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Beam-beam weak-strong simulations for LHC and HL-LHC

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Introduction

- **Beam-beam effects** are responsible for the largest part of “losses” at LH<u>**C**</u>!
  - The BB potential quickly becomes **non-linear** as the amplitude of the particle is increased...
  - ... but we want to **stay** at collisions for as long as effectively possible. *Well... it is a collider!*

- **LHC** is a complex machine!
  - Non-linear magnet elements, fringe fields, two states of energy regime, etc

*Can my simulations drive the **machine performance** <u>during</u> its operation?*

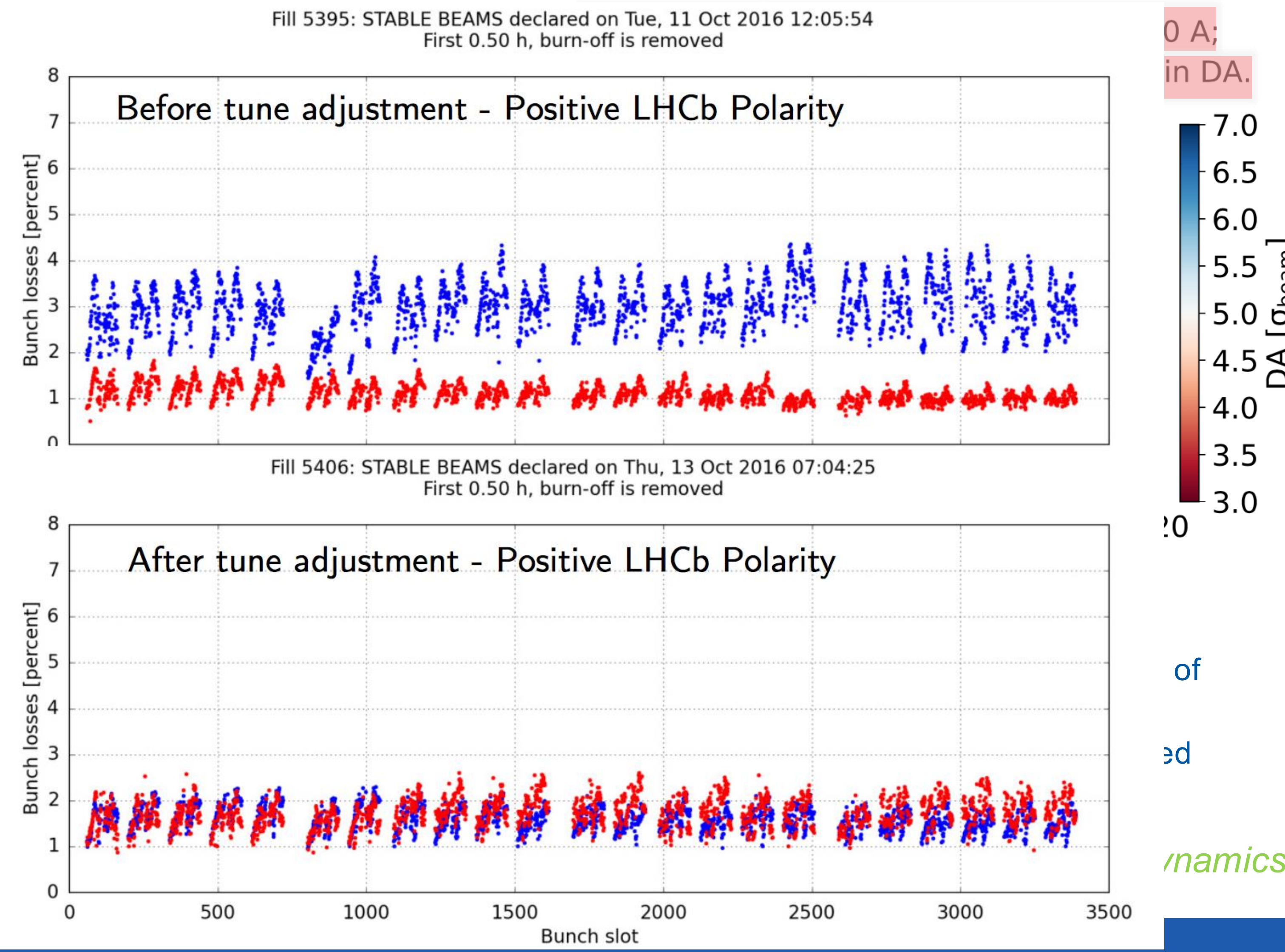
- **Dynamic Aperture within the Weak-Strong Approximation**:
  The strong beam generates the fields while the weak beam just probes them, without reciprocal perturbation
  ➔ computationally easier, while captures adequately all the necessary beam dynamics

Setting the Stage: DA Scans

Dynamic Aperture

- Choose the ma
- Specify the ava
- Choose two pa
  in terms of DA
- Fix the rest of
  for the scan;
- "Time evolution
  the "fixed" para
  emittance evol

0 A;
in DA.



- **DA multi-param**
  performance opt
  identifying and a
  - Operationa

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- The non-linear n
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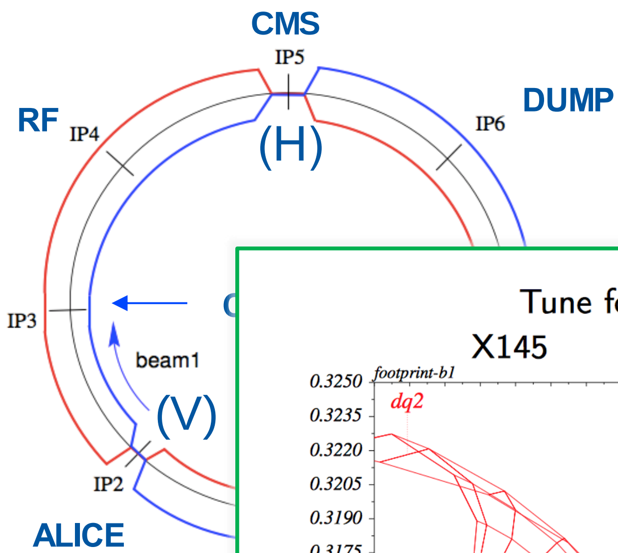
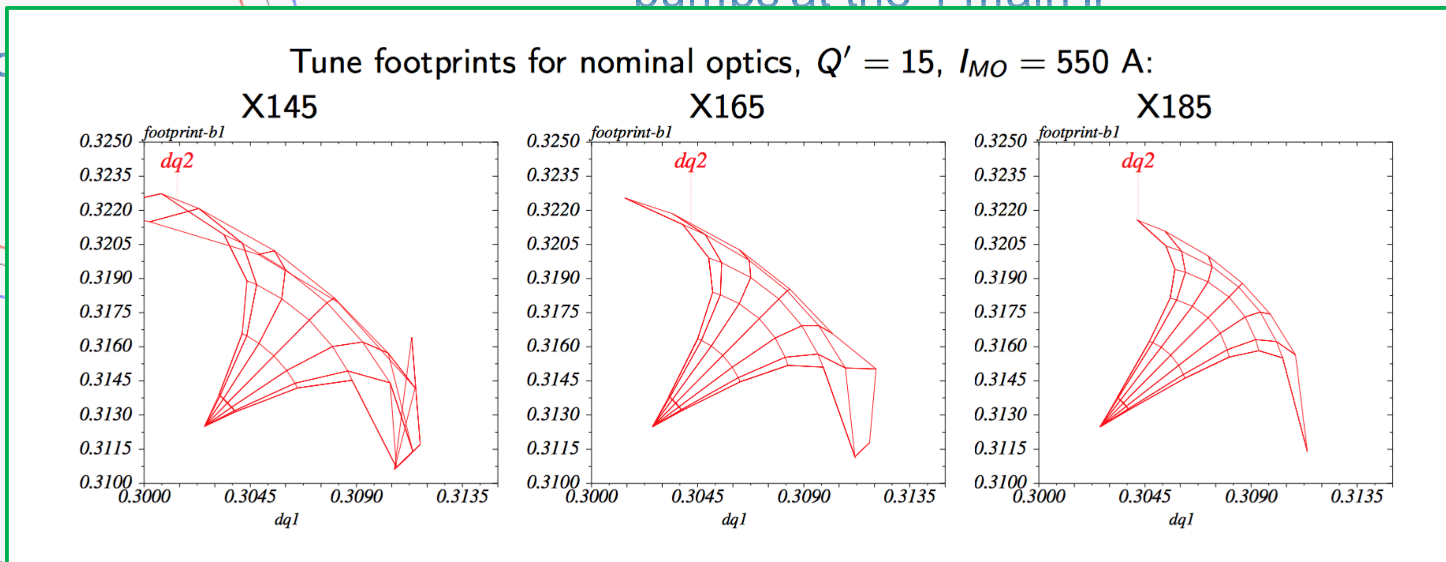
ynamics!

LHC Crossing Scheme



- Two counter rotating beams in two separate rings…
  - come into collision using separation bumps at the 4 main IP



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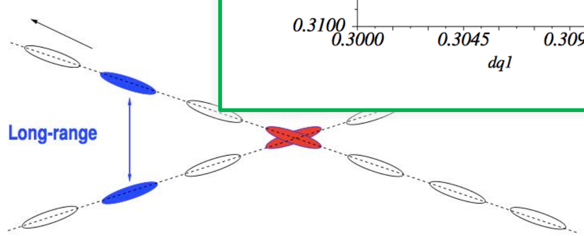
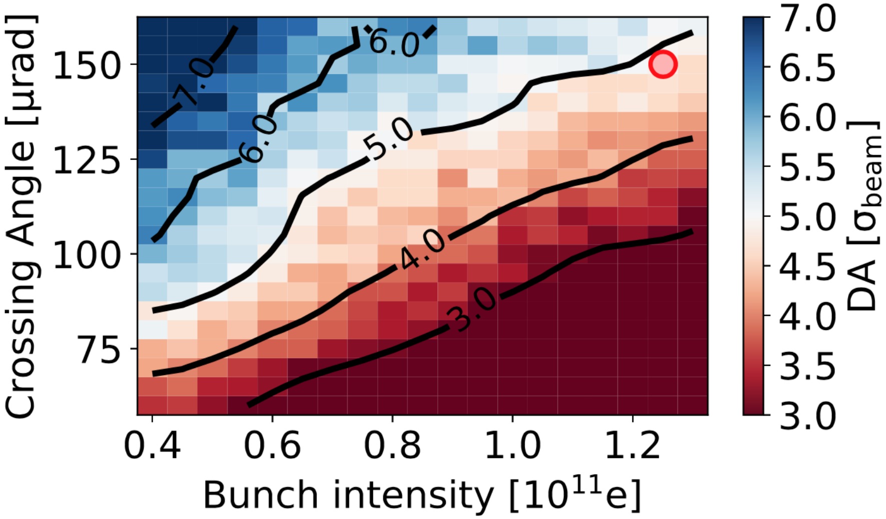


- Reduce β*
- Reduce φ

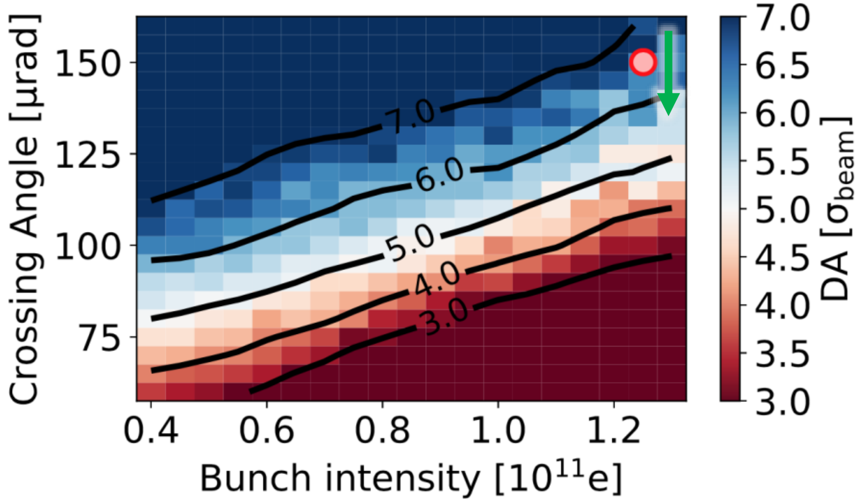
But can I? ➔ **Dynamic Aperture Simulations as Lifetime indicator**

Which crossing for my intensity?



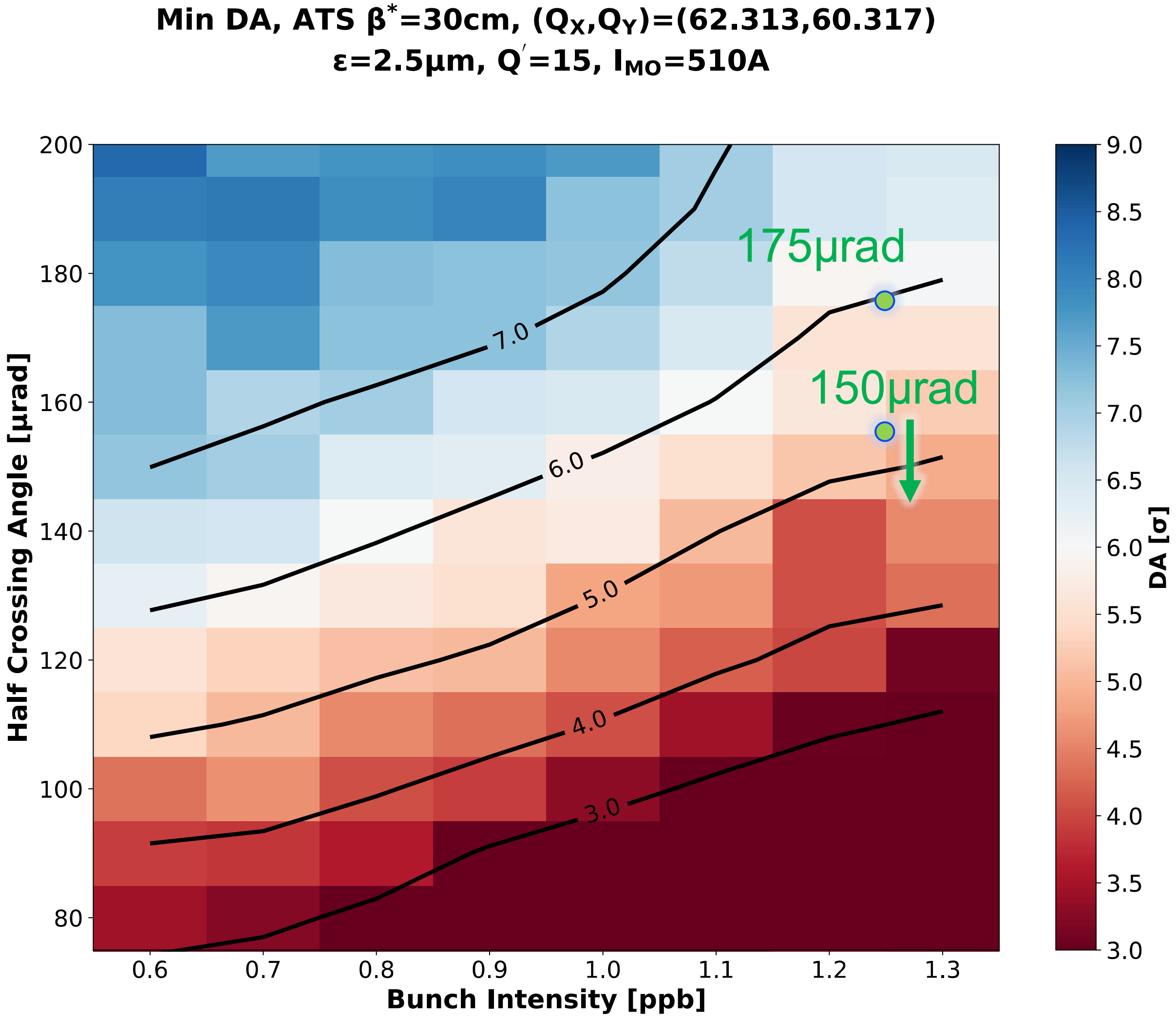
Nominal LHC parameters (2017):

- Init. Bunch Intensity = 1.25 10^{11} ppb
- Half-Crosing Angle = 150μrad
- β* (IP1/5) = 40cm
- Positive Landau Octupoles (500 A)
- Large Chromaticity (15)
- **(Qx, Qy) = (62.31, 60.32)**



- Optimized Tune LHC:
  - **(Qx, Qy) = (62.313, 60.317)**
  - ➔ Margin to push for performance

What about 30cm β*?



- At the nominal working point, 30cm β* was very tight
- **With the tune adjustment, 30cm totally feasible with 175μrad**
- **150μrad** are within reach (no change)
- Based on **operational experience** could even push for **140μrad** at start of the fill!
  - ➔ tested during operation

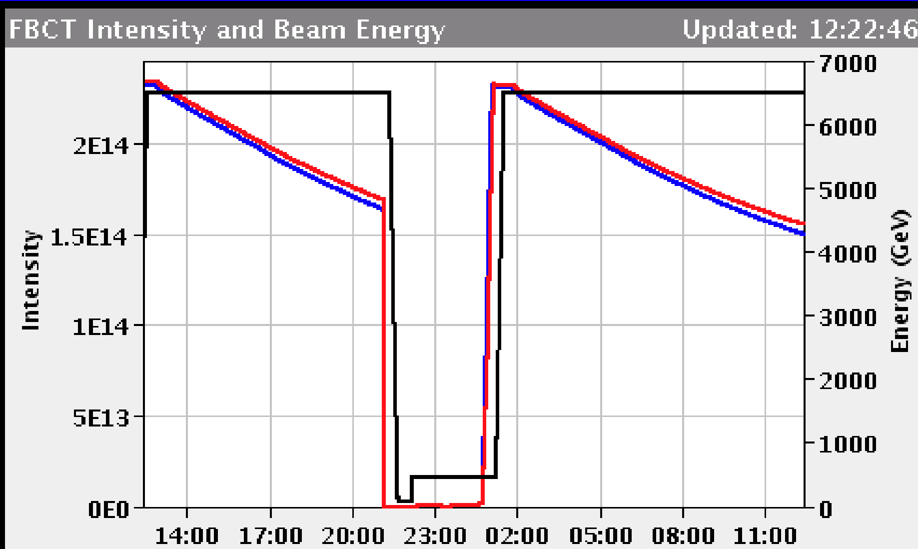
How can I push more?

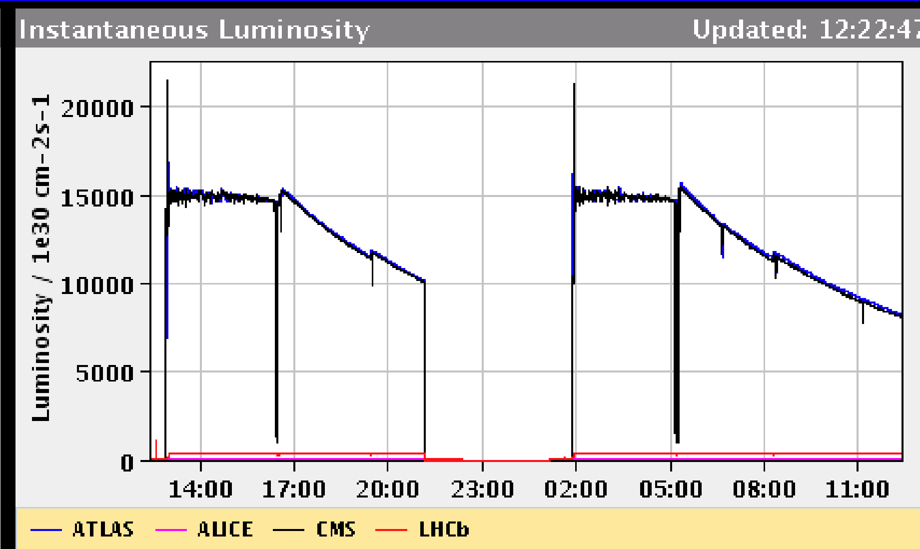
LHC Page1 Fill: 6308 E: 6499 GeV t(SB): 10:25:07 19-10-17 12:22:46

PROTON PHYSICS: STABLE BEAMS

Energy:	6499 GeV	I(B1):	1.51e+14	I(B2):	1.55e+14

Inst. Lumi [(ub.s)^-1]	IP1: 8249.90	IP2: 2.54	IP5: 8121.98	IP8: 332.18





Comments (19-Oct-2017 08:20:34)

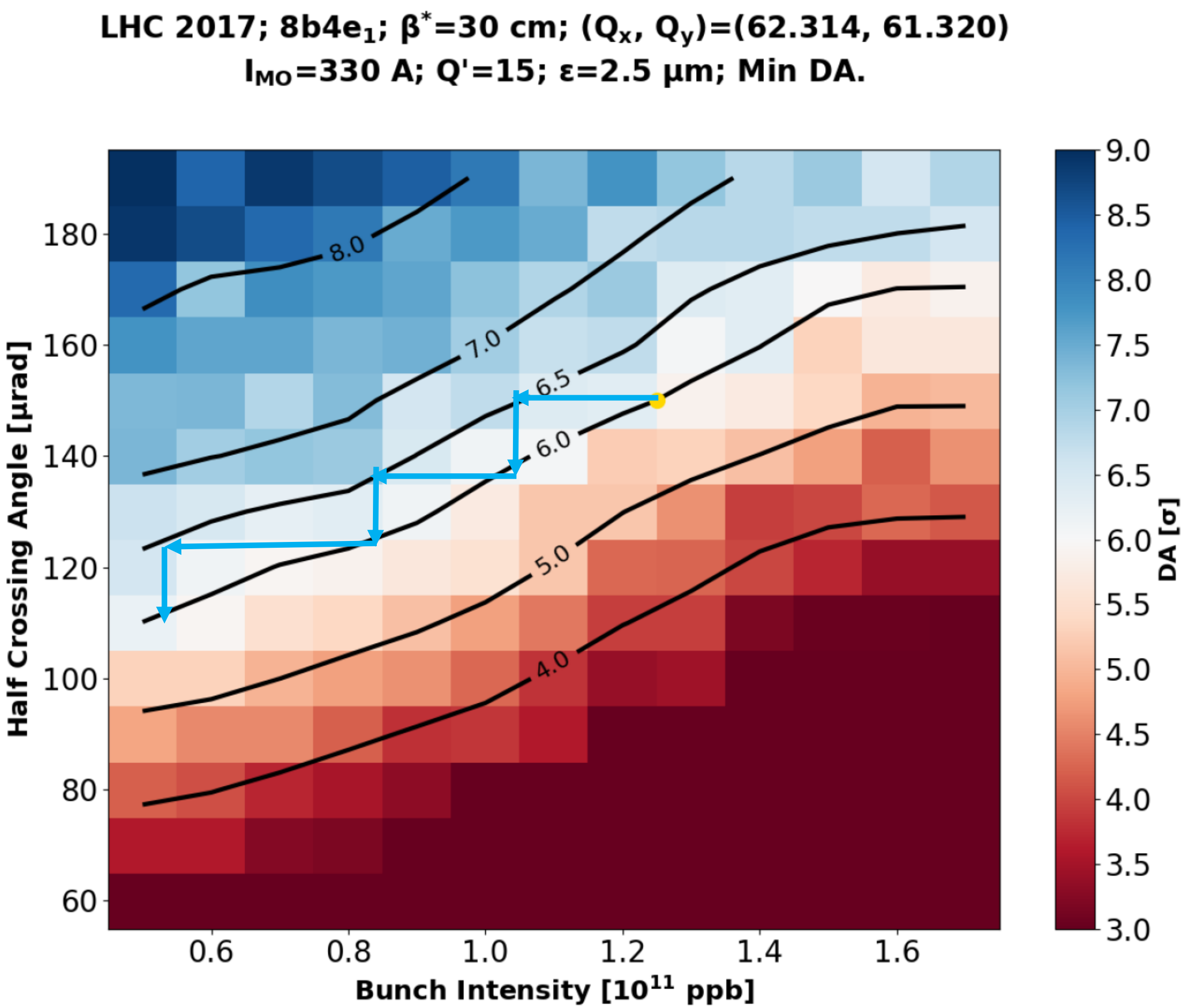
Crossing angle @120urad

Roman pots in

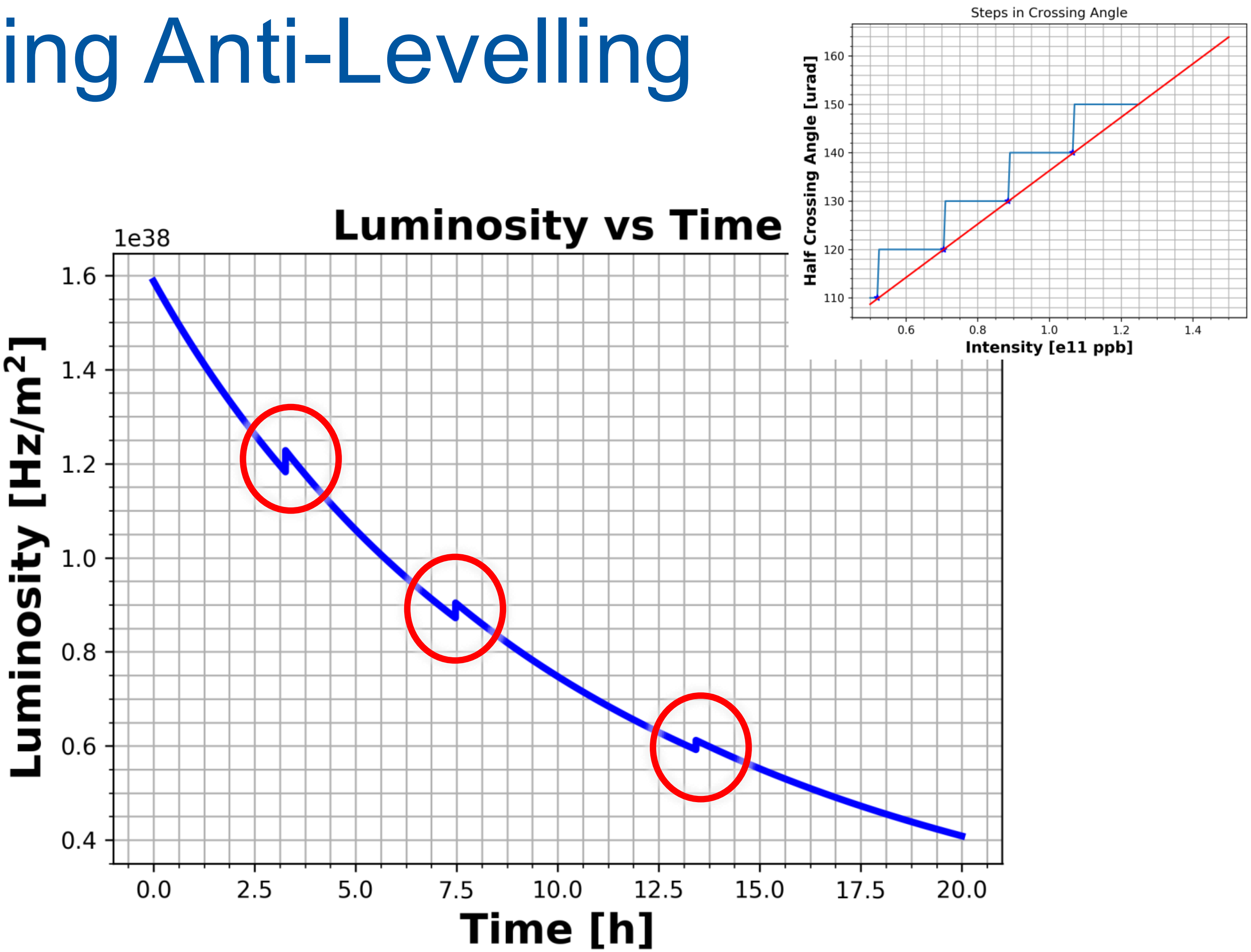
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 25ns_1868b_1866_1089_1749_128bpi_17i8b4e PM Status B1 ENABLED PM Status B2 ENABLED

Crossing Anti-Levelling

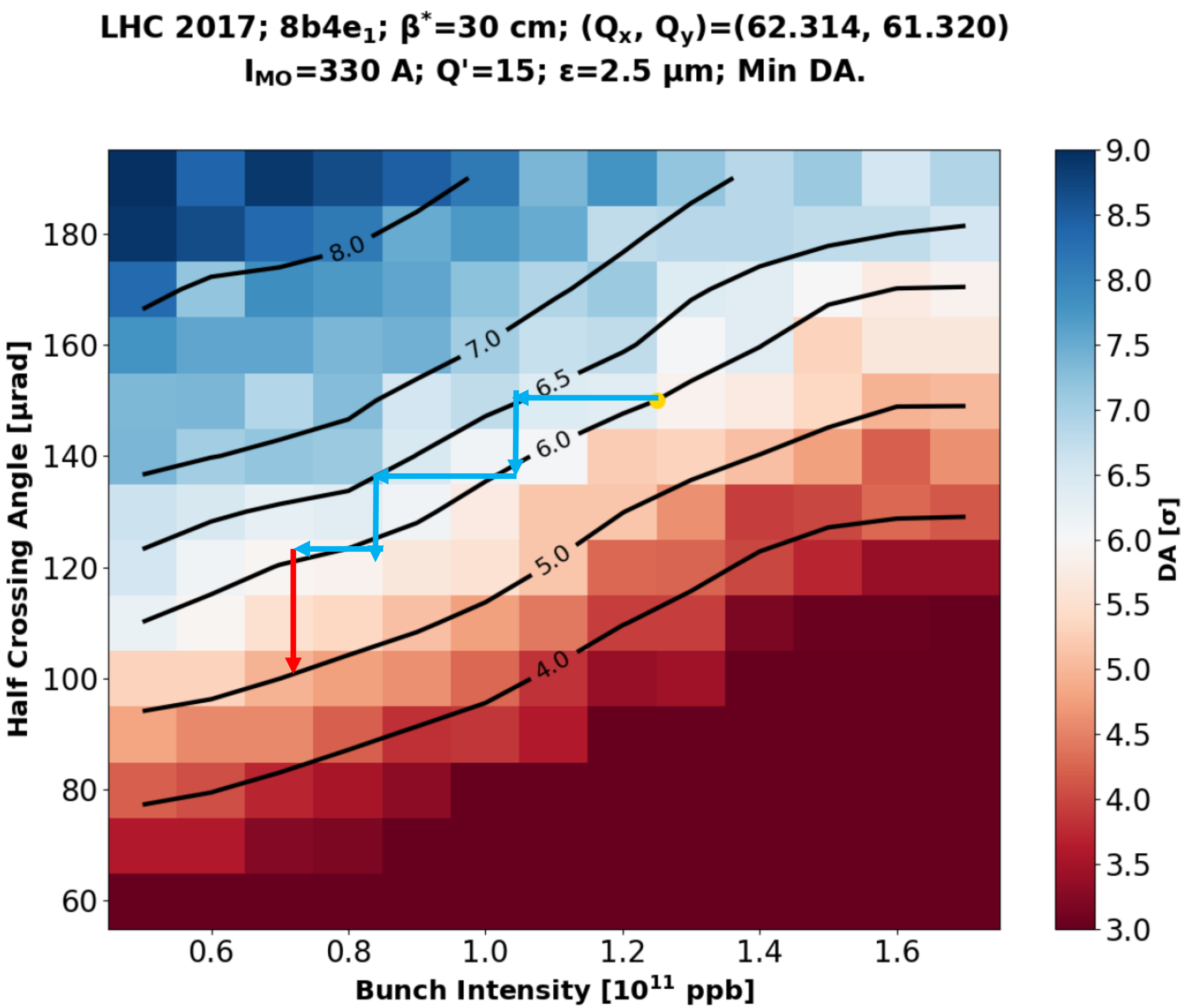


Crossing Anti-Levelling

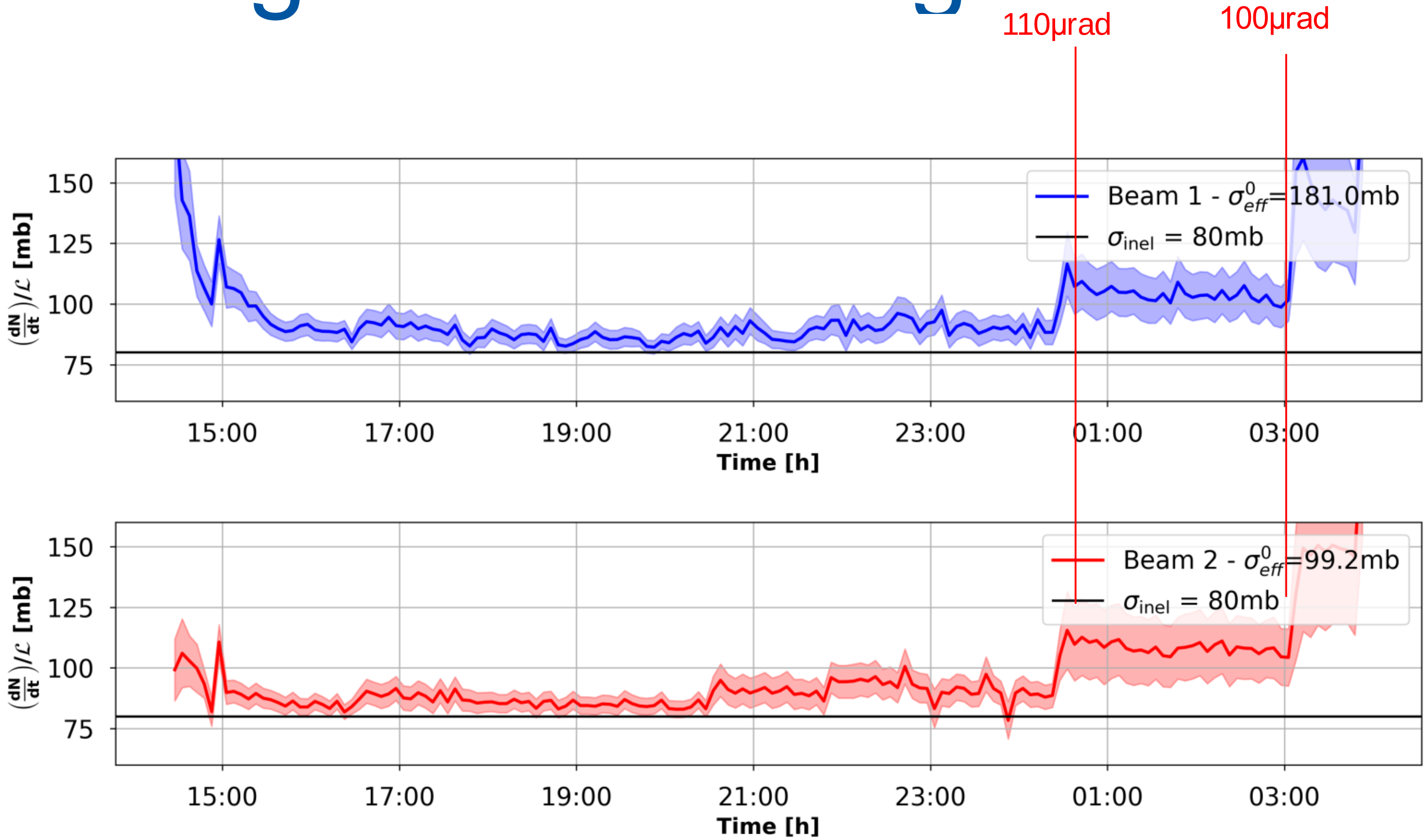


With **careful** steps, gain in integrated luminosity of ~3-5% for 10h in Stable Beams

Crossing Anti-Levelling



Crossing Anti-Levelling



When you are in a regime with reduced DA beam lifetime suffers and losses appear!

Careful handling is required, but experience on changing the crossing angle in operation is very valuable for the future...

HiLumi
LARGE HADRON COLLIDER

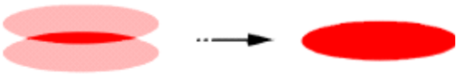
HL-LHC Era: Adaptive Levelling

HL-LHC TDR:

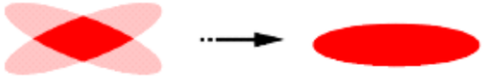
*"Both the consideration of **energy deposition** by collision debris in the interaction region magnets, and the necessity to **limit the peak pile-up** in the experimental detector, impose an a priori **limitation upon peak luminosity**. The consequence is that HL-LHC operation will have to rely on **luminosity levelling**."*

Levelling Scenarios:

- ✓ So far LHC has successfully operated **levelling by separation**.



- ✓ HL-LHC design includes the installation of **crab cavities** around the IR1/IR5.



- ✓ The size of the luminous region can be modified by changing the **β*** at the IP.

Levelling Proposal:

- "Adaptive Levelling Scenario"
  - Depending on the time within the fill (during levelling, i.e. bunch intensity) and driven by the available DA, adapt the **crossing angle** and **β*** at the interaction points to keep the target 5 Hz/cm/cm.

Adaptive Levelling

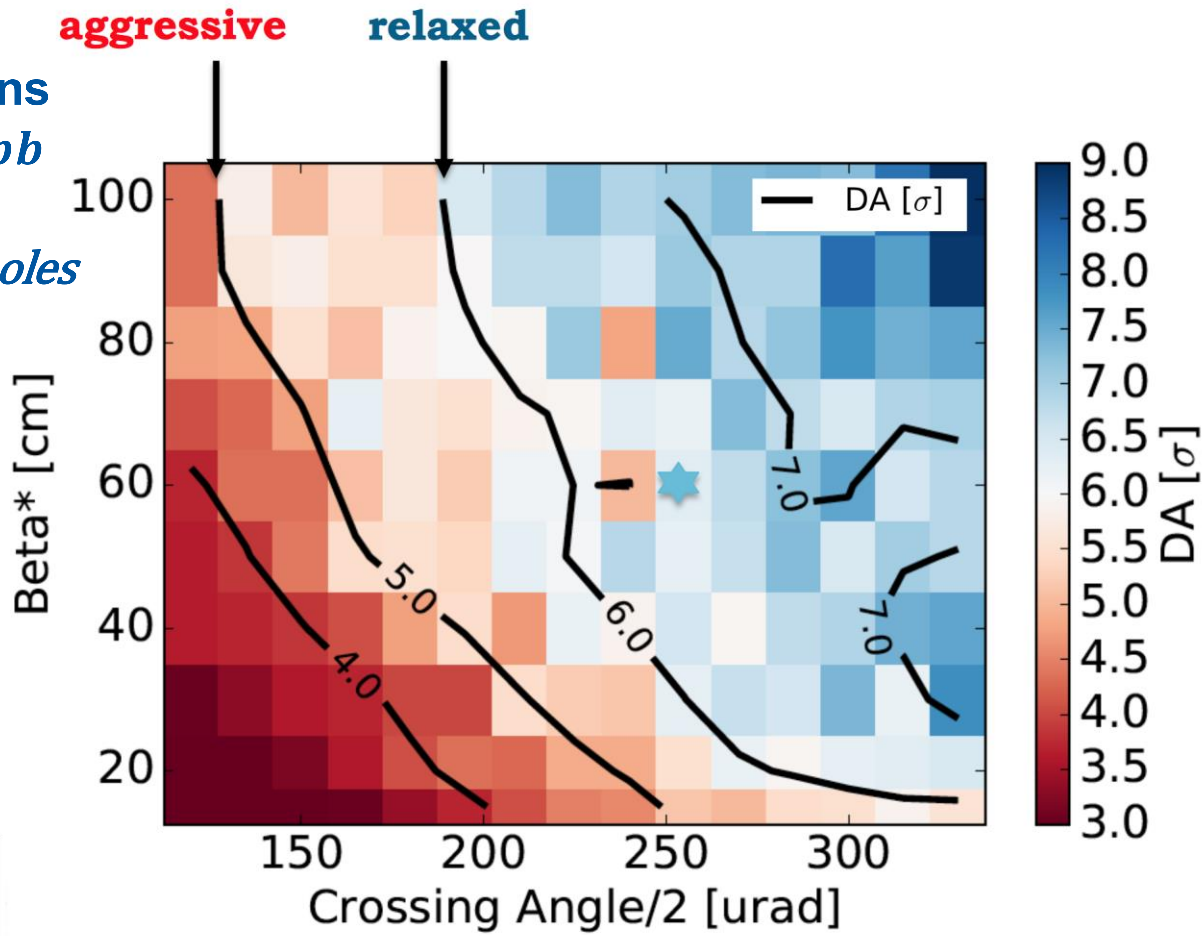
Min DA Scan for Half Crossing Angle and β* at the start of the collisions.

Start of Collisions

$I_b = 2.2\ 10^{11} ppb$

$Q' = 3$

No Landau Octupoles



Adaptive Levelling

Overlay iso-luminosity lines.

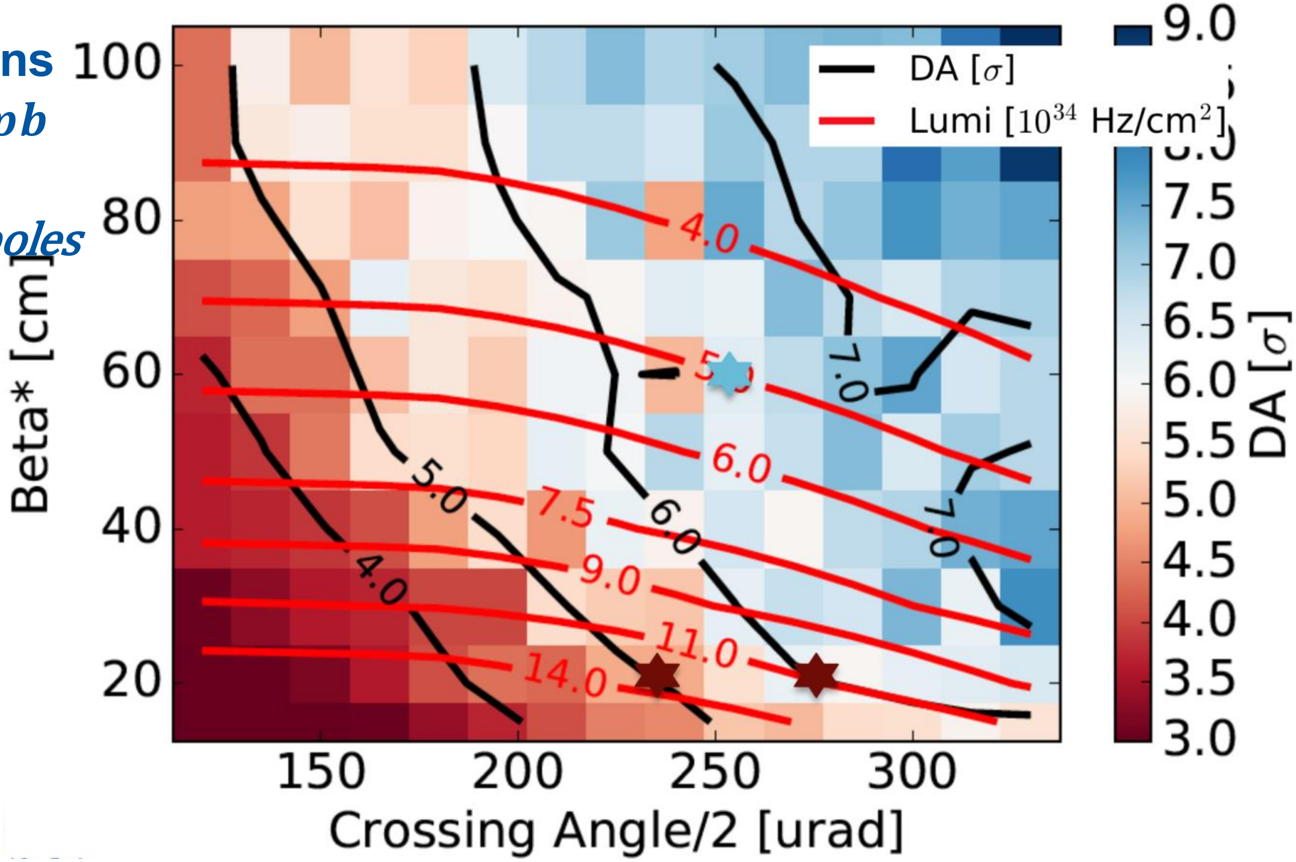
Peak luminosity $\mathbf{1.1\ -1.4\ 10^{35}}\boldsymbol{Hz/cm^2}$ can be achieved with 20cm β* ... but with **PU>300 events.**

Start of Collisions

$\boldsymbol{I_b = 2.2\ 10^{11} ppb}$

$\boldsymbol{Q' = 3}$

No Landau Octupoles



Adaptive Levelling

Overlay iso-length of luminous region lines.

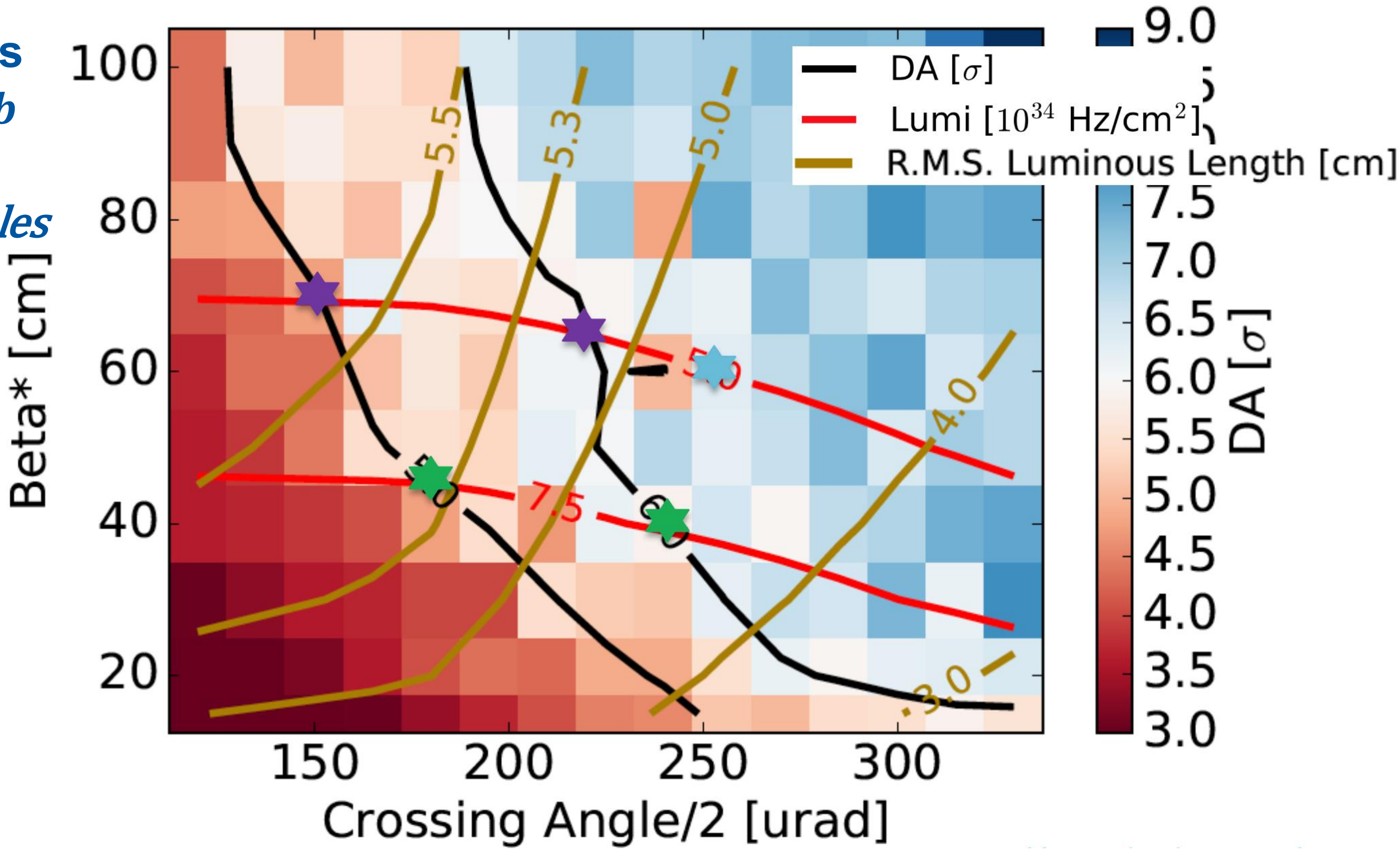
Reduction of **crossing angle** at **constant luminosity** enables the reduction of **PU density** (increase of luminous region) and triplet irradiation.

Start of Collisions

$I_b = 2.2\ 10^{11} ppb$

$Q' = 3$

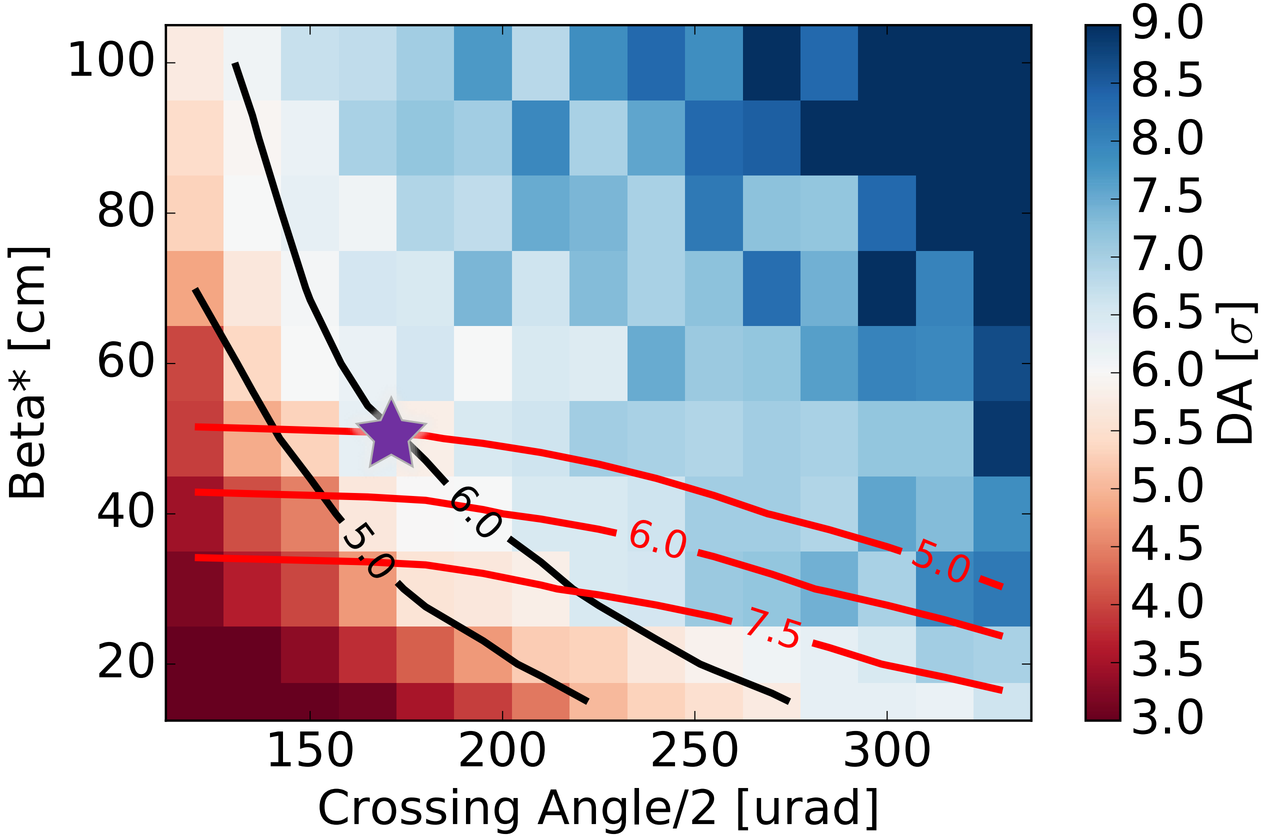
No Landau Octupoles



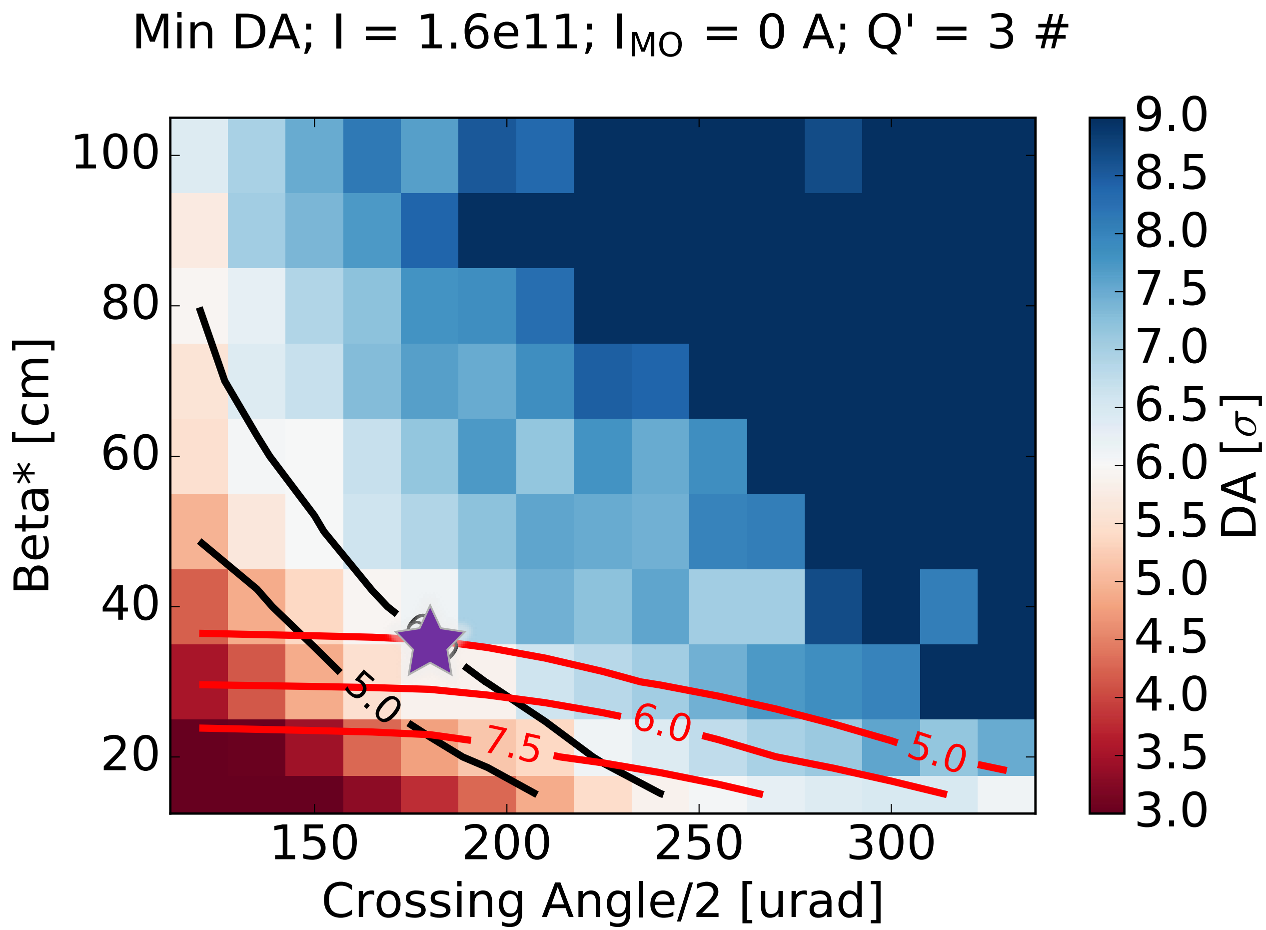
Adaptive Levelling

Time evolution can be folded in in terms of bunch intensity.

Min DA; I = 1.9e11; I_{MO} = 0 A; Q' = 3 #

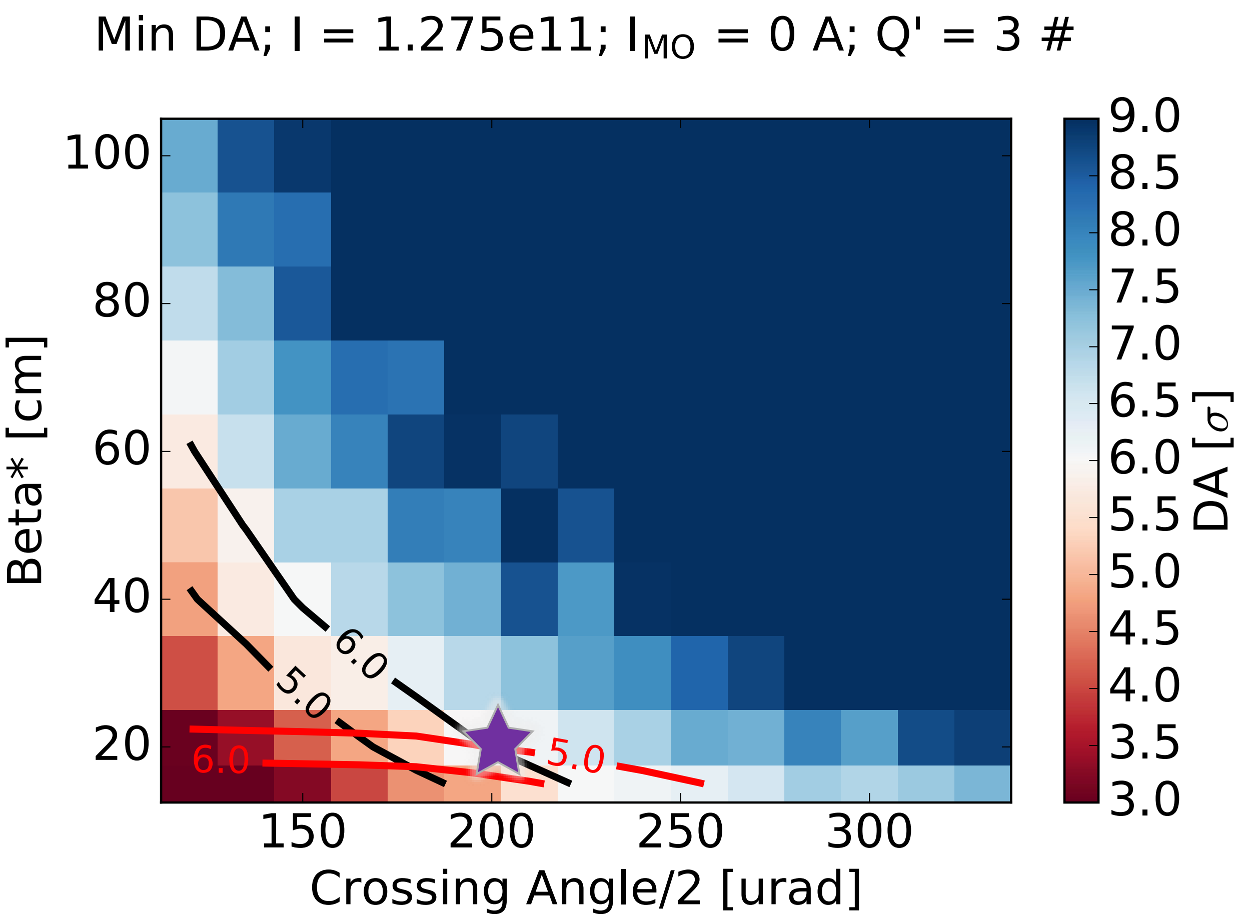


Adaptive Levelling

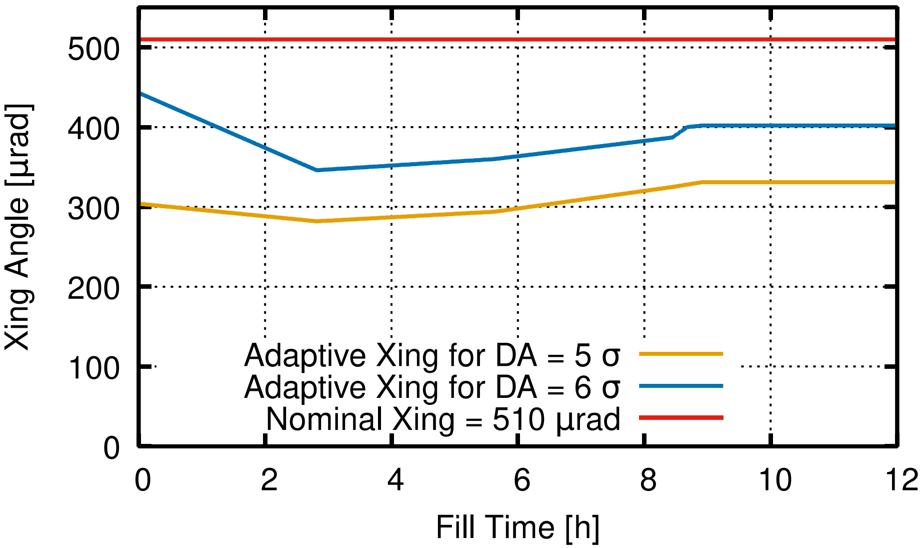


Adaptive Levelling

Following the intersection of the **iso-luminosity** and **iso-DA** lines one can define a levelling path



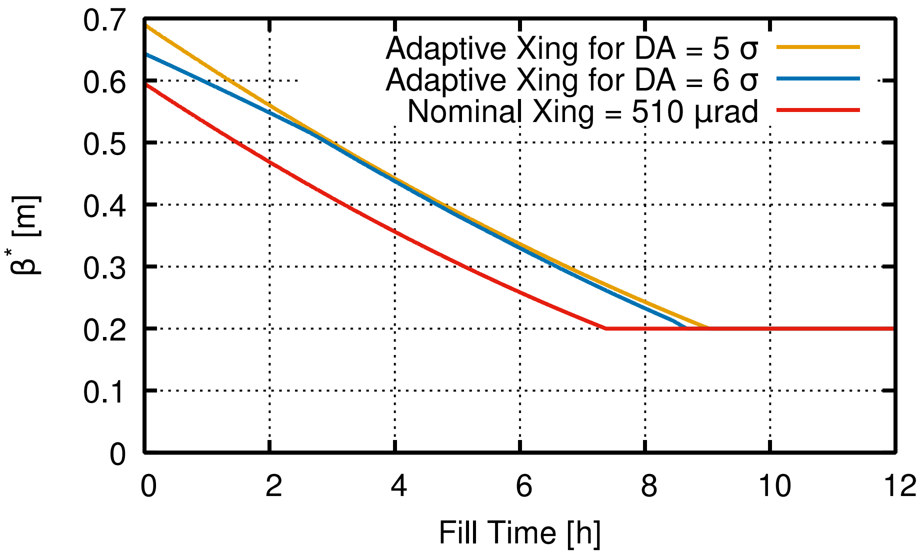
Adaptive Levelling – What do I gain?



Comparing:

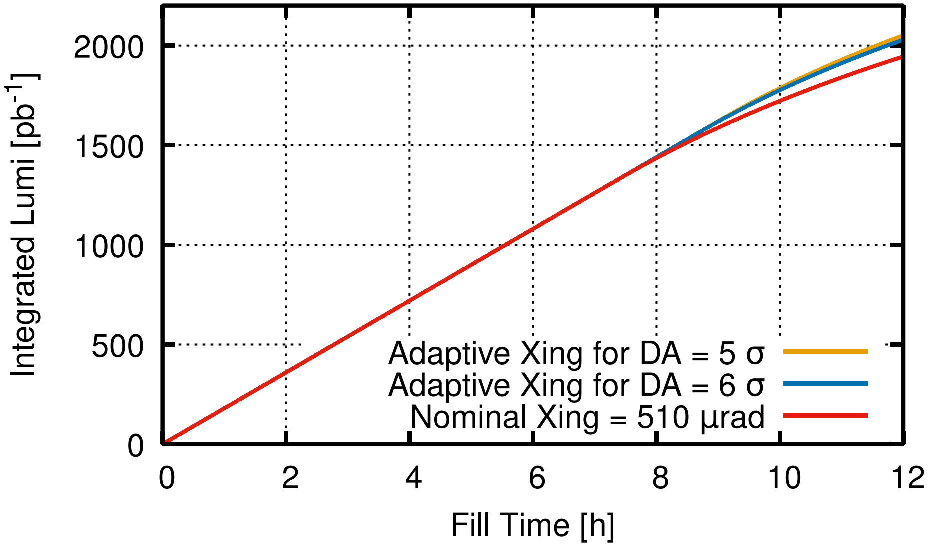
- Constant crossing at 510μrad
- Adaptive scenario of 6σ DA
- Adaptive scenario of 5σ DA

Assuming a cross-section of 80mb



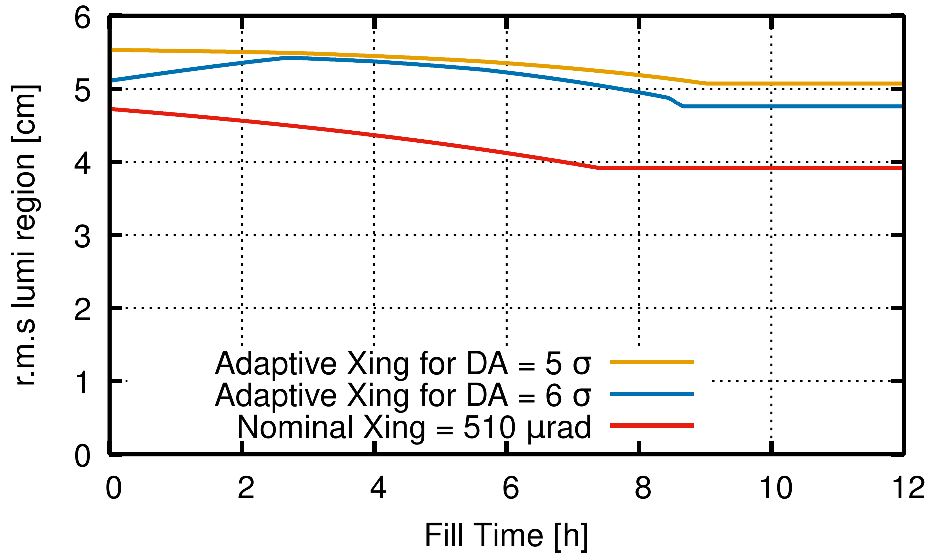
- In terms of **crossing angle**, I can operate with **less voltage** in the crab cavities (max crabbing 380μrad).
- In terms of **β* delayed** exit from the levelling (here: 20cm target, design: 15cm).

Adaptive Levelling – What do I gain?



- This provides me with a bit of gain in terms of **integrated luminosity**.
  - Bit more if I continue with “anti-levelling” after the levelling is finished.

- ... while the experiments are recording data comfortably at a reduced **pileup density**.



Overview

- **Weak-strong** simulations are heavily used to estimate the **long term conditions** in the presence of **beam-beam** for a given configurations;
  - *Fast, reliable, accurate* thanks to the continuous development & extension of computational frameworks & infrastructure
  - Identify margins ➔ construct operational scenarios

- The **excellent** LHC performance and the **operational experience** allows to push the beam and machine parameters to extract more **luminosity**, eg:
  - 2017: ATS & reducing β^* ➔ increased performance
  - 2017: crossing angle anti-levelling ➔ increased performance

- The knowledge and experience gained are propagated in the **HiLumi LHC** era, e.g:
  - Adaptive levelling scenario ➔ increased performance

Thank you for your attention!

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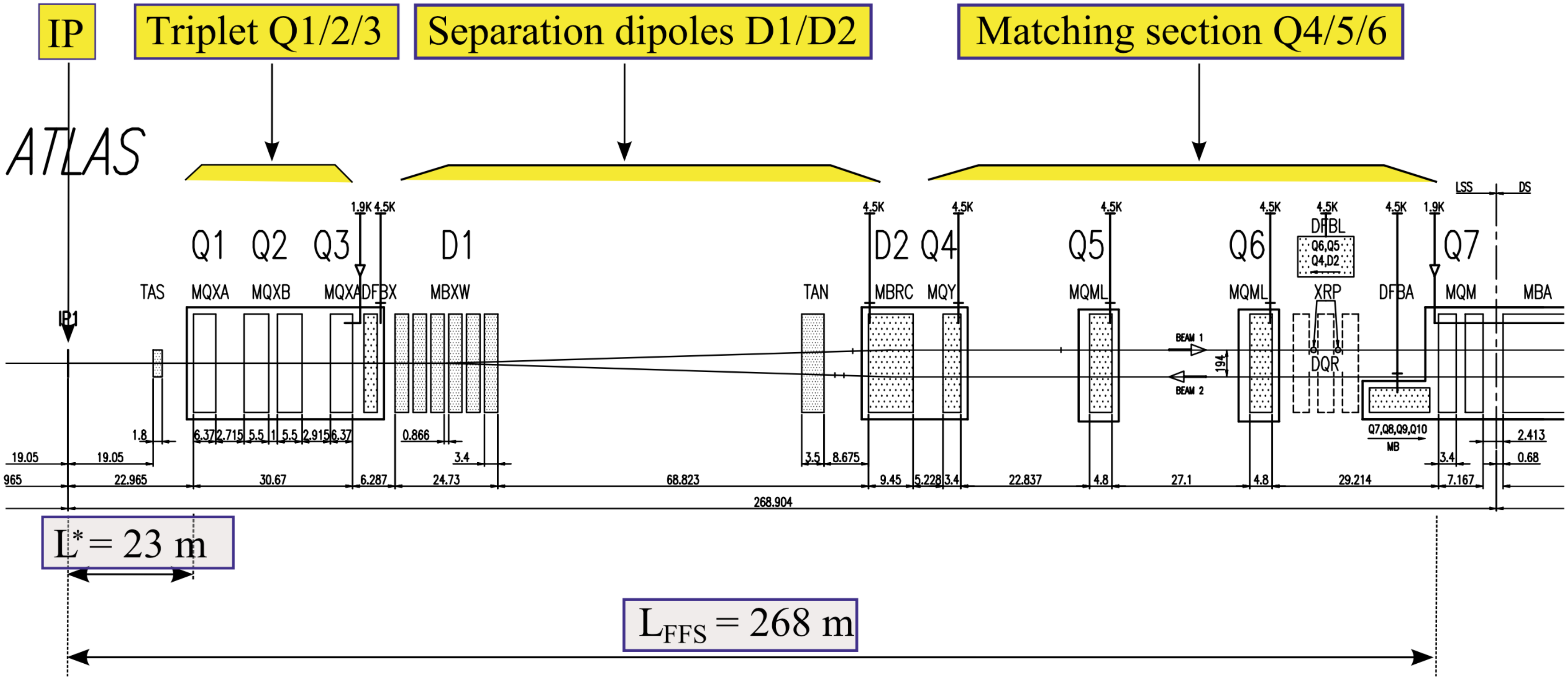
SPARE SLIDES

IR1


IP
Triplet Q1/2/3
Separation dipoles D1/D2
Matching section Q4/5/6
ATLAS
Q1 Q2 Q3 D1 D2 Q4 Q5 Q6 Q7
TAS MQXA MQXB MQXA DFBX MBXW TAN MBRC MQY MQML MQML XRP DFBA MQM MBA
DFBL
DQR
BEAM 1
BEAM 2
LSS DS
268.904
$L^* = 23$ m
$L_{FFS} = 268$ m

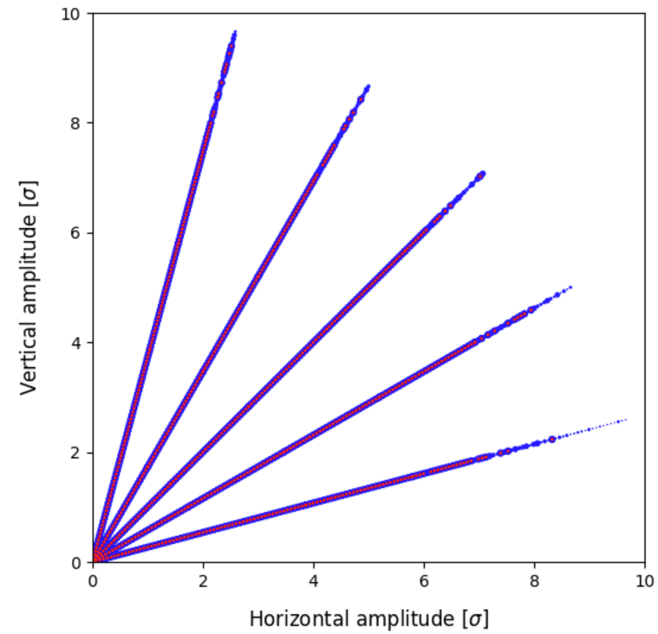
2017 Settings

Parameter	BCMS 144b 40 cm 300 urad	BCMS 144b 31 cm 340 urad	BCMS 288b 31 cm 340 urad	BCMS 144b 31 cm 310 urad	BCMS 288b 31 cm 310 urad	Standard 288b 31 cm 340 urad
Beam energy in collision [TeV]	6.5	6.5	6.5	6.5	6.5	6.5
Particles per bunch, N [10^{11}]	1.25	1.25	1.25	1.25	1.25	1.25
Number of bunches per beam	2556	2556	2748	2556	2748	2760
Number of collisions in IP1 and IP5*	2544	2544	2736	2544	2736	2748
Number of collisions in IP2/IP8	2205/2308	2205/2308	2258/2378	2205/2308	2258/2378	2494/2572
Maximum number of bunches per injection	144	144	288	144	288	288
Crossing angle in IP1 and IP5 [μrad]	300	340	340	310	310	340
Minimum normalized LRBB separation [σ]	10	10	10	9	9	8.4
Minimum β^* [m]	0.40	0.31	0.31	0.31	0.31	0.31
e_n [μm]	2.5	2.5	2.5	2.5	2.5	3.5
ε_L [eVs]	2.2	2.2	2.2	2.2	2.2	2.2
R.M.S. bunch length [cm]	8.3	8.3	8.3	8.3	8.3	8.3
Peak luminosity L_{peak} [10^{34} cm^{-2} s^{-1}]	1.7	1.9	2.1	2.0	2.2	1.63
Max pile-up	48	54	54	57	57	42
Levelling time [h] for levelling at $1.7x10^{34}$ $cm^{-2}s^{-1}$	0.	2.5	4.25	3.5	5.25	0.
L_{int} with levelling ($1.7x10^{34}$) [fb^{-1}/day] – no heat load lim.	0.79	0.85	0.91	0.88	0.93	0.82
L_{int} without levelling [fb^{-1}/day] – no heat load lim.	0.79	0.86	0.92	0.89	0.95	0.82
L_{int} with levelling ($1.7x10^{34}$) [fb^{-1}/day]–heat load lim. (160 W)	0.74	0.80	0.78	0.83	0.81	0.64
L_{int} without levelling [fb^{-1}/day] – heat load limited (160 W)	0.74	0.80	0.78	0.83	0.81	0.64

Setting the Stage: DA Scans

Which Tools & How?

- The geometry and basic optics are generated using MADX;
- The tracking is done in SixTrack
  - Particles (weak beam) are tracked through the lattice under the impact of the external fields;
  - The particles are uniformly distributed in terms of amplitude... (here: 2σ-10σ);
  - ... and laying on a number of angles (here: 5 angles);
  - … the longitudinal initial conditions of the weak beam are fixed;
  - The particles are tracked for a number of turns (here: 1M), with the view to find the survival at 1M turns ➔ DA;
  - The final result is quoted in terms of rms transverse beam size units (LHC: protons ~ round beams).



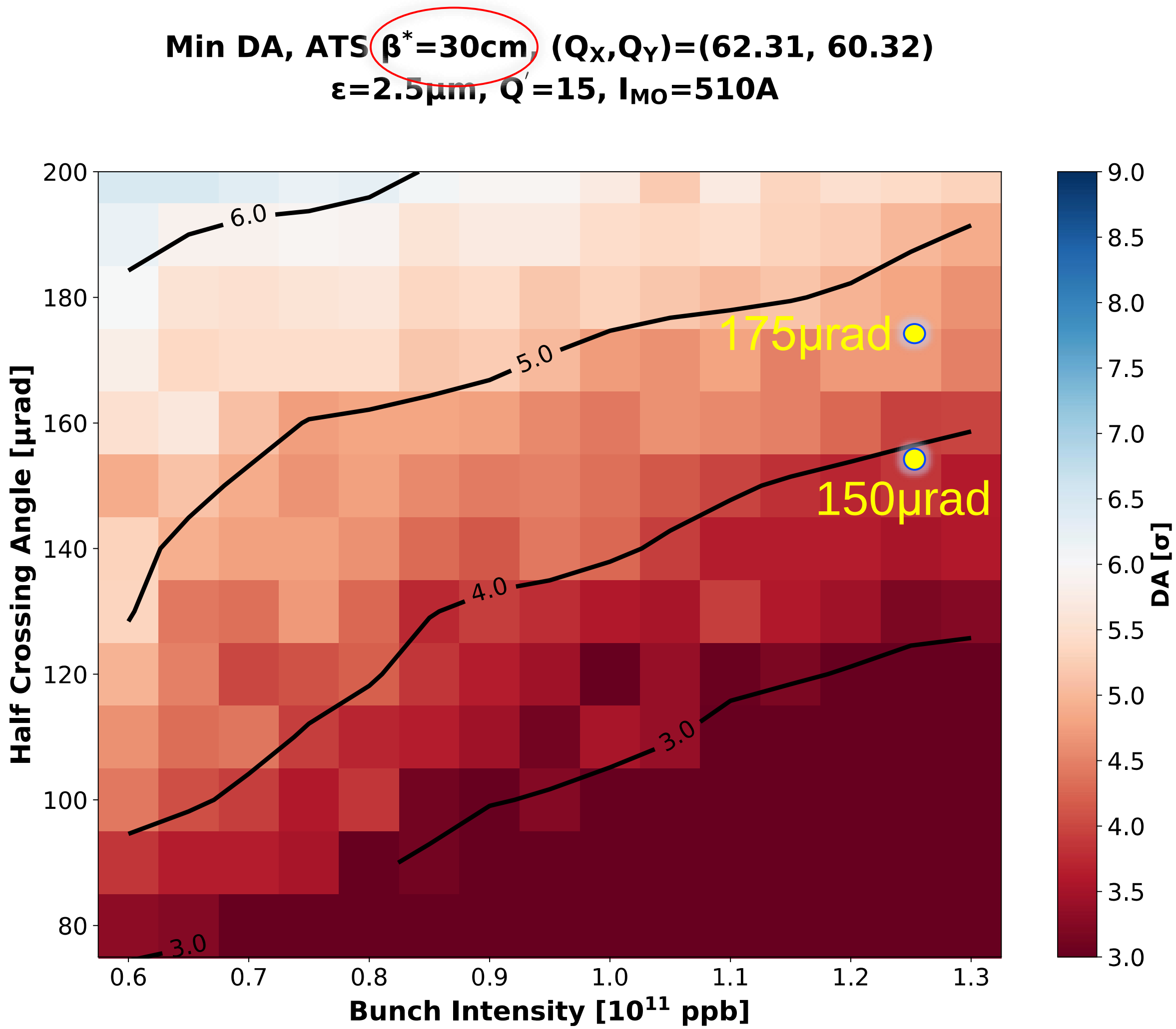
Is this perfect?

- Tracking for 1M turns is only ~90s of machine time
- The initial longitudinal action is fixed
- Beam phase space distribution is not taken into account, no diffusion information

No.

... but it captures all the relevant aspects of beam dynamics

Which crossing for my intensity?



I would need **175μrad** to have the same normalized separation at the start of the fill

For **β*=30cm** and nominal tune gives me **DA < 5σ**

Continuous crossing