MD on halo control with the wire

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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.

LHC experiment:

- single beam: beam 2
- first test at injection with \(Q' = 4\), \(I_{\text{octupoles}} = +10.0 \, \text{A}\) (same settings as for halo control MDs)
- maximum separation jaw ↔ beam: 13 \(\sigma\) (TCT settings at injection)
- minimum separation jaw ↔ beam: 5.7 \(\sigma\) (TCP settings at injection)
- maximum wire current: 350 A
- wire polarity: both polarities (for long-range beam-beam compensation \(I_{\text{wire}} < 0\) for beam 2)
LHC experiment:

- one nominal bunch to check that the core stays unaffected
- one blown up bunch to be sensitive to the halo

⇒ ideally we see losses in the blown up bunch and no effect on the nominal bunch

- do several injections as beam distributions might change considerably

⇒ do a first quick scan in current to determine the minimal current for which an effect is seen

⇒ do a scan in current for a few points and inject each time a new bunch
Some theory …

Multipole expansion of wire field [1]:

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

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

\[ p \cdot Q_x + q \cdot Q_y = n, \quad n \in \mathbb{N} \text{ with} \]

\[ p \in \mathbb{N}, q = 0 \text{ or } p \mod 2 = 0, q \in \mathbb{N} \]

[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]:

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

$$\Rightarrow c_{p,q}^w \sim \sum_{k=L,R} \frac{1}{r} \frac{1}{d_w |p|+|q|}(s_k)[\sigma]$$

with $$r = \frac{\beta_x(s_k)}{\beta_y(s_k)}$$

$$d_w = \text{distance between wire and beam}$$

$$\Rightarrow \text{at injection wires on left and right can not be simply lumped together in one interaction as the phase advance between the two wires is } 1.4 \pi$$

$$\Rightarrow \text{RDTs scale with ratio of the } \beta\text{-function } r \text{ and the distance } d_w [\sigma] \text{ between wire and beam}$$

[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 beam 2, IP5

- $\beta_x$
- $\beta_y$
- $D_x$
- $D_y$
- $\mu_x$
- $\mu_y$

- IP5
- BBWIRE_L5.B2
- BBWIRE_R5.B2
- TCL.4L5.B2
- TCTPH.4R5.B2

Halo control with wire

CoLUSM #85, 17/03/2017
Optics @ injection

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$d_{\text{jaw} \leftrightarrow \text{wire}}$</td>
<td></td>
<td>3 mm</td>
</tr>
<tr>
<td>$\beta_x$ [m]</td>
<td>81.2</td>
<td>169.6</td>
</tr>
<tr>
<td>$\beta_y$ [m]</td>
<td>166.5</td>
<td>81.3</td>
</tr>
<tr>
<td>$\beta_x / \beta_y$</td>
<td>0.5</td>
<td>2.1</td>
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<tr>
<td>$D_x$ [m]</td>
<td>-0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$\Delta \mu_x (TCL.4L5,TCTPH.4R5)$ [π]</td>
<td></td>
<td>1.43</td>
</tr>
<tr>
<td>$\Delta \mu_y (TCL.4L5,TCTPH.4R5)$ [π]</td>
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<td></td>
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<tr>
<td>$d_{\text{jaw} \leftrightarrow \text{beam}}$ [σ]</td>
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<tr>
<td>for $d_{\text{wire} \leftrightarrow \text{beam}} = 9.6 , \sigma , (\varepsilon_N=3.5 , \mu\text{m})$</td>
<td>5.7</td>
<td>6.9</td>
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<td>$d_{\text{jaw} \leftrightarrow \text{beam}}$ [mm]</td>
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<td>6.5</td>
<td>9.3</td>
</tr>
</tbody>
</table>

⇒ larger effect for wire on left side
Tune footprints, no octupoles

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

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

maximum current, minimal separation: \( I_{\text{wire}, R} = I_{\text{wire}, L}, \ d(\text{jaw,beam})_L [\sigma] = d(\text{jaw,beam})_R [\sigma] \)
Tune footprints, with octupoles

\[ I_{\text{wire}} < 0 \Rightarrow \text{long-range beam-beam compensation} \]

- \[ I_{\text{MO}} = 0 \text{ A}, I_{\text{wire}} = 0 \text{ A} \]
- \[ I_{\text{MO}} = +10 \text{ A}, I_{\text{wire}} = 0 \text{ A} \]

no tune rematch,

- \[ I_{\text{MO}} = 0 \text{ A}, I_{\text{wire}, L} = -350 \text{ A}, I_{\text{wire}, R} = 0 \text{ A}, \]
  \[ d_{\text{beam} \leftrightarrow \text{jaw}, L} = 5.7\sigma \]

- \[ I_{\text{MO}} = +10 \text{ A}, I_{\text{wire}, L} = -350 \text{ A}, I_{\text{wire}, R} = 0 \text{ A}, \]
  \[ d_{\text{beam} \leftrightarrow \text{jaw}, L} = 5.7\sigma \]

no tune rematch,

- \[ I_{\text{MO}} = 0 \text{ A}, I_{\text{wire}, L} = +350 \text{ A}, I_{\text{wire}, R} = 0 \text{ A}, \]
  \[ d_{\text{beam} \leftrightarrow \text{jaw}, L} = 5.7\sigma \]

- \[ I_{\text{MO}} = +10 \text{ A}, I_{\text{wire}, L} = +350 \text{ A}, I_{\text{wire}, R} = 0 \text{ A}, \]
  \[ d_{\text{beam} \leftrightarrow \text{jaw}, L} = 5.7\sigma \]

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
FMA analysis:
• turns tracked: $10^4$
• quadratic grid up to 8 $\sigma$

Long term tracking:
• distribution: uniform distribution in $r=\sqrt{x^2+y^2}$ between 0-5.7 $\sigma$
• turns tracked: $10^6$
• single aperture in IP3 @ 5.7 $\sigma$ (only betatron part) -> any diffusion above this aperture doesn’t matter!

Notation:
Separation $d_{\text{wire}<-\text{beam}}$ is always given in terms of $d_{\text{jaw}<-\text{beam}}$ for the wire on the left side. The right side is then set so that $d_{\text{wire}<-\text{beam},L [\sigma]} = d_{\text{wire}<-\text{beam},R [\sigma]}$. 
$I_{\text{wire}} < 0$

Injection optics

Injection tunes $Q_x = 62.28$, $Q_y = 60.31$

$Q_x' = Q_y' = 4$

$I_{\text{oct}} = 0$ A
$I_{\text{wire}} < 0$, no octupoles, wire R

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

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

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

$\frac{dp}{p} = 0$
\( I_{\text{wire}} < 0, \) no octupoles, wire L, wire L+R

**WIRE LEFT:** \( I_{\text{wire,L}} = -350 \ \text{A}, \ I_{\text{wire,R}} = 0 \ \text{A}, \ d_{\text{jaw-beam,L}} = 5.7 \ \sigma, \ I_{\text{oct}} = 0 \ \text{A} \)

\[
\frac{\Delta p}{p} = 0
\]

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

- WIRE LEFT more efficient than WIRE RIGHT
- cleaning only in the horizontal plane
- on-momentum: clear cleaning above \( \sim 6 \ \sigma \)
- off-momentum: cleaning down to \( \sim 4 \ \sigma \)
- adding wire on right appears to decrease diffusion
\[ I_{\text{wire}} < 0 \]

injection optics

injection tunes \( Q_x = 62.28, \ Q_y = 60.31 \)

\( Q'_x = Q'_y = 4 \)

\( I_{\text{oct}} = +10 \text{ A} \)
LARP

Halo control with wire

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

NO WIRE: I_{oct} = +10 A

- resonances from octupoles enhanced with wire
- 1Q_{x} - 4Q_{y} resonances results in cleaning also in vertical plane
- on-momentum: clear cleaning above \sim 6 \sigma
- off-momentum: cleaning down to \sim 4 \sigma

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

WIRE LEFT: I_{wire,L} = -350 A, I_{wire,R} = 0 A, d_{jaw-beam,L} = 5.7 \sigma, I_{oct} = +10 A
\[ I_{\text{wire}} < 0, \quad I_{\text{oct}} = +10 \, \text{A}, \quad \text{wire R, wire L+R} \]

**WIRE RIGHT:** \( I_{\text{wire, L}} = 0 \, \text{A}, \quad I_{\text{wire, R}} = -350 \, \text{A}, \quad d_{\text{jaw-beam, L}} = 5.7 \, \sigma, \quad I_{\text{oct}} = +10 \, \text{A} \)

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

\[ \text{dp } / \text{p} = 0 \]

**WIRE LEFT+RIGHT:** \( I_{\text{wire, L}} = -350 \, \text{A}, \quad I_{\text{wire, R}} = -350 \, \text{A}, \quad d_{\text{jaw-beam, L}} = 5.7 \, \sigma, \quad I_{\text{oct}} = +10 \, \text{A} \)

\[ \text{dp } / \text{p} = 0 \]
$I_{\text{wire}} > 0$

injection optics

injection tunes $Q_x=62.28$, $Q_y=60.31$

$Q_x' = Q_y' = 4$

$I_{\text{oct}} = +10 \text{ A}$
$I_{wire} > 0$, wire L

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

- without octupoles cleaning down to $\sim 6$ σ
- with octupoles cleaning down to small amplitudes in both planes, even better than for $I_{wire} < 0$
- tune footprint collapses to thin line with octupoles $\rightarrow$ beam stability?
\( I_{\text{wire}} < 0 \)

injection optics

dechange of working point

\( Q_x' = Q_y' = 4 \)

\( I_{\text{oct}} = +10 \text{ A} \)
$I_{\text{wire}} < 0$, $I_{\text{oct}} = +10 \, \text{A}$, wire L

$Q_x = 0.28, Q_y = 0.31$, WIRE LEFT: $I_{\text{wire,L}} = -350 \, \text{A}$, $I_{\text{wire,R}} = 0 \, \text{A}$, $d_{\text{jaw-beam,L}} = 5.7 \, \sigma$, $I_{\text{oct}} = +10 \, \text{A}$

$Q_x = 0.31, Q_y = 0.32$, WIRE LEFT: $I_{\text{wire,L}} = -350 \, \text{A}$, $I_{\text{wire,R}} = 0 \, \text{A}$, $d_{\text{jaw-beam,L}} = 5.7 \, \sigma$, $I_{\text{oct}} = +10 \, \text{A}$
$I_{\text{wire}} < 0$

injection optics

injection tunes $Q_x = 62.28$, $Q_y = 60.31$

$Q_x' = Q_y' = 4$

$I_{\text{oct}} = +10 \text{ A}$

Dependence on $d_{\text{wire-<->beam}}$ and $I_{\text{wire}}$
$I_{\text{wire}} < 0, I_{\text{oct}} = +10 \, \text{A}, \text{wire} \, L+R$

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

- weak dependence on current $I_{\text{wire}}$ compared to $d_{\text{wire} \leftrightarrow \text{beam}}$

- effect of wire rapidly decreases with $d_{\text{wire} \leftrightarrow \text{beam}}$ -> most likely have to use minimal separation of $d_{\text{jaw} \leftrightarrow \text{beam}} = 5.7 \, \sigma$
$I_{\text{wire}} < 0$

Injection optics

Injection tunes $Q_x = 62.28$, $Q_y = 60.31$

$Q_x' = Q_y' = 4$

$I_{\text{oct}} = +10$ A

Dependence on errors
(non-linear + b2)
\( I_{\text{wire}} < 0, I_{\text{oct}} = +10 \, \text{A}, \text{wire L+R} \)

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

- 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”.

\( 1 \sigma_{dp/p} \) 2016 optics

no errors

seed 1

seed 2

seed 3
Histograms for long term tracking (10^6 turns)
Halo control with wire

Injection tunes ($Q_x = .28$, $Q_y = .31$)

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

no change

small and well defined depletion down to $4\,\sigma$

$\varepsilon_N = 3.5\,\mu\text{m}$
Histograms

collision tunes ($Q_x = 0.31$, $Q_y = 0.32$)

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

losses down to small amplitudes, higher vertical losses above $4 \sigma$

$\varepsilon_N = 3.5$ $\mu$m
Conclusion
Conclusions $I_{wire}<0$

- Measurable effect likely only for smallest distance $d_{jaw->beam} = 5.7 \, \sigma$
- Effect of WIRE RIGHT is small compared to WIRE LEFT
- WIRE LEFT is more effective than WIRE LEFT+RIGHT with and without octupoles
  \[\Rightarrow\] focus on WIRE LEFT and if time permits also try WIRE RIGHT and WIRE LEFT+RIGHT

- No octupoles:
  - Wire cleans in horizontal plane for high amplitudes
  - Minimum effected amplitude lies above TCP opening $\Rightarrow$ no cleaning
- With octupoles:
  - Cleaning in horizontal plane due to wire
  - Due to octupoles also cleaning in the vertical plane
  \[\Rightarrow\] Cleaning in both planes expected for MD

- For collision tunes ($Q_x=.31, Q_y=.32$) the wire cleans down to smaller amplitudes compared to injection tunes ($Q_x=.28, Q_y=.31$)
  \[\Rightarrow\] Try both injection and collision tunes in MD
Conclusions $I_{\text{wire}} > 0$

- without octupoles:
  - similar effect as for $I_{\text{wire}} < 0$
- with octupoles:
  - collapse of tune spread to thin line
  - cleaning down to small amplitudes

⇒ interesting to try both polarities, but bunches might become unstable due to line-like tune spread?
Wire for halo control

- for injection tunes and also collision tune the wire would need to be set at $d_{\text{jaw-beam},L} = 5.7 \sigma$ and operated at maximum current in order to obtain cleaning at amplitudes $< 5.7 \sigma = \text{TCP @ 450 GeV}$
- effect of wire in amplitude space depends strongly on chosen working point
- wire does not necessarily clean uniformly in X and Y above certain amplitudes as the cleaning behavior depends on the excited resonances
- tune spread in the presence of octupoles and wire can be reduced to a thin line (e.g. $I_{\text{wire}} > 0$, $I_{\text{oct}} > 0$) -> beam might become unstable? Wire thus counteracts the octupole knob used for stabilizing the beam.

$\Rightarrow$ wire generates a highly non-linear field which makes it a difficult tool for halo control
$\Rightarrow$ current and minimum separation might not sufficient to clean particles down to $4 \sigma$
Backup
Lossrate

- uniform distribution 0-5.7 $\sigma$
- $dp=0$ or $dp/p$ and $\sigma_s$ Gaussian
- Losses not folded with distribution!!!
Lossrates $I_{MO}=0$
Loss rates $I_{\text{MO}} = +10$

**Graph 1:**
- Injection, $I_{\text{MO}} = +10$ A, $Q' = 4$, no errors, $\frac{\Delta r}{r} = 0$, $z = 0$
- $I_{\text{bus}} = 0$
- $d_{\text{beam+} \omega \text{av}} = 5.7$, $I_{\text{bus}} = -66$
- $d_{\text{beam+} \omega \text{av}} = 13$, $I_{\text{bus}} = -66$
- $d_{\text{beam+} \omega \text{av}} = -5.7$, $I_{\text{bus}} = -33$
- $d_{\text{beam+} \omega \text{av}} = -9.35$, $I_{\text{bus}} = -66$

**Graph 2:**
- Injection, $I_{\text{MO}} = +10$ A, $Q' = 4$, no errors, $\frac{\Delta r}{r} = \text{Gauss}$, $z = \text{Gauss}$
- $I_{\text{bus}} = 0$
- $d_{\text{beam+} \omega \text{av}} = 5.7$, $I_{\text{bus}} = -66$
- $d_{\text{beam+} \omega \text{av}} = 13$, $I_{\text{bus}} = -66$
- $d_{\text{beam+} \omega \text{av}} = -5.7$, $I_{\text{bus}} = -33$
- $d_{\text{beam+} \omega \text{av}} = -9.35$, $I_{\text{bus}} = -66$
Crossing scheme

Calculation of $d_{\text{jaw-beam}}$:
1. use sigma of ideal beam optics to calculate the opening of the distance between the beam and the jaw $d_{\text{jaw-beam}}$
2. add the distance between collimator and wire with $d_{\text{jaw-wire}} = 3$ mm
   \[ d_{\text{beam-wire}} = d_{\text{jaw-beam}} + d_{\text{jaw-wire}} = n \sigma_{\text{col}} + 3\text{mm} \]
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 adjustment etc.)
   b. assume that wire is at inner jaw between the two beams (see x-scheme)
   \[ x_{\text{wire, left}} = -(d_{\text{jaw-beam}} + d_{\text{jaw-wire}}) + x_{\text{closed orbit}} \]
   \[ x_{\text{wire, right}} = (d_{\text{jaw-beam}} + d_{\text{jaw-wire}}) + x_{\text{closed orbit}} \]
   \[ y_{\text{wire, left}} = y_{\text{closed orbit}} \]
   \[ y_{\text{wire, right}} = y_{\text{closed orbit}} \]
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