Use of Automated Commissioning Simulations for Error Tolerance Evaluation for the APS-U

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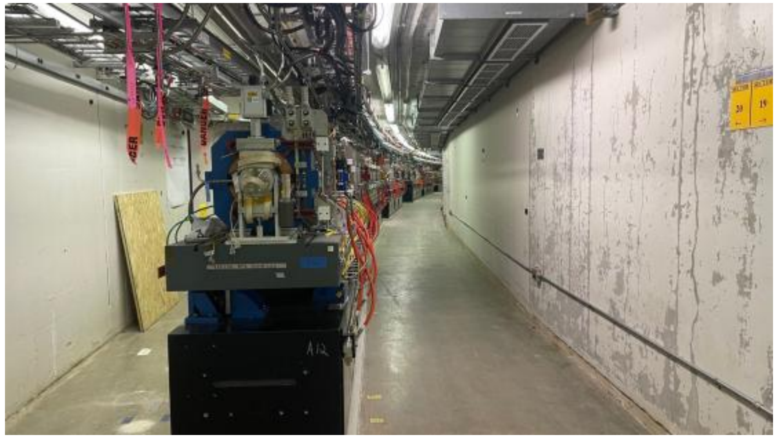
Workshop on Future Light Source 2023

APS-U – the nearest Future Light Source

- APS is in dark time now – started April 2023
- The first light will be delivered in April 2024
  - Brightness increase factor: up to 500
- Installation progresses on schedule

Quantity	APS Now	APS MBA Timing Mode	APS MBA Brightness Mode	Units
Beam Energy	7	6	6	GeV
Beam Current	100	200	200	mA
Number of Bunches	24	48	324	
Bunch Duration (rms)	34	104	88	ps
Energy Spread (rms)	0.095	0.156	0.135	%
Bunch Spacing	153	76.7	11.4	ns
Emittance Ratio	0.013	1	0.1	
Horizontal Emittance	3100	31.9	41.7	pm-rad
Horizontal Beam Size (rms)	275	12.9	14.7	μm
Horizontal Divergence (rms)	11	2.5	2.8	μrad
Vertical Emittance	40	31.7	4.2	pm-rad
Vertical Beam Size (rms)	10	8.7	3.2	μm
Vertical Divergence (rms)	3.5	3.6	1.3	μrad



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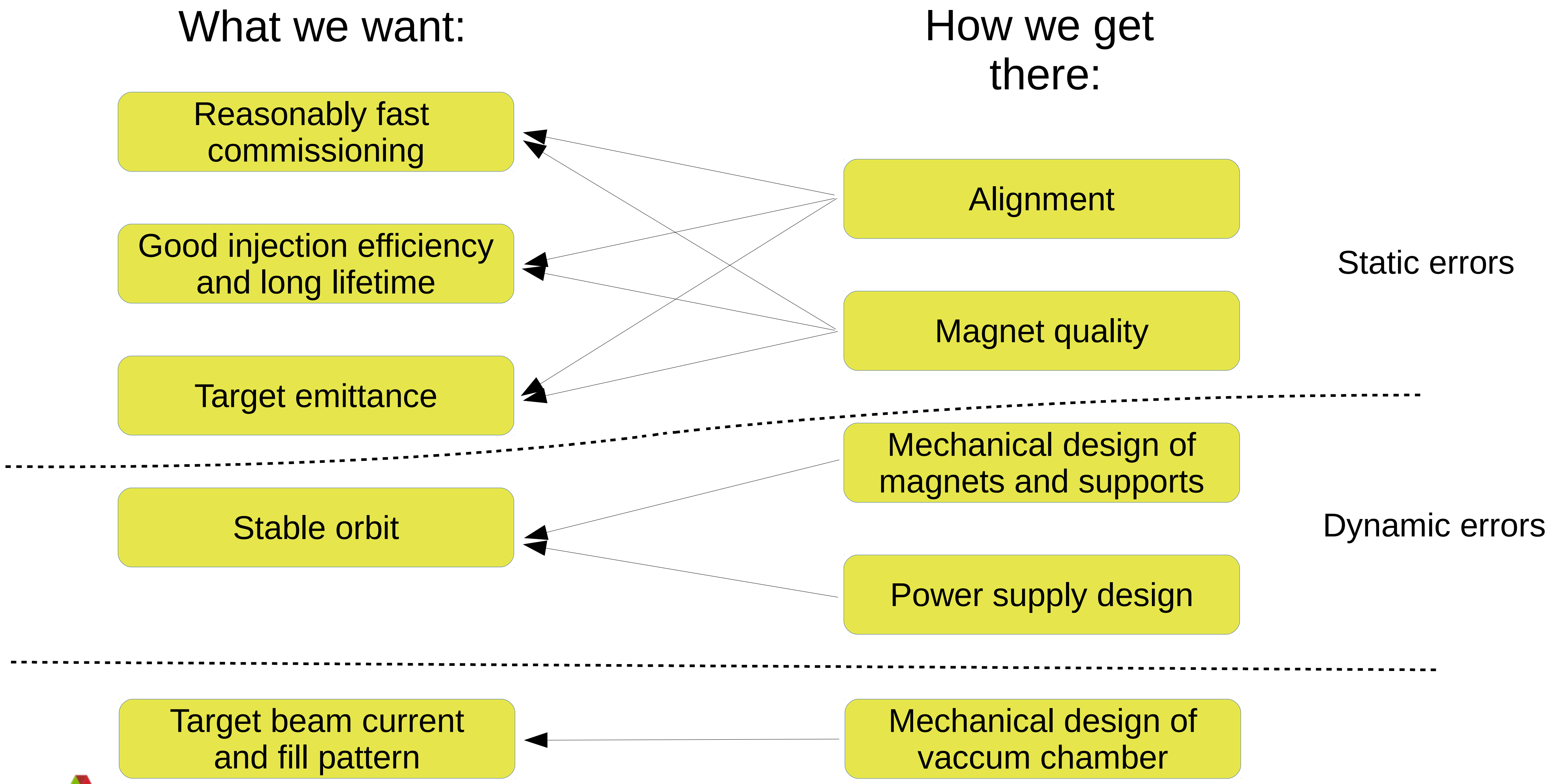
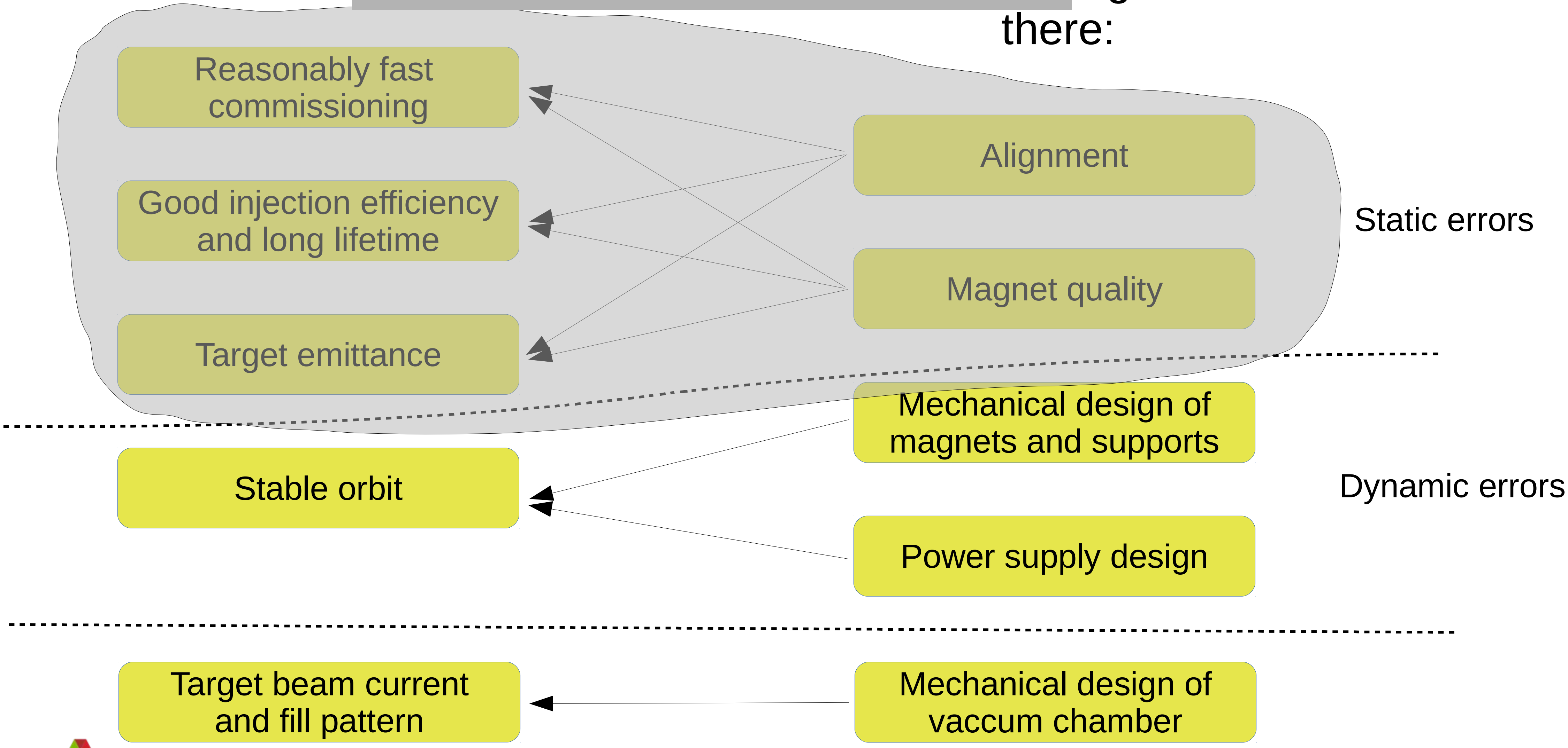
General approach when considering tolerances



General approach when considering tolerances

Commissioning simulations cover static errors

What we ... e get there:



Static errors: How it was done for earlier machines

- Assume some distribution and magnitude of errors (alignment and/or manufacturing), calculate resulting machine distortions, limit distortions to reasonable values
  - Orbit and beta functions errors; could be done semi-analytically
- As focusing increased, orbit errors became too big – required including orbit correction in assumptions
  - Included dynamic aperture in considerations, required simulations[1] with orbit correction
  - No lattice correction yet considered
- In early 2000s, lattice correction based on response matrix fit[2] became widely used but light sources designed at the time still didn't consider lattice correction in tolerance calculations
  - Some designs even included remote girder movers[3] to improve girder alignment post-construction to improve accelerator performance
  - Tolerances were likely overspecified

[1]E. Crosbie, et. al., 1993 PAC Proc.
[2]J. Safranek, NIM A 388, 27 (1997)
[3]S. Zelenika et al., NIM A 467-468, 2001

Typical pre-MBA workflow for error effect evaluation

- Generate error ensembles
- Correct closed orbit
- Correct lattice
- Calculate expected injection efficiency (or DA) and lifetime (or MA)
- Repeat 100s times, calculate statistics
- Limit amplitudes of error distributions to those that provide acceptable performance

- For simplicity, one can isolate a single kind of error and treat its effect separately
- Example of isolated treatment: tolerance on longitudinal quad alignment
  - Use ideal lattice, add longitudinal quad misalignment with Gaussian distribution
  - Calculate resulting beta function errors
  - Limit median rms beta functions errors to 1%, obtain requirement for quad misalignment
    - Resulted in 70 μm rms for APS-U

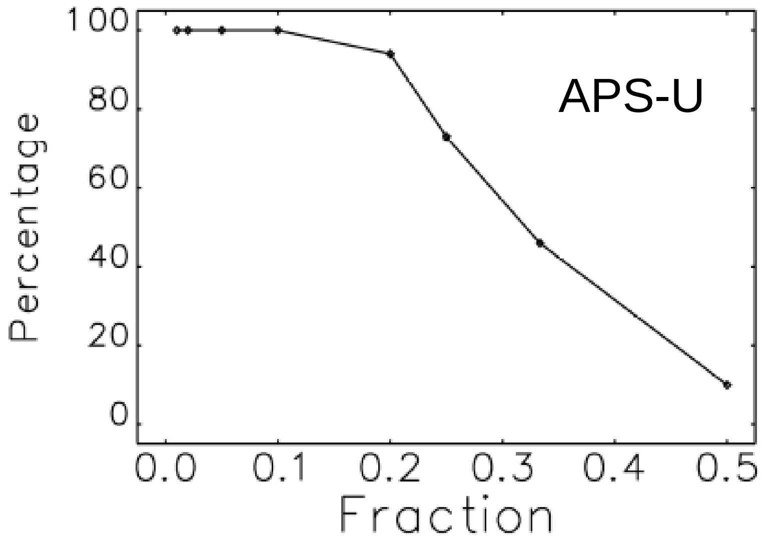
Old approach did not work for new rings

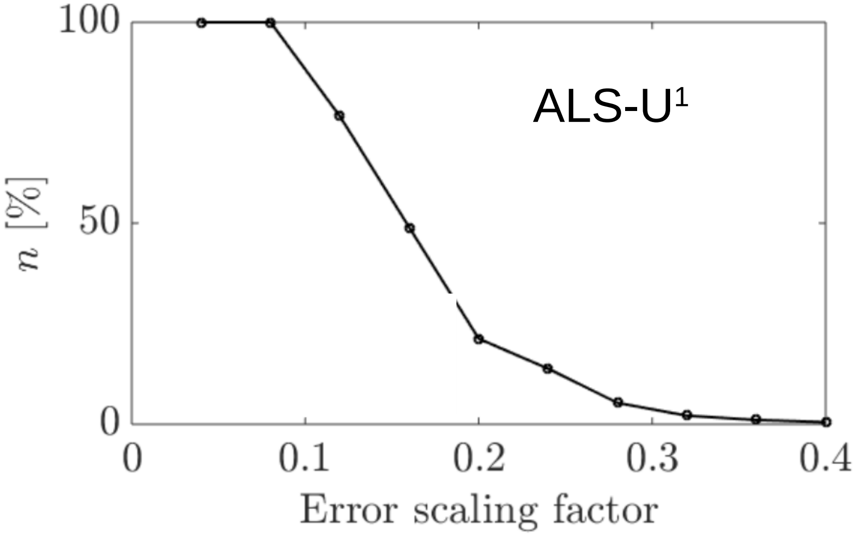
- Evaluated hundreds of APS-U error sets – no closed orbit exists for reasonable error sets in 100% of cases
- Repeated the same study for different fractions of the nominal error set
- To ensure closed orbit existence, one needs to reduce errors by a factor of 5-10 – unrealistic!

APS-U alignment and strength errors (rms, 2σ cutoff)

Girder misalignment X/Y/Z (1σ cutoff)	100 μm
Elements within girder X/Y	30 μm
Elements within girder Z	250 μm
Dipole/Quadrupole/Sextupole/Girder tilt	0.4 mrad
Dipole pitch/yaw	0.1 mrad
Quadrupole/Sextupole pitch/yaw	0.7 mrad
Dipole/Quadrupole fractional strength error	$1 \cdot 10^{-3}$

Percentage of error ensembles with existing closed orbit as a function of a fraction of the nominal error set





[1]Courtesy T. Hellert, C. Steier, M. Venturini

Commissioning simulation is the new way to evaluate errors

- Two ways to get around the orbit existence problem
  - Ramping of errors
    - Straightforward ramping while correcting orbit with reasonable ramping steps didn’t work
    - Required extra thinking
  - Simulation of “real” machine commissioning
    - Start with trajectory correction and go forward as we would do for real commissioning
    - More complicated that ramping
    - In addition, allows to study actual commissioning strategies

Commissioning simulation is made as realistic as possible[1,2,3]

- Procedure is based on multi-particle bunch tracking and consists of the following steps:
  - Error generation – alignment, strengths, multipoles, injection, etc.
  - First-turn correction with zero sextupoles
  - Global trajectory correction
  - Beam-based alignment
  - Sextupole ramping while performing correction of pseudo-orbit (multi-turn trajectory averaged on each BPM)
    - Betatron tune and RF adjustments
    - Results in beam capture
  - Orbit correction
  - Beta functions and coupling correction using response matrix fit
  - Calculate DA/MA or injection efficiency and lifetime
- Single run requires about 2-3 days to complete on a single core
  - Hundreds of runs are essential to generate statistics
- Blue color shows steps not needed if one only wanted to evaluate tolerances – quasi-commissioning

[1] V. Sajaev, PRAB 22, 040102 (2019)
[2] T. Hellert et al., PRAB 22, 100702 (2019)
[3] T. Hellert et al., PRAB 25, 110701 (2022)

Commissioning simulations allow to evaluate many effects

- Commissioning simulations are complex, but allow for evaluation of many errors:
  - Misalignment, magnet strength errors, and high-order multipoles
  - Injection errors, injected beam parameters
  - BPM offset/noise
  - Realistic aperture
- Due to many dimensions, hard to perform scans

Alignment and strength errors (rms, 2σ cutoff)

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Dipole/Quadrupole/Sextupole/Girder tilt	0.4 mrad
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Dipole/Quadrupole fractional strength error	$1 \cdot 10^{-3}$

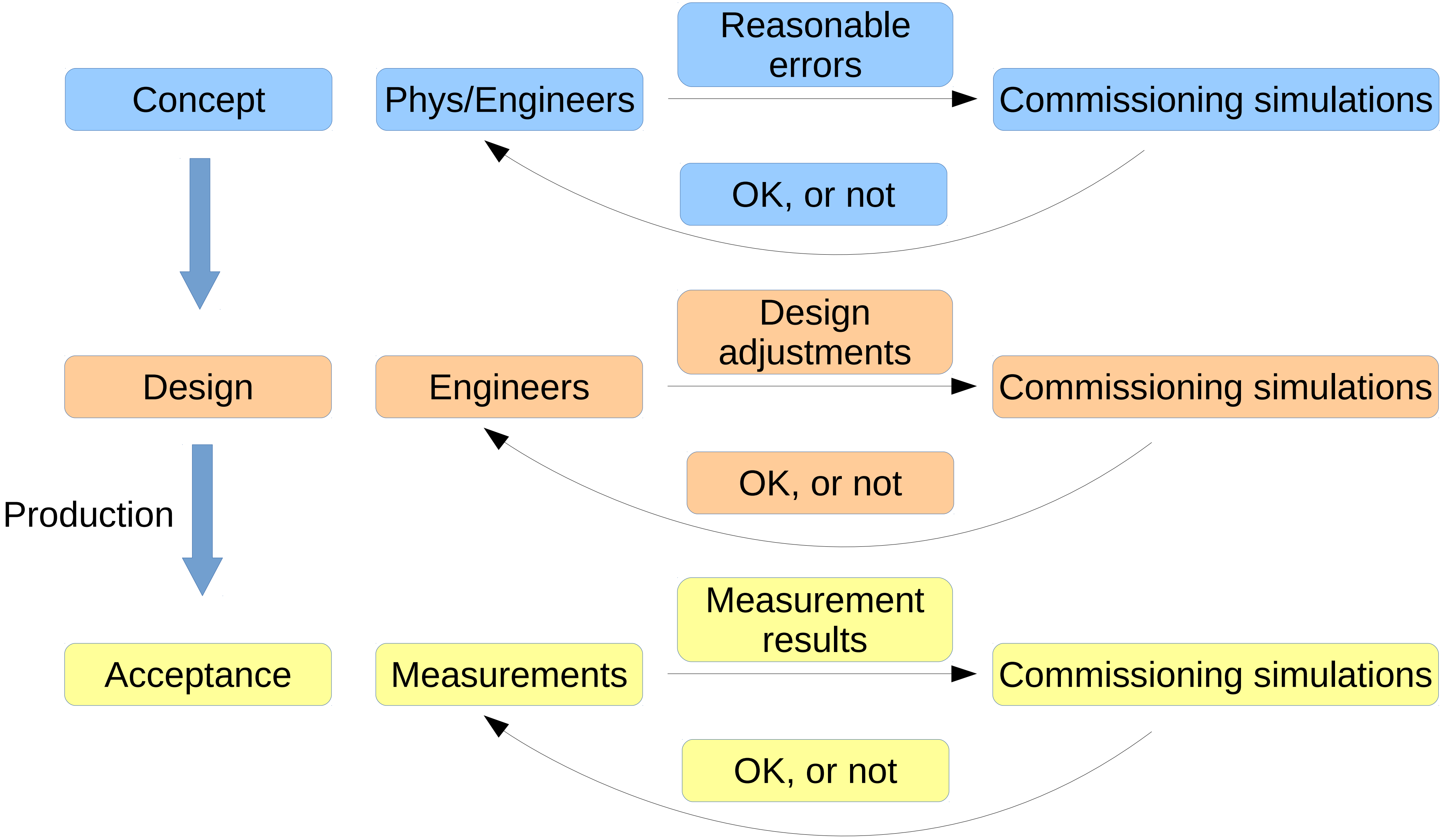
BPM/corrector errors (rms)

Corrector calibration error	5%
Initial BPM offset error	500 μm
BPM calibration error	5%
BPM single-shot measurement noise	30 μm
BPM orbit low-current noise	3 μm
BPM orbit high-current noise	0.1 μm
BPM-to-BPM sum signal variation	10%
BPM and corrector tilts	1 mrad

Injection errors

	Static errors (rms)	Jitter (rms)
Horizontal position	2 mm	100 μm
Horizontal angle	0.5 mrad	10 μrad
Vertical position	0.5 mm	25 μm
Vertical angle	0.3 mrad	15 μrad
Energy	0.5%	10^{-4}

Typical APS-U workflow



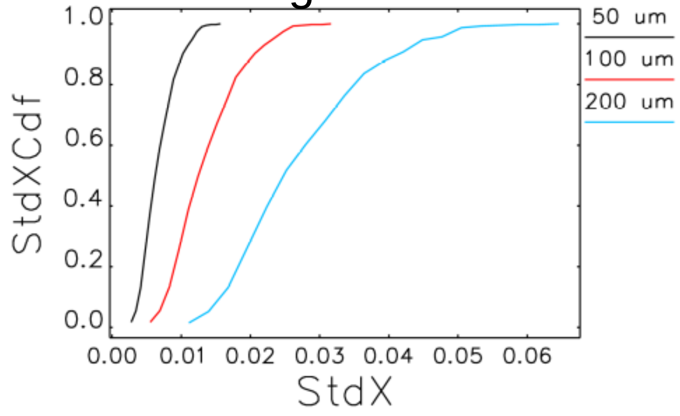
Use examples

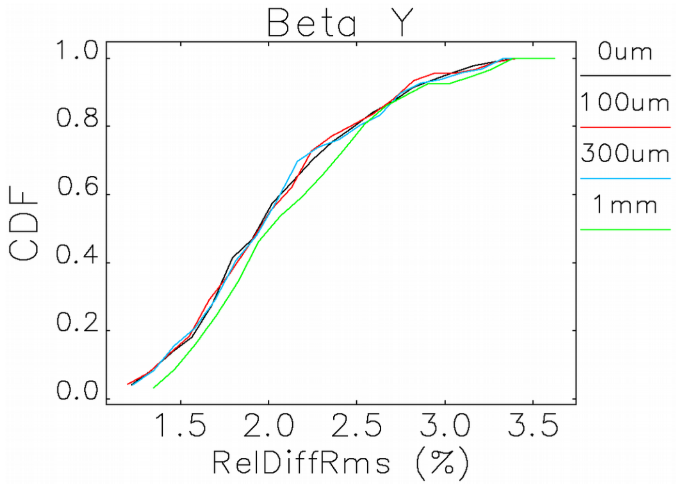
- For every request, we re-run commissioning simulations and analyze statistics
- Design step:
  - Switch from support design using 3 large girders to 3 smaller girders + 2 mini-girders – confirmed that performance is comparable
- Acceptance step:
  - 2 quad families and 1 focusing dipole family came with non-zero average tilts and tilt errors exceeding twice the requirements – performance was found to be acceptable
  - 2 sextupoles came with 12 mrad and 4 mrad tilts (requirement is 0.4 mrad) – accepted
  - Longitudinal alignment of one magnet family on girders was exceeding tolerance by a factor of two – relaxed the requirements by a factor of 4

Lattice evaluation could relax requirements a lot

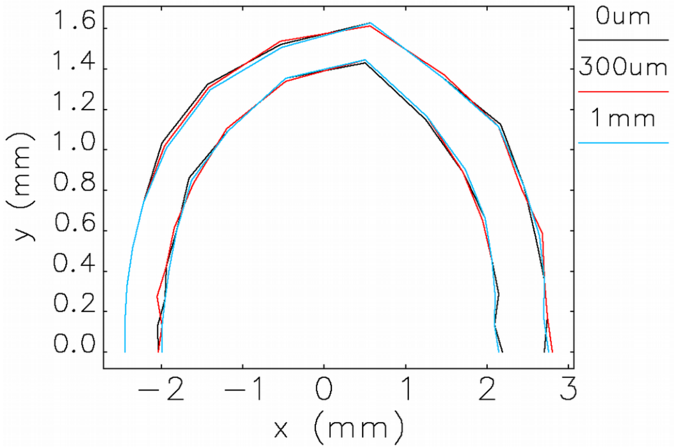
- Longitudinal alignment tolerance: initial simplified tolerance determination
  - Final accuracy of beta function correction after commissioning is 2-3% rms (without longitudinal misalignment)
  - Allow for 1% rms beta function distortion from longitudinal misalignment only
  - Results in 70 μm rms alignment tolerance (on-girder placement)
- To relax, ran commissioning simulations
  - Results showed that even 1 mm rms was acceptable
  - Relaxed requirements to 250 μm rms

Relative β_x error CDF for different longitudinal errors





10th and 90th percentile DA



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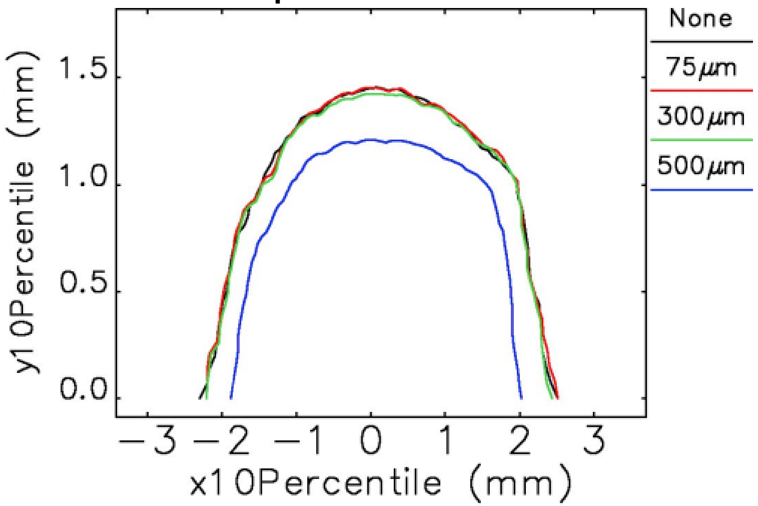
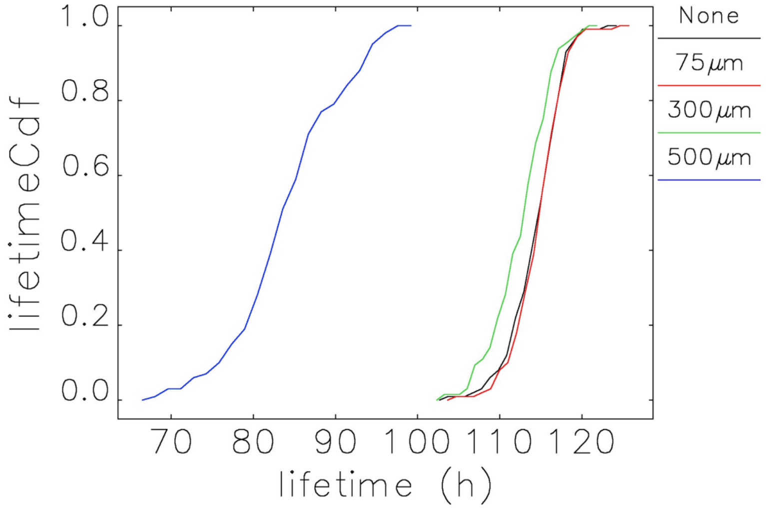
ID vacuum chamber misalignment tolerance[1]

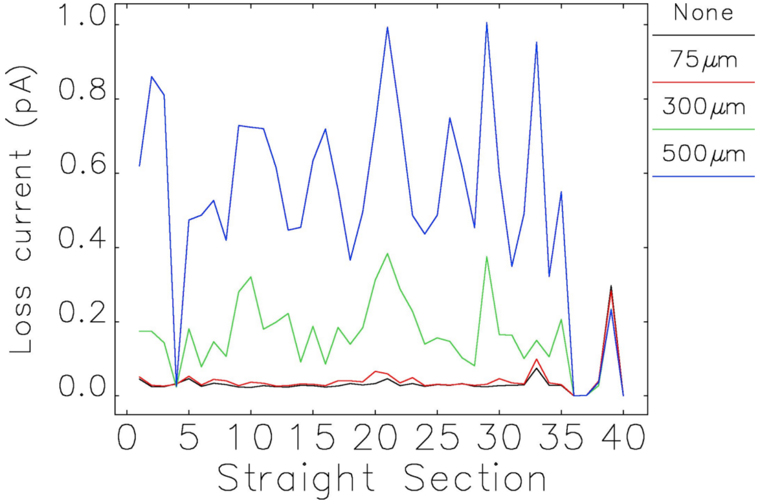
- Concern: lifetime and/or particle loss distribution can change significantly
- Added ID chamber misalignment to commissioned ensembles, evaluated DA, lifetime, and losses
  - Based on DA and lifetime only, 300 μm would be acceptable
  - However, losses at IDs increase significantly above 75 μm

10th percentile DA





Losses at IDs

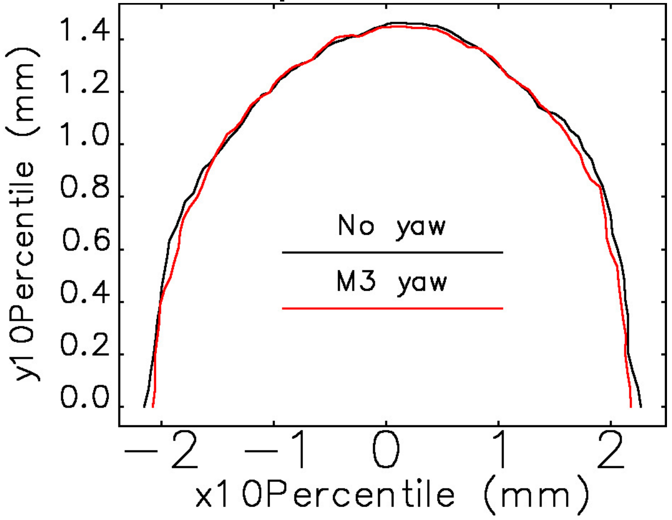


[1]Courtesy M. Borland

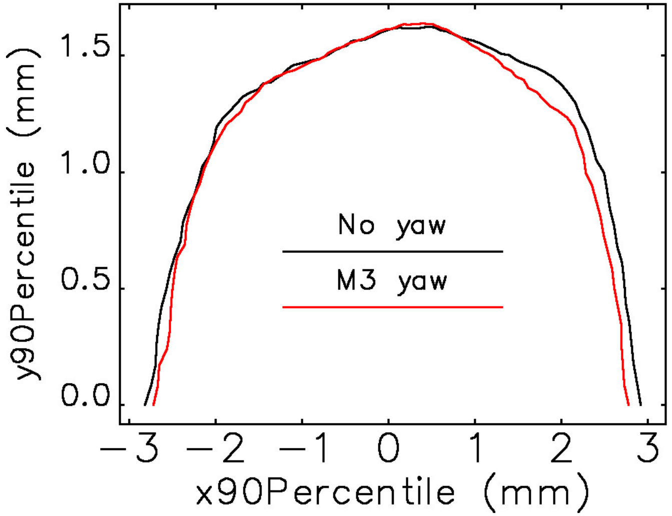
Effect of increased M3 yaw

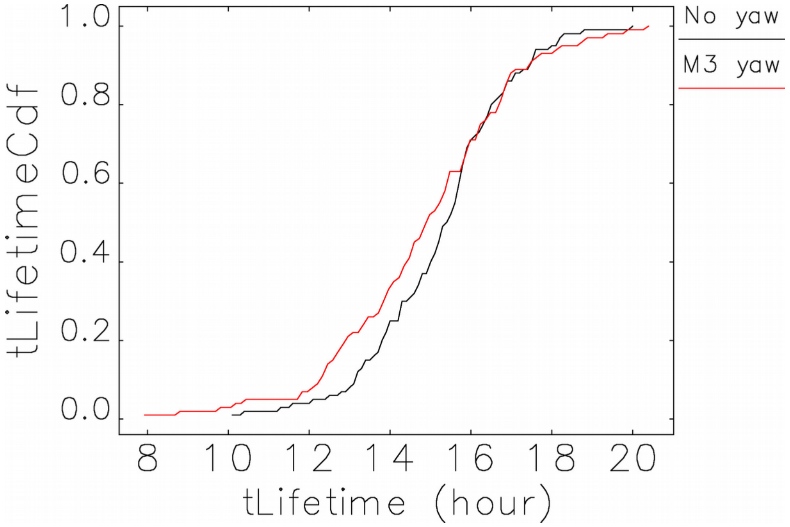
- Production M3 magnet family was determined to have possible yaw errors of up to 0.5 mrad
- Full commissioning simulation was run with increased M3 yaw errors
- Effect on DA is rather small, but 20% reduction of the minimum lifetime is a concern

10th percentile DA



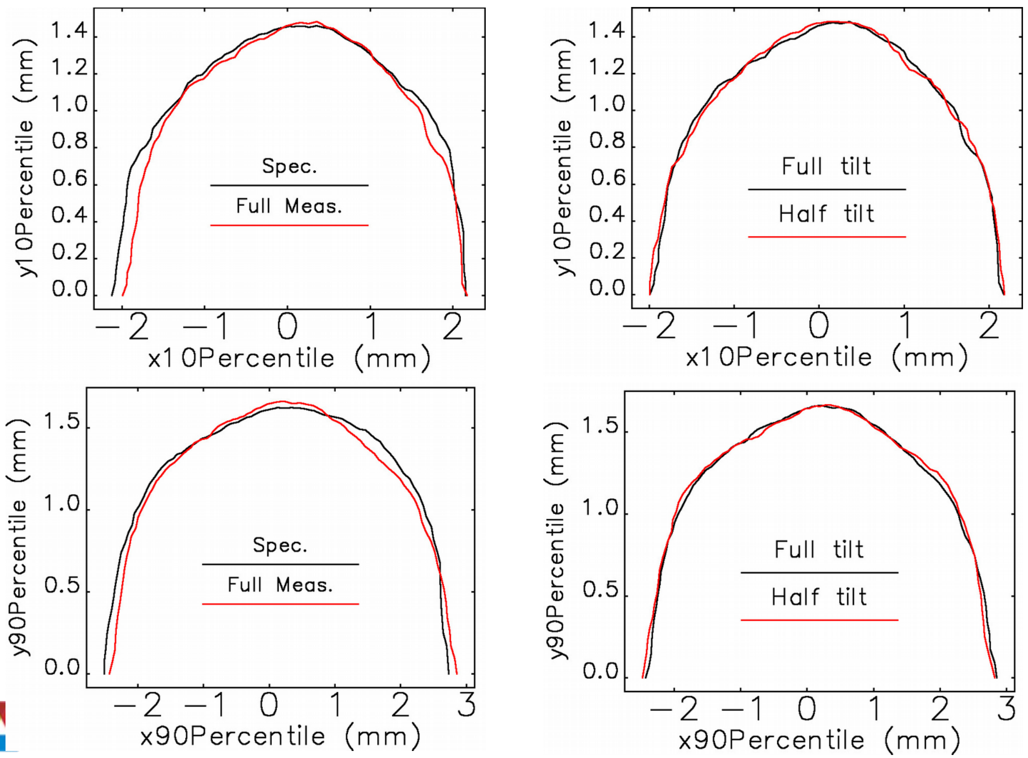
90th percentile DA

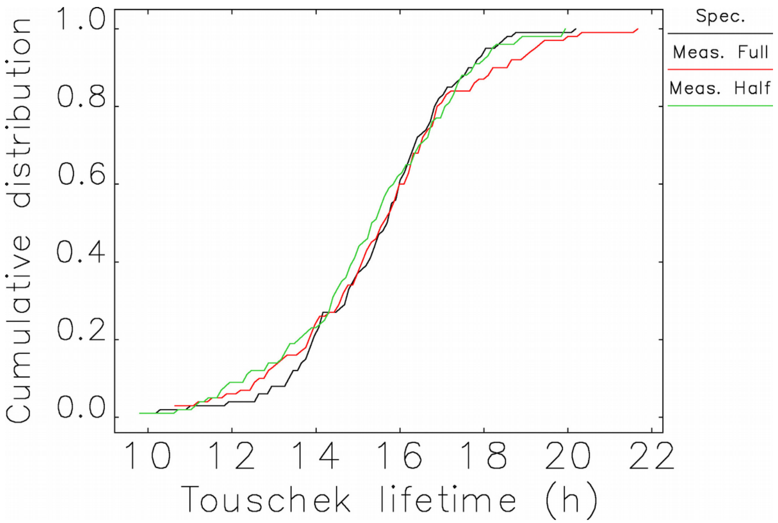




Performance with actual measured magnets

- Performance evaluation was performed using magnetic measurements (multipoles and tilts) of 80% of production magnets
- Additionally, M3 family had slightly larger than spec tilts, tested if reduction would be beneficial
- Very small reduction of DA with measured multipoles/tilts, lifetime effect is also very small
- Reduction of M3 tilts does not provide any improvements





M. Borland, V. Sajaev, AOP-TN-2021-068

Summary

- Various ways exist to calculate effect of errors on the machine performance if one considers error types separately or combines a few types of errors
  - Typically requires careful choice of assumptions or proxies for lifetime/injection
  - Different error types may require different approaches
  - Hard to consider effect on commissioning
- If one wants to consider many errors together – commissioning simulations are the best way
  - Allow to see effect of any type of errors on the accelerator performance
  - Give answer in terms of actual machine performance (injection, lifetime)
  - Do not rely on initial existence of closed orbit
  - Same simulations for all types of errors
  - Too many variables – hard to do error amplitude scans
- Commissioning simulations can be used for acceptance of production items
- Automation of the entire commissioning process is essential