The material presented is the result of the work of the whole ESRF ASD, TID and ISDD divisions.
In particular for these slides: P.Raimondi, L.Farvacque, N.Carmignani, S. White, L.Carver, T.Perron, D.Martin, B.Roche, L.Torino, K.Scheidt, E.Plouviez, E.Taurel, F.Poncet, R.Versteegen, G.Le Bec, J.Chavanne.

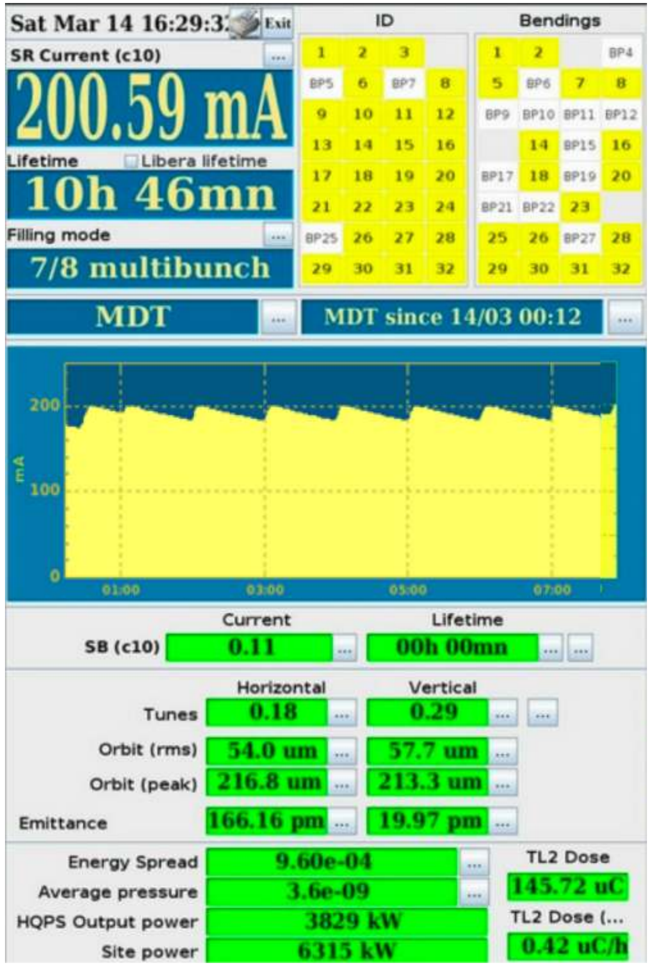
ESRF | The European Synchrotron

Optics corrections & experience at ESRF-EBS

With a focus on what could be useful for FCC-ee commissioning-like simulations

S.M.Liuzzo, A.Franchi, FCCIS WP2, CERN, 6th December 2021

OUTLINE



EBS commissioning **simulations**

EBS commissioning **tests** with beam

EBS commissioning **realization**: differences real-life / simulations (towards more realistic tuning simulations)

Optics tuning simulations applied to FCC-ee Z

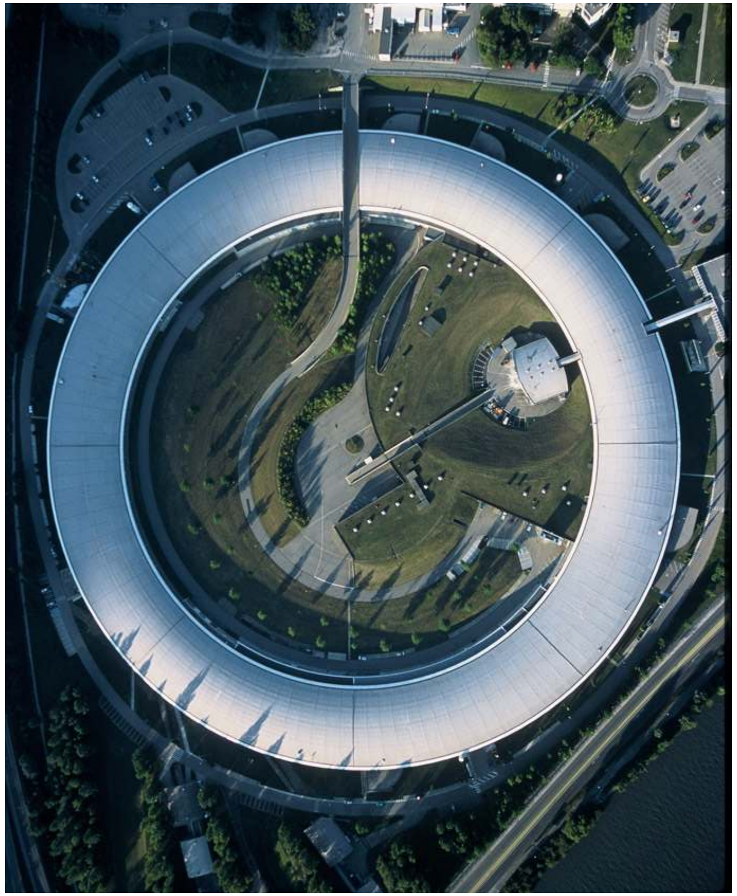
Extension to include optics tuning to non linear elements: NOECO

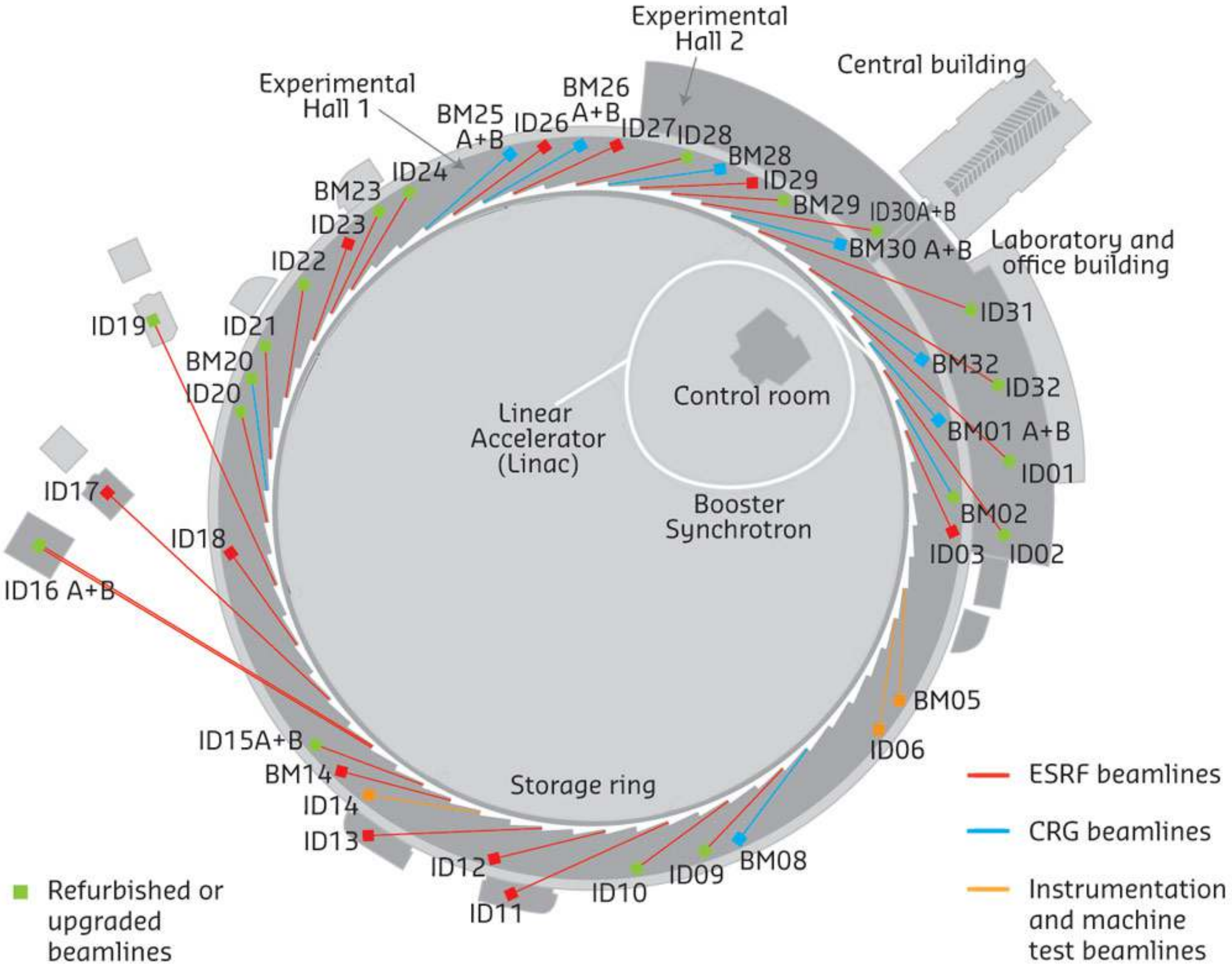
PHYSICAL REVIEW ACCELERATORS AND BEAMS **23**, 102803 (2020)

Nonlinear optics from off-energy closed orbits

David K. Olsson,* Åke Andersson, and Magnus Sjöström
MAX IV Laboratory, Lund University, SE-22100 Lund, Sweden

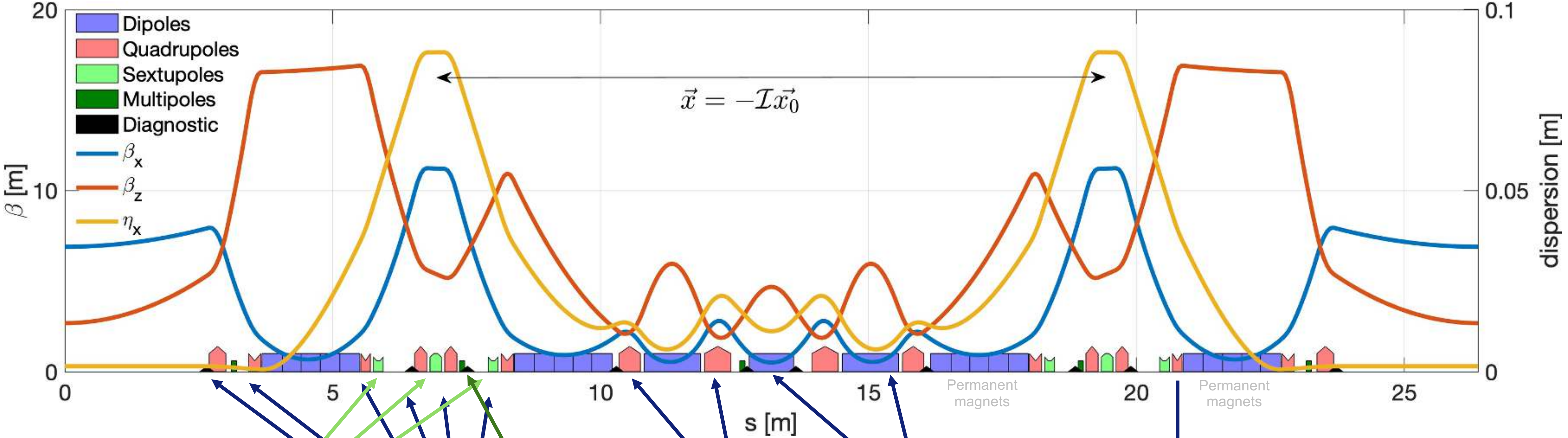
ABOUT ESRF: EUROPEAN SYNCHROTRON RADIATION FACILITY





Cell 4 Injection,
Cell 5, 7, 25 RF

EBS LATTICE OPTICS AND GRADIENTS



$|K_{Sext}|<1800T/m^2$

All sextupoles are also H/V steerers and skew quad. correctors

<60T/m

Moderate gradient quadrupoles

$<36000T/m^3$

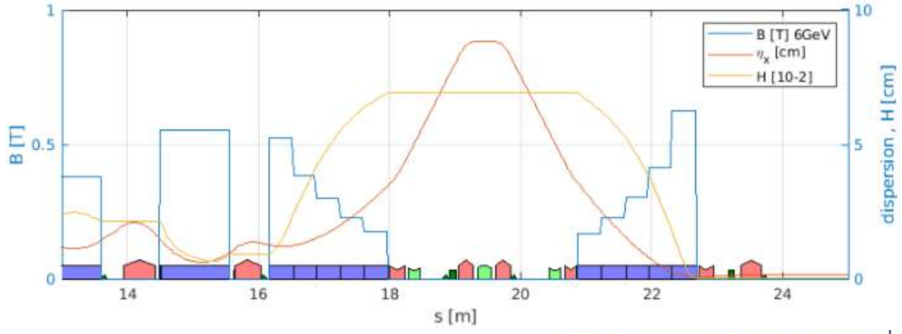
91T/m

High gradient quadrupoles

$K_{quad}<36T/m$

Dipole-Quadrupole (DQ)

Longitudinal gradient dipoles



GUN, LINAC, TL1, SY, TL2 to be restarted

Storage Ring tuning:

- **make first turn : tuning & phasing chain of injectors, threading & tune correction**
- **make few turns : RF on, beam accumulation**
- **storing beam : orbit, tunes, BPM-QUAD offsets (BBA), chromaticity, orbit response matrix (optics/coupling)**

~~**close collimators / optimize losses**~~

Low current

~~**implement SB, 2PW optics adaptations**~~

~~**ID commissioning**~~

optimize injection efficiency / lifetime

~~**high current per bunch, feedbacks**~~

Ramp current

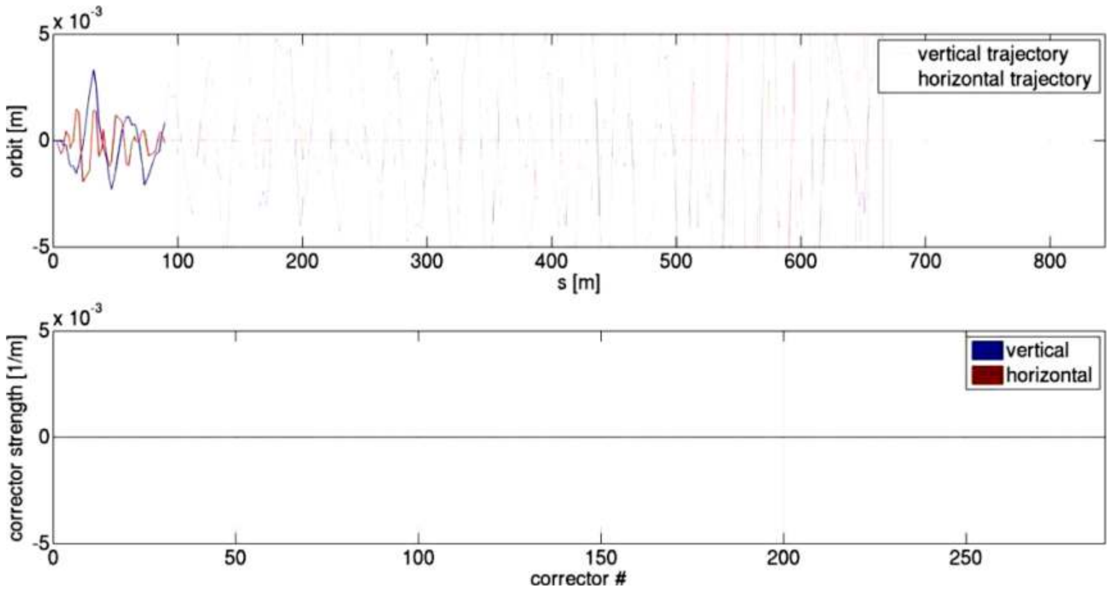
2 month

2 shifts/day

Beam accumulation

1) Injection on axis (static bump) or off axis (fit injected beam oscillation) available. Start from injection **off axis** **(soon realized on-axis was necessary) .**
2) Power orbit steerers to achieve first turn (from simulations, beam survives about 3-4 cells without orbit steering, if magnets & alignment within tolerances).
3) Measure and correct tune (most relevant for off-axis injection)
4) Switch on RF, search for correct frequency and phase
5) Beam accumulation

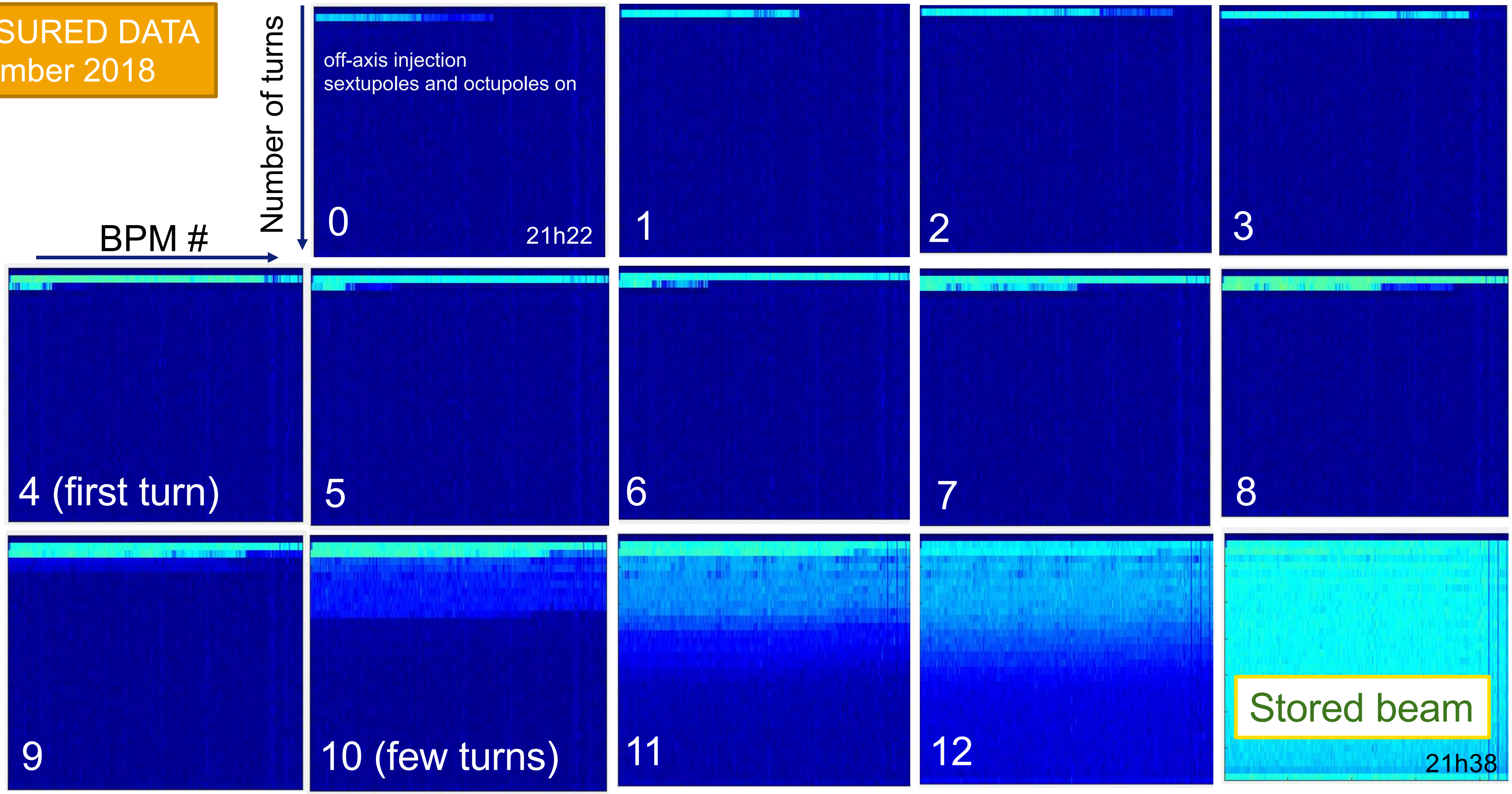
Video: first turn correction simulations for beam injected on axis. Large BPM offsets are included.



Simulations

FIRST-TURNS TRAJECTORY CORRECTION PROGRESS ON TBT BPMS NOVEMBER 2018, OLD ESRF RING

MEASURED DATA
November 2018

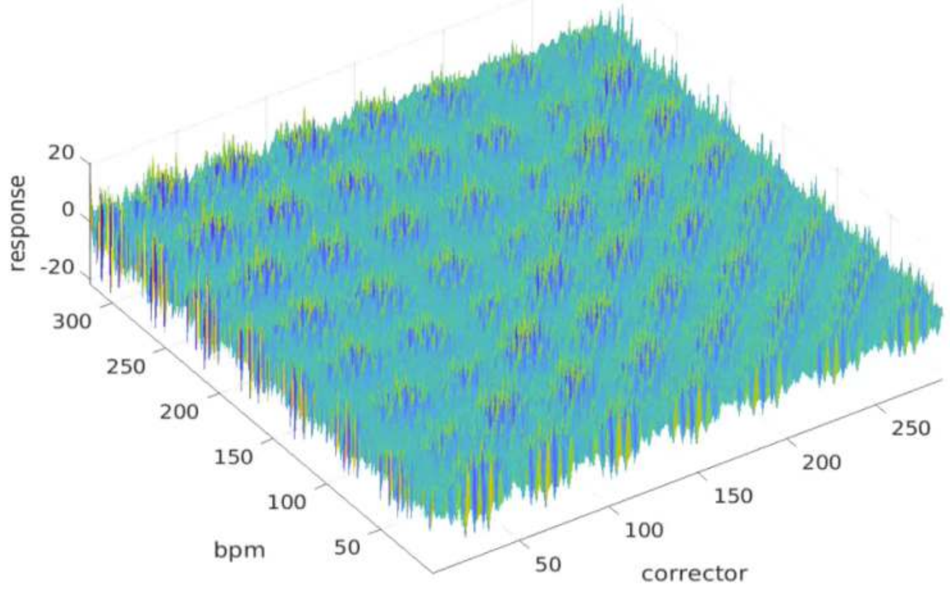


Optics tuning

- orbit response matrix
- beam-based alignment
- tune working point
- emittances
- chromaticity
- dynamic apertures
- specific optics tuning (ex: phase advance between sextupoles)

Losses tuning

Check losses and tune collimators when needed while ramping current.



Orbit response matrix (ORM) measurements will be used for:

- Precise orbit control (full, 8h, not used)
- Optics and coupling (partial, 60 min / 64 steerers)
- Check magnet calibrations
- At a later stage, use of Fast Orbit Feedback for fast partial response measurement (3 AC cor. / 10 Libera BPM per cell). (10 minutes / 96 steerers)

Injection efficiency and lifetime require online optimization. Many knobs allow large room for optimization but also need a very long time.

Automated optimizers and resonance correction available.

MEASURED DATA OLD RING 2018

Injection efficiency:

- Single-turn injection efficiency measurement
- TL2/SR optics trimming, sextupoles, octupoles

Lifetime:

- Lifetime or BLD measurement
- SR optics tuning, sextupoles, octupoles

See later

Figure: normalized lifetime evolution during optimization, vs tested correctors sets

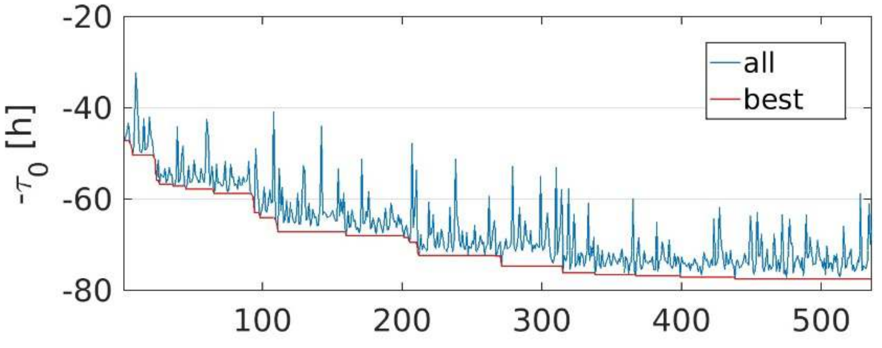
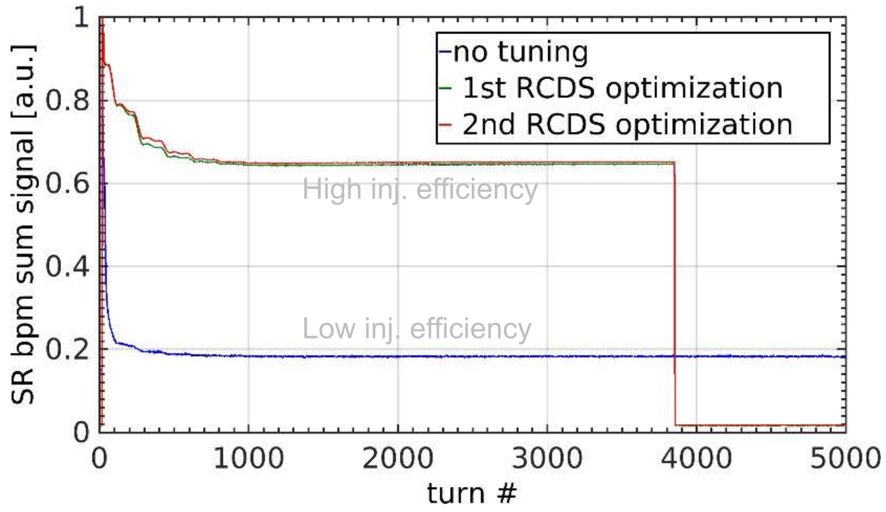


Figure: injected beam current evolution during for 2 RCDS* optimizations



* X. Huang, J. Corbett, J. Safranek, J. Wu, "An algorithm for online optimization of accelerators", Nucl. Instr. Meth., A vol. 726,pp. 77-83, 2013.

EXAMPLE OF CORRECTION OF RANDOM ERRORS

Simulation of the whole correction sequence, from transfer line to ORM* fit.

- Find a closed orbit correcting open trajectories
- Correct orbit
- Create lattice error model fitting ‘measured’ RM (partial, 14/288 cor.)

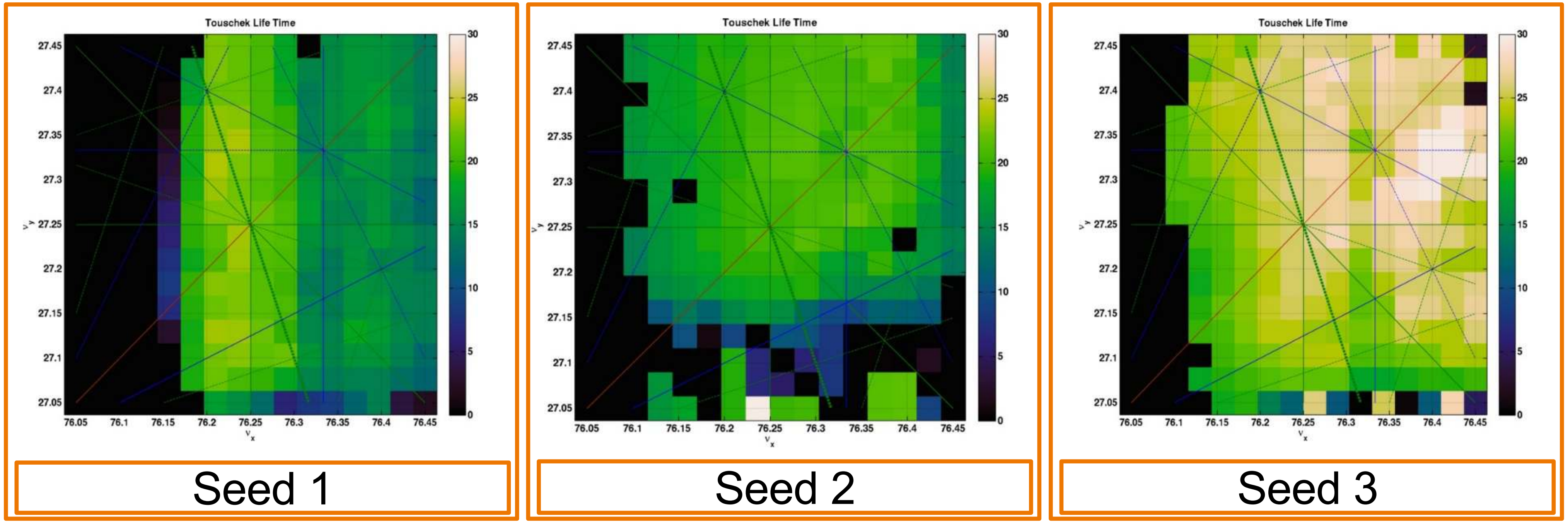
  $ORM_{err} = [\Delta\ ORM/\Delta K\ ] * \Delta K_{fit}$

- Compute Resonance Driving Terms and correct simultaneously normal and skew quadrupole RDT and dispersion
- Fix tune and chromaticity
- Iterate a few times

*Orbit Response Matrix

	Closed orbit only	After tuning	<2018 ESRF
X [μm]	160(675)	116	61
Y [μm]	111(250)	58	70
$Dx-Dx_0$ [m]	0.017	0.001	0.028
Dy [m]	0.002	0.0002	0.002
β–beating x [%]	26.2	0.7	4.9
β–beating y [%]	26.5	0.8	3.3
Tune x [.21]	0.208	0.21	0.44
Tune y [.34]	0.336	0.34	0.39
Q'_x [6]	6.328	6.00	3.89
Q'_y [4]	3.971	4.00	6.92
ε_x [134.7 pmrad]	250.4	134.7	4099
ε_y [0.04 pmrad]	2.2	0.18	3.123

TUNE SCAN VARIATION WITH ERROR SEED



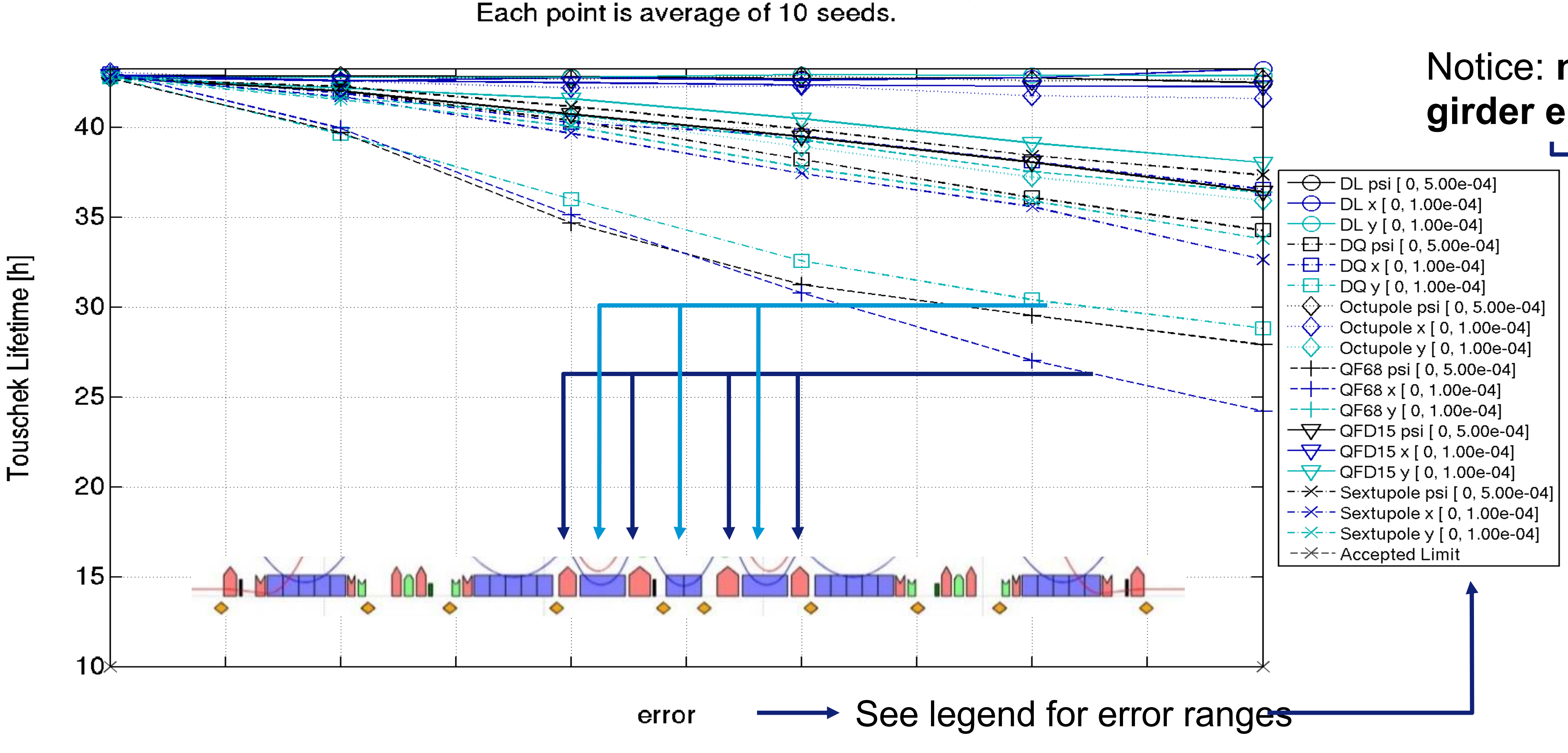
Repeat for N seeds, as the result is varying significantly from seed to seed.

For each point in the scan a full commissioning-like sequence of corrections is applied

LIFETIME AFTER COMMISSIONING-LIKE SIMULATIONS VS ERRORS AMPLITUDE

◀ As many as possible error seeds

Notice: **no girder errors**



See legend for error ranges

Alignment tolerances from simulations 2019: **70µm**

Alignment tolerances from beam measurement 2020: **Hor. 53 µm, Ver. 30 µm**

Test of correction tools in a simulated control system with “beam”

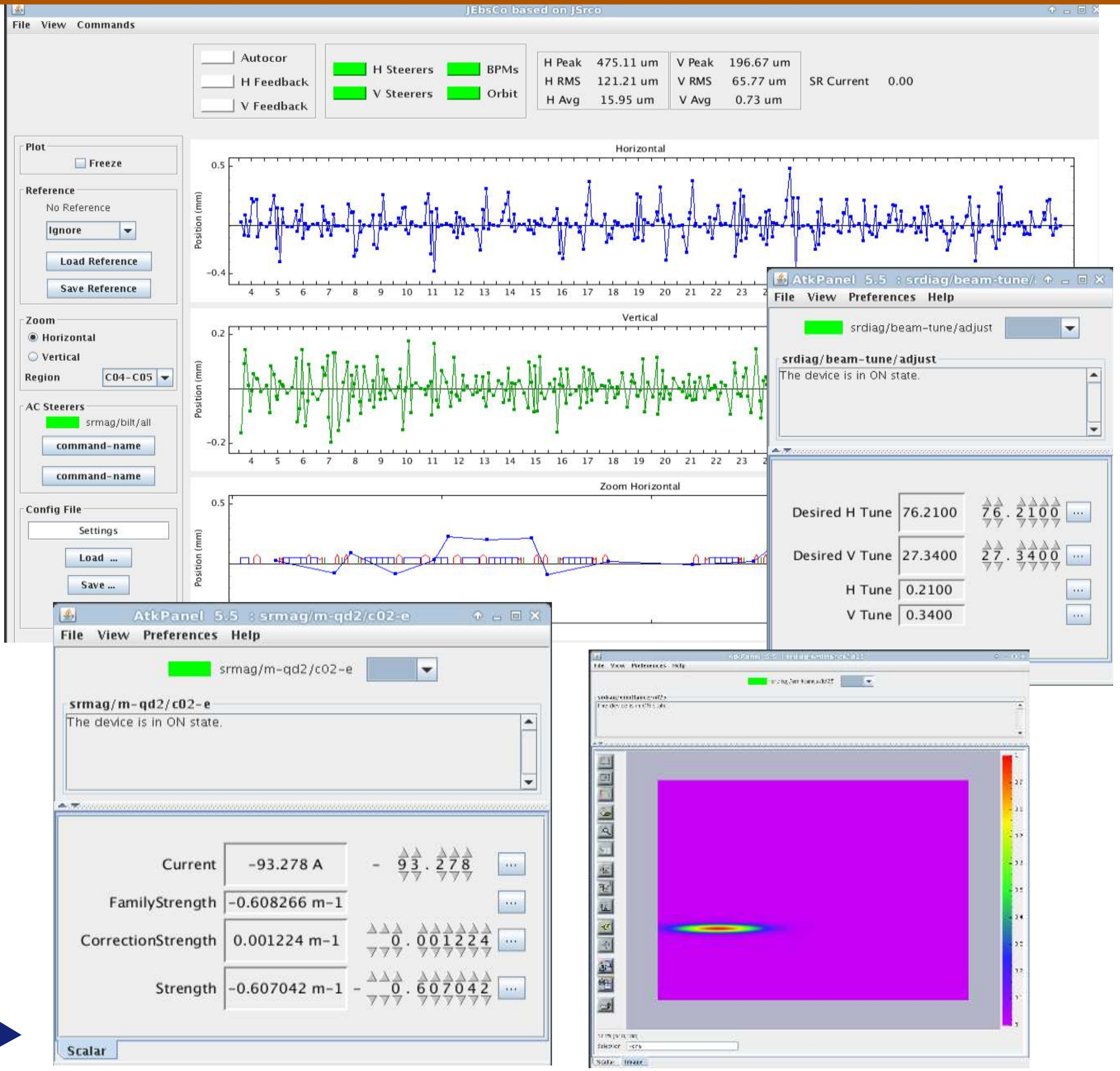
EBS simulator:

The beam-dynamics control system was **available 2 years before commissioning**.

All software required for commissioning **tested** on the latest EBS lattice model with errors.

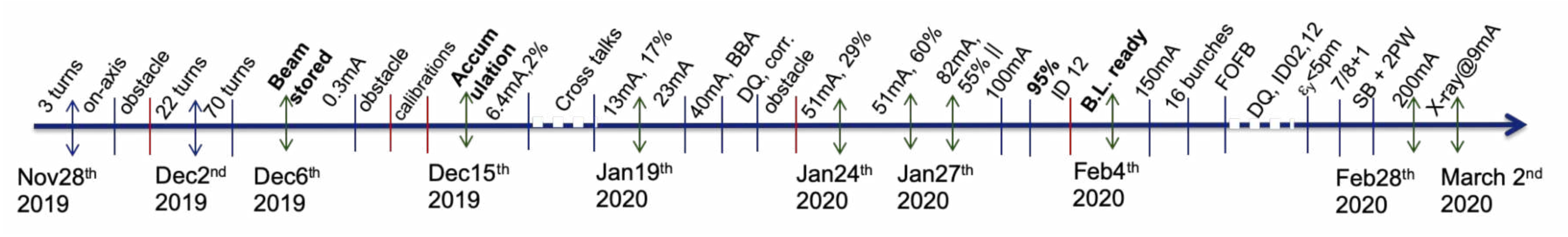
Magnets can be set as families or individually and include global and individual calibration curves.

The **EBS simulator allowed to develop, debug**, familiarize with the EBS control system much before the commissioning!



pyAT based Tango Device Servers

Storage ring commissioning history time line (when things really happened):



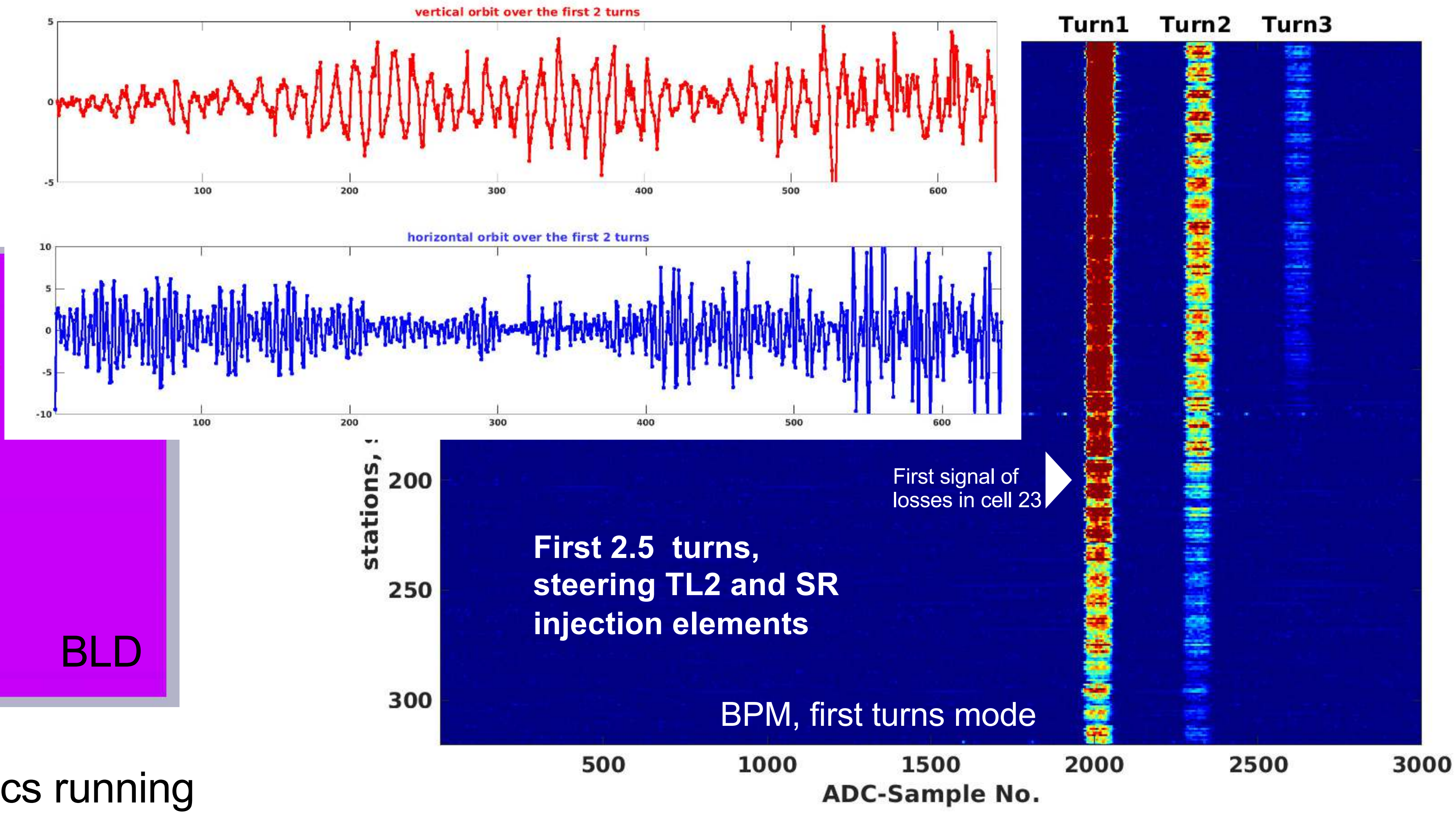
Steps/obstacles up to accumulation | **Optics: cross talks, BBA, ORM, …** | **Current ramp**

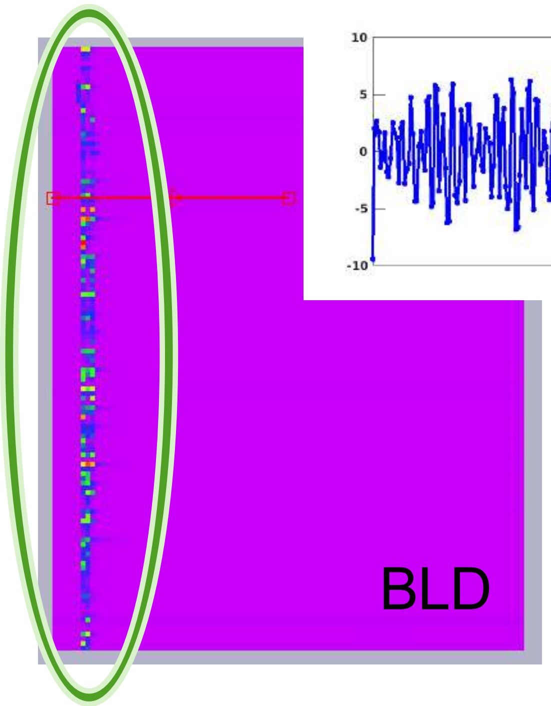
The following slides will show mostly the *non-ordinary events*, those **not included in commissioning-like simulations**.

1. **Obstacles**
2. **Sextupoles for accumulation**
3. **Cross-talks, calibrations**
4. **Singular vector studies**
5. **Hysteresis / combined function magnet**

2019 NOVEMBER 28TH AT 19.00: FIRST TURNS IN EBS-SR

Injection:
ON-AXIS





Diagnostics running greatly from first day!

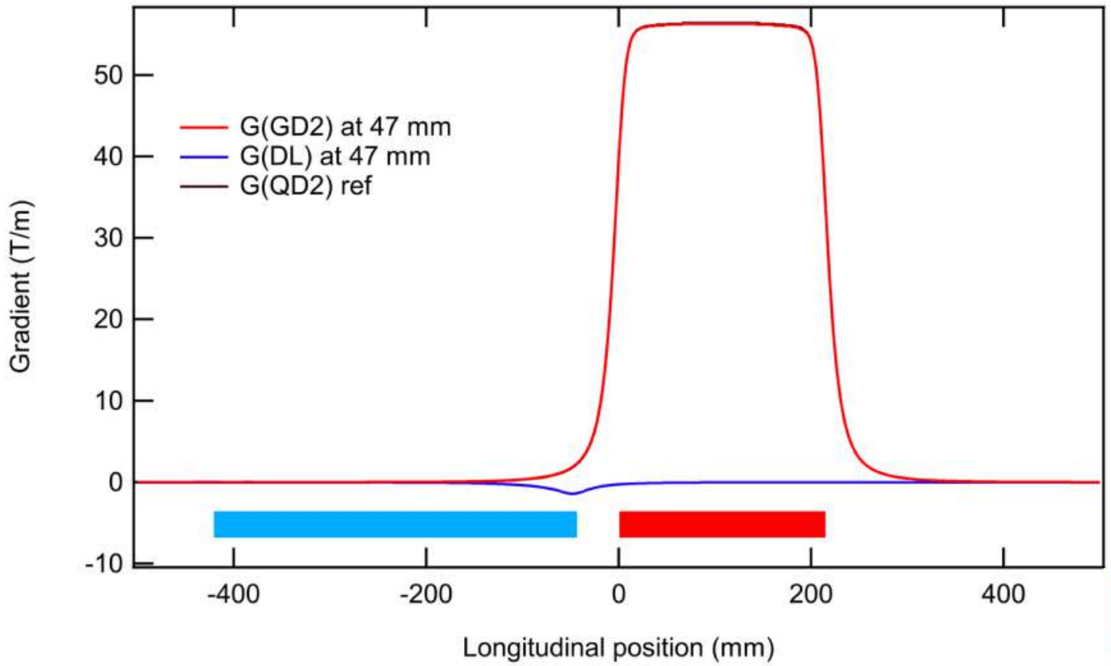
Tune estimated from trajectory oscillations induced by a known source.

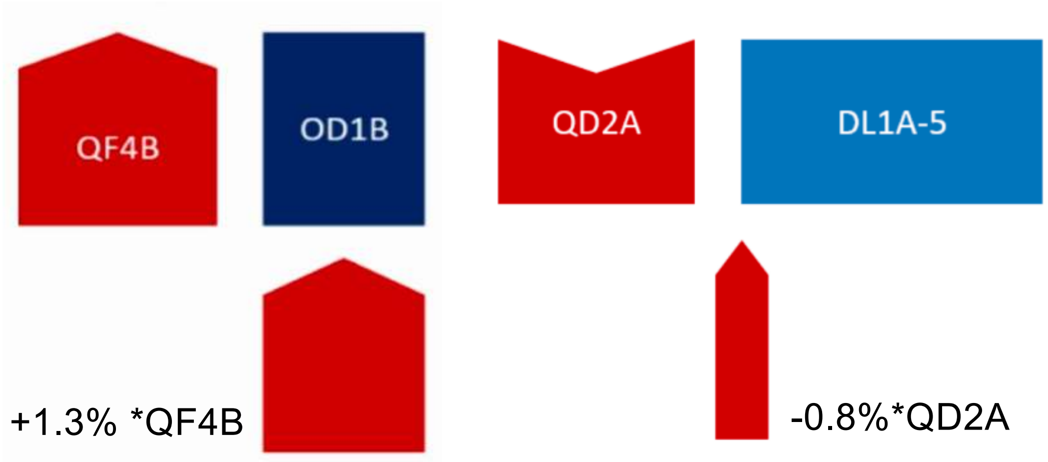
ΔTune H ~ -0.4 **ΔTune V ~ -1.4** compared to model

G.Le Bec, J.Chavanne

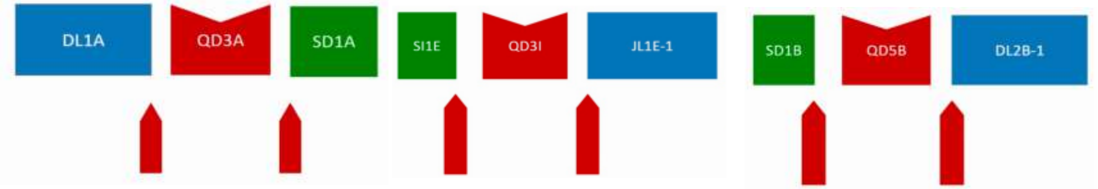
G. Le Bec et al. Cross talks between storage ring magnets at the Extremely Brilliant Source at the European Synchrotron Radiation Facility: https://doi.org/10.1103/PhysRevAccelBeams.24.072401

Magnetic simulations show a **cross-talk** effect among neighboring magnets.





This effects is added to the AT lattice model using thin magnet slices.



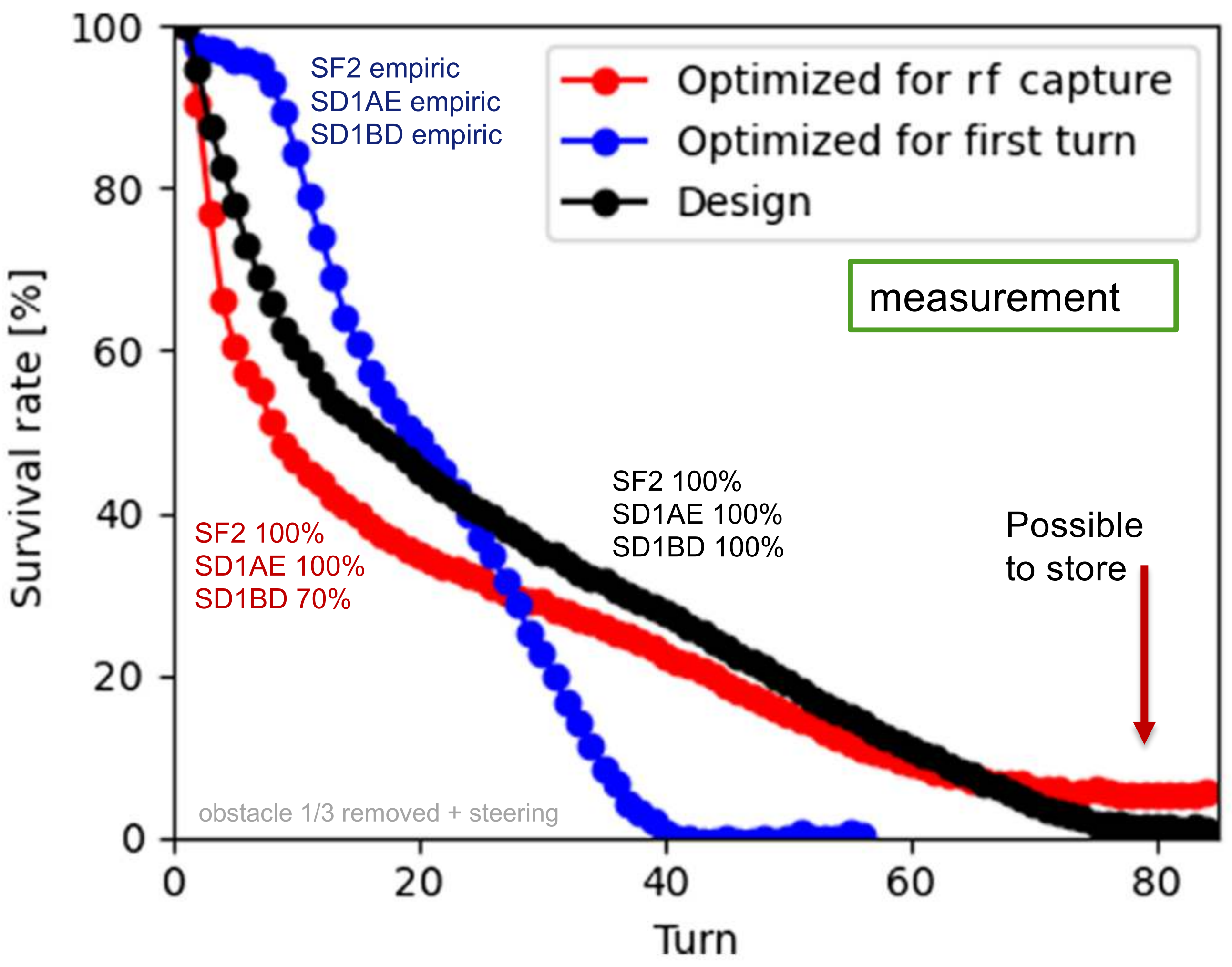
Tune variation introduced by cross-talks **ΔTune V ~ -1.4 . Explains early measurements**

OPTIMAL SEXTUPOLES FOR RF CAPTURE

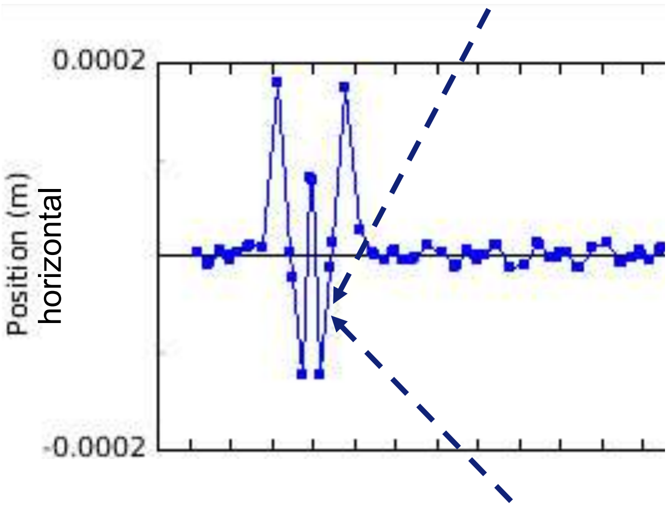
Specific SEXTUPOLE SETTING for ACCUMULATION with LARGE ORBIT 750 μm (rms)

Settings found based on simulations

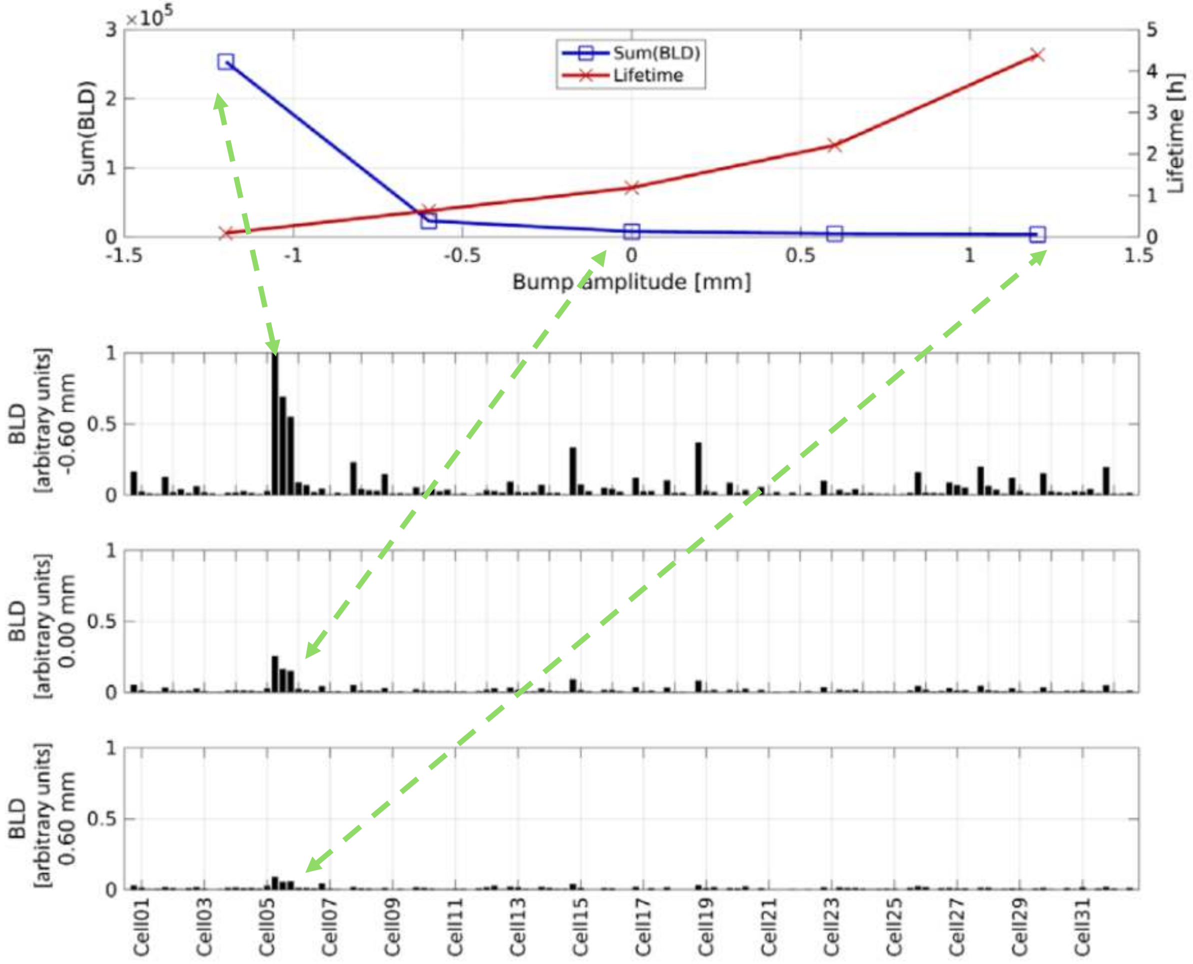
Could be included among commissioning-like procedures steps.



23ND JANUARY 2020: CORRECTIONS MINIMIZATION, OBSTACLE IN CELL05



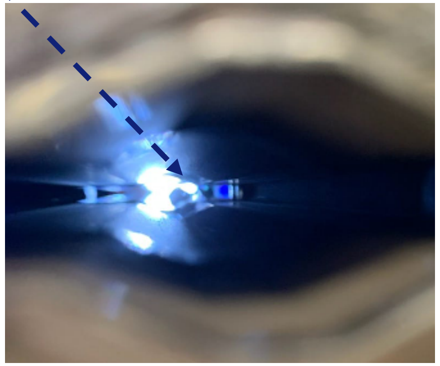
10% Inj. Eff. ⇨ **29% Inj. Eff.**



Trajectory/closed orbit data

Beam loss detectors

Closed orbit bumps

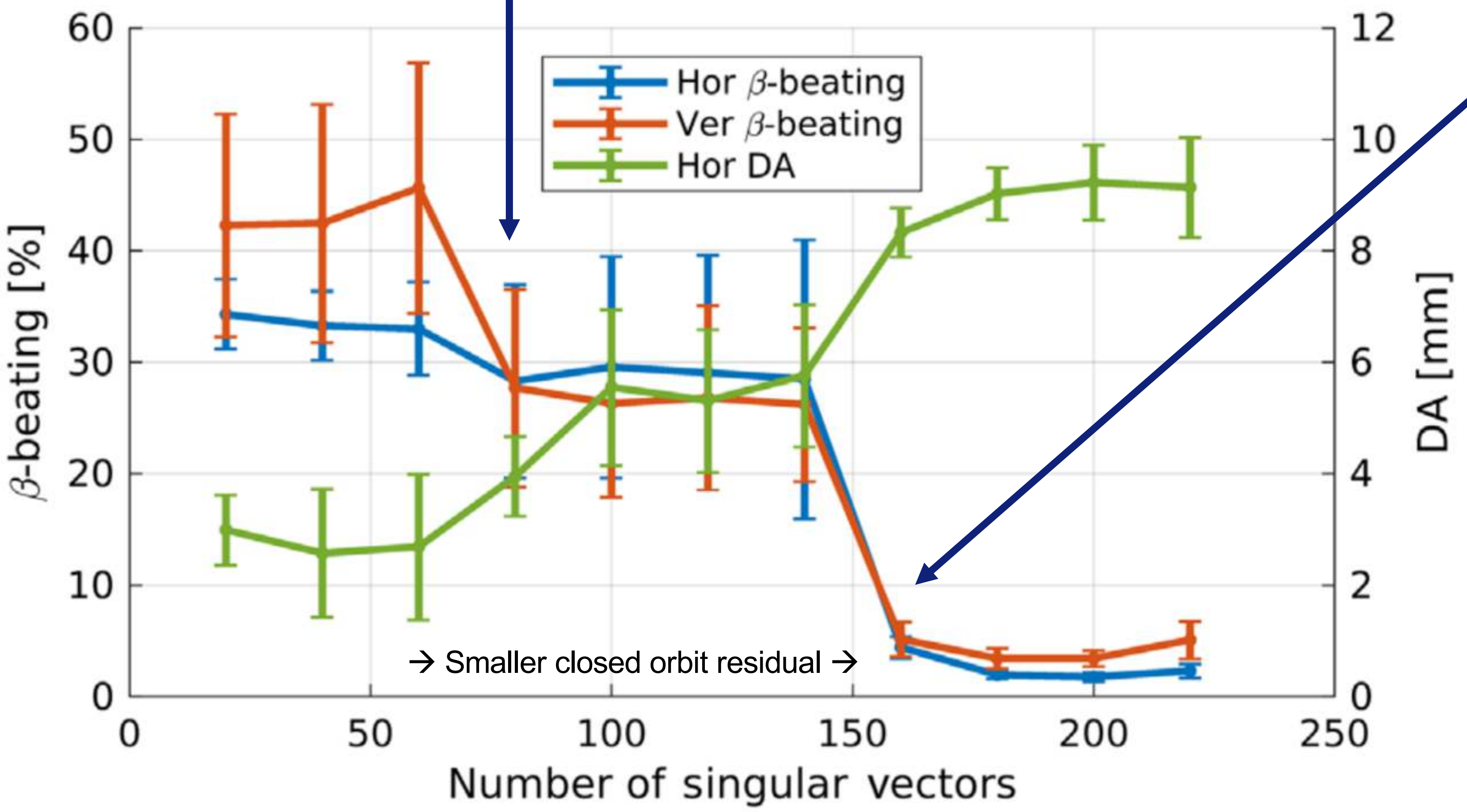


Local radiation check (final localization)

DA STUDIES: DA VS ORBIT CORRECTION

We use to stick to maximum 64 singular values

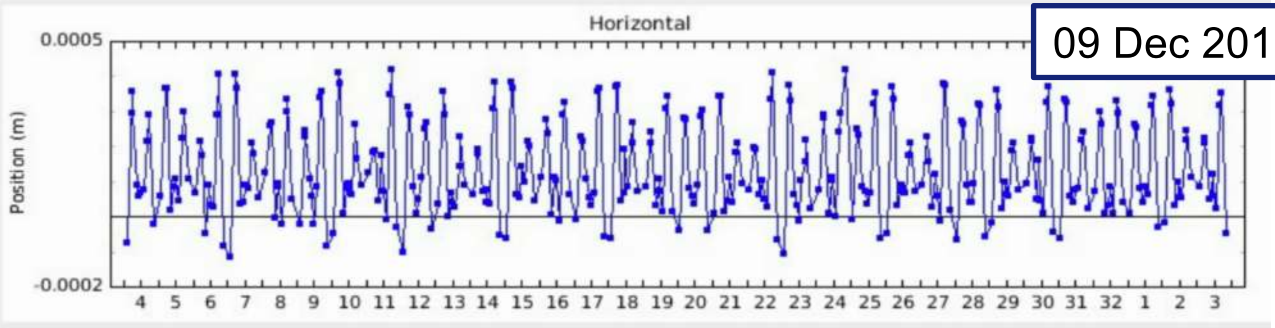
Decided from these simulations to go to 162 singular vectors



ALL CALIBRATIONS SCALE FACTORS WRONGLY ASSIGNED

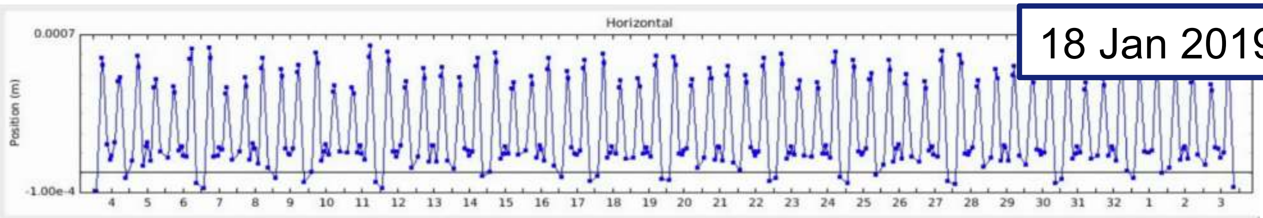
ALL CALIBRATION SCALE FACTORS FOR QUADRUPOLES, SEXTUPOLES, DQ, OCTUPOLES WHERE **WRONG** (>1% errors).

Hor. dispersive orbit



09 Dec 2019 first measurement

After debugging, in theory we should have reached rms error 3e-4 on scaling factors.



18 Jan 2019 first correction 2020

Several simultaneous layers of error: optics software, signs, serial numbers, outliers, inverse calibration

The use of the **simulator** could have been crucial to spot ahead most of these errors. We should have made more use of it prior the commissioning!

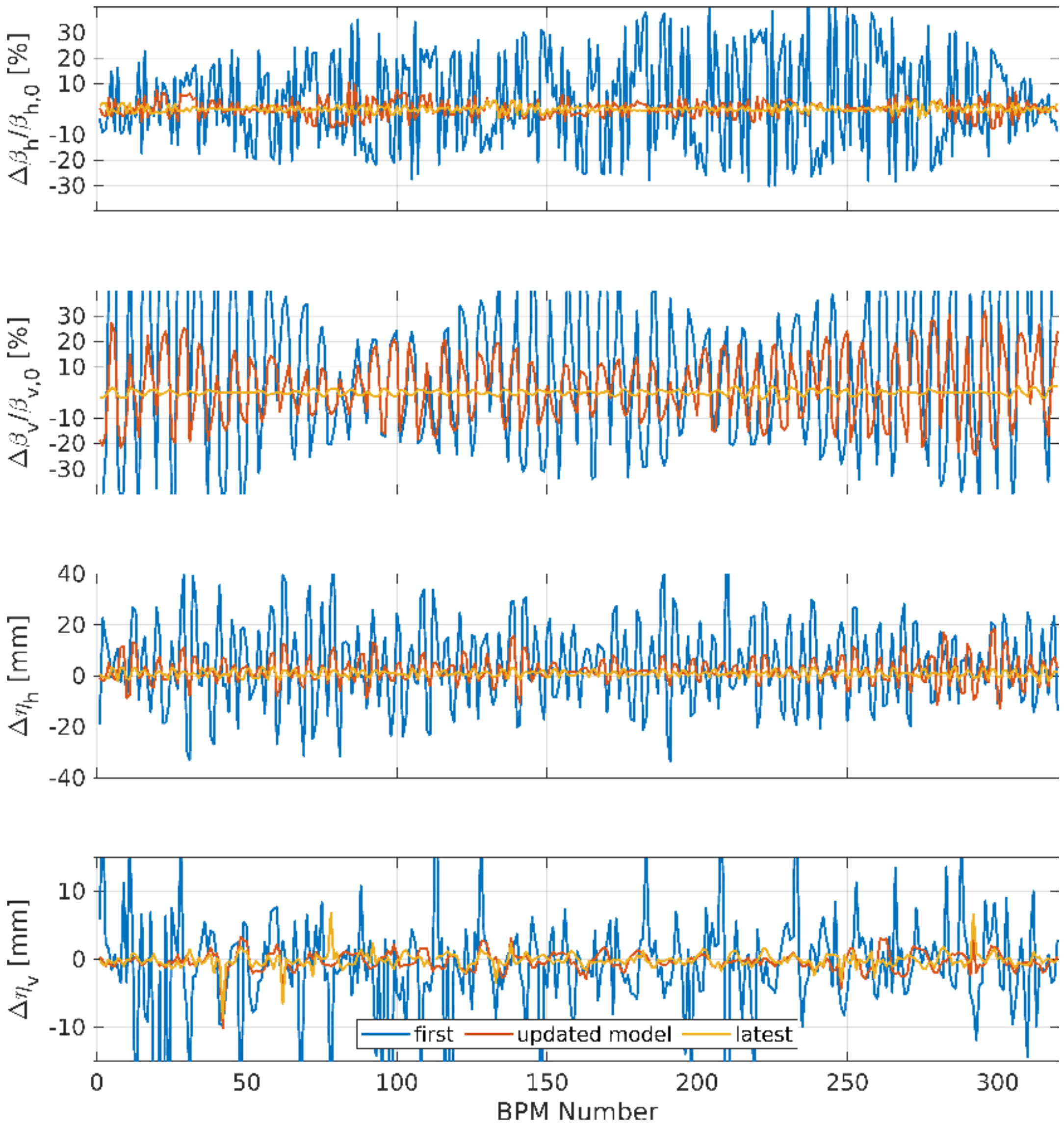
Large teerers scale factors ~6% for sextupole trim coils (common yoke) and up to 30% for stand-alone (SH, errors due to calibration at very low current working point, backup for more info**).**

Strong **hysteresis effects** compared to the expect

Not trivial ORM measurement

Cycling of steerers possible without beam

OPTICS CORRECTION PROGRESS



09 Dec 2019 first measurement

$\Delta\beta/\beta_h \sim 20\%$ $\Delta\beta/\beta_v \sim 30\%$

30 Jan 2020 Machine is "corrected" based on theory

calibrations, cross talks, steering with 162,128 eigenvectors, **BBA**,

← **NO** quadrupole correction (apart tune)

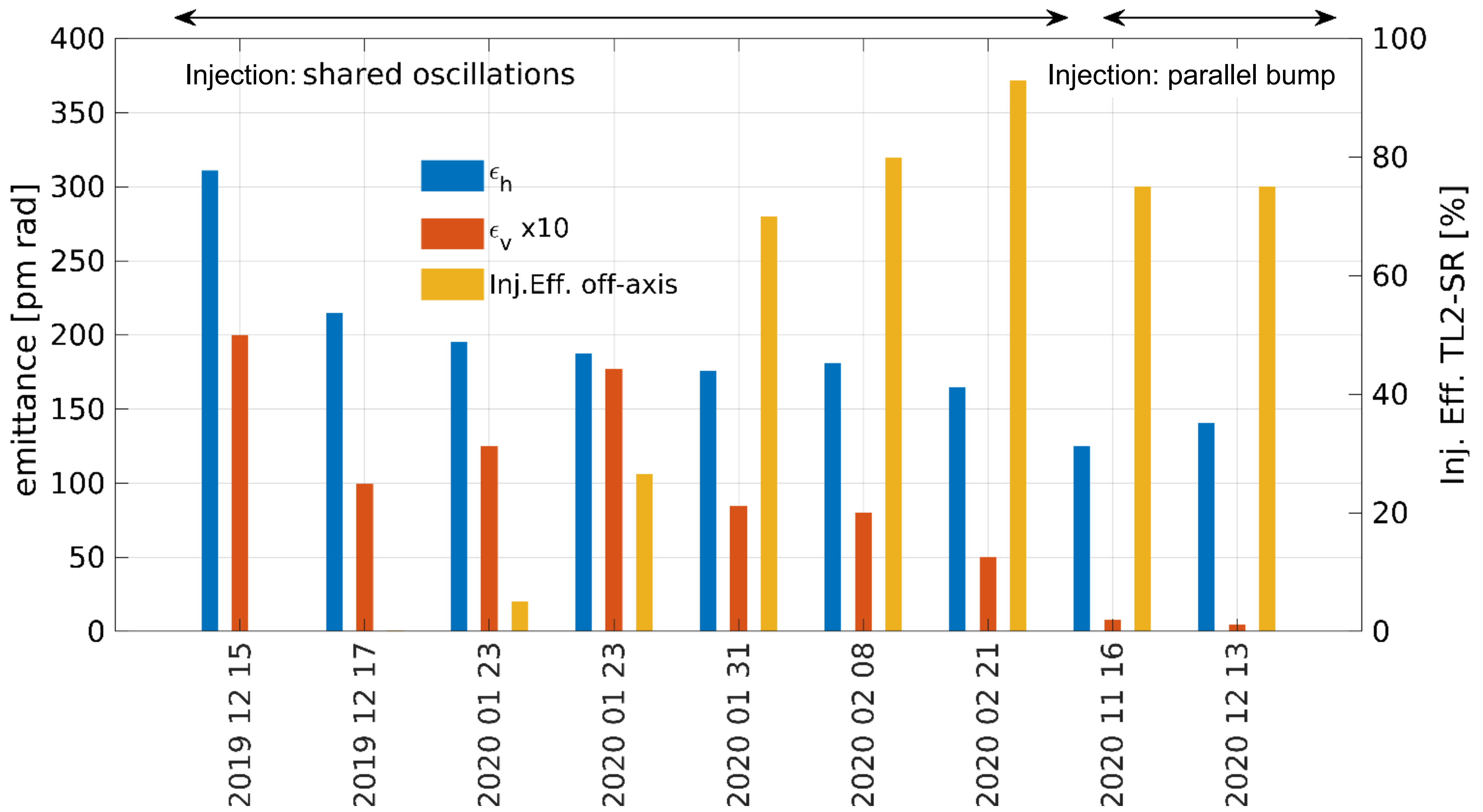
$\Delta\beta/\beta_h \sim 3\%$ $\Delta\beta/\beta_v \sim 13\%$ 45% injection efficiency

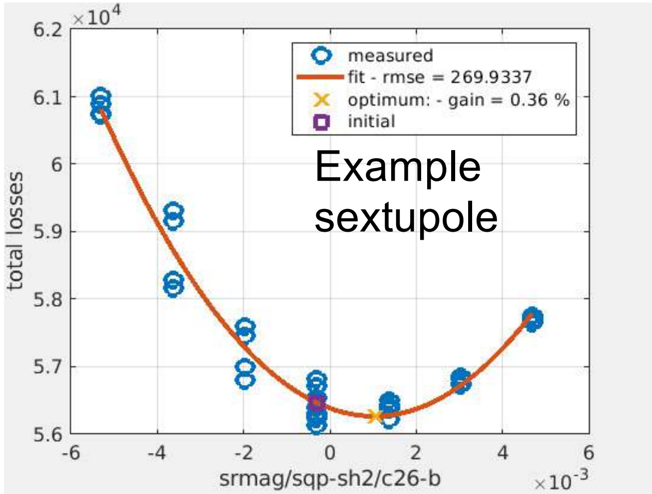
Today

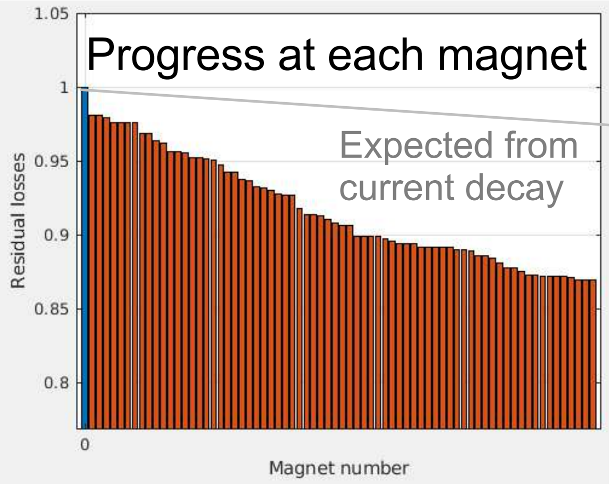
$\Delta\beta/\beta_h \sim 1.5\%$ $\Delta\beta/\beta_v \sim 1.5\%$

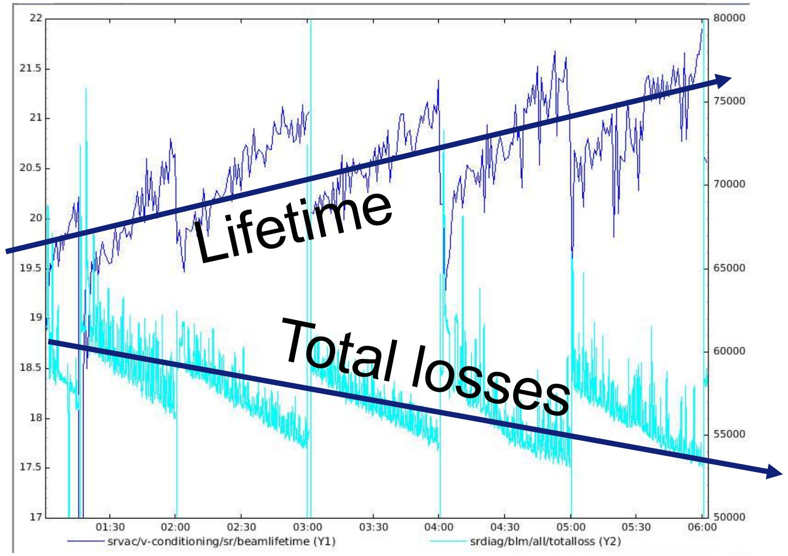
$\Delta\eta_h \sim \Delta\eta_v \sim 1.0$mm

EMITTANCES LIFETIME INJECTION EFFICIENCY EVOLUTION









Total losses as objective of empiric optimization, (ID gaps closed to minimum):

~114k a.u. total losses

$\tau_{Tot.}$ **~15h**

Several MDT nights:
192 sextupoles
64 octupoles
288 skew quadrupoles
one after the other,
several times

~60k a.u. total losses

$\tau_{Tot.}$ **>20h**

Total current: 200mA
Emit. Vertical: 10pm (white noise)

White noise has no impact on optics

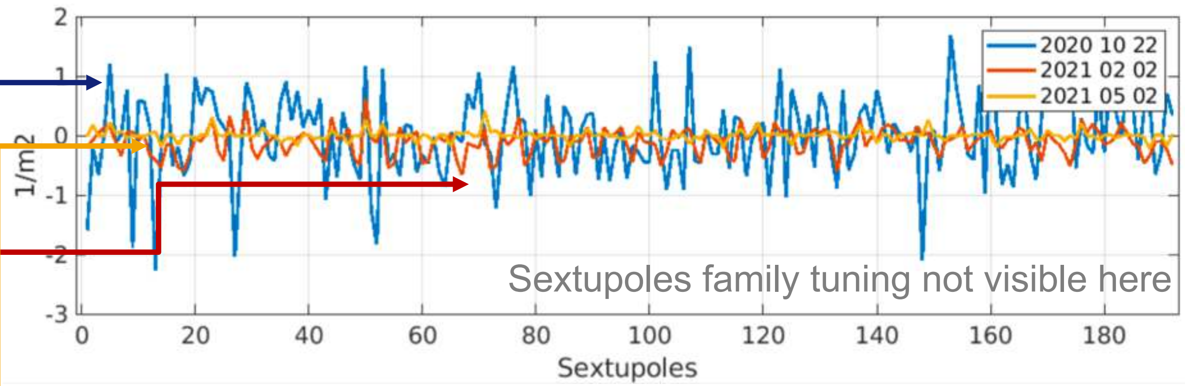
SEXTUPOLE, OCTUPOLE AND SKEW QUAD. STRENGTHS REDUCE AS THE OPTIMIZATION IMPROVES

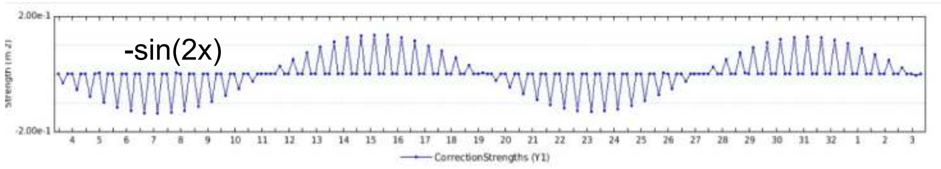
Initial single magnet scans — Several MDTs in 2020

Faster scans, optimized procedure — One MDT

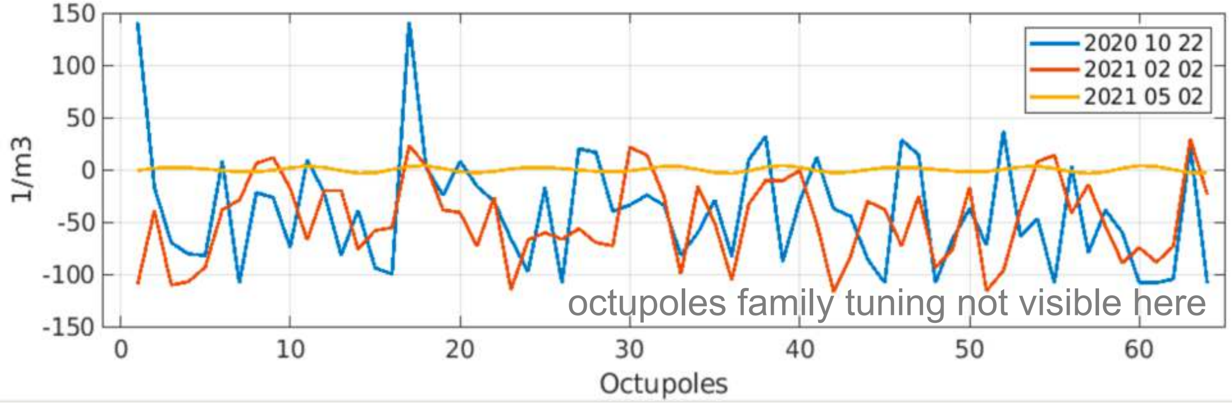
Selection of most significant **knobs** — 4h in 2021

Not resonance knobs, those tested are ineffective





sextupoles



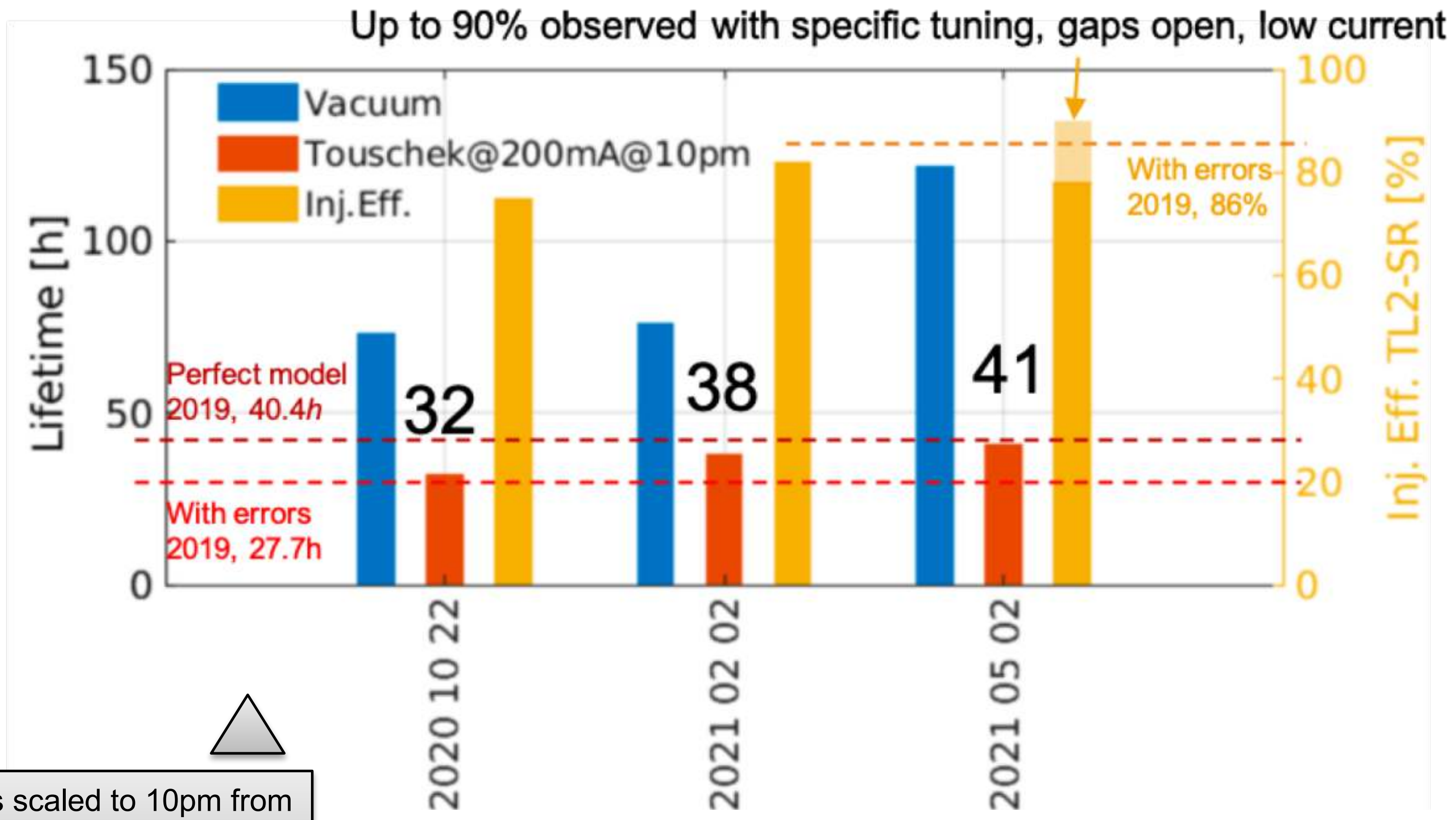
Today we have **smaller correction strengths** then those obtained with the initial single magnets scans, for better final performances (Touschek lifetime).

This procedure of optimization is extremely long to set up in simulations.
NOT a good idea for commissioning-like simulations.

Lifetime computed in 7s with beam, in 1h on 100s of CPUs

85 days to simulate 4h MDT.

TOUSCHEK LIFETIME EXPECTATIONS ARE EXCEEDED EVEN COMPARED TO A PERFECT LATTICE !



Lifetimes scaled to 10pm from 5pm simulations of July 2019. Errors are as in TDS, approx. x2 the real SR ones.

For operation:

7/8+4mA,
200mA,
10pm,
collimators closed

τ_{beam}>26.5h
(~= previous run)

Inj. Eff. ~85%
(unaffected by optimization process)

Touschek Lifetime >40h, exceeding all TDS simulated predictions.

Sextupoles tuning not included in simulations.

COMMISSIONING EXPERIENCE SUMMARY: WHAT WAS USELESS AND WHAT WOULD HAVE BEEN USEFUL

Was NOT used:

- Energy tuning (good only for large energy shifts, not used)
- TbT data analysis for localization of bumps (too long analysis)
- Calibration issues spotter (good for few, all were wrong)
- Automated chroma/tune scan (too long, needed quick progress)
- Quadrupole/sextupole/octupole resonance knobs (ineffective)
- Relaxed optics (not used)

Was used but not prepared:

- On-axis injection with parallel bump + static bump impacting SR optics
- Beam threading tuning "launch conditions" with injection element (Hor. and Ver.)
- Optimal sextupoles to store beam with large orbit
- Cross talks
- Hysteresis of steerers during optics measurements
- Singular vectors studies: optimal DA/TLT, lower then expected dipole field in DQ (backup slide)
- Beam waving for faster vacuum conditioning (backup slide)

Was not used enough:

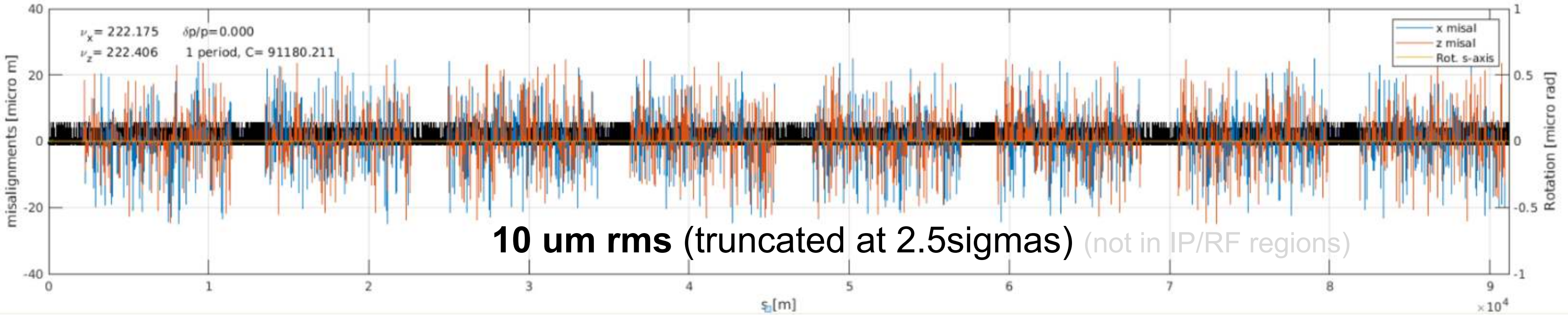
- Beam dynamics control system simulator (could have been used to spot calibration issues without beam)

COMMISSIONING-LIKE CORRECTION SEQUENCE APPLIED TO FCC-EE (V10 Z ENERGY)

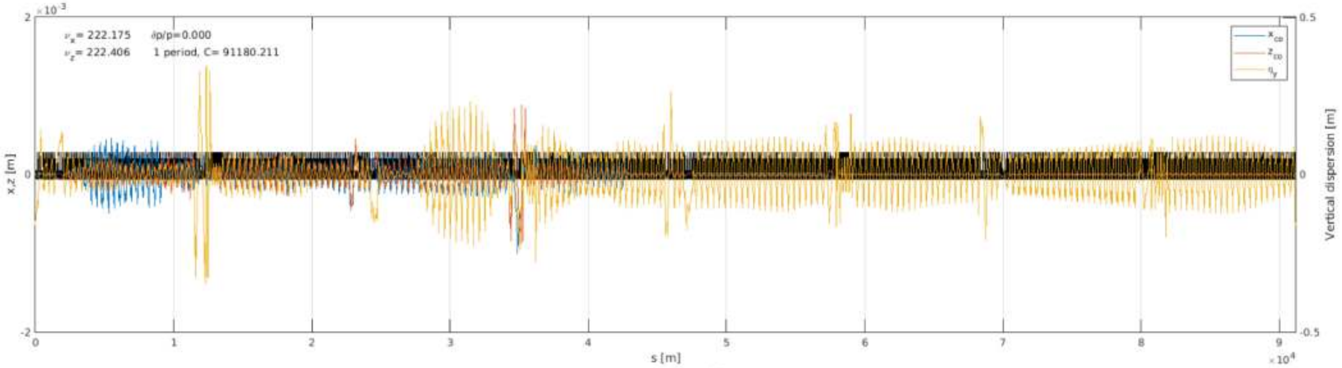
COMMISSIONING LIKE CORRECTION SEQUENCE COMPLETED FOR SEVERAL SEEDS WITH LIMITED ERRORS.

No radiation

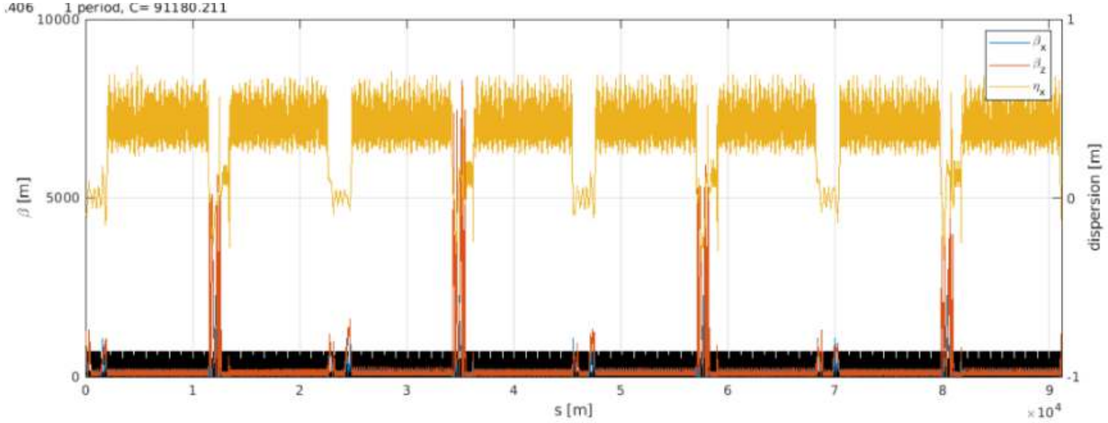
AT lattice conversion by **F. Carlier**
+ BPMs and correctors at each quadrupole



10 um rms (truncated at 2.5sigmas) (not in IP/RF regions)



Hor. Ver. orbit and vertical dispersion after commissioning-like simulations



Hor. Ver. beta and horizontal dispersion after commissioning-like simulations

COMMISSIONING LIKE CORRECTION SEQUENCE COMPLETED FOR SEVERAL SEEDS WITH LIMITED ERRORS.

SEQUENCE OF Commissioning-like CORRECTIONS

```
open trajectory (steerers) Tikhonov
tune (quadrupoles, 2 families)
RF cavity
orbit (steerers) Tikhonov
tune (quadrupoles, 2 families)
chromaticity (sextupoles, 2 families)
orbit (steerers) Tikhonov
tune (quadrupoles, 2 families)
chromaticity (sextupoles, 2 families)
Fit Quad+Dip Errors
Correct RDT and Dispersion of fitted model
orbit (steerers) Tikhonov
tune (quadrupoles, 2 families)
chromaticity (sextupoles, 2 families)
Fit Quad+Dip Errors
Correct RDT and Dispersion of fitted model
RF cavity
tune (quadrupoles, 2 families)
```

+ injection elements tuning (kickers, septa, steerers)

+ Sextupole tuning to maximize #turns?

+ sing. Vectors vs DA/TLT

No BBA (assumed to work)

+ BBA

+ hysteresis effects?

+ Sextupole tuning ex: NOECO, in progress (see later)

+ …

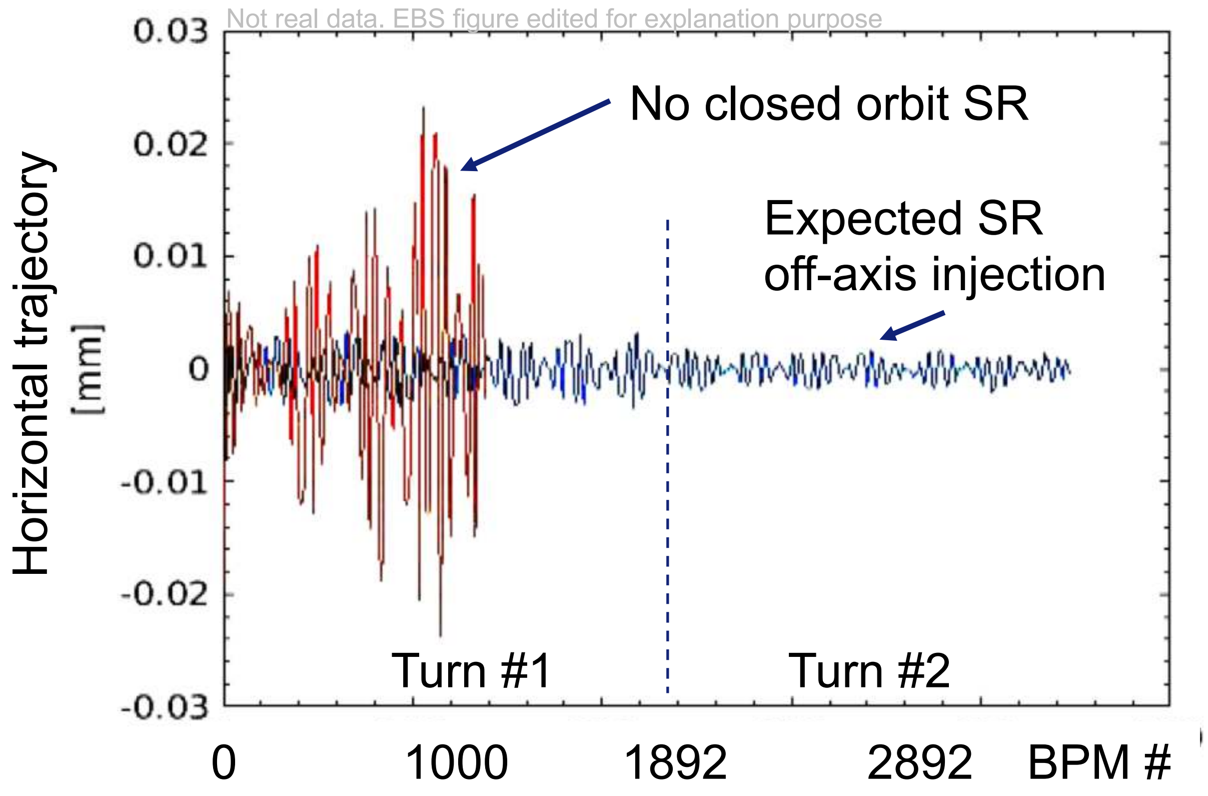
+ …

All parameters of each step have to be tuned for FCC-ee!

```
------------------------------------------------------------
------ total std corrector values applied --------
------                                        --------
     HK (1892) [1/m]: 0.00e+00 -> 9.67e-08
     VK (1892) [1/m]: 0.00e+00 -> 6.64e-08
     SK (1892) [1/m2]: 0.00e+00 -> 1.11e-06
     QK (1892) [1/m2]: 4.17e-07 -> 5.14e-06
------                                        --------
------   residual orbit and dispersion   --------
------                                        --------
     OH (13363) [m]: 4.29e-04 -> 1.99e-05
     OV (13363) [m]: 2.23e-04 -> 1.60e-05
     DH (13363) [m]: 9.43e-02 -> 1.25e-01
     DV (13363) [m]:7.39e-02 -> 5.36e-03
     BBH (13363) %: 2.9 -> 1.6
     BBV (13363) %: 116.7 -> 2.4
     PhH (13363) : 2.28e-02 -> 1.22e-02
     PhV (13363) : 8.48e-02 -> 3.30e-02
------                                        --------
------      tune and emittance           --------
------                                        --------
     Qx [222.172]: 222.176 -> 222.175
     Qy [222.400]: 222.387 -> 222.402
     Cx [-0.070]: -0.354 -> -0.065
     Cy [-0.123]: -13.748 -> -1.718
     EX [705.313 pm]: -183082.420 -> 787.625
     EY [0.000pm]: -3340463.956 -> 0.105
```

For this first run, with 10μm rms alignment errors, 7/10 seeds survived the process. There is margin to improve.

BEAM THREADING IN FCC-EE Z



Tested up to 30µm rms errors for FCC-ee

```
V PLANE
correcting available V trajectory
X: 238.640 -> 118.656 um
Y: 257.369 -> 127.705 um
Search closed orbit
Trajectory correction: nbpms= 1441 ncor: 1441, 1441,
computing ORM for available trajectory
H PLANE
correcting available V trajectory
V PLANE
correcting available V trajectory
X: 335.070 -> 166.596 um
Y: 736.083 -> 365.489 um
Search closed orbit
Trajectory correction: nbpms= 1699 ncor: 1699, 1699,
computing ORM for available trajectory
H PLANE
correcting available V trajectory
V PLANE
correcting available V trajectory
X: 395.169 -> 167.364 um
Y: 1073.800 -> 571.294 um
Search closed orbit
Trajectory correction: nbpms= 1697 ncor: 1697, 1697,
computing ORM for available trajectory
H PLANE
correcting available V trajectory
V PLANE
correcting available V trajectory
X: 167.222 -> 130.869 um
Y: 566.189 -> 273.673 um
Search closed orbit
Trajectory correction: nbpms= 1866 ncor: 1866, 1866,
computing ORM for available trajectory
H PLANE
correcting available V trajectory
V PLANE
correcting available V trajectory
X: 134.897 -> 81.426 um
Y: 304.474 -> 191.540 um
```

It may "go back"!

100/1892 BPMs
40/1892 steerers

SVD for trajectory correction
(to reference off-axis injection trajectory)

Acceptable signal on more BPMs or smaller rms trajectory

iterate

PROCEDURE FOR OPTICS CORRECTION

```
%% RDT+DISPERSION CORRECTION from lattice error model

    % fit lattice errors model
    [rfit]=FitResponseMatrixAndDispersionEBSsimple(...
        rerr,...
        r0,...
        inCOD,...
        indBPM,...
        indHCor(1:9*2:end),... % 4 correctors, 1 every 8 cells
        indHCor(1:9*2:end),...  % 4 correctors, 1 every 8 cells
        [neigQuadFit,neigDipFit,neigSkewFit,neigDipFit],...
        4,...
        [speclab 'fitrm']);

    % get change of strength of correctors
    fq=atgetfieldvalues(rfit,indQuadCor,'PolynomB',{1,2});
    fs=atgetfieldvalues(rfit,indSkewQuadCor,'PolynomA',{1,2});

    % correct RDT and dispersion of fitted error model
    [~,inCOD,fcq,fcs]=atRDTdispersioncorrection(...
        rfit,... <<--- fitted error model! not lattice with errors!
        r0,...
        indBPM,...
        indQuadCor,...
        indSkewQuadCor,...
        inCOD,...
        [[floor(linspace(1,neigQuad,5)),neigQuad,neigQuad];...
        [floor(linspace(1,neigSkew,5)),neigSkew,neigSkew]]',...
        [true],...
        1.0,...
        [0.8 0.1 0.8],...
        ModelRM);

    %fcq=atgetfieldvalues(rfitcor,indQuadCor,'PolynomB',{1,2});
    %fcs=atgetfieldvalues(rfitcor,indSkewQuadCor,'PolynomA',{1,2});

    % store proposed correction
    dcq(1,:)=(fcq-fq);
    dcs(1,:)=(fcs-fs);
```

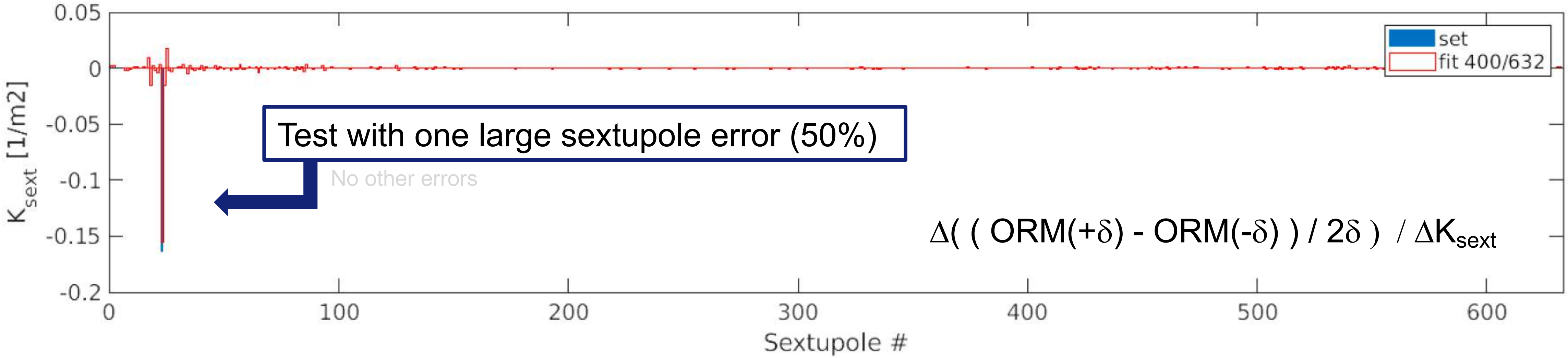
Fit of “measured” partial Orbit Response Matrix (slow)
→ **FITTED OPTICS MODEL**

Computation of normal and skew quadrupoles RDTs + dispersion and correction
→ **Normal and skew quadrupole correction strengths**

This is LOCO equivalent (+ RDTs)
Linear problem + generalize potentially different fit and correction locations

33. A. Franchi, L. Farvacque, J. Chavanne, F. Ewald, B. Nash, K. Scheidt, and R. Tomás, *Vertical emittance reduction and preservation in electron storage rings via resonance driving terms correction*, Phys. Rev. ST Accel. Beams **14**, 034002 (2011).

FCC-EE Z V10 : NOECO



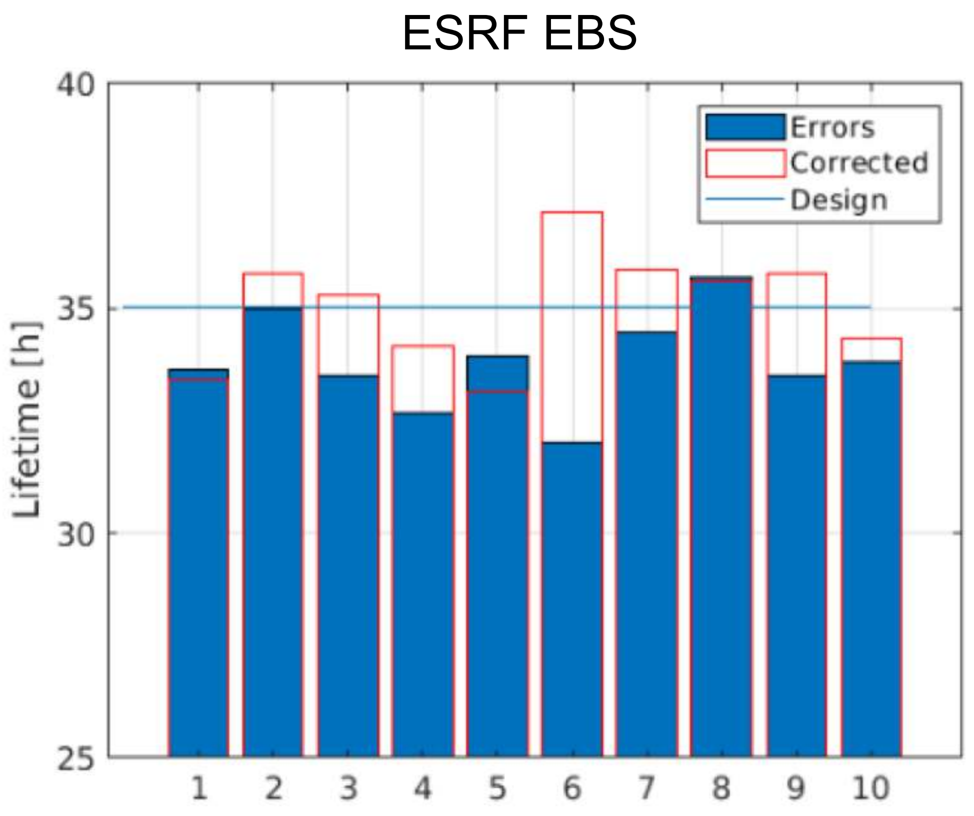
PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 102803 (2020)

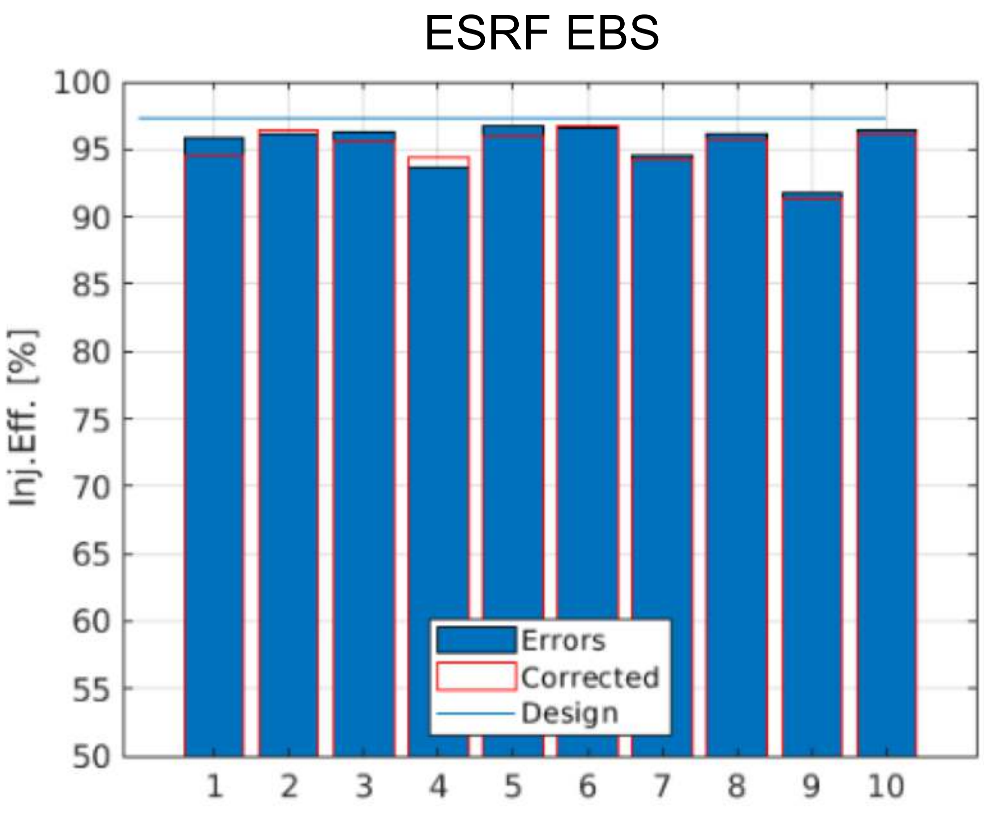
Nonlinear optics from off-energy closed orbits

David K. Olsson,* Åke Andersson, and Magnus Sjöström
MAX IV Laboratory, Lund University, SE-22100 Lund, Sweden

A.Franchi, N. Carmignani, Sextupole calibrations via measurements of off-energy orbit response matrix and high order dispersion, presented at the *25th European Synchrotron Light Source Workshop (ESLS'17), Dortmund, Germany, Nov. 2017*, https://indico.cern.ch/event/657829/contributions/2782617/attachments/1569843/2475779/ESLS17_Carmignani_SextCalibration.pdf.

NOECO LIFETIME IMPROVEMENT SIMULATIONS FOR ESRF EBS





For most of the seeds tested the lifetime is improved after sextupole correction using NOECO
(with different parameters also the seeds that do not seem to improve actually improve)

TEST in Machine Dedicated Time planned for January 2022.

THANK YOU FOR YOUR ATTENTION!

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References:

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- Liuzzo et al., HMBA optics correction experience at ESRF: doi:10.18429/JACoW-IPAC2021-TUPAB048
- Liuzzo et al., Preparation of the EBS commissioning: doi:10.1088/1742-6596/1350/1/012022
- Liuzzo et al., Influence of errors on the ESRF upgrade lattice, TUPWA014, IPAC 2015, Richmond, VA, USA, http://accelconf.web.cern.ch/AccelConf/IPAC2015/papers/tupwa014.pdf
- Biasci, J C et al., A low emittance lattice for the ESRF, Synchrotron Radiation News, vol. 27, Iss.6, 2014
- Liuzzo, The ESRF-EBS Simulator: a commissioning booster. ICALEPCS 2021, MOPV012
- David K. Olsson et al., Nonlinear optics from off-energy closed orbits, 10.1103/PhysRevAccelBeams.23.102803
- G. Le Bec et al. Cross talks between storage ring magnets at the Extremely Brilliant Source at the European Synchrotron Radiation Facility: https://doi.org/10.1103/PhysRevAccelBeams.24.072401

FCC MoU signature under scrutiny by the ESRF management