Picosecond X-ray pulses at Elettra 2.0 with "crab cavities"

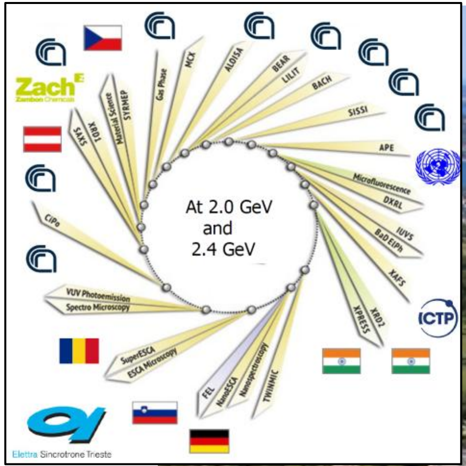
Simone Di Mitri

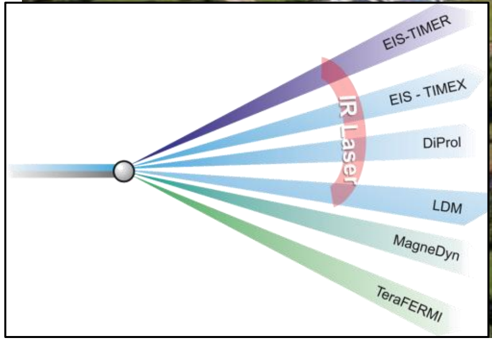
Elettra Sincrotrone Trieste & University of Trieste

simone.dimitri@elettra.eu

Elettra Sincrotrone Trieste

Elettra Sincrotrone Trieste is an international multidisciplinary research centre of excellence, open to the international research community, featuring a 2.0/2.4 GeV, third-generation synchrotron light source (**Elettra**), a free-electron laser light source (**FERMI**) and a variety of support laboratories.





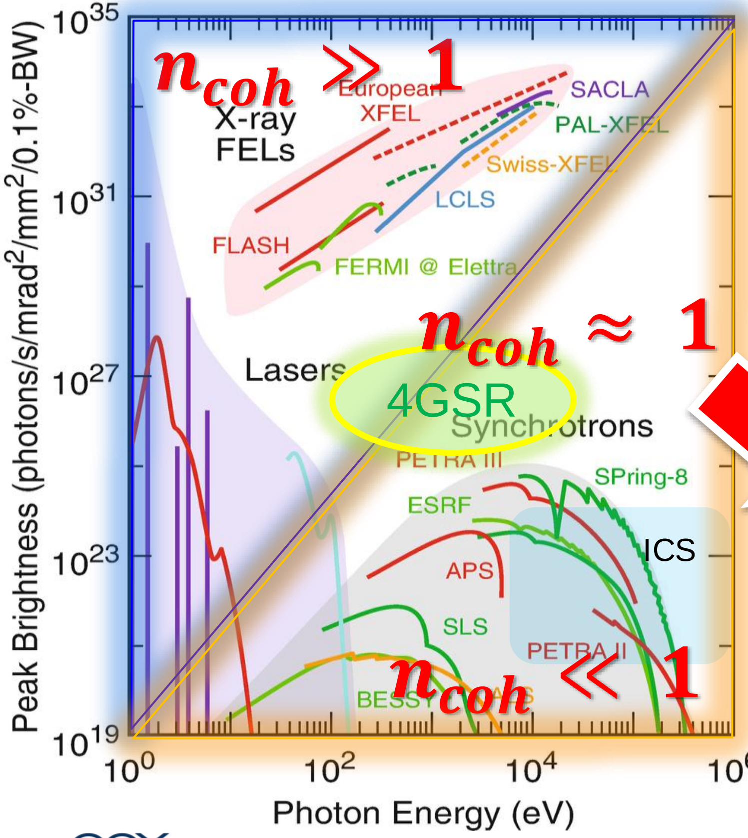
Shut down in July for major upgrade

ELETTRA, 2-2.4 GeV *SRLS*:
in operation since 1994

FERMI, 1.5 GeV *FEL*:
in operation since 2010

Z. Ebrahimpour's talk today

Elettra 2.0 – Diffraction Limit



- Almost all experimental techniques gain from either a large 6-D photon density (*brilliance*) or a large coherent flux (*degeneracy parameter*):

$$\boxed{n_{coh} = \frac{B\lambda^3}{8c}} \quad \text{and} \quad \boxed{B \leq \frac{dN_\gamma/dt}{\Delta\omega/\omega}\frac{1}{(\lambda^2/2)}}$$

Diffraction Limit

for $\boxed{\sigma_u\sigma_{u'} = \varepsilon_u \leq \frac{\lambda}{4\pi}}$

- **More flux at the sample**, for any given λ-range
- **Higher λ-harmonics** by means of low-gap IDs
- **Shorter integrated time** of measurement
- Micro- and nano-**focusing**
- Transverse x&y **coherence** up to 1 keV

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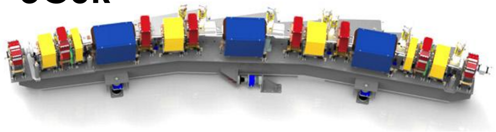
Science drivers of timing modes at SRLS

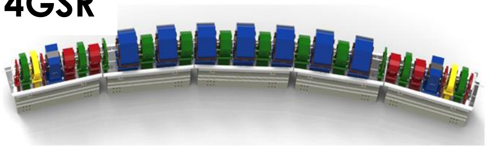
3GSR



1. Avoid **sample burning** or ablation
2. Avoid **space charge** shielding
3. Multi-**MHz** rep. rate
4. **Wide & continuous λ-tuneability**
5. Full **polarization** control

- Track *non-equilibrium* states (e.g. aerosol in free-flight)
- Map *reversible dynamics* of molecular systems
- Probe *charge transfer* dynamics
- Image orbital, spin, and lattice *degrees of freedom*

4GSR



+ Improve ***lateral resolution***

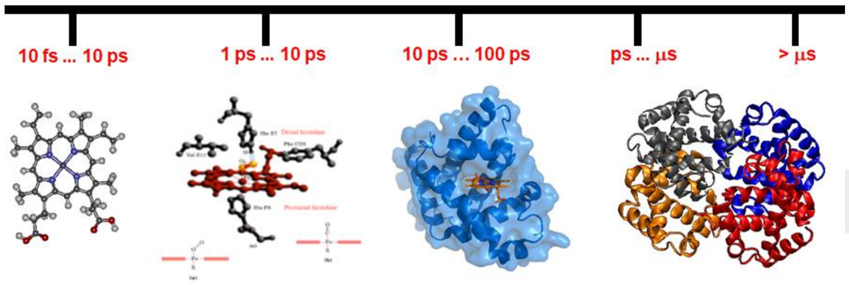
+ Improve ***energy resolution***

+ Reduce the ***integrated time*** *of measurements*

50–100 ps:
PES, ***EXAFS****,*
imaging

New science

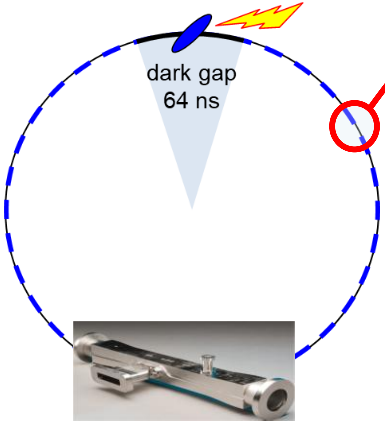
- ***1–5 ps processes @ nm size:***
  - *Elementary conformational protein dynamics &* ***protein-protein interaction****.*
  - *Atomic motion in molecular vibrations.*
  - *Chemical reaction intermediates.*

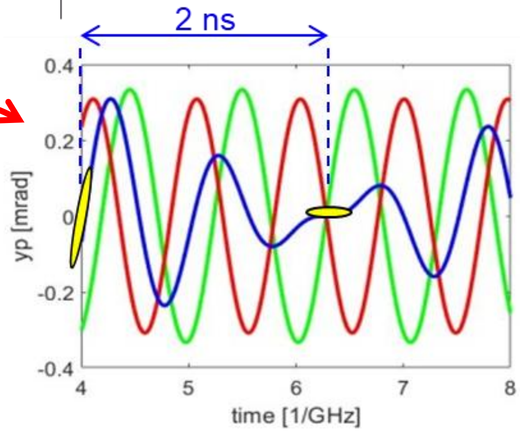


Elettra 2.0 – Timing Mode

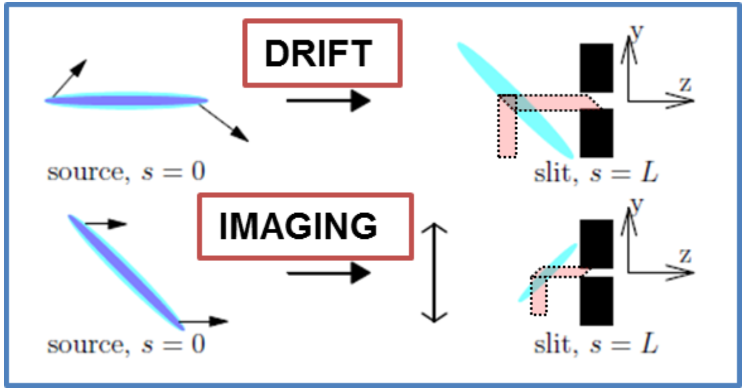
Parameter	Elettra 2.0	FERMI	Units
Spectral range	0.02 - 50	0.01 – 0.7	keV
Rep. rate	1 – 400	0.05	MHz
Pulse duration, rms	30	0.005 – 0.1	ps
Flux at sample, ave	$10^6 – 10^{13}$	$10^9 – 10^{13}$	ph/sec
Spectral resolution	$10^{-5} – 10^{-4}$	$10^{-4} – 10^{-3}$ (w/o mono)	
Polarization	all	all	
Coherence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

"Crab cavities" working principle





- **Fill pattern:**
  - 200 regular bunches, 2 mA/bunch, 4 ns-time sep.
  - 1 tilted bunch, 2 mA , ±32 ns time sep., 1.157 MHz



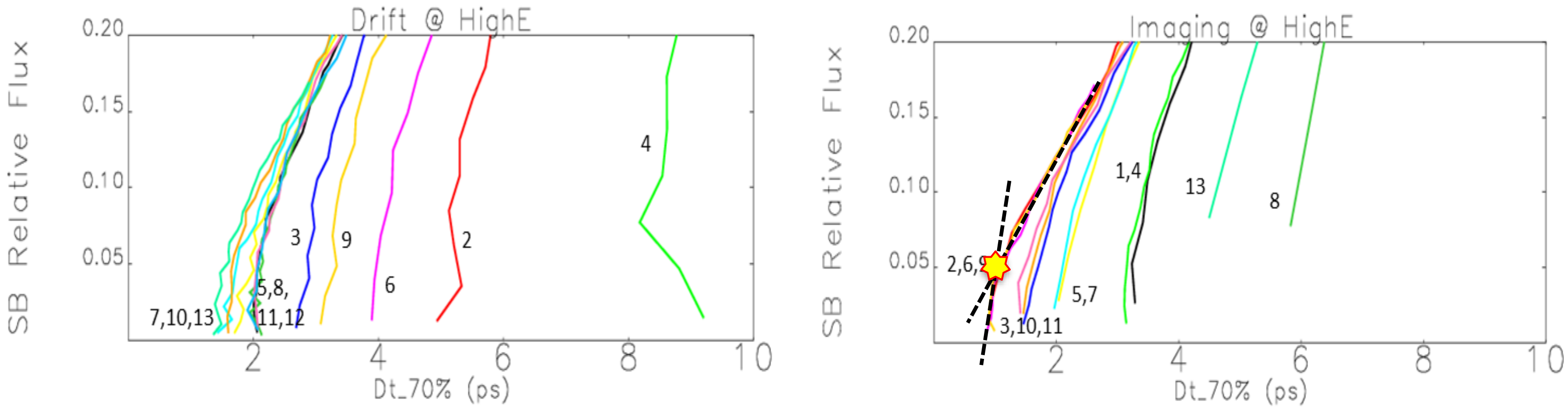
- **Pulse selection:**
  - Temporal gating
  - distorted orbit
  - chopper

A. Lunin et al., Phys. Proc. 79 (2015) 54.
A. Lunin, T. Khabiboulline, V. Yakovlev , "A White Paper on Design and Fabrication of SRF Deflecting Cavities for Elettra 2.0", FNAL note.

A. Zholents, NIM A 798 (2015) 111

See also: X. Huang, PRAB 2016, 2019, 2023

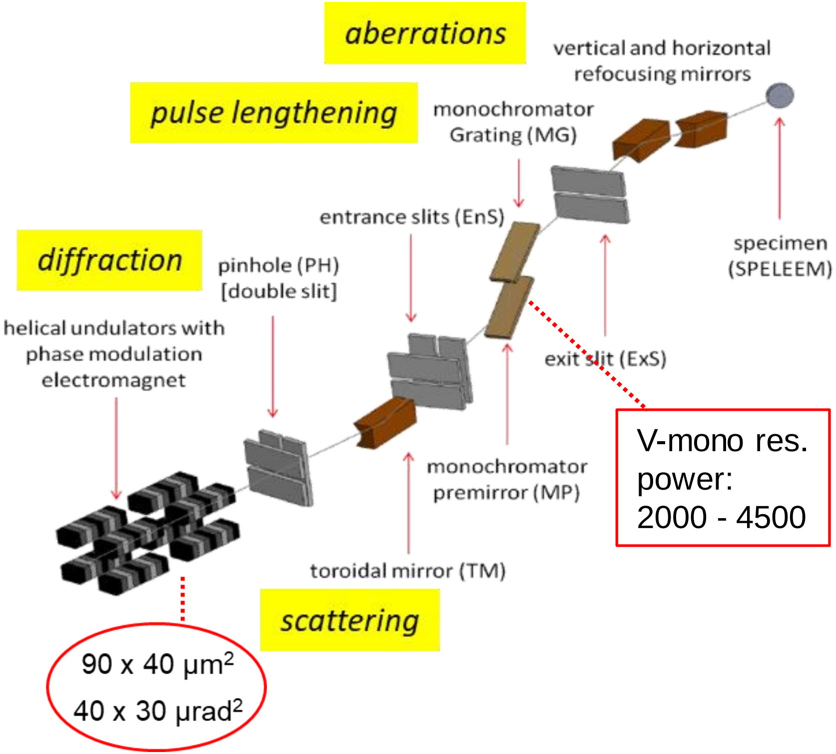
Flux *vs.* pulse duration



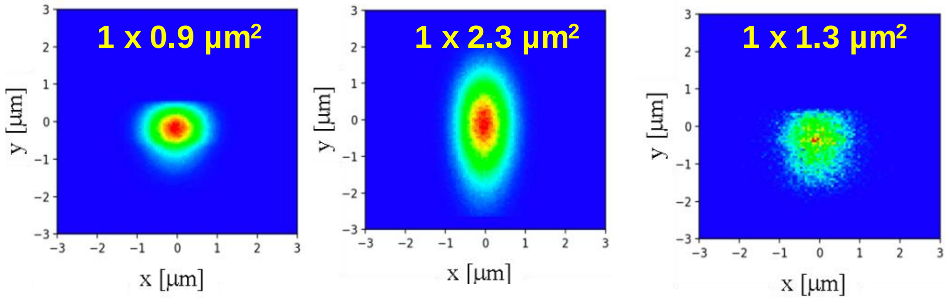
1.2 MV @ 3GHz

- **On-the-fly control** of pulse duration, flux, rep. rate (chopper), polarization (ID)
  - *At each beamline, without interference with neither other beamlines nor accelerator operation*

Nanospectroscopy @ 800 eV



From accelerator to sample (`elegant` + Spectra + ShadOUI):



REGULAR:	SHORT:	SHORT:
55 ps	4 ps, *drift*	4 ps, *hybrid*
1.3e10 ph/s	1.5e9 ph/s	1.8e9 ph/s

- The slit selects a sub-space of radiation emitted by the tilted e-bunch
- **Transverse coherence** and **energy resolution** largely **preserved**

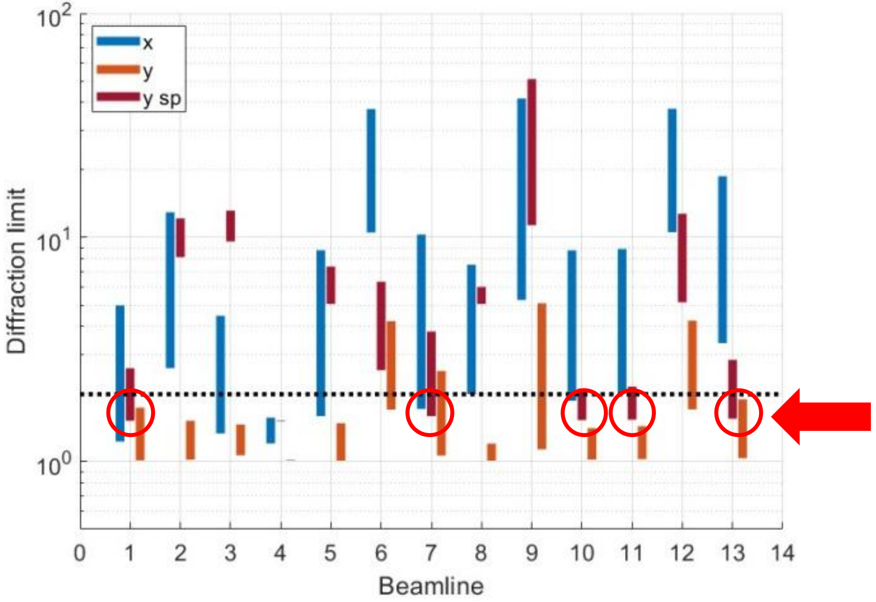
Diffraction limit, spectral flatness

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

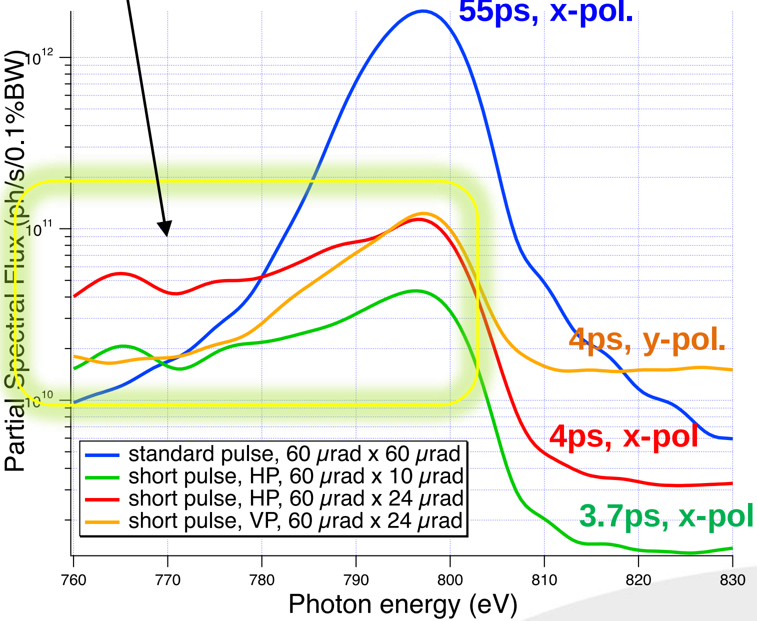
= 0.5 well below DL

= 1 @ DL

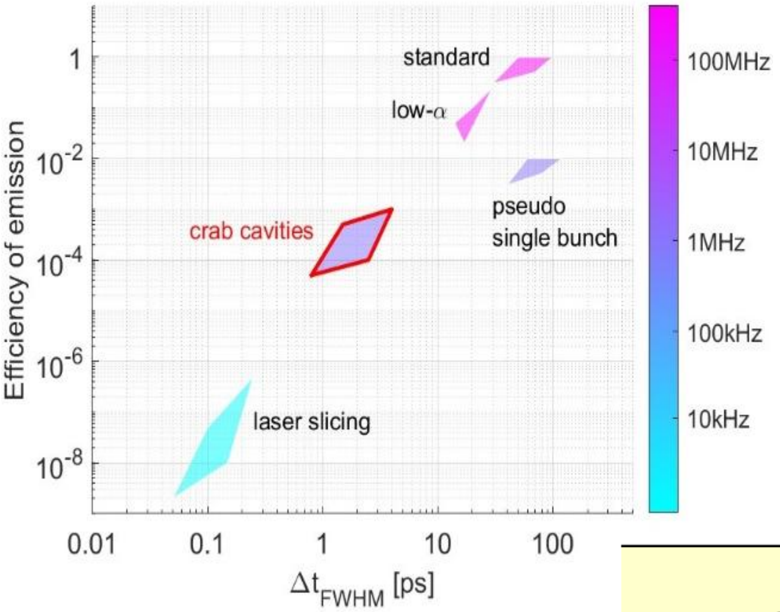
> 1 non-DL



Potentially useful for on-the-fly energy scan at EXAFS, XAS…



Timing modes @ SRLS



		Laser-slicing	PSB	Crab Cavities
Stored Current	mA	2 + 400	2 + 400	2 + 400
SP Duration, fwhm	ps	**0.5 – 2**	**50**	**1 – 5**
SP Repetition Rate	MHz	0.001 – 0.01	1	1 (<200)
$\frac{Flux(\boldsymbol{Short\ Pulse})}{Flux(\mathbf{400}\boldsymbol{mA})}$		$\frac{1}{10^8}$	$\frac{1}{200}$	$\frac{1}{20000} \dots \frac{(\times 100)}{2000}$

@ E2.0

	Bunch ave. current [mA]	Photon energy [keV]	Pulse duration, FWHM [ps]	Ave. spectral flux [ph/s/0.01%bw]	Ave. flux [ph/s]	Peak flux [ph/pulse]
E1.0 PSB	5	1	200	1.6×10^{10}	3.3×10^{10}	1.1×10^4
E2.0 PSB	4	1	60	1.3×10^{10}	2.7×10^{10}	1.1×10^4
E2.0 CC	2	1 – 10	1 – 4	$\sim 10^8 - 10^9$	$(0.2–2.8) \times 10^9$	$(0.3–2.4) \times 10^3$

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Summary

- Picosecond duration, at several beamlines, for E_{ph} > 100 eV
- Tunable 0.1–1 (100) MHz rep. rate, 1–10 % flux relative to standard single bunch emission
- Transverse coherence, energy resolution & polarization largely preserved
- Standard bunches pay a doubled vertical emittance (6 → 12 pm rad)
- Conceptual design report is being finalized. Technical design report is in progress
- *CCs are not in the Elettra 2.0 baseline. Still, full support from management, international committees and beamline scientists. Search for funds to prototype.*

Acknowledgements

A. Zholents (ANL)

X. Huang (SLAC)

R. Calaga, A. Grudiev (CERN)

for guidance to “Crab Cavs” simulations

The Elettra team for the Crab Cavities:

A. Bianco *(retired)*, M. Altissimo, E. Busetto, A. Carniel, S. Cleva, I. Cudin, S. Dastan, B. Diviacco, A. Fabris, E. Karantzoulis, S. Krecic, S. Lizzit, M. Lonza, **K. Manukian, C. Masciovecchio, M. Modica, E. Principi, N. Shafqat**

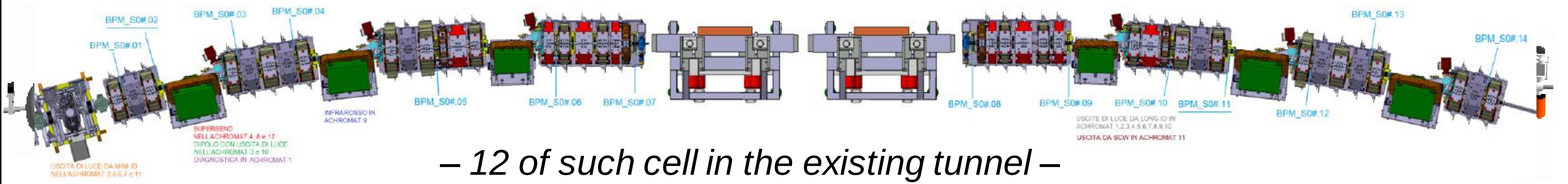
Thank you for your attention

Questions are welcome!

Back up slides

Magnetic lattice

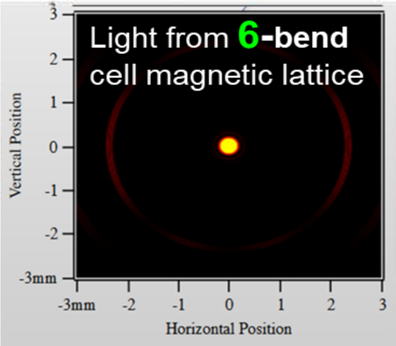
The present magnetic lattice will be entirely replaced by a denser and stronger one, including combined-function elements (3x dipoles, 4x quadrupoles).

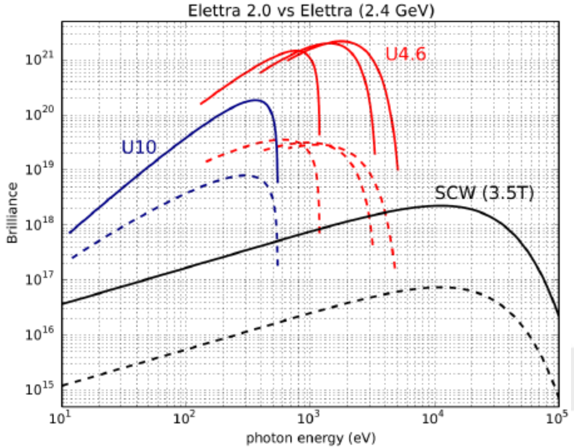


– 12 of such cell in the existing tunnel –

- **45-fold** smaller e-beam **emittances**
- **5-fold** smaller **beam sizes** at IDs
- **x100 brilliance** at the source (1-10 keV)

- Reduced **acquisition time**
- **Photon-hungry** techniques
- Lateral **resolution**
- **CDI** in keV range, ptychography, XPCS





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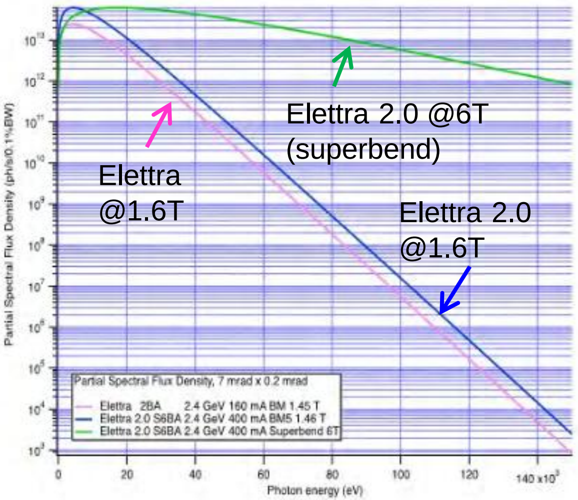
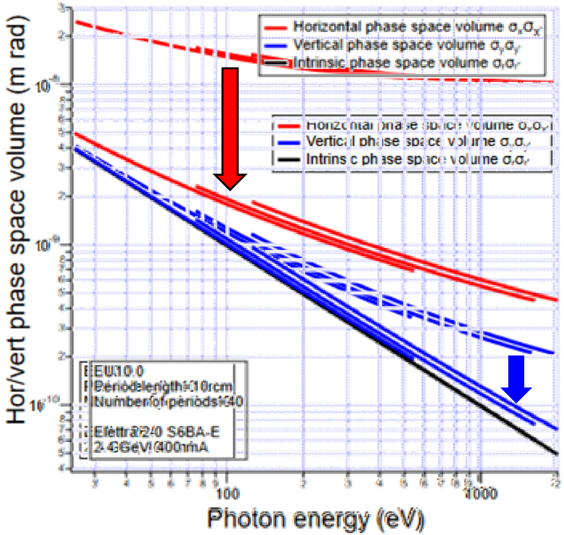
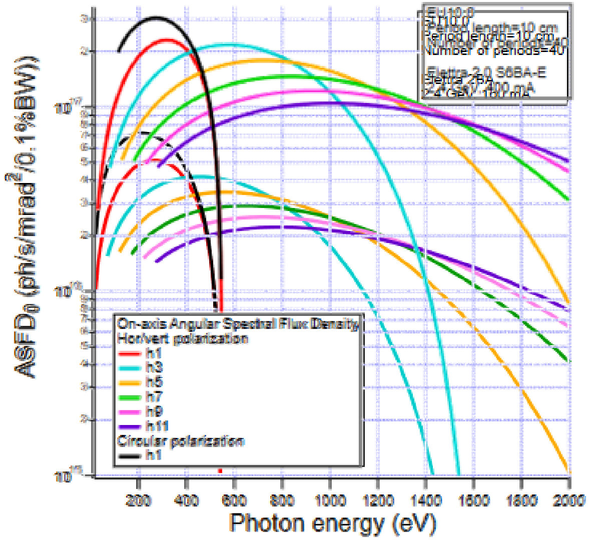
Improved radiation source



Dipole magnet: *spectral flux density*



EPU: *radiation 4-D volume at the source*



EPU: *on-axis Ang. Spectr. Flux Density of odd harmonics 3 – 11.*

Beamlines

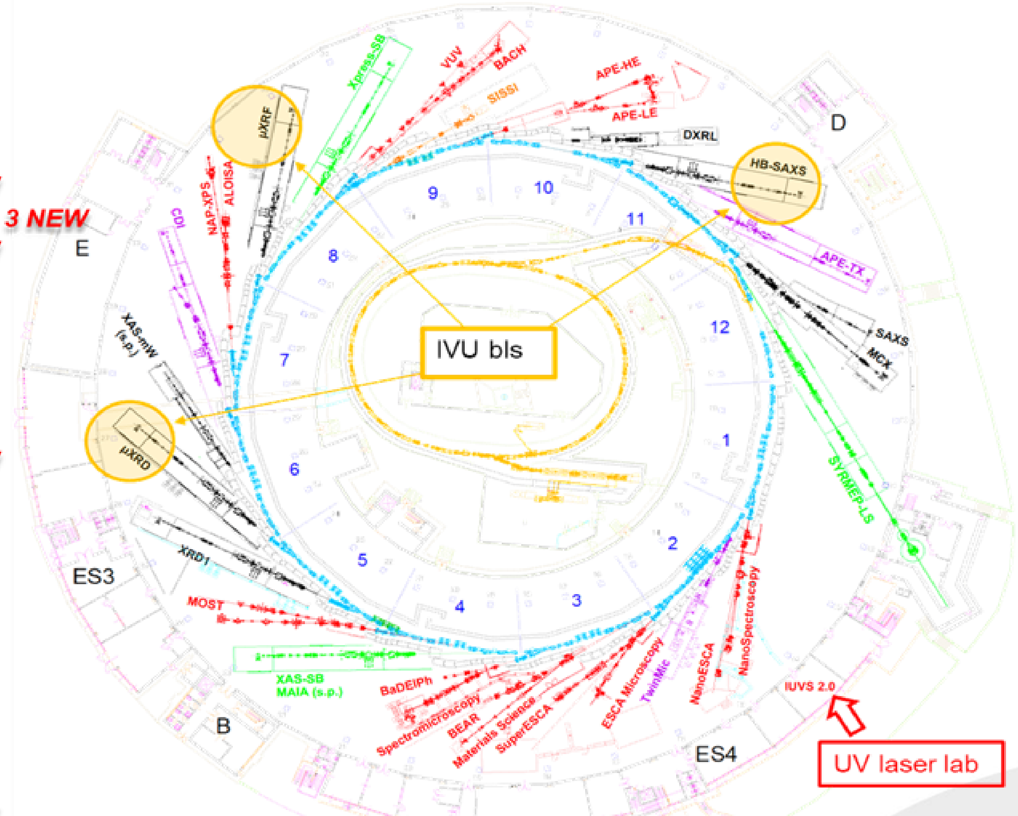
Up to 32 beamlines

9 → 12 Hard X-rays
- 2 on ScBM **2 NEW**
- 3 on IVU for micro-spot **3 NEW**
- 4 on sW in SS **1 NEW**
- 2 on SCW
- 1 on BM

0 → 3 Soft-tender X-rays
- 1 APU in SS
- 1 EPU in SS **1 NEW**
- 1 EPU in LS

17→15 VUV-Soft X-rays
- 7 on EPU in LS
- 2 on LPU in LS
- 2 on F8 in LS
- 2 on APU (LP) in SS
- 2 on BM

2 → 2 IR/THz beamline **1 NEW**



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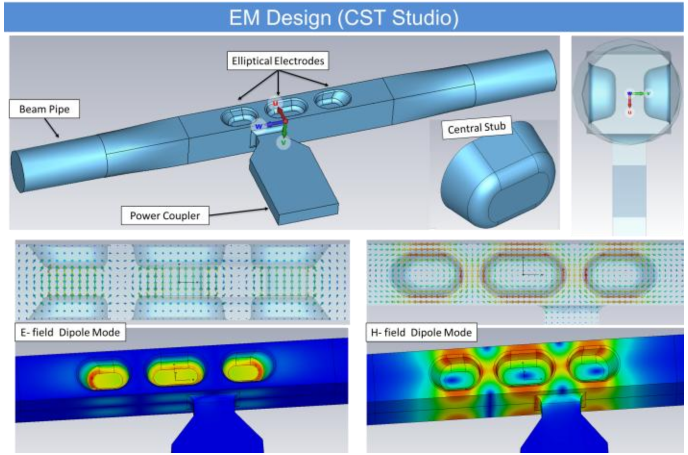
Deflecting voltages

A. Lunin et al., Phys. Proc. 79 (2015) 54.
A. Lunin, T. Khabiboulline, V. Yakovlev , "A White Paper on Design and Fabrication of SRF Deflecting Cavities for Elettra 2.0", FNAL note.

- **Quasi-waveguide Multicell Resonator (QMiR)** @ 2.815 GHz for **APS** (ANL).
- Intrinsic low-Q SOMs and HOMs in a sparse frequency pattern.
- Low gap, relatively high surface fields, nonlinear field components.

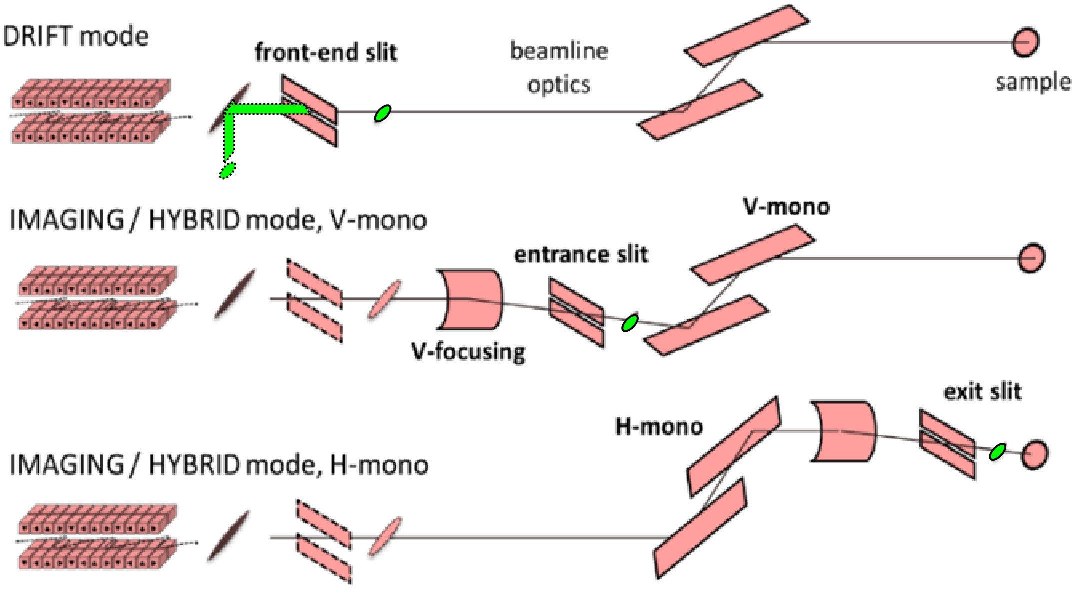


Design and optimization by N. Shafqat et al..

- *Re-design* of the ANL prototype for a larger beam aperture, to meet the requirements on short-range wakefields. Aperture > 8 mm-V x 12 mm-H.
- *2 + 2 pure-Nb* cavities *@ 4,5 K (extension of the 3HC cryogenic system).*
- RF source input power < *500 W* per cavity

Short pulse production

- The mode of short pulse selection depends on the **beamline layout**



- The **minimum pulse duration** depends on deflecting voltage, beam emittances, photon energy

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

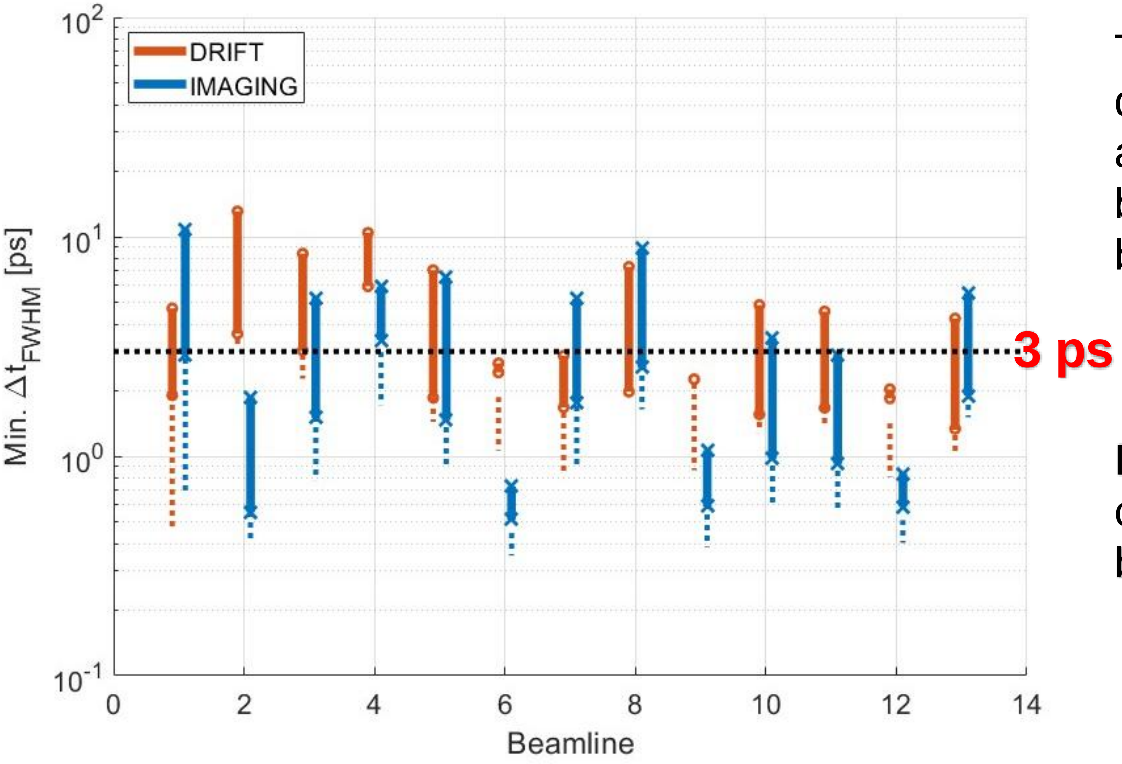
Deflecting voltage, vertical tune and phase advance

Small coupling

Small energy spread, small harmonic number, few ID periods

Short wavelength

Theoretical minimum pulse durations



Theoretical minimum FWHM pulse duration calculated for drift (orange) and hybrid optics (blue), across the beamline's full spectral range and for beam RMS energy spread of 0.1%.

Dashed vertical lines are for the ideal case of a monochromatic electron beam.

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Shortest durations at Elettra 2.0

Beamline		LOWEST photon energy				HIGHEST photon energy			
Name	[keV]	Δt_{FWHM} (ps)		$\Delta F/F$ (%)		Δt_{FWHM} (ps)		$\Delta F/F$ (%)	
		DR	HYB	DR	HYB	DR	HYB	DR	HYB
1.2	[0.03-1.7]	17	9	6	2.5	**3**	**1.7**	1.5	2.8
2.1	[0.13-4.0]	48.5	**1.2**	35	1.6	46	**0.8**	18	1.7
3.2	[0.01-0.2]	48	10.5	20	1.6	42	**2.1**	5	1.8
4.2	[0.01-1.5]	22	22	15	5	**3.1**	**3.6**	1	6.5
5.1	[4-21]	34	6.4	12	2.7	18	**3.0**	5	2.6
5.2	[3.5-15]	16	**0.9**	3	2	15	**0.9**	3	1.9
6.2	[0.34-4.0]	**3.7**	3.7	0.5	3.6	**1.7**	**1.9**	0.5	3
7.2	[3.5-15]	6.5	**1**	1	2	6.5	**0.9**	1.5	2
8.1	[0.15-1.5]	27	**1**	9	1.4	9.6	**0.8**	1	1.7
8.2	[0.04-1.5]	16	6	7	3	**3.2**	**1.7**	1	3.5
9.2a	[0.01-0.2]	38	6.7	15	1.9	13.5	**1.8**	3	2.0
9.2b	[0.08-1.5]	20	**2.8**	4	2	5.8	**1.1**	1	2.3
10.1	[0.5-7.0]	12.5	**0.7**	1	1.3	8.5	**0.7**	2	1.6
10.2	[4-15]	**2.1**	**1.2**	0.5	2.7	**2.2**	**1.2**	1	2.7
11.1	[3-15]	28	33	12	12	14	19	6	17
11.2	[9-25]	38	9	16	2	27	4.8	7	2.4

$\Delta F/F$(%) is *relative to* single bunch *emission @ ID*

simone.dimitri@elettra.eu

NanoSpectroscopy @ 800 eV *(1/3)*

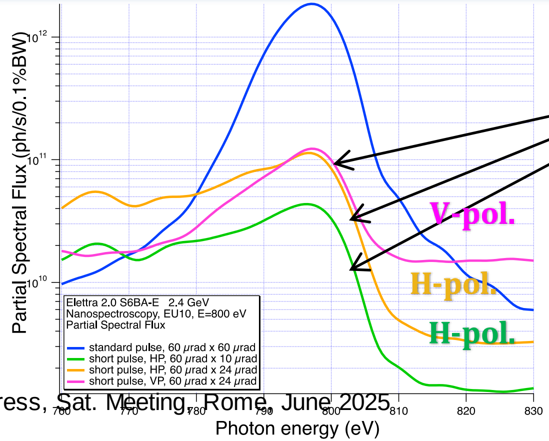
Spectral flux in central cone, V/H-polarization, 2 mA/bunch – ***DRIFT mode***

(blue) photon pulse from standard electron bunch, opening 60 μrad x **60 μrad**:
55 ps, 1.9e12 ph/s/0.1%BW ; $S_1/S_0=1$ *(EU, λu = 10 cm, Lu = 4 m)*

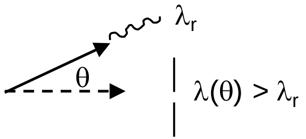
(green) short photon pulse from tilted electron bunch, opening 60 μrad x **10 μrad**:
3.7 ps FWHM, **4.3e10 ph/s/0.1%** or **~1e4 ph/pulse/0.1%, S_1/S_0= 0.98**

(orange-pink) short photon pulse from tilted electron bunch, opening 60 μrad x **24 μrad**:
4 ps FWHM, **1.1e11 ph/s/0.1%** or **~1e5 ph/pulse/0.1%, S_1/S_0= 0.98/-1**

Single pulse useful spectral flux: **6%**



Intensity drop at higher energies, off-axis electrons motion



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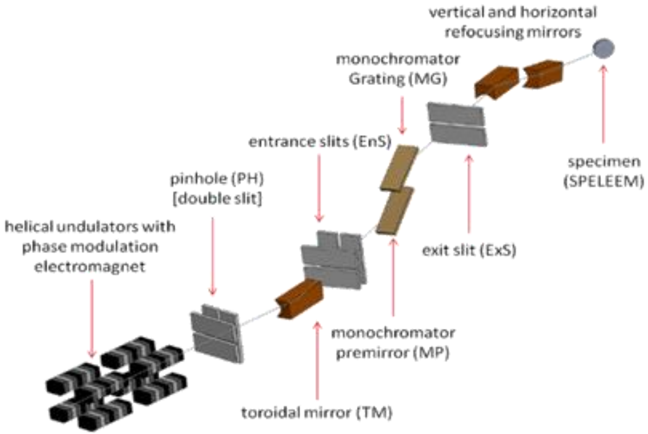
Example @ 0.8 keV



Nanospectroscopy-*like* soft x-ray beamline. 3% transmission efficiency.

Beamline optics	**Standard**	**SP Drift**	**SP Hybrid**
Photon energy [keV]	0.8	0.8	0.8
FE slit gap (x × y) [μm]	690 × 690	690 × 280	690 × 690
FE angular acceptance (x × y) [μrad]	60 × 60	60 × 24	60 × 60
Slit gap at the monochromator entrance (y) [μm]	8	-	10
Slit gap at the monochromator exit (y) [μm]	6	12	10
Energy resolving power	4500	2000	2900
Light pulse			
Spatial size* at the FE slit, FWHM [μm]	90 × 42	90 × 80	90 × 99
Angular divergence* at the FE slit, FWHM [μrad]	38 × 32	38 × 23	38 × 59
Duration, FWHM [ps]	55	4	4
Degree of linear polarization, S_1/S_0	1	0.98	0.98
Spectral flux at source point [10^{10}ph/s/0.01%bw]	19	1.1	1.7
Relative spectral flux at source point [%]	100	6	9
Flux at sample [10^{10}ph/s]	1.3	0.15	0.18
Relative spectral flux at sample [%]	100	12	14
Spatial size at sample, FWHM (x × y) [μm]	1.0 × 0.9	1.0 × 2.3	1.0 × 1.3

Example @ 12 keV

HBSAXS-*like* tender x-ray beamline. 11% transmission efficiency.

Beamline optics	**Standard**	**SP Drift-1**	**SP Drift-2**
Photon energy [keV]	12	12	12
FE slit gap (x × y) [μm]	550 × 550	550 × 400	550 × 200
FE angular acceptance (x × y) [μrad]	48 × 48	48 × 35	48 × 17
Energy resolving power	5700	5700	5700
Light pulse			
Spatial size* at the FE slit, FWHM [μm]	86 × 13	86 × 80	86 × 65
Angular divergence* at the FE slit, FWHM [μrad]	24 × 24	24 × 35	24 × 28
Duration, FWHM [ps]	55	2.7	2.3
Spectral flux at source point [10^{10}ph/s/0.01%bw]	3.8	0.2	0.1
Relative spectral flux at source point [%]	100	6	3
Flux at sample [10^{10}ph/s]	0.73	0.04	0.02
Relative spectral flux at sample [%]	100	6	3

simone.dimitri@elettra.eu