

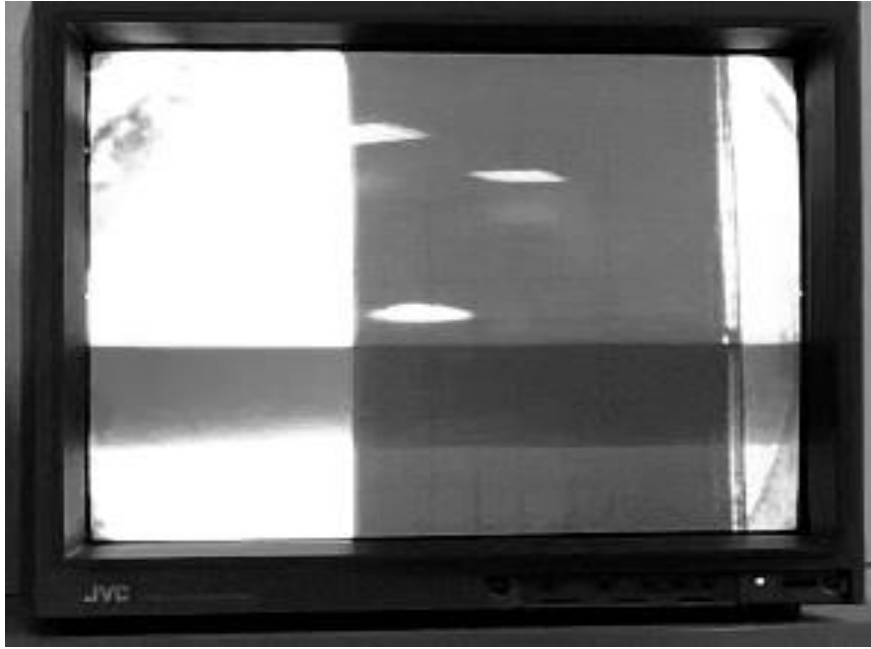
# *Lessons from low-emittance light source designs for future e+e- circular colliders*

Pantaleo Raimondi

eeFACT2022 Sept 13<sup>th</sup> 2022

- EBS commissioning
- Performances highlights
- Low emittance lattice tuning
- Non-linear dynamics
- Conclusions



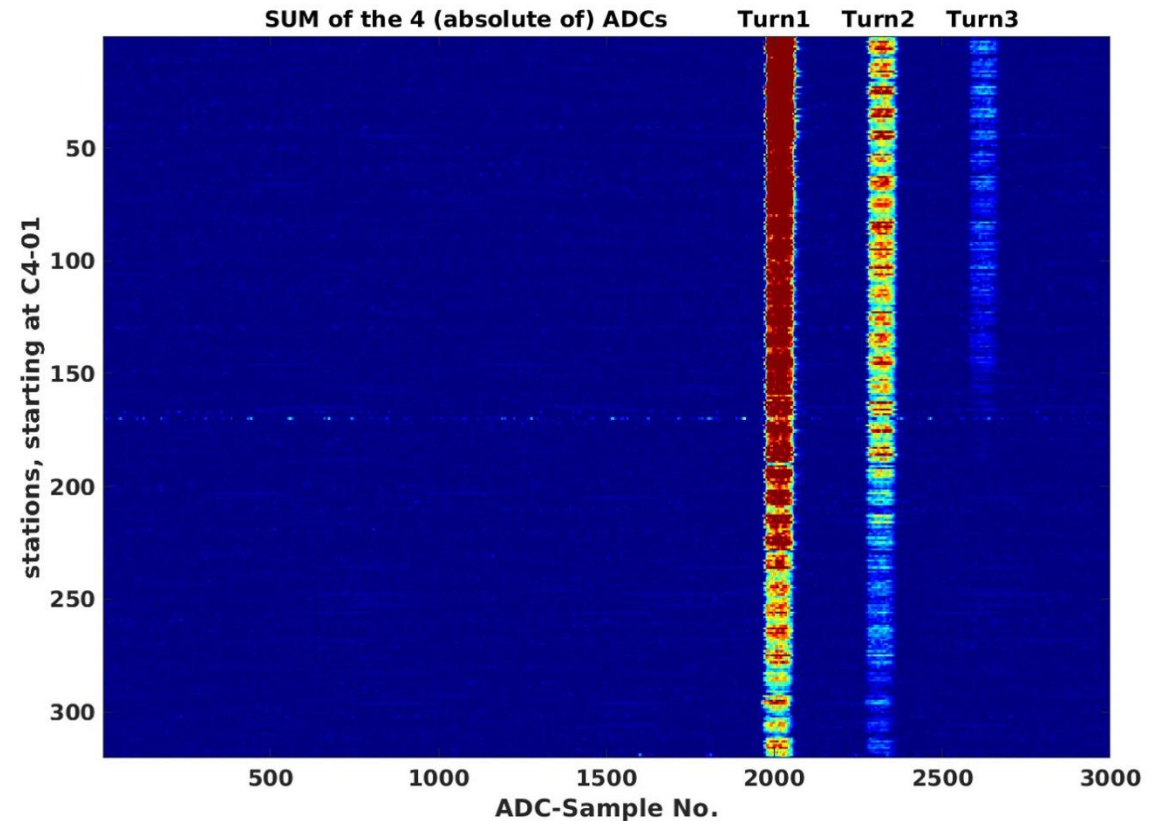


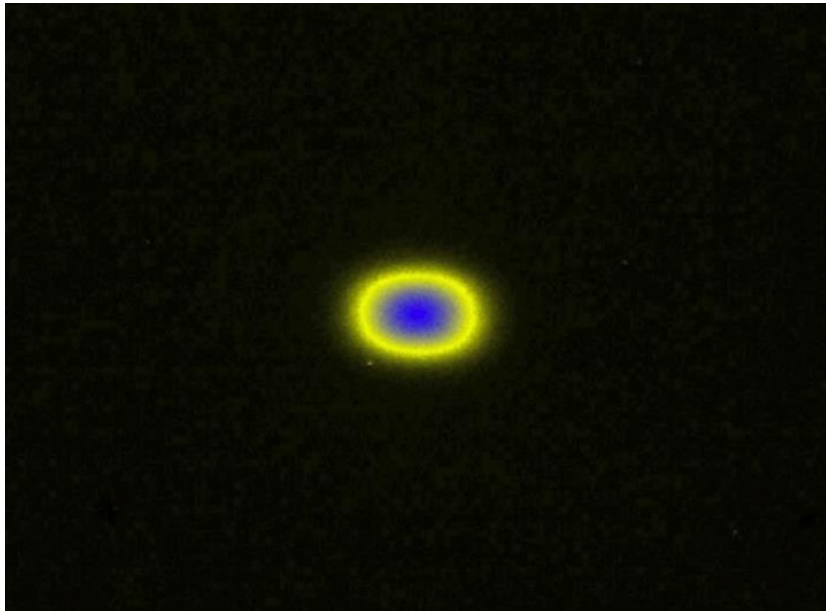
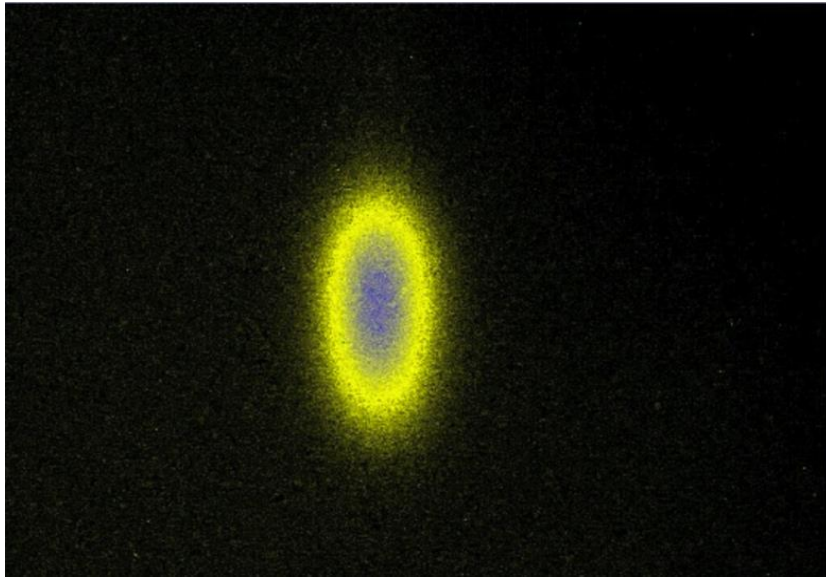
Beam at the entrance of the SR

2.5 turns in the SR achieved ! =>

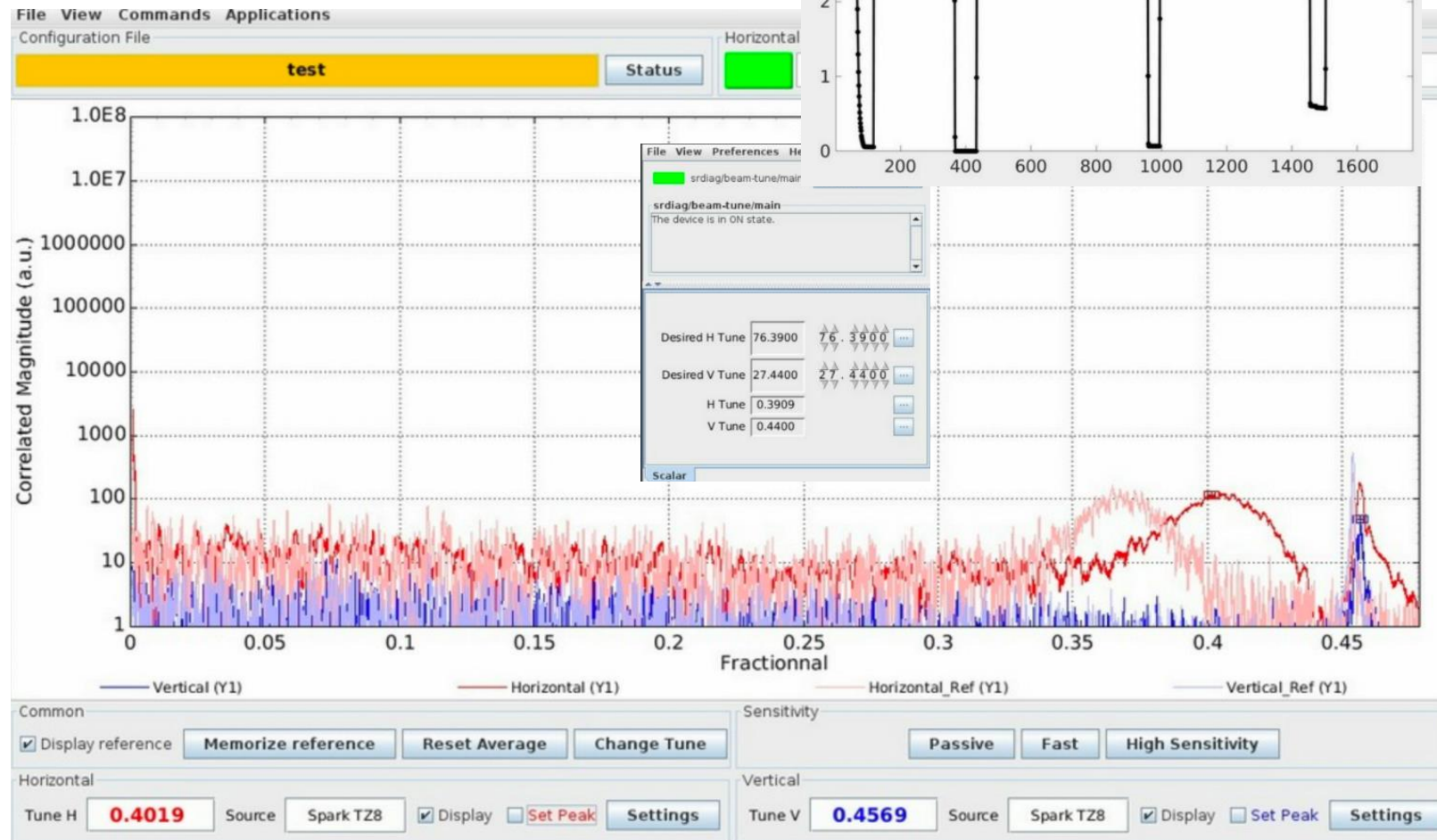
5 days ahead of schedule !!!

FIRST THREE TURNS IN THE EBS  
STORAGE RING, 28-11-2019

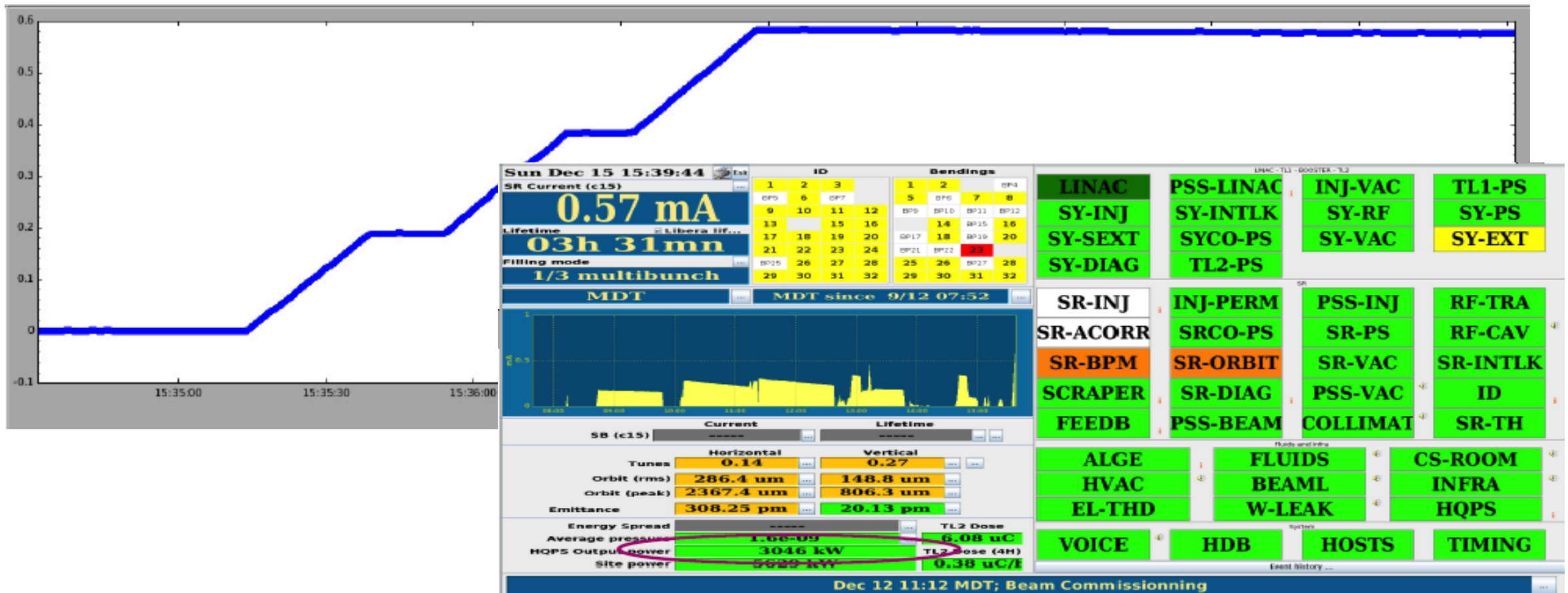


**BEAM STORED!**

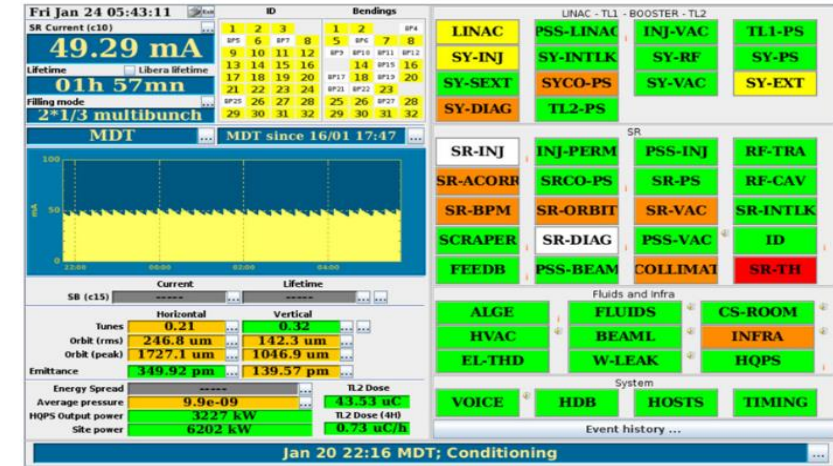
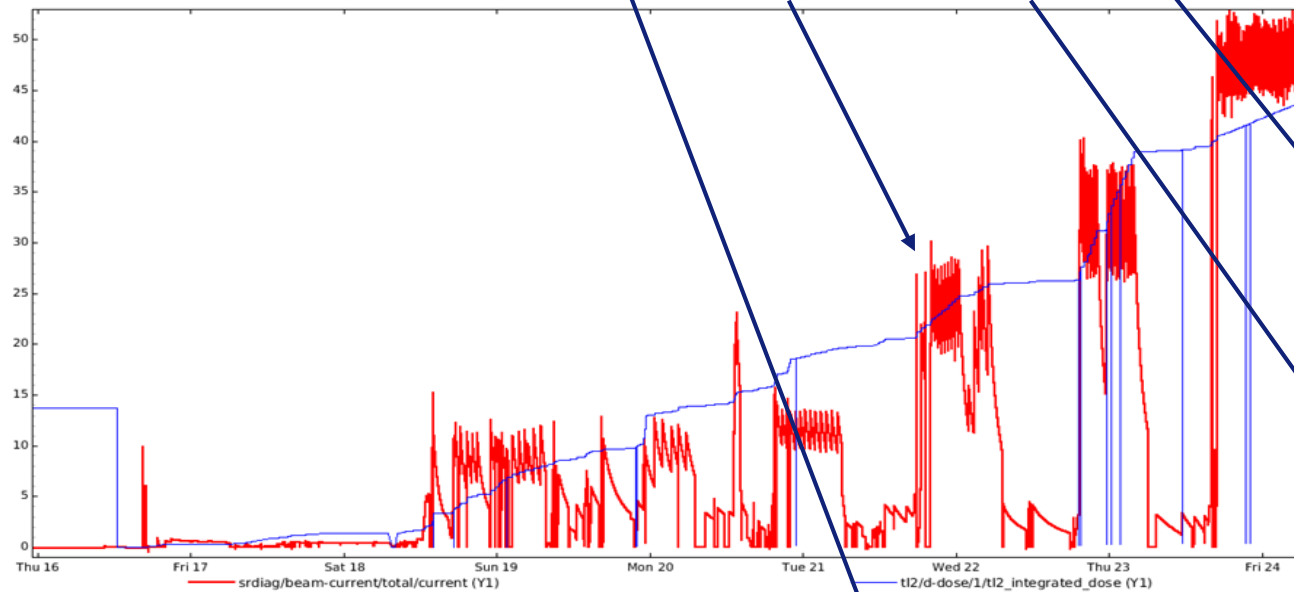
← Signal at DL and DQ pinholes



**15 DECEMBER 2019 – 15.39 PM: FIRST e-ACCEMULATION**  
 - Accumulation demonstrated for a high energy 4<sup>th</sup> generation SR!  
 - Injection efficiency about 0.8%



January 2020: tuning and debugging  
Steady improvements  
of all machine performances



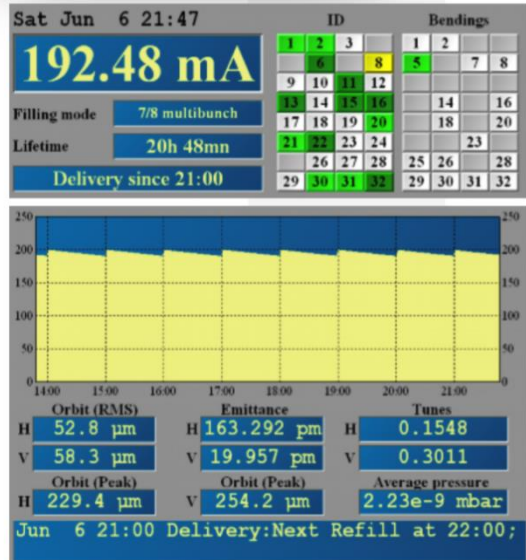
Top Up routine  
Re-commissioned and implemented  
during vacuum conditioning

```
>> inject(15)
Injection Efficiency: 91.97 %
>> inject(15)
Injection Efficiency: 94.27 %
>> inject(15)
Injection Efficiency: 95.09 %
>> inject(15)
Injection Efficiency: 94.77 %
>> inject(15)
Injection Efficiency: 92.25 %
>> inject(15)
```



# MARCH 02: HIGH BRIGHTNESS BEAMS DELIVERED TO BEAMLINES

## MACHINE STATUS



## EBS commissioning status

### Beam Current



7/8 multibunch

21:04:50 Lifetime

2.2e-9 mBar Average Pressure

### Status

Sat 06 Jun 2020 21:52:45

User Service

Delivery since 21:00

00:07:07 Countdown

162.824 pm EmittanceH

20.021 pm EmittanceV

### Beamlines



14 MARCH 2020  
THE NEW EBS STORAGE RING  
ACHIEVES USM PARAMETERS  
5 MONTHS AHEAD OF SCHEDULE

Jun 6 21:00 Delivery: Next Refill at 22:00;

last messages

Lifetime still dominated by vacuum

Top Up operation consolidated  
No failures in the first two weeks of beam delivery  
Accelerator availability > 98%

# EBS COMMISSIONING: BEAM PARAMETERS GOALS (PRESENTED AT 2019 COUNCIL)

Parameters\*\* ensuring that no major problem remain in the new hardware or tuning of the new machine

Goal: to be exceeded by 01-March-2020  
Start of Beamline Commissioning

Achieved Jan 30

Parameters\*\* that could allow “comfortable” USM operation

Goal: to be exceeded by 24-August-2020, start of USM

Achieved Mar 14

Design EBS parameters

Goal: to be exceeded by Dec 2021

All exceeded Sept 1, 2020  
16 months ahead of schedule

|               |                               |                                |                 |
|---------------|-------------------------------|--------------------------------|-----------------|
| Total current | > 50 mA * 120mA               | 200 mA 201mA                   | 200 mA          |
| MTBF          | > 12h >12h                    | > 30h >100h                    | > 50h           |
| Up-time       | > 90% >90%                    | > 95% *** >98%                 | > 97%           |
| Inj. Eff.     | > 50% >90%                    | > 70% >90%                     | > 80%           |
| Lifetime      | > 5h 3.5H @50mAmps            | > 10h >10.5h                   | > 20h           |
| H emittance   | 950 pm                        | 150 pm                         | 105 pm          |
| V emittance   | < 50 pm ~8pm@3mAmps           | < 20 pm < 15pm@200mA           | < 10 pm         |
| stability     | < 0.2 $\sigma$ <0.05 $\sigma$ | < 0.1 $\sigma$ < 0.02 $\sigma$ | < 0.05 $\sigma$ |

Now about 99.7%

⇒ TLT ~ 40Hrs in 2021

Theoretical TLT of the lattice with no errors

EBS is a very solid design, it works!

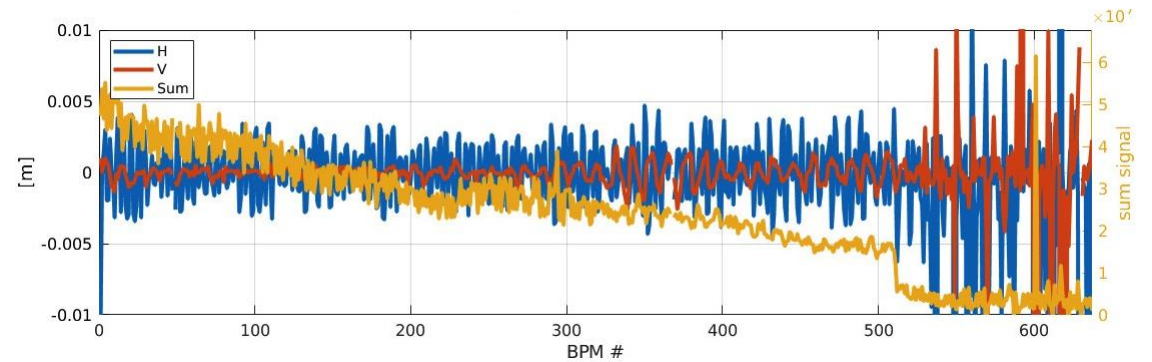
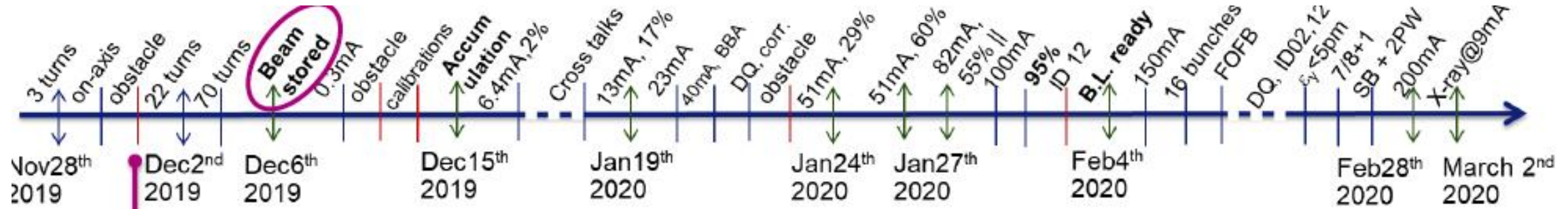
\*\* Parameters have to be achieved simultaneously

\*\*\* increasing then 1-2% each year

Project completed on-time and on-budget

- RF extremely **reliable**: apart the new HOM cavities, the system (power-wise) was dimensioned for the former machine that required about twice more RF power. “A car designed to run at 100km/h seldom fails if runs at 60km/h”
- Power Supplies (more than 600 LGPS) have a MTBF > 500000Hr and in addition an HOT-SWAP system is implemented: **beam losses due to PS failures negligible**
- Vacuum levels and conditioning **at least a factor 2 better than expected**
- Machine alignment **about a factor 2 better than requested => greatly beneficial to commissioning and final performances**
- Beam stability **5 times better than the old machine**: about 15% of the total cost of the project went in the support system (girders, technical choices for magnets supports etc...)
- **Optics very stable in time**: support and diagnostic (5% of the total cost)

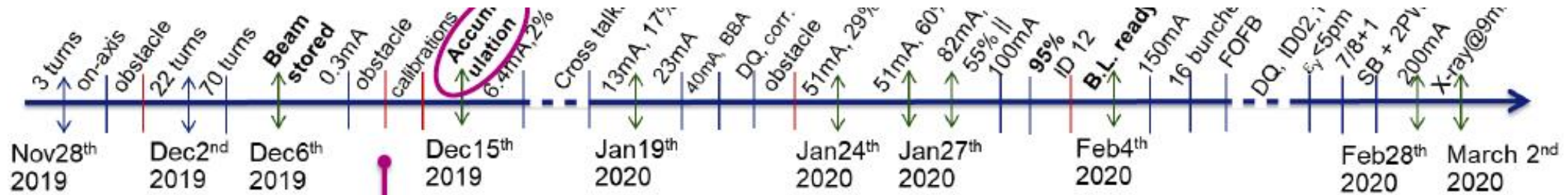
# VACUUM SYSTEM: THE QUEST FOR OBSTRUCTIONS !!!



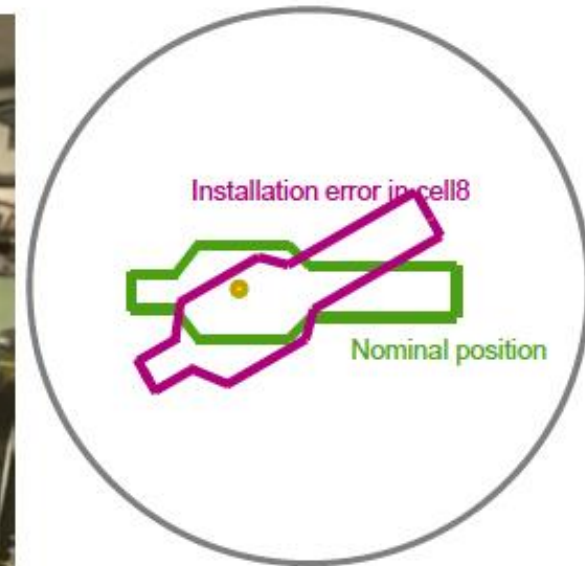
Obstacle in SS-23 ID chamber

Obstacle found with turn by turn data in the early days of commissioning, SS-23 immediately identified (20turns reached before removal)

# VACUUM SYSTEM: THE QUEST FOR OBSTRUCTIONS !!!

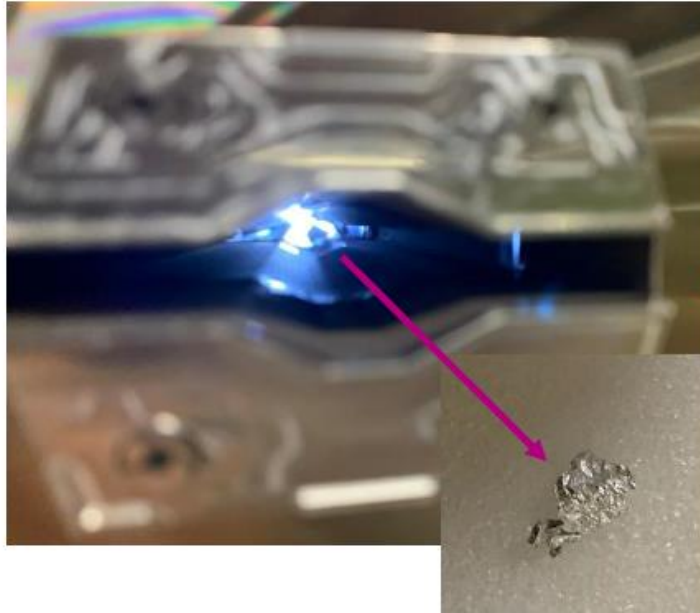
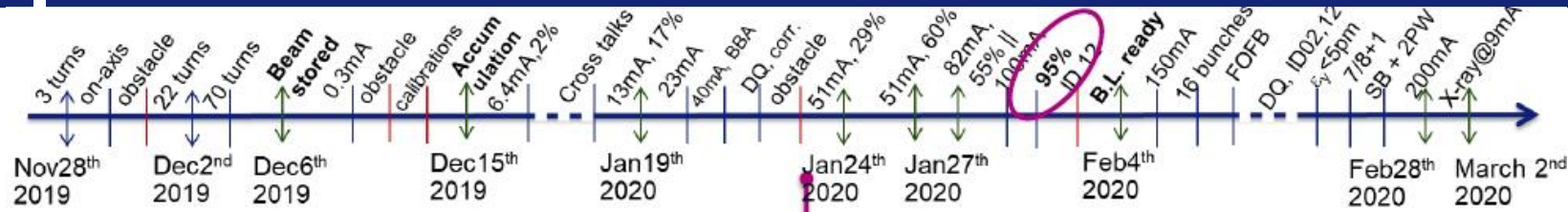


Installation mistake  
Cell-8 - Bellow 9-11  
Remounted correctly



Obstacle found with turn by turn and data (accuracy 20cm, confirmed by radiation survey)  
in the early days of commissioning  
Accumulation was achieved after removal

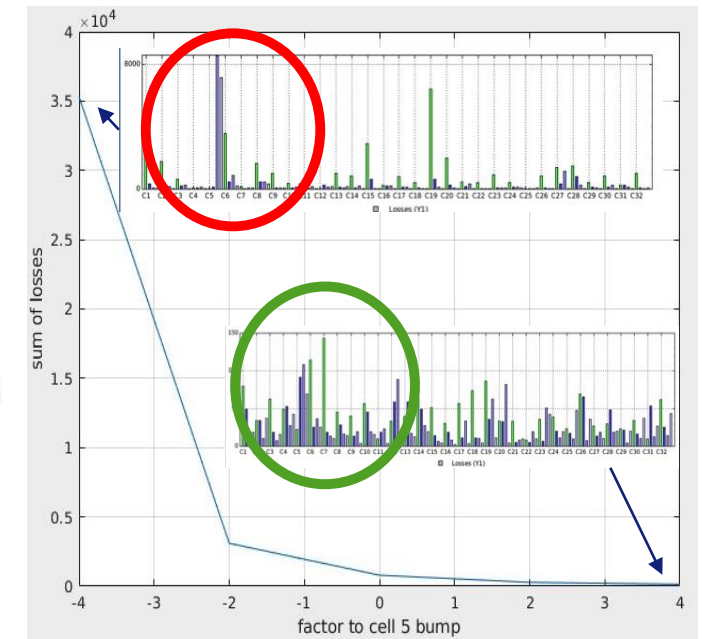
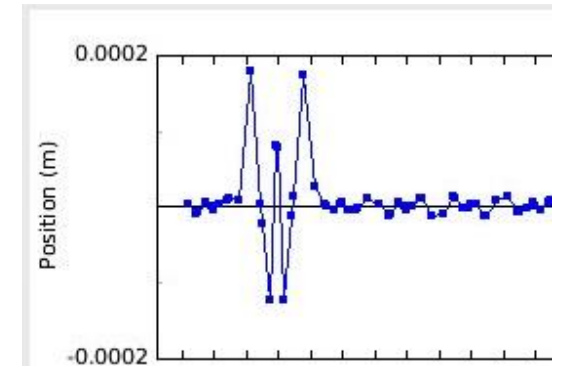
# VACUUM SYSTEM: THE QUEST FOR OBSTRUCTIONS !!!



Obstacle in  
Cell-5 in Chamber-7

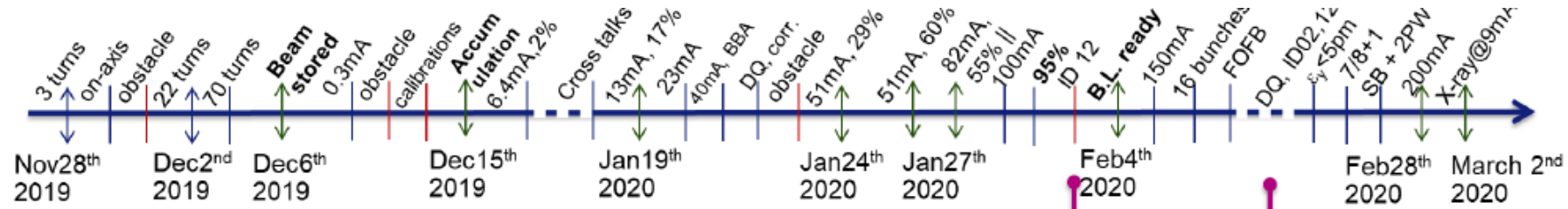
Al foil piece fall during installation  
of DQ2

-> very difficult protect flanges but  
no way to inspect them after!



Obstacle found with BeamLossMonitor data and local horizontal bump (final accuracy about 50cm) in the suspected area in the early days of january.  
Injection efficiency did increase from 10% to 60%, lifetime doubled

# VACUUM SYSTEM: THE QUEST FOR OBSTRUCTIONS !!!



ID-12 - Replacement of ID-5000 - Good conditioning,  
but after for

**Vacuum diagnostic**

**BPM diagnostic**

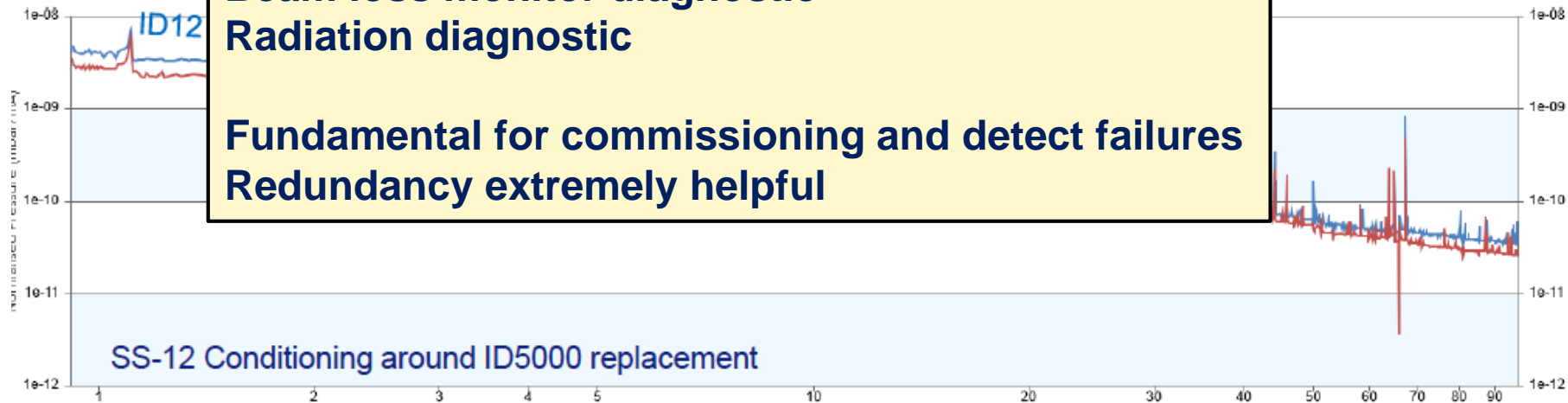
**Beam loss monitor diagnostic**

**Radiation diagnostic**

**Fundamental for commissioning and detect failures**

**Redundancy extremely helpful**

Replacement of ID2



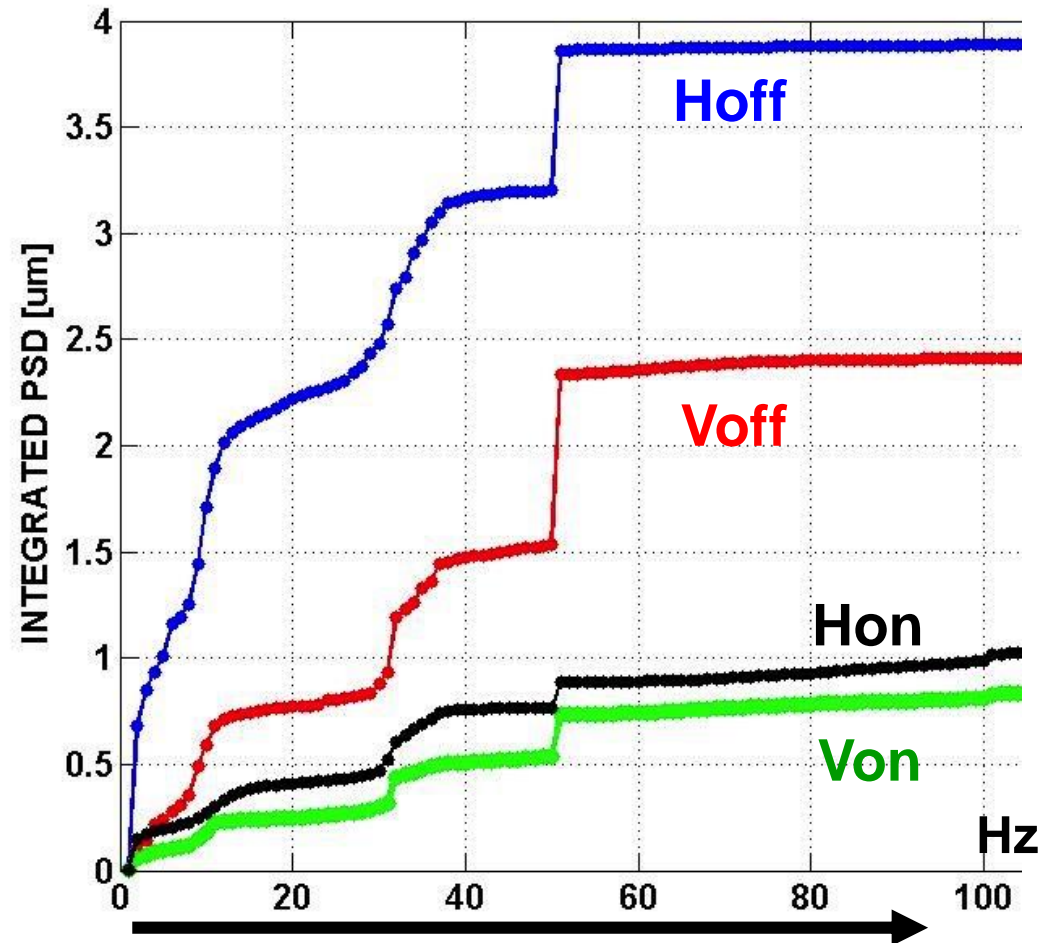
SS-12 was contaminated, vacuum inside the vessel was estimated to be around  $10^{-5}$ .

Problem found by BLM analysis and radiation survey in the tunnel

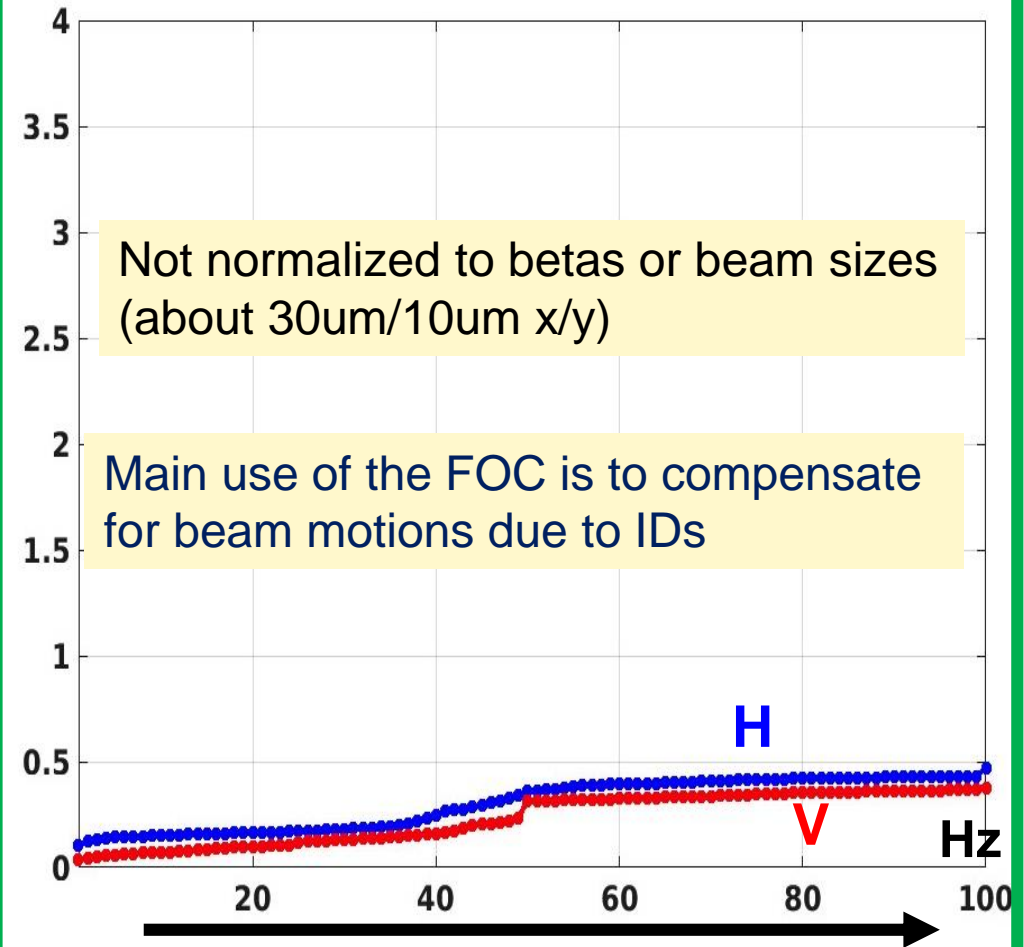
After replacement in early february the beam lifetime increased 10time at low current and 3 times at high current

## Stability in the low-AC domain (1 – 100Hz)

old ring 2010, FOC On & Off



new ring, no FOC (yet)



30<sup>th</sup> Jan 2020 : 26/27 BEAMLINES see Synchrotron radiation at White Beam viewer

From simulations the estimated SR alignment errors are:

**H 30-45  $\mu\text{m}$**

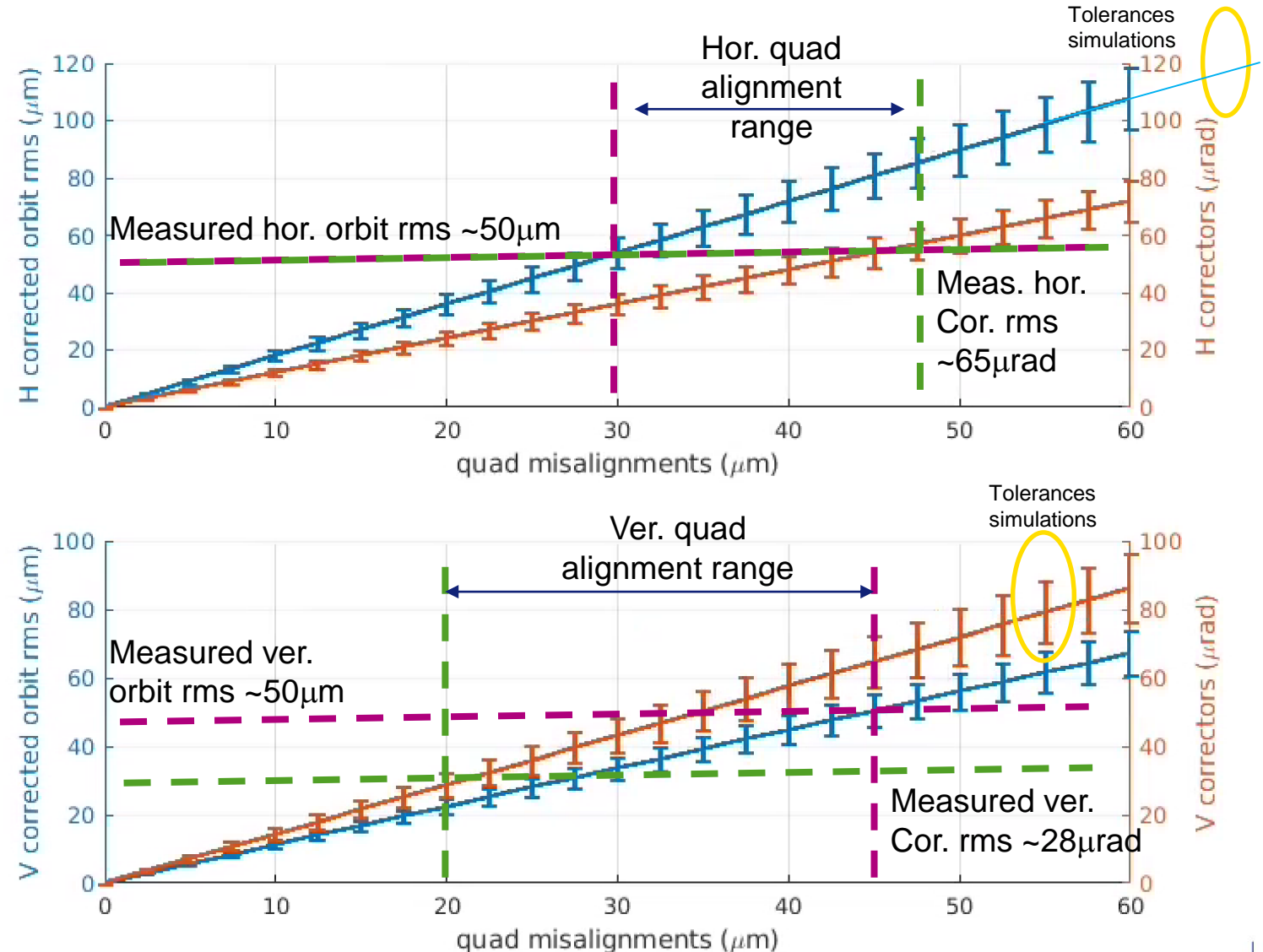
**V 20-45  $\mu\text{m}$**

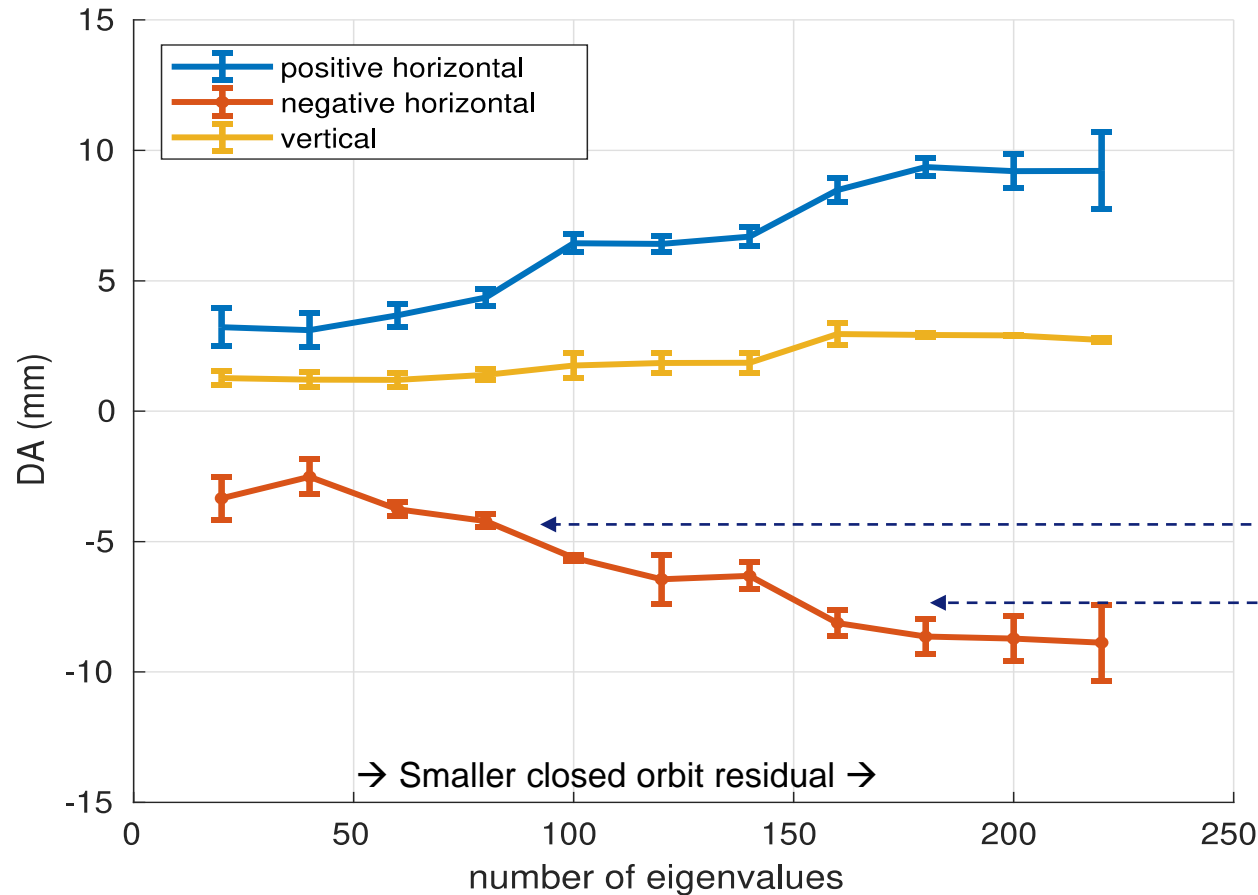
The quadrupole alignment tolerances required where:

**H 50  $\mu\text{m}$**

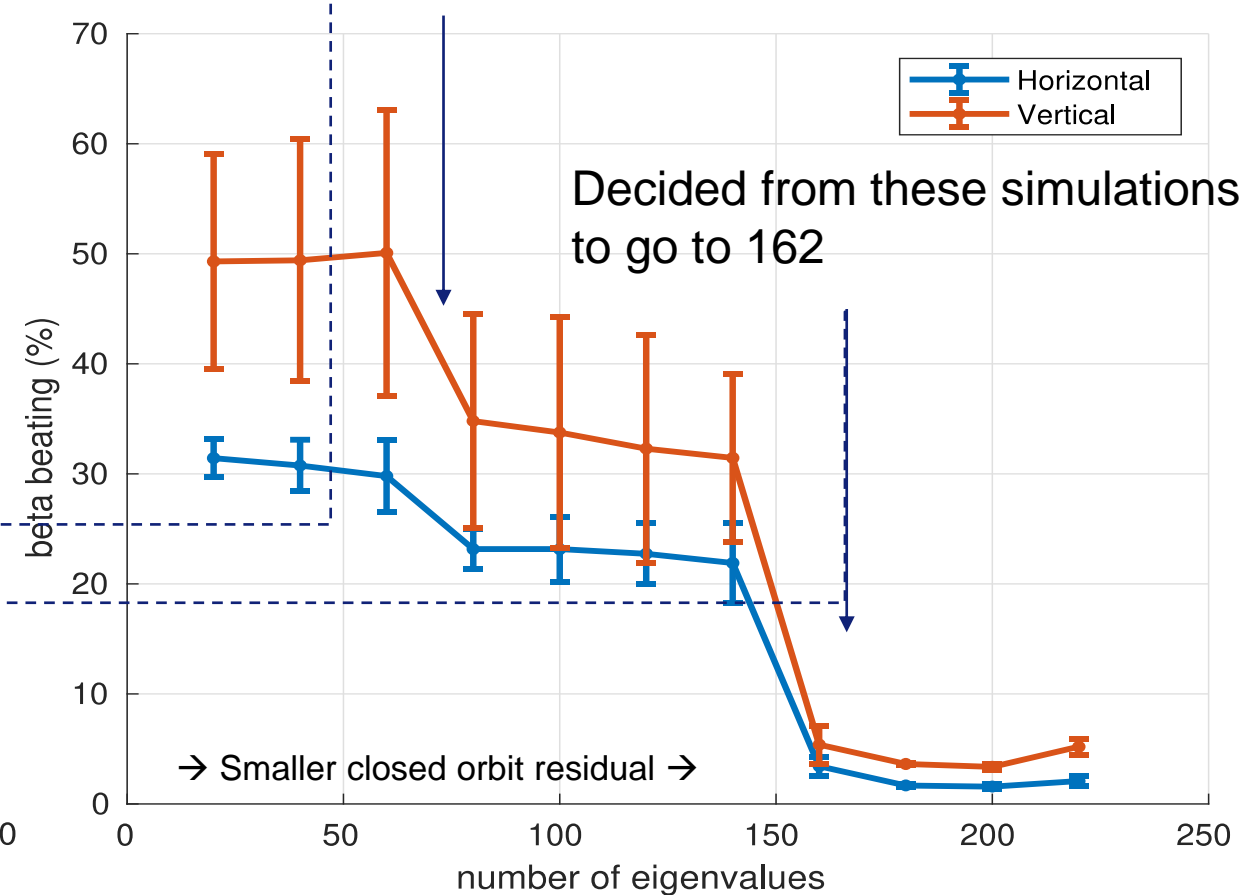
**V 50  $\mu\text{m}$**

Rough estimation.  
Errors only in quadrupoles.



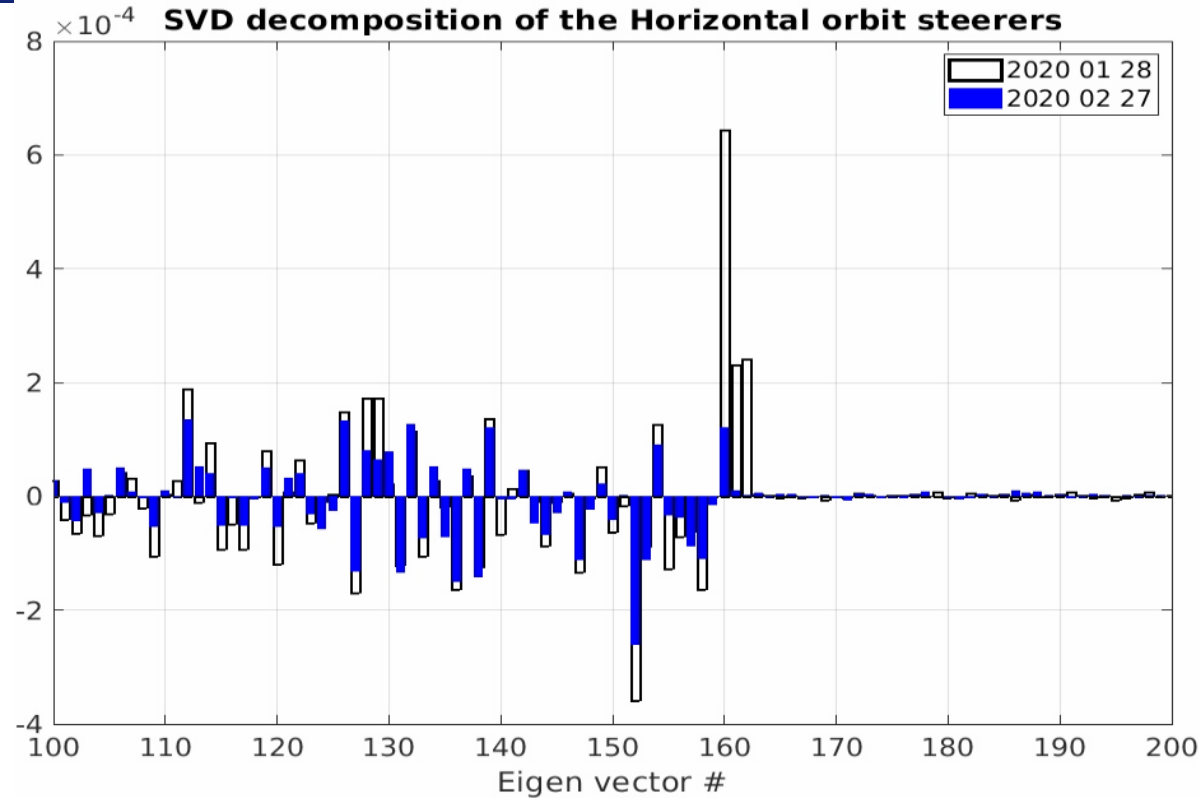


We use to stick to maximum 64



There is a magic number in the horizontal plane (160) eigenvalues that corrects the orbit locally across the sextupoles triplets. When these eigenvalues are used the betabeating is minimal and DA maximal. Increasing this number just adds noise to the system and slowly degrades the DA

## THE DQS PUZZLE



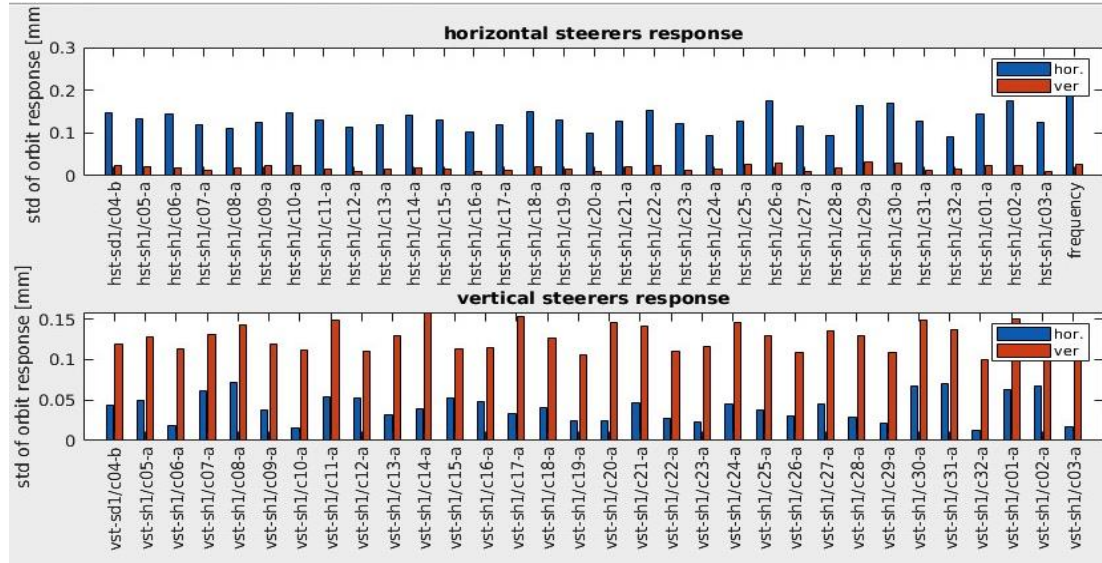
DQs are very strong gradient dipoles

Using 162 eigenvalues did initially produce a clear pattern in the steerers also visible in the svd decomposition. We did identify the cause to be due an improper horizontal positioning of the DQs. The prediction estimated by the eigenvalue analysis did agree with the identified positioning error(s).

After realignment the eigenvalues content was greatly improved, orbit and steerer rms improved as well. The machine energy did finally increase to 6GeV (confirmed by booster energy, tune correction etc...)

The analysis of the SVD decomposition proved to be an extremely useful tool.

This analysis has been done for the optics correction as well, leading to the identification of systematic errors (but not isolated ones)

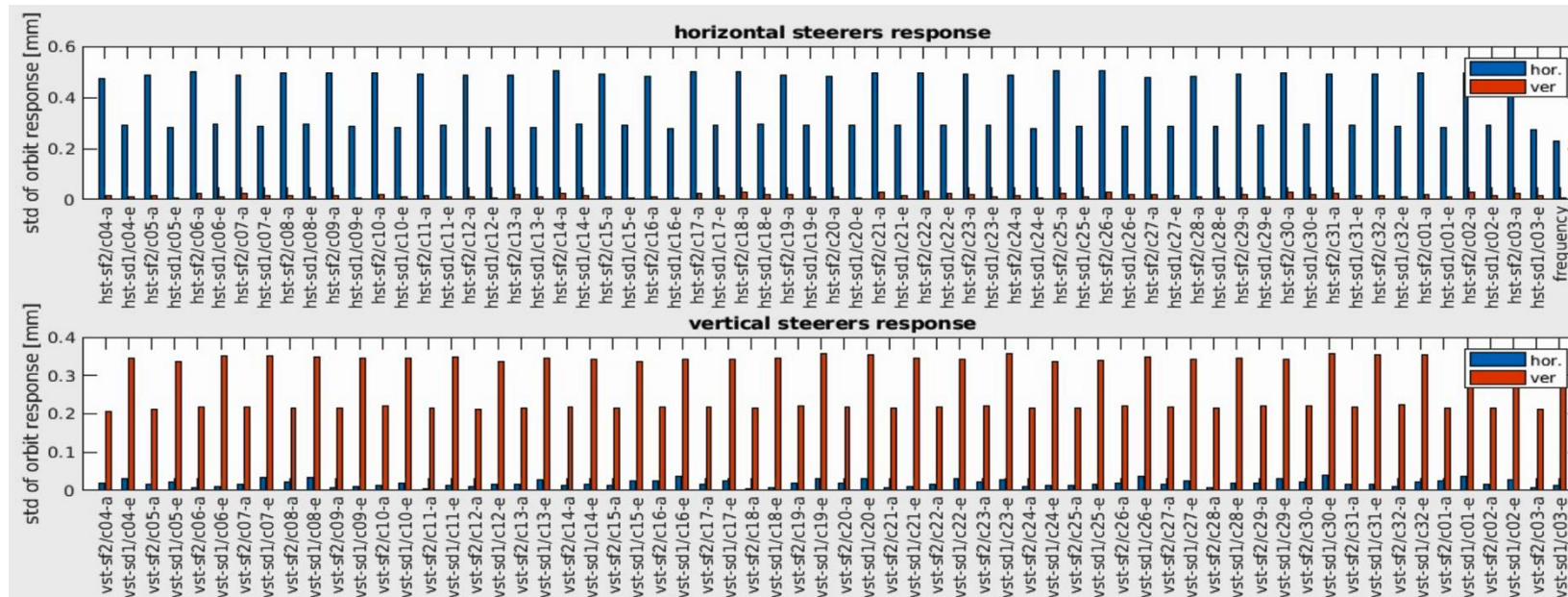


**First  
Response matrix**

$$\Delta\beta/\beta > 12\% \text{ H}, 15\% \text{ V},$$

$$\Delta\eta > 3 \text{ mm H}, 3 \text{ mm V}$$

Magnet Calibrations, cross talks, optics correction,  
BBA, all fundamental steps to achieve this result

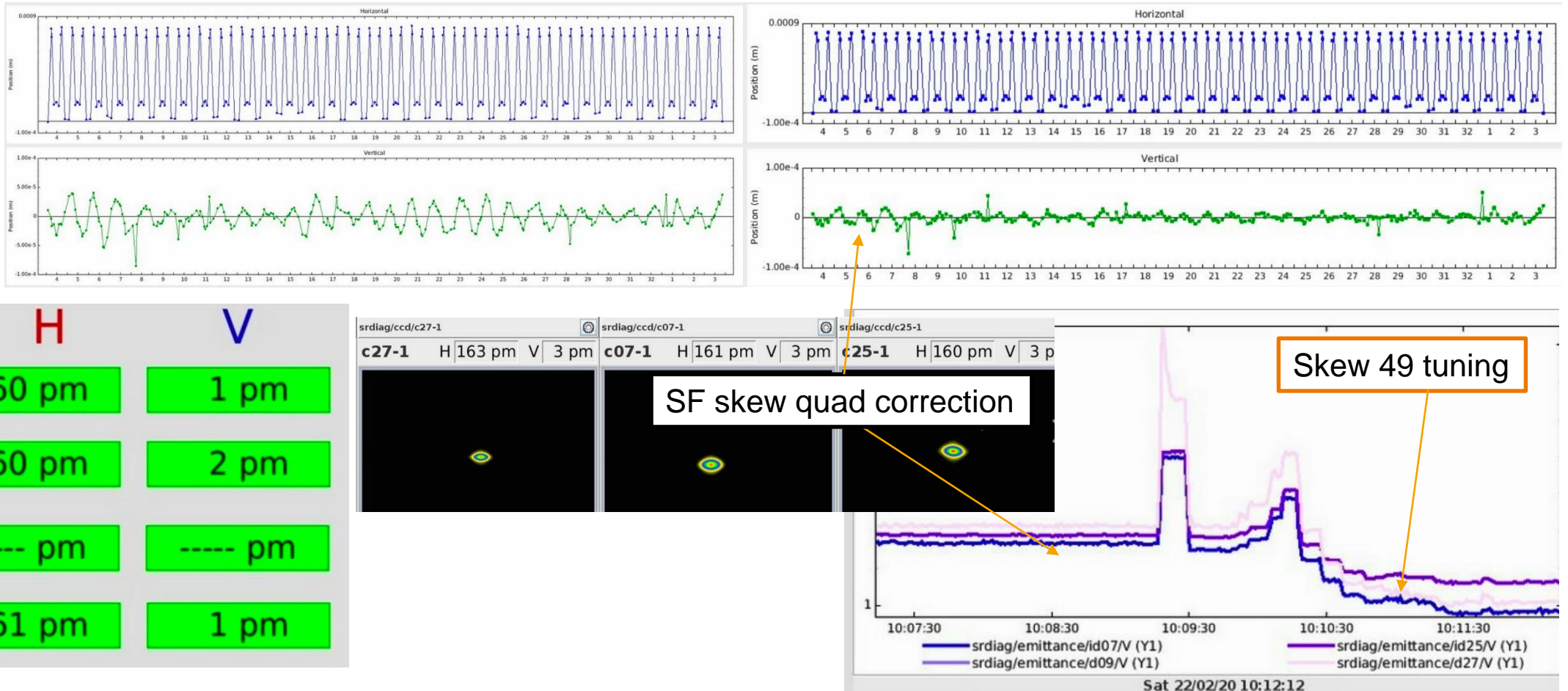


**Latest  
response matrix.**

$$\Delta\beta/\beta > 1.5\% \text{ H}, 1.5\% \text{ V},$$

$$\Delta\eta \sim 0.7 \text{ mm H}, 0.7 \text{ mm V}$$

- At startup due to many bugs all the gradients were wrongly set by about 2% rms
- Optics correction could decrease the mismatch around 5% but unable to locally correct the gradients (increasing the eigenvalues above 25% of the total was degrading the matching)
- After correcting all the bugs, all the magnets gradients have been set with an error of about 0.04% ( estimated from combined measurements made at the factories and at ESRF => **It proved fundamental to have the magnets fiducialization made by two completely independent teams** )
- The optics correction is made assuming gradient errors just on the quads nearby the sextupoles (to incorporate the errors due to orbit offsets in the sextupoles) and we empirically determined the optimal number of eigenvalues (96 out of about 600, after that the reduction of betabeating was unmeasurable) by just applying solutions with increasing eigenvalues and checking all significant parameters (lifetime, inj\_eff etc..)
- The strength of the correction is consistent with the gradient errors introduced by orbit errors in the sextupoles
- **Despite 320 BPMs, 224 correctors, there is not enough resolution to detect errors on a shorter scale (more eigenvectors)**

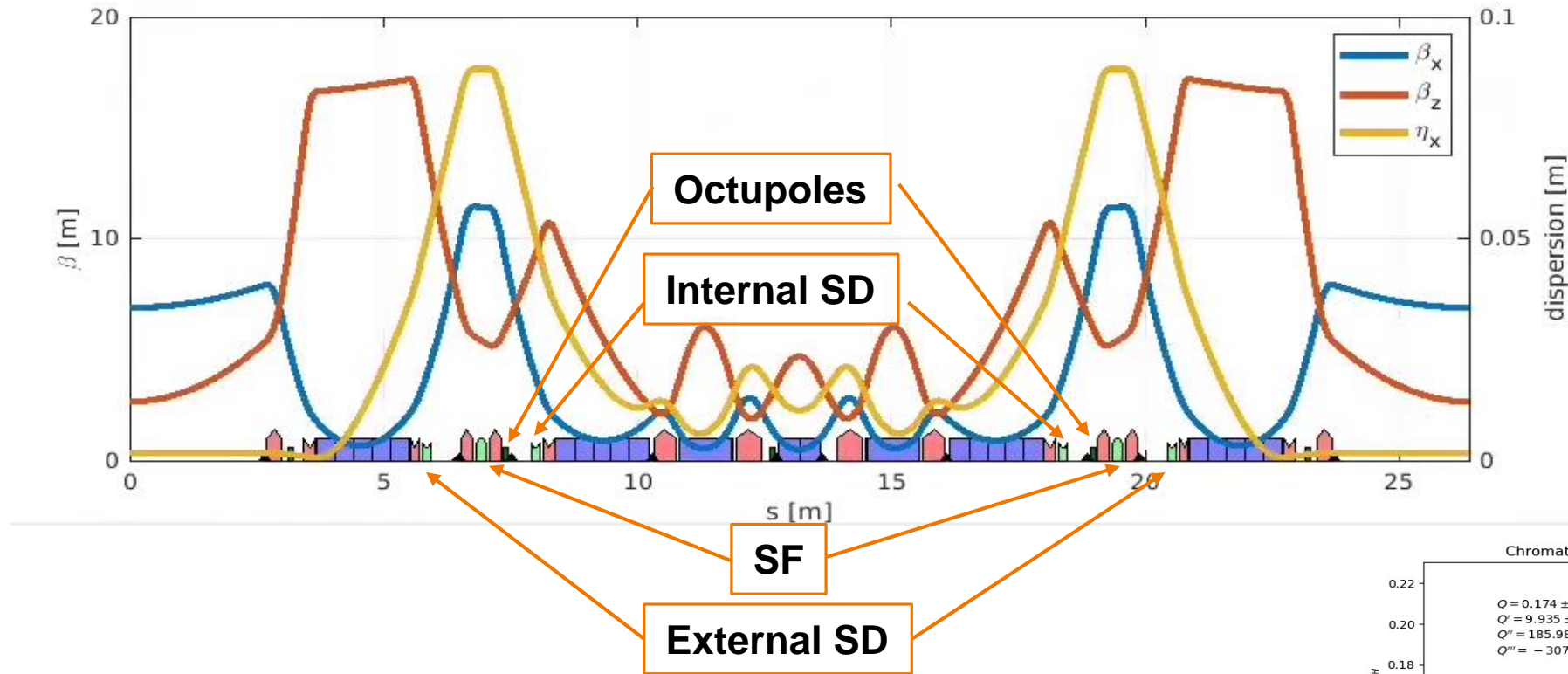


93% injection efficiency, 160mA ,  $\Delta\beta/\beta \sim 1.0\%$ , Hor. Ver. Emittances\*: 160pm,  $\sim 1.23\text{pm}$

\*measurement to be verified. Fully coupled beam does not give 80 pm in both planes as expected but  $\sim 110, 75$

All Response matrix measurements are made using “self-steering” to cancel the effect of hysteresis.

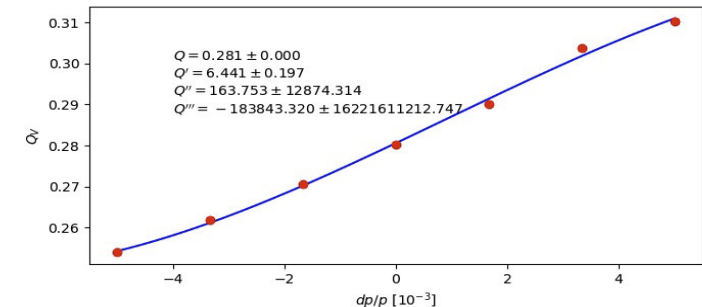
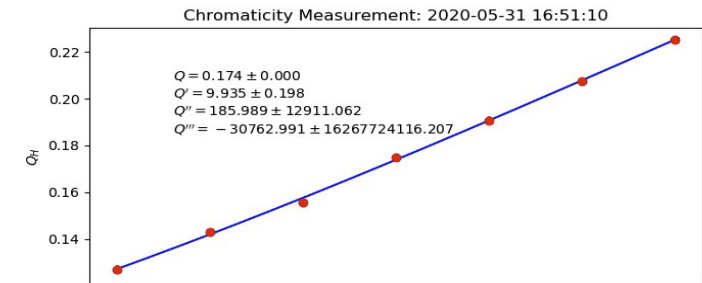
- The coupling correction is extremely efficient to reduce the coupling and vertical dispersion to unmeasurable levels
- However the optimal number of eigv (64 out of 288) leads to skews gradients much weaker (at least a factor 3) than the ones expected by vertical offsets on the sexts (and quads rotations as well).
- Increasing the eigv just degrades performances
- The coupling correction is extremely efficient, fast and stable in time (month(s)):  
Skew quads at each sextupoles and additional ones (every 4 quads)  
Coupling of the order of  $10^{-3}$  routinely achieved, however diagnostic not able to measure emittance ratio  $< 10^{-2}$



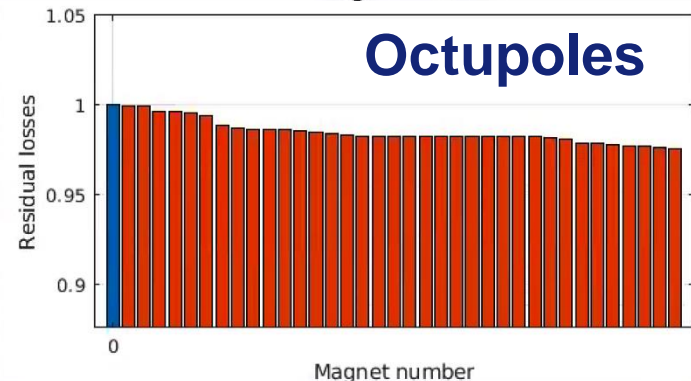
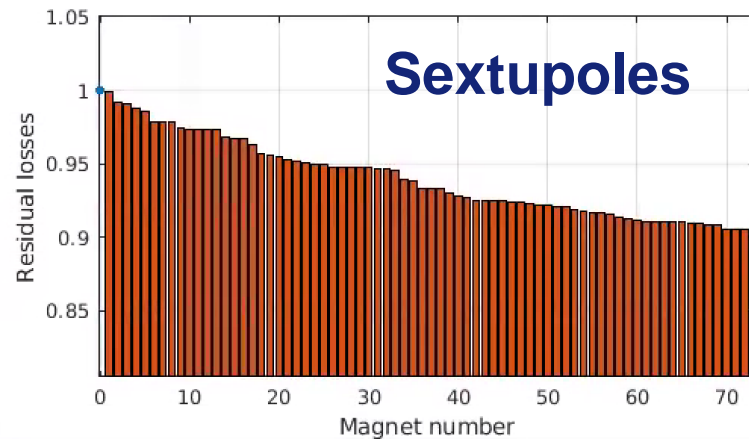
Online optimizations of sextupole and octupole families performed from very first stored beam.

4 designed families: SF, internal SD, external SD, Octupoles.

Optimal chromaticity for lifetime was found to be around (10, 6), close to the model prediction.

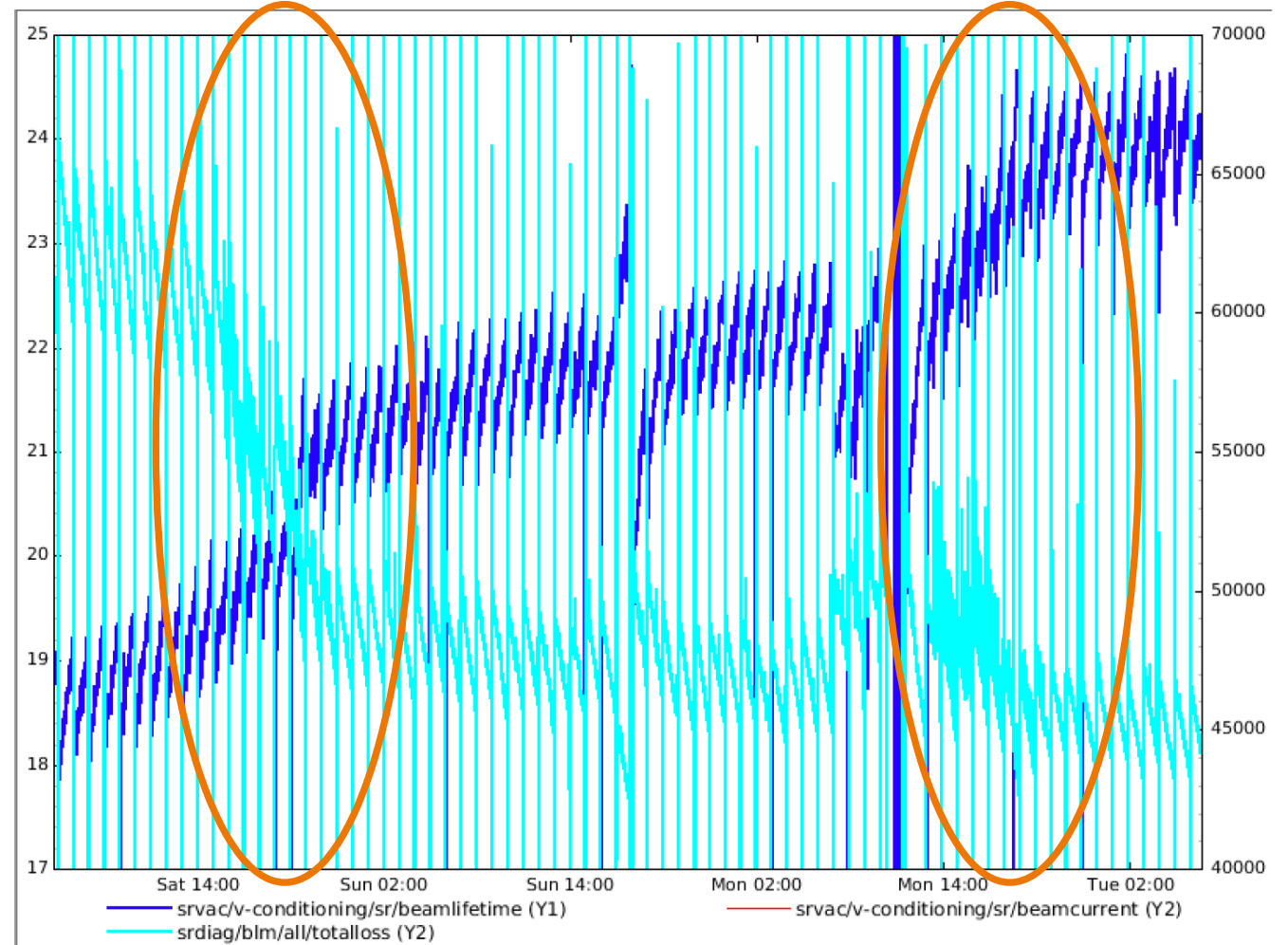


**Skew quads scan,  
sextupoles scan and  
octupoles scan improved  
both total losses and  
lifetime (mostly lifetime).**

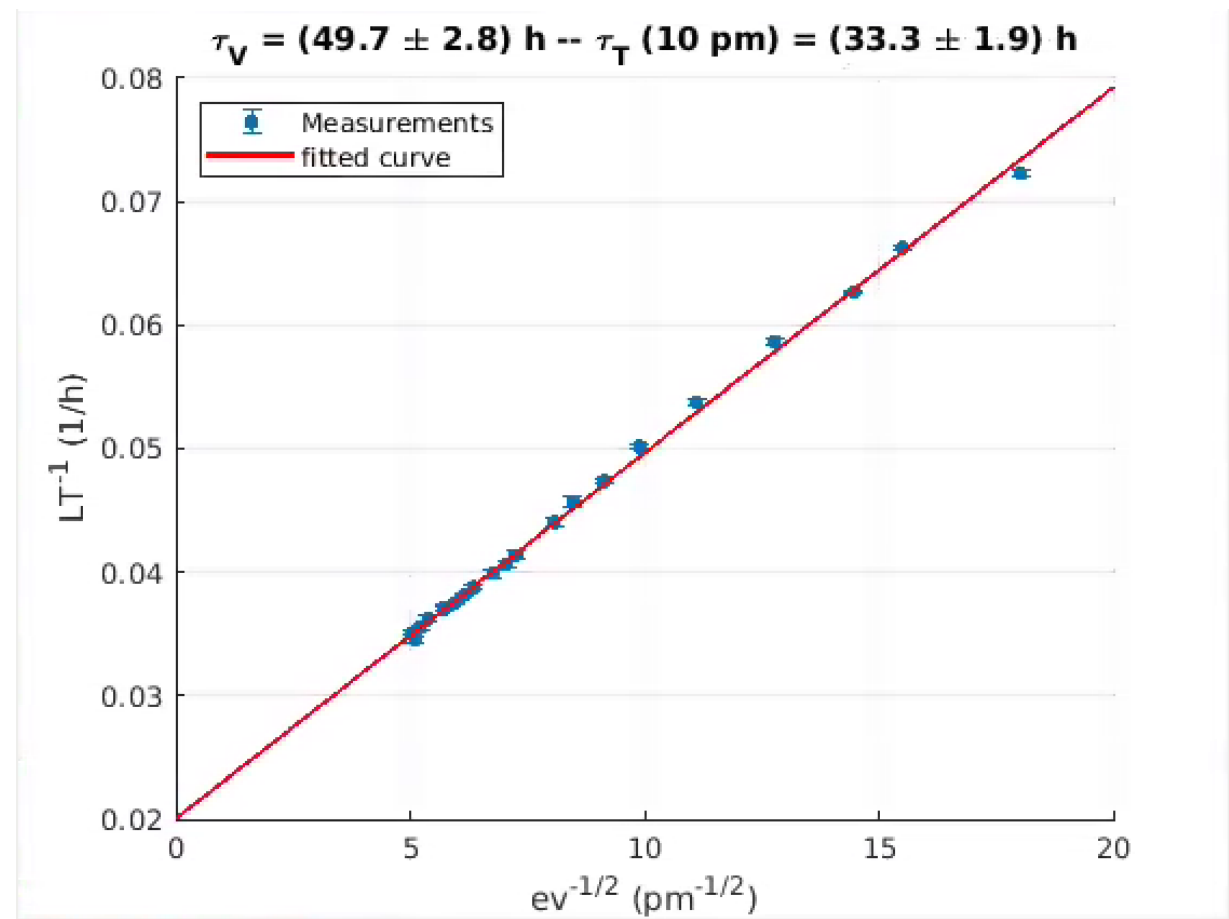
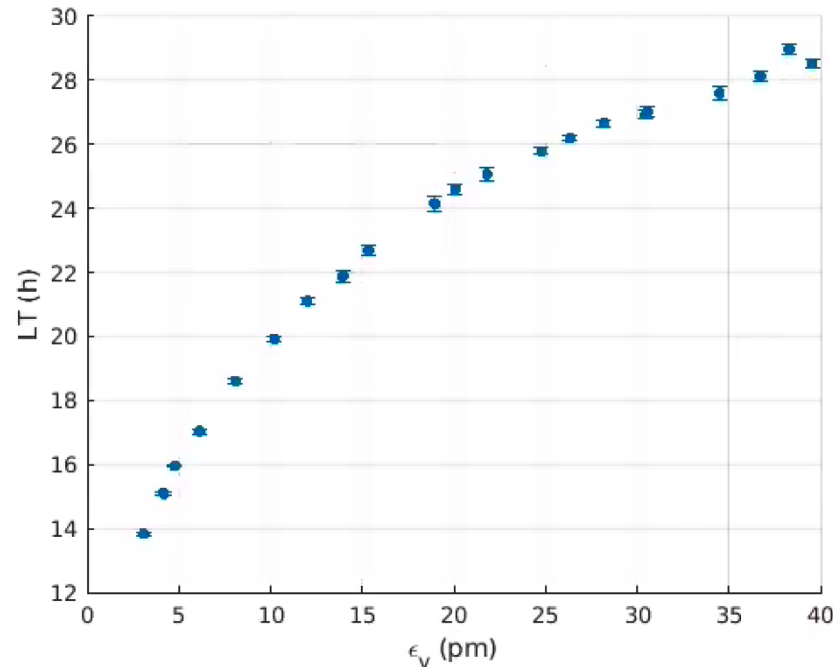


Saturday  
29/08/2020

Monday  
31/08/2020



Lifetime vs vertical emittance  
measured on Tuesday  
01/09/2020 night

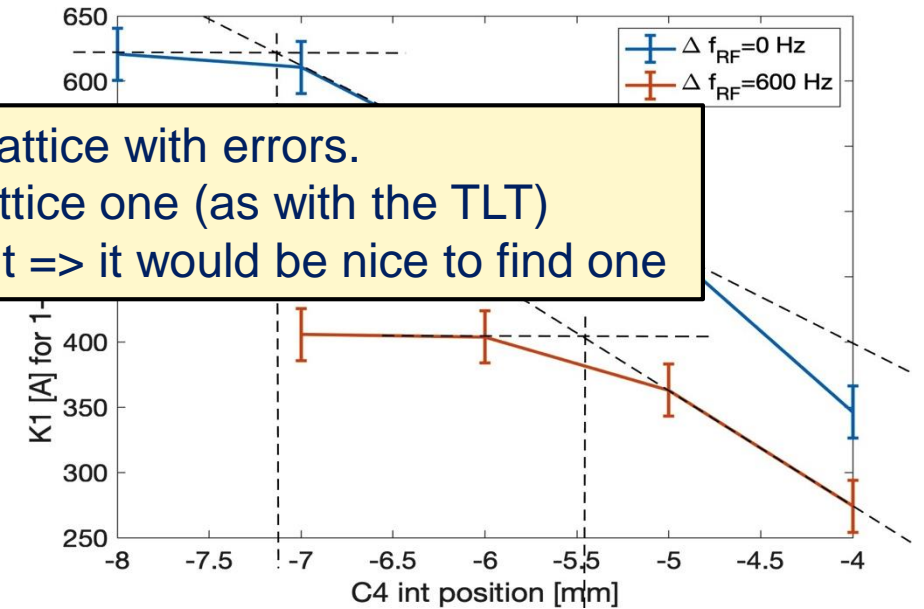
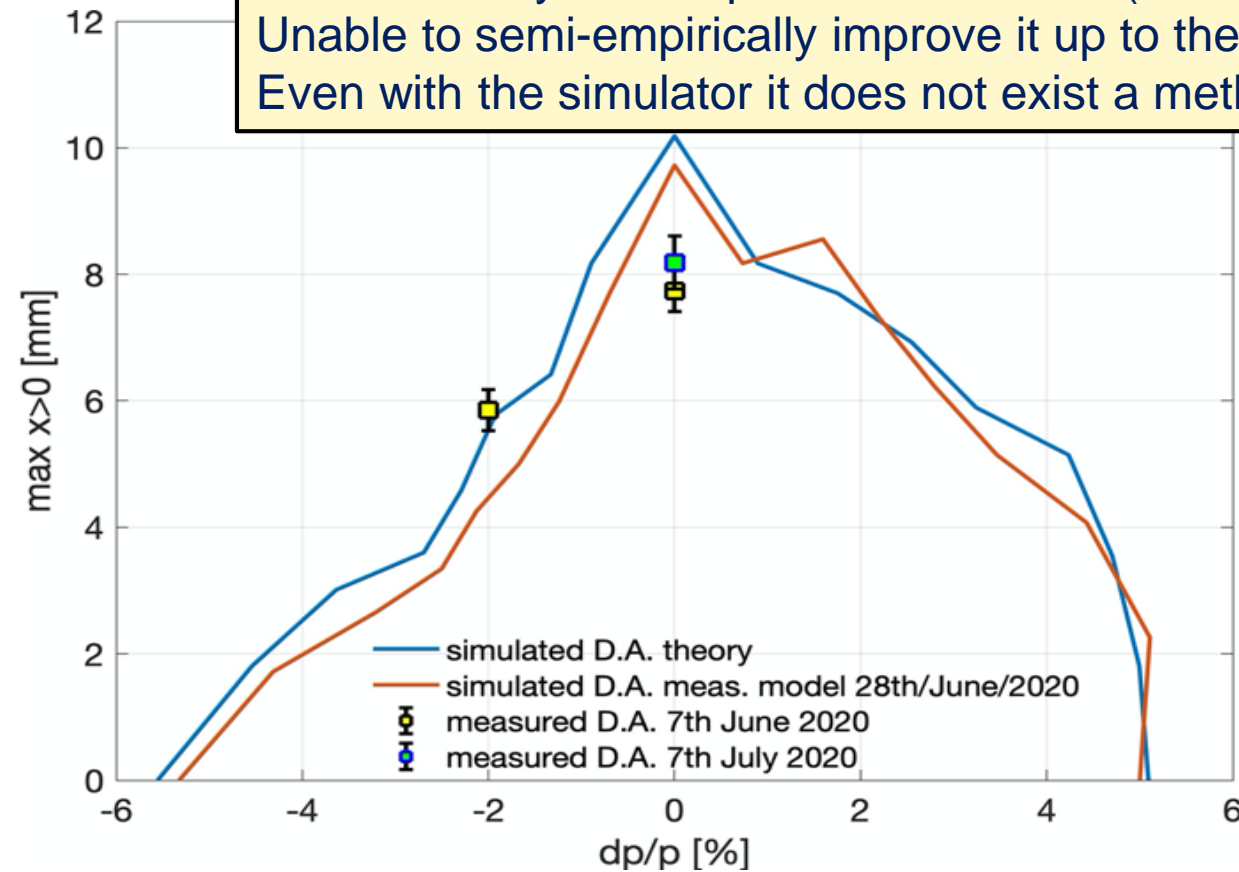


$\tau_T$  at 10 pm is  $33.3 \pm 1.9 \text{ h}$

$\tau_T$  at 5 pm is  $23.5 \pm 1.3 \text{ h}$

Touschek lifetime is above design values!

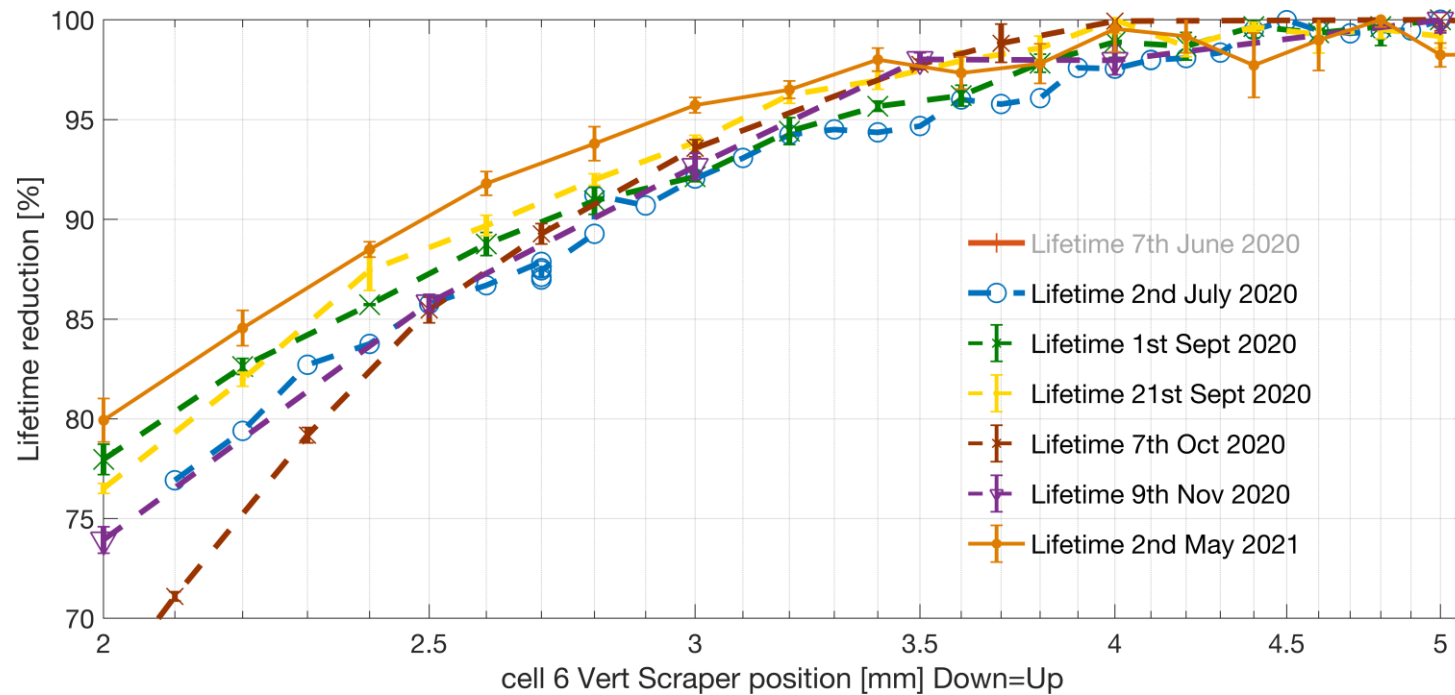
Transverse dynamic aperture consistent (low side) with lattice with errors.  
 Unable to semi-empirically improve it up to the perfect-lattice one (as with the TLT)  
 Even with the simulator it does not exist a method to do it => it would be nice to find one



We have measured on-energy and off-energy (at -2%) dynamic aperture.

Off-energy DA is slightly larger than expected.

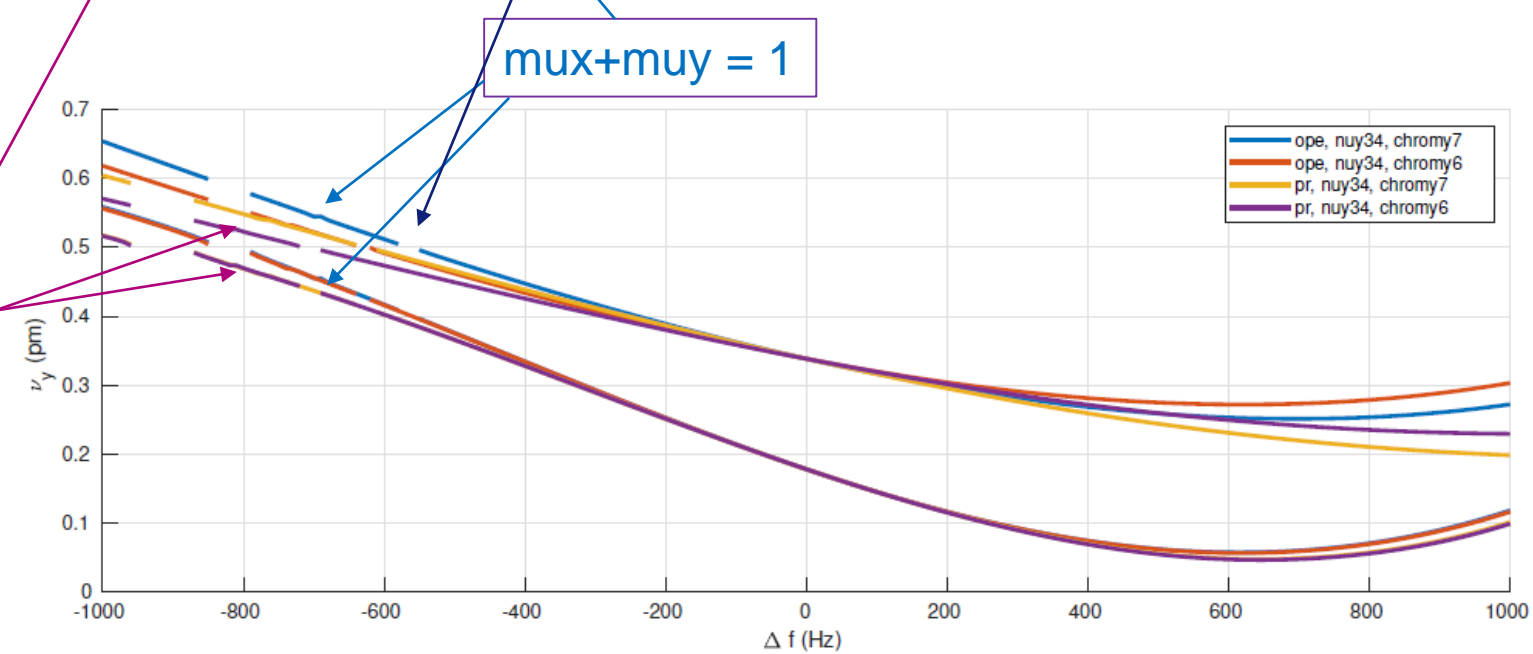
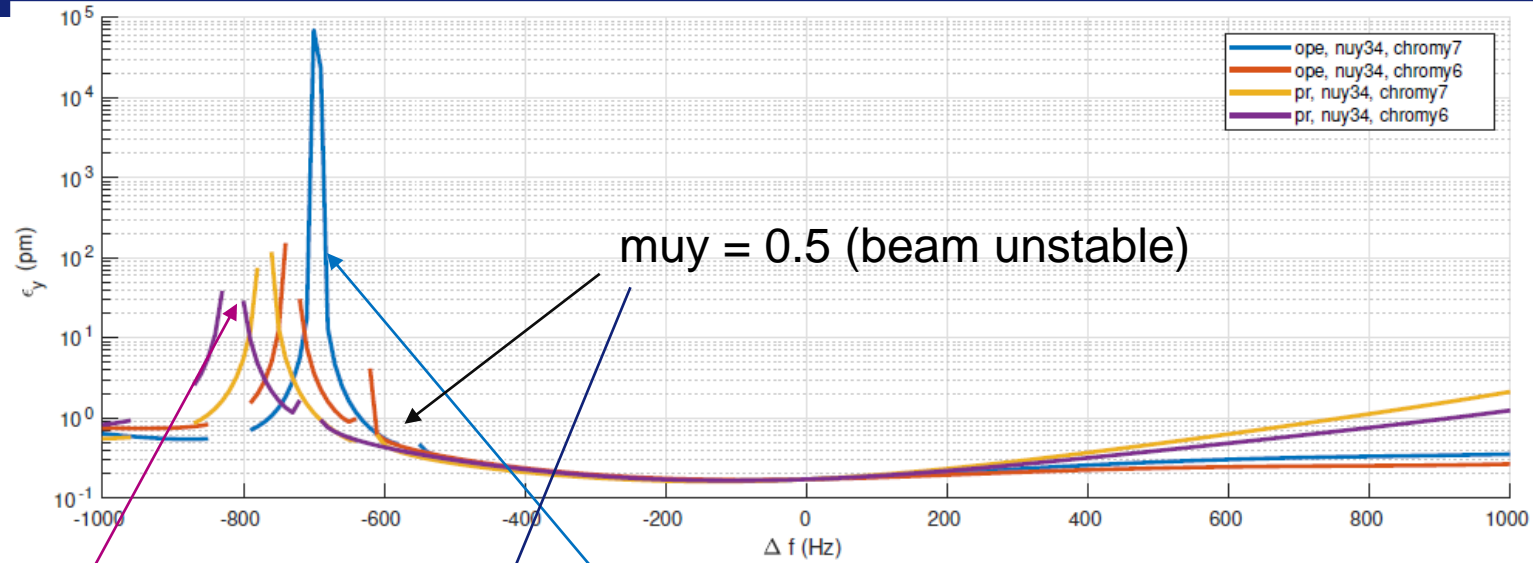
Additional measurements will be done.



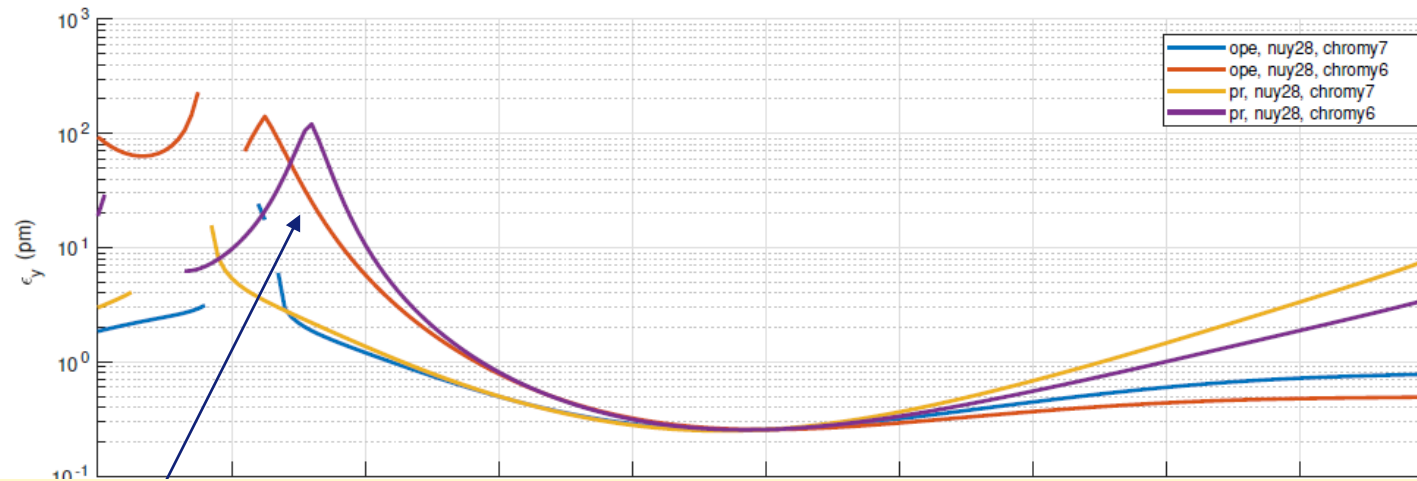
A vertical halo of stable electrons that extends up to 4mm at the scraper position has been measured as early as June 2020

The halo is composed by off energy electrons, unfortunately the model predicts a much smaller one.

# VERTICAL HALO



N Carmignani



N. Carmignani

Off energy electrons ( $dE/E > 1.5\%$ ) are stable but due to second order chromaticity hit the  $\mu_{xy}=0.5$  or the main coupling resonances.

The ideal machine should have to tune footprint as small as possible and never cross the half quadrant

It is very hard to model such a few electrons: it would be nice to find a way to generate this halo in a computing-time-effective way.

For EBS this resulted in the fact that vertical collimators have not been installed: we thought that in order to start to collimate the beam they had to have gaps unphysically small.

The horizontal collimation is less effective than predicted in minimizing IDs losses

=> More benchmarking of models with machine/datas is desirable

# CONCLUSION

- EBS has been extremely useful to develop system-integration tools that finally allows the realization of a new generation of low emittance rings.
- Our optics know-how and present tuning capabilities are up to the needs to timely achieve and maintain design performances.
- Solutions that implies the use of fewer non-linear elements and local linear and non-linear corrections are extremely effective.
- EBS had some surprise that in principle could have been studied/optimized prior construction.
- The need of finalizing the design and start construction imposes limits to the design phase. To cope with the unforeseen, the machines should have a degree of flexibility as large as possible. For EBS this flexibility could be estimated in about 10% (individual PS, extended diagnostic, etc) of the total cost.



**MANY THANKS FOR YOUR ATTENTION**