Simulation of LRBB Impact on Lifetime

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Second Workshop on Wire Experiment for Long Range Beam-Beam Compensation
20 March 2017, Divonne-les-Bains

Motivation

- BBLR potential for HL-LHC and impact on performance discussed in talk by S.Fartoukh
- We address the proof-of-principle demonstration experiments with wire-in-collimator devices in the LHC in 2017 and 2018
  - 2 wires at IP5 available in 2017
  - Full set of 4 wires in 2018
  - Aim at demonstration with minimum machine configuration changes

Basic Parameters

- Minimum changes to the machine / optics configuration from the nominal operation
- The study scenario would be weak-strong with 1(2,3) weak bunches and trains in the 'strong' beam.
- Machine: 6.5TeV, collisions at IP1 and IP5
- Optics: β^*=40cm, '2016 collision' and/or ATS
- Beam parameters
  - 'Strong' beam1: ε=2.5μm N_p=1.15×10^{11}
  - 'Weak' beam2: ε=2.5μm or 5μm
- Parameter to vary: crossing angle θ
- Constants:
  - Betatron tunes Q_x=0.31, Q_y=0.32 (with and without wire)
  - Chromaticity = 15
  - I_MO=550A

Simulation Tools

- Sixtrack – major developments
  - Wire element
  - Modeling of macroscopic observables
    - Beam intensity lifetime
    - Emittances
    - 10^4 particles over 10^6 turns
- Lifetrac
  - FMA for visualization and quick assessment
  - Long-term macroparticle bunch tracking
    - 10^4 particles over 10^6 turns / 90s
  - Wire simulated as long-range beam-beam σ=0.3mm

Sixtrack Development – Field of Straight Wire

Vector potential of straight wire centered at the origin of Cartesian system:

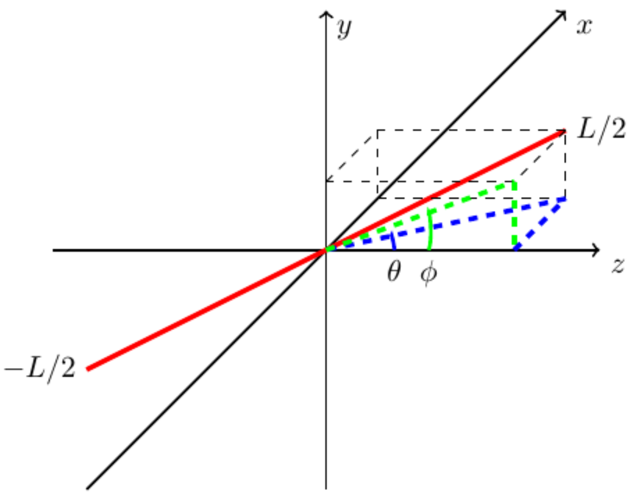
$$A_i(x,y,z) = \frac{I\mu_0 \cos(c_i)}{4\pi} \cdot \left(\operatorname{asinh}\left(\frac{L/2-a}{\sqrt{b-a^2}}\right) - \operatorname{asinh}\left(\frac{-L/2-a}{\sqrt{b-a^2}}\right)\right), \; i = x,y,z,$$

where the parameters a and b are defined as

$$a = x \cdot \cos(c_x) + y \cdot \cos(c_y) + z \cdot \cos(c_z),$$
$$b = x^2 + y^2 + z^2,$$

Direction cosines:

$$\cos(c_x) := \frac{\tan(\phi)}{\sqrt{\tan^2(\phi)+\tan^2(\theta)+1}}$$
$$\cos(c_y) := \frac{\tan(\theta)}{\sqrt{\tan^2(\phi)+\tan^2(\theta)+1}}$$
$$\cos(c_z) := \frac{1}{\sqrt{\tan^2(\phi)+\tan^2(\theta)+1}}.$$



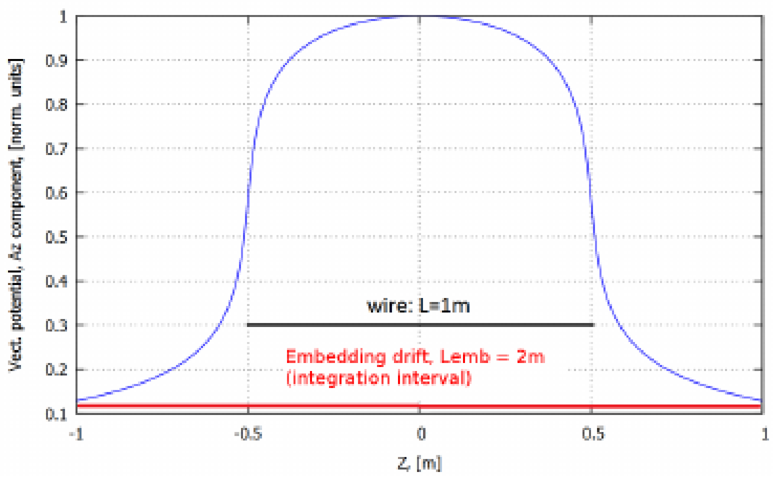
The potential is fully described by 4 parameters: 2 tilt angles, wire's length and current.

Sixtrack Development – Wire Map

First order integrator – needs additional parameter – integration interval (or embedded drift)

$$\Delta p_x = \int_{-L_{\text{emb}}/2}^{+L_{\text{emb}}/2} \frac{\partial A_z(x,y,s)}{\partial x} ds,$$

$$\Delta p_y = \int_{-L_{\text{emb}}/2}^{+L_{\text{emb}}/2} \frac{\partial A_z(x,y,s)}{\partial y} ds,$$



Transport MAP for arbitrary oriented wire was implemented into SixTrack code.

The explicit formula for the kick is:

$$p_x \to p_x - 10^{-7} \cdot I \frac{e}{P_0} \frac{r_x}{r^2} \left(d^+ - d^-\right) - p_{co,wire}$$

$$p_y \to p_y - 10^{-7} \cdot I \frac{e}{P_0} \frac{r_y}{r^2} \left(d^+ - d^-\right) - p_{co,wire}$$

with d^+ and d^- defined as:

$$d^+ = \sqrt{(L_{\text{emb}} + L)^2 + 4r^2}$$

$$d^- = \sqrt{(L_{\text{emb}} - L)^2 + 4r^2}$$

$P_{co,wire}$ closed orbit kick due to the wire (can be subtracted during SixTrack simulations in the consistent way with Beam-Beam element)

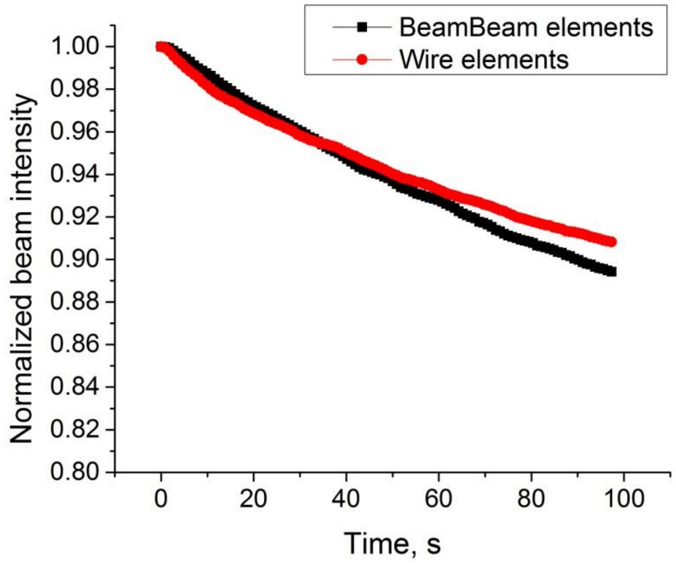
Sixtrack Development – Wire vs. Beam-Beam

LHC optics: MD2016, Collisions at IP1&5
Crossing angle 180 murad.; Emit. = 2.5.
6 sigma separation for compensators

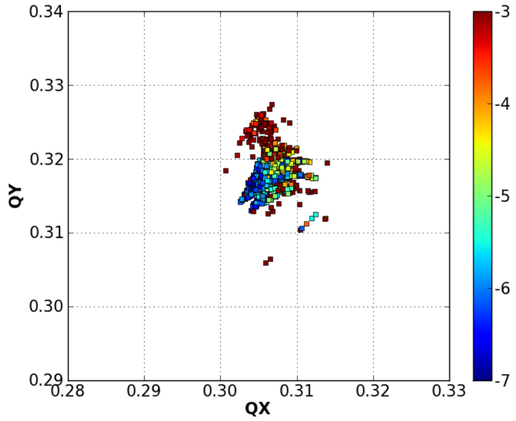
4 wires per beam (2 per IP), I=55 Amps

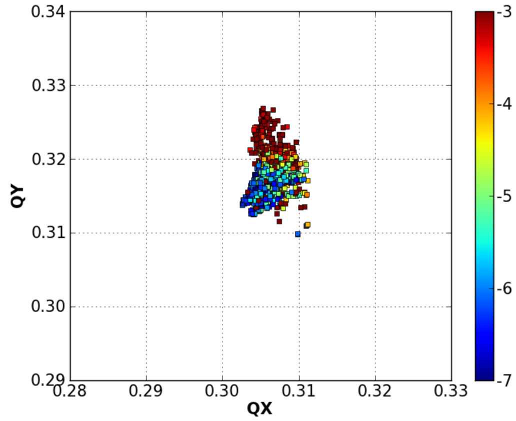
4 beam-beam elements per beam, S=8
(eq. current 46 Amps)

Top left - effect on beam life time, beam decay constants:
3.98 for wires, 4.4 for beam-beam.

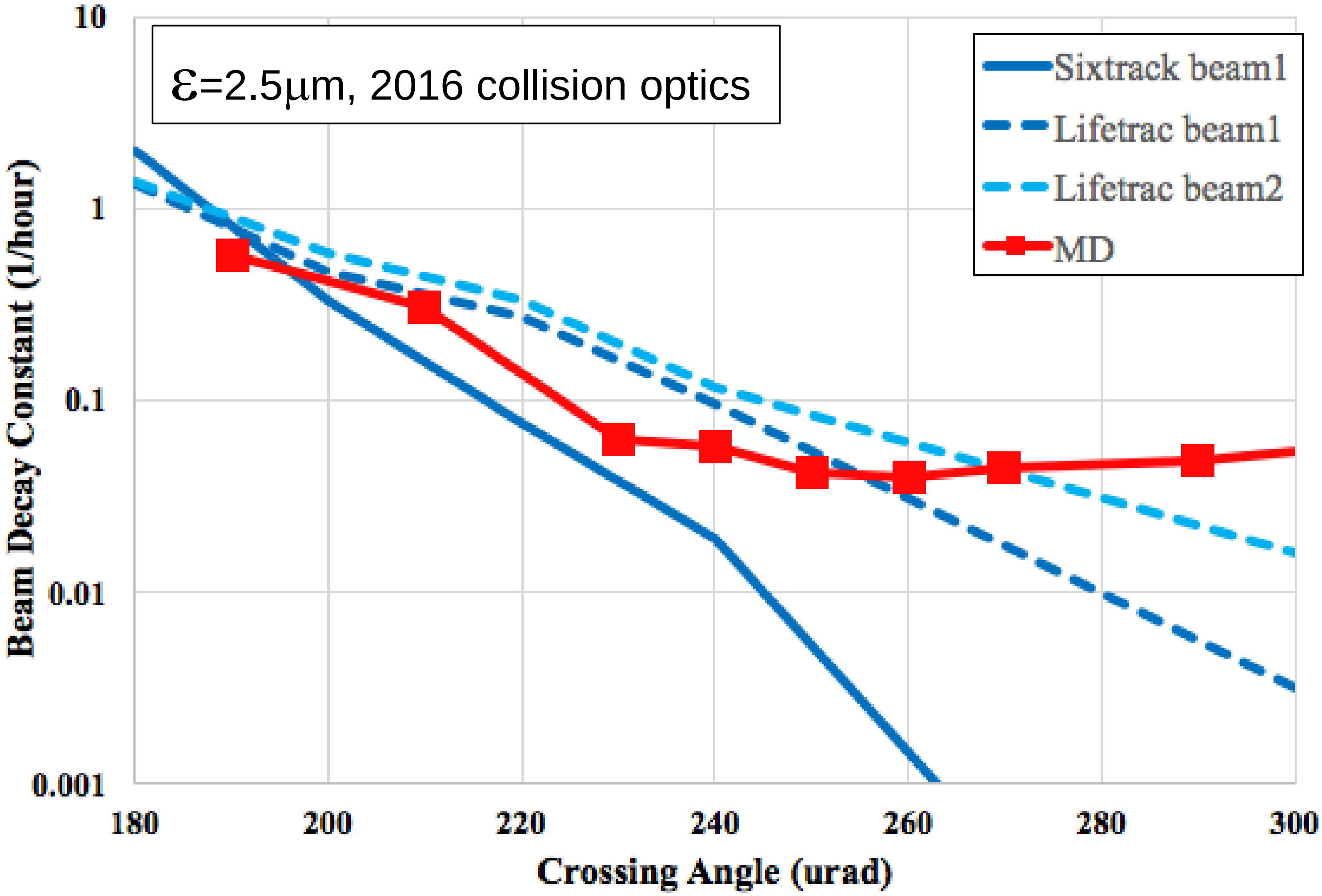


Bottom – effect on tune shift: left – beambeam elements; right – wires





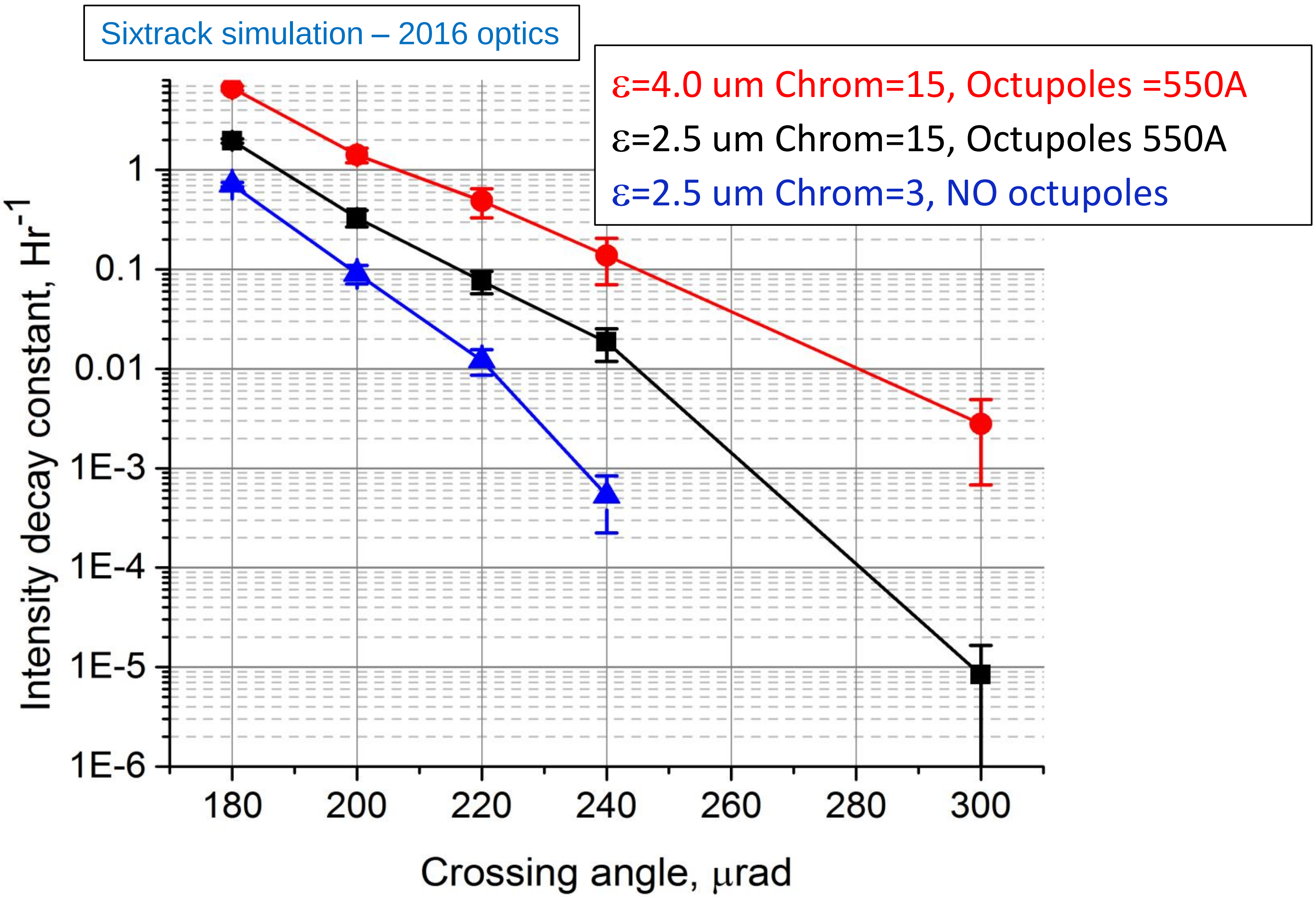
Benchmarking vs. MD



6σ beam **10σ**

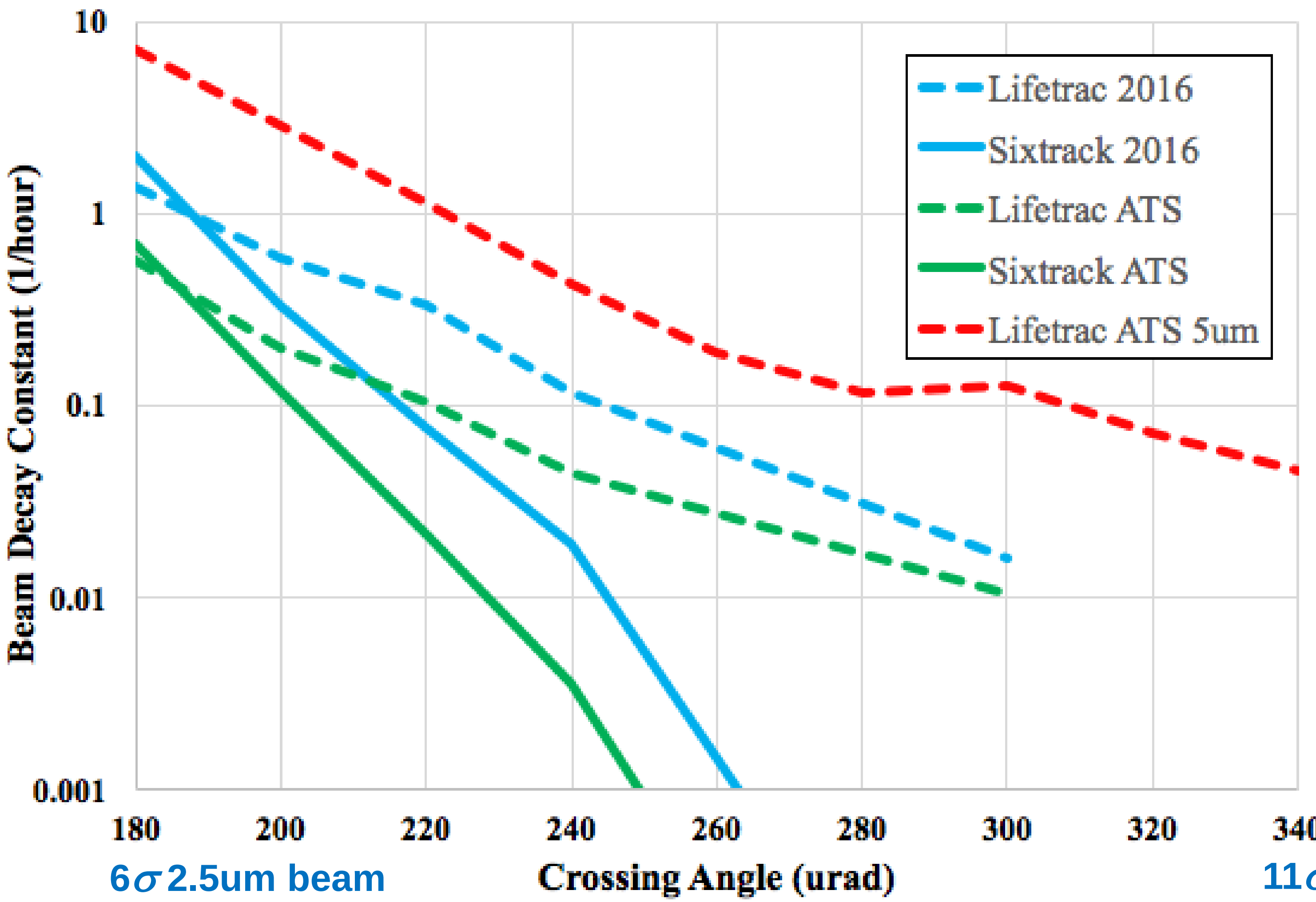
- Difference in treatment of aperture between two codes
- Big statistical error at low loss (large separation)
- Losses at 180urad → 90% vertical

Effect of Optics Parameters



More on the effect of optics in the following talk by D.Pellegrini

Effect of Optics and Beam Emittance



6σ 2.5um beam

4σ 5um

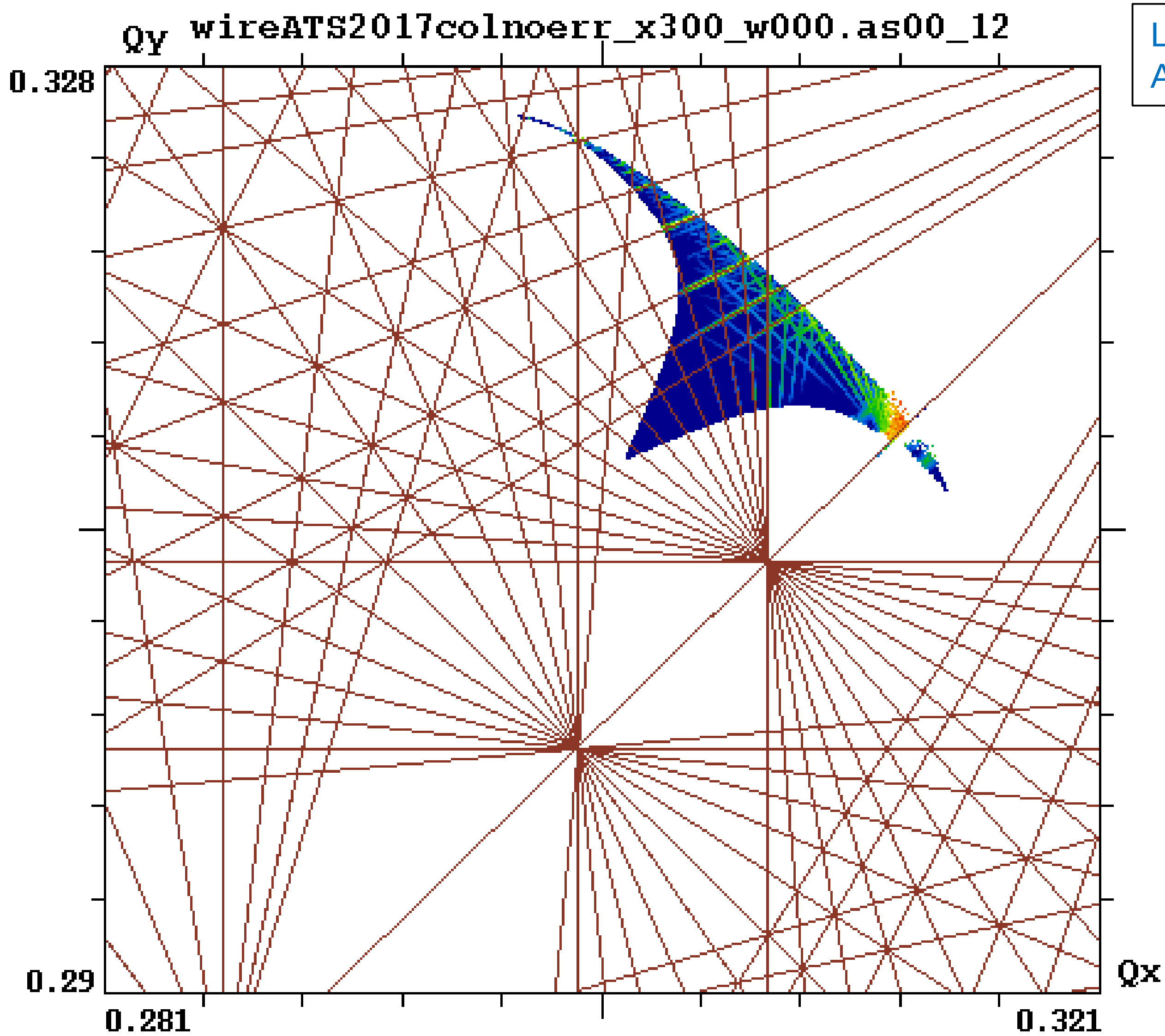
6σ 5um

11σ 2.5um

8σ 5um

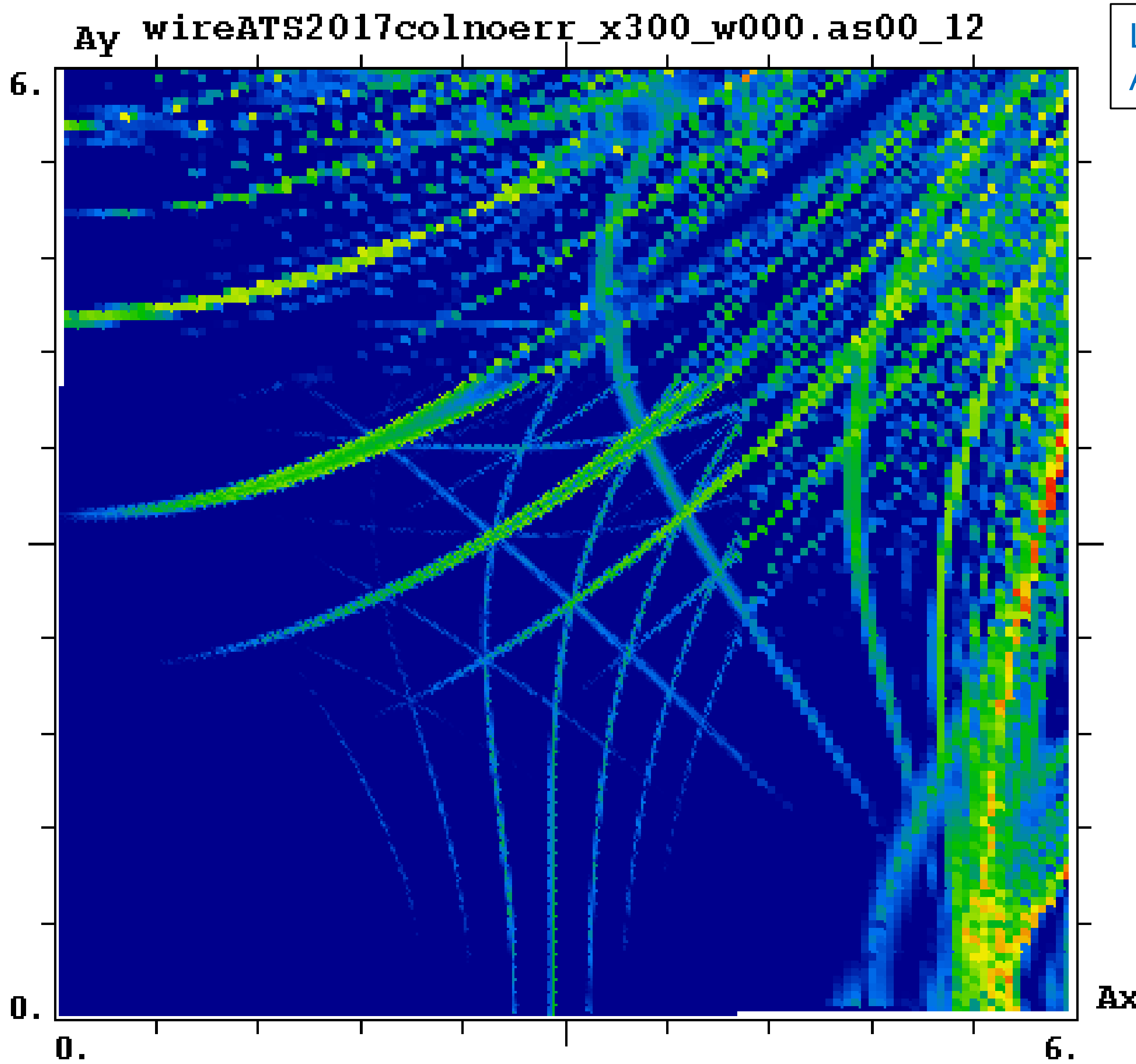
- Difference in treatment of aperture between two codes
- Big statistical error at low loss (large separation)
- Losses at 180urad → 90% vertical (70% in ATS)

Effect of Crossing Angle on Footprint



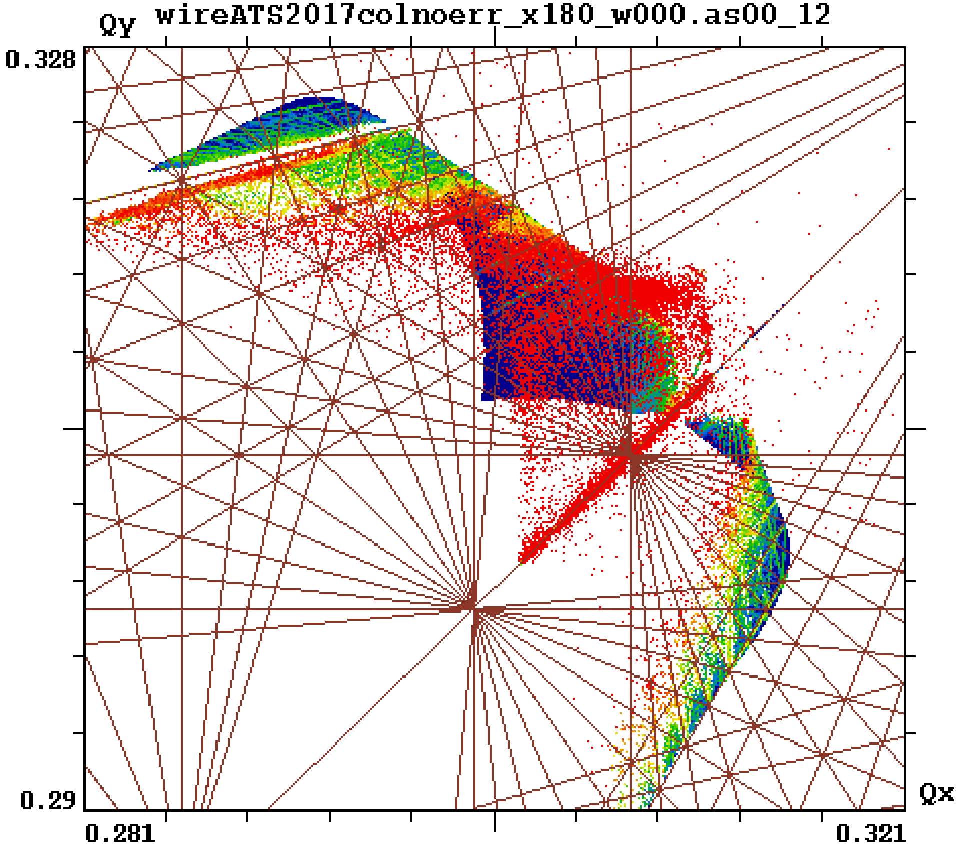
Lifetrac simulation
ATS optics

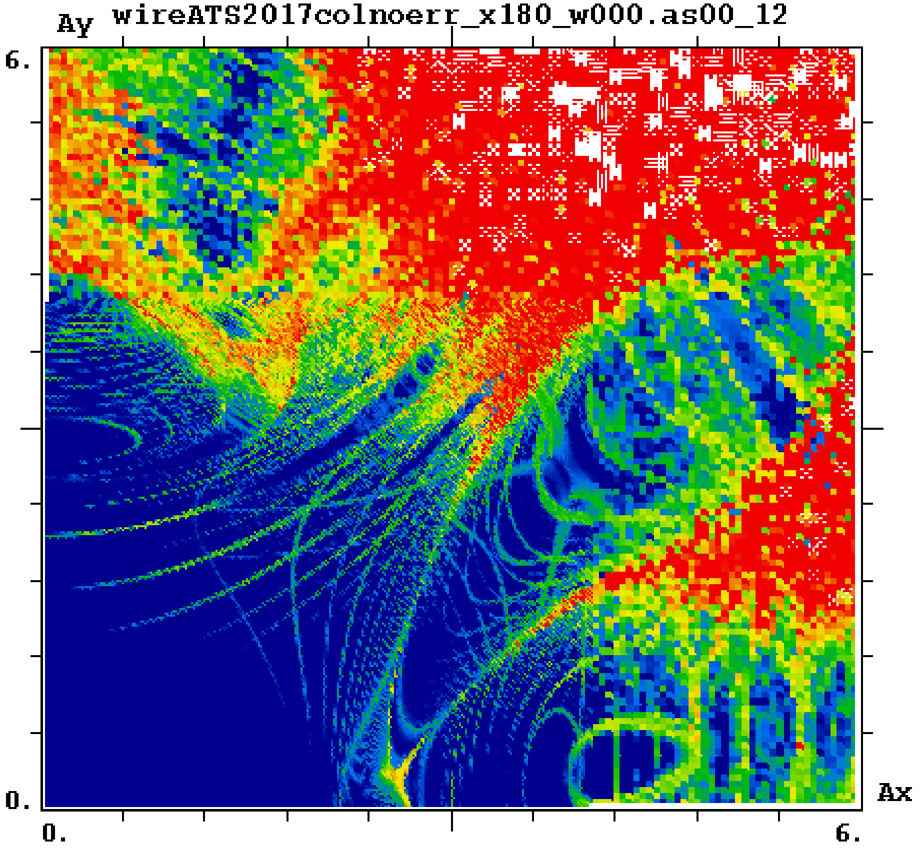
Effect of Crossing Angle on DA



Lifetrac simulation
ATS optics

Impact of Wires at θ=180urad (6σ sep.)



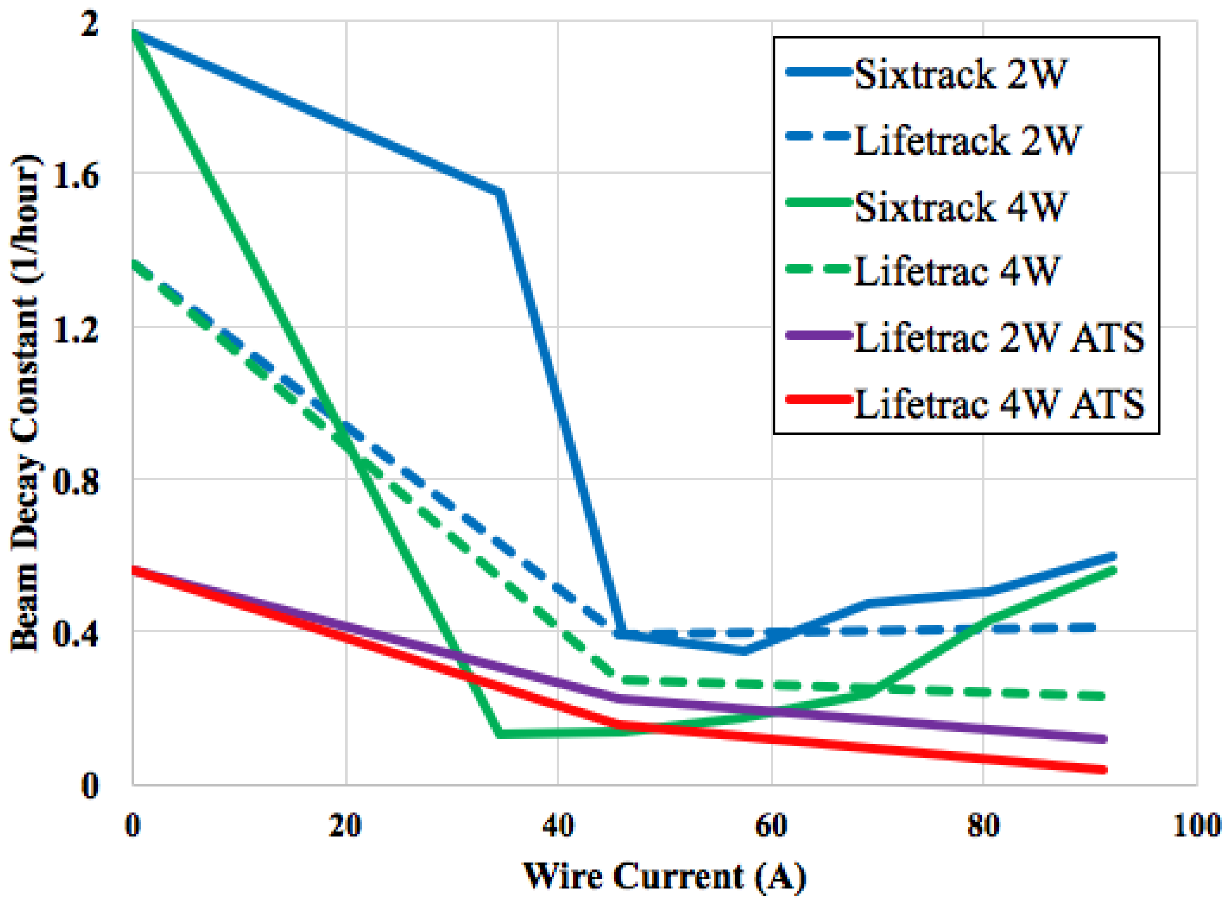


Lifetrac simulation
ATS optics, ε=2.5um

Frames:

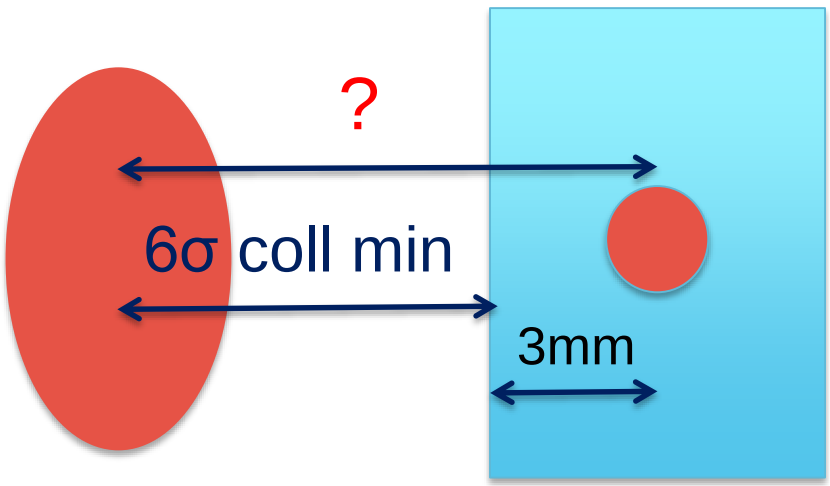
1. Wires OFF
2. 2 IP5 wires at 6σ, I=16×e·N_p·c=16×5.7A
3. 2 IP5 and 2 IP1 wires at 6σ, I=16×e·N_p·c

Impact of Wires on Lifetime at θ=180urad



- Weak beam emittance 2.5um
- Wires at 6 beam sigma – proper for 180urad
- L5 collimator jaw at 0.6 collimation sigma □

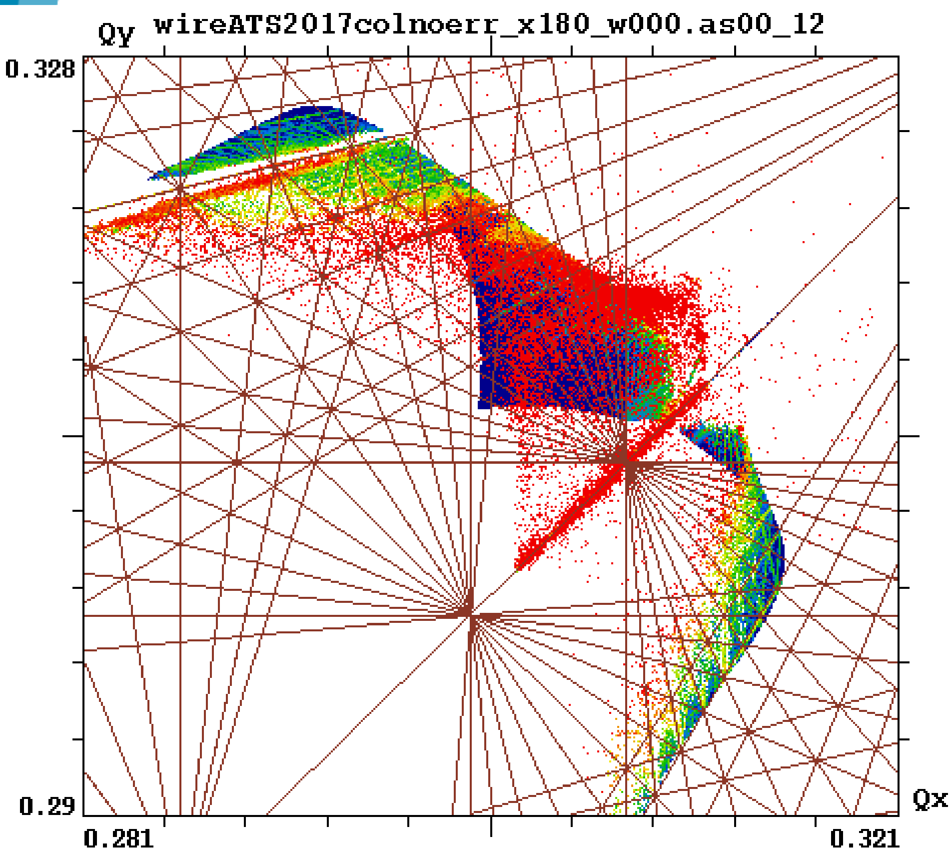
Boundary Conditions for Wires

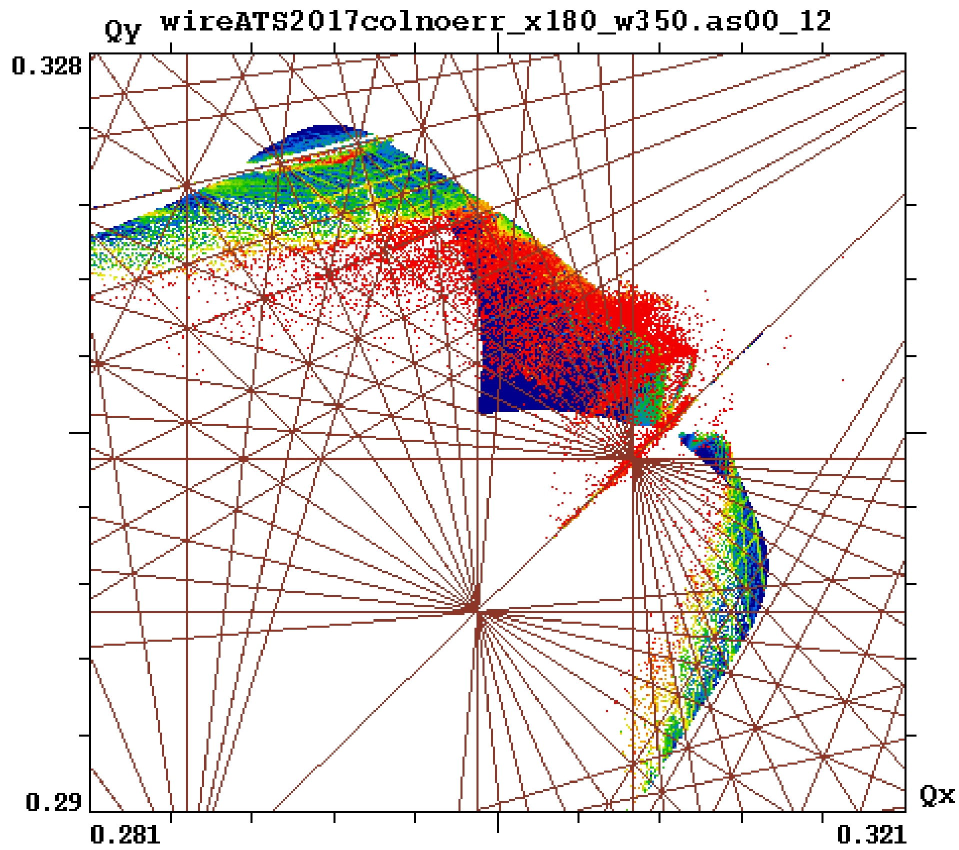


ATS Optics (3/2017 S.Fartoukh)

Place	β_x (m)	β_y (m)	σ_x coll (mm)	σ_y coll (mm)	Min. Sep. (mm)	Min Sep. (σ 2.5 μm)	Min Sep. (σ 5 μm)
L5 TCL.4L5.B2	887	1297	0.67		7.0	12.4	8.8
R5 TCTPH.4R5.B2	1319	945	0.82		7.9	11.4	8.1
L1 -172.2 from IP1	400	1029		0.72	7.3	12.0	8.5
R1 TCTPV.4R1.B2	1341	1003		0.71	7.2	12.0	8.5

Impact of 2 IP5 Wires at θ=180urad (6σ sep.) Increased Wire Distance

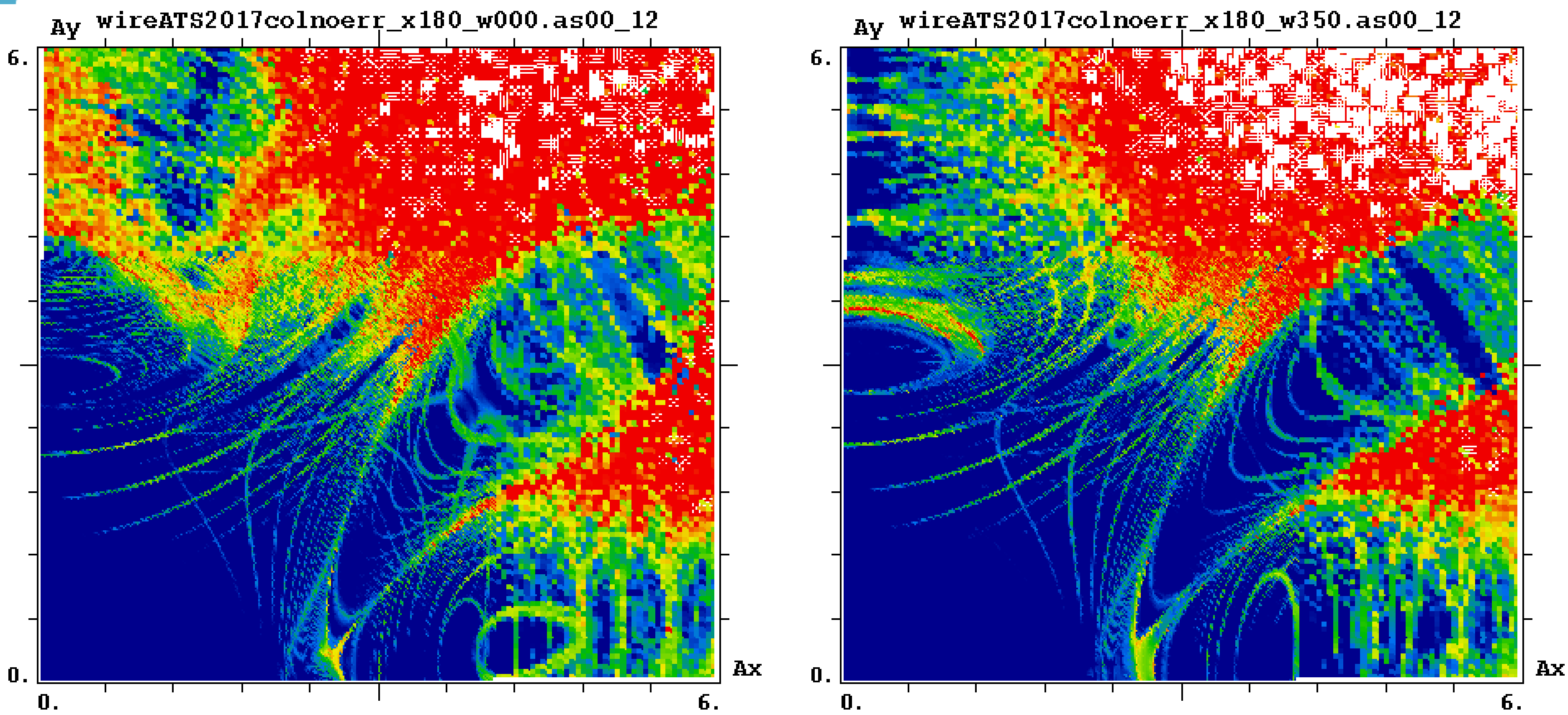




Lifetrac simulation
ATS optics, ε=2.5um

- Wires at 12.4 beam sigma – current increased to 350A
- L5 collimator jaw at 6 collimation sigma □

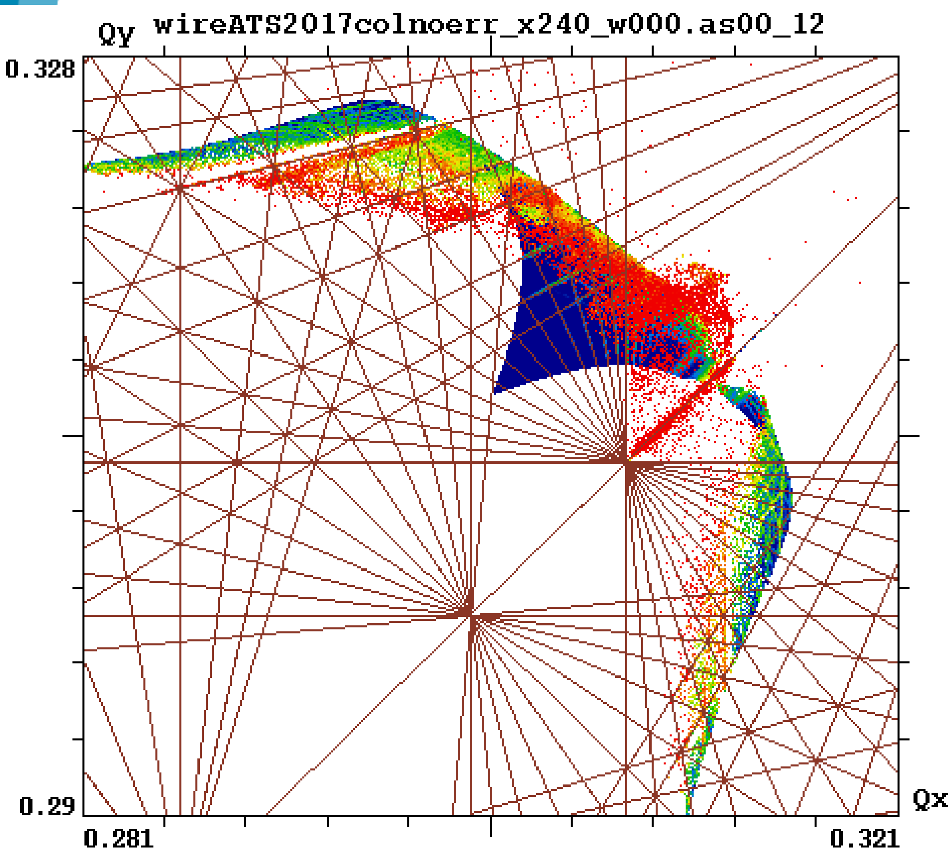
Impact of 2 IP5 Wires at θ=180urad (6σ sep.) Increased Wire Distance

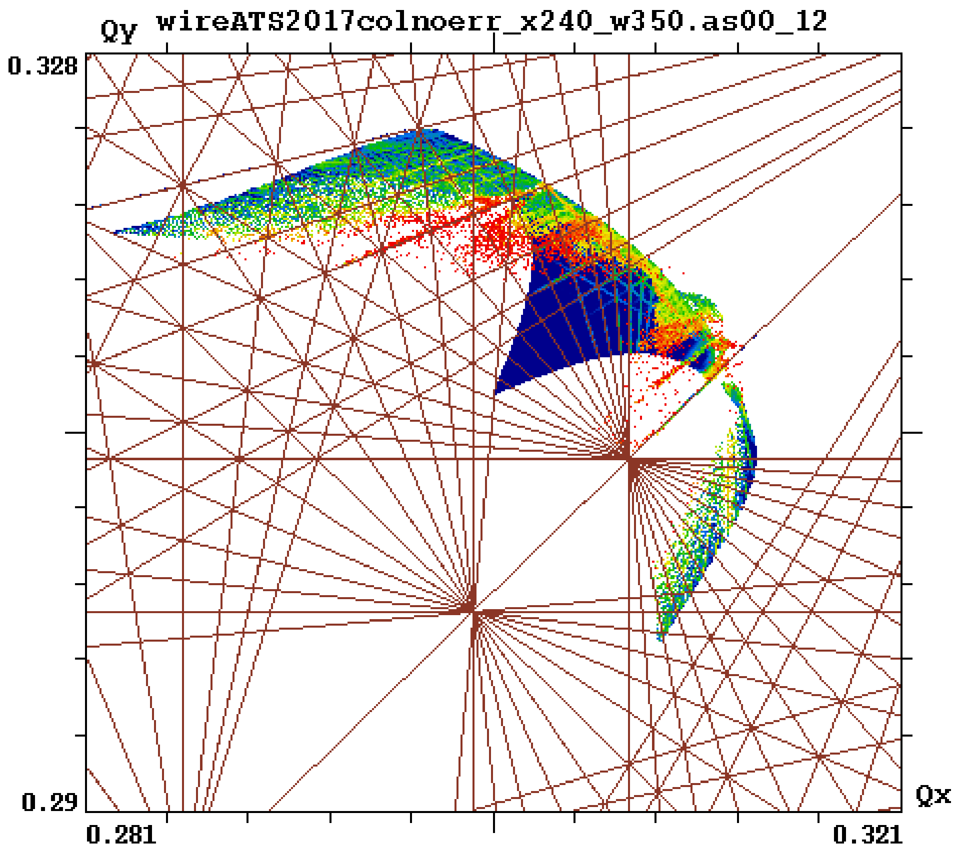


Lifetrac simulation
ATS optics, ε=2.5um

- Wires at 12.4 beam sigma – current increased to 350A
- L5 collimator jaw at 6 collimation sigma □

Impact of 2 IP5 Wires at θ=240urad (5.6σ sep.) Increased Wire Distance

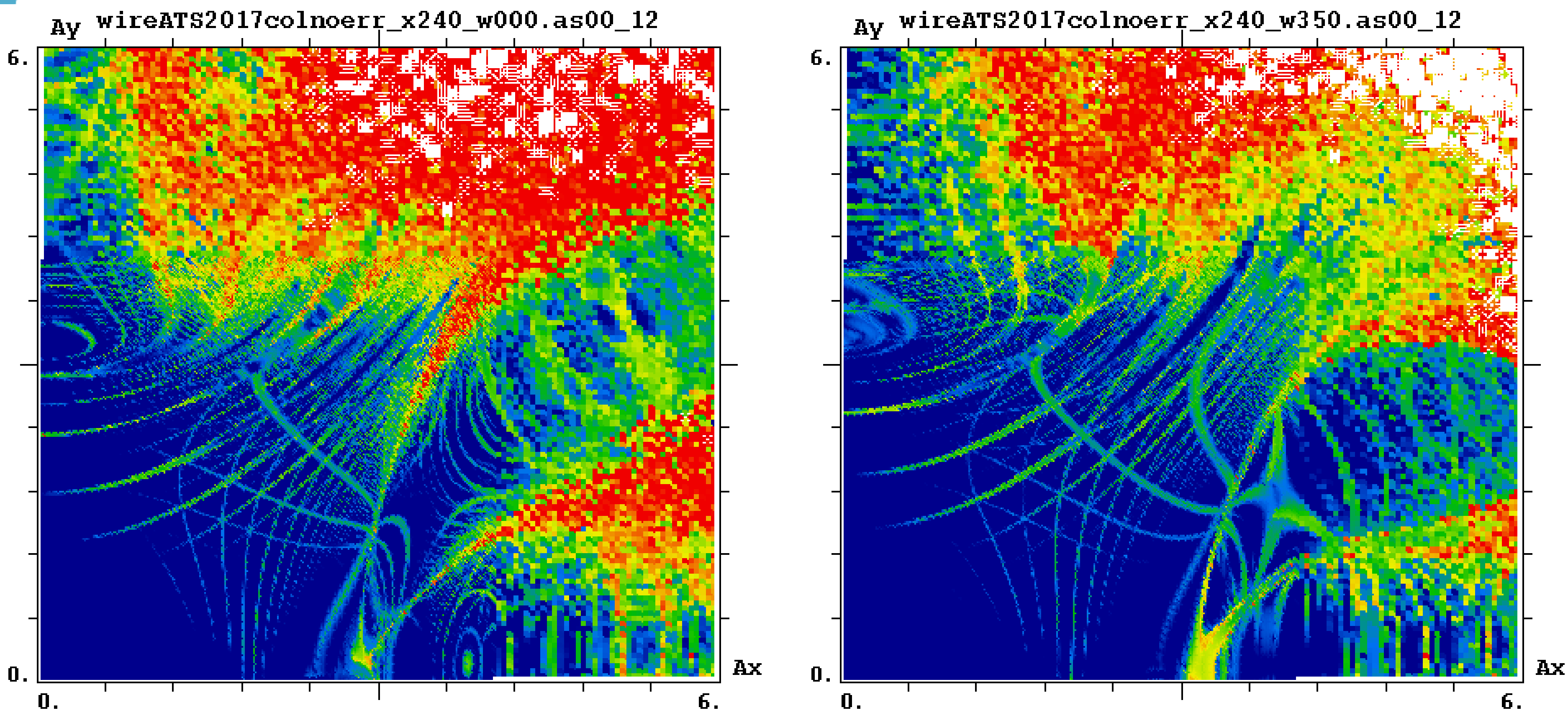




Lifetrac simulation
ATS optics, ε=5um

- Wires at 8.8 beam sigma – current increased to 350A
- L5 collimator jaw at 6 collimation sigma □

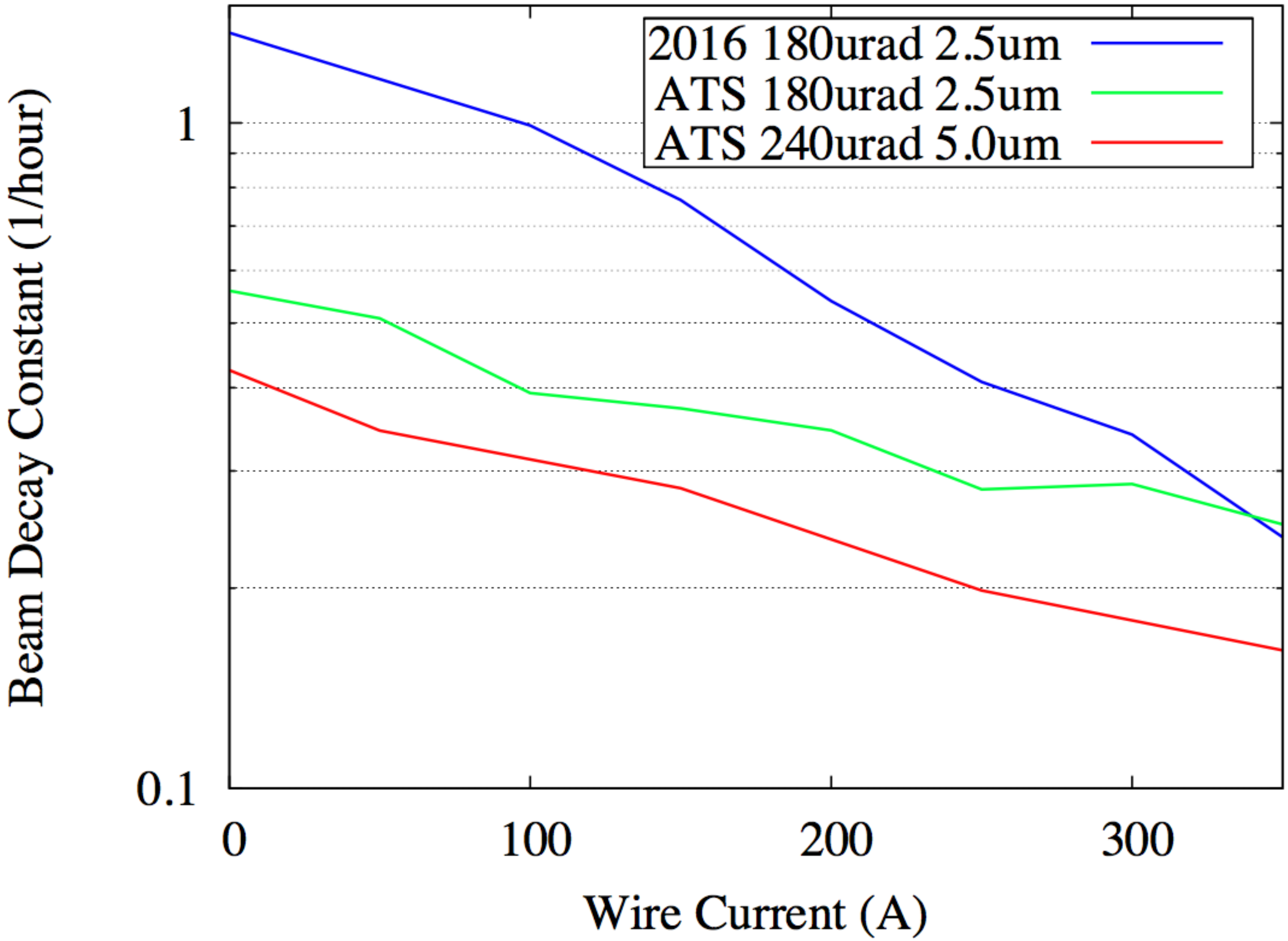
Impact of 2 IP5 Wires at θ=180urad (5.6σ sep.)
Increased Wire Distance



Lifetrac simulation
ATS optics, ε=5um

- Wires at 8.8 beam sigma – current increased to 350A
- L5 collimator jaw at 6 collimation sigma □

Impact of 2 IP5 Wires on Lifetime
L5 collimator jaw at 6σ coll.



Summary

- Without major changes to machine configuration, beam lifetime degradation due to long-range begins at separations of <6σ.
- Wire-in-collimator compensators present a less than ideal option for long-range beam-beam compensation at small crossing angle
- However, even a 2-wire scheme can show measurable benefit to lifetime
  - 4x in 2016 optics at θ=180urad
  - 2x in ATS optics and θ=180urad
  - 2x in ATS optics, ε=5um and θ=240urad

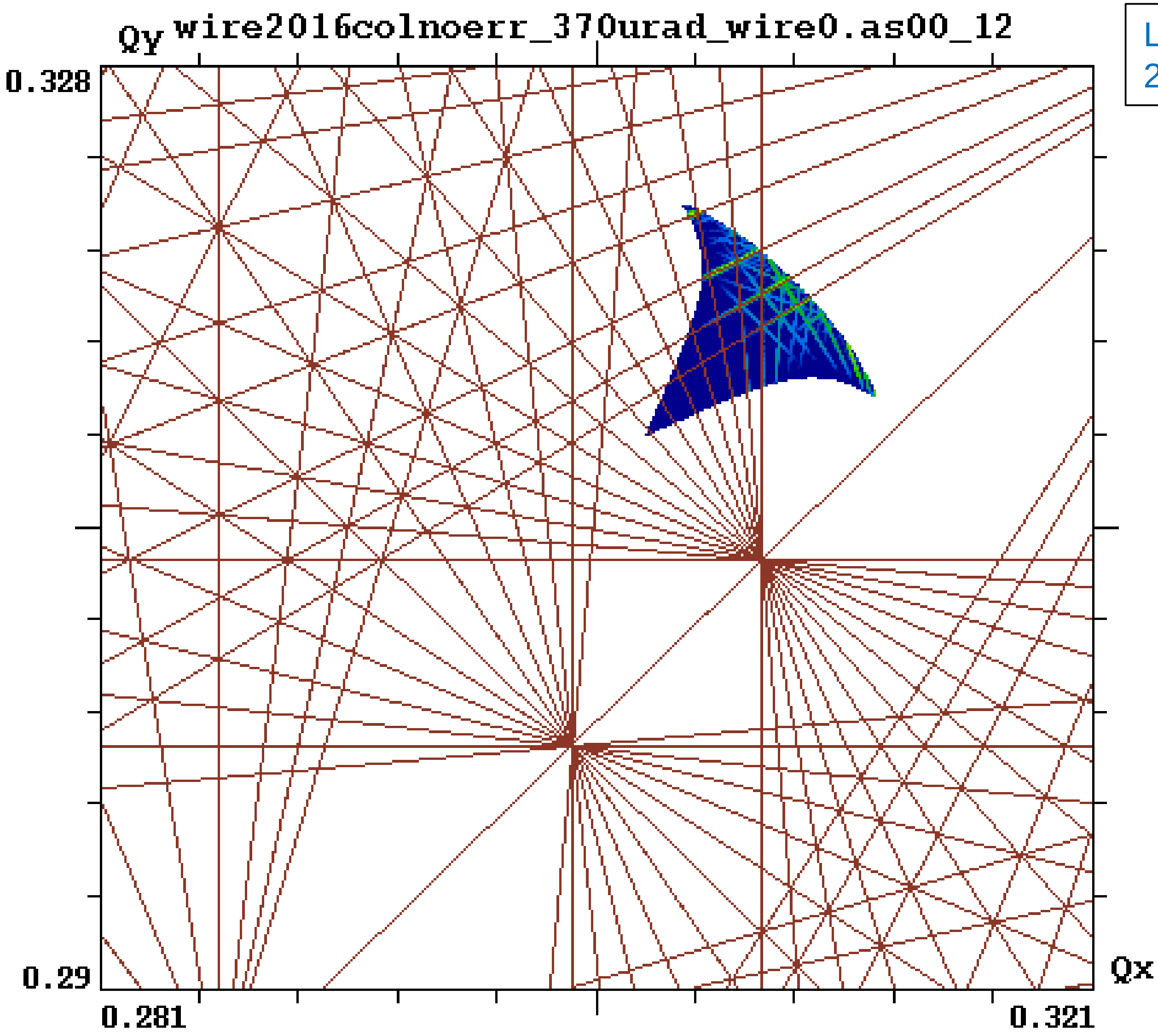
Extra Slides

Sixtrack Development – Beam Life Time

	ALGORITHM:	
I	SIXTRACK input generating with MADX*	Wires are switched OFF
II	SIXTRACK wires tune shift calculation	Wires are switched ON
III	SIXTRACK input generating with MADX, Wires tune shift compensation	Wires are switched OFF
IV	SIXTRACK: 6D Gaussian distribution tracking, Data accumulation. 6D Gaussian distribution generated with Sigma matrix = $T^{T}ET$ (T is calculating in SixTrack: one turn map M= $T^{-1}RT$) Initial distribution: Beam Core + Beam Halo [Halo statistically weighted with the core and transverse emittance 10 times bigger ~ 3 times wider beam]	Wires are switched ON
V	Data processing: Beam intensity decay constant calculation	

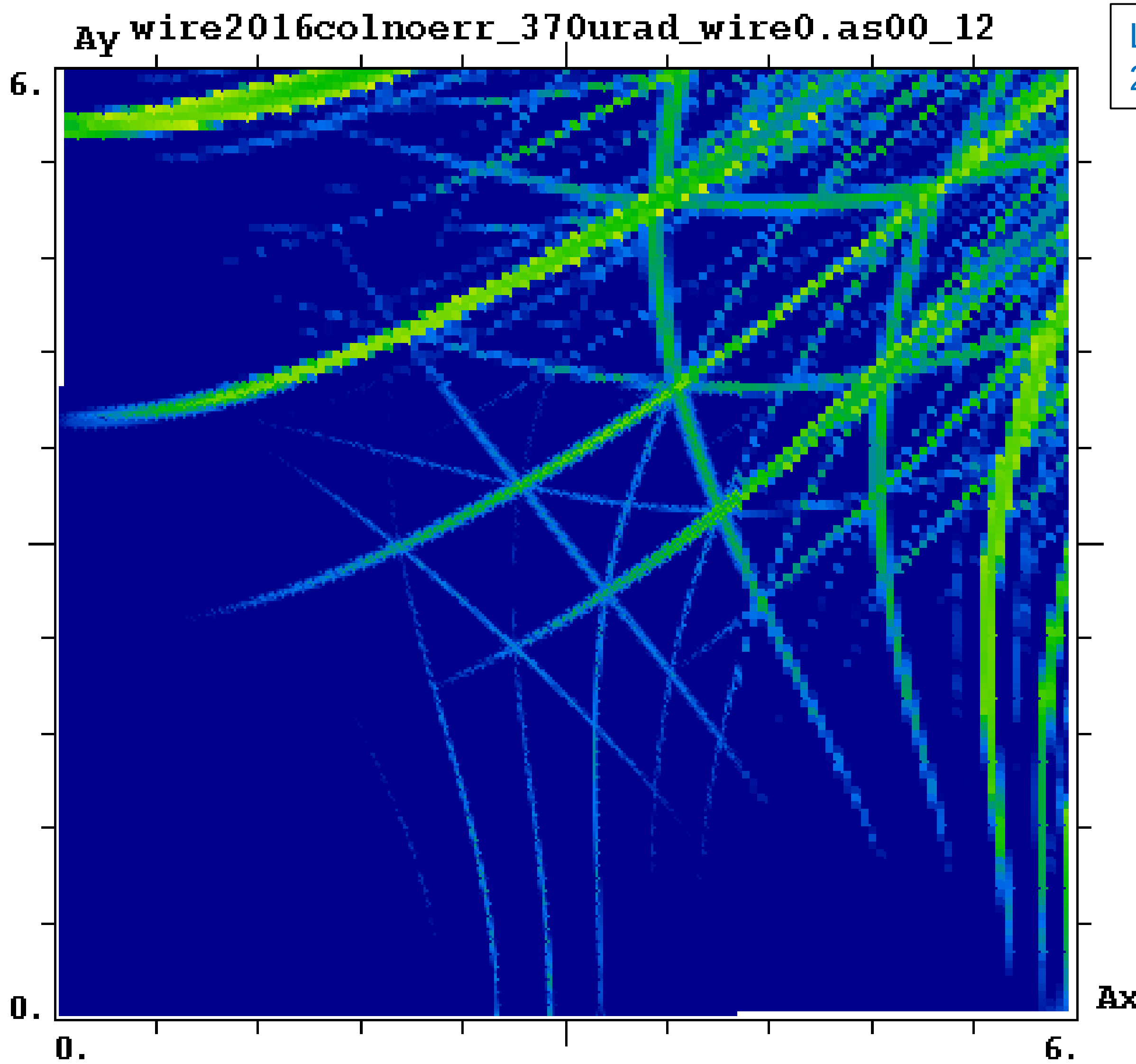
HiLumi HL-LHC PROJECT
LARP

Effect of Crossing Angle on Footprint



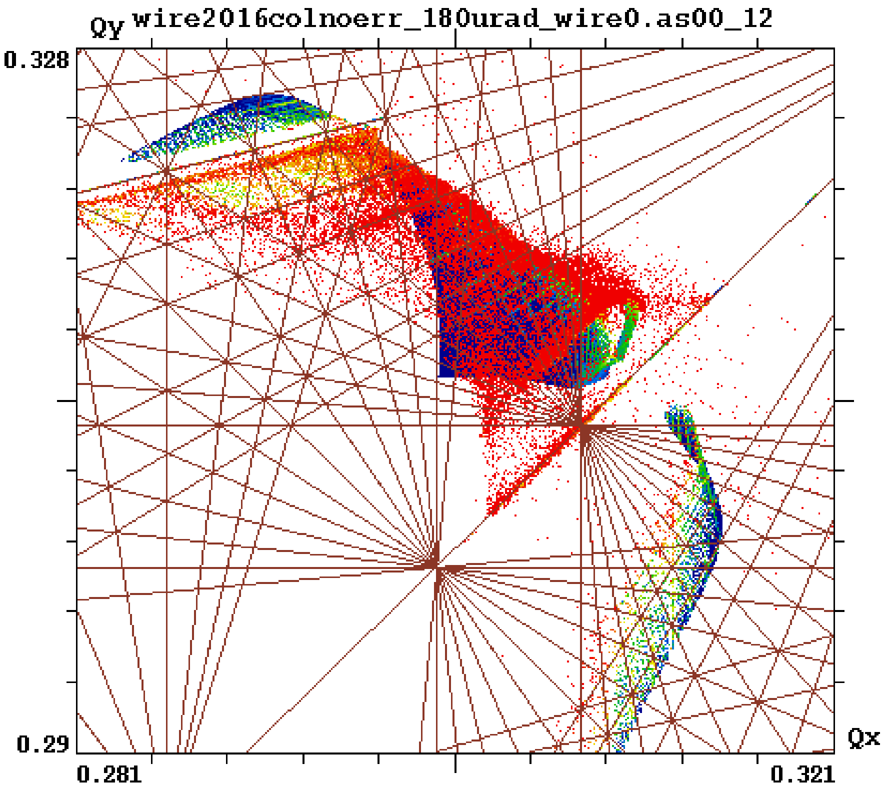
Lifetrac simulation
2016 optics

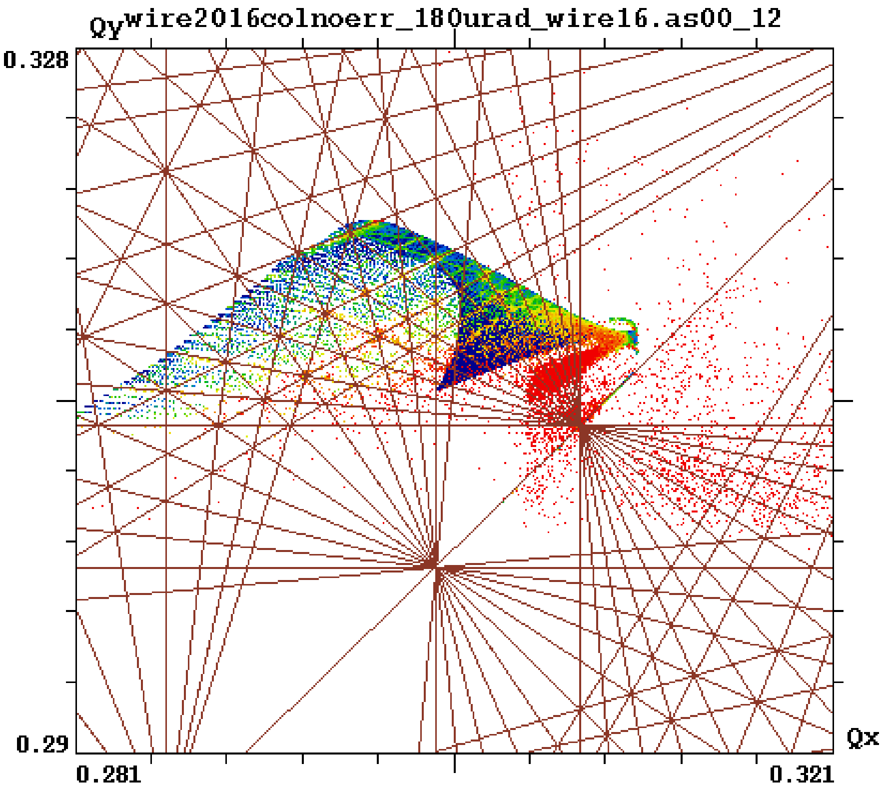
Effect of Crossing Angle on DA



Lifetrac simulation
2016 optics

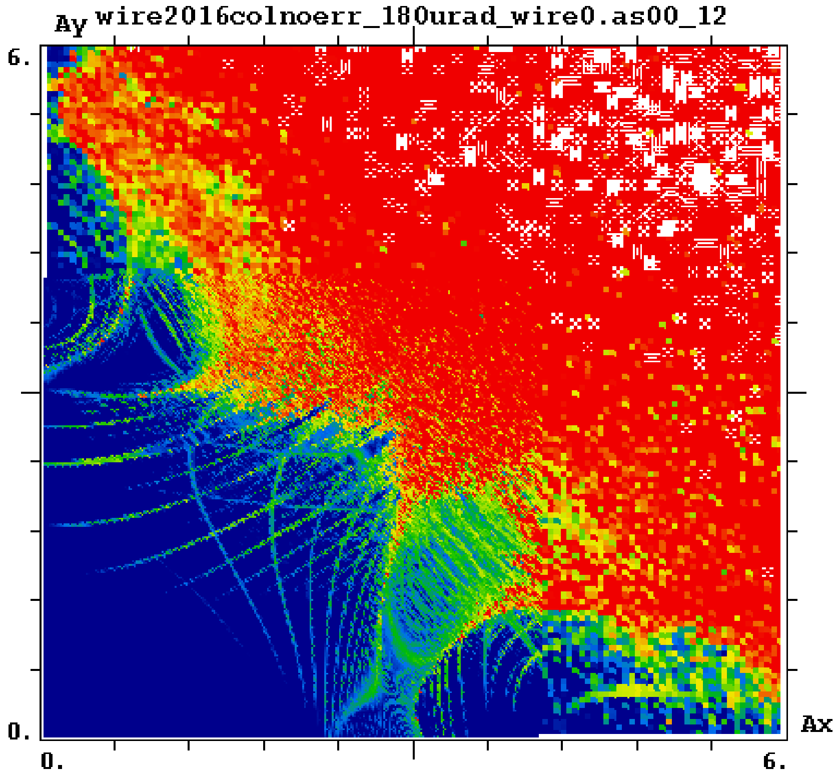
Impact of 2 IP5 Wires at 180 μrad

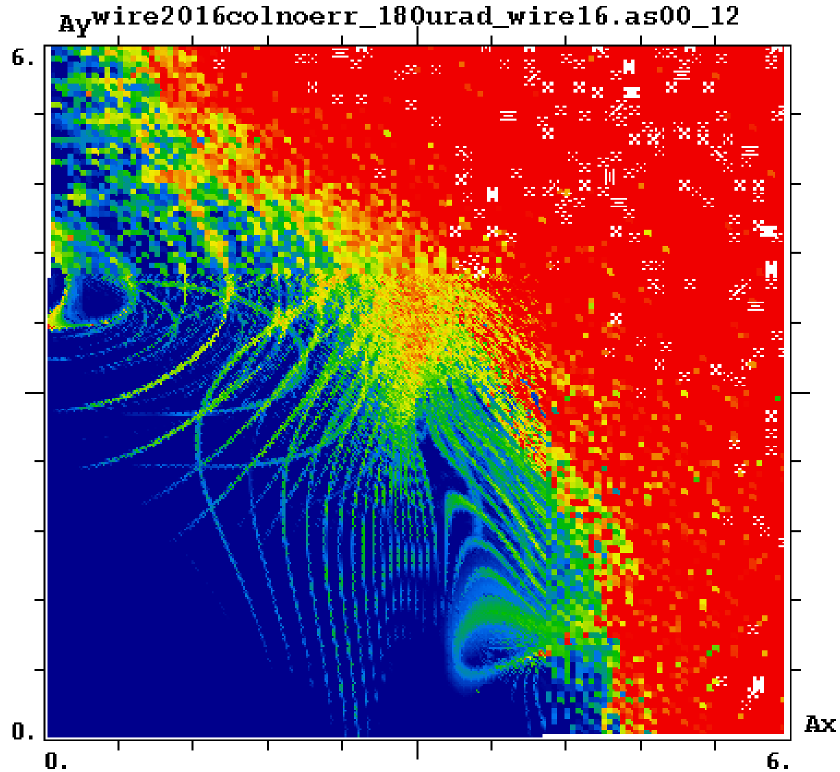




Lifetrac simulation
2016 optics, ε=2.5um

Impact of 2 IP5 Wires at 180 μrad





Lifetrac simulation
2016 optics, ε=2.5um