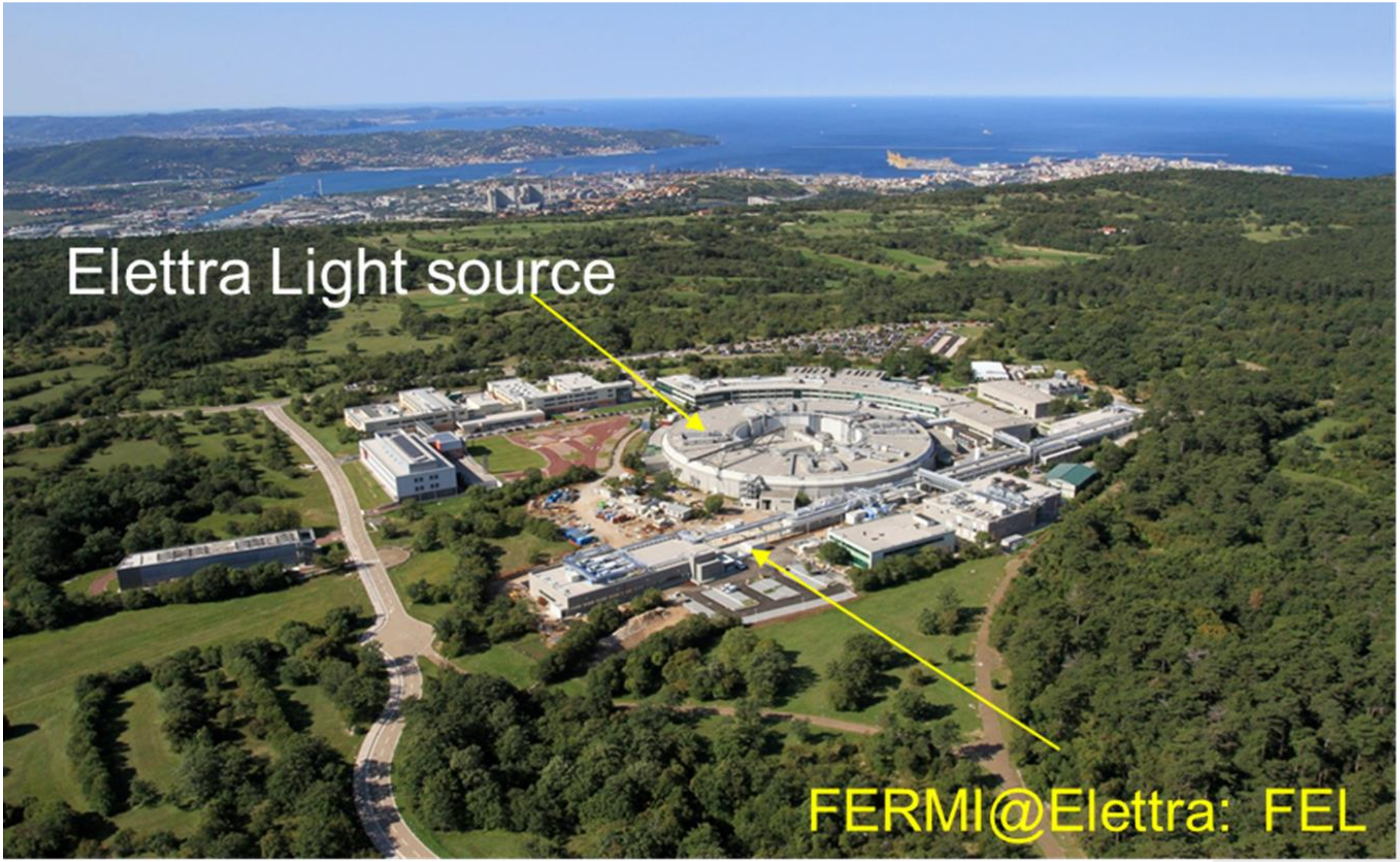
Elettra 2.0 Lattice and technical challenges

Elettra
Sincrotrone
Trieste

E. Karantzoulis



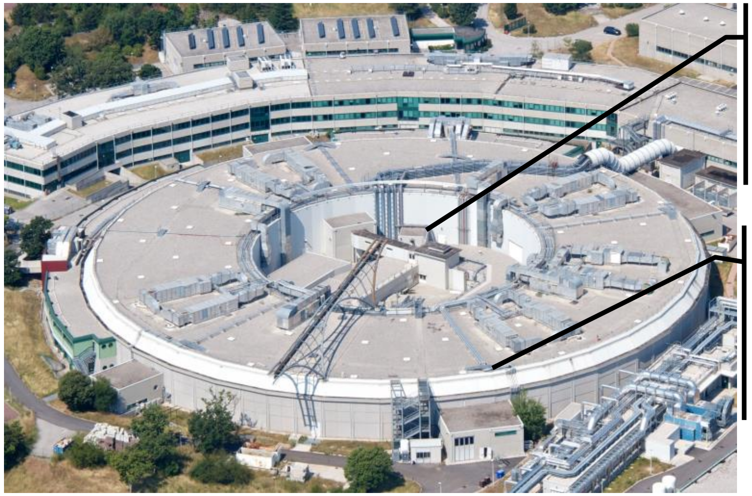
Elettra Sincrotrone Trieste

Elettra

- First 3rd generation light source in Europe for "soft" x-rays (*now also hard*) (DBA lattice, 12 fold symmetry) , commissioned in October 1993 – >   In 2023 celebrated 30 years of light.

Operating modes for users (all in top-up since 2010):

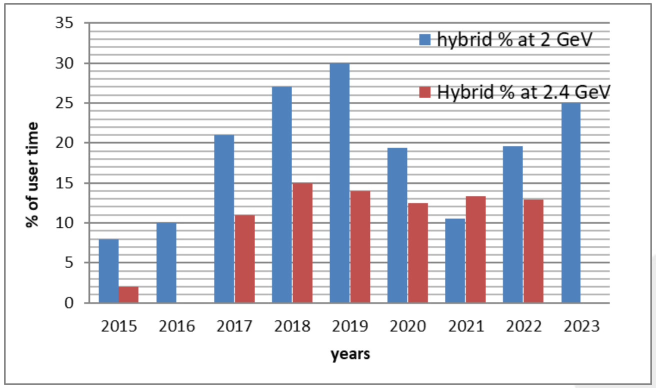
- Usually operates for about 6400 hours per year (24h, 7/7), 5016 hours reserved for users in 2 energies:
- 2.0 GeV,   7 nmrad, 310 mA for 75 % of users time with about 20 hours LT
- 2.4 GeV, 10 nmrad, 160 mA for 25 % of users time with about 33 hours LT
- 28 beamlines open to users– over 1000 user and user poposals / year
- Filling patterns: multi-bunch 95 % filling or hybrid, single bunch, few bunches or other multi-bunch fillings



Linac + Booster (114 m)

Storage Ring (259 m)

Super-conducting systems: 3HC at 1.5 GHz and SCW at 12 keV



I.FAST Low Emittance Rings workshop, Feb 13-16, 2024, CERN, Geneva

Emanuel Karantzoulis

Science Drivers

Although Elettra performs very well and is serving the user community with excellent results since 1994, in order to keep the light source competitive for synchrotron research and enable new science and new technology developments, a ***diffraction limited*** *storage ring Elettra 2.0 will replace Elettra giving much smaller beam size and higher brilliance.*

The Elettra 2.0 project is running and is fully financed since 2019 by the Italian government

- ***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 (horizontal) **coherence** will open unique opportunities for coherence-hungry methods:

•***Coherent Diffraction Imaging*** (CDI) with chemical specificity

•***Ptychography***

•***X-ray photon correlation spectroscopy*** (XPCS)

- Let open the possibility also for **longitudinal coherence** for time resolved experiments (fully coherent source)

Elettra 2.0
Design boundary conditions

☐ **Target:**

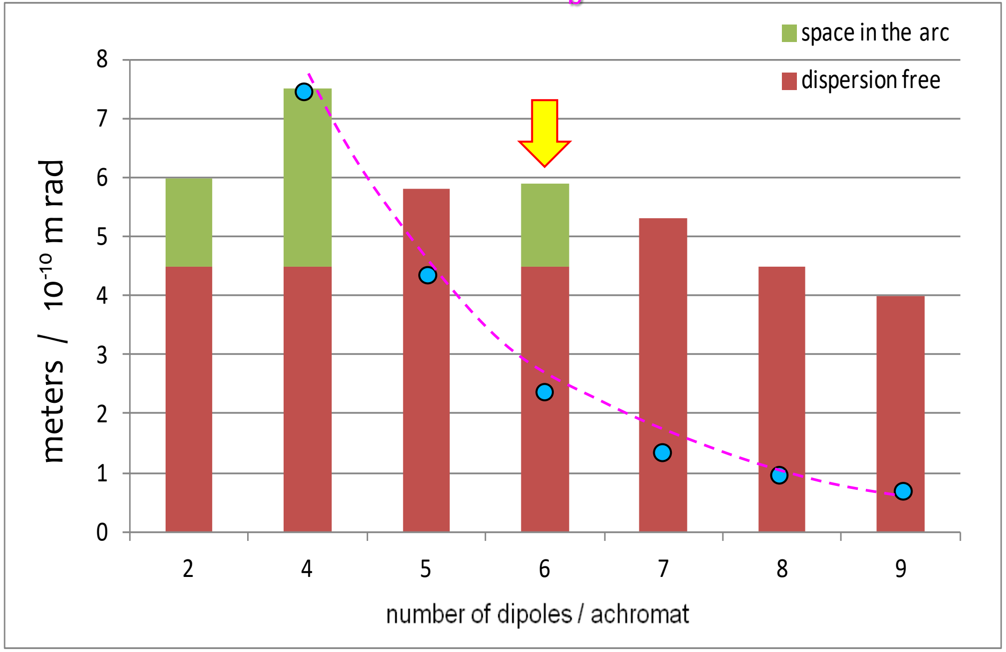
Bare emittance	✓	Reduce (achieved 47-fold)
Conserve (increase) ID occupancy	✓	30% (5 new spots for IDs)
Increase Intensity	✓	400 mA @ 2.4 GeV
Let open the possibility for bunch compression	✓	crab cavities
e-beam energy(-ies)	✓	**2.4 GeV** (and only initially also at 2 GeV)

☐ **Constraints:**

Same building and circumference	✓	**259.2 m**
Conserve long SS-ID positions and length	✓	Conserve length to reuse IDs
Reuse Injector	✓	Off axis injection
Minimize beam off (dark time) period	✓	Reduce to less than 18 months

Choice of Lattice: beyond simple MBA

Elettra/N_b^3



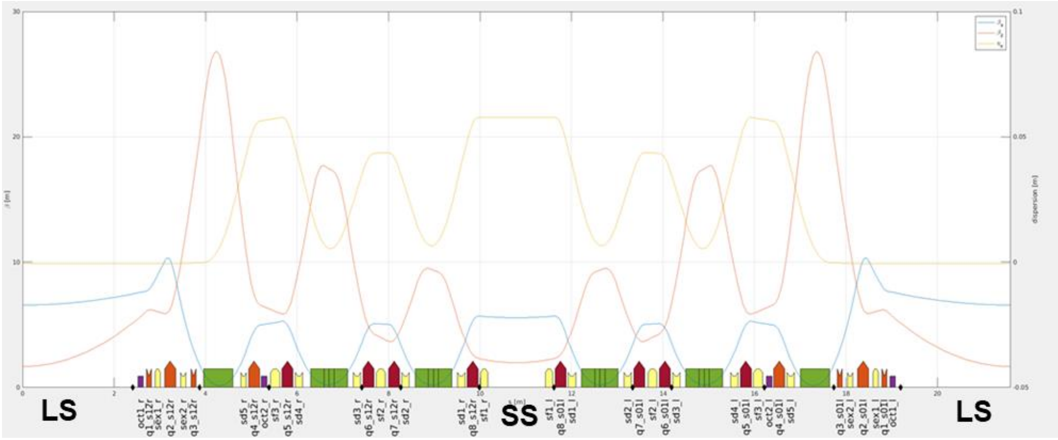
$$\alpha_c = 1.2 \times 10^{-4},\ \sigma_{t,0} = 6\,ps$$

$$\xi^{nat}/\nu = -2, -8$$

$$U_0 = 620\ keV, IDs\ included,$$

$$V_{RF}T_{tr} = 4 \times 0.5MV$$

S6BA-E : Emittance 212 pm rad at 2.4 GeV

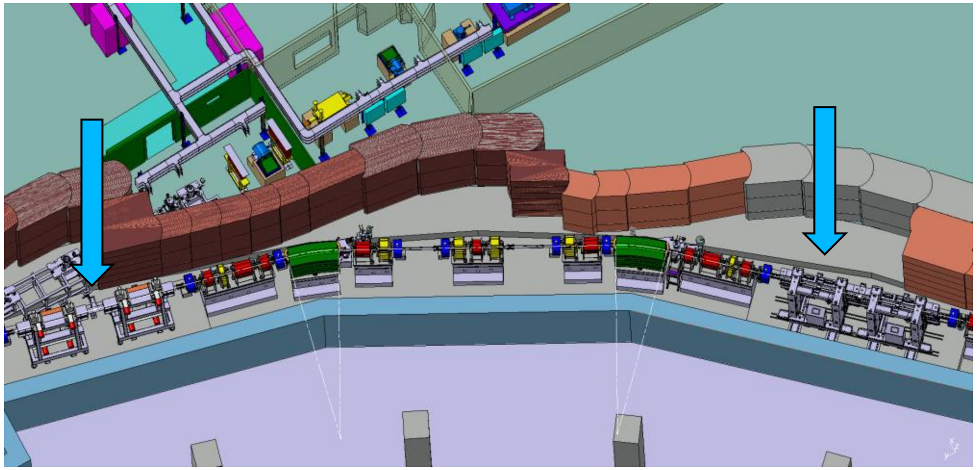


Machine parameters

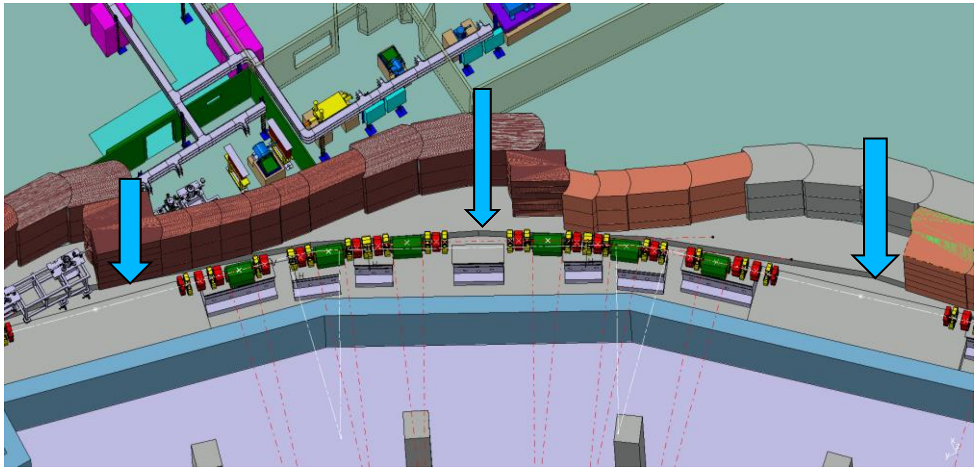
Circumference (m)	259.2	259.2
Energy (GeV)	2	2.4
Number of cells	12	12
Geometric emittance (pm-rad) 2% coupling	148	212
Horizontal tune	33.27	33.27
Vertical tune	9.14	9.14
Beta functions in the middle of straights (x, y) m	(6.3 , 1.7)	(6.3 , 1.7)
Horizontal natural chromaticity	-73	-73
Vertical natural chromaticity	-67	-67
Horizontal corrected chromaticity	+1	+1
Vertical corrected chromaticity	+1	+1
Momentum compaction	1.3e-004	1.3e-004
Energy loss per turn no IDs (keV)	217	450 (w SBs 486)
Energy spread	7.7e-004	9.3e-004
Jx	1.625	1.625
Jy	1.00	1.00
JE	1.376	1.376
Horizontal damping time (ms)	9.8	5.7
Vertical damping time (ms)	15.9	9.2
Longitudinal damping time (ms)	11.6	6.7
Dipole field (T)	<0.88 + 1.16T central	<1.03+1.46T central
Quadrupole gradient in dipole (T/m)	<19	<22
Quadrupole gradient (T/m)	<50	<60
Sextupole gradient (T/m^2)	<3500	<4000
RF frequency (MHz)	499.654	499.654
Beam revolution frequency (MHz)	1.1566	1.1566
Harmonic number	432	432
Orbital period (ns)	864.6	864.6
Bucket length (ns)	2	2
Natural bunch length (mm, ps)	1.3 , 4.3	1.7 , 5.7
Synchrotron frequency (kHz)	3.17 (@2MV)	2.86 (@2MV)

Elettra 2.0 Lattice in the tunnel

***259 m circumference with 12 identical sectors** and 12 long straight section for insertion devices. Elettra 2 will have also 12 short straight sections*

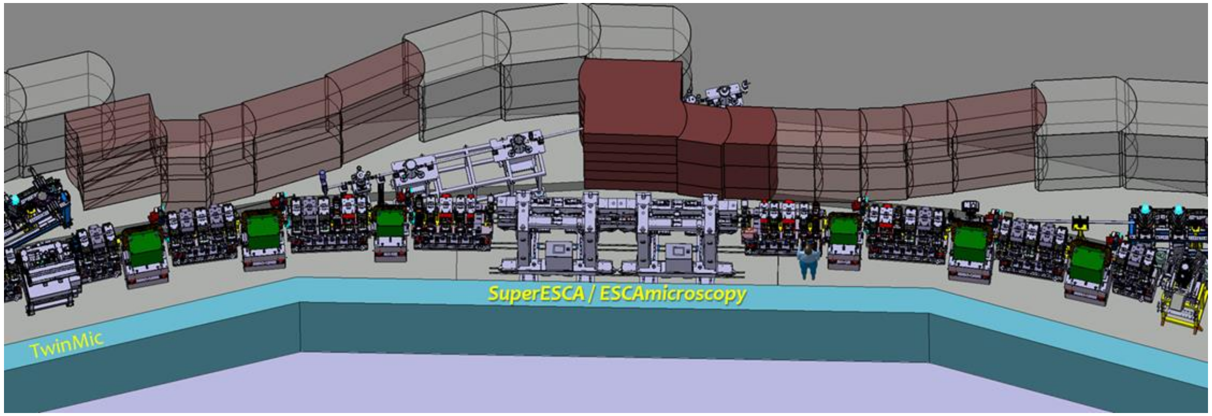


Elettra



Elettra 2.0

The Lattice is based on our developed enhanced symmetric six-bend achromat (S6BA-E) using DLQs and DQs (reverse-bends)



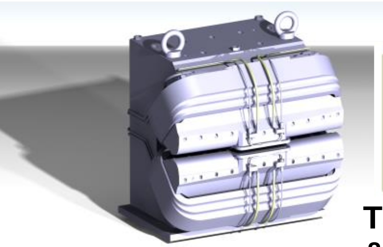
- The lattice is 12-fold symmetric (24 arcs) with **LS=5.104 m and SS=1.26 m (from magnet to magnet)** this way the LSs coincide with those of the actual Elettra i.e. no radial shift of the IDs beam lines on the LSs.

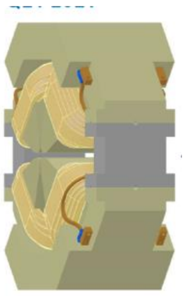
Lattice

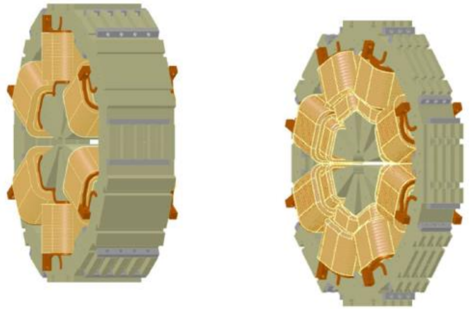
G_{quad} ≤ 46 T/m (8 x 2 x 12)
G_{sext} ≤ 4000 T/m² (2x10 families)
$G_{sk\text{-}quad}$ ≤ 1 T/m (2x2 families, in sexts.)
G_{oct} ≤ 120000 T/m³ (2x2 families)

All magnets (552):

- The coils of the dipoles and quadrupoles do not protrude
- water-cooled
- independently powered
- Correctors 24 + coils embeded in multipoles i.e. 192 CHVs

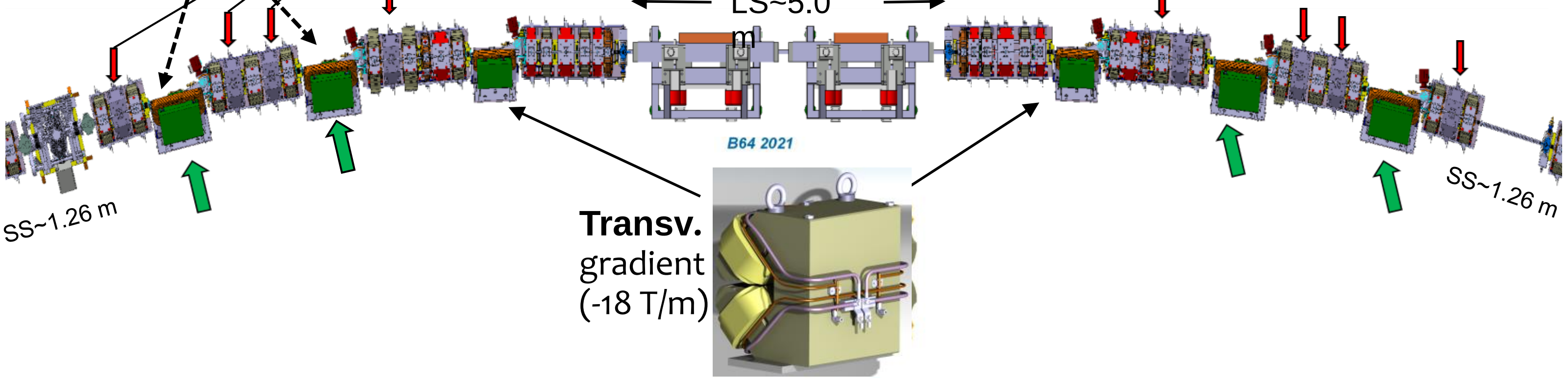




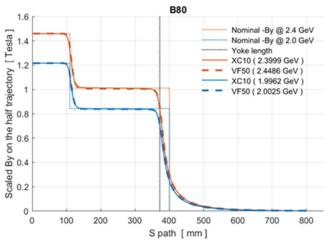


Transv. (-21 T/m) **& Long.** gradient

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

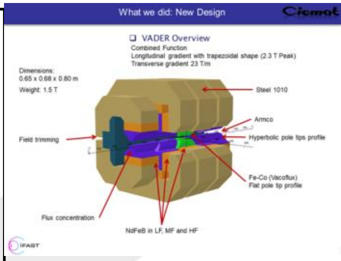


Transv. gradient (-18 T/m)



2.4 GeV	L1 T G=21T/m	L2 T G=0	L3 T G=21 T/m	Emittance pmrad
VH-LG	0.77 T	2.16	0.77	140
H-LG	0.92 T	1.78	0.92	150
M-LG	1.036 T	1.46	1.036	177

Use of permanent magnets (Future)*. The joint project (VADER) with CERN, Elettra, KYMA and CIEMAT is financed from the EU (Horizon 2020 - Innovation Pilot Project for Particle Accelerators*



What we did: New Design

- ☐ VADER Overview

Combined Function
Longitudinal gradient with trapezoidal shape (2.3 T Peak)
Transverse gradient 23 T/m

Dimensions:
0.65 x 0.68 x 0.80 m
Weight: 1.5 T

Elettra
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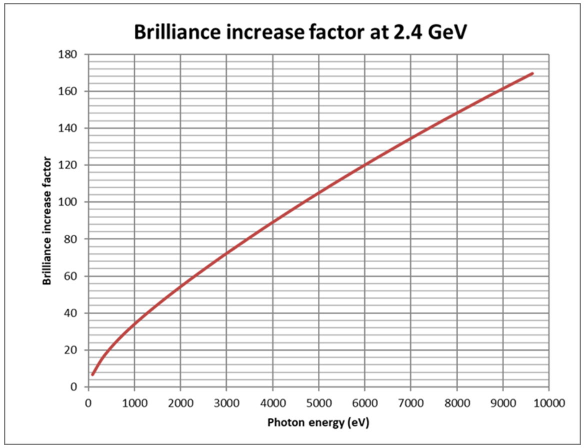
Trieste

From Elettra to Elettra 2.0

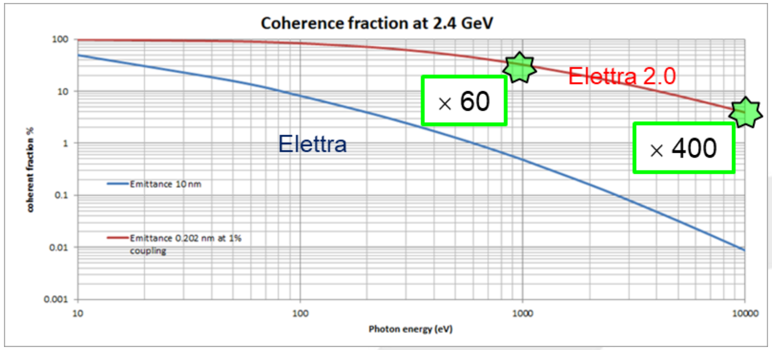
		Elettra	Elettra 2.0
Operating for users		1994-2025	2027-
Beam energy	GeV	2.4 (25%) --- 2.0 (75%)	2.4 GeV (2.0 for some time)
Photon energies	keV	0.003-25	0.015 - 60
e – emittance - coupling	nm-rad	10 --- 7 - 1%	0.212 --- 0.150 – 3%
ID slots		11 Long + 1 short	11 Long + 5 short
Beam lines (IDs, Dipoles)	#	28 (19, 9)	32 (25 $_{3\ \mathrm{IVU}}$, 7 $_{3\ \mathrm{SB}}$)
e-beam size at LS (σx,σy)	μm	286,16	36,6
Brilliance $(ph/s/mm^2/mrad^2/0.1\%bw)$		$2x10^{19}$	10^{22}
Coherence ratio at 1 keV	%	0.5	30
e - intensity	mA	160 --- 310	400
Lattice -symmetry		2BA - 12 fold	S6BA-E(nhanced)-12 fold
Fill patterns		multi-bunch, single or few bunch, hybrid	whatever

Brilliance and coherent fraction between the present and Elettra 2.0
Emittance reduction 47 times


Brilliance increase factor at 2.4 GeV

Elettra 2.0 beam size and divergence @3% coupling

	Long Straights	Short Straights
σ_x (um) / σ_x'(urad)	36 / 5.7	63 / 6
σ_y (um) / σ_y'(urad)	3.2 / 1.9	3.5 / 1.8


Coherence fraction at 2.4 GeV

Technical challenges (some)

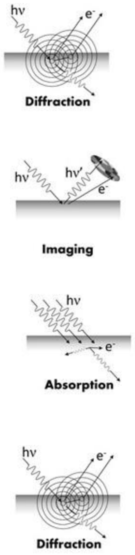
- ✓ Small intra-magnet space-> lack of space (coils not protruding)
- ✓ Strong and combined magnets -> calibration
- ✓ Presence of reverse bends-> BBA
- ✓ Alignment on the girder-> consider cross talk
- ✓ Injector system reused, due to a smaller (3x) dynamic aperture -> emittance swap (beam too large for pulsed multipole and no space for aperture sharing)
- ✓ Shorter long straight sections and small beams separation -> septa disturbing during top up
- ✓ Users now require 5% or less of beam size variation-> many implications (ID field variations, feedbacks, etc)
- ✓ …..

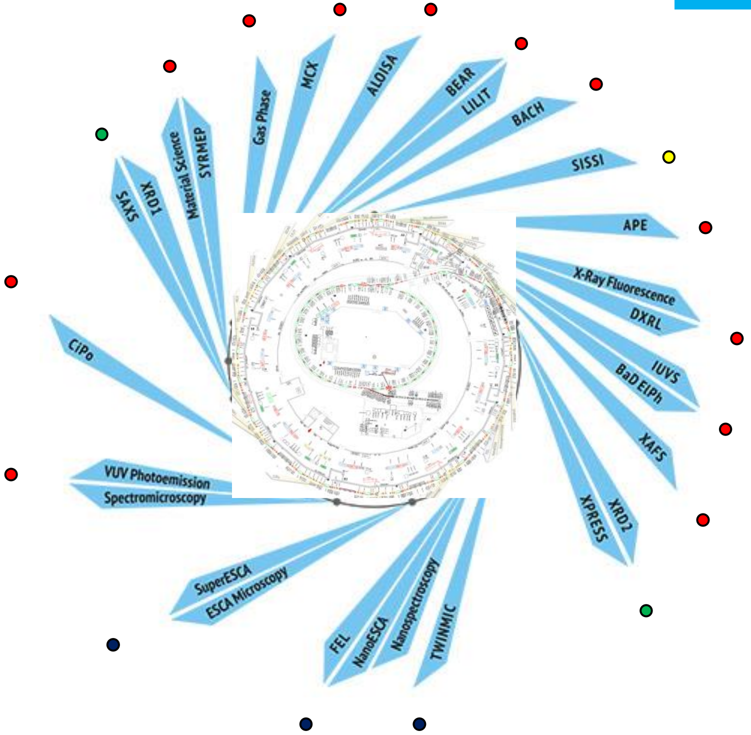
A main challenge: Points of view of a Light source

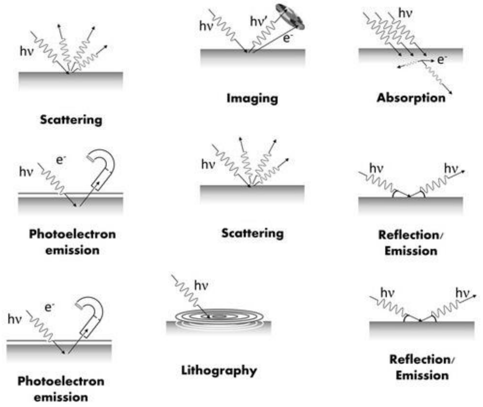
Accelerator people

Beam Lines people

Users (experiments)





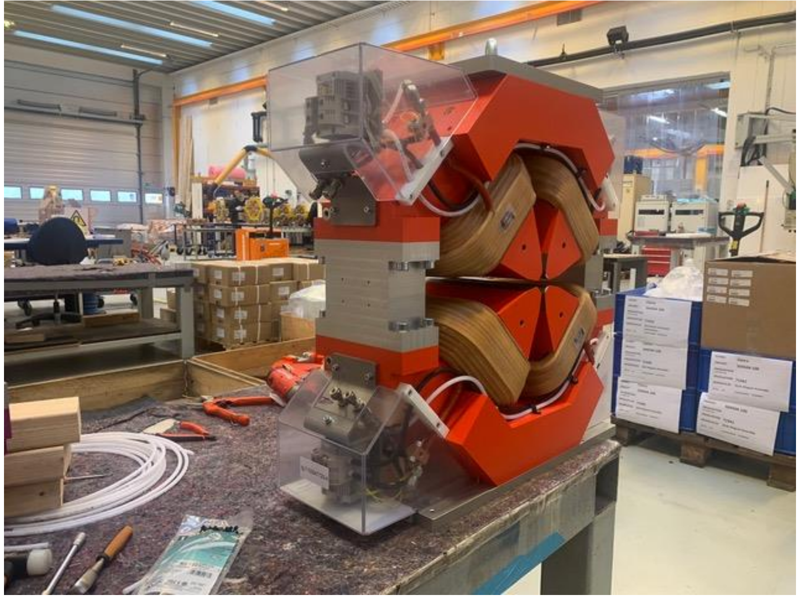


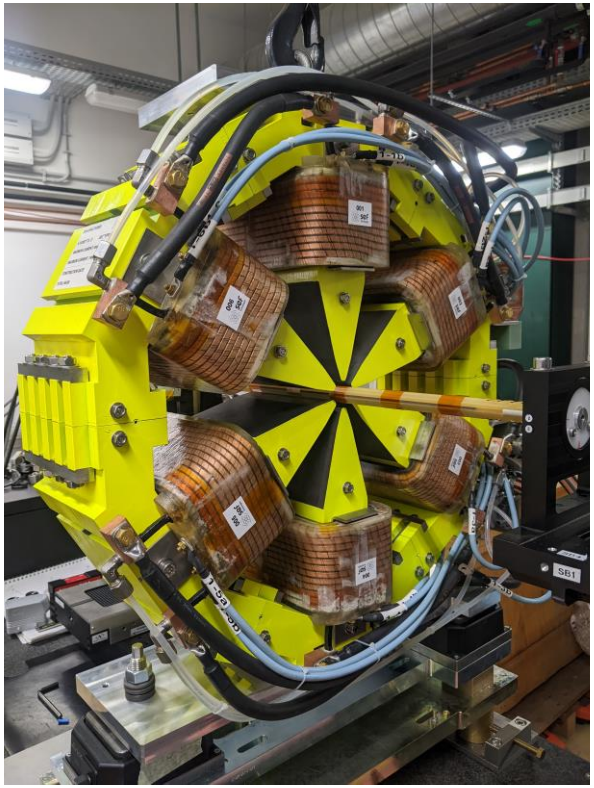
For best results, Experiments, Beam lines and Machine people MUST closely interact . But even so the project went through some changes after many discussions especially due to the fact that users wanted almost everything…

Magnets

prototype

First of the series





prototype

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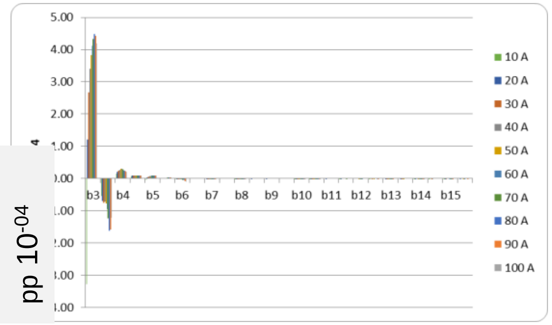
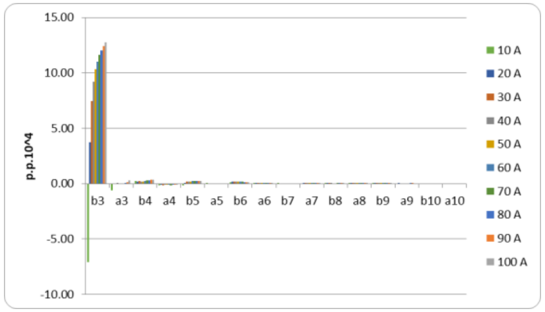
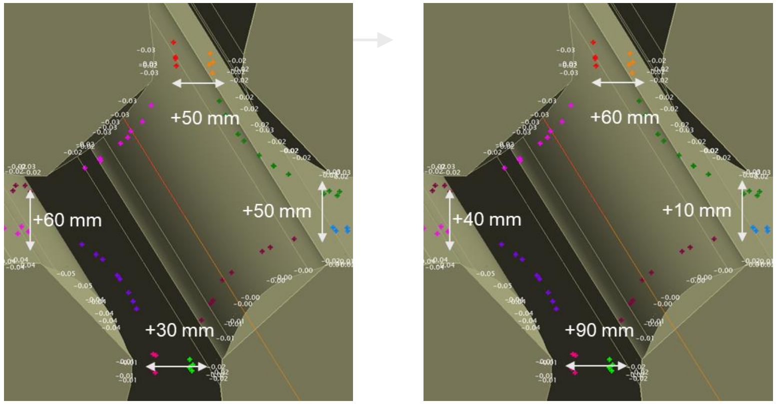
Field errors	Normal		Skew	
Errors for 6 mm radius	systematic	random	systematic	random
DIPOLE	T	3.00E-04		3.00E-04
quadrupole	3.00E-03	3.00E-03	3.00E-03	3.00E-03
sextupole	6.00E-04	6.00E-04	2.00E-04	2.00E-04
octupole and higher	3.00E-04	3.00E-04	1.00E-05	1.00E-05
QUADRUPOLE	T/m			
quadrupole		2.00E-03		2.00E-03
sextupole	2.00E-04	1.00E-04	2.00E-04	1.00E-04
octupole and higher	2.00E-04	2.00E-04	2.00E-04	2.00E-04

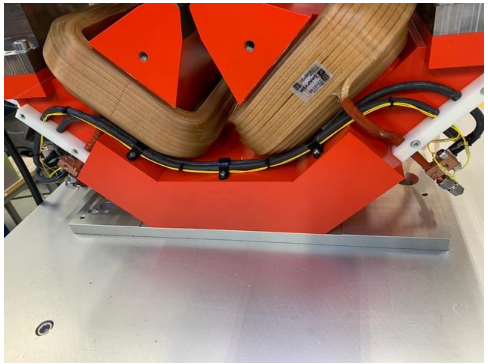




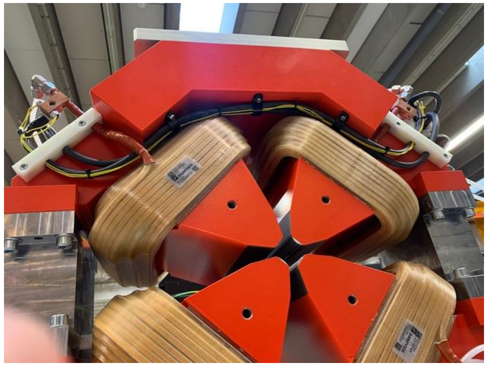


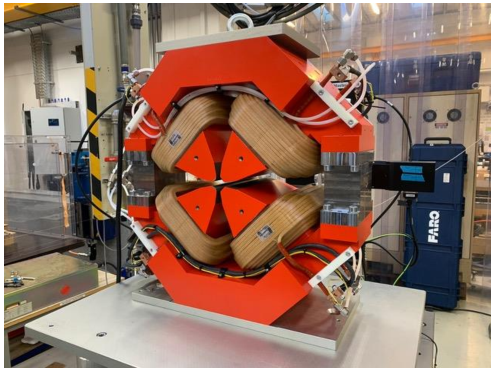
Suspect: Electrical connections, pole’s alignment but mainly it was Alu spacers

After fixing connections and alignment and replacing the spacer material with iron the magnets got it perfect (better than specified)



n	3	3	4	4
Current [A]	Normal %	Skew %	Normal %	Skew %
0.0	-0.583	0.090	0.006	0.014
10.0	-0.004	-0.002	-0.002	-0.001
50.0	0.006	0.000	-0.003	-0.001
100.0	-0.009	0.000	-0.003	-0.001
50.0	0.007	0.002	-0.005	0.000
10.0	-0.009	0.004	-0.006	0.001
0.0	-0.041	-0.005	0.066	0.047
	0.000	0.000	0.000	0.000

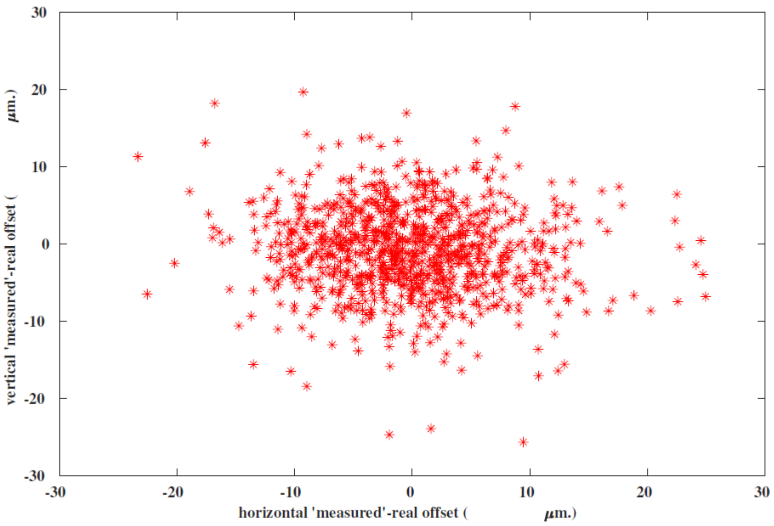


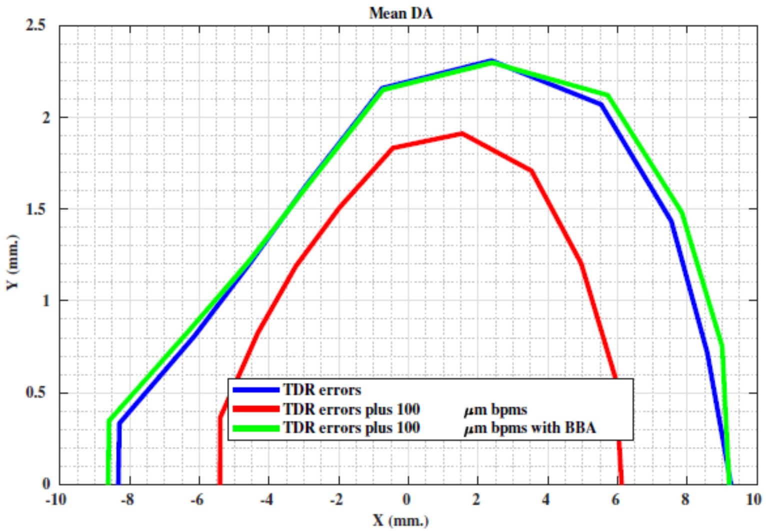


BBA

Looking to the experience of other light sources (ESRF-EBS and SIRIUS) even after careful correction of mechanical and electrical offsets of the BPMs the remaining offsets are in the range of 100 um rms. If we consider 100-150 um rms bpm offsets at 2 sigma cut there is a ~30-40% reduction of the DA that reduces the efficiency.

Classical beam based alignment require nearby quadrupole magnet. For Elettra 2.0 this is the case for only 6 BPMs flanking the long straights. For the remaining 8 BPMs our solution is to use the corrector coils of the multipoles in skew quadrupole configuration, this way it is possible to bring the BPMs offsets with respect to the sextupoles to 8/4 um rms in horizontal/vertical plane.

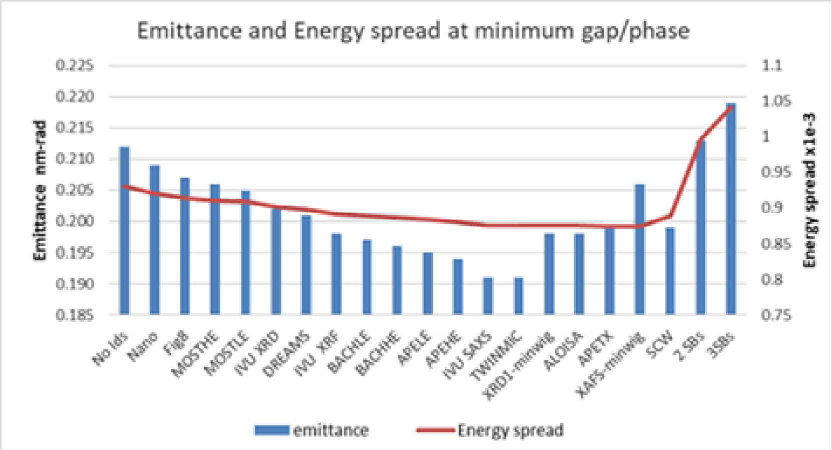




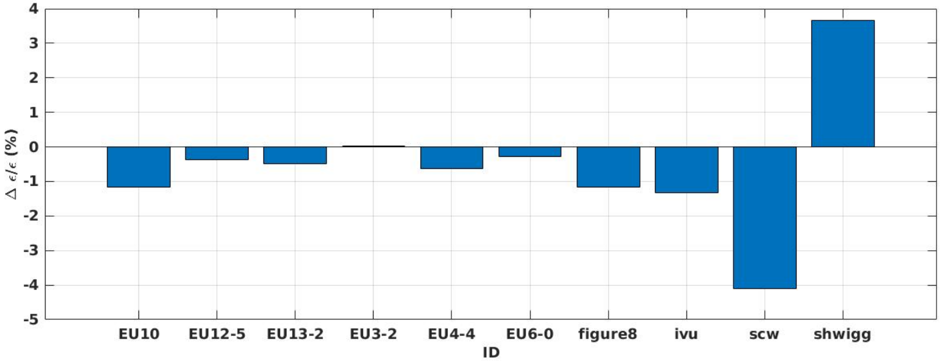
Ref. K. Manukyan

Beam size change due to ID emittance change

Elettra Sincrotrone Trieste

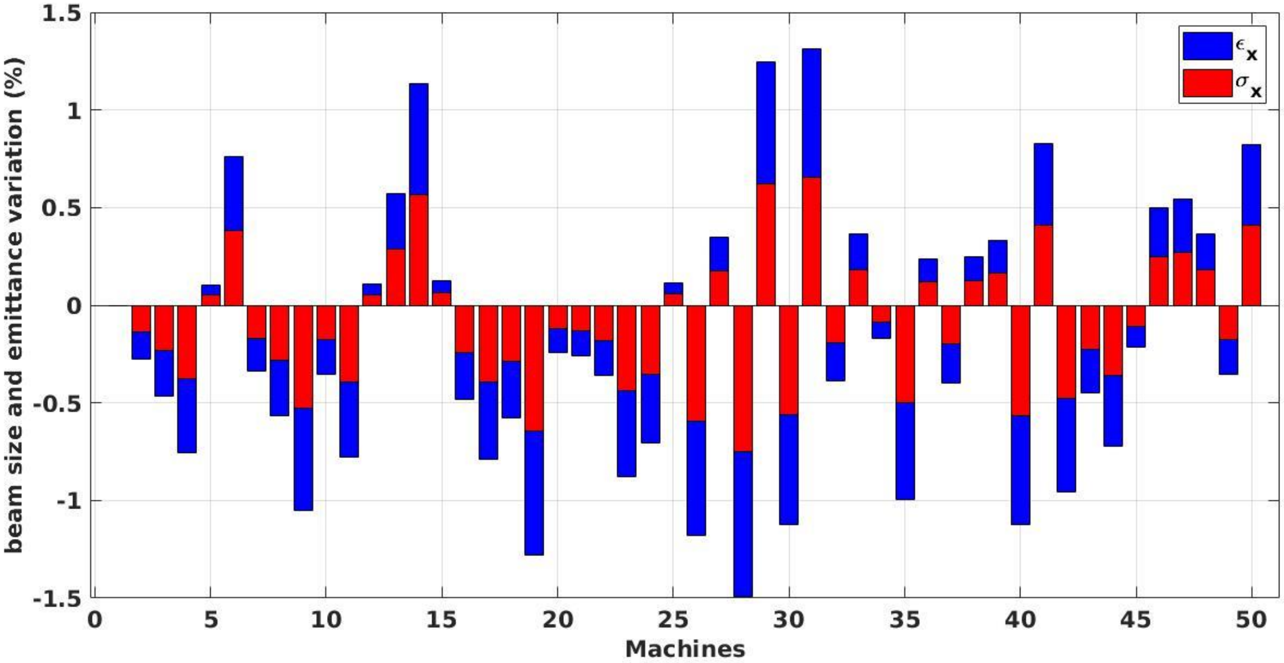


Cumulative emittance change with IDs and SBs



% of emittance change for each type of ID from 0 to full field.

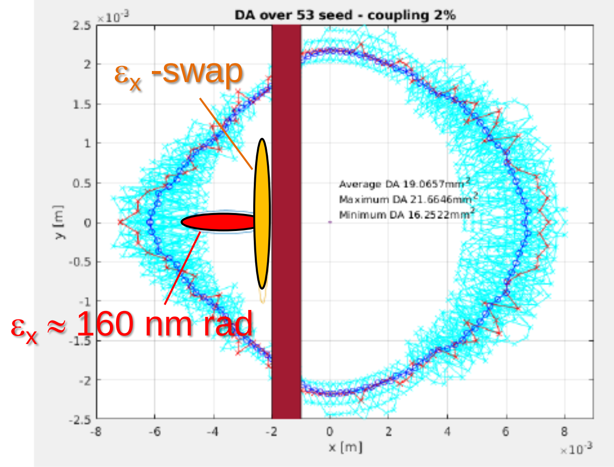
Considered 50 sets of random values for the undulators K value.
Field values in each set vary from 50% to full field.
Total beam size variation is less then 1% in all cases.

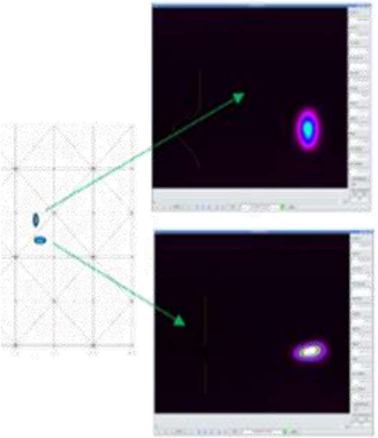


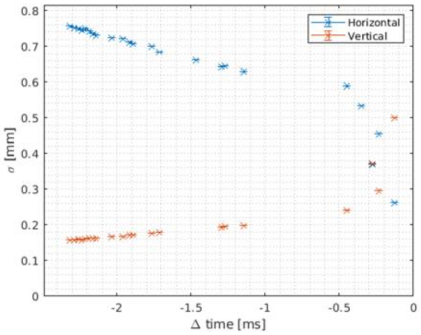
Off-axis injection

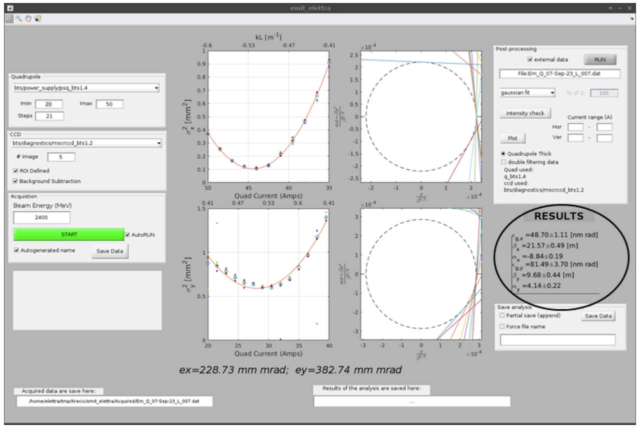
- ☐ **“Emittance swap” to achieve 100% efficiency,** without swap i.e. use normal booster beam is 65%
- ☐ **On-axis injection possible (but of course no accumulation)**

J. Kallestrup, S. Krecic and A. Carniel









Quadrupole: bts/power_supply/psq_bts1.4

Imin 20 Imax 50

Steps 21

CCD: bts/diagnostics/mscrccd_bts1.2

Image 5

☑ ROI Defined

☑ Background Subtraction

Acquistion

Beam Energy (MeV) 2400

START ☑ AutoRUN

☑ Autogenerated name Save Data

Acquired data are save here: /home/elettra/tmp/Krecic/emit_elettra/Acquired/Em_Q_07-Sep-23_L_007.dat

● Quadrupole Thick

☐ double filtering data

Quad used: q_bts1.4

ccd used: bts/diagnostics/mscrccd_bts1.2

RESULTS

$\epsilon_{g,x}$ =48.70±1.11 [nm rad]

β_x =21.57±0.49 [m]

α_x =-8.84±0.19

$\epsilon_{g,y}$ =81.49±3.70 [nm rad]

β_y =9.68±0.44 [m]

α_y =4.14±0.22

Save analysis

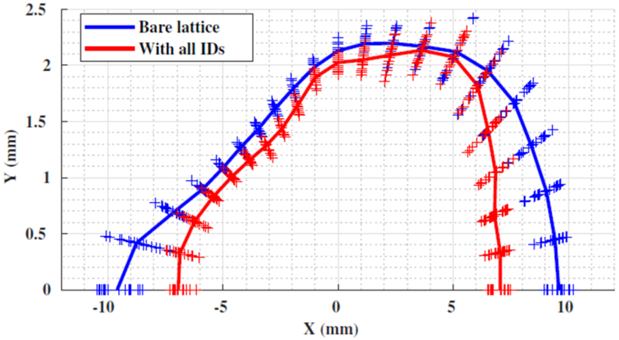
☐ Partial save (append) Save Data

☐ Force file name

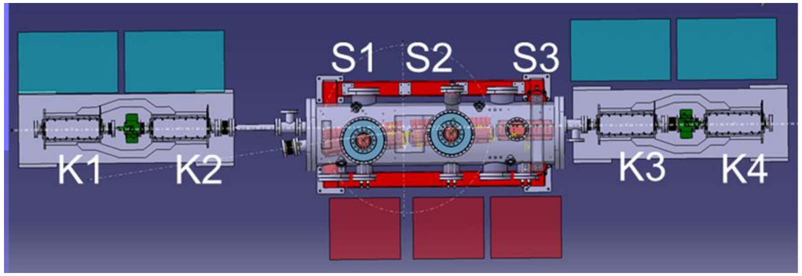
ex=228.73 mm mrad; ey=382.74 mm mrad

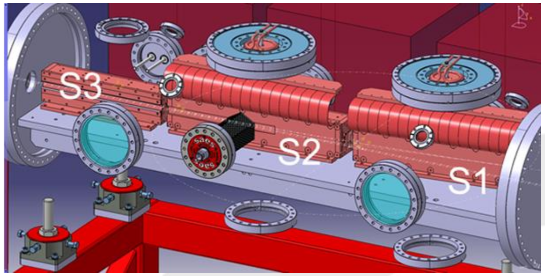
Results of the analysis are saved here: ...

The stored beam is bumped by -6 mm and the injected beam is placed by -10 mm using the 3 septa. Beam separation 4 mm, pulse 3-5 us half sine wave for kickers, thin septum separation thickness 1 mm.



Momentum aperture ~±3%
Lifetime 5 hours w/o 3HC

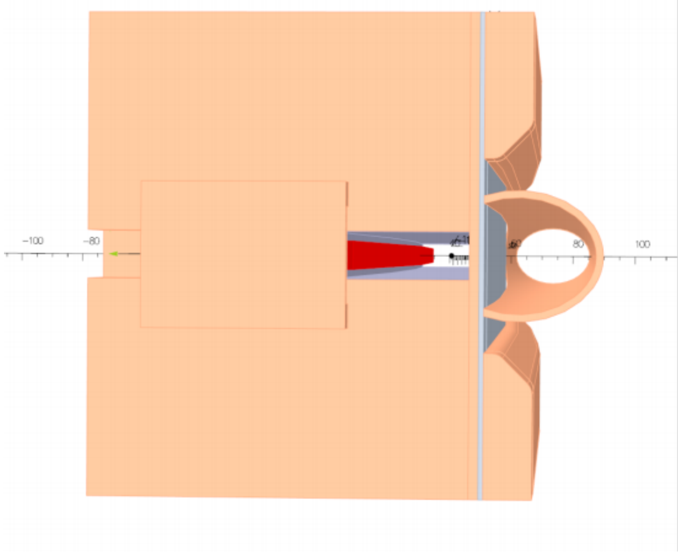


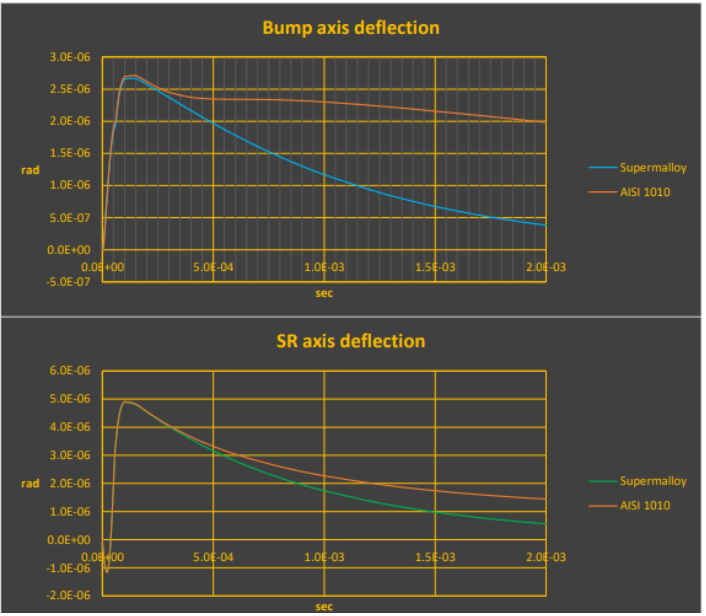


Septum S2 **Disturbance during top-up**

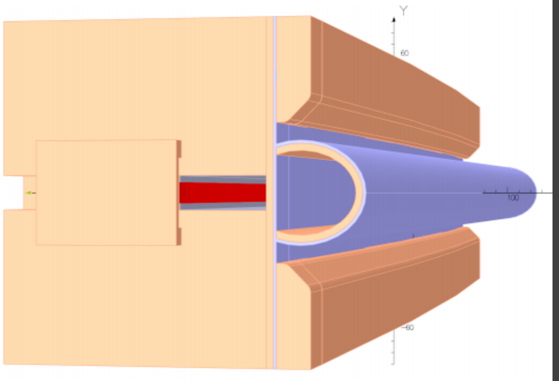
Specified <1 μrad to meet the 5%

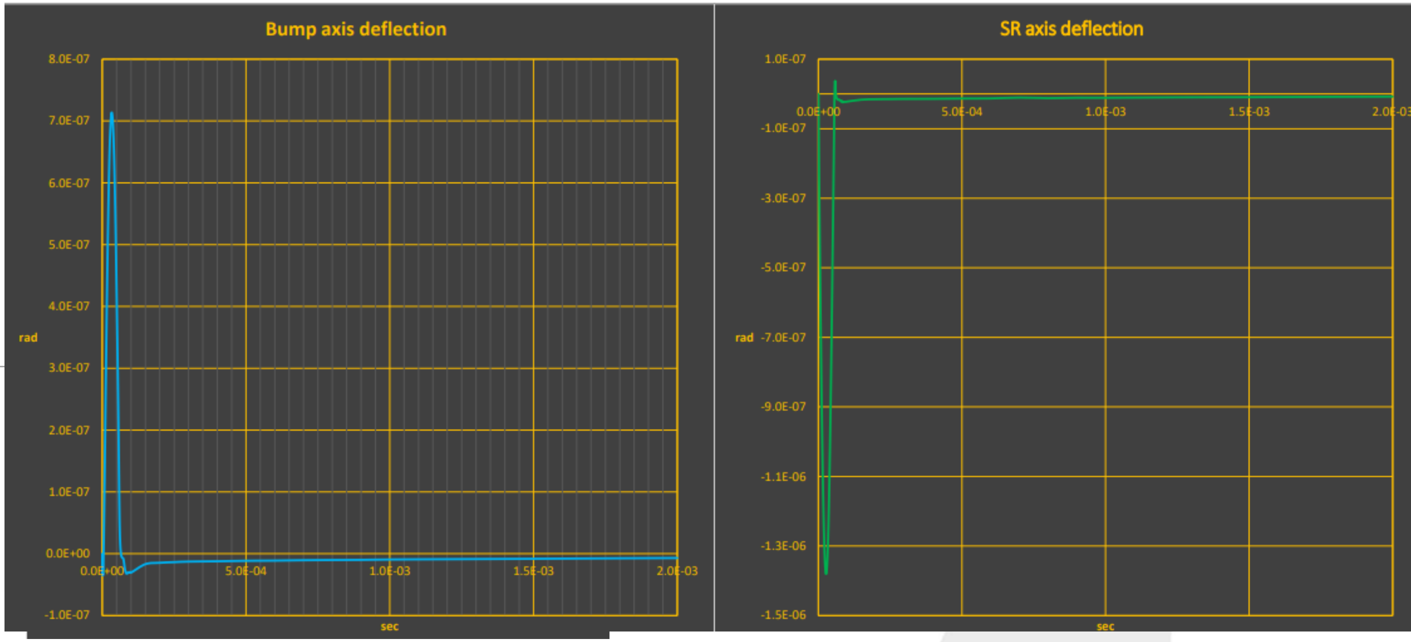
Thick septum magnets S1 and S2 @ 2.4 GeV		
Core length	510	mm
Hor and ver aperture	25 x 10	mm
Total deflection	8.02 72[1]	deg
Peak magnetic field (S1 – S2)	1.09 – 1.09	T
Peak current (S1 – S2)	8.74 – 8.74	kA
Total inductance	2.6	μH
Circuit capacitance	120	μF
Current pulse duration	57	μs
Charging voltage (S1 – S2)	1.29 – 1.29	kV
Pulse repetition rate (assumed)	3.33	Hz
Total magnet power losses	142	W





Septum S2



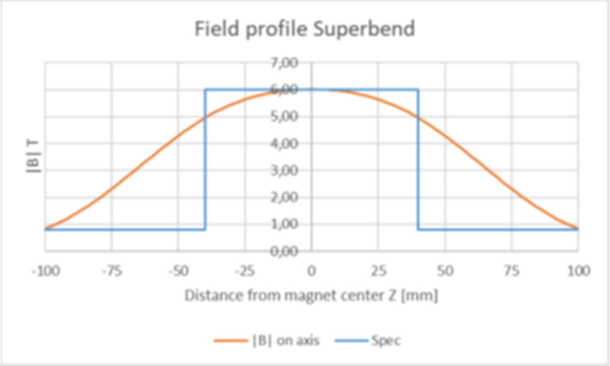


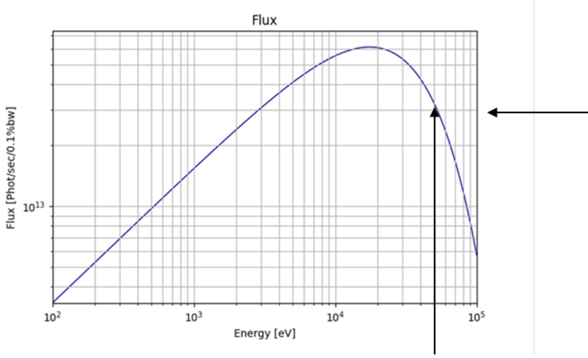
Ref: R. Fabris

Superconducting dipoles

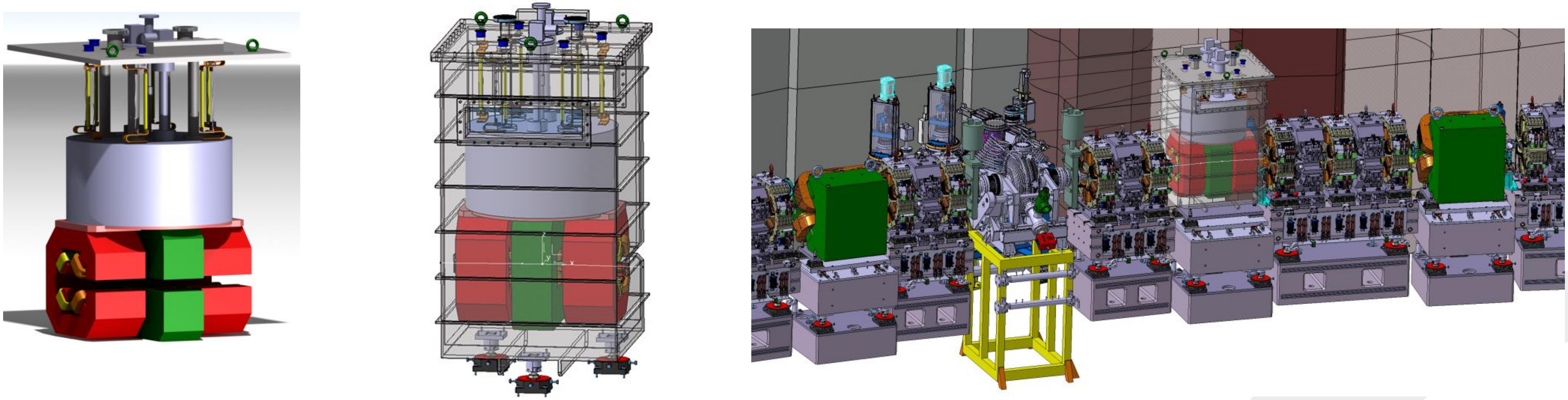
Three beam lines at 35 and 50 keV and with flux above **10^{13} ph/sec** will be constructed and will be served by 6 T SC-Dipoles (combined) to be installed after commissioning in sectors 4,8,12. Installation is expected from 2027.

Special design to have the lowest impact on emittance

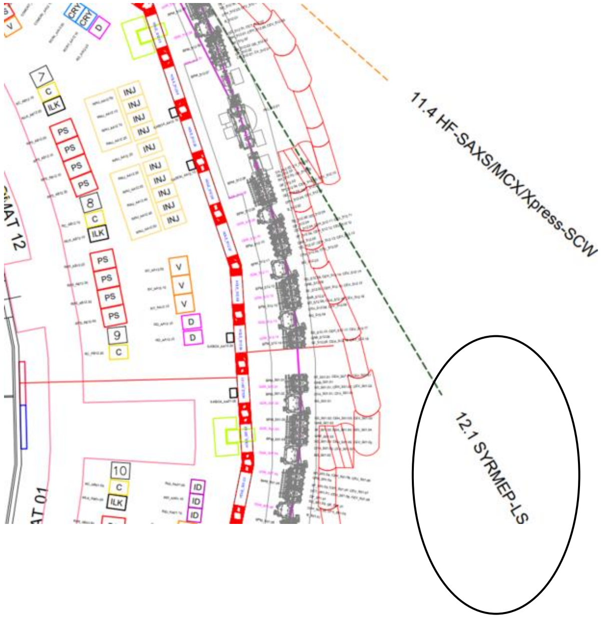


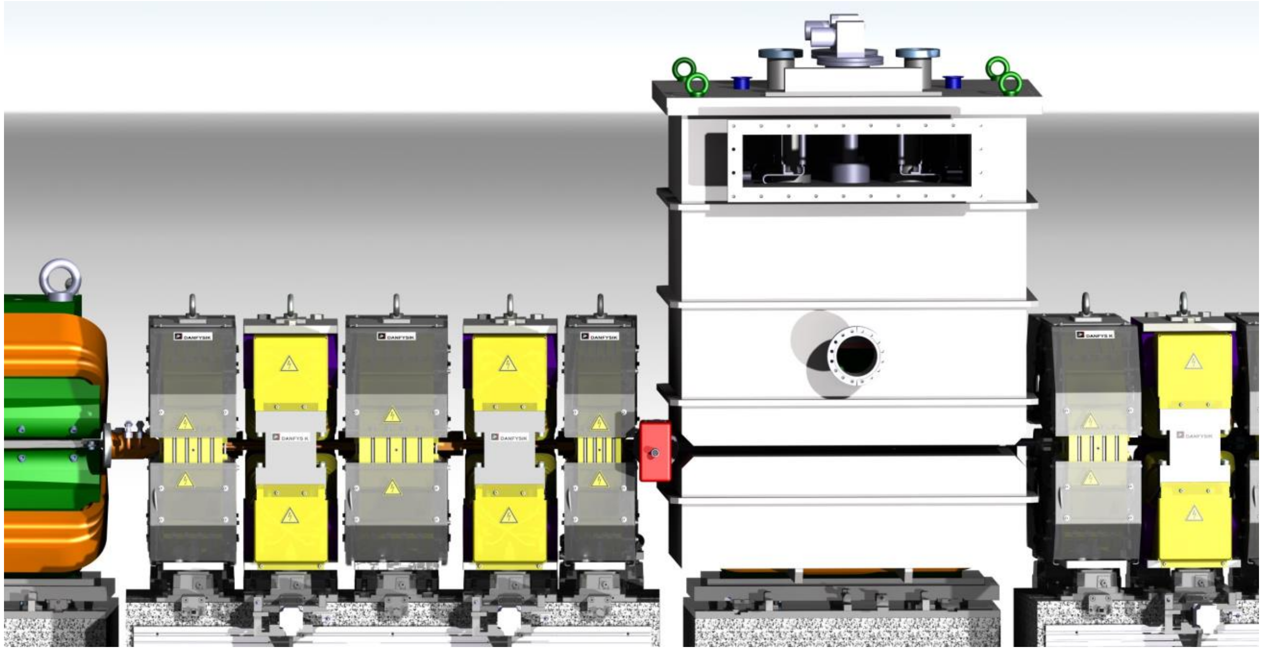


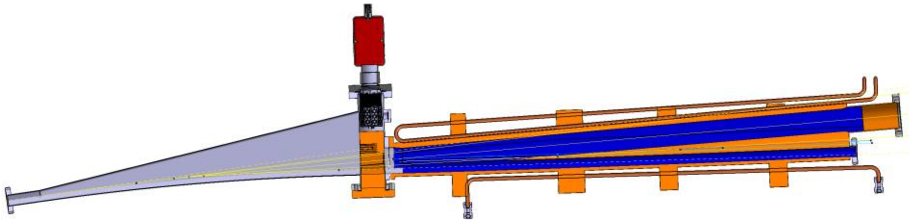
- For the super-bends we opt for a C-shape magnet, technical specs done, **call for tender end 2024**.



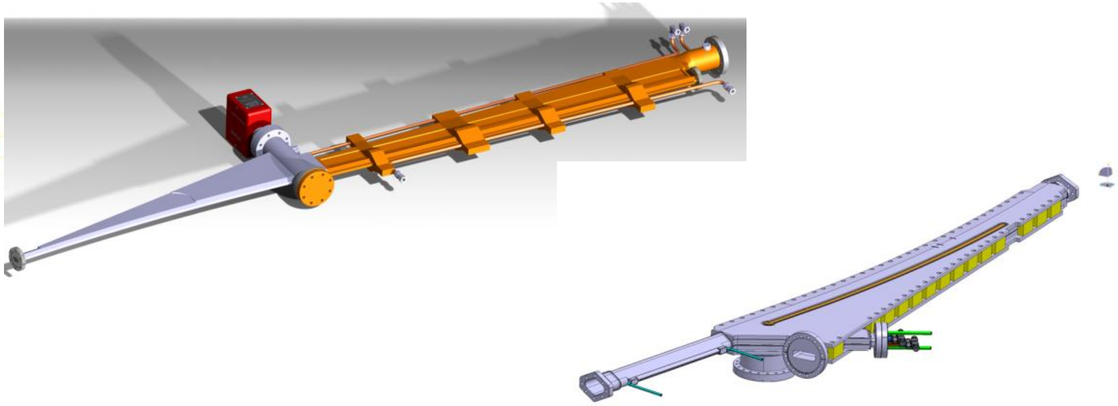
Other technical challenges





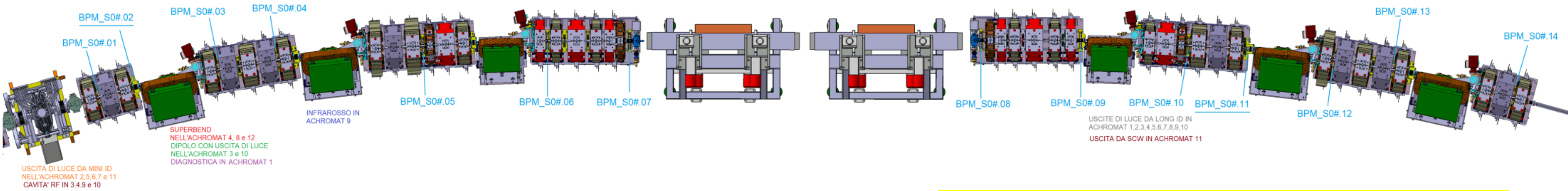


4 kW on the chamber

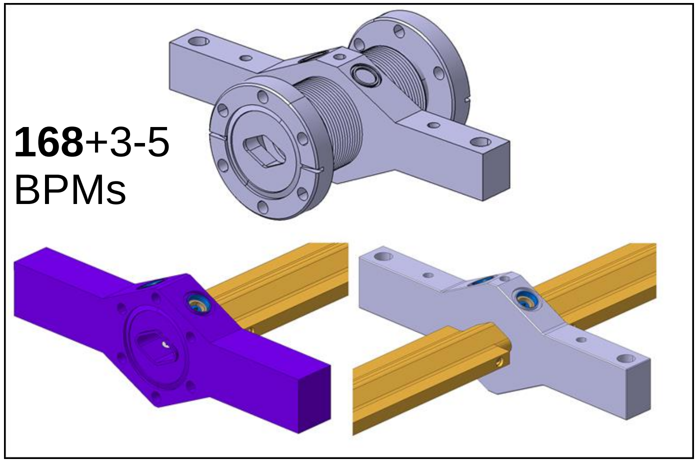


NEG coating the light exits is really challenging - CERN collaboration

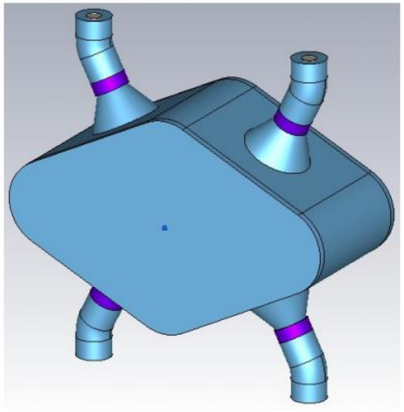
BPMs 14/achromat



Careful analysis for good measurements even at μA level since we will be based on BPMs and not on FLS (space for only one)

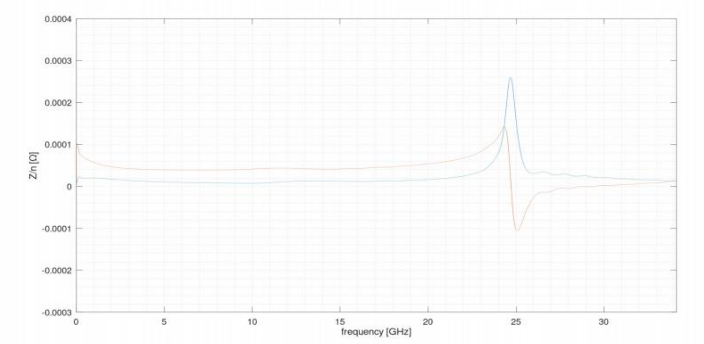


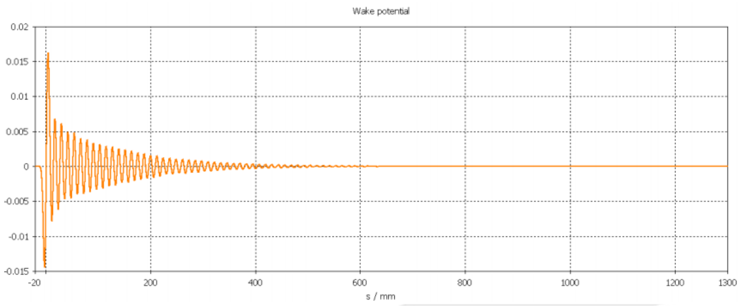
168+3-5 BPMs



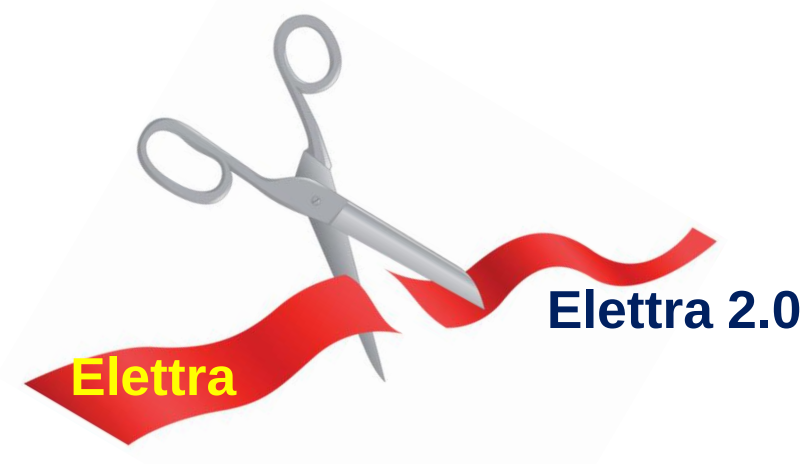
Beam and wake on longitudinal axis (Xoffset = Yoffset = 0 mm).
Charge: 1 nC
SigmaRMS: 3 mm
device length: 11 mm
Wake Loss Factor: 3.846455e-03 V/pC
Total Power extracted from the beam at 400 mA (MB): 1.23 W
Wake Length: 1300 mm

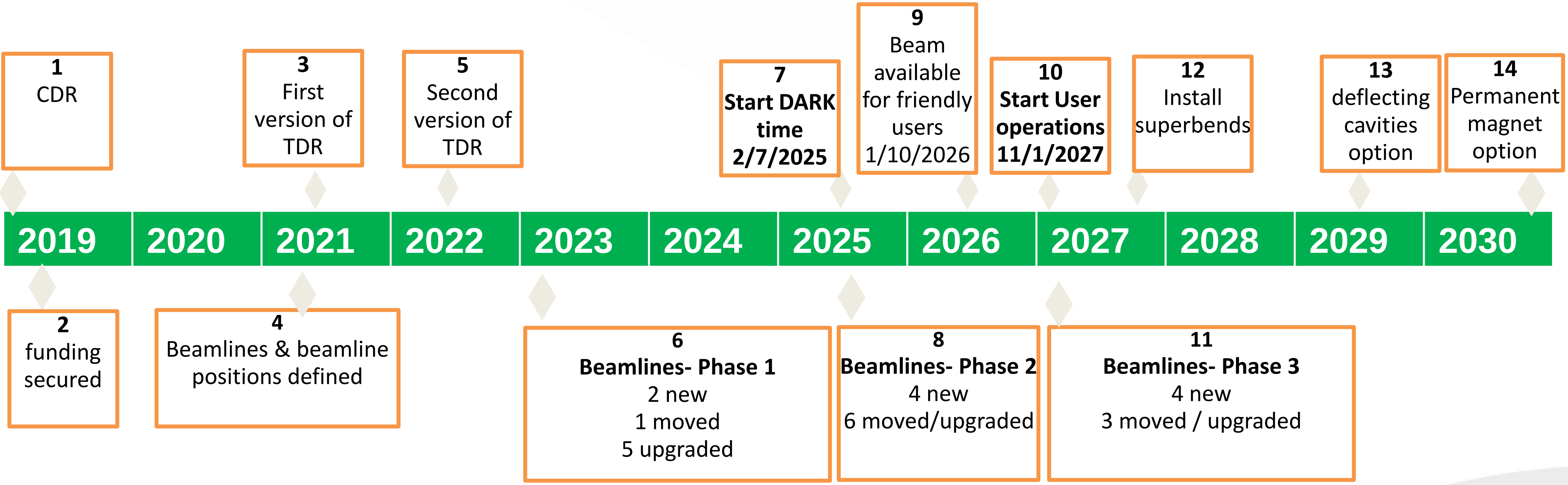
BPM electronics





Elettra 2.0 Master Milestones





1
CDR

2
funding secured

3
First version of TDR

4
Beamlines & beamline positions defined

5
Second version of TDR

6
Beamlines- Phase 1
2 new
1 moved
5 upgraded

7
Start DARK time
2/7/2025

8
Beamlines- Phase 2
4 new
6 moved/upgraded

9
Beam available for friendly users
1/10/2026

10
Start User operations
11/1/2027

11
Beamlines- Phase 3
4 new
3 moved / upgraded

12
Install superbends

13
deflecting cavities option

14
Permanent magnet option

Thank you for your attention

Elettra
Sincrotrone
Trieste

Errors

Element Type	Parameter	Value	Unit
Dipoles	Δx	50	µm
	Δy	50	µm
	Δz	300	µm
	Roll angle	100	µrad
Quadrupoles on the girder	Δx	25	µm
	Δy	25	µm
	Δz	300	µm
	Roll angle	50	µrad
Sextupole /multipoles on the girder	Δx	25	µm
	Δy	25	µm
	Δz	300	µm
	Roll angle	50	µrad
Correctors	Δz	300	µm
	Roll angle	150	µrad
BPMs	Δx	150	µm
	Δy	150	µm
	Δz	300	µm
	Roll angle	150	µrad
Girders	Δx	50	µm
	Δy	50	µm
	Δz	300	µm
	Roll angle	100	µrad

Field errors	Normal		Skew	
Errors for 6 mm radius	systematic	random	systematic	random
DIPOLE	T	3.00E-04		3.00E-04
quadrupole	3.00E-03	3.00E-03	3.00E-03	3.00E-03
sextupole	6.00E-04	6.00E-04	2.00E-04	2.00E-04
octupole and higher	3.00E-04	3.00E-04	1.00E-05	1.00E-05
QUADRUPOLE	T/m			
quadrupole		2.00E-03		2.00E-03
sextupole	2.00E-04	1.00E-04	2.00E-04	1.00E-04
octupole and higher	2.00E-04	2.00E-04	2.00E-04	2.00E-04
SHIFTED QUADRUPOLES	T/m			
quadrupole		2.00E-03		2.00E-03
sextupole	3.00E-04	2.00E-04	3.00E-04	2.00E-04
octupole and higher	6.00E-04	6.00E-04	6.00E-04	6.00E-04
SKEW QUADRUPOLES	T/m			
quadrupole		3.00E-03		3.00E-03
sextupole	1.30E-01	1.00E-02	1.50E-01	2.00E-02
octupole and higher	2.00E-03	5.00E-04	2.00E-03	5.00E-04
SEXTUPOLES	T/m^2			
dipole	1.00E-03	2.00E-04		
sextupole		2.00E-04		
octupole	2.00E-04	1.00E-04	2.00E-04	1.00E-04
higher multipoles (decapoles etc.)	1.00E-03	5.00E-04	1.00E-03	5.00E-04
OCTUPOLES	T/m^3			
octupole		3.00E-04		
higher multipoles (decapoles etc.)	1.00E-03	5.00E-04	1.00E-03	5.00E-04