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On Electron Beam Brightness for Compact X-ray Sources

S. Di Mitri, ELETTRA SINCROTRONE TRIESTE

Uppsala Univ., Angstrom Laboratory, 28-29 October 2019

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Outline

- ☐ Linac-Driven X-ray Sources
  - Can an XFEL be compact?
  - Give up on coherence for compactness: ICS source
- ☐ Electron Beam Brightness for ICS
  - Photon brilliance, e-beam brightness
  - High average brightness e-sources
- ☐ Other ideas for compact X-ray sources
  - SR-ICS *(ref. M. Dierolf et al.)*
  - FEL-ICS *(ref. M. Placidi et al.)*
  - FEL-HHG *(ref. R. Hajima et al.)*

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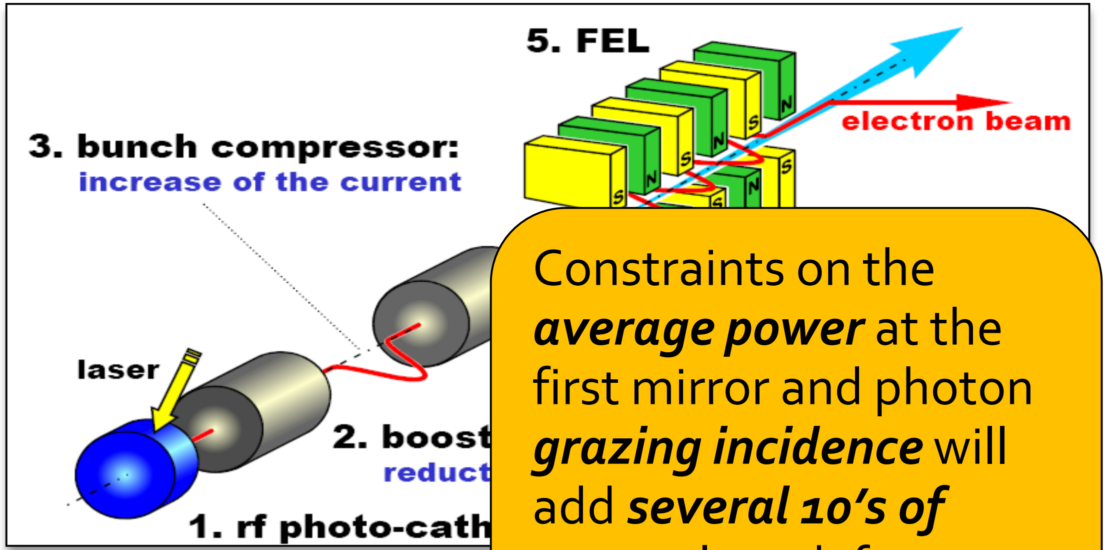
Compact XFEL ?



Constraints on the ***average power*** at the first mirror and photon ***grazing incidence*** will add ***several 10's of meters*** length for photon transport

- Hard x-rays: $\lambda_R \sim$ **1 Å**, or $E_R \sim$ 12 keV
- R&D planar CPMU or SCU (*LEAPS initiative*): $\lambda_u =$ **10 mm**, K ~ 0.5

$$E_e = m_e c^2 \sqrt{\frac{\lambda_u}{2\lambda_R}\left(1+\frac{K^2}{2}\right)} = 3.8\ \text{Ge}$$

- X-band NC linac at **1 kHz** (*CERN*, *CompactLight*): **G = 65 MV/m**

$$L_{linac} = \frac{E_e}{G} = 60\ \text{m}$$

- Injector (+5 m), Compressors (+20 m), Quads (+25 m), Undulator for saturation (+20 m)

$$L_{source} = 130 - 170\ m$$

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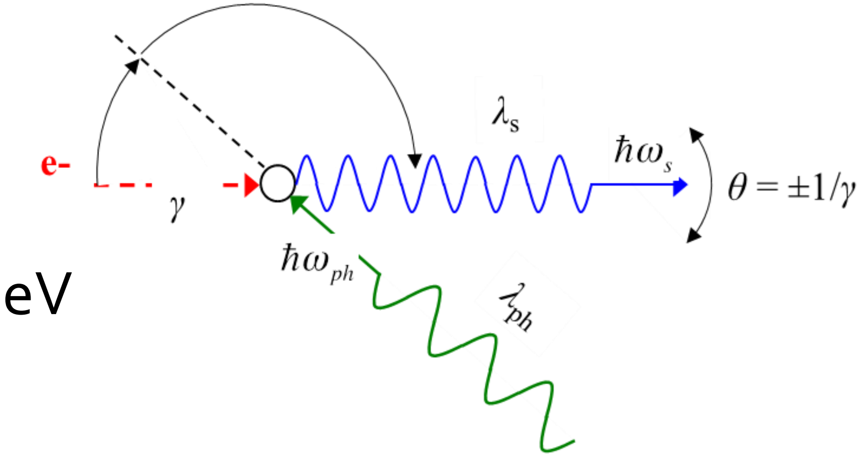
Inverse Compton Scattering

From undulator…

…to laser

- λ_U = 10 mm → λ_L = 1 μm, ⇒ $E_e \times 10^{-2}$
- K = 0.5 → $a_L < 1$, ⇒ $E_e \times 1$

E_e = 38 MeV



- X-band NC linac at 1 kHz: **G = 65 MV/m**
- Injector (+5 m), Quadrupoles (+5 m)

$L_{source} = 10 - 15\, m$

But, you give up on:

- Peak flux in 0.1% bw, × ~10^{-8}
- Longitudinal coherence, bw × ~ 50
- Transverse coherence, < 0.1 keV

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  - Photon brilliance, e-beam brightness
  - High *average* brightness e-sources

☐ Other ideas for compact X-ray sources
  - SR-ICS *(ref. M. Dierolf et al.)*
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Photon Brilliance

Peak Brilliance = 6-D photon density:

$$B_\gamma = \frac{dN_\gamma/dt}{4\pi^2\Sigma_x\Sigma_{x'}\Sigma_y\Sigma_{y'}\Delta\omega/\omega}$$

Effective radiation size (at IP)

$$\Sigma_u = \sqrt{\sigma_{u,e}^2 + \sigma_{u,L}^2} \cong \sqrt{(\beta\varepsilon)_{u,e} + (\beta\varepsilon)_{u,L}}$$

$$\Sigma_{u'} = \sqrt{\sigma_{u',e}^2 + \sigma_{u',L}^2} \cong \sqrt{(\varepsilon/\beta)_{u,e} + (\varepsilon/\beta)_{u,L}}$$

It is maximized by laser-electrons optical **matching,** at the laser **diffraction limit**:

$$B_\gamma = \left(\frac{dN_\gamma/dt}{\Delta\omega/\omega}\right)\frac{1}{\lambda_L^2} \propto \frac{dQ}{dt}\frac{\beta_u}{\varepsilon_u}\frac{1}{\lambda_L^2} \propto \frac{\widehat{I_e}}{{\sigma'_e}^2\lambda_L^2}$$

*Both are proportional to the charge density in phase space (**e-beam brightness**)*

Average brilliance:

$$\bar{B}_\gamma = B_\gamma \times dt \times f_p \propto \frac{\bar{I}_e}{{\sigma'_e}^2\lambda_L^2}$$

Peak Brightness

5-D normalized beam brightness

$$B_{5\mathrm{D}} = \frac{I}{\epsilon_{n,x}\epsilon_{n,y}}$$

Matching to laser params is not an issue:

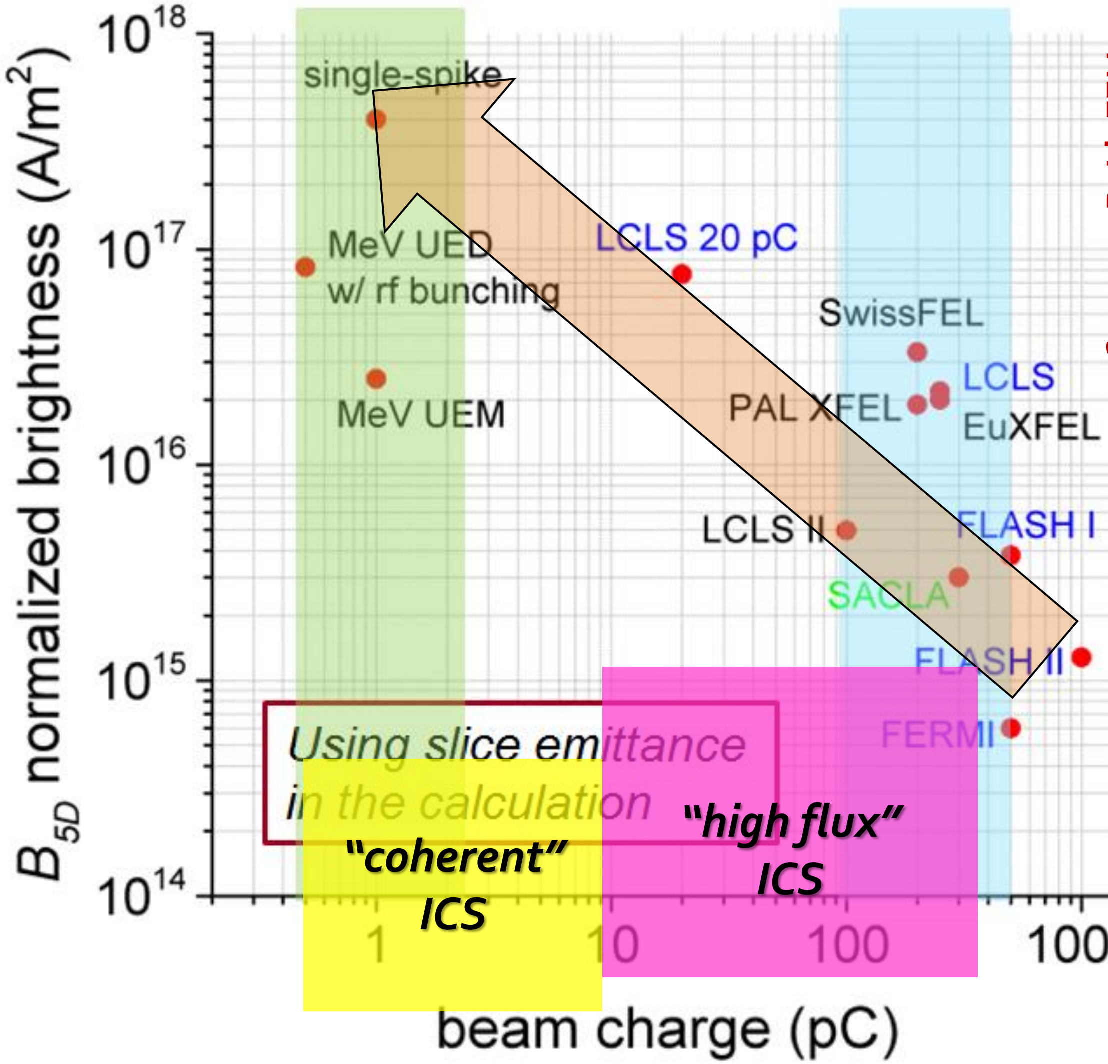
λ_L = 1 μm → $\varepsilon_e \equiv \lambda/(4\pi) = 0.08\ \mu m\ rad$

$E_e \approx$ 50 MeV → $\varepsilon_{n,e} = \beta_z \gamma \varepsilon_e \approx 8\ \mu m\ rad$

We guess **$\varepsilon_{n,e}\sim 0.5\ \mu m\ rad$** at **Q ~ 100 pC,** **$\beta{*}\sim 10\ mm$** at IP:

$$\sigma_{u,e}@\ IP = \sqrt{\beta_u \varepsilon_n/\gamma} \sim 7\ \mu m$$

ICS does *not* need high I (no amplification)



Courtesy R. Li, FEL'15

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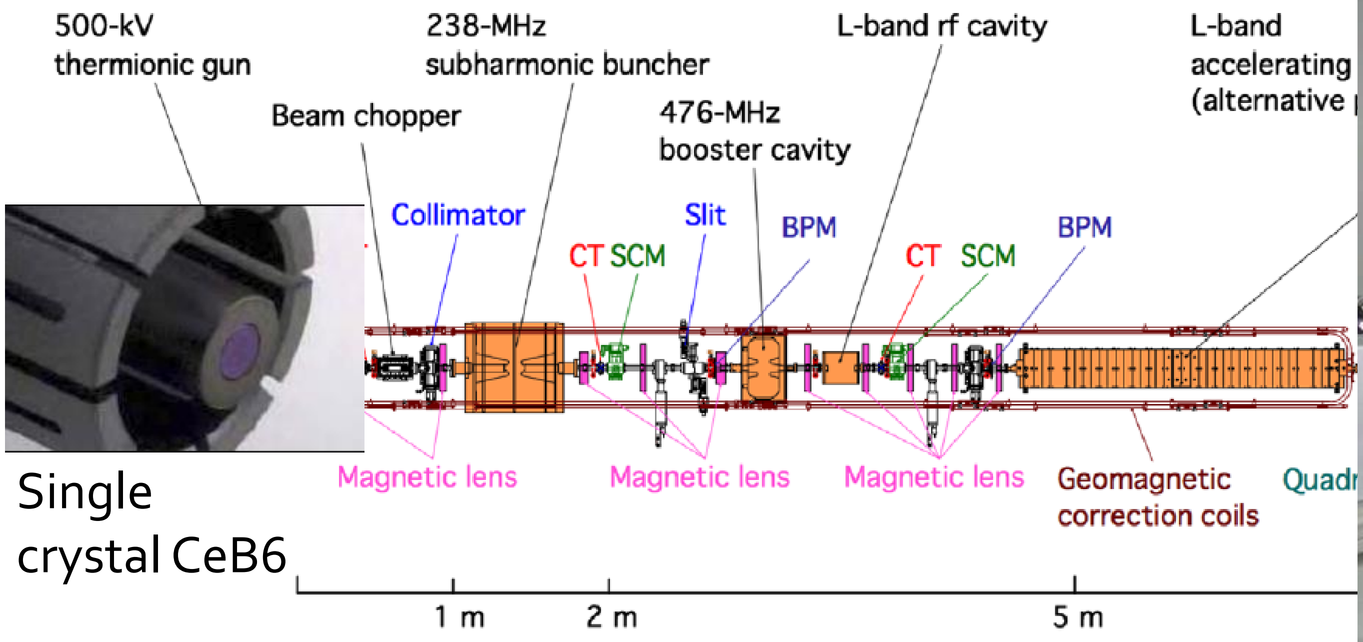
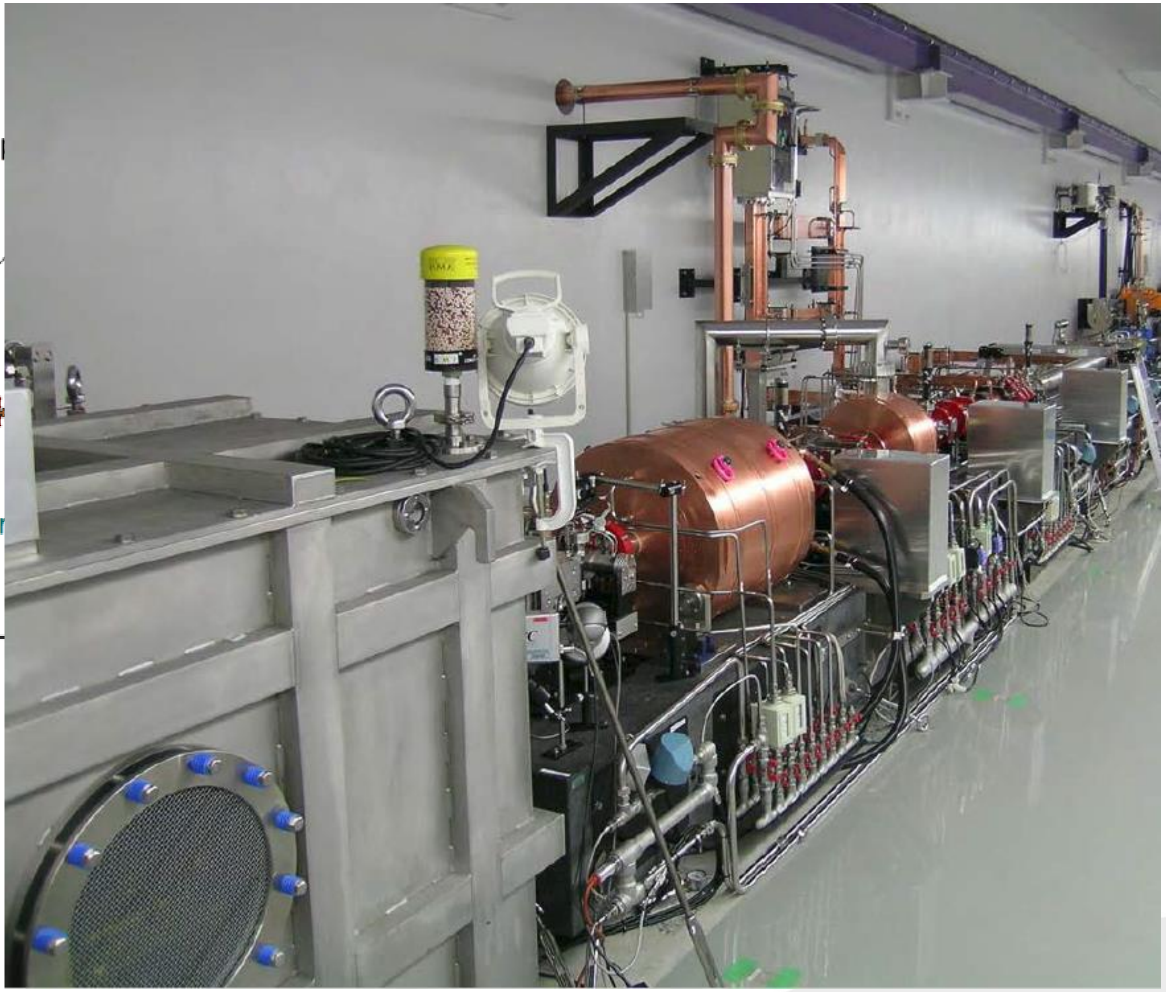
Thermoionic Gun

T. Asaka et al., PRAB 20 (2017)
Courtesy T. Shintake, FEL'12



Single
crystal CeB6



$Q < 1$ nC, $I \sim 25$ A
$\varepsilon_n < 1$ μm
$f_p < 60$ Hz

Scaling to kHz and above ?

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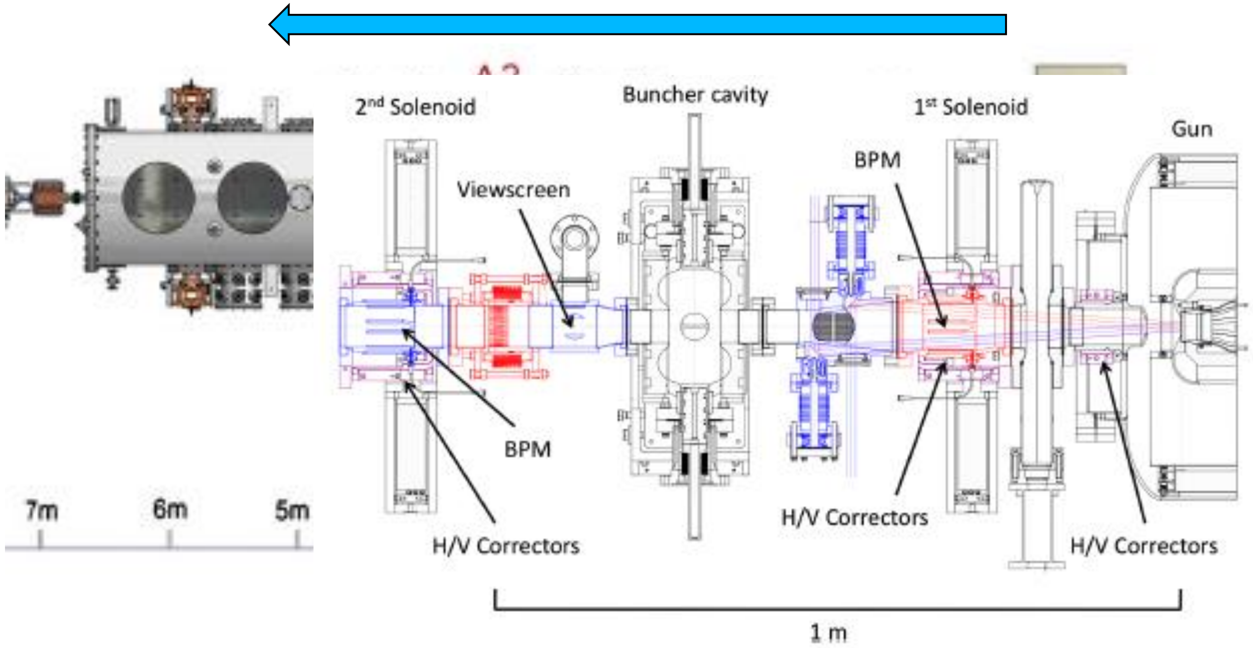
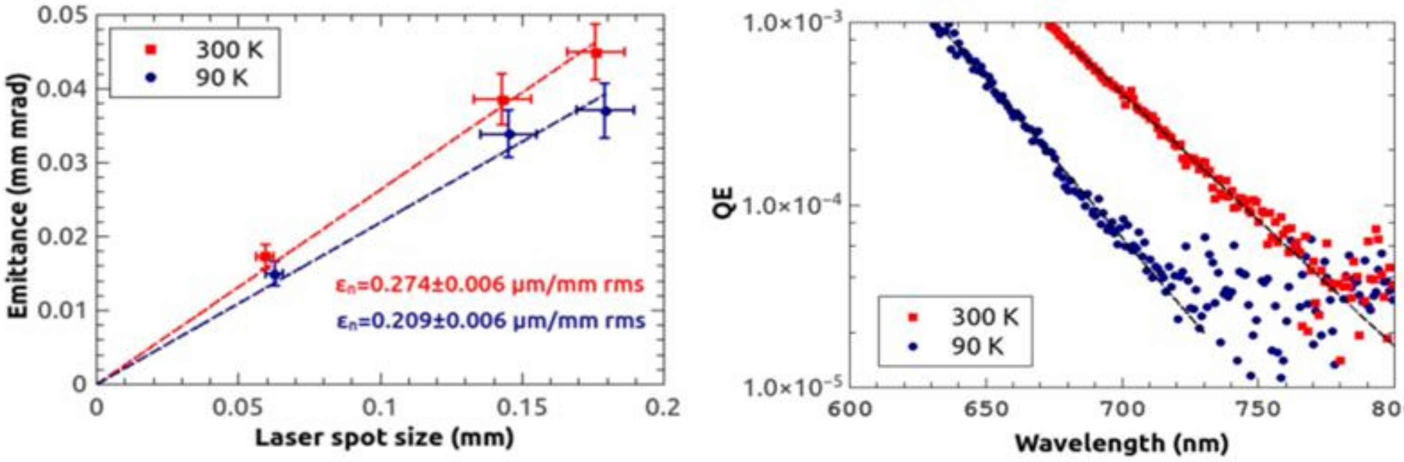
DC Photoinjector

C. Gulliford et al., PRST-AB 16 (2013)



- ❑ NC-PC plus Buncher (*Cornell Univ.*)
  - DC gun with GaAs cathode
  - <I> ~ 10's mA, ~ 10 MeV, <50 MHz
  - Up to 80 pC, ~ 0.3 μm rad
  - 9-cell SC linac

> ➢ QE increased & emittance reduced at cryo-temperatures
>
> ➢ ***R&D*** required for 100's of pC bunch charge

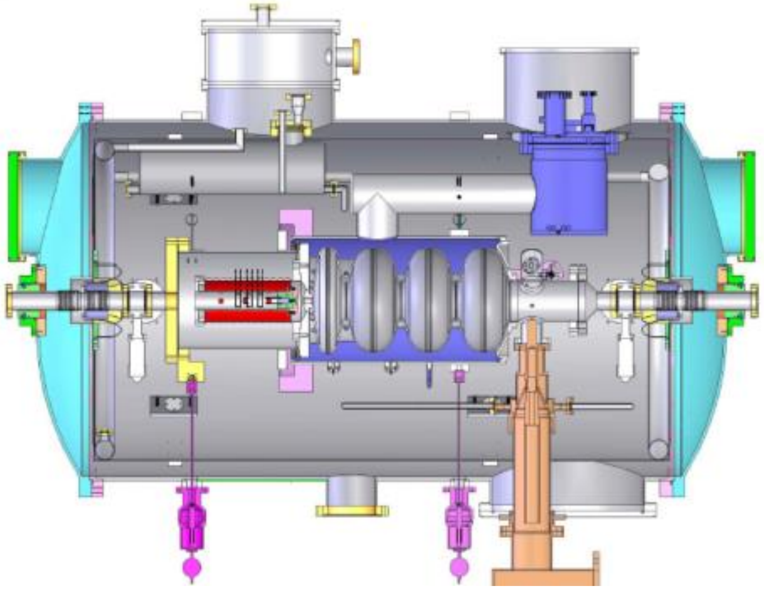


L. Cultrera et al., PRSTAB 18 (2015)

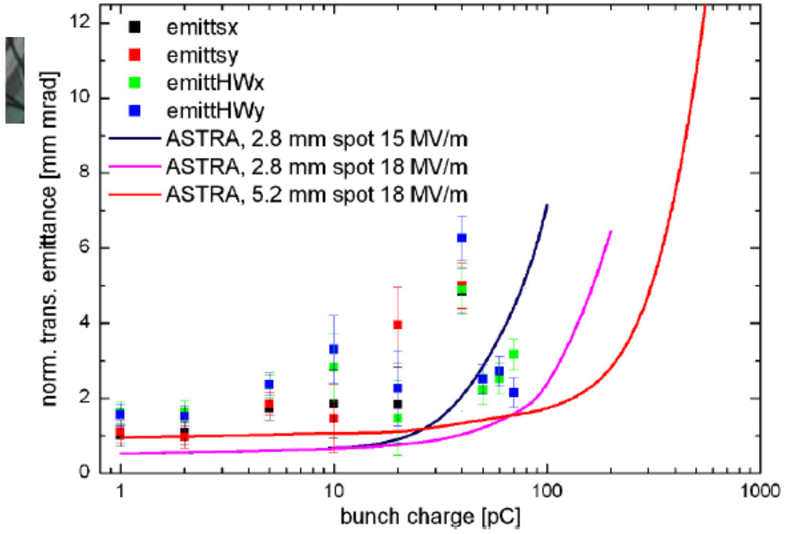
SR-RF Photoinjector

Courtesy S. Huang, FEL'17

- NC-PC plus SC-RF (*Peking Univ.*)
    - 3.5-cell DC gun with Cs$_2$Te cathode
    - <I> ~ 1 mA, ~ 3 MeV, <27 MHz
    - Up to 100 pC, ~ 1 μm rad
    - SC-RF at 2 K



- Increased complexity
- ***R&D*** required for 100's of pC bunch charge and low emittance



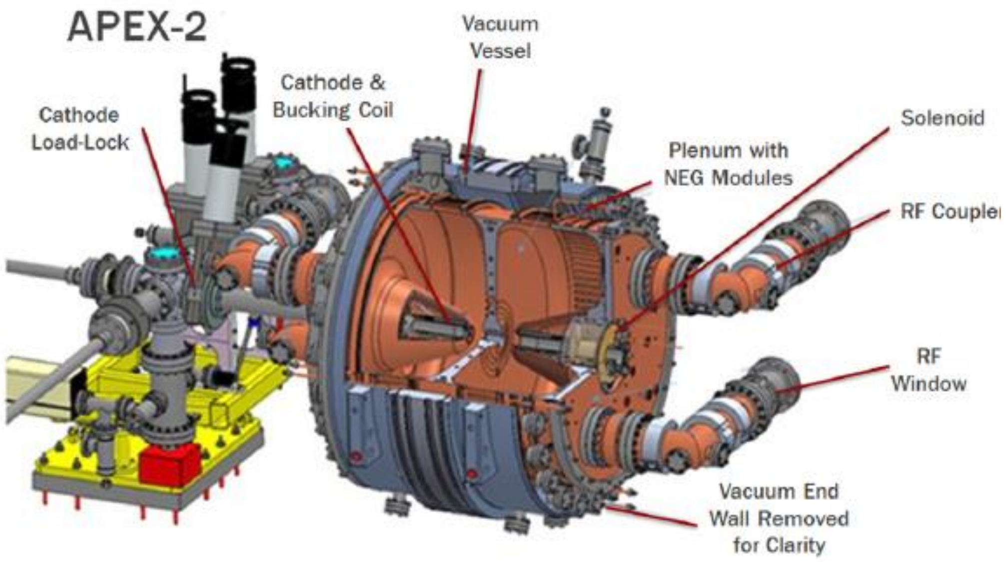
In A. Arnold & J. Teichert, PRST-AB 14 (2011)

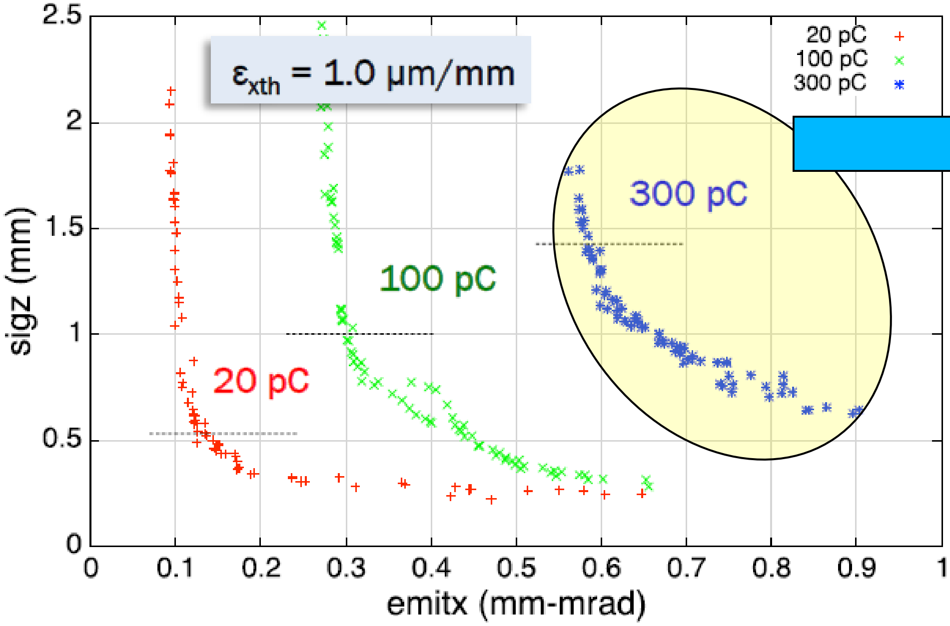
NC-RF Photoinjector

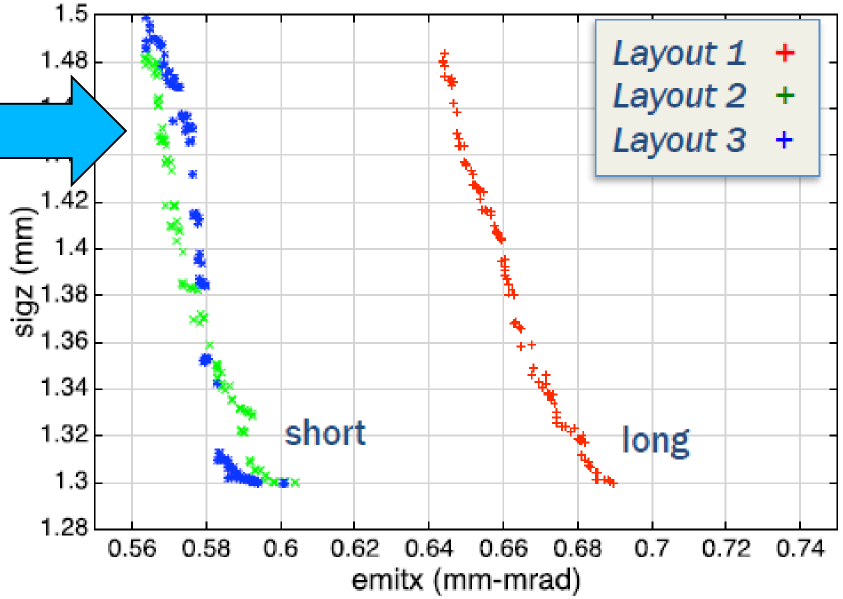
Courtesy C. Mitchell & F. Sannibale, FEL'17

☐ NC RF Gun (*APEX@LBNL*)

- 1(2)-cell CW-RF gun with Cs_2Te cathode
- <I> ~ 0.1 mA, <2 MeV, 1 MHz
- I = 5–25 A, up to 100's of pC, ~ 0.4 μm rad
- 15 MeV in 10 m







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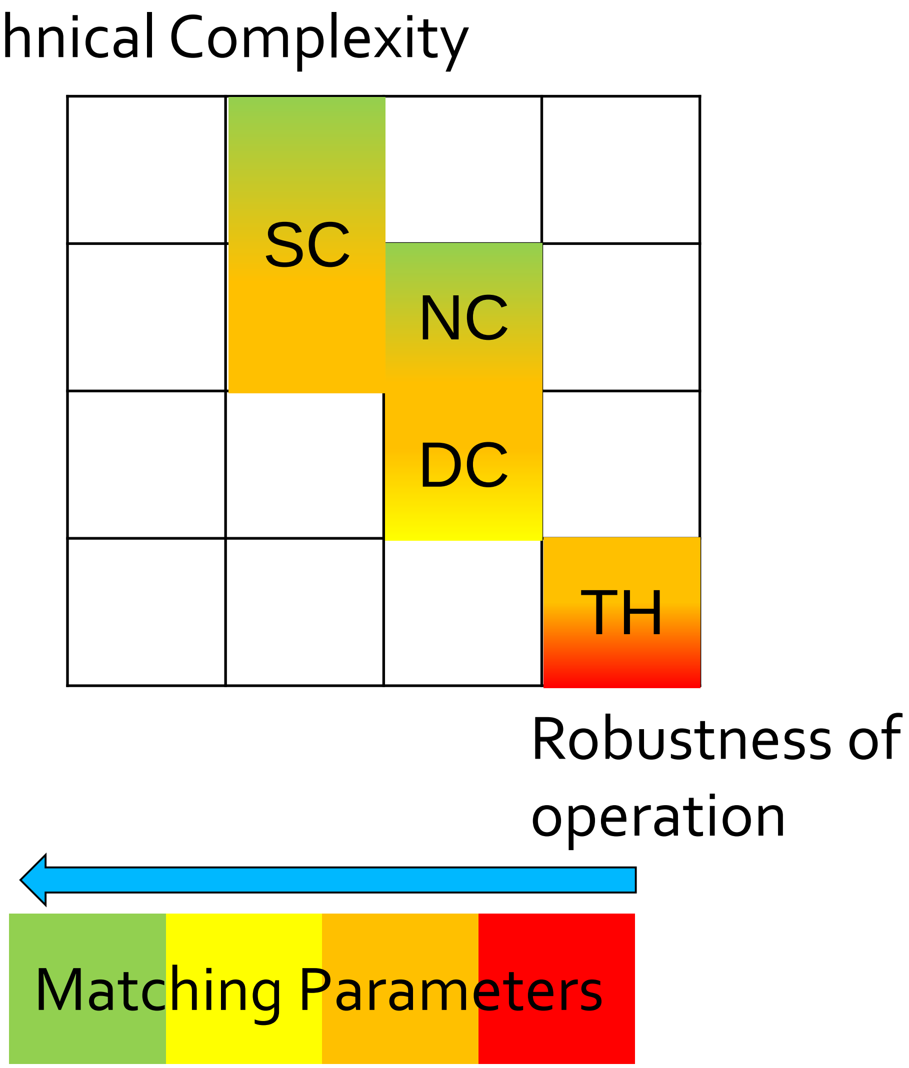
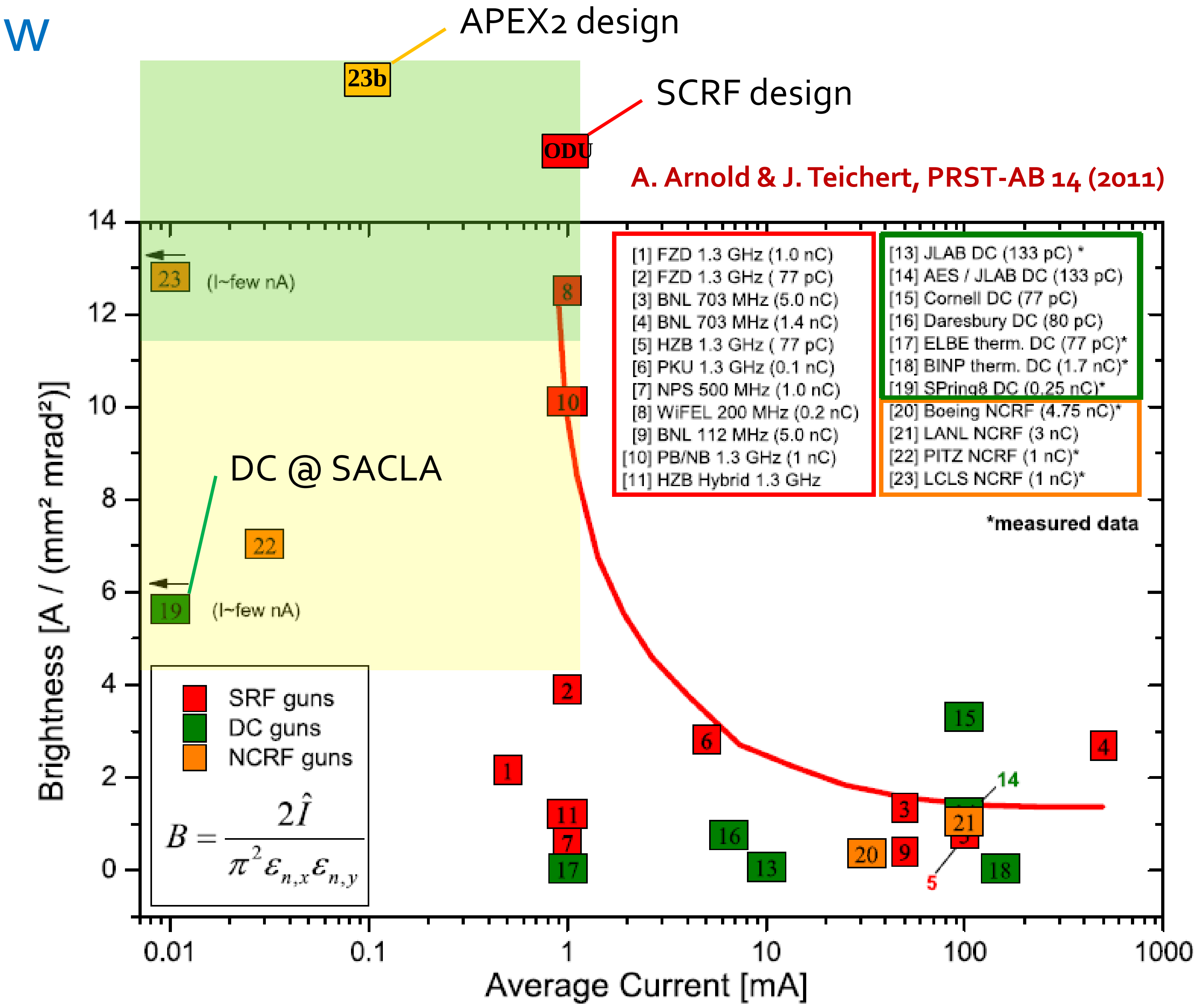
Overview





$$B = \frac{2\hat{I}}{\pi^2 \varepsilon_{n,x} \varepsilon_{n,y}}$$

A. Arnold & J. Teichert, PRST-AB 14 (2011)

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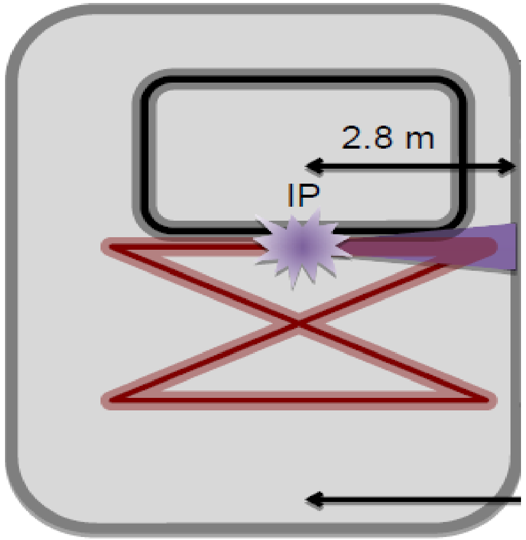
SR-ICS

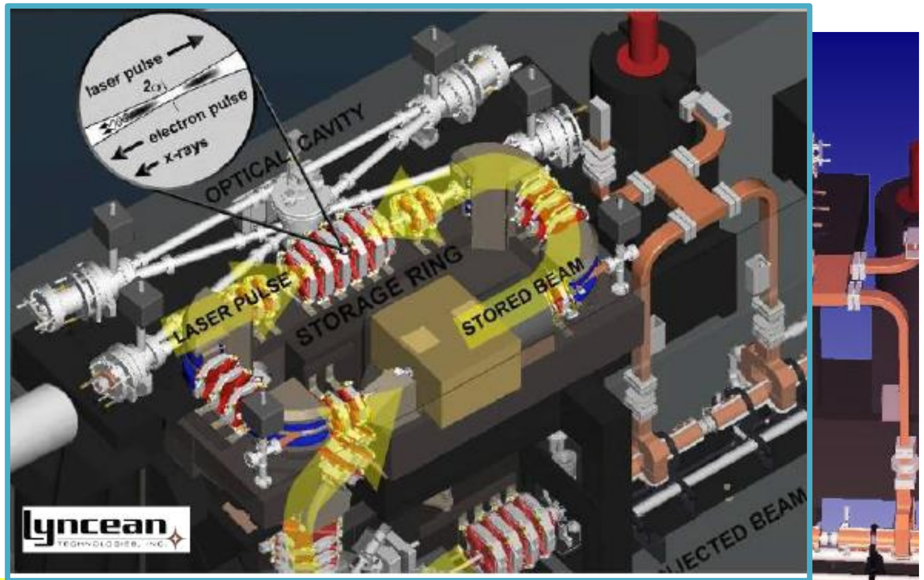
ICS driven by a *desktop-size* **storage ring + optical cavity:**

- f_p = 65 MHz (refilled at 25 Hz)
- e-beam: 250-500 pC, 25-45 MeV, 50 ps, 45 μm@IP
- Selected photon energies

- Stable, reliable
- Limited tuneability of e-beam parameters

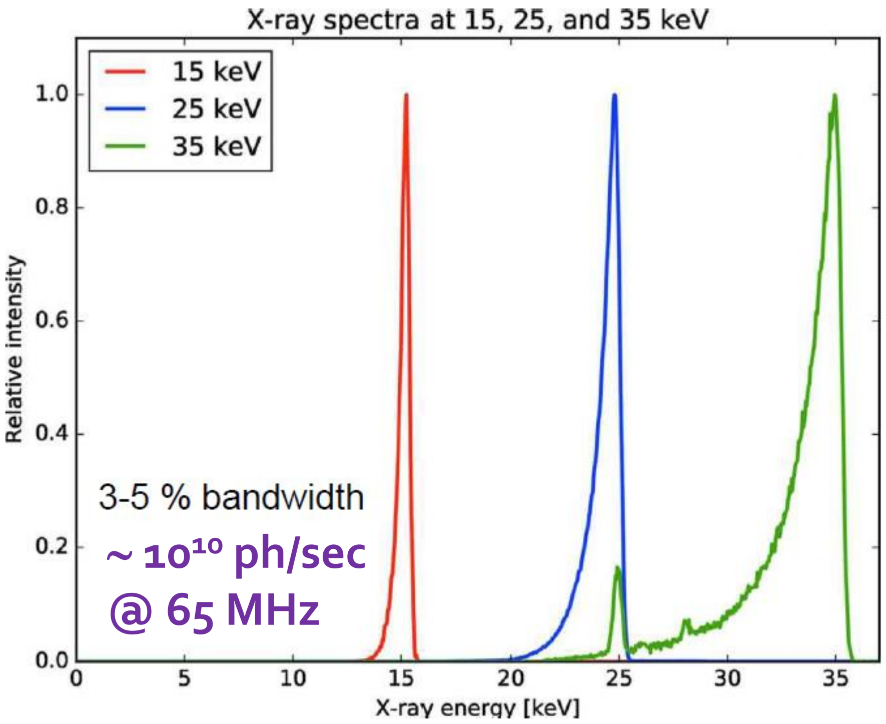


Courtesy of M. Dierolf



FOOTPRINT : ~6 x 20 m²

Eggl et al., JSR 23 (2016)



3-5 % bandwidth

~ 10^{10} ph/sec @ 65 MHz

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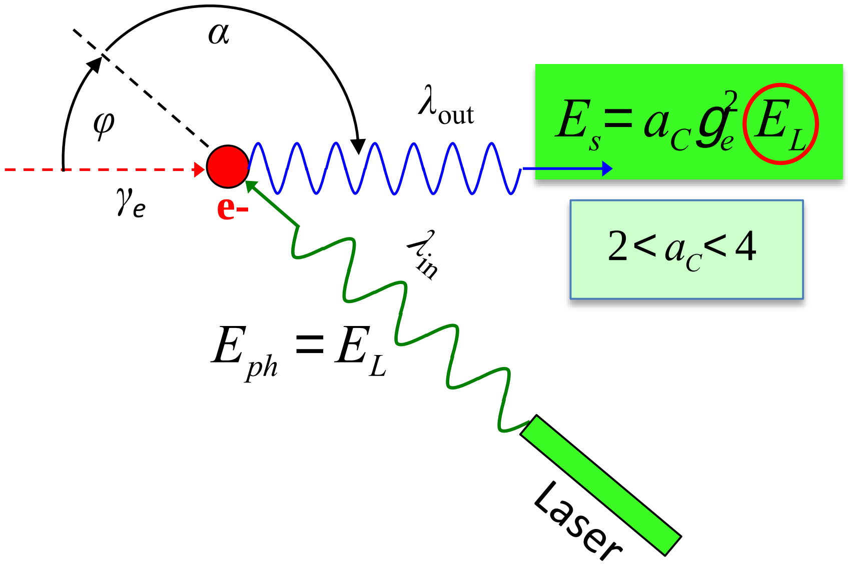
FEL-ICS: Concept

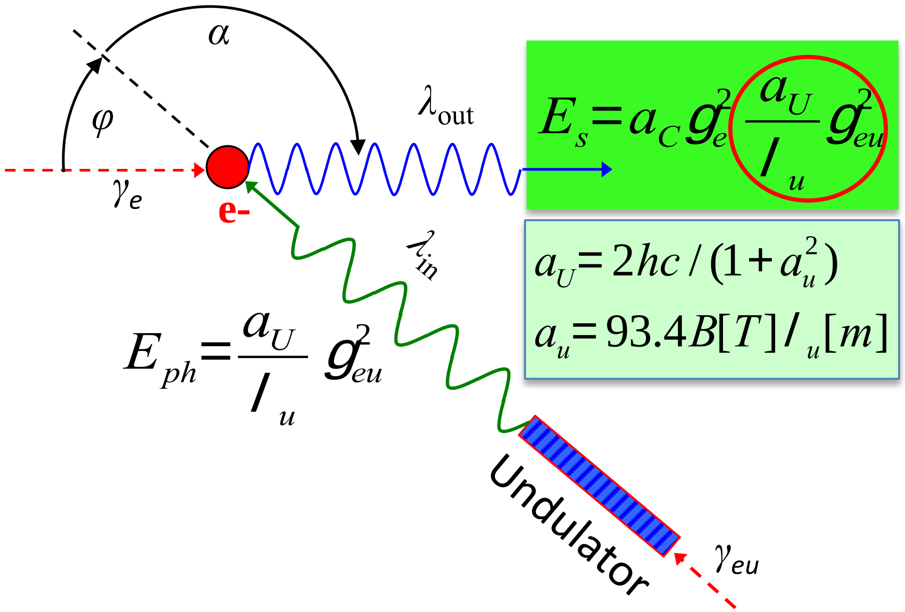
☐ ICS driven by UV FEL: more convenient electron energy scaling → compactness !



$$E_s = a_C \gamma_e^2 E_L$$

$$2 < a_C < 4$$

$$E_{ph} = E_L$$



$$E_s = a_C \gamma_e^2 \frac{a_U}{\lambda_u} \gamma_{eu}^2$$

$$a_U = 2hc/(1 + a_u^2)$$

$$a_u = 93.4 B[T] \lambda_u[m]$$

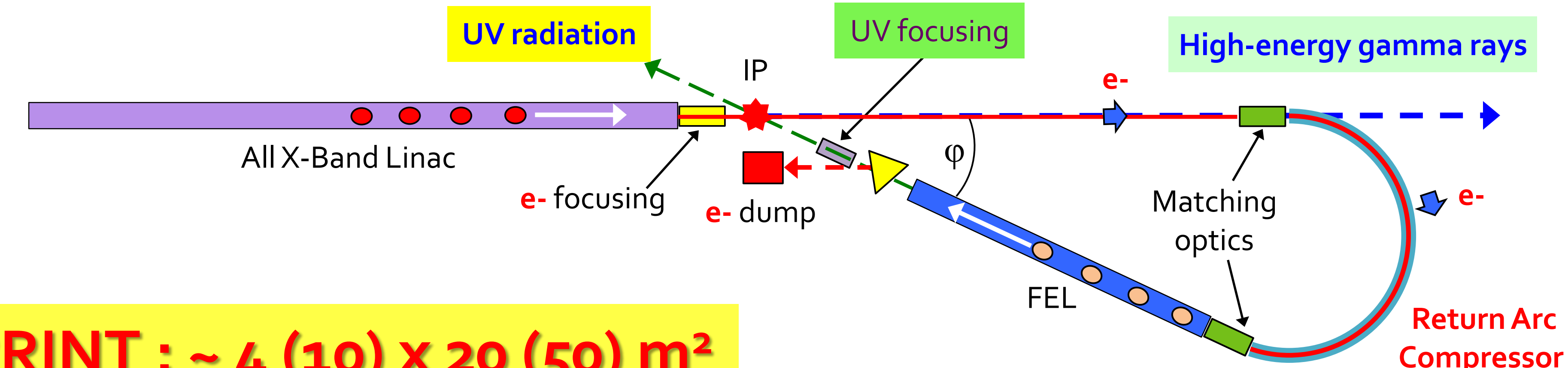
$$E_{ph} = \frac{a_U}{\lambda_u} \gamma_{eu}^2$$

Scattered Photon Energy scales as the **square** of the electron Energy

Scattered Photon Energy scales as the **4th power** of the electron Energy

FEL-ICS: Footprint

M. Placidi et al., NIM A 855 (2017)



FOOTPRINT : ~ 4 (10) x 20 (50) m²

- ☐ Electron bunches (train of ?) from an ***all X-band Linac @ 1 kHz***
- ☐ Peak current increased in a ***return arc compressor*** to drive a SASE UV FEL
- ☐ ICS of UV on trailing e-bunches. ***ICS and UV self-synchronized.***
- ☐ e- and UV focusing optimize ICS luminosity via overlap and matching at IP

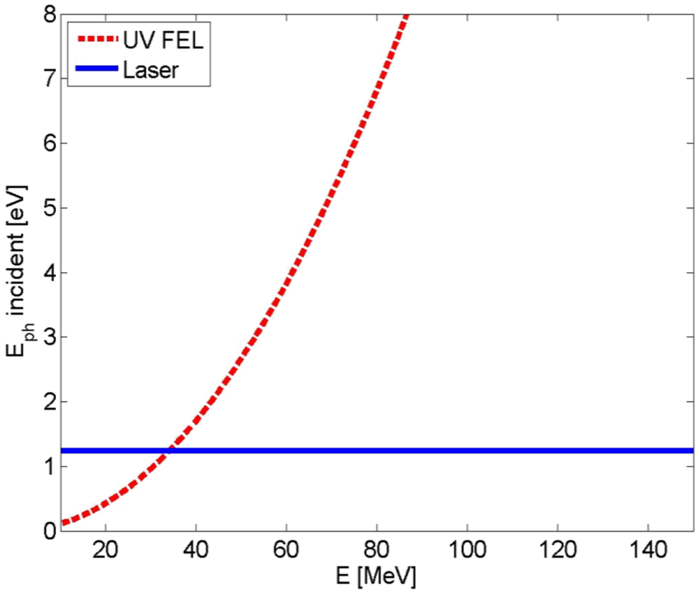
FEL-ICS: Pros and Cons

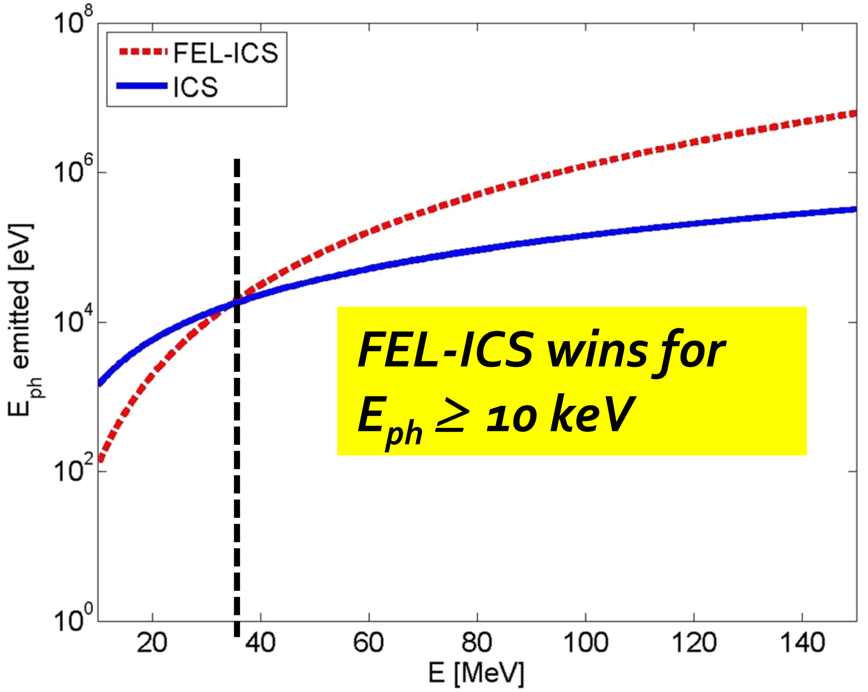
☺

- **Shorter linac** at any given λ_R
- **Self-synchronized UV** also available
- Net gain at $\boldsymbol{E_e}$ **> 50 MeV** & $\boldsymbol{I}$ **> 100 A**
- 10's of keV – MeV photon energy

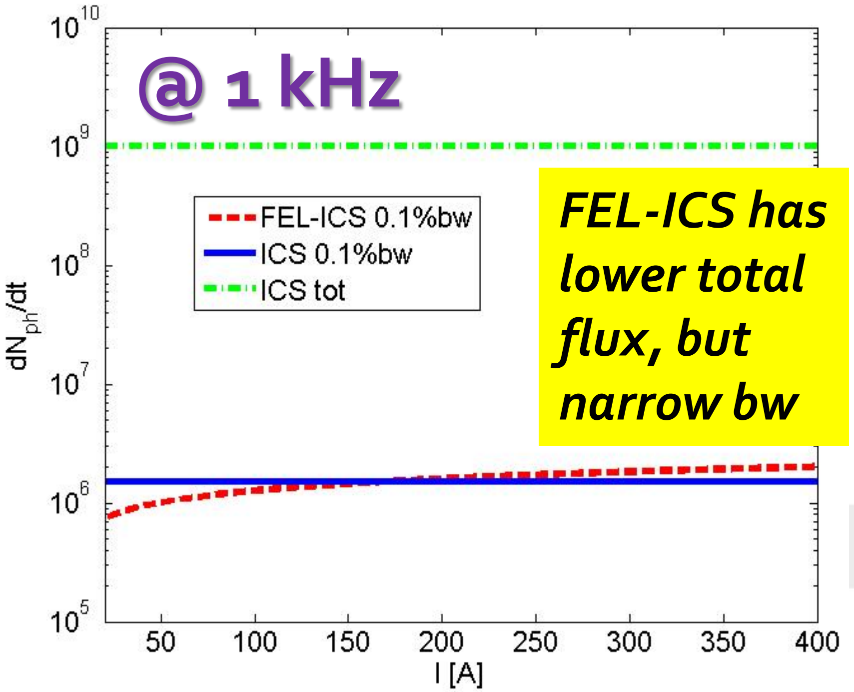
☹

- **Complexity:**
  - Undulator
  - Arc compressor
  - UV focusing





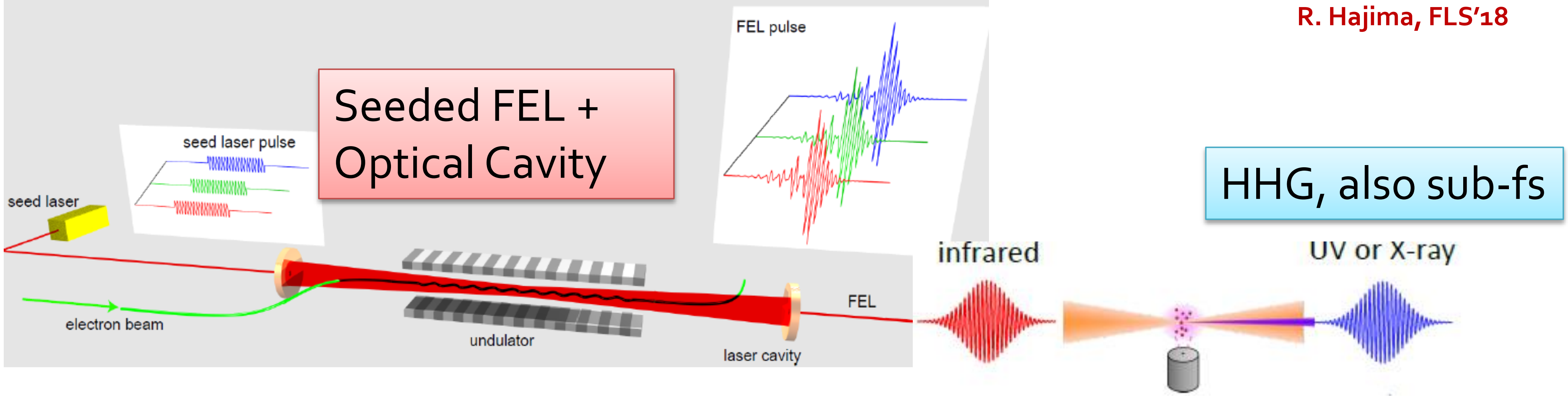
FEL-ICS wins for $E_{ph} \geq 10$ keV



FEL-ICS has lower total flux, but narrow bw

FEL-HHG: Performance

R. Hajima & R. Nagai, PRL 119 (2017)
R. Hajima, FLS'18



- Electrons: 50-100 MeV, 100 pC, 300 A, *1 MHz*
- Seeding laser: >4 μm, 2-cycles, 3 mJ
- MIR-FEL: ~ 0.1 mJ pulse energy, 6 μm, few cycles, CEP-stabilized

~10⁴ ph/**pulse**/0.1%bw @ 1-10 keV

~10¹⁰ ph/**sec**/0.1%bw @ 1-10 keV

(sub-)fs pulse duration possible

FOOTPRINT :
~ 5 (10) x 20 (50) m²

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Final Remarks

❑ Guns ~available for high average e-brightness. Up to **~ 100's pC @ MHz** conceivable

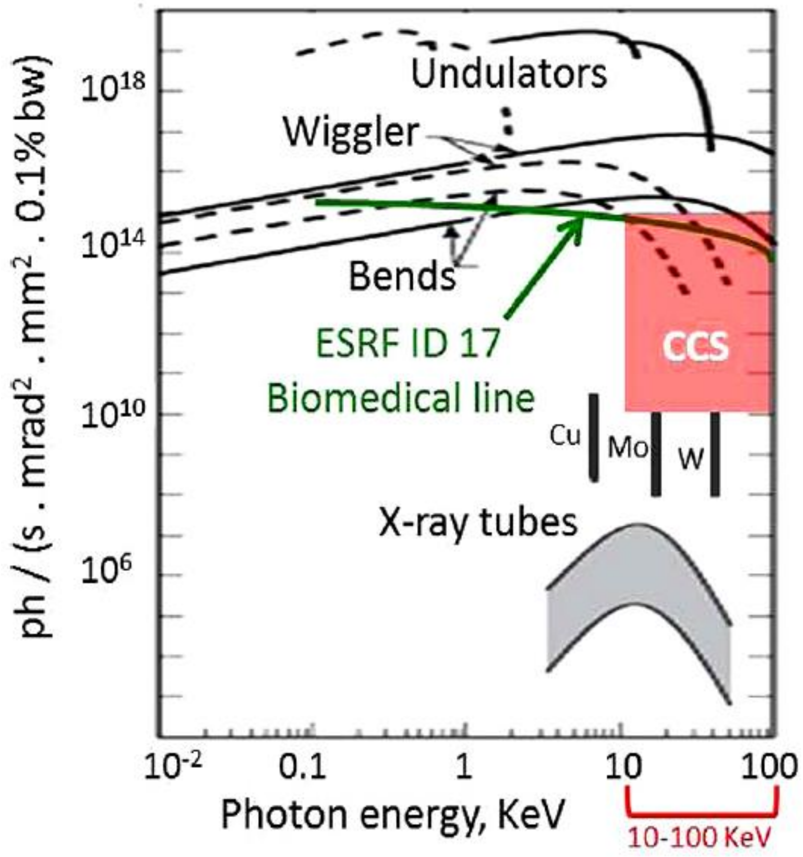
- *<u>Transverse coherence:</u>*
  - 1 keV --> 50 nm rad @ 250 MeV, < 10 pC @ k/MHz
  - 1 keV --> 5 nm rad @ 25 MeV, < 1 pC @ k/MHz

❑ NC RF technology (C-/ X-band) moving towards **1 kHz**.

❑ Schemes for high rep. rate (SR-ICS), high photon energy (FEL-ICS) and ultra-short pulses (FEL-HHG) available.

- *<u>Niche</u>* <u>for ICS</u> *<u>sources</u>*<u>:</u> > 10 keV tuneable, < ps, kHz–MHz

M. Jacquet, NIM B (2014)



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Thank you for Your attention

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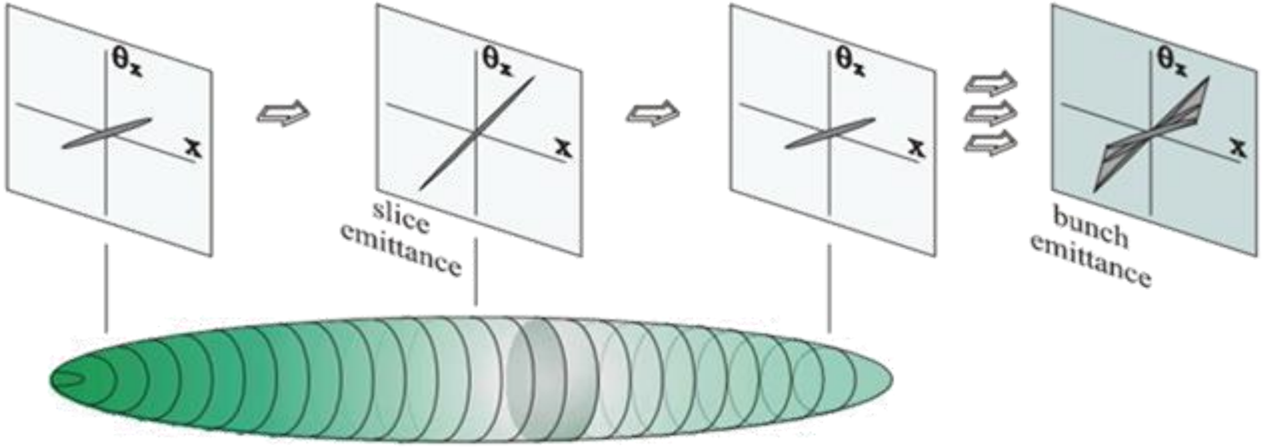
e-Beam Emittance

Courtesy I. Bazarov



$$\varepsilon_{tot}^2 = \overbrace{\varepsilon_{cath}^2\sigma_r^2 + \varepsilon_{rf}^2 + \varepsilon_{chrom}^2}^{\propto \sigma_r^2} + \overbrace{\varepsilon_{nlsc}^2}^{\propto 1/\sigma_r^2}$$

~0.3 μm/mm (thermal) → ~0.6 μm/mm (effective)

< 0.1 μm (S/L-band)

< 0.1 μm

~0.6 μm (1 nC)

$$|E_{rf}| > \frac{Q}{\pi\varepsilon_0 r^2}$$

e.g., Q=100pC, E_{rf} > 30 MV/m

⇒ **r ~ 100's μm**

$$\varepsilon_{rf} \propto \frac{|E_{rf}|}{f_{rf}}\sigma_r^2\sigma_z^2$$

e.g., E_{rf} > 30 MV/m, 0.15 GHz

⇒ **$\sigma_r\sigma_z$ ~ 0.3 mm × 1 mm**

$$\varepsilon_{chrom} \propto \frac{\sigma_r^2\sigma_\delta^2}{f_{sol}}$$

e.g., B_{sol} = 1T, σ_r ~ 0.3 mm

⇒ **σ_δ < 1%**

$$\varepsilon_{nlsc} = F\frac{Q}{\sigma_r^2\sigma_z}$$

e.g., F=0.5, Q=100pC

⇒ **$\sigma_r\sigma_z$ ~ 0.3 mm × 1 mm**

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