MAX IV light source upgrade: MAX 4^U

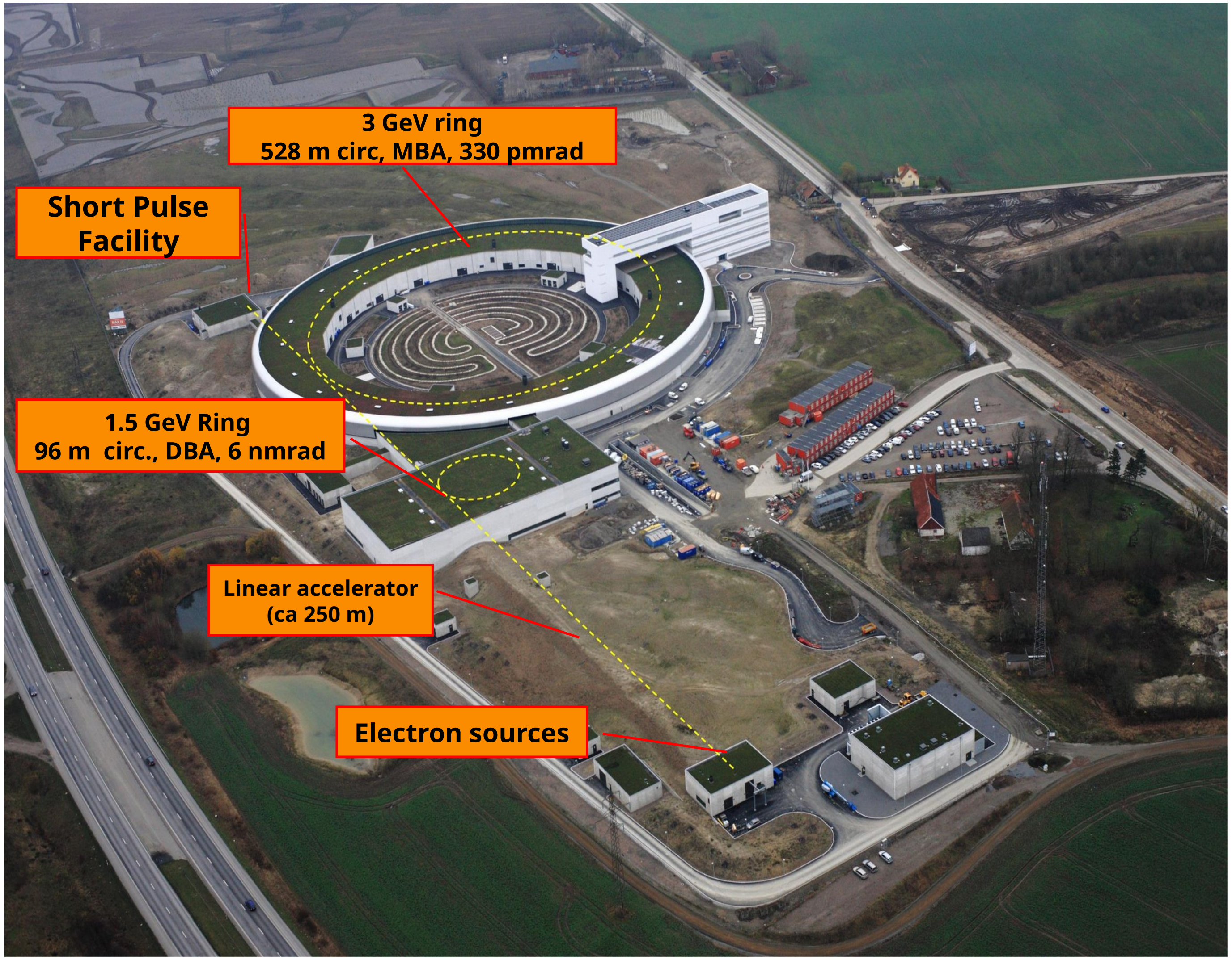
LER 2025 workshop

Magnus Sjöström

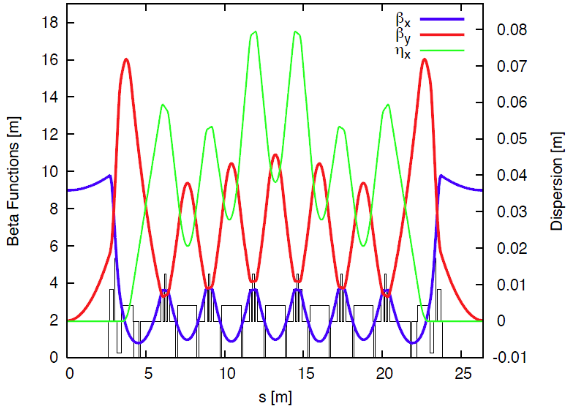
Outline

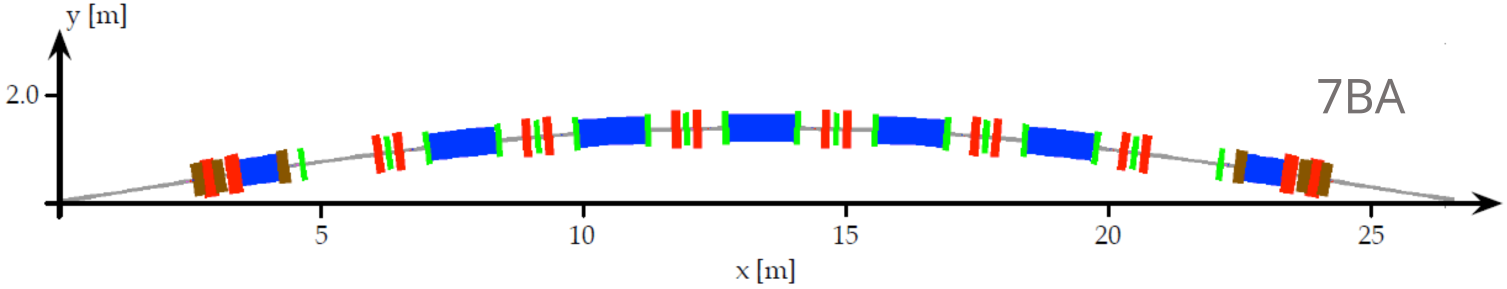
- MAX IV overview and MAX 4^U
- Status of MAX 4^U lattice design
  - Lattice candidate overview
  - Engineering
  - Performance
  - Error modelling and correction
- Summary

The MAX IV Accelerators



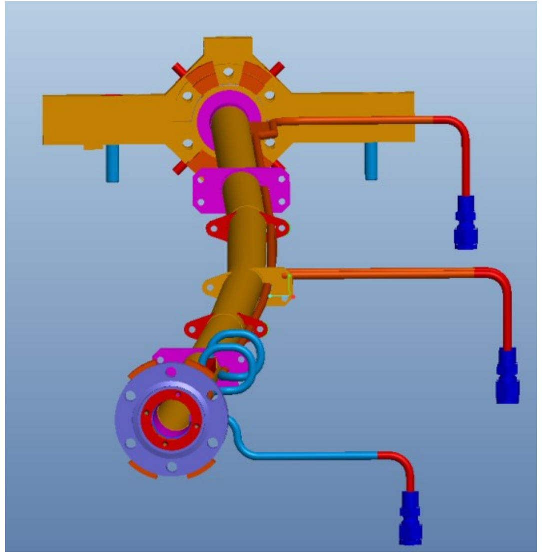
MAX IV 3 GeV Ring: 528 m, 328 pmrad





100 MHz RF

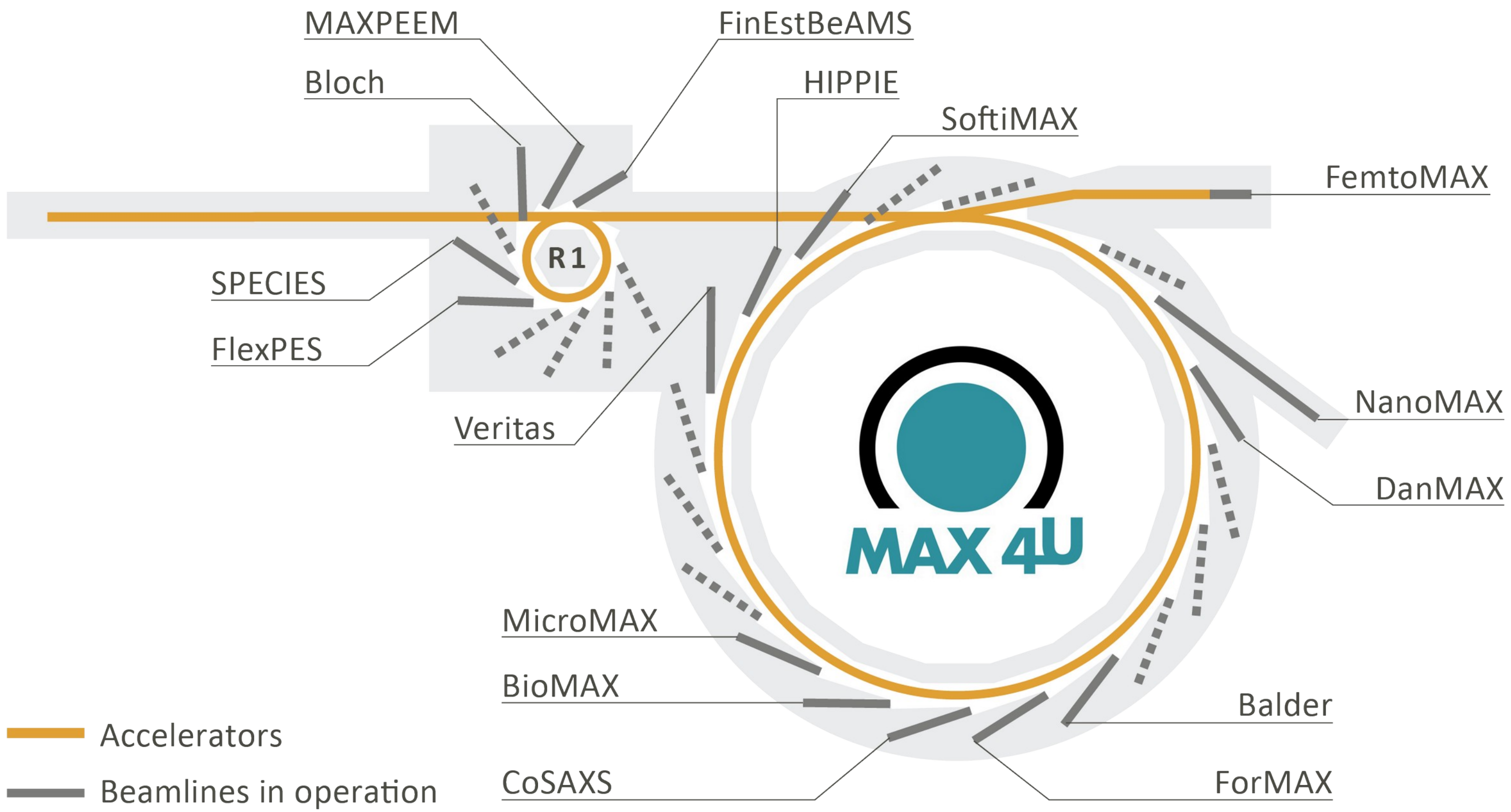
Circular Cu chambers, NEG-coated



Compact magnets

Slide by P. F. Tavares

MAX 4^{U} Conceptual Design



- ❑Emittance ≲ **100 pmrad.**
- ❑Energy : 3 GeV
- ❑Keep shielding wall
- ❑Keep light source positions
- ❑Keep injector - accumulation
- ❑Limited dark period
- ❑Cost-effective
- ❑Realizable until the early part of the next decade

MAX4^{U} status

- Conceptual Design Report (CDR) being produced
  - Goal is to finish by end-of-year
  - Scope encompasses accelerator Physics and Engineering design studies at the conceptual level for two lattice options:
    - **AR** : ***Absolute Requirement*** Lattice that **meets** all MAX 4^{U} requirements at the lowest possible cost.
    - **SG** : ***Stretch-Goal Lattice*** that **surpasses** the MAX 4^{U} emittance requirement accepting an increase in cost.
- The Accelerator CDR does NOT include the Science Case and beamline-related improvement plans, which will part of a separate document
- Decision on a lattice to go on to technical design expected spring next year

Lattice design: Overview

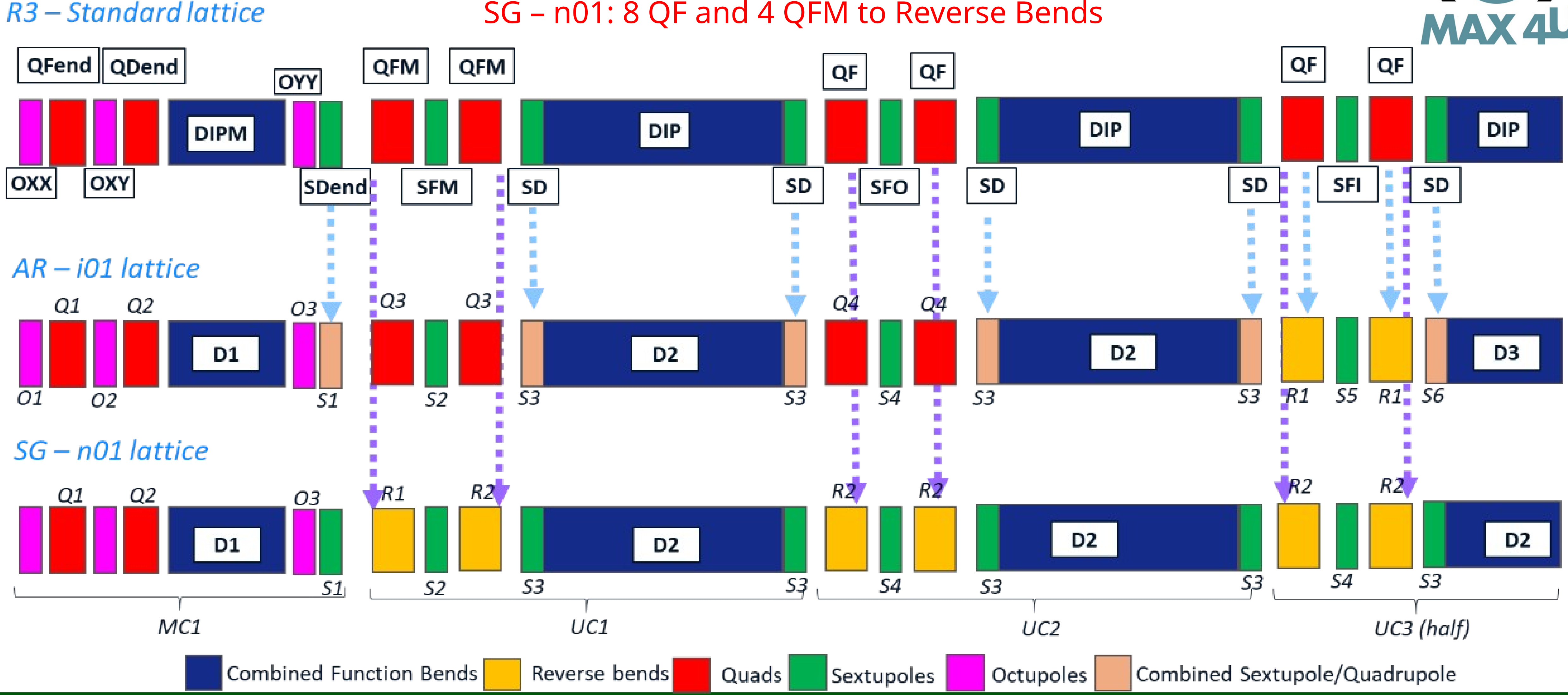
Standard conditions for presented results, deviations will be highlighted

- 8 pm rad vertical emittance
- Physical apertures included
- No lengthening via harmonic cavities
- No IBS (treated separately)
- No IDs (on to-do list)
- "Reduced" error model corresponding to expected errors post-correction w. BBA, LOCO, etc.

R3 Standard Lattice Vs MAX 4U Lattices

Slide by A. Sharma

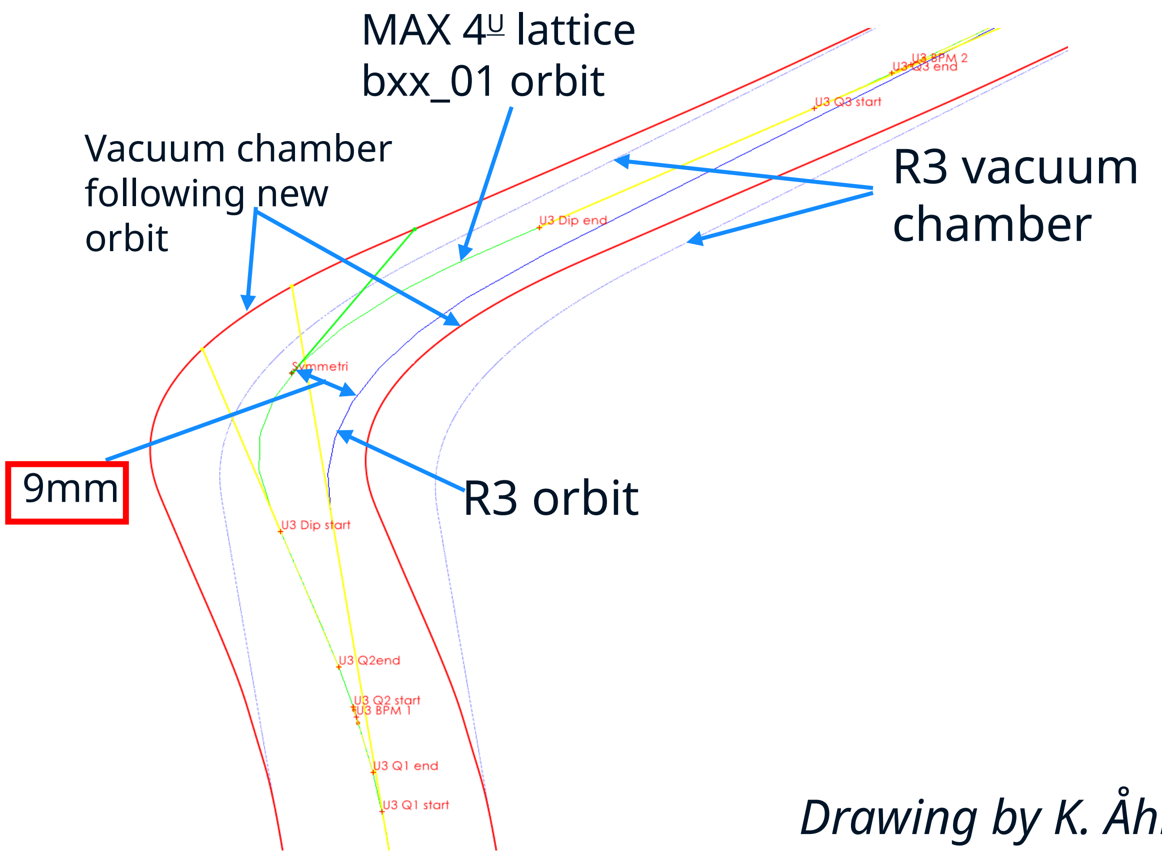
AR – i01: 4 QF to RB, 12 Sextupoles changed to combined function
SG – n01: 8 QF and 4 QFM to Reverse Bends



	R3 (as designed)	AR (i01-04-01-01)	SG (n01-01-01-01)	Units
Natural Emittance	328	95	65	pm rad
Natural Energy spread	7.69	7.55	8.46	10^{-4}
β @ long straights (x/y)	9.0 / 2.0	6.8 / 3.3	4.2 / 4.4	m
Natural Bunch length	8.8	6.7	5.7	mm
Betatron tunes (x/y)	42.20, 16.28	55.28, 16.20	58.29, 17.15	
Natural chromaticity per achromat	-2.50, -2.51	-4.46, -2.83	-4.87, -2.88	
Corrected chromaticity	+1, +1	+2, +2	+2, +2	
Momentum compaction factor	[3.06, 1.63, 15.8]	[0.944, 2.92, -4.49]	[0.54, 3.63, -4.47]	10^{-4}
Total abs. deflection angle	360	395	442	deg
M1 block deflection angle	1.50	1.50	1.29	deg
Max. orbit shift	0	8.8	21.3	mm
Radio-frequency change	0	-1.91	TBD	kHz
Energy loss per turn	364	414	474	keV
Damping times (H/ V/ L)	15.73 / 29.05 /25.19	14.75 / 25.51 / 20.08	11.44 / 22.29 / 21.18	ms
RF Voltage	1.8	1.0	1.0	MV

Vacuum System : chamber design

- For the AR lattice, a new chamber would be VERY similar to the existing one
- Why not keep the chamber and bend it into the new shape ?
- Do not even need to break vacuum.
  - *Cheaper*
  - *Faster to install*
  - *Faster to conditioning*

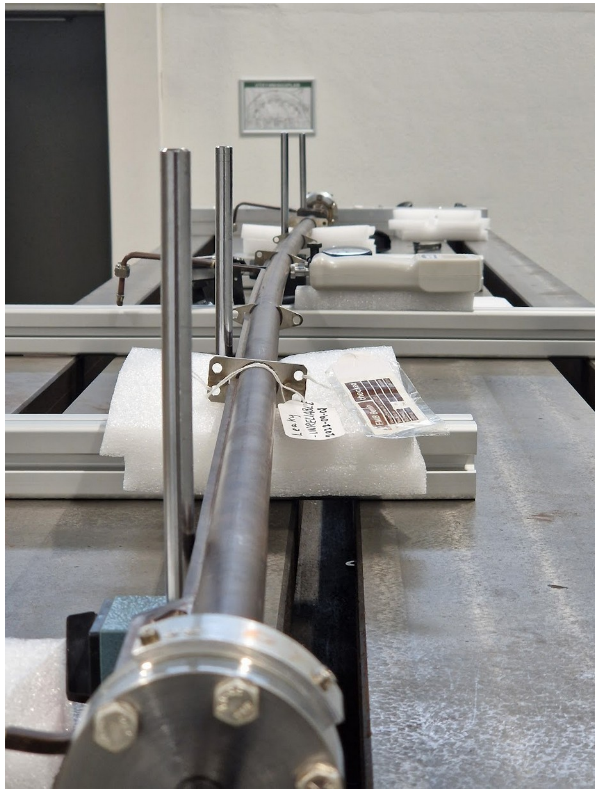


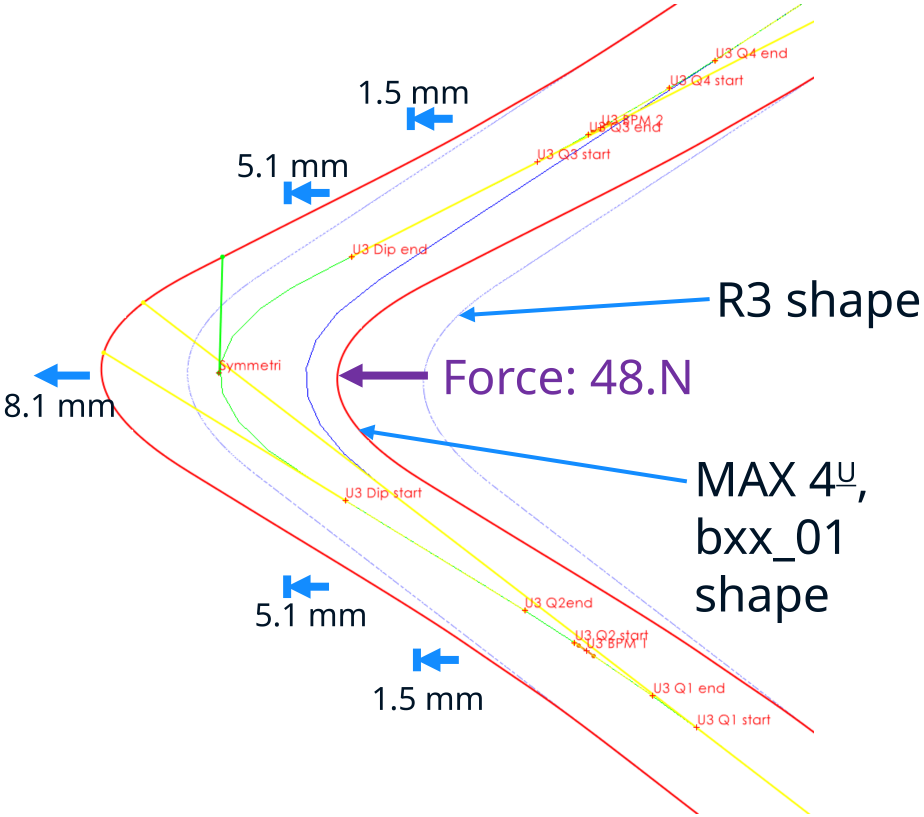
Slide by P. F. Tavares

Drawing by K. Åhnberg

Bending tests

- Bending vacuum chamber to a path following MAX 4^{U} –bxx_01
- Validation of the FEA

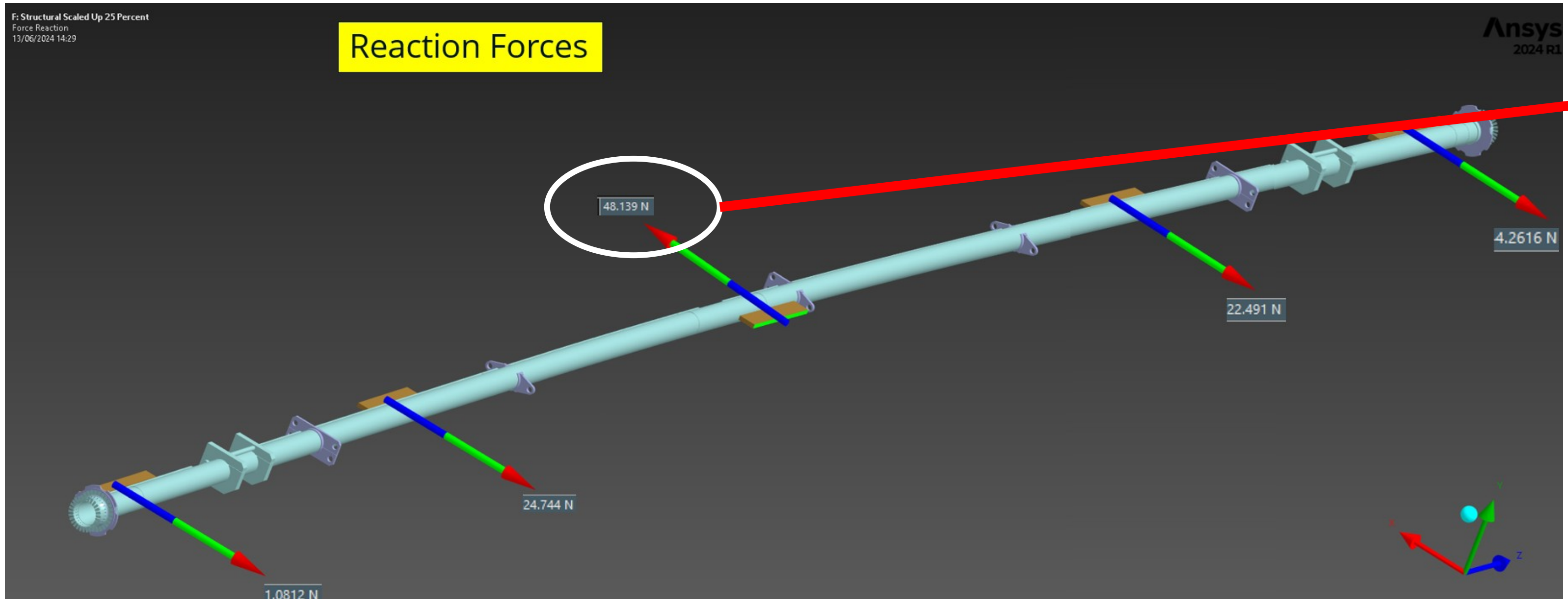




Slide by E. Al-Dmour

FEA and Bending Tests

Slide by E. Al-Dmour



Lattice candidates: Magnet strengths

(green)	Existing magnet can do the job
(yellow)	Existing magnet can do the job
(orange)	Existing magnet can do the job
(magenta)	Need to add material to the existing blocks or build a new block
(black)	New or re-machined block needed
(red)	No solution identified yet

"Can it be built?"
"Yes, both of them."

Since Dec. 2024 the lattice design work has coalesced around two candidates; the AR (Absolute Requirement) and SG (Stretch Goal) lattices.
In both cases there are engineering solutions to construct magnets capable of delivering the needed fields.

	magnet	location	T.m	T	T/m	T/m²
c.f. bends	D1	MC1,2	0.262	-4.014		
c.f. bends	D2	UC1,2,4,5	0.524	-9.97		
c.f. bends	D3	UC3	0.678	-10.05		
r	R1	UC3	-0.038	8.05		
quadrupoles	Q1	MC1,2		9.93		
quadrupoles	Q2	MC1,2		-6.61		
quadrupoles	Q3	UC1,5		6.37		
quadrupoles	Q4	UC2,4		8.33		
sextupoles	S1	MC1,2		0.226	-149	
sextupoles	S2	UC1,5			270	
sextupoles	S3	UC1,2,4,5		-0.229	-236	
sextupoles	S4	UC2,4			271	
sextupoles	S5	UC3			264	
sextupoles	S6	UC3		0.006	-231	
octupoles	O1	MC1,2				900
octupoles	O2	MC1,2				-1553
octupoles	O3	MC1,2				2489

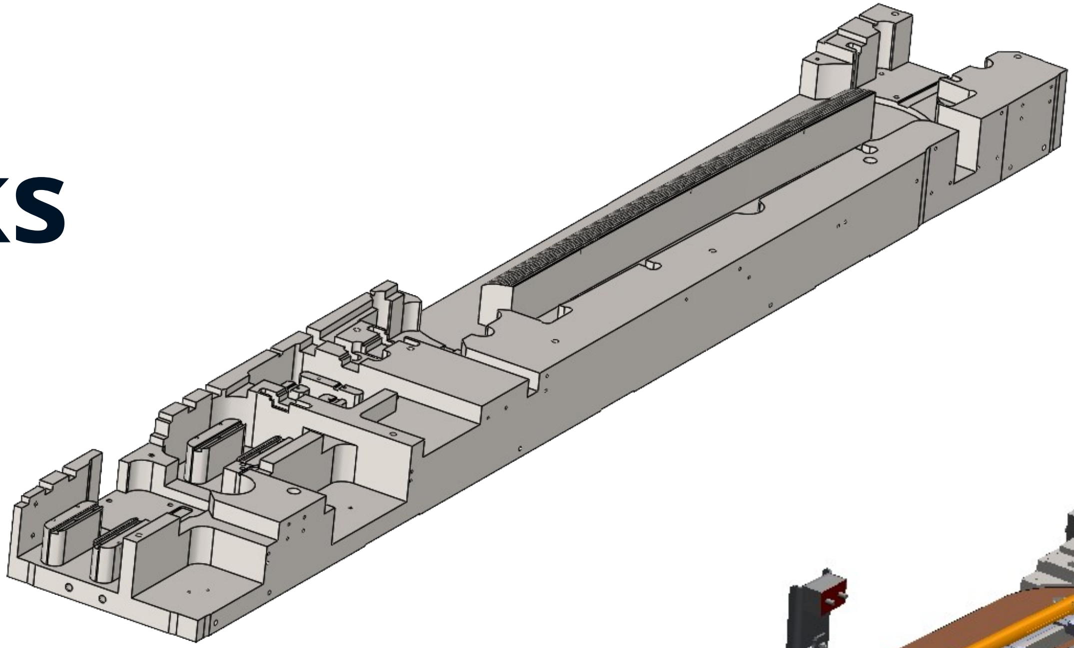
AR lattice

	magnet	location	T.m	T	T/m	T/m²
c.f. bends	D1	MC1,2	0.227	-0.48		
c.f. bends	D2	UC1,2,4,5	0.607	-10.51		
rb	R1	UC1,5	0.008	4.75		
rb	R2	UC2,3,4	-0.038	8.05		
quads	Q1	MC1,2		11.83		
quads	Q2	MC1,2		-10.74		
sextupoles	S1	MC1,2			-115	
sextupoles	S2	UC1,5			238	
sextupoles	S3	UC1,2,4,5			-300	
sextupoles	S4	UC2,4			331	
octupoles	O1	MC1,2				995
octupoles	O2	MC1,2				-1581
octupoles	O3	MC1,2				-4637

SG lattice

Magnet blocks

- Solid low carbon steel
- Integrated consecutive magnet elements
- Split in beam plane



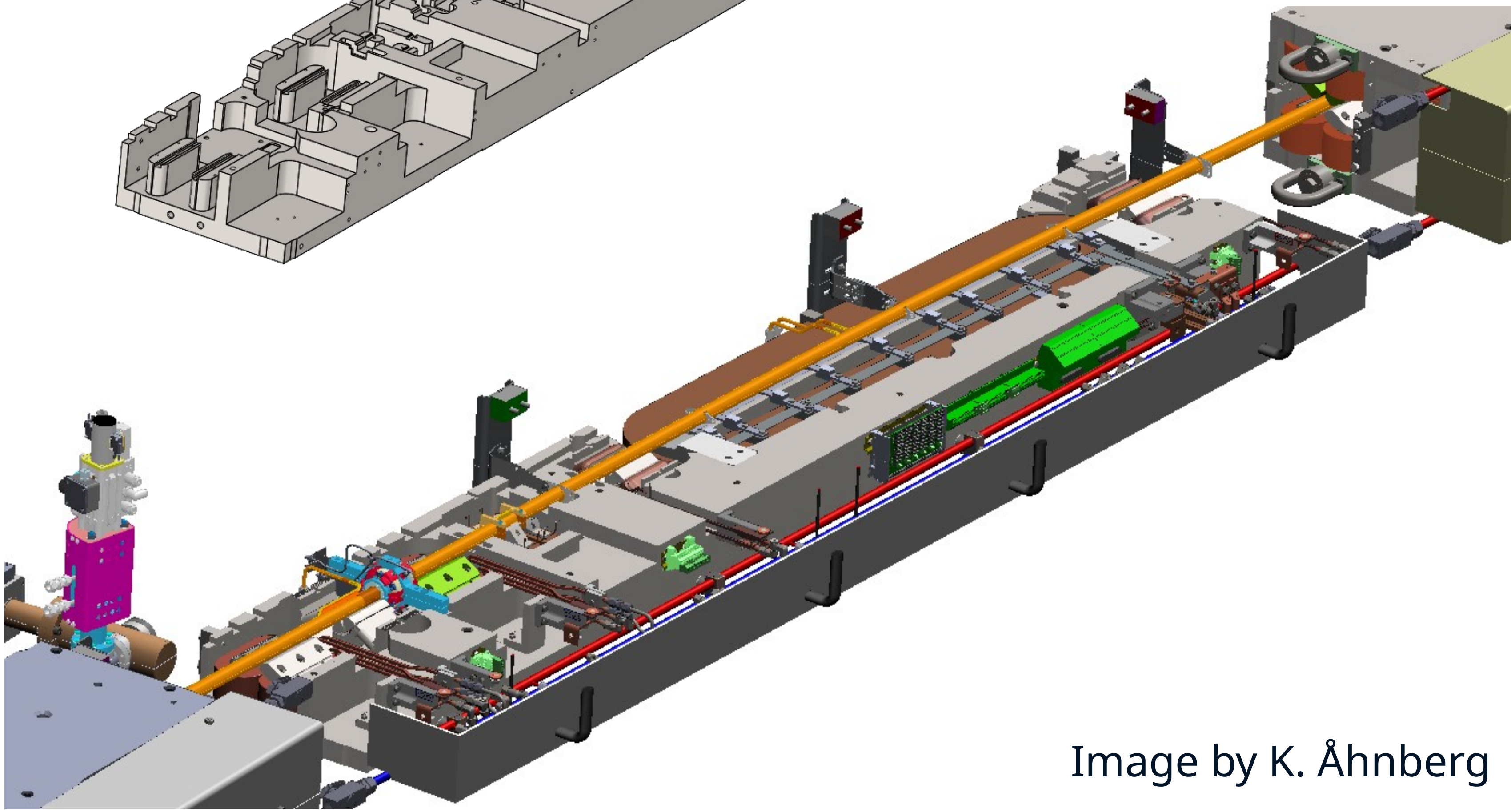
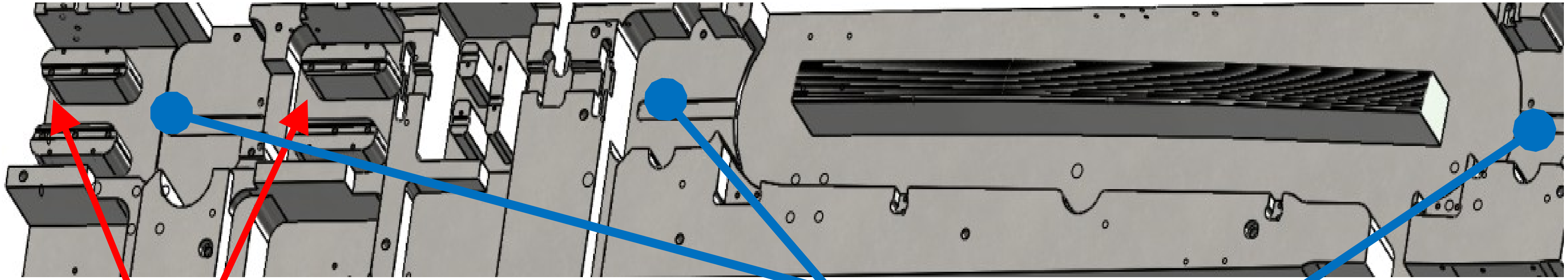
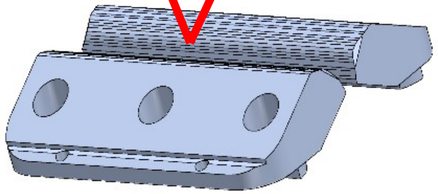


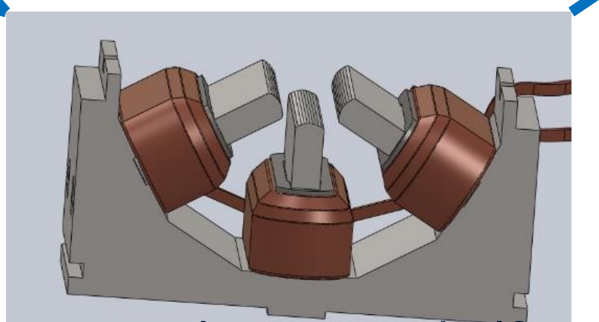
Image by K. Åhnberg

A closer look

- Poles of a dipole, pole roots of quadrupoles and correctors are machined out of the iron block.
- Sextupole and Octupole magnets are **separate units** mounted into guiding slots in a block as well as pole tips of quadrupoles and correctors







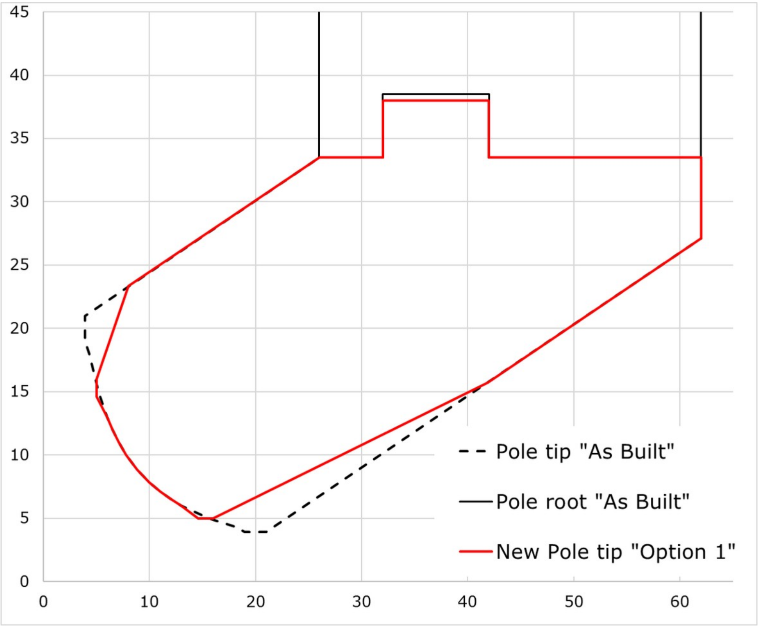
sextupole magnet half

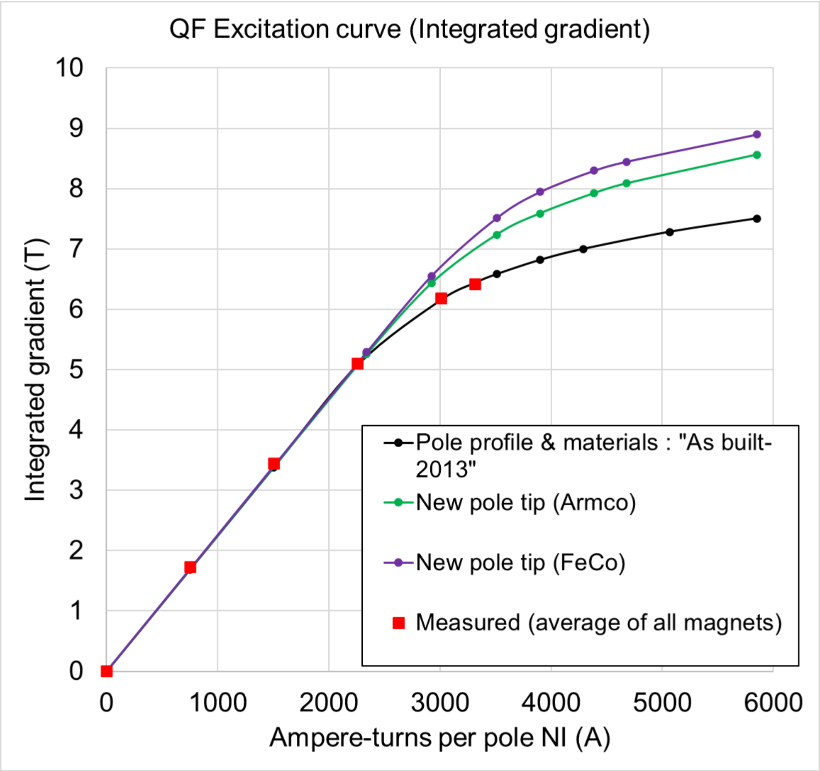
Figures by A. Vorozhtsov

Exchanging pole tips

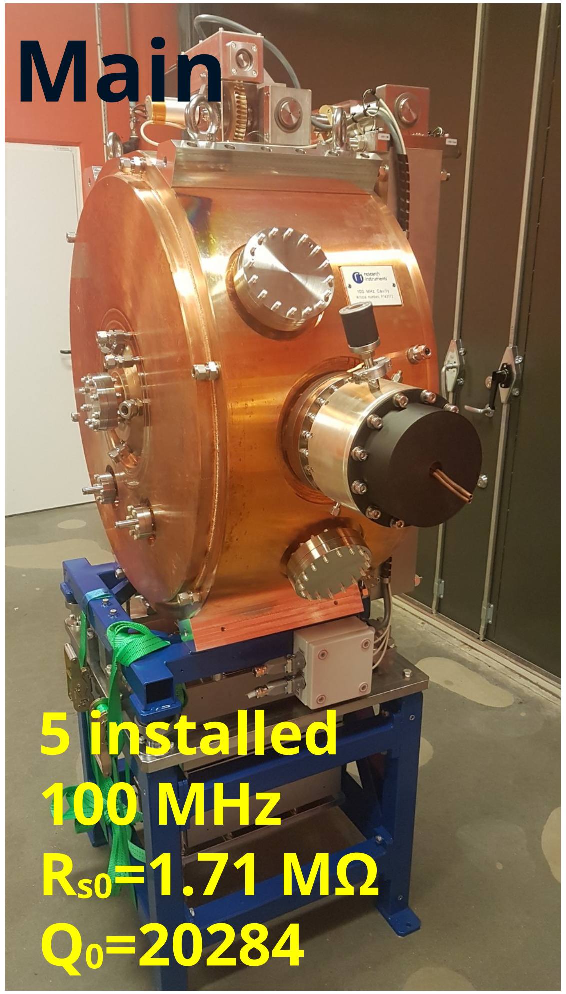
- New pole profile made of Armco or FeCo
- Pole roots, coils & magnet overall dimensions remain the same
- Integrated gradient increases from 6.5 T to 8.0 T
- Reduced good field region radius 10 mm → 7.0 mm

Figures by A. Vorozhtsov



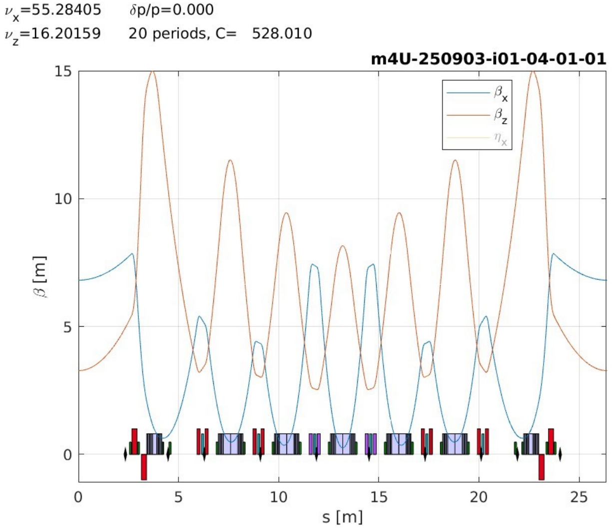


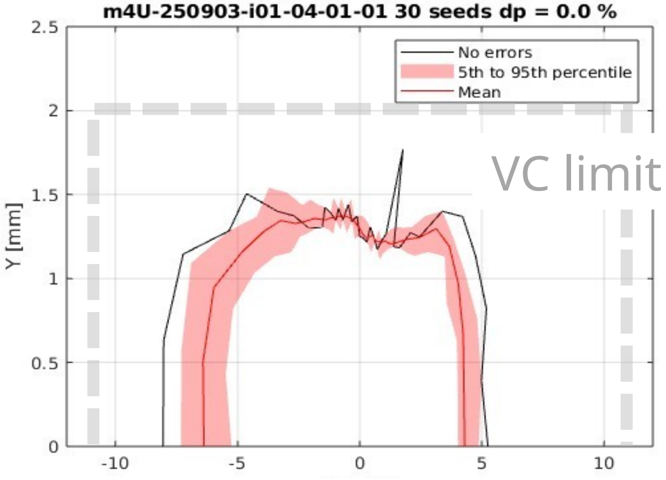
The Triple RF system at hand in MAX IV:

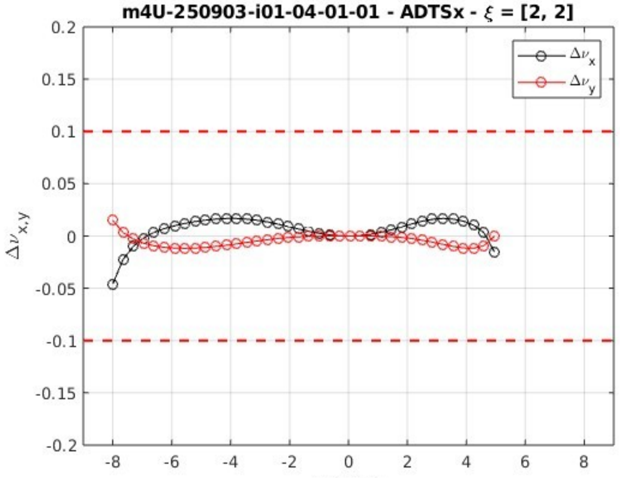


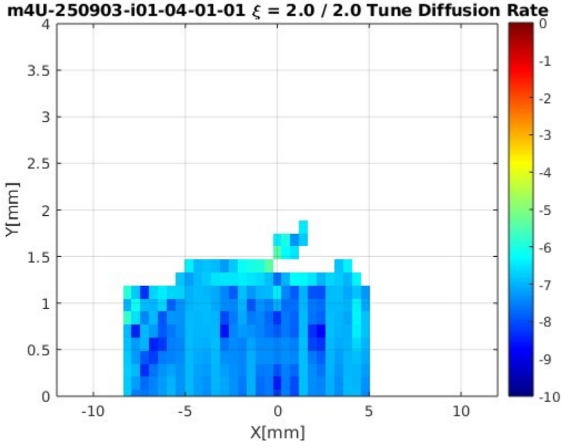
Slide by Åke Andersson

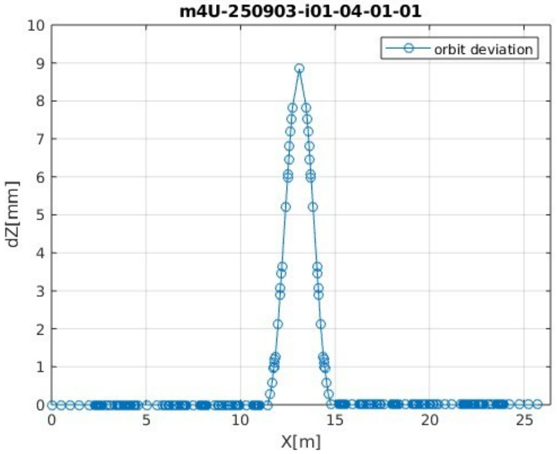
AR (Absolute Requirement) lattice: 95 pm rad

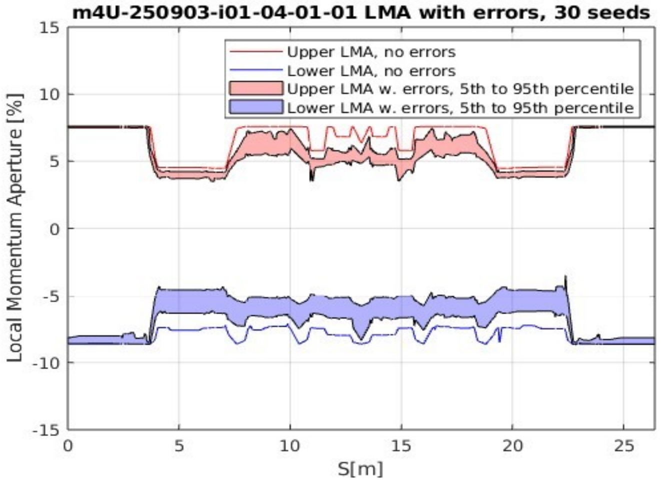


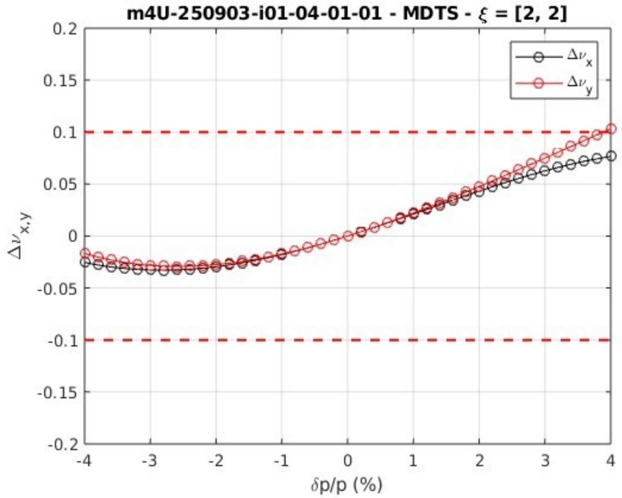


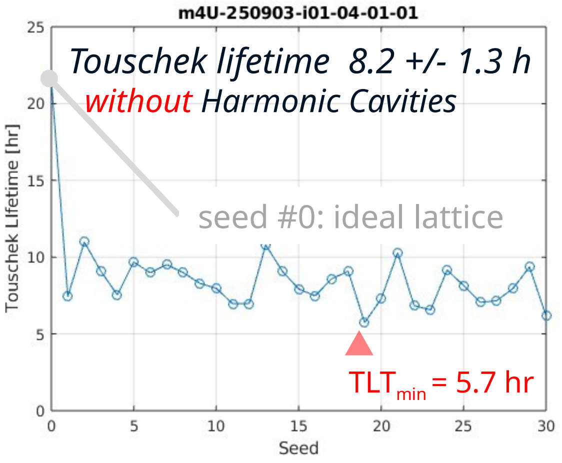




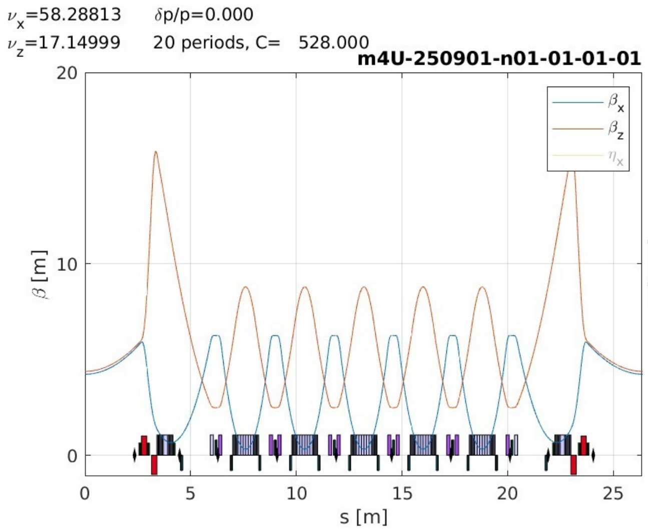


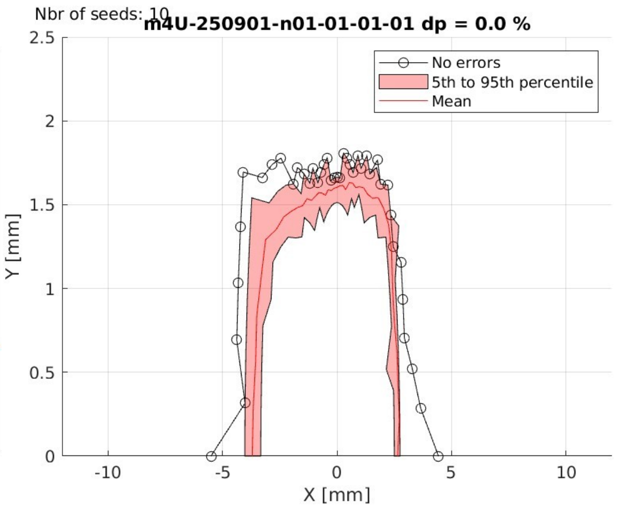


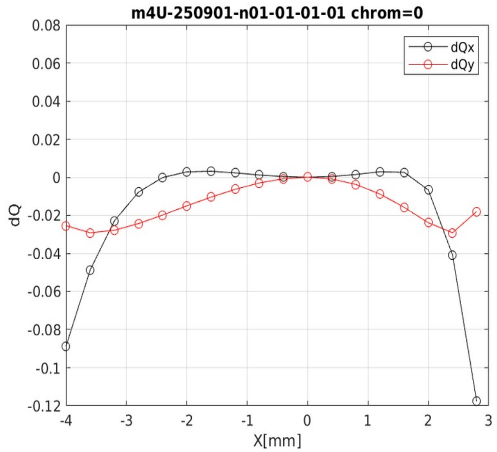


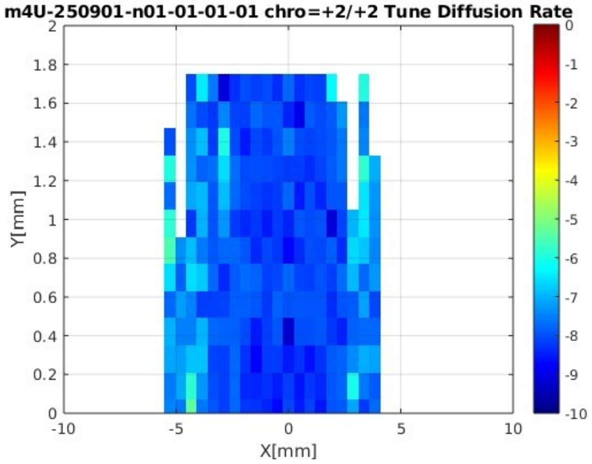


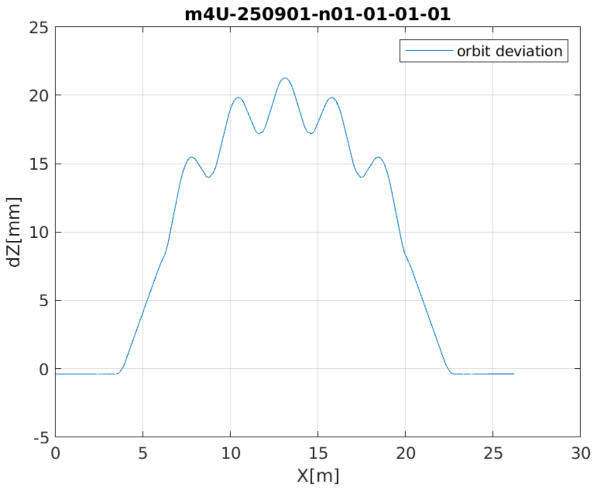
SG (Strech-Goal) lattice: 65 pm rad

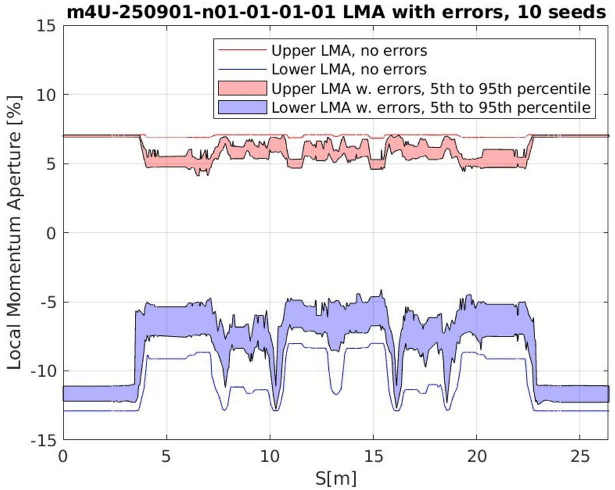


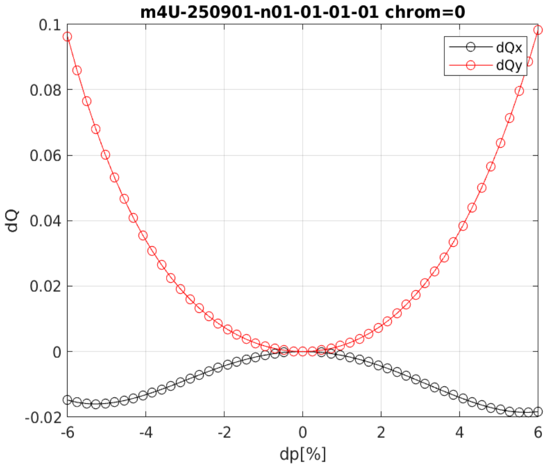








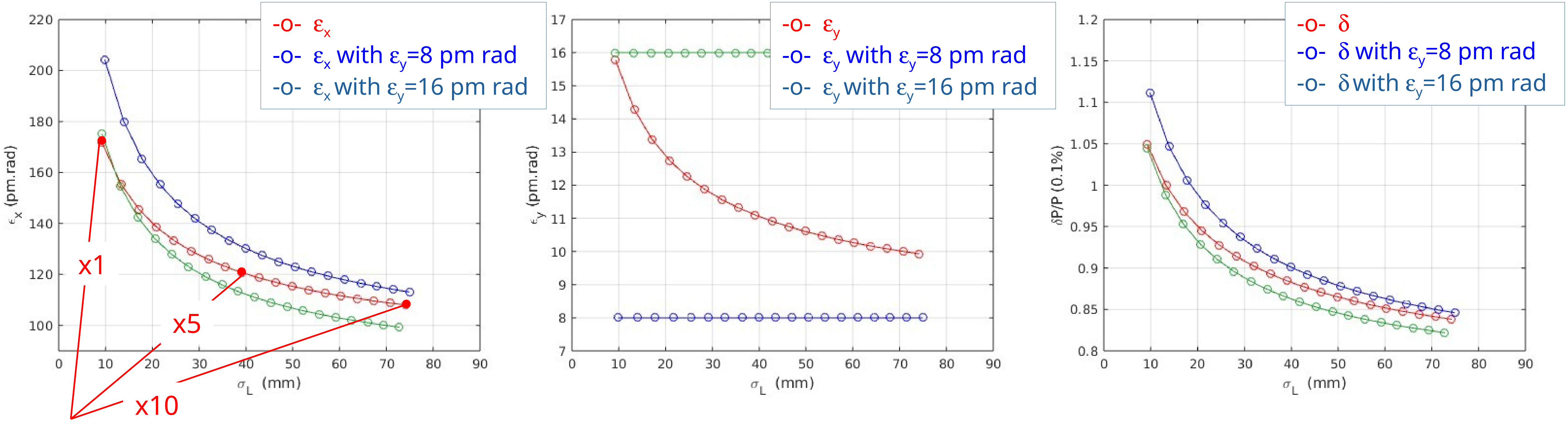




Touschek lifetime ≃ 19.1 +/- 5.4 h

without Harmonic Cavities

function `atcalcIBS` part of the suite developed at MAX IV



HC stretching factor

Slide by M. Apollonio

Error models

Error models include (systematic and random):
- Magnet alignment errors within each block
- Block/girder alignment errors
- BPM calibration errors
- Field errors (power supply calibration, higher order multipoles, etc.)

Reduced Model, alignment

	Magnet	Girder	BPM
Sway [μm]	15	0	5
Heave [μm]	15	0	5
Surge [μm]	0	0	0
Pitch [μrad]	0	0	0
Yaw [μrad]	0	0	0
Roll [μrad]	100	0	10

In use during lattice development. Early guesstimate to provide beta-beats, etc. equivalent to lattice post-correction

Updated Model, alignment

	Magnet	Girder	BPM
Sway [μm]	4	27	3
Heave [μm]	9	21	3
Surge [μm]	0	16	0
Pitch [μrad]	0	21	0
Yaw [μrad]	0	21	0
Roll [μrad]	100	157	100
Sag		20	

Relies on estimates of achievable alignment tolerances from SAM, as well as measurements of 3 GeV ring magnet block series production and installation

Lattice correction: overview

Simulated commissioning: full chain remains to be implemented and tested.

Implementation status for various components differs:

- Threading: to be done
- Beam-Based Alignment (BPM calibration): simplified (part of error model)
- Orbit correction: fully functional
- Beam-Based Girder Re-alignment: to be done
- LOCO: recently implemented for both lattices, results being evaluated
- NOECO: to be done

Summary

- CDR work ongoing; aim is to finalise it around end-of-year 2025.
- Two lattice options being studied; Absolute Requirement (AR) @ 95 pm rad and Stretch-Goal (SG) @ 65 pm rad.
- Both candidates appear buildable

Complementary Material:
Status

To-Do list

- Full simulated commissioning
- Investigations into implementing/improving correction methods (girder re-alignment, LOCO, NOECO)
- Continue iterating with engineering
- Include insertion devices
- Test off-phase on-axis injection (capture)
- ***Continue to optimise lattices!***

Lattice Design Status

	AR	SG
Linear lattice matching	Done	Done*
Non-linear optimization	Done	Done
Amplitude and Momentum Dependent Tune shifts	Done	Done
Dynamic Aperture	Done	Done
Local Momentum Aperture	Done	Done
Touschek Lifetime	Done	Done
Intrabeam scattering	Done	Ongoing
Error Analysis and Correction	Reduced Errors	Reduced Errors
Orbit and Tune correction	Done	Done
BBA	Simplified	Simplified
LOCO	Initial studies	TBD
Injection Trajectory	Done	Done
Injection Efficiency	Done	TBD
Impact of Insertion devices	TBD	TBD

* Minor fixes remaining: orbit shift in long straights, turn R1 bend into pure quadrupole

R3 lattice: 328 pm rad

************* Summary for 'R3 -- MAX IV 3 GeV ring' ************

2025-Apr-30 10:32:54

Energy: 3.0 GeV

Circumference: 528.0 m

Full tunes H/V: 42.20 / 16.28

Average Betas: 3.73 / 6.85 m

Average Dispersion: 0.0298 m

Momentum Compaction Factor: $(3.06e\text{-}04\ d + 1.62e\text{-}04\ d^2 + 1.59e\text{-}03\ d^3)$

Chromaticity H: +1.02

Chromaticity V: +0.99

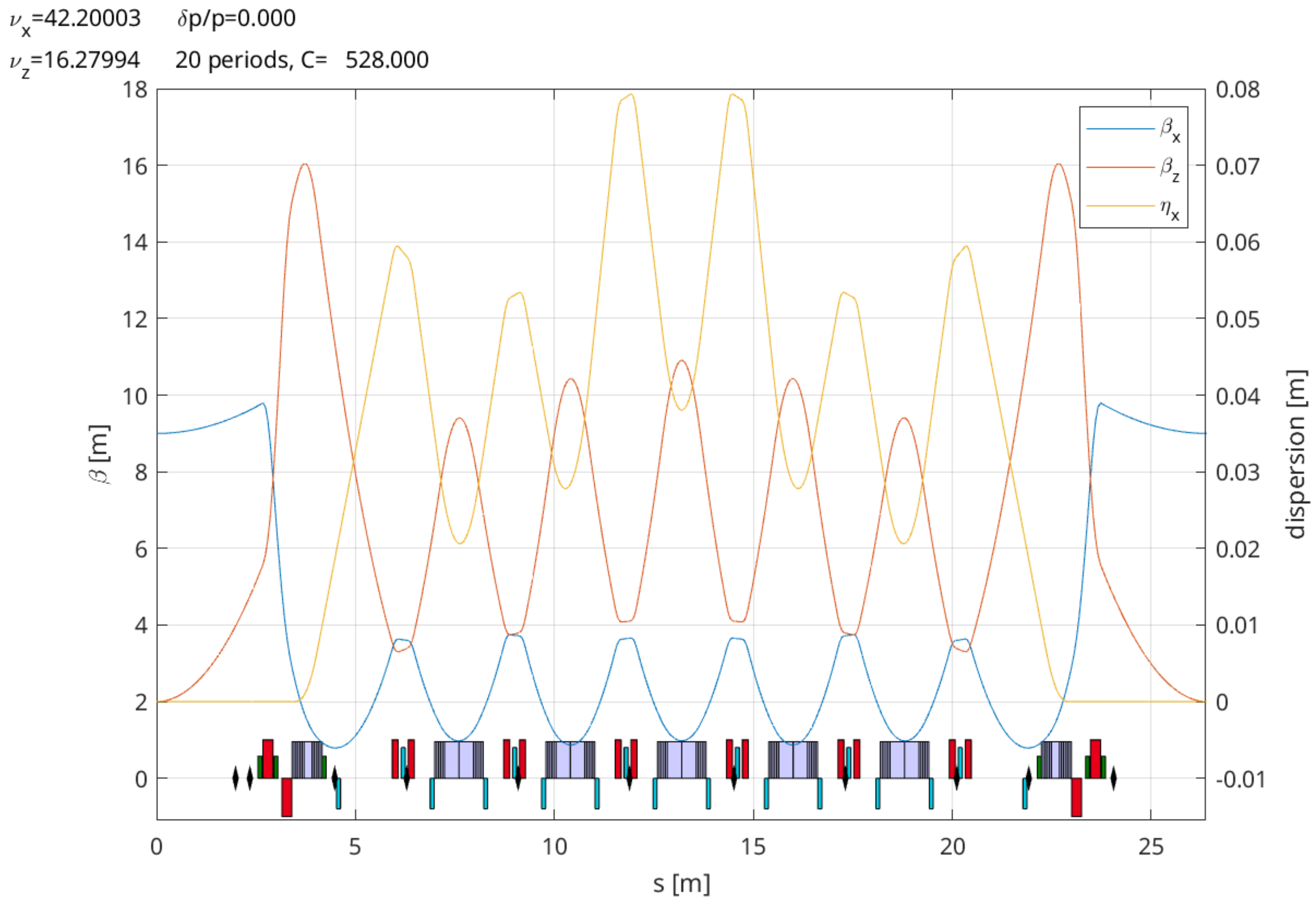
Increased to 1.4 / 1.4 to avoid partial beam losses

Radiation Loss: 363.8 keV

Natural Energy Spread: 0.08 %

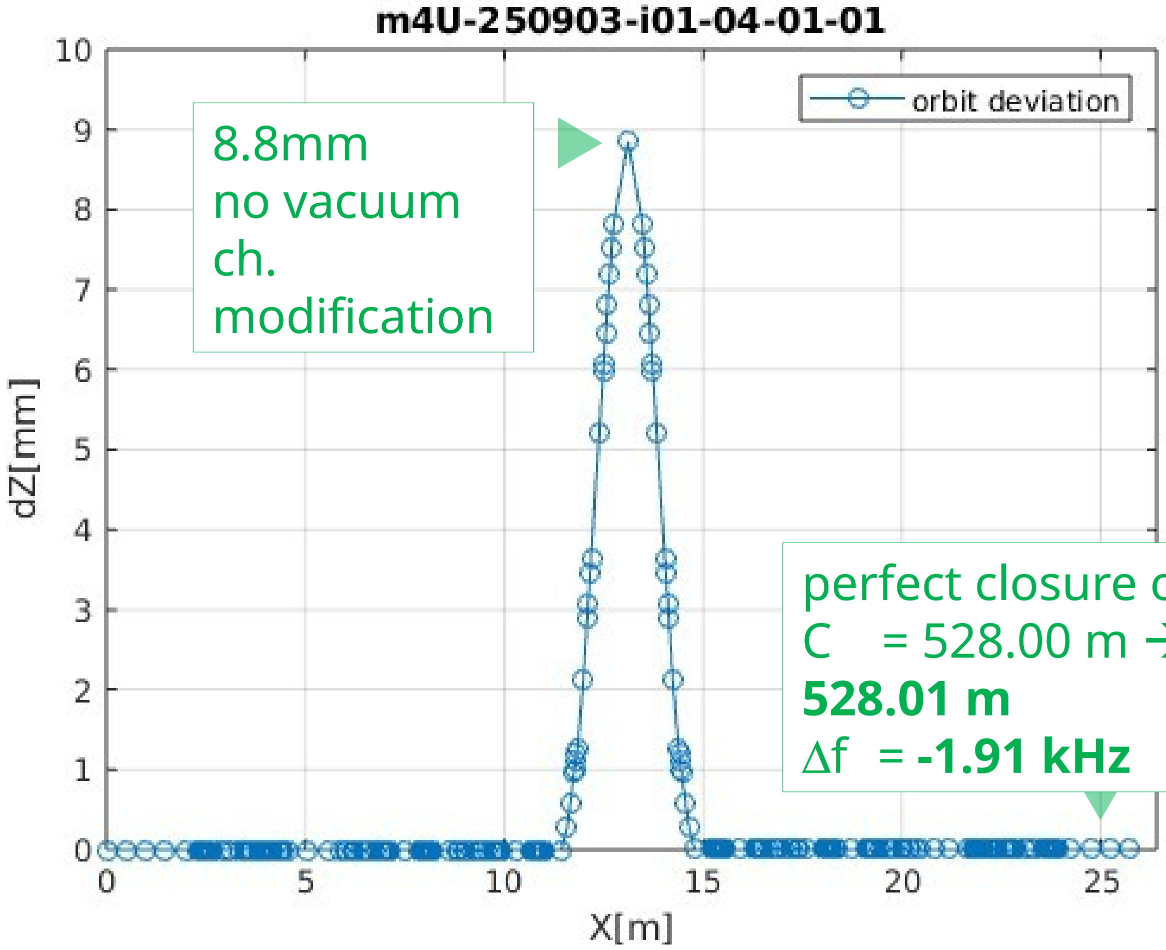
Natural Emittance: 328.2 pmrad

RF Voltage: 1.8 MV



Complementary Material:
AR lattice

AR orbit deviation



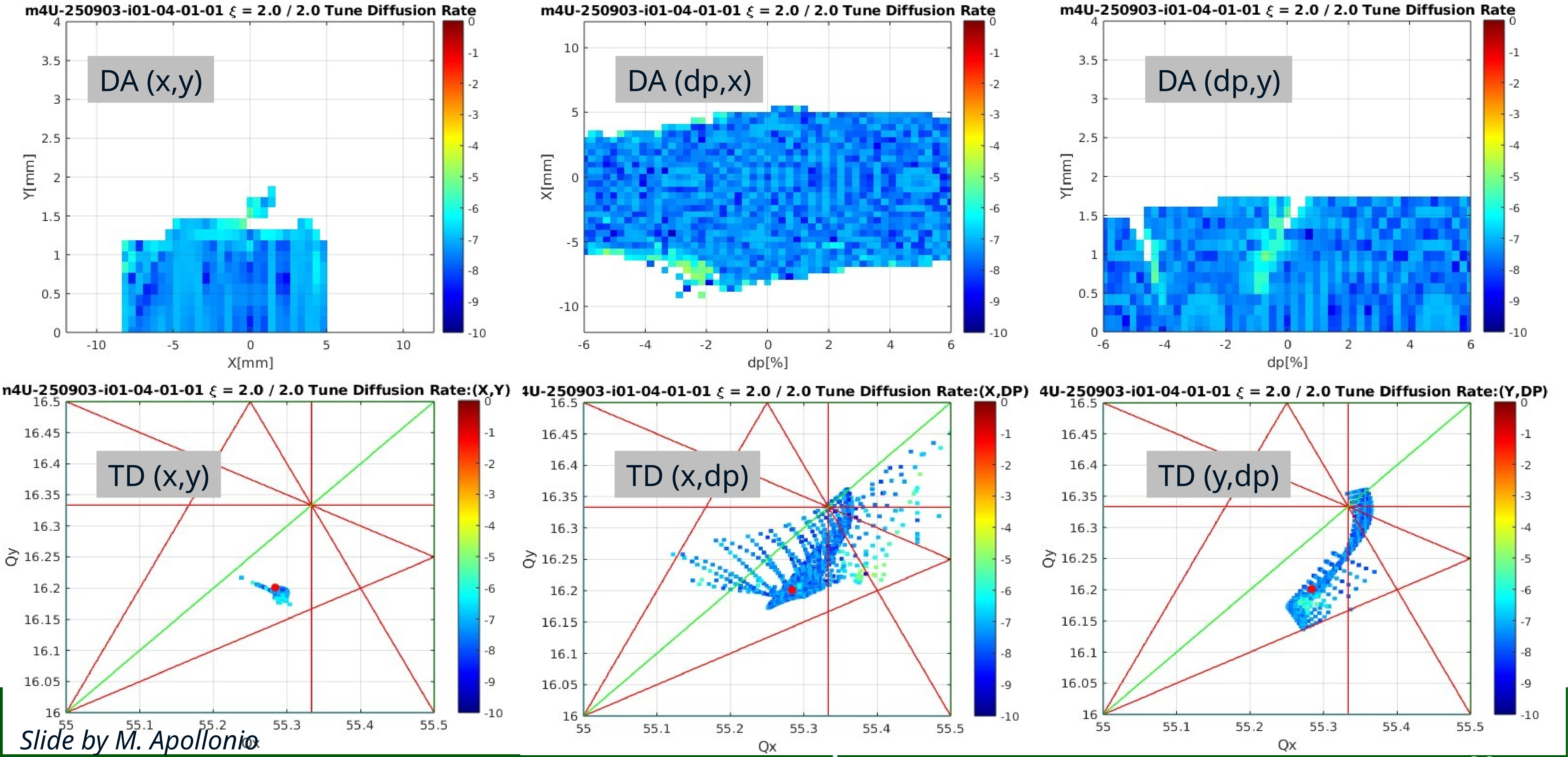
8.8mm
no vacuum ch. modification

perfect closure of orbit
C = 528.00 m → **528.01 m**
Δf = **-1.91 kHz**

Slide by M. Apollonio

AR Diffusion Maps / Tune Footprint – ξ = [2,2]

ideal lattice



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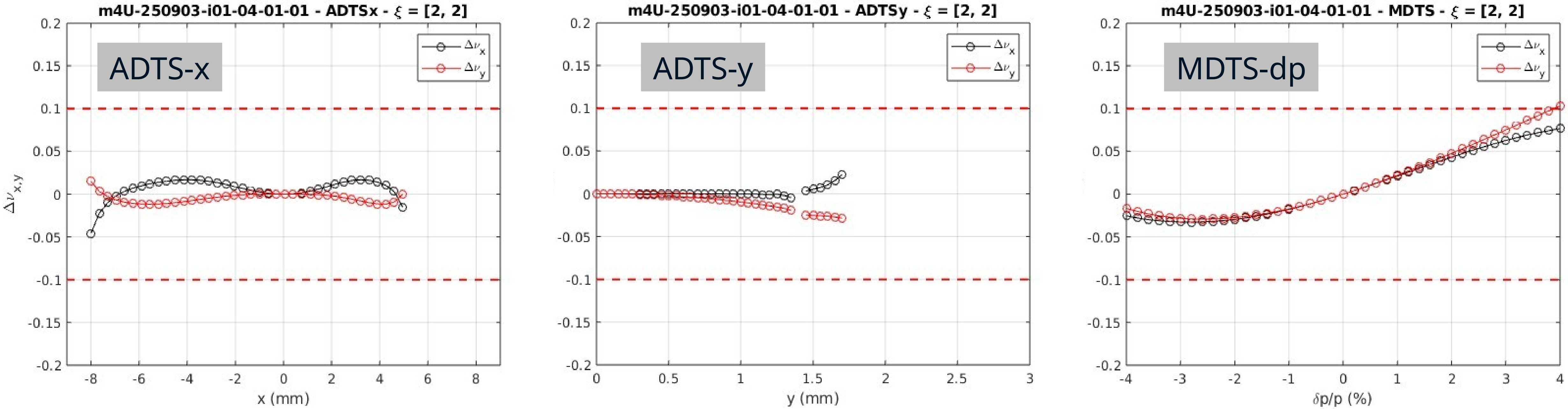
AR ADTS / MDTS – ξ = [2,2]

ideal lattice



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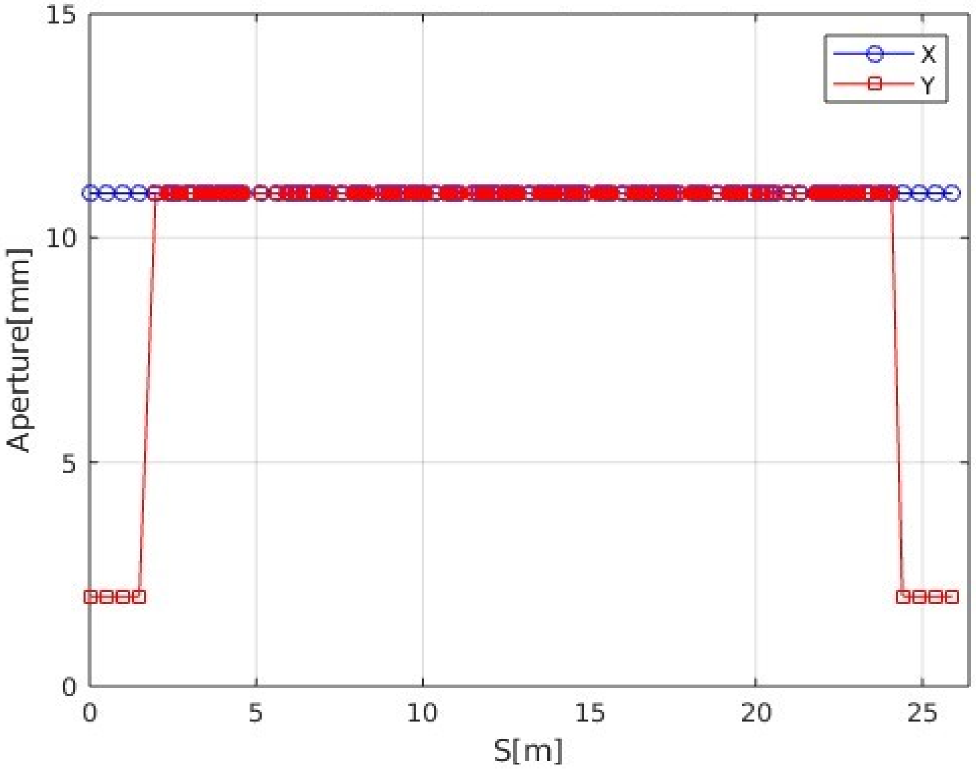
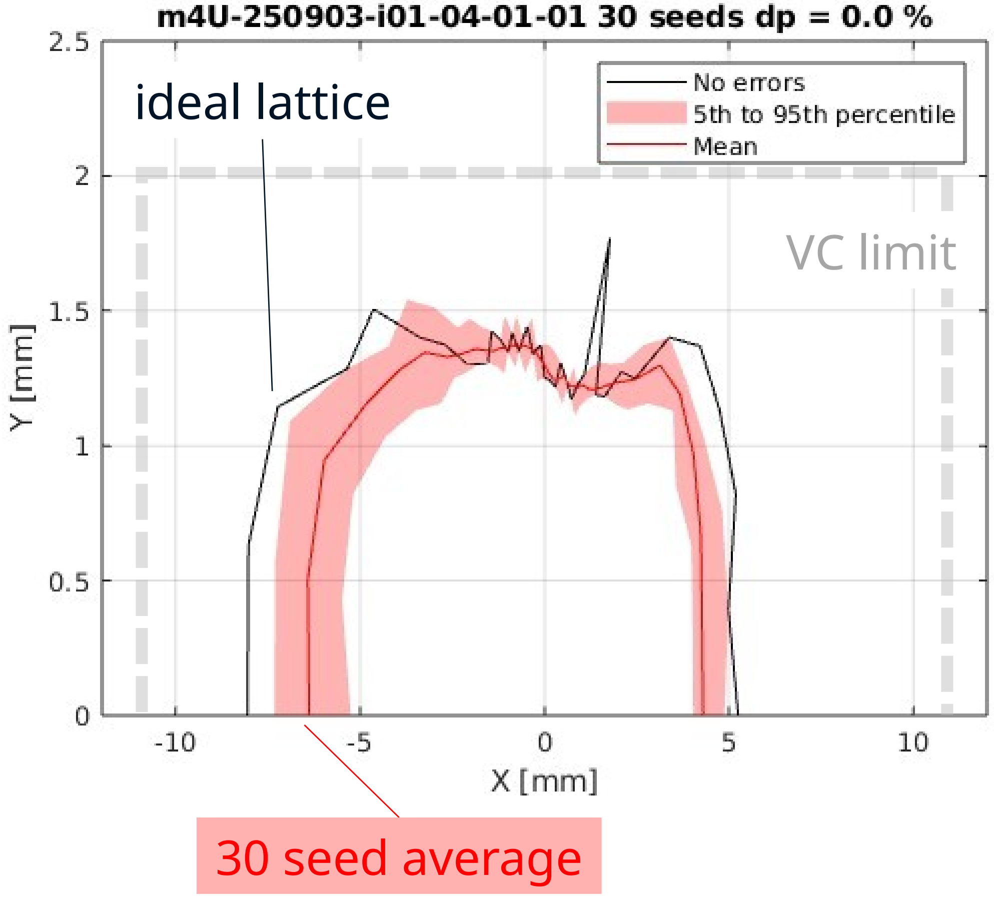
AR Dynamic Aperture

reduced error model (1)

(1) see M. Sjöström's presentation



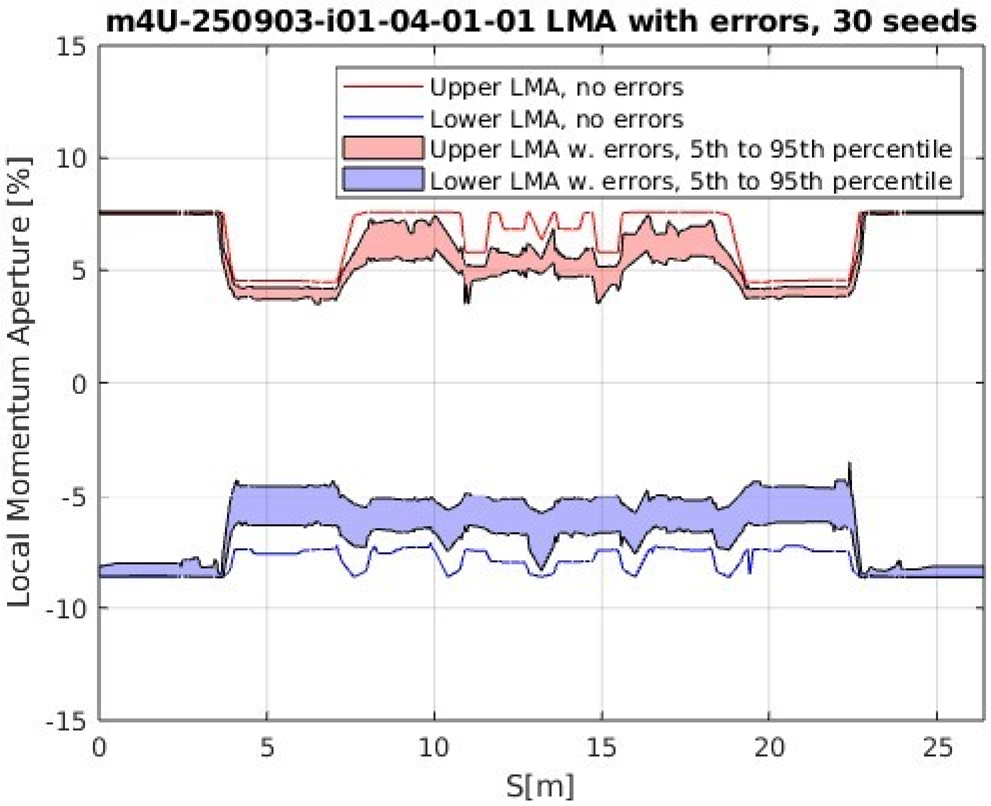


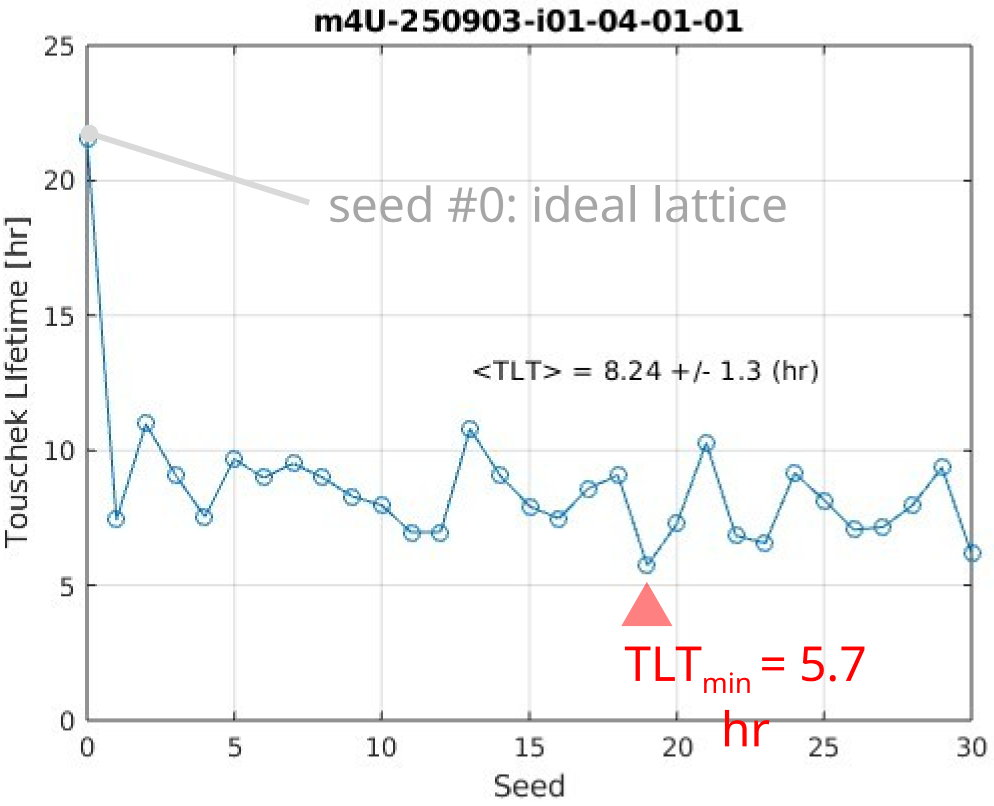
Slide by M. Apollonio

AR Local Momentum Aperture

reduced error model (1)

(1) see M. Sjöström's presentation



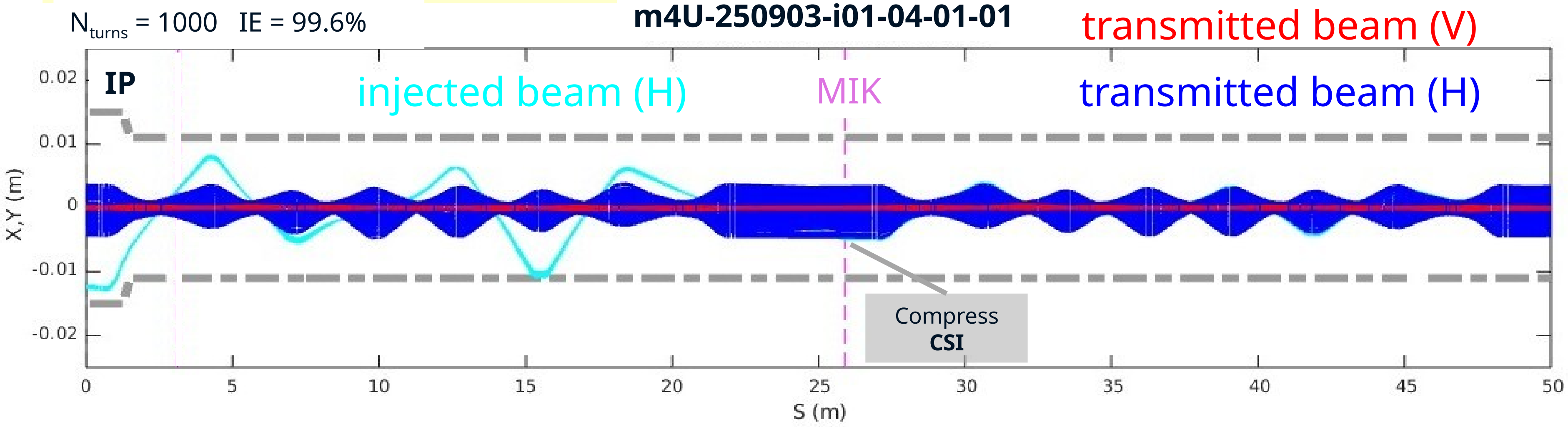


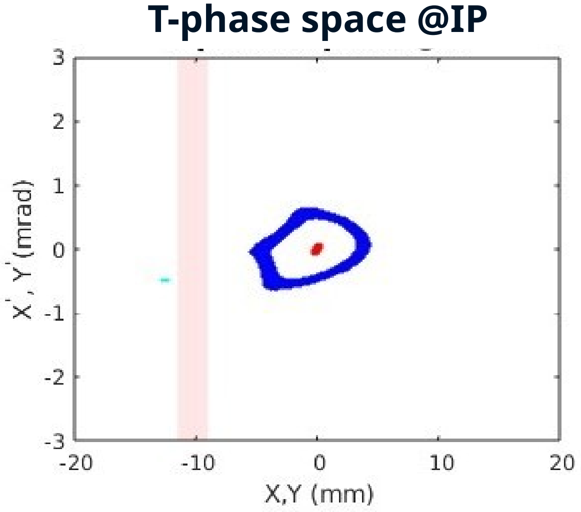
Slide by M. Apollonio

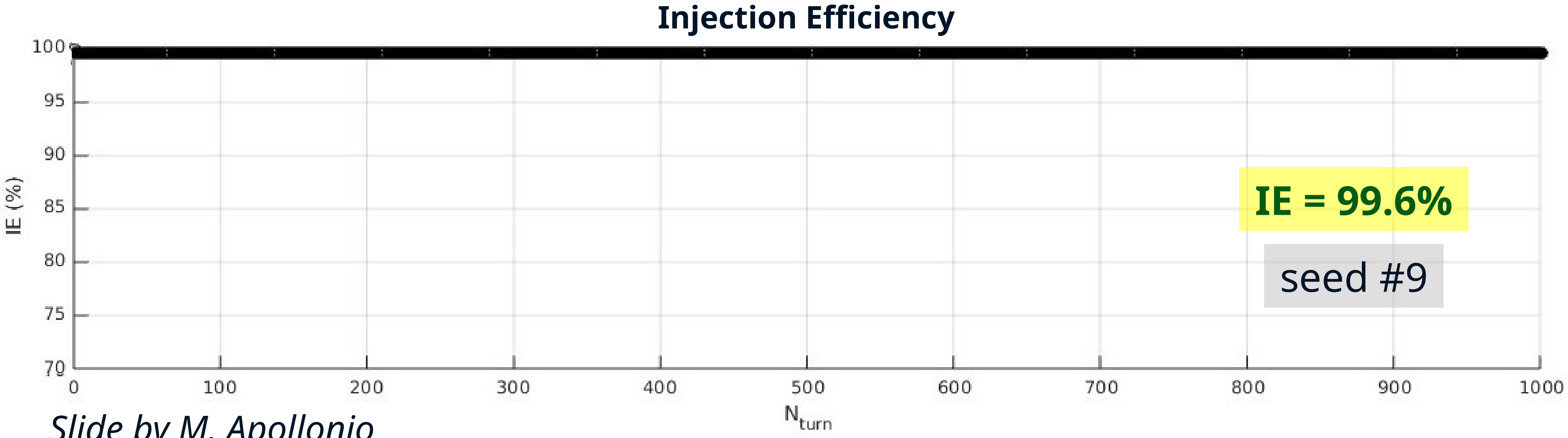
Complementary Material:
Injection

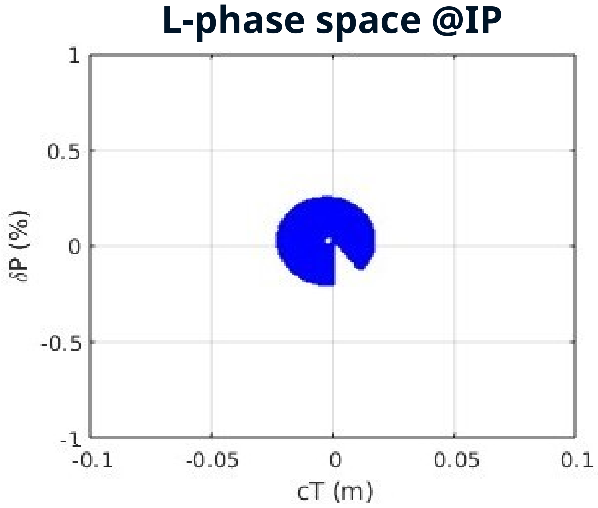
AR OFF-axis injection – photo-gun source

S. Thorin's elegant simulation: PG TR3 exit









Slide by M. Apollonio

Off-phase injection

Off-phase injection /accumulation into MAX 4U is enabled by

- ❑ full energy injector linac: small injected beam phase-space volume.
- ❑ low RF frequency (100 MHz): longer time in-between electron bunches in the ring

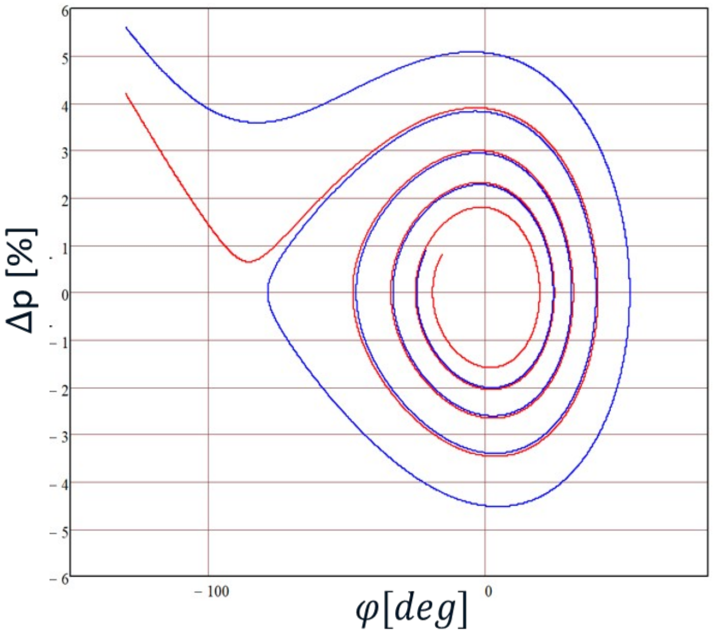
Off-phase injection allows:

- ❑ Small horizontal aperture insertion devices
- ❑ Better top-up transparency
- ❑ Accumulation into restricted dynamic aperture

Slide by P. F. Tavares

Off-phase injection

- Injected beam comes into the ring with a time (phase) offset with respect to the already circulating electron bunches
- Injected beam is kicked on-axis by a very fast kicker magnet. The stored beam is not perturbed and the injected beam damps down to the centre of the bucket after a few tens of ms



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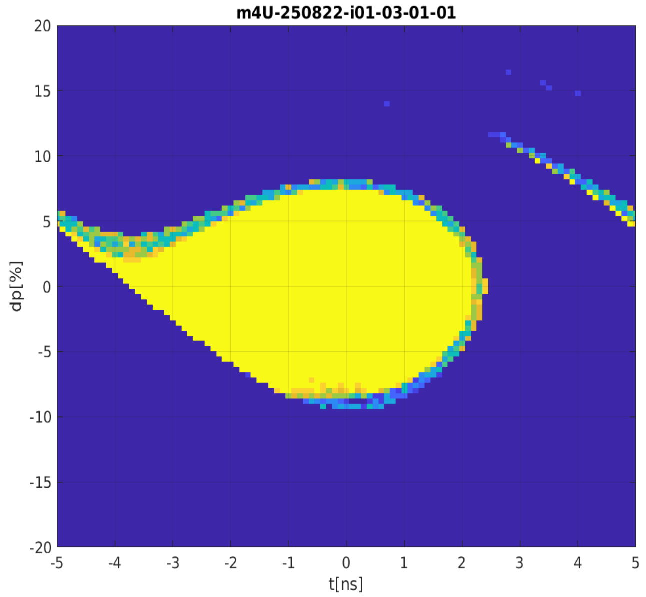
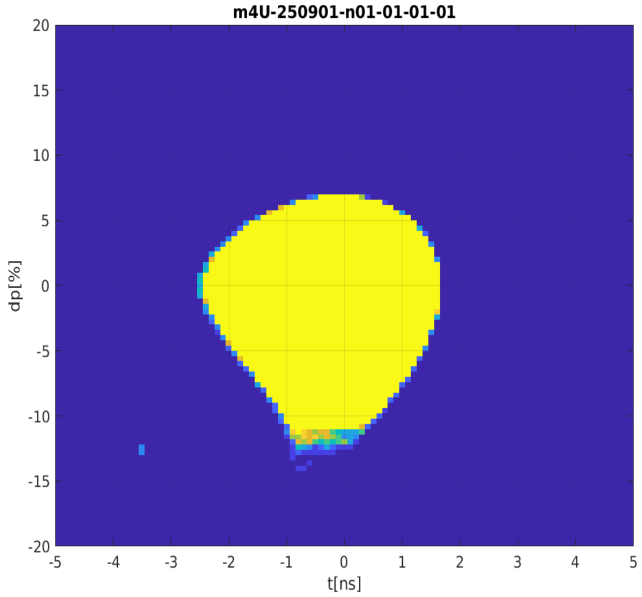


SG



Slide by P. F. Tavares

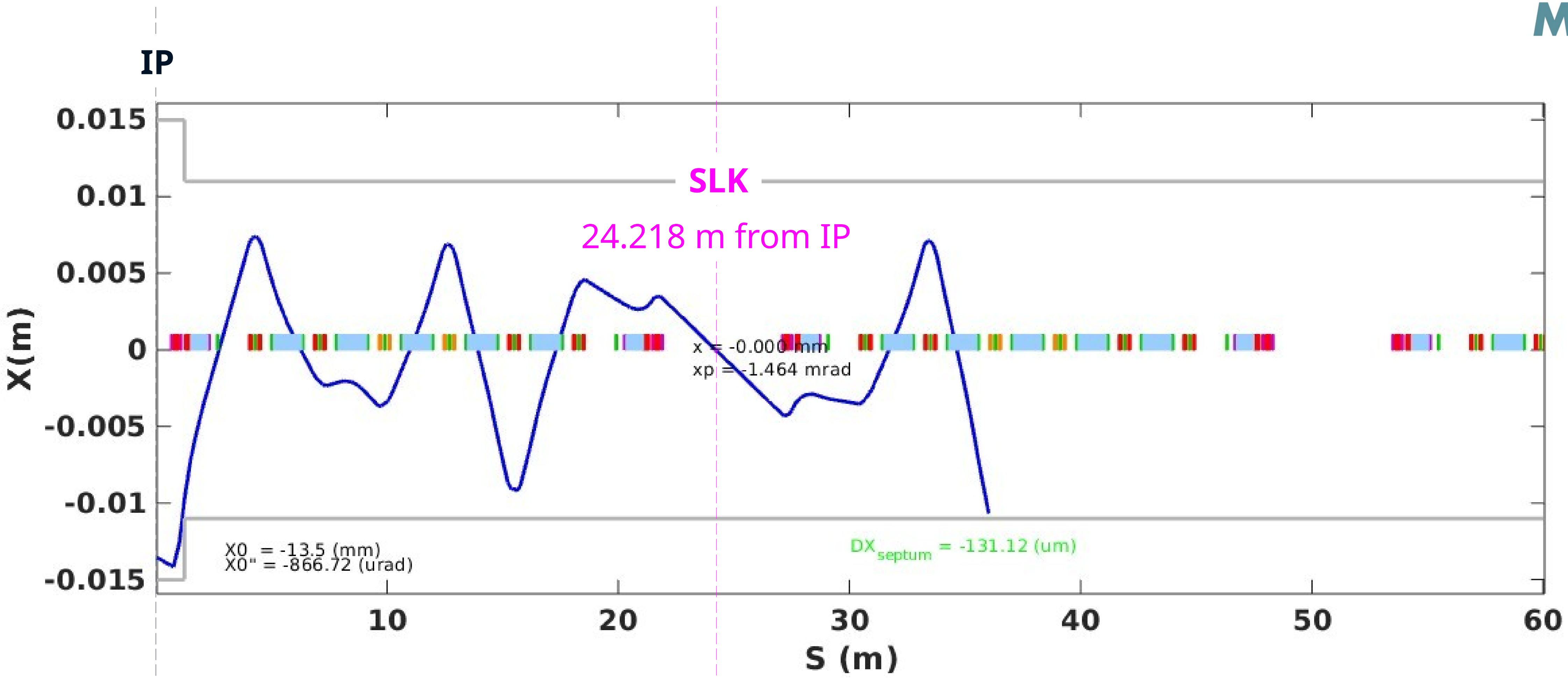
Challenges

- Accelerator Physics: obtaining enough phase acceptance to capture the beam stably

- Accelerator Engineering:
  - Building the required high voltage (~tens of kV), fast (~ns fall time) pulsers.
  - Appropriate high voltage vacuum feedthroughs
  - Building the require striplines without unduly creating too much impedance for the beam

Slide by P. F. Tavares

AR ON-axis/OFF-phase injection: kick at stripline mid-plane

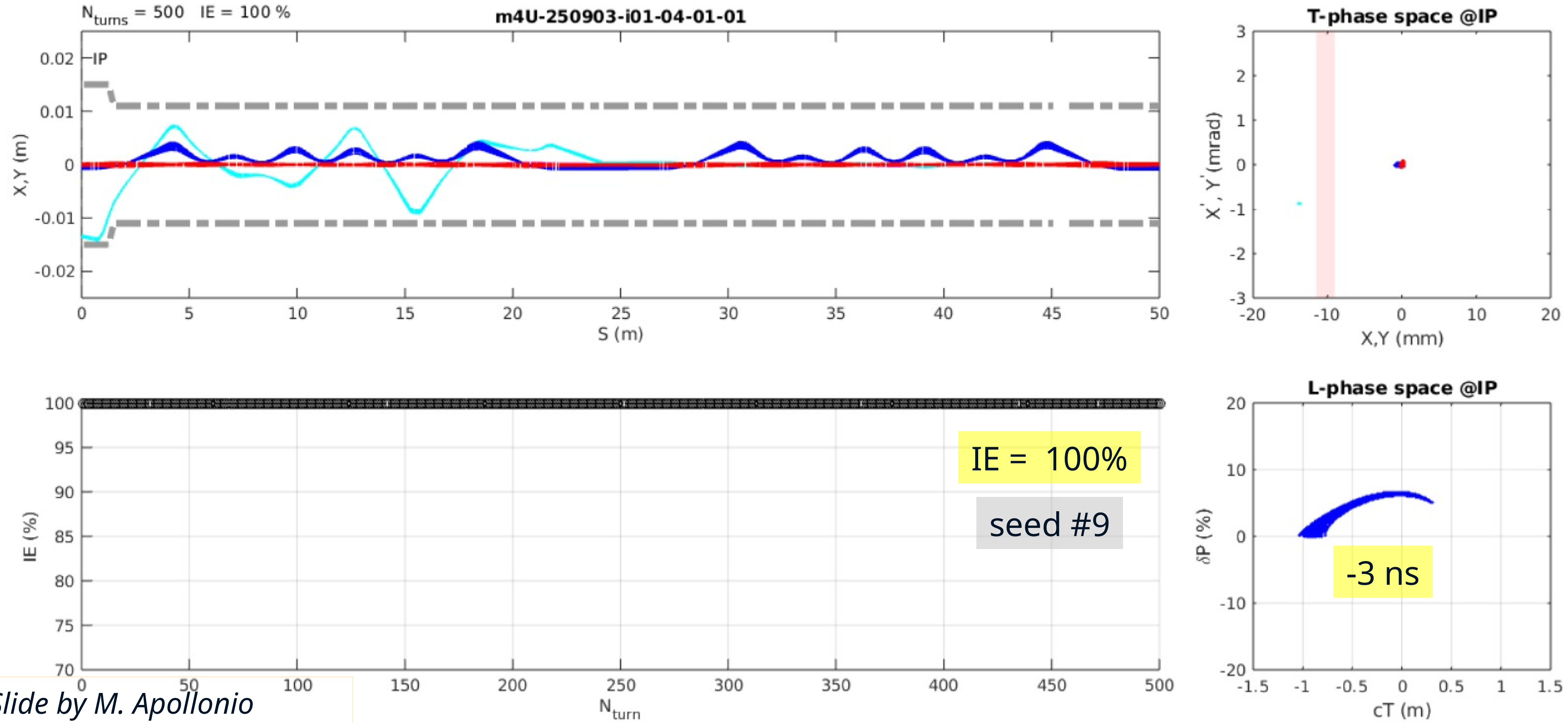


Slide by M. Apollonio

AR ON-axis/OFF-phase injection: kick@stripline (PG source)

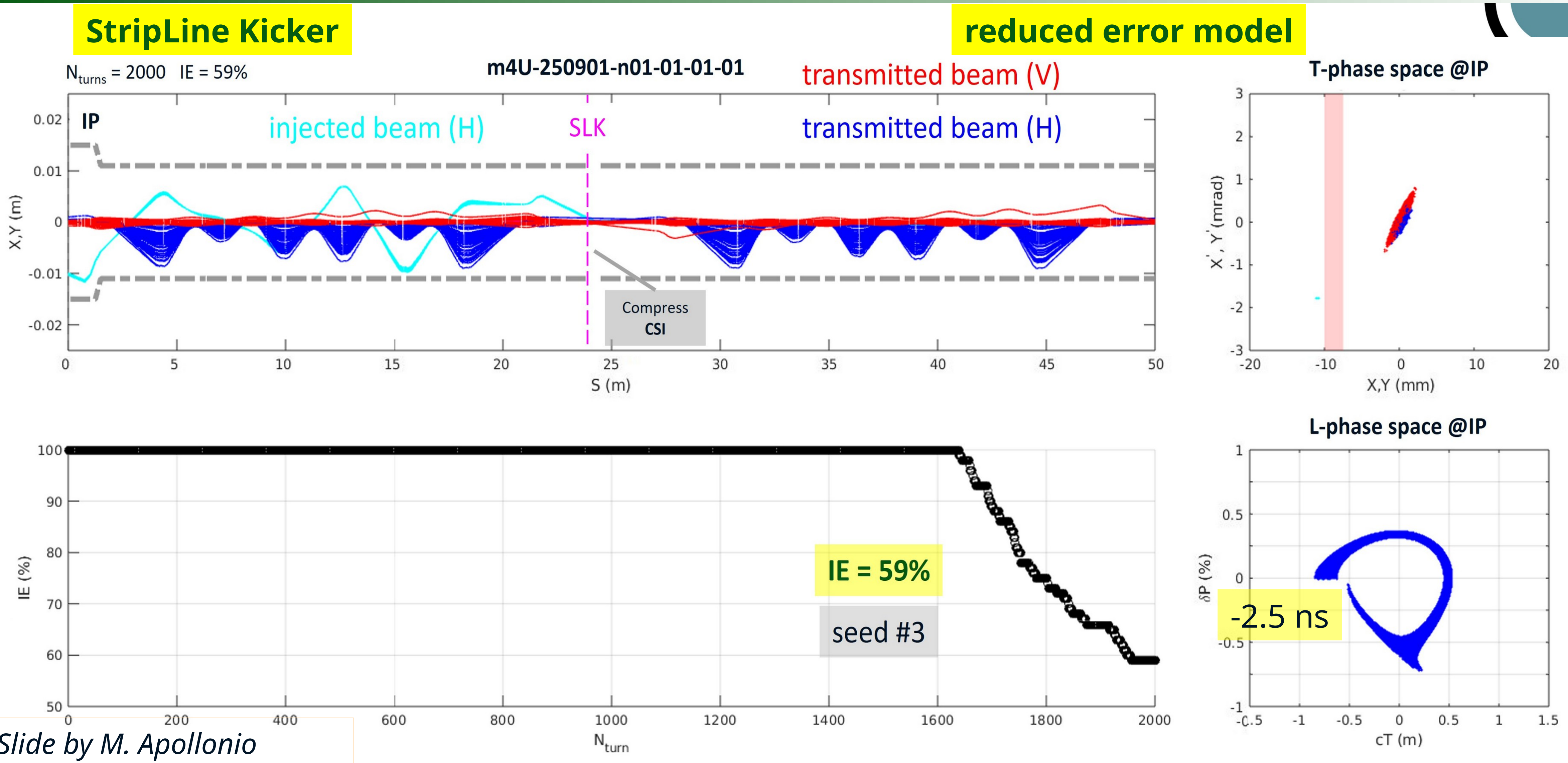
StripLine Kicker

reduced error model



Slide by M. Apollonio

SG ON-axis/OFF-phase injection: kick@stripline (PG source)

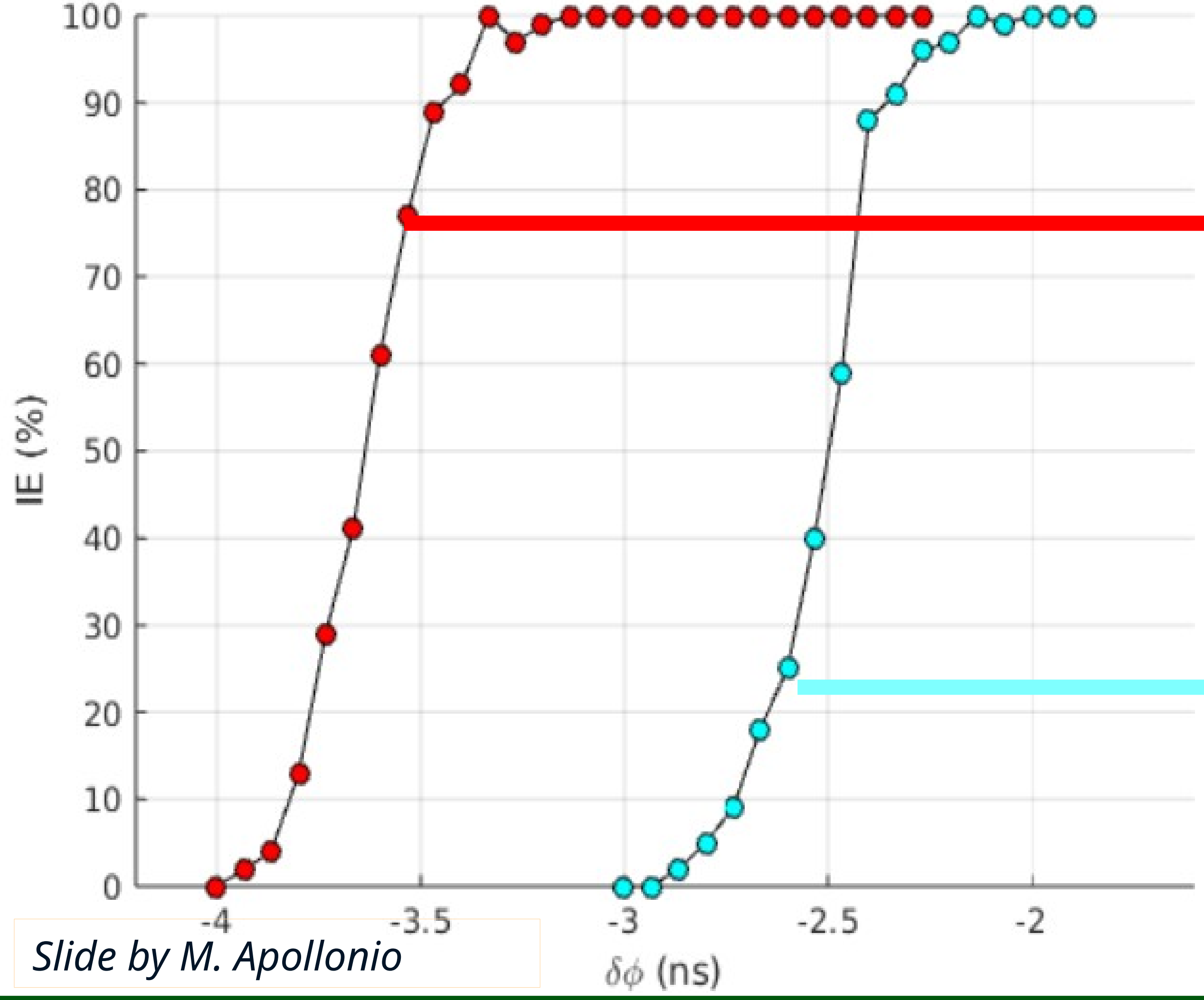


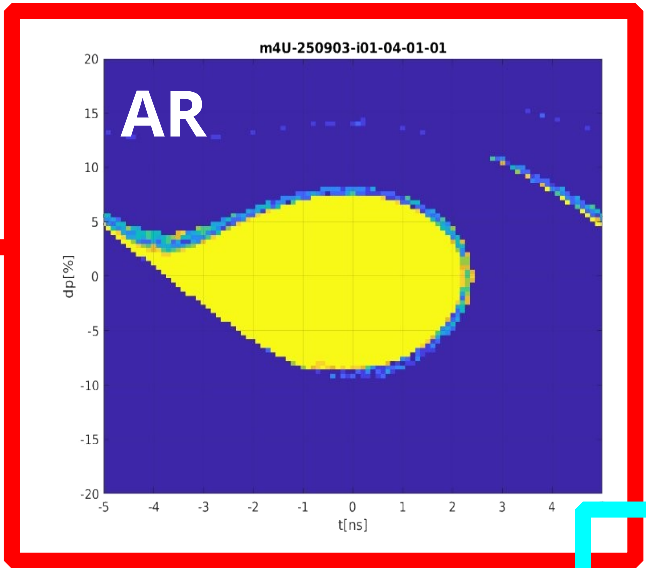
Slide by M. Apollonio

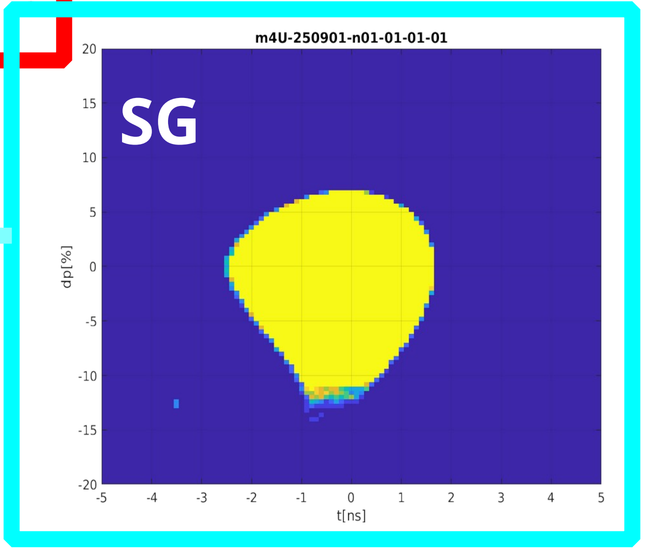
AR/SG injection – ON-axis/OFF-phase: PG source, IE vs ph.-shift

StripLine Kicker

reduced error model



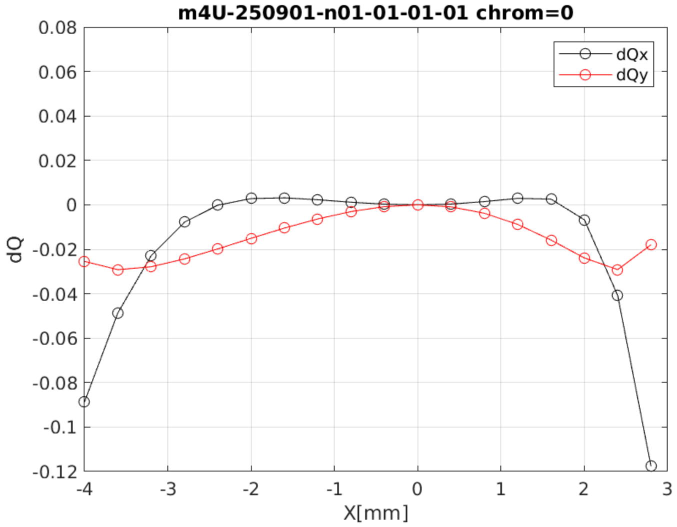


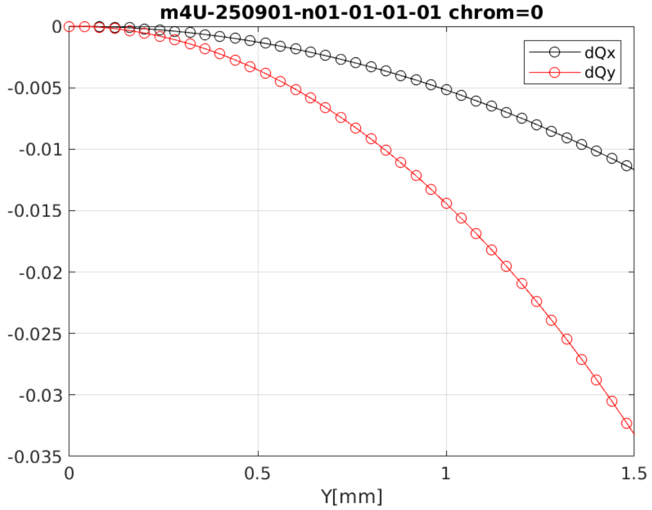


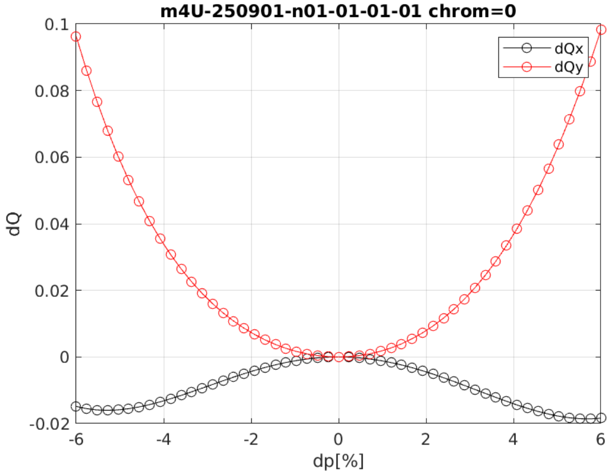
Slide by M. Apollonio

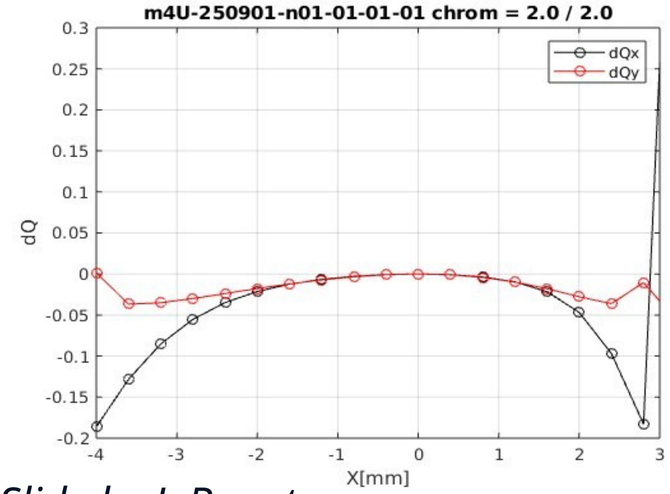
Complementary Material:
SG lattice

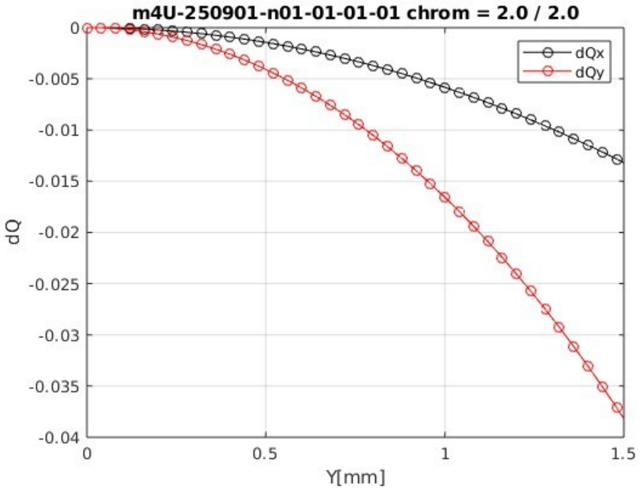
Lattice Performance-Ideal lattice (cont.)

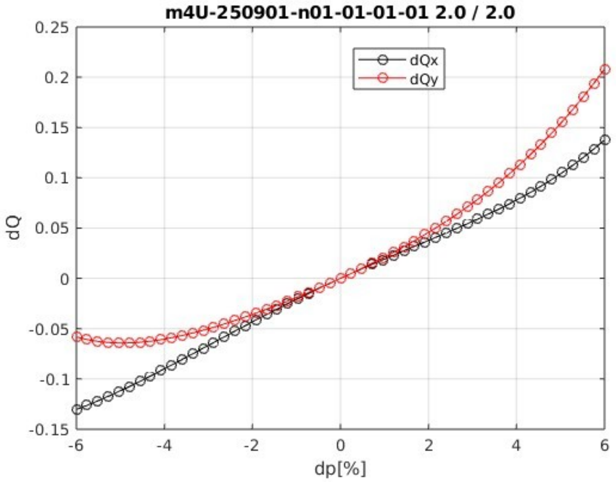






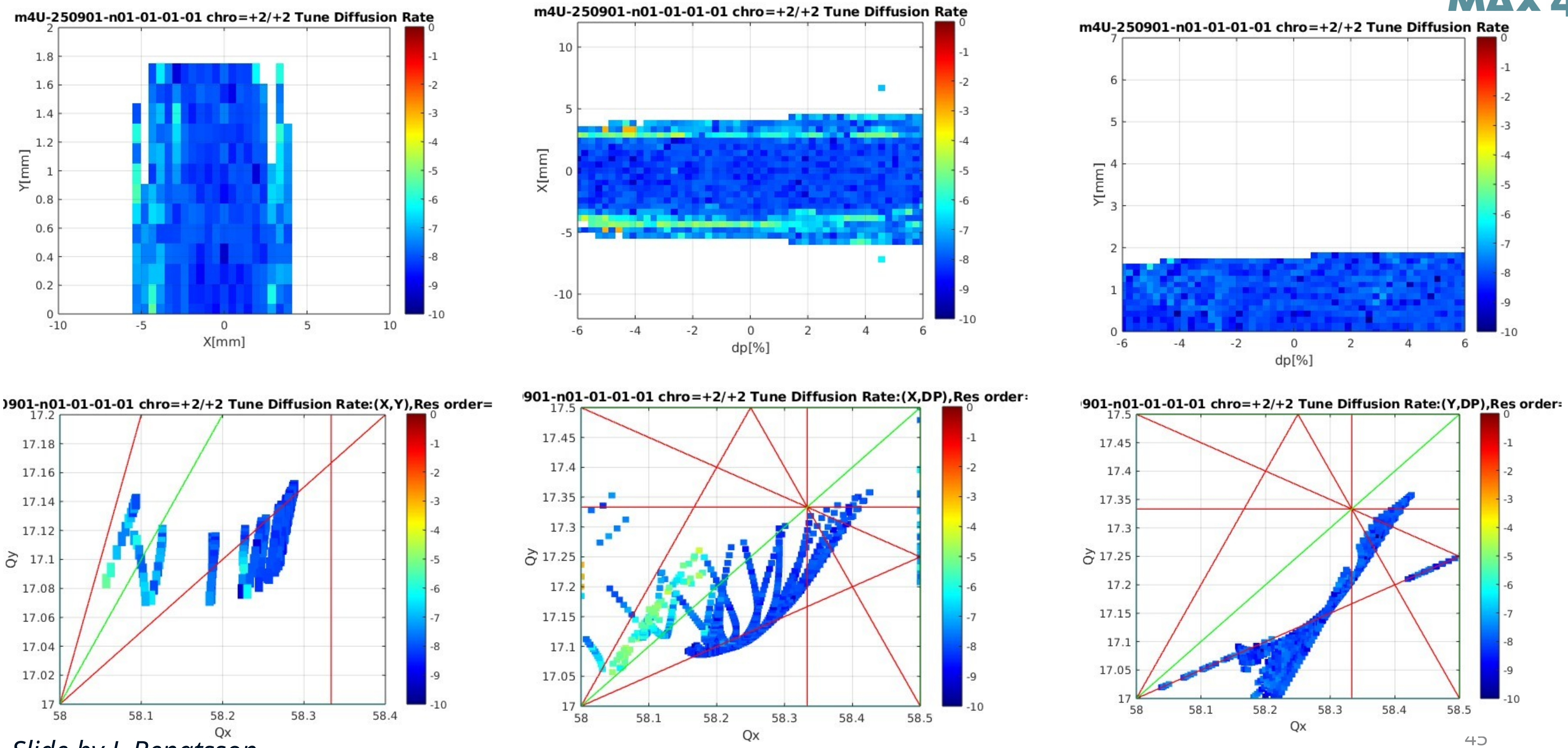






Slide by J. Bengtsson

Lattice Performance-Ideal Lattice (cont.)

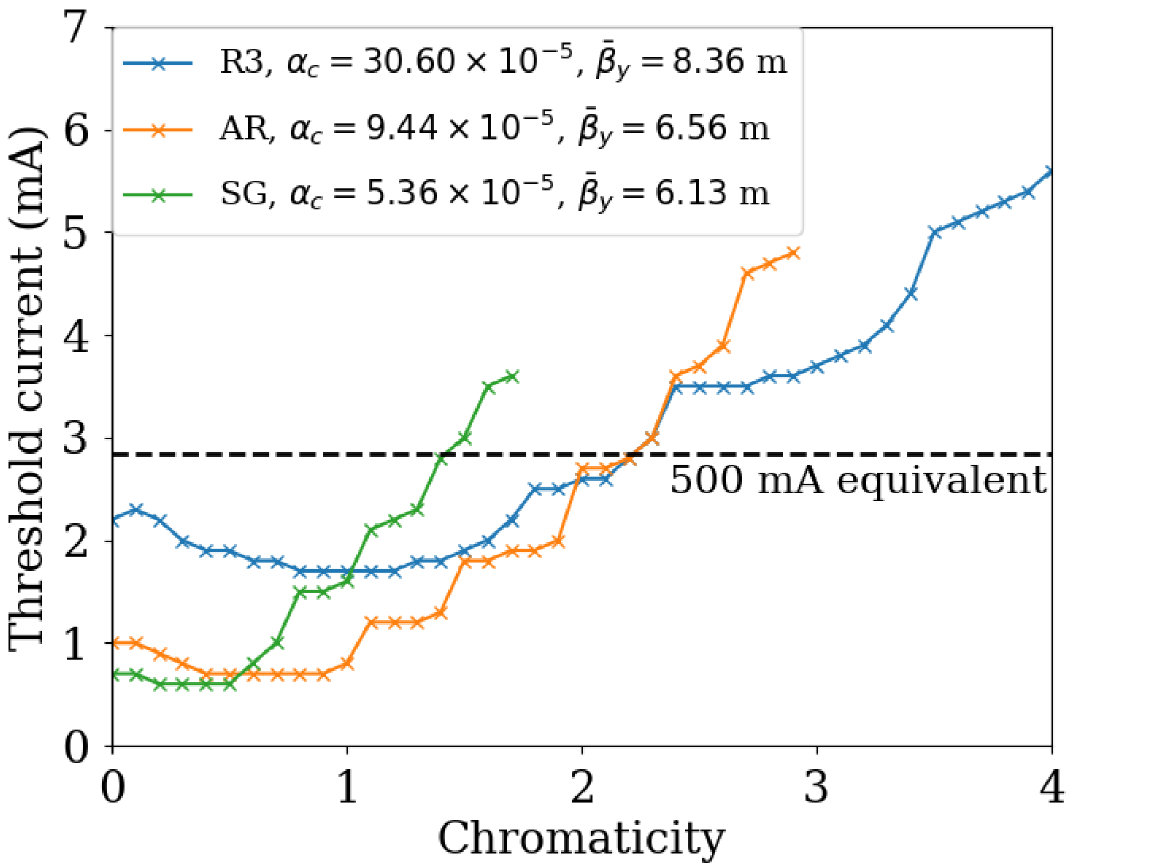


Slide by J. Bengtsson

Complementary Material:
Collective effects

Vertical TMCI Threshold Calculations

- 1 MV RF Voltage and bare lattices, scaled-up impedance model (Gdfidl+RW)
- Potential-well distortion not included
- Bunch lengthening not included
- Lower threshold at low chromaticity due to lower α_C, lower average beta compensates
- Chromaticity more effective but will still need to be increased compared to R3 lattice
- Still to develop impedance model consistent with all experimental observations



Complementary Material:
Error models

Modelling, positioning errors

Element misalignment applied in sequence:

- ❑Lattice elements belonging to the same (sliced) magnet are grouped together, and receive the same positioning error
- ❑Blocks/girders are treated as rigid bodies; girder pitch/yaw/roll/sway/heave/surge errors recalculated using affine matrices into element misalignment adjustment
- ❑Rigid body deformation from gravity (sag) approximated as a 2nd degree polynomial and deployed as a heave (y) adjustment throughout the block

Modelling, field errors

Field errors currently modelled are:

- Main component field errors (e.g. manufacturing errors)
- Multipole errors (e.g. manufacturing errors)
- Scaling errors (e.g. PS current error)

They are applied in order.

For all types systematic errors are applied (currently on a magnet type basis, e.g. all quadrupoles are treated equally), then random errors are generated using a truncated gaussian distribution (2 sigma) and added on top.

Lastly the field components are scaled to account for power supply errors.

Updated error model: magnitudes

No truly complete error model exists; reality is always more complex

	Magnet misalignment (µm/µrad) [2,3]	Girder misalignment (µm/µrad) [1,4]	BPM "misalignment" (µm/µrad) [5]
Sway	**4**	**27**	3
Heave	**9**	**21**	3
Surge	(0)	**16**	(0)
Pitch	(0)	**21**	(0)
Yaw	(0)	**21**	(0)
Roll	100	**157**	100
Sag	-	**20**	-

Bold – based on data (references below)
(parenthesis) – ignored as impact reasoned to be negligible
Red – proxy value used (measured BBA reproducibility, i.e. only includes random component)
Blue – unavailable, historical assumption used. NB! Magnet roll errors show up as skew components in evaluation of series production field measurement data.

Sources

1. Internal MAX IV report by SAM
2. M. Johansson et al., "Magnet design for a low-emittance storage ring", Journal of Synch. Rad., July 2014
3. M. Johansson et al., "MAX IV 3 GeV STORAGE RING MAGNET BLOCK PRODUCTION SERIES MEASUREMENT RESULTS", Proc. of IPAC 2015
4. Internal communication, Design Office
5. Experimental data

Updated error model: magnitudes

No truly complete error model exists; reality is always more complex

	Main field variation, standard dev. (10^{-3}) [2,3]
Dipole	**0.87**
Dipole gradient	**1.1**
Quadrupole	**1.8**
Sextupole	**2.3**
Octupole	**2.4**

NB! Data was available per family; the above are weighted averages.

Bold – based on data (references below)
(parenthesis) – ignored as impact reasoned to be negligible
Red – proxy value used (measured BBA reproducibility, i.e. only includes random component)
Blue – unavailable, historical assumption used. NB! Magnet roll errors show up as skew components in evaluation of series production field measurement data.

Sources

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4. Internal communication, Design Office
5. Experimental data

Updated error model: magnitudes

No truly complete error model exists; reality is always more complex

Table 2.8: Multipole errors used in the MAX IV error model. The data has been taken from magnet measurements of the SLS storage ring magnets [7]. The order column refers to the multipole order defined by 2 = quadrupole, 3 = sextupole, etc.

Magnet family	Error type	Order	Maximum multipole component (relative to main field component) Upright	Skew
Quadrupoles	Systematic	6	0.5×10^{-4}	—
		10	0.5×10^{-4}	—
		14	0.1×10^{-4}	—
Sextupoles	Systematic	9	0.5×10^{-4}	—
		15	0.5×10^{-4}	—
		21	0.5×10^{-4}	—
Quadrupoles	Random (rms)	2	2.5×10^{-4}	—
		3	2.8×10^{-4}	2.9×10^{-4}
		4	1.9×10^{-4}	1.4×10^{-4}
		6	1.3×10^{-4}	—
		10	3.0×10^{-5}	—
Sextupoles	Random (rms)	3	5.0×10^{-4}	—
		4	5.2×10^{-4}	4.9×10^{-4}
		5	3.5×10^{-4}	—
		9	8.0×10^{-5}	—
		15	5.0×10^{-5}	—

Table on the left shows the multipole errors used in the more complete error model. They are not currently based on measurements from the production series but are instead conservative estimates, using data from the Swiss Light Source (SLS).

E.I. Antokhin et al., "Precise Magnetic Measurements of the SLS Storage Ring Multipoles: Measuring System and Results", Proc. of APAC'01, Beijing, China.

Reduced error model

Description: Lower amplitude error model that produces BPM errors and machine function beatings similar to those present in a corrected lattice (i.e. after BBA, LOCO)

Use case: evaluation short-cut of expected impact of errors, e.g. during MOGA evaluations, until simulated commissioning is available (ongoing)

	Magnet misalignment [μm/μrad]	Girder misalignment [μm/μrad]	BPM "misalignment" [μm/μrad]
Sway	15	0	5
Heave	15	0	5
Surge	0	0	0
Pitch	0	0	0
Yaw	0	0	0
Roll	100	0	10

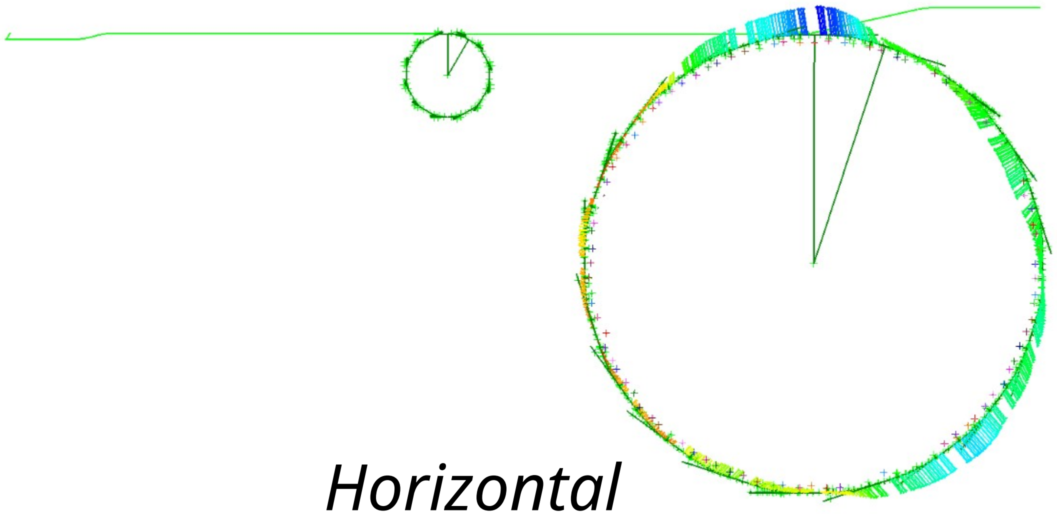
NB! A more extensive error model based on measurements is available but not in use pending the implementation of full simulated commissioning; see supplementary slides for details…

Global misalignment "waviness"

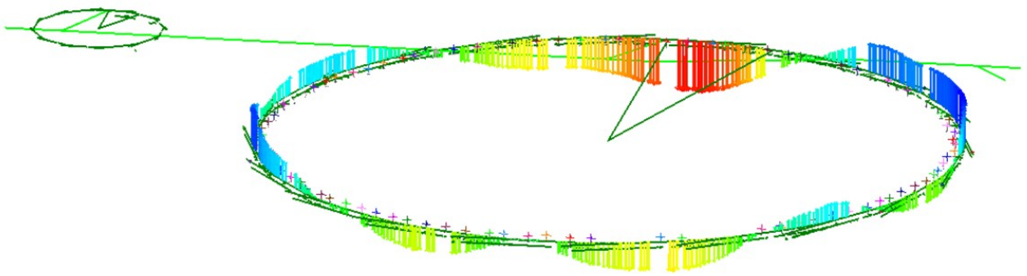
Figures: Waviness estimation for 2016 network (post-installation).

Table 2: Waviness misalignment of R3 (without measurement uncertainty and based on the geodetically corrected solution)

Networks	Horizontal (σ)	Vertical (σ)	Unit
R3-2016	211	226	μm
R3-2017	267	207	μm
R3-2021	389	271	μm
Average	289	235	μm



Horizontal



Vertical

Complementary Material:

Lattice correction

Lattice correction: BPM BBA

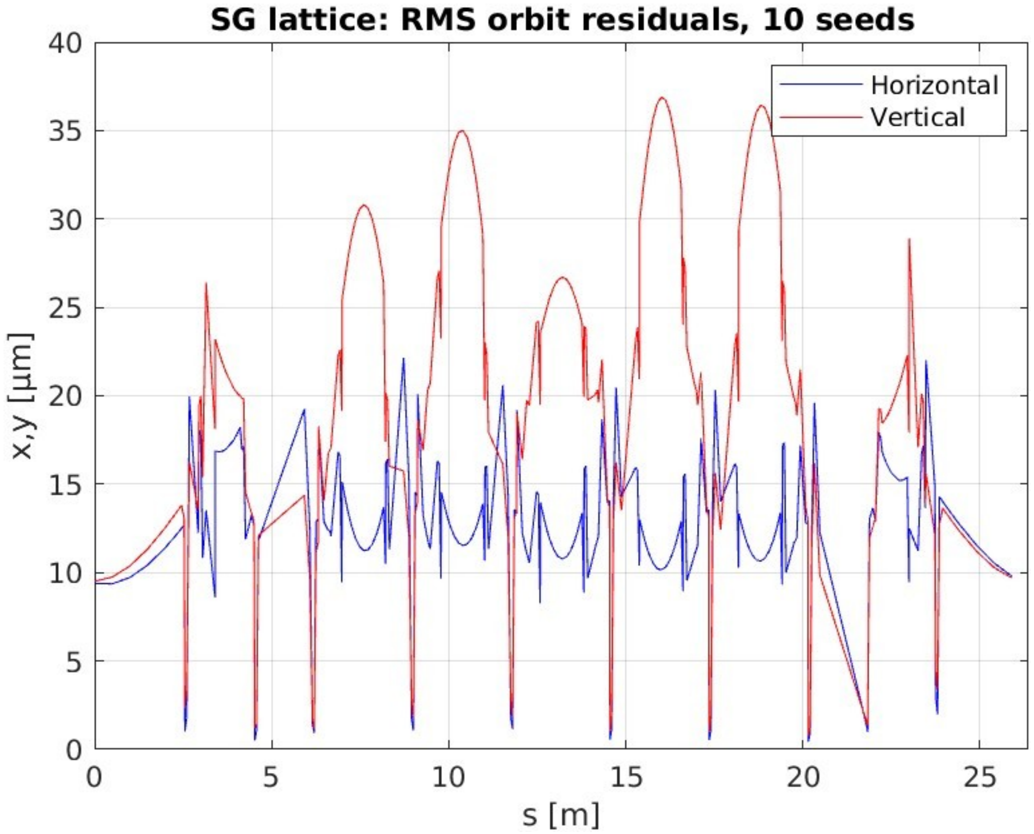
- Vacuum system retention --> nbr. of BPMs will not increase --> sampling of orbit will not increase
- BBA for current ring currently done using quadrupole trim (configurable) in neighbouring sextupoles and octupoles
  - Underlying assumption is magnetic centre of quad and sextupole fields do not differ greatly
  - Iron saturation will skew results: currently the main coil is disabled during the BBA, dropping into linear region likely sufficient. Bipolar gradient excitation also cancels out the effect to a large degree.
  - Open question regarding effect of trims on a combined quad/sextupole
- Electrical offsets of BPMs ~100 μm RMS
- During lattice design the BBA has so far been approximated by an additional BPM transverse misalignment (see error models for amplitude).

Lattice correction: orbit

Standard MIMO I-controller feedback solution:

- 10 BPMs, 10 hor. correctors, 9 ver. correctors (due to SR light pipe) per achromat; SVD used to deal with non-square matrix
- Prioritizing BPMs flanking the straights done via matrix weighting

Lack of vertical corrector in M1 block leads to orbit excursion inside the arc; dealt with by reconfiguring 1 trim coil into static vertical corrector. Not part of feedback currently.



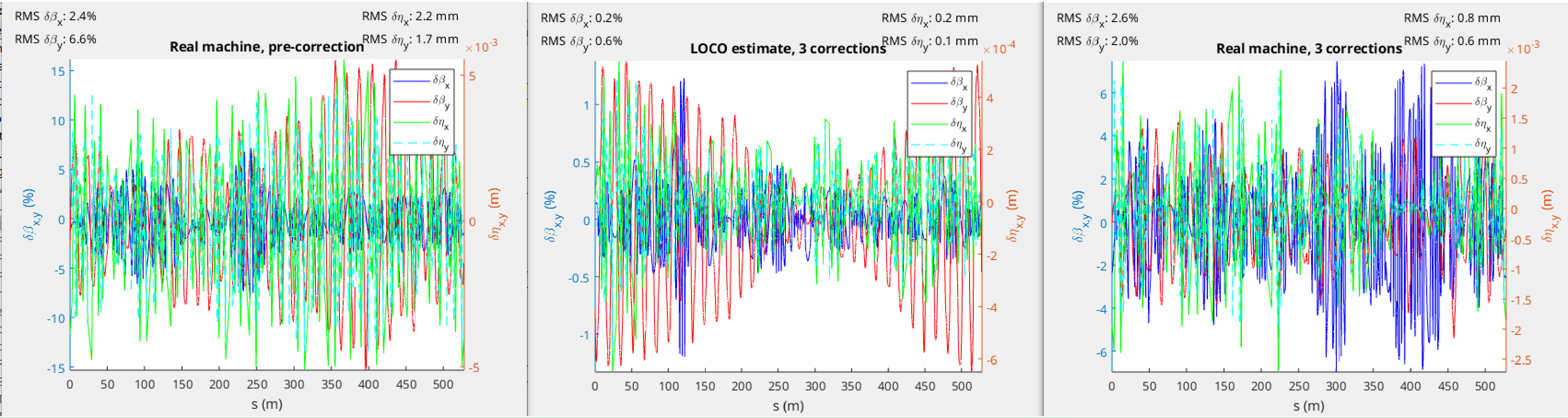
Above: RMS orbit error post-correction (to 1 μm) relative to lattice element centre, calculated over 10 seeds x 20 achromats.

Lattice correction: LOCO

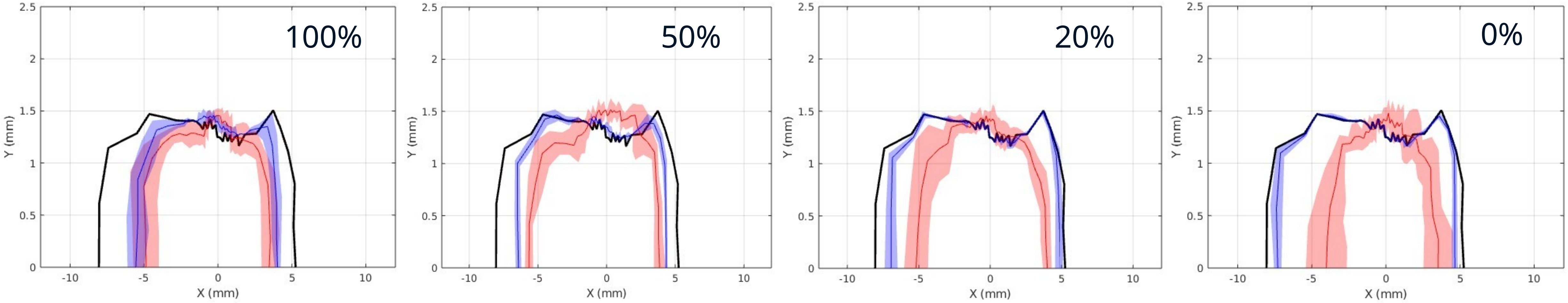
LOCO is recently operational as part of the lattice design.

Significant work will be needed to minimize the amount of needed "gradient knobs" for each, as it is a cost and risk driver via the implied amount of power supplies (most gradient power supplies are single-points-of-failure).

Unfortunately, even with individual gradients LOCO has trouble correcting beta-beat below a floor at roughly 2% RMS.



Lattice correction: LOCO



Above: AR lattice DA before (red) and after (blue) recovery by LOCO using the updated error model with various scaling of girder alignment errors.

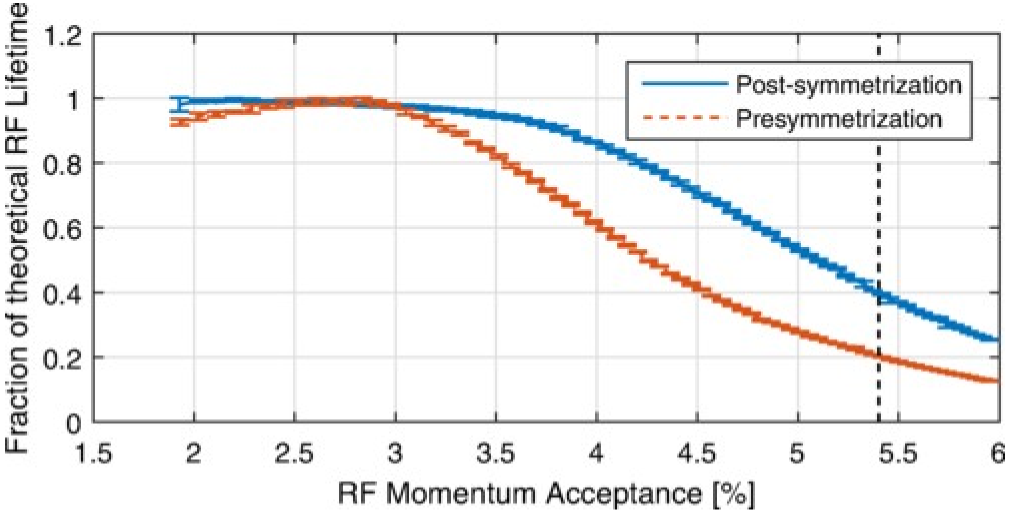
Further study has recently shown that LOCO has limited effectiveness in recovering DA in the presence of girder misalignments.

Beam-based realignment of magnet blocks is therefore to be investigated and evaluated in terms of effectiveness.

Plots by M. Apollonio

Lattice correction: NOECO

- Non-linear optics from Off-Energy Corrected Orbits (NOECO)
- Functionally very similar to LOCO
  - brings off-energy machine functions to match a reference lattice
  - relies on additional response matrices measured off-energy
  - able to fit dispersive sextupole fields only (condition fulfilled for all presented lattices)
- Observations in R3:
  - Large improvement in lifetime (from 11 to 19 h)
  - Improved momentum acceptance (measured in injection straight)
  - Improved dyn. aperture
- Not yet included as part of simulated commissioning



D. Olsson et al., "Nonlinear optics from off-energy closed orbits", Phys. Rev. Accel. Beams **23**, 102803, Oct. 2020

Complementary Material:
Engineering