Lattice Design of Intrabeam Scattering dominated LERs

The CLIC DR design

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Outline

- General introduction to intrabeam scattering (IBS)
- The CLIC Damping Rings
- Optics optimization for reducing IBS
  - Theories and tracking codes comparison
  - TME cell optimization
  - Energy optimization
  - Wiggler cell optimization
  - The new alternative design
- Summary

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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
  - Classical models of Piwinski (**P**) and Bjorken-Mtingwa (**BM**)
  - High energy approximations **Bane, CIMP, etc** ▶
    - Integrals with analytic solutions

The Intrabeam scattering effect

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

$$\boxed{\frac{1}{T_i} \propto \frac{N}{\gamma \varepsilon_{xn} \varepsilon_{yn} \varepsilon_{sn}} f(optics, \gamma, \varepsilon_{xn}, \varepsilon_{yn}, \varepsilon_{sn})}$$

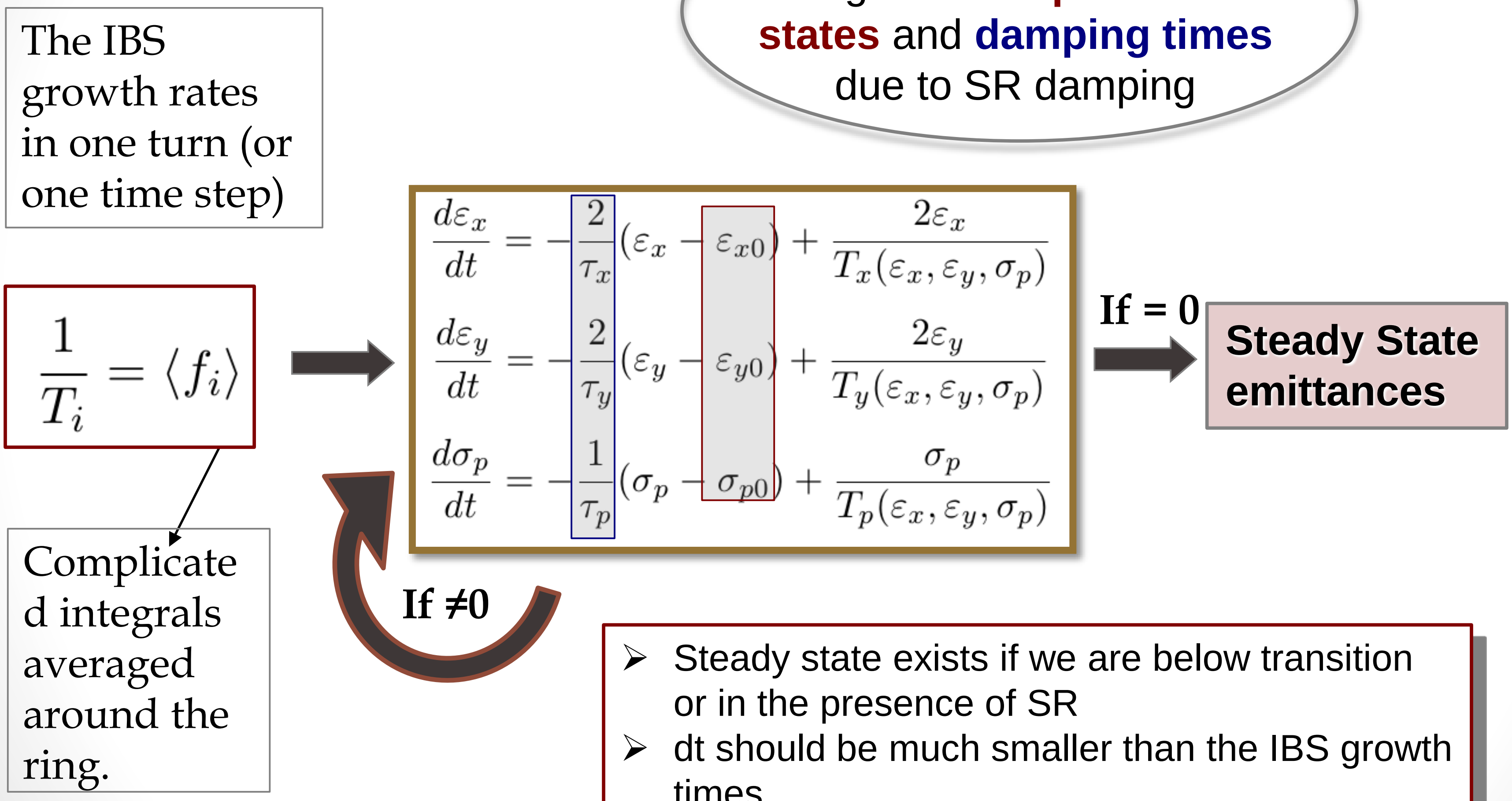
- Complicated integrals averaged around the rings
  - Depend on optics and beam properties

✓ They have been well benchmarked for hadron machines

- For lepton machines the work is in progress
  - Need to benchmark the IBS effect in the presence of SR and QE
  - Studies and publications from: ATF(2001), CesrTA, SLS, SPEAR3
- Main drawbacks:
  - Gaussian beams assumed
  - Betatron coupling not trivial to be included
  - Impact on damping process (especially in strong IBS regimes)?
- Tracking codes **SIRE** (A. Vivoli) and **CMAD-IBStrack** (M. Pivi, T. Demma)
  - Based on the classical Rutherford cross section

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

Steady State emittances

If ≠0

- Steady state exists if we are below transition or in the presence of SR
- dt should be much smaller than the IBS growth times
- Good scanning of optics is important in order not to skip large IBS kick points

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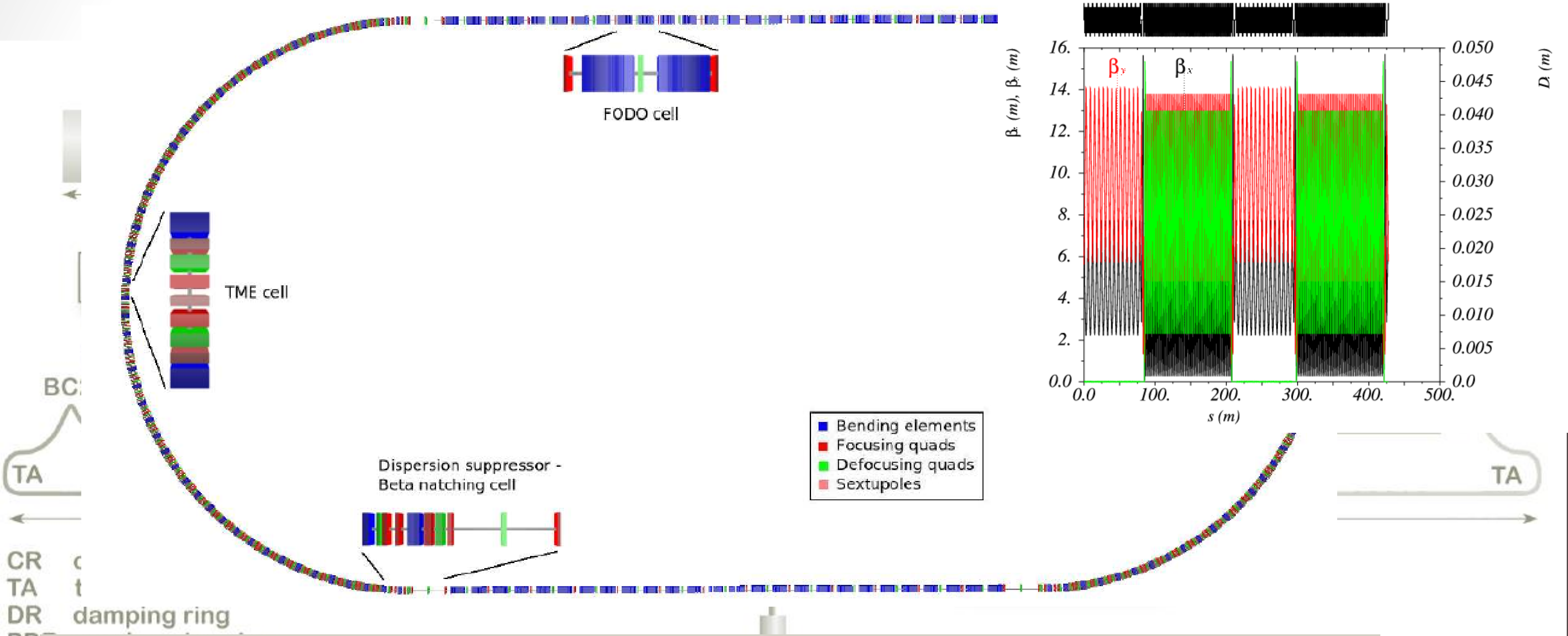
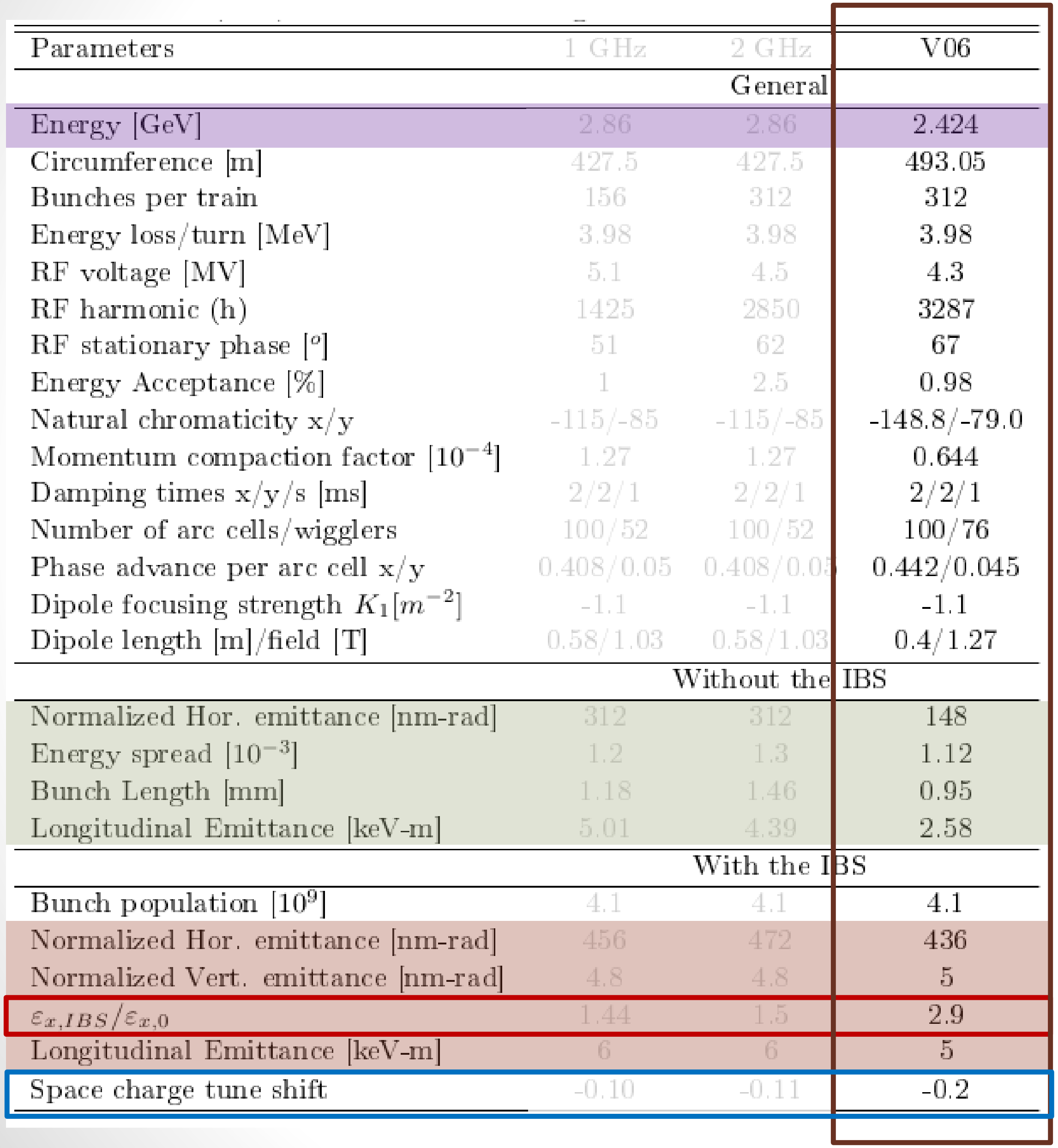
The CLIC DR layout



- ❑ Racetrack configuration with 2 arc sections filled with TME (Theoretical minimum emittance) cells and 2 long straight sections filled with FODO cells.
- ❑ FODO cells accommodate the wigglers
  - ❑ Necessary for the fast damping and the ultra-low emittance

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 [^{o}]	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
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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

- CLIC DRs need to provide:
  - $\varepsilon_{xn} = 500$ nm – rad
  - $\varepsilon_{yn} = 5$ nm – rad
  - $\varepsilon_{ln} = 6$ keV-m
- Requirement of ultra-low emittances in all three planes triggers collective effects
- V06: Intermediate design stage
  - The output emittances strongly dominated by the IBS effect
  - The effect will be even stronger in a low energy CLIC option where the bunch current should be increased
  - Large Laslett space charge tune shift
    - **$\delta Q_y \approx -0.2$**
  - Large RF stable phase
    - **$\phi_s \approx 70^o$**

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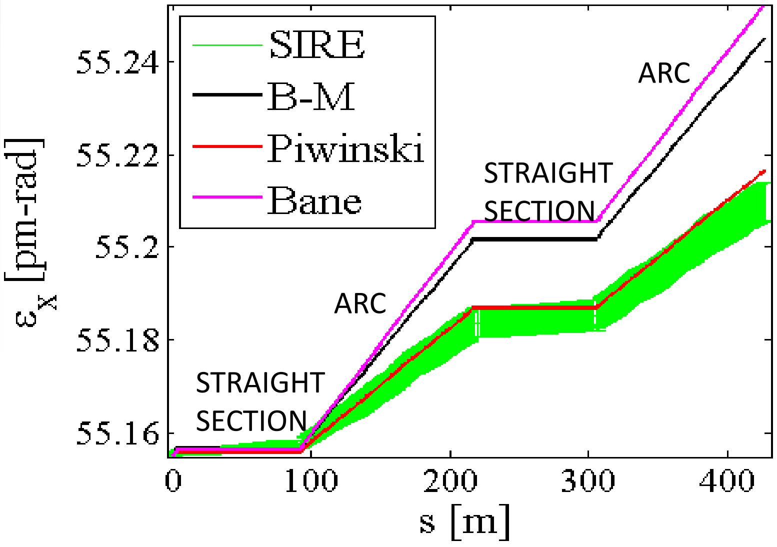
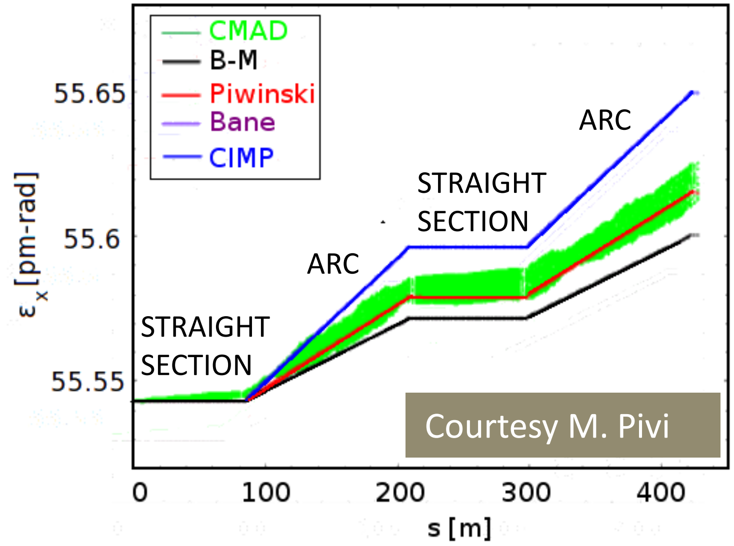
Theories and tracking codes comparison

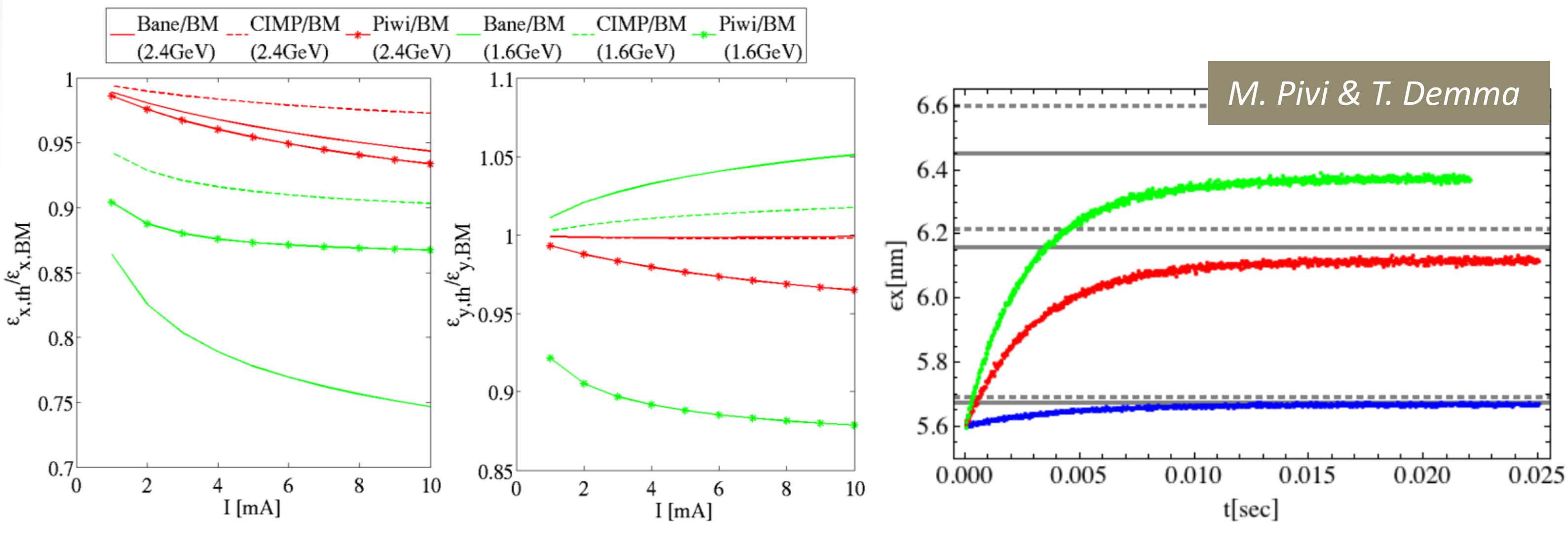




Courtesy M. Pivi

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

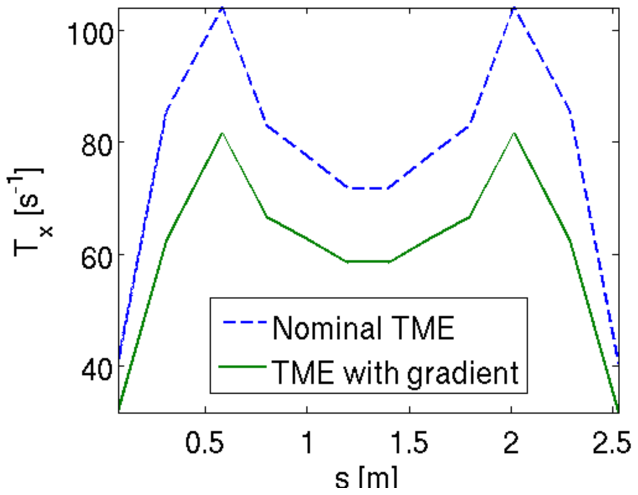
Theories and tracking codes comparison

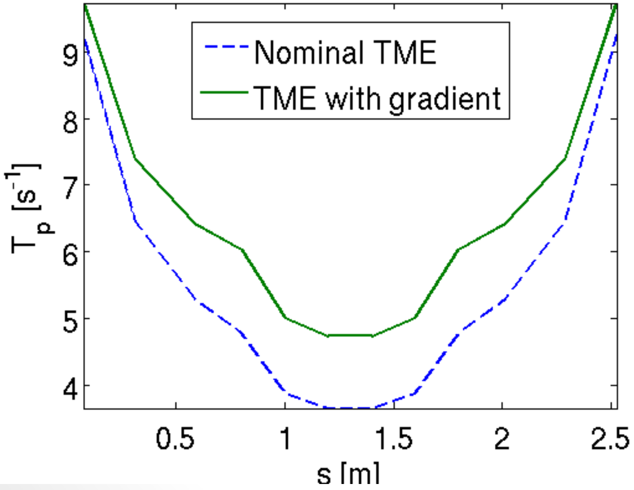


M. Pivi & T. Demma

- Comparison between the theoretical models for the SLS lattice (left) and between CMAD-IBSTrack, Piwinski (dashed-gray) and Bane (solid-gray) for the SLS lattice (right) for three different bunch current values (**1mA**, **10mA**, **17mA**)
- Good **agreement** at **weak** IBS regimes
- **Divergence** grows as the IBS effect **grows**

TME optimization with respect to IBS – Dipole gradient



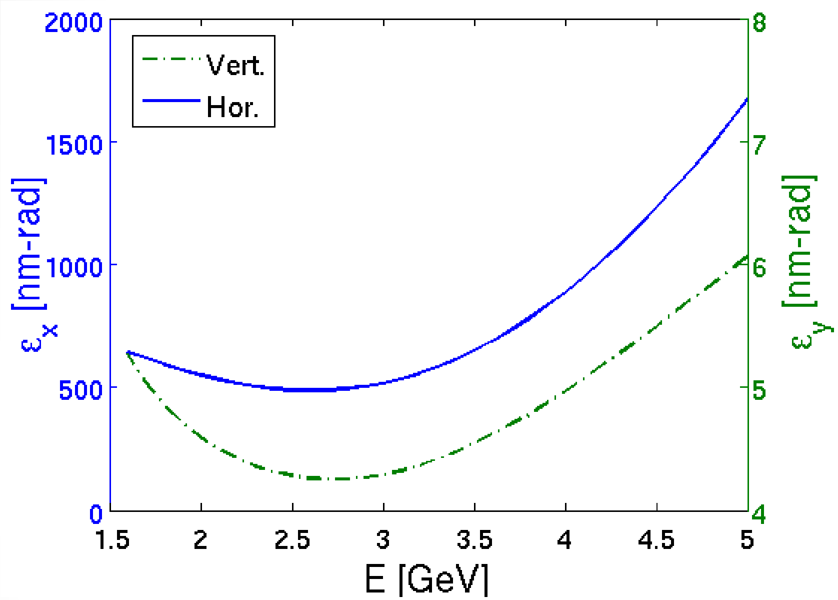


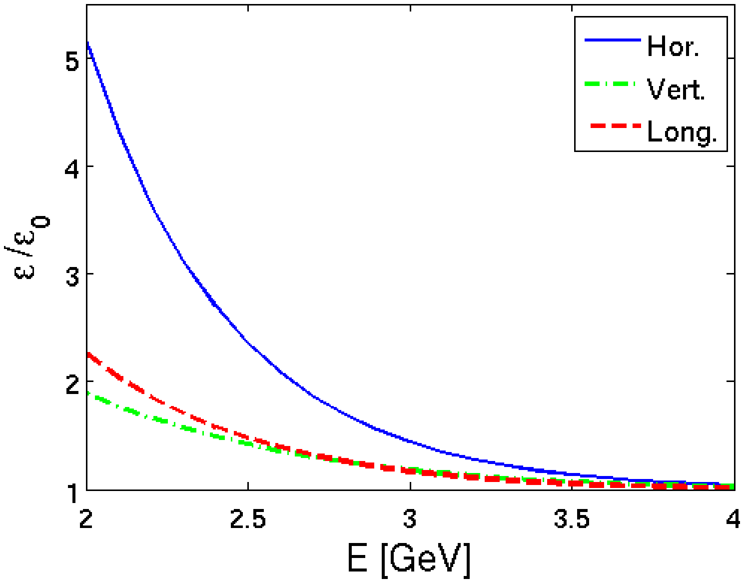
- IBS growth rate in the initial (2007) design a factor of 6
- The main contribution to the IBS growth comes from the arcs (small dispersion and beta functions at the center of the TME dipole)
- Using a modified TME cell, with a combined function dipole with small defocusing gradient, has a positive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

E. Levichev, S. Siniatkin et al, CLIC-Note-849

- Reduced the effect by a factor of 2 (from 6 → 3)
- Still room for improvement!

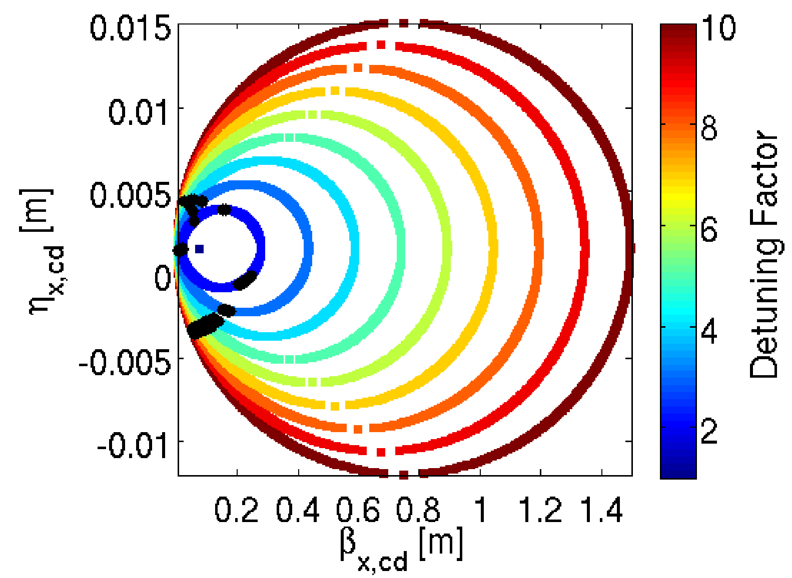
Energy choice for IBS reduction



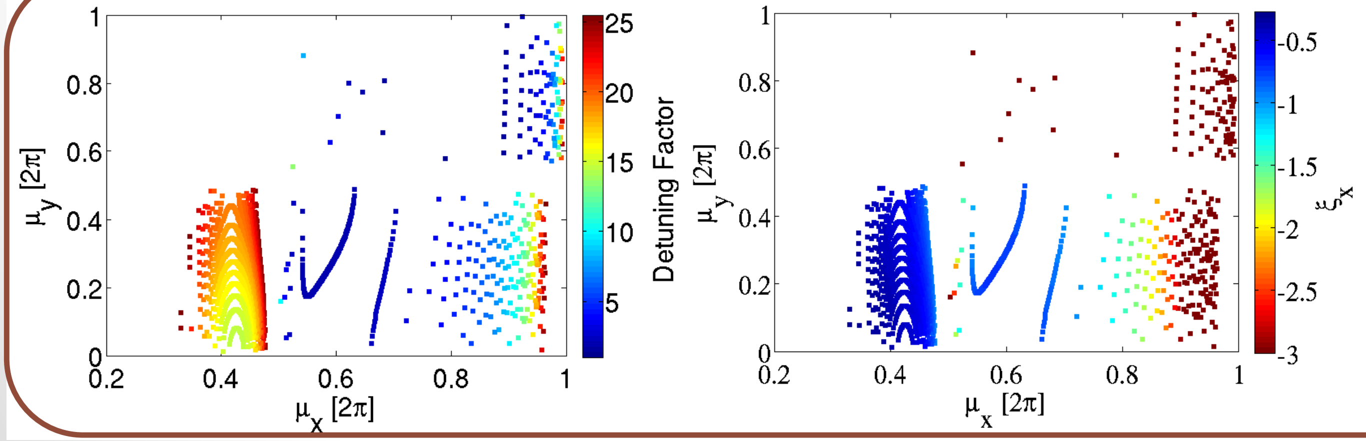


- **Scaling** of output transverse emittances with **energy** (taking into account IBS)
- Broad minimum of the emittances around 2.5 GeV (left) while the IBS effect becomes weaker with energy (right)
  - Higher energies are interesting for IBS but not for the emittance requirements
- **Energy increase**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

The TME cell

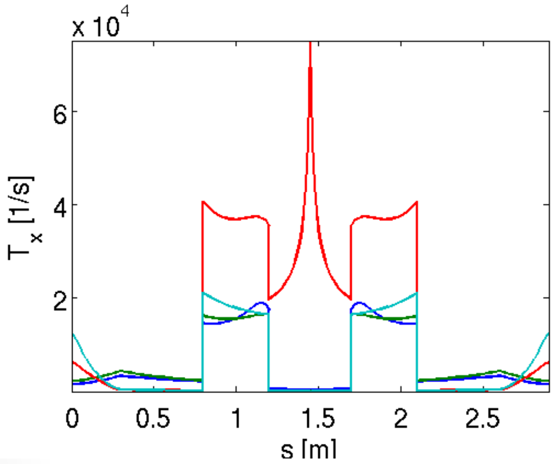


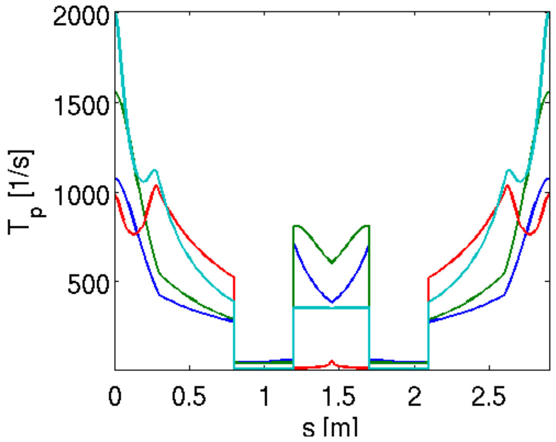
- Analytical parameterization of the TME cell
  - All cell properties globally determined
- Solutions of the hor. beta and dispersion in the center of the dipole lie in ellipses
- For the same detuning factor different optics options
- Only the solutions in black satisfy the stability criteria in both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

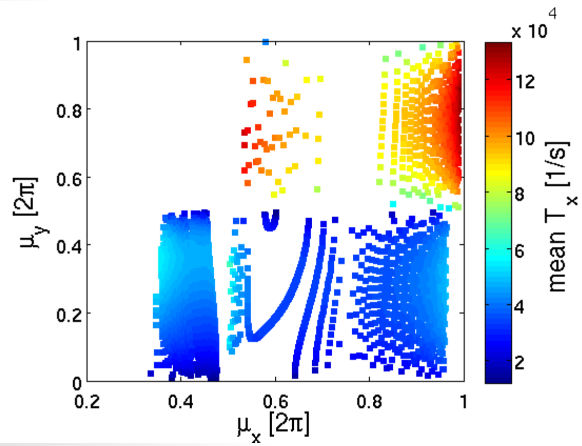


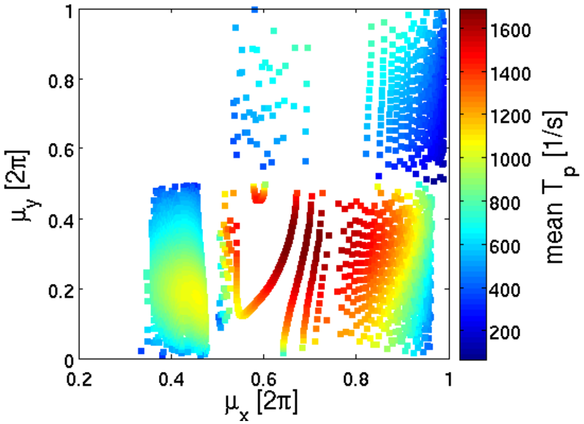
Large detuning factor and small hor. and vert. phase advances for small chromaticity

TME optimization with respect to IBS









- For the same detuning factor (here DF=6) different optics options leading to different IBS growth rates (top)
- Mean growth rates parameterized with the cell horizontal and vertical phase advances (bottom)

Careful optics choice very important for the IBS optimization

Optimization of the DR TME cell

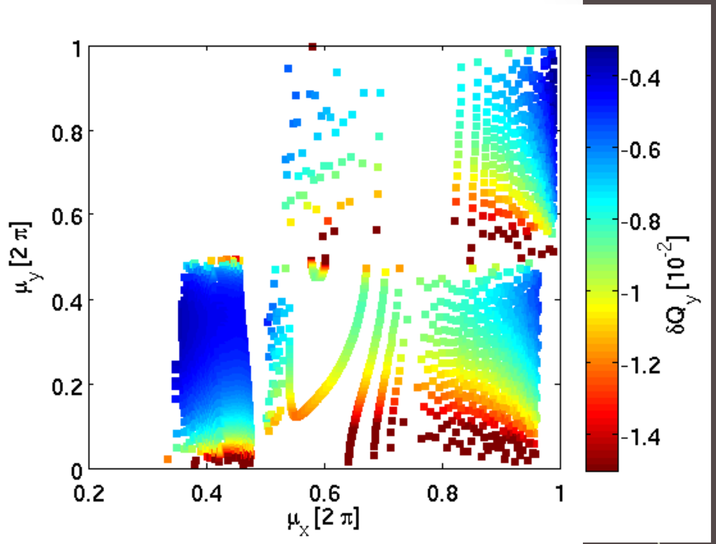
$$\delta Q_{x,y} = -\frac{N_b r_e}{(2\pi)^{3/2}\gamma^3 \boxed{\sigma_s}} \oint \frac{\beta_{x,y}}{\sigma_{x,y}(\sigma_x+\sigma_y)}\, ds$$

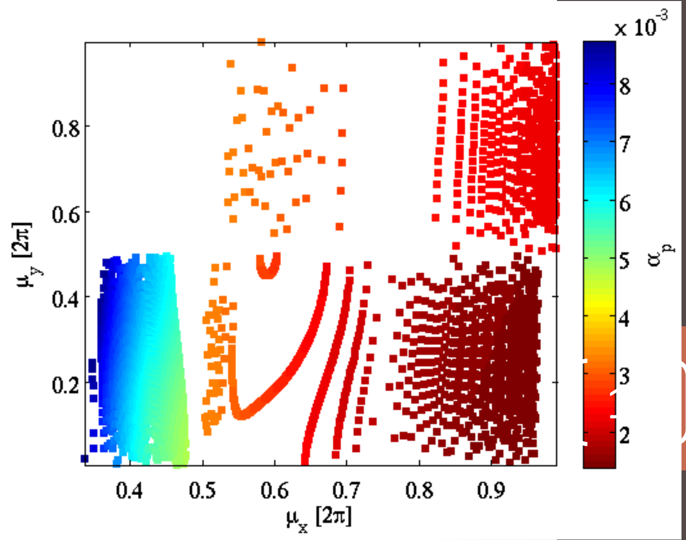
$$\sigma_{s0} = \sigma_{p0} C \left(\frac{\boxed{\alpha_p} E}{2\pi h(\boxed{V_0^2} - U_0^2)}\right)^{1/2}$$

$$\phi_s = \arcsin\left(\frac{U_0}{\boxed{V_0}}\right) \approx 70^o$$

Contradiction

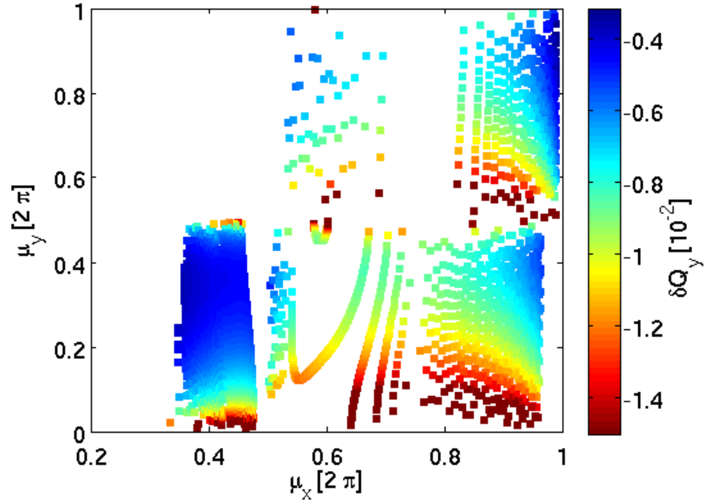
- **Reduction** of Laslett space charge tune shift → **Increase** of **bunch length**
  - For same optics
- **Increase** of **bunch length** → **Increase** of momentum compaction factor α_p or **decrease** of voltage V_0
- **Decrease** of voltage V_0 → **Increase** the RF stable phase ϕ_s

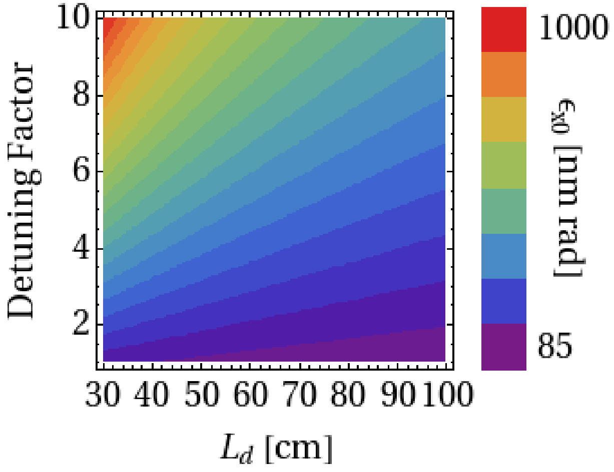


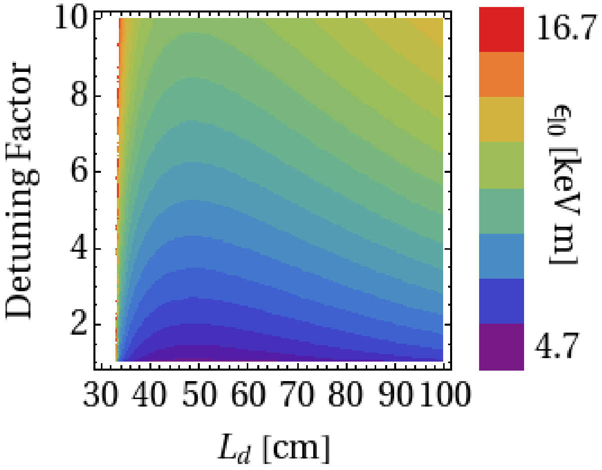


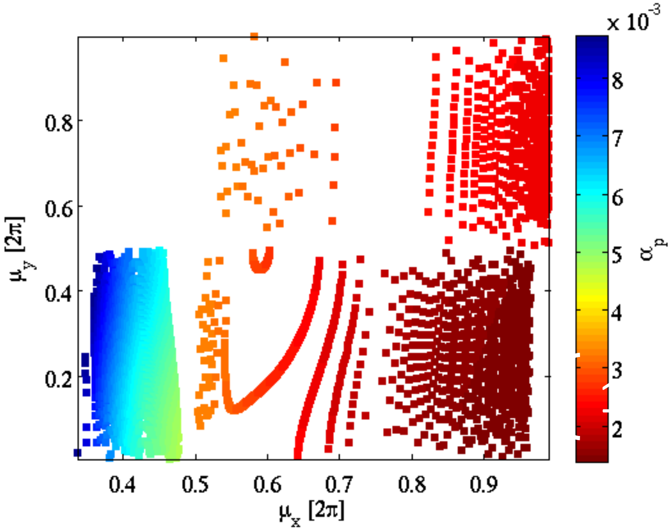
Optimization of the DR TME cell

- Increasing α_p by racing the detuning factor→ Larger dipole length (or smaller field) to keep the output emittance the same
- Positive impact on the longitudinal emittance



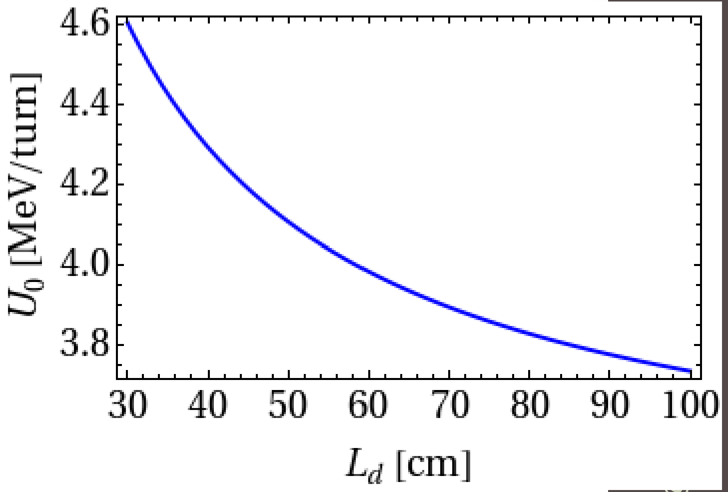


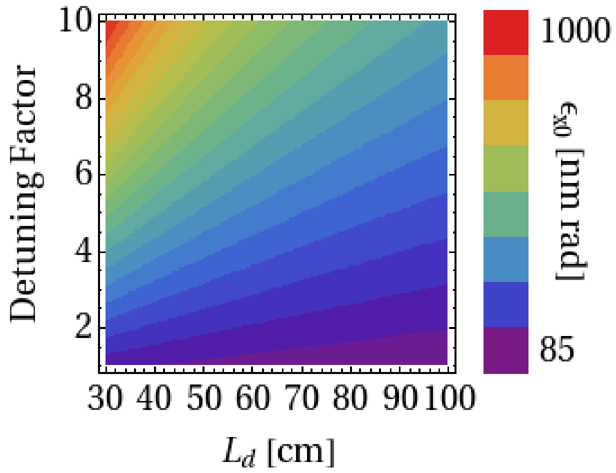


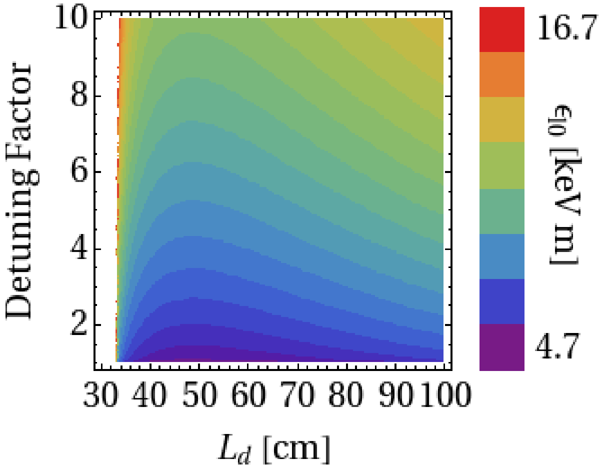


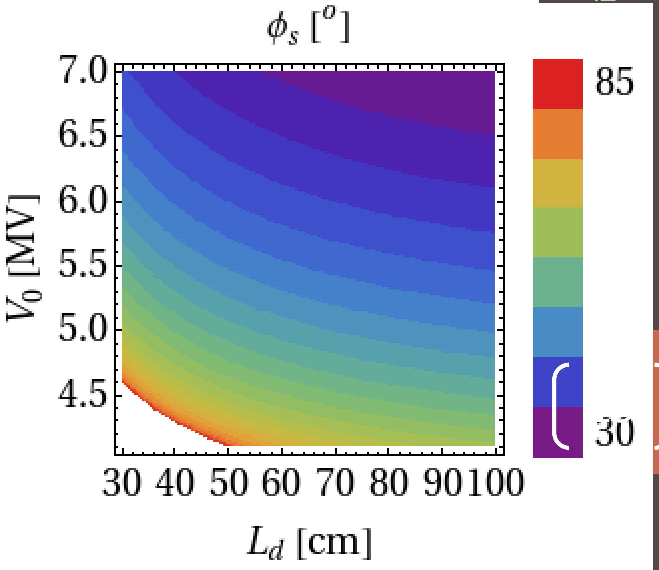
Optimization of the DR TME cell

- Increasing α_p by racing the detuning factor→ Larger dipole length (or smaller field) to keep the output emittance the same
- Positive impact on the longitudinal emittance
- **Reduction of energy loss per turn and of the RF stable phase**

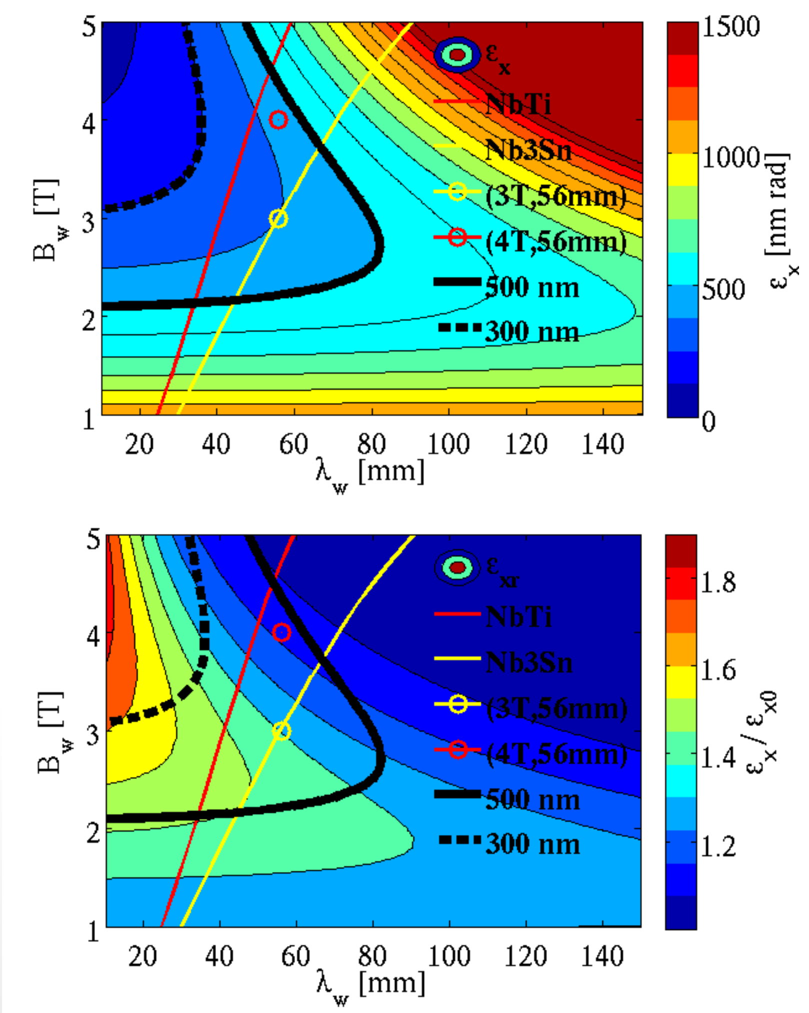






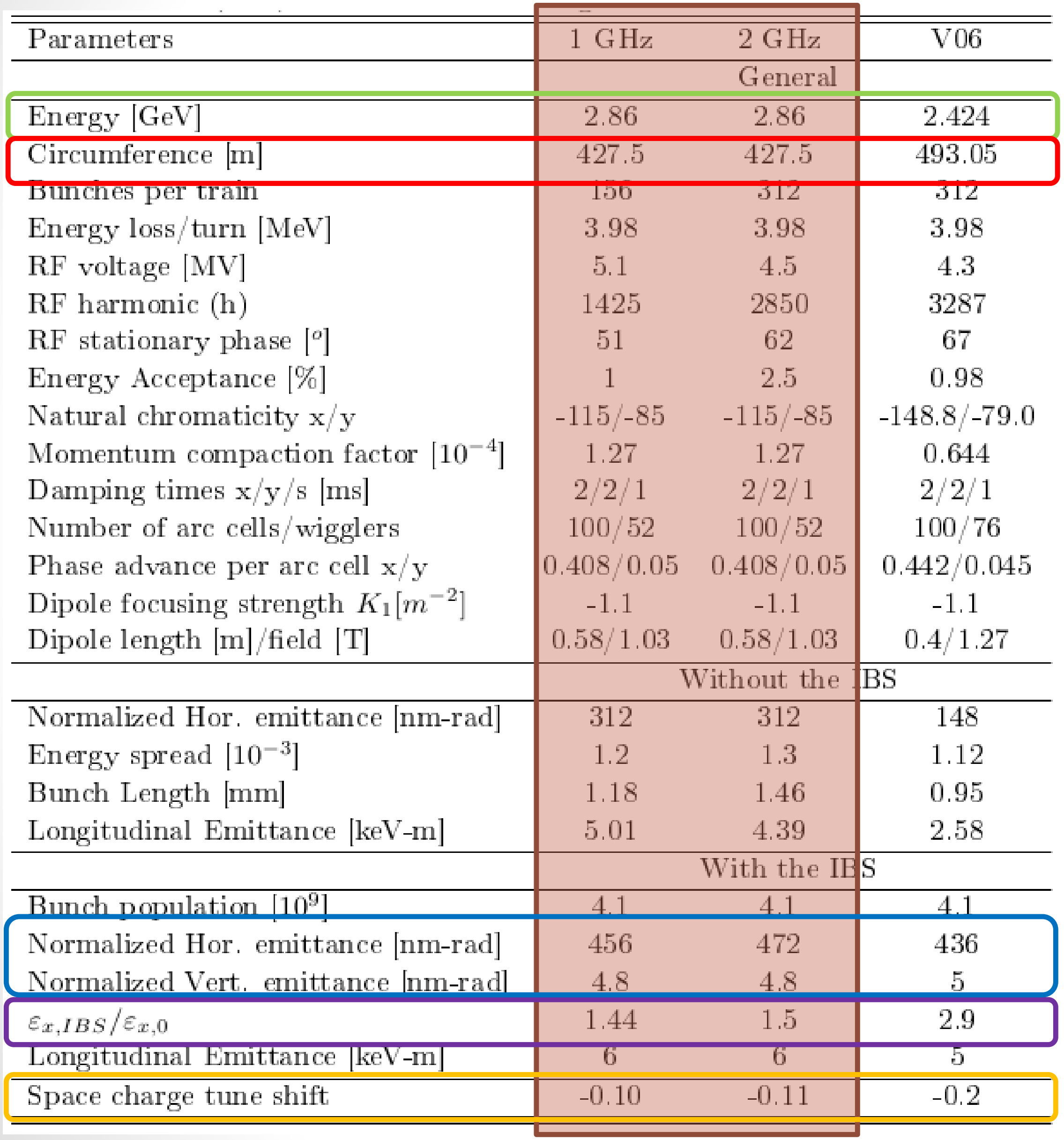


Optimization of the wiggler FODO cell



- The output **emittance** is **minimized** at large wiggler peak fields and small wiggler periods
- The IBS effect is maximized in this regime
- Large wiggler peak fields and moderate wiggler periods are interesting for low emittance and reduced IBS effect
- **Superconducting wigglers** can achieve the high fields required for the emittance requirement
  - Nb3Sn & NbTi technologies

The CLIC DR CDR design



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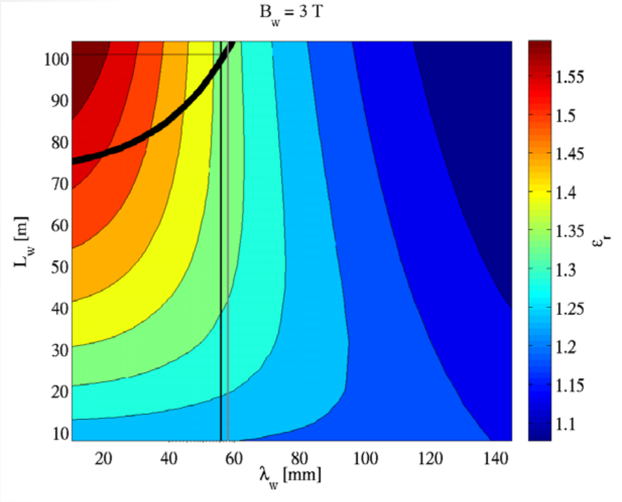
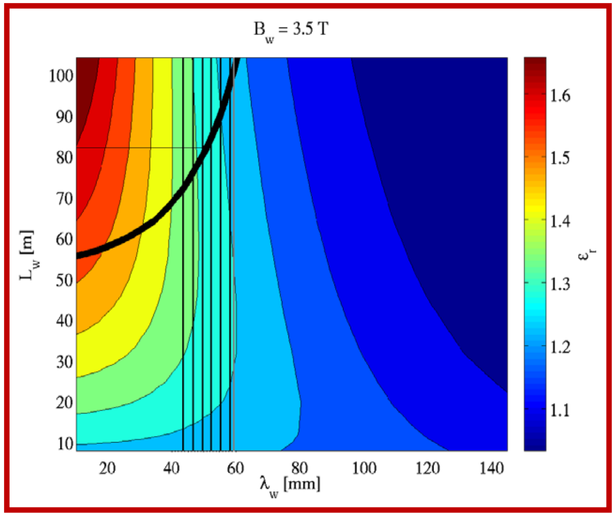
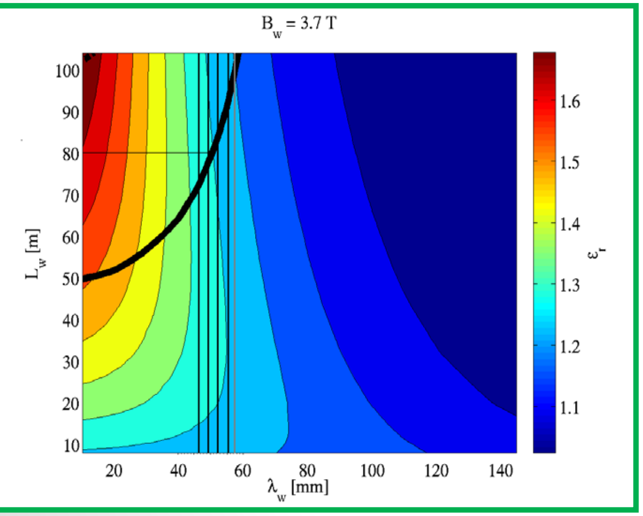
Longitudinal Emittance [keV-m]	6	6	5
Space charge tune shift	-0.10	-0.11	-0.2

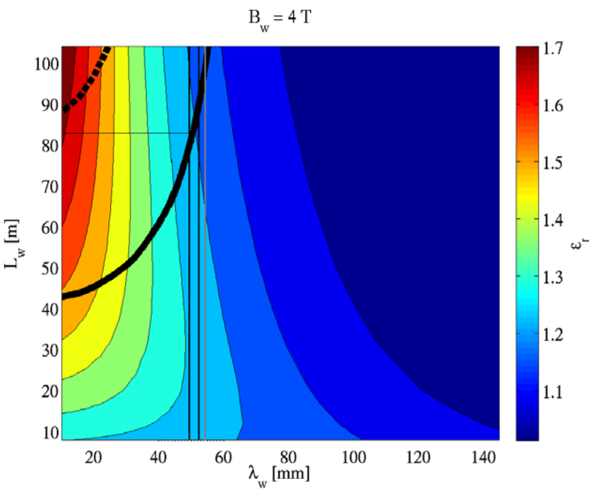
- **Performance parameters** of the CLIC DR for the **1 GHz** and **2 GHz** options in comparison to the V06
  - Increased energy (2.424→2.86 GeV)
  - Reduce the circumference by 15%
  - Ultra-low emittances in all 3 planes
  - Reduced IBS effect (from 3 to 1.5)
  - Reduced space charge tune shift (-0.2 → -0.1)
  - Lower RF stable phase (70°→51° (62°))

Further optimization of the wiggler FODO cell









- Parameterization of the IBS effect with the wiggler period and the total wiggler length for different cases of constant wiggler field
  - Black solid line → the 500nm contour
- 2 new interesting wiggler working points

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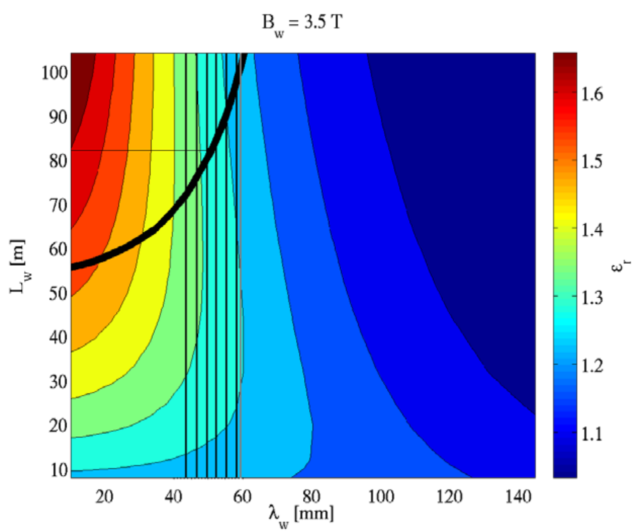
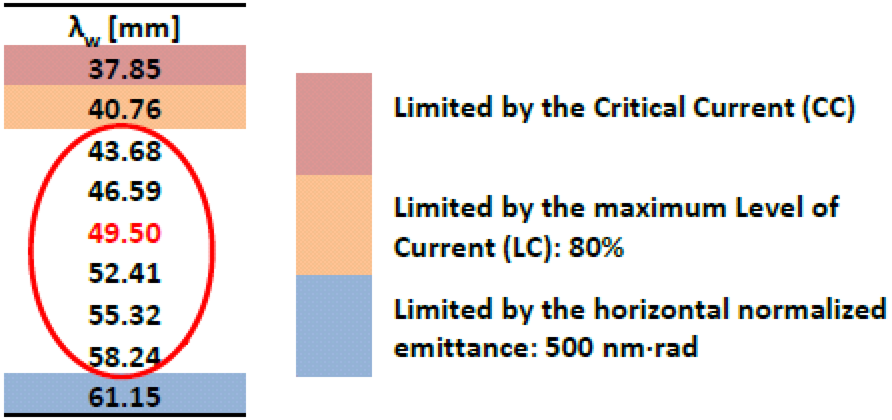


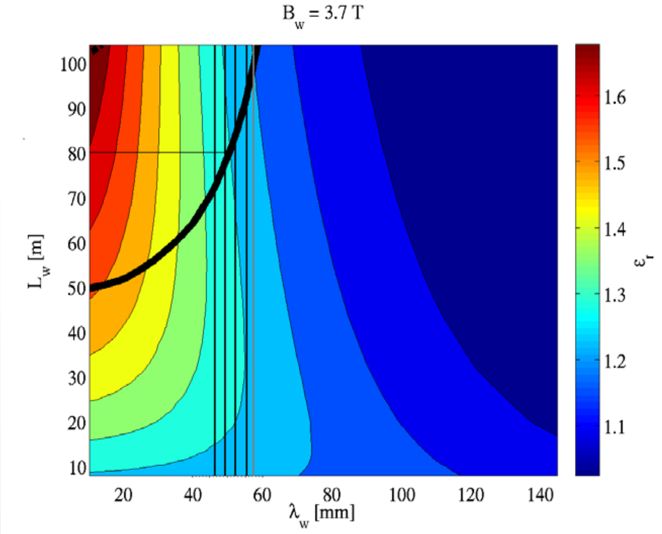


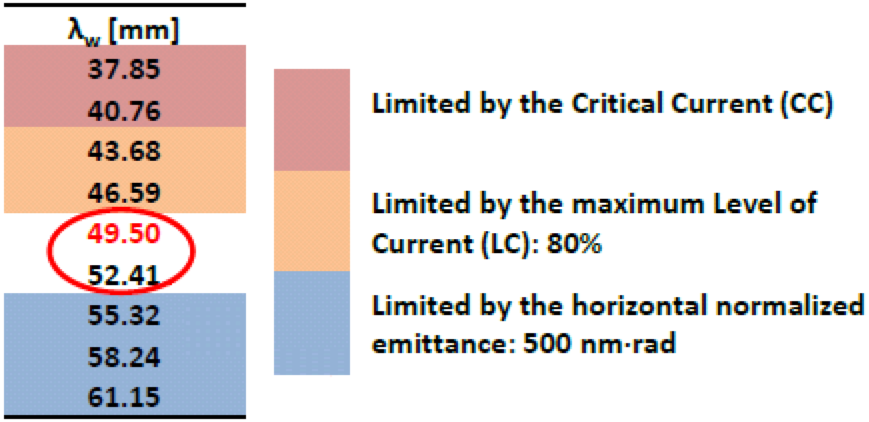
λ_w [mm]
37.85
40.76
43.68
46.59
49.50
52.41
55.32
58.24
61.15

🟥 Limited by the Critical Current (CC)

🟧 Limited by the maximum Level of Current (LC): 80%

🟦 Limited by the horizontal normalized emittance: 500 nm·rad





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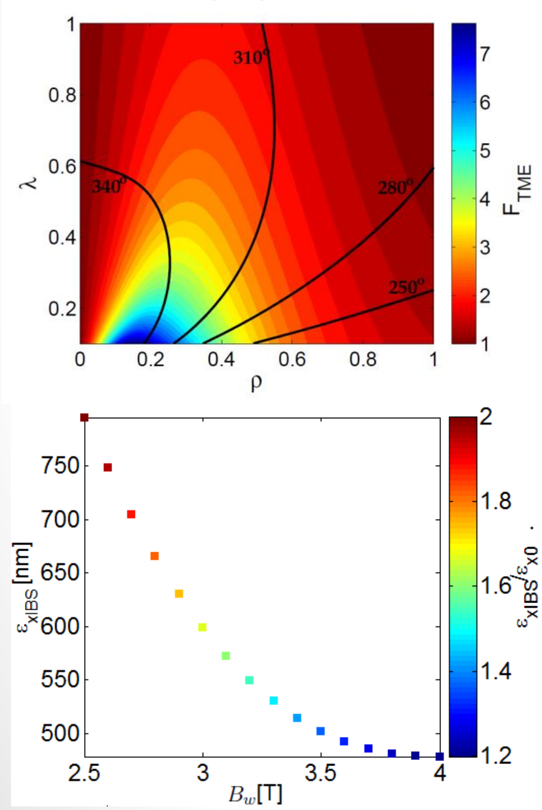
Courtesy: L. G. Fajardo

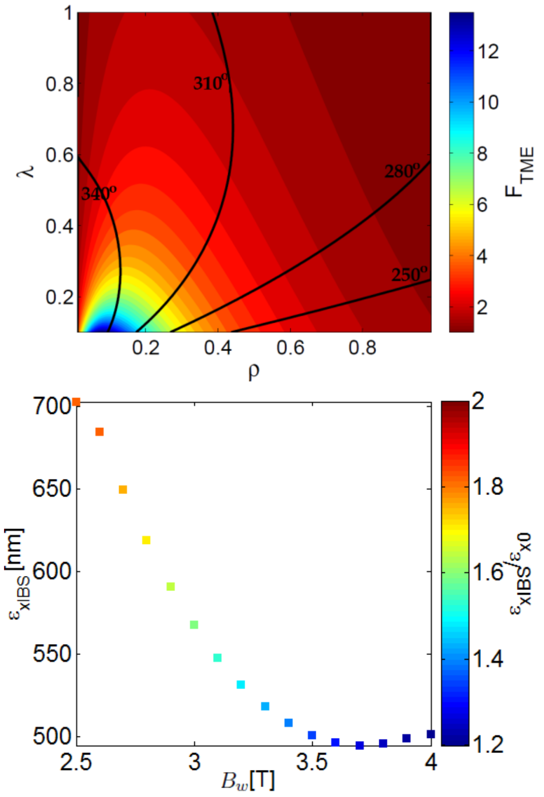
The new alternative design

- See talk of S. Papdopoulou: “Optics for TME cells with longitudinally varying fields and a new CLIC DR design”

Step profile



Trapezium profile



- Arc optimization using variable field dipoles
  - Further emittance reduction from the arcs
  - Reduction of the arc lengths
- Straight section optimization using the new proposed wiggler working points
  - Reduction of the LSS length

S. Papdopoulou

Summary

- Intrabeam scattering is an important limitation to the ultralow emittance
  - 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
  - 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
- Careful optics design (from the linear lattice design stage) is important and can help on the minimization of the effect
  - The analytical approach was very helpful in our design

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Thank you!

The Bjorken-Mtingwa formalism

$$\frac{1}{T_i} = 4\pi A(\log)\left\langle \int_0^\infty \frac{\delta\lambda\lambda^{1/2}}{\left|L+\lambda I\right|^{1/2}} \left\{ TrL^{(i)}Tr\left(\frac{1}{L+\lambda I}\right) - 3TrL^{(i)}\left(\frac{1}{L+\lambda I}\right)\right\}\right\rangle$$

$$L^{(p)} = \frac{\gamma^2}{\sigma_p{}^2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$L^{(x)} = \frac{\beta_x}{\varepsilon_x}\begin{pmatrix} 1 & -\gamma\phi_x & 0 \\ -\gamma\phi_x & \gamma^2 H_x/\beta_x & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$L^{(y)} = \frac{\beta_y}{\varepsilon_y}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \gamma^2 H_y/\beta_y & -\gamma\phi_y \\ 0 & -\gamma\phi_y & 1 \end{pmatrix}$$

$$L = L^{(p)} + L^{(x)} + L^{(y)}$$

$$\boxed{A = \frac{r_0{}^2 cN}{64\pi^2\overline{\beta}^3\gamma^4\varepsilon_x\varepsilon_y\sigma_s\sigma_p}}$$

The Piwinski formalism

$$\frac{1}{T_p} = A\left\langle \frac{\sigma_H{}^2}{\sigma_p{}^2} f(a,b,q) \right\rangle$$

$$\frac{1}{T_x} = A\left\langle f\left(\frac{1}{a},\frac{b}{a},\frac{q}{a}\right) + \frac{H_x{}^2\sigma_{\mathrm{H}}{}^2}{\varepsilon_x} f(a,b,q) \right\rangle$$

$$\frac{1}{T_y} = A\left\langle f\left(\frac{1}{b},\frac{a}{b},\frac{q}{b}\right) + \frac{H_y{}^2\sigma_{\mathrm{H}}{}^2}{\varepsilon_y} f(a,b,q) \right\rangle$$

$$\frac{1}{\sigma_{\mathrm{H}}{}^2} = \frac{1}{\sigma_p{}^2} + \frac{H_x{}^2}{\varepsilon_x} + \frac{H_y{}^2}{\varepsilon_y}$$

$$a = \frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_x}{\varepsilon_x}}, \qquad b = \frac{\sigma_H}{\gamma}\sqrt{\frac{\beta_y}{\varepsilon_y}}, \qquad q = \sigma_H \beta \sqrt{\frac{2d}{r_0}}$$

$$f(a,b,q) = 8\pi \int_0^1 du \frac{1-3u^2}{PQ}\left\{2\ln\left[\frac{q}{2}\left(\frac{1}{P}+\frac{1}{Q}\right)\right] - EulerGamma\right\}$$

$$P^2 = a^2 + (1-a^2)u^2, \qquad Q^2 = b^2 + (1-b^2)u^2$$

Bane’s high energy approximation

- Bjorken-Mtingwa solution at high energies
- Changing the integration variable of B-M to $\lambda' = \lambda \sigma_H^2/\gamma^2$

- Approximations
  - a,b<<1 (if the beam cooler longitudinally than transversally)→ The second term in the braces small compared to the first one and can be dropped
  - Drop-off diagonal terms (let ζ=0) and then all matrices will be diagonal

$$(L+\lambda' I) = \frac{\gamma^2}{\sigma_H^2}\begin{pmatrix} a^2+\lambda' & -a\zeta_x & 0 \\ -a\zeta_x & 1+\lambda' & -b\zeta_y \\ 0 & -b\zeta_y & b^2+\lambda' \end{pmatrix}$$

$$\zeta_x = \phi_{x,y}\sigma_H\sqrt{\frac{\beta_{x,y}}{\varepsilon_{x,y}}}$$

$$\frac{1}{T_p} \approx \frac{r_0^2 cN(\log)}{16\gamma^3 \varepsilon_x^{3/4} \varepsilon_y^{3/4} \sigma_s \sigma_p^3}\left\langle \sigma_H g(a/b)(\beta_x\beta_y)^{-1/4}\right\rangle$$

$$\frac{1}{T_{x,y}} \approx \frac{\sigma_p^2 \langle H_{x,y}\rangle}{\varepsilon_{x,y}}\frac{1}{T_p}, \qquad g(a) = \frac{2\sqrt{a}}{\pi}\int_0^\infty \frac{du}{\sqrt{1+u^2}\sqrt{a^2+u^2}}$$

The CIMP formalism

- Piwinski formalism at high energies

$$g(\omega) = \sqrt{\pi/\omega}\left[P^{0}_{-1/2}\left(\frac{\omega^2+1}{2\omega}\right) \pm \frac{3}{2}P^{-1}_{-1/2}\left(\frac{\omega^2+1}{2\omega}\right)\right]$$

$$\frac{1}{T_p} \approx 2\pi^{3/2}A(log)\left\langle \frac{\sigma_H^2}{\sigma_p^2}\left(\frac{g(b/a)}{a}+\frac{g(a/b)}{b}\right)\right\rangle,$$

$$\frac{1}{T_x} \approx 2\pi^{3/2}A(log)\left\langle -ag(\frac{b}{a}) + \frac{\mathcal{H}_x\sigma_H^2}{\varepsilon_x}\left(\frac{g(b/a)}{a}+\frac{g(a/b)}{b}\right)\right\rangle$$

$$\frac{1}{T_y} \approx 2\pi^{3/2}A(log)\left\langle -bg(\frac{a}{b}) + \frac{\mathcal{H}_y\sigma_H^2}{\varepsilon_y}\left(\frac{g(b/a)}{a}+\frac{g(a/b)}{b}\right)\right\rangle$$