Measurements of beam halo diffusion and population density in the Tevatron and in the Large Hadron Collider

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Outline

‣ Introduction: halo population and halo dynamics
‣ Measurements with collimator scans in Tevatron and LHC
  ‣ Tail populations
  ‣ Diffusivity vs. betatron amplitude
‣ Nondestructive halo diagnostics
‣ Comments on halo populations and diffusivity
‣ Conclusions
Halo dynamics and accelerator performance

Halo dynamics influences global accelerator performance

- beam lifetime
- emittance growth
- dynamic aperture
- collimation efficiency

It depends on a multitude of effects, some of which are stochastic in nature

- lattice resonances
- intrabeam scattering
- coupling
- lattice nonlinearities
- beam-gas scattering
- ground motion
- beam-beam forces
- power-supply ripple
Stochastic character of halo dynamics

Dynamics is in general very rich: regular and chaotic regions, resonance islands, etc.

Superposition of many effects (some random) can make halo dynamics stochastic
Stochastic character of halo dynamics

Stochastic nature of halo dynamics often empirically confirmed by relaxation of losses $\sim (\text{time})^{-1/2}$ during collimator setup ($\sim$ random walk process)
Collimation and beam halo populations are critical for LHC

- LHC and HL-LHC represent huge leaps in stored beam energy

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<tr>
<td>Stored energy per beam</td>
<td>2 MJ</td>
<td>140 MJ</td>
<td><strong>362 MJ</strong></td>
<td><strong>692 MJ</strong></td>
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- No scrapers exist in LHC for full beam at top energy
- Halo populations (e.g., $4\sigma$ to $6\sigma$) in LHC are not well known. Collimator scans and van-der-Meer luminosity scans indicate 0.1%-2% of total energy, which translates to 0.7 MJ to 14 MJ for HL-LHC at 7 TeV. Comparable to the whole Tevatron beam!

*Yesterday’s sensation is today’s calibration and tomorrow’s background.*

—Anonymous physicist
Collimation and beam halo are critical for LHC

- Quench limits, magnet damage, or even collimator deformation will be reached with fast crab-cavity failures ($\sim 2\sigma$ orbit shift) or other fast losses
  
  Schmidt et al., IPAC14; Yee-Rendon et al., IPAC14

- Hence the need to measure and monitor the halo, and to remove it at controllable rates. Beam halo monitoring and control are essential for safe operation.

- Hollow electron lenses are the most established and flexible tool for active halo control of high-power beams

Some estimates of beam tails in LHC

Extinction scans at 450 GeV

Lost intensity vs. collimator position

2-4% beyond 4σ
Discrepancy between slow and fast scraping
Assumption: static distribution

Burkart, PhD (2012)

Van-der-Meer luminosity scans

Luminosity vs. beam separation

0.1% above 4σ
Assumption: equal beams

CMS-PAS-EWK-11-001 (2011)
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Collimator scans in Tevatron and LHC

Primary collimator is moved towards or away from beam axis in small steps. Other collimators are retracted.

Time evolution of losses is recorded.
Tevatron measurements

- Beam studies with antiprotons at 0.96 TeV
- Motivated by hollow electron beam collimator and beam-beam dynamics
- Many experiments at the end of regular collider stores
- One experiment with special antiproton-only store
- Scans using primary vertical collimator on antiprotons
- Minimum step: 25 µm in 20 ms

Stancari et al., IPAC11, p. 1882
Stancari et al., HB2012
Stancari et al., BB2013, arXiv:1312.5007
LHC measurements

- Beam studies at 4 TeV
- One nominal bunch per beam, $10^{11}$ p/bunch (no long-range)
- Scans using primary collimators: vertical on beam 1, horizontal on beam 2
- 1 scan with separated beams, 1 scan in collision
- Minimum step: 5 µm in 2.5 ms

Valentino et al., PRSTAB 16, 021003 (2013)
Halo population density in LHC at 4 TeV with collimator scans

- Gaussian core from wire scans and sync light
- Halo estimates beyond $4\sigma$
- Integrated loss rate from calibrated beam loss monitors
- Intensity loss from current transformer

Beam density, $f(J)$ [protons/µm]

Action, $J$ [µm]

$J \equiv \frac{\chi_c^2}{2\beta_c}$ (half gap$^2$ amplitude function)
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Analytical and numerical studies on collisions and halo dynamics

Just a few examples...

› **SSC**: long-range, diffusive dynamic aperture
  › Irwin, SSC-233 (1989)

› **HERA at DESY**: nonlinearities, tune modulation, fluctuations in orbit offset and beam size
  › Zimmermann, Part. Accel. 49, 67 (1995)
  › Sen and Ellison, PRL 77, 1051 (1996)

› **LHC at CERN**: head-on, long-range, triplet nonlinearities
  › Papaphilippou and Zimmermann, PRSTAB 2, 104001 (1999)
  › Papaphilippou and Zimmermann, PRSTAB 5, 074001 (2002)
  › Assmann et al., EPAC (2002)

› **Tevatron at Fermilab**: beam-beam, nonlinearities, electron lenses
  › Sen et al., PRSTAB 7, 041001 (2004)
  › Stern et al., PRSTAB 13, 024401 (2010)
  › Previtali et al., IPAC (2012)

› **RHIC at BNL**: beam-beam, nonlinearities, electron lenses

› **Beam / electron cloud**:
  › Ohmi and Oide, PRSTAB 10, 014401 (2007)

Experiments are challenging and data is scarce...
Measurement of diffusion rate vs. amplitude with collimator scans

Mess and Seidel, NIMA 351, 279 (1994)

Transient is faster at large amplitudes (higher diffusion rate)

Previous observations

SPS Burnod et al., CERN-SL-90-01

Transient interpreted as distribution of drift speeds

SPS Meddahi, PhD (1991)

Relaxation time is strong function of amplitude

HERA Seidel, PhD (1994)

Calculated beam-beam and tune modulation close to measured diffusion rate

RHIC Fliller et al., PAC (2003)

Large systematics

Comparison of \( p \), \( d \), and \( Au \)
Beam population density, $f(x, t)$

Diffusion coefficient, $D(x)$

Local loss rate (flux)

$$R \propto -D \cdot [\partial_x f]_{x=x_c}$$

1-dimensional diffusion cartoon of collimation

Transverse position, $x [\sigma]$
Diffusion model of loss rate evolution in collimator scans

Distribution function of tails evolves under diffusion with boundary condition at collimator

\[ \partial_t f = \partial J \left( D \cdot \partial J f \right) \]

Instantaneous loss rate is proportional to slope of distribution function

\[ R = -k \cdot D \cdot \left[ \partial J f \right]_{J=J_c} + B \]

loss monitor calibration

background rate
The diffusion coefficient depends mostly on the transient in the data.

Particle fluxes before and after the step are determined by the steady-state loss levels.
Beam halo diffusion rates in the Tevatron and in the LHC

Effect of beam-beam is 1-2 orders of magnitude

Near core, diffusivity consistent with emittance growth

Very low noise and nonlinearities in LHC

curves from measured core emittance growth

$$D_J = \dot{\varepsilon} \cdot J$$
Effect of hollow electron lens on diffusion in the Tevatron

To our knowledge, first direct observation of controlled diffusion enhancement in specific amplitude range!
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The rate of electrons backscattered towards the gun by Coulomb collisions is a sensitive probe of the overlap between electron and circulating beam.

High dynamic range, promising for continuous nondestructive halo monitoring.

Thieberger et al., IBIC 2014
Backscattered electron detector tested with ions in RHIC

Counting rate vs. electron beam position in overlap region

Thieberger et al., IBIC 2014
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Relationship between diffusion and halo population

The diffusion equation relates density and diffusivity \[ \partial_t f = \partial_J (D \partial_J f) \]

Simple example of given distribution (assumed known):
- Gaussian with long lifetime and slow emittance growth
- 
  \[ f_G(J,t) = \left( \frac{N}{\varepsilon} \right) \cdot \exp \left[ -\frac{J}{\varepsilon} \right] \]
  \[ N(t) = N_0 \exp (-\lambda t) \]
  \[ \varepsilon = \varepsilon_0 \exp (\gamma t) \]

The diffusion equation gives relations between diffusivity, decay rate, and emittance growth

\[ \gamma = 2 \left\langle \left( \frac{D}{\varepsilon} - D' \right) \cdot J \right\rangle / \varepsilon^2 \]
\[ D(J) = \gamma \varepsilon J + \lambda \varepsilon^2 \left[ \exp \left( \frac{J}{\varepsilon} \right) - 1 \right] \]

Diffusivity grows exponentially with action
In realistic case \((D \sim J^n)\), tails are inevitable

In general, analysis of collimator scans must take drift and diffusion into account: integrated loss rates (“fluxes”) are not necessarily proportional to local population densities (“tails”)!
Discussion and conclusions

-Understanding **halo populations and dynamics** is essential for machine protection, accelerator performance, and experimental backgrounds.

- **Collimator scans** in small steps allow one to measure populations and diffusivities simultaneously, reducing systematics.

- **Population densities** were measured over two orders of magnitude over a wide range of amplitudes.

- **Diffusivities vs. amplitude**
  - were consistent with emittance growth near core
  - showed the effects of collisions and of the hollow electron lens
  - will be calibrated against known transverse damper excitations

- **Nondestructive, continuous halo monitoring** in LHC
  - synchrotron light with coronagraph or wide-range camera
  - backscattered electrons? (needs electron lens and scanning)

- Option for **active halo control**: hollow electron lenses

Thank you for your attention!
Backup slides
What’s an electron lens?

- Pulsed, magnetically confined, low-energy electron beam
- Circulating beam affected by electromagnetic fields generated by electrons
- Stability provided by strong axial magnetic fields

5-kV, 1-A electron gun
thermionic cathode
200-ns rise time

6 m total length

superconducting solenoid
1–6 T

protons

3-m overlap region

antiprotons

collector

Tevatron electron lens

conventional solenoids
0.1–0.4 T

Electron lens (TEL-2) in the Tevatron tunnel

Electron gun

Superconducting solenoid

Collector
First main feature: control of electron beam profile

Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields.

Flat profiles for bunch-by-bunch betatron tune correction

Hollow profile for halo scraping

Gaussian profile for compensation of nonlinear beam-beam forces
Second main feature: pulsed electron beam operation

*Beam synchronization in the Tevatron*

Pulsed electron beam could be **synchronized with any group of bunches**, with a different intensity for each bunch.
Example of loss-rate analysis after collimator step

Loss rate, $S_j [V]

Time, $t_j [s]

Loss rate analysis after collimator step

Data set 6, 8527.tel
Step 15, $t = 13.7001 \text{ h}$
3474 data points

Step info:
From 318 to 320 mils
$y = -1.45 \text{ mm (4.49) mm}$
$J = 0.072 \mu m$
Spike / fluctuations: 7.43

Residuals, $r [V]

Time, $t_j [s]

$\chi^2/\text{d.o.f.} = 5863/3471 = 1.689$
$x = 0.24$
Convergence code: 0

Residuals, $r [V]

Time, $t_j [s]

MEDIAN(r) = -0.00228$
$\text{MAD}(r) = 0.333$

Initial guess:
$S_i = 1.34$
Result:
$S_i = 1.51 \pm 0.0093$

Initial steady-state rate, $S_f [V]

Initial guess:
$S_f = 1.5$
Result:
$S_f = 0.00214 \pm 0.0012$

Diffusivity, $D [\mu m^2/s]

Acceptable range:
$D_M = 0.000529$
$D_m = 2.04e-08$

Initial guesses:
$D = 2.64e-06$
$\hat{D} = 2.42e-05$

Result:
$D = 2.64e-06 \pm 5.3e-08$

Final steady-state rate, $S_f [V]

Initial guess:
$S_f = 1.5$
Result:
$S_f = 0.00214 \pm 0.0012$