Karlsruhe Institute of Technology

Beam Tests and Commissioning of Low Emittance Storage Rings

Lessons Learned from the MAX IV 3 GeV Ring Commissioning

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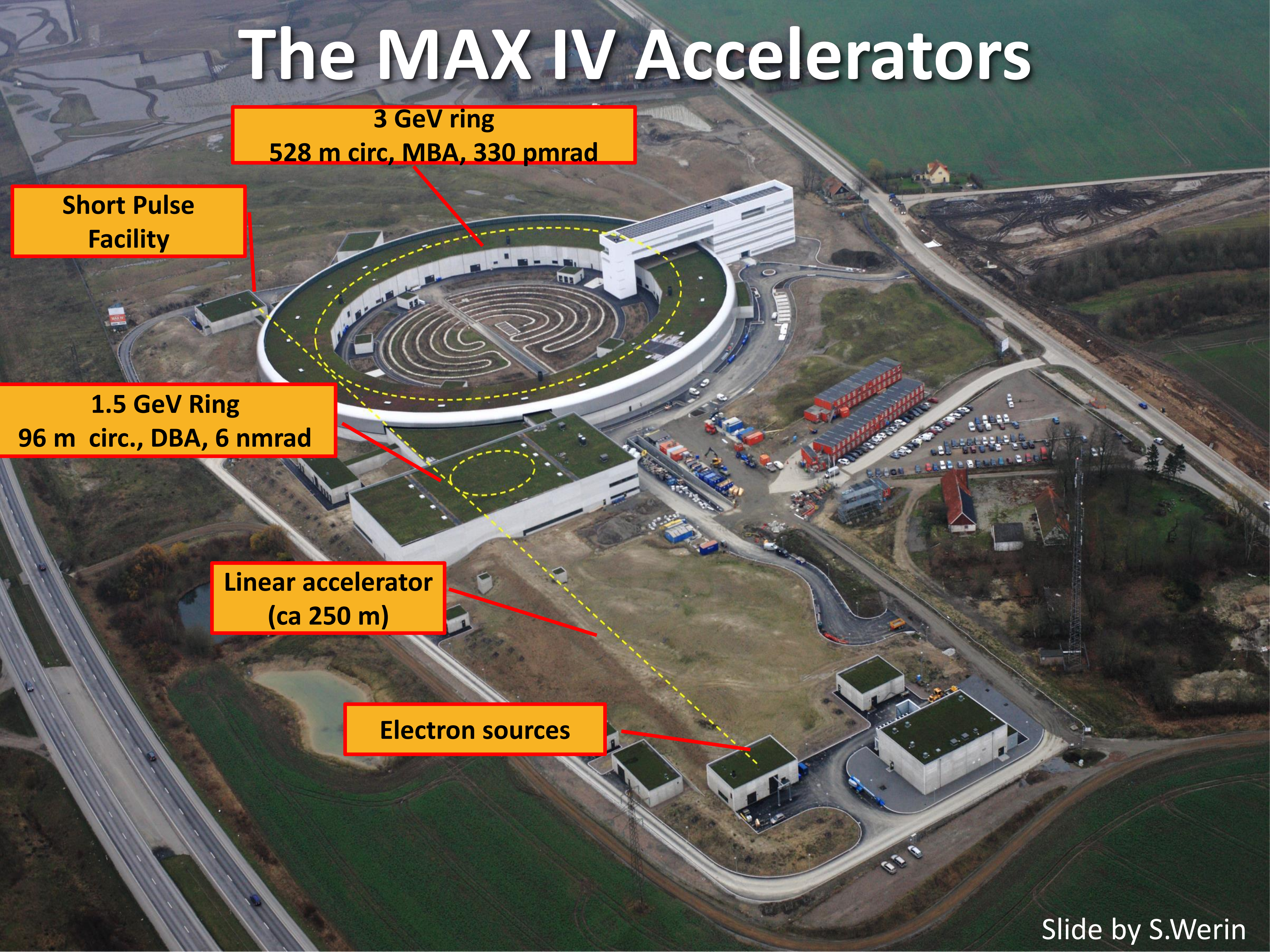
on behalf of the MAX IV team

Outline

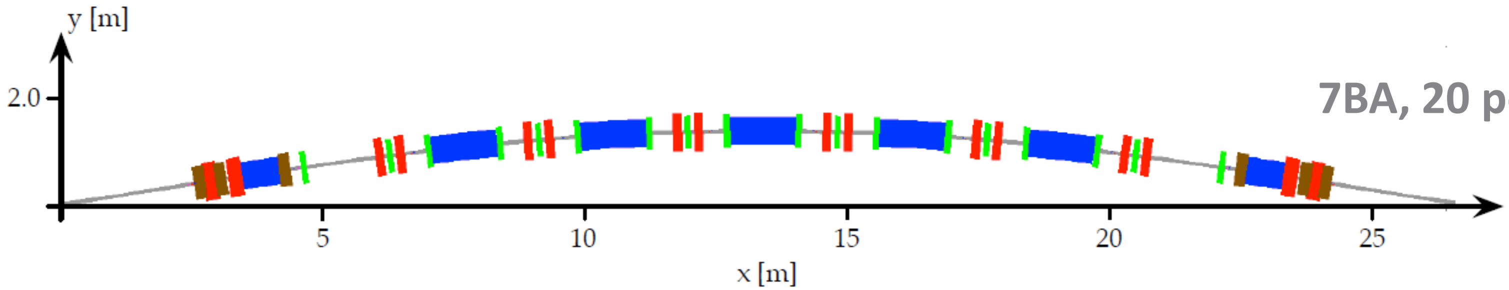
- The MAX IV Accelerators: an overview
- The MAX IV 3 GeV ring
  - Achieved Performance
  - Commisssioning Timeline
  - Main Challenges in Commissioning & Lessons learned
  - Things that went particularly well
  - Risk Analysis: foreseen problems vs actual problems
- Lessons Learned Summary & Conclusions

The MAX IV Accelerators



Slide by S.Werin

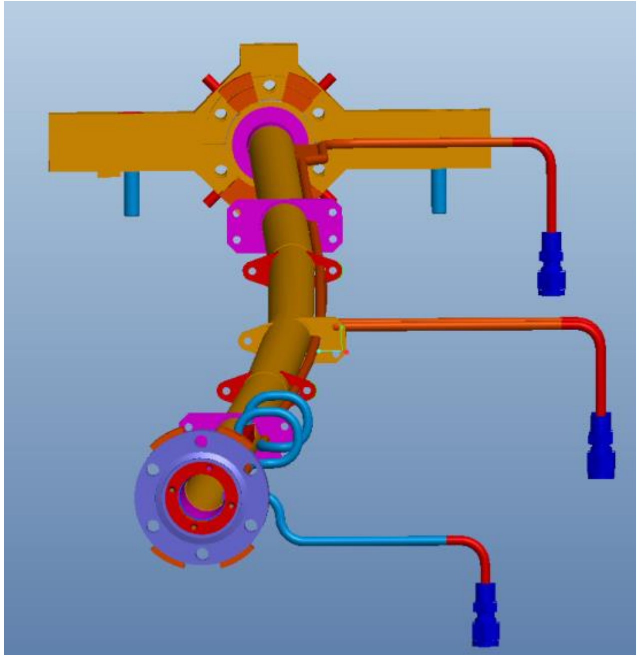
MAX IV 3 GeV ring: 528 m, 330 pmrad



7BA, 20 periods

100 MHz RF
Pasive HC

Circular, copper NEG-coated chambers



Compact Magnets

3 GeV Ring – achieved performance

- 500 mA stored current in multibunch mode demonstrated during accelerator studies
  - Regular delivery to beamlines at ~ 250 mA (RF power limitations)
- $\sim$ 9 mA stored current in single-bunch mode.
- ~ 20 A.h lifetime.current product from gas scattering
- $\gtrsim$ 90% injection efficiency
- Emittances: ε_x=320 ± 18 pm rad; ε_y =6.5 ± 0.1 pm rad (down to 2 pm rad observed)
- RMS orbit stability (up to 100 Hz) better than 1.3/5.5 % of beam size (H/V).
- Beta beats < ± 2 %, Residual Vertical Dispersion < 0. 6 mm RMS

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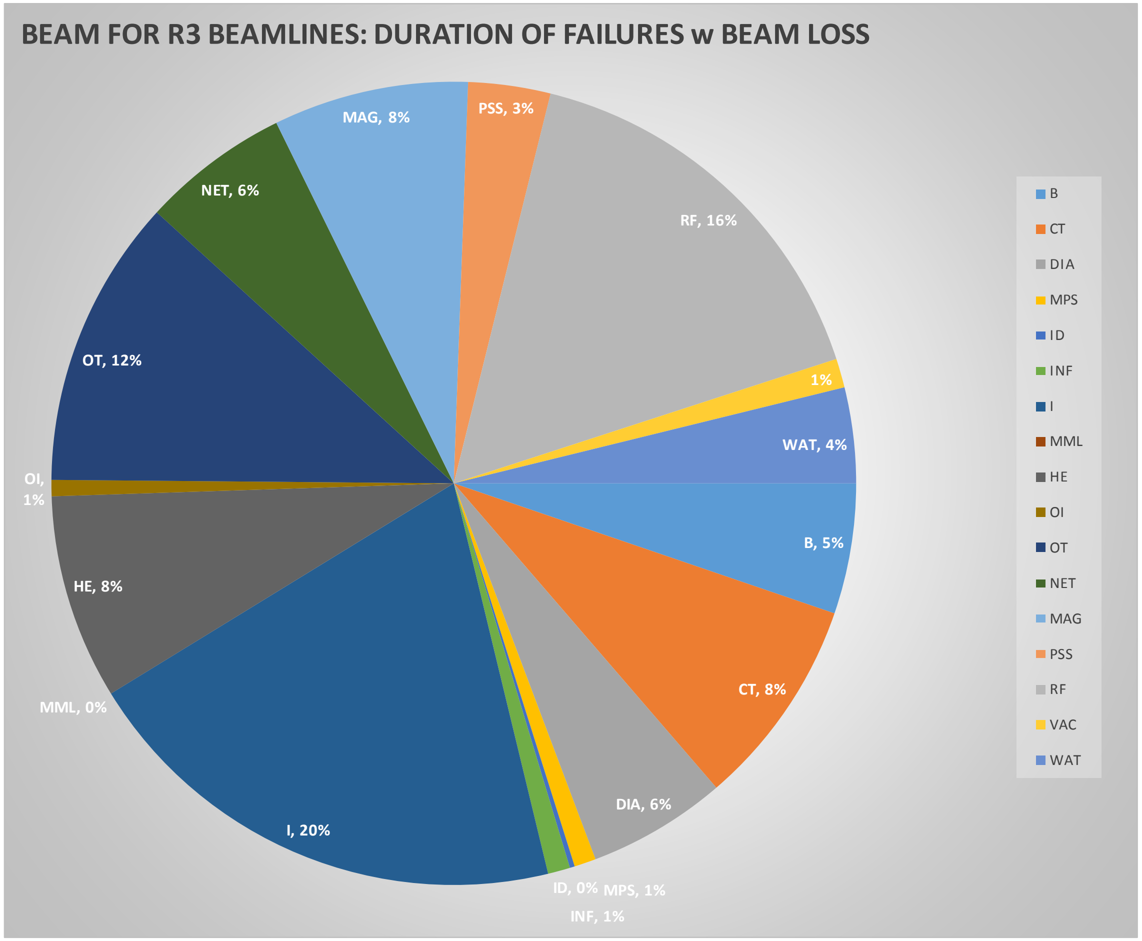
2018 3 GeV Ring Operations Summary

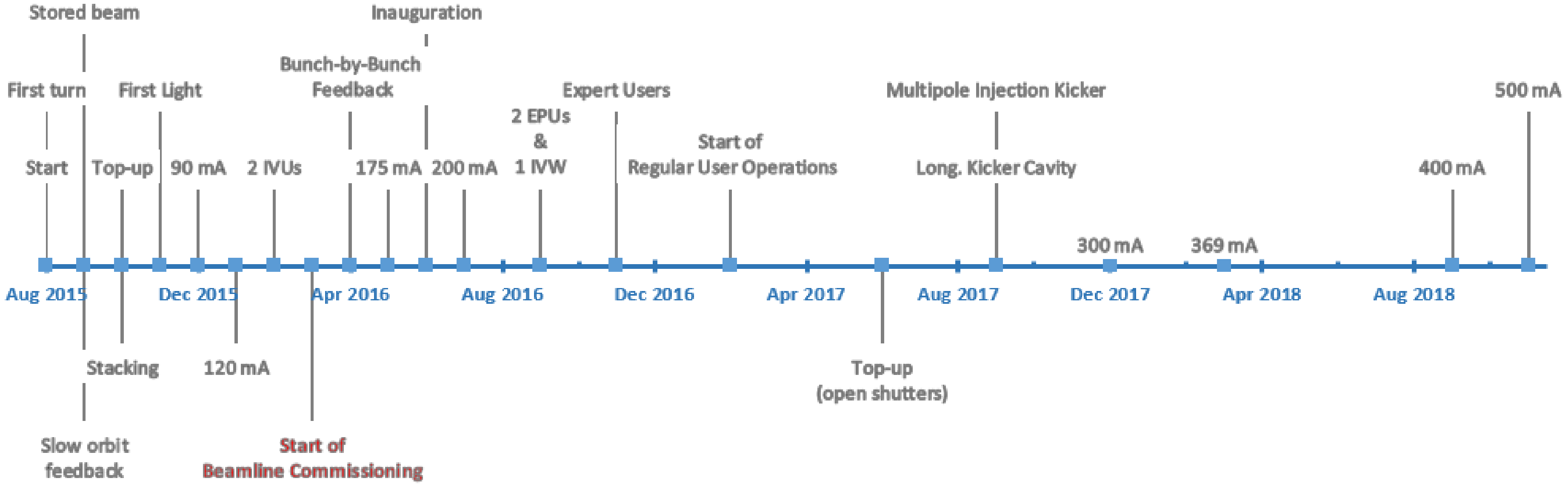
- 24/7 Accelerator operations since January 2018.



- 4068 scheduled delivery hours
- 96.2 % availability
- 34.5 h MTBF
- 1.3 h MTTR

Plots and data by Stephen Molloy

3 GeV Ring Commissioning & Operations Timeline



Commissioning Challenges: Our share of pain

- Beam commissioning was preceded by a comprehensive sub-system test campaign.
- Most subsystem issues were discovered and solved early on during subsystem tests, but a few could only be addressed at the very end of sub-system tests or even early into the beam commisioning phase.

- **Main commissioning challenges were related to ”simple” problems that risked slow down progress rather than fundamental issues.**

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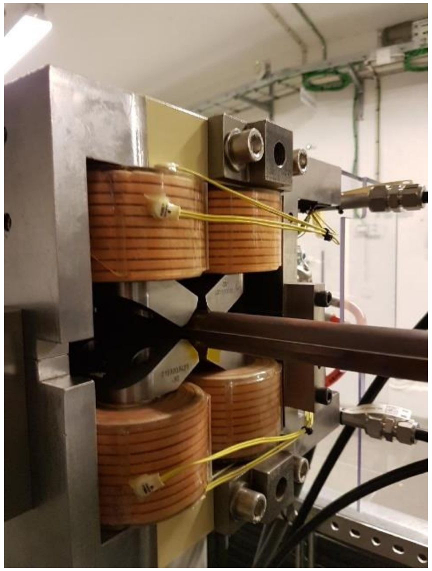
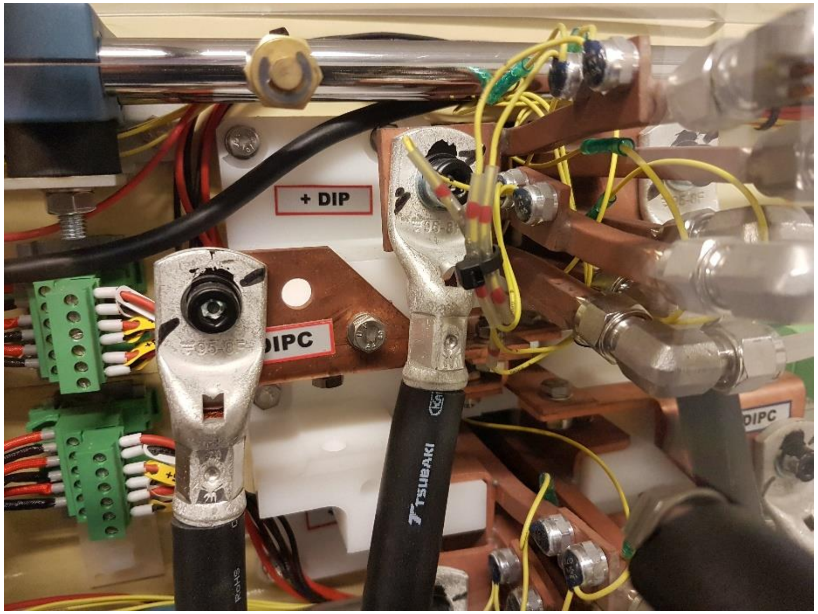
Short-circuited pole-face strips

- A number of pole-face windings were shorted to ground
  - Insulation was not thick/robust enough and was damaged during assembly.
  - Not noticed at the manufacturer (tests without chamber).
  - Only noticed when all magnets were in place and connected to ps.
  - Quick solution was to improve insulation with kapton foils.
  - In some cases, the magnets had to be open.
  - Fortunately, no chambers had to removed (which would have delayed the start of beam commissioning).

Misplaced thermal sensors on magnet coils

- Thermal switches on coils were found to be almost insensititive to the coil temperature (switches would not open even if water cooling was removed with full current flowing in the coils).
- Problem was that the long and thick cables acted as a heat sink and created a large temperature gradient between the coil body and the coil leads (where the sensors were located).
- A number of solutions
  - Quick fix: implement on-line verification of circuit resistances on high-level alarm system (implemented in Tango).
  - Permanent fix: change positions / replace sensors on all magnets (this took several months)





Misaligned Vacuum Chambers

- We focussed on getting the chambers in the right place inside the magnets (given the very tight margin – 0.5 mm), but missed to do proper alignment of the dummy chambers in the long straights.
- Consequences:
  - Early commissioning : after getting the first few tens of turns, progress was hampered by grossly missaligned chambers as revealed by visual inspection.
  - Later, finer chamber alignment problems were the cause of chamber hot spots.

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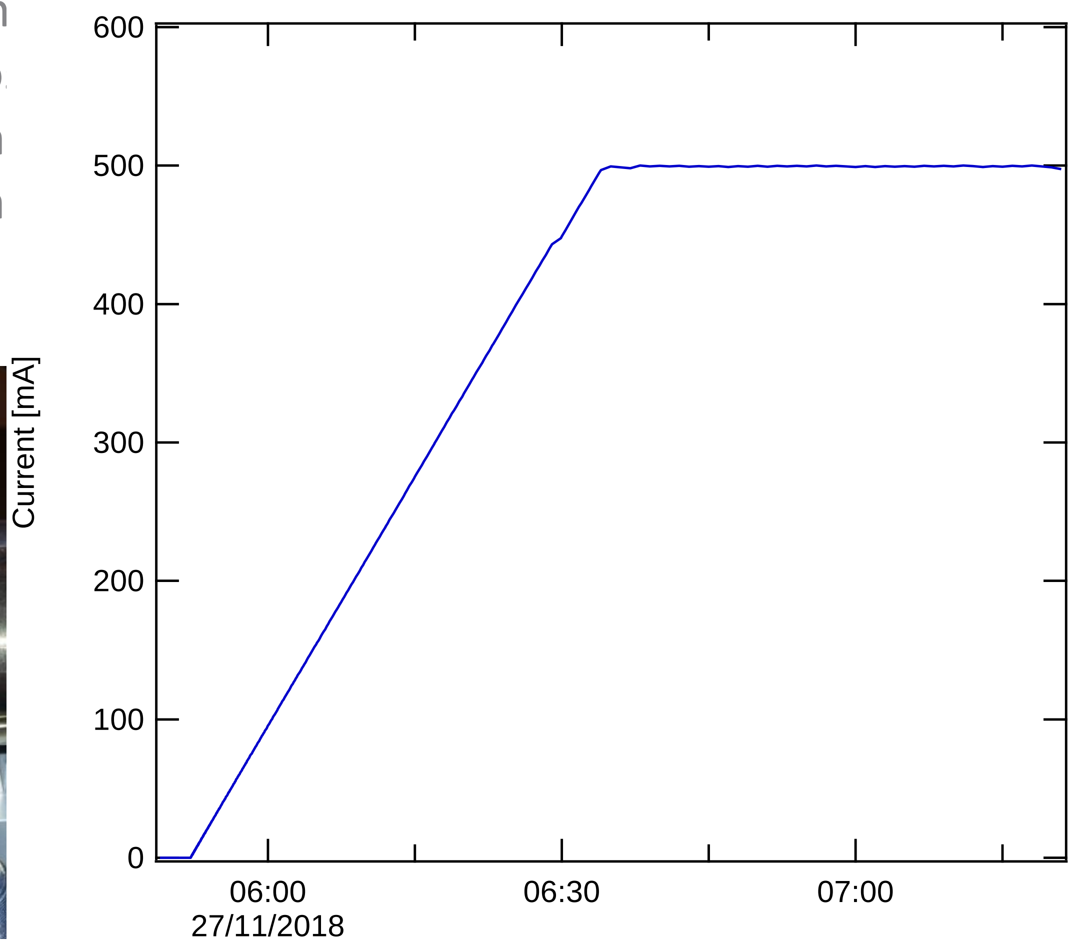
Chamber hot-spots

Local heating from synchrotron radiation from dipoles

- Reason
  - Po
  - Ch
  - Ch

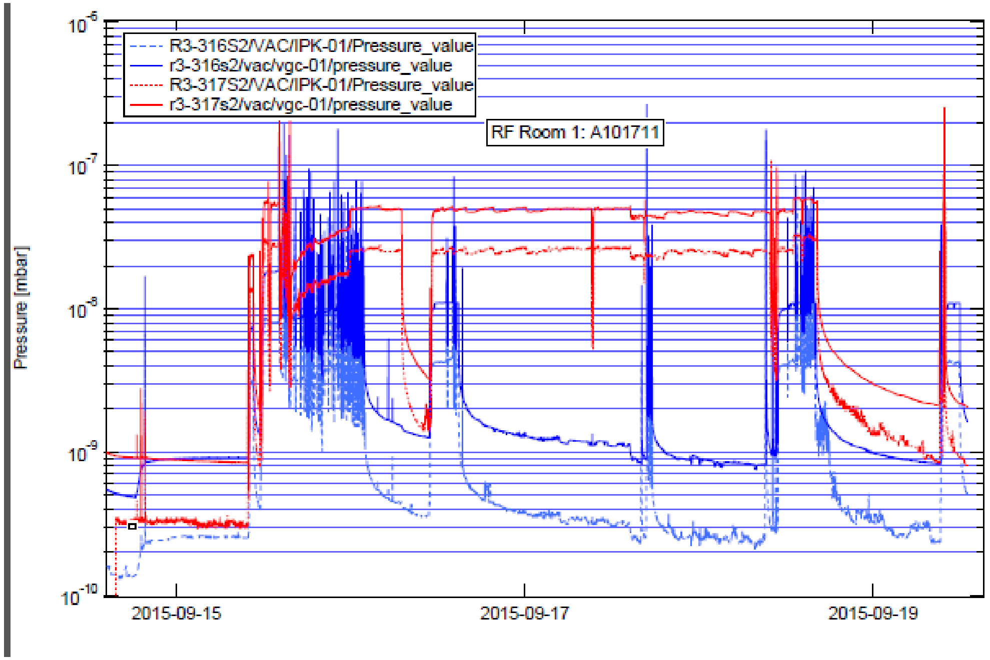


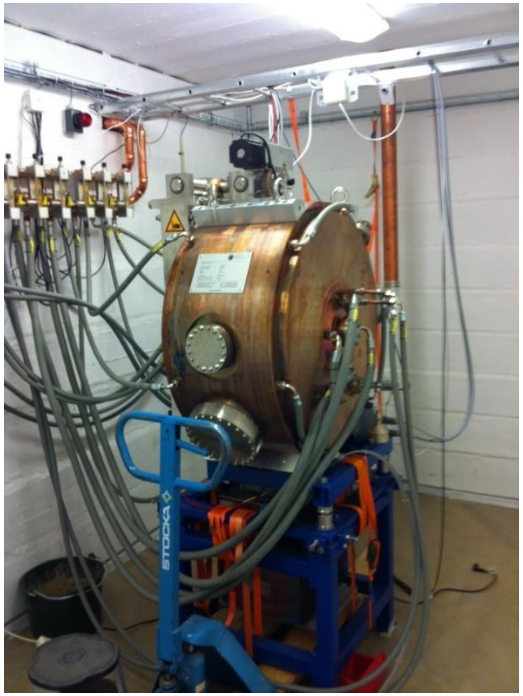
In Ach 4 S1, replaced an absorber (outside mechanical tolerances).

In Ach 8 M1, a chamber was damaged little too much thermocouple glue.

RF cavity conditioning

- Main and Harmonic Cavity conditioning done prior to installation proved insufficient:
  - limited power available
  - limited conditioning time
  - not possible to condition high power feedthroughs at full power





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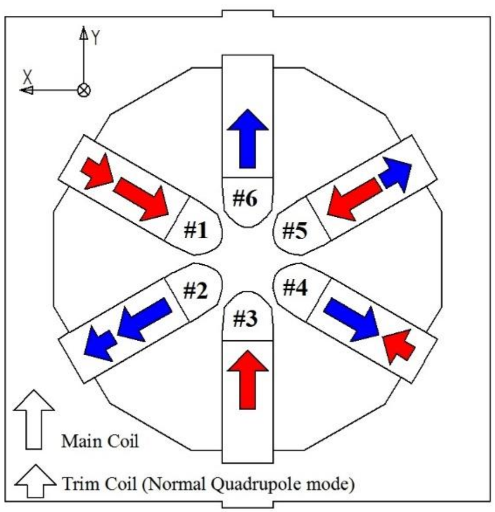
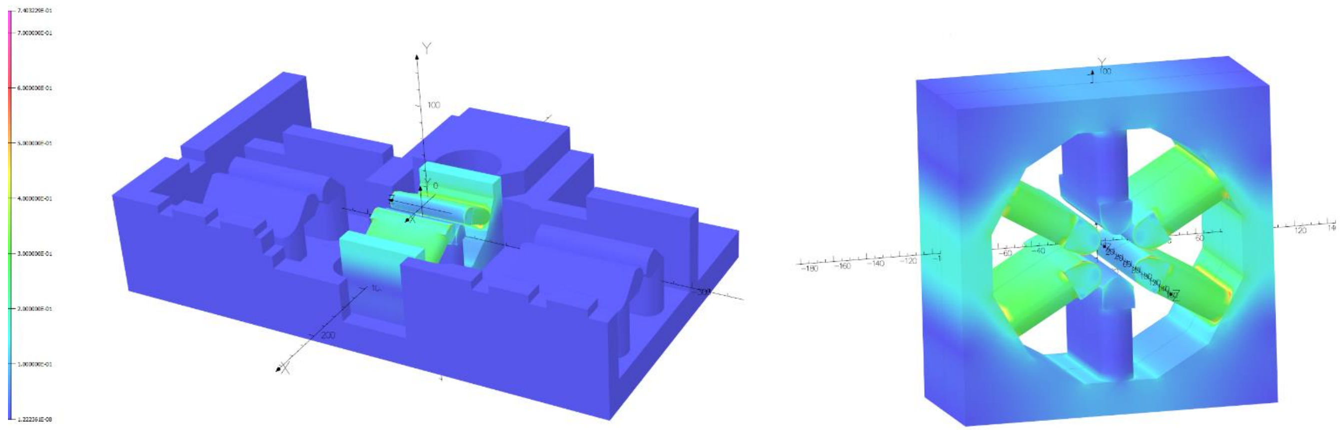
Beam-based BPM calibration and magnet saturation

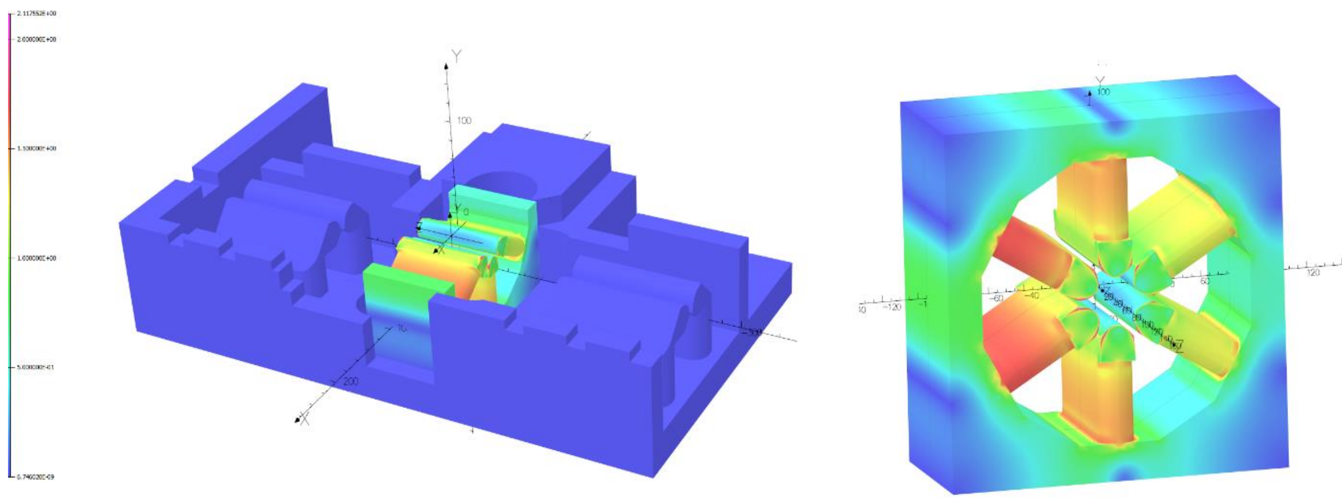
- At MAX IV, BPM based callibration is done with respect to nearby *sextupoles.*
- Trim coils are used to generate a quadrupole field on a sextupole yoke
- Early during commissioning a dependence of the measured offsets on the excitation of the sextupole main coils
- Magnet saturation was suspected early on, but 2D simulations could not explain the magnitude of the effect



Only Trim Coils ON



Trim Coils + Main Coils ON



Calculations and pictures by Alexey Vorozhtsov

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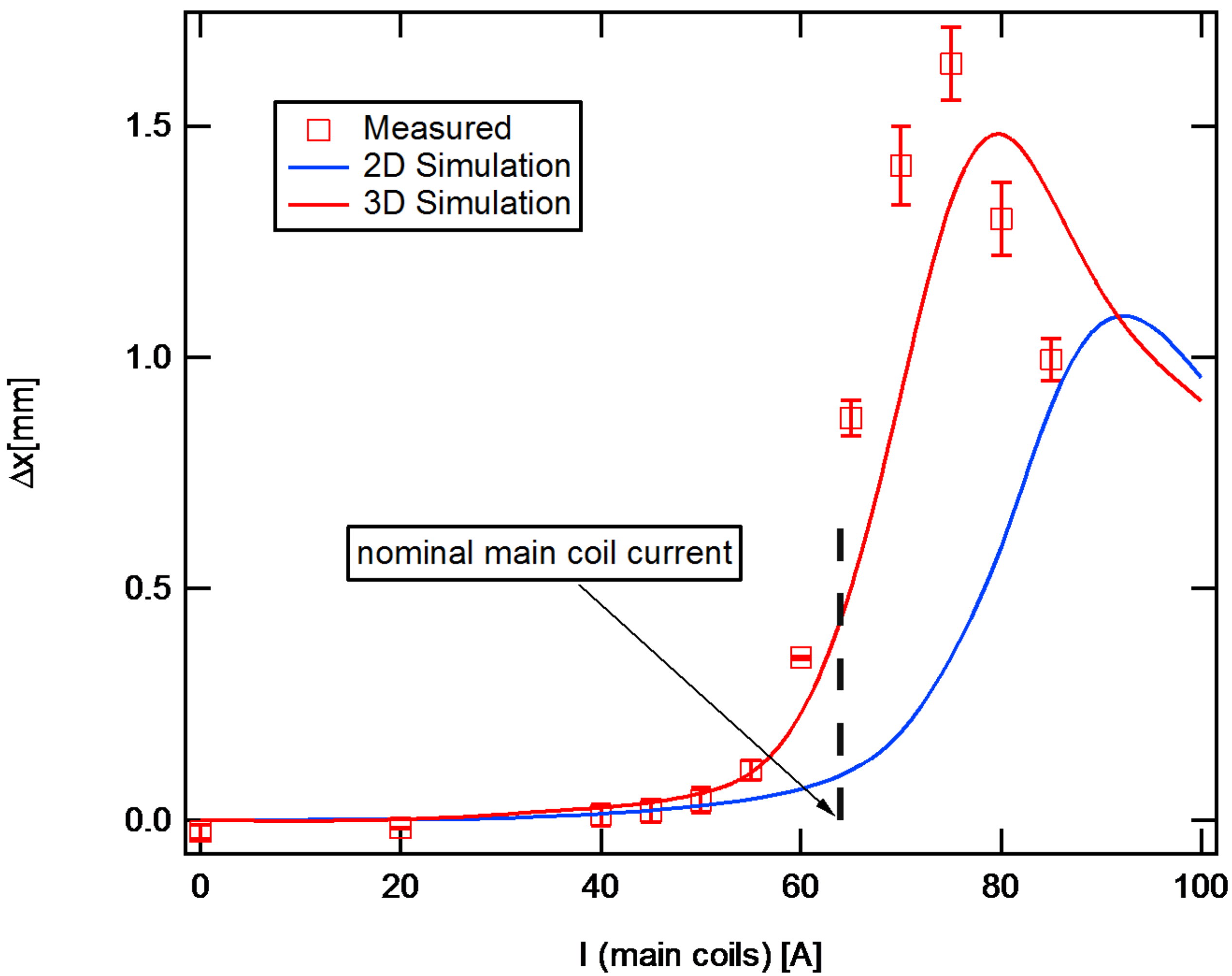
Simulation vs Experiments

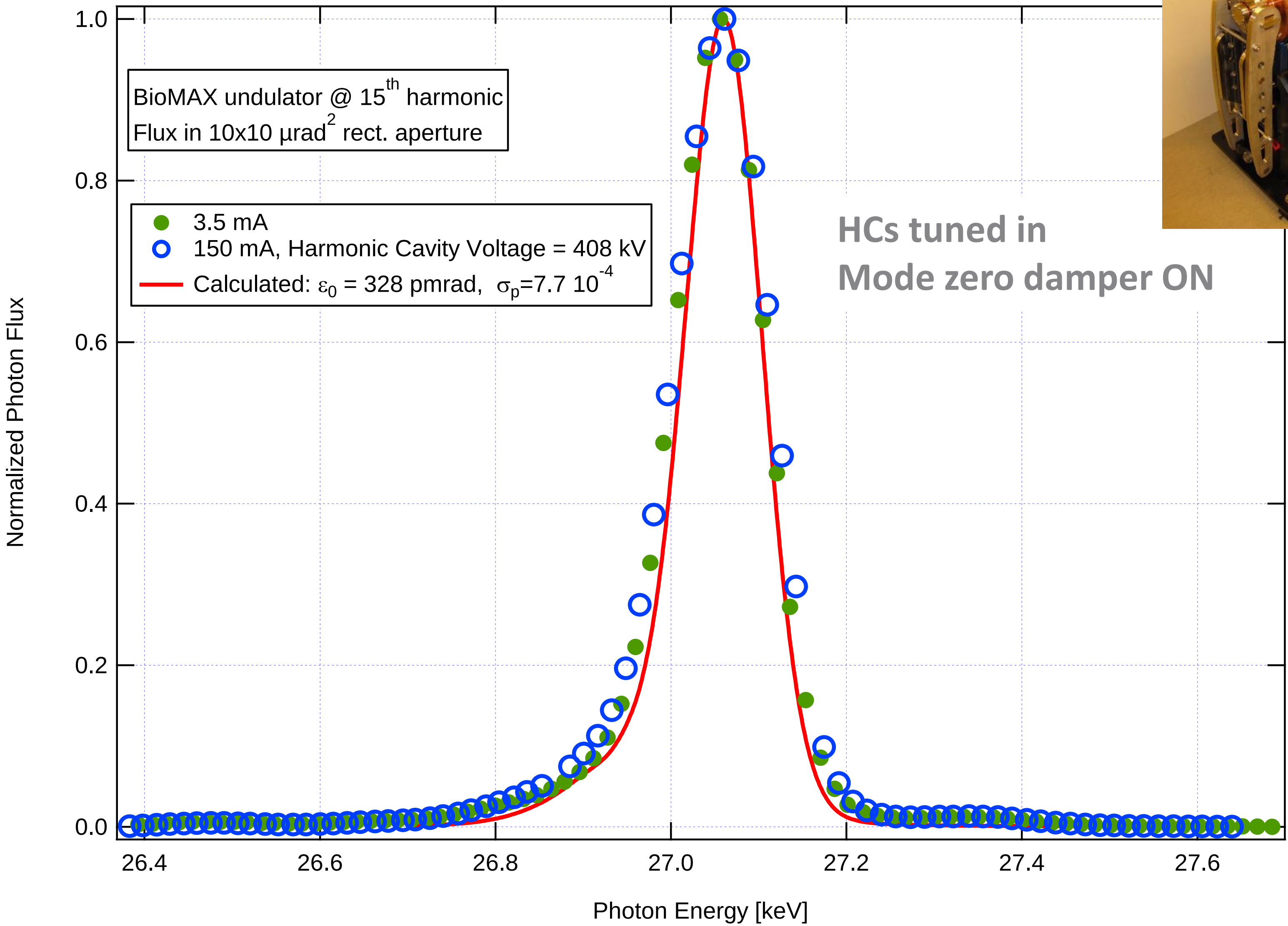


simulated data by Alexey Vorozhtsov
experimental data by Robin Svärd

Longitudinal Coupled-Bunch Instabilities

- Bunch-by-bunch feedback used initially to achieve longitudinally stable beam when Harmonic Cavitiues were only partially tuned in
- Required ingredients to achieve longitudinal stability (with long bunches):
  - Harmonic cavities well conditioned.
  - Mode-zero damper.
  - Short gap in the bunch train.
- Benefical effects of bunch lengthening also seen on
  - Increased lifetime
  - Reduced wake-field induced heating of vacuum chambers

Long Bunches and ID spectra



HCs tuned in
Mode zero damper ON

Experimental data courtesy Thomas Ursby
and Ana Gonzalez

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Things that went particularly well

- Several turns obtained with all correctors OFF.
- Vacuum Chamber Conditioning was fast.
- Accumulation with a single kicker (no closed bump).
- Accumulation with Multipole Injection Kicker (MIK) gave just as high a stacking rate.
- No magnet polarity errors in initial commissioning, despite some initial suspicions.
  - *But the MIK was indeed intially wired with the wrong polarity !*

Risk Management for the MAX IV Project

Early risk identification exercise (Autumn 2010)

Risks	Probability	Impact	Mitigating Measure
General Risks			
Delays due to procurement procedures	High	High	Detailed procurement planning with participation from technical personnel. Reinforce procurement team.
Errors in Planning and/or need to direct manpower to other activities	Medium	High	Close follow-up of milestones; Unambiguous declaration of priorities by upper management.
Exchange rate Fluctuations	Low	High	Follow market trends; Financial management
Dependence on few suppliers for long lead items	Medium	High	Make the design such that more competition from different suppliers is possible
Loss of Key personnel	Low	High	Maintain team motivation

Early Risk Identification Exercise (cont.)

Risks	Probability	Impact	Mitigating Measure
Technical/Development Risks			
Delays in Conventional Facilites Project	Medium	High	Close follow-up of milestones
Changes to Requirements on Conventional Facilities	Medium	High	Active integration management
Delays in Long Lead Items - Magnets, Vacuum	Low	High	Close follow-up of milestones
Difficulties in reaching magnet machining tolerances	High	High	Early prototyping
Delays in Long Lead Items - RF Cavities - operation at high power.	Medium	High	Close follow-up of milestones; Close interaction in development with supplier
Vibration and Support Design	Medium	High	Early Testing and Prototyping
Delays in installation due to cabling	Medium	Medium	Detailed planning; Early set up adequate integration tools; design for simple installation
Neg coating - single supplier	Medium	High	Early technical discussions and early procurement.

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Lessons Learned Summary

- Invest time and effort in sub-system testing ***prior*** to beam commissioning.
- Perform susystem-tests as much as possible using the **final control system configuration** and GUIs. Use subsystem-tests as an oportunity to drive the control system development and deployment schedule.
- Design subsystem tests to reproduce as much as possible real operating conditions.
- Allow time for correcting errors found during those tests.
- Make sure radiation safety understands and agrees to the commissioning plan.
- Allow plenty of time for RF cavity conditioning.
- Have spare parts on-site during commissioning.
- Have an on-line model of the accelerator for quick testing.
- **Be ready to improvise !**

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Conclusions

It is often the simple stuff that causes trouble…

Der liebe Gott steckt im detail.

Ludwig Mies van der Rohe

Thank You !