Challenges of short light pulses in 4th generation storage rings

Simone Di Mitri

Elettra Sincrotrone Trieste & University of Trieste

References (*not* exhaustive) & credits

❖ Acknowledgments: F. Cullinan, M. Ries, L. Stingelin, M. Lonza, E. Karantzoulis

- *I. Martin, PhD Thesis, Wolfson College, University of Oxford, UK (2011)*
- Papers:
  - *X. Huang et al., PRAB 22, 090703 (2019); PRAB 26, 120701 (2023).*
  - *Feng, C. & Zhao, Z. (2017). Sci. Rep. 7, 4724.*
  - *Zholents, A., NIM A 798 (2015) 111–116.*
  - *Evain, C., et al., NJP, 14, 023003 (2012).*
  - *Wustefeld, G., Jankowiak, A., Knobloch, J. & Ries, M., IPAC'11, Spain, THPC014.*
  - *Feikes, J., Holldack, K., Kuske, P. &Wustefeld, G., EPAC'04, Switzerland, WEPLT051.*
  - *Zholents, A., Heimann, P., Zolotorev, M. & Byrd, J., NIM A 425 (1999), 385–389.*
  - *Zholents, A. A. & Zolotorev, M. S. (1996). Phys. Rev. Lett. 76, 912–915.*
- For a review and list of refs.: *S. Di Mitri, J. Synchrotron Rad. 25 (2018)*

Outline

- Scientific motivations
- Timing modes
- Challenges @ 4GSR
- Conclusions

simone.dimitri@elettra.eu

Elettra Sincrotrone Trieste

Scientific motivations to timing mode

- 3rd gen. SRLS: *high average brilliance, moderate peak intensity*
  - Track aerosol in free-flight, non-equilibrium states
  - Map reversible dynamics of molecular systems
  - Photo-electron spectroscopy

    } avoid sample **damage** (burning, ablation) and **space charge**

  - Probe charge transfer dynamics
  - Image orbital, spin, and lattice degree of freedom

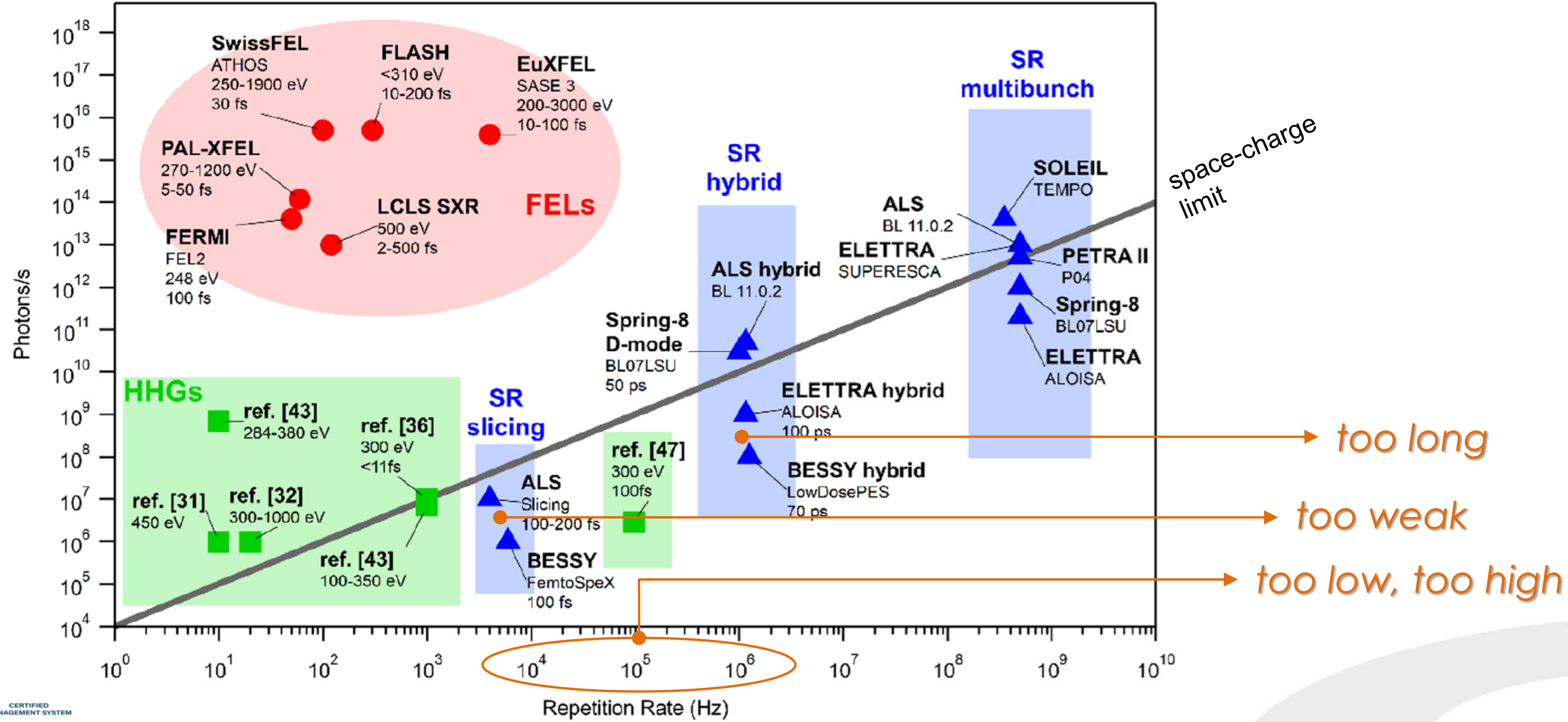
    } nano- to pico-second time scale at **nanometer size**

  - EXAFS } Large wavelength **tuneability**

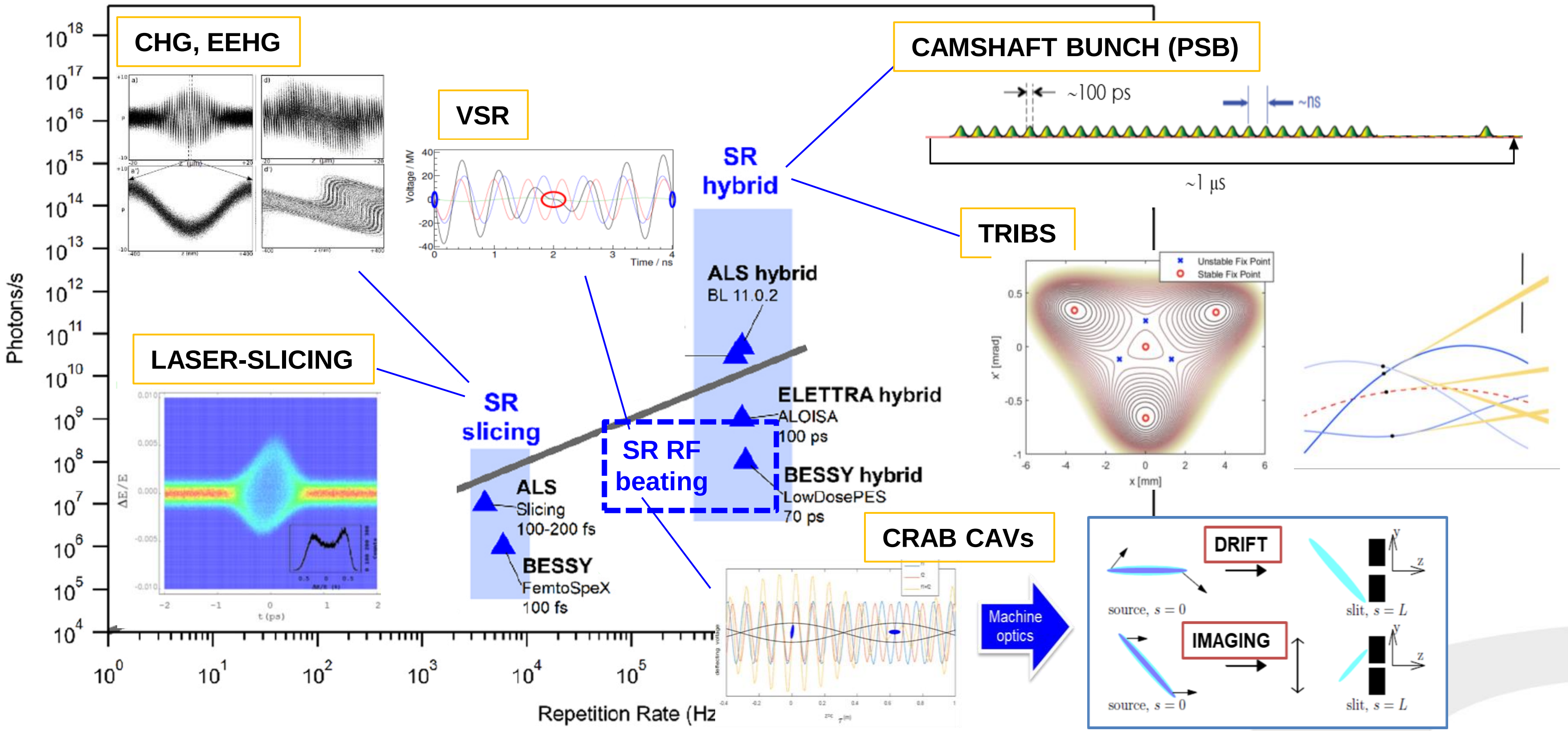
- 4th gen. SRLS: *high degree of transverse coherence in x-rays*
  - *improves* ***lateral resolution***
  - *preserves high* ***energy resolution*** *(monochromators)*
  - *reduces the* ***integrated time*** *of measurements*

Strong and weak points

R. Costantini et al., J. Electr. Spectr. Rel. Phen. 254 (2022)



Timing modes – *simultaneous to standard operation*



Features of 4GSR

Tight lattice, small dispersion (<60 mm), DL-optics imposes limited flexibility

Small $\varepsilon_{x/y}$ $(< 200/2\ pm)$, small sizes $\sigma_{x/y}$@IDs $(< 50/5\ \mu m)$, small ID gap (< 5 mm)

Large $|Z_{\parallel}/n|$ $(\sim 1\Omega)$, low Ω_s (< 2 kHz), long bunches (>50 ps fwhm)

Elettra Sincrotrone Trieste

Features of 4GSR

Tight lattice,…

Small $\varepsilon_{x/y},\ldots$

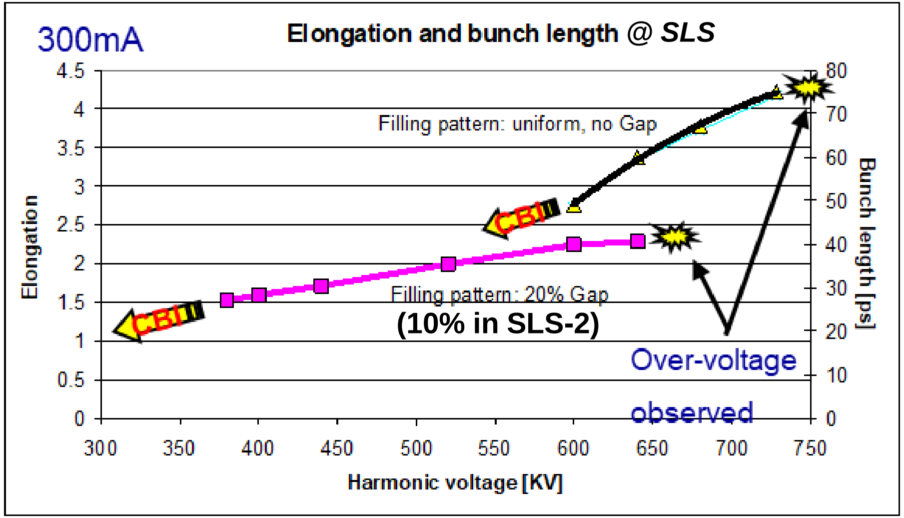
Large $Z_{\parallel},\ldots$

PSEUDO-SINGLE BUNCH

Tight lattice,…

Small $\varepsilon_{x/y}$,…

Large $Z_{\parallel}$,…



Courtesy of M. Pedrozzi, L. Stingelin et al.

- MWI & IBS, large harmonic voltage, TBL & PTBL
- Non-uniformity of lifetime and transverse emittance (IBS)
- *Ad hoc* tuning of dark gap and HC. Still, good for CBI and Ion Trapping.

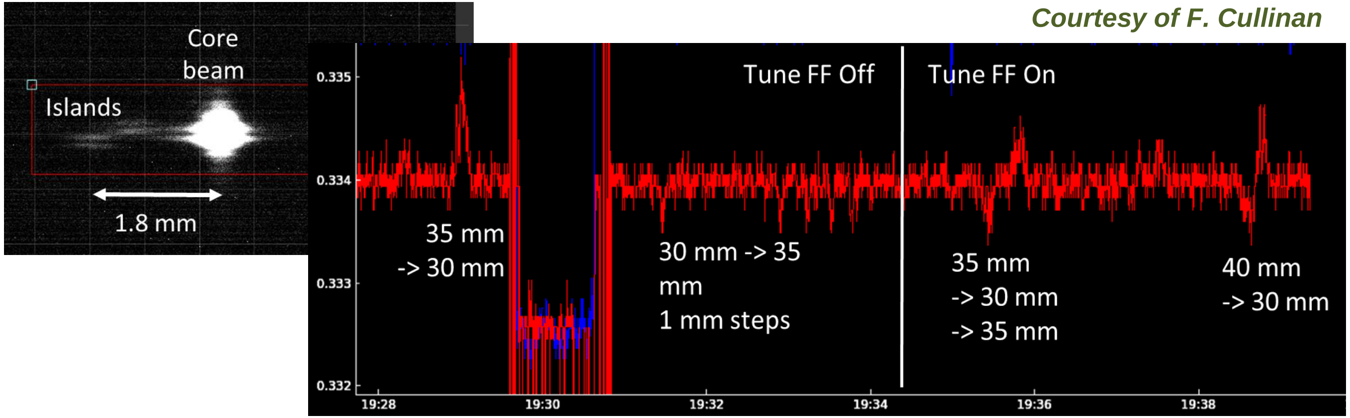
Tight lattice,…

Small $\varepsilon_{x/y}$,…

Large $Z_{\parallel}$,…

TRIBS

Courtesy of F. Cullinan



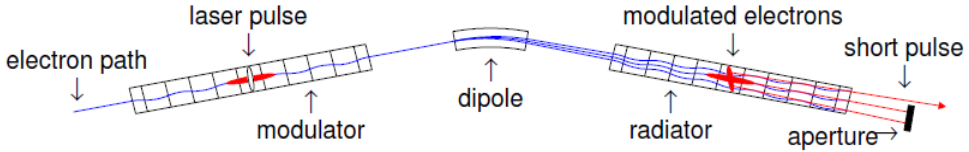
- 3p resonance, optimized nonlinear dynamics.
- IDs' roll-off, special compensation.
- Charge diffusion, radiation background (S/N~0.1%), intensity fluctuation (<5%), energy resolution (mono ΔE/E~0.1%).
- Tailored hybrid fill pattern for few mA's in the islands (TBL).

LASER-SLICING, CHG, EEHG

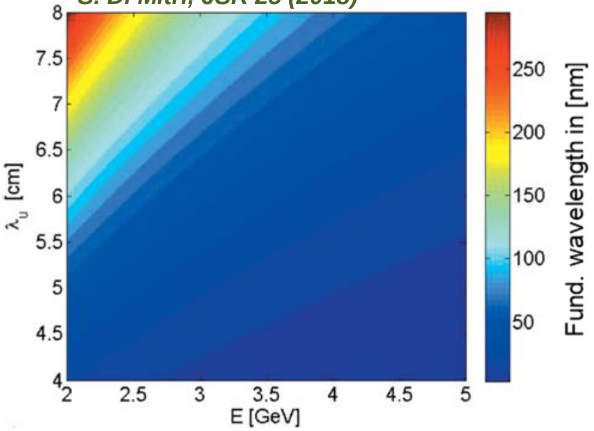
Tight lattice,…

Small $\varepsilon_{x/y}$,…

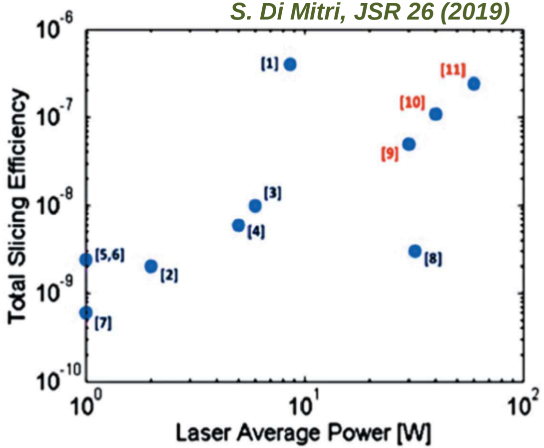
Large $Z_{\parallel}$,…



S. Di Mitri, JSR 25 (2018)



S. Di Mitri, JSR 26 (2019)



- Space for MOD & RAD
- Dispersion (R_{56})

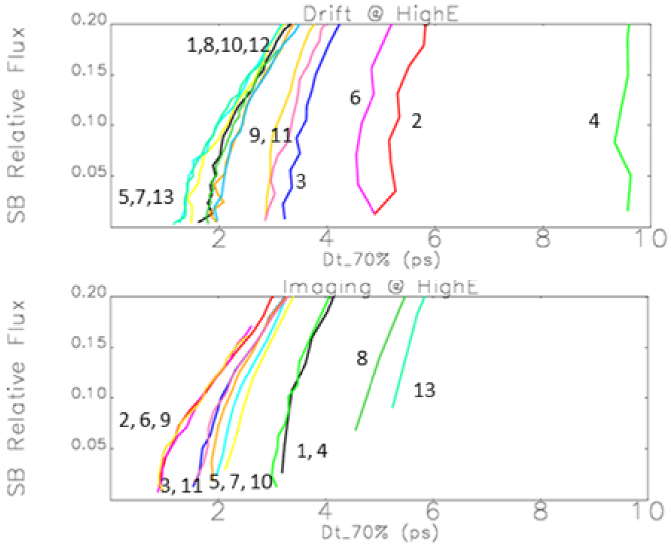
- Charge dilution
- Camshaft bunch (TBL)

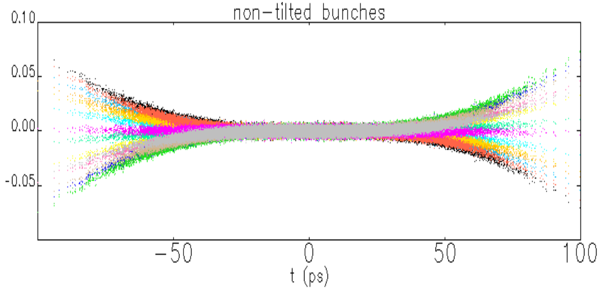
CRAB CAVITIES *(TRANSV. RF BEATING)*

Tight lattice,...

Small $\varepsilon_{x/y}$,...

Large $Z_{\parallel}$,...





- Vertical tune and phase advance
- ID gap, deflecting voltage

- Kicks cancellation: multiple CCs, vert. emittance

Elettra Sincrotrone Trieste

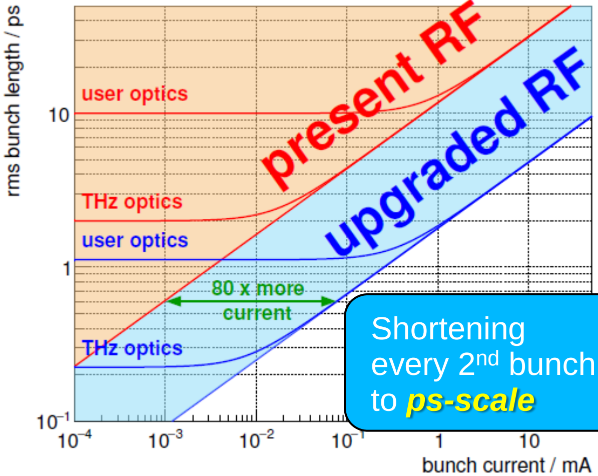
VARIABLE PULSE LENGTH *(LONG. RF BEATING)*

Tight lattice,...

Small $\varepsilon_{x/y}$,...

Large $Z_{\parallel}$,...

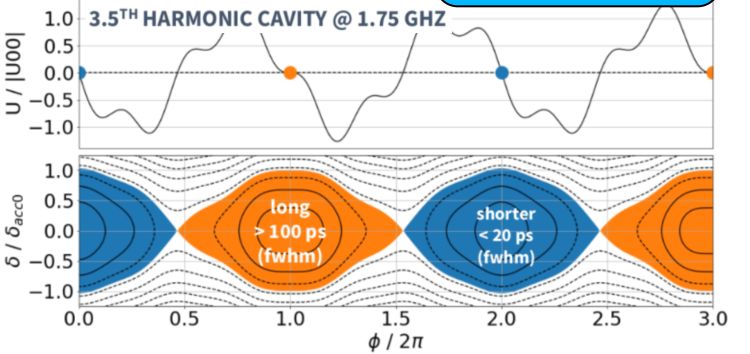
BESSY VSR TDR – SC RF



Shortening every 2nd bunch to ***ps-scale***

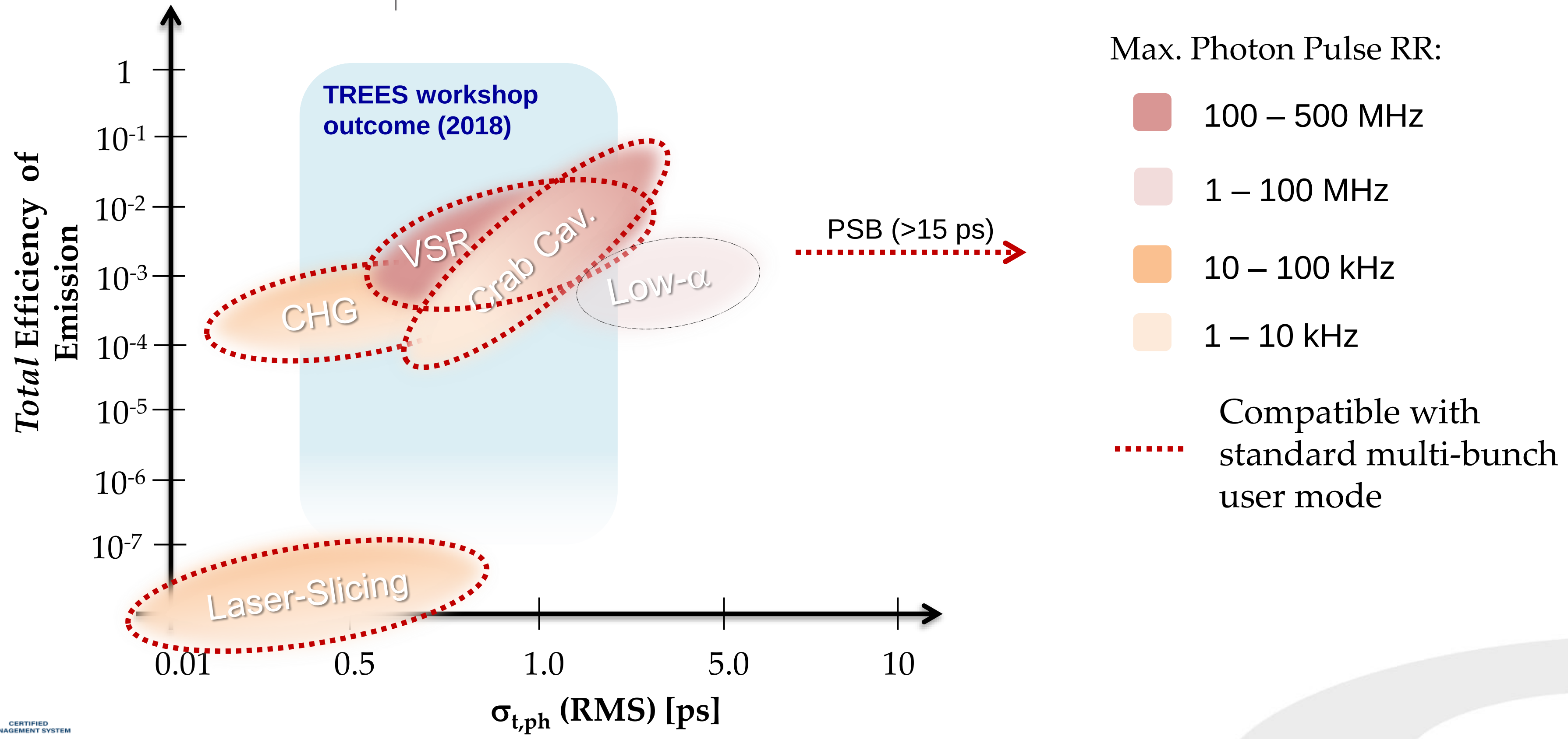
Courtesy of M. Ries – NC RF

Keep length of every 2nd bunch to ***10 ps-scale***



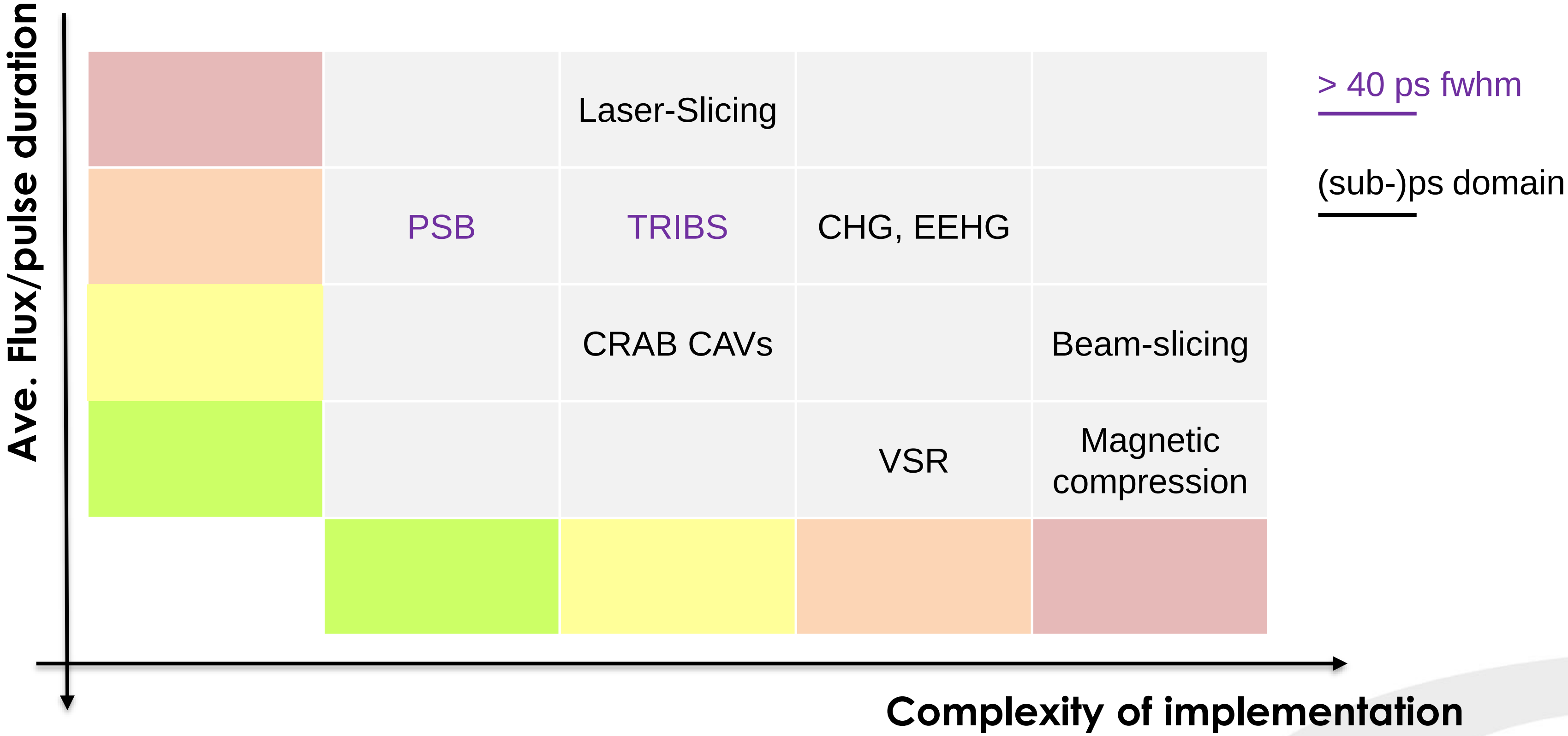
- Charge density, IBS & MWI (mostly for SC option)
- Non-uniformity of lifetime of short and long bunches
- Tailored hybrid fill pattern for pump-probe experiments (TBL)

(Sub-)Picosecond X-ray pulses



simone.dimitri@elettra.eu

Complexity vs. performance



Elettra Sincrotrone Trieste

Elettra 2.0 – Options for timing mode

		Low current ❶	Hybrid	Crab Cavities	Laser-slicing
Stored Current	mA	0.25 × 400 bn.	2 + 400	2 + 400	2 + 400
SP Duration, fwhm	ps	**9**	**40**	**1**	**0.5**
SP Repetition Rate	MHz	500	1.157	1.157	0.01 – 0.1
$\frac{Flux(\boldsymbol{SP})}{Flux(\boldsymbol{400mA})}$		$\frac{1}{2000}$	$\frac{1}{200}$	$\frac{1}{10000}$	$\frac{1}{10^8}$

❶ Total stored current in *low current* mode is 100 mA

Concluding remarks

- **No *universal* show-stoppers** in 4GSR to timing modes *simultaneous to standard multi-bunch operation*.
- **TBL** looks like the main challenge, both in long and short pulse modes. It challenges beam-synchronized systems, implies specific tuning of HC and dark gap.
- **TRIBS** constraints several aspects of the 4GSR design (optics, injection).
- **Laser-based** schemes are hardly compatible with 4GSR lattice and linear optics.
- **RF-based** schemes look almost transparent to 4GSR optics, but still dealing with TBL and technology R&D.

- *Not touched in this talk:*
  - **α-buckets**, hardly compatible with nonlinear dynamics and low dispersion of 4GSR.
  - **Magnetic compression**, suitable for swap-out footprints, but invasive + synchronization issues.
  - **Injection** efficiency, critical for RF-schemes and depending from on-/off-axis injection.

Elettra Sincrotrone Trieste

Thank you for your kind attention

Comments and questions are welcome

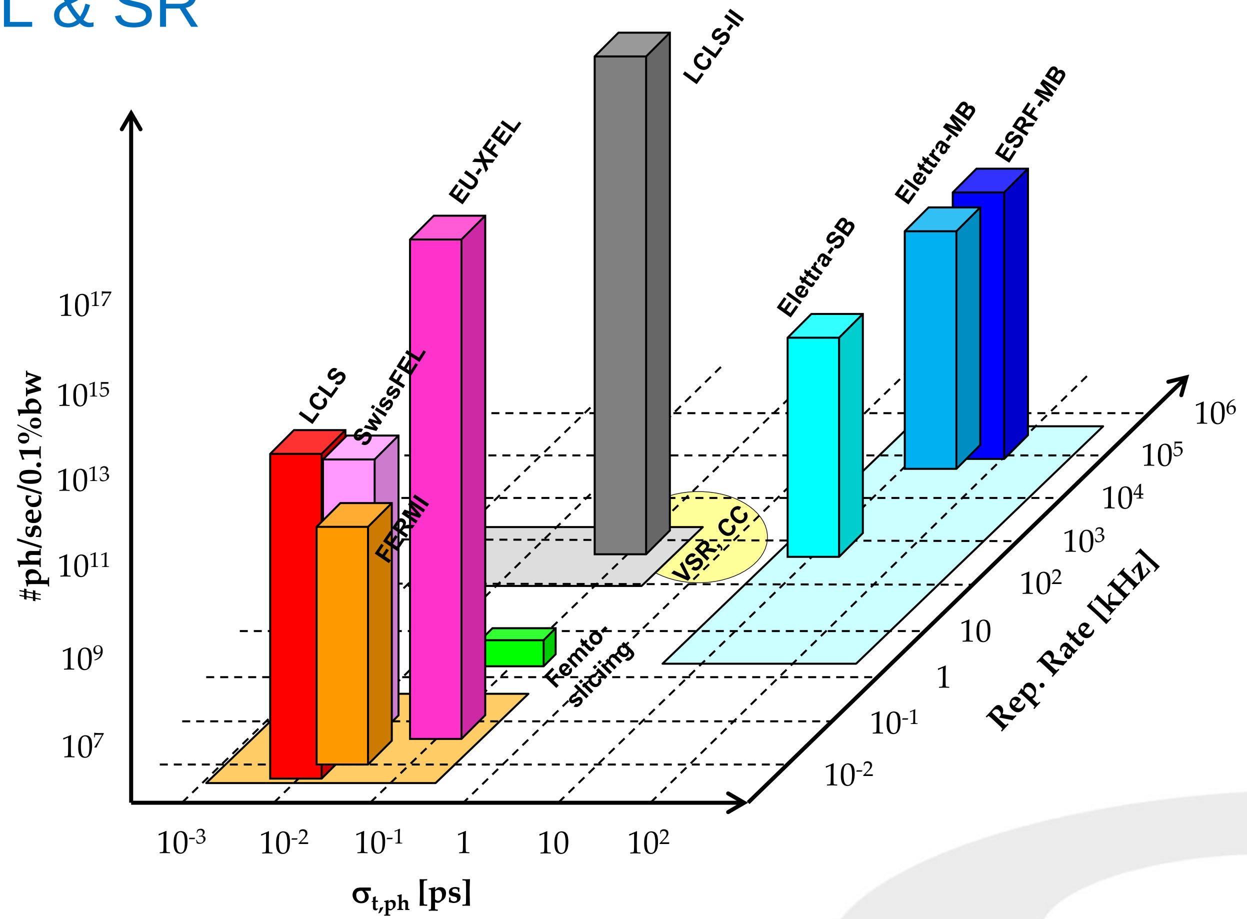
CERTIFIED MANAGEMENT SYSTEM
CQY CERTIQUALITY
UNI EN ISO 9001:2015
UNI ISO 45001:2018

simone.dimitri@elettra.eu

FEL & SR

Examples of accelerator-based X-ray sources:

- 0.1 – 1 keV photon energy
- # of phs. at the source
- FEL in short pulse mode



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

- ❑ **What flux and pulse duration can be produced up to MHz RR ?**

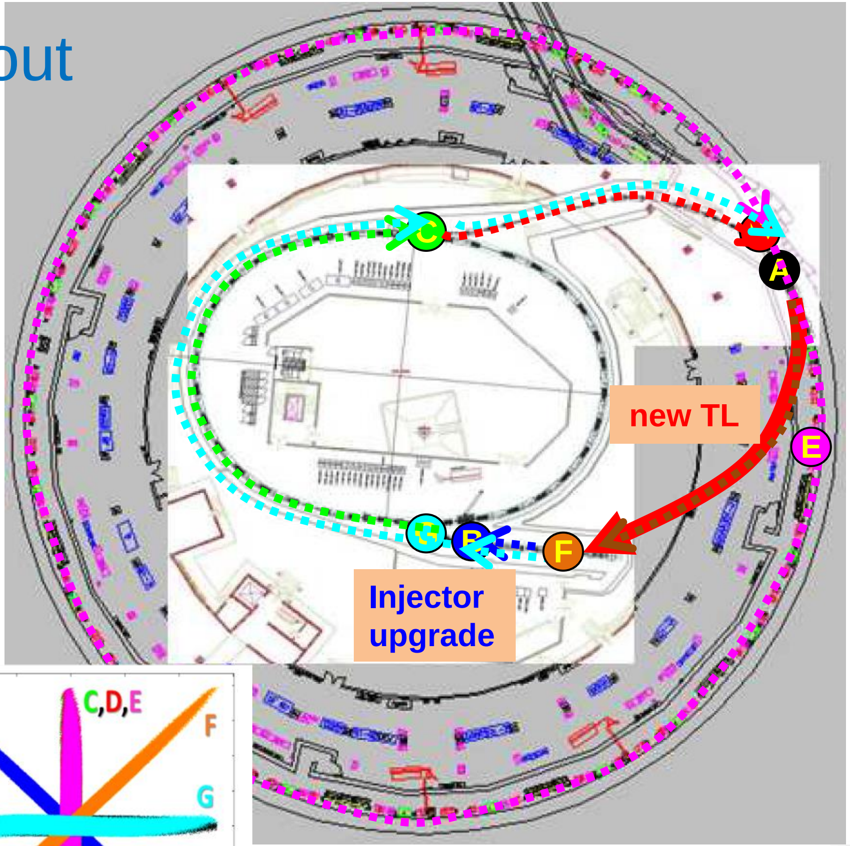
- ❑ Lattice-invasive ?
- ❑ Standard user operation ?

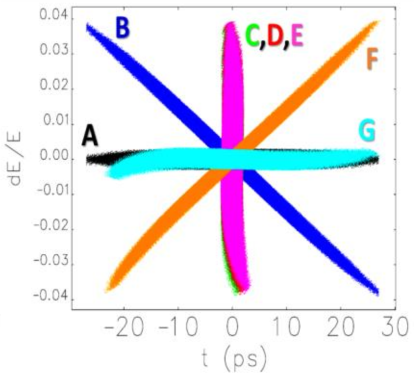
By-pass / Swap-out

- **e-Beam magnetic compression**
  - $\sigma_{t,ph} \approx$ **0.5 – 3 ps**
  - **Full flux form single bunch**

- *Pros:*
  - transparent to DLSR lattice and optics
  - short pulses at all the (existing) beamlines
  - DLSR ~nominal flux, but at the expense of lower spectral brilliance

- *Cons:*
  - new fast stripline kicker
  - injector upgrade (0.1-2.5 GeV, ≥ 100Hz)
  - new ring-to-booster transfer line
  - low-α (÷3) optics in Booster





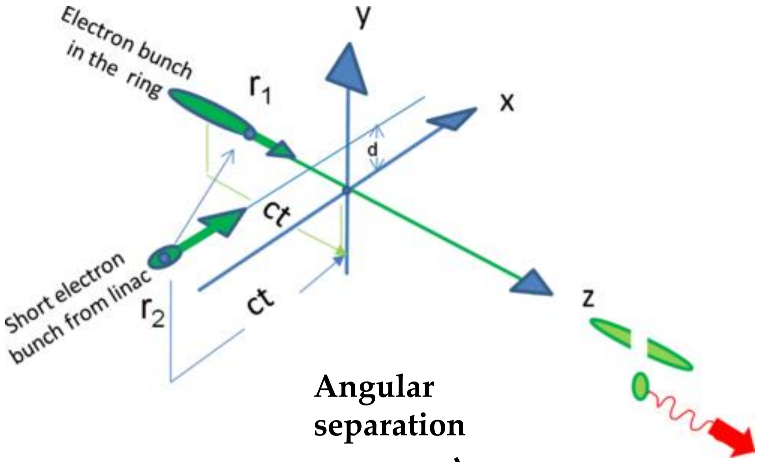
S. Di Mitri, M. Cornacchia, New J. Phys. 2015
S. Di Mitri, JSR 2018
S. Di Mitri, A. Bianco, S. Lizzit, NIM A 1051 (2023(168197

Beam-slicing

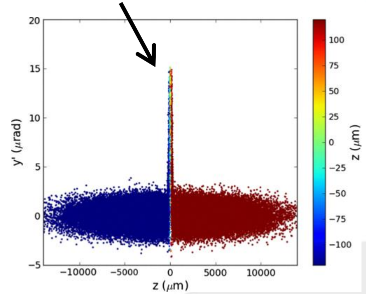
A. He, F. Willeke, L.-H. Yu (2014)

$$\Delta\vartheta_y \propto \frac{Q_2}{\sigma_{y,2}}\frac{1}{E_1} \qquad \Delta t_{slice} \propto \frac{\Delta t_2}{sin\varphi_{1,2}}$$

- **Energy-sliced electrons must be separated from the bunch**
  - ➢ *Angular* separation is more efficient, but typically invasive on SR lattice.
  - ➢ $\boldsymbol{\sigma_{t,ph}} \approx$ **0.01 – 0.1 ps**



Angular separation



- *R&D and limitations:*
  - Promised slicing efficiency is 10^{-7}
  - Background radiation limits the contrast ratio to ~10
  - Requires kHz (NC) to 1 MHz (SC) e-Gun + Linac + Magnetic Compressor