LHC Electron Lenses: What Are They Good For?

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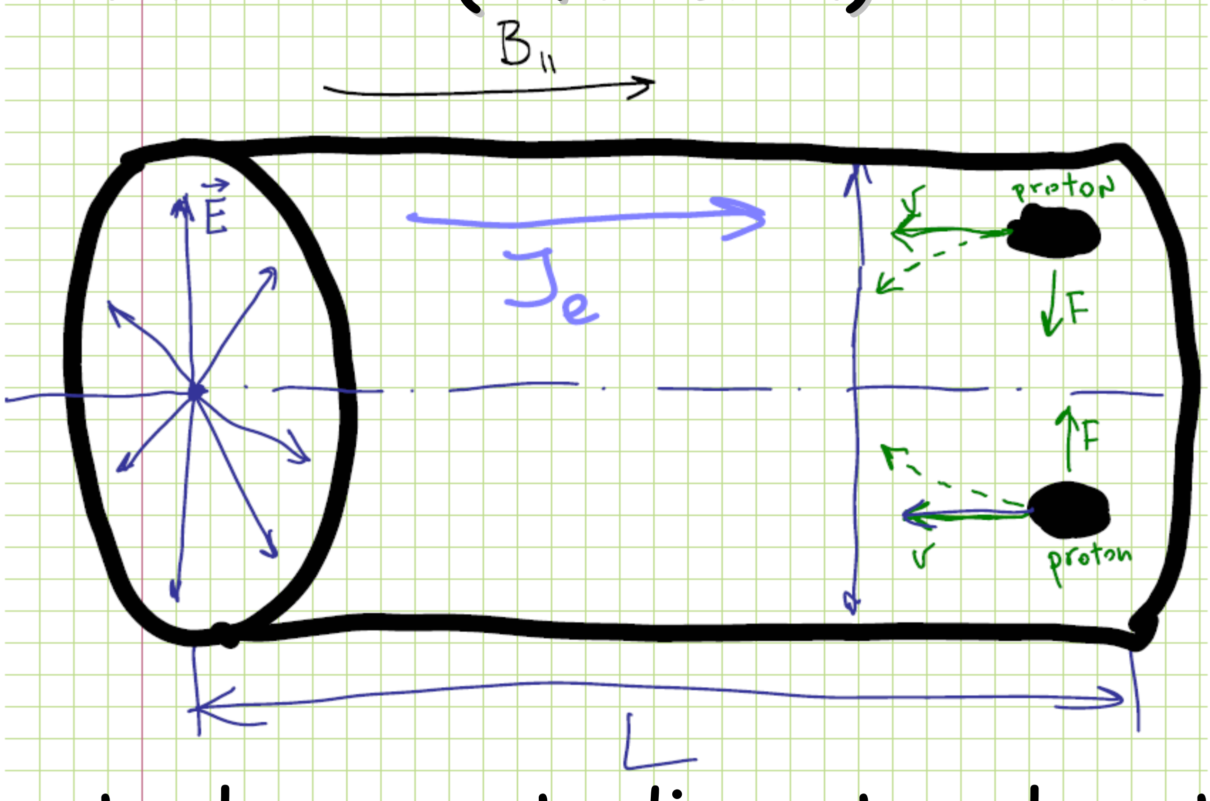
Fermilab

What Is Electron Lens?

- it is very stable and very well controlled (~frozen) electron cloud



~10^{12} e-

Can control current, diameter, length, position, timing, velocity, shape, angle, direction

What is it good for?

- **IT CAN KILL**
  - blow up emittances in controlled fashion
  - drive particles out – randomly or via resonance drive
  - remove unwanted particles, bunches, e.g.:
    - only in between bunches
    - just 1 out of 3000
    - only satellites
    - only those with a>5 x Sigma , etc, etc

What is it good for?

- **IT CAN HEAL**
  - reduce emittance blowup caused by other processes:
    - space-charge forces
    - beam-beam forces, etc
  - reduce beam loss rates by moving particles away from dangerous resonances
  - selective resonant extraction
  - introduce incoherent tune spread to stabilize beams

How strong is it?

- **Figure of merit- tuneshift dQ:**
  - Similar to space-charge and beam-beam

$$dQ_{x,y} = \mp \frac{\beta_{x,y}}{2\pi} \cdot \frac{1 \pm \beta_e}{\beta_e} \cdot \frac{J_e \cdot L_e \cdot r_p}{e \cdot c \cdot a_e^2 \cdot \gamma_p}$$

this product is const(E)

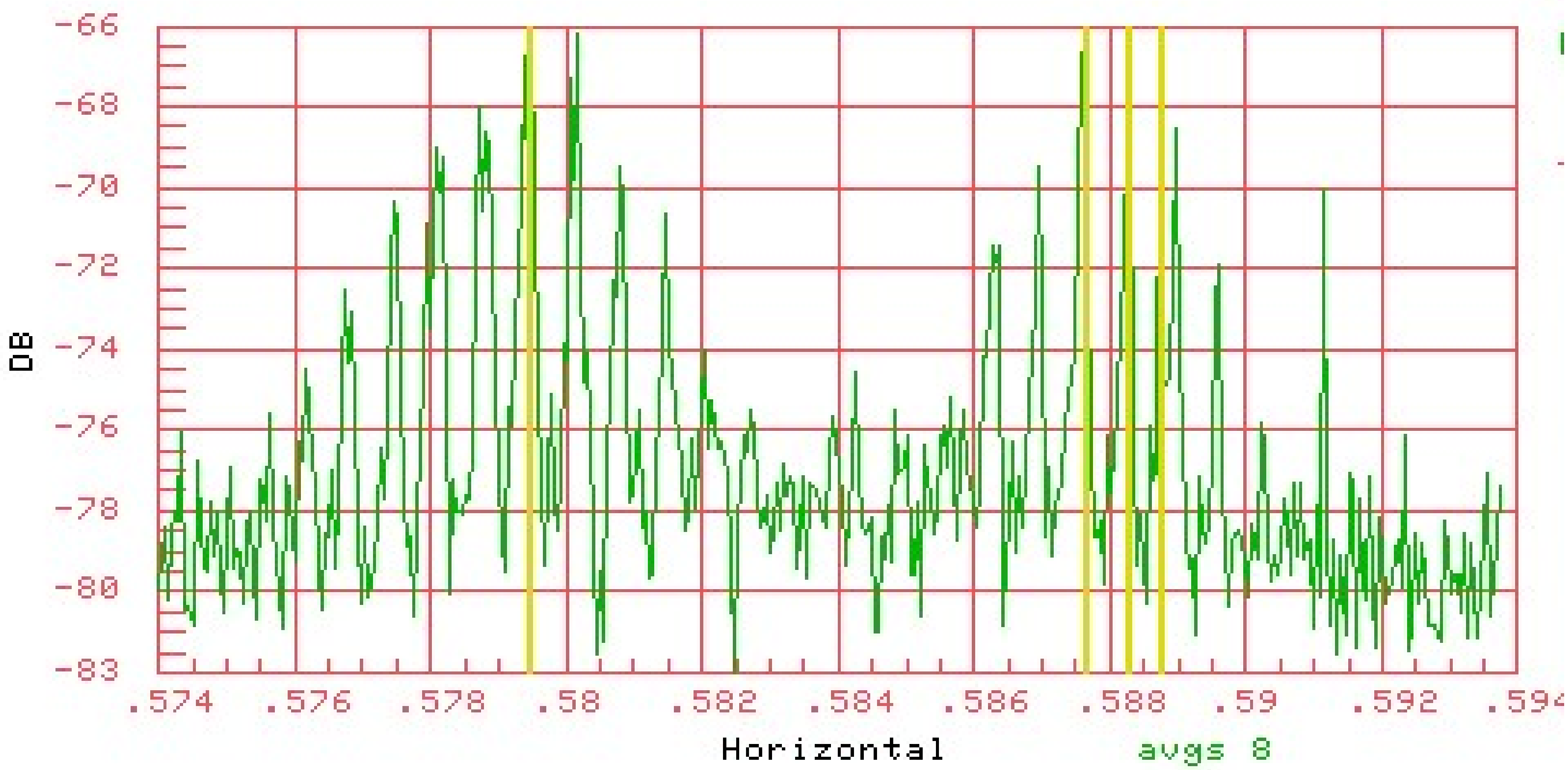
For many applications electron beam size needs to be nxσ protons e.g. n=1 for head on BBC

→RHIC
→Tevatron
→LHC

SAME!

Tuneshift dQ_{hor}=+0.009 by TEL

J_e=2A, a=1.7mm L=2m E=980GeV beta_e=0.2



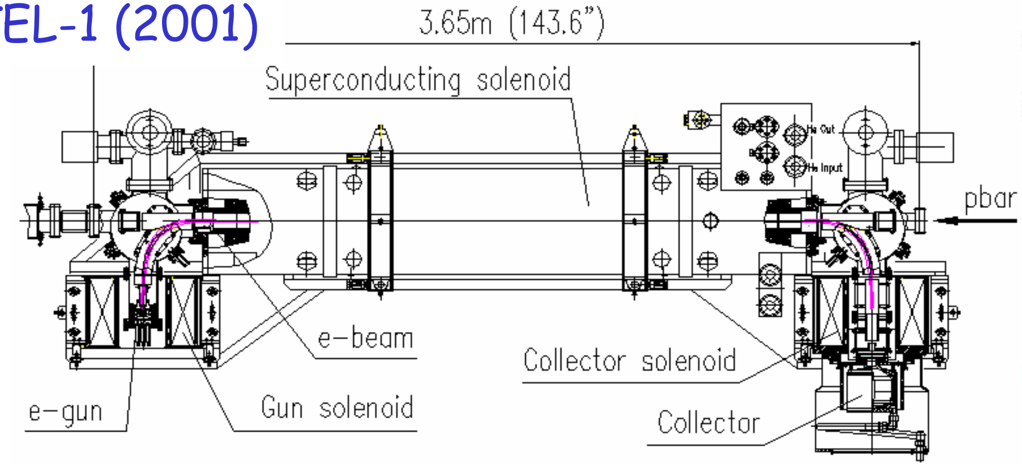
- Three p-bunches in the Tevatron, the TEL acts on one of them

Can that "beast" be safe for operation?

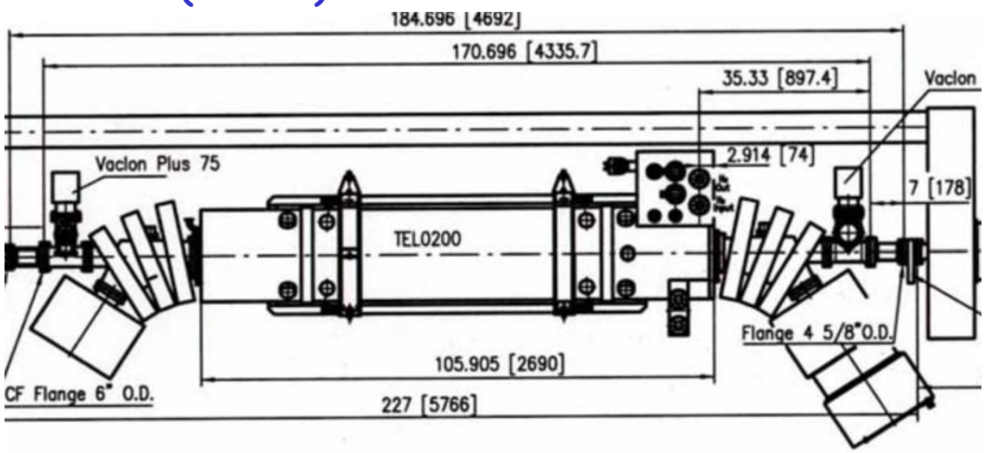
- **Yes!- look at the Tevatron:**
  - TEL-1 is used for abort gap cleaning
    - 5 years in 24/7 operation (since 2002)
    - >1000 HEP stores
    - No store lost because of TEL – best record
    - Only 8-hr accesses (over 5 yrs) to the tunnel required to replace failed TEL components
  - TEL-2 used for Beam-Beam Compensation
    - Installed in June'06, commissioned for operation in August
  - used for studies in ~15 HEP stores for few (upto 8) hours, almost every store in Sep
    - No quenches/problems/complaints

Is Technology Available?

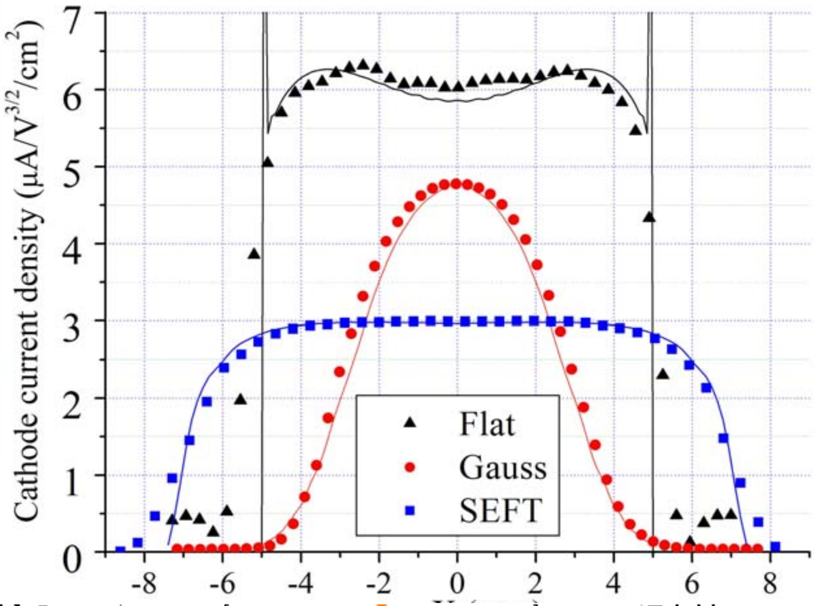
TEL-1 (2001)

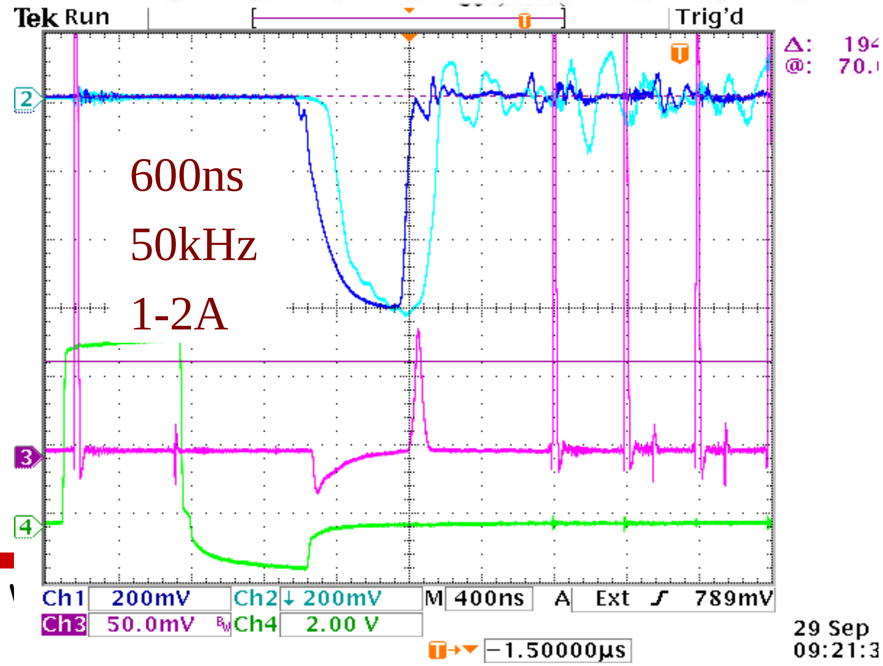


TEL-2 (2006)

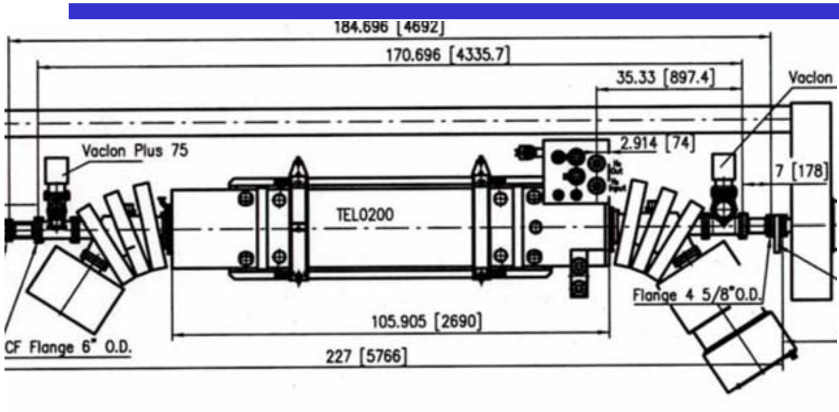


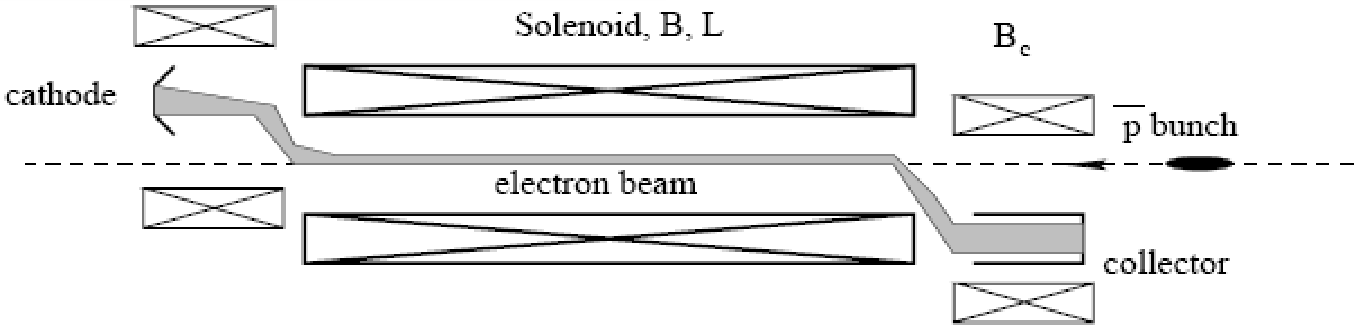
+ Marx HV Modulator, SEFT gun, 2 Cryo bypasses, 4-plate BPMs & Cables

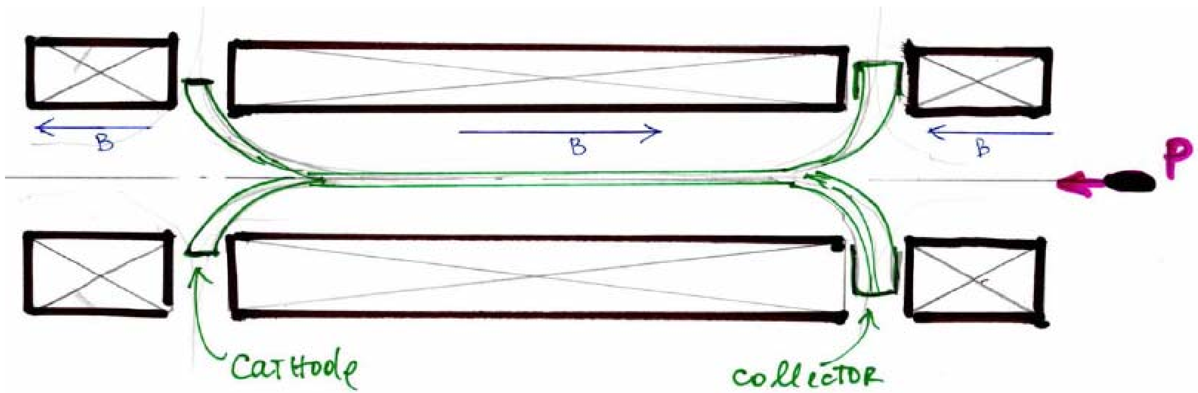




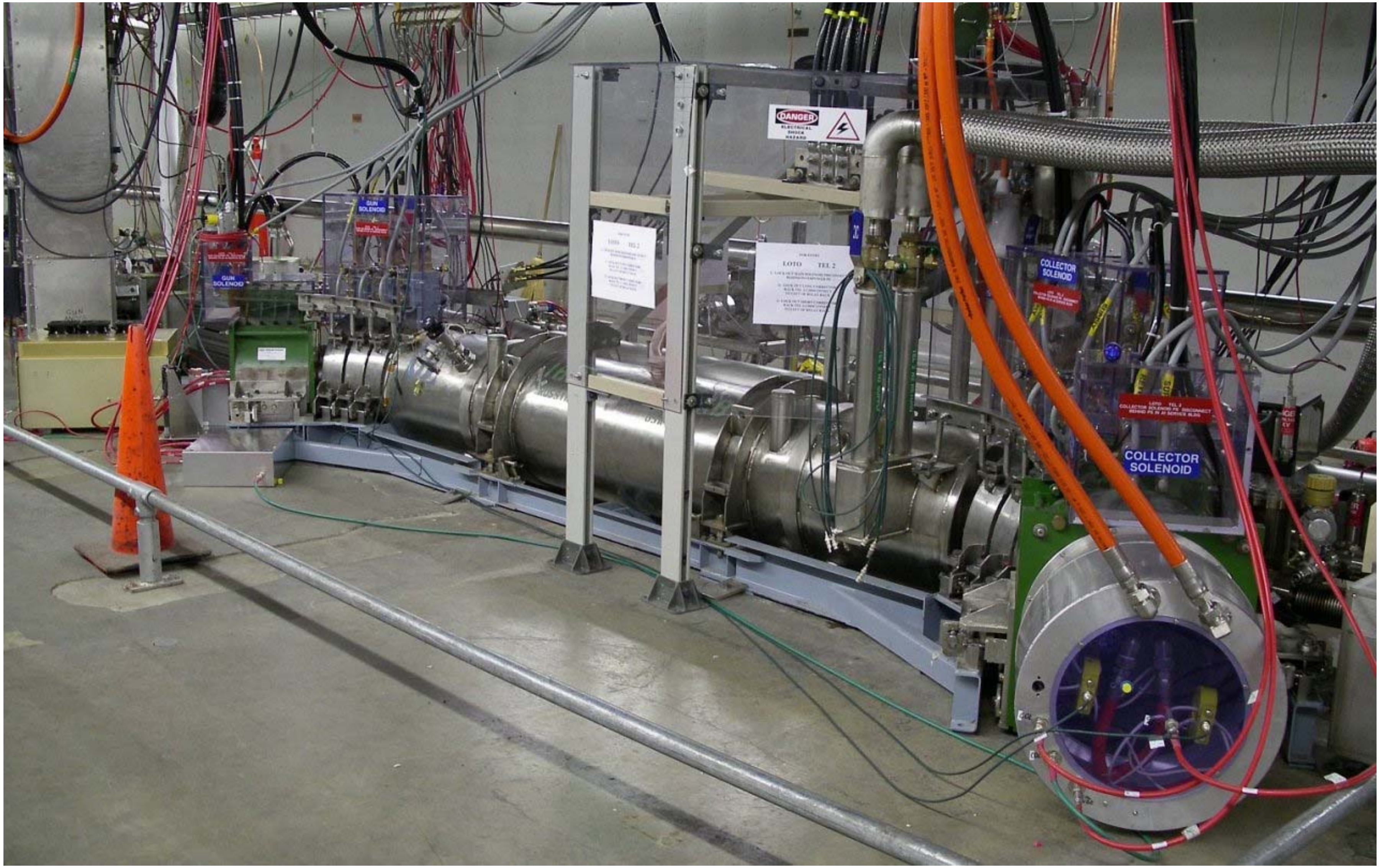
Possible e-Lens Configurations







TEL-2 in the Tunnel (July 2006)



TEL-2 Parameters for Vert. LR-BBC

- **Generates dQ~0.004 :**
  - Compensates b-by-b vert tune spread
  - J_e=1-2A
  - pulsed, dt=600ns, rep.rate=50kHz x Nb
  - beta_y=136, beta_x=50 m
  - "flattop+smooth edge" distribution
  - a_e=2.5 mm at 980GeV
  - L_e=2 m, U_e=5kV
  - B_gun=3kG, B_main=31kG

LHC Electron Lenses Can:

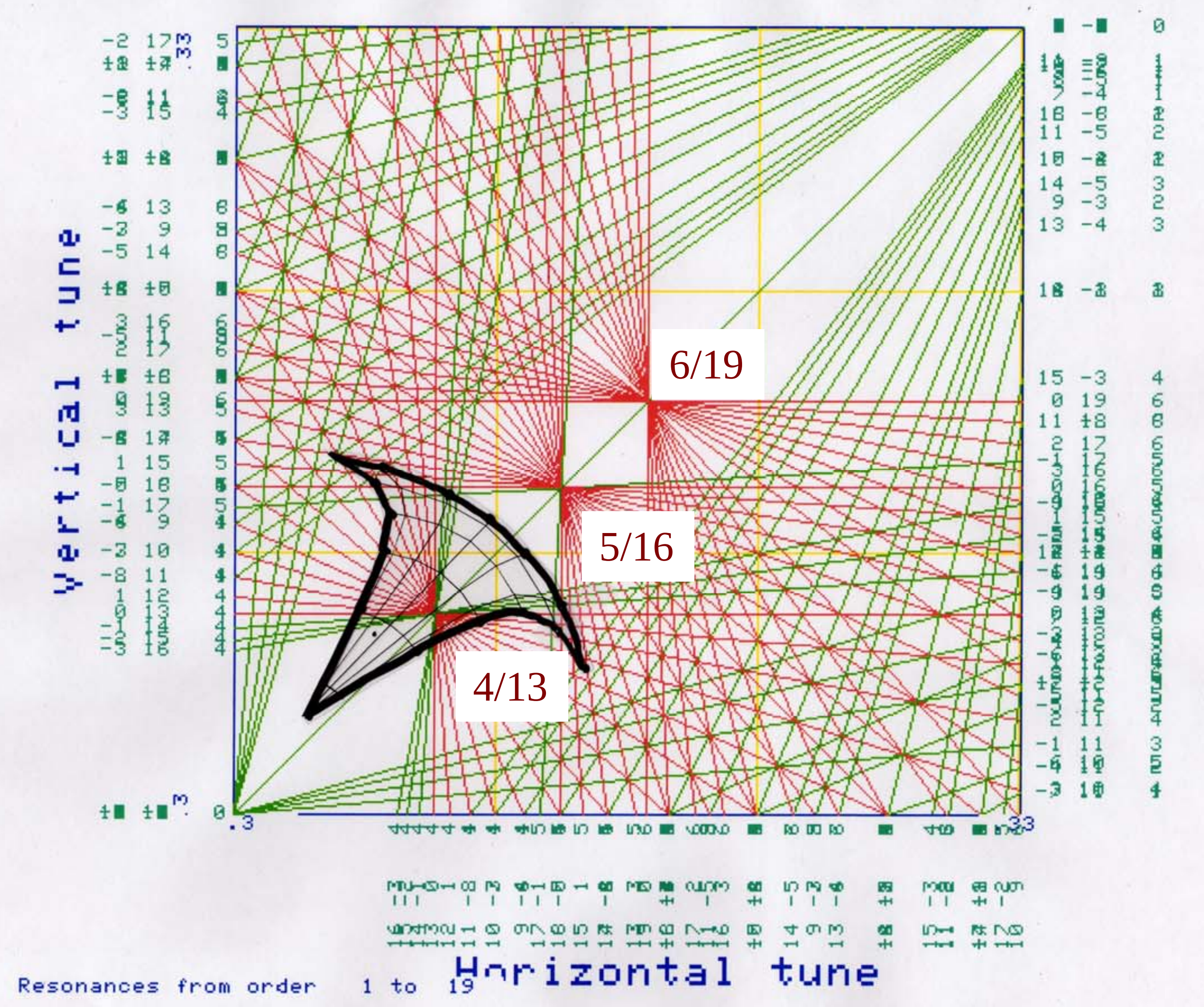
#1: LEL as Head-On Compensator at design intensities and with x(2…4?)Np/bunch

#2: LEL as Beam Stabilizer (Tune Spreader) to help octupoles @ design Np=1.15e11

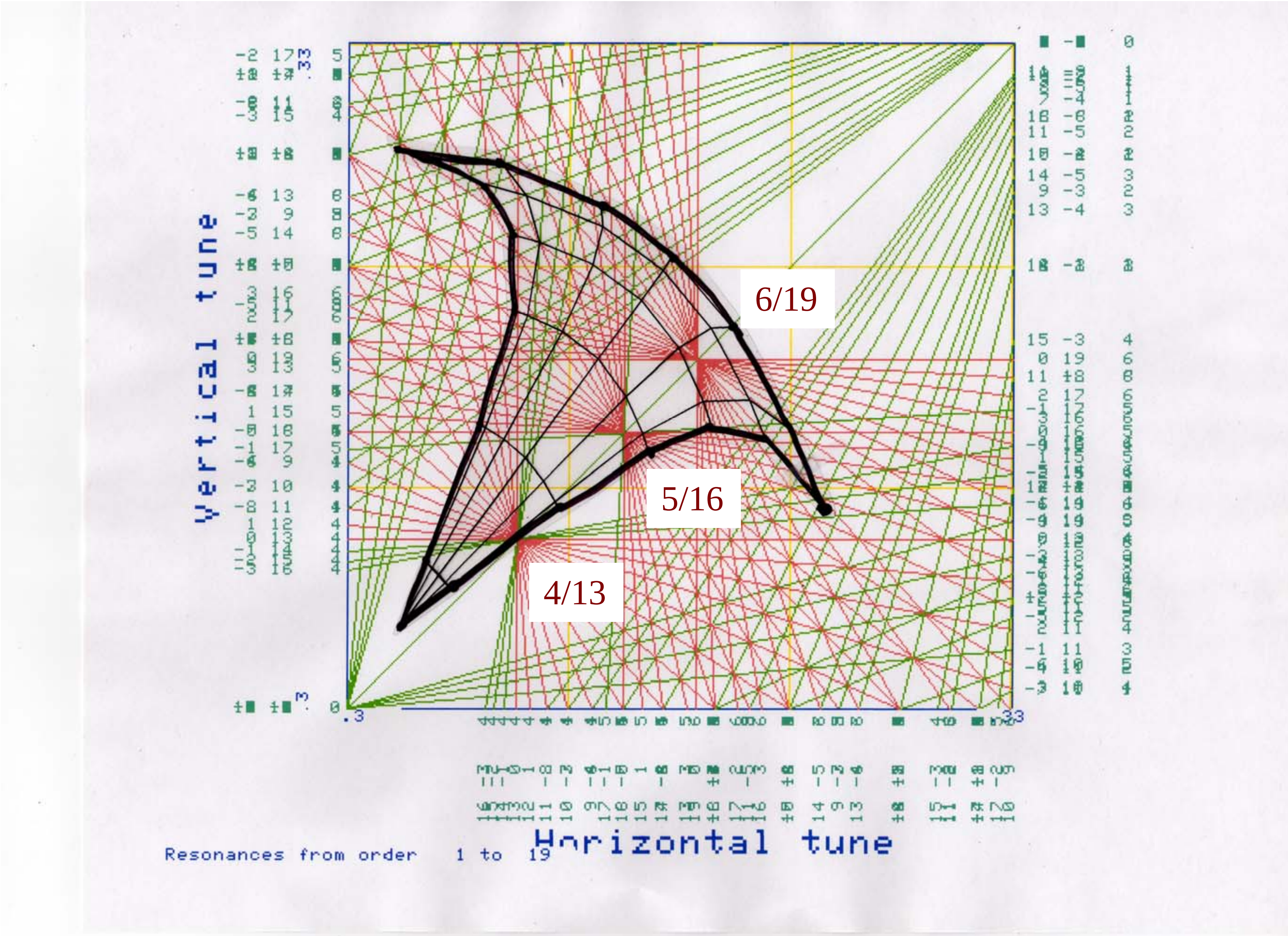
#3: LEL as soft hollow collimator

#4: LEL as soft "beam conditioner"

LHC footprint (design)



LHC footprint (x2 Np/bunch)



Head-on beam-beam compensation

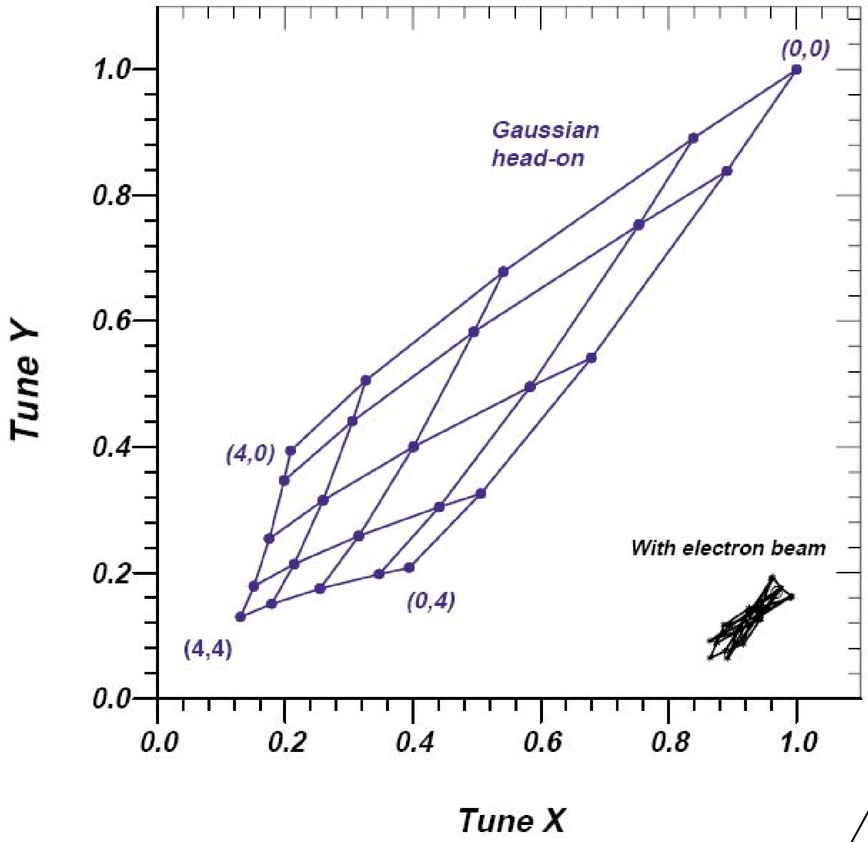


FIG. 6. (Color) Electron compression of the head-on $\bar{p}$ footprint. Tunes are given in units of the head-on beam-beam parameter ξ^p. Numbers in parentheses show the horizontal and vertical betatron amplitudes in units of the rms antiproton beam size. The case with electron beam is displaced for clarity.

$$N_e = N_{\mathrm{IP}} N_p / (1 + \beta_e) .$$

- If beam sizes and shapes are matched (e=p)

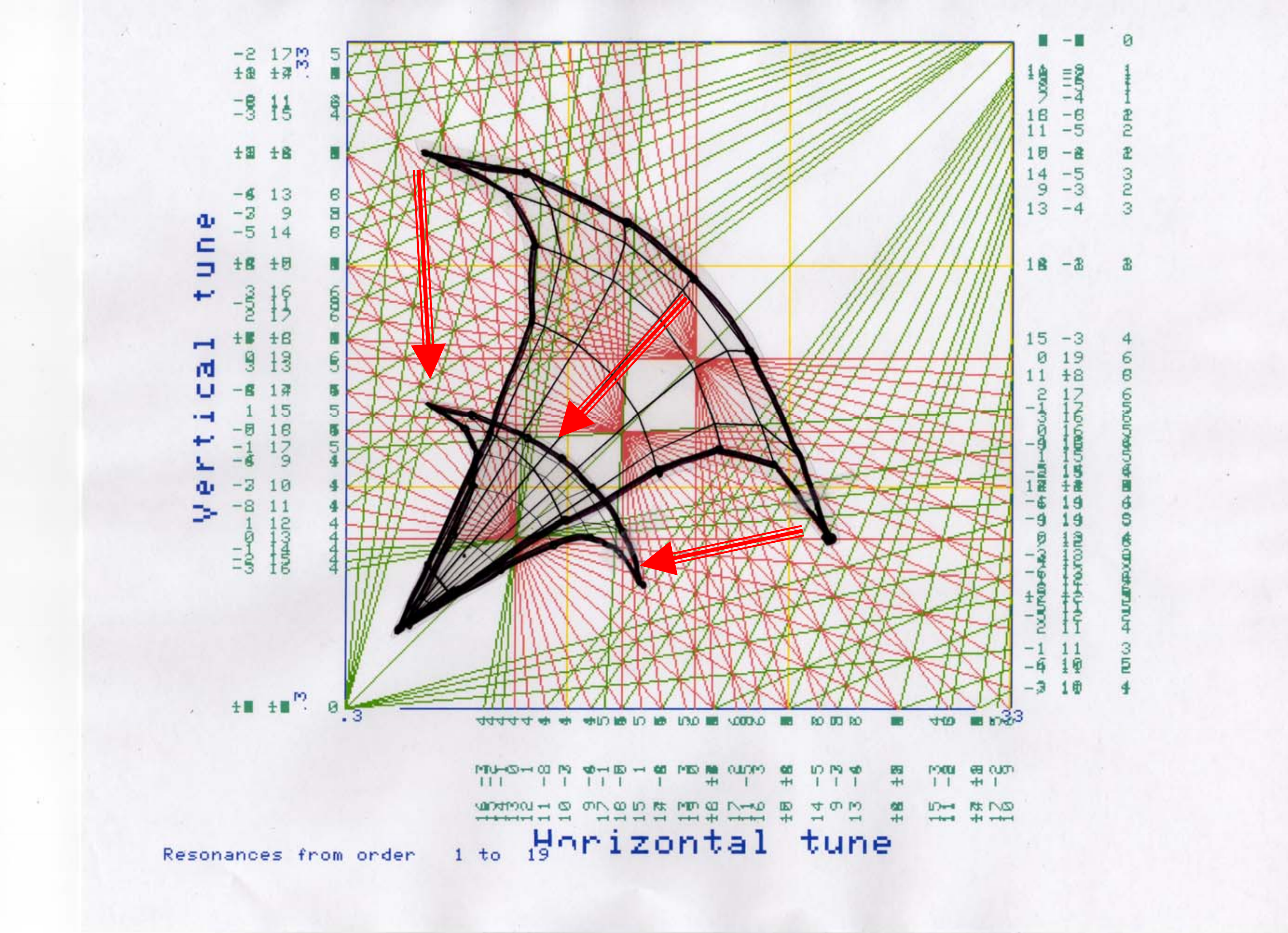
- for LHC N_p=1.1e11, N_ip=4, for 10kV electrons (beta=0.2) one needs N_e=4.4e11 or

J_e=1.2 A in L=3 m long e-beam

- approx Gaussian e-current distribution with rms = 0.3-0.5 mm

… or donut shape?

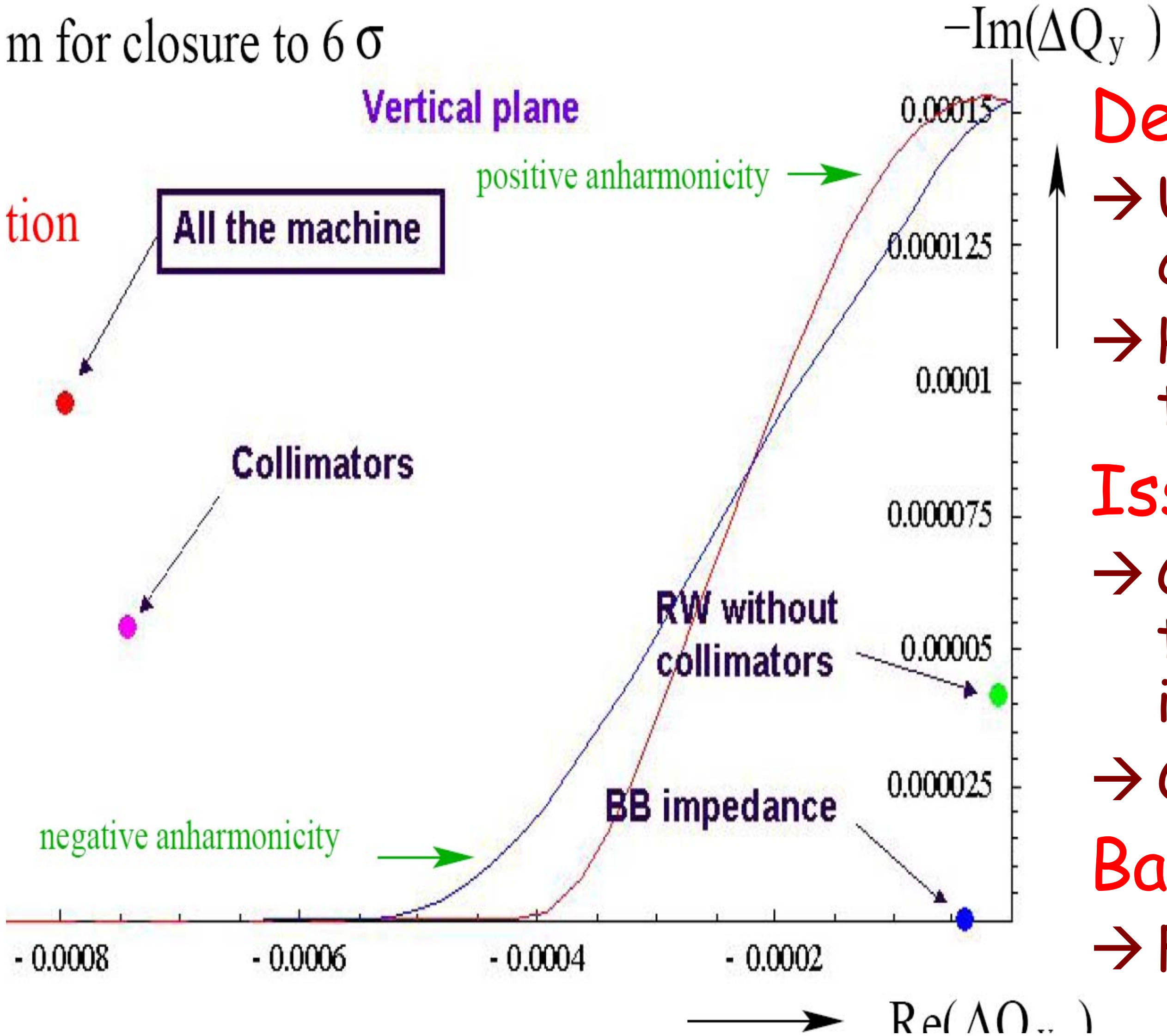
50% Head-On Compensation by LEL



LEL Parameters for Job #1:

- **To compensate 1.15e9 head-on:**
  - will help 1x and 2xNp operation
  - J_e=1.2A
  - DC
  - beta_x=beta_y=200 m
  - Gaussian or optimzed distribution
  - a_e=0.3 mm rms at 7TeV
  - L_e=3 m, U_e=10kV
  - B_gun=2kG, B_main=65kG
  - One eLens/beam

Stability of LHC Beams



Design approach:

→ Use octupoles before collisions

→ Hope for head-on tunespread

Issues:

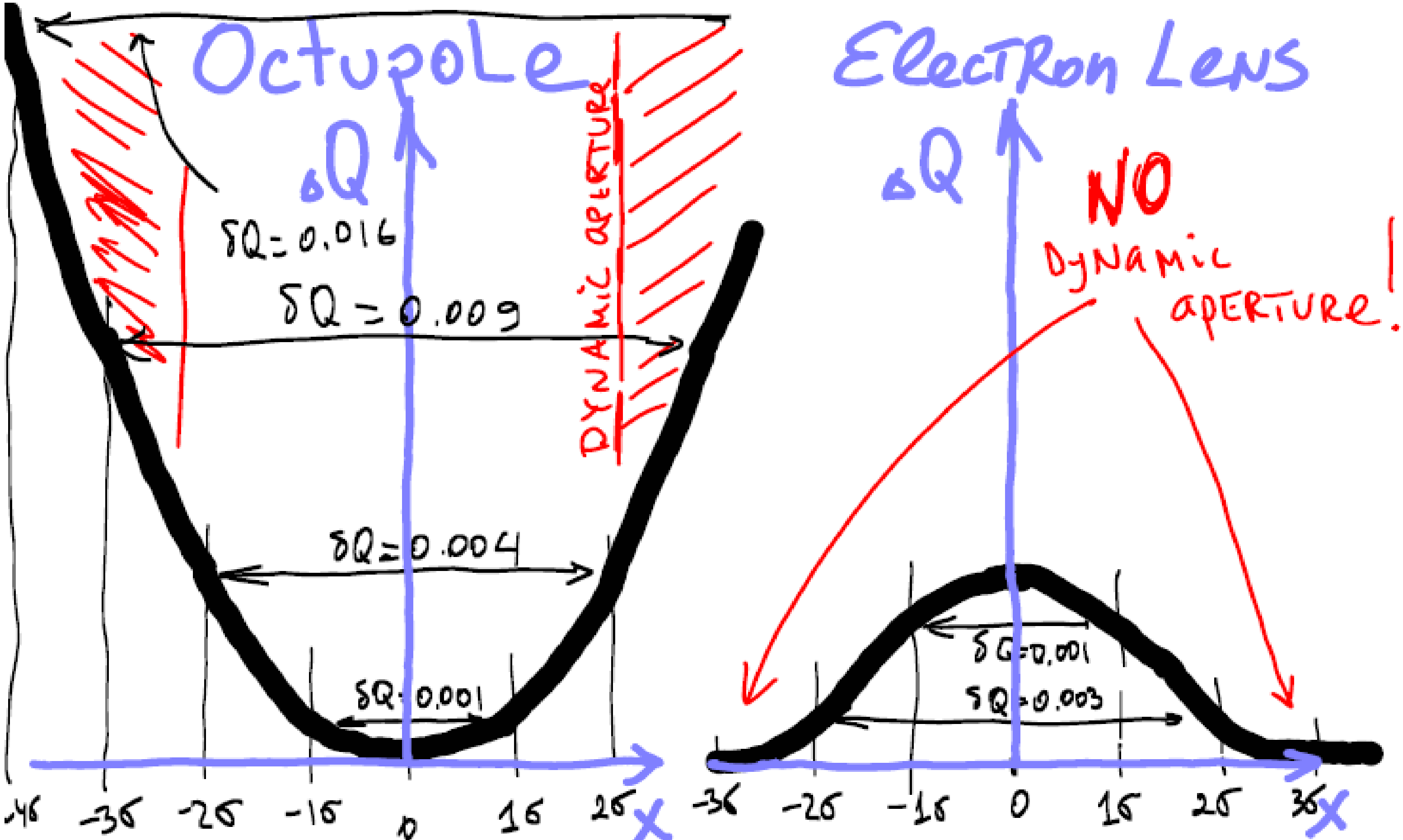
→ Collimators too close to beam → extra impedance

→ Octupoles limit DA

BackUp solution:

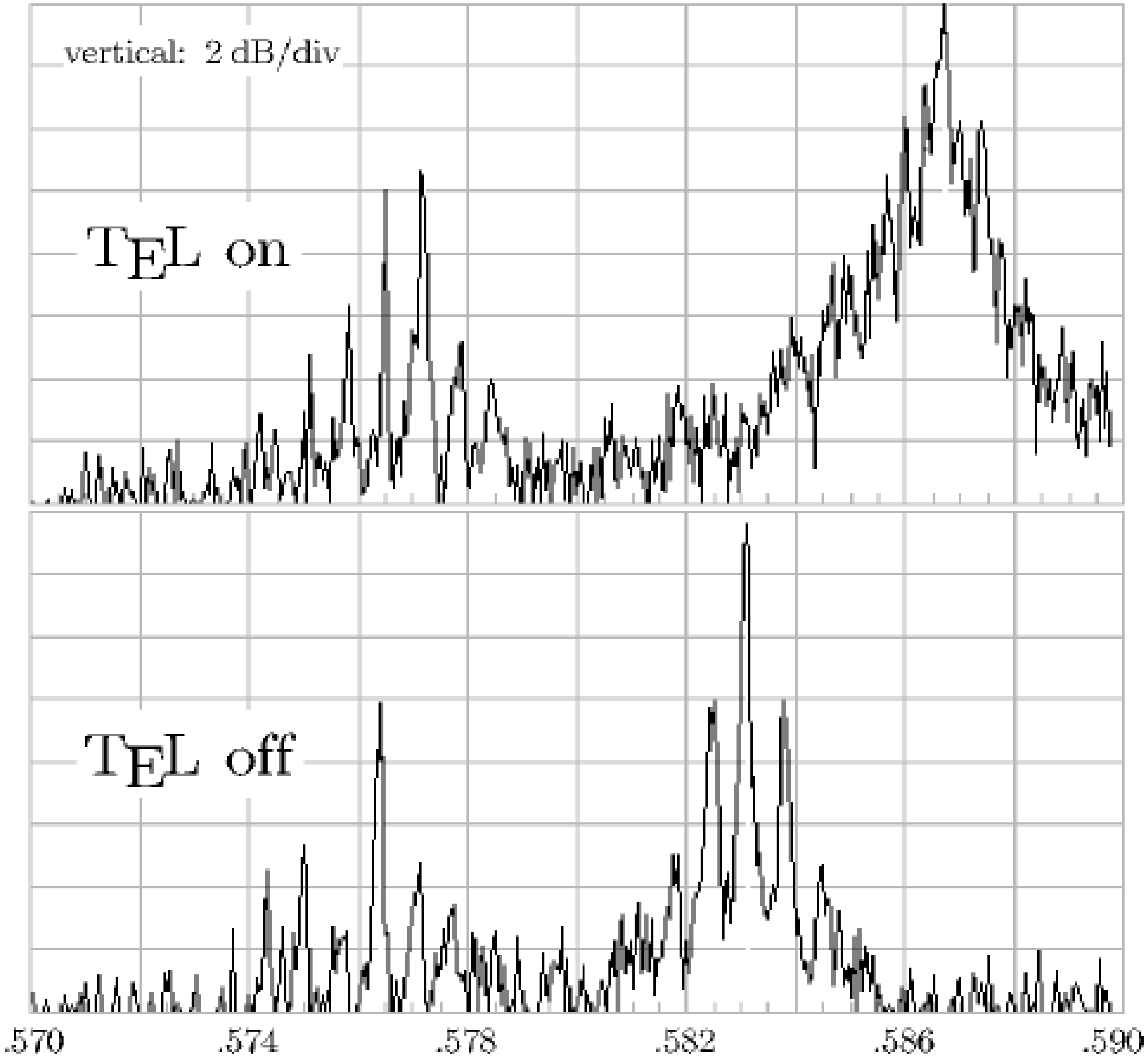
→ Feedback (noise?)

#2: LEL as Beam Stabilizer



- Such tune spreader does not limit DA → can replace octupoles before collisions
- Note that p-p beam-beam tune spread by itself does not help stability much in multibunch regime because of both beams are movable and many coherent modes outside incoherent spectrum (Tevatron, Yu.Alexahin) - in contrast, e-beam does not move (= NL lens).

Example: TEL as Tune Spreader



980 GeV protons

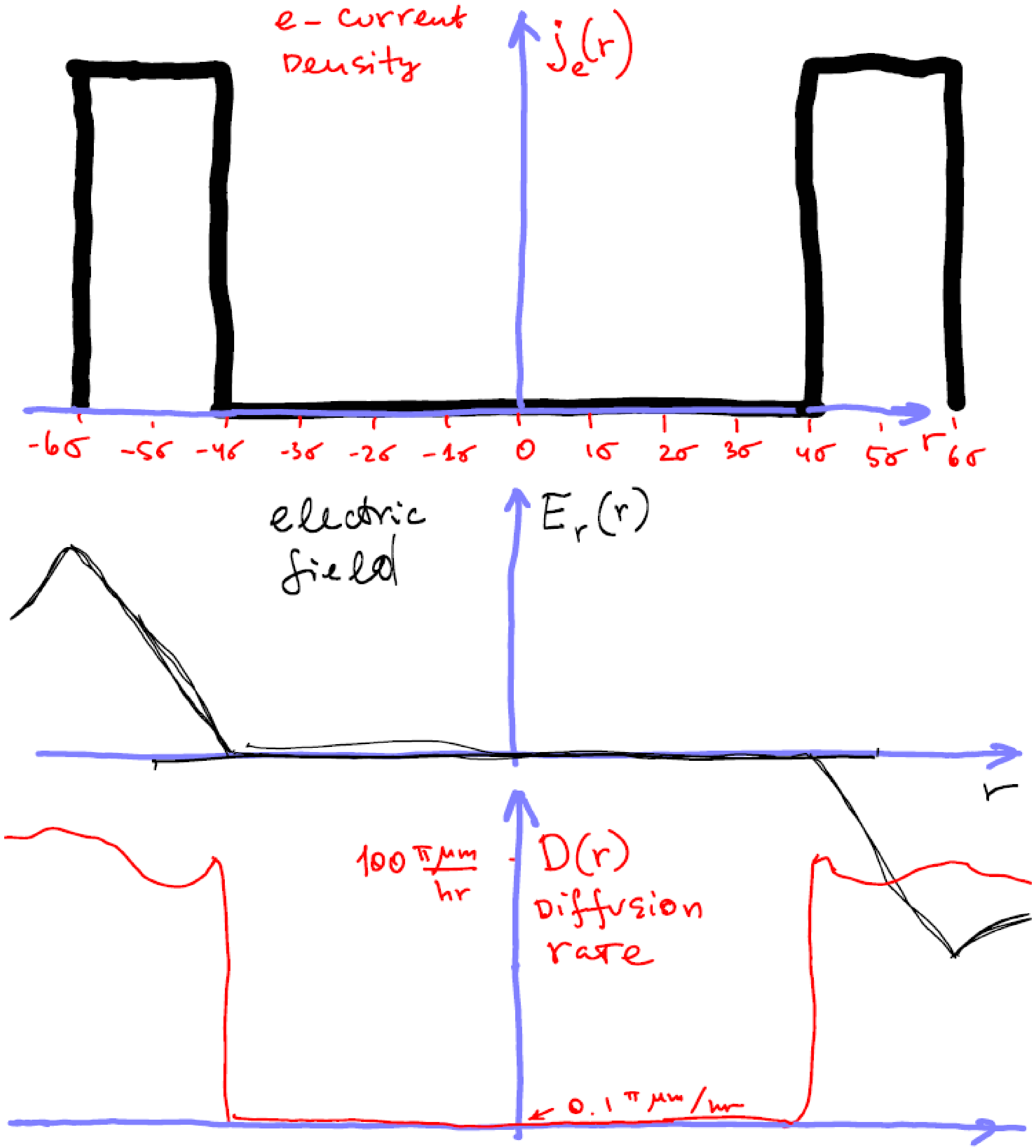
extra tune spread dQ~0.003

Tune shift ~0.004

LEL Parameters for Job #2:

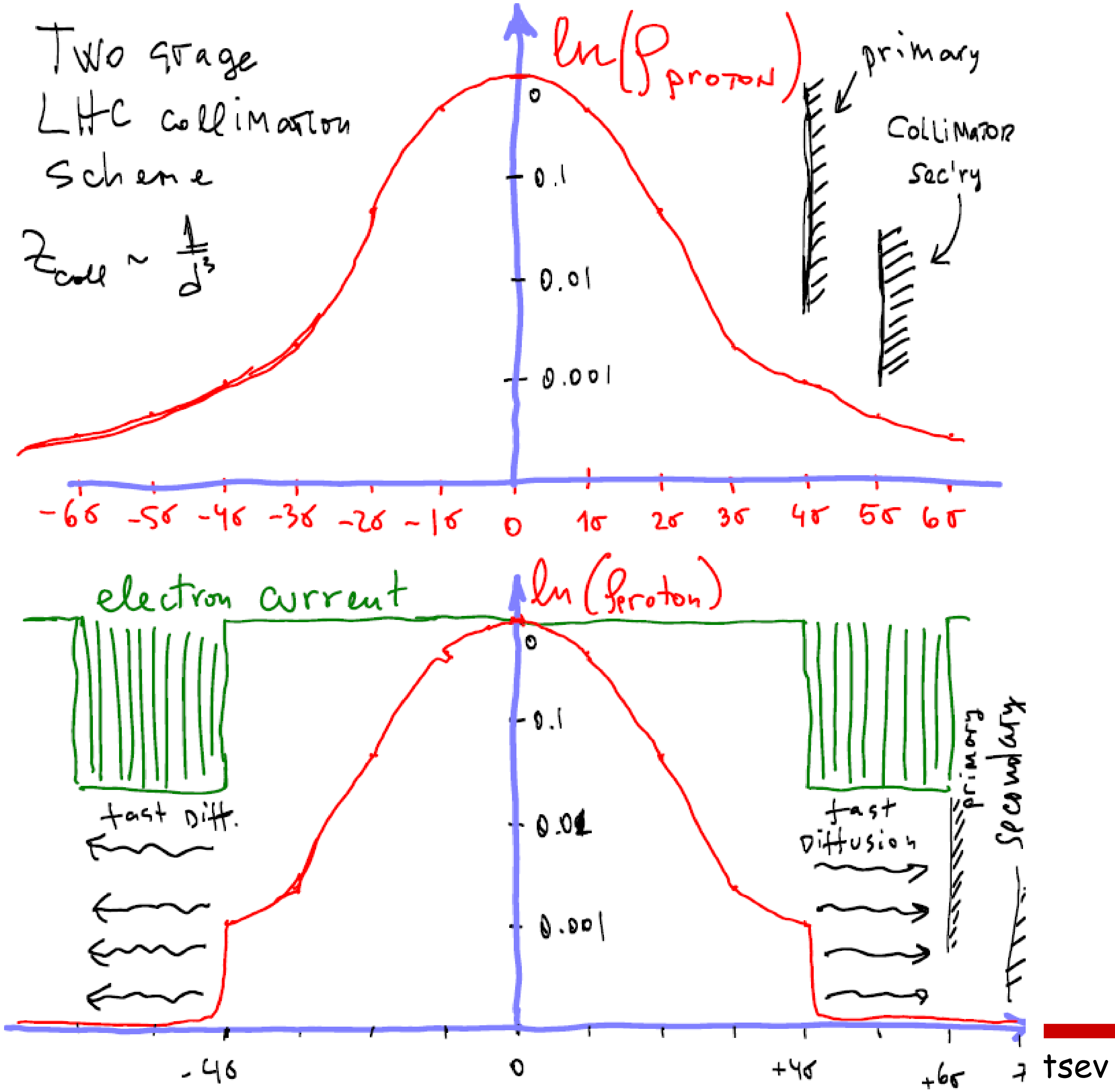
- **To generate dQ~0.004 :**
  - will suffice for 2xNp operation
  - J_e=0.5-1A
  - DC
  - beta_x=beta_y=200 m
  - Gaussian or bell-shape distribution
  - a_e=0.3 mm rms at 7TeV
    =0.9 mm rms at 0.45 TeV
  - L_e=2 m, U_e=10kV
  - B_gun=2kG, B_main=65kG

#3: Hollow Electron Beam as Collimator



Duffusion enchanced by Non-linear fields and/or resonant pulsing Structure (e.g. every 13th turn)

"LEL-Combo" Collimation



Phase I Collimation

LEL-Combo Collimation:

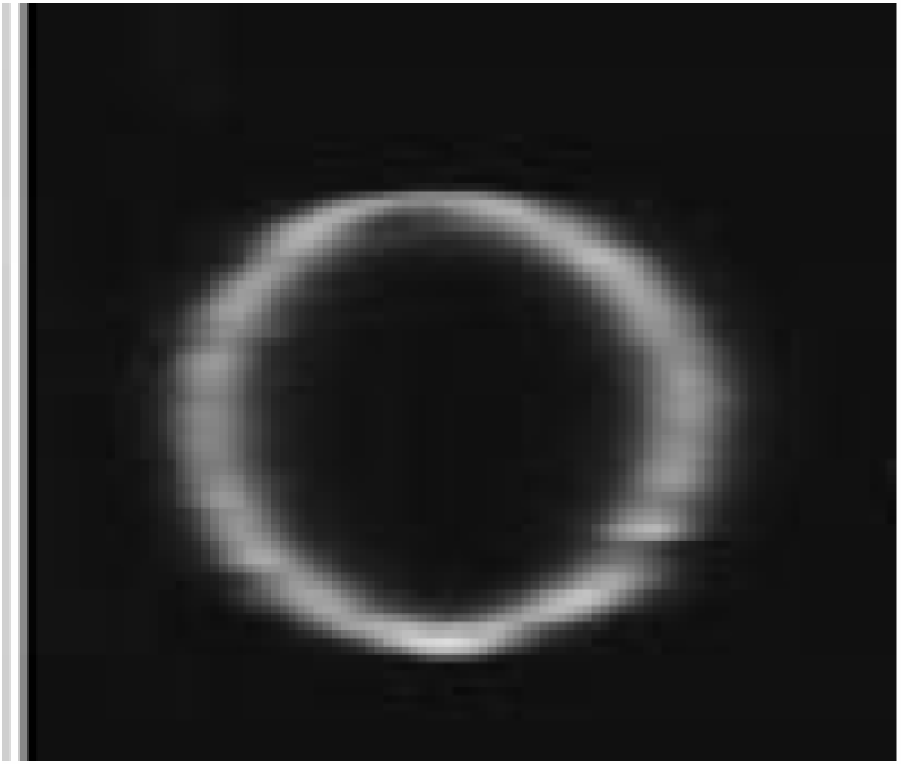
LEL drives particles from 4 to 6 sigma,

Collimators 2 sigma

FARTHER

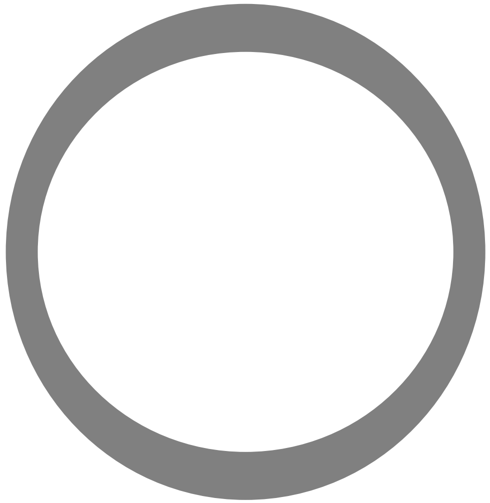
Multi-A Hollow Electron Beams Generated

Tunable profile



A.Bubley, et.al. PTE, 49(1), 2006

Ring cathode

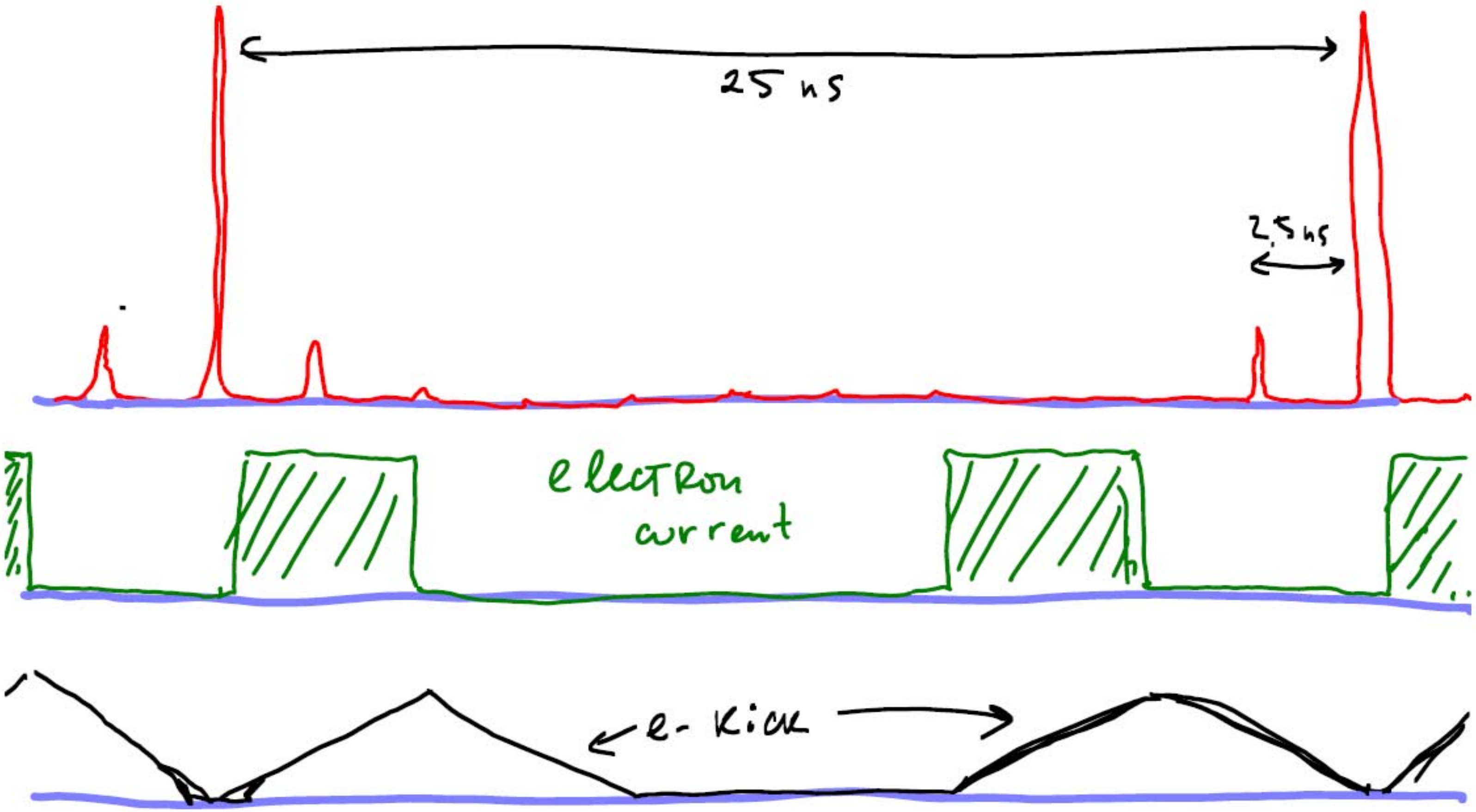


A.Shemyakin, et.al. NIM A, 1996

LEL Parameters for Job #3:

- **To clean 4-6 sigma protons :**
  - Will allow collimators ~50% farther
  - J_e=0.5-3A
  - DC or pulsed resonantly (10th or 13th turn)
  - beta_x=beta_y=200 m
  - Hollow beam distribution
  - r_min=1.2 mm at 7TeV
    r_max =1.8 mm at 7 TeV
  - L_e=2 m, U_e=10kV
  - B_gun=2kG, B_main=65kG

#4: Killing Satellites

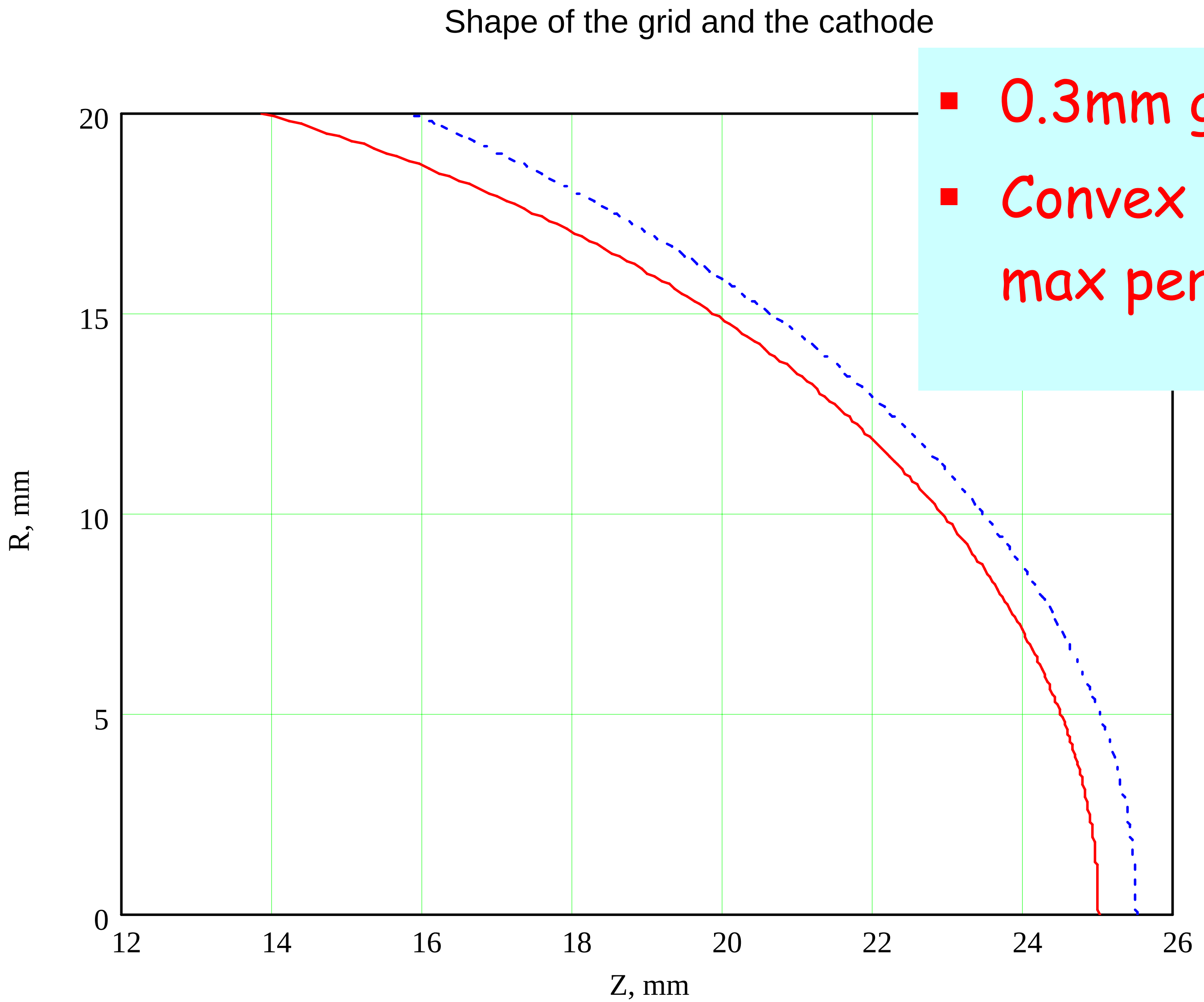


- Easier to do at 450GeV
- But more time at 7TeV
- Drive resonantly

LEL Parameters for Job #4:

- **To kill all satellites in ~1 hr :**
  - Will allow collimators ~50% farther
  - J_e=(n~300pulses/turn)x 2A
  - Varied resonantly (10^{th} or 13^{th} turn)
  - beta_x=beta_y=200 m
  - Flat beam distribution
  - r_e=0.6 mm at 7TeV
  - L_e=2 m, U_e=80kV
  - B_gun=4kG, B_main=32kG

Gridded e-Gun for Fast 5ns Modulation



- 0.3mm grid-to-cathode
- Convex cathode for max perveance

RHIC and Tevatron as Testbeds

possible to test at	RHIC	TeV
#1 head-on compensation	+	-
#2 Q-spreader/stabilizer	+	+
#3 soft hollow collimator	+	tested
#4 satellite killer	+	tested
in addition to		
#5 wire bblr compensation	*+*	*-*
#6 bunch-by-b dQ compens	*-*	*+*

Proposed Action Path

- Form an LHC eCompensation Task Force with a charge to perform feasibility study in ~1 year (FNAL, RHIC, KEK, LHC)
- Goal is to explore parameter space and effectiveness of head-on BBC in LHC and RHIC
- Same for jobs #2,3,4 (spreader, collimator, satellite-killer)

In case of positive outcome, next steps may include:

- Design of the TEL for RHIC 2008
- Modification of TEL for RHIC 2009-2010
- Demonstrate head-on compensation 2010-2011
- Install ELs in LHC and commission 2011-2012

First Step: Theory and Simulations

- Will Gaussian or truncated Gaussian e-current density distribution work (improve lifetime and reduce diffusion rates)?
  - Straightforward tracking with a weak-strong code
  - Is partial distribution helpful?
- Is there a better distribution?
  - from first principles, theory, analytical consideration
  - Effects are beta_LEL/beta*/sigma_z; or dP/P
  - check in numerical tracking
- Importance of e-p interaction in bending sections
  - Which of three configurations is better?
  - Is the choice tune dependent?
- Lifetime deterioration due to e-p misalignment:
  - e-beam straightness tolerances
  - relative e-p displacement, angle
- Effect of low-frequency variations dJ, dX on beam lifetime
- Ion cleaning efficiency tolerances
- Cross-interaction with wires in LHC – if there is any
- e-beam effect on coherent stability or strong-strong beam-beam effects

…finally – a hint for LHC:

up-to-date experience tells us that only hadron colliders which employ electron lenses can achieve luminosities above 2.3e32 cm-2 s-1