Status of the CLIC Damping Rings Optics and IBS studies

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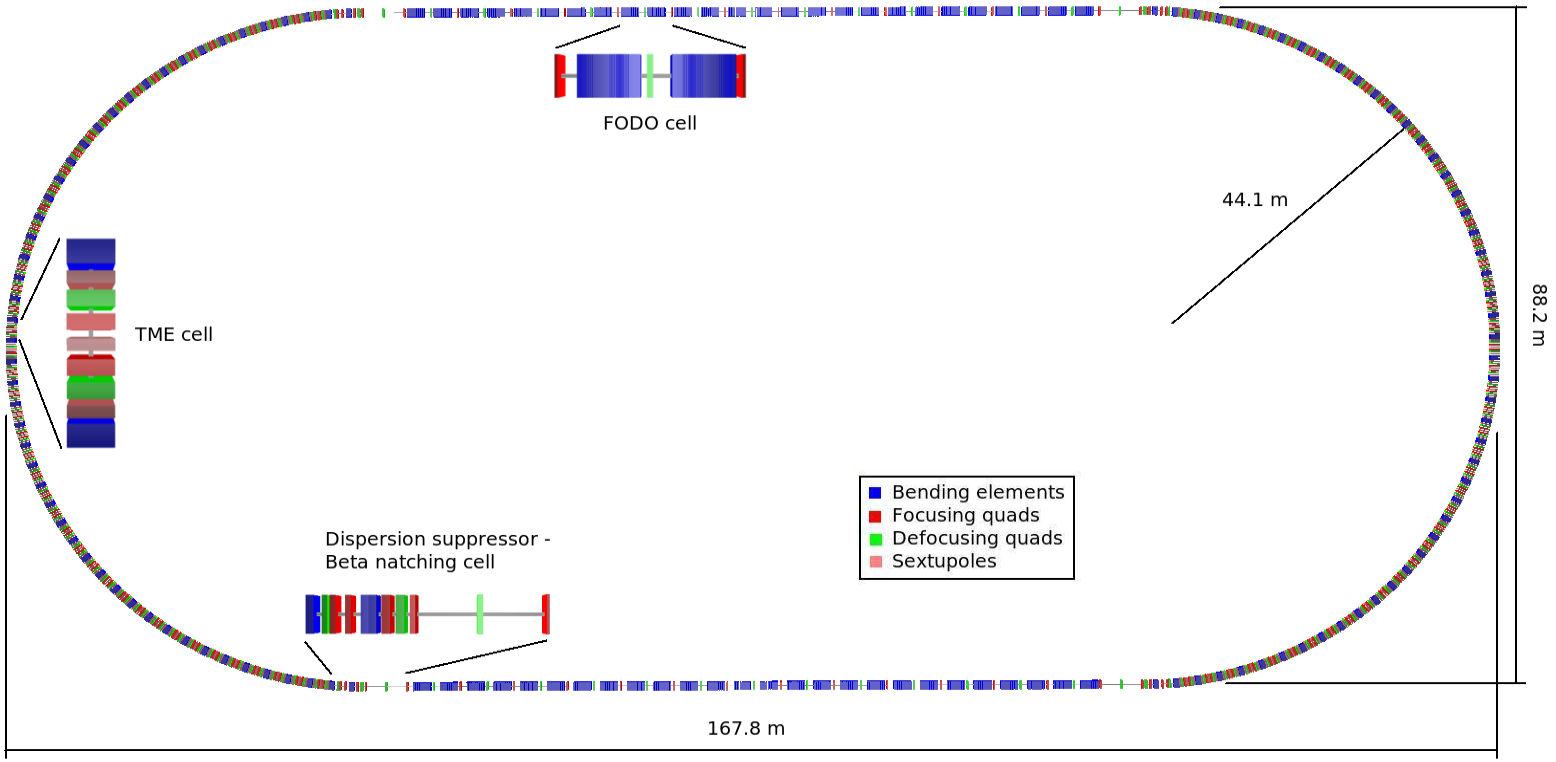
Outline

- The CLIC Damping Rings lattice
  - Layout
  - Parameters
  - Optimization
- IBS studies
  - CLIC DR
  - SLS
  - CESR-TA
  - IBS – MADX
- Next steps

The CLIC DR optics

Damping Rings
Complex layout

DR layout



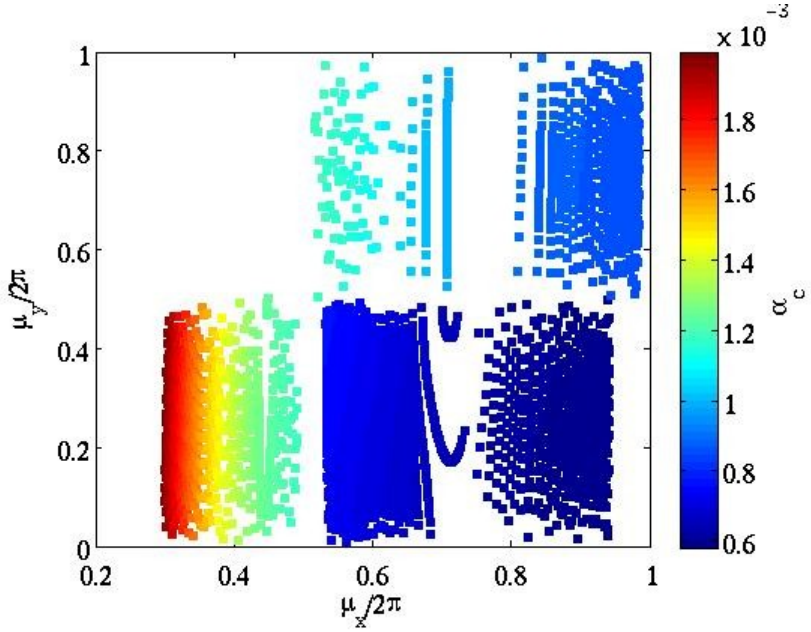
- Racetrack shape with
  - 96 TME arc cells (4 half cells for dispersion suppression)
  - 26 Damping wiggler FODO cells in the long straight sections (LSS)

The CLIC Damping Rings CDR parameters

Parameters	1GHz	2GHz
Energy [GeV]	2.86	
Circumference [m]	**427.5**	
Energy loss/turn [MeV]	**4.0**	
RF voltage [MV]	**5.1**	**4.5**
Stationary phase [°]	**51**	**62**
Natural chromaticity x / y	**-115/-85**	
Momentum compaction factor	**1.3e-4**	
Damping time x / s [ms]	**2.0/1.0**	
Number of dipoles/wigglers	100/52	
Cell /dipole length [m]	**2.51 / 0.58**	
Dipole/Wiggler field [T]	**1.0**/2.5	
Bend gradient [1/m2]	-1.1	
Phase advance x / z	**0.408/0.05**	
Bunch population, [e9]	4.1	
IBS growth factor x/z/s	**1.5/1.4/1.2**	
Hor./Ver Norm. Emittance [nm.rad]	**456/4.8**	**472/4.8**
Bunch length [mm]	**1.8**	**1.6**
Longitudinal emittance [keVm]	**6.0**	**5.3**
Space charge tune shift	**-0.10**	**-0.11**

- The latest DR lattice parameters (CDR version)
  - 2 RF options at 1 and 2 GHz with the 1 GHz option as the baseline
- Main problems of the previous lattice
  - Large space charge tune shift (~-0.2) ➔ warning by ACE
    - Larger longitudinal emittance needed
  - Large RF stable phase (70°) → warning by Alexej
    - Larger RF voltage needed (goes to the opposite direction for longitudinal emittance)
  - Stay always within the requirements for the transverse emittances

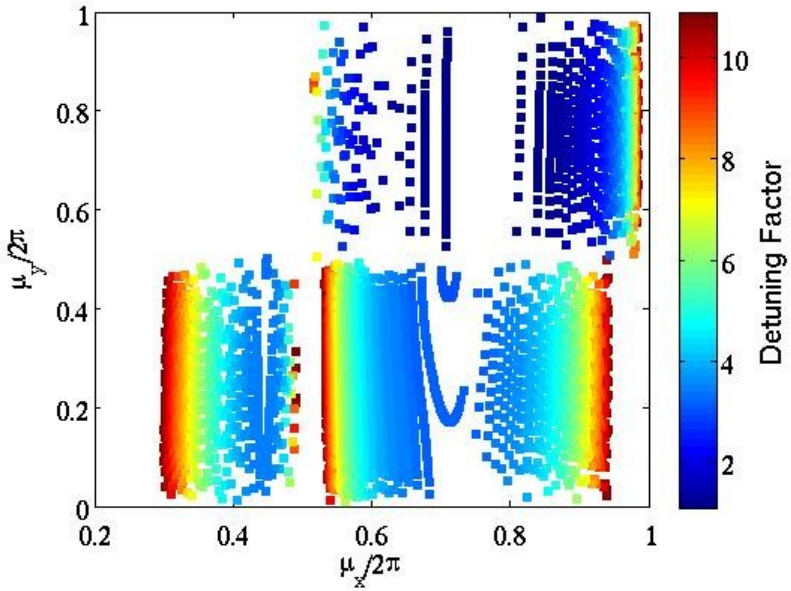
Optimization procedure - α_c



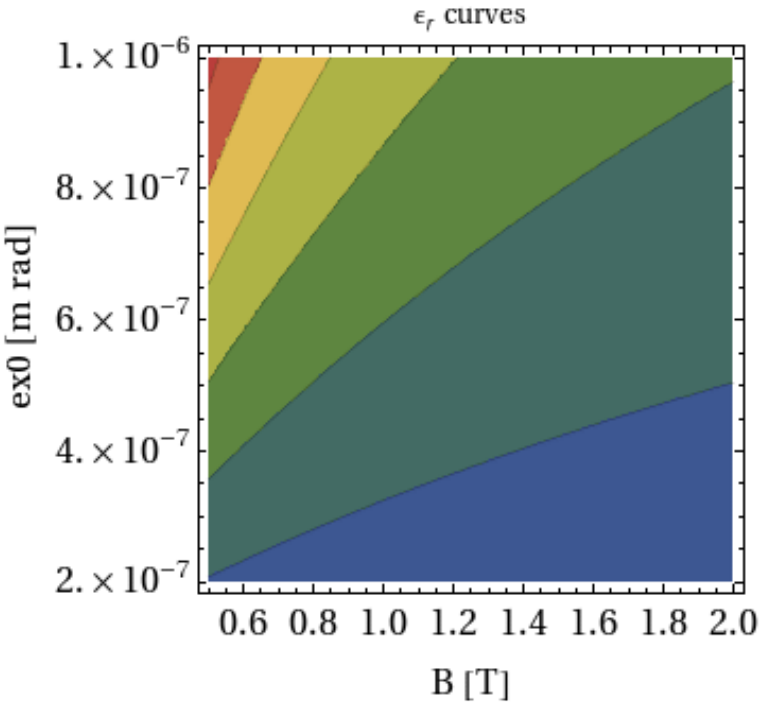
- Plots from the analytical solution for the TME cells
- Go to lower phase advance in the TME cell
  - Detune to higher emittance from the arcs but stay always within the requirements

- In order to increase the bunch length
  - Increase of the momentum compaction factor

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



Optimization procedure



- For smaller emittance keeping the wiggler working point unchanged:
  - Smaller detuning factor (high phase advance and small momentum compaction factor)
  - Lower dipole field (larger dipole length)

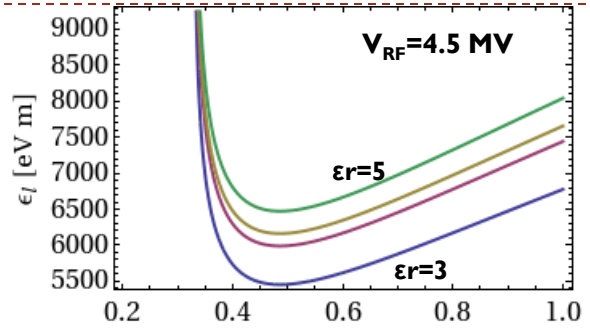
- From the expression for the zero current horizontal emittance:

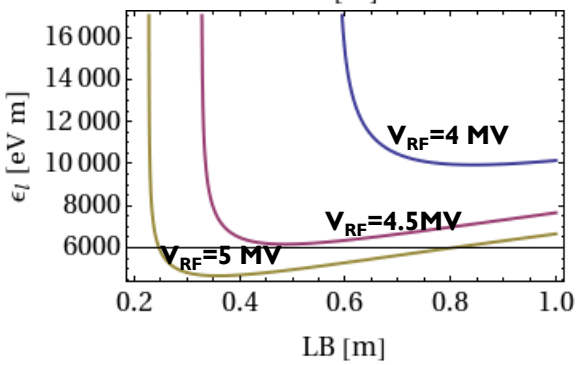
$$\epsilon_x = \frac{C_q \gamma^3}{12(Jxa + Fw)} \left(\frac{\epsilon_r \theta^3}{\sqrt{15}} + \frac{F_w B_w^3 \lambda_w^2 \beta_{xw}}{16(B\rho)^3} \right)$$

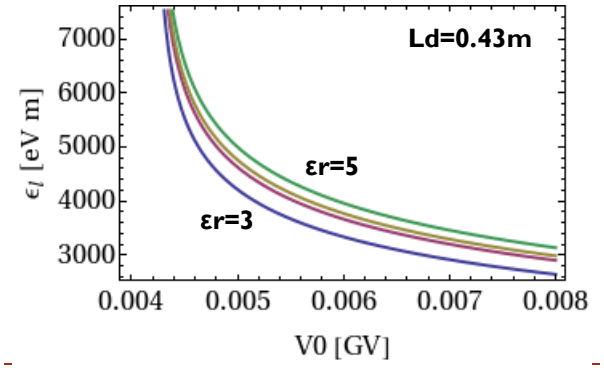
$$F_w = \frac{L_w B_w^2}{4\pi(B\rho)B_a}$$

  - ε_r : Detuning Factor
  - J_{xa}: Damping partition number from arc
  - L_w: wiggler length
  - B_w: wiggler field
  - λ_w: wiggler period
  - β_{xw}: wiggler mean beta function
  - θ: dipole bending angle

Optimization procedure







- The longitudinal emittance is defined as $\varepsilon_l=\sigma_{p0}\,\sigma_{s0}$ En

$$\sigma_{p0} = \gamma \left(\frac{B_a(C_q(1+F_w\frac{B_w}{B_a}))}{(B\rho)(3-(1+F_w)J_{x0}+3F_w} \right)^{1/2}$$

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

- At V_{RF}=4.5 MV and L_d=0.43m (our previous dipole length) we are at a minimum of the longitudinal emittance
- The minimum is moved to lower L_d values for larger V_{RF}
- We gain some margin in the RF voltage and we can go to higher values

Optimization procedure

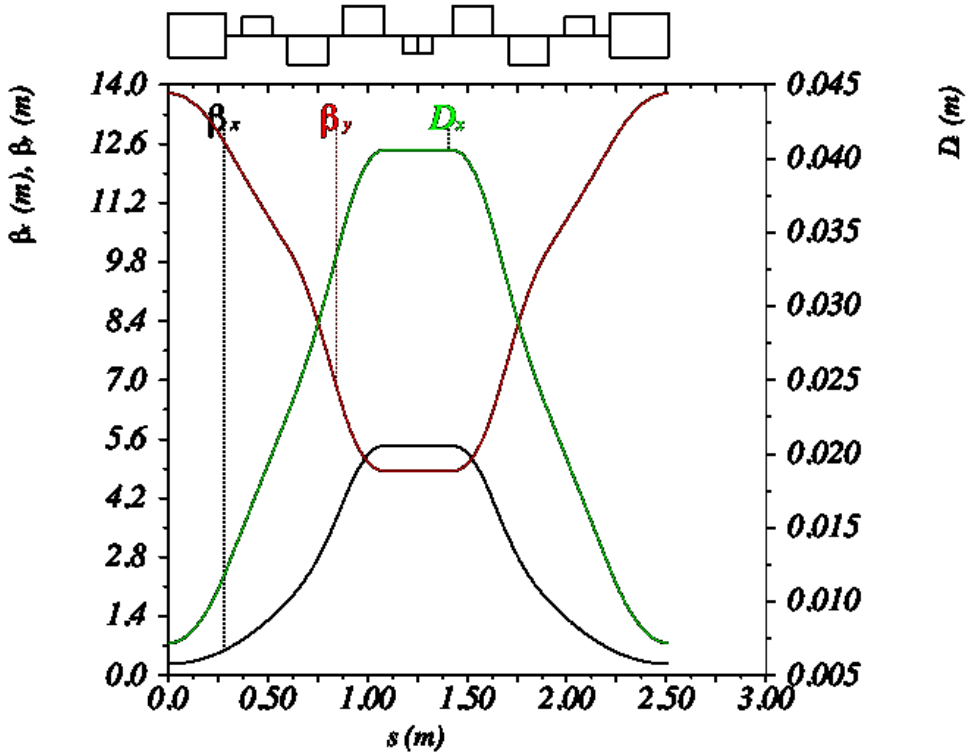
$$U0 = C_\gamma \frac{En^4}{L_d}\theta\left(1 + \frac{L_w B_w^2}{4\pi(B\rho)B_a}\right)$$

$$\phi_s = ArcSin\left(\frac{U_0}{V_0}\right)$$

- For smaller RF stable phase
  - Small U_0/V_0
- For smaller U0 (keeping same wiggler characteristics)
  - Smaller dipole field (larger dipole length)

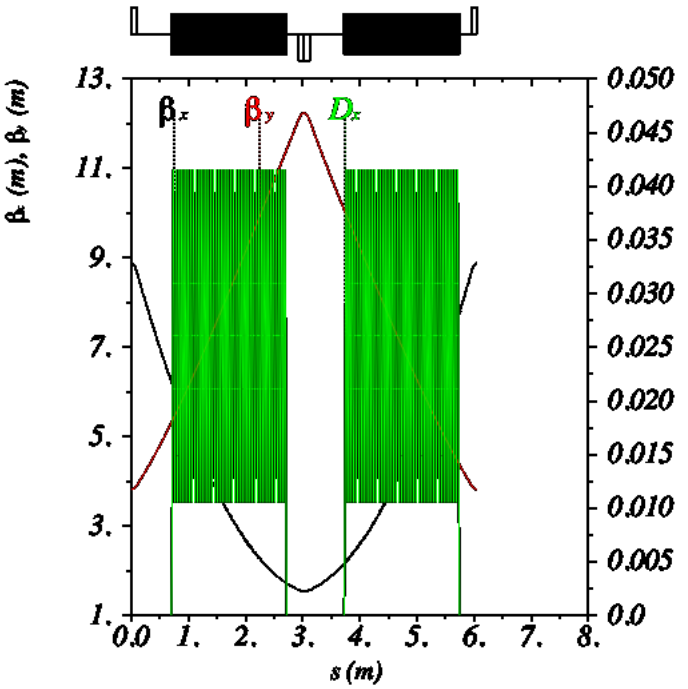
- In summary, the way to go is to:
  - Increase the momentum compaction factor by tuning the TME cell in lower phase advance (thus higher detuning factor)
  - Decrease the dipole field (increase dipole length) with positive impact in the RF stable phase and the longitudinal emittance
  - After several iterations between these parameters, the optimum solution was found to be: L_d=0.58m (from 0.43m), μ_{xTME}=0.408 (from 0.452) and V_{RF}=5.1MV (from 4.5MV) resulting in the performance parameters of the ring presented in the beginning.

Ring optics – Arc TME cell

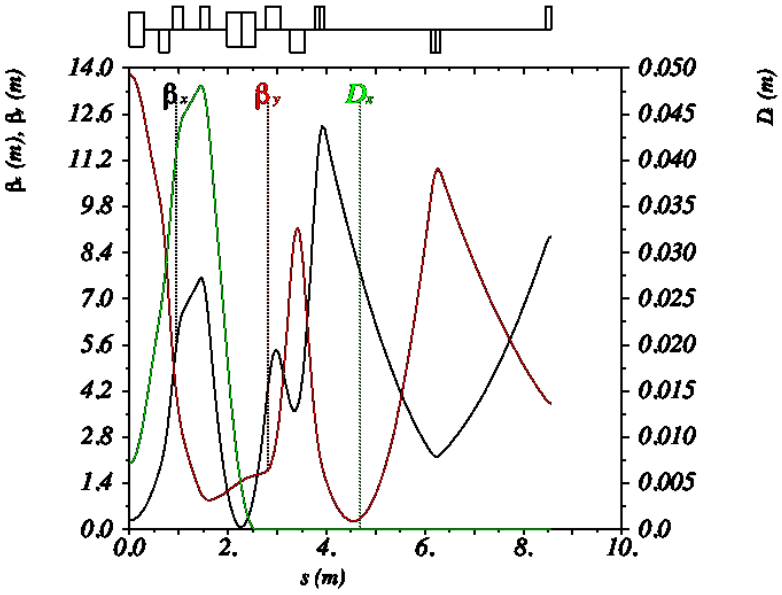


- 2.51 m - long TME cell with bends including small gradient ➔ To inverse βy and reduce IBS effect (S. Sinyatkin, et al)
- Phase advances of 0.408/0.05 and chromaticity of -1.5/-0.5
- Dipole length of 0.58 m

Ring optics – wiggler cell & dispersion suppressor

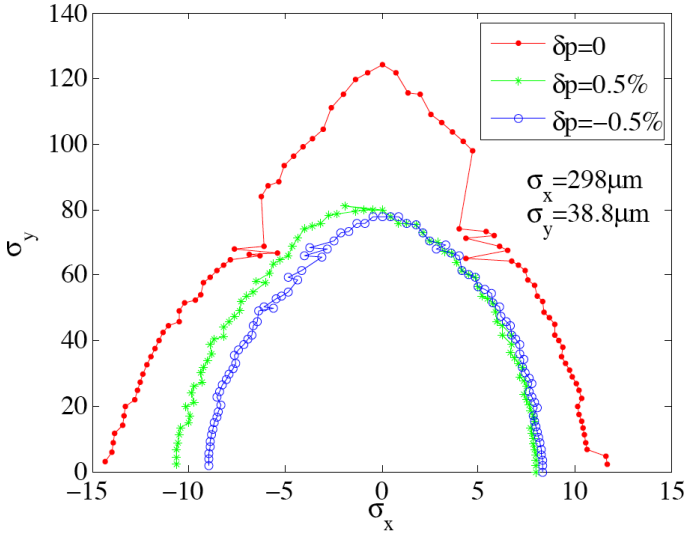


- LSS filled with wiggler FODO cells of around 6m
- Horizontal phase advance optimised for minimizing emittance with IBS, vertical phase advance optimised for aperture
- Drifts of 0.6 m downstream of the wigglers (more length for absorbers, vacuum equipment and instrumentation needed – ongoing work)

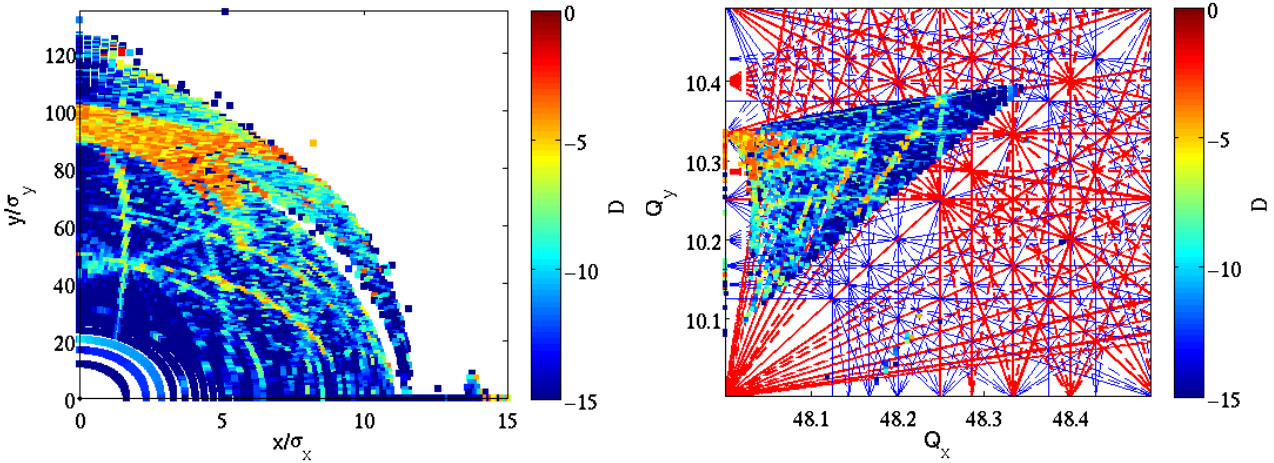


- Dispersion suppressors re-designed
  - Adding space for for RF cavities and beam transfer elements (will also be revised)
  - All dipoles of the same type (used to be 2 different types for arcs and DS)

Dynamic aperture



- Dynamic aperture plot (up): 1000-turn madx-ptc tracking with chromatic sextupoles and misalignments
  - Very large DA translated to around +/- 5mm in both planes for on-momentum
  - Further DA optimization on-going
- Frequency maps for δp/p=0(bottom): 1056-turn madx-ptc tracking with chromatic sextupoles and misalignments.



- D: Diffusion coefficient

$$D = log\left(\sqrt{(\nu_{x1}-\nu_{x2})^2+(\nu_{y1}-\nu_{y2})^2}\right)$$

  - $\nu_{(x,y)1}$: the tune from the first 1056/2 turns
  - $\nu_{(x,y)2}$: the tune from the second 1056/2 turns

Intrabeam-scattering studies

IBS @ the CLIC DR

- Intra-beam scattering is a small angle multiple Coulomb scattering effect which results in an increase of the emittance in all three dimensions
- IBS is one of the main limitations of the CLIC DR due to the ultra low emittances. The effect depends on:
  - The optics of the machine
  - The beam properties
- The classical IBS theories by Piwinski (classical approach) and by Bjorken-Mtingwa (quantum-field theory approach) and the high energy approximation by Bane are studied
- A multi-particle tracking code was developed (A. Vivoli) based on the Rutherford cross-section in order to simulate and study the effect

Bjorken-Mtingwa

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

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

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

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

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

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

Piwinski

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

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

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

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

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

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

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

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

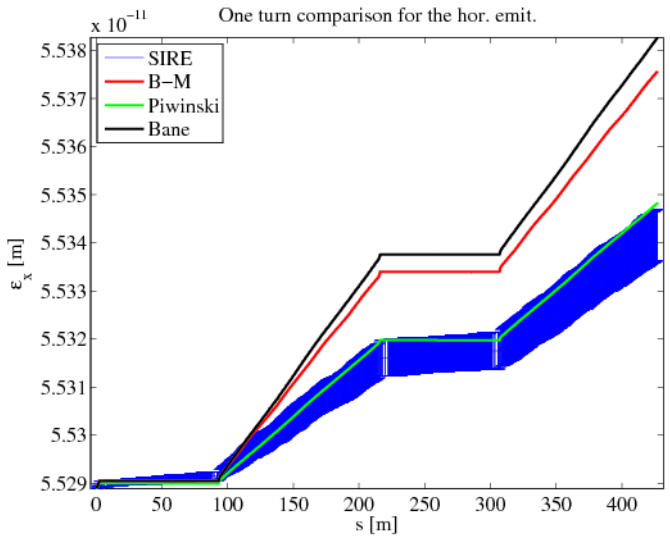
$$(L+\lambda' I)=\frac{\gamma^2}{\sigma_H^{\,2}}\begin{pmatrix} a^2+\lambda' & -a\zeta_x & 0 \\ -a\zeta_x & 1+\lambda' & -b\zeta_y \\ 0 & -b\zeta_y & b^2+\lambda' \end{pmatrix}$$

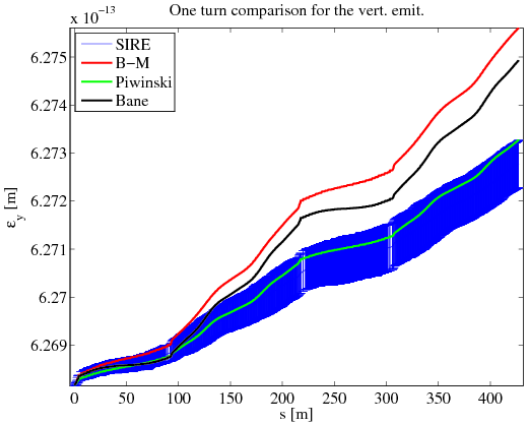
$$\zeta_x=\phi_{x,y}\sigma_H\sqrt{\frac{\beta_{x,y}}{\varepsilon_{x,y}}}$$

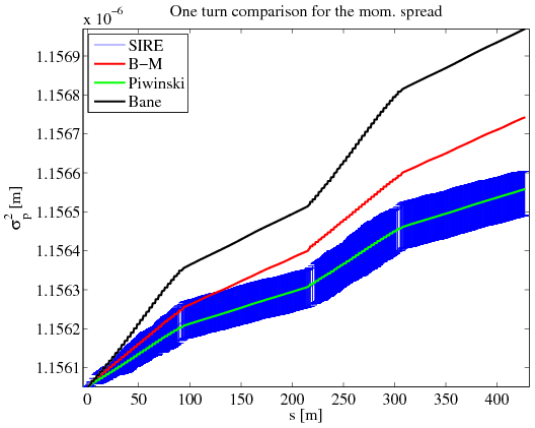
$$\frac{1}{T_p}\approx\frac{r_0^{\,2}cN\,(\log)}{16\gamma^3\varepsilon_x^{\,3/4}\varepsilon_y^{\,3/4}\sigma_s\sigma_p^{\,3}}\left\langle\sigma_H g(a/b)(\beta_x\beta_y)^{-1/4}\right\rangle$$

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

SIRE Benchmarking with theories



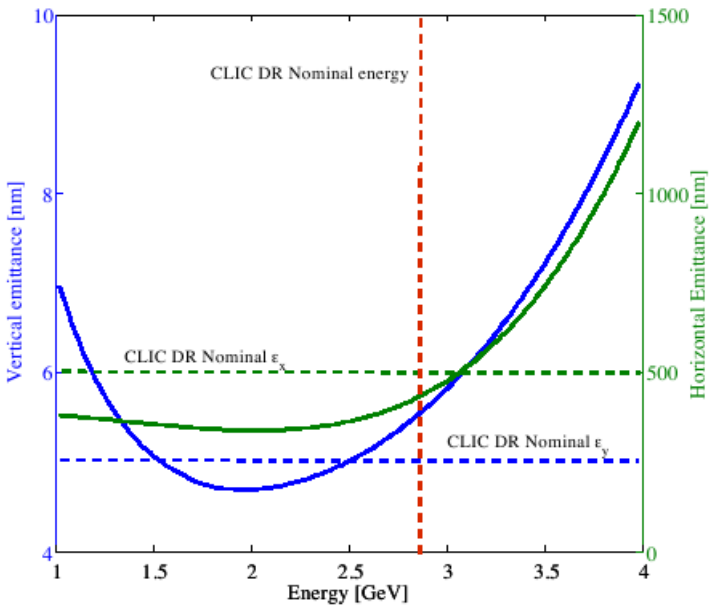




- Comparison of SIRE results (dark-blue) and Bjorken-Mtingwa (red), Piwinski (green) and Bane (light-blue) theories
- One turn behavior of the horizontal (top) and vertical (bottom,left) emittance and energy spread (down, right). For the SIRE results the 1σ error bars are also shown.
- SIRE and Piwinski in very good agreement
- Same trend on the emittance evolution!

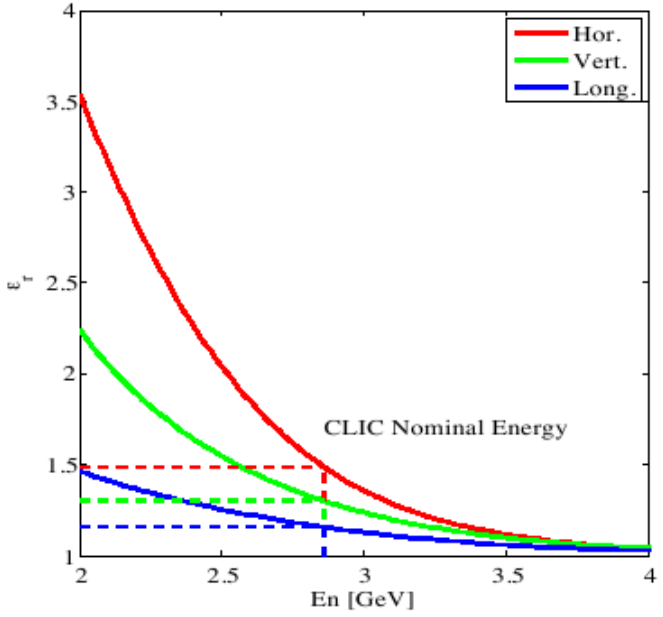
Thanks to A. Vivoli

IBS effect – Scan on Energy

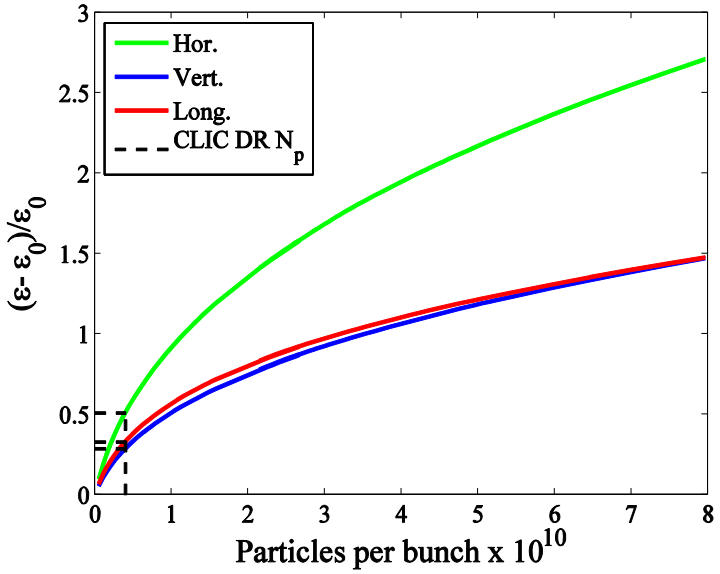


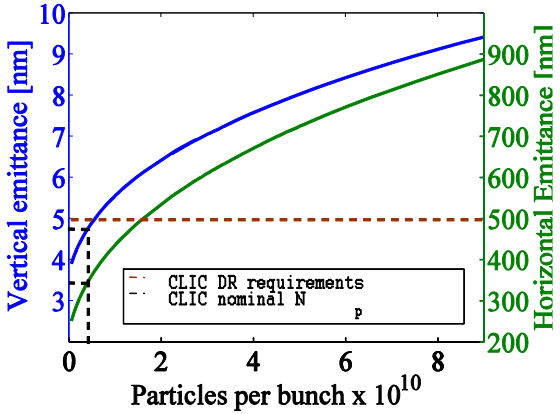
- Steady-state normalized horizontal and vertical emittances for constant output longitudinal emittance.

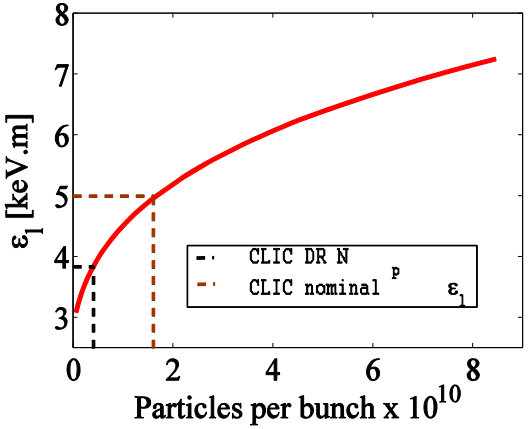
- Ratio between steady state and zero current emittances (indicates the IBS effect) for constant longitudinal emittance.



Bunch charge

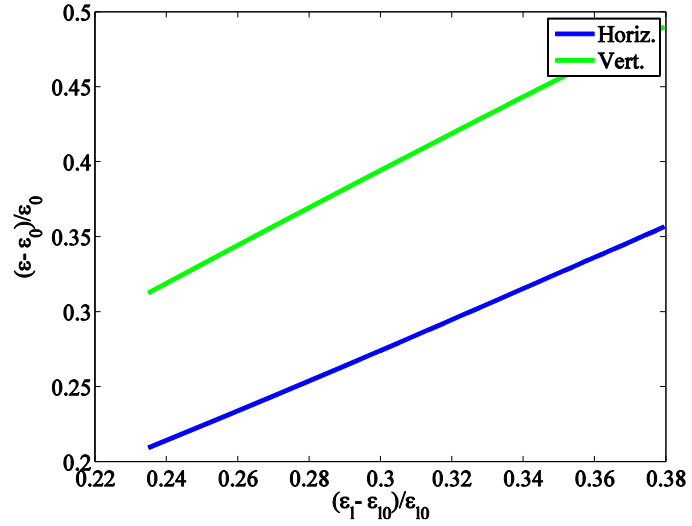


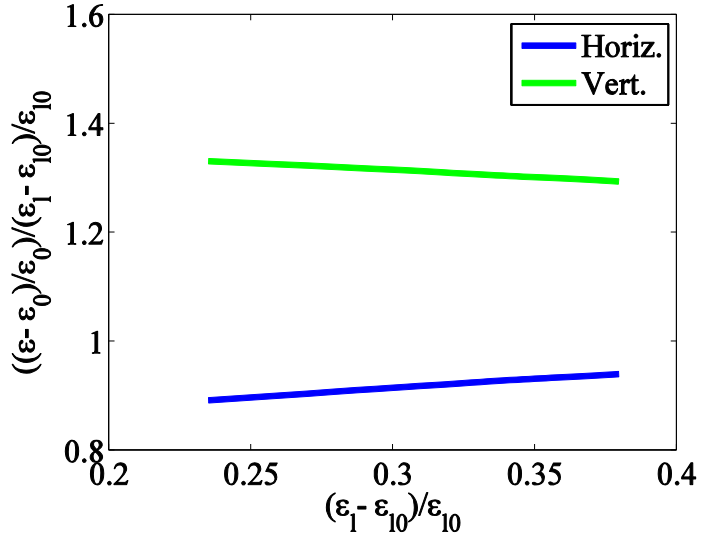




- Relative difference of steady-state and zero-current horizontal, vertical and longitudinal emittances (top) with bunch charge (Np)
- Steady-state hor., vert. and long. Emit. (bottom) with bunch charge (Np)
- Power dependence $(\varepsilon-\varepsilon_0)/\varepsilon_0 \sim N_p^k$, where k changes for different regimes.
- Larger blow-up in h. than v. and l. planes, while the later behave similarly with each other

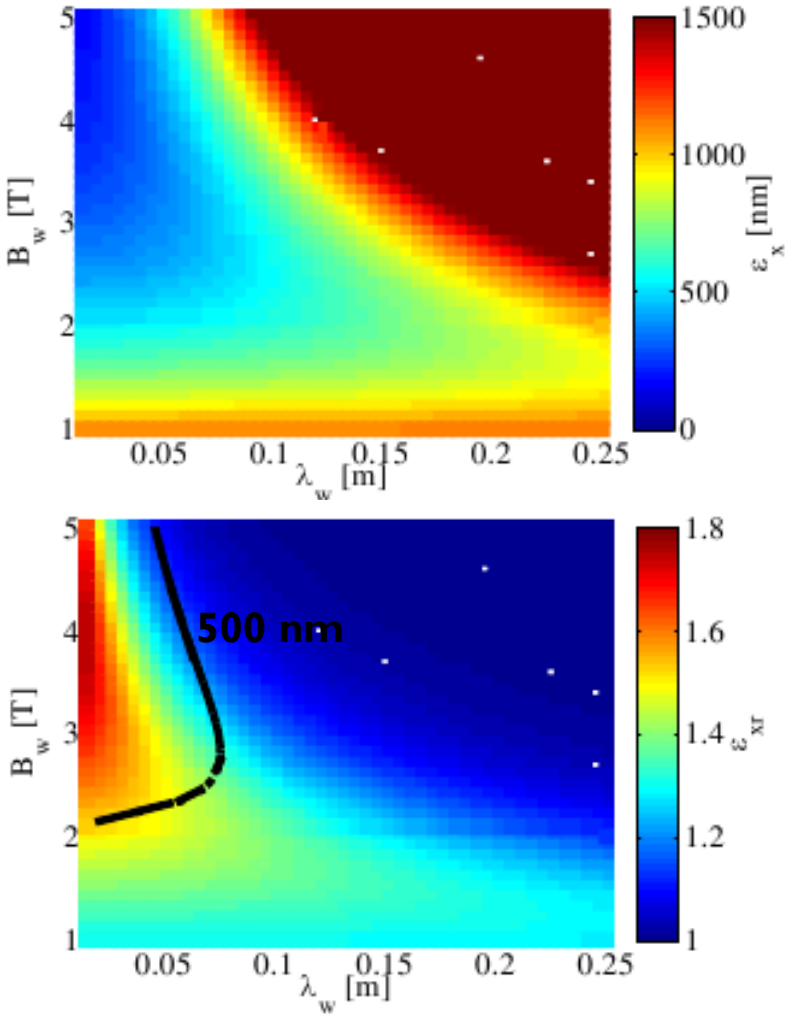
Longitudinal emittance





- Relative difference of steady-state and zero-current horizontal and vertical with longitudinal emittances
- Relative differences in the three planes scale linearly with each other

IBS effect – Scan on wiggler characteristics



- Steady-state emit. (top) and steady-state to zero-current emit. ratio (bottom), for constant output long. emit.
- Interested in regions where the output emittance lower than the target one (500 nm hor. and 5 nm vert.) and also the effect of IBS is not strong
- The black curves indicates the 500nm steady state horizontal emittance
- The requirements are met for high wiggler field and moderate wiggler period
- The self dispersion in the wigglers is not taken into account here but is expected to affect the vertical plane (work in progress)

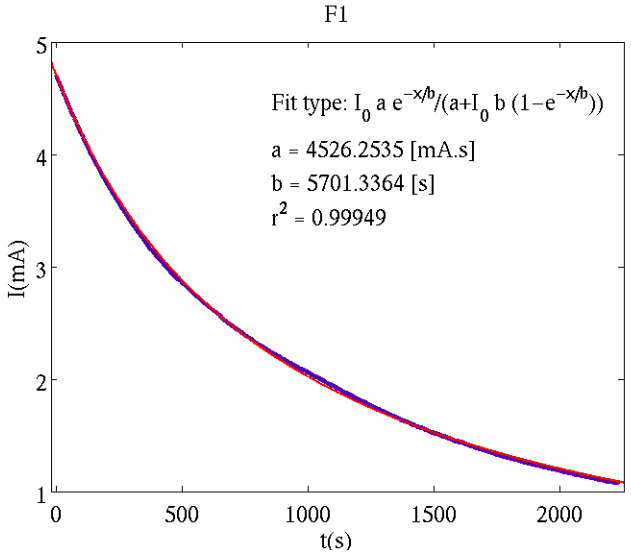
IBS measurements

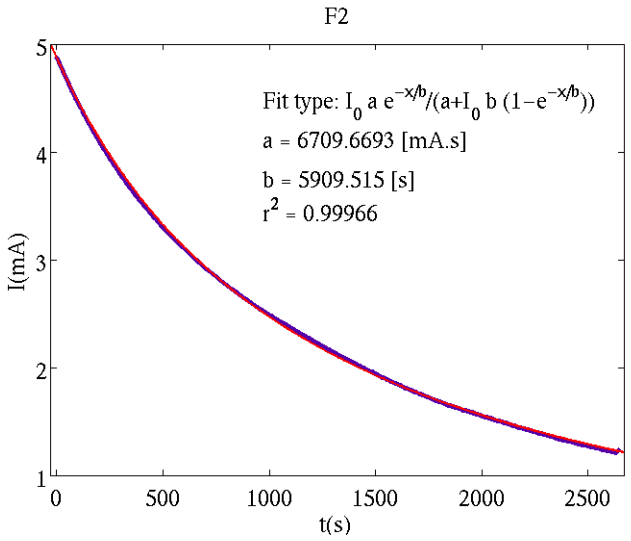
- Interesting results but only in simulations
- Measurements needed in order to:
  - Benchmark the theories and our simulation tools
  - Really study and understand the effect
- However not easy to measure the effect as
  - Very good instrumentation needed (precise beam size measurements (h/v), bunch length and energy spread)
  - A test-bed machine very well understood needed
  - A very good impedance model in order to be able to disentangle from other emittance blow up effects
- In December 2009 we visited CESR-TA in order to get some measurements and understand the possibilities of measuring the effect there
  - We were able to get some lifetime measurements
- In March 2011 we visited PSI/SLS in the framework of TIARA/WP6 and we mainly discussed the possibilities of IBS studies at the SLS.
  - Some IBS simulations were done for the SLS lattice

Cesr-TA data

- Visit at Cesr-TA in December 2009
  - Mainly to understand the possibilities of IBS measurements
- Advantages of the machine
  - Scan in different energies
  - Scan in different bunch currents
- Disadvantages
  - Not able to have beam size measurements neither bunch length measurements
  - Not a good impedance model exists
- We were able to get some Touschek lifetime measurements
  - They can be used for estimation of vertical beam size if we are in a Touschek parameter regime
  - Easy measurements with standard instrumentation (beam current monitor and clock)
  - However not very precise estimation as the Touschek effect is complicated and involves many parameters that may not be well known
  - The IBS effect is on top of the Touschek effect

Cesr-TA data





$$\frac{1}{\tau} = \frac{N r_e^2 c}{8\pi\sigma_z\gamma^2}\left\langle \frac{D(\epsilon)}{\delta_{max}^3\sigma_x\sigma_y}\right\rangle \qquad \epsilon = \left(\frac{\delta_{max}\beta_x}{\gamma\sigma_x}\right)^2$$

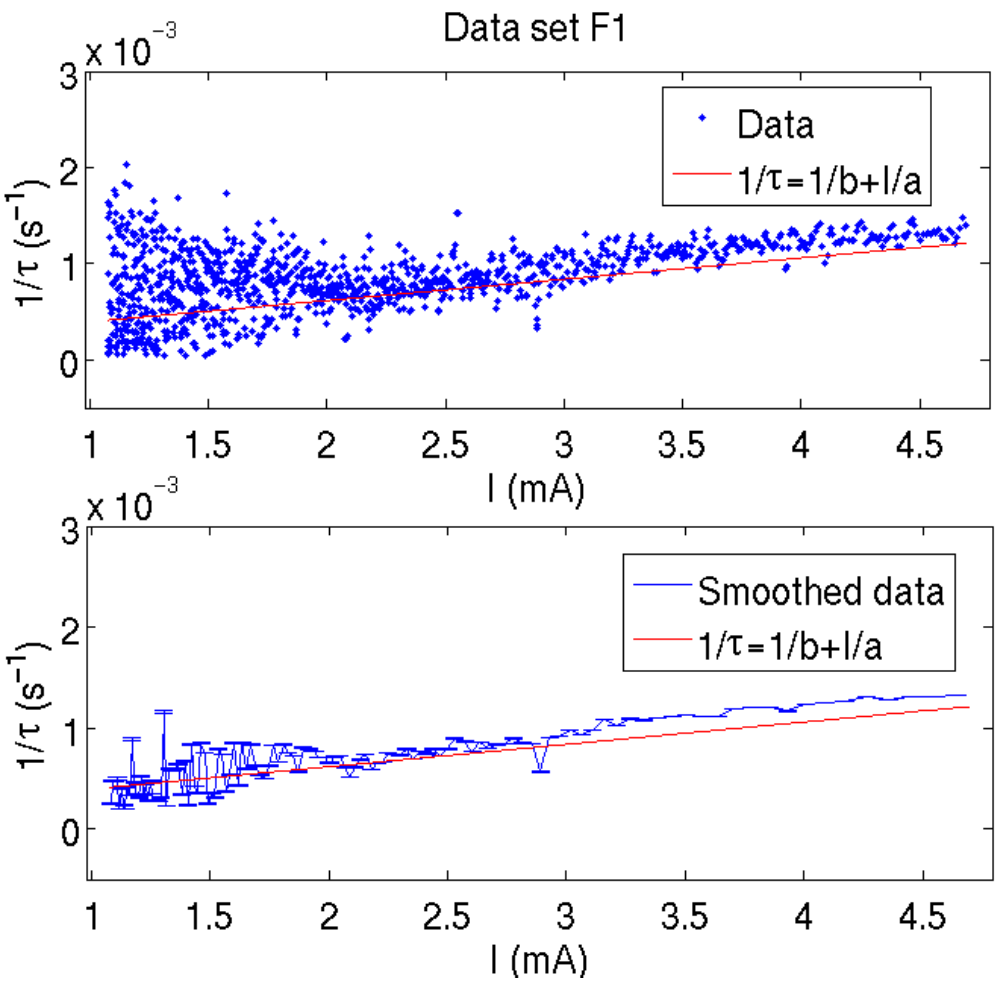
$$D(\epsilon) = \sqrt{\epsilon}\left(-\frac{3}{2}e^{-\epsilon} + \frac{\epsilon}{2}\int_\epsilon^\infty \frac{e^{-u}\ln u}{u}du + \frac{1}{2}(3\epsilon - \epsilon\ln\epsilon + 2)\int_\epsilon^\infty \frac{e^{-u}}{u}du\right)$$

$$\frac{dI}{dt} = -\frac{I}{b} - \frac{I^2}{a}$$

Touschek term

- 4 sets of measurements for different RF values
  - 2 examples are shown here
  - F1:V_{RF}=6.32 MV
  - F2:V_{RF}=4.9MV
- a: Touschek parameter
- 1mA ≈1.6x10^{10} e^-

Cesr-TA data

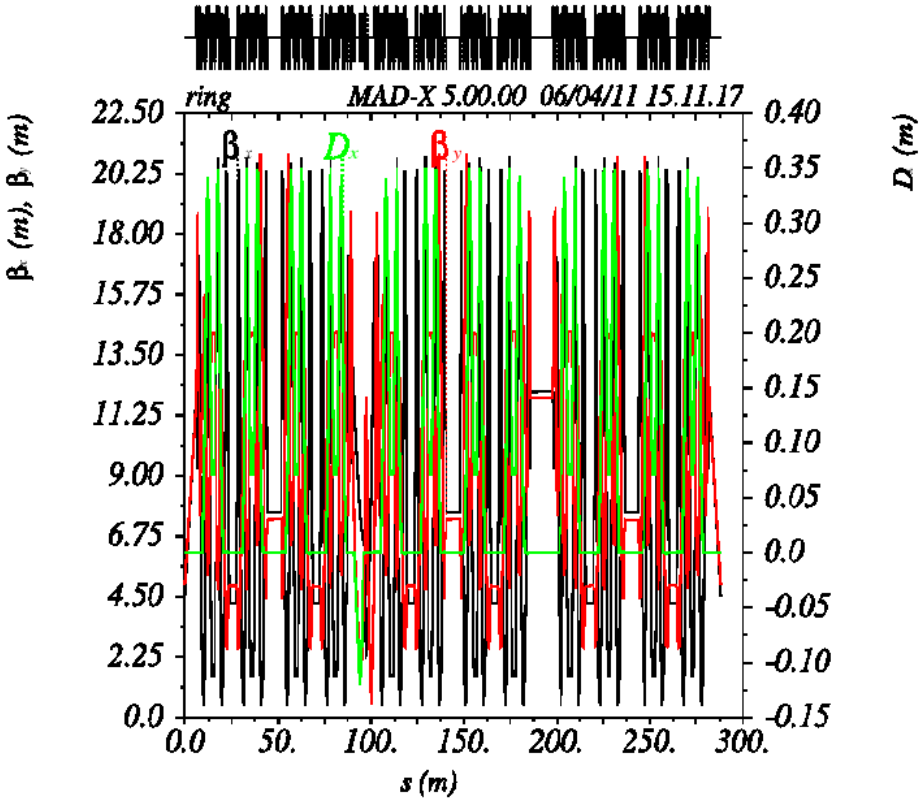


- Comparison of lifetime data and fit line
- There is an effect at high currents (clearly seen if smooth out the data)
  - Needs to be understood where this comes from
  - IBS or some other effect like potential well distortion?
- The fact that we don't have any beam size measurements or any impedance model of the machine makes the analysis very difficult!

Cesr-TA data

- Calculating the Touschek parameter analytically for different RF voltage values and different vertical emittance values (taking the horizontal emittance and the bunch length from the model) one can estimate the vertical emittance (in the region where we are Touschek dominated)
- Some ideas:
  - Calculate the Touschek parameter in groups of points and check if it changes with I ➔ a=f(I)
  - Calculate all the emittance values with the above method for low currents (equilibrium values) and at high currents and compare the difference. Compare also with the IBS theories predictions.
- However
  - Very indirect methods and not precise
  - Maybe a good exercise for educational reasons but not for a conclusion that we can trust

The SLS lattice



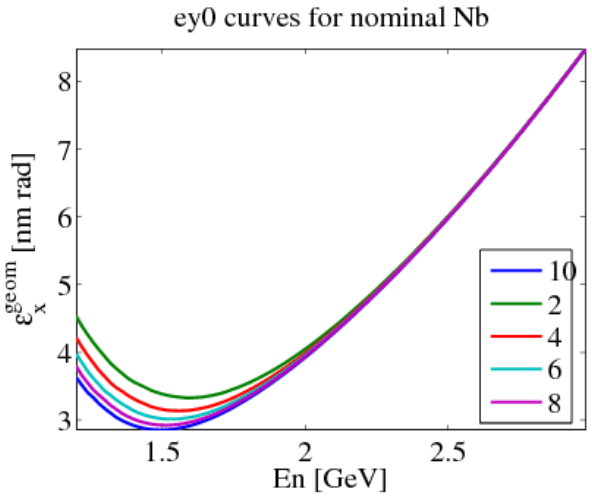
Parameter	Value
Energy [GeV]	2.411
Circumference [m]	288
Energy loss/turn [MeV]	0.54
RF voltage [MV]	2.1
Mom. Comp. factor	$6.05e^{-4}$
Damping times h/v/l [ms]	8.59/8.55/4.26
Hor. emittance [nm rad]	5.6
Vert. emittance [pm rad]	2
Bunch length [mm]	3.8
Energy spread [%]	0.086

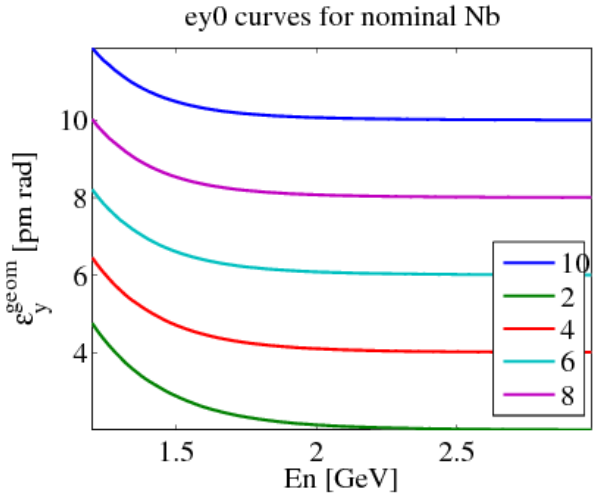
- Thanks to A. Streun and M. Aiba for providing the lattice
- Random misalignments were added in order to get the 2 pm vertical emittance

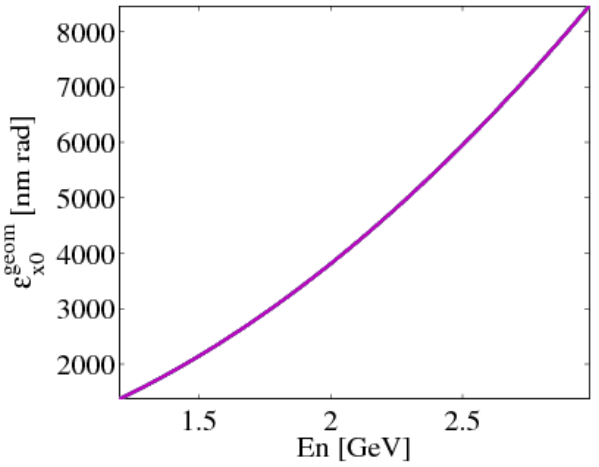
IBS calculations for the SLS

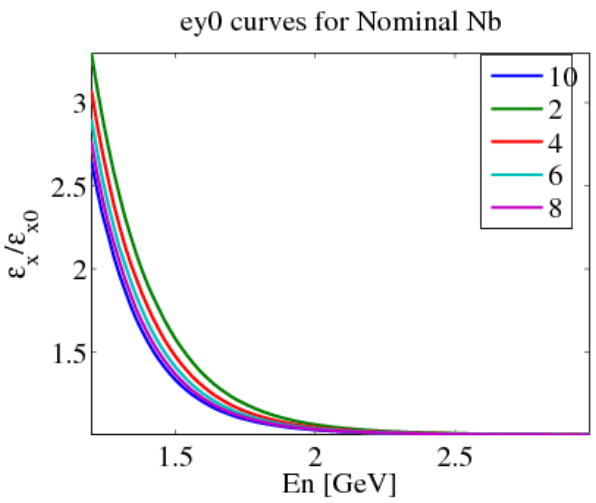
- The Piwinski formalism was used in order to calculate the IBS effect in the SLS lattice
- For the nominal energy (2.411 GeV) and the nominal bunch current (400/390 mA/bunch or 6 x10^9 e-/bunch) no effect is predicted.
- Scanning on the energy for different bunch currents and different zero current vertical emittances and on the bunch charge for different energies and different vertical emittances is performed.
- We consider that the optics remain the same and the longitudinal emittance is kept constant for all cases.
- In the plots the zero index indicates the zero current emittances while the rest the steady state emittance (with IBS)

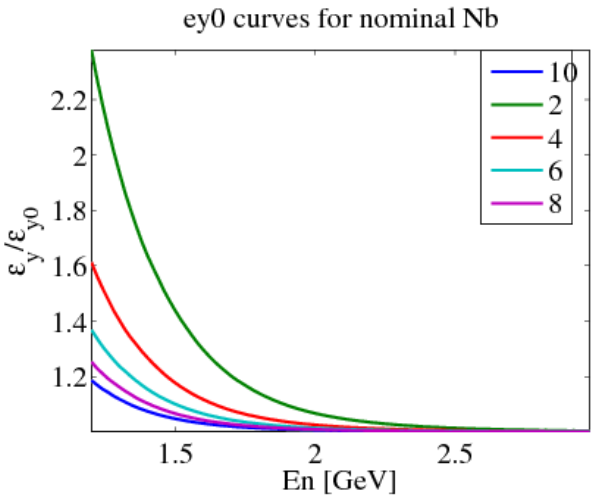
IBS effect – Energy Scan (1)

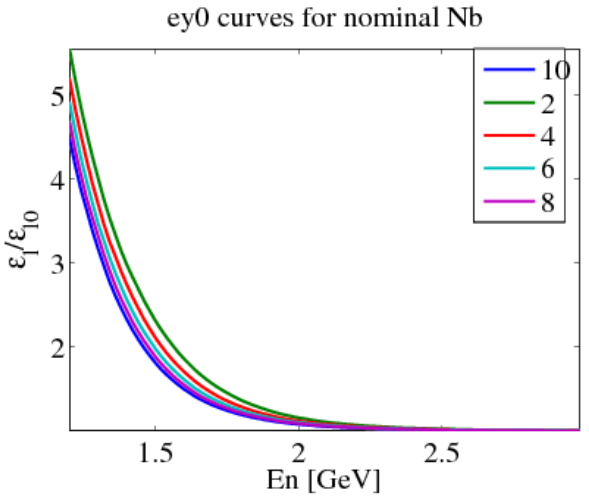




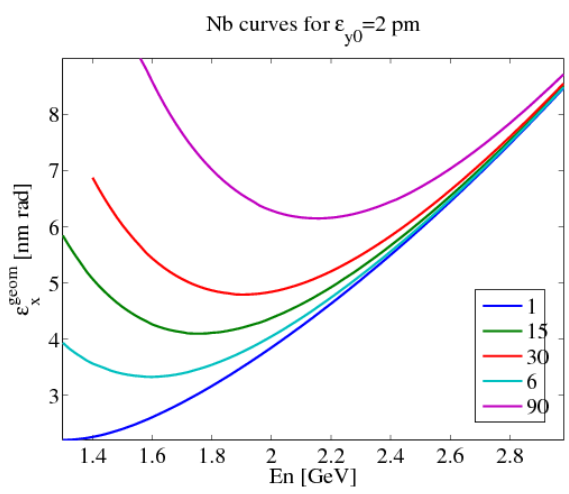


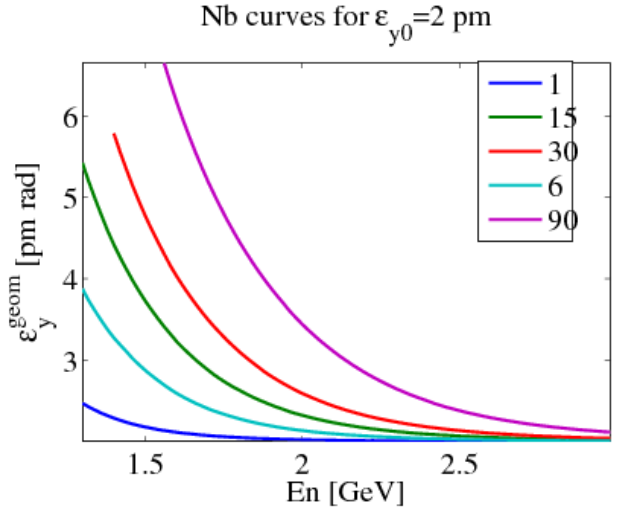


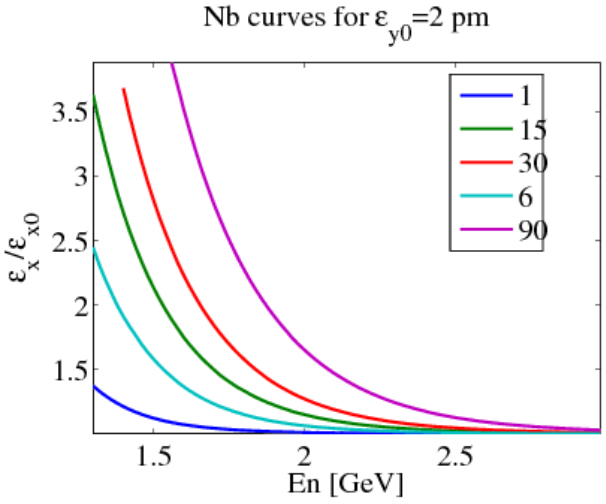


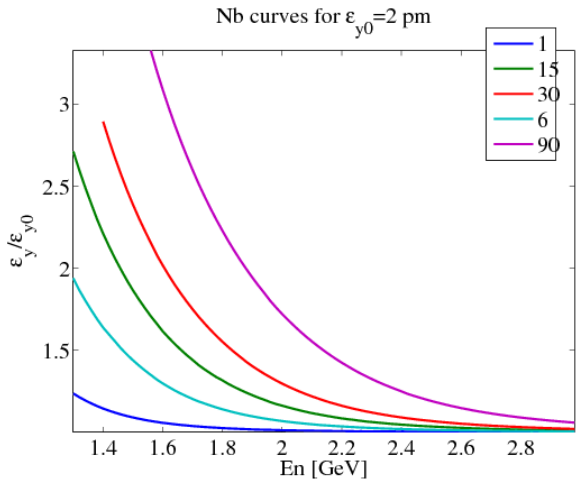


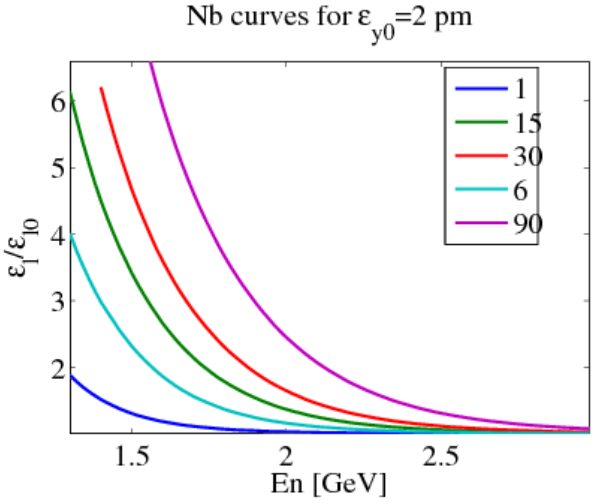
IBS effect – Energy Scan (2)



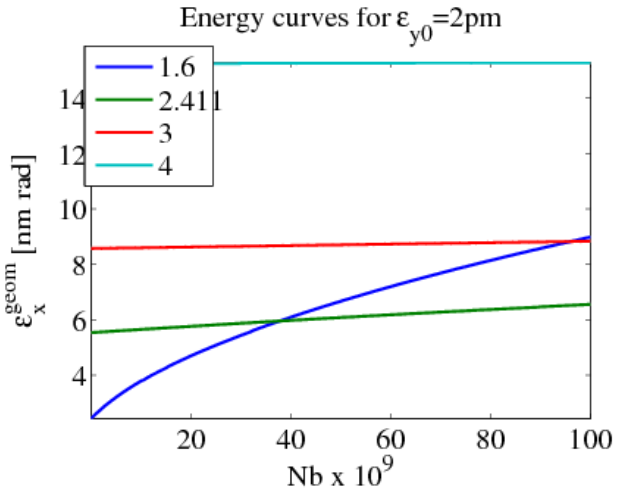


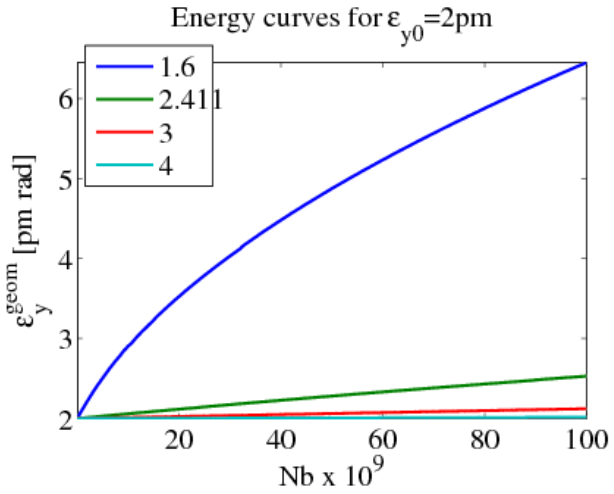


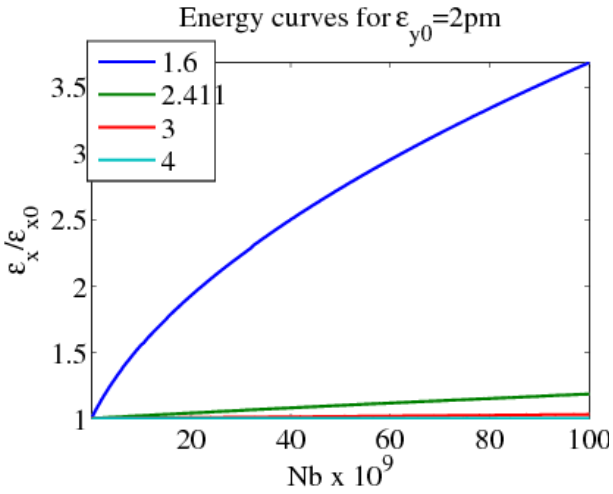


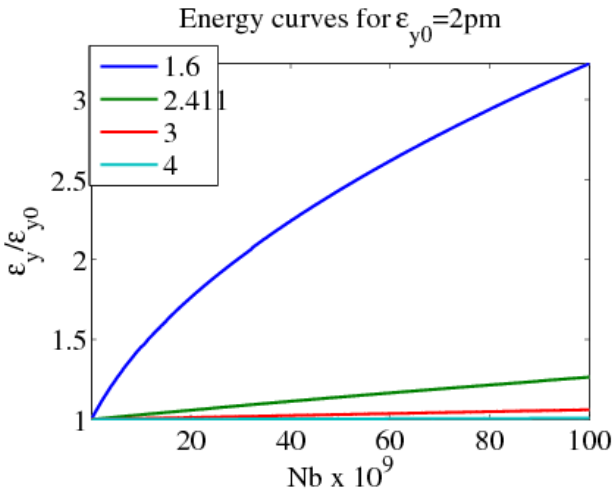


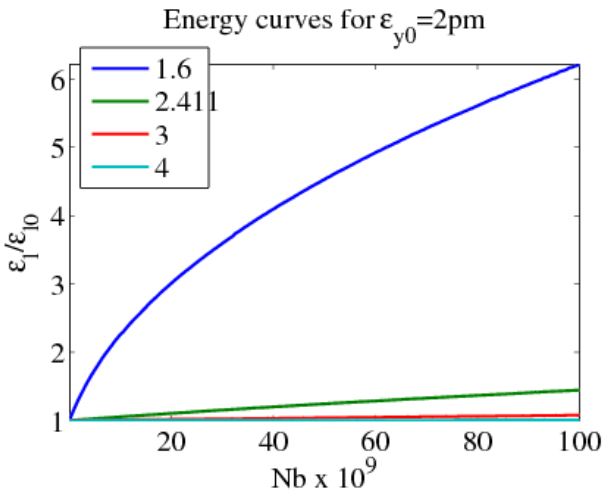
IBS effect – Bunch charge scan (1)



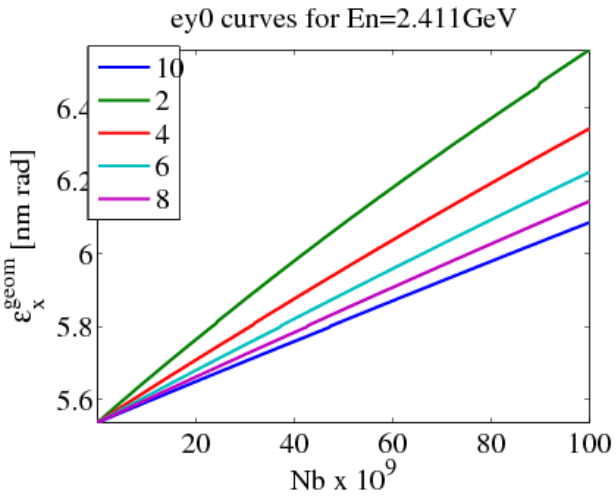


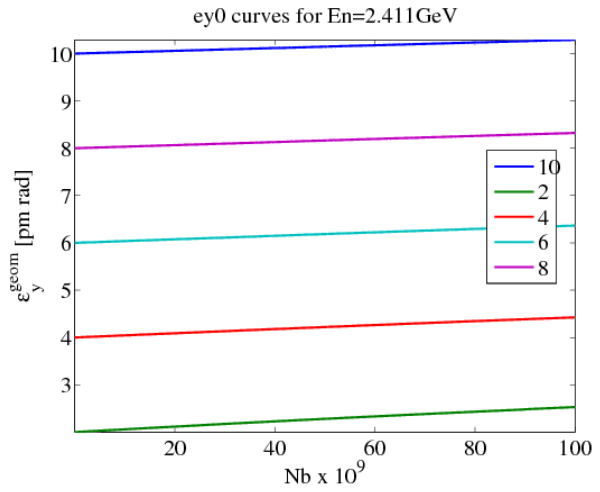


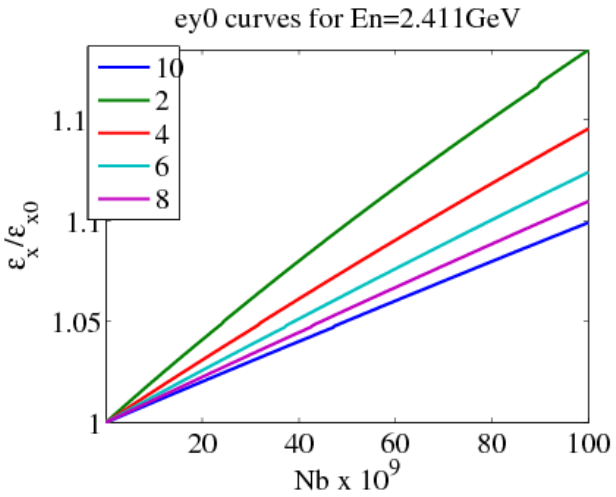


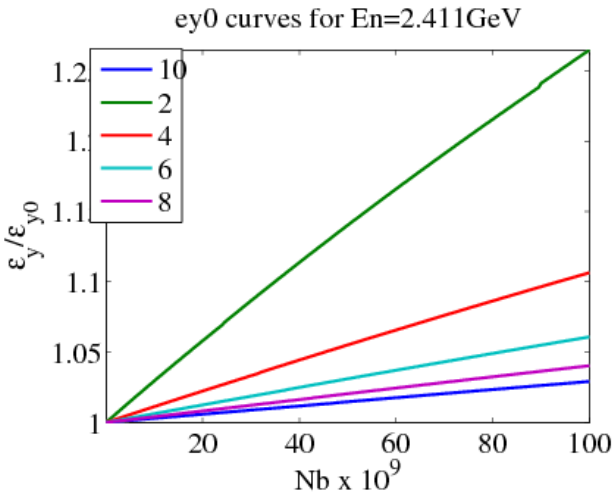


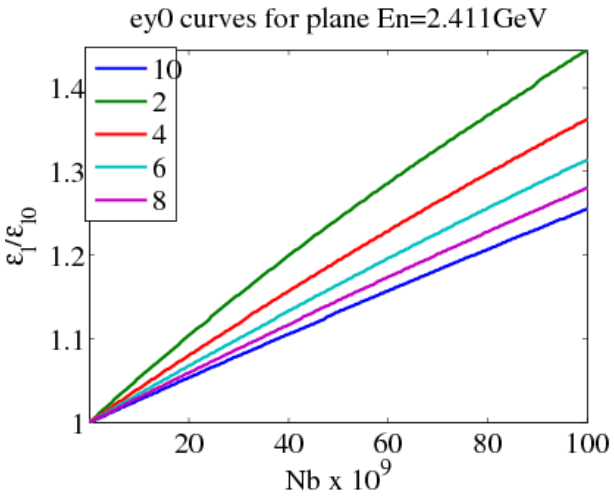
IBS effect – Bunch charge scan (2)



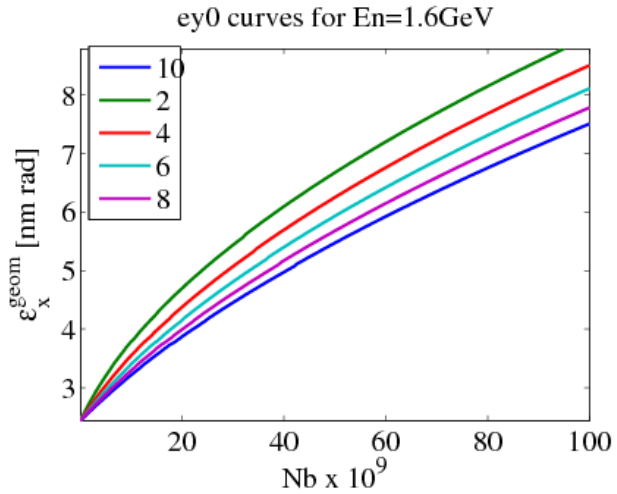


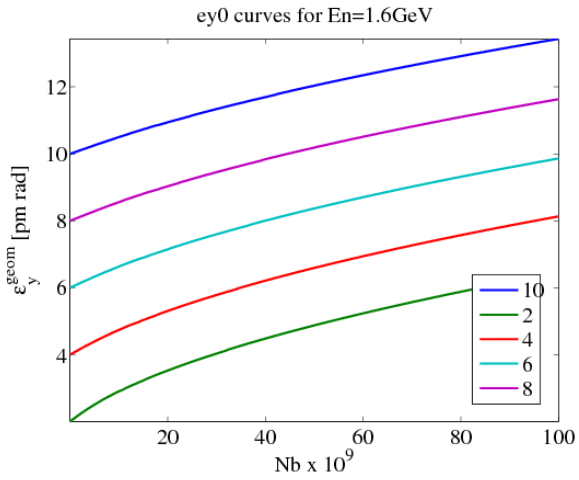


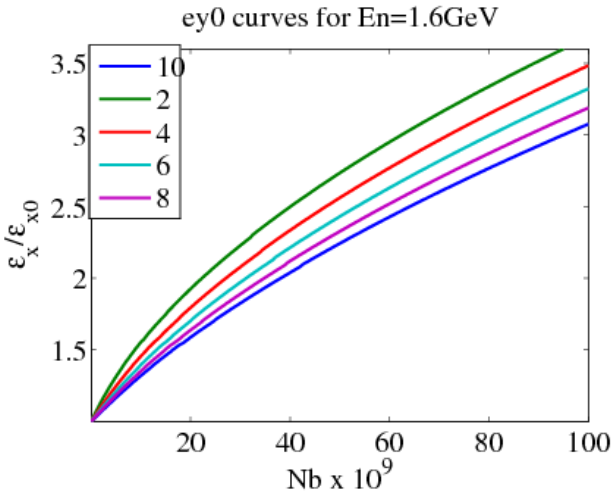


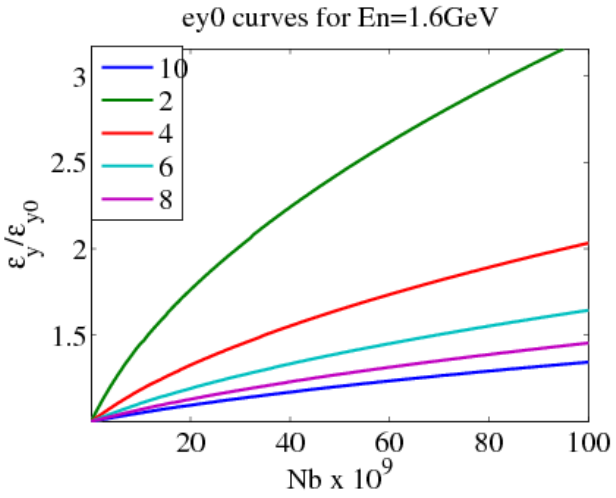


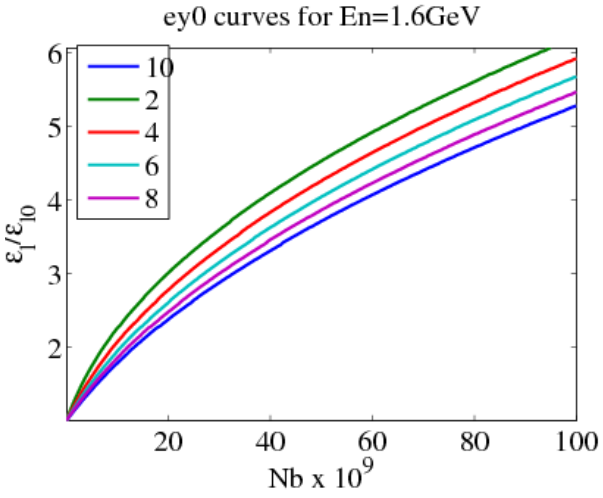
IBS effect – Bunch charge scan (3)











IBS effect @ SLS in numbers

- Table 1 (top):Values calculated at En=1.6 GeV @ nominal bunch current

εy0 [pm rad]	εx [nm rad]	εxr	εyr	εlr
2	3.33	1.37	1.3	1.86
4	3.15	1.29	1.12	1.71
6	3.05	1.25	1.07	1.61
8	2.97	1.22	1.04	1.55
10	2.92	1.198	1.03	1.498

- Table 2 (bottom): Values calculated at En=2.411 GeV @ nominal bunch current

εy0 [pm rad]	εx [nm rad]	εxr	εyr	εlr
2	5.56	1.013	1.0018	1.033
4	5.54	1.01	1.007	1.026
6	5.531	1.008	1.004	1.021
8	5.525	1.007	1.003	1.019
10	5.521	1.006	1.002	1.016

Possibilities and limitations of measurements (1)

- Visit at PSI: 29-30 March at SLS/PSI under the framework of TIARA
  - The SLS colleagues described the possibilities and limitations of measurements of the IBS effect at the SLS
- The theoretical predictions indicate that the effect could be measured at the SLS but not for the nominal lattice and beam.
  - The effect is visible at lower energies and/or higher bunch current
- In order to disentangle the effect from other collective effects → run the machine in one bunch mode (or multi-bunch with empty buckets). However the one bunch mode with higher current not trivial as:
  - The orbit is not measured exactly
  - The BPMs are calibrated for the full current full train -> recalibration of the BPMs will be needed
  - For very high currents -> saturation of the electronics
  - The current measurement not very precise

Possibilities and limitations of measurements (2)

- There is the possibility to use the 3rd harmonic cavity in bunch shortening mode but:
  - The RF cavity needs to be retuned
  - Very sensitive system
- Already tried the optics for lower energy at 1.6 GeV!! The effect there according to theory can be visible even at nominal current. However again not trivial:
  - Different temperature of the machine -> Not exact measurement of the orbit
  - Recalibration of BPMs is needed
  - Retuning of the RF cavity needed in order to be able to go at nominal current
- It is better to try to measure the effect in the horizontal plane
  - Easier to detect
  - A small difference in the vertical plane is not clear where it comes from
- The SLS colleagues are very interested to participate and help so there is a possibility that some first measurements will come by the end of this year.

MADX IBS module

- The ibs module in madx calculates the ibs growth rates at the equilibrium emittance using the B-M formalism
- The implementation had some bags and F. Ziemmermann ask if I could help in the correction of the module
  - The module is now debugged and verified that the formulas are implemented correctly
  - Comparison between madx and Mathematica B-M implementation for 4 examples (PDR, DR, SLS, testRing)
    - Very good agreement for all the examples except the vertical plane for the DRs
    - The debugging is continued in order to understand were this difference comes from

Conclusions & Next steps

- A solid designed ready for the CDR
- More optimization studies are ongoing
  - FODO – wiggler cell optimization
    - IBS scan on wiggler characteristics taking into account self dispersion and wiggler focusing
    - New wiggler working points are under consideration (higher field and larger period)
    - Study the effect of wiggler length on beam dynamics and IBS
  - TME – arc cell
    - Add the IBS calculations on the analytical solution for the TME cell ➔ Arc optimization with respect to IBS
- IBS studies are ongoing
  - Many things to be understood from theories
  - SLS seems to be a very good testbed for IBS studies
- Corrected IBS module has been released
  - A last verification step is ongoing
- A Twiki page under the CLIC web/Accelerator (https://twiki.cern.ch/twiki/bin/view/CLIC/DampingRings) with all the information about the DR complex is coming soon.

Thank you!!

Many thanks to:
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M. Palmer (Cesr-TA)
A. Streun, M. Boege, M. Aiba (PSI/SLS)