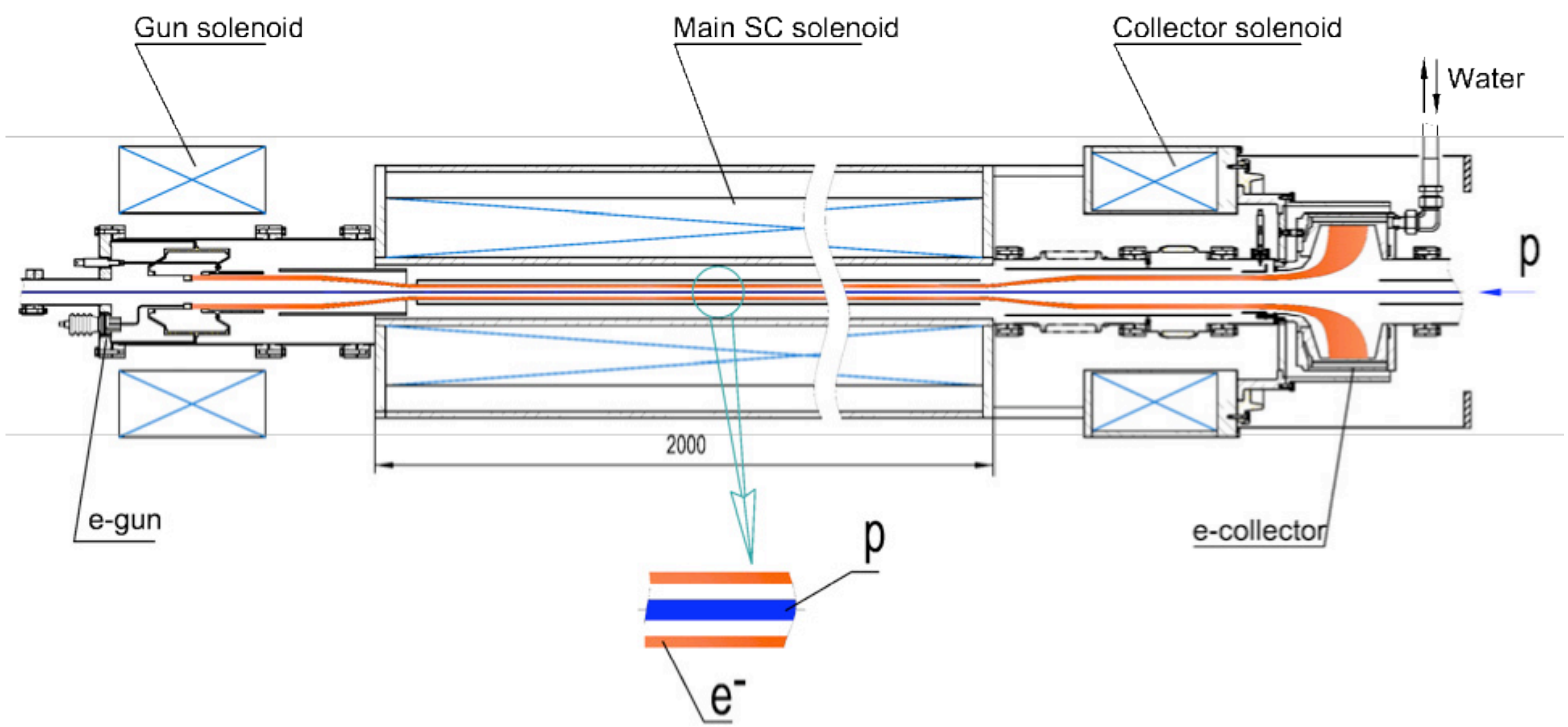
US LHC Accelerator Research Program

BNL - FNAL- LBNL - SLAC

Prospects for Using a Hollow Electron Lens as a Beam Scraper in the LHC



Jeff Smith
SLAC
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Motivation

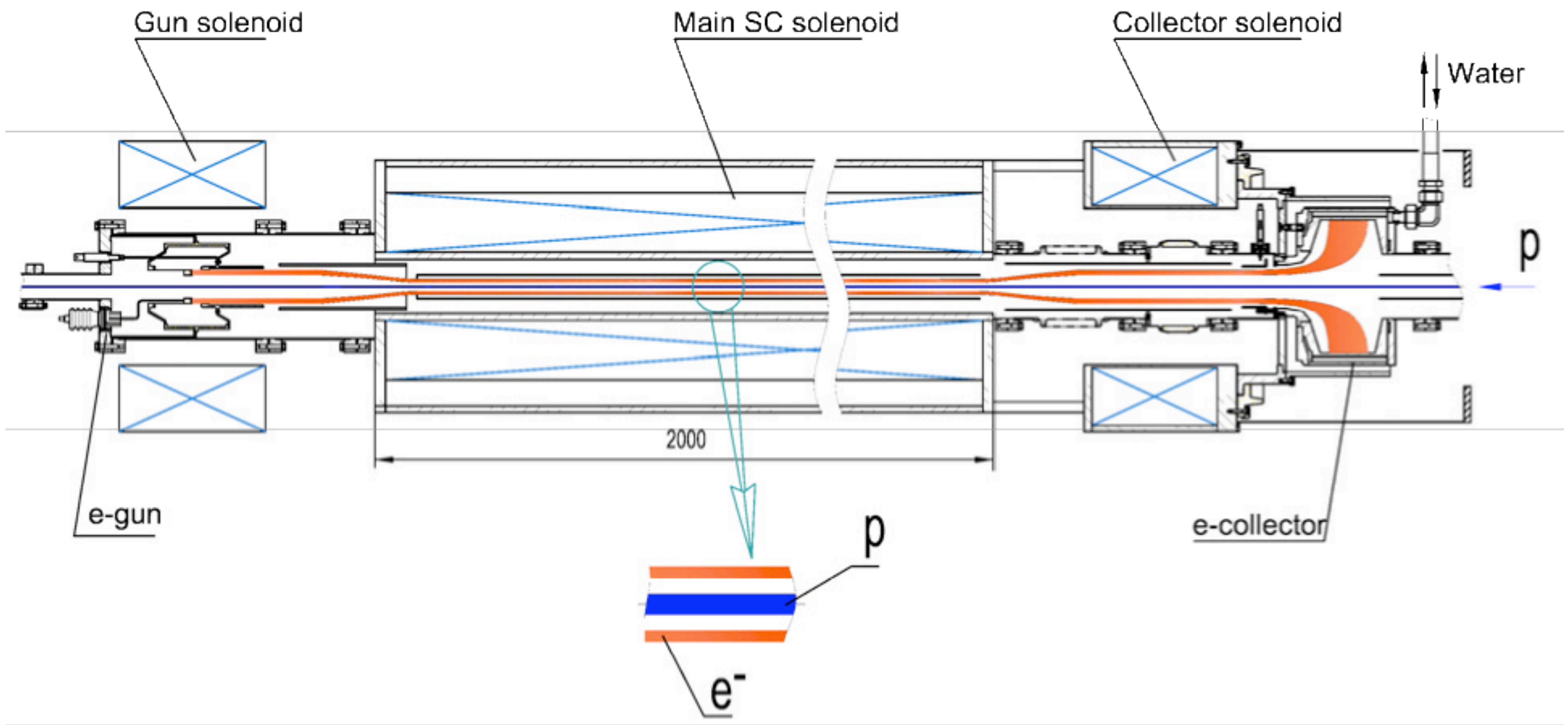
- As of now, there are no beam scrapers in the LHC
- We have low Z graphite primaries at 6 sigma, then secondaries at 7 sigma
- It would be great if we could have a beam scraper within a smaller radius to help remove (increase the dispersion rate) of halo particles.
- It may also allow us to pull the primaries out to greater sigma with no loss of performance.
- Electron lenses have been used for some time with much success at Fermilab.
- The idea would be to turn one (or more) on just long enough to clean out the beam halo. Repeat as many times as necessary.
- Could also be used for ion collimation
  - No direct interaction with material, just an E-field

Inspiration

- Work based on:
  - V. Shiltsev, *et al.*“LHC Particle Collimation by Hollow Electron Beams,” EPAC08, MOPC098
  - V. Shiltsev, “Electron Lenses For Particle Collimation in LHC,” FERMILAB-CONF-07-698-APC
    - Some results presented are from these papers.

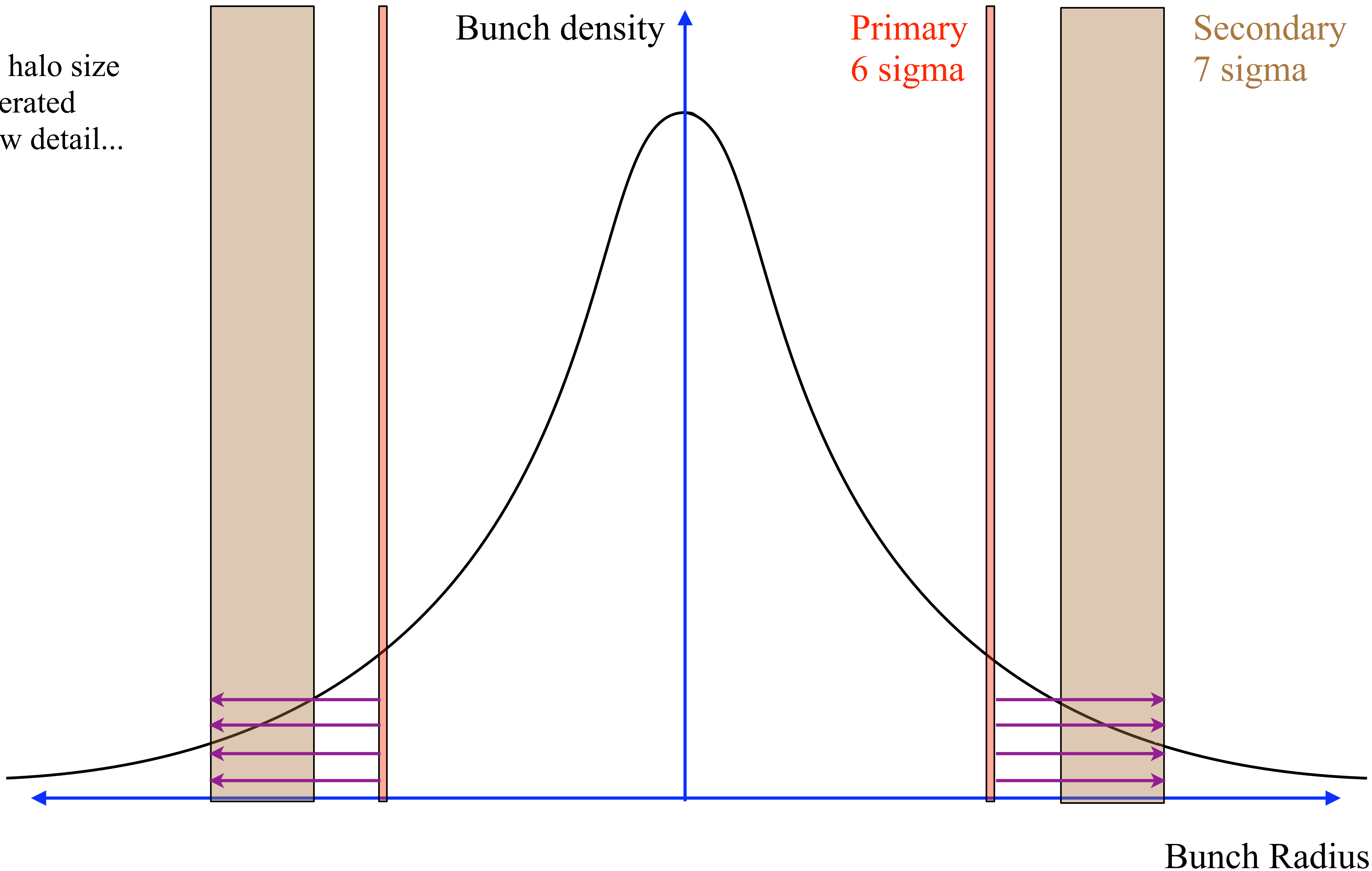
Basics of an Electron Lens

- An electron lens is a very stable thin, long very straight cylinder of electrons with kinetic energy around 5 to 10 keV.
- The lens is controlled with a ~3 Tesla longitudinal (solenoidal) magnetic field.
- The electric field established by the electrons is roughly 0.3MV/m radially which can repulse passing protons.
- A Hollow Electron Lens is a hollow cylinder of electrons. Inside the cylinder there is no electric field.

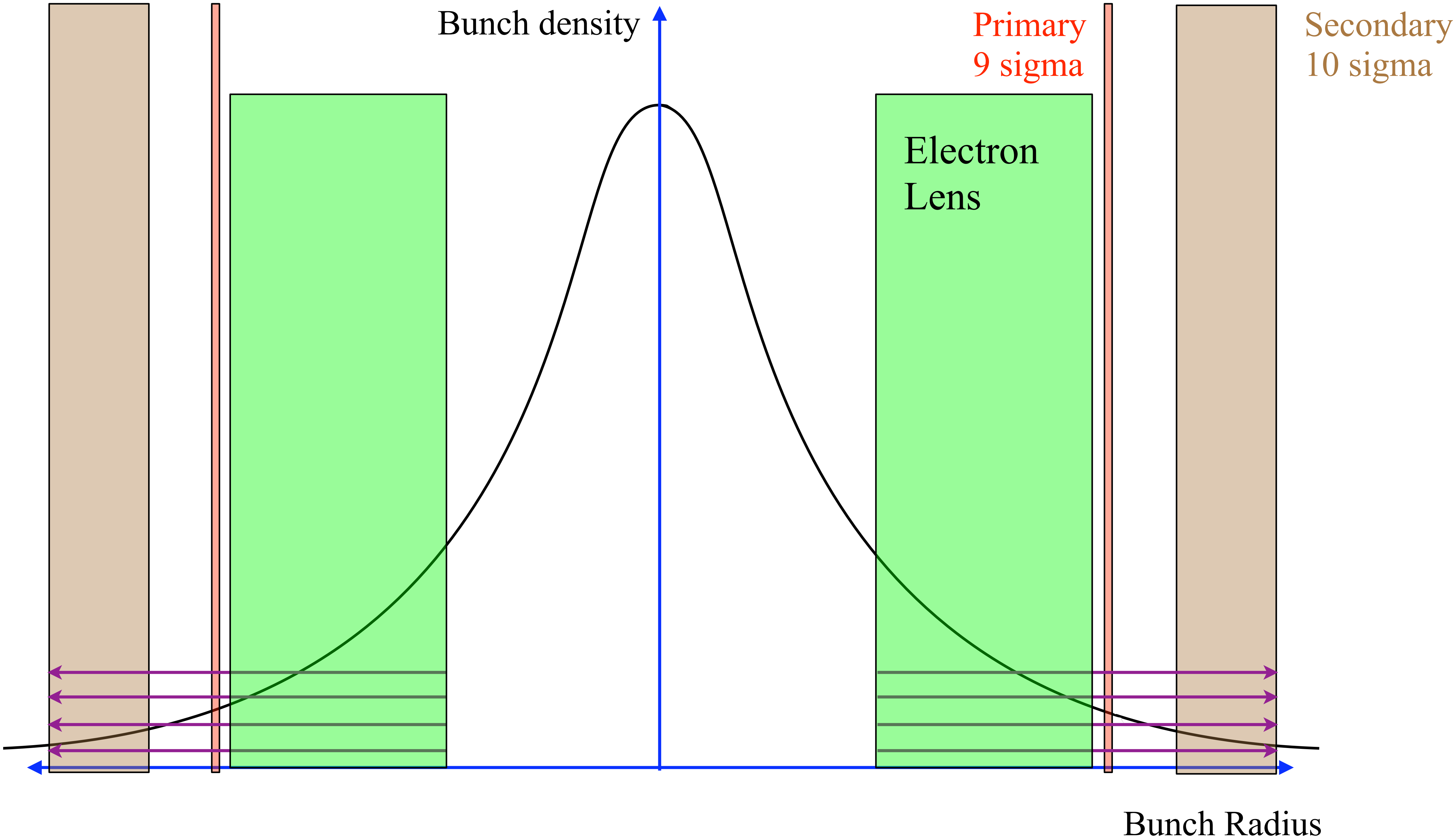


Current system

bunch halo size
exaggerated
to show detail...



With Hollow Electron Beam Collimator

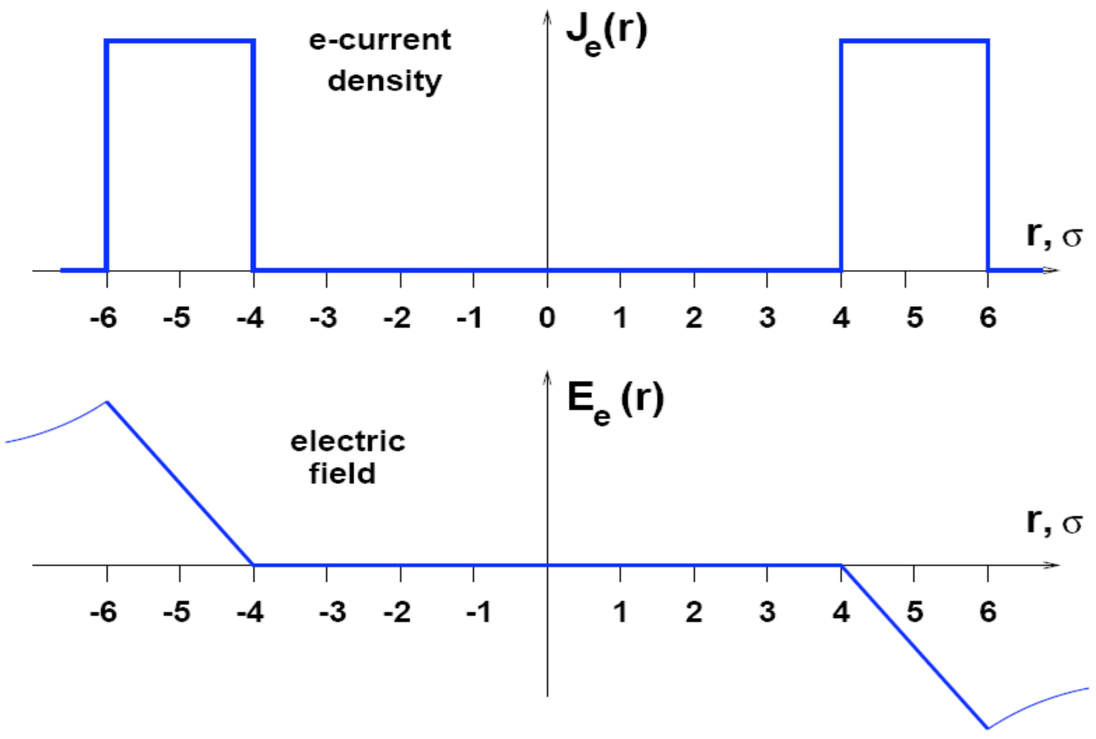


Electron Lens Element

- Using simple model from Shiltsev's EPAC paper. Just models the E-field produced by the electron beam as a thin lens, no scattering

$$\Theta(r) = \Theta_{max} \begin{cases} 0, & \text{if } r < r_{min}; \\ \frac{r - r_{min}}{r_{max} - r_{min}}, & \text{if } r_{min} < r < r_{max}; \\ \frac{r_{max}}{r}, & \text{if } r > r_{max}. \end{cases}$$

$$\Theta_{max}\,[\mu rad] = \frac{0.2L[m]J[A]}{(B\rho)\, r_{max}} \cdot \frac{1+\beta_e}{\beta_e}$$



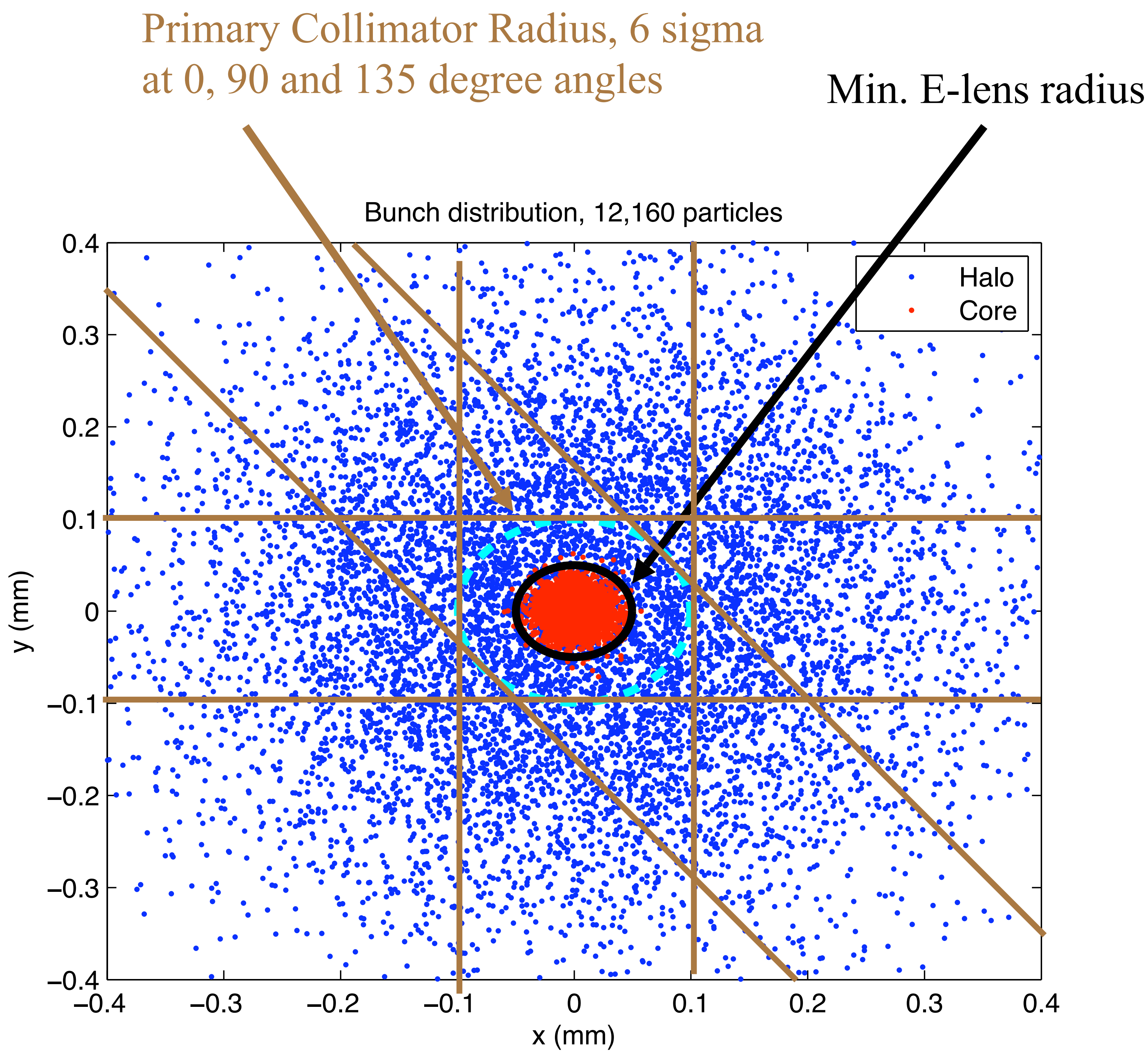
- This is a very simple model
  - Should include:
    - AC current, right now, it's DC
    - More realistic field distribution (Gaussian)
    - Field errors

Experimental Setup

- Using Sixtrack with collimation as obtained from Ralph Assmann's LHC Collimation Group
  - Created simple Electron lens element in SixTrack
  - Placed electron lens at radius less than primary collimators
  - Electron Lens Parameters:
    - Length = 1 meter
    - Inner diameter = 3.0-4.0 sigma (absolute diam. depends on beta function at location: 0.786 mm - 3.65 mm)
    - Beam width = 1.1 mm
    - Current = 20 Amps
    - These are acceptable electron lens parameters and not unlike those already used at Fermilab
    - Maximum kick with these parameters ~ 0.2 urad
      - Small compared to 4.5 urad kick of primaries but can act over many turns.
  - Setup Gaussian beam distribution with over-populated beam halo

Bunch Distribution

- Using two Gaussian distributions
  - Core population at nominal emittance
  - Halo populated at 100 times emittance (10x sigma)
  - Halo populated 3 times as much as core
- Everything outside the Primaries should get absorbed within a couple turns
- Between the Electron lens and primaries is what we are really looking at.
- Beam heating not turned on, works on a much longer time scale than collimation



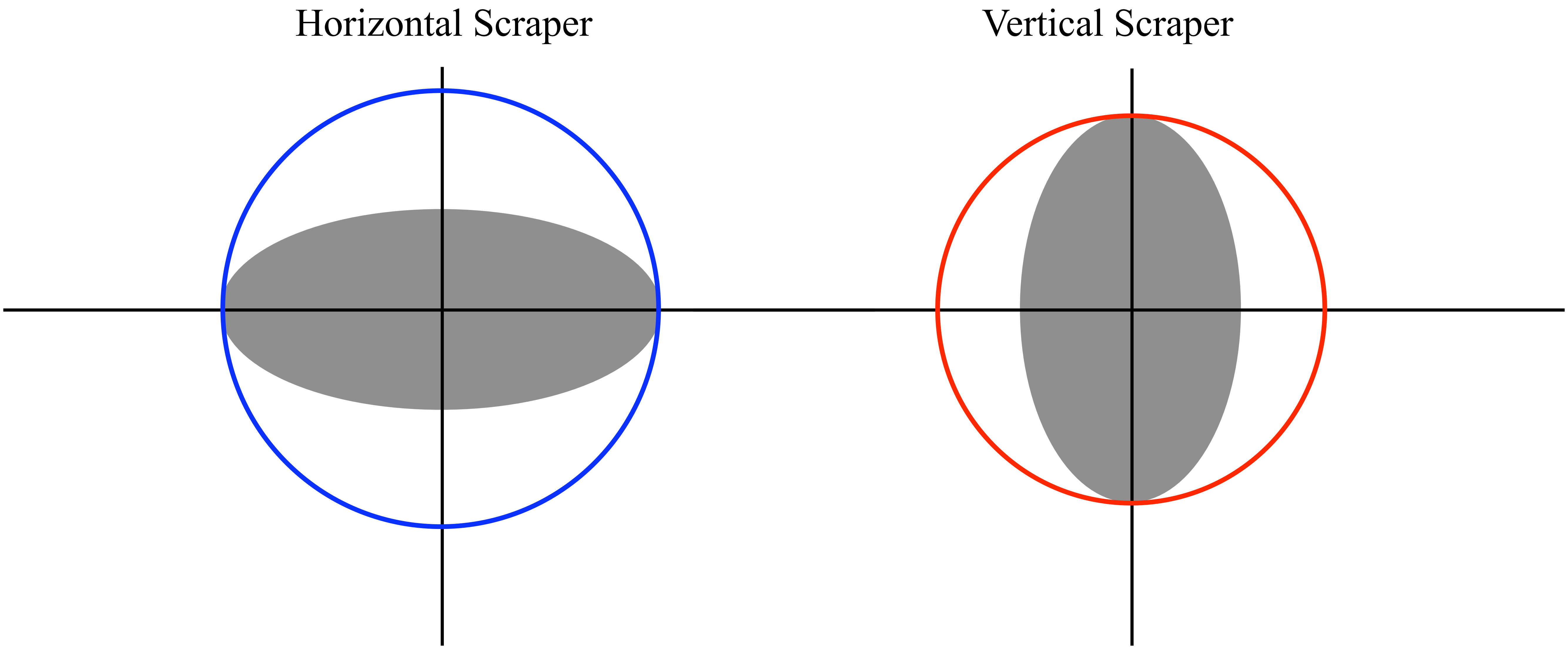
Location of Electron Lens

- Using V6.500 Low B 7 TeV collision optics Beam 1
- A couple locations tried
  - Replaced LHC element TCP.A617.B1 as this is a placeholder for a future primary collimator (crystal simulations also place crystal here)
  - At the BBC elements which are for the electron lenses for beam-beam compensation (actually placed at the TAN elements nearby the BBC elements).
  - at TCDQM.4R6 another collimator placeholder with particularly small gamma

E-lens location	Beta-x	Beta-y	Alpha-x	Alpha-y	Phase-x (mod 2pi)	Phase-y (mod 2pi)
TCP.A6l7	137	90	1.91	-1.27	4.92	4.49
BBC.4R1	719	1661	16.8	1.87	7.64	7.09
BBC.4L5	1661	718	-1.87	-16.8	2.42	2.28
BBC.4R5	719	1661	16.8	1.87	2.50	2.36
BBC.4L1	1661	719	-1.87	-16.8	7.56	7.01
TCDQM.4R6	539	177	-1.67	-0.75	3.78	3.43

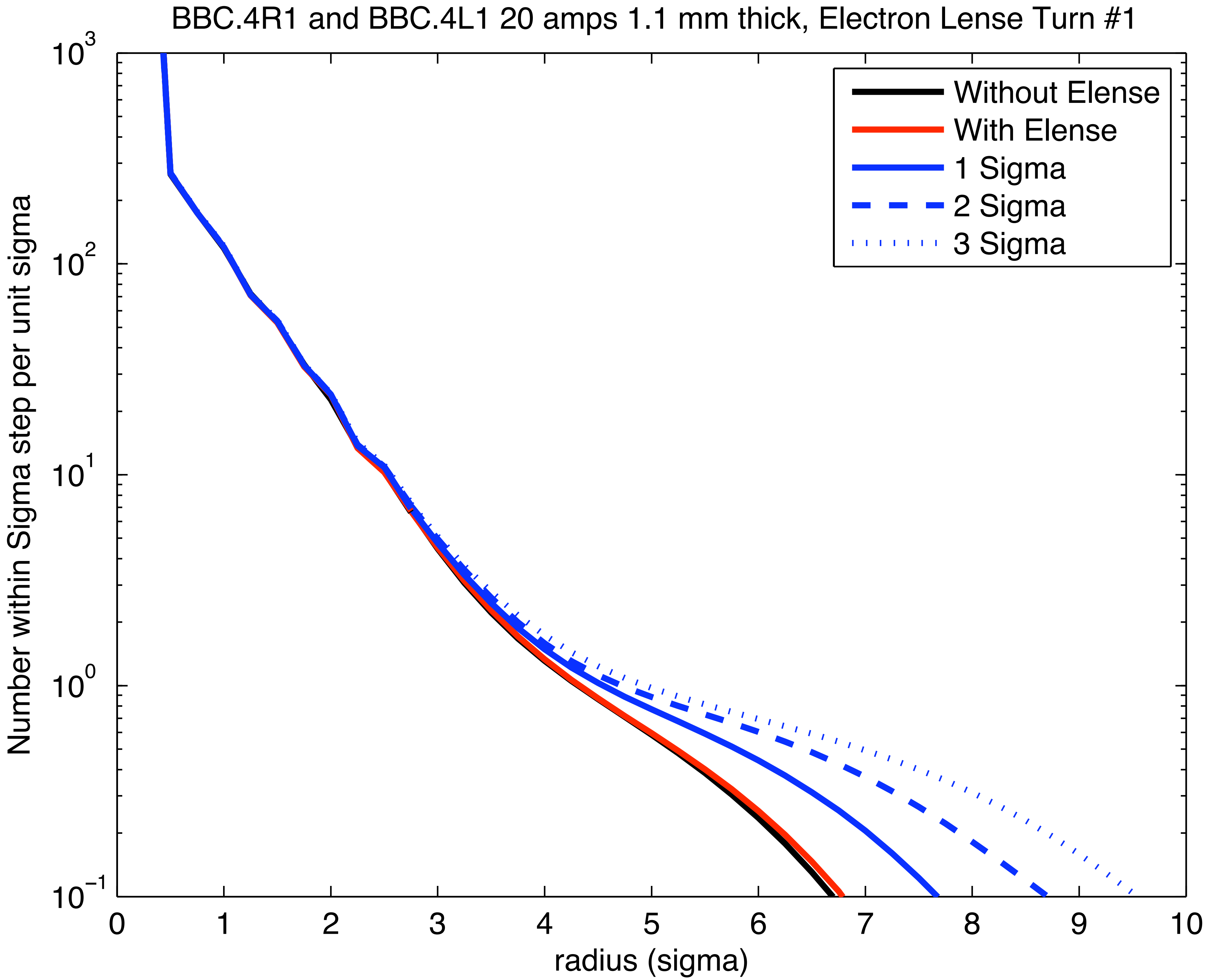
Round Electron Lens

- The electron lens can only be round. Beta-x and beta-y should therefore be ideally equal. This is not the case at any locations investigated.
- Two e-lenses were therefore used in some simulations, one for horizontal and one for vertical.



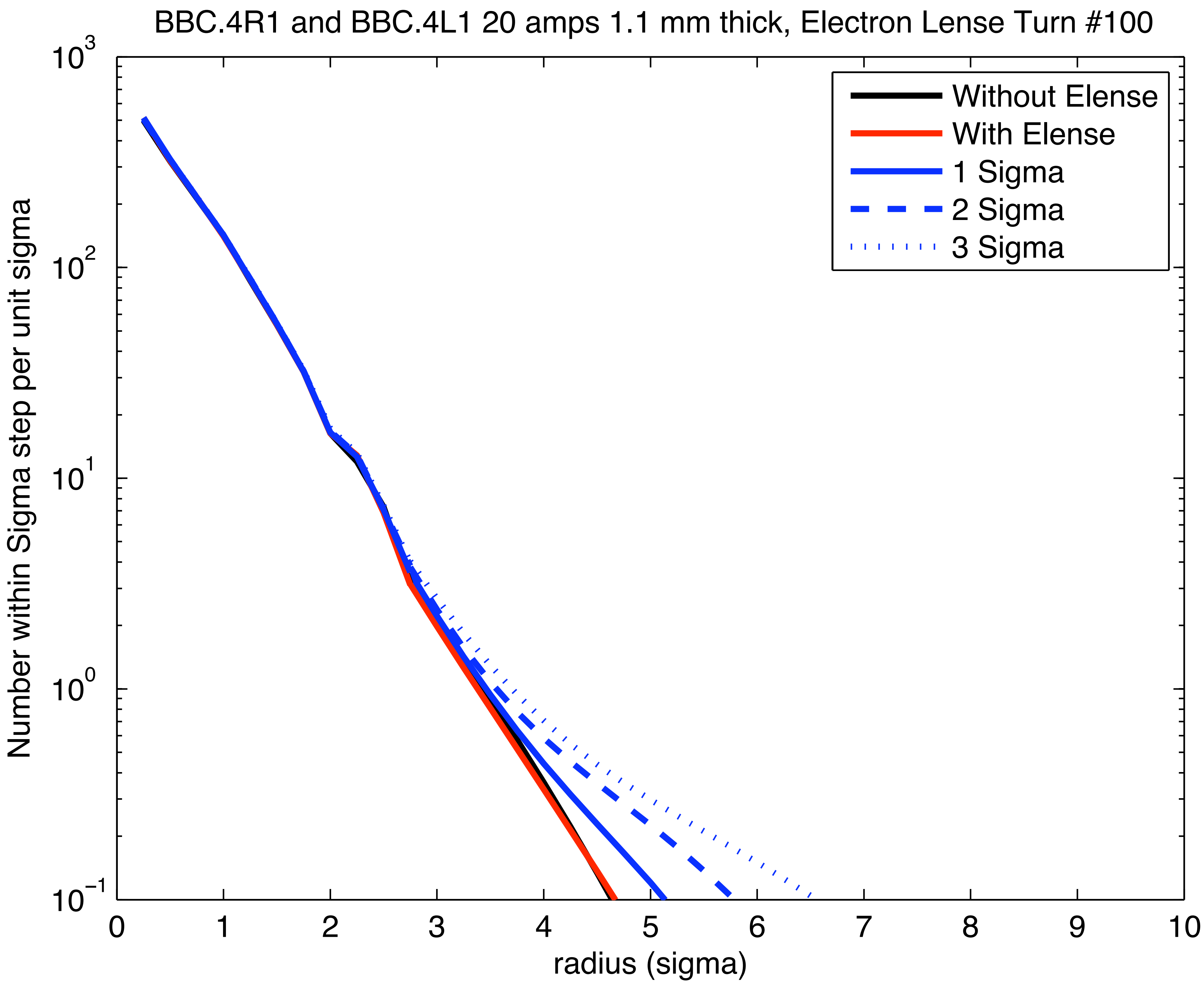
Example: two BBC

- Turn #1
- Here the beam profile is plotted in four cases:
  1. Nominal phase I collimation system
  2. Electron lens added
  3. Electron lens but with primary and secondary collimators pulled out by 1 sigma
  4. ...pulled out by 2 sigma
  5. ...3 sigma
- Beam halo overpopulation clearly evident to make measurement of effect possible



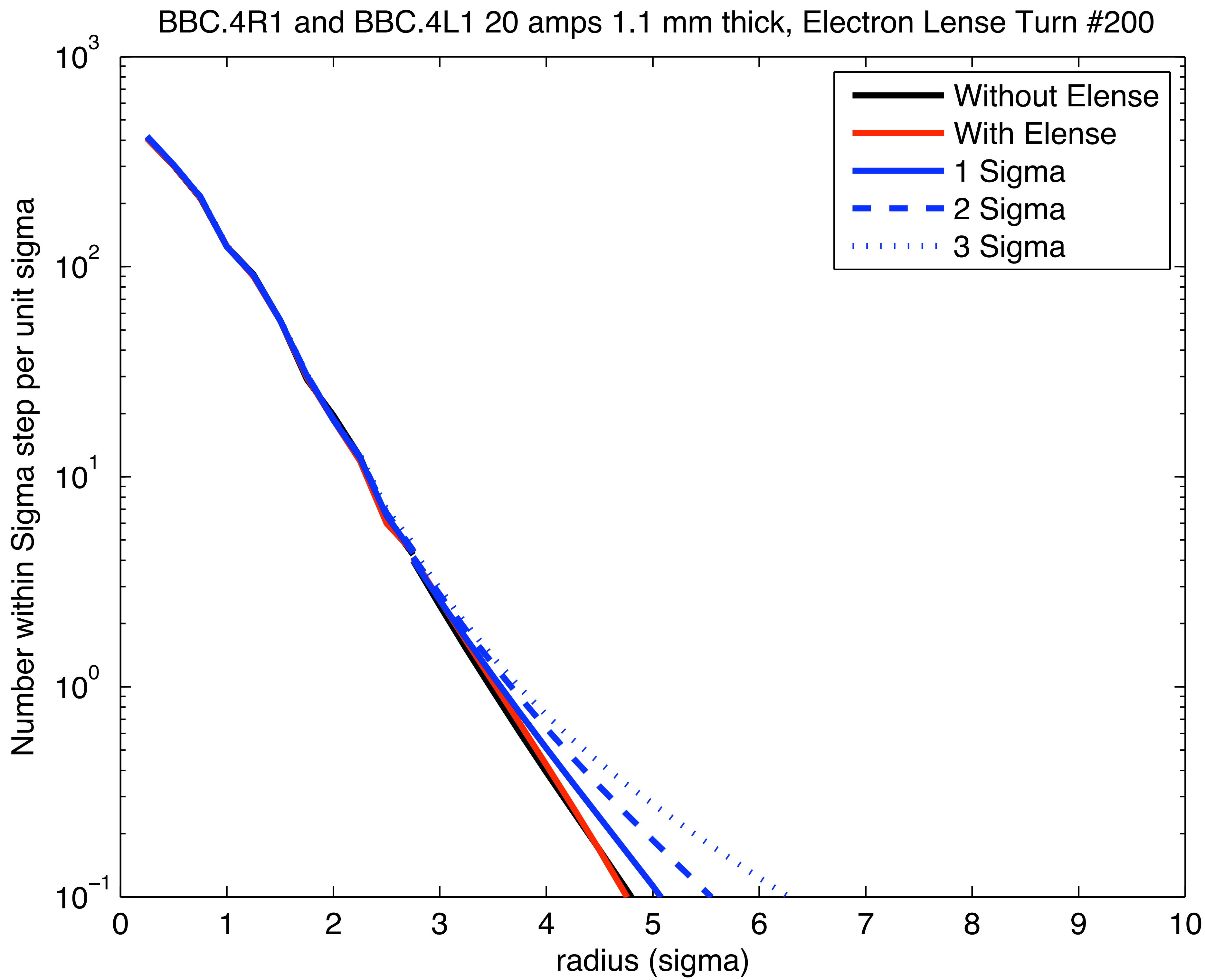
Example: two BBC

- Turn #100
- Note red curve and that nominal collimation system removing beam halo well within 100 turns



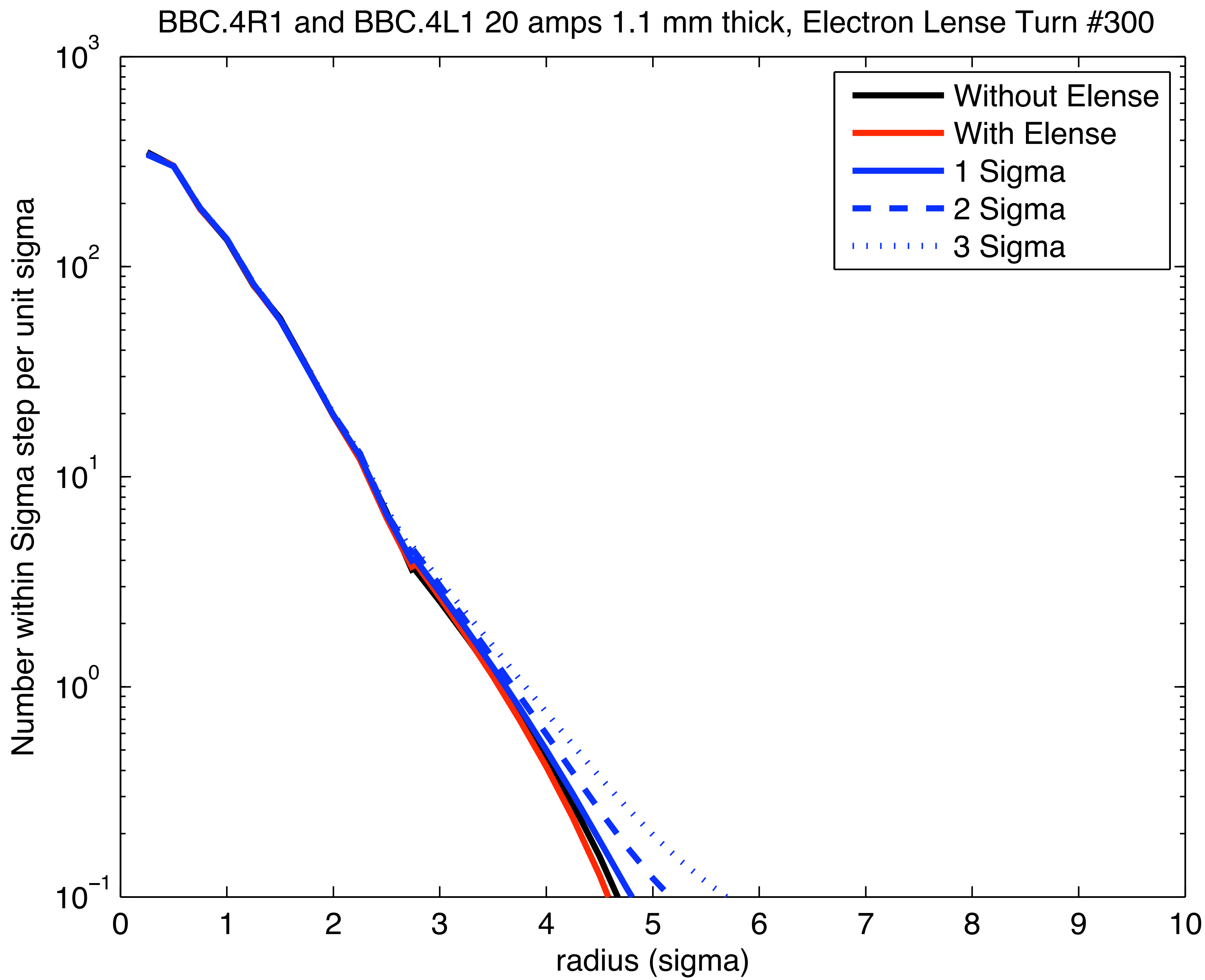
Example: two BBC

- Turn #200



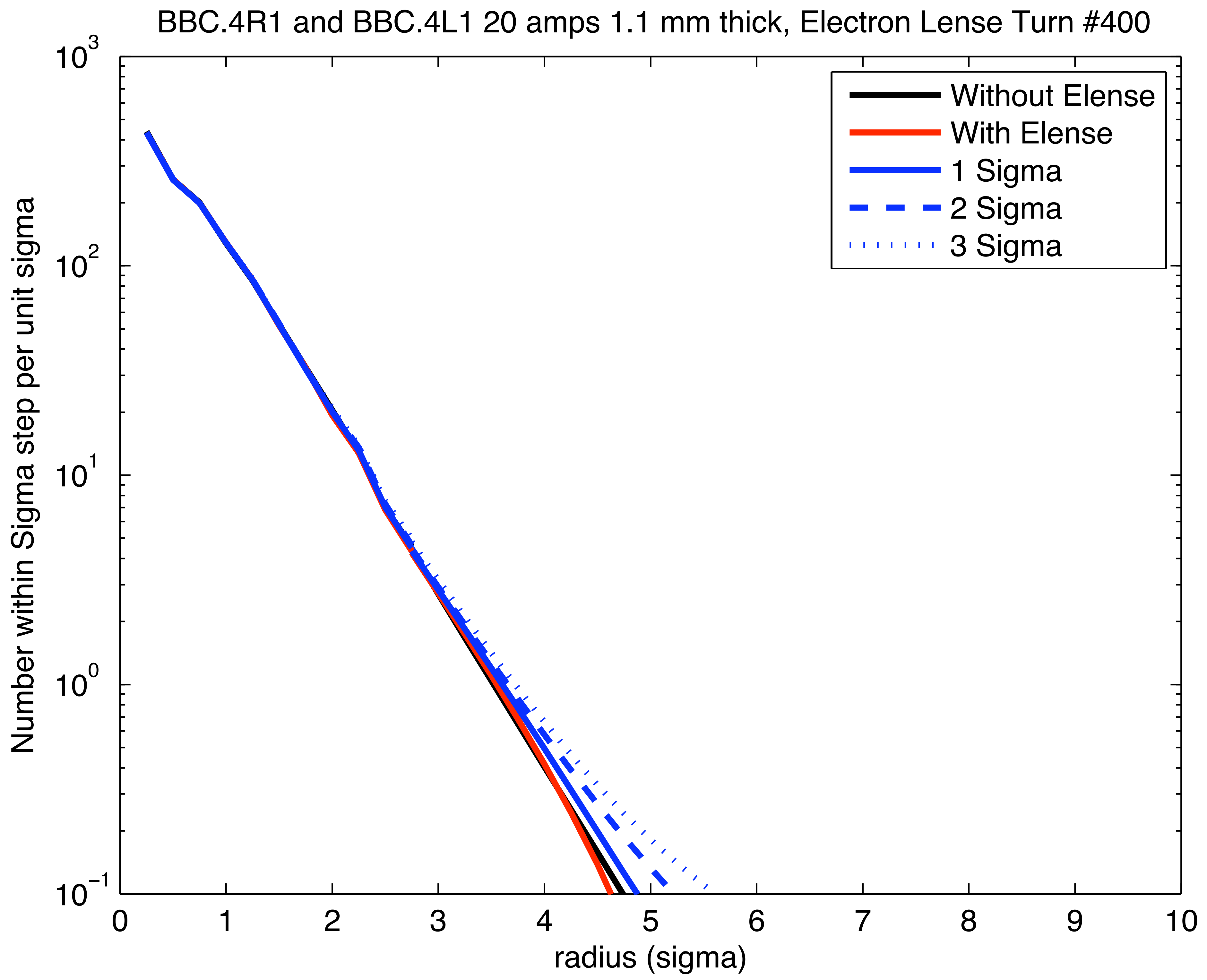
Example: two BBC

- Turn #300



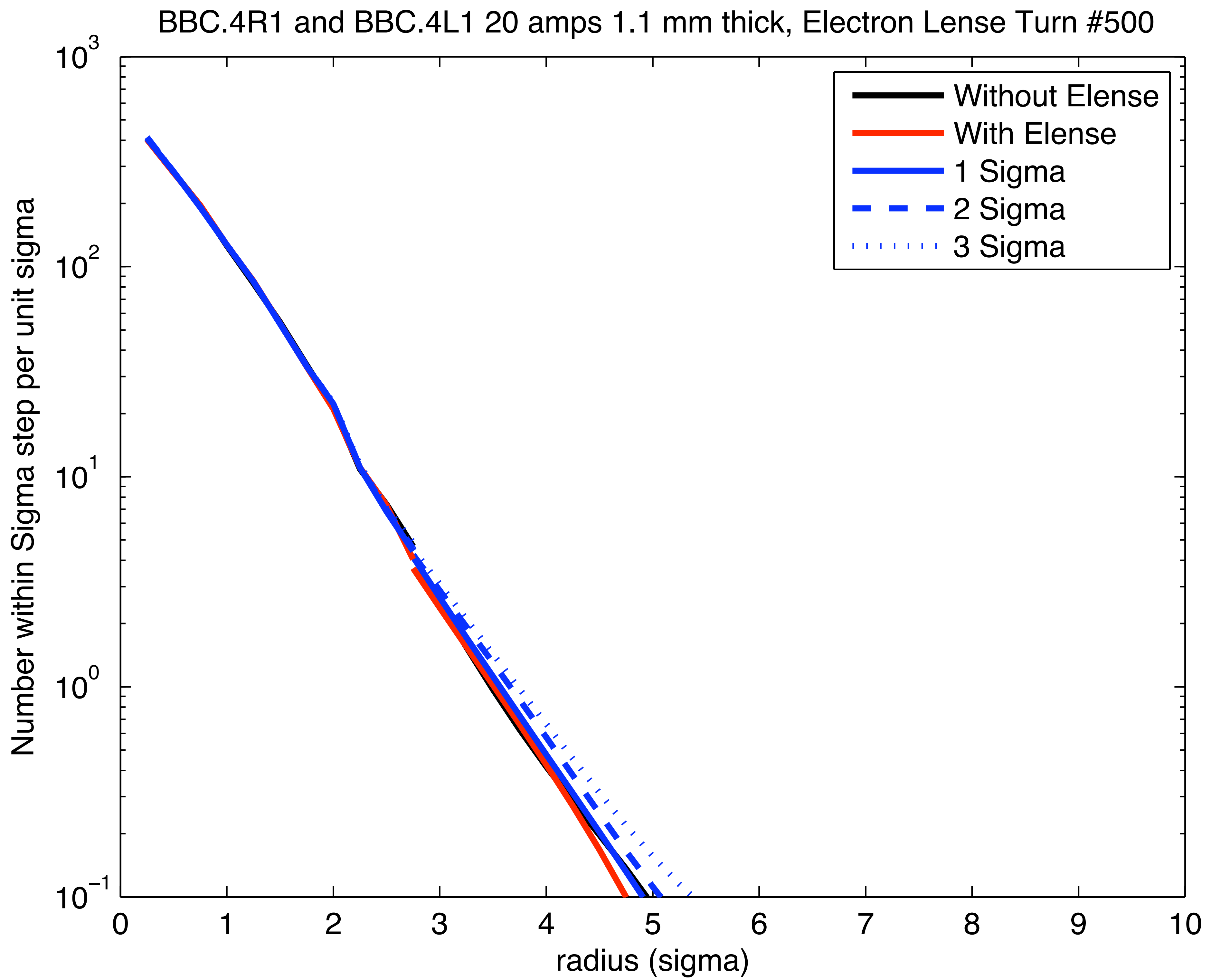
Example: two BBC

- Turn #400



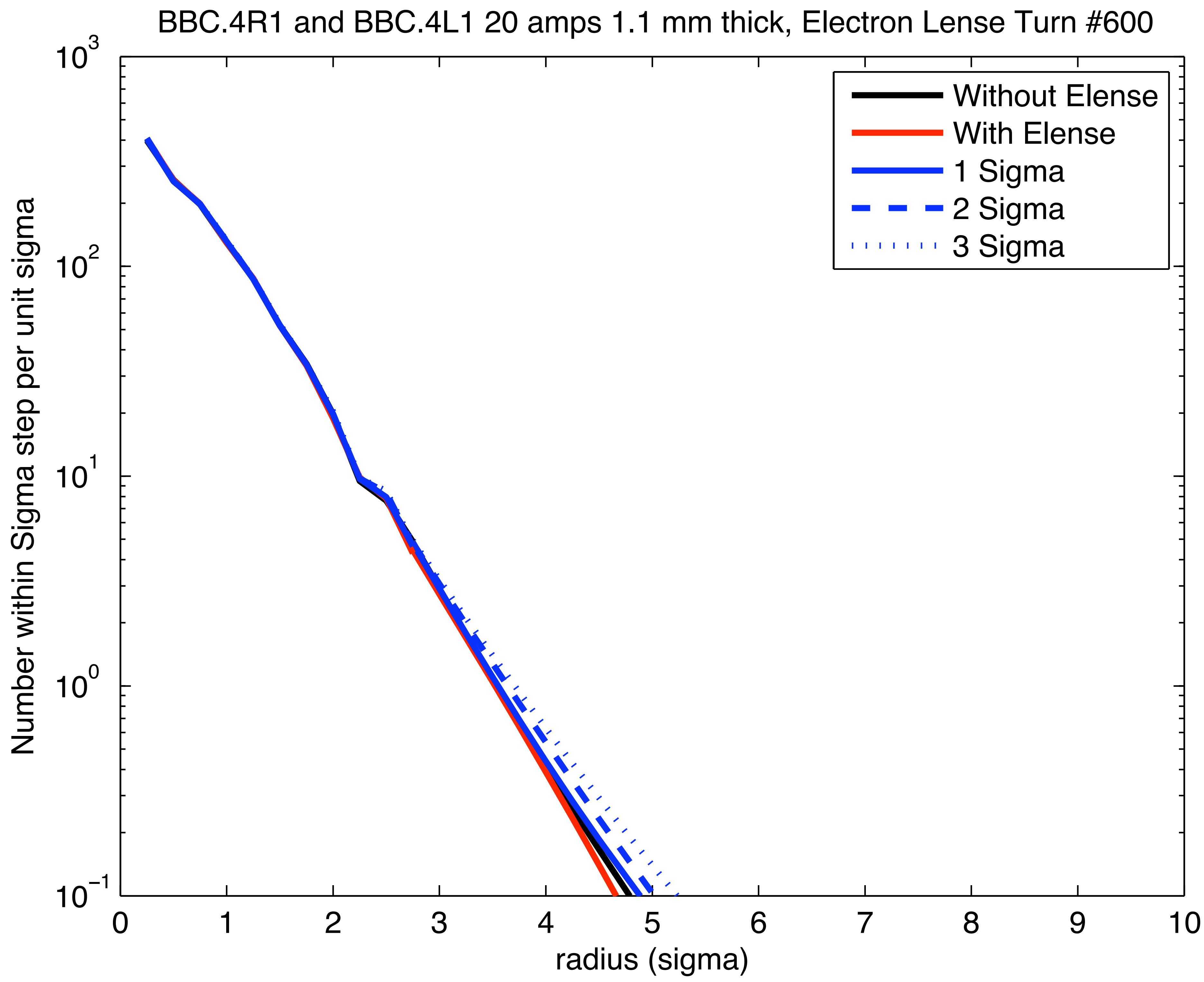
Example: two BBC

- Turn #500



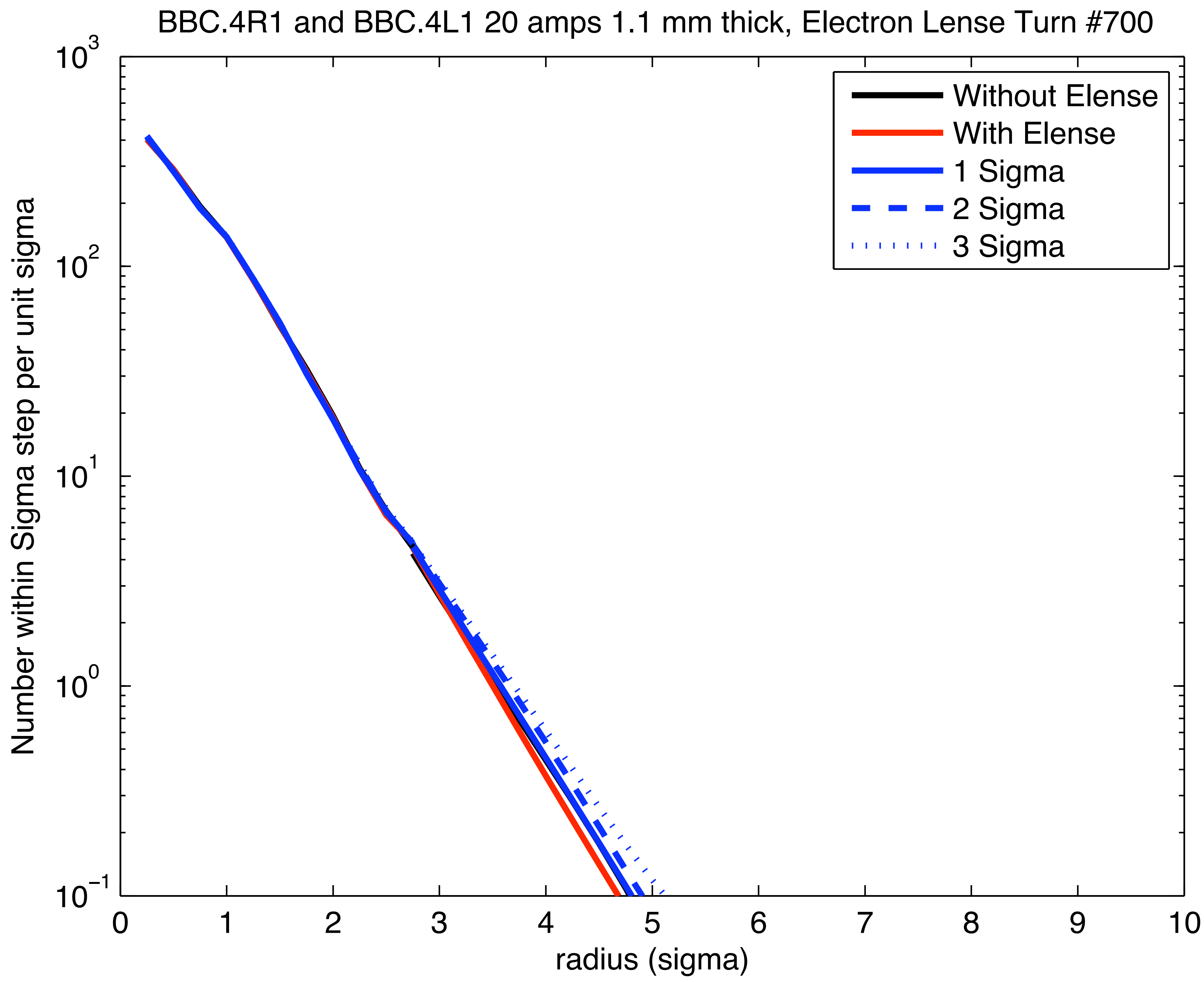
Example: two BBC

- Turn #600



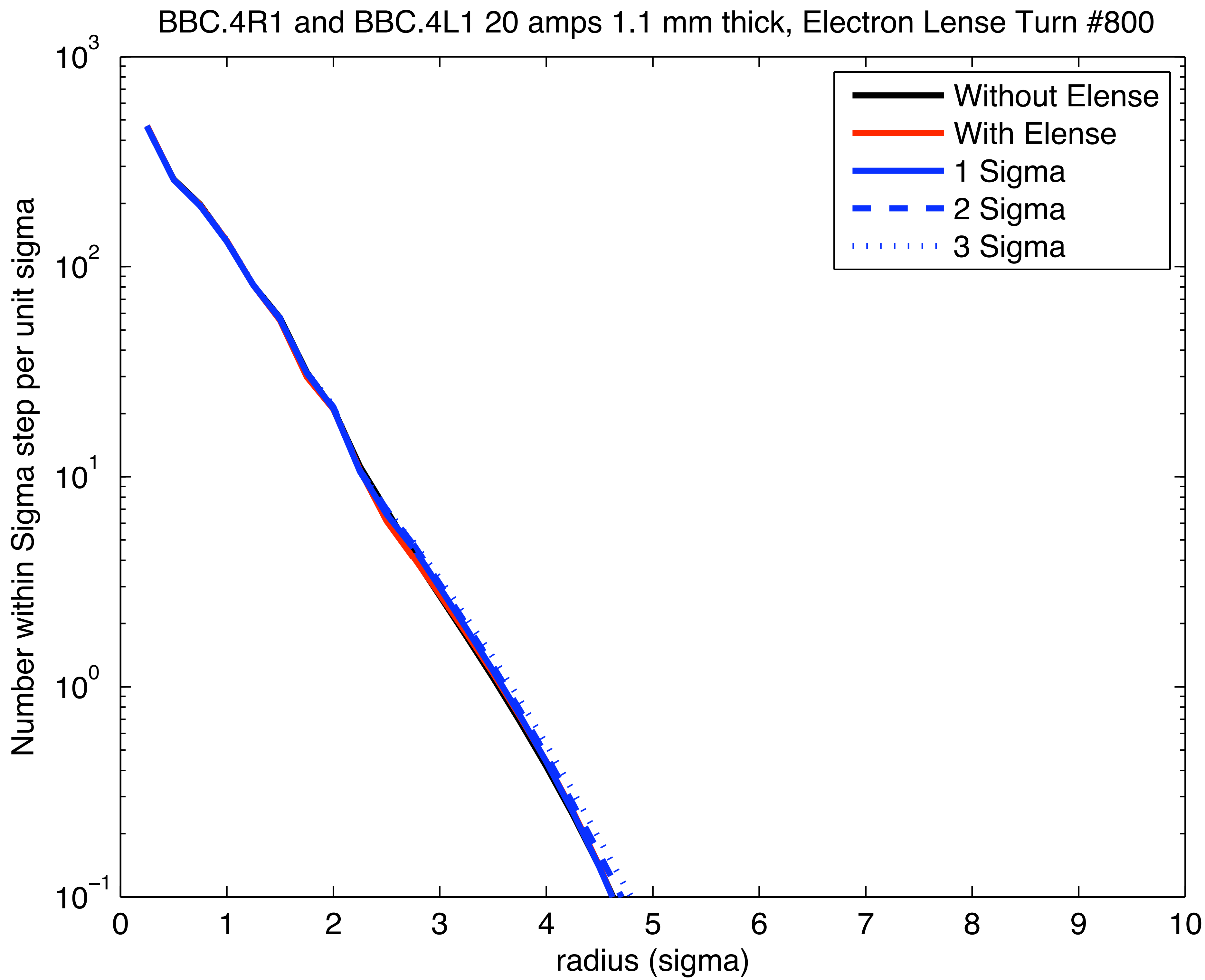
Example: two BBC

- Turn #700



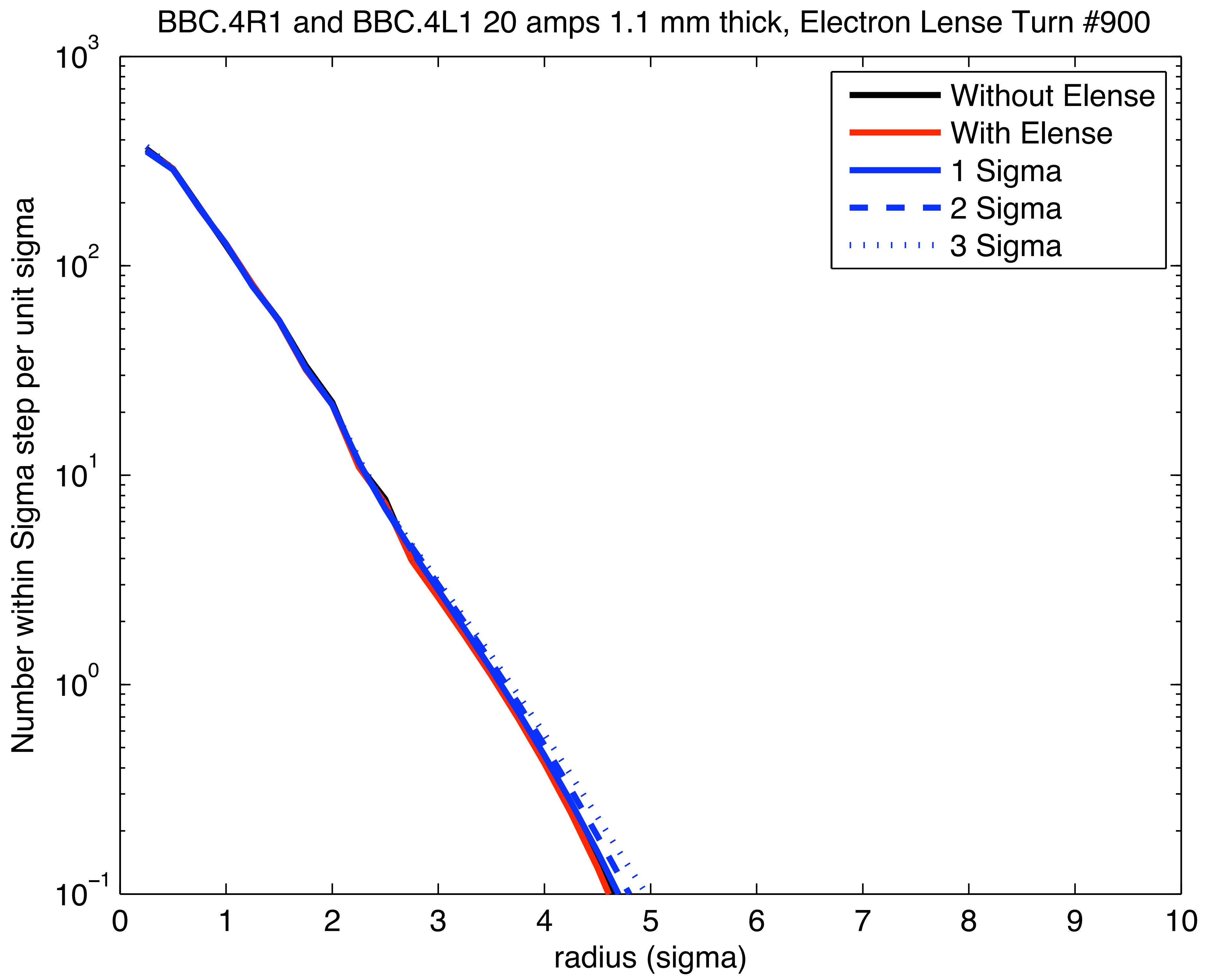
Example: two BBC

- Turn #800



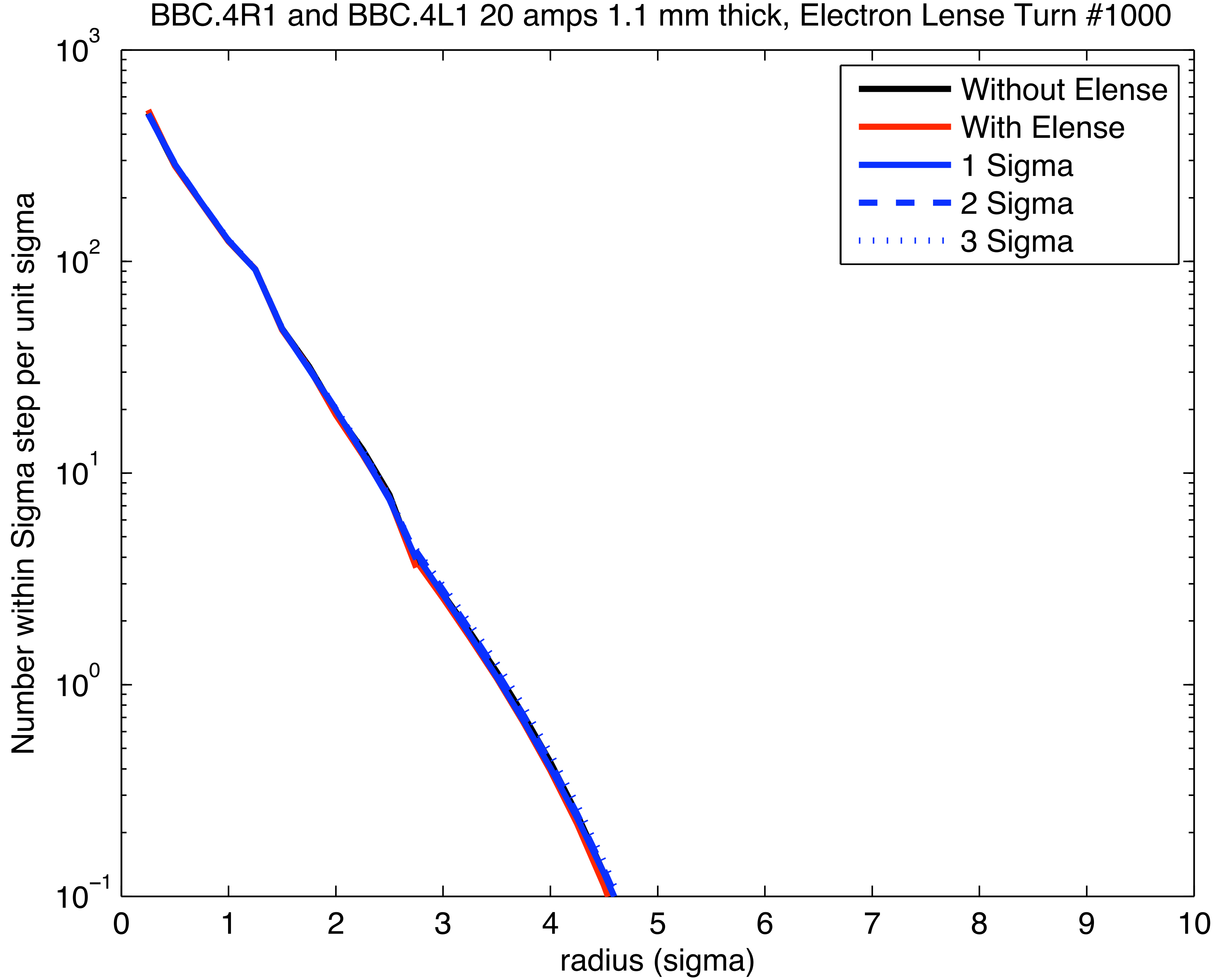
Example: two BBC

- Turn #900



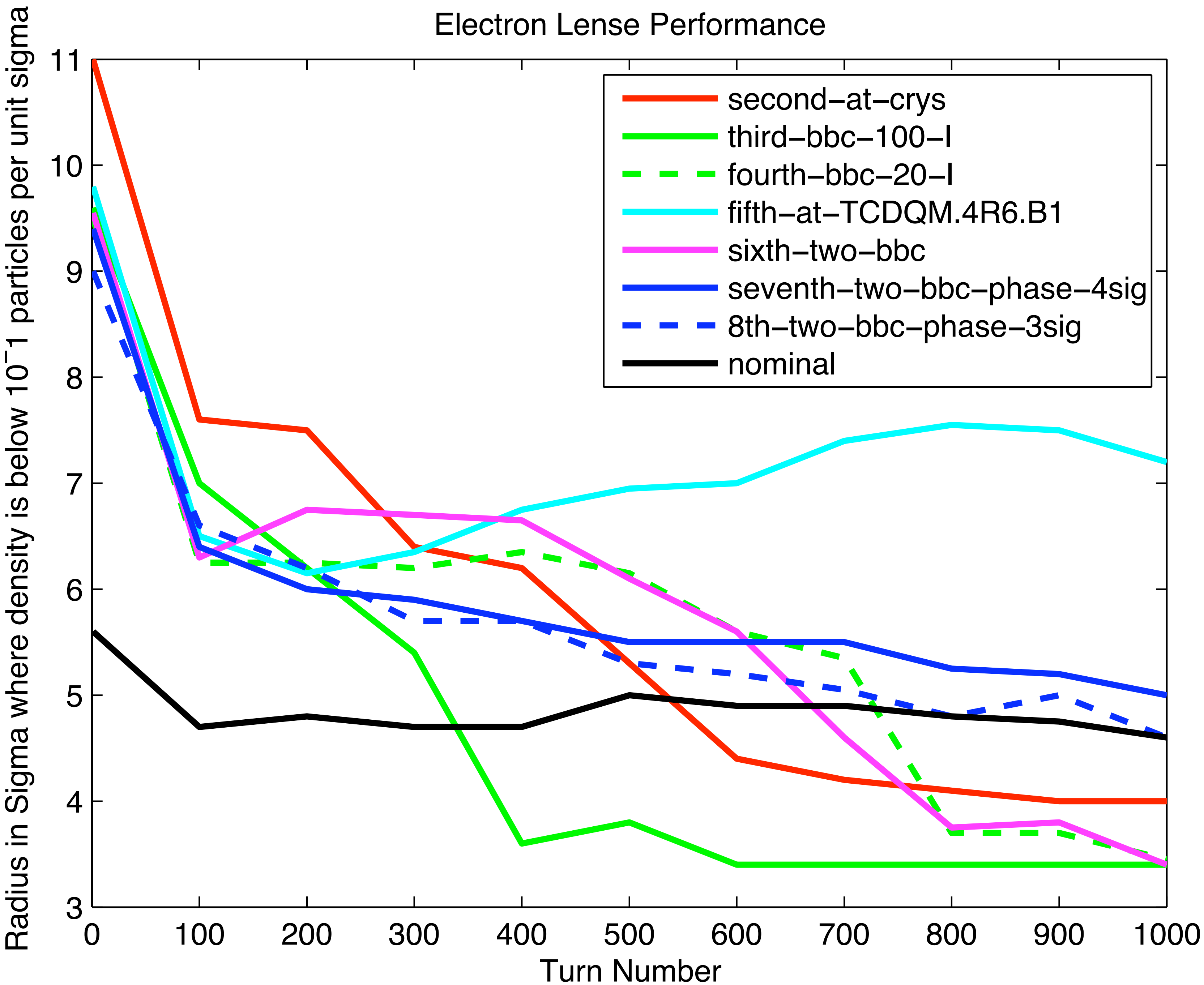
Example: two BBC

- Turn #1000
- Within 1000 turns system the same as if primaries were at nominal (6 sigma)



Data of several different runs

- Here is a summary of several different runs plotting the maximum extent of the beam halo for the 3-sigma data (worst case).
- Other than the one at TCDQM, any location and parameters results in acceptable behavior where within 1000 turns the beam halo population has hit the nominal case (no E-lens and primaries at 6 sigma).
- A single E-lens appears adequate, adding a second adds little.



Impact Parameter

- In principle, by increasing the Halo particle diffusion rate, the impact parameter on the primary should increase, thereby increasing collimation efficiency.
- However, what we really see is a varying effect.
  - For the Horizontal primary the average impact parameters halves
    - Presumably due to more particles just barely hitting the primary (after being pulled out by the electron lens)
  - The other two primaries have roughly the same impact parameter
  - My setup isn't really appropriate for determining the impact parameter

		Avg. Impact Param. (mm)	Avg. Impact Param. (mm)	Avg. Impact Param. (mm)	Avg. Impact Param. (mm)	Avg. Impact Param. (mm)
primary	Orientation	Without Elens	With Elens	1 Sigma	2 Sigma	3 Sigma
TCP_D6L7.B1	90.0º	0.226	0.230	0.235	0.232	0.244
TCP.C6L7.B1	0.0º	1.039	0.506	0.553	0.577	0.520
TCP_B6L7.B1	135.0º	0.375	0.381	0.281	0.282	0.242

Number of Impacts

- This may be explained by looking at the number of particle impacts
  - The electron lens is mainly resulting in more impacts on the horizontal primary
  - The increase in number of impacts as collimators are pulled out is due to more particles hitting the primaries first after being heated with the E-lens (versus hitting other collimators first within the first turn)
  - So, a more controlled study of individual particles needed to measure the effect on the impact parameter.

		Number of Impacts	Number of Impacts	Number of Impacts	Number of Impacts	Number of Impacts
primary	Orientation	Without Elens	With Elens	1 Sigma	2 Sigma	3 Sigma
TCP_D6L7.B1	90.0º	437	416	495	533	555
TCP.C6L7.B1	0.0º	802	1615	1609	1623	1780
TCP_B6L7.B1	135.0º	285	320	366	448	591

E-lens radius

- Most of these simulations have been with an E-lens at 3 sigma. This is rather close and a small scraping of the beam core is evident. 4-sigma is a much more reasonable radius. Little drop in performance has been found going from 3 to 4 sigma.

AC Current

- Additional resonance effect is possible with modulating the E-Lens current with the Betatron frequency of the beam.

$$\begin{pmatrix} x \\ \dot{x} \end{pmatrix} = \begin{pmatrix} \cos 2\pi Q & \sin 2\pi Q \\ -\sin 2\pi Q & \cos 2\pi Q \end{pmatrix} + \begin{pmatrix} 0 \\ \theta_{elens} \end{pmatrix}$$

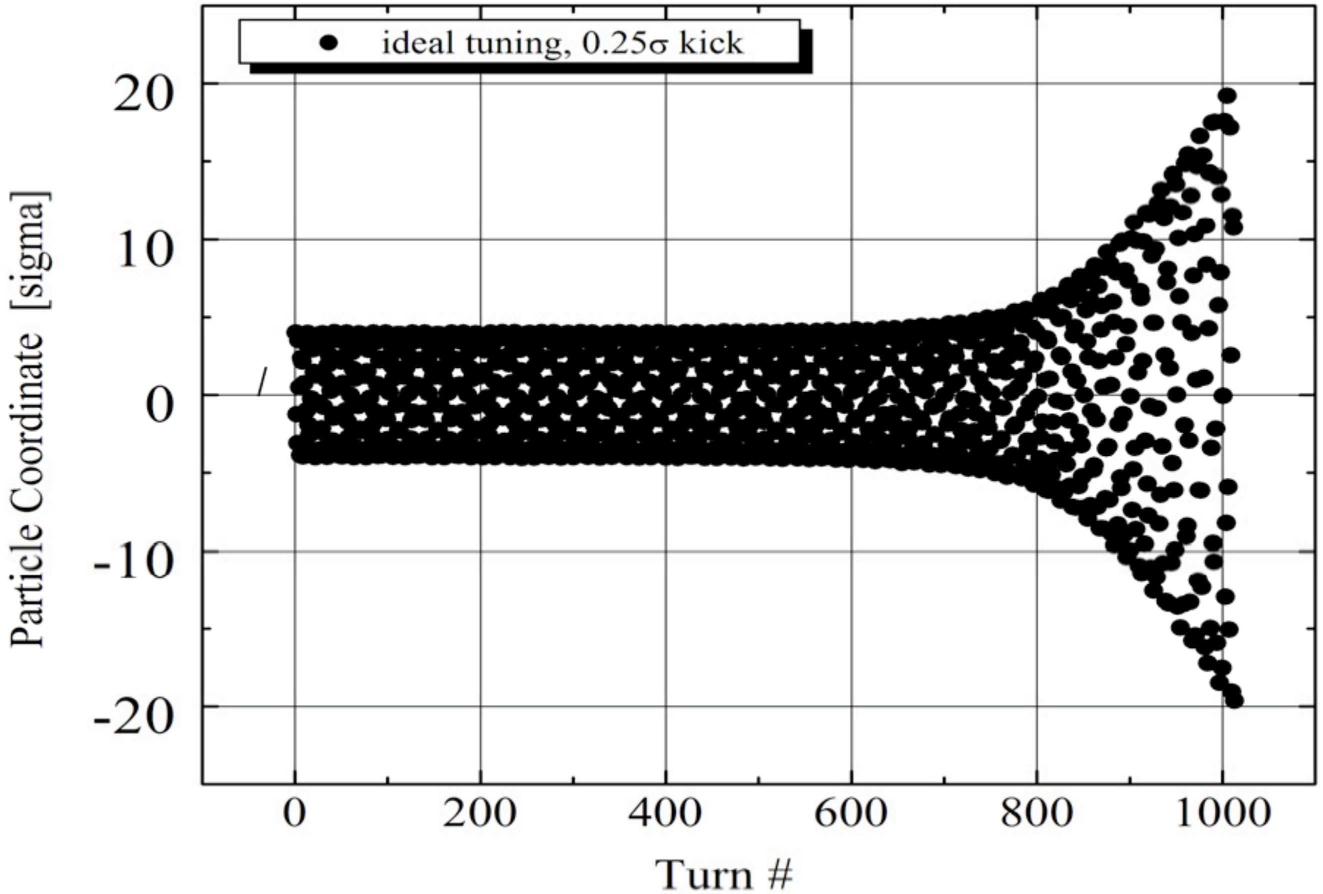
$$\dot{x} = -x \sin 2\pi Q + \dot{x} \cos 2\pi Q + \theta \cos(\omega t + \psi)$$

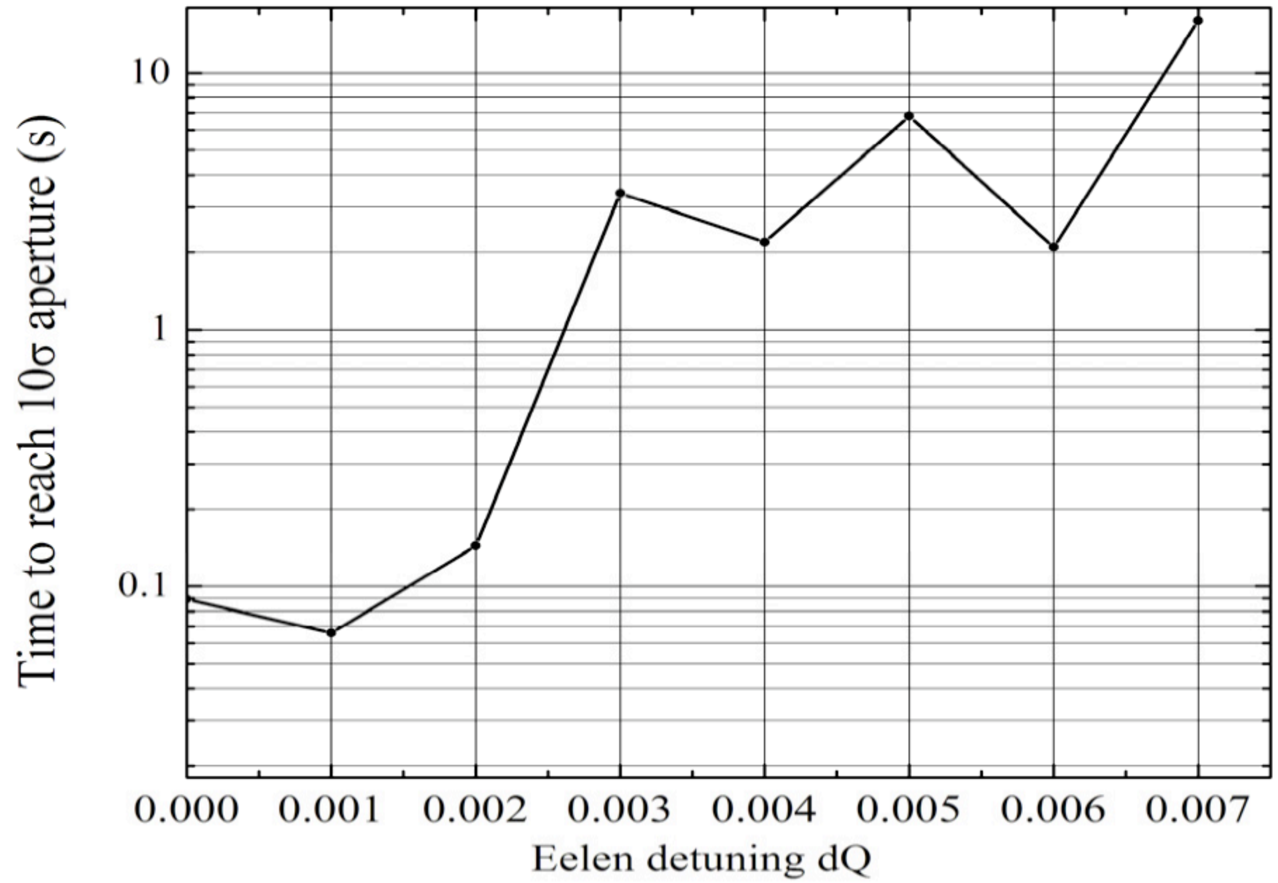
$$\text{resonance when: } 2\pi Q = \omega t + \psi$$

- This has not yet been studied in Sixtrack but studies by Valdimir Shiltsev and Alexander Drozhdin at FNAL have shown potentially an order of magnitude faster cleaning time!
- The DC effect is quite evident, but AC beam may improve performance much more.

Performance vs E-lens Modulation

- From EPAC08 MOPC098
- Single particle motion
- Factor 100 improvement in time!
  - Of course, this is only for on-tune particles. In reality there will be a rather large tune spread, especially for the large amplitude halo particles.
  - Nevertheless, this will be included in future Sixtrack studies.





Practicalities in E-lens Construction

- Electron lenses have been used for some time at Fermilab for Beam-beam compensation (Tevatron Electron Lens: TEL)
- The basic E-lens parameters for collimation are similar to those for the TELs already built
  - Hollow electron beams are widely used in electron cooling devices
  - However, never in an electron lens and R&D will be required but no known roadblocks.

Current Conclusions

- A hollow electron lens has been demonstrated to improve the cleaning of the beam halo in the LHC.
- Incorporating an electron lens allows for the pulling of the primary and secondary collimators to larger sigma with no degradation in performance.
- Specific location of electron lens evidently somewhat important.
- AC current has been demonstrated (in separate studies) to improve the dispersion rate dramatically.

TODO

- Use a different bunch distribution.
  - No need to really simulate the bunch core
  - Determine effect on impact parameter
  - Modify lattice to insert BBC elements at appropriate locations. As is, MAD-X removes BBC elements when creating Sixtrack lattice.
- Use a more realistic Electron Lens
  - AC current
  - Errors
    - Effects of small deviations of the electron beam trajectory from straight line
    - Field leaking into beam core
  - Realistic Gaussian shape to electron beam
- Look at varying electron lens parameters
  - What size/current E-lens is ideal
  - Look at E-lens phase and tune
- Look at local cleaning efficiency with electron lens added
  - Up to now just looking at evolution of beam profle

Thanks to:

- Vladmir Shiltsev, Shasha Drozhdin, V. Kuznetsov, L. Vorobiev and Alex Valishev
- Ralph Assmann and Valentina Previtali for recommending this project to me.