Overview of sensitivities against errors, measures developed to enhance robustness, and commissioning strategies

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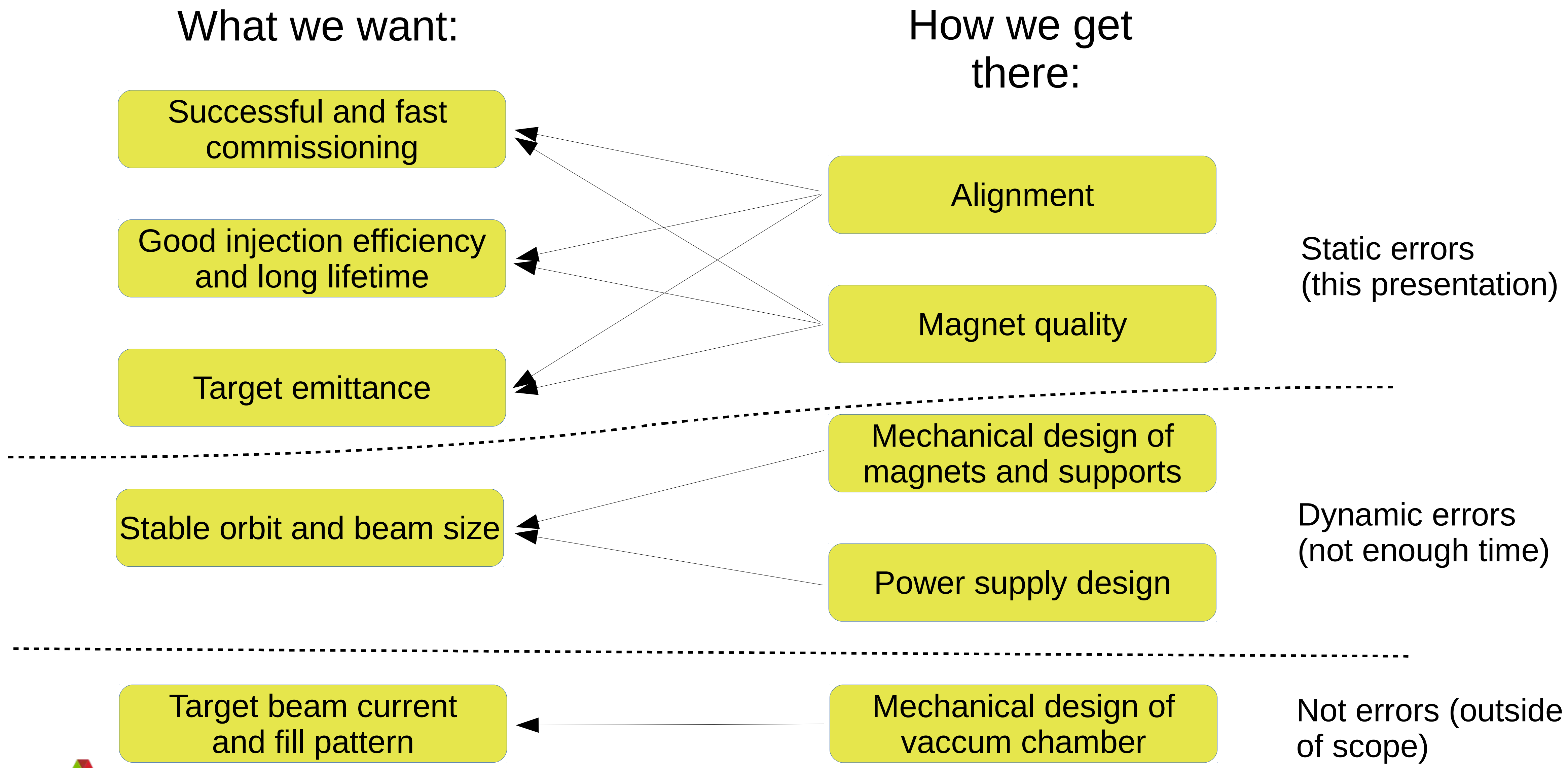
3rd LEL design Workshop

How errors affect machine performance



Error requirements for new rings are not much better than those of older rings

Alignment error requirements for MBA storage rings (most numbers are rms with 2σ cutoff)

	Girder to girder	Element to Element
ALS-U	30/100 μm (R2R/S2S[1])	30 μm
APS-U	100 μm (1σ cutoff)	30 μm
Diamond-II	150 μm	35-50 μm
ESRF EBS		60 μm
MAX-IV	100/50 μm (H/V)	25 μm
Petra-IV	100 μm	30 μm
SIRIUS	80 μm	40 μm
SLS-2	20 μm (remote)	30 μm
SOLEIL Upgrade	30/50 μm (H/V)	

[1]Raft to raft, sector to sector

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Error tolerances: 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, so people started considering orbit correction in their 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 became widely used[2] but light sources designed at the time still didn't consider lattice correction in tolerance calculations
  - Tolerances were likely overspecified

[1]E. Crosbie, et. al., 1993 PAC Proc.
[2]J. Safranek, NIM A 388, 27 (1997)

Typical workflow for error effect evaluation

- Generate error ensembles
- Correct closed orbit
- Correct lattice (only became available ~20 years ago)
- 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: 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

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Existence of closed orbit is the key.
No closed orbit – no luck!

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- Example: 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

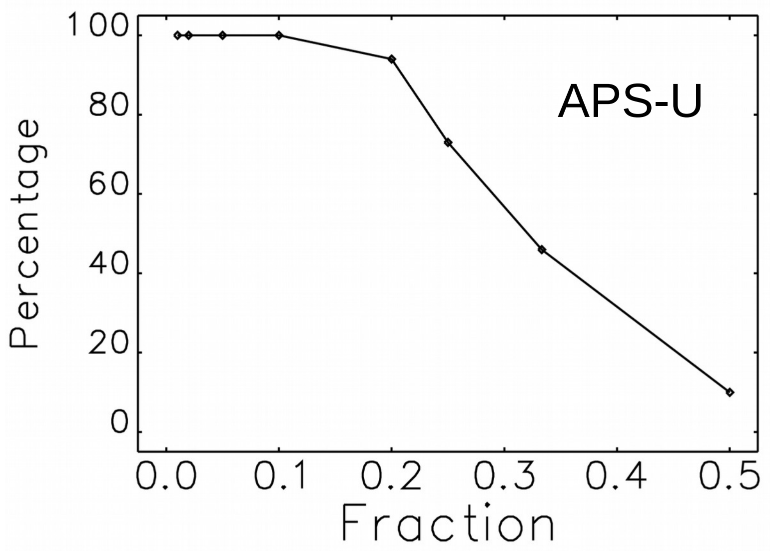
Old approach did not work for new rings

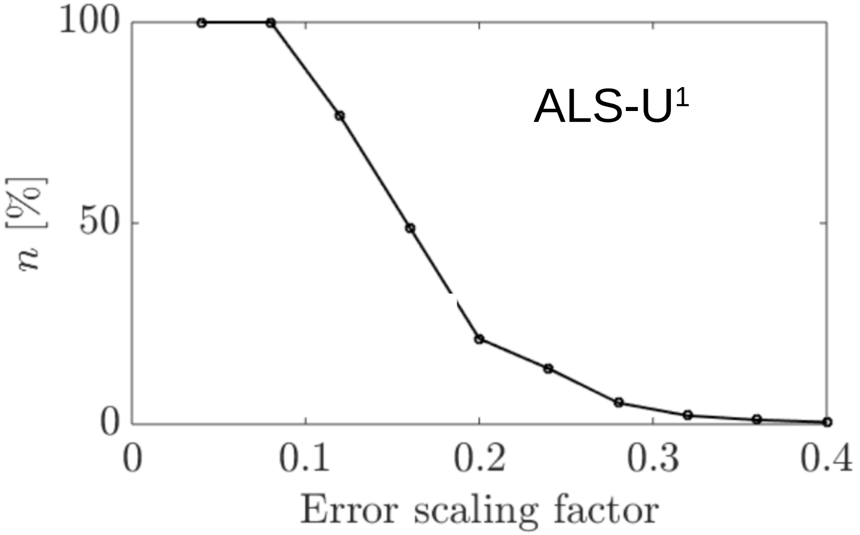
- Evaluated hundreds of error sets – no closed orbit exists for reasonable error sets in 100% of cases
- Repeated the same study for different fractions of the nominal error set
- To ensure closed orbit existence, one needs to reduce errors by a factor of 10 – unrealistic!

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 exist 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]

- Procedure is based on multi-particle bunch tracking and consists of the following steps:
  - Error generation – alignment, strengths, injection, etc. (mostly Gaussian distributions)
  - 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 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, P. Amstutz, C. Steier, M. Venturini, PRAB 22, 100702 (2019)

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Commissioning simulations allow to evaluate many effects

- Commissioning simulations are complex, but allow for evaluation of many errors:
  - Misalignment
  - Magnet strength errors
  - 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)

Girder misalignment X/Y/Z (1σ cutoff)	100 μm
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Dipole/Quadrupole/Sextupole/Girder tilt	0.4 mrad
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Dipole/Quadrupole fractional strength error	$1 \cdot 10^{-3}$

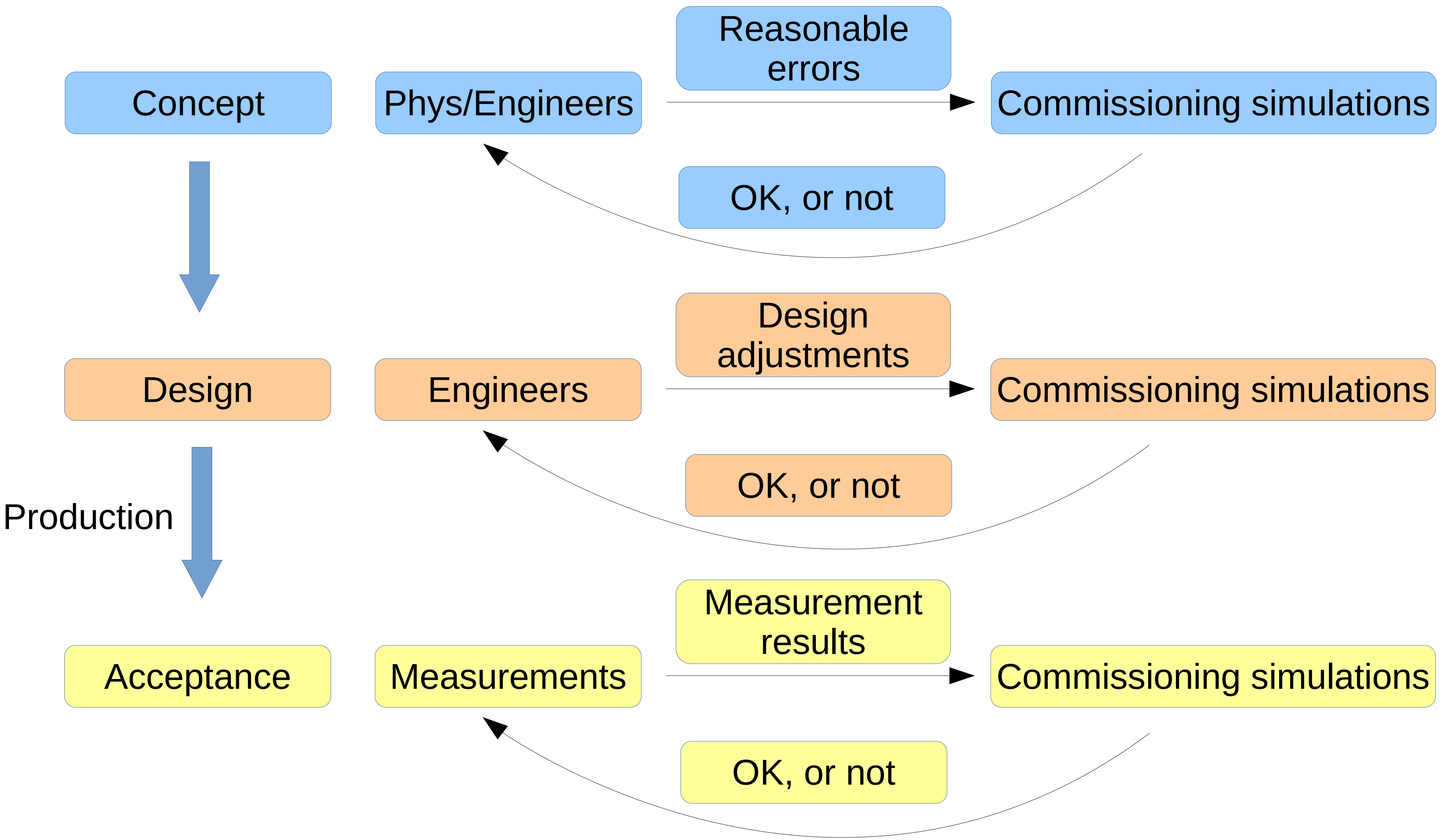
Injection errors

	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}

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

Typical APS-U error evaluation workflow



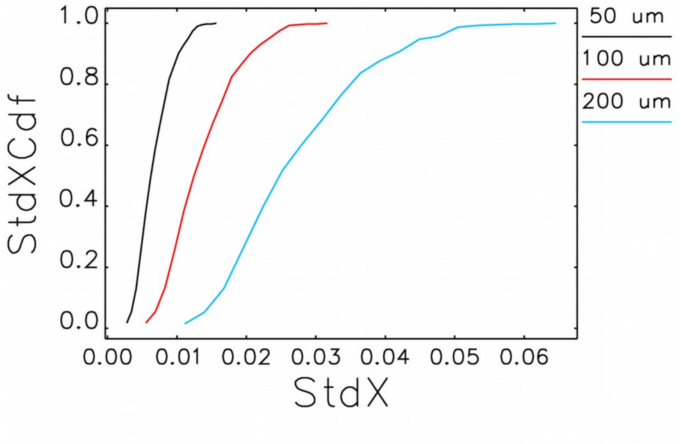
Use examples

- Design stage:
  - Switch from support design using 3 large girders to 3 smaller girders + 2 mini-girders – confirmed that performance is comparable
- Acceptance stage:
  - 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

Commissioning simulations 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)

Relative β_x error CDF for different longitudinal errors (no other errors)



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- Longitudinal alignment tolerance: initial simplified tolerance determination
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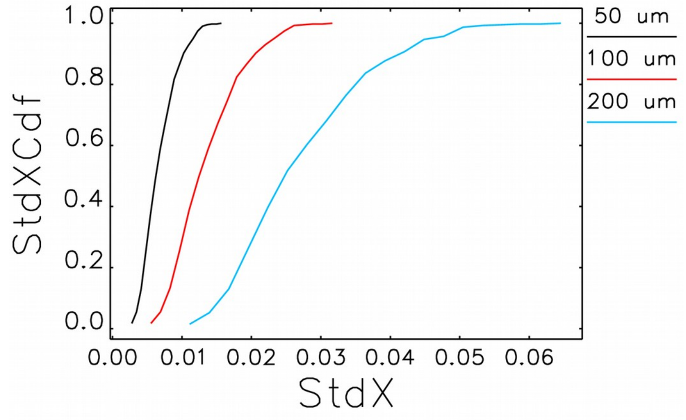
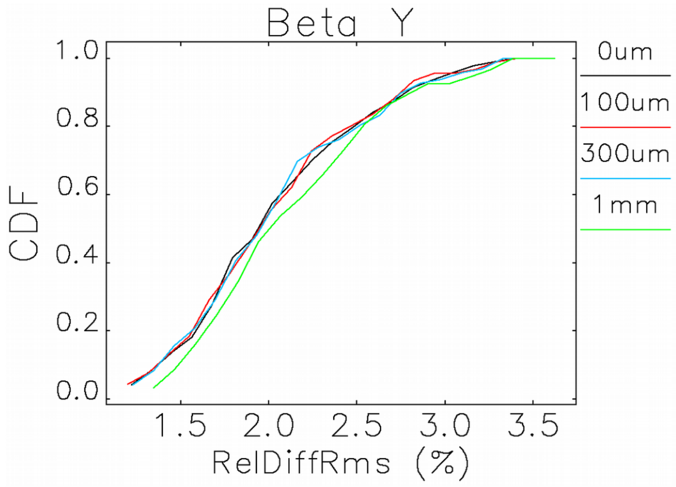
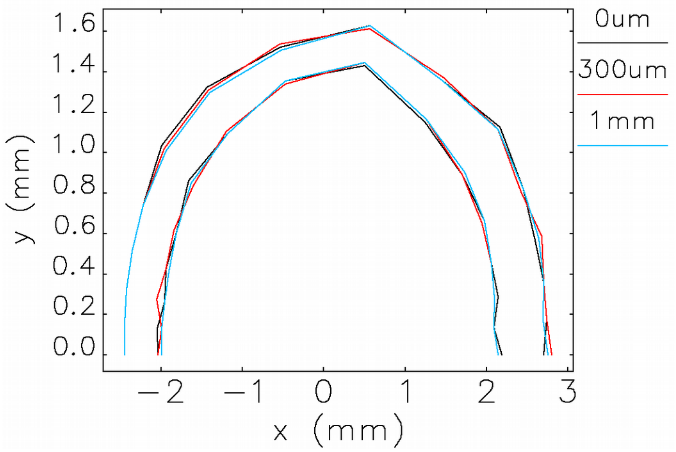
  - Results in 70 μm rms alignment tolerance (on-girder placement)
- To relax, ran commissioning simulations
  - Results showed that even 1 mm rms was acceptable
  - Relaxed requirements to 250 μm rms

Relative β_x error CDF for different longitudinal errors (no other errors)





10th and 90th percentile DA



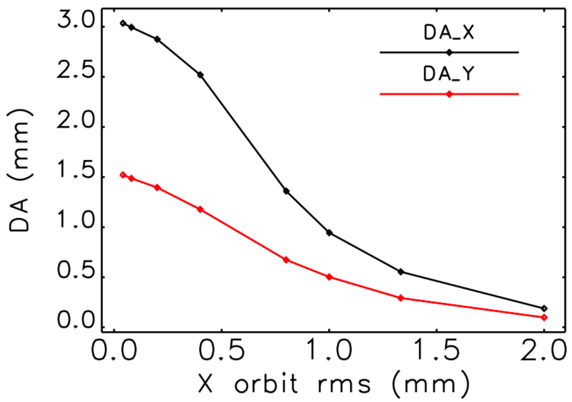
Commissioning simulation results for different longitudinal misalignments (all other errors included)

CDF: cumulative distribution functions

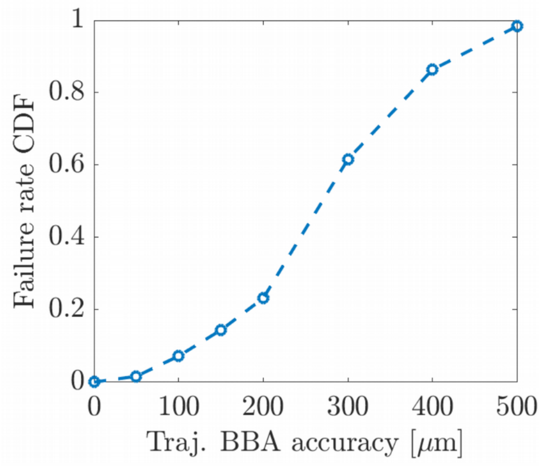
Commissioning simulations allow to test out commissioning algorithms

- APS-U:
  - Initial plan was to commission with sextupoles on
  - Simulations showed that correcting trajectory didn't result in beam capture for some test lattices
  - Investigation showed the possibility that distance between closed orbit and corrected trajectory could be smaller than DA
  - Solution: Commissioning will start with sextupoles off
- ALS-U:
  - Trajectory correction didn't result in beam capture
  - Investigation showed that BPM offset errors are too large
  - Solution: introduce trajectory-based BBA step into commissioning sequence

APS-U: at 1 mm closed orbit rms, DA is smaller than CO



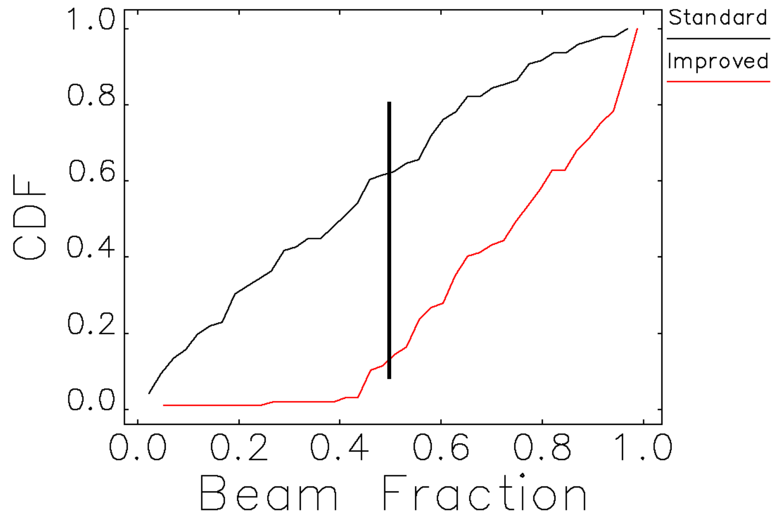
ALS-U: Failure rate as a function of BPM offset errors[1]



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

Commissioning simulations allow testing safety margins of algorithms

- We expect actual errors to be at or better than specified, but we prepare for the worst
- Increase errors until commissioning starts failing, then try to resolve the issues
- Result: prepared tools that would improve chances of storing beam in case of larger than expected errors:
  - Trajectory-based BBA – if the commissioning program fails to ramp sextupoles
  - Optics correction based on multi-turn trajectory – if the program fails to achieve stored beam with ramped sextupoles and corrected trajectory



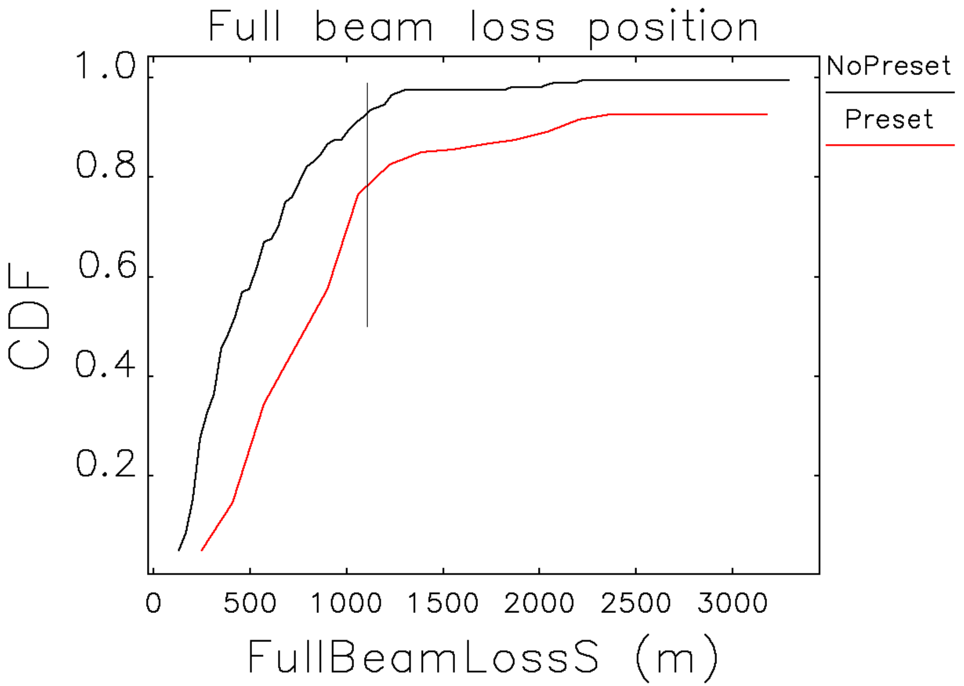
Surviving beam fraction after 5k turns, data sets with increased errors

Probability of achieving stored beam is increased from 38% to 87%

Stored beam is defined as having half of beam after 5k turns

Commissioning simulations allow to test various ideas

- **Survey accuracy is typically better than alignment accuracy**
- Magnet survey on girders has rms accuracy of 10 μm[1], girder survey can achieve 25 μm rms
- Correctors could be preset to survey results
- Test that used corrector presetting based on magnet survey only (no girders) showed increased probability of the beam going through first turn without correction from 5% to 20%
  - No too impressive, but comes for free
  - Addition of girders could further improve transmission
- Transportation of girders from lab to tunnel may move magnets
  - Easy to compare first-turn transmission for "zero correctors" case vs "preset correctors" case



[1]B. Jansma, A. Jain, J. Nudell, private comm.

Conclusions

- MBA-based lattices are more sensitive to errors, require more detailed evaluation of error effects
  - Previous error evaluation methods relying on existence of closed orbit do not work well
- Commissioning simulations started out as commissioning simulations but evolved into an important tool for error evaluation and tolerance calculations
  - Allow to see effect of any type of errors on accelerator performance
  - Do not rely on a priori existence of closed orbit
  - Allow to consider any type of static errors
  - Any type of errors is treated uniformly
  - Can be used for acceptance of production items
- As actual commissioning simulations, allow to test out algorithms
  - Increase our confidence in successful commissioning