ICFA mini-workshop on
"Beam-Beam Effects in Hadron Colliders"
March 18th to 22nd, 2013

Summary: Theory and simulations session

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ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Talks

- M. Vogt (DESY) "Analytical and Simulation Tools"
- J. Qiang and S. Paret (LBNL) "Poisson solvers for self consistent multi-particle simulations"
- A. Valishev (Fermilab) "Modeling beam-beam in the Tevatron"
- A. Burov (Fermilab) "Beam-beam, impedance and damper"
- X. Buffat (EPFL/CERN) "Stability diagrams of colliding beams"
- C. Montag (BNL) "Beam-beam effects in space charge dominated ion beams"

M. Vogt
Analytical and Simulation Tools

Motivations weak-strong, strong-strong (coherent and collective), 4D-6D

Summary

- The growing hunger of the experiments for Luminosity assures beam beam theory & simulation will be hot topics as long as colliders are built/operated!

← BB can drive resonances and action diffusion and thus severely degrade beam- & luminosity–lifetime, and background conditions at the experiments.

← It can however, also help provide (incoherent) tune spread and Landau damping.

← Coherent, collectively driven beam–beam modes have been predicted by theory and simulation and have been observed in real machines.

- It appears however, that in many cases they are not by-themselves unstable, i.e. growing.
- Instead they often tend to be either Landau damped or neutrally stable.
- Collective BB–modes are an active interesting field.

- Progress in parallel computing will strongly enhance the simulations in the strong–strong regime.

Beam Beam Models ("Time"–Continuous)

For the moment : only one short bunch per beam and **head–on w/o crossing angle**, only one IP.

- **Phase space densities :**
  $\Psi(\vec{z},\theta)$ & $\Psi^\star(\vec{z},\theta)$
- **SSBB (the real thing!) :**
  dependence of H ($H^\star$) on $\Psi^\star$ (Ψ) :
  $H[\Psi^\star] = H_0 + U^{ss}[\Psi^\star]$
  $H^\star[\Psi] = H_0^\star + U^{ss\star}[\Psi]$
- via $\rho(\vec{q},\theta) := \int \Psi(\vec{q},\vec{p},\theta)\, d^n p$
  & $\rho^\star(\vec{q},\theta) := \int \Psi^\star(\vec{q},\vec{p},\theta)\, d^n p$
- $U^{ss}[\Psi^\star](\vec{q}) \propto \int G(\vec{q}-\vec{q}\,')\rho^\star(\vec{q}\,')d^n q'$,
  G : Green's function

$\Rightarrow$ Evolution of trajectories $\vec{z}(\theta)$, $\vec{z}^\star(\theta)$ needs **up to date** densities Ψ, $\Psi^\star$ (both!) : ($\underline{J}$: symplectic structure)

$$\frac{d}{d\theta}\vec{z} = \underline{J}\,\partial_{\vec{z}} H[\Psi^\star](\vec{z},\theta)$$
$$\frac{d}{d\theta}\vec{z}^\star = \underline{J}\,\partial_{\vec{z}} H^\star[\Psi](\vec{z}^\star,\theta)$$

$\rightarrow$ so, why not skip the trajectories ?!

$$\partial_t\Psi = \{H[\Psi^\star],\Psi\} \equiv (\partial_{\vec{z}}\Psi)^{\mathrm{T}}\underline{J}\,(\partial_{\vec{z}}H[\Psi^\star])$$
$$\partial_t\Psi^\star = \{H[\Psi],\Psi^\star\} \equiv (\partial_{\vec{z}}\Psi^\star)^{\mathrm{T}}\underline{J}\,(\partial_{\vec{z}}H[\Psi])$$

$\rightarrow$ SSBB coupled Vlasov–Poisson eq's
$\rightarrow$ **coupled system of 2 non–linear 1-st order PIDEs**

$\rightarrow$ Can treat coherent (and incoherent) motion and **collective** interactions

- **WSBB :** $\Psi^\star$ given & **fixed** $\forall$ turns
  $\rightarrow$ study only $\vec{z}(\theta)$ (and/or $\Psi(\vec{z},\theta)$)
  $\rightarrow$ $U^{ws}(q) \equiv U^{ss}[\Psi^\star_{\text{fixed}}](q)$
- $\frac{d}{d\theta}\vec{z} = \underline{J}\,\partial_{\vec{z}} H^{ws}(\vec{z},\theta)$ $\leftarrow$ Can. eq's
- $\partial_t\Psi = \{H^{ws},\Psi\}$ $\leftarrow$ Liouville eq.
  $\rightarrow$ **linear 1-st order PDE**

$\rightarrow$ Can **NOT** treat collective effects.

6 D multi particle is the ultimate way to have FULL PHYSICAL PICTURE of the BB effects. interaction, but time consuming, also parallel computation limited NlogN. Not enough! New Technology? Can we make it faster? Simplify where we think is possible (based on physical arguments)!

J. Qiang and S. Paret

Poisson solvers for self-consistent multi-particle simulations

Different Boundary/Beam Conditions Need Different Efficient Numerical Algorithms

BERKELEY LAB

FFT based Green function method:

- Standard Green function: low aspect ratio beam
- Shifted Green function: separated particle and field domain
- Integrated Green function: large aspect ratio beam
- Non-uniform grid Green function: 2D radial non-uniform beam

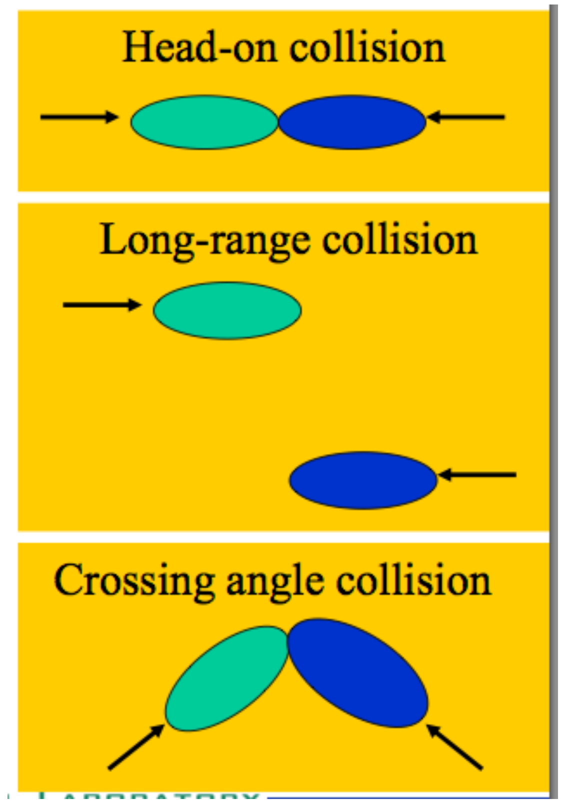
Fully open boundary conditions

Spectral-finite difference method:

2D open boundary
Transverse regular pipe with
longitudinal open

Multigrid spectral-finite difference method:

Transverse irregular pipe

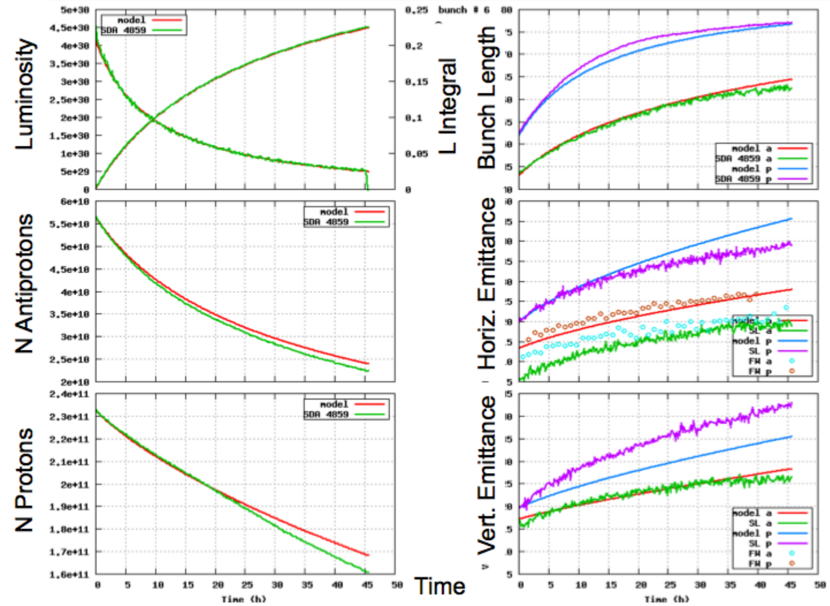


- BB modeling depends on Poisson Solvers
- Choice of solver depends on interaction type
- Right choice makes things easier (reduce computing time), **optimization is FUNDAMENTAL**

A. Valishev

B. Modeling beam-beam in the Tevatron

Store 4859, L_0=1.70x10^{32} New Helix



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Modeling is essential to track improvements or degradation of performance and spot the sources

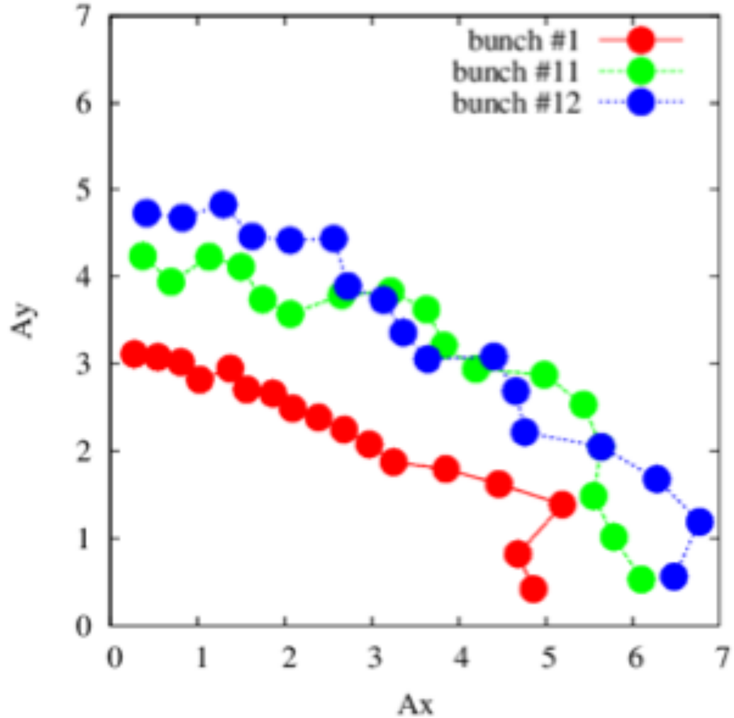
Beam-Beam in Overall Picture

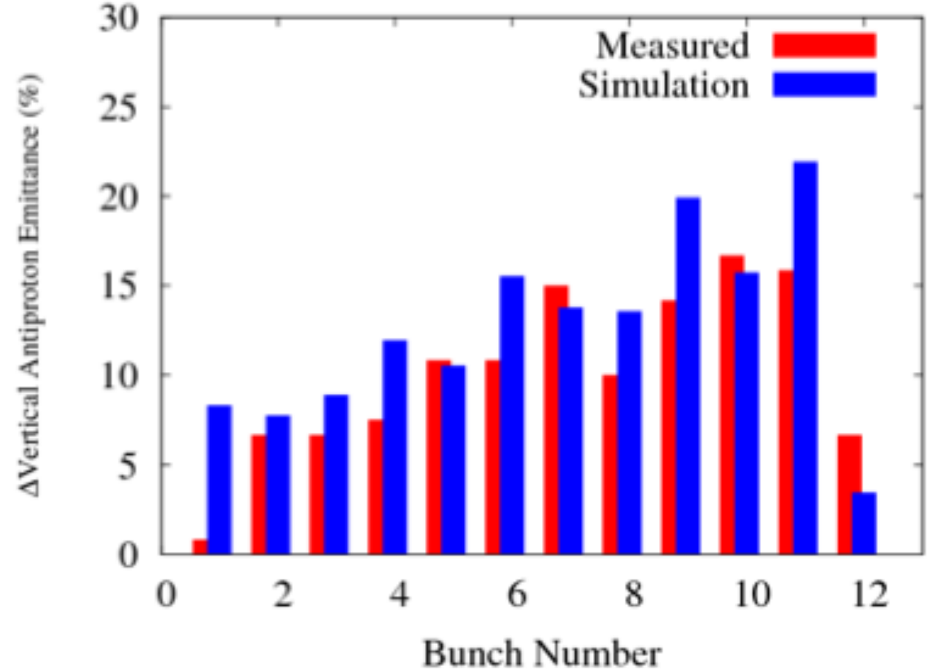
- Beam-beam is not the single effect determining the evolution of luminosity. Tevatron luminosity lifetime was significantly affected by
  - Luminous particle losses
  - Intrabeam scattering
  - Beam-gas scattering
  - Noise
- Tevatron strived to extract every % of potential integrated luminosity from beams delivered by injectors
- A comprehensive model of luminosity evolution was necessary to understand the quantitative significance of beam-beam effects

- **Develop models to get as close as possible to the reality**
- **To define how far you are from reality!**
- **All data → means DIAGNOSTIC as input and as out-put to verify models**

A. Valishev
B. Modeling beam-beam in the Tevatron

DA vs Multiparticle: Emittance





All modeling should take into account for PACMAN diversities.
Confidence in model when LR variations are reproduced.
We model multi-bunch so we need MULTI BUNCH DIAGNOSTIC to validate models.

A. Burov
B. Beam-beam, impedance, damper

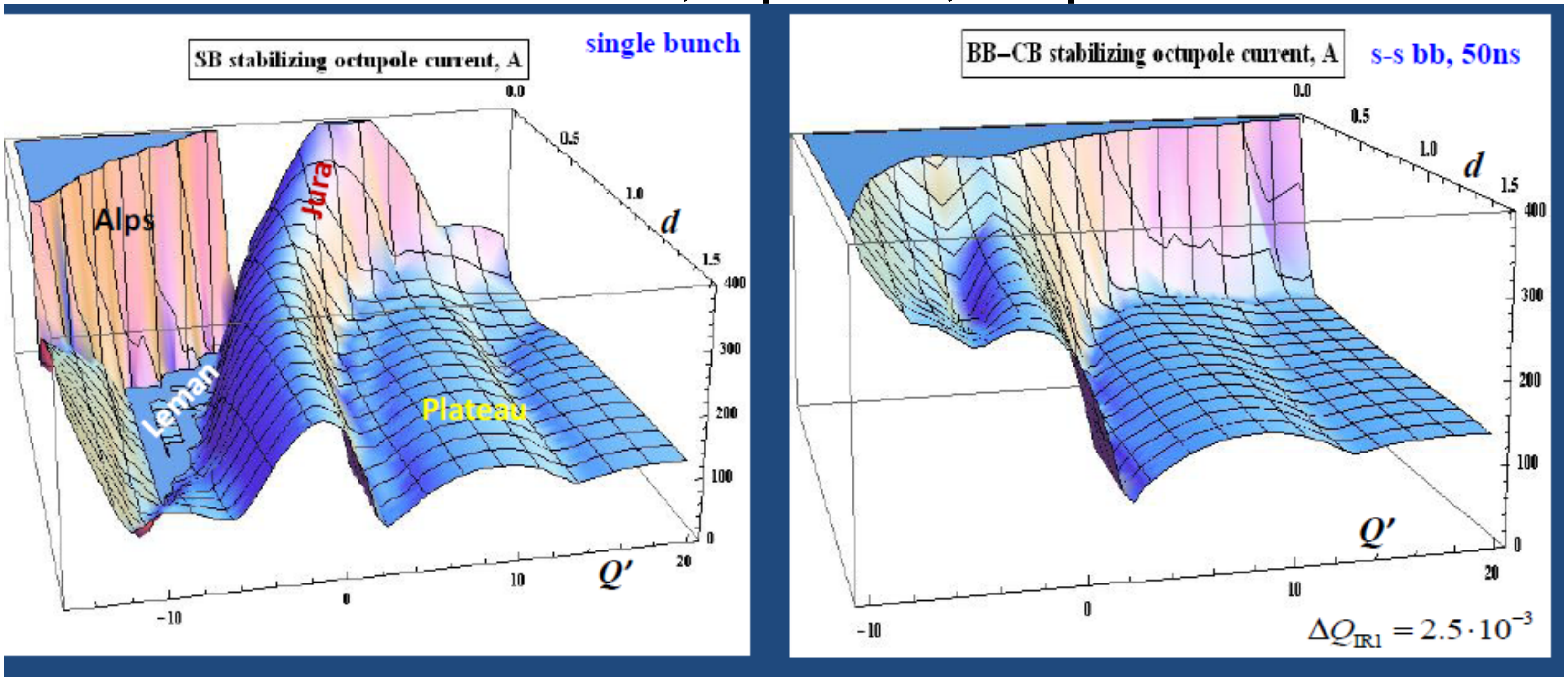
Nested Head-Tail Vlasov Solver (AP Forum 4/12/12)

- NHT is my Mathematica-based program for LHC-type beam stability analysis. It accepts the following external data:
  - Inter- and intra-bunch wakes (arbitrary functions);
  - Damper with provided gain frequency profile;
  - Beam-beam collision scheme;
  - Octupoles and beam-beam nonlinearity;
  - Bunch distribution function.
- The code computes:
  - Azimuthal, radial, coupled-bunch and beam-beam modes;
  - Beam stability thresholds.

- NHT was cross-checked with BeamBeam3D tracking simulations (S. White), showing a full agreement.

- **INTERPLAY of effects is the key to understand the complex picture of beam-beam in an operating machine.**
- **Complexity needs step by step understanding and going to the FULL picture.**
- **Different models should agree within their approximations**

A. Burov
B. Beam-beam, impedance, damper



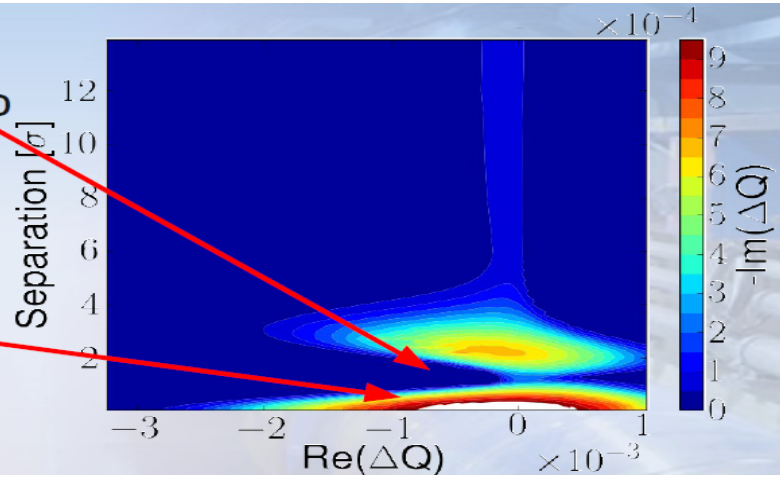
→ NHT model predicts very little differences for the cases with and without beam-beam
In the presence of high damper gain and chromaticity

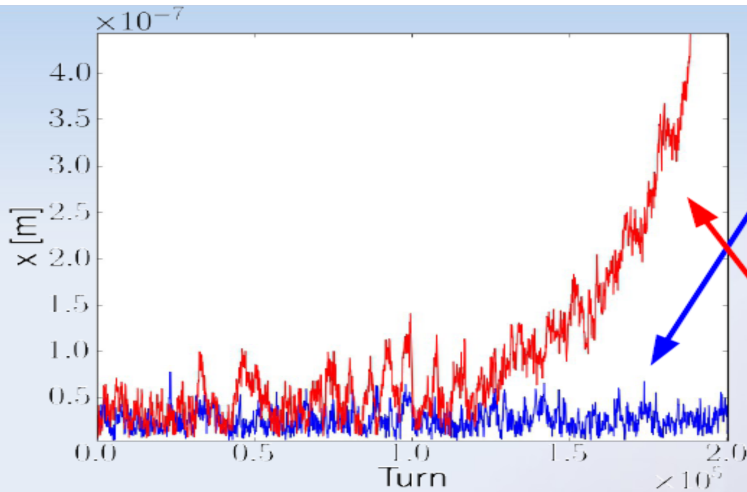
- A model of three-beam instability was suggested: 2 LHC beams plus e-cloud in the high-beta area of IR1 and IR5.

Interplay of effects changes stability.
By increasing complexity in models we get new picture.
Speculations are useful to boost new ideas but models have to follow the reality,
bench-mark to data should be a priority progressing with development!

X. Buffat
Stability diagrams of colliding beams

- Reduction of the stability diagram, possibly leading to loss of Landau damping for impedance driven mode
- Very large stability diagram once colliding head-on



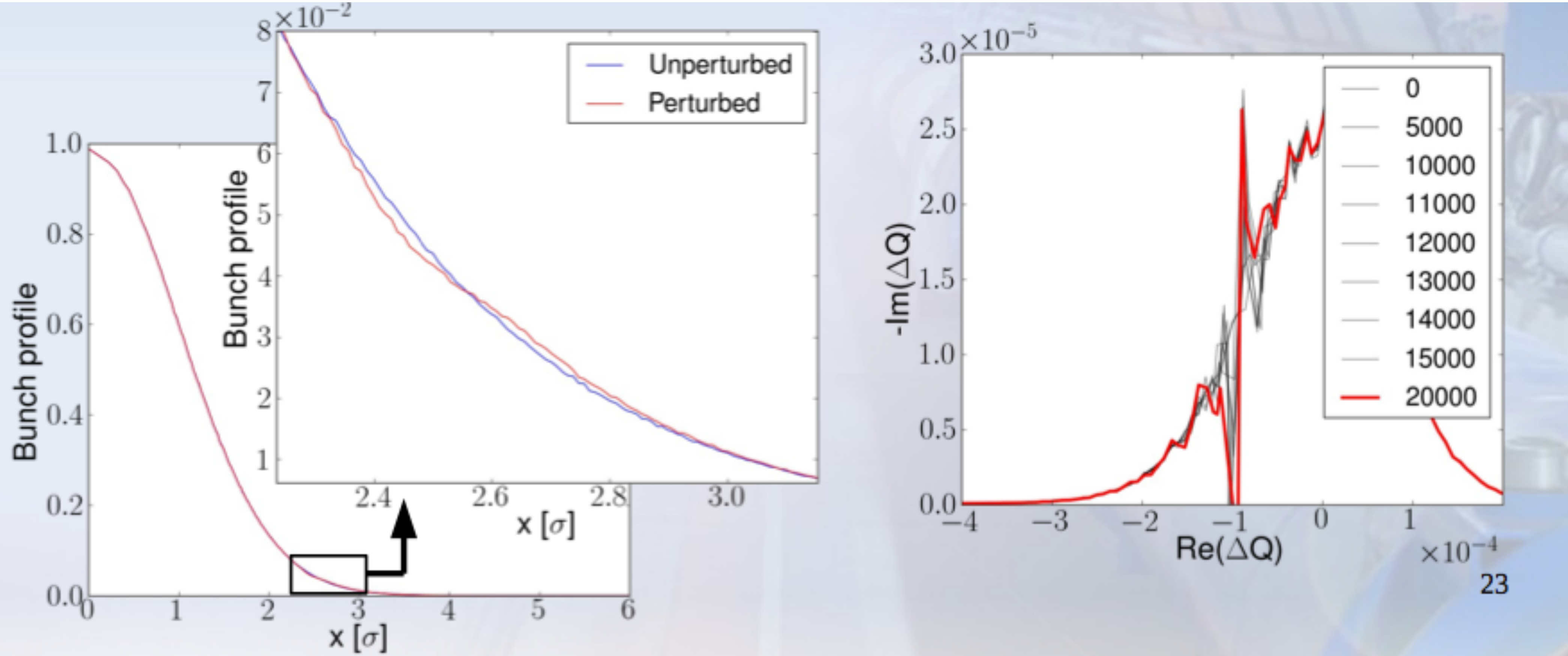


Stable with transverse damper and octupole

Rendered unstable by wide band noise of amplitude $10^{-4}\sigma_{px}$

Stability has to be ensured at any moment during a fill.
Modeling as to go on-line with the machine to avoid unforeseen moments?
Modeling and simulations should follow operation.
Finer studies offline.
How can we make BB tools flexible, fast and reliable?

X. Buffat
Stability diagrams of colliding beams



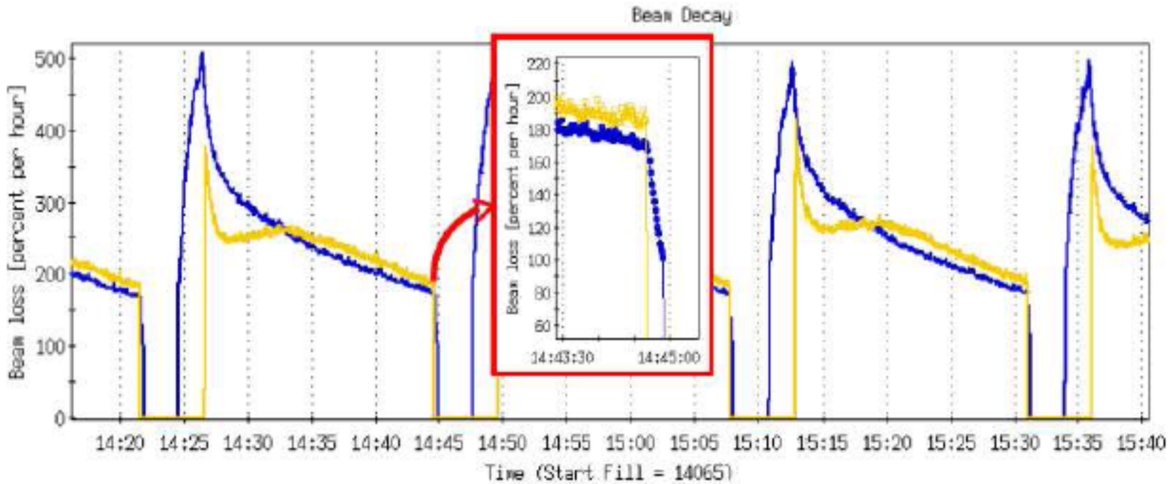
Stability is guaranteed by octupoles, LR, ….all rely on tails particle.

Can tails be deteriorated? How can deterioration in tails affects stability?

Detailed studies needed !

How can we make sure we have the stability we calculate? Halo monitor!

C. Montag and A. Fedotov
Beam-beam effects in space charge dominated ion beams



Blue beam decay improves dramatically as soon as Yellow Is dumped

Though DQBB << DQSC, strong effect on lifetime

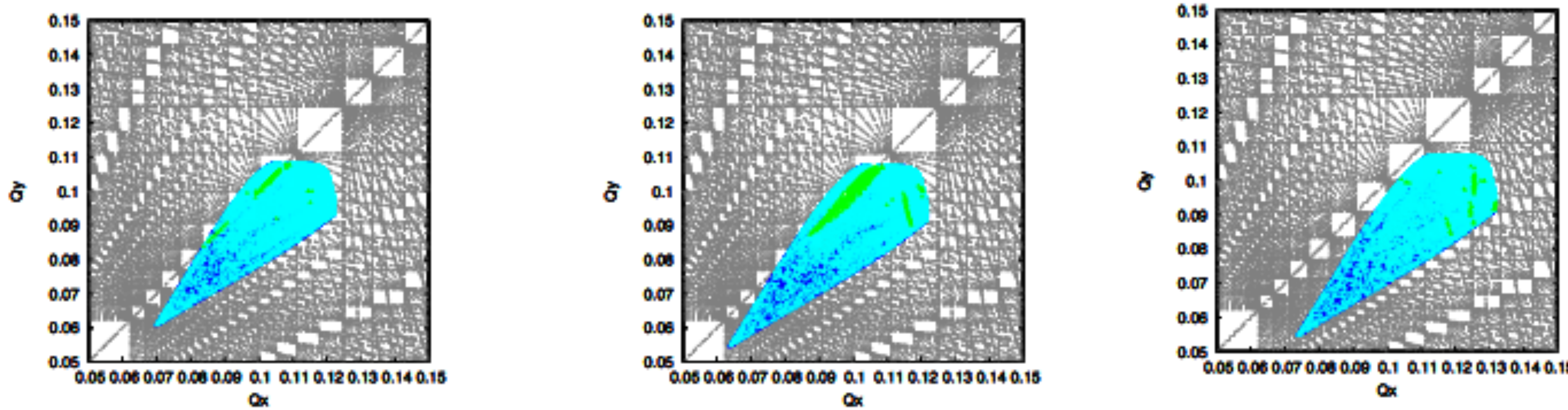
Space Charge Tune Shifts, Beam-Beam Parameters, and Lifetime

E [GeV/n]	ΔQ_{sc}	$\xi_{beam-beam}$	τ [sec]
9.8	0.03	0	2000
9.8	0.03	0.002	600
5.75	0.05	0	1600
5.75	0.05	0.0015	400
5.75	0.09	0	700
5.75	0.09	0.0027	260
3.85	0.11	0	70
3.85	0.08	0.003	70

Typical beam-beam parameter is more than factor 10 smaller than space charge tune shift
Lifetimes drop by factor 3-4 when beam-beam collisions are added

C. Montag and A. Fedotov
Beam-beam effects in space charge dominated ion beams

Tune footprints



- Beam-beam enhances coupling resonance
- Greater tune split may be beneficial

Beam-beam alone seems armless and dynamics should be dominated by Space Charge.
INTERPLAY of the two effects shows deterioration of parameters.
Sensitivity to coupling resonances

Keywords:

- **Optimization** calculations
- **Right Poisson solver** for right problem! Makes life (computation time) easy
- **Interplay** of effects NOT only beam-beam (SC, Impedance, damper…)
- **Bench-mark to data** during evolution of complex models multi-bunch
- **Multi-bunch Diagnostic** essential!
- **“On-line”** to avoid un-foreseen settings of the machine

Thanks you