LHC Beam-Beam Compensator

– Physics Concepts and Constraints –

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for and with input from:
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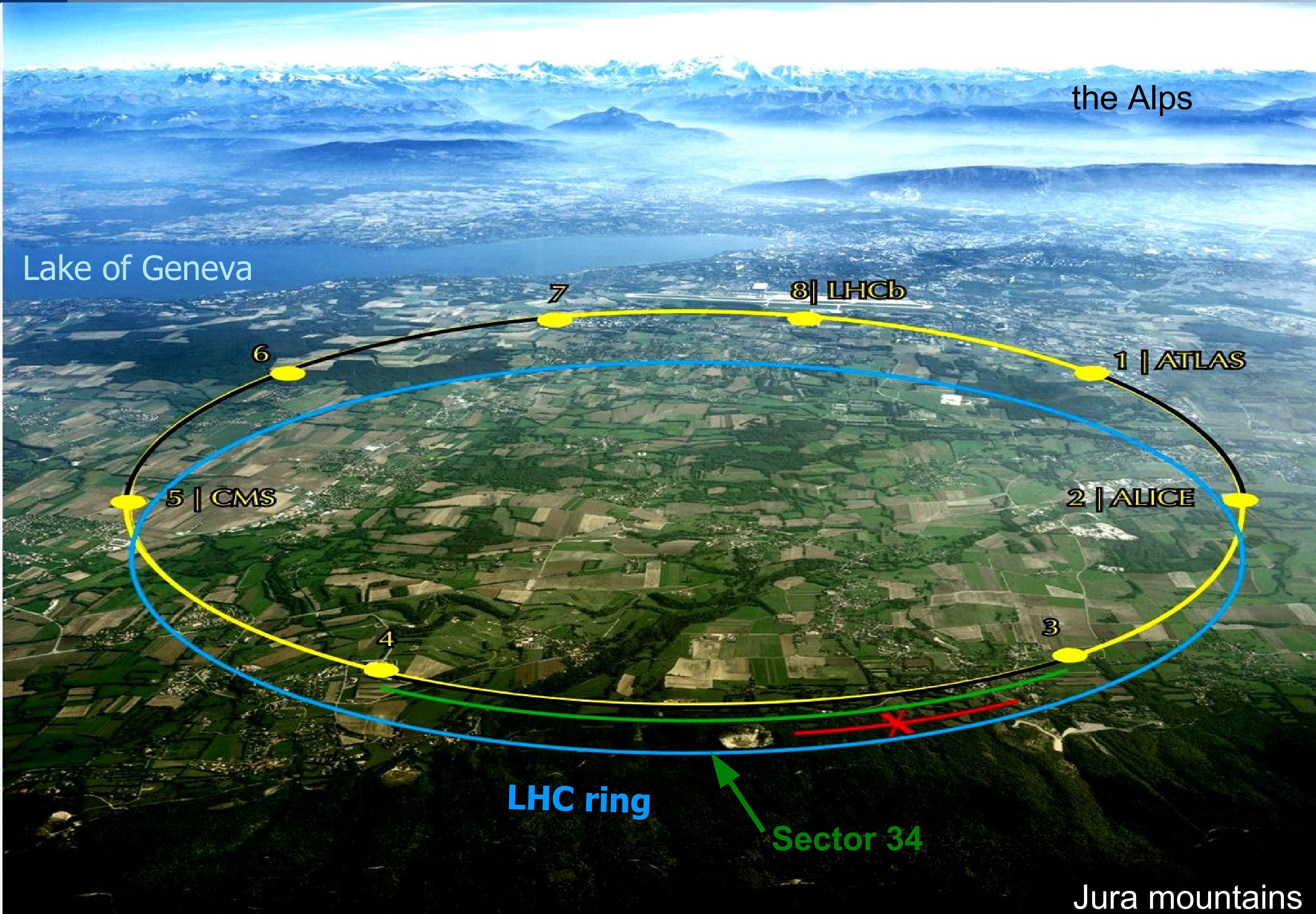
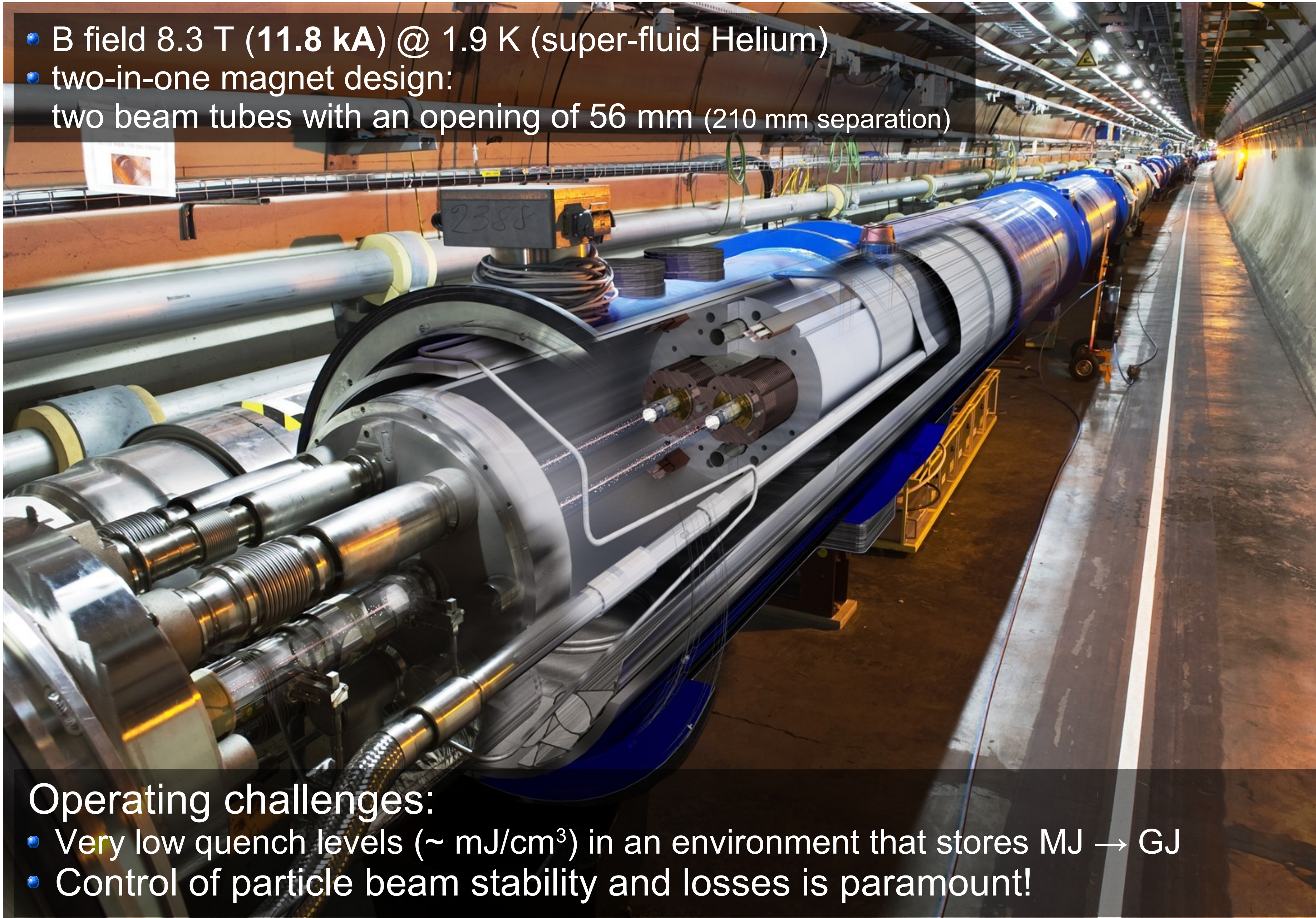
J. Wenninger (MPP), F. Zimmermann (ABP lead), M. Zerlauth

The Large Hadron Collider LHC
Installed in the LEP tunnel, 27 km, Depth of 70-140 m



27 km Circumference – 1232 LHC dipole magnet

- B field 8.3 T (**11.8 kA**) @ 1.9 K (super-fluid Helium)
- two-in-one magnet design:
  two beam tubes with an opening of 56 mm (210 mm separation)



Operating challenges:

- Very low quench levels (~ mJ/cm^3) in an environment that stores MJ → GJ
- Control of particle beam stability and losses is paramount!

Maximum LHC Energy of 7 TeV

- LHC superconducting dipoles may loose superconducting state (“quench”)

  minimum quench energy E_{MQE} @7 TeV for t~10 – 20 ms

  $$E_{MQE} < 30\ \text{mJ/cm}^{-3} \quad \text{vs.} \quad E_{stored} = 350\ \text{MJ/beam}$$

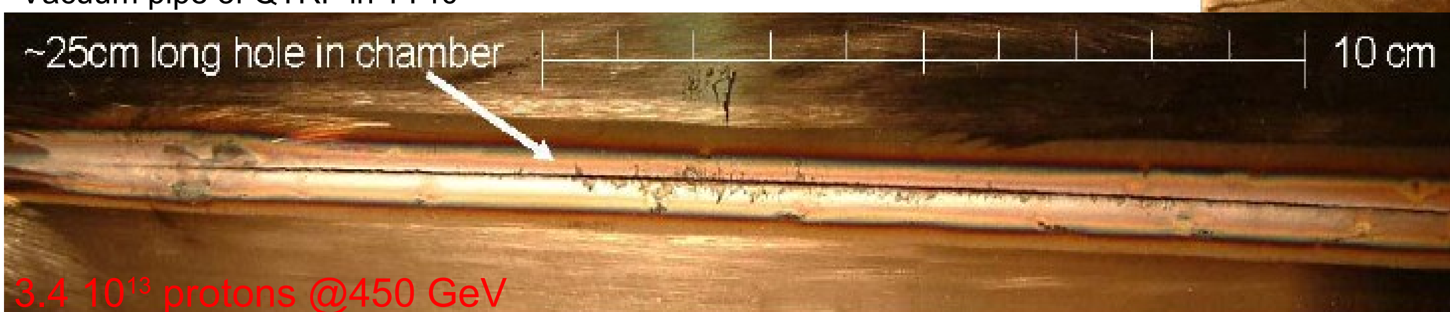
  → sufficient to quench all magnets and/or may cause serious damage

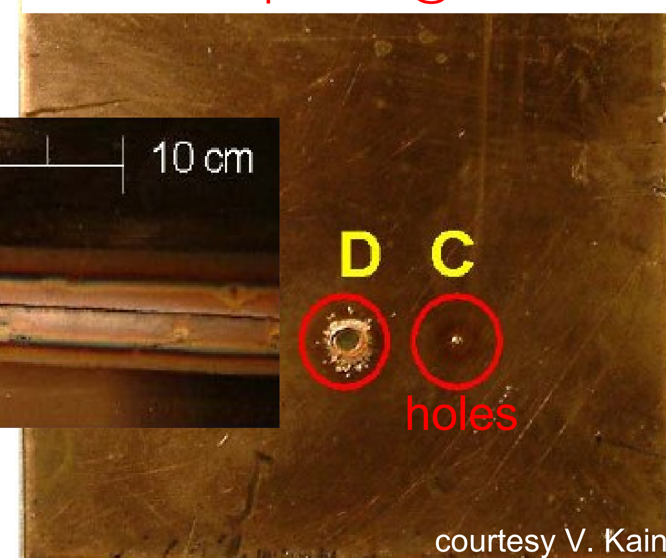
  - requires excellent control of particle losses

Example: un-controlled vs. controlled energy release

C = 5.4 10^{12} protons @ 450 GeV
D = 7.9 10^{12} protons @ 450 GeV

Vacuum pipe of QTRF in TT40

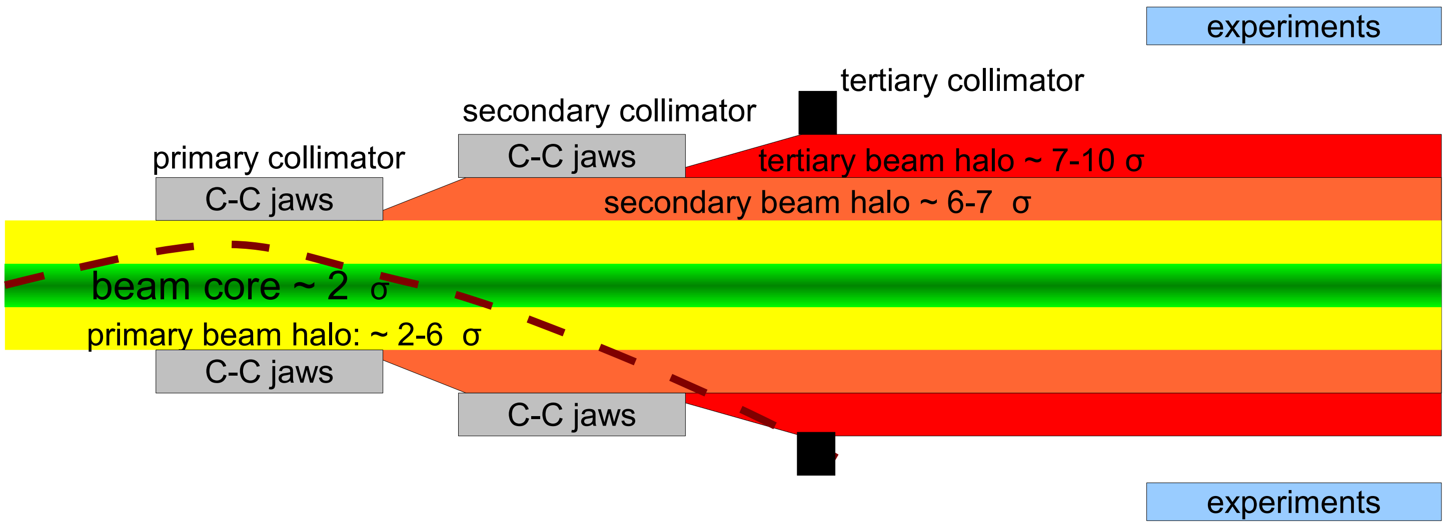




for details see: Chamonix XIV:
“Damage levels - Comparison of Experiment and simulation” and PAC'05

LHC Collimation and Protection System

A) Passive protection: two(/three)-stage cleaning and collimation system



- requires tight orbit stability requirement ~ 25 µm at collimator jaws
  → ~¼ of human hair thickness
- strong robustness requirement of objects closer than tertiary collimators

B) Active Protection: detect unsafe beam conditions → extract beam

- suite of highly redundant devices: beam loss monitor, beam position monitor, quench protection system, …
  → aims at Safety-Integrity-Level SIL-3 to SIL4
  (one critical failure every 10k yrs.)

The Large Higgs Factory at CERN
Collider Ingredients for Mass-Production

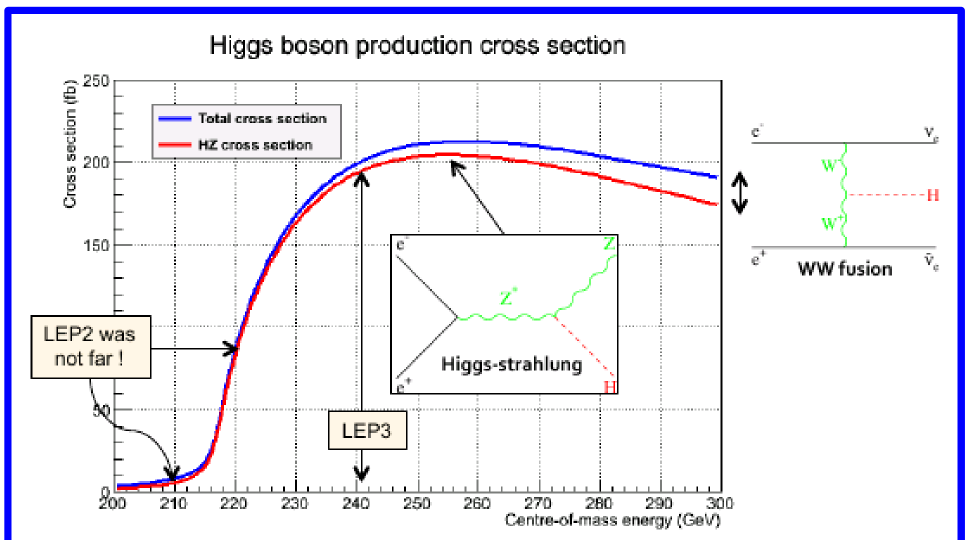
Event Rate → the frequency a given particle is created per second
Physics detectors

cross-section → probability that a given particle is created
Mother Nature defines that for us and typically depends on energy

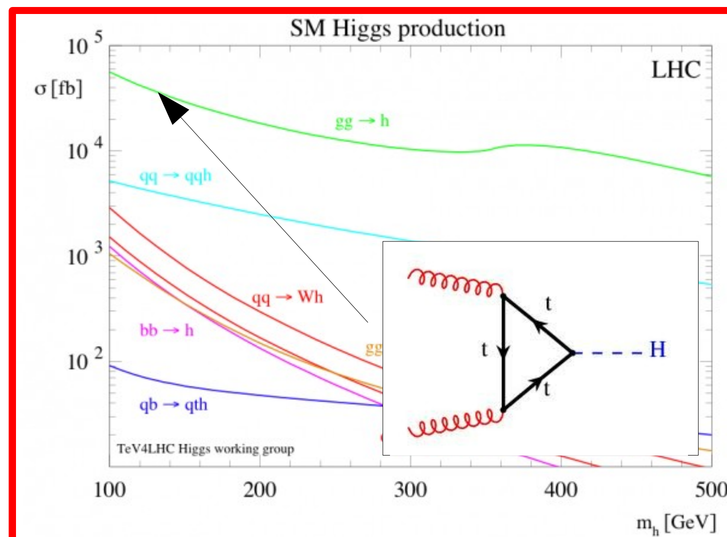
$$\dot{N}_{event} = L \cdot \sigma_{physics}$$

Luminosity → the frequency of how often the particles are brought in to collisions
Accelerator design and operation

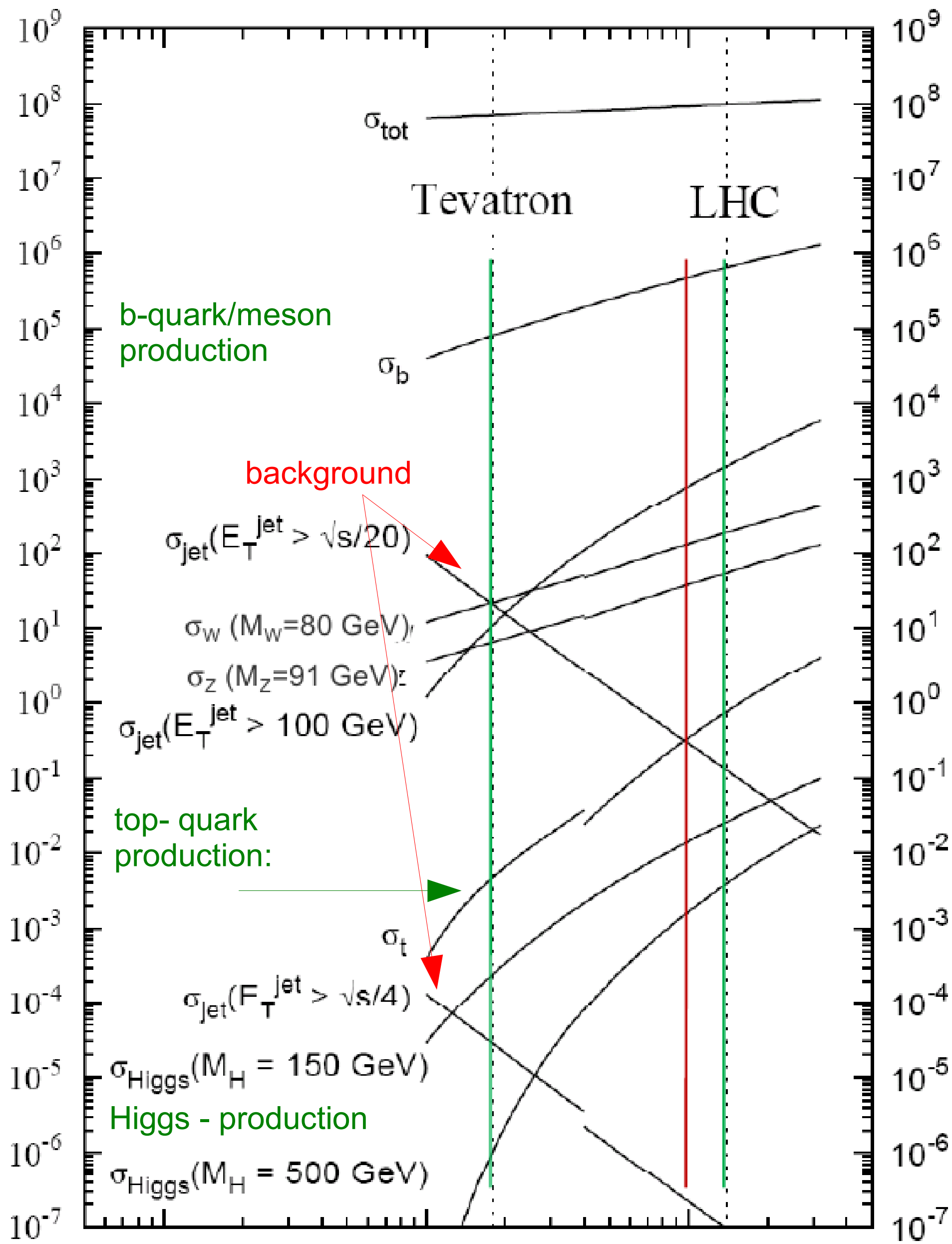
e^+e^- Collider: $\sigma_H < 0.2$pb



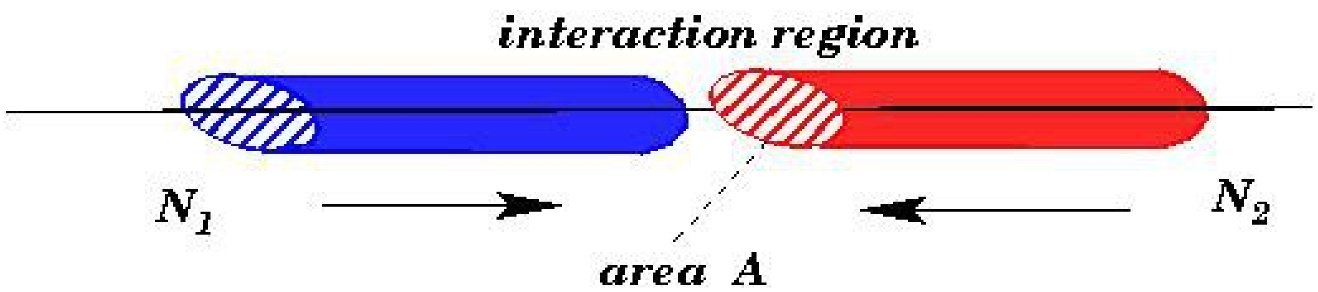
Hadron Collider: $\sigma_H \approx 30$pb !!
vs. $\sigma_{total} \approx 70$ mb



Competitive HEP needs highest possible collision energies



- Collider design:



$$L_{peak} \approx \frac{f_{rev} k_b \cdot N_b^2}{4\pi\sigma_x\sigma_y} \cdot F = \frac{f_{rev}\,\gamma\,k_b \cdot N_b^2}{4\pi\beta^*\epsilon_n} \cdot F$$

$$\sigma_{x,y} = \sqrt{\frac{\epsilon^*\beta(s)}{\gamma}} + \ldots$$

- N_b: number of particles per bunch,
- k_b: total number of bunches,
- σ_x, σ_y: hor./vert. r.m.s. beam size in IR,
- f_{rev}: revolution or repetition frequency,
- $F_{corr.}$: numerical correction factors (hour-glass, crossing angle, ...),
- ε: emittance (invariant of motion, ~”temperature of bunch”)

Recipe to Maximise Luminosity Production

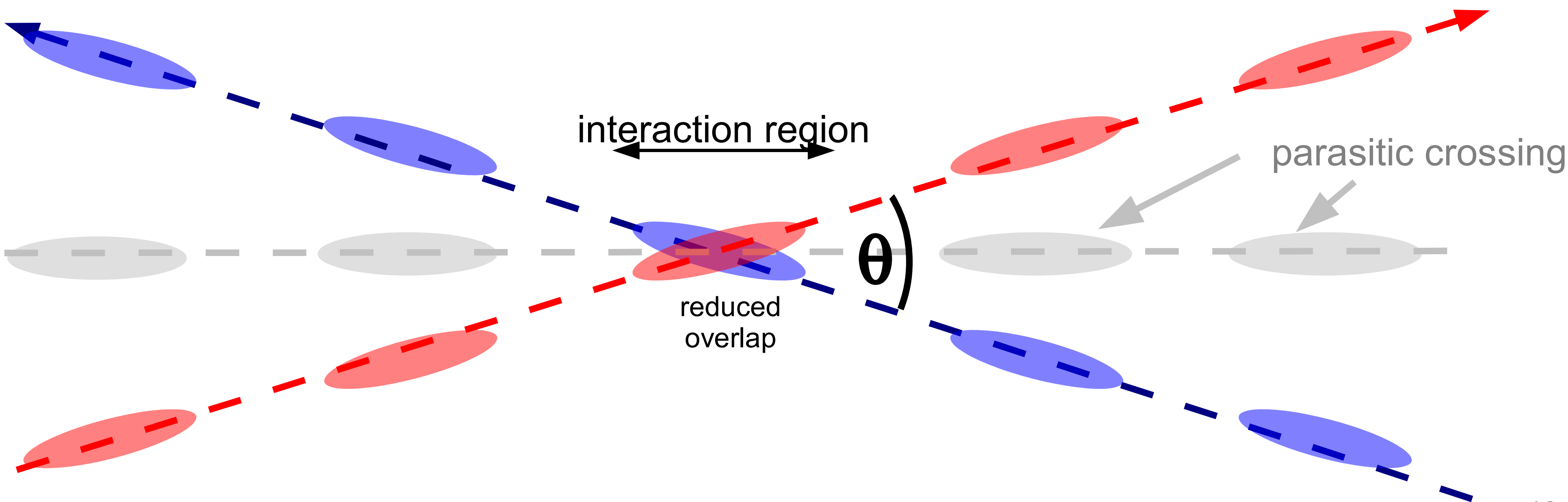
$$L_{peak} \approx \frac{f_{rev} k_b \cdot N_b^2}{4\pi\sigma_x\sigma_y} \cdot F = \frac{f_{rev}\gamma k_b \cdot N_b^2}{4\pi\beta^*\epsilon_n} \cdot \boxed{F}$$

crossing-angle/
beam-beam

- Minimise final focus β* – ultimate limit: hour-glass effect
- Maximise beam brightness 'N_b/ε' – limited by pre-injectors
    - typ. beam sizes: σ_{IP} ~ 15 μm & σ_{arc} ~ 200 – 1000 μm
- Maximise number of bunches/stored beam '$k_b N_b$'
    - limits: collective effects, beam power, collimation and MP
        - typ. N_b ~ 1.2, 1.7, $2.2 \cdot 10^{11}$ protons per bunch
- Minimise lumi-reduction factor, i.e. for LHC "$F_{crossing\text{-}angle}$"
- Provide "useful" integrated luminosity
    - trade-off between peak-luminosity and pile-up
    - overall efficiency, minimise instabilities or down-times

- Need to introduce crossing angle θ to avoid additional parasitic crossings
  → reduces bunch overlap (reduced luminosity), two optimisations:
  - "crab cavities" rotating the bunches before and after the IR
  - beam-beam compensator (BBC) mitigating effect of long-range interactions
  - present LHC: $F_{crossing} \approx 0.7 \rightarrow$ future ~ 0.2

$$L = L_0 \cdot F_{crossing} \cdot \ldots \qquad F_{crossing} = \frac{1}{\sqrt{1 + \frac{\sigma_s}{\sigma_{x,y}} \tan(\theta/2)}}$$



Example: Squeezing in ATLAS Beam Envelope

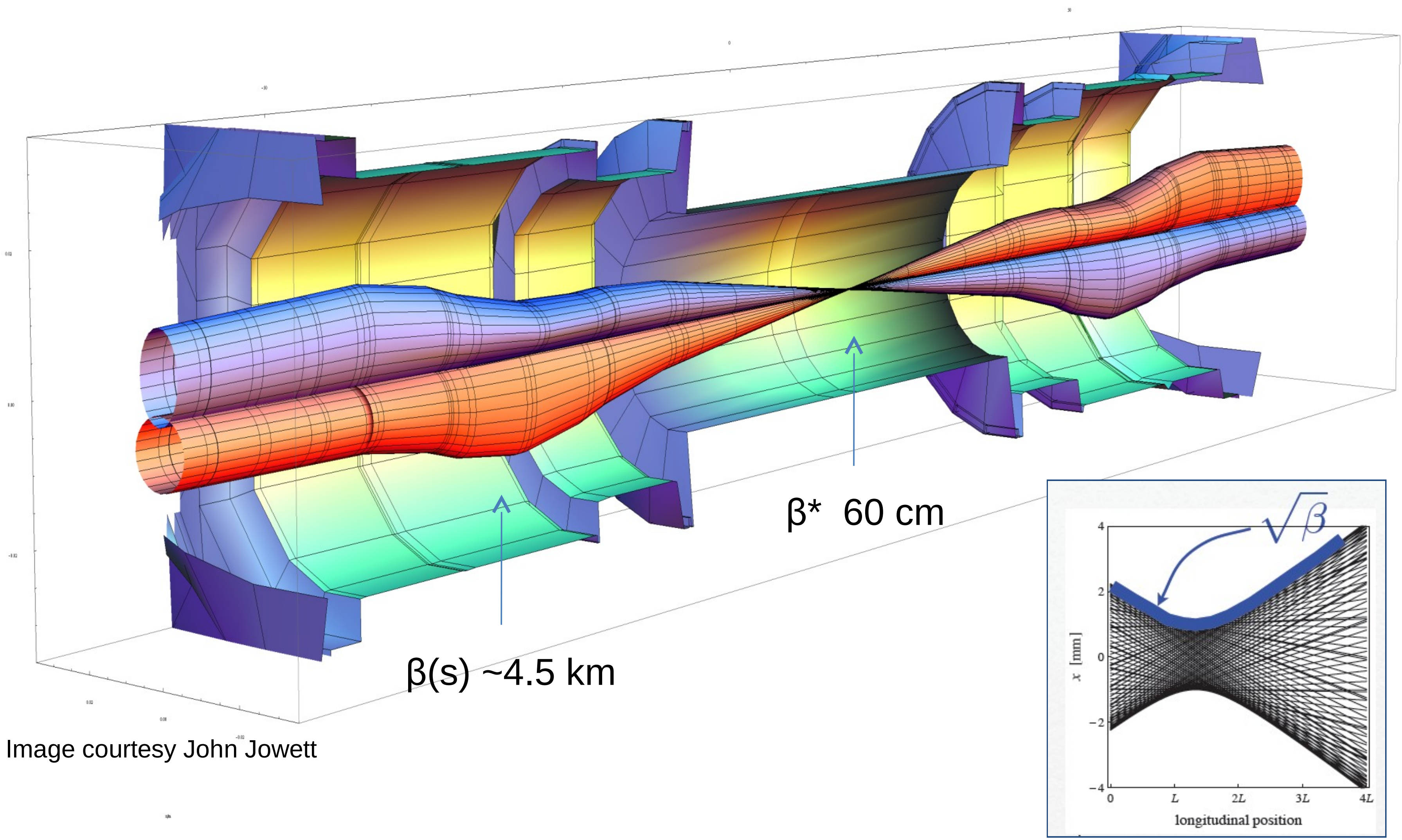


Image courtesy John Jowett

A more formal Approach: Hill's Equation

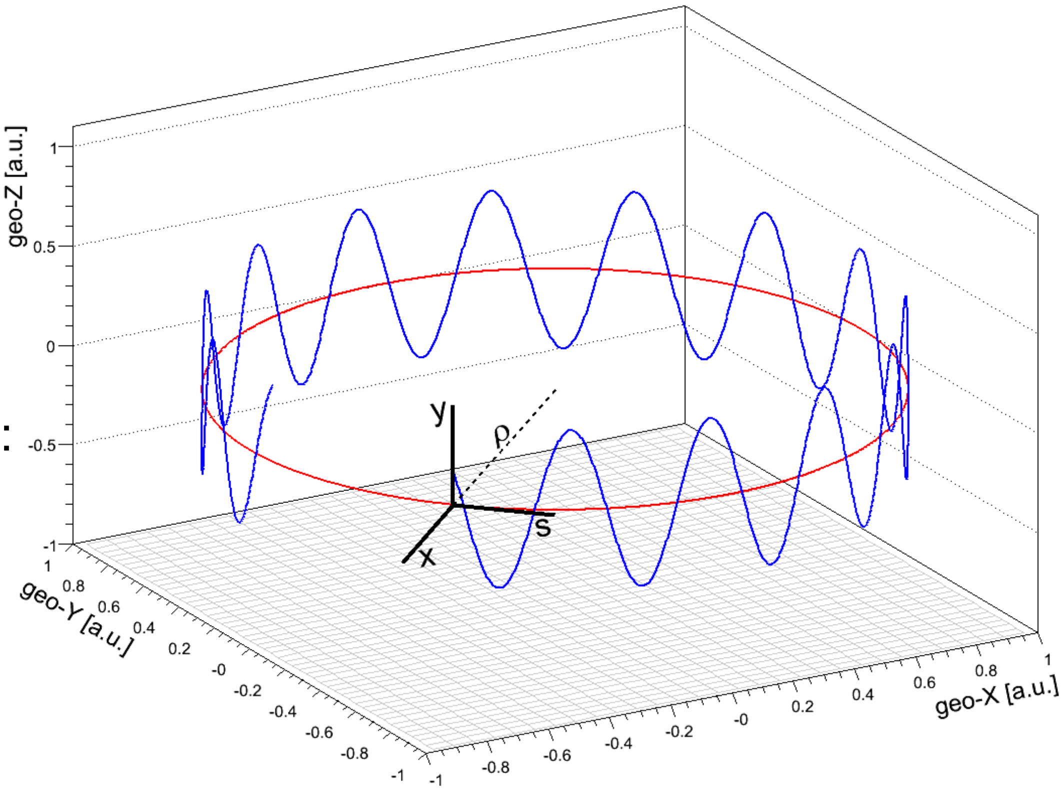
Hill's equation

... the mother of all accelerator physics:

$$z'' + k(s)\cdot z = f(s,t)$$

k(s): focusing strength, defines:
phase advance μ(s)
betatron function β(s)

f(s,t): driving force



first-order solution:

$$z(s) = \underbrace{z_{co}(s)}_{closed\,orbit} + \underbrace{D(s)\cdot\frac{\Delta p}{p}}_{dispersion\,orbit} + \underbrace{z_\beta(s)}_{betatron\,oscillations}$$

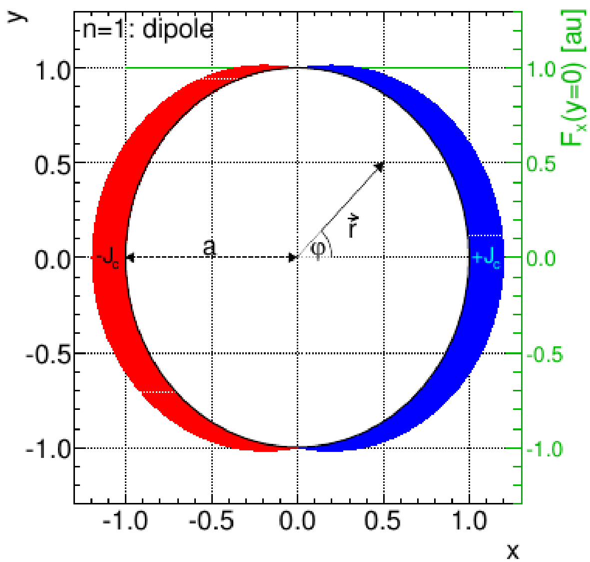
$$z_\beta(s) = \sqrt{\epsilon_i \beta(s)} \cdot \sin(\mu(s) + \phi_i)$$

ε_i, Φ_i *: initial particle state*

- Hill's Equation

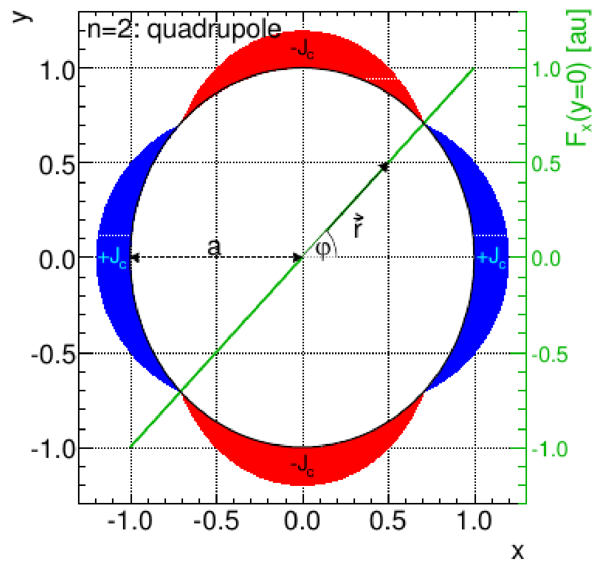
$$z'' + k(s)\cdot z = f(s,t)$$

Dipole:
constant field



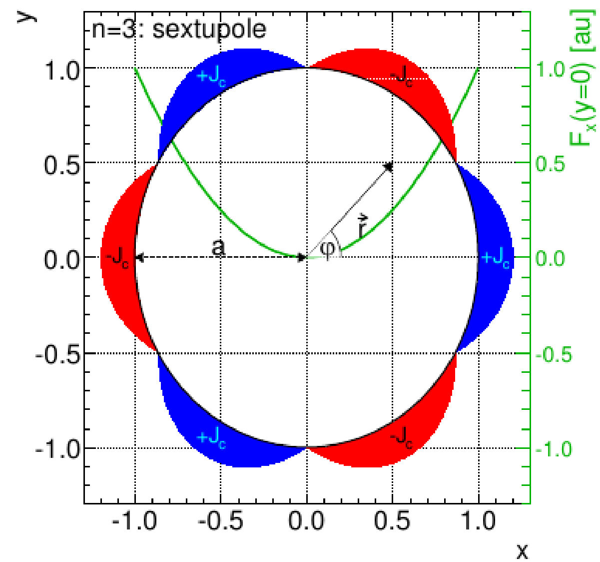
→ defines circular trajectory/orbit

Quadrupole:
linear field



→ defines transverse focusing and periodic betatron oscillation

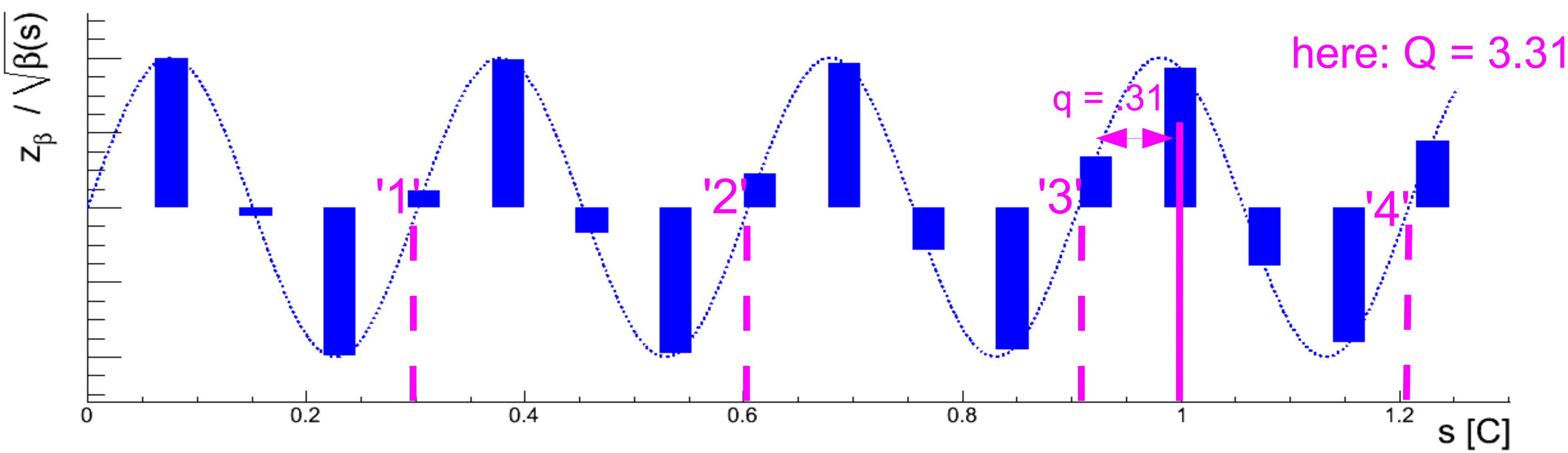
Sextupole:
quadratic field



→ corrects for non-linear /chromatic effects
→ defines dynamic aperture
LHC: up to 12 order

Tune Principle

Free Betatron Oscillations: $$z_\beta(s) = \sqrt{\epsilon_i \beta(s)} \cdot \sin(\mu(s) + \phi_i)$$



Betatron Phase Advance: $\mu(s)$

Tune defined as betatron phase advance over one turn:

$$Q := \frac{1}{2\pi} \oint_C \mu(s)\, ds$$

common: $$Q = \underbrace{Q_{int}}_{integer\ tune} + \underbrace{q_{frac}}_{fractional\ tune}$$

Tune Stability Requirements & Constraints I/II

- Unstable particle motion reduces beam-lifetime if resonance condition is met:

$$p = m \cdot Q_x + n \cdot Q_y \quad \wedge \quad m, n, p \in \mathbb{Z}$$

Resonance order:

$$O = |m| + |n|$$

Lepton accelerator: avoid up to ~ 3rd order

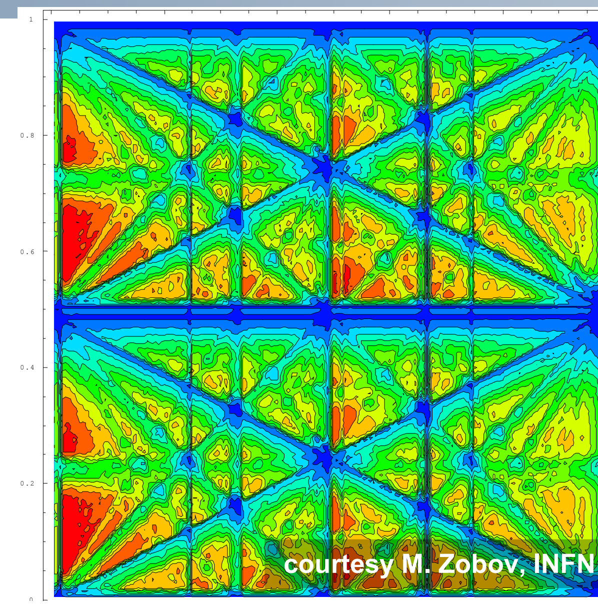
Hadron colliders:

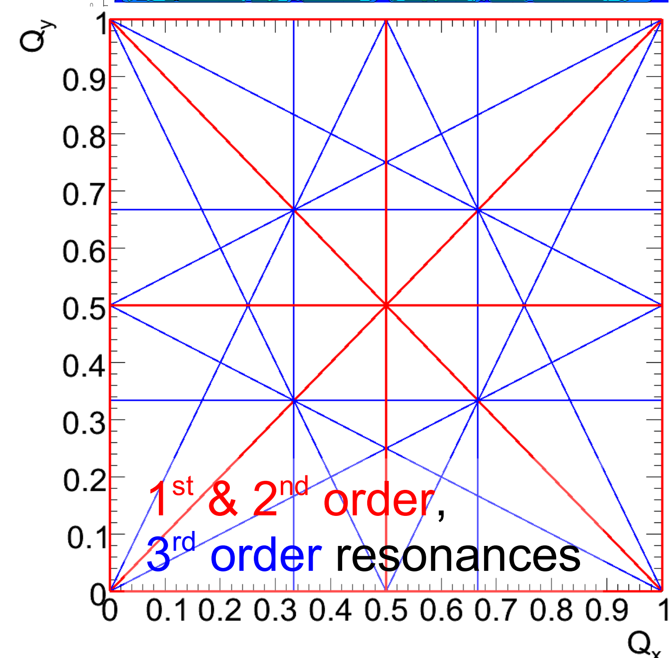
negligible synchrotron radiation damping

need often to avoid up to the 12th order

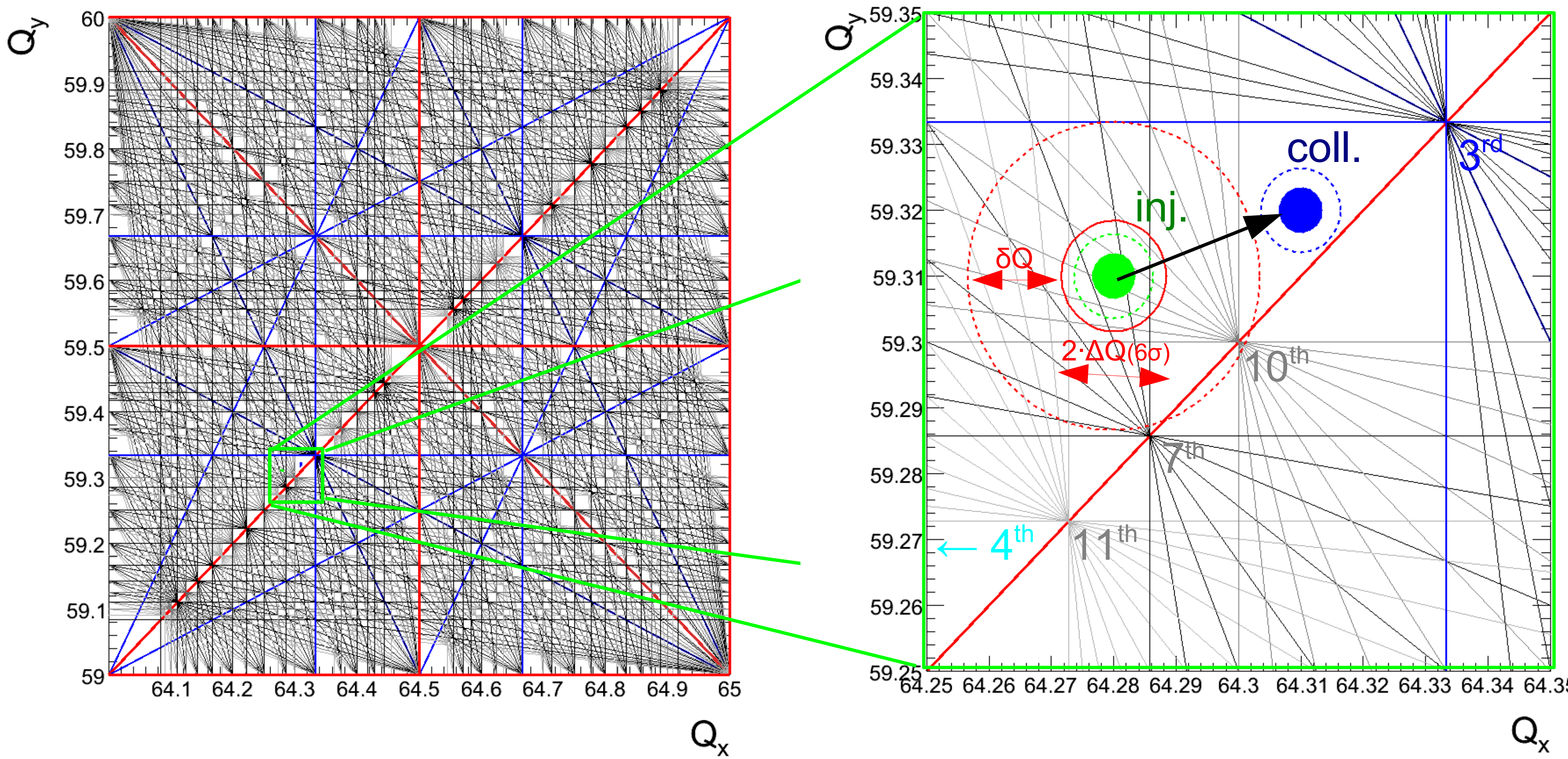
"Hadron beams are like elephants –

treat them bad and they'll never forgive you!"





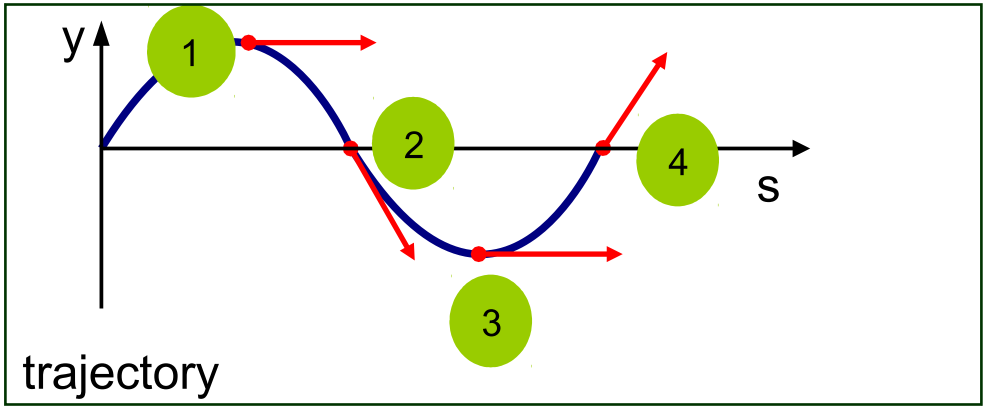
Example LHC: Tune stability requirement: $\Delta Q \approx 0.001$ vs. exp. drifts ~ 0.06

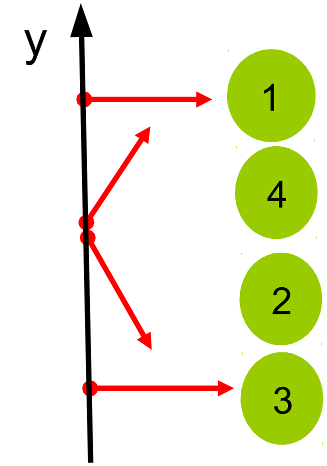


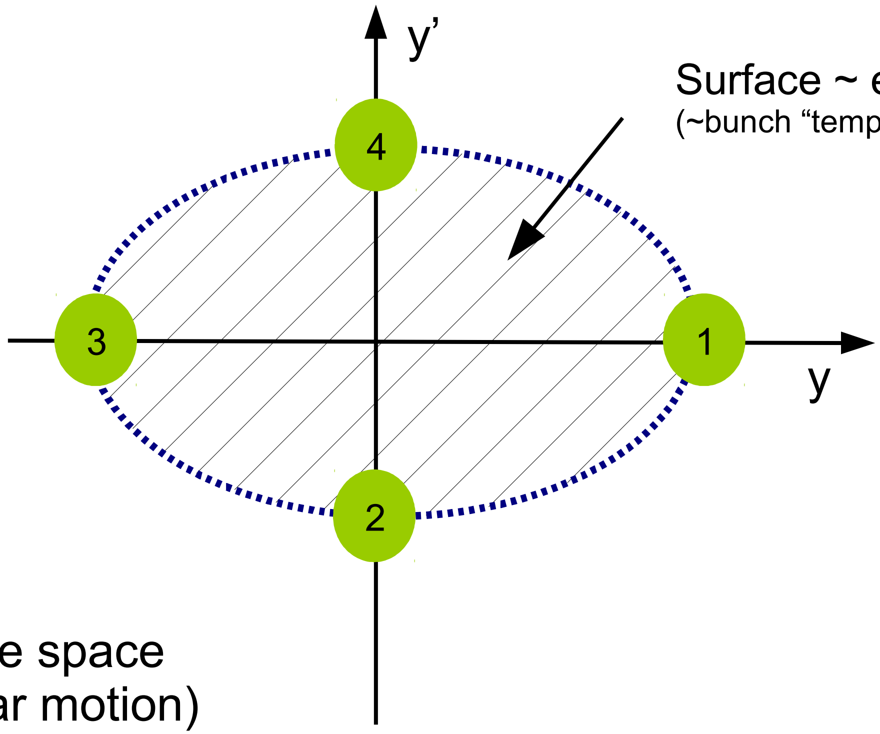
N.B. need to stay much further off these resonance lines due to

finite tune width: chromaticity, space charge, momentum spread, detuning with amplitude and resonance's stop band itself

Phase Space I/II



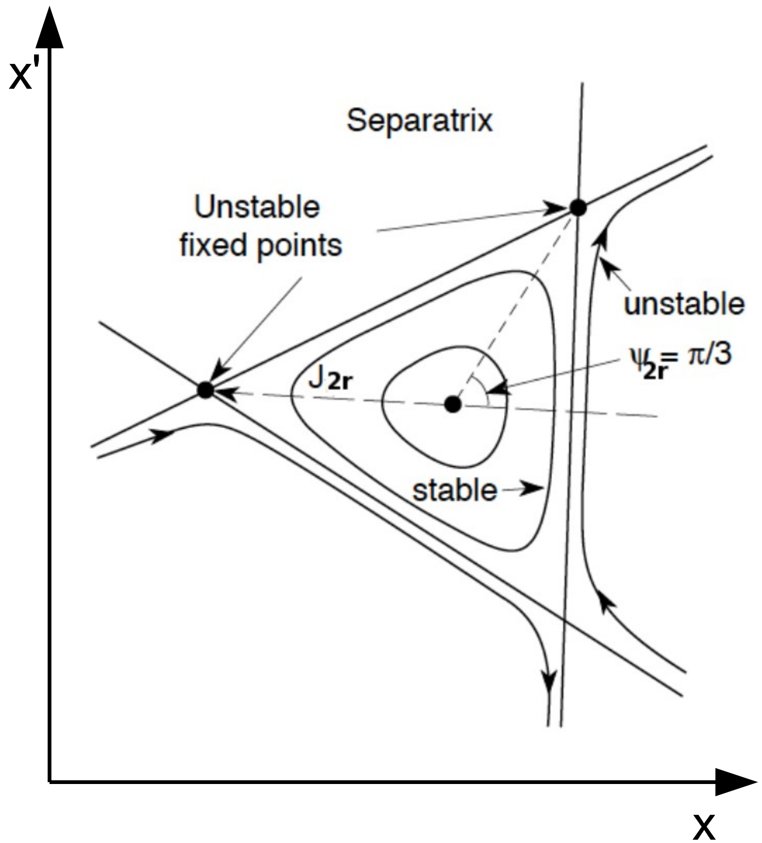




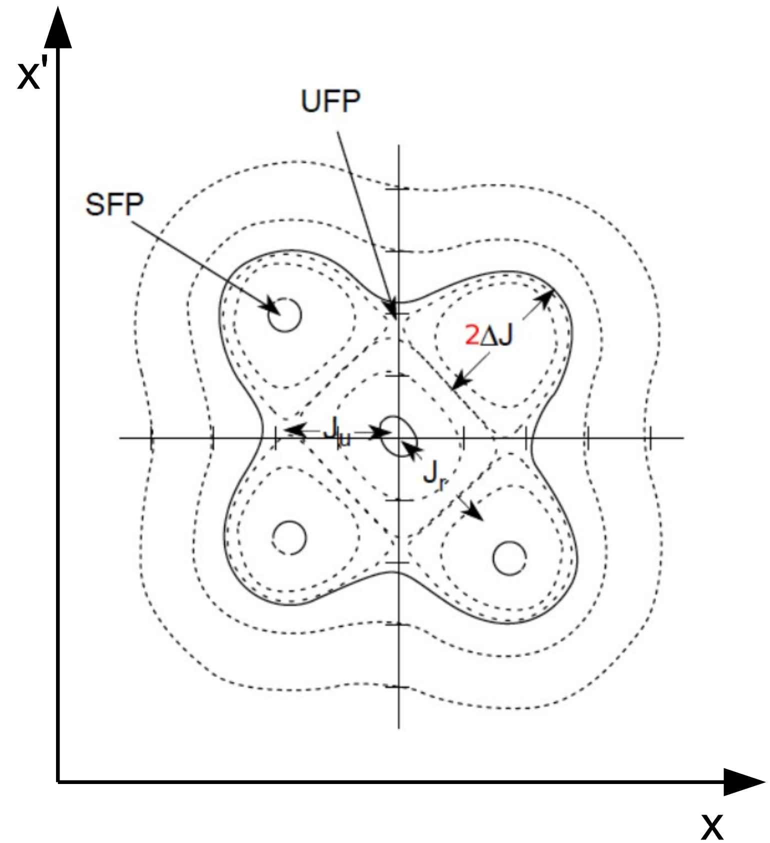
phase space
(linear motion)

Phase Space II/II

- What happens if you add strong non-linear sextupole & octupole-components
  - 'separatrix' (aka. 'dynamic aperture') being the border between stable and unstable beam motion regime

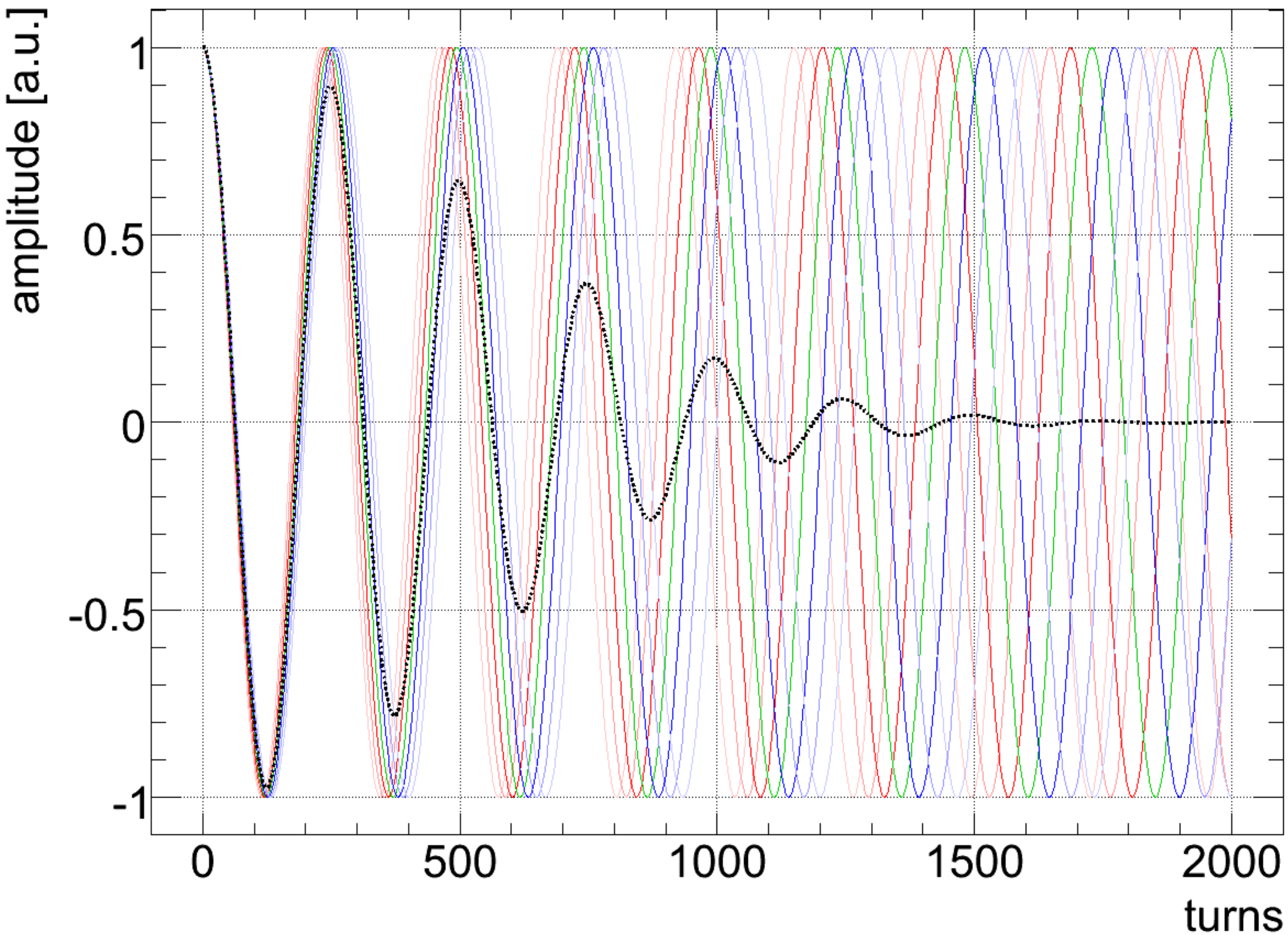


sextupole resonance



octupole resonance

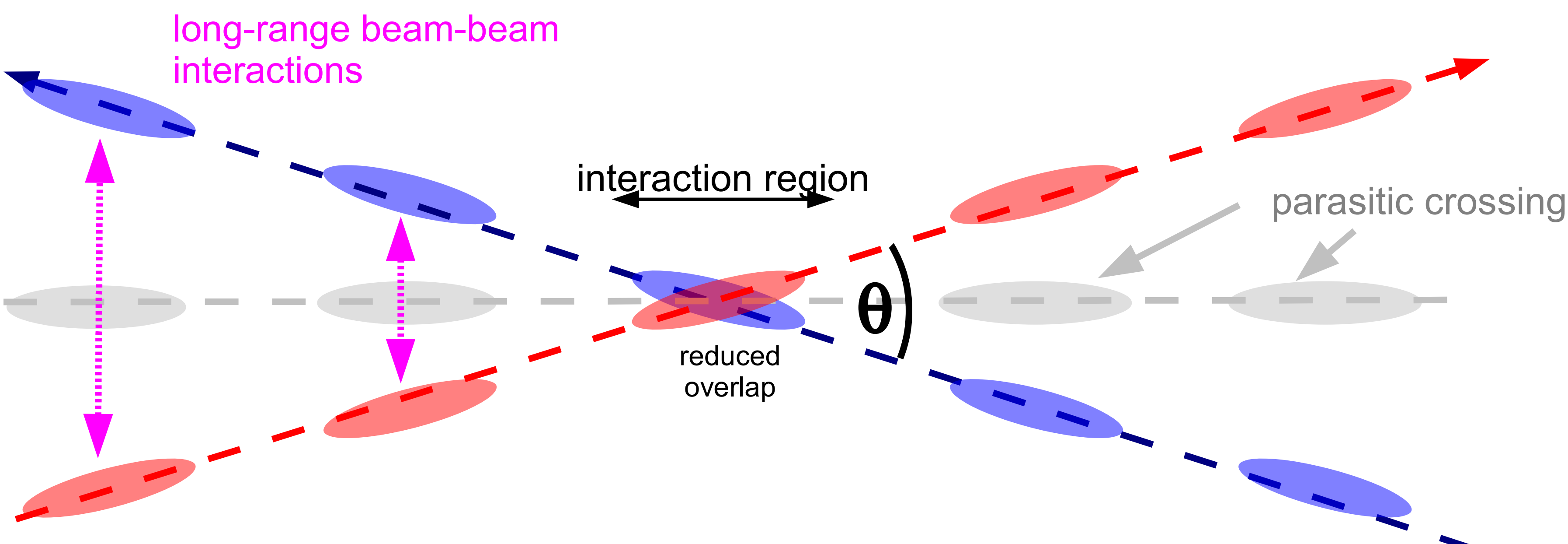
Individual bunch particles usually differ slightly w.r.t. their individual tune
→ Literature: “Landau Damping” (historic misnomer: particle energy is preserved!)



– causes filamentation → need to correct imperfections locally and/or in-time

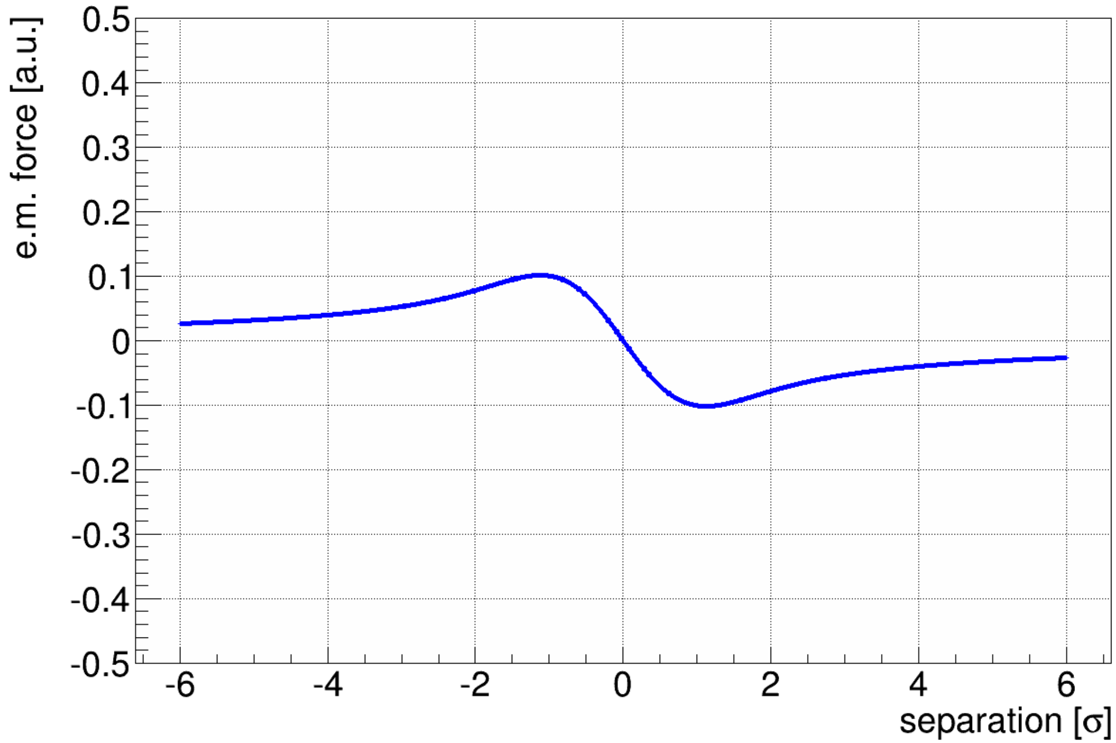
- Crossing angle to avoid parasitic and long-range beam-beam interactions
  - Nominal crossing angle θ ≤ 290 μrad
    ↔ 9.5 σ avg. beam-beam separation

$$L = L_0 \cdot F_{crossing} \cdot \ldots \qquad F_{crossing} = \frac{1}{\sqrt{1+\frac{\sigma_s}{\sigma_{x,y}}\tan(\theta/2)}}$$



Beam-Beam Field I/II

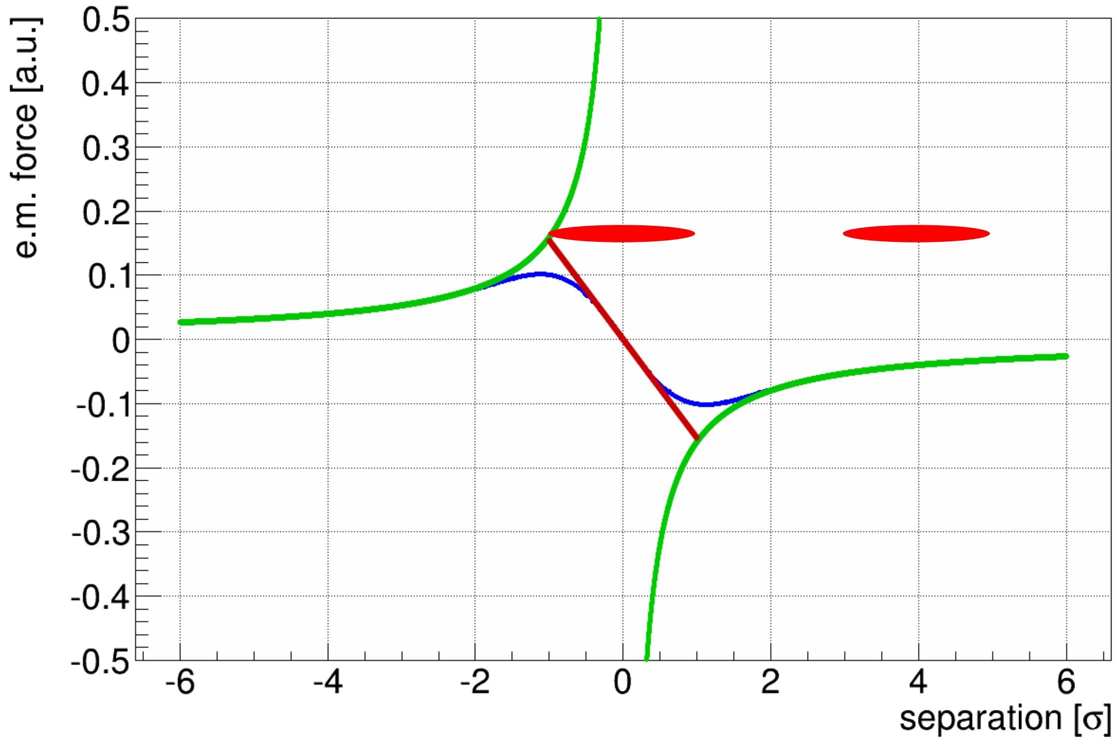
$$E(\vec{r}) = -\frac{Ne(1+\beta^2)}{2\pi\epsilon_0 \, \boldsymbol{r}} \cdot \left[1 - e^{-\frac{1}{2}\left(\frac{\boldsymbol{r}}{\sigma}\right)^2}\right] \cdot \frac{\vec{\boldsymbol{r}}}{\boldsymbol{r}}$$



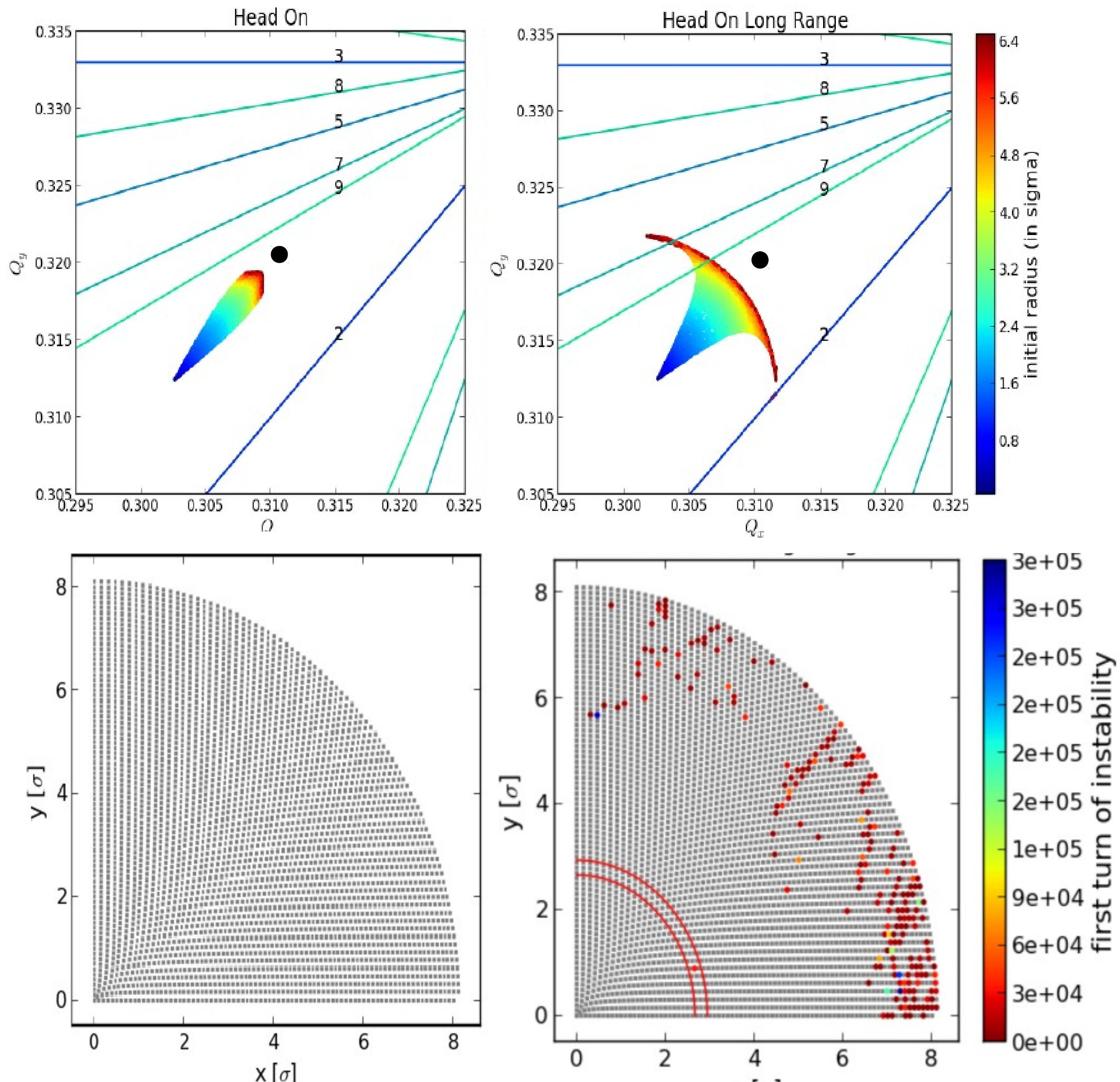
$$E(\vec{r}) = -\frac{Ne(1+\beta^2)}{2\pi\epsilon_0 \; \boldsymbol{r}} \cdot \left[1 - e^{-\frac{1}{2}\left(\frac{\boldsymbol{r}}{\sigma}\right)^2}\right] \cdot \frac{\vec{r}}{\boldsymbol{r}}$$

long-range ~ 1/r

head-on ~ r

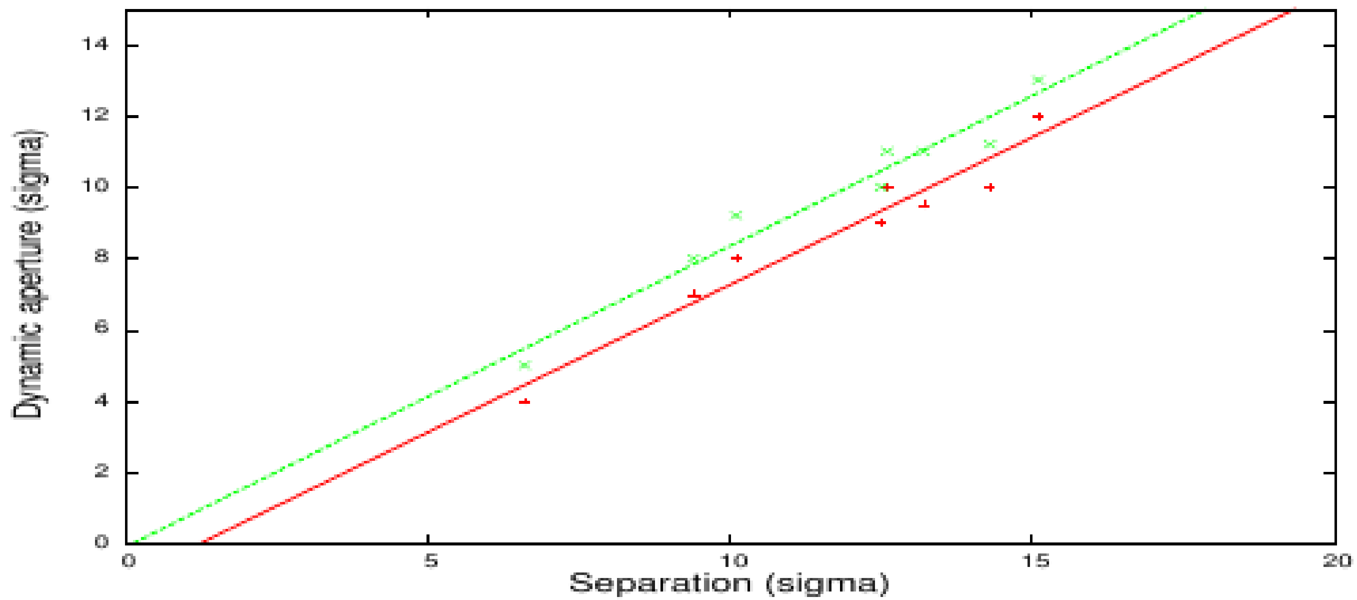


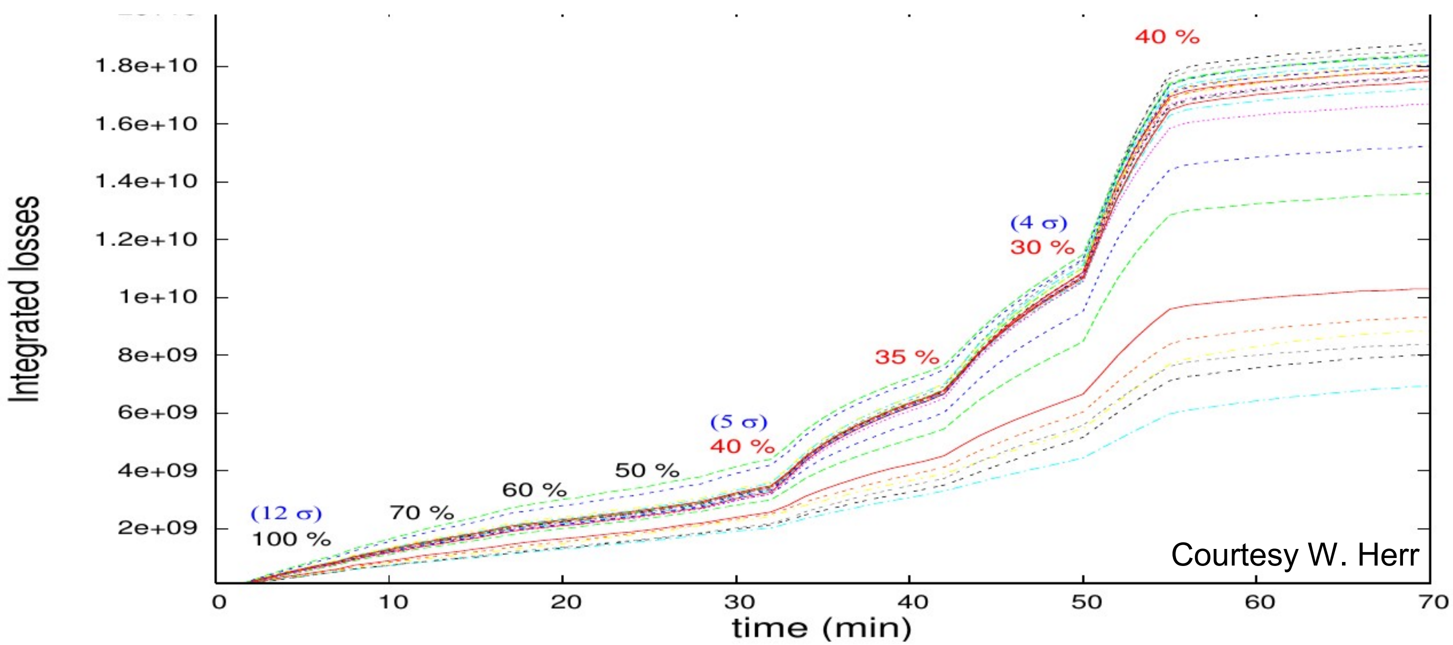
Beam-Beam Interactions – Simulations



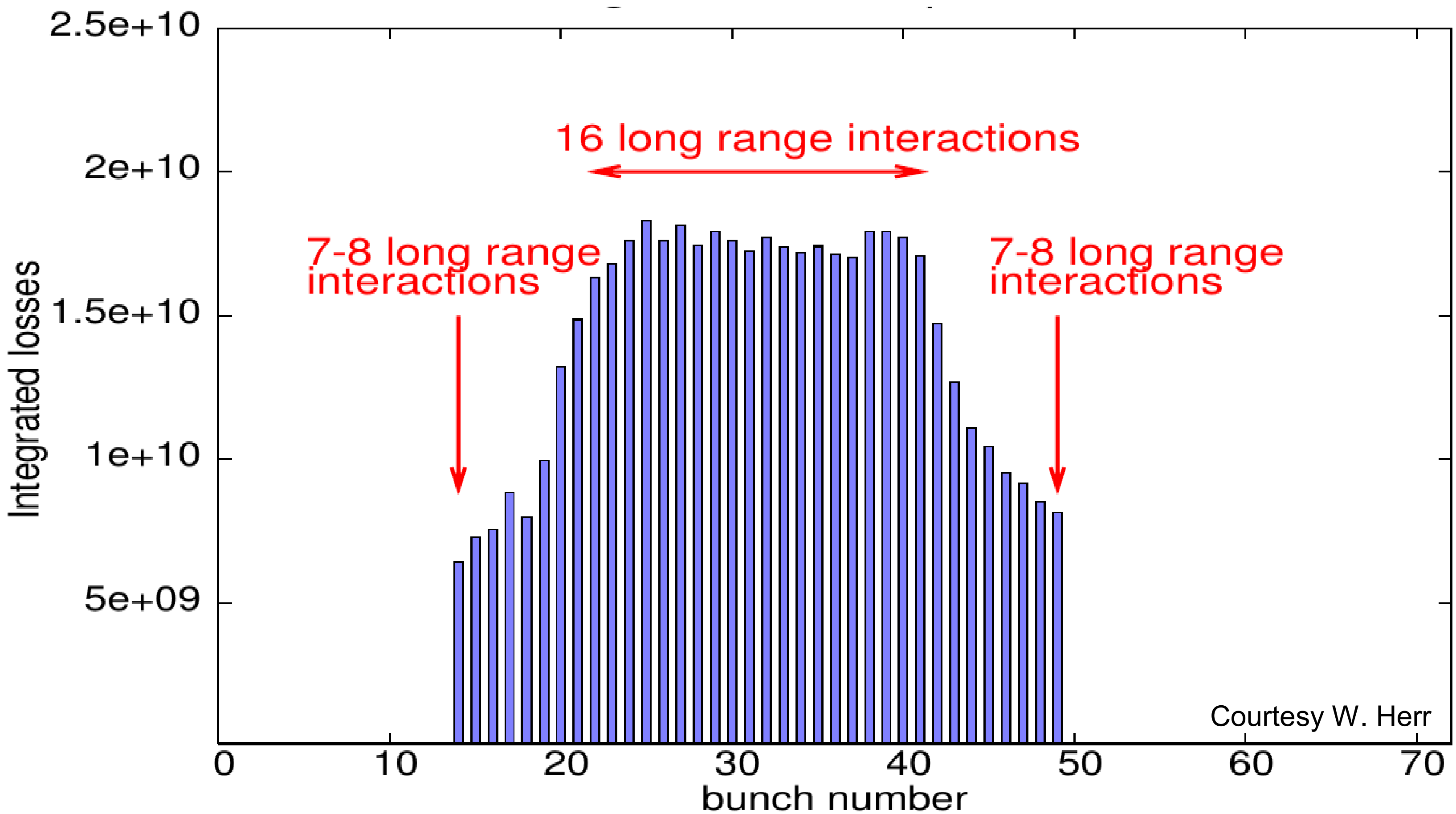
analysis: T.Rijoff & F. Zimmermann

Beam-Beam Interactions – LHC Experiments I/II





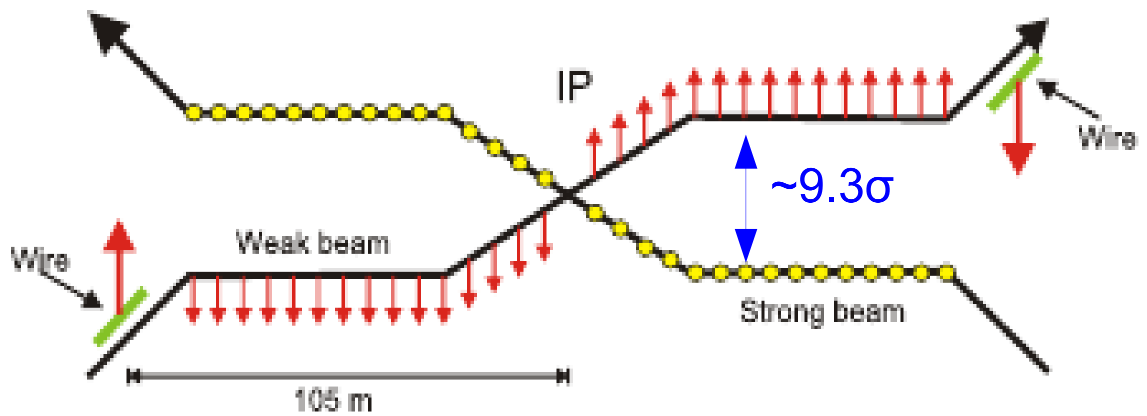
- Distribution of integrated bunch-by-bunch losses across the train



  – more long-range encounter ↔ higher losses

Motivation for Installing a BBC Prototype in the LHC I/II - Passed several Milestones

- Initial proposal based on to J.-P. Koutchouk's note: CERN-SL-2001-048-BI

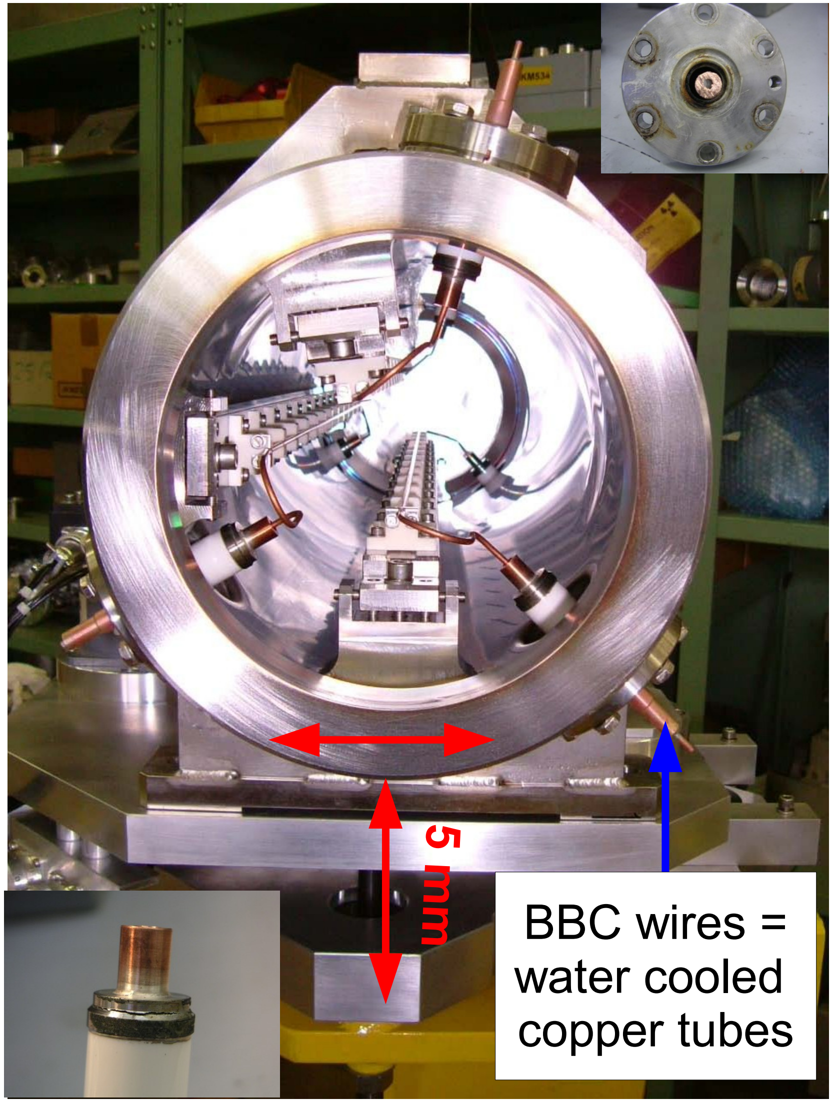


- Since, SPS wire-wire and RHIC beam-wire experiments demonstrated that:
  1. *"detrimental wire effect on life-time can be compensated by another wire"*
  2. *Benchmark of numerical tool chain → indication of what to expect at LHC*

- Further tests require a true long-range beam-beam limited machine...
→ proof-of-principle requires BBC prototype into machine before HL-LHC

Motivation for Installing a BBC Prototype in the LHC II/II
- Initial SPS Prototype Proof-of-Concept Design

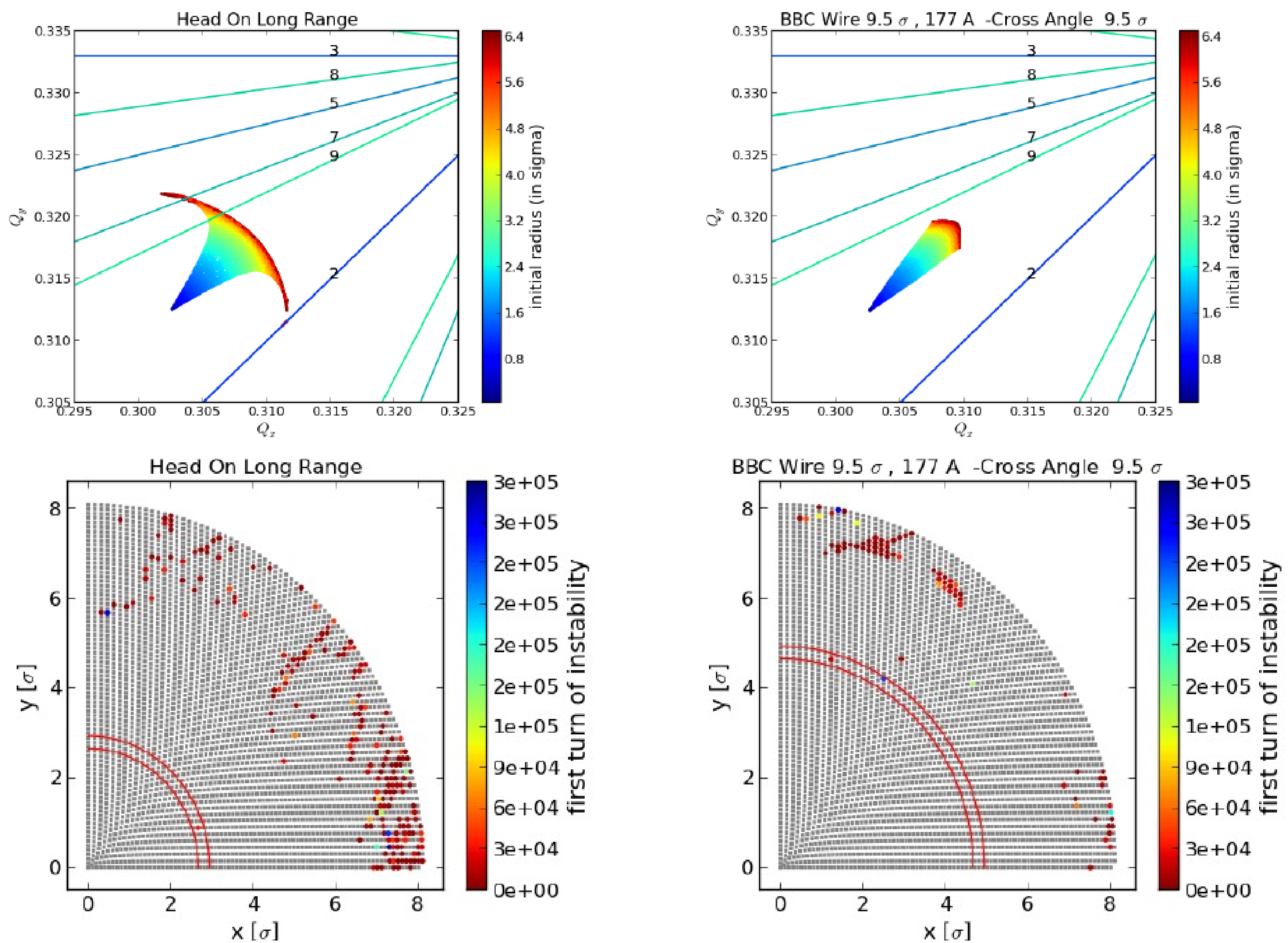
- SPS and donated RHIC design are incompatible for installation in LHC:



- Diff. aperture, beam pipe, mechanics, ...
- Wire needs to be in between beams
- Free-standing wire & RF resonances
  ↔ classic *λ/n*-antenna (impedance issues)
- Not robust w.r.t. beam impact
- Moveable tank bears the inherent risk of breaking and of bursting of:
  - vacuum bellows ↔
    require movement of > 10 mm
  - water cooled interconnects
  - bursting/water leaks inside the vacuum chamber ie. in response to impact of nominal bunch, n-flux fatigue or 1kW heat load

→ unacceptable due to too big impact on LHC operation in case of failure.

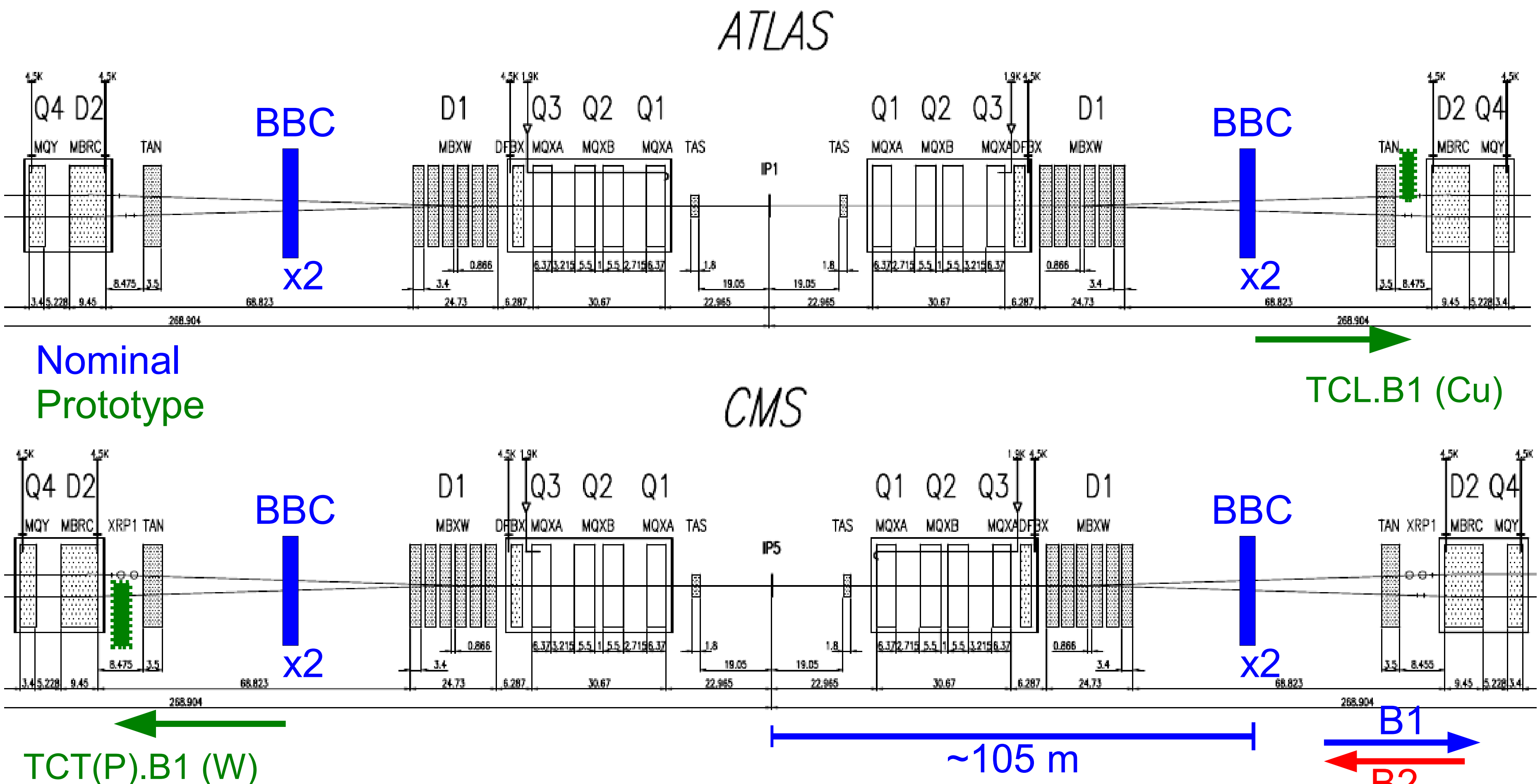
Predicted BBC Performance for Nominal LHC



~2σ dynamic aperture gain! → can reduce crossing angle → more Luminosity!

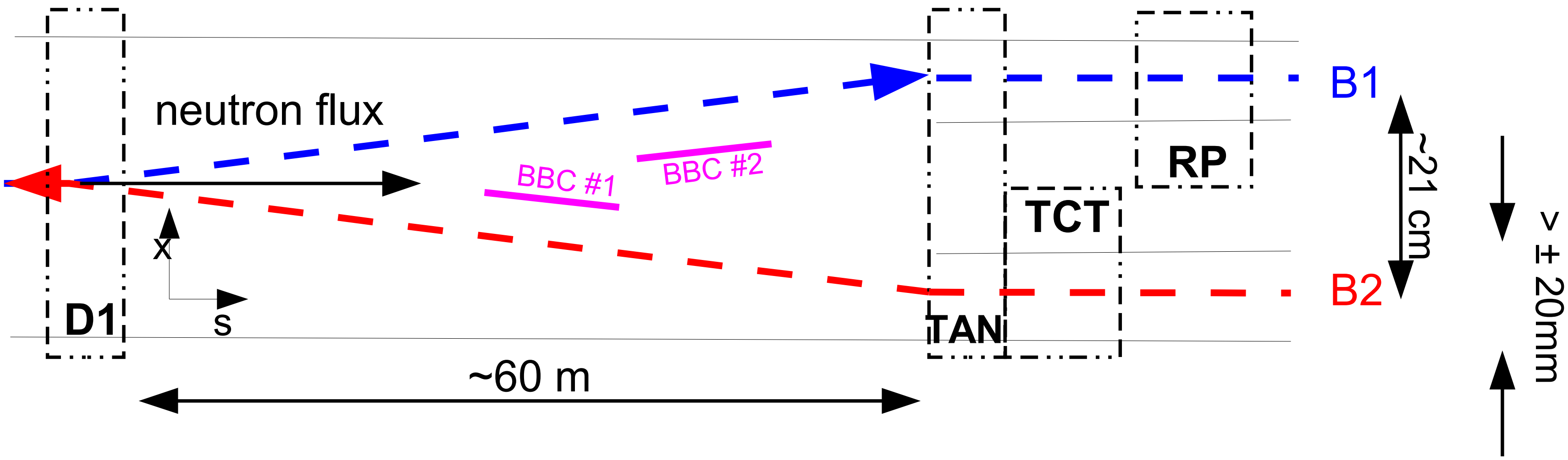
Proposed Prototype Layout after LS-1

- Global B1/B2 merging/separation is in the horizontal plane (21 cm → 0 cm → 21 cm)
  - However, crossing angle θ is in different plane for IP1 (V) and IP5 (H)



Nominal BBC Parameters for HL-LHC I/II

simplified schematic:



- Of note, assume r.m.s. beam width of σ ≈ 0.7..1 mm at BBC

- 4 BBC per beam/IP needed based on H-V crossing scheme
  - from physics point-of-view BBC has to be between crossing beams
  - nominal B1-B2 separation after TAN about 210 mm
  - min beam clearance/aperture > 15 mm (w/o BBC)
  - sub-σ level of BBC position/angle control

- N.B. Non-neglible *n*-flux, RF impedance, and TAN aspects (radiation environment)

Nominal BBC Parameters for HL-LHC II/II

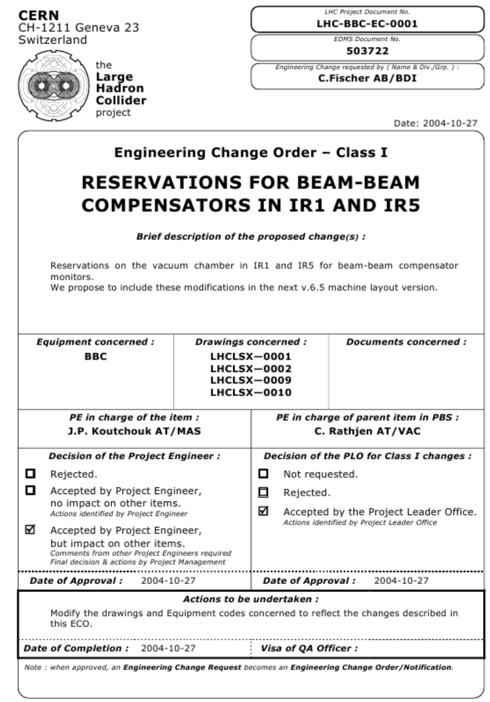
- BBC electrical parameters:
  - absolute current $I_{max} \cdot l_{BBC} = I_{peak} \cdot \sqrt{2\pi} \cdot \sigma_s \cdot n_{parasitic}$ = 72 … 350 Am
    - current stability $\Delta I \sim 10^{-5}\, I_{max}$
    - l_{BBC} is a priori a free parameter (i.e. 350 A over 1 m or 35 A over 10 m)
  - 40 MHz pulsed operation to accommodate bunch-to-bunch differences
  - charge density r.ms. width ~ 1mm → 1kW power dissipation in Cu
    - Wire diameter is a trade-off between available aperture and cooling
- Wire-beam distance: average LR beam-beam separation of 9.7 σ
  → implies a-priori similar nominal BBC position
  - very close to the beam ↔ similar to tertiary collimators
  - critical w.r.t. asynch. dump failure mode, in particular for B2 in IP5
    → not without issues, few MJ heat dissipated on impact
- Impedance is of concern i.e. don't want electro-magnetically resonating structures or materials with high resistivity

Reserve slides

- Reservations around IR1&IR5, LHC-BBC-EC-0001:

	name	Position and longitudinal dimensions
IR1	BBC.4L1	-104.931 m ± 1.5m wrt IP1
	BBC.4R1	104.931 m ± 1.5m wrt IP1
IR5	BBC.4L5	-104.931 m ± 1.5m wrt IP5
	BBC.4R5	104.931 m ± 1.5m wrt IP5

- Min. LRBB → BBC phase advance: $\Delta\mu \approx 2.6°$ (→ 3.1°)
- Symmetric beta-function: $\beta_{x/y} \approx 1000$ m (for $\beta^* = 0.55$ m)
- N.B. single vacuum pipe for B1 & B2:
  110 mm full beam separation (only D1 only)
  (→ 165 mm, if shifted more towards TAN)


CERN
CH-1211 Geneva 23
Switzerland

the **Large Hadron Collider** project

LHC Project Document No.
LHC-BBC-EC-0001

EDMS Document No.
503722

Engineering Change requested by (Name & Div./Grp.) :
C.Fischer AB/BDI

Date: 2004-10-27

Engineering Change Order – Class I

RESERVATIONS FOR BEAM-BEAM COMPENSATORS IN IR1 AND IR5

Brief description of the proposed change(s) :

Reservations on the vacuum chamber in IR1 and IR5 for beam-beam compensator monitors.
We propose to include these modifications in the next v.6.5 machine layout version.

Equipment concerned :	***Drawings concerned :***	***Documents concerned :***
BBC	**LHCLSX–0001** **LHCLSX–0002** **LHCLSX–0009** **LHCLSX–0010**	

PE in charge of the item :	***PE in charge of parent item in PBS :***
J.P. Koutchouk AT/MAS	**C. Rathjen AT/VAC**

Decision of the Project Engineer :

- ☐ Rejected.
- ☐ Accepted by Project Engineer, no impact on other items. *Actions identified by Project Engineer*
- ☑ Accepted by Project Engineer, but impact on other items. *Comments from other Project Engineers required. Final decision & actions by Project Management*

Date of Approval : 2004-10-27

Decision of the PLO for Class I changes :

- ☐ Not requested.
- ☐ Rejected.
- ☑ Accepted by the Project Leader Office. *Actions identified by Project Leader Office*

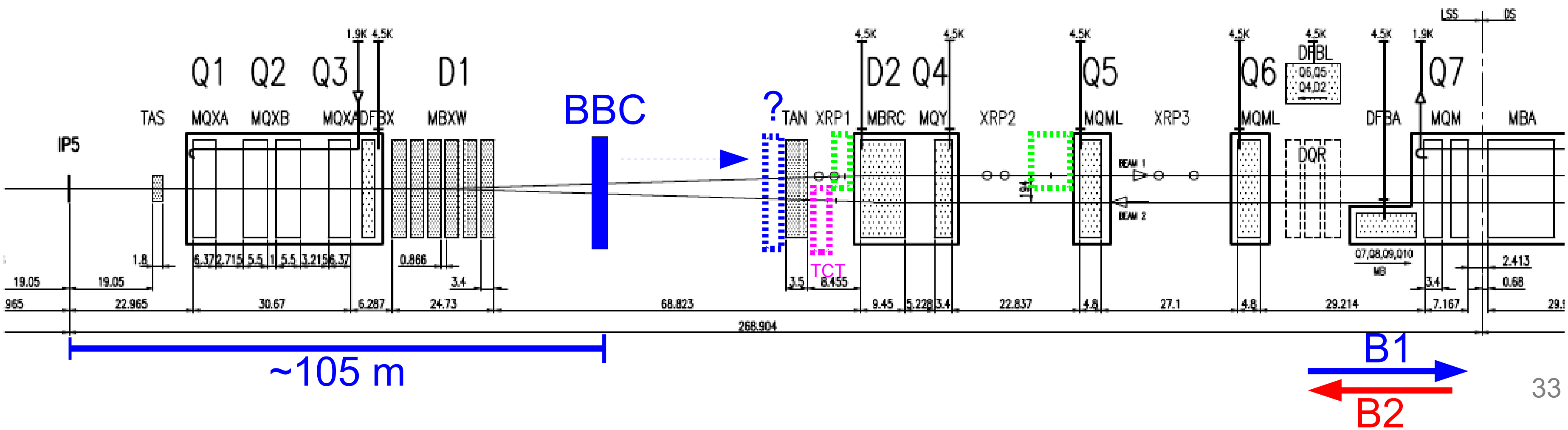
Date of Approval : 2004-10-27

Actions to be undertaken :

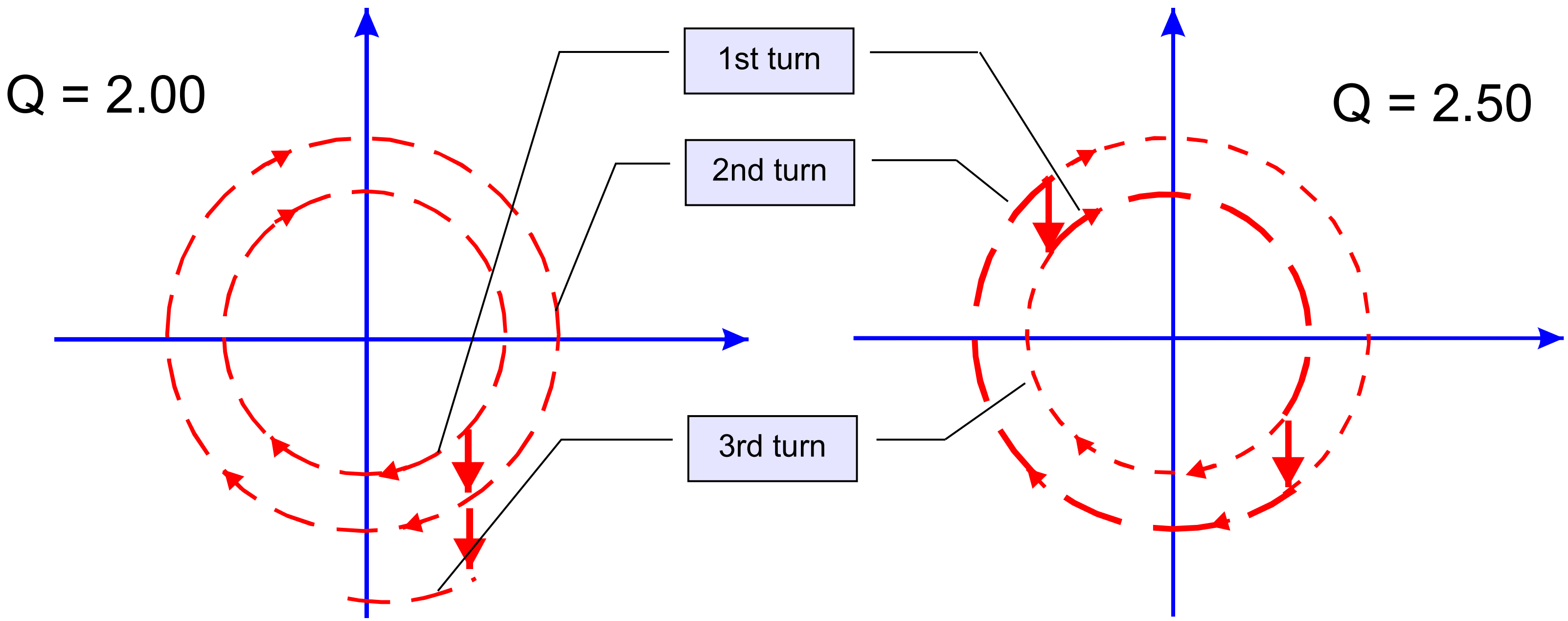
Modify the drawings and Equipment codes concerned to reflect the changes described in this ECO.

Date of Completion : 2004-10-27 ***Visa of QA Officer :***

Note : when approved, an ***Engineering Change Request*** *becomes an* ***Engineering Change Order/Notification****.*



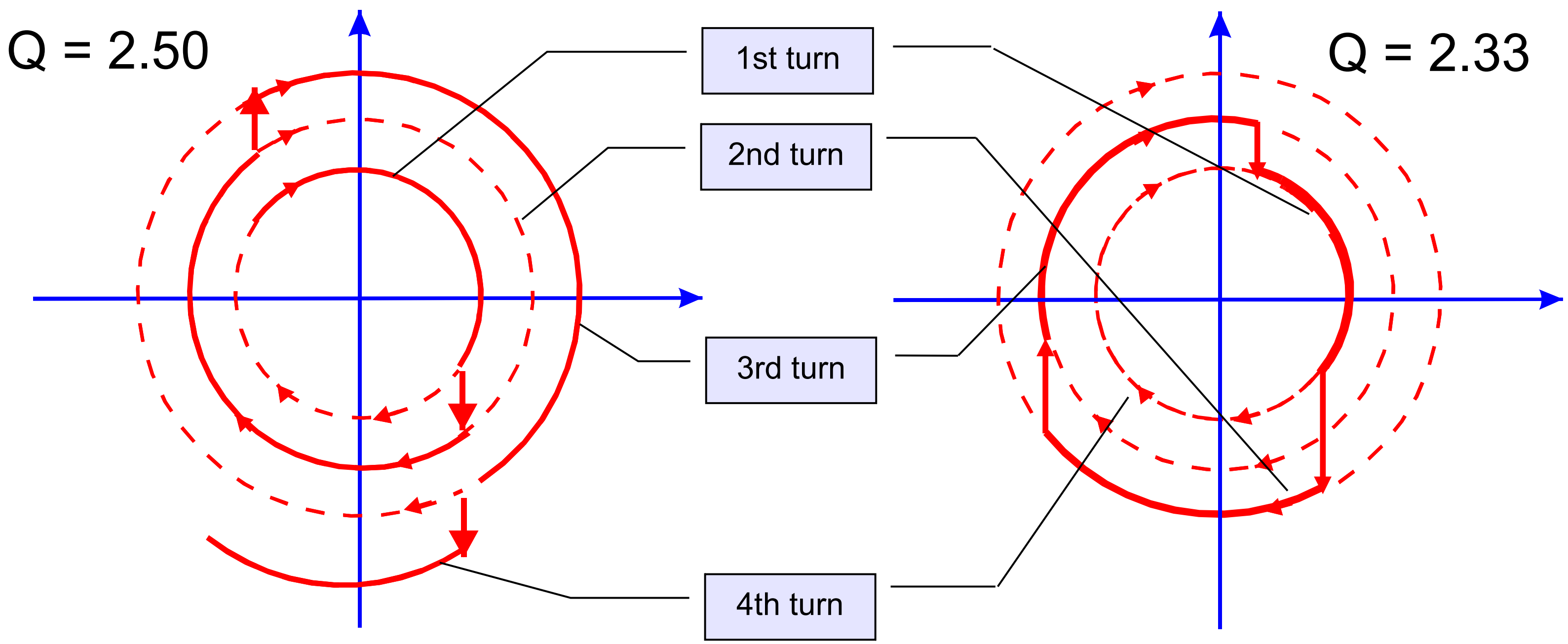
Non-Linear Dynamics – Dipolar Resonance



- For Q = 2.00: Oscillation induced by the dipole kick grows on each turn and the particle is lost (1st order resonance Q = 2).
- For Q = 2.50: Oscillation is cancelled out every second turn, and therefore the particle motion is stable.

courtesy R. Steerenberg

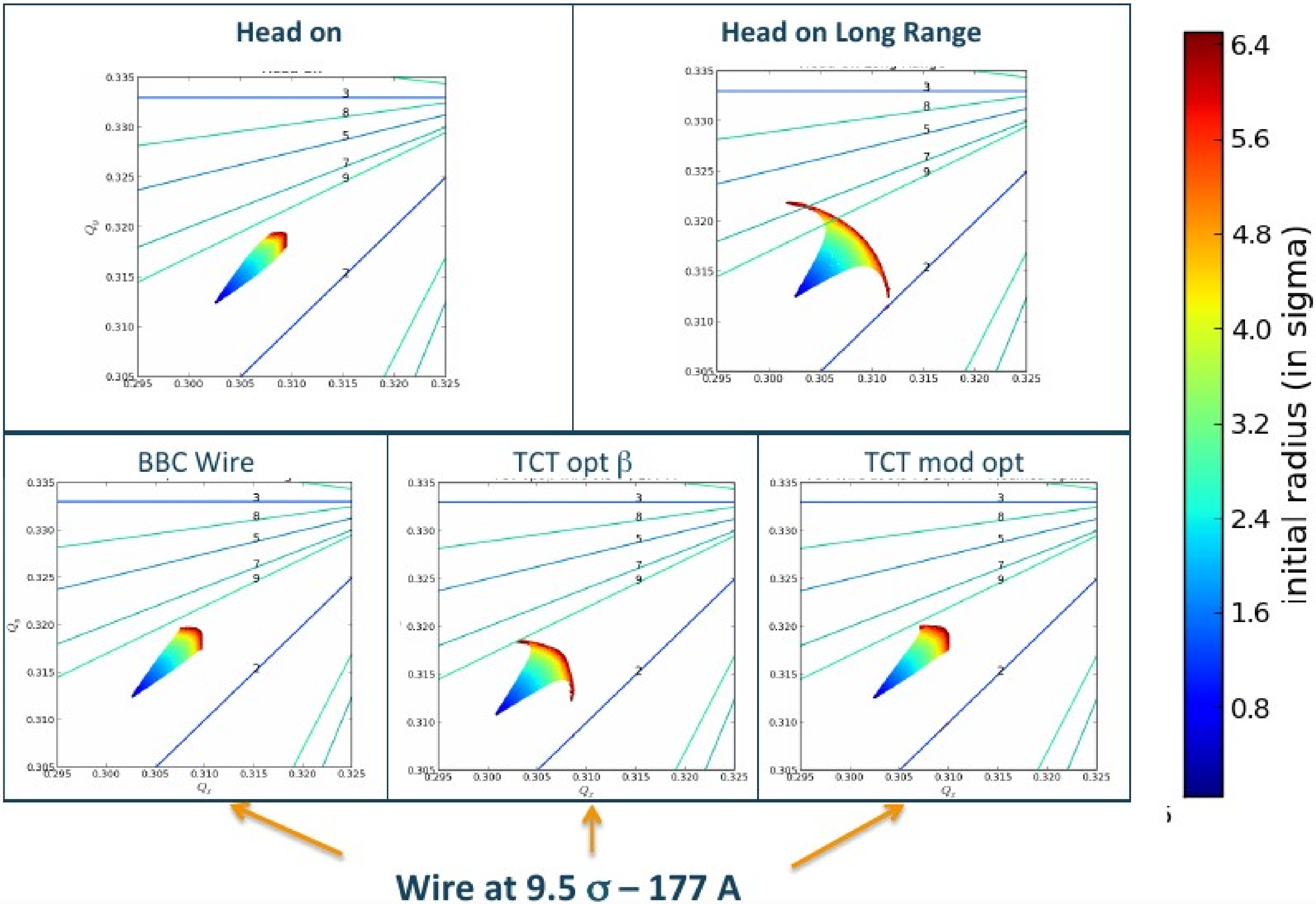
Non-Linear Dynamics – Quadrupolar Resonances



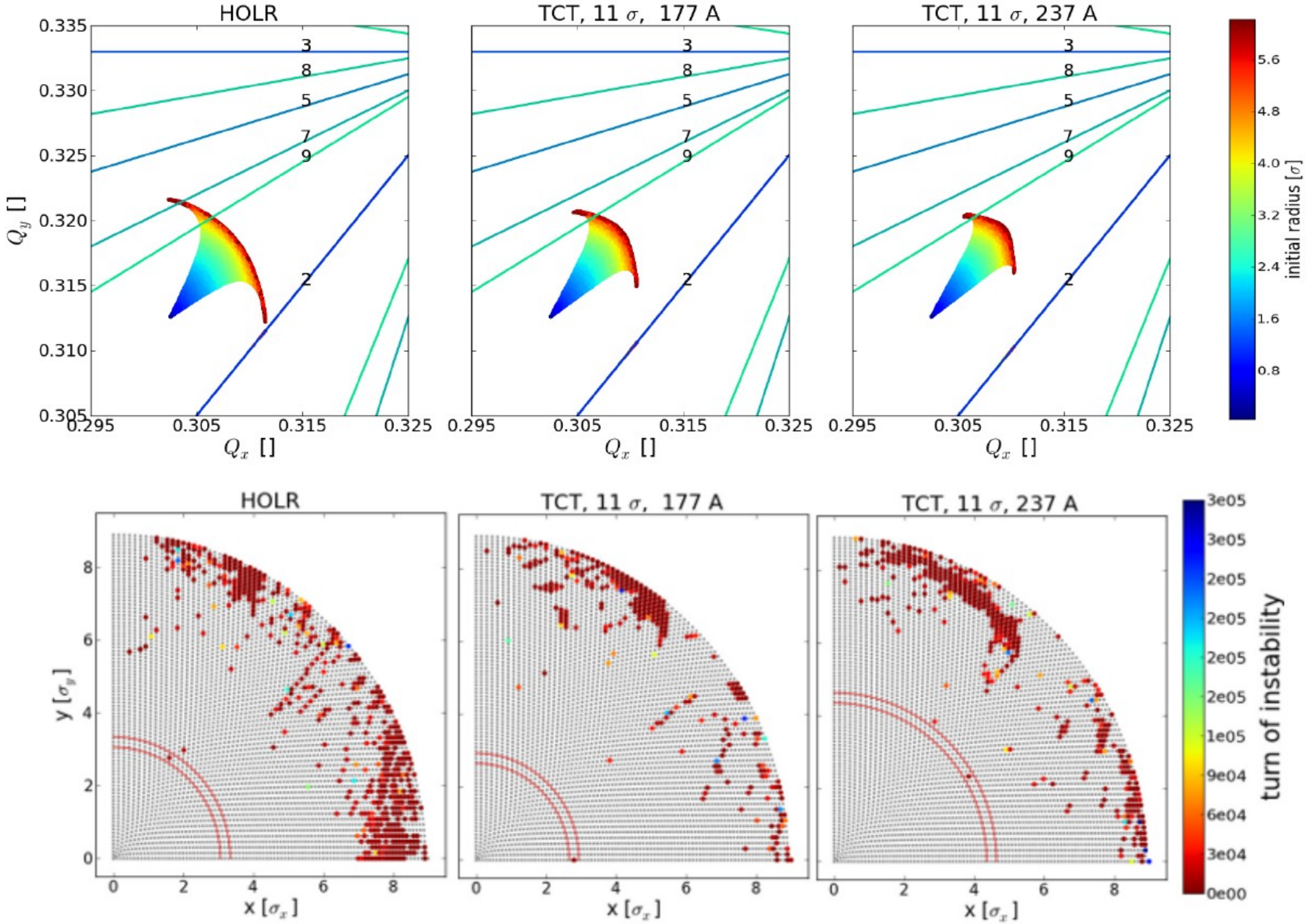
- For Q = 2.50: Oscillation induced by the quadrupole kick grows on each turn and the particle is lost (2nd order resonance 2Q = 5)
- For Q = 2.33: Oscillation is cancelled out every third turn, and therefore the particle motion is stable.

courtesy R. Steerenberg

Long-Range Beam-Beam Compensator



Analysis: T.Rijoff & F. Zimmermann


HOLR
TCT, 11 σ, 177 A
TCT, 11 σ, 237 A
3
8
5
7
9
2
Q_y []
Q_x []
0.335
0.330
0.325
0.320
0.315
0.310
0.305
0.295
0.305
0.315
0.325
initial radius [σ]
5.6
4.8
4.0
3.2
2.4
1.6
0.8
y [σ_y]
x [σ_x]
turn of instability
3e05
2e05
1e05
9e04
6e04
3e04
0e00

Physical Space IR5 Requires Horizontal BBC