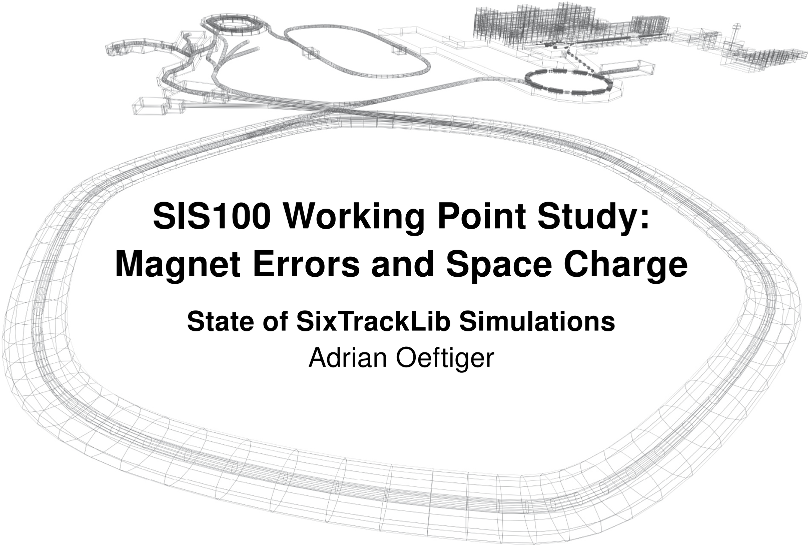


SIS100 Working Point Study: Magnet Errors and Space Charge

State of SixTrackLib Simulations

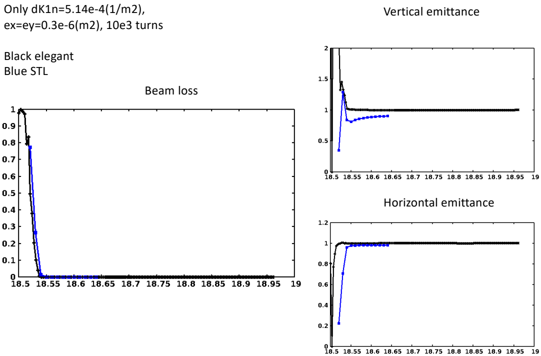
Adrian Oeftiger

Overview

Previously open questions:

1. **no-SC comparison**: why stronger beam loss for ELEGANT than MAD-X / STL? Are magnet errors defined equivalently?
2. **9 dipole slices**: why significantly weaker beam loss in MAD-X / STL setup for 9 slices/dipole compared to 1 slice/dipole?
3. $4Q_y - 2Q_x$ **lines**: why only visible with warm quadrupoles (locally induced beta-beat) and not with symmetric cold lattice + distributed random `K1n` errors? (Driven harmonics of $2Q = 37, 38$ should equal in both cases)
4. **SC vs. magnet errors**: why does ELEGANT predict such strong impact by non-linear magnet multipole errors, while only limitation predicted by MAD-X / STL are $4Q_y - 2Q_x$ lines + shifted half-integer and coupling line?
5. **SC strength**: is it the same in ELEGANT and STL? Do we find equivalent tune footprints of $\max \Delta Q_y^{SC} = -0.3$?
6. **Montague**: why does ELEGANT predict no emittance exchange around coupling line, while MAD-X and SixTrackLib (adaptive, matched and fixed frozen SC) exhibit Montague resonance induced emittance exchange?

Without SC, compared ELEGANT and SixTrackLib results for symmetric cold lattice with (1) fixed $\mathtt{K1n} = 5.14 \times 10^{-4}$

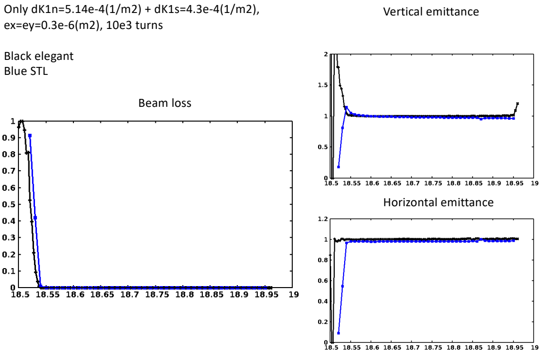


$\Longrightarrow$ stop-band width is equivalent (within error induced tune shift bounds)

No-SC Comparison ELEGANT - STL

Without SC, compared ELEGANT and SixTrackLib results for symmetric cold lattice with (1) fixed $\mathtt{K1n} = 5.14 \times 10^{-4}$

and (2) fixed $\mathtt{K1n} = 5.14 \times 10^{-4}$ + $\mathtt{K1s} = 4.3 \times 10^{-4}$:



$\Longrightarrow$ stop-band width is equivalent (within error induced tune shift bounds)

Identified Problem

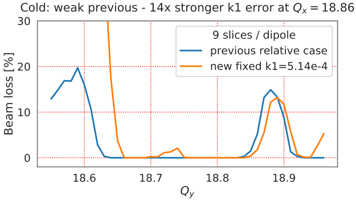
The follow-up comparison between absolute and relative magnet multipole error definitions identified an incorrect factor $L_{magnet}/n_{thin\,slices}$ in the relative set-up (thanks, Stefan Sorge!!):

- the relative set-up had been used in all MAD-X (and thus also SixTrackLib) simulations so far
- originally, the faulty factor was only in the definition of the quadrupole multipole errors $\implies L_{magnet}/n_{thin\,slices} = 1/7$ weaker QUADRUPOLE multipole errors in all previous MAD-X and SixTrackLib simulations when comparing to ELEGANT results
- with the introduction of 9 slices in the dipole, I (Adrian) copied the quadrupole set-up (with this $L_{magnet}/n_{thin\,slices}$ factor!) into the dipoles leading to correspondingly weaker dipole multipole errors!

$\implies$ in all comparisons between MAD-X / SixTrackLib and ELEGANT, the magnet multipole errors (linear and non-linear) have been implemented $\mathcal{O}(10)$ stronger in the ELEGANT case

This factor explains many of the open questions:

- ✓ **1. no-SC comparison**: no, magnet errors not equivalent!
- ✓ **2. 9 dipole slices**: this factor additionally multiplies the already considered length and number of slices in the relative set-up w.r.t. the main component of the multipole, effectively retrieved $1/7$ weaker errors with 9 dipole slices than in 1 dipole slice set-up!
- ✓ **3.** $4Q_y - 2Q_x$ **lines**: with the now stronger `K1n` errors in STL, the induced beta-beat level is similar to the warm quadrupoles. Fixed frozen SC simulations also show the $4Q_y - 2Q_x$ lines in both set-ups now – warm quadrupoles as well as distributed random `K1n` errors



Answers to Open Questions

This factor explains many of the open questions:

- ✓ **1. no-SC comparison**: no, magnet errors not equivalent!
- ✓ **2. 9 dipole slices**: this factor additionally multiplies the already considered length and number of slices in the relative set-up w.r.t. the main component of the multipole, effectively retrieved $1/7$ weaker errors with 9 dipole slices than in 1 dipole slice set-up!
- ✓ **3.** $4Q_y - 2Q_x$ **lines**: with the now stronger `K1n` errors in STL, the induced beta-beat level is similar to the warm quadrupoles. Fixed frozen SC simulations also show the $4Q_y - 2Q_x$ lines in both set-ups now – warm quadrupoles as well as distributed random `K1n` errors
- ✓ **4. SC vs. magnet errors**: now also in STL and MAD-X, the corresponding impact of the magnet multipole errors should be much more enhanced!

corrected, new magnet multipole error definitions

(based on Vera Chetvertkova's setup)

Dipole Module Errors

The dipole module multipole error definition in MAD-X (using SIS100 Beam Dynamics Wiki rev. 15, 2020-04-07, by Vladimir Kornilov ↗):

```
!!Absolute systematic errors of the main dipoles
RSys2n  =   2.38928e-4;
RSys4n  =   1.73183e-4;
RSys6n  =   0.14863e-4;

!!Absolute random errors of the main dipoles
rErr0n  =   0;! 2.0e-4; // not considering orbit errors
rErr1n  =   0.47083e-4;
rErr1s  =   0.72449e-4;
rErr2n  =   0.22275e-4;
rErr2s  =   0.35647e-4;
rErr3n  =   0.18323e-4;
rErr3s  =   0.28647e-4;
rErr4n  =   0.09162e-4;
rErr4s  =   0.11519e-4;
rErr5n  =   0.08633e-4;
rErr5s  =   0.03804e-4;
rErr6n  =   0.04670e-4;
rErr6s  =   0.09034e-4;
```

The dipole module multipole error definition in MAD-X (using SIS100 Beam Dynamics Wiki rev. 15, 2020-04-07, by Vladimir Kornilov ↗):

```
!!Adding field errors to dipoles
select, flag=error, clear;
select, flag=error, PATTERN = mh1\.\.slice,  class=multipole;
select, flag=error, PATTERN = mh2\.\.slice,  class=multipole;
EFCOMP, radius=0.03, order=0,
    dknr:={rErr0n*tgauss(2), rErr1n*tgauss(2), RSys2n+rErr2n*tgauss(2),
           rErr3n*tgauss(2), RSys4n+rErr4n*tgauss(2),
           rErr5n*tgauss(2), RSys6n+rErr6n*tgauss(2)},
    dksr:={0, rErr1s*tgauss(2), rErr2s*tgauss(2), rErr3s*tgauss(2),
           rErr4s*tgauss(2), rErr5s*tgauss(2), rErr6s*tgauss(2)};
```

Quadrupole Module Errors

The quadrupole module multipole error definition in MAD-X (using SIS100 Beam Dynamics Wiki rev. 15, 2020-04-07, by Vladimir Kornilov ↗):

```
!!Relative systematic errors of the main quadrupoles
RSysQD5n        =       6.9e-4;

!!Relative random errors of the main quadrupoles
rErrQD_1n = 24e-4;
rErrQD_1s = 20e-4;
rErrQD_2n = 0.7e-4;
rErrQD_2s = 1.2e-4;
rErrQD_3n = 2.7e-4;
rErrQD_3s = 2.6e-4;
rErrQD_4n = 1.0e-4;
rErrQD_4s = 0.7e-4;
rErrQD_5n = 3.45e-4;
rErrQD_5s = 1.0e-4;
rErrQD_6n = 0.3e-4;
rErrQD_6s = 0.3e-4;
```

Quadrupole Module Errors

The quadrupole module multipole error definition in MAD-X (using SIS100 Beam Dynamics Wiki rev. 15, 2020-04-07, by Vladimir Kornilov ↗):

```
!!Adding field errors to quadrupoles
select, flag=error, clear;
select, flag=error, pattern=qd11\.\.slice;
select, flag=error, pattern=qd12\.\.slice;
EFCOMP, radius=0.04, order=1,
    dknr:={0, rErrQD_1n*tgauss(2), rErrQD_2n*tgauss(2),
           rErrQD_3n*tgauss(2), rErrQD_4n*tgauss(2),
           (RSysQD5n+rErrQD_5n*tgauss(2)), rErrQD_6n*tgauss(2)},
    dksr:={0, rErrQD_1s*tgauss(2), rErrQD_2s*tgauss(2),
           rErrQD_3s*tgauss(2), rErrQD_4s*tgauss(2),
           rErrQD_5s*tgauss(2), rErrQD_6s*tgauss(2)};
```

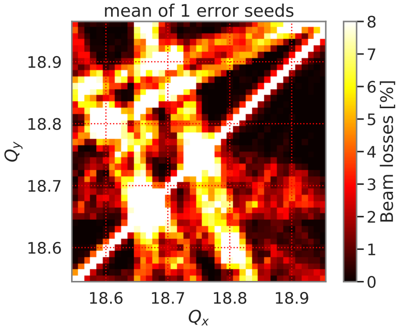
fixed frozen SC SixTrackLib simulations based on this set-up[1]

Comparison to ELEGANT

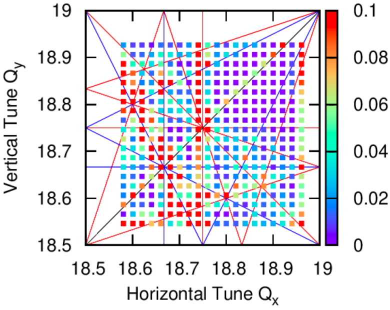
[1] running with 1'000 macro-particles, 501 SC nodes per turn, 20'000 turns – no orbit distortion i.e. `K0` and misalignment errors $= 0$, all other errors as defined above

No SC – all errors

Without space charge (SC), the multipole errors give equivalent beam loss figures in SixTrackLib and ELEGANT (up to random seed variation):



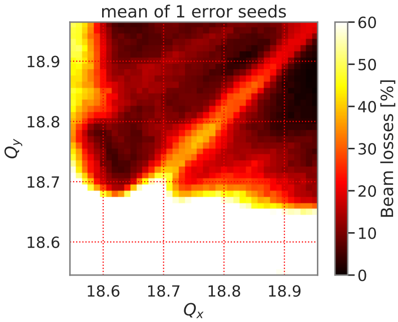
(a) SixTrackLib



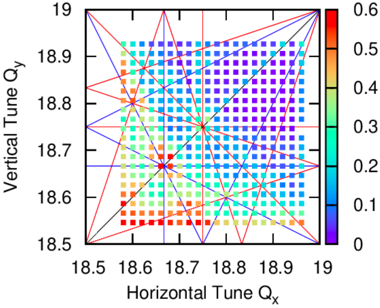
(b) ELEGANT

$\Longrightarrow$ no difference between ELEGANT and STL / MAD-X any more!

Running SixTrackLib with *fixed frozen SC*, the tune diagram looks even more limited compared to ELEGANT *matched frozen SC*:



(a) SixTrackLib

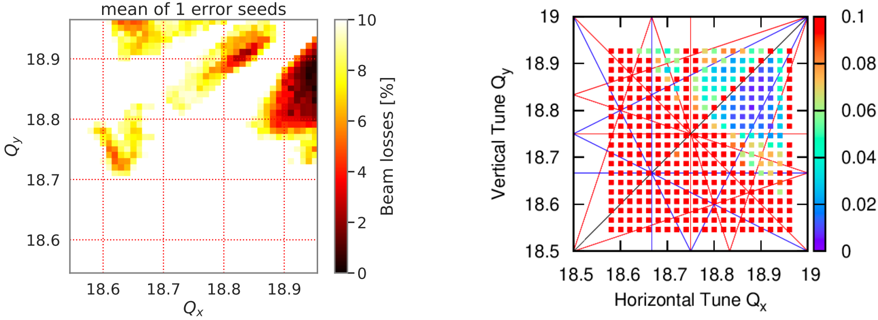


(b) ELEGANT

Figure: 60% maximum on the beam loss scale

$\Longrightarrow$ fits expectation of more conservative results in fixed frozen SC case

Running SixTrackLib with *fixed frozen SC*, the tune diagram looks even more limited compared to ELEGANT *matched frozen SC*:



(a) SixTrackLib

(b) ELEGANT

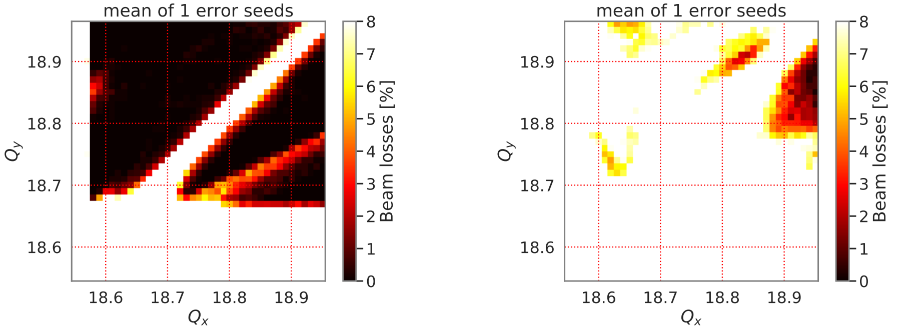
Figure: 10% maximum on the beam loss scale

$\Longrightarrow$ fits expectation of more conservative results in fixed frozen SC case

fixed frozen SC SixTrackLib simulations based on this set-up

various SixTrackLib scenarios

With SC, adding only linear-order errors in the quadrupole modules:

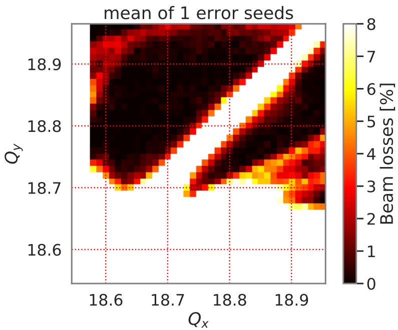


(a) only K1n in SixTrackLib (b) reference all errors in SixTrackLib

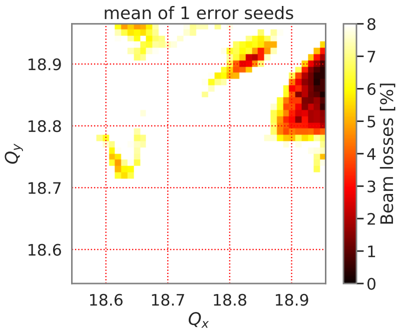
Figure: Comparison with only linear normal error component

SC – Linear errors

With SC, adding only linear-order errors in the quadrupole modules:



(a) only `K1n` + `K1s` in SixTrackLib

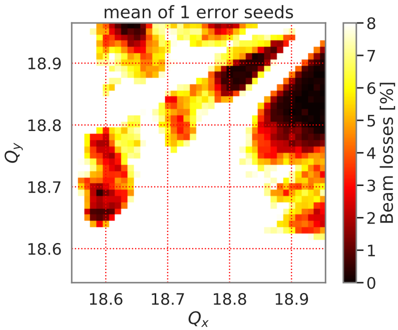


(b) reference all errors in SixTrackLib

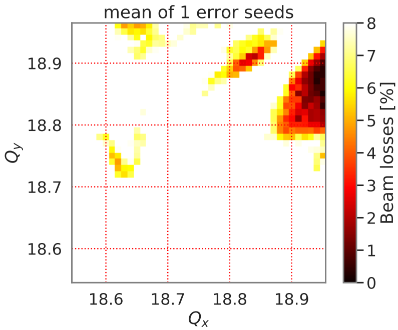
Figure: Comparison with only linear normal + skew error component

60% of SC – all errors

With all errors, scaling down SC by setting only 60% of intensity:



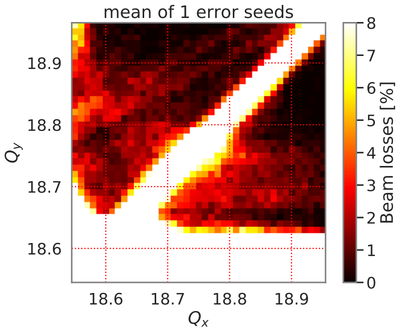
(a) 60% SC in SixTrackLib



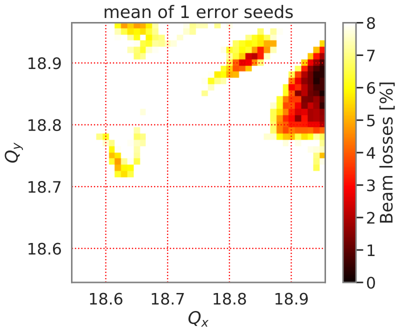
(b) reference 100% SC in SixTrackLib

SC – all errors in Dipoles

With (100%) SC, applying all multipole field errors only in dipole modules (i.e. perfect quadrupole modules without errors):



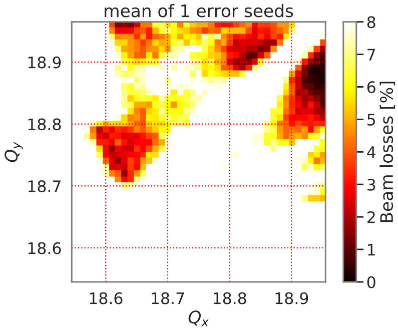
(a) all errors in dipole magnets in SixTrackLib



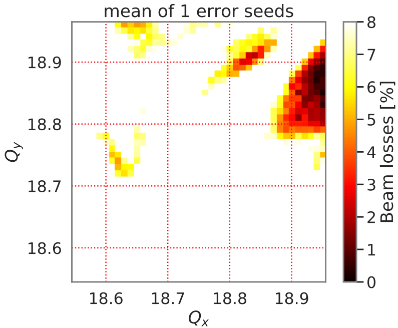
(b) reference all errors in SixTrackLib

SC – all errors in Quadrupoles

With SC, applying all multipole field errors only in quadrupole modules (i.e. perfect dipole modules without errors):



(a) all errors in quadrupole magnets in SixTrackLib

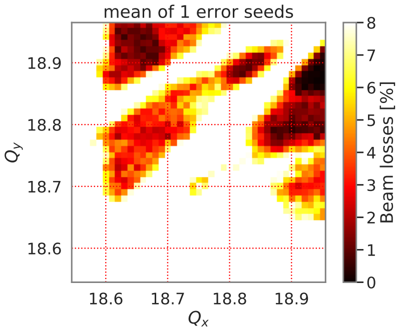


(b) reference all errors in SixTrackLib

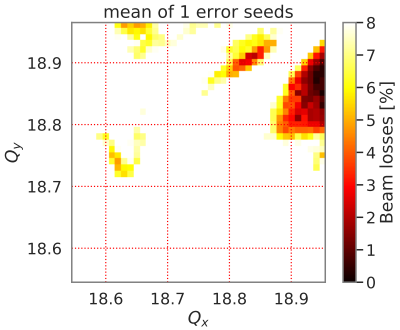
$\Longrightarrow$ non-linear quadrupole module errors account for majority of beam loss apart from half-integer and coupling line

SC – all errors with warm Quads

With SC and all errors, consider also warm quadrupoles (i.e. longer than cold quadrupoles):



(a) all errors + warm quadrupoles in SixTrackLib



(b) reference all errors only cold quadrupoles in SixTrackLib

Conclusion

Summary:

- found and removed weakening field error factor in MAD-X / STL
- no space charge (SC) results equivalent in ELEGANT and STL
- STL fixed frozen SC modell predicts more conservative beam loss figures than ELEGANT matched frozen SC
- with SC, beam loss besides half-integer and coupling line mainly attributable to assumed quadrupole module errors

$\Longrightarrow$ area below coupling line around $Q_x, Q_y = 18.9, 18.85$ safest

Remaining open questions for code benchmark:

5. **SC strength**: compare tune footprints STL vs. ELEGANT
6. **Montague**: emittance exchange in STL, absent in ELEGANT

Outlook

Next steps:

- running 10'000 macro-particles case with SC + all errors to assess convergence with STL fixed frozen SC modell
- run case with finite orbit offset (alignment errors + `K0`): weakening losses effect like in localised beta-beat case with warm quadrupoles?
- comparison with other SC modells within STL for reality check?

  ⟶ already running PIC for warm quadrupole case (no random errors), $Q_x = 18.65$ and Q_y scanned across $4Q_y - 2Q_x = 38$ resonance