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# Machine Protection of LHC Crab Cavities

*LHC-CC11*

***Tobias Baer***

***November, 15th 2011***

*Acknowledgement: F. Burkart, R. Calaga, R. de Maria, J. Tuckmantel, J. Wenninger.*

# Content

# Content

1. Introduction and Scaling Laws
2. Dynamic Failure Simulations (MAD-X)
3. Mitigation and Conclusion

# Analytical Approach

- Crab cavity kick is equivalent to z-dependent **dipolar** orbit kick.
- Maximal displacement by Crab Cavity:

*assuming optimal voltage to compensate crossing angle,*

*(cf. T. Baer et. al, „LHC Machine Protection Against Very Fast Crab Cavity Failures“, IPAC’11)*

$$\frac{\bar{x}_{cc}(z)}{\sigma_x} = -\underbrace{\frac{c \cdot \tan(\frac{\Theta}{2})}{\omega \cdot \sigma_{x,IP} \cdot \sin(\Delta\varphi)}}_{= 3.98} \cdot \sin\left(\Phi + \frac{\omega \cdot z}{c}\right)$$

**= 3.98** (1.02 for nominal optics)

| |
|---|
| $\sigma_x$ = horizontal beam size |
| q = particle charge |
| E = particle Energy (7 TeV) |
| V = voltage of crab cavity |
| Φ = phase of crab cavity |
| Θ = full crossing angle (580/285 μrad) |
| φ = phase advance CC ->IP (≈ π/2) |
| ω = angular frequency of CC (2 π·400 MHz) |
| z = longitudinal position of particle |
| c = speed of light |

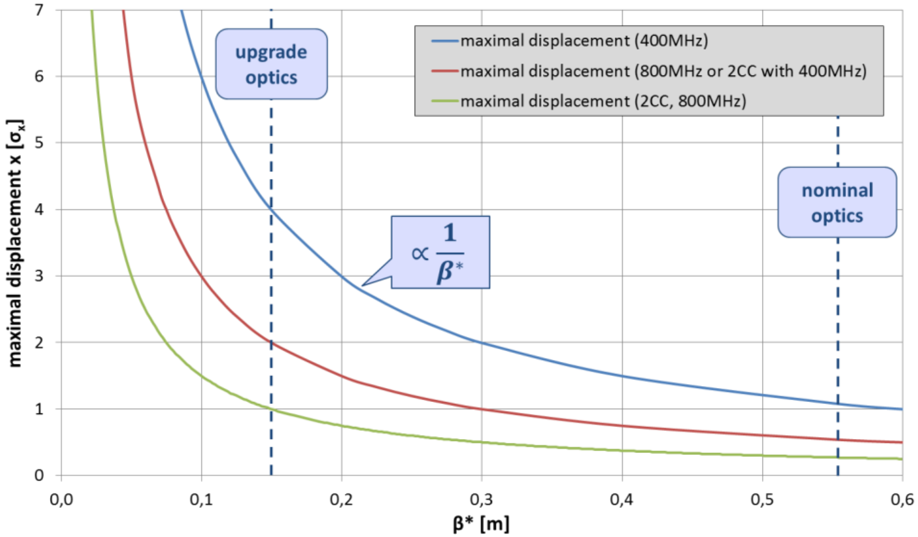
| | Upgrade optics | Nominal optics |
|---|---|---|
| Maximal kick with $sin\left(\Phi + \frac{\omega \cdot z}{c}\right) = 1$ $\bar{x}_{cc} \approx$ | **$4\sigma_x$** | **$1\sigma_x$** |
| For z = 7.55cm (= $1\cdot\sigma_z$): $\bar{x}_{cc}(z = 7.55\text{cm}) \approx$ | **$2.36\sigma_x$** | **$0.60\sigma_x$** |

# Scaling laws

$$\frac{\bar{x}_{cc}(z)}{\sigma_x} = -\frac{c \cdot \tan(\frac{\Theta}{2})}{\omega \cdot \sigma_{x,IP} \cdot \sin(\Delta\varphi)} \cdot \sin\left(\Phi + \frac{\omega \cdot z}{c}\right)$$

$$\propto \frac{1}{\omega \cdot \beta^* \cdot n_{cc}}$$

$\omega$ = angular frequency of crab cavity
$\beta^*$ = beta function at IP
$n_{CC}$ = number of **independent** crab cavities on each side of IP.




*The maximal displacement for* $\sin\left(\Phi + \frac{\omega \cdot z}{c}\right) = 1.$

# Failure Dynamics

- Time constant of crab cavity failures:

  *With $Q_{ext}$ = 1'250'000, f = 400MHz ->* $\boldsymbol{\tau_0 = \frac{Q_{ext}}{\pi \cdot f} \approx 1ms}$.

- Voltage decay in first turn: $\frac{\Delta V}{V} = 1 - \exp\left(-\frac{89\mu s}{1ms}\right) = \mathbf{9\%}$.

- Phase change in first turn: $arctan\left(\frac{\frac{\Delta V}{V}}{1-\frac{\Delta V}{V}}\right) = \mathbf{5.3°}$.

**$Q_{ext}$ determines time constant of failures.**

*cf. T. Baer et. al, „LHC Machine Protection Against Very Fast Crab Cavity Failures", IPAC'11, J. Tuckmantel, CERN-ATS-Note-2011-002 TECH*

# Content

# Dynamic Failure Simulations

- Optics:
  - **SLHCV3.0 4444_thin**, **β* = 0.15m** (IP1/5), β* = 10.0m (IP2/8), Θ = 580μrad.
  - SLHCV3.0 8228_thin, β* = 0.075m/0.3m (IP1H,IP5V/IP1V,IP5H), β* = 10.0m (IP2/8), Θ = 410μrad.
  - Nominal optics**, β* = 0.55m** (IP1/5), β* = 10.0m (IP2/8), Θ = 285μrad.
- Crab cavity **local scheme IP5**, no splitting of crab cavity kicks.
- Dynamic failure evolution with $Q_{ext} = 1'250'000$.
- Tracking for ≈20 turns.
- Particle distribution:
  - In order to separate effect of CCs: x, x’, y, y’, dp/p=0.

# Voltage Failure

- Dynamic voltage change of CC.R5 from $V_0$ to $-V_0$.

  *Failure starts after turn 10.*

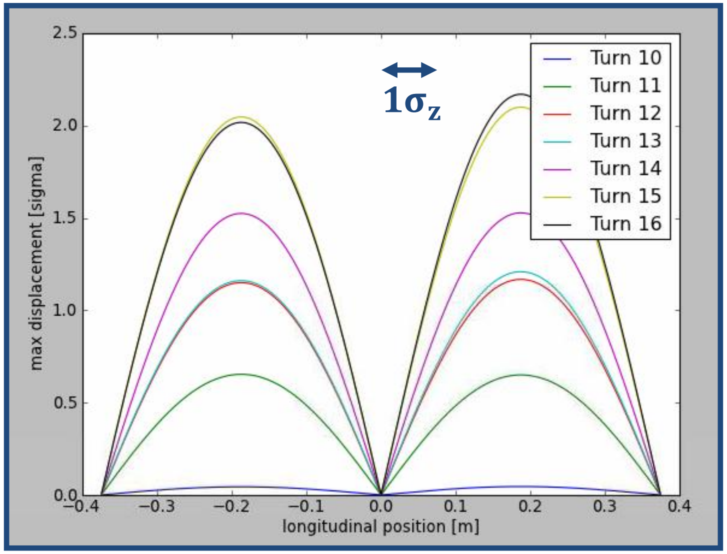
- Resulting maximal displacement after 5 turns:

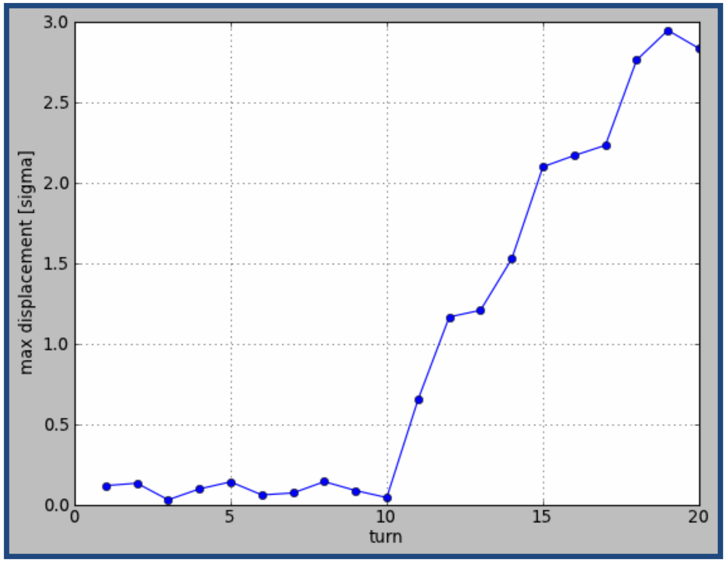
$$\bar{x} = \sqrt{x_\beta^2 + (\alpha \cdot x_\beta + \beta \cdot x'_\beta)^2}$$

$$= 2.2\sigma_x \text{ at } z = \pm 2.4\sigma_z,$$

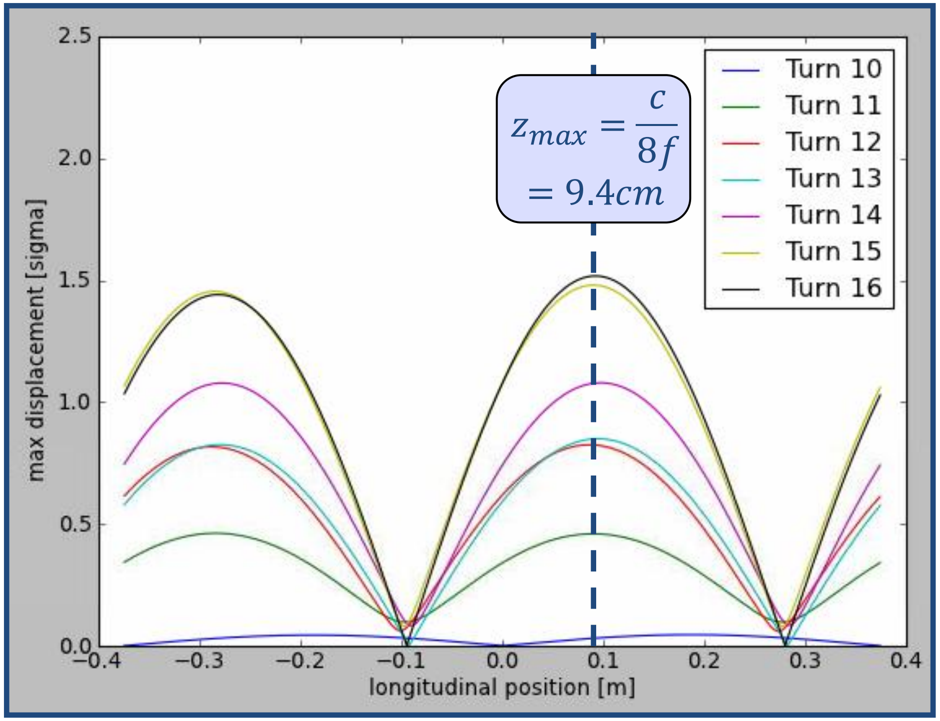
with $x_\beta = x - D_x * \frac{\Delta p}{p}$, $x'_\beta = x' - D_{px} * \frac{\Delta p}{p}$.

- The (longitudinal) bunch center is not displaced.

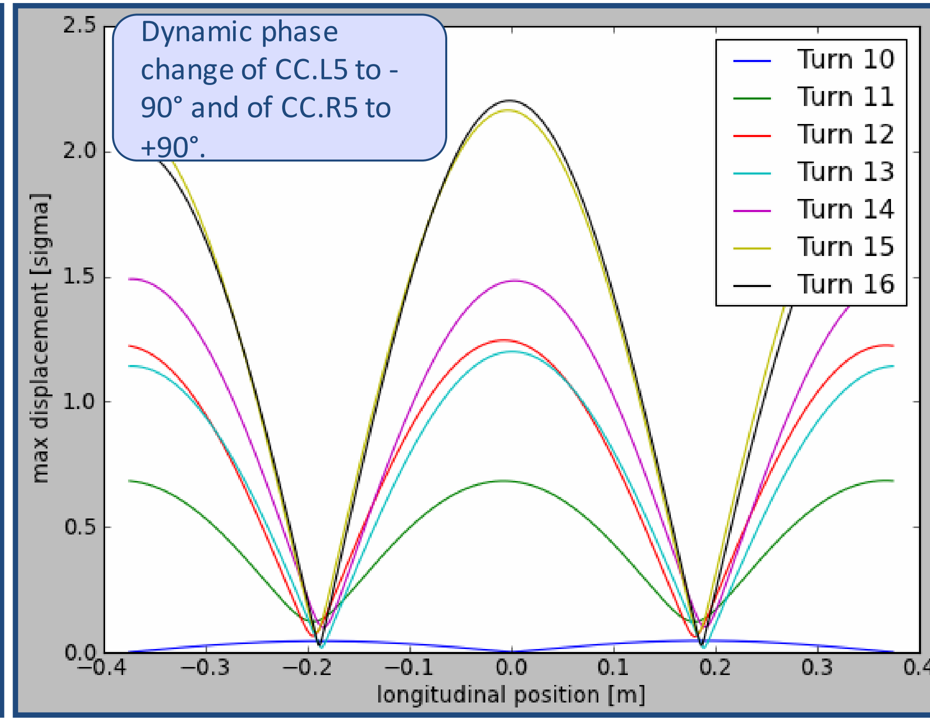


# Phase Failure



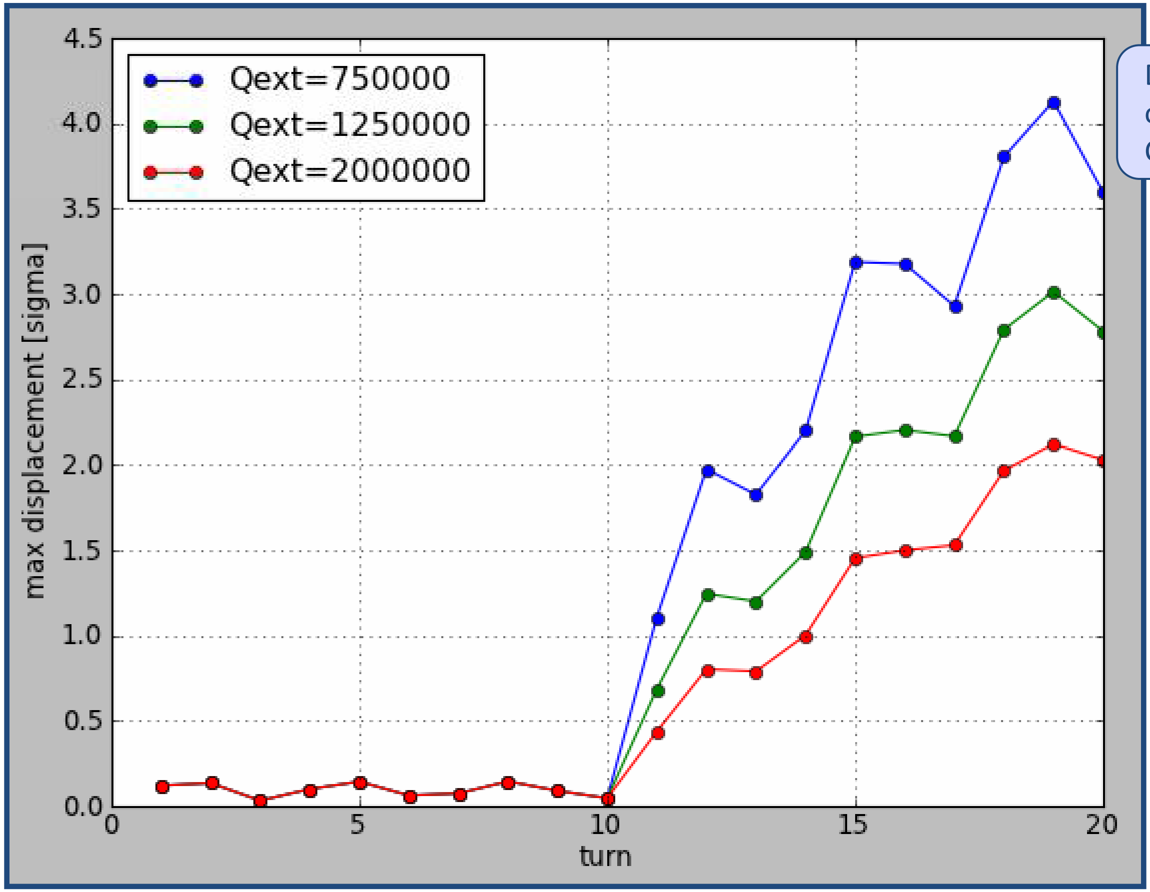

*Dynamic phase change of CC.R5 by 90°.*




*Opposite phase change of both CCs.*

In case of a **dephasing** of the crab cavities, the (longitudinal) **bunch center** is maximally displaced by up to $\mathbf{2.2\sigma_x}$ **in 5 turns**.

# Dephasing and $Q_{ext}$




Dynamic phase change of CC.L5 to -90° and of CC.R5 to +90°.

The failure dynamics strongly depends on $Q_{ext}$.

# Content

# Transverse Beam Distribution

- Highly overpopulated tails observed:

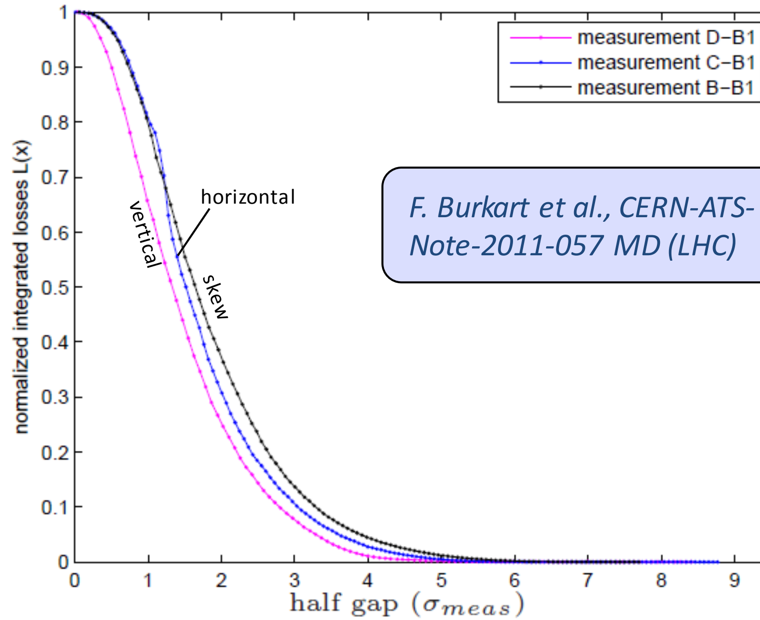
  *In horizontal plane about* ***4%*** *of beam beyond* $\mathbf{4\sigma_{meas}}$*.*

  *Cooresponds to* ***≈20MJ*** *with HL-LHC parameters.*

- Collimation system designed for fast accidental losses of up to **1MJ**.

  *R. Assmann, „Collimation for the LHC High Intensity Beams", HB2010*

- Need to **deplete tails** (e.g. by **hollow electron lens**) such that crab cavity failures are compliant with collimation system specifications.




*F. Burkart et al., CERN-ATS-Note-2011-057 MD (LHC)*

Table 3: Measured fraction of beam intensity in the tails of the beam outside selected multiples of the measured beam size, $\sigma_{meas}$, at 450 GeV.

| u [$\sigma_{meas}$] | $I_{tot,lost}(u)/I_{total}$ vertical | $I_{tot,lost}(u)/I_{total}$ horizontal | $I_{tot,lost}(u)/I_{total}$ skew |
|---|---|---|---|
| | B1 | B1 | B1 |
| 4 | 9.4e-3 | 3.8e-2 | 4.5e-2 |
| 5 | 2.2e-3 | 7.8e-3 | 1.3e-2 |
| 5.7 | 8.4e-4 | 1.6e-3 | 3.8e-3 |

*F. Burkart et al., CERN-ATS-2011-115.*

# Possible Scenarios

Tolerable scenarios with losses below 1MJ in max 5 turns:

*Magnet quenching in failure case not excluded.*

| | Scenario 1: $\beta^* = 30cm$ | Scenario 2: 800 MHz or Independent CCs | Scenario 3: large $Q_{ext}$ |
|---|---|---|---|
| **CC frequency (f)** | 400 MHz | 400 MHz / **800 MHz** | 400 MHz |
| **Number of independant CCs ($n_{cc}$)** | 1 | **2** / 1 | 1 |
| **$Q_{ext}$** | 1'250'000 | 1'250'000 | **2'000'000** |
| **$\beta^*$** | **30 cm** | 15 cm | 15 cm |
| **Fraction to be depleted below 1MJ.** | 1.1σ | 1.1σ | 1.5σ |

\+ single turn failure detection and interlock.

- *on cavity level.*
- *on beam level (head-tail-monitor?).*

# Conclusion

- Failure scenarios are **strongly optics (β*) dependent** .
- **Dephasing** of crab cavities can lead to a transverse displacement of the (longitudinal) **bunch center** by up to **2.2σ**.

  *Unacceptable with multi-MJ tails.*
- Mitigation options:
  - *Lower voltage (partial compensation of crossing angle), or larger $\beta^*$.*
  - *Crab kick by several **INDEPENDENT** crab cavities.*
  - *Larger cavity frequency.*
  - *Larger $Q_{ext}$ (= slower time constant of failures).*
  - ***Hollow electron lens** to deplete transverse tails (essential).*
- Plans for future studies:
  - *Simulations with realistic beam distribution and beam -> cavity interaction.*
  - *Sixtrack simulations and quench predictions (Bruce Yee).*

# Thank you
# for your Attention

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Further information:

- T. Baer, "Beam Dynamics Aspects of Crab Cavity Failures", December 2010.
- J. Tuckmantel, "Failure scenarios and mitigation", LHC-CC10, December 2010
- J. Wenninger, "Machine Protection", LHC-CC10, December 2010

Backup slides

# Analytical Approach

- Horizontal kick by crab cavity:

$$p_{x,cc}(z) = -\frac{q \cdot V}{E} \cdot \sin\left(\Phi + \frac{\omega \cdot z}{c}\right)$$

optimal voltage (local scheme, IP5):

$$\boldsymbol{V} = \frac{\boldsymbol{c} \cdot \boldsymbol{E} \cdot \tan(\frac{\Theta}{2})}{\boldsymbol{q} \cdot \boldsymbol{\omega} \cdot \sqrt{\boldsymbol{\beta}^* \cdot \boldsymbol{\beta}_{cc}} \cdot \sin(\Delta\varphi)}$$

maximal displacement:

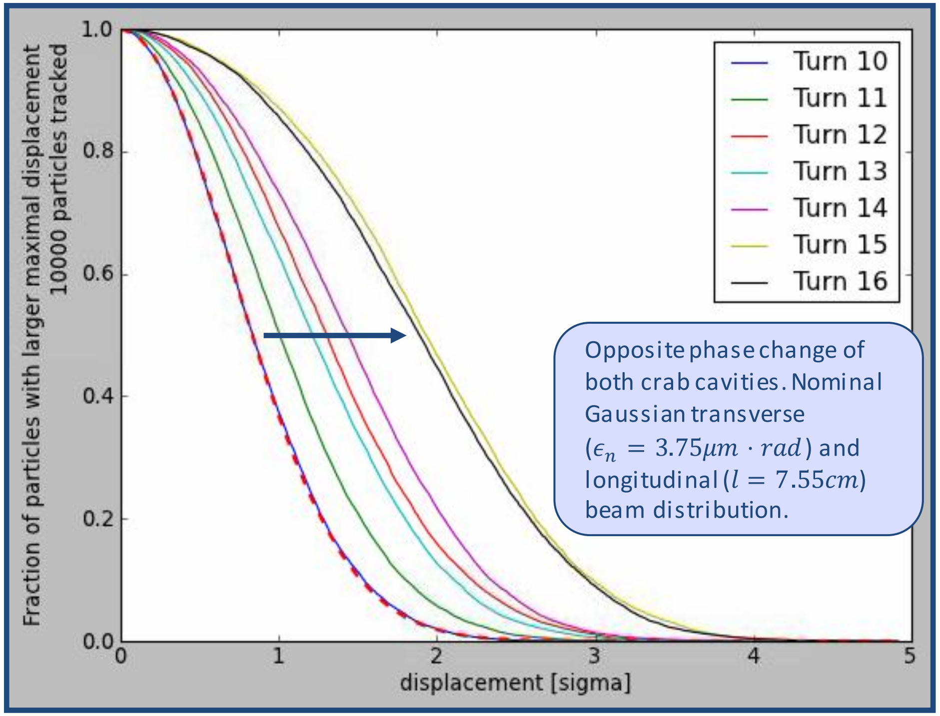
$$\frac{\boldsymbol{x}_{cc}(\boldsymbol{z})}{\boldsymbol{\sigma}_x} = -\underbrace{\frac{\boldsymbol{c} \cdot \tan(\frac{\Theta}{2})}{\boldsymbol{\omega} \cdot \boldsymbol{\sigma}_{x,IP} \cdot \sin(\Delta\varphi)}} \cdot \sin\left(\boldsymbol{\Phi} + \frac{\boldsymbol{\omega} \cdot \boldsymbol{z}}{\boldsymbol{c}}\right)$$

**= 3.98** (1.02 for nominal optics)

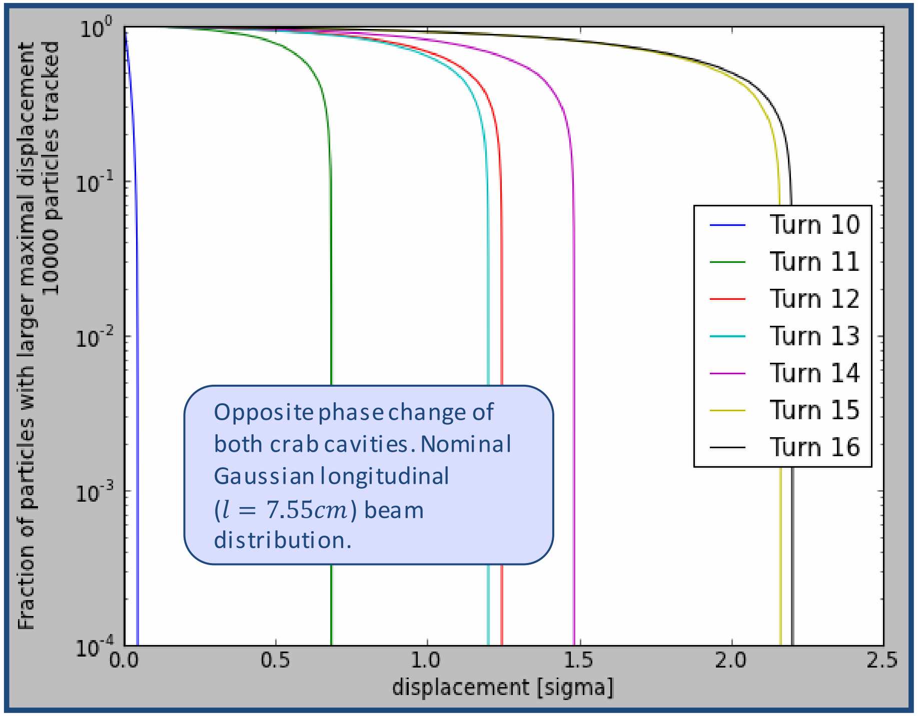
| q | = particle charge |
|---|---|
| E | = particle Energy (7 TeV) |
| V | = voltage of crab cavity |
| Φ | = phase of crab cavity |
| Θ | = full crossing angle (580/285 μrad) |
| φ | = phase advance CC ->IP (≈ π/2) |
| ω | = angular frequency of CC (2 π·400 MHz) |
| z | = longitudinal position of particle |
| c | = speed of light |

| | Upgrade optics | Nominal optics |
|---|---|---|
| Maximal kick by crab cavity: x ≈ | **$4\sigma_x$** | **$1\sigma_x$** |
| For z = 7.55cm (= $1 \cdot \sigma_z$): $x_{cc}$(z = 7.55cm) ≈ | **$2.36\sigma_x$** | **$0.60\sigma_x$** |

# Phase Change




*Maximal displacement with Gaussian transverse and longitudinal beam distribution.*




*Maximal displacement with Gaussian longitudinal beam distribution.*

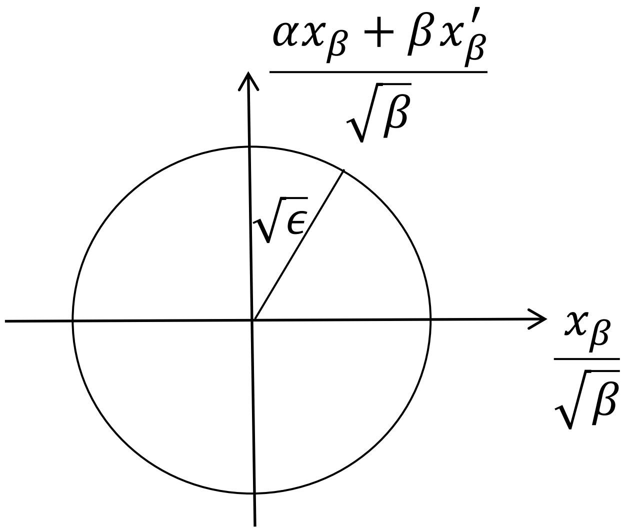
In case of a **dephasing** of the crab cavities left and right of the IP, the (longitudinal) **bunch center** is maximally displaced, by up to **$2.2\sigma_x$ in 5 turns**.

# Normalized Phase Space

Single particle emittance:

$$\epsilon = \frac{\left(\alpha x_\beta + \beta x'_\beta\right)^2}{\beta} + \frac{x_\beta^2}{\beta}$$

with $x_\beta = x - D_x * \frac{\Delta p}{p}$, $x'_\beta = x' - D_{px} * \frac{\Delta p}{p}$.




Maximal displacement:

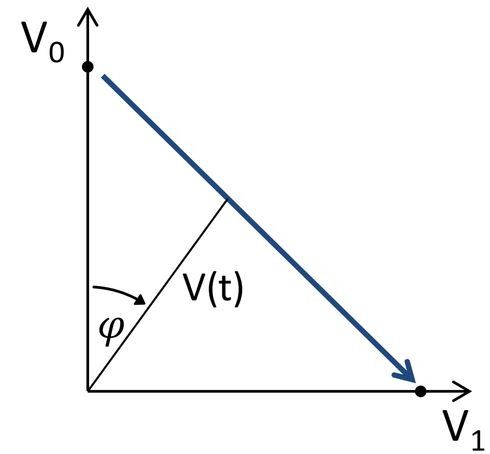
$$\bar{x} = \sqrt{\epsilon \cdot \beta} = \sqrt{x_\beta^2 + \left(\alpha \cdot x_\beta + \beta \cdot x'_\beta\right)^2}.$$

# 90° Phase Change

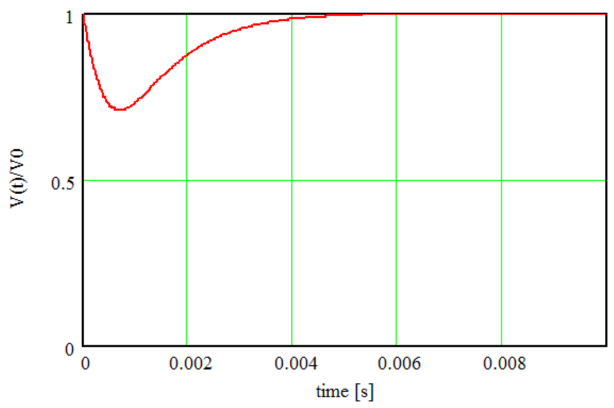
- Maximal phase change in first turn:

$$\varphi = arctan\left(\frac{\frac{\Delta V}{V}}{1-\frac{\Delta V}{V}}\right) = \mathbf{5.3°}.$$

- Phase change is fastest if cavity voltage changes as well.




*Illustraction of 90° voltage change.*



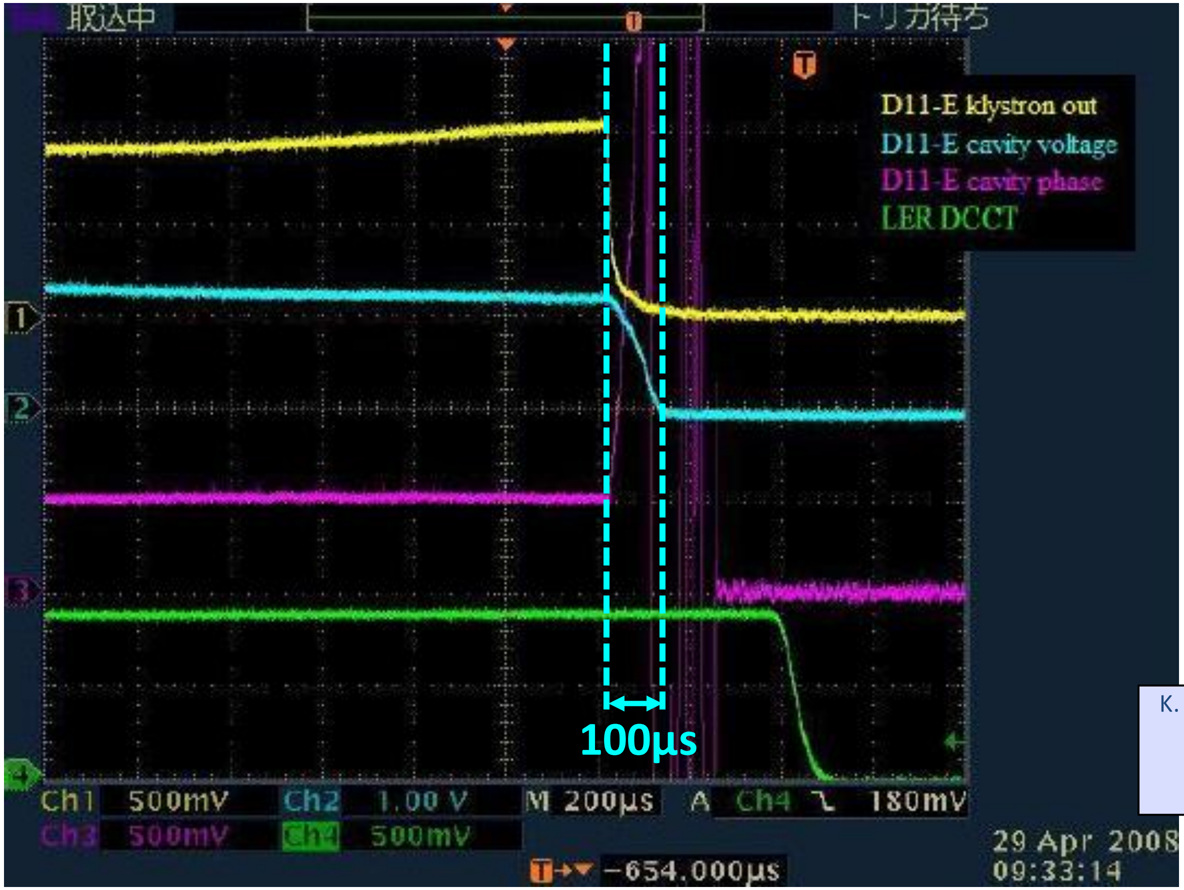

*Amplitude of cavity voltage.*

# Content

Static Failure Scenarios

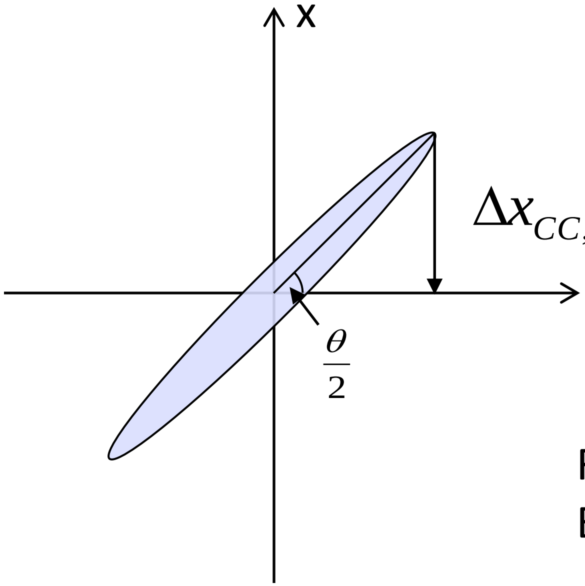
# KEK Crab Cavity Quench

- Full decay of crab cavity in **≈100μs**.
- Oscillations of Crab Cavity phase (**up to 50° in 50μs**).




K. Nakanishi et al., *Beam Behaviour due to Crab Cavity Breakdown*, Proceedings of IPAC'10, Kyoto

# Very Simple Approximation




$$\Delta x_{CC,IP}(z) = -\frac{\theta}{2} \cdot z$$

Displacement at IP needed to compensate the crossing angle (Θ, z small)

For $\Theta = 580\mu rad$, $\beta_{IP} = 0.15m$, $\varepsilon_{norm} = 3.75\mu m \cdot rad$,
$E = 7TeV$, $\sigma_z = 7.55cm$:

**$\Delta x = -2.52\ \sigma_x \cdot z/\sigma_z$**

Expected beamlosses from simple Monte Carlo:

Particle is lost if $|RAND_{Gauss} + 2.52 \cdot RAND_{Gauss}| > 5.7$

-> Expected loss: **(3.5 ± 0.2)%**

# Simple Approximation (MC)

Beamloss approximation with simple Monte Carlo (upgrade optics):

- Failure of single cavity (V -> 0):

  Particle is lost if $|x + x_{cc}(z) \cdot k(\Delta\varphi_{CC\text{->}TCP})| > 5.7 \cdot \sigma_x$

  Scaling factor (≈ 1.12)

  1. Gaussian Distribution

  2. Gaussian Distribution

  -> expected loss: **(0.88 ± 0.06)%**

- Phase error of single cavity (Φ -> π/2):

  Particle is lost if $|x + x_{cc}(z, \Phi = \pi/2) \cdot k - x_{cc}(z, \Phi = 0) \cdot k| > 5.7\sigma_x$

  CC with failure

  CC without failure

  -> expected loss: **(24.8 ± 0.3)%**

# Content

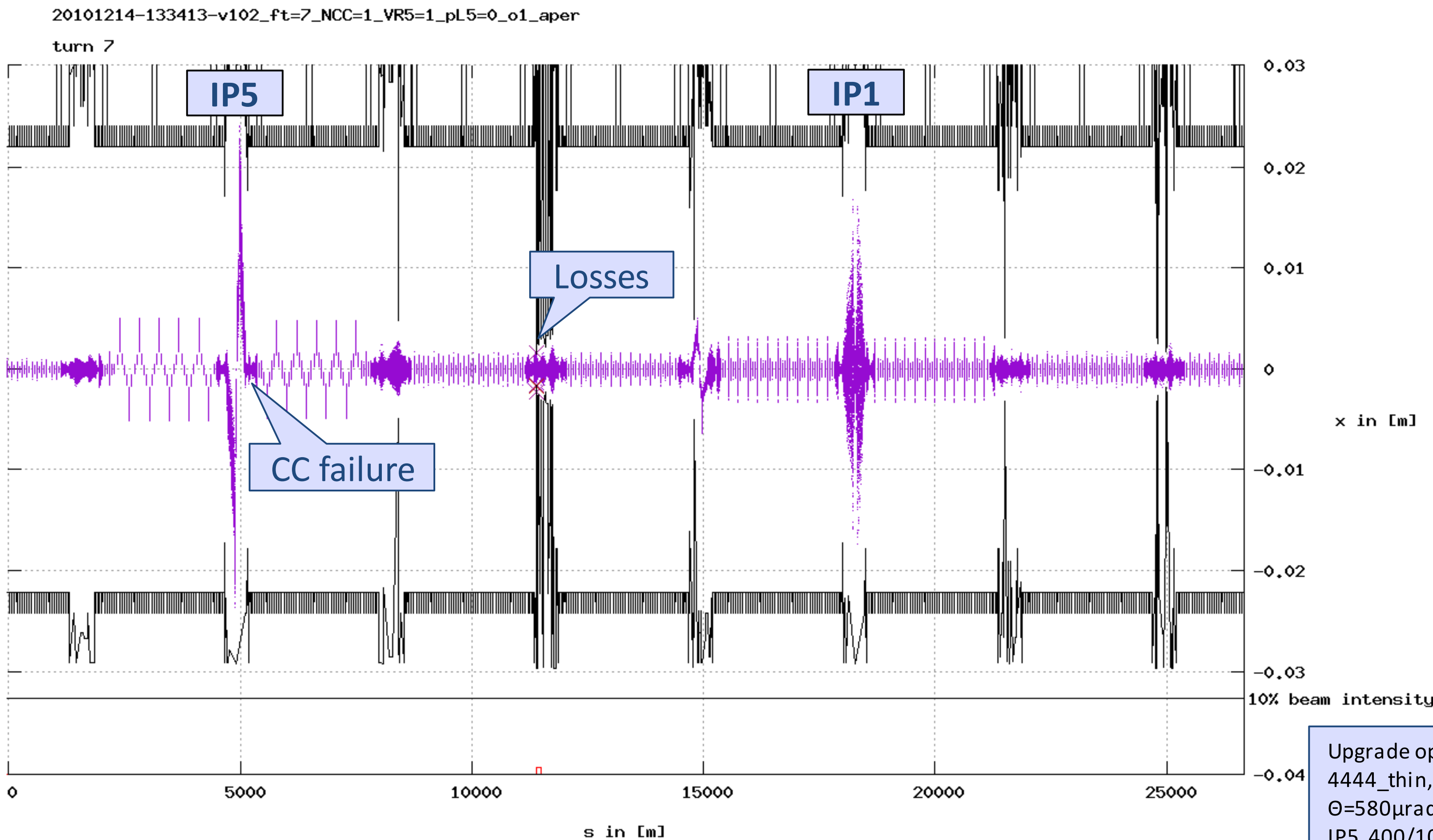
Static Tracking Studies with upgrade optics (MAD-X)

- Fast Voltage Decay
- Phase Error

# Failure of CRAB.R5.B1

Voltage of Crab.R5.B1 = 0.

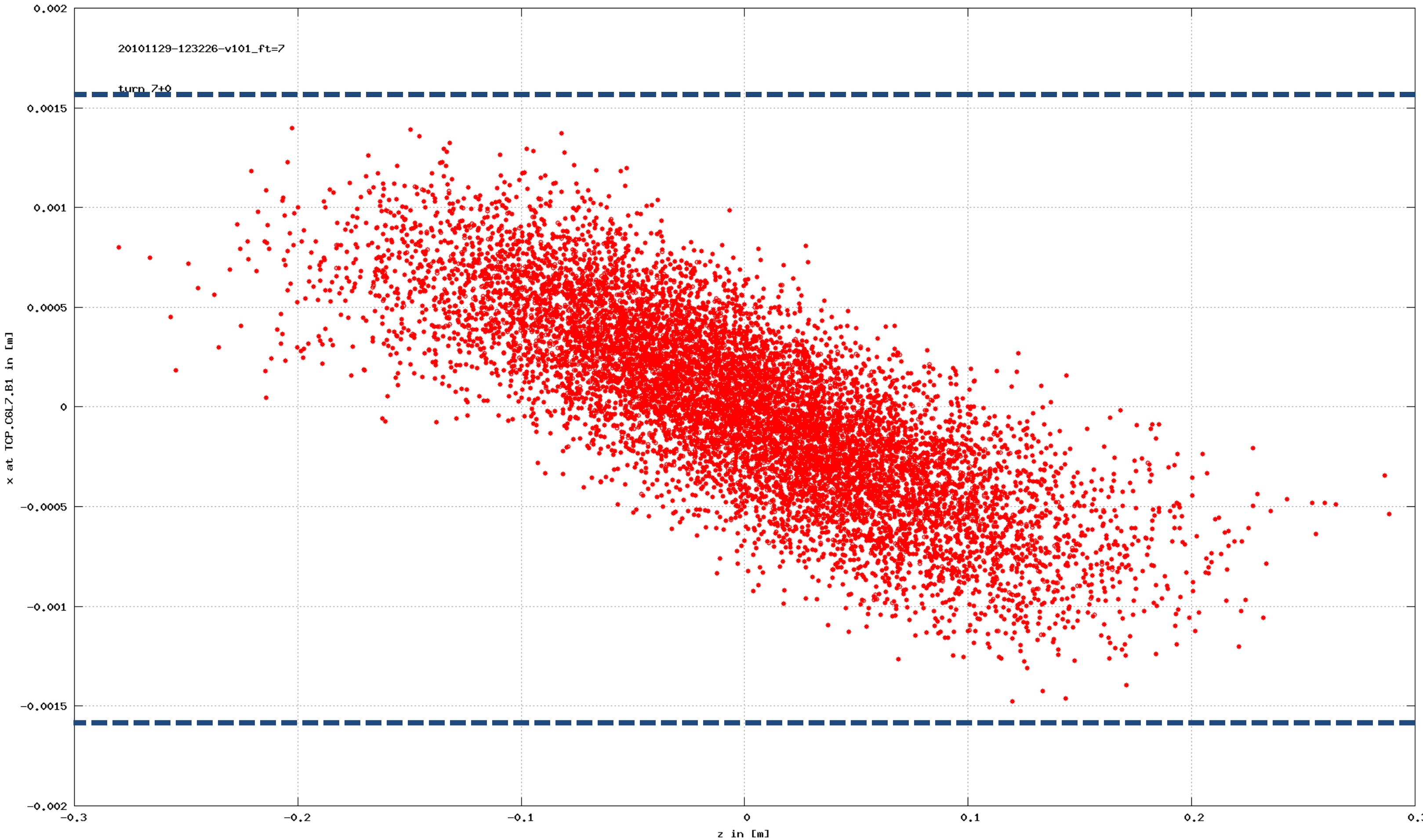
Total beam loss: **1.3%** in 2 turns (2% in first 10 turns), mainly at **TCP.C6L7.B1**.




Upgrade optics SLHCV3.0
4444_thin, IP1/5: β* = 0.15m,
Θ=580µrad, CC Local scheme
IP5, 400/10,000 particles

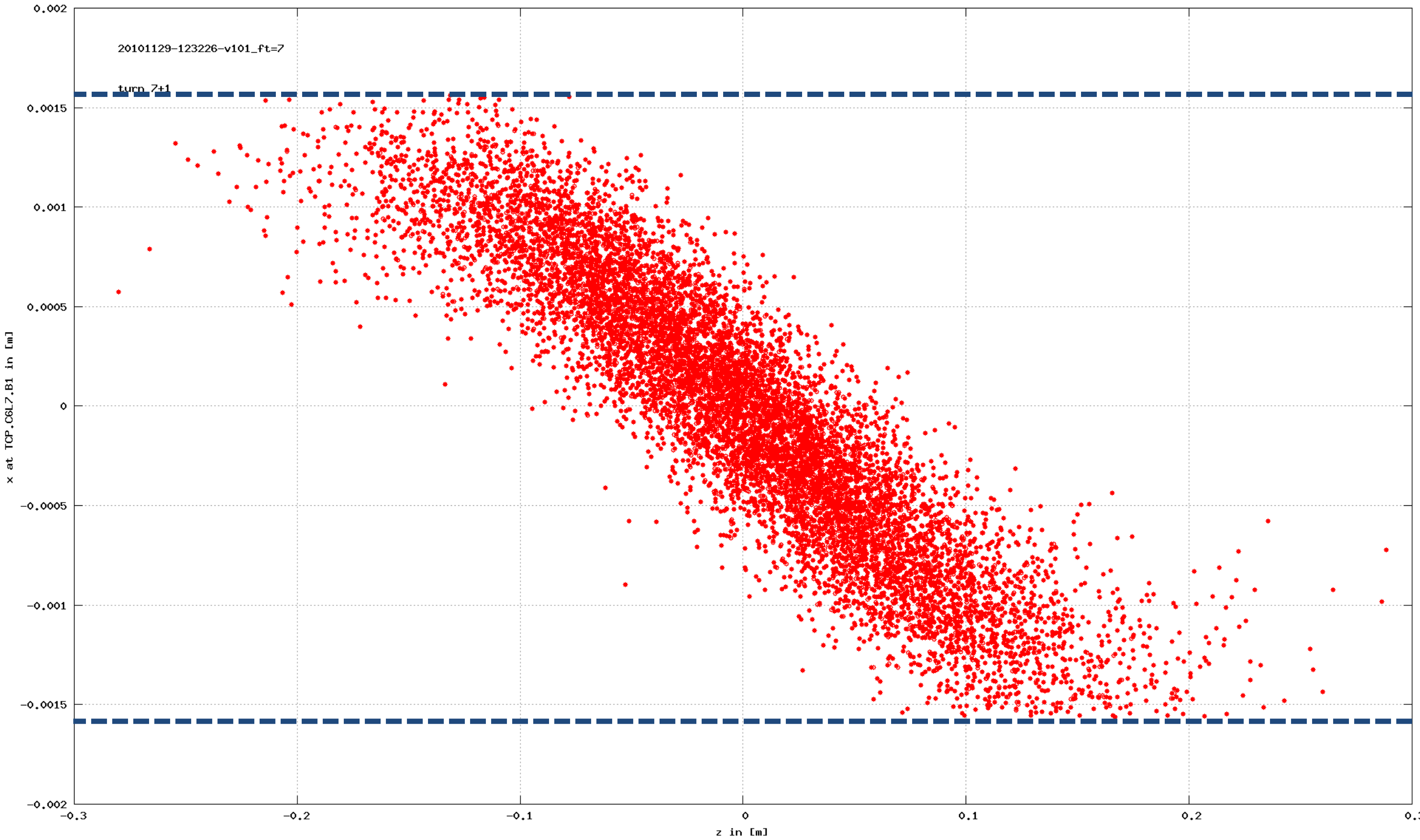
# Failure of CRAB.R5.B1

Bunchshape at **TCP.C6L7.B1** directly after failure.



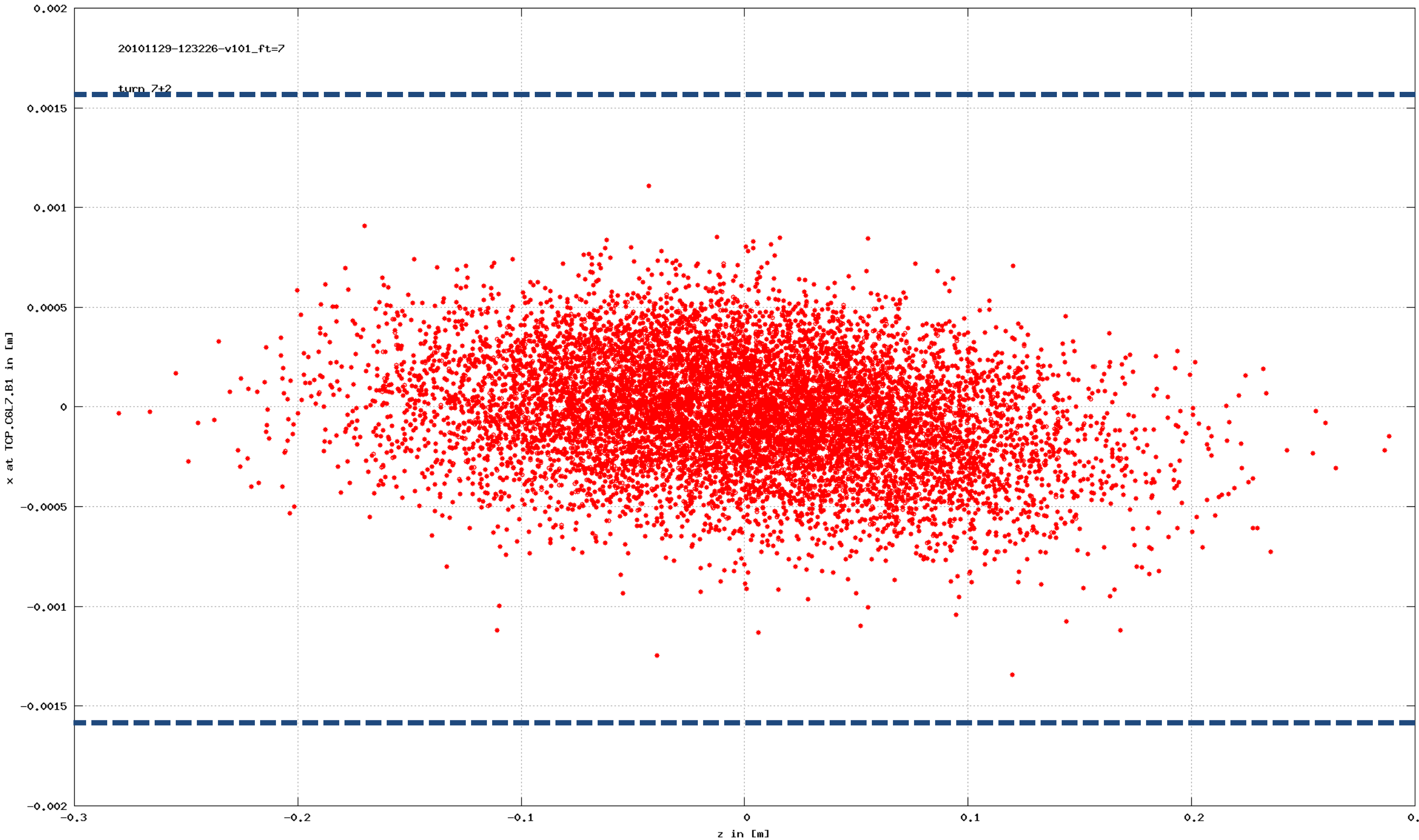
# Failure of CRAB.R5.B1

Bunchshape at **TCP.C6L7.B1**, 1 turn after failure.



# Failure of CRAB.R5.B1

Bunchshape at **TCP.C6L7.B1**, 2 turns after failure.



# Content

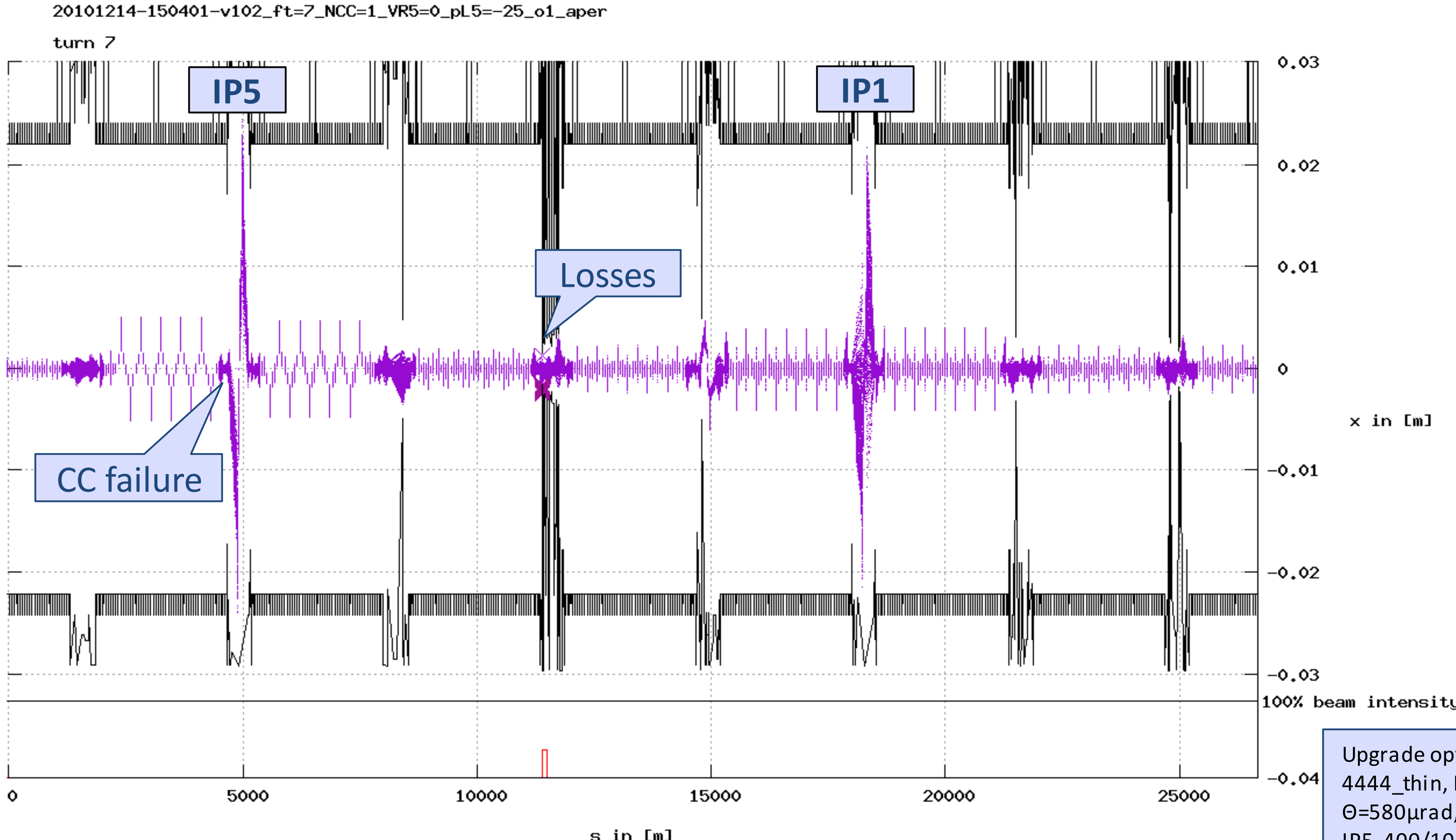
Static Tracking Studies with upgrade optics (MAD-X)

- Fast Voltage Decay
- Phase Error

# Phase Error of CRAB.L5.B1

Upgrade Optics, Phase of Crab.L5.B1 = -π/2.

Total beam loss: **15% - 35%** in 2 turns, mainly at **TCP.C6L7.B1**

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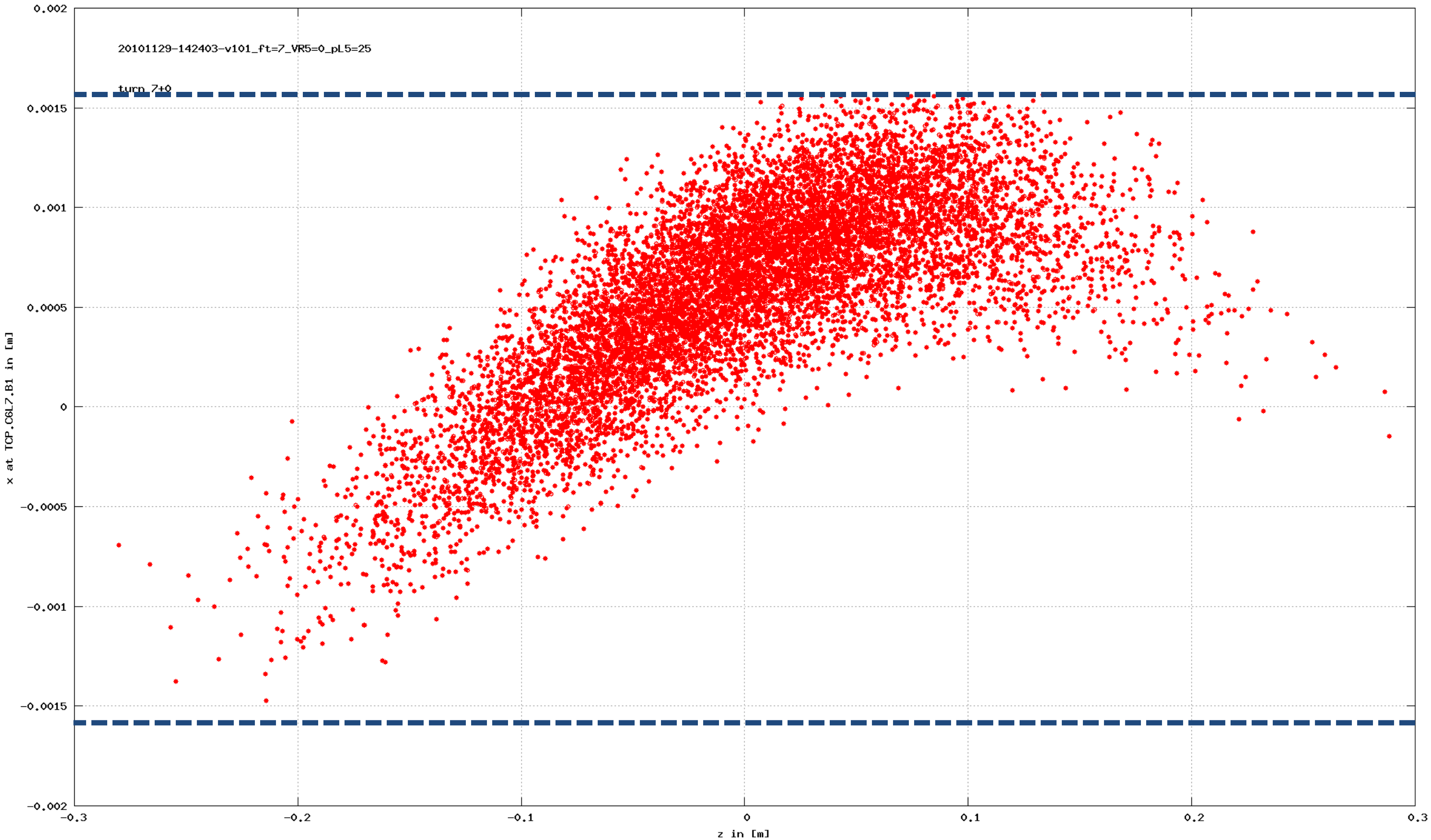
IP5, 400/10,000 particles

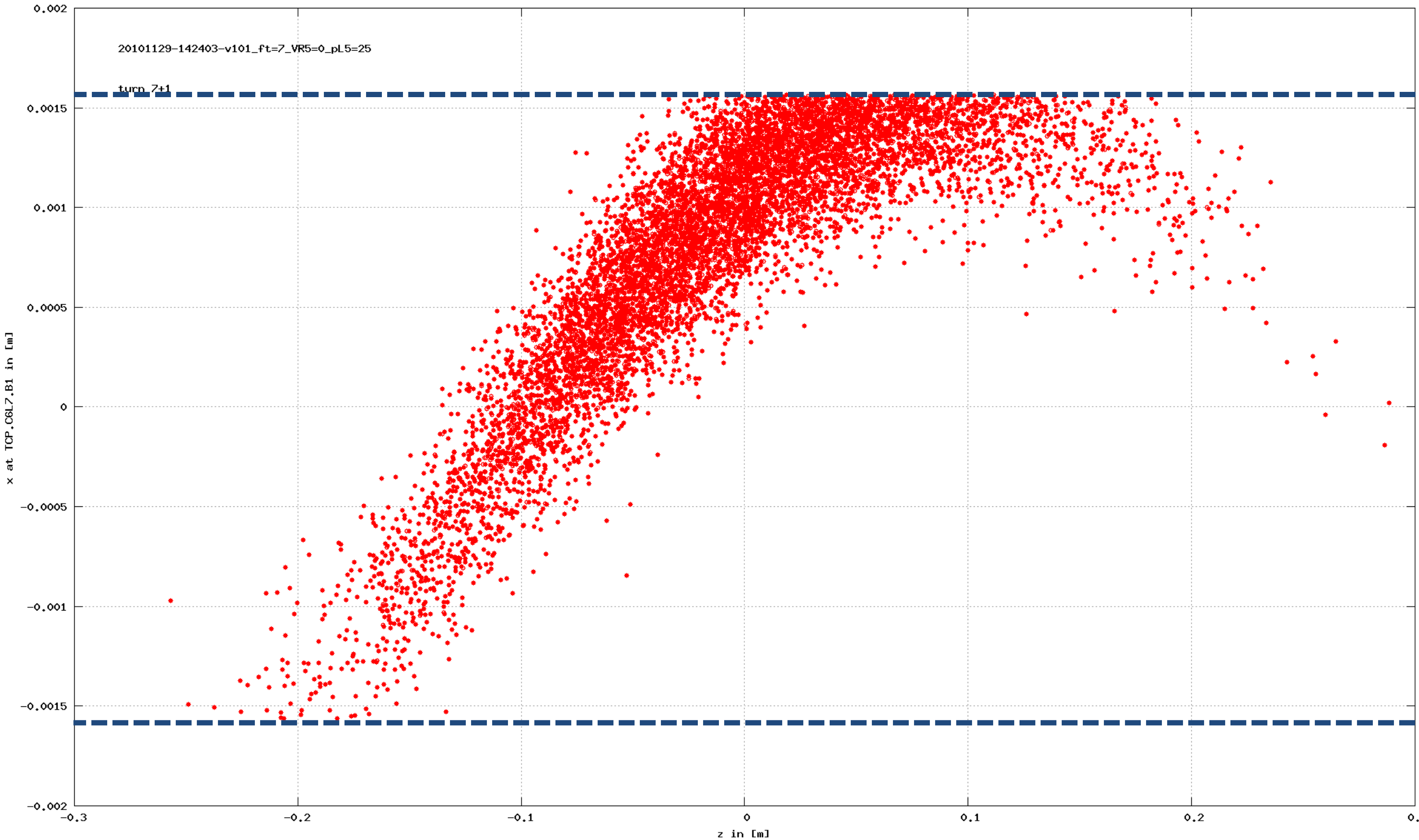
# Phase Error of CRAB.L5.B1

Bunchshape at **TCP.C6L7.B1** directly after failure.

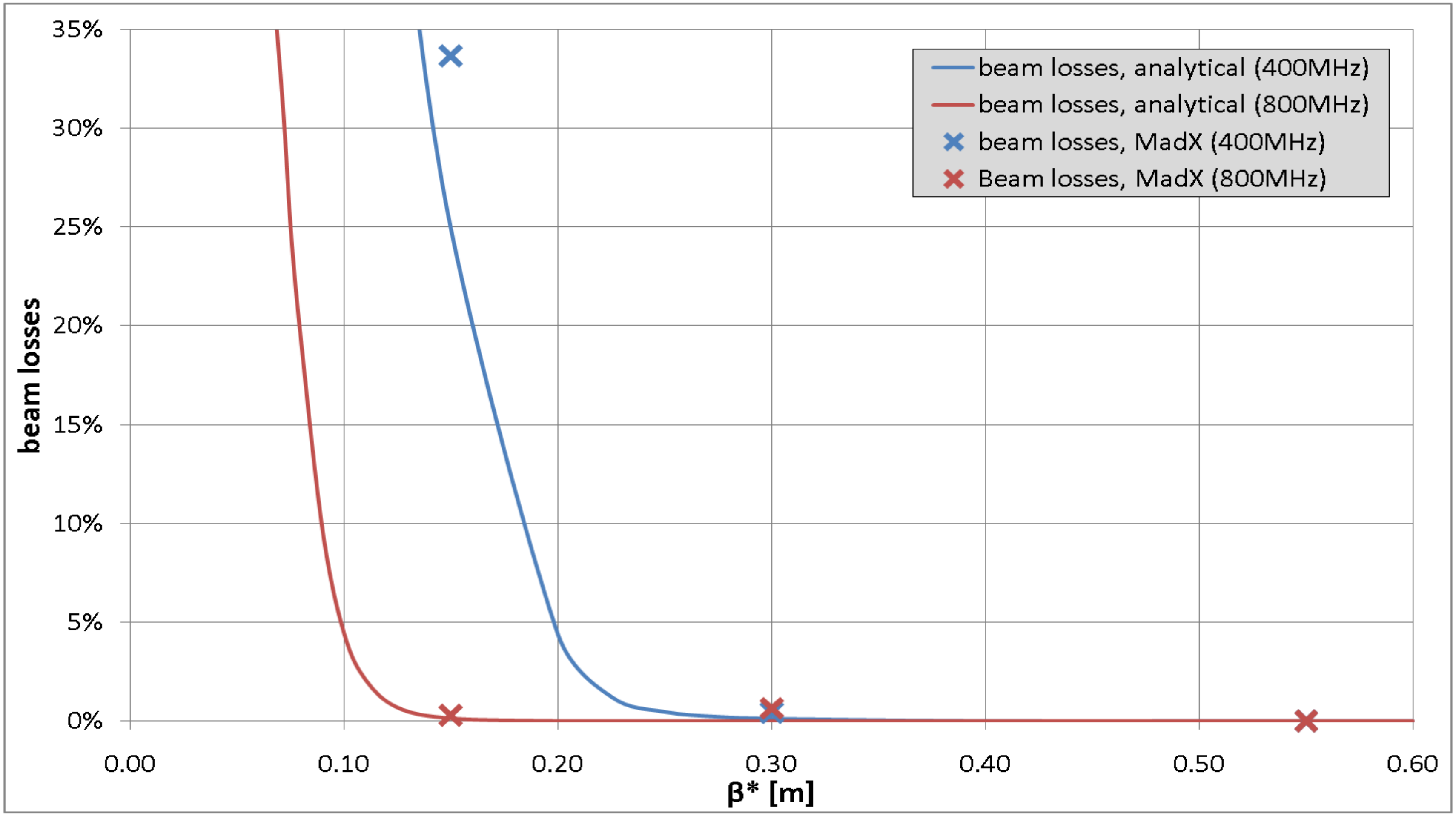


# Phase Error of CRAB.L5.B1

Bunchshape at **TCP.C6L7.B1**, 1 turn after failure.



# Losses vs β*




Beam losses for 90° phase shift of single CC (local scheme IP5)