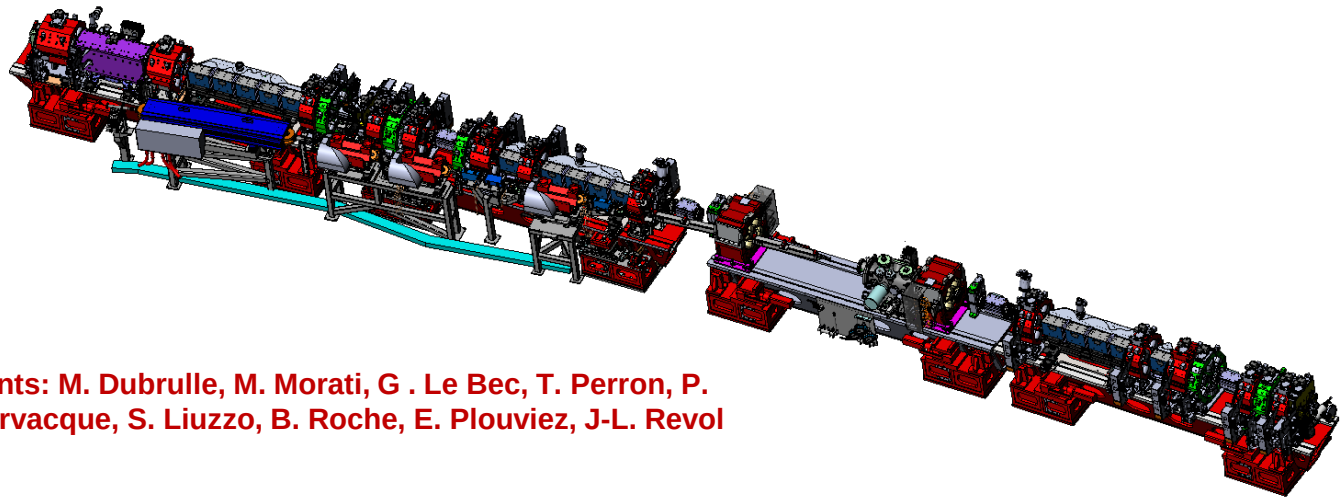
Topical Workshop on Injection and Injection Systems

Berlin, 28th – 30th August 2017

ESRF Experience

S. White



Acknowledgments: M. Dubrulle, M. Morati, G . Le Bec, T. Perron, P. Raimondi, L. Farvacque, S. Liuzzo, B. Roche, E. Plouviez, J-L. Revol

ESRF | The European Synchrotron

OUTLINE

ESRF injection

Accelerator complex, booster extraction,

storage ring injection

Tuning and experience with top-up

Procedures, performance

operation, sequencer

Injection perturbations

Sources, mitigations

Plans for EBS

Design, new equipment

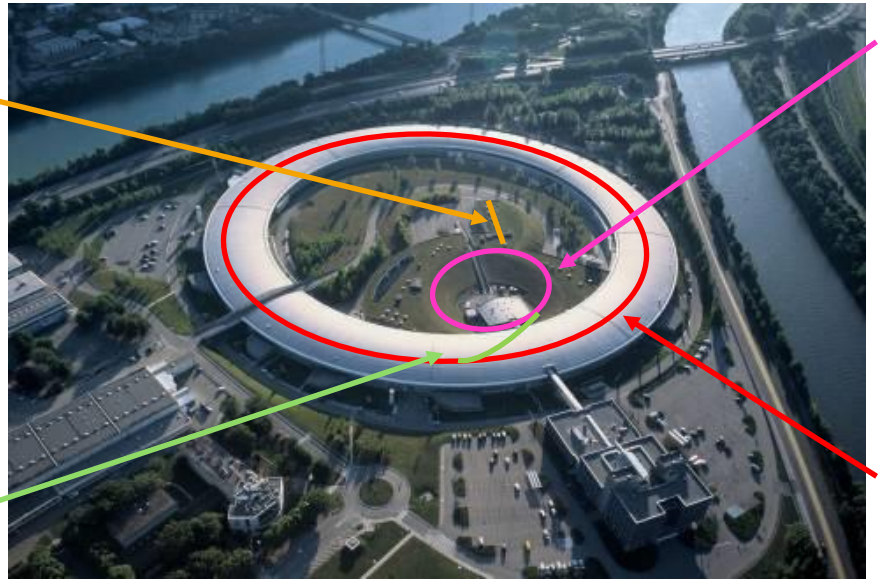
Summary and outlook

ACCELERATOR COMPLEX UPGRADE

- **The whole accelerator complex is undergoing significant upgrades. Main objective:**
  - Reduction of the horizontal equilibrium emittance
  - Increased brilliance and coherence

- **200 MeV linac:**
- New buncher installed
- Refurbishment of ageing component (ongoing)

- **TL2 transfer line:**
- Pulsed elements replacements
- Improved diagnostics (ongoing)
- Adaptation to the new Booster/Storage ring layout



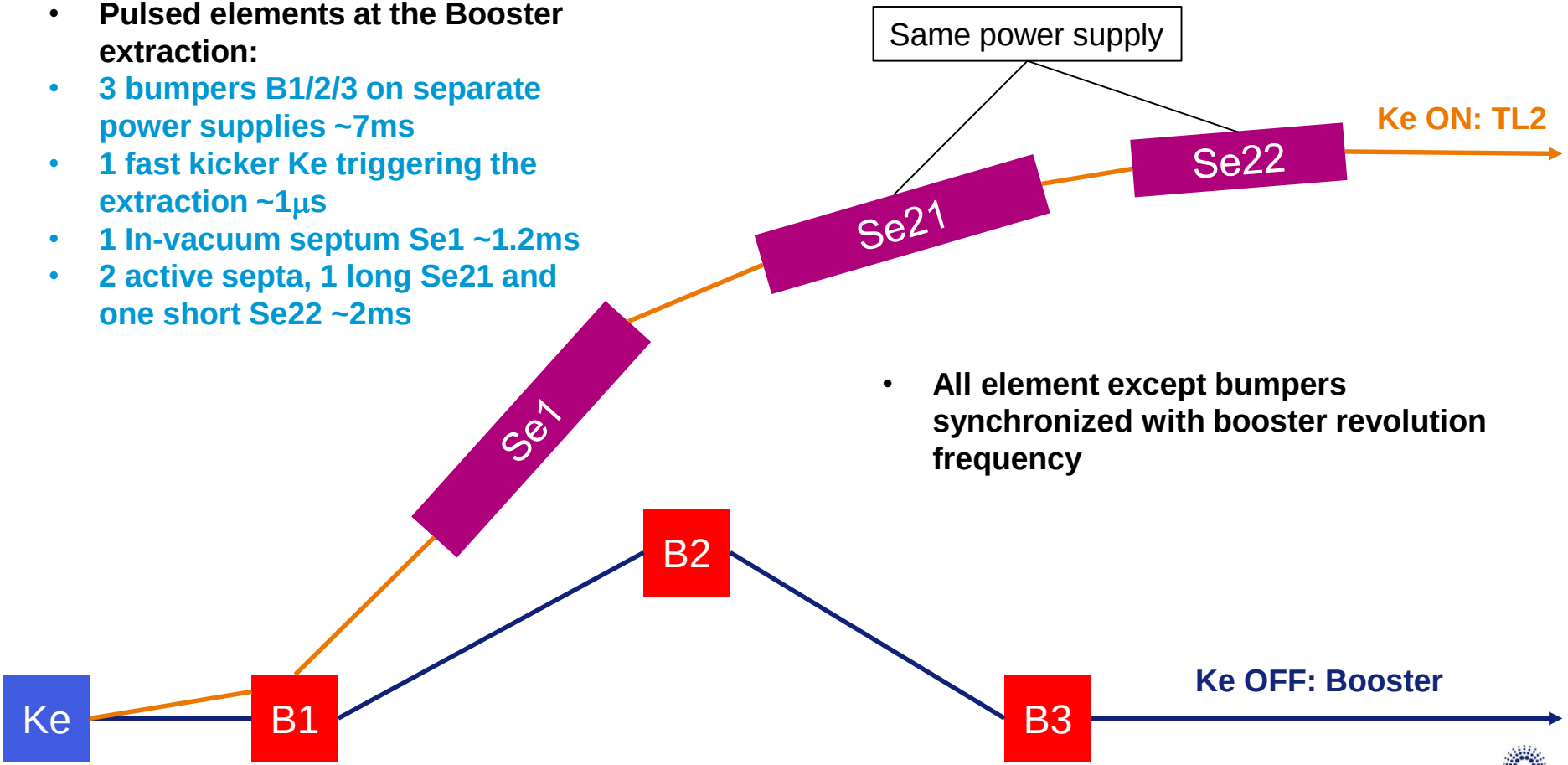
- **6GeV booster:**
- New power supply system based on IGBT technology: now in operation
- Emittance reduction campaign
- Circumference reduction
- Partial extraction upgrade

- **6GeV storage ring:**
- Accelerator replacement: only the straight sections are kept
- New injection kickers

	ESRF	upgrade
Hor. Emittance [pmrad]	4000	134
Vert. Emittance [pmrad]	3	2
Energy spread [%]	0.1	0.09
β_x[m]/β_z [m]	37/3	6.9/2.6

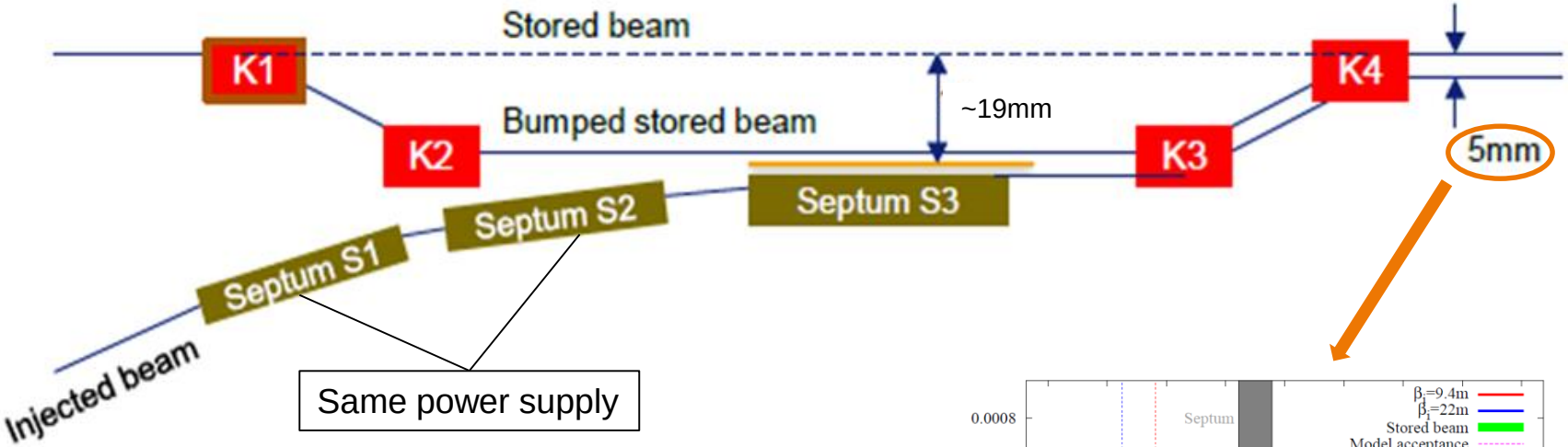
BOOSTER EXTRACTION

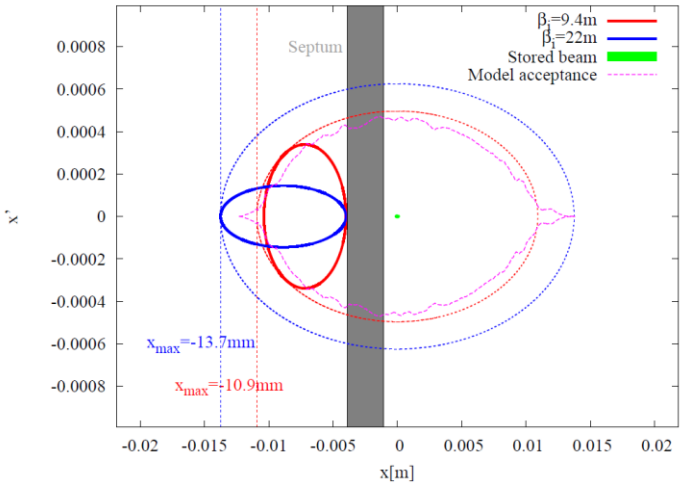
- **Pulsed elements at the Booster extraction:**
- **3 bumpers B1/2/3 on separate power supplies ~7ms**
- **1 fast kicker Ke triggering the extraction ~1μs**
- **1 In-vacuum septum Se1 ~1.2ms**
- **2 active septa, 1 long Se21 and one short Se22 ~2ms**



- **All element except bumpers synchronized with booster revolution frequency**

INJECTION INTO THE STORAGE RING





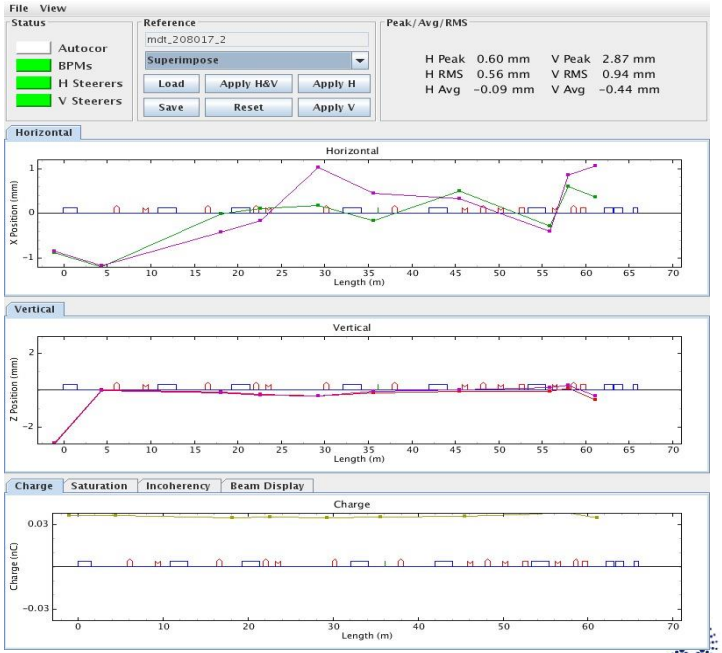
- **Pulsed elements at the end of TL2:**
  - **2 active septa S1 and S2 – 2ms on the slow timing ~32μs jitter**
  - **1 in-vacuum septum S3 – 66μs on the fast timing ~1μs (booster revolution)**

INJECTION TUNING

- **In-depth injection tuning and optimization is done at the beginning of each run (~2 month). Mostly done “by hand”:**
  - **Phase / timing between accelerators**
  - **Booster (FODO lattice) tune orbit, chromaticity, injection and extraction**
  - **TL2 trajectory and extraction**
  - **Vertical injection oscillations and bump closure**

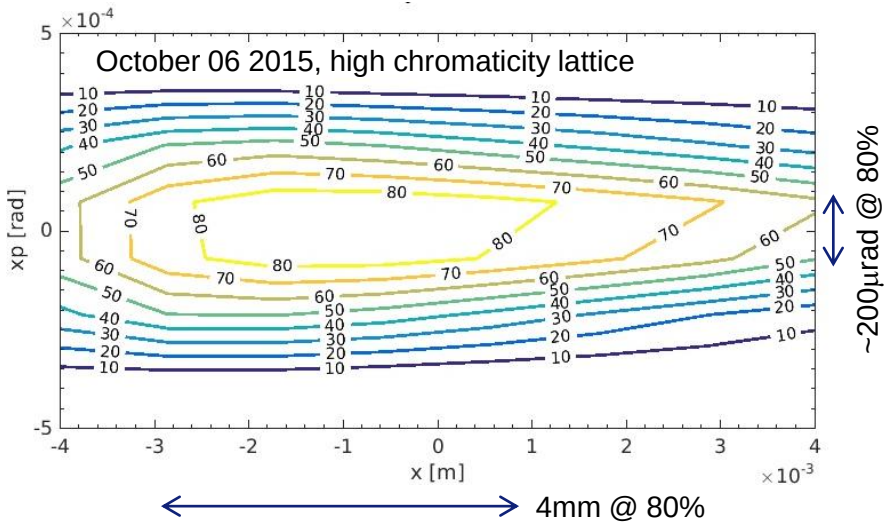
- **Recently installed striplines pick-ups in TL2 transfer line:**
  - **Trajectory monitoring**
  - **Automated correction**
  - **Losses in TL2**
  - **Data archived for statistics**

- **Very useful during machine restart to establish trajectory or MDTs, i.e., quadrupole scans at constant trajectory**

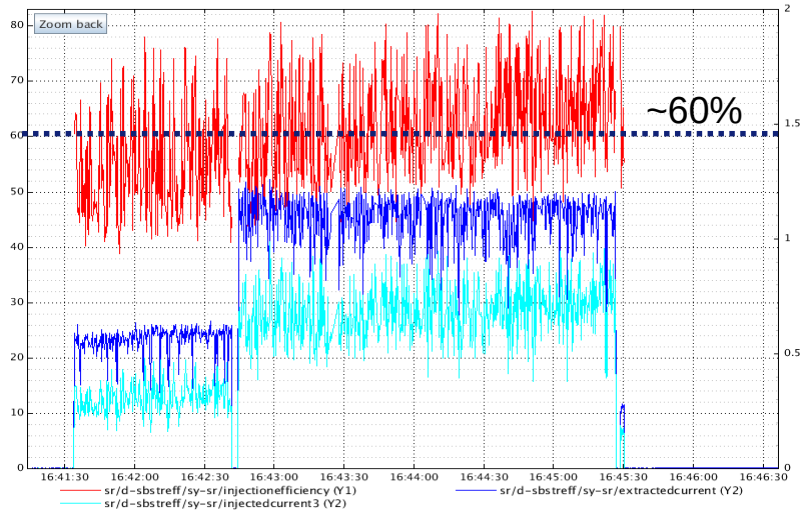


INJECTION EFFICIENCY

- **After optimization ~70% efficiency can be achieved depending on the mode (80% max)**
- **Slowly degrades during the run (thermalization? Tuning done with "hot" magnets?) down to 40-50%**
- **Operators slightly retune pulsed elements (septa, bump amplitude) when necessary**



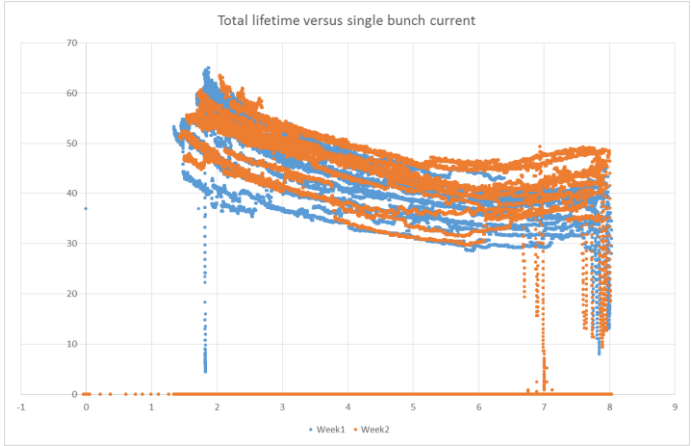
Simulated ESRF injection efficiency

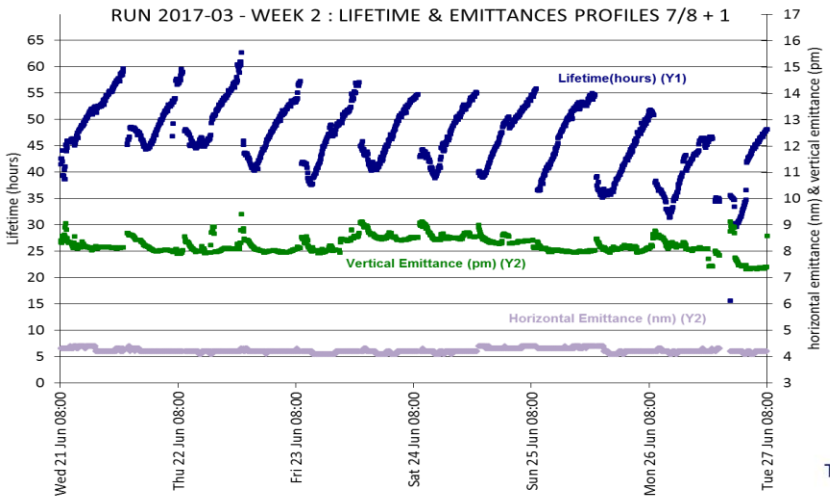


Measured injection efficiency in 16 bunch mode 20/08/17. Source of the fluctuations unknown

LIMITATION ON SINGLE BUNCH CURRENT

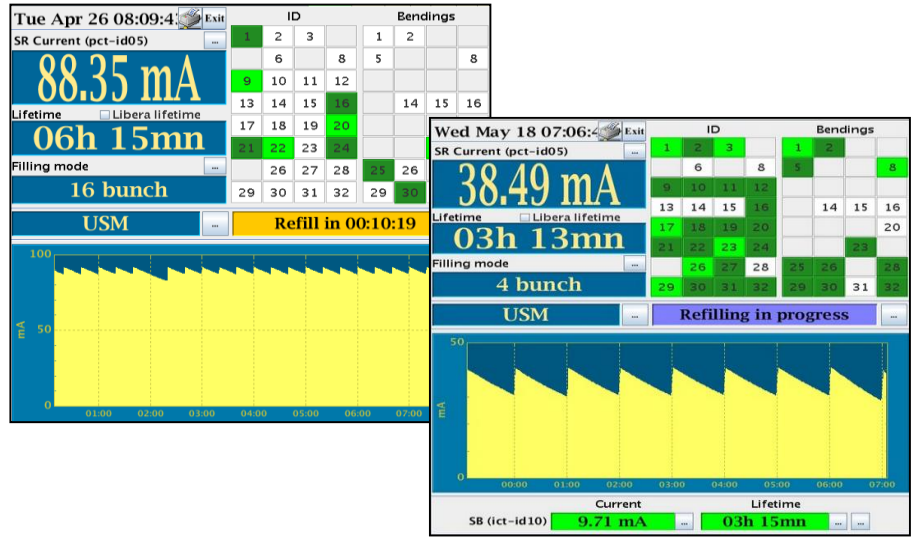
- **ESRF is operated with Q_x=36.44 and Q_y=13.39**
- **As the bunch current is increased two effects appear:**
  - **Stabilization of horizontal instability near 0.5 resonance**
  - **Strong emittance blow-up near 0.5 resonance**
- **Injection saturated at around 8mA with gaps closed: most likely losses on the septum blade**
- **Top-up with closed gaps in 4x10mA not yet achieved**
- **Horizontal instabilities observed in 7/8+1 on the single bunch (8mA)**
- **Indirect observation through lifetime**



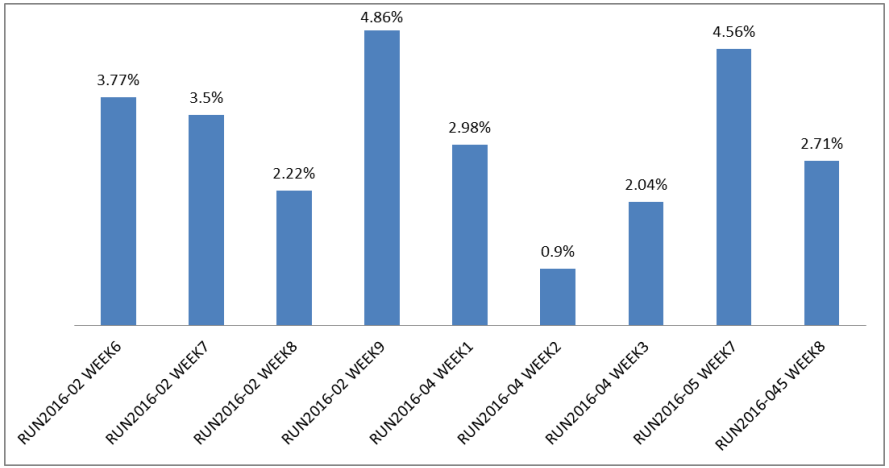


EXPERIENCE WITH TOP-UP

- **Top-up operation in 16x6 and 4x10 bunch modes since April 2016:**
  - **Refill every 20 minutes in 16 bunch, every hour in 4 bunch (need to open the gaps + cleaning in SR)**
  - **Last 4 bunch mode done with 8mA/bunch to allow injection with closed gaps**



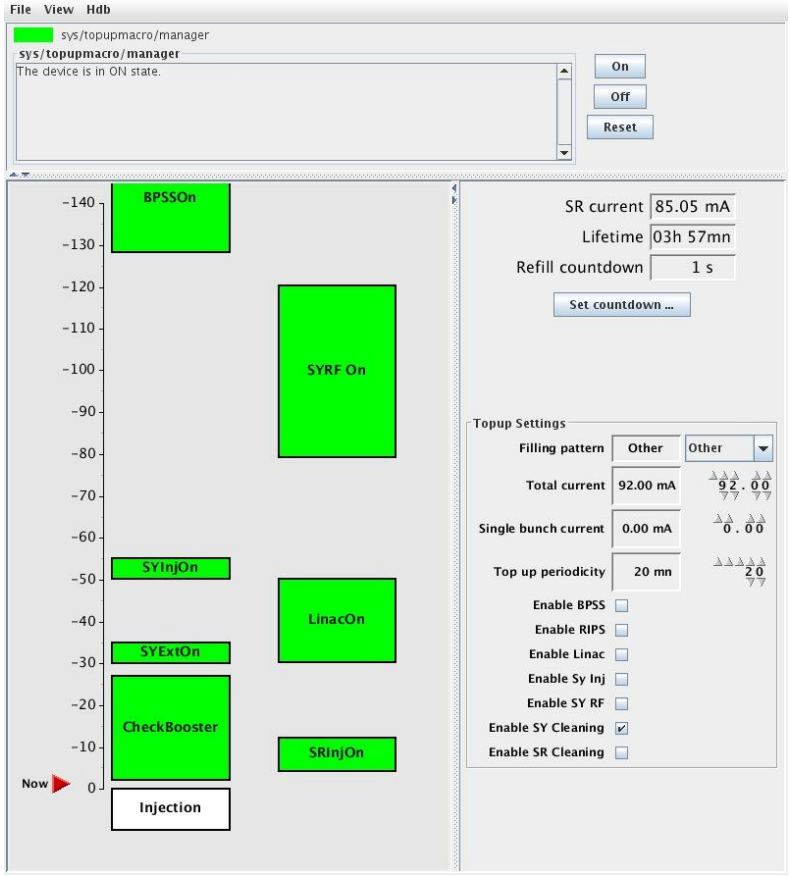
- **Time between injections: request from users**



- **3.0% skipped injections on average over year 2016:**
  - **Mostly BPSS faults**
  - **RIPS should be more robust: operation started this run**

- **No top-up in multi-bunch mode: perturbations**

TOP-UP SEQUENCER



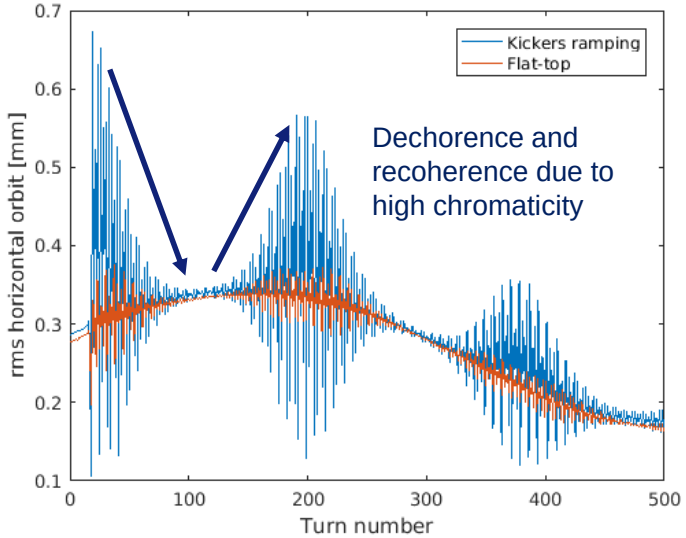
- **Full sequence takes 140s, mostly starting / warming-up equipment:**
  - **Fully automated sequencer**
  - **Countdown signal sent to the beam lines**
  - **Perturbation observed during SRinjOn (septa, kickers)**
  - **Injection lasts ~15s**

- **CheckBooster:**
  - **Current in Booster < I_{ref} : injection skipped**
  - **Test of cleaning in the Booster: fails -> cleaning in the SR, strong perturbation ~45s**

- **Septa started ~5s before injection: warming-up**
- **Kickers started at the last moment**

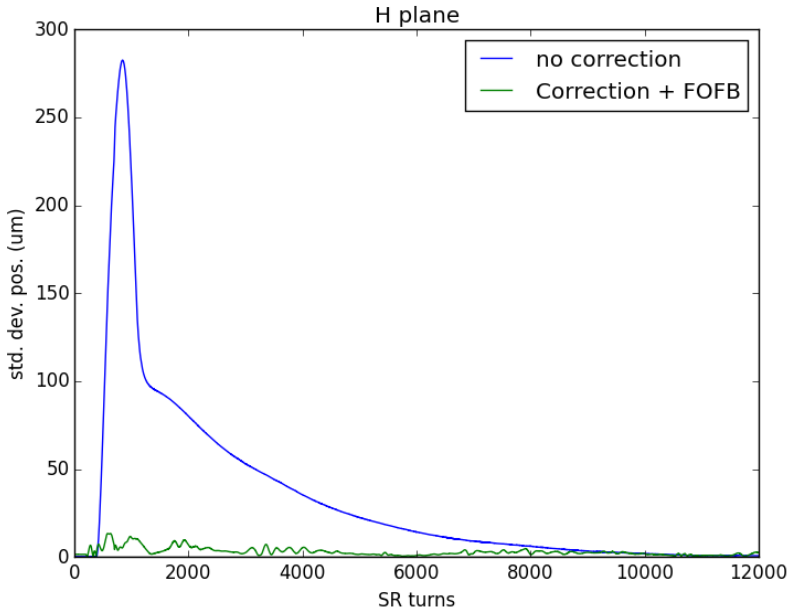
INJECTION PERTURBATIONS

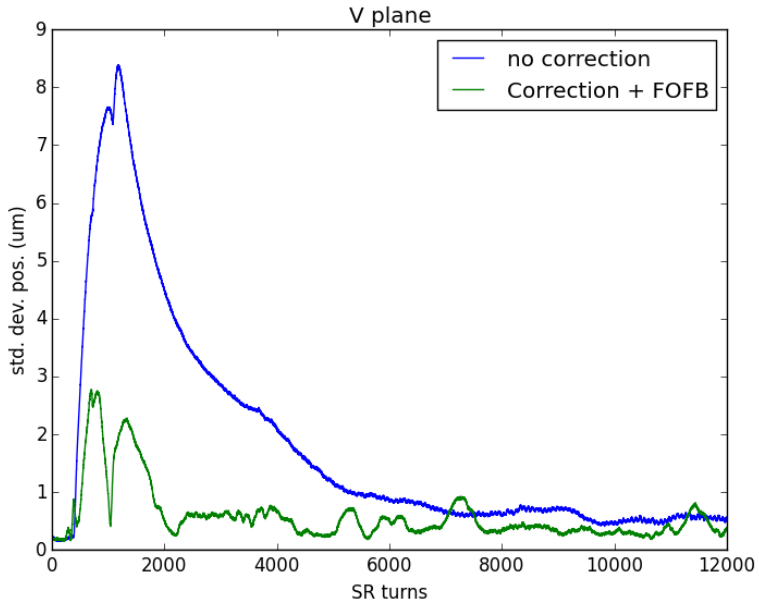
- **Injection pulsed magnets:**
  - **Septa:** fringe fields, depends on field strength and distance to the stored beam dominated by S1/2. Un-shielded current leads
  - **Kickers:** bump non-closure, 4 identical kickers pulse shape (timing, pulse shape,…)
- **Storage ring:**
  - **Sextupoles inside the bump:** non closure, envelop oscillations
- **Vertical perturbations also observed:**
  - Coupling, misaligned elements,...
- **Now running in top-up mode: significant effort ongoing to reduce these perturbations**



- **Typical rms orbit perturbation:**
- Slow perturbation from septa fringe fields
- Fast oscillation from kickers, ramp-up and ramp-down much larger because of sextupoles, small non-closure
- Vanishing with same time constant as radiation damping time

SEPTA





- **The perturbation is well reproducible but the Fast Orbit Feedback (FOFB) system is too slow:**

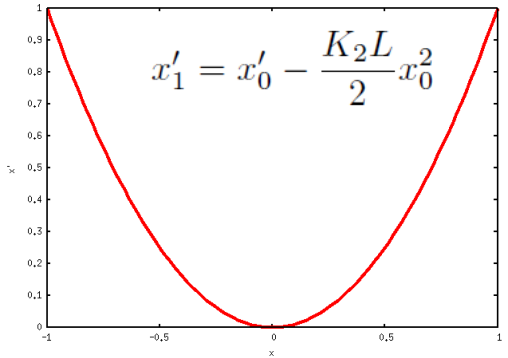
- Feed-forward correction send to the FOFB
- Allows to use correctors spread over 2 cells (injection+RF) to compensate the perturbation locally
- Perturbation reduced to a few microns in both planes
- **This system will be operational for the new machine**

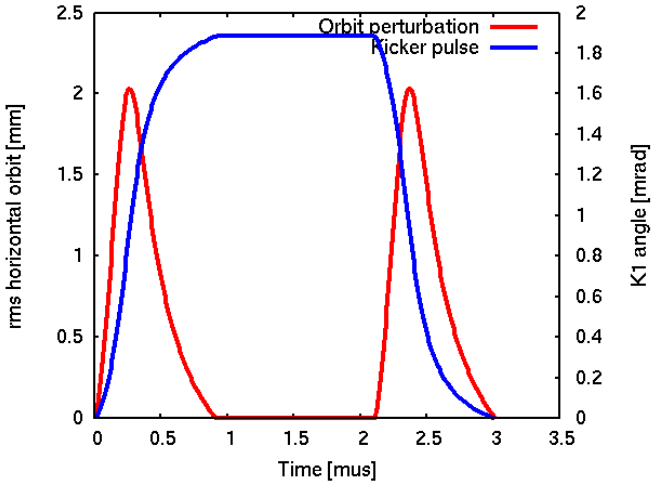
KICKERS

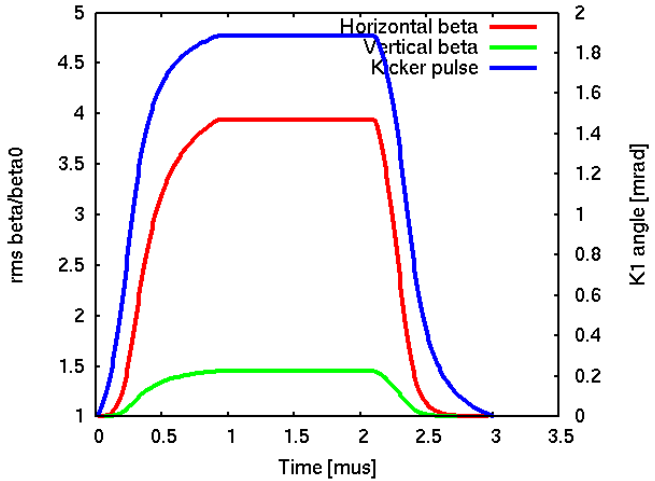
- **Sextupoles are located inside the injection bump:**
  - $B_y(x)$ evolves quadratically
  - Amplitude (time) dependent orbit distortion
  - Amplitude (time) dependent β-beat

→ **Both resulting in apparent emittance increase**

→ **Presently dominating effect**

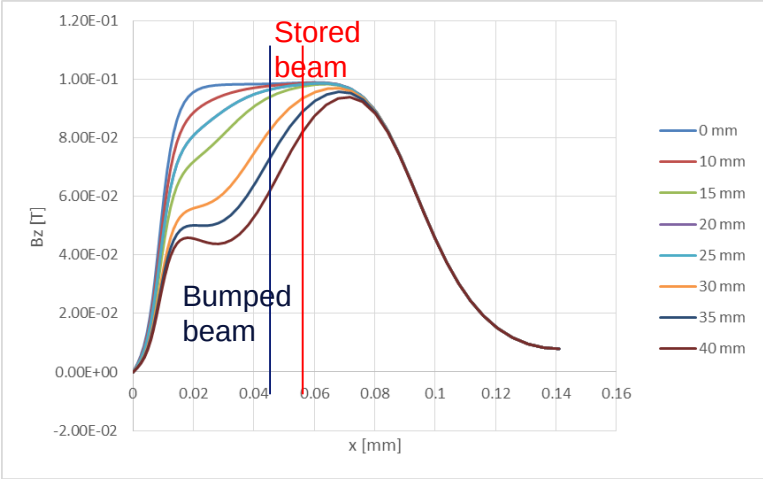




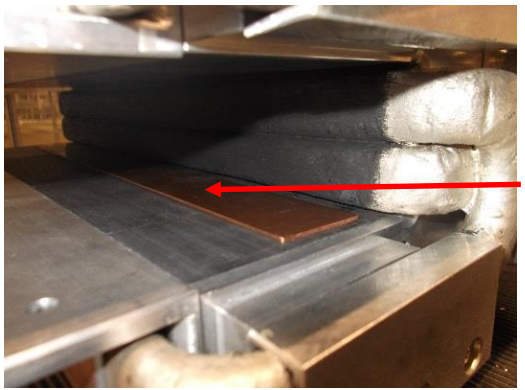


- **Orbit distortion:**
- Matched on the flat top
- Maximum reached during ramp up/down
- In horizontal plane only (no coupling)
- **β-beating:**
- Follows amplitude
- In both planes

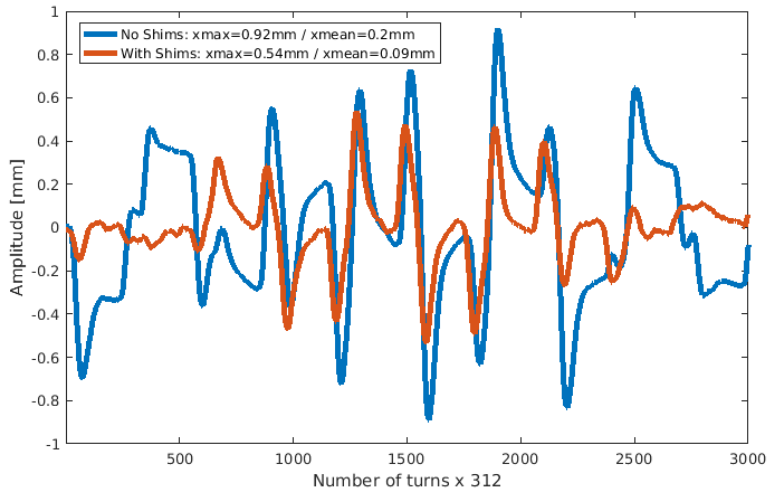
PASSIVE COMPENSATION



- **Idea: add copper shims inside the kickers ferrite gap to generate a non-linear field**
- Shape this field with the shims dimension in order to cancel the sextupole field: **reduction of both beta-beat and orbit distortions**
- Creates vertical field gradient: **alignment is now critical**



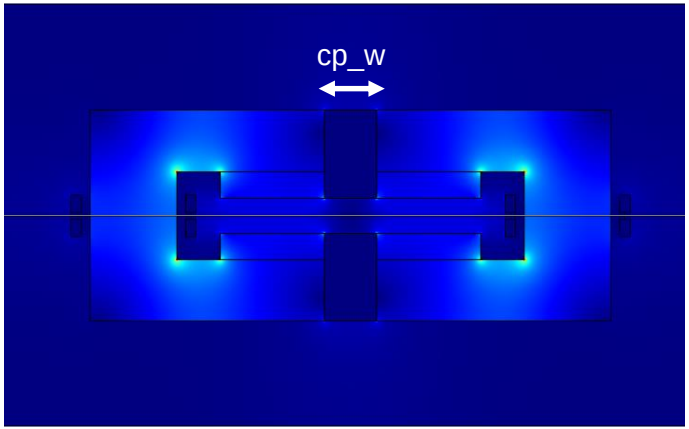
- **40mm Copper plates top and bottom of the 4 kickers**
- **This shut-down: stronger c-shaped shims installed**



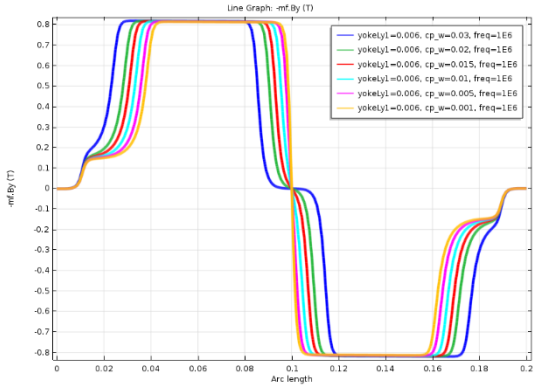
POSSIBLE OTHER APPLICATION

- **The injection straight section features the same vertical b-function as ID straights**
- **We need to top-up with closed gap, i.e. through a 6mm vertical aperture**

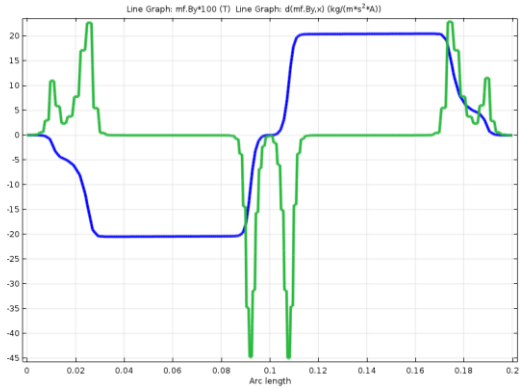
➢ **Use this principle to design a low gap in-vacuum non-linear kicker/bladeless septum**



- **Width of copper plates determines:**
- **Central gradient**
- **Distance to achieve maximum field**

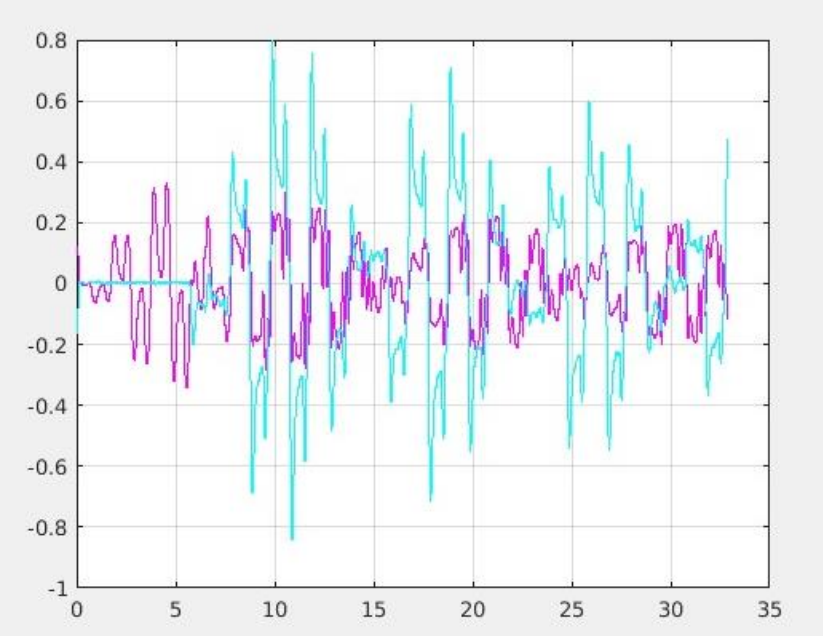


- **2 c-shape kickers separated by copper plates:**
- **Zero dipole on axis, small quadrupole**
- **Injected beam sees almost no gradient (interesting in case of large injected emittance)**
- **Low gap: very high field achievable**



- **Additional coil can be used to cancel the remaining gradient**

ACTIVE COMPENSATION

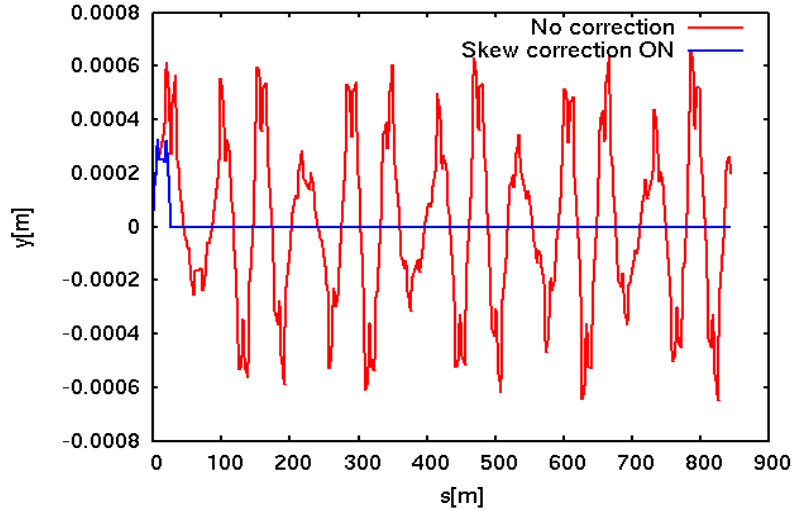


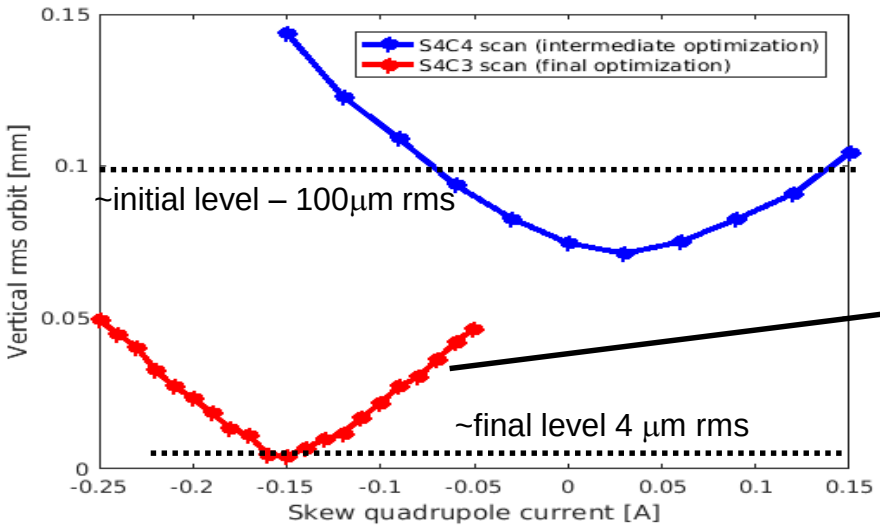
- **In parallel an active feed-forward system is under development:**
- **Latest results show significant improvement (problem with non-closure?)**
- **Presently limited by maximum current in kicker power supplies and limited power in shaker amplifier**

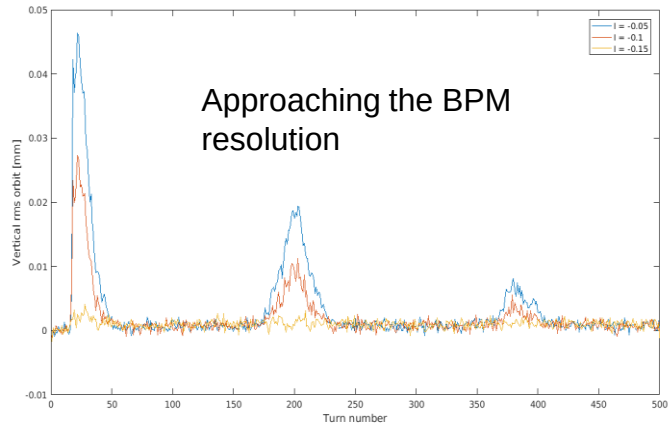
- **Corrects only dipolar oscillation, shims both dipolar and envelop: beam lines still observe significant perturbations, stronger shims should help, diagnostics needed**
- **Fortunately the new design is not impacted by sextupoles inside the bump with large amplitude variations: diagnostics developed are very useful and will be kept**

VERTICAL PERTURBATIONS

- **Vertical perturbation dominated by non-linear kicker vertical offsets and roll angles:**
- **Use a pair of skew quadrupoles to correct locally the vertical perturbations**
- **For the new machine only roll angles are an issue, method can still be applied**







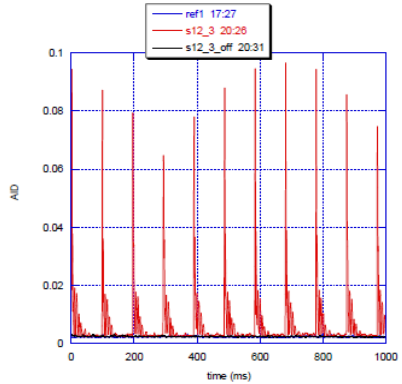
SEEN FROM THE USERS

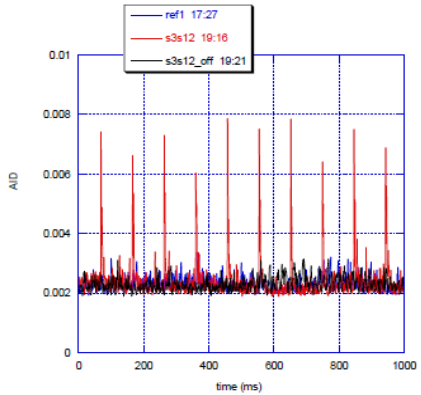
- **Dedicated experiments conducted with beam lines:**
  - **Probed the various sources of perturbations: kickers , septa, booster, tune monitor, energy modulation**
  - **Most experiment can take out / normalize the perturbed data: only a few cannot operate -> constrains time between injections**

- **Data from ID24: one of the most sensitive beam line, clearly dominated by the kickers, plans to sent fast trigger signal**

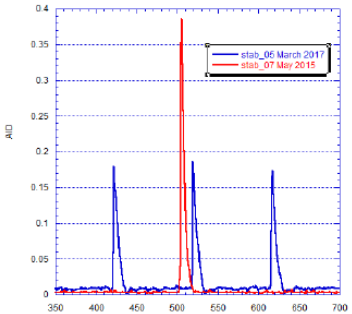
- **Not only the amplitude but also the duration matters: large perturbation < 1ms acceptable**

Septa only: with and without compensation

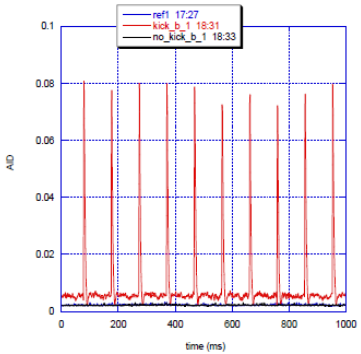




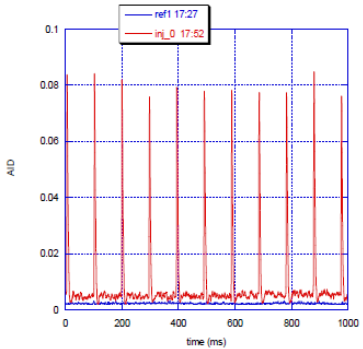
Full injection: no compensation vs first optimization



Full injection: present situation

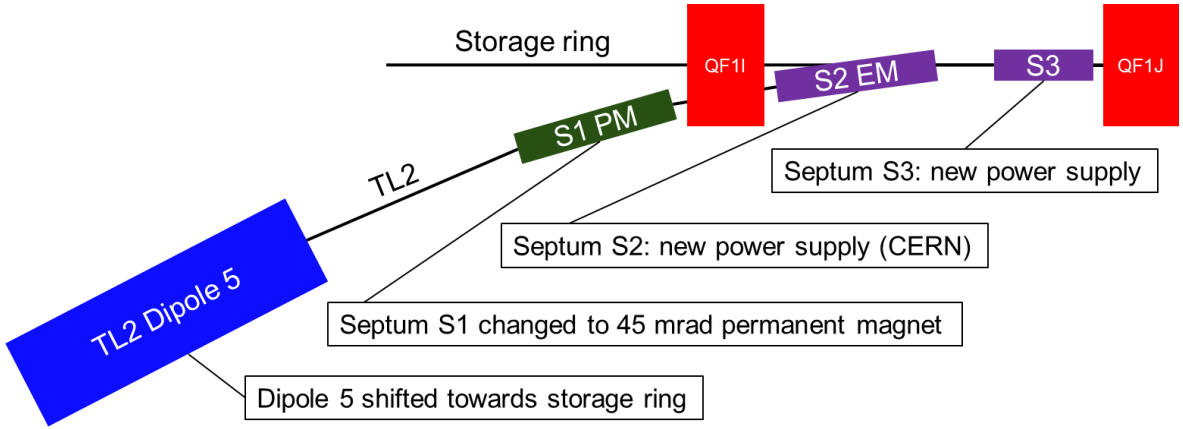


Kickers only: present situation



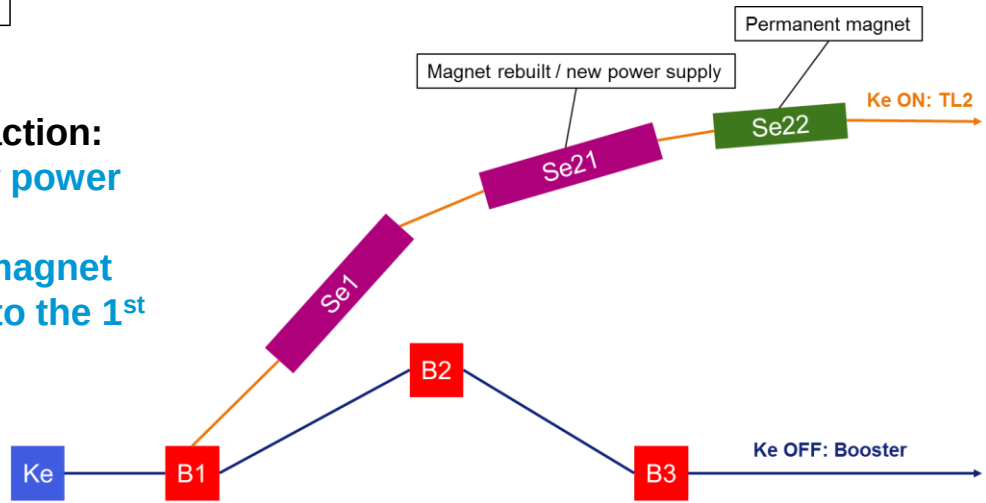
PLANS FOR ESRF-EBS

Design constraint: minimize changes

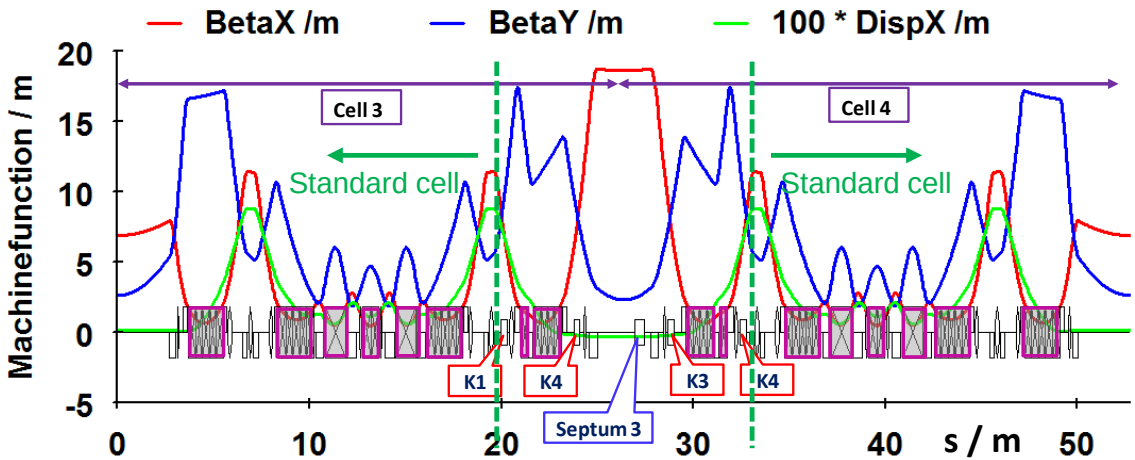


- **Partial upgrade of the SR injection:**
  - **S2 rebuilt with new power supply**
  - **S1 replaced with permanent magnet**
  - **S3 kept with new power supply**
  - **New Kickers with present power supplies**

- **Partial upgrade of the Booster extraction:**
  - **Se21 Septum rebuilt with new power supply**
  - **Se22 replaced by permanent magnet**
  - **Modification of TL2 layout up to the 1st dipole**



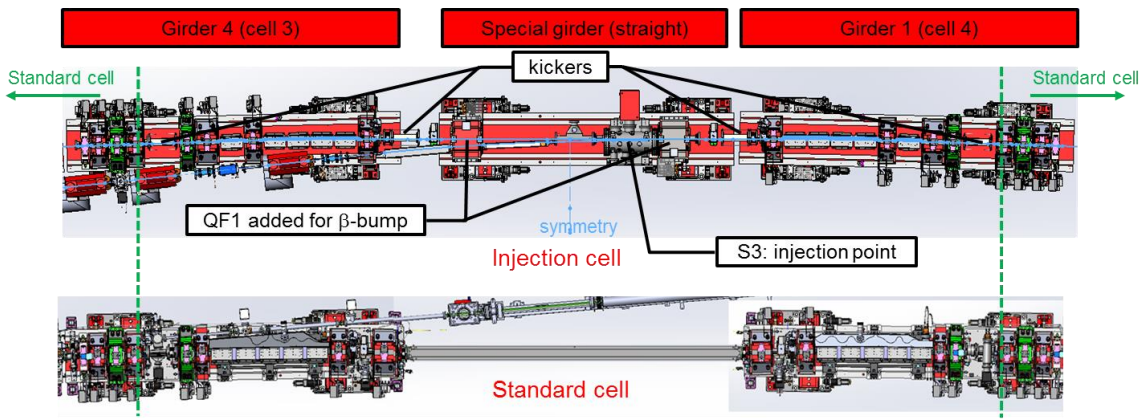
STORAGE RING INJECTION CELLS

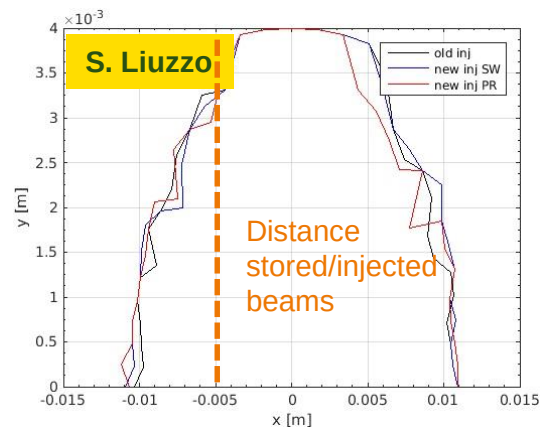


- **Dedicated injection cells:**
- Increased β_x at injection point
- Identical to standard cell up to QF4, sextupole optics function and phase advance unchanged

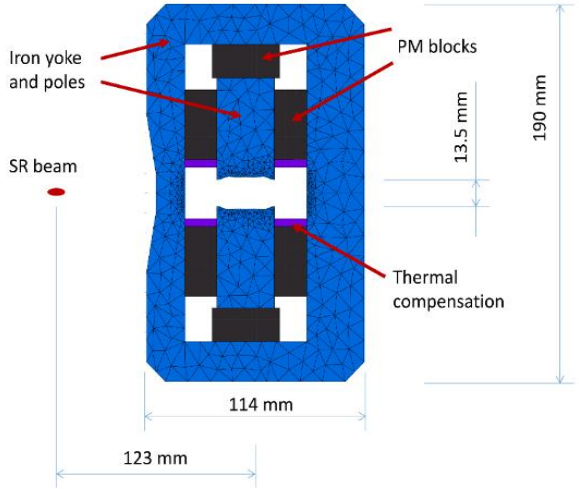
- **Minimize symmetry breaking:** optimized dynamic aperture

- **No sextupole at large bump amplitude**



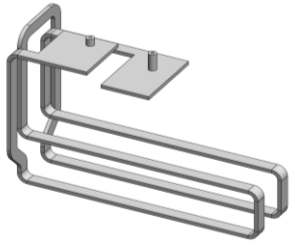


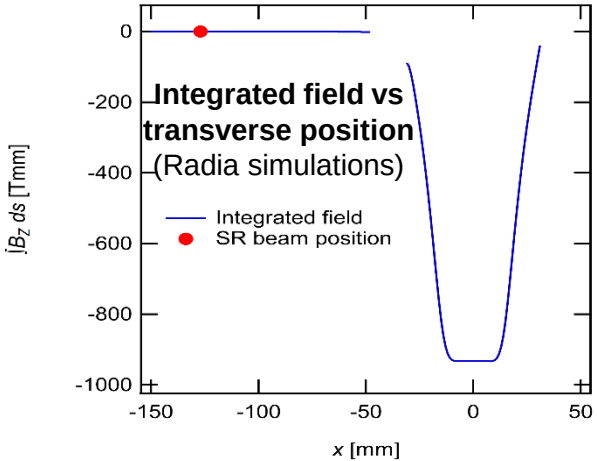
PERMANENT MAGNET AND KICKERS DESIGN

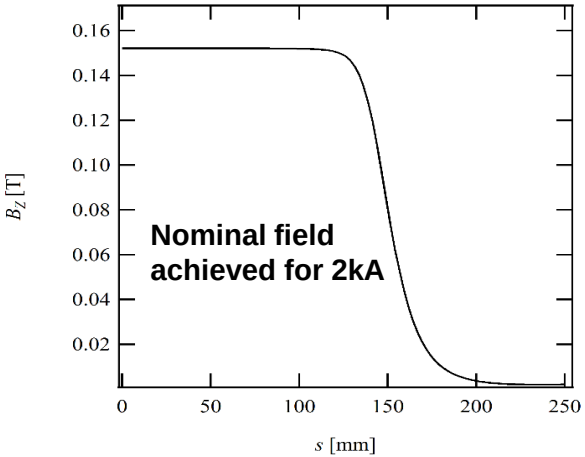


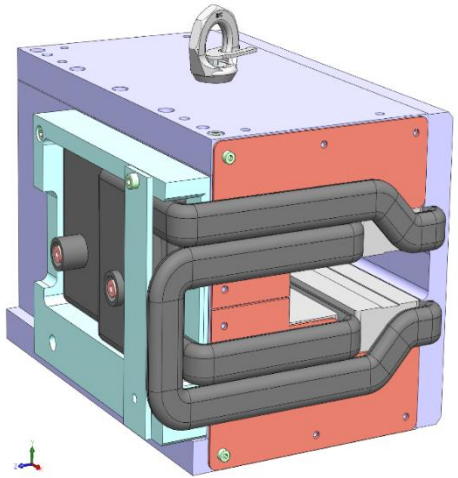
- **Design finished within specifications**
- **Longer terms plans:**
  - **S2 and Se21 as PM**
  - **Requires novel very compact design**
  - **R&D to start after commissioning**

Kicker coil
(Designed by Omexom)

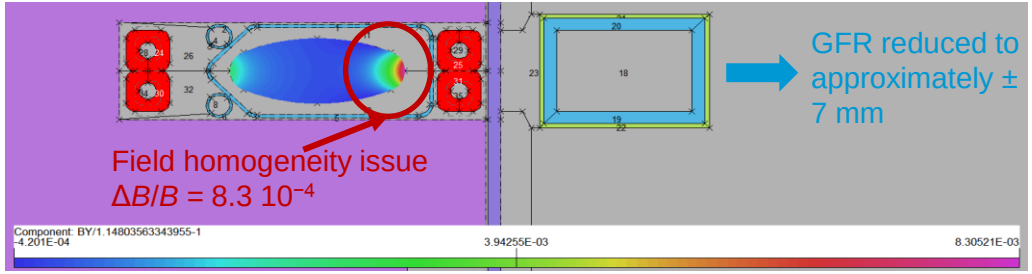


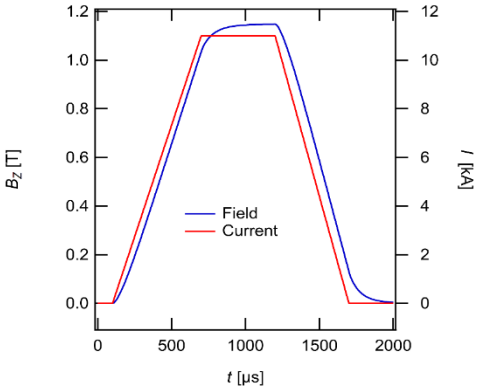




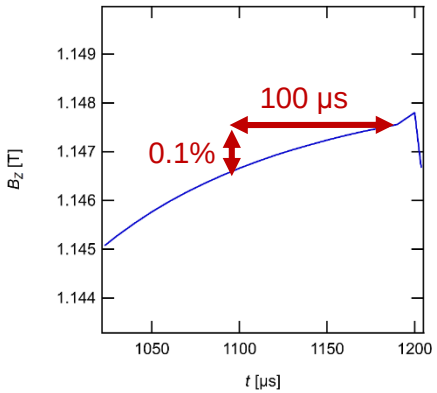


EM SEPTA





Field and current vs time
(Opera/Elektra simulation, Sigmaphi)



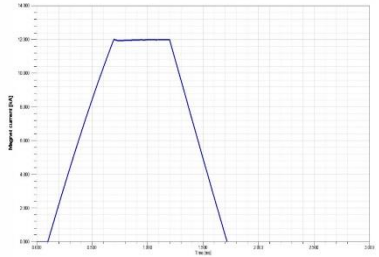
Field stability on the flat top
for a 500 µs flat top (Opera/Elektra simulation, Sigmaphi)

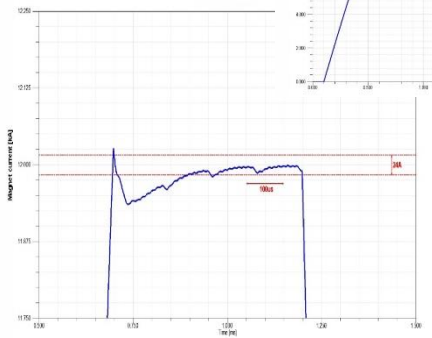
- **EM septa S2 and Se21 design done by Sigmaphi**
- **Facing issues with eddy current in the thin stainless steel chamber:**
  - **Degradation of the good field region**
  - **Field flatness over the pulse flat-top**
- **Still within specifications**
- **Started prospecting about ceramic chamber:**
  - **Positive answer from constructor**
  - **Acceptable reduction of vertical aperture**
  - **R&D to start as soon as possible**

SEPTA POWER SUPPLIES

CERN MegaDiscap

Pulse shape

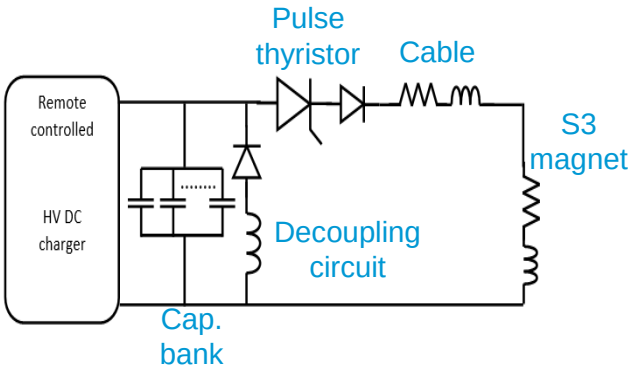


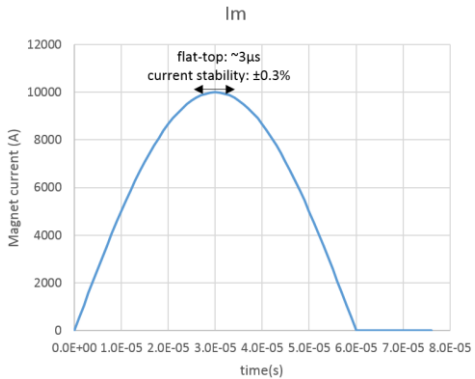


Flat-top zoom

- **S2 and Se21 to be equipped with CERN Megadiscap power supplies**
- **Dynamic and precise current control for Se2/1 and S2 magnets**

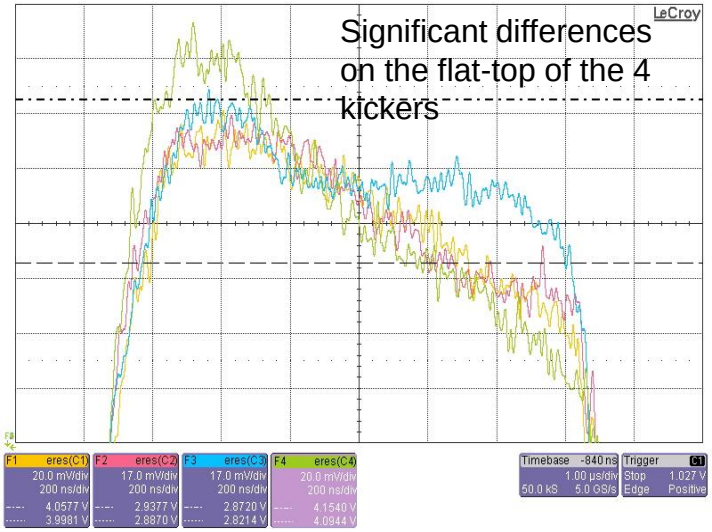
- **In house development power supply for S3 magnet (½ sinus current waveform)**





KICKERS POWER SUPPLIES

- **Expected to be the main source of perturbation for the future machine:**
  - **Time averaged pulse shape needs to be identical for the 4 kickers: new monitoring diagnostic developed**
  - **Power supply fluctuations are not negligible with the present system - random fast process: very difficult to correct, no feed-forward possible**



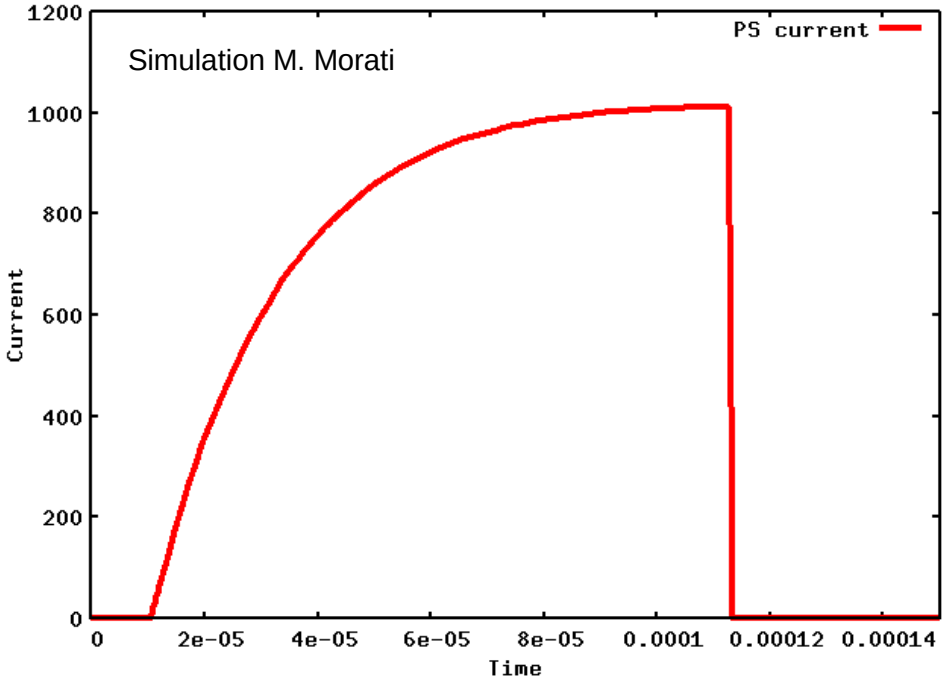
- **Latest measurements: 0.29% (at 1500A) amplitude jitter**

	ESRF	ESRF-EBS
ε_x[pm]	4000	132
$<\beta_x>$[m]	5.0	6.5
$<\delta x'>$ [rad]	1.5e-3	2.3e-3
$\sqrt{\varepsilon/\beta}$	2.8e-5	4.5e-6
$\delta x < 0.1\sigma$ [%]	0.2	0.02

- **Present machine almost good, future machine needs factor 10 improvement:**
  - **power supply upgrade?**
  - **Feedback system?**

UPGRADE POWER SUPPLY

- **R&D to start as soon as possible on new kicker power supplies:**
  - **In-house design and validation**
  - **Use solid state technology**
  - **Considering slow rise time: simpler design and operation, could reduce perturbations**



- **Principle design done:**
  - **Rise time: 100mus**
  - **Fall time: < 1mus**
- **Arbitrary parameters: to be defined/optimized**
- **Low charger voltage: few 100V required**
- **Fall time: fast switch opening + energy absorption in passive components (R+C)**
- **Low current prototype planned for testing**

SUMMARY

- **ESRF features a standard 4-kickers + in-vacuum septum injection scheme:**
  - Tuning is done at each restart: ~2 month providing injection efficiency drifting down to 50% in USM
  - Automated tools recently developed: very useful
- **Top-up operation started in April 2016 for 16 and 4 bunch modes:**
  - Procedure well established, sequencer fully operational
  - Single bunch current limited to 8mA due to injection saturation with closed gaps: alternate working point?
  - No top-up operation in multi-bunch modes due to perturbation
- **Strong injection perturbation observed:**
  - Septa: active compensation operational, significant improvement
  - Kickers: dominated by sextupoles in the bump, tried passive and active compensation with visible improvements
  - Overall the perturbation is still too large for continuous operation of some beam lines: considering fast triggers
- **ESRF-EBS:**
  - Design constraint: minimize changes -> 4-kicker scheme kept, no sextupole at large amplitude
  - Improvements: new power supplies and permanent magnets
  - Users are extremely sensitive (20 years of operation with 2 injections/day…): fully transparent injection looks out of reach
  - Longer term: we will be looking for alternative schemes once the commissioning is behind us