Elettra
Sincrotrone
Trieste

LEAPS

HarmonLIP 2024

Superconducting RF Transverse Deflecting (a.k.a. Crab) Cavities for Short X-ray Pulses at Elettra 2.0

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Acknowledgements & References

- **Core team @ Elettra-ST:** A. Bianco (radiation), A. Fabris (RF & chair of TDC panel), K. Manukyan (beam physics), M. Modica (cryo & SC), N. Shafqat (RF design).
- **Collaborators:** A. Zholents@*ANL*, X. Huang@*SLAC* (beam physics), A. Lunin, T. Khabiboulline, V. Yakovlev@*FermiLab*, R. Calaga, F. Gerigk, A. Grudiev@*CERN* (RF design).

- *Zholents, A., Heimann, P., Zolotorev, M. & Byrd, J., Generation of subpicosecond X-ray pulses using RF orbit deflection, NIM A 425 (1999), 385–389.*
- *Zholents, A., A new possibility for production of sub-picosecond x-ray pulses using a time dependent radio frequency orbit deflection, NIM A 798 (2015) 111–116.*
- *X. Huang, T. Rabedeau, J. Safranek, Generation of picosecond electron bunches in storage rings, J. Synch. Rad. 21 (2014) 961–967.*
- *X. Huang, Coupled beam motion in a storage ring with crab cavities, PRAB19, 024001 (2016).*
- *X. Huang, B. Hettel, T. Rabedeau, J. Safranek, K. Tian, K. P. Wootton and A. Zholents, Beam dynamics issues for the two-frequency crab cavity short pulse scheme, PRAB 22, 090703 (2019).*
- *X. Huang et al., Obtaining picosecond x-ray pulses from fourth generation synchrotron light sources, PRAB 26, 120701 (2023).*

Outline

- Motivations
- Working principles, beam dynamics, performance
- Project status
- Conclusions

TDCs for a new timing mode

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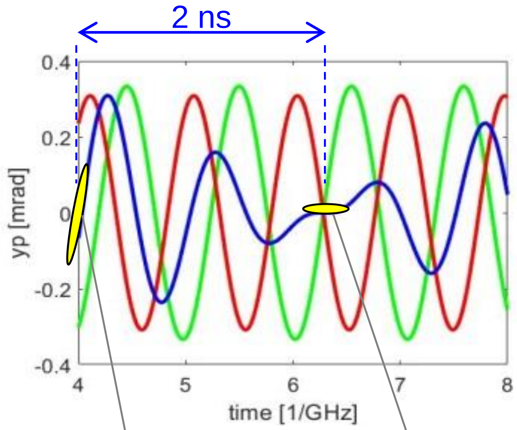
Brilliance × 100-1000 (1-10 keV)

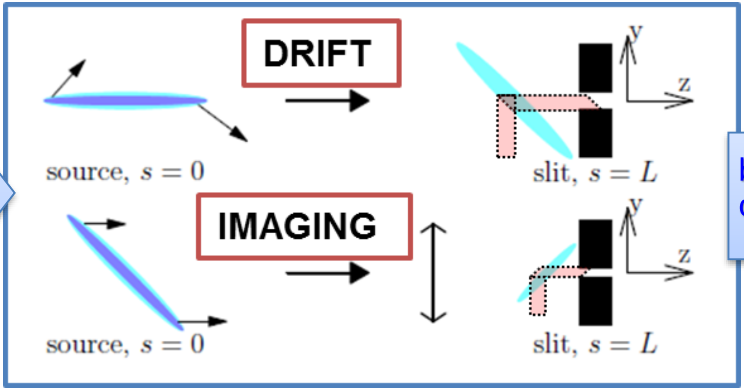
Parameter	Elettra 2.0	FERMI	Units
Spectral range	0.02 - 50	0.01 – 0.7	keV
Rep. rate	1 – 400	0.05	MHz
Pulse duration, rms	30	0.005 – 0.1	ps
Flux at sample, ave	$10^6 – 10^{13}$	$10^9 – 10^{13}$	ph/sec
Spectral resolution	$10^{-5} – 10^{-4}$	$10^{-4} – 10^{-3}$ (w/o mono)	
Polarization	all	all	
Coherence	Hor. < 0.5 keV	full	
# Beamlines / Run	31	< 2	

Working principle

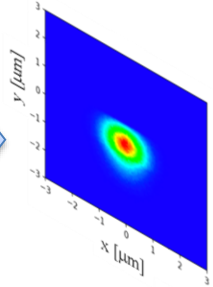


electron optics + equilibrium

Ref. Zholents, A., NIM A 798 (2015) 111–116.



beamline optics



$$\delta y'_{sb}(t) = \frac{eV_1}{E}\sin(2\pi f_1 t) - \frac{eV_2}{E}\sin(2\pi f_2 t) \approx 0$$

$$y'_{tb}(t) \cong 2\frac{eV_1}{E}\sin(2\pi f_1 t)$$

~MV defl. voltage @ 3.0 & 3.25 GHz

- ❑ **Deflecting voltages vs. flux/duration**
- ❑ **Perturbations to regular bunches**
- ❑ **Properties of short pulse**

Deflecting voltages

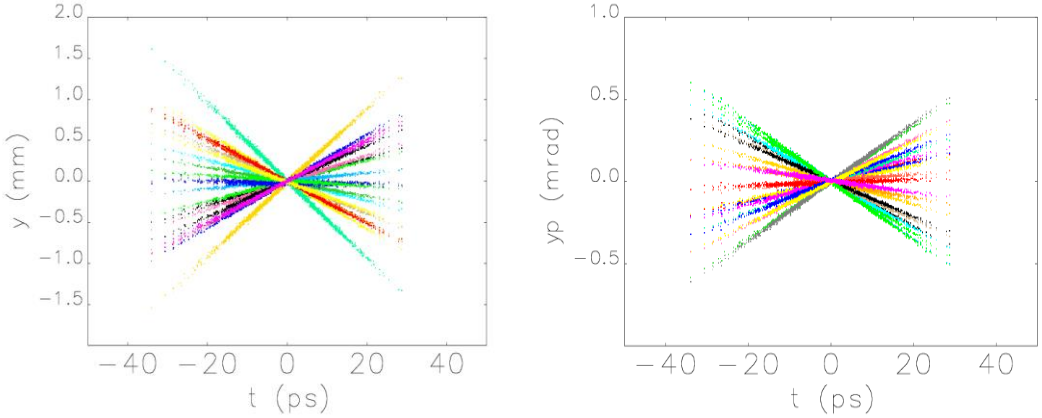
- ✓ Physical restrictions during injection (losses)
- ✓ Dynamic restrictions when stored (quantum lifetime)

$$V_{1,2} < y_{min}\frac{E}{e}\frac{\sin(\pi\nu_y)}{\beta_y} = \mathbf{1.36\ MV}$$

$$\tau_q = \frac{1}{2}\tau_y\frac{e^{\xi}}{\xi} > 100\ hrs,\quad \xi = \frac{A_y^2}{2\Sigma_y^2(V_{1,2})}$$

$$V_{1,2} \le \frac{A_y}{6.5k_1\sigma_z}\frac{E}{e}\frac{\sin(\pi\nu_y)}{\beta_y} = \mathbf{1.25\ MV}$$

bunch@IDs, equilibrium distribution



- ***Yet, additional constraints by: injection transients, residual kick to regular bunches, RF stability…***

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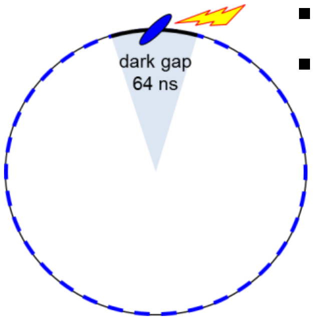
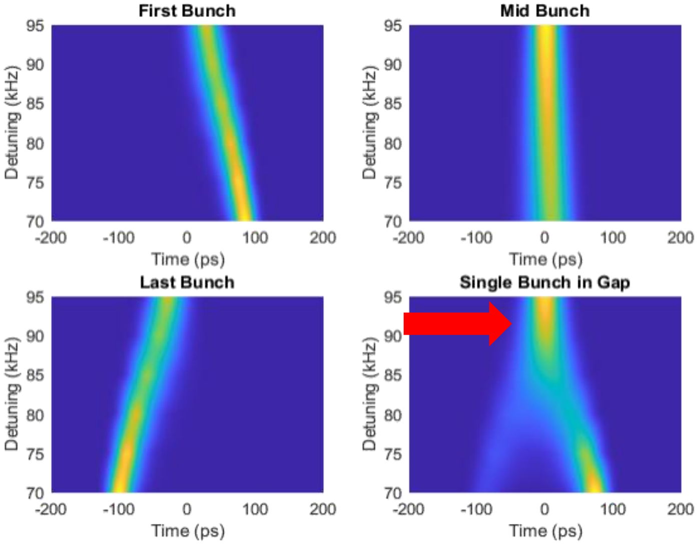
Equilibrium of the tilted bunch



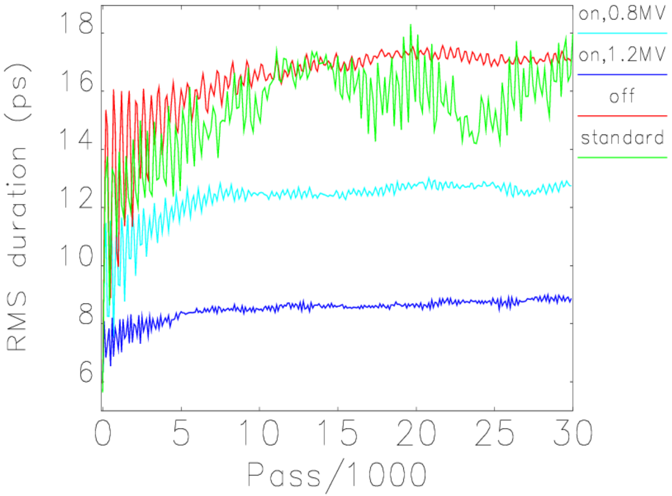
- 200 regular bunches, 2 mA/bunch, 4 ns-time sep.
- 1 tilted bunch in the gap, 2 mA , 1.157 MHz

Transient beam loading by main RF + 3HC, vs. 3HC detuning



80 kHz detuning ensures lengthening factor between 2.7 and 3.0 of regular bunches, and no bunch splitting.

Off-axis longitudinal focusing by the CCs shortens the tilted bunch (Panofsky-Wenzel th., in agreement to X.Huang's PRAB 2016).



Minimum pulse duration

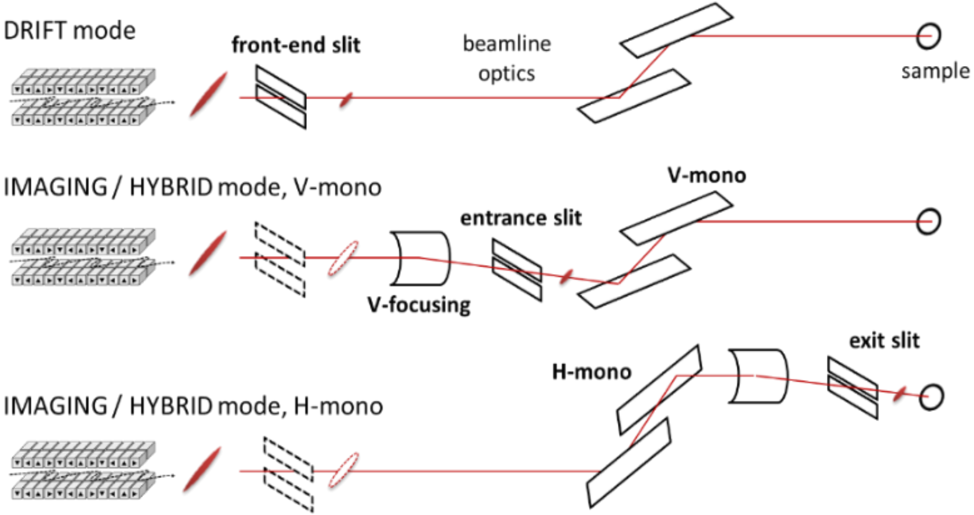
Ref. *A. Bianco & B. Diviacco*

Minimum light pulse duration:

$$\begin{cases} \sigma_{z,min}^{DR} \approx \dfrac{1}{C_{21}}\sqrt{\dfrac{\varepsilon_y}{\beta_y} + Q_a^2 \dfrac{\lambda}{4L_u}} \\ \sigma_{z,min}^{IM} \approx \dfrac{1}{C_{11}}\sqrt{\varepsilon_y \beta_y + Q_s^2 \dfrac{\lambda L_u}{4\pi^2}} \end{cases}$$

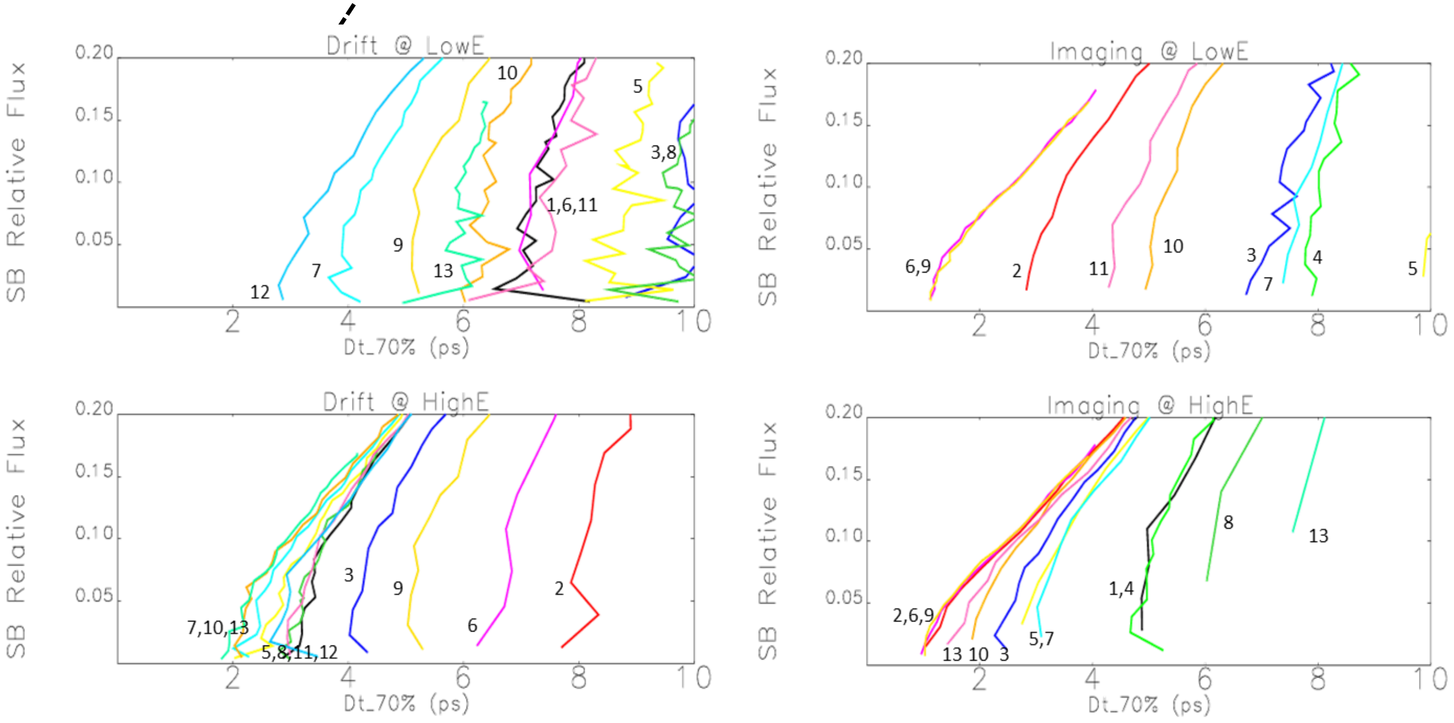
- Deflecting voltage, vertical tune and phase advance
- Small coupling
- Small energy spread, small harmonic number, few ID periods
- Short wavelengths

Beamline optics zoo at Elettra 2.0:



Performance

1.20MV@3GHz,
1.15MV@3.25GHz,



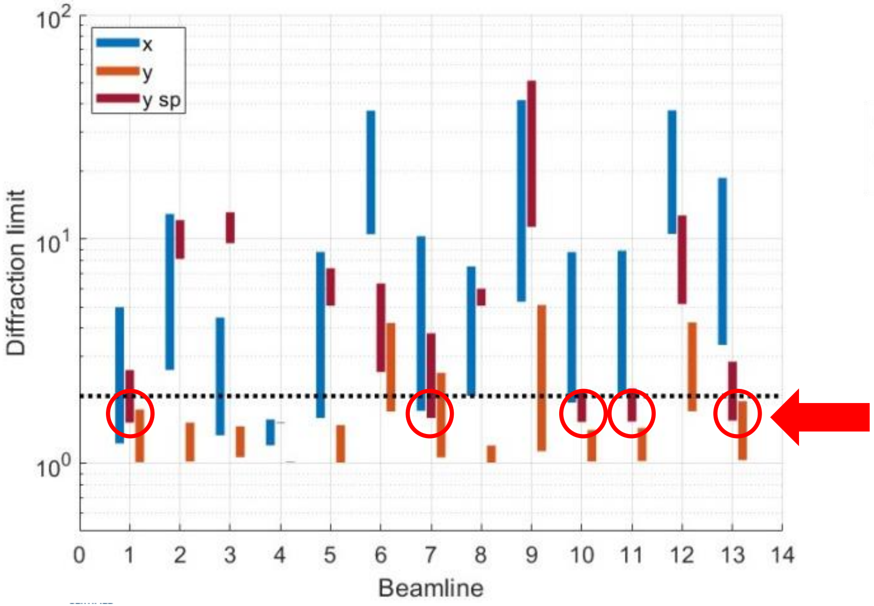
0.80MV@3GHz,
0.75MV@3.25GHz,

Diffraction limit

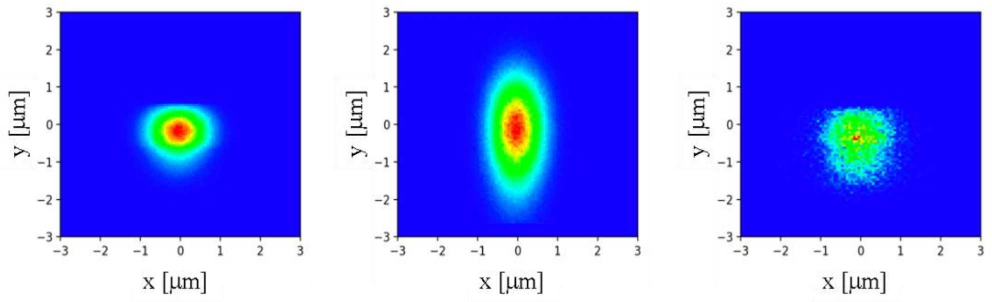
Ref. A. Bianco

$$\frac{\varepsilon_r}{2\varepsilon_0} := \frac{\sigma_r \sigma_{r'}}{2\sigma_{r,0}\sigma_{r',0}} = 2\pi\sigma_r\sigma_{r'}/\lambda$$

- = 0.5 well below DL
- = 1 @ DL
- > 1 not DL



<u>From ring to sample</u>: `elegant` + Spectra (benchmarked with ShadOUI) @ **0.8 keV**



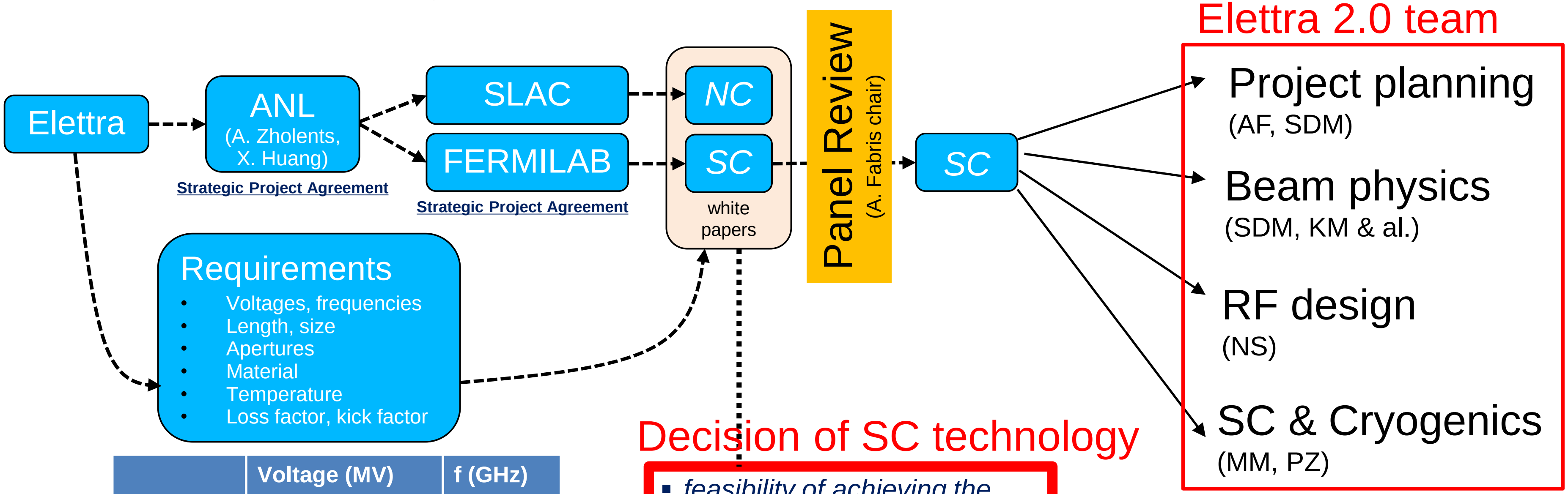
From regular bunch: **55 ps**

From tilted bunch, ***drift*** mode: **4 ps**

From tilted bunch, ***hybrid*** mode: **4 ps**

Ref. *A. Fabris*

Project evaluation



	Voltage (MV)	f (GHz)
Cavity 1	< 1.5 (2.0)	3.0
Cavity 2	< 1.2 (1.8)	3.25

Shunt impedance HOMs below cutoff frequency	
Vertical plane	<1.5 (MΩ/m)
Horizental plane	<4.0 (MΩ/m)
Longitudinal plane	<0.4 (MΩ/m*GHz)

Decision of SC technology

- *feasibility of achieving the performance*
- *duration of the design work*
- *cost of the design work*
- *anticipated cost of operation and maintenance*
- *identify risks*

QMiR design, FNAL–Elettra–CERN

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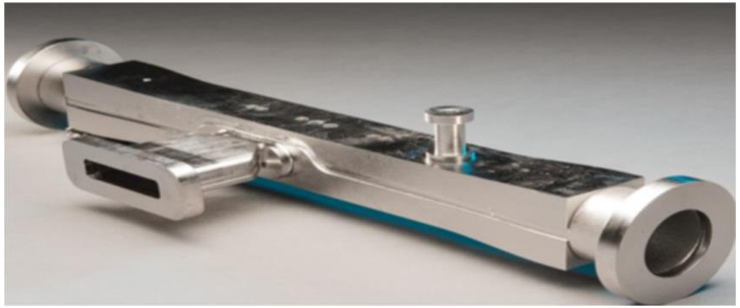
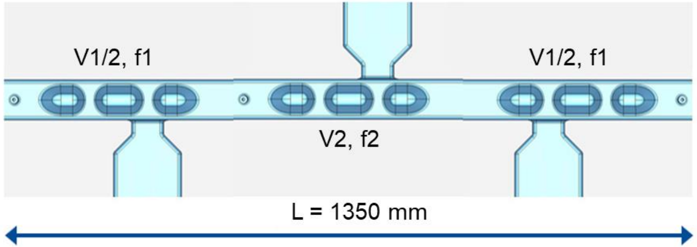




Best cancellation of residual kicks for standard bunches

Quasi-waveguide Multicell Resonator (QMiR) **designed for 2.815 GHz** frequency for APS-U@ANL. Cavity successfully **tested @2K** in a vertical cryostat, demonstrated a **2.6 MV transverse voltage.**

A. Lunin, T. Khabiboulline, V. Yakovlev , "A White Paper on Design and Fabrication of SRF Deflecting Cavities for Elettra 2.0", FNAL

- **Optimization of the FermiLab/ANL prototype *to 3.0 GHz and 3.25 GHz,* larger apertures, lower HOMs, and weaker multipoles.**
- **RF source input power < *500 W* per cavity.**
- ***3 pure-Nb cavities @ 4,5 K (extension of the Elettra 3HC cryogenic system).***

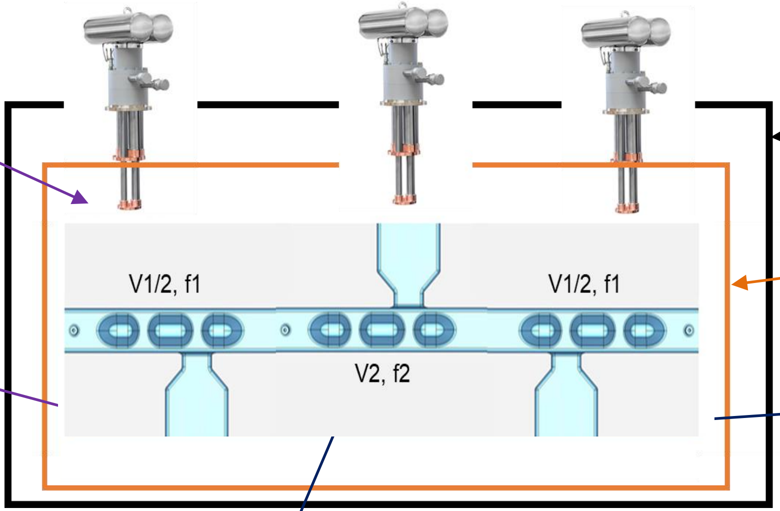
Cryogenic system

Ref. *M. Modica*

PT450 Cryomech cryo-coolers: 4 cold heads @ 3.4 K

75L LHe reservoir above the cavities (135g/L@3.4K)

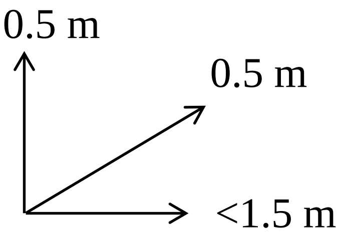
25L LHe around the cavities



Vacuum pipe

Thermal shield

LHe vessel



Total Nb mass ~ 25 kg/cavity
Total heat load < 25 W

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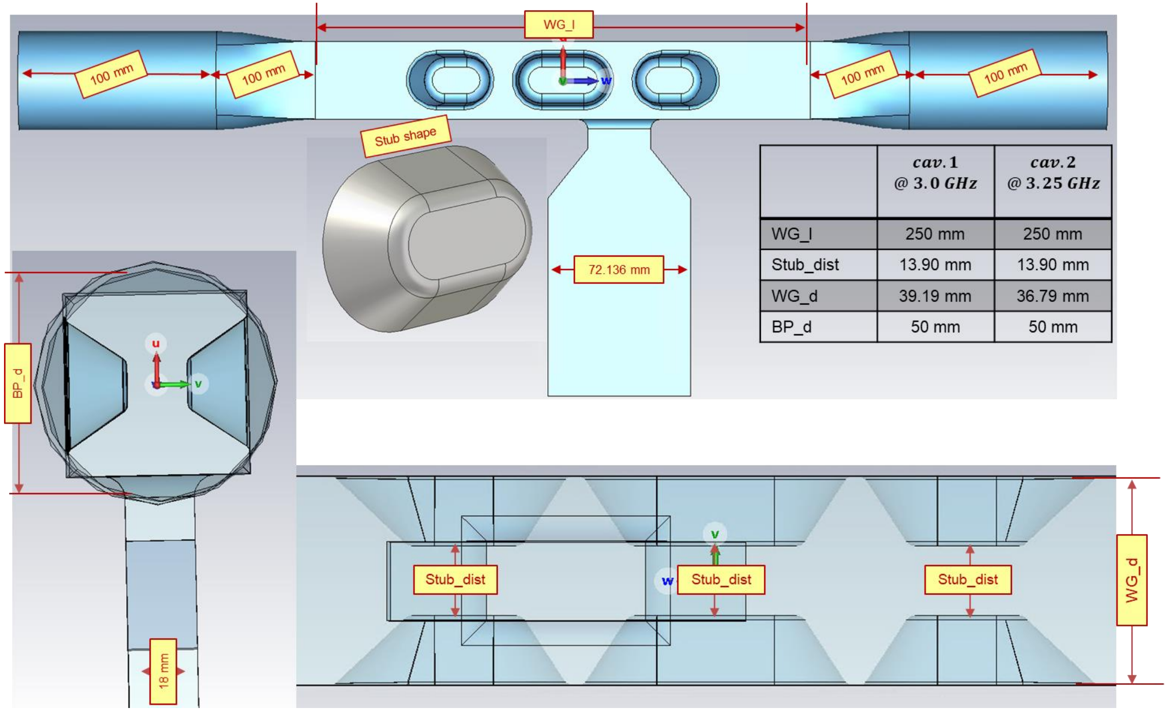
Geometry and parameters

Courtesy *N. Shafqat*



	cav.1 @ *3.0 GHz*	*cav.2* @ *3.25 GHz*
WG_l	250 mm	250 mm
Stub_dist	13.90 mm	13.90 mm
WG_d	39.19 mm	36.79 mm
BP_d	50 mm	50 mm

	Version 3.0		Units
	cav.1 @ *3.0 GHz*	*cav.2* @ *3.25 GHz*	
R/Q_y	656.744	446.14	Ω
E_{peak}	23.5	44.59	MV/m
B_{peak}	45	91.93	mT
Dy variation	4.62%	5.07%	
G factor	109.86	109.14	

Impedance budget

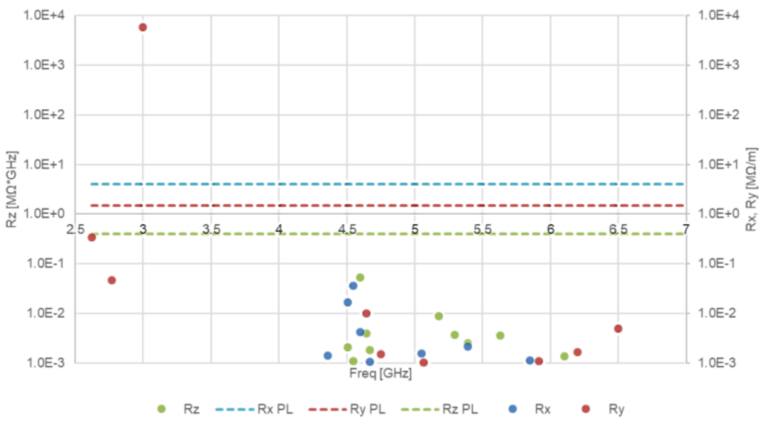
Courtesy *N. Shafqat*

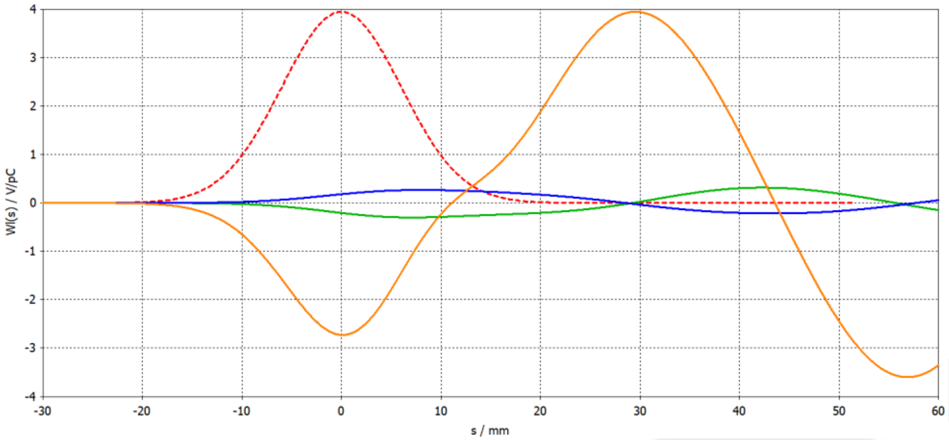
Design Criterion

Available space = 1.0 m			
	f [GHz]	D.V. [MV]	% change in D.V. @ 5.0 mm offset
Cav. 1	f1: 3.0	V1: 1.5	≤10 %
Cav. 2	f2: 3.25	V2: 1.2	≤10 %

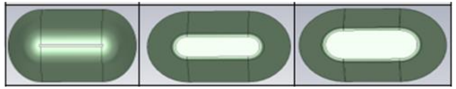
Shunt impedances HOMs below cutoff		
Vertical	<1.5	(MΩ/m)
Horizontal	<4.0	(MΩ/m)
Longitudinal	<0.4	(MΩ*GHz)

Short range wakefields		
Loss factor	4	(V/pC)
Horizontal kick factor	1.3	(V/pC/mm)
Vertical kick factor	1.3	(V/pC/mm)



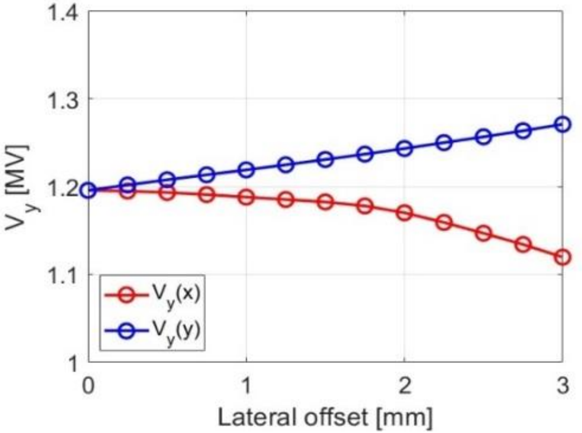


Multipolar field components



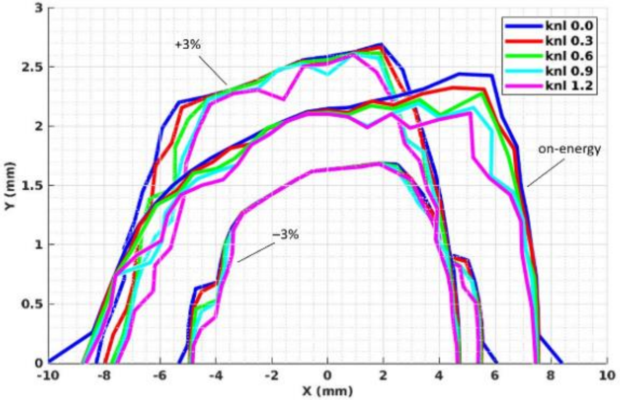
TDC stubs design

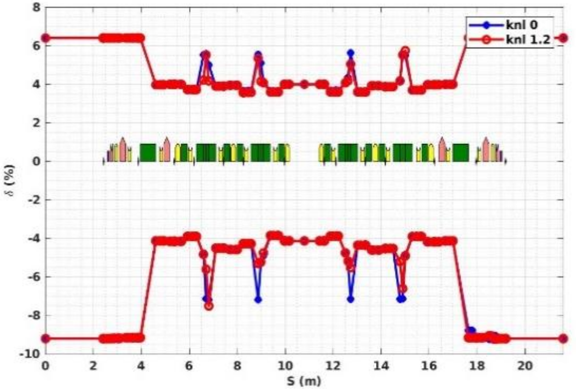
field transverse uniformity



Our preliminary design of the TDC system is largely transparent to the stability and lifetime of the regular bunches

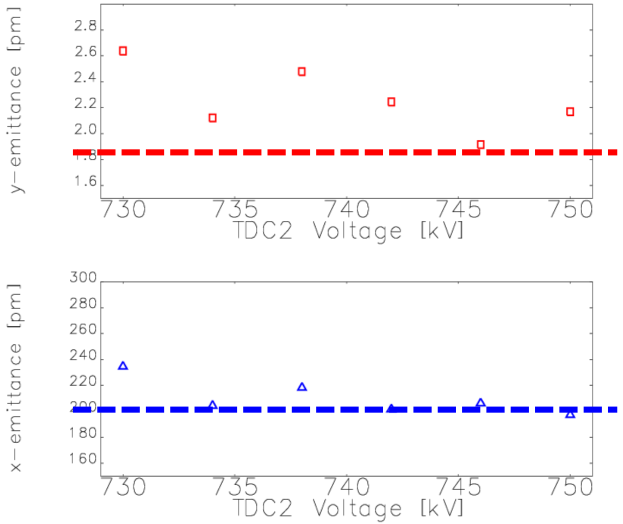
DA and MA of regular bunches w/ TDCs



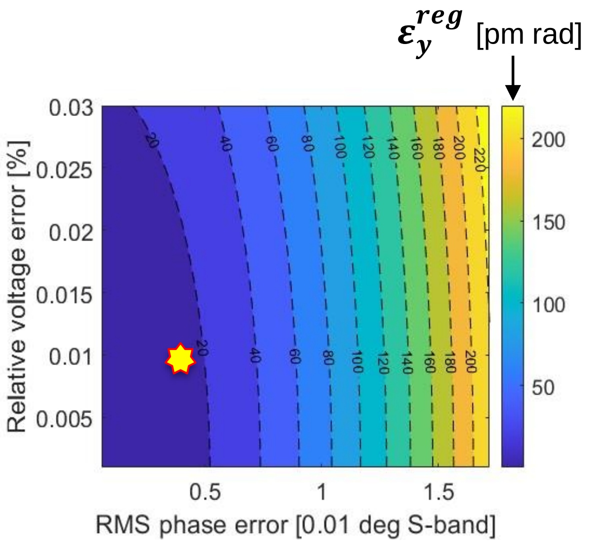


RF stability

Static ε_y^{reg}-growth (drifts)



Dynamic ε_y^{reg}-growth (shot-to-shot)

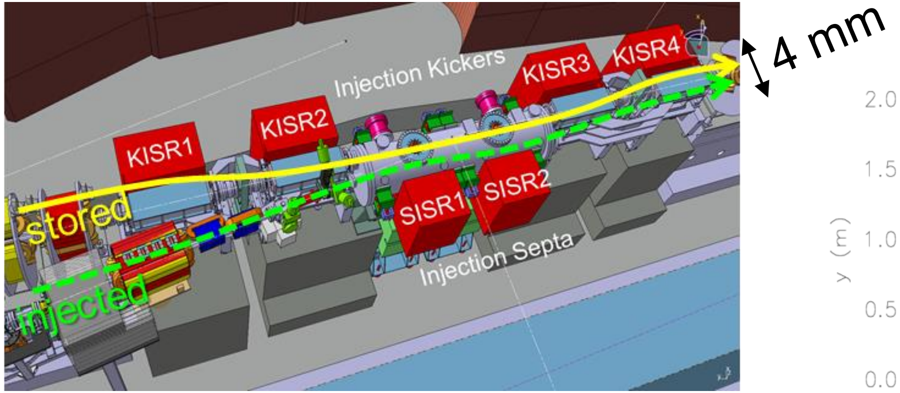


Tolerance is **2-fold** ε_y^{reg} −growth

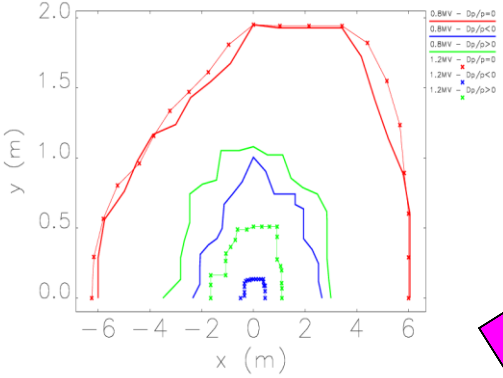
RMS variation	ΔV/V [%]	Δϕ [deg]
Simulations @ 1.2 MV	0.02	0.005
Analytical @ 1.2 MV	0.01	0.004
Analytical @ 0.8 MV	0.02	0.006

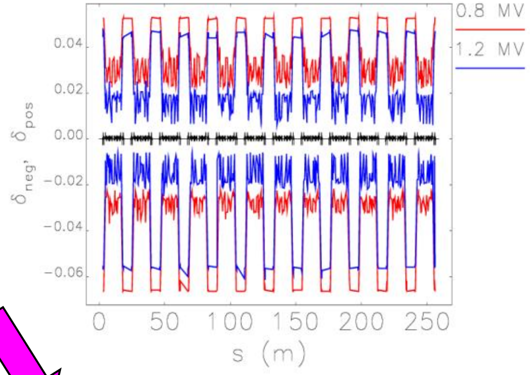
Specification of RF stability under study. Some R&D of D-LLRF expected.

Off-axis injection

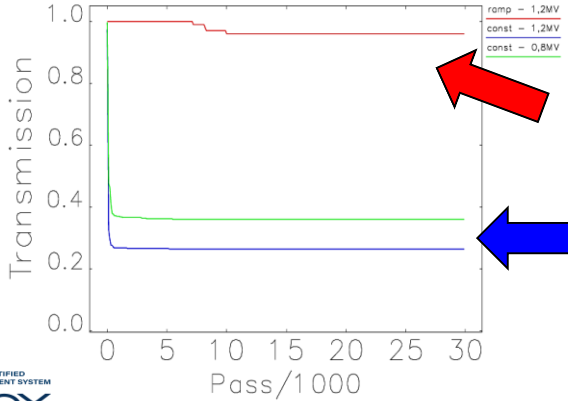


DA and MA of the tilted bunch





< 1 hour Touschek lifetime



Injection into the tilted bucket,
TDC power ***ramp in 10 ms***

Injection into the tilted bucket,
TDC ***at full power***

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Conclusions

- The installation of TDCs at Elettra 2.0 aims to provide extreme ultra-violet and x-ray pulses of **1–5 ps FWHM** duration from IDs, with maximum repetition rate of **1 MHz** and relative flux at the sample in the range **1–10%** of the standard ***single* bunch** emission.

- Two SC RF cavities resonant at 3 & 3.25 GHz. Impact on longitudinal and transverse dynamics evaluated both for standard and tilted bunches. Design studies and prototypes also ongoing for ILC (see A.Lunin SRF'23).

- TDCs are ***not*** in the baseline of Elettra 2.0, hence not funded yet. Still, supported by management, scientific community, SAC and MAC as they would make Elettra 2.0 unique worldwide.

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Thank you for your kind attention

Comments and questions are welcome

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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

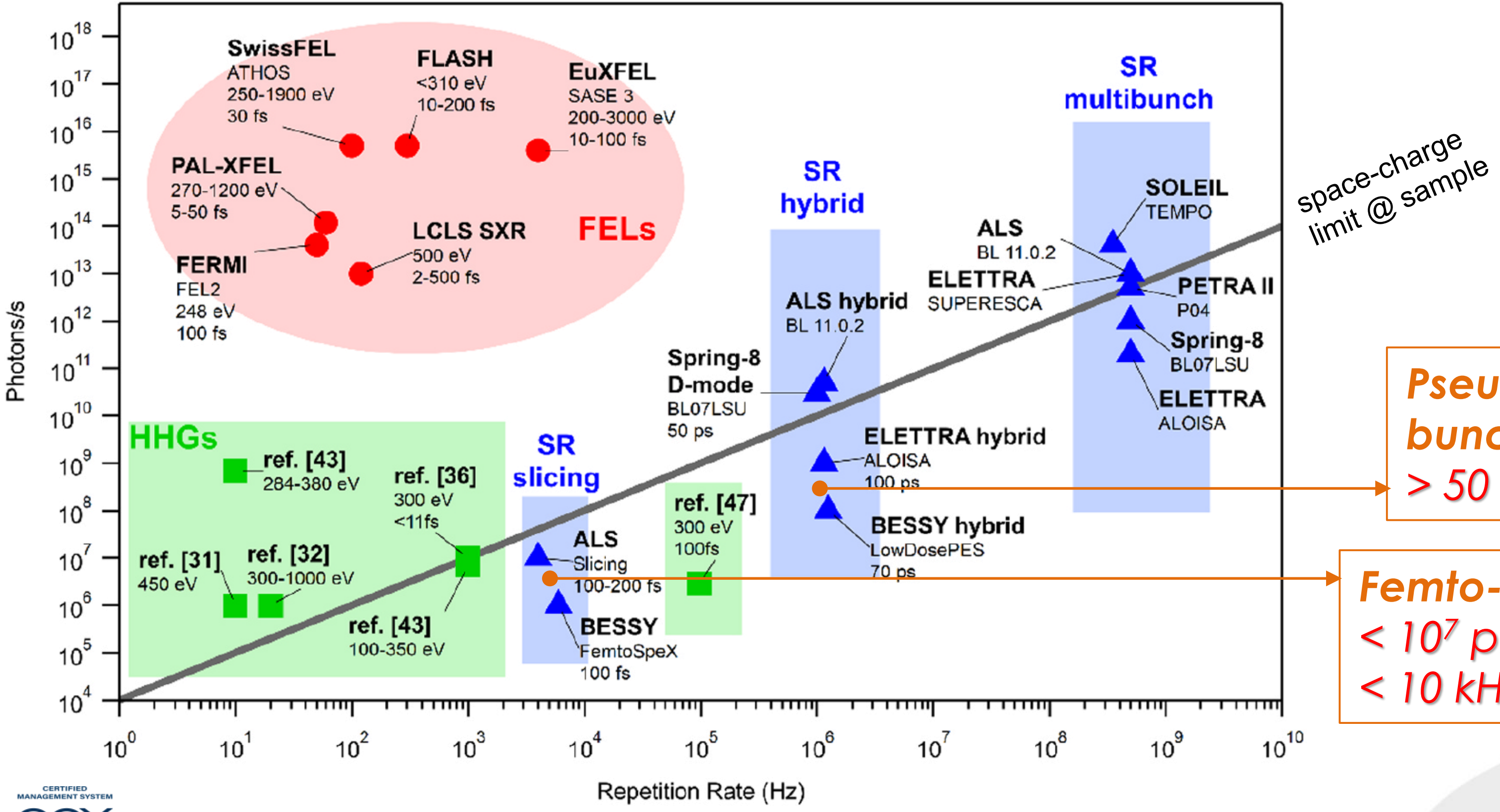
  } nano- to pico-second time scale at **nanometer size**

  - 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*

Sub-picosecond X-ray sources

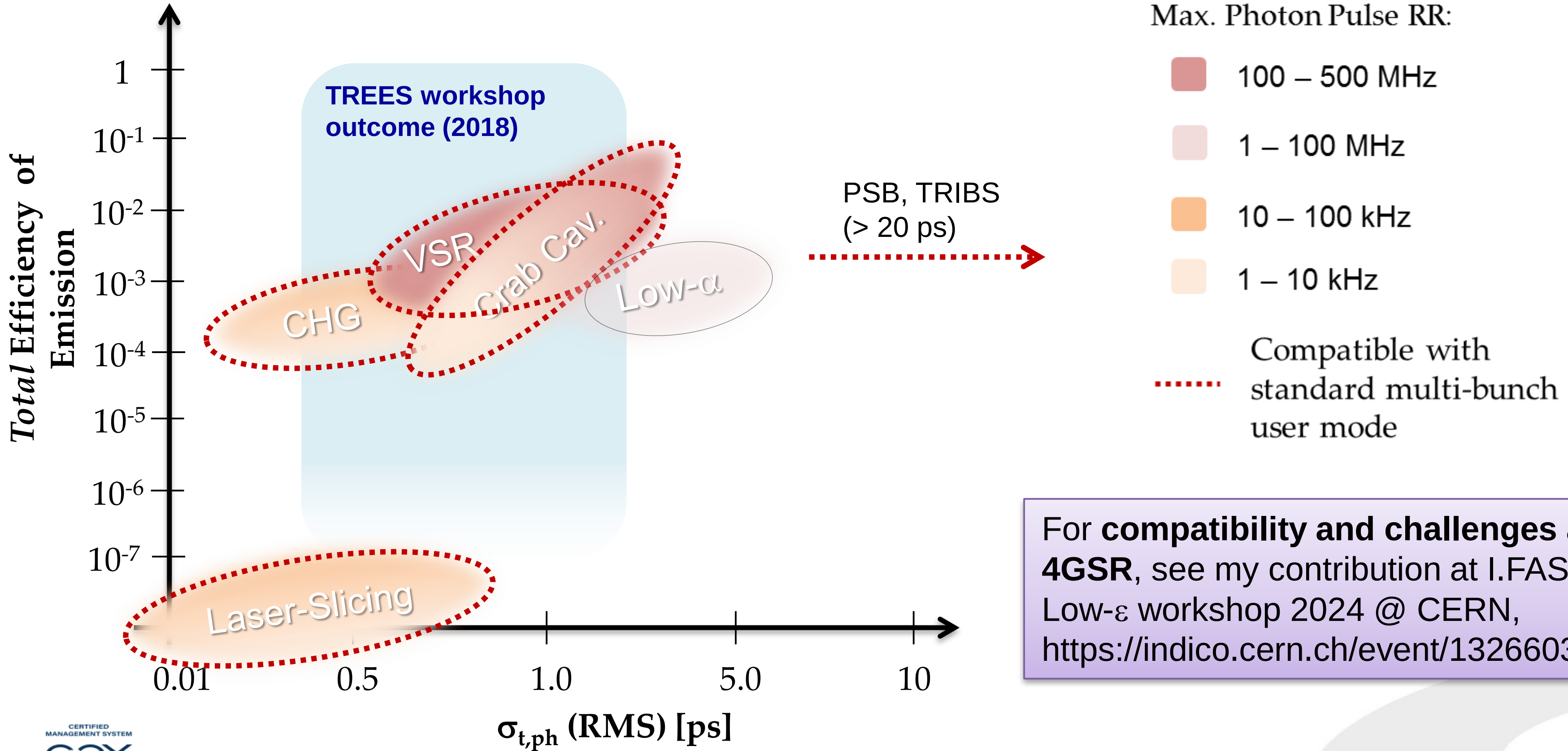
R. Costantini et al., J. Electr. Spectr. Rel. Phen. 254 (2022)



Pseudo single bunch, TRIBS:
> 50 ps fwhm

Femto-slicing:
< 10^7 ph/s/0.01%bw,
< 10 kHz

Efficiency of Emission



For **compatibility and challenges** at **4GSR**, see my contribution at I.FAST Low-ε workshop 2024 @ CERN, https://indico.cern.ch/event/1326603/

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