Trends and challenges in the future storage ring light sources

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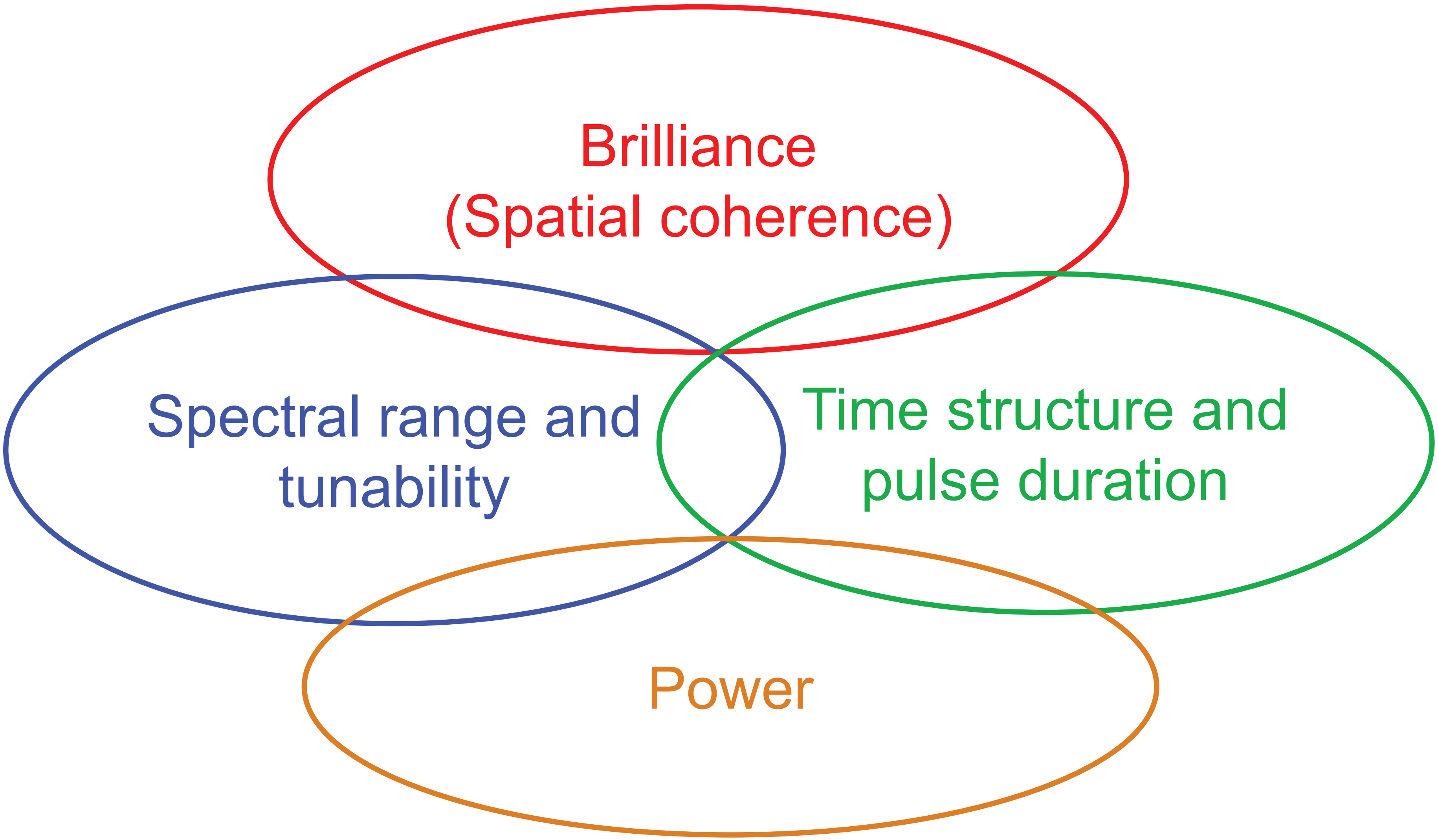
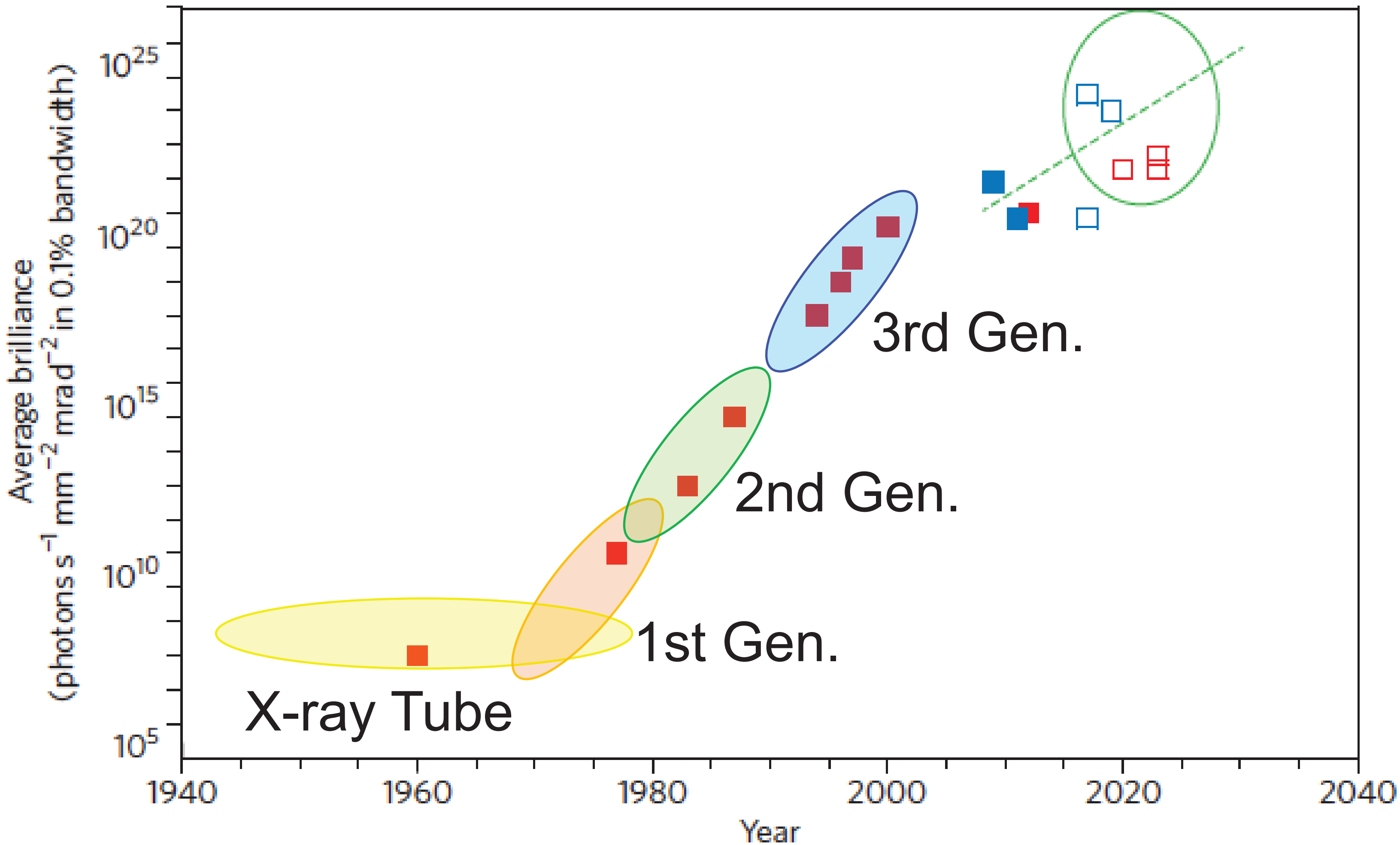
Outline

1. Overview of ring-based light source development
2. Short and medium term trends and challenges
3. Towards the future
4. Summary

Ring-based source performance

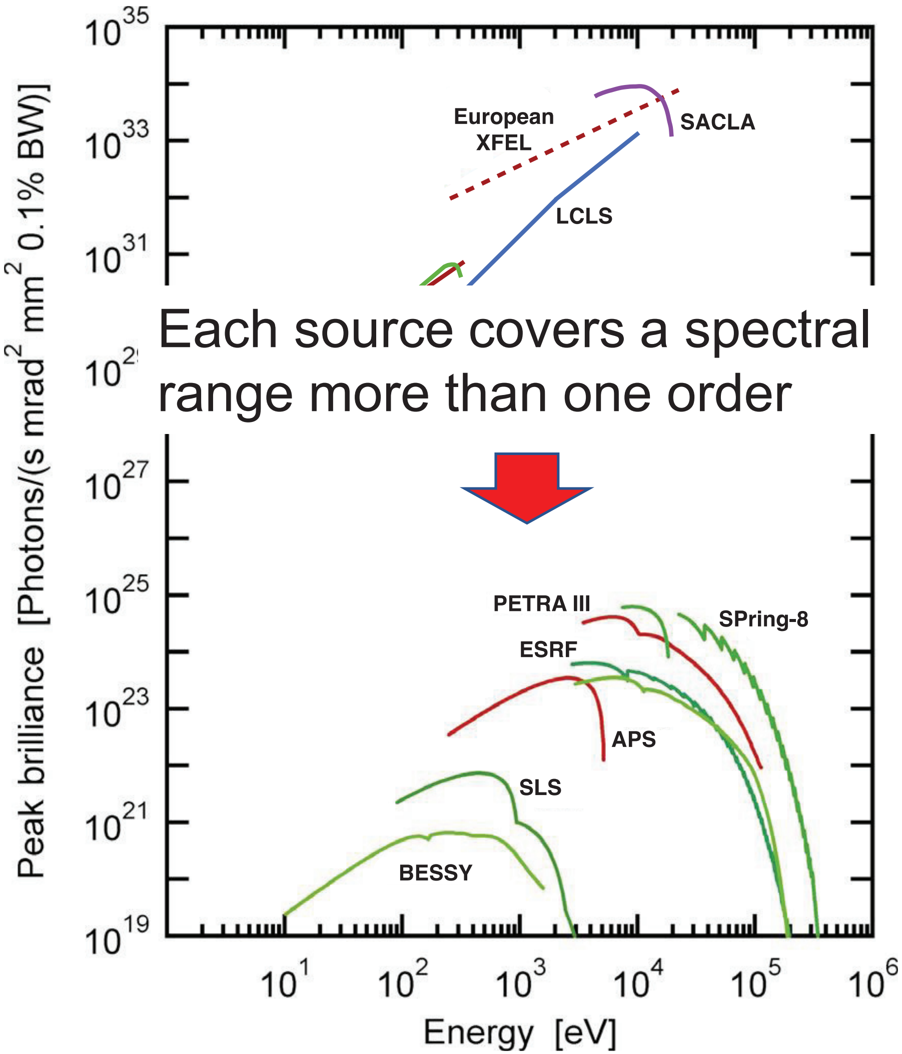


Brilliance enhancement



M. Yabashi & H. Tanaka, Nat. Photon **11**, 12-14 (2017).

Broad spectral range and tunability



Each source covers a spectral range more than one order

High performance variable gap undulators have provided tunability and broad spectral range.

P. Schmuser, M. Dohlus, J. Rossbach and C. Behrens, Free-Electron Lasers in the Ultraviolet and X-Ray Regime, 2nd edn. (Springer, 2014)

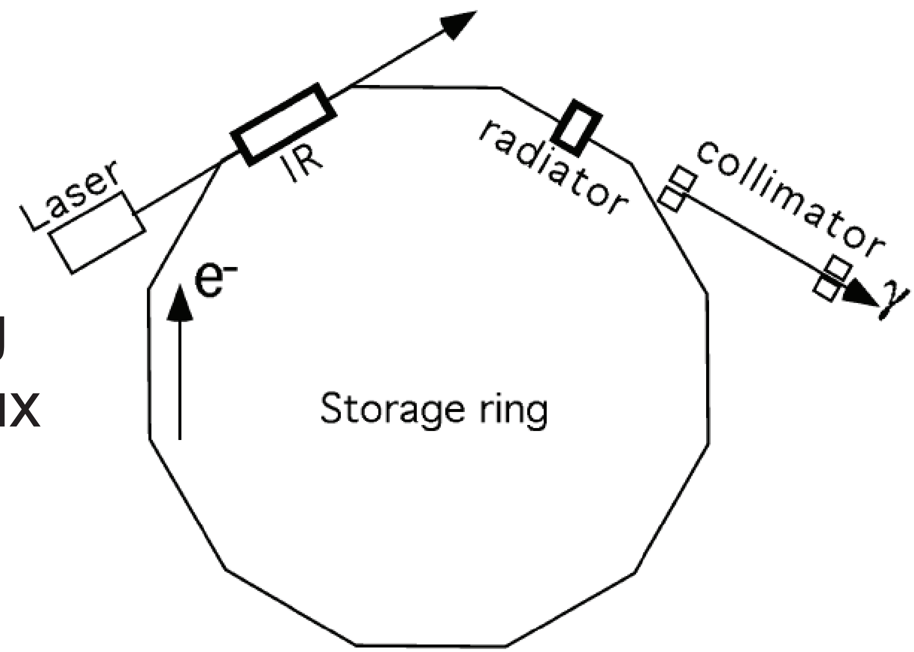
Time structure and pulse duration

Time structure:

Combination of a special beam filling pattern (single bunch, hybrid with high current bunches, etc.) with a bunch selector

Pulse duration:

Shortening the duration has been pursued by low-Alfa operation, RF potential modulation and laser slicing techniques, which still limit photon flux available



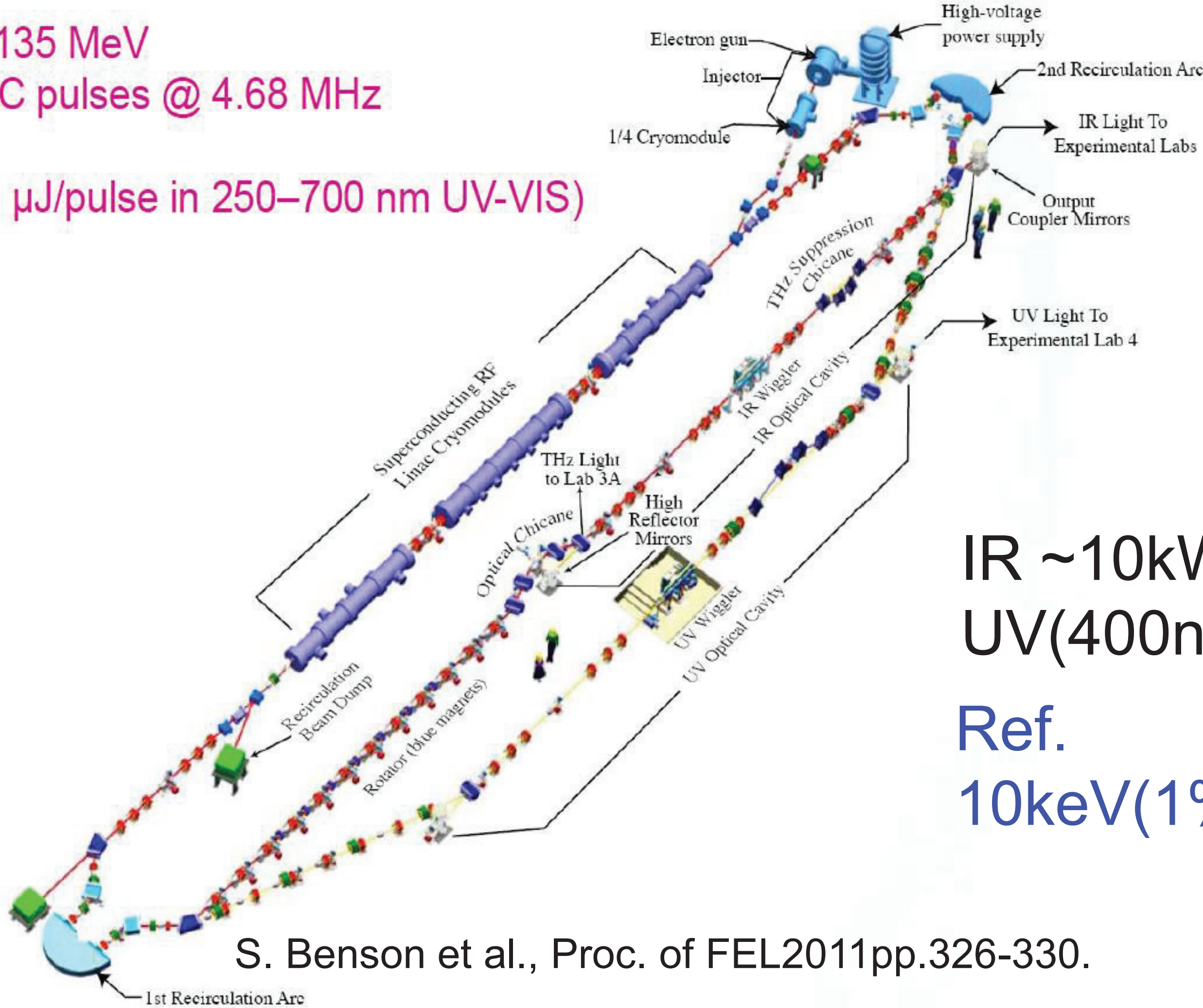
A. A. Zholents and M. S. Zolotorev, PRL 76, No.6, 912-915 (1996).

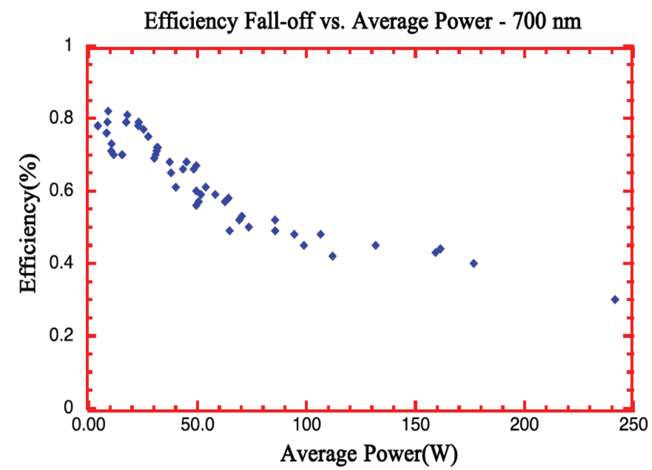
Radiation power enhancement

Frontier of high average power has been pursued using a ERL ring and FEL technologies.

E = 135 MeV
67 pC pulses @ 4.68 MHz

(>20 μJ/pulse in 250–700 nm UV-VIS)





IR ~10kW
UV(400nm) ~0.1kW

Ref.
10keV(1%bw) ~ 0.1W@SPring-8

S. Benson et al., Proc. of FEL2011pp.326-330.

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2. Short and medium term trends

Brilliance (Spatial coherence)

- (Near) Diffraction limited X-ray SR sources
  - by MBA
  - by Round Beam

Spectral range and tunability

- CW XFEL by XFELO+ERL

High power

- High power EUV SR sources with high efficiency
  - by ERL-base SASE FEL/Highly efficient FEL
  - by CSR using steady-state micro-bunching
  - by PEHG (HGHG) source

Time structure and pulse duration

- Advanced short-pulse generation

MBA enables smaller emittance

Scaling of emittance

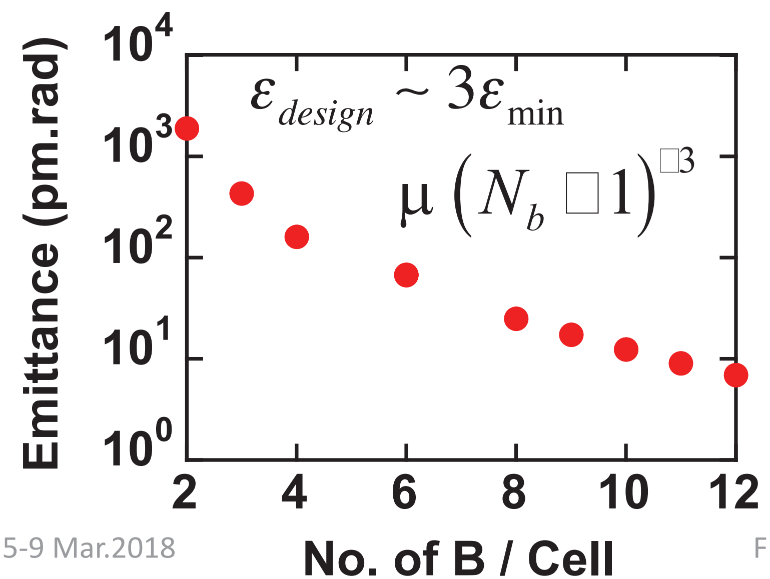
understood since 1980's

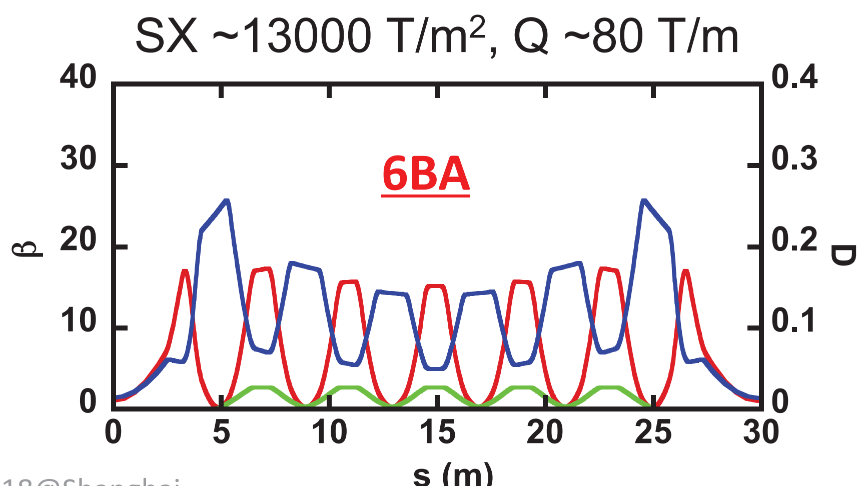
MBA reducing θ by increasing the number

$$\varepsilon_{nat} = C_q \frac{\gamma^2 \left\langle H/\rho^3 \right\rangle}{J_x \left\langle 1/\rho^2 \right\rangle} \propto \frac{\gamma^2 \theta^3}{J_x}$$

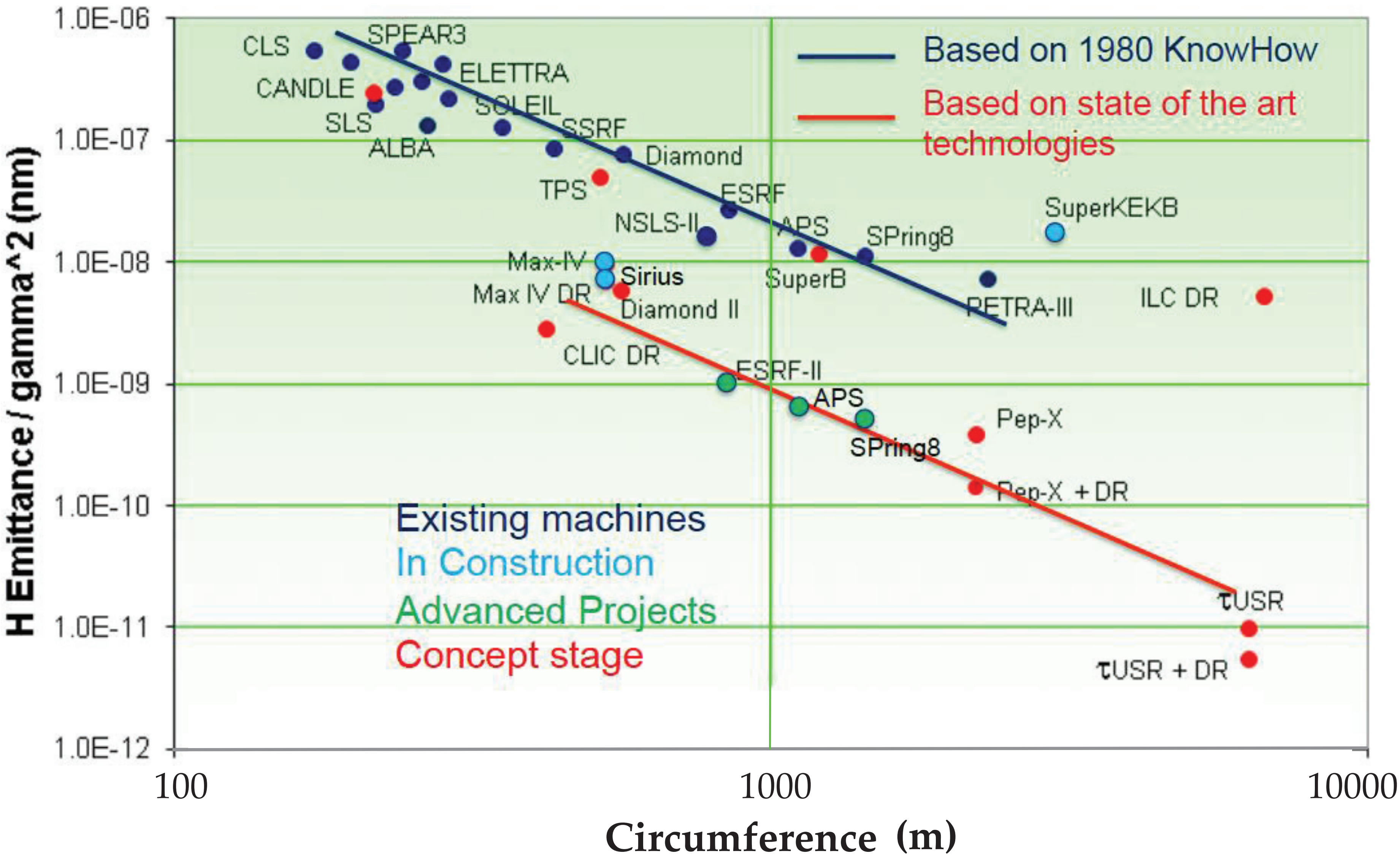
γ : Lorentz factor
θ : Bending angle
ρ : Bending radius
H : H-function
J_x: Damping partition number

Example of emittance reduction by MBA, SPring-8 case





MBA driving the new trend



P. Raimondi, Invited talk(wexa01)@IPAC2016

Challenges in MBA approach

Physics:

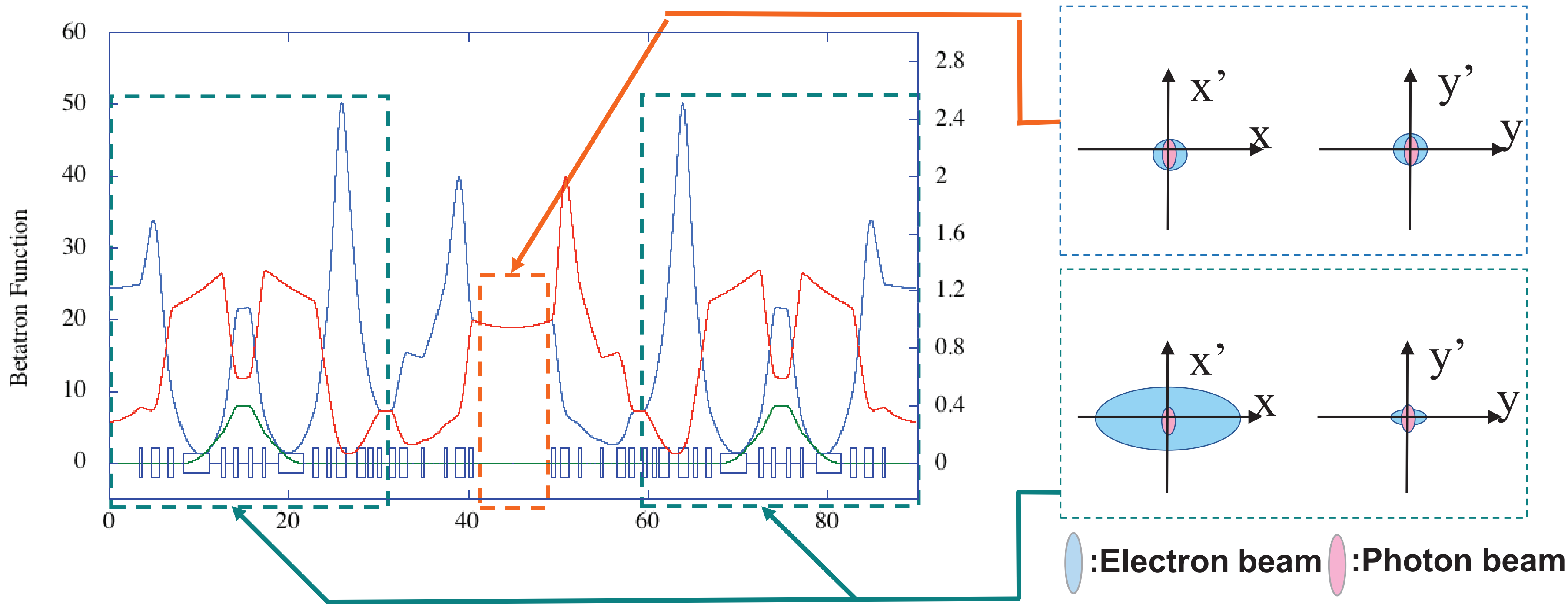
- Straight forward nonlinear optimization scheme

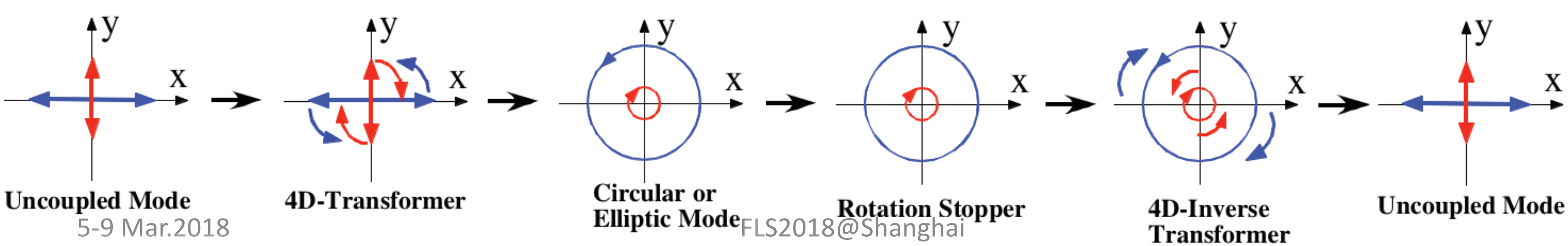
Engineering/Operation:

- Component size reduction →MAX IV approach?
- Beam injection scheme fit to smaller DA
- Beam control to utilize a longitudinally peaky BM field
- Precise photon axis control over multi beamlines

Round beam enables smaller emittance

Phase space adapter gives a “vortex mode” of which emittance is ~$\sqrt{\varepsilon_x \varepsilon_y}$.





Challenges in round beam approach

Physics:

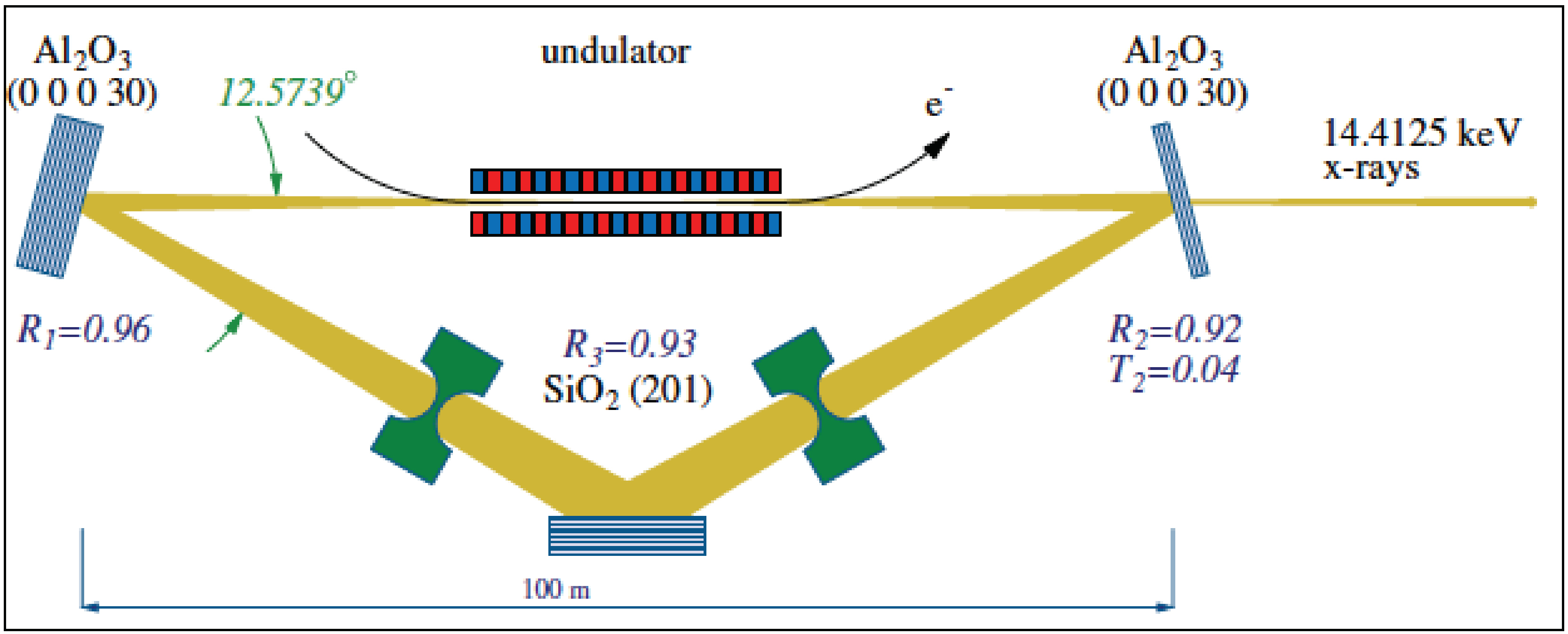
- Vertical emittance growth due to radiation from round beam

Engineering/Operation:

- Quite strong solenoid field required to a smaller beam size of a few tens um
- How to make the total system compact
- Beam control to keep ideal condition over ”phase space adapter” for long period

CW XFEL by XFELO

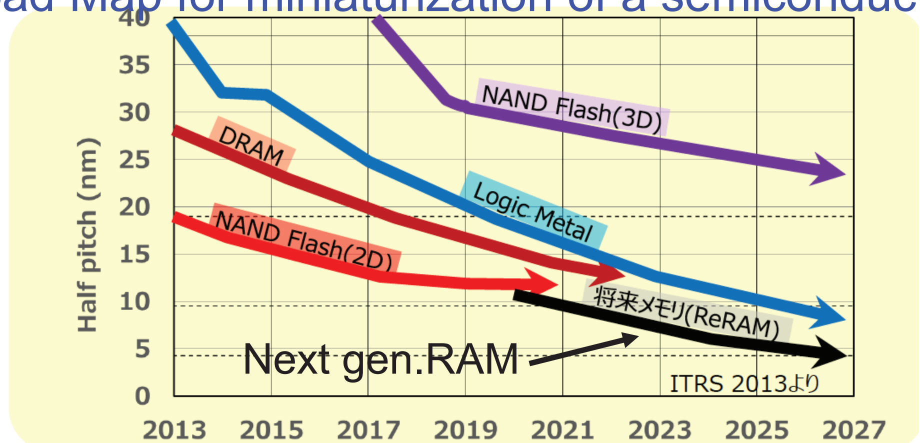
Recent progress of SC-RF accelerator technology seems to be ready for providing a suitable electron driver. The main challenge will shift to the development of X-ray optical cavity composed of plural crystals including high heat load-related issues, alignment of crystals, etc.



K. J. Kim et al., PRL 100, 244802 (2008).

EUV high power source (~a few tens kW)

Load Map for miniaturization of a semiconductor device



$$\text{Resolution} = k1\frac{\lambda}{NA}$$

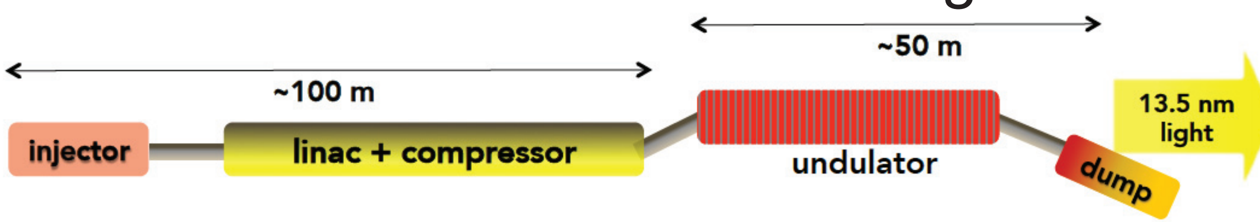
λ	NA	k1	Resolution
436nm(g線)	0.6	0.75	550nm
365nm(i線)	0.65	0.6	350nm
248nm(KrF)	0.86	0.31	90nm
193nm(ArF)	0.93	0.31	65nm
193nm(ArF)	1.35	0.26	38nm
13.5nm(EUV)	0.25	0.3	16nm
13.5nm(EUV)	0.33	0.3	12nm
13.5nm(EUV)	0.50	0.3	8nm

13.5 nm is required for the next device

Target >10kW

SCRF-based SASE source with high FEL efficiency

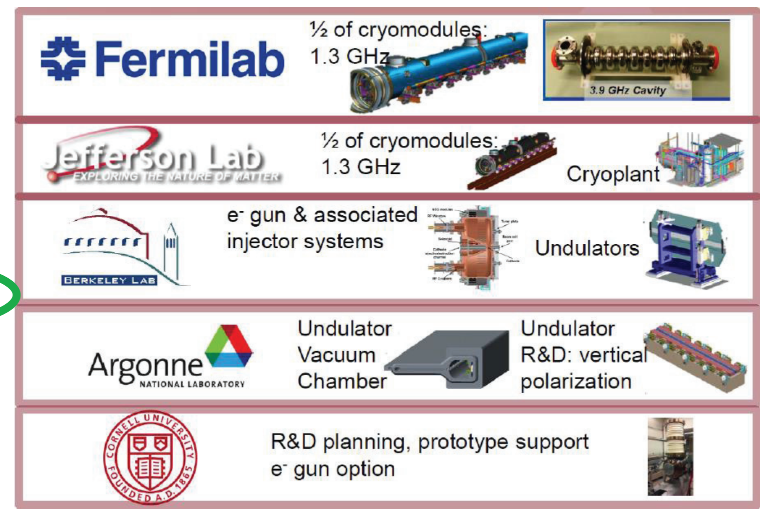
radiabeam TECHNOLOGIES



A. Murokh, “High efficiency 10 kW class FEL for EUV lithography@2014 Int, WS on EUV and Soft-X0ray Sources

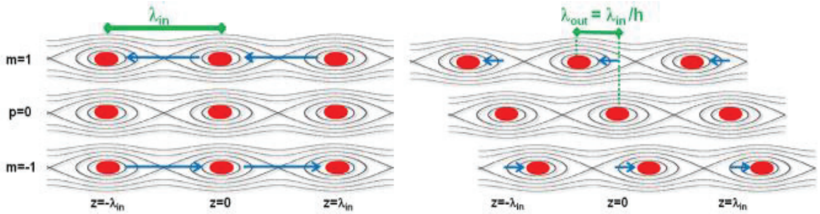
- **Benefits:**
  - Simplest approach, used for all existing and planned XFELs
  - All components are demonstrated and many are industrialized
  - Enables highest FEL efficiency
- **Risks:**
  - High power beam dump

Avg. EUV power	10 kW
Avg. beam current	3 mA
Avg. beam power	2 MW
FEL efficiency	0.5%
Energy @FEL	650 MeV
Energy recovery?	NO
Power at dump	2 MW



EUV high power source (~a few tens kW)

D. Ratner and W. Chao, PRL 205, 154801 (2010).
A. Chao et al., Proc. of IPAC2016, Busan, Korea (2016) pp. 1048-1053.

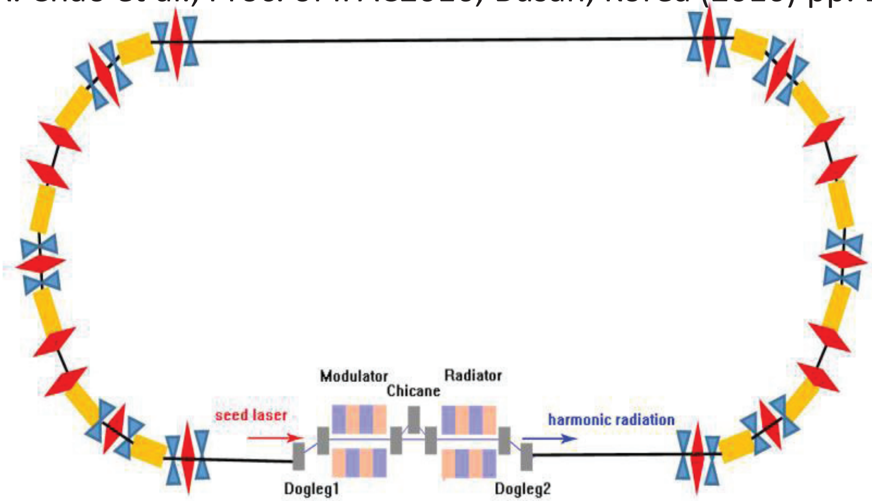


This original scheme builds micro-buckets in usual RF buckets by introducing high power laser interaction through undulator. It looks challenging to access EUV (shorter) wavelength range.

Staggered microbucket SSMB

SR-based PEHG FEL for EUV lithography

C. Feng et al., "Storage ring based PEHG FEL for EUV lithography @2016 OSA.
A. Chao et al., Proc. of IPAC2016, Busan, Korea (2016) pp. 1048-1053.



Reversible SSMB with PEHG

By using a phase-merging enhanced harmonic generation (PEHG), sustainable HHG generation has been investigated. It looks challenging to assure long term stable operation by suppressing electron beam heating.

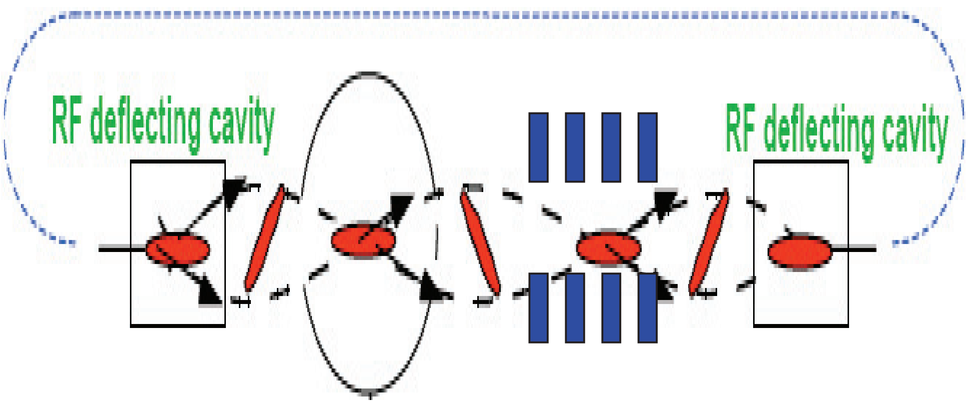
Advanced short-pulse generation – directions -

1. Brighter

- High density bunch before slicing, low alpha operation, etc

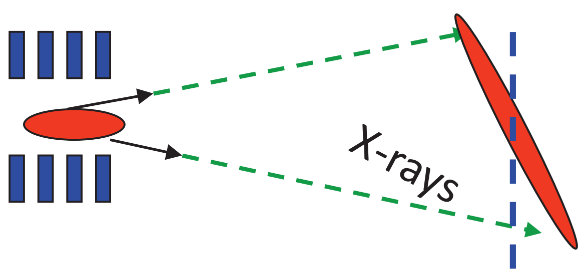
2. Simultaneously available short and long (small emittance) bunches

- Tilt-and-cancel scheme (crabbing + asymmetrically cut crystal [1])
- Multi-frequency schemes (cf. [2])

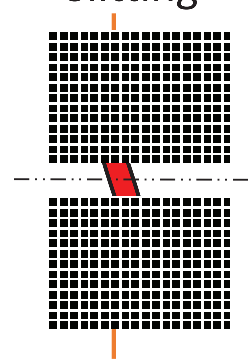


[1] A. Zholents, et al., NIM A 425(1999), 385.
[2] A. Zholents, NIM A 798 (2015) 111.

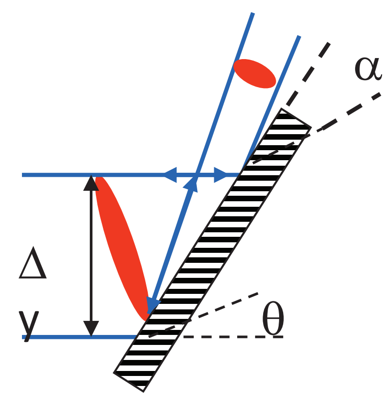
Figures by A. Nassiri, ICFA Mini-workshop, Shanghai, 2008.



Slitting



X-ray pulse compression



Advanced short-pulse generation – challenges -

Challenges:

- Overcome IBS (for better brilliance, if required)
- Overcome TMCI and other instabilities (for higher bunch current)
- Suppress perturbation to other small emittance bunches

Despite the increase of XFEL sources, it is likely that short SR pulses are still required to meet varieties of user demands:

> short pulse duration (1ps or less)
> high repetition rate/high average brightness
> large number of beamlines
> availability of short and long bunches at the same BL
> coherent radiation
etc.

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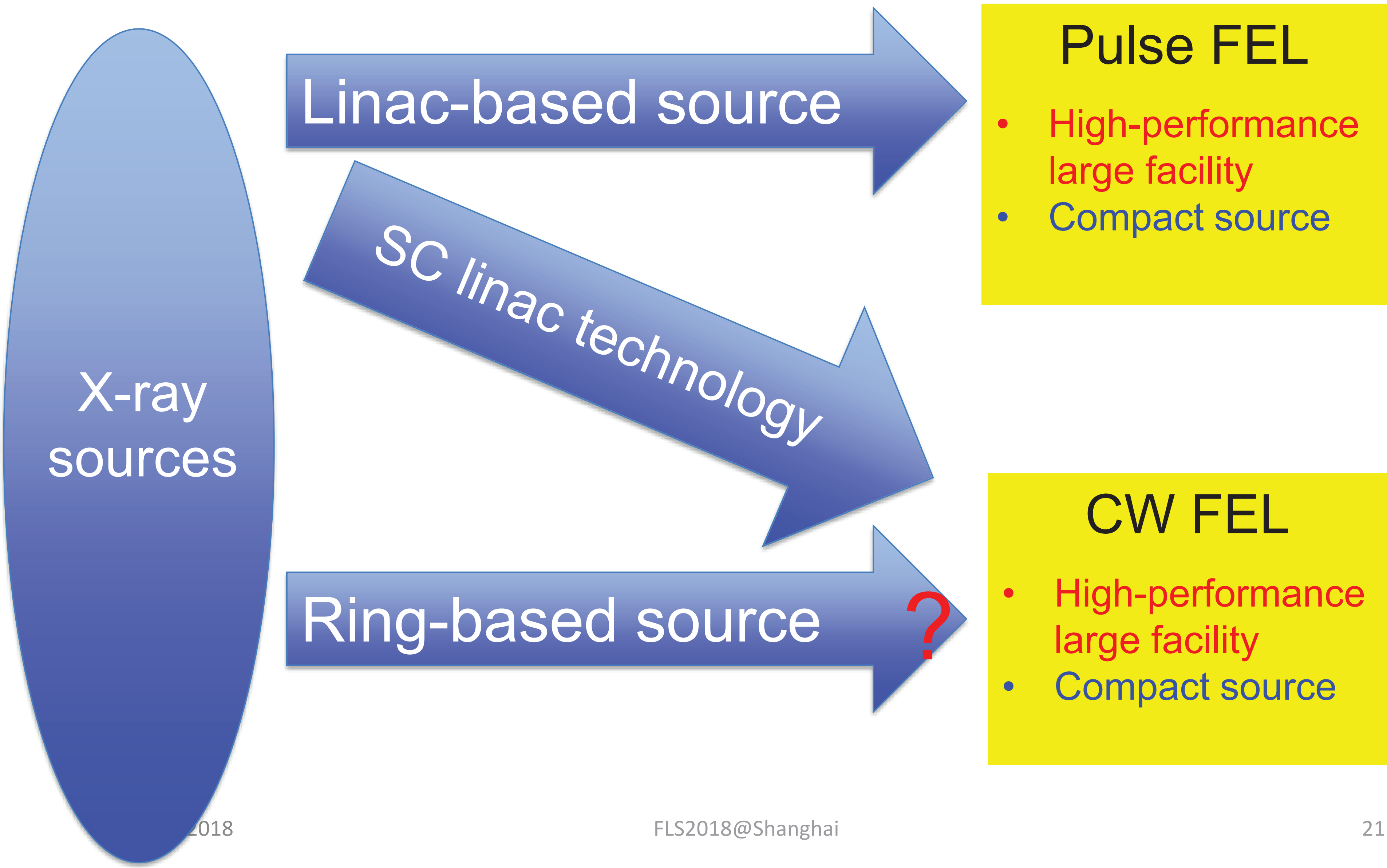
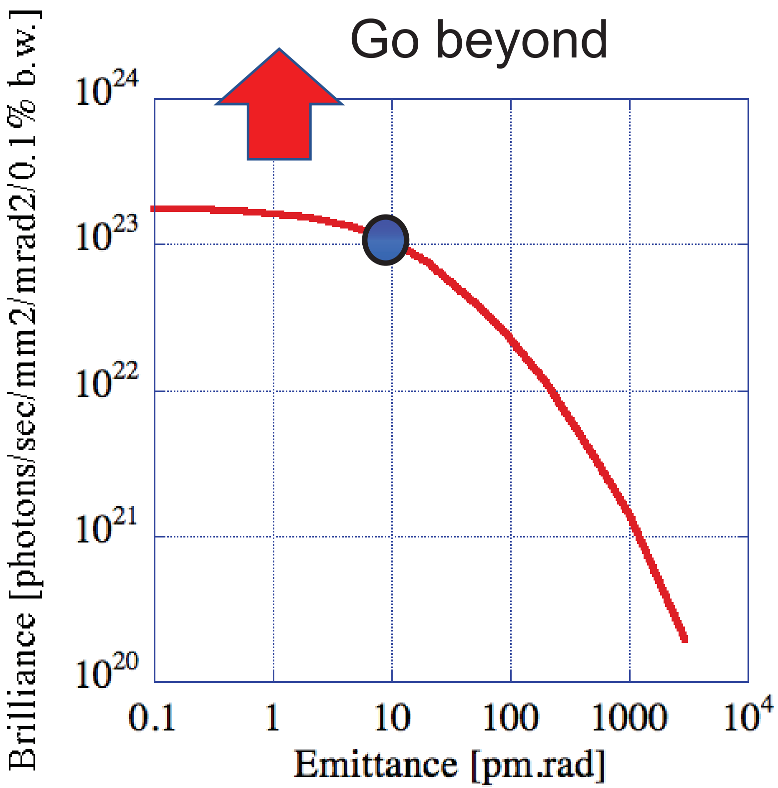
Direction of X-ray Source Development



Why do we go towards FEL?

Brilliance of spontaneous undulator radiation is limited and beyond the “Diffraction limit” efficiency improving performance, “gain vs. efforts” becomes extremely poor. To break this limit, we need FEL or some coherent radiation mechanism.



Calculation condition

Energy = 6GeV
Current = 100mA
Coupling = 0.02
E_spread = 0.12%
Beta_x = 1 m
Beta_y = 1 m
Photon Energy = 10 keV

Ring-based vs. linac-based

Ring-Based Source

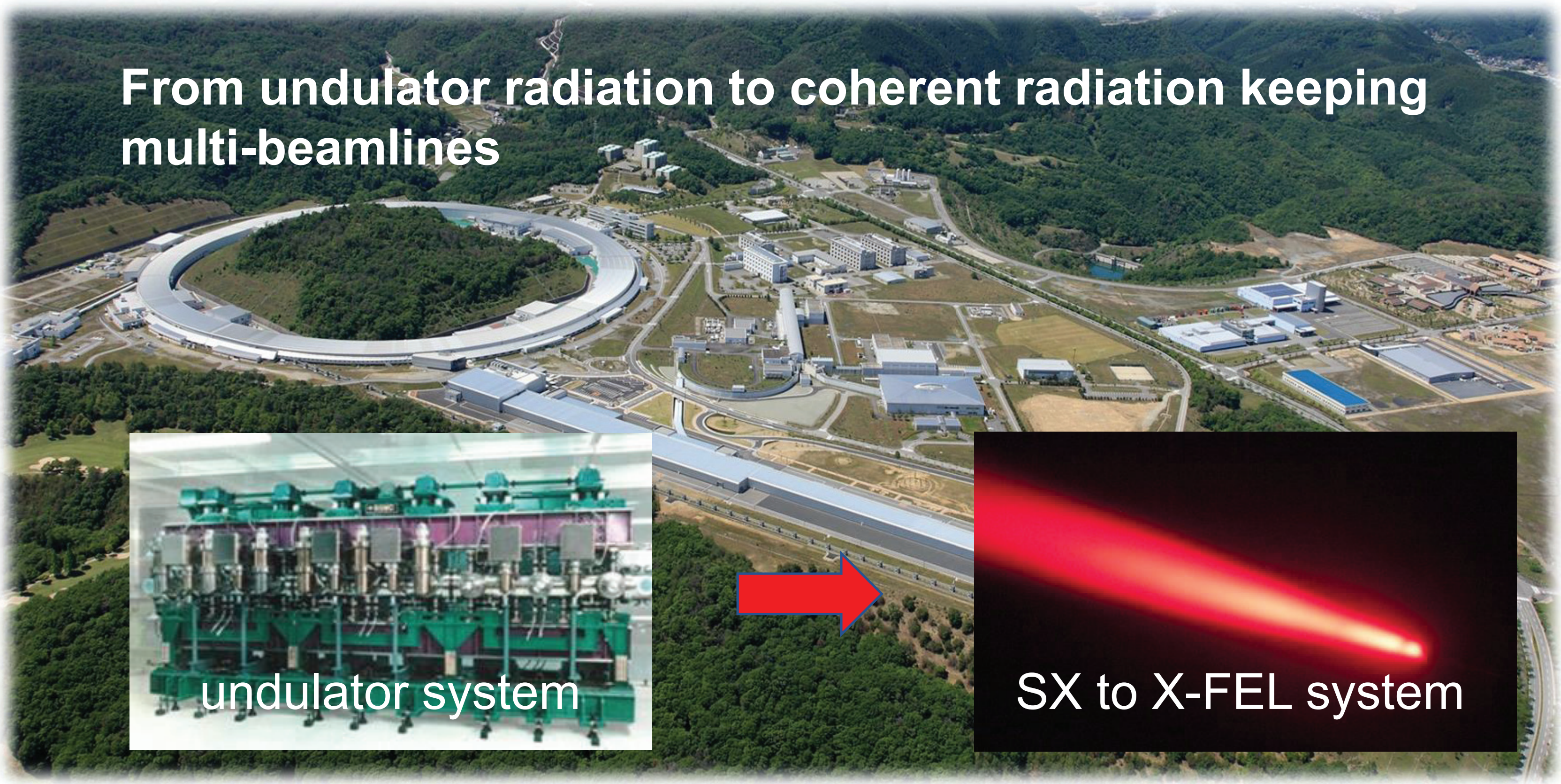
- Stable (Close Looped)
- Multi-user oriented
- High efficiency
- Stored electron beam

Linac-Based Source

- Unstable (Open Looped)
- Single user oriented
- Low efficiency
- Fresh electron beam

Dream ring-based source

Near diffraction limited SR in which all the undulator systems are replaced by compact laser systems providing SX to X-FELs, which are independently usable with arbitrary wavelengths.



Challenges

So many, for example,

- Compact HHG generation scheme with smaller heating effect,
- Electron beam handling to make the HHG generation scheme transparent to other BLs,
- Shortening HHG wavelength to cover the wide spectral range by current SR facility,
- Development of high power, short wavelength (~several nm or shorter) seed laser,
- ….

4. Summary

A near diffraction limited SR is certainly our mid-term target. However, it is important to tackle with R&D subjects expecting the next step after the diffraction limited SR.

Electron beam manipulation with high power lasers will be critically important technique to bridge the gap between the next target and post next.