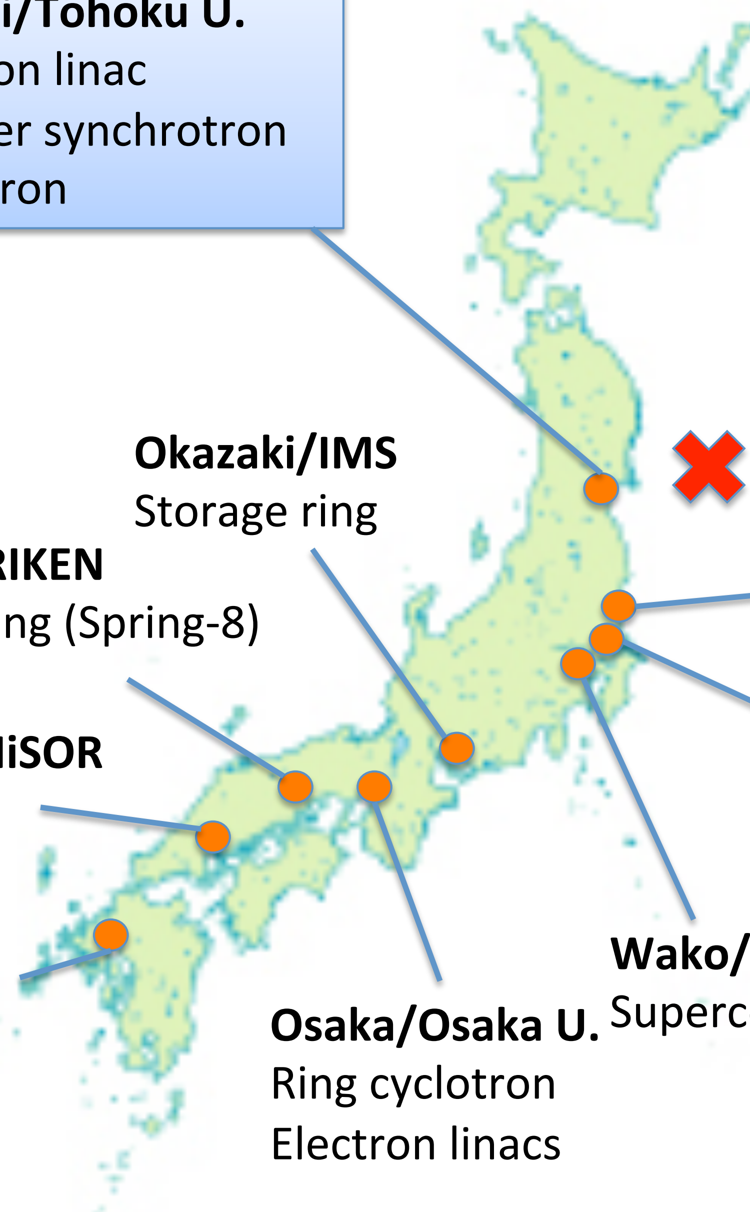
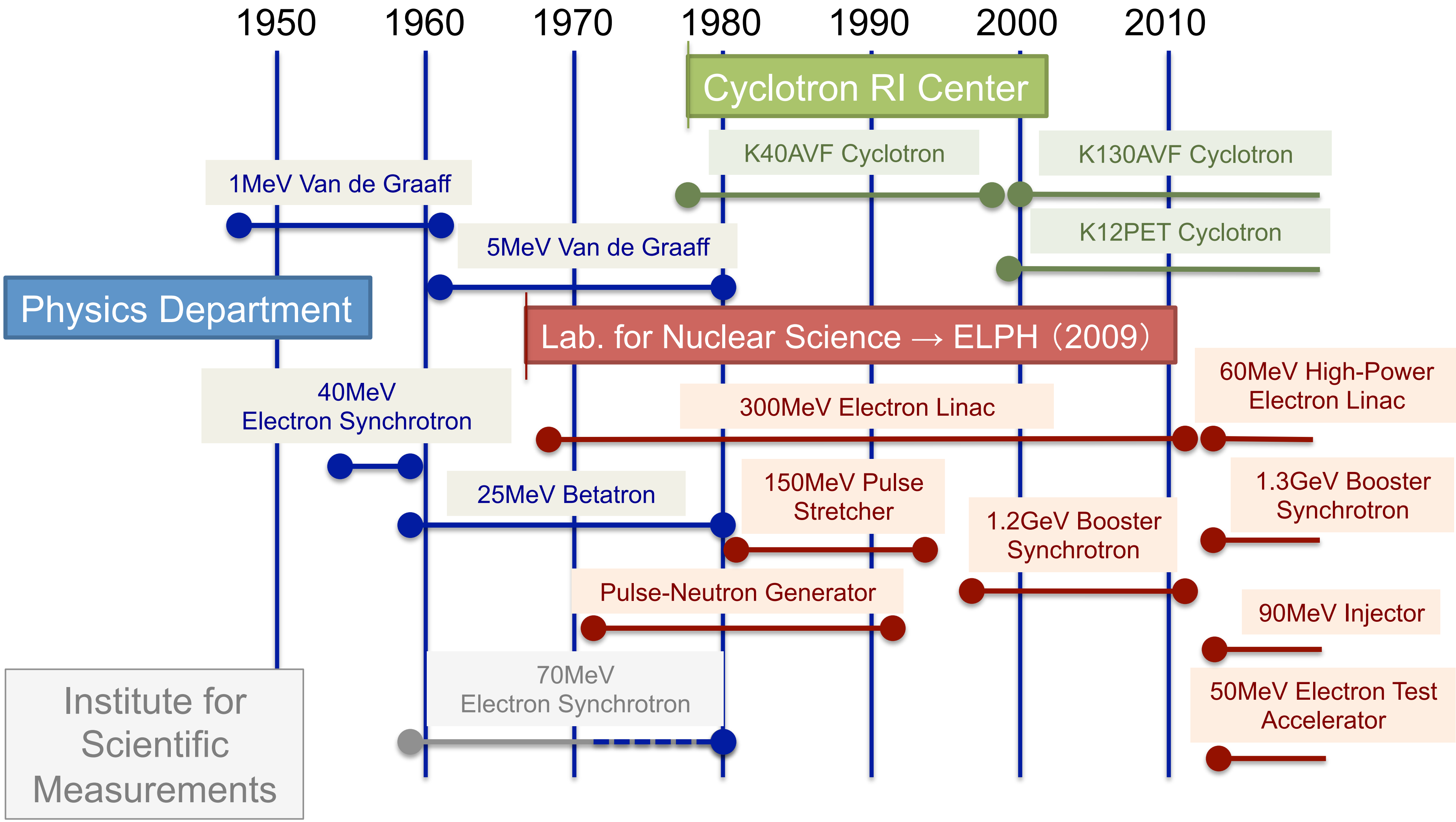
Major Accelerator Facilities in Japan



Accelerators in Tohoku University

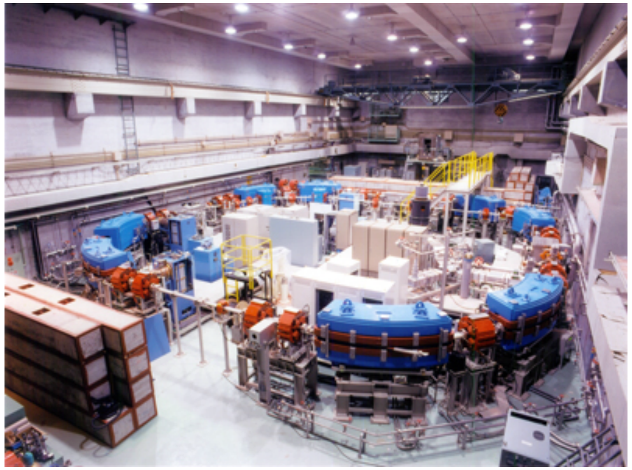


Research Center for Lectron Photon Science (ELPH)

Short history

1966	Laboratory of Nuclear Science (LNS) established
1967	Completed 300 MeV Electron Linac
1971	Start Pulse Neutron Generation
1976	Completed 150 MeV Pulse-Beam Stretcher (SSTR)
1988	First Observation of Coherent Synchrotron Radiation
1997	Completed 1.2 GeV Booster Ring (STB ring)
2009	LNS => ELPH
2010	Install t-ACTS Project, rf-gun injector
2011	Great East Japan Earthquake
2013	Recovering the Earthquake Damages
2013	Completed 50MeV test accelerator for t-ACTS Project

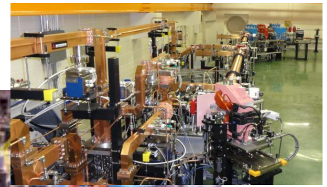
300MeV-300Hz Electron Linac（1967-2011）
☞ 60MeV High Power Linac (2013-)



1.2GeV Stretcher Booster Ring（1997-2011）
☞ 1.3GeV Booster Storage RIng (2013-)

Current Research Activities at ELPH

90MeV Injector



High-energy γ source via internal target wire

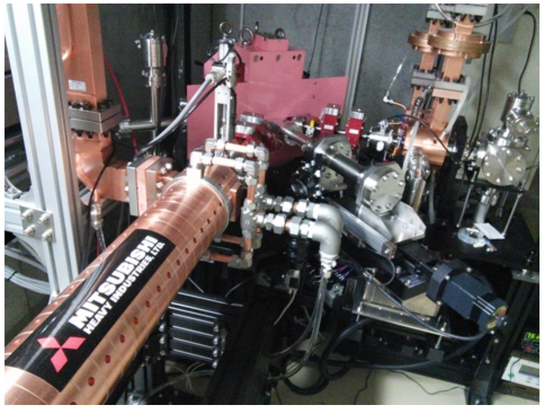
- Quark-meson physics
- Hyper nuclei physics
- Counter test for particle physics

1.3 GeV Booster-Storage Ring
Internal target wire for Bremsstrahlung

RI production via nuclear photoreaction

- Radiation chemistry
- Activation analysis
- Medical application

60 MeV High Power Linac
Max. beam power ~ 8kW

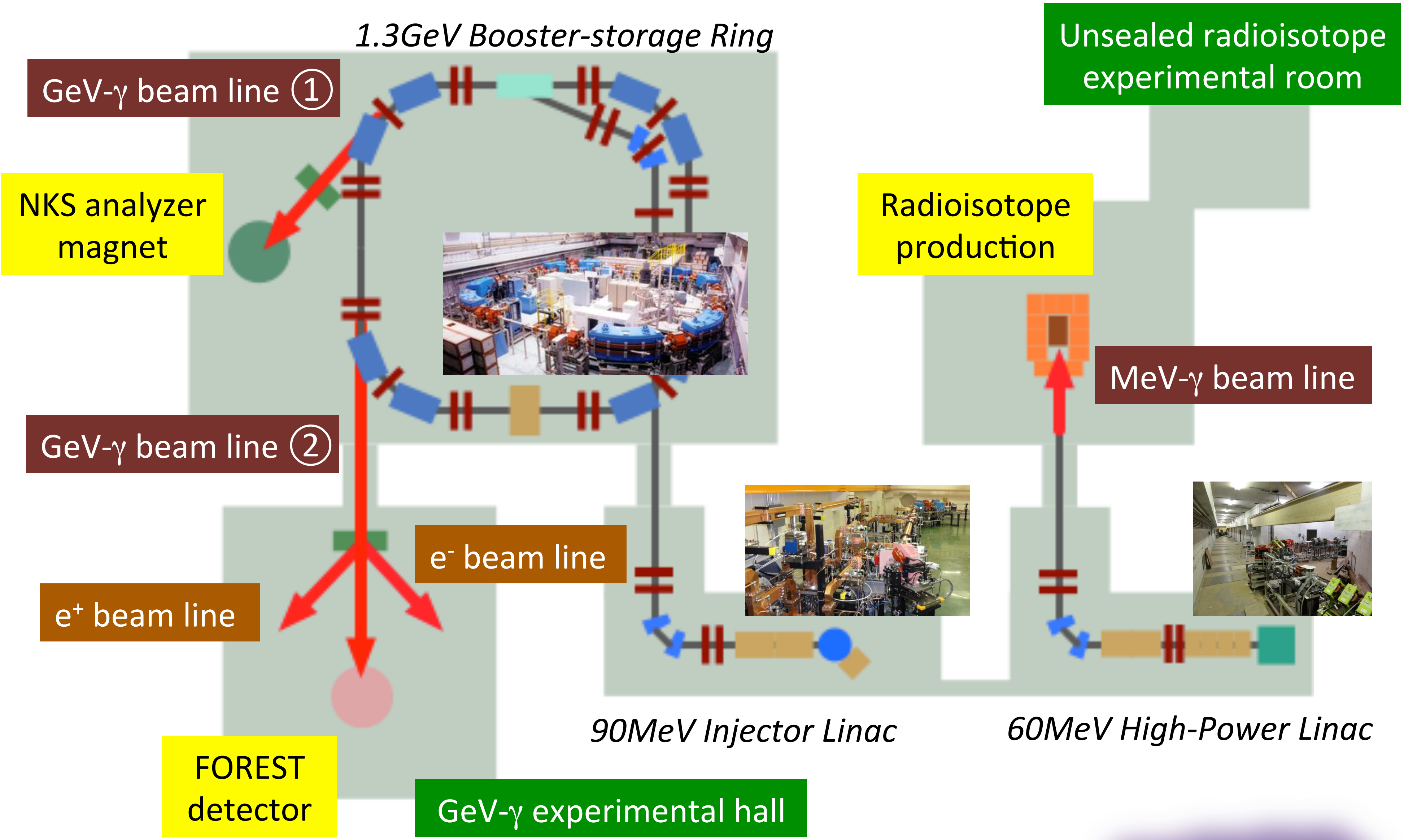


Accelerator physics and photon science

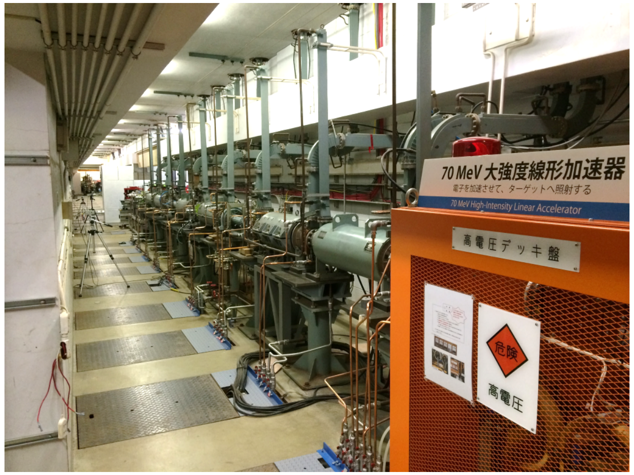
- Femtosecond beam pulse
- Superradiance
- Variable polarized THz source

50 MeV Test Linac
Velocity bunching toward 100fs beam

γ - Beamlines at ELPH



MeV- γ Beamline for RI Production



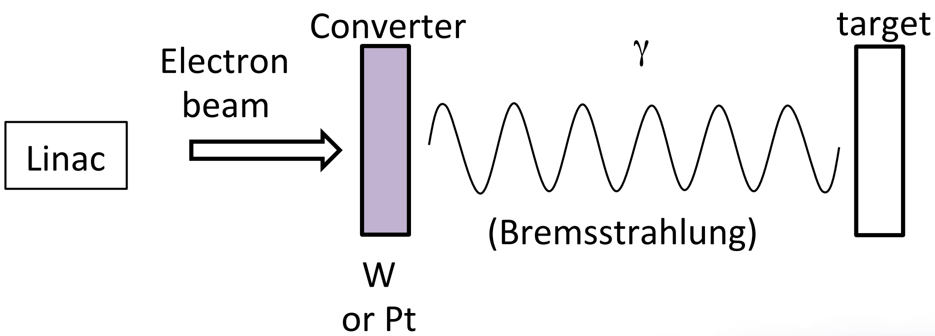
60MeV High-power Linac

Irradiation beam line

Beam parameter	
•Max. energy	60 MeV
•Repetition	300 pps
•Peak current	100mA
•Average current	~ 120 uA
•Max. beam power	~ 8 kW

Highest in Japan

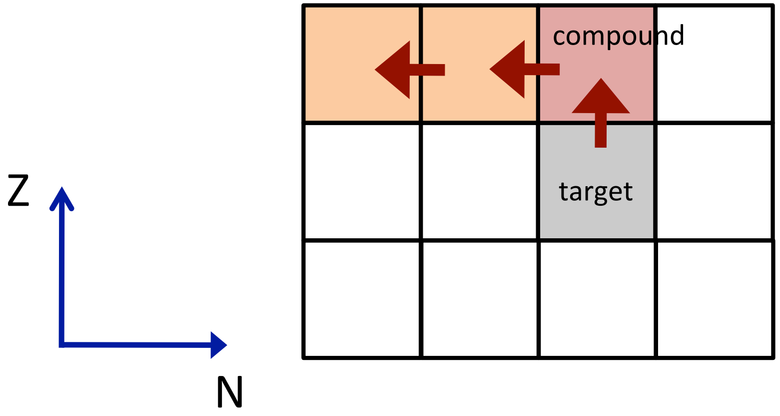
Radioisotope production via photo-nuclear reaction



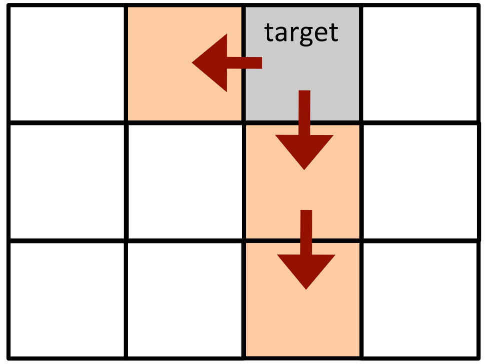
MeV- γ Beamline for RI Production

Photoreaction can produce unique isotopes

Via proton beam : (p, n), (p, 2n)

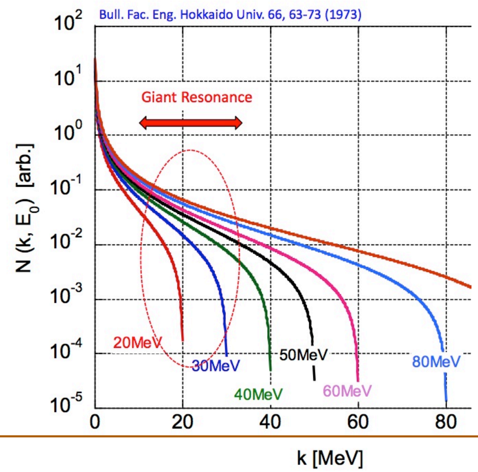


Via photon beam : (γ, n), (γ, p) , (γ, 2p)



(γ, *n*p) reaction produces neutron-rich side

E1 Giant resonance enhances cross section

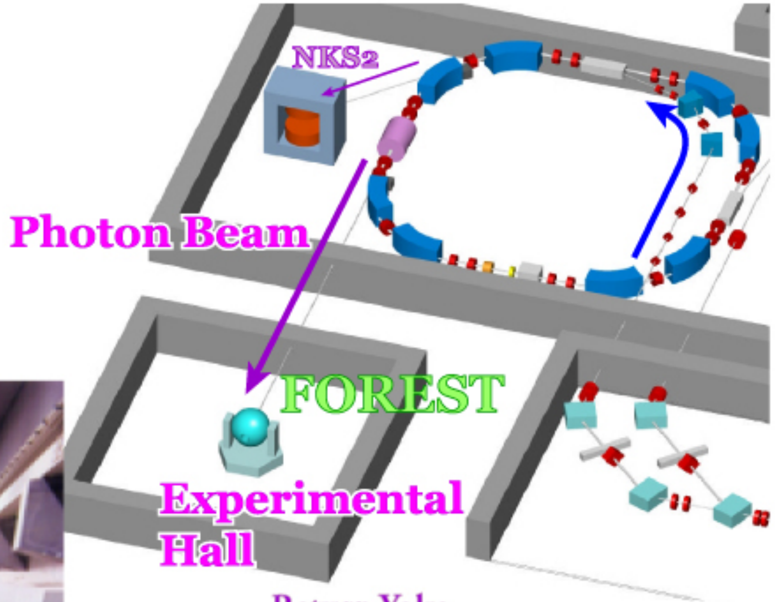


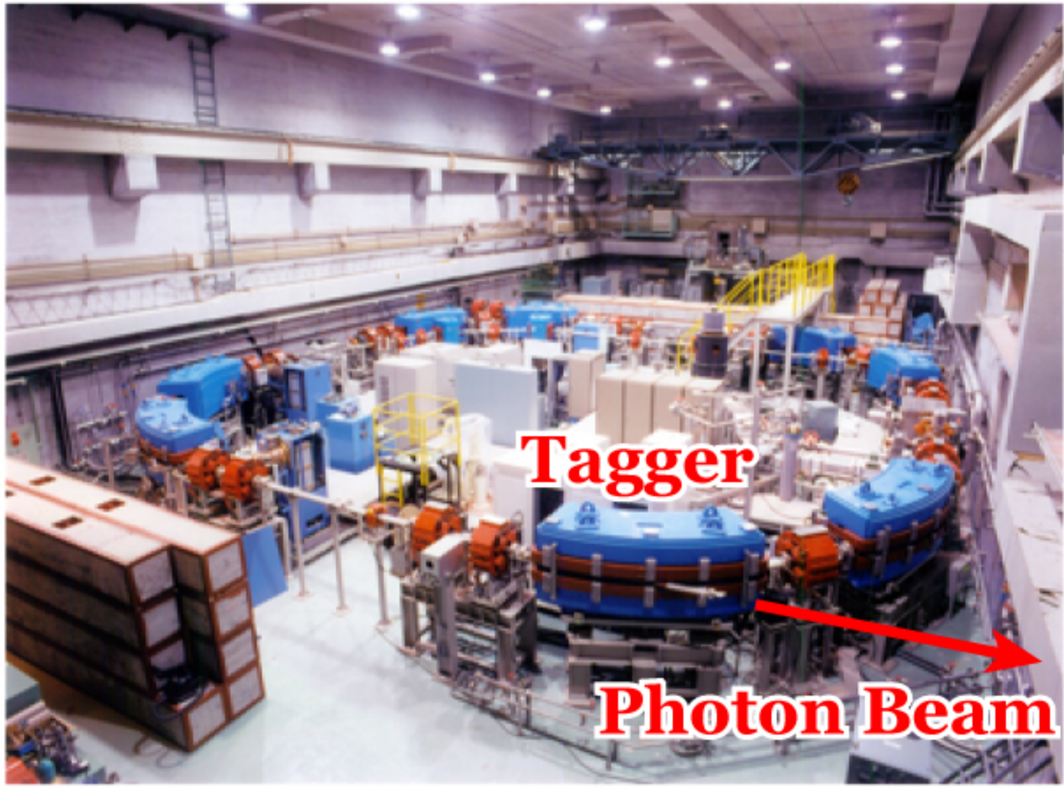
Applications

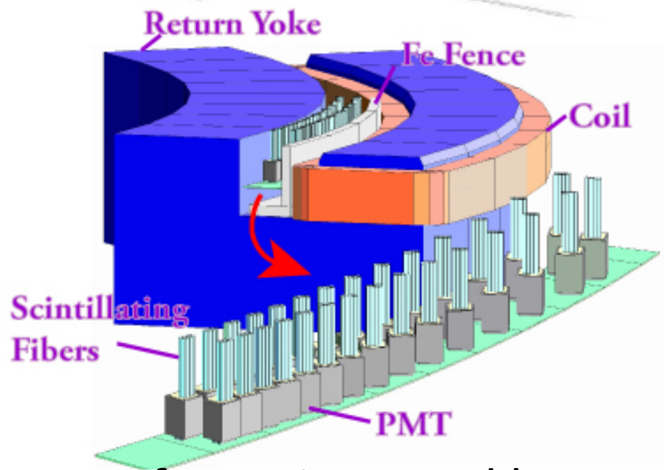
- Activation analysis
- Radioisotope tracer
- Medical isotopes

GeV-γ Beamline for Hadron Physics

GeV-class Bremmstrahlung γ ray
from Internal Target Wire



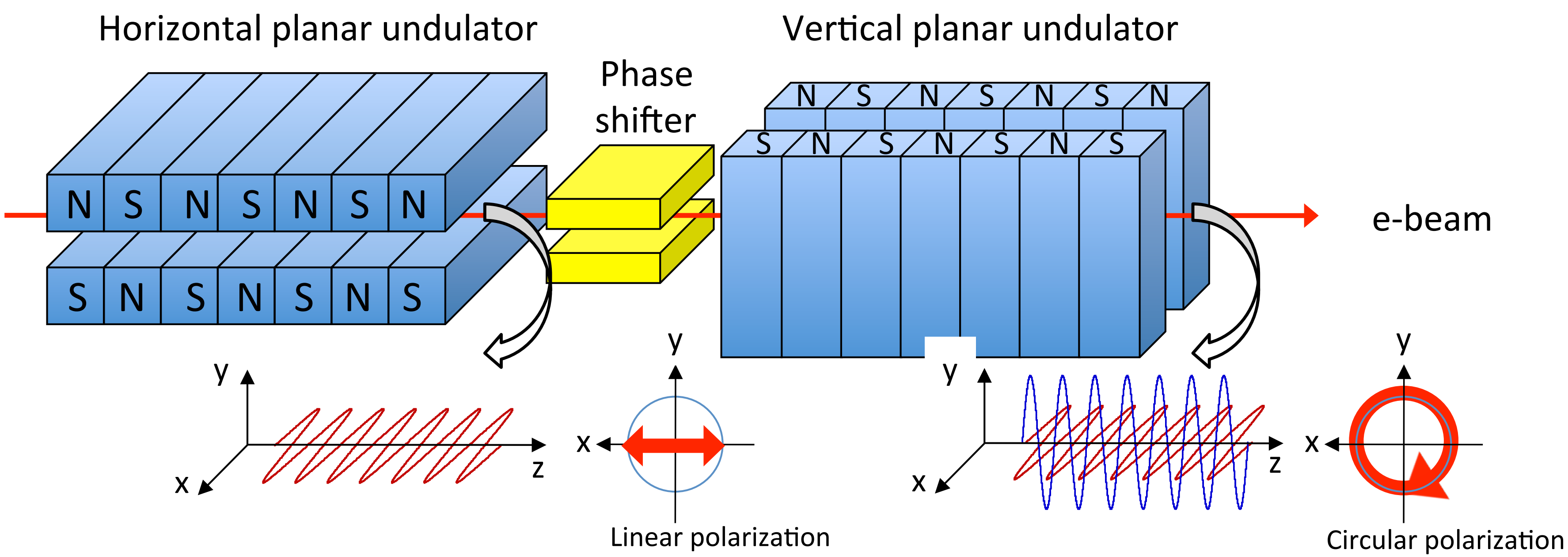


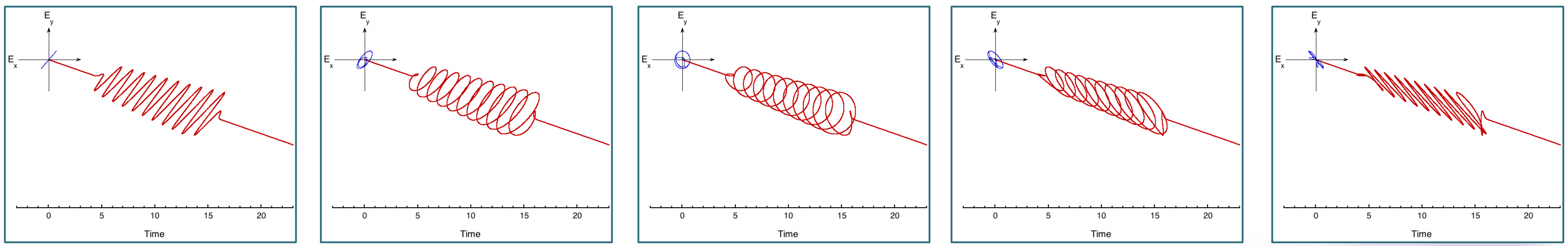


Energy of γ ray is tagged by
recoiled electron

t-ACTS for Photon Science

Crossed-Undulator for variable polarized superradiance





Test accelerator

SLiT-J, a project of high brilliant compact 3 GeV light source in Japan

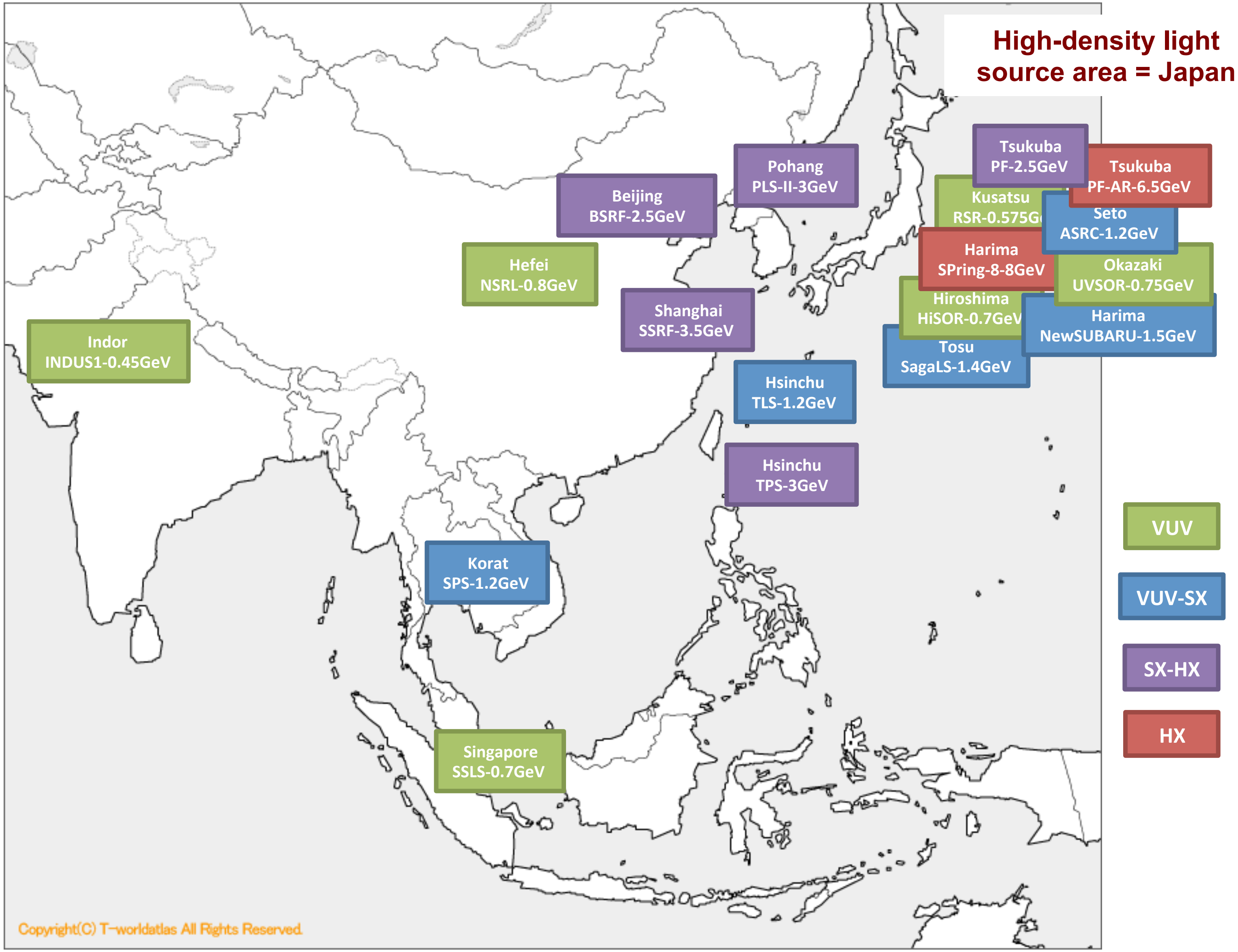
2017.11.14@ALBA, Barcelona

SLiT-J : Synchrotron Light in Tohoku, Japan

Hiroyuki Hama[1)], Nobuyuki NIshimori[2)], Sadao Miura[1,3)]
for SLiT-J design team

[1)]Research Center for Electron Photon Science, Tohoku University
[2)]Institute of Multidisciplinary Research for Advanced Materials, Tohoku University
[3)]Mitsubishi Heavy Industries Machinery Systems

Light source stream in Asia and Japan



Third generation light sources in the world -1-

Low emittance 3 GeV class light source is dominant trend in the world

Before 2000

Year	Name	Energy (GeV)	Nation
1992	ESRF	6	France
	ALS	1.5 -1.9	USA
1993	TLS	1.5	Taiwan
1994	ELETTRA	2 - 2.4	Italy
	PLS	2	Korea
	MAX-II	1.5	Sweden
1996	APS	7	USA
	LNLS	1.35	Brazil
1997	SPring-8	8	Japan
1998	BESSY-II	1.9	Germany

After 2000

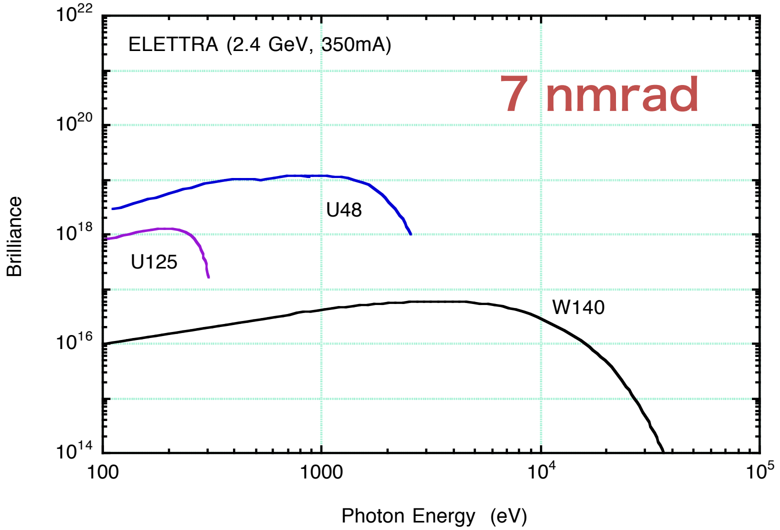
Year	Name	Energy (GeV)	Nation
2000	ANKA	2.5	Germany
	SLS	2.4	Swiss
2004	SPEAR-3	3	USA
	CLS	2.9	Canada
2006	SOLEIL	2.8	France
	DIAMOND	3	GB
	ASP	3	Australia
	MAX-III	0.7	Sweden
2008	SSRF	3.4	China
2009	PETRA-III	6	Germany
2011	ALBA	3	Spain
2012	PLS-II	3	Korea
2014	NSLS-II	3	USA
2015	TPS	3	Taiwan
2016	MAX-IV	3	Sweden

VUV-SX source
SX source
HX source

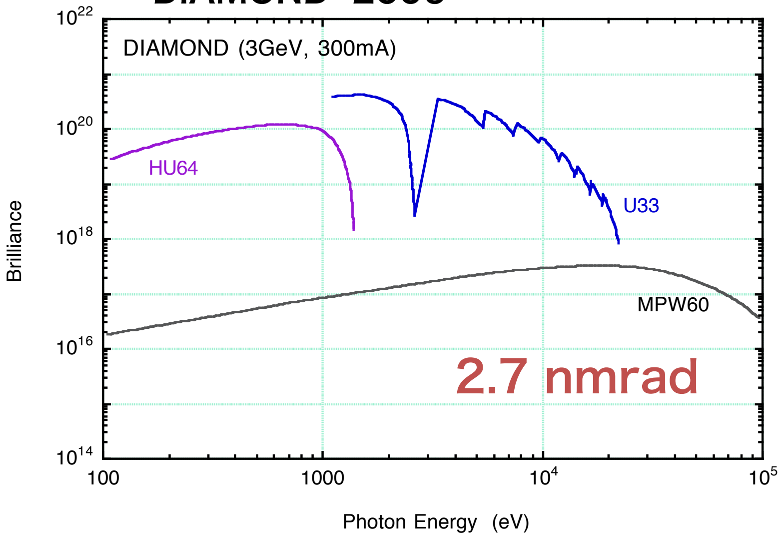
3 GeV is more versatile !!!

Light source stream in the world

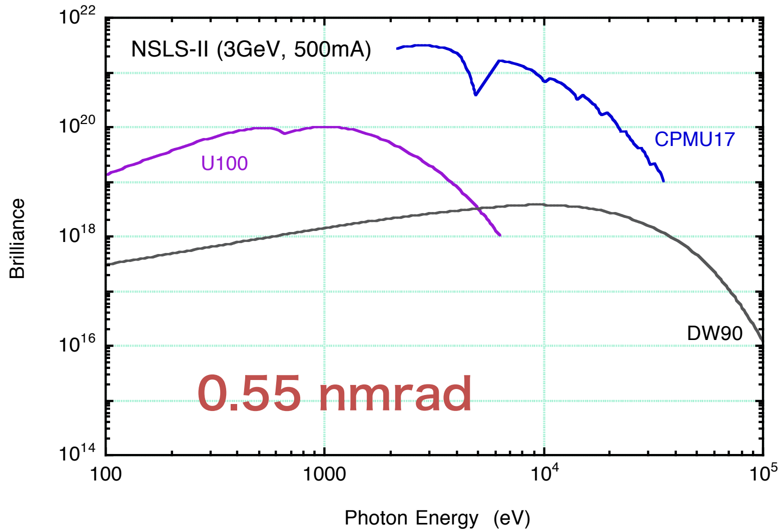
ELETTRA 1994 -



DIAMOND 2006 -

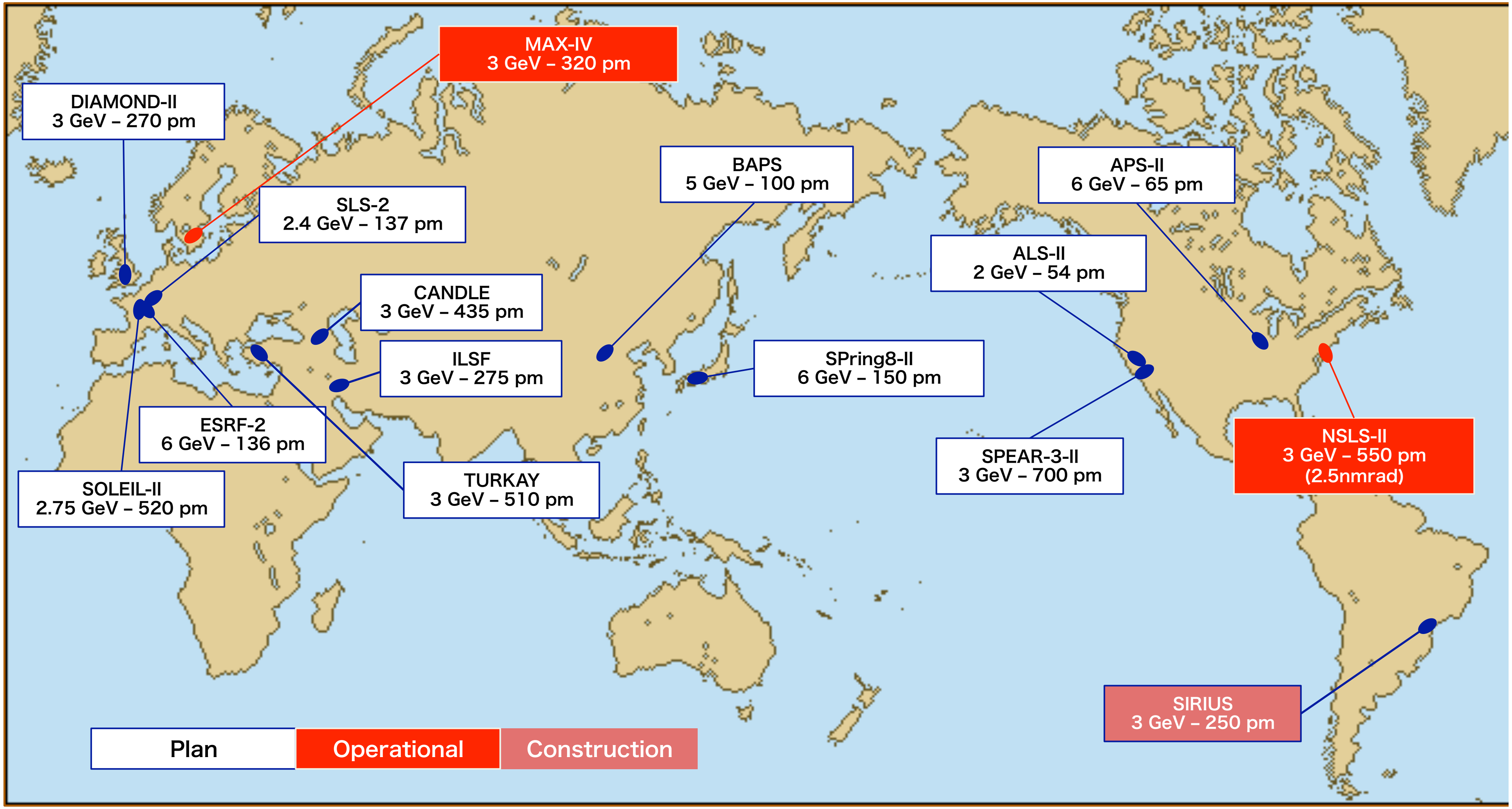


NSLS-II 2014 -



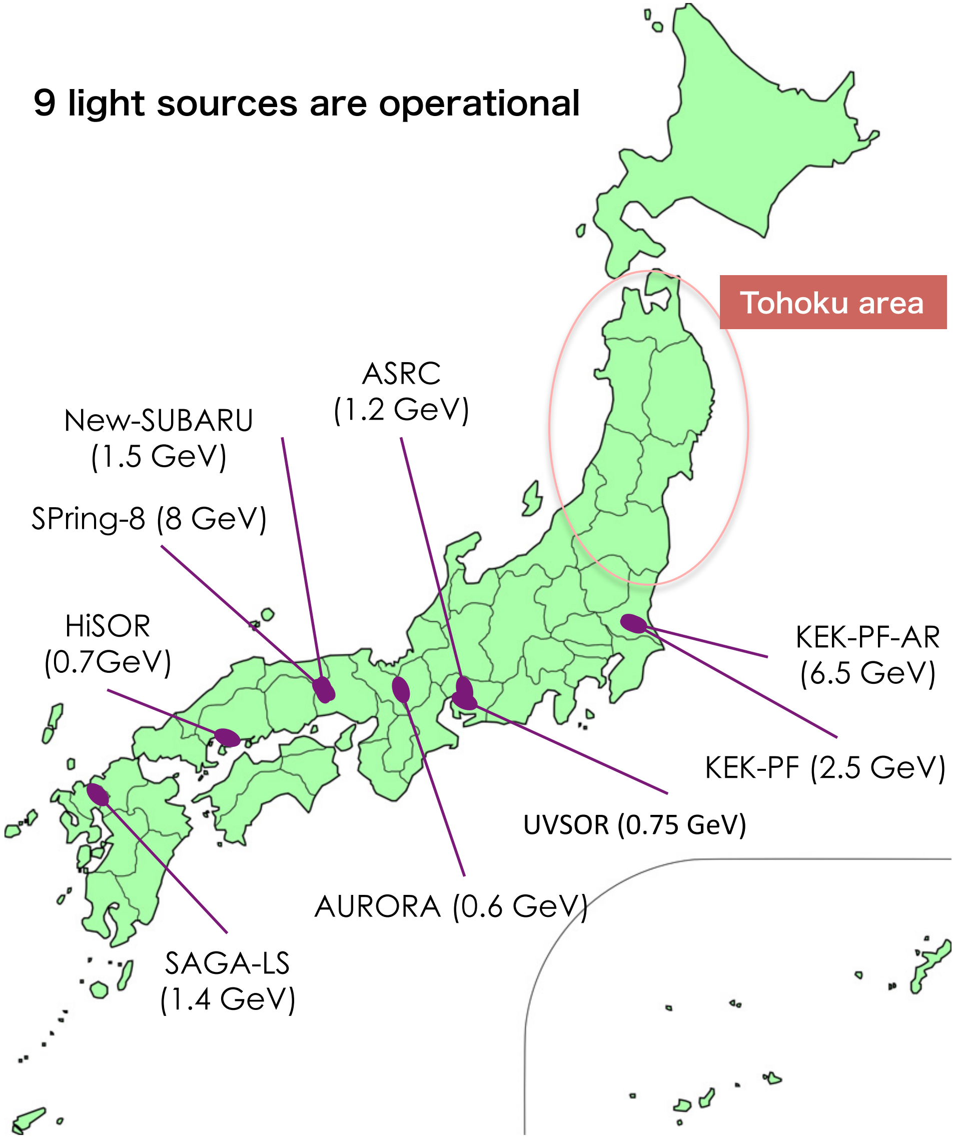
- Exceed 10^{21} at several keV
- 3 GeV machine covers VUV to hard-X

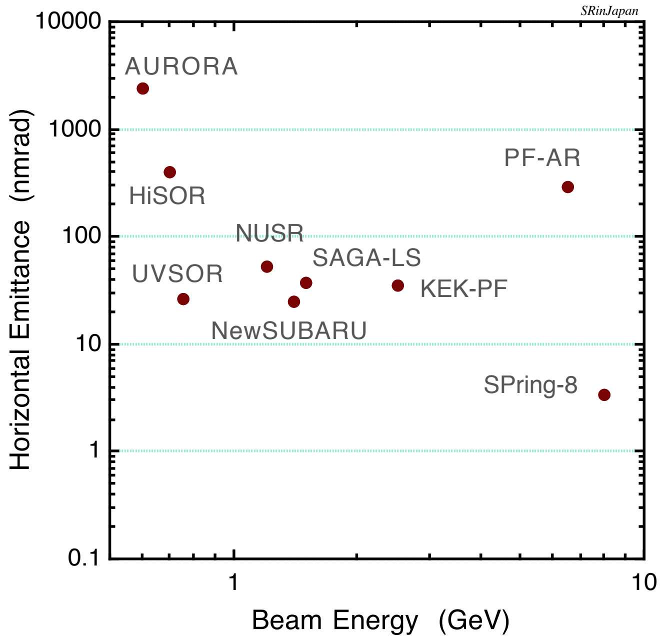
Sub-nm rings / diffraction-limited rings - the new era of SR -



Japanese light sources -1-

9 light sources are operational

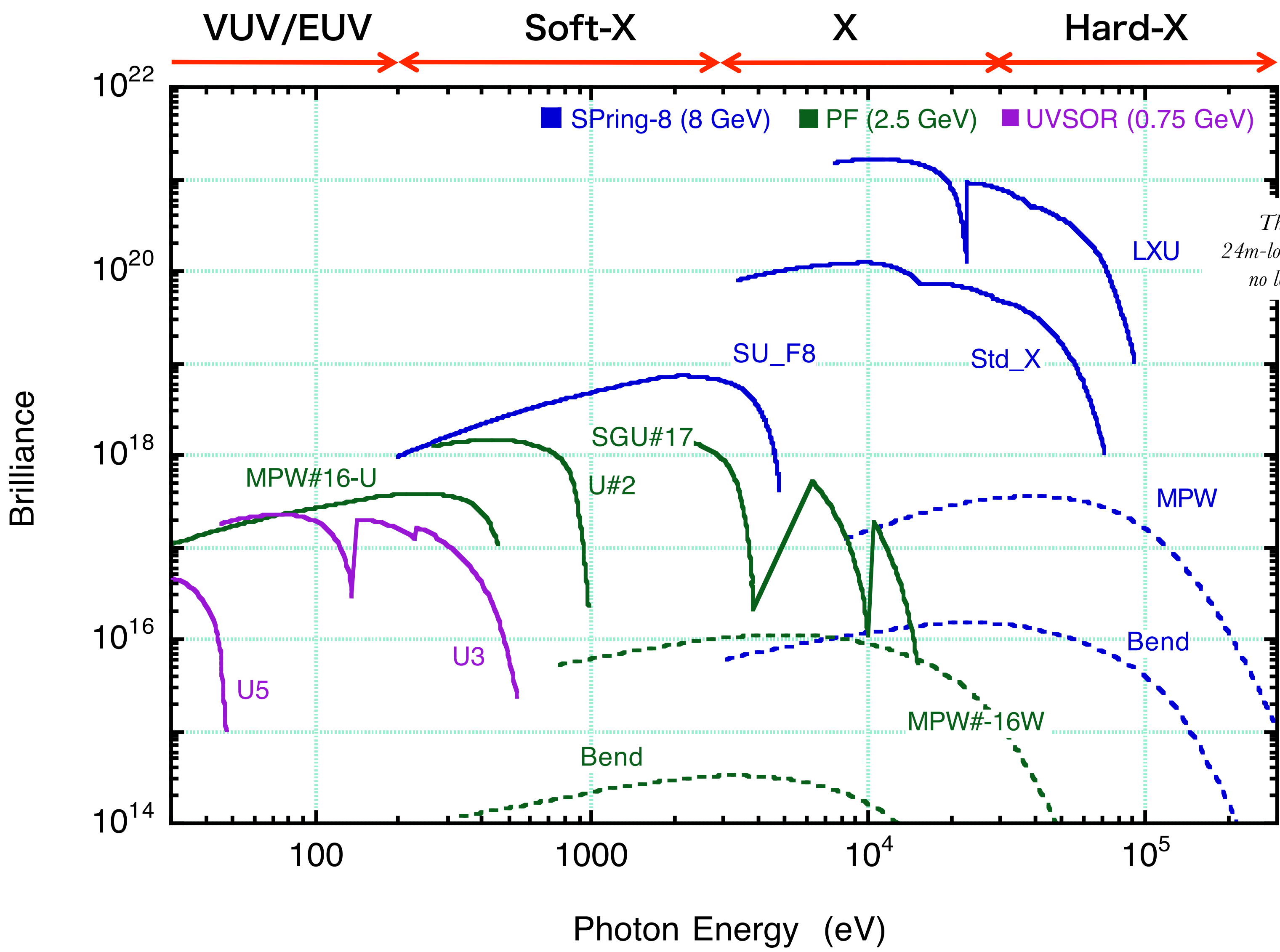




3-No

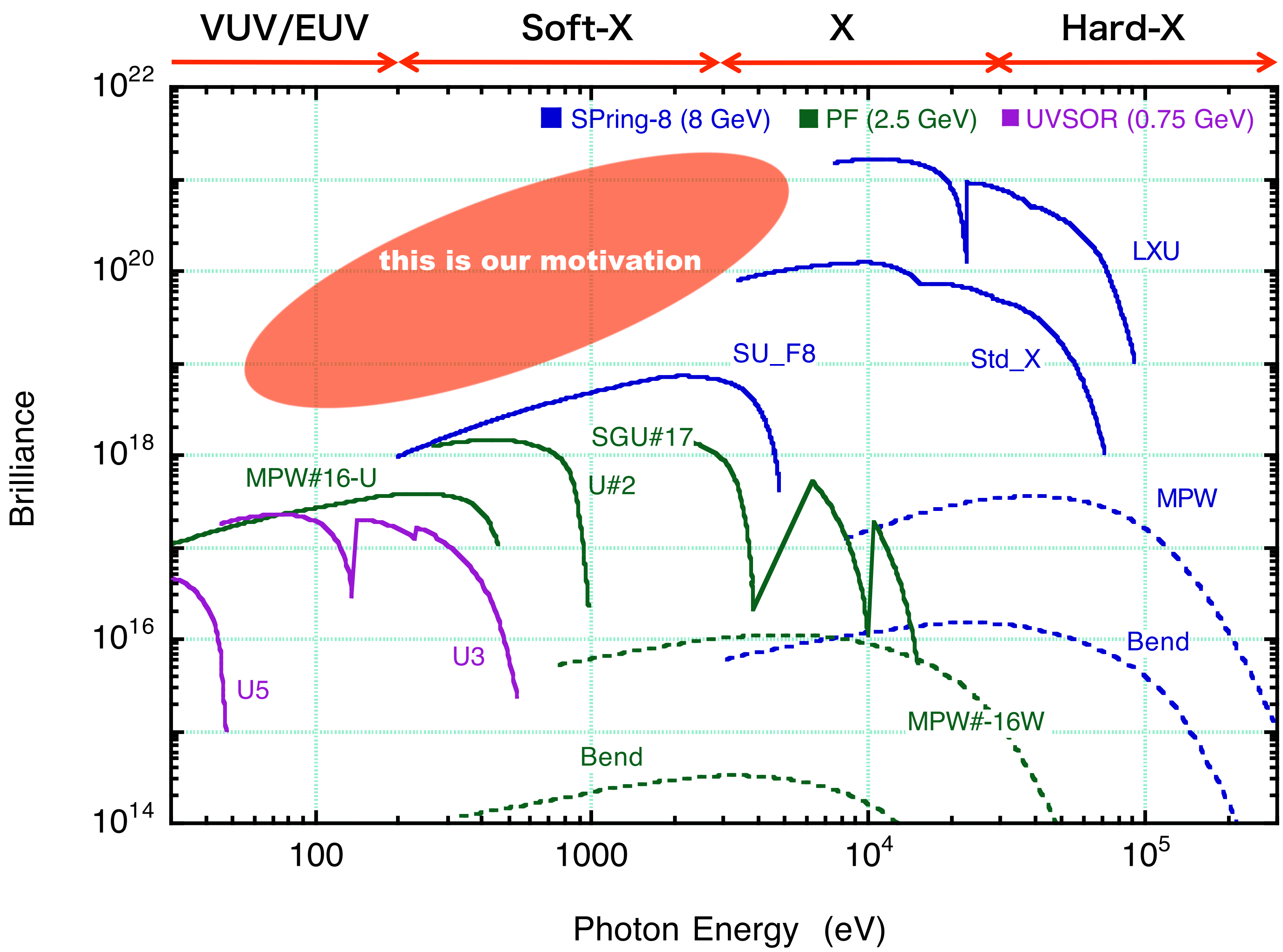
- No 3rd generation light source except SPring-8.
- No modern 3 GeV class machine for advanced science and technology.
- No SR facility in northern Japan.

Japanese light sources -2-



This is a special 24m-long straight section, no longer a treasure

Japanese light sources -2-



Our targets and restriction

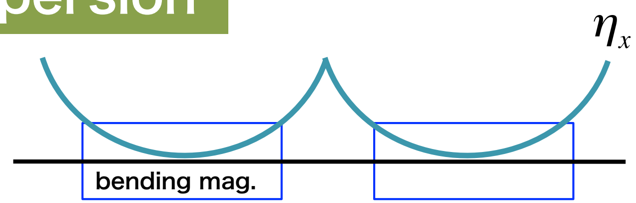
• Horizontal emittance	ε_x	< 1 nmrad
• Beam current	I	> 400 mA
• Life time	τ	> 10 h
• Number of beam lines		> 20
• Injector future option		soft-X FEL

• Circumference	C	< 360 m
• Length of injector		< 130 m
• Construction budget	€	182 M
(including buildings)	£	160 M
	$	211 M
	¥	240 M
• No R&D time	as soon as possible !!	

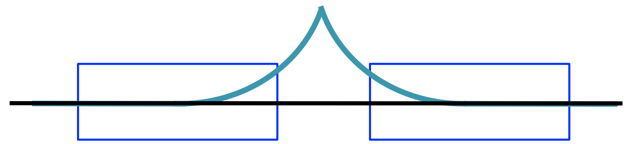
How to achieve the low emittance -1-

Strategy-1. Distributed dispersion

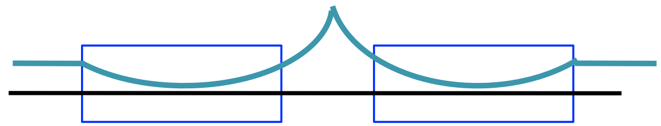
Theoretical minimum $\varepsilon_x^{TM} = \frac{1}{12\sqrt{15}} \frac{C_q \gamma^2 \theta_{Bend}^3}{J_x}$



Conventional achromat $\varepsilon_x = 3\varepsilon_x^{TM}$



Non-achromat $\varepsilon_x \sim 2\varepsilon_x^{TM}$



NOTE: Beam size is composed of emittance and energy spread

$$\sigma_{x^*} = \sqrt{\varepsilon_x \beta_x + \left(\eta_x \frac{\sigma_E}{E}\right)^2}$$

- Compromise between emittance and dispersion
- Synchro-beta coupling in RF cavity
- Quantum excitation by insertions

TPS (Taiwan): ε_x ~ 4.9 (achromat) ☞ 1.6 nmrad (non-achromat)

How to achieve the low emittance -2-

Strategy-2. Damping enhancement

In principle, increasing the radiation power leads damping effect.

$$\varepsilon_{xW} \approx \frac{P_0}{P_0 + P_W}\varepsilon_x$$

P_0; Radiated power from dipoles

P_W; Radiated power from wigglers/undulators

Power from bends $\quad P\,[\text{MW}] = 8.846\times 10^{-2}\dfrac{E^4\,[\text{GeV}]}{\rho\,[\text{m}]} I\,[\text{A}]$

Power from insertions $\quad P_W\,[\text{MW}] = 6.336\times 10^{-6} E^2\,[\text{GeV}] B_0^{\,2}\,[\text{kG}]\, L_u\,[\text{m}]\, I\,[\text{A}]$

NOTE: Valid for dispersion-free section

- Lower dipole field and long straight section are preferred. => large circumference
- In case of non-achromat lattice, the quantum excitation increases the emittance.

NSLS-II (USA): ε_x ~ 2.5 (bare) ☞ 1 nmrad (3.5mDW × 6)

☞ 0.6 nmrad (3.5mDW × 16)

How to achieve the low emittance -3-

Strategy-3. Multi-bend lattice

Introducing many dipoles in a cell to reduce θ_{Bend}.

NOTE: Huge number of magnets in a cell

- Decreasing the emittance effectively.
- Focusing power has to be much stronger.
- Distance between magnets is very short. => complicate device design

conventional DBA: ~20 magnets/cell   MAX-IV: 45 magnets/cell

MAX-IV(SW): *7-bend achromat* ε_x = 0.326 (0.263 with DW × 4)

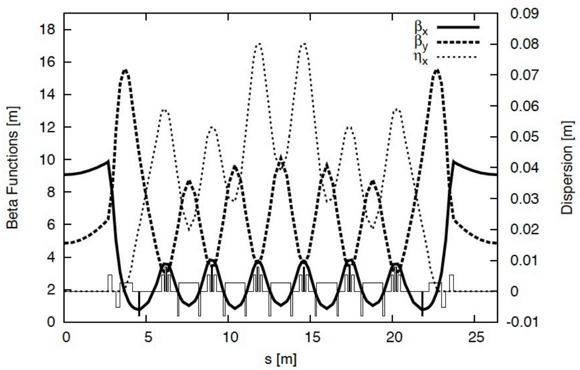
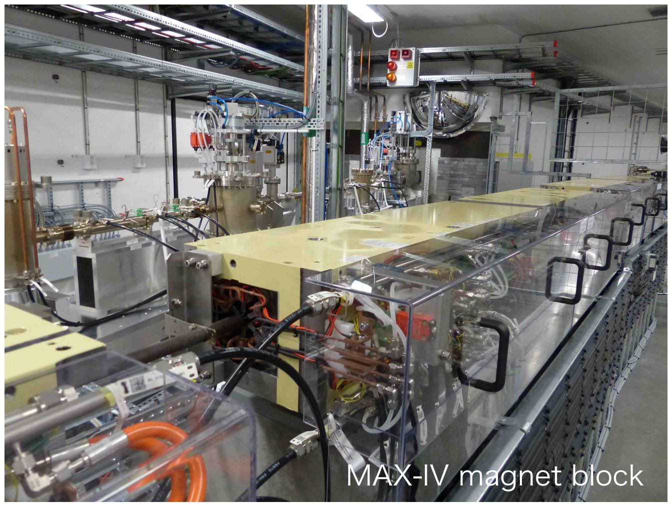
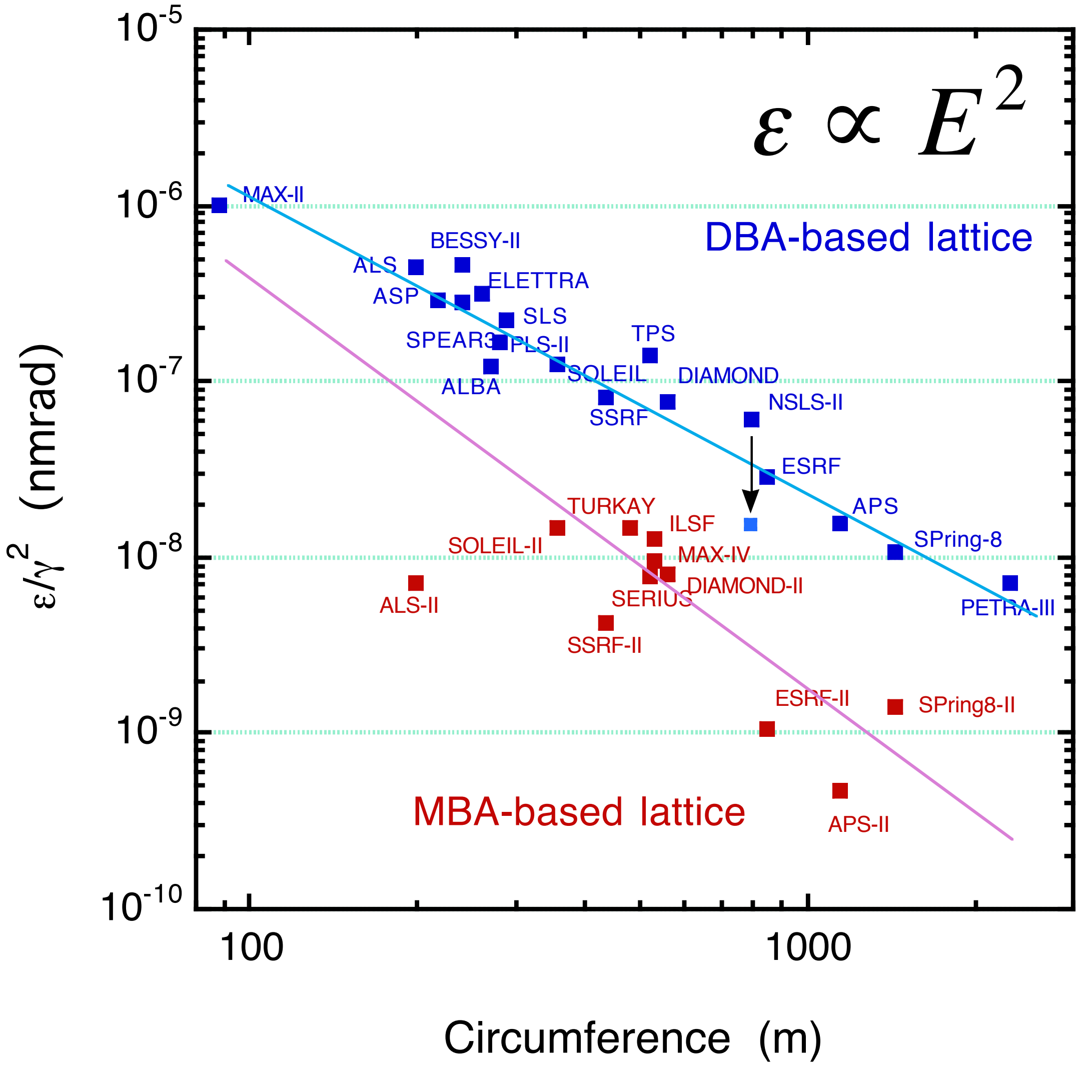


FIG. 2: Beta functions β_x, β_y and dispersion η_x for one achromat of the 3 GeV storage ring. The position of the dipoles, quadrupoles, and sextupoles are indicated at the bottom.



How to achieve the low emittance -4-

from DBA to MBA



MAX-IV is the first MBA light source

SLiT-J design strategy -1-

		TPS (DBA)	MAX-IV (7BA)
Bend.	Gap (mm)	46	28
	Max. field (T)	1.191	0.524
Quad.	Bore (mm)	37	25
	Max. field (T/m)	~20	~40
Sext.	Bore (mm)	39	25
	Max. field (T/m^2)	~500	~2000

To suppress a cell length (ring circumference), magnet packing factor is really bigger. MAX-IV's magnet block is special device, not usual.

↓

1. Vacuum issue due to small vacuum pipe.
2. Configuration issue for other components such as absorber, valve and ….
3. Design issue for magnets and vacuum chamber to extract SR.
4. Extraction issue of SR from bending magnet.

SLiT-J storage ring – design concept -

1. 4 bends in a cell
   => Double-Double Bends Achromat, DDBA lattice

2. Sub-nm emittance
   => preserving dispersion-free straight section

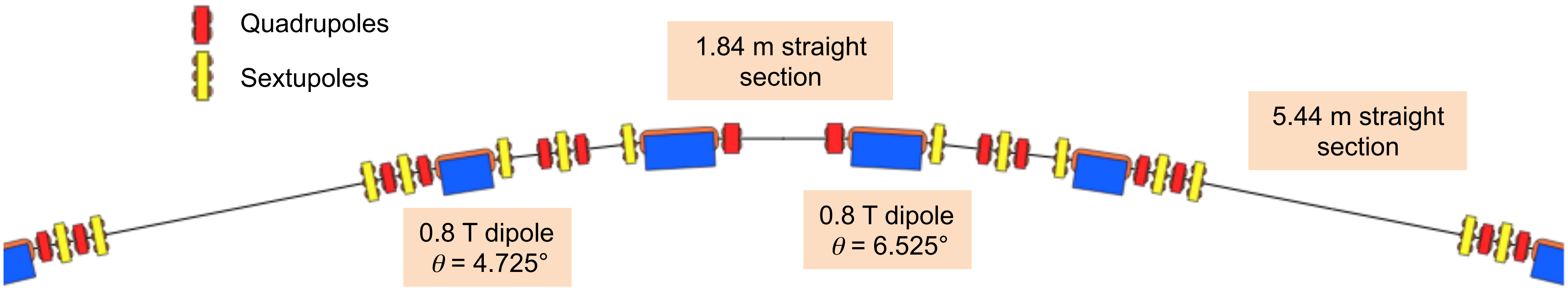
3. Circumference around 350 m
   => 16 cells is maximum

4. 5 m-long straight section for insertions
   => Brilliance exceeds 10^{21} at few keV

5. No beamline for SR from bends
   => Short straight section for multi-pole wiggler

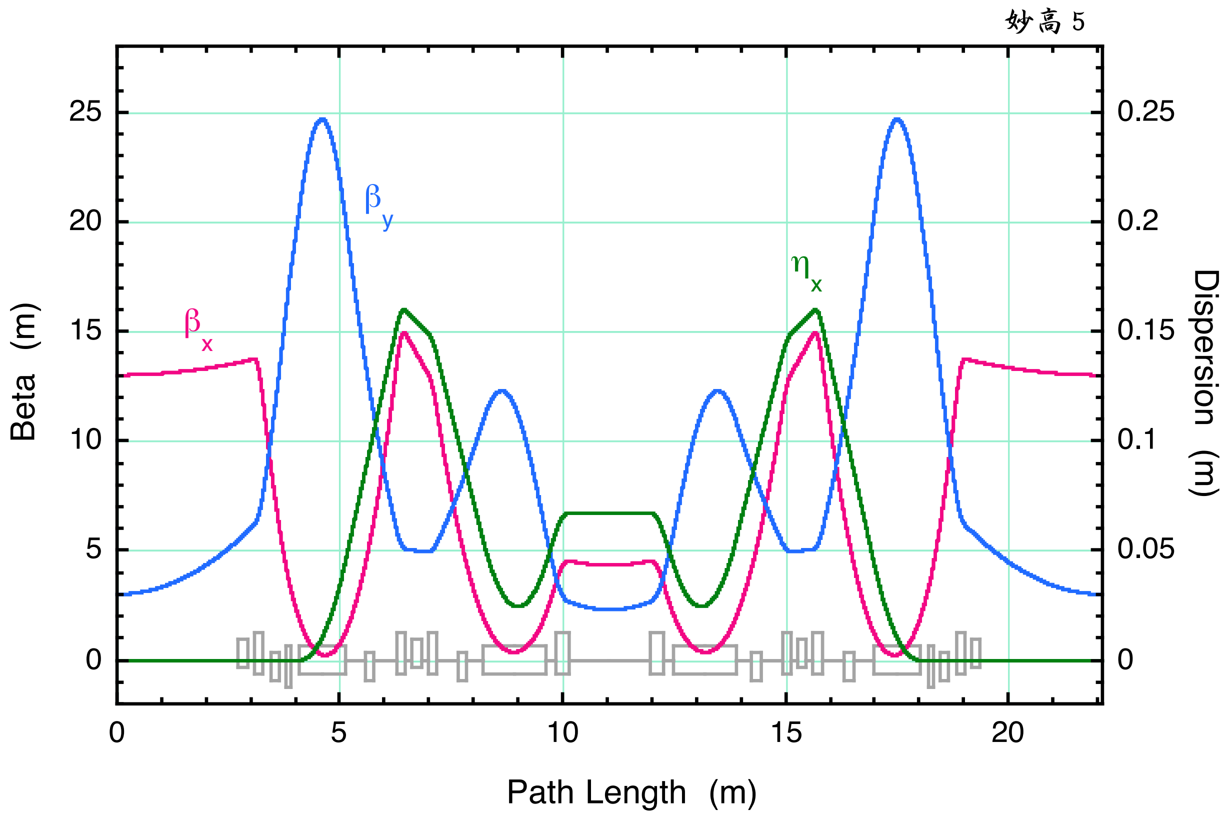
6. Simple lattice, simple devices !
   => should not be difficult structure

SLiT-J storage ring – main parameters -



- Energy: 2.998 GeV ($B\rho$ = 10)
- Circumference: 353.74 m (L_{cell} = 22.11 m)
- Natural emittance: 0.92 nmrad (/w.o insertions)
- Lattice: DDBA with two types of 0.8 T dipoles
- Straight sections: 5.44 m × 16 (long s.s.)
  1.84 m × 16 (short s.s.)
- Beam size: 109 μm × 5.3 μm – L.s.s.
  (1%-coupling) 85 μm × 5.5 μm – S.s.s.

SLiT-J storage ring – linear lattice 1 -



Field strength

- combined dipole-A 0.8 T - 6.8 T/m
- combined dipole-B 0.8 T - 7.0 T/m
- quadrupole < 40 T/m
- sextupole < 1300 T/m^2

Moderate strength

Number of magnets

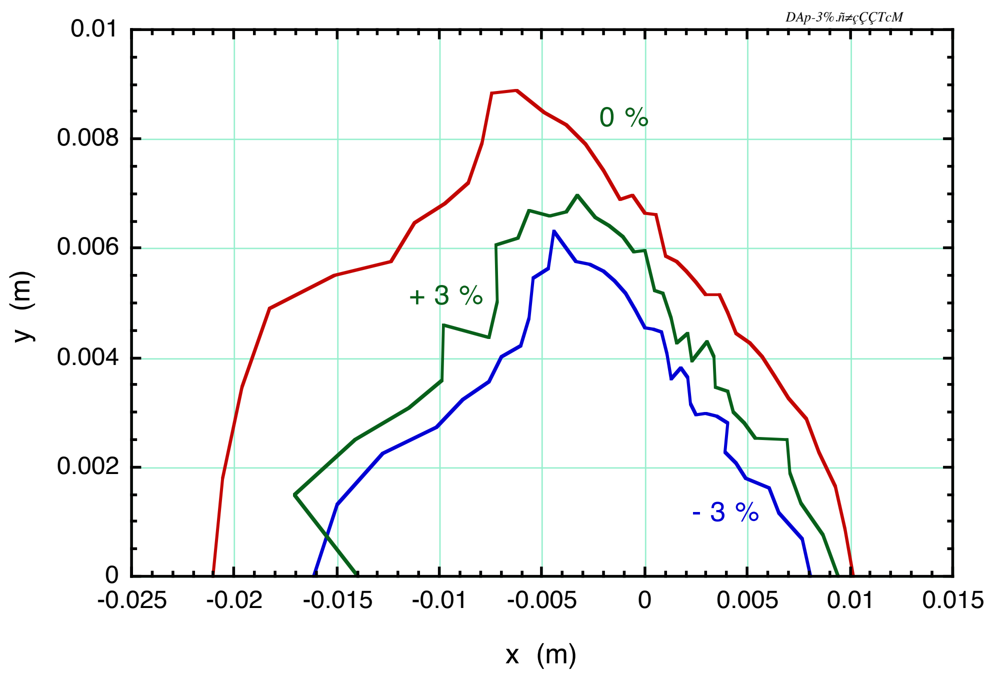
- dipole 64 (2-family)
- quadrupole 160 (5-family)
- sextupole 160 (5-family)

SLiT-J storage ring – linear lattice 2 -

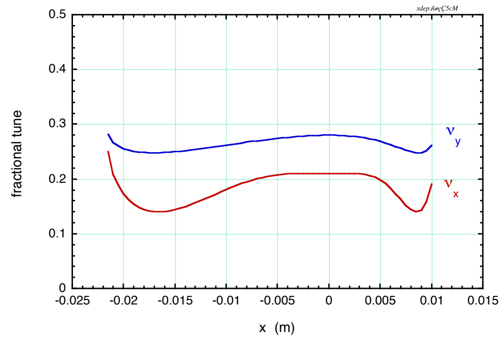
Lattice parameter		妙高５cMversion
Beam energy	E (GeV)	2.998
Lattice structure		DDBA
Circumference	C (m)	353.740
Number of cells	N_s	16
Long straight section	(m)	5.44 × 16
Short straight section	(m)	1.84 × 16
Betatron tune	x / y	29.21 / 10.28
Natural chromaticity	x / y	-70.655 / -40.405
Natural horizontal emittance	(nmrad)	0.92
Momentum compaction factor	α	0.00045
Natural energy spread	σE/E (%)	0.082
Lattice functions at LSS	β_x / β_y / η_x (m)	13.0 / 3.0 / 0.0
Lattice functions at SSS	β_x / β_y / η_x (m)	4.33 / 2.30 / 0.067
Damping partition number	J_x / J_s	1.432 / 1.568
Damping time	τ_x / τ_y / τ_s (ms)	8.62 / 12.34 / 7.87
Energy loss in bends	(MeV/turn)	0.573
RF frequency	(MHz)	508.51
Harmonic number	h	600

SLiT-J storage ring – nonlinear dynamics -

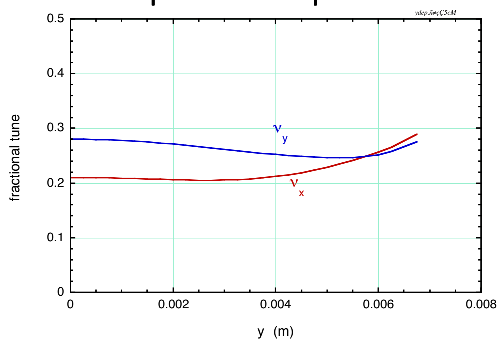
Dynamic aperture



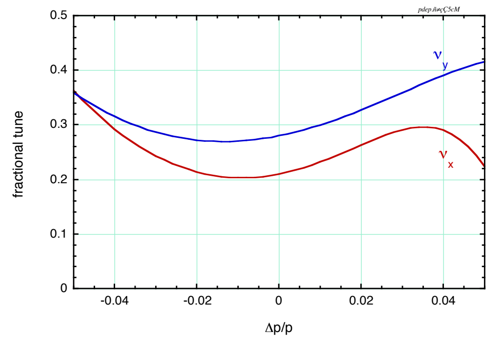
Horizontal amplitude-dependent tune shift



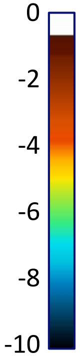
Vertical amplitude-dependent tune shift

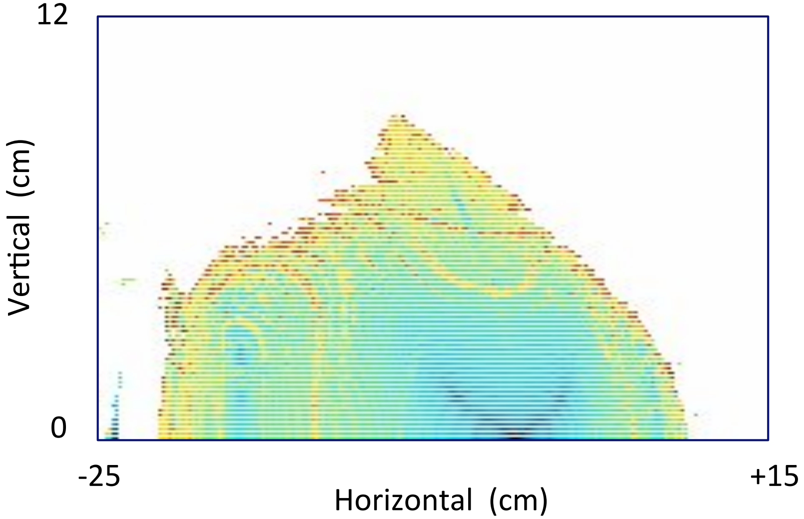


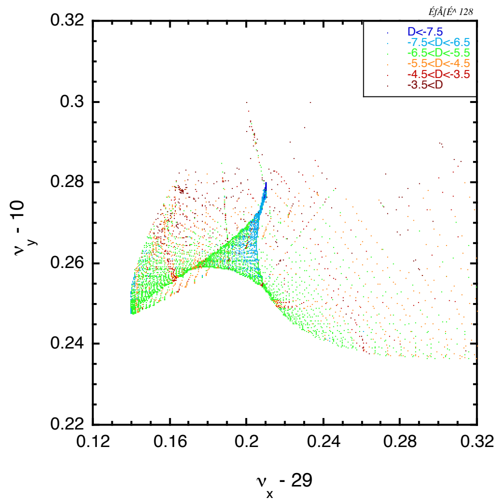
Momentum-dependent tune shift

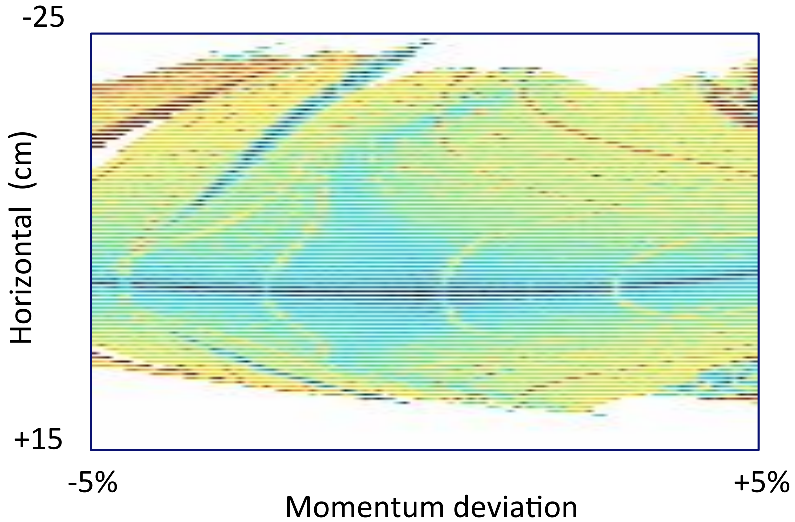


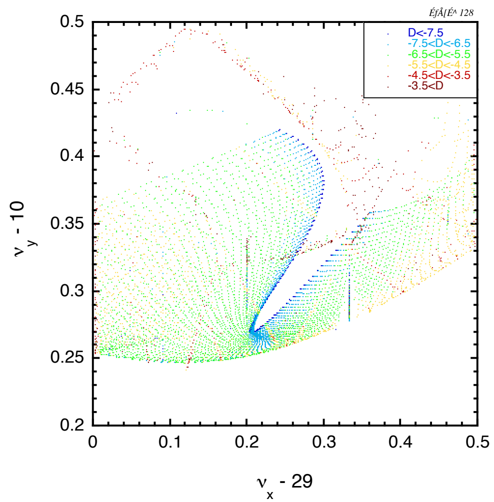
SLiT-J storage ring – frequency map -



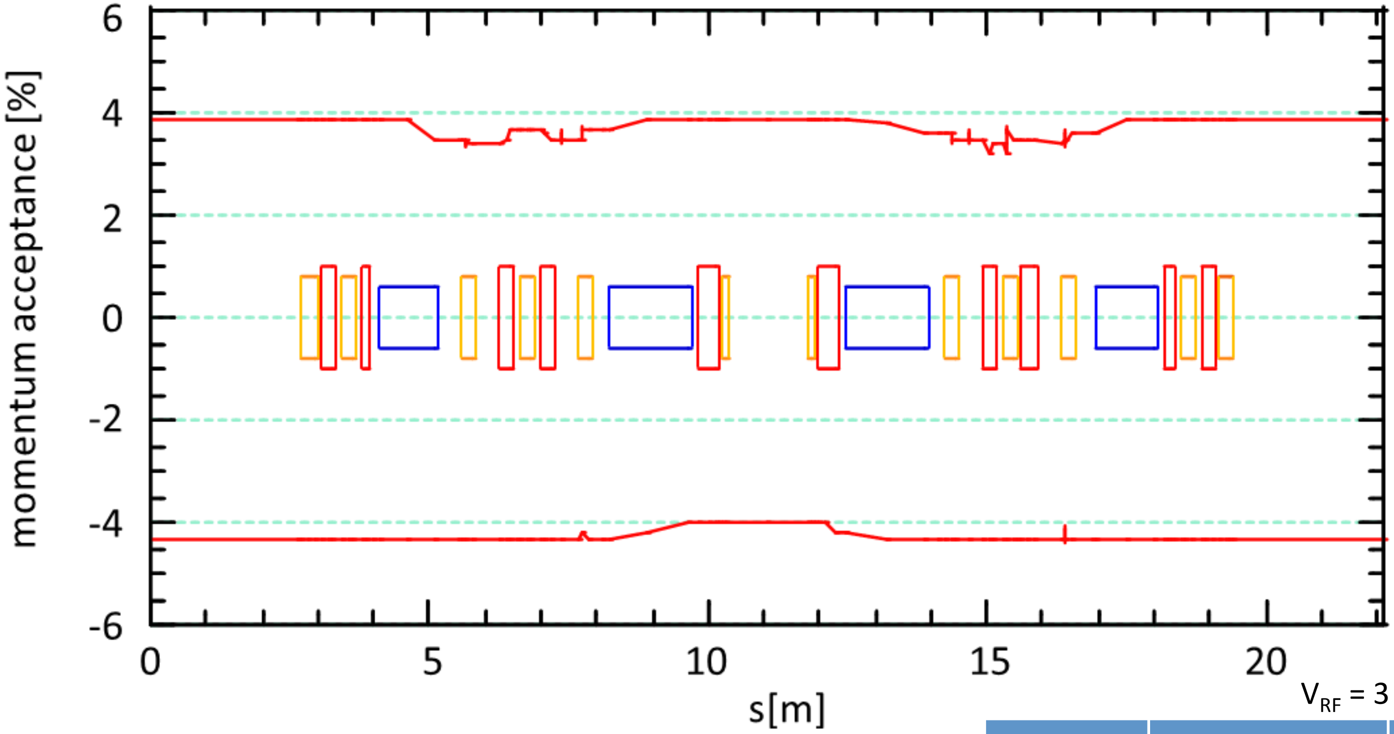








SLiT-J storage ring – Touschek lifetime -



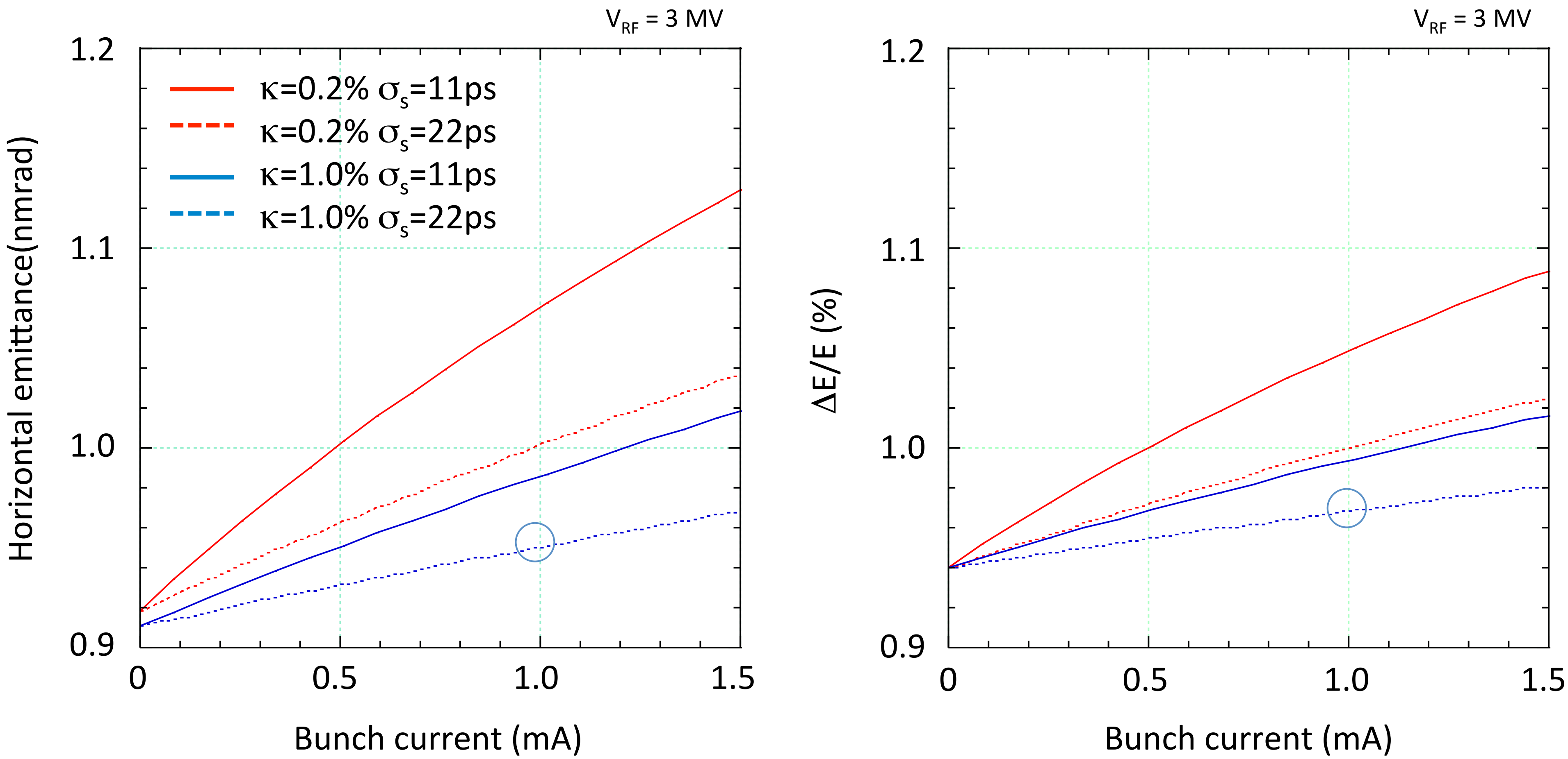
V_{RF} = 3 MV & 1 mA/bunch

κ (%)	σ_s (ps)	τ (hours)
0.2	11	3.8
1.0	11	8.5
0.2	22	7.6
1.0	22	17

If the bunch does not lengthen, Touschek life is miserably short. (The bunch length is expected to be twice of natural one due to the resistive ring impedance.)

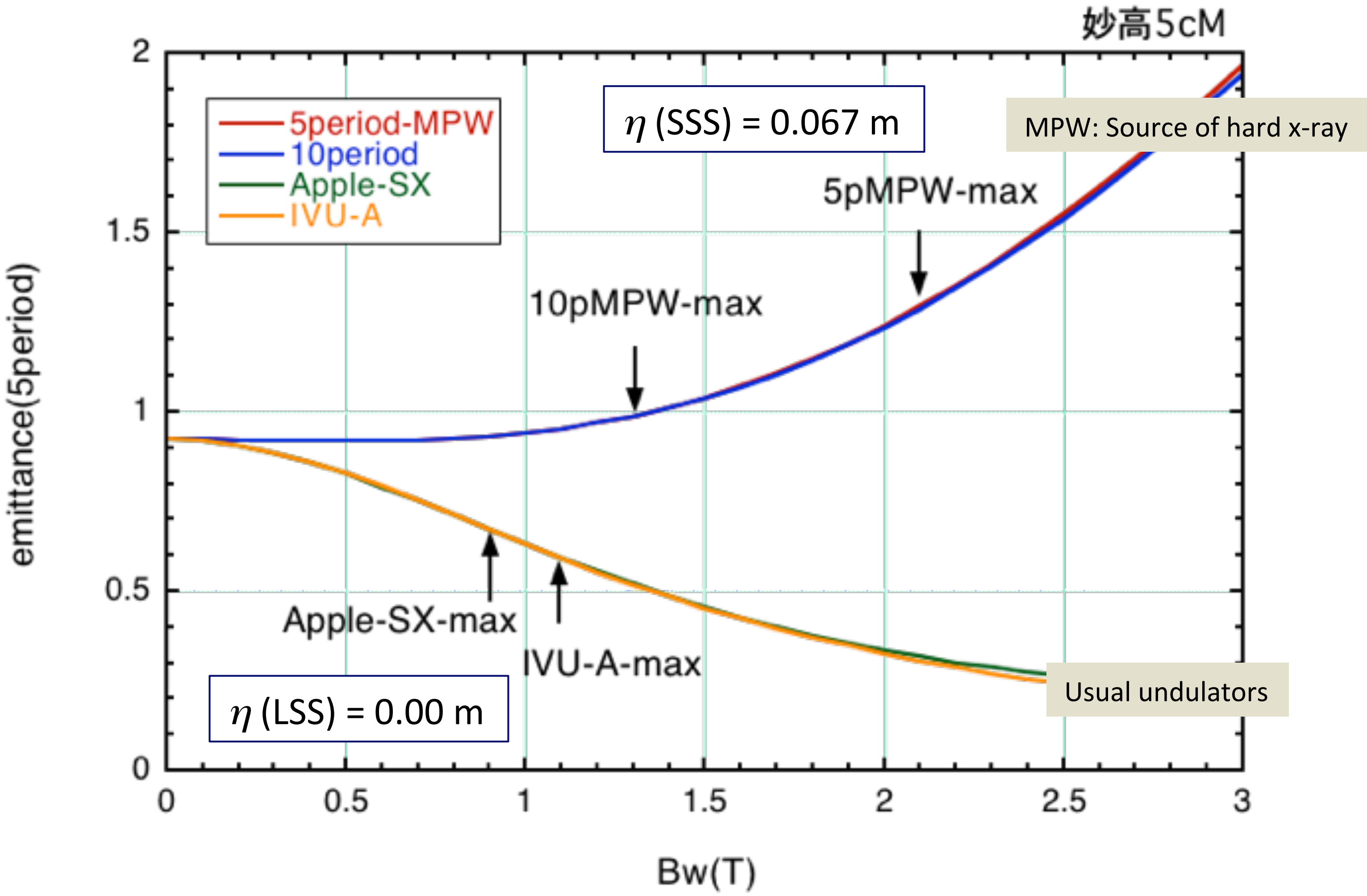
Harmonic cavity to lengthen the bunch has to be considered.

SLiT-J storage ring – Intra beam scattering -



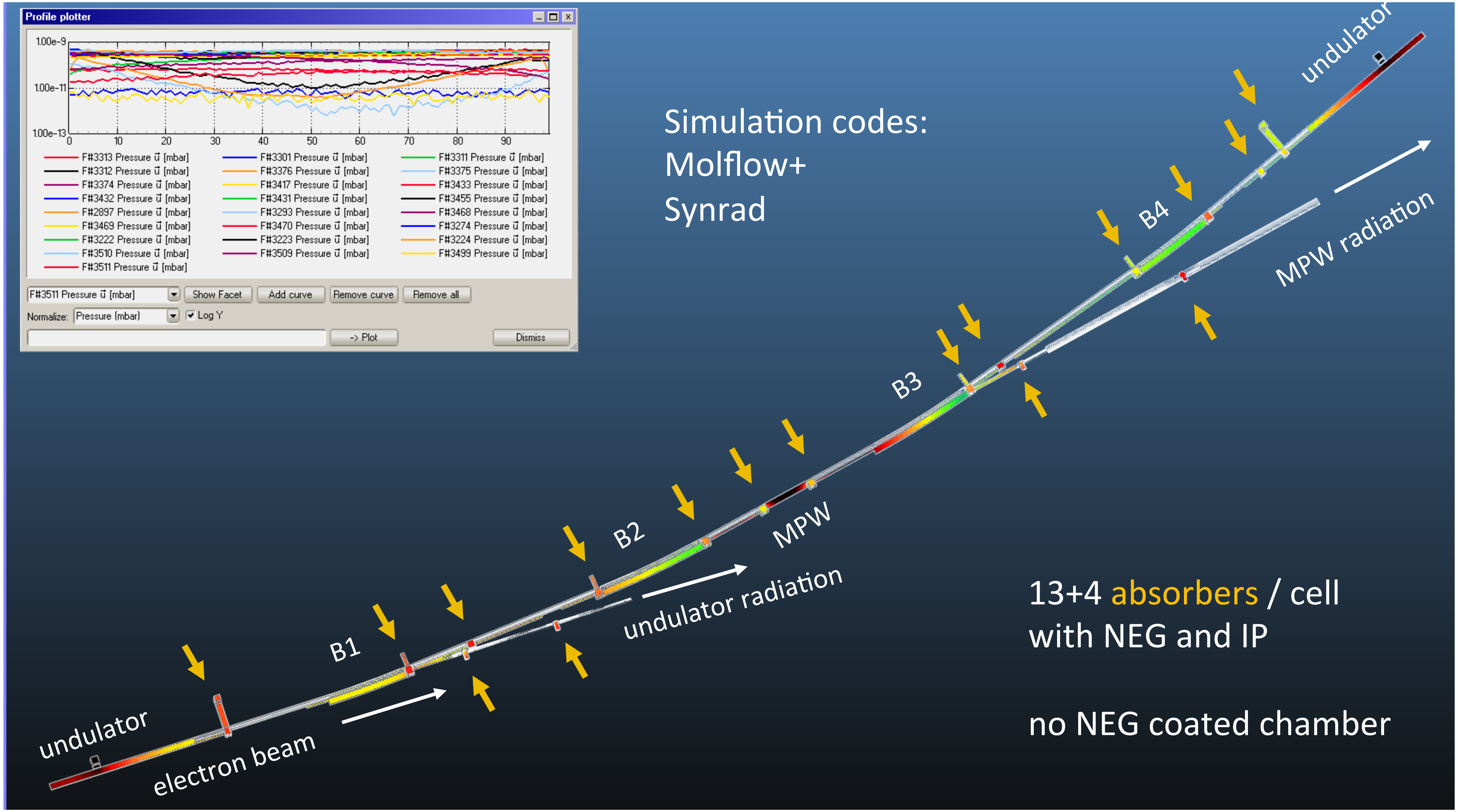
The emittance growth at 400mA operation would be small for κ=1%, σ_s=22ps.

SLiT-J storage ring – with insertions -



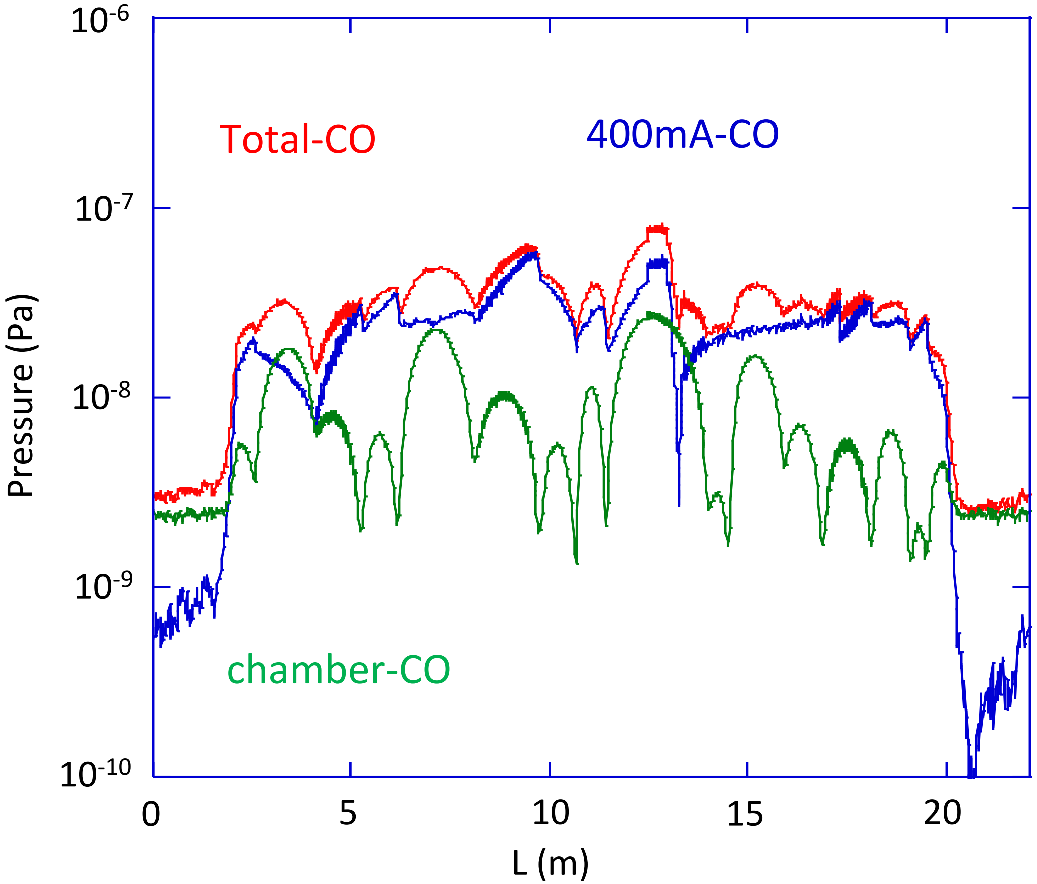
We expect the emittance range would be 0.83 ~ 0.97 nmrad for usual operation.

SLiT-J storage ring – vacuum system -



SLiT-J storage ring – vacuum system -

Partial pressure profile of CO along 1 cell

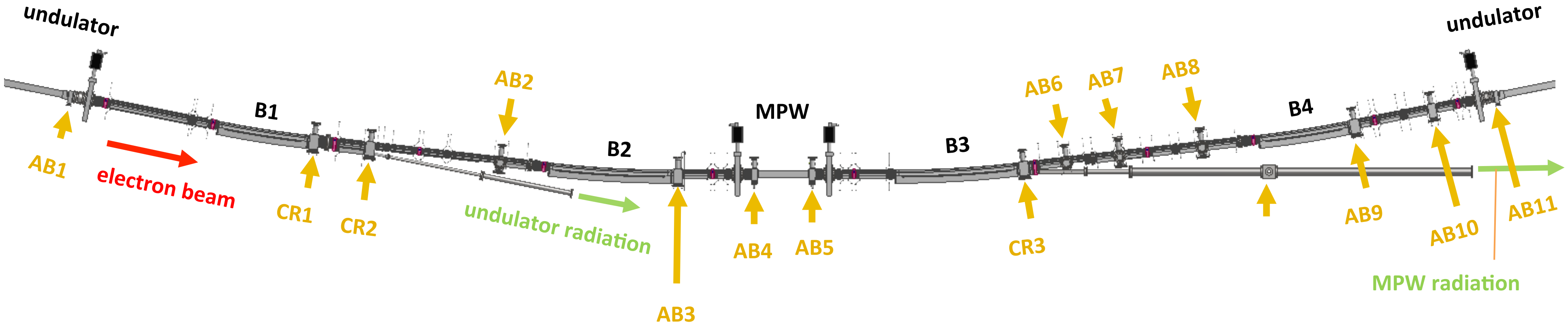


	Partial pressure (Pa)	Life (h)	PSD (400Ah)	Gas desorption rate (Pa m/s)
H_2	1.2e-7	293	7.6e-6	5.4e-9
CO	2.9e-8	35	7.7e-7	1.3e-9
CH_4	2.9e-8	67	7.5e-8	
CO_2	4.2e-9	102	1.2e-7	
total		18		

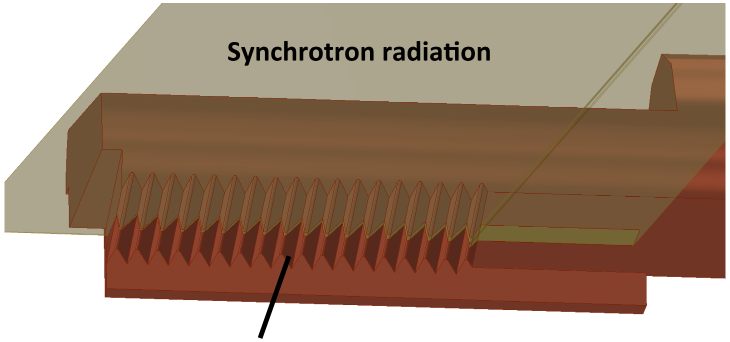
SLiT-J Photon absorber

	AB1	CR1	CR2	AB2	AB3	AB4	AB5	CR3	AB6	AB7	AB8	AB9	AB10	AB11
Offset from beamline [mm]	17	24	17	17	26	42	17	39.5	35.5	34	17	22.5	20	17
Power density [W/mm^2] (Normal incident)	2.6	127.3	67.7	16.1	77.2	35.4	35.6	72.7	56.7	31.6	23.0	118.5	58.9	24.4
Total power [W]	219.9	853.8	1376.6	422.7	2362.5	847.6	871.3	1463.7	1141.1	604.8	593.5	1385.5	1284.2	292.7

Beam current: 400 mA



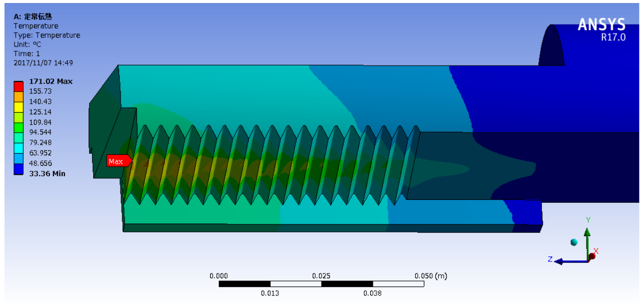
SLiT-J Photon absorber AB3



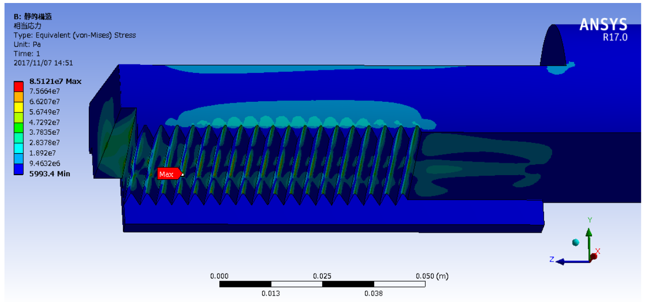
Toothed geometry[1]

Photon absorber AB3

Item	AB3
Offset from beamline [mm]	26
Power density [W/mm^2] (Normal incident)	77.2
Total power [W]	2362.5
Maximium tenperature [℃]	171
Maximum thermal stresses [MPa]	85



Temperature distribution



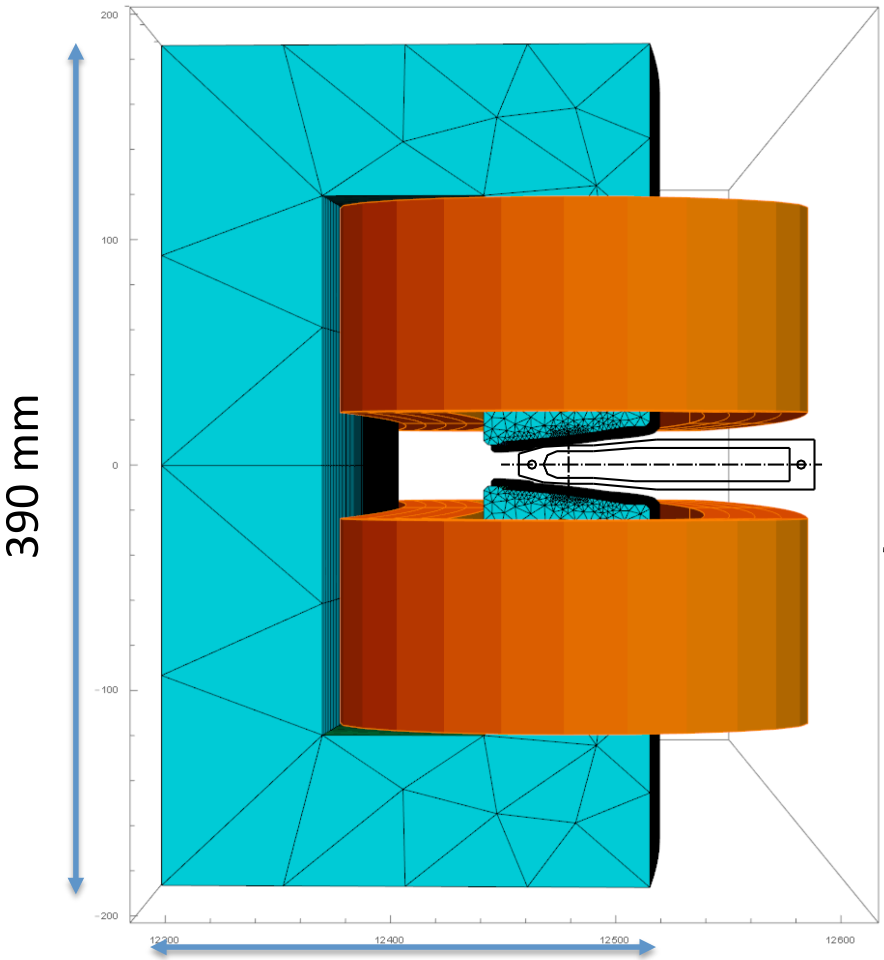
Mises stress distribution

[1] F. Thomas et al., "X-RAY ABSORBER DESIGN AND CALCULATIONS FOR THE EBS STORAGE RING", Proceedings of MEDSI2016, Barcelona, Spain (2016) .

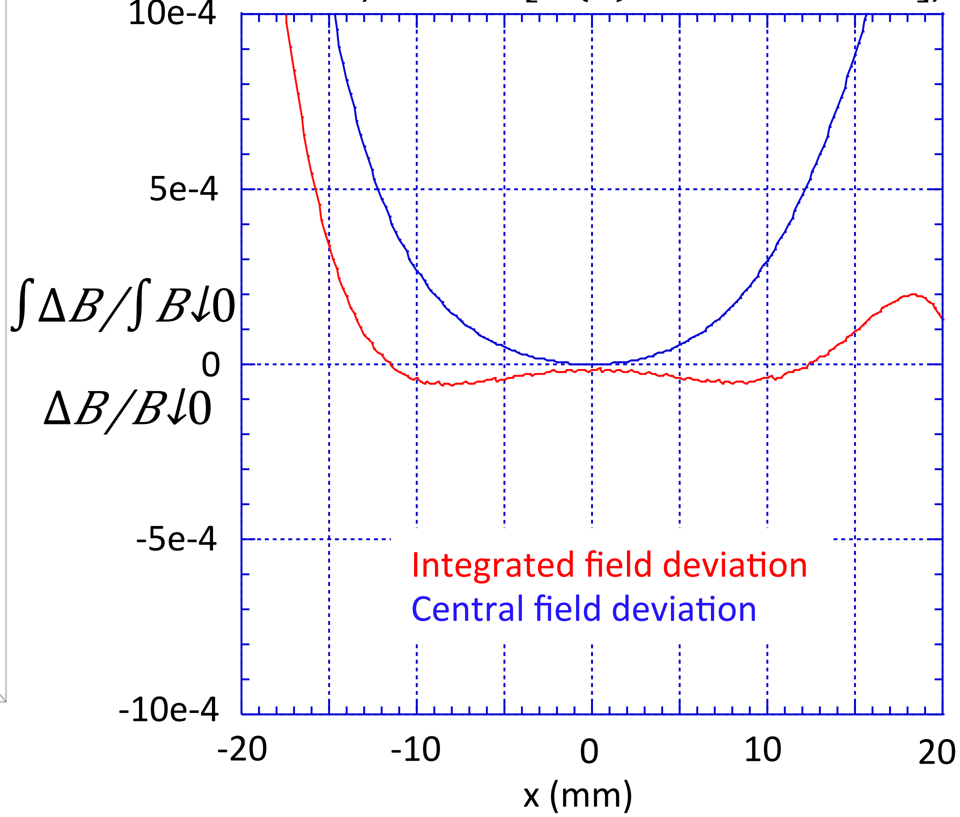
SLiT-J storage ring – magnet 1 -

Combined bending magnet (gap =28 mm)

	design
B [T]	0.8
B' [T/m]	~~-6.7~~ -> -6.8
ρ [m]	12.5
θ [deg]	6.525



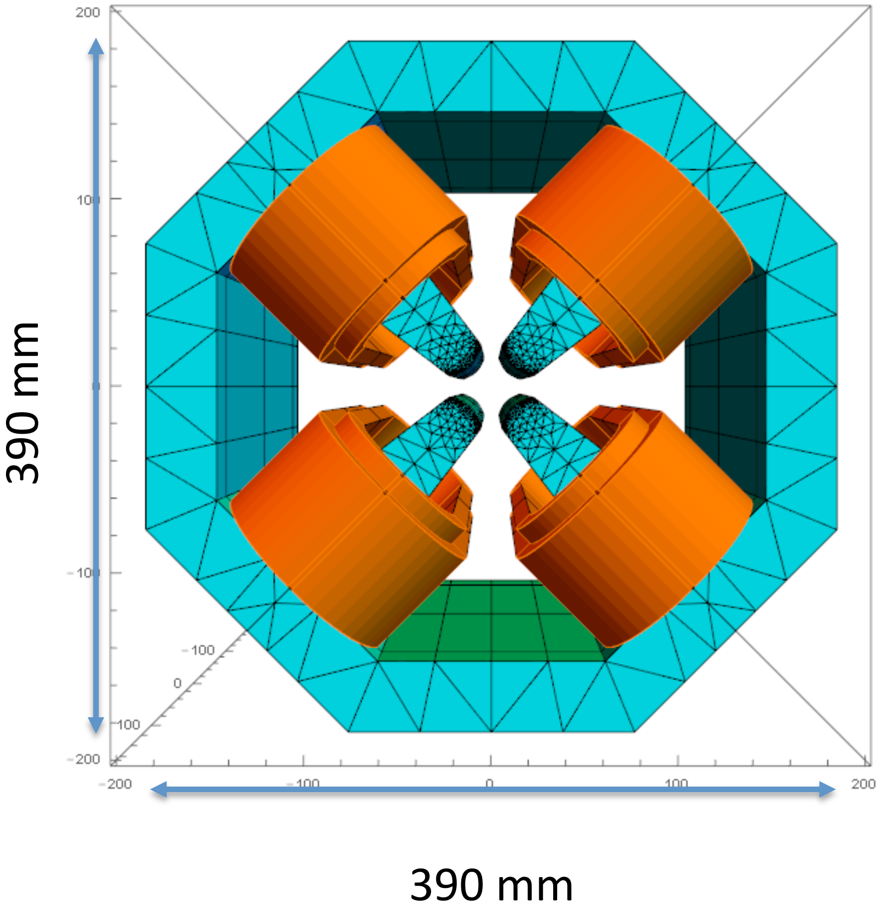
$$\Delta B/B_0 = [B(x) - b_1 x - b_0]/B(x)$$

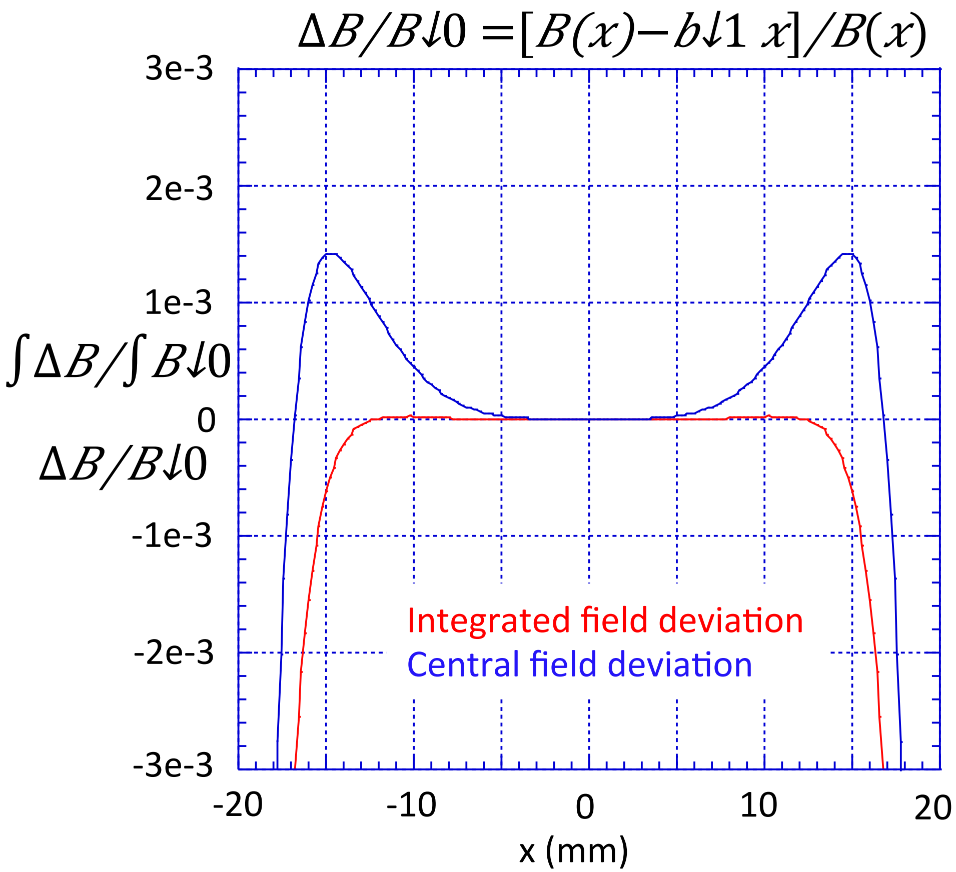


SLiT-J storage ring – magnet 2 -

Quadrupole magnet (ϕ =34 mm)

	design
B’ [T/m]	33.7
L [m]	0.3



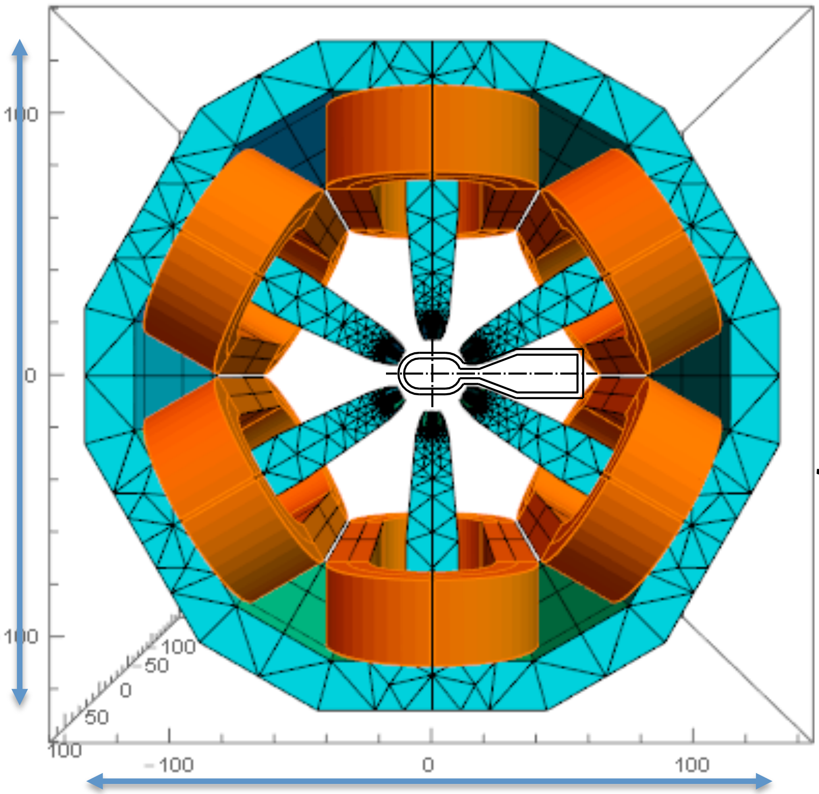


SLiT-J storage ring – magnet 3 -

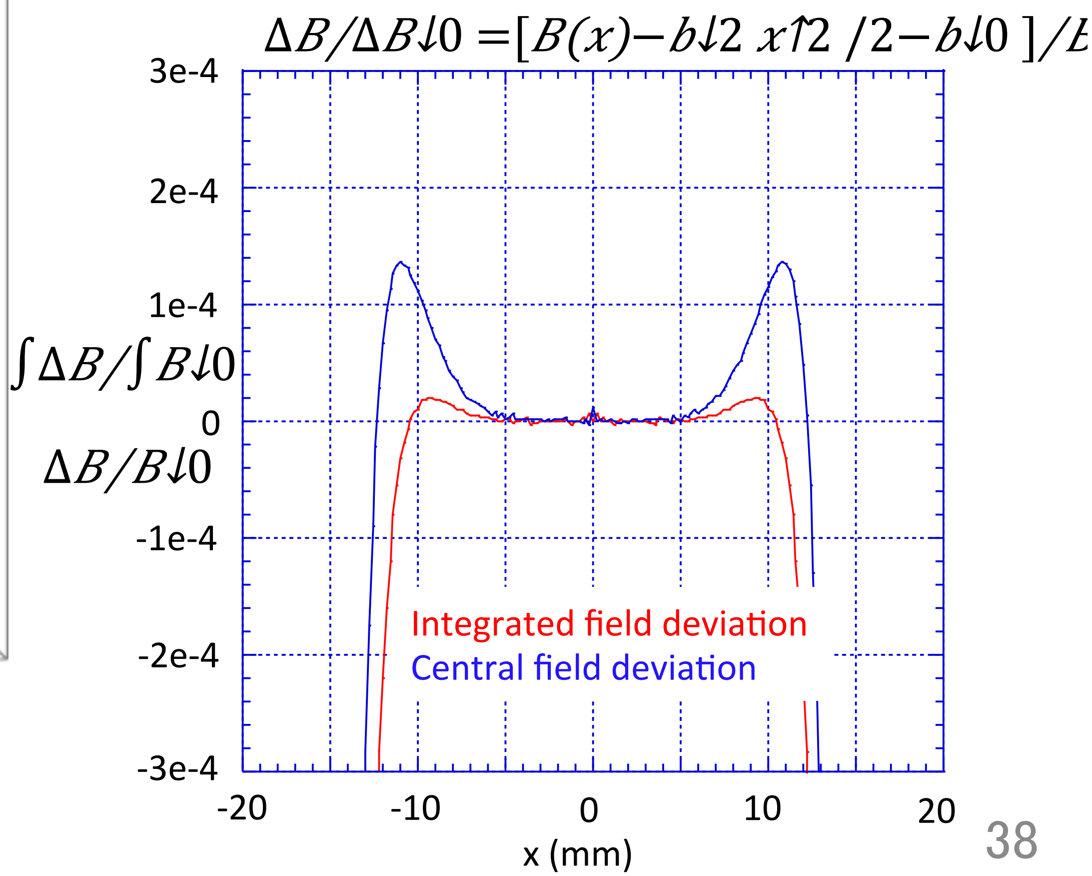
Sextupole magnet (ϕ =40 mm)

	design
B'' [T/m²]	1050
L [m]	0.2

270 mm



280 mm

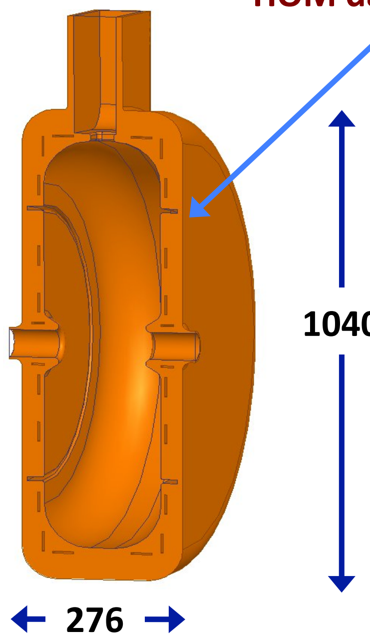


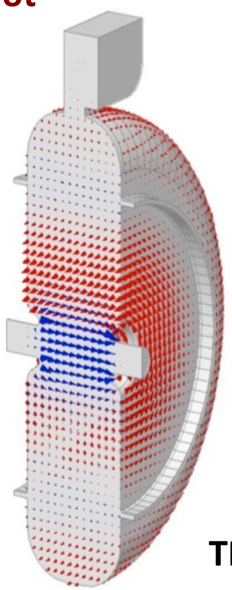
SLiT-J storage ring – TM_{020} cavity-
(designed and developed Dr. Ego's team @ SPring-8)

It is compact and high-Q !

RF frequency	508 MHz
Mode	TM020
Shunt impedance	6.8 MΩ
Unloaded-Q	60300
Acc. voltage	900 kV (max.)

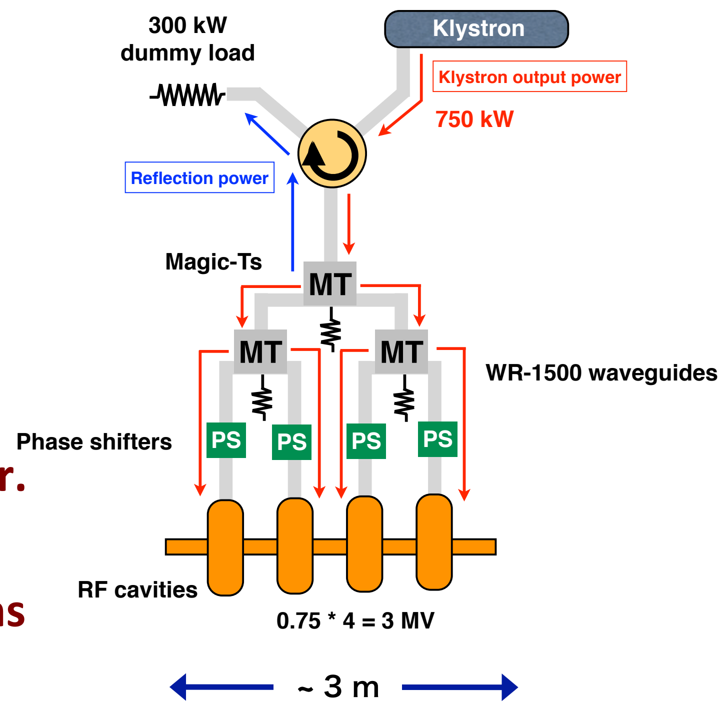
HOM damper slot





TM020 mode

High-power test is being carried out.

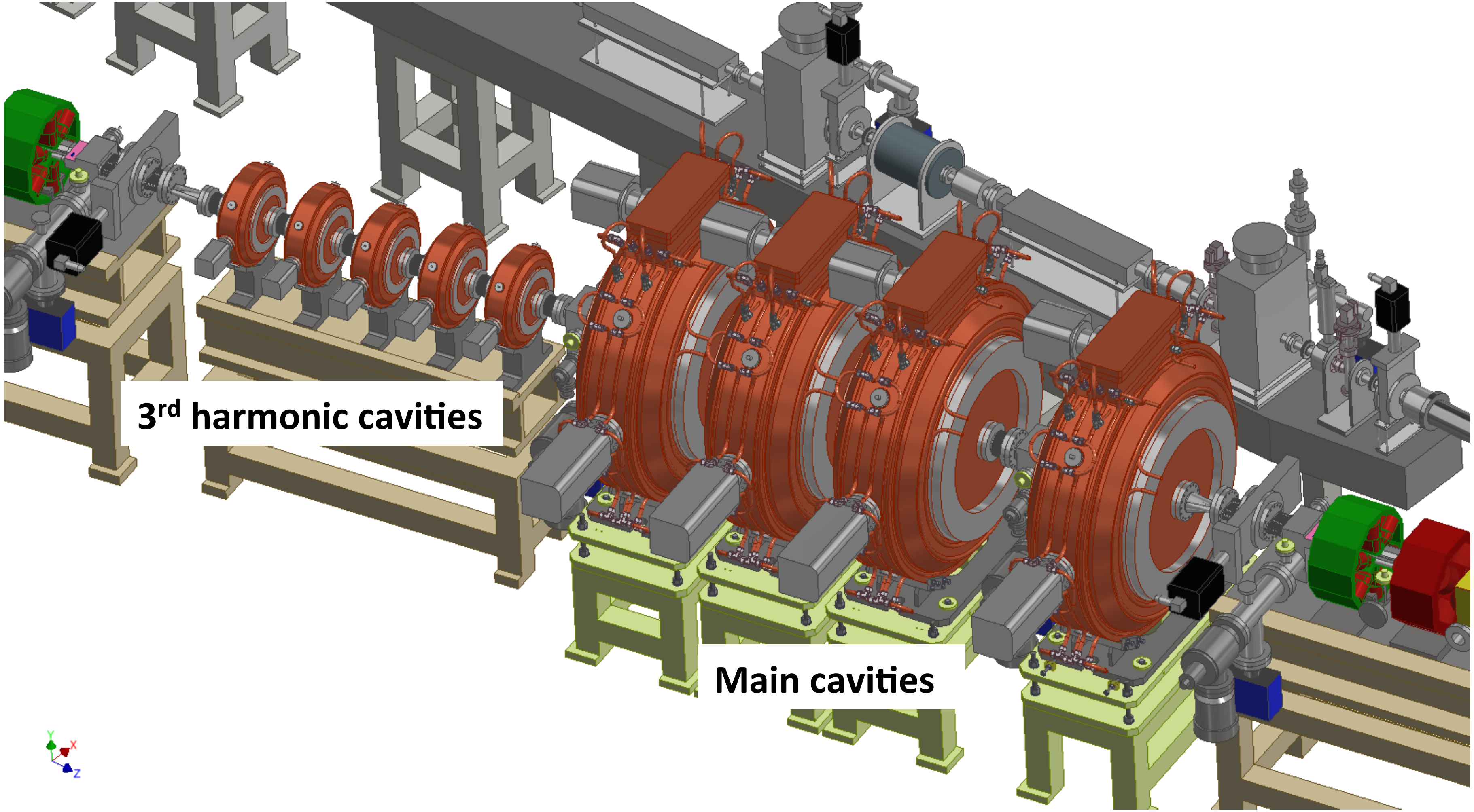


- Only one new device to be developed !
- A 4-cavity system is sufficient to provide the beam power.

  =>

- Among 16 straight sections, 14 are available for insertions (RF cavity station 1, beam injection 1)

SLiT-J storage ring – 3rd harmonic cavity -



Passive operation is considered

SLiT-J injector -1-

Full energy injector is required for top-up operation

- Lower beam emittance is necessary for efficient beam injection

1) Large circumference booster synchrotron (SLS, TPS …)
2) High brilliant linac (MAX-IV)

↓

Our choice: 3/8 of SACLA@SPring-8 linac

1) Japanese original C-band technology
2) Sufficient beam quality and stability
3) Future soft-X FEL combined use with high brilliant SR from the storage ring

However ....

1) XFEL system is too much expensive for the injector
   (particularly timing system and high brilliant electron gun)

Our temporal choice:

1) Thermionic RF gun, very stable, is employed
2) Timing system and high charge gun will be upgraded as 2^{nd} stage project

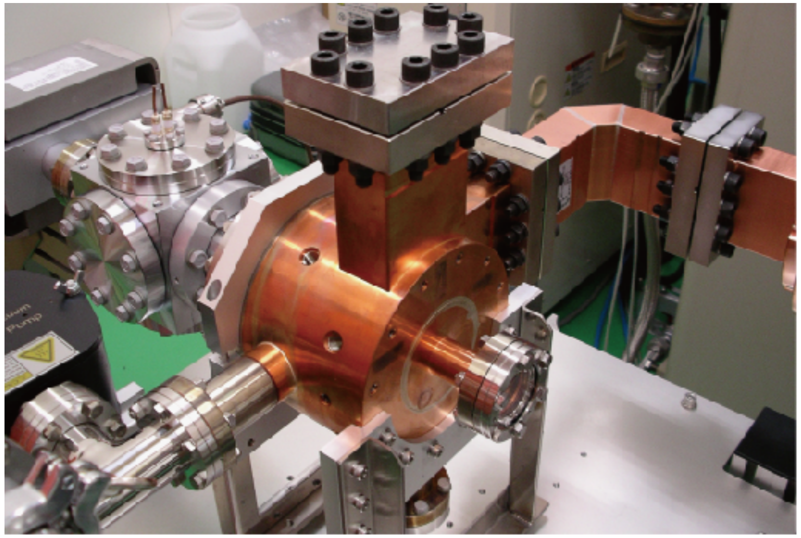
SLiT-J injector -2-

Thermionic RF gun with chopper + c-band linac

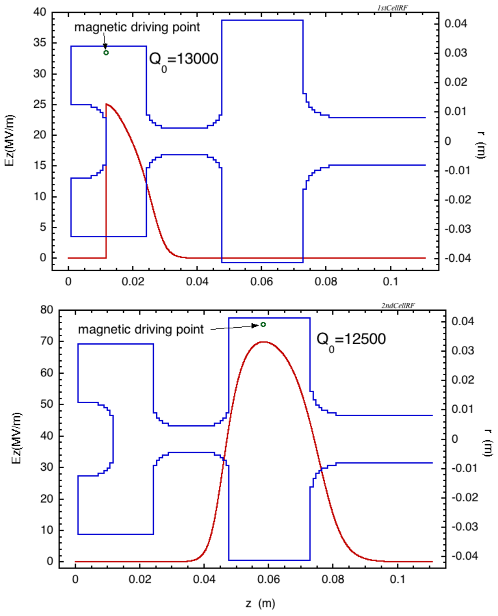
A 1ns chopper makes 3-bunch into one 500 MHz bucket

ITC-RF gun (Independently Tunable Cells)

- Developed at ELPH, Tohoku University to produce femtosecond bunch
- Longitudinal phase space can be controlled
- Bunch charge 20 pC/ microbunch and normalized emittance less than 5 mmmrad

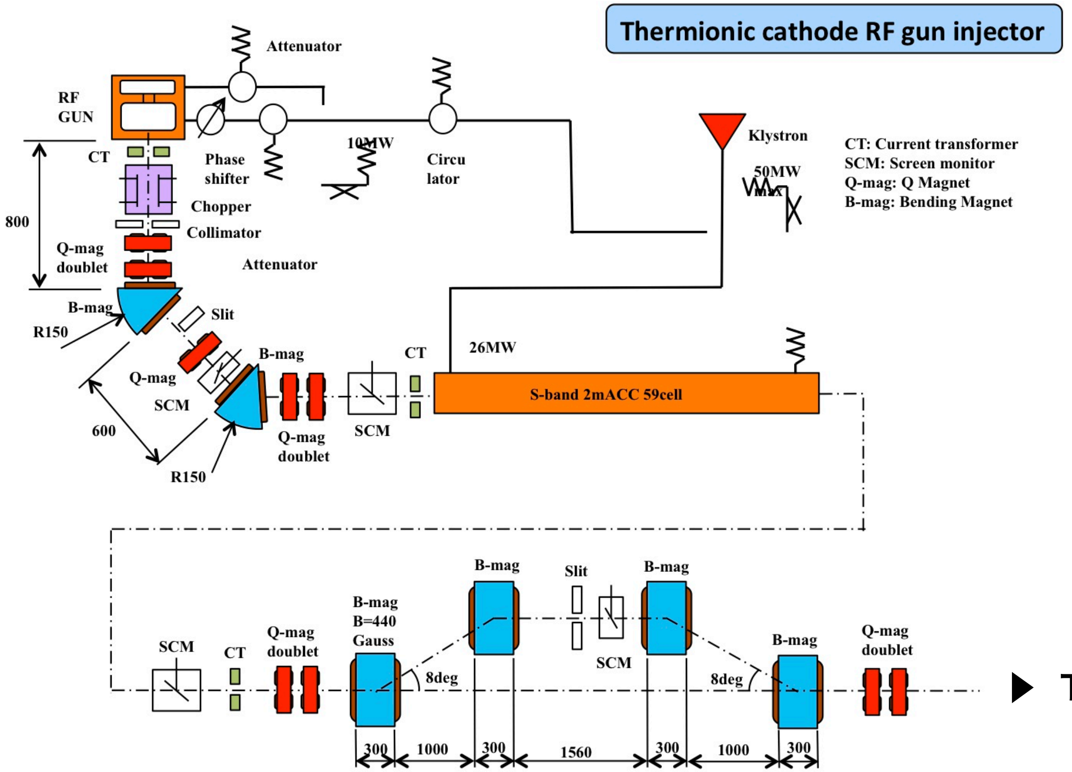


S-band Thermionic RF gun (ITC RF Gun)



It has been used for an injector of 1.3 storage ring at ELPH.
Very stable but less bunch charge.

SLiT-J injector -3-



▶ To C-band acc. ▶ To Ring

Characteristics of Injector Beam

Beam energy	E	3GeV
Energy spread	$\Delta E/E$	<0.1% (1σ)
Energy stability	δE	<0.1% (1σ)
Beam charge	Q	0.3nC/sec
Charge stability	δQ	~1%
Normalized emittance	$\beta\gamma\varepsilon$	<5πmm・mrad
Un-normalized emittance	ε	<1nmrad
Bunch length	σ_z	<5ps
Repetition rate	f_{rep}	25Hz(max)

C-band Linac

50MW klystron	× 19
2m-acc structure	× 38 (max. gradient 45 MV/m))
Max repetition	25 Hz

Linac total length ~120 m

ε @3GeV ~ 1nmrad

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SLiT-J insertions -1-

Available straight section

Straight section	Structure	Minimum gap	Total length
LSS	In-vacuum	5mm	4.2m
LSS	Out-vacuum	15mm	4.2m
SSS	Out-vacuum	13/15mm	0.6m

Spec of beam line

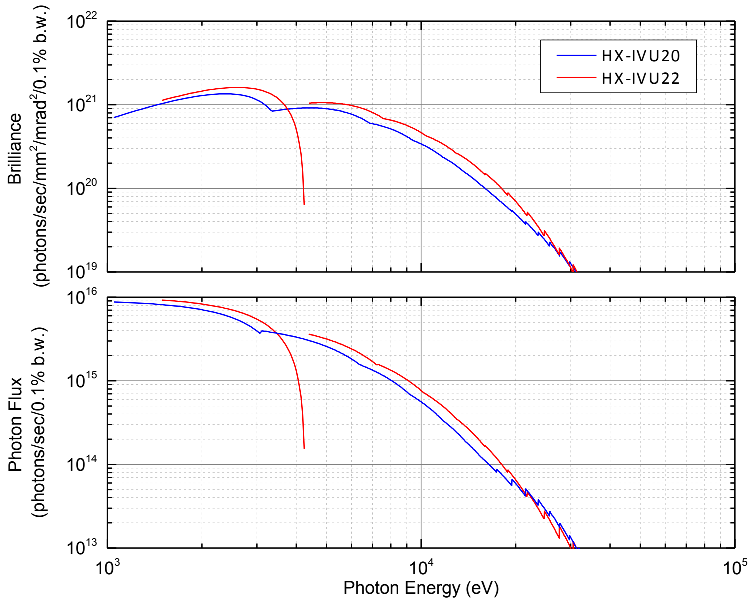
Name	Straight Section	Polarization	Photon energy
HX	LSS	Horizontal	4keV~
MPW	SSS	Horizontal	10keV~
SX	LSS	Variable	200eV~
SX-LPR	LSS	H or V	200eV~
EUV	LSS	Variable	50eV~
EUV-LPR	LSS	H or V	50eV~

SLiT-J insertions -2-

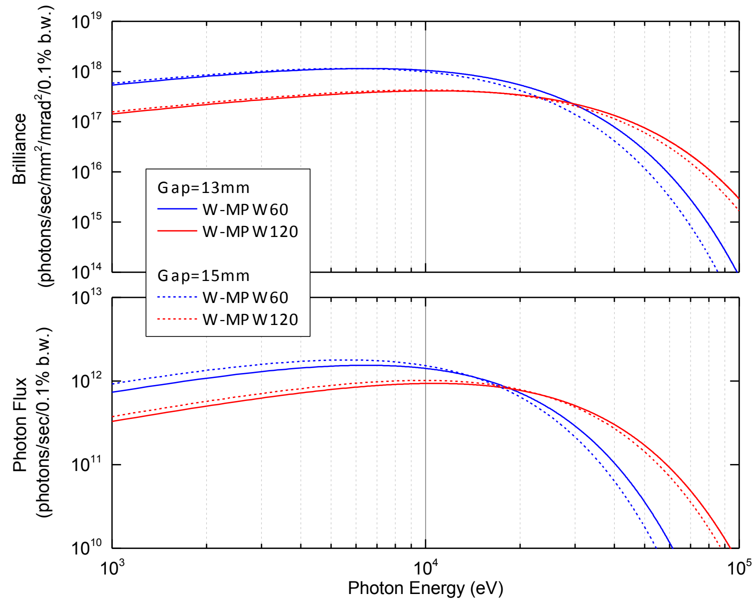
NAme	Type	Period (mm)	K_{max}	Energy range (eV)	Beamline
IVU20	In-vacuum	20	1.97	>4360	HX
IVU22	In-vacuum	22	2.36	>3130	HX
MPW	wiggler	60~ 120	2.53~17.4 (0.71~1.97T)	-	W
APPLE-SX	APPLE	56	CPR:2.75 HPR:4.67 VPR:3.39	>178 >128 <226	SX
F8-SX	Figure-8	46	Kx:2.81 Ky:3.23	>183	SX-LPR
APPLE-EUV	APPLE	75	CPR:4.84 HPR:7.73 VPR:6.21	<46.6 <36.9 <56.1	EUV
F8-EUV	Figure-8	64	Kx:4.55 Ky:5.99	<45.5	EUV-LPR

SLiT-J insertions -3-

HX

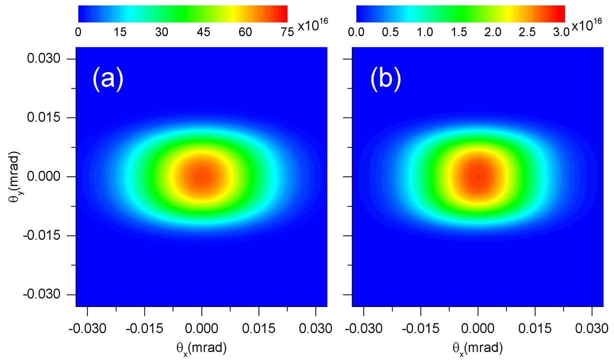


MPW



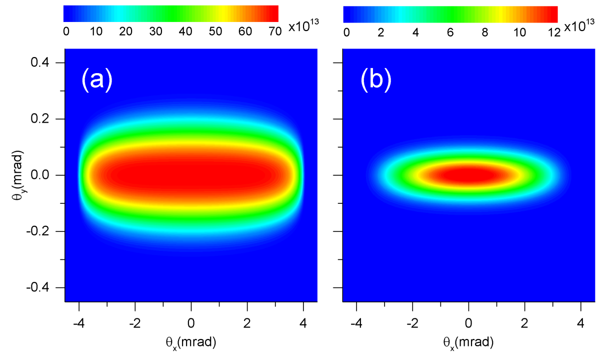
IVU-20

@10 keV @22 keV



MPW120

@10 keV @50 keV



SLiT-J insertions -4-

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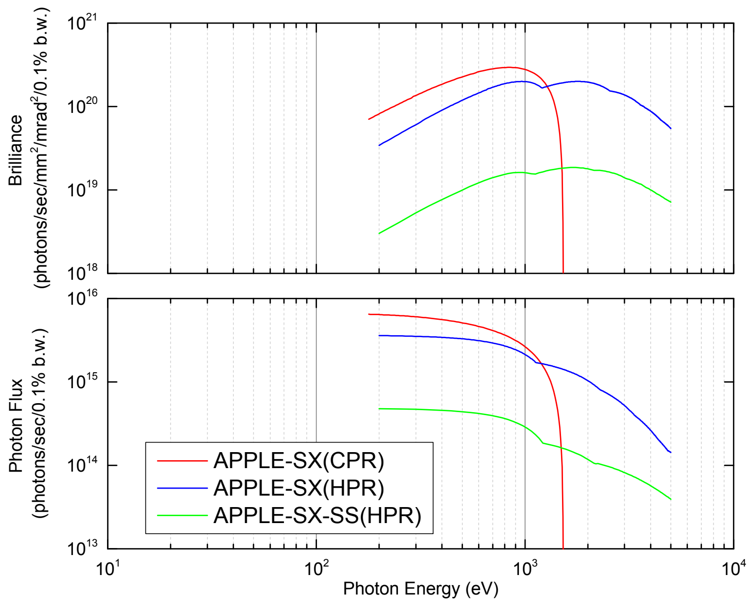
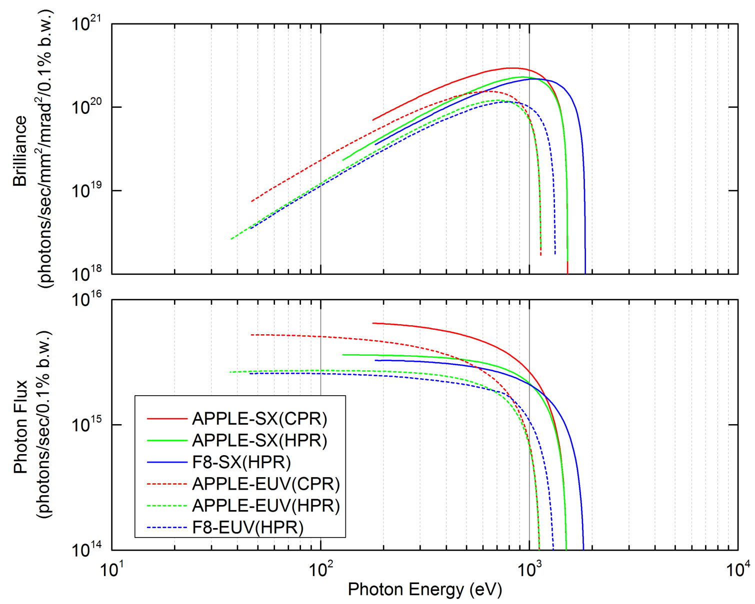
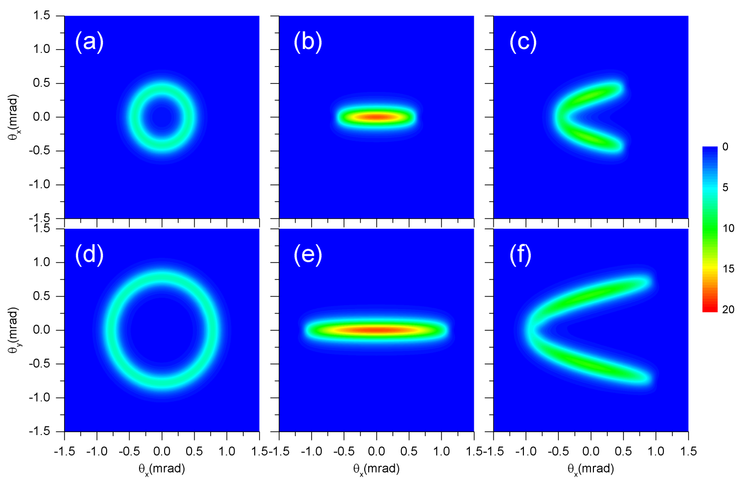
SX



SX-EUV

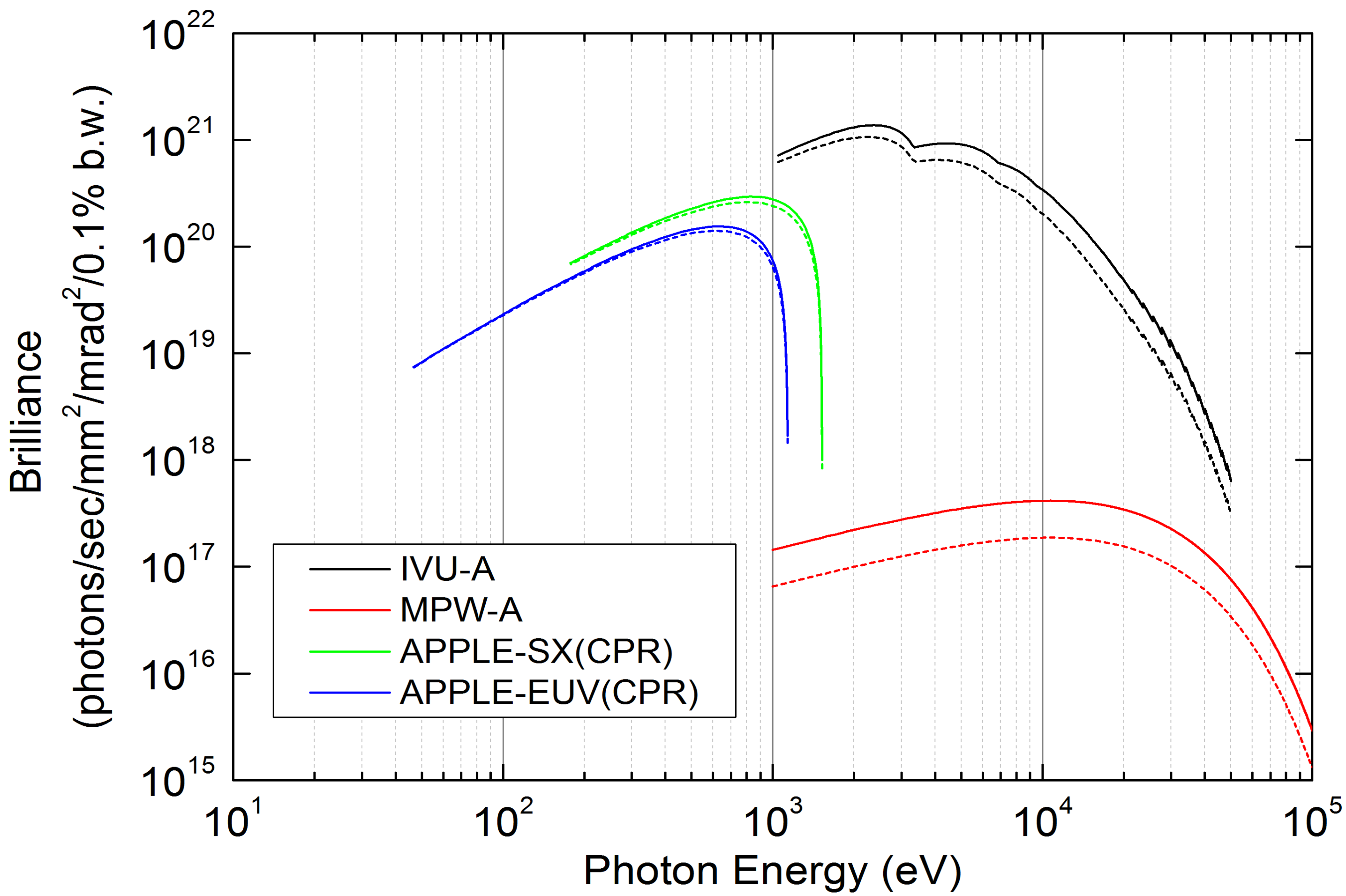




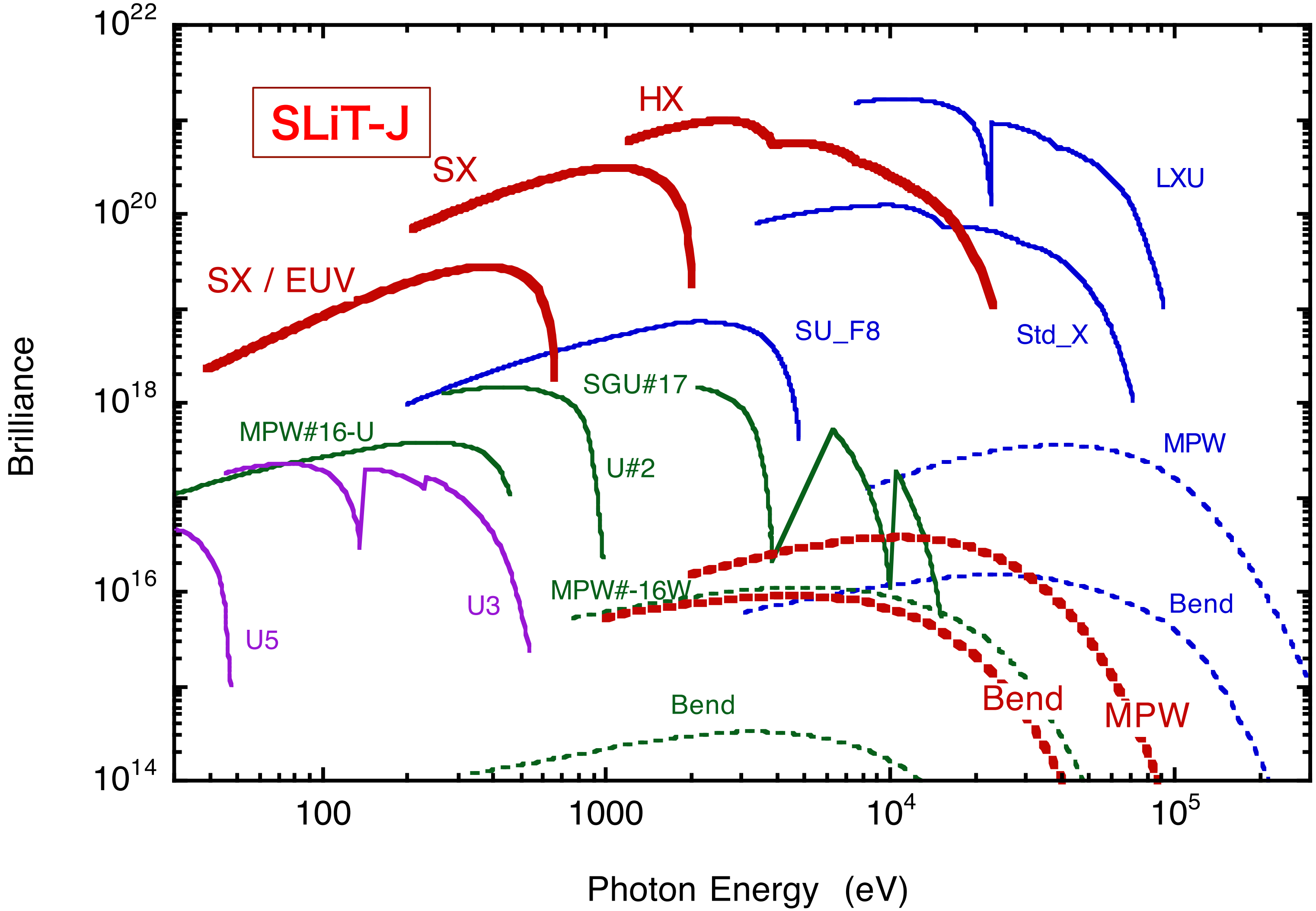
Spatial power distribution at SX/EUV beam line (kW/mrad²)

(a) APPLE-SX (CPR)
(b) APPLE-SX (HPR
(c) F8-SX (HPR
(d) APPLE-EUV (CPR)
(e) APPLE-EUV (HPR)
(f) F8-EUV (HPR)

SLiT-J insertions -5-



SLiT-J insertions -6-



SLiT-J summary

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- Conceptual design of 3 GeV SLiT-J accelerators is performed

Light source
DDBA lattice of 16 cells, circumference 354 m
emittance 920 pmrad (~700 pmrad with insertions)
26 beamlines available
brilliance 10^{21}@ a few keV

Injector
C-band technology, 120 m long
thermionic RF gun, 3-bunch injection
future XFEL option

Power consumption	
Storage ring	2.00
Injector linac @1Hz	0.26
Control system	0.10
Beam line (26 stations)	0.28
Utility and others	1.70
Total	4.34 MW

SPring-8 ~40MW

GOAL: Integrated package of the facility
- ☞ easy maintenance
- ☞ small energy consumption
- ☞ low running cost

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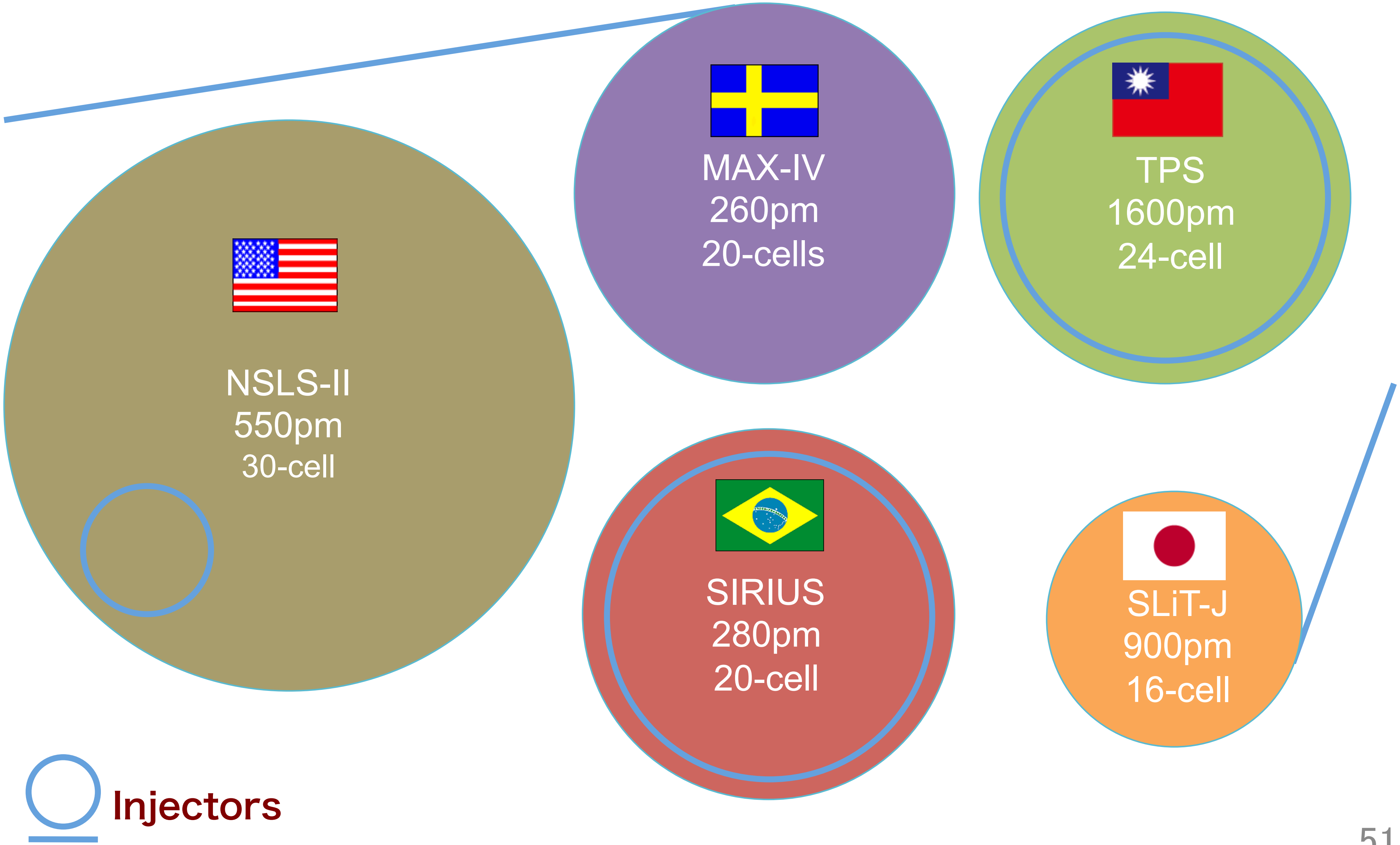
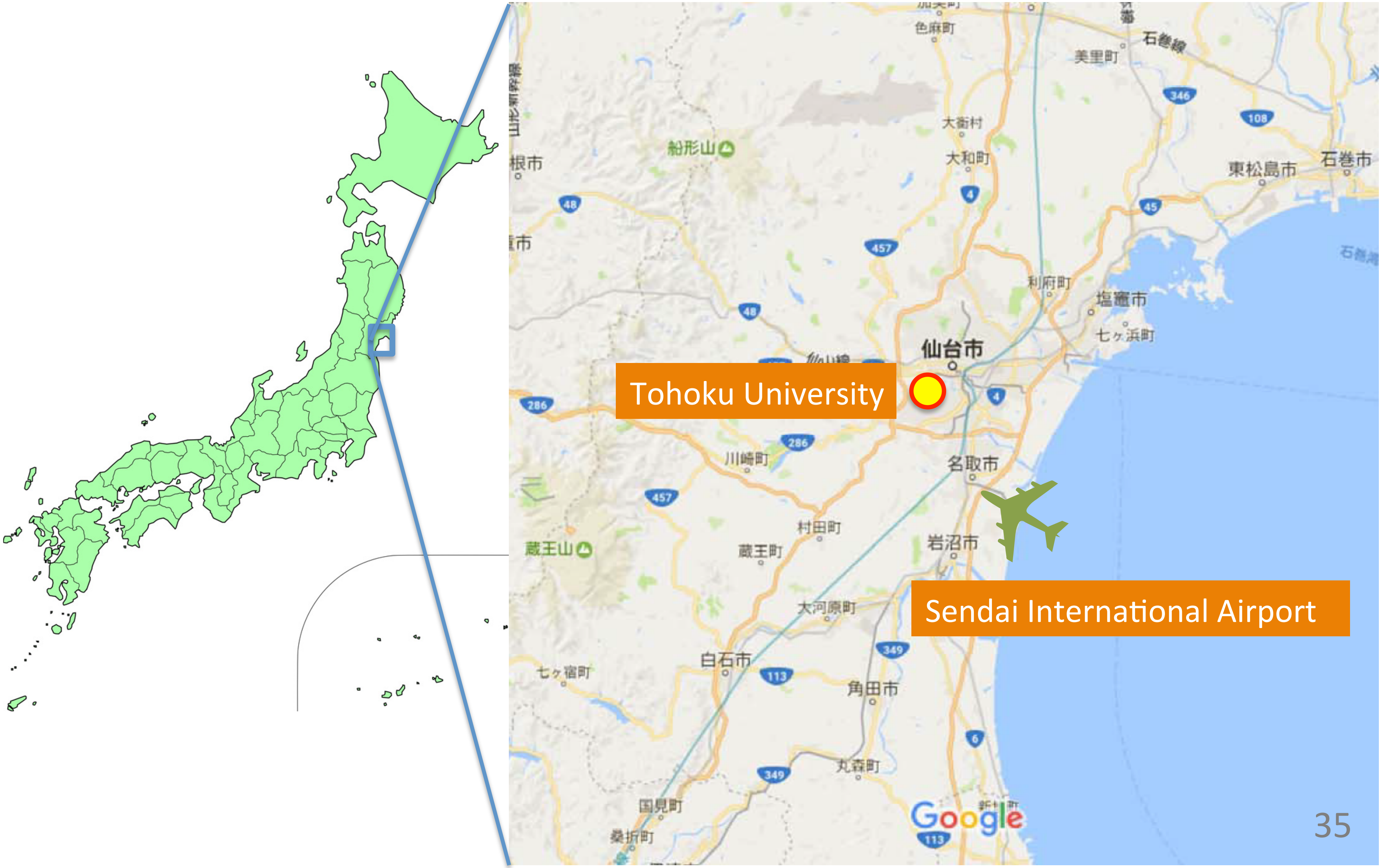
SLiT-J facility size



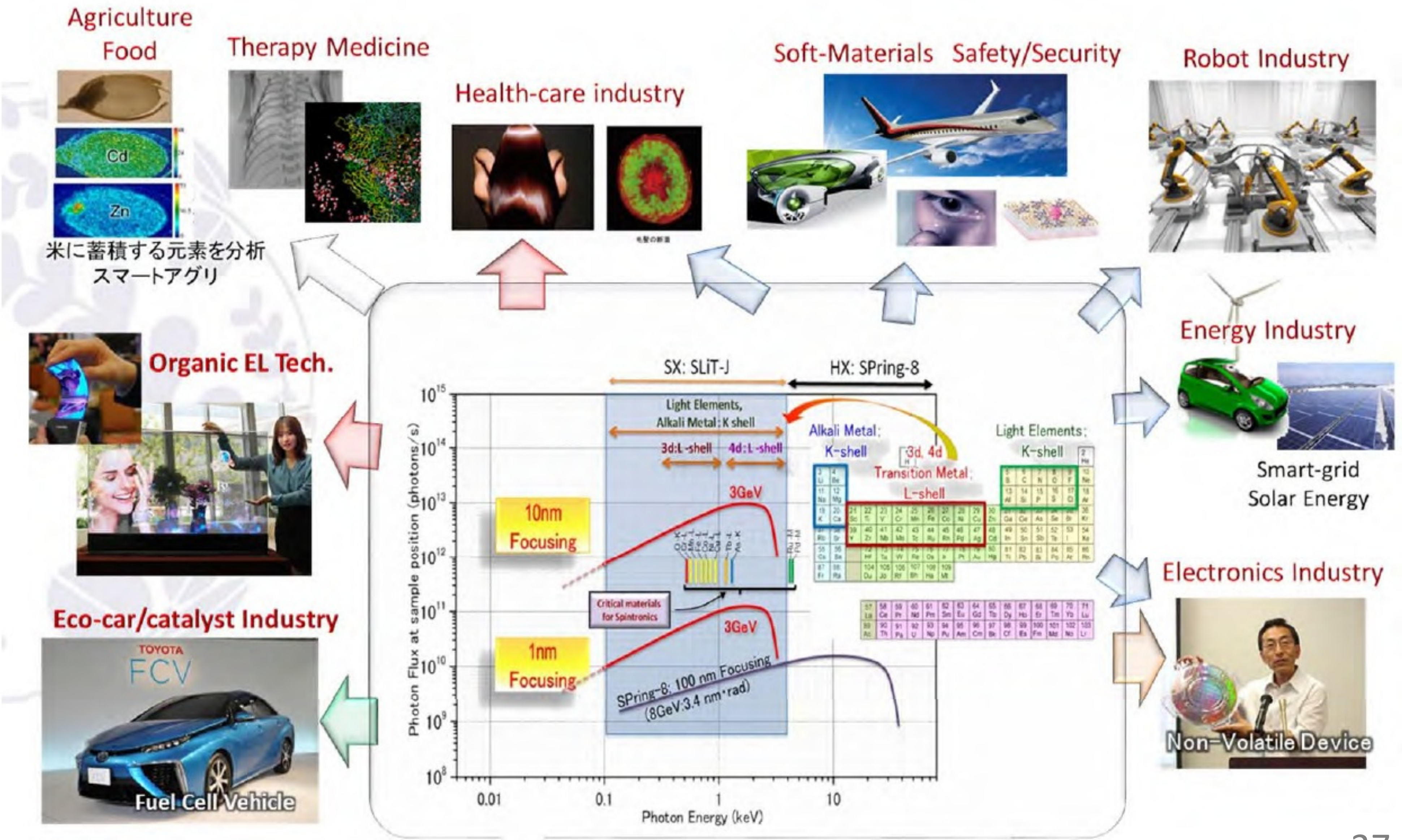
SLiT-J Location



History of SLiT-J project

Apr.	2011	Start discussion of 3 GeV light source in Tohoku area.
Jun.	2012	“Council for the Project of Synchrotron Light in Tohoku, Japan” is established by the 7 national universities in Tohoku district: Fukushima University, Miyagi University of Education, Yamagata University, Hirosaki University, Akita University, Iwate University and Tohoku University.
May	2014	"Needs survey on the next generation synchrotron radiation facility" is consigned to Tohoku University by MEXT (The Ministry of Education, Culture, Sports, Science and Technology).
Jun.	2015	Survey on Facility Location is conducted by a third-party committee. "Survey on technical issues" is consigned to Tohoku University.
May	2016	Conceptual Design Report ver. 2.1 “Moegi Book” is released.
Jun.	2016	International Review Committee of the SLiT-J Project is held.
Nov.	2016	“Design competition for End-Stations” for user‘s committees of synchrotron facilities is held.
Jan.	2017	“SLiT-J User Community” is launched.
Feb.	2017	“Synchrotron Radiation Innovation Center”, general incorporated foundation for SLiT-J project is established by Tohoku Economic Federation & Tohoku University.
Jul.	2017	National Institutes for Quantum and Radiological Science and Technology (QST) constructs and manages the 3 GeV source. Tohoku University will be hosted.

Research market of SLiT-J



From M. Takata, “SLiT-J Strategic Plan”, International Review Committee of the SLiT-J project, Jun. 2016

SLiT-J 2021?

We ask your strong support. Thank you.

Thank you for your strong support