Effects of wire on tails at injection

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Experiment at the LHC

Motivation:

- halo is depleted in collision in presence of strong long range beam-beam effects
- wire mimics the long-range beam-beam force => show that halo can be depleted while core stays unchanged.

Relevant questions for halo depletion:

- What is the effect of the wire/long-range beam-beam on tail particles and the beam distribution?
- Does the wire/long-range beam-beam deplete the halo?
- If long-range beam-beam anyway depleted the halo, would we then acutally still need further halo control?

Some theory …

Multipole expansion of wire field [1]:

$$\int ds\,[B_y + iB_x] = \sum_{k=1}^{\infty} [B_k + iA_k]\, z^{k-1}$$

$$\text{with } B_k + iA_k = \frac{\mu_0 IL}{2\pi} \times \frac{1}{z_0^k}$$

z = transverse position of test particle in respect to the beam centroid

z_0 = distance between wire and beam

I = current of wire, L = length of wire

$\Rightarrow$ for wire in the horizontal plane (z_0=x_0 real) only normal multipole components (A_k = 0 for all k)

$\Rightarrow$ wire drives only resonances with

$$p \cdot Q_x + q \cdot Q_y = n,\ \ n \in \mathbb{N} \text{ with}$$
$$p \in \mathbb{N}, q = 0 \text{ or } p \bmod 2 = 0, q \in \mathbb{N}$$

[1] S. Fartoukh et al., Compensation of the long-range beam-beam interactions as a path towards new configurations for the high luminosity LHC, PRSTAB 18, 121001 (2015)

Some theory …

Driving terms [1]:

$$c^{w}_{p,q} = \sum_{k=L,R} \frac{\beta_x^{|p|/2}(s_k)\beta_y^{|q|/2}(s_k)}{d_w^{|p|+|q|}(s_k)[\mathrm{m}]} e^{i(p\mu_x(s_k)+q\mu_y(s_k))}$$

$$\Rightarrow c^{w}_{p,q} \sim \sum_{k=L,R} \frac{1}{r}^{|q|/2} \frac{1}{d_w^{|p|+|q|}(s_k)[\sigma]} \text{ with } r = \frac{\beta_x(s_k)}{\beta_y(s_k)}$$

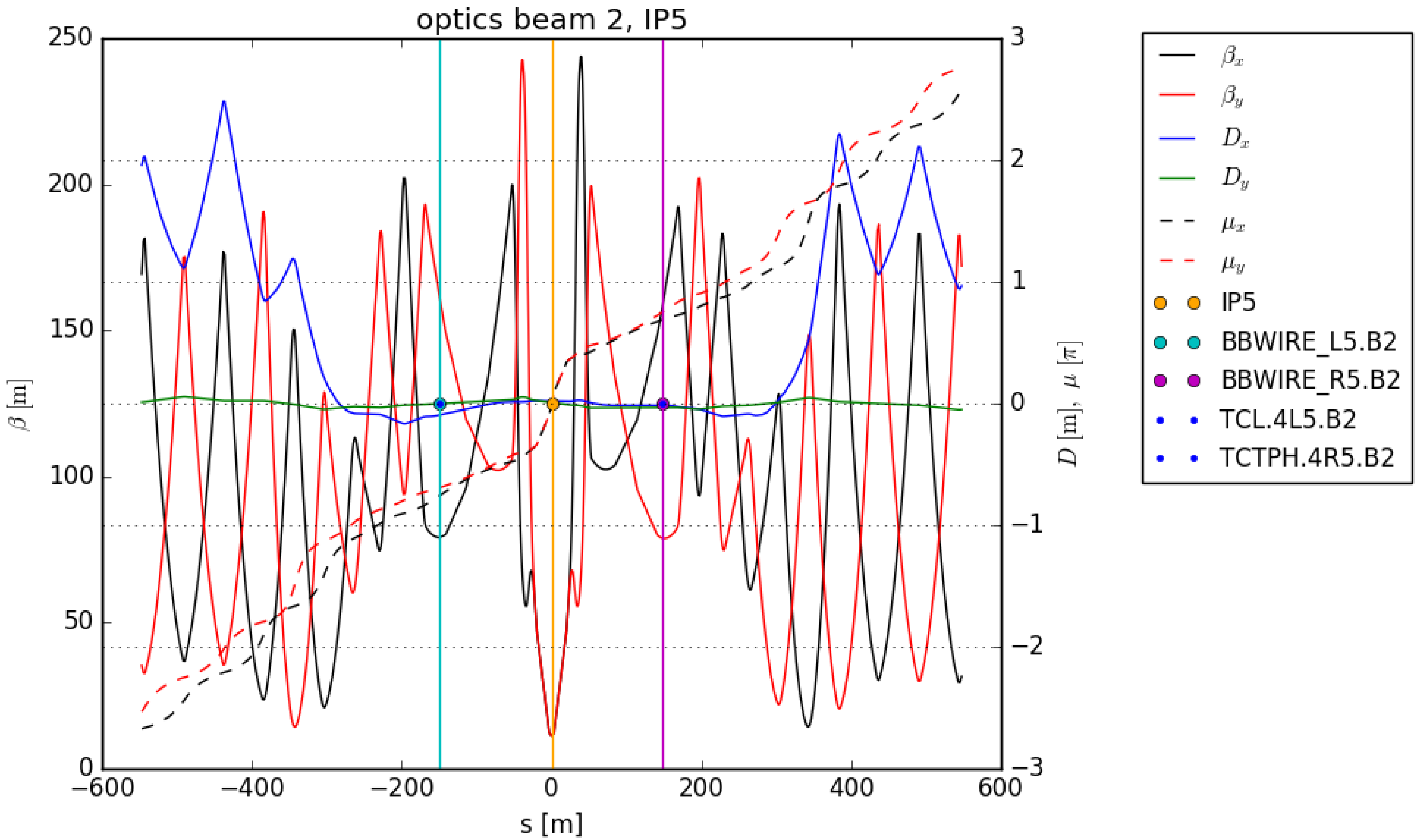
d_w = distance between wire and beam

⇒ at injeciton wires on left and right can not be simply lumped together in one interaction as the phase advance between the two wires is 1.4 π

⇒ RDTs scale with ratio of the β-function r and the distance d_w [σ] between wire and beam

[1] S. Fartoukh et al., Compensation of the long-range beam-beam interactions as a path towards new configurations for the high luminosity LHC, PRSTAB 18, 121001 (2015)

Optics @ injection

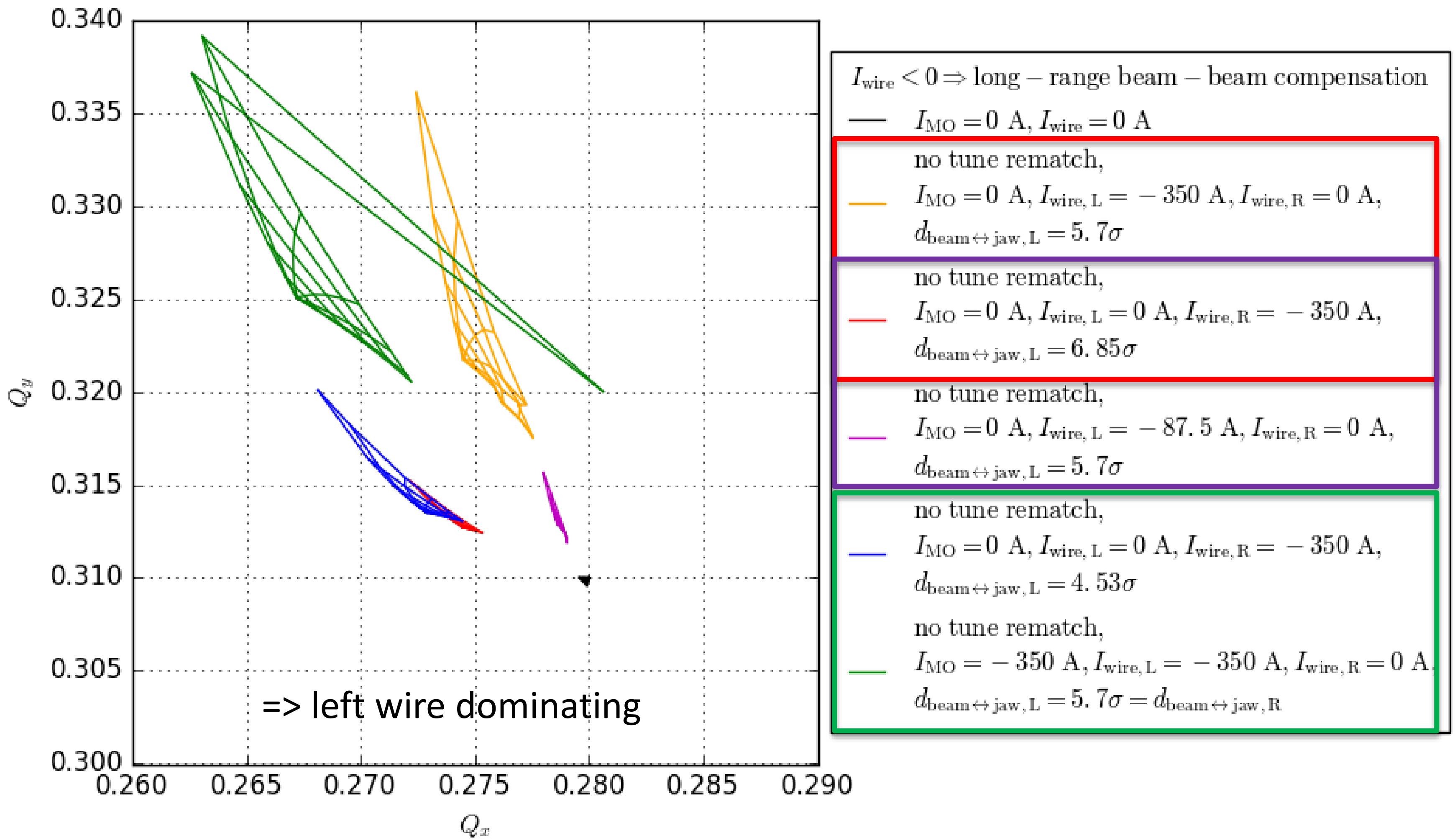


Optics @ injection

	TCL.4L5.B2	TCTPH.4R5.B2
$d_{jaw<->wire}$	3 mm	
β_x [m]	81.2	169.6
β_y [m]	166.5	81.3
β_x / β_y	**0.5**	**2.1**
D_x [m]	-0.1	0.1
$\Delta\mu_x$(TCL.4L5,TCTPH.4R5) [π]	**1.43**	
$\Delta\mu_y$(TCL.4L5,TCTPH.4R5) [π]		
$d_{jaw<->beam}$ [σ] for $d_{wire<->beam}$ = 9.6 σ (ε_N=3.5 μm)	5.7	6.9
$d_{jaw<->beam}$ [mm] for $d_{wire<->beam}$ = 9.6 σ (ε_N=3.5 μm)	6.5	9.3

⇒ larger effect for wire on left side

Tune footprints, no octupoles

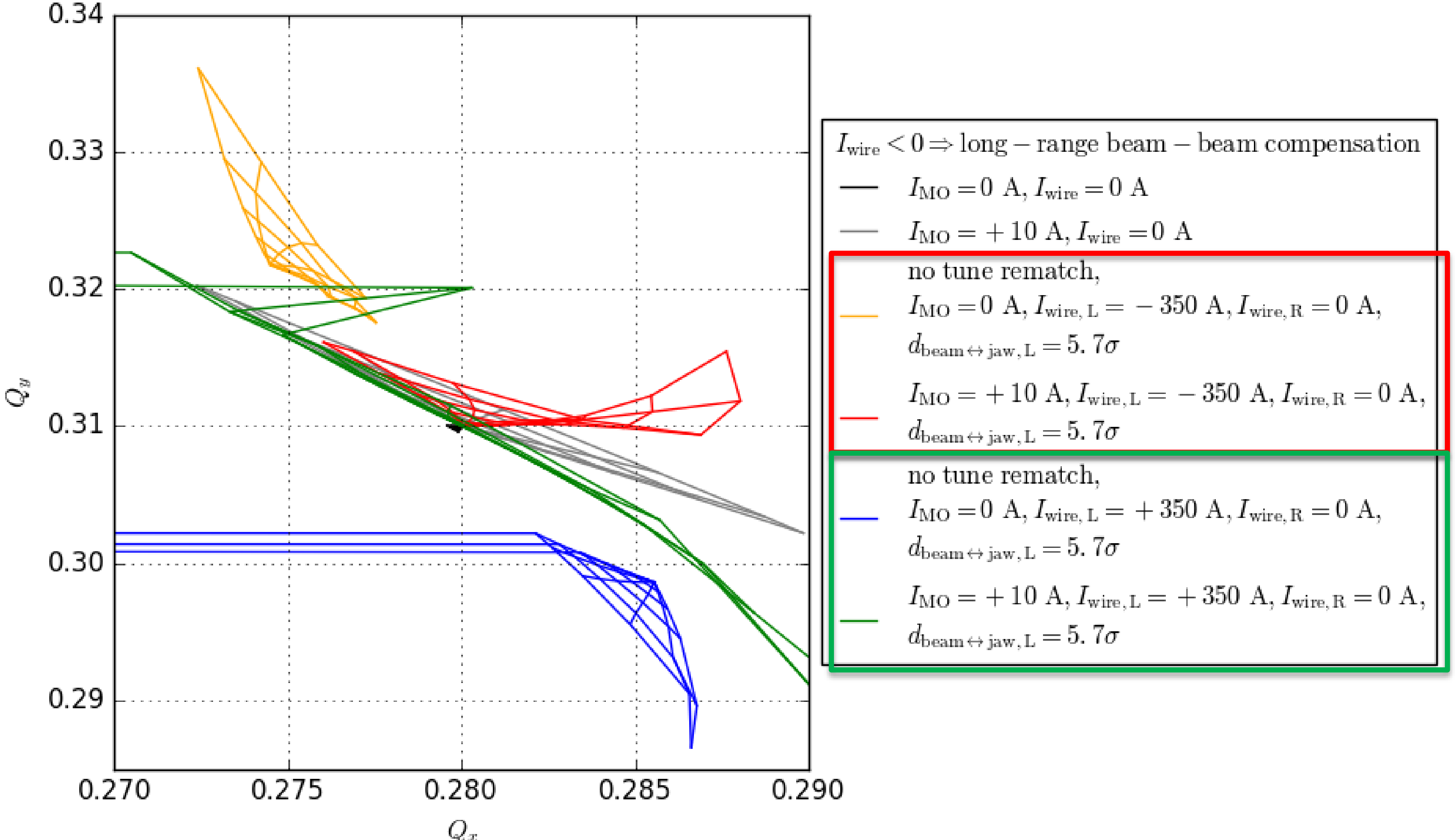


same separation and current: $I_{wire,R} = I_{wire,L}$, d(wire,beam)$_L$ = d(wire,beam)$_R$

same tune spread: $I_{wire,R} = 4 \cdot I_{wire,L}$, d(wire,beam)$_L$ = d(wire,beam)$_R$

maximum current, minimal separation: $I_{wire,R} = I_{wire,L}$, d(jaw,beam)$_L$ [σ]= d(jaw,beam)$_R$ [σ]

Tune footprints, with octupoles



negative current (same sign as for BBLR compensation)

positive current

Simulation setup

Code: Lifetrac

Optics: 2016 and 2017 injection optics (changes are marginal)

Beam: beam 2, $N_b=1.1\times10^{11}$, $\varepsilon_N=3.5$ µm

FMA analysis:

- turns tracked: 10^4
- quadratic grid up to 8 σ

Long term tracking:

- distribution: uniform distribution in x and y within [-5.7,5.7] σ
- turns tracked: 10^6
- single aperture in IP3 @ 5.7 σ (only betatron part) -> any diffusion above this aperture doesn't matter!

Notation:

- Separation $d_{wire<->beam}$ is always given in terms of $d_{jaw<->beam}$ for the wire on the left side. The right side is then set so that $d_{wire<->beam,L}$ [σ]= $d_{wire<->beam,R}$ [σ].
- LEFT and RIGHT wire refer to the position from the IP: LEFT = TCL.4L5, RIGHT = TCTPH.4R5

$I_{wire} < 0$

injection optics

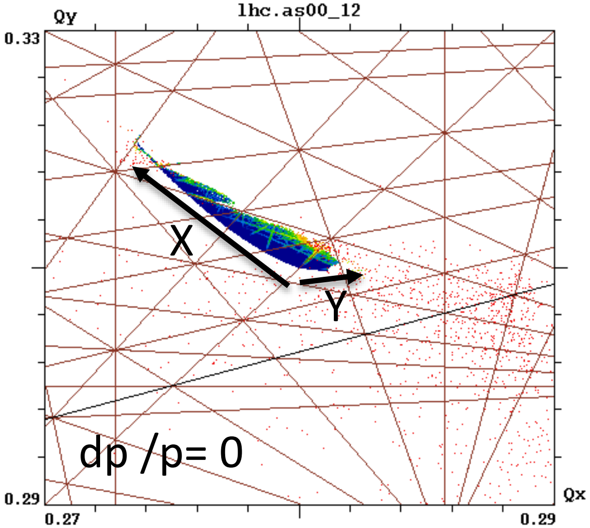
injection tunes Q_x=62.28, Q_y=60.31

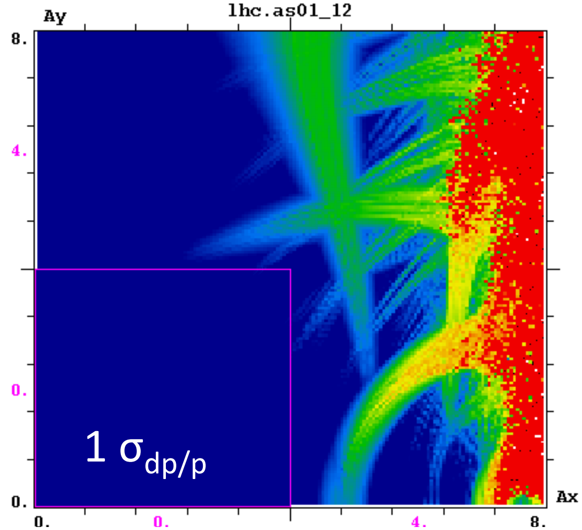
Q_x'=Q_y'=4

I_{oct}=0 A

I_{wire}<0, no octupoles, wire R

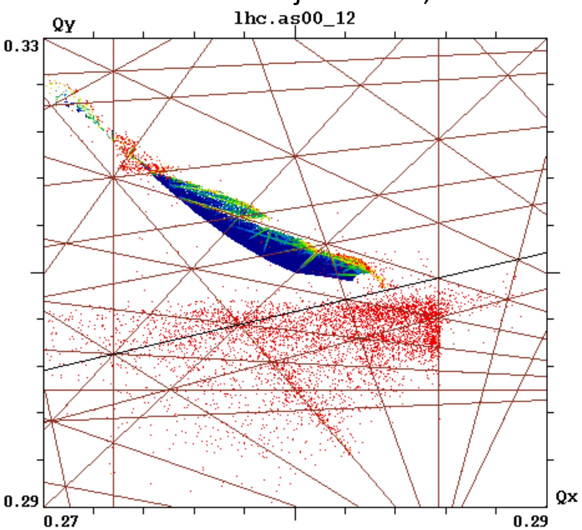
WIRE RIGHT, $d_{jaw\text{-}beam,L}$ =5.7 σ ($d_{jaw\text{-}beam,R}$ =6.9 σ): $\mathbf{I_{wire,L}}$**=0 A,** $\mathbf{I_{wire,R}}$**=-350 A,** I_{oct}=0A

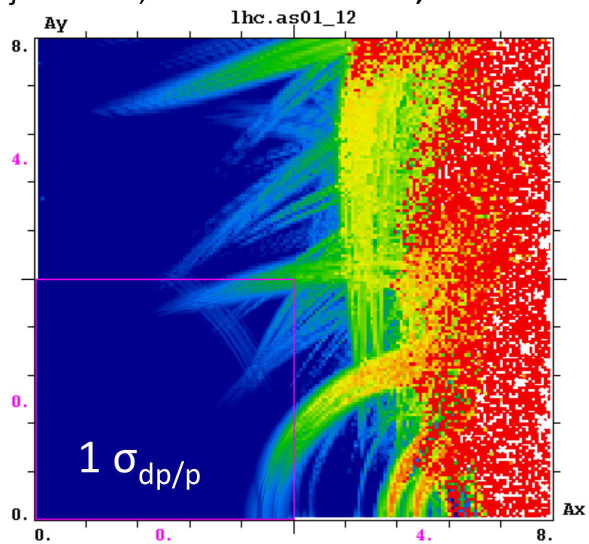


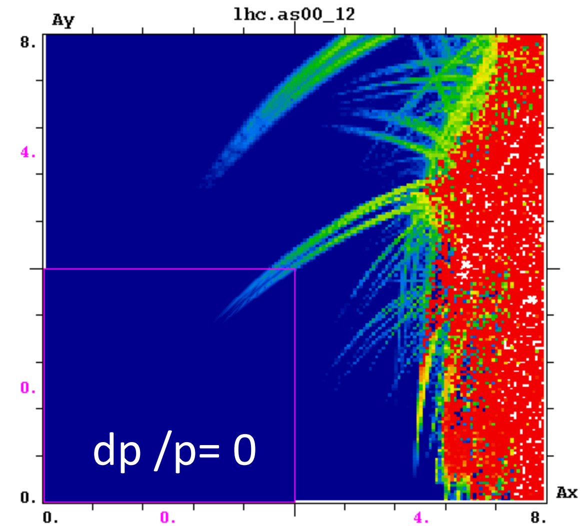


- cleaning only in the horizontal plane
- cleaning only for high amplitudes
- also for the minimal distance $d_{jaw\text{-}beam,R}$ =5.7 σ the wire only cleans for amplitudes above ~6.5 σ

WIRE RIGHT, $d_{jaw\text{-}beam,L}$ =4.5 σ ($d_{jaw\text{-}beam,R}$ =5.7 σ): $\mathbf{I_{wire,L}}$**=0 A,** $\mathbf{I_{wire,R}}$**=-350 A,** I_{oct}=0A

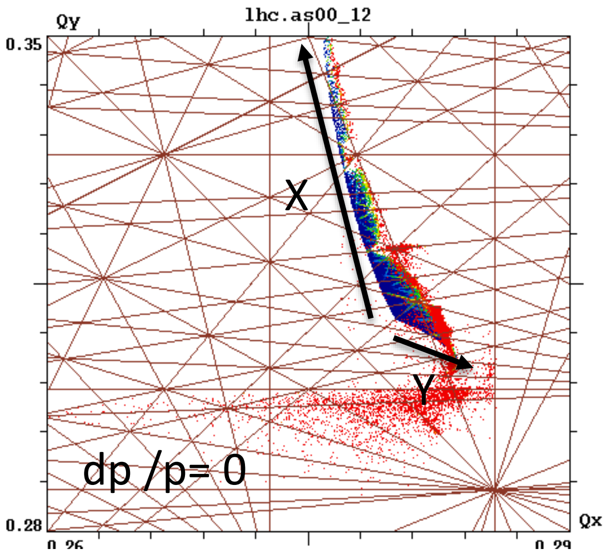


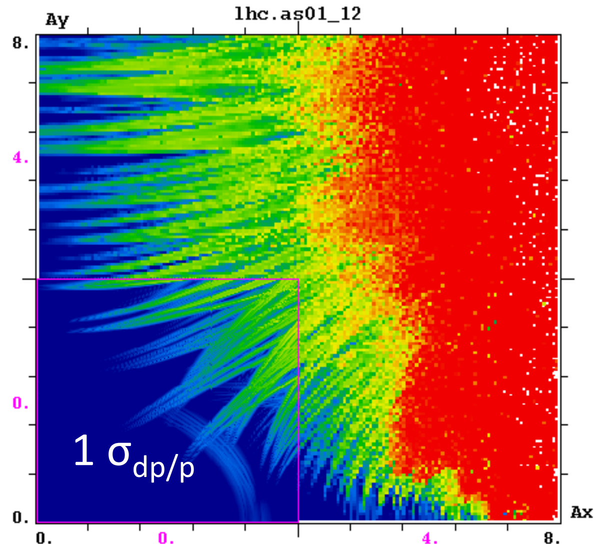


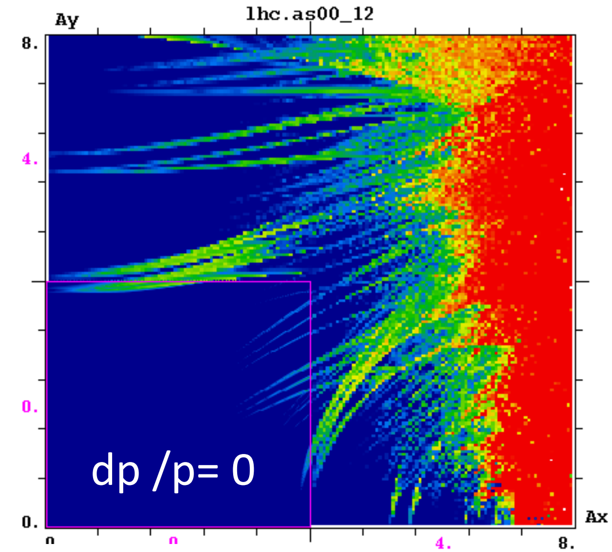


I_{wire}<0, no octupoles, wire L, wire L+R

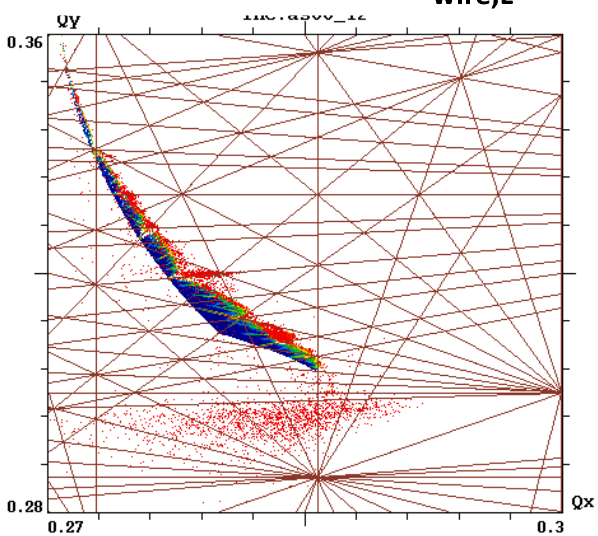
WIRE LEFT: $I_{wire,L}$=-350 A, $I_{wire,R}$=0 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=0A

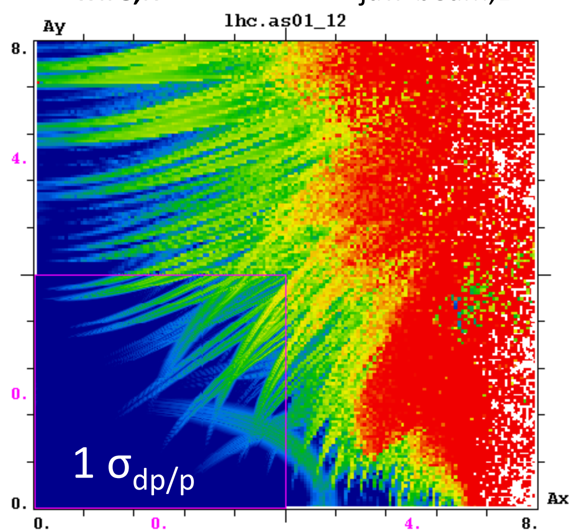






WIRE LEFT+RIGHT: $I_{wire,L}$=-350 A, $I_{wire,R}$=-350 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=0A





- WIRE LEFT more efficient than WIRE RIGHT
- cleaning only in the horizontal plane
- on-momentum: clear cleaning above ~6 σ
- off-momentum: cleaning down to ~4 σ
- adding wire on right appears to decrease diffusion

$I_{wire} < 0$

injection optics

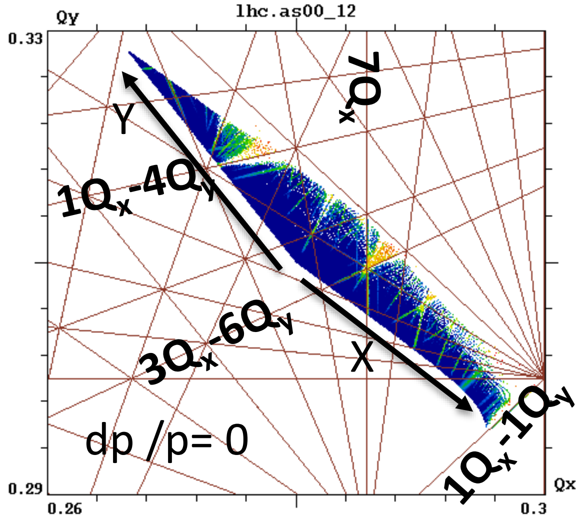
injection tunes Q_x=62.28, Q_y=60.31

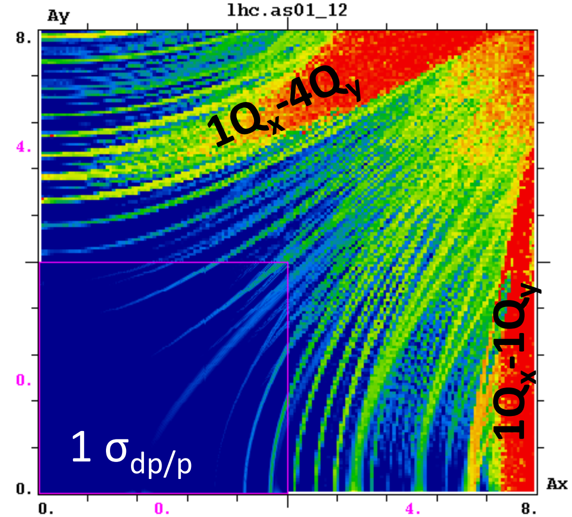
Q_x'=Q_y'=4

I_{oct}=+10 A

I_{wire}<0, I_{oct} = +10 A, no wire, wire L

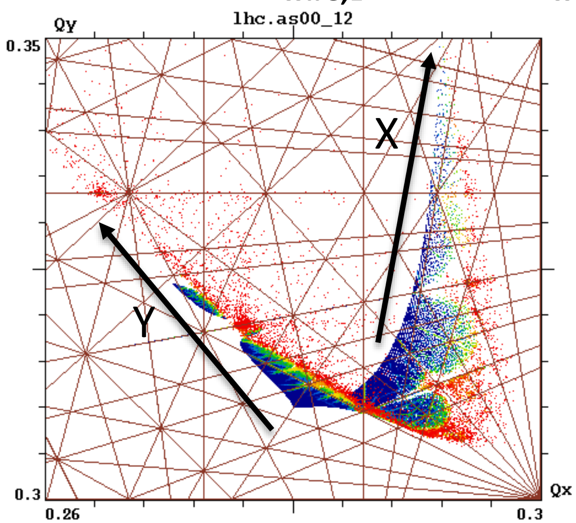
NO WIRE: I_{oct}=+10A

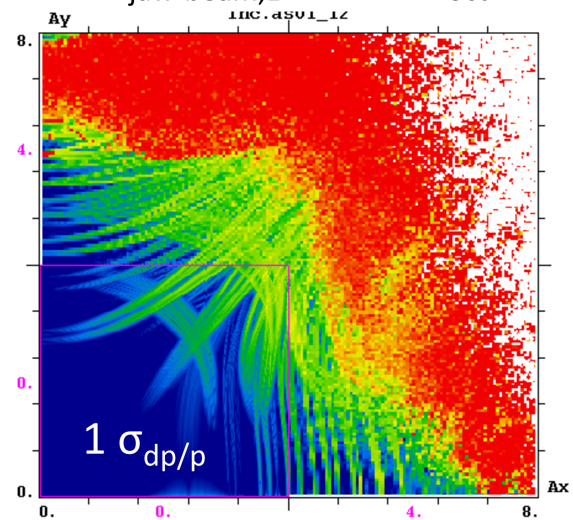


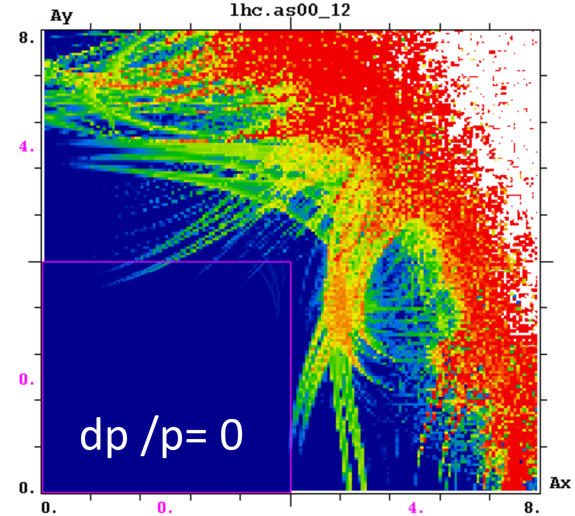


- resonances from octupoles enhanced with wire
- $1Q_x$-$4Q_y$ resonances results in cleaning also in vertical plane
- on-momentum: clear cleaning above ~6 σ
- off-momentum: cleaning down to ~4 σ

WIRE LEFT: $I_{wire,L}$=-350 A, $I_{wire,R}$=0 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=+10A

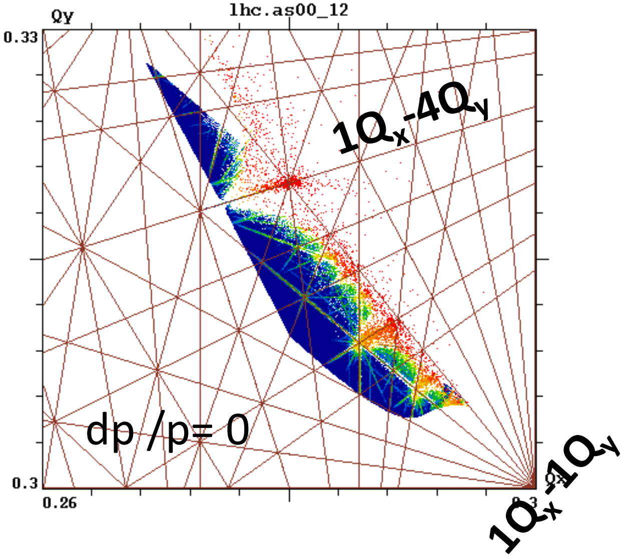


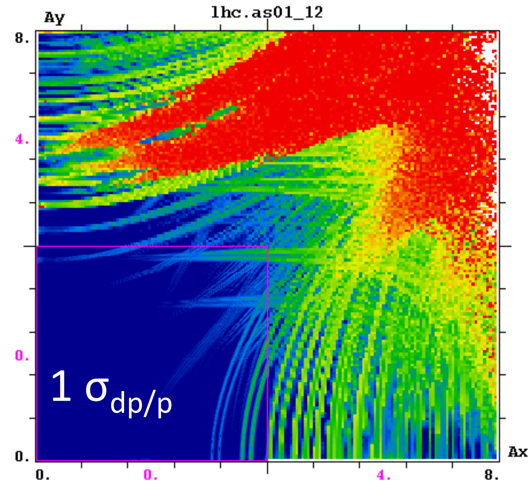




$I_{wire}<0$, I_{oct} = +10 A, wire R, wire L+R

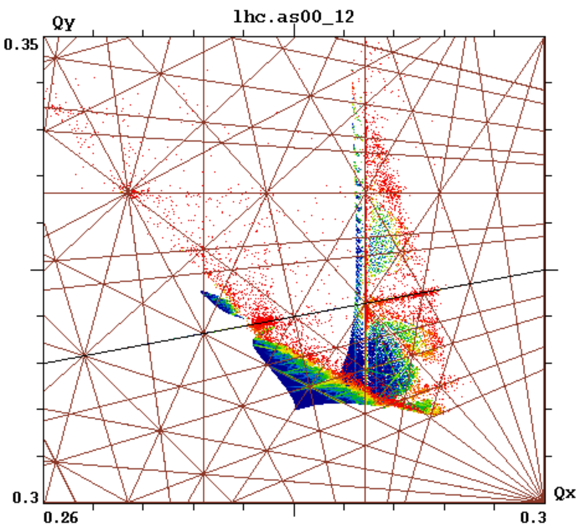
WIRE RIGHT: $I_{wire.L}$=0 A, $I_{wire.R}$=-350 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=+10A

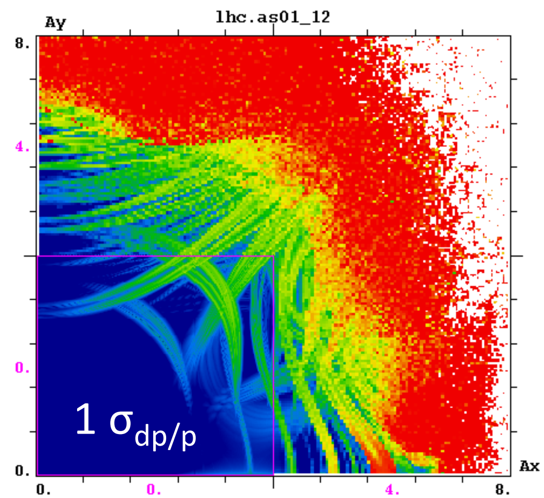


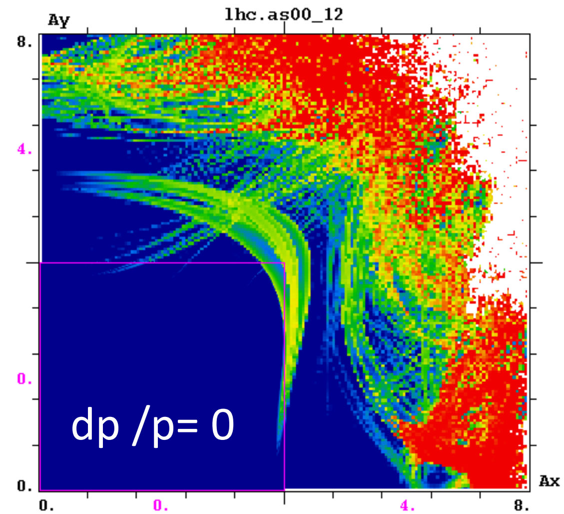


- WIRE RIGHT: small effect, octupolar resonances are enhanced
- WIRE LEFT+RIGHT: additional wire on right does not have a considerable effect

WIRE LEFT+RIGHT: $I_{wire,L}$=-350 A, $I_{wire,R}$=-350 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=+10A







$I_{wire} > 0$

injection optics

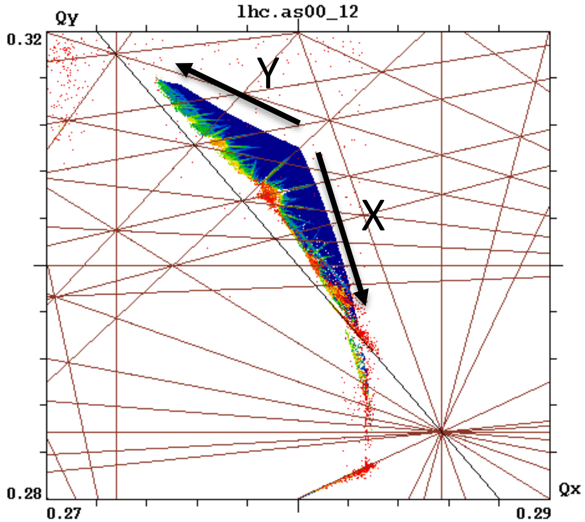
injection tunes Q_x=62.28, Q_y=60.31

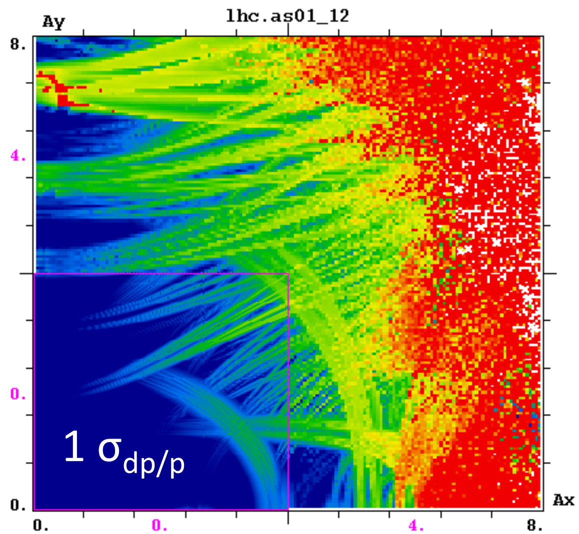
Q_x'=Q_y'=4

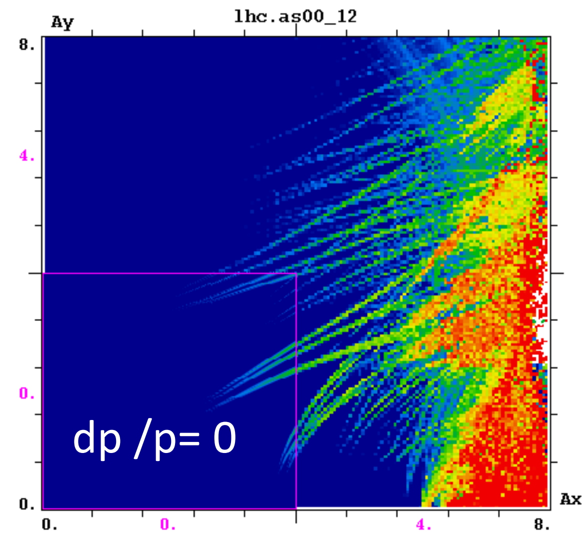
I_{oct}=+10 A

I_{wire}>0,wire L

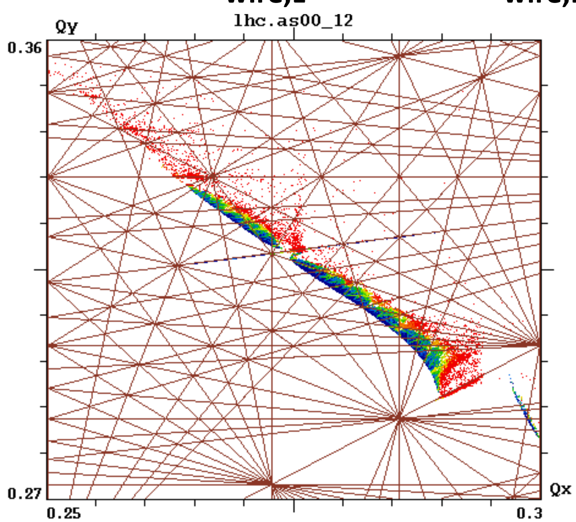
WIRE LEFT: $I_{wire,L}$=+350 A, $I_{wire,R}$=0 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=0A

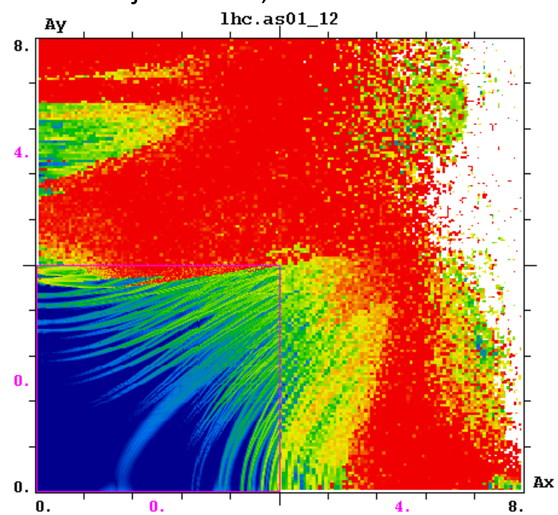






WIRE LEFT: $I_{wire,L}$=+350 A, $I_{wire,R}$=0 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=+10A





- without octupoles cleaning down to ~6 σ
- with octupoles cleaning down to small amplitudes in both planes, even better than for Iwire<0
- tune footprint collapses to thin line with octupoles -> beam stability?

$I_{wire} < 0$

injection optics

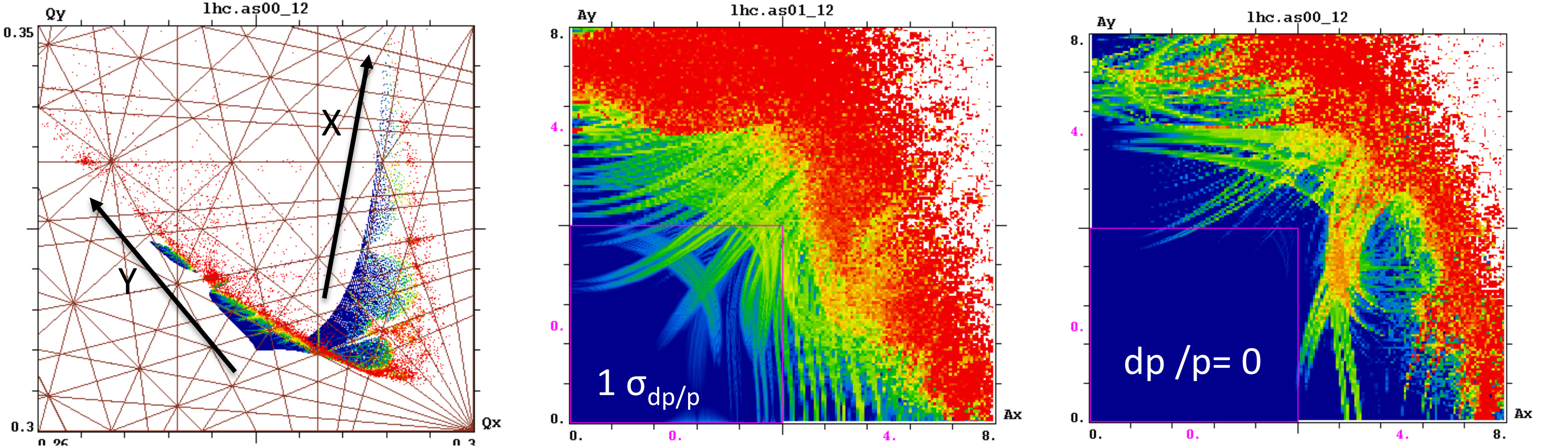
change of working point

$Q_x' = Q_y' = 4$

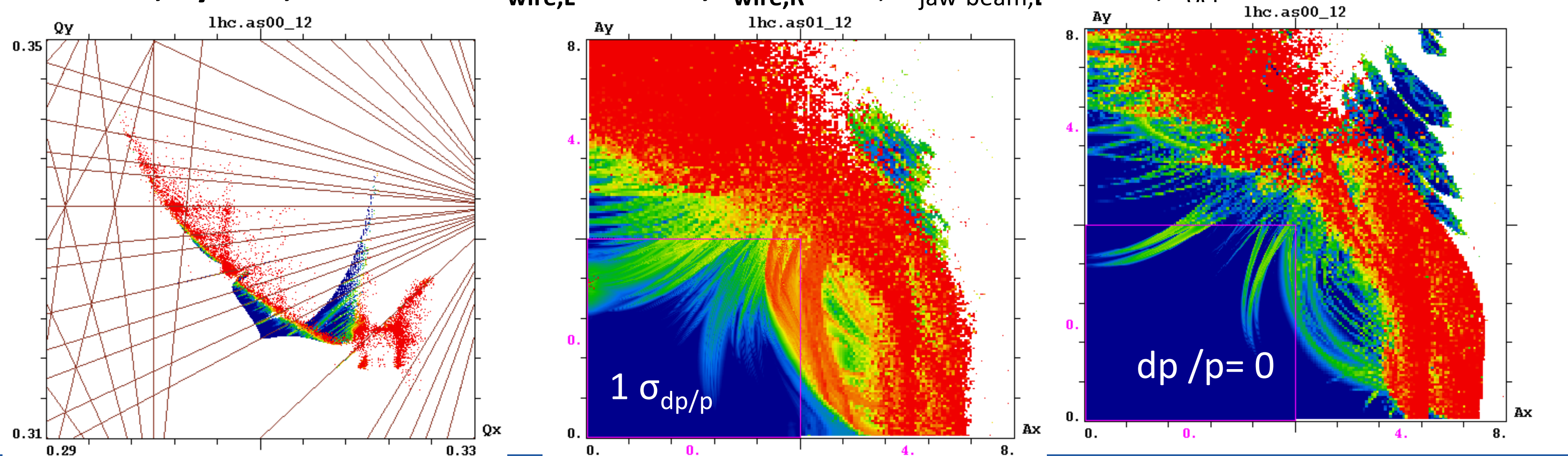
$I_{oct} = +10\ A$

$I_{wire}<0$, I_{oct} = +10 A, wire L

Qx=.28,Qy=.31, WIRE LEFT: $I_{wire,L}$=-350 A, $I_{wire,R}$=0 A, $d_{jaw-beam,L}$ =5.7 σ, I_{oct}=+10A



Qx=.31,Qy=.32, WIRE LEFT: $I_{wire,L}$=-350 A, $I_{wire,R}$=0 A, $d_{jaw-beam,L}$ =5.7 σ, I_{oct}=+10A



$I_{wire} < 0$

injection optics

injection tunes Q_x=62.28, Q_y=60.31

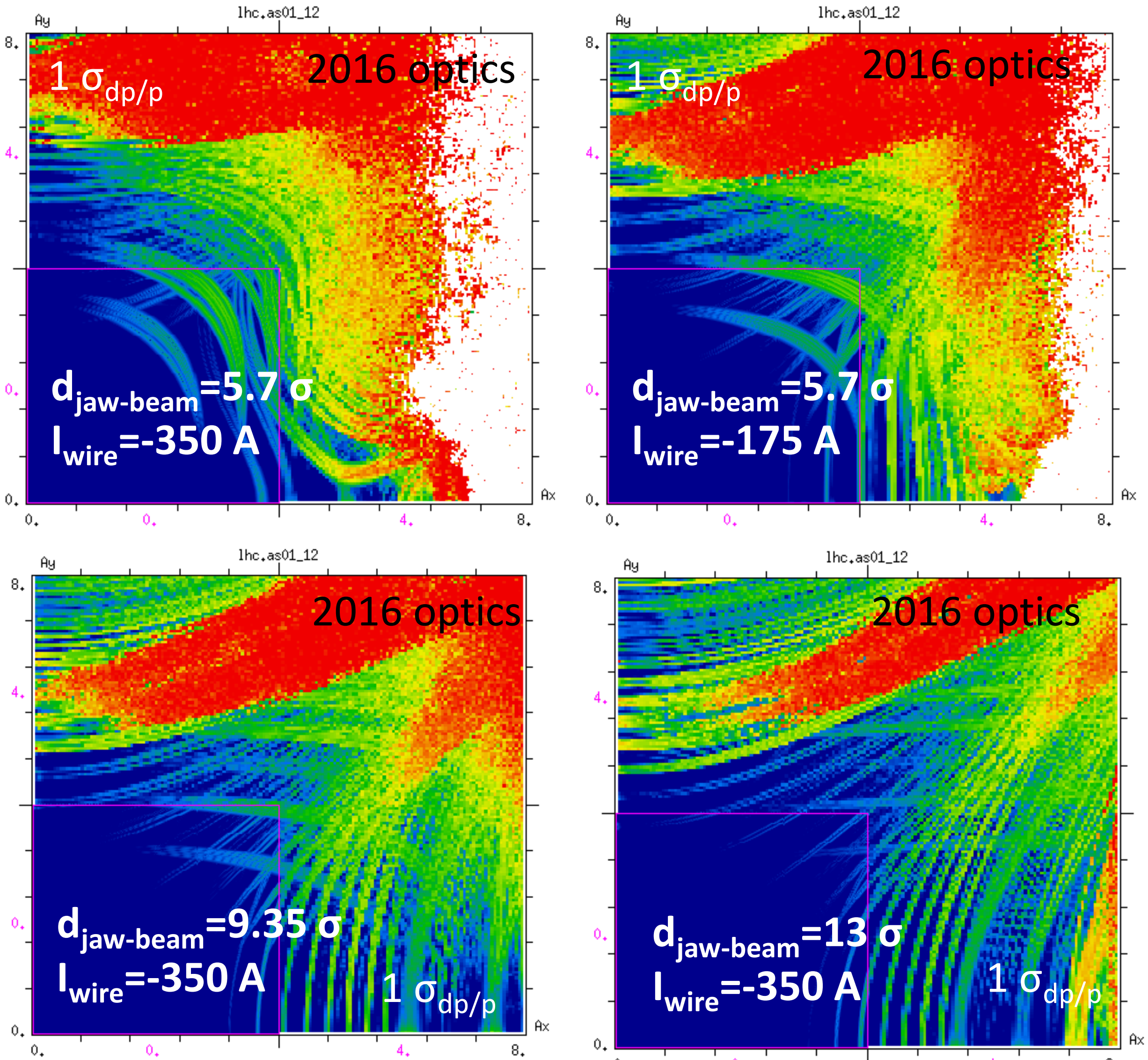
Q_x'=Q_y'=4

I_{oct} = +10 A

Dependence on $d_{wire<->beam}$ and I_{wire}

$I_{wire}<0$, I_{oct} = +10 A, wire L+R

WIRE LEFT+RIGHT, $d_{jaw\text{-}beam,L} = d_{jaw\text{-}beam,R}$ **:** $I_{wire,L}=I_{wire,R}$, I_{oct}=+10A



- weak dependence on current I_{wire} compared to $d_{wire<->beam}$

- effect of wire rapidly decreases with $d_{wire<->beam}$ -> most likely have to use minimal separation of $d_{jaw<->beam}$ =5.7 σ

$I_{wire} < 0$

injection optics

injection tunes Q_x=62.28, Q_y=60.31

Q_x'=Q_y'=4

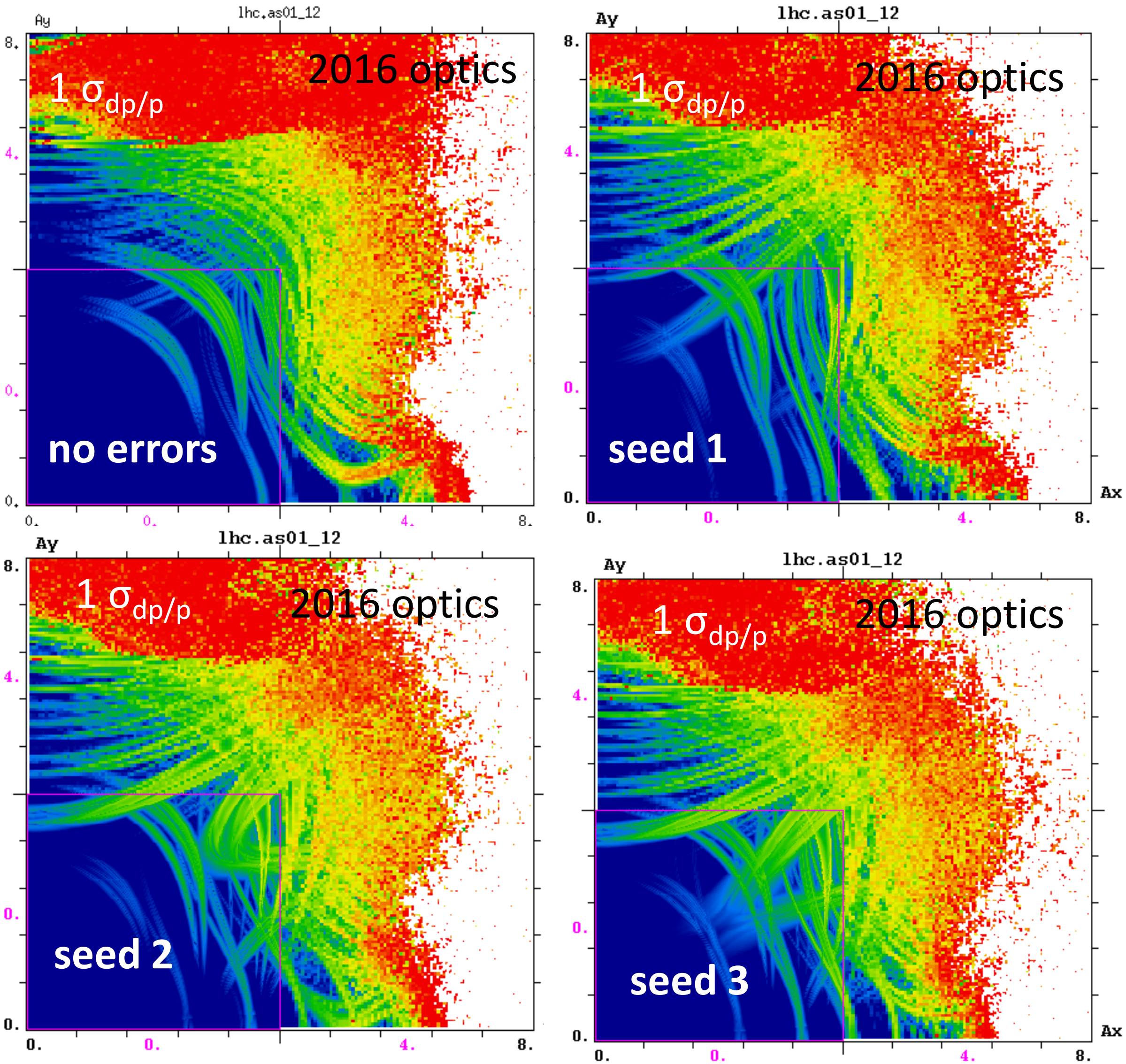
I_{oct} = +10 A

Dependence on errors

(non-linear + b2)

$I_{wire}<0$, I_{oct} = +10 A, wire L+R

WIRE LEFT+RIGHT, $d_{jaw\text{-}beam,L} = d_{jaw\text{-}beam,R}$ =5.7 σ, $I_{wire,L}=I_{wire,R}$=-350 A, I_{oct}=+10A



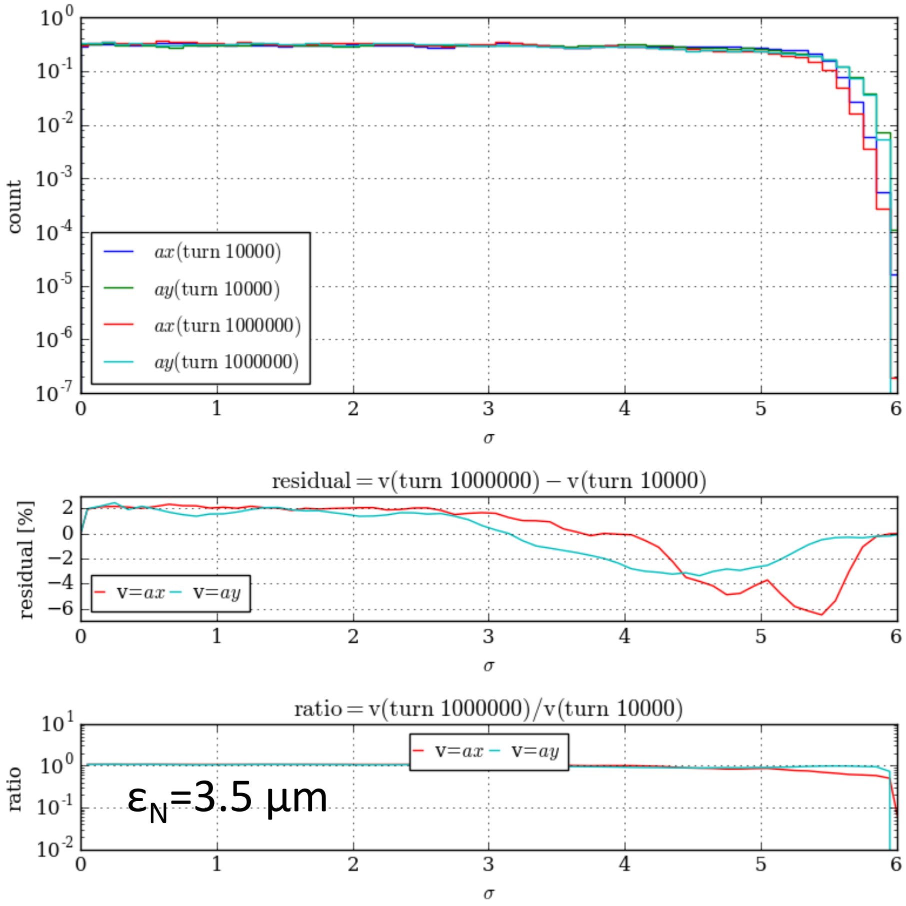
- small impact due to beta-beat and non-linear errors expected
- closed orbit distortions are not taken into account as collimator alignment is considered to be “good enough”.

Histograms for long term tracking (10^6 turns)

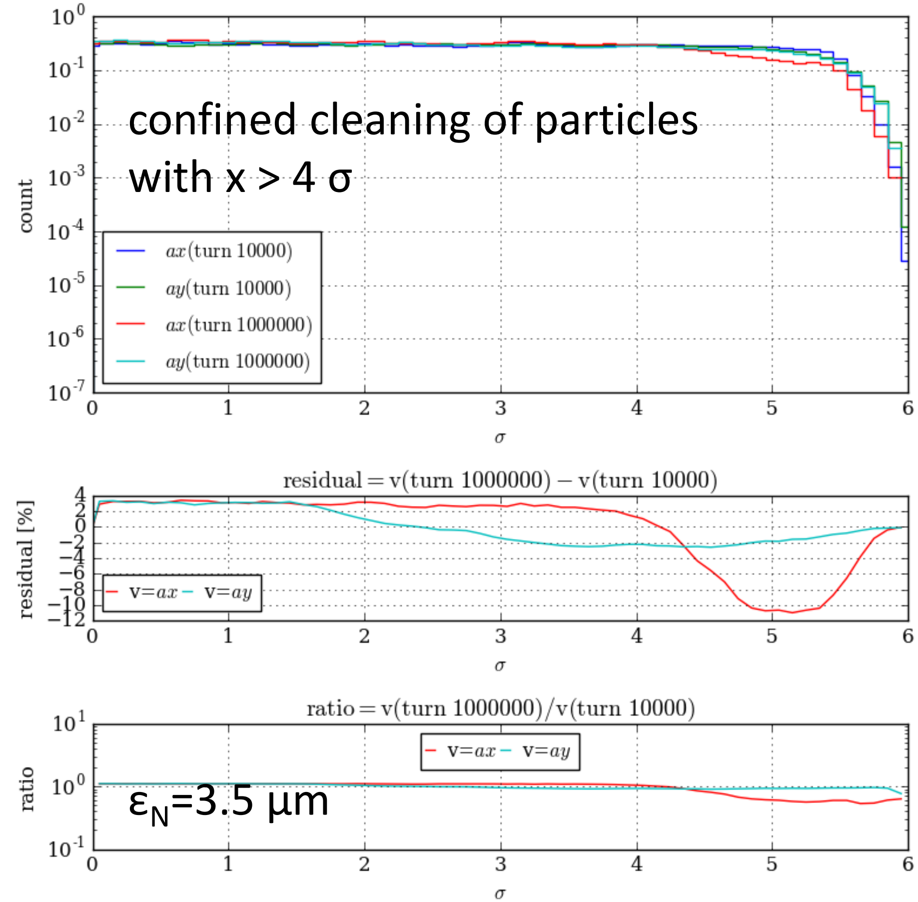
Histograms

Injection tunes (Q_x=.28, Q_y=.31), I_{wire} < 0

WIRE LEFT: $I_{wire,L}$=-350 A, $I_{wire,R}$=0 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=0A



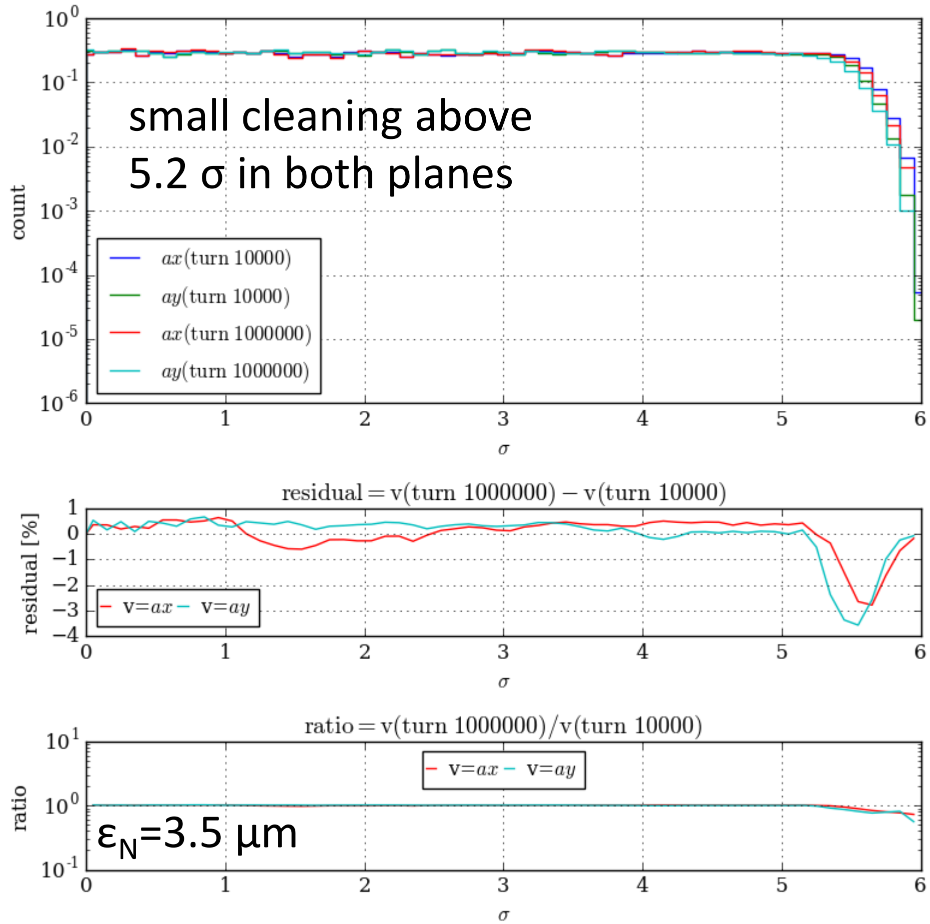
WIRE LEFT: $I_{wire,L}$=-350 A, $I_{wire,R}$=0 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=+10A



Histograms

Injection tunes (Q_x=.28, Q_y=.31), I_{wire} < 0

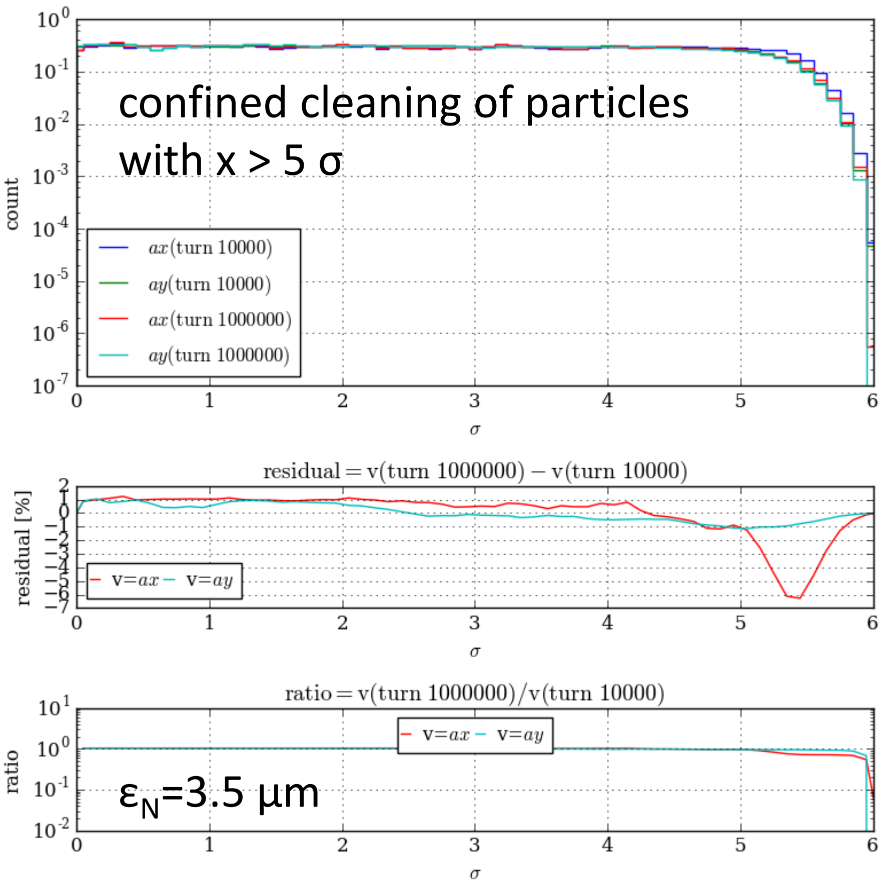
WIRE RIGHT: $I_{wire,L}$=0 A, $I_{wire,R}$=- 350 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=+10A



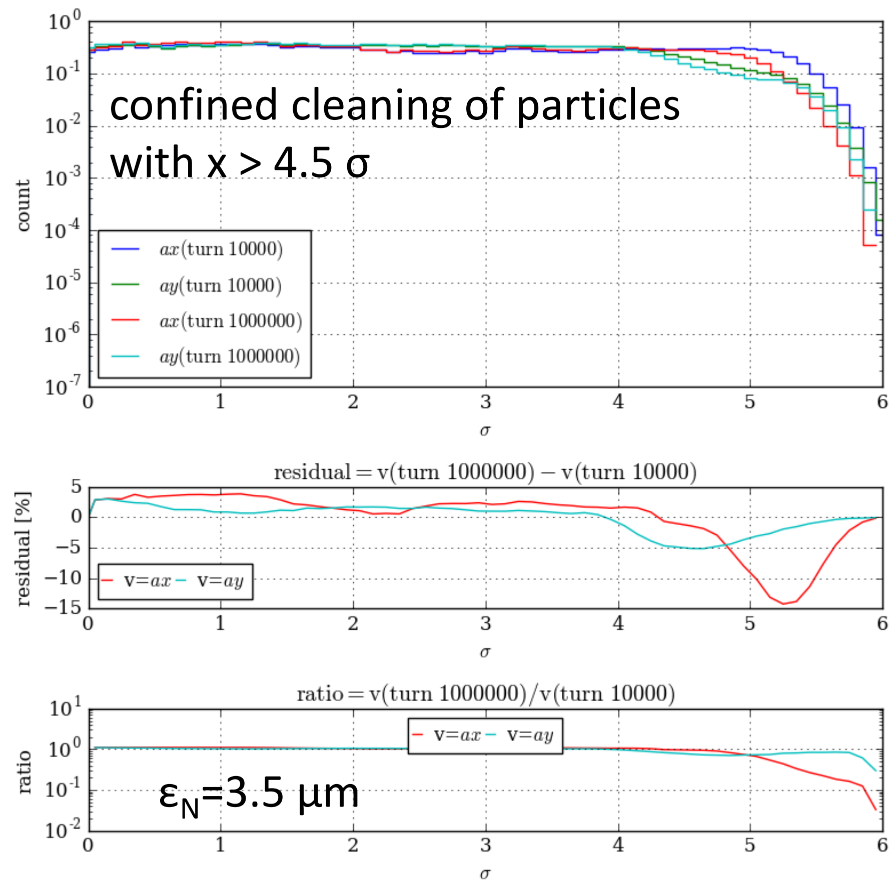
Histograms

Injection tunes (Q_x=.28, Q_y=.31), I_{wire} > 0

WIRE LEFT: $I_{wire,L}$=+350 A, $I_{wire,R}$=0 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=0A



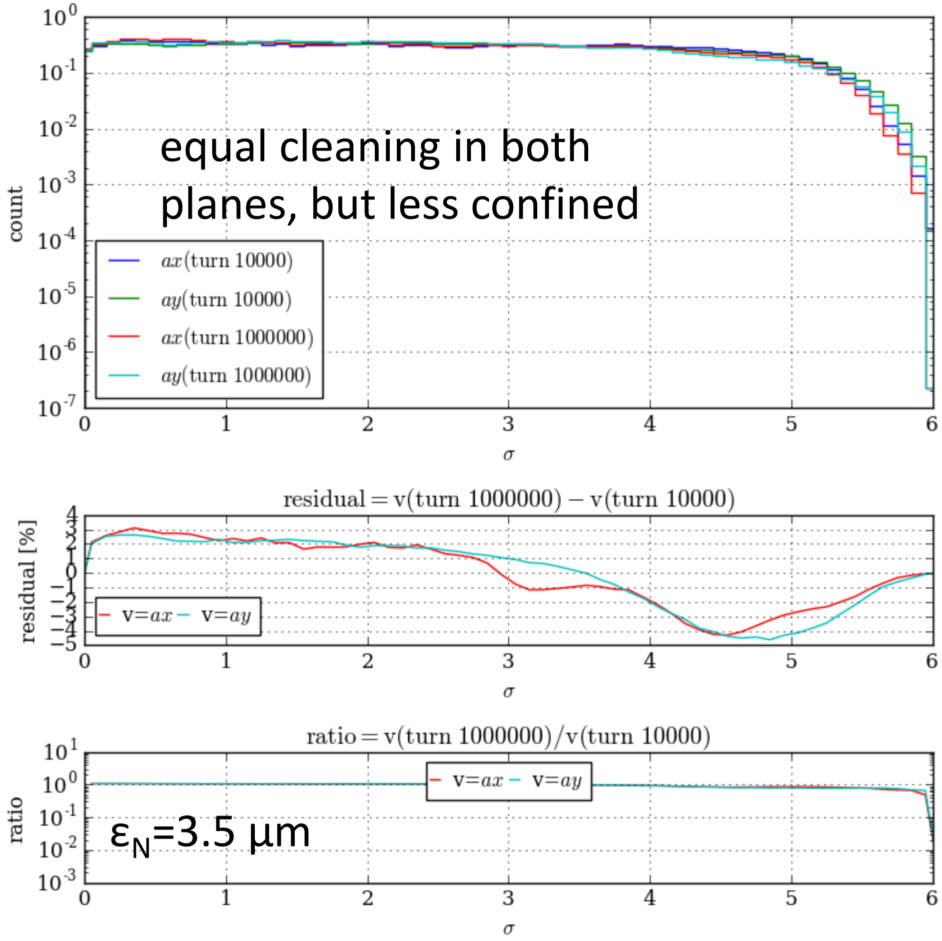
WIRE LEFT: $I_{wire,L}$=-350 A, $I_{wire,R}$=0 A, $d_{jaw\text{-}beam,L}$ =5.7 σ, I_{oct}=+10A



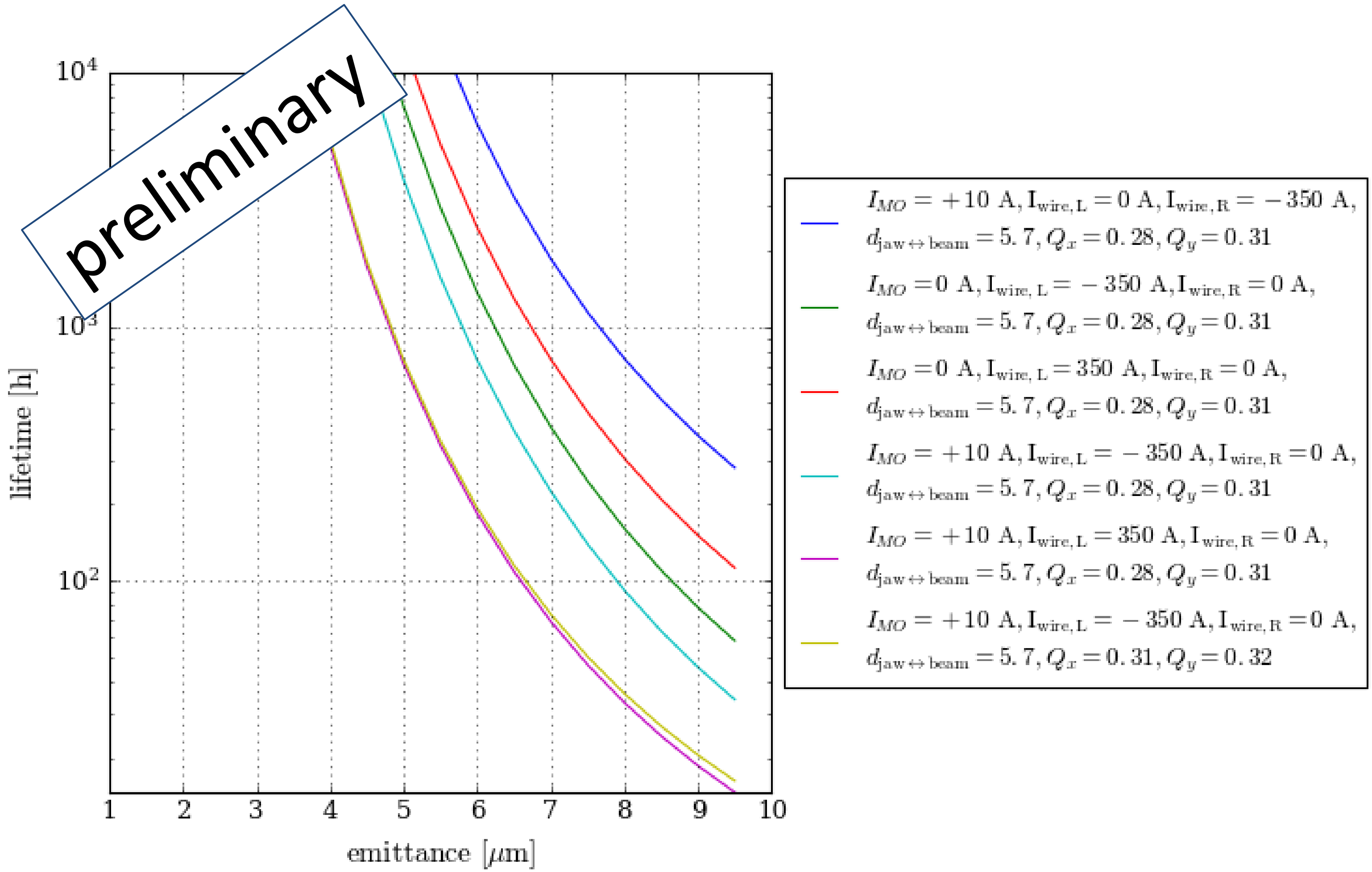
Histograms

collision tunes (Q_x=.31, Q_y=.32)

WIRE LEFT: $I_{wire,L}$=-350 A, $I_{wire,R}$=0 A, $d_{jaw-beam,L}$ =5.7 σ, I_{oct}=+10A



Expected lifetimes



- Gaussian distribution assumed for lifetime calculation. Lifetime obtained from uniform distribution in x and y.
- from 100 – 700 of 10 000 are lost -> still small statistics?

Conclusion

Conclusions

- effect of wire on lifetime is small at injection even at minimal separation of $d_{jaw<->beam} = 5.7\ \sigma$ and current of $I_{wire} = 350$ A
- effect of WIRE RIGHT is small compared to WIRE LEFT due to different ratio in beta function

- wire contributes considerably to the tune spread

⇒ tune spread generated by octupoles might be compensated by wire (e.g. thin line for $I_{wire} > 0$)

- without octupoles, wire cleans in horizontal plane (1/r potential)
- with octupoles, the effect of the wire on the tail particles depends on:
  - the non-linearities present
  - the working point

⇒ effect of wire on tail particles depends strongly on machine configuration (mainly tune and octupoles)

⇒ **wire does not necessarily deplete particles uniformly in x and y**

Backup

Crossing scheme

Calculation of $d_{jaw\text{-}beam}$:

1. use sigma of ideal beam optics to calculate the opening of the distance between the beam and the jaw $d_{jaw\text{-}beam}$
2. add the distance between collimator and wire with $d_{jaw\text{-}wire}$ = 3 mm

$$d_{beam\text{-}wire} = d_{jaw\text{-}beam} + d_{jaw\text{-}wire} = n\,\sigma_{col} + 3\text{mm}$$

3. calculate displacement of wire:
   a. assume that collimator will be perfectly aligned around orbit -> calculate orbit at wire at the end (after bb, error assignment, tune adjustement etc.)
   b. assume that wire is at inner jaw between the two beams (see x-scheme)

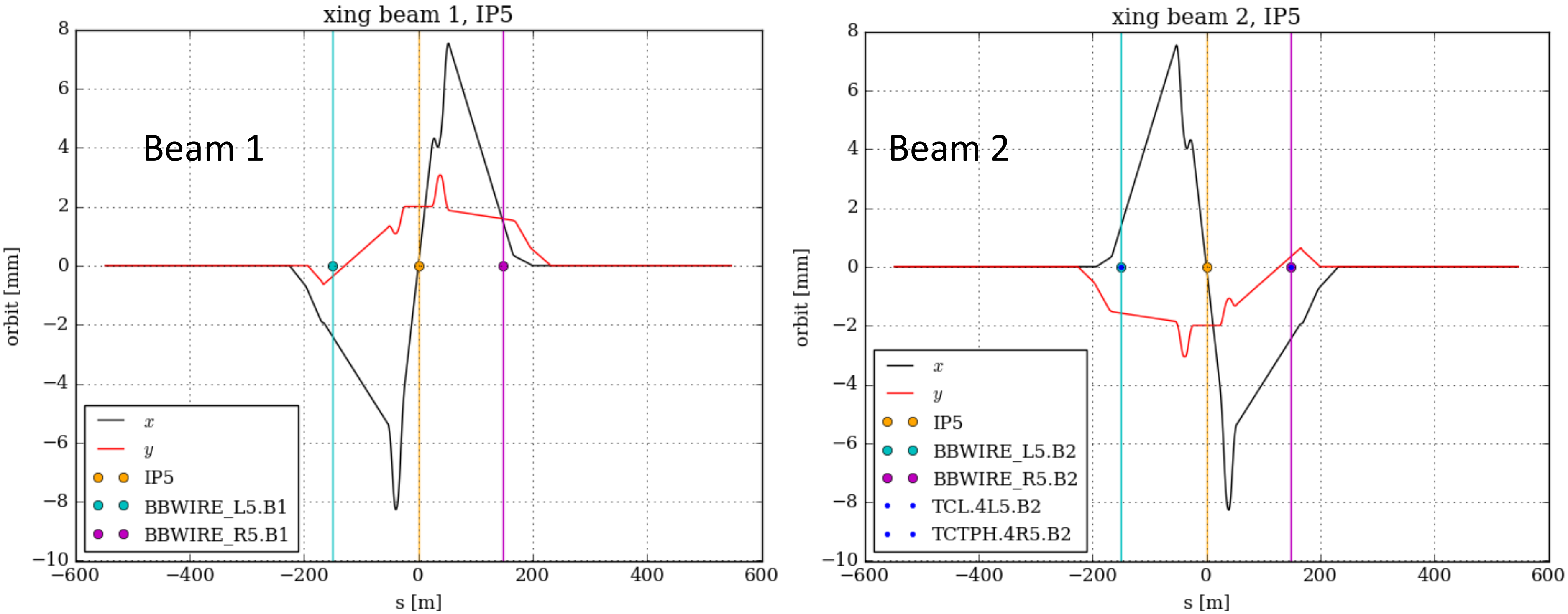
$$x_{wire,left} = -(d_{jaw\text{-}beam} + d_{jaw\text{-}wire}) + x_{closed\ orbit}$$

$$x_{wire,right} = (d_{jaw\text{-}beam} + d_{jaw\text{-}wire}) + x_{closed\ orbit}$$

$$y_{wire,left} = y_{closed\ orbit}$$

$$y_{wire,right} = y_{closed\ orbit}$$

Crossing scheme



wire placed between both beams in H, on orbit in V:
BBWIRE_L5: x<0, y<0
BBWIRE_L5: x>0, y>0