Beam Halo

Bernhard Auchmann, Mark Harrison, Yichen Ji, Igor Tropin, Piotr Warzybok

Beam Halo

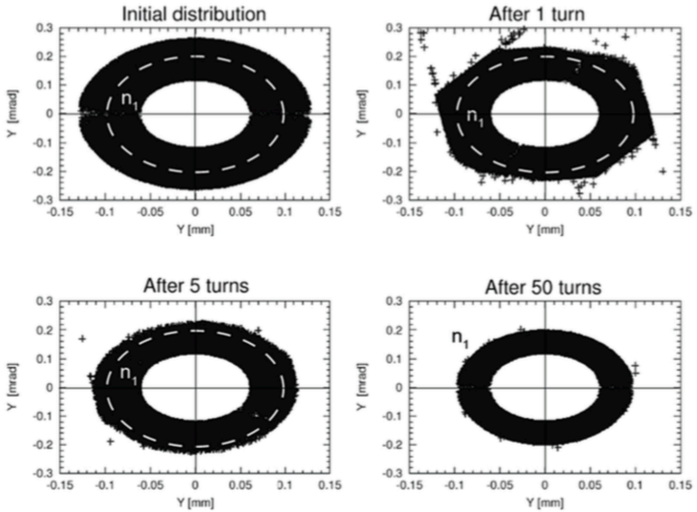
Particles away from the beam center which lead to unavoidable beam losses. No *one* definition exists.

- Starts at some multiple of beam width (3-4 σ)
- Based on the beam life-time

Problems with halo:

1. Background noise for physics experiments;
2. Risk of loss spikes
   a. induce magnet quenches,
   b. create damage on collimators.

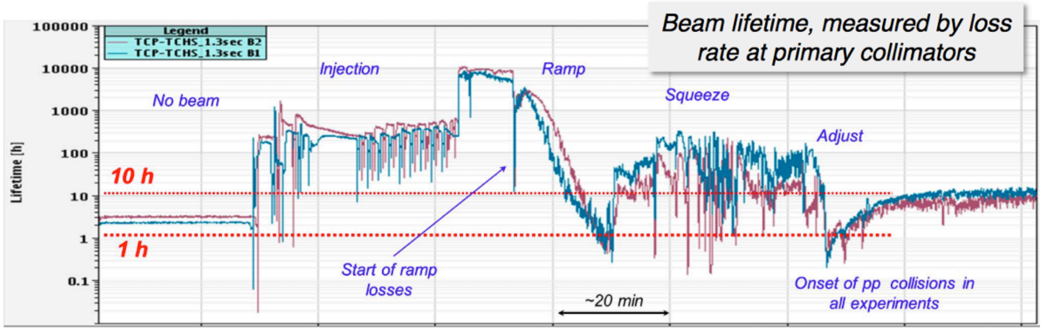
Multi-stage collimation is designed to intercept halo particles without destroying collimators or irradiating everything around them.



Source: R. Aßmann, ICAP 2012.

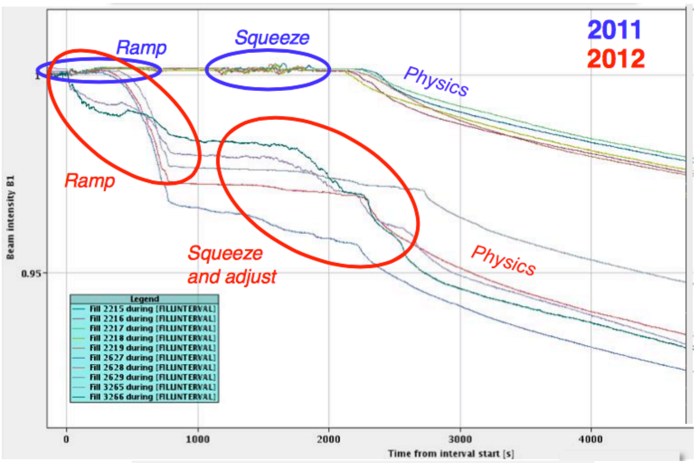
Stages of Acceleration

During certain stages of operation, sudden instabilities cause more of the halo to be intercepted by the primary collimators (see J. Wenninger lecture).



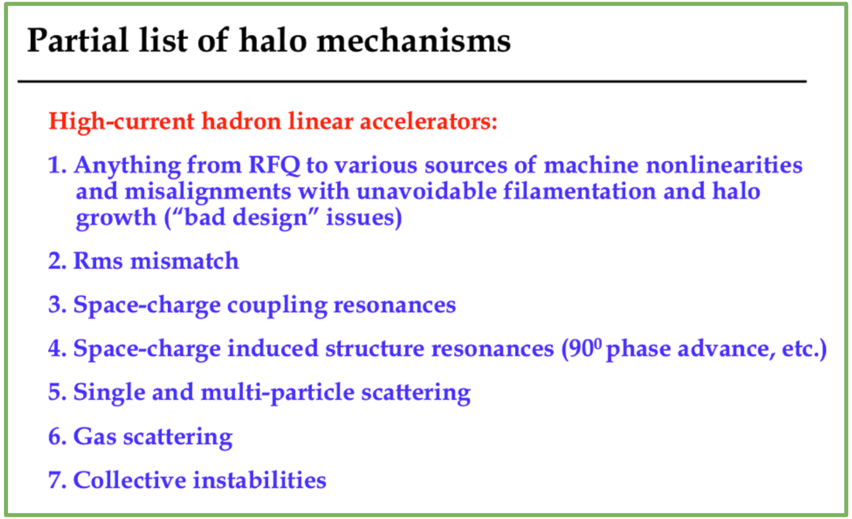
Beam lifetime, measured by loss rate at primary collimators

Example of a typical physics fill in 2012.



Courtesy B. Salvachua, S. Redaelli

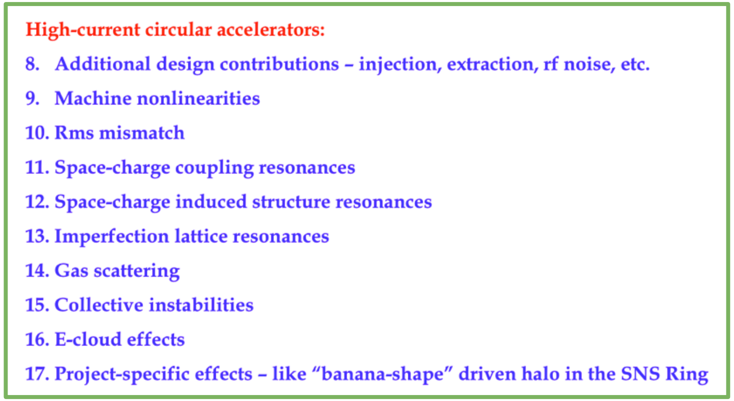
28 Sources of Halo by A. Fedotov



Partial list of halo mechanisms

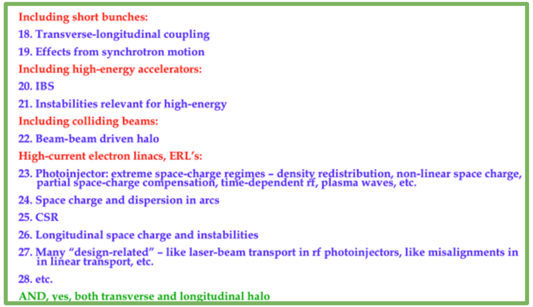
High-current hadron linear accelerators:

1. Anything from RFQ to various sources of machine nonlinearities and misalignments with unavoidable filamentation and halo growth (“bad design” issues)
2. Rms mismatch
3. Space-charge coupling resonances
4. Space-charge induced structure resonances (90^0 phase advance, etc.)
5. Single and multi-particle scattering
6. Gas scattering
7. Collective instabilities



High-current circular accelerators:

8. Additional design contributions – injection, extraction, rf noise, etc.
9. Machine nonlinearities
10. Rms mismatch
11. Space-charge coupling resonances
12. Space-charge induced structure resonances
13. Imperfection lattice resonances
14. Gas scattering
15. Collective instabilities
16. E-cloud effects
17. Project-specific effects – like “banana-shape” driven halo in the SNS Ring



Including short bunches:

18. Transverse-longitudinal coupling
19. Effects from synchrotron motion

Including high-energy accelerators:

20. IBS
21. Instabilities relevant for high-energy

Including colliding beams:

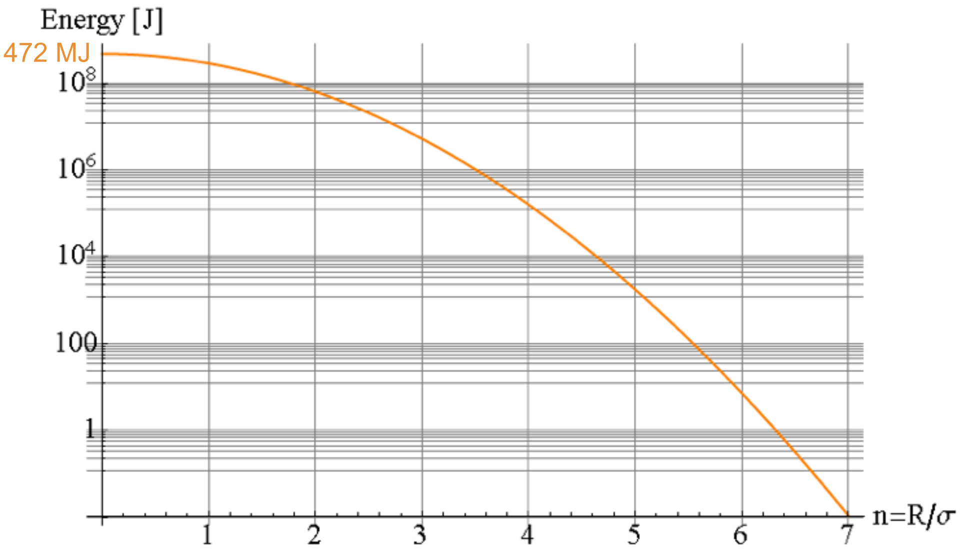
22. Beam-beam driven halo

High-current electron linacs, ERL’s:

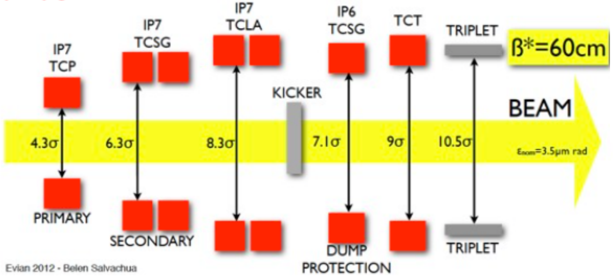
23. Photoinjector: extreme space-charge regimes – density redistribution, non-linear space charge, partial space-charge compensation, time-dependent rf, plasma waves, etc.
24. Space charge and dispersion in arcs
25. CSR
26. Longitudinal space charge and instabilities
27. Many “design-related” – like laser-beam transport in rf photoinjectors, like misalignments in in linear transport, etc.
28. etc.

AND, yes, both transverse and longitudinal halo

Energy Stored in Halo



Collimator gaps as small as 2 mm



Evian 2012 - Belen Salvachua

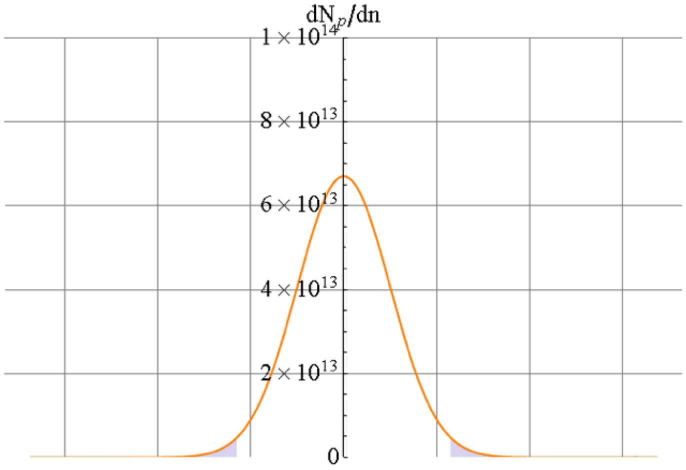
2012 tight collimator settings accompanied by increased losses. Courtesy B. Salvachua. See also J. Wenninger lecture.

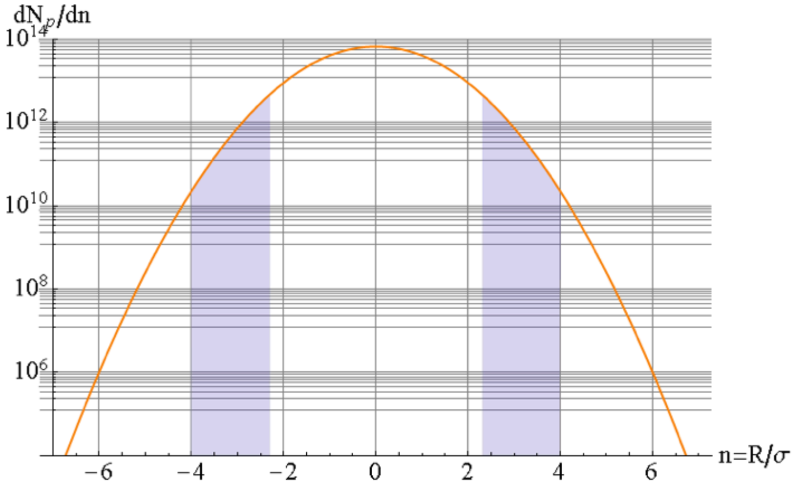
$$
\begin{aligned}
E_{\mathrm{h}} &= \frac{N_{\mathrm{p}} N_{\mathrm{b}} E_{\mathrm{p}}}{2\pi\sigma^2} \int_0^{2\pi} \int_R^{\infty} \mathrm{e}^{-\frac{r^2}{2\sigma^2}} r \, \mathrm{d}r \, \mathrm{d}\varphi \\
&= \frac{N_{\mathrm{p}} N_{\mathrm{b}} E_{\mathrm{p}}}{2\pi} \int_0^{2\pi} \int_n^{\infty} \mathrm{e}^{-\frac{\eta^2}{2}} \eta \, \mathrm{d}\eta \, \mathrm{d}\varphi \\
&= N_{\mathrm{p}} N_{\mathrm{b}} E_{\mathrm{p}} \mathrm{e}^{-\frac{n^2}{2}} .
\end{aligned}
$$

where for HL-LHC $N_{\mathrm{b}} = 2808$, $N_{\mathrm{p}} = 1.5 \cdot 10^{11}$, $E_{\mathrm{p}} = 7 \cdot 10^{12} \cdot 1.6 \cdot 10^{-19}\ \mathrm{J} = 1.04 \cdot 10^{-6}\ \mathrm{J}$. We have used the coordinate transformation $r = n\sigma$.

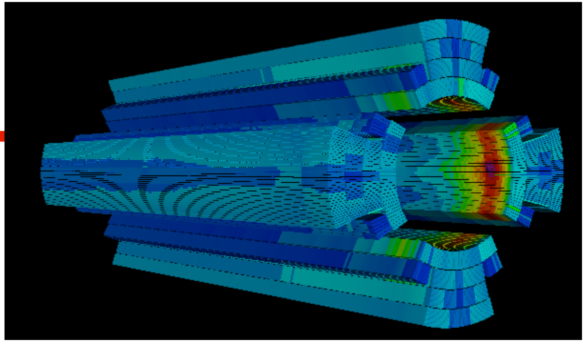
Halo and Orbit Excursion

Assumption: Orbit excursion by 1.7σ, corresponding to worst-case crab-cavity failure (see R. Schmidt 2nd lecture) for fixed collimator position at R=nσ.





Halo-Induced Quenches



Beam-induced energy deposition in a quadrupole magnet.

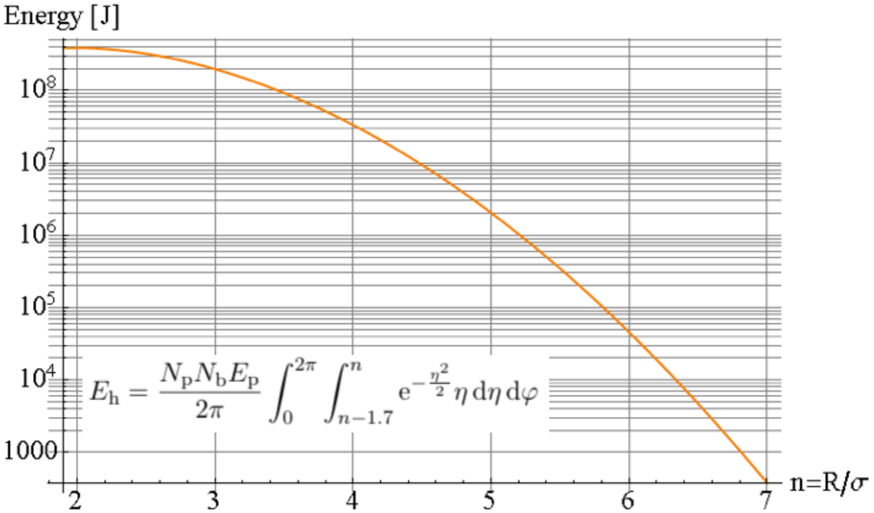
<ins>Assumption</ins>: Orbit excursion by 1.7σ (see R. Schmidt 2nd lecture) for fixed collimator position at R=nσ.

<ins>Question 1</ins>: How much of the halo will a downstream magnet quench?

1 MW on TCP → ~50 mW/cm^3 average power across the hotspot-turn of the SC coil. (source: E. Skordis, FLUKA & SixTrack)

Quench Level from electro-thermal simulation.

Δt	Quench Level	TCP Energy	n=R/σ
1 ms	2.9 mJ/cm^3	58 kJ	5.9
1 s	68 mJ/cm^3	1.36 MJ	5.1



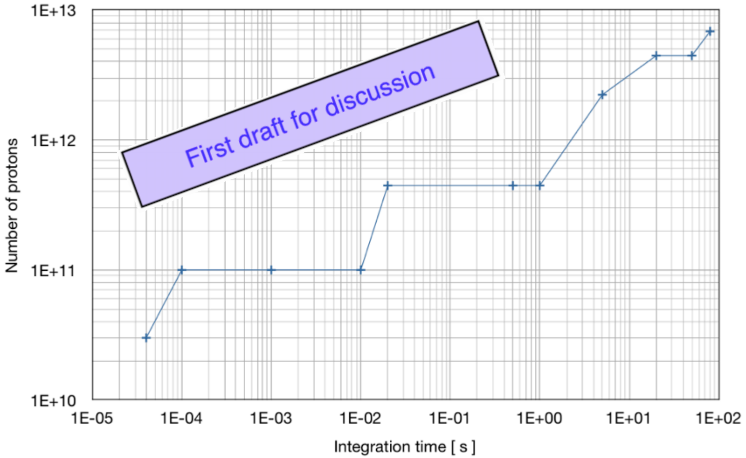
$$E_{\mathrm{h}} = \frac{N_{\mathrm{p}} N_{\mathrm{b}} E_{\mathrm{p}}}{2\pi} \int_0^{2\pi} \int_{n-1.7}^{n} \mathrm{e}^{-\frac{\eta^2}{2}} \eta \, \mathrm{d}\eta \, \mathrm{d}\varphi$$

Halo-Induced Collimator Damage

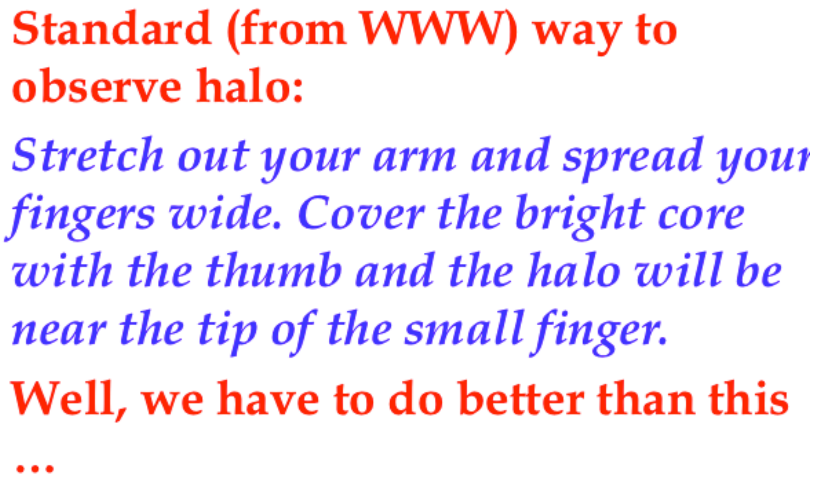
<u>Assumption</u>: Orbit excursion by 1.7σ (see R. Schmidt Talk 2) for fixed collimator position at R=nσ.
<u>Question 2</u>: How much of the halo is equal to the protection level for primary collimators?

Protection levels in terms of number of particles impacting on the primary collimator, based on simulations, design criteria, and HiRadMat experiments (see A. Bertarelli, S. Redaelli).
Compare to TCP position at 6σ (S. Redaelli lecture).

Δt	N	TCP Energy	n=R/σ
1 ms	$1.0\ 10^{11}$	112 kJ	5.7
1 s	$4.2\ 10^{11}$	470 kJ	5.4



Halo Monitoring



Standard (from WWW) way to observe halo:

Stretch out your arm and spread your fingers wide. Cover the bright core with the thumb and the halo will be near the tip of the small finger.

Well, we have to do better than this …

From A. Fedotov, ERL 2005.

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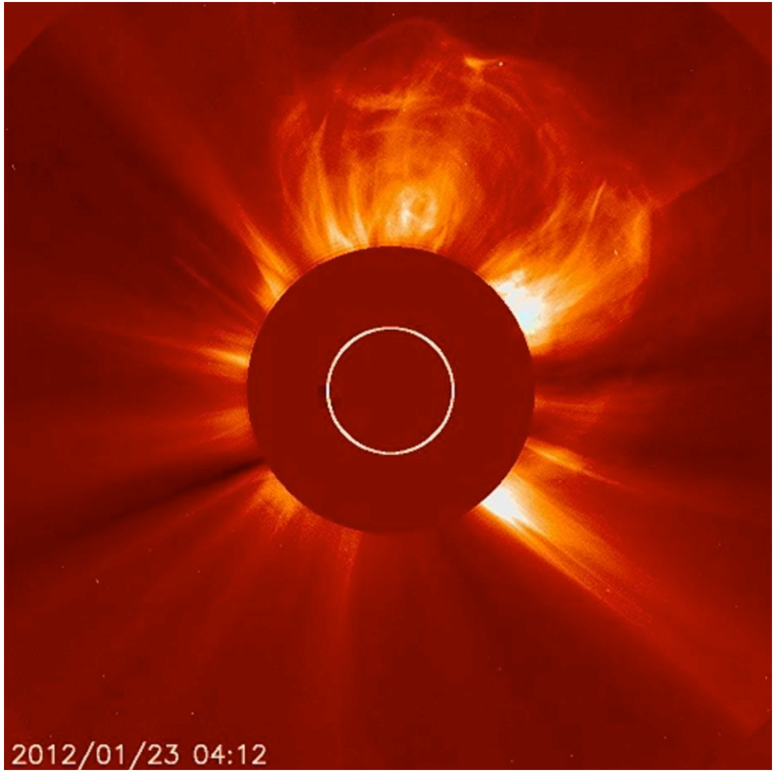
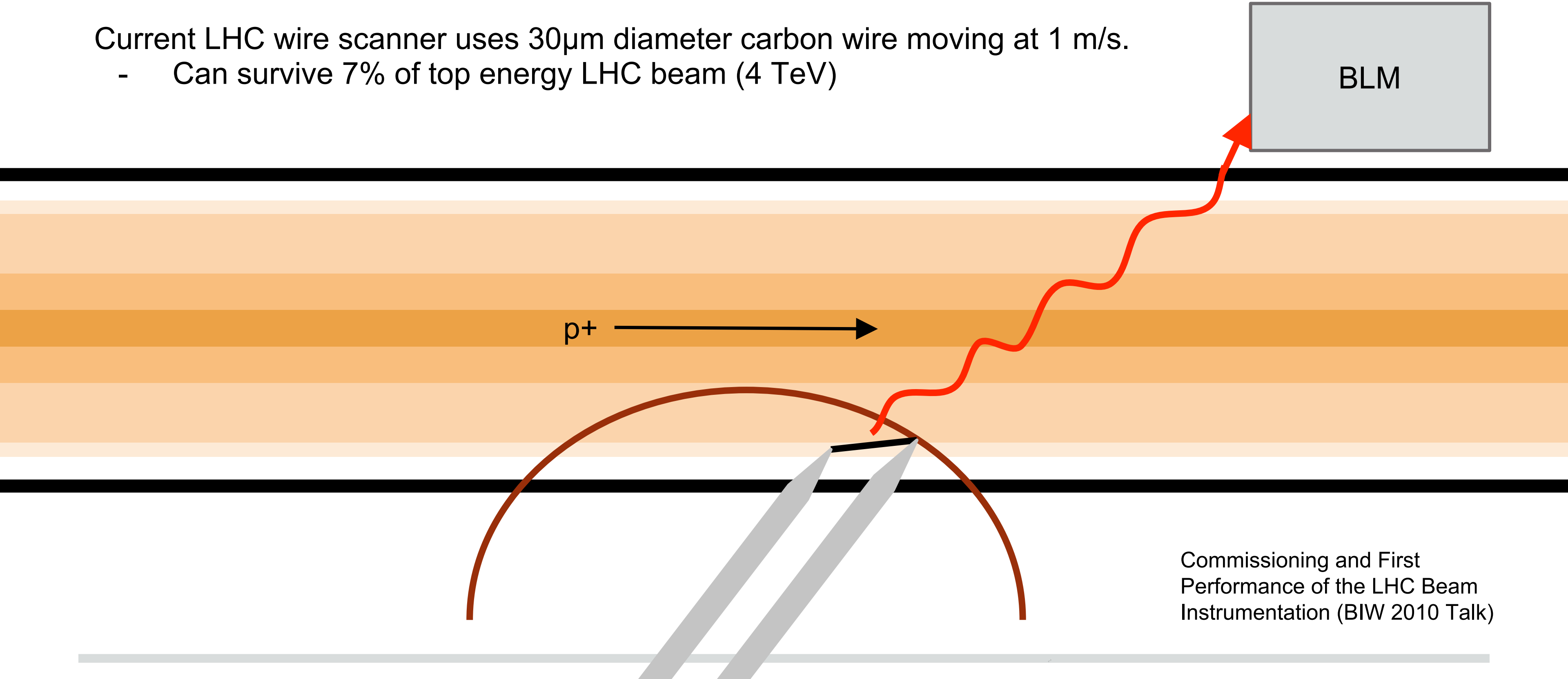


Wire Scanner

Current LHC wire scanner uses 30μm diameter carbon wire moving at 1 m/s.

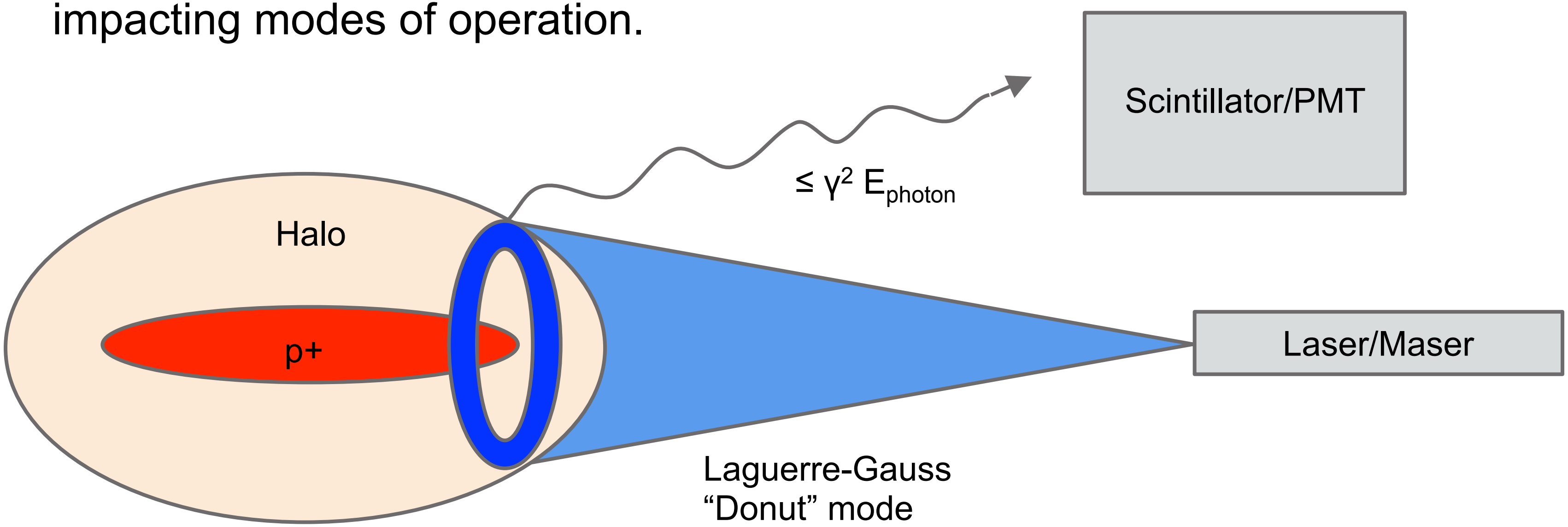
- Can survive 7% of top energy LHC beam (4 TeV)



Commissioning and First Performance of the LHC Beam Instrumentation (BIW 2010 Talk)

Hollow Laser Halo Monitor

As beam energies and powers increase, diagnostic tools must move to non-impacting modes of operation.



H. Aksakal et al, “Laser Collimation For Linear Colliders”. PAC07

Halo Cleaning - Electron Lens

Hollow electron beam collimation is a novel technique for beam collimation and halo scraping. It was tested experimentally at the Fermilab Tevatron collider. A magnetically confined, possibly pulsed, low-energy (a few keV) electron beam with a hollow current-density profile overlaps with the circulating beam over a length of a few meters. If the electron distribution is axially symmetric, the beam core is unperturbed, whereas the halo experiences smooth and tunable nonlinear transverse kicks. The electron beam is generated by a hollow cathode and transported by strong solenoidal fields. The size, position, intensity, and time structure of the electron beam can be controlled over a wide range of parameters.

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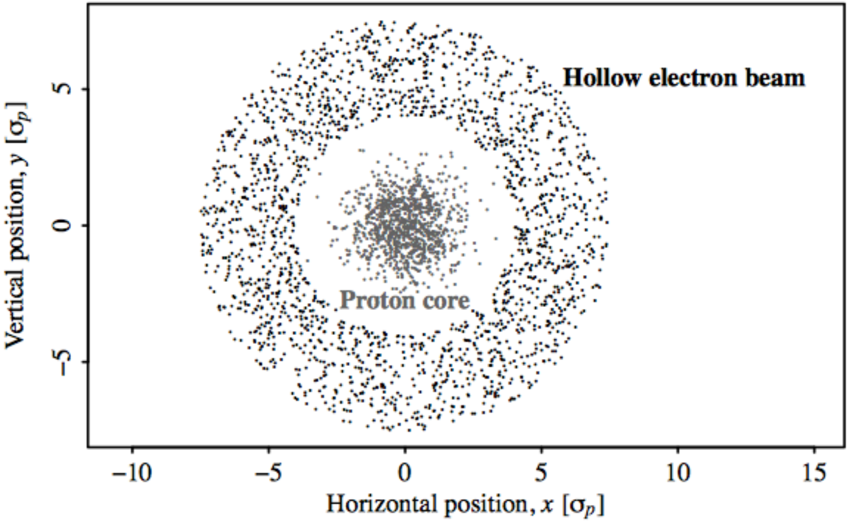

Halo Cleaning - Electron Lens

Advantages of Electron Lens

- Compatible with collider operations during measurements
- Easy alignment of the electron beam with the circulating beam
- Halo removal rates were controllable, smooth, and detectable
- No lifetime degradation or emittance growth in the core
- Suppression of loss spikes due to beam jitter and tune adjustments

$$\theta = \frac{2I_{er}L(1 \pm \beta_e \beta_p)}{r\beta_e \beta_p c^2 (B\rho)_p} \left(\frac{1}{4\pi\varepsilon_0} \right)$$

I = electron beam current
L = length of interaction beam pipe
β = relativstic beta (v/c)
r = radius (distance from beam center)

This equation give the kick in radians given the radius distance r and the electron beam enclosing current I.

The strength of the kicks is proportional to the electron beam current and can be easily controlled. The particles in the core of the circulating beam (whose amplitudes are smaller than the inner electron-beam radius) are unaffected if the distribution of the electron charge is axially symmetric.

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Halo Cleaning - Crystal Collimator

- Crystal structure coherently deflects all particles in a single direction
  - Amorphous materials (carbon, copper, steel, etc.) results in azimuthally symmetric multiple scattering [1].
- Allows retraction of secondary collimator further from the beam.
- Works efficiently at very high intensities.
- One crystal scraper works efficiently over full energy range.
- Cleaner collimation
  - Study for LHC shows that the losses in the DS are reduced using a crystal-assisted collimation compared to standard collimators [2].

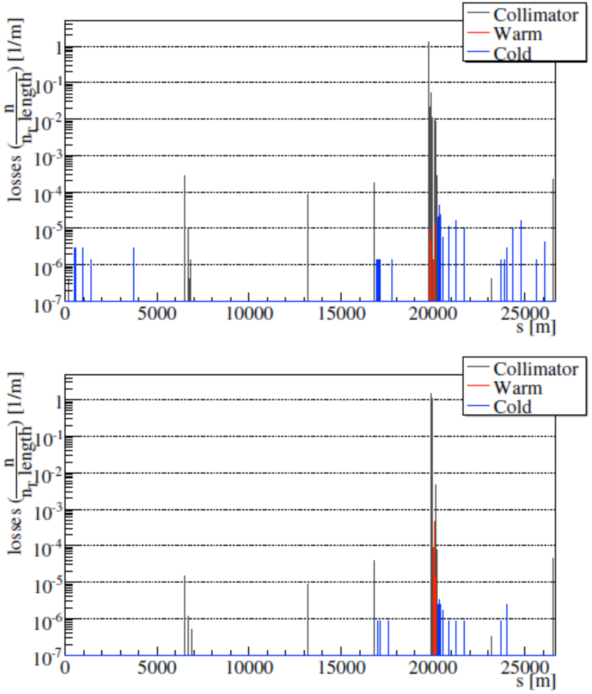

Figure 4: Horizontal loss map at 7 TeV for standard (top) and crystal-assisted collimation (bottom). [2]

[1] V.M. Biryukov, Crystal Cleaning of the LHC Beam, Institute for High Energy Physics, Frankfurt 2003;
[2] D. Mirarchi†, S. Montesano, S. Redaelli, W. Scandale, A. M. Taratin, A. M. Taratin, FINAL LAYOUT AND EXPECTED CLEANING FOR THE FIRST CRYSTAL-ASSISTED COLLIMATION TEST AT THE LHC, proceeding of IPAC2014, Dresden.

HALO 4