Electron lens cookbook

Recipies from simulations

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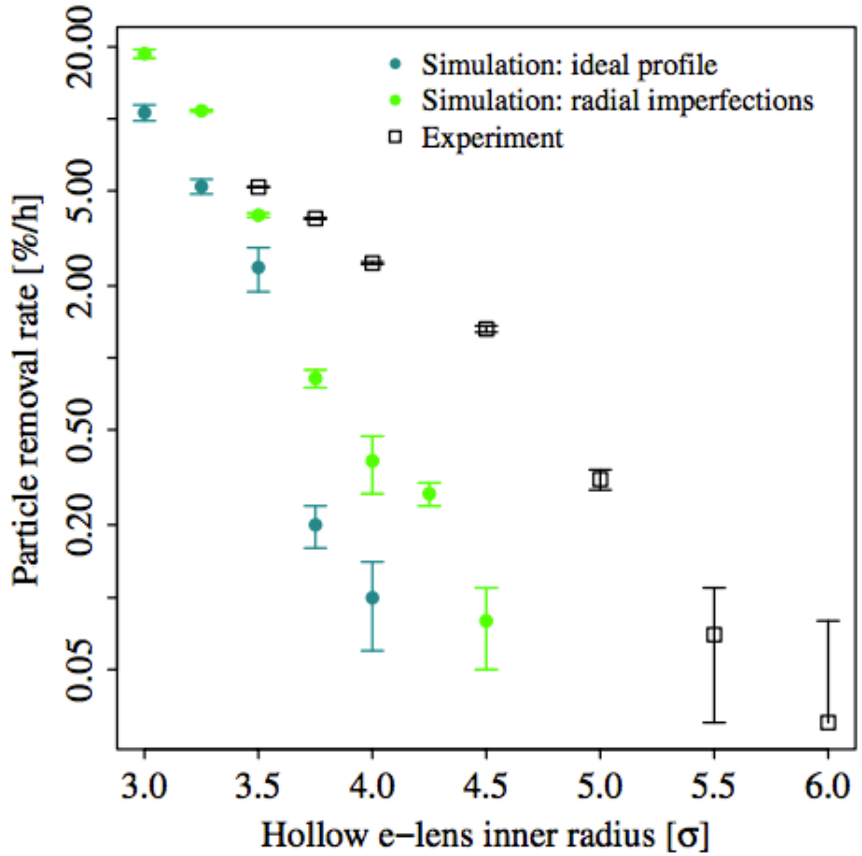
G. Stancari, I. Morozov, D. Shatilov

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



Simulations performed with Lifetrack (code benchmarked with Sixtrack).

Tevatron pbar beam in collision.

Elens model including e-beam profile imperfections

Summary of Tevatron experimental results:

1. halo removal rate reproduced within a factor 2-5
2. core not affected qualitatively reproduced

CERN: simulation tools

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

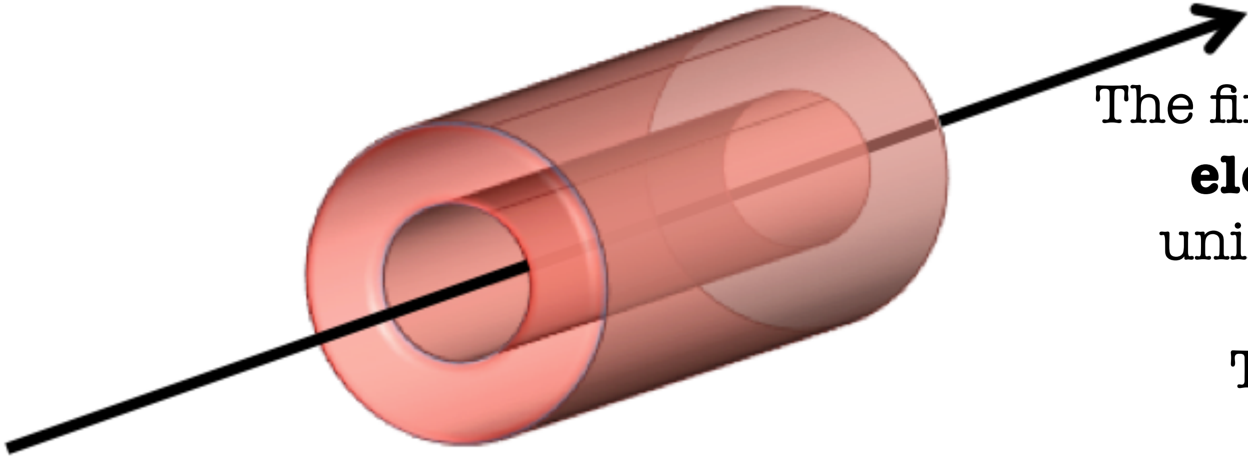
A minimal LHC collimation system

name	angle[rad]	betax[m]	betay[m]	halfgap[m]	Material	Length[m]	sigx[m]	sigy[m]
ELENSE.TRY.1	0.00000E+00	0.18181E+03	0.17991E+03	0.12092E-02	C	0.20000E+01	0.30230E-03	0.30072E-03
TCP.D6L7.B1	0.15710E+01	0.15887E+03	0.78263E+02	0.13130E-01	C	0.60000E+00	0.28259E-03	0.19834E-03
TCP.C6L7.B1	0.00000E+00	0.15053E+03	0.82763E+02	0.18210E-01	C	0.60000E+00	0.27507E-03	0.20396E-03

- 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



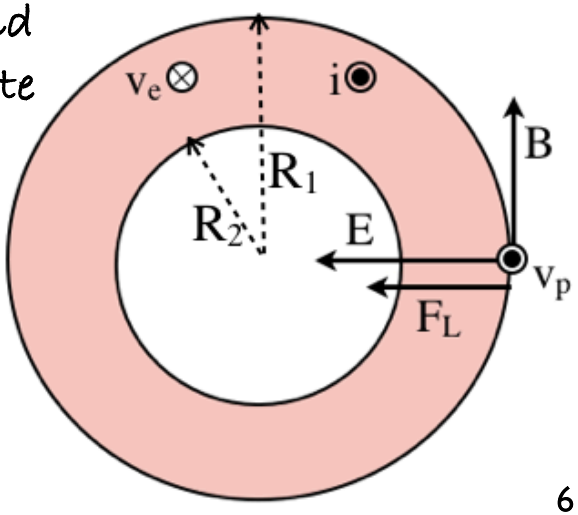
The first model is **the perfect elens**: hollow cylinder uniform current density

Total current 1.2 A

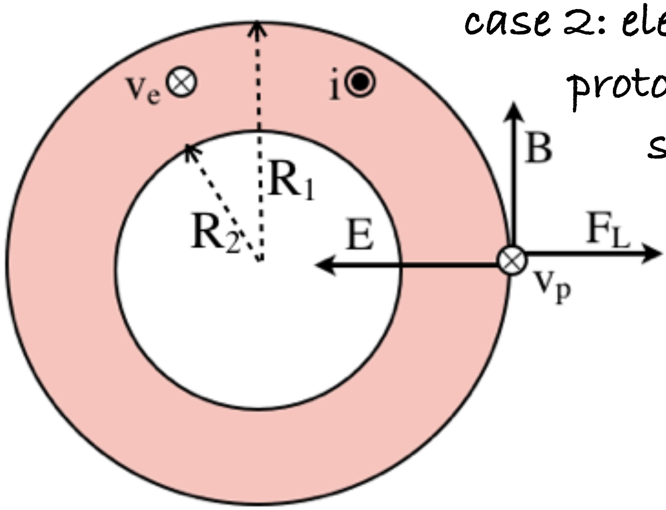
Electric and Magnetic fields

case 1: electrons and protons have opposite versus

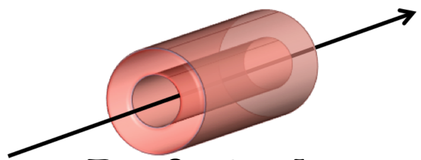
desired configuration: e.m. forces add up



case 2: electrons and protons have the same versus

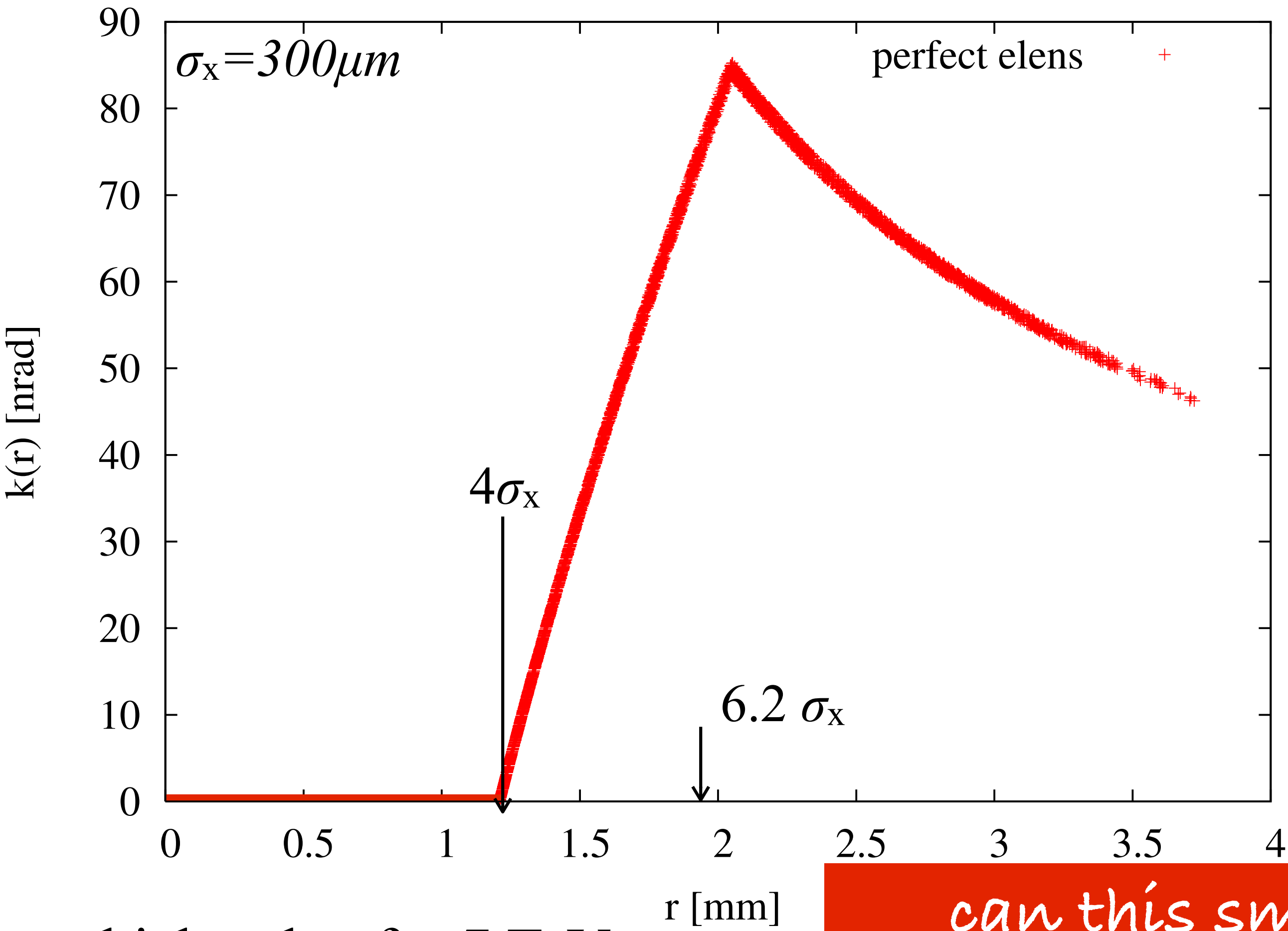


The perfect e-lens: the nominal kick



Perfect e-lens, linear machine

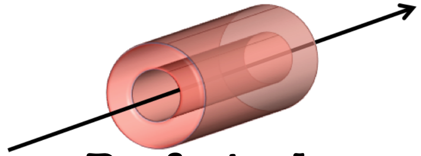
Highly non linear field, focusing in both planes. For symmetry reasons, F=0 within the electron lens inner radius.



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



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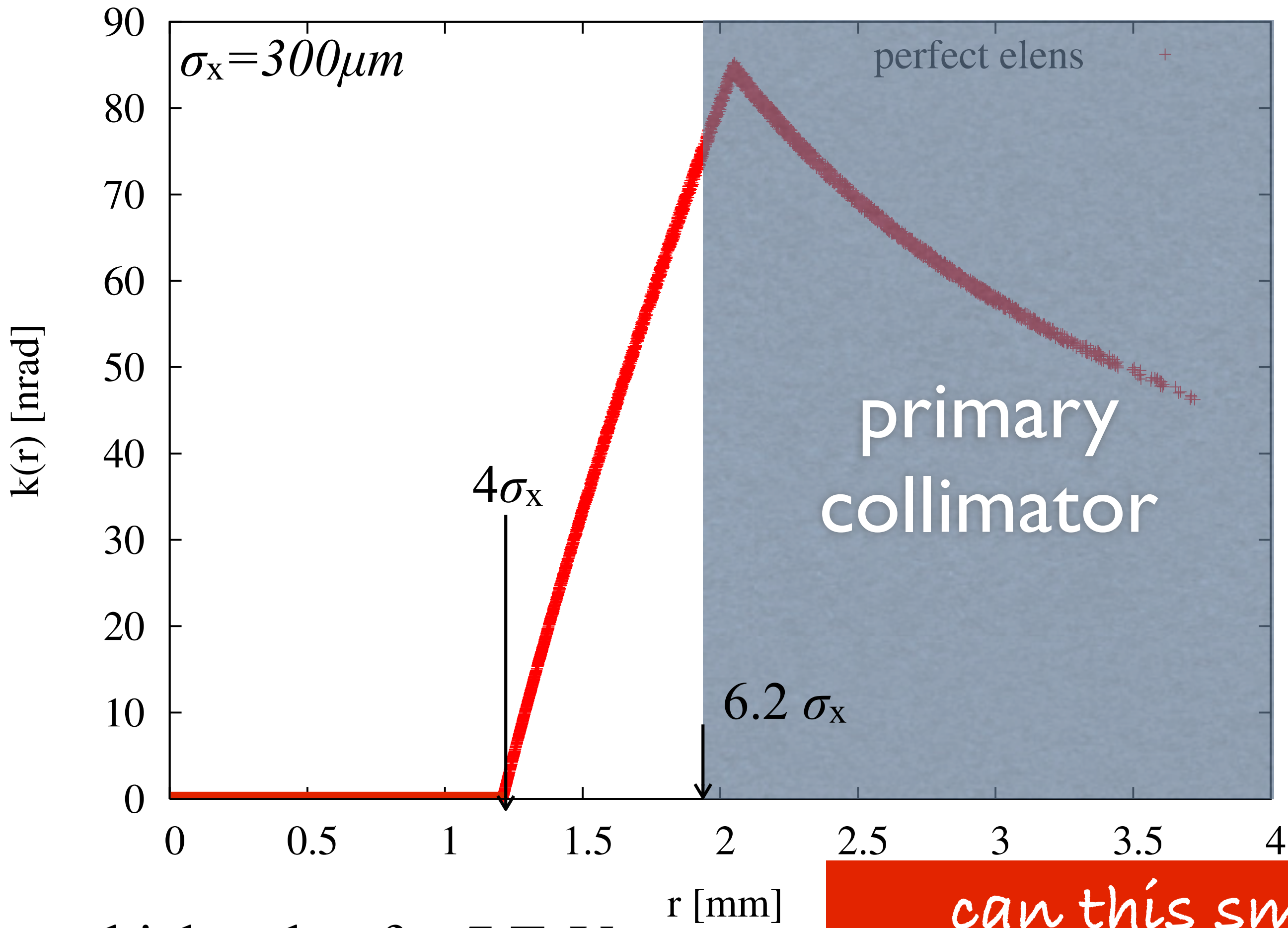

maximum kick value for 7 TeV of the order of 10^2 nrad (about 1% of sigma)

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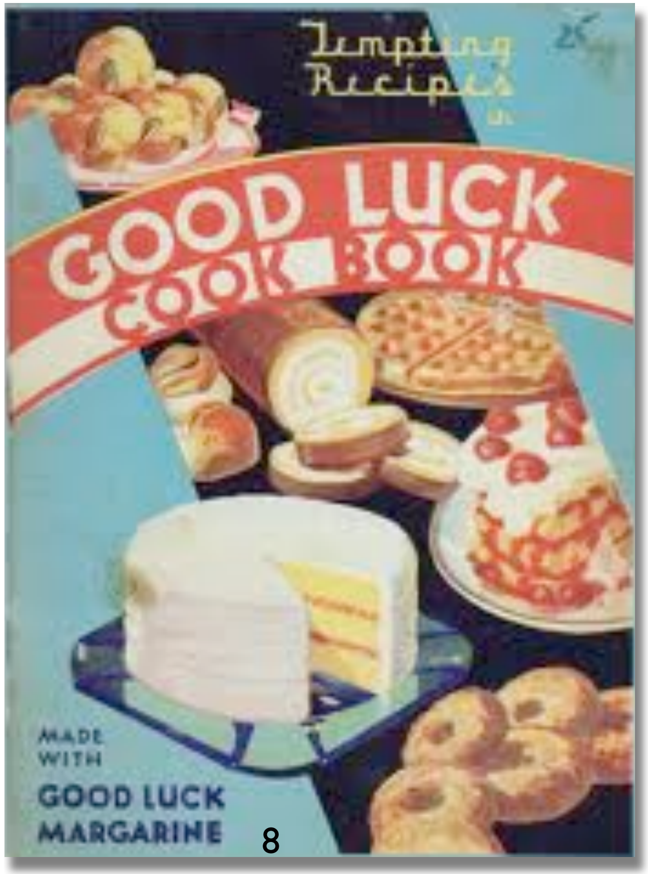
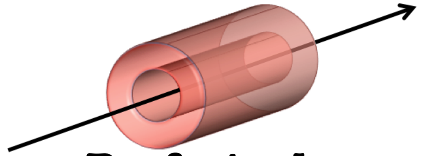
can this small kick be efficient for scraping the 7 TeV LHC halo?

Yes, but you need to know how to use it



4 basic recipes


Perfect e-lens, linear machine

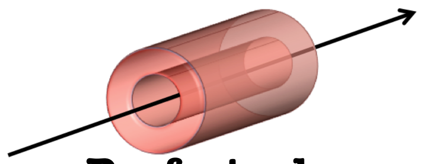
1. DC mode: e-lens is always ON

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

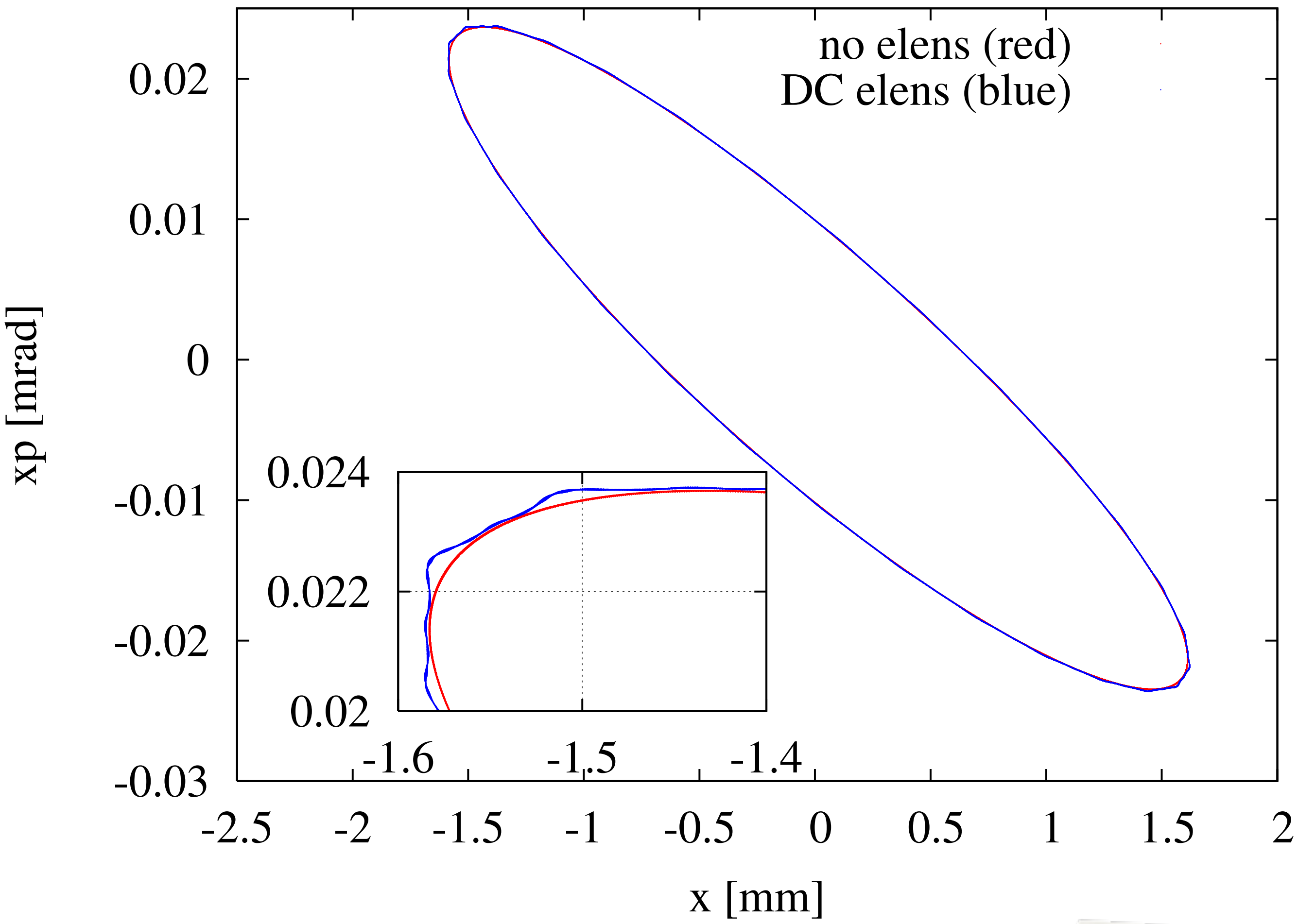
3. random mode: e-lens is randomly switched on-off turn by turn (coin toss!)

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

1. DC mode: e-lens is always ON



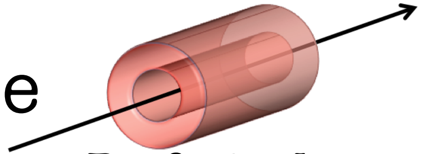
Perfect e-lens, linear machine



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



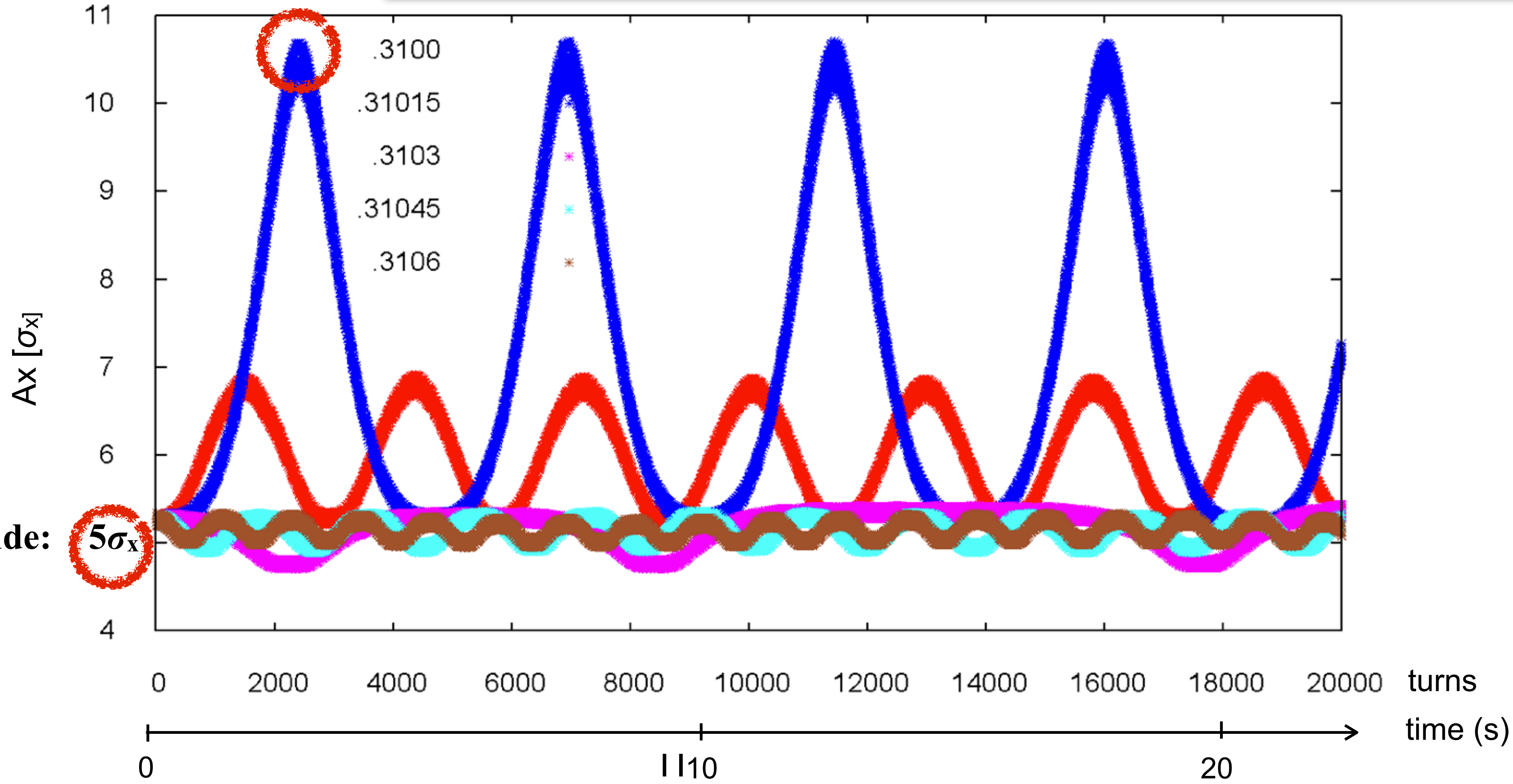
Perfect e-lens, linear machine

response of the particle to different AC frequencies

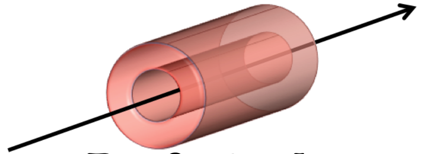
with the good frequency, AC mode induces large amplitude oscillations which quickly drive the particles on the collimator

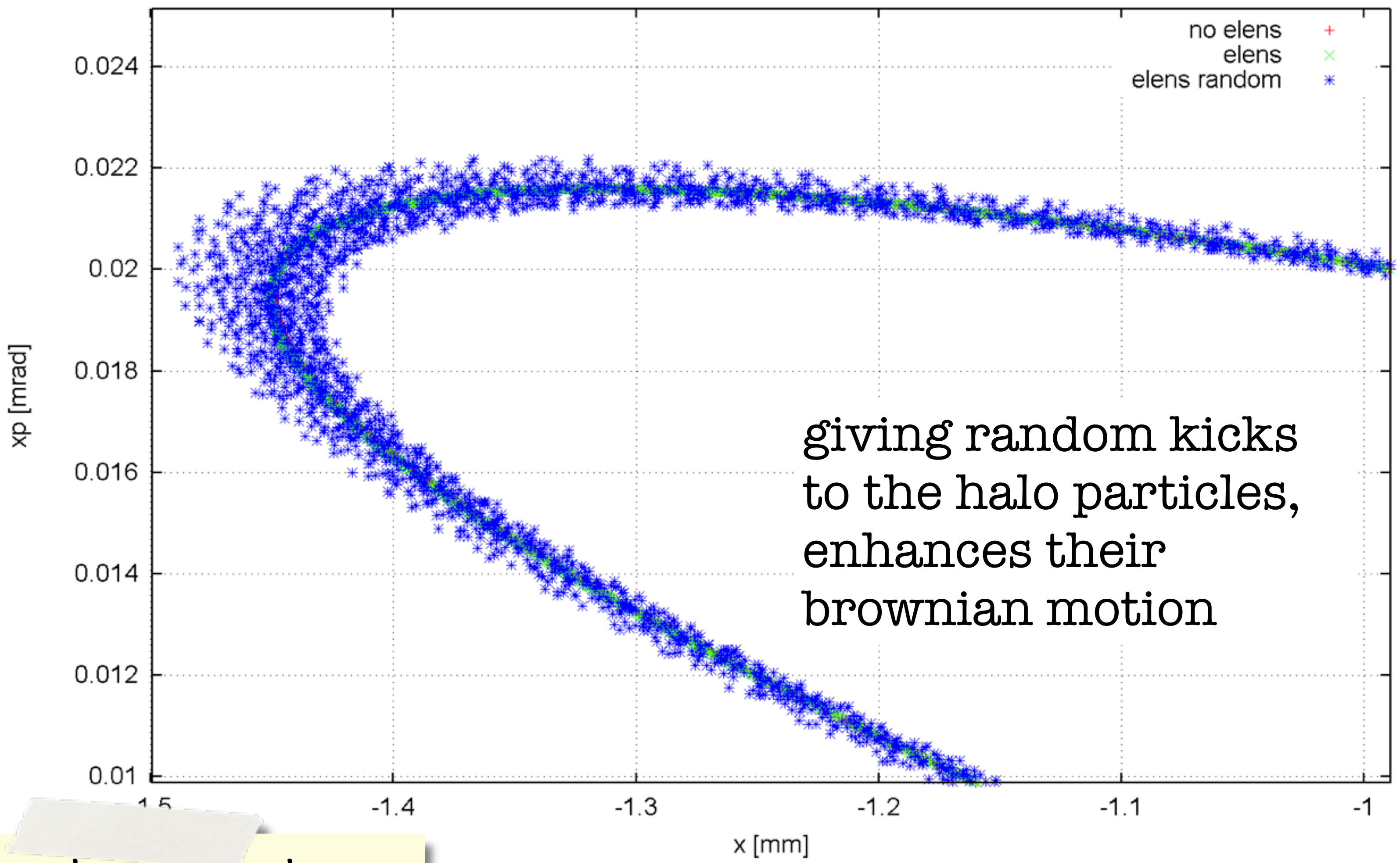
to $11\sigma_x$ in 2 sec!

initial amplitude: $5\sigma_x$



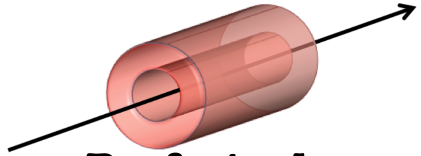
3. <u>random mode:</u> e-lens is randomly switched on-off turn by turn





random mode increases diffusion.

4 basic recipes



Perfect e-lens, linear machine

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which mode for what?

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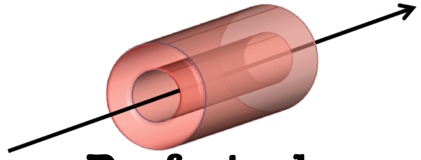

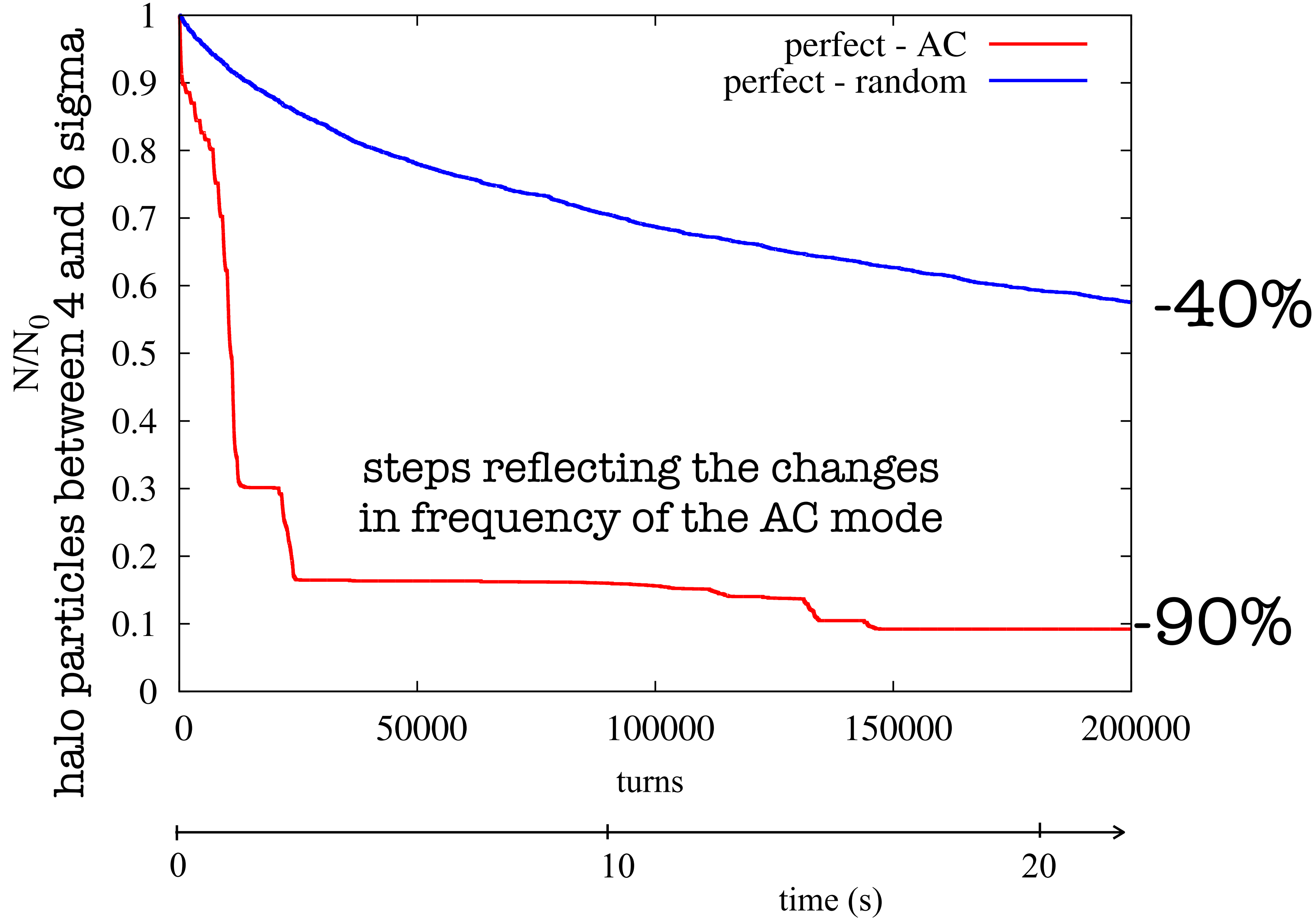

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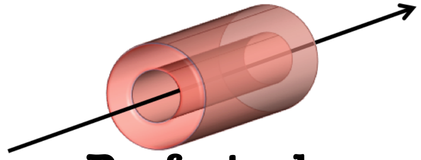

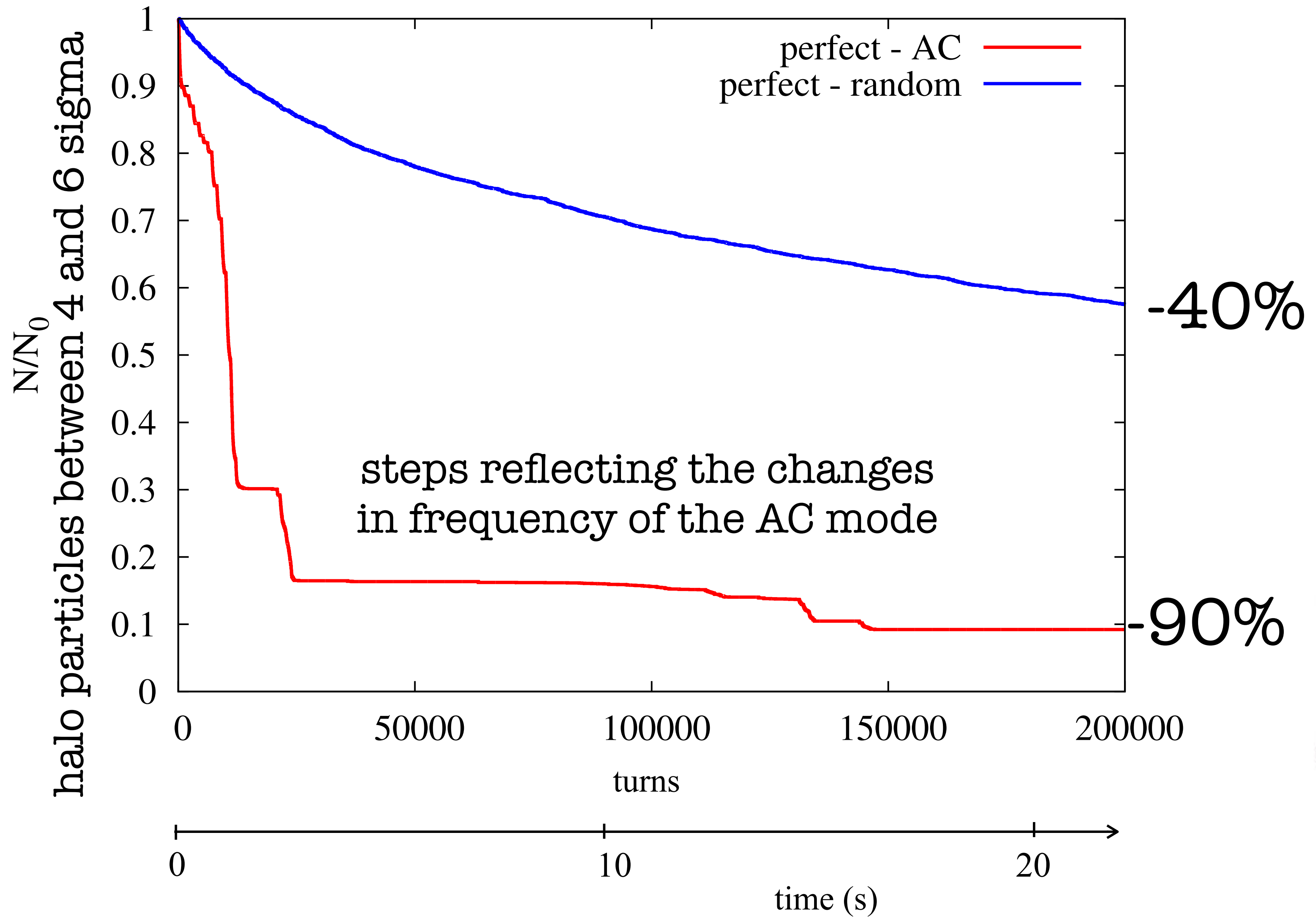

(unfortunately?)
Real life is complicated...

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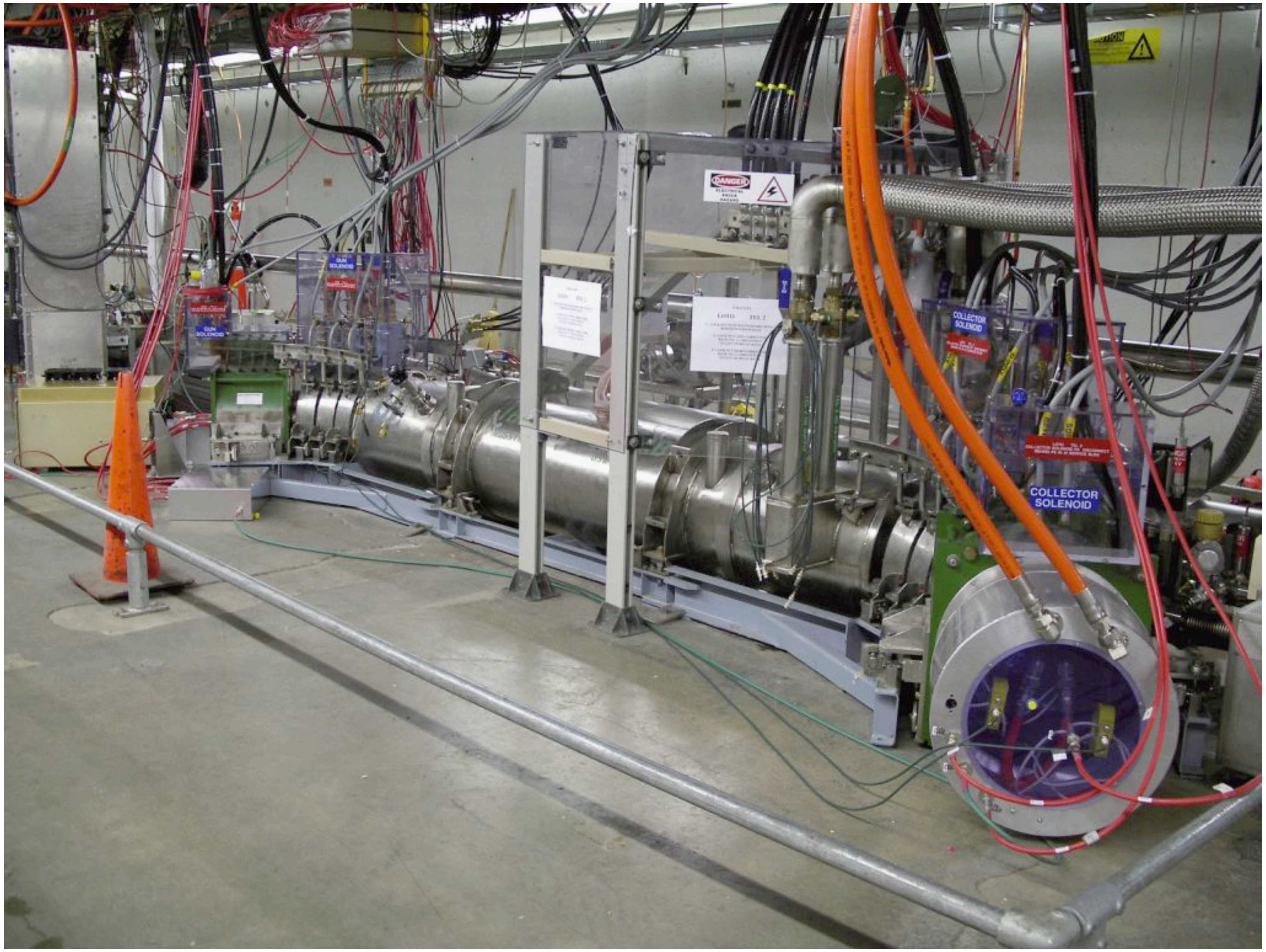
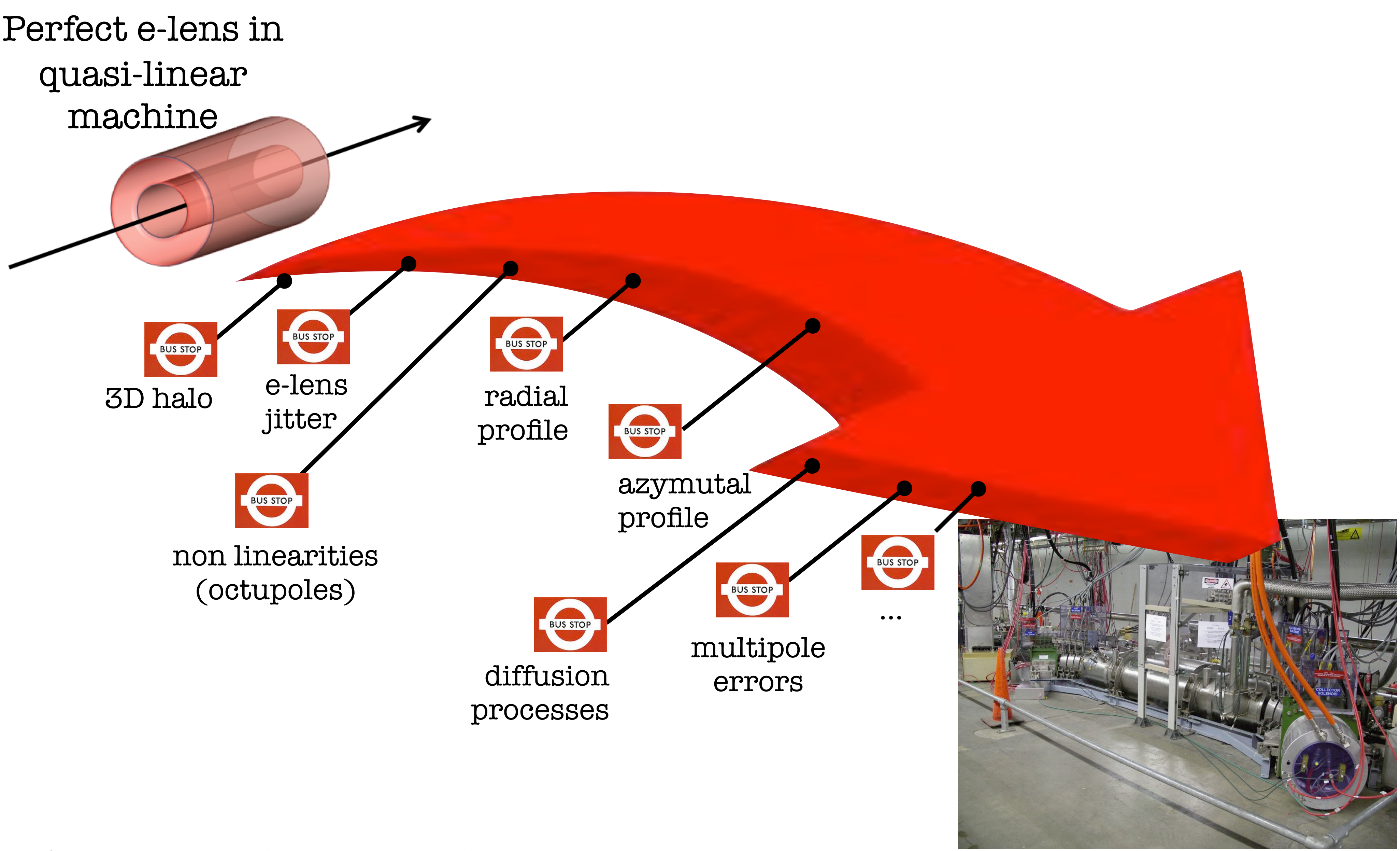
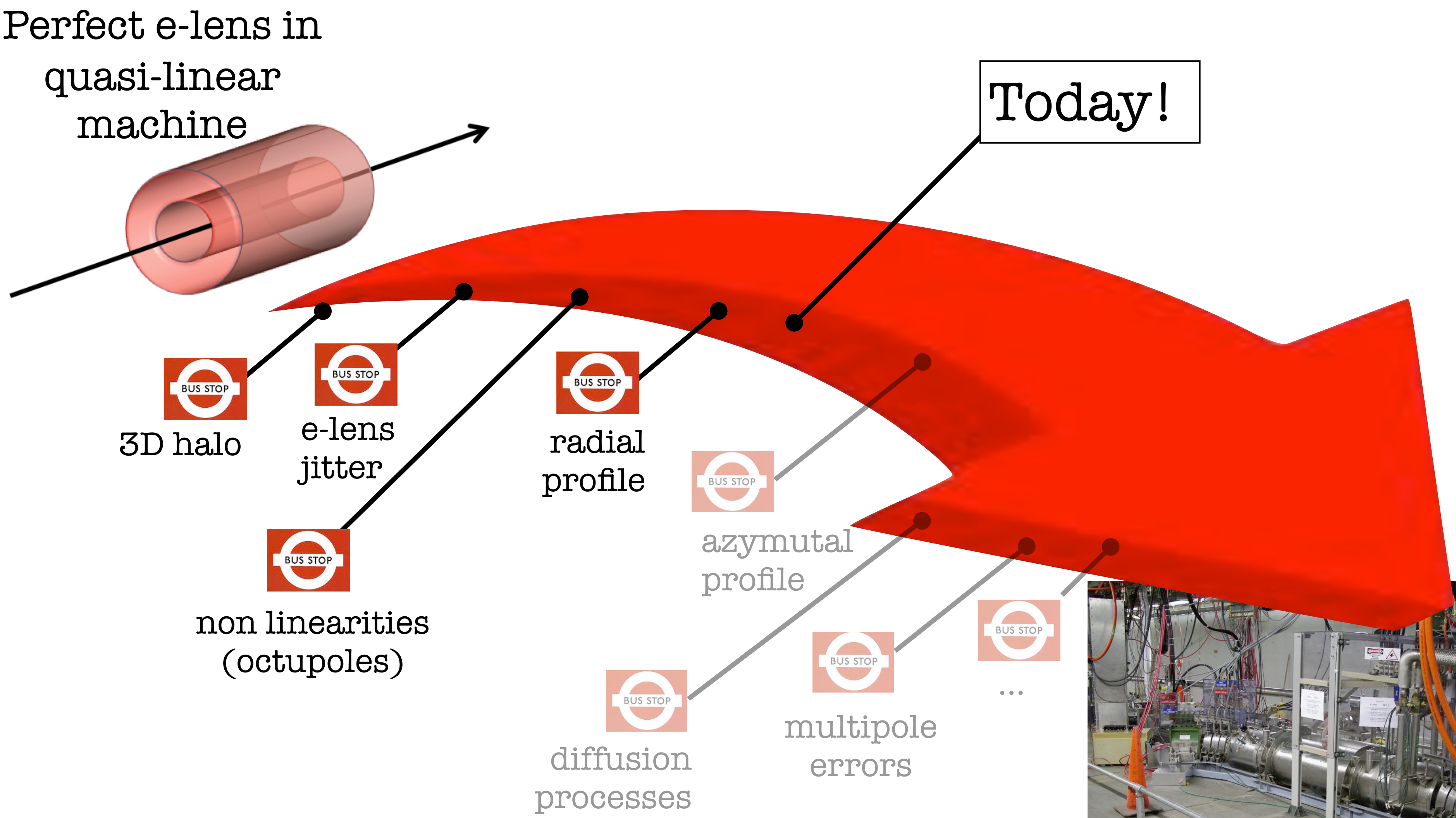
Real life is complicated...

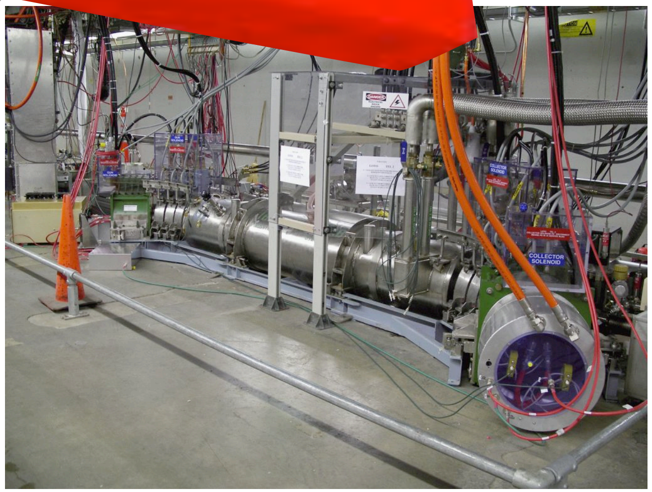




Real e-lens in real machine

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





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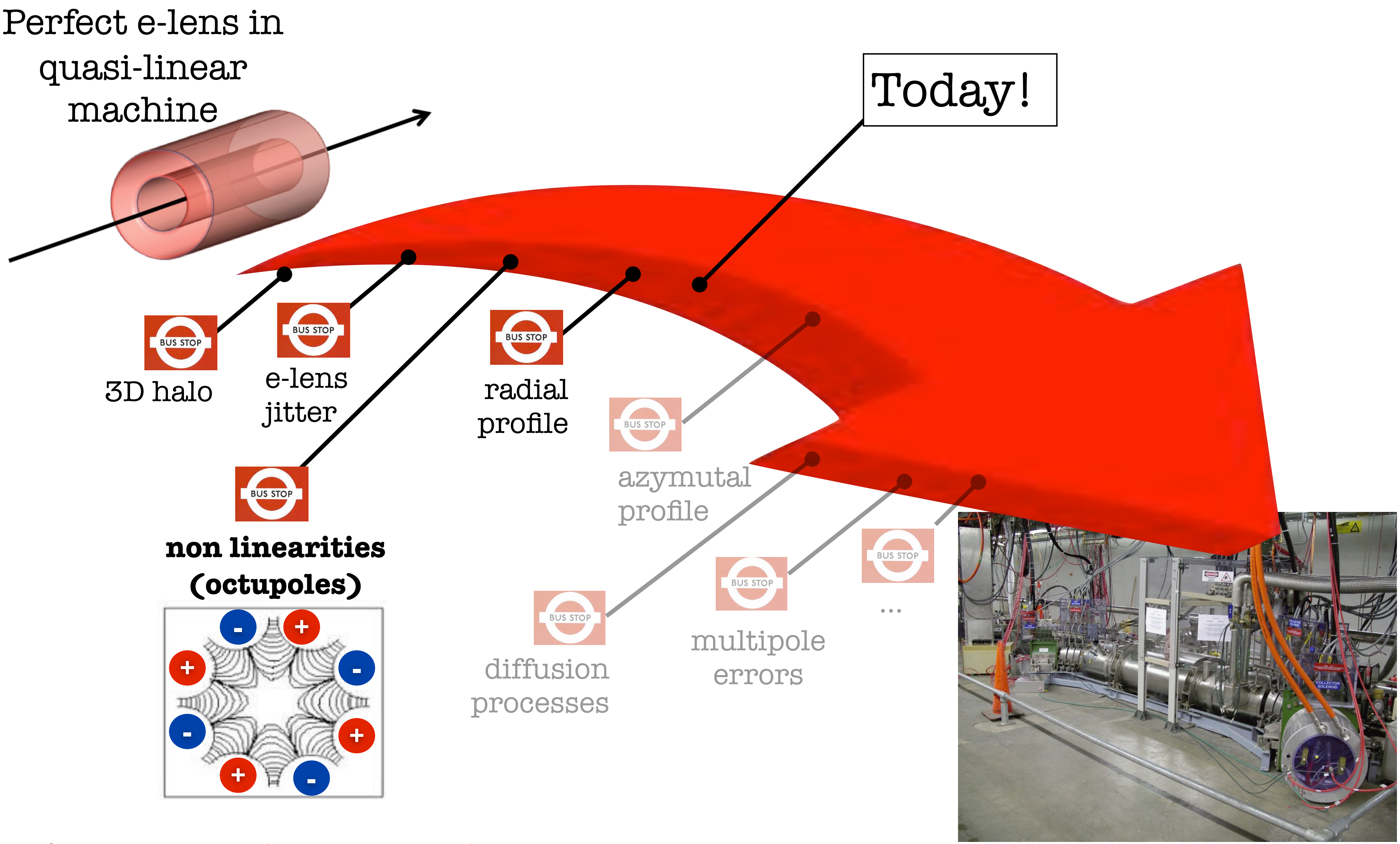

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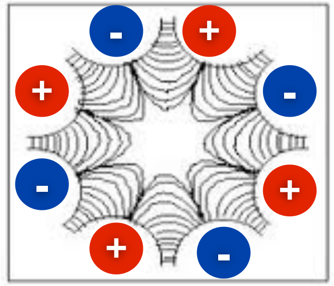
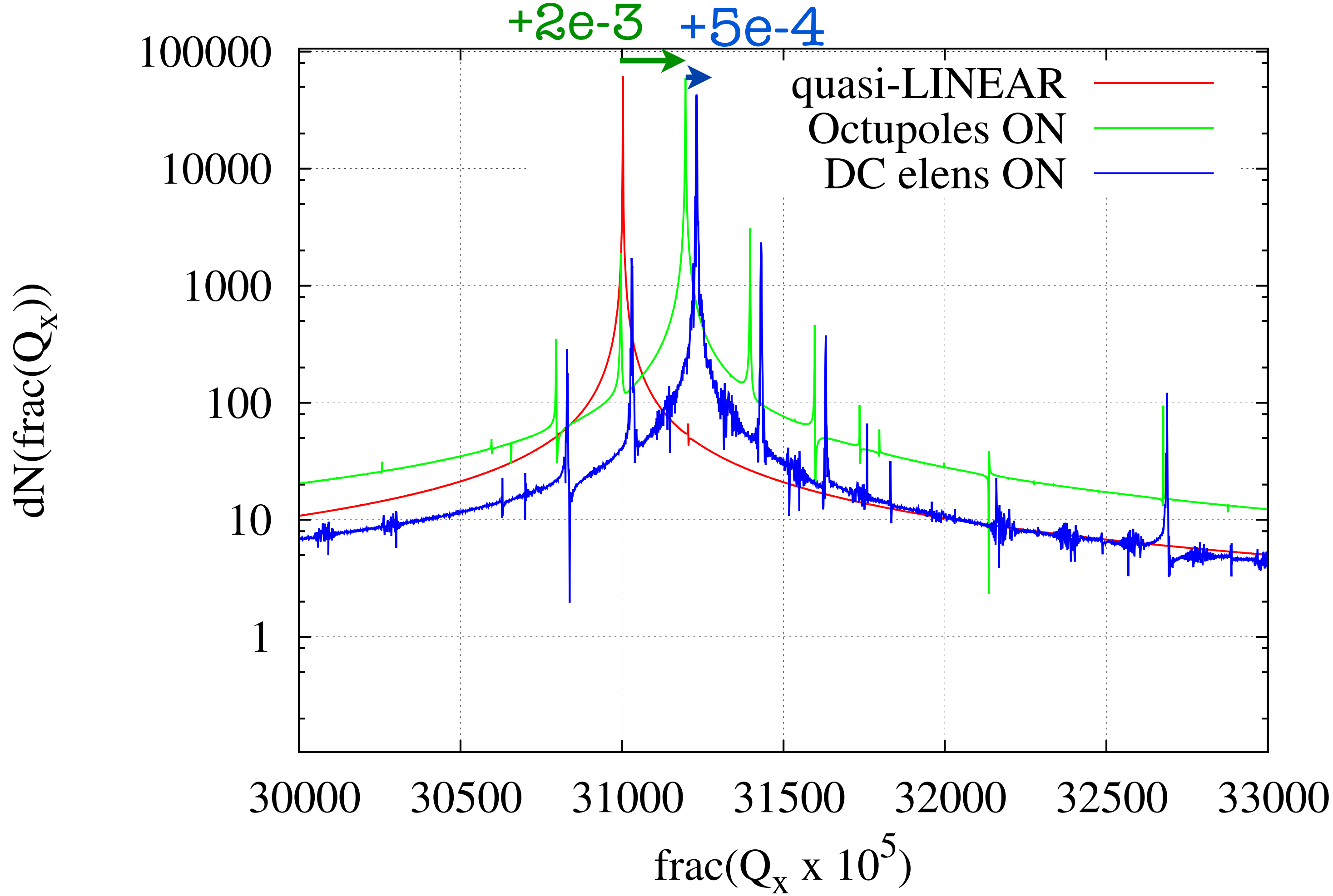
non linearities (octupoles)



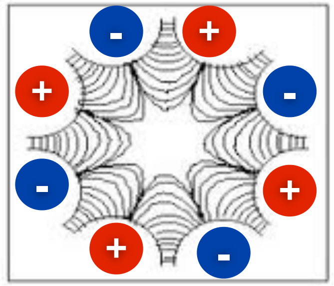


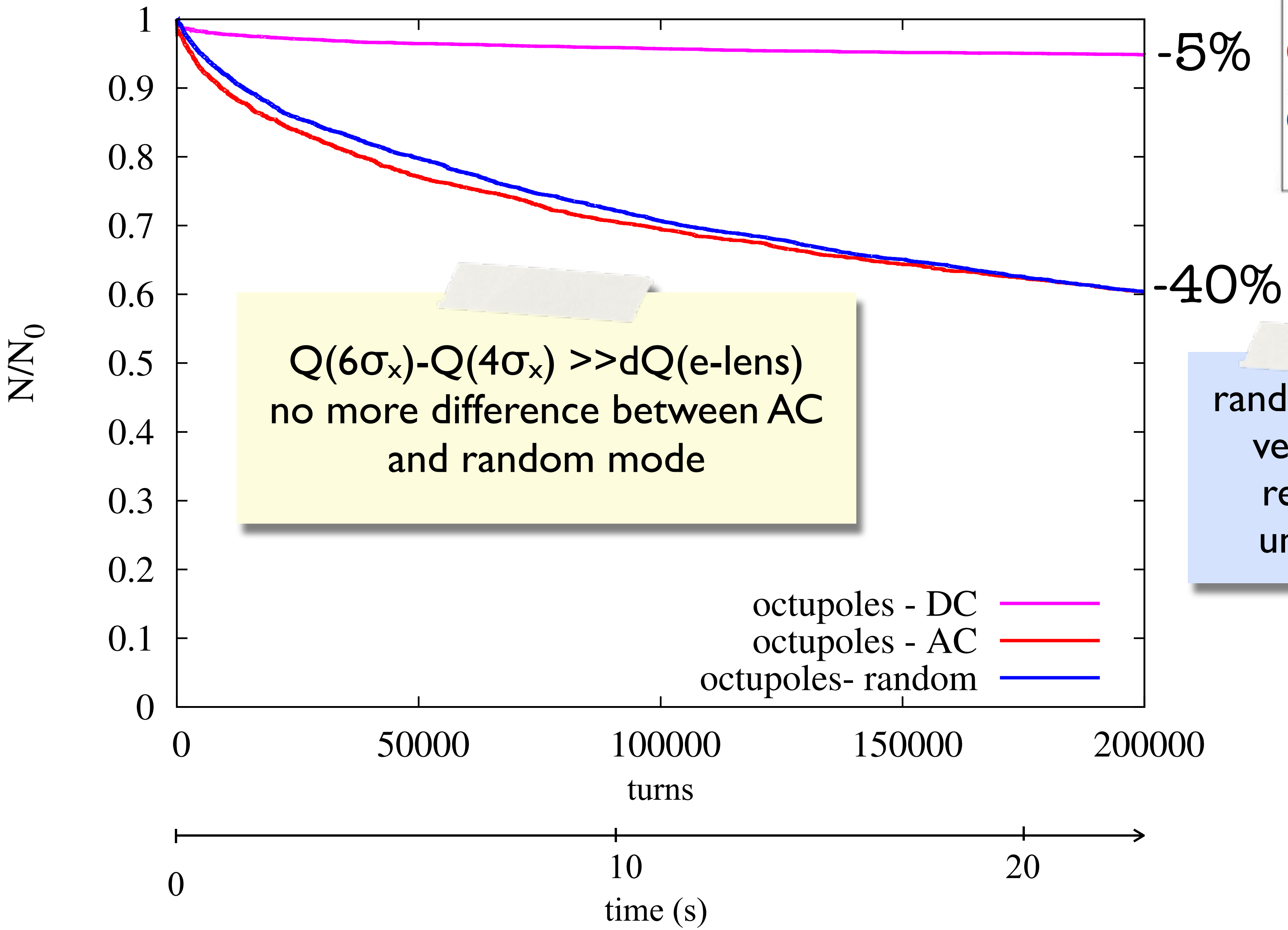
$Q(6\sigma_x)-Q(4\sigma_x) \sim 1.5e\text{-}3$

$dQ(\text{e-lens}) \sim 5e\text{-}4$

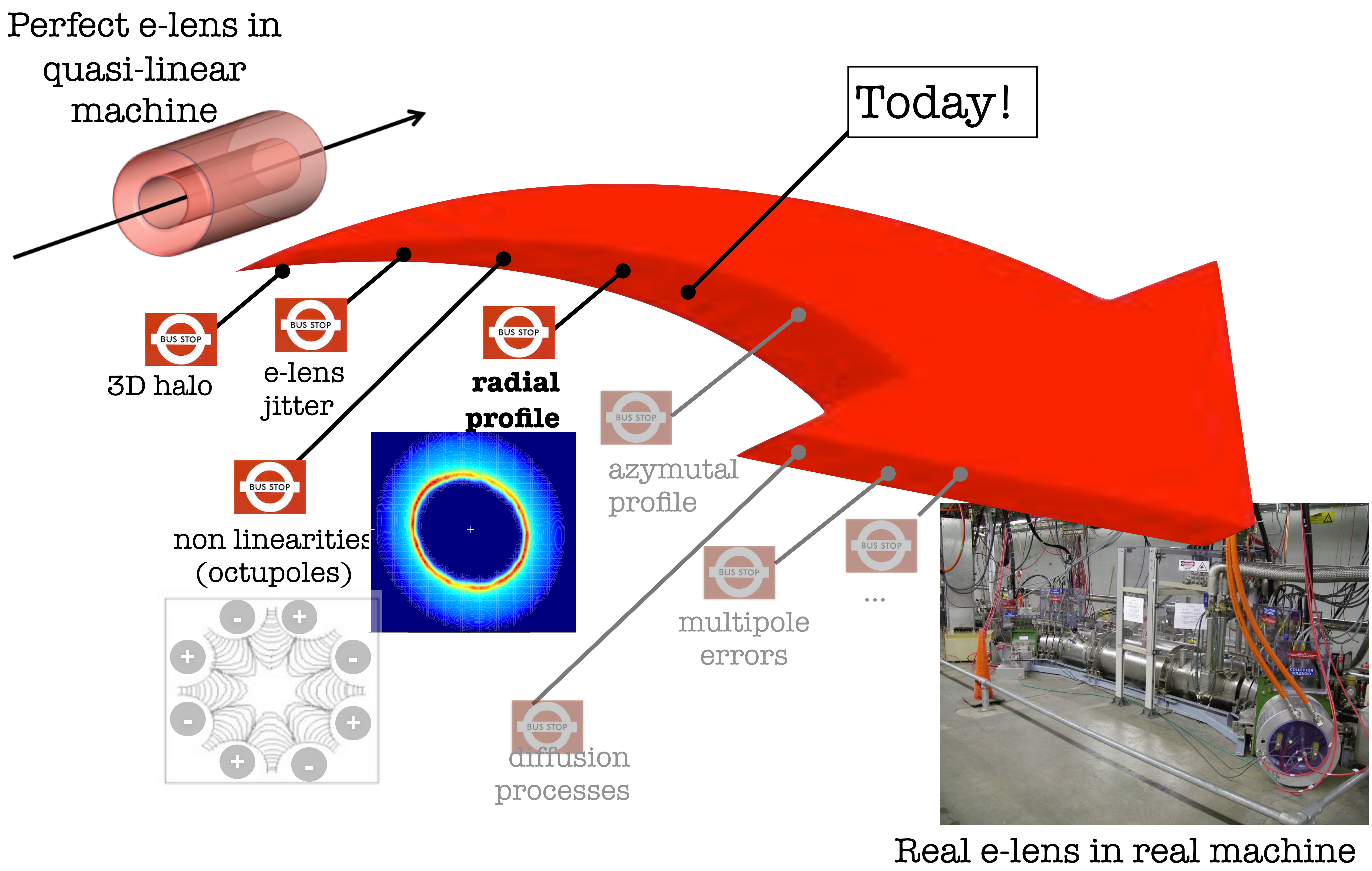
DC mode start to act as a smooth scraper

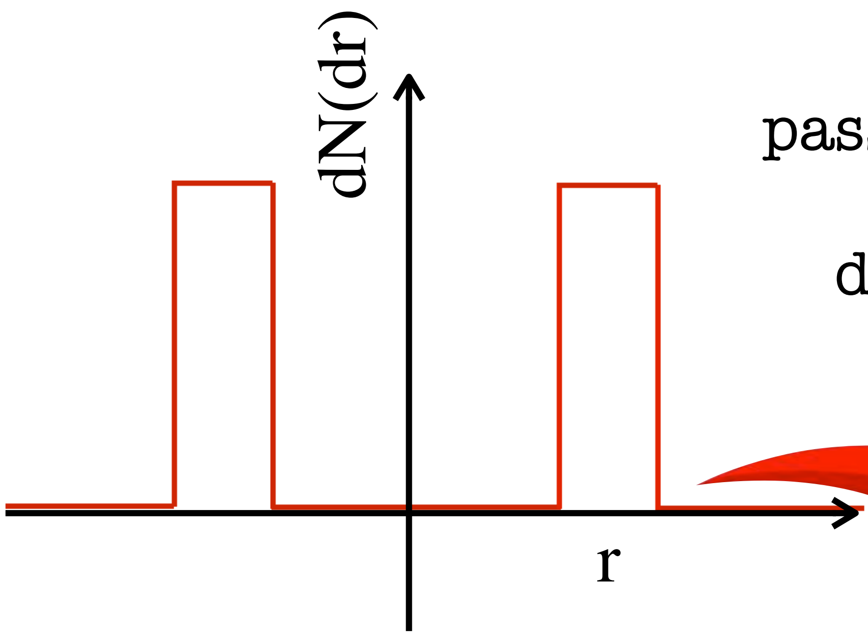
non linearities (octupoles)





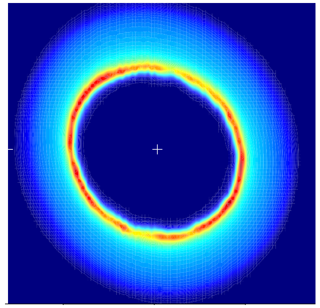
random mode is very robust results are unchanged.


Perfect e-lens in quasi-linear machine
Today!
BUS STOP
3D halo
BUS STOP
e-lens jitter
BUS STOP
radial profile
BUS STOP
non linearities (octupoles)
BUS STOP
azymutal profile
BUS STOP
multipole errors
BUS STOP
...
BUS STOP
diffusion processes
Real e-lens in real machine

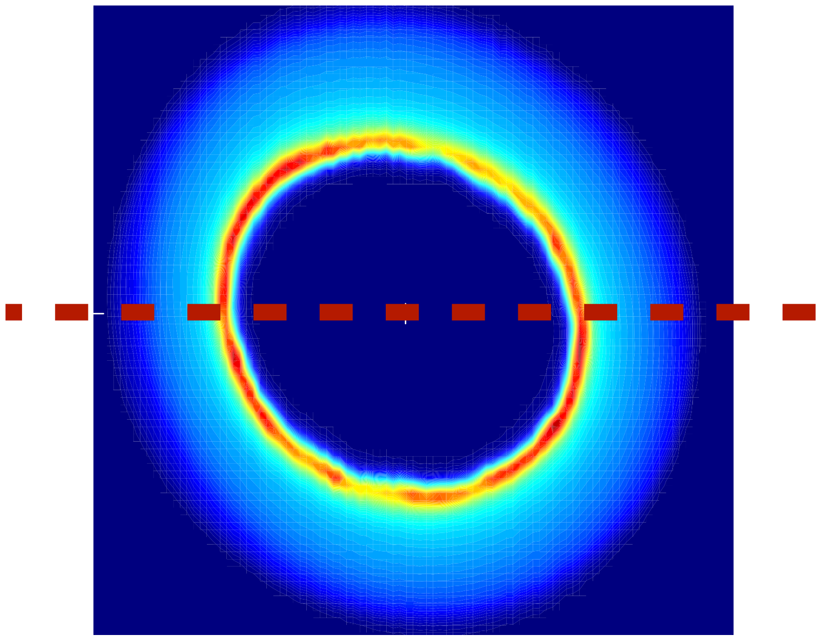


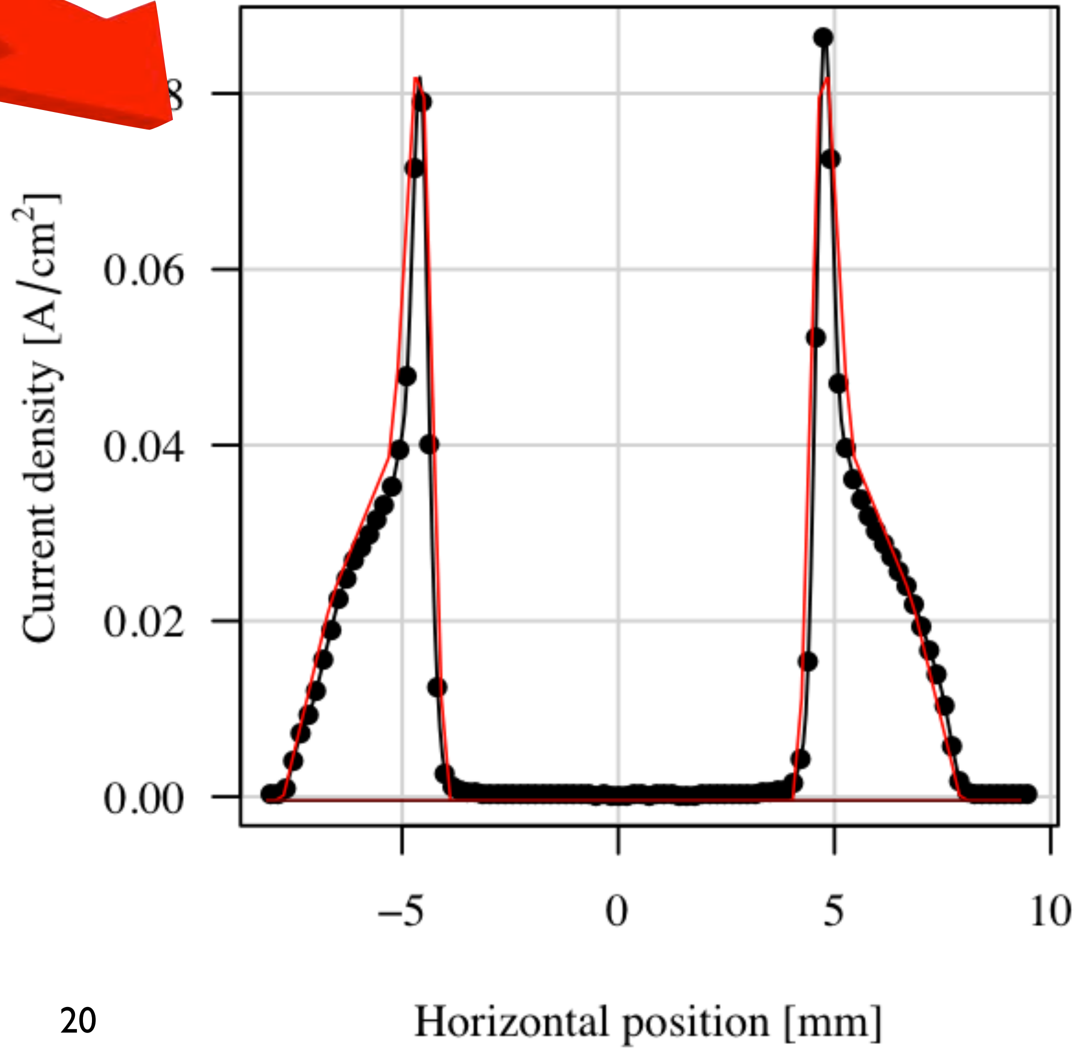
passing from a flat current distribution...

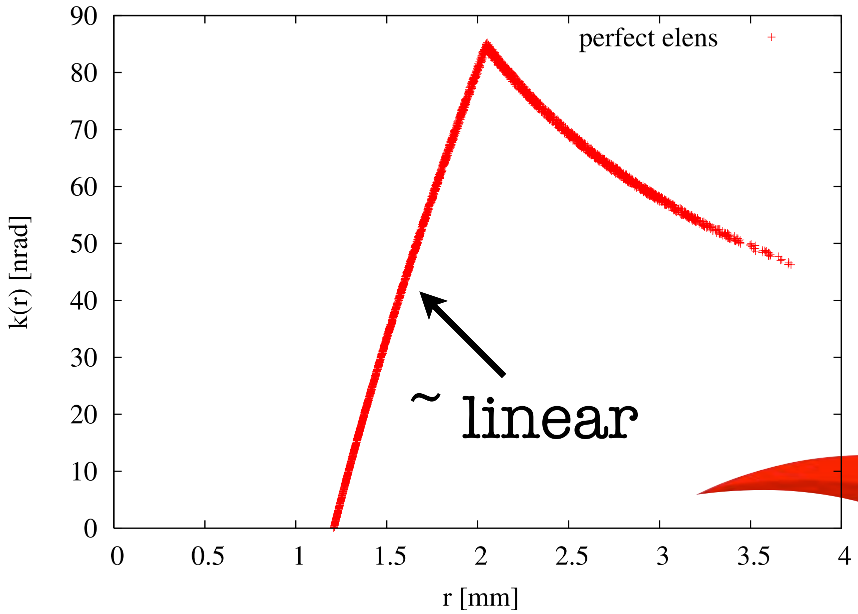
radial profile



...to a more realistic distribution

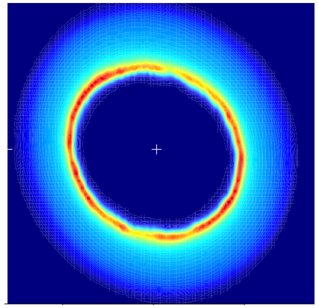






effect on the electric field

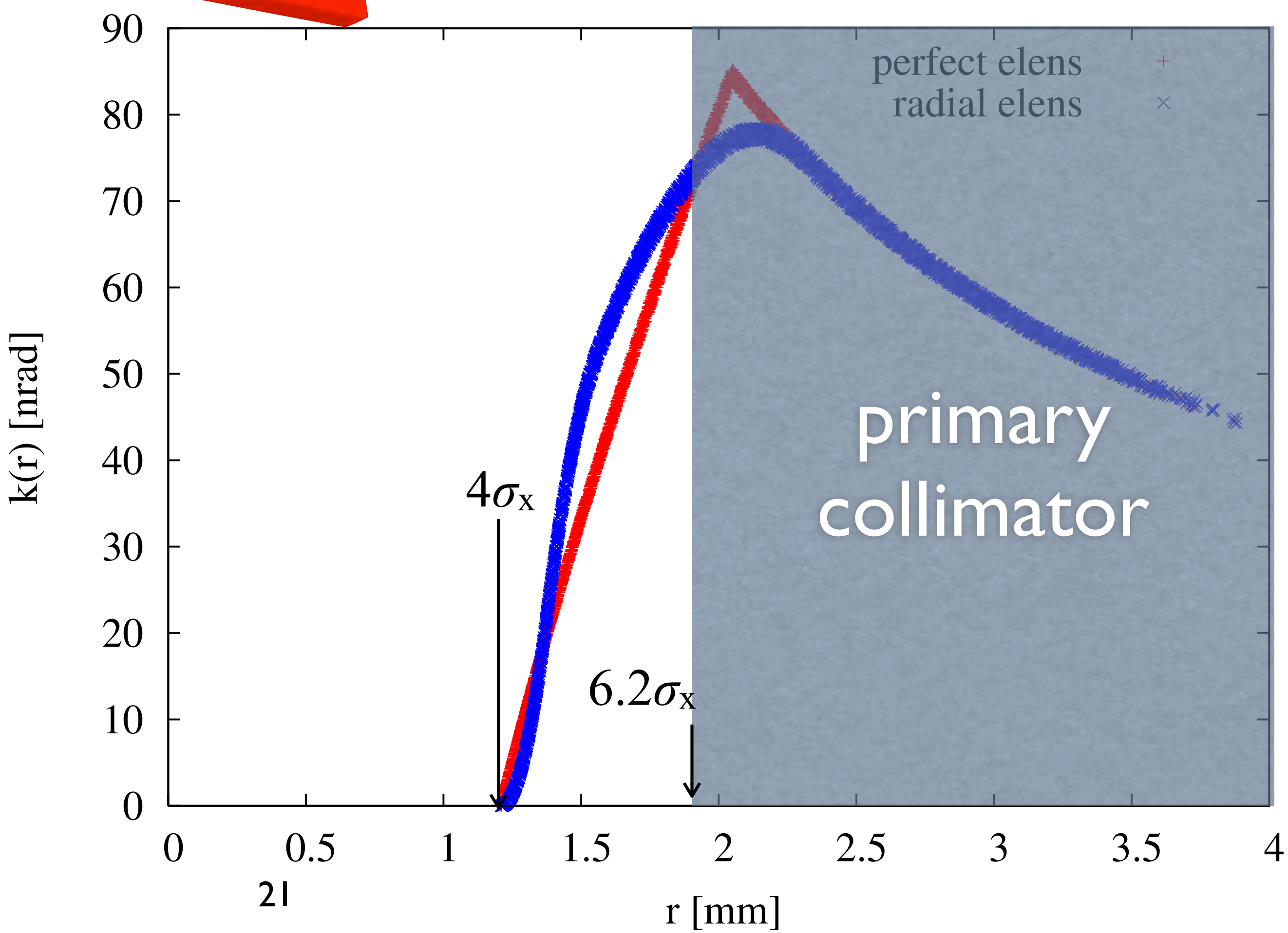
radial profile



The effect on the integrated function is less evident.

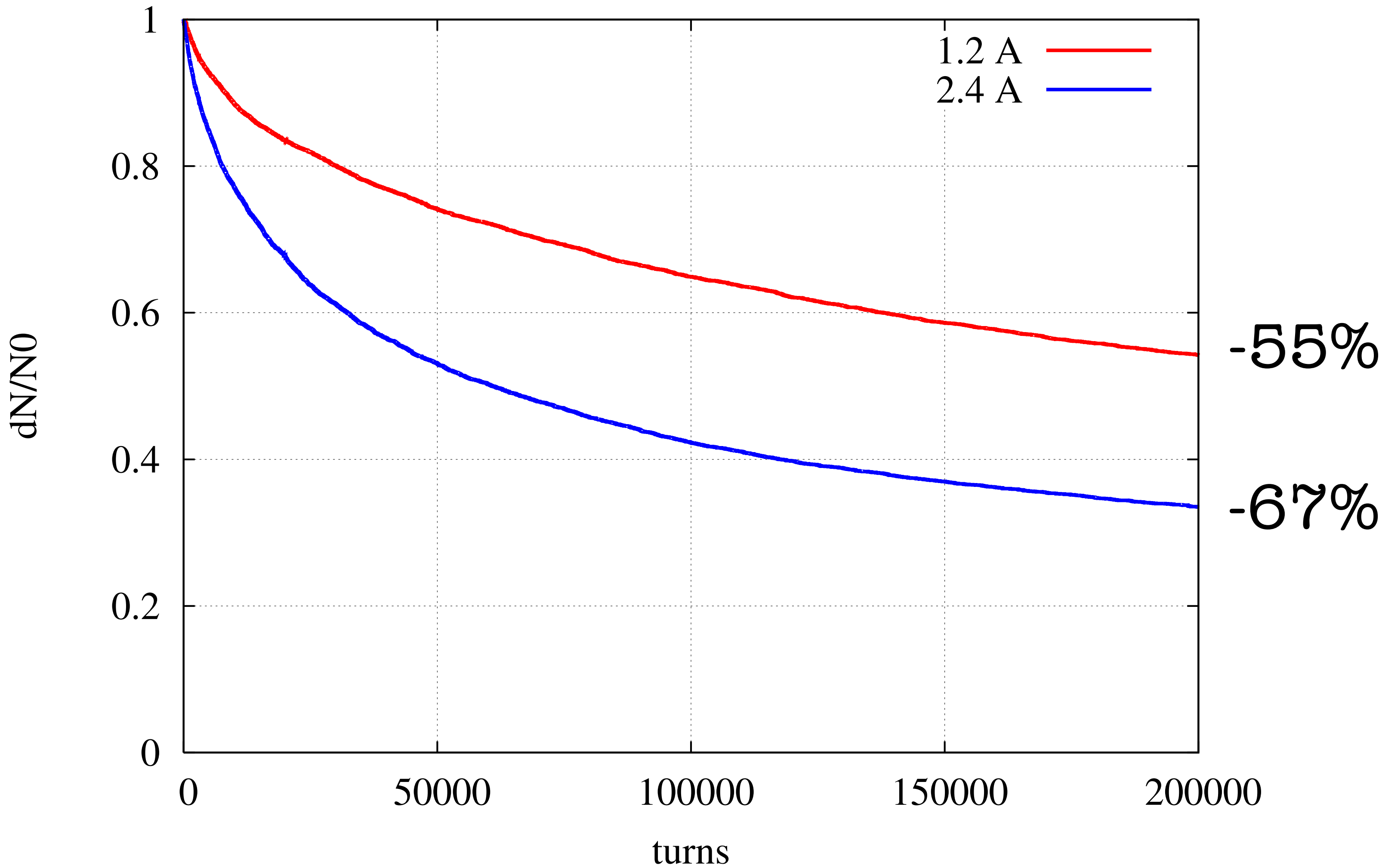
We get slightly larger kicks in the region between 4 and 6 sigma.

An improvement of cleaning of about 10% is achieved for random and AC mode



can we tune the speed?

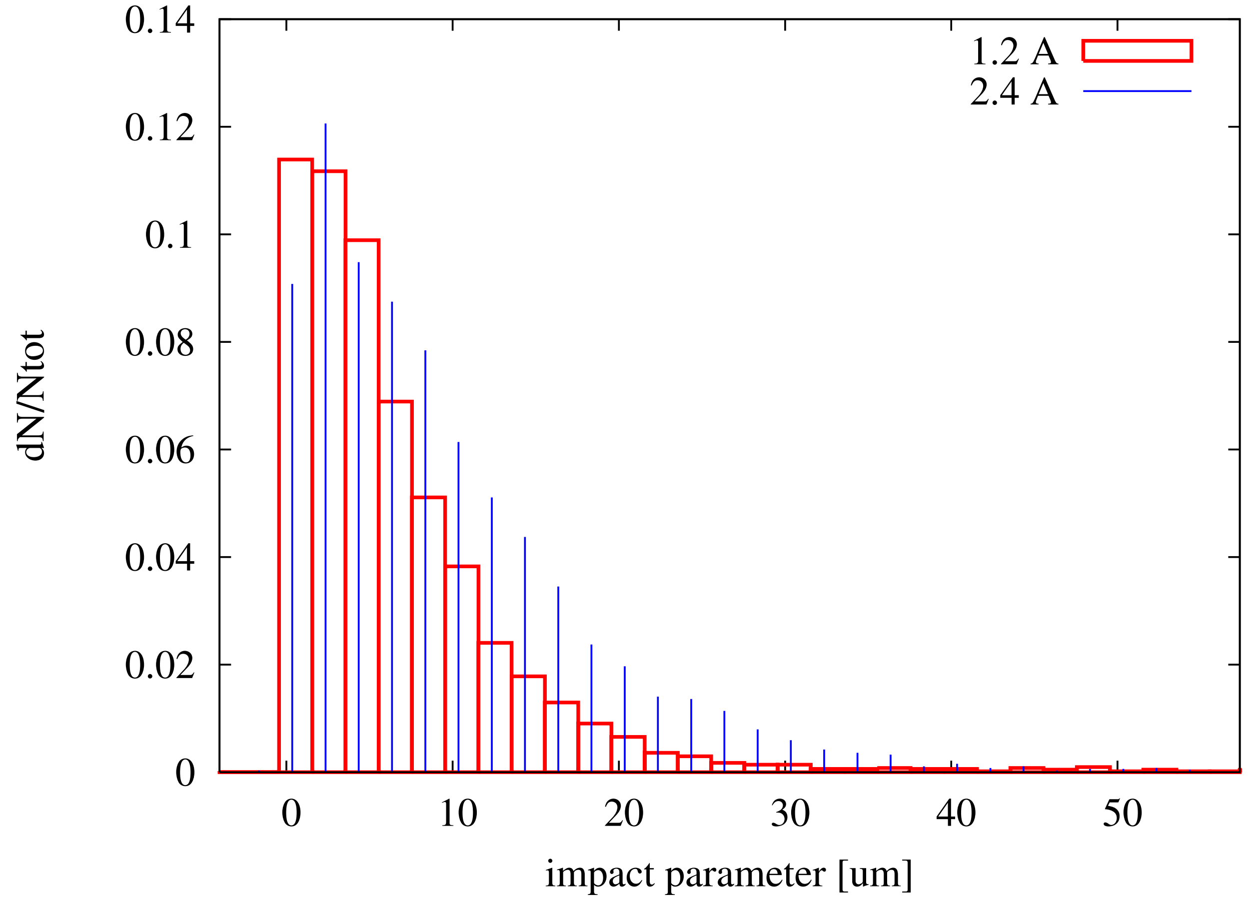
a current of 1.2 A is a conservative estimate. With the new cathode (ready) for the LHC we can easily reach higher values.



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?

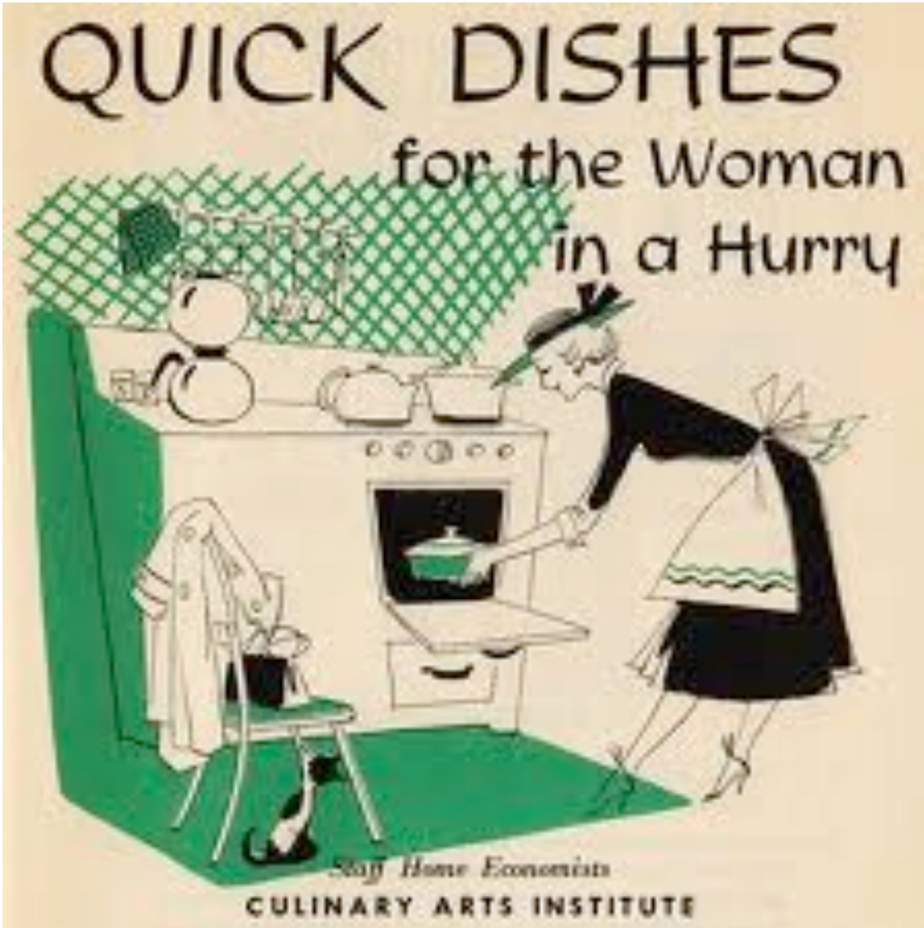
what happens to the scraped particles?



impact parameter on primary collimator.

the impact on primary collimator is about <u>10 times larger than the usual assumed values</u>. 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...



Long story short...

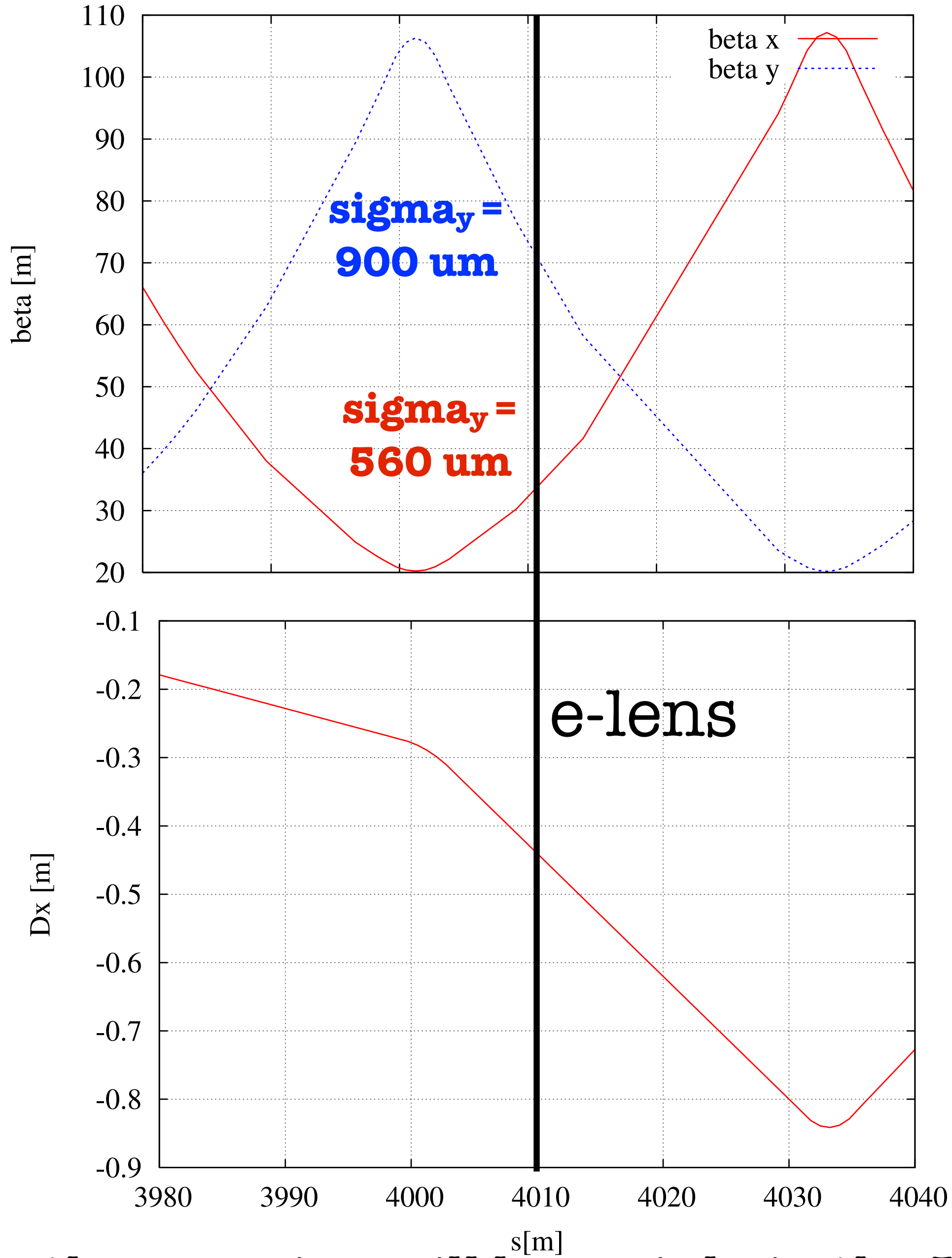
- The simulation of e-lens is an on-going work, however few important statements can be already done:
  - among the possible e-lens usage, the **random mode** seems to be the most robust and efficient for **fast scraping**
  - With relatively achievable e-lens currents, **more than 65% of the halo particles 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?

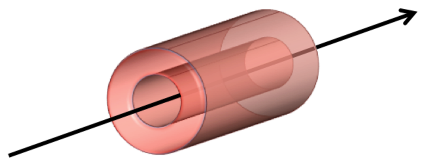
CONS	PROS
• coast of 270 GeV (~1/4 of Tevatron energy) • Less instrumentation	✓SPS is more similar to the LHC than Tevatron (proton machine, same LHC working point, weakly coupled...) ✓ reproduce Tevatron results at CERN ✓validate simulation results ✓acquiring experience with the object (cryogenics, 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 sigma$_y$** VERT
scraping at **4.7 sigma$_x$** HOR

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

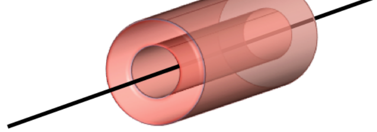


Perfect e-lens, linear machine

the scraping will be mainly in the Vertical plane. Nowadays the LHC-type collimator is oriented in the horizontal plane.

CONS	PROS
• 1/4 of the TeV energy • Less instrumentation • Optimal layout would require a vertical collimator	✓ SPS is more similar to the LHC than Tevatron (protons, 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

a shift of 5 m would be already enough to solve the issue - and the space is available (see integration talk - Adriana)



Perfect e-lens, linear machine

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

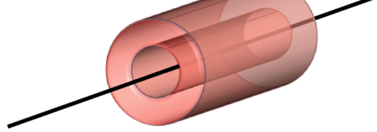
$$f(r) = \begin{cases} 0 & r < R_1 \\ \frac{r^2 - R_1^2}{R_2^2 - R_1^2} & R_1 < r < R_2 \\ 1 & r > R2 \end{cases}$$

maximum kick for SPS case ~ 1urad (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)

DC	AC	random
0%	(90% in 20 sec for the LHC) 91%	(42% in 20 sec for the LHC) 35%



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to be verified with non linearities

Removal rates in 20 seconds 76%

CONS	PROS
• 1/4 of the TeV energy • Less instrumentation • Optimal layout would require a vertical collimator	✓ SPS is more similar to the LHC than Tevatron (protons, 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 ✓ The e-lens operation is identical to the LHC case, the timescale of the effects is only a factor 4 different

a shift of 5 m would be already enough to solve the issue - and the space is available (see Adriana)

all prototypes for the LHC collimation system have been tested in SPS: experience has been always precious

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

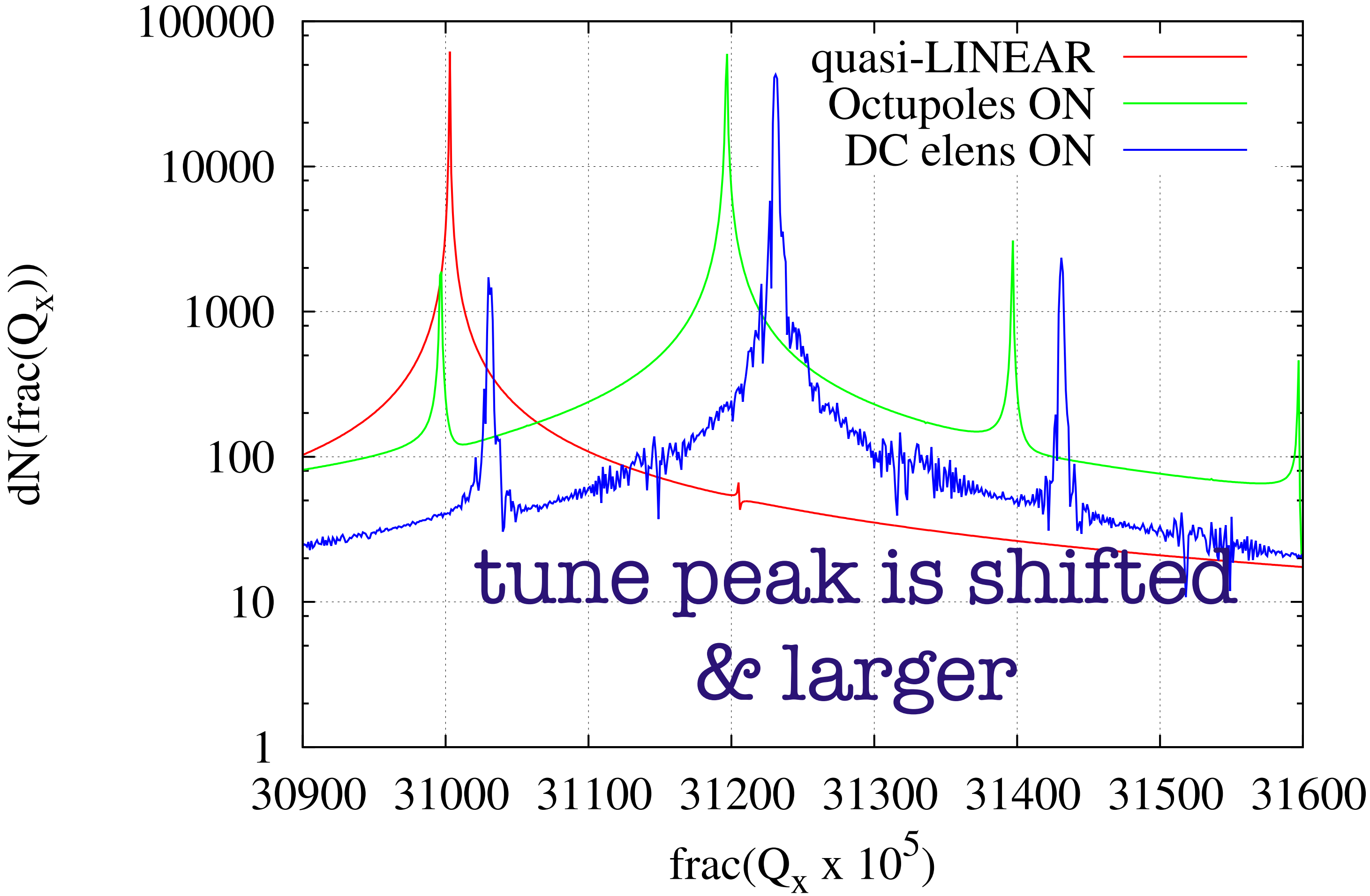
e-lens in the SPS?

summary

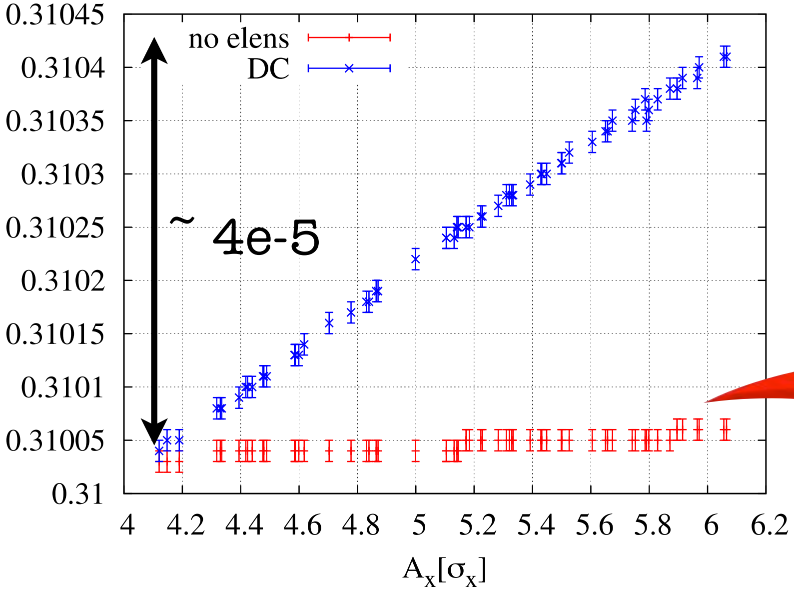
- SPS has been simulated with Sixtrack, using the linear machine and the perfect e-lens model
- Results for the LHC have been qualitatively confirmed in the SPS
- **From the simulations at 270 GeV it is clear that the current e-lens can be used for meaningful beam studies**
- The only shoe-stopper could 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.



100000
10000
1000
100
10
1
30900 31000 31100 31200 31300 31400 31500 31600
dN(frac(Q_x))
frac(Q_x x 10^5)
quasi-LINEAR
Octupoles ON
DC elens ON
tune peak is shifted
& larger

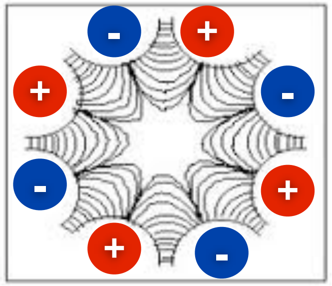


purely H halo, quasi linear machine

For each frequency there is a narrow, well defined tune

Total tune range ~ 4e-5

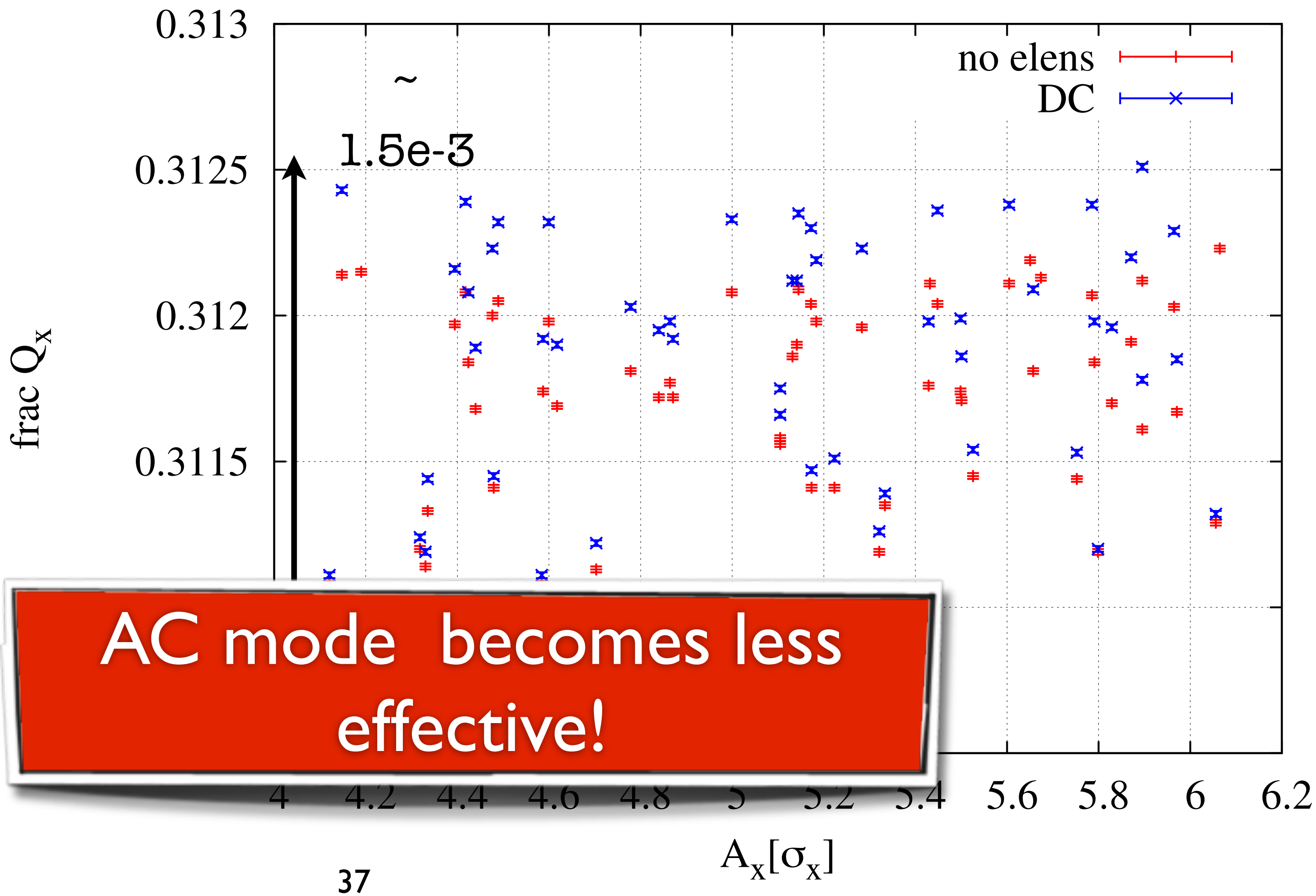
non linearities (octupoles)



3D distribution + octupoles

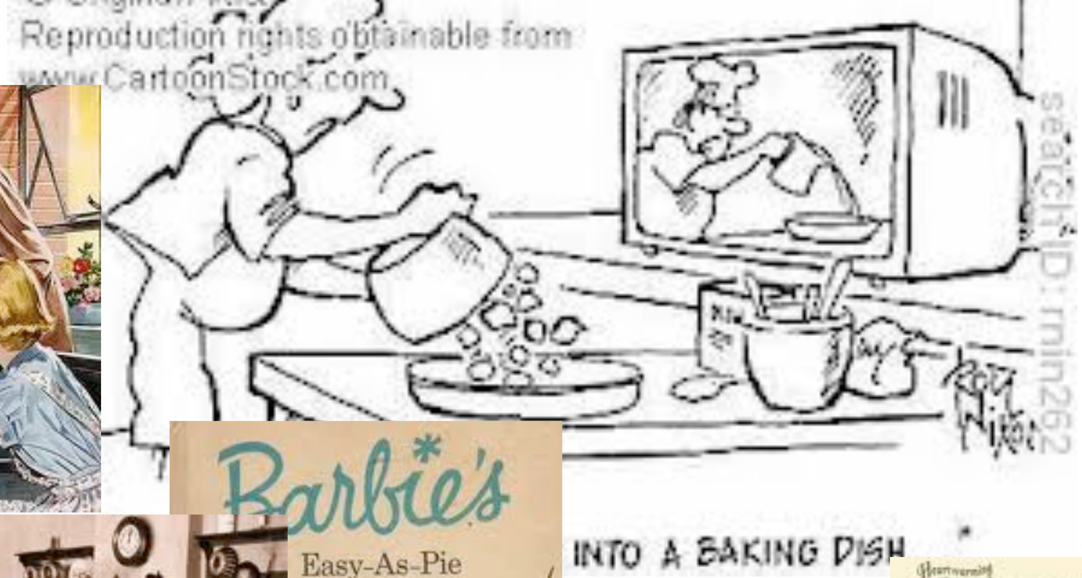
Tune peaks are larger → **difficult to keep particle in a resonance**

Total tune range ~ 1.5e-3 → **covering all the interesting tunes takes more time!**



AC mode becomes less effective!


Home Baking Made Easy
FOR BEGINNERS AND EXPERTS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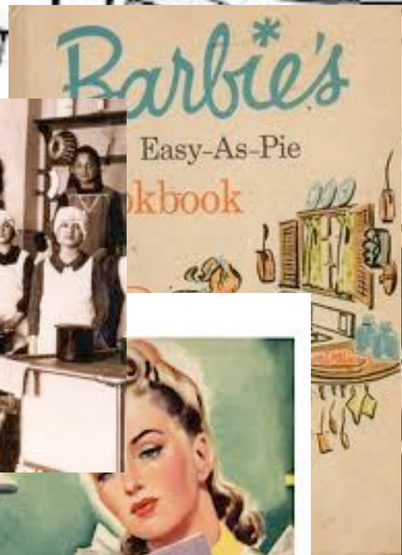
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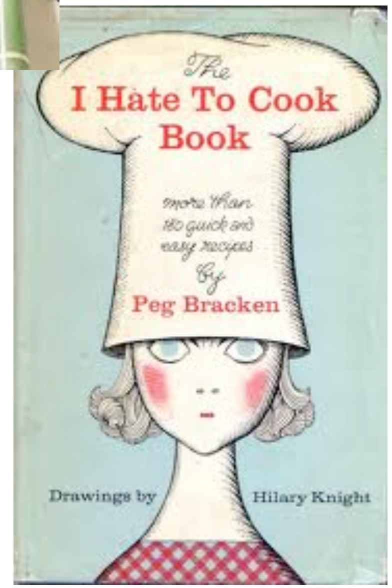
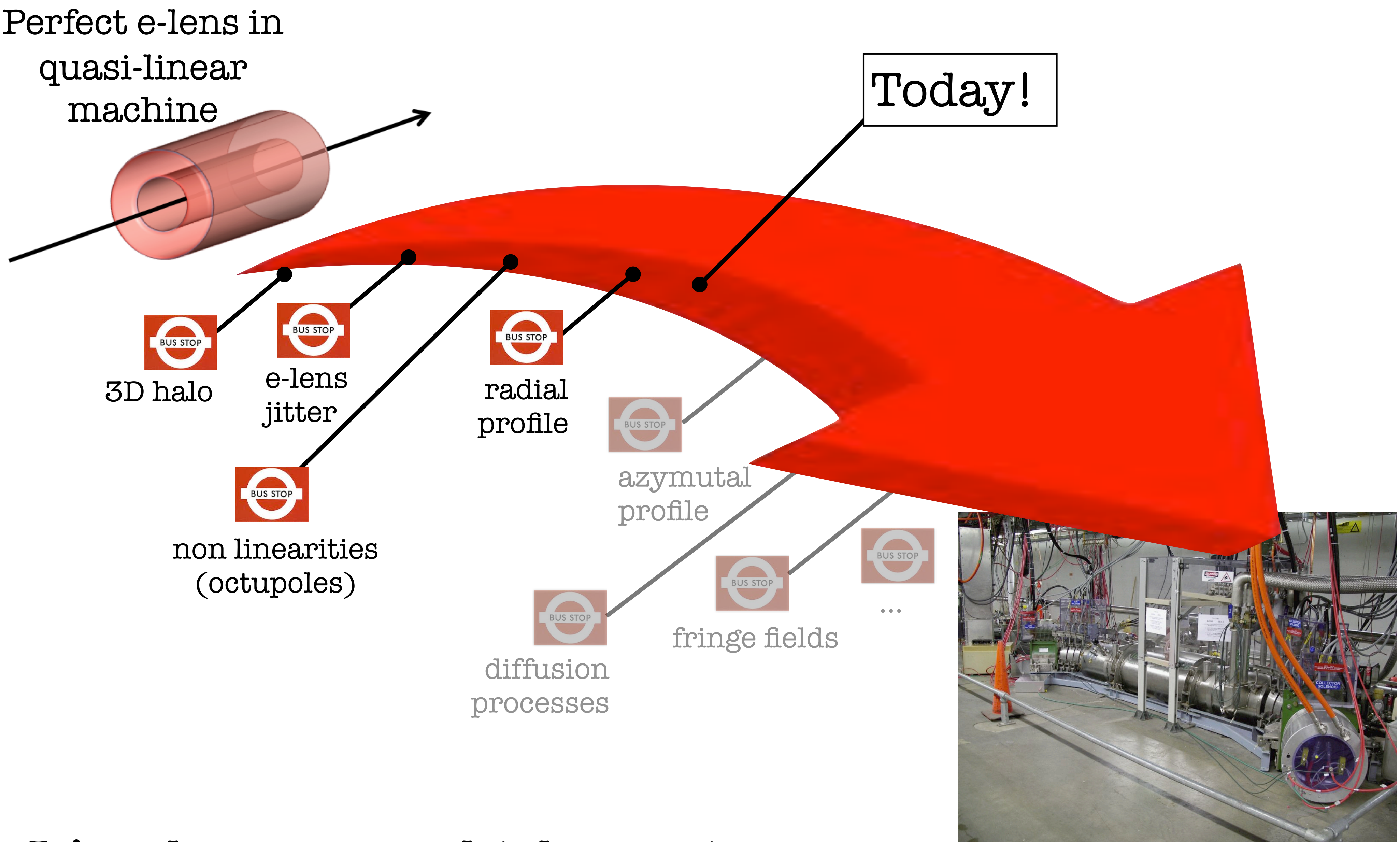
COOKING


Favorite Recipes


The
I Hate To Cook
Book
more than
180 quick and
easy recipes
by
Peg Bracken
Drawings by
Hilary Knight

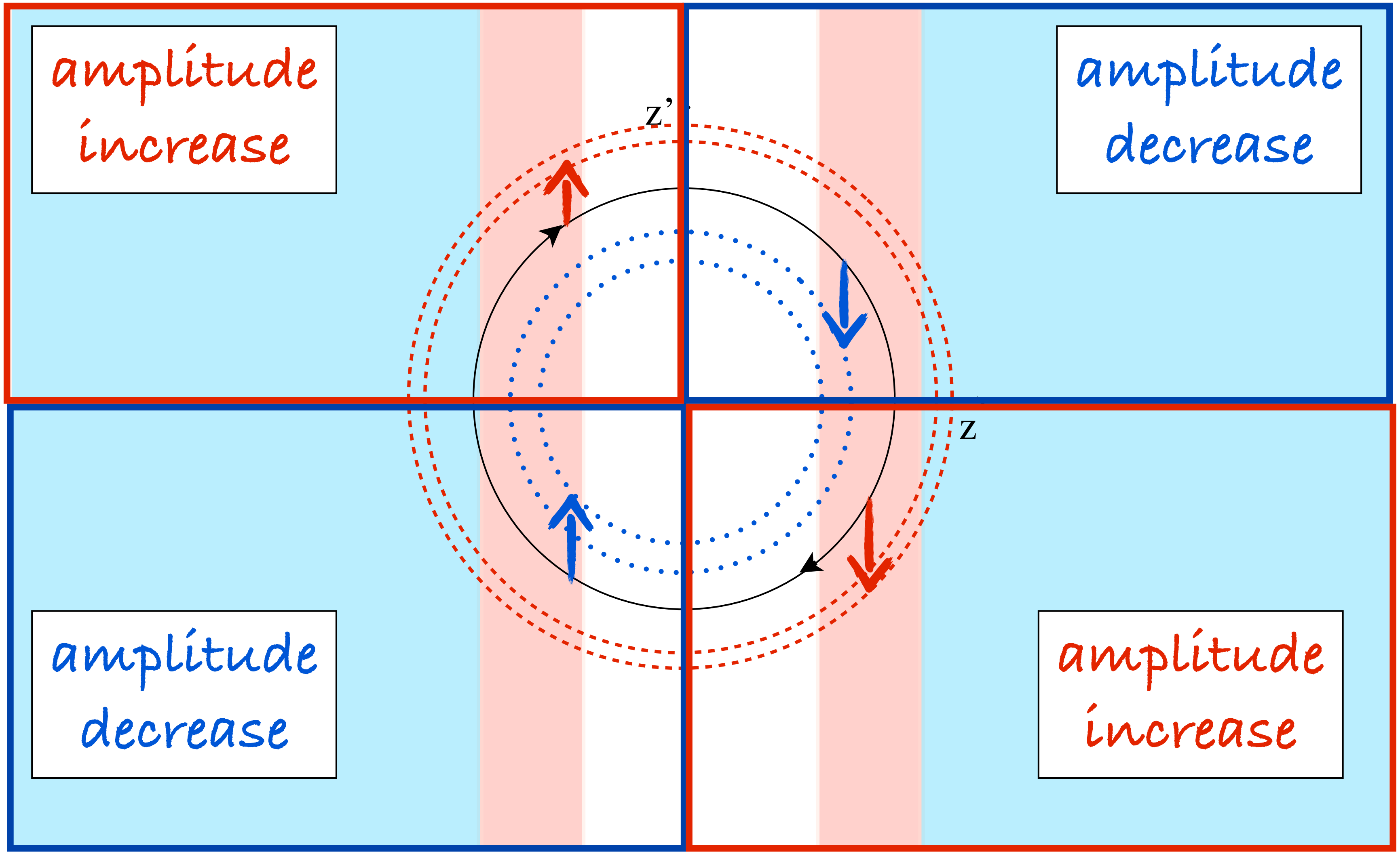

I'm really cooking!



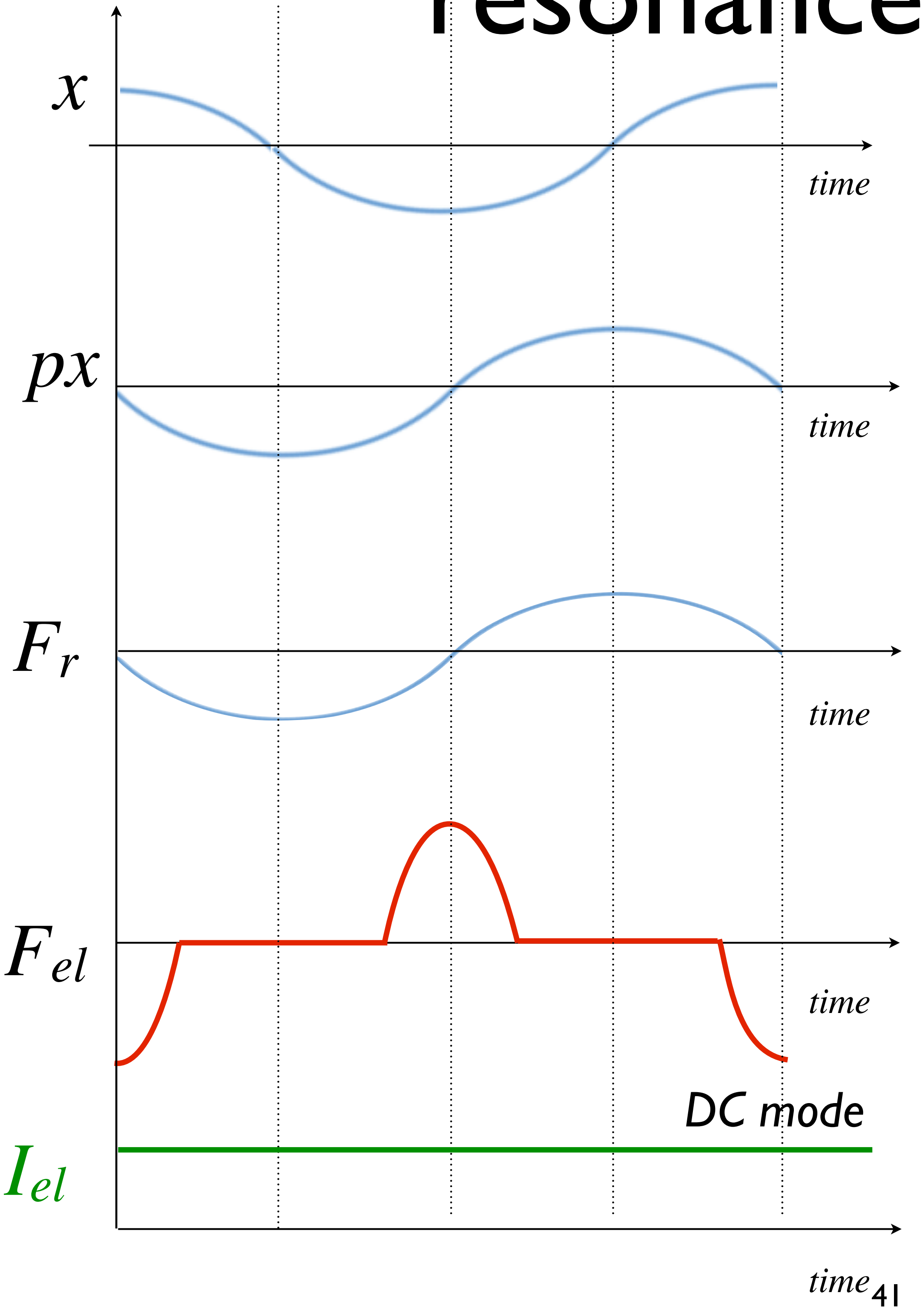
Real e-lens in real machine

It’s a long way, which requires many intermediate stops

(normalized) phase space



resonance mode

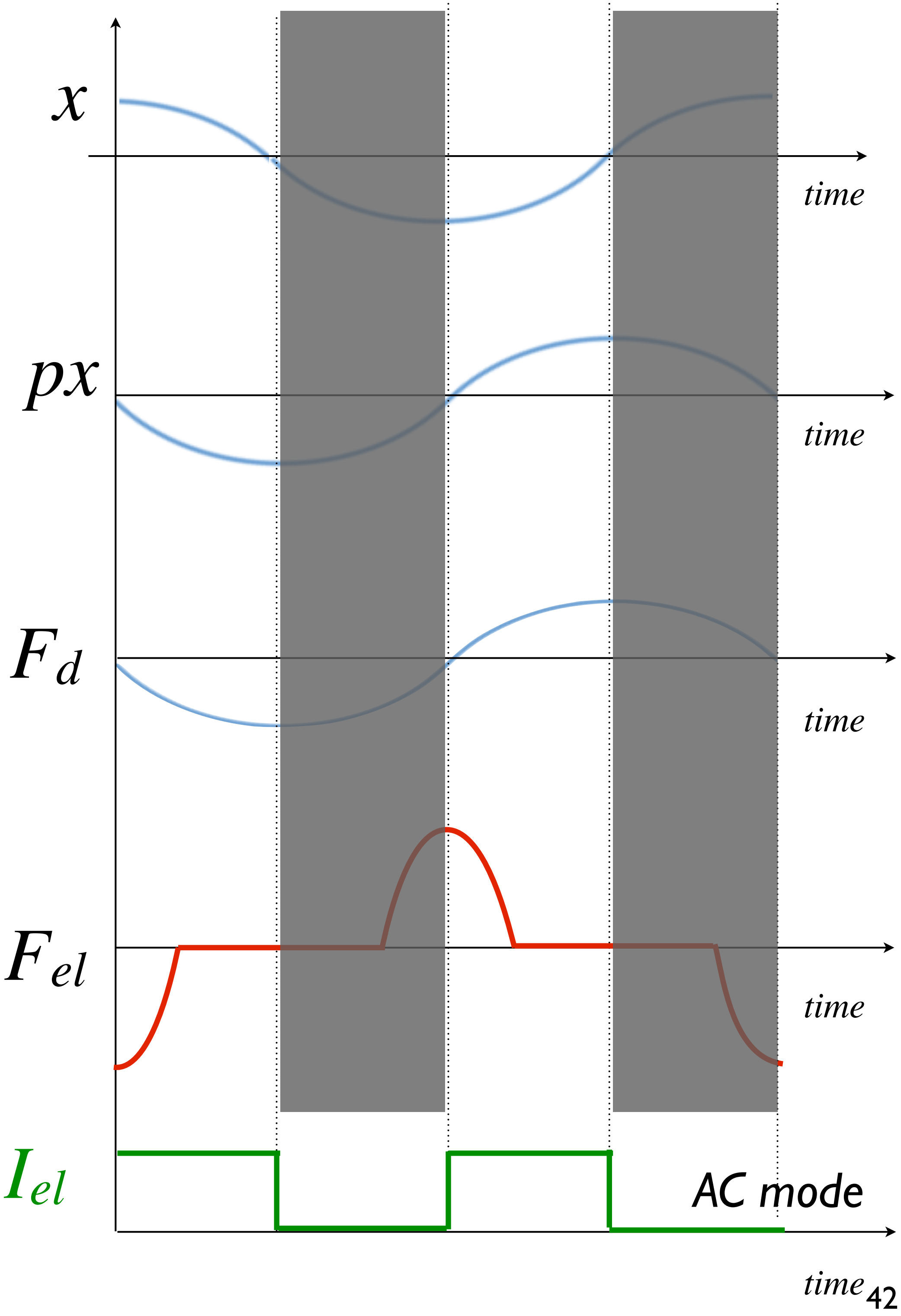


taking a particle with initial phase =0

this is its 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 => ALWAYS shifted in phase (90 degrees) with respect with the particle momentum



taking a particle with initial phase =0

this is its its momentum

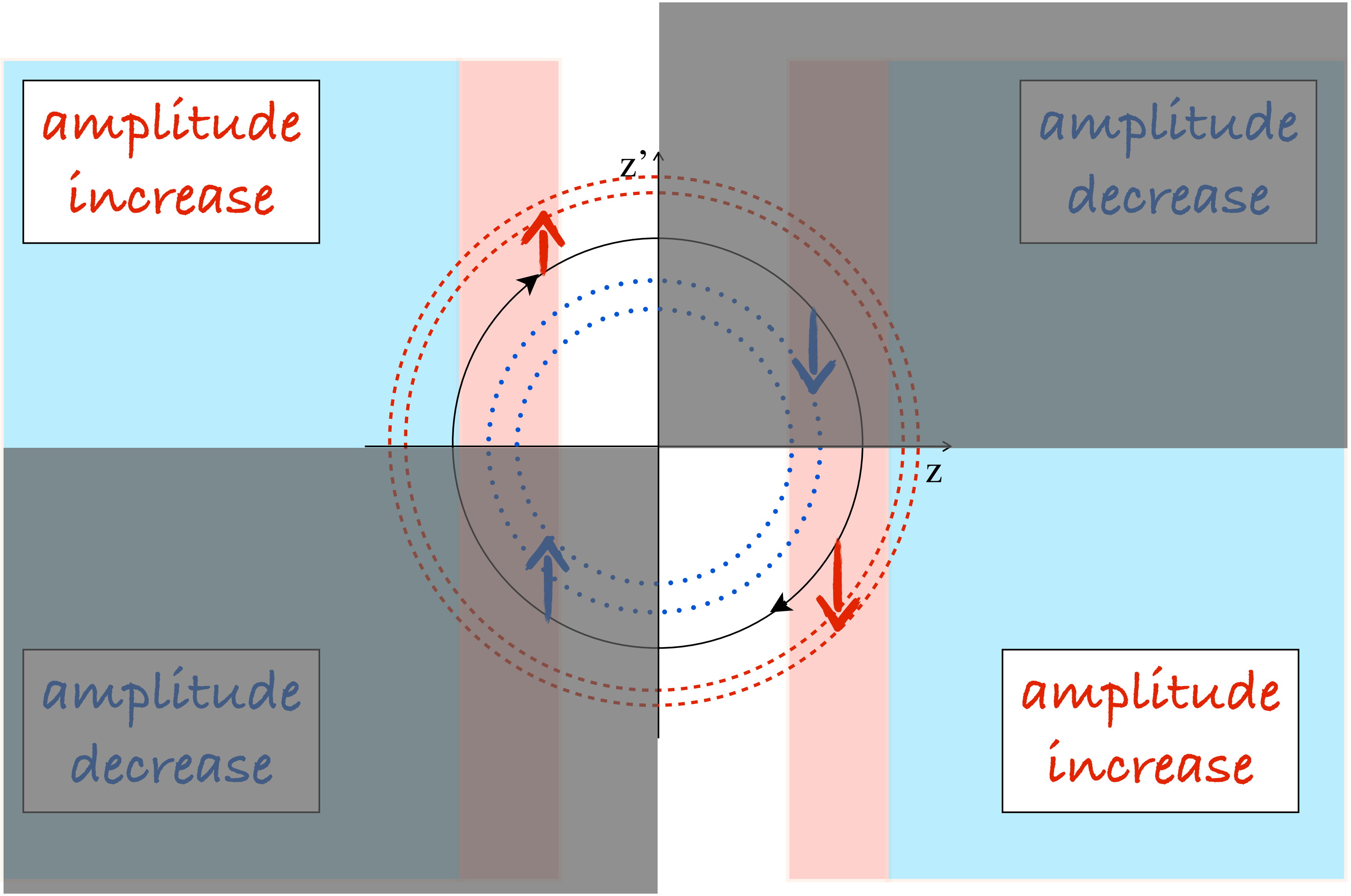
the resonance driving force which acts on this particle must be in phase with the momentum, and with the same oscillation period

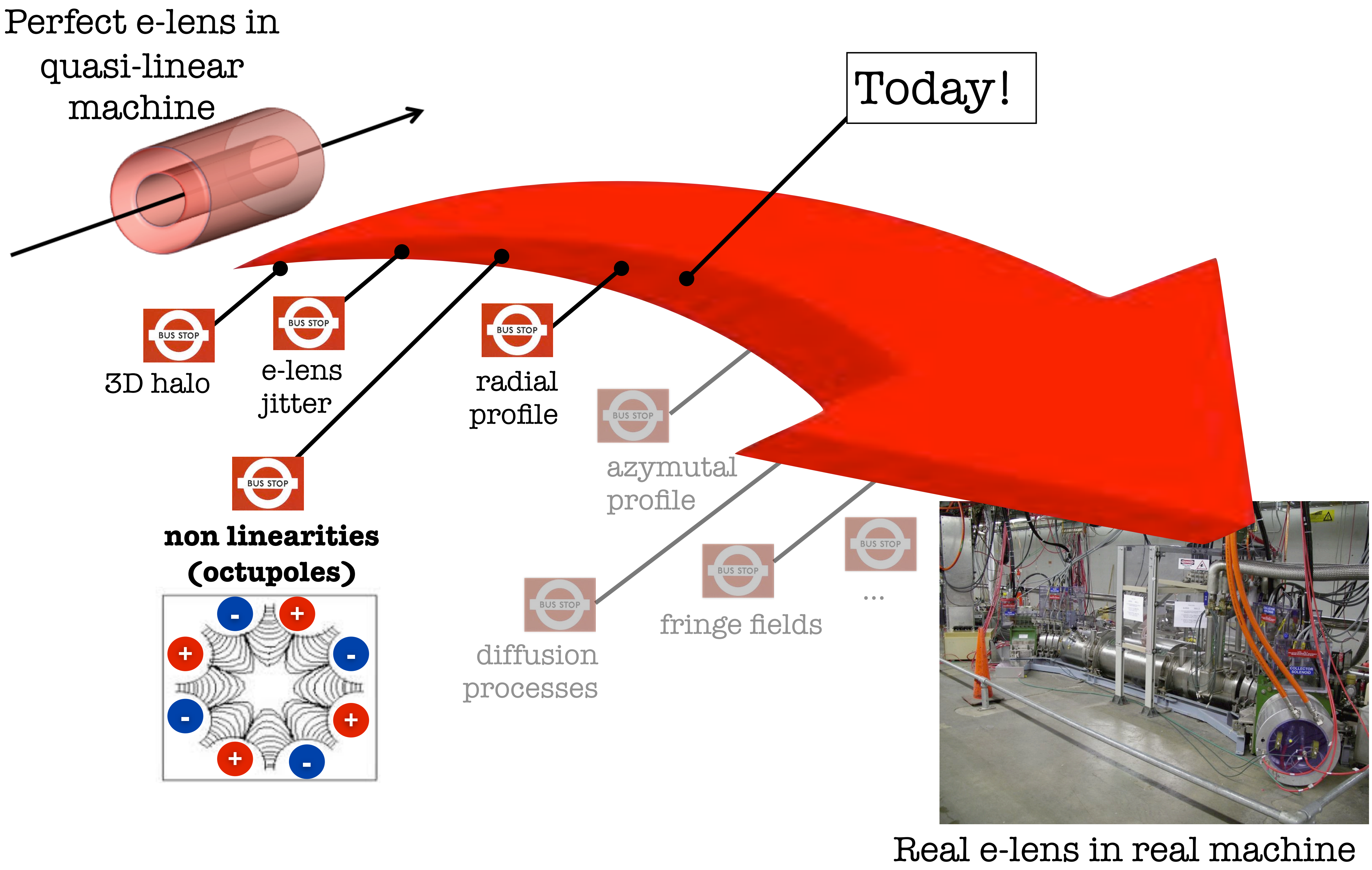
the electron lens is proportional to the particle position => ALWAYS shifted in phase (90 degrees) with respect with the particle momentum

Resonant condition:

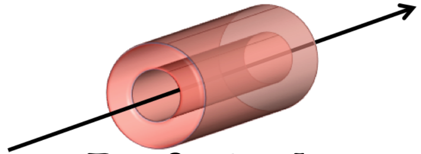
I switch the ELENS on only when it gives a kick in the same direction as xp

(normalized) phase space

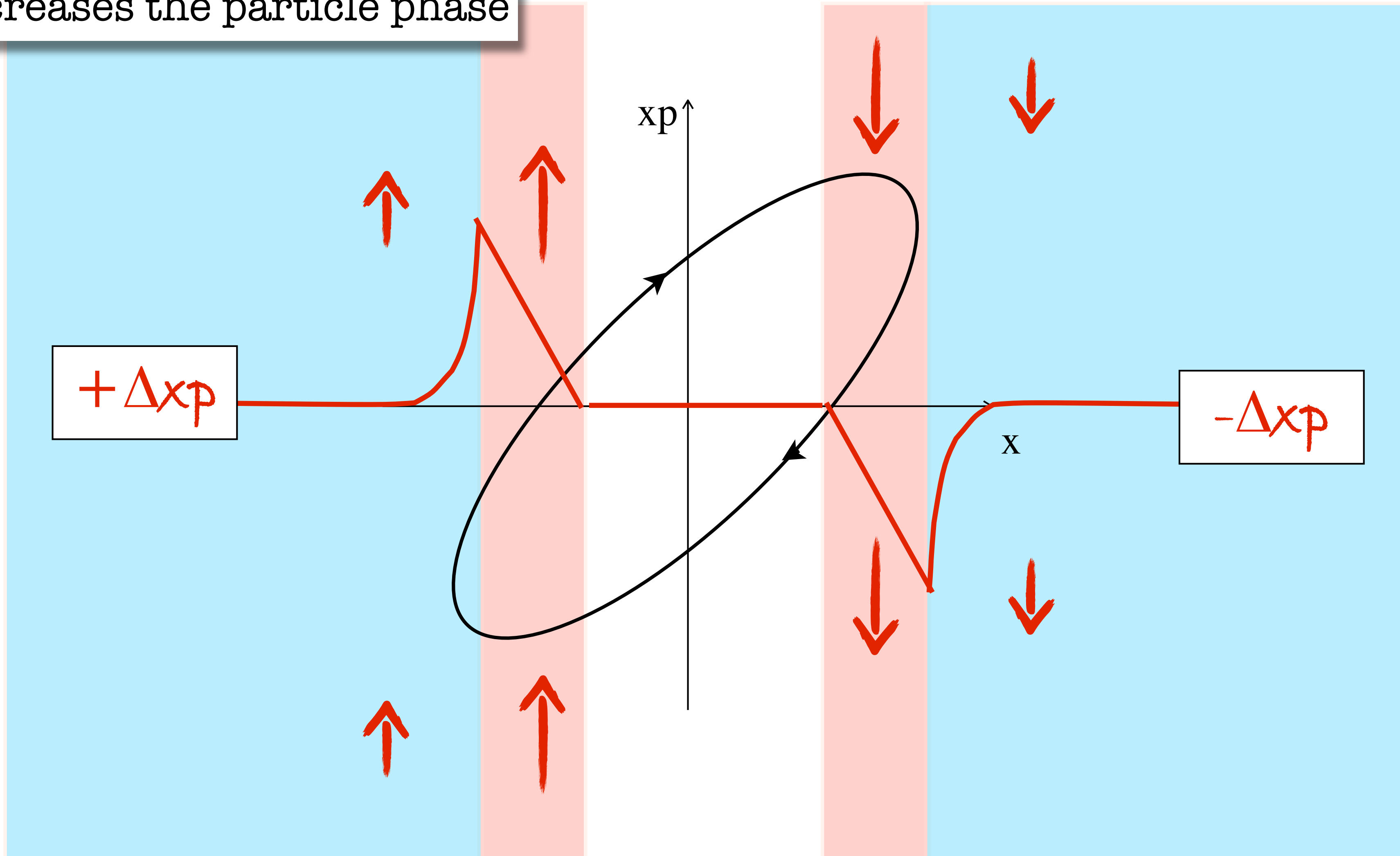


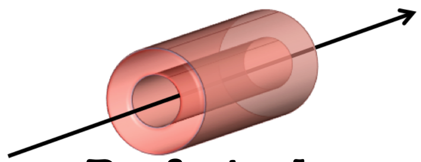

Perfect e-lens in quasi-linear machine
Today!
3D halo
e-lens jitter
radial profile
non linearities (octupoles)
azymutal profile
diffusion processes
fringe fields
...
Real e-lens in real machine

The perfect e-lens: the nominal kick



the kick is focussing
⇒ always inward
⇒ increases the particle phase

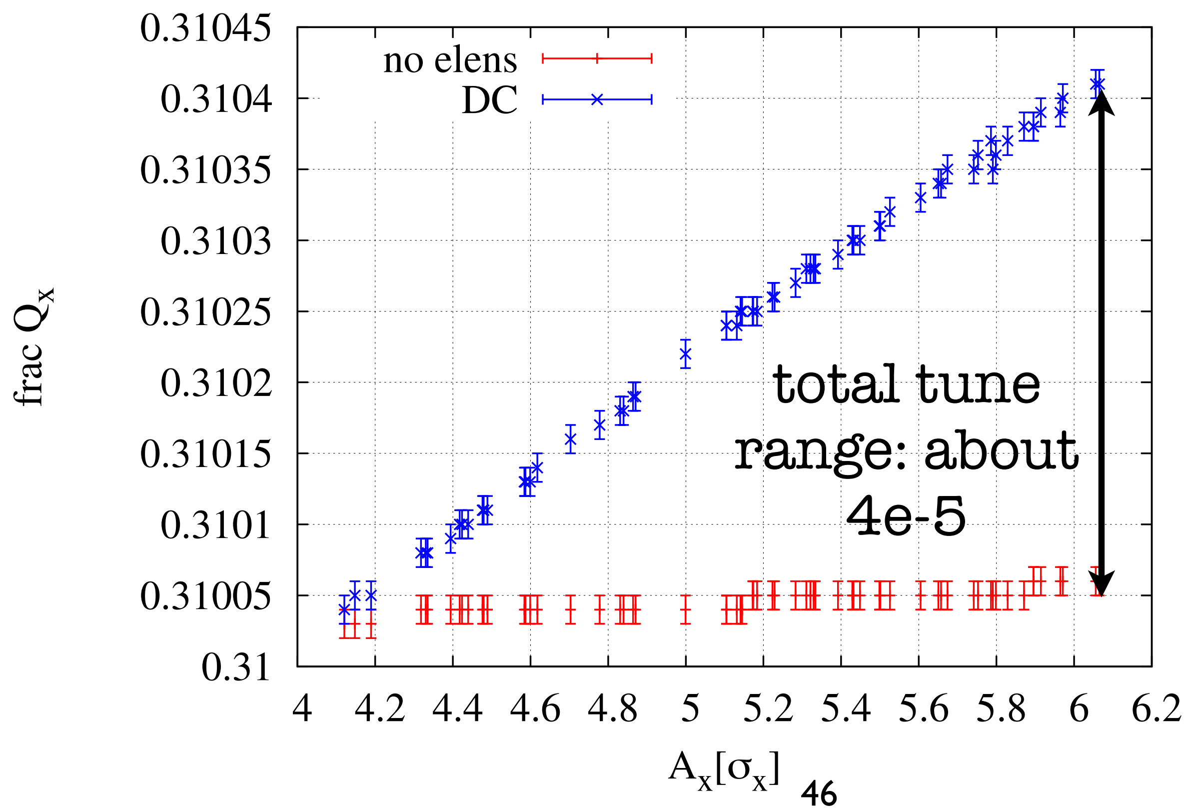




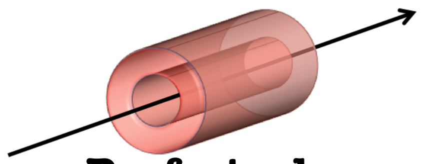
Perfect e-lens, linear machine

2. AC mode: e-lens switched on-off in resonance with the betatron tune

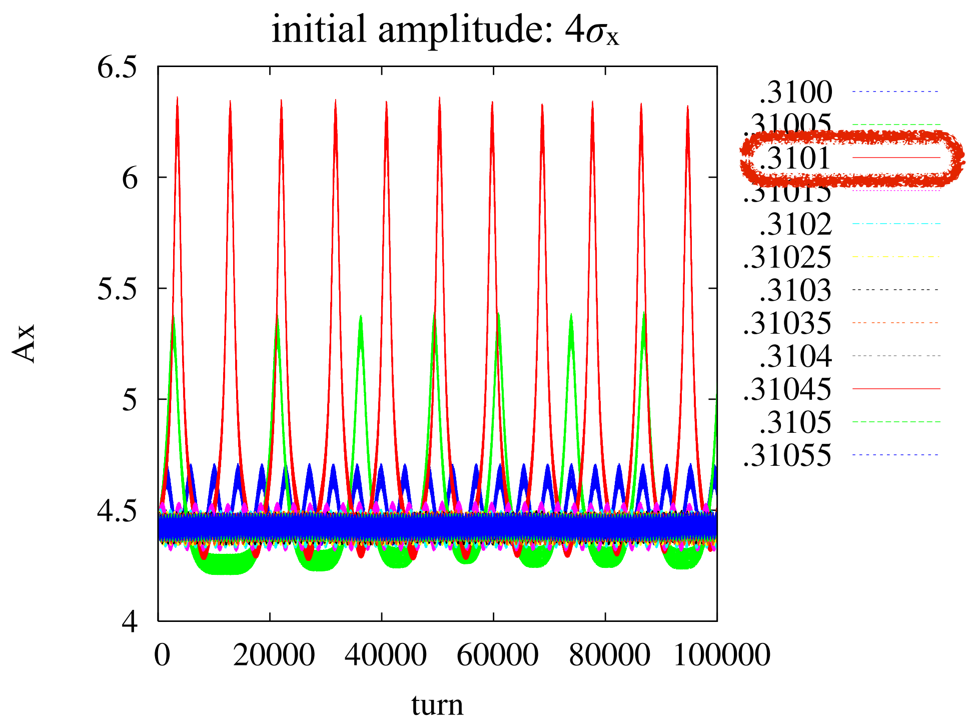
which tune?

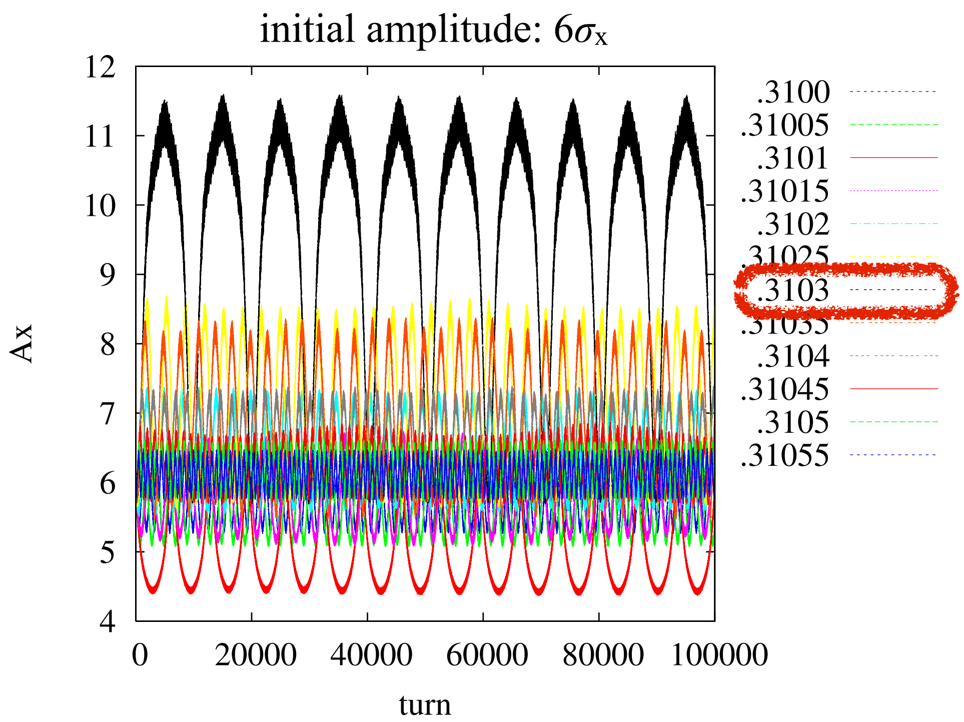


the e-lens itself introduces a tune shift, so that different (amplitude) particles have different tunes



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