Crab cavity failure scenarios and their tracking

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Plenary session with the experiments,
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Thanks to Anton Lechner / FLUKA team, Roderik Bruce / Collimation team, Rama Calaga and Alick Macpherson / RF group, Graeme Burt, Moritz Guthoff and Antonello Sbrizzi / CMS&ATLAS, and many more for discussions, tools etc.

Outline

Beam failure scenarios: Introduction

- Stored energy in the HL-LHC beam $\approx$ 700 J $\approx 2\times$ stored energy today

$\Rightarrow$ A small fraction of the beam can cause significant damage to the machine and the experiments

- Downtime $\Rightarrow$ reduced $\int \mathcal{L}\,\mathrm{d}t$

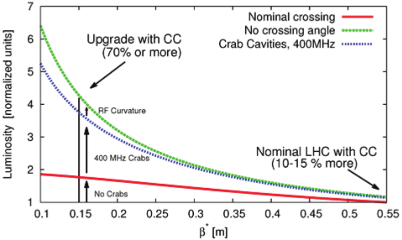
$\Rightarrow$ Need to balance performance vs. safety

- Most worrying: Failures too fast to detect and dump the beam before damage occurs
  - Dump system delay: 3–10 turns
- Need to map out and eliminate the most likely/damaging scenarios

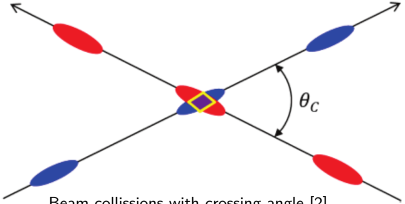
Effect of the SPS beam exiting a 60 cm copper cylinder [1]

Crab cavities

- At HL-LHC, small $\beta^* \Rightarrow$
  - $\Rightarrow$ Fast β growth around IP
  - $\Rightarrow$ Need large crossing angle to avoid long-range collissions and beam-beam effects
  - $\Rightarrow$ Bunches no longer fully overlap: Lower peak luminosity, higher pile-up density
- Crab cavities "tilts" the bunches
  - Recovers luminosity
  - Works by applying a strong kick to the head and tail of the bunch
  - Useful, but powerful and fast-acting devices



Luminosity dependence on β^* for the LHC [2]



Beam collissions with crossing angle [2]

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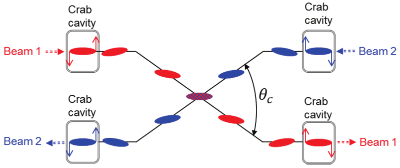
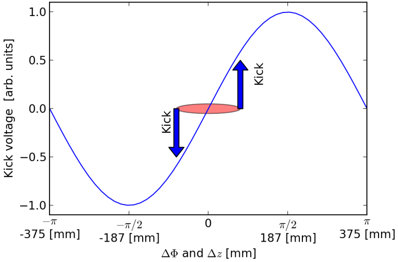


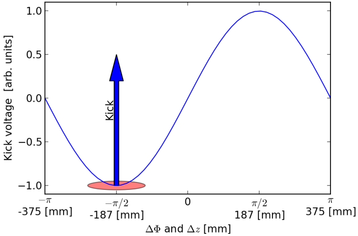
Beam collissions with crab cavity [2]



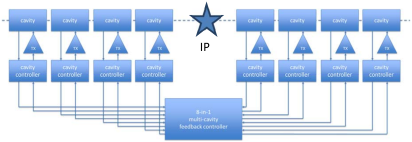
Mechanism of bunch crabbing

Crab cavity failure scenarios

- Vulnerabilities:
  - Superconductivity quenches
  - Control system failures
  - Vacuum arcs etc.
- As seen by the beam:
  - Voltage change
  - Phase change
- Effect on the beam:
  - Head-tail oscillations
  - Global betatron oscillations

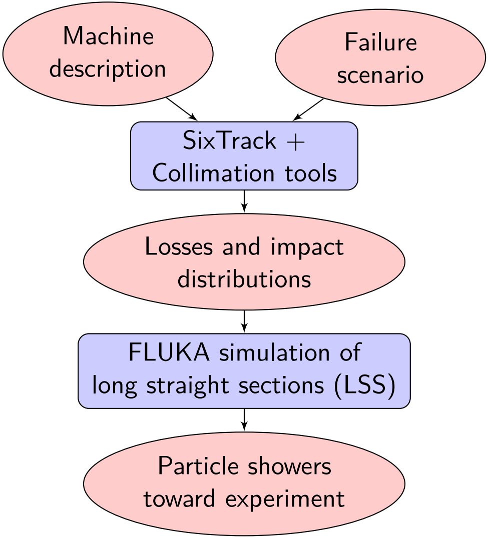


DQW CC prototype in SM18



Proposed CC LLRF architecture for one ring and IP [3]

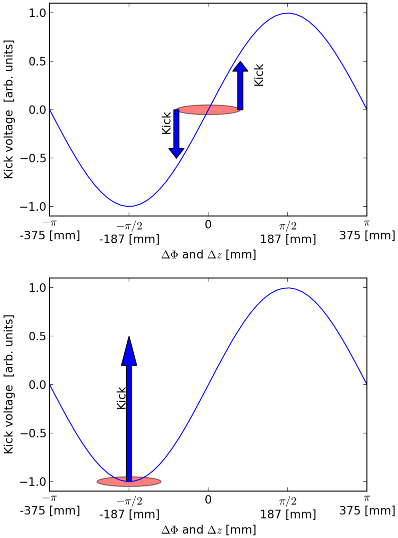
Simulation setup



Scenario: Loss of phase control

- CC phase 0° → 90° in 1 turn
- Useful and simple benchmark case, but would require a serious controller failure to actually happen
- Applied to all 4 cavities downstream of IP1, beam 1
- Creates a strong but not growing transverse oscillation (coherent betatron + head-tail)

⇒ Large (≈ 21 %) and fast losses



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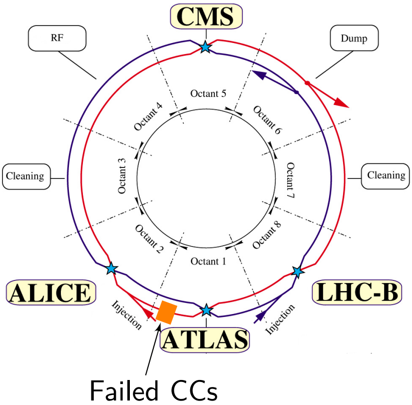

Figure adapted from
http://cds.cern.ch/record/841573
by Jean-Luc Caron

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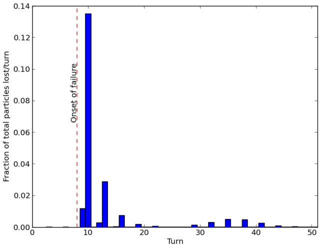

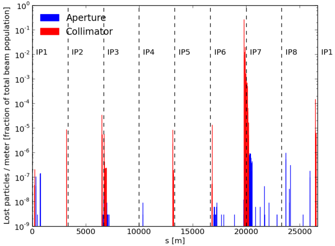

Scenario: Quench

- Loss of cavity superconductivity
  - Material imperfections
  - Beam losses
  - Multipacting and discharges
- Draining of cavity field
- Drop in internal radiation pressure
  $\Rightarrow$ Lorentz-force detuning
- Model of cavity behavior:
  - Field strength:
    $V = V_0 e^{-\frac{t}{2\tau_U}}$
  - Detuning:
    $\Delta f = \Delta_f' \left(1 - e^{-\frac{t}{\tau_U}}\right)$
- For nominal parameters, no significant losses during a quench
- In case of fewer cavities quenching, losses are further reduced

- Model parameters:
  - $\tau_U = \frac{Q_{\mathrm{ext}}}{\omega} \approx 159 - 198\ \mu\mathrm{s}$
    $= 1.8 - 2.23\ \mathrm{turns}$
  - $\Delta_f' \approx 0.4 - 4.0\ \mathrm{kHz}$

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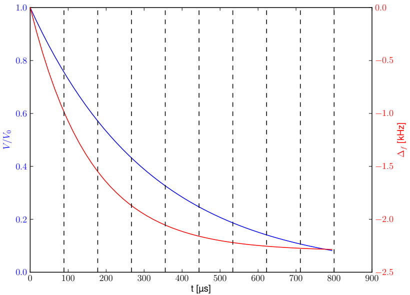

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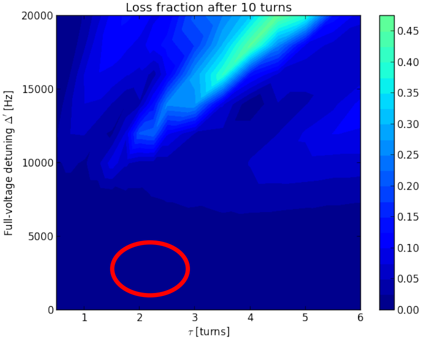

4 cavity trip, 3 turns after failure

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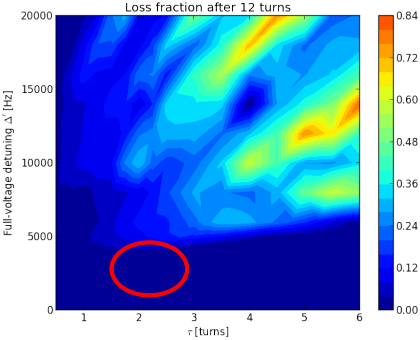

4 cavity trip, 5 turns after failure

Scenario: Quench

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- Draining of cavity field
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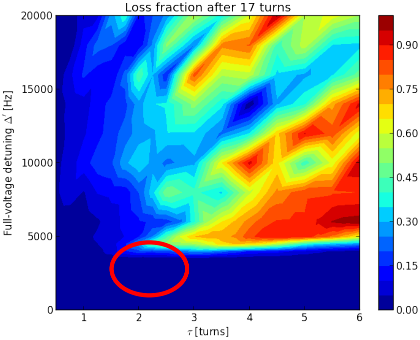

4 cavity trip, 10 turns after failure

Scenario: Quench

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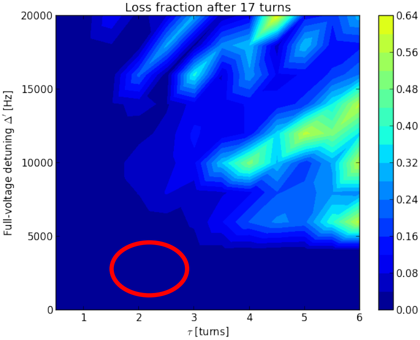

3 cavity trip, 10 turns after failure

Scenario: Quench

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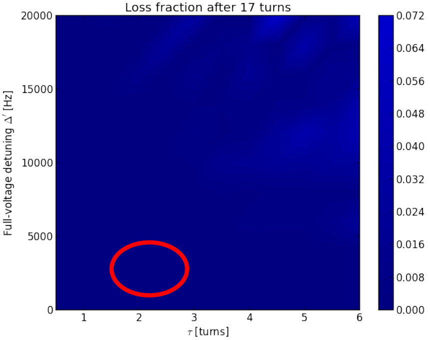

2 cavity trip, 10 turns after failure

Scenario: Quench

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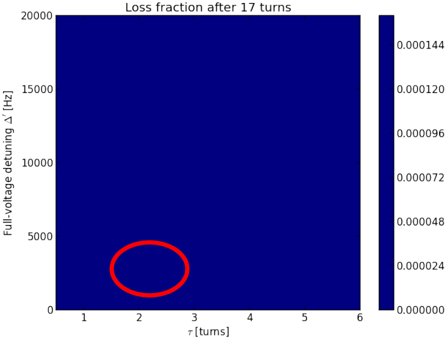
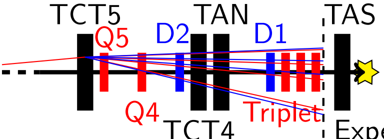


1 cavity trip, 10 turns after failure

Crab accident scenario: Impact on machine

- Use the 90° phase failure as a reference scenario
- Fast and heavy losses, corresponding to a very serious CC accident
- Most is intercepted in the betatron cleaning section (IP7)
    - Very serious failures may damage the collimators
- Some of it hits the TCTs just before IP1
    - Showering towards the IP



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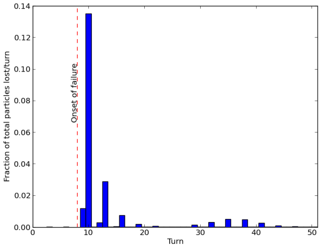
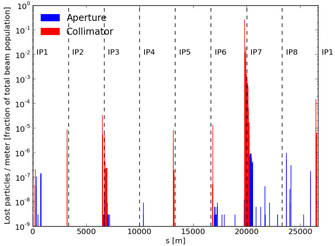




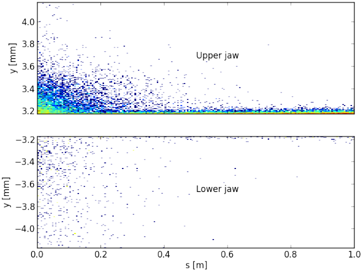
Impact distribution on TCTs

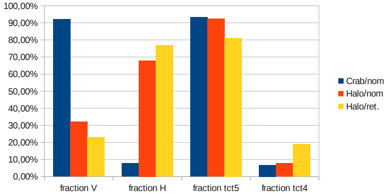
- In the phasejump scenario, 0.018% of the beam hits the TCTs near IP1

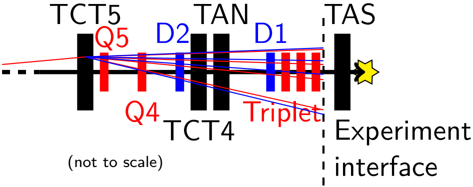
⇒ Shower towards the experiment

- The impacts are:
  - Concentrated on single jaw
  - Concentrated on TCT5
  - Single plane:
    IP1 crab failure → V
    IP5 crab failure → H
    Extraction kicker → H

Impact distribution on TCTVA5:



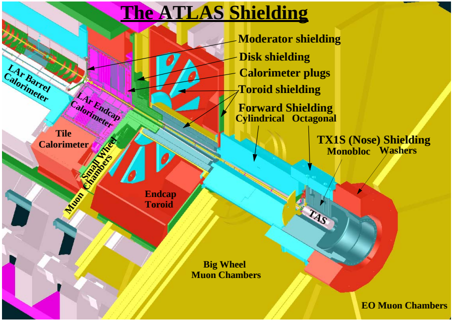




(not to scale)

Opening of the TA(X)S aperture

- Plan to open the TAS: $\varnothing = 34\text{cm} \rightarrow 54$ cm [5]
- Gain aperture for crossing angle and smaller β^*
- Need to quantify effect of protecting the experiments from accidental beam losses and machine background

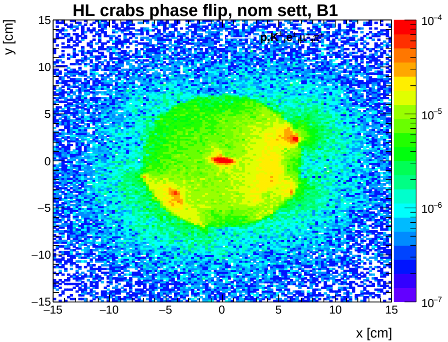


Current ATLAS shielding

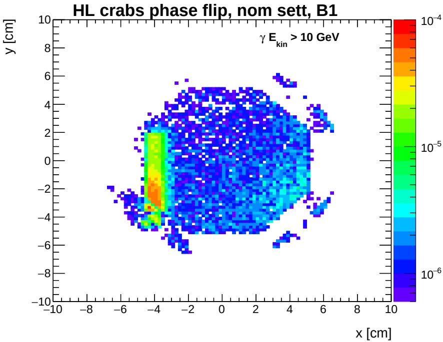
`http://atlas.web.cern.ch/Atlas/GROUPS/Shielding/shielding.htm`

Particles streaming towards the detector

Charged particles



Photons



- Particle density distributions on the interface plane, CC accident scenario
- Distribution depends on source (accident, halo, etc.) and collimator settings
- Opening the TAS allows more particles to reach the inner detector

Particles streaming towards the detector

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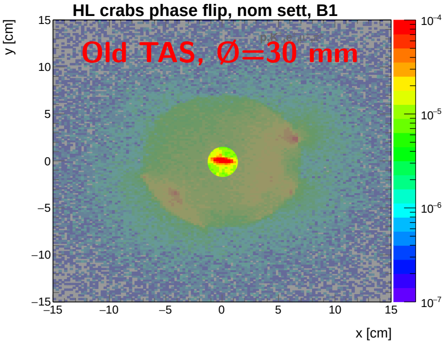

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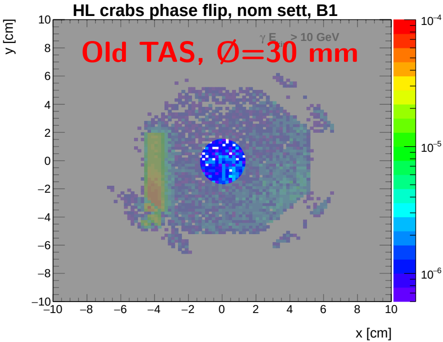

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Particles streaming towards the detector

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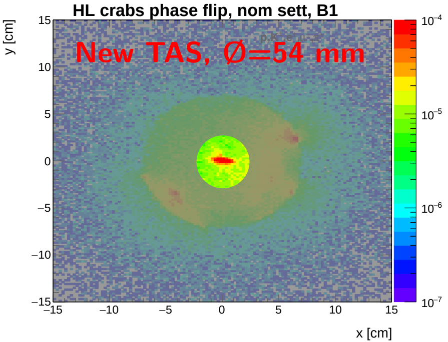

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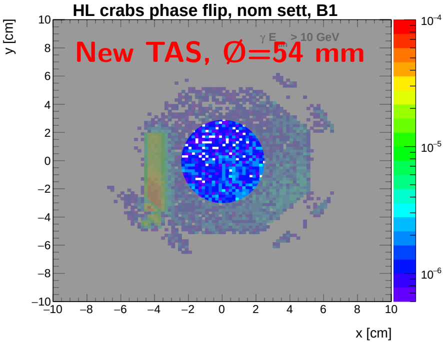

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Summary and conclusions

- Tracking simulations for CC failure scenarios in progress, looking for cases with heavy & fast losses
- Losses on TCTs $\Rightarrow$ showers toward experiment
- Knowing the scenarios, we can mitigate:
  Device design, interlocks, collimators, ...
- Quenches do not appear to be a threat
  - Losses $< 0.1\%$ in realistic scenarios
  - Must keep Lorentz force detuning during quench < 3.5 kHz
- "Powered mishaps" can create large & fast losses
  - Cavity control must be safe!
- Single cavity failures much less damaging than correlated failures

Outlook

- More detailed modeling of cavity & control behavior during a failure
- Evaluate likelihood of scenarios
- Also check beam 2 and IP5
- Update to HL-LHC v1.2
- Mitigation:
  - Collimator settings
  - Hollow electron lens
  - Active mitigation
- Correlated failures: A problem may not come alone. . .
- Damage thresholds for experiments: **Next talk!**

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- Damage thresholds for experiments: **Next talk!**

A non-conforming RF insert [6]

Relevant presentations

Yesterday:

- Philippe Baudrenghien
  Transverse emittance growth due to CC RF noise, and requirements for the CC RF
  https://indico.cern.ch/event/400665/session/15/contribution/54
- Andrea Santamaria:
  Crab cavity failure modes and IR protection
  https://indico.cern.ch/event/400665/session/19/contribution/77
- Regina Kwee-Hinzman:
  Collimation backgrounds at HL-LHC
  https://indico.cern.ch/event/400665/session/21/contribution/109

This session:

https://indico.cern.ch/event/400665/timetable/#20151029.detailed

- Helmut Burkhardt:
  Overview of aperture, risks, losses, collimation and background
- Roderik Bruce:
  Collimation hierarchy and tracking for extraction failures
- Moritz Guthoff:
  Effects of losses and LHC/HL-LHC comparison in ATLAS and CMS

Bibliography I

[1] F. Burkart, R. Schmidt, V. Raginel, D. Wollmann, N. A. Tahir, A. Shutov and A. R. Piriz: *Analysis of 440 GeV proton beam-matter interaction experiments at the High Radiation Materials test facility at CERN*; J. Appl. Phys. 118, 055902 (2015), `http://dx.doi.org/10.1063/1.4927721`

[2] Q. Wu: *Crab cavities: Past, present and future of a challenging device*; IPAC'15

[3] *HL-LHC Preliminary design report*, November 2014

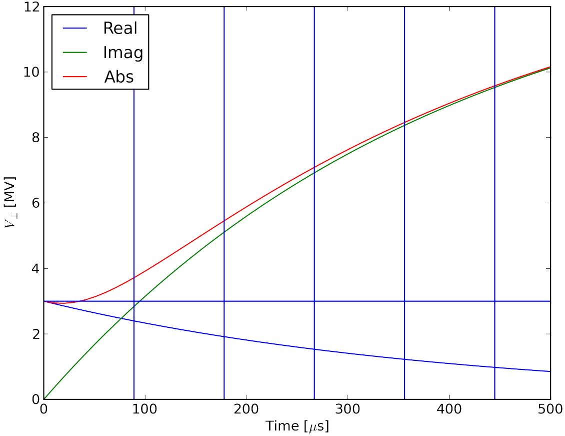
Bibliography II

[4] Marija Cauchi, O. Aberle, R. W. Assmann, A. Bertarelli, F. Carra, K. Cornelis, A. Dallocchio, D. Deboy, L. Lari, S. Redaelli, A. Rossi, B. Salvachua, P. Mollicone, and N. Sammut: *High energy beam impact tests on a LHC tertiary collimator at the CERN high-radiation to materials facility*; PRST'14

[5] R. De Maria, S. Fartough, M. Fitterer: *HLLHCV1.1: Optics version for the HL-LHC UPGRADE*; IPAC'15.

[6] Katy Foraz: *LS1: summary of project development and results.*; CERN A&T Seminar, 4 June 2015.

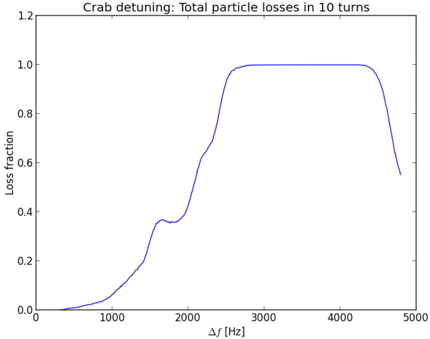
Estimate of minimum phase flip time



- Initial condition: RF on, steady state, crabbing phase (real)
- Input after $t = 0$: RF on, maximum input power (100 kW) at 90° (imag)
- Does not take amplifier bandwidth into account

Scenario: Detuning the cavities

- Full voltage, detuned cavities
- Would need "cooperation" of mechanical tuners and RF due to cavity bandwidth
- If main betatron line is excited ($\approx 1/3\ f_{\mathrm{rev}} = 3.7\ \mathrm{kHz}$), beam is quickly lost



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