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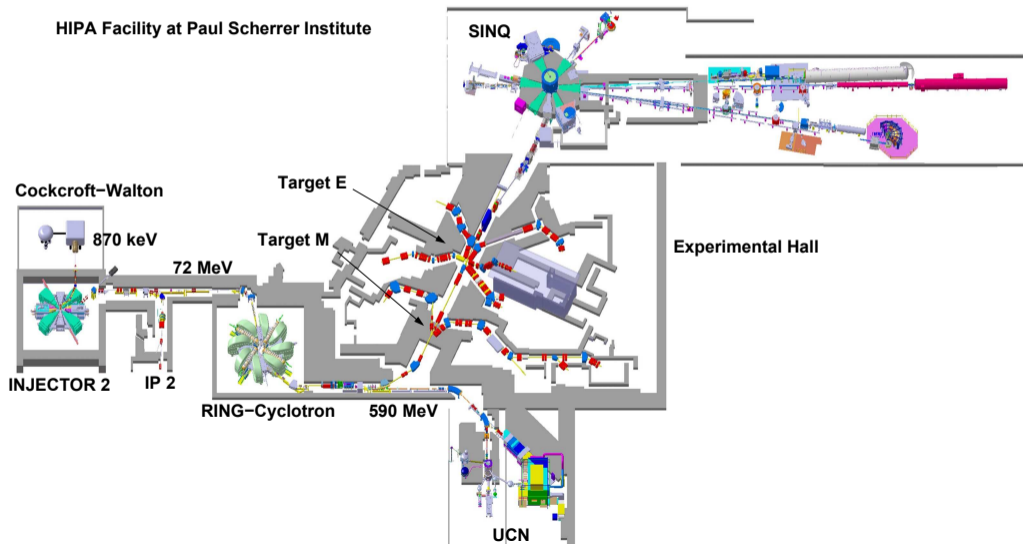
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Paul Scherrer Institut

Precise Modelling and Large Scale Multiobjective Optimization of Cyclotrons

26/09/2019 - CYC2019 Cape Town

- Motivation
- New Trimcoil Model in OPAL
- Multi-Objective Optimisation
- Local Search
- Final Results & Conclusions

HIPA Facility at Paul Scherrer Institute



Obtain Isochronicity in Cyclotrons

- **Uncertainties** in

- magnetic field (calculation and construction)
- **injection** parameters (E_{kin} , r , p_r , ...)
- element **positioning** (RF cavities)
- etc.

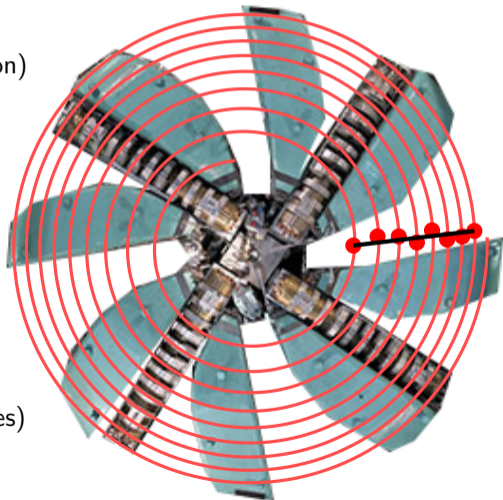
- **Restored / Achieved:**

Additional B-field with **trimcoils** (TCs)

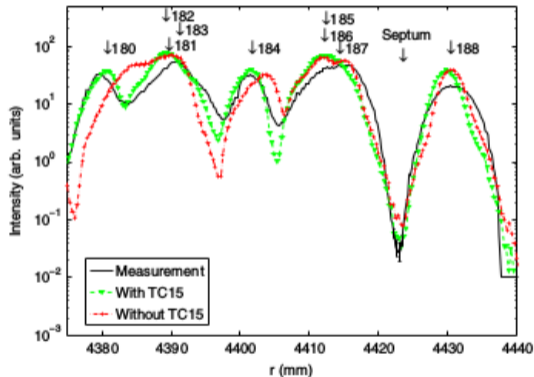
⇒ phase shift

(beam gets more/less energy by RF cavities)

⇒ turn radius shift



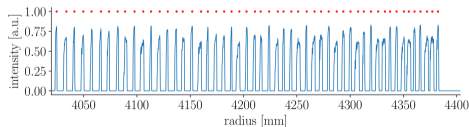
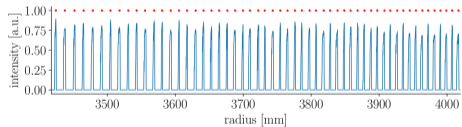
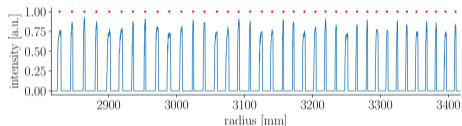
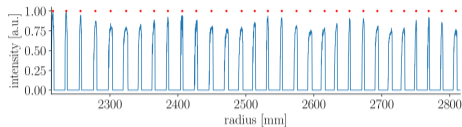
- **Discrepancies / Error** in
 - measured magnetic field due to **measuring conditions, technique and machine accessibility**
 - **simulation model:**
 - discretisation in time and space
 - simplified device models
 - missing device models
 - etc.
 - **injection** parameters (E_{kin}, r, p_r, \dots)
 - element **positioning** (RF cavities)
 - etc.



Towards quantitative simulations of high power proton cyclotrons.

Y. J. Bi, A. Adelman, R. Dölling, M. Humbel, W. Joho, M. Seidel,
and T. J. Zhang. Phys. Rev. ST Accel. Beams 14, 054402

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- OPAL PSI-Ring model only contains special TC15
 - but** 18 trim coils in PSI-Ring Cyclotron
- TC-model in OPAL approximated profile with analytical model
 - but** there are TC measurements available
- TC-field contribution in OPAL for 360 degree
 - but** in reality only on sector magnets

- Radial TC profile description with rational function

$$TC(r) = B_{\max} \frac{\sum_{i=0}^n a_i r^i}{\sum_{j=0}^m b_j r^j} \quad n, m \in \mathbb{N}_0 \wedge r \in [r_{\min}, r_{\max}]$$

```
tc1:  TRIMCOIL, TYPE = "PSI-PHASE",
      RMIN = ..., // inner radius [mm]
      RMAX = ..., // outer radius [mm]
      BMAX = ..., // B-field peak value [T]
      COEFNUM   = {a0, a1, a2, a3},
      COEFDENOM = {b0, b1, b2, b3, b4, b5};
```

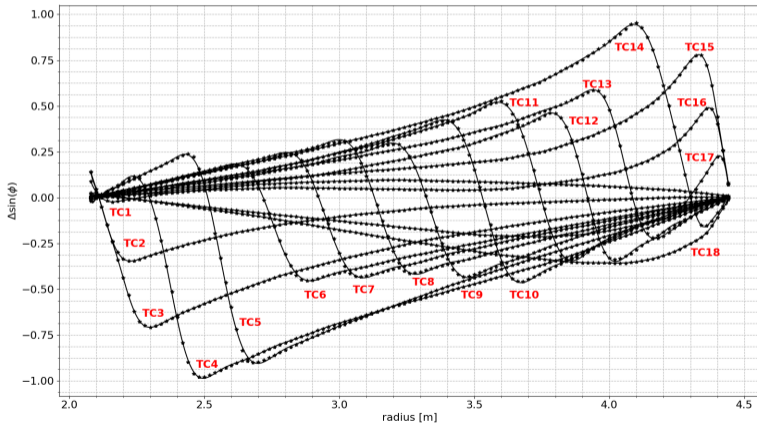
- **Supported types:**

- new: PSI-BFIELD, PSI-PHASE
- old: PSI-BFIELD-MIRRORED

- **Cyclotron-Definition:**

```
Ring: CYCLOTRON, TRIMCOILTHRESHOLD = ... ,  
      // lower limit of TC contribution [T]  
      TRIMCOIL = {tc1, tc2, tc3, ...} ,  
      ... ;
```

- **Starting point:** Measurement of phase shift effect¹ $\Delta B \sim -\frac{d\Delta \sin(\phi)}{dr}$



¹S. Adam and W. Joho, PSI Technical Report No. TM-11-13, 1974.

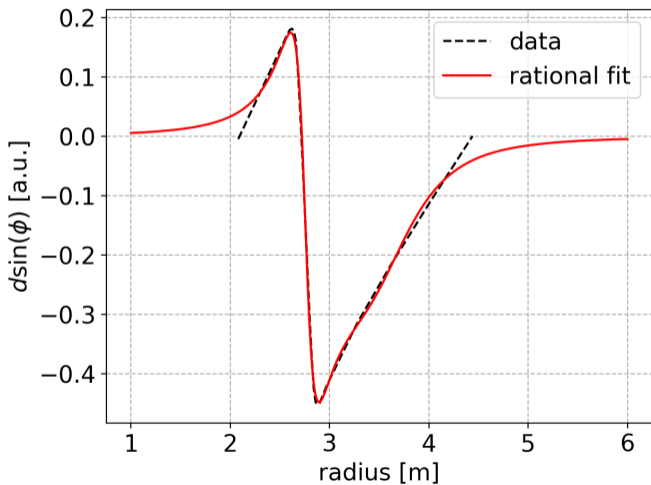
- **Fit of phase shift curves:**

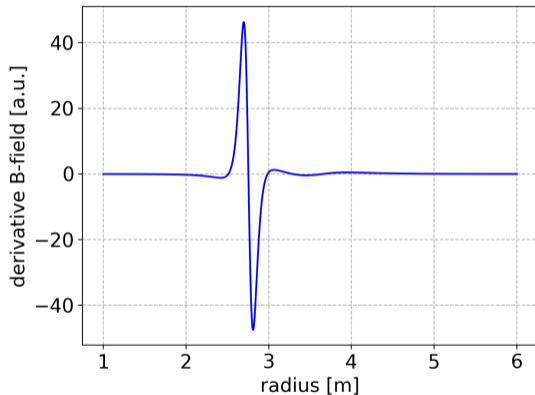
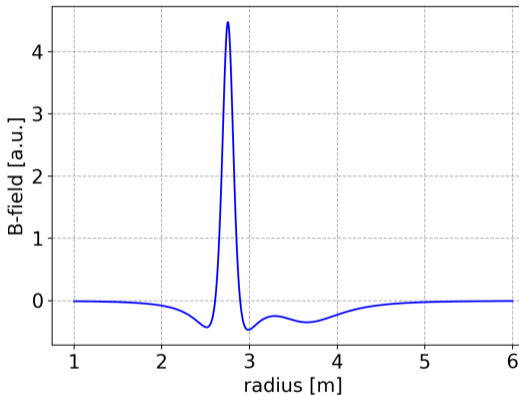
$$\Delta \sin(\phi)(r) \approx h_{\text{phase}}(r) = \frac{f(r)}{g(r)} = \frac{\sum_{i=0}^n a_i r^i}{\sum_{j=0}^m b_j r^j}$$

with $m > n \in \mathbb{N}_0$

- **TC2 - TC15:** $n = 2, m = 4$
- **TC1, TC16 - TC18:** $n = 4, m = 5$
- **Magnetic field:**

$$B(r) = -\frac{dh_{\text{phase}}}{dr} = -h'_{\text{phase}} = -\frac{f'g - fg'}{g^2}$$





- **Built-in MOO²:**

$$\begin{array}{lll}
 \text{optimize objectives} & \mathbf{f}(\mathbf{x}) & \dim(\mathbf{f}) \geq 1 \\
 \text{subject to constraints} & \mathbf{g}(\mathbf{x}) \geq 0 & \dim(\mathbf{g}) \geq 0 \\
 \text{within design variables bounds} & x_i^L \leq x_i \leq x_i^U &
 \end{array}$$

- **Design variables \mathbf{x} :** E_{kin} , p_r , φ , TC1 - TC16 max. B-field, etc.
- **Objectives:** Measure between simulation and real data

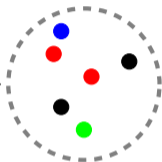
Note: \mathbf{f} is our PSI-Ring model + evaluation of objectives!

²Toward massively parallel multi-objective optimisation with application to particle accelerators. PhD Thesis. Y. Ineichen. 2013

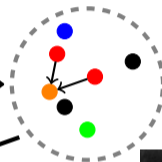
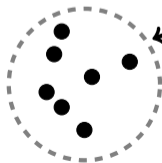
Multi-Objective Genetic Algorithm (MOGA)

1st generation

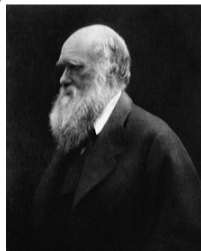
mutation



crossover

2nd generation

...

Charles Darwin³

³Image: https://en.wikipedia.org/wiki/Charles_Darwin

- **Measurements:** Peak intensity of radial profile of probes to distinguish turns

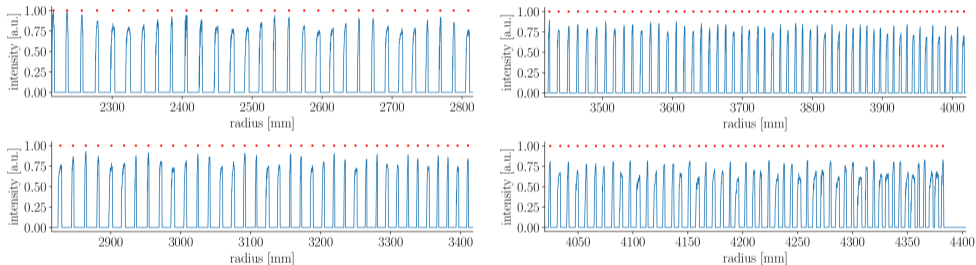
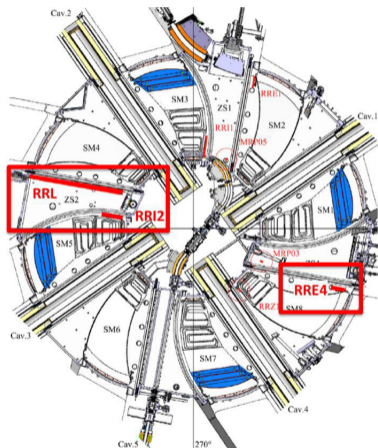


Figure: Histogram of RRL measurement

- **Goal:** Match radial peaks of measurement and simulation
- **RRI2:** turns 1 - 16
- **RRL:** turns 9 - 182

190 peaks \Rightarrow Infeasible number of objectives!



OPAL simulations of the PSI ring cyclotron and a design for a higher order mode flat top cavity. N. J. Pogue, A. Adelman. Proceedings of IPAC2017. THPAB077. 2017.

- **Turn - Aggregation:**

- L_2 -norm

$$\sigma_{[l,u]} = \frac{1}{N} \sqrt{\sum_{i=l}^u (r_i^m - r_i^s)^2}$$

- L_∞ -norm

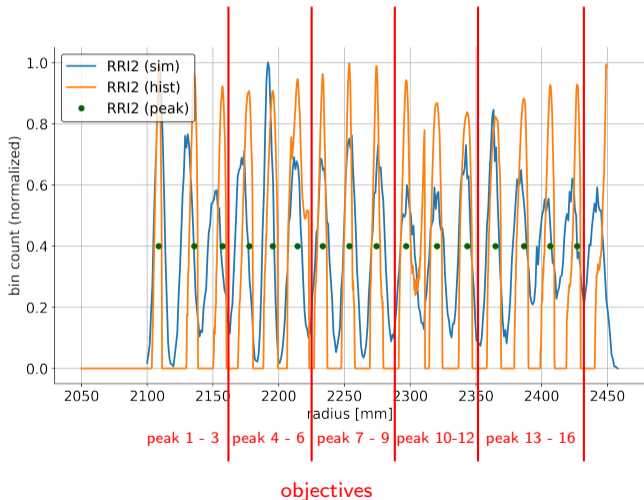
$$\sigma_{[l,u]} = \max_{i=l\dots u} |r_i^m - r_i^s|$$

$N = u - l + 1$: number of aggregated turns

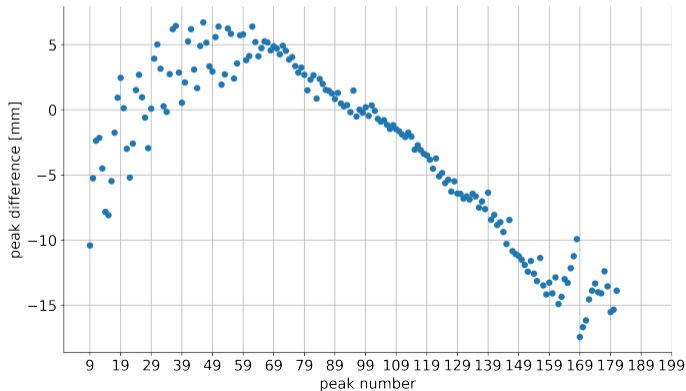
r_i^m : i -th turn radii of measurement

r_i^s : i -th turn radii of simulation

- **Goal:**
Find initial injection values
- **Design variables:**
 - beam energy E_{kin}
 - injection angle
 - injection momentum
 - injection radius
 - TC1 - TC4
- **MOO:** (504 cores)
 - #generations 500
 - #individuals 502
- 5000 particles per individual

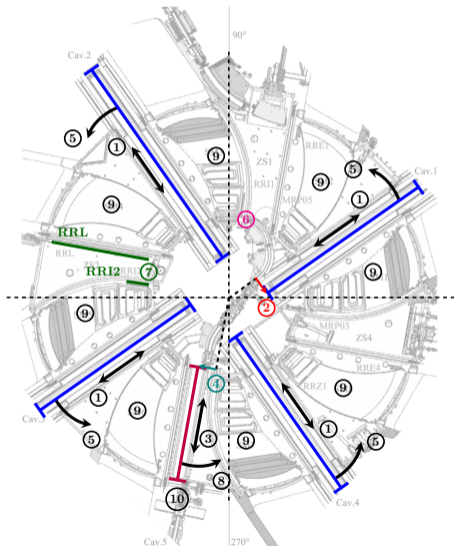


- Optimising a few TCs after the other (i.e. optimise sub-problems) leads to divergence! → Optimise full cyclotron at once
- RF cavity voltages not correct → more design variables needed!



- **Single particle tracking** instead of bunch (5000 particles) tracking
⇒ full PSI-Ring simulation in 1 - 2 s
- **Design variables:**
 - injection angle, radius, momentum and energy
 - main cavity voltages
 - phase of Flat-Top cavity
 - voltage of Flat-Top cavity
 - radial position of main cavities
 - radial position of Flat-Top cavity
- **Turn number constraint** to guarantee feasible solutions

Design Variables (48)



- ① main RF cavity displacement in radial direction; RF voltage on main cavity 1 - 4
- ② displacement of main cavity's axis from global center
- ③ flat top cavity displacement in radial direction
- ④ displacement of flat top's axis from global center
- ⑤ main cavity's angle w.r.t. the center line of sector magnet 1
- ⑥ injection beam energy, injection radial momentum, injection angle of beam, injection radius w.r.t. the global coordinate system
- ⑦ positioning of probes (2*3 parameters)
- ⑧ flat top cavity angle w.r.t. global coordinate system
- ⑨ trim coil maximum magnetic field
- ⑩ phase of flat top; RF voltage on flat top cavity

Evolution of best individual during MOGA

>8k individuals/generation

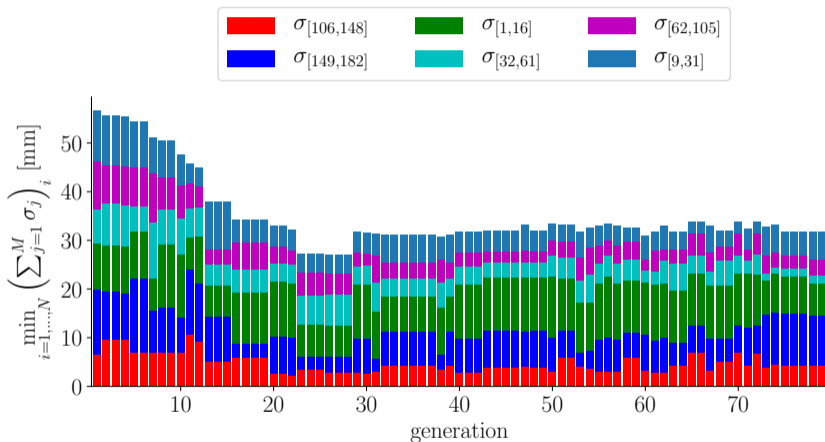


Figure: The label $\sigma_{[l,u]}$ indicates an objective for the turns in the range $[l, u]$.
 M : number of objectives; N : number of individuals per generation.

Result of best individual obtained by MOGA

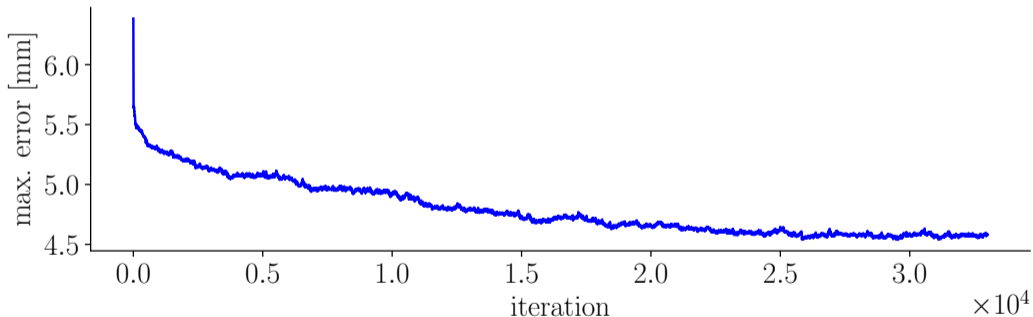
Objective $\sigma_{[l,u]}$	l_∞ -error (mm)	Probe
$\sigma_{[1,16]}$	6.38	RRI2
$\sigma_{[9,31]}$	3.76	RRL
$\sigma_{[32,61]}$	6.34	RRL
$\sigma_{[62,105]}$	4.39	RRL
$\sigma_{[106,148]}$	2.91	RRL
$\sigma_{[149,182]}$	3.27	RRL

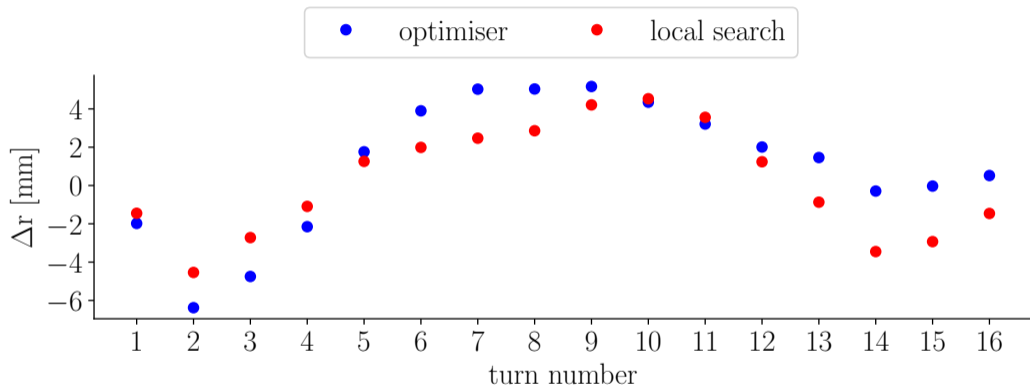
Table: The label $\sigma_{[l,u]}$ indicates an objective for the turns in the range $[l, u]$.

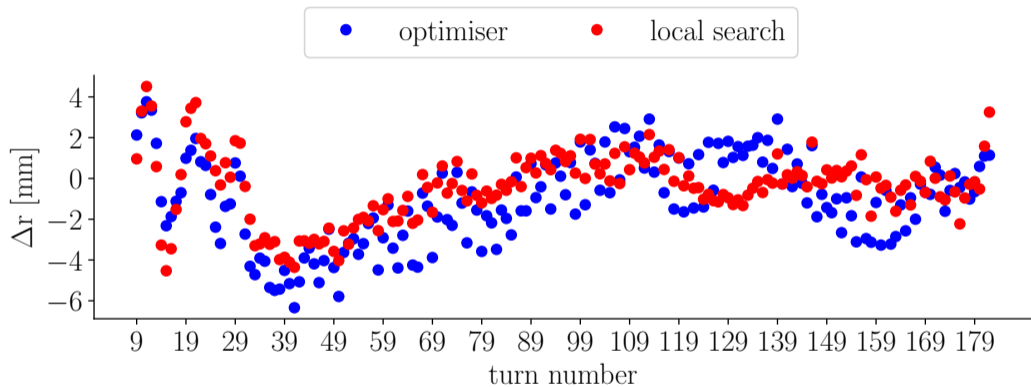
- **Issues:**
 - Optimiser suffered with individual selection
 - No further improvements observed
 - Changing many parameters at same time might be disadvantageous
- **Idea:** Local search by simple parameter scanning
 - Often used strategy after genetic algorithm
 - Starting from best MOO individual
 - Change input parameters only in per-mille magnitude
 - Iteratively find worst turn and vary parameters to obtain better individual
(check L_∞ - and L_2 -norm, 2nd and 3rd worst turn not to get stuck with only L_∞)

Evolution of maximum absolute error during local search

> **1 mm error reduction after a few iterations**







Method	l_∞ -norm (mm)	MAE (mm)	MSE (mm ²)
optimiser	6.4	2.0	6.3
local search	4.5	1.4	3.4

Table: Maximum absolute error (l_∞ -norm), mean absolute error (MAE) and the mean squared error (MSE) of the best individual of the optimiser and local search compared to the measurement. In both cases the maximum error is at turn 2.

- More realistic generic trimcoil model implemented in OPAL
- Multi-Objective Optimization (MOO) performed to match measurement
 - massively parallel (used with $> 1'000$ cores)
 - good for finding reasonable solutions fast
 - MOGA possibly not optimal for high-dimensional (> 9) design variable space
 - other algorithms could be considered (e.g. simulated annealing)
- Local search of design variables
 - to improve on MOO solutions
 - may get stuck and stop improving (alternating between metrics helped)
- Realistic model for HIPA Ring cyclotron obtained
 - basis for further studies
- For details please check out Phys. Rev. Accel. Beams 22, 064602 (June 2019)

Thanks to

R. Dölling

M. Humbel

W. Joho

M. Kranjčevic

H. Zhang

