Electron lens

cookbook

Recipes from simulations

V. Previtali, A. Valishev
G. Stancari, I. Morozov, D. Shatilov

Thanks for the helpful discussions with
S. Redaelli, B. Salvachua Ferrando, A. Rossi
Goal: can we use the available hardware for meaningful beam tests at the LHC and SPS?

- past experience at Tevatron shows promising results

- Extrapolation of the e-lens effect on the LHC / SPS beam is not straightforward. Simulations are required.

- Preliminary question: what is the actual status of the simulations? is it possible to have a realistic evaluation from simulations?
  - past simulations at FNAL with Lifetrack
  
  - New simulations for LHC with Sixtrack.
    - scraping time (how fast can we remove the particle halo?)
    - what are the side effects?

- Does it make sense to test the device in the SPS first?
Tevatron simulations

Summary of Tevatron experimental results:
1. halo removal rate reproduced within a factor 2-5
2. core not affected qualitatively reproduced

Simulations performed with Lifetrack (code benchmarked with Sixtrack).

Tevatron pbar beam in collision.

Elens model including e-beam profile imperfections
A possible integration of a new device in the LHC collimation system requires a validation from the standard software used for the simulations of the LHC collimation system: Sixtrack.

Sixtrack is a full 6D tracking code capable of computing the interactions with several collimator types (standard CFC collimator, metallic collimators, crystal collimators ..).

A new routine describing the electron lens has been implemented in the code. Details on the different models are given in the presentation.
Sixtrack simulations: the ingredients

The beam
- 7 TeV beam 1
- Purely H or V halo between 4 and 6 sigma, no off-momentum
- no diffusion (the halo is not replenished)
- 6400 particles, 200K turns (standard jobs)

The machine: a quasi linear approximation
- thin nominal LHC optics, no collision
- linear machine + sextupoles

A minimal LHC collimation system

<table>
<thead>
<tr>
<th>name</th>
<th>angle[radi]</th>
<th>betax[m]</th>
<th>betay[m]</th>
<th>halfgap[m]</th>
<th>Material</th>
<th>Length[m]</th>
<th>sigx[m]</th>
<th>sigy[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELENSE.Try.1</td>
<td>0.00000E+00</td>
<td>0.18181E+03</td>
<td>0.17991E+03</td>
<td>0.12092E-02</td>
<td>C</td>
<td>0.20000E+01</td>
<td>0.30230E-03</td>
<td>0.30072E-03</td>
</tr>
<tr>
<td>TCP.D6L7.B1</td>
<td>0.15710E+01</td>
<td>0.15887E+03</td>
<td>0.78263E+02</td>
<td>0.13130E-01</td>
<td>C</td>
<td>0.60000E+00</td>
<td>0.28259E-03</td>
<td>0.19834E-03</td>
</tr>
<tr>
<td>TCP.C6L7.B1</td>
<td>0.00000E+00</td>
<td>0.15053E+03</td>
<td>0.82763E+02</td>
<td>0.18210E-01</td>
<td>C</td>
<td>0.60000E+00</td>
<td>0.27507E-03</td>
<td>0.20396E-03</td>
</tr>
</tbody>
</table>

- Only the e-lens with two primary collimators in IP7 at 6.2 sigma
- the beam is round at the e-lens location (1 sigma about 300 um)
- electron lens in IP4 (see integration talk)
- typical parameters for the electron lens, as used in Tevatron (current 1.2 A, extraction voltage 5 KeV), inner radius 4 sigma
The hollow e-lens: a first model

Charge distribution

The first model is **the perfect elens**: hollow cylinder, uniform current density

Total current 1.2 A

Electric and Magnetic fields

**case 1**: electrons and protons have opposite versus

**desired configuration**: e.m. forces add up

**case 2**: electrons and protons have the same versus
The perfect e-lens: the nominal kick

Highly non linear field, focusing in both planes. For symmetry reasons, $F=0$ within the electron lens inner radius.

Maximum kick value for 7 TeV of the order of $10^2$ nrad (about 1% of sigma)

Can this small kick be efficient for scraping the 7 TeV LHC halo?
The perfect e-lens: the nominal kick

Highly non linear field, focusing in both planes. For symmetry reasons, $F=0$ within the electron lens inner radius.

maximum kick value for 7 TeV of the order of $10^2$ nrad (about 1% of sigma)

Can this small kick be efficient for scraping the 7 TeV LHC halo?
can this small kick be efficient for scraping the 7 TeV LHC halo?

Yes, but you need to know how to use it
4 basic recipes

1. **DC mode:** e-lens is always ON

2. **AC mode:** e-lens switched on-off in resonance with the particle transverse motion

3. **random mode:** e-lens is randomly switched on-off turn by turn (coin toss!)

4. **harmonic mode:** e-lens is switched on every n turns (tevatron mode), simulations in progress
1. mild effect on the phase space
2. induces a small tune shift
3. negligible tune jitter (<1e-5)

DC mode is not effective for scraping in a linear machine
2. **AC mode**: e-lens switched on-off in resonance with the particle oscillation

response of the particle to different AC frequencies

with the good frequency, AC mode induces large amplitude oscillations which quickly drive the particles on the collimator

to $11\sigma_x$ in 2 sec!

- initial amplitude: $5\sigma_x$
3. **random mode**: e-lens is randomly switched on-off turn by turn giving random kicks to the halo particles, enhances their brownian motion.

Random mode increases diffusion.
4 basic recipes

1. **DC mode**: e-lens is always ON

2. **AC mode**: e-lens switched on-off in resonance with the particle transverse motion

3. **random mode**: e-lens is randomly switched on-off turn by turn (coin toss!)

4. **harmonic mode**: e-lens is switched on every n turns (tevatron mode), simulations in progress

**which mode for what?**
which mode for what?

Perfect e-lens, linear machine

-40%  
-90%

steps reflecting the changes in frequency of the AC mode
which mode for what?

-40%

-90%

steps reflecting the changes in frequency of the AC mode
(unfortunately?)
Real life is complicated...
(unfortunately?)
Real life is complicated...
Perfect e-lens in quasi-linear machine

3D halo

e-lens jitter

non linearities (octupoles)

radial profile

azymutal profile

diffusion processes

multipole errors

...
It’s a long (infinite?) way, which may requires many intermediate stops
Perfect e-lens in quasi-linear machine

non linearities (octupoles)

3D halo e-lens jitter radial profile azymutal profile diffusion processes multipole errors

It’s a long (infinite?) way, which may requires many intermediate stops

Real e-lens in real machine
\[ \frac{dN}{d\frac{Q}{x}} \] quasi-LINEAR

Octupoles ON

DC elens ON

\[ +2 \times 10^{-3} \]

\[ +5 \times 10^{-4} \]

non linearities (octupoles)

\[ Q(6\sigma_x) - Q(4\sigma_x) \sim 1.5 \times 10^{-3} \]

\[ dQ(e\text{-}lens) \sim 5 \times 10^{-4} \]
Q(6\sigma_x) - Q(4\sigma_x) \gg dQ(e\text{-}lens)
no more difference between AC and random mode

DC mode start to act as a smooth scraper

random mode is very robust
results are unchanged.

Q(6\sigma_x) - Q(4\sigma_x) \gg dQ(e\text{-}lens)
no more difference between AC and random mode

octupoles - DC
octupoles - AC
octupoles - random
Perfect e-lens in quasi-linear machine

3D halo

e-lens jitter

radial profile

azymutal profile

diffusion processes

multipole errors

...
passing from a flat current distribution...

...to a more realistic distribution
The effect on the integrated function is less evident.

We get slightly larger kicks in the region between 4 and 6 sigma.

**An improvement of cleaning of about 10% is achieved for random and AC mode.**
can we tune the speed?

A current of 1.2 A is a conservative estimate. With the new cathode (ready) for the LHC we can easily reach higher values.

It is perfectly acceptable to assume that we can clean about 70% of the halo particles (from 4 to 6 sigma) in 20s.
any side effect?
what happens to the scraped particles?

![Graph showing impact parameter on primary collimator.]

The impact on primary collimator is about 10 times larger than the usual assumed values. According to past studies this should not affect the cleaning efficiency of the standard system, but it could **increase the crystal collimation efficiency**.
long story short...
The simulation of e-lens is an on-going work, however few important statements can be already done:

- among the possible e-lens usage, the random mode seems to be the most robust and efficient for fast scraping
- With relatively achievable e-lens currents, more than 65% of the halo particles between 4 and 6 sigma can be lost in about 20 s.
- Many effects like natural diffusion, beam-beam, multipole errors (non included yet) are expected to enhance the electron lens effect.
- In general, non linearities tends to increase the efficiency of the DC mode as a slow scraper. Already with octupoles a loss of about 5% is achieved in about 20 s.
**e-lens in the SPS?**

Even if the physics case has been studied for the LHC, time/practical constraints could prevent us from an early installation of the e-lens in the LHC.

A possible alternative could be to perform the first beam tests in SPS. Does it make sense?

<table>
<thead>
<tr>
<th>CONS</th>
<th>PROS</th>
</tr>
</thead>
</table>
| • coast of 270 GeV (~1/4 of Tevatron energy)  
• Less instrumentation | ✓ SPS is more similar to the LHC than Tevatron (proton machine, same LHC working point, weakly coupled...)  
✓ reproduce Tevatron results at CERN  
✓ validate simulation results  
✓ acquiring experience with the object (cryogenics, vacuum)  
✓ developing dedicated control software |
coldex location (LSS4). different beta function values (H=30m vs V=76 m)

Example: **inner radius at 2.7 mm**
scraping at 3 $\text{sigma}_y$ VERT
scraping at 4.7 $\text{sigma}_x$ HOR

scraping has been simulated separately in V and H, using the same collimator (changing its orientation)

the scraping will be mainly in the Vertical plane. Nowadays the LHC-type collimator is oriented in the horizontal plane.
<table>
<thead>
<tr>
<th>CONS</th>
<th>PROS</th>
</tr>
</thead>
<tbody>
<tr>
<td>● 1/4 of the TeV energy</td>
<td>✓ SPS is more similar to the LHC than Tevatron (protons, same LHC working point, weakly coupled...)</td>
</tr>
<tr>
<td>● Less instrumentation</td>
<td>✓ reproduce Tevatron results at CERN</td>
</tr>
<tr>
<td>● <strong>Optimal layout would require a vertical collimator</strong></td>
<td>✓ validate simulation results</td>
</tr>
<tr>
<td>a shift of 5 m would be already enough to solve the issue - and the space is available (see integration talk - Adriana)</td>
<td>✓ acquiring experience with the object (cryogenics, vacuum)</td>
</tr>
<tr>
<td></td>
<td>✓ developing dedicated control software</td>
</tr>
</tbody>
</table>
maximum kick for SPS case ~ 1 urad (10x the LHC case)

For 270 GeV and normalized emittance of 3.5 mm mrad, this corresponds to about 5% of the sigma.

Removal rates in 200K turns (5 sec)

<table>
<thead>
<tr>
<th></th>
<th>DC</th>
<th>AC</th>
<th>random</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
<td>91%</td>
<td>35%</td>
</tr>
</tbody>
</table>

(90% in 20 sec for the LHC)

(42% in 20 sec for the LHC)
\[ \theta(r) = \frac{2L f(r) I_T}{4 \pi \varepsilon_0 r (B \rho)_p \beta e \beta_p c^2} \]

\[ f(r) = \begin{cases} 
0 & r < R_1 \\
\frac{r^2 - R_1^2}{R_2^2 - R_1^2} & R_1 < r < R_2 \\
1 & r > R_2 
\end{cases} \]

maximum kick for SPS case ~ 1 urad (10x the LHC case)

For 270 GeV and normalized emittance of 3.5 mm mrad, this corresponds to about 5% of the sigma.

**Removal rates in 200K turns (5 sec)**

<table>
<thead>
<tr>
<th></th>
<th>DC</th>
<th>AC</th>
<th>random</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>90%</td>
<td>91%</td>
<td>(42% in 20 sec for the LHC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>?</td>
<td>(42% in 20 sec for the LHC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>35%</td>
<td></td>
</tr>
</tbody>
</table>

Removal rates in 20 seconds 76%

to be verified with non linearities
<table>
<thead>
<tr>
<th>CONS</th>
<th>PROS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 1/4 of the TeV energy</td>
<td>✓ SPS is more similar to the LHC than Tevatron (protons, same LHC working point, weakly coupled...)</td>
</tr>
<tr>
<td>• Less instrumentation</td>
<td>✓ reproduce Tevatron results at CERN</td>
</tr>
<tr>
<td>• Optimal layout would require a vertical</td>
<td>✓ validate simulation results</td>
</tr>
<tr>
<td>collimator</td>
<td>✓ acquiring experience with the object (cryogenics, vacuum)</td>
</tr>
<tr>
<td></td>
<td>✓ developing dedicated control software</td>
</tr>
<tr>
<td></td>
<td>✓ The e-lens operation is identical to the LHC case, the timescale of the effects is only a factor 4 different</td>
</tr>
<tr>
<td></td>
<td>all prototypes for the LHC collimation system have been tested in SPS: experience has been always precious</td>
</tr>
<tr>
<td></td>
<td>a shift of 5 m would be already enough to solve the issue - and the space is available (see Adriana)</td>
</tr>
</tbody>
</table>
Recently an operational use of the device in SPS was also suggested:

**e-lens as a scraper in SPS?**

following discussions with S. Redaelli, B. Salvachua Ferrando, A. Rossi

...modifications of the layout are probably required...

1. Integration for beam test (add collimators? both planes?)
2. Minimum duration of excitation to have effective scraping (can we do it in short times before extraction?)
3. Can we change the size of the hole to match the variation of beam size during the ramp?

likely, but still have to be addressed in details

the 450 GeV case still have to be addressed
e-lens in the SPS?

summary

- SPS has been simulated with Sixtrack, using the linear machine and the perfect e-lens model
- Results for the LHC have been qualitatively confirmed in the SPS
- From the simulations at 270 GeV it is clear that the current e-lens can be used for meaningful beam studies
- The only shoe-stopper could be the required modification of the layout - but this can be solved if we shift the device of 5-6 m
- The usage of the current e-lens as an operative device is likely, but further investigations and possible hardware modifications will be required.
special thanks to
Riccardo de Maria, Guido Sterbini, and the whole collimation team for the useful discussions.
tune peak is shifted & larger

\[ \frac{dN}{d\left(\frac{Q_x}{10^5}\right)} \]

quasi-LINEAR
Octupoles ON
DC elens ON
purely H halo, quasi linear machine

For each frequency there is a narrow, well defined tune

Total tune range $\sim 4e-5$

3D distribution + octupoles

Tune peaks are larger → difficult to keep particle in a resonance

Total tune range $\sim 1.5e-3$

→ covering all the interesting tunes takes more time!

AC mode becomes less effective!
It’s a long way, which requires many intermediate stops
(normalized) phase space

- Amplitude increase
- Amplitude decrease

Arrows indicate direction of change in amplitude.
Taking a particle with initial phase $= 0$ this is its momentum. The resonant force which acts on this particle must be in phase with the momentum, and with the same oscillation period. The electron lens is proportional to the particle position $\Rightarrow$ **ALWAYS shifted in phase (90 degrees)** with respect with the particle momentum.
taking a particle with initial phase = 0

dis its its momentum

the resonance driving force which acts on this particle must be in phase with the momentum, and with the same oscillation period

the electron lens is proportional to the particle position => ALWAYS shifted in phase (90 degrees) with respect with the particle momentum

Resonant condition:

I switch the ELENS on only when it gives a kick in the same direction as xp
(normalized) phase space
Perfect e-lens in quasi-linear machine

Today!

3D halo
e-lens jitter
radial profile
azymutal profile
diffusion processes
fringe fields
...
The perfect e-lens: the nominal kick

The kick is focusing ⇒ always inward ⇒ increases the particle phase
2. **AC mode**: e-lens switched on-off in resonance with the betatron tune

The e-lens itself introduces a tune shift, so that different (amplitude) particles have different tunes.

\[ \Delta Q \approx 4 \times 10^{-5} \]

Perfect e-lens, linear machine
2. **AC mode**: e-lens switched on-off in resonance with the betatron tune

... it follows that different (amplitude) particles respond to different excitation frequencies