ADVANCED AND ARTIFICIAL INTELLIGENCE TECHNIQUES TO MITIGATE LINEAR AND NON-LINEAR IMPERFECTIONS IN FUTURE CIRCULAR COLLIDERS

26 NOV,

ARTIFACT WORKSHOP

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CONTEXT

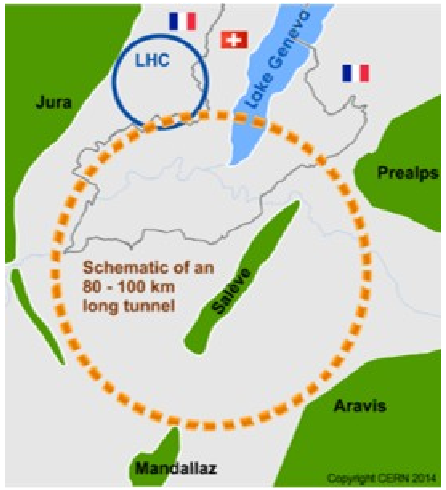
International **FCC** **collaboration (CERN as host lab) to study:**

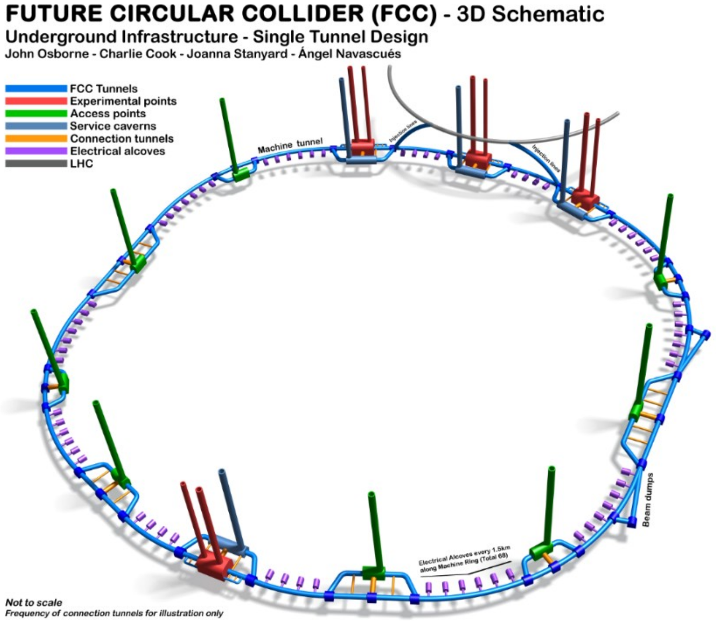
- ***pp*-collider (*FCC-hh*)** main emphasis, defining infrastructure requirements
- **~100 km tunnel infrastructure** in Geneva area, site specific
- ***e⁺e⁻* collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e⁻ from ERL

CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

Summary documents provided to EPPSU SG

- **FCC-integral, FCC-ee, FCC-hh, HE-LHC**
- Accessible on http://fcc-cdr.web.cern.ch/





AXES ENVISIONED

1) De-noising BPM turn-by-turn optics measurements
   used to define beta-beating, dispersion, coupling and non-linear corrections

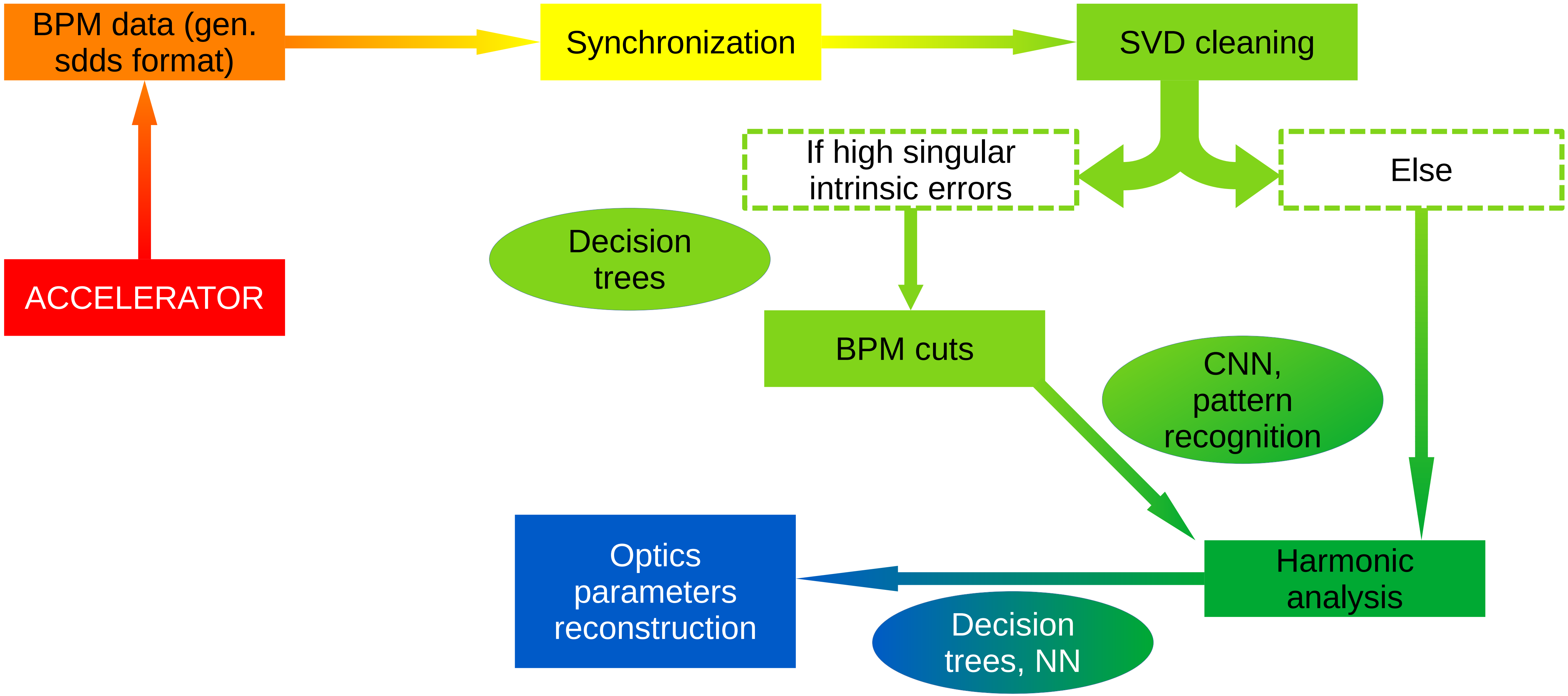
2) General purpose optimization for orbit, beta-beating, dispersion and coupling control in presence of imperfections

3) DA prediction/optimization
   Fast surrogate for non-linear correction optimization
   Beam lifetime optimization

1. De-noising BPM turn-by-turn optics measurements

- We will look into superKEKB data (displacement beginning of February), possibility to use also IOTA data, LHC…
- Standard and advanced techniques: use tool developed at CERN for LHC optics measurements (SVD cleaning, FFT analysis, definition of bad BPMs cut)
- AI techniques: auto-encoders(?), decision trees algorithms for best BPM choice in optics parameters reconstruction (phase-advance based or amplitude-based), reinforcement learning?

FROM BPM DATA TO ACCELERATOR OPTICS



2. General Purpose Optimization (Emittance Tuning)

Emittance : area of the beam in phase-space, related to beam size

Find corrections strategy for linear and non-linear imperfections

- Standard techniques: beam-based alignment, solve inverse problem (SVD, newton, simplex) following tools developed at CERN and SLAC

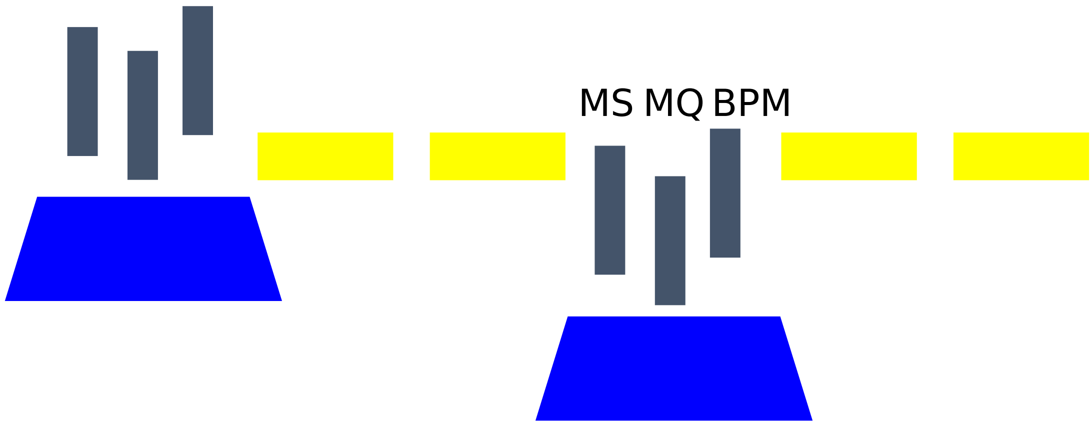
- AI techniques: MOBO, Neural Networks (TM-PNN?)

MAIN CONSTRAINT

The developed technique need to be scalable at FCC size (up to ~ 3000 correctors/BPMs readings)

The technique or a sub-product of it could be tried on superKEKB or IOTA

ORBIT CORRECTION



Error type	value
Dipole relative field error	
Main dipole roll error	300 µrad
Offset quadrupoles	200 + 50 µm
Offset BPMs	200 + 50 µm
Offset sextupoles	200 + 50 µm
BPMs resolution error	50 µm

correlation matrix

observations (x,y beam positions at BPMs)

$$A\vec{k}=\vec{b}$$

correctors (kickers for the orbit)

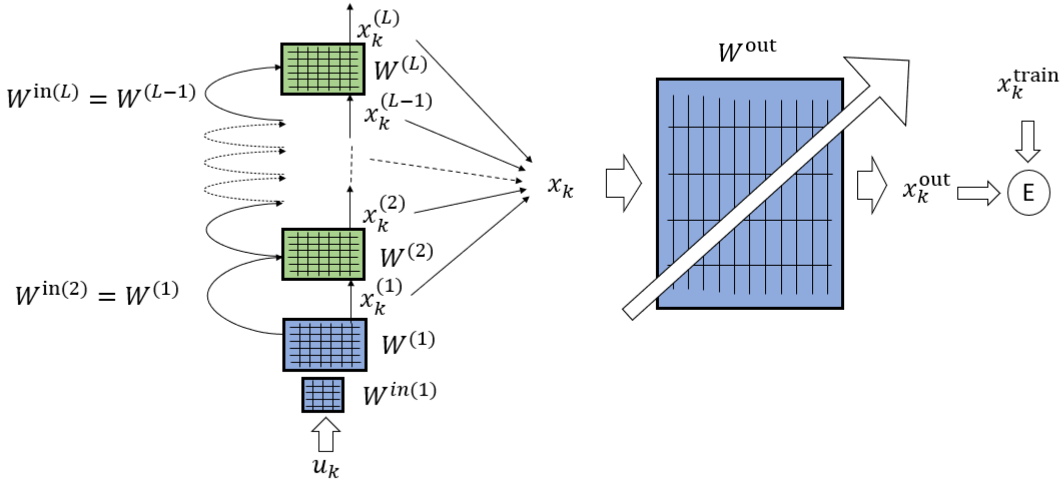
All errors are randomly distributed with 3 Gaussian rms.

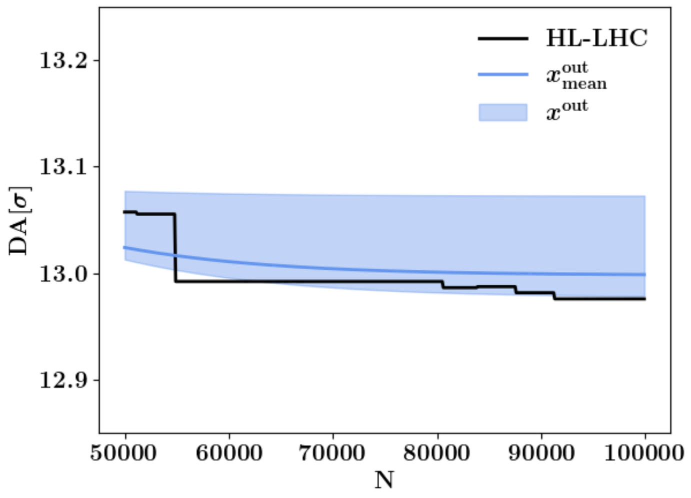
INVERSE PROBLEM

3. DA Prediction/Optimization

- Use fast surrogate models to predict DA replacing tracking simulations
- Include imperfections (and collectives effects?) in DA computation
- Try AI techniques to search for sextupoles and correctors settings to optimize DA/MA (so far genetic algorithms, BO have been tried in US labs) aim at improve beam lifetime (maybe can try something on IOTA)

FAST SURROGATE MODELS





M. Casanova, B.D. et al. , Eur. Phys. J. Plus (2023) **138**: 559

AIM: Replace CPU costly tracking simulations with fast surrogate model of the time evolution of Dynamic Aperture

MODEL: Deep Echo State Network

First results: RRMSE around 1%, but in 2hours per run (mostly hyperoptimization)

Evolution axes:
- Finalize automatic data split using Scaling Law derivatives
- Fast Hyper-parameters tuning using Bayesian techniques

SUMMARY

- Existing machine (commissioning or optics control)
- Future design (design optimization)

Orbit correction
Beta-beating, dispersion, coupling correction
Tune, chromaticity correction
Tracking, DA optimization/prediction

INPUTS

Known errors (simulations)

Known excitations (measurements)

BPMs readings, BLM, beam profiles (measurements)

Beam-lifetime (simulations)

METHODS

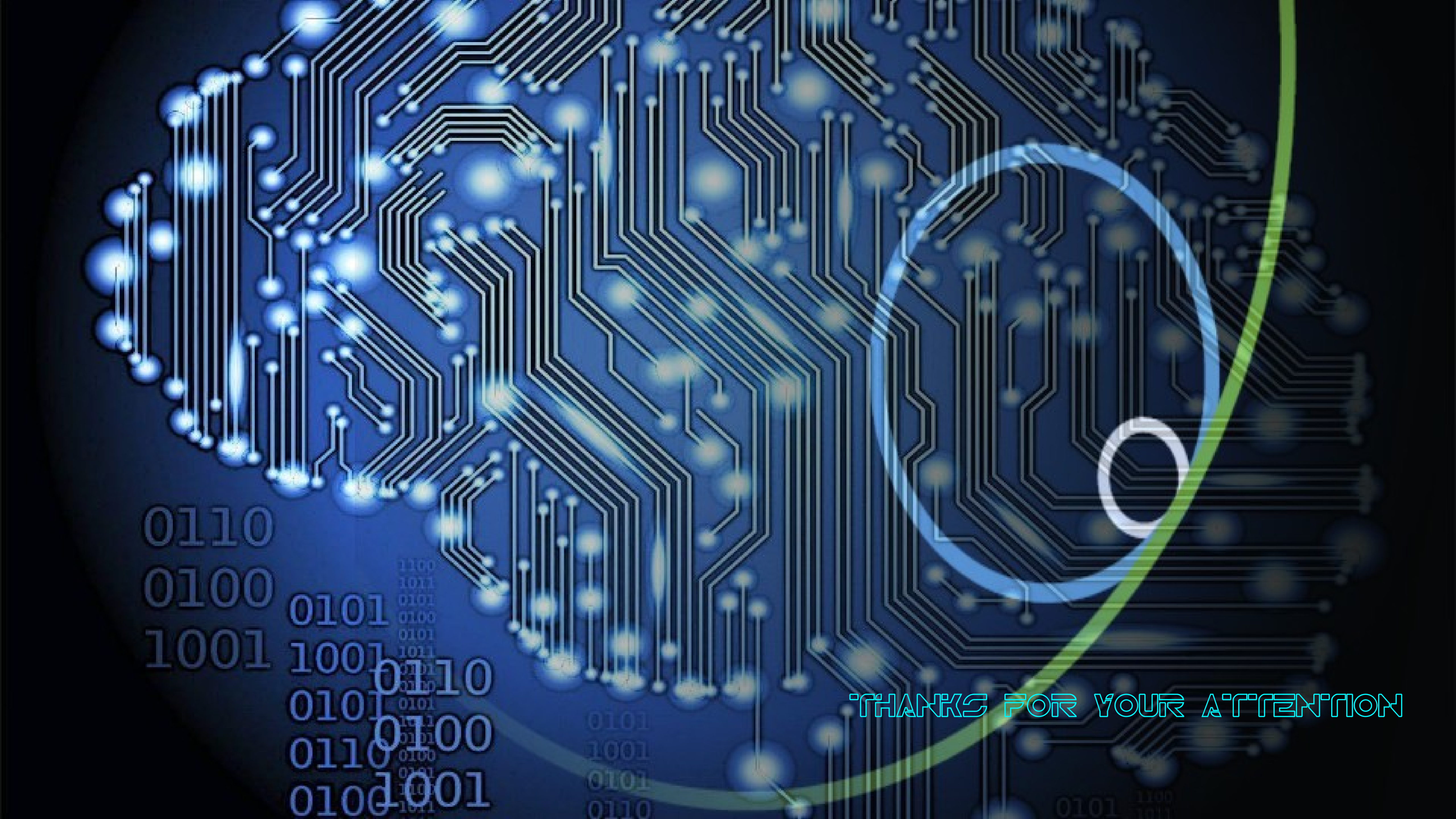
Standard:
SVD, MICADO, Gradient based algorithms, others
Beam-based alignment
Tracking

AI:
Genetic Algorithms, Particle Swarm,
BO, Reinforcement Learning, surrogate models, others

OUTPUTS

Definition of corrections (linear/non-linear)

Definition of tolerances (simulations)


THANKS FOR YOUR ATTENTION