European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

High Luminosity LHC

LHC Crab Cavities and Related Machine Protection

DESY & UHH AccPhySem

Tobias Baer

July, 3rd 2012

Acknowledgement: P. Baudrenghien, F. Burkart, R. Calaga, R. De Maria, E. Elsen, S. Fartoukh, E. Jensen, R. Tomas, J. Tuckmantel, J. Wenninger, B. Yee Rendon, F. Zimmermann.

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1. LHC Upgrade Scenarios and Crab Cavities
2. Failure Scenarios and Analytical Approach
3. Static Failure Simulations (MAD-X)
4. Dynamic Failure Simulations (MAD-X)
5. Mitigation and Conclusion

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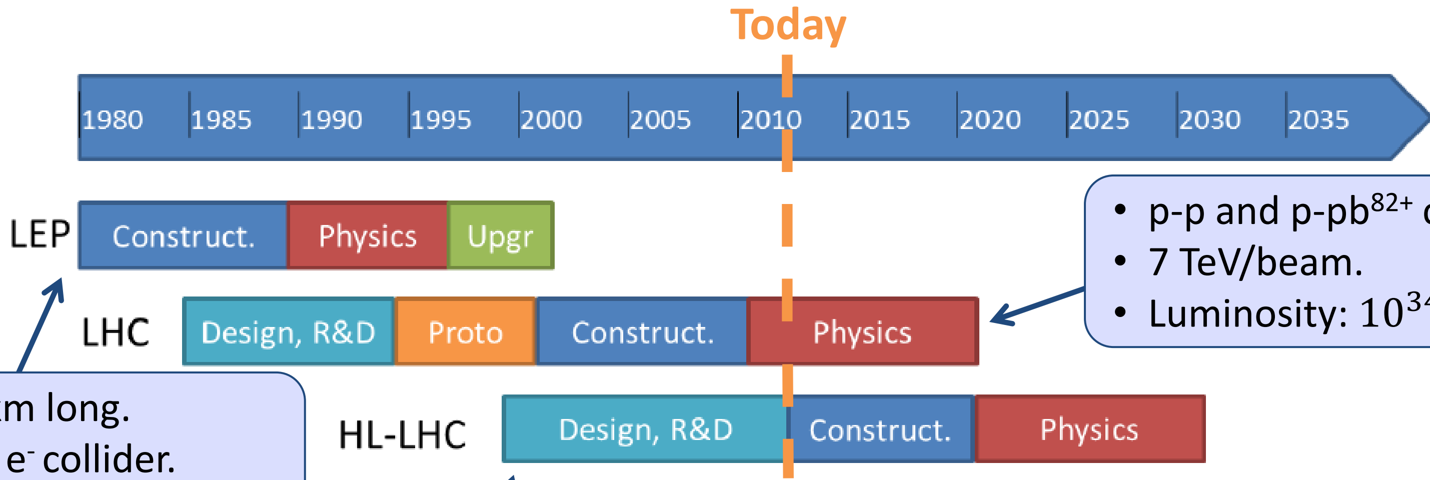
LHC Upgrade Programs



- p-p and p-pb^{82+} collider.
- 7 TeV/beam.
- Luminosity: $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

- 27 km long.
- $e^+ - e^-$ collider.
- 105 GeV/beam.

LHeC: hadron-e^- collider.

LEP3: $e^+ - e^-$ collider, >120 GeV/beam.

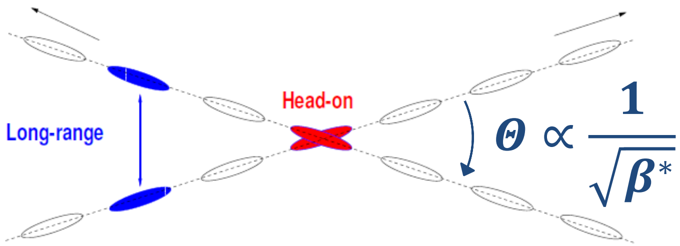
HE-LHC: 20T dipole magnets, **16.5 TeV**/beam.

- Peak luminosity (virtual) $> \mathbf{2 \cdot 10^{35} cm^{-2} s^{-1}}$.
  - Larger bunch intensity.
  - **Smaller beam size** at interaction point (β^*).
- Requires **luminosity leveling** to limit average **pile-up to ≈140**.

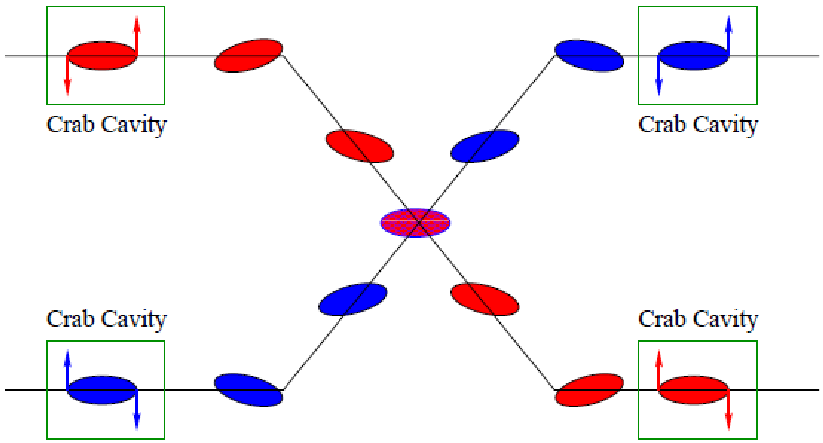
O. Brüning and F. Zimmermann, IPAC12, MOPPC005

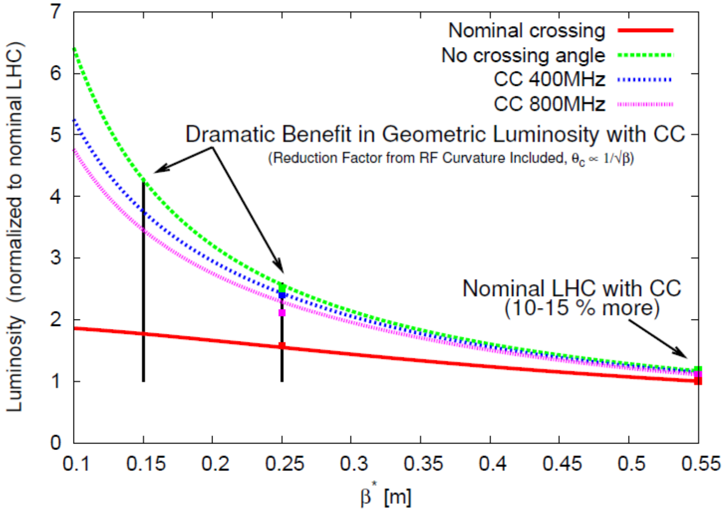
Geometric Luminosity Loss

- The crossing angle (to mitigate long-range beam-beam) leads to a **geometric luminosity reduction**.
- **Crab cavities** have a **time dependent transverse deflection** and can restore the geometric luminosity loss (and level the luminosity).



W. Herr





I. Ben-Zvi et al., HHH-2008

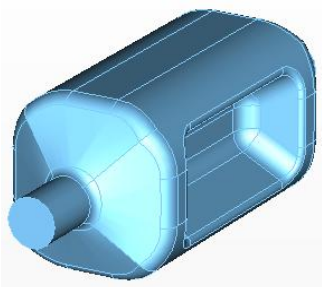
Crab Cavity Status

- Crab cavities are used in KEKB since 2007.
- Enormous advance in **compact** crab cavity design.

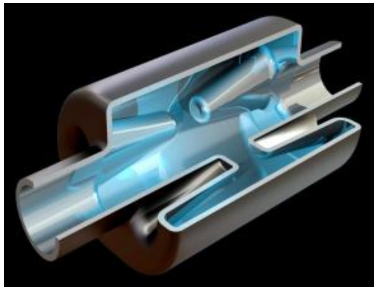
  Three designs, 400 MHz, 3 MV kick, r < 150 mm.

  First prototypes are constructed.

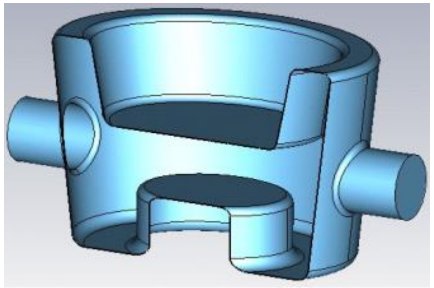
KEKB crab cavity.



ODU/JLAB/SLAC



ULANC



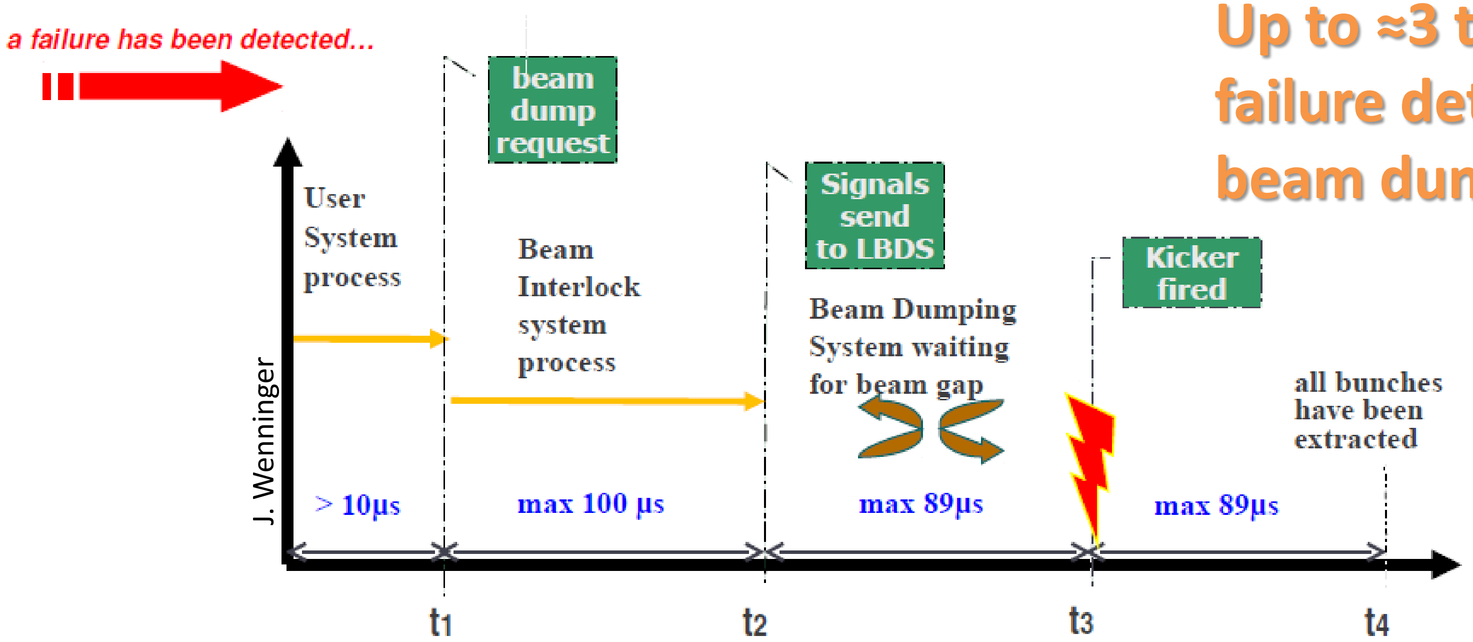
BNL

- Still several main challanges ahead:

  RF noise, impedance, **machine protection**, …

LHC Machine Protection

- Main challenge: Beam energy of **362MJ** (HL-LHC: up to **700MJ**)
  - *Damage level (sensitive equipment): **≈10kJ*** *R. Schmidt, Pac07*
  - *Quench limit of superconducting elements: few mJ/cm³*
- Over 200 protection systems can request a beam dump
  - *4000 BLMs (40µs resolution), power converter, software interlock system, etc.*



Up to ≈3 turns between failure detection and beam dump.

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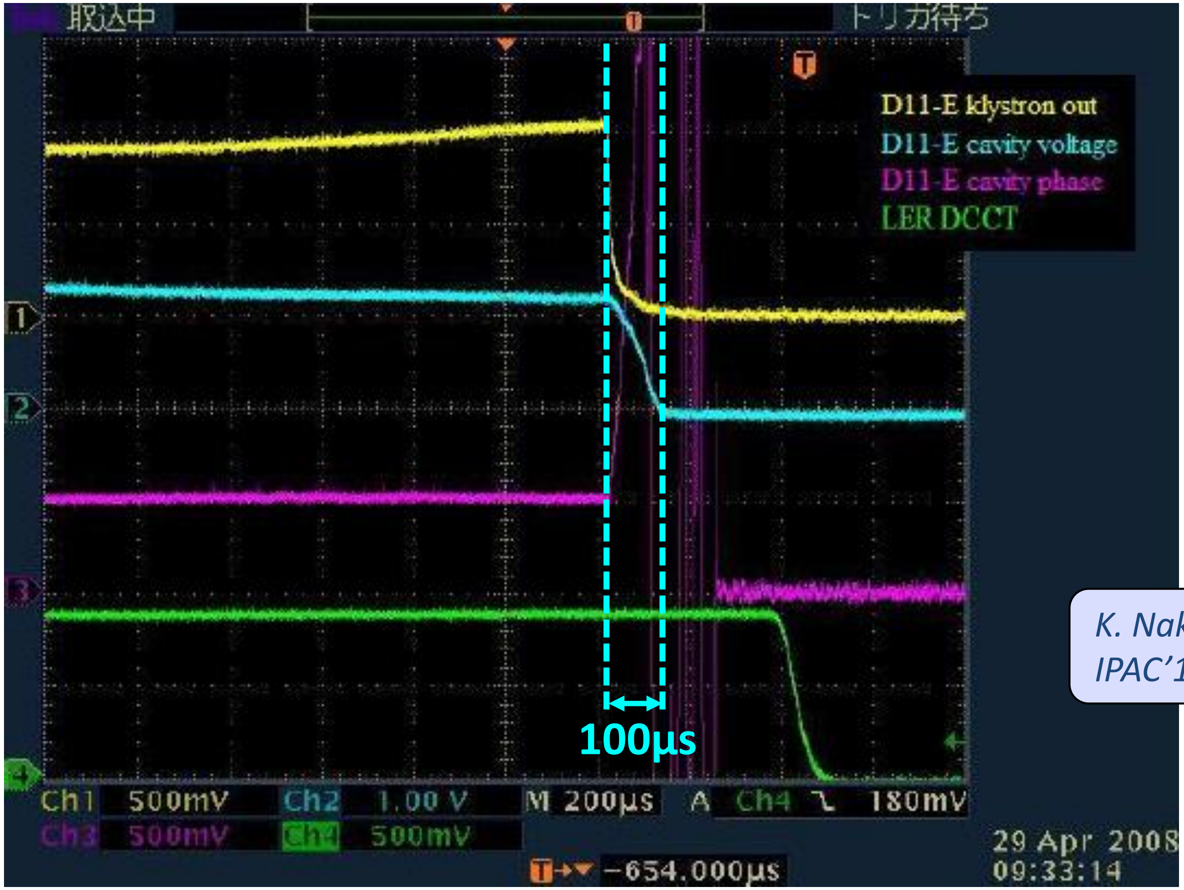
KEK Crab Cavity Quench

- 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

- Transverse deflection 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:

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

- Maximal transverse displacement by CC:

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

= 4.05 (upgrade optics, $\beta^* = 15cm$, n_{cc}=1) *T. Baer et al., IPAC'11*

σ_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 (590/285μrad)
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
n_{cc} = number of independent CCs per beam on either side of IP.

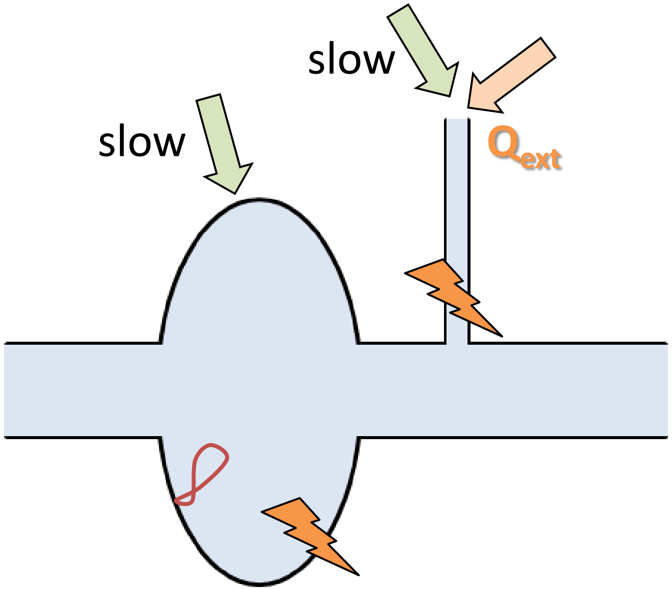
	upgrade optics	nominal optics
Maximal displacement with $sin\left(\Phi + \frac{\omega \cdot z}{c}\right) = 1$ $\bar{x}_{cc} \approx$	**$4\sigma_x$**	**$1\sigma_x$**
For z = 7.55cm (= 1·σ_z): $\bar{x}_{cc}(z = 7.55\text{cm}) \approx$	**$2.36\sigma_x$**	**$0.60\sigma_x$**

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.

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

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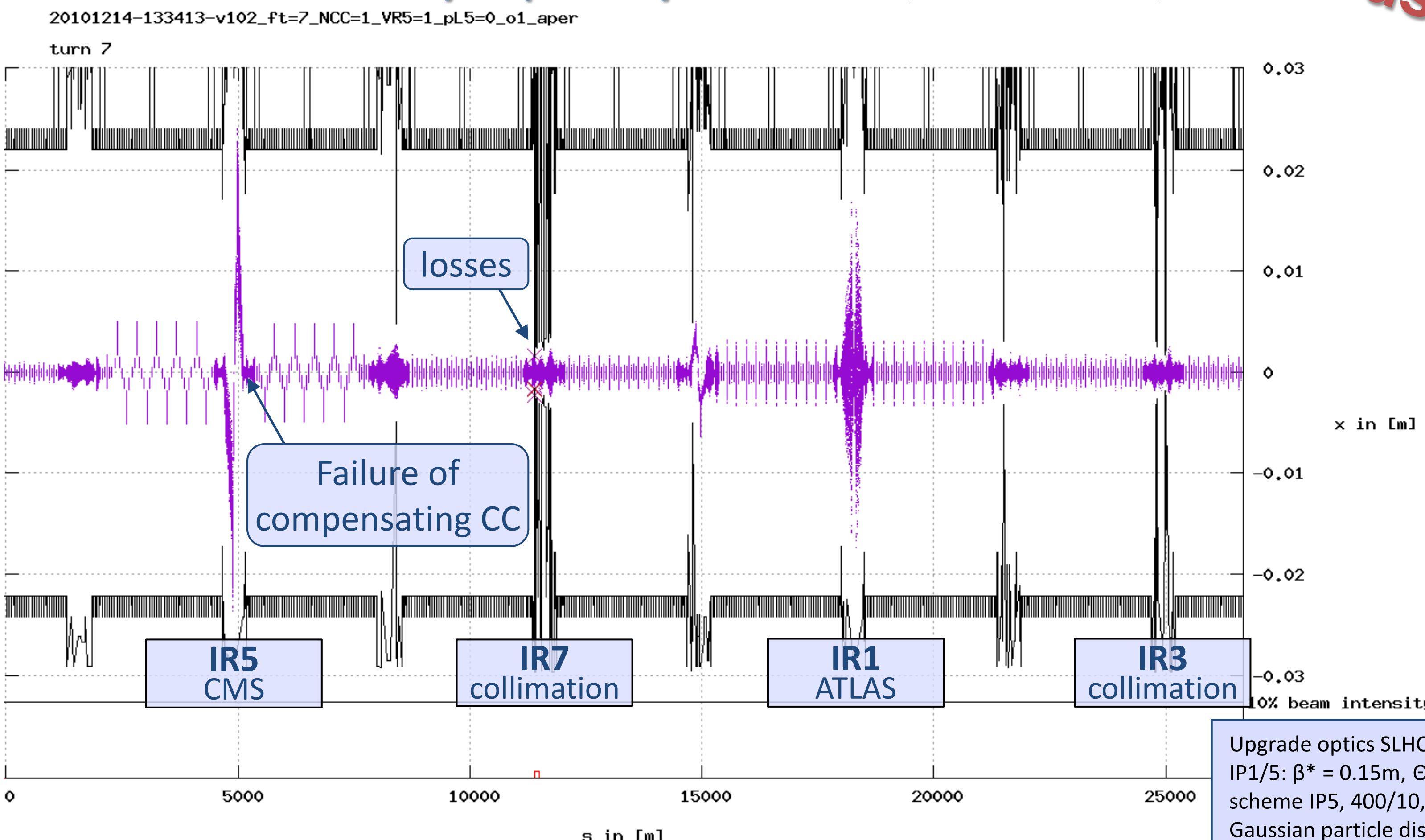
Failure Simulations

- MAD-X tracking studies (thintrack module)
- 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

For Illustration

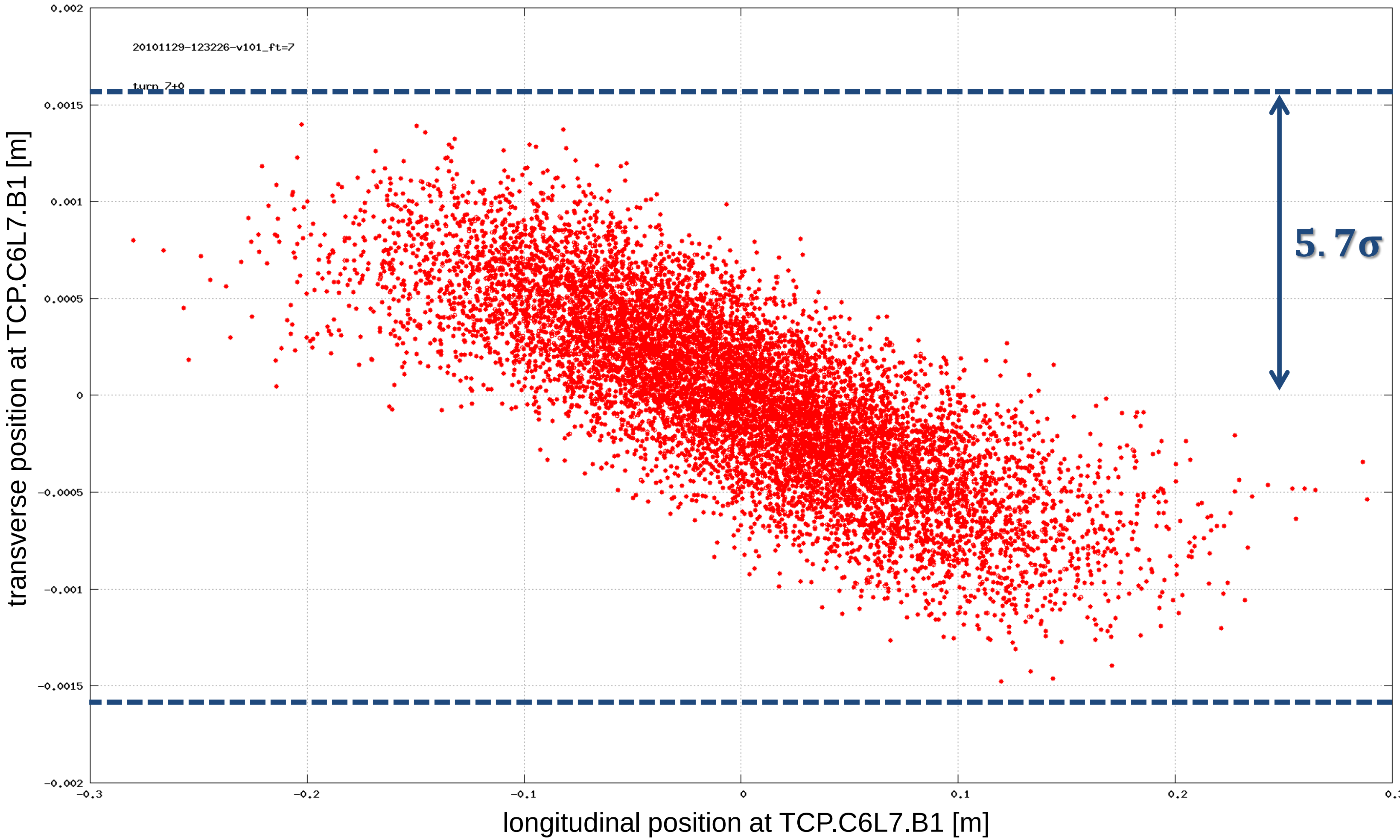
- Instantaneous change of voltage of CC.R5.B1 to zero.
- **Beam losses mainly at primary collimator** (TCP.C6L7.B1).



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

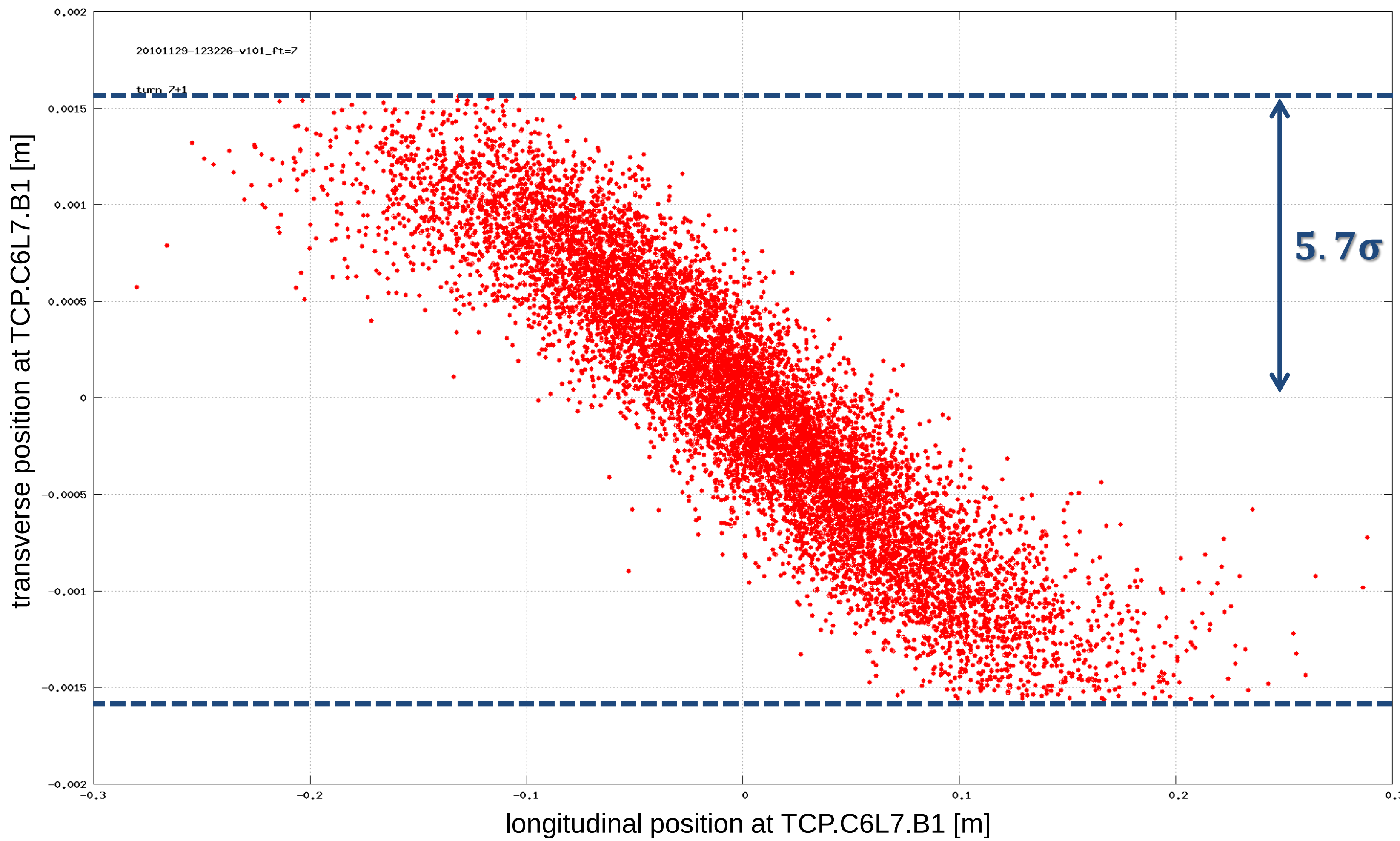
Static Failure of CC.R5.B1

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



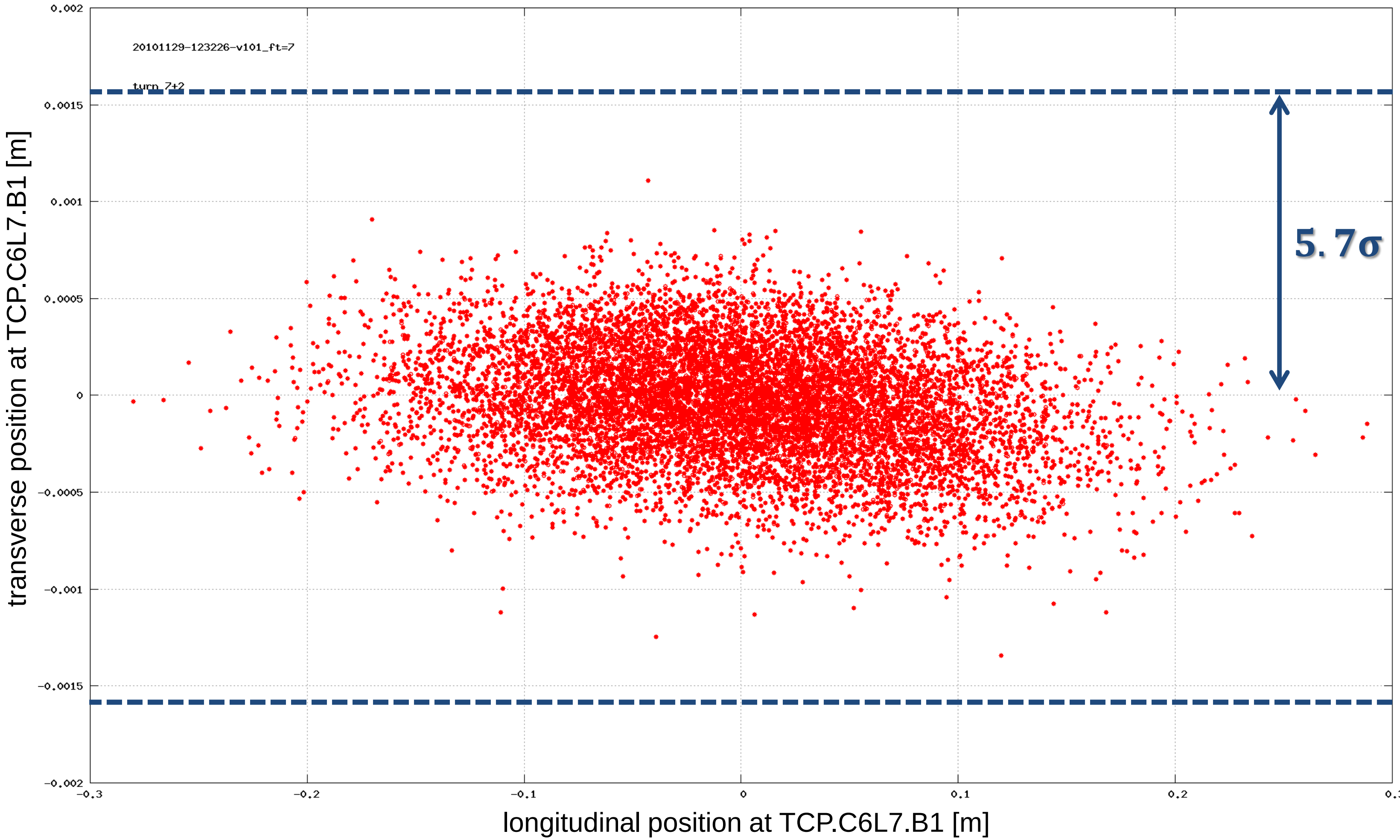
Static Failure of CC.R5.B1

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



Static Failure of CC.R5.B1

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



Maximal Displacement

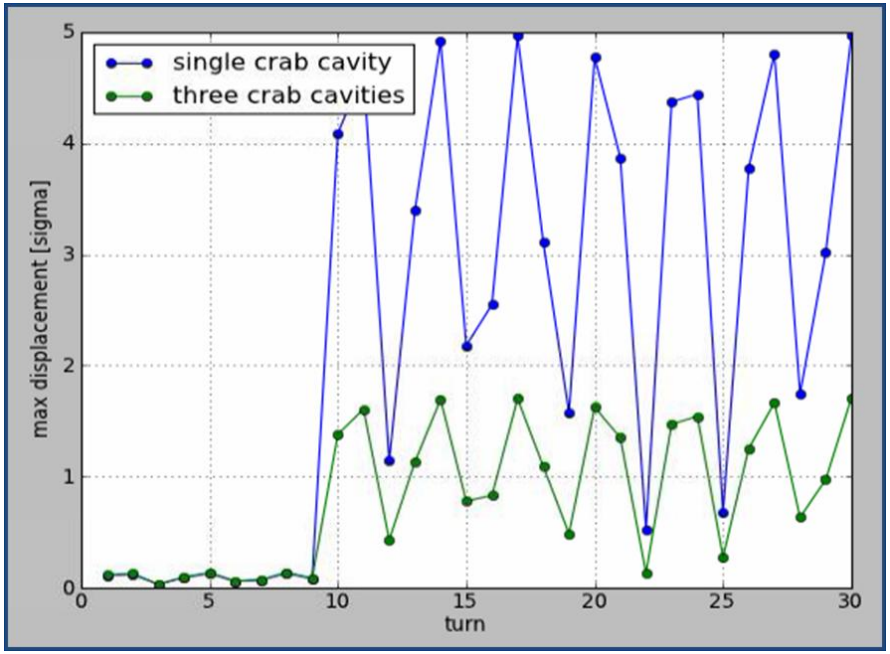
To **isolate effect of CC failure** and to be **independent of particle distribution:**

- **Maximal displacement**:

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

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 -> $\boldsymbol{\tau_0 = \frac{Q_{ext}}{\pi \cdot f}} \approx \mathbf{1ms}$ (≈11 turns).

- 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.

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: $V_0 \rightarrow -V_0$.

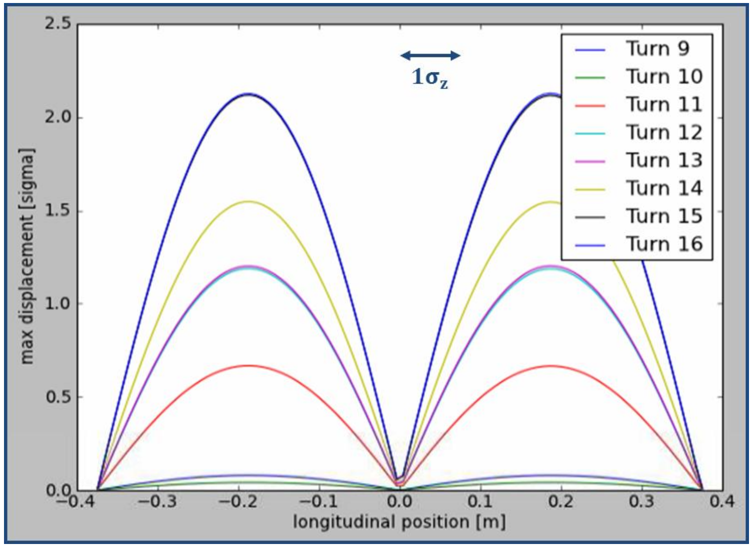
  $Q_{ext} = 1'250'000.$

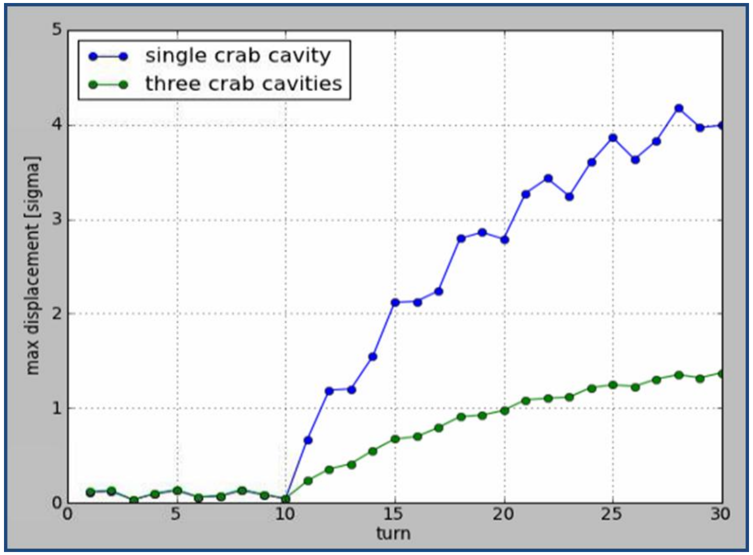
  Failure starts after turn 10.

- Resulting maximal displacement in 5 turns with n_{cc}=1:

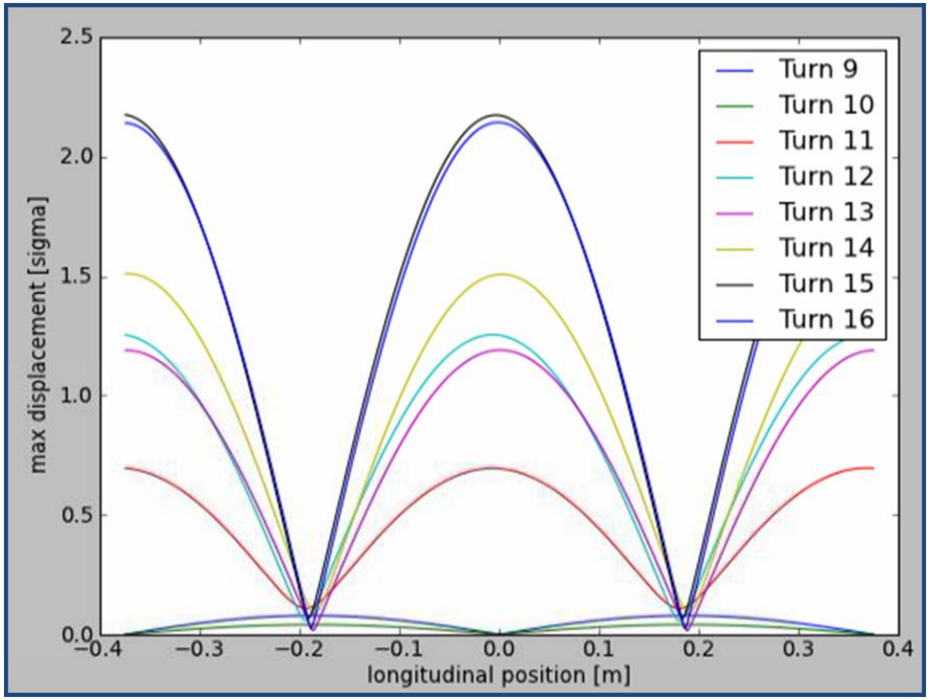
$$\bar{x} = 2.1\sigma_x \text{ at } z = \pm 2.4\sigma_z,$$

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

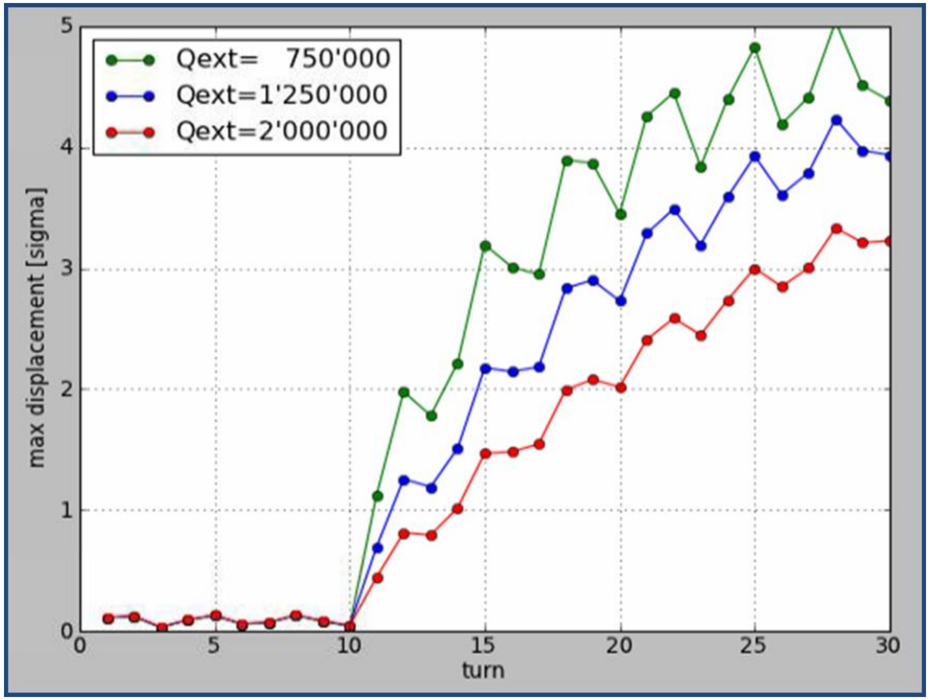




Phase Failure



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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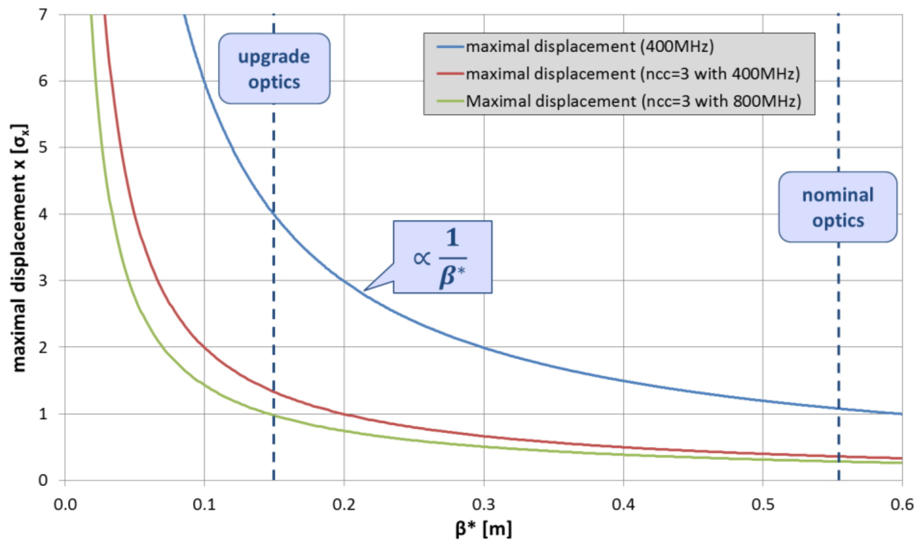
Scaling Laws

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

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

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:

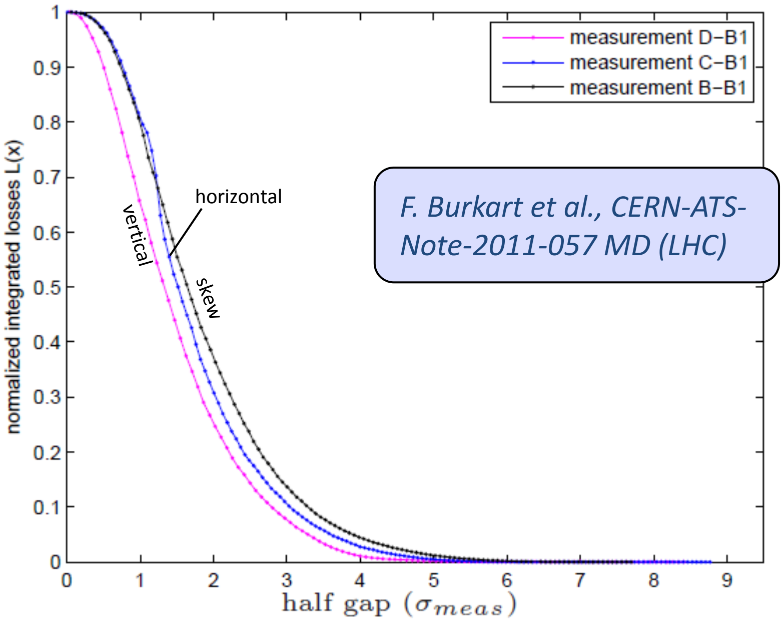
  *In horizontal plane about **4%** of beam beyond **4σ**$_{meas}$.*

  *Corresponds to **≈20-30 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)

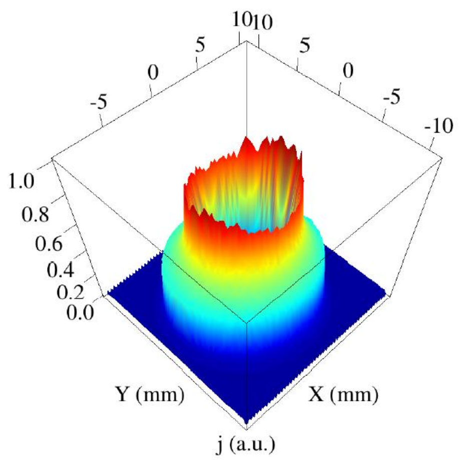
Table 3: Measured fraction of beam intensity in the tails of the beam outside selected multiples of the measured beam size, σ_{meas}, at 450 GeV.

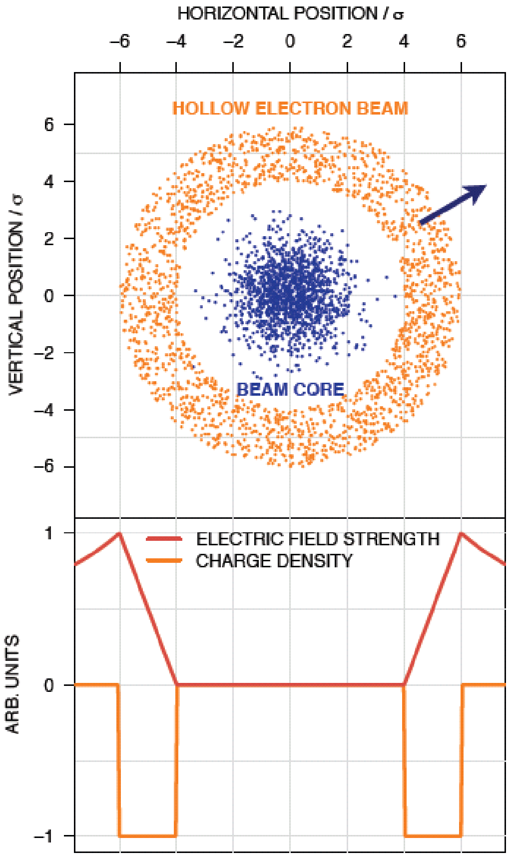
u [σ_{meas}]	$I_{tot,lost}(u)/I_{total}$ vertical	$I_{tot,lost}(u)/I_{total}$ horizontal	$I_{tot,lost}(u)/I_{total}$ skew
	B1	B1	B1
4	9.4e-3	3.8e-2	4.5e-2
5	2.2e-3	7.8e-3	1.3e-2
5.7	8.4e-4	1.6e-3	3.8e-3

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

Hollow Electron Lens

- **Hollow e⁻ beam** around proton beam core to **increase transverse diffusion rate** for particles with large betatron amplitues.
  Depletion of transverse tails (not efficient for luminosity production) without effect on beam core.
- **Positive experience in Tevatron**, particularly no emittance growth or instabilities observed.
- Fast gating on dedicated bunch trains possible.



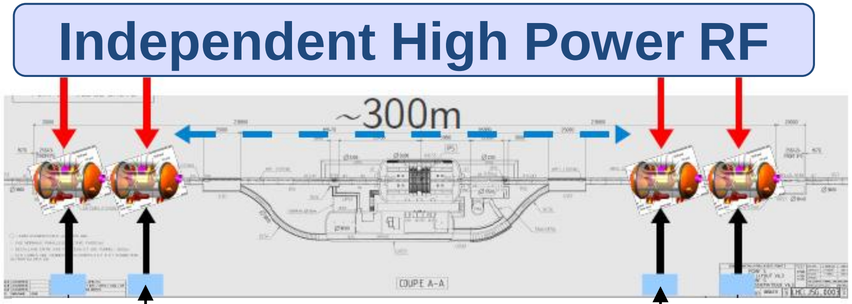


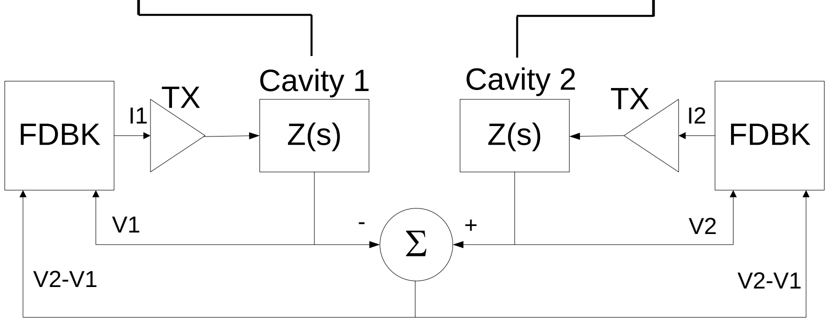
courtesy of G. Stancari et al.,
Physical Review Letters 107, 2011.

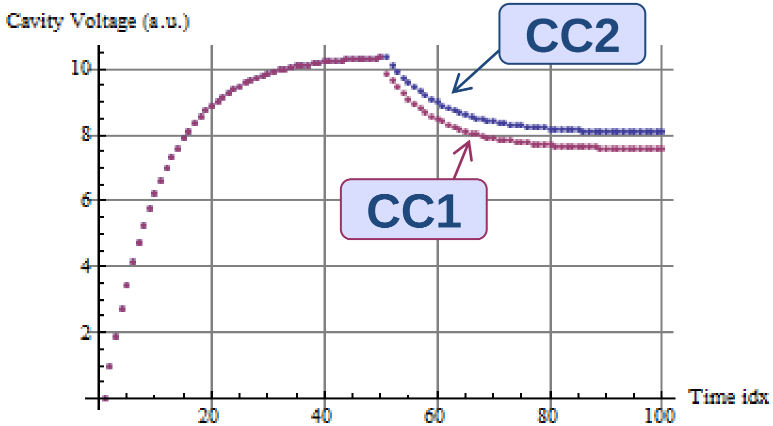
Coupled RF Feedback

- Strongly coupled RF Feedback to **regulate voltage difference** of CCs on either side of IP.
- Similar coupled feedback loop is planned to be installed for 200MHz traveling wave cavities in CERN SPS.
- Can provide **additional mitigation** for certain failures but cannot replace **passive protection** against severe failure scenarios.

courtesy of P. Baudrenghien et al., LHC-CC11.







Mitigation Options

- Mitigation options:
  - *Larger β^* (flat IR optics).*
  - *Smaller crossing angle (beam-beam 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.*
  - ***Hollow electron lens** to deplete transverse tails (essential).*
- Requires: **single turn redundant failure detection** and interlock.
  - *on cavity level.*
  - *on beam level, e.g. head-tail-monitor.*

Possible Scenarios

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

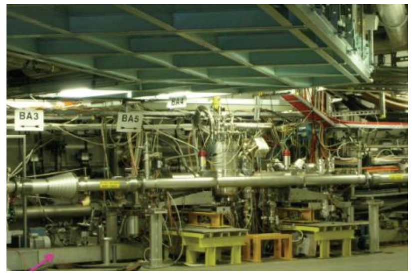
	Scenario 1: 3 CCs	Scenario 2: $\beta^* = 25cm$	Scenario 3: 800 MHz
CC frequency (f)	400 MHz	400 MHz	**800 MHz**
Number of independant CCs (n_{cc})	**3**	3	3
Q_{ext}	1‘250‘000	1‘250‘000	1‘250‘000
$\boldsymbol{\beta^*}$	15 cm	**25 cm**	15 cm
Distance from collimators to be depleted below 1MJ.	1.7σ	1.0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

T. Baer et al., IPAC’12, MOPPC003

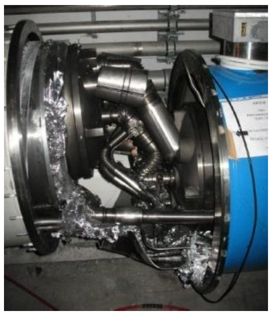
Magnet quenching in failure case not excluded.

Outlook

SPS CC Test



Long shutdown 1
Splice consolidation



LHC CC Test Pt. 4

Long shutdown 2
LHC injector upgrade

Long shutdown 3
HL-LHC and
CC installation

2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Technical Design

Construction

Conclusion

- Crab Cavities are essential to **compensate the geometric luminosity loss** (and to level the luminosity) for HL-LHC.
- **Crab cavity failures** can lead to **global betatron oscillations with large amplitudes** (up to **5σ** for n_{cc}=1) on very fast timescales.
  - *Unacceptable with multi-MJ tails.*
  - *Better understanding of failure scenarios (e.g. quench dynamics) needed.*
- Many **mitigation options.** In general: The more effective the crab cavities, the worse are their failure scenarios.
  - *Transverse tail depletion with **hollow e-lens** is essential.*
  - *Counteract failures with **strongly coupled RF feedback.***
- Crab cavity tests in SPS and LHC are foreseen prior to final installation in 2022.

Thank you

for your Attention

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Further information:

- T. Baer et al., "Very Fast LHC Crab Cavity Failures and Their Mitigation", IPAC'12, May 2012.
- 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.
- R. Calaga et al., "Beam Losses due to Abrupt Crab Cavity Failures in the LHC", PAC'11, March 2011.
- T. Baer, "Beam Dynamics Aspects of Crab Cavity Failures", December 2010.
- J. Tuckmantel, "Failure scenarios and mitigation", LHC-CC10, December 2010

Backup slides

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):

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

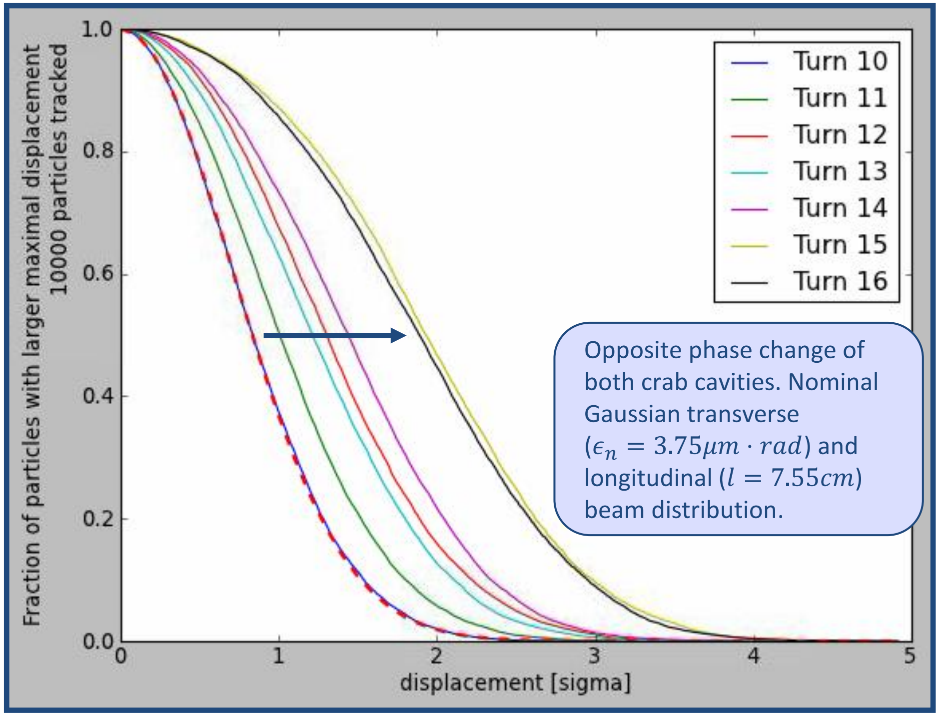
- Optimal voltage for compensating cavities:

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

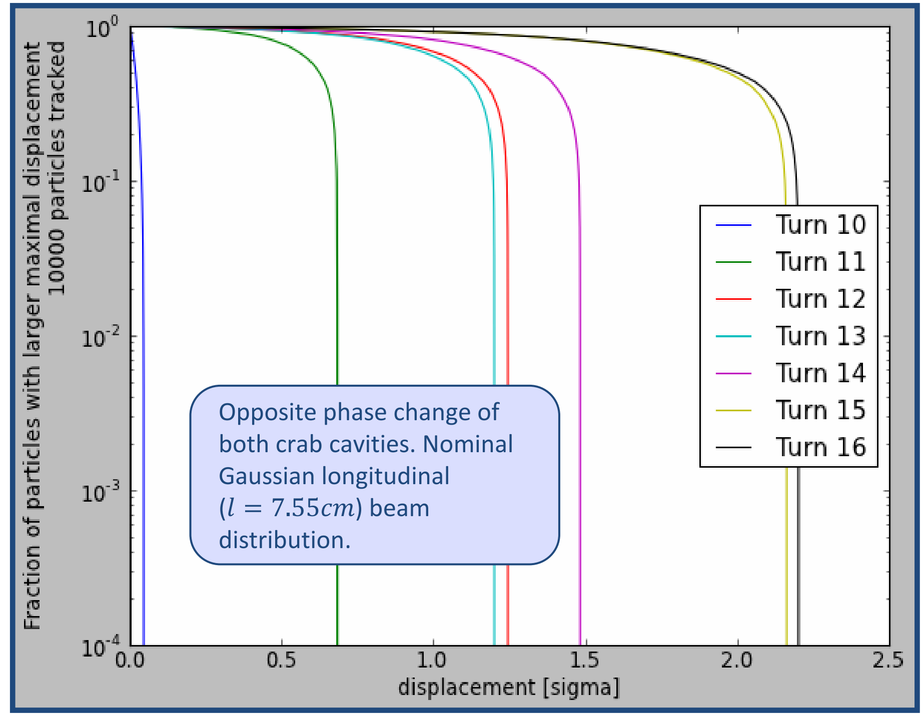
ideally 180°

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.

Phase Change



Maximal displacement with Gaussian transverse and longitudinal beam distribution.



Maximal displacement with Gaussian longitudinal beam distribution.

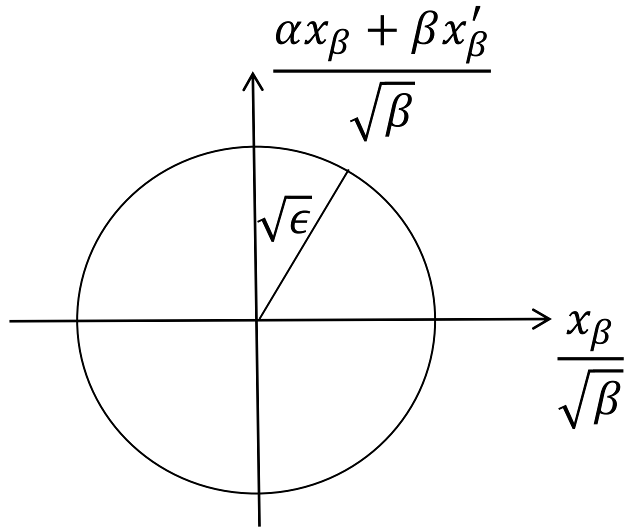
In case of a **dephasing** of the crab cavities left and right of the IP, the (longitudinal) **bunch center** is maximally displaced, by up to **$2.2\sigma_x$ in 5 turns**.

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:

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

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

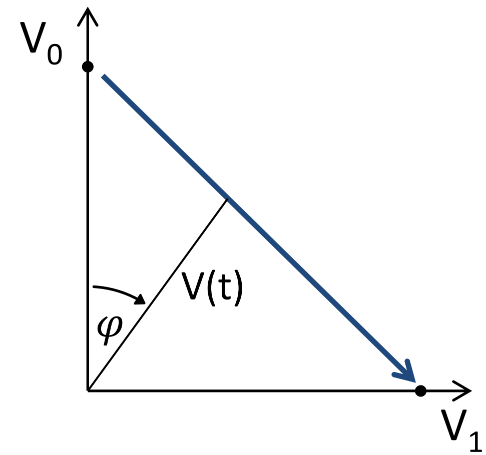
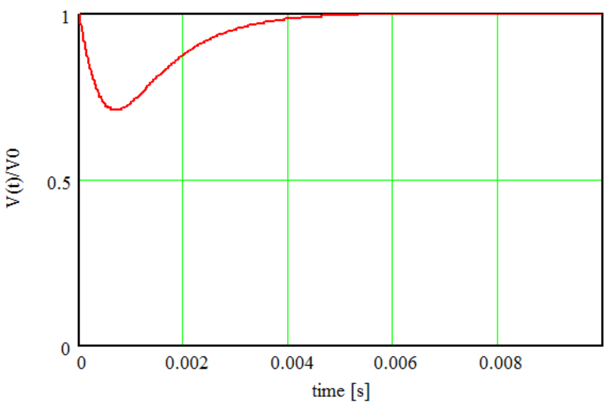


Illustration of 90° voltage change.

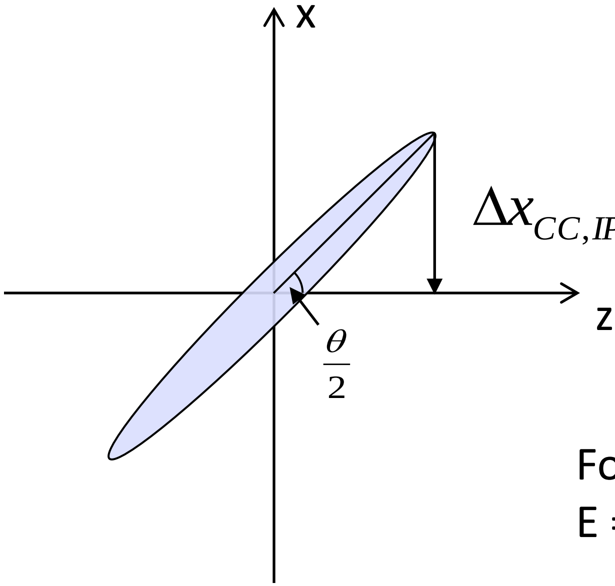


Amplitude of cavity voltage.

Content

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):

  Scaling factor (≈ 1.12)

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

  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)

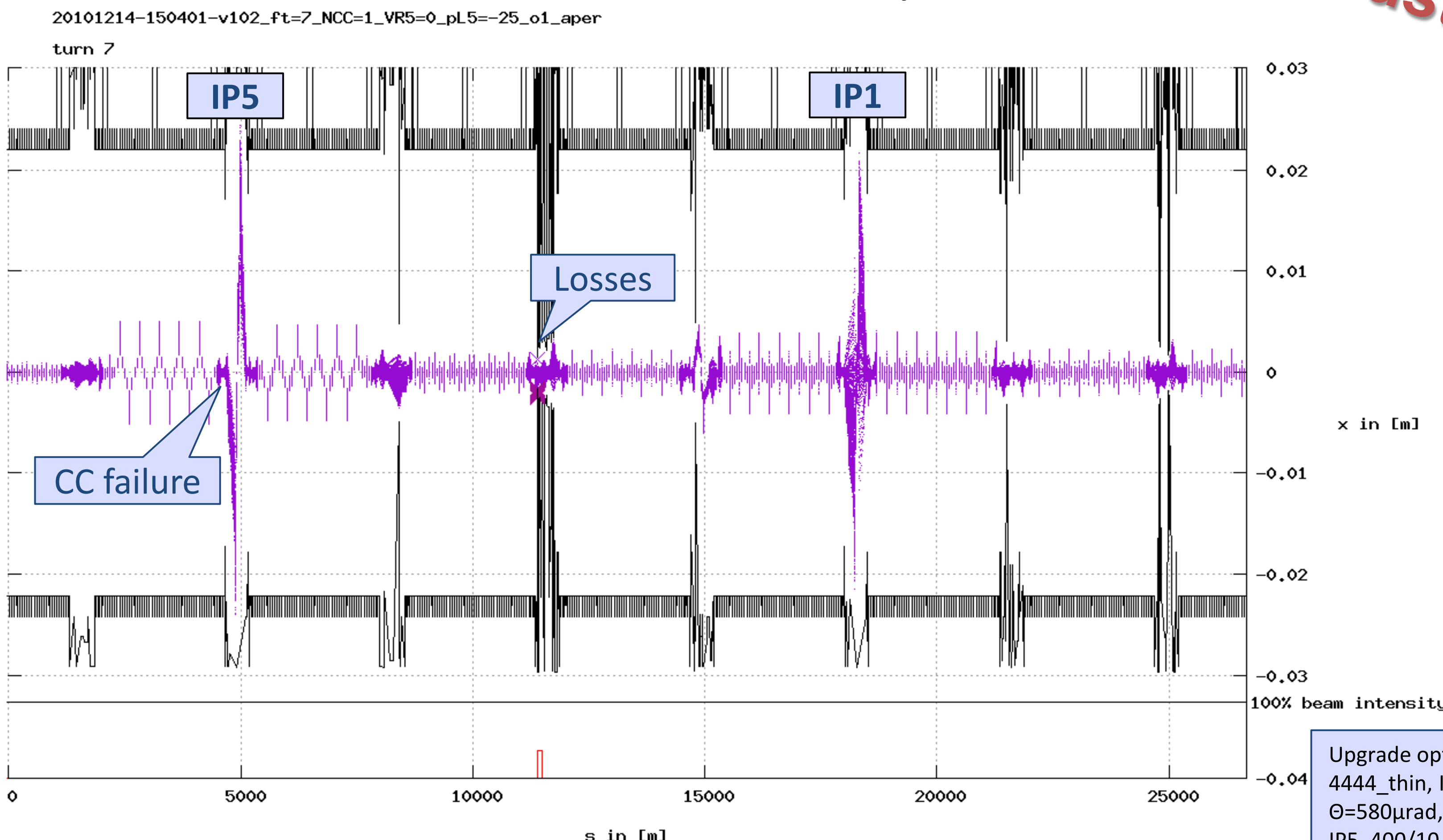
- Fast Voltage Decay
- Phase Error

Phase Error of CRAB.L5.B1

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

Massive beam loss within few turns, mainly at **TCP.C6L7.B1**

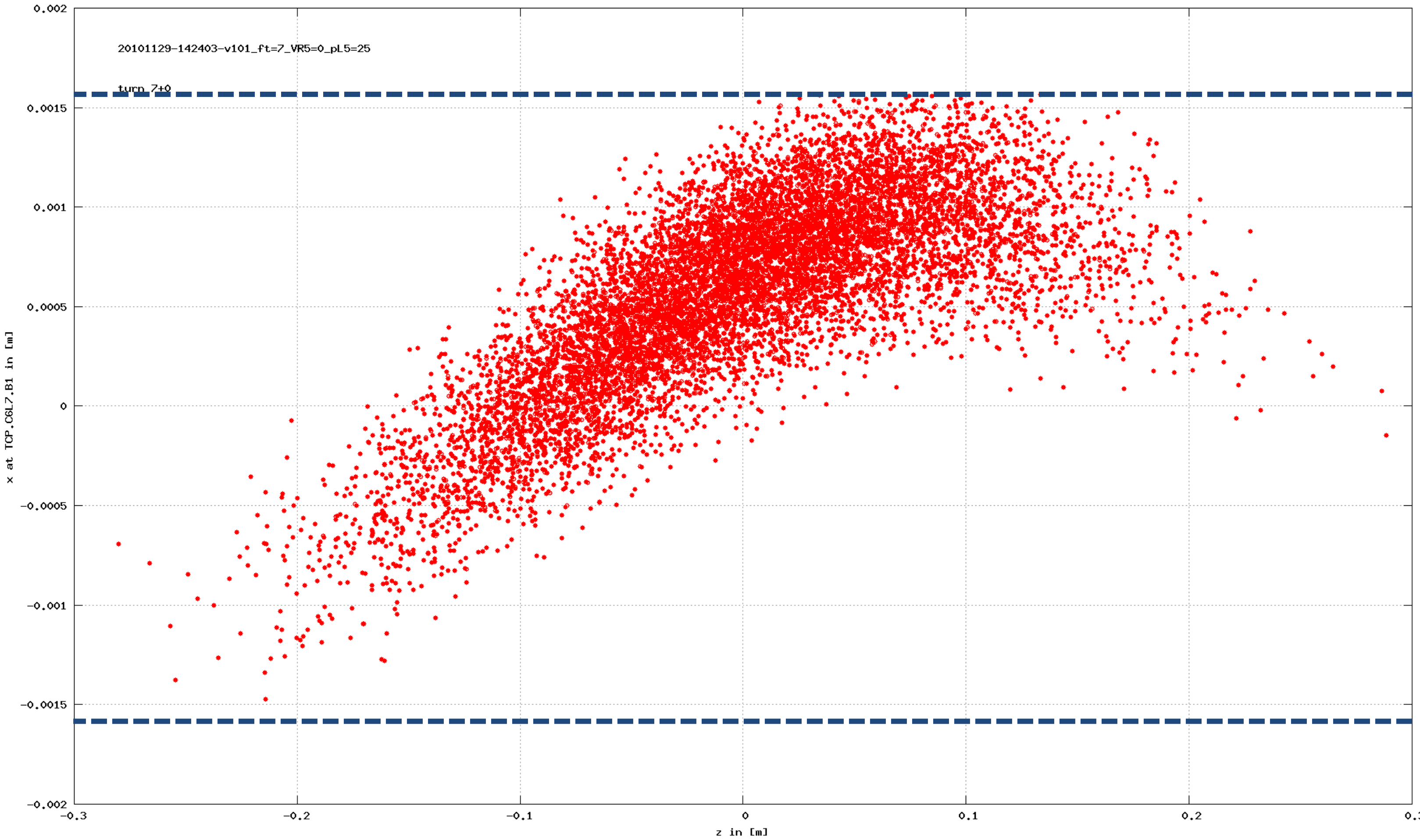
For Illustration



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

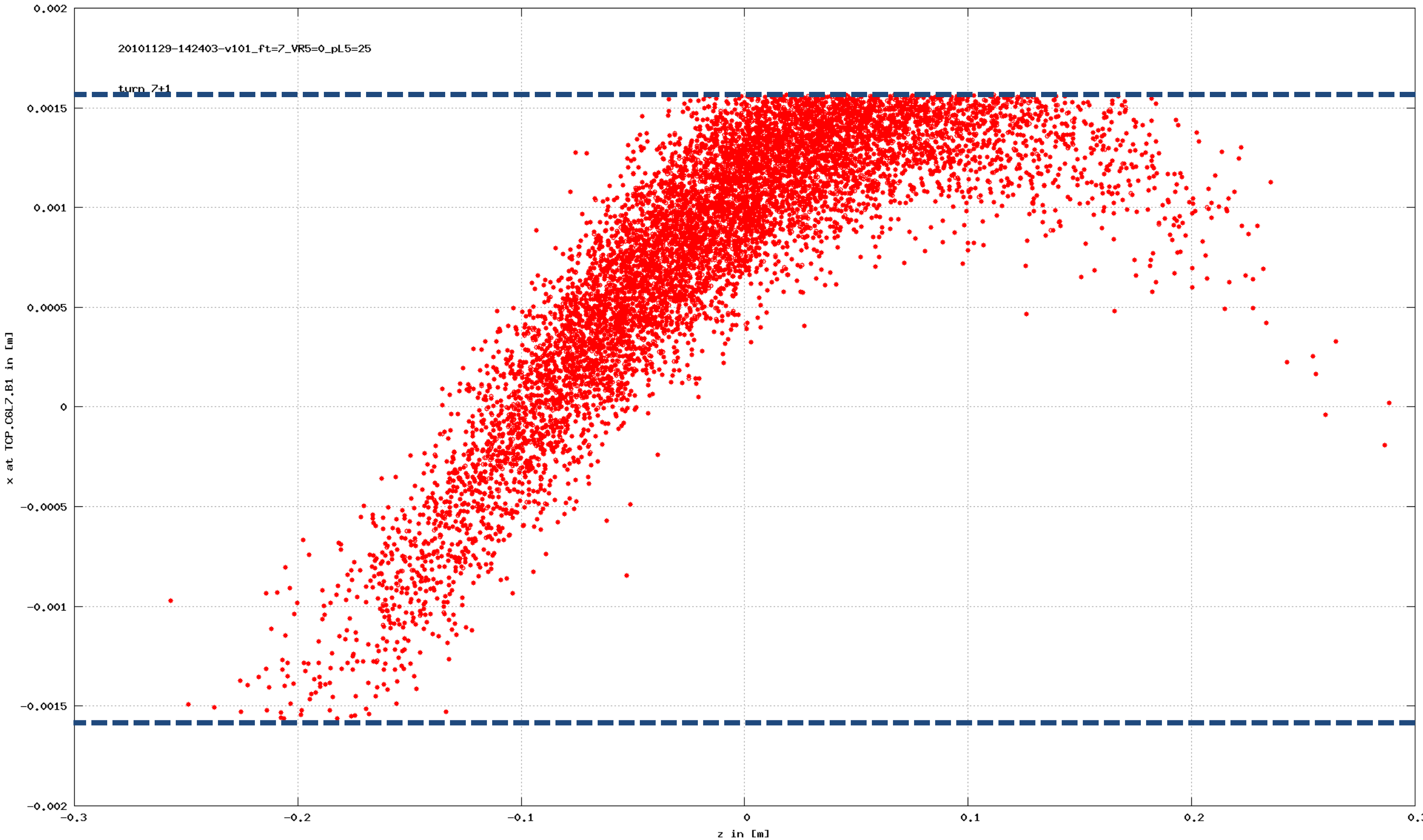
Phase Error of CRAB.L5.B1

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

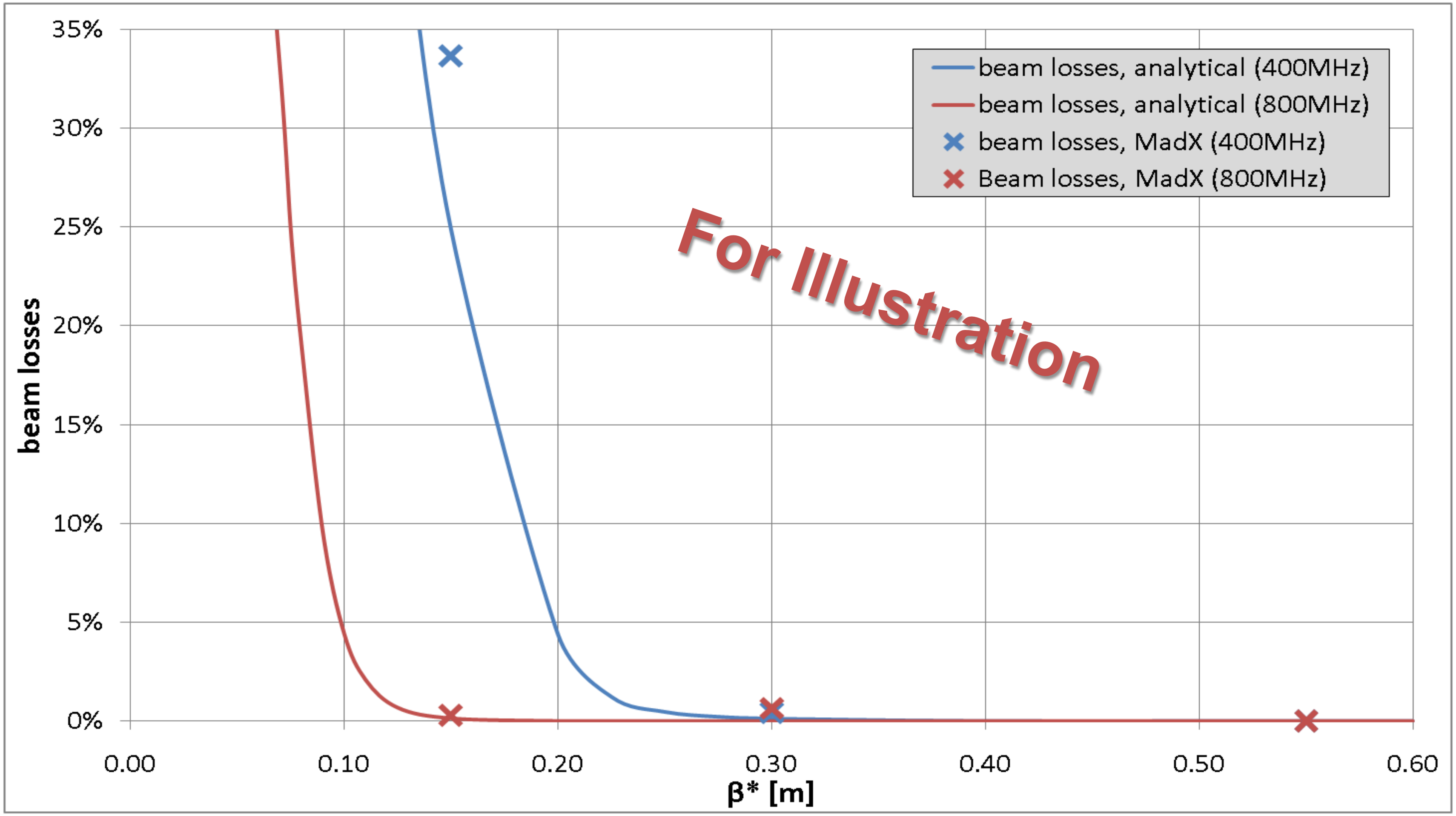


Phase Error of CRAB.L5.B1

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)
For Illustration