Design of IBS dominated low emittance rings

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Layout

- General introduction to intrabeam scattering (IBS)
- CLIC DR parameters
- Benchmarking of theoretical models and existing Monte Carlo codes
- Optics optimization steps for reducing IBS
  - TME cell optimization
  - Energy optimization
- IBS measurements at the SLS
- Summary

The Intrabeam scattering effect

- Small angle **multiple Coulomb scattering** effect
  - Redistribution of beam momenta
  - Beam diffusion with impact on the beam quality
    - Brightness , luminosity, etc

- **Different approaches** for the probability of scattering
  - Classical Rutherford cross section
  - Quantum approach
    - Relativistic “Golden Rule” for the 2-body scattering process

- **Several theoretical models** and their **approximations** developed over the years → three main drawbacks:
  - Gaussian beams assumed
  - Betatron coupling not trivial to be included
  - Impact on damping process?

The Intrabeam scattering effect

- Theoretical models calculate the **IBS growth rates**:

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

- Complicated integrals averaged around the rings
  - Depend on optics and beam properties

- Classical models of Piwinski (**P**) and Bjorken-Mtingwa (**BM**)
  - Benchmarked with measurements for hadron beams but not for lepton beams in the presence of synchrotron radiation (SR) and quantum excitation (QE)
- High energy approximations **Bane** and **CIMP**
  - Integrals with analytic solutions
- Tracking codes **SIRE** and **CMAD-IBStrack**
  - Based on the classical approach

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)

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

Complicated 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**

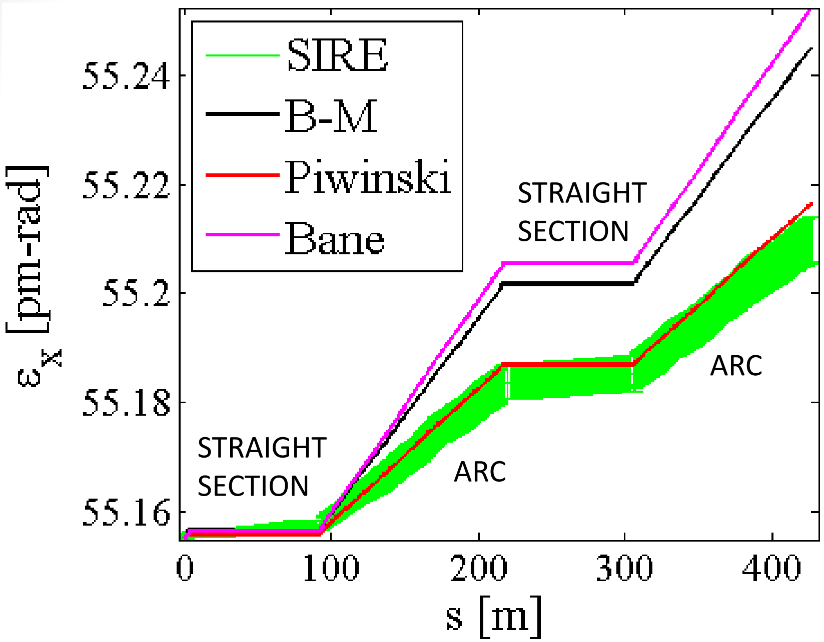
Steady state exists if we are below transition or in the presence of SR .

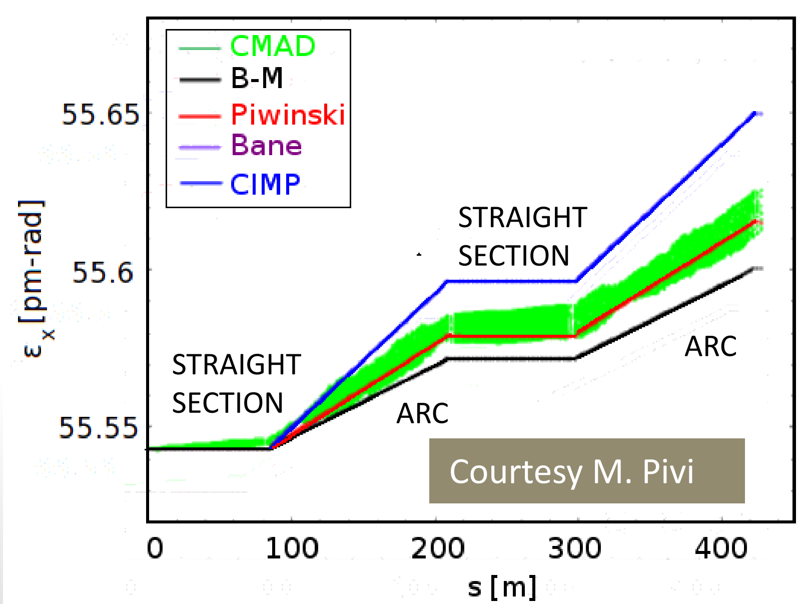
The CLIC DR parameters

Parameters	1 GHz	2 GHz	V06
	General		
Energy [GeV]	2.86	2.86	2.424
Circumference [m]	427.5	427.5	493.05
Bunches per train	156	312	312
Energy loss/turn [MeV]	3.98	3.98	3.98
RF voltage [MV]	5.1	4.5	4.3
RF harmonic (h)	1425	2850	3287
RF stationary phase [°]	51	62	67
Energy Acceptance [%]	1	2.5	0.98
Natural chromaticity x/y	-115/-85	-115/-85	-148.8/-79.0
Momentum compaction factor [10^{-4}]	1.27	1.27	0.644
Damping times x/y/s [ms]	2/2/1	2/2/1	2/2/1
Number of arc cells/wigglers	100/52	100/52	100/76
Phase advance per arc cell x/y	0.408/0.05	0.408/0.05	0.442/0.045
Dipole focusing strength $K_1[m^{-2}]$	-1.1	-1.1	-1.1
Dipole length [m]/field [T]	0.58/1.03	0.58/1.03	0.4/1.27
	Without the IBS		
Normalized Hor. emittance [nm-rad]	312	312	148
Energy spread [10^{-3}]	1.2	1.3	1.12
Bunch Length [mm]	1.18	1.46	0.95
Longitudinal Emittance [keV-m]	5.01	4.39	2.58
	With the IBS		
Bunch population [10^9]	4.1	4.1	4.1
Normalized Hor. emittance [nm-rad]	456	472	436
Normalized Vert. emittance [nm-rad]	4.8	4.8	5
$\varepsilon_{x,IBS}/\varepsilon_{x,0}$	1.44	1.5	2.9
Longitudinal Emittance [keV-m]	6	6	5
Space charge tune shift	-0.10	-0.11	-0.2

- Performance parameters of the CLIC Damping Rings
- 2 RF options (1 & 2 GHz)
- V06: Intermediate design stage
- The output emittances strongly dominated by the IBS effect
  - The motivation of our IBS studies
  - The effect will be even stronger in a low energy CLIC option where the bunch current should be increased

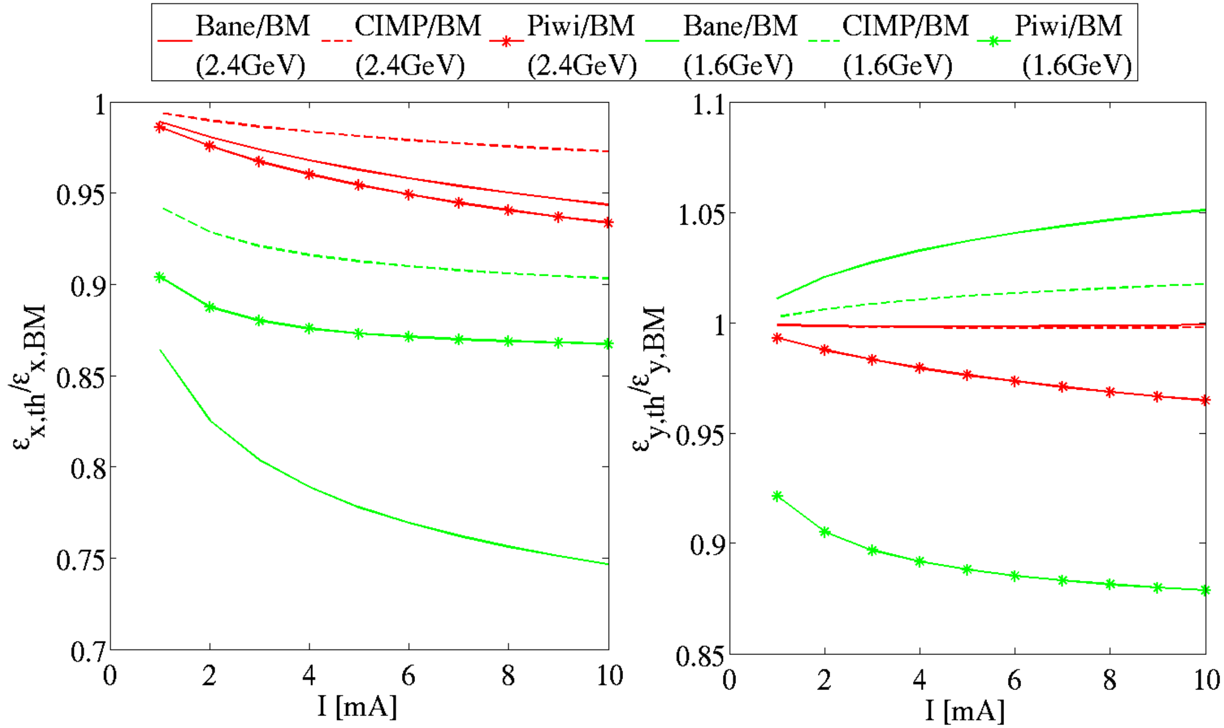
Benchmarking of MC codes with theories





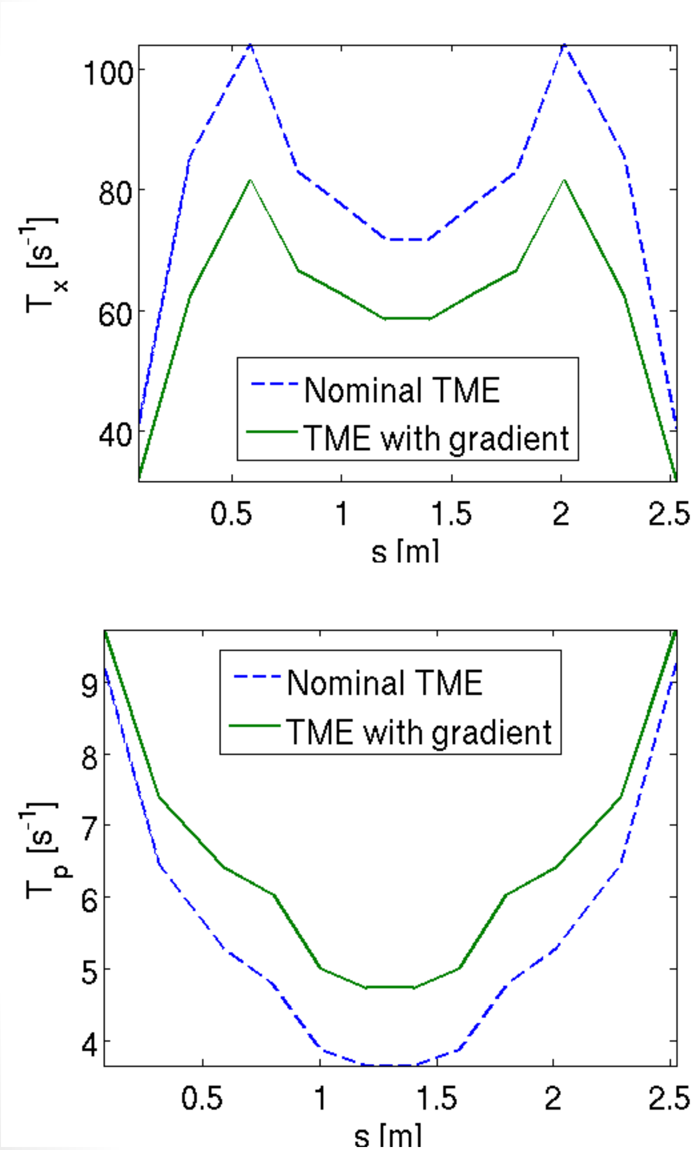
- SIRE (top) and CMAD-IBStrack (bottom) benchmarking with theoretical models for the CLIC DR lattice
  - 1 turn emittance evolution comparison
- **Excellent** agreement with **Piwinski** as expected
- All models and codes follow the **same trend** on the emittance evolution
- Clear **dependence** on the **optics**
  - Large contribution from the arcs

Comparison between theoretical models



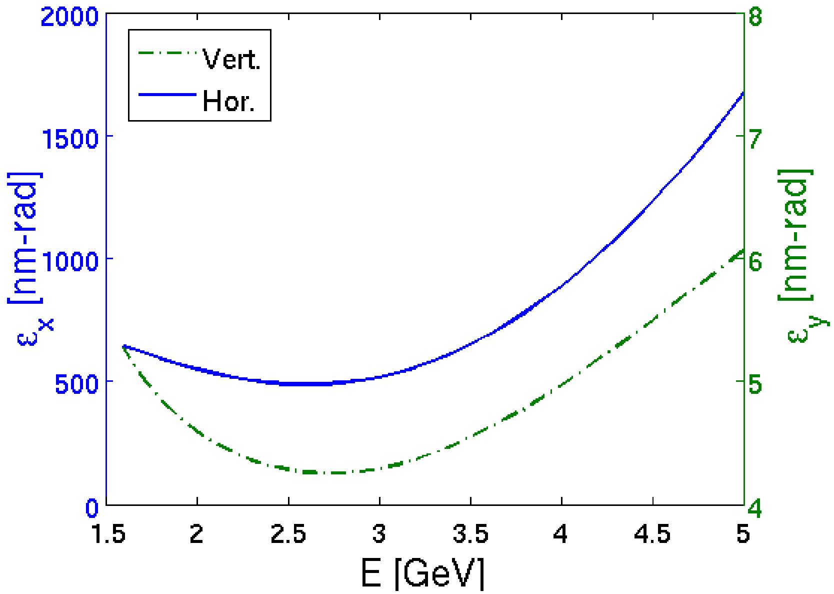
- Comparison between the theoretical models for the SLS lattice
- All results normalized to the ones from BM
- Good agreement at weak IBS regimes
- Divergence grows as the IBS effect grows
    - Benchmarking of theoretical models and MC codes with measurements is essential

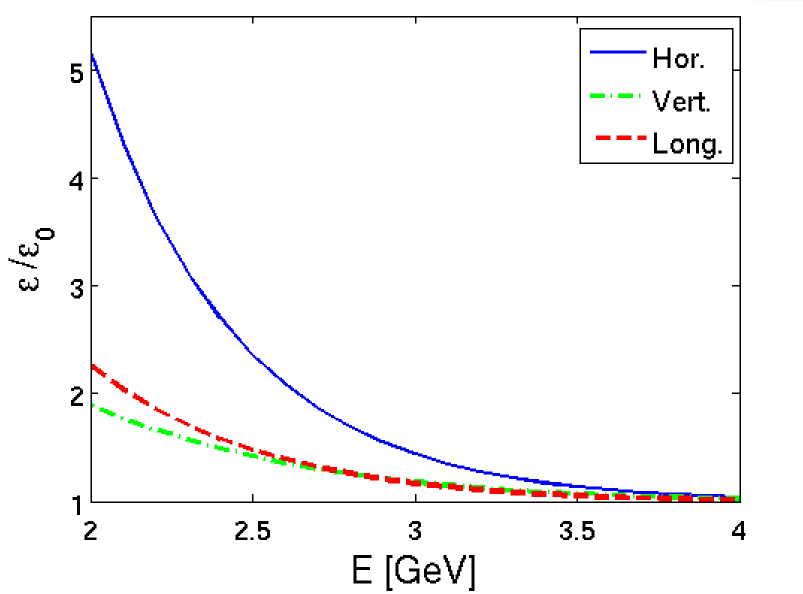
TME optimization with respect to IBS



- IBS growth rate in the initial (2007) design a factor of 6
- The main contribution to the IBS growth comes from the arcs (small dispersion and beta functions at the center of the TME dipole)
- Using a modified TME cell, with combined function dipole with small defocusing gradient, has a positive impact on the IBS effect → Reduced the effect by a factor of 2 (from 6 → 3)
  - Still room for improvement!

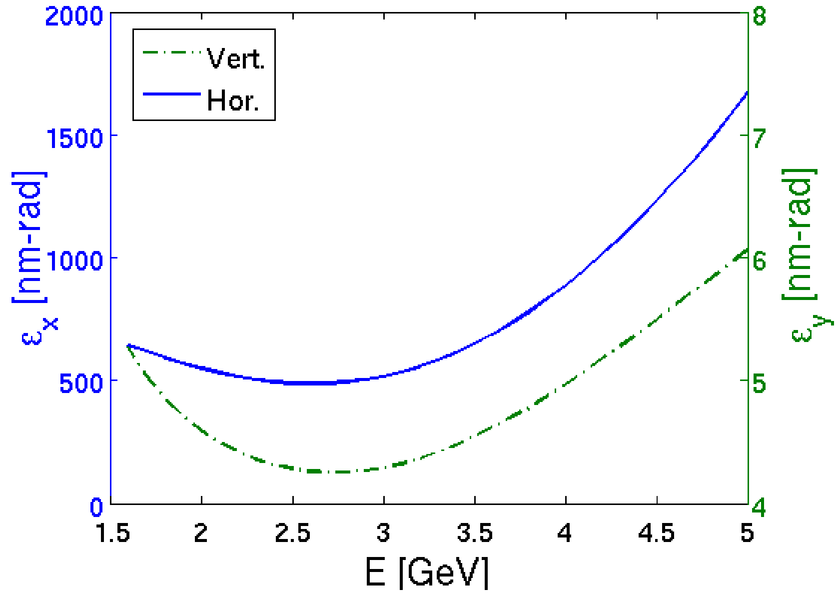
Energy choice for IBS reduction

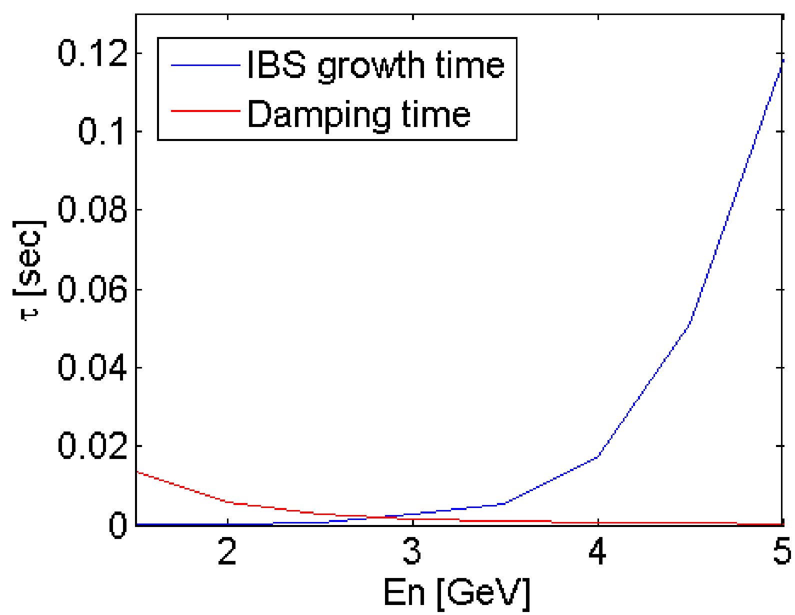




- **Scaling** of output transverse emittances with **energy** (taking into account IBS)
- Broad minimum of the emittances around 2.5 GeV (left) while the IBS effect becomes weaker with energy (right)
  - Higher energies are interesting for IBS but not for the emittance requirements
- **Energy increase** (2.424 → 2.86 GeV) → **reduction of the IBS effect** by a factor of 2 (3 → 1.5)

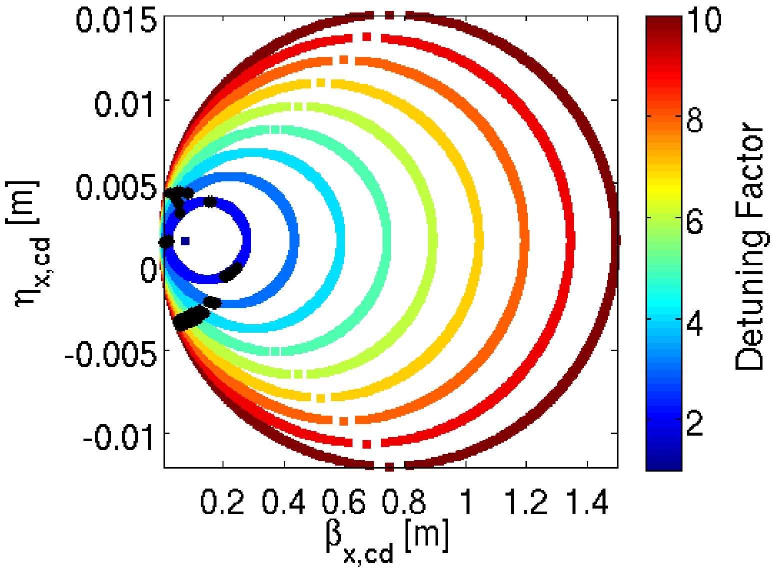
Energy choice for IBS reduction



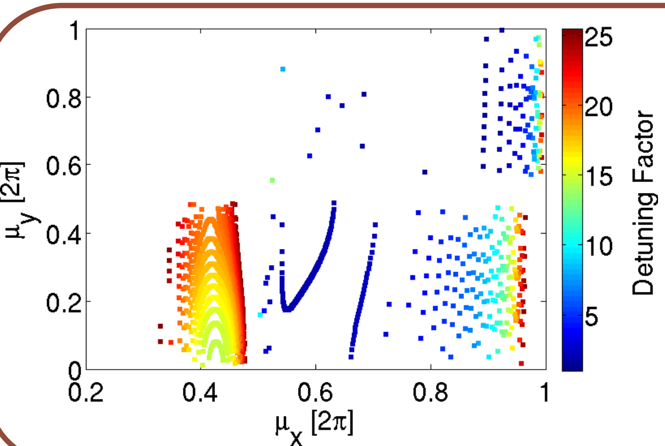


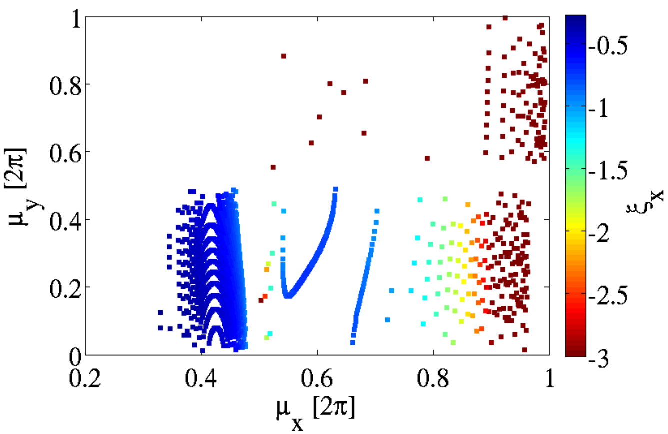
- Interesting to notice that the scaling of the output emittance with energy reflects the domination of damping time or IBS growth time in each energy regime.

TME cell optimization with respect to IBS



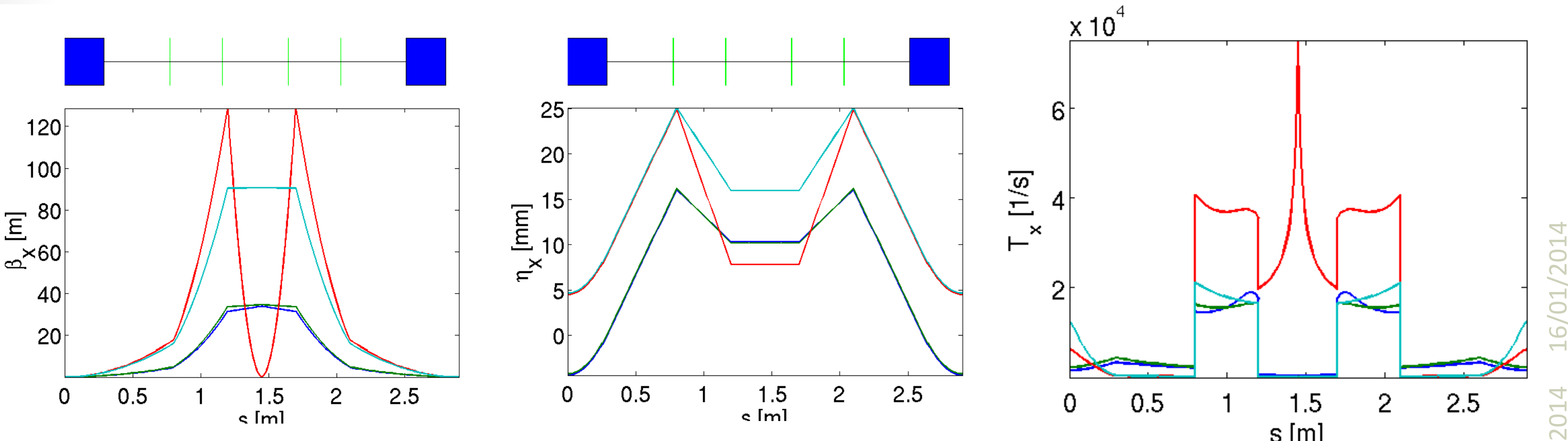
- Analytical parameterization of the TME cell
  - All cell properties globally determined
- Solutions of the hor. beta and dispersion in the center of the dipole lie in ellipses
  - Each ellipse corresponds to different emittance
- For the same detuning factor different optics options
- Only the solutions in black satisfy the stability criteria in both horizontal and vertical planes



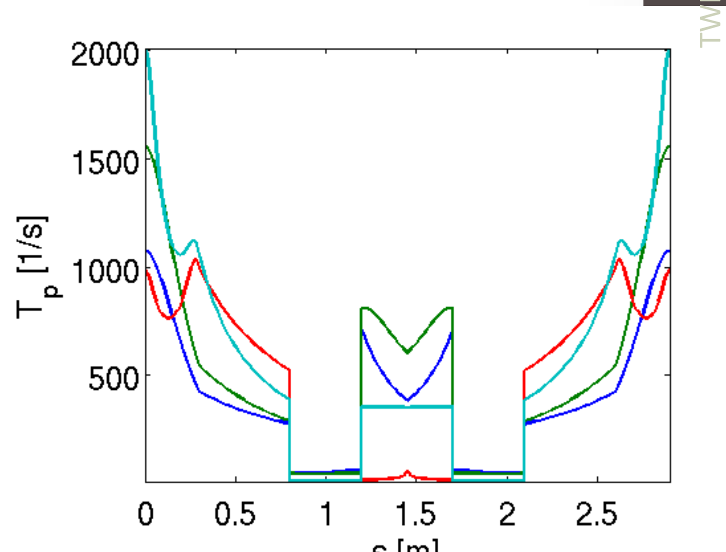


Large detuning factor and small hor. and vert. phase advances for small chromaticity

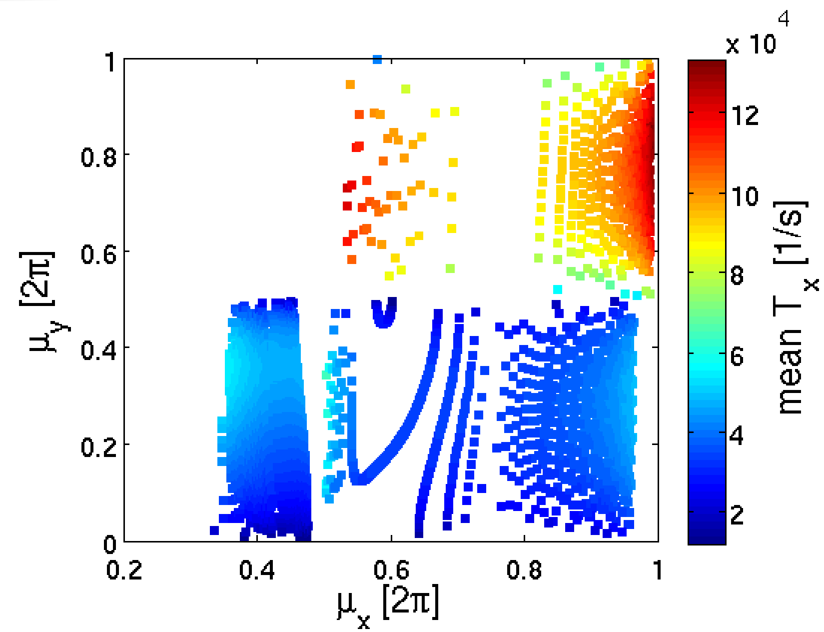
TME optimization with respect to IBS



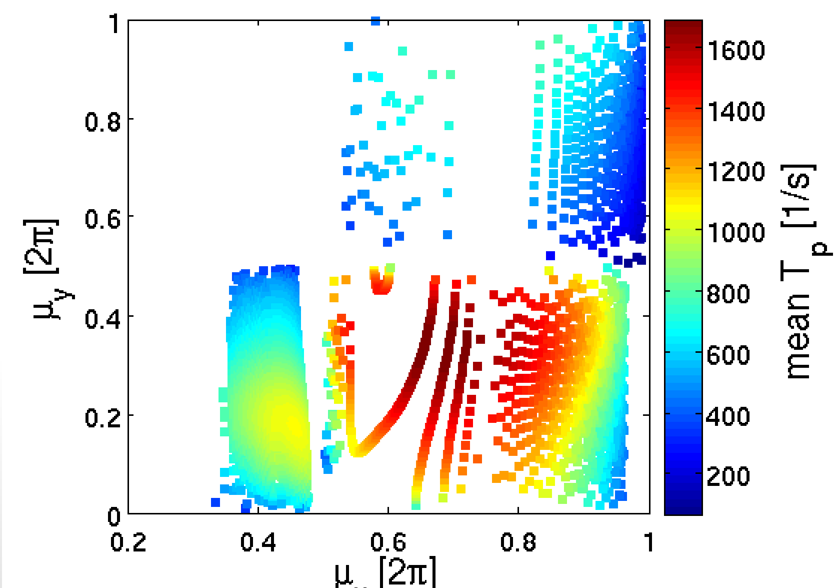
- For the same detuning factor (here DF=6) different optics options (top plots)
- The corresponding horizontal and longitudinal growth rates along a TME cell (right plots)
- **Careful optics choice very important for the IBS optimization**

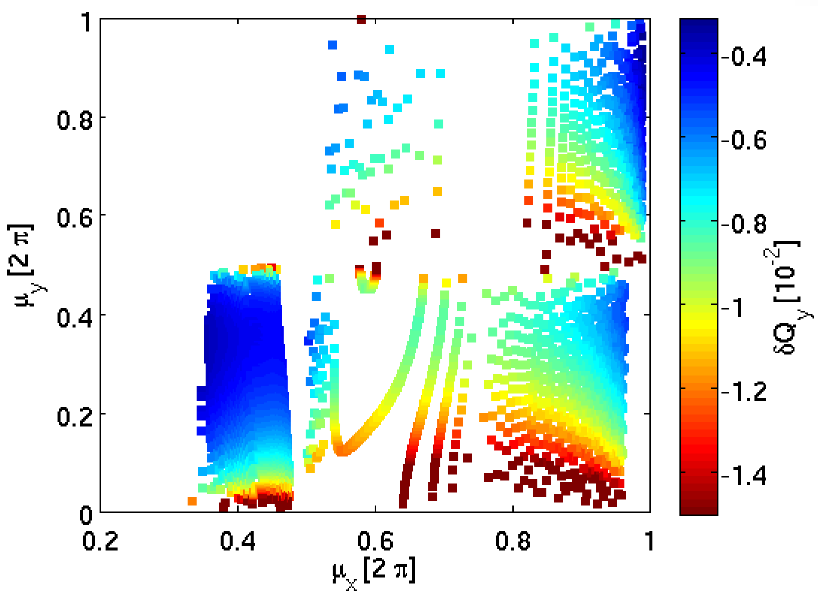


TME optimization with respect to IBS



- Scanning on the detuning factor (here DF=1..25), optimal phase advances can be found where chromaticity, IBS growth rates and space charge detuning are minimized
- Other interesting regions according to the requirements of the design also exist





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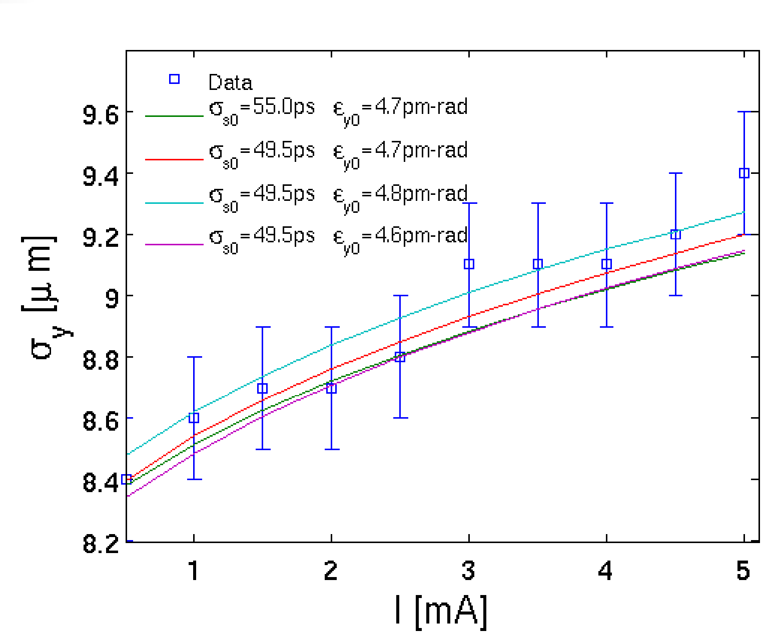
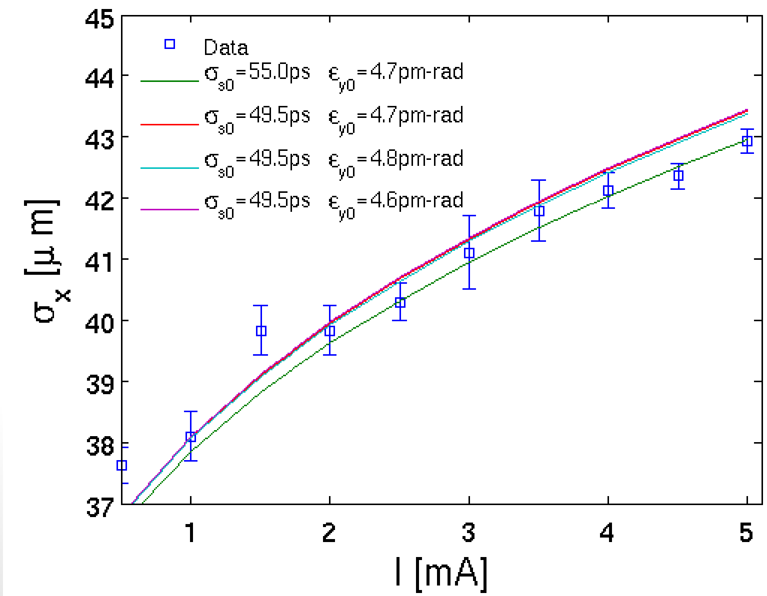
- **Performance parameters** of the CLIC DR for the **1 GHz** and **2 GHz** options and for an intermediate design **(V06)**
  - Increased energy (2.424→2.86 GeV)
  - Ultra-low emittances in all 3 planes
  - Reduced IBS effect (from 3 to 1.5)
  - Reduced space charge tune shift (-0.2 → -0.1)
  - Lower RF stable phase (70°→51° (62°))

✓ **Fullfills the requirements of the design**

✓ **Included in the CLIC CDR**

IBS measurements at the SLS





- Beam size measurements with the **vis-UV** (v) and the **pinhole** (h) cameras.
  - **Multi-bunch** measurements with always same total current (Optimum performance of the pinhole camera for **I_{tot}>60 mA)**
- Longitudinal phase space dominated by the **3rd harmonic cavity** (due to high current)
  - Non-Gaussian bunch length profiles
- Comparison with **CIMP** predictions
  - Different assumptions for the zero current energy spread and vertical emittance
- **Agreement** in the **transverse** plane
- Information from the **longitudinal** plane is **missing**
  - Non-gaussian bunch length profiles
  - Unknown energy spread model (under developmenet)

Summary

- Intrabeam scattering is the main limitation to the ultralow emittance of the CLIC DR
  - The effect is well understood for the core particles or if the effect is a perturbation (of the order of a few percent)
  - We don't know what is the effect on the tails and in the ultra-high brightness regime
- Tools used to study the effect
  - Theoretical models (Bjorken-Mtingwa, Piwinski, Bane, CIMP, etc)
  - Multiparticle tracking codes (SIRE, CMAD-IBStrack → both frozen)
- Tools' drawbacks
  - Always assume Gaussian beam distributions
  - Impact on the damping process is not known
  - Inclusion of coupling not trivial
  - The interaction between IBS and spin is not known
    - Important for the Damping Rings where the beam stays in the ring for a very short amount of time
- Benchmarking of theoretical models and tracking codes
  - All agree very well at weak IBS regimes (the effect on the final steady state emittance not very strong)
  - Divergence grows as the IBS effect on the output emittance grows

Summary

- Carefull optics design is important and can help on the minimization of the effect
  - The analytical approach was very helpful in our design
  - Can/Need to be extended to other type of low emittance cells
  - It is now extended to variable bends as well (see poster of S. Papadopoulou in the students' poster session)
- Benchmarking of all theoretical models and tracking codes with measurements is very important
  - At weak IBS regimes already good agreement between tools and measurements has been demonstrated (see for example results from CESR-TA, SLS)
  - We need to understand what is happening at strong IBS regimes (i.e. does the beam distribution remain Gaussian?)
  - A good knowledge of the machine model is important in order to disentangle IBS from other current dependent effects

Thank you!