Optics design optimization for IBS dominated beams

On behalf of:

F. Antoniou, H. Bartosik, T. Bohl, Y. Papaphilippou (CERN),

N. Milas, A. Streun (PSI/SLS), M. Pivi (SLAC), T. Demma (LAL)

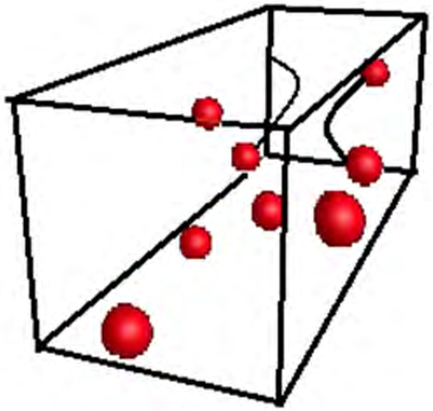
HB2010, Institute of High Energy Physics, Beijing September 17-21 2012

OUTLINE

- General introduction to intrabeam scattering
- IBS calculations for the CLIC Damping Rings
  - Analytical parameterization of the TME cell considering also IBS
  - DRs optics optimization with respect to IBS
- Simulation tools
  - SIRE
  - CMAD-IBStrack
- Measurements
  - IBS measurements at the SLS
  - IBS observations at the SPS - ion beams
- Conclusions - Outlook

Intrabeam scattering (IBS)
General introduction

About Intra-beam scattering



- Different approaches for the probability of scattering
  - Classical Rutherford cross section (Piwinski & tracking codes)
  - Quantum approach (Bjorken-Mtingwa)
    - The relativistic "Golden Rule" for the 2-body scattering process

- Small angle multiple Coulomb scattering effect leading to:
  - Redistribution of beam momenta
  - Beam difussion with impact on the beam quality
    - Brightness
    - Lumnosity

- Several theoretical models and their approximations were developed over the years having three main drawbacks:
  - Gaussian beams assumed
  - Betatron coupling not included
  - Ambiguous Coulomb log

Fanouria.Antoniou@cern.ch

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

w/o synchrotron radiation this term is not needed

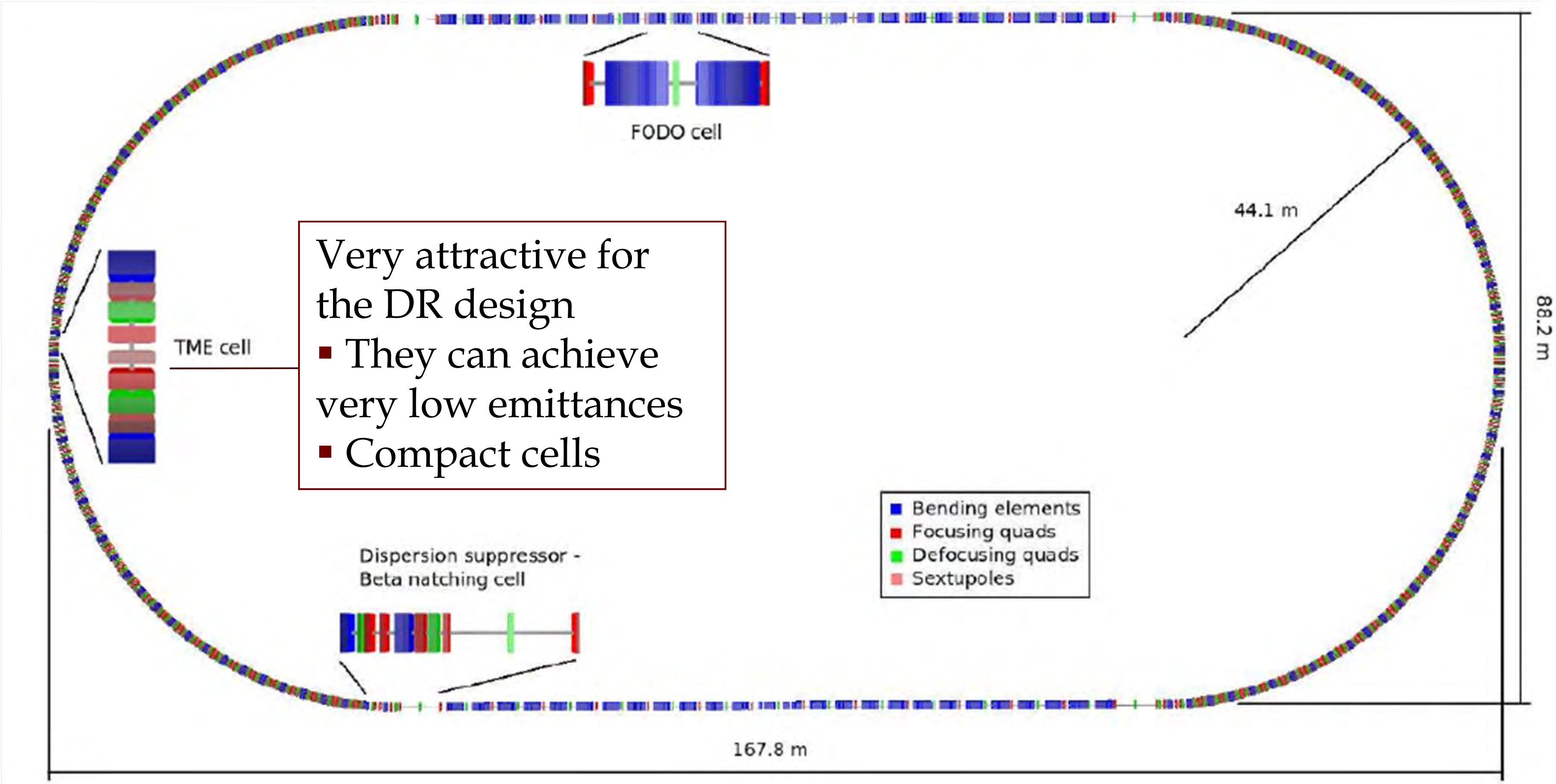
If = 0

Steady State emittances

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

IBS studies at the CLIC Damping Rings (DR)

The CLIC DR

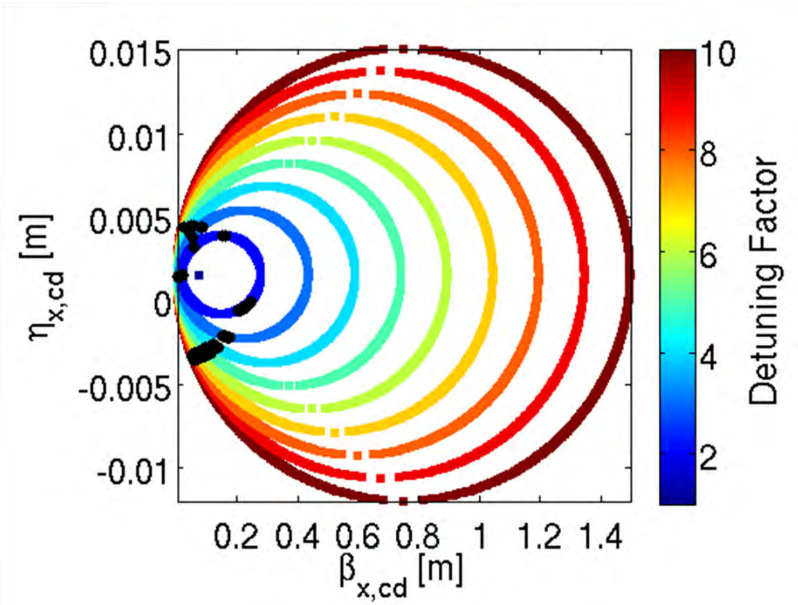


Very attractive for the DR design

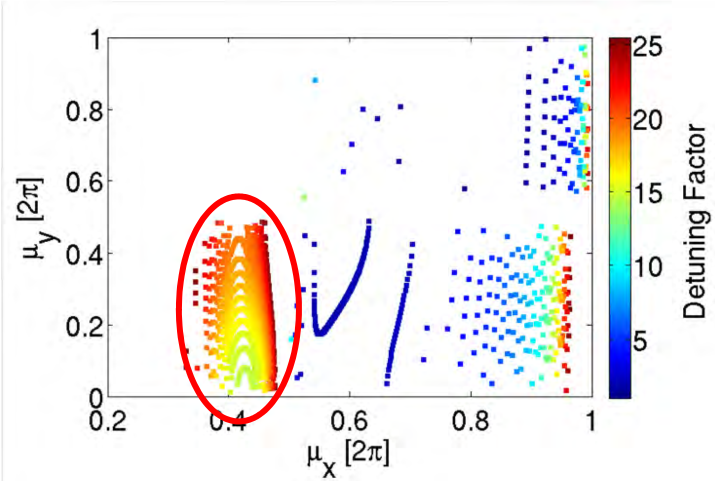
- They can achieve very low emittances
- Compact cells

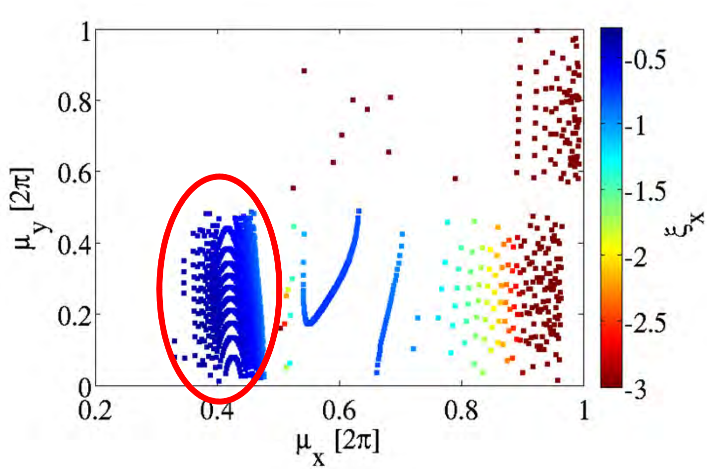
- Racetrack configuration with 2 arc sections filled with TME (Theoretical minimum emittance) cells and 2 long straight sections filled with FODO cells.
- FODO cells accommodate the wigglers
  - Necessary for the fast damping and the ultra-low emittance

TME 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

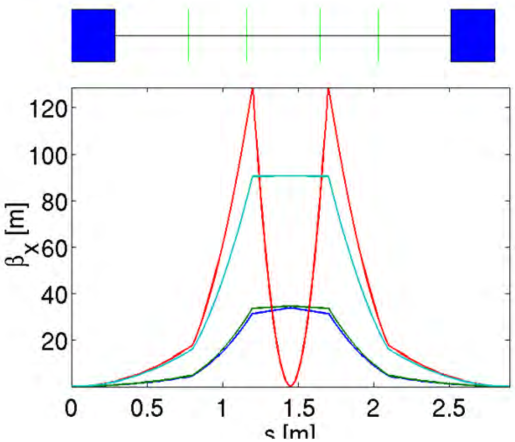


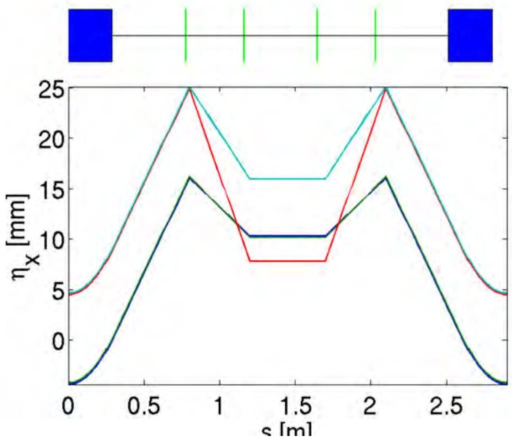


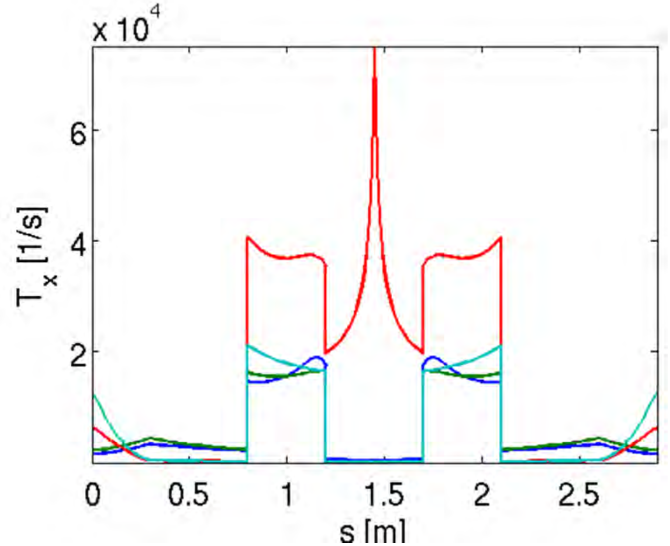
Large detuning factor and small hor. And vert. phase advances for small chromaticity

Fanouria.Antoniou@cern.ch

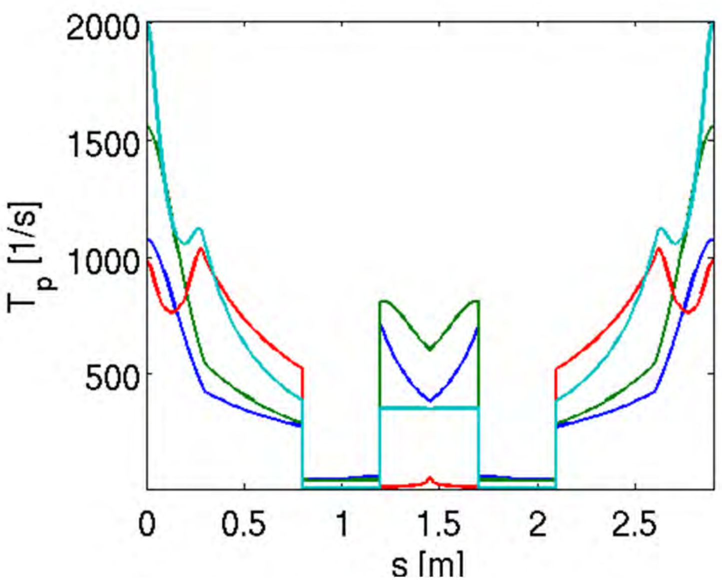
TME optimization with respect to IBS



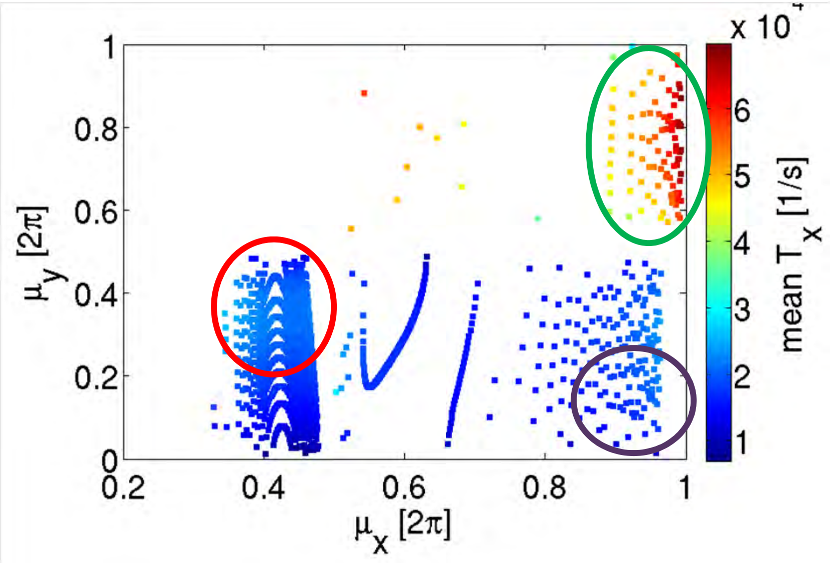




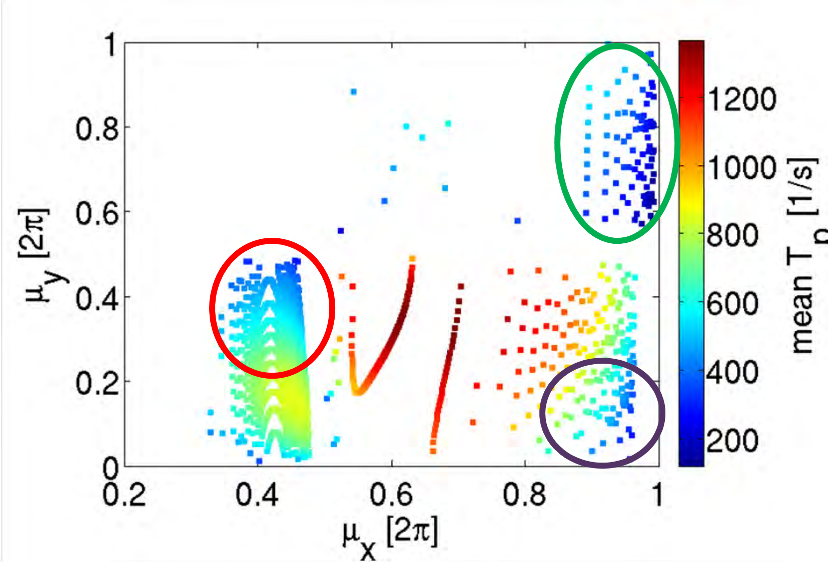
- For the same detuning factor (here DF=6) different optics options (top plots)
- The corresponding horizontal and longitudinal growth rates along a TME cell (right plots)
- Careful optics choice very important for the IBS optimization

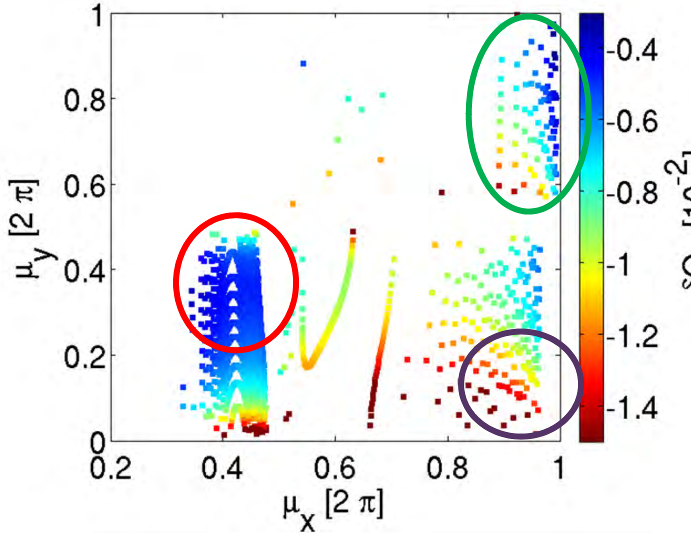


TME optimization with respect to IBS



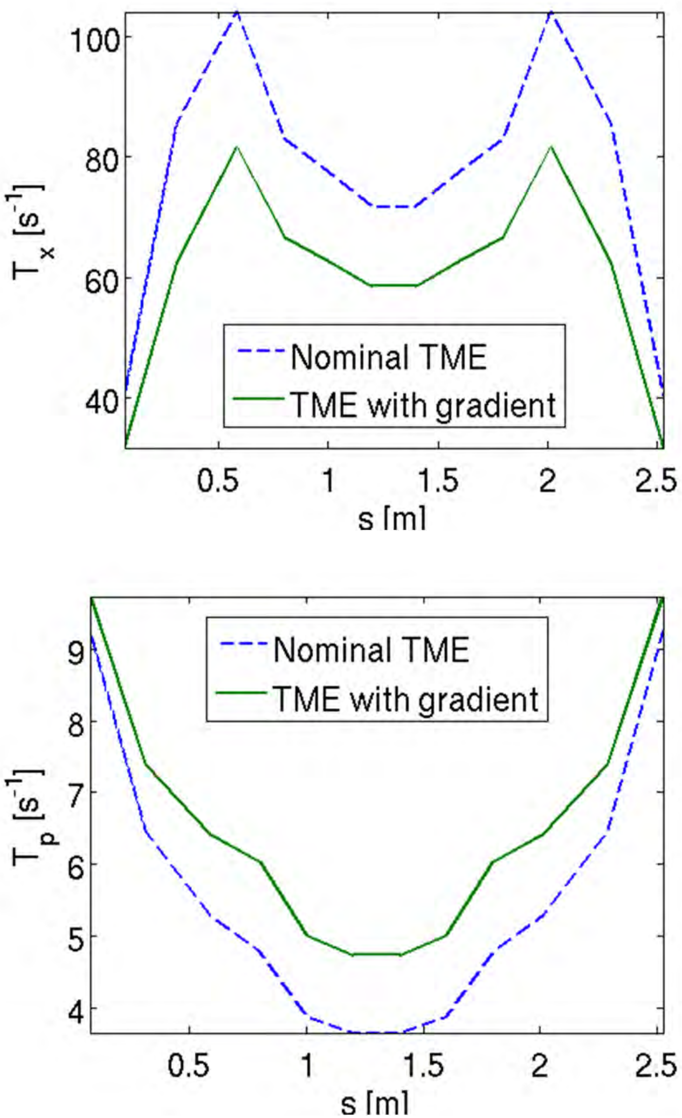
- Scanning on the detuning factor (here DF=1..25), optimal phase advances can be found were chromaticity, IBS growth rates and space charge detuning are minimized!!
- Other interesting regions according to the requirements of the design also exist!!





Fanouria.Antoniou@cern.ch

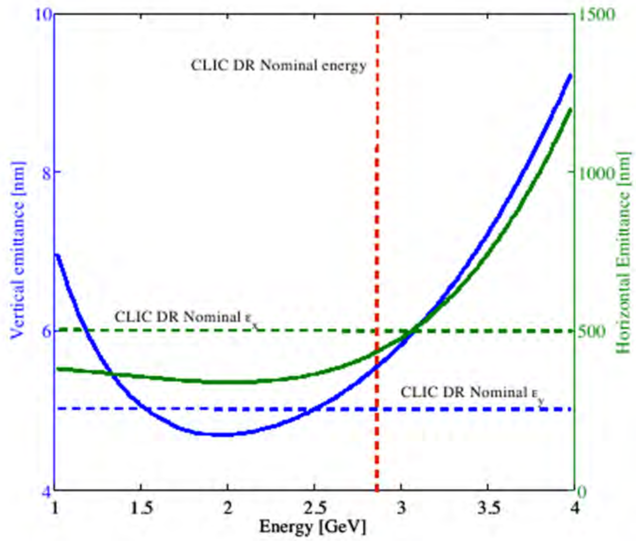
DR optics optimization with respect to IBS

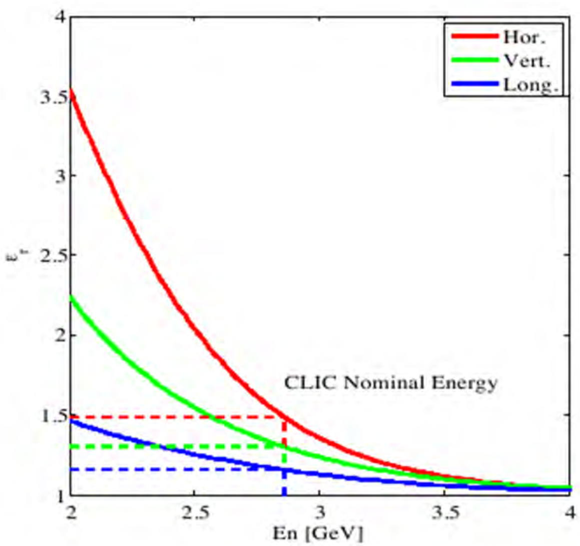


- IBS growth rate in the initial (2007) design a factor of 6 ***!***
- The main contribution to the IBS growth comes from the arcs (small dispersion and beta functions at the center of the TME dipole)
- Using a modified TME cell, with combined function dipole with small defocusing gradient, has a positive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

Fanouria.Antoniou@cern.ch

DR optics optimization with respect to IBS





- The zero current equilibrium emittance (due to synchrotron radiation) and the output IBS dominated emittance depend on energy
  - It is interesting to study the scaling of the output emittances with energy
- A broad minimum around 2 GeV for the output transverse emittances (top) while the IBS effect becomes weaker with the energy (bottom)
  - Higher energies are interesting for IBS but not for the emittance requirements
- A reduction of the energy was decided (from 2.424 -> 2.86 GeV) reducing the IBS effect by a factor of 2 (from 3 → 1.5)

Fanouria.Antoniou@cern.ch

The CLIC DR

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

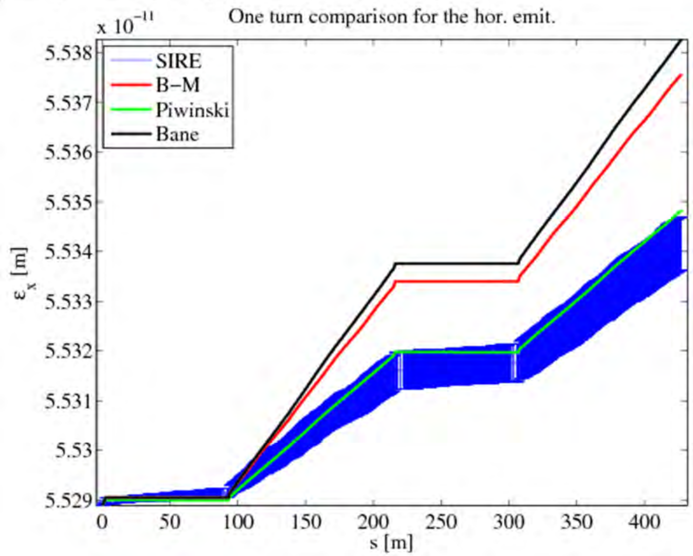
- Performance parameters of the CLIC DR for the 1 GHz and 2 GHz options and for an intermediate design (V06)
  - Ultra-low emittances in all 3 planes for the luminocity requirements of the collider
- Optics manipulation and energy change reduced the IBS effect form a factor of 6 → 3 → 1.5

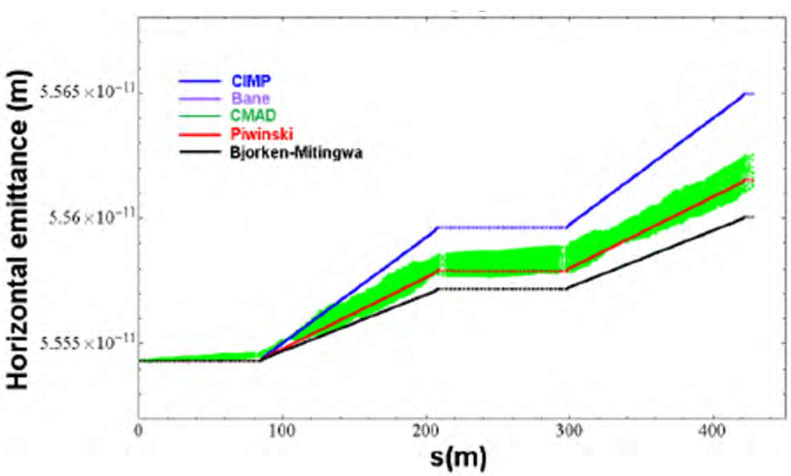
IBS simulation tools

IBS multi-particle tracking codes

- The IBS theoretical models consider Gaussian beam distributions and uncoupled frames
  - In reality it is not obvious if this is valid, especially in strong IBS regimes
  - Coupling could play an important role, especially for flat beams
- Those effects can be studied only with multi-particle tracking codes
- Recently two codes have been developed
  - SIRE (A. Vivoli, M. Martini)
    - Currently on "pause"
  - CMAD-IBStrack (T. Demma, M. Pivi)
    - It has the advantage that it can run in parallel mode
    - The work for taking into account the betatron coupling is already in progress

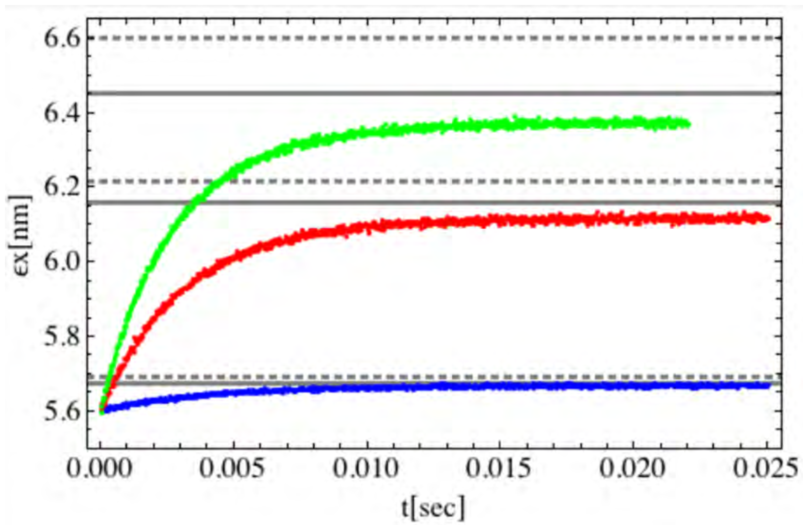
SIRE & CAMD-IBSTrack benchmarking @ the CLIC DR

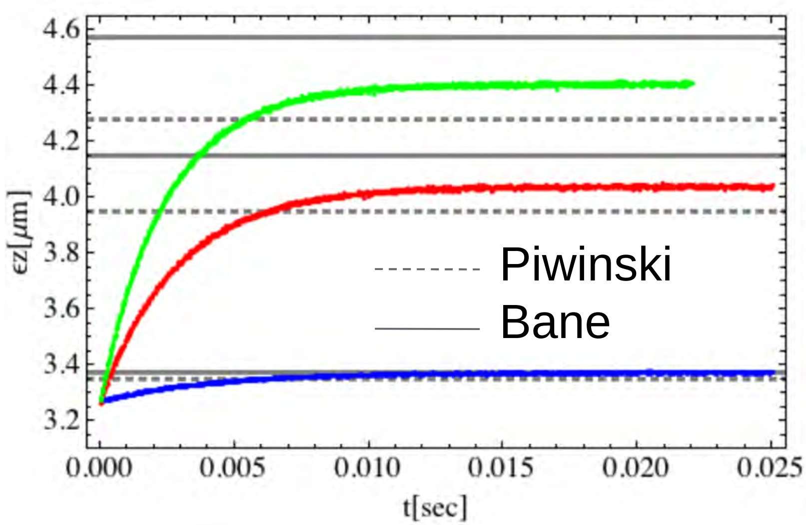




- The SIRE (taking into account vertical dispersion) and CMAD-IBStrack (for zero vertical dispersion) have been benchmarked with the theoretical models (Piwinski, Bjorken-Mtingwa, Bane and CIMP)
- Here the one turn horizontal emittance evolution is shown
  - The agreement with Piwinski is excellent for both cases as expected
  - Even if the agreement with the other models is not perfect, the trend of the emittance evolution is the same
  - Similar are the results for the other two planes too.

CMAD-IBStrack benchmarking @ the SLS





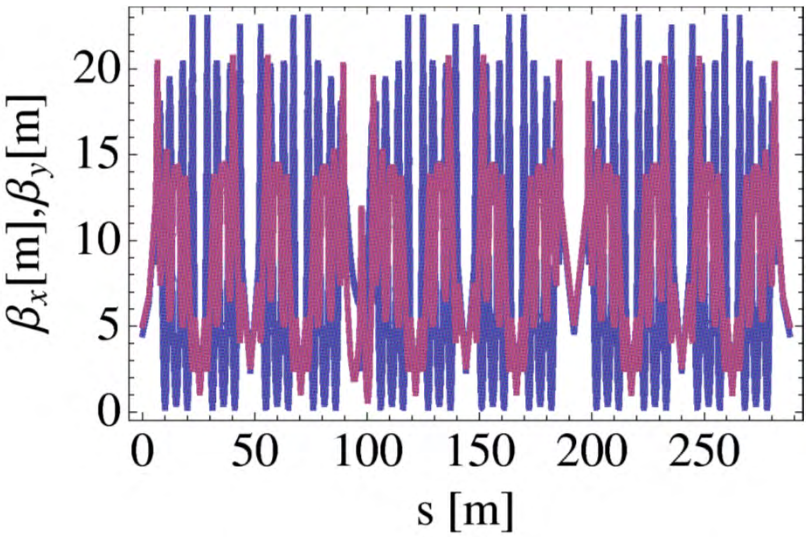
- The output emittances of CMAD-IBStrack was benchmarked with Piwinski (solid, gray) and Bane (dashed, gray), for three different bunch current values (**1mA**, **10mA**, **17mA**), thus at different IBS regimes
  - Excellent agreement between models and code at weak IBS regimes
  - When the effect becomes stronger, the disagreement grows.

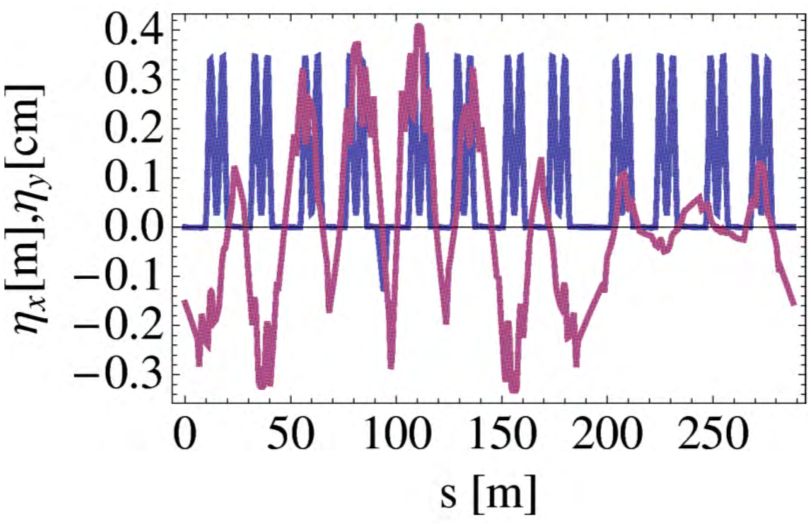
Status of the simulation tools

- *SIRE* has been in "pause" the last 1-2 years but hopefully the development will continue soon
- ***CMAD-IBStrack*** is a very attractive tool, well advanced and with the ability to run in parallel mode which speeds up a lot the calculations
  - We hope to have it installed at CERN too within the next year
- ***ibs-madx*** not a tracking tool but ruther analytical tool → it has been now debugged and crosschecked giving very good results.
  - However, needs to be used carefully
    - There are some notes in the madx-ibs manual and more will come soon

IBS measurements at the SLS and observations at the SPS

IBS measurements at the SLS

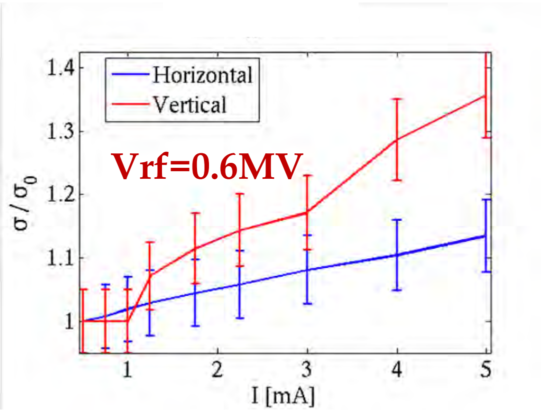


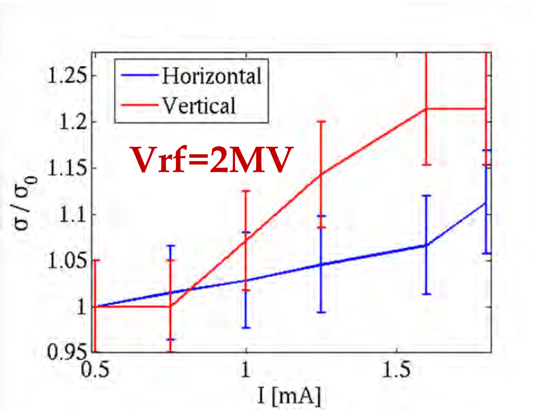


- The SLS is an ideal test-bed for IBS studies as it has:
  - The record vertical emittance of 1 pm rad at nominal energy (2.4 GeV)
  - Availability of emittance monitoring diagnostics (hor./vert. beam size monitors and streak camera for bunch length)
  - Ability to run at lower energies
- A previous study (IPAC12) showed that the effect is not visible at nominal energy, while it is enhanced at low energy.
- 2 measurement campaigns at low energy:
  - May 2012
  - August 2012

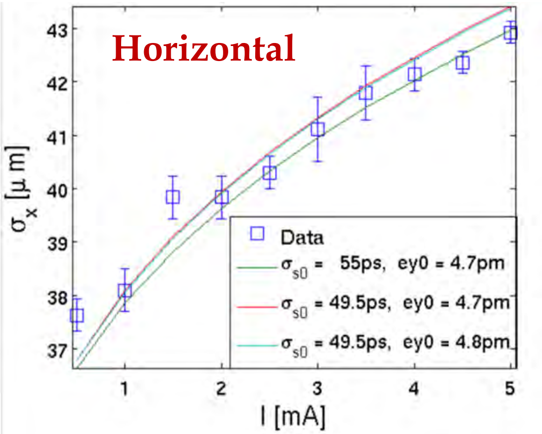
IBS measurements at the SLS

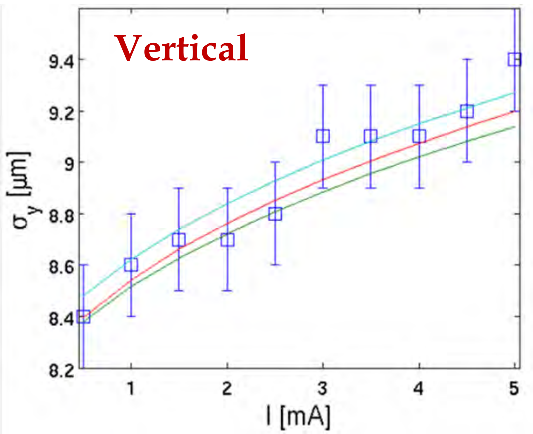
First measurements results of May 2012





Recent measurements results of August 2012



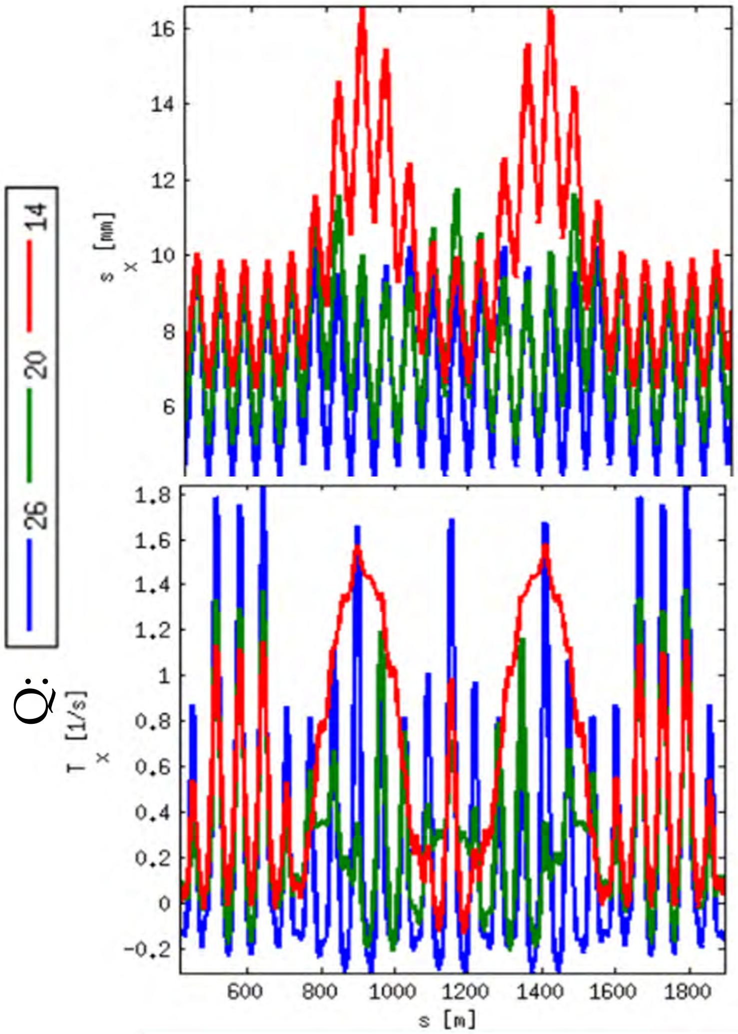


- Beam size measurements at low energy at the SLS
- Results from May measurements at two different RF voltage settings (IPAC12)
  - No comparison with theoretical predictions is possible, due to the fact that the longitudinal motion is dominated by the microwave instability (MI)
- Recent measurements (blue, squares) and IBS expectations (based on CIMP formalism) for different zero current vertical emittance and bunch lengths (solid lines)

Fanouria.Antoniou@cern.ch

Observations for the ion beams at SPS

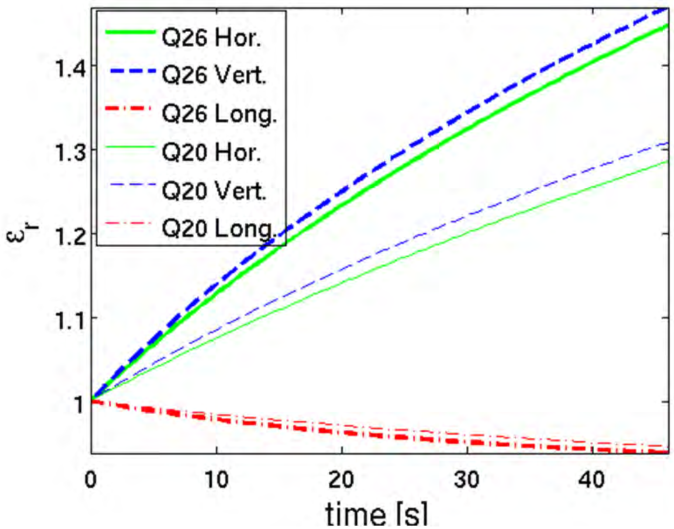
Horizontal beam size in an arc

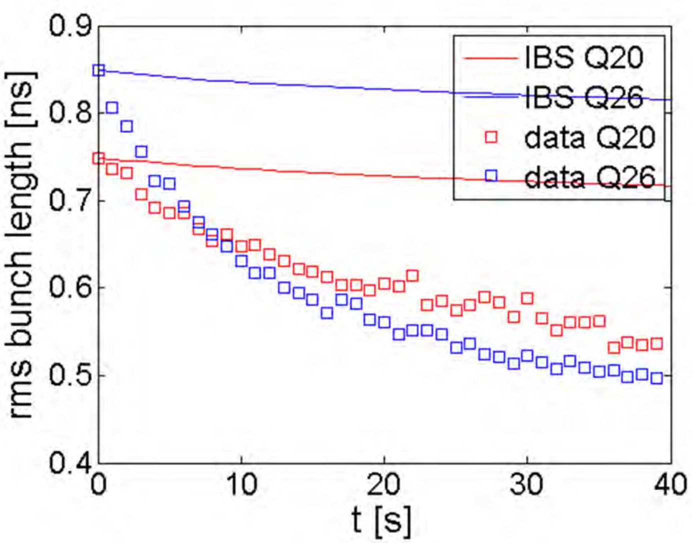


Horizontal IBS growth rates

- During the setting up of the ion beams, it was observed a spread on the parameters of the different bunches
- This doesn't seem to be a limitation for the injection into the LHC
  - However, it is interesting to understand the effect
- Candidate effects:
  - RF noise
  - Scattering effects (IBS, Touschek scattering)
- Proposal to use the Q20 optics to mitigate scattering effects due to larger beam sizes

IBS calculations for the SPS (ions)





- Comparison between the Q20 and Q26 optics under the same initial conditions (transverse emittances, longitudinal emittance and current
- For both optics the theoretical model predicts blow up in the transverse plane and damping in the longitudinal plane (we are below transition)
- For Q20 the blow up of the transverse plane is smaller (~15%) due to larger beam sizes while the effect in the longitudinal plane is almost the same
- Doing the same exercise using the measured current and the measured initial bunch-length → IBS cannot explain the observed damping *!*

Fanouria.Antoniou@cern.ch

Touschek lifetime

- The Touschek effect refers to single particle scattering events with large exchange of momentum
  - Particles get lost due to acceptance limitations (RF or dynamic) with Touschek lifetime given by:

$$\frac{1}{T_\ell} = \left\langle \frac{c r_p^2 \beta_x \beta_z \sigma_h N_p}{8\sqrt{\pi}\beta^2\gamma^4\sigma_{x\beta}^2\sigma_{z\beta}^2\sigma_s\sigma_p} \int_{\tau_m}^{\infty} \left(\frac{\tau}{\tau_m} - 1 - \frac{1}{2}\ln\frac{\tau}{\tau_m}\right) e^{-\tau B_1} I_o(\tau B_2) \frac{d\tau}{\tau^{3/2}} \right\rangle$$

- Considering a general current lifetime expression:

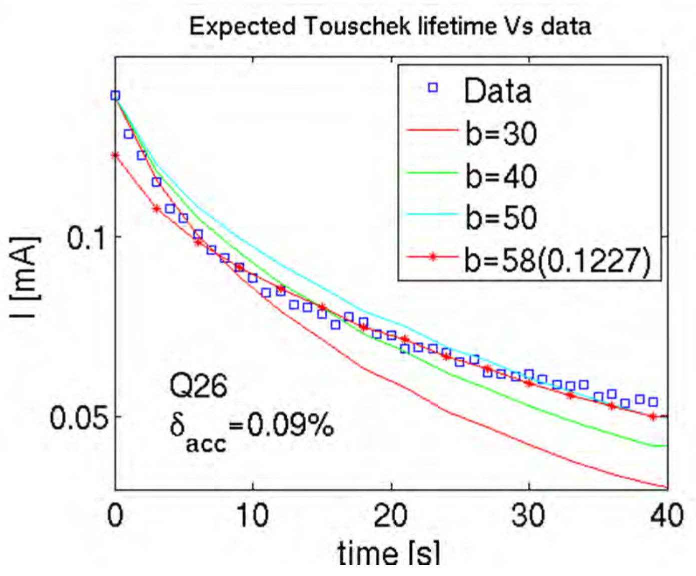
$$\frac{dI}{dt} = -\frac{I}{b} - \frac{I^2}{a} \Rightarrow I(t) = \frac{aI_0 e^{-t/b}}{bI_0(1 - e^{-t/b}) + a}$$

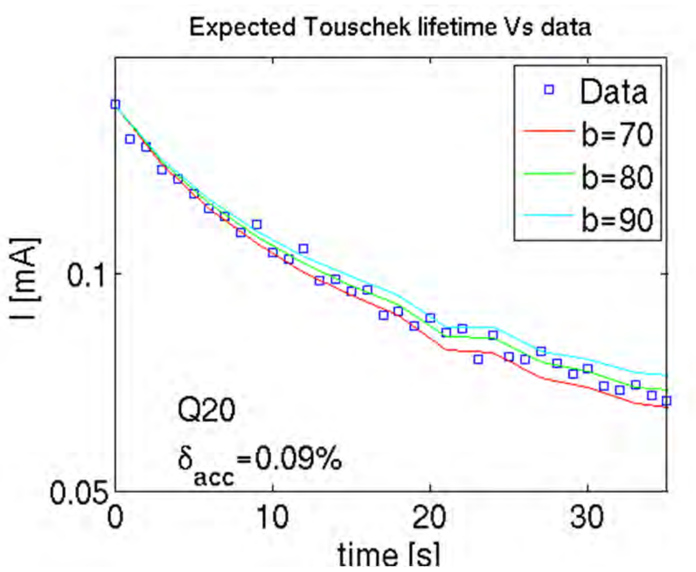
$$\alpha = \frac{e n_e 8\sqrt{\pi}\beta^2\gamma^2\sigma_z\sigma_p\epsilon_x\epsilon_y}{r_e^2 c T_o \left\langle \sigma_H F(\delta_m) \right\rangle}$$

Touschek parameter

δm: minimum acceptance
εx, εy: transverse emittances
σz: bunch length
σp : energy spread

Touschek calculations SPS (ions)





- The touschek parameter was calculated for each meausred bunch length and from this the current
  - The acceptance is considered a constant of the machine (as first approximation)
  - Scan on the acceptance was performed
- The b parameter is a free parameter representing all other (linear) effects and needs to be defined
  - Solid lines show the expected current decay with time for different b values
- For the data with Q26 no b factor can be found for which the "Touschek" curves match with the data
  - Ignoring the first seconds considering fast losses in the beginning, ➔ "Touschek like" behavior
- For the data with Q20 "Touschek like" behavior almost from the beginning which are less sensitive to the b factor
- Those are preliminary results and for the moment what we can state is that a quadratic term is for sure needed in order to describe the current decay for the ion beams

CONCLUSIONS & OUTLOOK

- Intrabeam scattering is an effect which becomes important in high brightness machines and becomes a limitation for their performance
- Systematic optics design optimization is important in order to mitigate the effect
- The theoretical models are not sufficient in order to understand interesting aspects of IBS (generation of non-Gaussian tails, coupling), especially in strong IBS regimes
- Multiparticle tracking codes are very important in order to study and understand those effects and are currently under development
- The ultimate goal is the benchmarking of the codes with the theoretical models and with measurements
- First measurement results are encouraging, however, not easy as it is very important first to be able to disentangle IBS from other collective effects!

THANK YOU!