Fast Failures in the High Luminosity LHC

Björn Lindström

CERN and Uppsala University

With input from:

L. Bortot, M. Valette, C. Wiesner, R. Schmidt, A. Verweij,

E. Ravaioli, M. Mentink, P. Bélanger, M. Väänänen

4th April 2019

Outline

Project definition and motivation

Failures

CLIQ

Beam Beam Kick

Triplet Quench

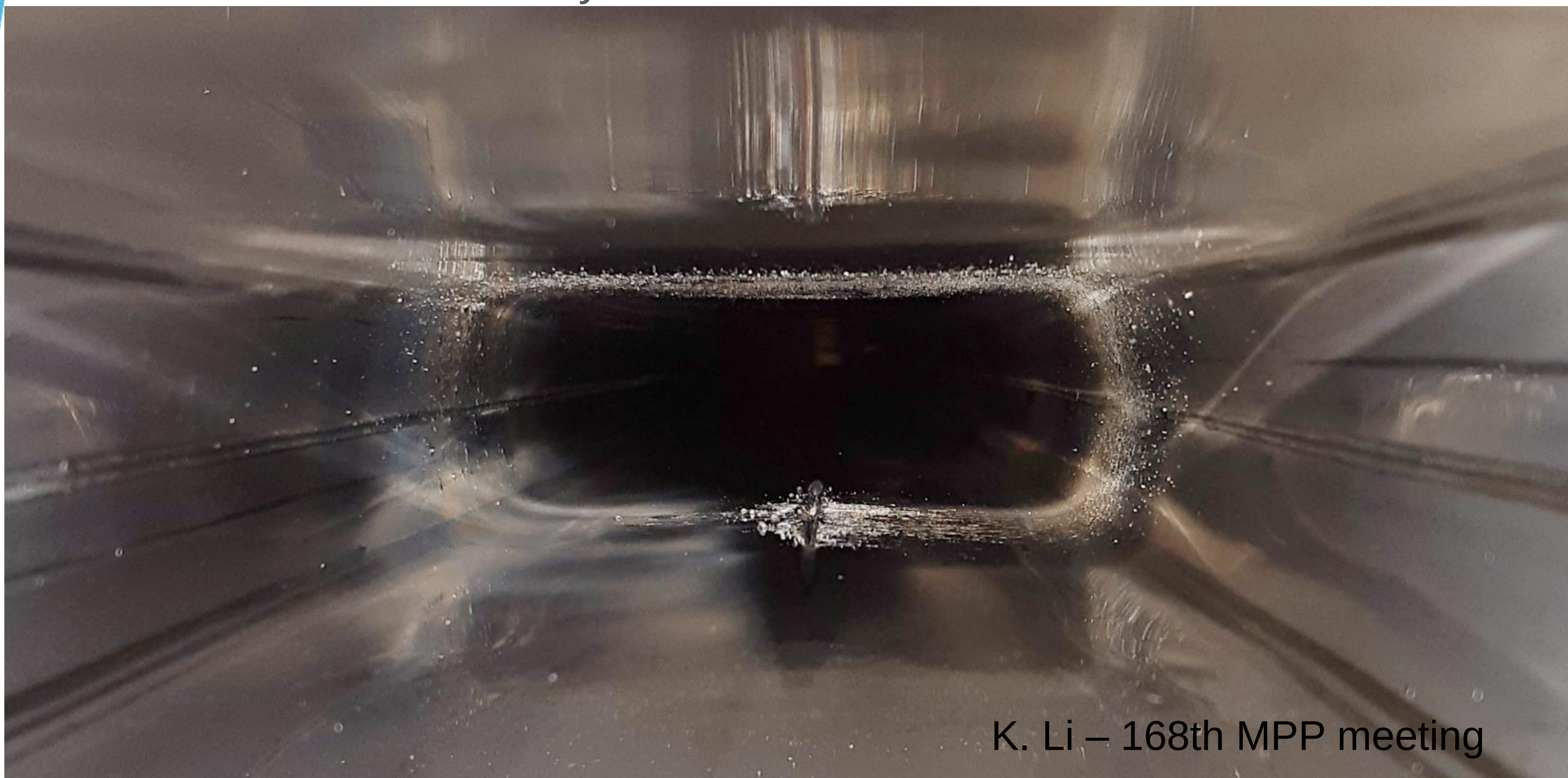
Beam induced damage

- 1.52 MJ deposited energy

Courtesy of F. Burkart

SPS vacuum leak

- 2 MJ lost in 15 ms
- LHC is cryogenic:
  SPS downtime ~3 days – LHC downtime ~3 months



Scope of project

- Study of failure scenarios causing uncontrolled beam losses
  - Source of failures
  - Effect on the beam
  - Subsequent beam losses (intensity, location)
  - Time scales
- Detection of failures
  - How to limit time between detection of failure and beam dump → time sufficient before critical losses occur?
- Identify new failures, e.g. due to new equipment

Goal: Understand criticality of failures to determine protection strategy / how to design safer system

(current machine protection system sufficient? new interlocks required? other mitigation strategies?)

High Luminosity LHC (HL-LHC) changes

- To attain higher luminosity, higher bunch intensity and smaller beam size in collision point
- New layout and **new HW** (crab cavities, triplets, 11T dipoles)

	LHC (6.5 TeV)	HL-LHC
# bunches	2556	2748
Protons per bunch	**1.15e11**	**2.2e11**
Beam size collision [µm]	95	60
Stored Beam energy [MJ]	**306**	**678**
Peak luminosity cm^-2 s^-1	2.2 * 10^34	17 * 10^34

Increased stored beam energy important parameter, but also the smaller beam size in collision point!

Beta function

- Beam size related to **emittance** and **beta function**

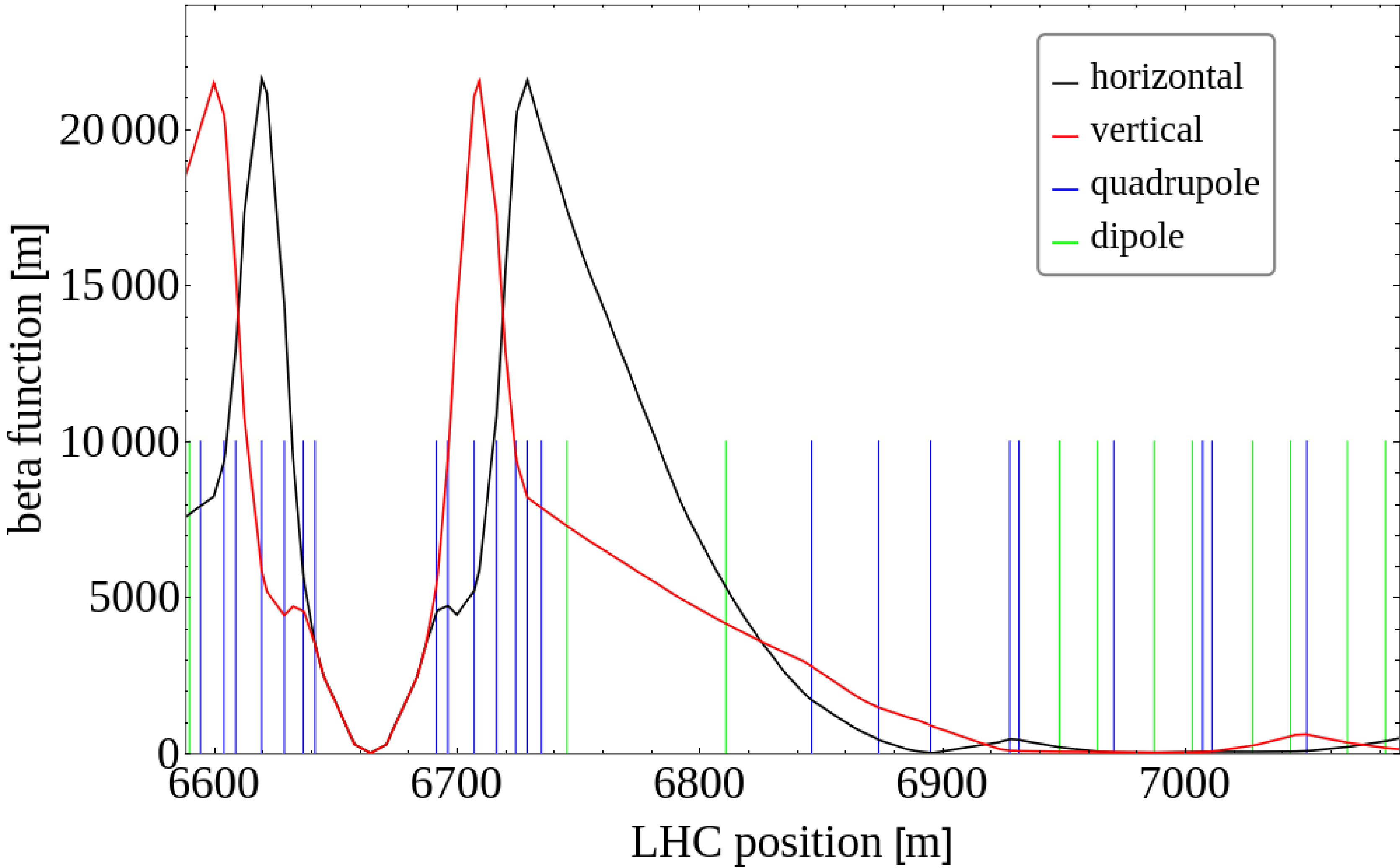
$$\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$$

- emittance, statistical measure of the deviation of the position and momentum of all particles in a bunch from its average
  - initially determined by particle source, then it grows
- beta function is determined by the optics lattice (focusing + defocusing quadrupoles)
  - when beam is focused, size decreases but transverse momentum increases
  - emittance is (quasi-)constant, beam size modulated by beta function
- **Beta function determines sensitivity to perturbations:**

$$\frac{x}{\sqrt{\beta(s)}} = \Delta x' \sqrt{\beta_0} \sin(\varphi)$$

Beta function

- $\beta(s) = \beta^* + \frac{s^2}{\beta^*}$: β^* is beta function in IP
- Small $\beta^* \rightarrow$ large beta function in Triplets, implying large effects on beam due to errors



Methodology

- Observe an event in LHC
  - Understand the failure
  - Simulate in HL-LHC optics to determine future criticality
  - Verify with experiments
- New Hardware
  - Study how it can malfunction and what would happen to the beam
  - Simulate and determine criticality
  - Verify with dedicated experiments when possible

→Determine mitigation and interlock strategies

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Overview of Fast Failures

- **Magnets/Circuits**
  - Triplet Quench
  - D1, D2 power loss
  - Quench Heaters
  - CLIQ
- **Active Equipment**
  - ADT
  - Crab Cavities
  - Beam-Beam Wire Compensator
- **Others**
  - UFO
  - UFO type 2
  - Beam-beam Kick

Overview of Fast Failures

Failure in/due to:		Time to critical losses
Triplet Quench	Quench in final focusing magnets	> 50 LHC turns (4.5 ms)
D1,D2	Power Failure in the dipoles next to the collision points	> 10 LHC turns (0.9 ms)
QH	Quench protection for magnets	> 1 LHC turn (0.1 ms)
CLIQ	Quench protection for magnets	~1 LHC turn (0.1 ms)
ADT	Transverse beam damper	> 10 LHC turns (0.9 ms)
Crab Cavities	Required for counteracting loss in luminosity due to Xing angle	> 10 LHC turns (0.9 ms)
BBCW	Long Range Beam-Beam compensating wires	> 100 LHC turns (9 ms)
UFO	Dust-particles interacting with beam	~3 LHC turns (0.3 ms)
UFO type 2	Beam instability driven by remaining gas cloud after UFO interaction	> 10 LHC turns
Beam-beam kick	Loss of beam-beam kick due to dumping only one beam	~2 LHC turns (0.2 ms)

Failures covered below

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Triplet Quench

Magnet protection

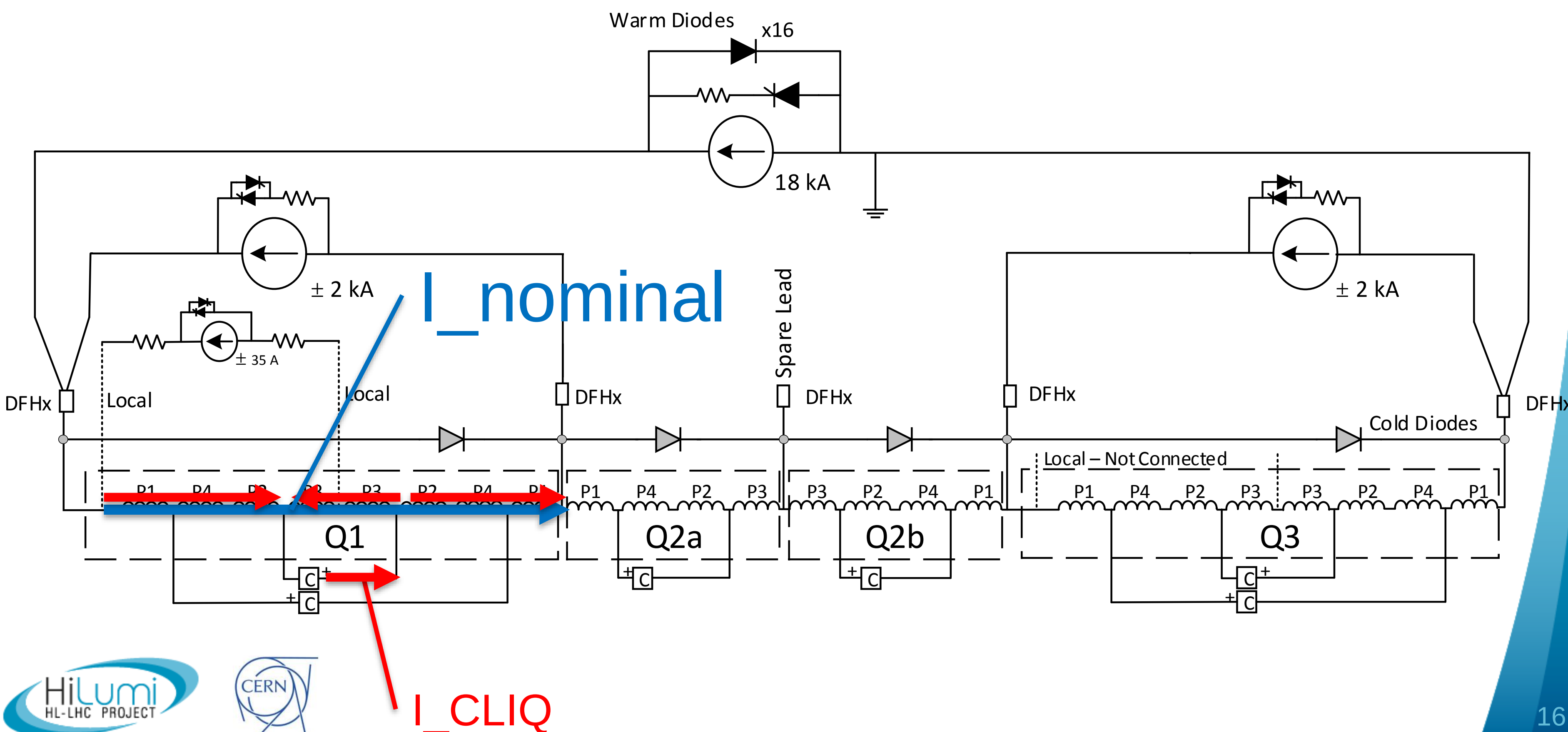
- High current in magnets (up to ~16 kA)
- Quench – loss of superconductivity
- Risk of cable damage
- Need active system to protect magnet
- Active system changes current – magnetic field in beam region

In LHC, magnet protection did not consider effects on beam

Coupling Loss Induced Quench (CLIQ)

- Up to **2.5 kA** discharged directly into magnet coil!
- Q1 electrically same as Q3, but Q2 different
- **Q2**: **Symmetric** discharge *(opposite poles, same current change)*
- **Q1/Q3**: **Asymmetric** discharge *(one pole increased current, three poles decreased)*

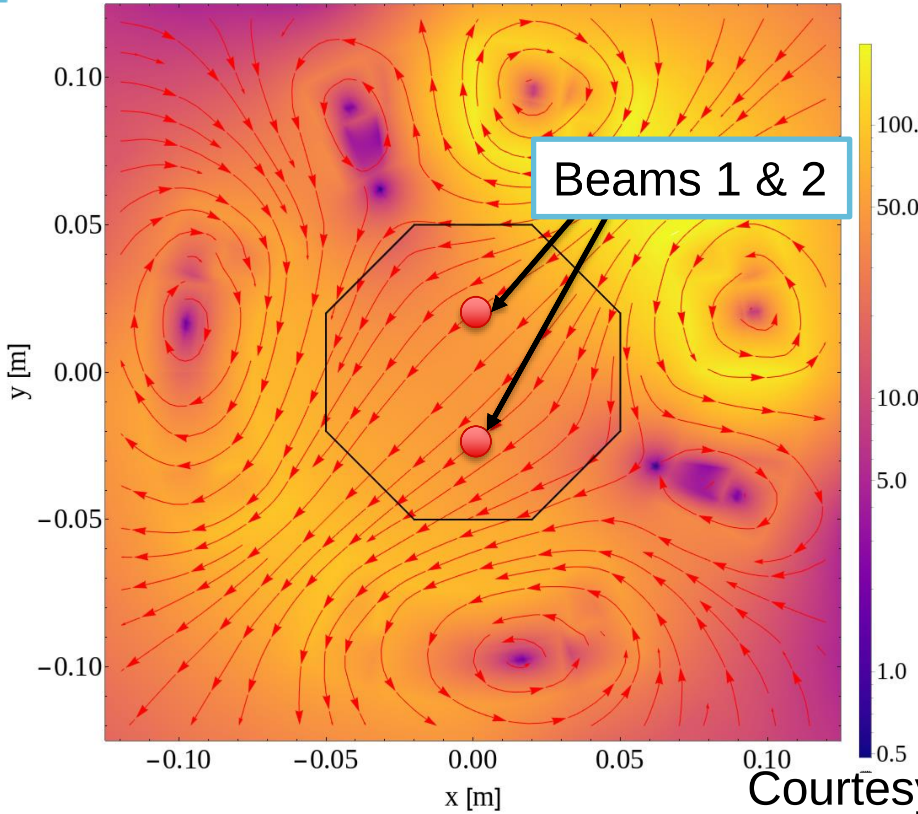
Need circuit and beam simulations



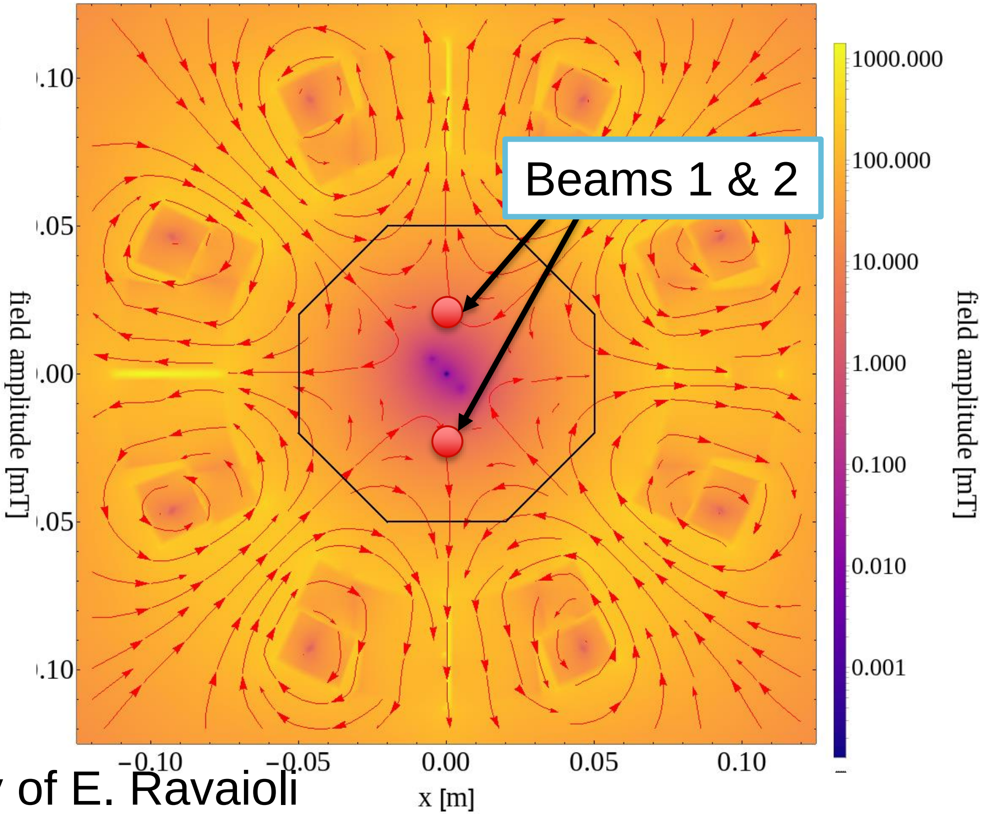
CLIQ – spurious discharge of single unit

Three magnets – two different connection schemes

Dipolar field → beam kick

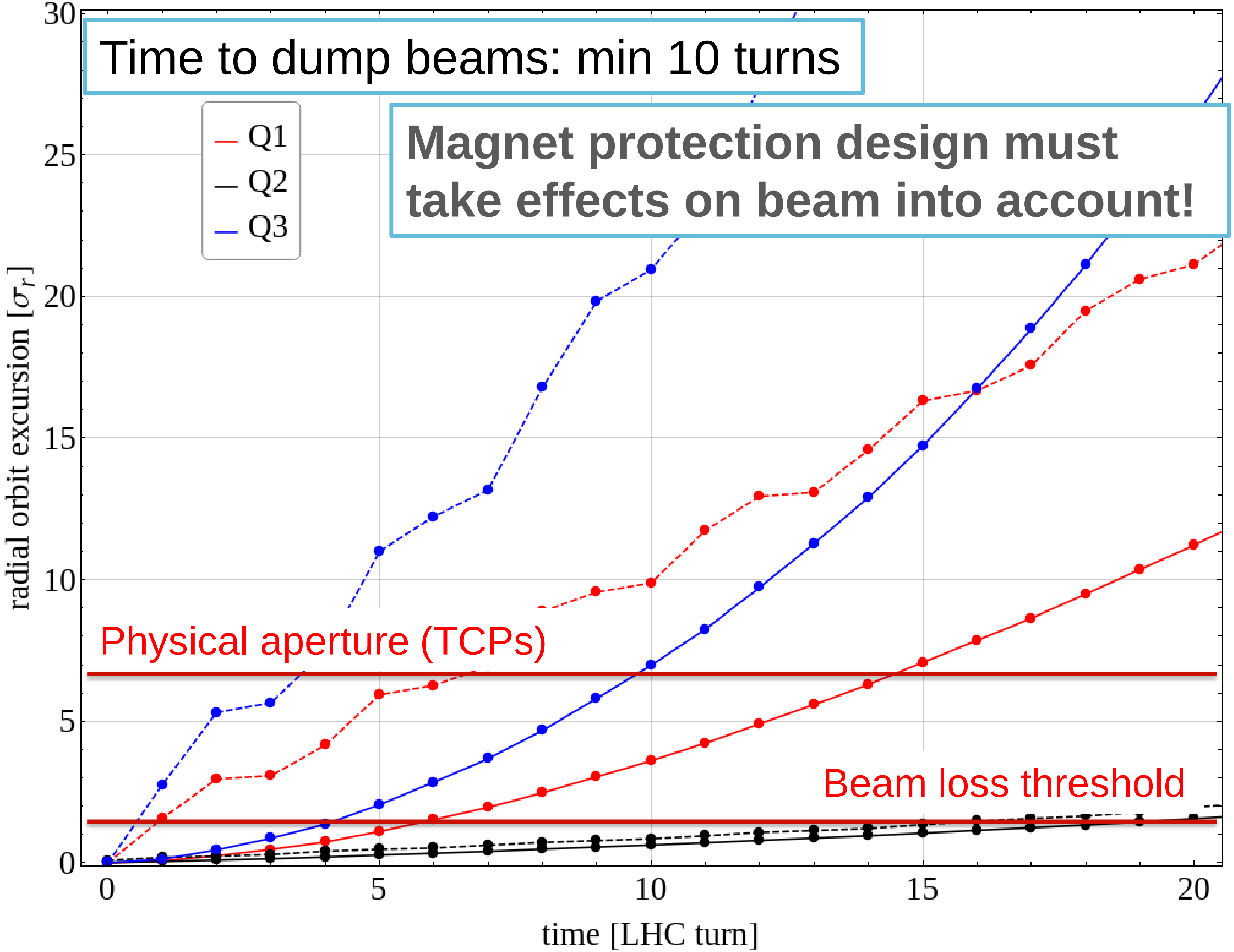


Octupolar field → beam size



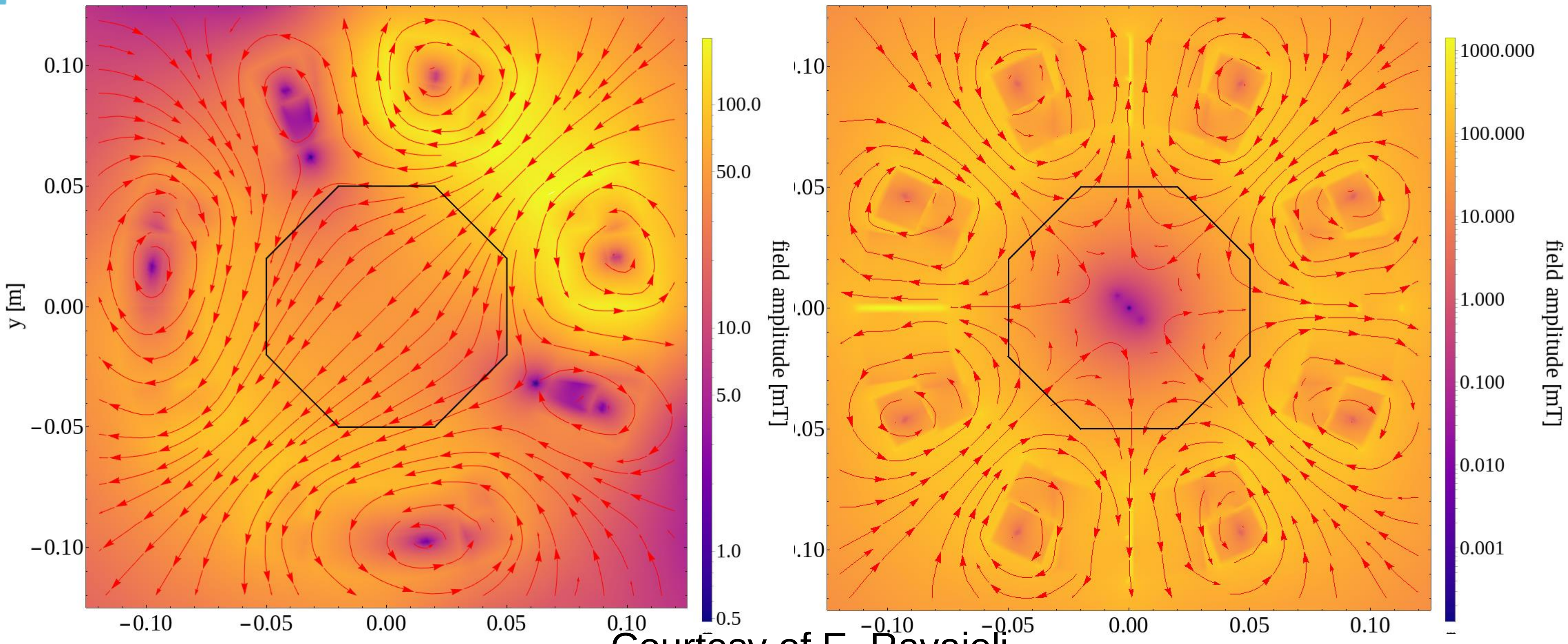
Courtesy of E. Ravaioli

Spurious discharge – Beam orbit change



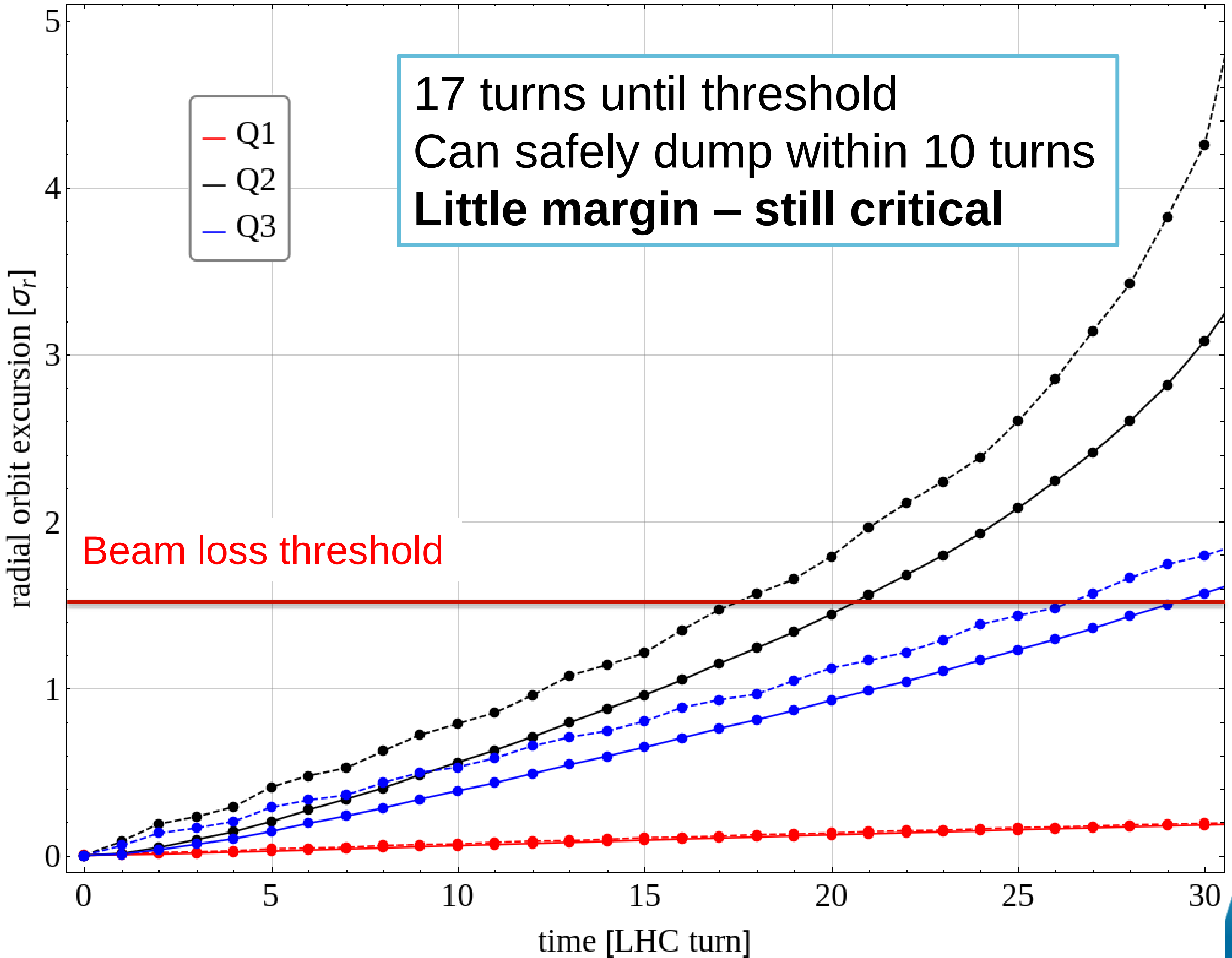
Solution?

- Ensuring CLIQ can never fire spuriously
  - Cannot be 100 % failsafe, expensive, and increased complexity
- Use Q2-like connection scheme
  - New triplet circuit baseline



Courtesy of E. Ravaioli

Q2-like connection – beam orbit change



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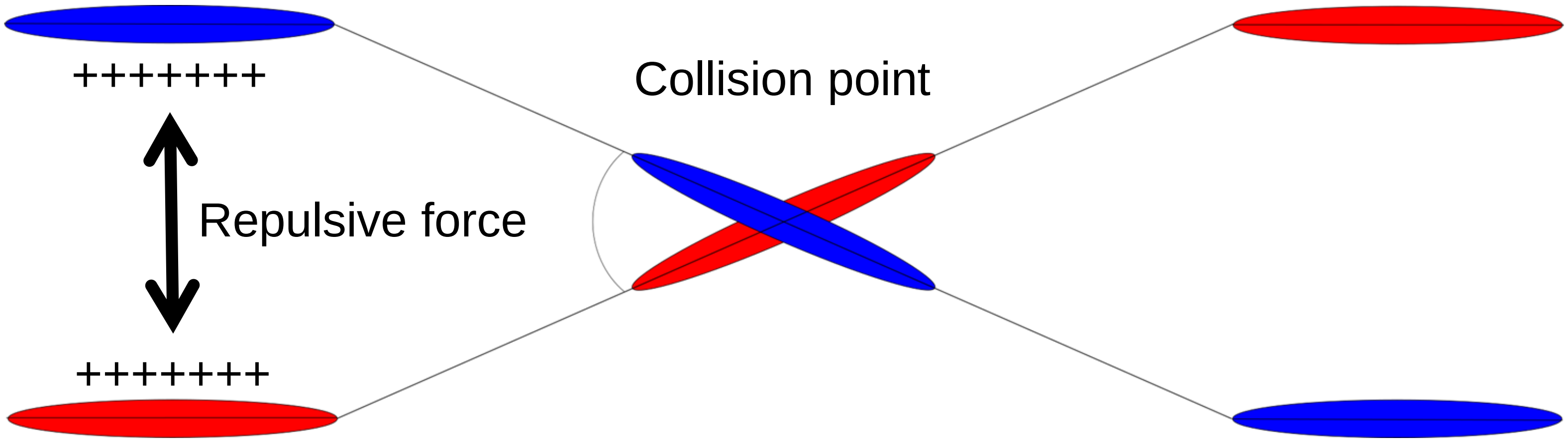
Beam Beam Kick

Triplet Quench

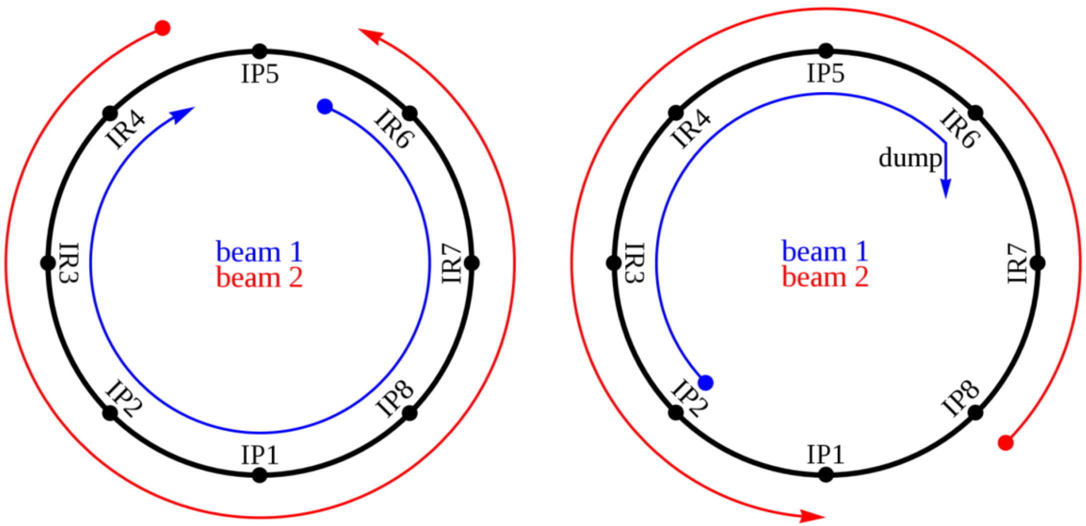
Beam beam kick

- The two beams are charged and, thus, interact around collision points
  - Transverse kick (orbit change, main issue for Machine Protection)
  - Beam size growth
  - Tune spread
  - ...



Beam beam kick

- The two beams are charged and, thus, interact around collision points
  - Transverse kick (orbit change, main issue for Machine Protection)
  - Beam size growth
- Beams cannot be dumped simultaneously:



Remaining beam is distorted due to loss of BBK!

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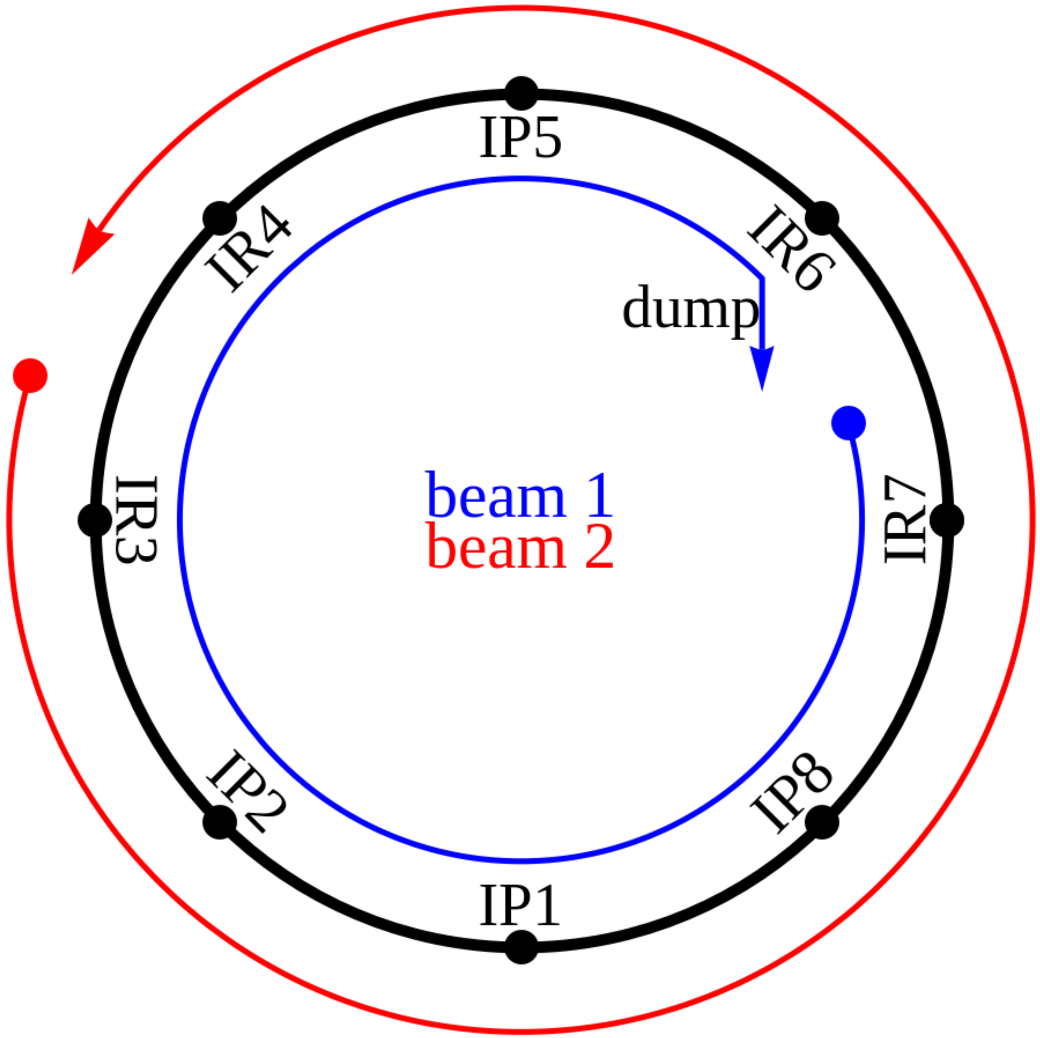
Dump animation

- The order in which the BBK is lost in different IPs matter

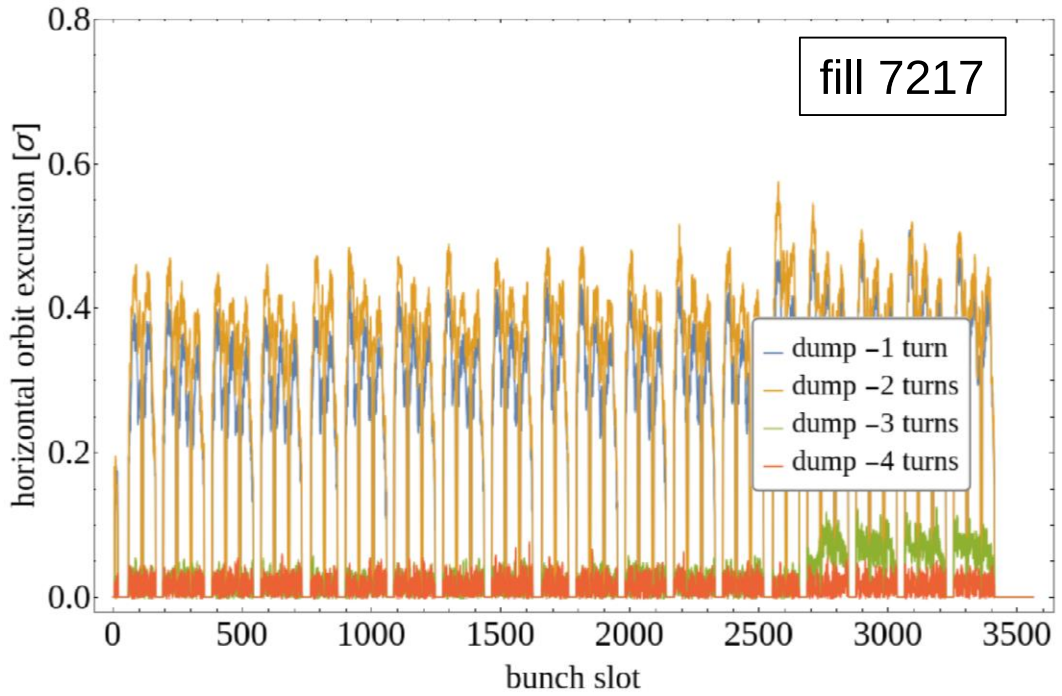


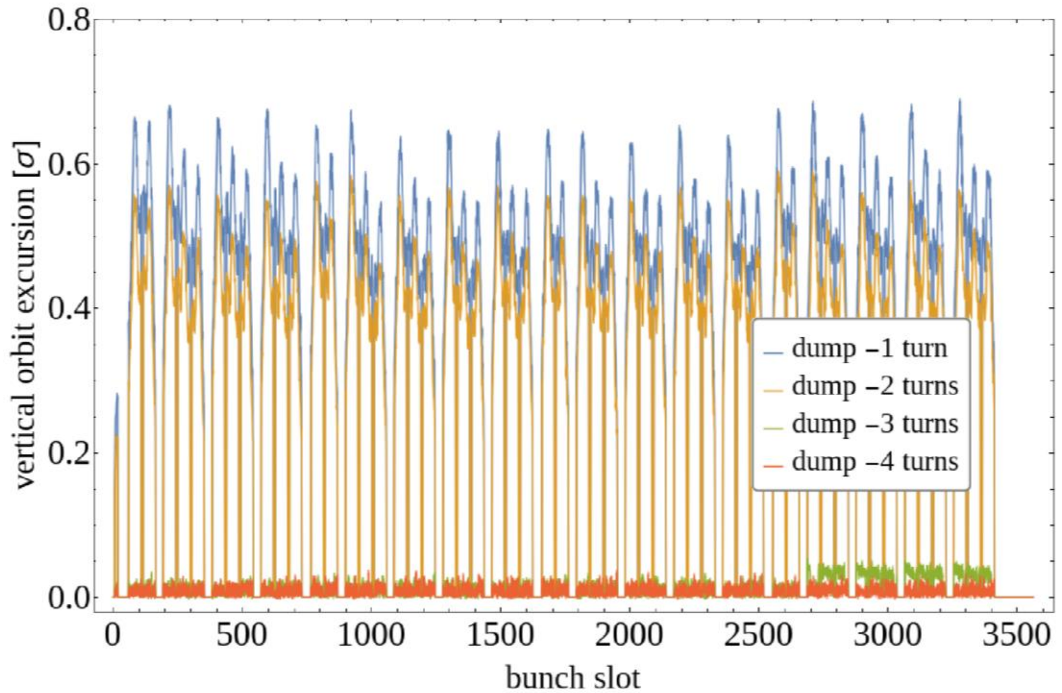
Measured BBKs

Since Aug 1 2017:

- b1: 27 observations
- b2: 21 observations
- Up to 3 turns of offset measured in both beams
- Dump reasons: RF trips, EOF programmed dumps, collimator temperature, SIS interlock, BPMS interlock

Beams have separate beam permits, and some systems only remove permit of one beam. Even when both permits removed, there are delays in the communication and beam synchronization.





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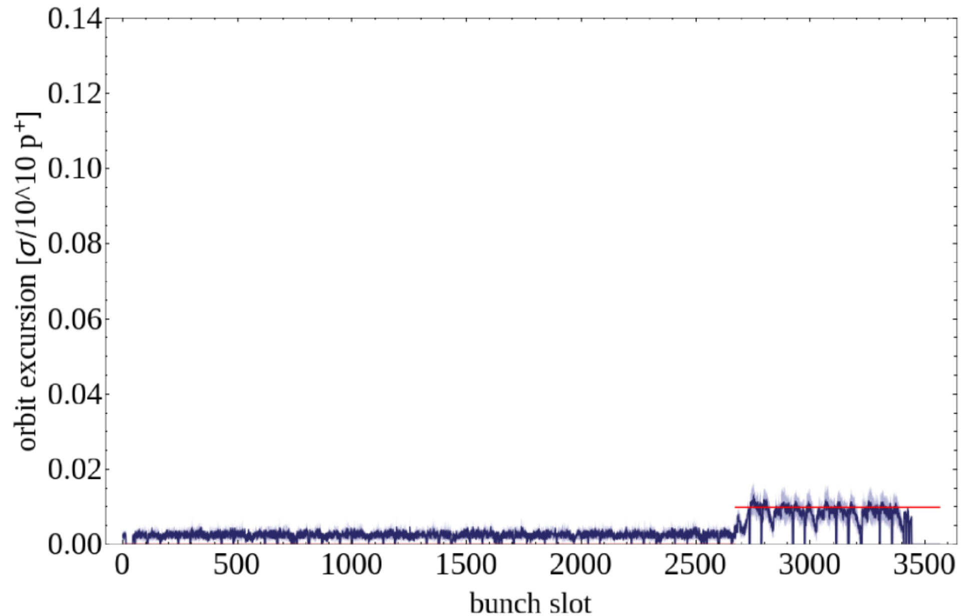
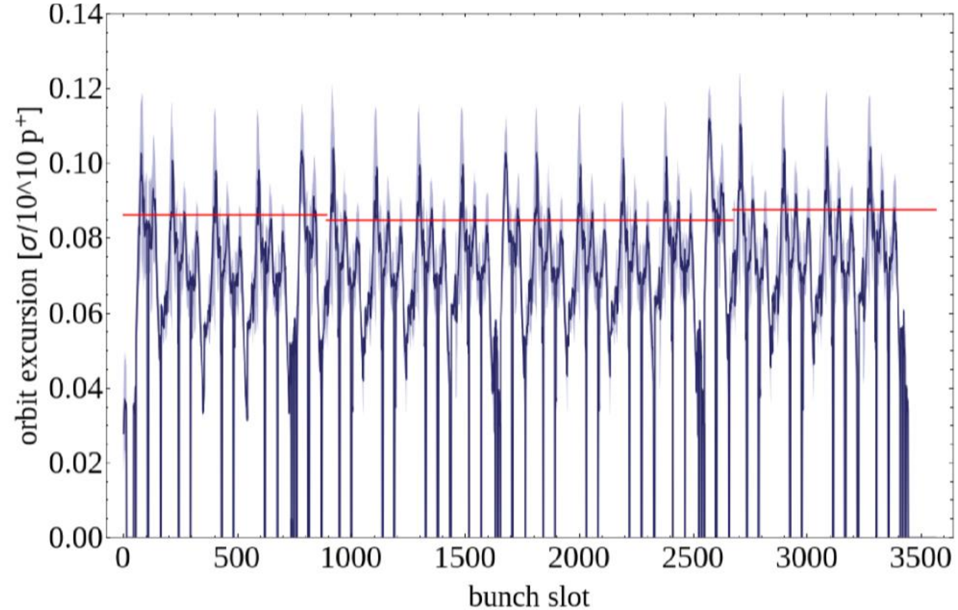
Comparison with simulations

- BBK proportional to bunch intensity → normalize the measurements
- Dark blue line: average of all measurements
- Light blue shade: standard deviation of measurement
  - all fills very consistent!
- Red line: estimate from simulations
  - good agreement!





Run III and HL-LHC projections

- Bunch intensity increase significantly
- Small beta star in HL, but increased crossing angle
- In Run III worst case, kick is significant but within threshold
- In HL-LHC, kick is above limit on second turn
- Flat optics would be better from this perspective, but is not baseline

Beam 1 orbit excursion [σ]

Optics	turn 1	turn 2	turn 3
Run III			
Start of SB	0.37	0.76	0.76
End of SB	0.46	0.78	0.67
Worst case	0.85	1.45	1.23
HL-LHC			
Round	0.86	1.60	1.56
Flat	0.72	1.21	0.89

In HL-LHC, both beams should be dumped with minimum delay (one turn is unavoidable)

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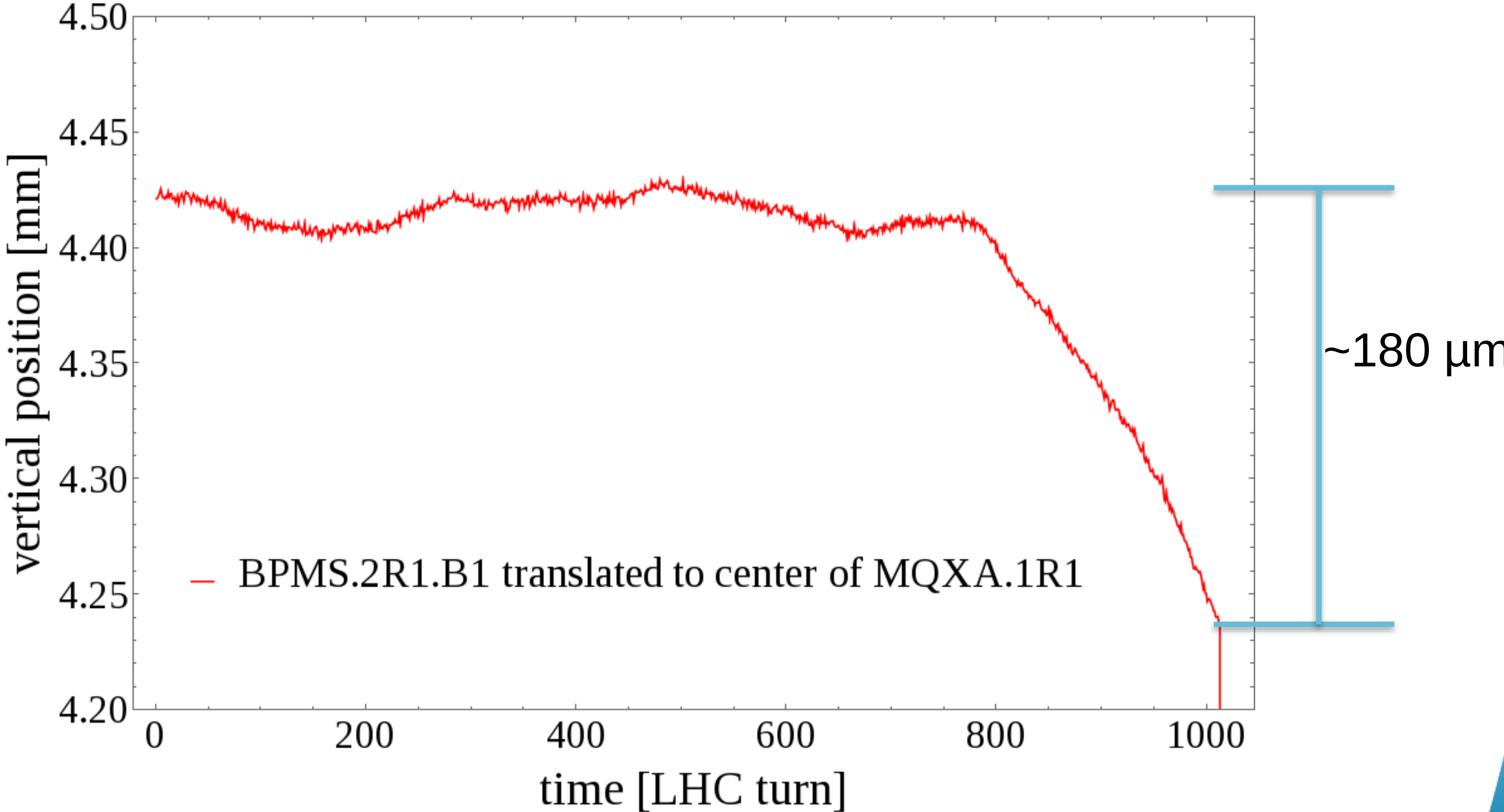
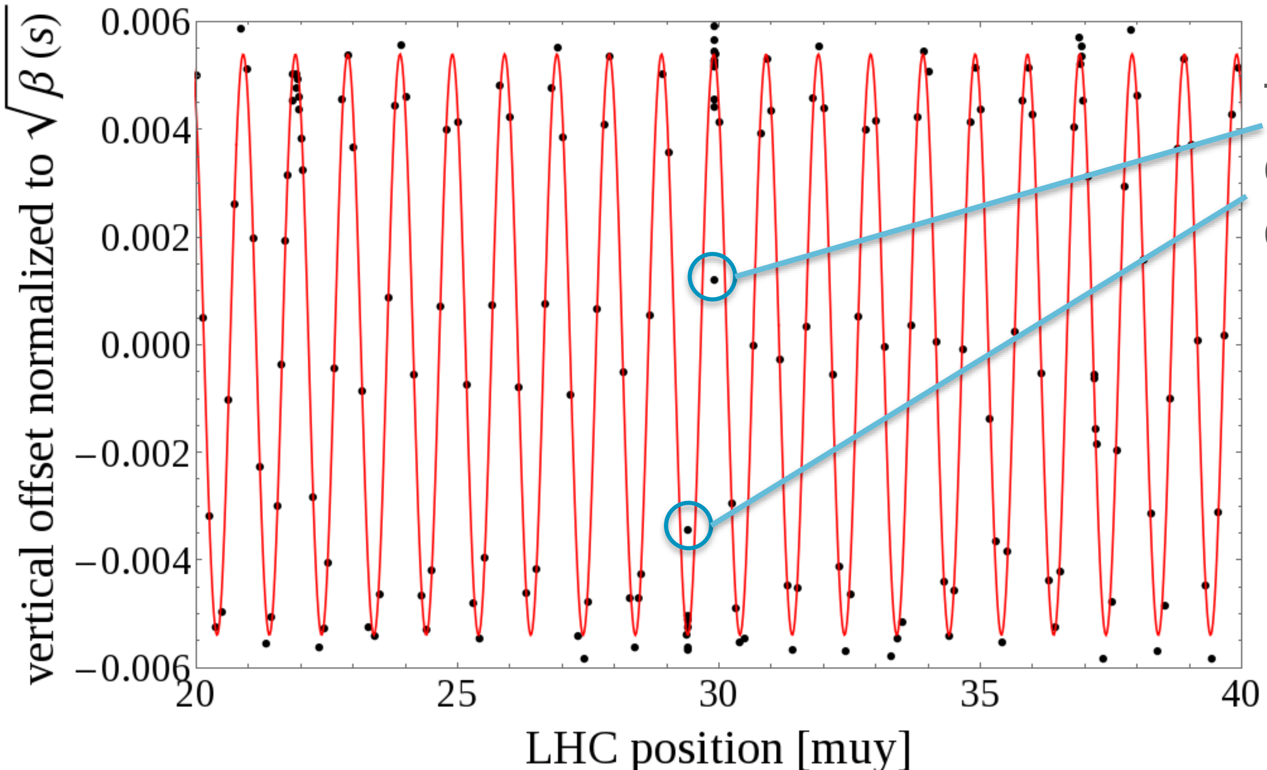
Triplet Quench observed 2018-06-03

- Vertical orbit offset only in b1
- ~180 µm change in center of MQXA.1R1 (Q1)



”Slow” kick – Closed orbit change

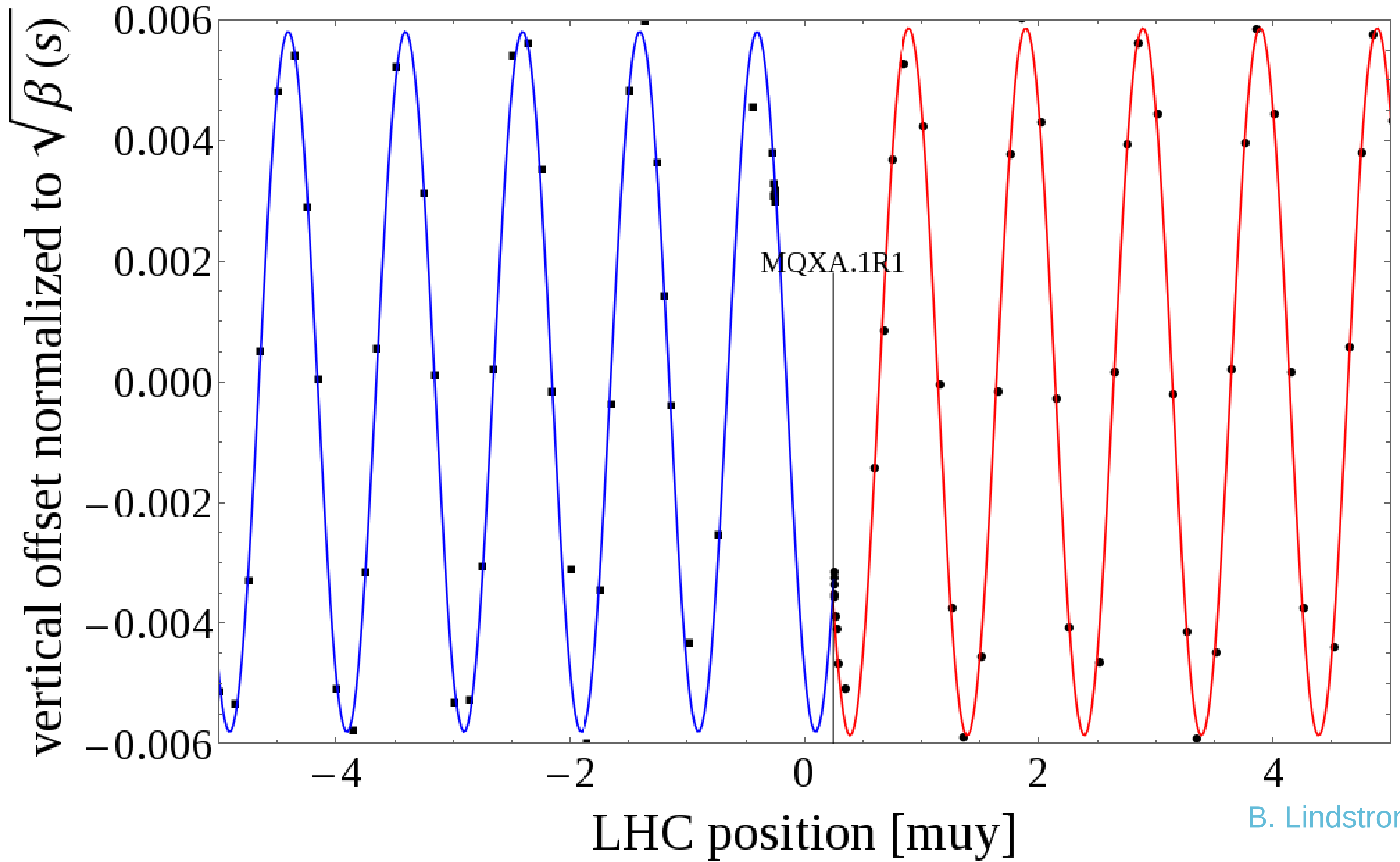
- $\frac{x}{\sqrt{\beta(s)}} = \frac{\Delta x\prime\sqrt{\beta_0}\cos(|\phi(s)-\phi_0|-\pi Q_y)}{\sin(\pi Q_y)}$
- The kick $\Delta x'$ was fitted to all BPM measurements
- Black dots are BPMs



Two BPMs in IP5 consistently lower value, otherwise good fit

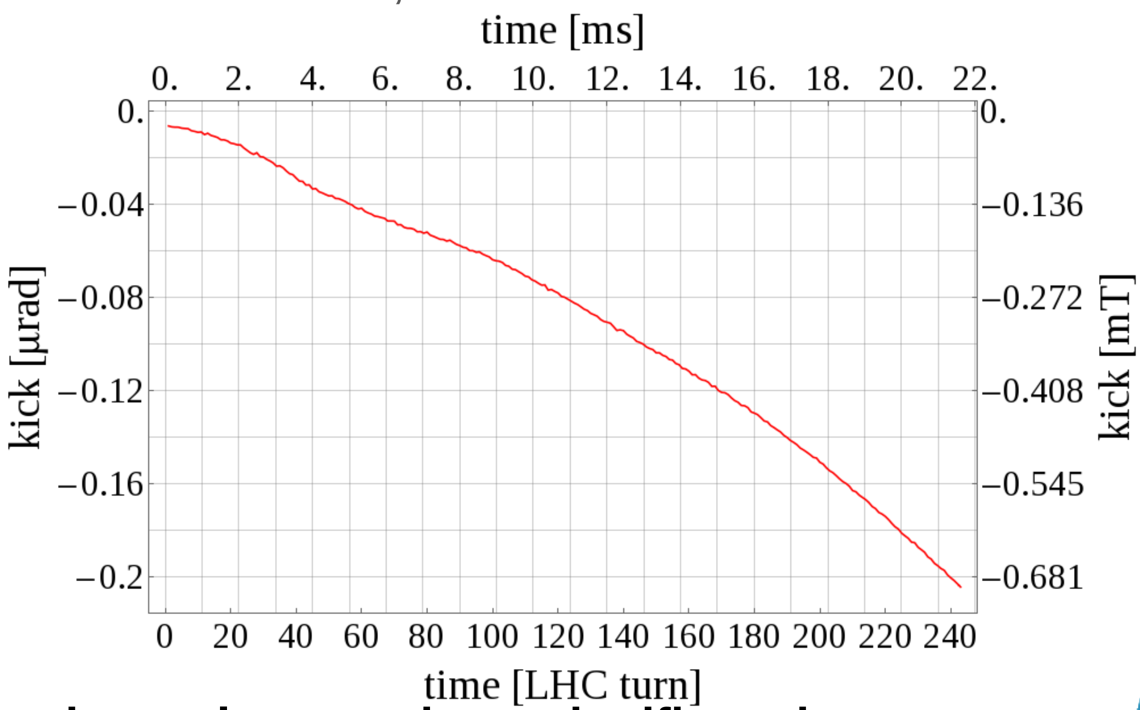
Origin of kick

- Plotting two consecutive turns around IP1 shows discontinuity at Triplet location
- Together with RQTX.R1 circuit data, confirm kick originates in MQXA.1R1



Kick time evolution

- Due to cryo issue, quench propagation speed was abnormally fast
- From circuit simulations, magnetic field expected to be **~0.23 mT** at dump, but beam kick implies **0.7 mT**
- Emmanuele showed discrepancy possibly due to current redistribution in the wire
- In HL-LHC, due to larger beta functions, critical limit could be reached in ~50 LHC turns



Quenches by themselves can have significant impacts on the beam but not critical due to long time-scales

Conclusions and Outlook

- Criticality of failures in Magnets/Circuits, Active Elements, and other scenarios has been determined
- CLIQ would create the fastest failure in the LHC
  – mitigation method has been proposed and implemented
- Simulations validated by dedicated experiments / beam observations

- Proposed & validated novel method for studying UFOs
  – strong indication UFO movement also horizontal
- First Machine Protection experiments with Crab Cavities in a hadron beam were prepared, executed and analysed
  – observations confirm expectations, fast interlocks are required

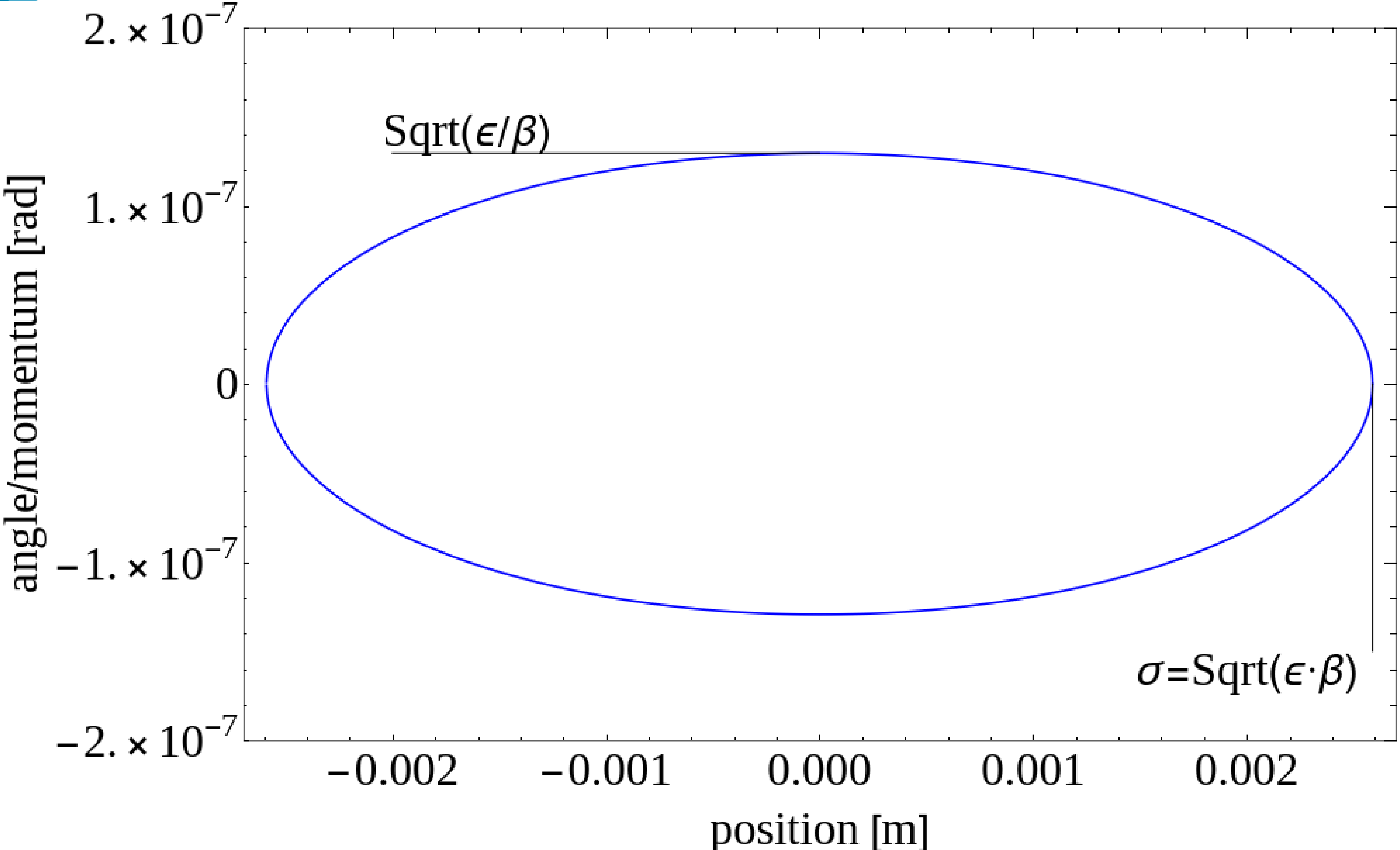
- UFO dynamics studies ongoing (with Philippe)
- Wrap-up failure studies
  - PRAB paper summarizing most failures nearly ready for submission
  - UFO paper together with Philippe in preparation

Run III and HL-LHC optics

	Run III		HL-LHC	
	Start SB	End SB	Round	Flat
β^* $IP1/IP5$ $[cm]$	150	28	15	7.5/30
β^* $IP2$ $[cm]$	1000	1000	1000	1000
β^* $IP8$ $[cm]$	150	150	150	150
$crossing$ $IP1/IP5$ $[\mu rad]$	102 V/H	162 V/H	295 V/H	245 V/H
$crossing$ $IP2$ $[\mu rad]$	200 V	200 V	270 V	??
$crossing$ $IP8$ $[\mu rad]$	250 H	250 H	115 H	??
$bunch$ $intensity$ $10^{11} p^+$	1.8	0.97	2.2	2.2
RMS $bunch$ $length$ $[ns]$	0.3	0.25	0.25	0.25
ϵ_n $[\mu m \cdot rad]$	2.5	2.5	2.5	2.5
$energy$ $[TeV]$	6.5/7	6.5/7	7	7

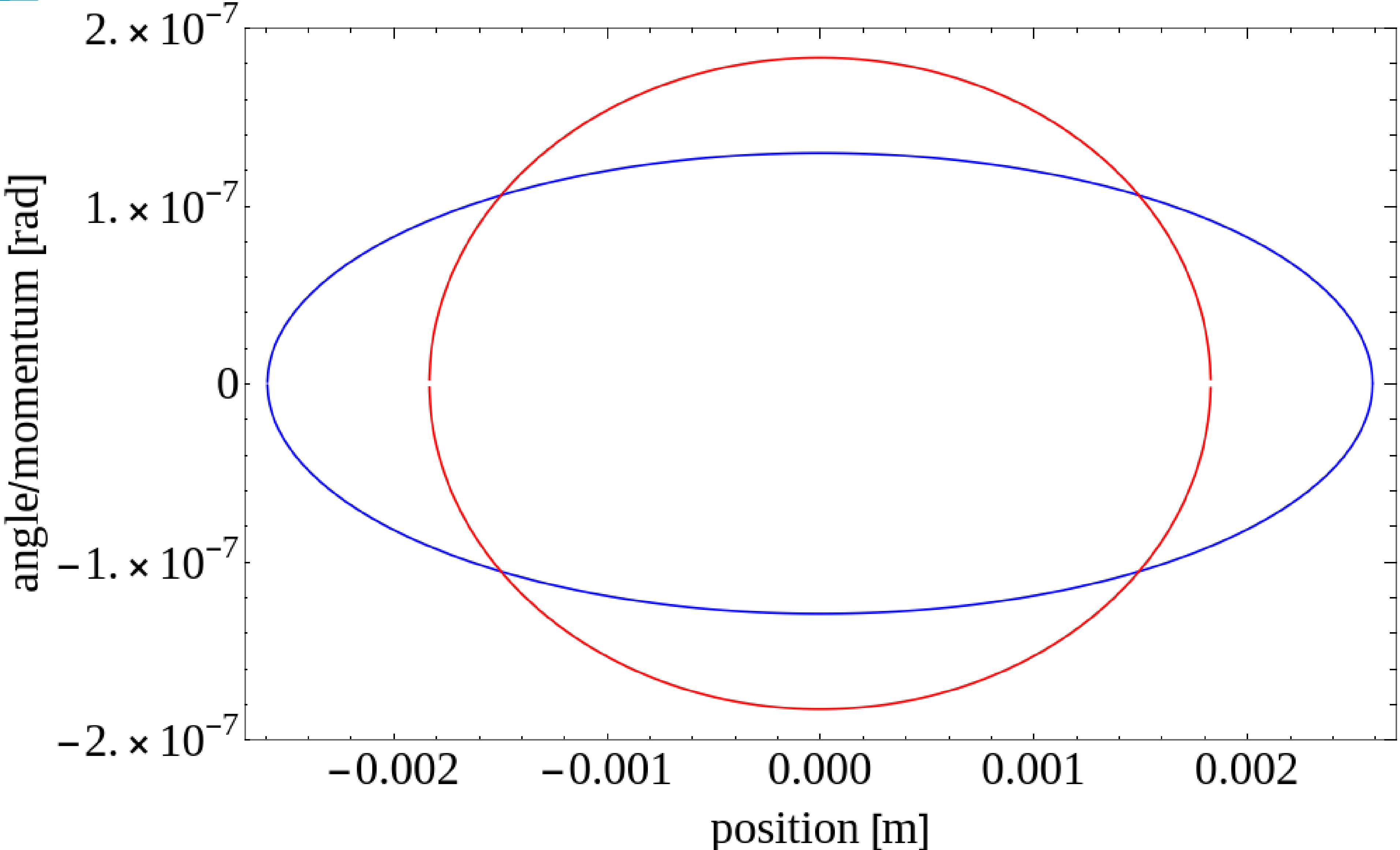
Beam sensitivity to perturbations

Constant area: $\pi \cdot \epsilon$



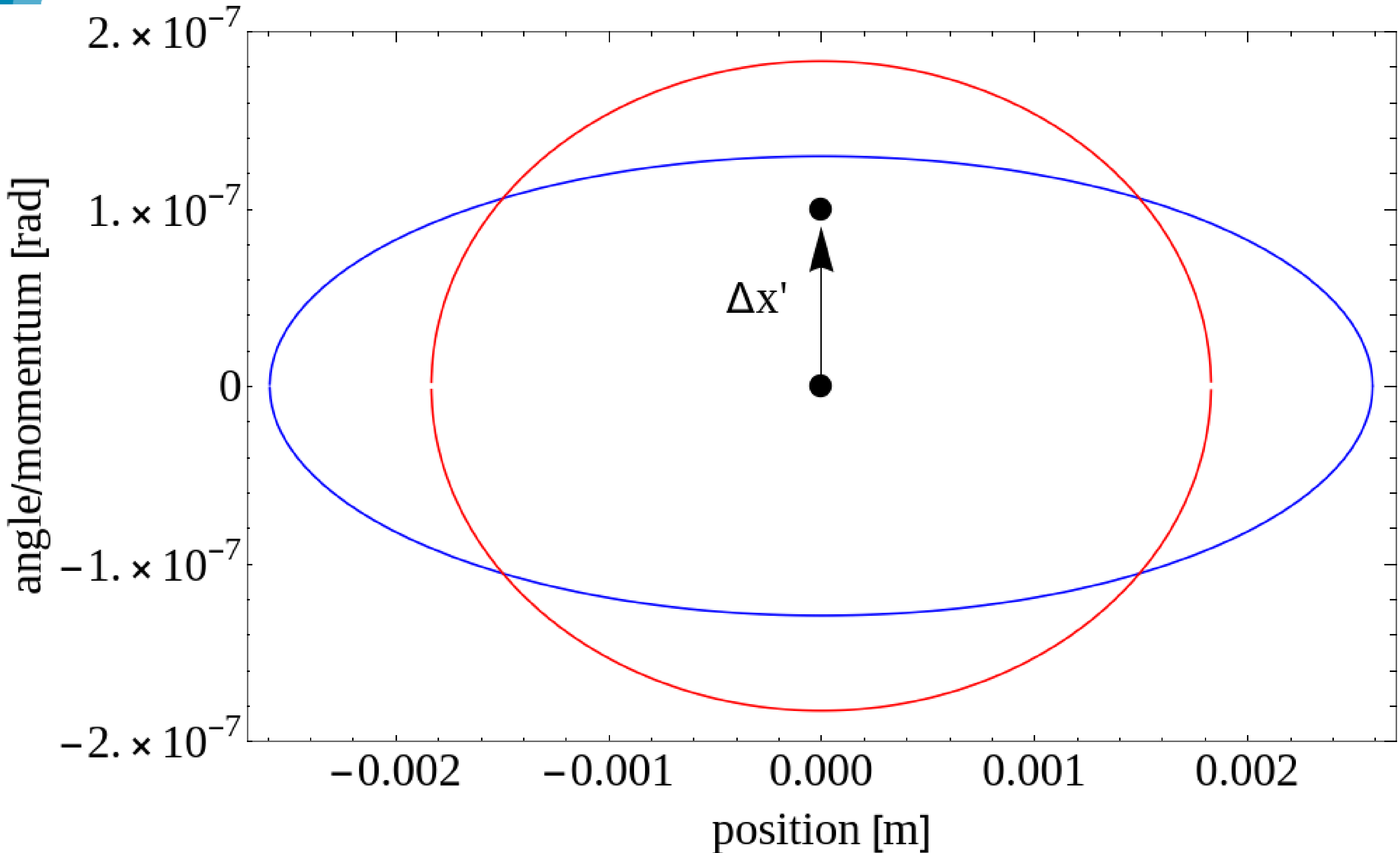
Beam sensitivity to perturbations

Ellipse at location with smaller beta function, area is the same



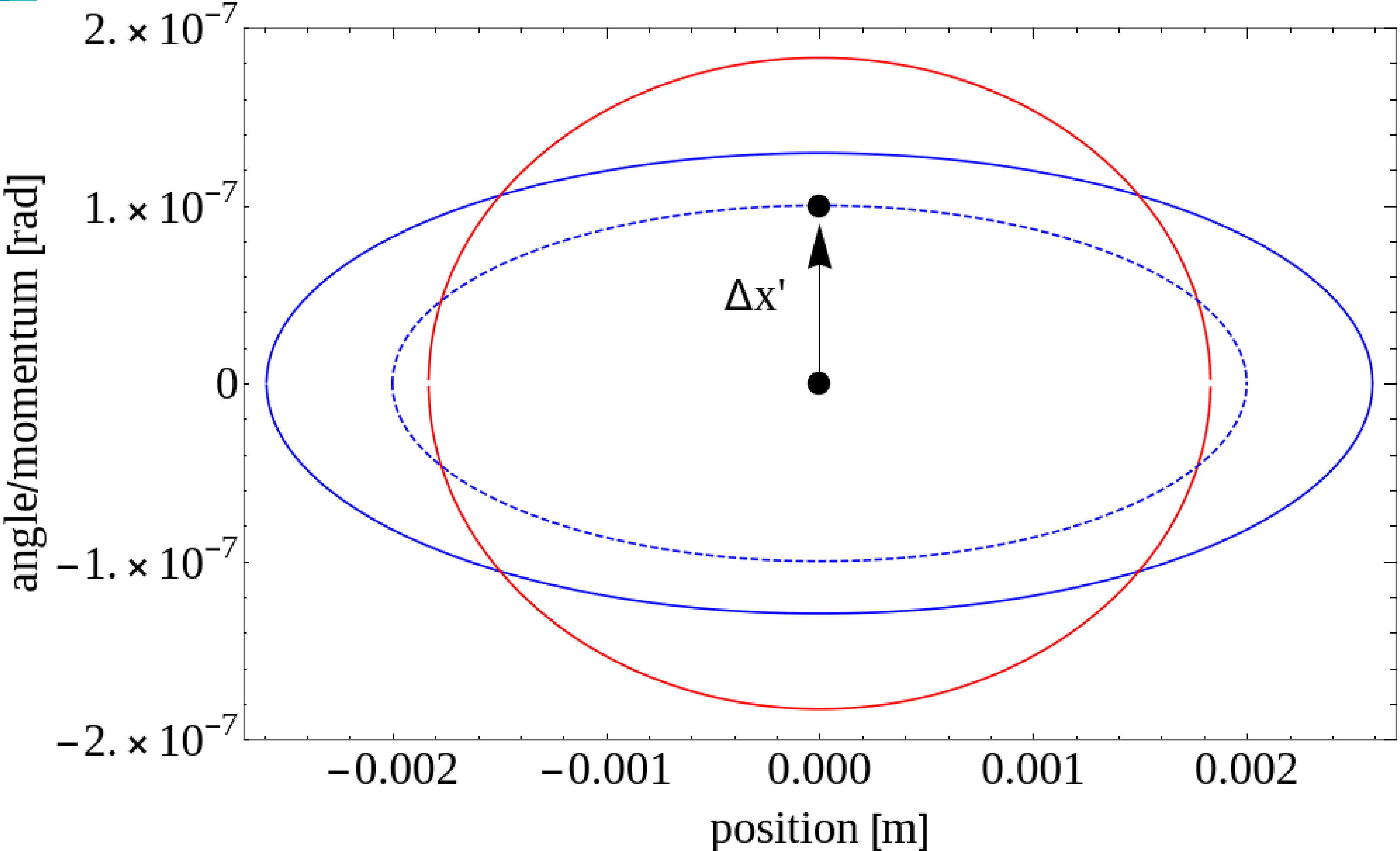
Beam sensitivity to perturbations

A particle receives a kick



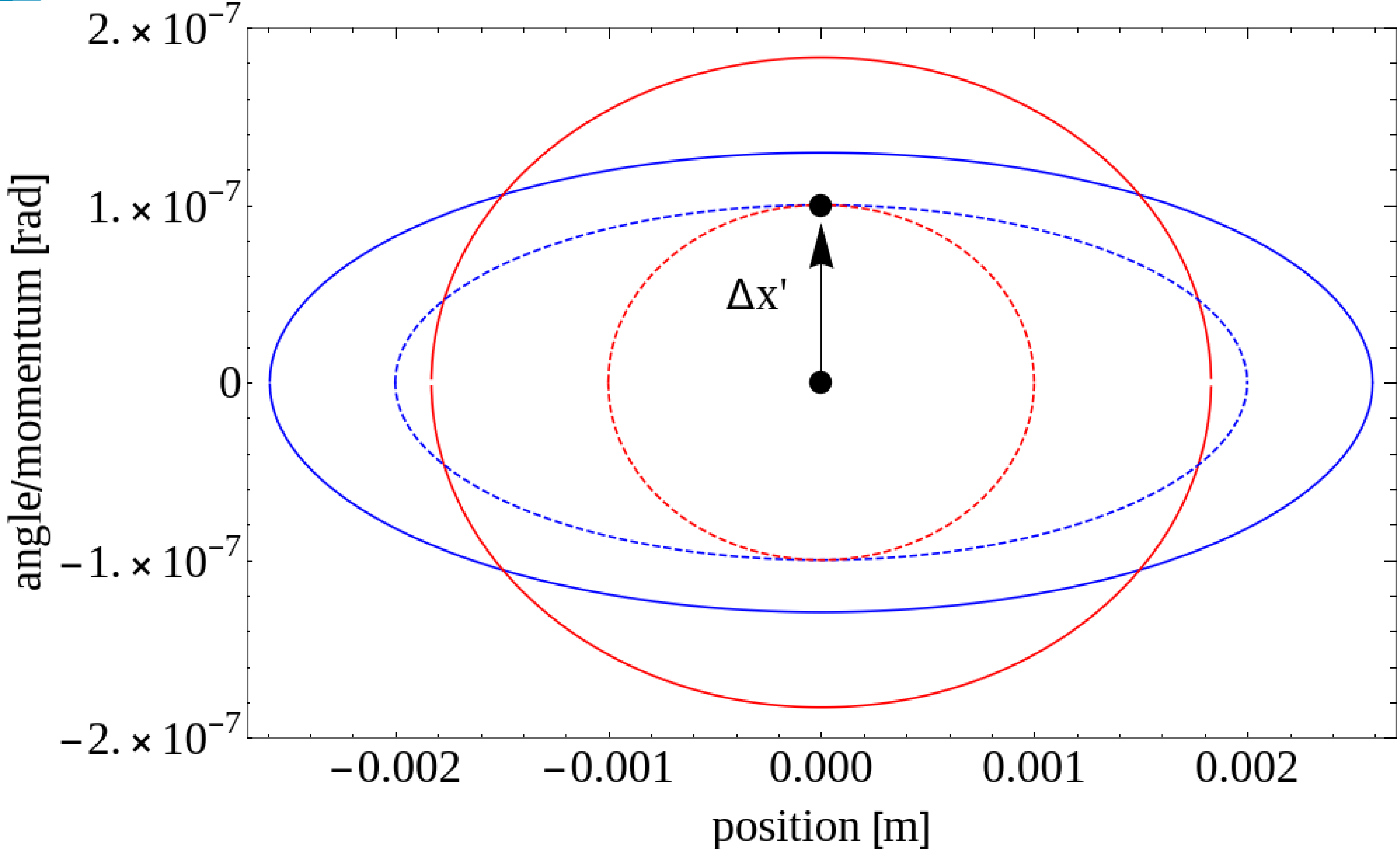
Beam sensitivity to perturbations

Particle traces out ellipse in phase space



Beam sensitivity to perturbations

Particle at other location traces out different ellipse



Beam sensitivity to perturbations

Observe Red particle at Blue location, transforms the ellipse