Space-charge matching of the transverse phase space at PITZ.

- Requirements of transverse beam matching at PITZ
- Transverse phase space tomography at PITZ
- Space-charge matching of periodic and dense lattices
- Space-charge matching of aperiodic and long lattices
- Summary and outlook

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Electron bunches with high space-charge influence

- 20 ps flat-top laser pulses
- 20 pC - 1 nC charge
- up to 25 MeV/c momentum

Various diagnostics and experiments require specific beam parameters at certain parts of the beamline → beam matching (e.g. PST)

PITZ is a test facility with constantly changing machine parameters → fast matching results are needed
Tomographic reconstruction of the beam’s phase space using 4 projections

Components:
1. PST lattice (FODO) for the data acquisition → periodic and dense quadrupole focusing
2. Matching lattice for the necessary beam parameters in front of the PST lattice → aperiodic and sparse focusing

Matching requirements:
1. equidistant phase advance values (45°) @ each PST screen
2. Twiss parameters @ 1st screen → $\beta_{x,y} = 1 \text{ m}$, $\alpha_{x,y} = \pm 1$
Under the conditions of: ✓ periodic focusing
✓ (fairly) constant emittance

the smooth-approximation theory* can be used to correlate the beam dynamics without and with space charge (linear component)

Enables codes with no space-charge consideration (MAD) to perform space-charge matching by a proper scaling of the used beam parameters

1. Requirements: space-charge density (emittance and generalized perveance)
2. The desired matching constrains (45°) are scaled accordingly (e.g. 55°)
3. A traditional MAD matching is performed using the scaled parameters
4. Reverse-scaling of the MAD results to obtain the actual corresponding values

* Martin Reiser: Theory and Design of Charged Particle Beams, Wiley
Matching result of a beam with 1 nC, 22 ps, 25 MeV/c, 1 mm·mrad evaluated with ASTRA

<table>
<thead>
<tr>
<th></th>
<th>Phase-advance mismatch @ 1&lt;sup&gt;st&lt;/sup&gt; screen</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; screen</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; screen</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X plane</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traditional MAD matching</td>
<td>-3.1°</td>
<td>-16.9°</td>
<td>-34.5°</td>
</tr>
<tr>
<td>MAD with space charge compensation</td>
<td>-0.9°</td>
<td>-0.9°</td>
<td>-1.2°</td>
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<tr>
<td><strong>Y plane</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Traditional MAD matching</td>
<td>-4.7°</td>
<td>-20.2°</td>
<td>-37.8°</td>
</tr>
<tr>
<td>MAD with space charge compensation</td>
<td>-1.9°</td>
<td>-4.5°</td>
<td>-3.6°</td>
</tr>
</tbody>
</table>

> The **phase-advance mismatch** is reduced from 38° to 5° with the space-charge compensation (significant improvement for tomography)

> Method yields almost instant results
The conditions of periodicity and constant emittance are no longer valid.

Except from its defocusing effect, space charge also induces correlated emittance growth.

Different slices of the beam obtain different transverse parameters, overlapping in the phase space.

In order to achieve the target values all along the bunch, the matching procedure has to suppress the emittance oscillations.

Solution comes from the SC software (HZB): linear space-charge fields (quick implementation) for each longitudinal slice of the bunch.

...more details on SC: Thursday, Andreas Ginter, AKBP 15.8
Test beam: 1 nC, 25 MeV/c, 20 ps, 0.8 mm·mrad

Matching goal (7.3 m downstream, 7 quads): $\beta_{x,y} = 1.0 \text{ m}, \alpha_{x,y} = \pm 1.1$

Matching result: SC (~20 min) $\rightarrow \beta_x = 1.1 \text{ m}, \beta_y = 0.8 \text{ m}, \alpha_x = 1.1, \alpha_y = -1.1$
ASTRA (~3.5 h / single run) $\rightarrow \beta_x = 1.2 \text{ m}, \beta_y = 1.0 \text{ m}$
Space-charge matching of aperiodic and long lattices (II)

- Test beam: 1 nC, 25 MeV/c, 20 ps, 0.8 mm·mrad

- Matching goal (7.3 m downstream, 7 quads): $\beta_{x,y} = 1.0$ m, $\alpha_{x,y} = \pm 1.1$

Matching result:
- SC (~20 min) → $\beta_x = 1.1$ m, $\beta_y = 0.8$ m, $\alpha_x = 1.1$, $\alpha_y = -1.1$
- ASTRA (~3.5 h / single run) → $\beta_x = 1.2$ m, $\beta_y = 1.0$ m, $\alpha_x = 1.0$, $\alpha_y = -0.8$

1. the delivered mismatch is well acceptable
> Test beam: 1 nC, 25 MeV/c, 20 ps, 0.8 mm·mrad

> Matching goal (7.3 m downstream, 7 quads): $\beta_{x,y} = 1.0$ m, $\alpha_{x,y} = \pm 1.1$

Matching result: SC (~20 min) $\rightarrow \varepsilon_x = 1.1$ mm·mrad, $\varepsilon_y = 1.0$ mm·mrad

ASTRA (~3.5 h / single run) $\rightarrow \varepsilon_x = 1.0$ mm·mrad, $\varepsilon_y = 0.9$ mm·mrad

1. the delivered mismatch is well acceptable
2. the non-linear space charge has a minor effect in the beam dynamics
Summary and outlook

> The incorporation of space charge in the transverse matching at PITZ is possible by:

- combining the smooth-approximation theory with MAD → instant solution for periodic lattices of dense focusing
- using the linear space-charge fields for a sliced bunch in SC → quick solution for irregular lattices

> Both solutions yield very good results in the most time-efficient way

> Useful also for compressed beams of high energy and peak current (e.g. bunch compressor exits of FELs)

> The performance of these methods has to be validated experimentally
Thanks to:

Alexey Bondarenko
Mikhail Krasilnikov
Barbara Marchetti
Aleksandr Matveenko
Backup Slides
Space-charge density → $K, \epsilon$ → $k_0$ → Quadrupole strengths

$\psi_0$ → MAD → $\beta_0, \alpha_0$

Input beam

Number of projections → $\psi$ → Table 3.1 → $\psi$

$\psi$ → $\psi_0$ → Eqs. 5.13, 5.25 → $\beta, \alpha$

$\psi$ → Eq. 5.14 → $u$

Eqs. 5.13, 5.25