Beam-beam effect on polarization in the Electron Storage Ring of the EIC

ICFA BB24 Mini-Workshop

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Overview

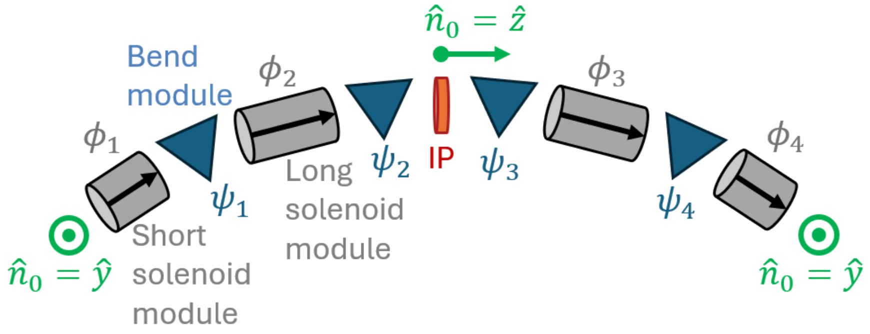
- **Background**
- **History: HERA**
- **Methods**
- **Results**
  - Linear and Nonlinear Beam-Beam
  - Tune Scan, No Beam-Beam
  - Tune Scan, Linear Beam-Beam
  - Tune Scan, Nonlinear Beam-Beam
  - Different Sextupole Settings
- **Conclusions/Future Plans**

Background

Electron-Ion Collider: longitudinally-polarized e-, light ion collisions

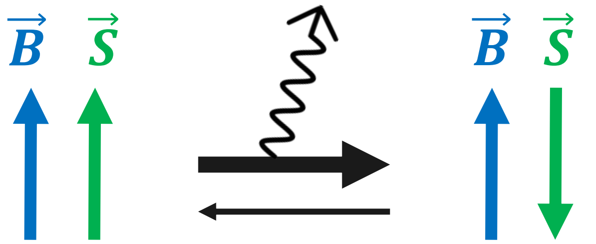
Electron Storage Ring (ESR) of the EIC

- Rotate spin to longitudinal ($\hat{z}$) at IP for each of 5, 10, and 18 GeV

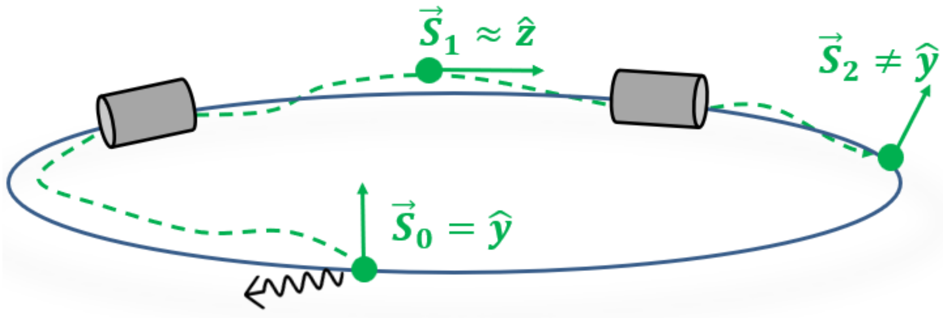


Electron polarization in storage rings is dominated by:

1. **Sokolov-Ternov (ST) Effect**
   - Spin may flip during radiation emission in homogenous field
   - Asymmetry A: higher rate to flip antiparallel to $\vec{B}$-field than parallel to
   - Polarizes anti-parallel to arc field, ***unavoidable effect***



2. **Radiative Depolarization**
   - Stochastic photon emission decoheres spins in a bunch
   - ***Remedy via "spin matching":*** choosing spin rotator configuration and/or quadrupole strengths to remove spin-orbit coupling



Both effects balance out to asymptotic P_∞:

$$P(t) = P_\infty\left(1 - e^{-t/\tau_{eq}}\right) + P_0 e^{-t/\tau_{eq}}, \qquad \tau_{eq}^{-1} = \tau_{ST}^{-1} + \tau_{dep}^{-1}$$

History: HERA

- **In HERA, the beam-beam effect did not have much impact on polarization in the real ring**

- However, **weak-strong simulations suggested a significant reduction in polarization**
  - One early study by M. Boge, T. Limberg found significant depolarization in SITROS simulations (https://accelconf.web.cern.ch/p95/ARTICLES/RAP/RAP08.PDF)
  - M. Berglund found similar results (https://www.desy.de/~mpybar/thesisdump/mbthesis.pdf)

- **Not enough information in the literature to understand why**
  - Were the optics corrected at all with the inclusion of beam-beam?
  - Just naively putting the beam-beam element into HERA I get an unstable lattice, how was this fixed?

- **While we hope for similar findings in the ESR (good in real life), we should understand this effect and have a procedure in place to fix it**
  - In HERA, the spin match was dependent on the betas. In ESR, this is not the case
  - In ESR, the linear beam-beam effect has no impact on the linear spin match. In HERA that is not true

Methods

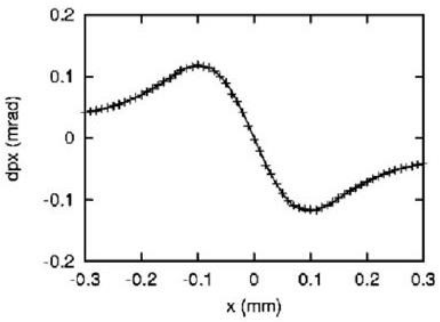
- Bmad toolkit is used for Monte Carlo tracking including spin

- **Maps tracking including radiation, 500-5000 particles**
  - Damped maps generated by PTC between each bend center, truncated at specified order
  - Stochastic radiation kick at bend centers
  - τ_{ST}^{-1} calculated analytically, τ_{dep}^{-1} calculated with nonlinear tracking

- **Weak-Strong Beam-Beam Interaction, Bassetti Erskine, 100 slices**
  - Strong beam is basically a wire
  - Particles propagated using first principles, no Hamiltonian (symplecticity not assured)
  - Energy kick due to "slingshot effect" included (see Appendix C in PhysRevAccelBeams.27.061002)
  - **Separate from maps: modelled as either "linear" or fully nonlinear in simulation**

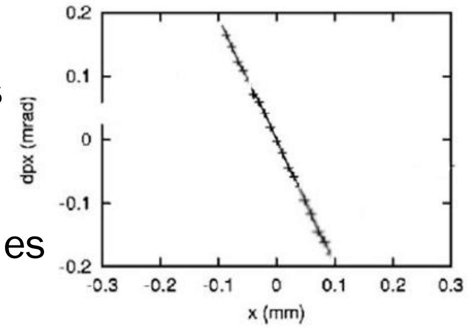
Beam-beam element

- Core sees a quadrupole focusing in both planes – tune shift
- High amplitude particles see no kick – no tune shift (bare lattice tunes)



"Linear" beam-beam element

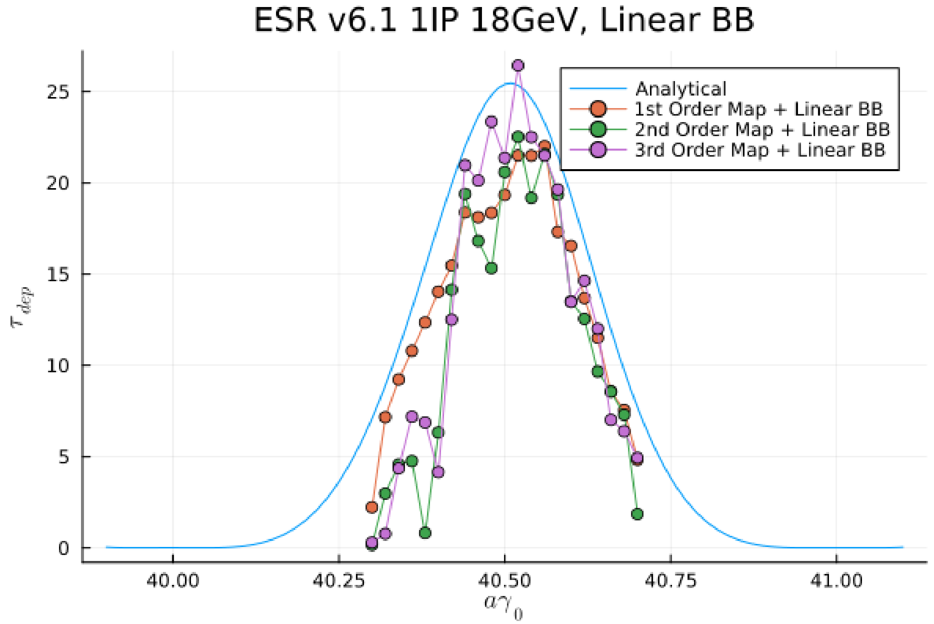
- An approximation to see what's happening in the **core**
- All particles see linear kick
- Tune shift is same for all particles



Results: Linear & Nonlinear BB

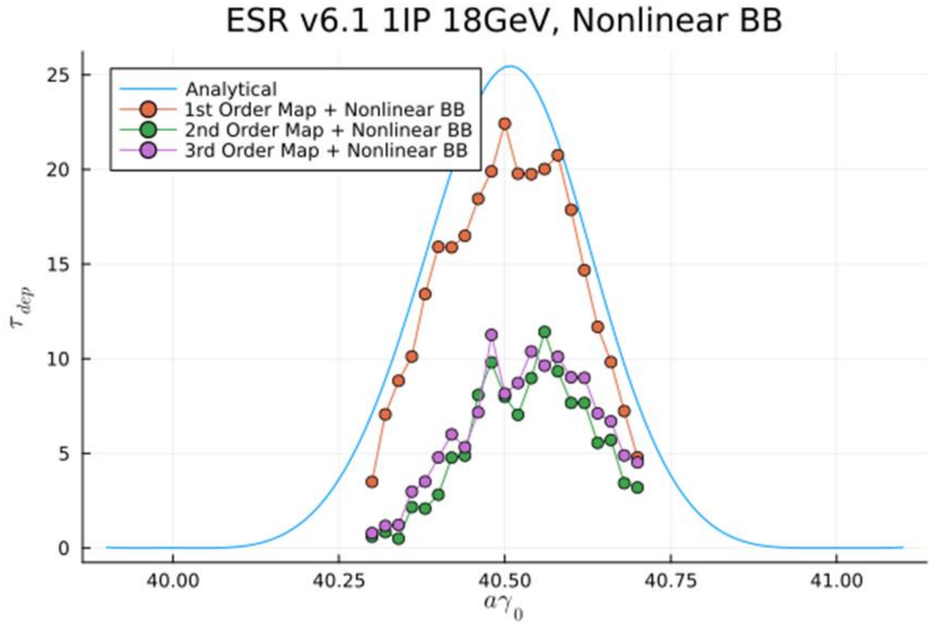
- ESR spin match is independent of betas: linear beam-beam effect has no impact on first-order polarization calcs.

Linear beam-beam effect, varying maps order in rest of ring:



- All particles have same tune shift
- **No problems! Good agreement of τ_{dep} calculated from nonlinear tracking with the linear calculation**
- Even beta-beating from BB is a non-issue

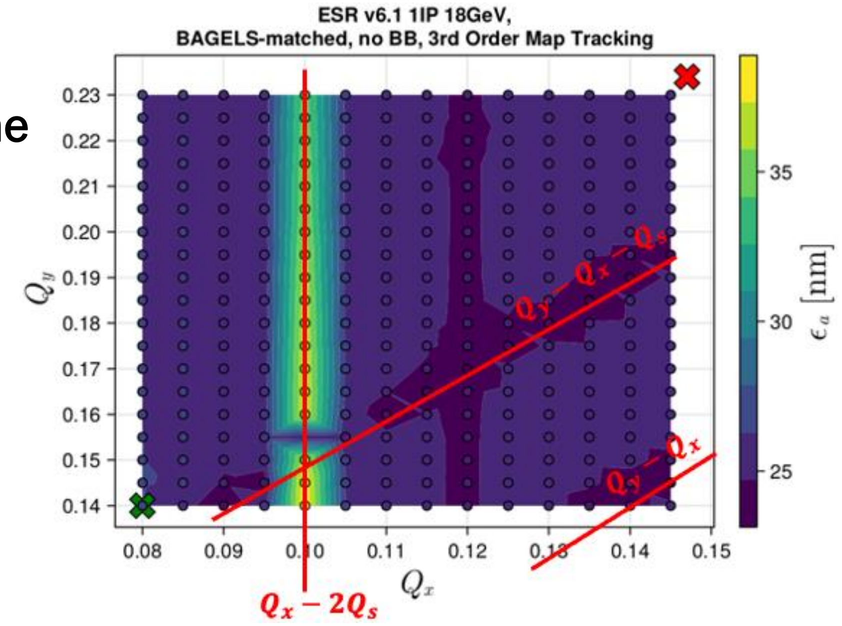
Nonlinear beam-beam effect, varying maps order in rest of ring:

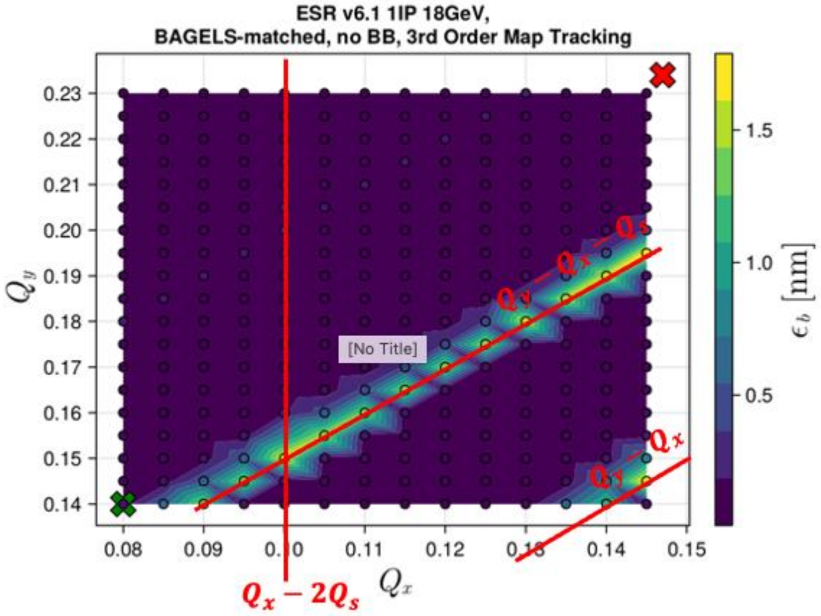


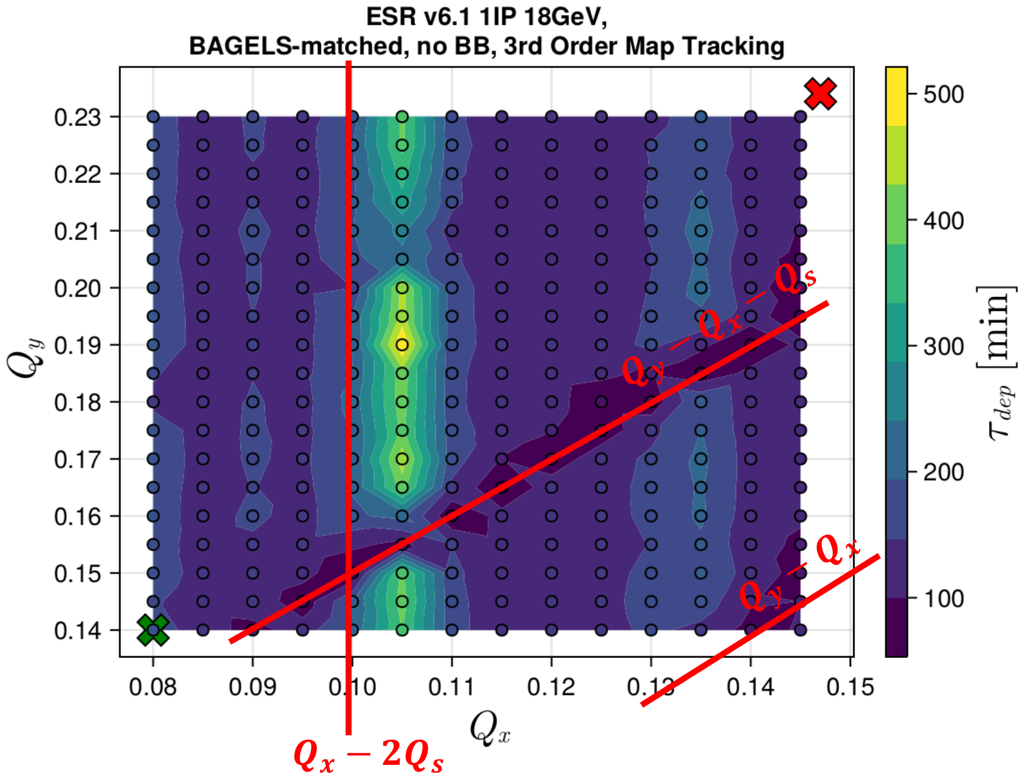
- **Full effect presents with 2nd order orbital motion in ring + nonlinear BB**
- Energy-dependent or sextupole effects in ring paired with nonlinear beam-beam
- **Could there be a dangerous nonlinear spin resonance in the tune footprint of the beam?**

Results: Tune Scan, No BB

- **Maybe there is a spin resonance somewhere in the tune footprint**
- Tune scan WITHOUT BB
  - X = bare lattice
  - X = core bunch w/ BB
- Adjusted arc quads to change tunes
- All 3rd order maps tracking, each dot 1000 particles for 7000 turns
- Shown are emittances (center) and depolarization time (right)





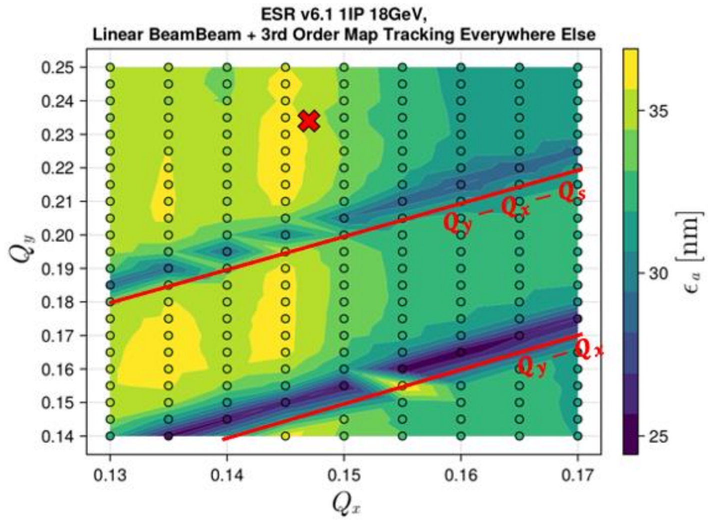


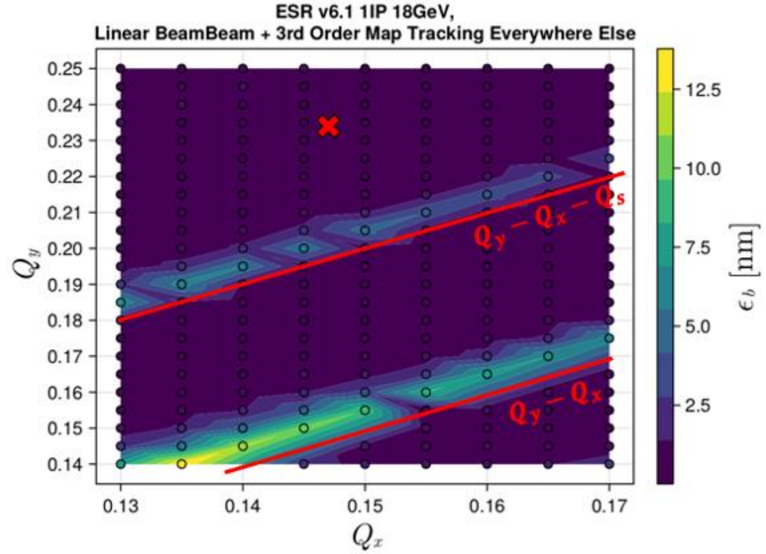
No spin resonances observed without beambeam in entire tune region

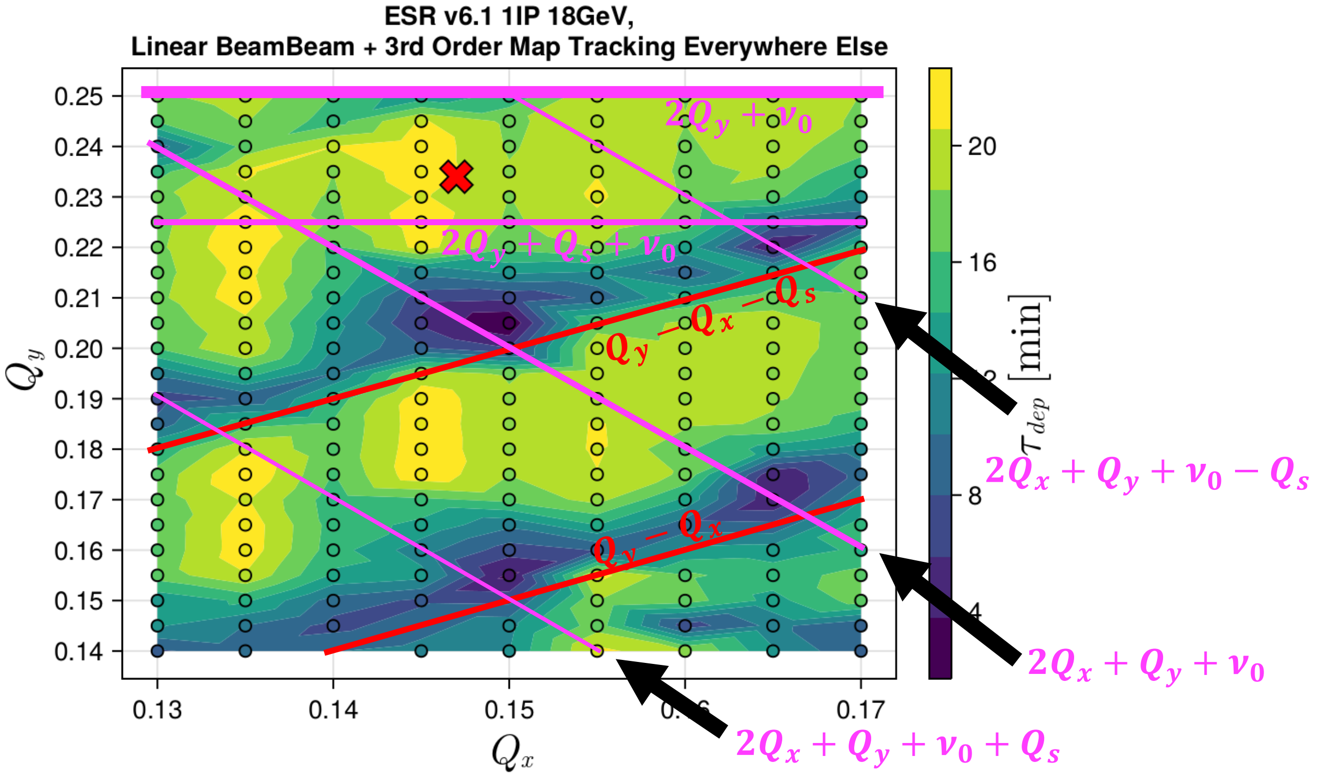
- Good region is caused by smaller J_z so less longitudinal spin-orbit coupling

Results: Tune Scan, Linear BB

- (Core) tune scan with linear BB (adjusted arc quads)



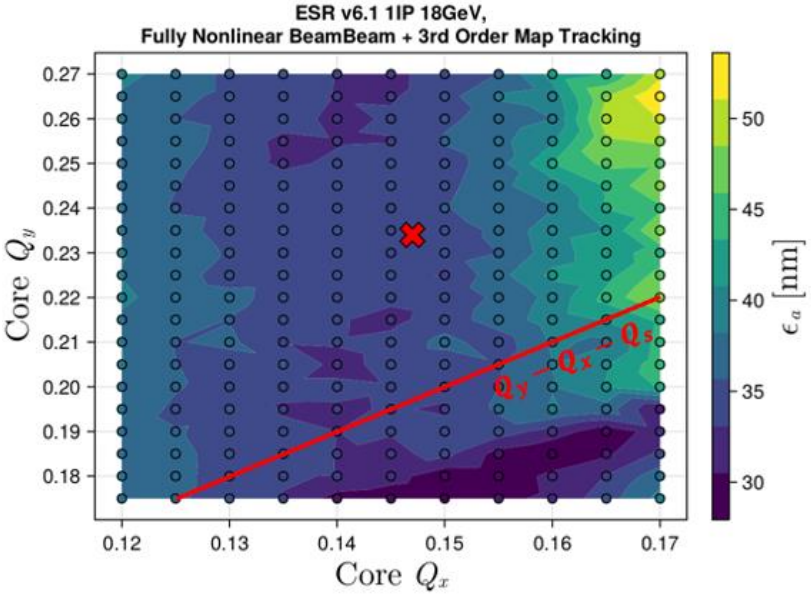


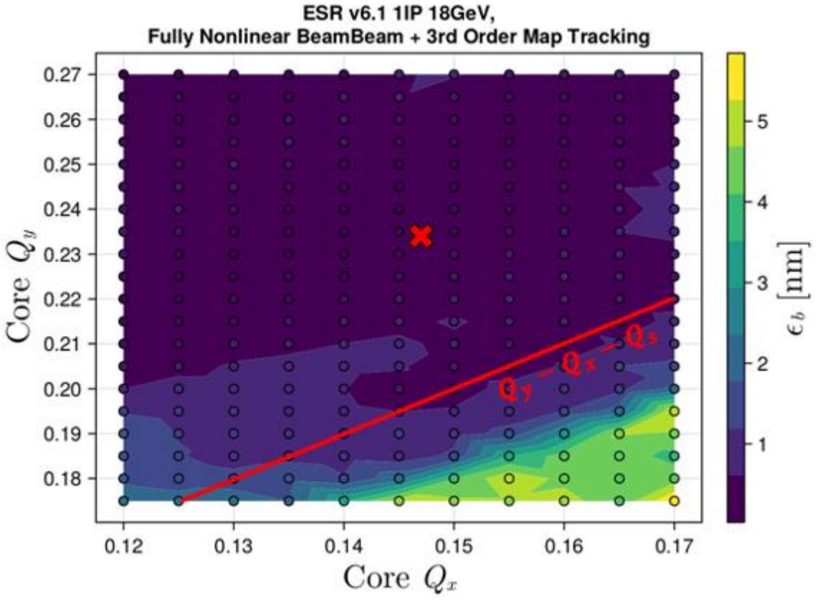


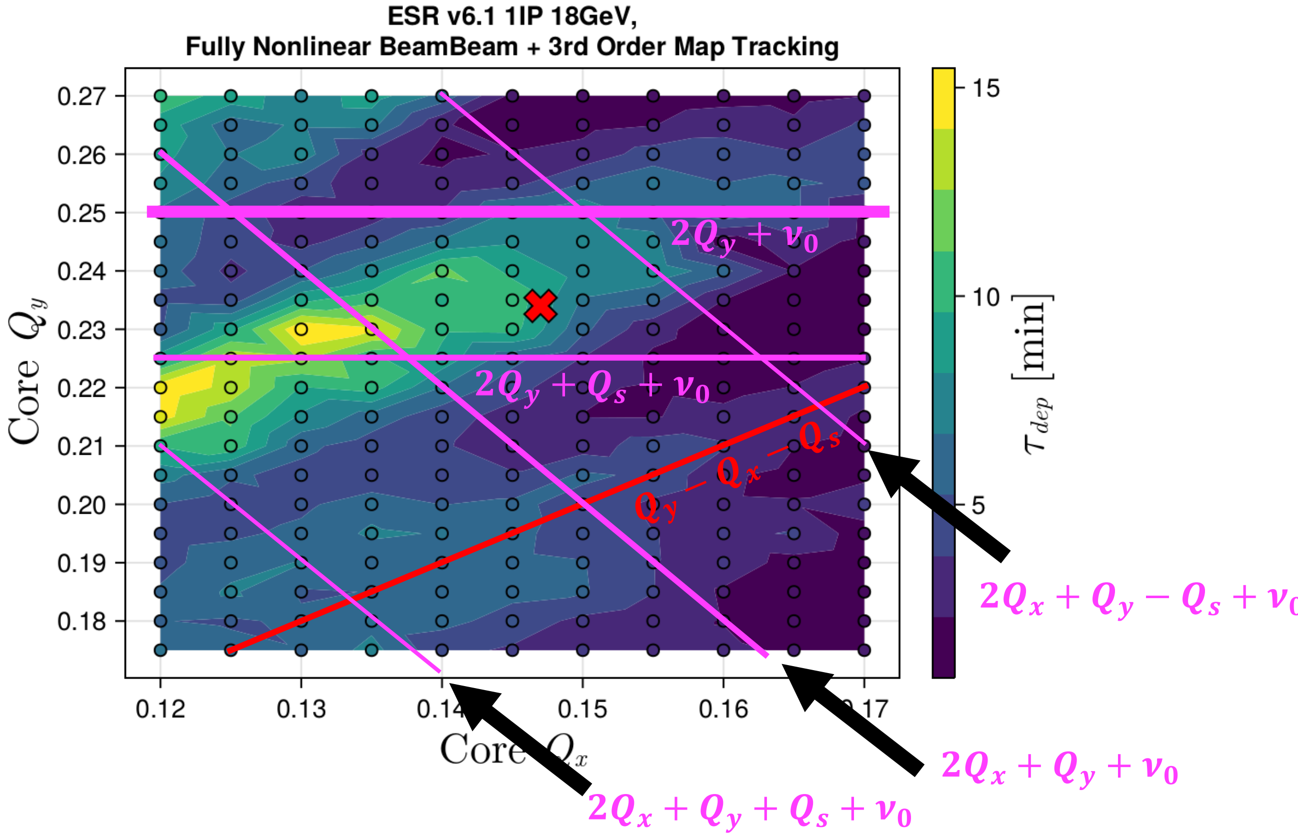
- **$2Q_x + Q_y + \nu_0$ and its synchrotron sidebands cause major problems when overlapping orbital resonances**
  - Parent resonance overlap with orbital is the strongest
- Move down Q_x away from super depolarizing 3rd order parent resonance overlap with orbital resonance?

Results: Tune Scan, Nonlinear BB

- **Horizontal emittance grows to 38 nm**





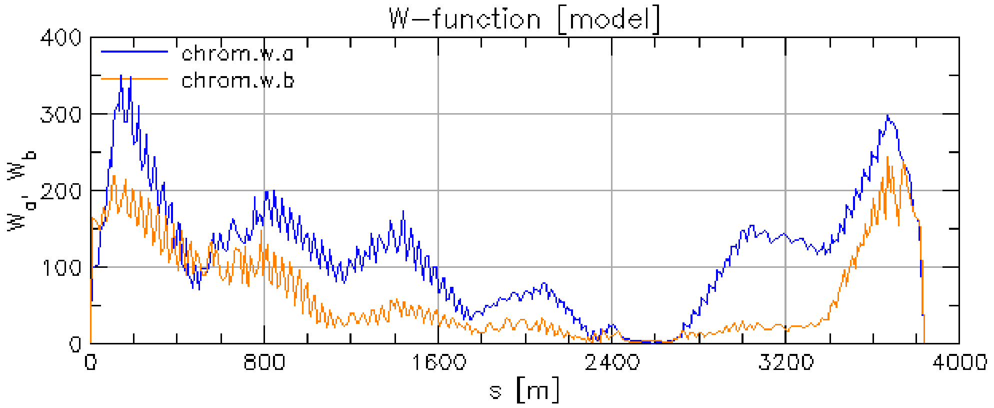


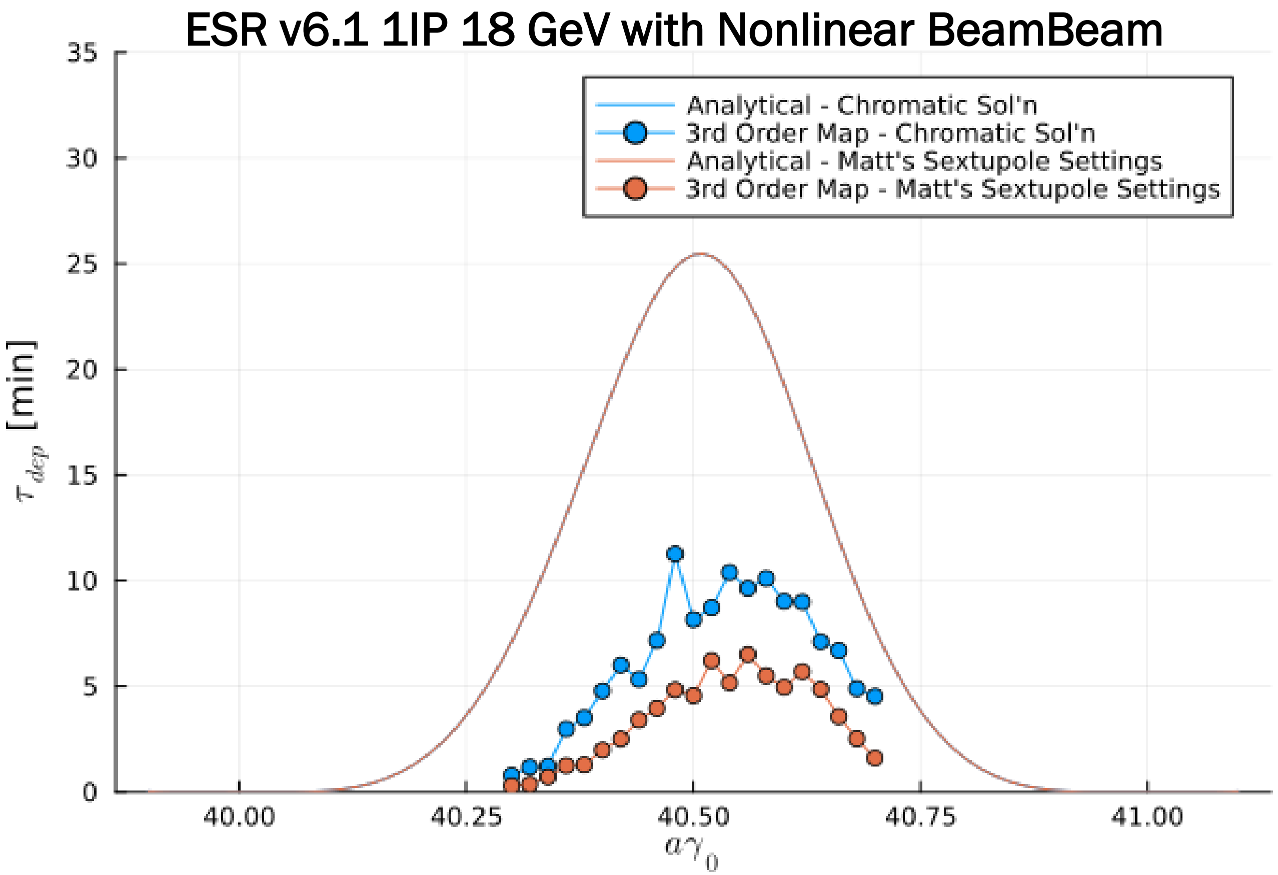
- Moving down Q_x away from the overlap of $\boldsymbol{2Q_x + Q_y + \nu_0}$ with the orbital resonance improves the polarization **9 min → 15 min**

- **But not back up to 25 min**

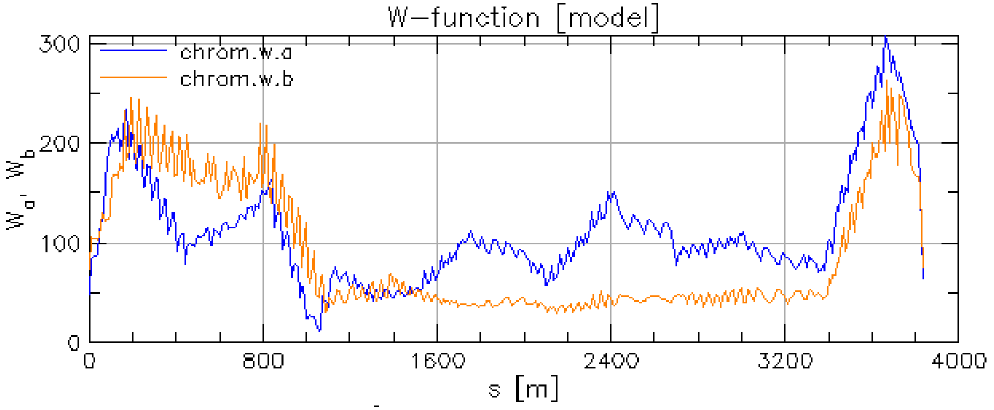
Different Sextupole Settings

- Before chromatic solution was ready, I did rudimentary optimization to not lose particles
- **"Matt's Sextupole Settings":**





- **Chromatic Solution 1:**



- **Clear dependence of polarization on the sextupole settings**

Conclusions

- **Weak-strong simulations in HERA gave pessimistic results for polarization, but in real life it was fine**

- **In the ESR, the nonlinear beam-beam effect causes substantial depolarization in simulations**
  - Specifically, nonlinear BB + 2nd order spin-orbit motion in rest of ring

- **Tune scan *with linear BB* reveals $2Q_x + Q_y + \nu_0$ (and synch. sidebands) to be particularly strong spin resonance**
  - Strongest when overlapping orbital resonances

- **Hypothesis:** linear part of beam-beam excites $2Q_x + Q_y + \nu_0$, which is then crossed when including nonlinear BB tune spread. Effect caused by sextupoles
  - Different sextupole settings showed different polarizations

Future plan of attack:

- The best way to both calculate, and reduce, higher order spin resonance strengths is via TPSA + normal form
- Parametric normal form calculation will give spin resonance strength as function of sextupole strengths
- Can then optimize to reduce spin resonance strength, and repeat nonlinear tracking to verify

Bmad-Julia project: NonlinearNormalForm.jl currently in development will provide all such tools and more

- Includes all features for normal form analysis uses Lie algebraic methods (eventually, everything in FPP)
- Uses GTPSA package of Laurent Deniau, wrapped in Julia programming language with GTPSA.jl