Updated scenario and simulations for the BBLR LHC test

Yannis PAPAPHILIPPOU, CERN

WP2 TL meeting, June 18th, 2015

Thanks to

F.Antoniou, G.Arduini, G.Campogiani, S.Fartoukh, R.Jones, R.deMaria, A.Patapenka, A. Rossi, T.Rijoff, H.Schmickler, A.Valishev, F.Zimmermann

Outline

- Wire compensation basic considerations
- Wire effect on the beam
  - Multipole expansion,
  - Orbit, coupling, tune, tune-spread
- Test of wire compensation in the LHC
  - Nominal and available positions
  - Present simulation status
- Experimental conditions, observables and associated instrumentation needs
- SPS wires status and plans
- Study plans

Wire compensation

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

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

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

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

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

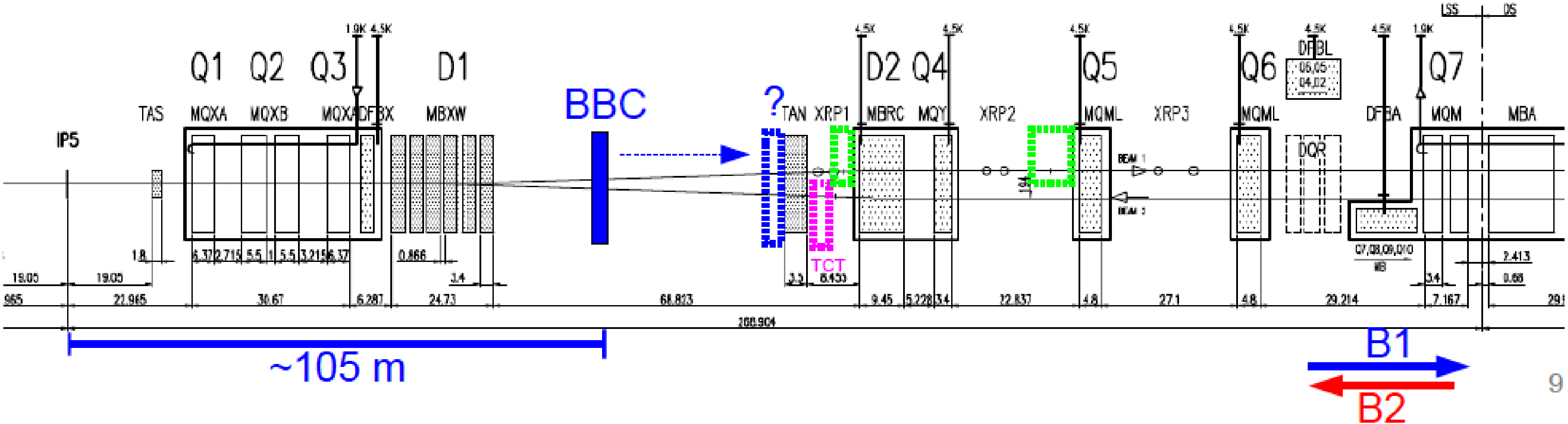
with $X_W = x + x_W \;, \quad Y_W = y + y_W$

- 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 and 10.6 Am for HL-LHC

Basic considerations

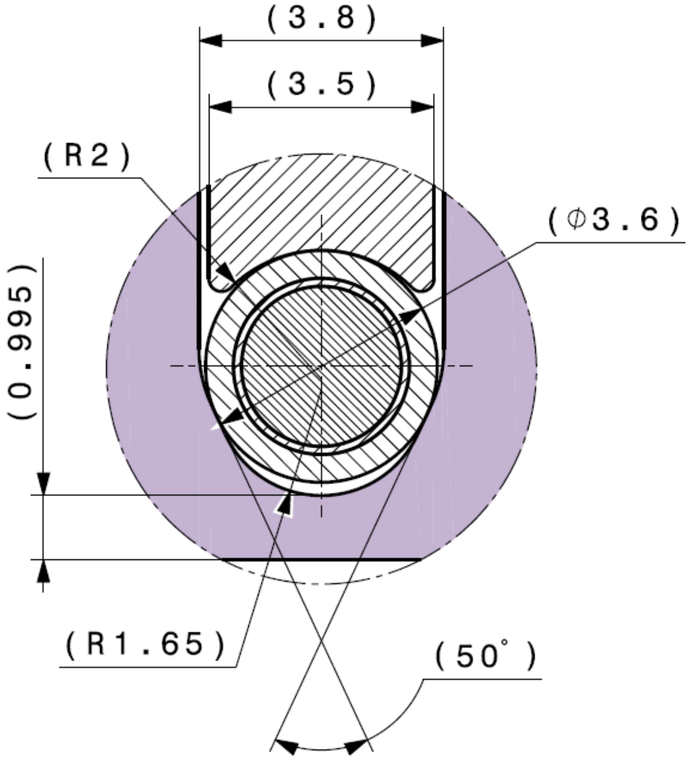
J.P. Koutchouk, 2001

- **Locality** of the compensation
  - ☐ Close to the BBLR encounters which occur at ~π/2 from either IP side
  - ☐ A lot of space available between D1 and TAN but integration may be difficult (idea of e-lens)
  - ☐ Phase advance still close to π/2 even up to Q5



Basic considerations

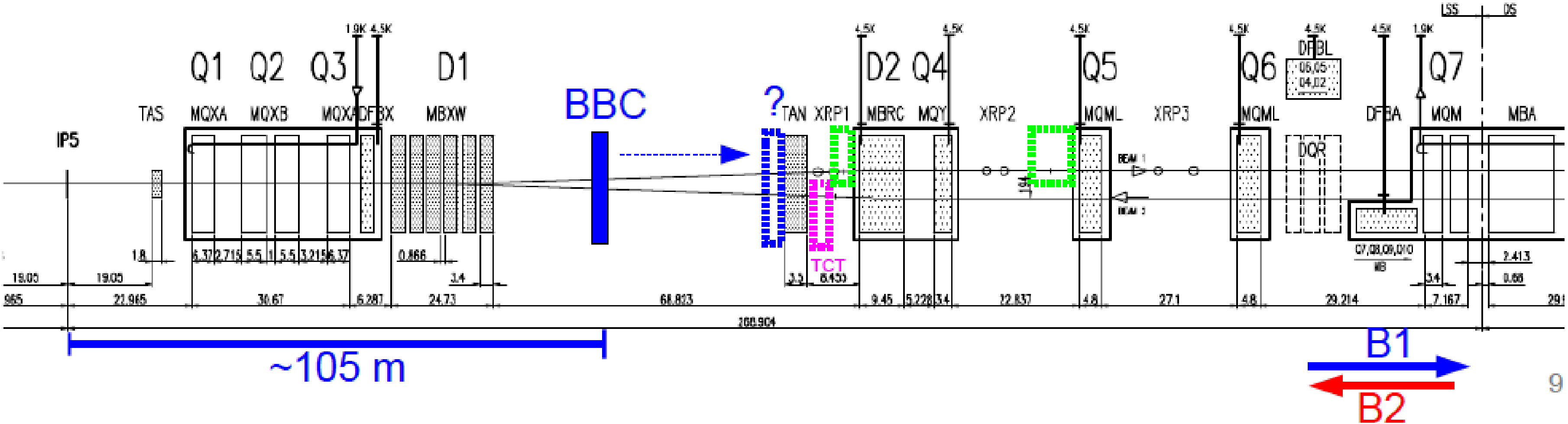
- **Position** of the wire with respect to the beam
  - ☐ As close as average BBLR separation (9.5σ)
  - ☐ Integrated kick is scaled inversely with distance, i.e. the smaller the distance the lower the required integrated current and vice versa
  - ☐ Difficulty with wire-in-jaw collimator to approach the beam closer to ~12-13σ
  - ☐ Some strength can be recovered by wire current but dependence is not uniform depending on resonance order (see below)



A. Bertarelli

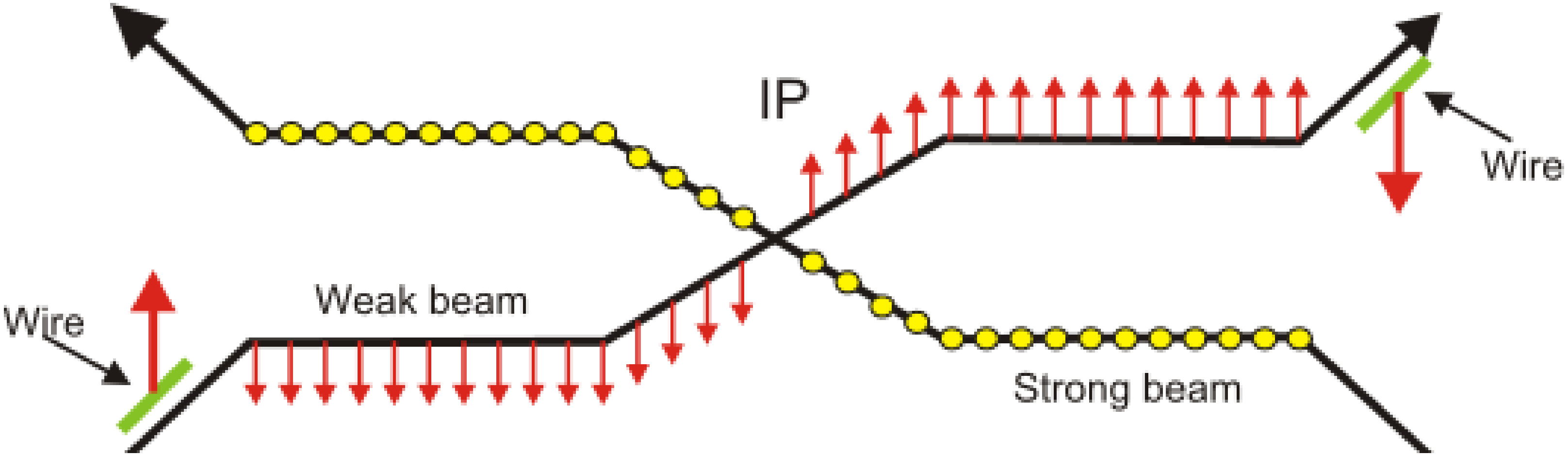
Basic considerations

- **Optics** considerations **J.P. Koutchouk, 2001**
  - ☐ Large and equal beta functions for efficient tune-shift compensations
  - ☐ The optics functions equality may be not optimal for resonance driving term compensation
    - Ratio of 2 or ½ is optimal **S. Fartoukh, 2015**
- 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
- 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 also anti-symmetric



Wire multi-pole expansion

- The multi-pole expansion of the wire can be written

$$B_y + iB_x = \frac{\mu_0 IL}{2\pi r_W} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_W} \right)^{n-1}$$

with the radial distance of the wire to the beam

$$r_W = (x_W^2 + y_W^2)^{1/2}$$

and the multipole coefficients

$$b_n = -\cos(n\phi_W) \quad , \quad a_n = \sin(n\phi_W)$$

with the angle $\phi_W = \arctan(\frac{y_W}{x_W})$

- The same expansion is applicable to the BBLR field for the round beam, $1/r$ approximation

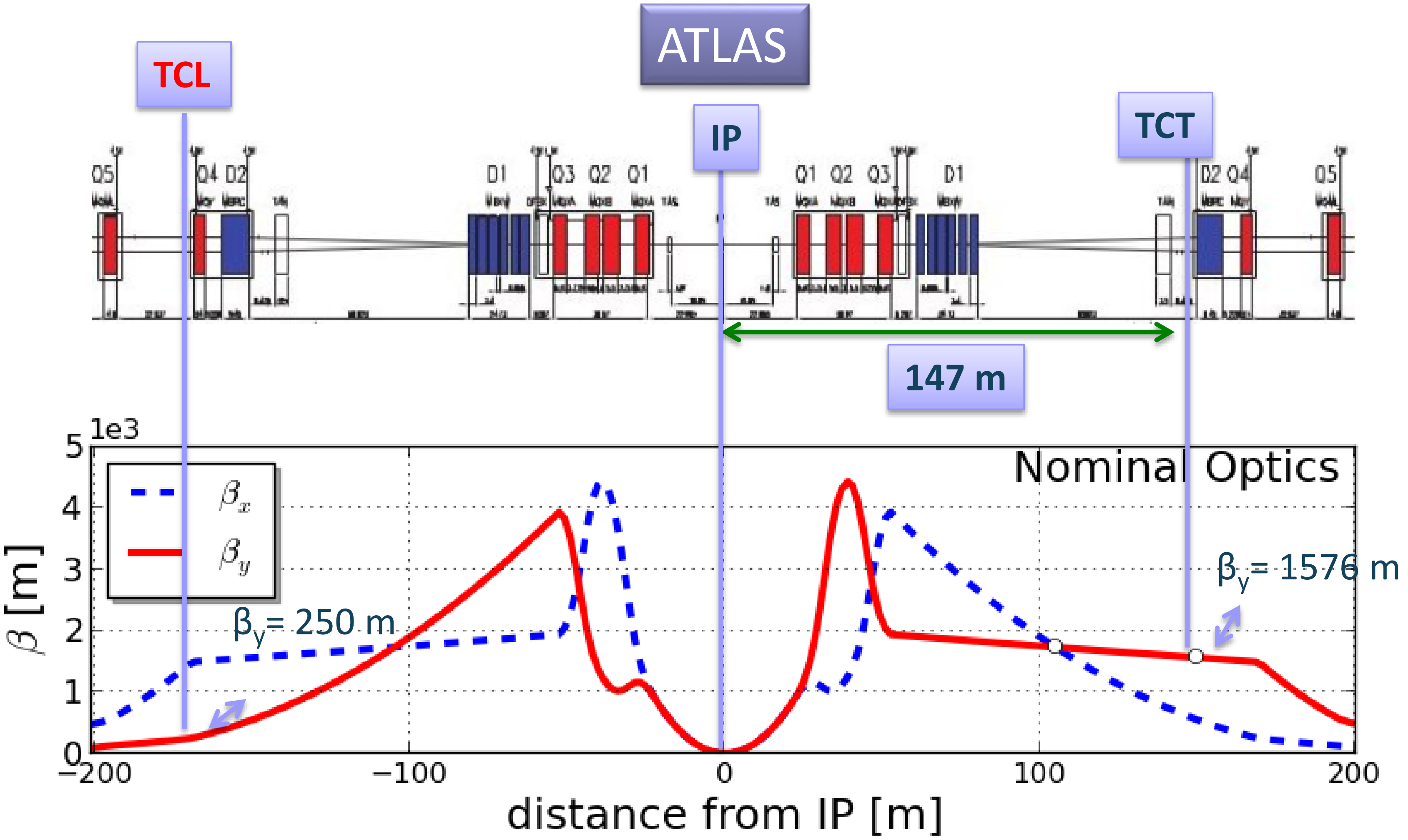
Wire multi-pole expansion

- For a wire positioned in the horizontal plane (or horizontal BBLR crossing), i.e. $r_W = |x_W|$
  - ☐ For $\phi_W = 0,\ a_n = 0$ and $b_n = -1$
  - ☐ For $\phi_W = \pi,\ a_n = 0$ and $b_{2n-1} = 1,\ b_{2n} = -1$
- For horizontal wire (or horizontal BBLR crossing), only normal multipoles are excited
- Putting the wire in the opposite side with respect to the "strong" beam will cancel only half of the multipoles (odd or even depending on the polarity of the wire)

Wire multi-pole expansion

- For a wire positioned in the vertical plane (or vertical BBLR crossing), i.e. $r_W = |y_W|$
  - For $\phi_W = \pi/2$, $a_{2n} = b_{2n-1} = 0$ and
    $a_{4n-1} = b_{4n} = -1$ $a_{4n-3} = b_{4n-2} = 1$
  - For $\phi_W = -\pi/2$, $a_{2n} = b_{2n-1} = 0$ and
    $a_{4n-1} = b_{4n-2} = 1$, $a_{4n-3} = b_{4n} = -1$
- For vertical wire (or vertical BBLR crossing), even skew and odd normal multipoles are not excited
- Putting the wire in opposite side with respect to "strong" beam cancels only half of the excited BBLR multipoles (odd skew or even normal, depending on the wire polarity)
- Alternating crossing cancels the effect of $b_2, b_6, b_{10}, \ldots$

Optics at wire locations



- 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)

Status of wire-in-jaw collimators

- 4 “wire-in-jaw“ collimators ordered from CINEL
  - ☐ Cost covered by HL-LHC
  - ☐ Design finished in late 2014
  - ☐ Delivery, although originally planned, will be impossible during 2015 (new estimated date 04/2016)
  - ☐ Installation in winter stop 2016/2017 (vacuum group approval)
    - Installing during a Technical Stop may not be easy but under investigation
  - ☐ Cabling to be finalised for 4 individual power supplies
- Full compensation of one beam: 2 collimators/IP
  - ☐ Compensation of both beams in the ingoing or outgoing side (2 collimators on the same side in IP1 and IP5) does not provide optimal reduction of tune-spread and resonance driving terms

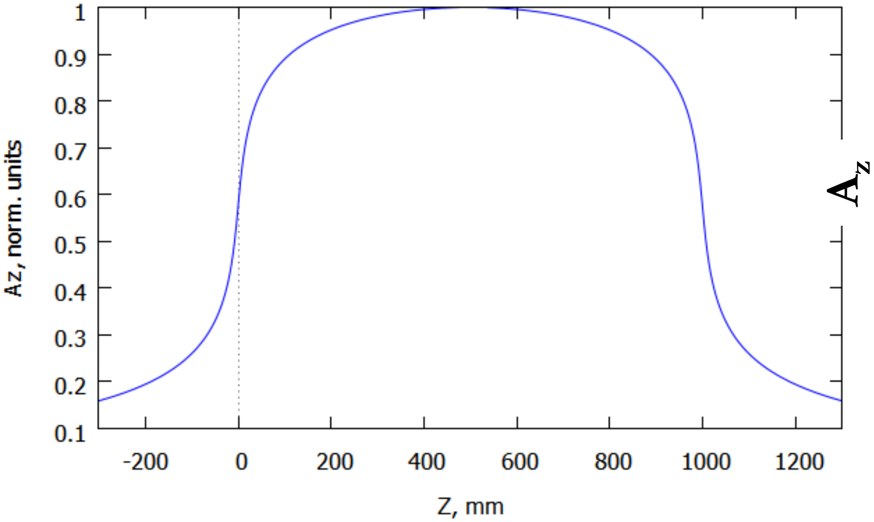
BBLR Simulations remarks

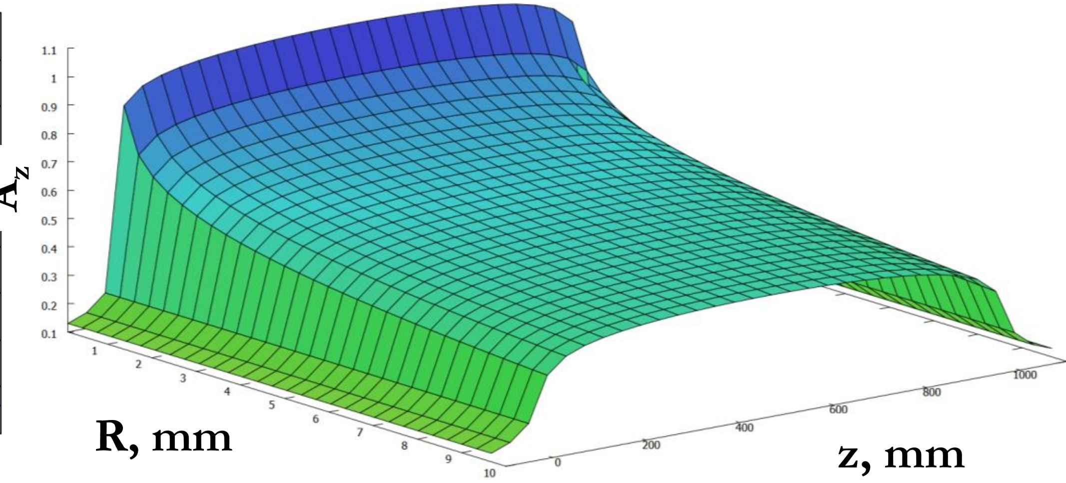
- All previous simulations studies made with 7 TeV nominal optics using BBTRACK code (U. Dorda, F. Zimmermann, T.Rijoff)
  - BBLR kicks lumped at the IP (phase advance of $\pi/2$)
    - No difference found with respect to distributed kicks in "correct" positions
  - No other effects included (noise,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

Wire modelling

A. Patapenka

- Vector potential for **finite** straight wire
  - Only one longitudinal component
  - z-dependent, with central symmetry
  - $$A_z(x,y,z)=\frac{\mu_0 I}{4\pi}\operatorname{asinh}\left(\frac{z_0-z}{\sqrt{x^2+y^2}}\right)$$
- Map constructed by integrating the kick over the z-direction

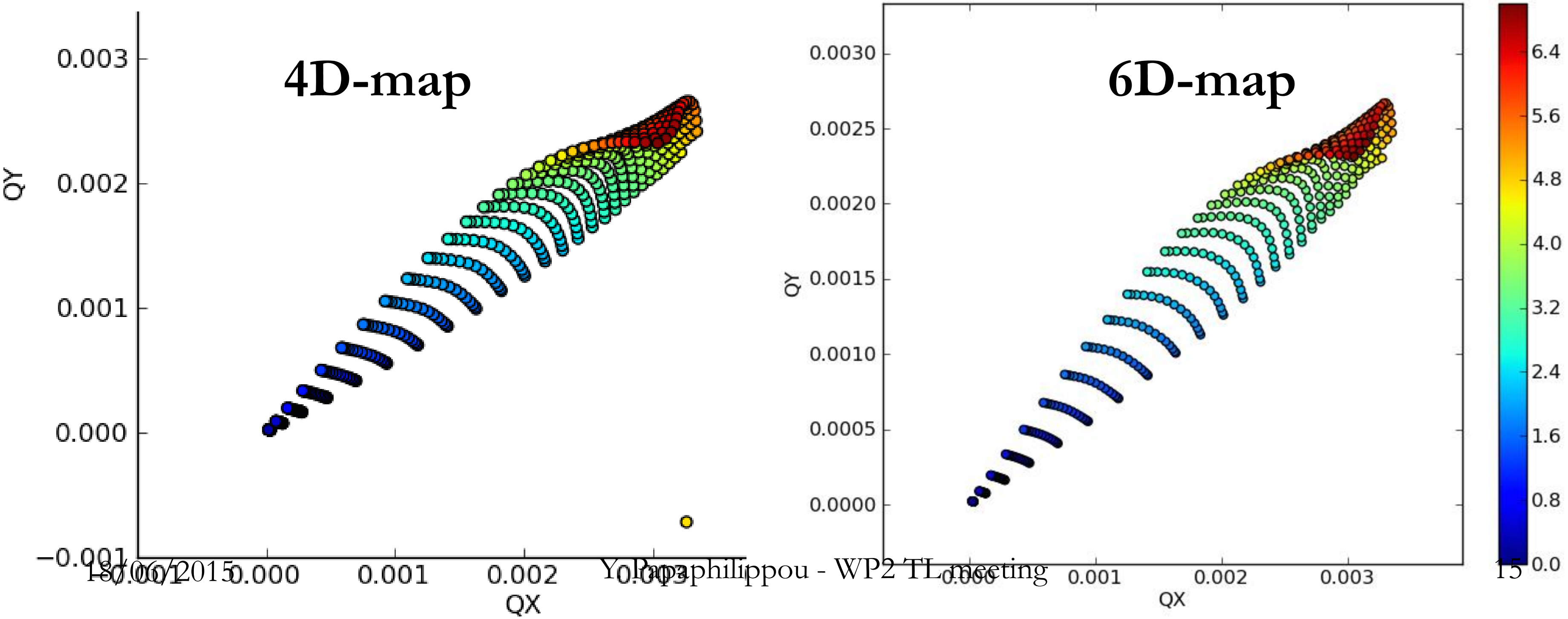




SIXTRACK implementation

A. Patapenka

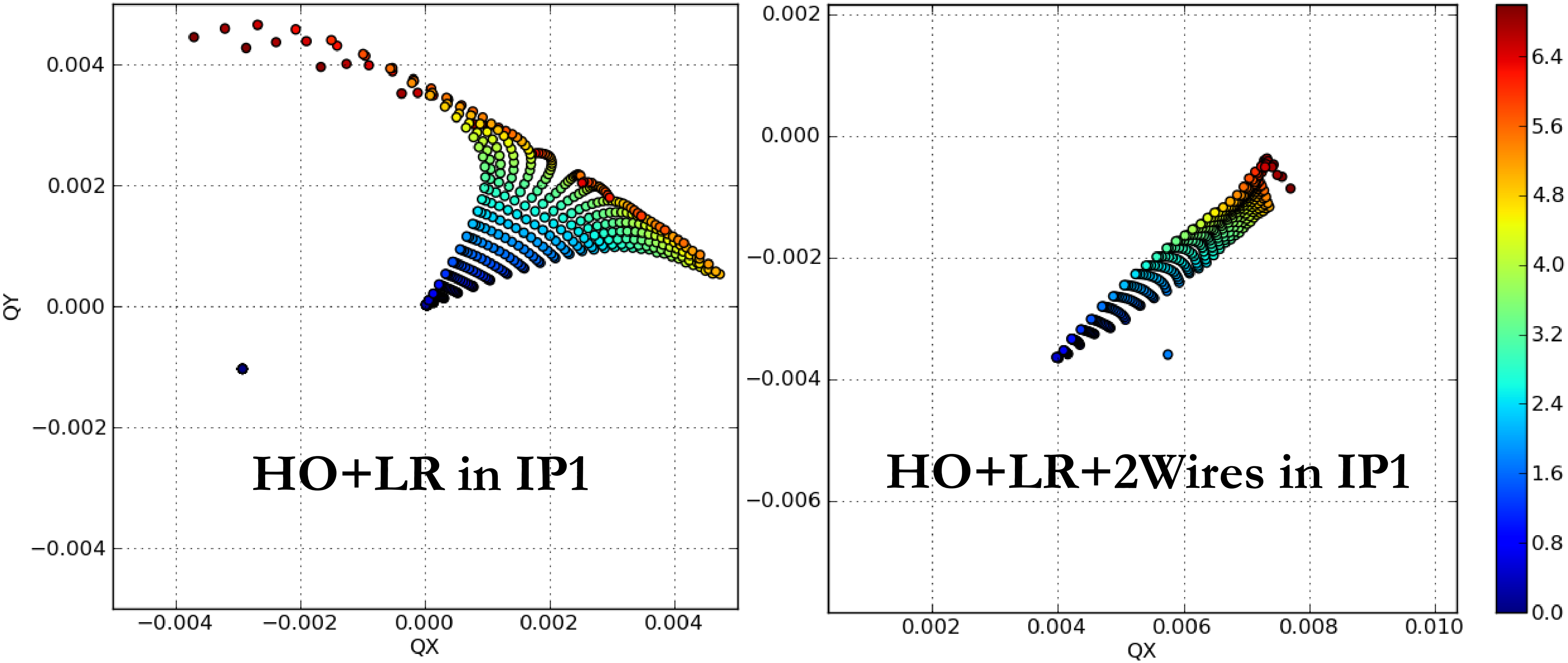
- Two models in SIXTRACK
  - ☐ Existing one debugged and fixed **see Erdelyi and Sen**
  - ☐ Implementation of a map for an arbitrary 3D vector potential, based on Euler integration method
    - Ability to integrate a generic field coming from a model or magnetic measurements
  - ☐ Tilts of the wire are treated as coordinate transformations before and after the element
  - ☐ The two models produce identical results for the wire element



Wire compensation 1 IP

A. Patapenka

- Compensation in IP1 with 2 wires of 110A in the BBC location (nominal 7TeV LHC beam parameters)



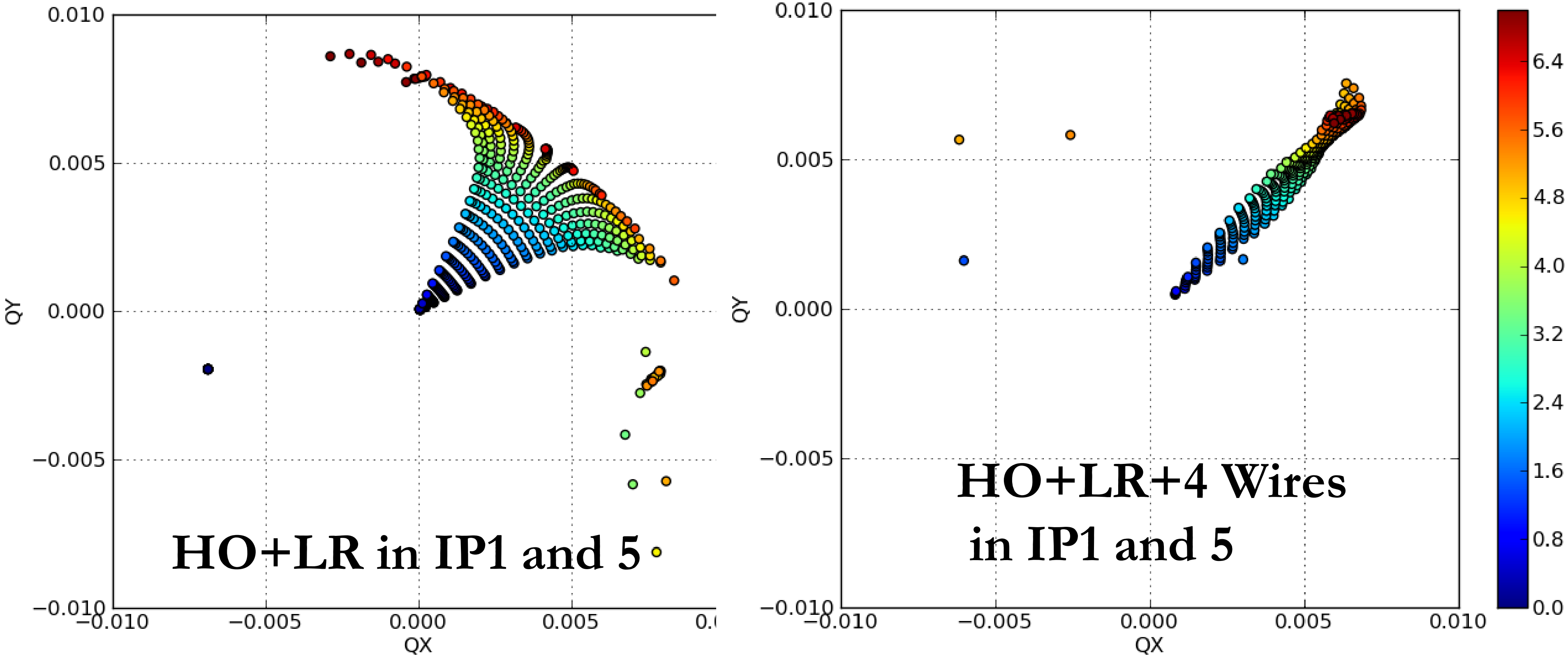
HO+LR in IP1

HO+LR+2Wires in IP1

Wire compensation 2 IPs

A. Patapenka

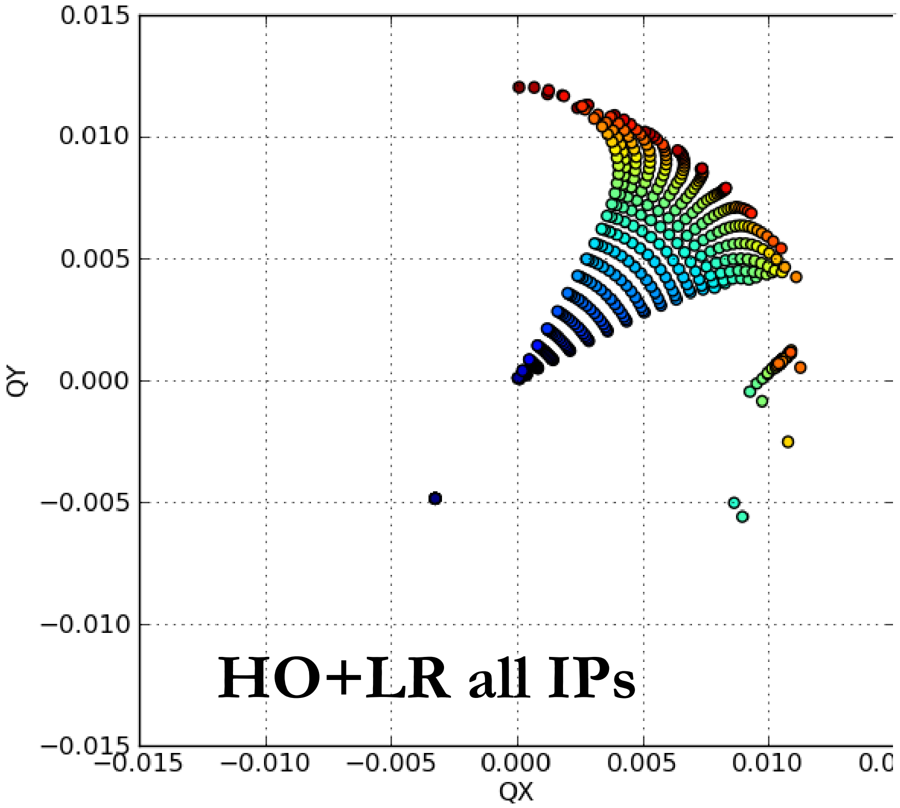
- Compensation in IP1 and IP5 with 4 wires of 110A in the BBC location (nominal 7TeV LHC beam parameters)

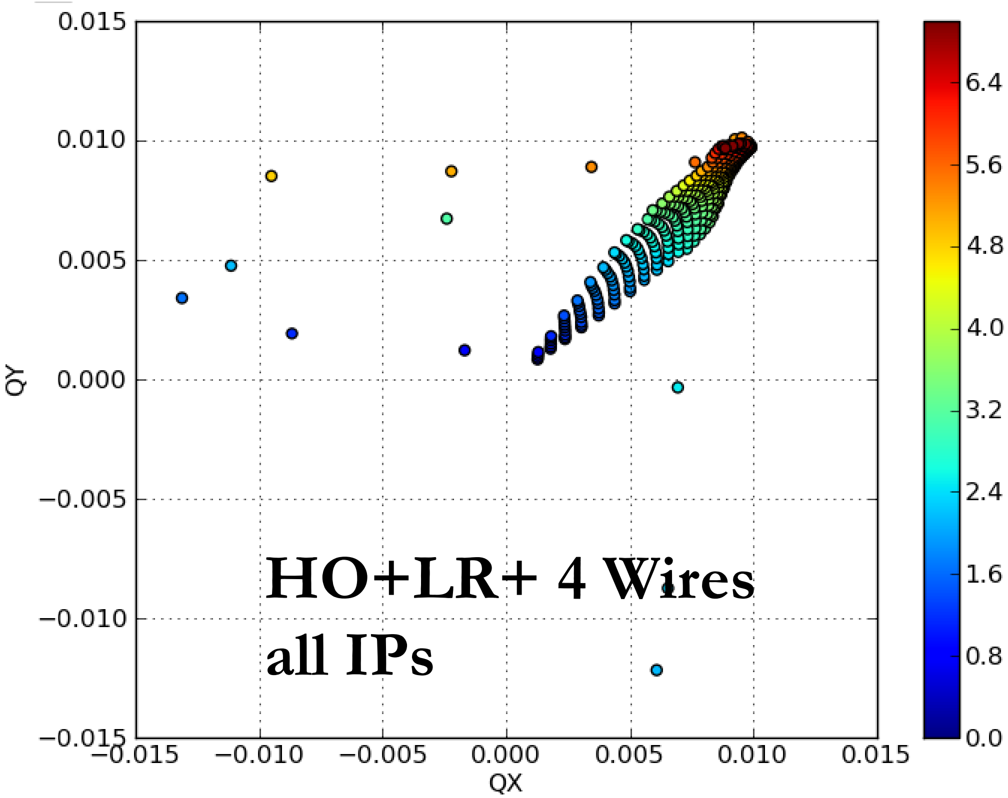


Wire compensation 4 Ips

- Compensation in IP1 with 4 wires of 110A in the BBC location, including effect of IP2 and IP8 (nominal 7TeV LHC beam parameters)

A. Patapenka



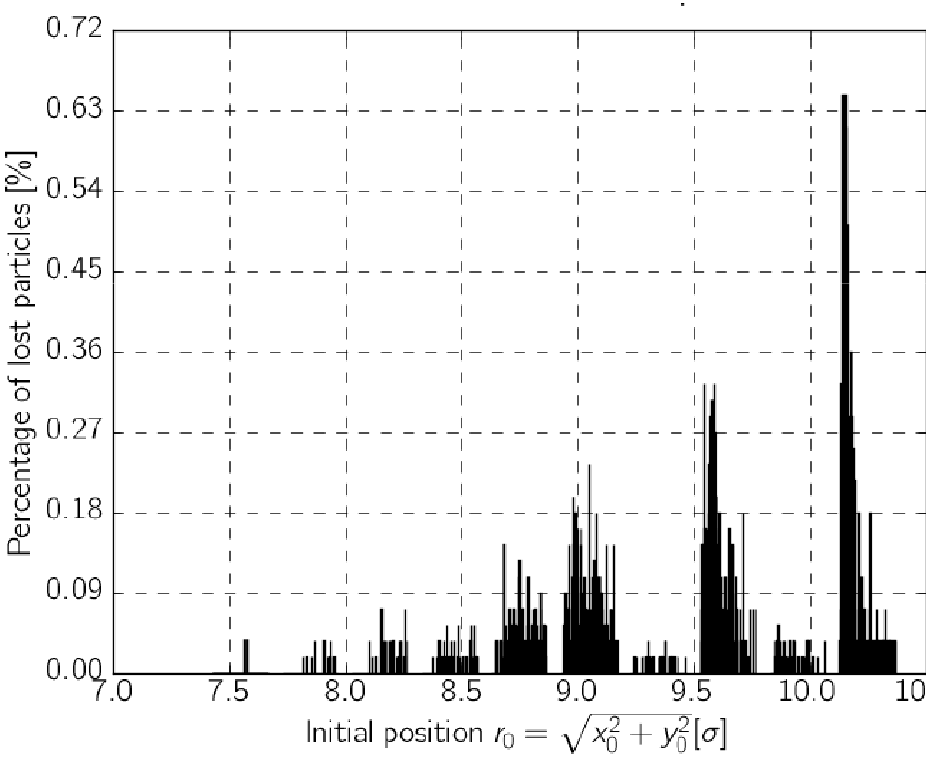


Wire simulations next steps

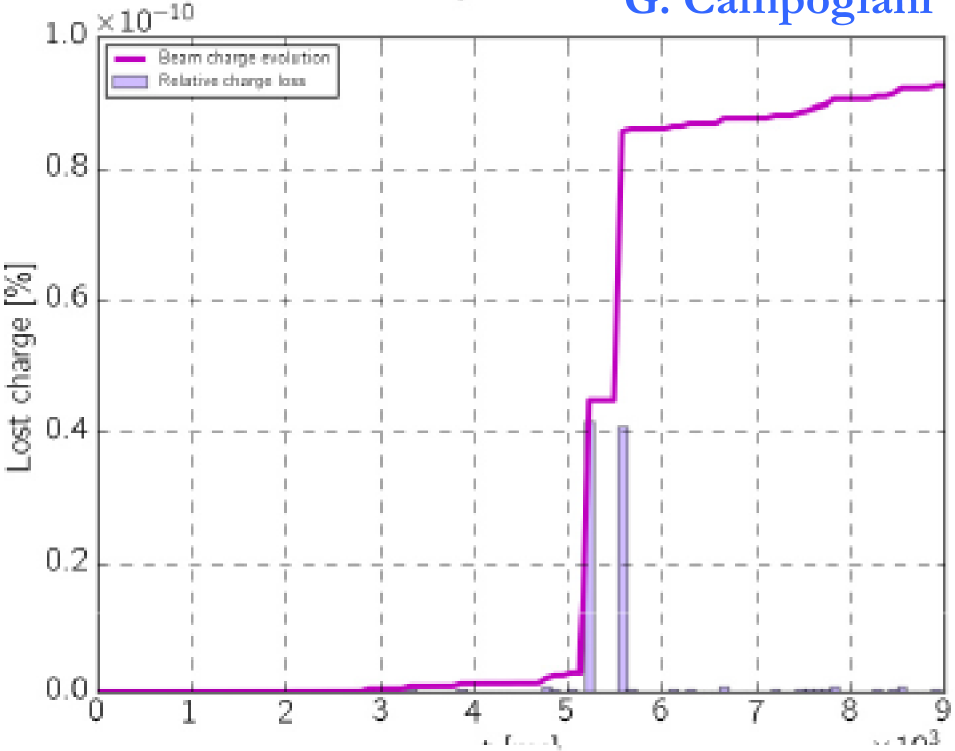
- Create MADX mask files with "fake" wires (BB long range elements with infinite separation) in the TCT/L locations
  - Eventually write a wire module for MADX
- Run SIXTRACK simulations for LHC@6.5TeV
  - For nominal but also BCMS beams
  - Nominal but also reduced crossing angles to enhance LR effect
  - Different wire separations and currents (average BB separation and larger separation taking into account collimator nominal settings)
  - With/without HO, with/without IP2 and IP8
  - Nominal and ATS optics
  - All magnetic non-linearities, sextupoles @ nominal chromaticity, with/without Landau octupoles
  - Different working points

Wire simulations analysis

- Dynamic aperture
- Frequency maps
- Resonance driving term estimation
- Track distributions and correlate them with lifetime (diffusion of tails)
  - ☐ Include IBS, burn-off, emittance blow-up (noise), synchrotron radiation



G. Campogiani



Experimental set-up - Train composition

- Two trains with unequal number of bunches, to avoid "all" PACMAN
  - ☐ Long one in 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
    - Usual train with 72 bunches from PS covers 1 LR encounter inside D1
    - New scheme of 80 bunches covers 3 LR encounters inside D1
  - ☐ "Weak" beam composition with two flavors:
    - Short train with maximum half the number of bunches as compared to the other beam, i.e. 36 to 40 bunches for nominal collimator settings and higher wire currents
    - Single bunches with nominal current may allow approaching wire in "nominal" average BB separation (depending on collimation considerations)
- Very short asymmetric trains may be interesting to study 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 timing one beam with respect to other by 12.5 ns, while maintaining 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)
- May need optics adjustment for optimising optics at wire location (need optics validation, may not be possible)
- Separating in 1 IP and colliding in other may be used to test correction efficiency separately
- If effect is weak, may need to reduce crossing angle
- **Final set-up should be tested in "running" LHC conditions**
- Different configurations need good preparation and sufficient amount of MD time (unfortunately 1 year already lost…)

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 **see Kim et al., HB2008**
  - ☐ 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

Required instrumentation

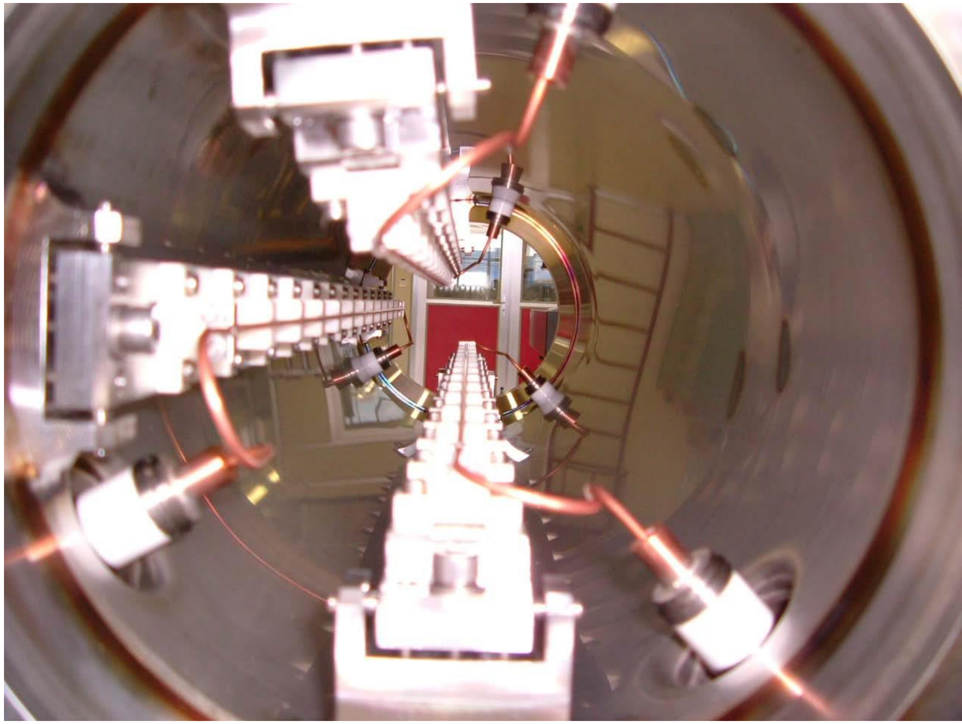
- Diagnostics for one beam needed for the test (the one compensated by the wire)
- Beam Current Transformer, tune-monitor, Beam Synchrotron Light monitor (BSRT), BPMs, Schottky, halo diagnostics
- Bunch-by-bunch diagnostics are essential
- For each observable, need to evaluate expected effect and compare with 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-spread, 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

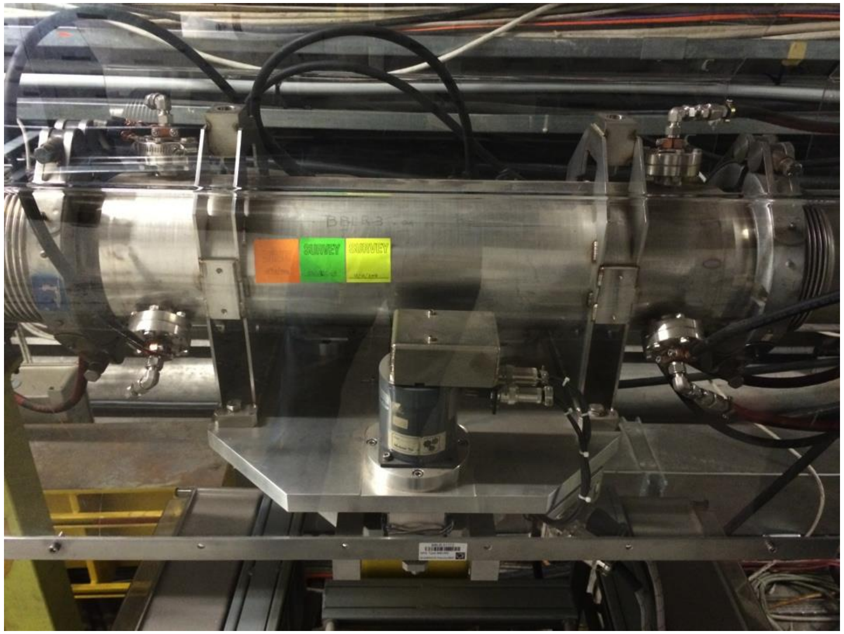
- Two 60cm long 3-wire compensators installed in the CERN SPS
  - Different "crossing" plane and even @ 45deg
- Movable in vertical by +/- 5mm (remote controlled)
- Water cooled
- About equal beta functions in the transverse planes (~50m)
- Separated by a phase advance of 3deg (similar between BBC and long range interactions in LHC)
- Powered with integrated DC current of up to 360A m (~60 LR collisions in LHC)



Wires at SPS

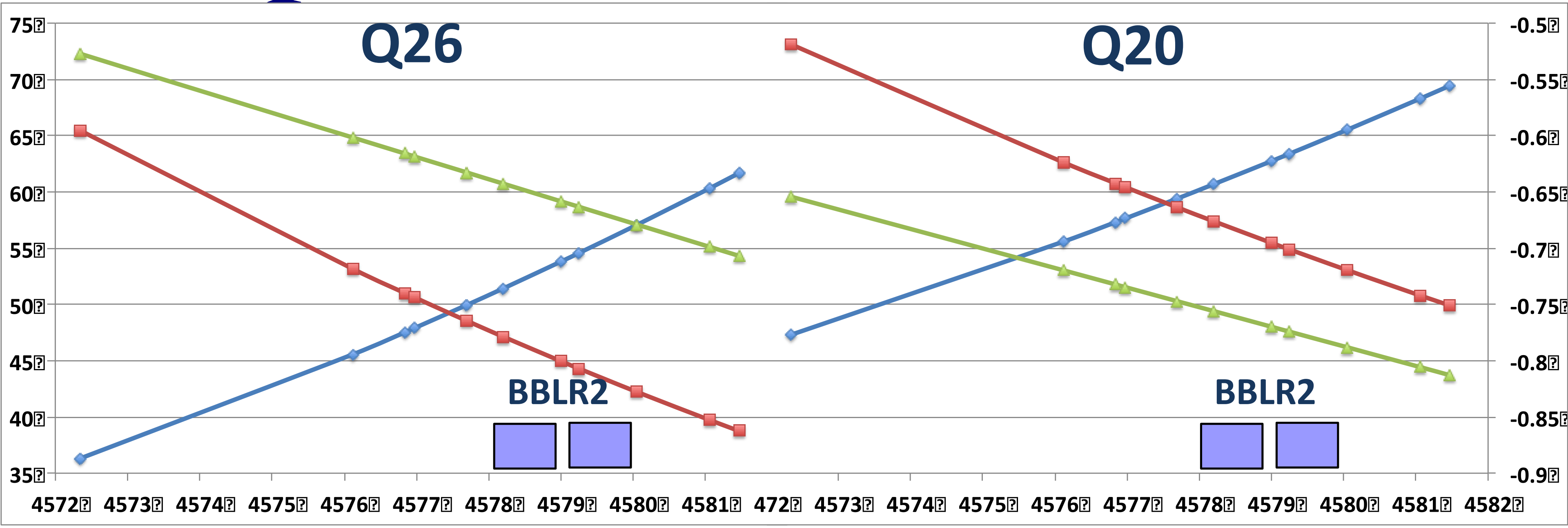
- Set-up re-evaluated
  - ☐ New power convertor able to pulse in PPM mode Powering H or V wire, with a switch
  - ☐ Step motors verified and controller in good shape
  - ☐ Vacuum integrity checked
  - ☐ Fine tuning of the PC needed for experiments already this summer

BBLR 51772



- MDs in 2015 for benchmarking wire models
  - ☐ At SPS flat bottom in parallel MD cycle (single LHC-type bunches)
  - ☐ Beam brought close to the wire with closed bump (already checked)
  - ☐ Effect of wire on orbit, tune, tunes-spread, coupling (alignment), resonance driving terms, beam distribution (tails)

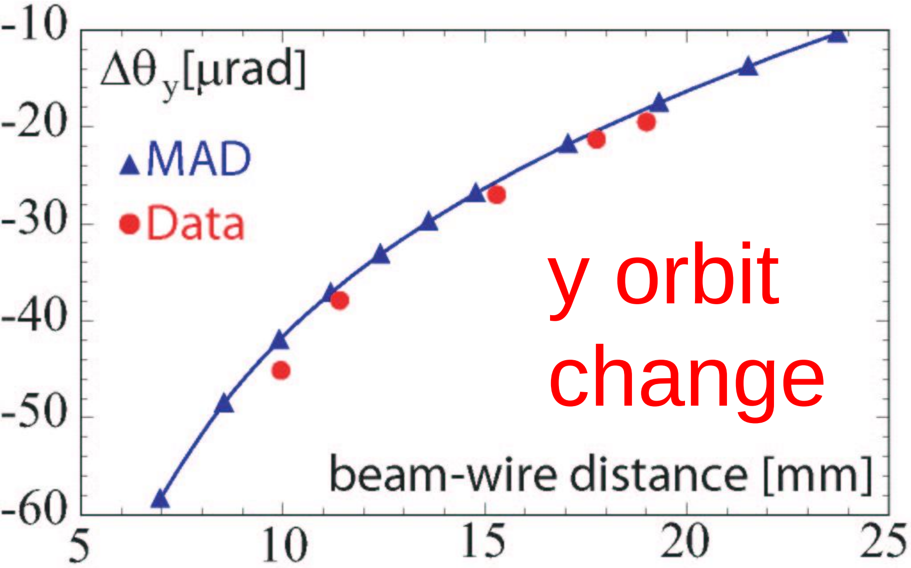
Optics at the SPS wires



- Q26 optics (nominal for FT beam)
  - β_x ~53m, β_y ~45m, D_x~-0.65m
- Q20 optics (nominal for LHC beam)
  - β_x ~63m, β_y ~55m, D_x~-0.75m

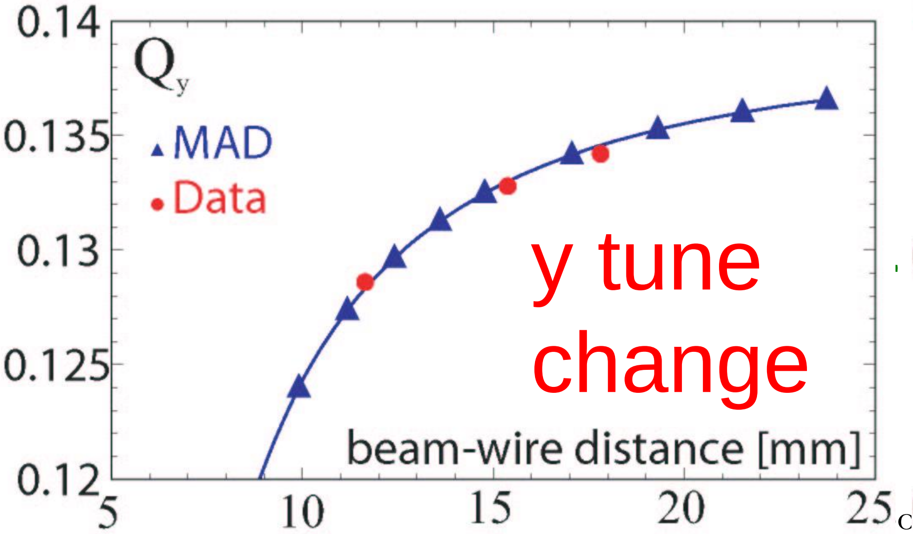
SPS wire calibration

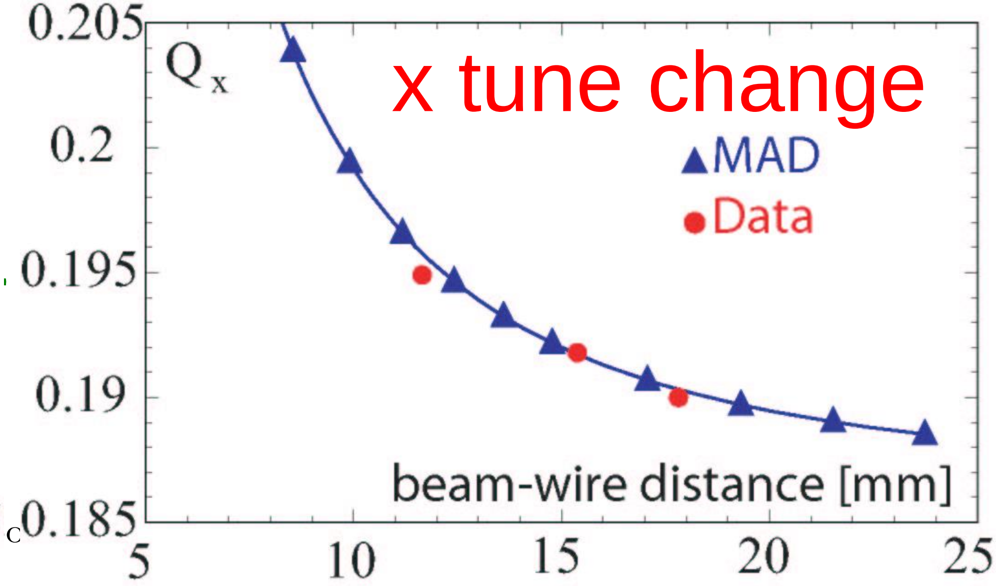
F. Zimmermann et al.



$$\delta y_0' = \frac{\mu_0 I L}{2\pi r_W B\rho}$$

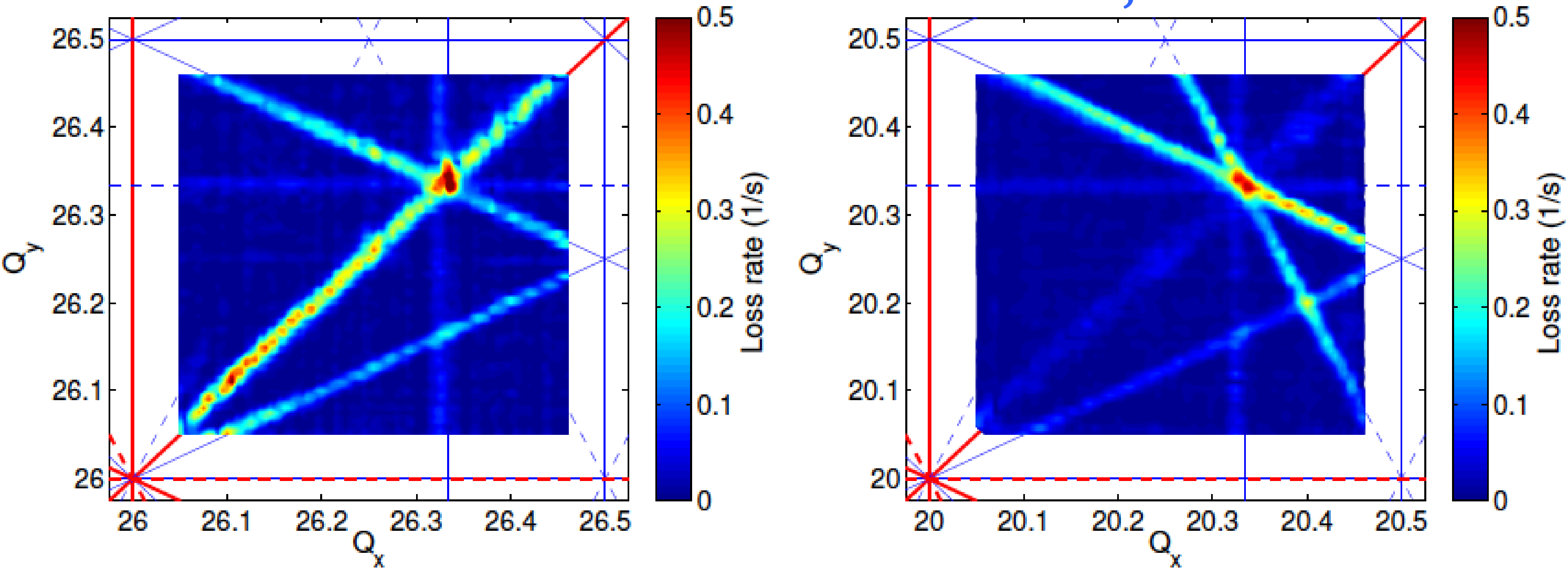
$$\delta\nu_{x,y} = \mp \frac{\mu_0 I L}{8\pi^2 B\rho}\frac{\beta_{x,y}}{r_W^2}$$





SPS frequency loss maps

H. Bartosik, PhD thesis



- Experimental tune scans in the SPS with the nominal Q26 (left) and Q20 optics (right).
- Color-code indicates the loss rate during a dynamic scan of the fractional tunes, as (averaging over 4 scan directions)
- Study effect of wire in both optics (measure resonance driving terms)

BBLR study plans – Short term (2015)

- Simulations considering the positions available with present layout, assuming nominal optics (also ATS)
- Simulate effect on PACMAN bunches
- Establish tolerances for positioning of the wire (hor/vertical alignment and tilt) and geometry (probably small effect)
- Establish observables for demonstrator measurement campaign and develop experimental program
- SPS wire experiments
- Simulate effect of wire with nominal HL-LHC parameters and flat beams (nominal HL-LHC parameters)
  - Integrate them in the present layout
    - Different options for physical wires or e-lenses

BBLR study plans – Medium, Long term (2015-2018)

- Establish wire 3D magnetic model and simulate
- Compare global vs. local correction, wire vs. other methods (electron lens, multipole magnets)
- Particle scattering on wire for heat deposition and damage (collimation/FLUKA team)
- Check alternative crossing scenarios and filling schemes
  - Same planes in both IPs, 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)
- BBLR modelling (effect of dispersion, longitudinal slicing, non-Gaussian beam distributions,…)
- Dynamics of e-lens and experimental program (work at FNAL)

Back up slides

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 positioning 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 beta functions ratio), orbit effect (π-bump)
  - ☐ To be used for calibration purposes

Coupling due to wire

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

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

- If the wire is positioned in one plane, there is no coupling
- Maximum coupling is induced for $\varphi_W=45^o$, 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 $\varphi_W=135^o$, in the opposite IP (and current follows square root of the product of beta functions)

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 chosen for having the same impact in both planes (**BBC** location)
- Induced tune-shift between wires in two IPs cancelled, if wire is positioned in equal distance but different planes, and integrated current follows beta function change
  - ☐ 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 (true also for BBLR)

Tune spread due to wire

- The first order tune-spread (octupole-like effect) is

$$\begin{pmatrix}\delta\nu_x\\ \delta\nu_y\end{pmatrix} = -\frac{3\mu_0 IL}{16\pi^2 B\rho}\frac{\cos(4\phi_W)}{r_W^4}\begin{pmatrix}\beta_x^2 & -2\beta_x\beta_y\\ -2\beta_x\beta_y & \beta_y^2\end{pmatrix}\begin{pmatrix}J_x\\ J_y\end{pmatrix}$$

- For alternating crossing in optically symmetric IPs, tune-spread adds up (same polarity)
- It can be cancelled for wire angle (or crossing) at π/8
- Because of triplet optics symmetry, diagonal terms of anharmonicity matrix for BBLR are equal
  - True also for the effect of two wires placed symmetrically in either side of the IP
- Ratio of beta functions at wire position can be chosen as to cancel completely tune-spread

Resonance driving terms

- The first order resonance driving terms are

$$\mathcal{H}_{n_x,n_y} \propto \left| \int_0^C \frac{b_n}{r_W^n} \beta_x^{n_x/2} \beta_y^{n_y/2} e^{i} \left(n_x \mu_x + n_y \mu_y \right) ds \right|$$

- For phase advances $\mu_x \approx \mu_y \approx \pm\pi/2$

$$\Re\left[e^{i}\left(\pm(2k+1)\pi/2\right)\right] \approx 0 \qquad \Im\left[e^{i}\left(\pm 2k\pi/2\right)\right] \approx 0$$

$$\Re\left[e^{i}\left(\pm 4k\pi/2\right)\right] \approx 1 \qquad \Im\left[e^{i}\left(\pm(4k-3)\pi/2\right)\right] \approx \pm 1$$

$$\Re\left[e^{i}\left(\pm(4k-2)\pi/2\right)\right] \approx -1 \qquad \Im\left[e^{i}\left(\pm(4k-1)\pi/2\right)\right] \approx \mp 1$$

- Due to the IP optics anti-symmetry, the contribution to purely H/V even resonances, from either side, is symmetric