ALBA-II Lattice Design

robustness and performances with Simulated Commissioning

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The ALBA-II lattice team

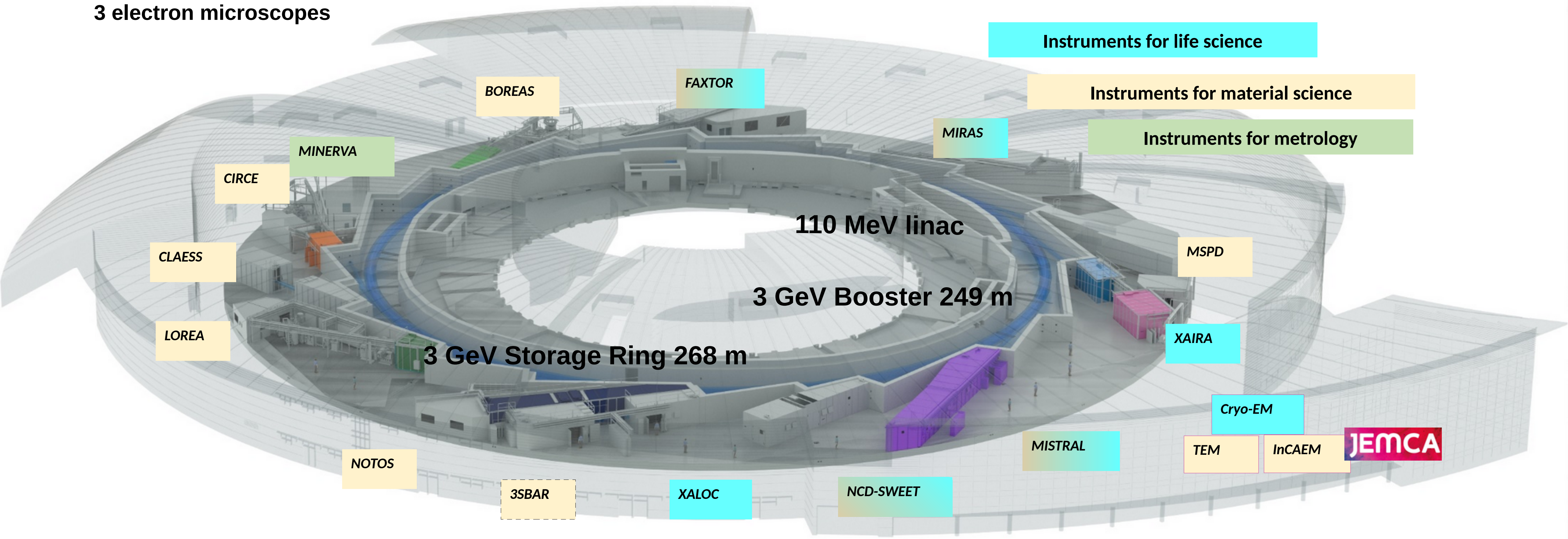
- Gabriele Benedetti: coordination, lattice design, injection
- Oscar Blanco: lattice design, non-linear optimisation, errors, injection, AT development
- Michele Carlà: lattice design, non-linear optimisation, UFO development, injection
- Zeus Martí: errors, tolerances and correction, commissioning, AT development

Outline

- ALBA at present, constraints and requirements for ALBA-II
- The 5BA cell for ALBA-II and pseudo 16-symmetry solution
- Injection scheme and optics for the injection section
- Lattice optimization process with UFO and NSGA2
  - Dynamic and Momentum Apertures
- Robustness and performances with errors evaluated with Simulated Commissioning
  - Injection efficiency and Touschek Lifetime

ALBA facility in 2026

13 operating beamlines + 1 in 2027
3 electron microscopes



Constraints, requirements for ALBA-II

Requirements:

- Emittance < 400 pm·rad
- Straight sections length > 4 m and $\beta_x^* \approx \beta_y^* \approx 2$ m
- Dynamic Aperture > 6 mm for off-axis injection → small tune shift with amplitude
- Lifetime > 10 h → full coupling + large momentum acceptance → small tune shift with energy
- Injection efficiency of 100%

Constraints:

- Preserve 12 ID source points + SR circumference → 3 different lenghts for straight sections
- Keep energy 3 GeV
- Re-use current booster 10 nm·rad
- Vacuum chamber aperture ~ 16 mm
  - Reverse bend gradient < 70 T/m
  - Quad gradient < 100 T/m
  - Octupoles < $7 \cdot 10^5$ T/m^3
  - Sextupoles < 5000 T/m^2

Choices for the ALBA-II MBA lattice

1) Lattice based on **5 Bend Achromat cell with distributed sextupoles**
   (*G.Benedetti, et al. Status of lattice studies for ALBA-II. IPAC'26*)

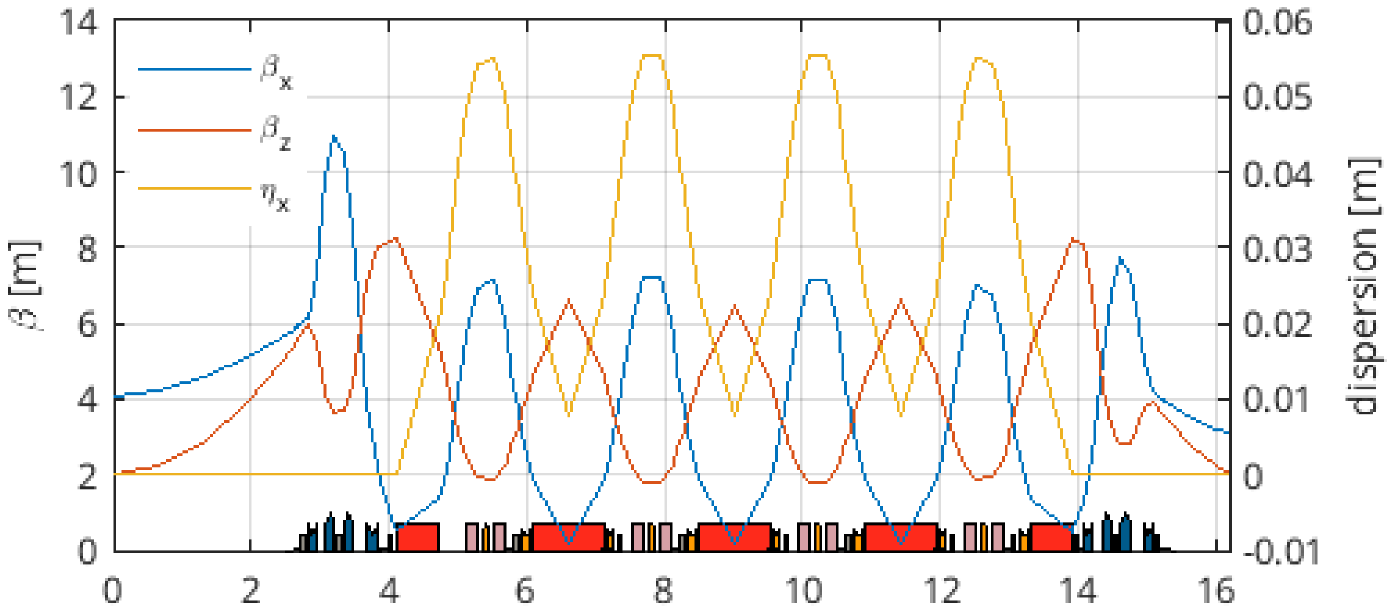
2) Developing a **lightweight, fast and efficient tracking code running on GPUs (UFO)** to speed-up the evaluation of lots of lattices
   (*M.Carlà. UFO, a GPU code tailored toward MBA lattice optimization. IPAC'22*)

3) **Injection** scheme based on **on-energy off-axis** technique with a **non-linear kicker**
   (G.Benedetti, et al. A double-dipole kicker for off and on-axis injection into ALBA-II. IPAC'22)

4) Increasing Touschek lifetime working with an **AC skew quadrupole tuned at Q_x-Q_y**
   (M.Carlà, et al. Phys.Rev.Accel.Beams, vol. 28, p. 082803, Aug. 2025,
   and dedicated ***talk by Michele Carlà in this workshop****)*

5) Test performances and robusteness of the lattice with the **Simulated Commissioning** toolkit
   (T.Hellert, et al., Phys.Rev.Accel.Beams, vol. 25, p. 110701, Dec. 2015)

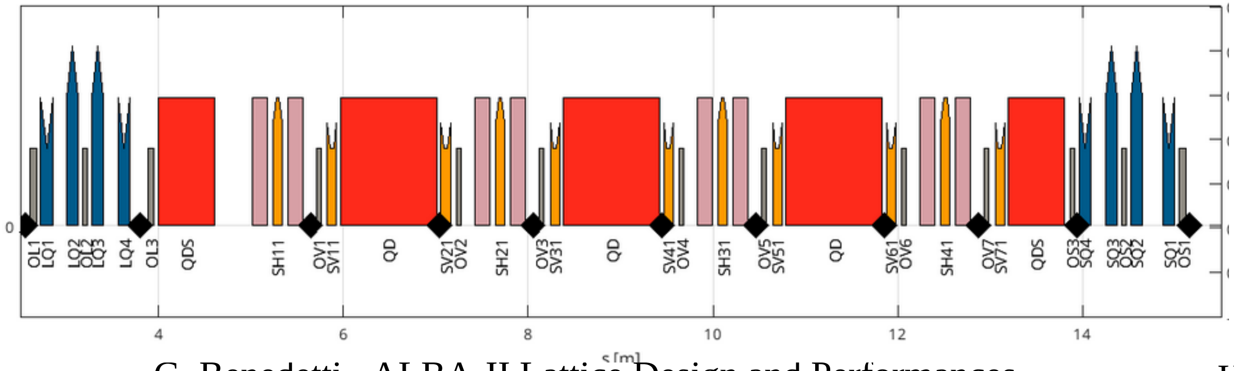
The 5BA cell



Arc:
5 bends with transverse gradient: QD/QDS
8 anti-bends: QF/QFS
11 sextupoles: 4 SH + 7 SV
7 octupoles/skew quads: OV

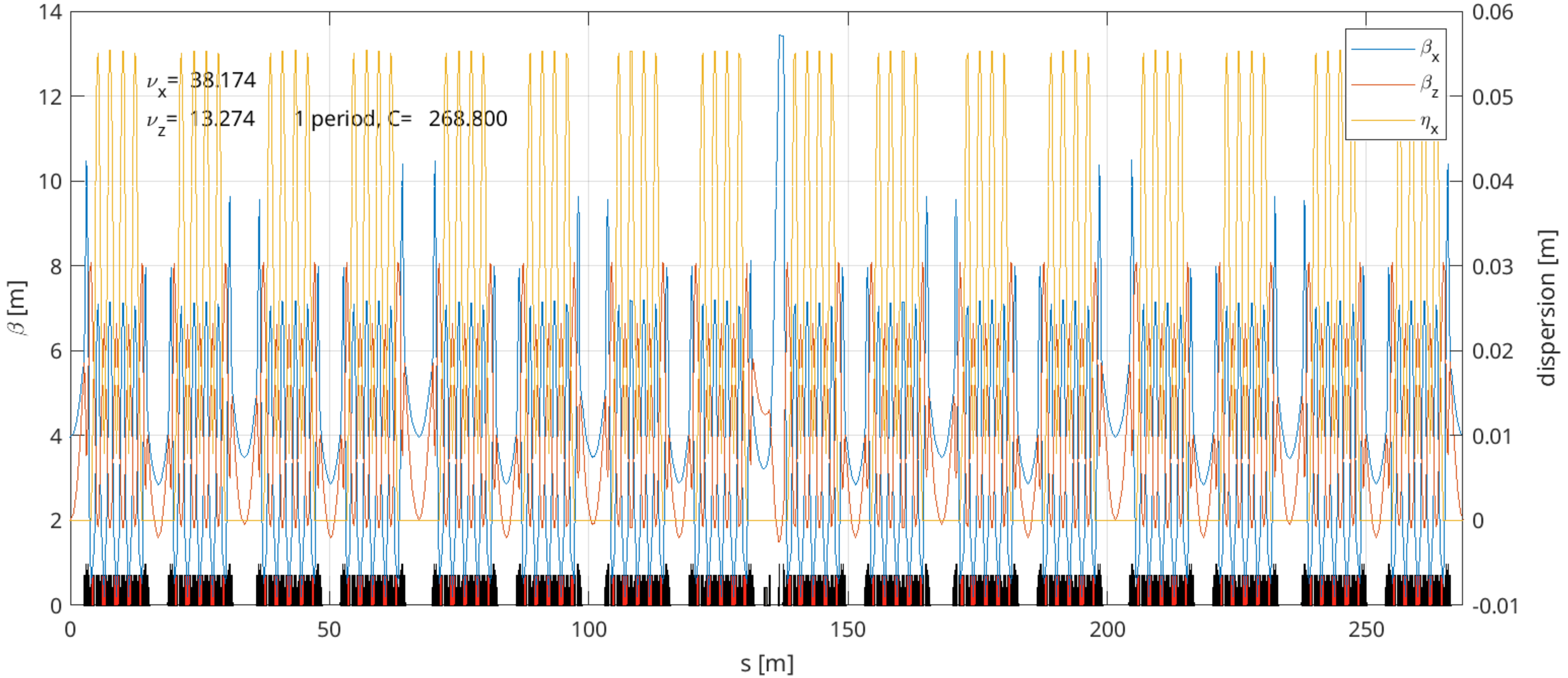
Matching section:
4 quads: Q1/Q2/Q3/Q4
3 octupoles: O1/O2/O3

3 different straight section lengths:
Same arc for the 16 cells, three different lengths of the straight section to match the the existing beamlines



Pseudo 16-periodic lattice (A2L007d)

16 cells with 3 different straight section lengths 5.2 m / 4.6 m / 3.9 m and same phase advance



- Emittance: 200 pm·rad (**154pm·rad / 77pm·rad @50% coupling**)
- Mom. Compaction: $1.1 \cdot 10^{-4}$
- β_x at SS: **4.1 / 2.9 / 3.6 m**
- β_y at SS: **1.9 / 1.6 / 1.8 m**
- Tunes: 38.17 / 13.28
- Chromaticity: -100 / -35

Pseudo 16-fold symmetry on- and off-energy

To obtain 16-fold periodicity:

1) The arcs of the 16 cells are identical

2) For **on-energy** periodicity:

   - 16 matching sections, included the injection one, tuned to the **same phase advances**

3) For **off-energy** periodicity

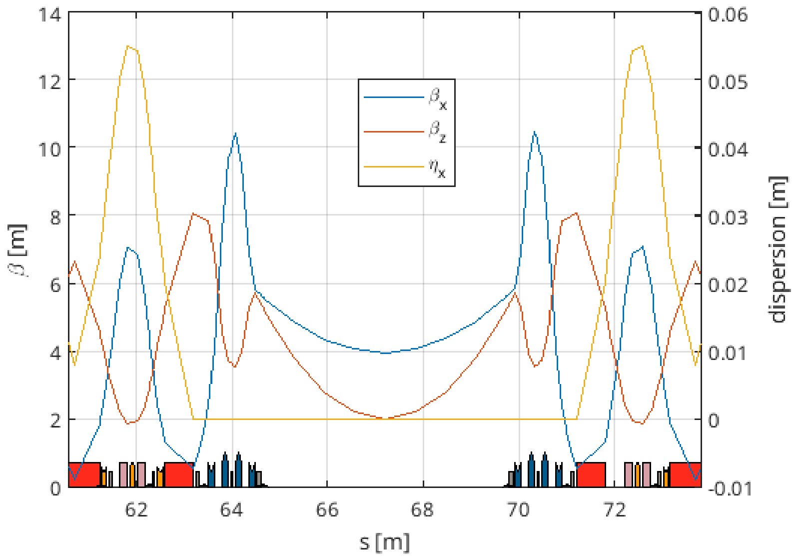
   - 16 matching sections, injection included, with horizontal **chromatic amplitude function (**W_x**) matched** at the ends

Main params of the storage ring A2L007d

LATTICE	ALBA	ALBA-II A2L007d	
Energy	3	**3**	*m*
Emittance ε_0 (ε_x/ ε_y w/ IDs and 50% coupling)	4500	**200 (154 / 77)**	*pm·rad*
Tunes	18.15 / 8.36	**38.17 / 13.28**	
Chromaticity	-39 / -29	**-100 / -35**	
Mom. compaction	$8.9\cdot10^{-4}$	**$1.1\cdot10^{-4}$**	
Energy spread	$1.0\cdot10^{-3}$	**$1.2\cdot10^{-3}$**	
Energy loss/turn	1025	**925**	*keV*
Damping times	4 / 5 / 3	**3 / 6 / 7**	*ms*
Lifetime @ 250 mA, 0.5% coupling	20	**...**	*h*
Lifetime @ 300 mA, 50% coupling, HC	...	**10**	*h*
Straight section length	7.8 / 4.2 / 2.3	**5.2 / 4.6 / 3.9**	*m*
β_x at straight centre	2.0	**4.1 / 3.6 / 2.9**	*m*
β_y at straight centre	1.8	**2.0 / 1.8 / 1.6**	*m*

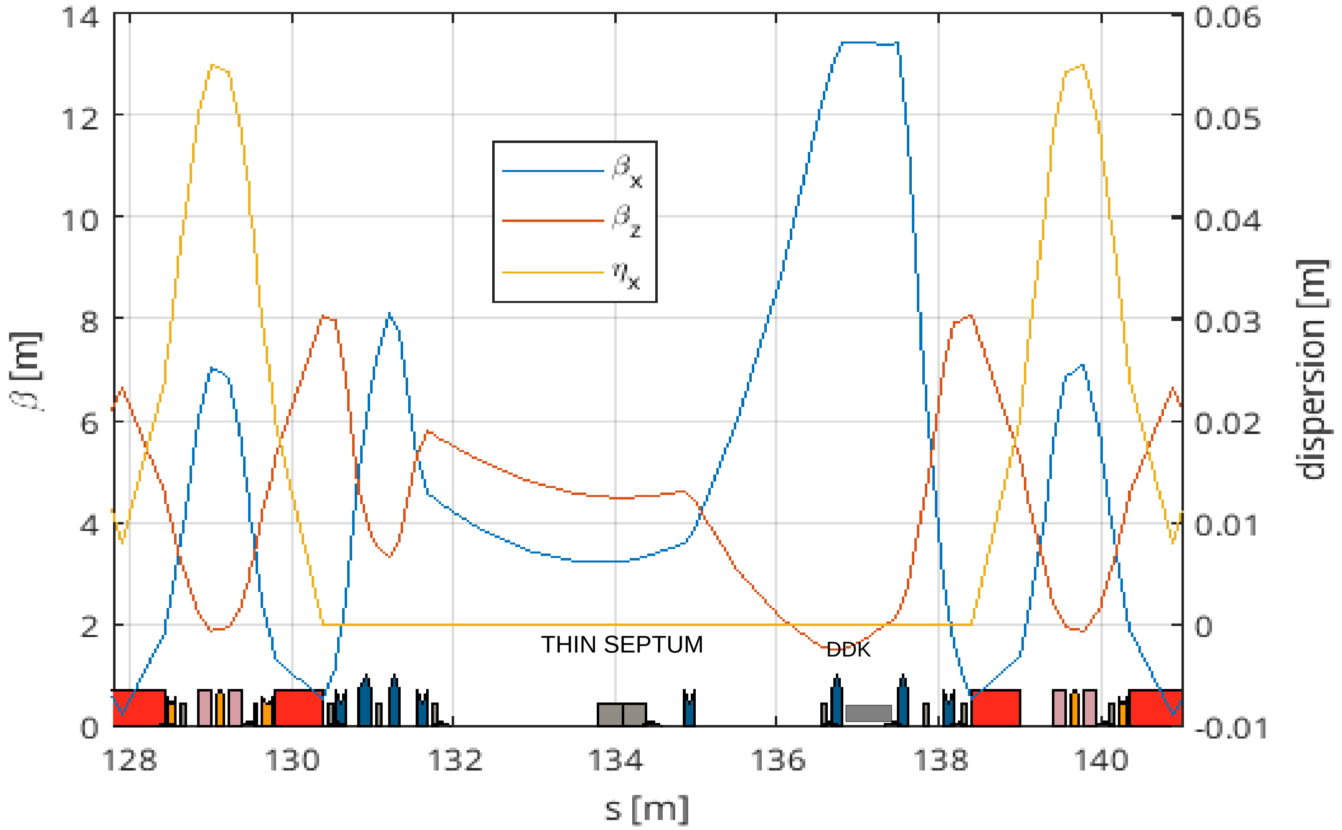
Optics for the injection section

Standard Long straight sections: betas with symmetric waist.
Two of them are used for the RF cavities and one for a beamline.



Medium and Short straight sections are similar to the Long one: all matched to have the same phase advance.

Injection section is a modified Long straight: low β_x at septum, high β_x at DDK kicker



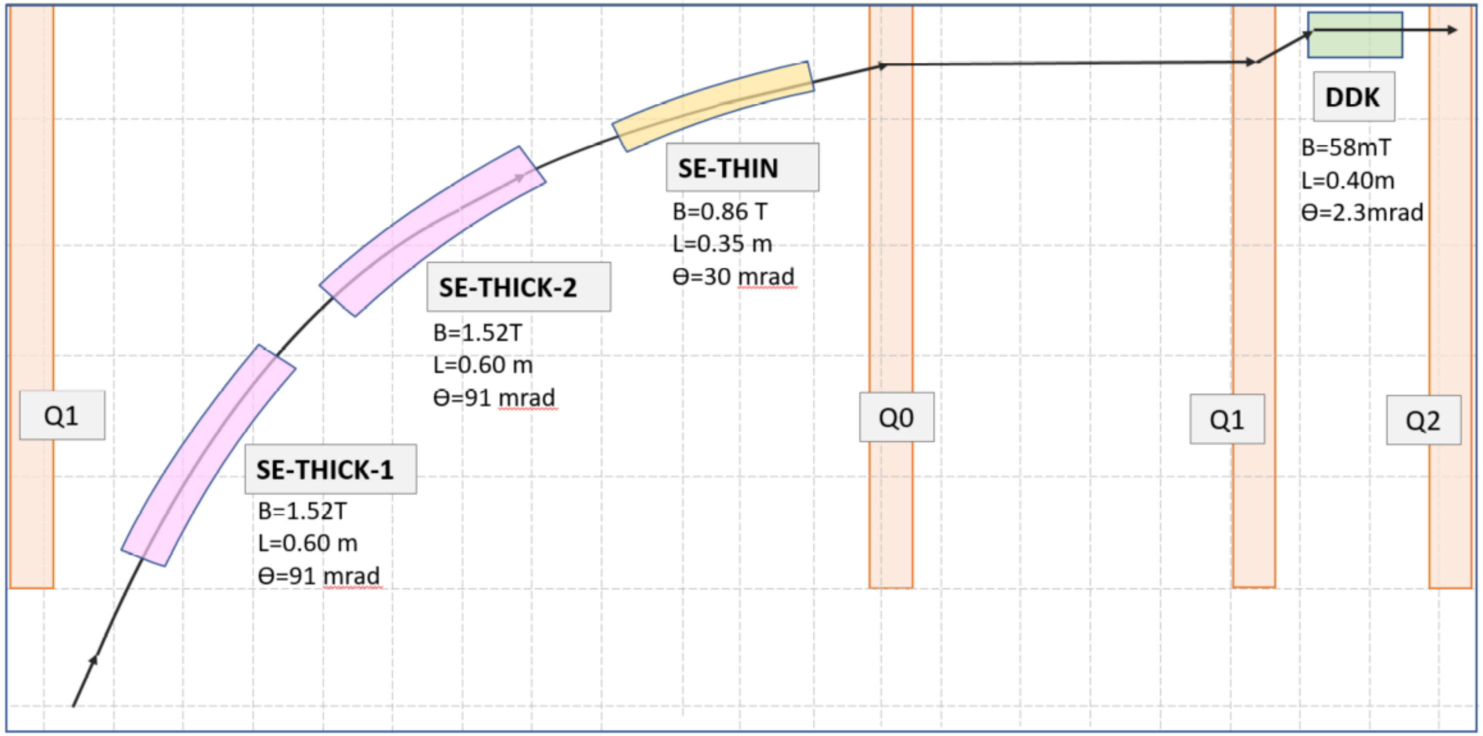
The phase advance is kept equal to all the other 15 straight sections
→ quasi 16-fold symmetry

G. Benedetti, et al. Progress on the 5BA lattice for ALBA-II. IPAC'25.

Magnets arrangement in the injection straight

All the magnets for the injection must be installed in one of our longest straight section which is only 5.2 m long.

- 2 thick septa (permanent magnets)
- 1 thin septum (pulsed)
- 1 pulsed non-linear kicker (DDK)

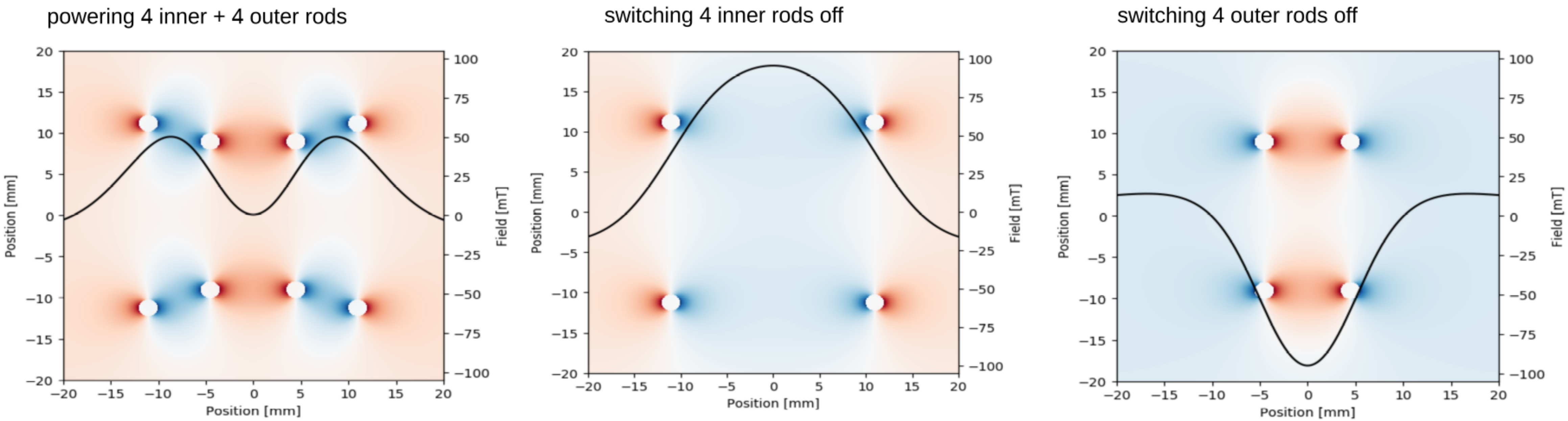


The low β_x at SE-THIN allows reducing the aperture of the thin septum → injected beam closer to the SR axis (-9 mm) → lower DDK kick

The high beta at DDK magnifies the dynamic aperture to more than 6 mm to allow off-axis injection at -5 mm

DDK: Double-dipole Kicker

The DDK is a novel pulsed non-linear kicker **developped at ALBA**:



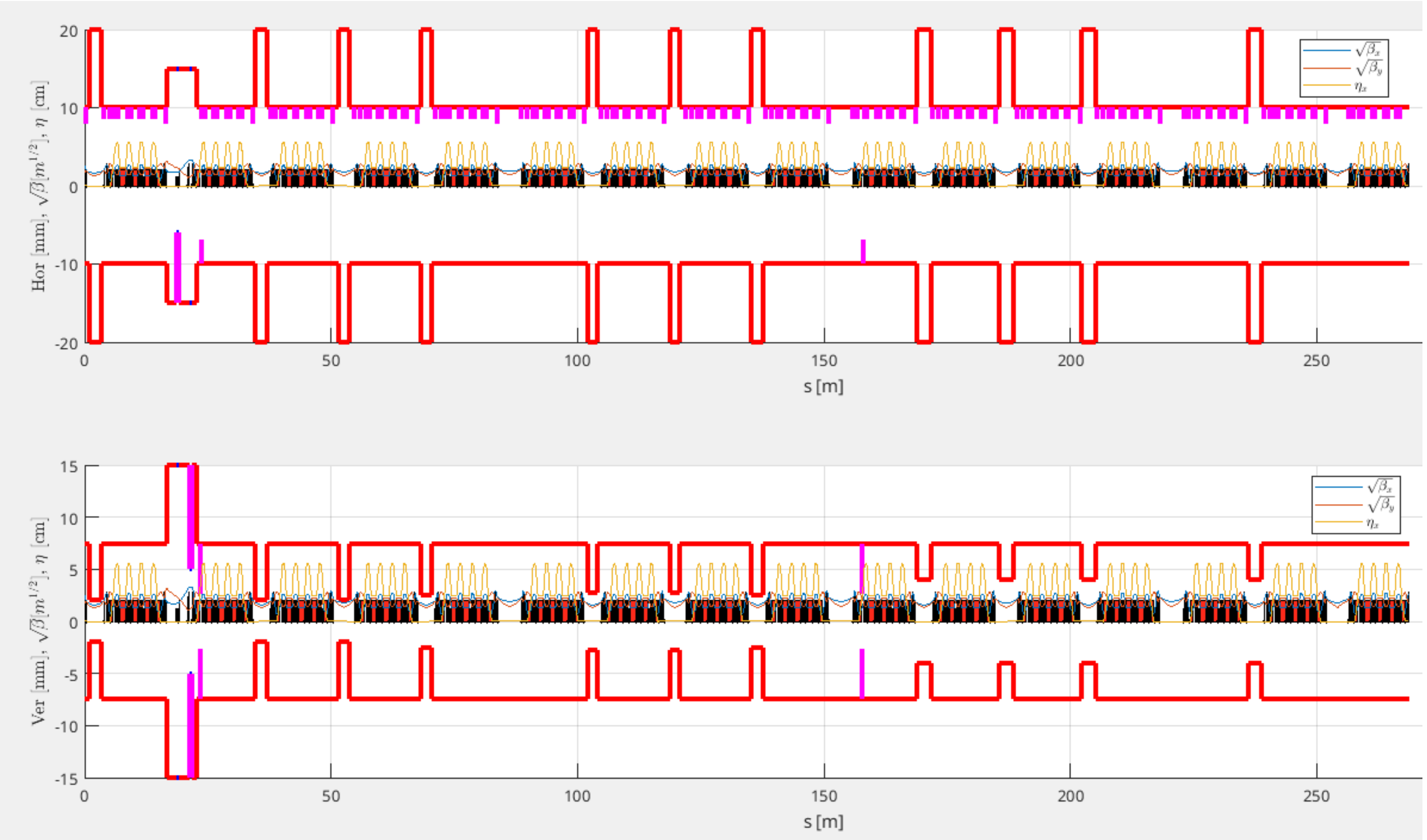
- Switching off either the inner or the outer rods, a dipole field is produced.
- **A dipole is needed for on-axis injection during the ALBA-II commissioning.**
- ALBA-II straight sections have very little room and **combining two kickers in one** will be very useful.

A **prototype of the DDK has been produced and successfully tested in ALBA in 2026**.
(*R.Muñoz, et al. Development and characterization of the double-dipole kicker prototype at ALBA. IPAC'26)*

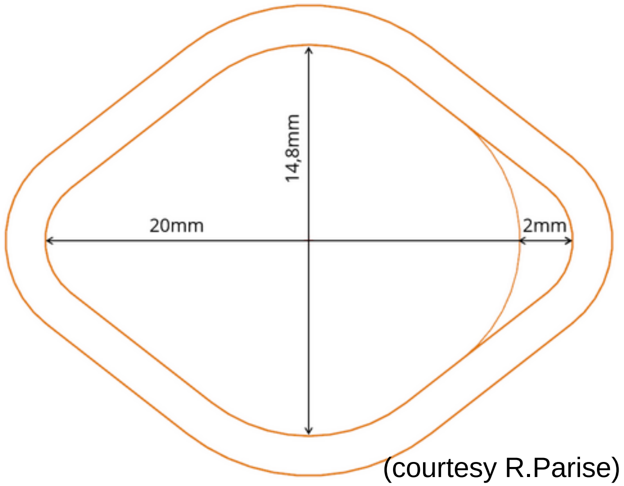
Lattice Optimization with UFO and 2 objectives

- Input is only the linear optics (tunes, betas at straights, drifts btw elements)
  - Systematic multipoles in anti-bends (QF, QFS) are included since they are the strongest ones
  - Initially, chromaticity corrected with 2 sextupole families, and 20% of the tune shift with horizontal amplitude with octupoles
- Tracking with UFO: 2 objectives NSGA2 algorithm for Python:
  - Used small random position errors per magnet (smaller than commissioning errors)
  - Calculate the 2 objectives: **Dynamic Aperture and Touschek Lifetime**
- Initial fast evolution (~2-3 hours) of about 100 generations with low population (100 rings), including :
  - Sextupole and Octupole ranges from 80% of initial value to maximum limit
  - Compare and evaluate the best solution
  - Cross-checking D.A. (“Flood Field” method) and Lifetime with AT2 code
- Keep optimising after adjusting ranges for a larger number of generations and population (typically 1000 rings per generation)
- Iterate increasing the number of sextupole and octupole families
  - Initial number of families: 11 sxt, 9 oct.
  - Final number of families: 33 sxt, 9 oct.
- The entire optimization process takes ~1-3 days

Rhomboid vacuum chamber physical apertures



Rhomboid vacuum chamber
H/V aperture = 20/14.8 mm



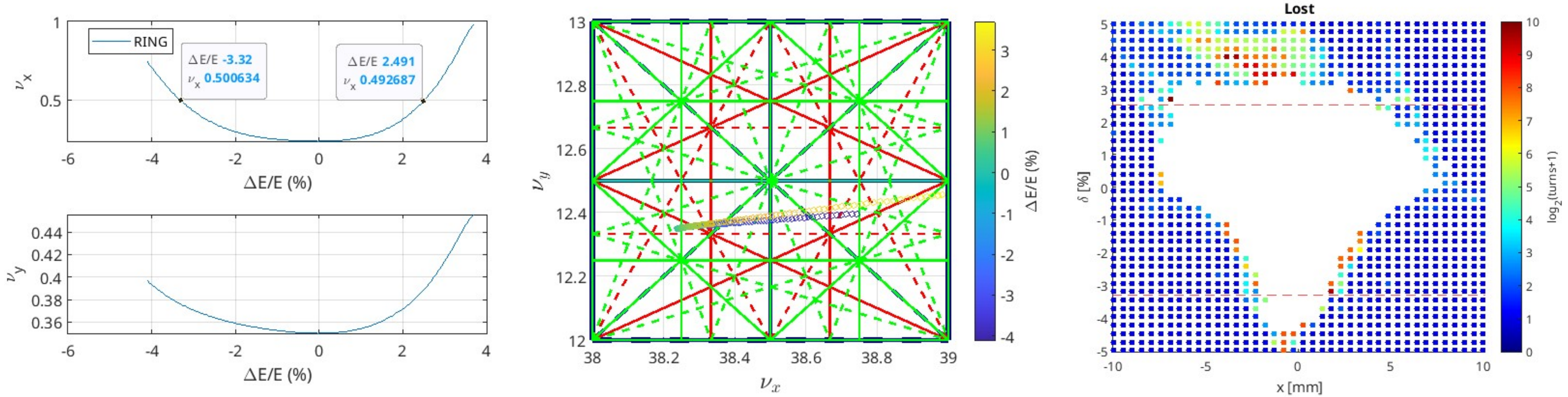
(courtesy R.Parise)

Asymmetric absorbers
Hor : +8 mm

Optimization and checks are calculated with these physical apertures.

Lifetime and crossing of resonance stopband

Touschek particles at +2.5% can cross the half-integer resonance without being lost if the passage is fast and the resonance stopband is sufficiently narrow

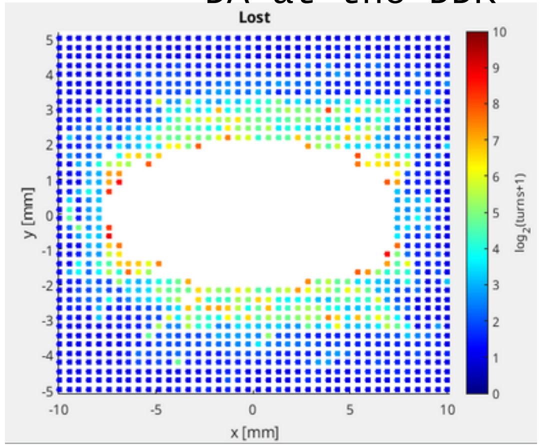


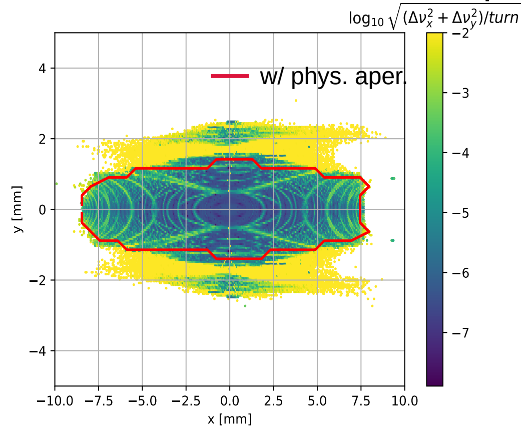
From +2.5% to +3.5% there is a small change in acceptance with a big contribution to Touschek lifetime.
For the lattice A2L007d case w/ HC and errors:
lifetime crossing ν_x= *0.5* is 15 hours, cutting at ν_x= *0.5* reduces to 11 hours

Only if our model of errors and corrections is very complete, particles crossing the stopband can be taken into account for lifetime.
Therefore, **we will take as educated guess the lifetime estimation cutting the energy acceptance when ν_x=*0.5*.**

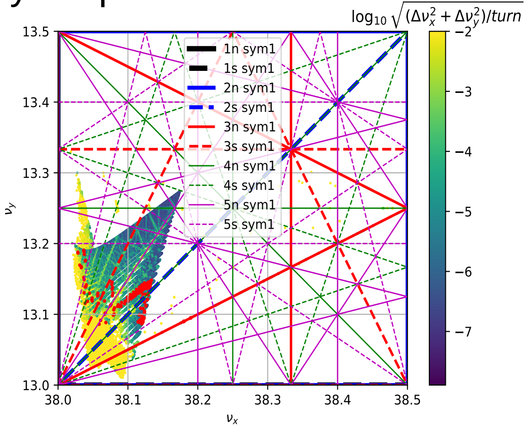
Dynamic and momentum aperture

DA at the DDK

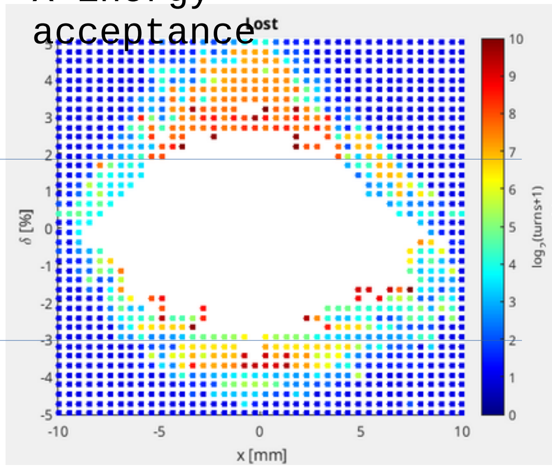




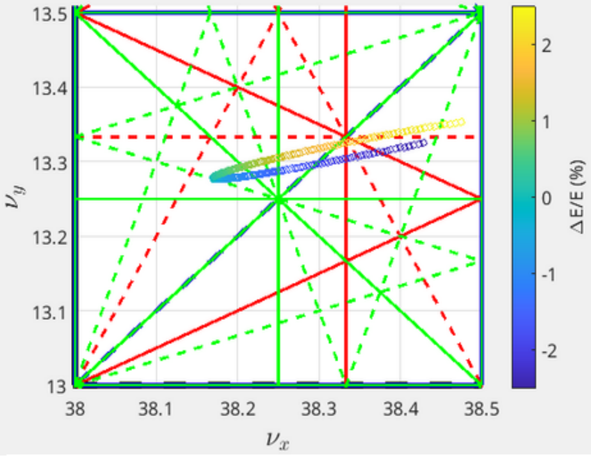
Frequency map at DDK

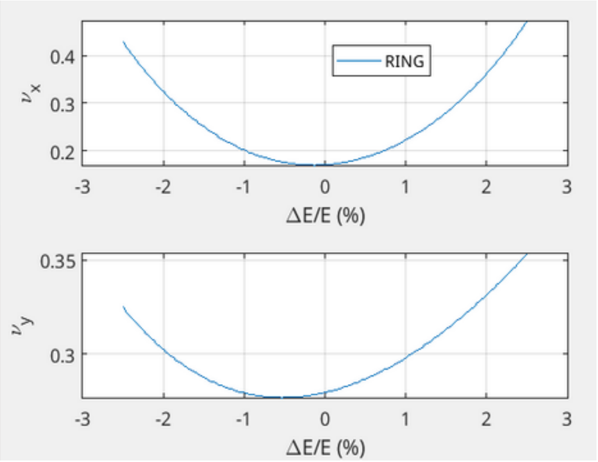


X-Energy acceptance



Tune shift with Energy



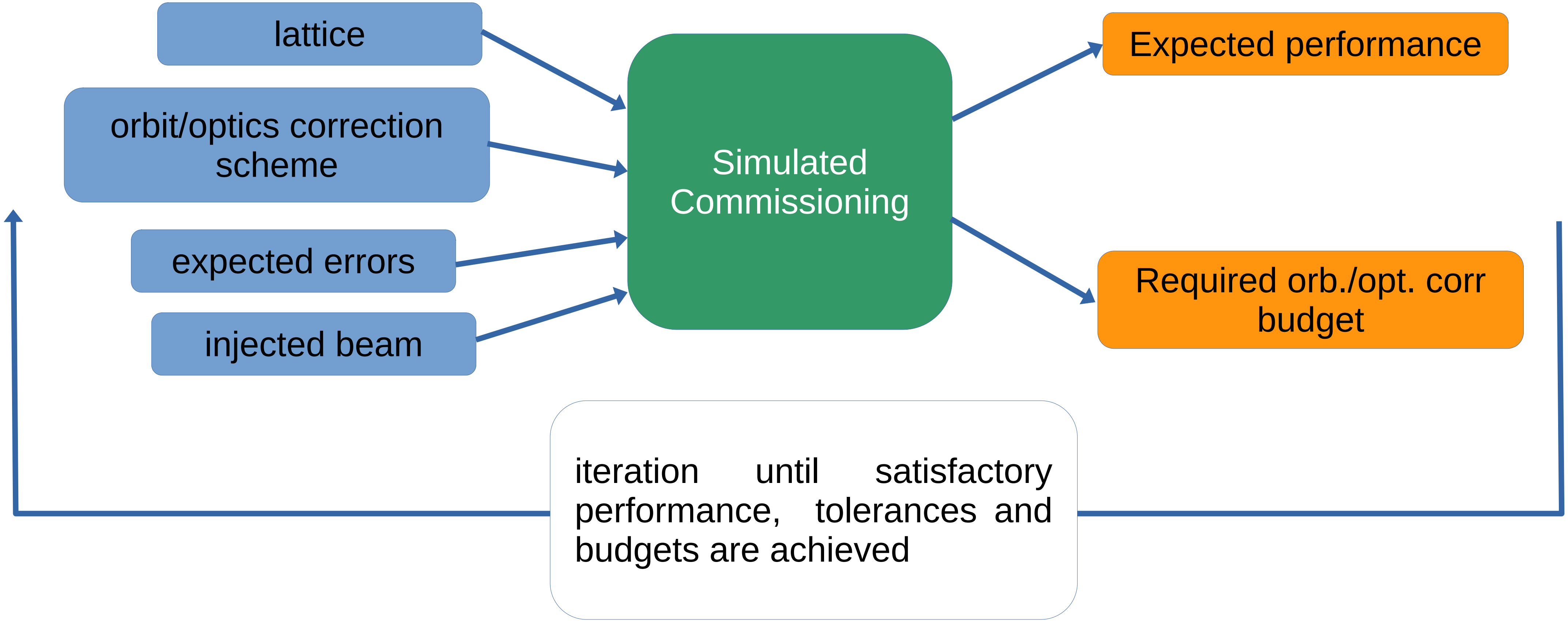


DA reaches -8 mm, which means the limit of the physical aperture

Momentum aperture renders a Lifetime of 10 hours.

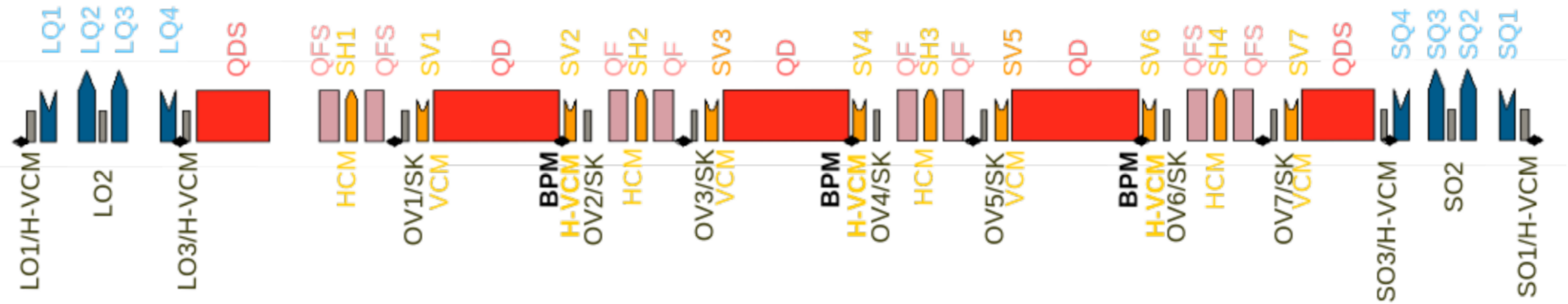
SC a tool for ALBA-II

The robustness, required correction budget and performances of the lattice are evaluated with the **Simulated Commissioning Matlab toolkit (SC)**



Correction Scheme

- **11 BPM**/Sector. BPM before and after **QD to allow fast angle polarization swich for beamlines (FaPS) .**
- H/V orbit corrector magnets (**HCM** and **VCM**) are **integrated** in octupoles and sextupoles. Total **11 CM** per plane and sector.
- Quads quadruplet (**Q1/Q2/Q3/Q4**) in the matching sections have independent power supply.
- **Combined Function dipoles** (CFD) QF, QFS and QD as optics knobs. Each magnet has a single power supply, used to correct the focusing errors, the combined dipole error is corrected with the HCM. **QDS (permanent magnet)** are not used for optics correction.
- **Arc BBA** performed with the skew quads embedded in the **octupoles**. Extra skews will be used to correct the DC coupling.
- **IDs** corrected with **matching quadruplet**, **QF** and **QFS**.



Commissioning simulations steps

DURING ON AXIS INJECTION:

- **Improve initial transmission. (Goal : 1st turn)**
  - Injection correction (3 BPM+BBA)
  - Perform trajectory corrections to reach one BPM at the time up to 1st BPM, 1st ARC, and 1st turn.
  - Perform correction to reach a 2nd turn.
  - Injection is now more realistic, starts at the Septum exit and includes a pulsed DDK.
  - Pre-BBA offset relaxation (a la M.Aiba).
- **TbT BBA (Goal : Reduce large unknown offsets in BPMS)**
  - Steer the beam through quads in the straights to estimate the BPM offsets in the straights
  - Steer the beam through skew quads in sextupoles to estimate the BPM offsets. In the arc.
  - Maybe not needed if BPM offset error < 300 μm.
- **Injection beam static error correction (Goal: Improve beam transmission in few turns)**
  - Identify and correct any mismatch at injection
  - Removed since we noticed it tends to go towards unrealistic corrections.
- **Sextupole (and octupole) ramp-up (Goal : Reduce sensitivity to energy loss/energy gain)**
  - Ramp up the sextupoles in steps to their nominal values while correcting the orbit
- **Main RF commissioning (Goal : Improve beam transmission over hundreds turns)**
  - Several cavities are included, synchronization step added.
  - Turn on the main cavities. Correct the phase and frequency while improving the beam transmission/signal.

Commissioning simulations steps

- **<u>TbT average orbit correction (Goal : Profit from ~1000 turns)</u>**
  - Since we use the new 1fold lattice, some seeds that have >1000 turns do not have closed orbit.
  - A proxy for the closed orbit correction is the TbT average orbit correction.
  - Not needed if we manage to correct injection trajectory…
- **BEAM HAS BEEN CAPTURED:**
- **<u>Closed Orbit Correction (Goal : Profit from better BPM readings to increase the stored current)</u>**
  - Measure Response Matrix. Correct the orbit to improve injection current. Check DA.
- **<u>Closed Orbit BBA (Goal : Reduce the BPM offsets to values adapted for LOCO)</u>**
  - Steer the beam through quads in the straights to estimate the BPM offsets in the straights
  - Steer the beam through skew quads in sextupoles to estimate the BPM offsets. In the arcs
  - Repeating the BBA with all triplet/quadrupled quads and combine the results is more precise.
  - Correct the orbit.
- **<u>LOCO optics correction (Goal: Recover enough DA and MA for off-axis injection)</u>**
  - Use loco to reduce beta-beat, restoring tune, and the expected dynamics of the ring.
  - New formula for the orbit response matrix derivative.
  - An offset relaxation is applied at every LOCO step.
- **<u>AC skew quad stripline simulations to crosscheck 50% coupling.</u>**

SC input errors table

The SC input **expected errors** (2σ cut) have been estimated together with other teams:

MAGNETS	QD/QF	Q1/Q2/Q3	CORR	SEXT	OCT
Dipole calib.	0.1 %			5%	
Corr limit			0.5 mrad	1.0 mrad	
Quad Calib.	0.07%	0.07%			0.07%
Skew limit					0.15 T

BPM	
Calibration	5%
Noise (TbT / CO)	200 / 1 μm
Offset	200 μm
Roll	4 mrad

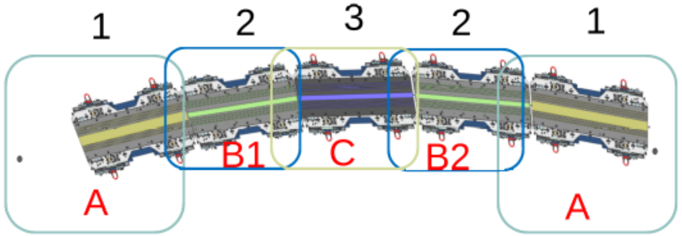
RF	
Frequency	0 (100Hz?)
Voltage	0.1%
Phase	90º

ALIGNMENT	Offsets H,V,L (μm)	Rotations around s,x,y (μrad)
Magnets	31, 31, 31	120, 120, 120
Girder	61, 61, 0	50, 0, 0
Circumference	0.63 mm	

Injected beam (x,x',y,y',δ,ct)	
Beam size	300 μm / 70 μrad / 200 μm / 40 μrad / 0.1% / 13 mm
Beam jitter	340 μm / 70 μrad / 100 μm / 40 μrad / 0.01% / 0.2 mm
Beam offset	1 mm / 0.1 mrad / 1 mm / 0.1 mrad / 0.1% / 1 mm

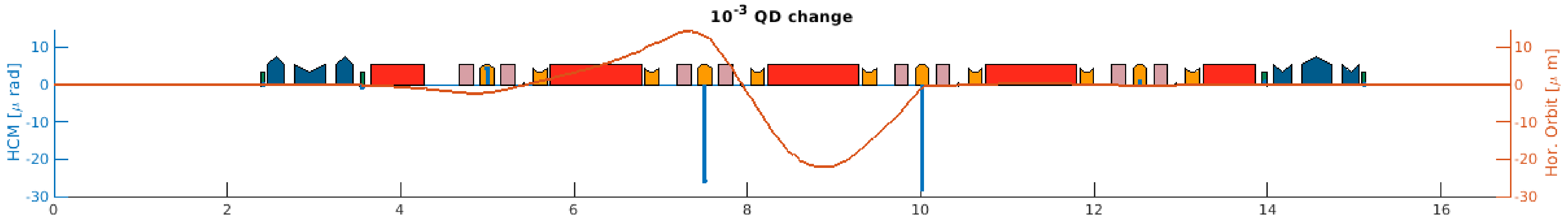
Also the alignment technique is taken into account:

*(dedicated **talk by Marta Llonch in this workshop**)*

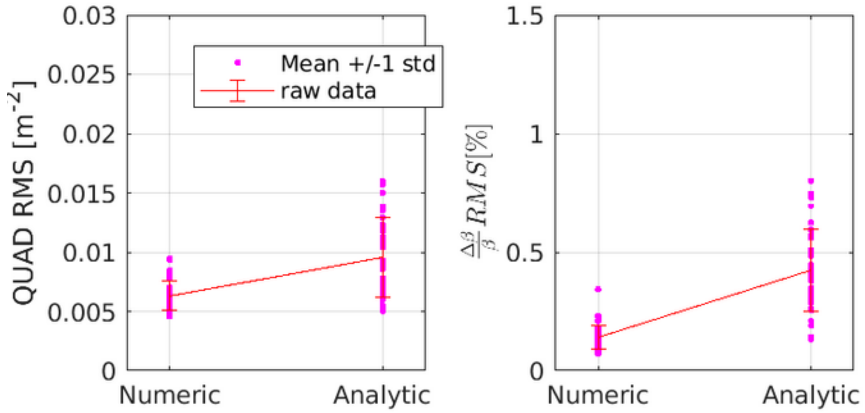


Optics correction with Combined Function Dipoles

- The ALBA-II lattice has 208 **CFD** and 176 of them are used to correct the optics.
- The magnetic design for the CFD has a **single power supply**.
- The **optics** correction implies **gradient+dipole** changes → it must be taken into account together with the **orbit** correction and a small **energy change**

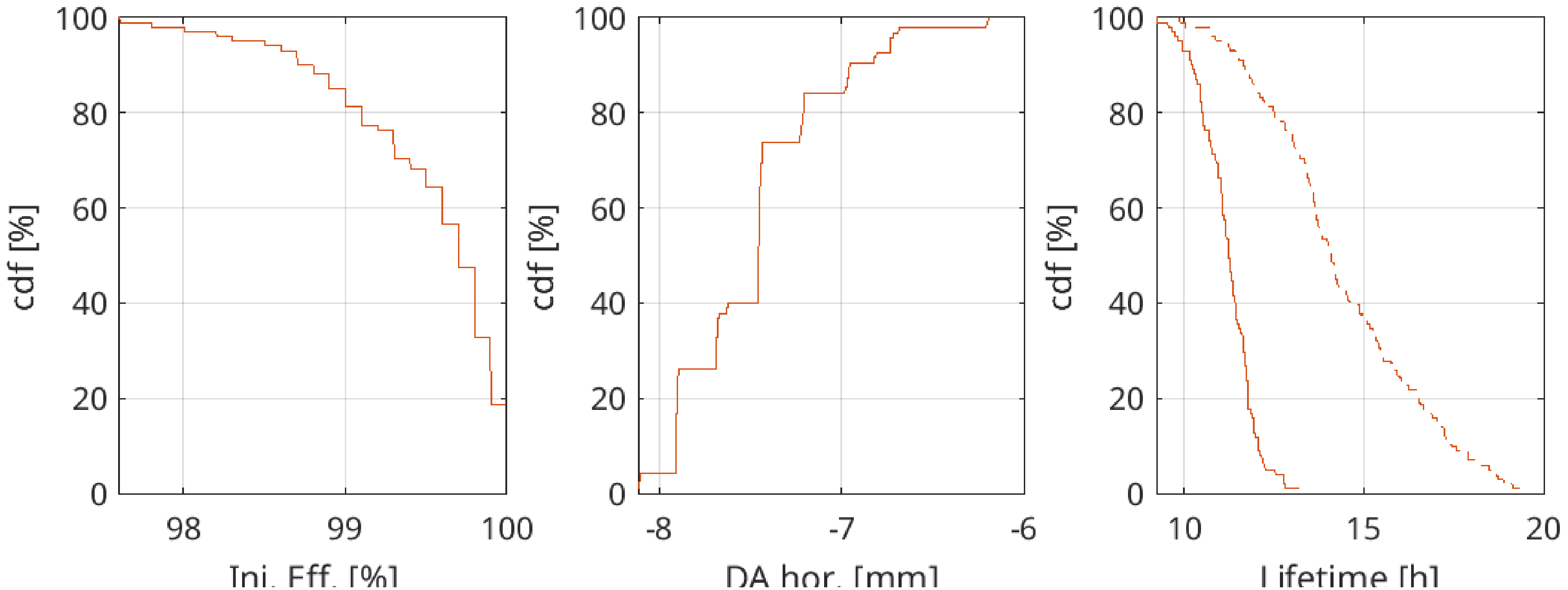


- **6D simulations of optics+orbit** correction have confirmed that the **CFD with single power supply design works well**.
- An optics correction iteration based on standard LOCO with numerical calculation of the Orbit Response Matrix Jacobian would take ~30min.
- At ALBA we have developped an **analytical version of LOCO for the CFD which takes few seconds**.



Performances with errors

With Simulated Commissioning **Injection efficiency**, **horizontal Dynamic aperture** and **Lifetime** are evaluated for 100 error seeds.
The Cumulative distribution function (cdf) is used to show the statistics and robustness of the performances.



Injection efficiency > 98.5% and Lifetime > 11 hours for more than 90% of the seeds.

Corrections budget

All the correction strengths needed are within the magnetic design ranges.

Family	SC	CO BBA	TbT BBA	Bumps	ID	total
QD	0.0031	0.0000	0.0000	0.0000	0.0000	0.0031 (0.2 %)
QF	0.0048	0.0000	0.0000	0.0000	0.0022	0.0070 (0.7 %)
QFS	0.0044	0.0000	0.0000	0.0000	0.0016	0.0060 (0.5 %)
Q1	0.0049	0.0077	0.0513	0.0000	0.0015	0.0562 (21.9 %)
Q2	0.0032	0.0397	0.2646	0.0000	0.0027	0.2678 (20.2 %)
Q3	0.0052	0.0273	0.1823	0.0000	0.0023	0.1875 (20.6 %)
OH +SKEW	0.0066	0.0000	0.0000	0.0000	0.0000	0.0066
OV +SKEW	0.0052	0.0150	0.0150	0.0069	0.0000	0.0202

Table 1: Normal and skew Quadrupolar budget. Values are integrated and given in m^{-1} units.

Family	SC	Beam capture	BBA	RM	Bumps	Ground	total
HCM arc	338	111	102	10	128	50-100	517-567
HCM str.	292	161	0	10	90	50-100	432-482
VCM arc	294	107	102	10	128	50-100	471-521
VCM FaPS	267	73	85	10	348	50-100	665-715
VCM str.	310	114	0	10	78	50-100	438-488

Table 2: Horizontal and vertical dipolar budget. Values are integrated and given in μrad units.

Summary

- Tools and algorithms for lattice design, non-linear optimization and SC: developed, tested and working.
- A baseline lattice (A2L007d) with 5BA cell and pseudo 16-fold symmetry is almost ready to be frozen.
- The dynamic aperture is optimized up to the physical aperture limit of 8 mm
- Injection will be performed off-axis with the current booster and a novel Double-dipole kicker
- The ALBA-II commissioning and operation would be allowed with the following average performances:
  - **Injection efficiency > 99%, DA = -7.5 mm, lifetime 11 hours at 300 mA and 3rd H.C.**
- Magnets butget for corrections is within design

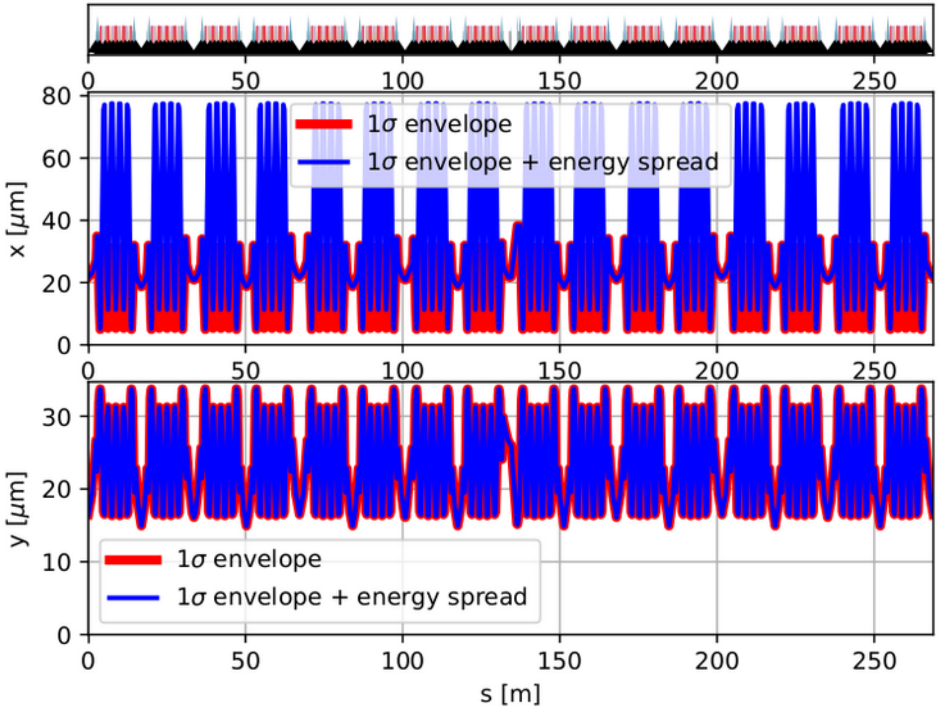
EXTRA SLIDES

Beam sizes, coupling and lifetime

Coupling has been fixed at 50% as a trade-off between lifetime (for the machine performance) and vertical beam size (for beamlines)

Beam size with 50% emittance ratio

ex = 160 pm, ey = 80 pm



Touschek Lifetime w/o H.C.:

ibunch=0.00075 A, σs=0.00243 m, σe=0.00126, emit0 = 200 pm

RFCAV : 2 sets of cavities at 1.2MV