Elettra
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Options for time-resolved experiments at diffraction limited storage ring light sources

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Outline

❖ *How short, and how intense x-ray pulses can be at DLSRs ?*

- ❑ Overview of pulse durations, trend, users wish list
- ❑ Short pulse schemes
  - *implementation aspects*
  - *(in)compatibility with DLSR*
- ❑ Conclusions

Short pulse schemes:
- Low-α
- *RF focusing (BESSY-VSR)*
- *Transverse deflecting cavities*
- Magnetic compression
- Laser/electron slicing

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X-ray facilities

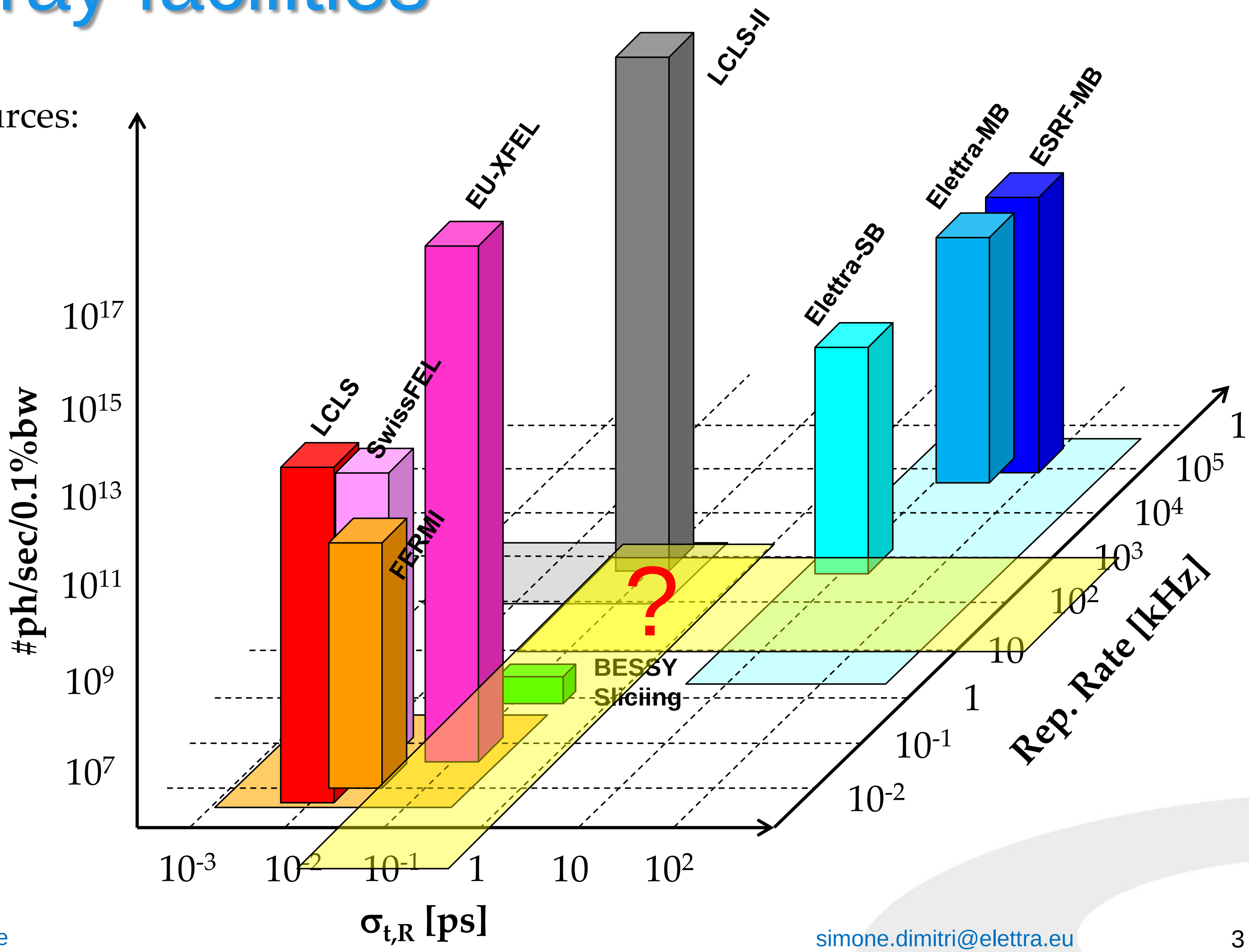
Examples of accelerator-based X-ray sources:

- 0.1 – 10 keV photon energy
- # of phs. at the source
- FEL in short pulse mode

❑ **Can a DLSR target**
~ sub-ps,
> 10 kHz,
> 10^8 ph/s/0.1%bw or
10^6 ph/pulse ?

❑ Lattice-invasive ?

❑ Standard user operation ?



Wish list from TREES workshop

*Opportunities for **T**ime-**RE**solved **E**xperiments at **S**ynchrotron light source facilities,* Trieste, December 2018

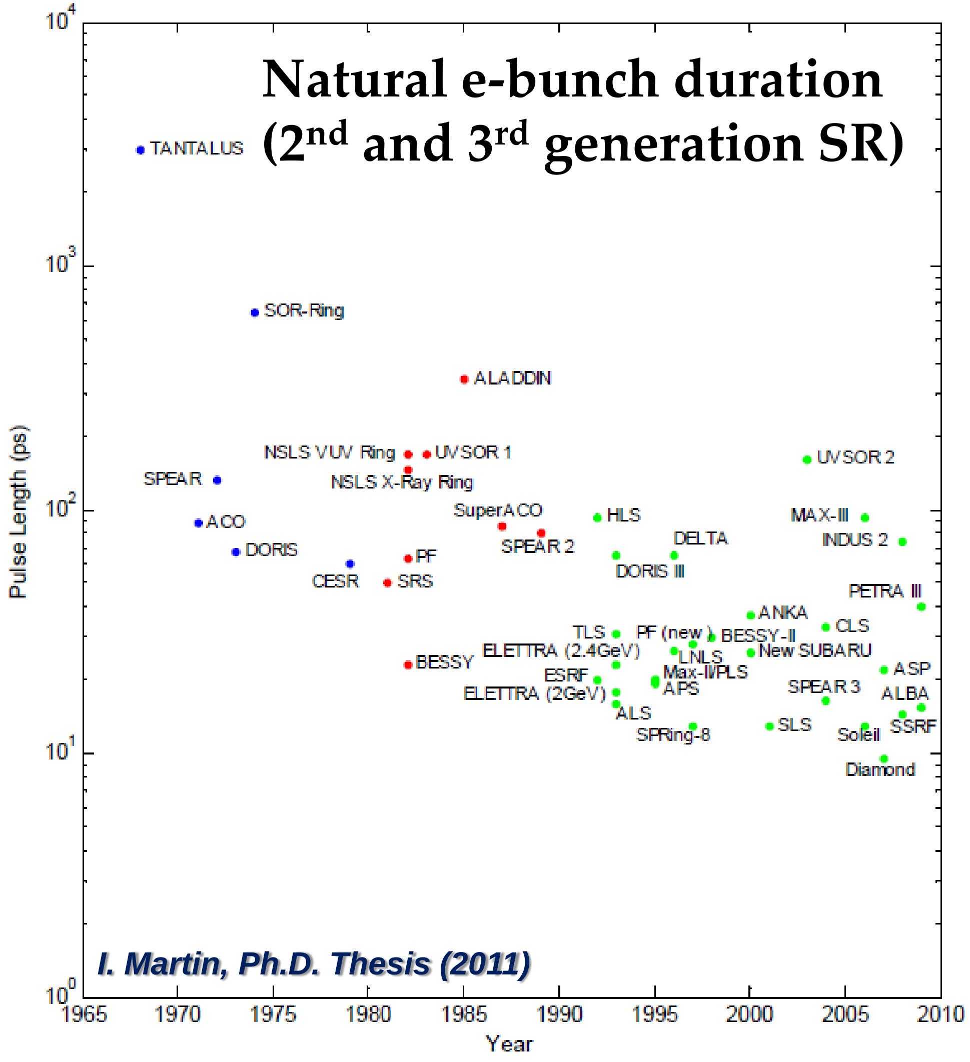
Science Case	E_{ph} [keV]	Δt_{FWHM} [ps]	Pump Laser Rep. Rate [kHz]	Technique
AMO	0.005	1– 5	10 - 100	PES, PECD, XAS, XES, Coincidences
Chemistry	[illegible]	1– 5	1 - 1000	XAS, XES, PES, RIXS, XRD, CD
Biology	[illegible] 10	[illegible]	1 - 10[illegible]	XRD, CD, XAS, XES, RIXS
Magnetism	0.3 - 1	[illegible]	[illegible]	PEEM, PCS, XAS, RIXS, XMCD
Strongly Correlated Materials	0.3 - 10	1 – 5	1 - 1000	XAS, RIXS, XMCD, REXS
Materials science	0.1 - 10	1– 3	1 - 1000	XAS,PES,

Tuneable, up to 10 keV → *NO coherent harmonic generation (seeding, EEHG, etc.)*

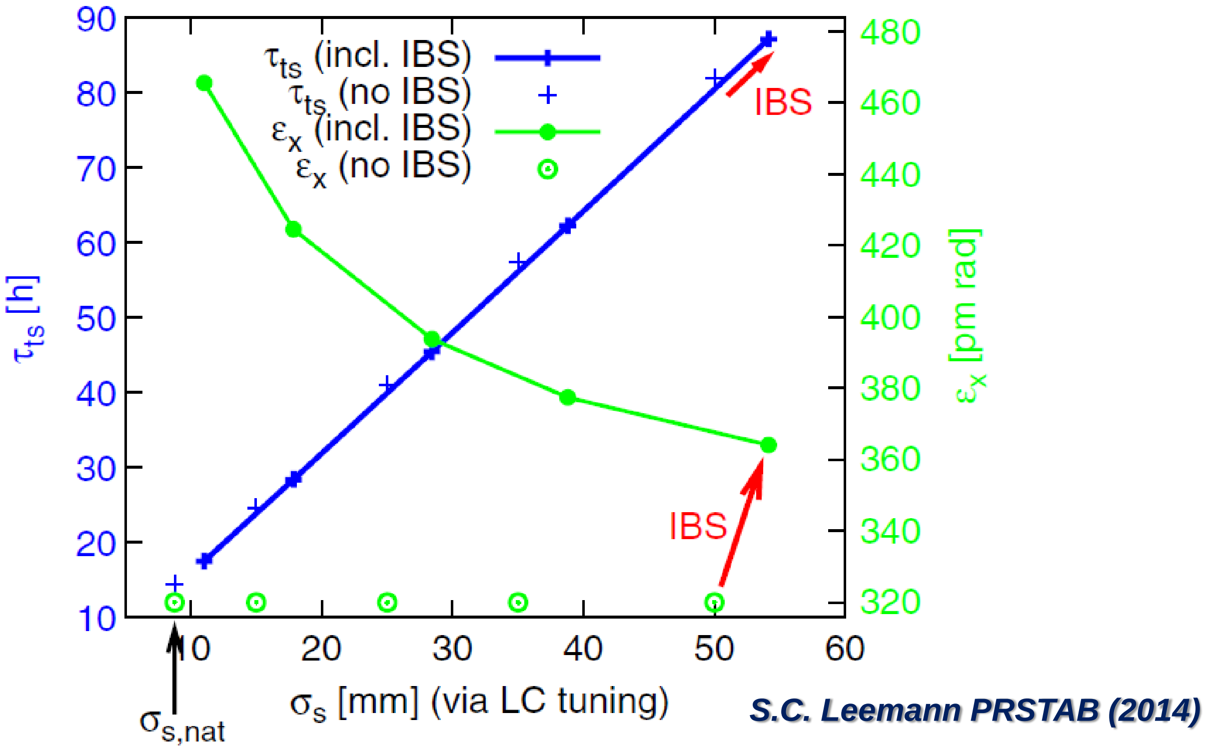
σ_t < 2 ps (RMS) → *NO "camshaft" bunch*

< 1 MHz → *Single bunch-turn*

e-Bunch duration



What trend in 4th generation (DLSR) ?



Shortening the e-bunches is *in conflict* with the diffraction limit

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Low-α optics

$$\sigma_{t,R} \approx \sigma_{t,e} \propto \sqrt{\frac{\alpha_c}{V_{RF} f_{RF}}}$$

optics tuning (α_c)

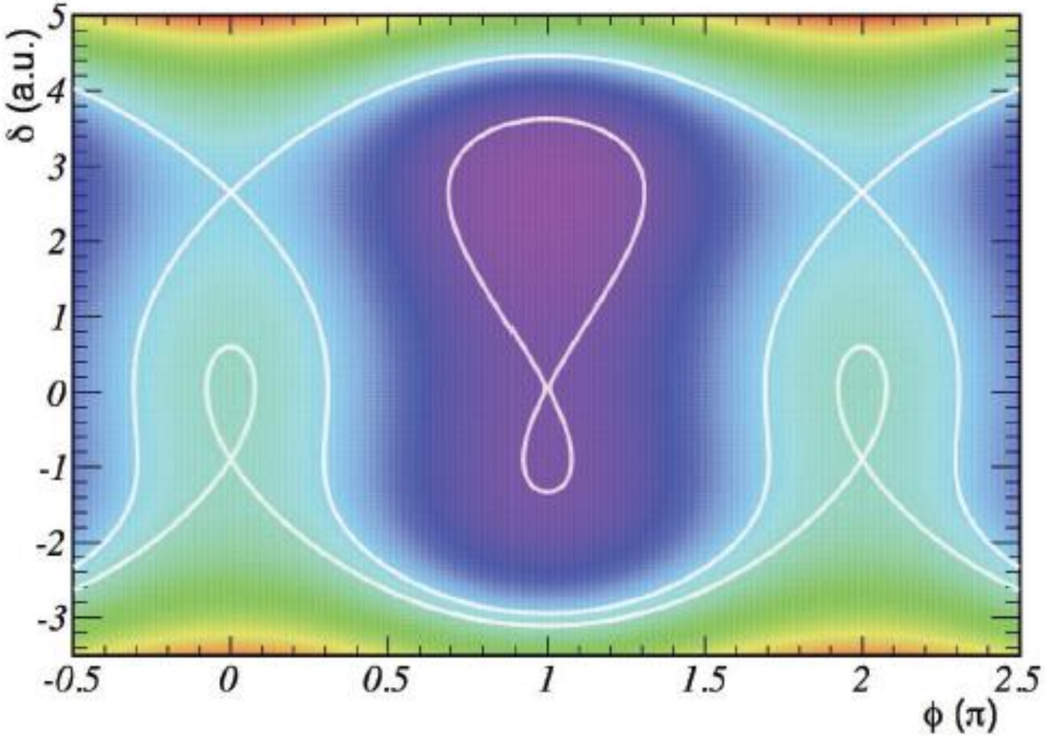
high RF gradient ($V_{RF} f_{RF}$)

DLSRs have natural low α_c

Short pulses available at all beamlines

Control of higher order-α_c with multipoles might allow the storage of short and long bunches. Not robust enough, yet.

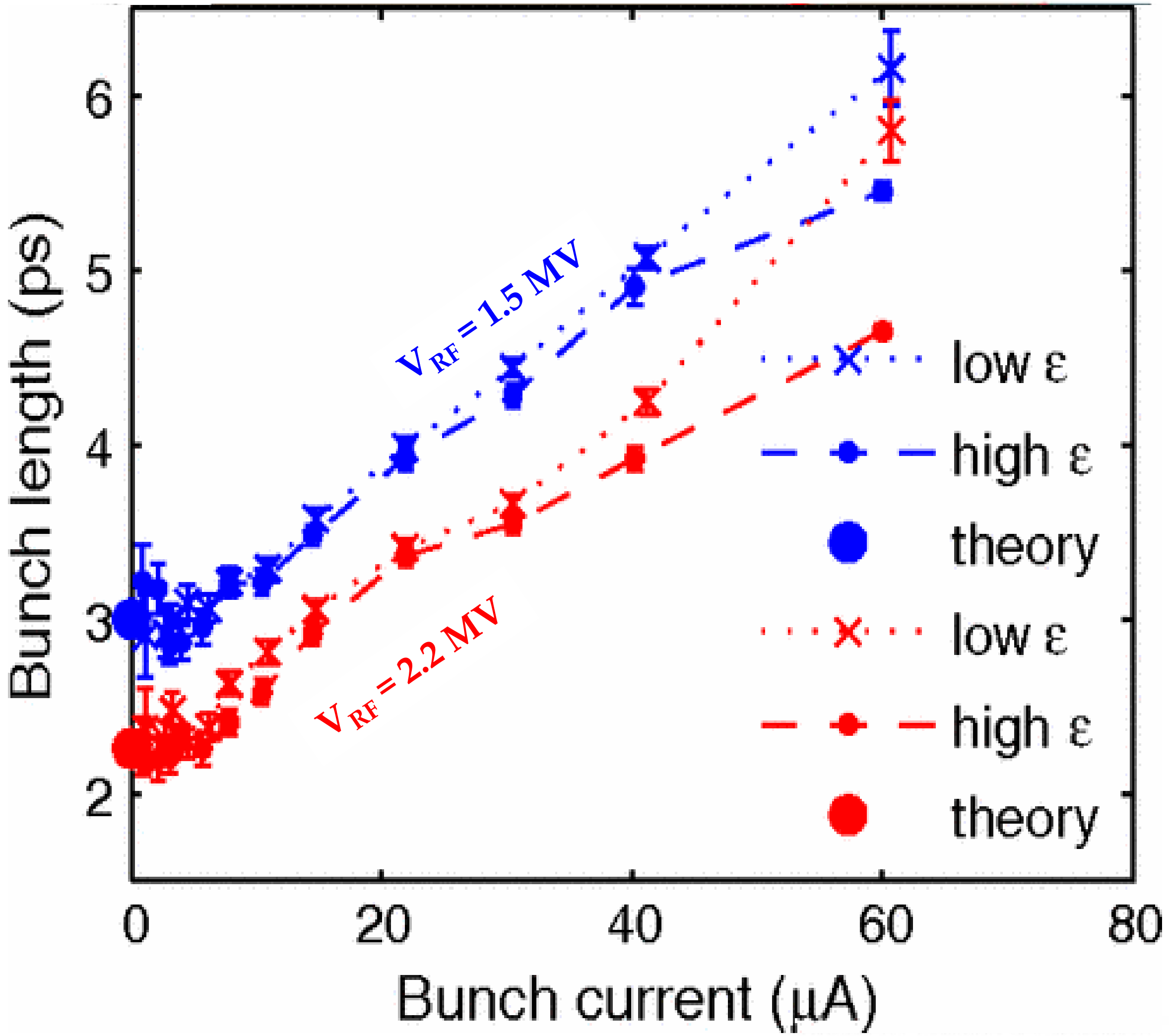
Optics squeezes the RF bucket



Low-α optics

Higher RF voltage shortens the bucket further

I. Martin et al., PRSTAB 2011



$$\sigma_{t,R} \approx \sigma_{t,e} \propto \sqrt{\frac{\alpha_c}{V_{RF} f_{RF}}}$$

optics tuning

high RF gradient

Elettra 2.0: $\alpha_c \approx 10^{-4}$

$\sigma_{t,R} \approx 4 - 6\ ps$, $I_{bunch} < 25\ \mu A$, below microwave threshold instability

RF peak voltage > 2 MV @ 500 MHz

Low flux

Machine is dark for other users

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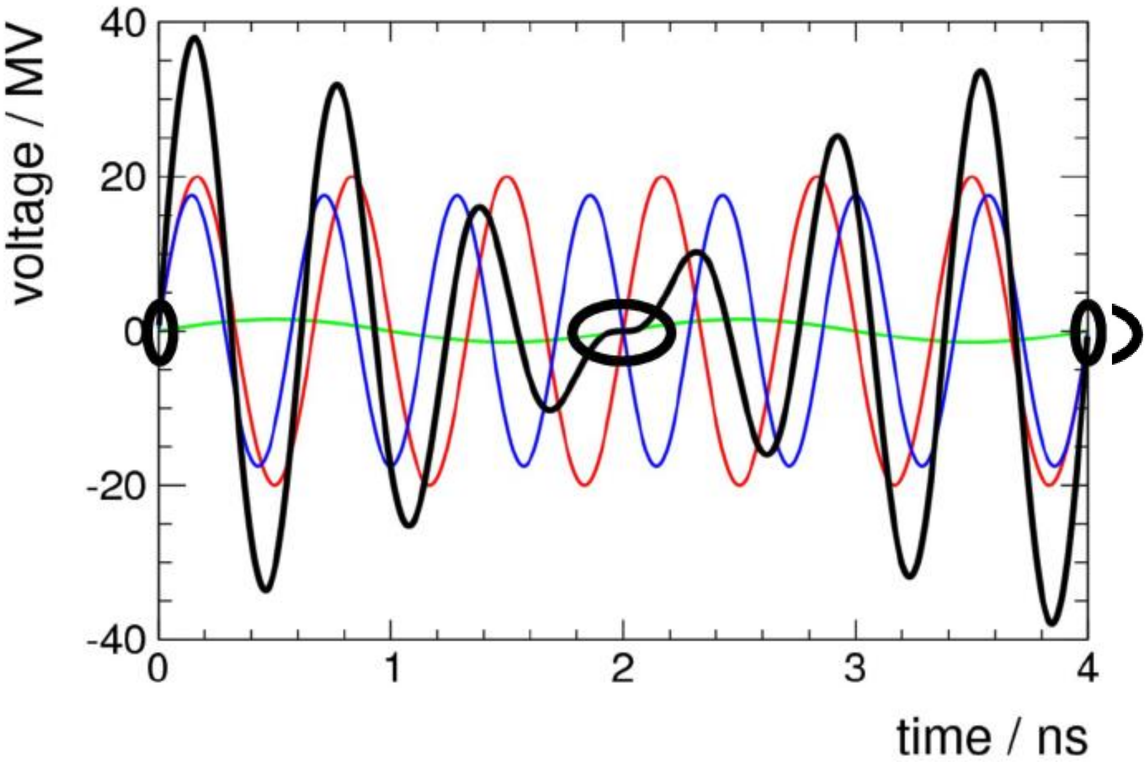
RF focusing (BESSY-VSR)

Courtesy A. Jankowiak, P. Goslawski

$$V'_{\rm rf}(t=0) = 2\pi(f_{\rm nc}V_{\rm nc} + f_{\rm sc,1}V_{\rm sc,1} + f_{\rm sc,2}V_{\rm sc,2})$$



☺ Short & long bunches stored simultaneously

$\sigma_t \approx$ 0.5 – 3 ps, $I_{short} \approx$ 5 - 50 mA

😐 At least 1 straight section dedicated to superconducting harmonic cavities

Short bunches from Booster ring (< 35 ps fwhm)

☹ ⊥ and // instabilities (HOMs)

Low injection efficiency

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Crab cavities: "tilt-and-cancel"

$$\sigma_{t,R} \propto \left(\frac{E}{k_{cc}V_{cc}}\right)\frac{\sigma_{y,ID}}{\sigma_{y,cc}}\sqrt{\sigma_{y'}^2+\sigma_{r'}^2} \ll \sigma_{t,e}$$

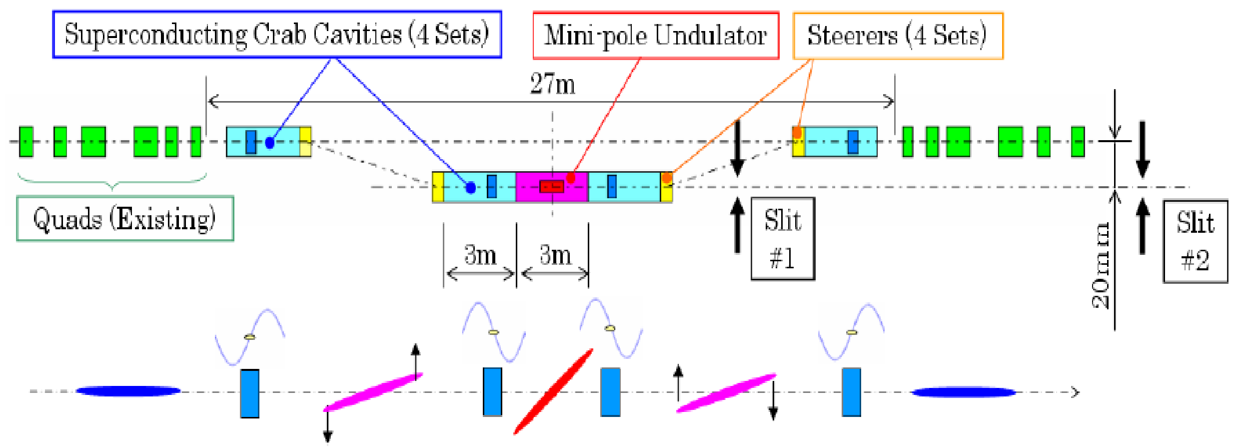
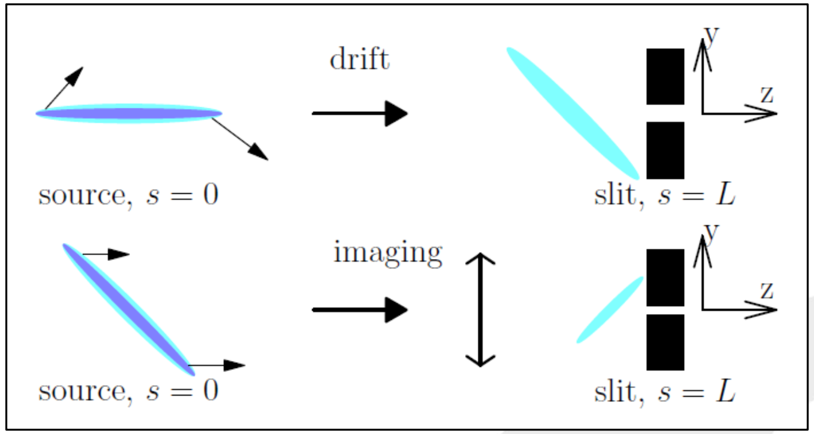


Figure 1: Planned layout of short-pulse generator at SPring-8.

Scaled down to 2.4 GeV → approximately ~9 m length required

electrons y'–z correlation translates into radiation y–z correlation at the slit

$\sigma_{t,R} \approx$ 1 – few ps, $I_{short} < 20$ mA



Two long straight sections occupied

Optics constraints (large β_y, π-phase adv.)

⊥ and // instabilities (HOMs)

Low injection efficiency

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Crab cavities: “frequency beating”

$$\sigma_{t,R} \propto \left(\frac{E}{k_{cc}V_{cc}}\right)\frac{\sigma_{y,ID}}{\sigma_{y,cc}}\sqrt{\sigma_{y'}^2+\sigma_{r'}^2} \ll \sigma_{t,e}$$

Elettra 2.0: $\sigma_{t,R} \approx$ 1.5 – 10 ps, $I_{short} \approx$ 8 mA

Both short and long pulses stored

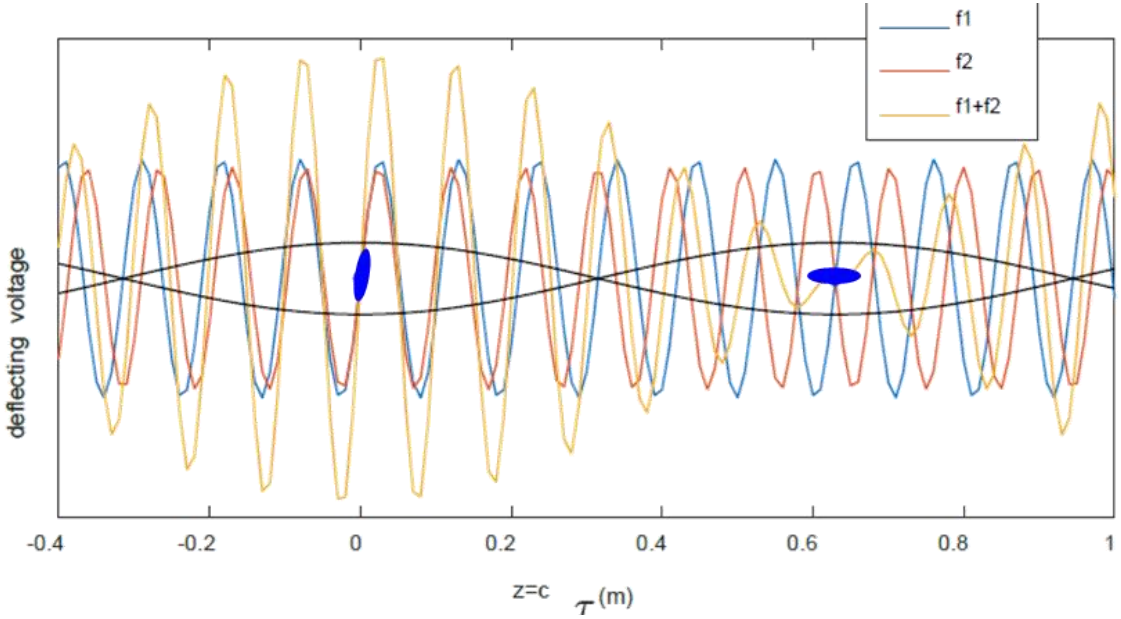
Electron optics constraints are relaxed

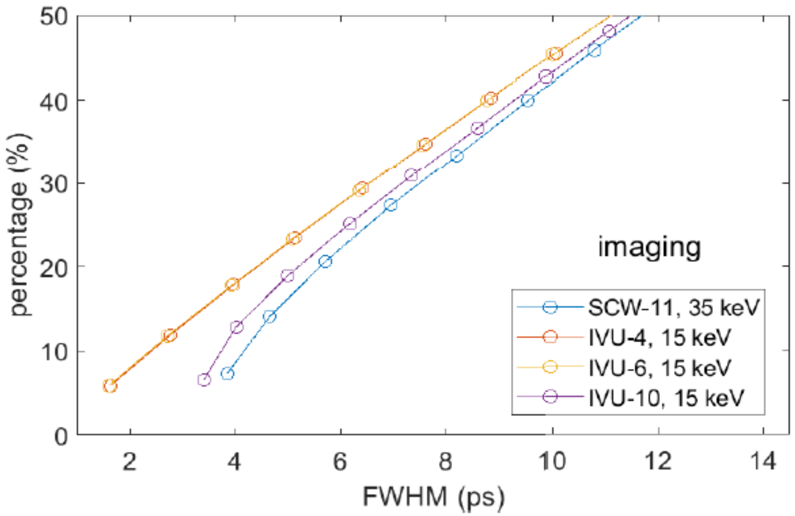
< 5% of nominal total average flux

RF cavities in *one* straight section

⊥ and // instabilities (HOMs)

Low injection efficiency





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By-pass (swap

$$\sigma_{t,R} \approx \sigma_{t,e} \propto \left(\frac{E}{k_{RF}V_{RF}}\right) R_{56}\, \sigma_{\delta,0}$$

$\sigma_{t,R} \approx 0.7 - 2\ ps,$

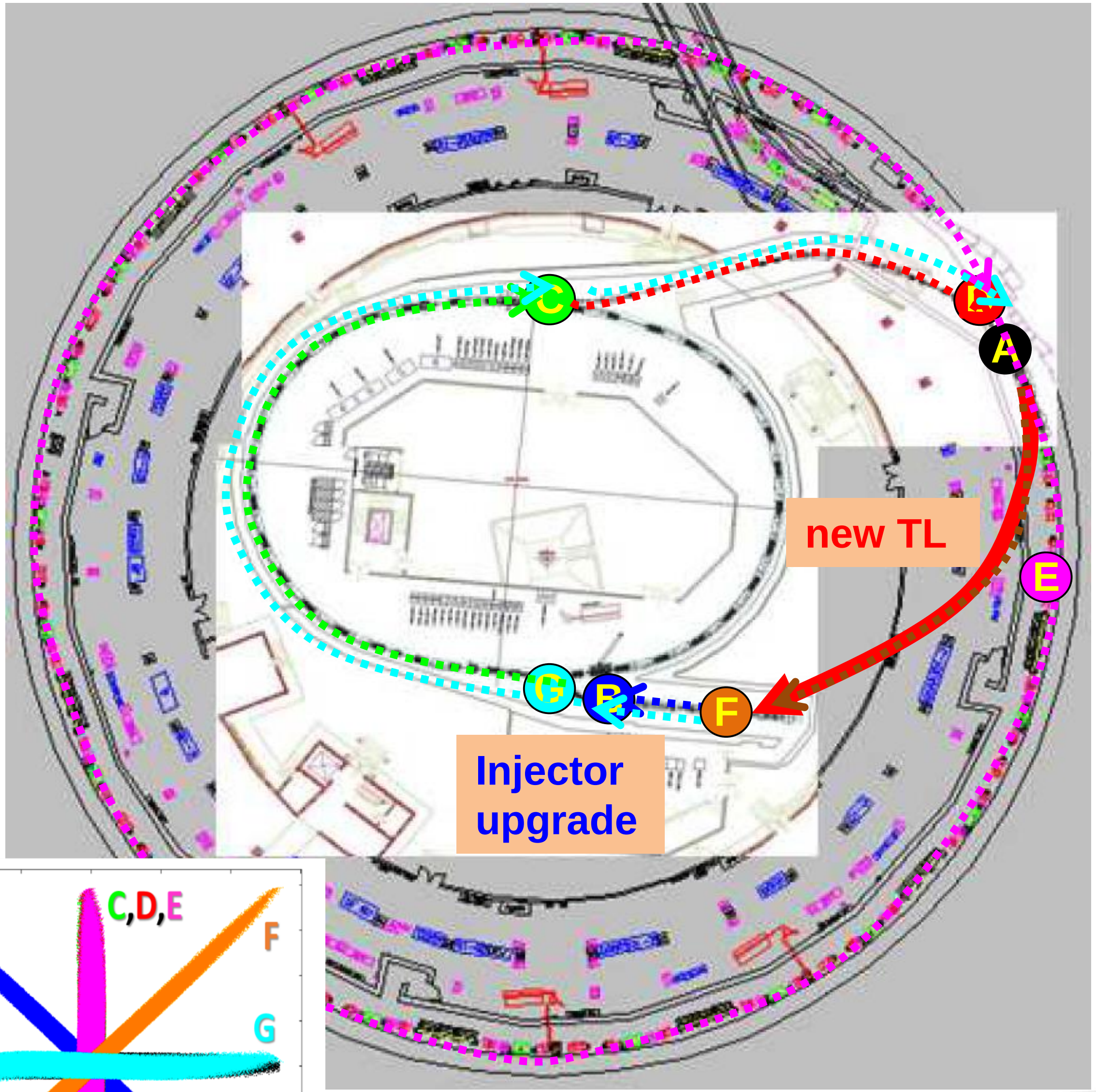
Short and long bunches *at full peak flux* at all beamlines

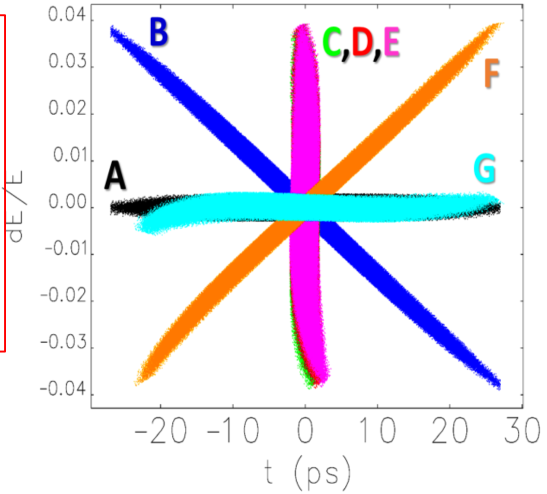
Transparent to DLSR optics

Swap-out injection/extraction

SC injector, MHz stripline kickers for high repetition rate

New ring-to-booster transfer line





S. Di Mitri, M. Cornacchia, New J. Phys. 2015
S. Di Mitri, JSR 2018

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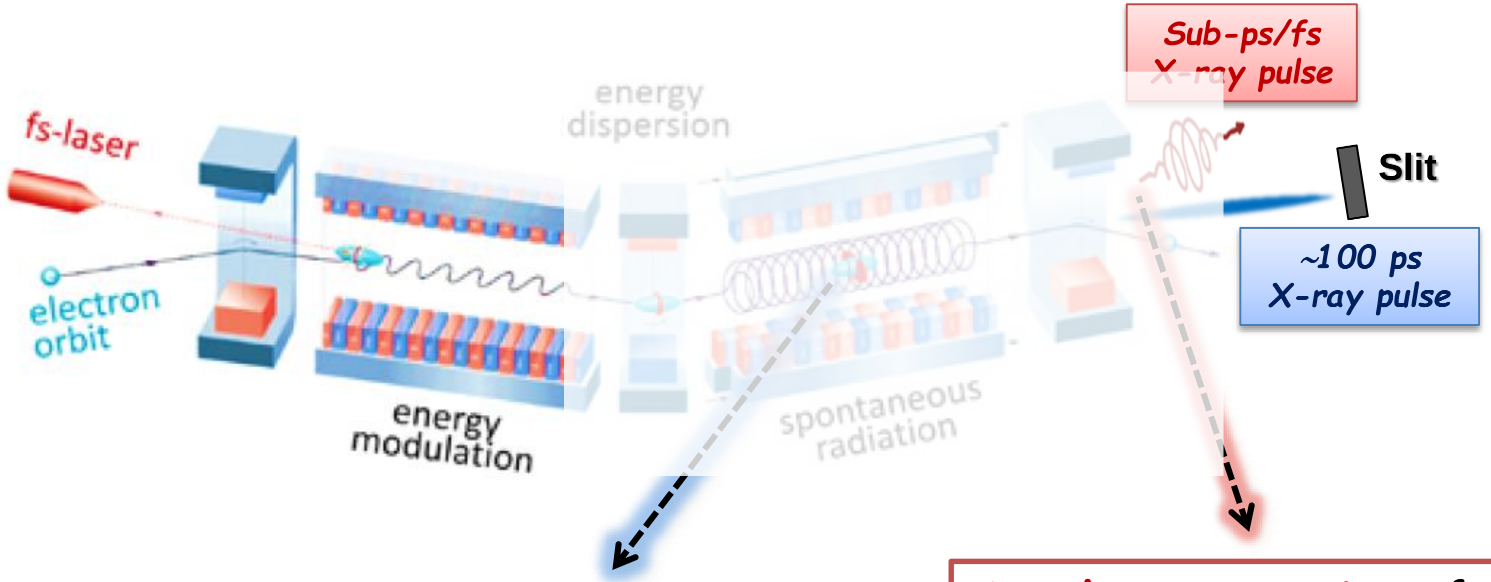
Laser-slicing



Angular separation (~1 mrad) of sliced **electrons**

Angular separation of the short **radiation** pulse

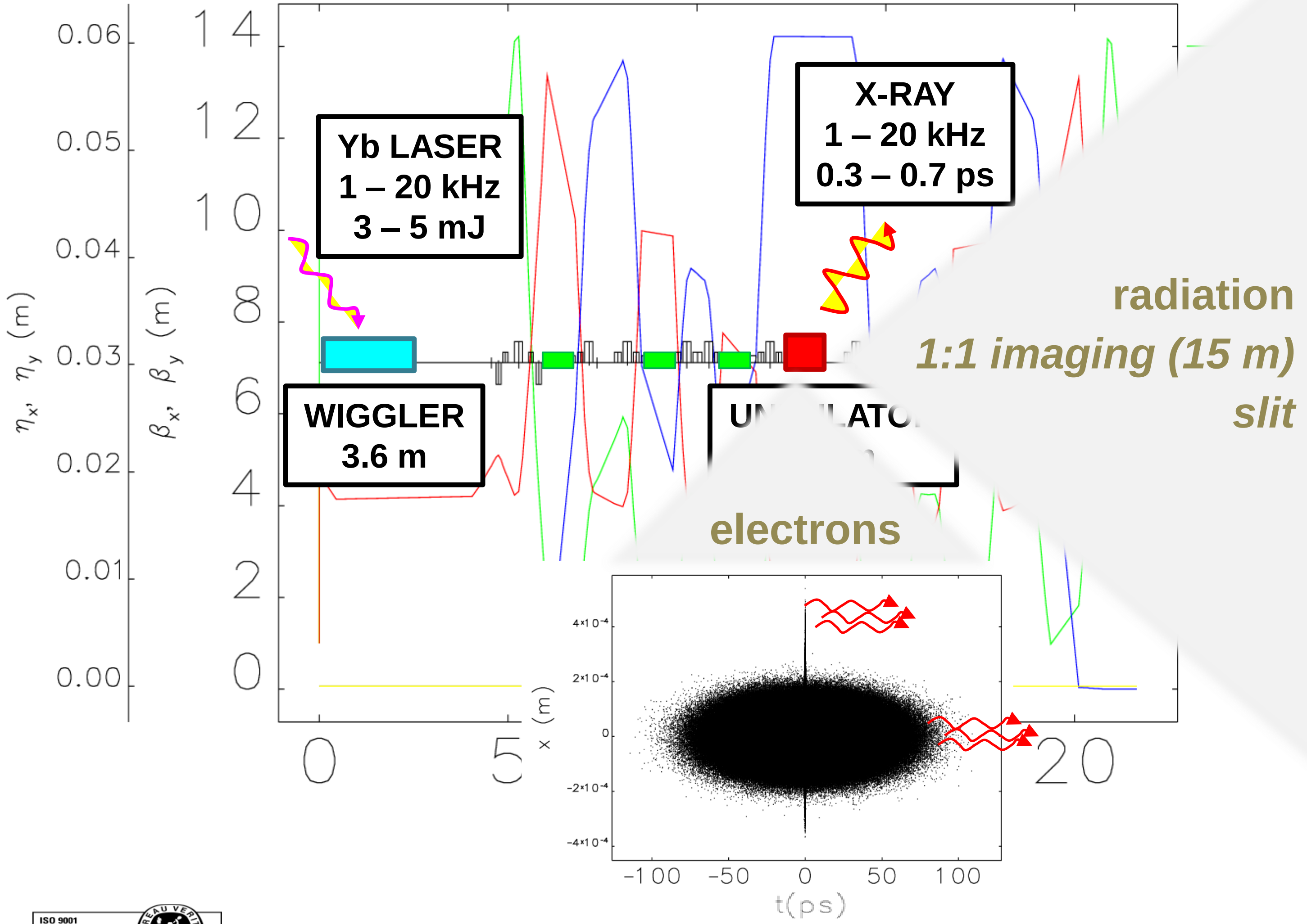
State-of-the-art @ BESSY-II

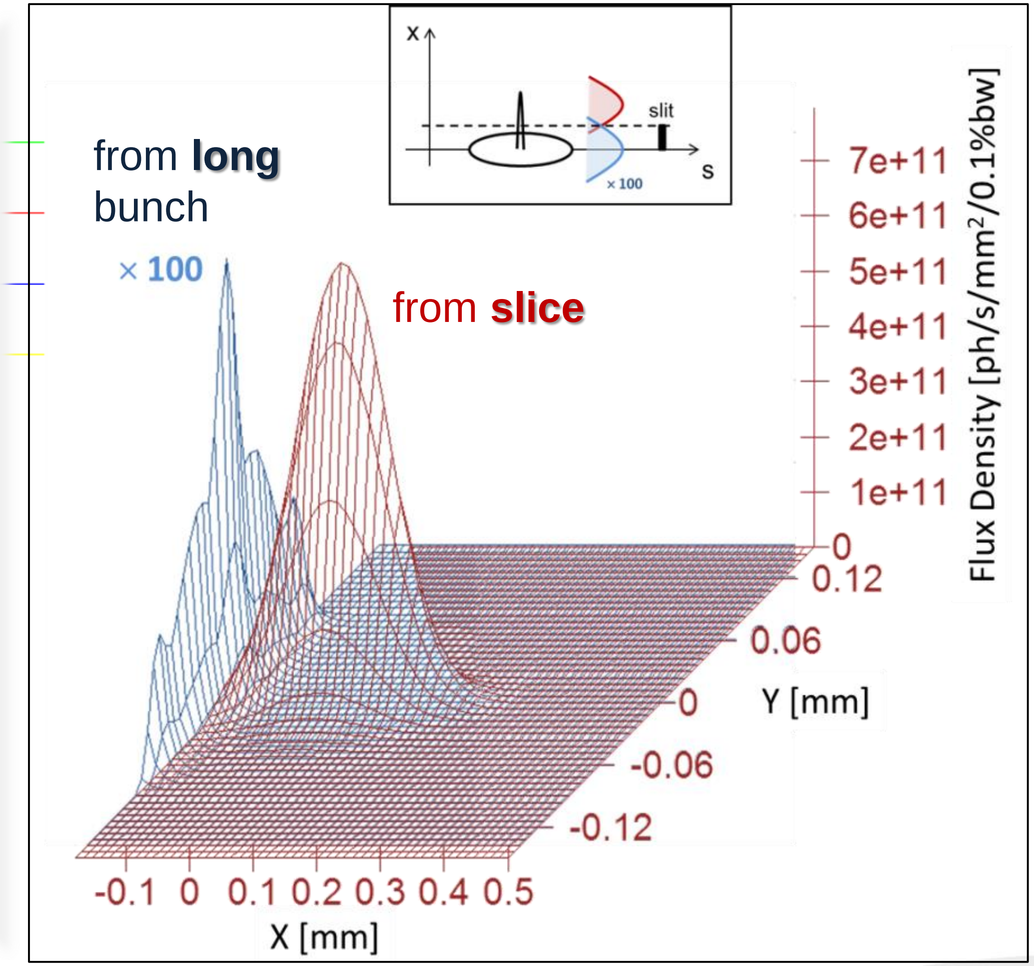
X-ray photon energy (linear and elliptical polarization)	400-1400 eV
Repetition rate	6 kHz
X-ray pulse length	100 fs
Photons on sample	˜ 10^5 ph / s / 0.1% BW
Intrinsic X-ray / laser synchronization	< 20 fs short term jitter < 200 fs day-to day

Table 1: Overview of the parameters of the BESSY II Femtoslicing source.

- ❑ Angular separation implies modification to a SR lattice → DL optics is screwed up
- ❑ DL e-beam emittance improves slicing efficiency → Elettra 2.0: consider pure spatial / spectral separation of radiation

Pure spatial separation





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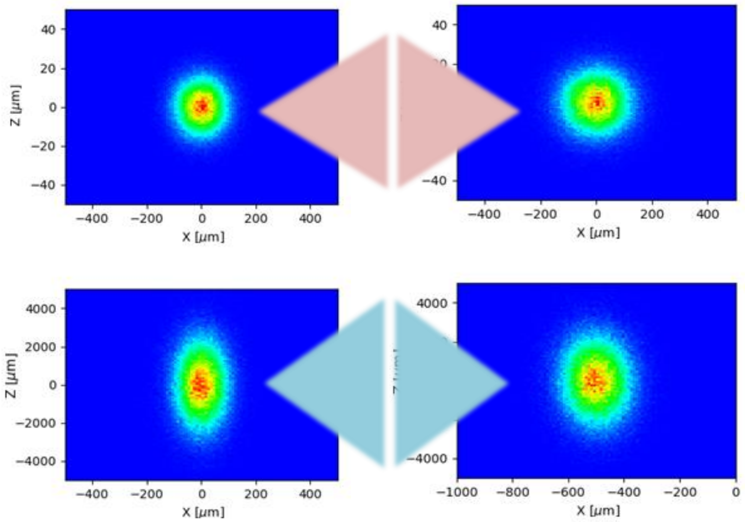
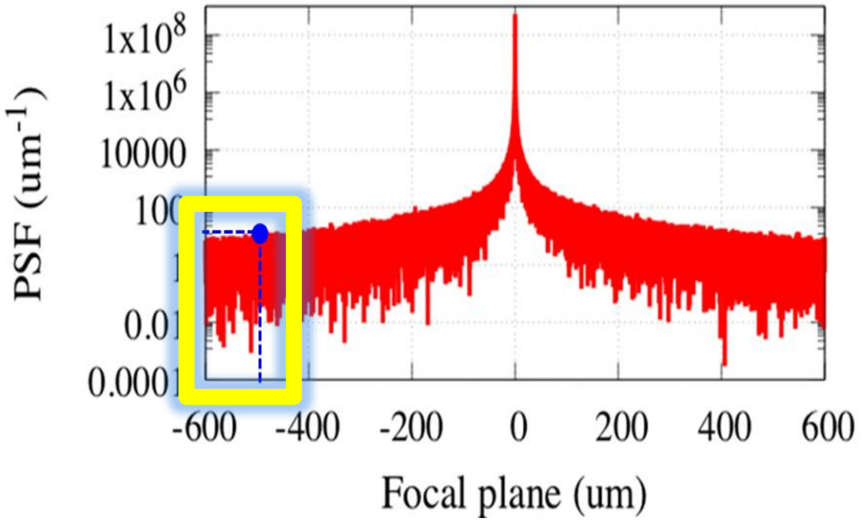
Aberration, scattering, mono

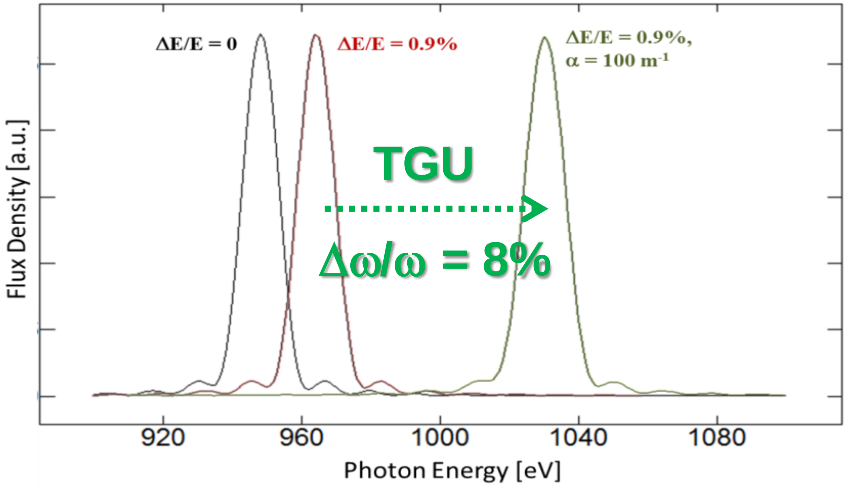
Aberrations: slope error ≤ 1 µrad



Scattering: roughness ≤ 0.5 Å



Transverse Gradient Undulator



$$\textbf{SNR at the detector} = \frac{\text{slicing efficiency}}{\text{background level}} = \frac{10^{-7}}{10^{-10}} = \mathbf{10^3}$$

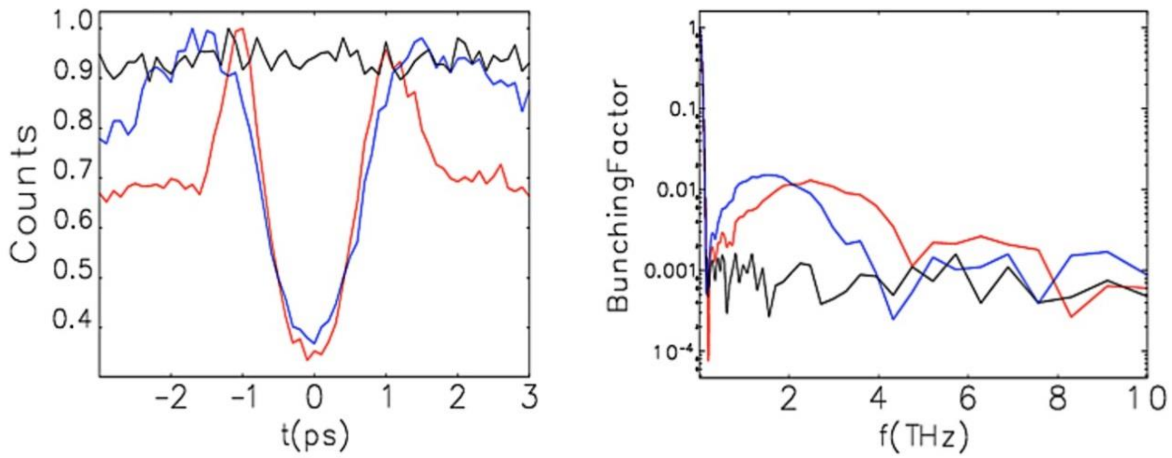
Additional improvements by: ns-detector gating, TGU

Pros and cons

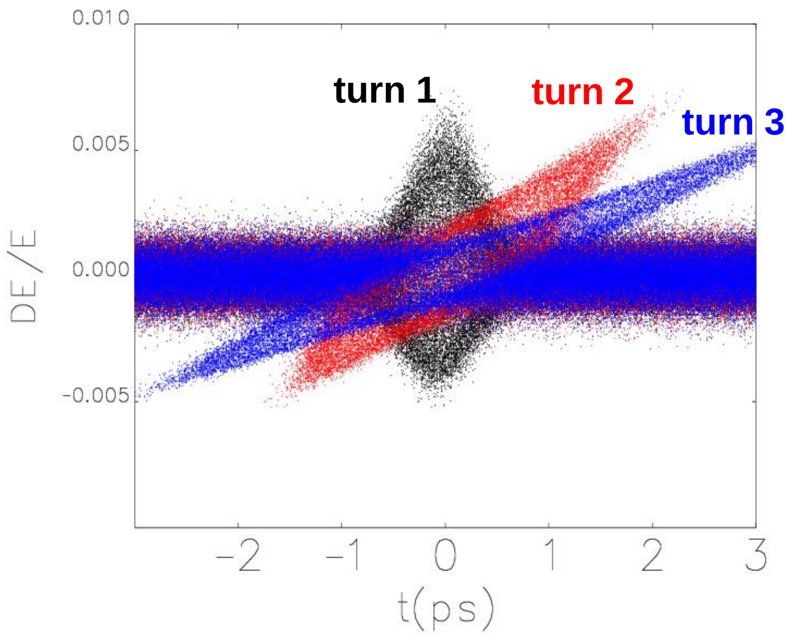
Low-emittance beam increases the SNR

$$SNR \propto \sigma_{E,mod} \propto \frac{1}{\sqrt{\sigma^2_{e,(x,y)} + \sigma^2_L}}$$

Coherent THz emission for laser-electrons synchronization

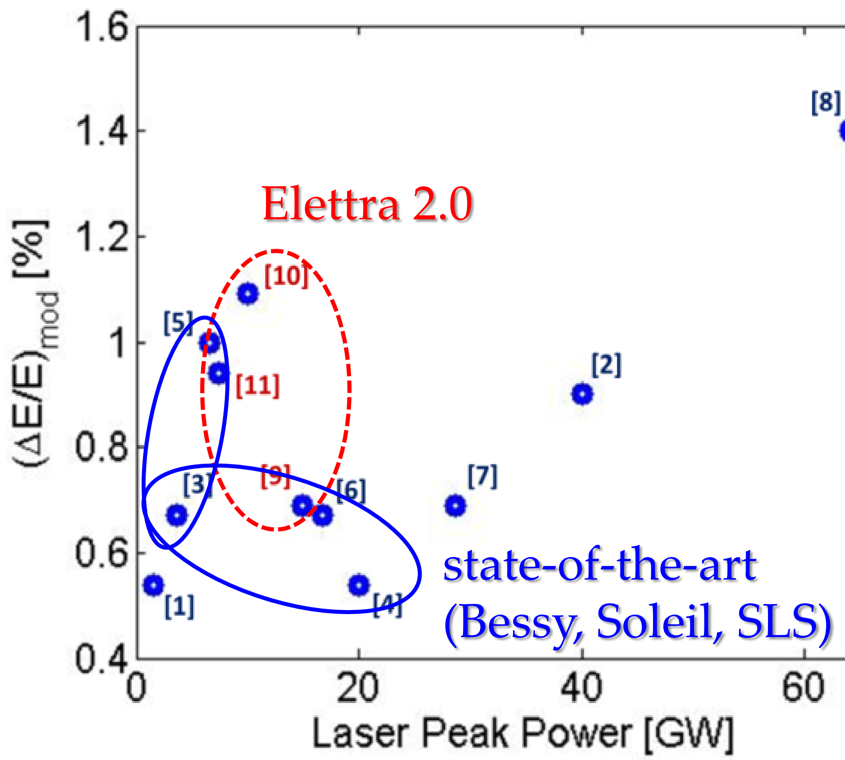


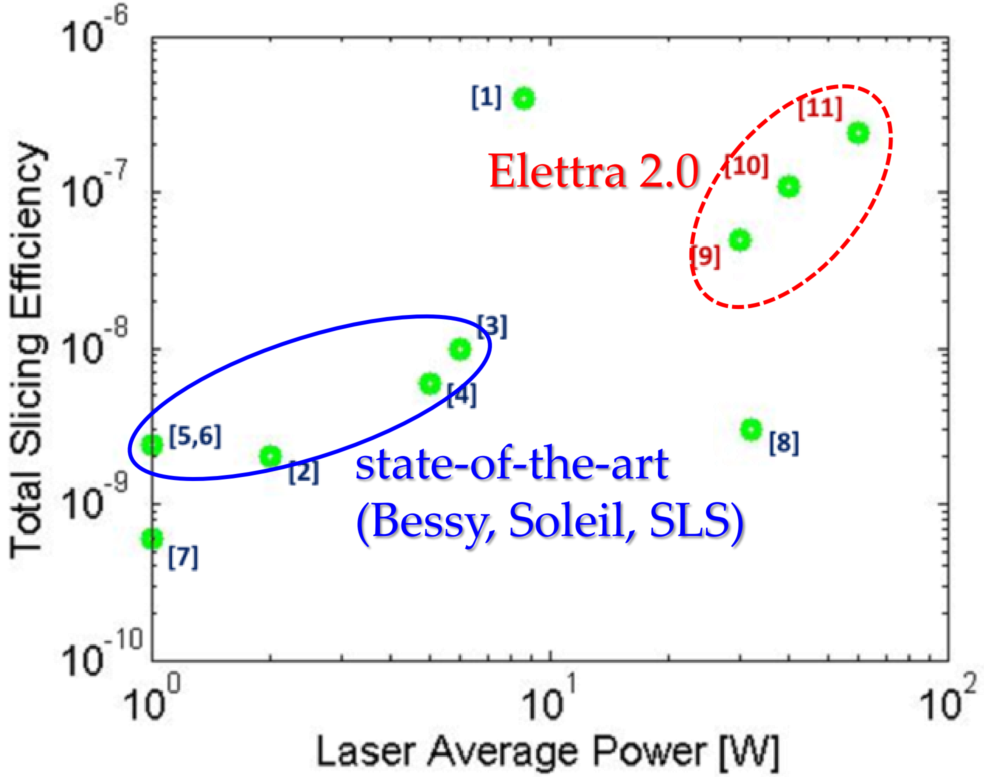
Short slice survives for 1 turn only



- ***High rep. rate*** laser on consecutive bunches
- ***Background*** issues suggest < 10-20 kHz

State-of-the-art





- $\langle P_L \rangle \approx$ **50 W @ 10 kHz**
- $\sigma_{t,R} \approx$ **0.2 ps**
- **10^8 ph/sec/0.1%bw = 10^5 ph/pulse @ 3 keV, *at the source***

Electron-slicing

$$\Delta\vartheta_y \propto \frac{Q_2}{\sigma_{y,2}}\frac{1}{E_1}$$

$$\Delta t_{slice} \propto \frac{\Delta t_2}{sin\varphi_{1,2}}$$

Short & long bunches stored simultaneously

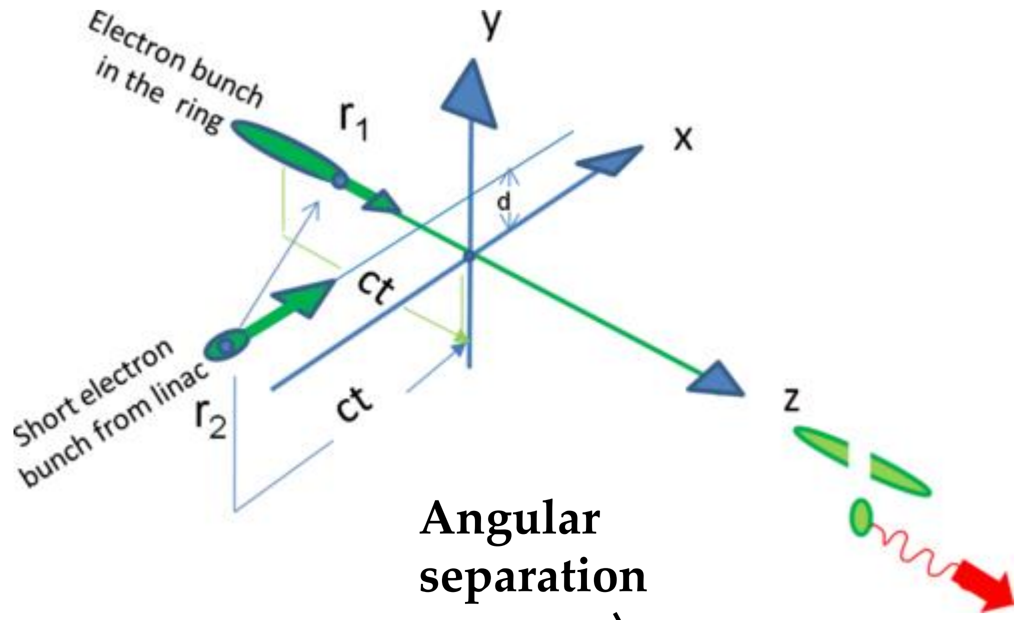
$\sigma_t \approx$ 0.01 – 0.1 ps, $I_{short} \approx$ 0.1 – 1 mA

Slicing efficiency can be higher than in laser-slicing

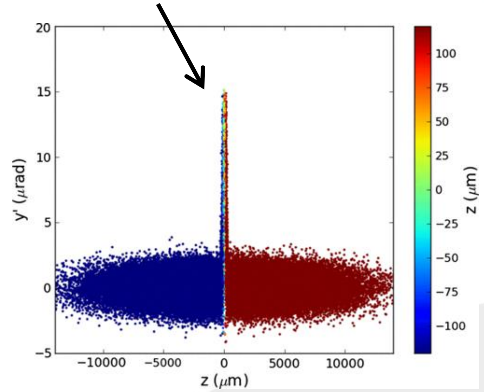
Background radiation limits the SNR to ~10

Requires MHz e-Gun + Linac + Magnetic Compressor

A. He, F. Willeke, L.-H. Yu (2014)



Angular separation



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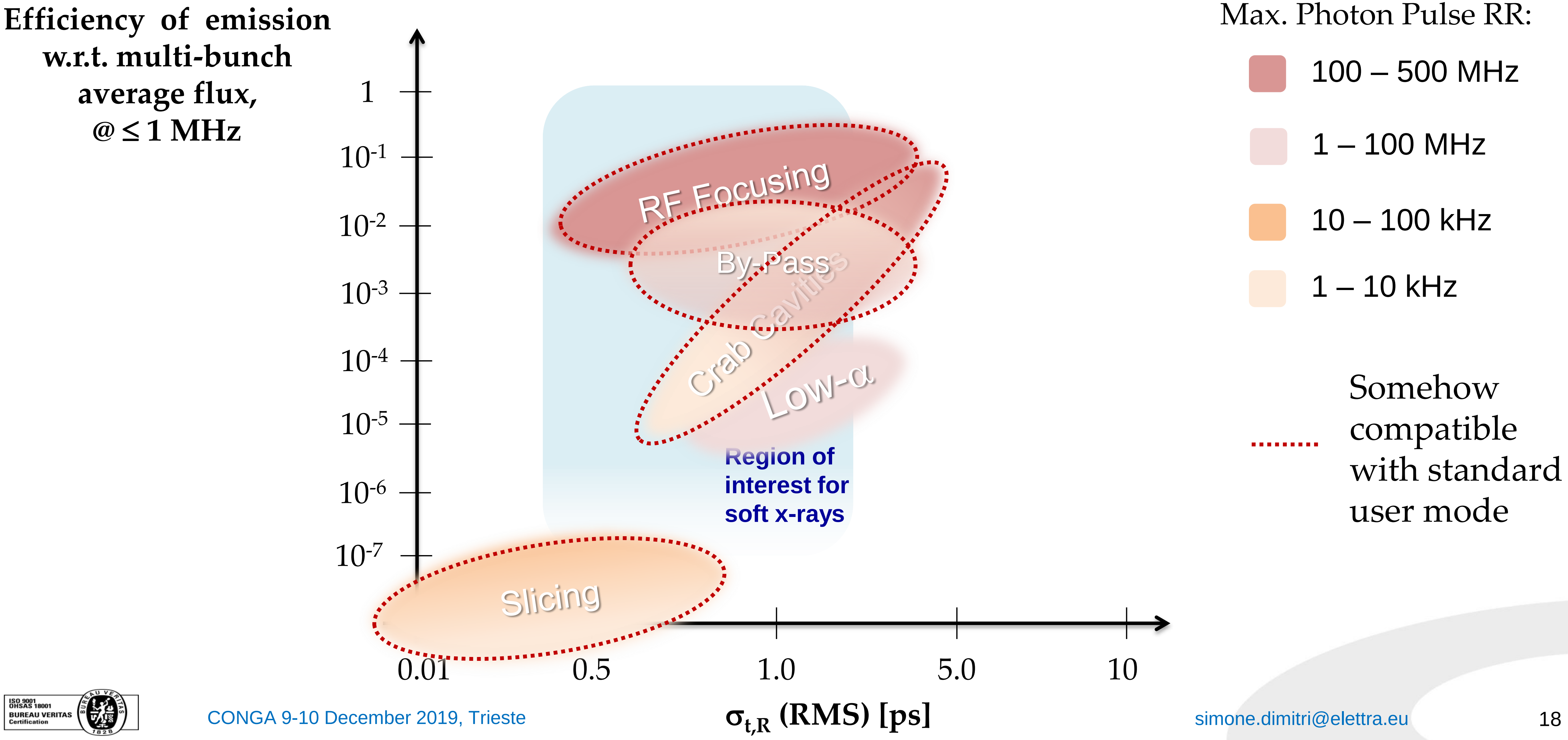
Efficiency of emission



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Conclusions

- All options offer short pulses at multiple beamlines
- Laser-slicing and crab cavities require dedicated beamline optics set up
- Laser-slicing, crab cavities and RF focusing require one straight section to install new hw
- By-pass is invasive on the infrastructure (injector, kickers, transfer line)

- Not considered here:
  - *Direct injection* from the FERMI linac (CSR, synchrotron oscillations, availability)
  - *Photon pulse manipulation*, e.g., fs NIR switches and CPC

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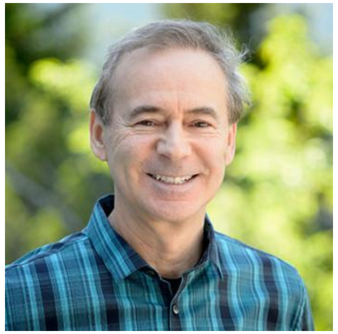
A. Zholents (ANL)

Thank you for Your attention

Questions are very welcome!

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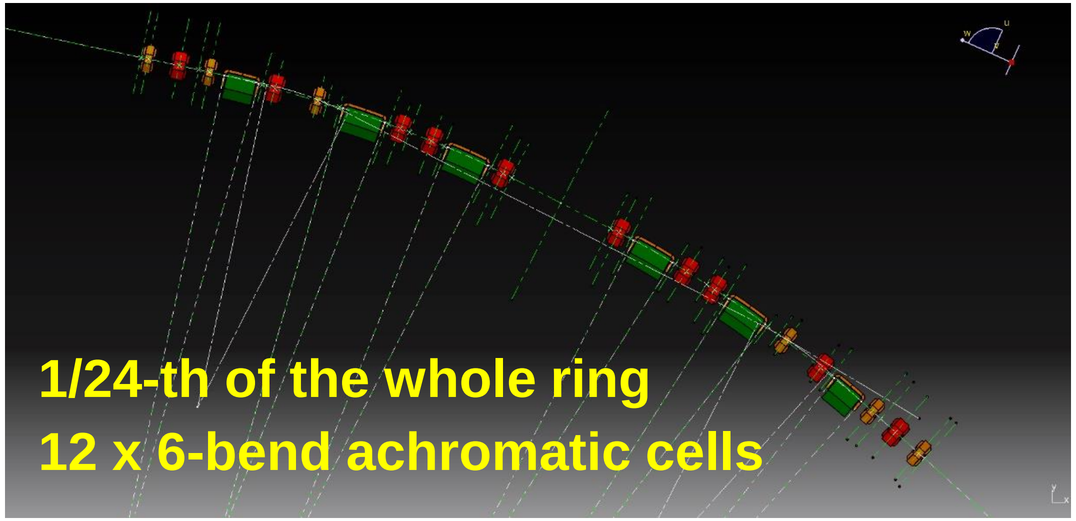
Elettra 2.0



Parameter	Units	Current Elettra	Elettra 2.0
Circumference	m	259.2	259.8
Energy	GeV	2 – 2.4	2 – 2.4
Horizontal emittance	nm rad	7	0.14 – 0.20
Vertical emittance (1% coupling)	pm rad	70	2.5
Beam size @ ID ($\sigma x,\sigma y$)	μm	245 , 14	43, 3
Beam size @ Bend	μm	150, 28	17, 7
Bunch length	ps	25 → 100	6 → 30
Energy spread	ΔE/E %	0.08	0.07
Bending angle	degree	15	6.6, 3.6, -1.8

- ✓ **Diffraction limited radiation** (both **x and y** plane) is guaranteed up to **~keV** photon energy
- ✓ Bunches shall be elongated up to ~**30 ps rms** for acceptable lifetime.

Comparison

	Measured	*Expected*	Measured
	BESSY II *(JSR 2014)*	**Elettra 2.0** *(JSR 2019)*	**Elettra** *(Hybrid)*
$<I_b>$, E_b	5 mA, 1.7 GeV	6 mA, 2 GeV	4 mA, 2 GeV
$<P_L>$ @ RR	10 W @ **6 kHz**	30 W @ **10 kHz**	400 – 1000 kHz
$\sigma_{t,ph}$	0.04 ps	0.2 ps	24 ps
Slicing Efficiency	1e-8	1e-7	
Photon Energy	0.2 – 1.4 keV	1 keV (h=3)	0.1 – 1.7 keV
Flux @ *Source*	10^7 ph/sec/0.1%bw # 10^4 ph/pulse #	10^8 ph/sec/0.1%bw 10^5 ph/pulse	
	Transm. 1-10%	Transm. 1-10%	Transm. 0.1%
Flux @ *Sample*	$10^5 – 10^6$ ph/sec/0.1%bw # $10^2 – 10^3$ ph/pulse #	$10^6 – 10^7$ ph/sec/0.1%bw $10^3 – 10^4$ ph/pulse	~10^{11} ph/sec/0.1%bw * 10^6 ph/pulse

K. Holldack, JSR (2014) 21

* courtesy of S. Lizzit