MAX 4^{U}

An Upgrade for the MAX IV 3 GeV Ring.

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On behalf of the MAX 4^{U} project team

21st May 2026

Outline

- MAX IV facility
- Why MAX 4^U?
- MAX 4^U Design Approach and Goals.
- Lattice Design
- Subsystem Engineering.
- Time Schedule
- Conclusion.

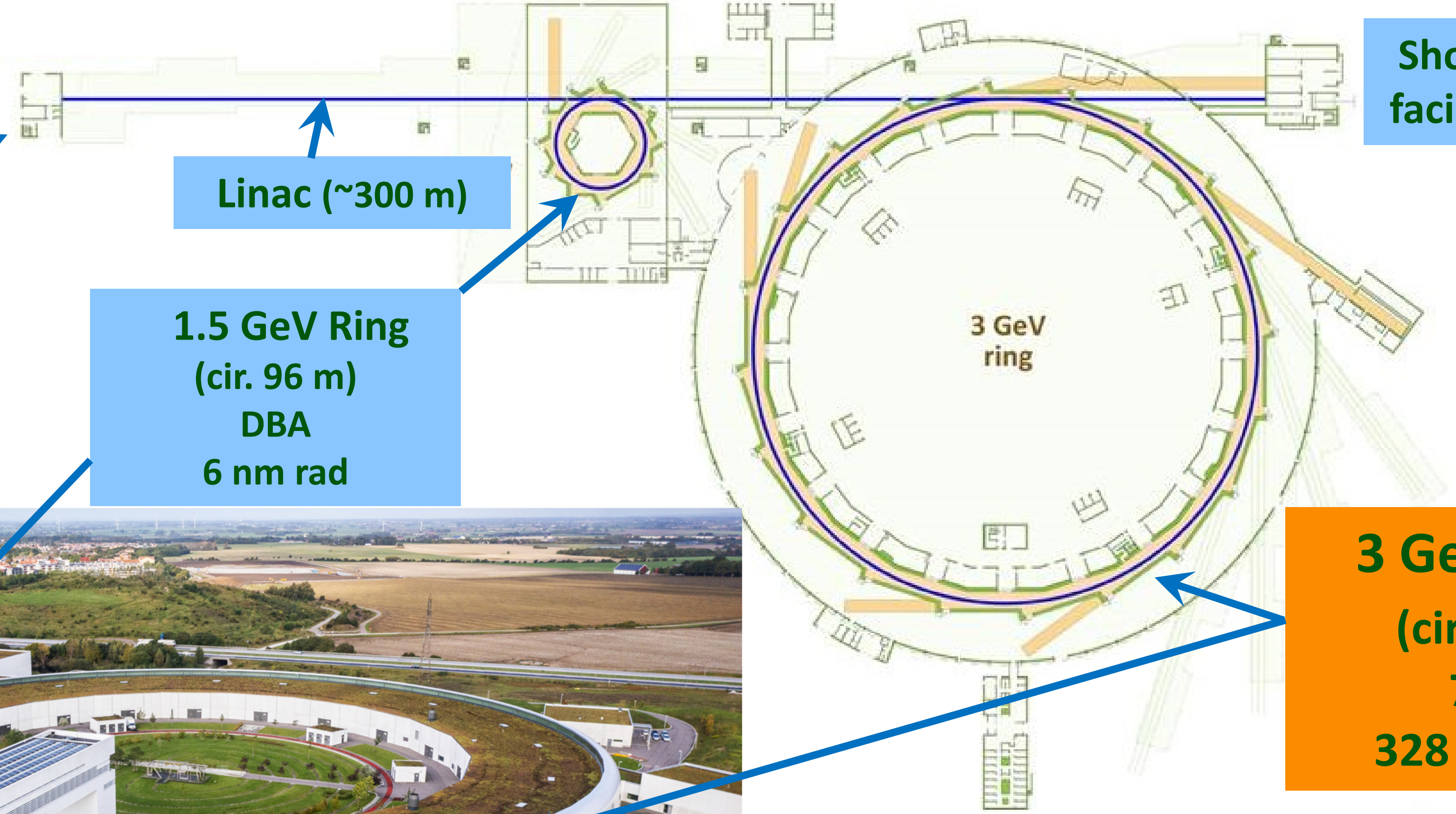
MAX IV Facility

MAX IV

This is MAX IV

- **Swedish national laboratory for X-ray research** with Lund University as host.
- Operates **the first fourth-generation light source** in the world.
- Inaugurated **June 2016**
- **16 beamlines** in user operation.
- >**2000** users/year, from > **300** institutes, from **38** countries.
- ~**5000** hours of delivery, with up-time of **98%**.

The MAX IV Accelerators



Short pulse facility (SPF)

Linac (~300 m)

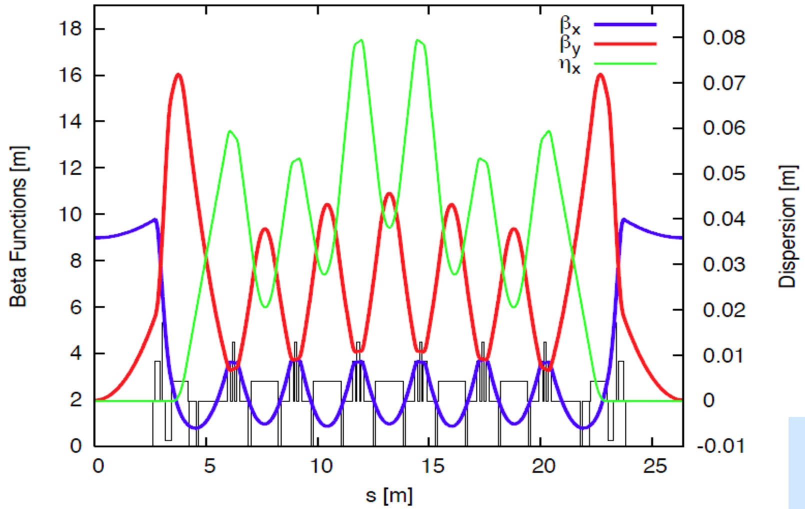
Electron Sources
(Thermionic RF gun and a photocathode gun)

1.5 GeV Ring
(cir. 96 m)
DBA
6 nm rad

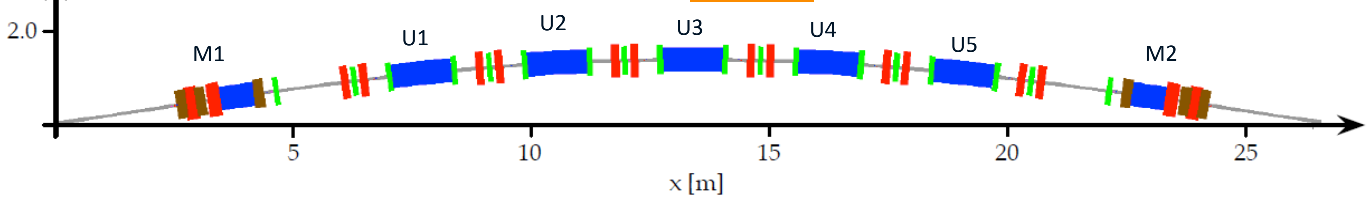
3 GeV Ring
(cir. 528 m)
7BA
328 pm rad

- 10 operational beamlines in the 3 GeV ring + 1 under construction.
- 5 operational beamlines in the 1.5 GeV ring
- One operational beamline in the SPF.

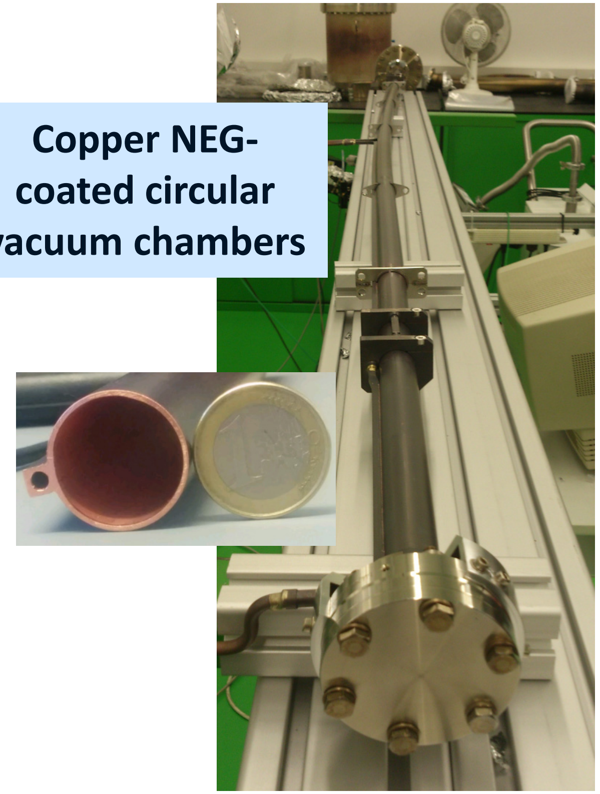
MAX IV 3 GeV Ring: 528 m, 328 pm rad



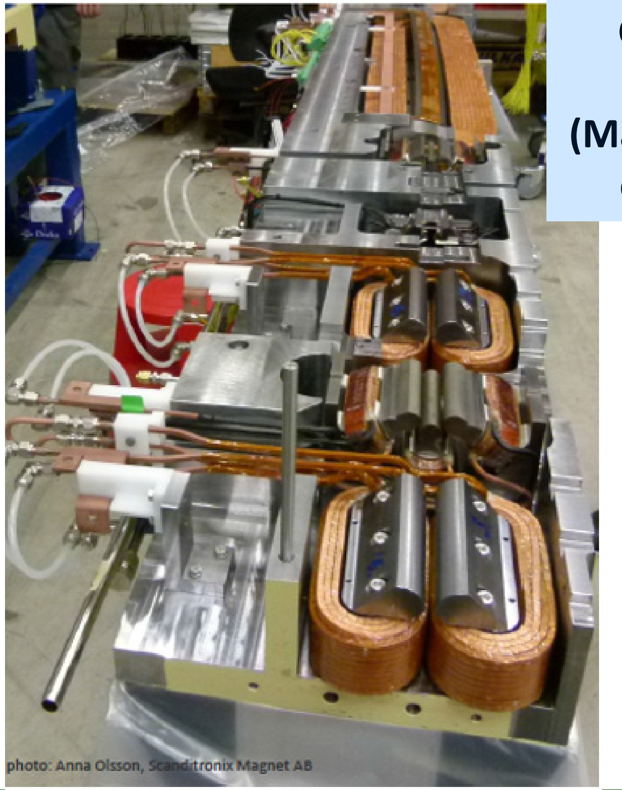
7BA



100 MHz main RF system, plus: 300MHz, 500MHz.



Copper NEG-coated circular vacuum chambers



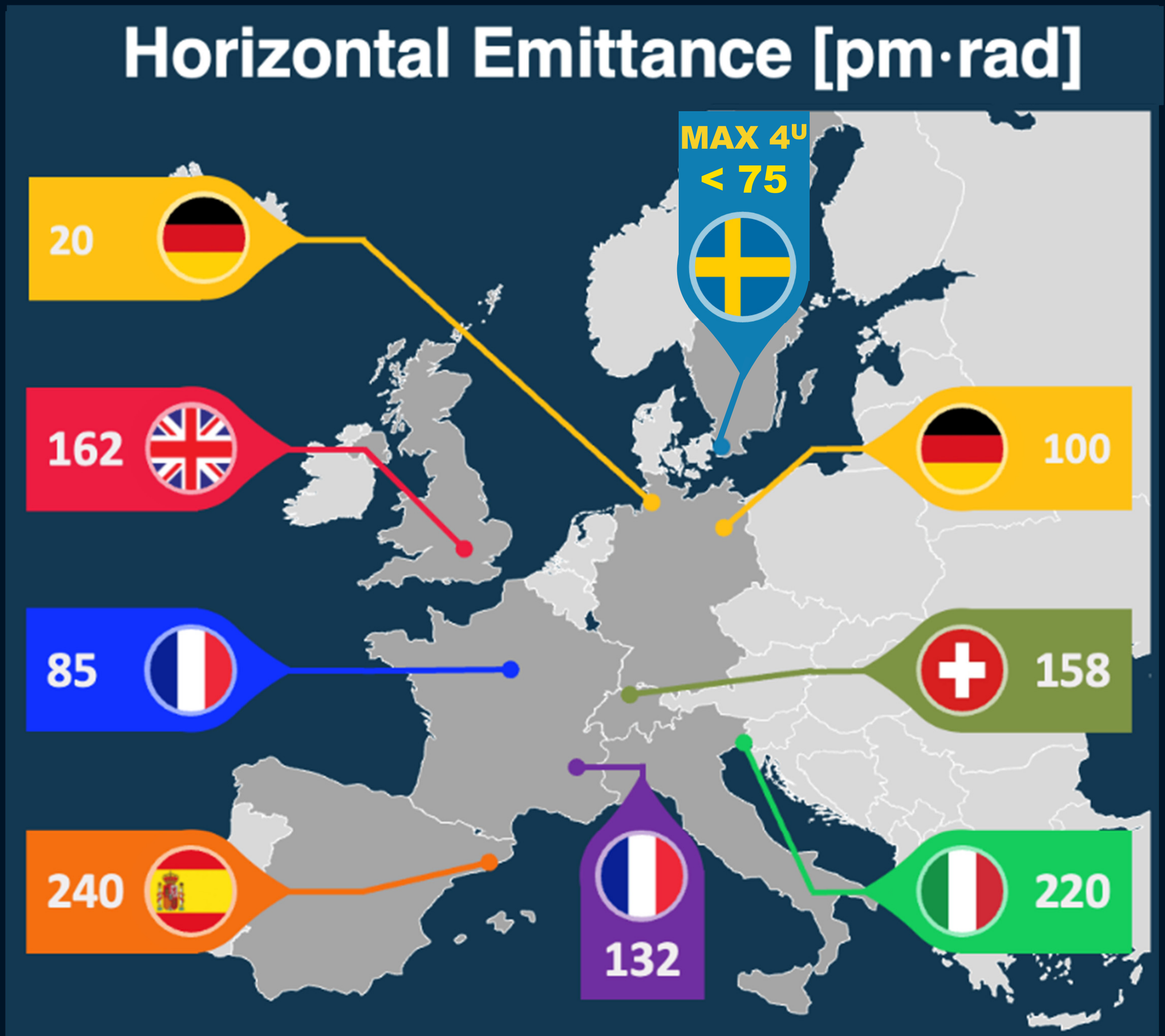
Compact Magnets (Magnet block concept)

Why MAX 4^{U}?

MAX 4^U

Why MAX 4^U ?

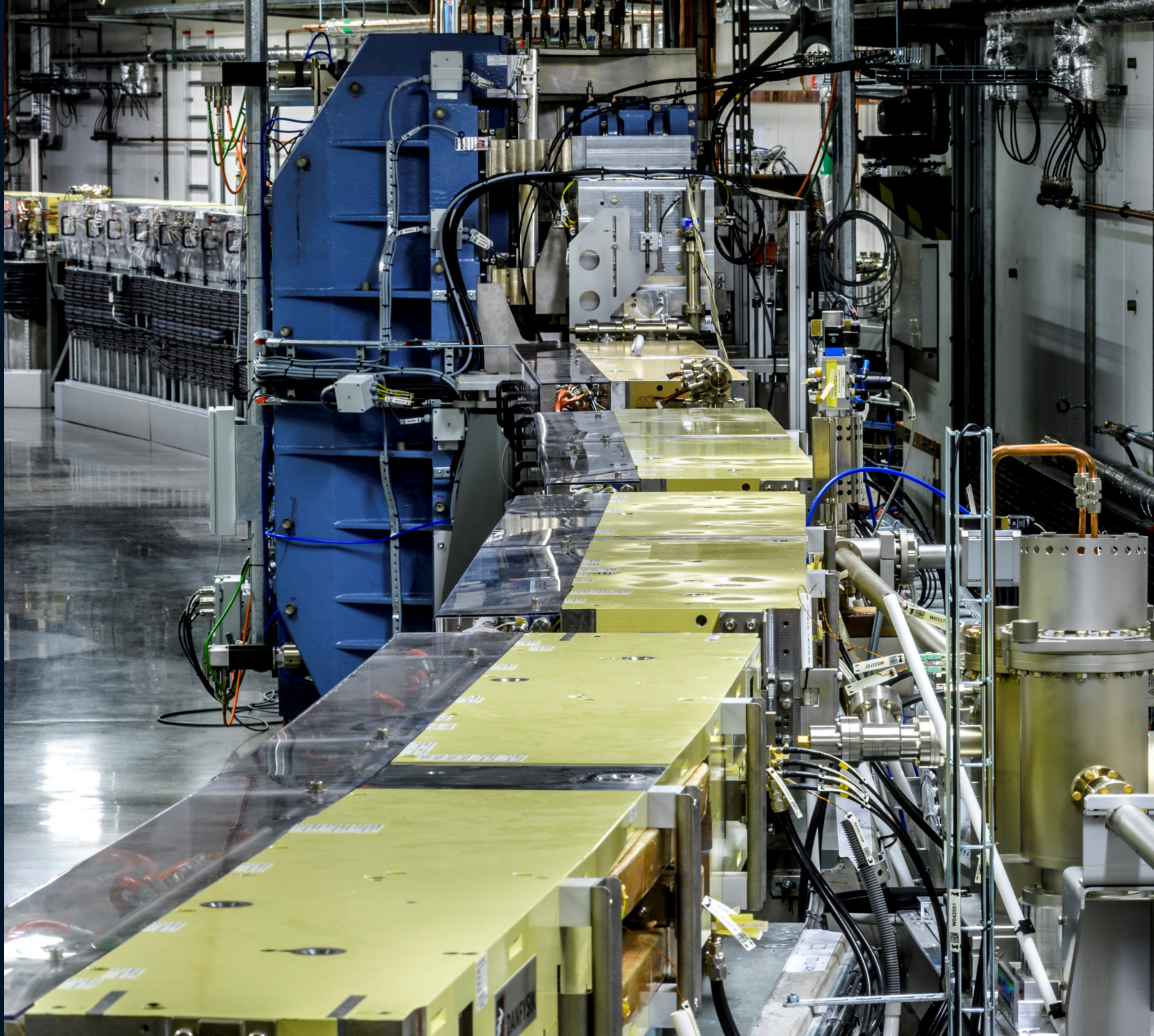
European Context in >2030



MAX IV

MAX 4^U Design Approach and Goals

MAX IV



MAX 4^{U} Design Approach

- **MAX 4^{U}** is ***NOT a conventional upgrade*****,** which requires the replacement of most components.
- **MAX 4^{U}** is a ***surgical intervention*** to provide an outstanding performance improvement while **maintaining much of the existing hardware**.

- **How come this is at all possible?**
  - The MAX IV 3 GeV ring **was designed with future upgrades** in mind.
  - **Innovative approaches are being explored,** including ultralong bunches and advanced injection techniques.
  - MAX 4^{U} can take advantage **of new developments in the accelerator** community in recent years.

MAX 4^{U} Design Approach

- Accelerator Physics (Lattice design) and Subsystem design go **hand-in-hand** from **the very start of the project**
- Subsystem Engineering Experts are asked NOT simply to deliver pre-determined specs but rather to **explore the performance envelope** that can be achieved **within the overall boundary conditions**.
- Provide a **very fast iteration of lattice design to Engineering validation** and back.
- Various tools have been developed to **share information and automate** the cycle.

The conceptual design phase for MAX 4^{U} began in 2024 and continued for two years.

CDR was completed on December 24th, 2025

https://www.maxiv.lu.se/beamlines-accelerators/max-4u/accelerator-design/

*The CDR studies defined the **design potential** of the upgrade, establishing a strong foundation for more **ambitious goals***

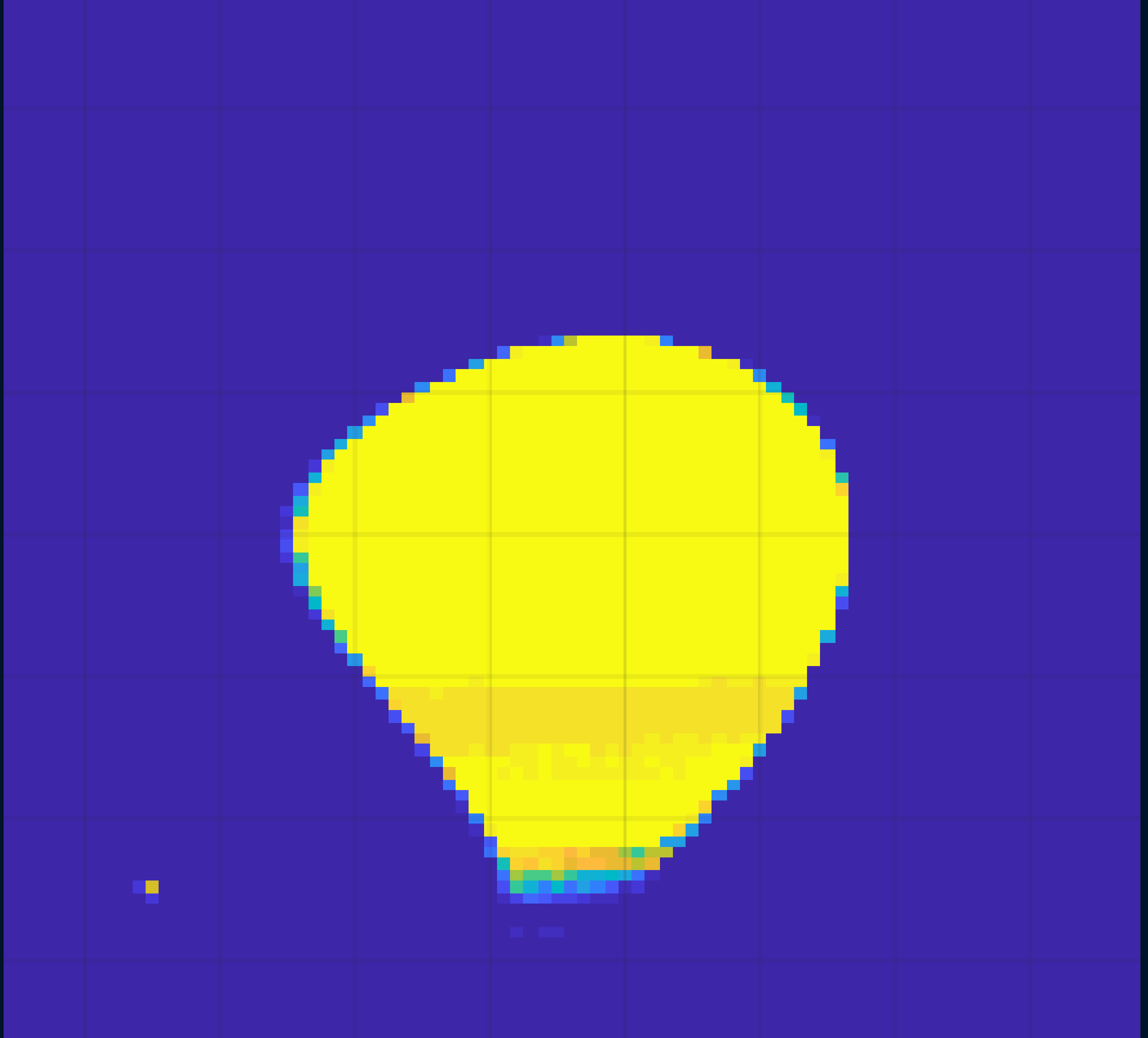
*The emittance goal during the conceptual design was to achieve under **100 pm rad**, and now during the technical design stage is under **75 pm rad.***

THP2115: M. Apollonio

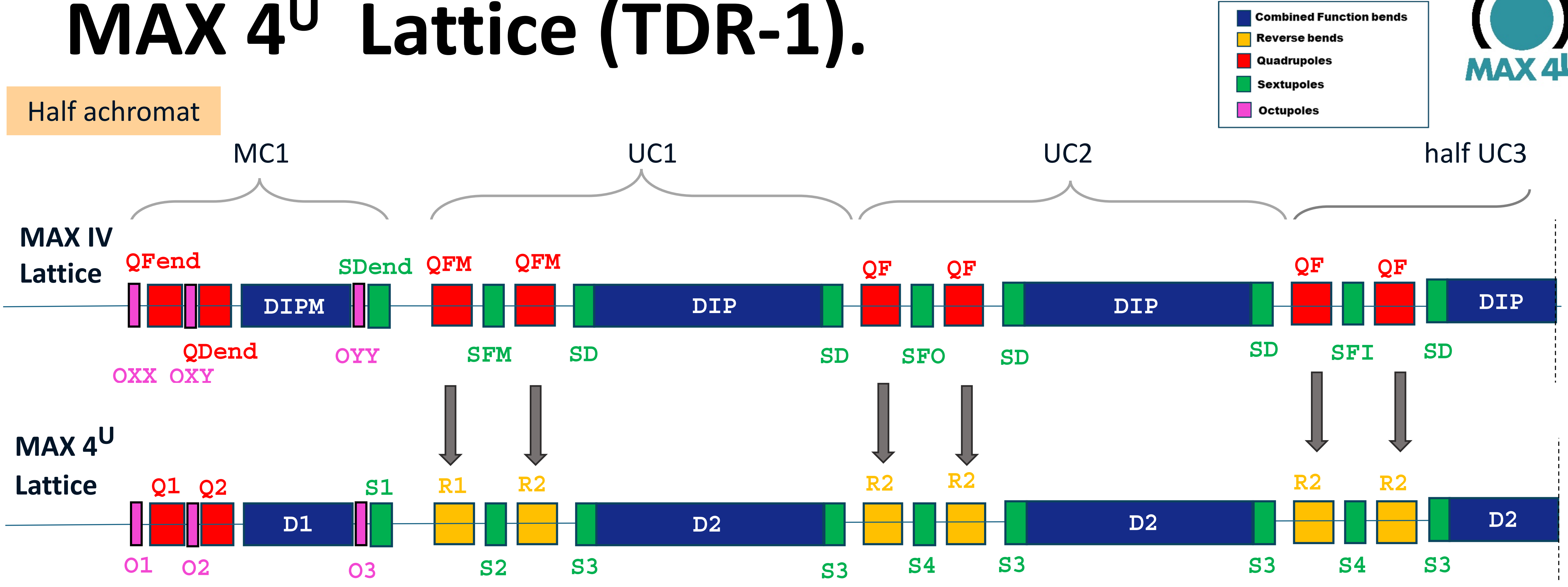
MAX 4^U Goals and Boundary Conditions

- Emittance $\lesssim$ **75 pm rad**,
- Keep the shielding wall,
- Keep the injector: accumulation,
- Keep existing light source positions,
- Limited dark period,
- Cost-effective,
- Realisable until the early part of the next decade,
- No impact on the operation of the 1.5 GeV ring/SPF

Lattice Design



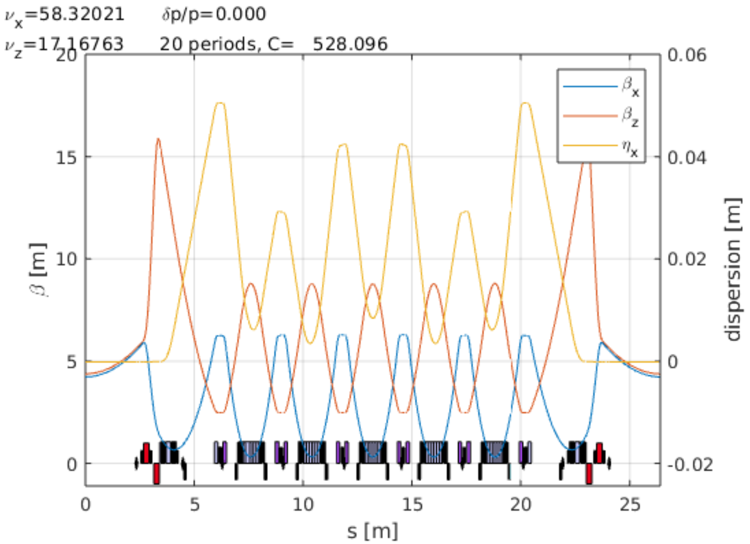
MAX 4^U Lattice (TDR-1).

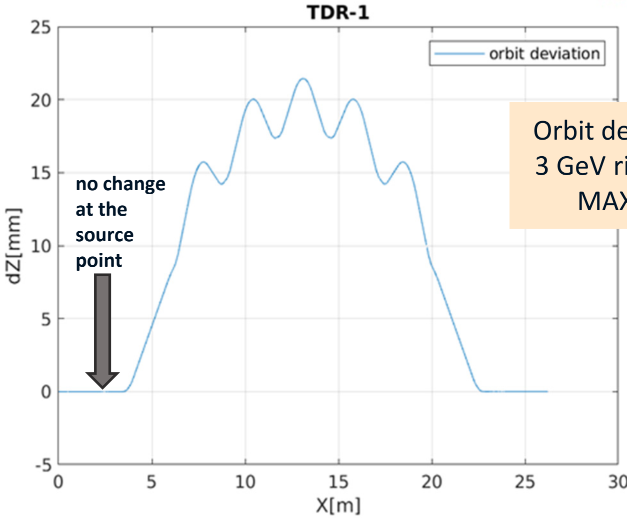


To reduce the emittance, **12 horizontally focusing quadrupoles** are turned into **reverse bends** grouped into **two families (R1, R2).**

MAX 4^{U} Lattice (TDR-1)

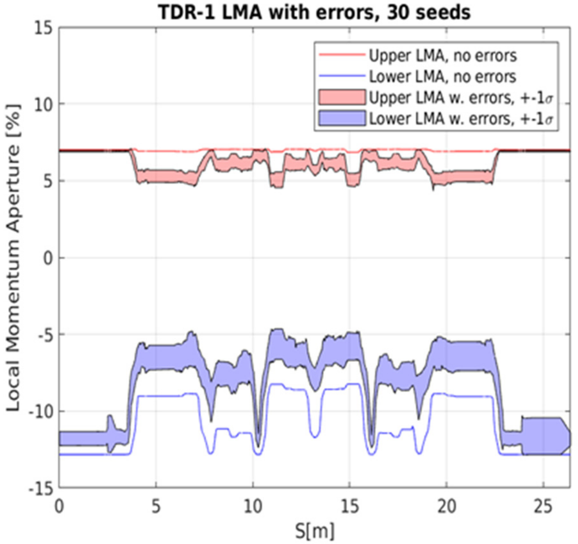
Parameter	MAX 4^{U}
Energy (GeV)	3.0
Circumference (m)	528.096
Achromat angle (deg.)	18
Tunes ν_x, ν_y	(58.32, 17.17)
Current (mA)	500
Average β_x, β_y (m)	(3.18, 6.13)
Average η_x (m)	0.0165
ξ_x, ξ_y	(2, 2)
Momentum comp. α_1, α_2 (10^{-4})	0.53, 3.6
Energy loss per turn (keV)	474.1
Nat. energy spread (%)	0.08
Nat. emittance (pmrad)	65.2

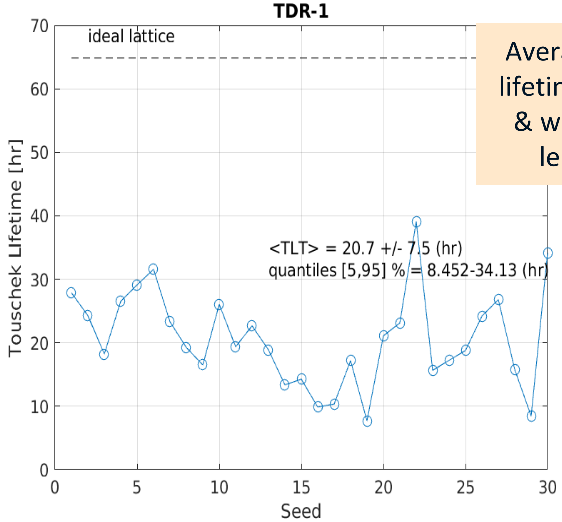




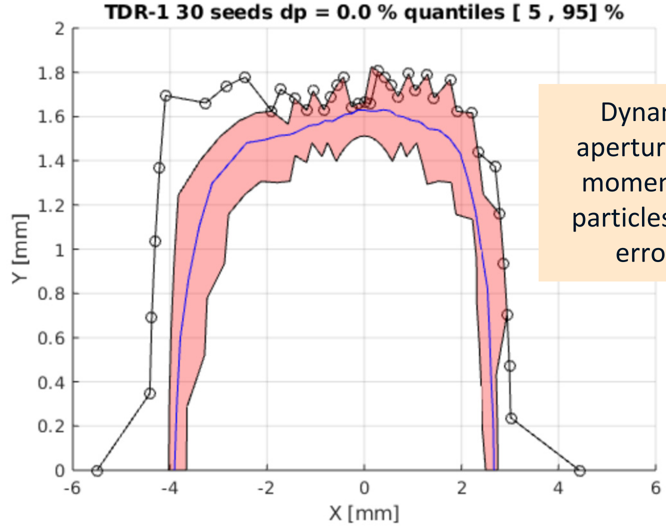
Orbit deviation 3 GeV ring and MAX 4^{U}

Local momentum acceptance with and without errors





Average Touschek lifetime with errors & without bunch lengthening.



Dynamic aperture on-momentum particles with errors

Off-phase injection

The baseline injection scheme for MAX 4^U.

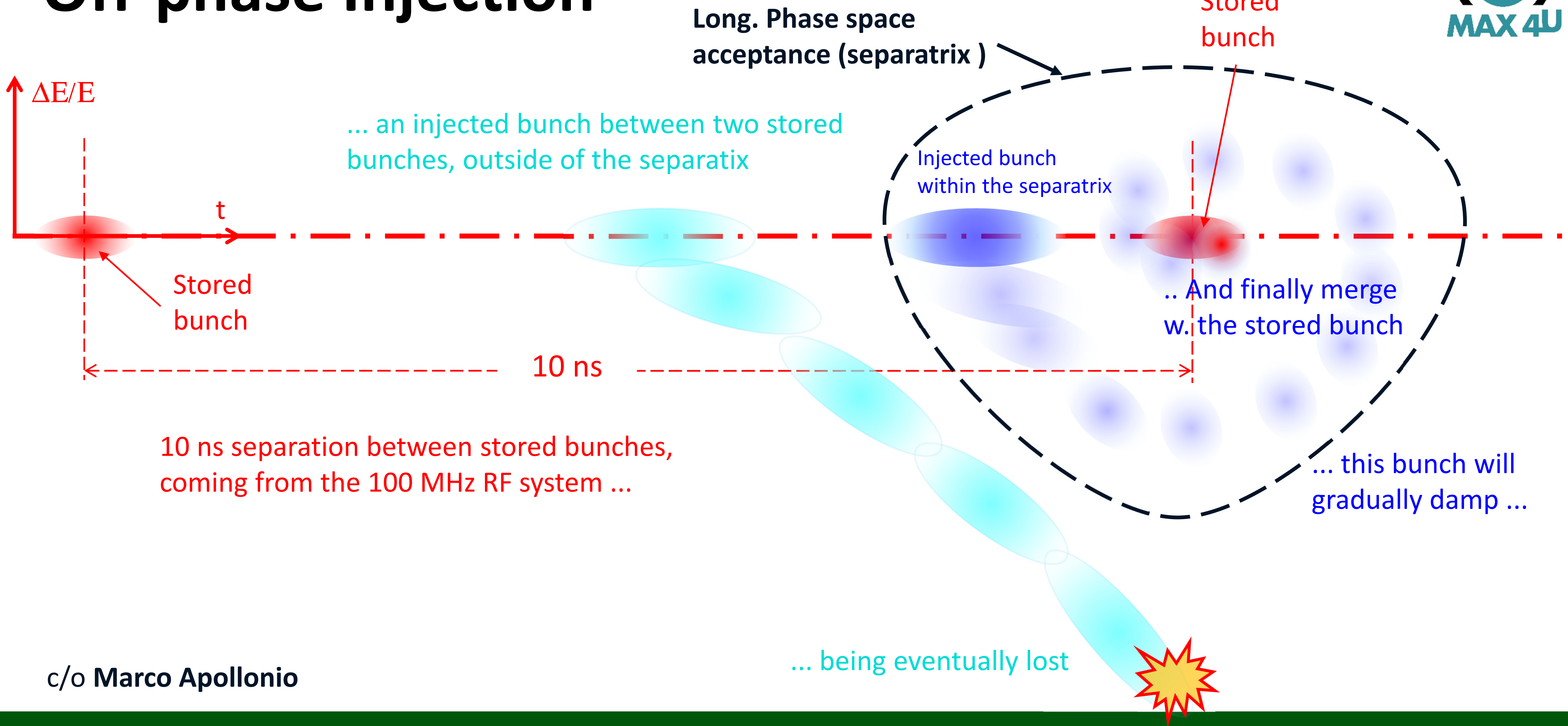
Off-phase injection /accumulation into MAX 4^U is enabled by:

- **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:

- Improved top-up **transparency.**
- The use of **small horizontal aperture** insertion devices.
- Accumulation into **restricted dynamic aperture.**

Off-phase Injection

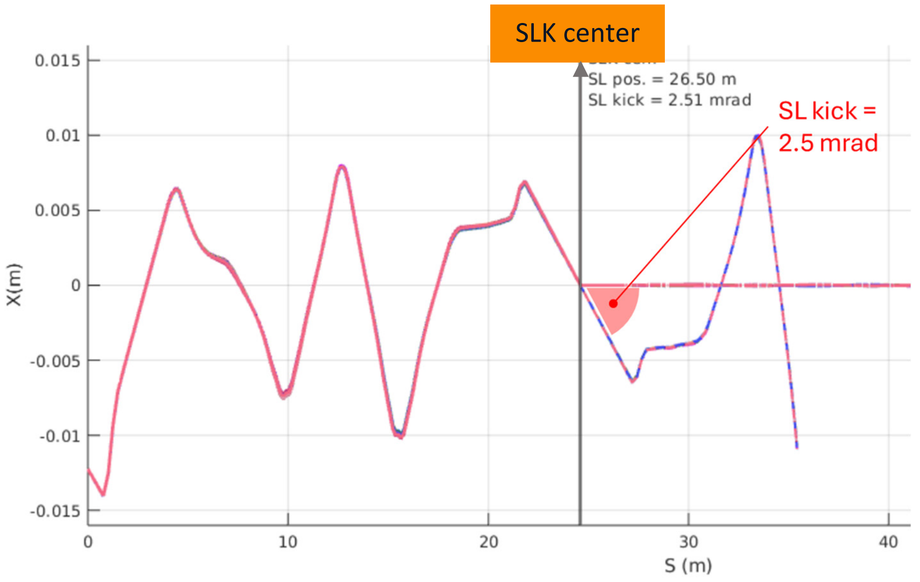


c/o **Marco Apollonio**

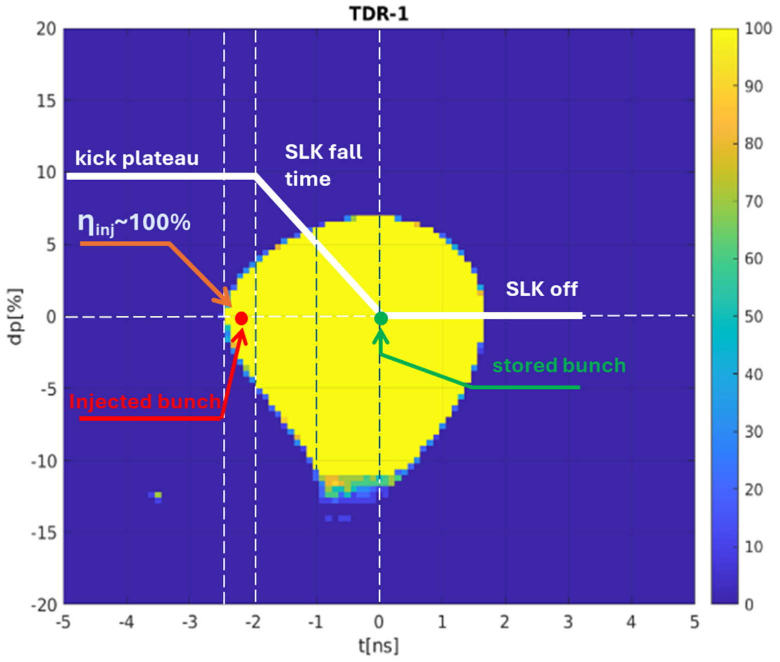
Off-phase Injection

On-**ax**is/off-**ph**ase/on-**en**ergy Injection $AX_{PH}EN$

- The injected beam comes into the ring with a time ¨**phase**¨ **offset** relative to the already circulating electron bunches
- The injected beam is kicked on-axis by a **very fast stripline kicker (SLK) magnet** (~2.5 mrad).
- The stored beam is **not disturbed**, and the injected beam damps down to the centre of the bucket after a few tens of milliseconds.



Injected bunch oscillation in the transverse plane, they are brought on-axis using a series of fast stripline kickers (SLK).



- Phase offset of −2.2 ns is required to reach close to 100% IE.
- SLK fall time < 2.2 ns.

THP2049: A. Dixon

c/o **Marco Apollonio**

Challenges

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

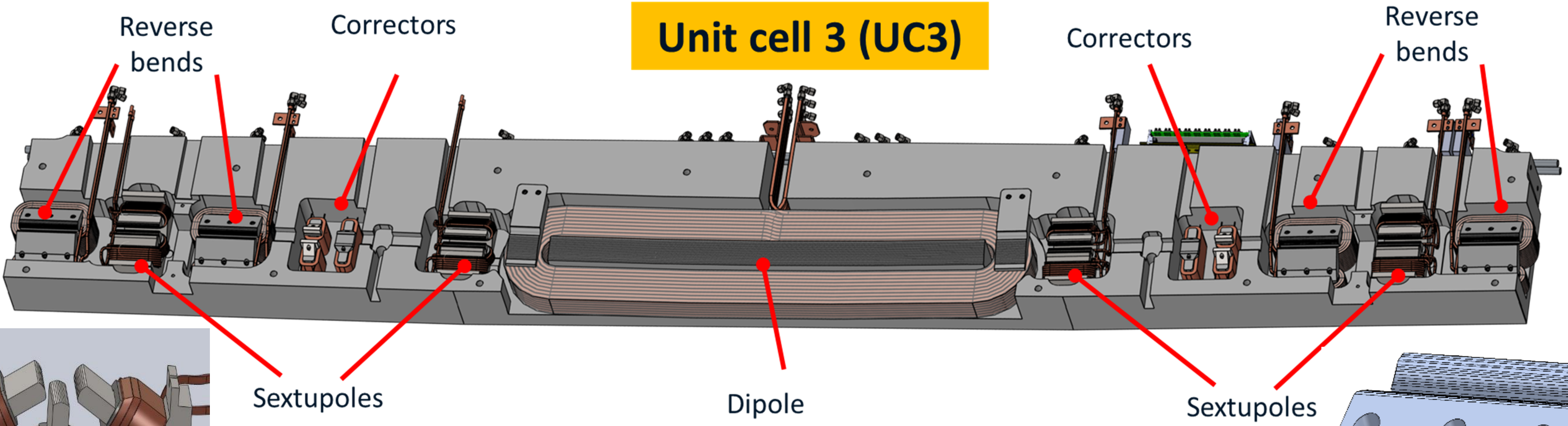
- Accelerator Engineering:
  - Development of **high-voltage (~tens of kV), fast pulsers with nanosecond-scale** fall times.
  - Achieving suitable **high-voltage vacuum feedthroughs** for reliable operation.
  - Implementation of stripline kickers that achieve the required performance without excessive beam **impedance**.

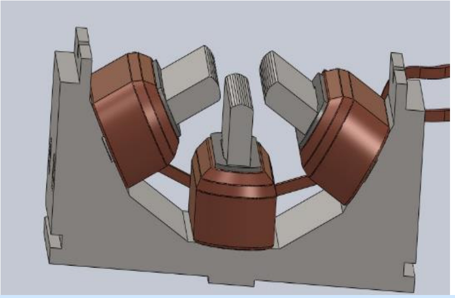
Prototyping and testing are underway to overcome those challenges.

Subsystem Engineering

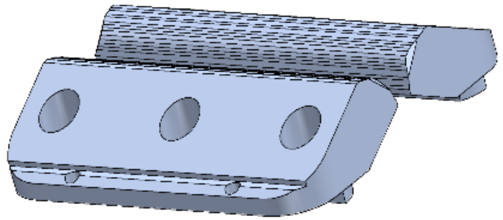
MAX 4U magnet system

- MAX IV is using the **magnet block concept** for the magnet system.
- 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 the **pole tips** of quadrupoles and correctors





Sextupole magnet half



Reverse bend pole tips

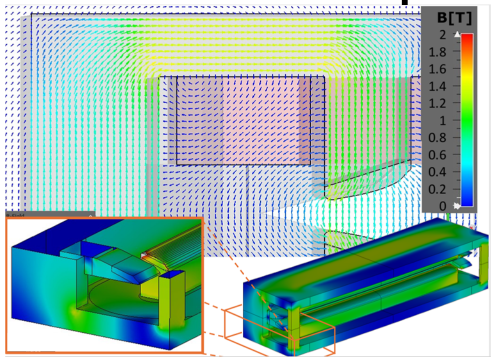
MAX 4^{U} magnet system

- The upgrade preserves the existing **7-bend achromat magnet-block layout** and **Ø25 mm aperture**.
- TDR-1 lattice requires **higher integrated magnet strengths for most of the magnet families.**
- New magnet family introduced: **Reverse Bend magnets.**
- Electromagnetic designs completed for **Dipole D2, Reverse bend R2, Quadrupole Q1, Q2 and Sextupole S1–S4,**
- **Magnetic cross-talk** between neighbouring magnets is being evaluated.

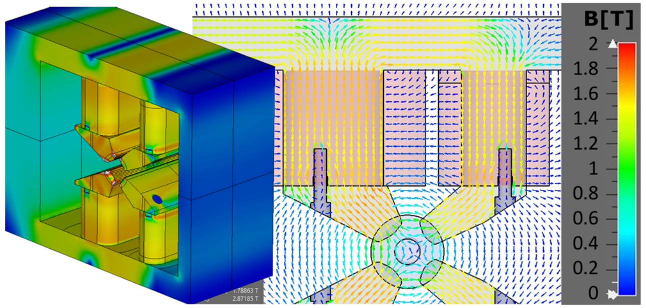
MOP7164 : A. Sharma

MOP7068 : H. O. C. Duarte

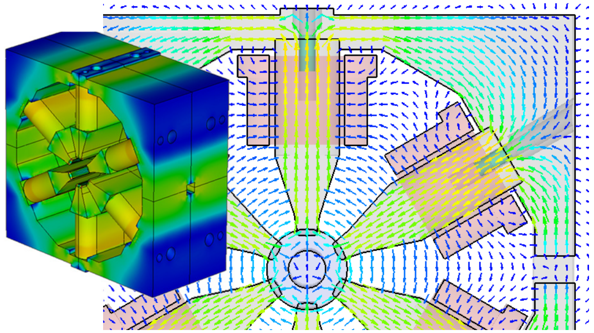
Combined Function Dipoles

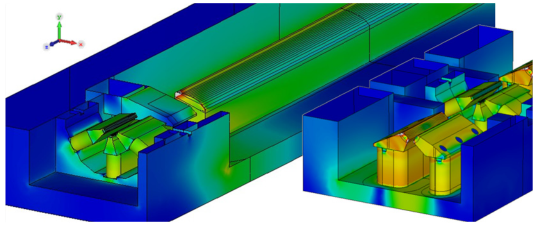


Reverse bends



Sextupoles

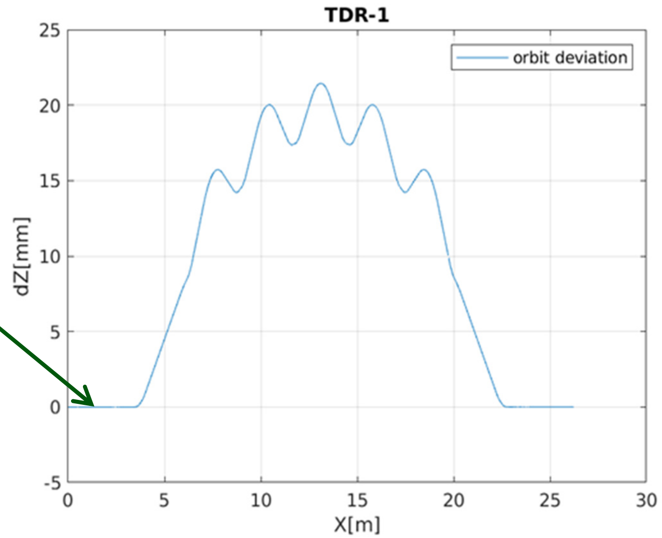


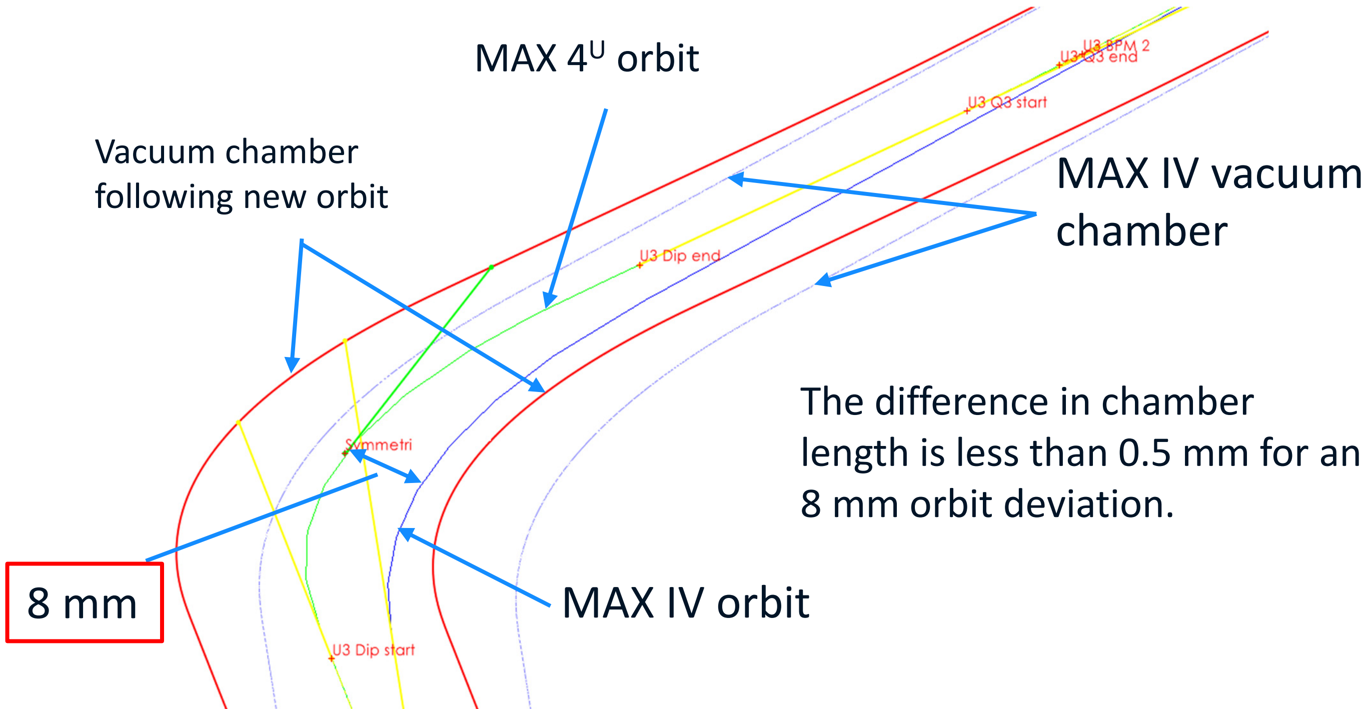


Cross talk simulations

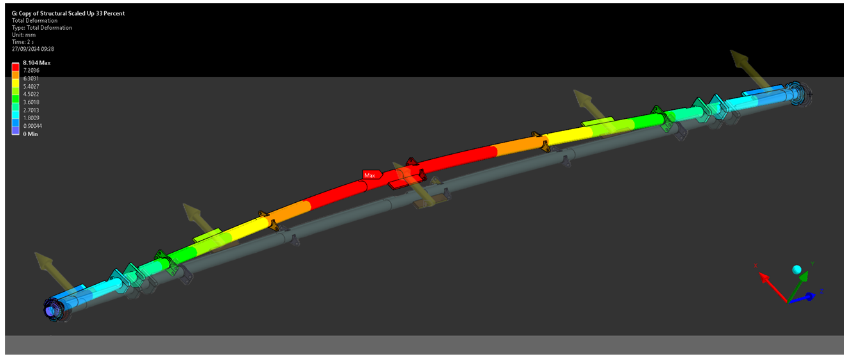
Vacuum System

Insertion devices source point maintained.





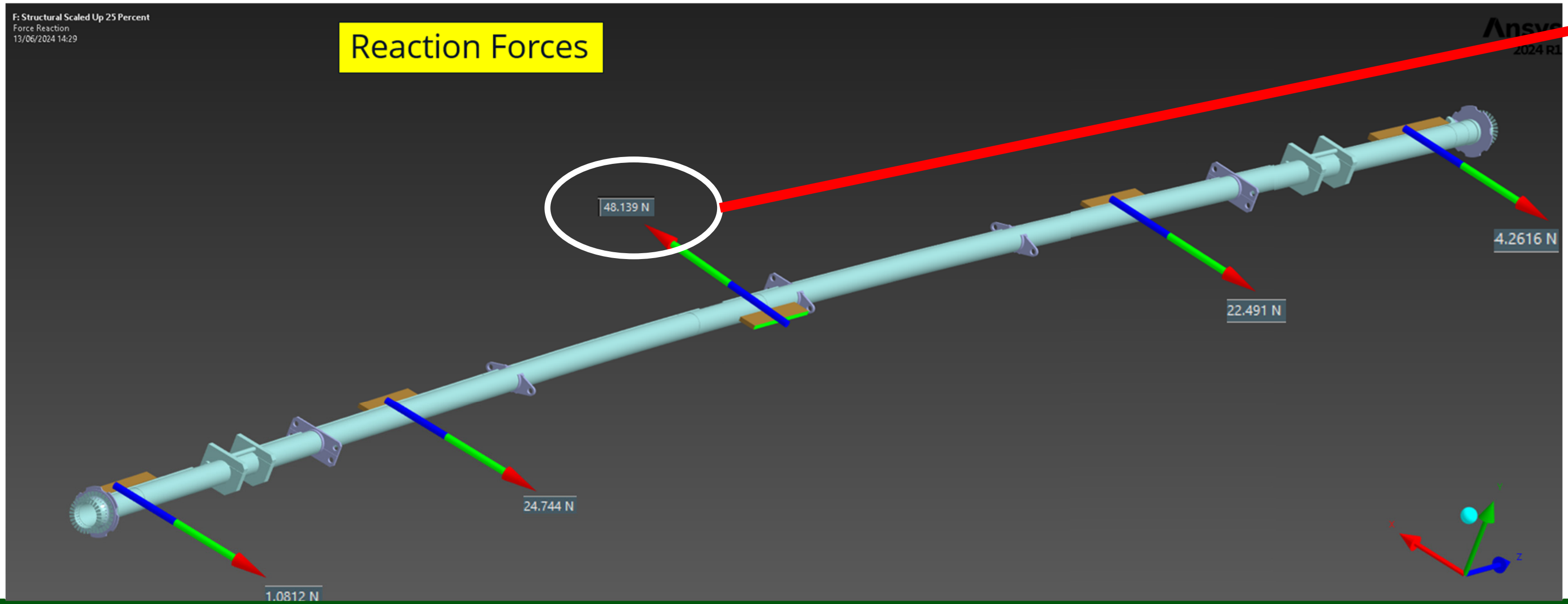
The difference in chamber length is less than 0.5 mm for an 8 mm orbit deviation.

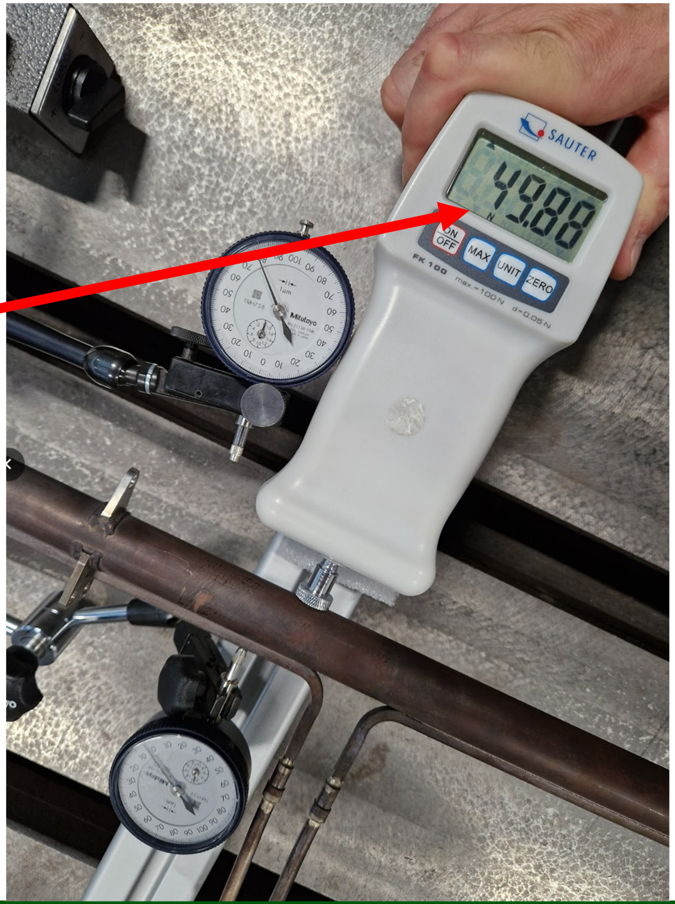


- The new chamber design would be **VERY similar** to the existing ones.
- Why not keep the existing chambers and **bend them** into the new orbit?!

Vacuum system

- Due to a smaller bending angle in the matching cells, we need to break the vacuum,
- 30 % of the chambers will be new.
- 70% of the chambers will be bent to follow the new orbit:
  - Cheaper
  - Faster to install
  - Faster conditioning
- Validation with FEA and prototyping with up to 8 mm bend was made successfully.





Synchrotron Rad. Power: Ray Tracing

Lattice fly-by provides a rapid visualisation of the new orbit path, enabling easy identification of where the photon beam impacts the chambers.

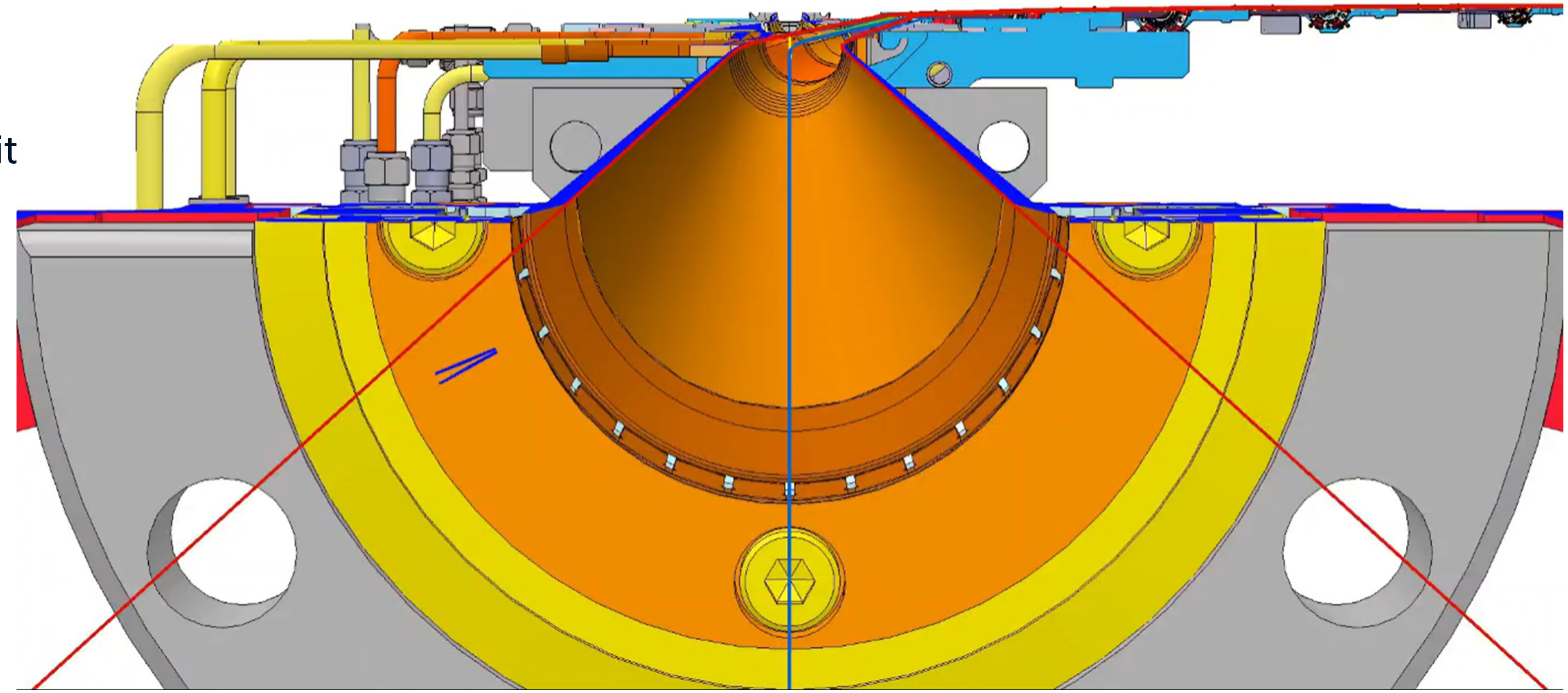
Green: MAX 4^U e-beam orbit.

Blue: MAX IV 3 GeV e-beam orbit

Yellow: photon beam

Black: max. power density

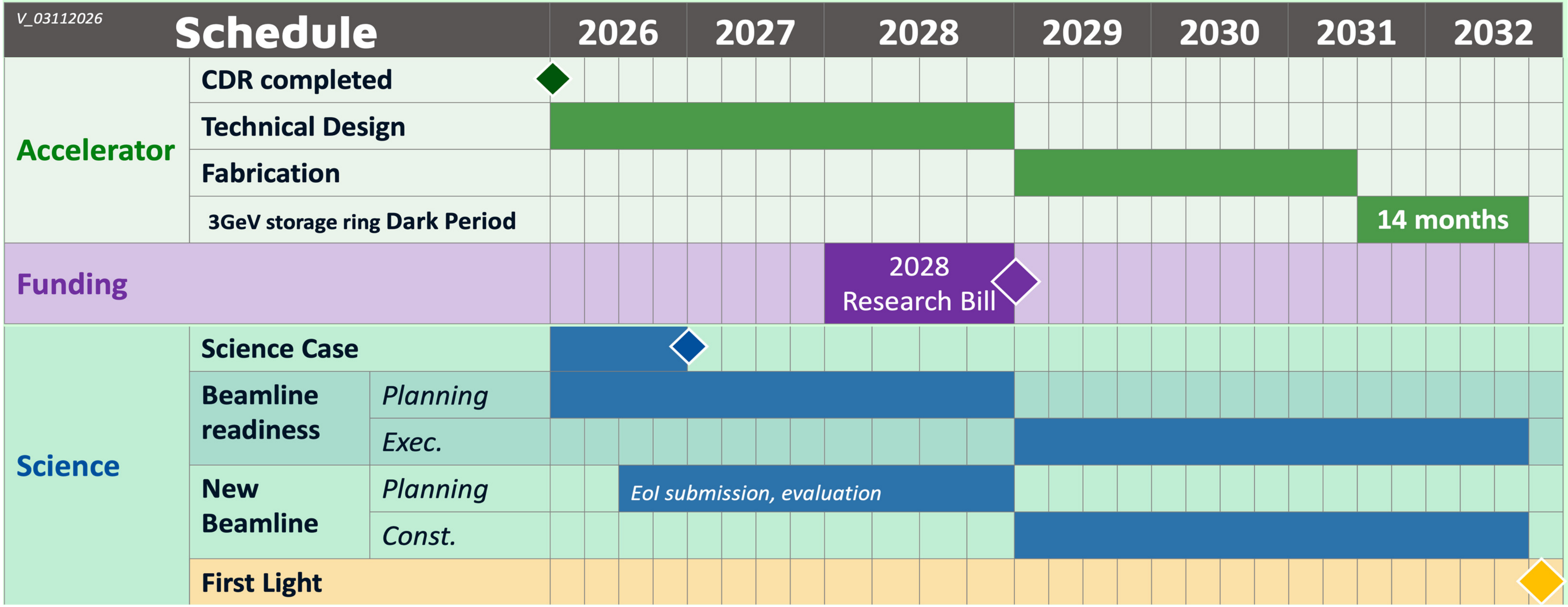
Rapid visualisation is performed first, followed by detailed Synrad+ and FEA simulations.



c/o Karl Åhnberg

Time Schedule

Time Schedule



Dark Period (14 months):

- 6 months: Installation
- 3 months: Subsystem testing
- 3 months: Beam commissioning
- 2 months of buffer.

No downtime for the 1.5 GeV storage ring or the SPF

c/o Aymeric Robert

Conclusion

Conclusion

- MAX 4^U is a **strategic, ¨surgical¨ upgrade** of the MAX IV 3 GeV ring, marking the **first upgrade** of a fourth-generation light source.
- MAX 4^U targets **<75 pm rad emittance,** while preserving existing infrastructure.
- Current lattice design meets **the emittance target** and boundary conditions.
- **Reuse of MAX IV infrastructure** reduces cost and minimises user downtime.
- **Off-phase injection** is the baseline injection scheme for MAX 4^U.

MOP7164 : A. Sharma

WEV5002: M. B. Alves

THP2115: M. Apollonio

MOP7068 : H. O. C. Duarte

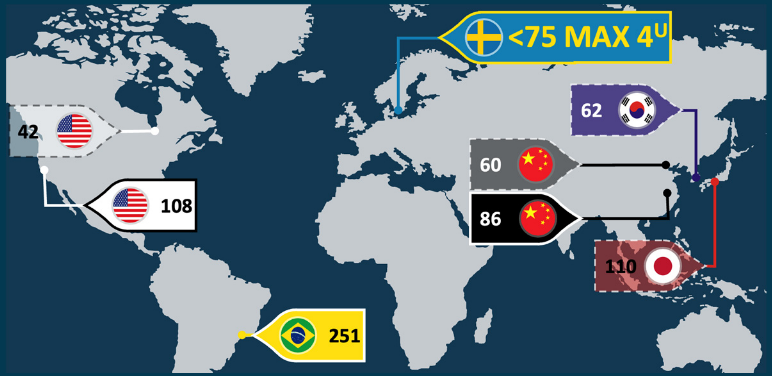
THP2049: A. Dixon

We gratefully acknowledge funding from the Crafoord Foundation (Crafoordska Stiftelsen).

MAX 4^U

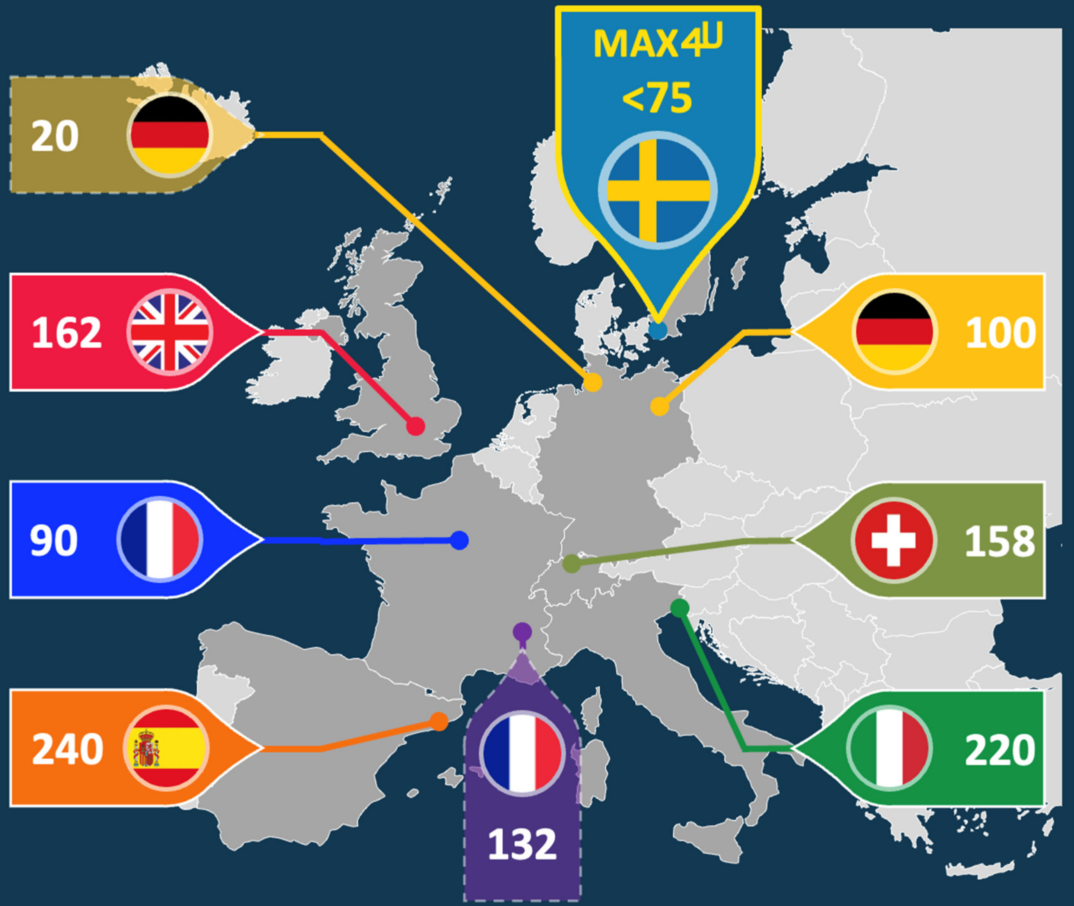
Securing leadership, excellence, resilience, and relevance of Swedish research an innovation with X-rays for the next decades

MAX 4^U website



A *"surgical"* upgrade of our 3GeV ring from 328 to below 75 pm·rad

Horizontal Emittance [pm·rad]



c/o A.ROBERT

V9.0126

Complementary Material

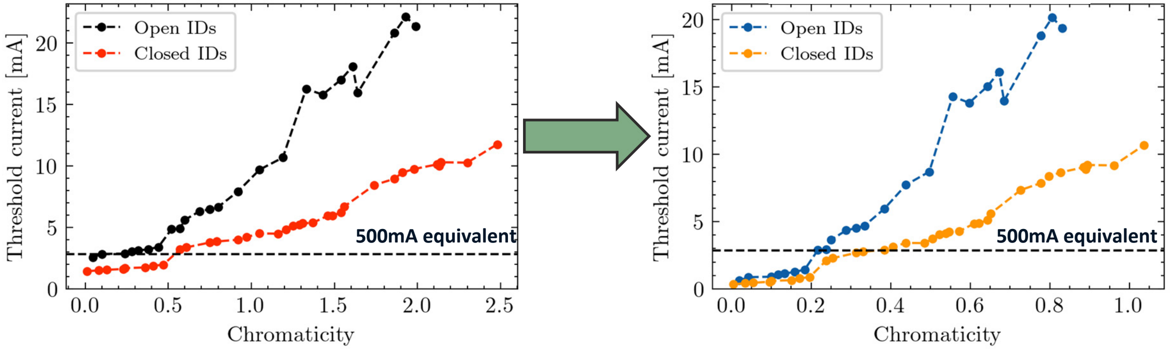
Collective effects

Current: 500 mA, uniform fill 176 bunches, 2.8 mA/bunch.

Single-bunch instabilities

TMCI

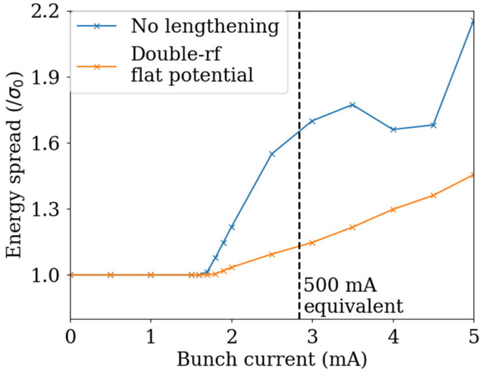
MAX IV 3 GeV ring | **MAX 4^U TDR-1**



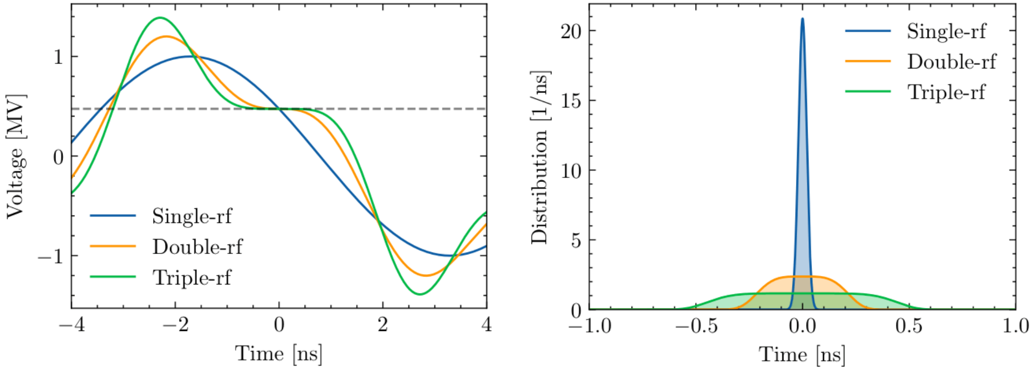
- TMCI thresholds measured in MAX IV 3 GeV ring and scaled to MAX 4^U TDR-1 lattice parameters
- Chromaticities above +0.7 are sufficient for stability margin

MWI

- Microwave instability simulated, threshold = 1.7 mA
- Double-rf system limits the energy spread increase to 13%

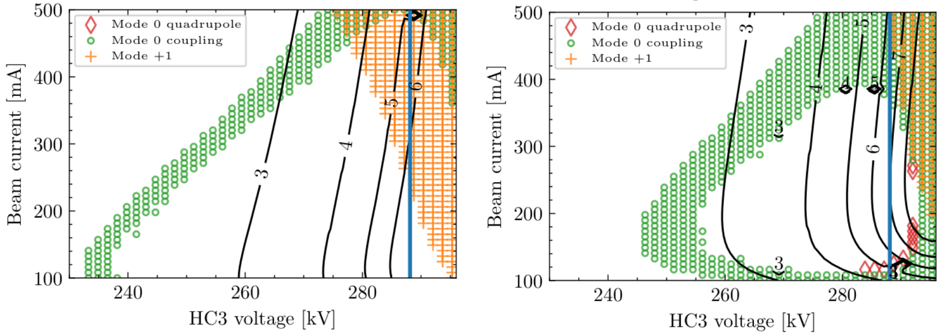


Bunch lengthening system and multi-bunch instabilities



Double-rf with main cavities (100 MHz) + passive 3rd harmonic (HC3). Lengthening factors of 6.
Better stability with single HC3

Two HC3s | Single HC3

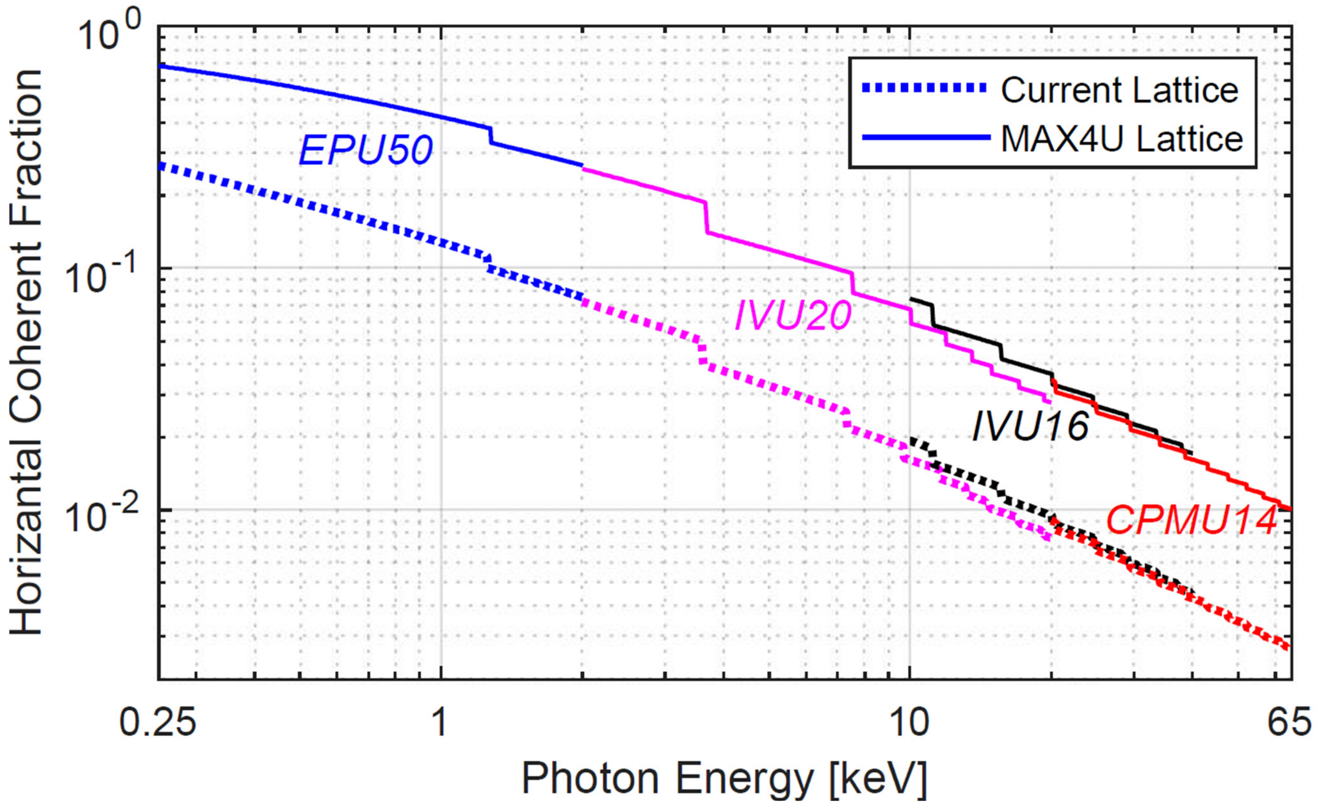


Triple-rf with additional active 5th-harmonic. Theoretical lengthening factors > 15. Studies on-going for experimental demonstration

WEV5002: M. B. Alves

Insertion Devices

- Existing and funded insertion devices can **operate unchanged** in MAX 4^{U} as beam energy, aperture, and K-values remain the same.
- **For hard X-rays,** substantial improvements in brilliance and coherence are expected, particularly with **IVUs and CPMUs.**
- **For soft X-ray,** APPLE II undulators (**EPU**) benefit significantly from improved horizontal coherence and brilliance, achieving diffraction-limited performance vertically.



Horizontal coherent fraction based on 65.2 pm rad natural emittance with 14% coupling.