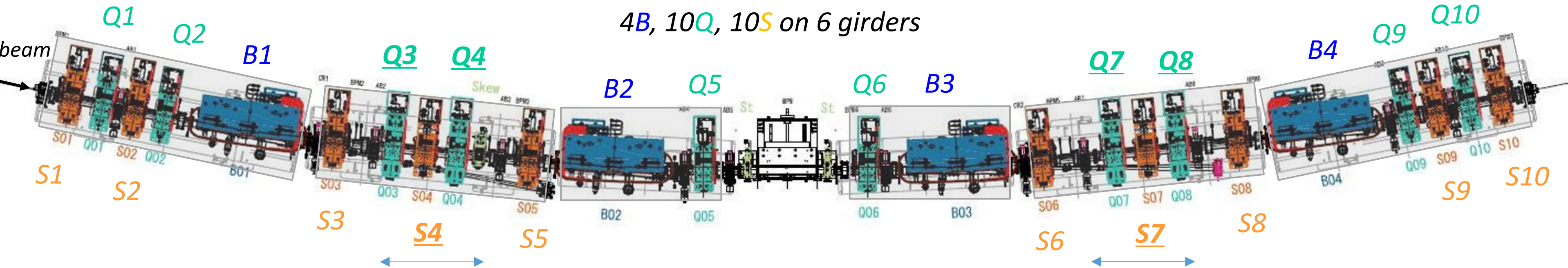
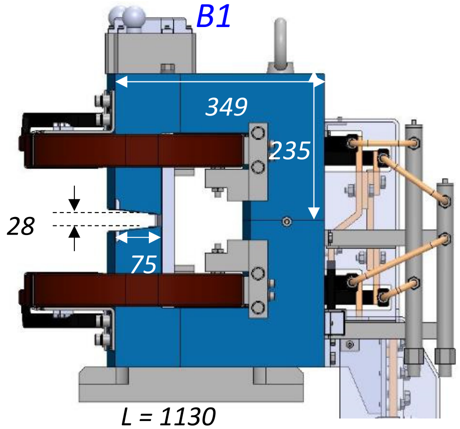
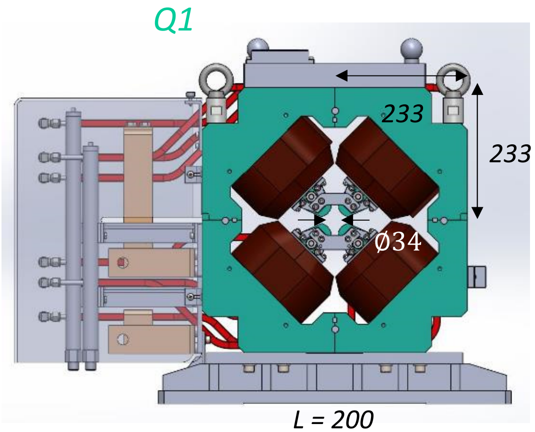
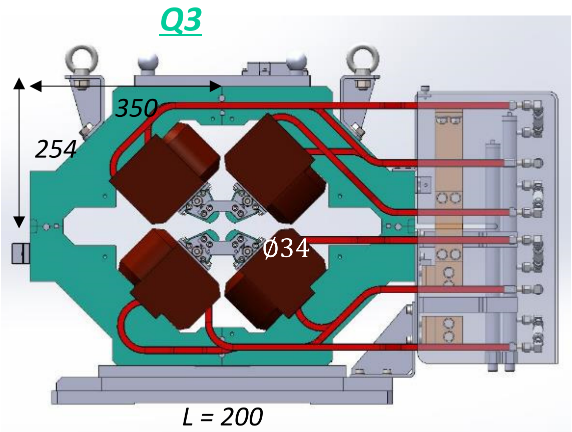


B-Q combined (massive steel)

Quadrupoles (laminated steel)







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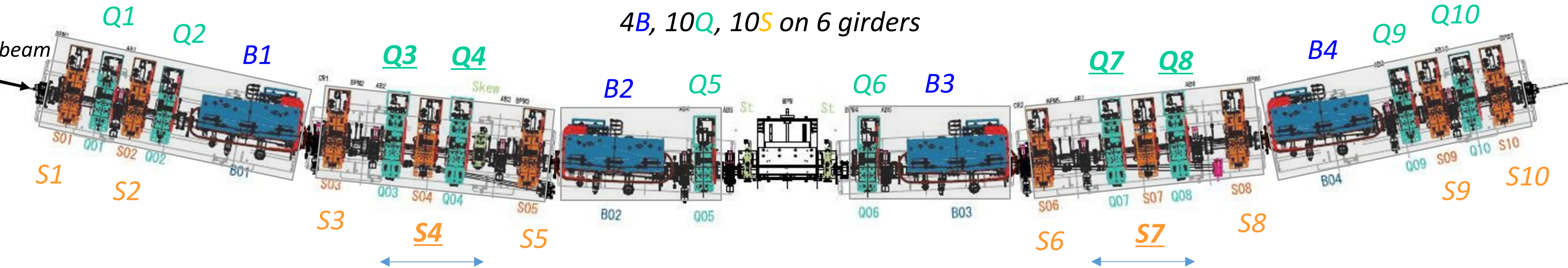
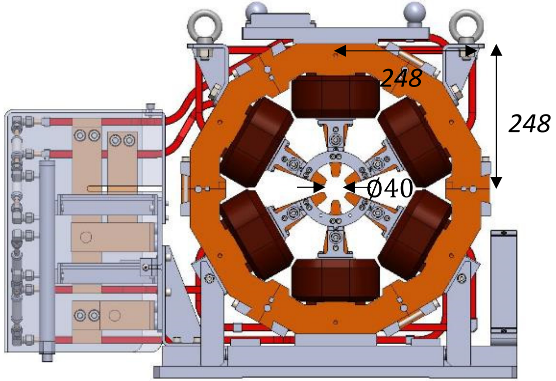
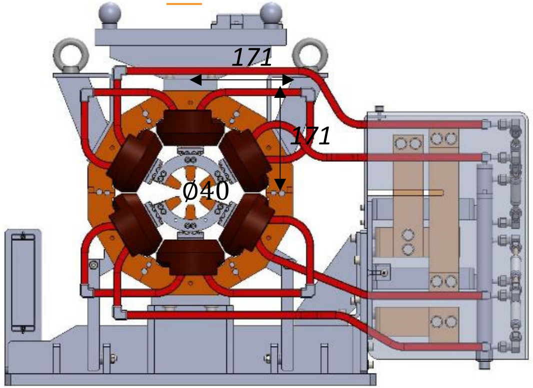


Sextupoles (laminated steel)





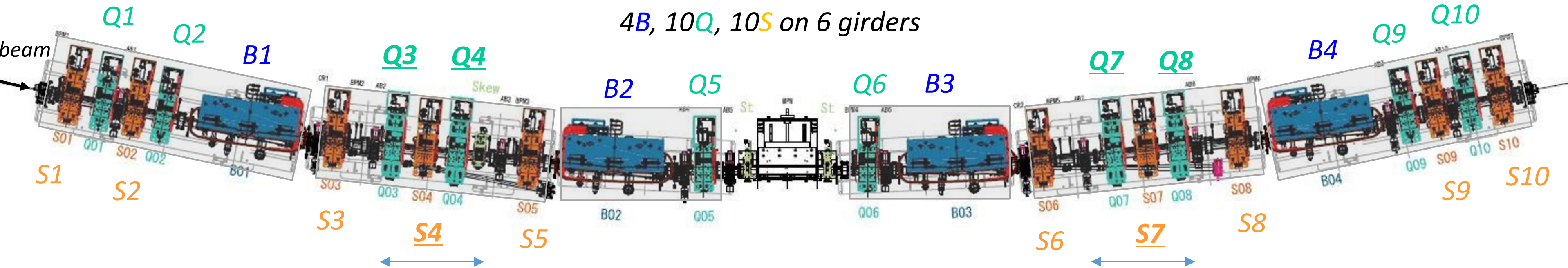
2-1. SR: Magnet

- *Aux. power supply to an individual Q for mag. field adjustment*
- *Aux. coils for SX as steering magnets and fine tuning of mag. field*

Concept

Magnet system with small number of types and power supplies for low cost and easy maintenance

4B, 10Q, 10S on 6 girders



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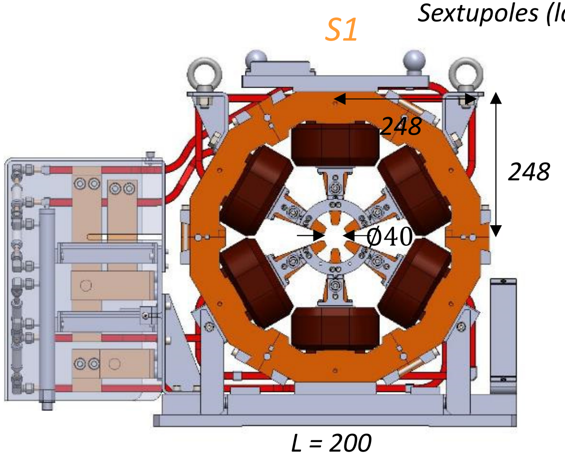
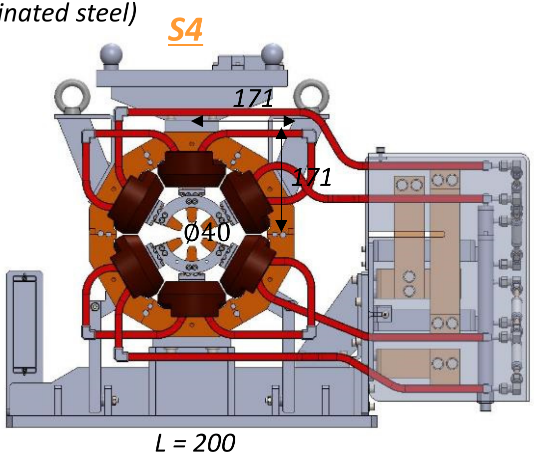




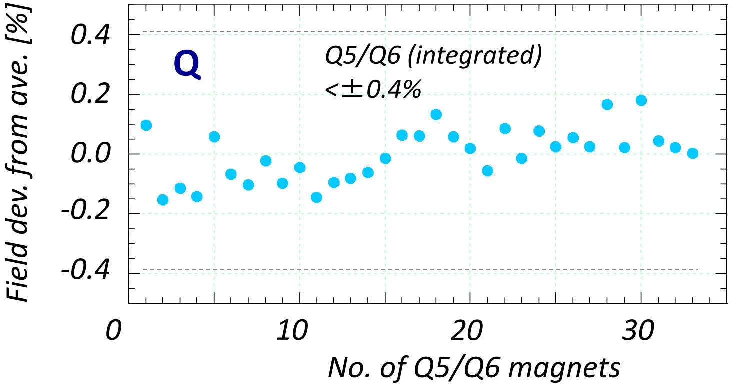
- *11 sets of family magnets: B, 5Q, 5S*
- *Common power supply for each family*
- *11 power supplies: B, 5Q (2 types), 5S*

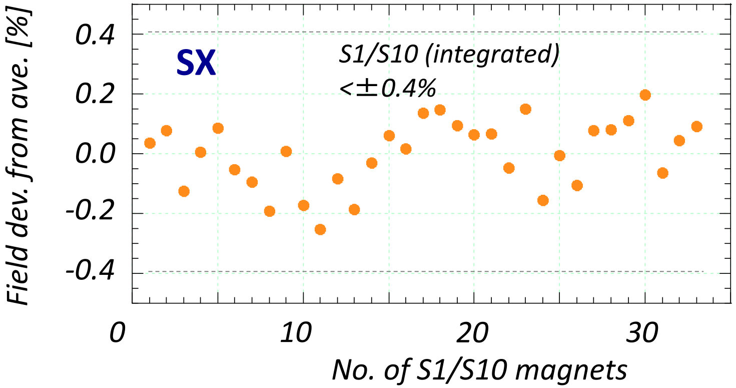
Requirement

Field deviation of magnets:
< ±0.2 % (B)
< ±0.4 % (Q, S)

2-1. SR: Mag. field deviation of mass products

Multipoles measured with SSW **(single stretched wire)**





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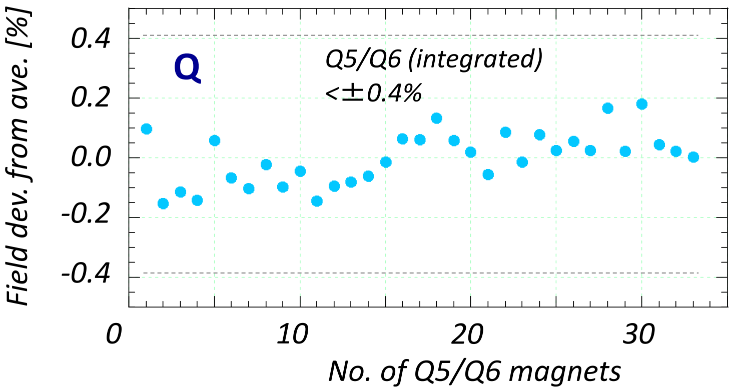
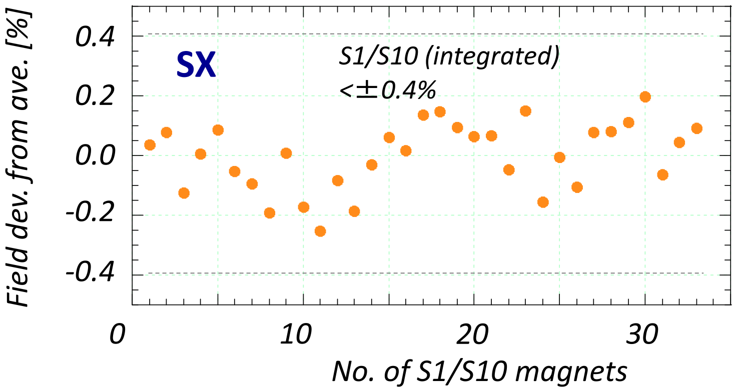
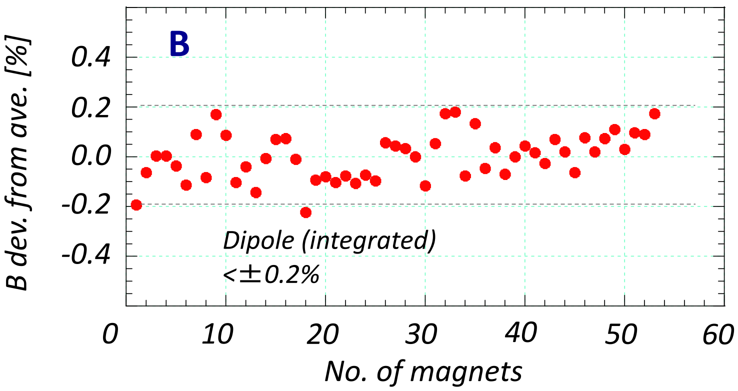
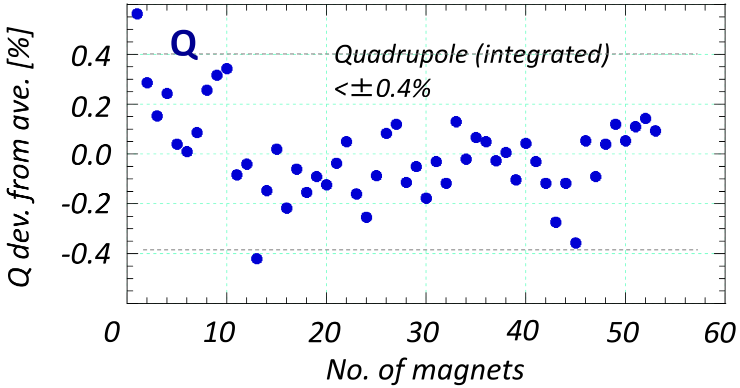




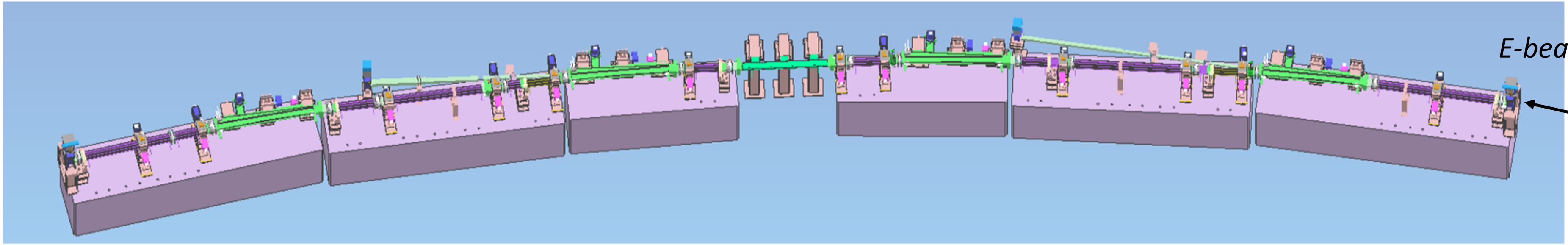
B-Q combined measured with 3D Hall-probe





2-1. SR: Vacuum

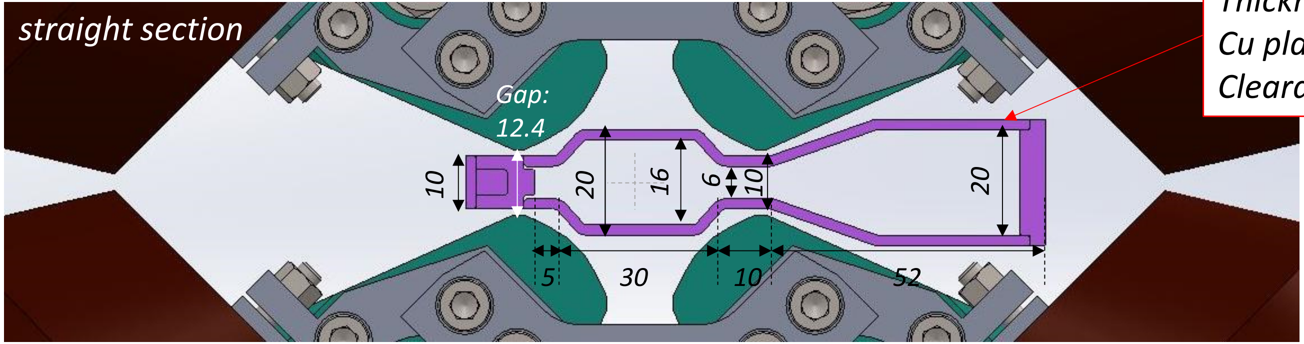
Goal: 20h of gas scattering lifetime for 400 mA current requiring 1×10^{-7} Pa CO equivalent



Features

- *Stainless steel (316) chamber with 2 mm thickness and Cu plating inside* to meet short gap and to reduce impedance

Cross section of vacuum chamber



Stainkess steel (316)
Thickness: 2mm
Cu plating: 0.1mm
Clearance: 1.2mm

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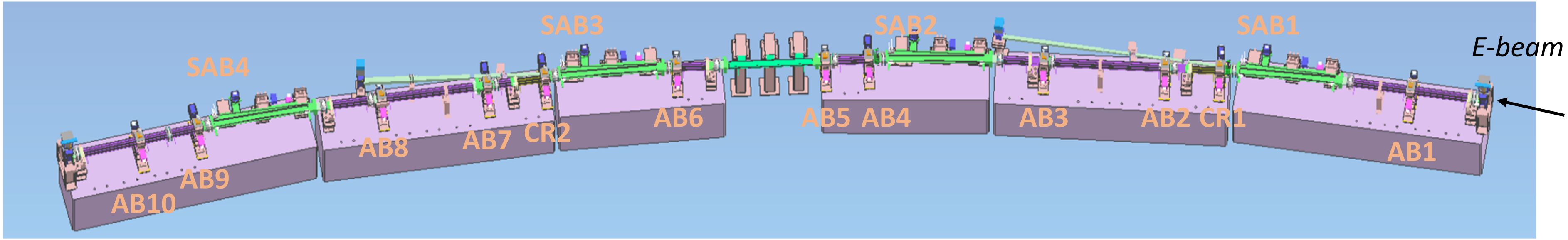
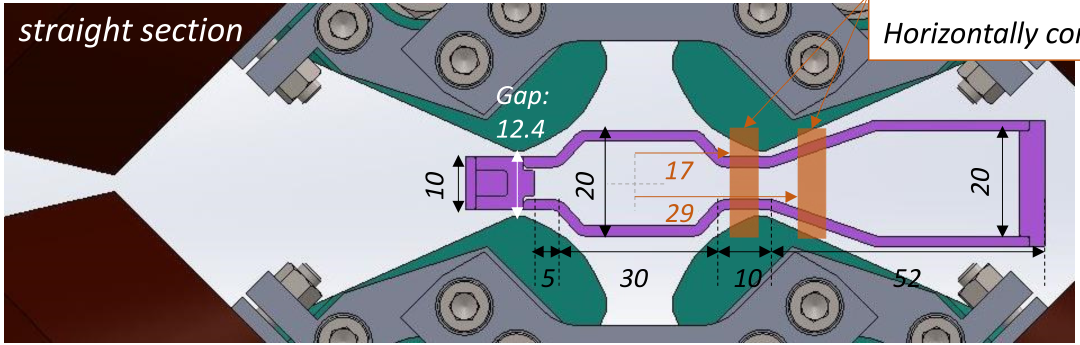


Features

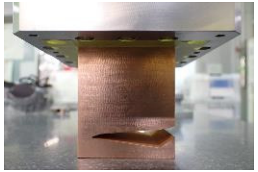
- *Stainless steel (316) chamber with 2 mm thickness and Cu plating inside* to meet short gap and to reduce impedance
- *Discretely arranged 10 photon absorbers (AB), 2 crotch ABs (CR), 4 supplemental ABs (SAB) and pumps*

Cross section of vacuum chamber



AB/CR placed at 17 or 29 mm from beam trajectory.

Horizontally compact vacuum chambers.



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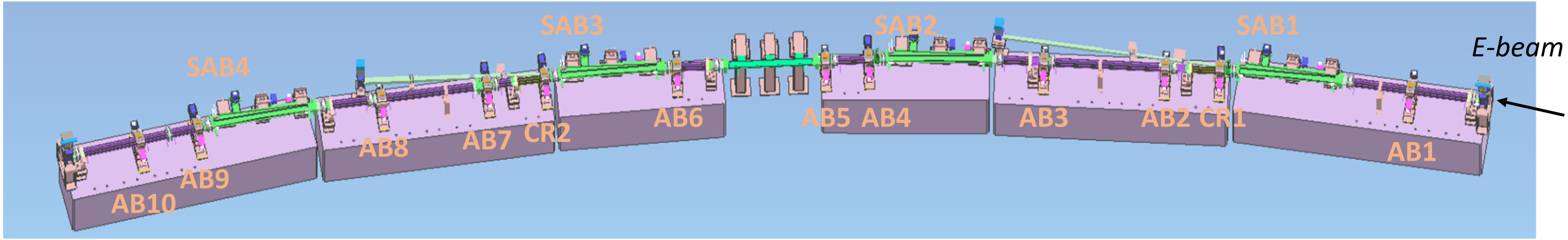

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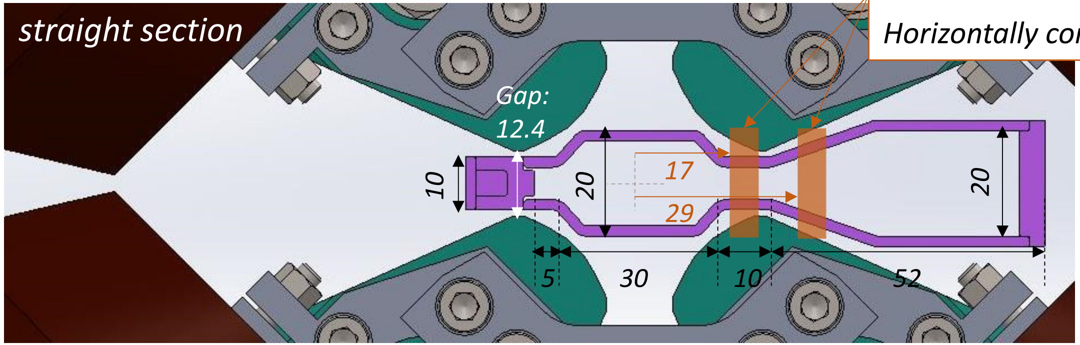

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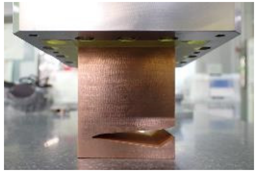

- *Only 4 types (1 AB, 2 CR, 1 SAB) for low cost and easy maintenance*
- *Max. SR peak power density of ~200 W/mm²*
- *Average pressure is 6 × 10^{-8} Pa (CO) at 400 mA after 1500 Ah dose → 22hrs. lifetime*

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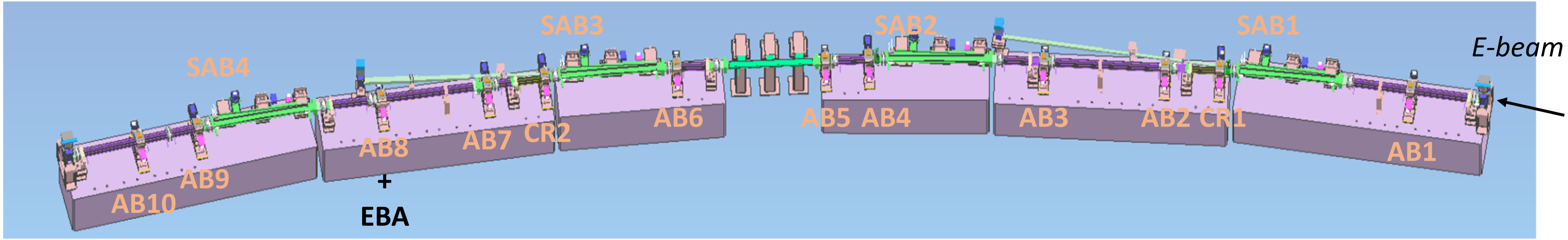

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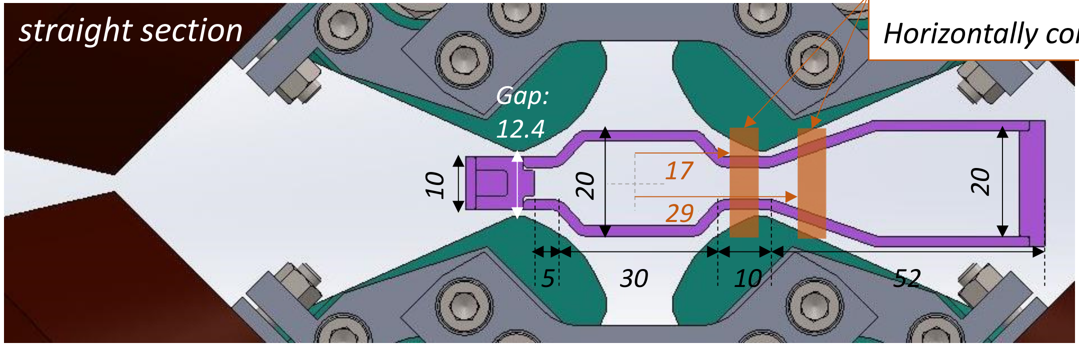
- *Stainless steel (316) chamber with 2 mm thickness and Cu plating inside* to meet short gap and to reduce impedance
- *Discretely arranged 10 photon absorbers (AB), 2 crotch ABs (CR), 4 supplemental ABs (SAB) and pumps*
- *Electron beam absorber* for the high intensity beam to be spread out during beam abort

Cross section of vacuum chamber



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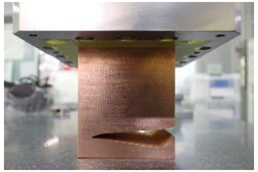

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2-1. SR: Electron beam absorber

T. Hiraiwa et al., PRAB 24, 114001 (2021)
T. Hiraiwa et al., PRE 102, 032211 (2020)

- *Stored electron beam needs to be dumped in a controlled way during beam abort.*
- *Electron beam absorber installed every cell.*

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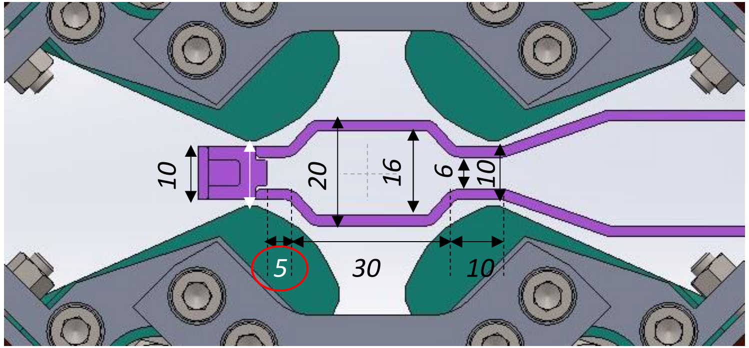

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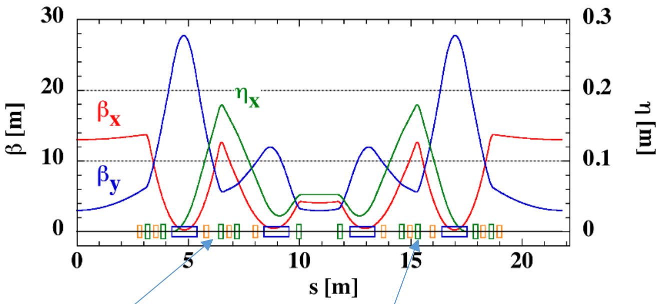
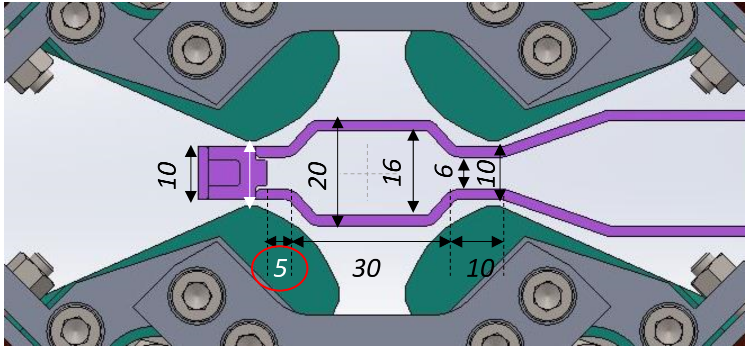
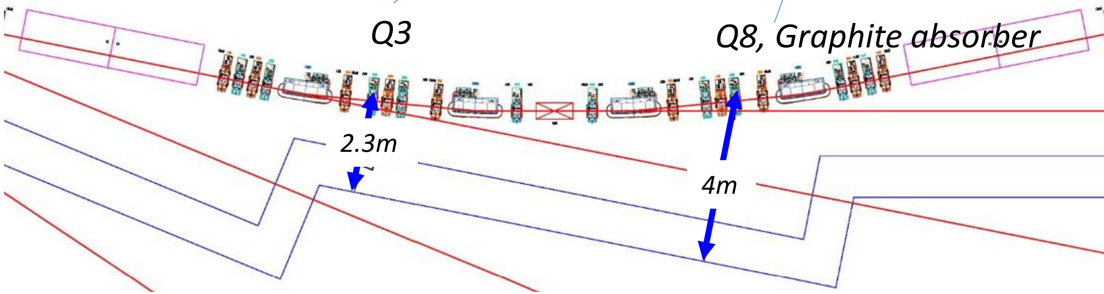




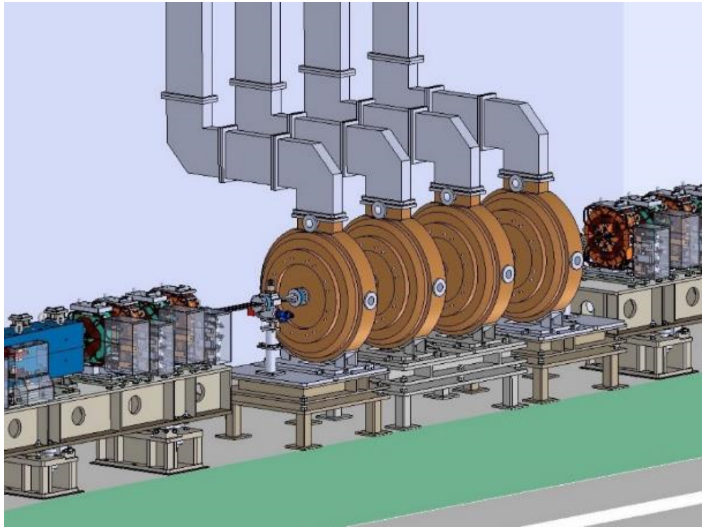


2-1. SR: RF

Concept

- *R&D of a new TM020 RF cavity with built in higher order mode (HOM) absorbers compact along trajectory*
- *Installation of 4 cavities in a straight for 3.6MV acceleration required for 15 hrs Touschek lifetime for 400 mA*
- *500 kW RF power to store 400 mA due to maximum radiation loss 1.26 MeV/turn (0.62 MeV for bend)*

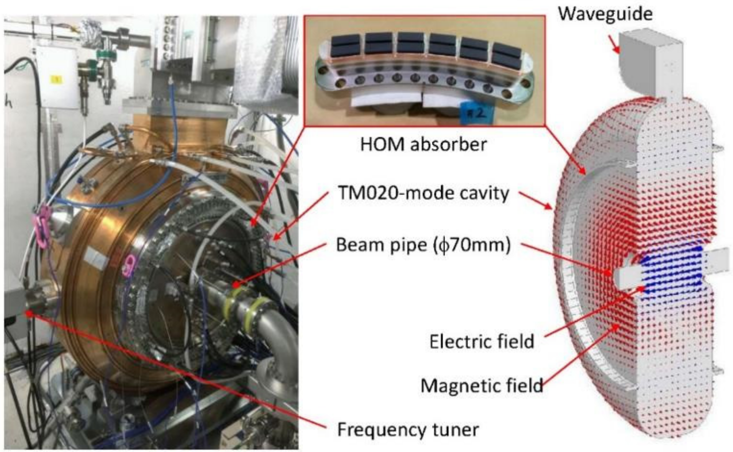
Parameter	Specification
Beam revolution frequency	*859.4 kHz*
RF frequency	*508.759 MHz*
Energy loss	*1.26 MeV/turn (0.62 MeV for bend, 0.64 MeV for ID)*
RF cavity voltage	*3.6 MV (0.9 MV per cavity)*
Synchronous phase	*160 - 170°*
Synchrotron frequency	*6.0 kHz*
Heat dissipation at cavity	*120 kW per cavity*
Input RF power	*245 kW per cavity max.*

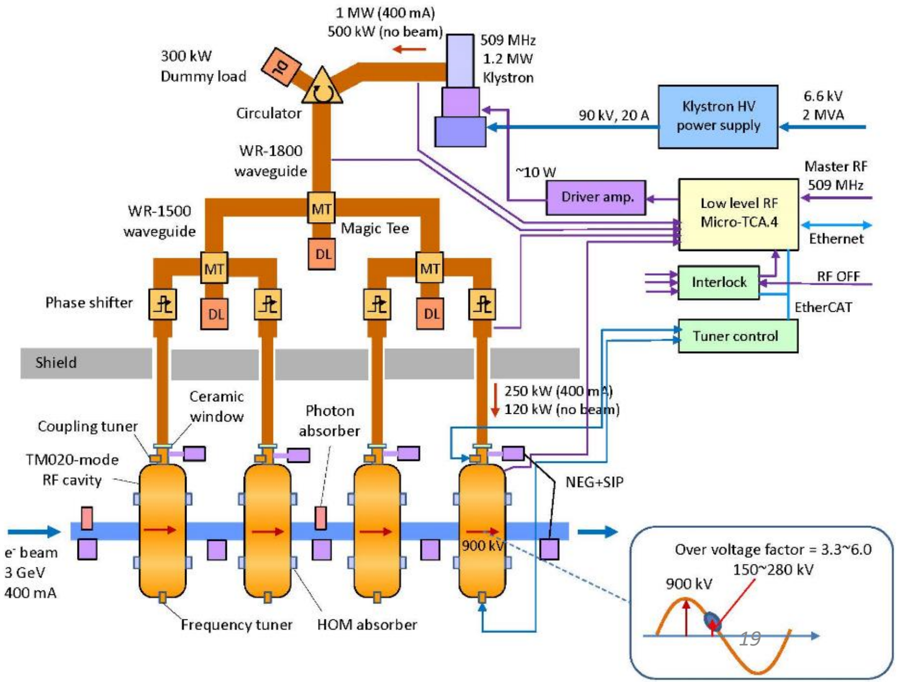


2-1. SR: TM020-mode cavity

Features

- *Along nodes of the TM020-mode magnetic field inside the cavity, slots and ferrite dampers are installed.*
- *HOM entering the slots are dissipated on the ferrite dampers*
- *Shunt impedance of 6.8 M , 120 kW for 0.9 MV acceleration per cavity, unloaded Q of 60,300*

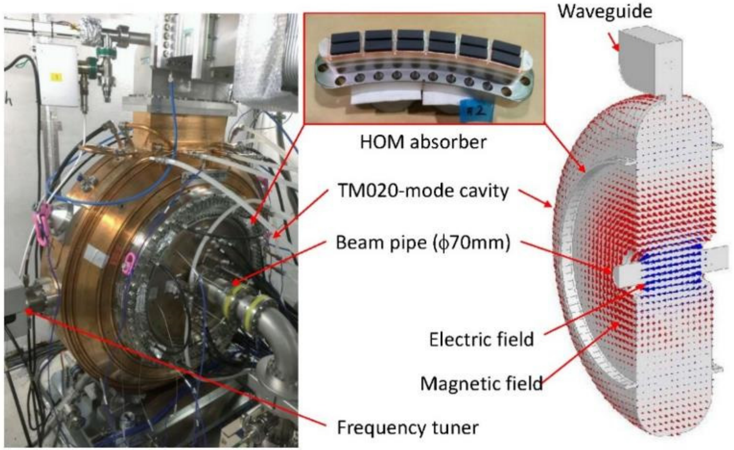


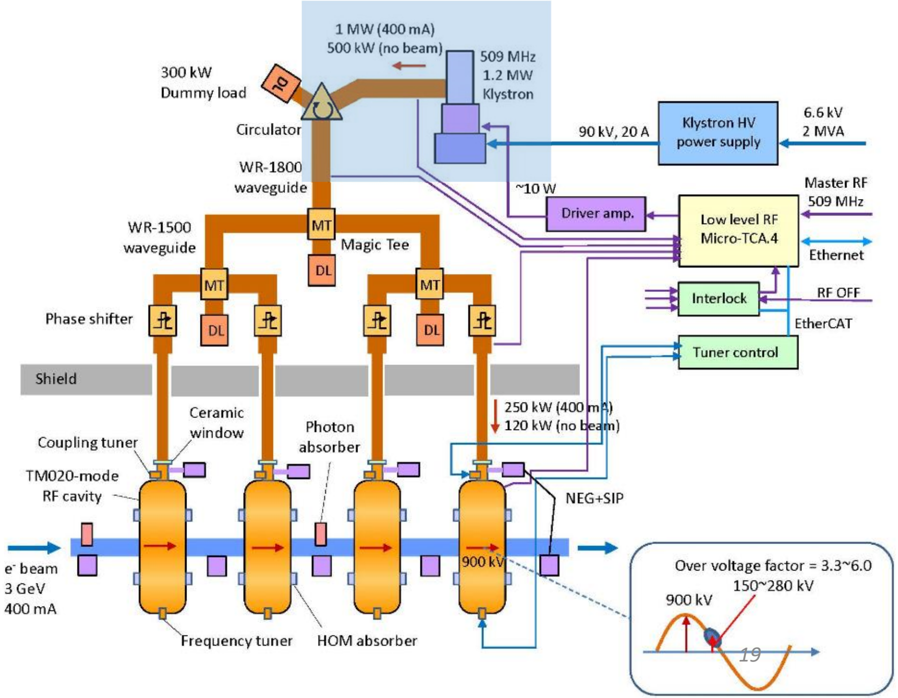


2-1. SR: TM020-mode cavity

Features

- *Along nodes of the TM020-mode magnetic field inside the cavity, slots and ferrite dampers are installed.*
- *HOM entering the slots are dissipated on the ferrite dampers*
- *Shunt impedance of 6.8 MΩ , 120 kW for 0.9 MV acceleration per cavity, unloaded Q of 60,300*





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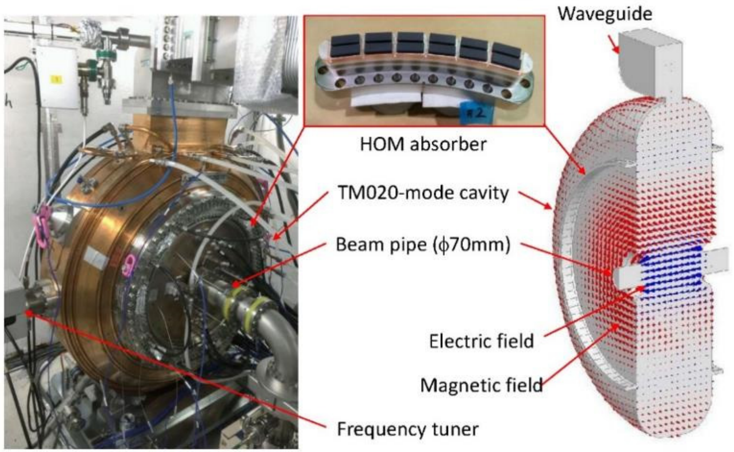
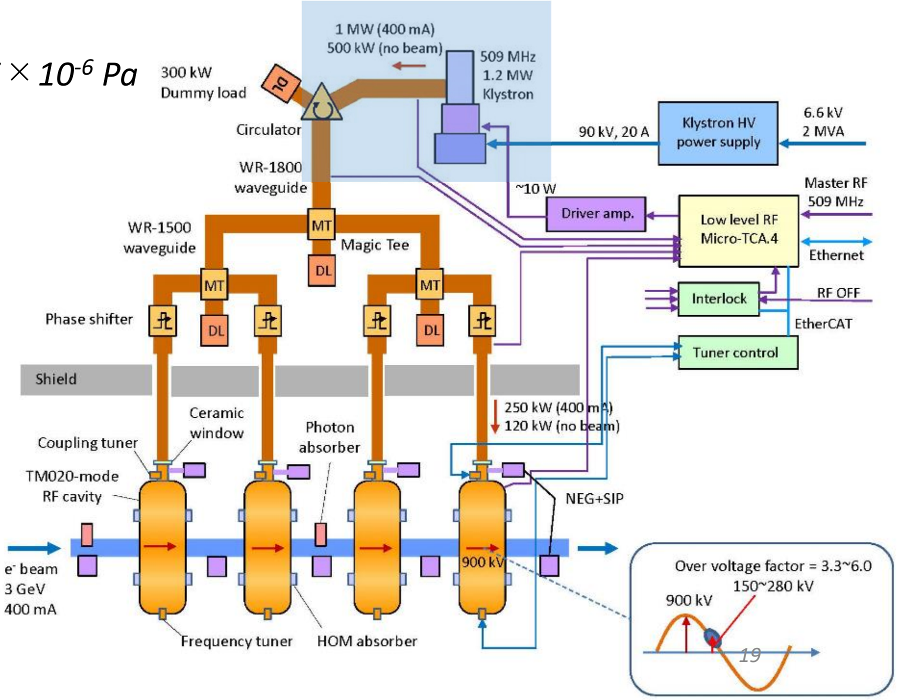
Features

- *Along nodes of the TM020-mode magnetic field inside the cavity, slots and ferrite dampers are installed.*
- *HOM entering the slots are dissipated on the ferrite dampers*
- *Shunt impedance of 6.8 MΩ, 120 kW for 0.9 MV acceleration per cavity, unloaded Q of 60,300*

Status

- *Reached 120 kW with 12 HOM absorbers with vacuum of 1.5 × 10^{-6} Pa*



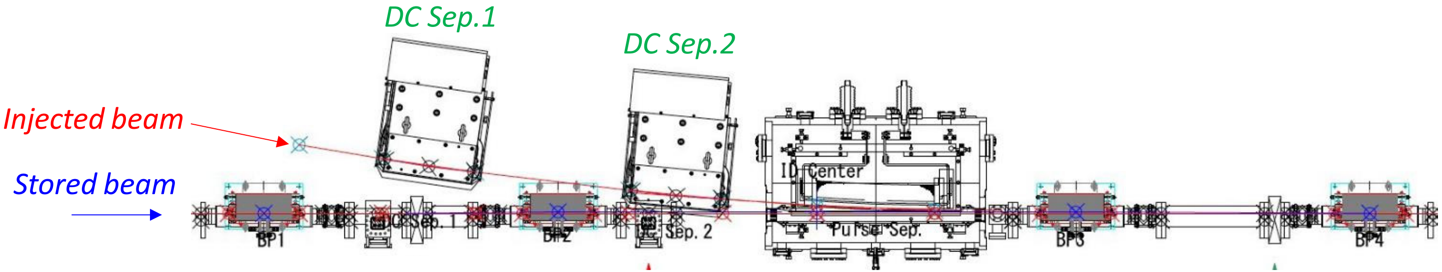


2-1. SR: Ring beam injection

S. Takano et al., Proc. of IPAC2019, p2318, WEPMP009, (2019)

Concept

- *In-vacuum windowless off-axis injection system from the ring inside for stable and transparent injection*



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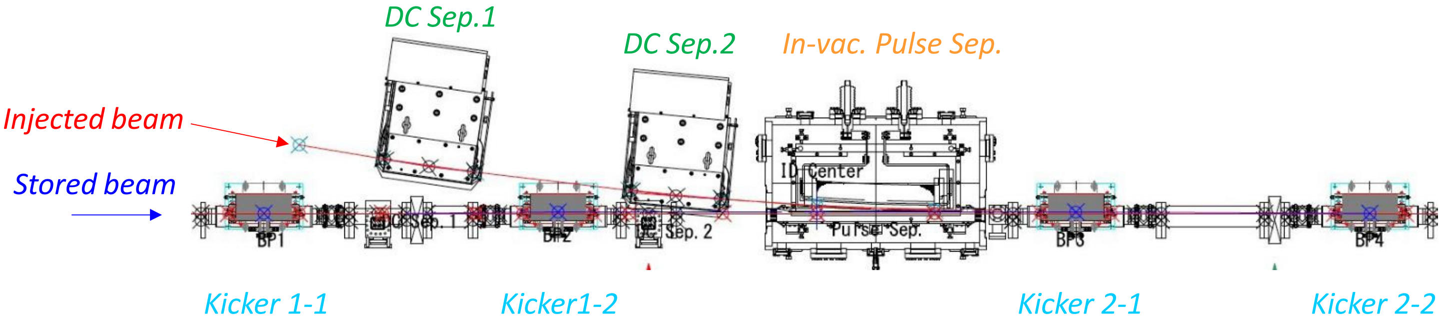
- *R&D of an in-vacuum pulse septum and a pair of twin-kickers having identical magnet characteristics*



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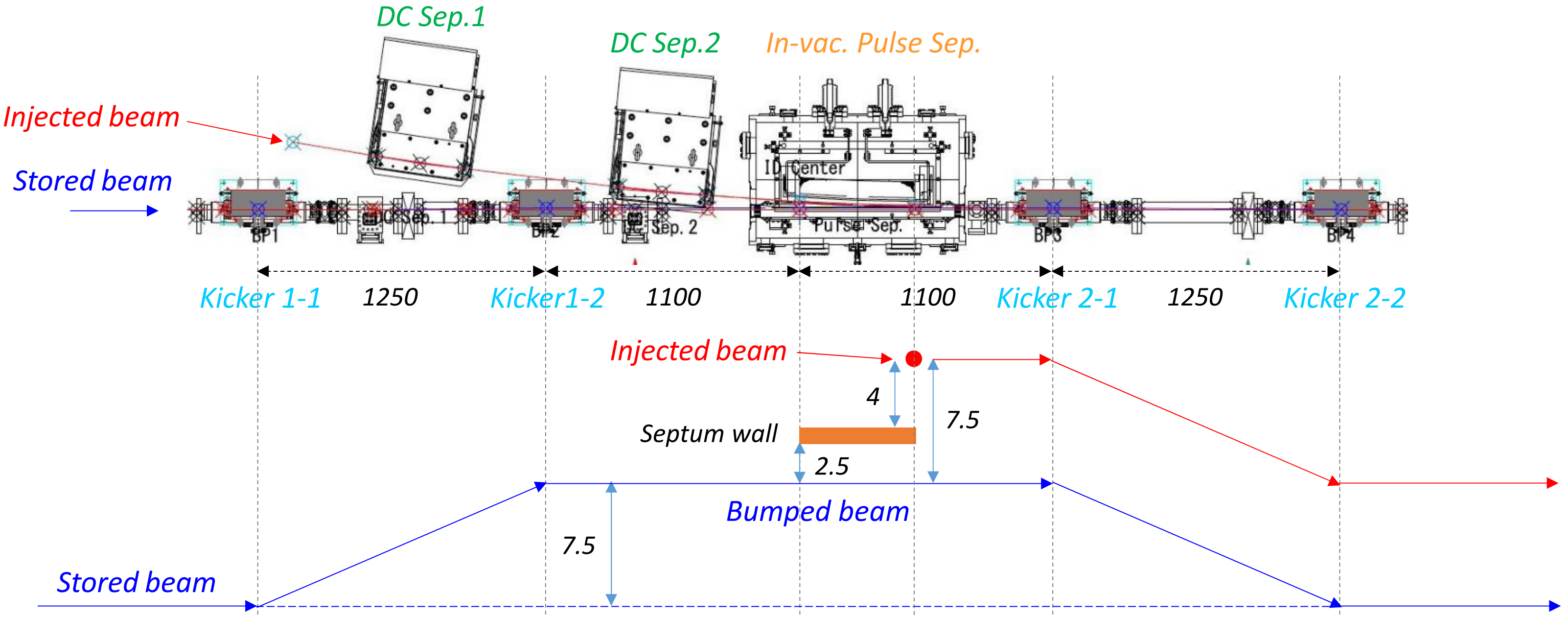
S. Takano et al., Proc. of IPAC2019, p2318, WEPMP009, (2019)

Concept

- *In-vacuum windowless off-axis injection system from the ring inside for stable and transparent injection*

- *R&D of an in-vacuum pulse septum and a pair of twin-kickers having identical magnet characteristics*
- *Injected beam amplitude of 7.5 mm thanks to thin septum wall*
- *Stored beam oscillation amplitude < 10□m by identical kickers*



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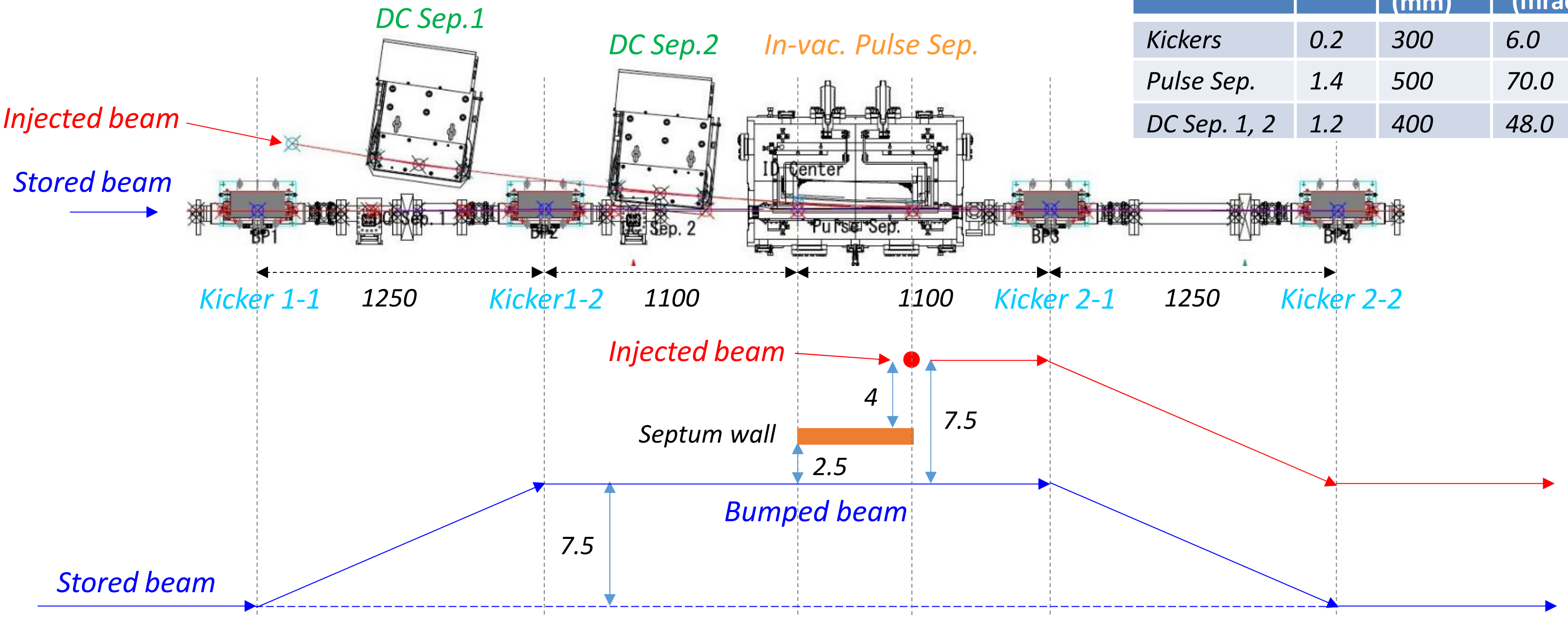
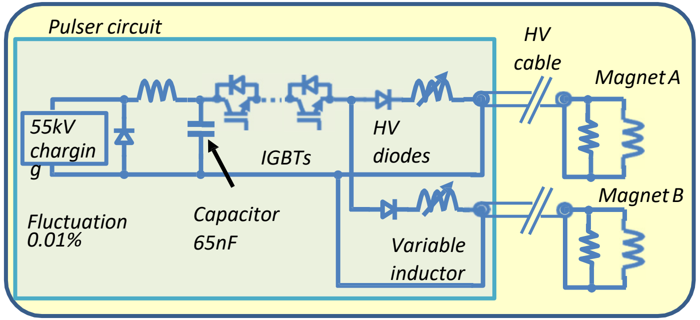
- *Injected beam amplitude of 7.5 mm thanks to thin septum wall*
- *Stored beam oscillation amplitude < 10□ m by identical kickers*

Magnet	B(T)	Length (mm)	kick angle (mrad)	Pulse width (us)
Kickers	0.2	300	6.0	3
Pulse Sep.	1.4	500	70.0	10
DC Sep. 1, 2	1.2	400	48.0	-



2-1. SR: Twin kickers driven by a single pulser

- *Twin kickers driven by a single pulser for identical kicker magnetic pulses*
- *Solid state pulser with precise charging circuit and fast IGBT switching*



Kicker magnet parameters

K. Fukami et al., Rev. Sci. Instrum. 93, 023301 (2022)
T. Inagaki et al., Proc. of IPAC2018, p1804, (2018)

Parameter	value
Pole gap	28mm
Pole length	236mm
Integrated flux density	0.066Tm
Coil turn number	2Turn/Pole
Peak current	1600A
Pulse waveform	Half sine
Pulse width	3μsec
Peak voltage	22.2kV

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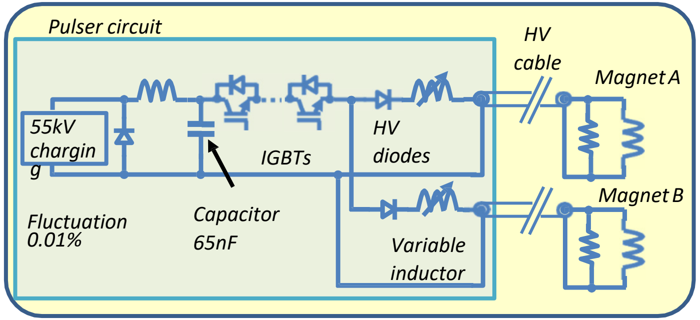

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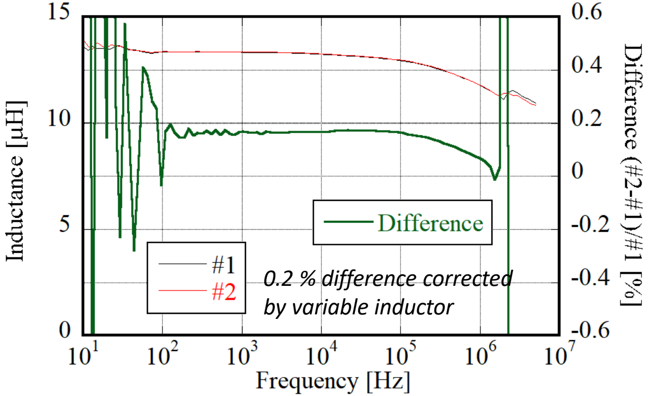
Inductances of twin kickers



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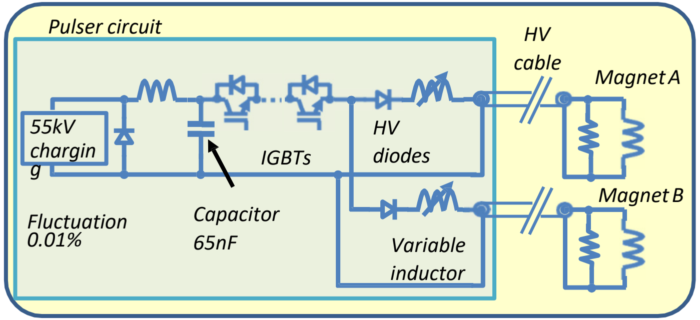
- *Twin magnetic fields identical within 0.1 % accuracy satisfy specification.*



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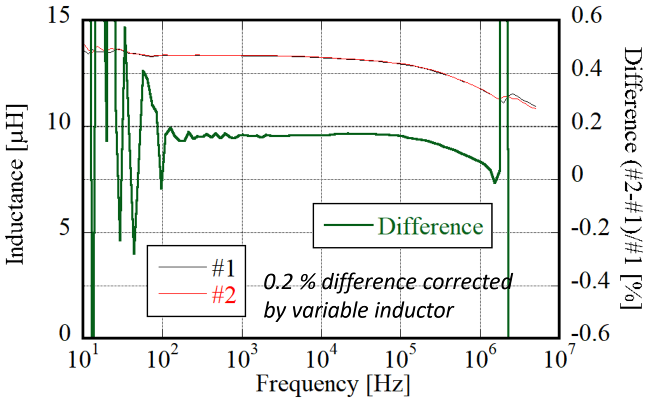
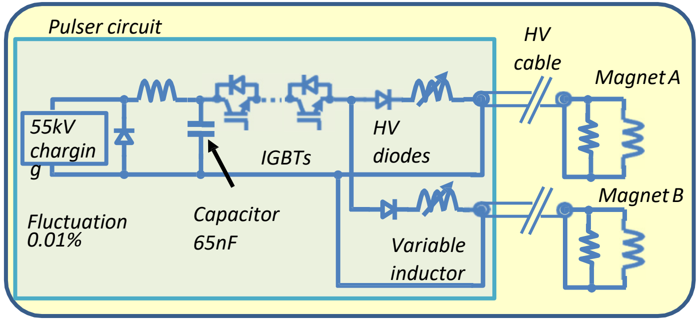


Magnetic fields of twin kickers

2-1. SR: Twin kickers driven by a single pulser

- *Twin kickers driven by a single pulser for identical kicker magnetic pulses*
- *Solid state pulser with precise charging circuit and fast IGBT switching*
- *Kickers with identical magnetic properties, e.g., inductance*
- *Twin magnetic fields identical within 0.1 % accuracy satisfy specification.*
- *Ceramic vacuum chambers with uniform Ti (3 m) coating*



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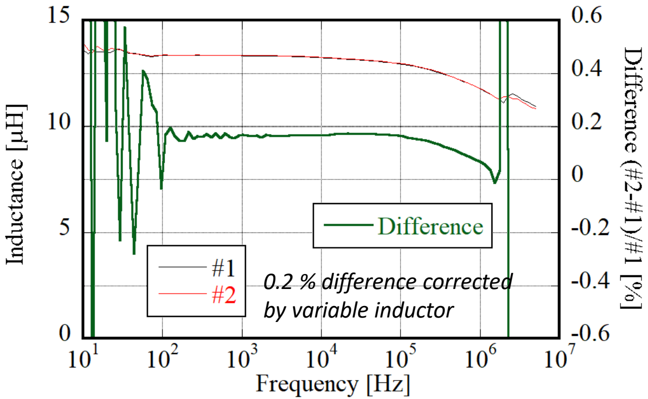


Magnetic fields of twin kickers

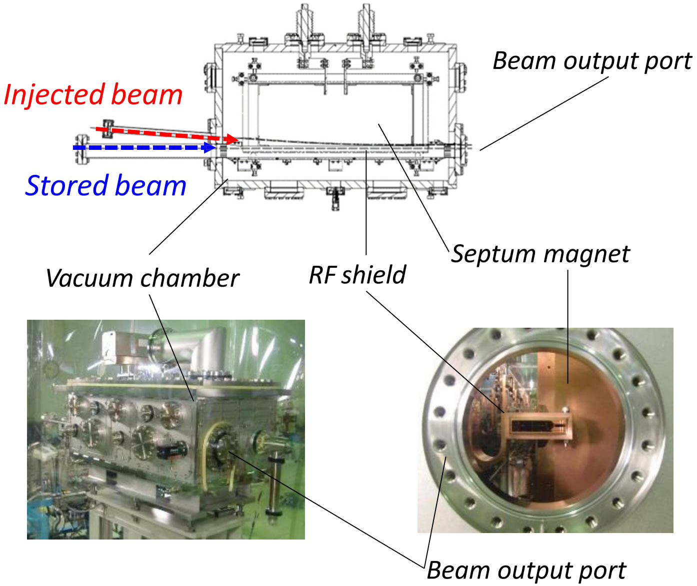
S. Takano et al., Proc. of IPAC2019, p2318, WEPMP009, (2019)

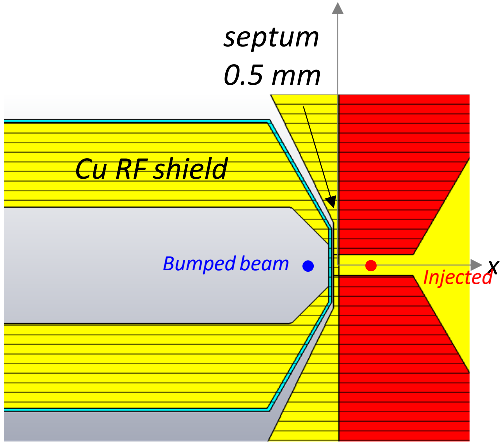
2-1. SR: In-vacuum pulse septum

- *Thin septum wall of 0.5 mm thickness for small injected beam oscillation amplitude*

In-vacuum pulse septum parameters

Parameters	Spec.
B [T]	*1.4*
Magnet length [m]	*0.5*
Magnet gap [mm]	*2*
Peak current [kA]	*2.3*
Coil turn number	*1*
Pulse width [μsec]	*10 (Half-sine)*
Septum thickness [mm]	*0.5*
Magnetic shield thickness [mm]	*<0.5*
Stray field integral [T.m]	*$<10^{-5}$*
Pressure [Pa]	*$<10^{-7}$*





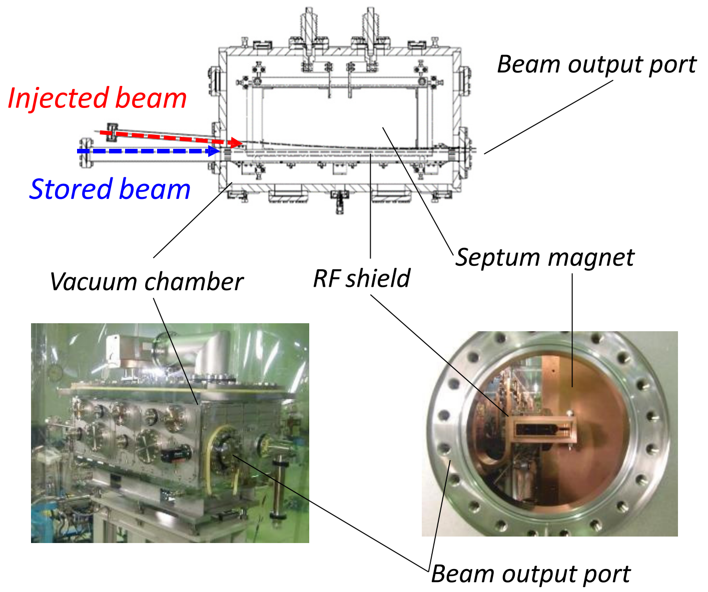
S. Takano et al., Proc. of IPAC2019, p2318, WEPMP009, (2019)

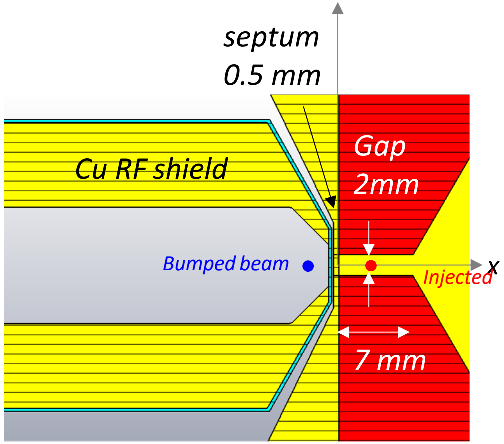
2-1. SR: In-vacuum pulse septum

- *Thin septum wall of 0.5 mm thickness for small injected beam oscillation amplitude*
- *Narrow magnet gap of 2 mm for 1.4 T mag. field uniformly along horizontal axis*

In-vacuum pulse septum parameters

Parameters	Spec.
B [T]	1.4
Magnet length [m]	0.5
Magnet gap [mm]	2
Peak current [kA]	2.3
Coil turn number	1
Pulse width [μsec]	10 (Half-sine)
Septum thickness [mm]	0.5
Magnetic shield thickness [mm]	<0.5
Stray field integral [T.m]	$<10^{-5}$
Pressure [Pa]	$<10^{-7}$





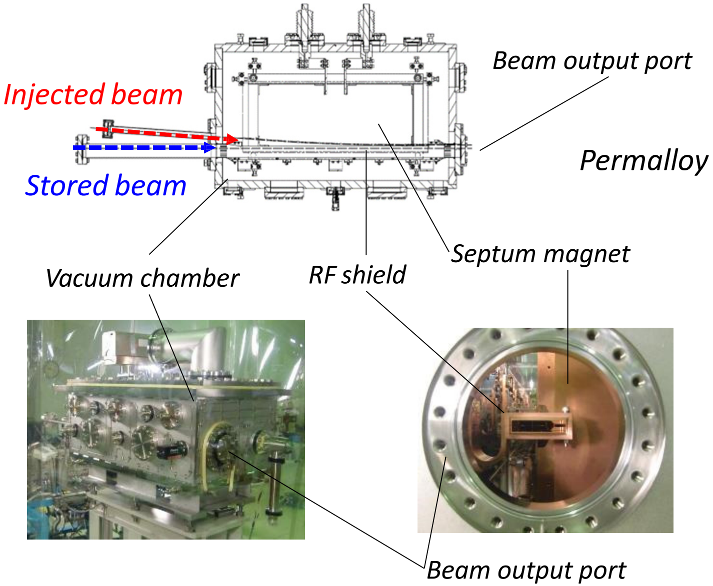
S. Takano et al., Proc. of IPAC2019, p2318, WEPMP009, (2019)

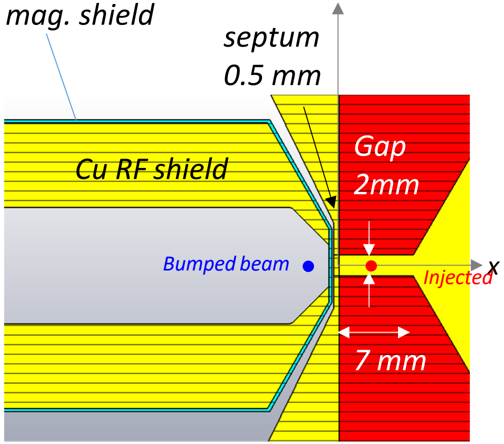
2-1. SR: In-vacuum pulse septum

- *Thin septum wall of 0.5 mm thickness* *for small injected beam oscillation amplitude*
- *Narrow magnet gap of 2 mm for 1.4 T mag. field* *uniformly along horizontal axis*
- *Stray field outside of the septum suppressed down to <10^{-5} Tm with permalloy shield*

In-vacuum pulse septum parameters

Parameters	Spec.
B [T]	1.4
Magnet length [m]	0.5
Magnet gap [mm]	2
Peak current [kA]	2.3
Coil turn number	1
Pulse width [μsec]	10 (Half-sine)
Septum thickness [mm]	0.5
Magnetic shield thickness [mm]	<0.5
Stray field integral [T.m]	<10^{-5}
Pressure [Pa]	<10^{-7}





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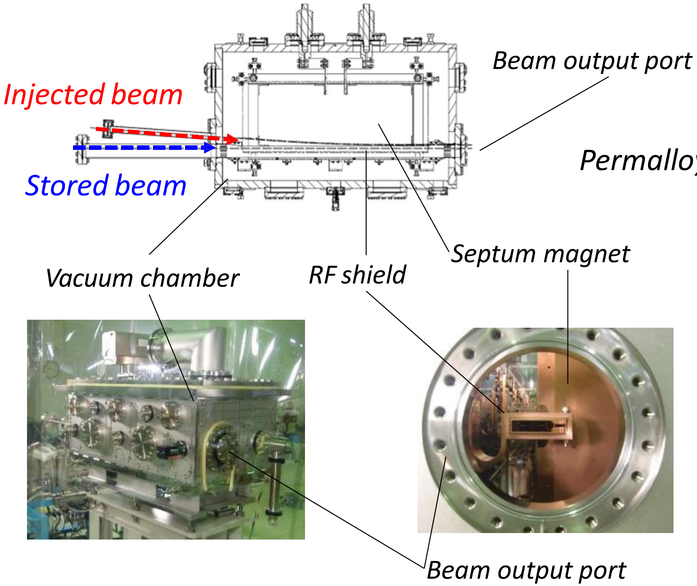
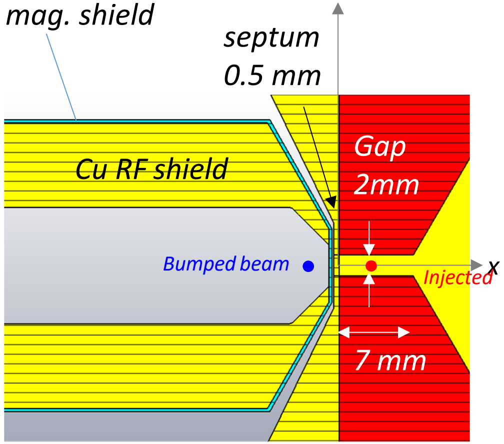
- *Thin septum wall of 0.5 mm thickness* *for small injected beam oscillation amplitude*
- *Narrow magnet gap of 2 mm for 1.4 T mag. field* *uniformly along horizontal axis*
- *Stray field outside of the septum suppressed down to <10^{-5} Tm with permalloy shield*
- *Vacuum pressure < 3×10^{-8} Pa*
- *Flat pulse septum field < ±0.2%*





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Magnetic shield thickness [mm]	*<0.5*
Stray field integral [T.m]	*<10^{-5}*
Pressure [Pa]	*<10^{-7}*

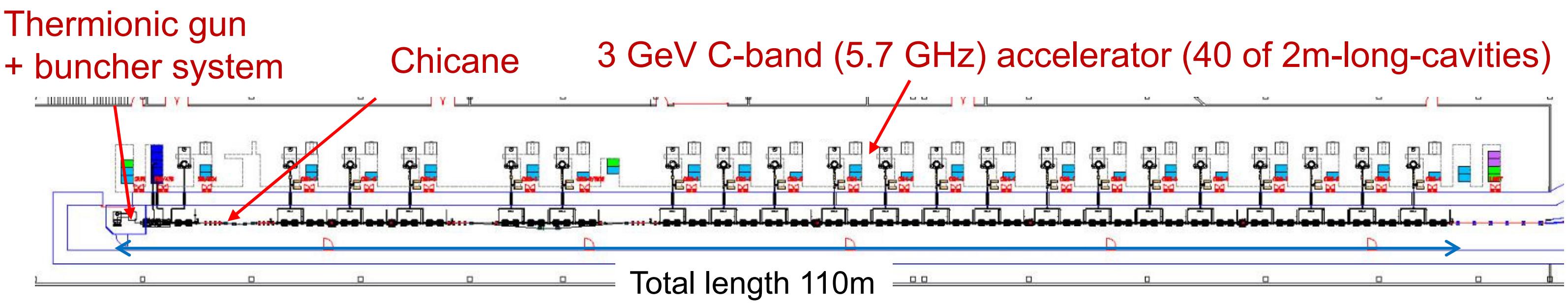
Pulse septum field

2-2. Injector linac

T. Asaka et al., PRAB 23, 063401 (2020)
T. Asaka et al., JJAP 60, 017001 (2020)

Features

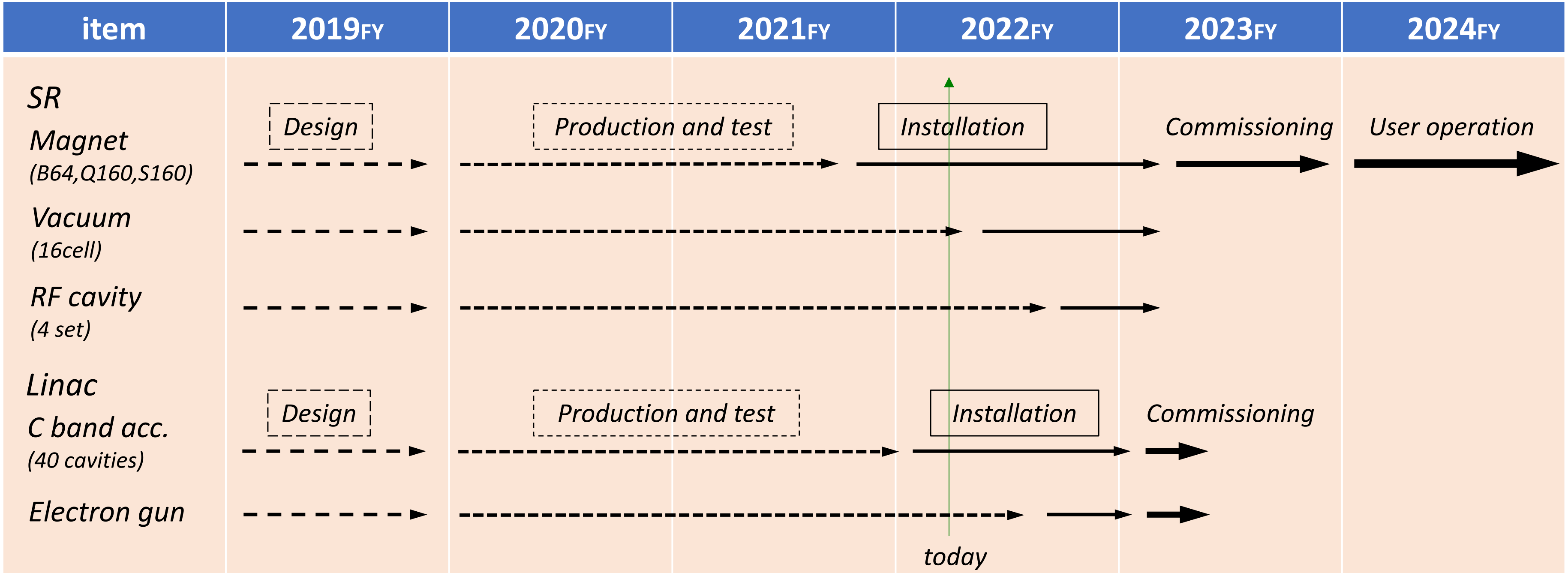
- *C-band disk loaded accelerating cavity (42MV/m) modified from the original choke mode type at SACLA*
- *R&D of a new thermionic cathode gun system for low cost and high reliability*
- *Future extension to SXFEL*



Parameters		Injector	SX-FEL
Beam energy	E (GeV)	3	
Normalized emittance	(*m*mrad)	<10	2 (1)
Emittance at 3 GeV	(nmrad)	<1.7	
Bunch charge	(nC)	0.3	
Repetition rate (Normal)	(Hz)	1	10

For SX-FEL, the same thermionic cathode gun and an additional bunch compressor will be used.

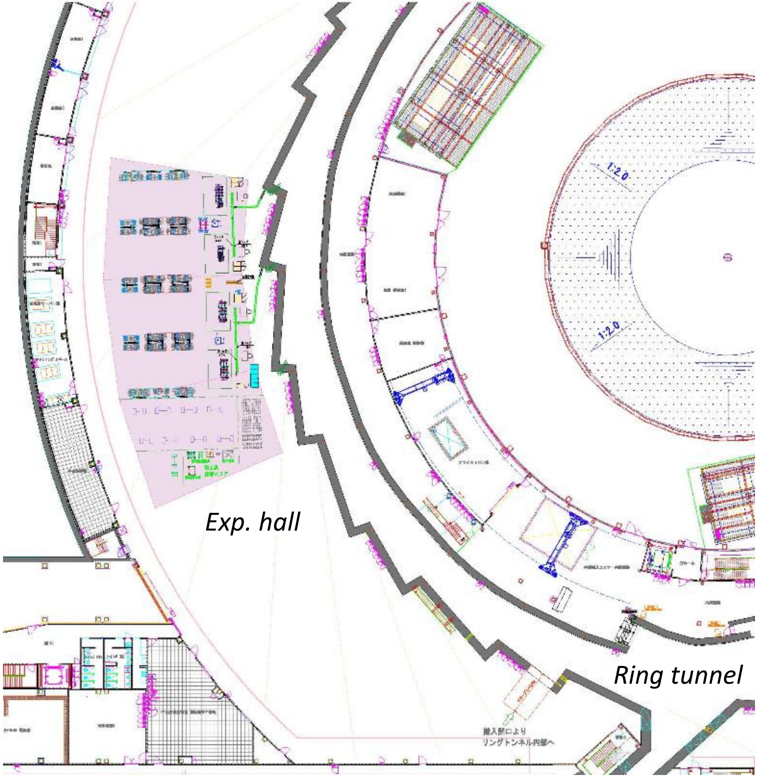
3. Schedule

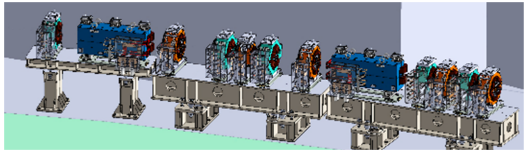


Designed by 2019
Production started in 2020
Some of components are under installation
Beam commissioning in 2023
User operation in2024

3. Status: On site alignment

- *All the magnets assembled on the girders in the factory*
- *Precise alignment for girder at on-site experimental hall*

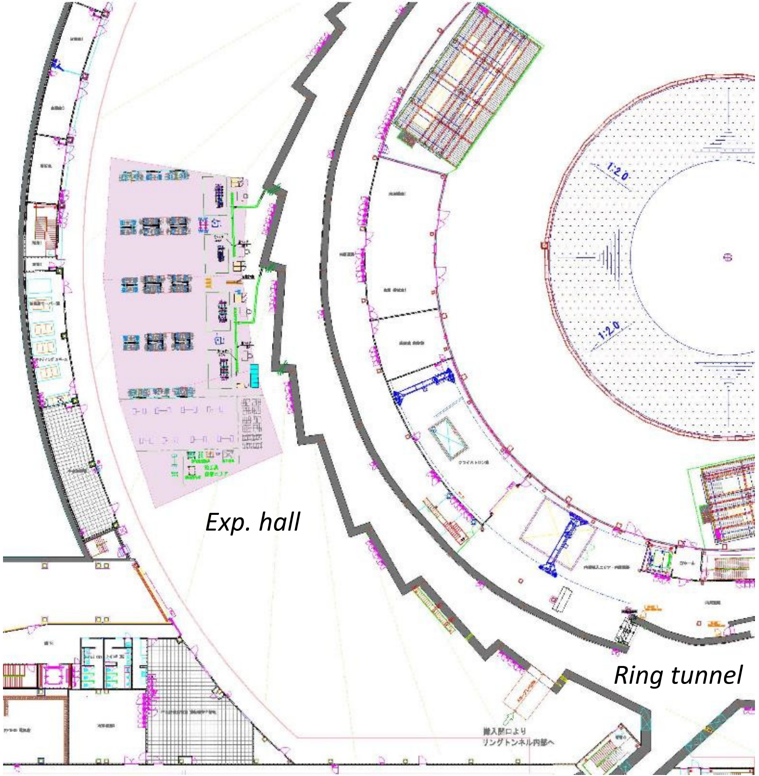


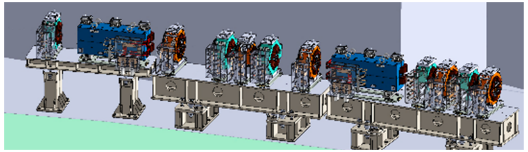


3. Status: On site alignment

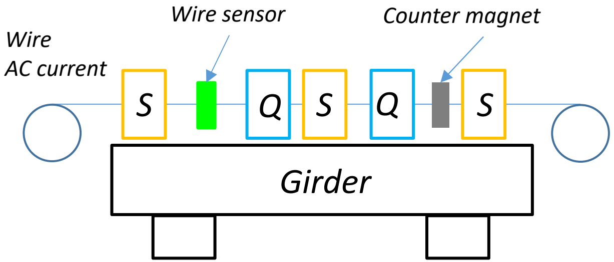
Target magnets	Alignment technique	Accuracy
On-girder multipole magnets	*VWM (Vibrating Wire Method)*	*< ±50 μm*
Between girders and bends	*Laser tracker*	*< ±90 μm*

- *All the magnets assembled on the girders in the factory*
- *Precise alignment for girder at on-site experimental hall*





K. Fukami et al., Rev. Sci. Instrum. 90, 054703 (2019)



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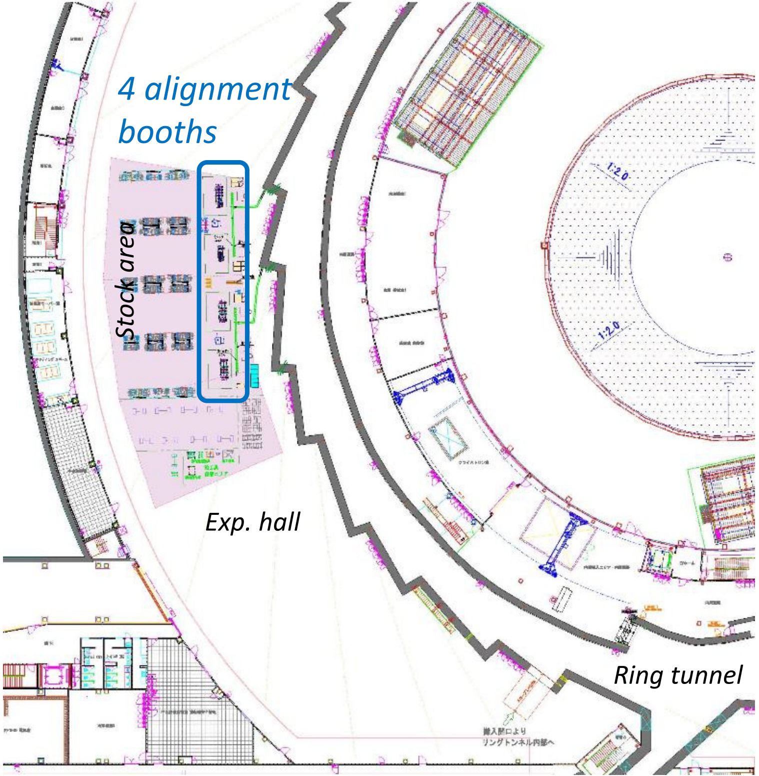
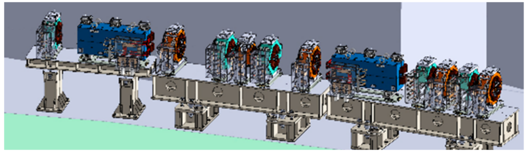
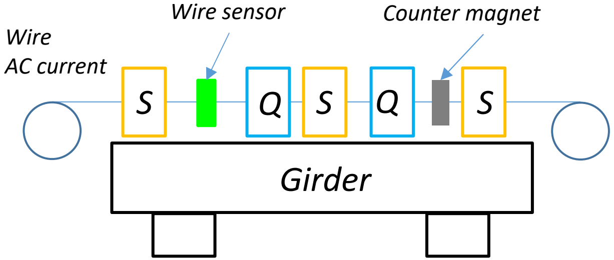
K. Fukami et al., Rev. Sci. Instrum. 90, 054703 (2019)

- *4 temp.-controlled booths for VWM alignment*







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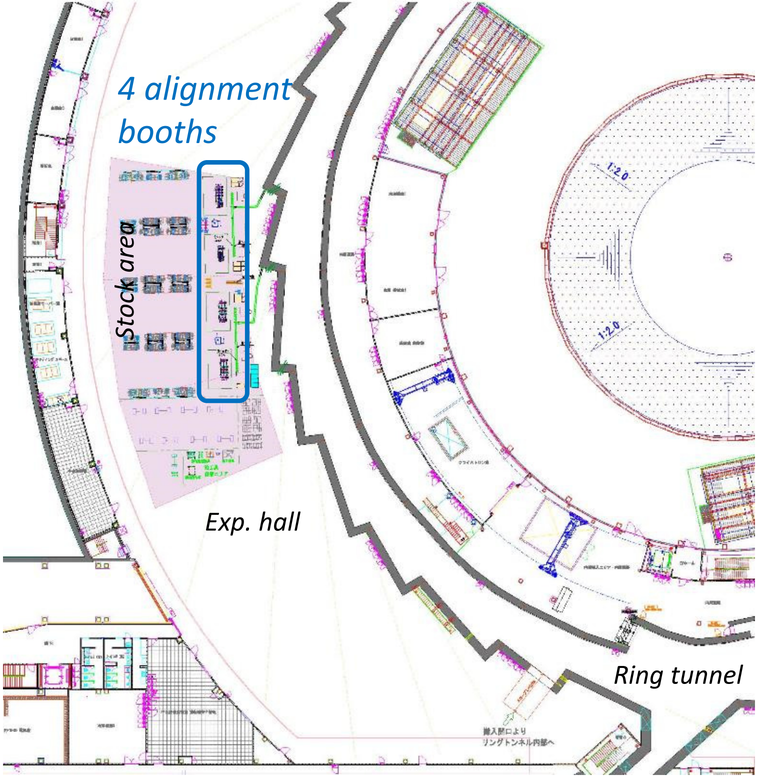
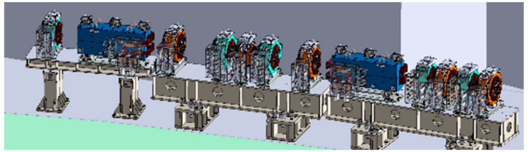
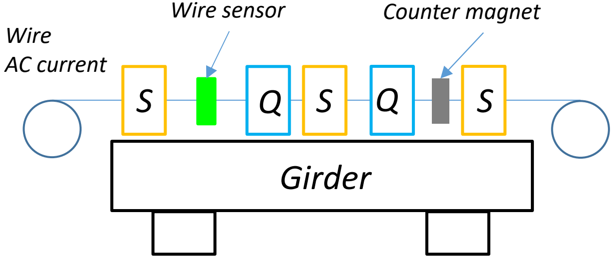
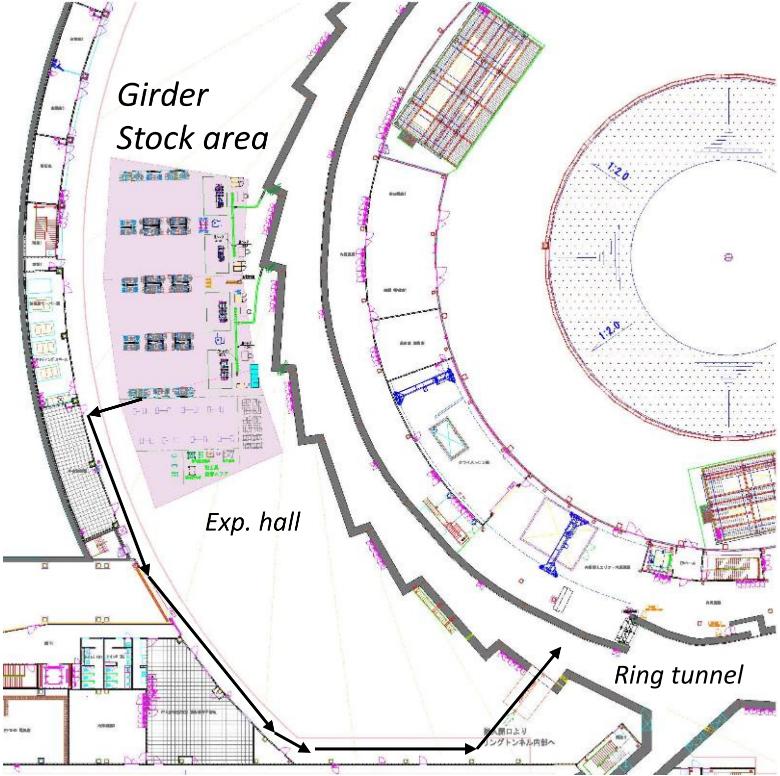






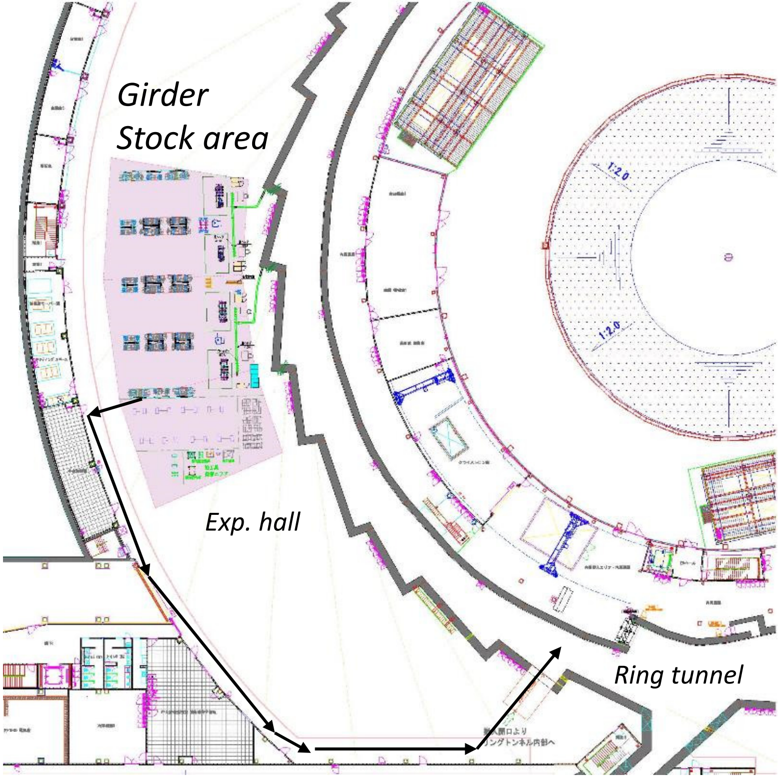
3. Status: SR-mag. Installation

- *Alignments of 6 girders in a week*



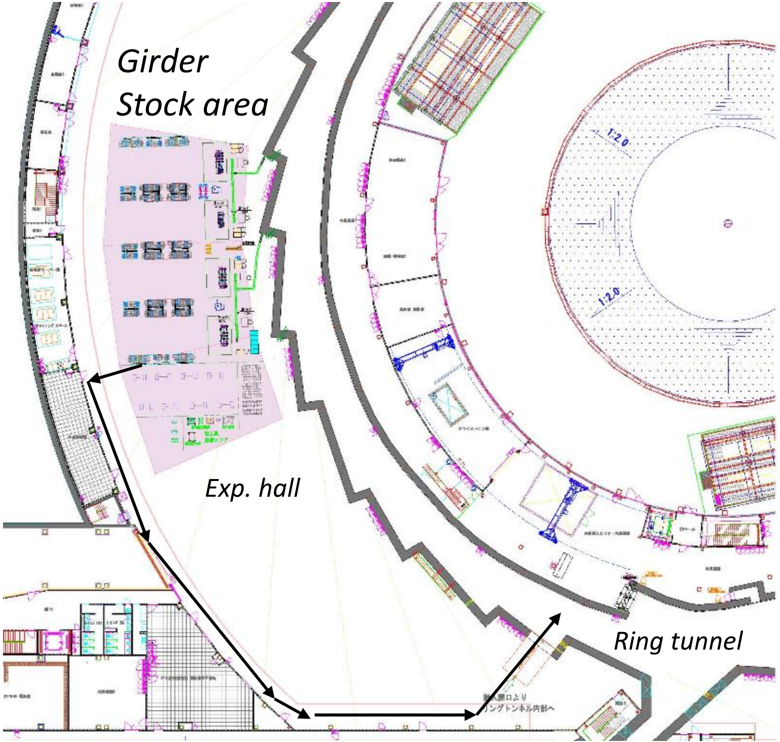
3. Status: SR-mag. Installation

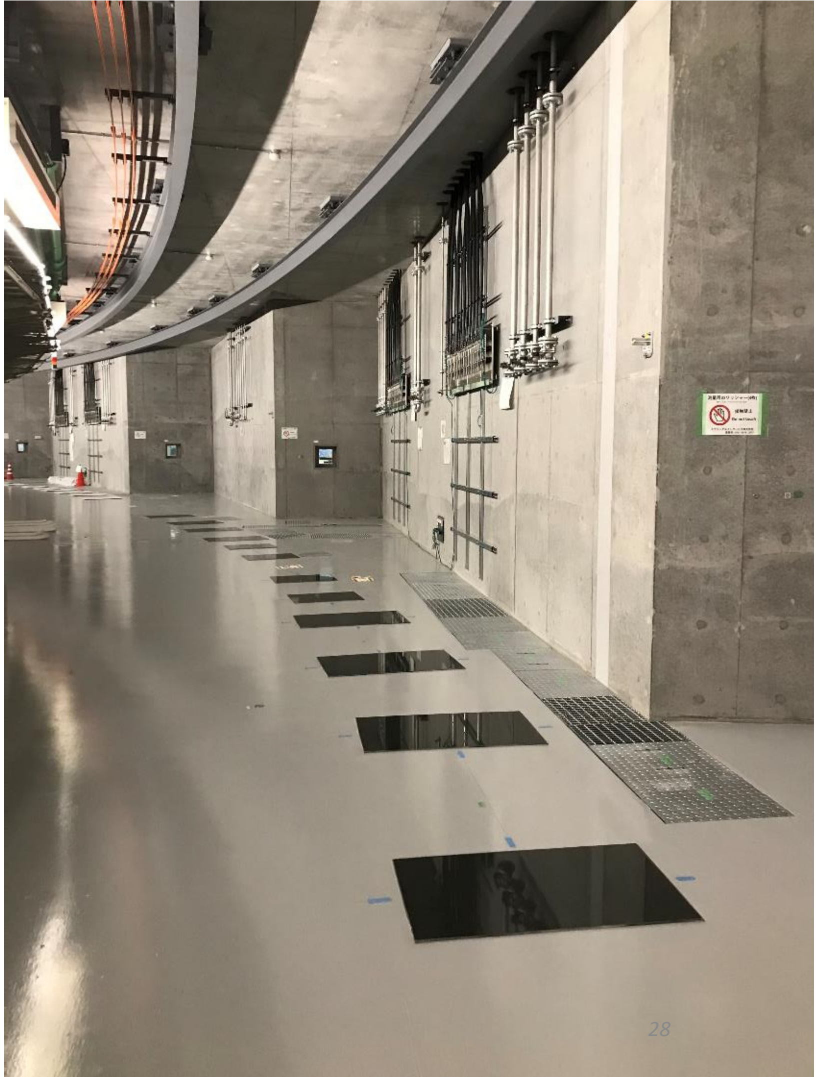
- *Alignments of 6 girders in a week*
- *Transport of girder from stock area to tunnel*



3. Status: SR-mag. Installation

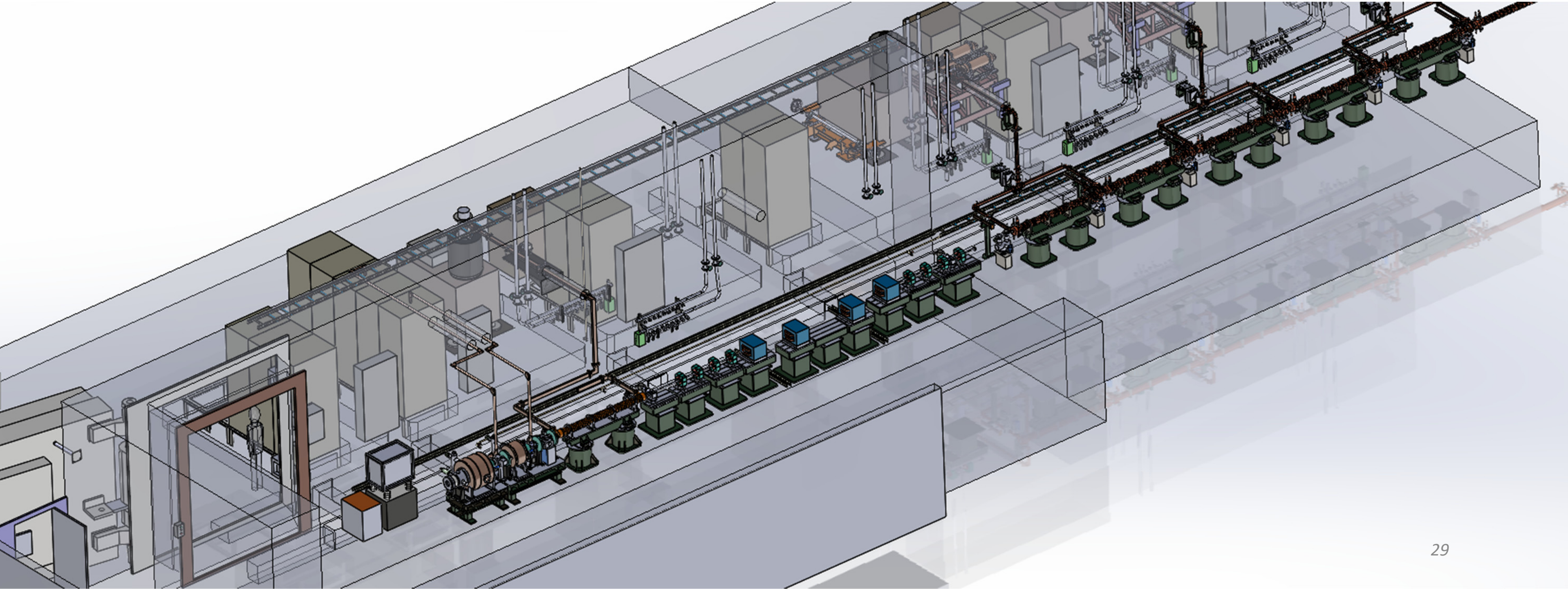
- *Flat floor surface made of epoxy resin by self-leveling (<50 m/m)*
- *No shim plate between pillar and floor*
- *Suppressed vibration transfer from floor to girder*
- *Radiation hardness verified up to 1 MGy*





3. Status: Linac acc. installation

- *SLEDs and modulators under installation at klystron gallery.*
- *C-band cavities are under installation at linac tunnel.*



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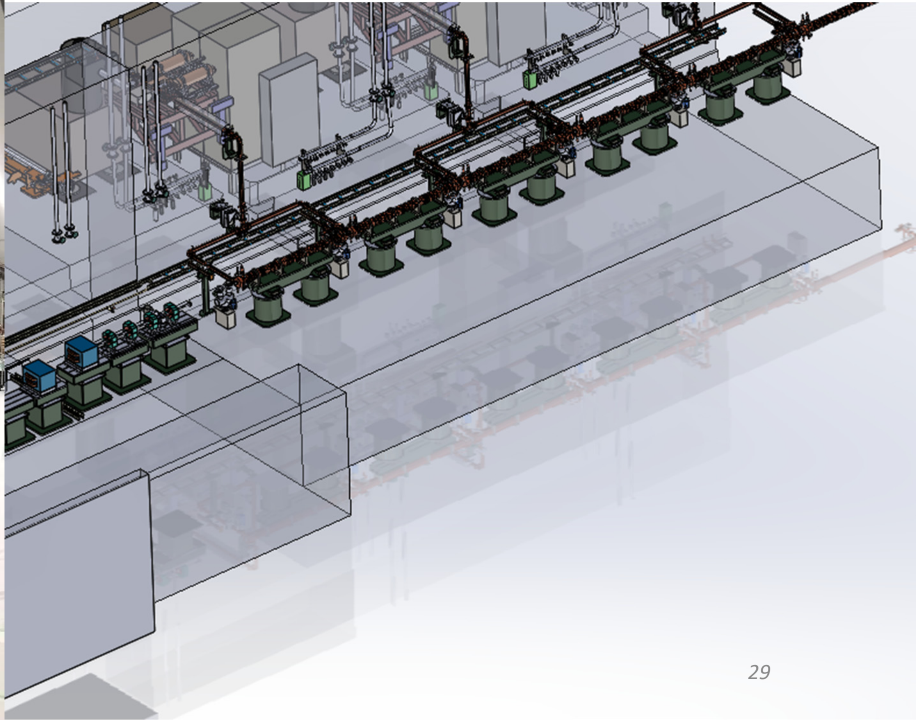

3. Status: Linac acc. installation

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Thank you for your attention!

天岩戸神話の天照大御神
（春斎年昌画、1887年）

AmaTerasu