Accelerators Development at Elettra Sincrotrone Trieste

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on behalf of Elettra Team & FERMI Team

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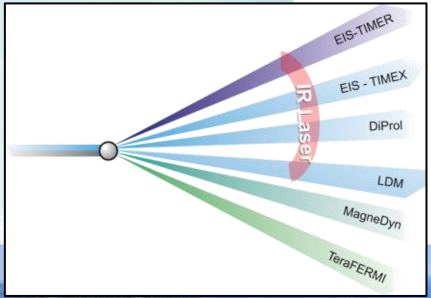
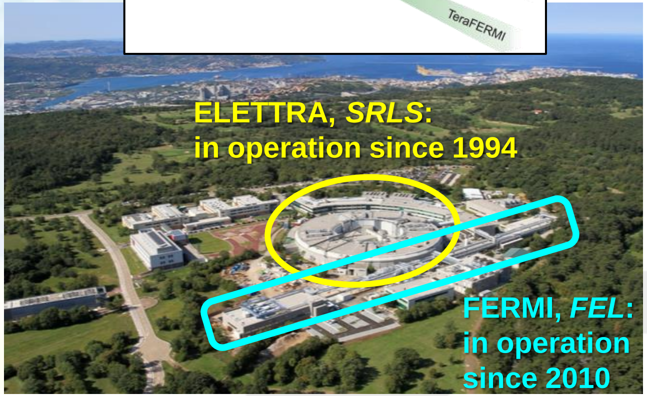
Light Sources





Elettra Sincrotrone Trieste

From Elettra to Elettra2.0

E. Karantzoulis, Project Leader
A. Fabris, Executive Officer

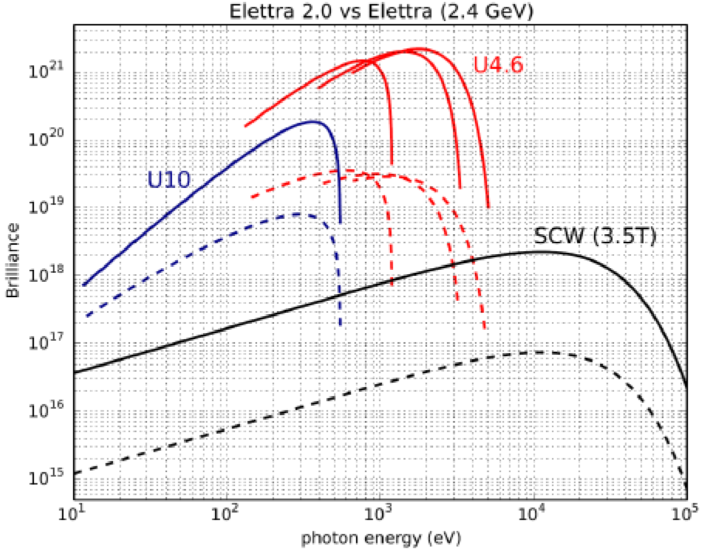
		ELETTRA	ELETTRA 2.0
In operation since		1994	2027
Availability		5000-user / 6400-tot	
e-Beam energy	GeV	**2.0** (75%) – 2.4 (25%)	**2.4** (2.0 for some time)
Photon energies	keV	0.020 – 35	0.060 – 50
#Beamlines (#ID, #Bends)		28 (17, 7)	32 (17, 3+2)
Hybrid filling patterns		yes	
ID occupancy	%	30	40
Circumference	m	259	
Magnetic Lattice		12 x 2BA	12 x S6BA-E
Hor. emittance, coupling	nm rad, %	7 – 10, 1%	bare 0.212, 3%
Max. ave. current	mA	310 – 160	400

Brilliance × 100-1000 (1-10 keV)

Science drivers

Reduction in e-beam **emittance** → reduced **beam size**, increased peak **brightness** will lead to:

- ***gain in the emitted/transmitted signals*** from samples
- ***reduced acquisition time*** for all types of spectroscopies and X-ray scattering techniques
- implementation of ***photon-hungry techniques*** (high pressure exps. with anvil cells and dilute samples, spin-resolved ARPES)
- improvement of the ***lateral resolution*** with focusing optics down to a few nm scale (e.g. nano-PES, nano-ARPES)



Transversal **coherence** will open unique opportunities for coherence-hungry methods:

- ***Coherent Diffraction Imaging*** (CDI) with chemical specificity
- ***Ptychography***
- ***X-ray photon correlation spectroscopy*** (XPCS)

Boundary conditions

❑ **Keep same:**	building and circumference	✓	
	long SS-ID position	✓	
	full-energy injection (linac+booster)	✓	emittance swap in booster
	e-beam energy(-ies)	✓	main operation at 2.4 GeV
	diverse filling patterns	✓	hybrid, single/few bunches

❑ **Improve:**	horizontal emittance	✓	47-fold
	beam dimensions @ LS-ID	✓	(35-x,6-y)μm, (6-x',2-y')μrad
	intensity	✓	400 mA @ 2.4 GeV
	ID occupancy	✓	~40%, +4 beamlines

Magnetic lattice

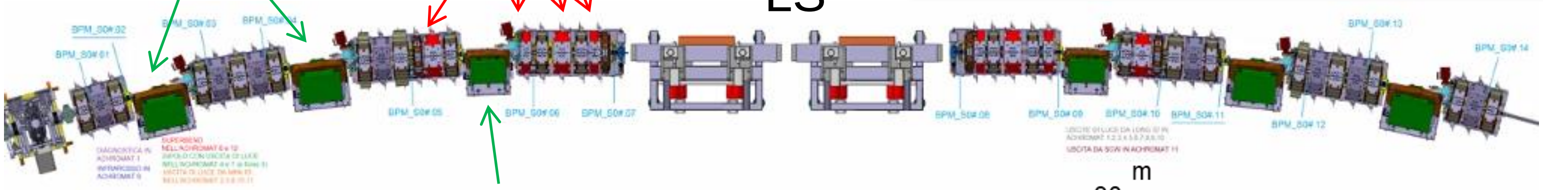
ref. E. Karantzoulis, D. Castronovo

All magnets:
- iteratively designed vs. extraction chambers
- independently powered
- water-cooled

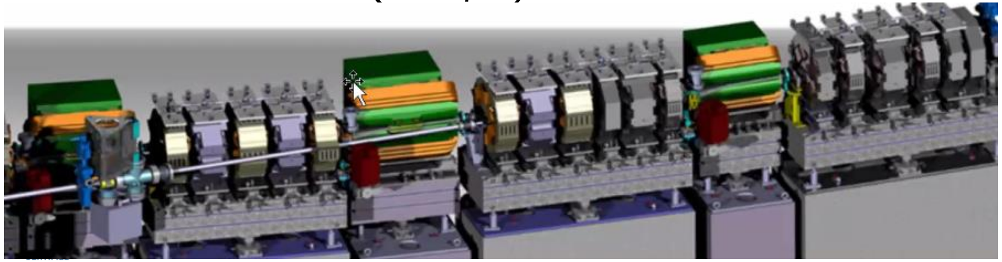
Transv. (-21 T/m) & **Long.** gradient

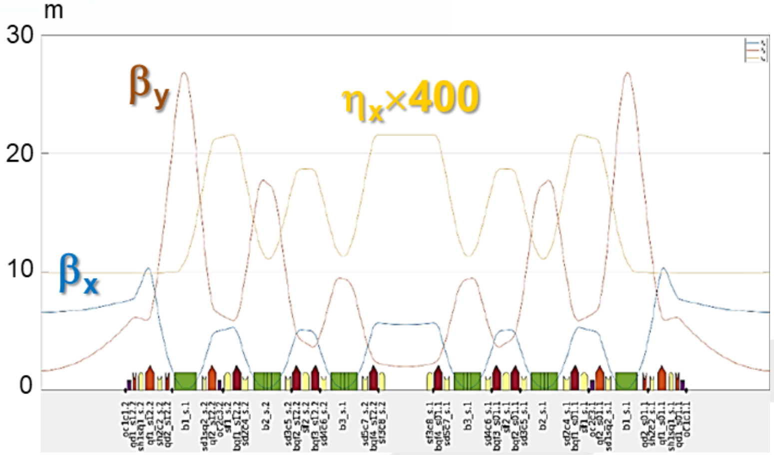
H-shifted quads by -5.6 mm (anti-bends, 0.4deg)

LS



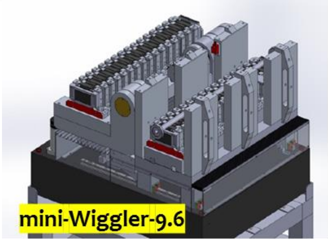
Transv. gradient (-18 T/m)

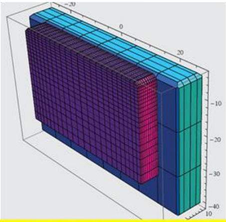


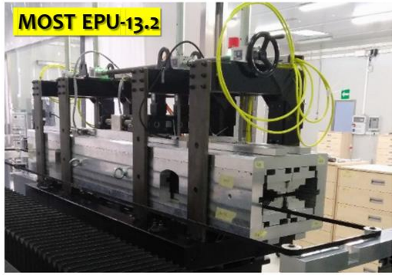


Other upgrades

❑ Insertion devices







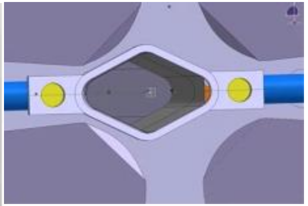
❑ Main RF

4 x up to 130 kW solid state RF transmitters

❑ Injection

Traditional off-axis 4-kickers bump & 3 septa, supplied by low-emittance optics and emittance swap in the Booster ring (near difference resonance at extraction)

❑ Vacuum chambers



27 x 17 internal (1.5 mm thickness)

Cu (45%), Al (20%), S. Steel (35%)
0.5 µm NEG-coated (90%)

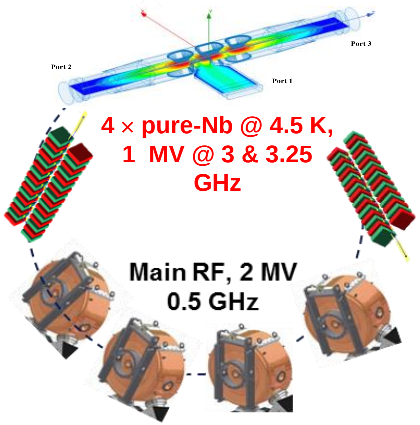
Multipoles

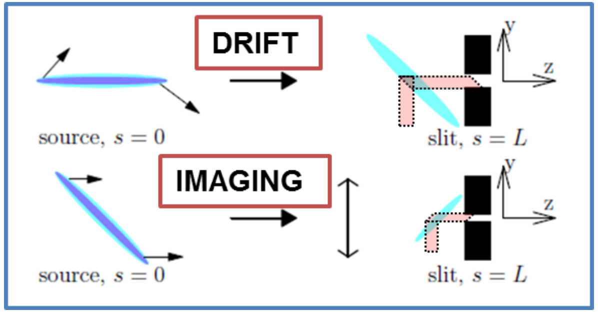
Long IDs

Short IDs, dipoles, injection

Elettra Sincrotrone Trieste

Crab cavities for MHz, ps-long X-rays



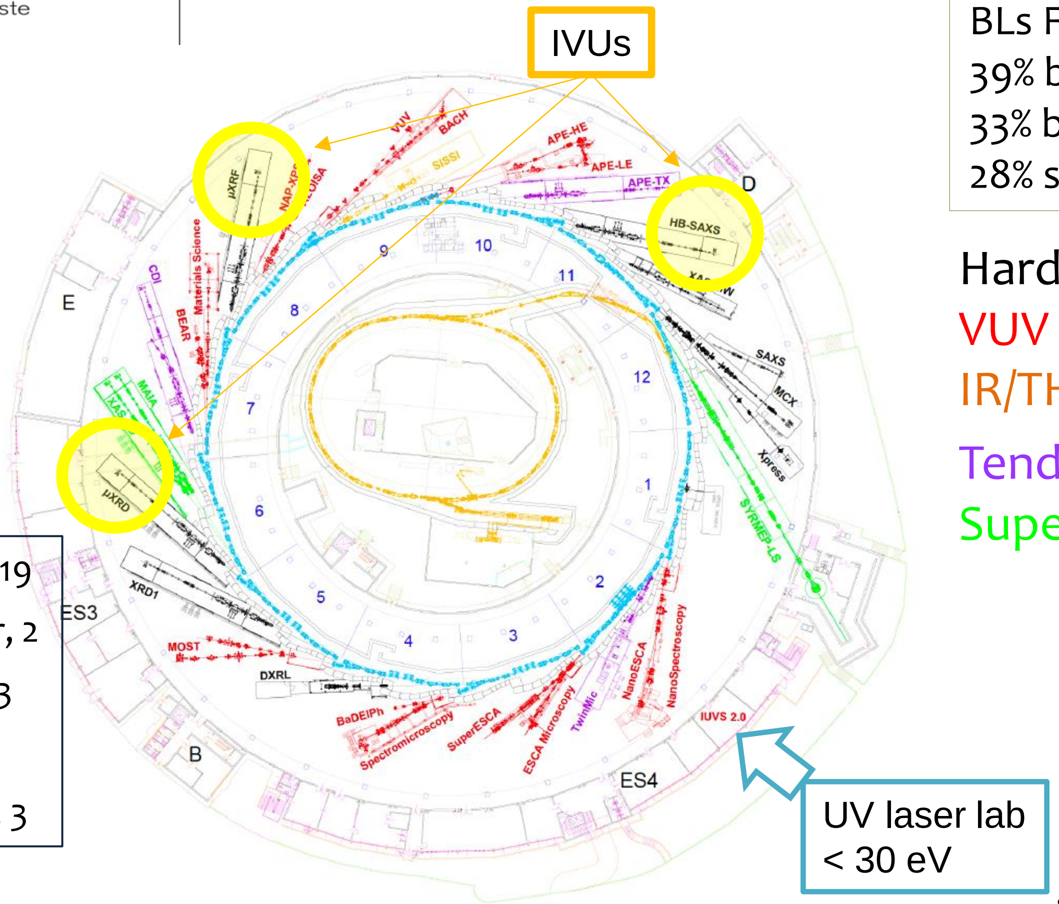


steady-state, periodic deflection of a camshaft bunch

Beamline	HIGHEST photon energy			
	Δt_{FWHM} (ps)		ΔF/F (%)	
	DR	HYB	DR	HYB
1.2	3	1.7	1.5	2.8
2.1	46	0.8	18	1.7
3.2	42	2.1	5	1.8
4.2	3.1	3.6	1	6.5
5.1	18	3.0	5	2.6
5.2	15	0.9	3	1.9
6.2	1.7	1.9	0.5	3
7.2	6.5	0.9	1.5	2
8.1	9.6	0.8	1	1.7
8.2	3.2	1.7	1	3.5
9.2a	13.5	1.8	3	2.0
9.2b	5.8	1.1	1	2.3
10.1	8.5	0.7	2	1.6
10.2	2.2	1.2	1	2.7

- **Sub/few ps pulse duration at multiple beamlines, at > 0.2 keV photon energies**
- **Up to 1 MHz rep. rate (1 tilted bunch in a dark gap)**
- **~1-few % flux relative to standard single bunch emission**
- **Preserving transverse coherence**
- **Impact on standard bunches: vertical emittance x 2, bunch charge x 2**

Beamlines



BLs Funding & Operation:
39% by Elettra
33% by CNR
28% shared, other Institutions

Hard x-rays, 10 → 9
VUV – soft x-rays, 17 → 15
IR/THz, 1
Tender x-rays, 0 → 4
Super-bends, 0 → 3

BLs kept as now, 14
BLs moved, 7
BLs new, 10

BLs from undulators, 19
BLs from mini-wiggler, 2
BLs from SC-wiggler, 3
BLs from bends, 4
BLs from Super-bend, 3

From FERMI to FERMI 2.0

C. Masciovecchio, Project Leader

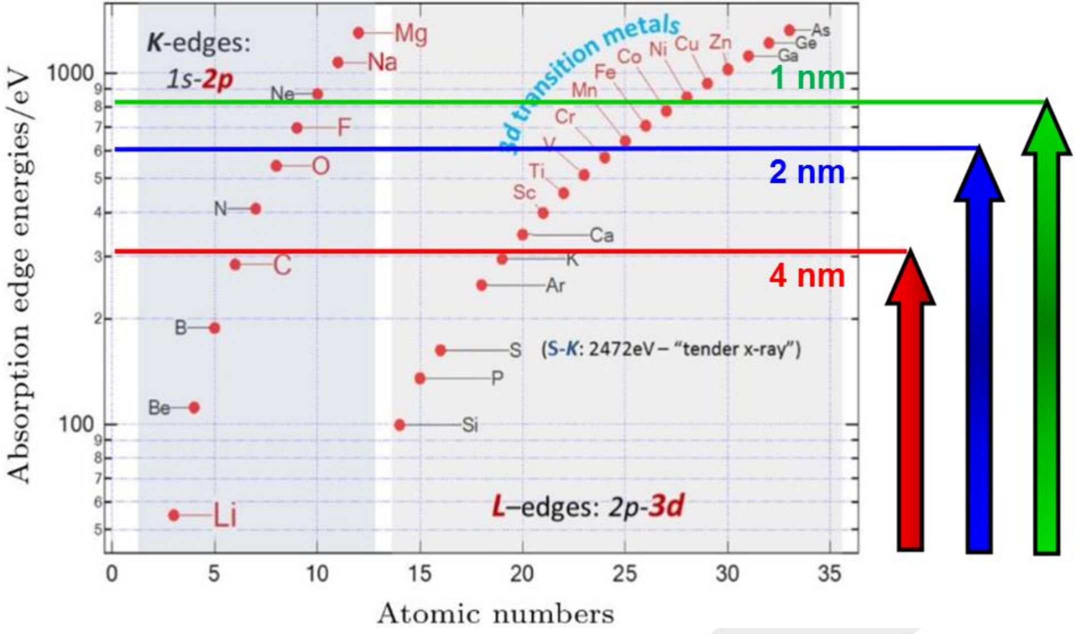
		FERMI	FERMI 2.0 (*concept*)
In operation since		2010	2029 ?
#Beamlines		6	
Repetition Rate		10, 50 Hz	
e-Beam energy	GeV	0.9 – 1.55	0.9 – 1.85
Peak current	kA	0.7	1.0
IDs		Apple-II,	Apple-II,
FEL scheme, *default*		HGHG, HGHG-FB	EEHG, EEHG-FB
Photon energies, *fundam.*	eV	FEL1: 12 – 62 FEL2: 62 – 310	FEL1: 15 – 124 FEL2: 62 – 620
Pulse duration	fs	10 – 150	< 5 – 50
Temporal and spectral shaping		yes	

Water window

Science drivers

ref. C. Masciovecchio

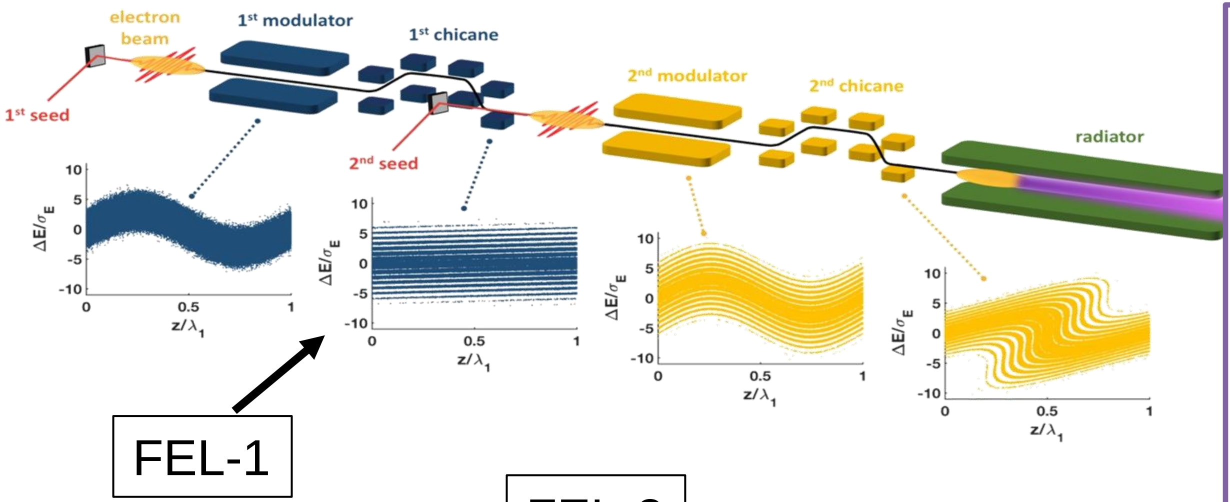
- Resonant exps. exploiting processes of few fs-lifetime (X-Abs., Small Ang. XS, CDI,…)
- Nonlinear optics (large wave-vectors)
- Ultra-fast chemistry
- Water window
- Coherent control

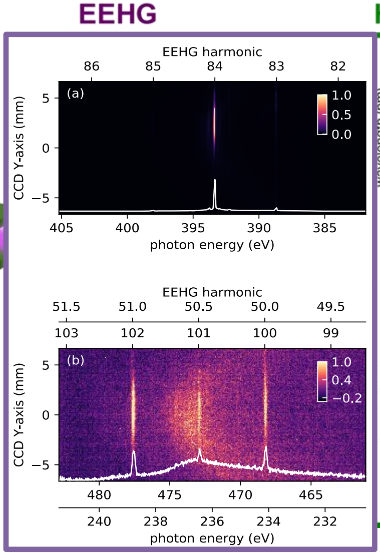


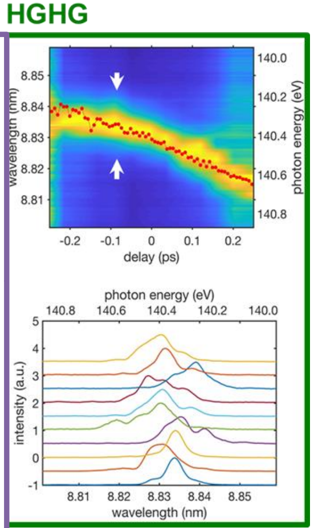
shorter Δt (<10 fs) +
shorter λ (N,O K-edge) +
longitudinal coherence

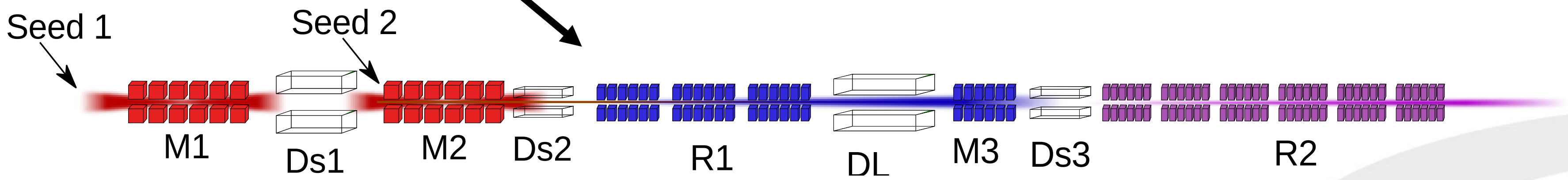
ref. E. Allaria, P. Rebernik, C. Spezzani

FEL upgrade to EEHG(-FB)







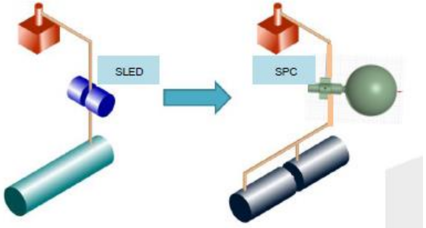


Linac upgrade

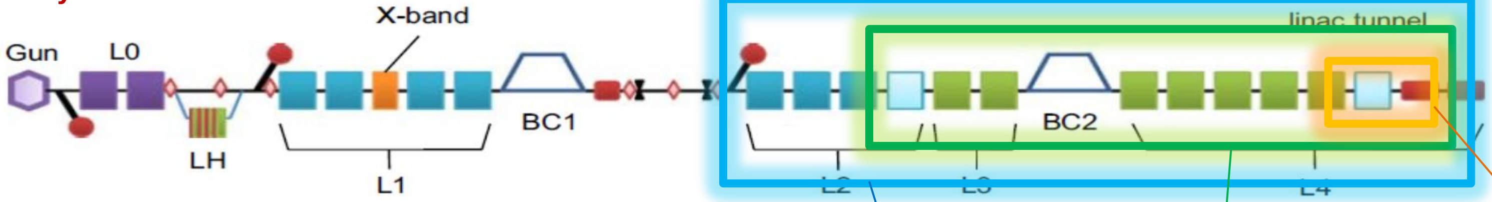
Present Linac Energy
1.5 GeV @ 10Hz

Target Linac Energy
1.8 GeV @ 50Hz

Solution
Low Wakefield S-band 30 MV/m



Arcing and rusting issues in 30-years old RF structures



- In-house RF design completed in 2019
- Commitment to PSI for the construction of a short prototype and 2 structures.

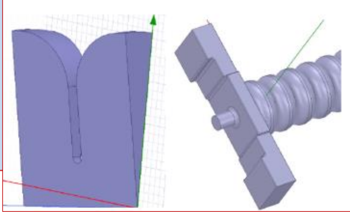
Replace L2-L4
→ **2 GeV** op.

Replace L3-L4
→ **1.87 GeV** op.

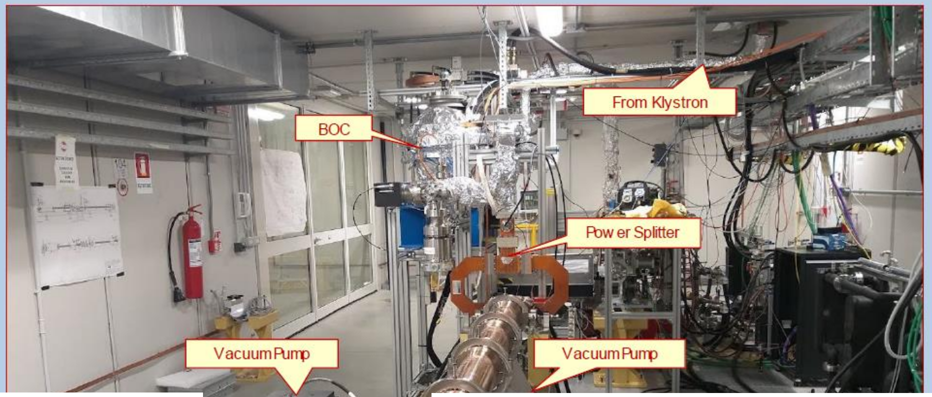
Replace L4.7, H-TDC
→ **1.67 GeV** op.
2 structures installed in 2022
(39 MV/m proven)

Design, prototype, full structure RF test

- The new accelerating module will be comprised of 3.0 m long, **constant gradient type** structures. **Double rounding** is introduced to reduce Ohmic losses and increase Q
- A customized version of **dual-fed-electric coupled (EC) coupler** is chosen for the new high gradient (HG) structures
  - Very low surface magnetic field
  - Easy to machine
  - Reduced cost of fabrication



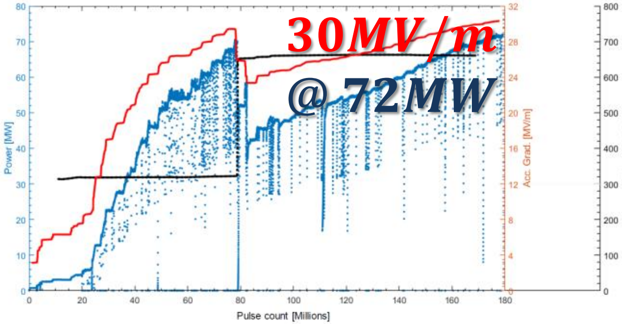
During the **Spring Shutdown (April 2022)** the HG structure was installed in FERMI Test Facility.



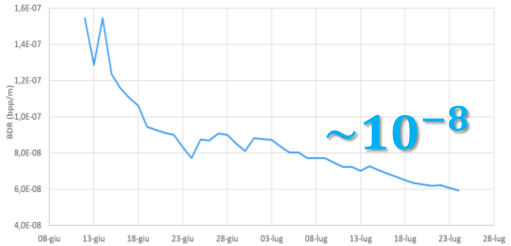
9-cells prototype RF test

Acc. Gradient (MV/m)	PWR @ Ptype (MW)	# of Pulses (Million)	BDR (bpp)
30	72	225	2.0×10^{-8}
35	98	229	7.3×10^{-8}
39	122	400	7.9×10^{-8}

RF conditioning history



BDR based on reflected power faults history

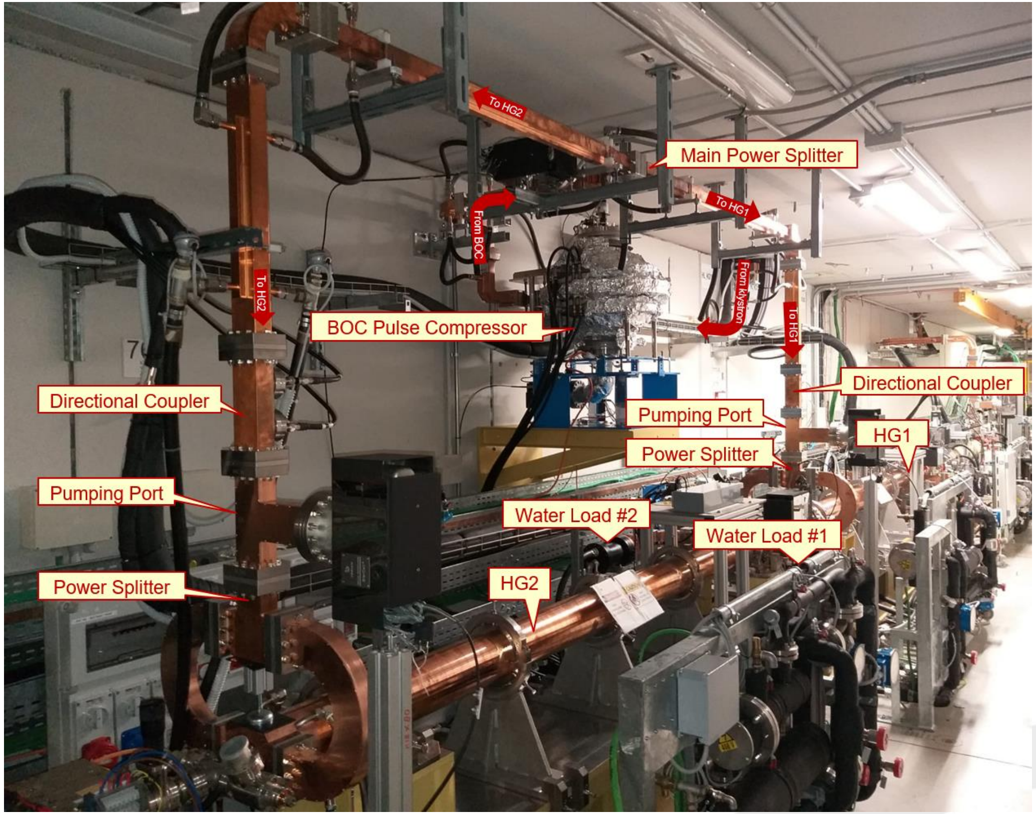


Installation and conditioning in FERMI

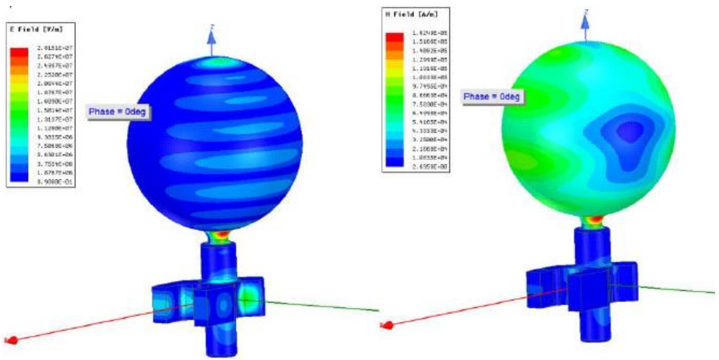
- The 2nd HG structure (HG2) was installed directly at FERMI linac without conditioning

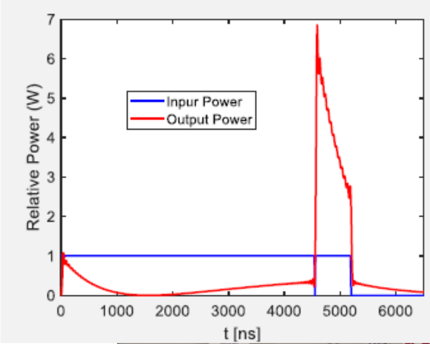
- Since installation is done **without any phase shifter** so precise phase calculations were done to ensure that both HG1 and HG2 are in phase.

- Due to user beam operation requirements and reduced operational hours due to power management the conditioning of HG2 is bit slower.

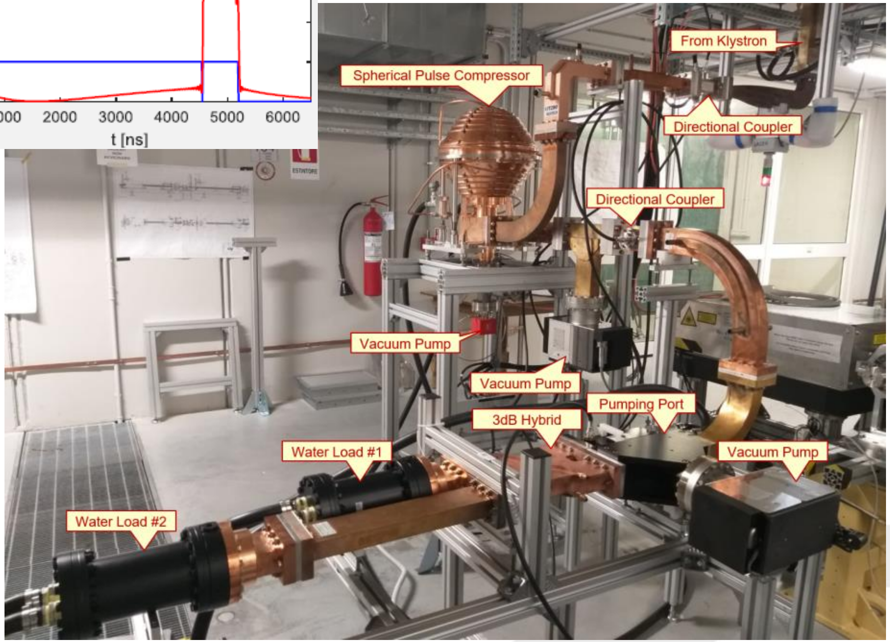


Spherical Pulse Compressor RF test





- 3.5-fold compression, up to 90 MW output power
- To be installed in 2023



$$\beta = \frac{1+|\Gamma|}{1-|\Gamma|} = 7{,}13$$

$$\beta_{optimal} = 7{,}3$$

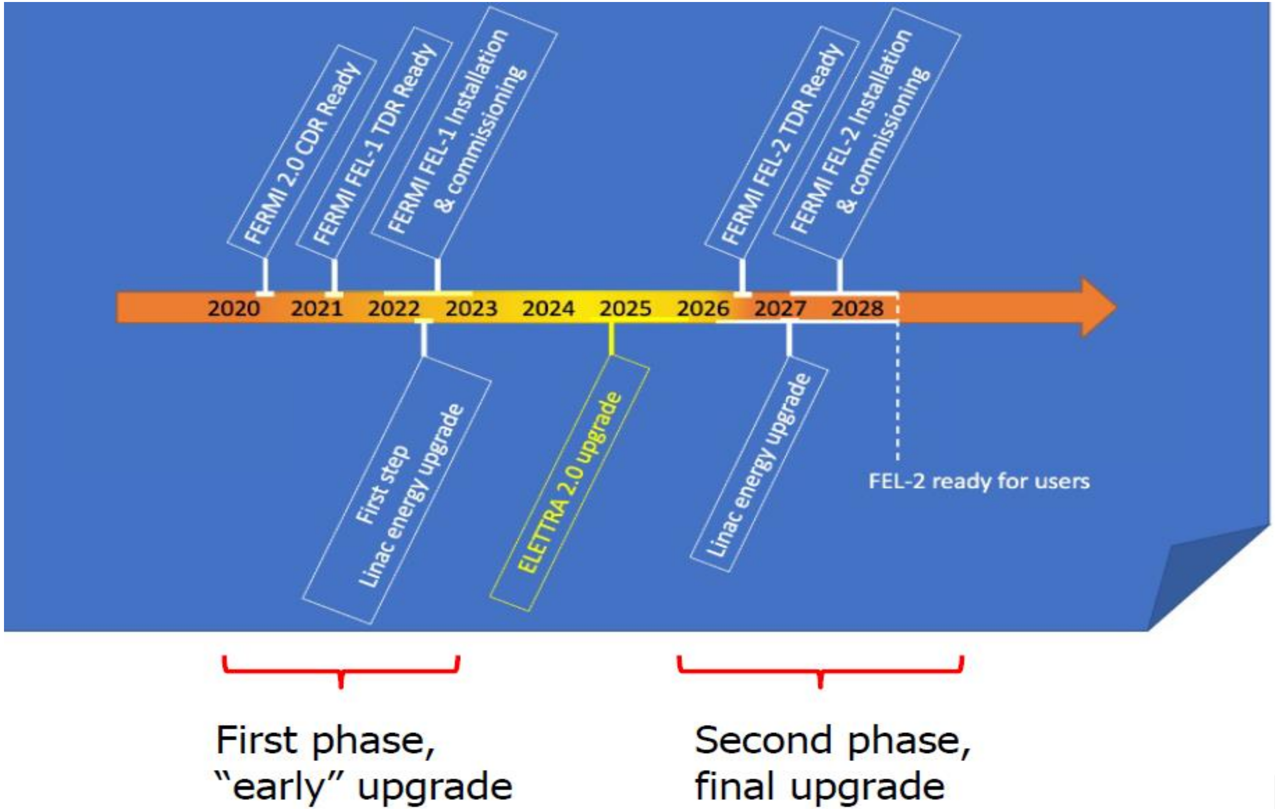
RF Parameters		
f_0	2.99801	GHz
Nominal Temperature	35	°C
Mode	TM13	
Q0	≈140000	
Coupling Coefficient	7.2±0.1	
E @ 45 MW	28.16	MV/m
H @ 45 MW	169.75	kA/m

Conditioning Results		
Output RF Power	90	MW
Pulse Length	700	ns
Input RF Power	26	MW
Pulse Length	4000	ns
Operating Temperature	32.25	°C
Power Multiplication Factor	3.45	

- In-house design
- Manufactured by

OMEB

Time plan


FERMI 2.0 CDR Ready
FERMI FEL-1 TDR Ready
FERMI FEL-1 Installation & commissioning
FERMI FEL-2 TDR Ready
FERMI FEL-2 Installation & commissioning
2020 2021 2022 2023 2024 2025 2026 2027 2028
First step Linac energy upgrade
ELETTRA 2.0 upgrade
Linac energy upgrade
FEL-2 ready for users
First phase, "early" upgrade
Second phase, final upgrade

Bibliography

- Elettra 2.0 TDR

https://www.elettra.eu/images/Documents/ELETTRA%20Machine/Elettra2/TDR-Machine-Infrastructures-Final-compresso.pdf

- Elettra 2.0 physics and design

  E. Karantzoulis and W. Barletta, "Aspects of Elettra 2.0 design", NIM A 927 (2019) 70–80

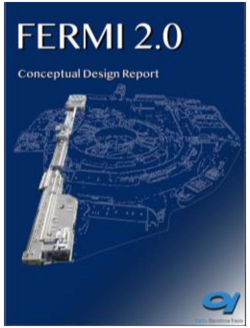
- Crab cavities

  X. Huang PRAB 2016 & NOCE 2017

  A. Zholents et al. NIM A 2015

- FERMI 2.0 CDR

https://www.elettra.eu/images/Documents/FERMI%20Machine/Machine/CDR/FERMI2.0CDR.pdf



- FERMI FEL physics & upgrade

  E. Allaria et al., Nat. Phot. 6 (2012), Nat. Phot. 7 (2013)

  P. Rebernik et al., Nat. Phot. 7 (2019)

  L. Giannessi, C. Spezzani et al., Proc. of IPAC 2022, TUPOPT018 and TUPOPT019

- FERMI linac physics & upgrade

  C. Serpico et al., Rev. Sci. Instr. 88 (2017)

  N. Shafqat et al., NIM A 867 (2017), NIM A 979 (2020)

Elettra
Sincrotrone
Trieste

Thank you for your attention

Elettra Sincrotrone Trieste

Collaborations and Commitments

SLS-2 (2020-2024)

- Magnets
- Power supplies
- RF system (waveguides)
- Kickers for MBFS

Diamond-II (2020)

- MBF electronics

BESSY VSR (2020-2027)

- Time-resolved techniques
- Blazed gratings production

DOE-APS (2019-2021)

- Crab cavities
- Simulations

DOE (2021-2022)

- Crab cavities
- Superconductive solution

CERN (2021-2024)

- NEG
- Vacuum simulations

- Solid state RF transmitters
- Multipole magnets
- BPM electronics
- CDI undulator
- CDI experimental station
- X-press detector
- Electron analyzers
- MCX diffractometer
- SYRMEP Life Science Beamline
- …

Elettra Sincrotrone Trieste

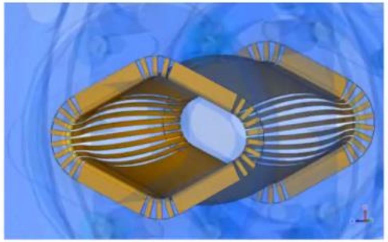
Impedances

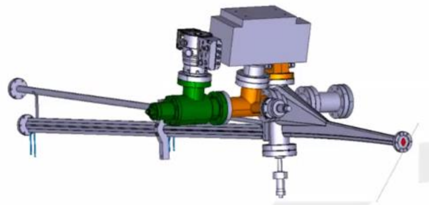
ref. A. Passarelli (INFN-NA), E. Karantzoulis, C. Pasotti, S. Cleva (Elettra)

- Estimated with well-known formulas, successfully benchmarked for Elettra. Low gap chambers and RF transitions "dominate" the BB impedance of vacuum components.
  - $|Z_{//}/n| = 0.8\ \Omega$, $|Z_{\perp}| = 0.5\ \text{M}\Omega/\text{m}$ $\rightarrow$ -0.8 kHz/mA *(0.6 @ Elettra)*
  - $k_{//}$ = 20 kV/pC $\rightarrow$ 3 kW parasitic loss @ 400 mA *(with 3HC)*
  - TMCI threshold ~5 mA

- HOMs in RF cavities modelled and measured in the past
  - HOM counteracted with shifters and temperature control, 3HC for longitudinal MB instabilities, transverse and longitudinal feedback.
  - Damping times ~ (5, 9) ms vs. (10, 13) ms in Elettra
  - RF L1 mode characteristic time ~0.04 ms vs. 0.003 ms in Elettra

Collaboration with INFN-NA for modelling of special chambers.





Elettra-TR *vs.* Elettra2.0-TR

❶ ***Maximum*** total stored current is 310 mA @ Elettra-*2GeV*, 400mA @ Elettra2.0-*2.4 GeV*

❷ Total stored current in ***Low Current*** mode is 100 mA

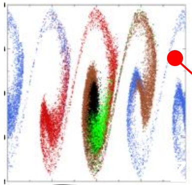
ELETTRA @ 2 GeV

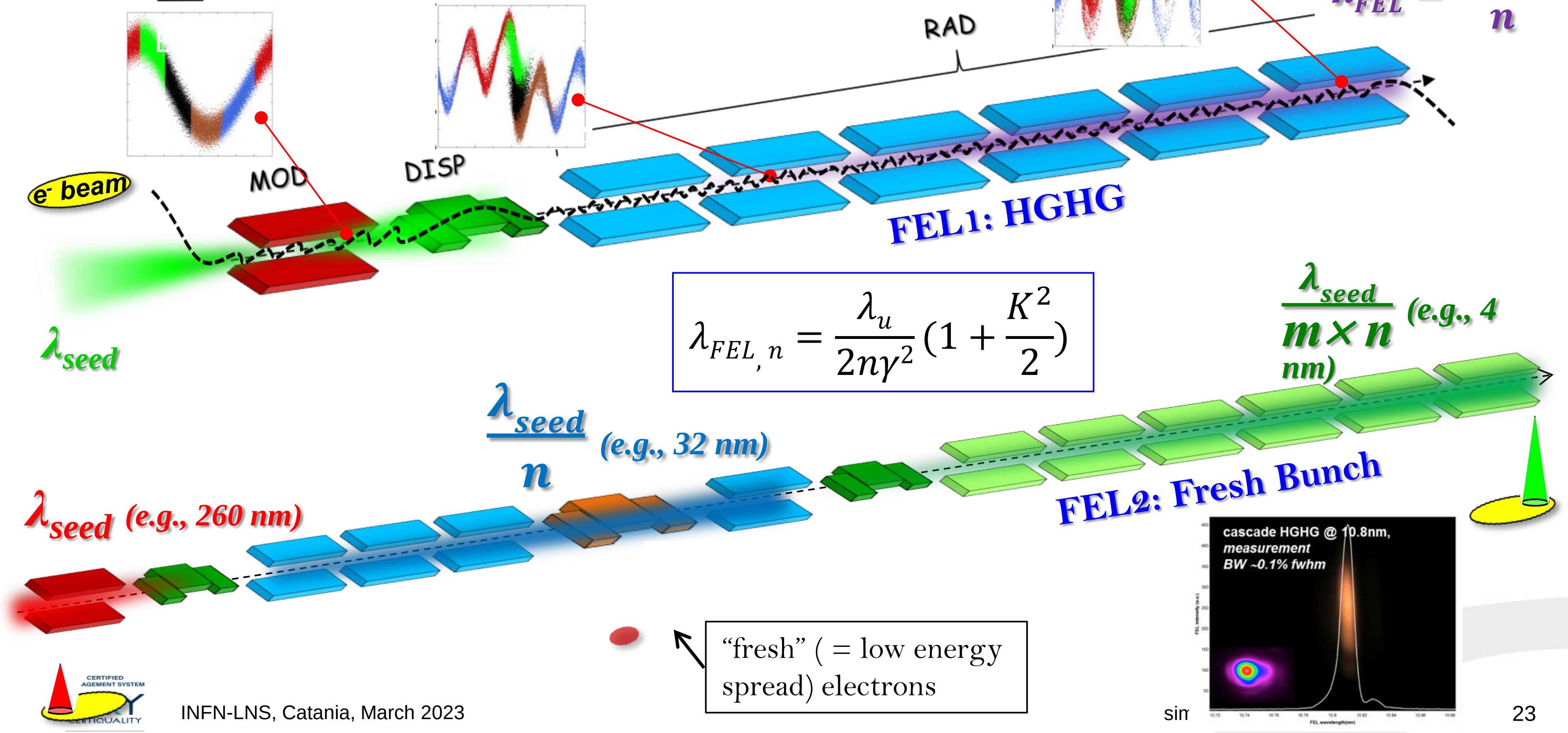
	Single Bunch	**Hybrid F.P.** ❶
mA	1 (5)	5 + 310
ps, FWHM	**~40 – 70**	**~200**
MHz	1.157	1.157
$\frac{Flux(SP)}{Flux@310mA}$	1/300 (1/60)	1/60

ELETTRA2.0 @ 2.4 GeV

	Low current ❷	**Hybrid F.P.** ❶	**CC** ❶
mA	0.25×400 bn.	2 (5) + 400	2 + 400
ps, FWHM	**14 – 17**	**≤ 100 (150)**	**1–5 @ sel. bls.**
MHz	500	1.157	1.157
$\frac{Flux(SP)}{Flux@400mA}$	1/1600	1/200 (1/80)	1/9000

HGHG and HGHG-FB

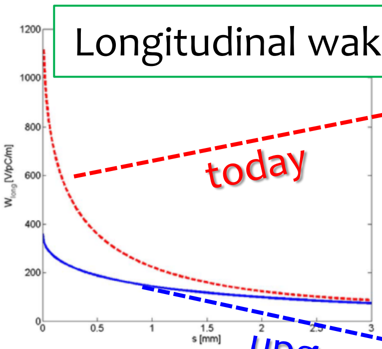


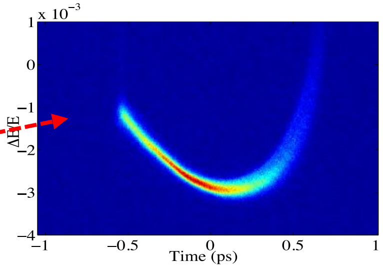


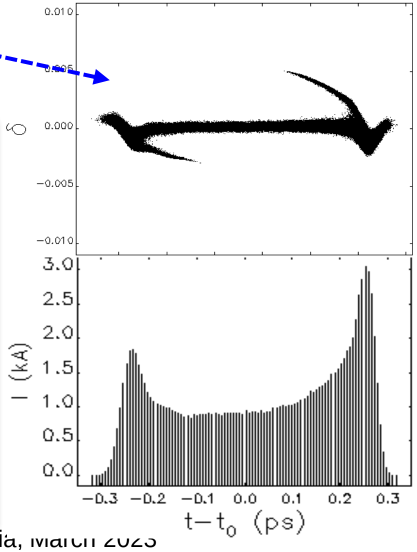
$$\lambda_{FEL,\,n} = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

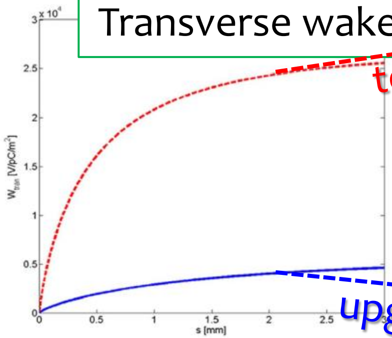
N. Shafqat et al., NIM A 867 (2017)

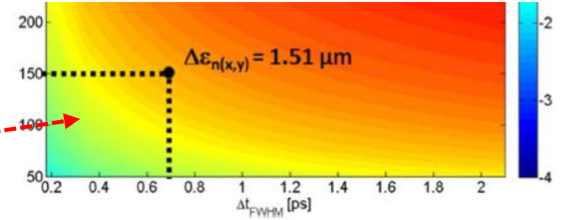
e-Beam phase space

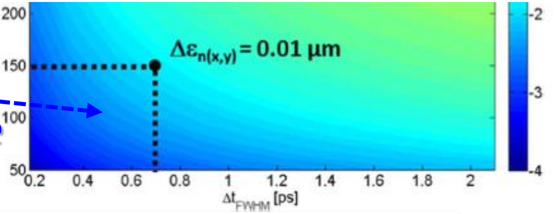












- **Higher order energy chirps suppressed**
- **Linear compression to 1 kA**

- **Transverse wakefield instability suppressed (proj. emittance / 100)**

- **700 pC, 400 fs for “*Fresh Bunch*” scheme**

Lasers upgrade

Lasers determine availability, reliability and ultimate performance:

- **PIL :** Ti:Sa amplifier upgraded to single pump for more reliable and stable operation.
- **Seed lasers:**
  < 60 fs-OPA on FEL1, **< 45** fs-THG on FEL2, now available to users; < 200 nm-OPA on FEL2 in preparation.
- **SLU** (pump on sample):
  hollow fiber pulse compressor for **< 15** fs-UV