LER 2020
EBS commissioning

Pantaleo Raimondi

On behalf of the EBS team

PIONEERING SYNCHROTRON SCIENCE

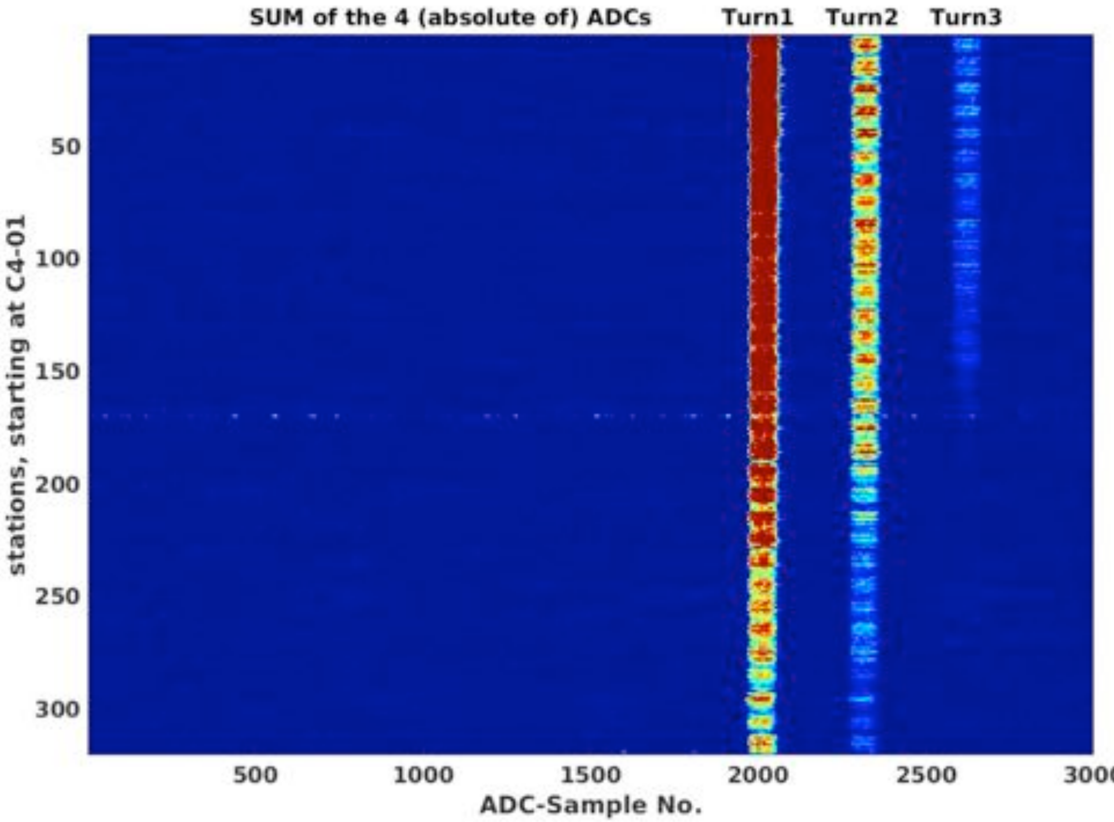
- EBS commissioning progression
- Present machine parameters
- Achievements highlights
- Conclusions

Beam at the entrance of the SR

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

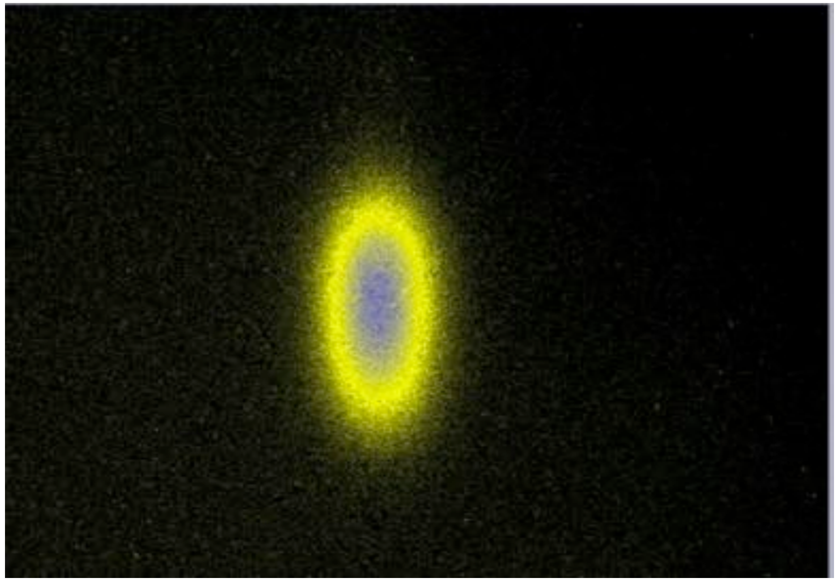
AN HISTORIC MOMENT FOR THE ESRF AND THE HMBA LATTICE

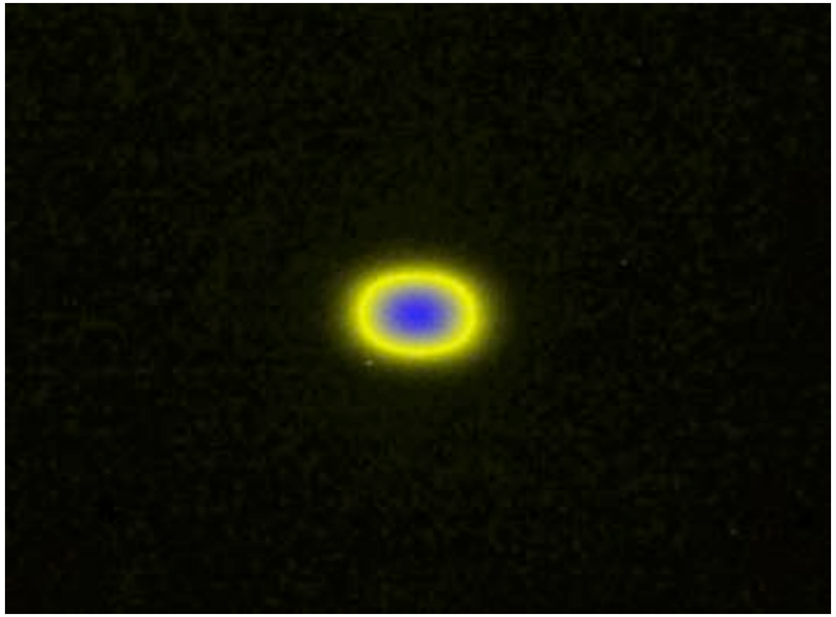
2.5 turns in the SR achieved ! =>



5 days ahead of schedule !!!

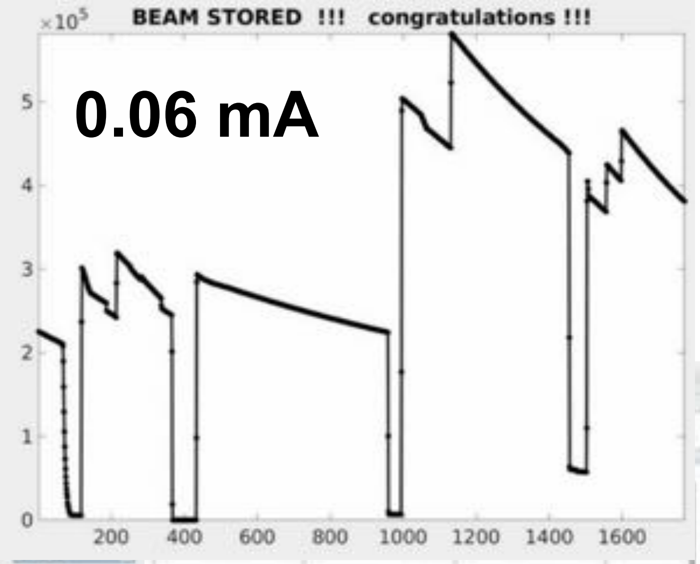
6 DECEMBER 2019: BEAM STORED AT 12:30 (MY BIRTHDAY BTW…)

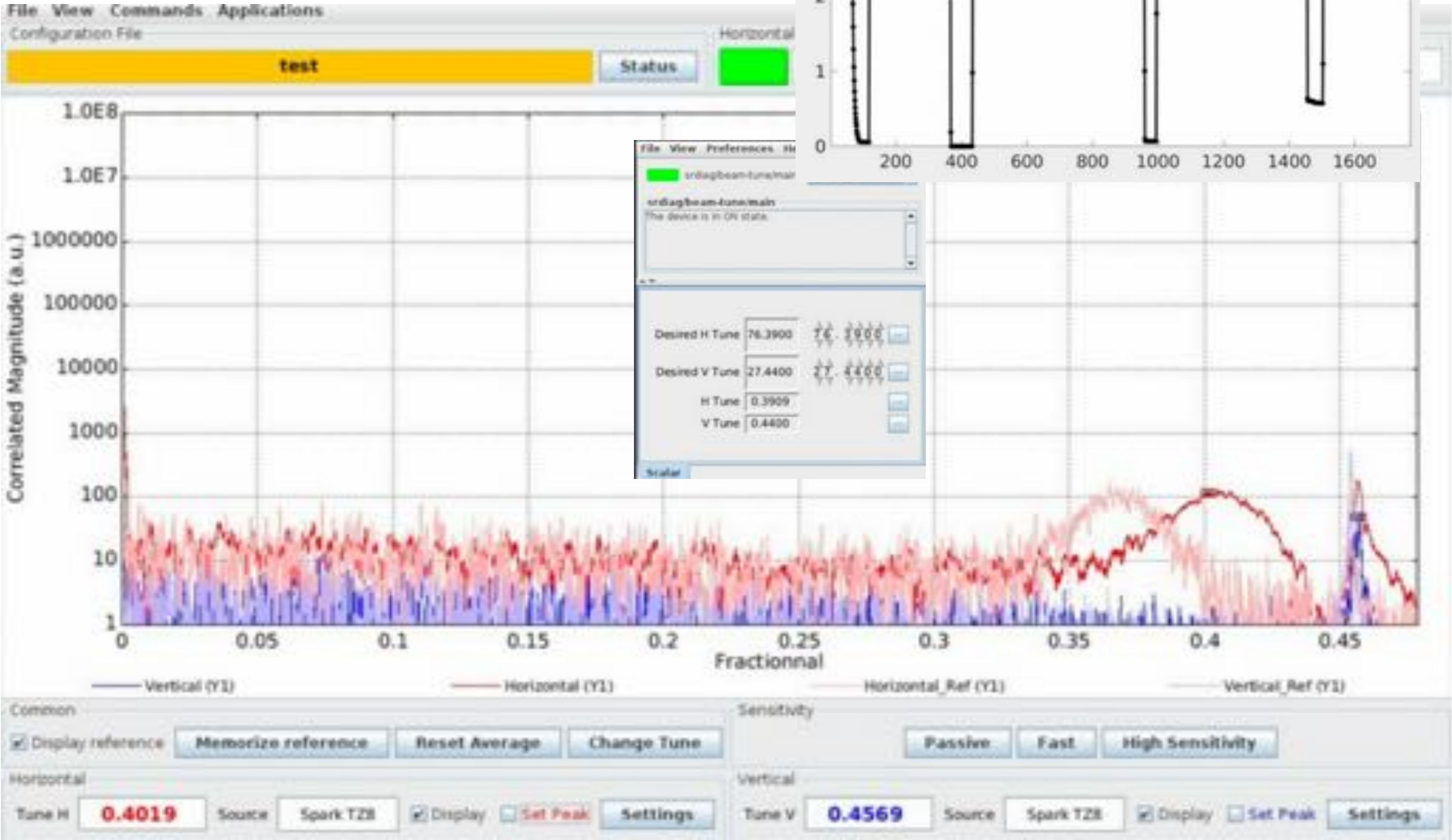




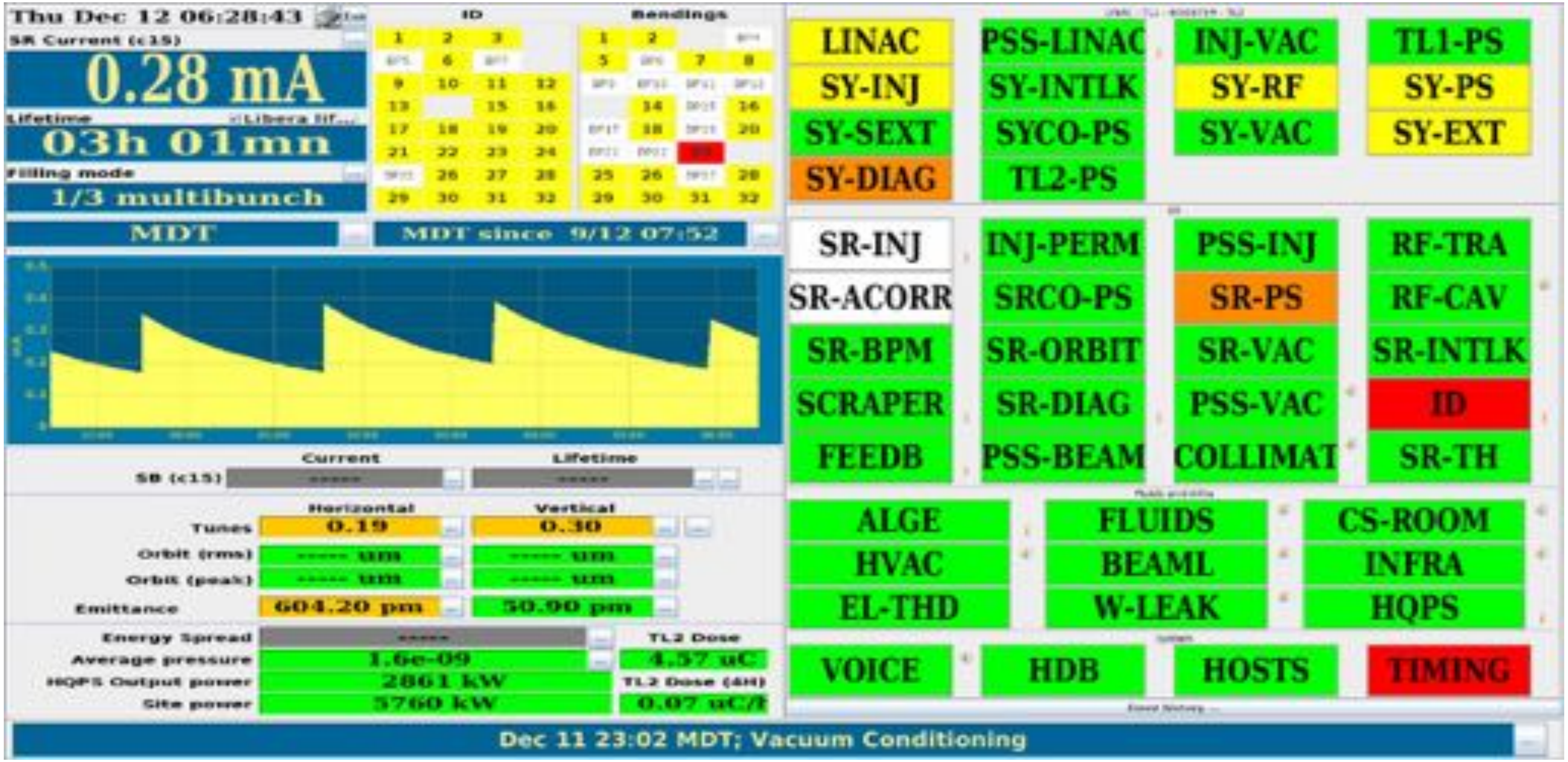
BEAM STORED!

← Signal at DL and DQ pinholes





START OF THE VACUUM CONDITIONNING
AS SCHEDULED

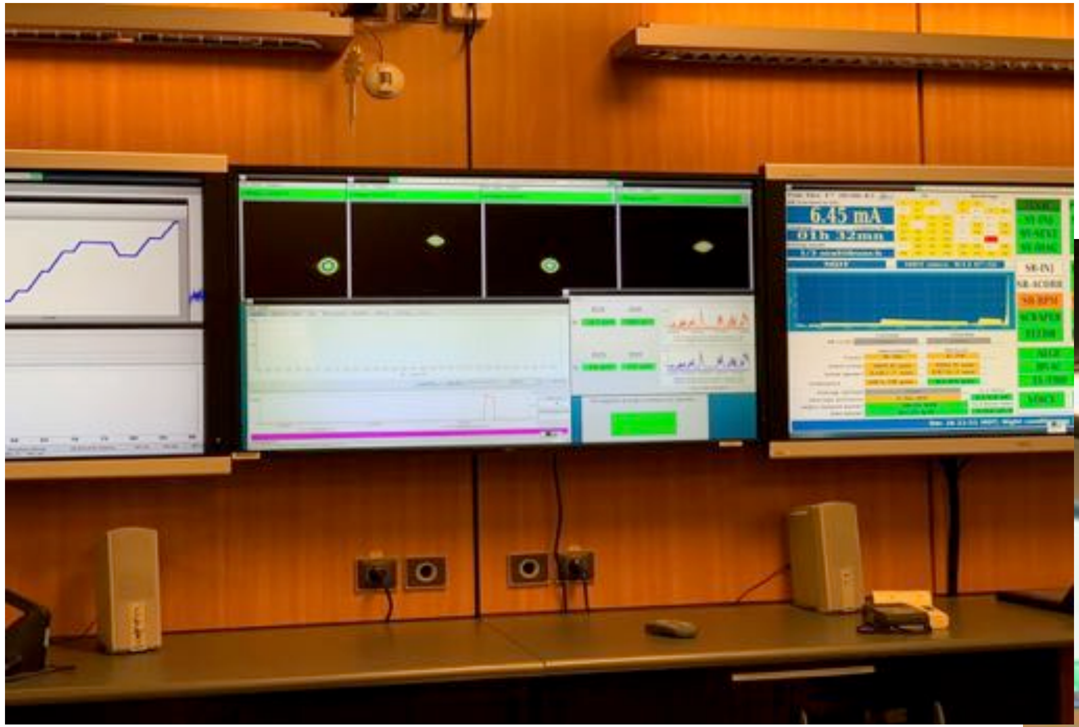


15 DECEMBER 2019 – 15.39 PM: FIRST e-ACCEMULATION

- Accumulation demonstrated for a high energy 4th generation SR!
- Injection efficiency about 0.8%

➢ **This was thought to be an almost impossible task among the accelerator community before EBS**

2019 RECORD CURRENT 6.45MAMPS AND EMITTANCE 220PM



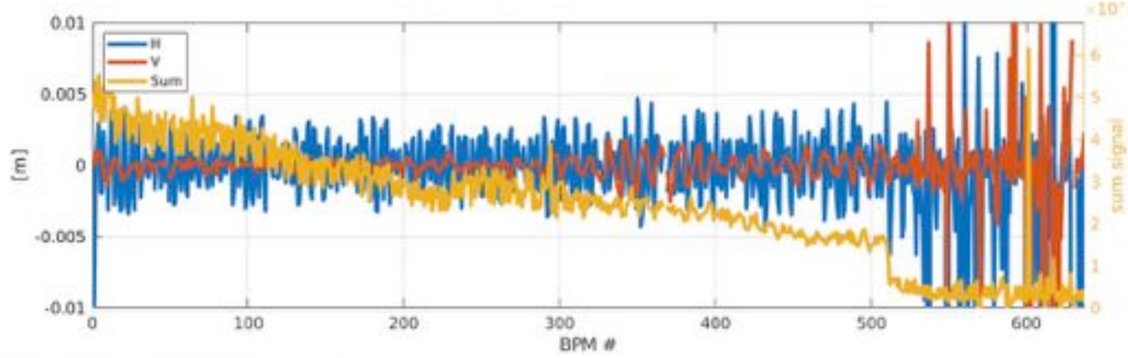
17 DECEMBER 2019
EBS exceeds former SR brightness

ASD has been able to produce brighter beams every year, including 2019!!!

18 DAYS OF COMMISSIONING IN 2019

- Start EBS commissioning on Nov 28th, 5 days ahead of schedule: achieved 2.5 turns
- Stored beam on Dec 6th
- Accumulation achieved on Dec 15th
- 6.4mAmps max stored current, limited by the need to enable the BPI protection
- 220pm (+/-20pm) horizontal emittance
- 15pm (+/-5pm) vertical emittance
- Beam stability better than 5% sigma
- 50% on axis injection efficiency
- 2% injection efficiency with accumulation
- Collimators successfully commissioned and used

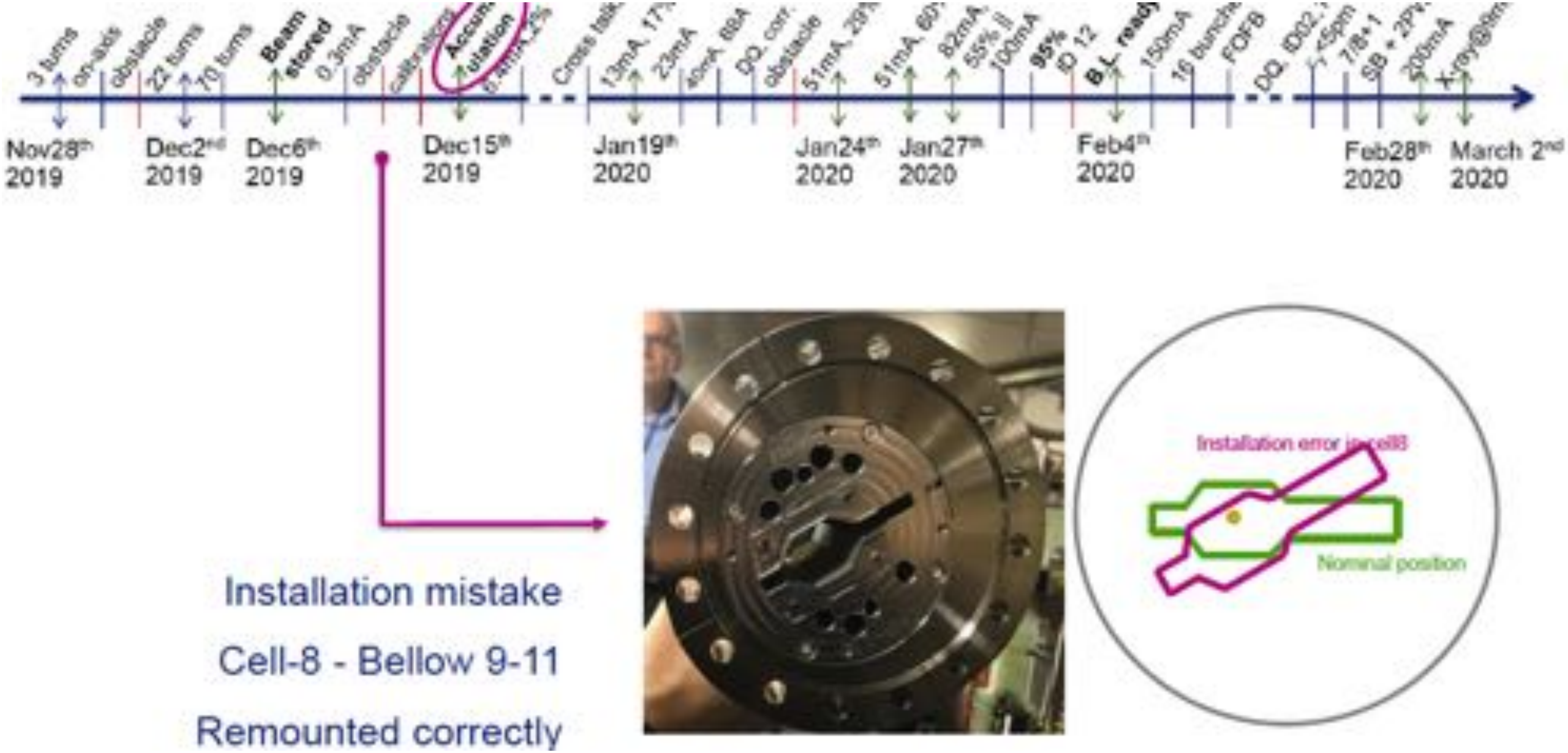
VACUUM SYSTEM: THE QUEST FOR OBSTRUCTIONS !!!



Obstacle in SS-23 ID chamber

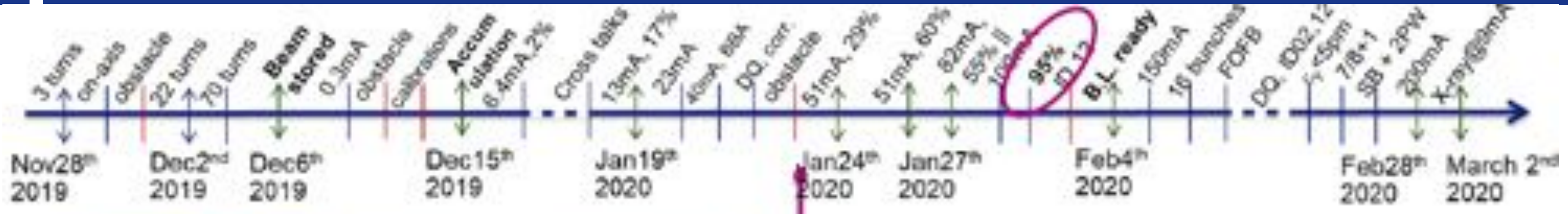
Obstacle found with turn by turn data in the early days of commissioning, SS-23 immediately identified (20turns reached before removal)

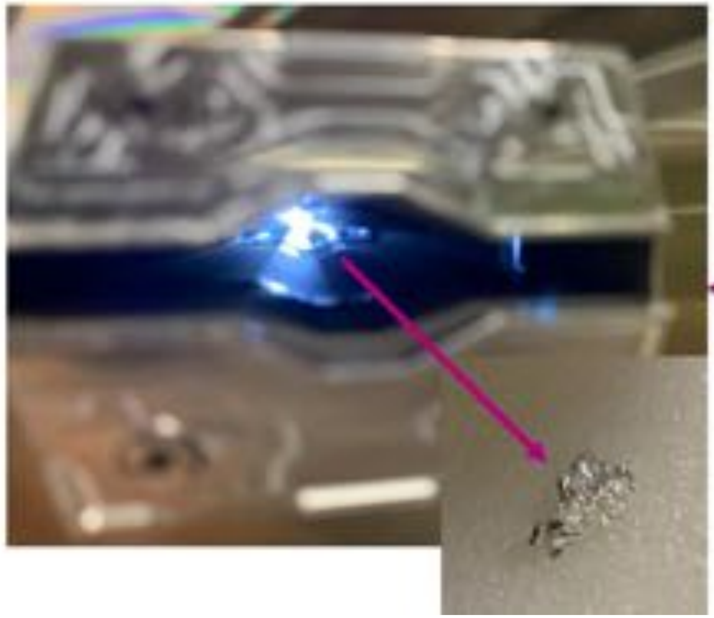
VACUUM SYSTEM: THE QUEST FOR OBSTRUCTIONS !!!



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 !!!



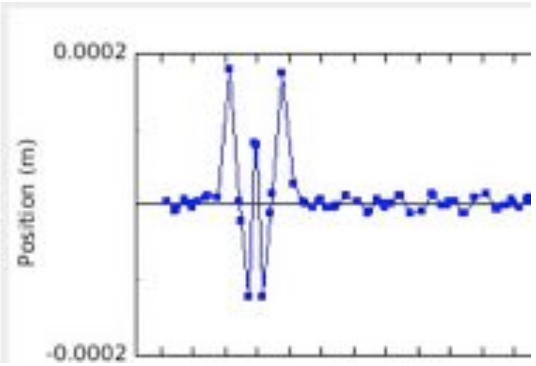


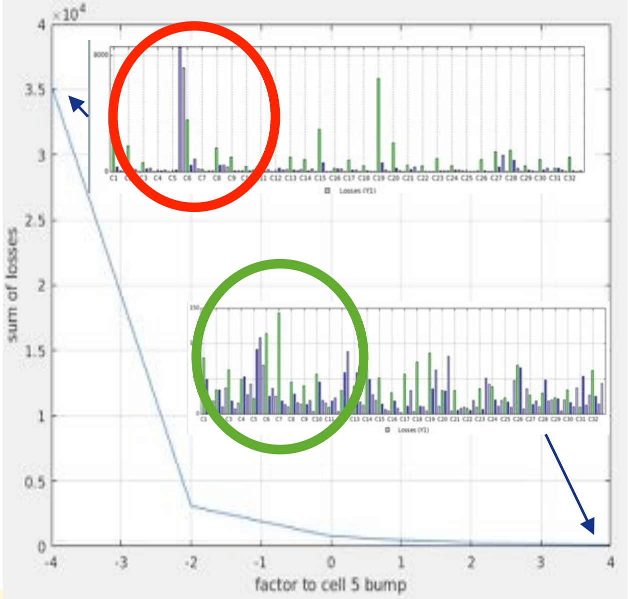
Obstacle in

Cell-5 in Chamber-7

Al foil piece fall during installation of DQ2

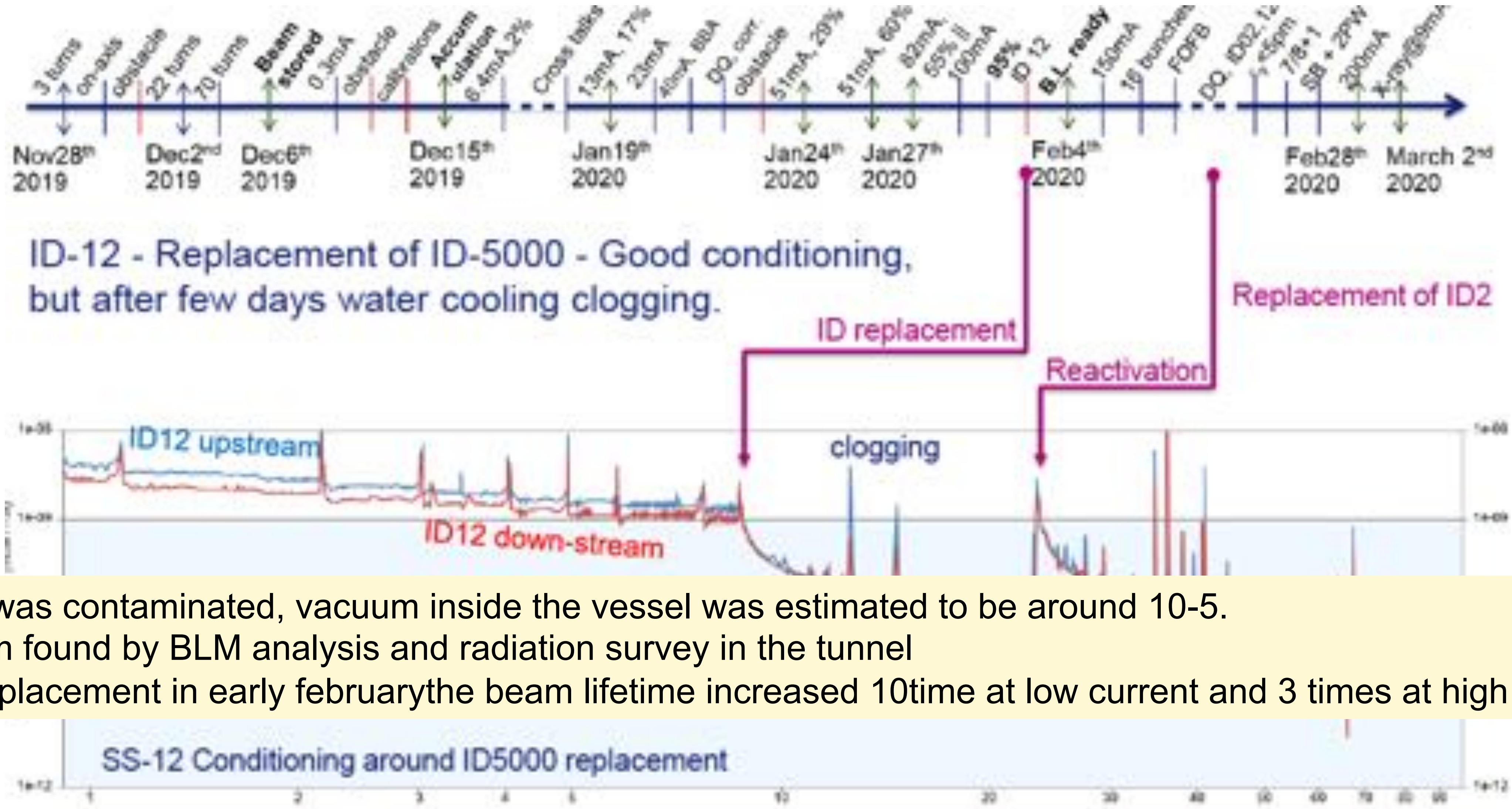
-> very difficult protect flanges but no way to inspect them after!





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 !!!



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 februarythe beam lifetime increased 10time at low current and 3 times at high current

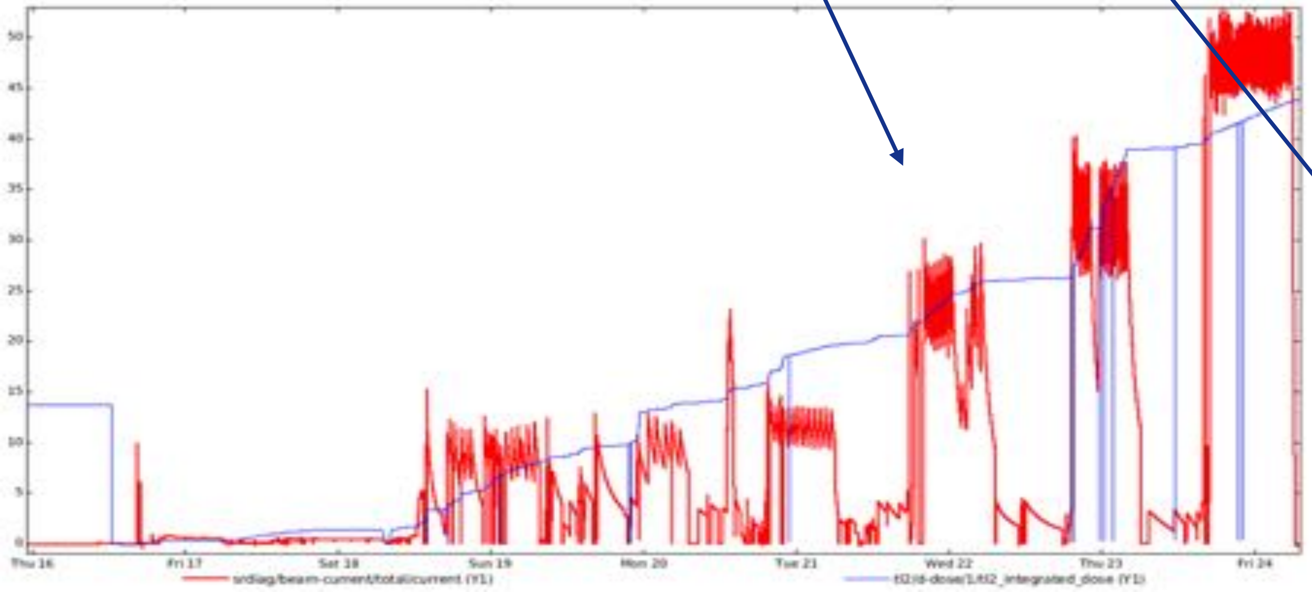
2020 COMMISSIONING STRATEGY

Strategy defined in Dec 2019

The Plan:

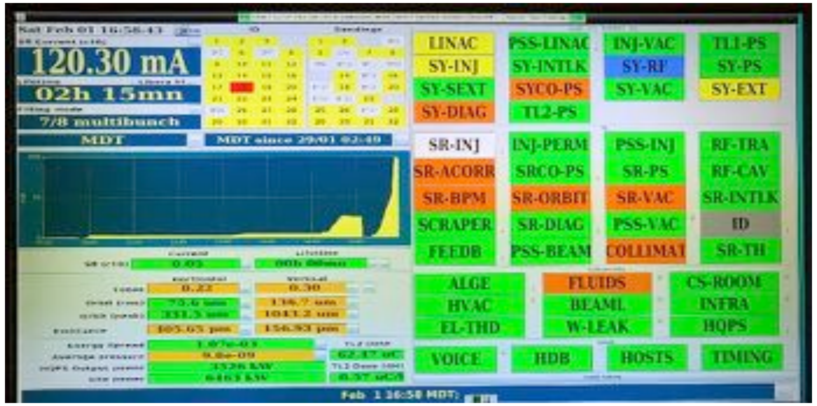
• continue to fully characterize all aspect of the machine in terms of hardware performances (vacuum system, RF, power supplies etc)
• identify potential weaknesses and adopt mitigation solutions
• use all our resources to improve the reliability and the uptime of the new machine to finally arrive at USM standards
• continue the debug of the hardware and software.
• use all the diagnostic tools and continuously evolving mathematical algorithms to identify potential problems and errors
• (simultaneously) tune the machine in order to improve its overall performances, in particular to bring the machine optic as close as possible to design specifications.

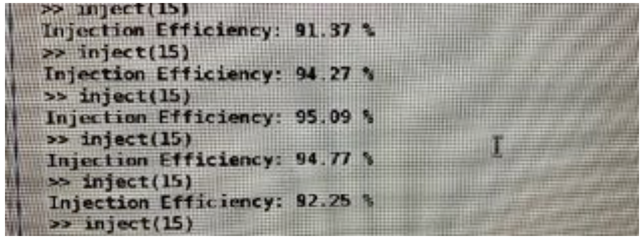
January 2020: the tuning and debugging
Has resulted in steady improvements
of all machine performances



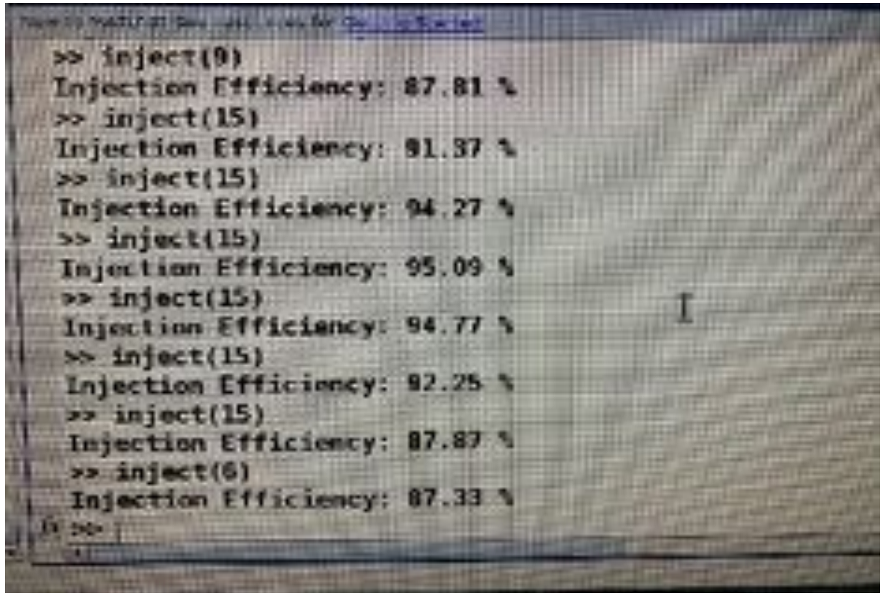
Top Up routine
Re-commissioned and implemented
during vacuum conditioning

February 2020: things do start to look very good!



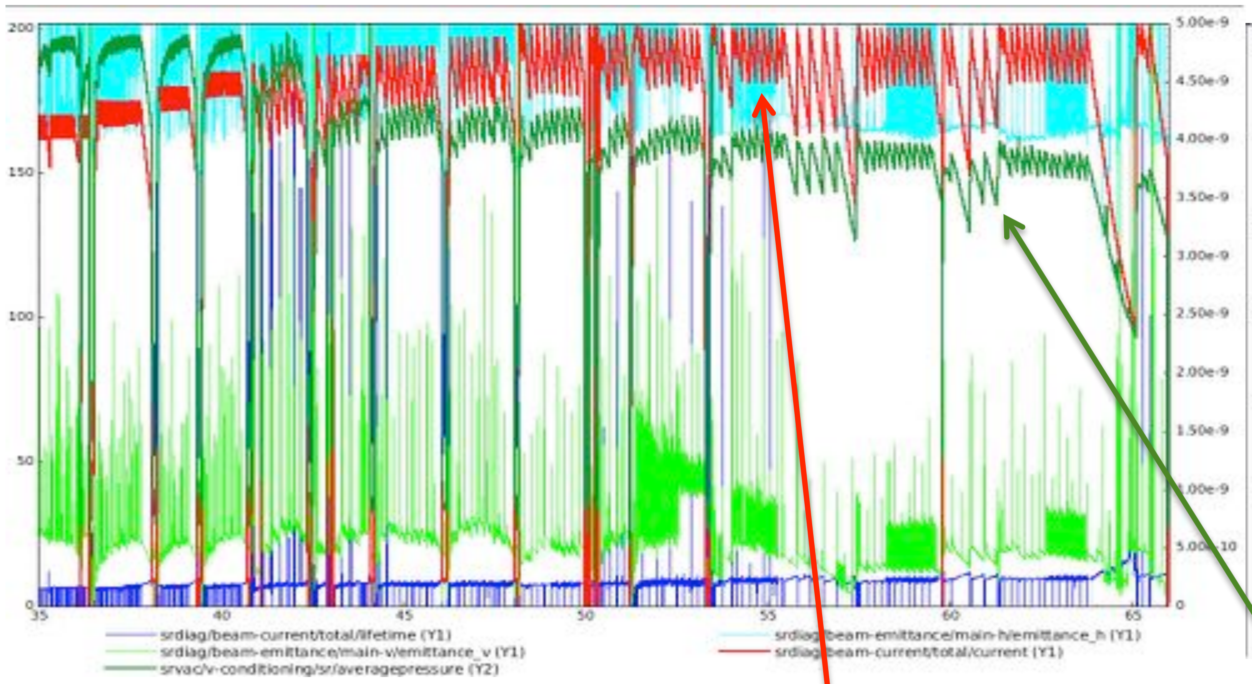


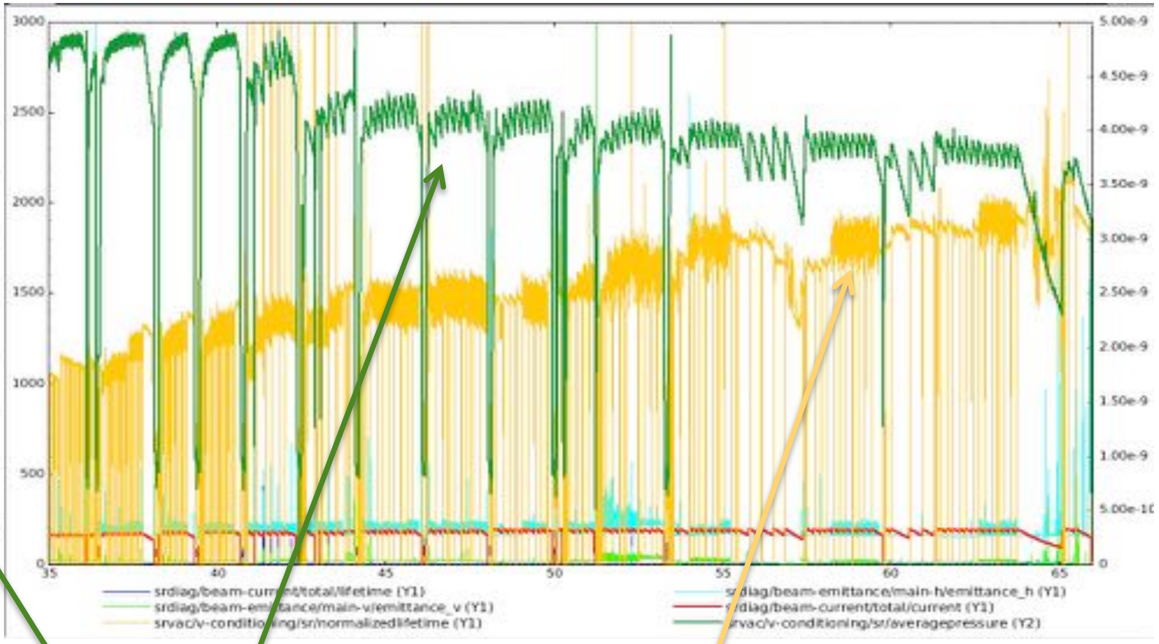
2020 TOPUP COMMISSIONING



Synopsis in the Central building mezzanine starts to look good

ACCELERATOR STATUS MARS 2020

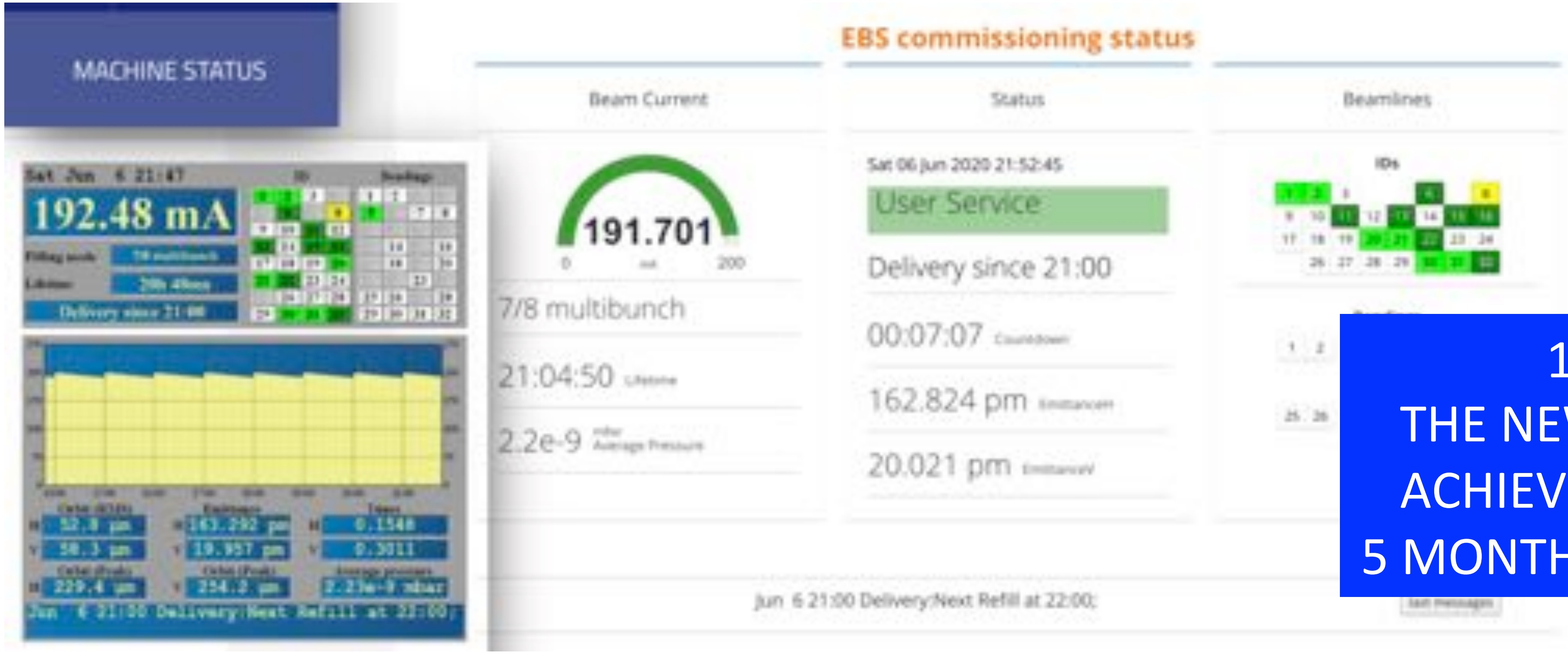




Routine 200mA operations reached

Average vacuum pressure steadily improving

Lifetime and normalized lifetime steadily improving with conditioning and tuning



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

Lifetime still dominated by vacuum

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

COVID IMPACT ON ACCELERATOR THE PROGRAM

16 March – 11 May
Closure & implementation of the ESRF continuity plan for pandemic

SAFE MODE

- **Reduced time for several activities** (set-up for USM, shutdown activities, vacuum conditionning) **BUT not critical thanks to the very advanced state of the machine**
- Delay in the installation of the CRGs sources – To be completed in August
- **200mA beam delivered for radiation certification despite the stop**

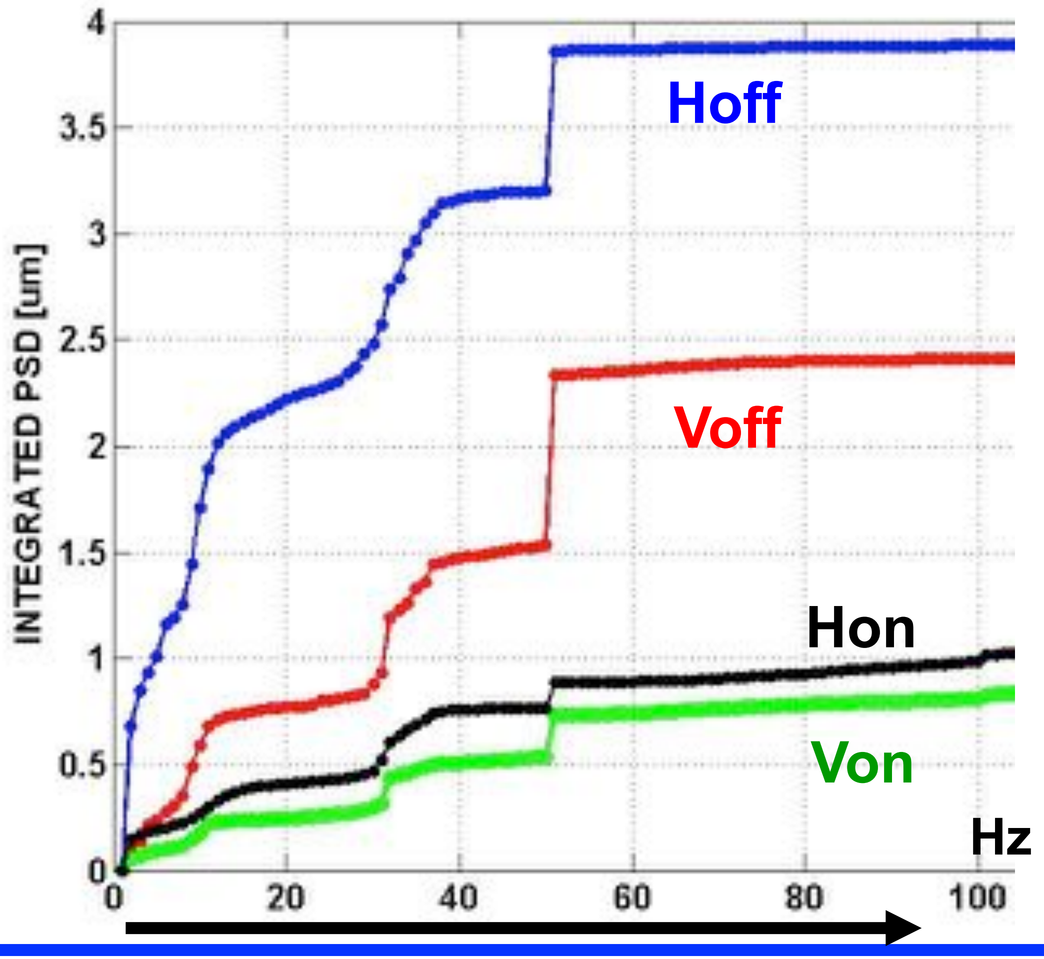
12 May – 1 June
Resume gradually storage ring commissioning

Less than 100 people on site

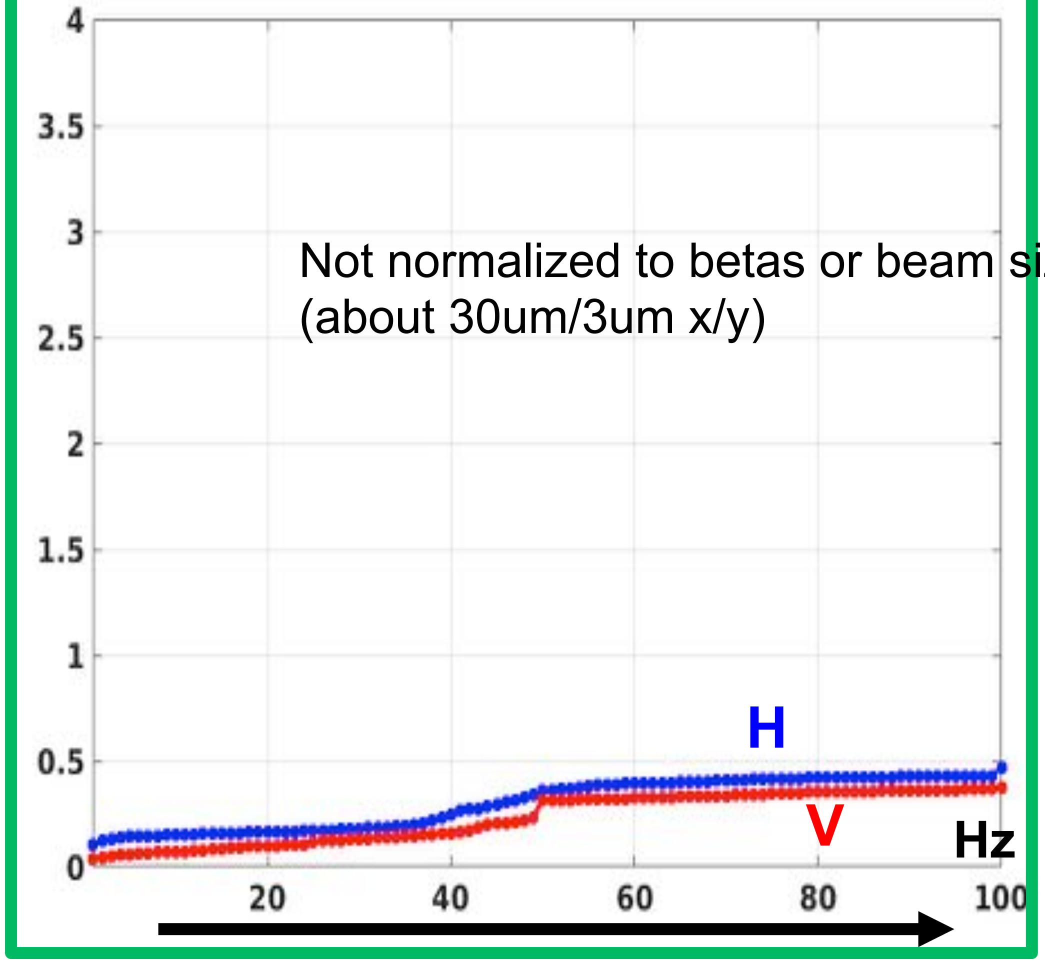
- RF went on when requested. **Extreme reliability**
- Power supplies **already close to meet the initial goal** of MTBF 1000Hr even before the HOT-SWAP commissioning
- Vacuum levels and conditioning **at least a factor 2 better than expected**
- Machine alignment **about a factor 2 better then requested**
- Beam stability **5 times better than the old machine**
- **Optics nearing perfection**, less then 1% beta-beating (unmeasurable) & injection efficiency > 80% with correction
- **Optics very stable**

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

old ring 2010, FOC On & Off



new ring, no FOC (yet)



Not normalized to betas or beam sizes (about 30um/3um x/y)

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

From simulations the estimated SR alignment errors are:

H 30-45 μm

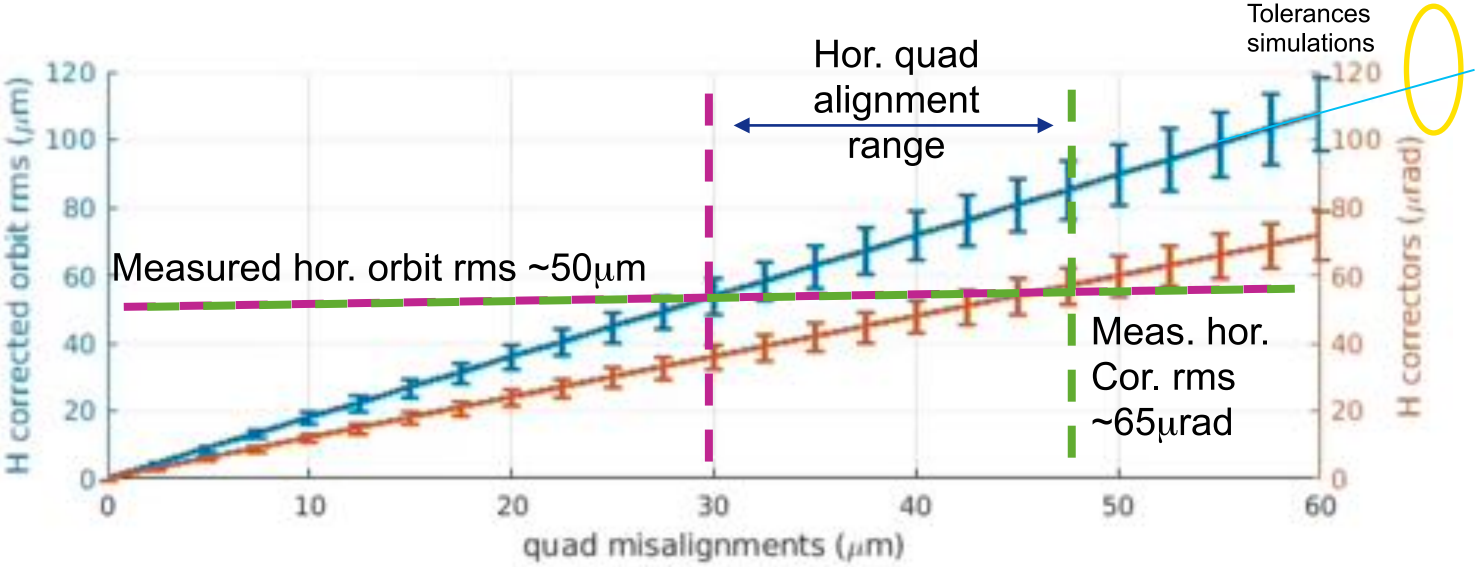
V 20-45 μm

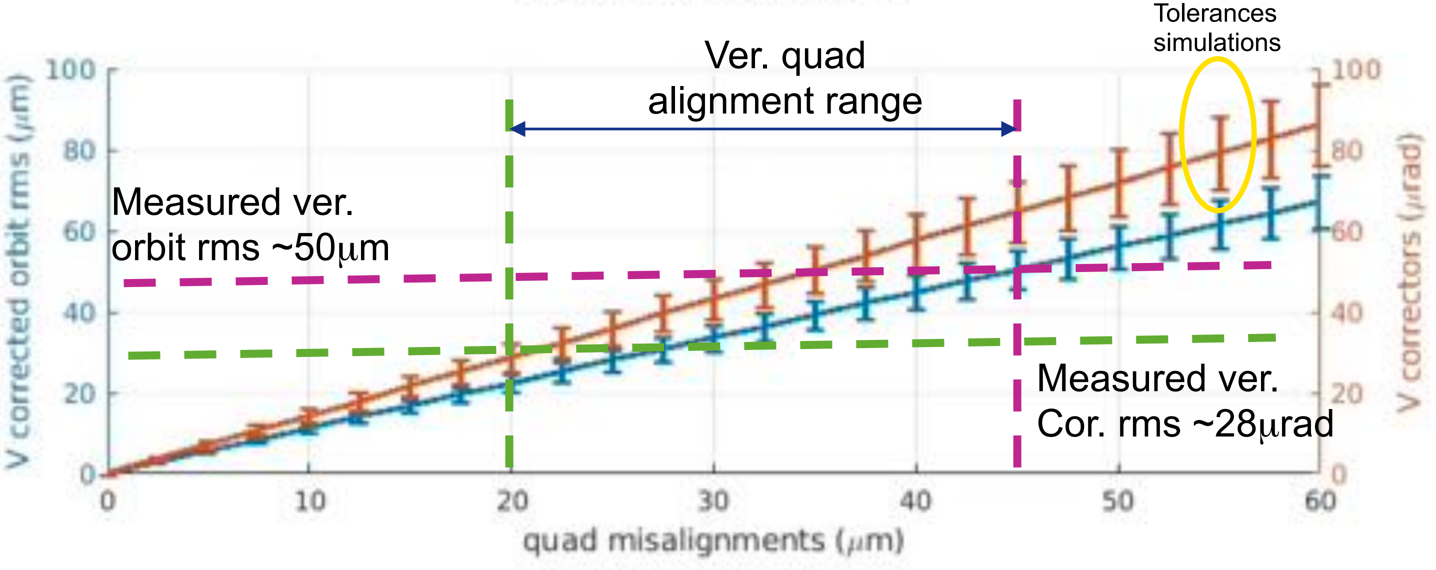
The quadrupole alignment tolerances required where:

H 50 μm

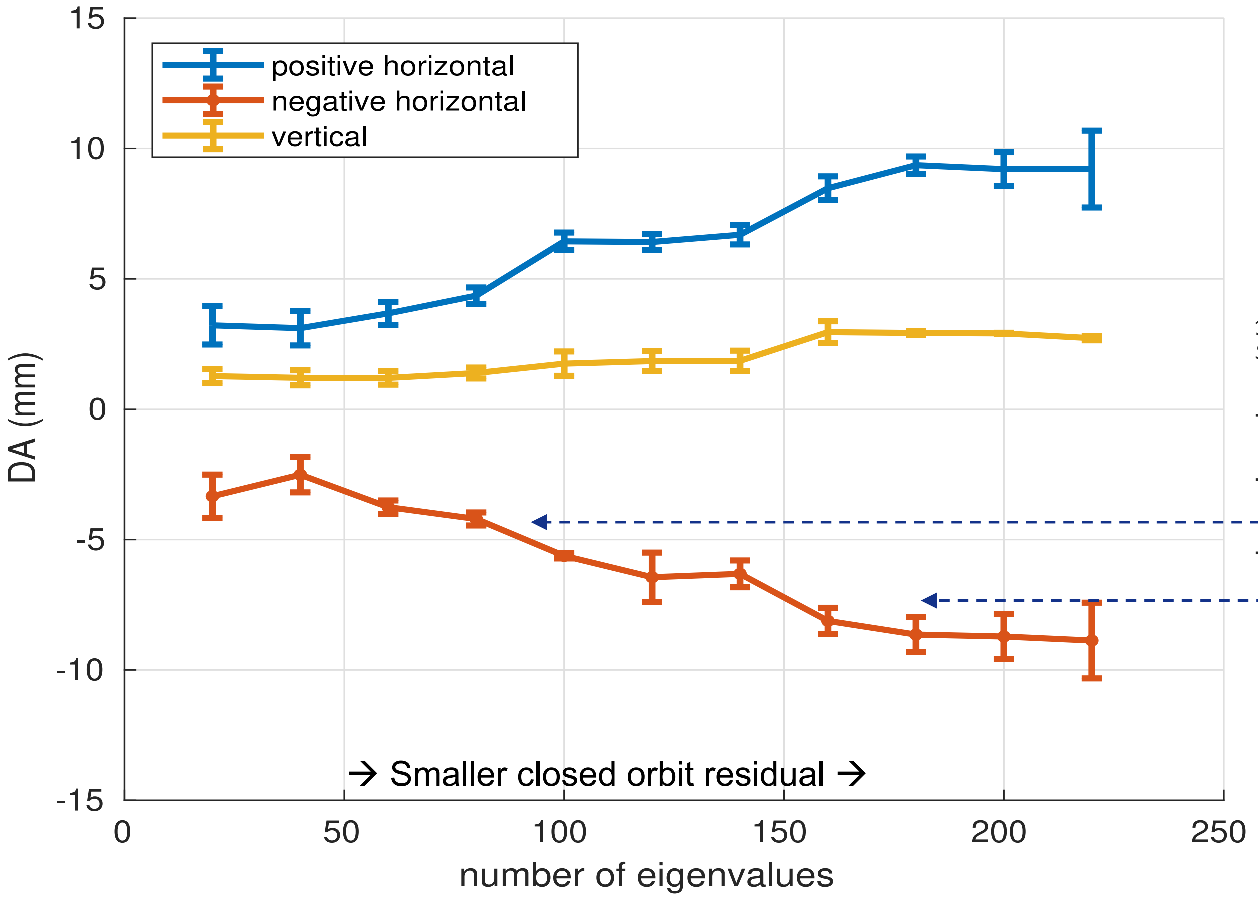
V 50 μm

Rough estimation.
Errors only in quadrupoles.

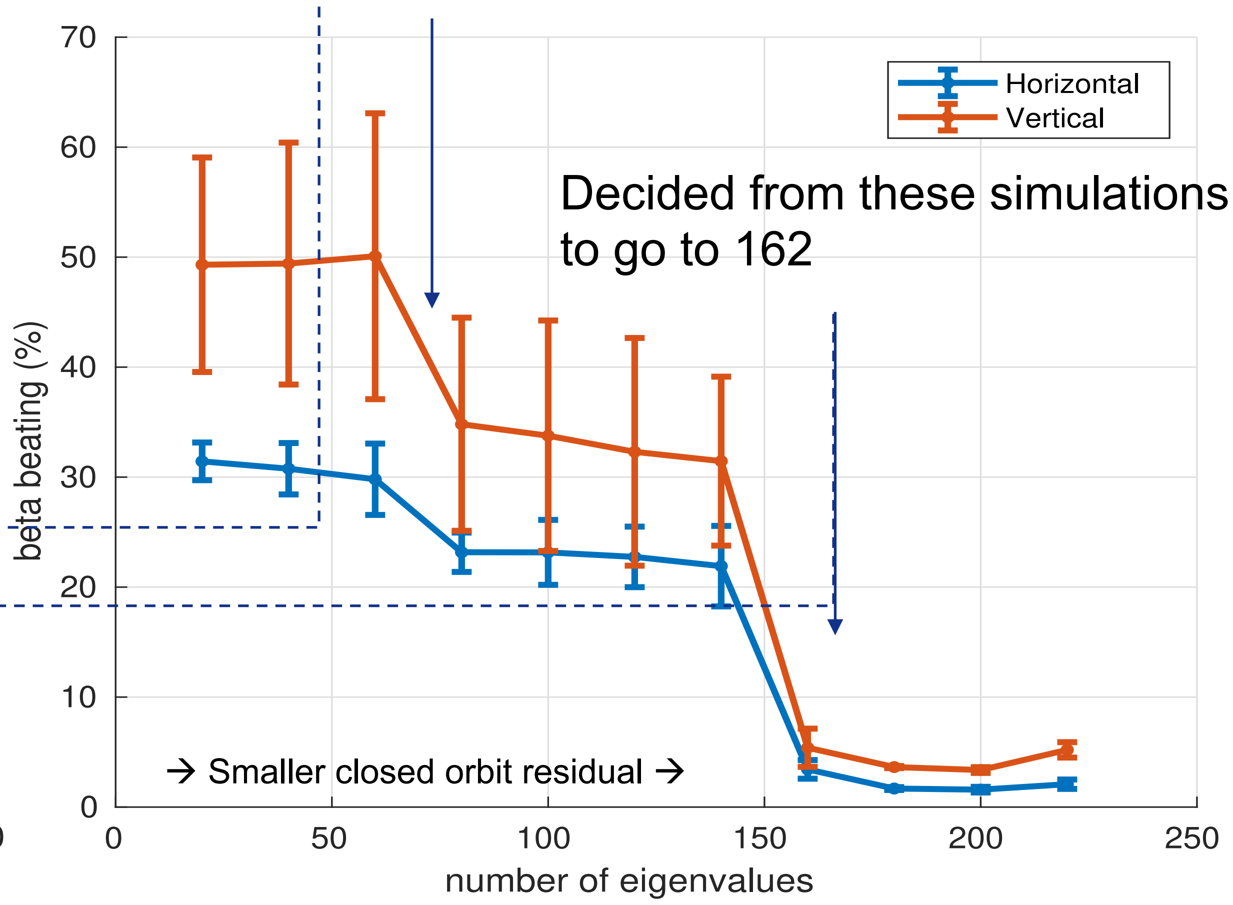




DA STUDIES: DA VS ORBIT CORRECTION

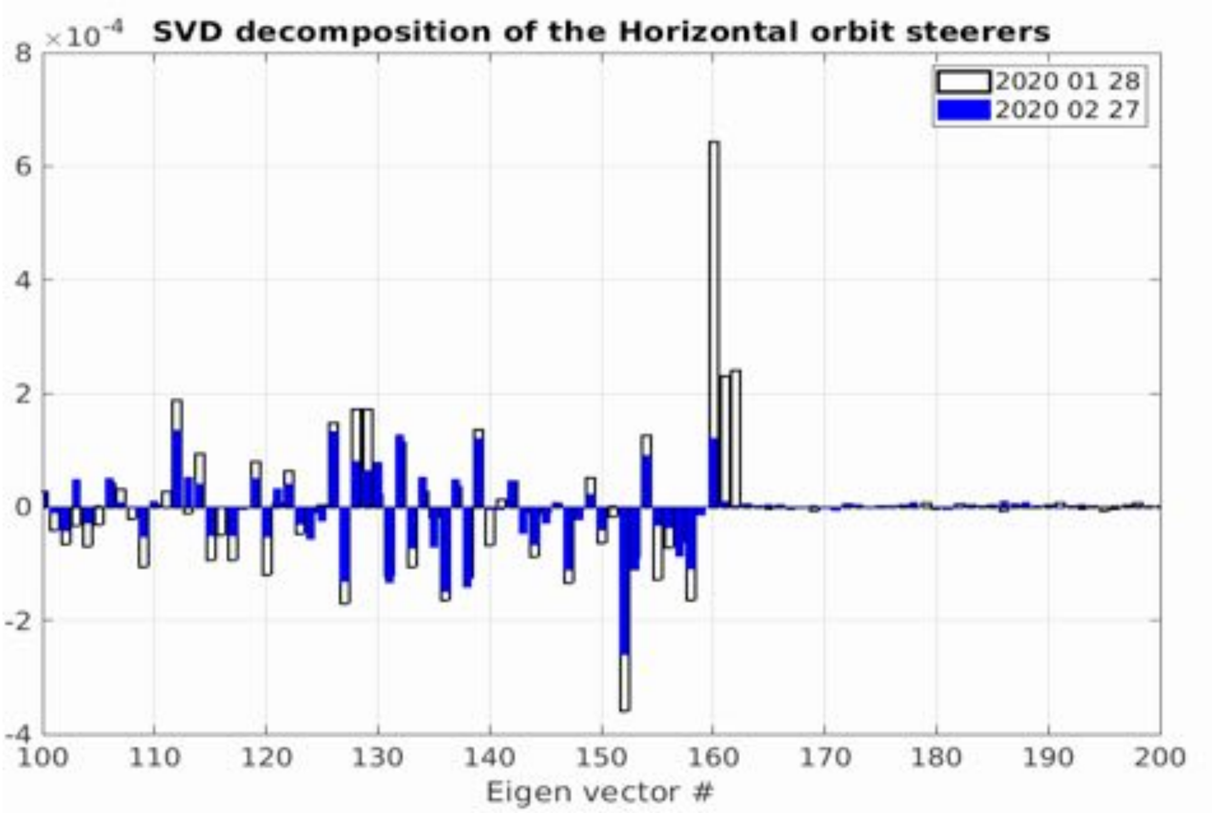


We use to stick to maximum 64

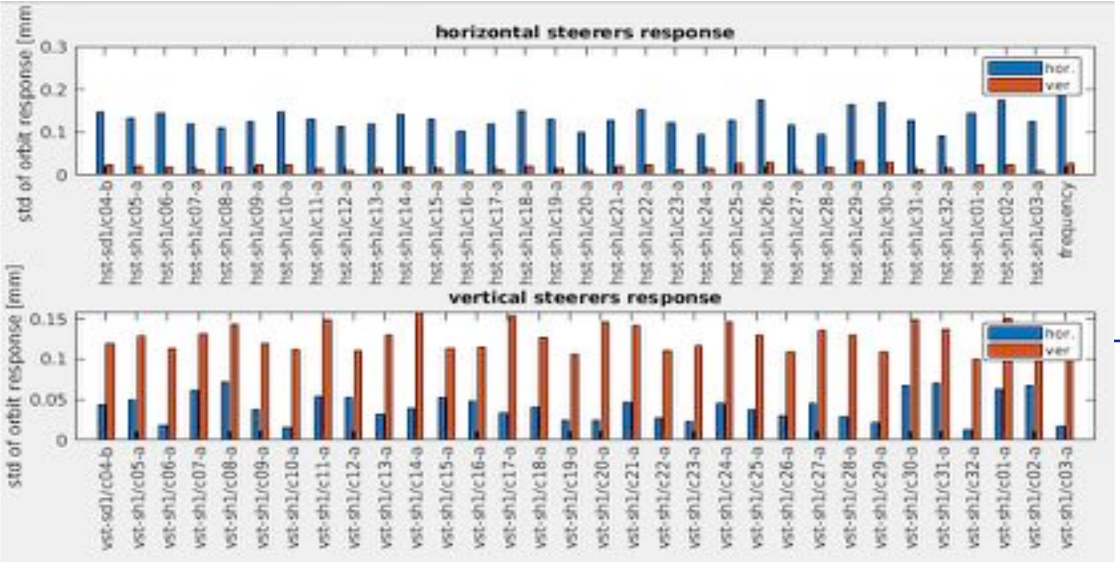


There is a magic number in the horizontal plane (160) eigenvalues that corrects the orbit locally across the sextupoles triplets. When these eigenvalues are used the betabeating is minimal and DA maximal. Increasing this number just adds noise to the system and slowly degrades the DA

THE DQS PUZZLE



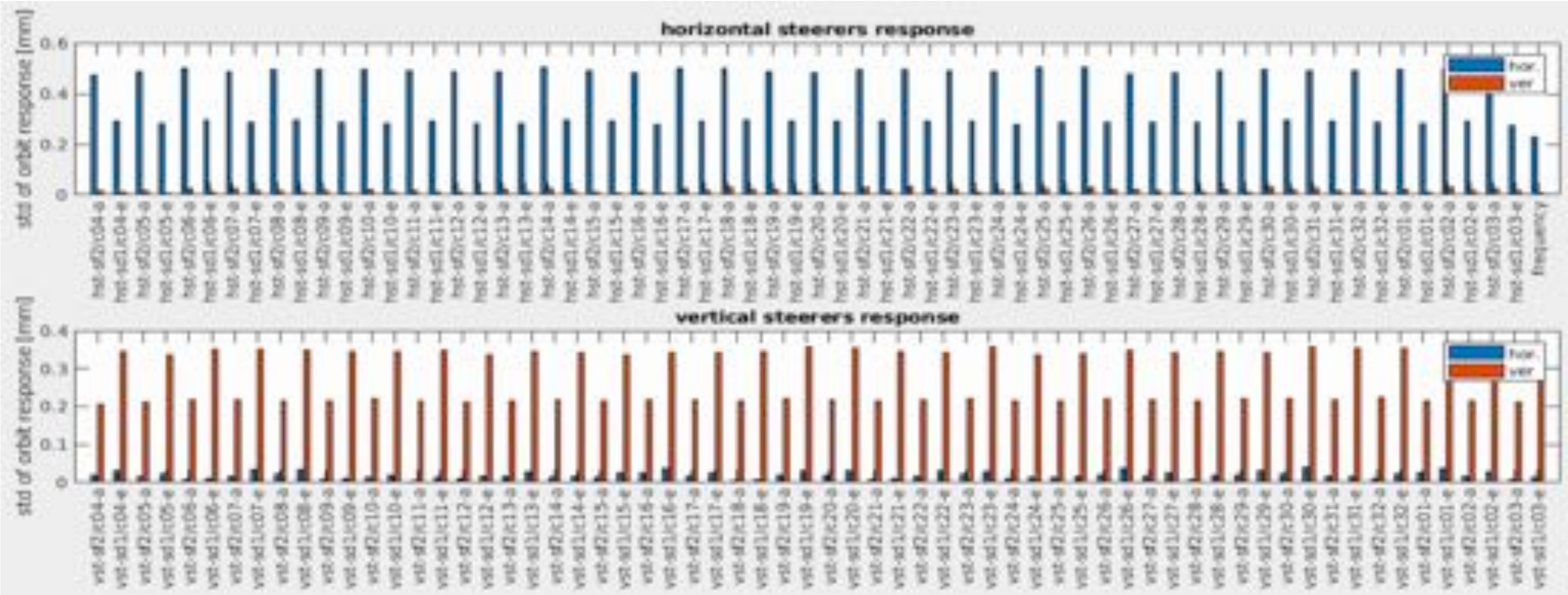
Using 162 eigenvalues did initially produce a clear pattern in the steerers also visible in the svd decomposition.
We did identify the cause to be due an improper horizontal positioning of the DQs.
After realignment the eigenvalues content was greatly improved, orbit and steerer rms improved as well
The machine energy did finally increase to 6GeV (confirmed by booster energy, tune correction etc…)



First
Response matrix

$\Delta\beta/\beta$ > 12% H ,15% V,
$\Delta\eta$ > 3 mm H, 3 mm V

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



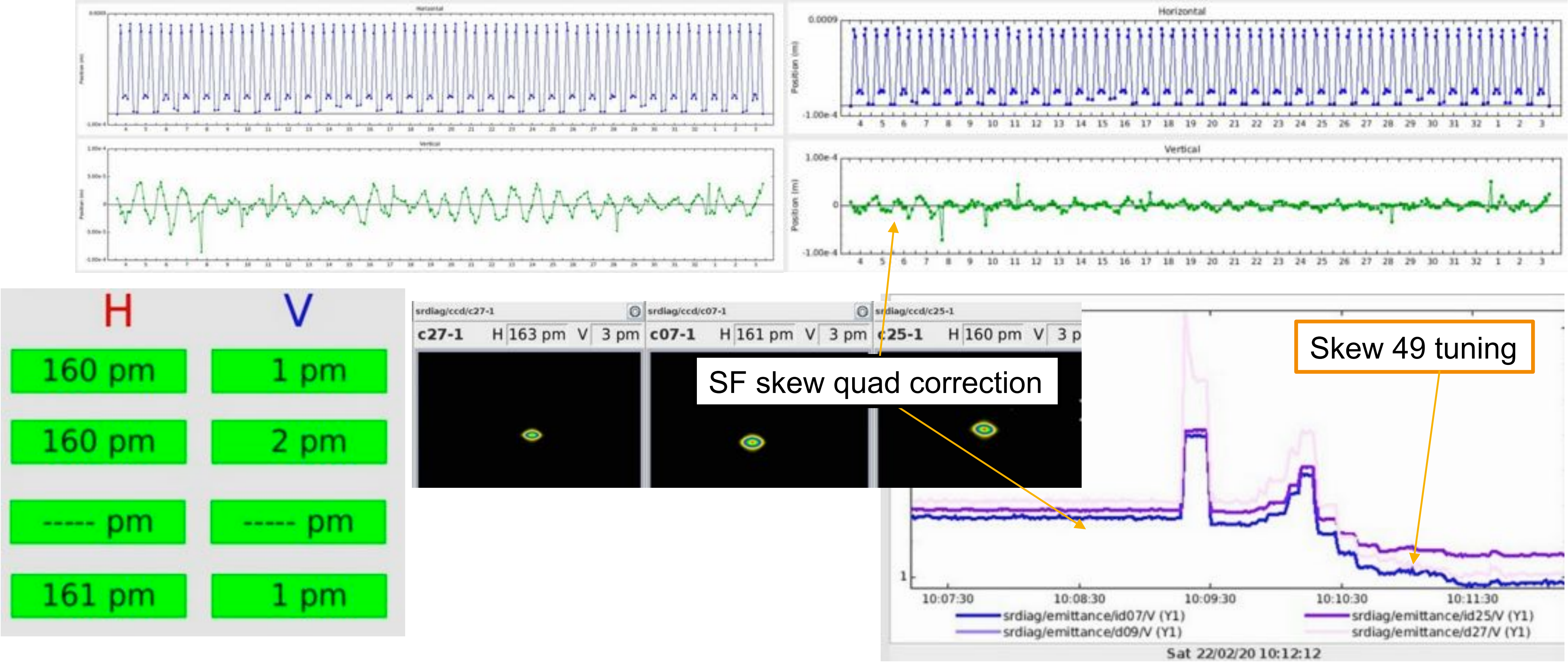
Latest
response matrix.

$\Delta\beta/\beta$ > 1.5% H ,
1.5% V,
$\Delta\eta$ ~ 0.7 mm H,
0.7 mm V

LESSONS LEARNED ON OPTICS CORRECTION WITH RESPONSE MATRIX DATA

- 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 we concluded that we had set all the gradients with an error of about 0.04% (estimated from combined measurements made at the factories and at ESRF => FUNDAMENTAL)
- Subsequently the correction was 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 eigv 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

FEBRUARY 22ND : OPTICS TUNING, SKEW QUADRUPOLES



93% injection efficiency, 160mA , $\Delta\beta/\beta$ ~1.0%, Hor. Ver. Emittances*: 160pm, *~1.23pm*
*measurement to be verified. Fully coupled beam does not give 80 pm in both planes as expected but ~110, 75

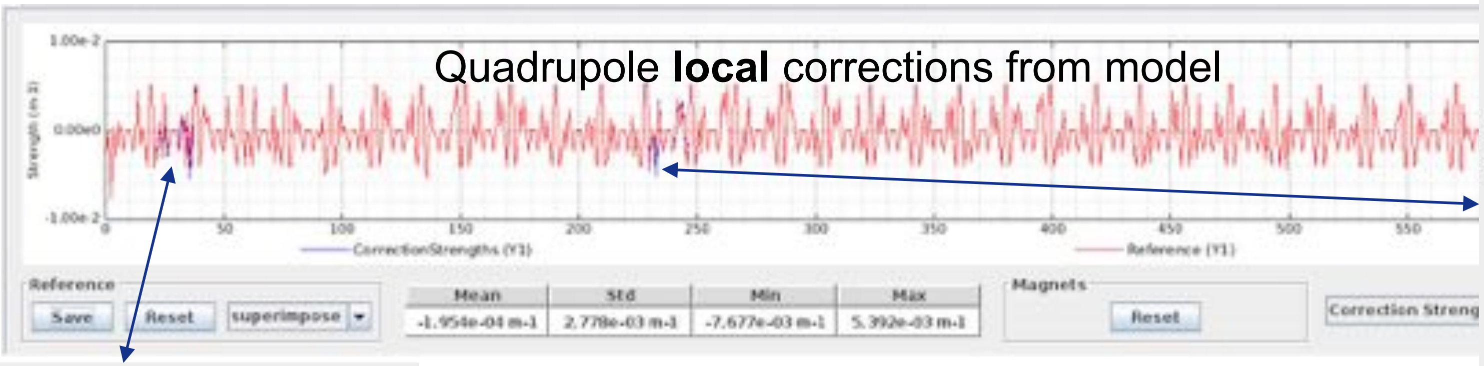
All Response matrix measurements are made using “self-steering” to cancel the effect of hysteresis.

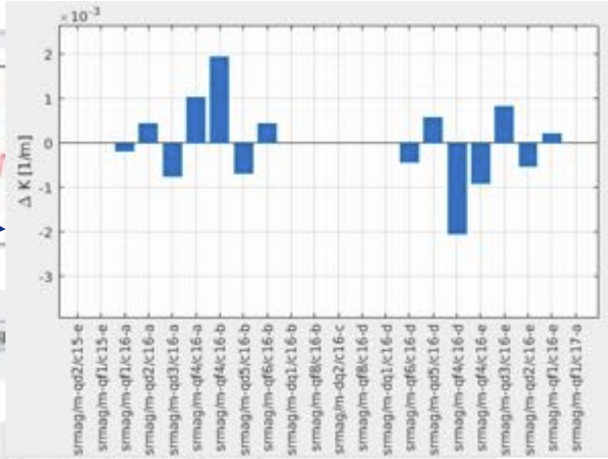
LESSONS LEARNED ON OPTICS CORRECTION WITH RESPONSE MATRIX DATA

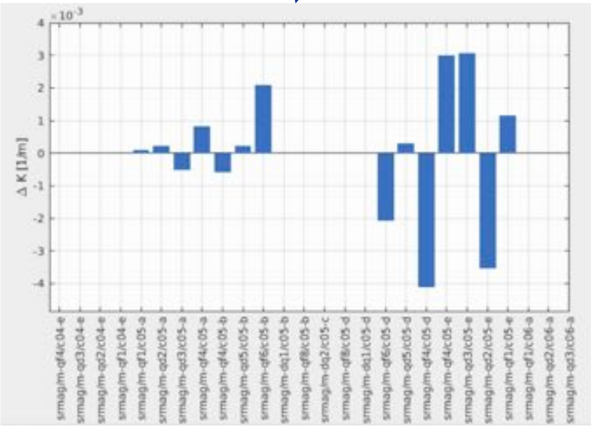
- The coupling correction is extremely efficient to reduce the coupling and vertical dispersion to unmeasurable levels
- However the optimal number of eigv (64 out of 288) leads to skews gradients much weaker (at least a factor 3) than the ones expected by vertical offsets on the sexts (and quads rotations as well).
- Increasing the eigv just degrades performances
- The response matrix method has limited capabilities to correct the coupling locally

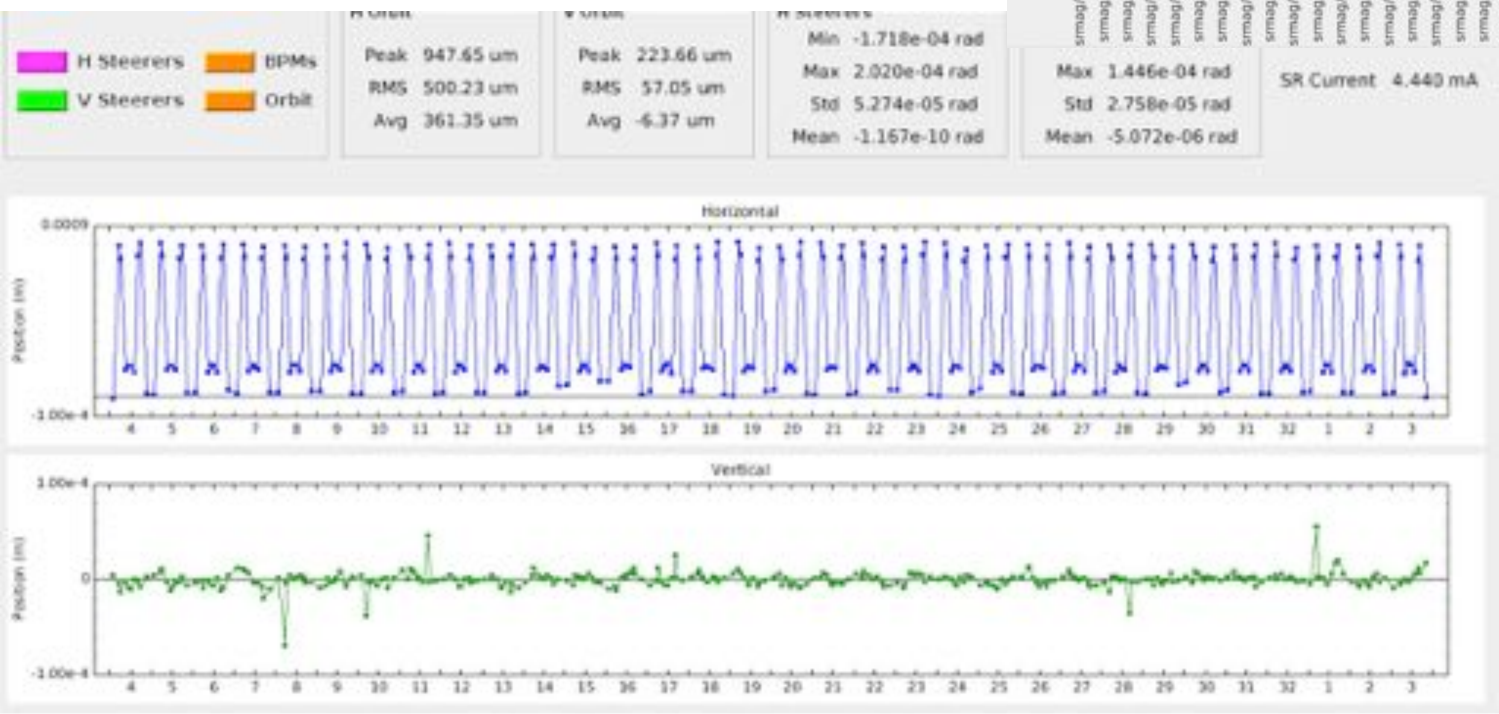
SB AND 2PW INSTALLATION: NO IMPACT ON THE MACHINE

Quadrupole **local** corrections from model



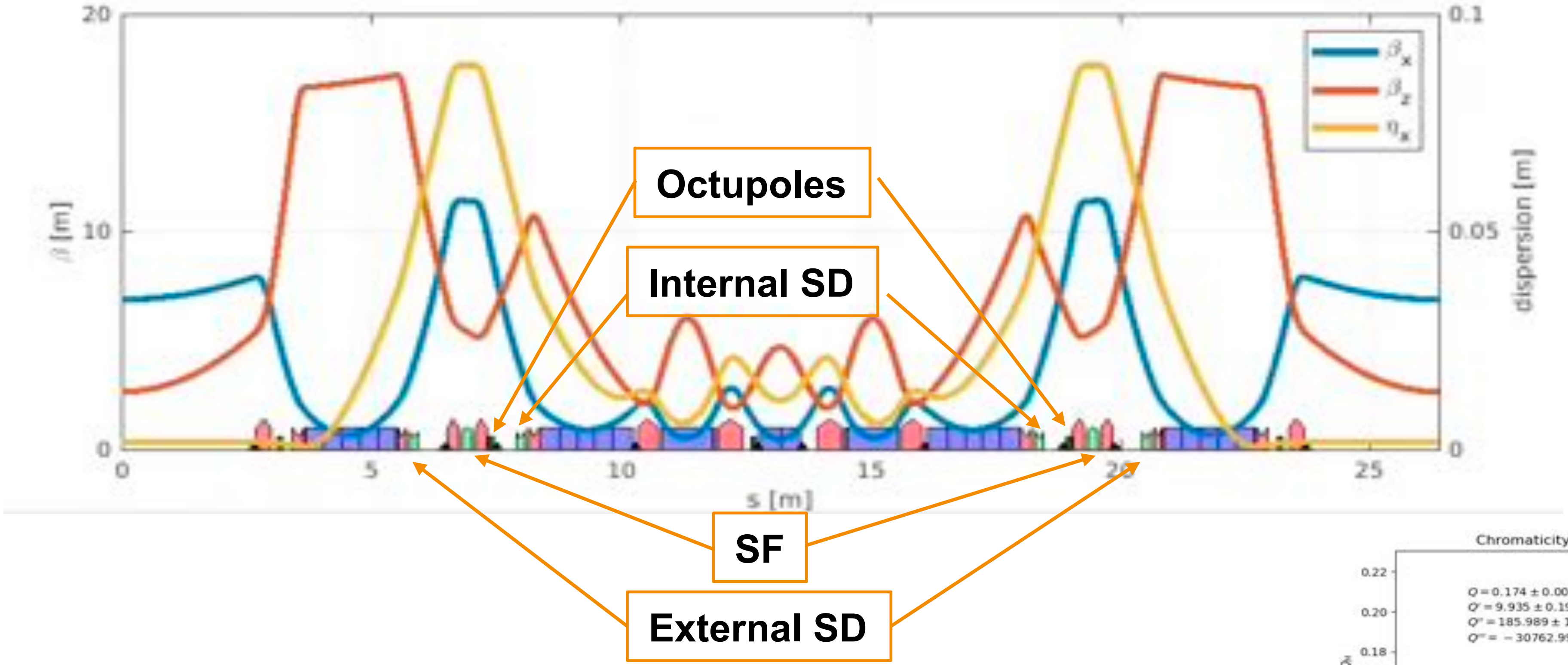


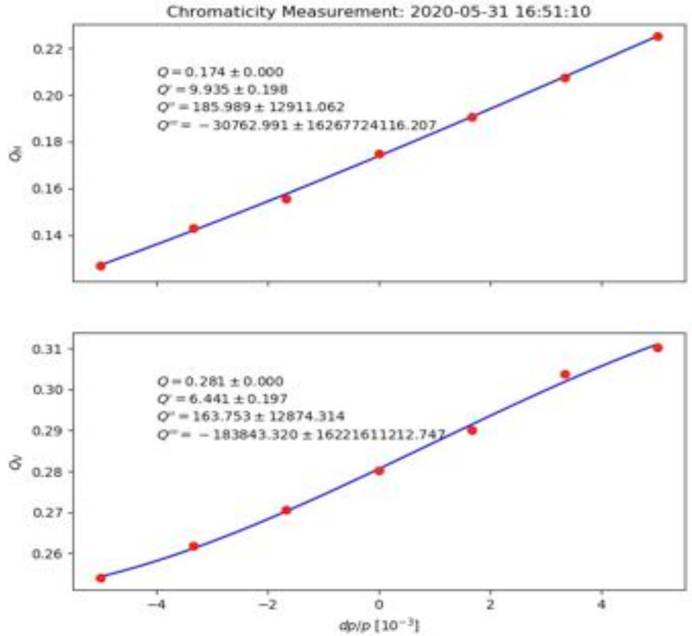




Dispersion after SB 2PW installation, looks perfect

< 1mm dispersion distortion in both planes





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

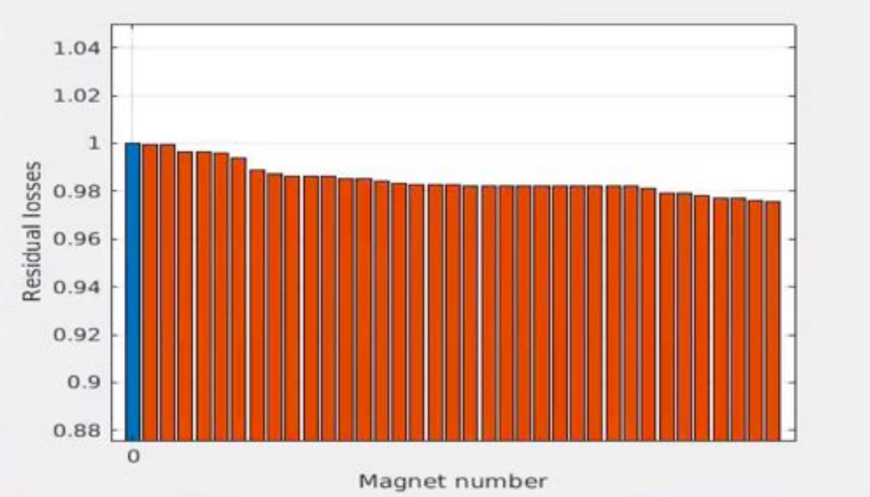
4 designed families: SF, internal SD, external SD, Octupoles.

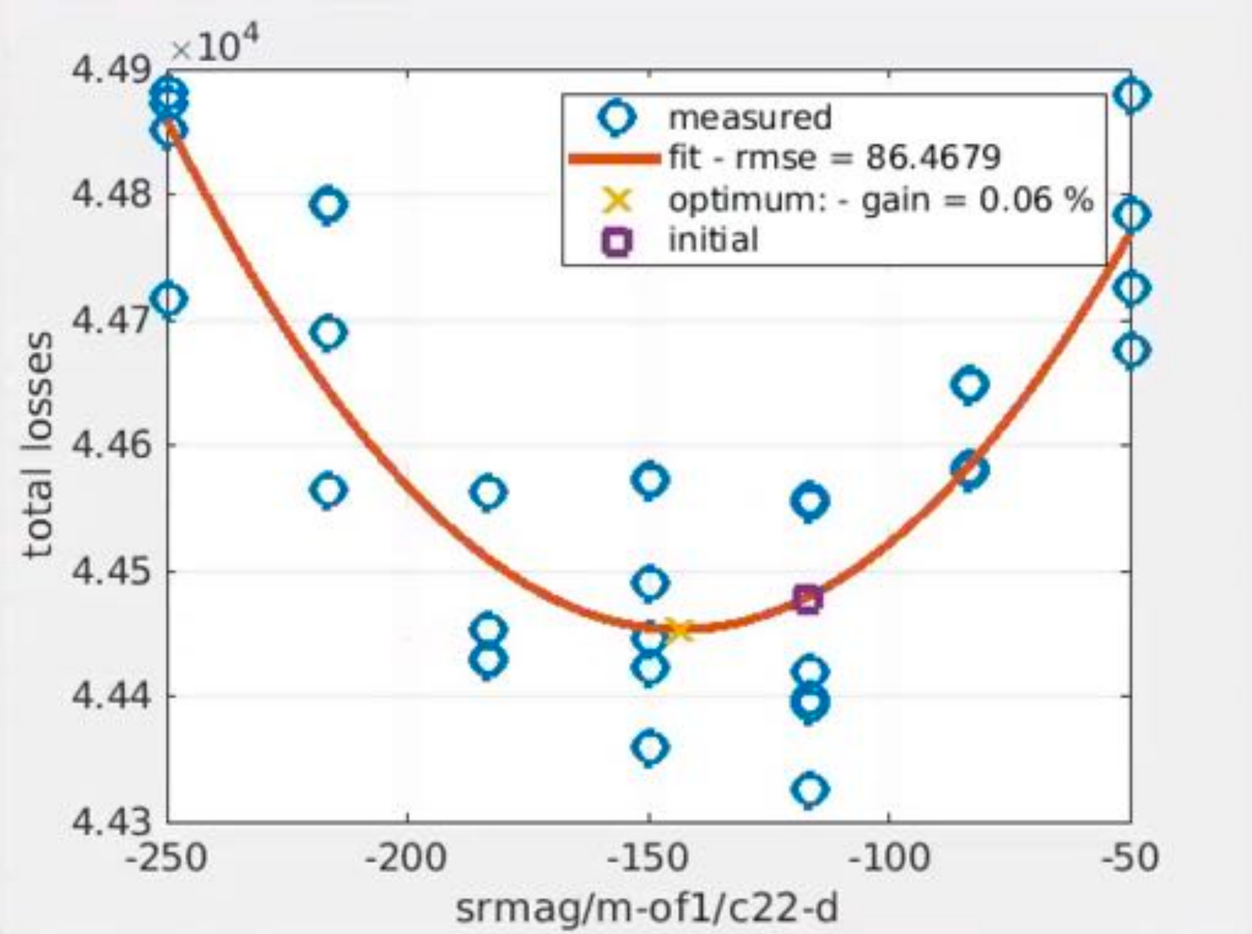
Optimal chromaticity for lifetime was found to be around (10, 6), close to the model prediction.

An automatic optimizer that scan sextupoles, octupoles and skew quadrupoles in a defined range and minimize the beam loss monitors losses and/or maximize the lifetime has been developed

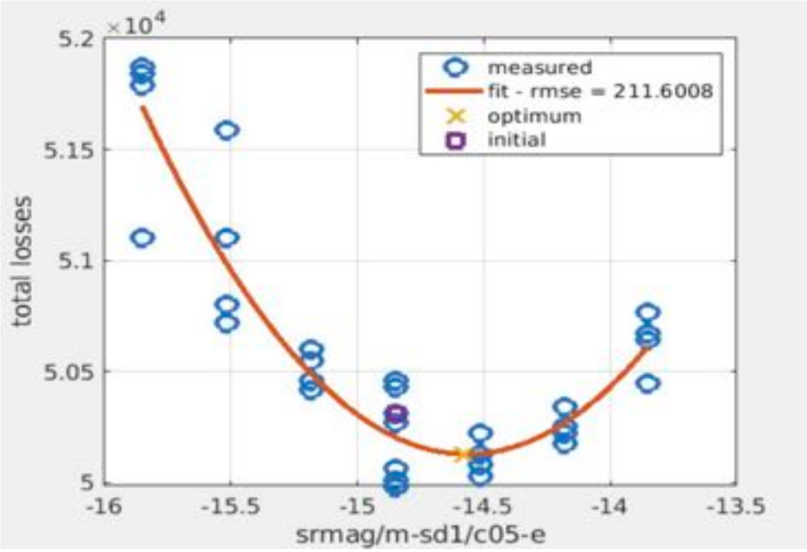
It has been used in several shifts of the last few weeks.

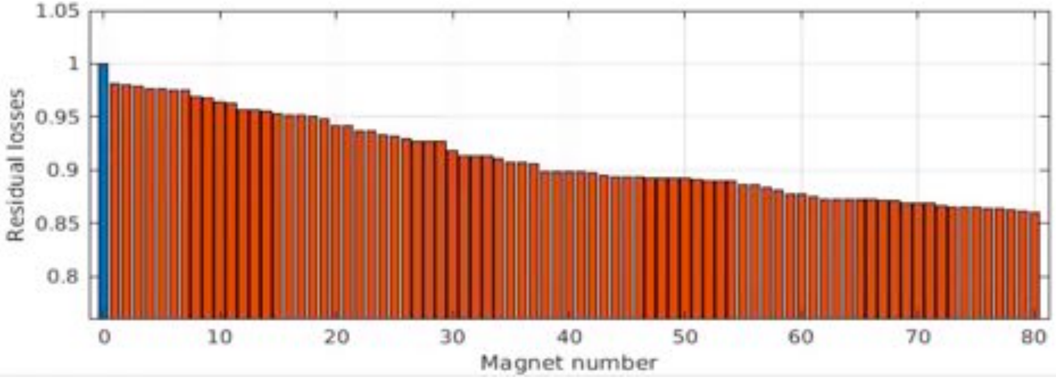
```
function run_by_hand_singlemagnets(MagType,Range,varargin)
%RUN_BY_HAND_SINGLEMAGNET Summary of this function goes here
%
%   run_by_hand_singlemagnets(MagType,Range,varargin)
%
%   MagType can be OCT, SEXT, SF, SD, SKEW
%
%   if Range is a single value then the range is from K0-range to K0+range
%   if Range is an arrray of 2 elements:
%      if MagType is SEXT then Range(1) is for SF, Range(2) is for SD
%      if MagType is OCT then the range is from Range(1) to Range(2)
%
%   run_by_hand_singlemagnets(MagType,Range,'Automatic')
%   will stop when SI3 is on and will save a magnet file
%
%   run_by_hand_singlemagnets(MagType,Range,'IDLosses')
%     will use only losses from the first BLM after SS except inj and RF
%
%
```

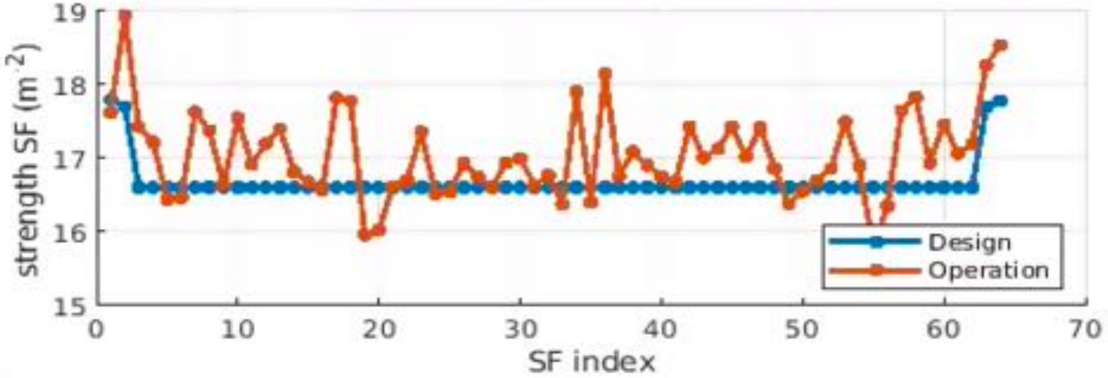


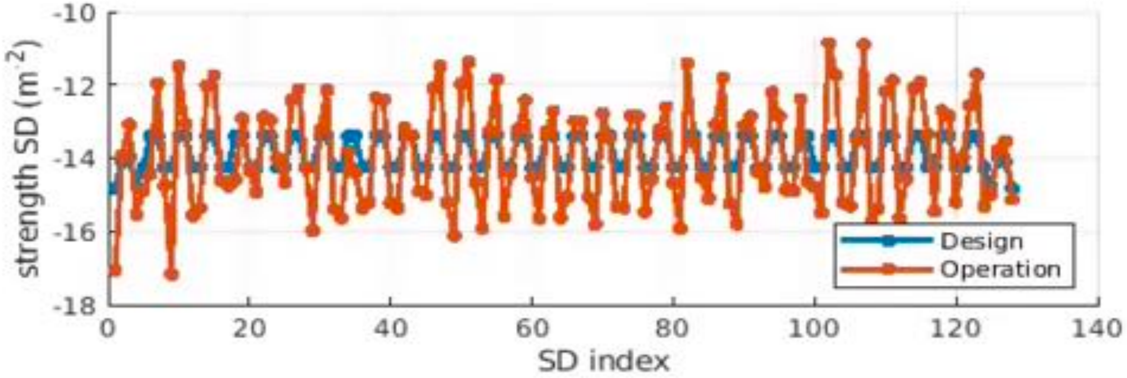


Loss decrease by scanning individual sextupoles.



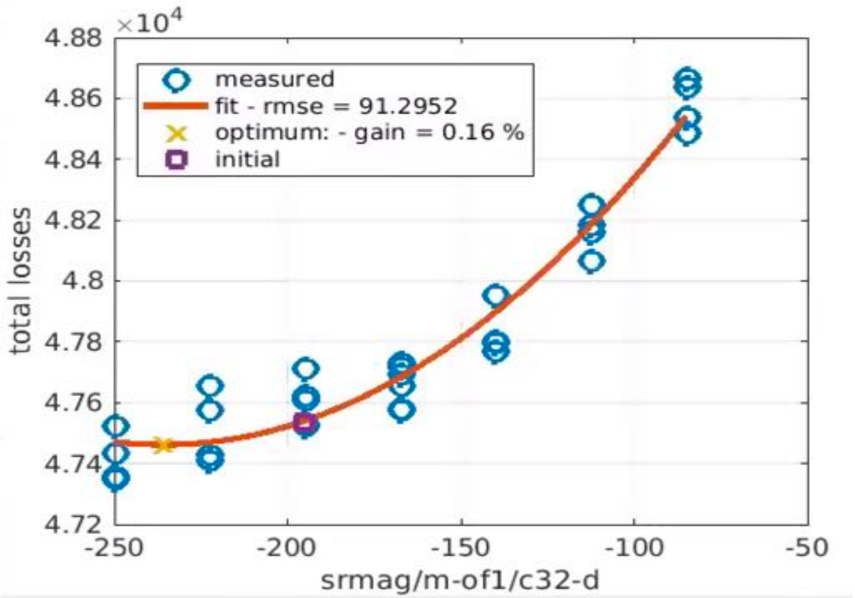


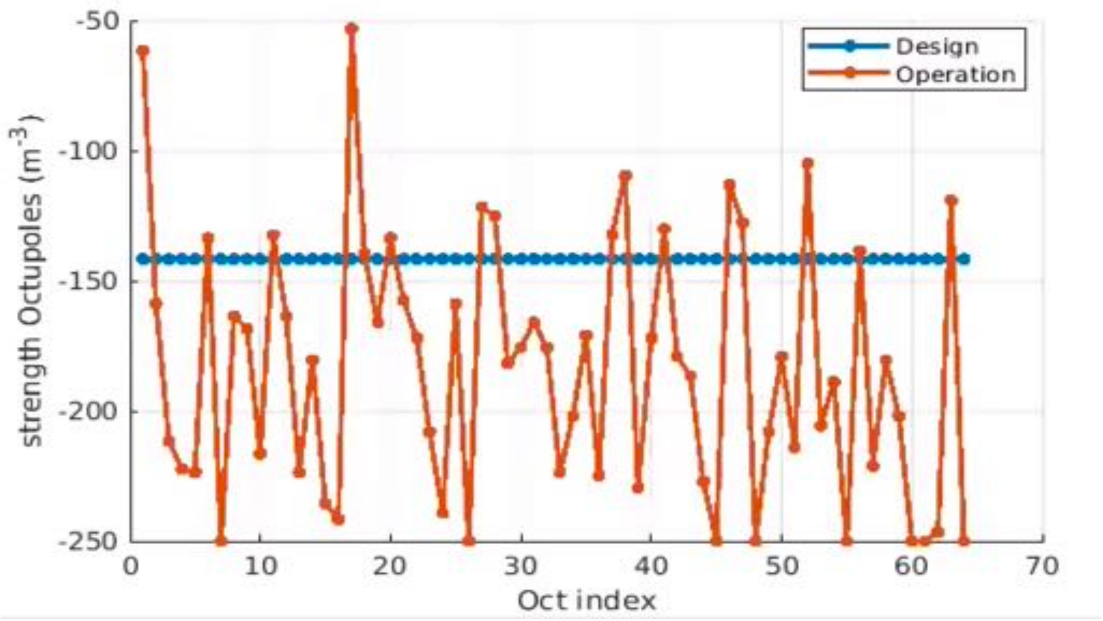


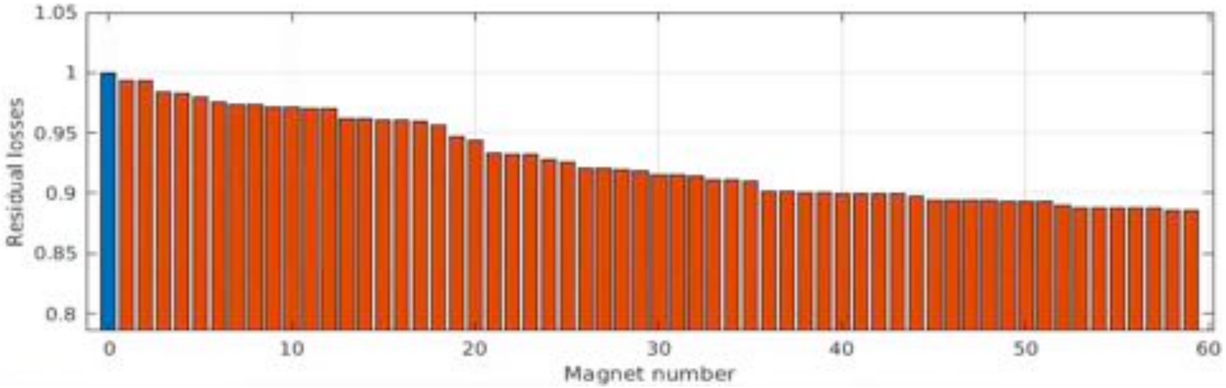


The present sextupoles operation setting is not periodic, with a variation of about 10% peak to peak wrt the design value.
The x/y chromaticity is built automatically during the scan and we measure 11/7 x/y very close to the expected best value from the model

Same strategy used for the sextupoles has been extended to the 64 octupoles.

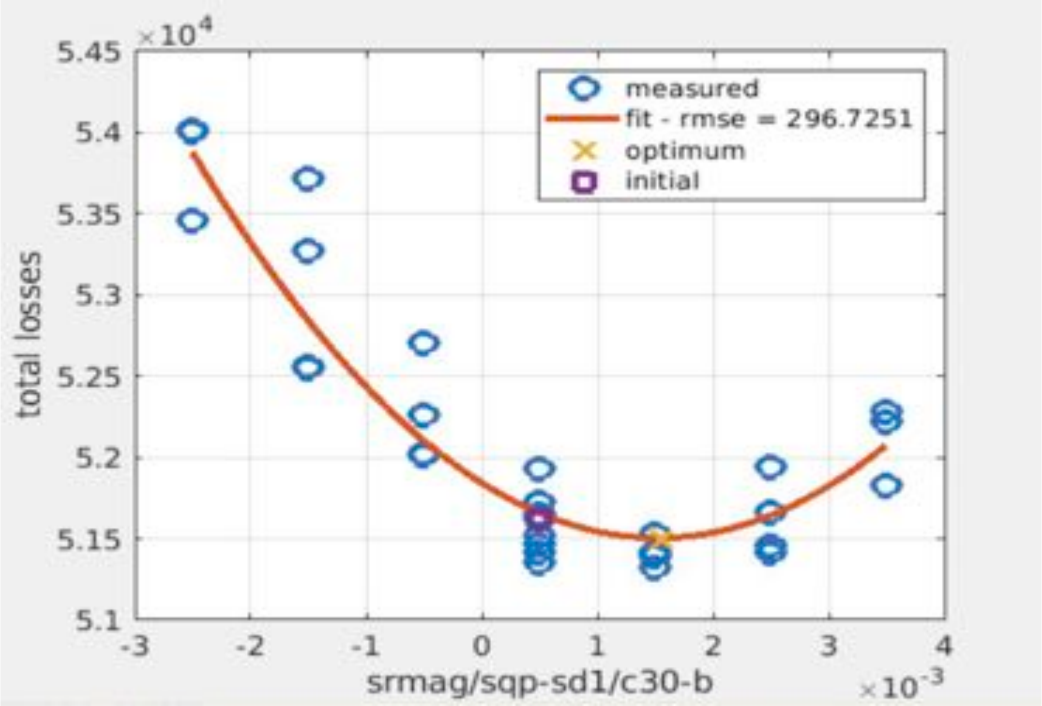






The present octupoles operation setting is not periodic, with a variation of about 70% of the design value. Such large spread did surprise us.

- Initially tuned with the FILO application, to correct the linear coupling down to ε_v<1pm
- Independent skew quadrupoles scan are very efficient to reduce total losses and improve lifetime, with constant vertical emittance (using emittance feed-back)



After skew quadrupoles tuning, the linear coupling is a bit degraded:
ε_v goes from about 0.5 pm to 1 pm (despite letting all the 288 skew quads vary freely)

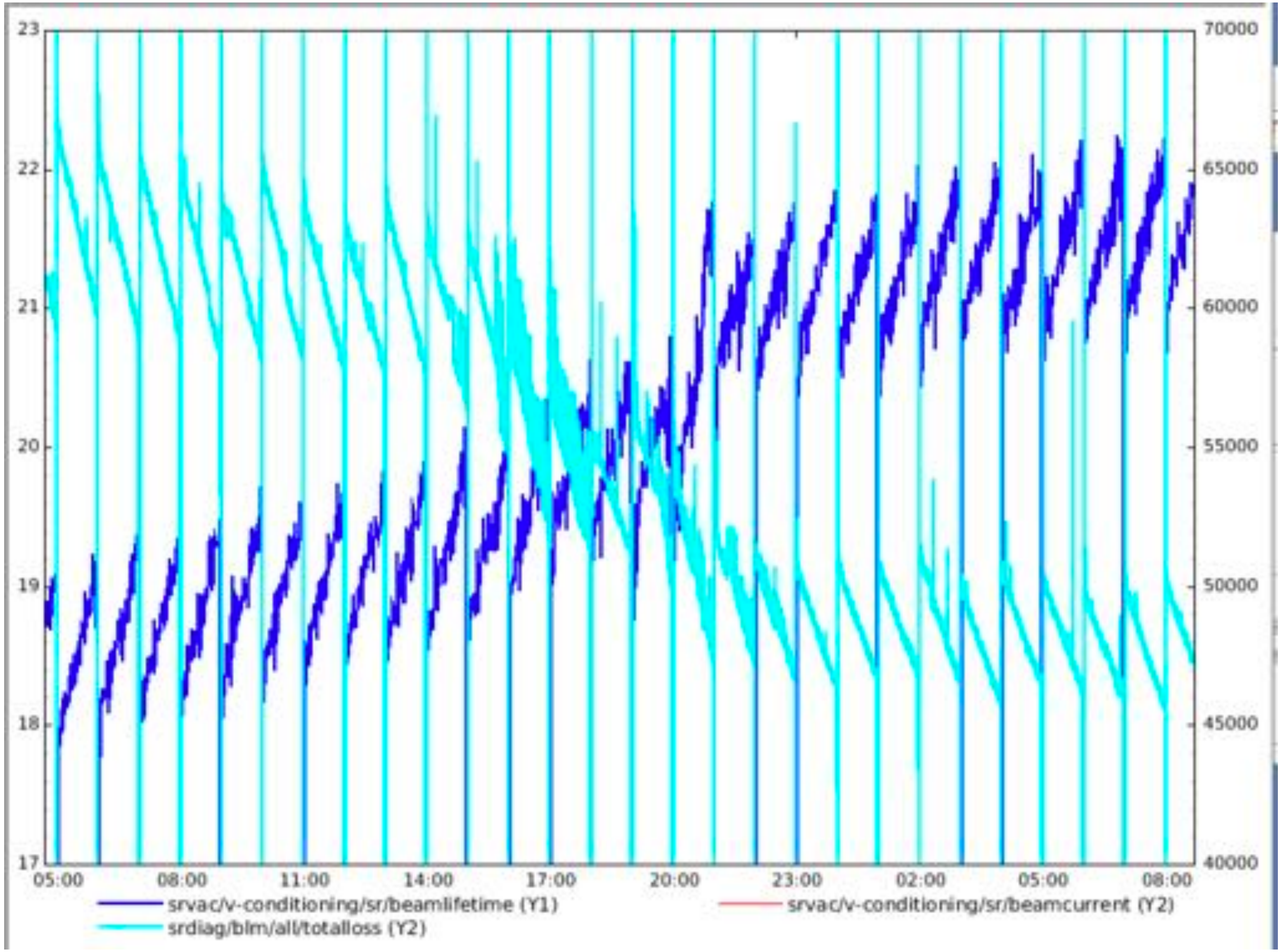
The guess that minimum losses and best energy acceptance are associated with local and global coupling correction was confirmed!

It has been verified that the residual coupling can be easily corrected with FILO, if wanted, by using only a few eigenvalues.

Skew quads scan (80 magnets)

sextupoles scan (60 magnets)

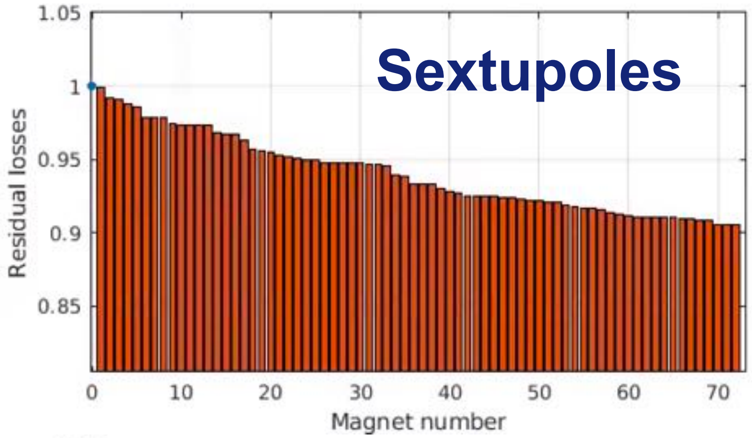
octupoles scan (20 magnets)

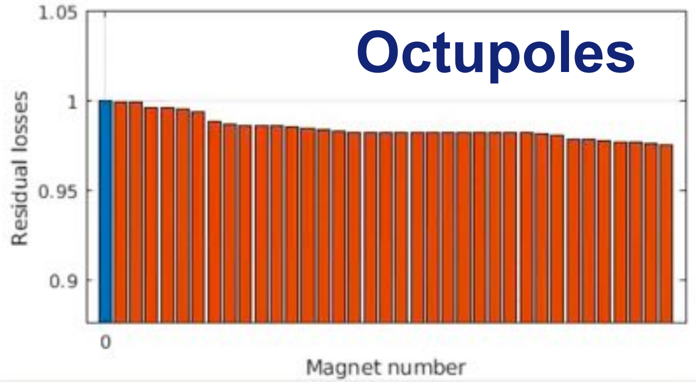


Both Lifetime and losses were improved in the shift

26/07/2013

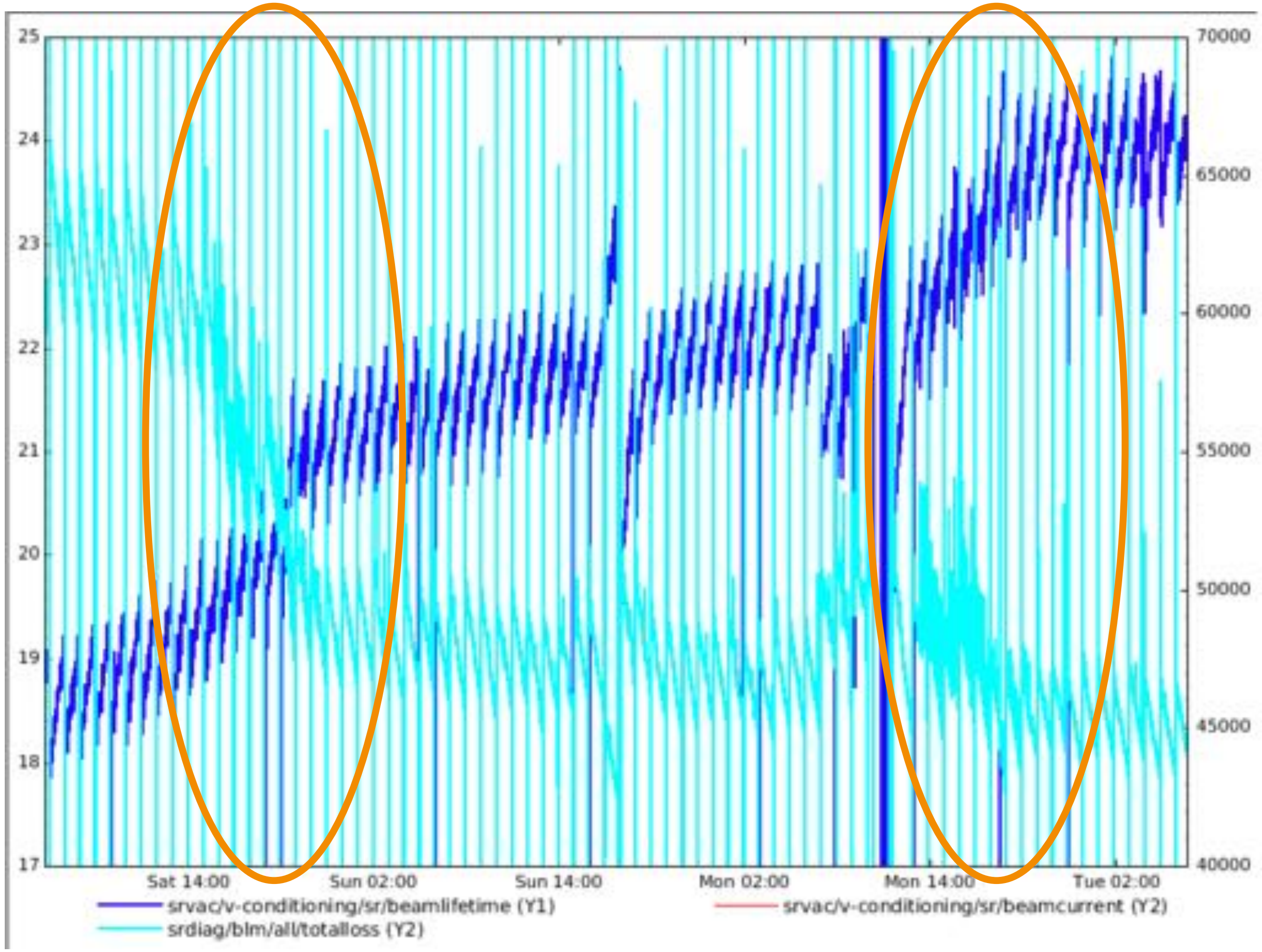
Skew quads scan, sextupoles scan and octupoles scan improved both total losses and lifetime (mostly lifetime).





Saturday 29/08/2020

Monday 31/08/2020

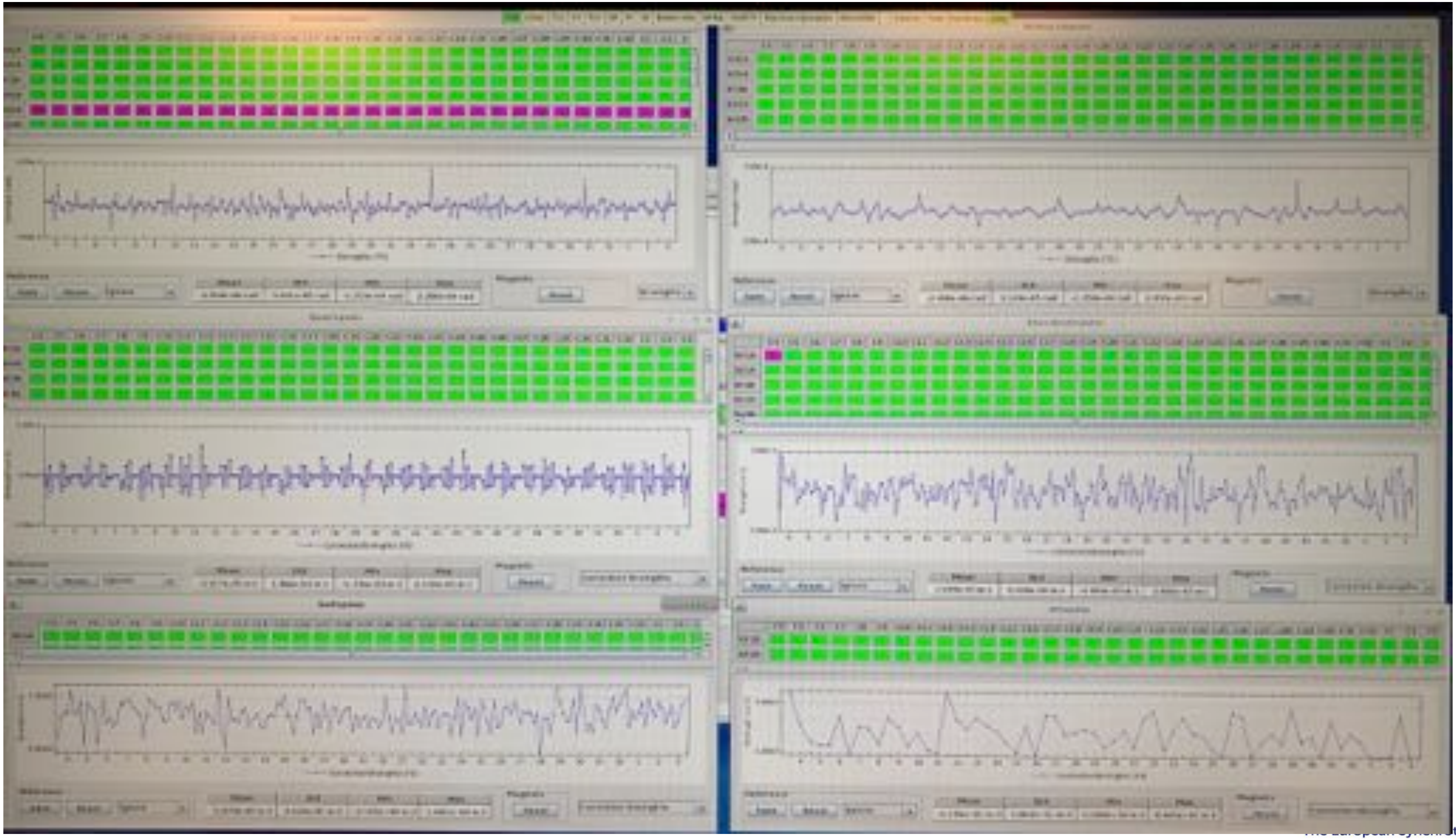


LC Tuning strategy:

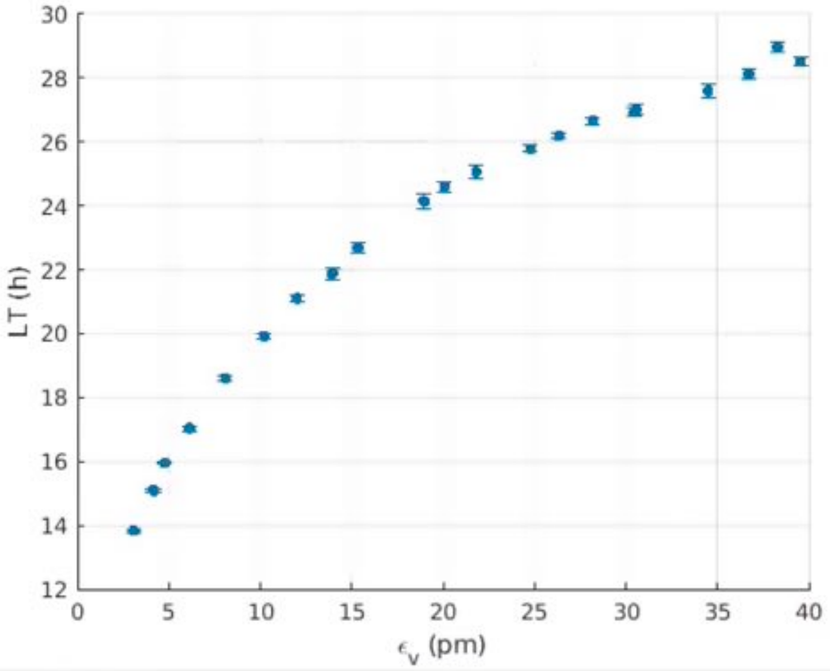
- The Local Non linear Coupling and DA tuning is very slow, but goes steady like a train.
- It has the great advantage that can (in fact it must) be done in USM-like
- The last few weeks it has always been a “free lunch (most likely dinner)” to take, after every shift we have always had better performances at the only cost of a constant dedication (and sleep) of the BDG people…
- The tuning converges after 2-3 shifts and about 5-10% final additional gain is obtained after about 3 more shifts (2 fullrounds of skews/sexts/octs)

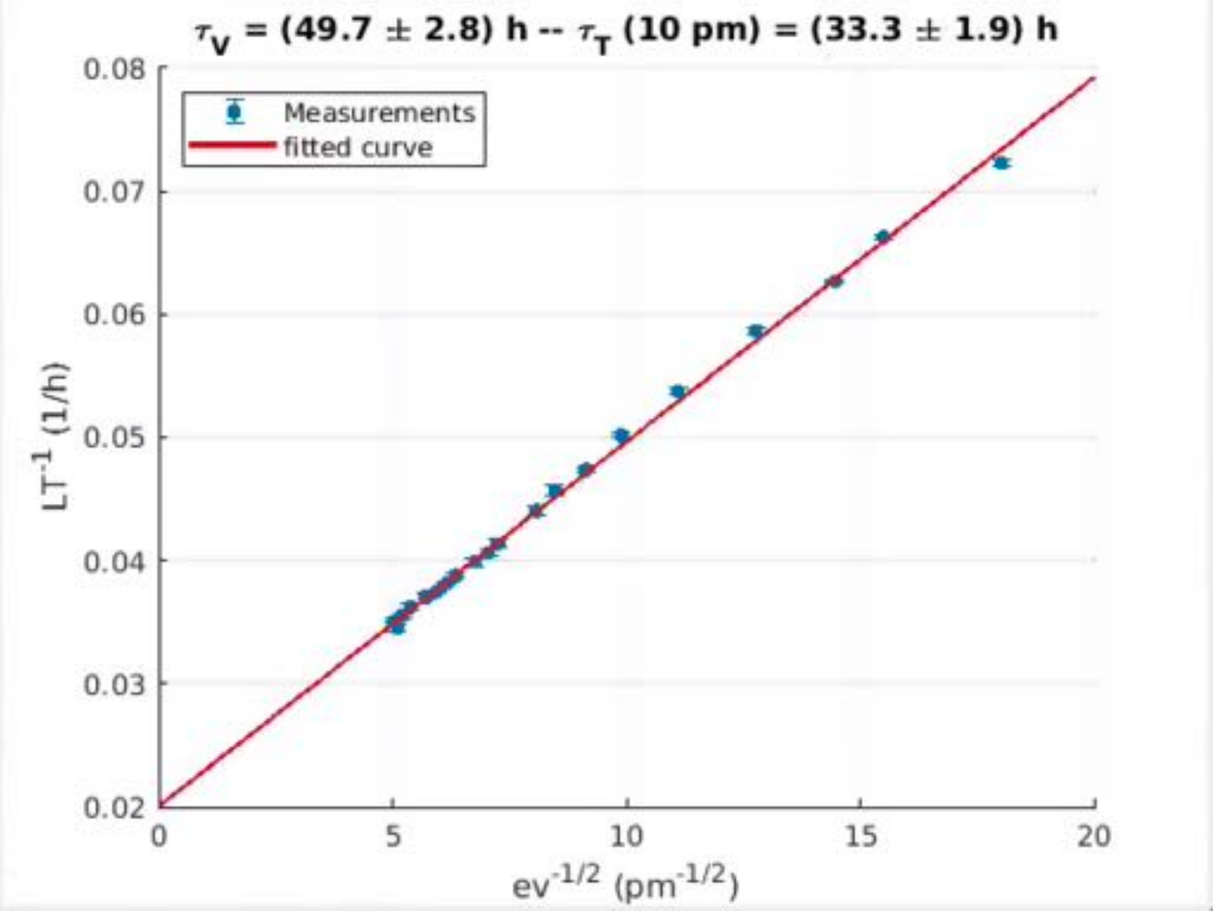
The LC tuning has improved overall the toushek lifetime by about a factor two and decreased the losses on the IDs by more than a factor 4 !!!!

The EBS Machine footprint



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



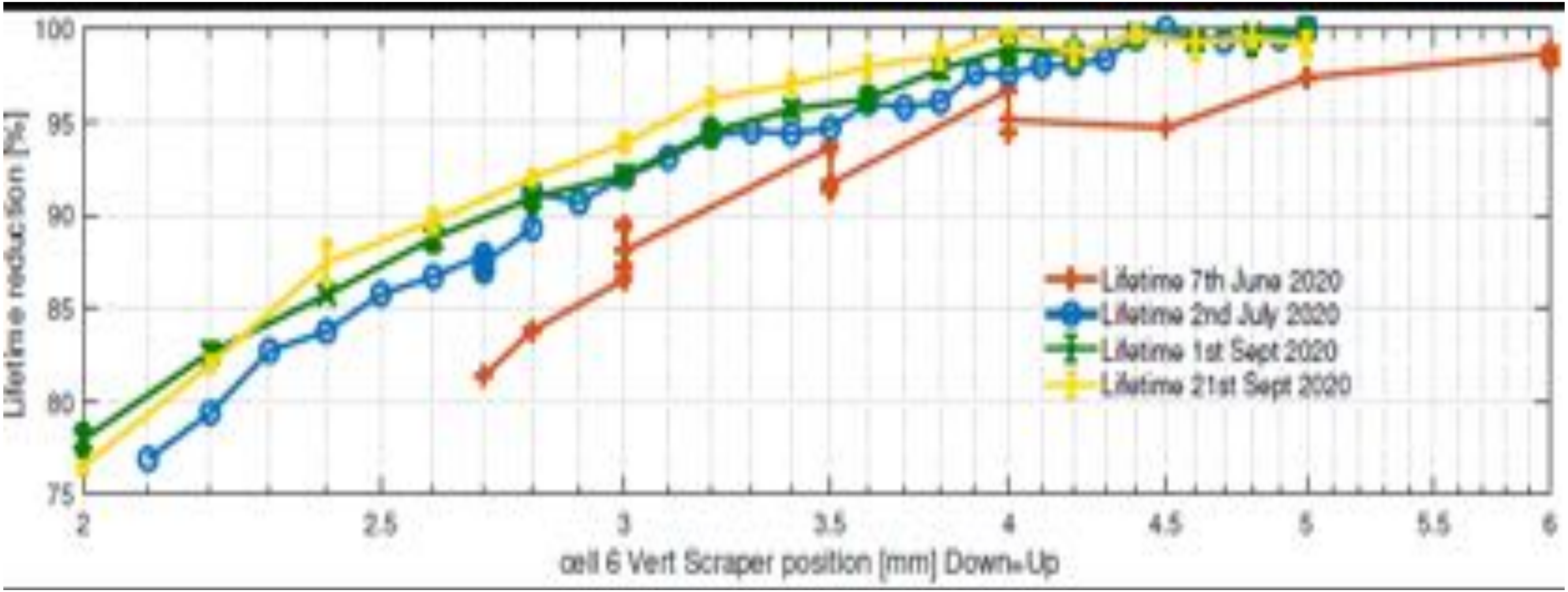


τ_T at **10 pm** is **33.3 ± 1.9 h**

τ_T at **5 pm** is **23.5 ± 1.3 h**

Touschek lifetime is above design values!

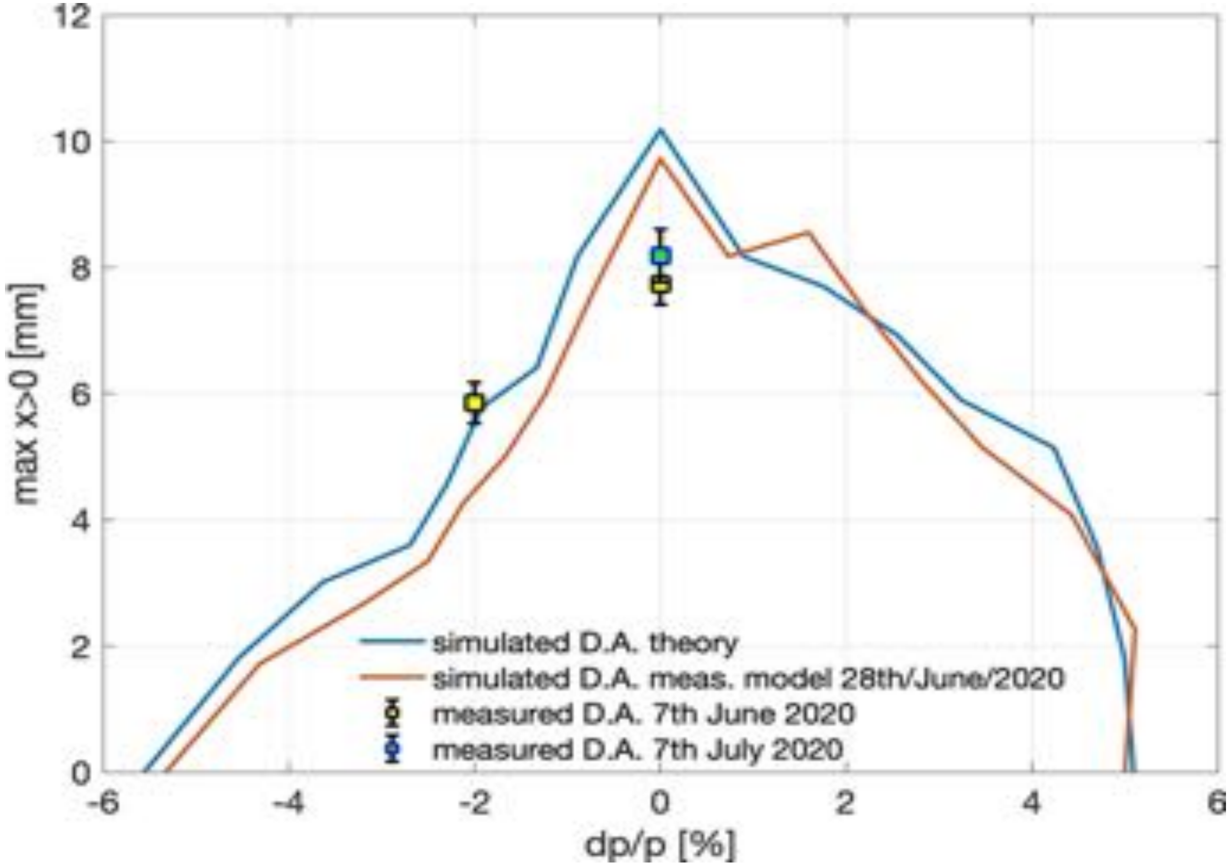
LIFETIME VS VERTICAL SCRAPER

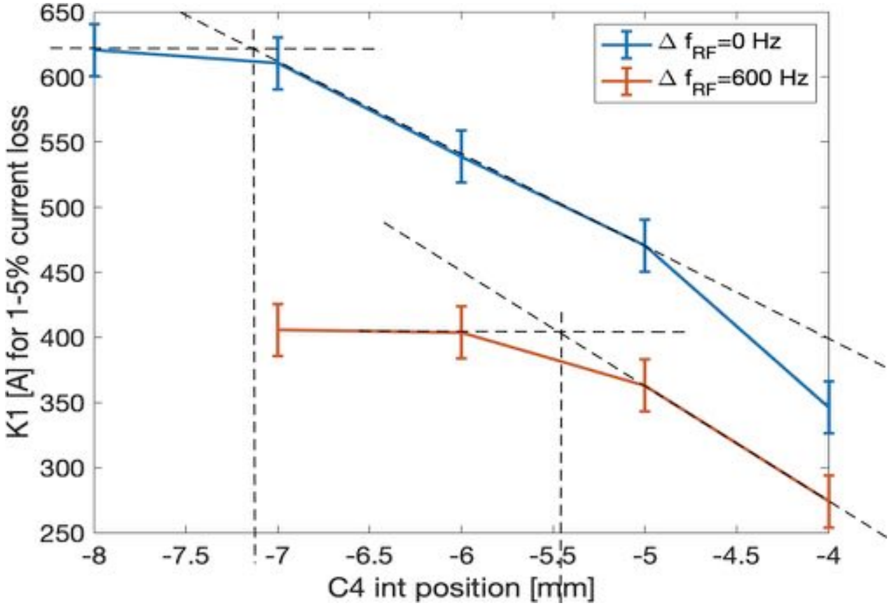


To be noted that our model does treat properly vacuum and tousheck scattering and we cannot use it yet to make predictions on the halo neither study and develop a method to minimize it in theory

Rescaling with betas, the horizontal scale roughly correspond to the vertical opening on ID31 => 4mm undulator gap seems at reach!

DYNAMIC APERTURE MEASUREMENTS



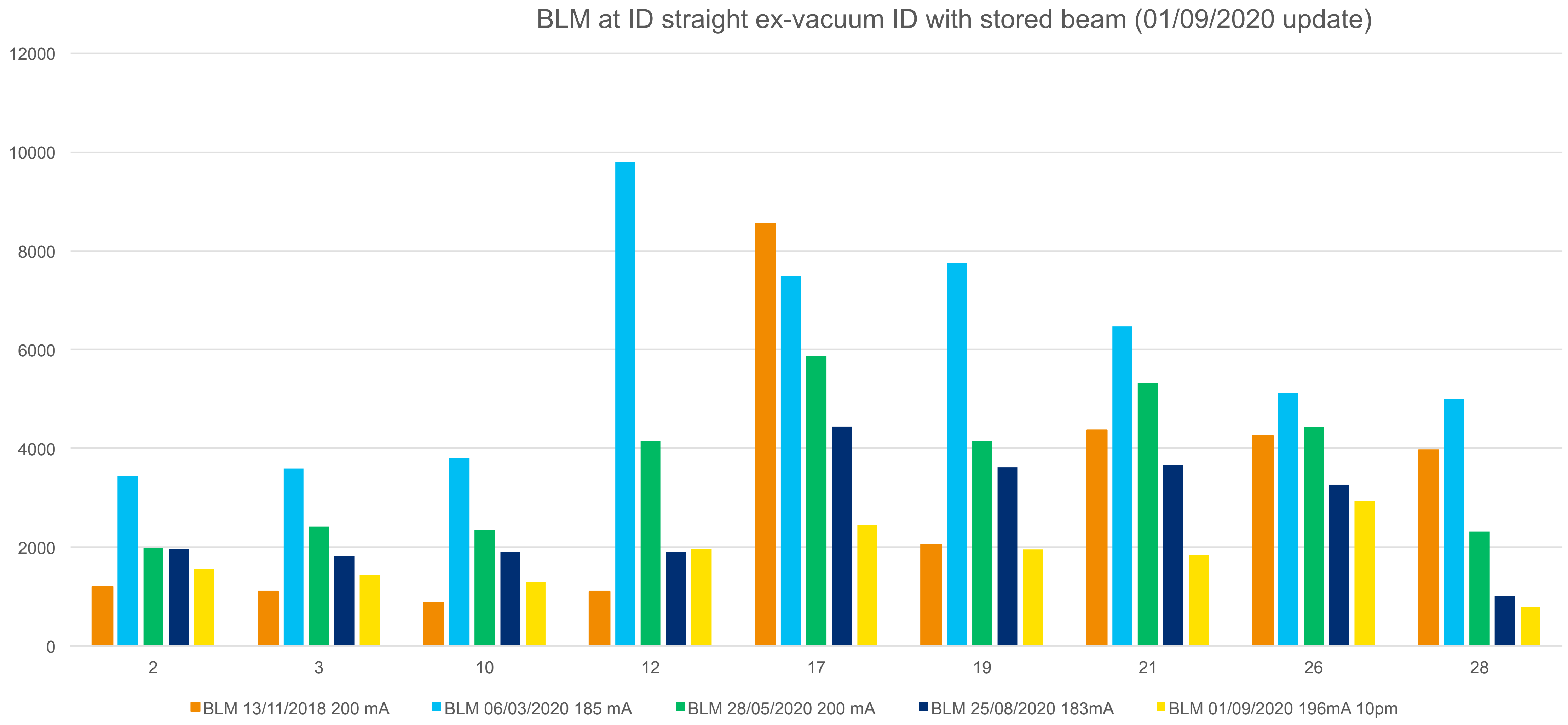


We have measured on-energy and off-energy (at -2%) dynamic aperture.

Off-energy DA is slightly larger than expected.

Additional measurements will be done.

OPTIMIZATION OF LOSSES ON THE INAIR IDS



OPTIMIZATION OF LOSSES ON THE INVAC IDS

PERFORMANCE PROGRESSION

July:
- 200mA in 7/8+1 (2mA) delivery
- 20pm vertical emittance
- 20hrs lifetime
- Injection efficiency > 70%

Constant tuning and improved tuning methods allowed to maintain design lifetime while reducing vertical emittance and increasing single bunch current

Sept 02:
- 200mA in 7/8+1 (2mA) delivery
- 10pm vertical emittance (30% reduction in tousheck lifetime)
- 20hrs lifetime
- Injection efficiency > 70%

Sept 15:
- 200mA in 7/8+1 (4mA) delivery (10% reduction in overall lifetime)
- 10pm vertical emittance
- 20hrs lifetime
- Injection efficiency > 70%

EBS STORAGE RING 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

Achieved Jan 30

Parameters** that could allow "comfortable" USM operation
Goal: to be exceeded by 24-August-2020

Achieved Mar 14

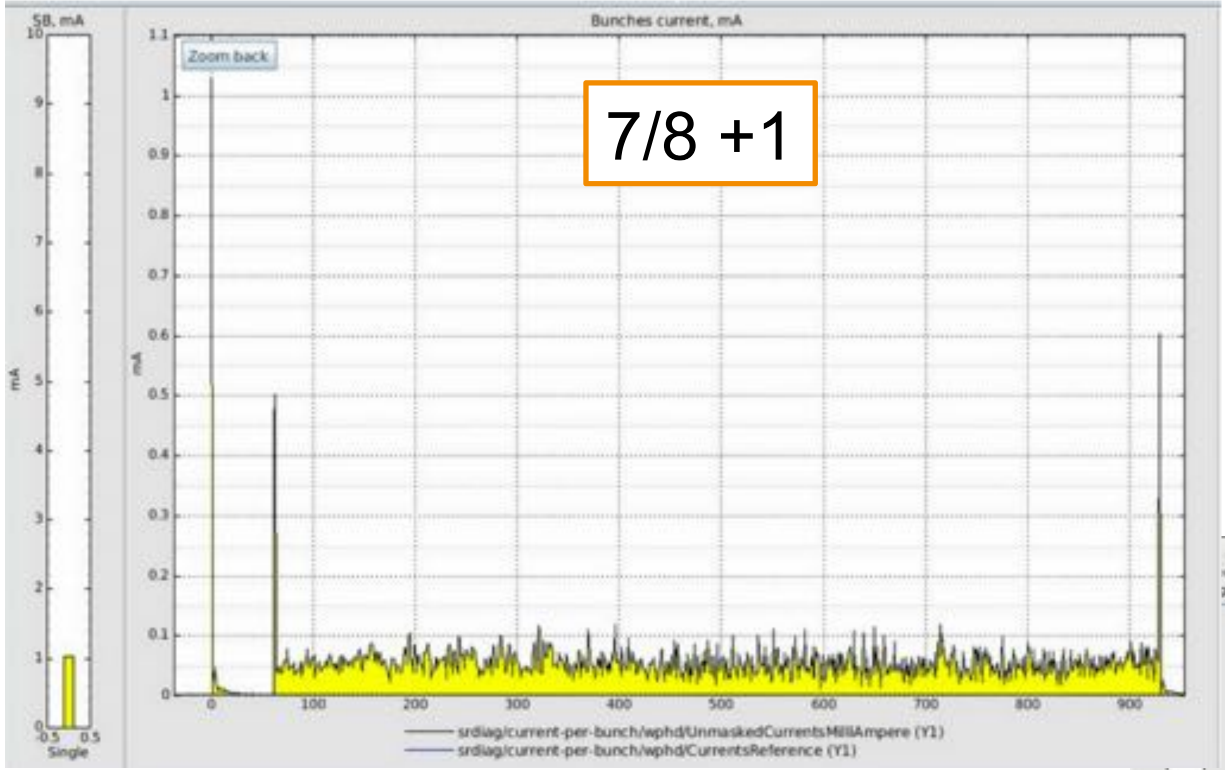
Design EBS parameters
Goal: to be exceeded by Dec 2021

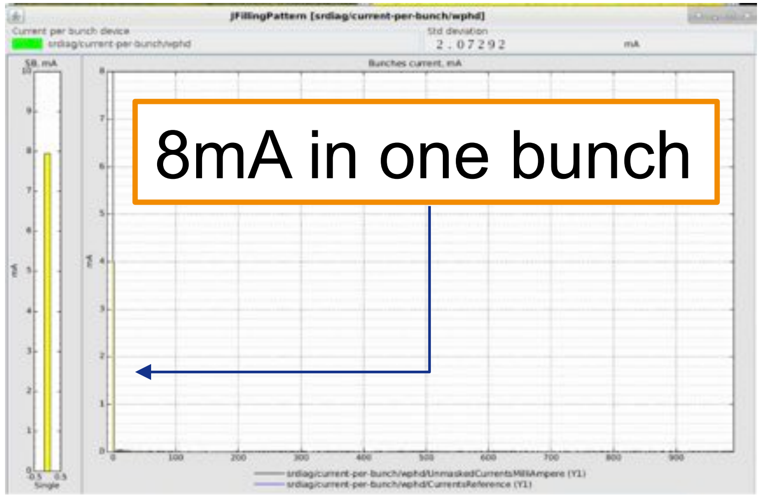
All exceeded Sept 1, 2020
16 months ahead of schedule

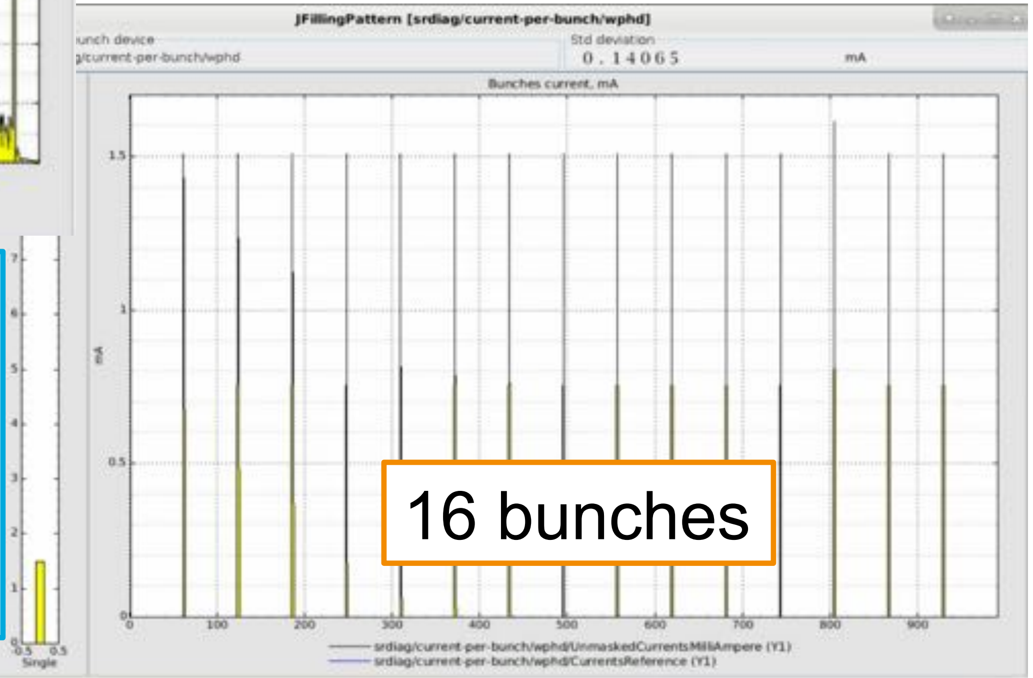
Total current	> 50 mA * 120mA	200 mA 201mA	200 mA
MTBF	> 12h >12h	> 30h >100h	> 50h
Up-time	> 90% >90%	> 95% ***>98%	> 97%
Inj. Eff.	> 50% >90%	> 70% >90%	> 80%
Lifetime	> 5h 3.5H @50mAmps	> 10h >10.5h	> 20h
H emittance	< 250 pm ~170pm@3mAmps	< 150 pm <150pm@200mA	~ 135 pm
V emittance	< 50 pm ~8pm@3mAmps	< 20 pm < 15pm@200mA	< 10 pm
stability	< 0.2 σ <0.05σ	< 0.1 σ < 0.02 σ	< 0.05 σ

** Parameters have to be achieved simultaneously
*** increasing then 1-2% each year

FILLING PATTERNS: 7/8+1, 16 BUNCH, 4 BUNCH, ALL OPERATIONAL







First tests of current thresholds (procedure yet to be established):

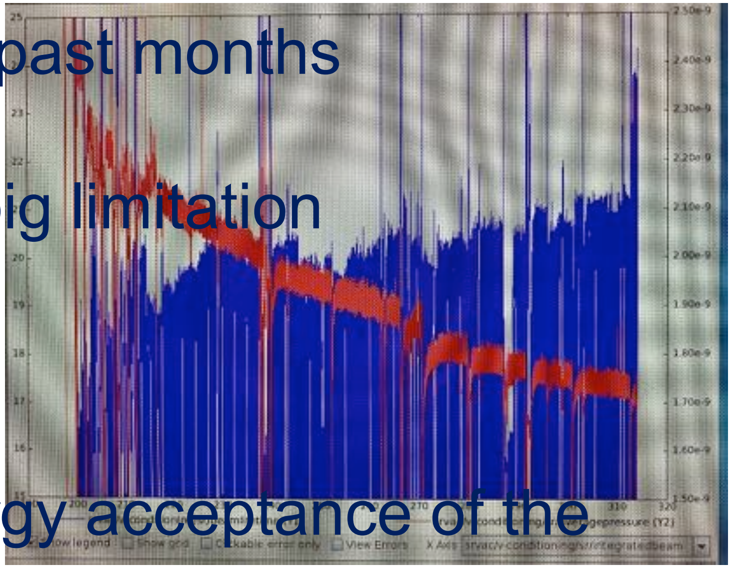
Single bunch current threshold limit in 16 bunch mode:
Beam lost at 6.9 mA/bunch (inj. bump at 13 mm)
Beam lost at 6.1 mA/bunch (inj. bump at 13.5 mm)

In a single bunch up to 8.0mA (with sextupoles tuning)

VACUUM LIFETIME

- **Tousheck lifetime has already exceeded design value**

- **Vacuum lifetime is still very low: about 80Hrs** for several reasons:
  1) A lot of vacuum interventions have been needed in the past months
  2) 2 months of beam conditioning are missing
  3) CV5000s conditioning, while still progressing, is still a big limitation



We will:
- continue the conditioning in order to improve vacuum
- continue machine tuning in order to improve the overall energy acceptance of the ring.

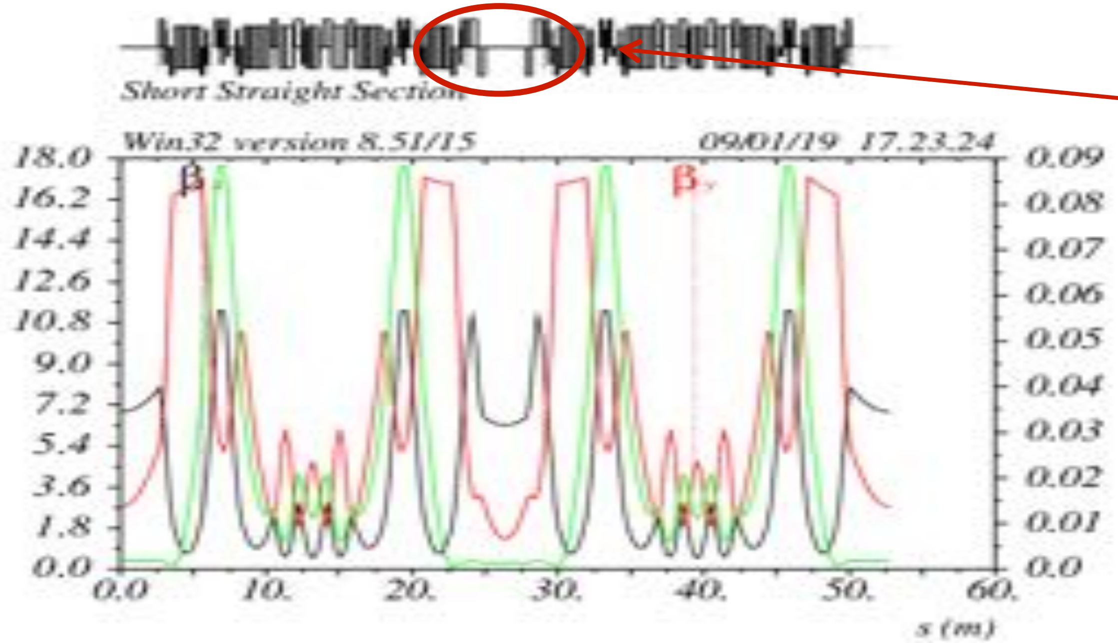
By the end of December we might approach 100Hrs, if this will be the case the vacuum lifetime and losses will become subcritical and not a big issue anymore for the overall machine performances. If not we should start to investigate solutions to ameliorate the vacuum in the CV5000s that are responsible for half of the vacuum lifetime

LONG TERM PERSPECTIVES

- In the last months we have made tremendous progress in understanding linear and non-linear optic and in tuning alghoritms.
- This has resulted in having exceeded design beam parameters, in particular in lifetime and DA and we are still on a “fast-track”.
- More striking we have already a vertical beam stay-clear consistent with operation of InVac undulators down to 4-4.5mm in an ID31-like configuration
- With additional tuning and possibly modified SS optic 3mm seems at reach as well.

  (and already granted with the implementation of the 4th harmonic cavity)
- We should investigate what kind of device could be realized with such minimum gap and if some beamline could profit from that. If this is the case we should start soon a corresponding R&D program. Such device could outperform the existing ones in terms of tunability and brilliance by a factor 2 to 4 !!!

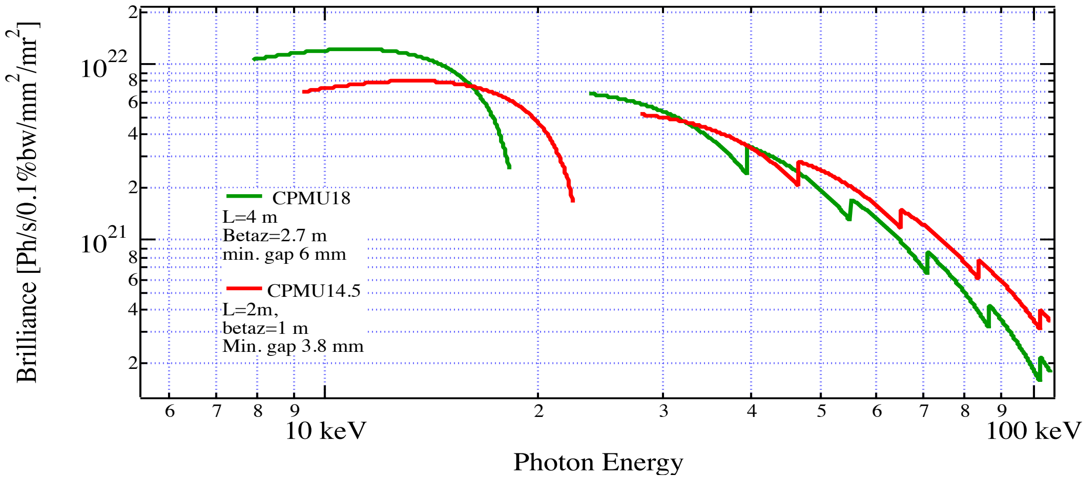
THE FUTURE: INCREASE INVAC IDS PERFORMANCES



Two doublets will be added in the SS on the side of the ID

The quest to MORE BRILLIANCE and EVEN SMALLER GAP… possibly down to 3mm!

We have installed an ID in the middle of the SS (ID31) and we will test an ad hoc optic with Beta_y = 1.2m (from 2.3m) => More brilliance and even smaller gap…possibly down to 3mm!!!



A 2m long InVac undulator with 4mm gap has better Performances of a 4m long undulator with 6mm gap

CONCLUSION

The commissioning of the new accelerator has been extremely successful and on August 25th 2020 USM operations started as planned

The EBS "Design parameters", supposed to be achieved by Dec-2021, have been achieved on Sep-01-2020 just after the first week of USM operations

A solid program of exploitation of the new source and adiabatic upgrade is in place and will secure a steady improvement of the new source for the next decade

A "dream" machine has come to life and is ready to deliver ultra small X-ray beams to push forward synchrotron-based research

MANY THANKS FOR YOUR ATTENTION

ONE LAST THING…

On Dec 6th 2019 we had (but we did not know then):

• All magnets settings randomly off by several % due to a combination of errors added many many times over on all of them (about 2000 errors on 610 quadrupoles):
- about 5% had wrong calibrations by more than 2%, 30% by more than 0.5%
- no correction of calibrations due to cross talk (of the order of 1% for all magnets)
- all indexes of magnets calibrations mixed (so they were randomly applied)
- all calibrations applied on reverse (so it did not even matter that were wrong as starting with)

(When now you run the model with the currents we had that day it does not even produce a stable optic)

- All the DQs bending angles were 2% weaker
- A transition chamber mounted reversed and rotated limiting the aperture horizontally to just positive orbits
- A piece of aluminum stuck in the beam pipe limiting the aperture horizontally to just negative orbits

- **The set of bugs that we were well prepared to deal with**

Still we managed to store the beam (and accumulate 9 days later)

…..but we did everything differently from our nice simulations