Elettra
Sincrotrone
Trieste

Elettra 2.0 –The upgrade of Elettra

Emanuel Karantzoulis

Outline:

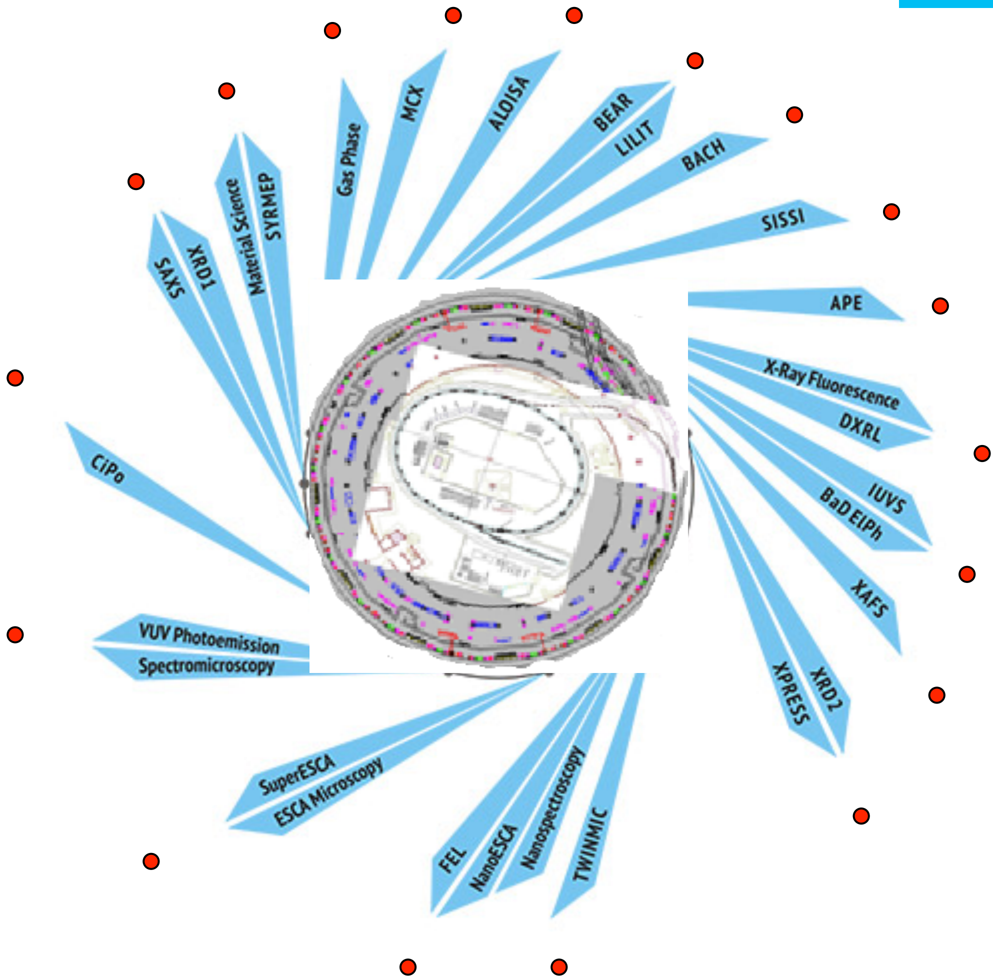
- *Elettra - points of view*
- *Trends and requirements*
- *Lattice analysis*
- *Best lattices*
- *Current Elettra 2.0*
- *Short pulses*
- *Brilliance and IDs*
- *Schedule and dark time*
- *Conclusions*

Elettra Points of View

Machine people

Beam Lines people

Users

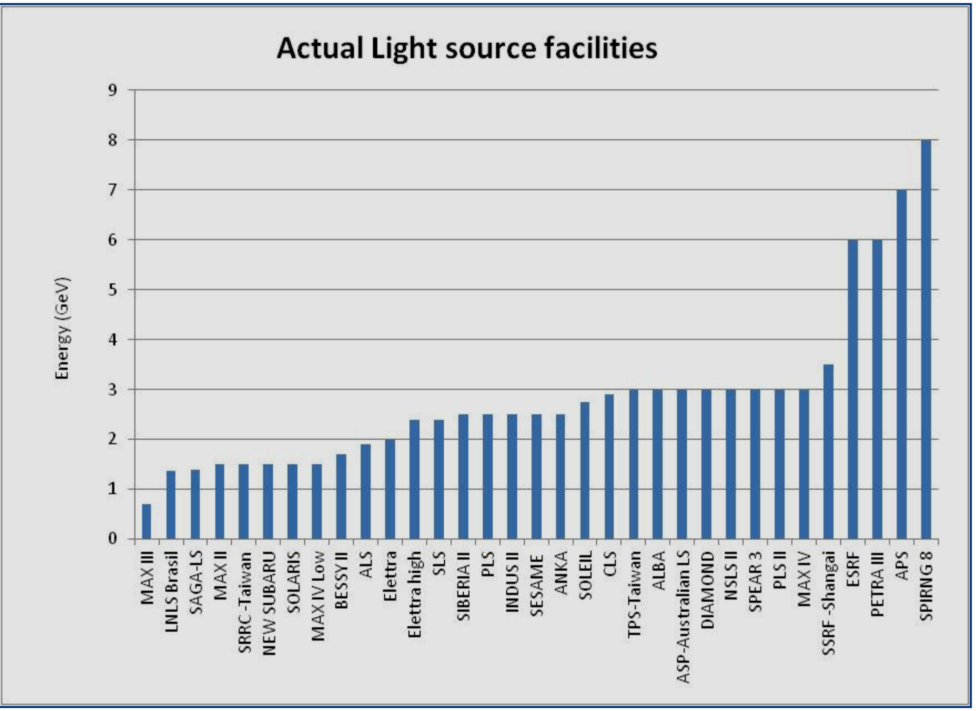


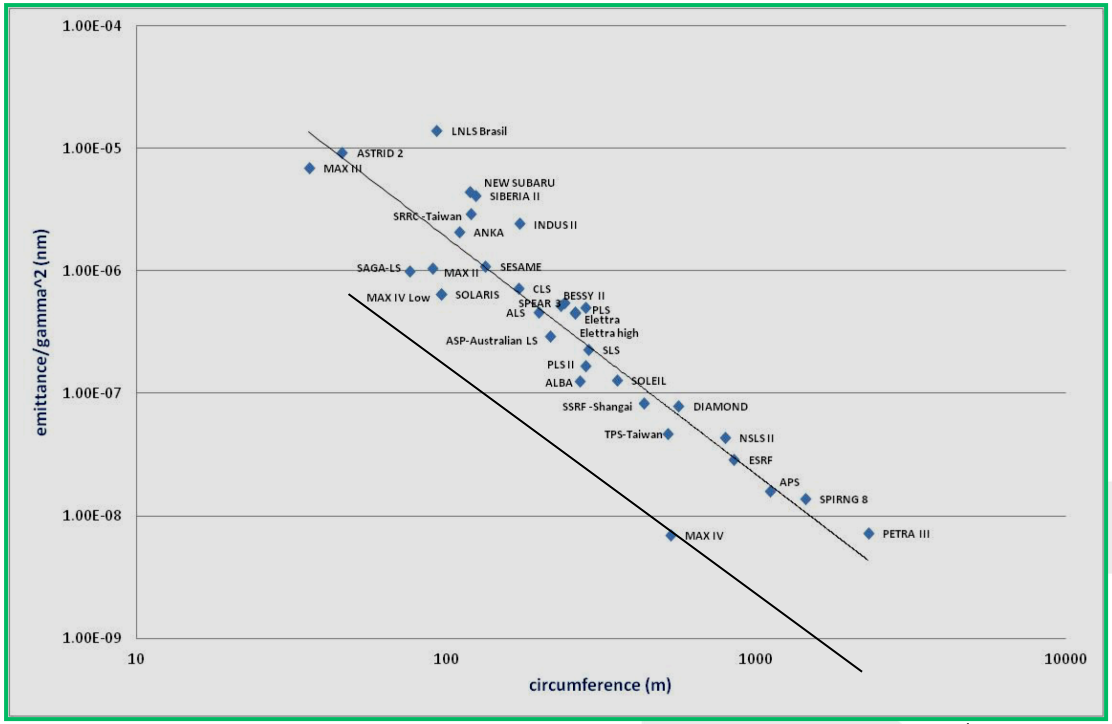
Different views but we MUST consider the whole picture in order to reach good and productive results -> scope of the workshop

SR generations and trends

Generation	Time period	Radiation use from	Energy range (GeV)	Emittance nm-rad
1	60s and early 70s	Parasitic	0.18-6	500
2	Mid 70s to 80s	Dipoles	0.7-2.5	100
3	90s to 2015	Wigglers and undulators	0.7-8 many in 2-3 GeV	1-20
NGSR	2015-2035	Undulators	2 – 6 for the moment	0.02-0.5

Average Brilliance
10^{13}
10^{16}
10^{19}
10^{22}





Next generation: Ingredients

Those are partially based on the trends in this field:

- Higher brilliance

$$B_n = \frac{F_n}{4\pi^2(\varepsilon_x + \lambda_n/4\pi)(\varepsilon_y + \lambda_n/4\pi)} \quad \rightarrow \quad \varepsilon_{x0}[mrad] = F_x(q_x, lattice)\frac{E^2(GeV)}{N_d^3}$$

- High level of coherence in both planes (3rd generation sources have only high vertical coherence),
- Smaller spot size and divergence
- Higher flux and a variety of undulators

However not all users ask for higher brilliance and coherence. Others instead are interested in:

- Short pulses
- High field dipoles (2 T and above)

Elettra 2.0 requirements

- The requirements for the new machine were based on the interaction with the beam lines and users' community.
- A dedicated workshop on the future of Elettra was held in April 2014 to examine the various requirements. At that time the requirements were defined as follows:

Design boundary conditions

Easier part

Beam energy: 2 GeV

Beam intensity: 400 mA

Emittance: to be reduced by more than 1 order of magnitude

Horizontal electron beam size: less than 60 μm

Conserve filling patterns: multibunch, hybrid, single bunch, few bunches

Keep the same building and the same ring circumference (259-260 m)

Existing ID beam lines and their position should be maintained

Conserve space available for IDs: not less than that of Elettra

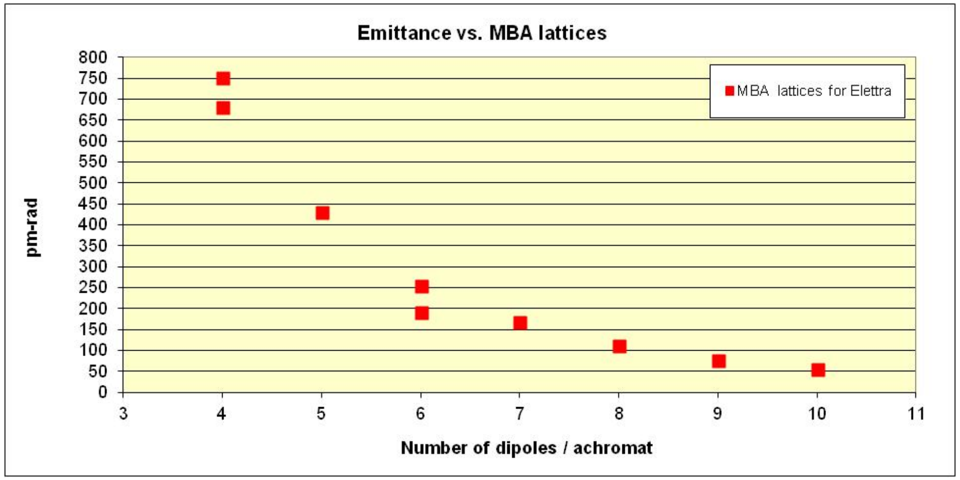
Conserve the existing beam lines from dipoles

Use the existing injectors, that means off-axis injection

Tougher part

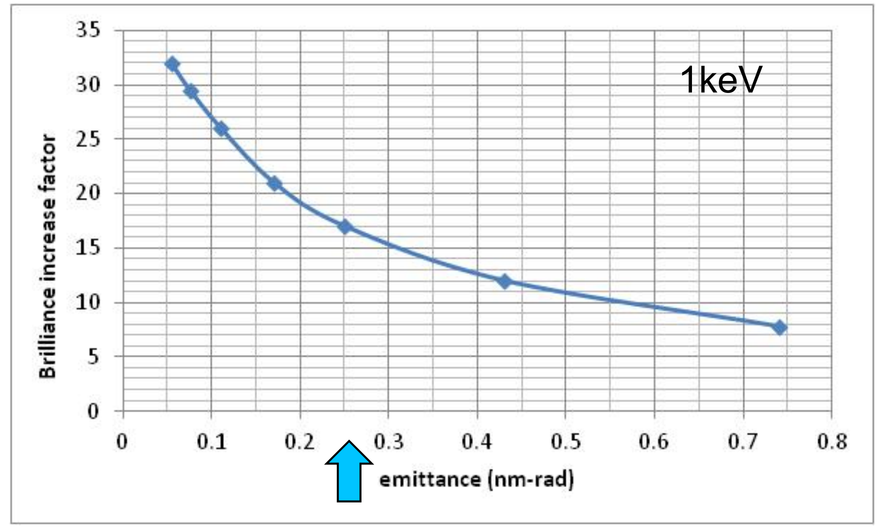
Search for the Elettra 2.0 Lattice

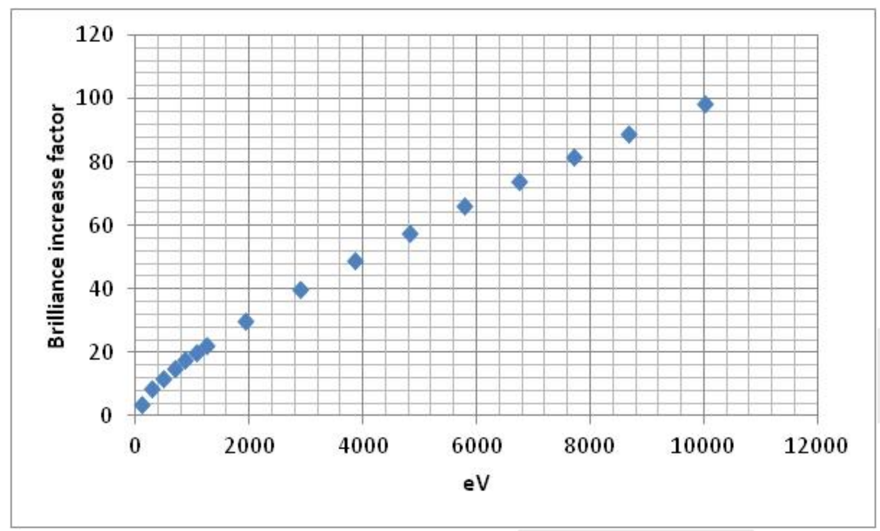
All Elettra-like multi-bend lattices have been created up to 10BA



Number of dipoles / achromat	Emittance (nm-rad) @ 2 GeV	σ_x (μm) @ LS	σ_y (μm) @1% coupling @ LS	Brilliance increase factor at 1keV
2	7	240	14	
4	0.74	80	4.5	8
5	0.43	70	3	12
6	0.25	55	2.2	17
7	0.17	40	1.9	21
8	0.11	26	1.7	26
9	0.075	22	1.5	29
10	0.054	20	1.3	32

Brilliance increase factor for a well matched undulator as compared with its brilliance in the actual Elettra.





Search for the Elettra 2.0 Lattice

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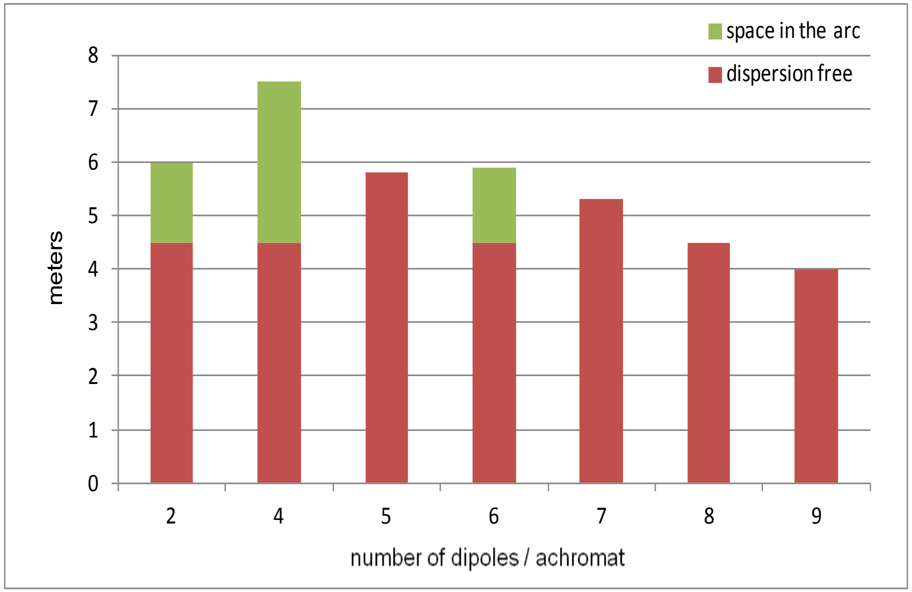
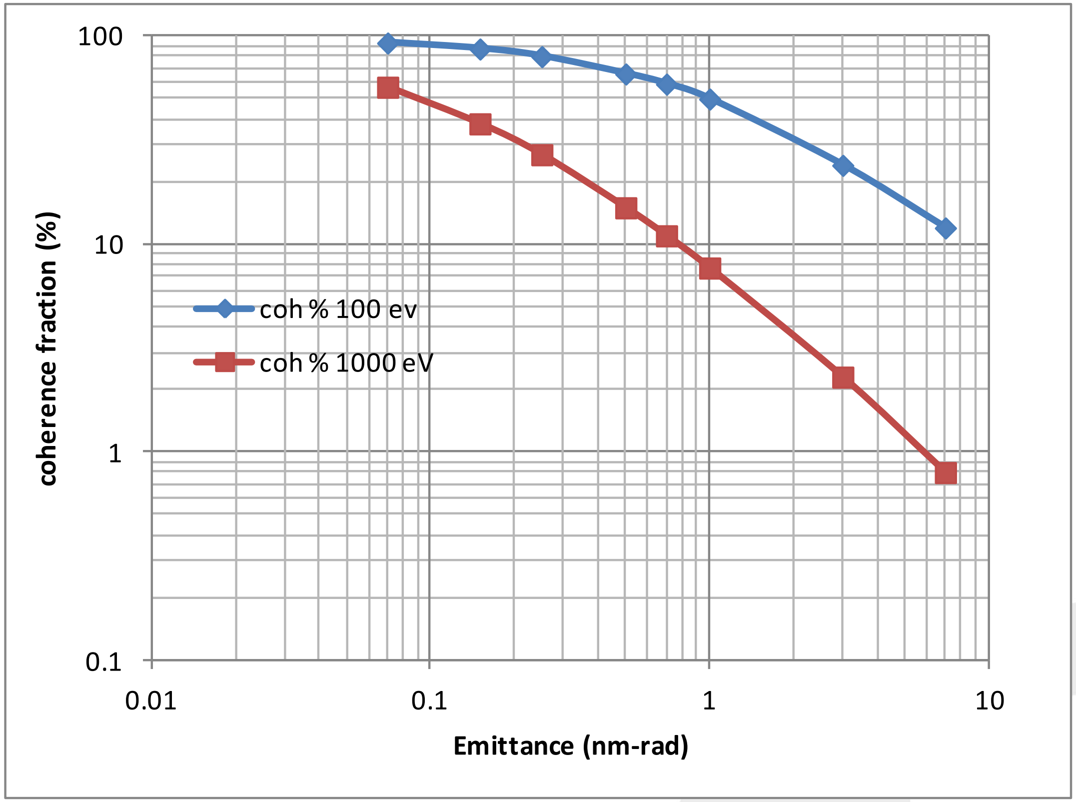
Free space is important. Also coherence for some users





Red: free space available for IDs in the long straight section (dispersion free)
Green: free space available for IDs in the arc (dispersive)

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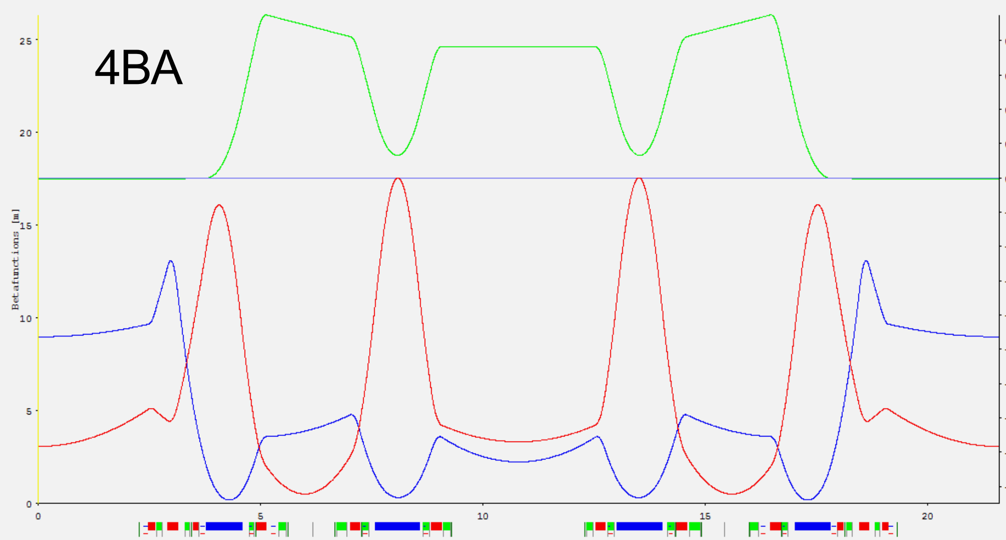
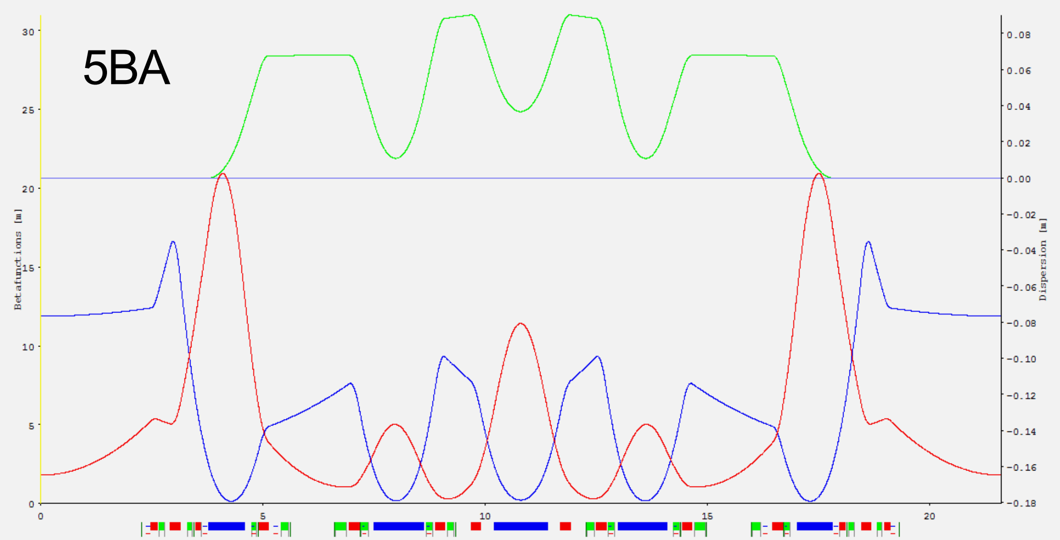
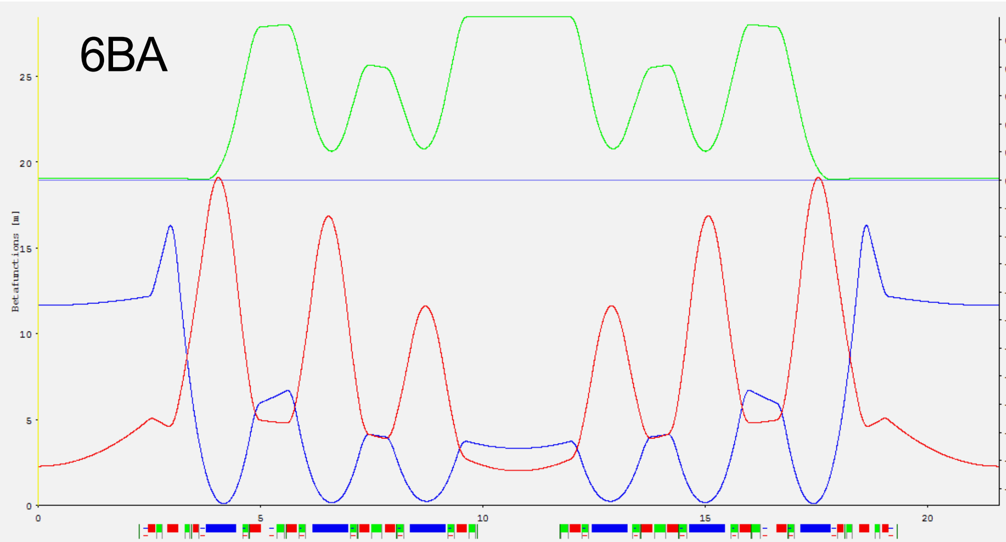
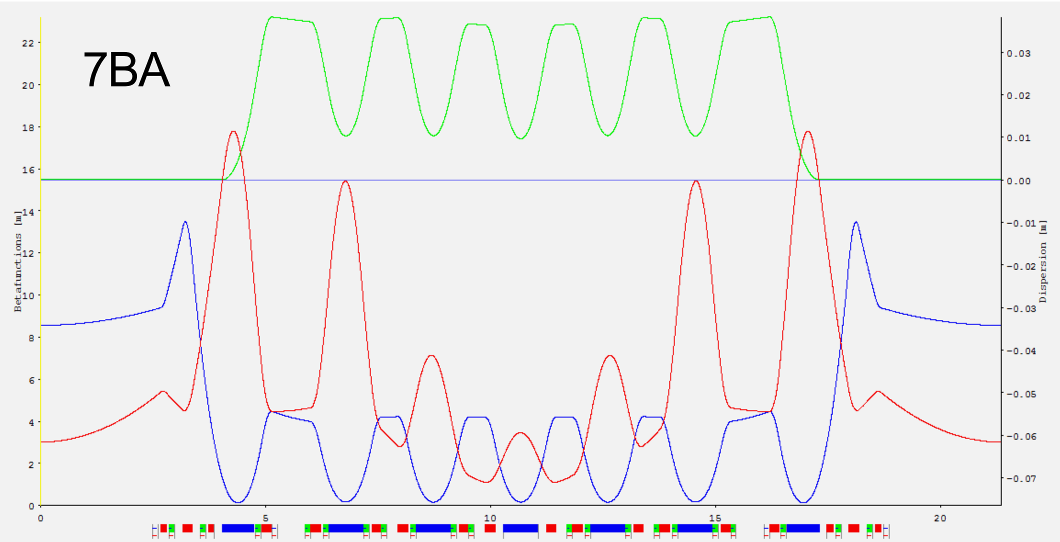
Lattices fulfilling the free space criteria





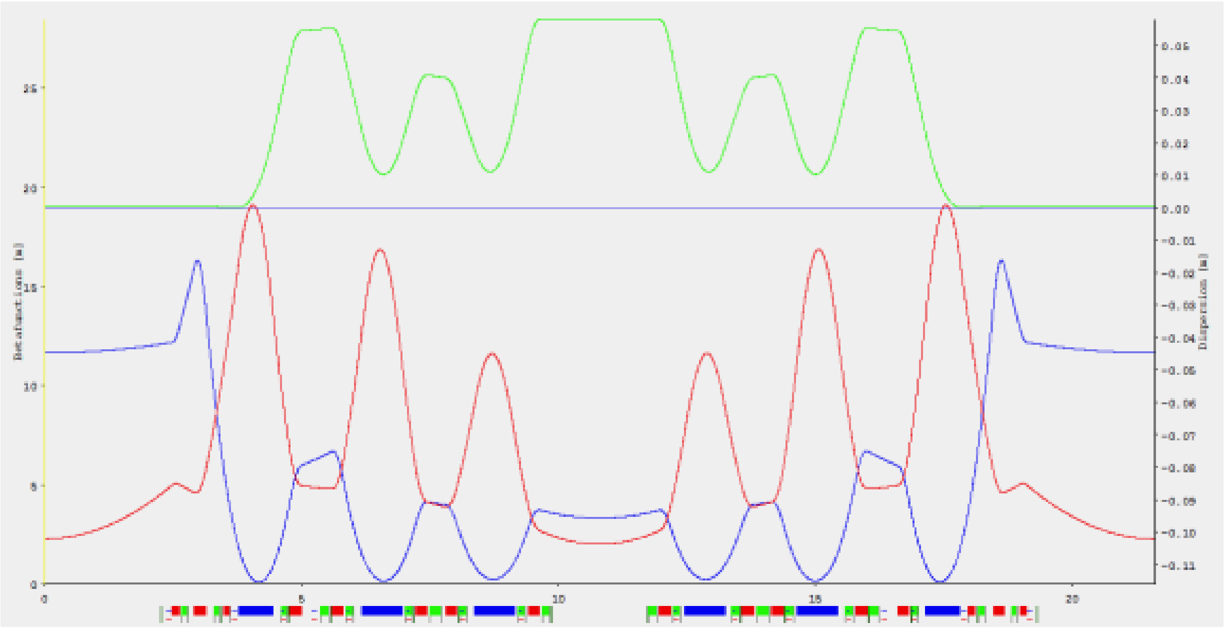




For optics + graphics used "OPA version 3.81", PSI, 2015 by A. Streun

S6BA Lattices; fulfill all criteria

Current version:
Emittance 0.25 nm-rad (0.15 if round beam) 169 keV/turn
Dipoles are electromagnets at 0.8 T
No Longitudinal Gradient in the dipoles



Free space for IDs (4.5 + 1.6 m) – fixed at 2 GeV

How to save the dipole beam lines?

Taking care of the Dipole beam lines in S6BA

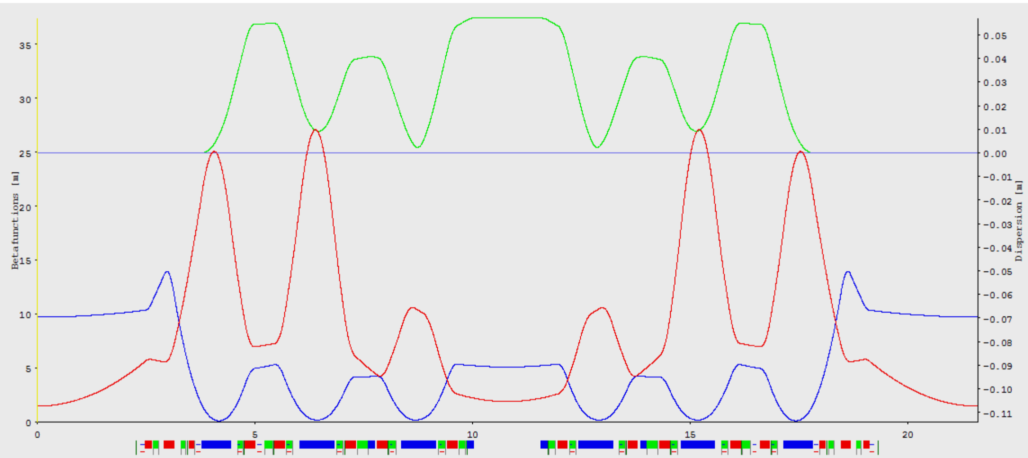
Our MBAs use dipoles with fields of about 0.8 T while at the actual Elettra the fields are 1.2 T at 2 GeV and 1.44 T at 2.4 GeV

Solutions:

- Use LG dipoles with central field of ~2 T (for ~**3.3 deg in S6BA**) and anti-bends, no emittance increase
- Use short wigglers, emittance increases depending on the field. For each 2 T is 2.7% but with the SCW at 3.5 T the increase is reduced to 1.0%
- Use separate super-bends for 5.7 deg - > Larger emittance increase

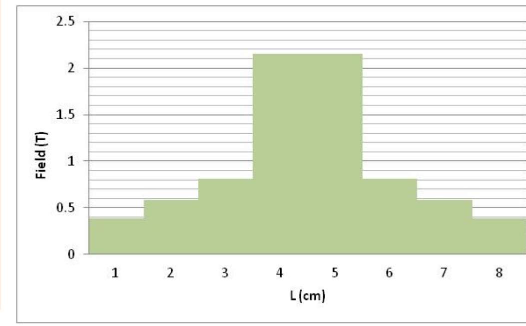
S6BA Lattices; fulfill all criteria

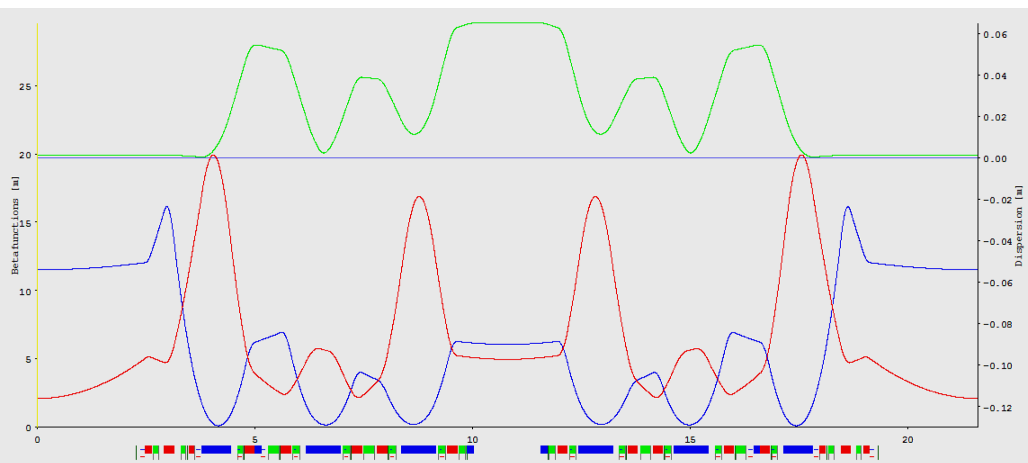
Elettra Sincrotrone Trieste



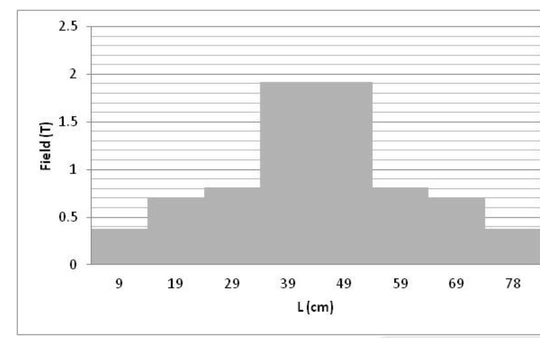
LG + anti-bend version:
Emittance 0.19 nm-rad (0.1 if round beam)

The 3 and 4 dipoles in LG with central field at ~2.2 T. **245 keV/turn**





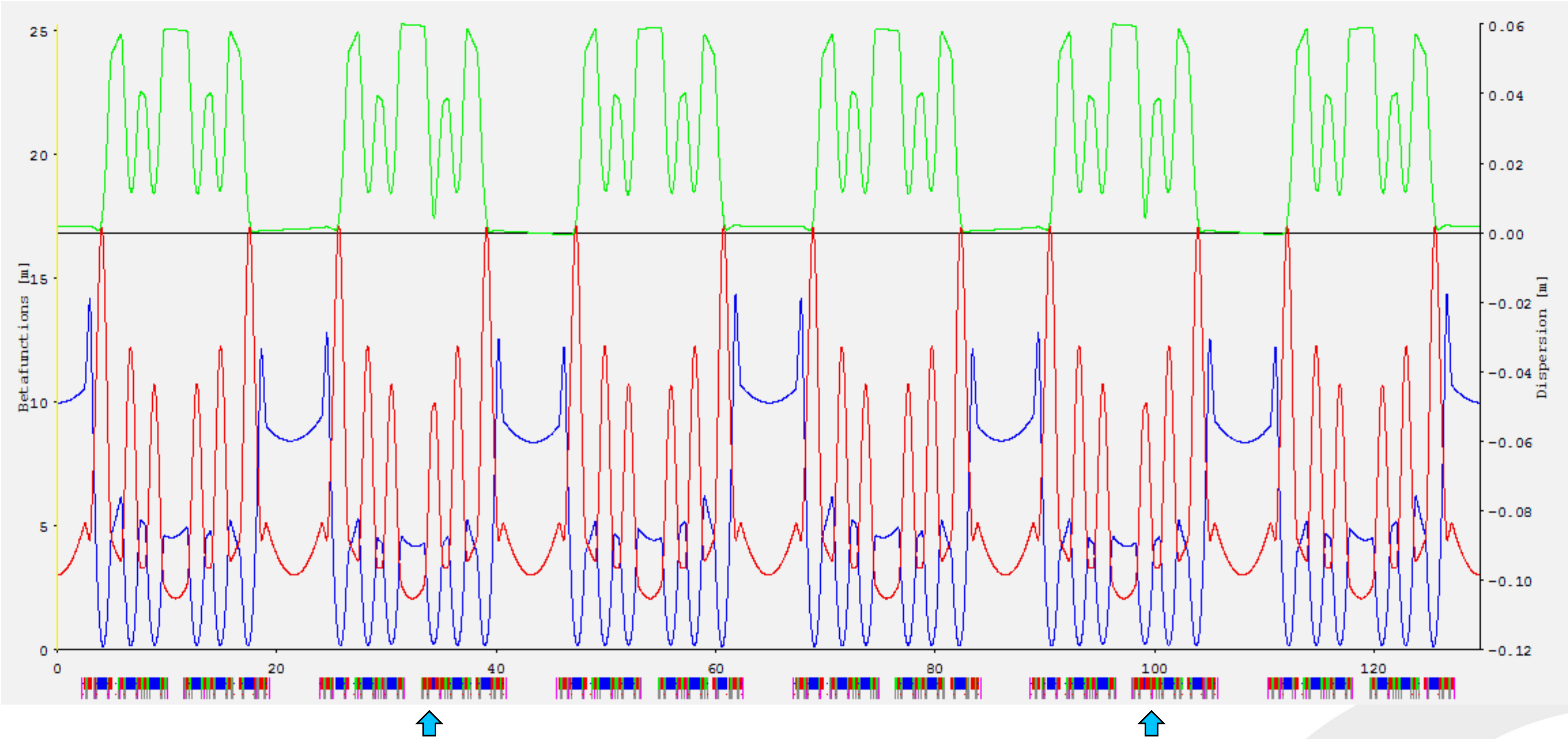
The 2 and 5 dipoles in LG with central field at ~2 T.
225 keV/turn



Free space for IDs (4.5 +1.55 m) – fixed at 2 GeV

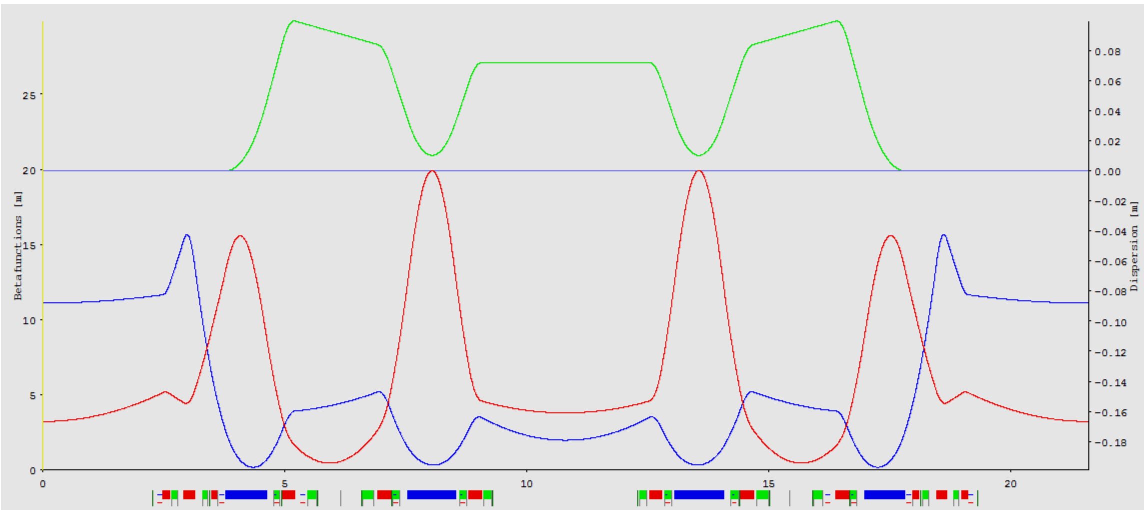
Super-bends

Some beam-lines cannot use 2T short wigglers e.g. SYRMEP (Mammography) and/or they need high critical energy (> 8.0 keV). Below is shown half of Elettra 2.0 with 2 super-bend sections. The emittance increases from 0.25 to 0.37 nm rad at 3.5 T (Ec=9.3 keV). The emission angle is 5.7 deg

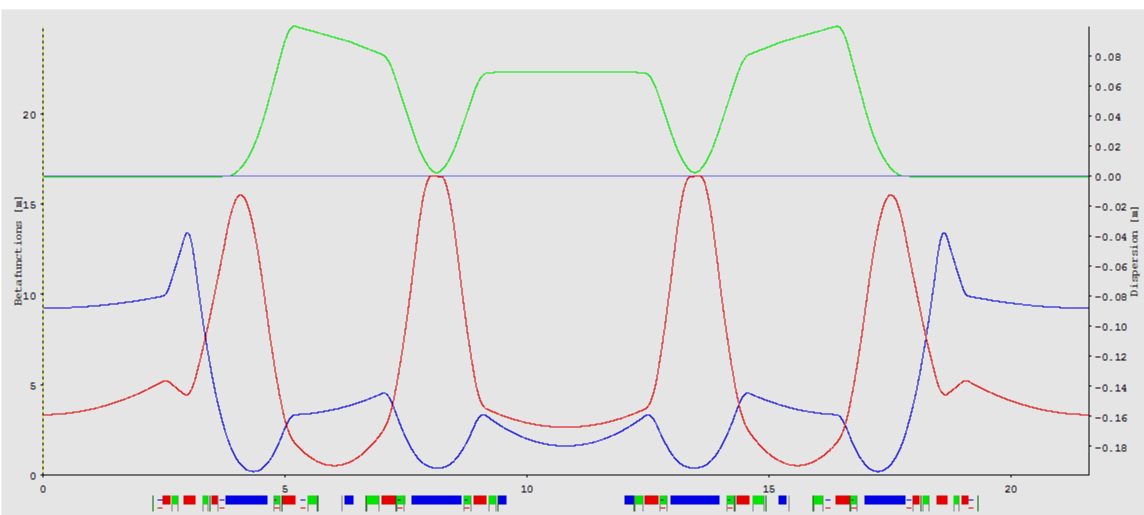


But also Elettra can accommodate super-bends

S4BA Lattices

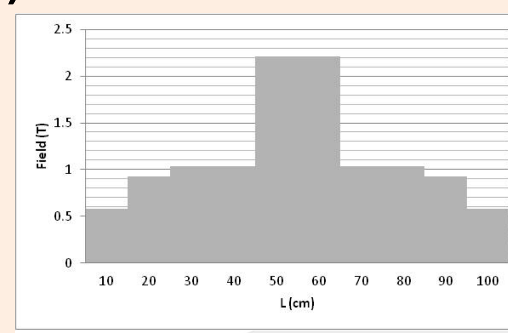


Emittance 0.75 nm-rad (0.43 if round beam) 207 keV/turn
Dipoles electromagnets at 0.8 T
No LG.



LG+anti-bend version:
Emittance 0.68 nm-rad (0.37 if round beam) 251 keV/turn

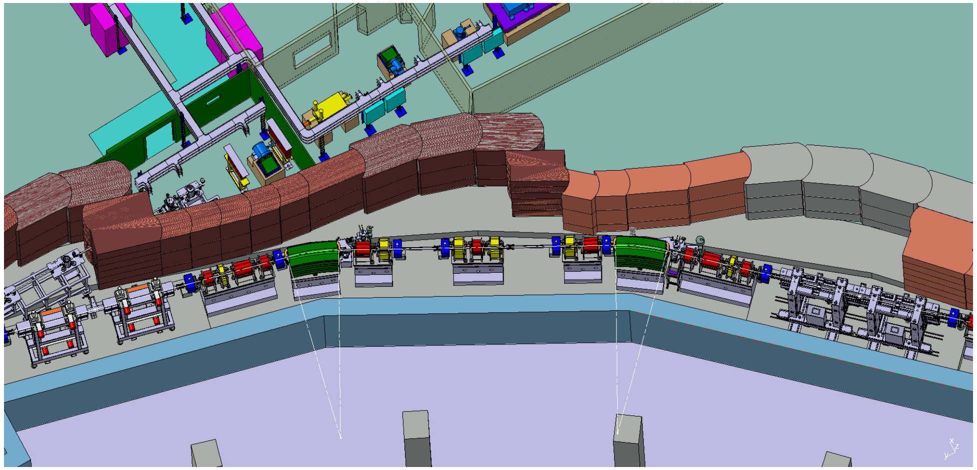
The 2 and 3 dipoles in LG with central field at 2.2 T.



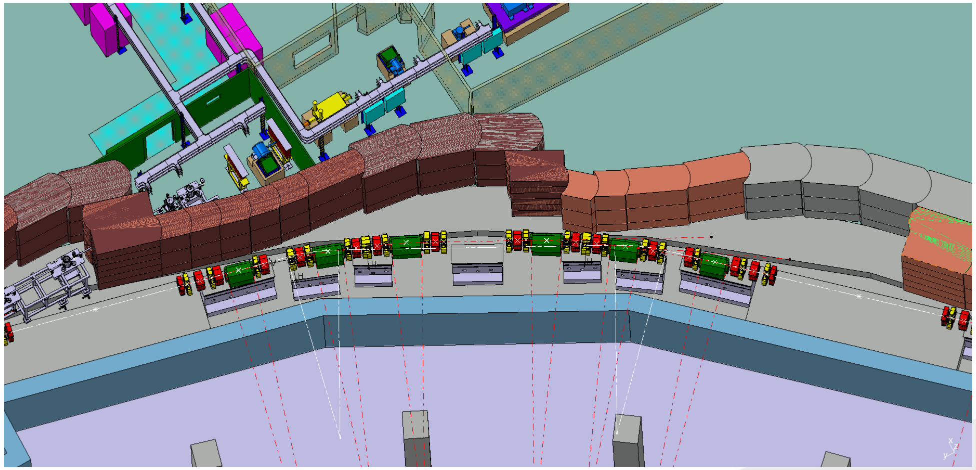
Large free space for IDs or other (4.5 + 3 m) , lower quadrupole strengths , less magnets, larger dynamic aperture. Higher energy possible (but at a higher emittance).

Elettra 2.0 Lattice

Best configuration up to now, satisfying all requirements, including the free space for IDs is based on a special six-bend achromat (S6BA). Versions that minimize interferences and induce minimal position shift of the dipole beam lines were examined.



Elettra



Elettra 2.0

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Magnet List for S6BA

Dipoles

name	L_{mag} (m)	k	B0 (T)	B1 (T/m)	Angle (°)	ρ (mm)	N	sum
BF1	0.75	-1.91	0.5585	12.7	3.6	11937	24	72
BF2	0.84	-2.03	0.7896	13.5	5.7	8444	48	

Quadrupoles

name	L_{mag} (m)	k	B1 (T/m)	Ø (mm)	$\|B_{pole}\|$ (T)	N	sum
Q1	0.13	-2.840	18.93	26	0.246	24	192
Q2	0.22	5.774	38.49		0.500	24	
Q33a	0.13	-0.450	3.00		0.039	24	
Q33b	0.22	6.200	41.33		0.537	24	
Q333a	0.22	6.780	45.20		0.588	24	
Q333b	0.22	6.492	43.28		0.563	24	
Q4_1	0.22	5.780	38.53		0.501	24	
Q4	0.22	6.220	41.47		0.539	24	

Sextupoles

name	L_{mag} (m)	m	B2 (T/m²)	Ø (mm)	$\|B_{pole}\|$ (T)	N	sum
SF	0.15	253.3	253.3	32	0.105	24	240
SD*	0.15	-254.7	3735.2		0.478	24	
SD2*	0.15	-253.3	6200.0		0.711	24	
SFIS	0.24	250.0	3666.7		0.469	24	
SDL*	0.15	-253.3	3715.5		0.476	48	
SFMSL	0.18	265.6	3894.9		0.499	24	
SDE*	0.12	-183.3	2688.4		0.344	24	
SD0	0.12	-33.3	489.0		0.063	24	
SEXP	0.12	45.0	660.0		0.084	24	

Correctors

name	L_{mag} (m)		N	sum
Comb (*)	nan		120	192
Alone	0.12		72	

In total
72+192+240+(120)+72
= 576 (696) magnets
(50 A - 20V)

Actual machine about half 24 + 108 + 72 + 88 = 292

Dipole power each (422 - 700 W)

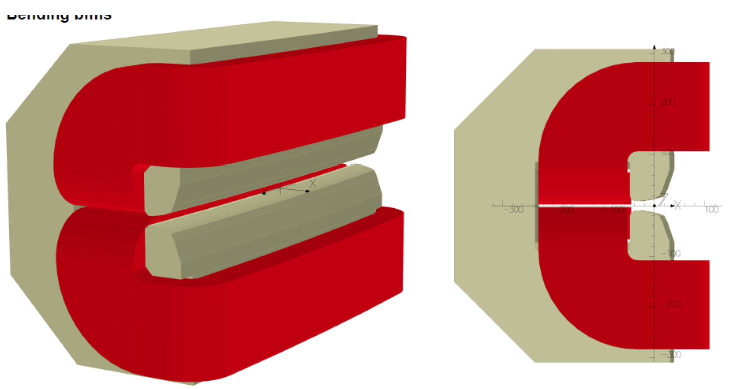
Quad power each range (60 - 178 W)

Sextupole power each range (73 - 222 W)

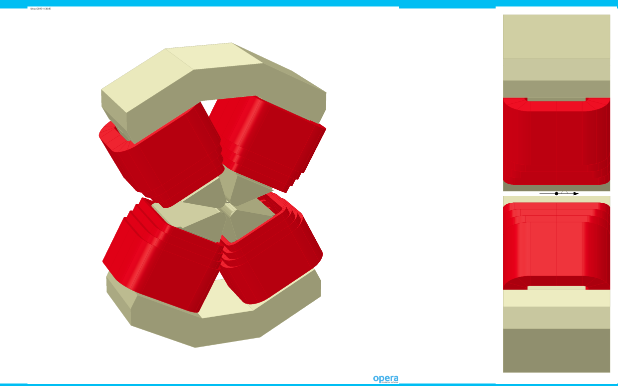
Magnets and PS's air cooled

Magnets

The short intra-magnet available space led us to design magnets with Lm≈Lp (max 10 mm difference). Use of new materials such as Cobalt – Iron alloys will also be considered

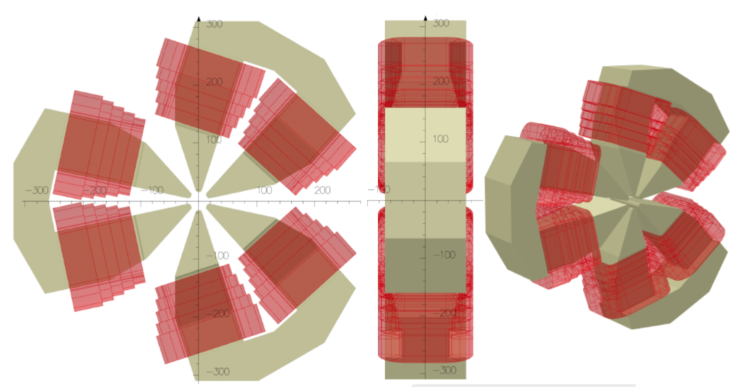


The bending integrated quadrupole component is done by only the pole profile geometry. In order to optimize space and performances, different coil and frame geometries are evaluated. Space between the pole terminations will be employed in order to obtain the requested frame stiff.



The quadrupole designs were developed with the vacuum chamber in order to resolve all the possible transversal interferences (beam lines). Asymmetric poles geometry has been opted.

The sextupole magnets have the higher design issue. The transversal interferences between coils and vacuum chamber are resolved.



Ref. D. Castronovo (Opera)

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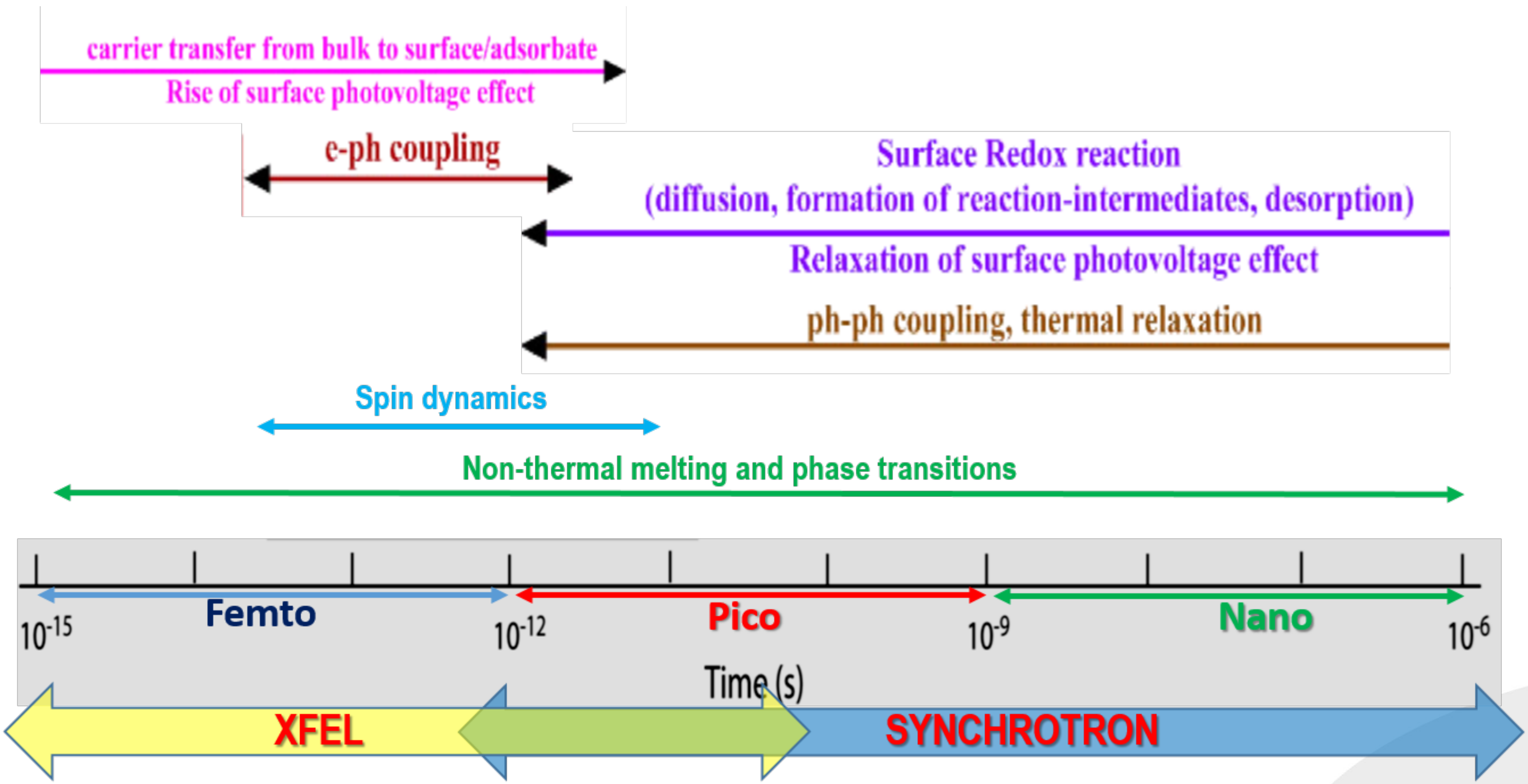
Other facts

- ✓ Use of some permanent magnet dipoles is also considered
- ✓ Including errors and the existing IDs the dynamic aperture is ±7 mm horizontally and ± 2.5 mm vertically. This aperture permits off axis injection with an efficiency of more than 95%
- ✓ Lifetime is 6 hours at 2 GeV and with the third harmonic cavity (3HC, bunch lengthening) will be 18 h
- ✓ Intra-beam scattering increases the emittance by 90% at 400 mA however using the 3HC the effect is reduced down to 40%
- ✓ Vacuum chamber best compromise (considering also the magnet power) seems to be a circular cross section with 25 mm external diameter. For the long straight sections the current vertical dimension of 9 mm is assumed. Material stainless steel and aluminium.
- ✓ The impedances of the low gap chambers and the rf transitions dominate. Estimated 230 kohm/m for both planes. Microwave threshold 0.6 mA for a bunch length of 5 ps.

Short pulses, why in SR?

There is a range of time resolved experiments that require high repetition rate without damaging the sample



Courtesy M. Kiskinova

Controlling the electron pulse

$$\sigma_\tau = \sqrt{\frac{\alpha E}{2\pi V_{RF} f_{RF} f_{rev} \cos(\varphi_s)}} \left(\frac{\sigma_E}{E}\right)$$

- Low alpha
- Increasing the rf power and/or frequency

Assuming 2.4 MV effective RF gap voltage for S6BA the bunch length is 5 ps. For 2.5 ps one needs 10 MV

But it is not all the story as we shall see…

- Employing double higher harmonic cavities
- Using crab cavities
- (Femto) bunch-slicing

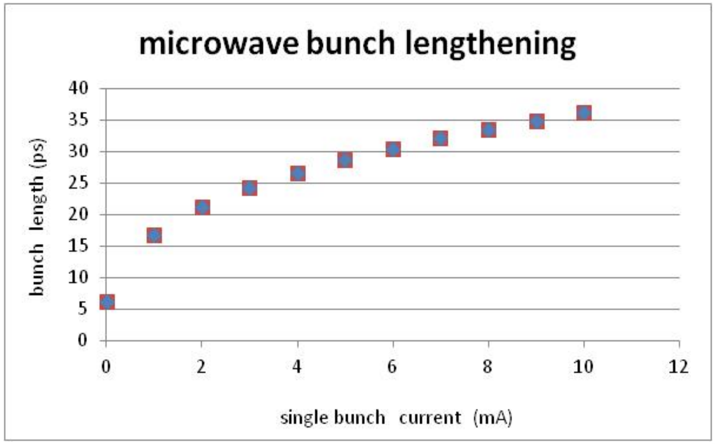
Intensity vs bunch length

Unfortunately the bunch length changes with the intensity. The smaller the emittance is the stronger the magnets should be resulting in smaller vacuum chamber cross sections which in its turn increases the electromagnetic impedance of the vacuum chamber which amongst other problems lengthens the electron bunch.

$$\left|\frac{Z_{//}}{n}\right| \leq \frac{8\ln 2}{2\pi}\frac{hV_{RF}\cos(\varphi_s)}{\sqrt{2\pi I_b}}\left(\frac{\sigma}{R}\right)^3$$

VRF MV	Threshold current (mA) / bunch	BL (sigma) ps
2.4	0.57	5
3	0.5	4.4
4	0.43	3.8
14	0.23	2

For higher than threshold



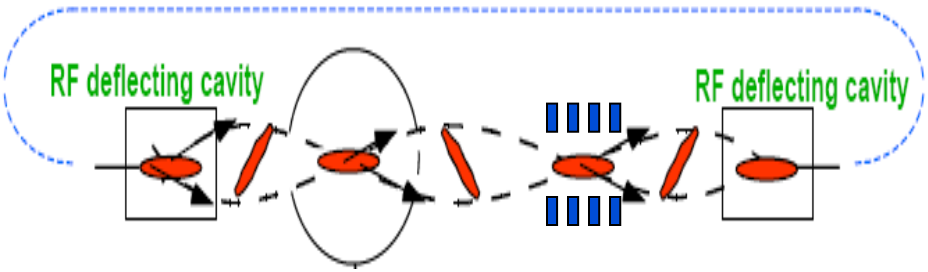
Thus increasing the main RF voltage or decreasing alpha does not always help since it cannot serve all users simultaneously

Tricks to mitigate

Crabbing

Double detuned higher harmonic RF.

Dedicated straight section is needed

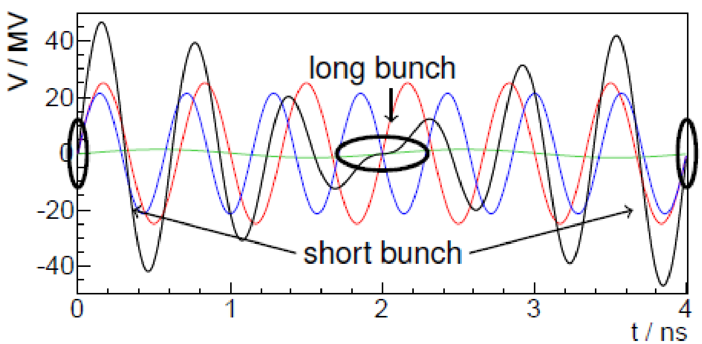


A. Zholents, P. Heimann, M. Zolotorev, J. Byrd, NIM A 425, 385, (1999).

$$\sigma_\tau = \frac{E}{2\pi V_c f_{c-rf}} \sqrt{\sigma^2_{y',e} + \sigma^2_{y',ph}}$$

Assuming a 3rd harmonic crab cavity (1.5 GHz with 3 MV) and beam divergences of the order of 15 micro-rad the x-ray produced pulse is 1 ps and since the bunch revolves the impedance does not have time to interfere and lengthen the bunch.

The variable bunch length scheme, proposed at HZB (BESSY) (*G. Wüstefeld et al. "Simultaneous long and short electron bunches in the BESSY II storage ring". In: Proceedings of IPAC201THPC014 (2011),pp. 2936–293)* , Claim to get 1.7 ps short bunch with some 0.8 mA per pulse



SE: Longitudinal space implications

Two frequency crab cavities scheme:
X. Huang, Phys. Rev. Accel. Beams ***19*** *024001 (2016)* Creating like above but half bunches are tilted thus show a shorter longitudinal profile.

Side Effects: Emittance growth, brilliance and transverse coherence loss

Elettra and Elettra 2.0

Parameter	Units	Elettra	Elettra 2.0
Circumference	m	259.2	259.2
Energy	GeV	2 - 2.4	2
Horizontal bare emittance	pmrad	7000	190-250
Vertical emittance	pmrad	70 (1% coupl)	2.5
Beam size @ ID (σx,σy)	μm	245 , 14 (1% coupl)	43 , 3
Beam size at short ID	μm	350 , 22 (1% coupl)	45 , 3
Beam size @ Bend	μm	150, 28 (1% coupl)	17 , 7
Bunch length (zero current)	ps	17 (100 with 3HC)	5.6 (70-100 with 3HC)
Energy spread	DE/E %	0.08	0.07
Bending angle half achromat	degree	15	3.6 and 2x5.7

Brilliance with existing IDs

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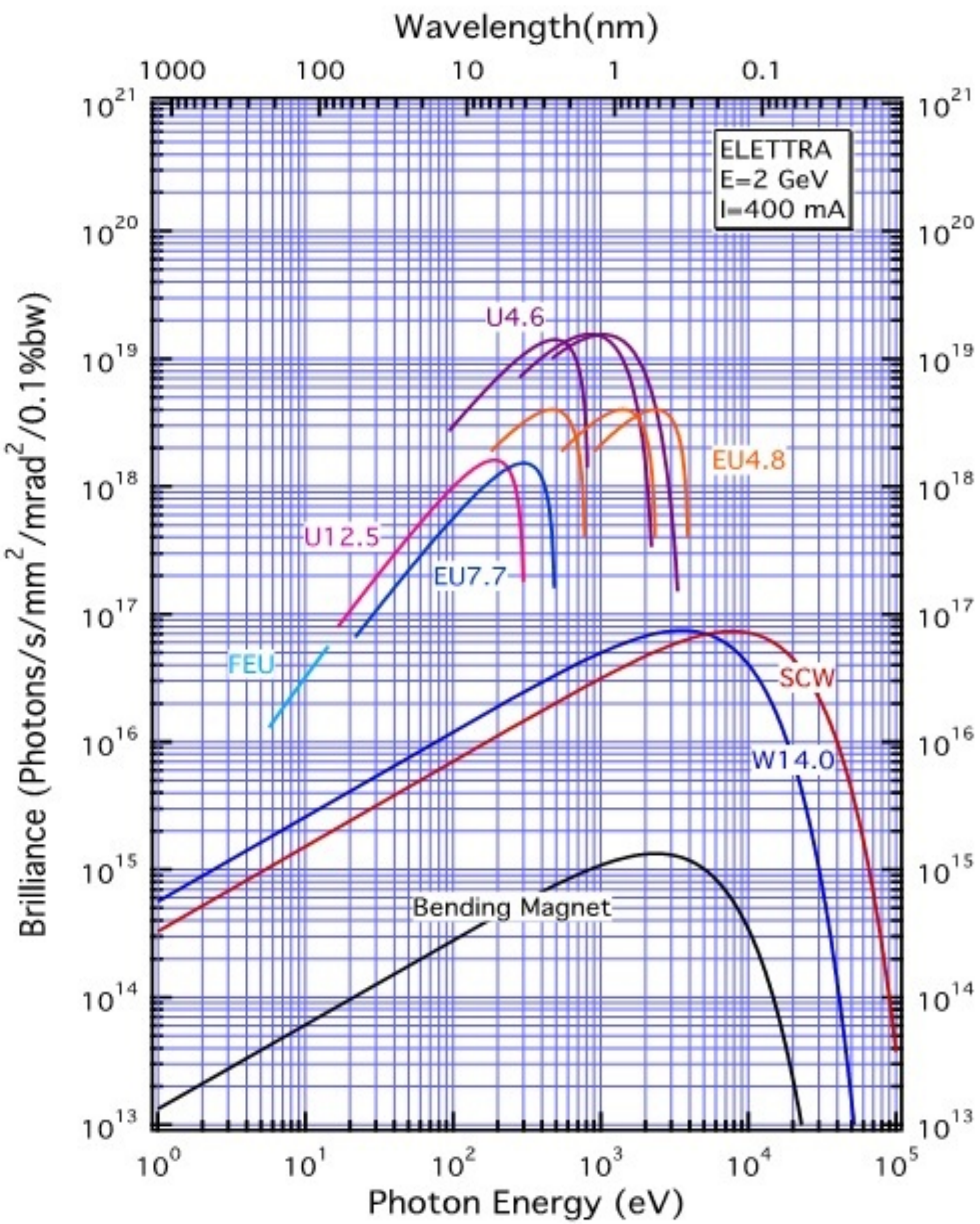
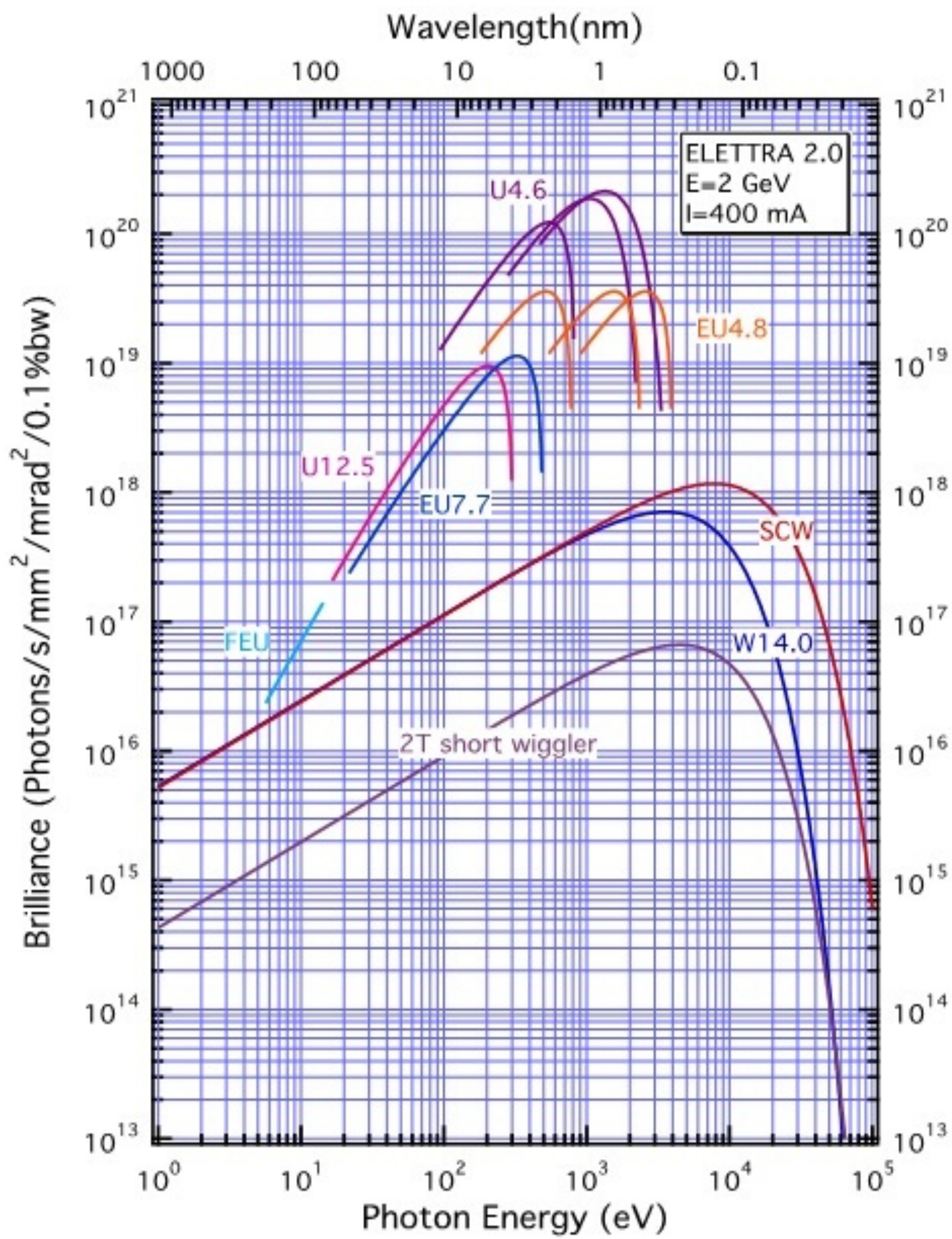




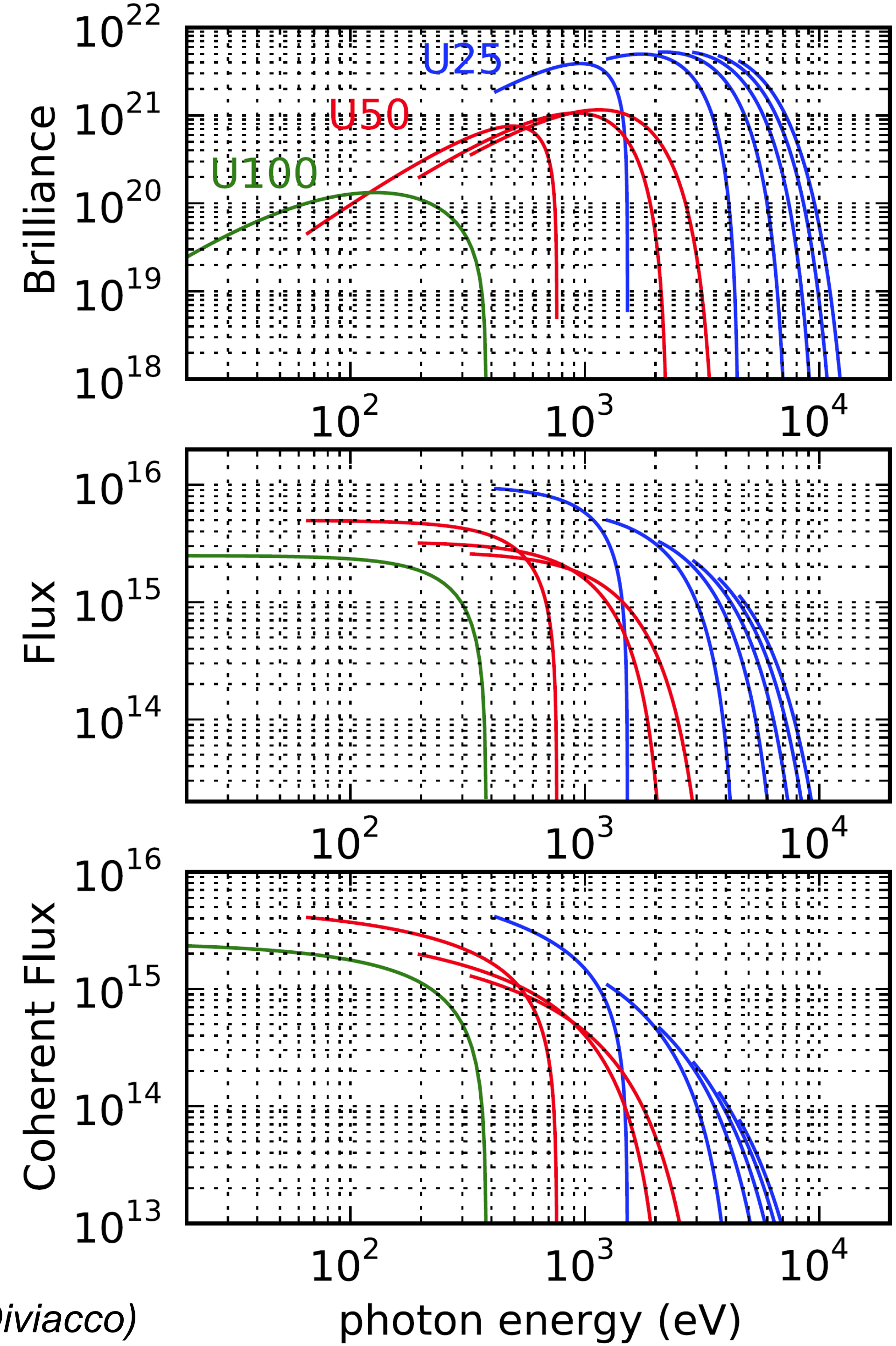
New IDs

Performance in case of new insertion devices (brilliance, flux and coherent flux of three hypothetical IDs well matched are shown) with the following characteristics:

U100 *period = 100 mm,*
N_{per} = 45, K_{max} = 9,

U50 *period = 50 mm,*
N_{per} = 90, K_{max} = 4.5,

U25 *period = 25 mm,*
N_{per} = 180, K_{max} = 2.3



(Ref. Bruno Diviacco)

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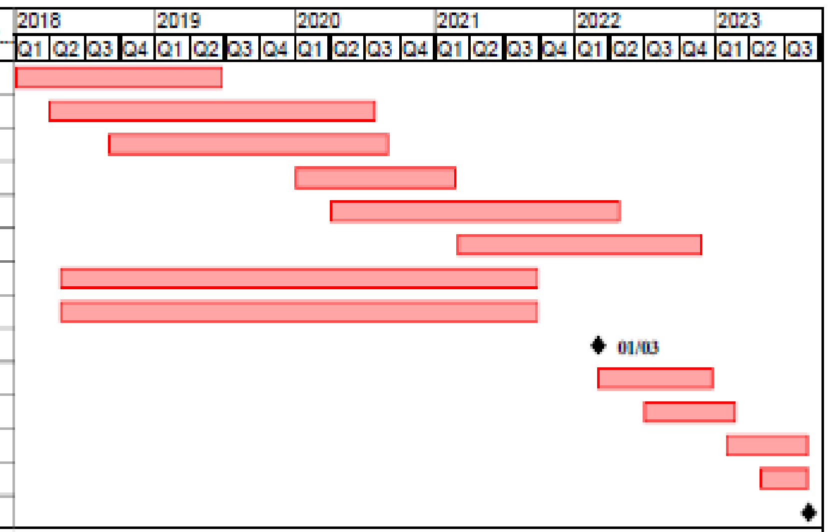
Scheduling

At the moment 5 years and 9 months with 50 FTEs are considered sufficient for the completion of the project.
This period includes final study and drawings, purchasing and construction, decommissioning of the old machine, installations and commissioning of Electra 2.0.
Additionally the system leaders were asked to consider also the Electra 2.0 requirements when upgrades of the present machine are needed.

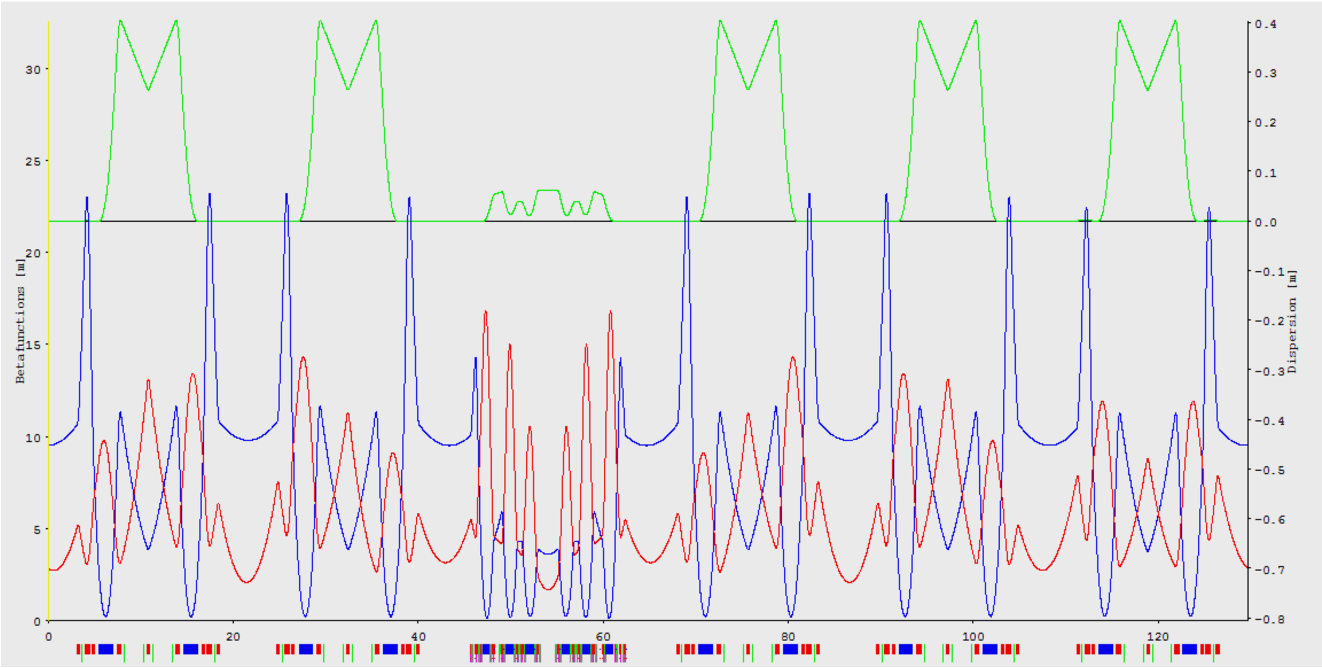
	Name	Durati...	Start	Finish	P...	R...
1	Technical design study	390 ...	01/01/18...	28/06/19...		
2	Engineering Design	610 ...	02/04/18...	31/07/20...		
3	Prototyping	524 ...	01/09/18...	03/09/20...		
4	Calls for tender	303 ...	01/01/20...	26/02/21...		
5	Manufactoring construction and t...	542 ...	02/04/20...	29/04/22...		
6	Preparation and assembly	458 ...	01/03/21...	30/11/22...		
7	Infrastructures upgrade	892 ...	01/05/18...	29/09/21...		
8	Beam Lines upgrade	892 ...	01/05/18...	29/09/21...		
9	End user mode	1 day?	01/03/22...	01/03/22...		
10	decommissioning	219 ...	01/03/22...	30/12/22...		
11	Installation	173 ...	01/07/22...	28/02/23...		
12	Accelerator tests/ commissioning	153 ...	01/02/23...	01/09/23...		
13	Beam line commissioning	90 d...	01/05/23...	01/09/23...		
14	Start Elettra2.0 user mode	1 day?	04/09/23...	04/09/23...		



Dark period

Dark period is estimated to 18 months. Can it be avoided? How?

Modular installations? Theoretically maybe yes, but practically it must be extremely complicated



Summary

- For Elettra 2.0 our S6BA optics is chosen as the best compromise to the various requests (up to now)
- The optics is very flexible and can accommodate a number of super-bends.
- Installation of insertion devices also possible in the middle of the arc. For the moment the space available there, is 1.6 m.
- The 1.0 version of the Elettra 2.0 conceptual design report is available.
- Other types of MBAs are also studied

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Elettra
Sincrotrone
Trieste