PAUL SCHERRER INSTITUT

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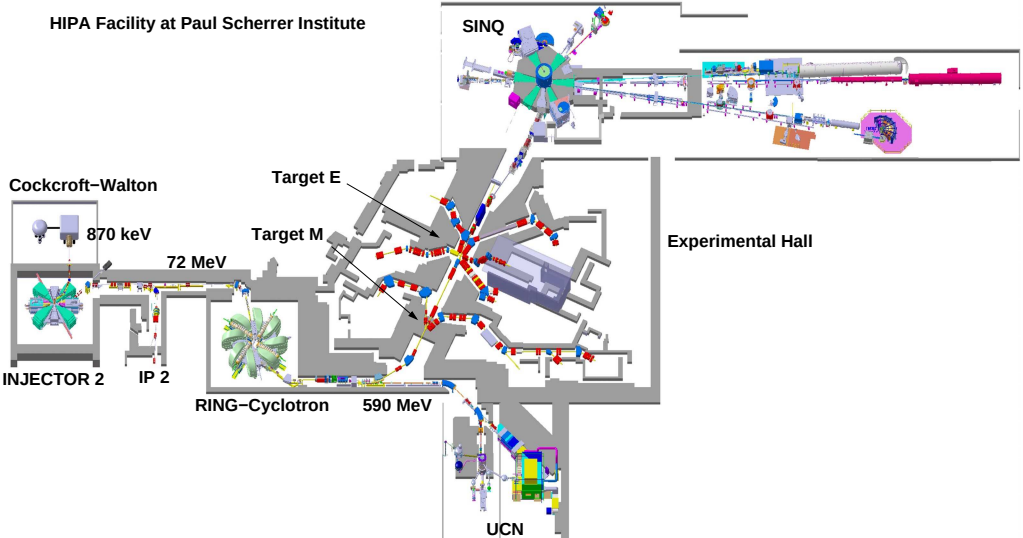
Precise Modelling and Large Scale Multiobjective Optimization of Cyclotrons

21/11/2019 - FFA2019 PSI

Outline

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

HIPA complex



Obtain Isochronicity in Cyclotrons

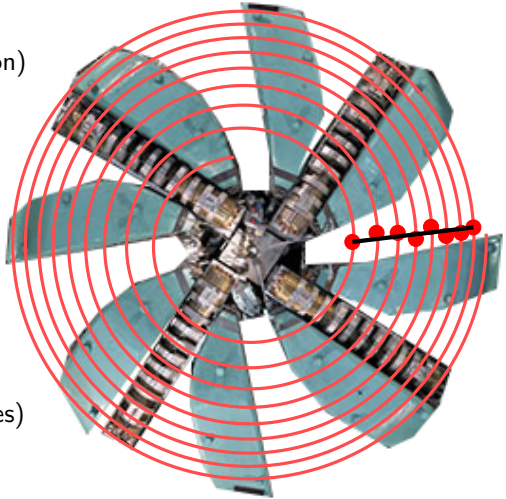
- **Uncertainties** in
  - magnetic field (calculation and construction)
  - **injection** parameters ($E_{kin}, r, p_r, \ldots$)
  - element **positioning** (RF cavities)
  - etc.
- **Restored / Achieved:**

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

  $\Longrightarrow$ phase shift

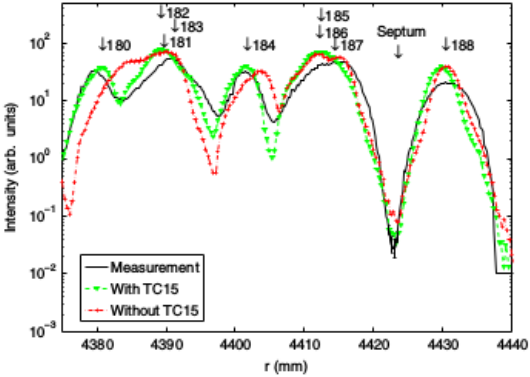
  (beam gets more/less energy by RF cavities)

  $\Longrightarrow$ turn radius shift



Mismatch between Measurements and Simulations

- **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 ($E_{kin}, r, p_r, ...$)
  - element **positioning** (RF cavities)
  - etc.



Towards quantitative simulations of high power proton cyclotrons.

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

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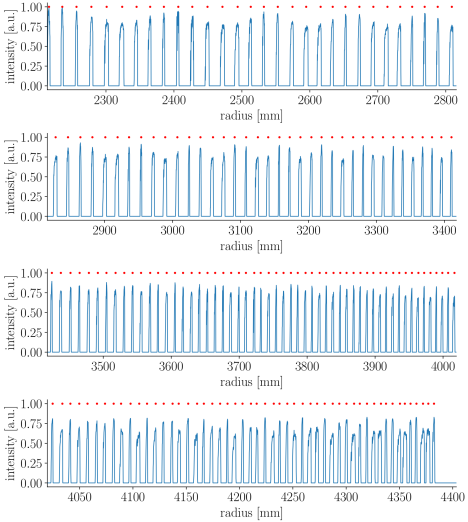
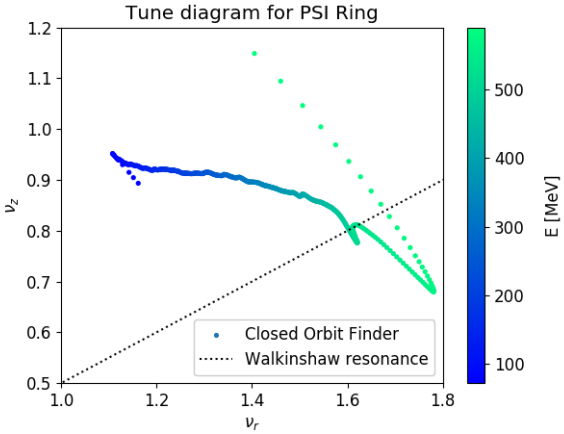
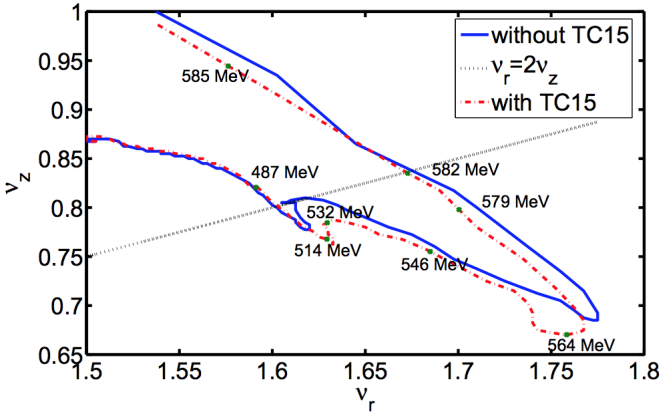


Ring tune diagram



Ring tune diagram with trim coil 15



New Trimcoil Model in OPAL

Towards More Realistic Trimcoil Simulations

- 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

New Trimcoil Model in OPAL

- Radial TC profile description with rational function

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

```
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};
```

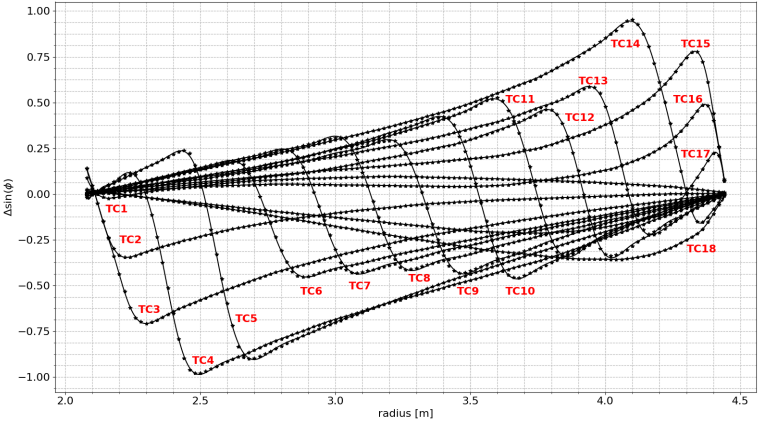
New Trimcoil Model in OPAL

- **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, ...},
                 ... ;
```

PSI-Ring Trimcoil Model

- **Starting point:** Measurement of phase shift effect[1] $\Delta B \sim -\frac{d\Delta \sin(\phi)}{dr}$



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

PSI-Ring Trimcoil Model

- **Fit of phase shift curves:**

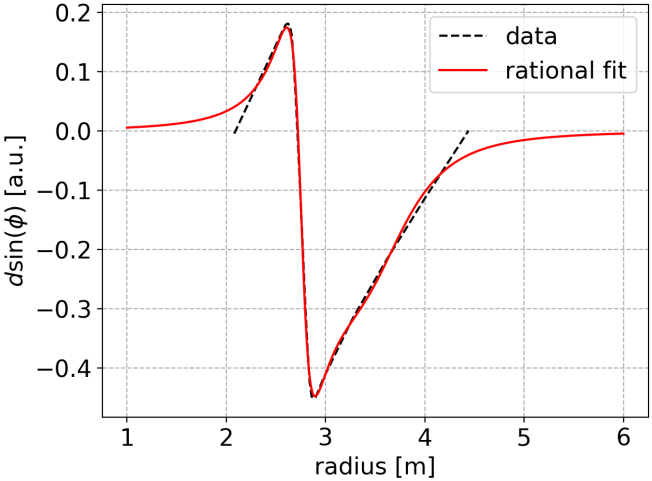
$$\Delta \sin(\phi)(r) \approx h_{phase}(r) = \frac{f(r)}{g(r)} = \frac{\sum_{i=0}^{n} a_i r^i}{\sum_{j=0}^{m} b_j r^j}$$

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

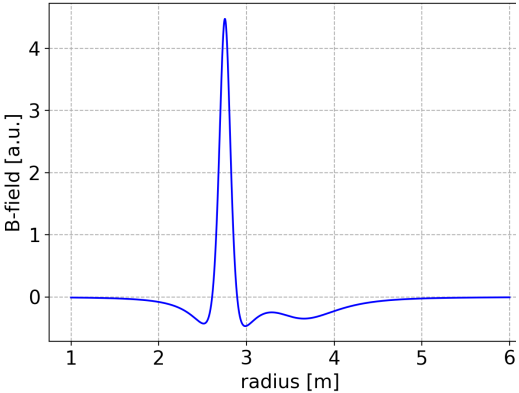
- **TC2 - TC15:** $n = 2,\ m = 4$
- **TC1, TC16 - TC18:** $n = 4,\ m = 5$
- **Magnetic field:**

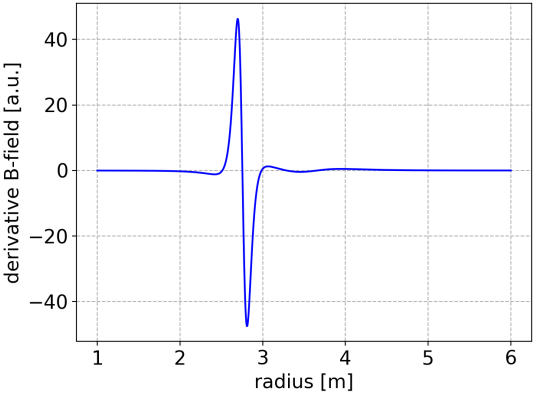
$$B(r) = -\frac{dh_{phase}}{dr} = -h'_{phase} = -\frac{f'g - fg'}{g^2}$$

PSI-Ring Trimcoil Model - Example TC6



PSI-Ring Trimcoil Model - Example TC6





Multi-Objective Optimisation

Multi-Objective Optimisation (MOO) in OPAL

- **Built-in MOO**[2]:

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

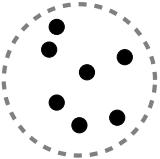
- **Design variables x:** E_{kin}, p_r, φ, TC1 - TC16 max. B-field, etc.
- **Objectives:** Measure between simulation and real data

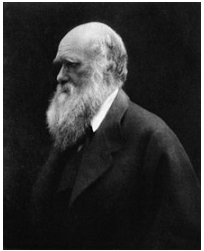
Note: f is our PSI-Ring model + evaluation of objectives!

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

Multi-Objective Genetic Algorithm (MOGA)

1st generation

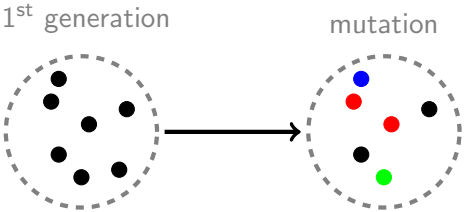


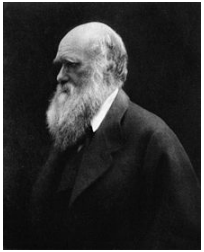


Charles Darwin[3]

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

Multi-Objective Genetic Algorithm (MOGA)





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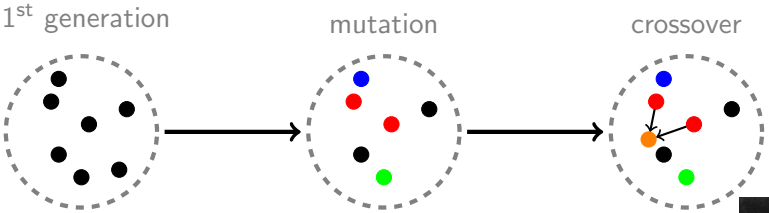

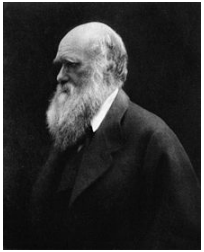

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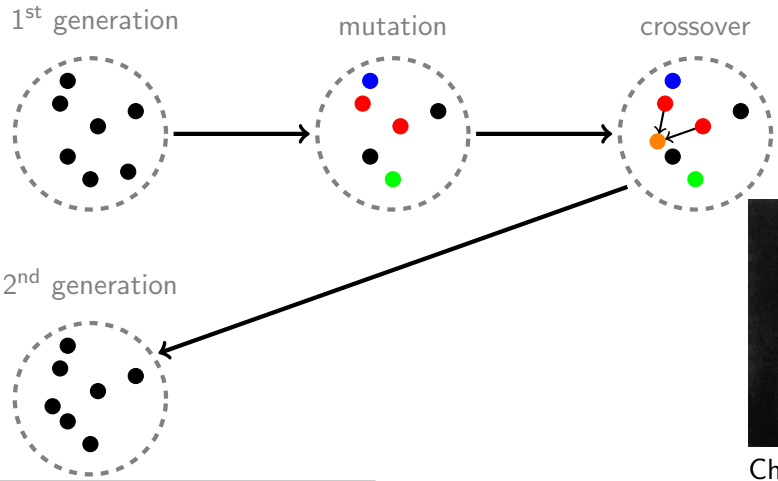

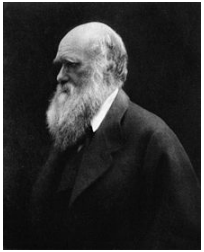

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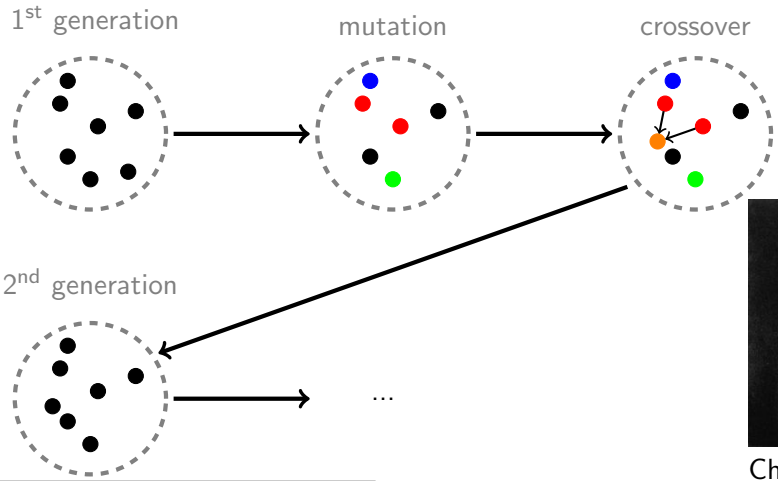

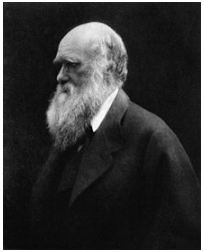

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Radial Profile Measurement – Centred Beam

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

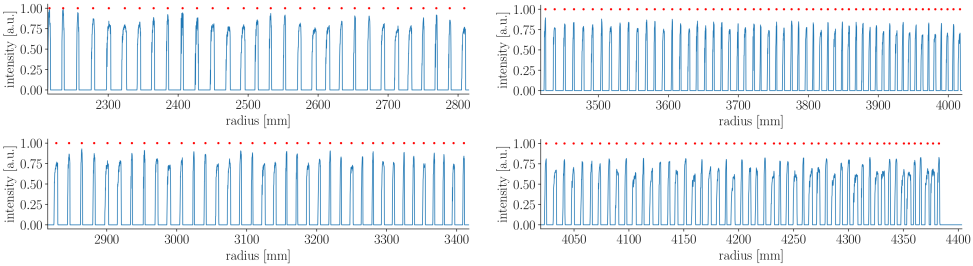
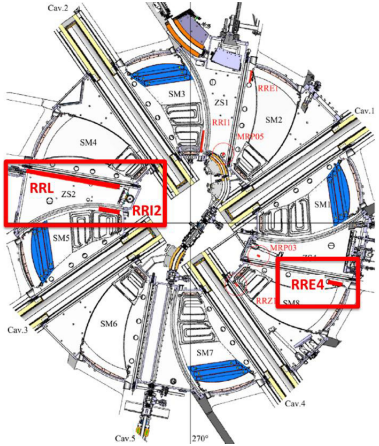


Figure: Histogram of RRL measurement

Trimcoil Optimisation in OPAL

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

190 peaks ⇒ 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. Adelmann. Proceedings of IPAC2017. THPAB077. 2017.

Problem Reduction

- **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

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

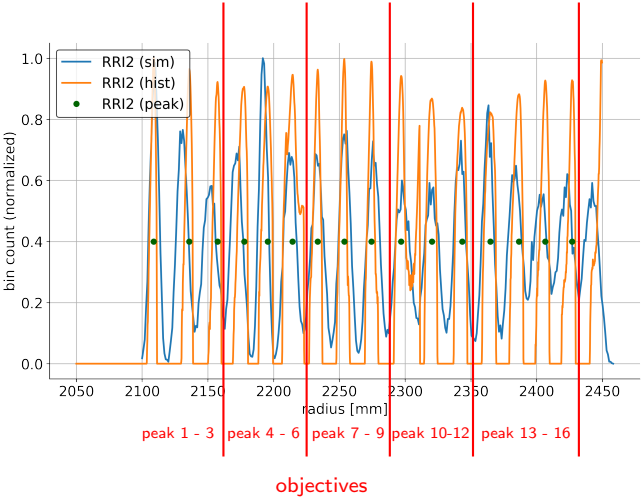
$N = u - l + 1$: number of aggregated turns

r_i^m: i-th turn radii of measurement

r_i^s: i-th turn radii of simulation

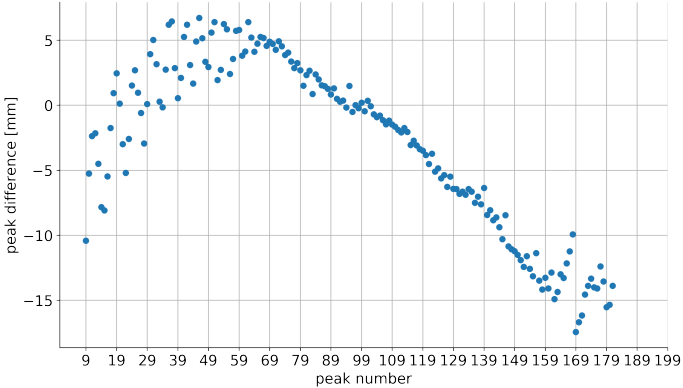
Trimcoil Optimisation in OPAL - Trial 1

- **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



Issue of Divergence - Trial 1

- 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!



Model Simplification + Design Variable Extension

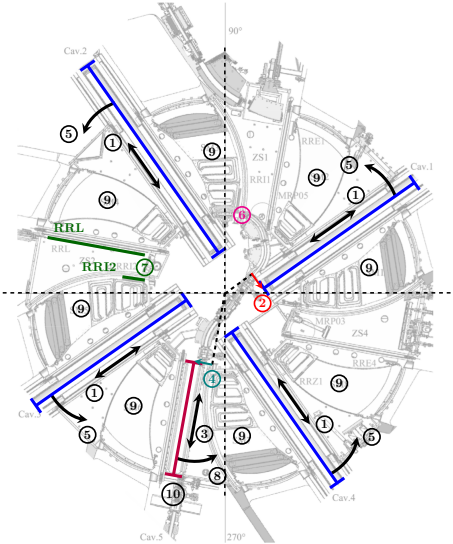
- **Single particle tracking** instead of bunch (5000 particles) tracking

  $\Longrightarrow$ 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

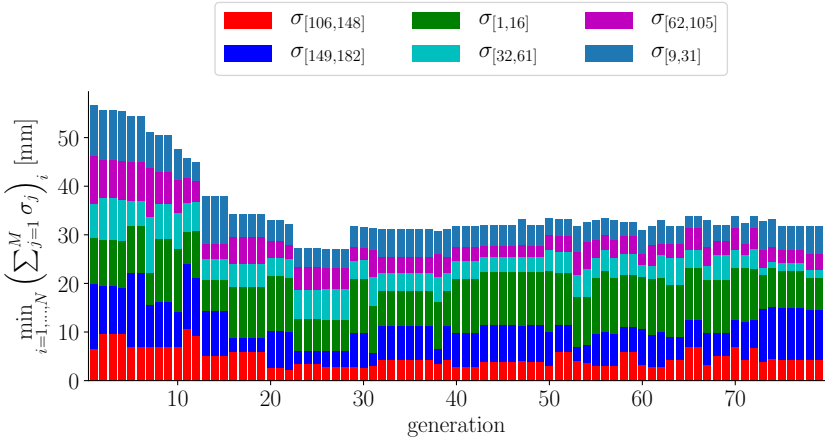


Figure: The label $\sigma_{[l,u]}$ indicates an objective for the turns in the range $[l, u]$.
M: number of objectives; N: number of individuals per generation.

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 $[l, u]$.

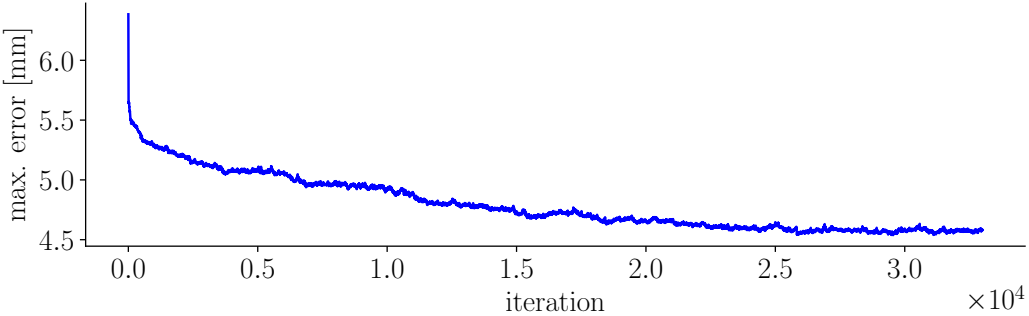
Local search after MOGA

- **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

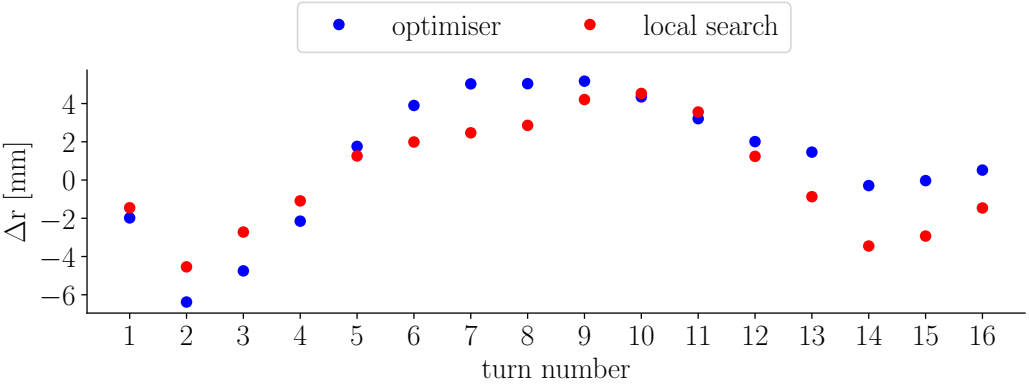
    (check L_∞- and L_2-norm, 2nd and 3rd worst turn not to get stuck with only L_∞)

Evolution of maximum absolute error during local search

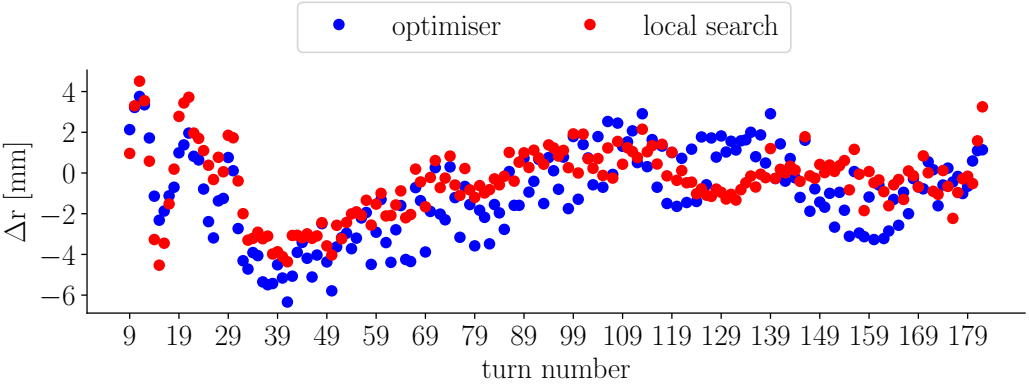
> 1 mm error reduction after a few iterations



Final Results - RRI2

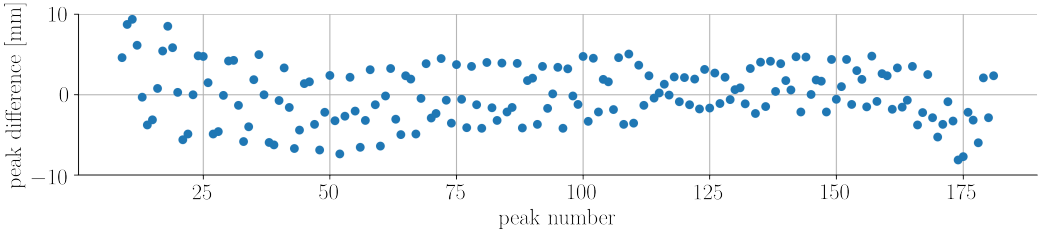


Final Results - RRL

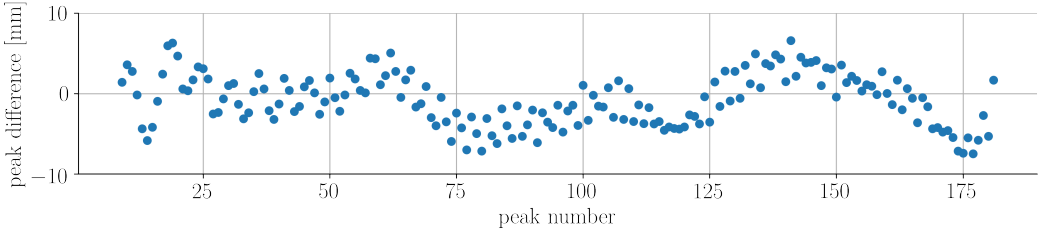


Wiggly Solution due to TCs - Long Probe RRL1

Optimisation (subset of DVARs) with TCs disabled



Optimisation of above with TCs only



Final Results

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.

Conclusions

- 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

Backup - Multi Particle Tracking

Comparison to	l_∞-norm (mm)	MAE (mm)	MSE (mm^2)
measurement	4.64	1.46	3.59
space charge	0.05	0.00	0.00

Table: Maximum absolute error (l_∞-norm), mean absolute error (MAE) and the mean squared error (MSE) of the measurement or multi particle tracking simulation including space charge to the multi particle tracking simulation neglecting space charge.