CERN

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A "review" of Intrabeam Scattering in Rings

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Content

- Intrabeam Scattering (IBS) **theoretical models**
- **Ring (optics) design** for reducing IBS
- IBS theory **benchmarking** vs **codes** and **measurements**
    - **SIRE** Monte-Carlo code development
- IBS impact on **beam distributions**
- Combining **IBS** with **space-charge, lattice non-linearities** and **Synchrotron radiation** (damping and quantum excitation)
    - “**Kinetic**” IBS approach for implementation in **Xsuite**

IBS theoretical models

Intrabeam scattering (IBS)

- Small angle **multiple Coulomb scattering** effect
  - Redistribution of beam momenta
  - Beam diffusion with impact on **beam quality**, i.e. brightness, luminosity, etc

- **Theoretical approaches** for the probability of scattering and thereby **growth rates**
  - Classical **Rutherford cross section** (Piwinski, 1974)
  - **Quantum approach** through relativistic “Golden Rule” for the 2-body scattering process (Bjorken - Mtiwngwa 1983)

- Above models and **several approximations** developed over years with three main **drawbacks**:
  - **Gaussian beams** assumed
  - **Betatron coupling** not included
  - Impact of **damping process**

Tracking simulations (Monte Carlo - MC) can investigate these.

Intrabeam scattering (IBS)

- **IBS growth rates** given as “complicated” integrals averaged around rings, depending on **optics** and **beam properties**

$$\boxed{\frac{1}{T_i} = f\,(optics,\ \ beam\ \ params)}$$

- Classical models of **Piwinski** (P) and **Bjorken-Mtingwa** (BM) widely **benchmarked** with **measurements** for **hadron beams** (since ‘80s) but to **lesser extent** for **lepton** beams in presence of **synchrotron radiation** (SR) and **quantum excitation** (QE)
- **High-energy approximations** (**Bane**, **CIMP**, **Nagaitsev**) provide integrals with analytic solutions
- Most tracking codes (e.g. **SIRE, CMAD-IBStrack**) based on **Piwinski**

IBS calculations

Horizontal, vertical and longitudinal **equilibrium states** and **damping times** due to SR damping

The IBS growth rates in one turn (or one time step)

$$\frac{1}{T_i} = \langle f_i \rangle$$

Integrals averaged around the ring.

$$\frac{d\varepsilon_x}{dt} = -\frac{2}{\tau_x}(\varepsilon_x - \varepsilon_{x0}) + \frac{2\varepsilon_x}{T_x(\varepsilon_x, \varepsilon_y, \sigma_p)}$$

$$\frac{d\varepsilon_y}{dt} = -\frac{2}{\tau_y}(\varepsilon_y - \varepsilon_{y0}) + \frac{2\varepsilon_y}{T_y(\varepsilon_x, \varepsilon_y, \sigma_p)}$$

$$\frac{d\sigma_p}{dt} = -\frac{1}{\tau_p}(\sigma_p - \sigma_{p0}) + \frac{\sigma_p}{T_p(\varepsilon_x, \varepsilon_y, \sigma_p)}$$

If ≠0

If = 0

Steady State emittances

Steady state exists if we are below transition or in the presence of SR .

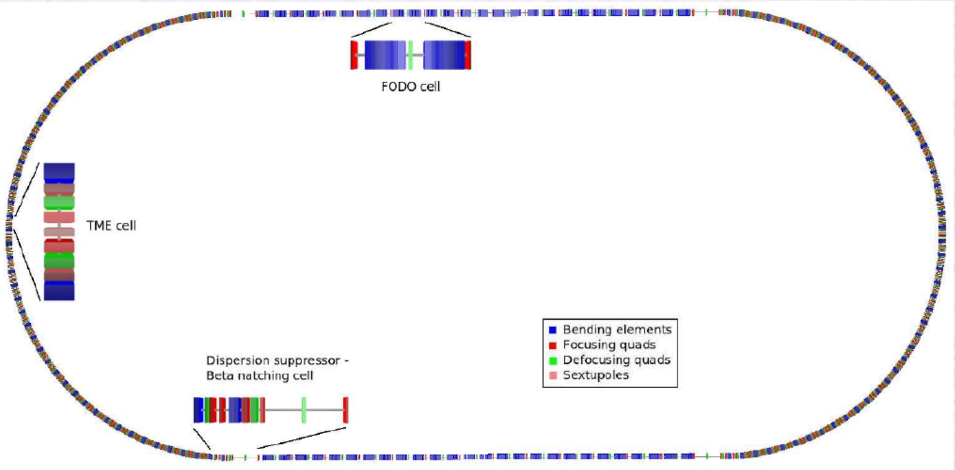
Ring design for reducing IBS

F. Antoniou, PhD thesis, 2013

CLIC damping rings design challenges

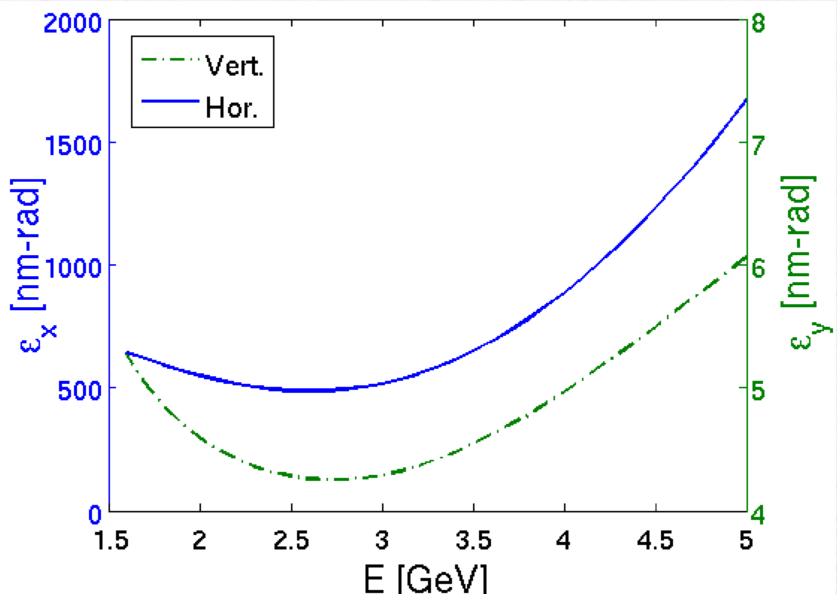
- ❑ **Ultra-low 3D emittances @ high bunch charge** (brightness) and high rep. rate (**50**-100 Hz) for **luminosity**
  - ❑ Several **collective effects**, including **Intra-beam scattering, space charge,** single and multi-bunch **instabilities** (ions, e-cloud)

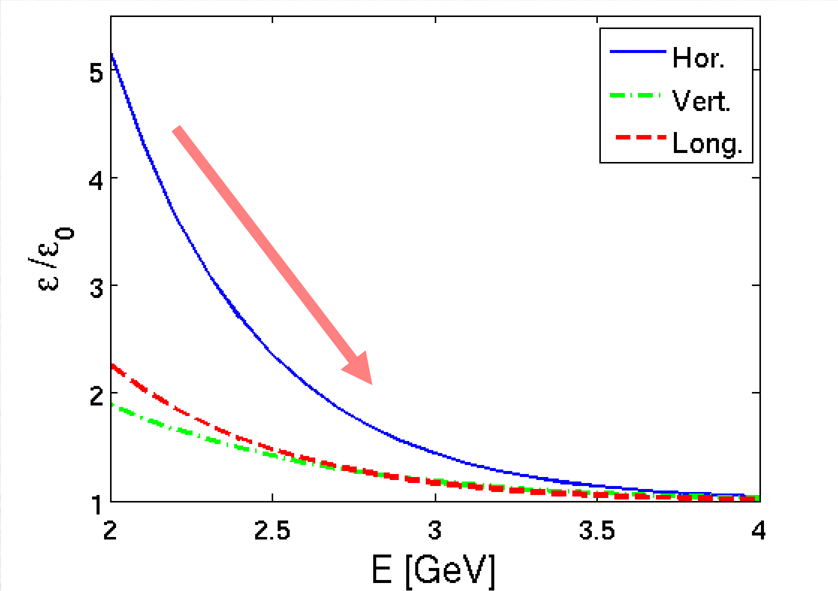
Extracted Parameters	**PDR** e^-/e^+	**DR** e^-/e^+
Energy [GeV]	2.86	2.86
Bunch population [10^9]	4.1-4.4	4.1
Bunch length [mm]	10	1.4
Energy Spread [%]	0.5	0.1
Long. emittance [eV.m]	143000	5000
Hor. Norm. emittance [nm-rad]	63000	500
Ver. Norm. emittance [nm-rad]	1500	5



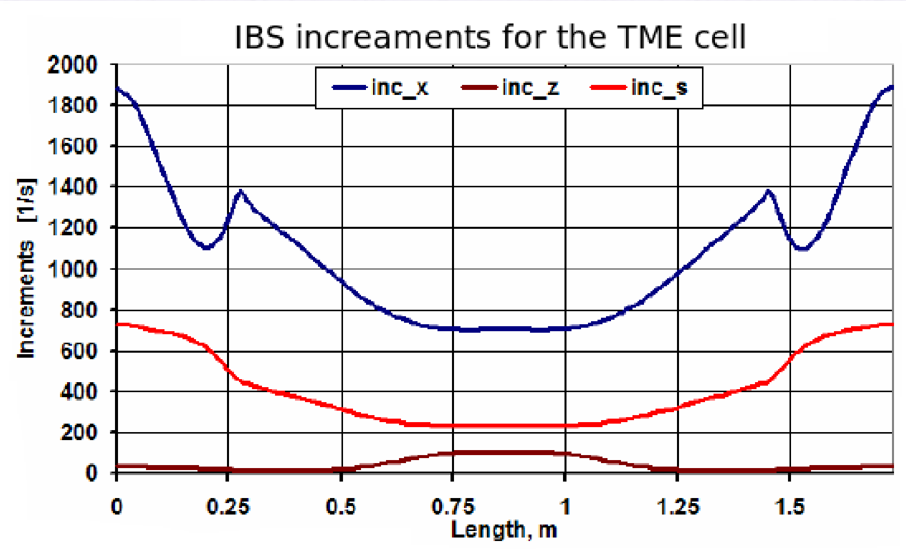
DR design optimization for IBS

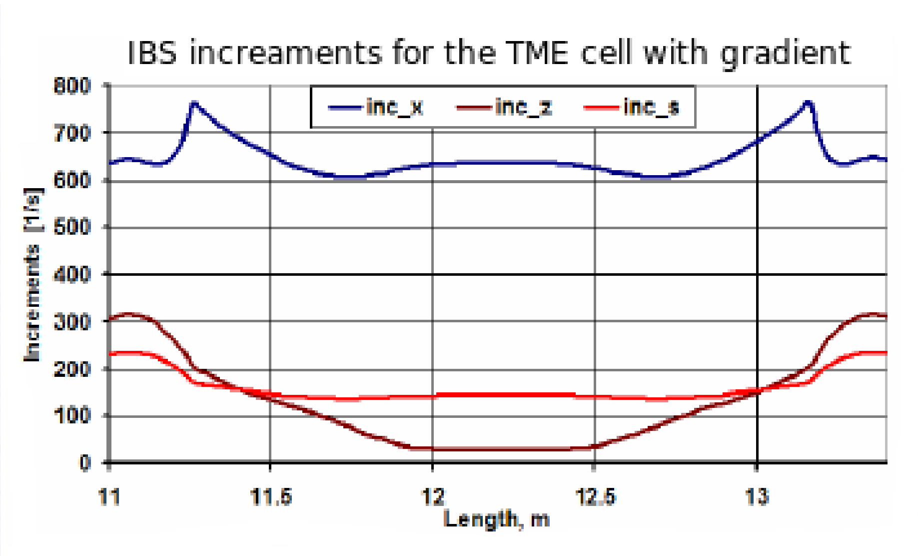
- Scaling of DR extracted **transverse emittances** (left) and ratio **with/without IBS** from (P) theory (right) versus **energy**
- Broad transverse emittance **minimum @ 2.5 GeV** while the **IBS** impact becomes **weaker** for **high energy**
- Emittance @ **higher energies** dominated by **quantum excitation** (~γ^3 scaling)
- Energy choice of **2.86 GeV** for **reduction** of **IBS**, while maintaining extracted emittance targets

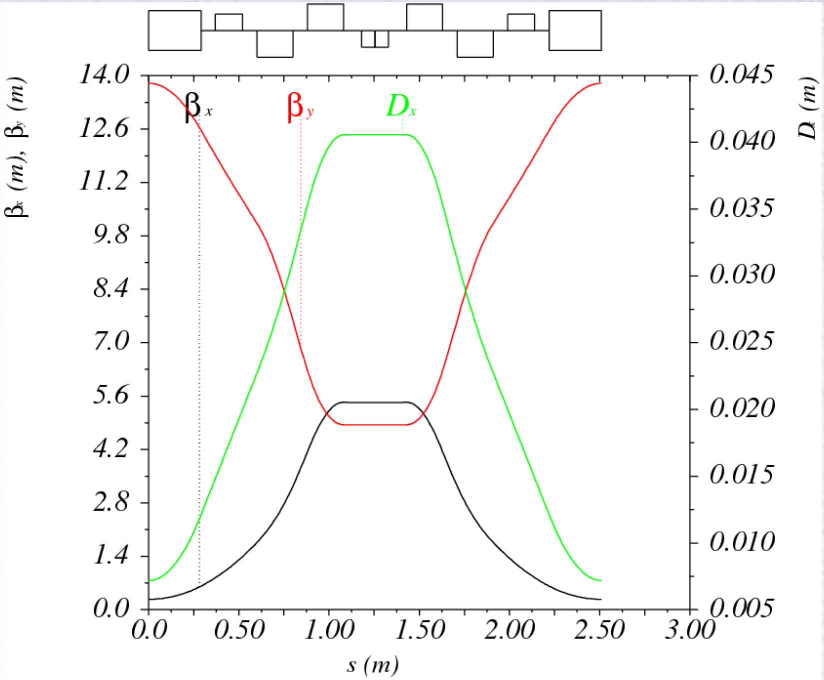




IBS growth rates in TME cell

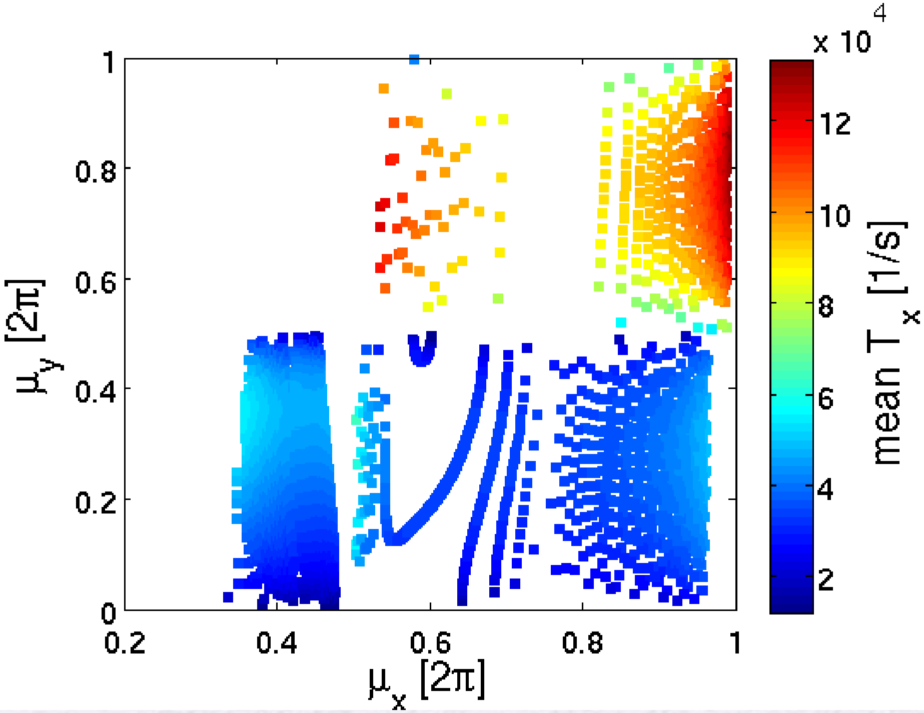






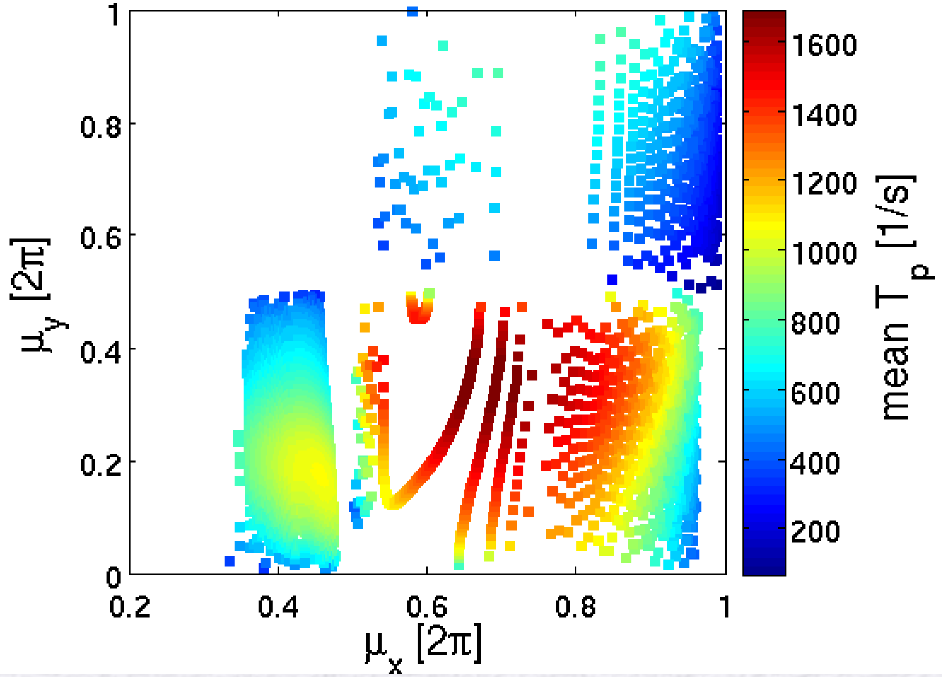
- TME cell with gradient in dipole (inverses exhibit **3-fold reduction** in IBS transverse **growth rates**

TME optics optimisation with IBS

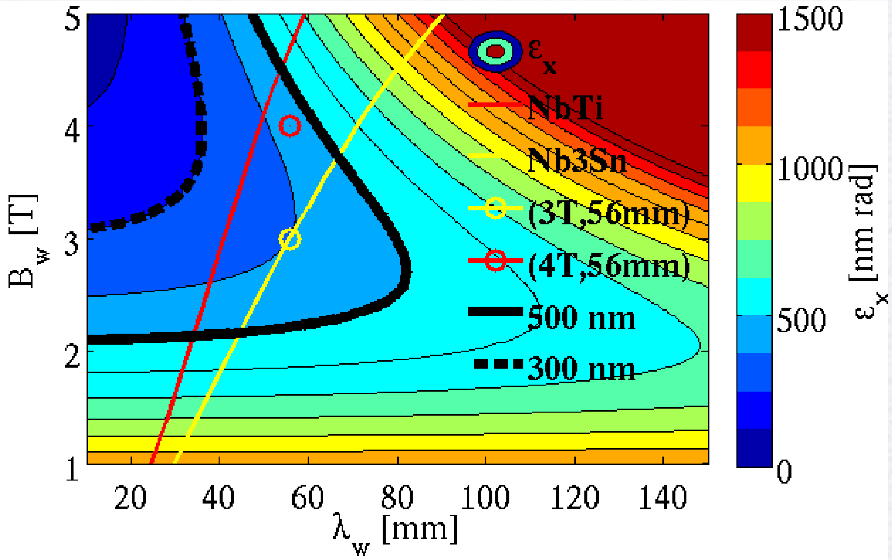


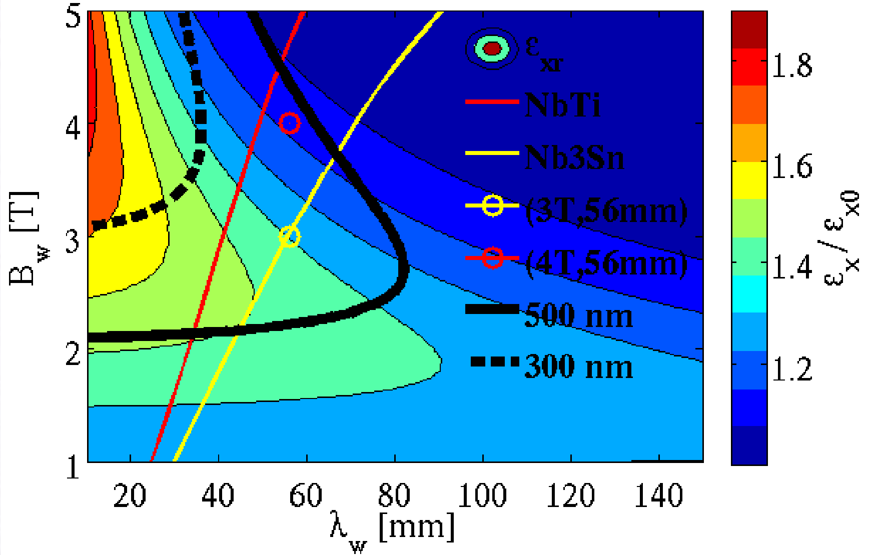
☐ Low phase advances **optimal** for horizontal IBS growth rate **minimization** for moderate long. IBS growth and vertical emittance determined by coupling control

☐ Low phase advances **also good** for low chromaticity and non-linear dynamics optimisation



Wiggler parameters optimisation

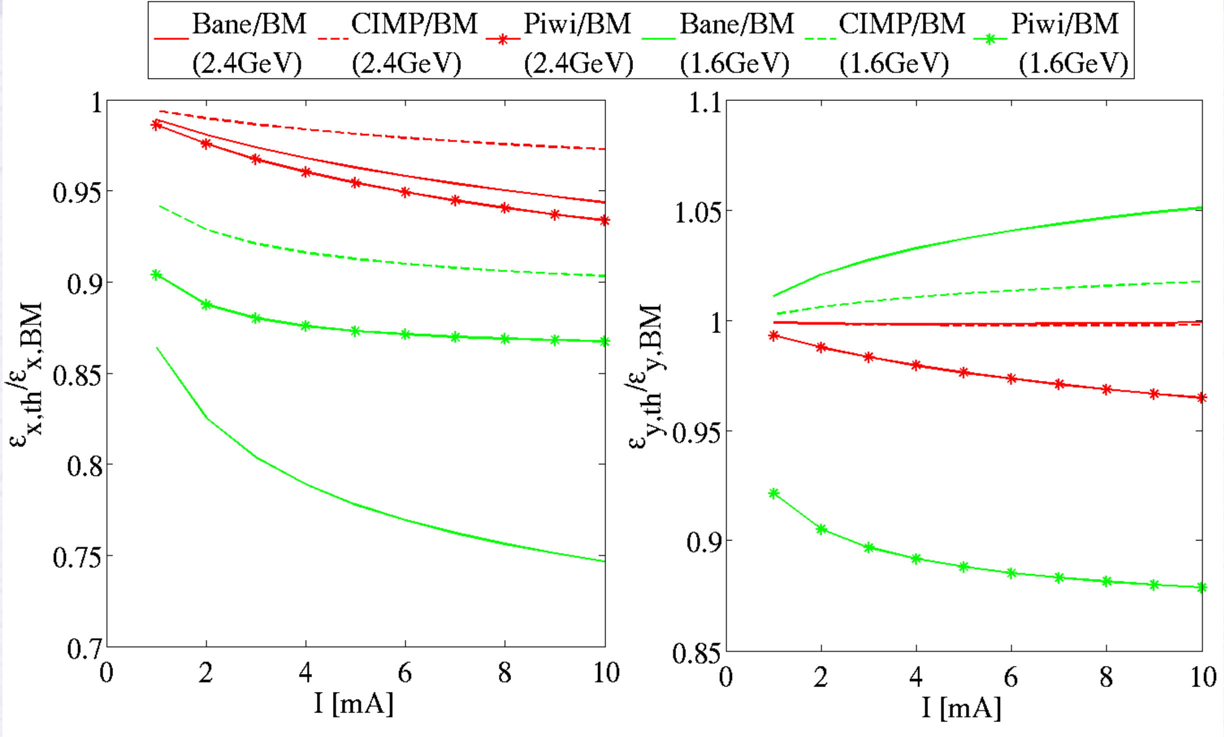




- ❑ Extracted emittance minimized at **large wiggler peak fields** and **small wiggler periods** whereas **IBS maximized**
- ❑ **Large wiggler peak fields** and **moderate periods** are lead to **low emittance** and **reduced IBS effect**
- ❑ Superconducting wiggler technologies (NbTi or Nb_3Sn) achieve target requirements

IBS theory benchmarking vs codes and measurements

Comparison between IBS models

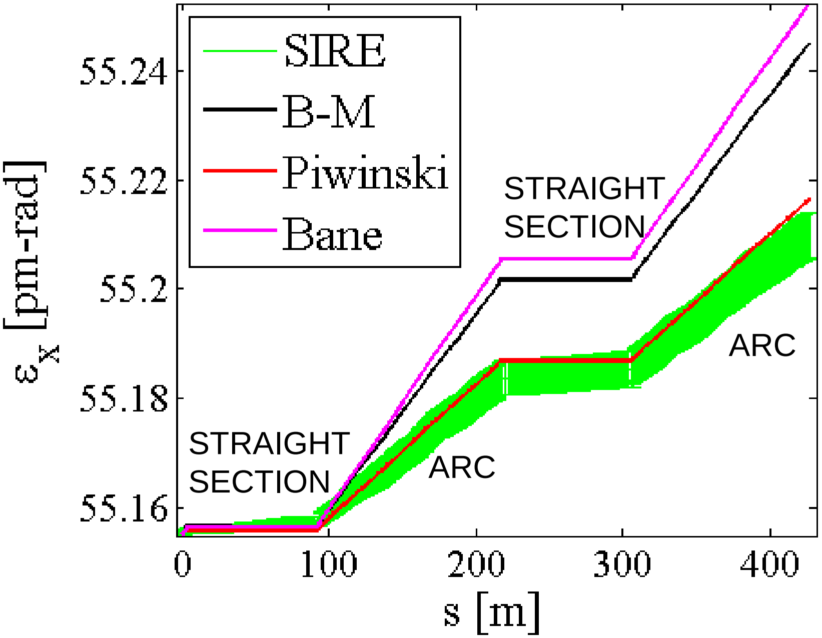


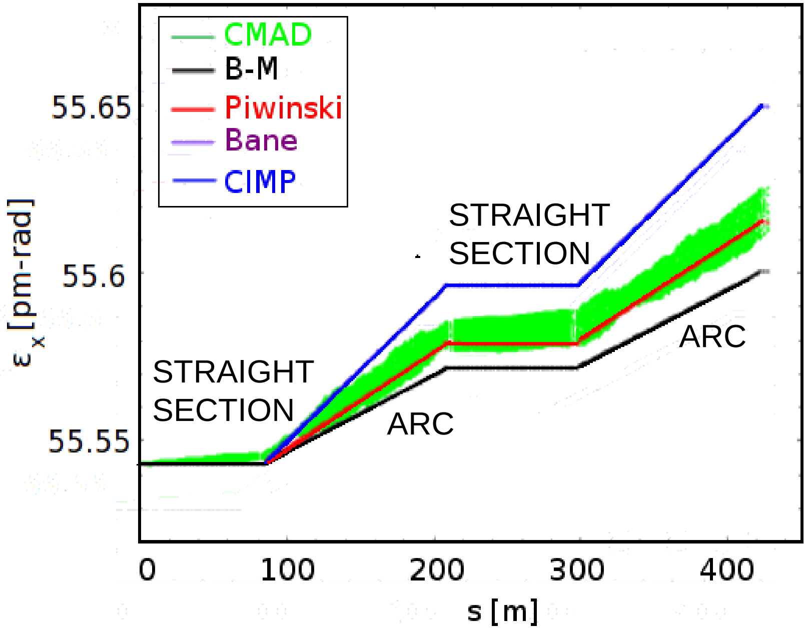
- Comparison between **theoretical models** for the **SLS storage ring** lattice (normalized to BM theory)
- Good agreement at **weak IBS regimes** but divergence grows for **larger IBS impact** (lower energy, higher current)
- **Benchmarking** of **theoretical models** and **MC codes** with **measurements** is essential

Software for IBS and Radiation Effects (SIRE)

- Monte Carlo multi-particle simulation code based on MOCAC (Zenkevich, Bolshakov)
- Inputs: **lattice optics** (e.g. MADX twiss file), **particle distribution** (default: Gaussian distribution)
- Computing IBS and Radiation effects through element tracking following 6D coordinates
- Macro-particles grouped in **cells** for binary collision
- **Particle momenta** changed through scattering routine, based on classical **Rutherford cross section**
- **Radiation effects** (damping, quantum excitation) also evaluated
- **Beam distribution** updated and rms **emittances** are recomputed, providing their **time evolution**

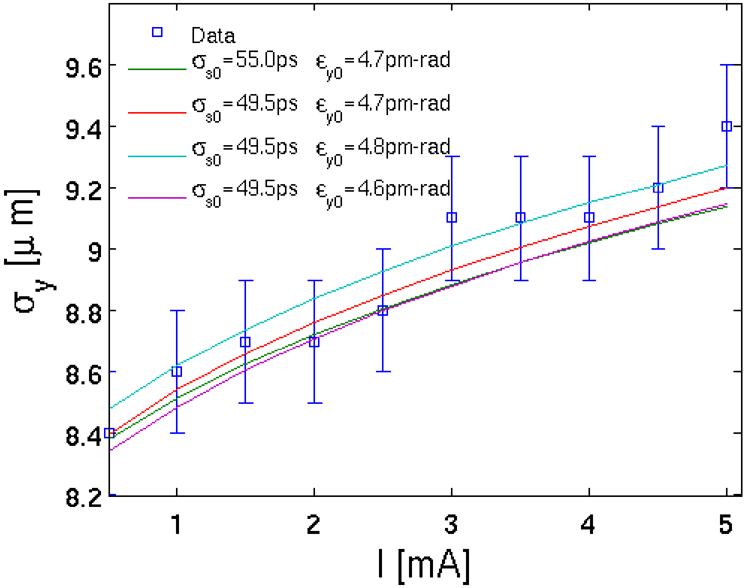
IBS MC codes vs theory

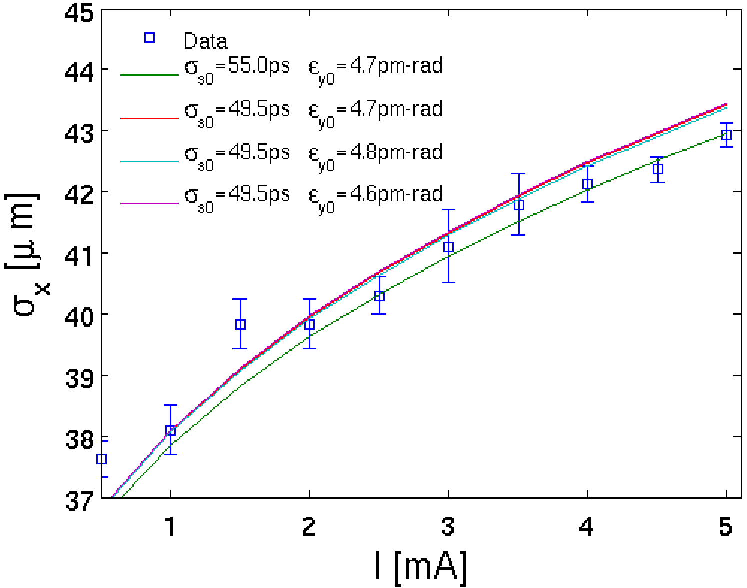




- **SIRE** and CMAD-IBStrack benchmarking with theoretical models for CLIC DR lattice
- Comparison of **1-turn emittance evolution** comparison
- Excellent **agreement** with **Piwinski** as expected
- **Same emittance evolution trend** for both theories and codes
- Large contribution from **arcs** (optics dependence)

IBS measurements at SLS





- ☐ **Multi-bunch measurements** with always **same total current** (instrumentation response constraints)
- ☐ **Longitudinal phase space** dominated by **3rd harmonic cavity**
- ☐ **Measurements** compared with **CIMP** predictions
- ☐ Quite good agreement in **transverse plane**

In collaboration with N. Milas, M. Boge, M. Aiba, A. Streun, A. Saa-Hernandez (PSI)

IBS impact on beam distribution

S. Papadopoulou, PhD thesis, 2019,
S. Papadopoulou, et al. PRAB 23, 2020

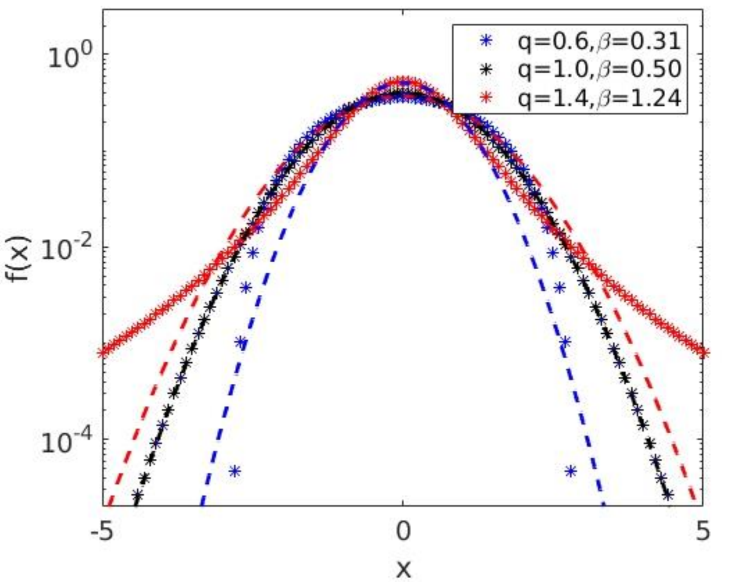
LHC bunch profiles

- ☐ LHC particle distributions appear non-Gaussian, at injection (450GeV) and collision (6.5TeV) energies
- ☐ q-Gaussian function

q<1→ light tailed
q=1→ Gaussian
q>1→ heavy tailed

$$f(x) = \frac{\sqrt{\beta}}{C_q} e_q(-\beta x^2), \; e_q(x) = [1 + (1-q)x]^{\frac{1}{1-q}}$$

$$\sigma = \sqrt{\frac{1}{\beta(5-3q)}}$$ **for q<5/3**



	q-Gaussian rms	Gaussian rms
light tailed	1.00	1.10
Gaussian	1.00	1.00
heavy tailed	1.00	0.74

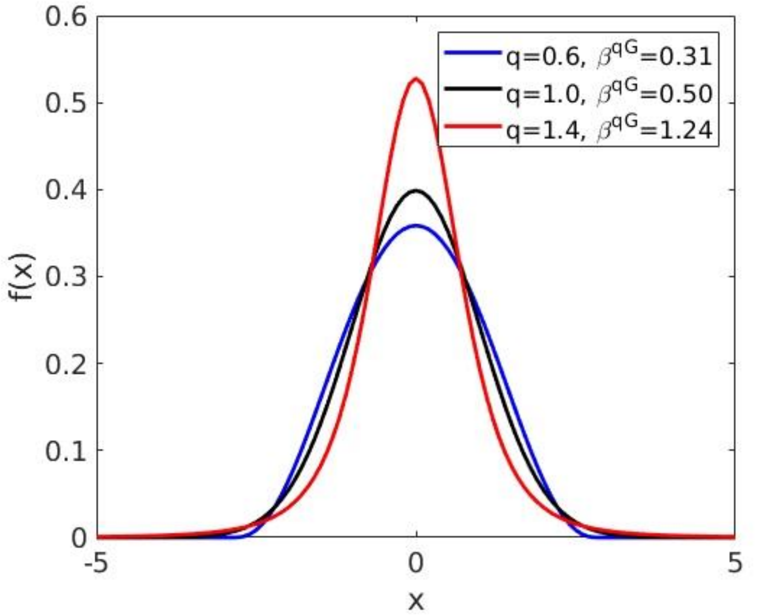
overestimated

underestimated

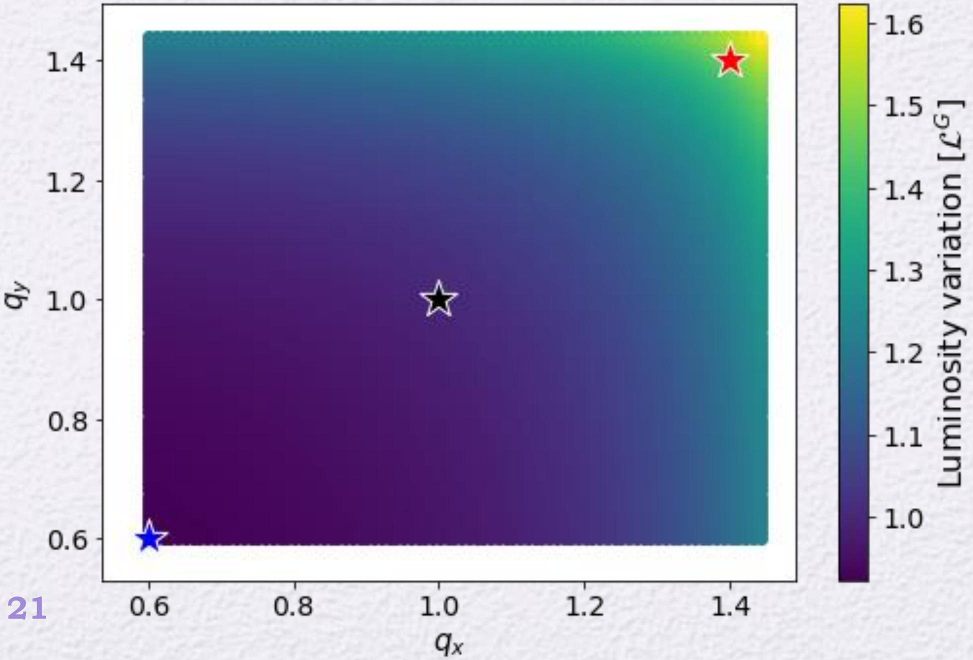
Impact on Luminosity

$$\mathcal{L}^{qG} = \frac{N_1 N_2 N_b f_{rev}}{4\pi \underbrace{\sigma_x^{qG}\sigma_y^{qG}}_{\text{transverse beam sizes}}} \underbrace{\mathcal{I}_x^{qG}\mathcal{I}_y^{qG}}_{\text{functions of the parameter q}}$$

rms beam size constant, varying the distribution tails q (and b)

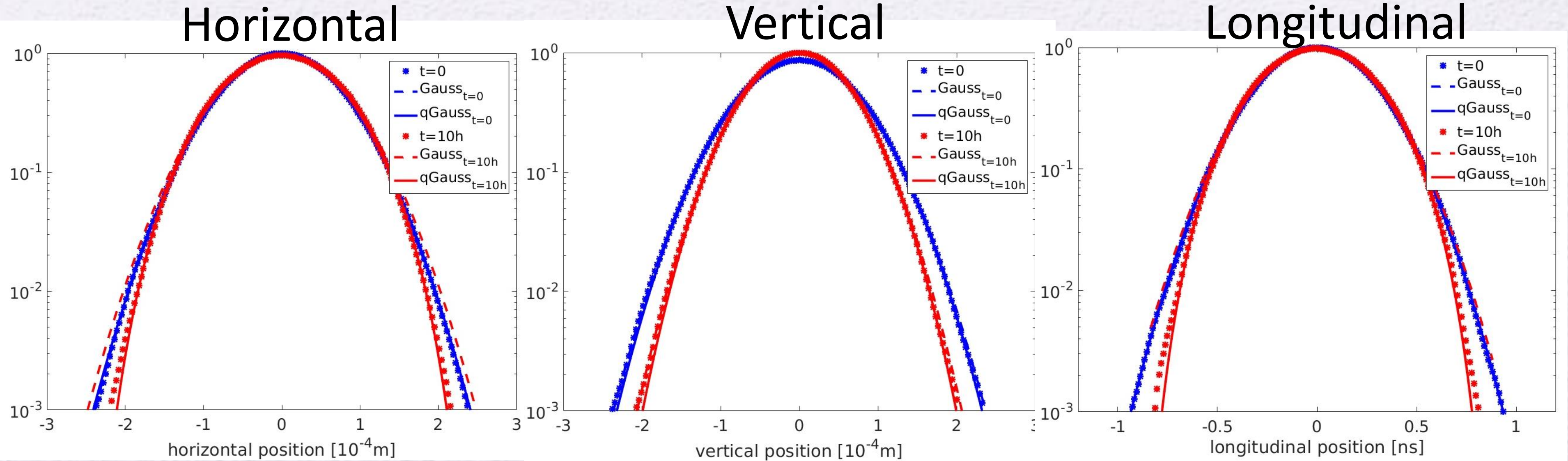


Luminosity variation with respect to the one for Gaussian distributions



IBS Simulations for the LHC

- **SIRE benchmarking** with analytical **IBS B-M formalism** for the nominal LHC and the HL-LHC parameters
- **Reduced LHC lattice** (from **>11000** to **90 elements**) → minimising computational time
- Convergence studies, to find **optimal values** of number for macro-particle and cell numbers
- Possibility to track **non-Gaussian distributions**


Horizontal

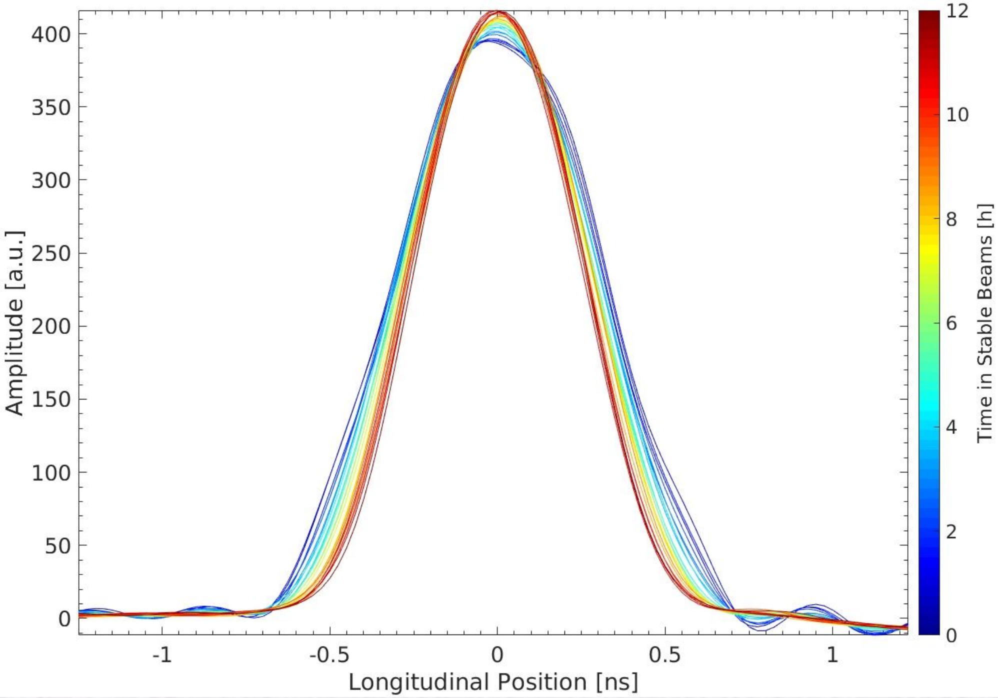
Vertical

Longitudinal

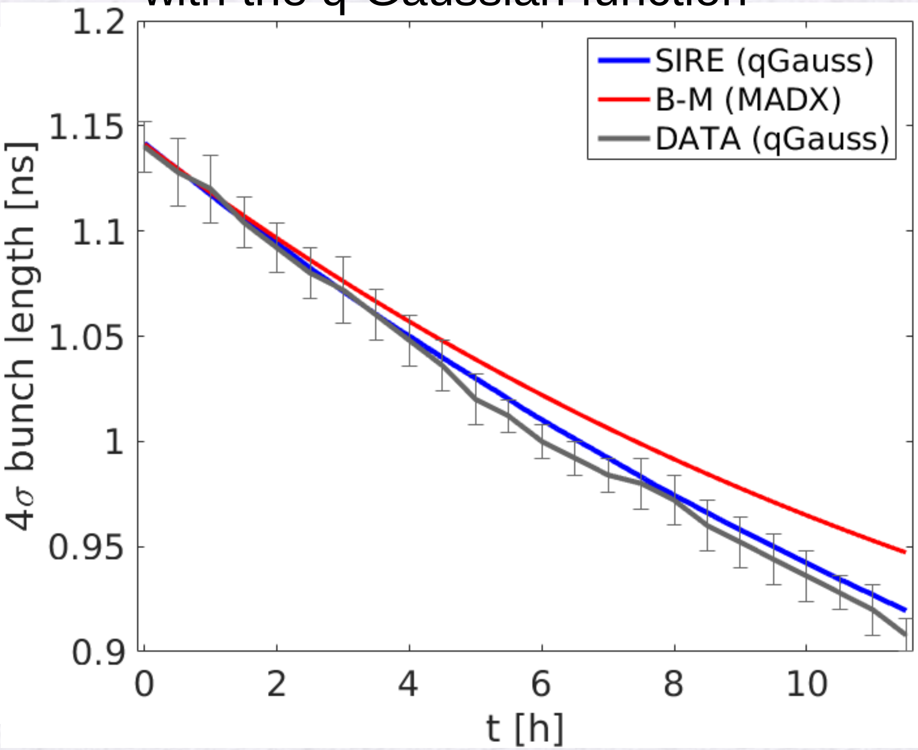
IBS Simulations vs measurements in the LHC

- ❑ At LHC flat-top **bunch length** distributions evolve from **heavy** to **light tailed,** with **IBS** dominating **core** and **SR** dominating **tails**
- ❑ **Excellent agreement** between data and SIRE, accurate reproduction of bunch length evolution

Non-Gaussian longitudinal bunch profile, at LHC collision energy (6.5 TeV during Run2)



Bunch length evolution at collision, fitted with the q-Gaussian function



IBS with space-charge and lattice non-linearities

M. Zampetakis et al., PRAB 27, 2024;
M. Zampetakis et al., arXiv:2310.03504, 2023

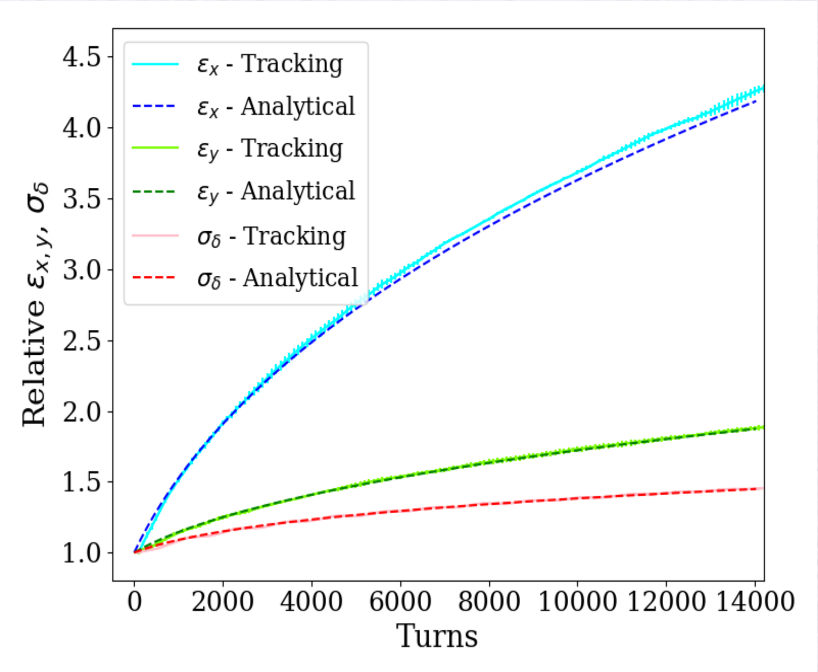
IBS implementation for combination with SC

Implementation in the PyORBIT macroparticle tracking code includes a momentum “kick” in each plane:

$$\Delta \mathrm{p}_u = R \cdot \sigma_{p_u} \sqrt{2 T^{-1}_{\mathrm{IBS},u} \mathrm{T}_{\mathrm{rev}} (2\sigma_z \sqrt{\pi} \lambda(z))}$$

- The IBS growth rates are calculated every 50 turns, using Nagaitsev’s approach

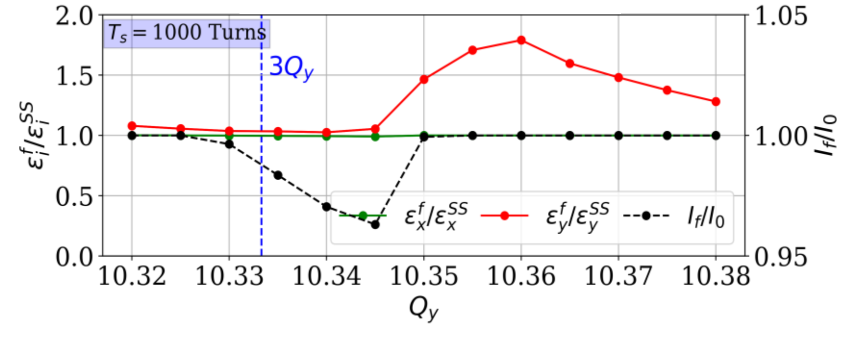
Excellent agreement against analytical calculations!



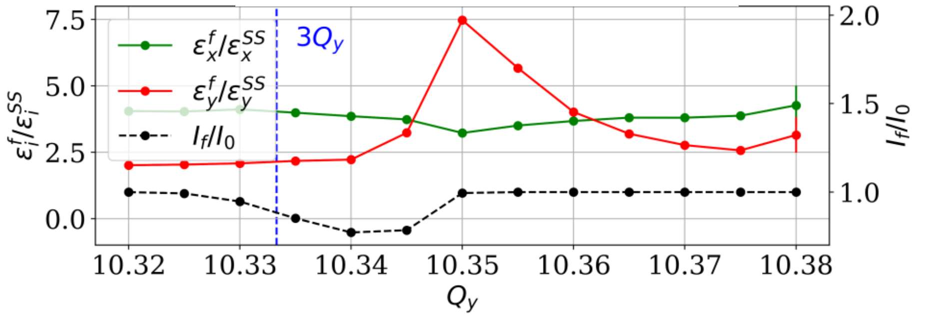
Combining SC with IBS and SR

Vertical tune scan around the $3Q_y$ resonance, with the addition of IBS

SC only

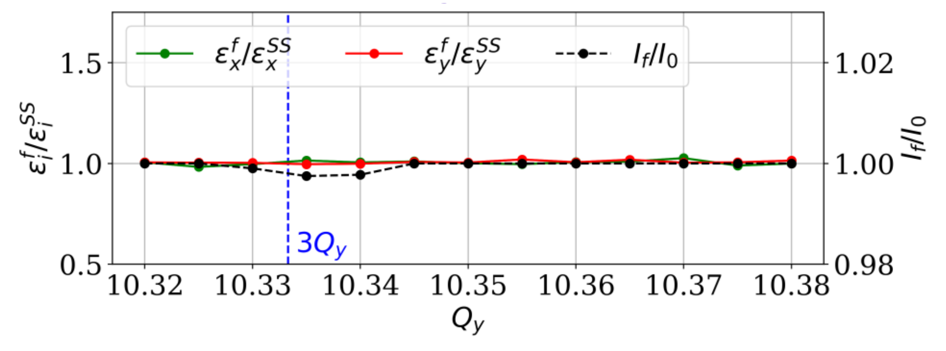


Space-Charge +IBS



- Sensitivity to $3Q_y$ resonance strongly enhanced when both IBS and SC are present, producing larger vertical emittance blow-up and more losses
- IBS dominates emittance growth for working points far from resonance
- SR strongly mitigates IBS and SC effect.

Space-Charge + IBS + SR



“Kinetic” IBS simulation

IBS momentum kick

$i = x, y, z$

$$P_i(t + \Delta t) = P_i(t) - F_i \cdot P_i(t) \cdot \rho(z) \cdot \Delta t + \sqrt{2 \cdot G_i \cdot \rho(z) \cdot \Delta t} \cdot \varsigma_i,$$

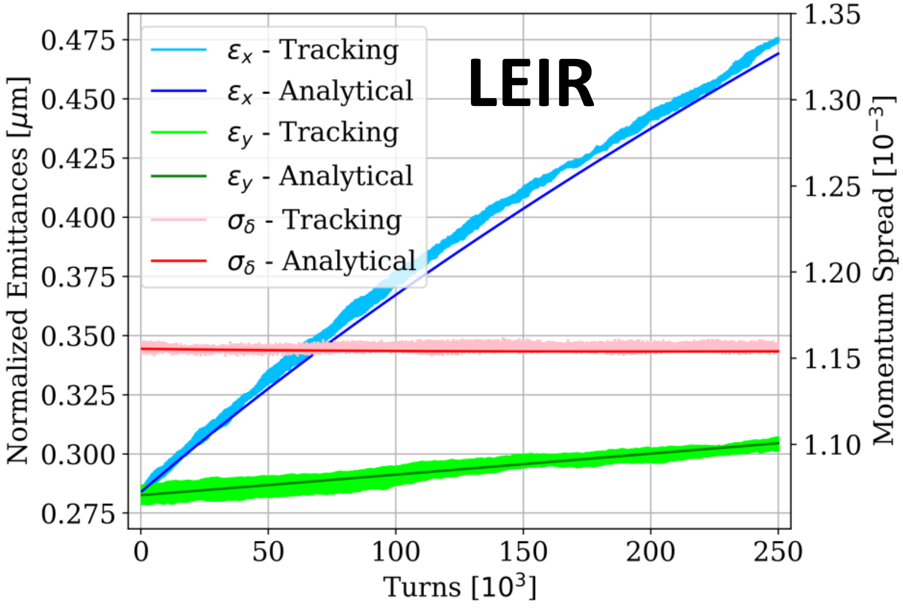
where $\rho(z)$ longitudinal line density, ς random number with unit standard deviation, friction and diffusion coefficients derived by IBS formalism

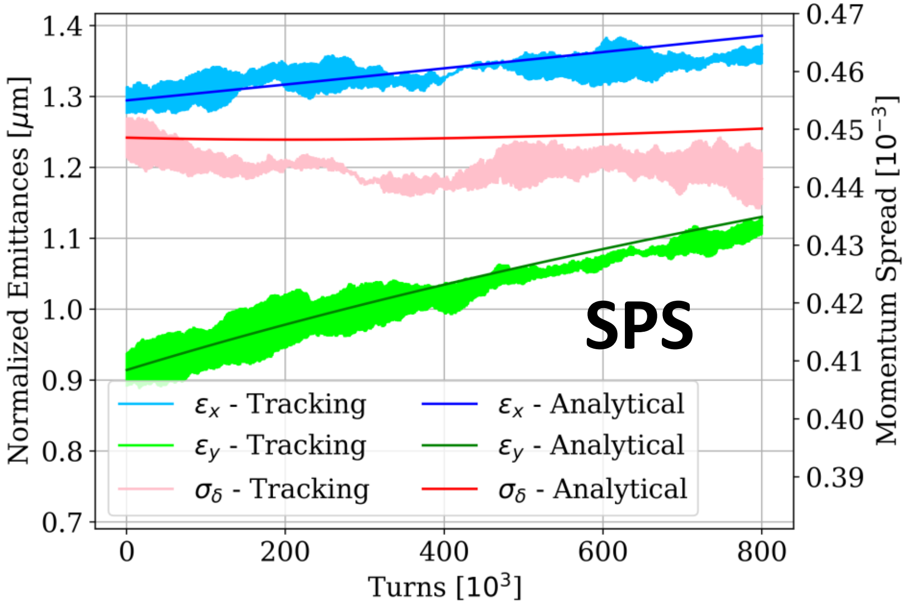
- Using **Nagaitsev** formalism (elliptical integrals) instead of Bjorken & Mtingwa
  - ⇒ Better integral **convergence, 20 - 80 times faster** integration
- Longitudinal line density also considered ⇒ Non-Gaussian profiles
- Implemented in **Xsuite** for enabling studies of interplay with lattice non-linearities, space-charge, etc.

Kinetic IBS kick benchmarking

Kinetic IBS kick for **LEIR** and **SPS heavy-ion beams**

- **Excellent agreement** with analytical calculations





Summary

- ☐ IBS theoretical models (even if **not accurate** on strong IBS regimes) can be used to efficiently **mitigate** its impact through careful **ring (optics) design** choices targeting **ultra-high brightness**
- ☐ **Monte-Carlo PIC codes (SIRE)** allow to understand impact of IBS (**core growth**) and SR (**tail reduction**) on **particle distribution**
- ☐ Combining **IBS** with **space-charge, lattice non-linearities, synchrotron radiation** and other effects (**Xsuite** library) allows to study interplay
  - ☐ Established beneficial effect of **strong radiation damping** in **ultra-low emittance rings**

Thank you!