4th Joint HiLumi LHC-LARP Annual Meeting

BBLR compensation test: present ideas on set-up, beam conditions and measurements

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Thanks to

G. Arduini, G. Campogiani, R. Jones R. deMaria, A. Patapenka, T. Pieloni, S.Redaelli, T. Rijoff, H. Schmickler, A. Valishev, F. Zimmermann

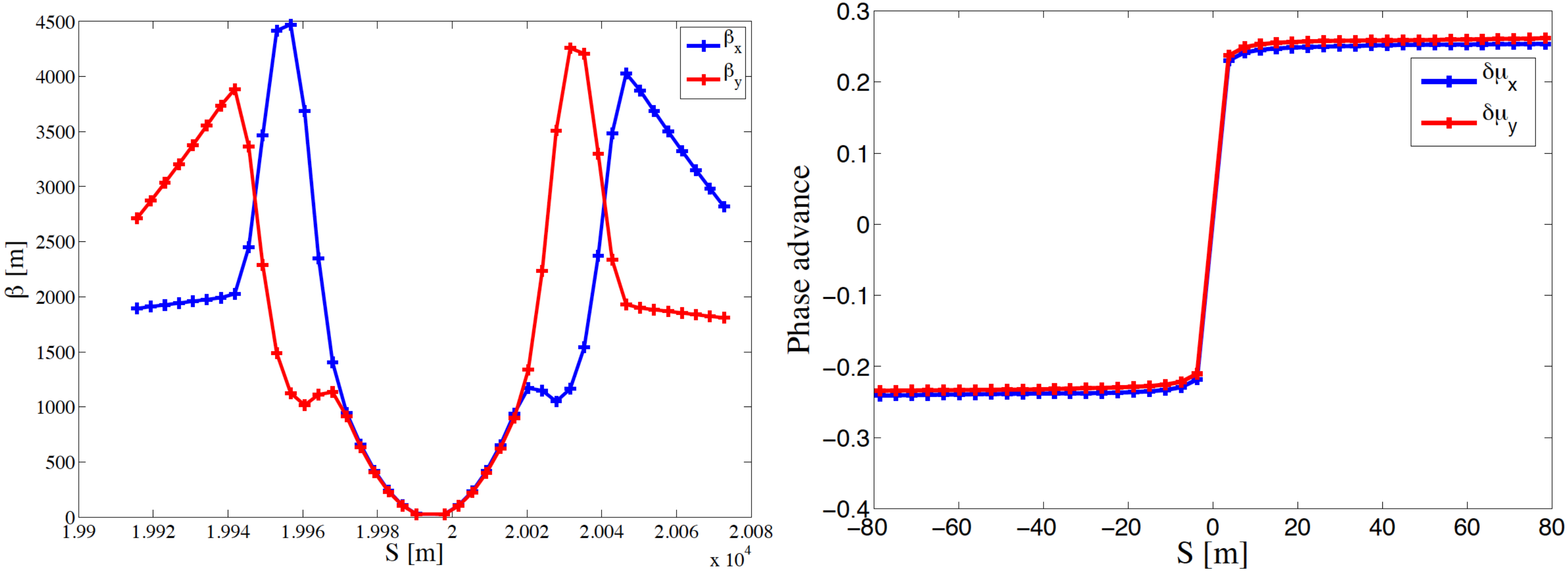
Outline

- Long range beam beam effect in the LHC and wire compensation
- Wire effect on the beam
  - ☐ Multipole expansion, tune
- Test of wire compensation in the LHC,
  - ☐ Nominal and available positions
  - ☐ Present simulation status
- Experimental conditions, observables and associated instrumentation needs
- Study plan

Reminder: BBLR in the LHC

- For 25ns beams, 16+16 parasitic "collisions" up to D1
  - Additional encounters inside D1 (5 shown here)
  - Due to effect of beam-beam, **small but non-negligible** optics distortion in IR (betas, dispersion, phase advance)

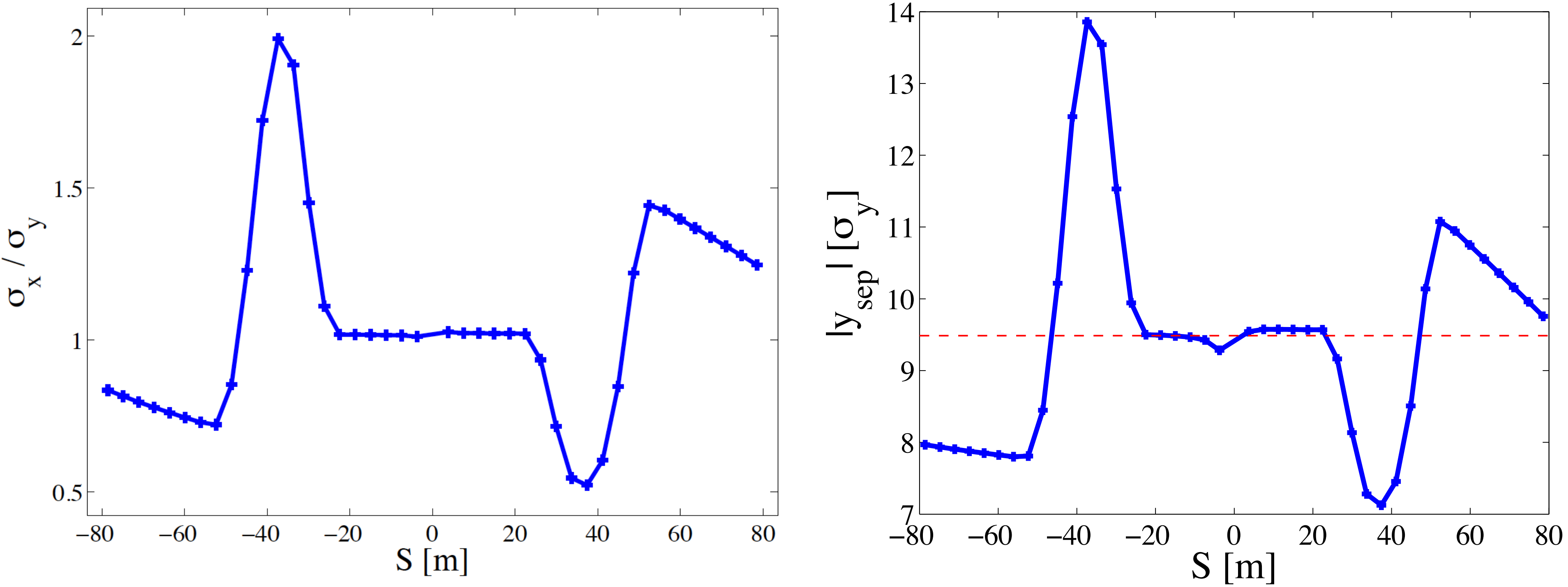
IR1, B1



Beam size ratio in the LHC

- The beams are “exactly” round for 6 long range encounters in either side of the IP
- The ratio of the beam sizes varies between 0.5 and 2
- The beam-beam separation varies from 7 to 14 σ, with average separation of 9.5 σ

IR1, B1

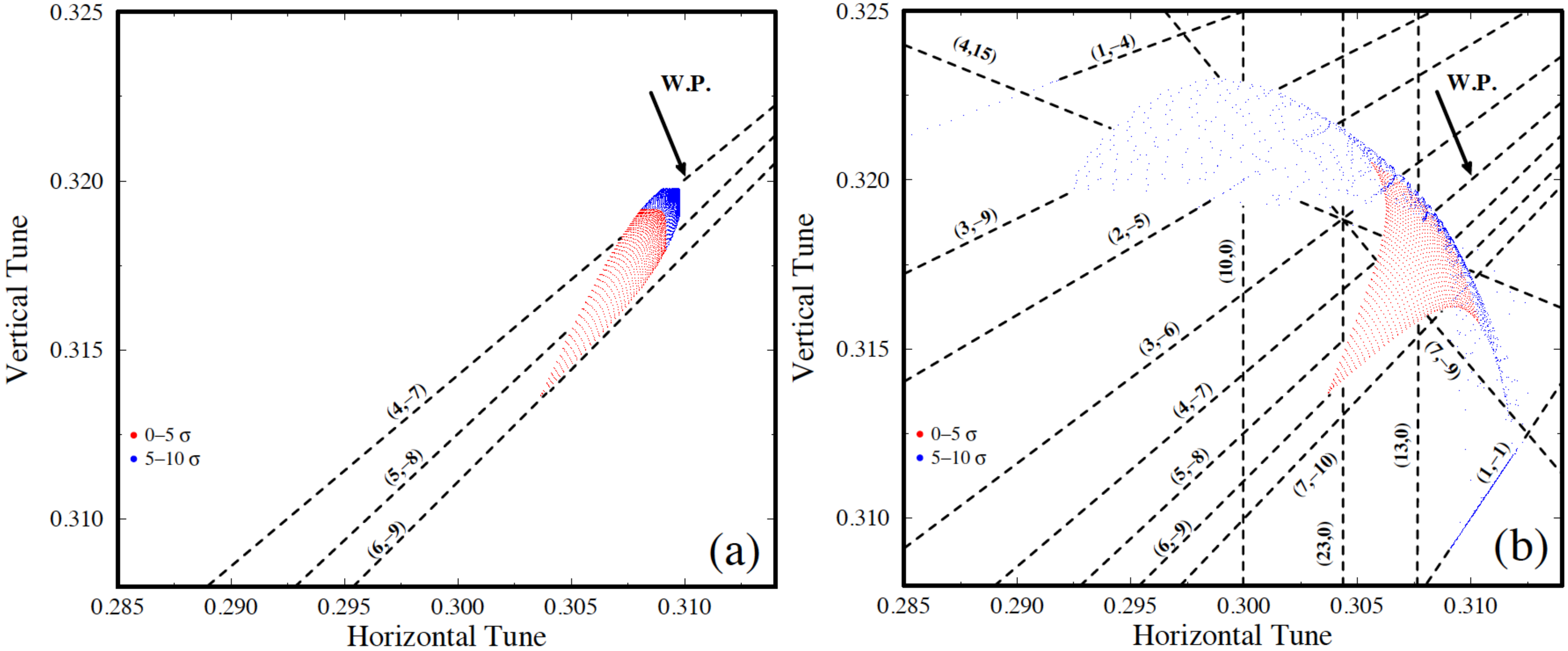


Long range beam-beam effect

- Head-on tune-spread alone has a minor effect in DA
- DA reduction is radical (<6σ) with long range beam-beam
  - ☐ Large tune-spread with opposite sign
  - ☐ Crossing of a variety of resonances

Y. Papaphilippou and
F. Zimmermann, 1999

Head-on **Head-on + BBLR**



Wire compensation

- Considering round beams and crossing in both planes, the BBLR kicks is

$$\Delta\{x',y'\} = -\frac{2N_b r_p}{\gamma}\frac{\{X,Y\}}{X^2+Y^2}(1-e^{-\frac{X^2+Y^2}{2\sigma^2}})$$

with $X = x + x_c \;, \quad Y = y + y_c$

- For an "infinite" round wire, the kicks are

$$\Delta\{x',y'\}_W = \frac{\mu_0}{2\pi}\frac{I_W L_W}{B\rho}\frac{\{X_W,Y_W\}}{X_W^2+Y_W^2}$$

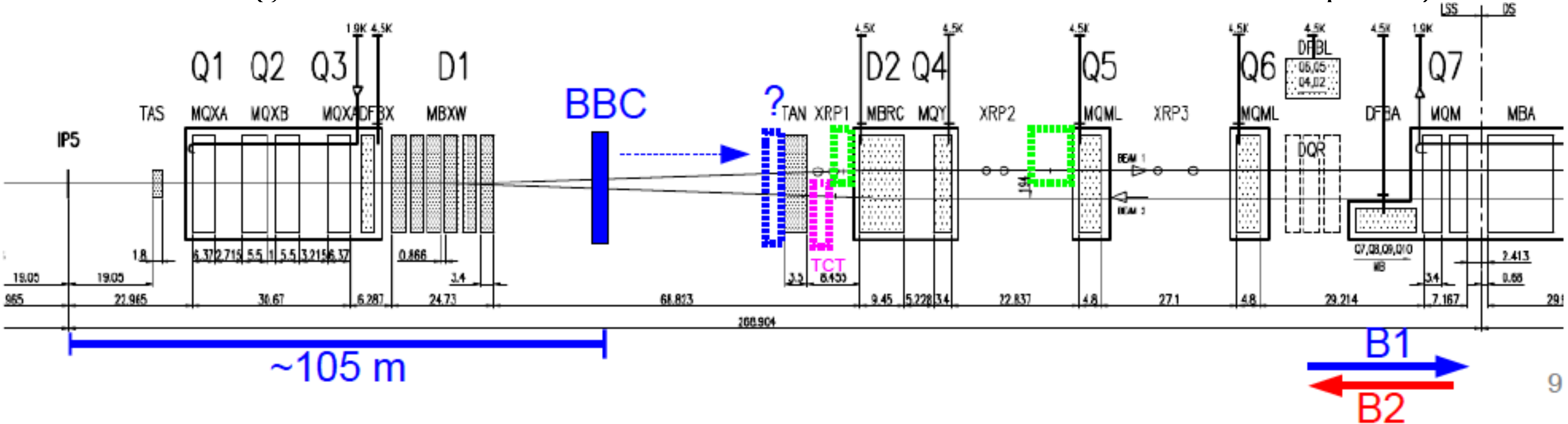
with $X_W = x + x_W \;, \quad Y_W = y + y_W$

- For cancelling the effect **for any position** (large separations) $x_W = x_c \;, \quad y_W = y_c \;, \quad I_W L_W = ecN_b$
- This gives **5.5 Am/encounter** for the nominal LHC

Compensation considerations

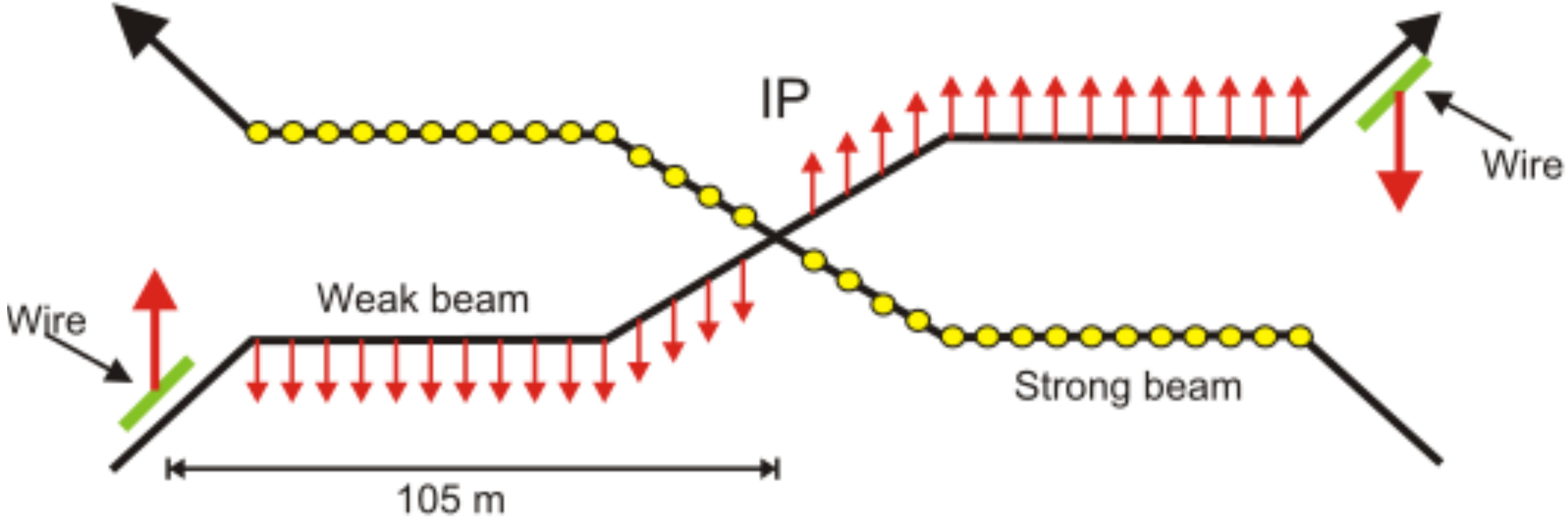
J.P. Koutchouk, 2001

- **Locality** of the compensation
  - ☐ Close to the BBLR encounters which occur at ~π/2 from IP
  - ☐ Ideally between D1 and D2 (phase advance difference of a few degrees wrt BBLR) but integration may be difficult
- **Position** of the wire with respect to the beam
  - ☐ As close as average BBLR separation (9.5σ)
  - ☐ Integrated kick is scaled inversely with distance, i.e. the smaller the distance the lower the required integrated current and vice versa
- **Optics** considerations
  - ☐ Large (and equal beta functions) for efficient tune-shift compensations
- The absolute criterion should be **non-linear compensation** (increase of DA, i.e. lifetime, through combined reduction of non-linear resonances and tune-spread)



Two wires per IP

- Integrated current can be reduced for the same correction reach
  - ☐ Ideally halved only if location with equal beta functions in both planes are used (round beam approximation)
- Powered independently to fit better the integrated kick on either side
- Due to optics anti-symmetry and different plane crossing, effect of two wires in the two planes is asymmetric
- Ability to move the wire in the non-crossing plane would be desirable
  - ☐ Additional knob, but also inducing some coupling (see below)



Wire multi-pole expansion

- The multi-pole expansion of the wire can be written as
$$B_y + iB_x = \frac{\mu_0 I}{2\pi r_W} \sum_{n=0}^{\infty} (b_n + i a_n) \left(\frac{x+iy}{r_W} \right)^n$$

with $r_W = (x_W^2 + y_W^2)^{1/2}$, $b_n = -\cos\left((n+1)\phi_W\right)$, $a_n = \sin\left((n+1)\phi_W\right)$

and $\phi_W = \arctan(\frac{y_W}{x_W})$

- For only horizontal or vertical wire position, there are only normal or skew components excited
- This is also consistent with the induced BBLR multi-poles with the round beam approximation
- Wire (as BBLR) affects orbit, tunes, coupling, chromaticity, tune-spread, **resonances**,…

Tune-shift due to wire

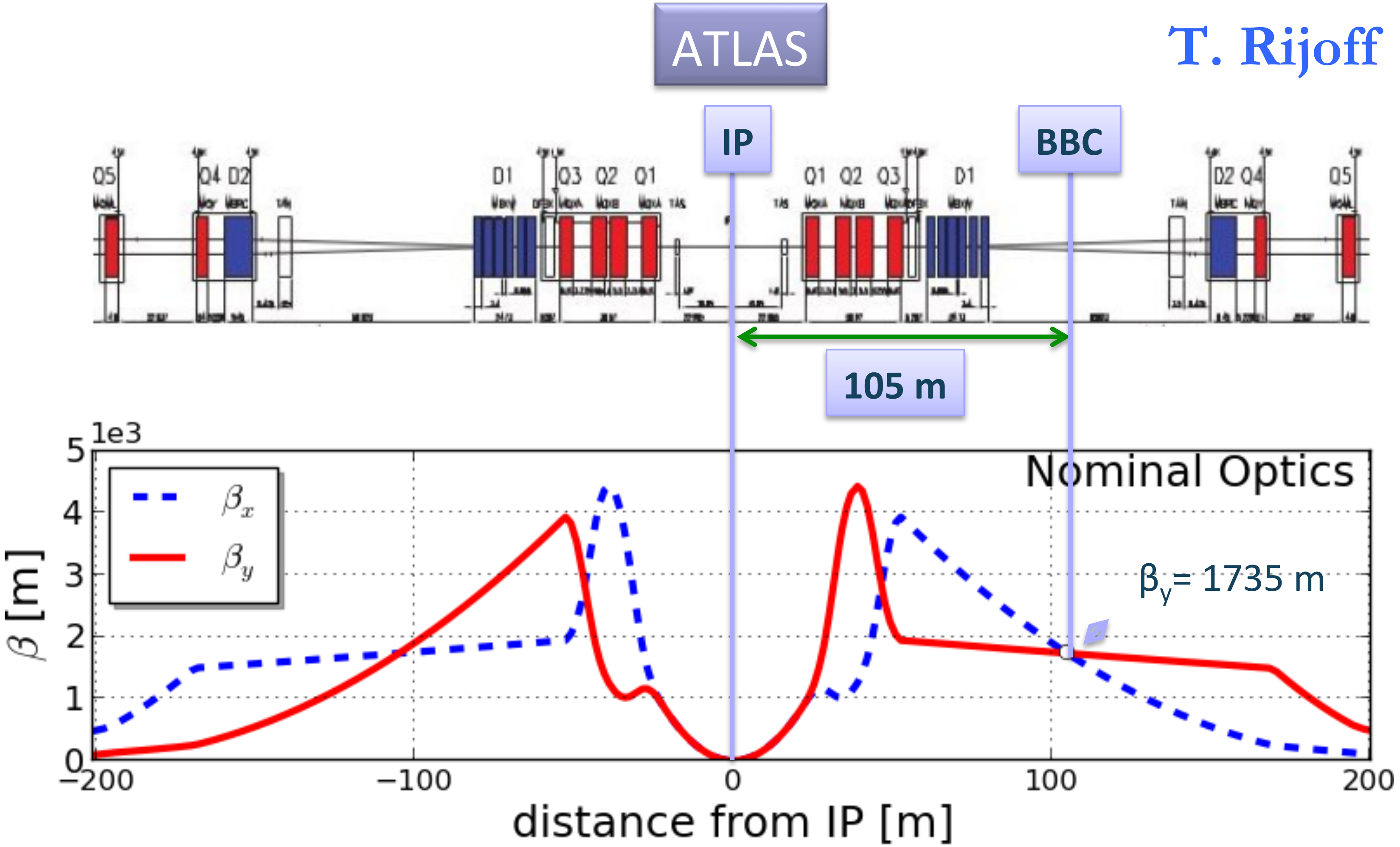
- The linear tune-shift induced by a wire is expressed as

$$\delta\nu_{x,y} = \mp \frac{\mu_0 I L}{8\pi^2 B\rho}\beta_{x,y}\frac{\cos 2\phi_W}{r_W^2}$$

- Equal beta functions in both planes are chosen for having the same impact in both planes (the reason for choosing **BBC** location)
- Induced tune-shift between wires in two IPs can be cancelled, if wire is positioned in equal distance but different planes, and integrated current is following the change of the beta function
  - ☐ Alternating crossing idea for cancelling BBLR tune-shift
- For equal distance of the wire in both planes at the same IP (ϕ_W=45°), tune shift is suppressed
  - ☐ This is also true for BBLR, and the reason why 45° crossing may be interesting (it is also partially true for tune-spread)
  - ☐ Ability to control the position of the wire in the non-crossing plane is **crucial**

Optics at BBC location

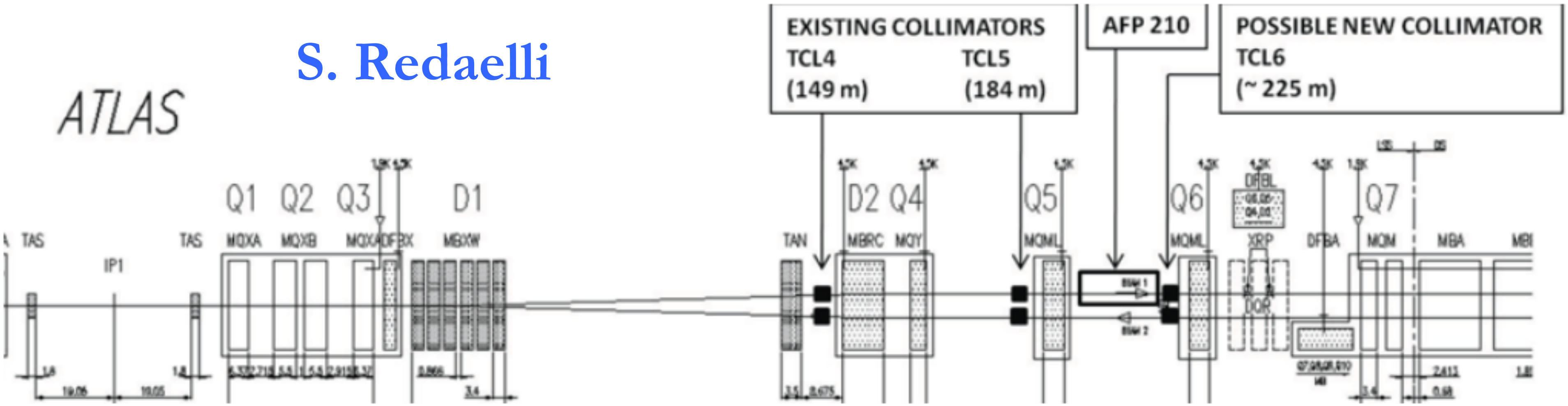
T. Rijoff



- BBC location not available for wire tests
  - ☐ Not the ideal location regarding integration and protection issues

Collimation considerations

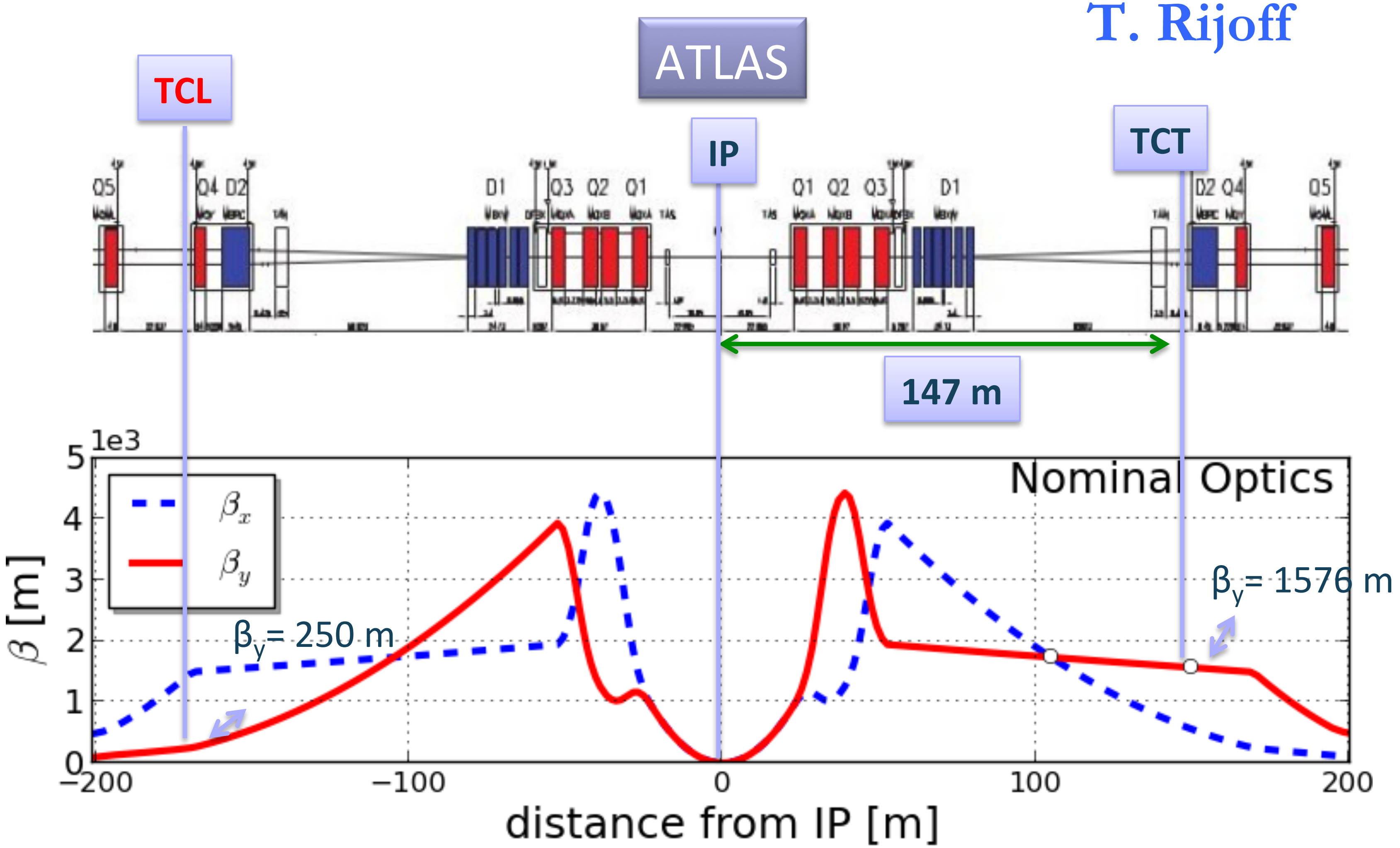
S. Redaelli



- Available collimators for IR1 and IR5 (post LS1):
  - ☐ Incoming beam: H and V tertiary collimators (TCT's), located in cell 4 (2 per beam per IP)
  - ☐ Outgoing beam: H physics debris absorbers (TCL's), located in cells 4, 5 and potentially 6 (3 per beam per IP)
- In conclusion
  - ☐ IR5: upstream+downstream slots available in Xing plane.
  - ☐ IR1: only upstream slots available for Xing plane. **Need to add a V collimator** (TCL) for downstream side (non-IP side of Q4 magnet)

Optics at wire locations

T. Rijoff



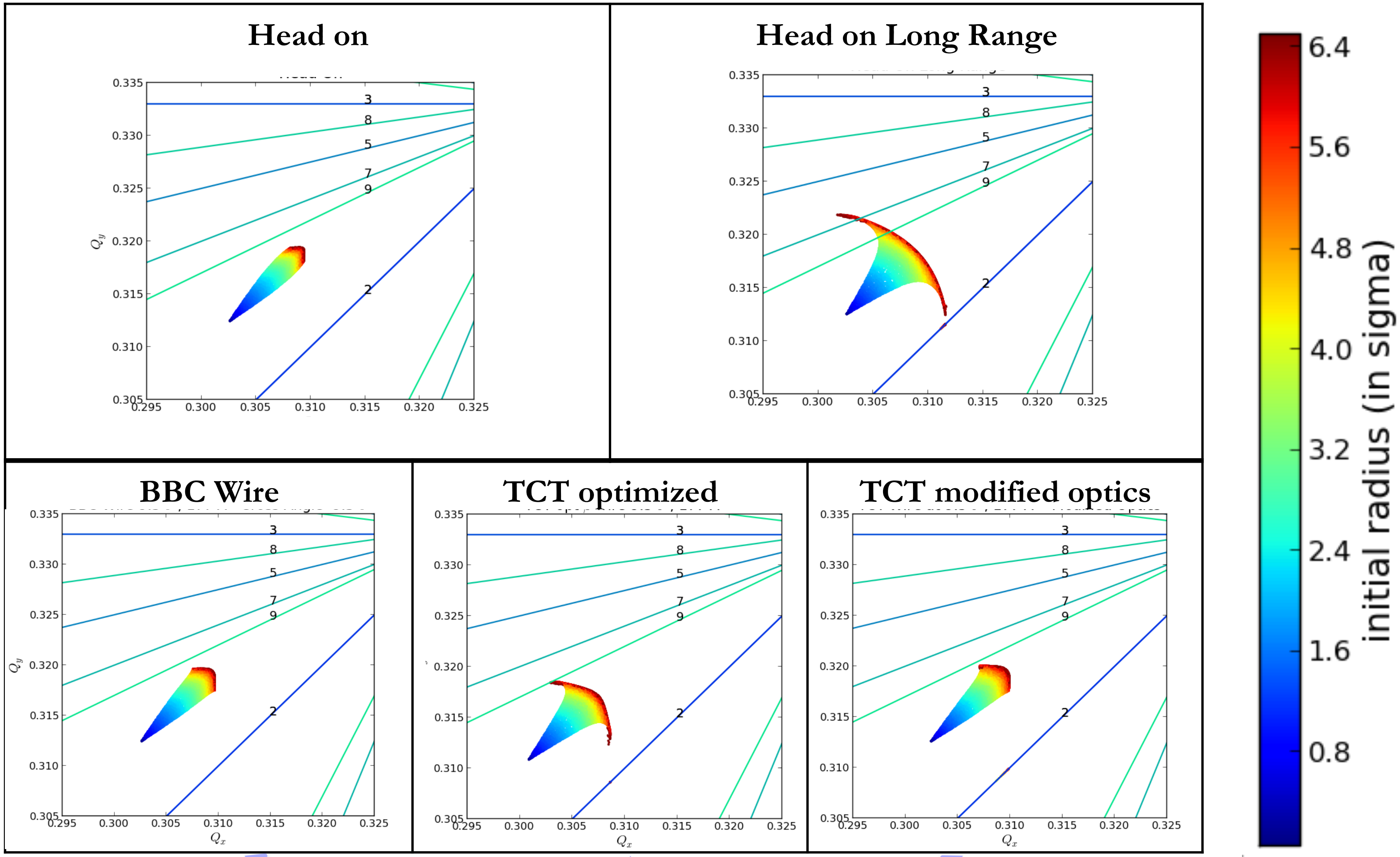
New TCL to be installed for wire tests

BBLR test simulation status

- Latest complete studies performed by **T. Rijoff (MSc Thesis, 2012)**
- Comparison of compensation performance for different wire locations (one per beam and IP)
  - Using an empirical particle stability criterion ("Lyapunov"-like) and frequency map analysis (tune footprints)
- **Best** location (not available) for the wire (BBC) at ~105m from IP (beta functions in both planes equal and large)
- Several cases with different wire distances (fixed current) and several currents (fixed positions) were studied showing that the best compensation is achieved for a wire at **9.5σ** with **177A** (one wire/per IP)
- Alternative locations were checked close to the TCTs (beam 1)
  - At ~150 m, downstream of IP1 and upstream of IP5, for nominal optics with $\beta^*=0.55$ (**adequate**)
  - At ~150 m upstream of IP1 and IP5, for modified optics with $\beta^*=0.6$ (**best**)
  - At ~200 m downstream of IP1 and upstream of IP5, close to Q5 (**worse**)
- Better stability obtained when beta function is big in the crossing plane
- Similar stability for BBLR without correction at $9.5\ \sigma$ separation as compared to $8\ \sigma$ with 237 A wire positioned at $9.3\ \sigma$ (TCT location or BBC)
- Wire shape does not play a significant role (but wire demonstrator is quite thick, with ~2 mm diameter)

BBLR simulations I

T. Rijoff


Head on

Head on Long Range

BBC Wire

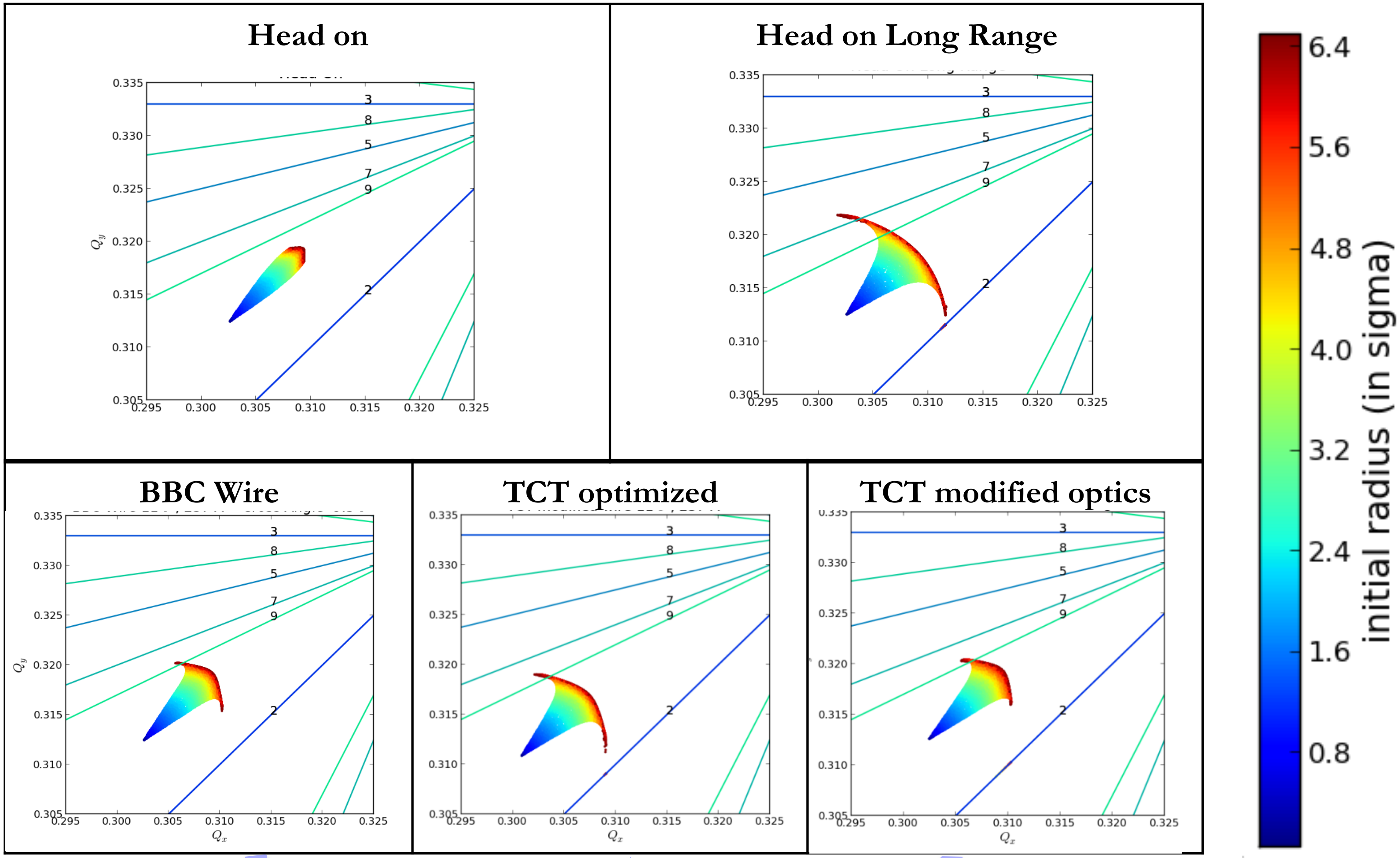
TCT optimized

TCT modified optics

Wire at 9.5 σ – 177 A

BBLR simulations II

T. Rijoff



Head on

Head on Long Range

BBC Wire

TCT optimized

TCT modified optics

Wire at 11 σ – 237 A

BBLR Simulations remarks

- All simulations studies made with 7 TeV nominal optics using BBTRACK code (U. Dorda, F. Zimmermann)
  - BBLR kicks lumped at the IP (phase advance of π/2)
    - No difference found with respect to distributed kicks in "correct" positions
  - No other effects included (noise, triplet non-linearities, PACMAN), although implemented in the code
- Complementary studies for fixing the experimental set-up
  - Evaluate round beam approximation and lumping of the effect on the IP
  - Simulate machine conditions after LS1 (optics, slightly lower energy then nominal, four wires, slightly modified locations,…)

Experimental set-up - Train composition

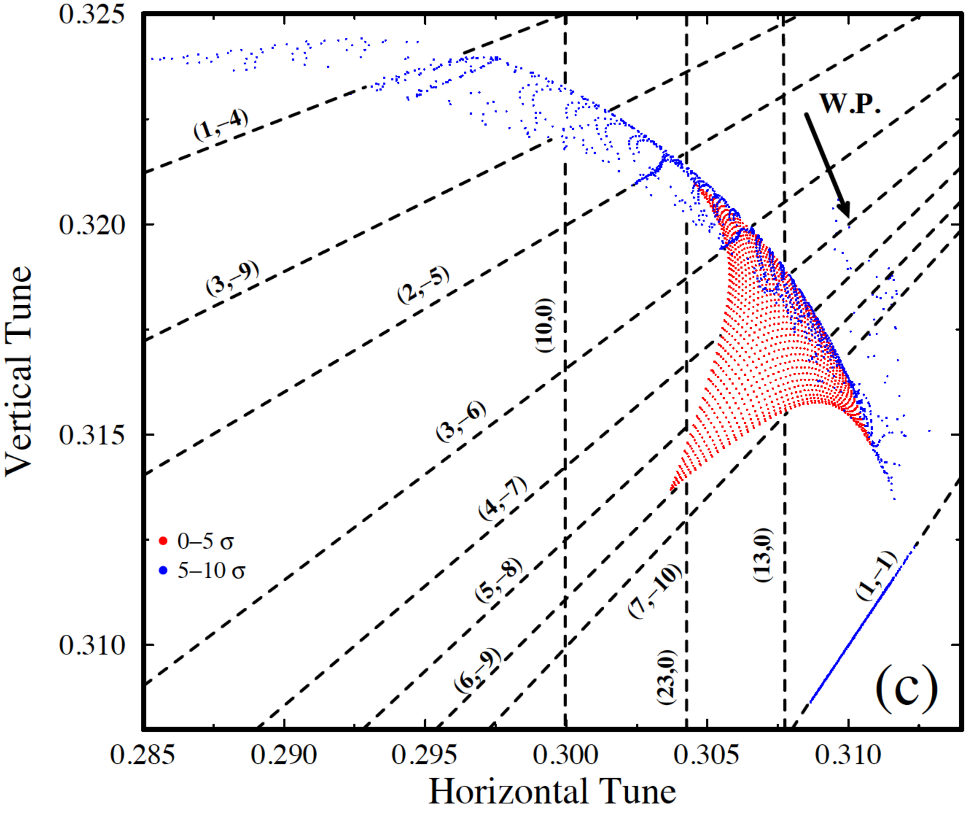
- Two trains with unequal number of bunches, to avoid "all" PACMAN
  - ☐ A long one in the non-compensated beam to cover twice the distance of long range collisions, i.e. at least ((16x2)+1)x2 = 66, neglecting the long-ranges inside D1
    - The usual train with 72 bunches from PS could cover also 1 LR encounter inside D1
    - The newly thought scheme of 80 bunches could cover 3 LR encounters inside D1
  - ☐ The "weak" beam should be composed by a short train (even single bunch), with maximum half the number of bunches as compared to the other beam, i.e. 36 to 40 bunches
- Very short asymmetric trains may be interesting to see only effect in the area of "round" LR encounters (6-7 per IP side), while keeping their number equal for each bunch
- Effect of head on collisions could be suppressed by cogging one beam with respect to the other by 12.5 ns to avoid collisions at the IP while maintaining the number of long range collisions

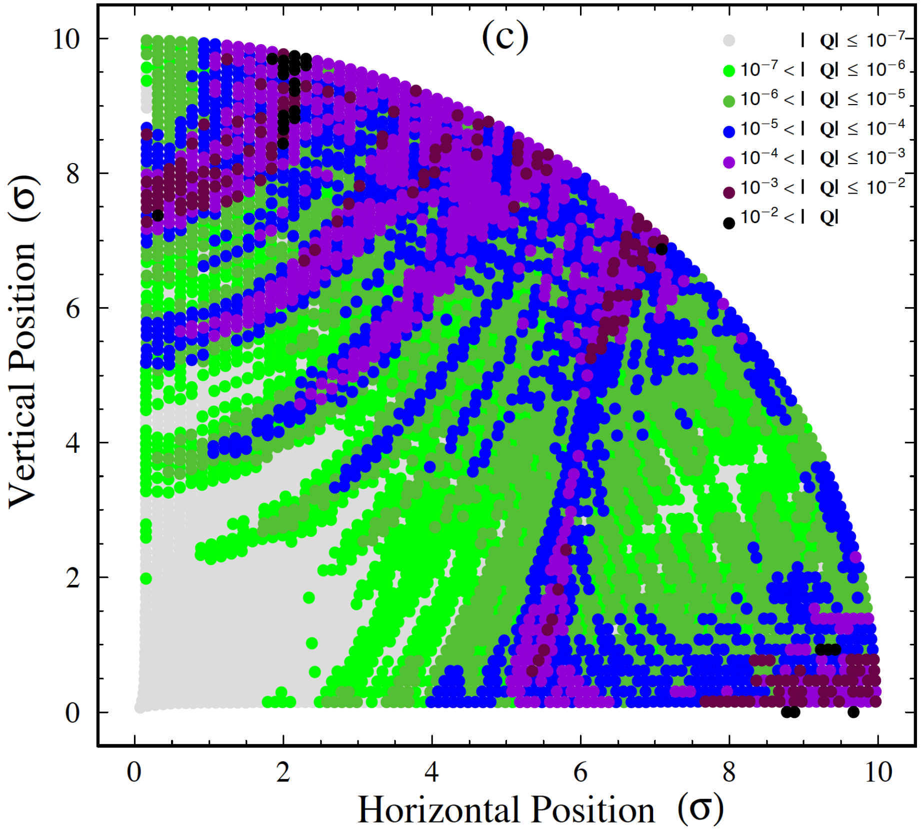
Experimental set-up (cont.)

- Beams should be initially separated in IP2 and 8
- Number of LR may be adjusted depending on efficiency of correction (location and number of wires)
- Separating in 1 IP and colliding in other may be used to test correction efficiency separately in each IP (see talk of S. Valishev)
- If effect is weak, may need to reduce crossing angle
- **Final set-up should be tested in "running" LHC conditions**
- Different configurations will need good preparation and sufficient amount of MD time

Effect of reduced crossing angle

Y. Papaphilippou and F. Zimmermann, 1999

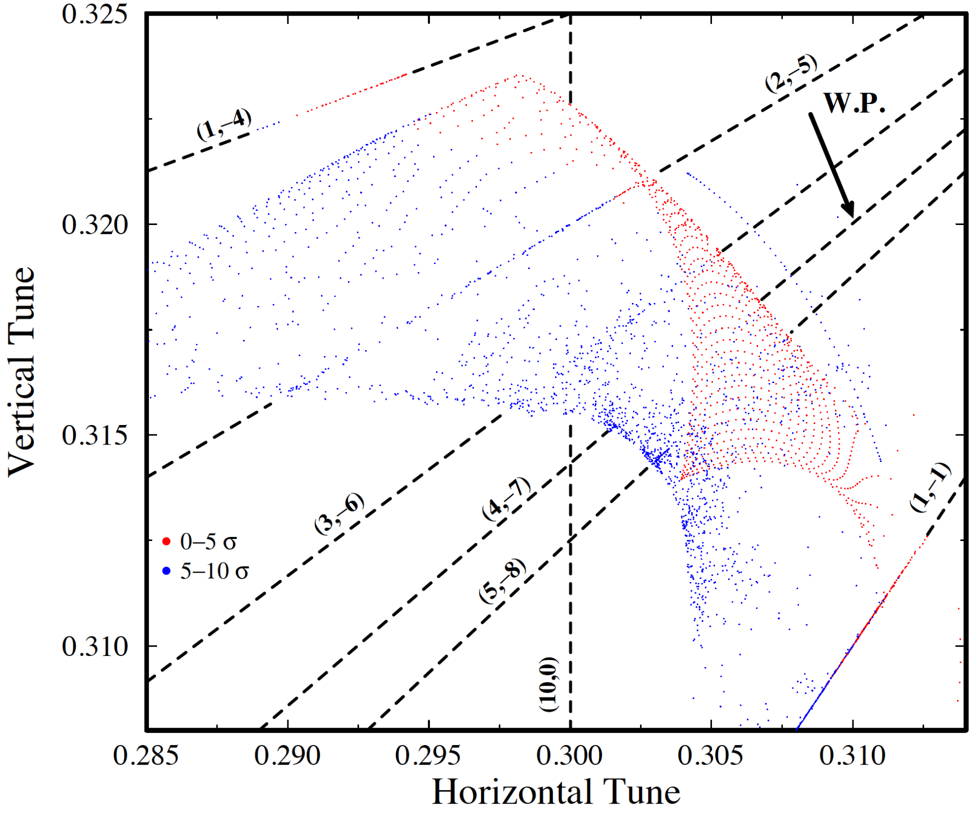


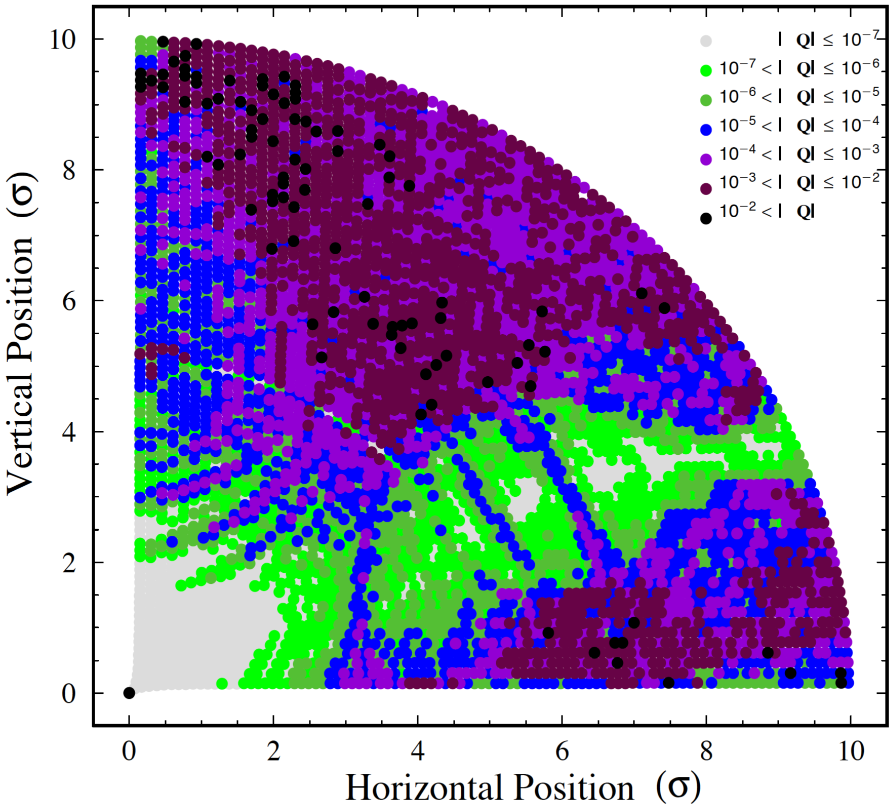


- Dynamic aperture of around 5-6σ for nominal separation of 9.5σ (300μrad full crossing angle)

Effect of reduced crossing angle

Y. Papaphilippou and F. Zimmermann, 1999





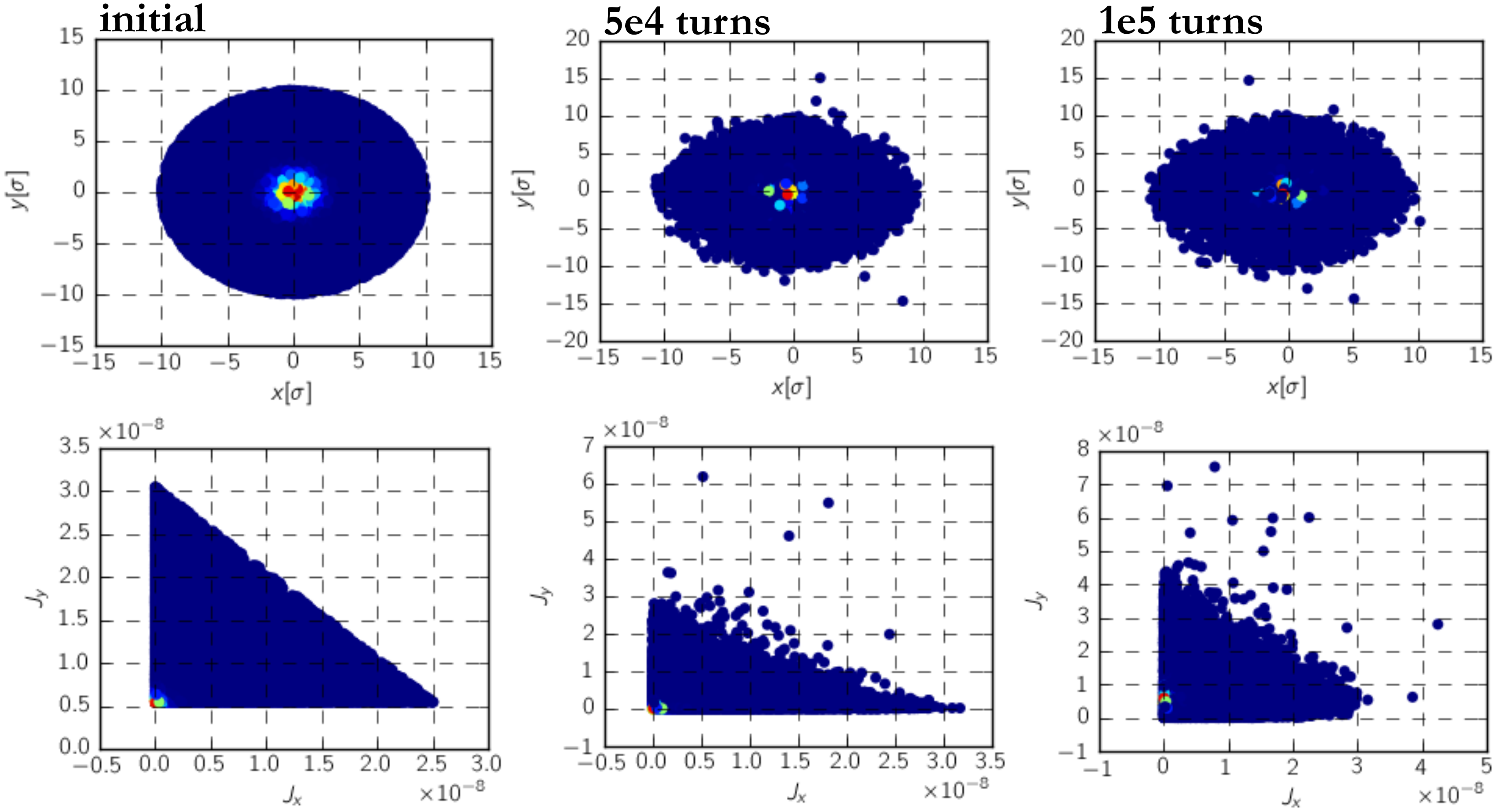
- Dynamic aperture of around 5-6 σ for nominal separation of 9.5 σ (300μrad full crossing angle)
- Reduced to 3-4 σ for separation of ~6 σ (200μrad)
- For the same wire position, its current has to be scaled accordingly

Main observables

- Lifetime (bunch-by-bunch)
  - ☐ Need simulations to benchmark the experiments, i.e. track distributions with BBLR + compensation (on-going work of G. Campogiani)
  - ☐ Disentangle BBLR with respect to other effects such as head on, burn-off, vacuum, IBS, noise,… (on going work of F. Antoniou for LHC luminosity modelling)
- Tails evolution
  - ☐ Losses on different collimator positions
  - ☐ **Halo diagnostics**
- Beam transfer function
  - ☐ Damper may not allow to have any relevant measurement (gating ?)
- Orbit, tune, tune-spread (coupling, chromaticity)
  - ☐ Last three are difficult to measure, while in collision

Modelling distributions

- Configuration and action space evolution for nominal LHC, no compensation, for estimating diffusion rates



initial **5e4 turns** **1e5 turns**

G. Campogiani

Required instrumentation

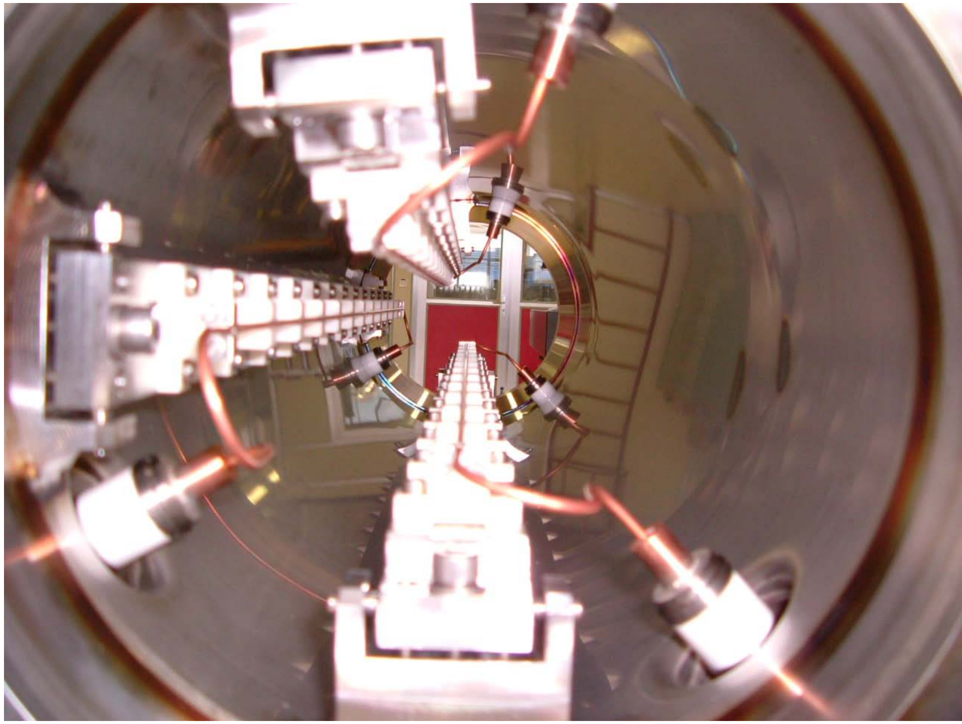
- Diagnostics for one beam will be needed for the test (the one compensated by the wire)
- Beam Current Transformer, tune-monitor, Beam Synchrotron Light monitor (BSRT), BPMs, Schottky, halo diagnostics (see talk by R. Jones)
- Bunch-by-bunch diagnostics are essential
- For each observable, need to evaluate expected effect and compare with the actual performance of instruments
- Need realistic scaling of long-range effect (elliptic beams) and wire for all observables and corresponding simulations

Wire effect in single beam

- Need to benchmark effect of wire
- Calibrate position and current with observables:
  - Orbit, tune, tunes-pread, coupling (alignment), resonance driving terms, effect on distribution (tails)
- Could be done even at injection energy and conditions (only 1 beam)
  - Experimental conditions and instrumentation as for LHC optics measurements
    - BPMs in orbit and TBT mode, BSRT, wire scanners, Q-Kicker, AC-dipole, etc…
  - A lot of information can be already gained with existing wires in SPS

Wires at SPS

- Two 60cm long 3-wire compensators installed in the CERN SPS
  - Different "crossing" plane and even @ 45deg
- Movable in vertical by +/- 5mm (remote controlled)
- Water cooled
- About equal beta functions in the transverse planes (~50m)



- Separated by a phase advance of 3deg (similar between BBC and long range interactions in LHC)
- Powered with integrated DC current of up to 360A m (60 LR collisions in LHC)
- Set-up re-evaluated during 2014, for MDs in 2015 (**see R. Jones talk for past experience**)

BBLR study plans – Short term (2014-2015)

- Repeat simulations considering the positions available with the present layout and assuming the nominal optics (also ATS)
  - ☐ Introducing wire in MADX and using SIXTRACK (benchmarking and debugging campaign, on-going work of Andrei Patapenka)
- Check alternative positions optimizing the impact of the BBLR with the nominal optics (ATS)
- Simulate effect on PACMAN bunches
- Establish tolerances for positioning of the wire (hor/vertical alignment and tilt) and geometry (probably small effect)
- Establish scaling laws for linear and non-linear optics effects with respect to wire configurations (see Tevatron work)
- Establish observables for demonstrator measurement campaign and develop experimental program
  - ☐ Tune-shift with amplitude, resonance driving, lifetime (luminosity modelling)

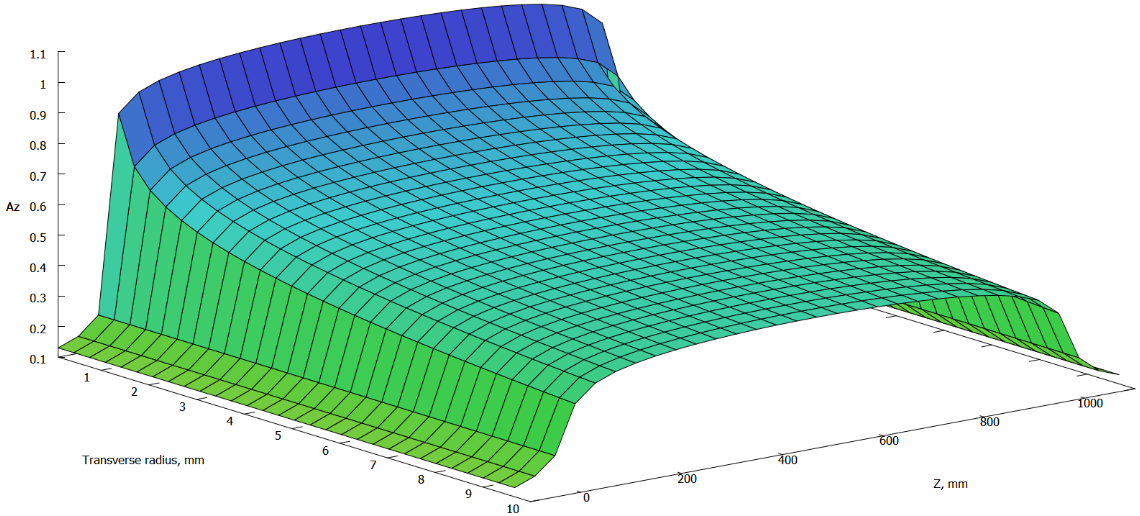
Wire modelling

A. Patapenka

- Vector potential for a **finite** wire

$$A_z(x,y,z) = \frac{\mu_0 I}{4\pi} \operatorname{asinh}\left(\frac{(z_0 - z)}{\sqrt{y^2 + x^2}}\right)$$

- Maps were implemented in SIXTRACK (thin kicks), including effect of misalignment and are currently under benchmark (plan to include effect of wire fringe field)



BBLR study plans – Medium, Long term (2014-2018)

- Simulate effect of wire with latest HL-LHC parameters (**talk by S. Valishev**)
  - Bunch characteristics, filling scheme, optics, wire position and current, inclusion of crab-cavities, etc.
- Compare global vs. local correction, one vs. many wires per beam and IP, wire vs. other methods (electron lens, multipole magnets)
- Particle scattering on wire for heat deposition and damage (collimation/ FLUKA team)
- Test the effect of wire compensation on flat beams (**talk by S. Valishev**)
- Check alternative crossing scenarios and filling schemes
  - Same planes in both IPs, inclined planes, micro-bunches
- Collective effects with wire compensation
  - Impact on beam stability due to tune-spread reduction by wire
- Impedance of wire (some results already exist)
- Impact of noise
- Considerations about different implementation of wire (material, etc.)
- BBLR modelling
  - Effect of dispersion, longitudinal slicing, non-Gaussian beam distributions,…

Thank you very much for your attention

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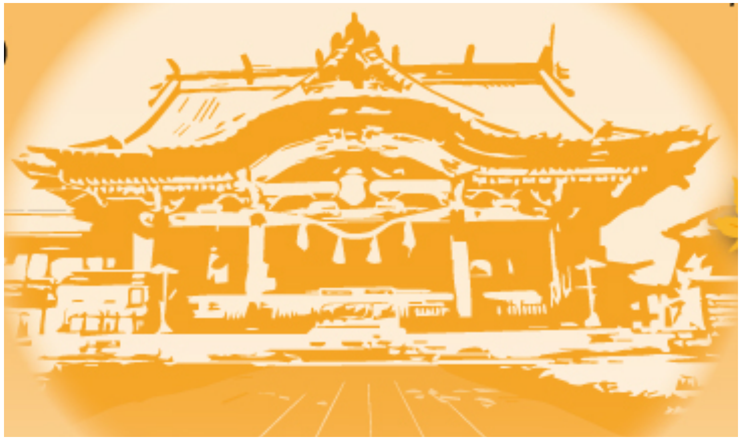


Spare slides

General Beam-beam kick

- Kicks to a test particle (weak beam) due to an elliptical Gaussian charge distribution (strong beam)

$$i\Delta x' + \Delta y' = -\frac{N_b r_p}{\gamma} F(x, y, \sigma_x, \sigma_y)$$

  - For $y \geq 0$, $\sigma_x > \sigma_y$, the function is written as

$$F(x, y, \sigma_x, \sigma_y) = \sqrt{\frac{2\pi}{\sigma_x^2 - \sigma_y^2}} \left[\mathrm{w}\left(\frac{x + iy}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right) - e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}} \mathrm{w}\left(\frac{x\frac{\sigma_y}{\sigma_x} + iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}} \right) \right]$$

  with the complex error function defined as

$$\mathrm{w}(z) = e^{-z^2}\mathrm{erfc}(-iz) = e^{-z^2}\left(1 - \mathrm{erf}(-iz)\right) \quad \text{and} \quad \mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2}\,\mathrm{d}t$$

  - For $y < 0$, $\sigma_x > \sigma_y$, the function becomes

$$F(x, y, \sigma_x, \sigma_y) = -F^*(x, -y, \sigma_x, \sigma_y)$$

  - For $\sigma_x < \sigma_y$, we have $F(x, y, \sigma_x, \sigma_y) = iF^*(y, x, \sigma_y, \sigma_x)$

Beam-beam kick for round beams

- The beam-beam function can be simplified further to

$$F(x,y,\sigma_x,\sigma_y) = -\sqrt{\frac{2\pi}{\sigma_x^2-\sigma_y^2}}\,e^{-\frac{(x+iy)^2}{2(\sigma_x^2-\sigma_y^2)}}\left[\mathrm{erf}\left(\frac{y-ix}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)-\mathrm{erf}\left(\frac{ix\frac{\sigma_y}{\sigma_x}-y\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

- Using the asymptotic expansion of the error function for large arguments $\mathrm{erf}(z) = 1 - \frac{e^{-z^2}}{z\sqrt{\pi}}\sum_{n=0}^{\infty}(-1)^n\frac{(2n-1)!!}{(2z^2)^n}$,

  and keeping only the leading order terms, the beam-beam function for round beams can be written

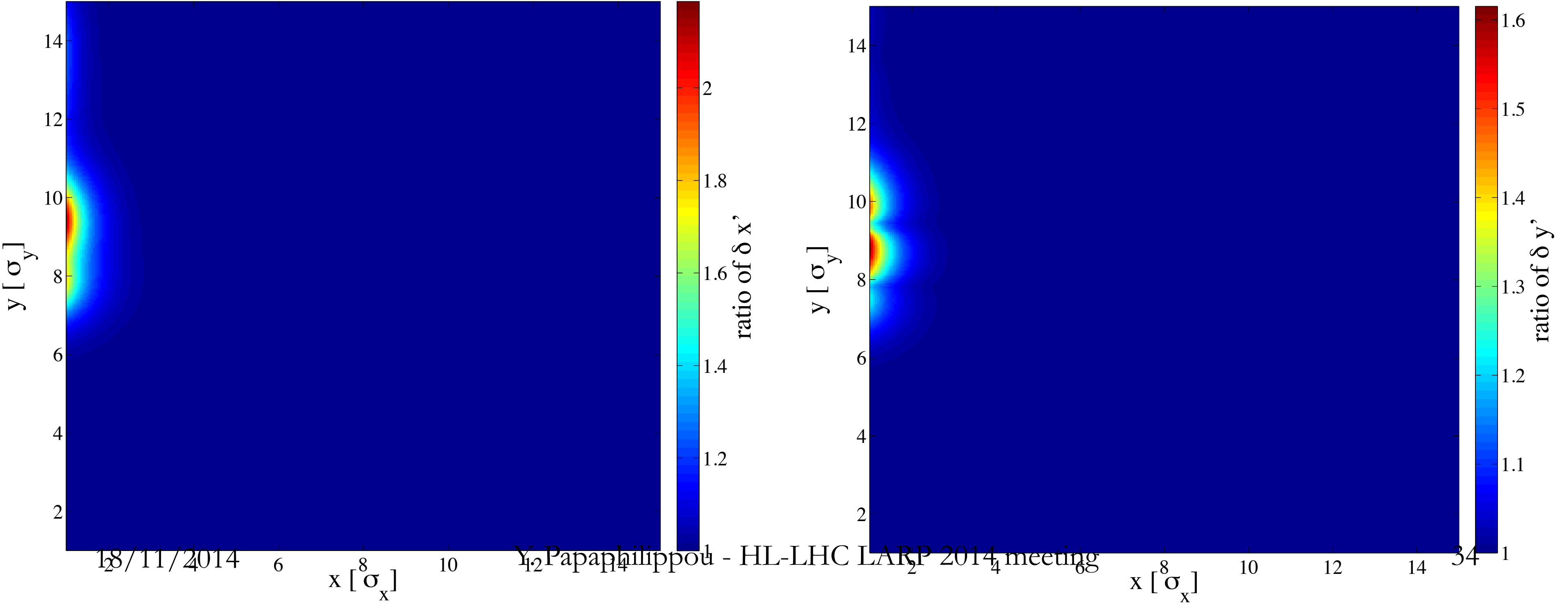
$$i\Delta x' + \Delta y' = -\frac{2N_b r_p}{\gamma}\,\frac{i\left(1-e^{-\frac{x^2+y^2}{2\sigma^2}}\right)}{x+iy}$$

- For separated beams (long range),

$$x \mapsto x + x_c\ , \quad y \mapsto y + y_c$$

Round vs. 1/r

- Calculating the "lumped" beam-beam kick for a grid of horizontal and vertical positions, for B1 in IP1
- The ratio between the round and 1/r approximation is always very close to 1, apart for the areas that both coordinates are close to the origin, i.e. horizontal close to zero and vertical close to the separation

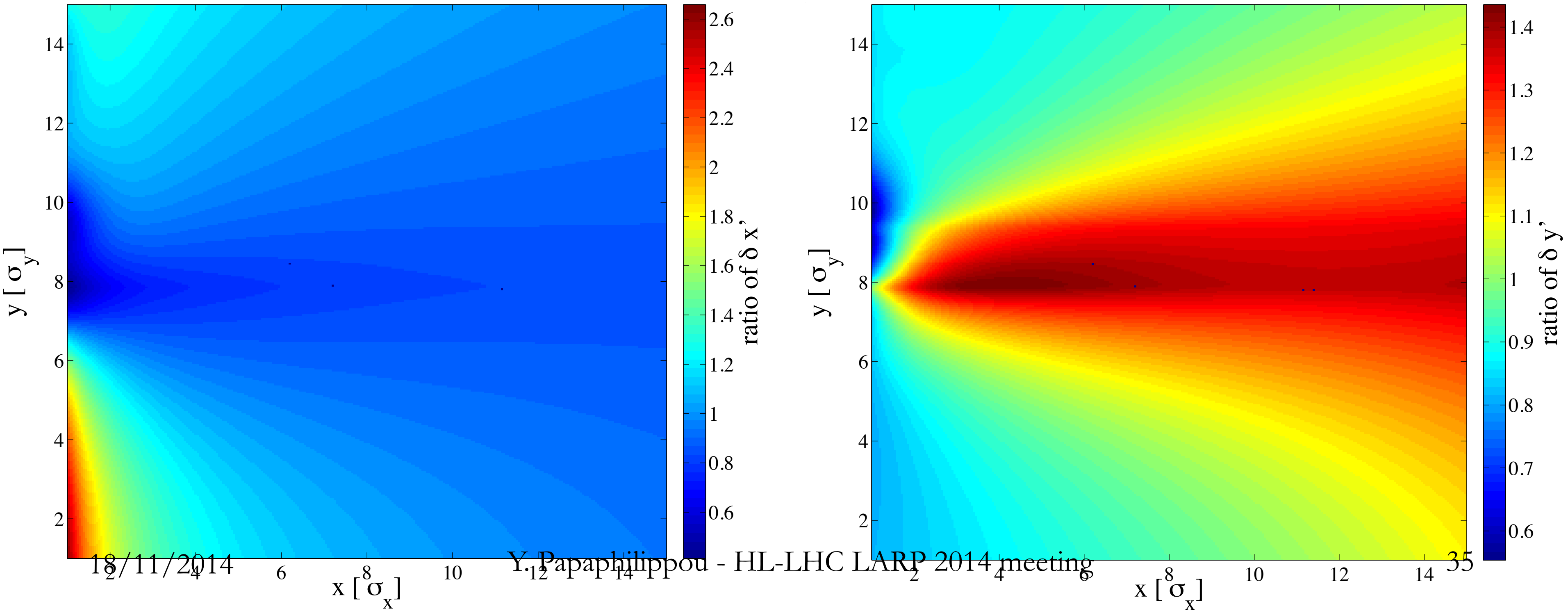


IR1, B1

Elliptic vs. round

- Calculating the “lumped” beam-beam kick for a grid of horizontal and vertical positions, for B1 in IP1
- The ratio between the elliptic and round beam kick is generally higher than 1, but with different (and somehow complementary) behavior in the horizontal and vertical plane

IR1, B1



Orbit effect due to wire

- The wire induces an orbit shift due to a “dipole” kick expressed as

$$\delta x_0' = \frac{\mu_0 I L}{2\pi B\rho}\frac{\cos\phi_W}{r_W} \quad \text{and} \quad \delta y_0' = \frac{\mu_0 I L}{2\pi B\rho}\frac{\sin\phi_W}{r_W}$$

- For only horizontal or vertical position of the wire, there is only an orbit kick in the corresponding plane
- In either side of the IP, powering the wires accordingly (opposite sign and with current following the square root of the beta functions ratio), the orbit effect (and not only) is supressed (π-bump)
  - ☐ To be used for calibration purposes

Coupling due to wire

- The minimum tune-split due to wire-induced coupling is

$$\delta\nu_{\min} = \frac{\mu_0 I L}{4\pi^2 B\rho}\sqrt{\beta_x\beta_y}\frac{\sin 2\phi_W}{r_W^2}$$

- If the wire is positioned in one plane, there is no coupling
- Maximum coupling is induced for $\phi_{\mathrm{W}}=45^{\circ}$, giving around 6e-3 tune-shift for wire in **BBC** position
- Global coupling can be cancelled, between wires in the two IPs , if wire is positioned in complementary phase $\phi_{\mathrm{W}}=135^{\circ}$, in the opposite IP (and current follows square root of the product of beta functions)