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Trimcoil Optimisation using Multi-objective Optimisation Techniques and HPC

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Outline

- Motivation
- New Trimcoil Model in OPAL
- Multi-Objective Optimization
- Scanning

Disturbed Isochronicity in Cyclotrons

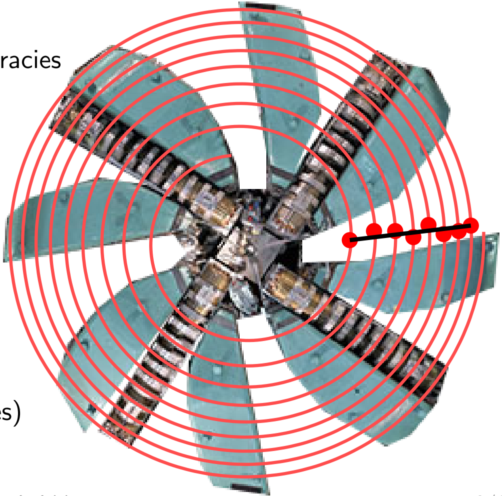
- **Discrepancies** in
  - magnetic field due to **construction** inaccuracies
  - **injection** parameters ($E_{kin}, r, p_r, \ldots$)
  - element **positioning** (RF cavities)
  - etc.
- **Restoration in reality:**

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

  $\Longrightarrow$ phase shift

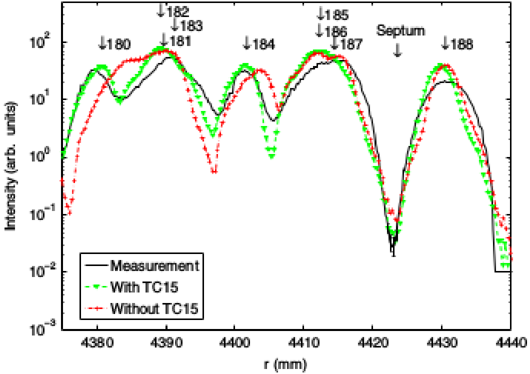
  (beam gets more/less energy by RF cavities)

  $\Longrightarrow$ turn radius shift



Mismatch between Measurements and Simulations

- **Discrepancies** in
  - magnetic field due to **measuring** inaccuracies
  - **simulation model:**
    - discretization in time and space
    - simplified device models
    - missing device models
    - etc.
  - **injection** parameters $(E_{kin}, r, p_r, \ldots)$
  - 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

Towards More Realistic Trimcoil Simulations

- OPAL PSI-Ring model only TC15

  but 16 TCs (TC17/18 not used) in PSI-Ring Cyclotron

- TC-model in OPAL approximated using analytical model mimicking profile

  but there are TC measurements available

- TC-field contribution in OPAL for 360 degree

  but in reality only on dipoles

New Trimcoil Model in OPAL

- Radially rational TC profile description

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

```
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};
```

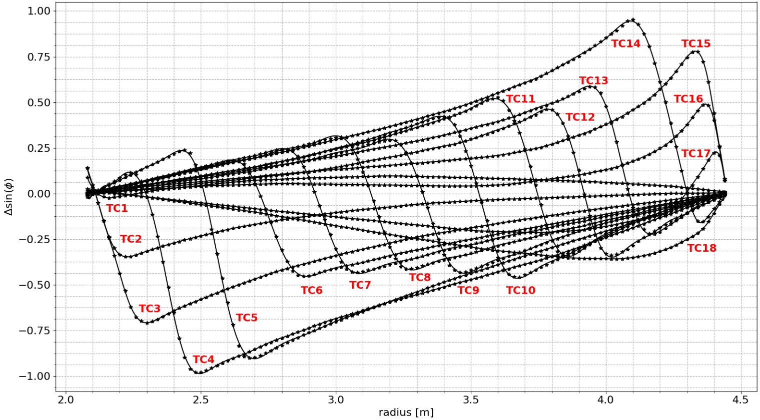
New Trimcoil Model in OPAL

- **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:**

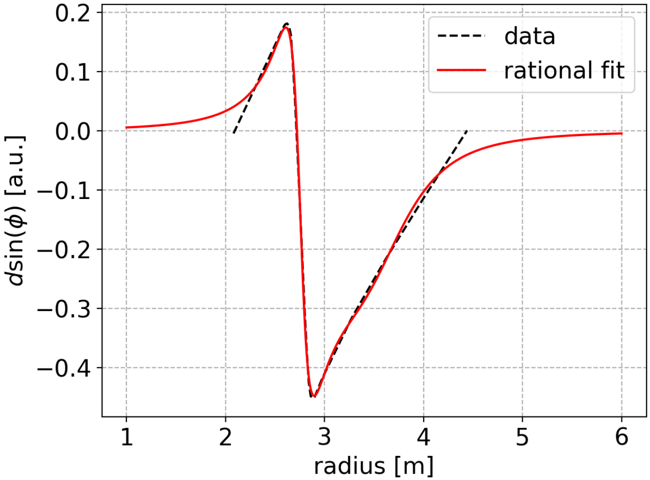
$$\Delta \sin(\phi)(r) \approx h_{phase}(r) = \frac{f(r)}{g(r)} = \frac{\sum_{i=0}^{n} a_i r^i}{\sum_{j=0}^{m} b_j r^j}$$

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

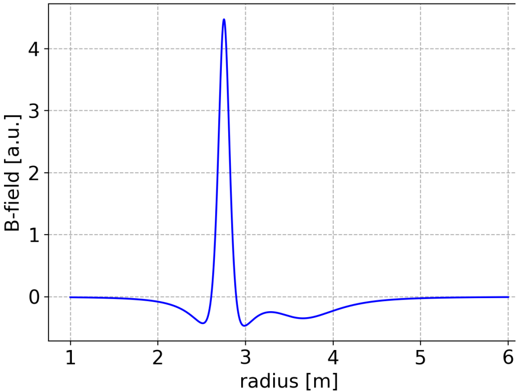
- **TC2 - TC15:** $n = 2, \ m = 4$
- **TC1, TC16 - TC18:** $n = 4, \ m = 5$
- **Magnetic field:**

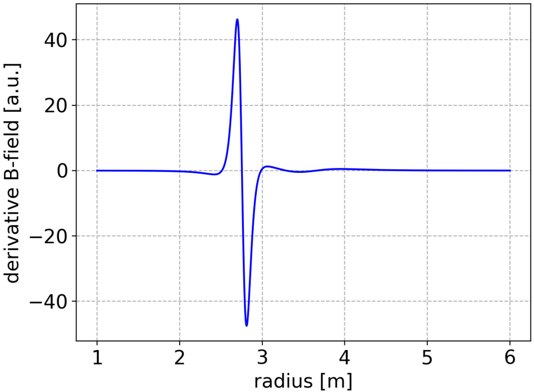
$$B(r) = -\frac{dh_{phase}}{dr} = -h'_{phase} = -\frac{f'g - fg'}{g^2}$$

PSI-Ring Trimcoil Model - Example TC6



PSI-Ring Trimcoil Model - Example TC6





Multi-Objective Optimisation (MOO) in OPAL

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

$$\begin{aligned} \min \quad & \mathbf{f}(\mathbf{x}), & \dim(\mathbf{f}) = M \in \mathbb{N}^{>0} \\ \text{s.t.} \quad & \mathbf{g}(\mathbf{x}) \geq 0, & \dim(\mathbf{g}) = J \in \mathbb{N}^{0} \\ & -\infty \leq x_i^L \leq \mathbf{x} = x_i \leq x_i^U \leq \infty, & \mathbf{x} \in \mathcal{X} \subset \mathbb{R}^n, \quad n \in \mathbb{N}^{>0} \end{aligned}$$

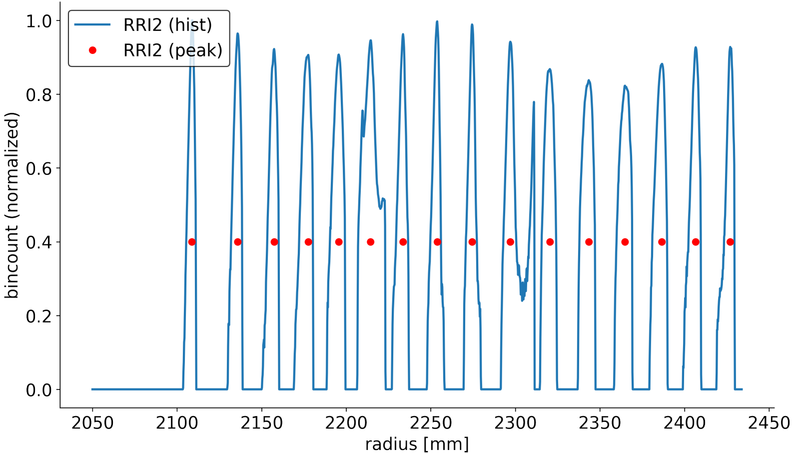
- **Design variables x:** E_{kin}, p_r, φ, TC1 - TC16 max. B-field, etc.
- **Objectives:** Measure between simulation and real data

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

Radial Profile Measurement

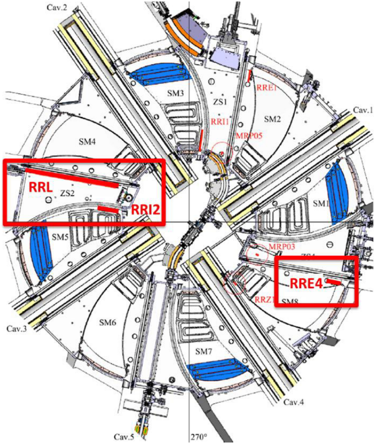
- **Measurements:** Peak intensity of radial profile of probes to distinguish turns



Trimcoil Optimisation in OPAL

- **Simulations:**
  - **Single particle** ⇒ probe hit = turn
  - **Multi particles** ⇒ peak finder routine
- **Good setting:** Radial peak of measurement and simulation at probes are close!
- **RRI2:** turns 1 - 16
- **RRL:** turns 9 - 182
- **RRE4:** turns 177(8) - 188(9)

188(9) turns ⇒ 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

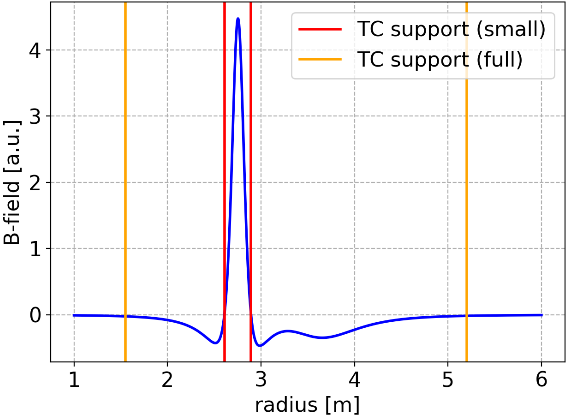
$$\text{err} = \frac{1}{N_{turns}} \sqrt{\sum_{i=1}^{N_{turns}} (p_{i,meas} - p_{i,sim})^2}$$

  - L_∞-norm

$$\text{err} = \max_{i=1,\ldots N_{turns}} \left| p_{i,meas} - p_{i,sim} \right|$$

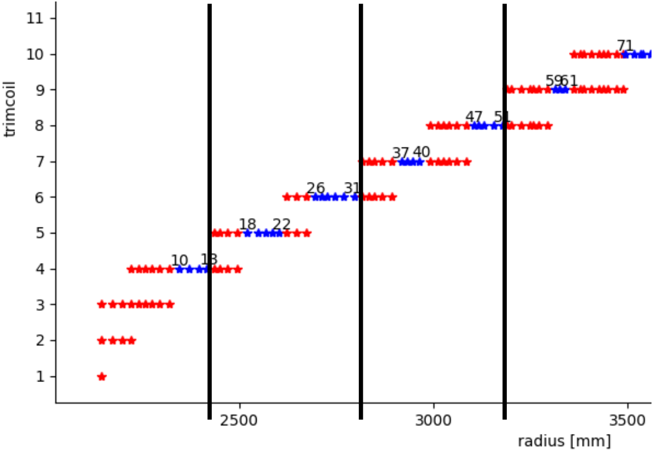
Problem Reduction

- **TC support reduction:**
  Feasible assumption for neighbouring TCs $\Rightarrow$ Cancellation of B-field tails



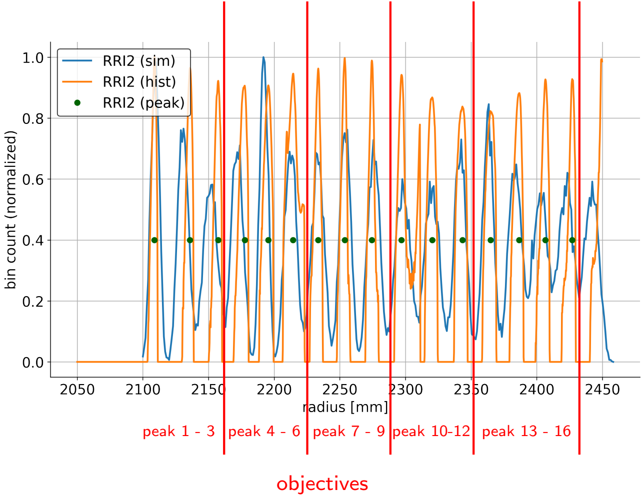
Problem Reduction

- **Optimise on sub-problems:**



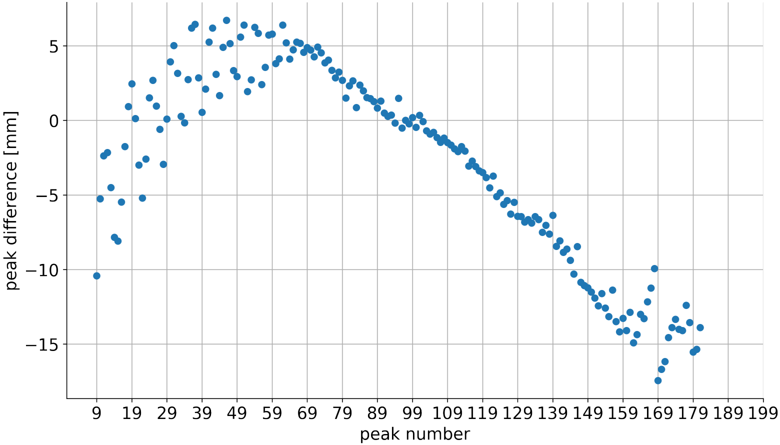
Trimcoil Optimisation in OPAL - Trial 1

- **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 others lead to divergence!

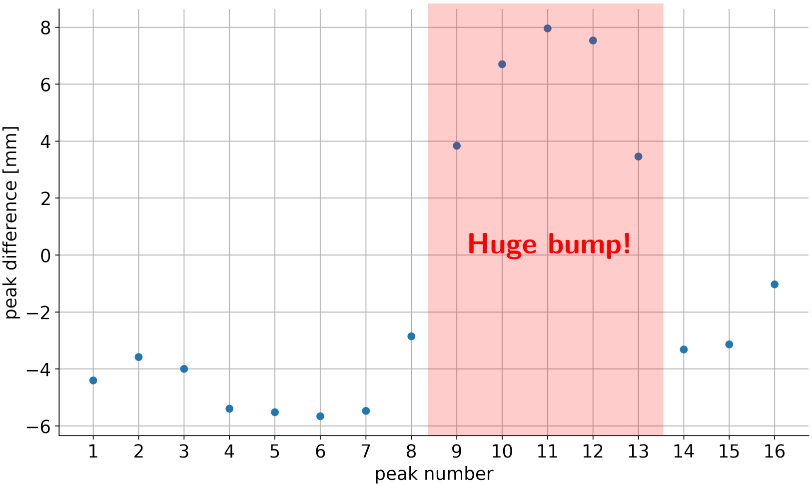


Model Simplification + Design Variable Extension

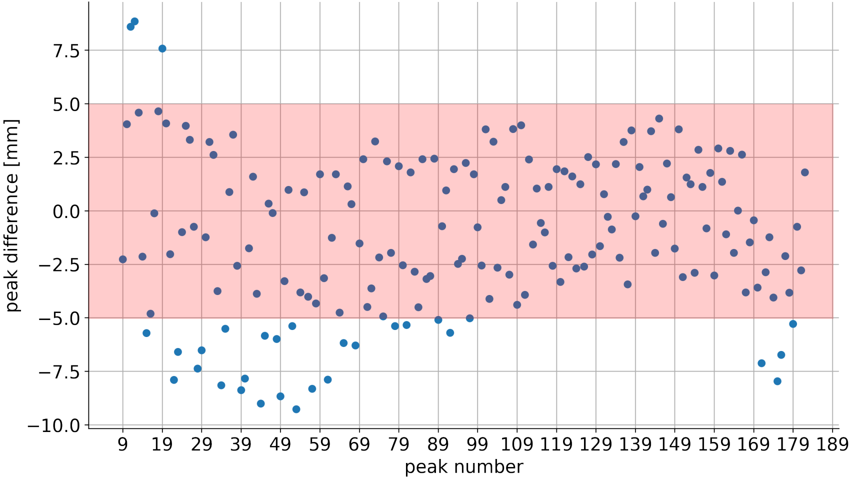
- **Single particle tracking** instead of bunch (5000 particles) tracking

  $\Longrightarrow$ 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

Injection Probe RRI2

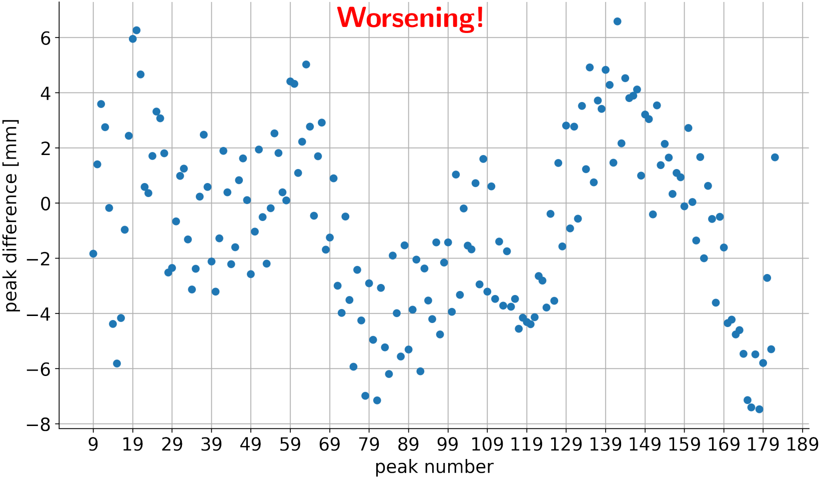


Long Probe RRL1 - No divergence anymore!



Injection Probe RRI2 - Optimising TC1 - TC16

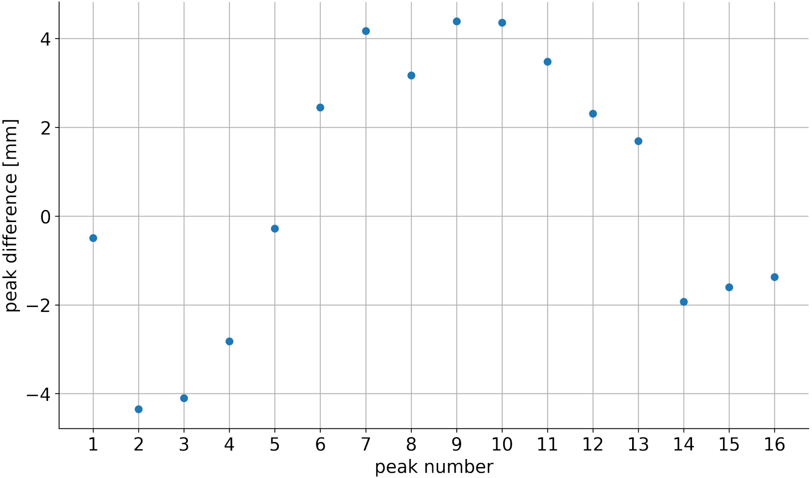
Long Probe RRL1 - Optimising TC1 - TC16



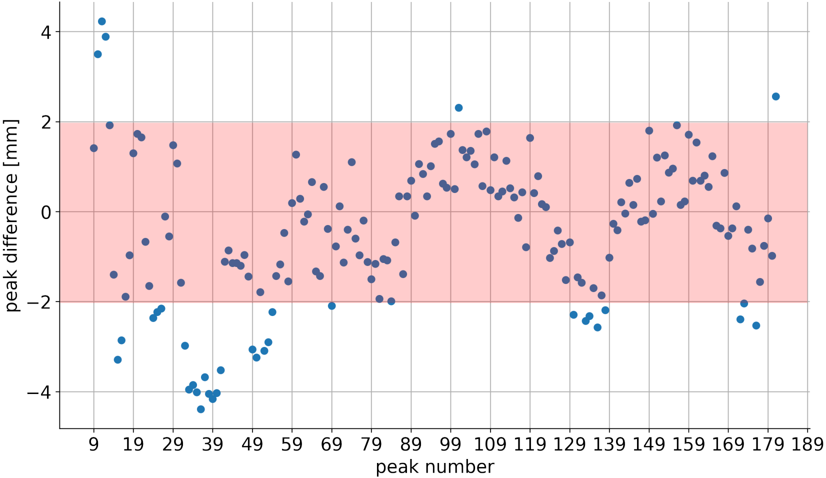
Scanning instead of MOO

- **Issues:**
  - Optimiser suffered with individual selection
  - No further improvements!
  - Changing all parameters at same time might be disadvantageous
- **Idea:** Do simple parameter scanning!
  - Python script (1 core)
  - Starting from best MOO individual
  - Iteratively find worst turn and vary parameters to obtain better individual (check L_∞- and L_2-norm to avoid getting stuck with only L_∞)

Injection Probe RRI2



Long Probe RRL1



Conclusions

- New Trimcoil model
  - successfully implemented and tested
  - more realistic
- Multi-Objective Optimization (MOO) in OPAL
  - massively parallel (used with $> 1'000$ cores)
  - suffers with individual selection in case of high-dimensional design variable space
  - other algorithms should be considered (e.g. simulated annealing)
- Scanning of design variables
  - improved error of simulation vs. measurement
  - may get stuck and stop improving (combination of L_∞- and L_2-norms helps)

Thanks to

A. Adelmann

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H. Zhang

M. Humbel

R. Dölling

W. Joho