European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

Machine Protection against Very Fast Crab Cavitiy Failures

MPP

Tobias Baer
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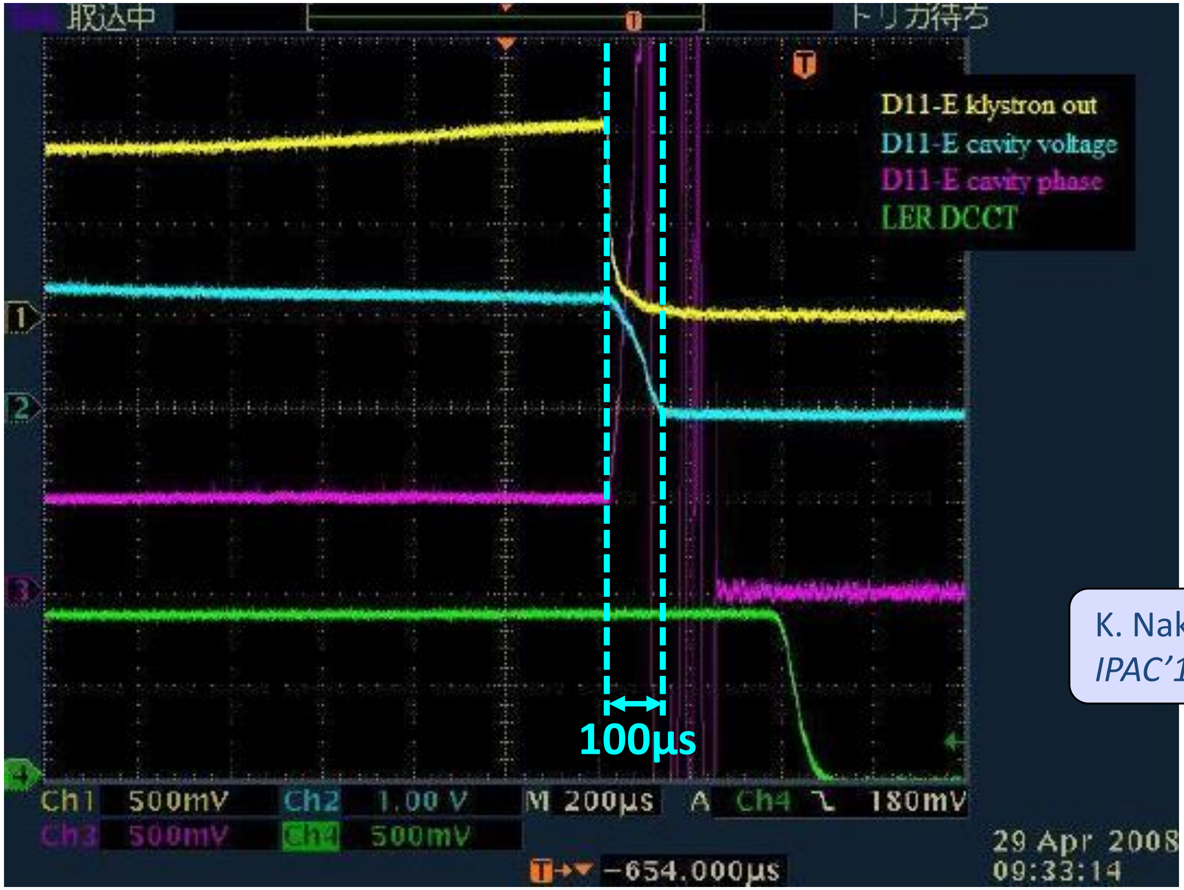
Acknowledgement: F. Burkart, R. Calaga, E. Jensen, R. de Maria, S. Fartoukh, R. Tomas, J. Tuckmantel, J. Wenninger, F. Zimmermann.

Content

Content

KEK Crab Cavity Quench

- Full decay of crab cavity in **≈100μs** (≈1 turn).
- Oscillations of Crab Cavity phase (**up to 50° in 50μs**).



K. Nakanishi et al., *IPAC'10, WEPEC022.*

Analytical Approach

- Horizontal kick by crab cavity:

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

- Optimal voltage to compensate crossing angle (local scheme):

$$V_0 = \frac{c \cdot E \cdot \tan\left(\frac{\Theta}{2}\right)}{q \cdot \omega \cdot \sqrt{\beta^* \beta_u} \cdot \sin(\Delta\varphi) \cdot n_{cc}}$$

- Optimal voltage for compensating cavities:

$$\tilde{V}_0 = -\sqrt{\frac{\beta_u}{\beta_d}} \cdot \cos(\Delta\varphi_{cc}) \cdot V_0$$

ideally 180°

q = particle charge
E = particle Energy (7 TeV)
V = voltage of crab cavity
Φ = phase of crab cavity (0°)
Θ = full crossing angle (590 µrad)
$\Delta\varphi$ = phase advance CC ->IP (≈ 90°)
$\Delta\varphi_{cc}$ = phase advance CC_u -> CC_d (181.4°)
ω = angular frequency of CC (2π·400 MHz)
z = longitudinal position of particle
c = speed of light
β^* = beta function at the IP
$\beta_{u,d}$ = beta function at upstream/ downstream CC.
n_{cc} = number of CCs per beam on either side of IP.

Analytical Approach

- Maximal transverse displacement by crab cavity:

  (assuming optimal voltage to compensate crossing angle)

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

= 4.05 (upgrade optics, $\beta^* = 15cm$, n_{cc}=1)

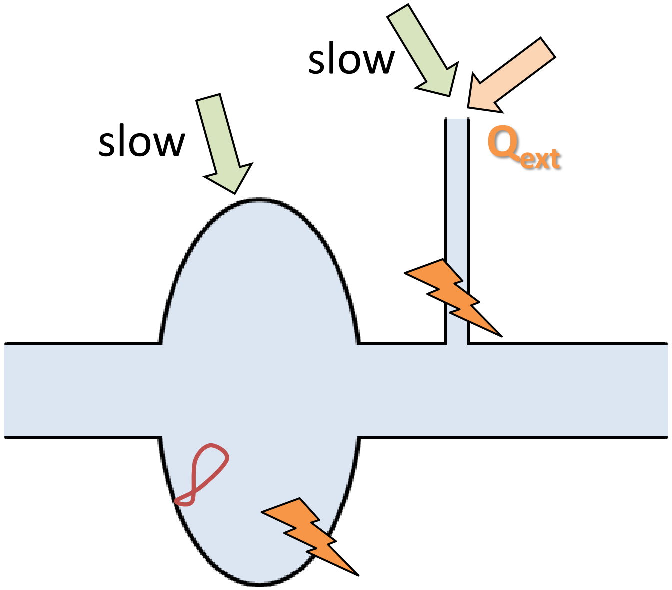
T. Baer et. al, IPAC'11, TUPZ009

	upgrade optics	nominal optics
Maximal displacement 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 (= $1 \cdot \sigma_z$): $\bar{x}_{cc}(z = 7.55\text{cm}) \approx$	**$2.36\sigma_x$**	**$0.60\sigma_x$**

Failure Scenarios

Slow (external) failures

- Power cut
- Thermal problems
- Mechanical changes (tuner problem)



Fast external failures

- Control-logics failure
- Operational failure
- Equipment failure
- …

Timescale determined by Q_{ext}.

Internal failures

- Arc in coupler
- Multipacting
- Cavity quench (?)

Timescales < 1 turn possible.

cf. J. Tuckmantel, „Failure Scenarios and Mitigation“, LHC-CC10

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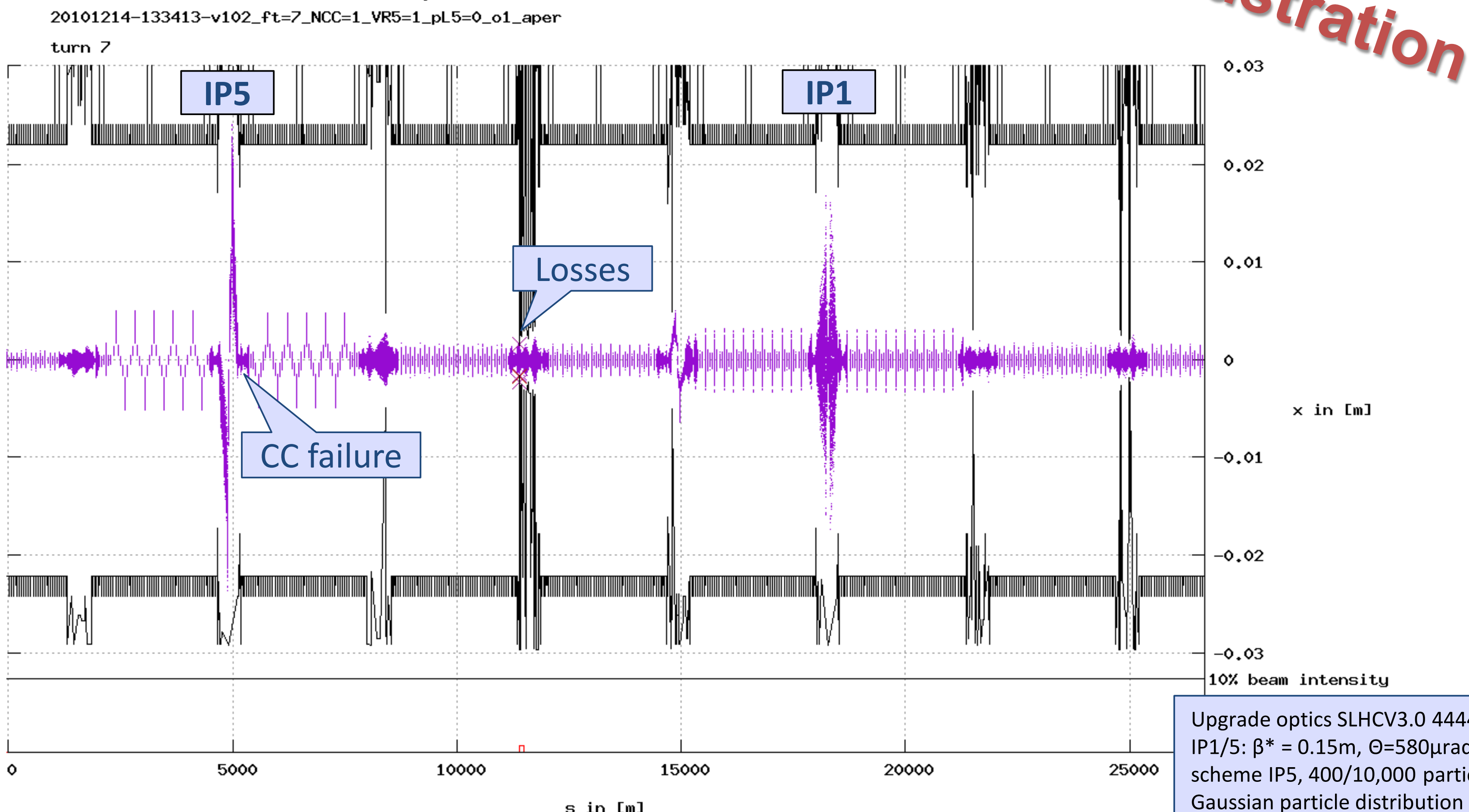
Failure Simulations

- Crab cavity **local scheme IP5**, beam 1.
- **No splitting of crab cavity kicks.**
- Optics:
  - **SLHCV3.1b**, **β* = 0.15m** (IP1/5), β* = 10.0m (IP2/8), ϴ = 590μrad.
  - Nominal optics**, β* = 0.55m** (IP1/5), β* = 10.0m (IP2/8), ϴ = 285μrad.
- Instantaneous failure of single crab cavity, constant (e.g. at V=0) afterwards.
- Tracking for ≈20 turns.

Voltage Failure of CC.R5.B1

Voltage of Crab.R5.B1 = 0.

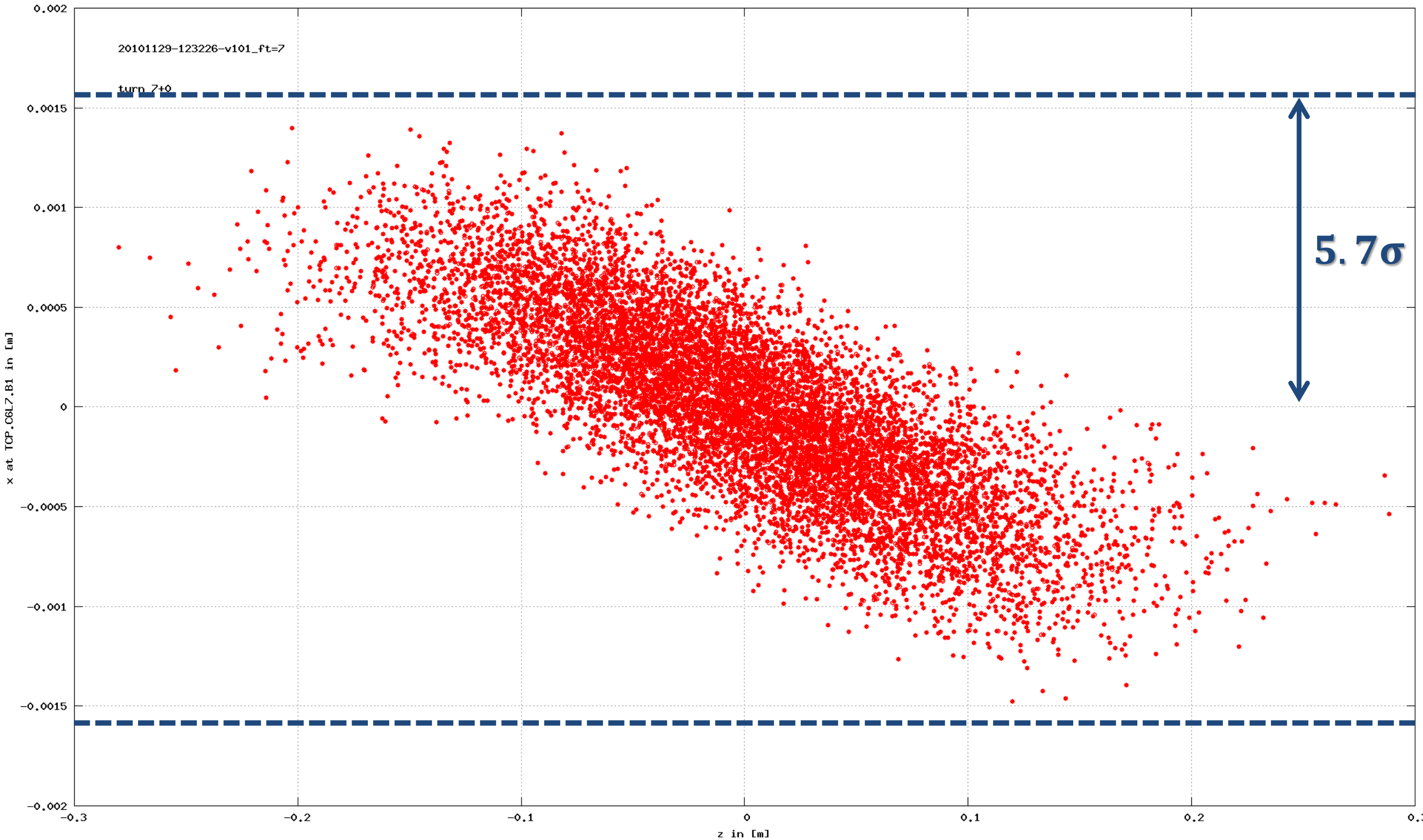
Beam losses mainly at **TCP.C6L7.B1**.



Upgrade optics SLHCV3.0 4444_thin, IP1/5: β* = 0.15m, Θ=580μrad, CC Local scheme IP5, 400/10,000 particles, Gaussian particle distribution $\epsilon_n = 3.75\mu m \cdot rad., \sigma_z = 7.55cm.$

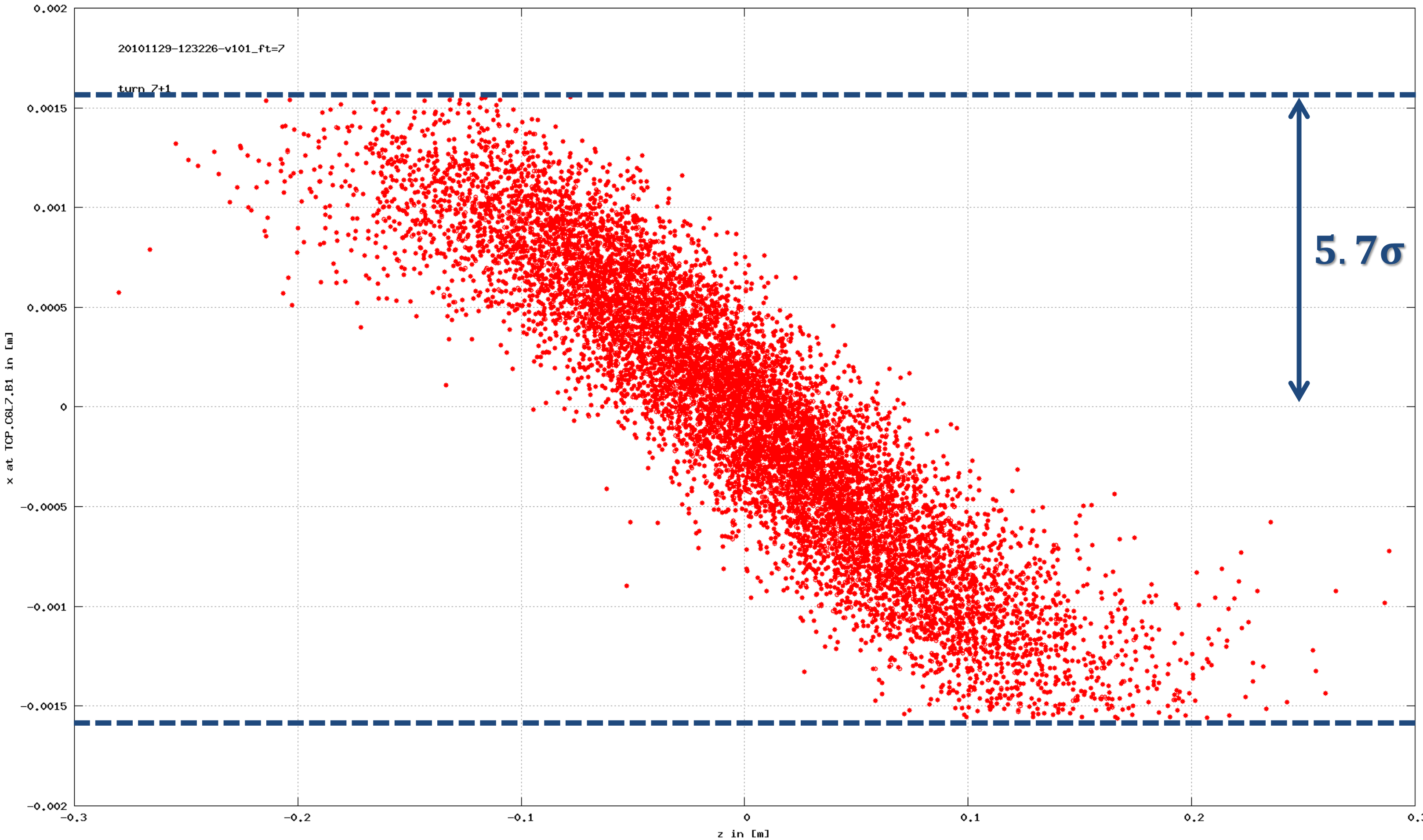
Failure of CRAB.R5.B1

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



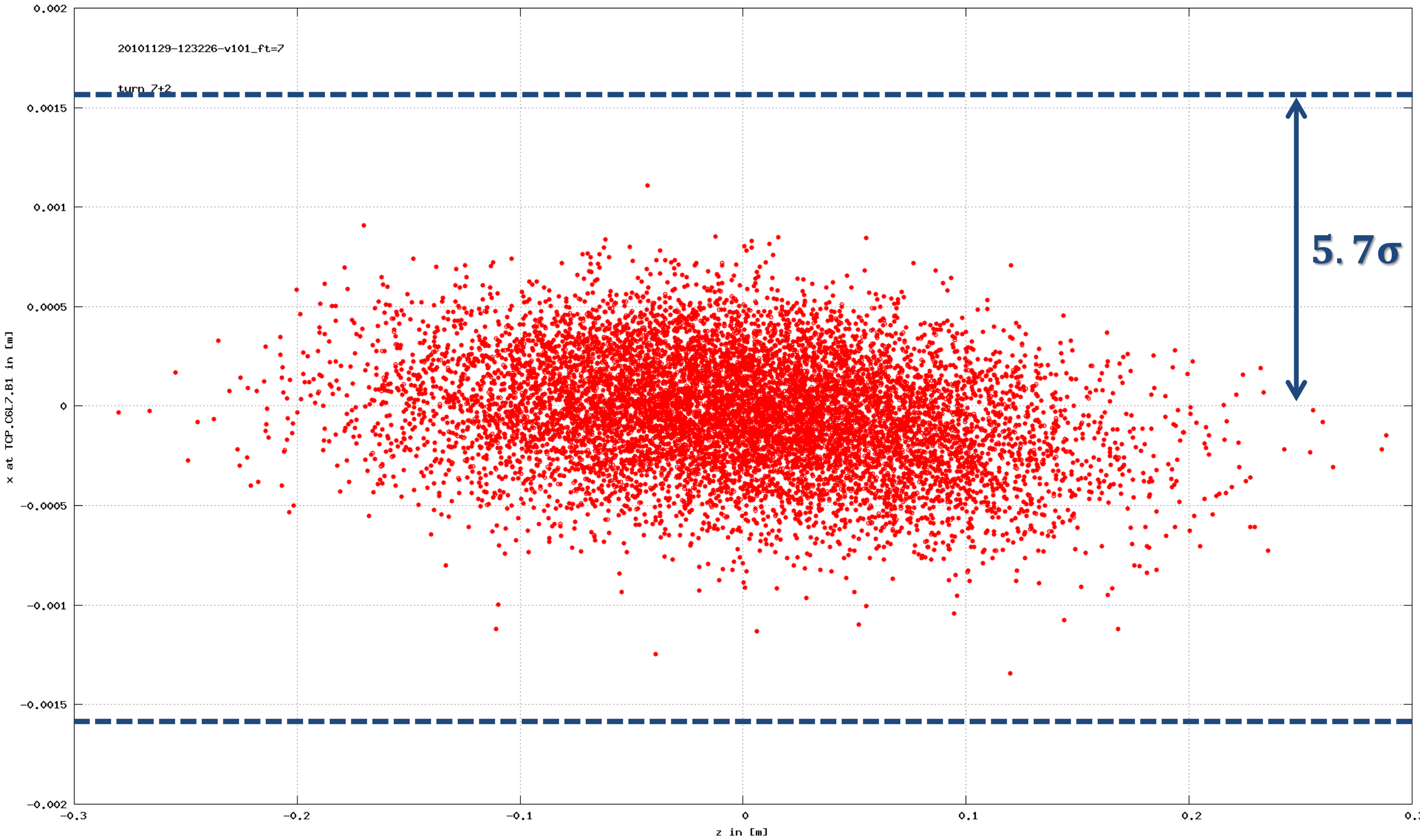
Failure of CRAB.R5.B1

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



Failure of CRAB.R5.B1

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



Maximal Displacement

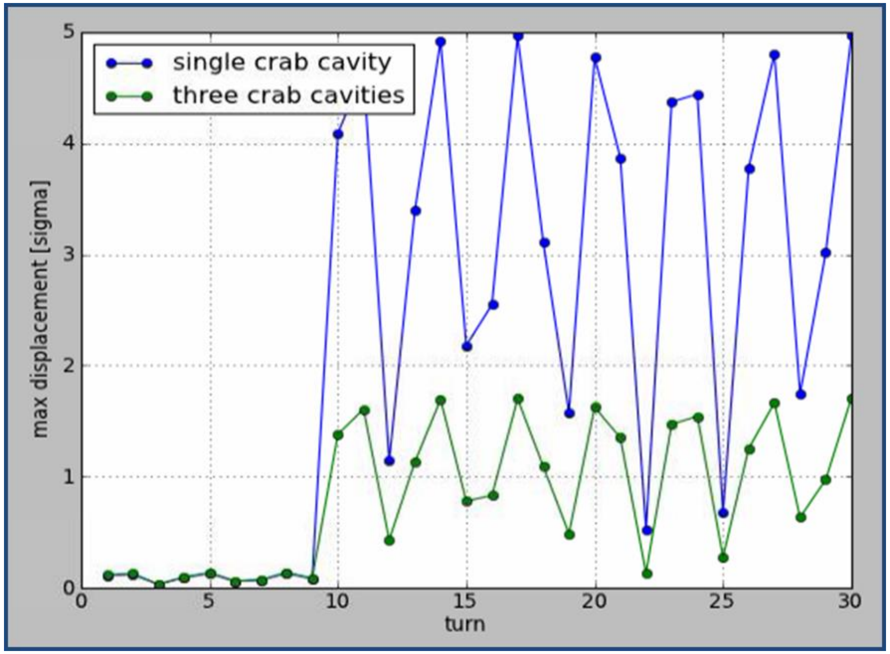
To **isolate effect of CC failure** and to be **independent of particle distribution:**

- **Maximal displacement**:

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

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

constant around LHC (apart from IRs).



- **Initial consitions:**

  x, x', y, y', dp/p = 0.

- Displacement of up to **5σ** (n_{cc}=1).

  *up to **1.7σ** with n_{cc}=3.*

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Failure Dynamics

Fast external failures (e.g. control/operational failure):

- Time constant of crab cavity failures:

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

- Maximal voltage change per turn: $\frac{\Delta V}{V} = 2 - 2\exp\left(-\frac{89\mu s}{1ms}\right) = \mathbf{17\%.}$

- 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 fast external failures.

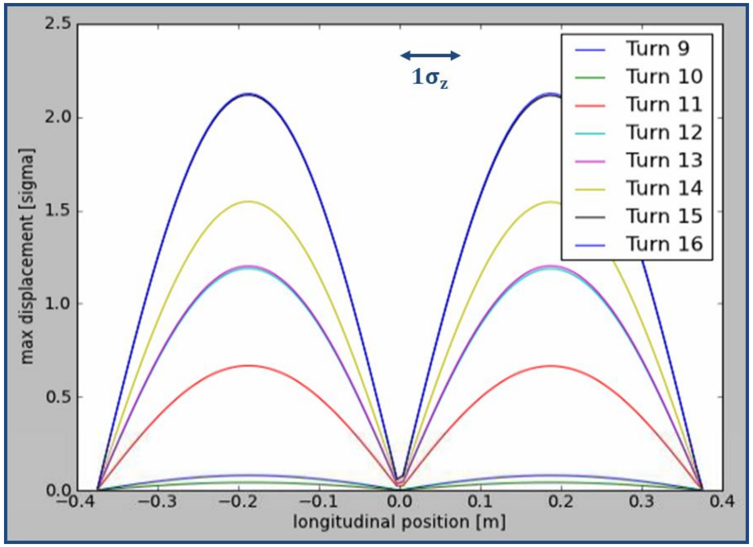
cf. T. Baer et. al, „LHC Machine Protection Against Very Fast Crab Cavity Failures“, IPAC’11,
J. Tuckmantel, CERN-ATS-Note-2011-002 TECH

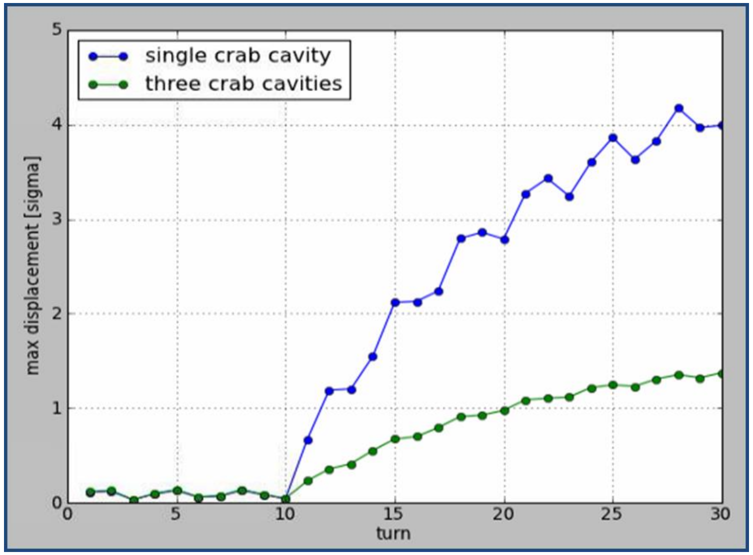
Voltage Failure

- **Dynamic voltage change** of CC.R5: $V_0 \rightarrow -V_0$.
  $Q_{ext} = 1'250'000$.
  Failure starts after turn 10.
- Resulting maximal displacement in 5 turns with n_{cc}=1:

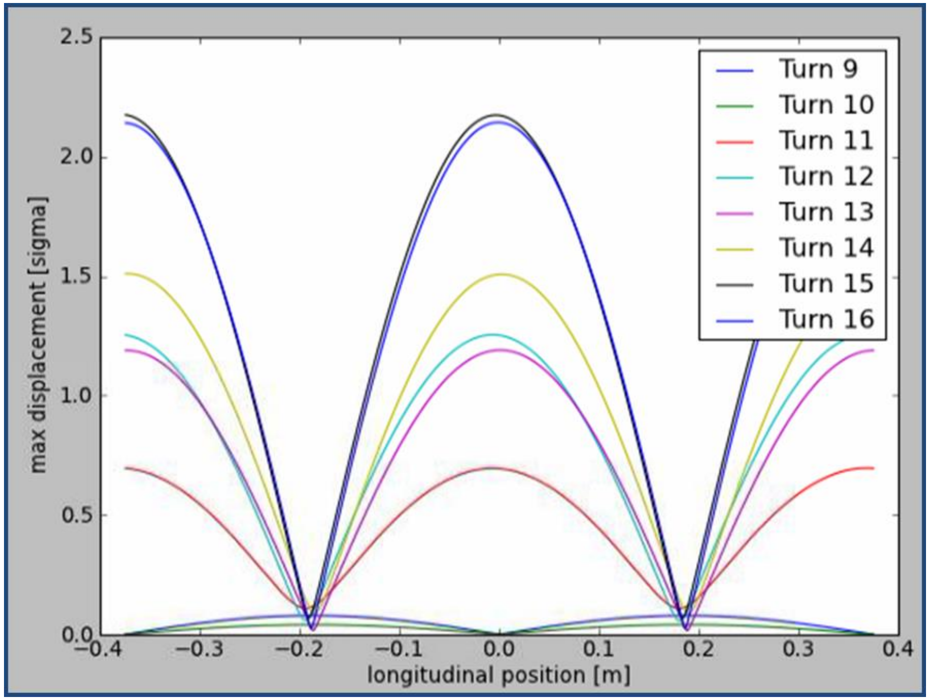
$$\bar{x} = 2.1\sigma_x \text{ at } z = \pm 2.4\sigma_z,$$

- **The (longitudinal) bunch center is not displaced.**

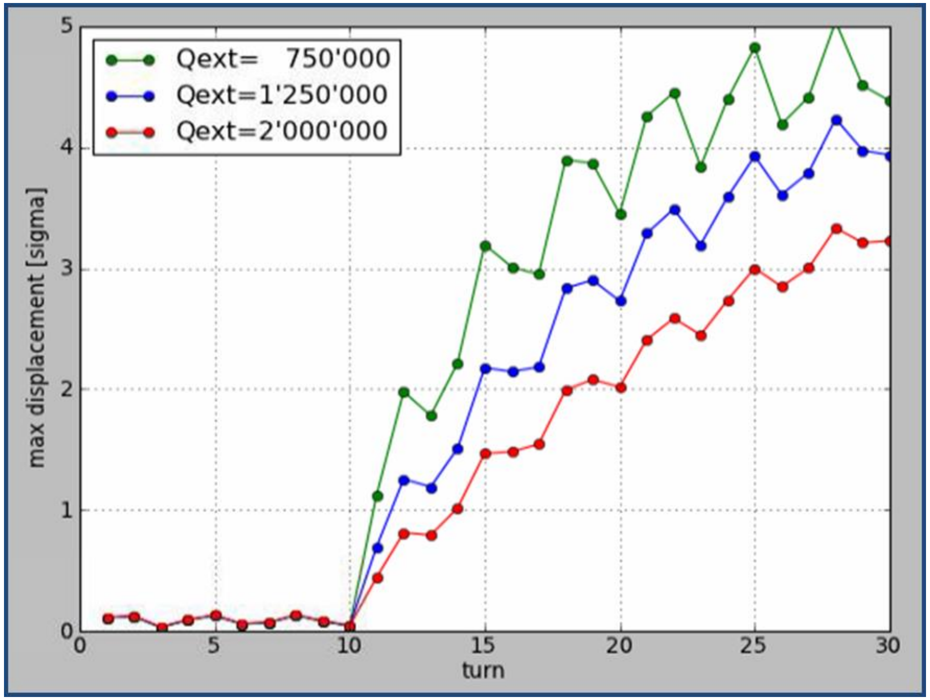




Phase Failure



Opposite phase change of both CCs.



Dependence on Q_{ext}.

In case of a **dephasing** of the crab cavities, the (longitudinal) **bunch center** is maximally displaced by up to **$2.1\sigma_x$ in 5 turns** (n_{cc}=1).

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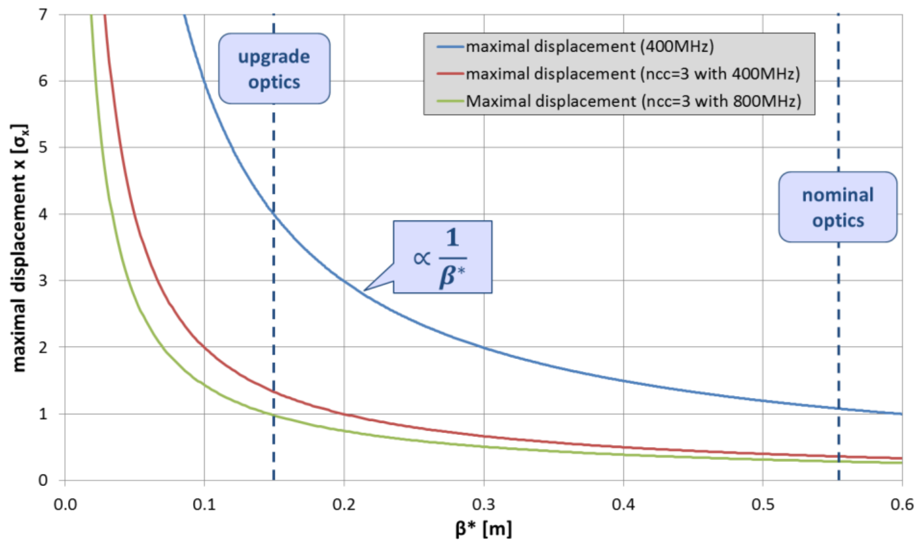
Scaling Laws

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

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

if only one CC is affected, i.e. no common failure scenarios



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

Transverse Distribution

- Highly overpopulated tails observed:

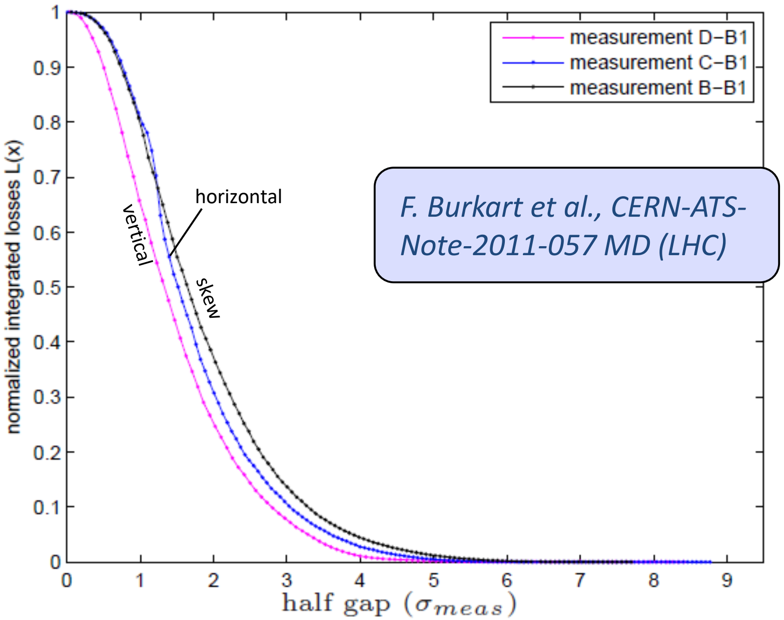
  *In horizontal plane about **4%** of beam beyond **4σ_{meas}**.*

  *Corresponds to **≈20-25 MJ** 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)

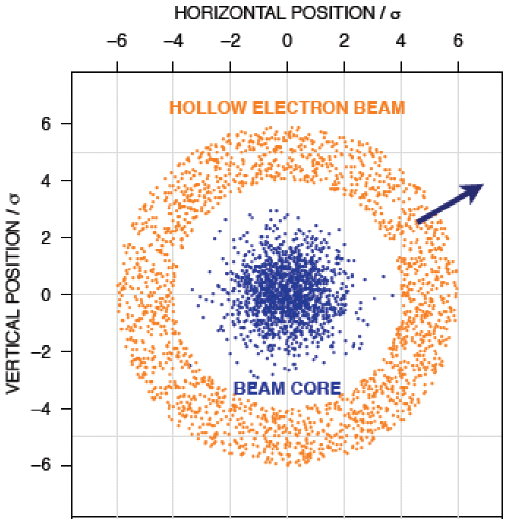
Table 3: Measured fraction of beam intensity in the tails of the beam outside selected multiples of the measured beam size, σ_{meas}, at 450 GeV.

u [σ_{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.

Mitigation Options

- Mitigation options:
  - *Larger β^* (flat IR optics).*
  - *Smaller crossing angle (wire compensator).*
  - *Higher crab cavity frequency.*
  - *Crab kick by several **INDEPENDENT** crab cavities.*
  - *Larger Q_{ext} (= slower time constant of ext. failures).*
  - *Coupled RF feedback.* *P. Baudrenghien, LHC-CC11*
  - ***Hollow electron lens** to deplete transverse tails.*
    (essential) *G. Stancari, FERMILAB-PUB-11-192-AD-APC*



Giulio Stancari

- Requires: **single turn redundant failure detection** and interlock.
  - *on cavity level.*
  - *on beam level (head-tail-monitor?).*

Possible Scenarios

Tolerable scenarios for internal and external failures with losses below 1MJ in max 5 turns:

	Scenario 1: 3 CCs	Scenario 2: $\beta^* = 25cm$	Scenario 3: 800 MHz
CC frequency (f)	400 MHz	400 MHz	**800 MHz**
Number of independant CCs (n_{cc})	**3**	3	3
Q_{ext}	1‘250‘000	1‘250‘000	1‘250‘000
$\boldsymbol{\beta^*}$	15 cm	**25 cm**	15 cm
Fraction to be depleted below 1MJ.	1.7σ	1.0 σ	0.9 σ

Magnet quenching in failure case not excluded.

Conclusion

- Failure scenarios are **strongly optics (β*) dependent.**
- **Very fast (internal) crab cavity failures** can lead to **global betatron oscillations** with amplitudes of up to **5σ** (n_{cc}=1).

  Unacceptable with multi-MJ tails.

  Better understanding of failure scenarios (e.g. quench) needed.
- **External crab cavity failures** can transversely displace the (longitudinal) **bunch center** by up to **2.1σ** within 5 turns (n_{cc}=1).
- Mitigation options:
  - *Lower voltage (partial compensation of crossing angle), or larger β^*.*
  - *Crab kick by several **INDEPENDENT** crab cavities.*
  - *Higher cavity frequency.*
  - *Larger Q_{ext} (= slower time constant of external failures).*
  - *Coupled RF feedback.*
  - ***Hollow electron lens** to deplete transverse tails (essential).*

Thank you

for your Attention

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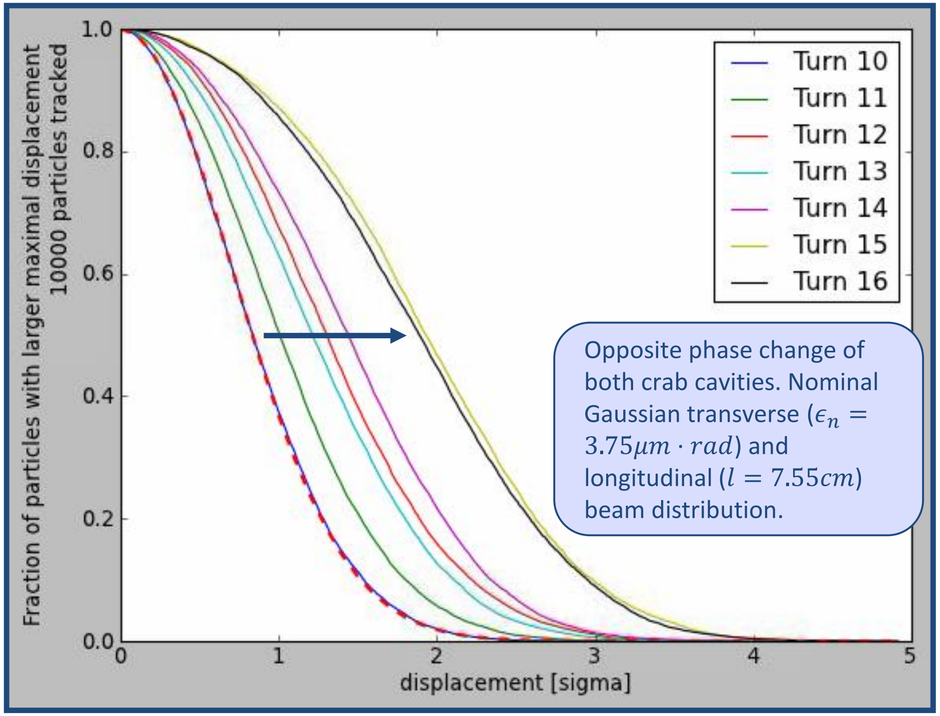
Further information:

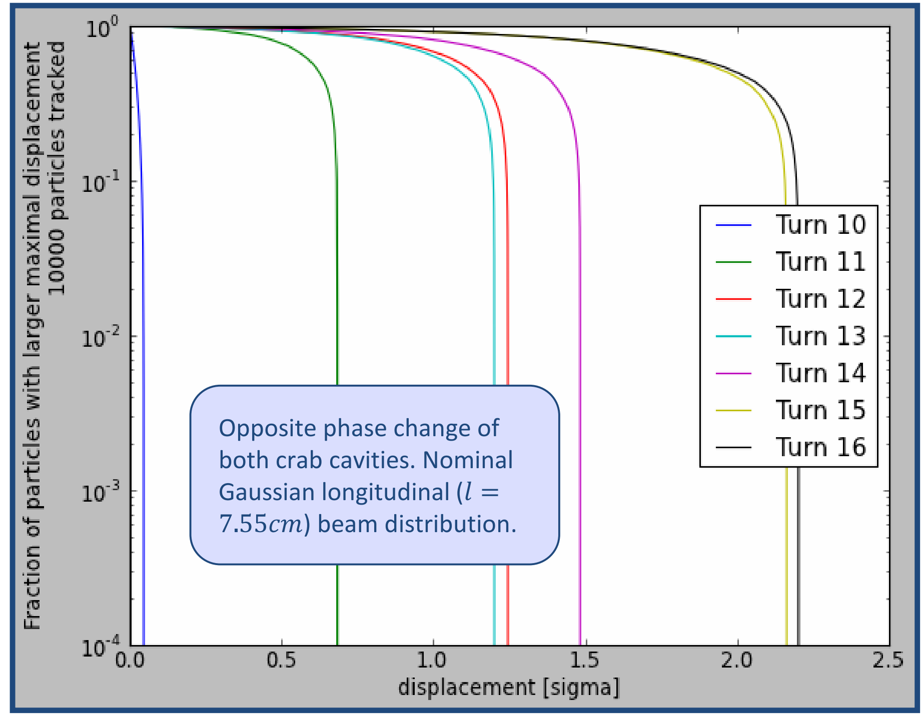
- T. Baer et al., "Machine Protection of LHC Crab Cavities", LHC-CC11, Nov. 2011.
- E. Jensen et al., "Crab Cavity", 1st HiLumi LHC / LARP Meeting, Nov. 2011.
- T. Baer et al., "LHC Machine Protection against Very Fast Crab Cavity Failures", IPAC'11, Sept. 2011.
- T. Baer, "Beam Dynamics Aspects of Crab Cavity Failures", December 2010.
- J. Tuckmantel, "Failure scenarios and mitigation", LHC-CC10, December 2010

Backup slides

Phase Change



Maximal displacement with Gaussian transverse and longitudinal beam distribution.



Maximal displacement with Gaussian longitudinal beam distribution.

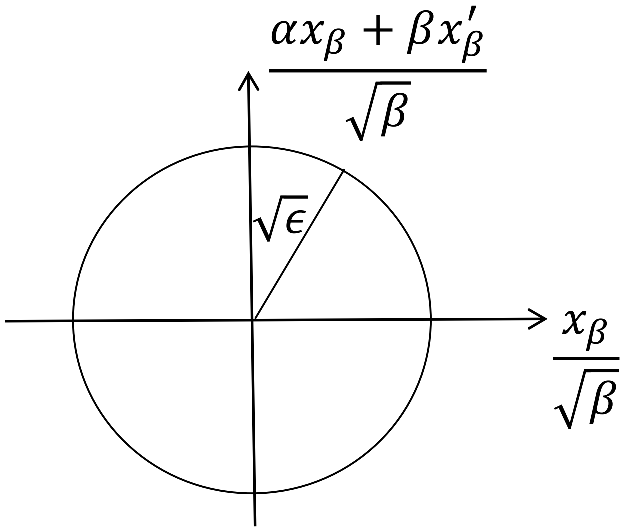
In case of a **dephasing** of the crab cavities left and right of the IP, the (longitudinal) **bunch center** is maximally displaced, by up to **$2.2\sigma_x$ in 5 turns**.

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:

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

90° Phase Change

- Maximal phase change in first turn:

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

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

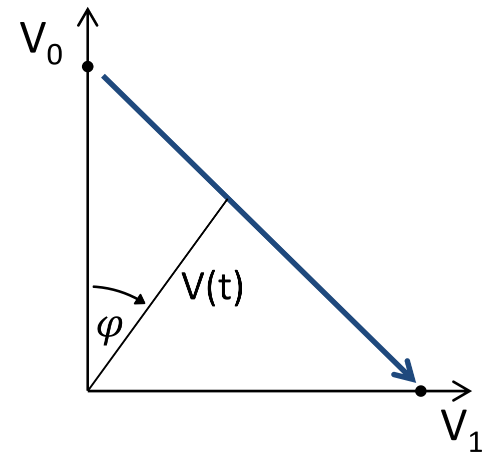
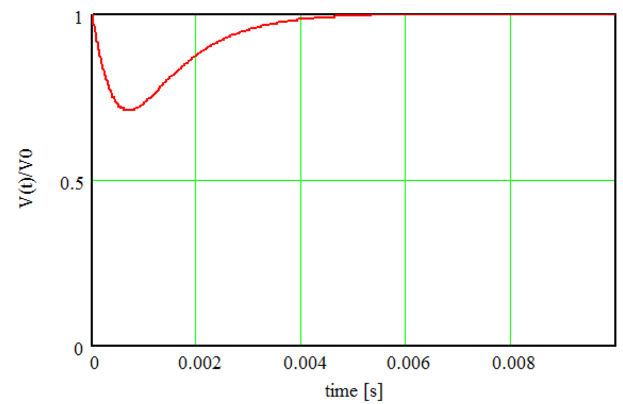


Illustration of 90° voltage change.



Amplitude of cavity voltage.

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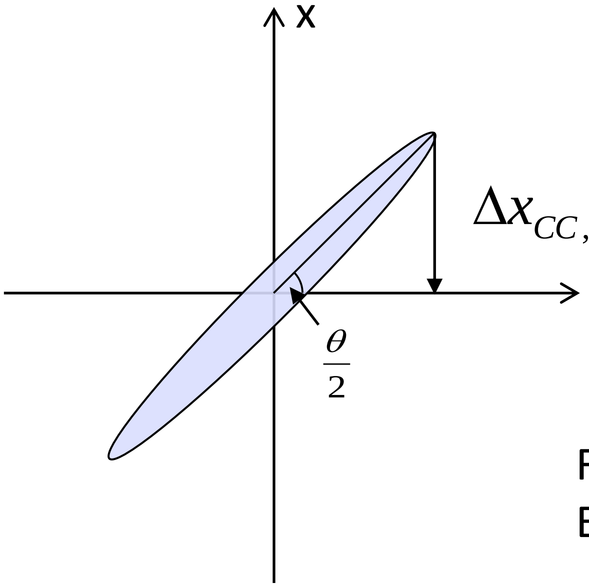
Static Failure Scenarios

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 Θ = 580μrad, β_{IP} = 0.15m, ε_{norm} = 3.75μm·rad, E = 7TeV, σ_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

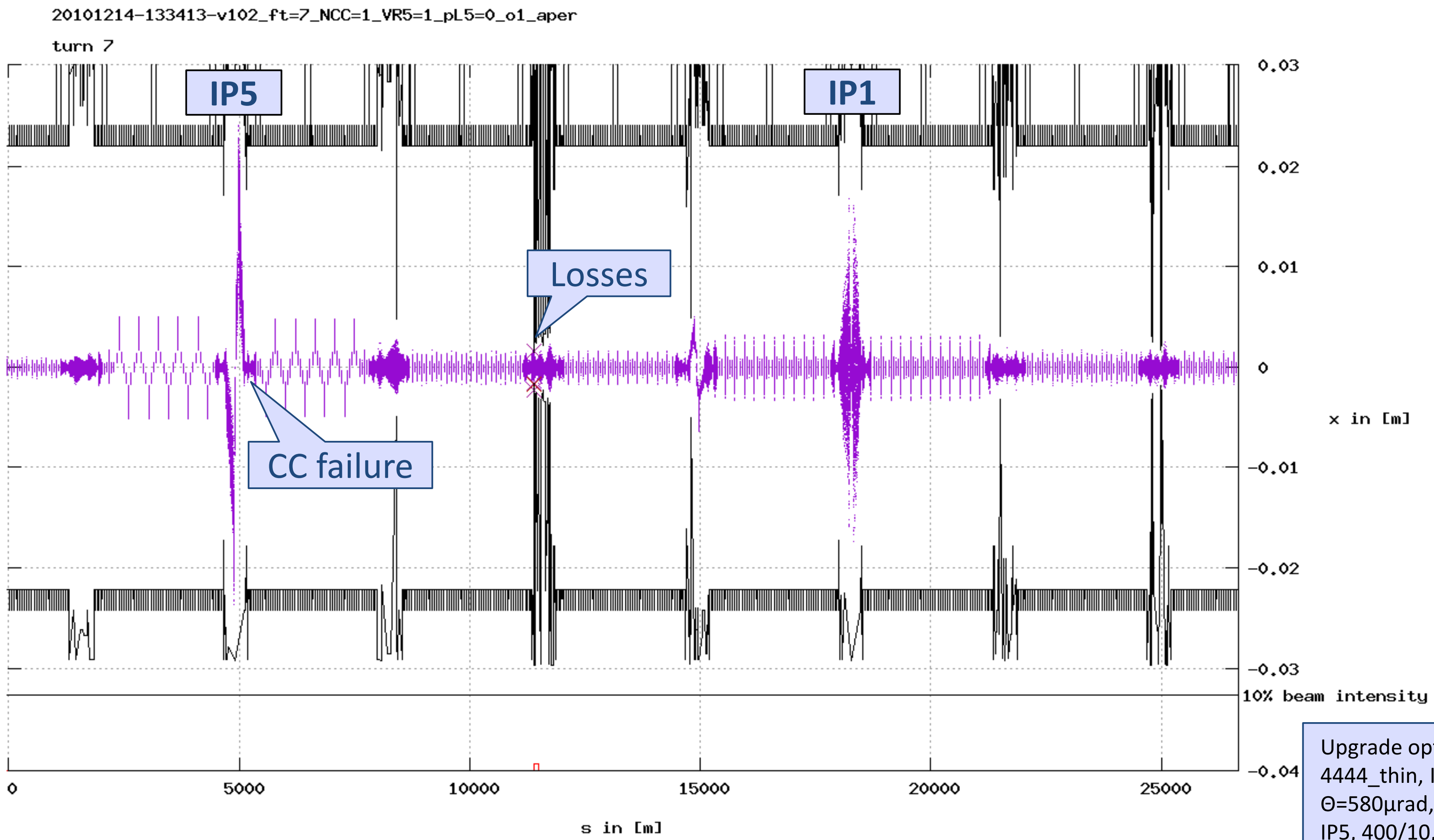
Static Tracking Studies with upgrade optics (MAD-X)

- Fast Voltage Decay
- Phase Error

Failure of CRAB.R5.B1

Voltage of Crab.R5.B1 = 0.

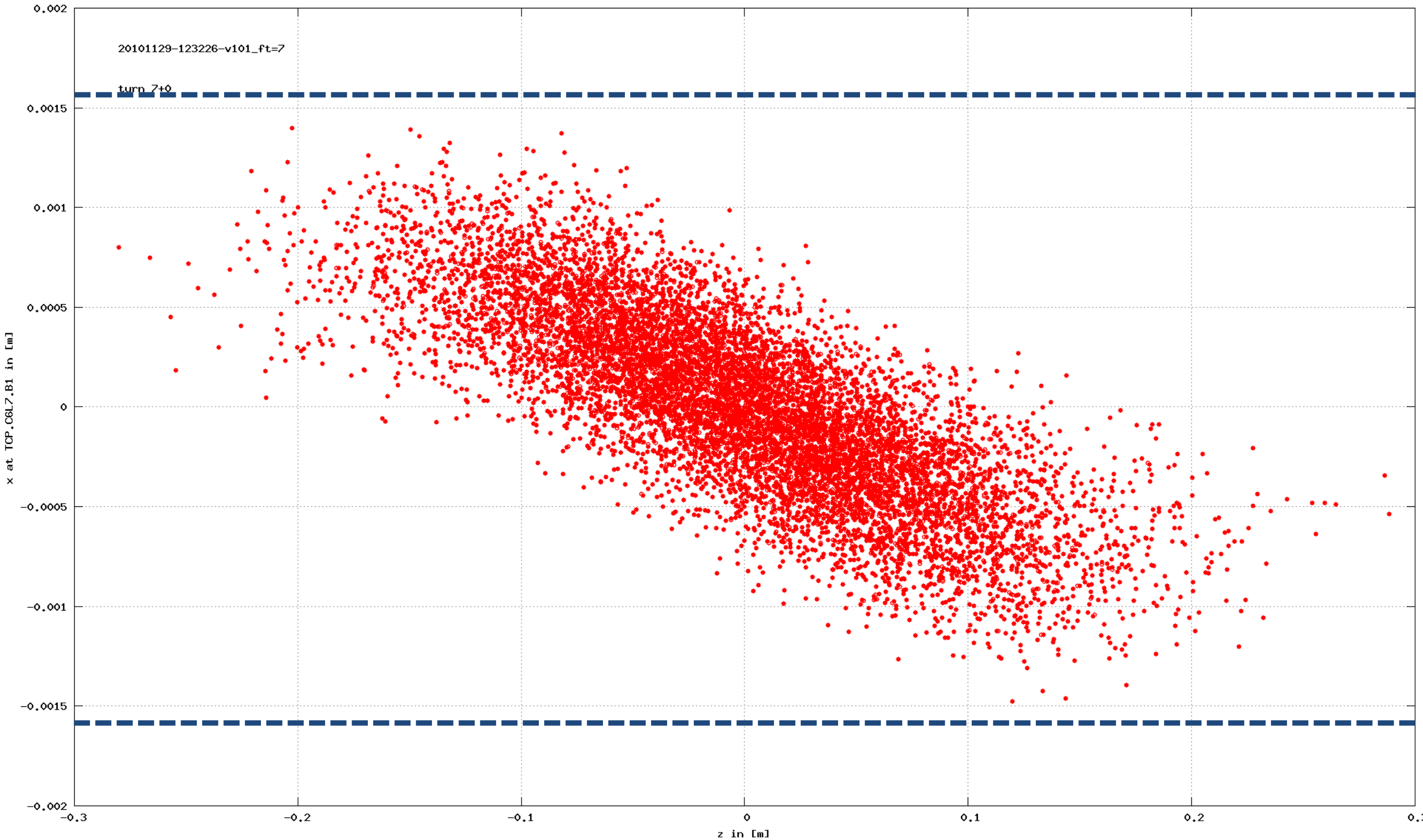
Total beam loss: **1.3%** in 2 turns (2% in first 10 turns), mainly at **TCP.C6L7.B1**.



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

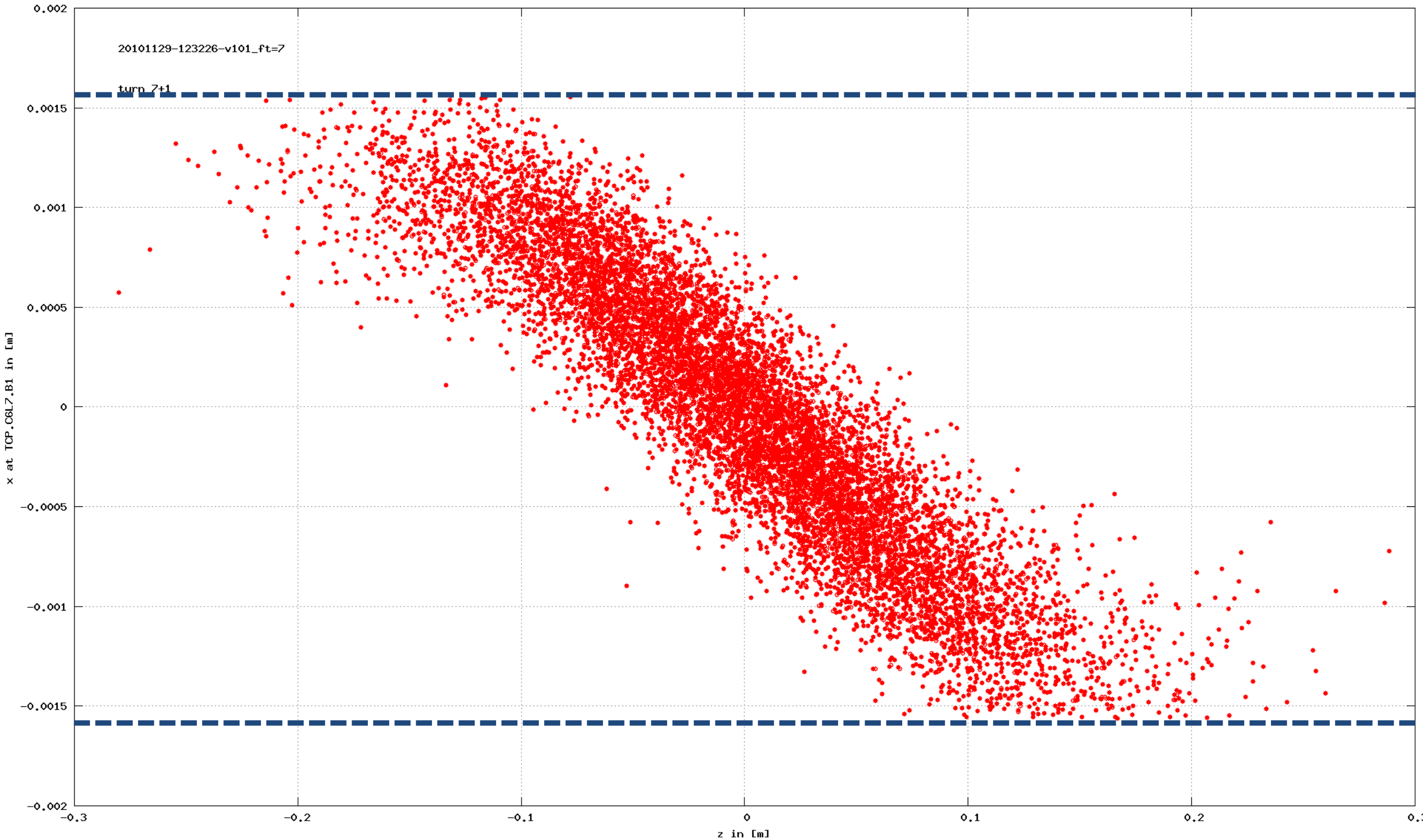
Failure of CRAB.R5.B1

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



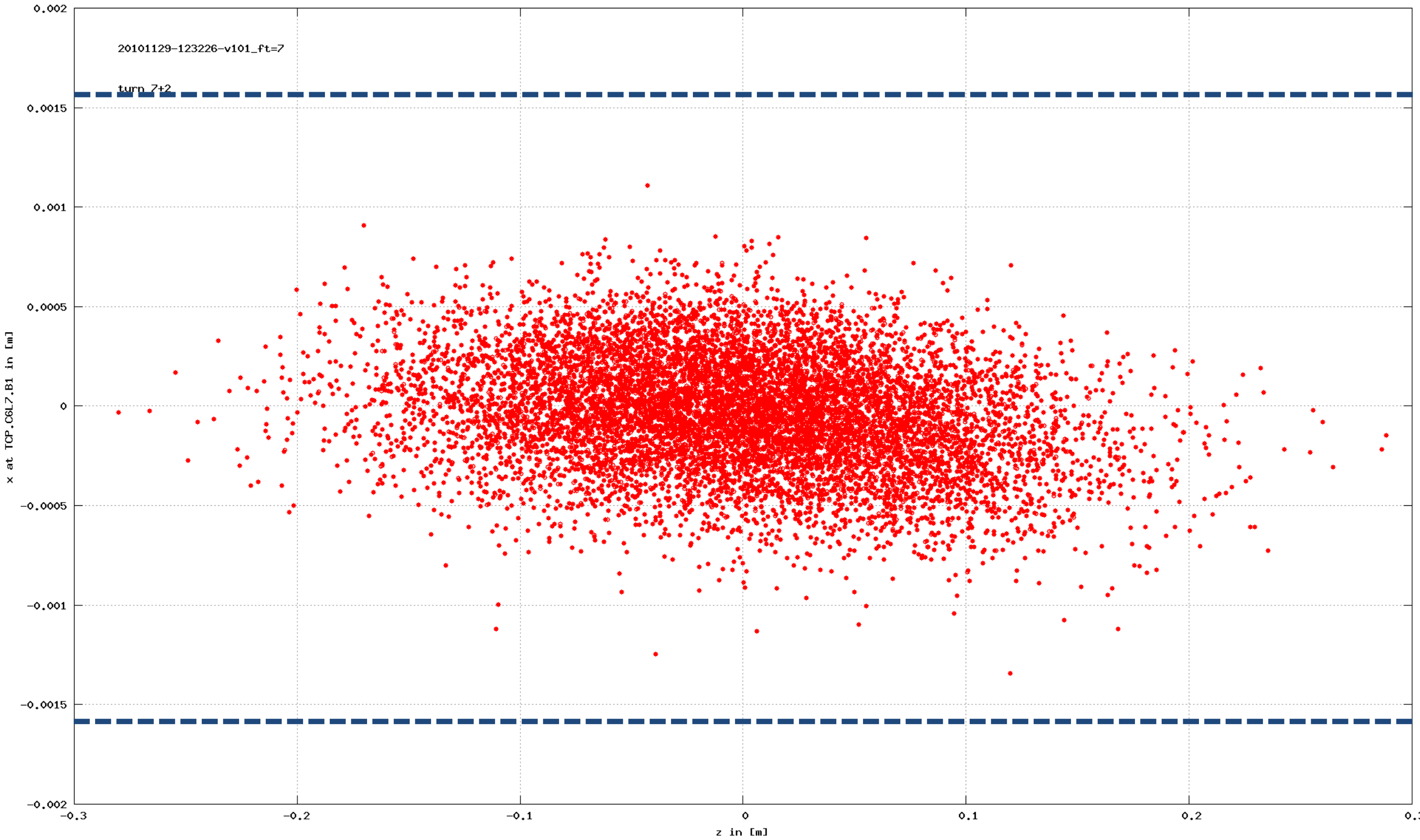
Failure of CRAB.R5.B1

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)

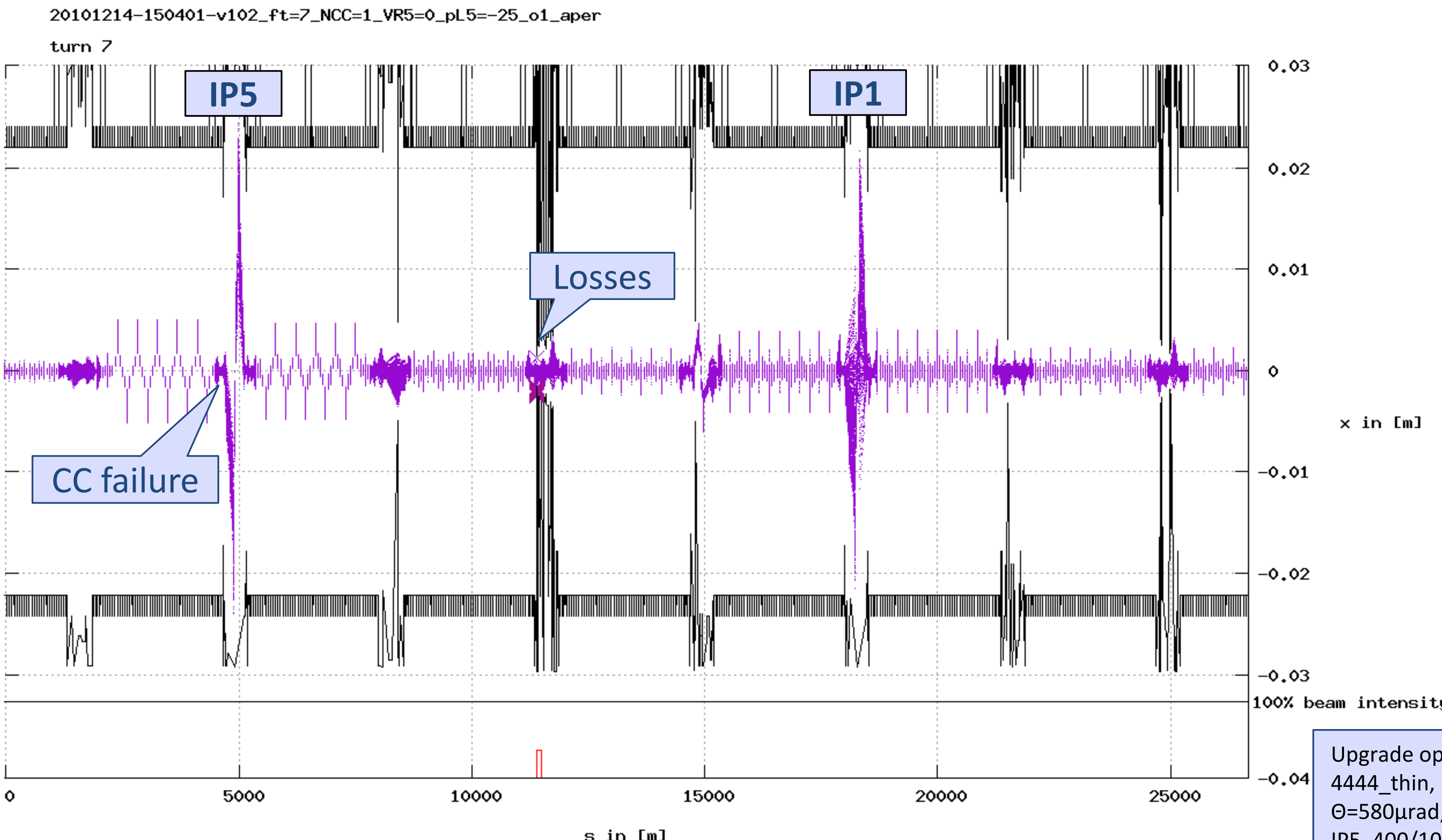
- Fast Voltage Decay

- Phase Error

Phase Error of CRAB.L5.B1

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

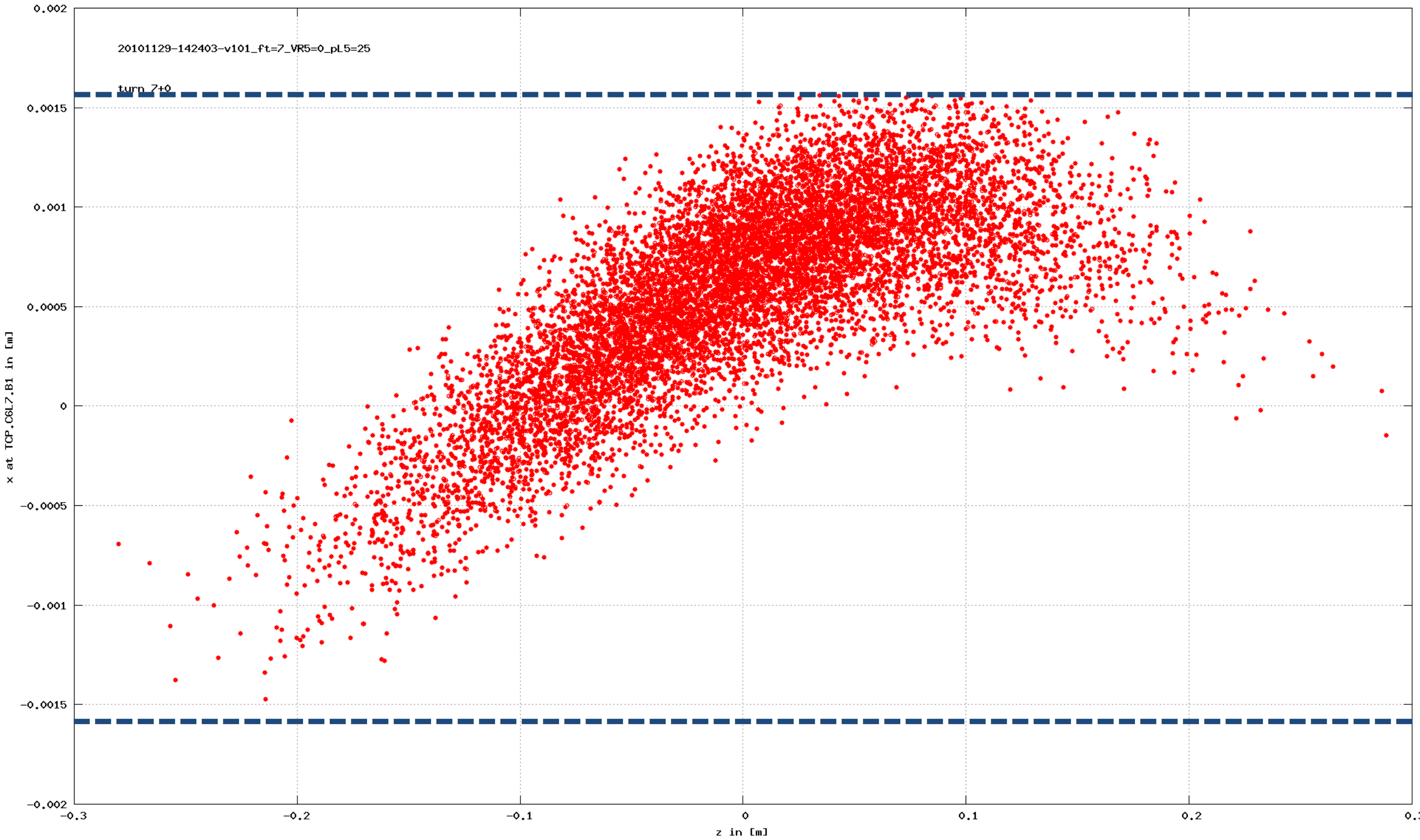
Total beam loss: **15% - 35%** in 2 turns, mainly at **TCP.C6L7.B1**



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

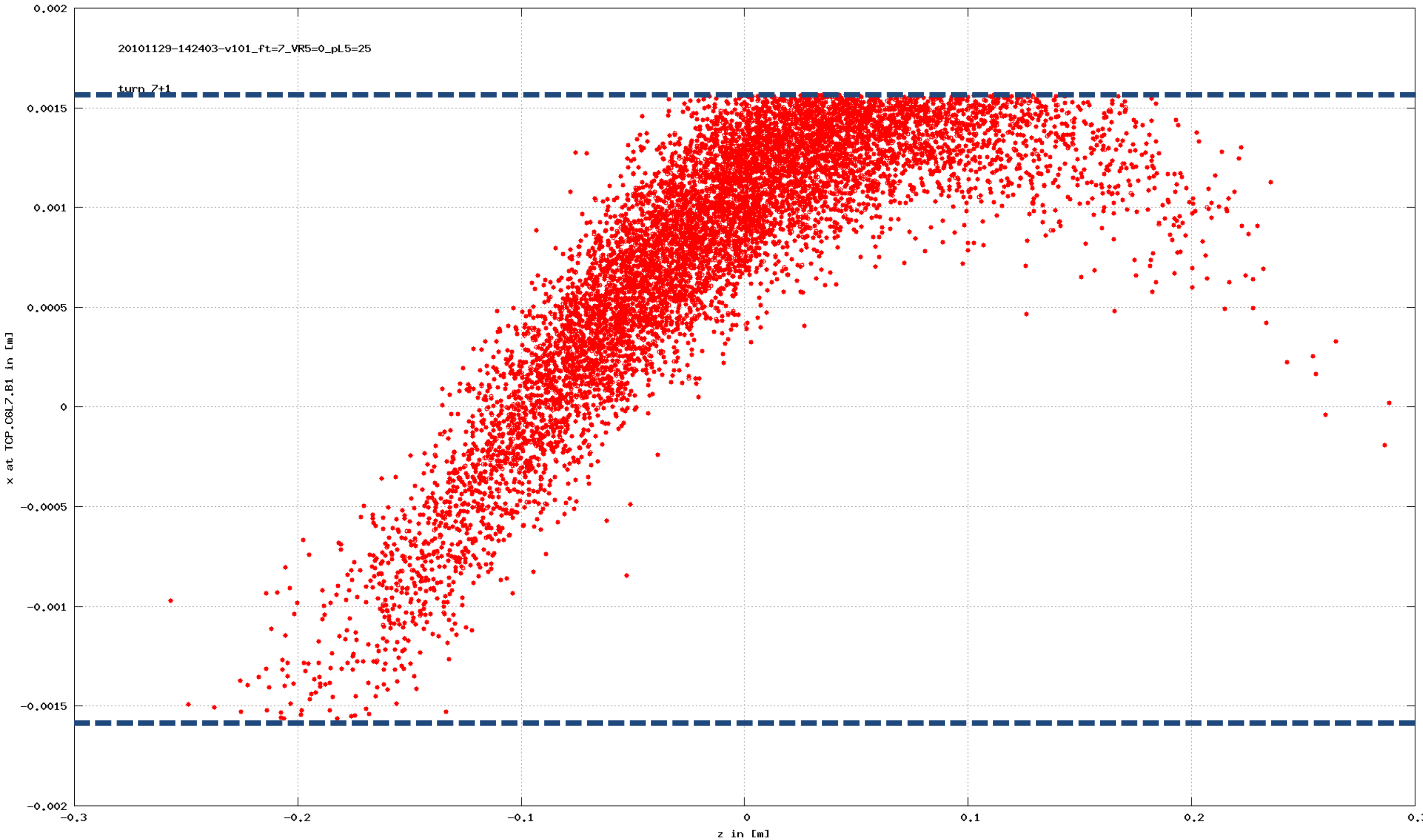
Phase Error of CRAB.L5.B1

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

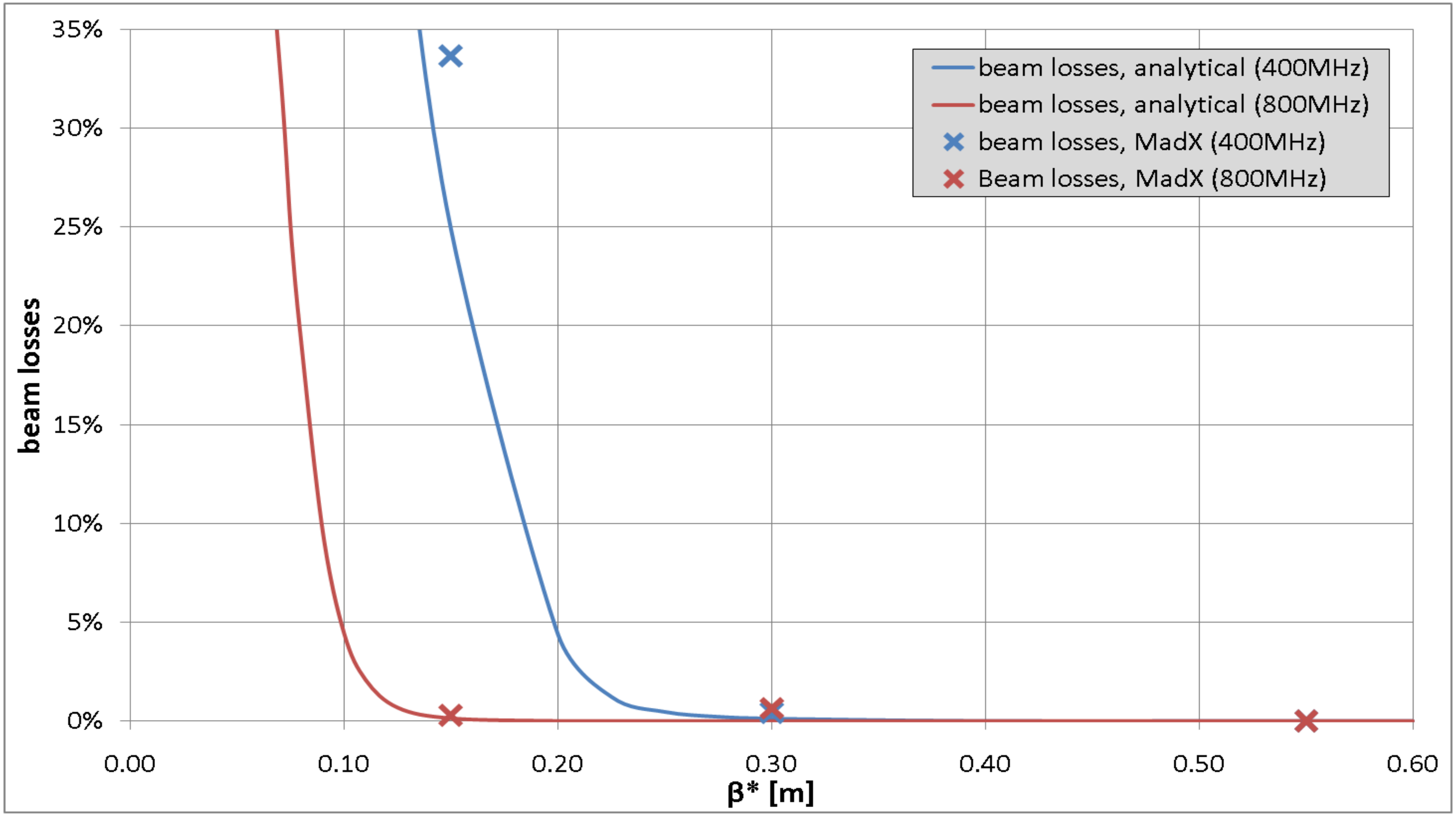


Phase Error of CRAB.L5.B1

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



Losses vs β*



35%
30%
25%
20%
15%
10%
5%
0%
beam losses
0.00
0.10
0.20
0.30
0.40
0.50
0.60
β* [m]
beam losses, analytical (400MHz)
beam losses, analytical (800MHz)
beam losses, MadX (400MHz)
Beam losses, MadX (800MHz)