Using Electron Space-Charge in High Intensity Proton Accelerators

"*Electron Lenses*"
"*Electron Columns*"
"*Hollow e-beam Colimators*"

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(with input from A.Burov, G.W.Foster, V.Kamerdzhiev, G.Kuznetsov, Yu.Alexahin, V.Kapin, F.Zimmermann, L.Vorobiev, G.Smith, A.Drozhdin, A.Valishev, R.Assmann)

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Novel Accelerator Component

- Over the past decade, a new type of accelerator component has been developed at Fermilab – "electron lenses"
- It employs strong space charge forces of magnetized beam of low energy electrons (~10 keV) which acts on high energy (anti)protons

  [B-field has little effect]
- Technology is proven and available
- Applications growing:
  1. Compensation of beam-beam effects
  2. Removal of DC beam particles
  3. Space-charge compensation
  4. Collimation of p-, ion- beams

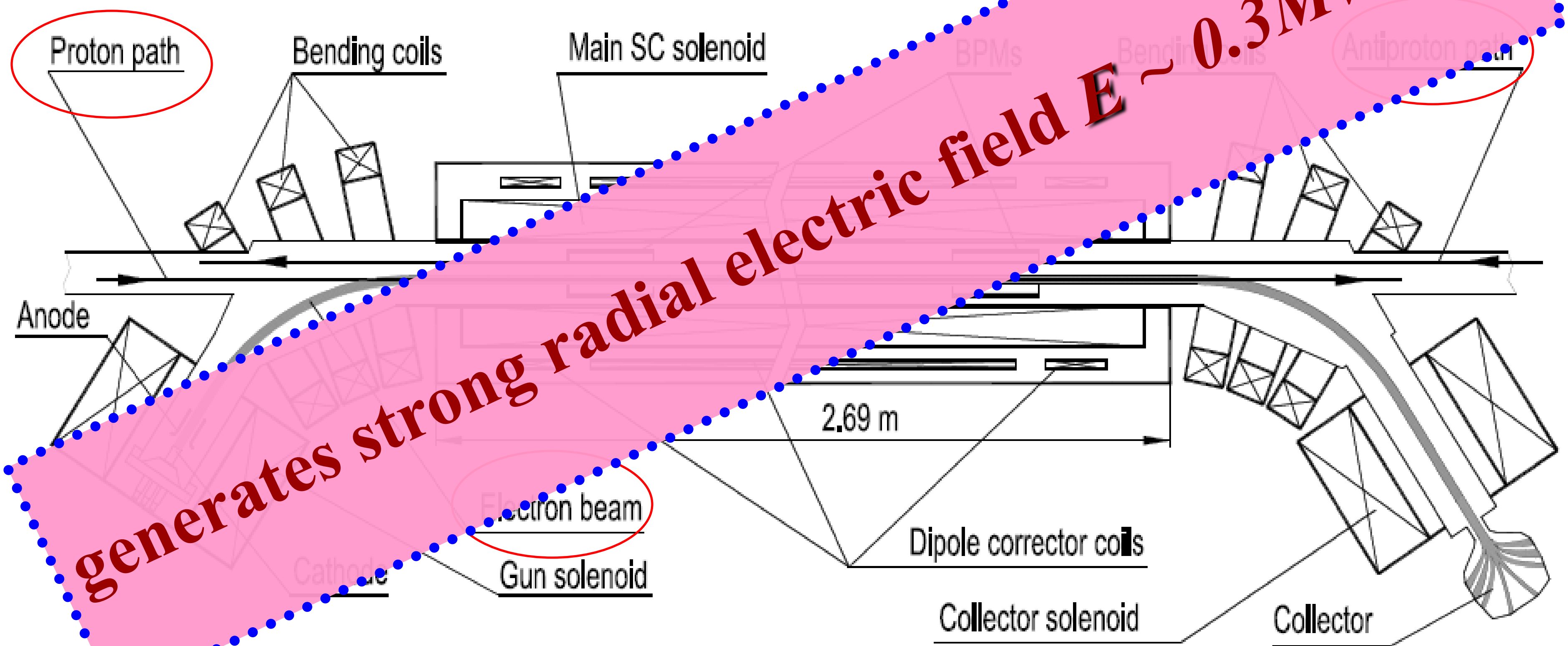
Content

- Overview of Tevatron "electron lenses"
- Beam-beam compensation in LHC and RHIC
- Space-charge compensation
  - Electron lenses
  - Electron columns
  - Possible R&D plan
- Hollow e-beam collimation
  - The idea
  - Possible R&D plan

What is Electron Lens

~4 mm dia 2 m long very straight beam of ~10kV

~1A electrons (~10^{12}) immersed in 3T solenoid

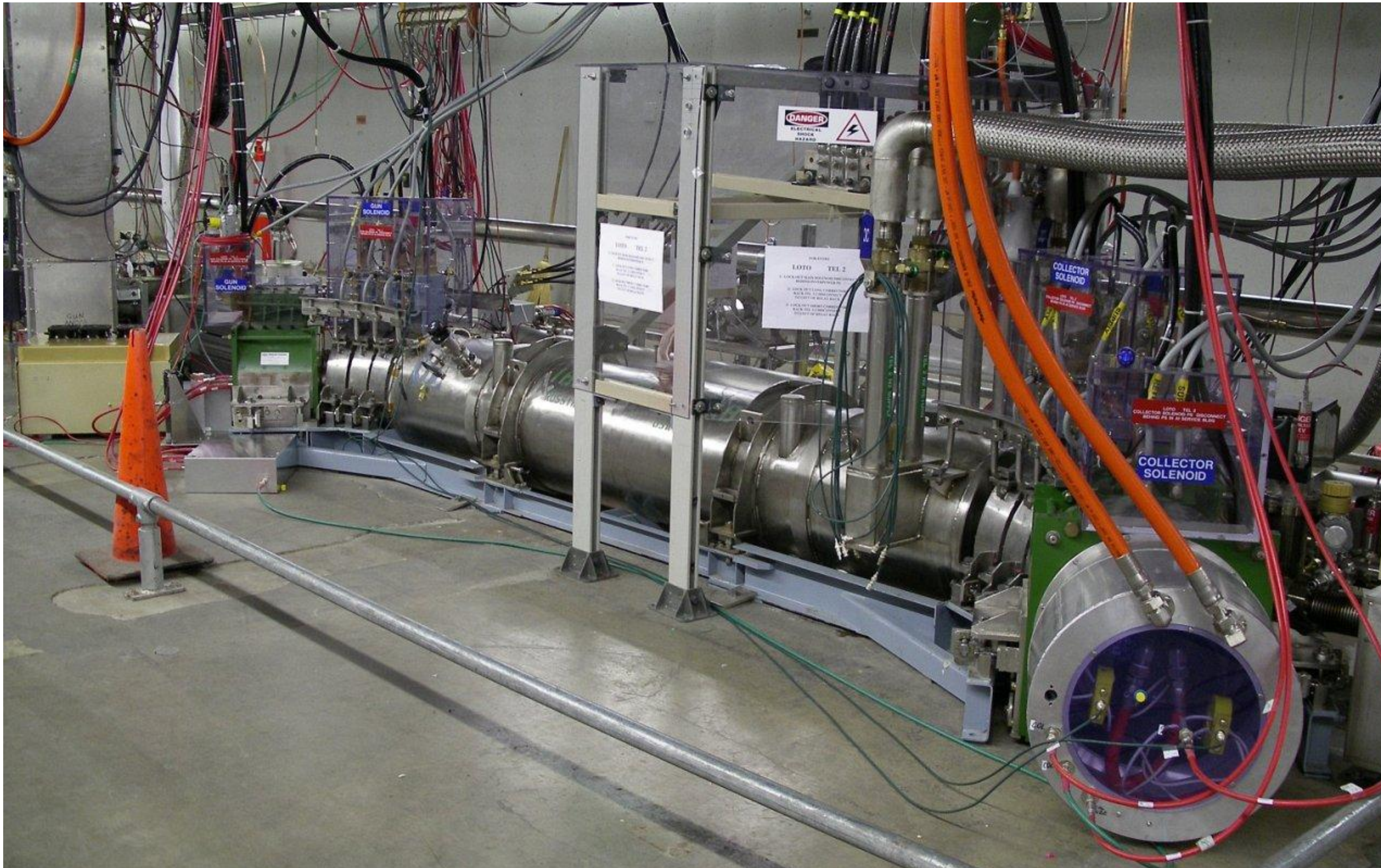


generates strong radial electric field $E \sim 0.3MV/m$

Technologies Developed/Employed

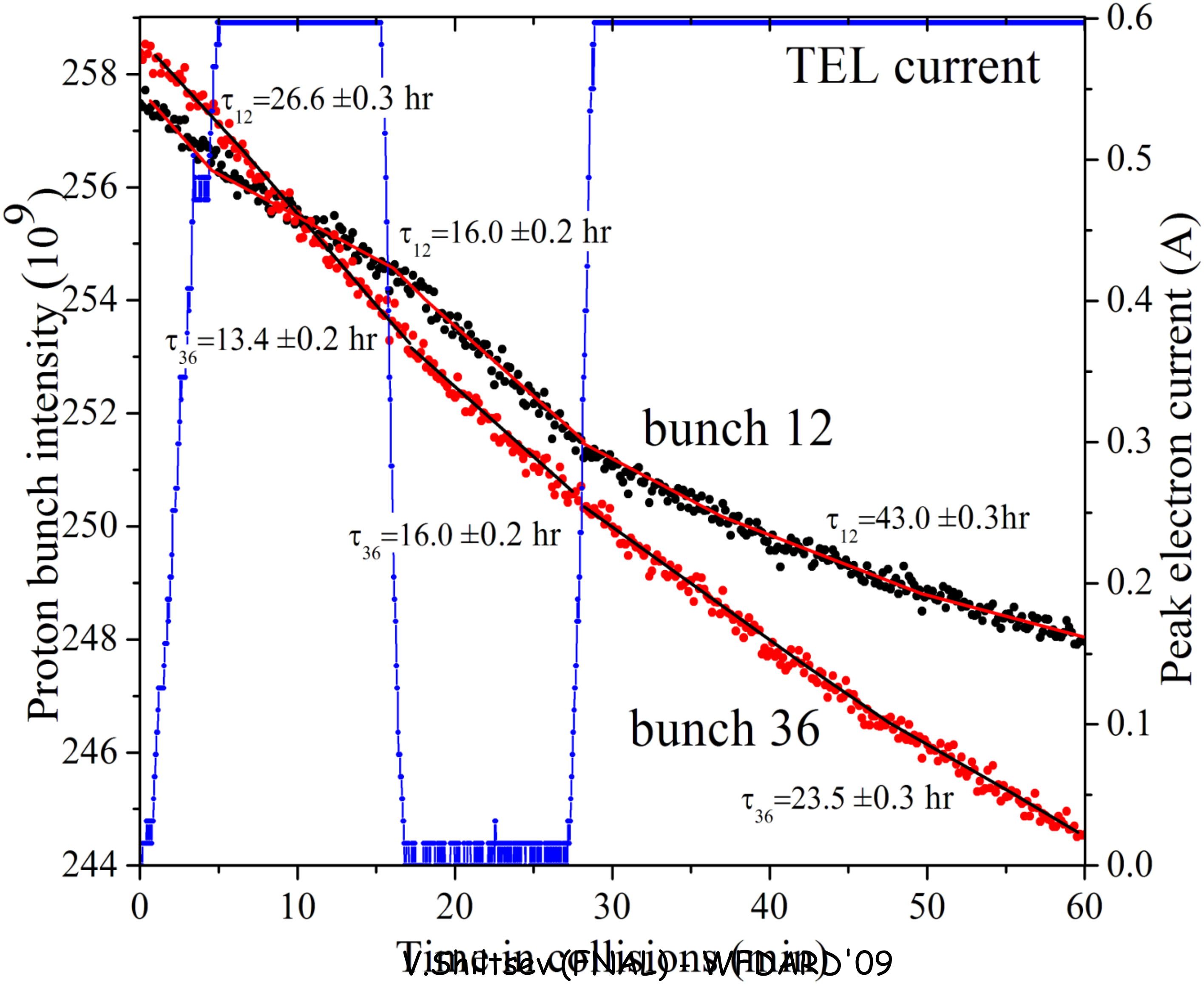
- >6T SC solenoids with very straight B-field lines and X,Y, X',Y' correctors
- Generation of magnetized electron beams with "any" (reasonable) profile of the current distribution from thermionic cathodes
- Fast CW HV modulators for e-guns
  - 8-15kV, 50kHz, 700 ns … very good t-to-t stability
- Novel beam diagnostics
  - Beam profile, 3-beam position monitors, etc

TEL2 In The Tunnel (A0)



Compensation of Beam-Beam Effects

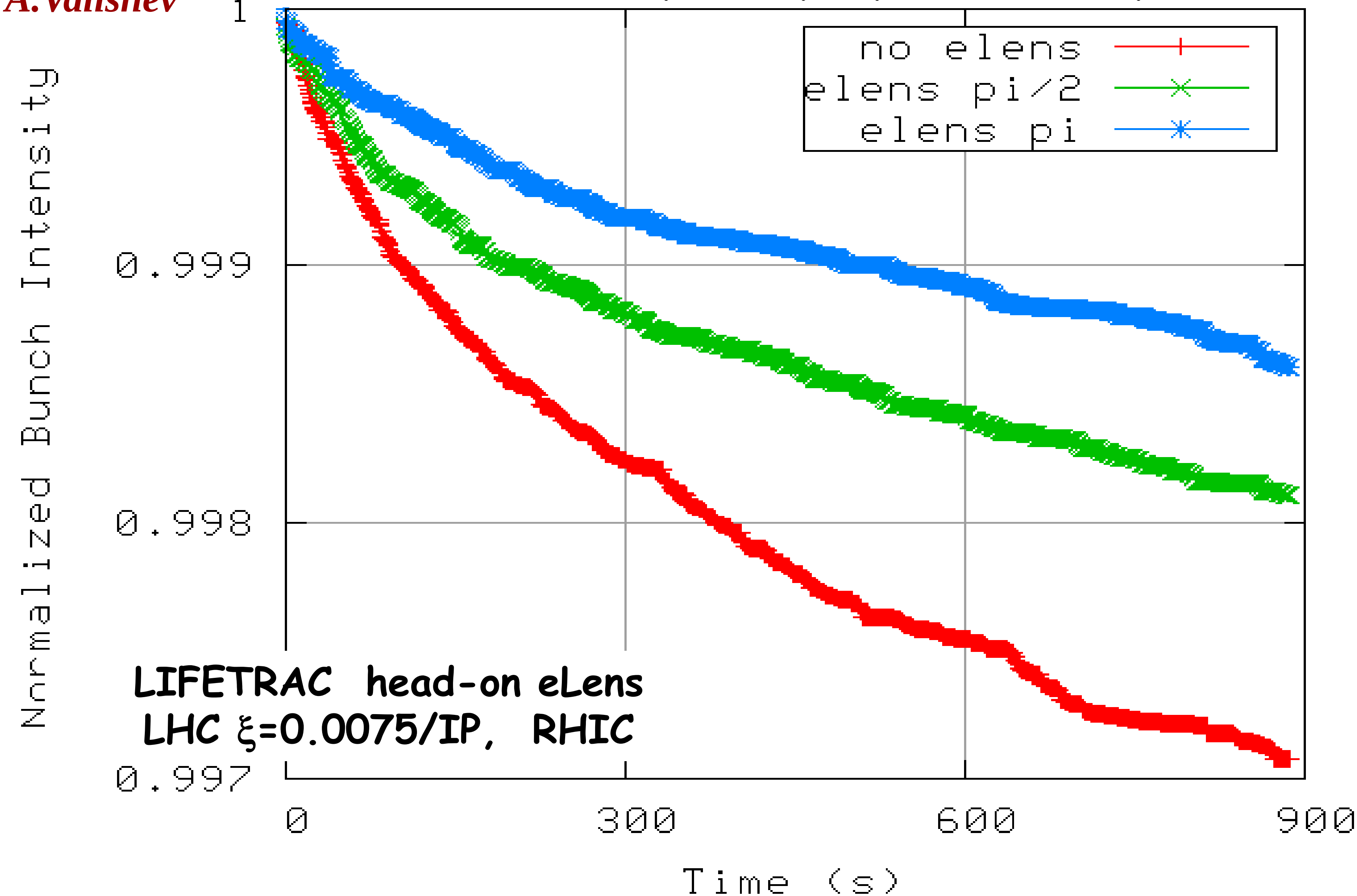
980 GeV proton lifetime improved by factor of 2, luminosity integral – by 5-10%



Electron Lenses for LHC and RHIC

A.Valishev

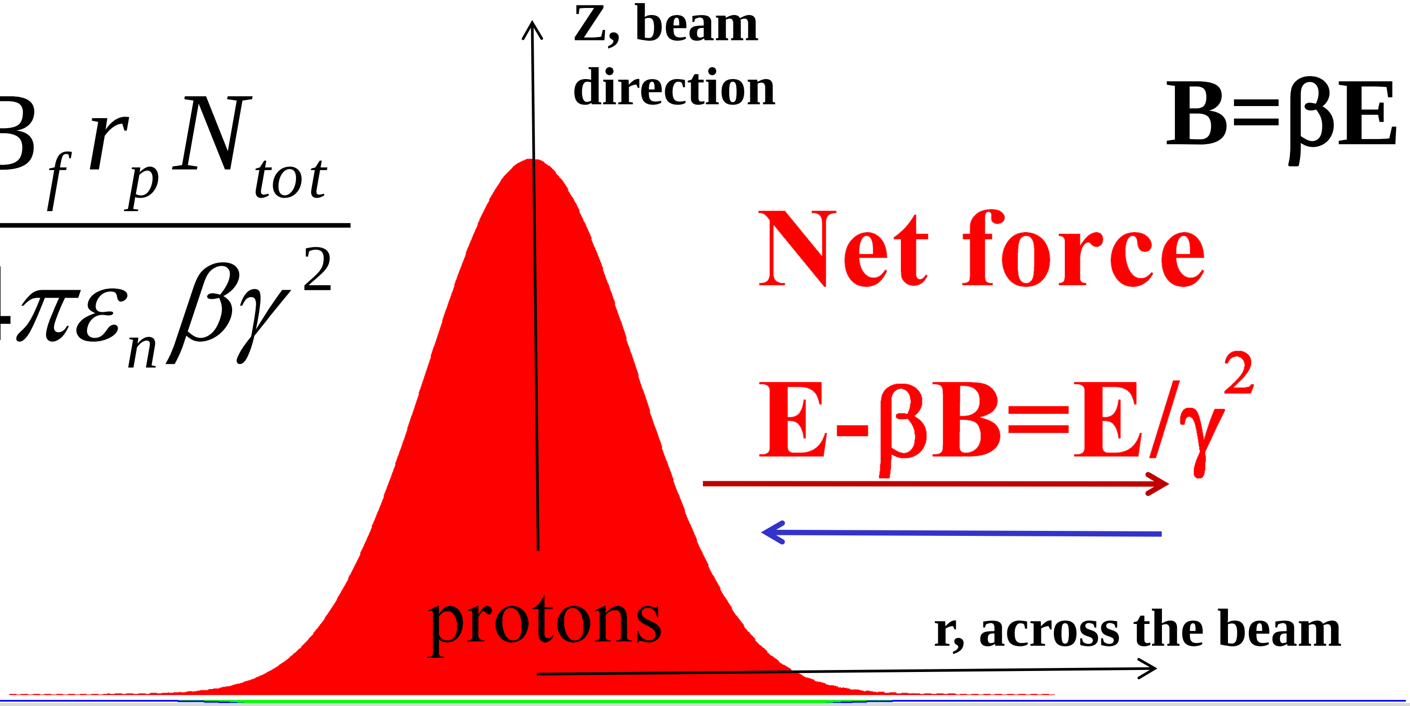
NB: Codes now can predict p-a(p) beam-beam performance



E-lenses for RHIC & LHC

- RHIC got ARRA funds to build 2 e-lenses for compensation of "head-on" beam-beam effects in proton-proton collisions
  - reduce emittance blowup, increase luminosity lifetime and allow high intensity p-bunches
- Fermilab and RHIC will collaborate
  - We'll help with "gaussian" beam e-gun, HV modulators
  - RHIC will develop promising technology of SC solenoids with cryo-coolers (of great interest for us)
- (I have no doubts that sooner or later) the LHC will need e-lenses for BBC (fewer Nb)

$$\xi_{SC} = \frac{B_f r_p N_{tot}}{4\pi \varepsilon_n \beta \gamma^2}$$

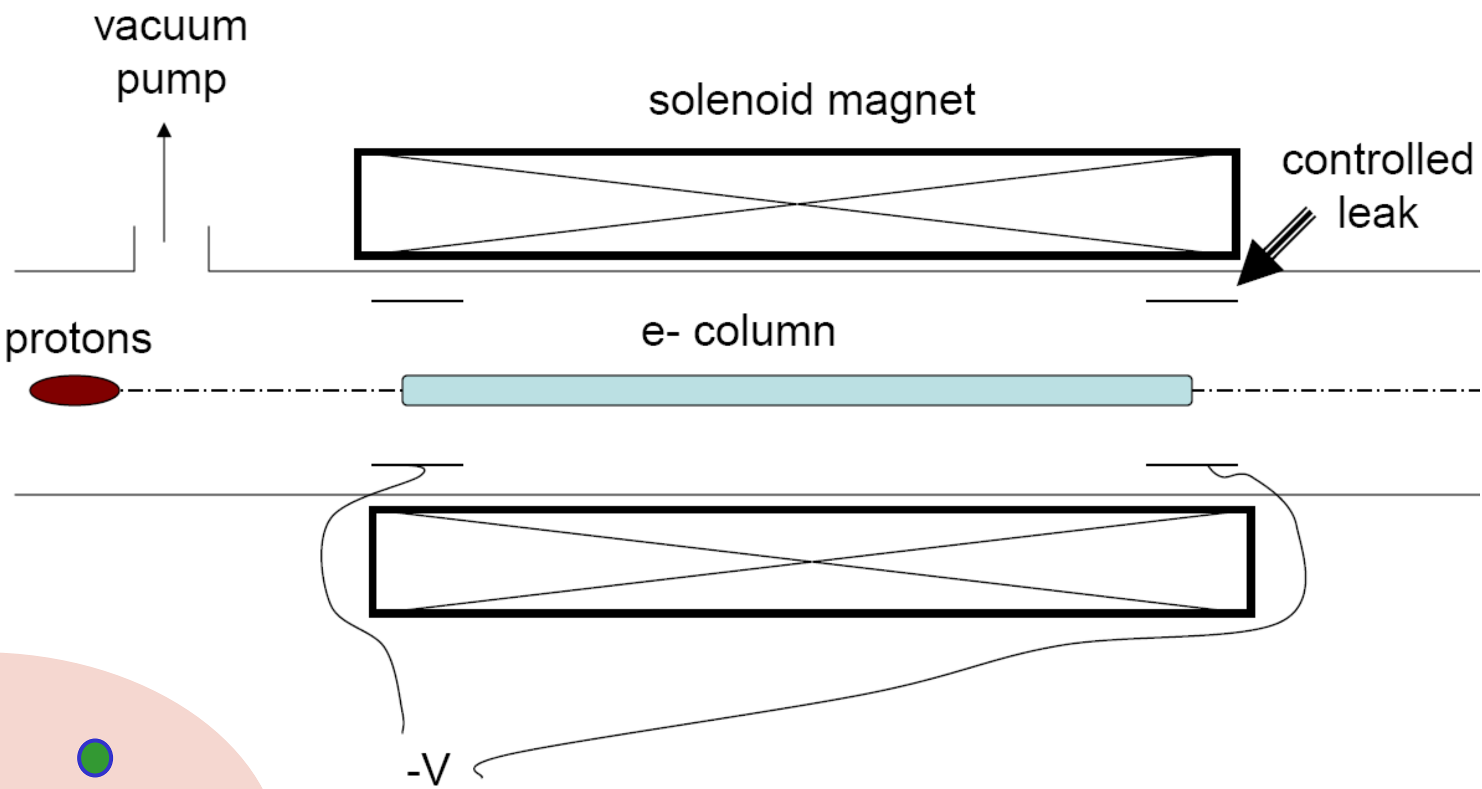


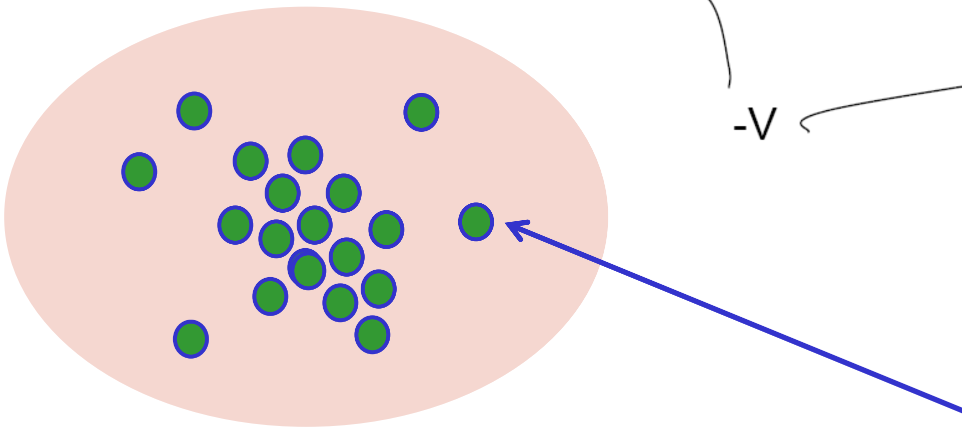
Issues, Ideas

1. Stability of the system (transverse motion)
2. (Dynamic) matching of transverse p-charge distribution
3. Appropriate longitudinal compensation (for not-flat proton bunches)

- System of "protons+electrons" is very unstable
  - ~"electron cloud": vacuum , instability, emitt. growth
- E-lenses for SCC proposed in 2000
  - Stable as e-beam is strongly magnetized
- Recent idea of *"electron columns"* looks very attractive (addresses #1, #2 and mb even #3)

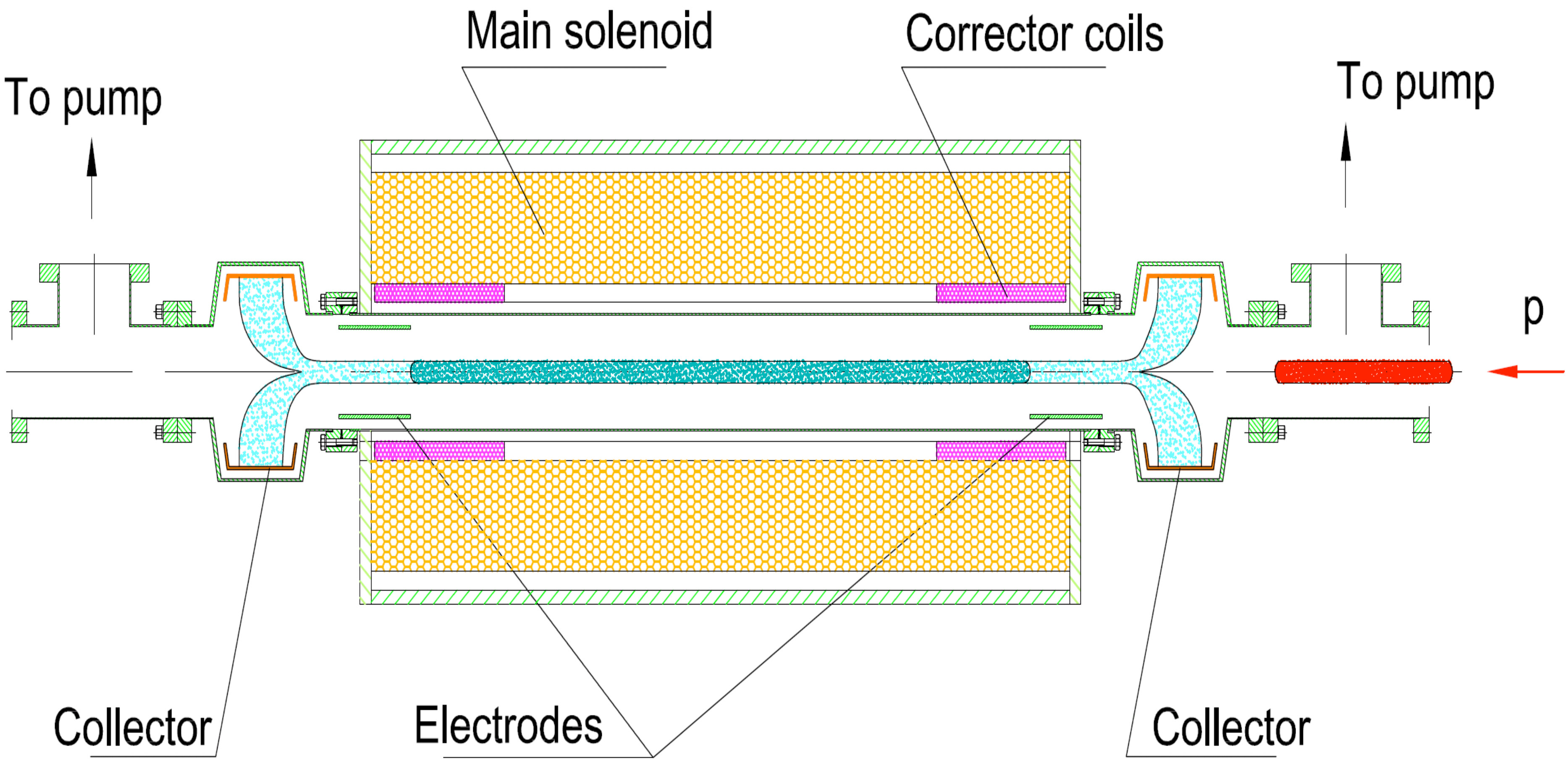
Electron Column (Idea)





Ionization electrons
Larmor circle, <1 μm

E-Column in reality



SCC with e-Columns

- Instead of uniformly distributing electrons around the ring with low concentration :

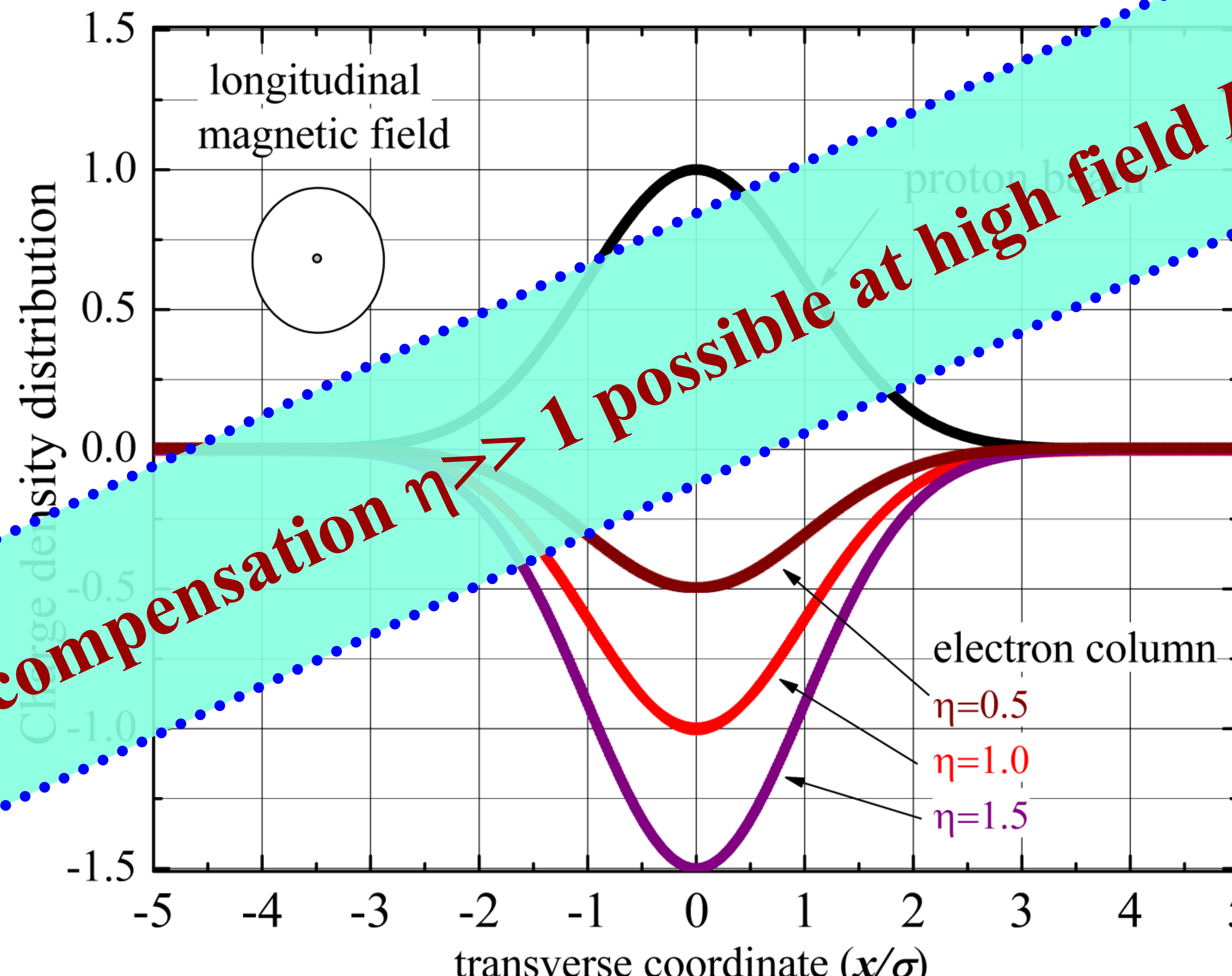
$$\eta = \frac{n_e}{n_p} = \frac{1}{\gamma^2}$$

- Electron columns will generate HIGH concentration of electrons but over a small fraction of ring circumference:

$$f = \frac{N_{EC} L_{EC}}{C} = \frac{\eta}{\gamma^2}$$

- It seems to be helpful to have Nec=P(eriodicity)

How high local η could be?



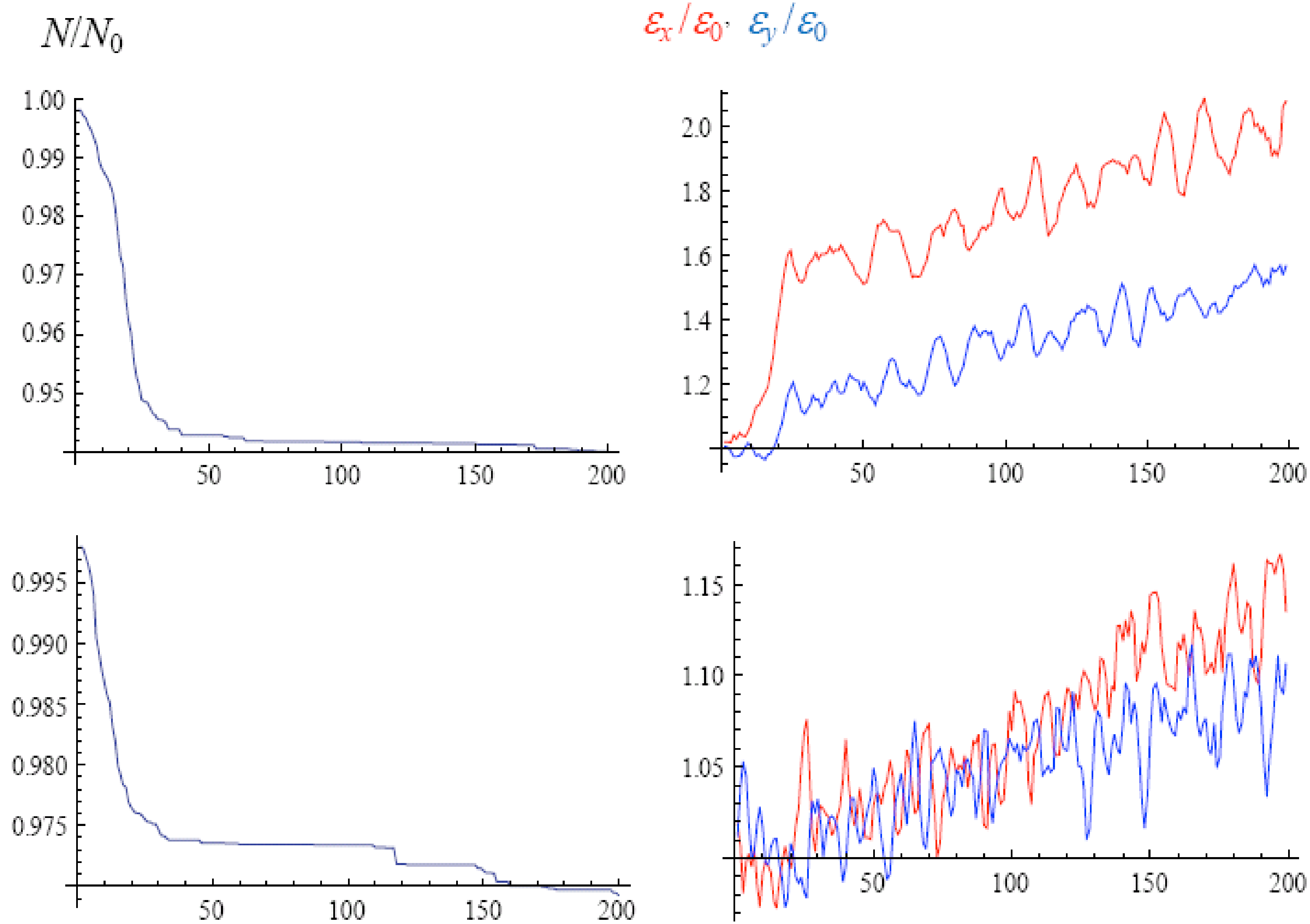
Overcompensation η>> 1 possible at high field *B*

SCC Simulations with e-Columns

Yu.Alexahin
V.Kapin

$f = 0$

$f = 0.5$



Some Examples

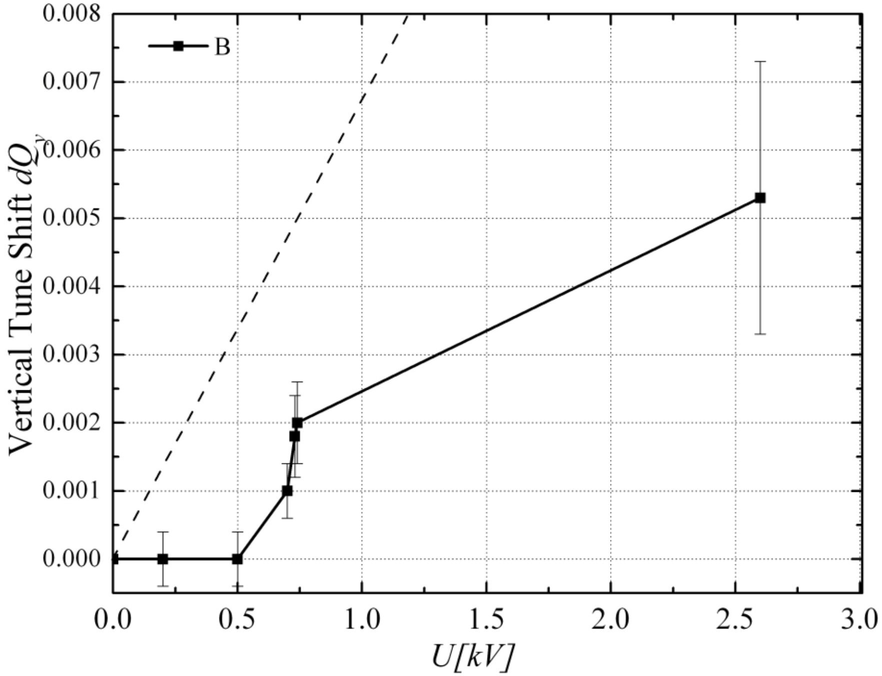
	C [km]	E[GeV]	ξ_{SC}	$N_{EC}L_{EC}$
Booster	0.48	0.4	~0.3	~120m
Main Injector	3.3	8	0.06+	~20m
Recycler PrX	3.3	8	0.12+	~40m
Debuncher μ2e	0.5	8	0.05-0.1	3x2m

Open Questions

1. Ideally, e-column tranverse density profile should be exactly as the proton one [B→∞]
2. That requires slow transverse diffusion
3. Rates of transverse and longitudinal diffusion, accumulation and e-column profile need to be understood
4. Technical specs need to be formulated (e.g. min B-field, vacuum, etc)

- First studies undertaken in Tevatron (TEL) and at a bench test facility →

Studies with TEL2 solenoid



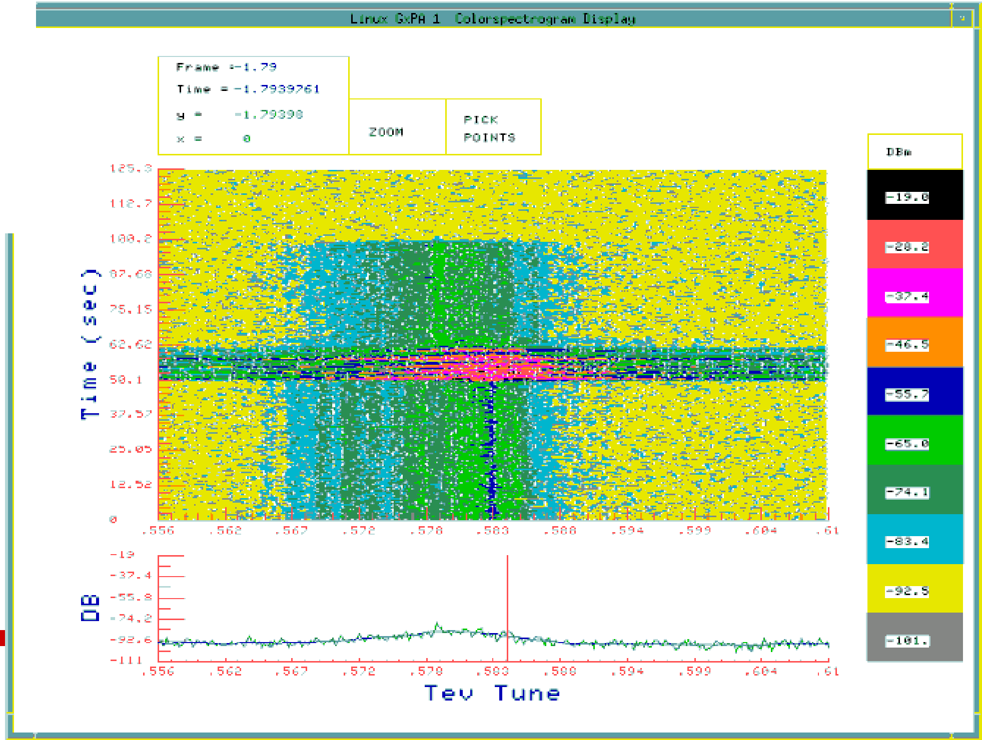
$$dQ_y = +\frac{N_e r_p \beta_y}{4\pi\gamma\sigma^2} \approx +0.0067\cdot U[kV] \qquad (1)$$

where r_p is the classic proton radius $1.53\cdot10^{-18}$ m, $\sigma\approx1.5$ mm is the rms proton beam and electron column radius, $\beta\approx100$ m is the vertical beta-function at the location of the TEL, and N_e is the total number of electrons accumulated if the voltage on the confinement electrodes is set to $-U$:

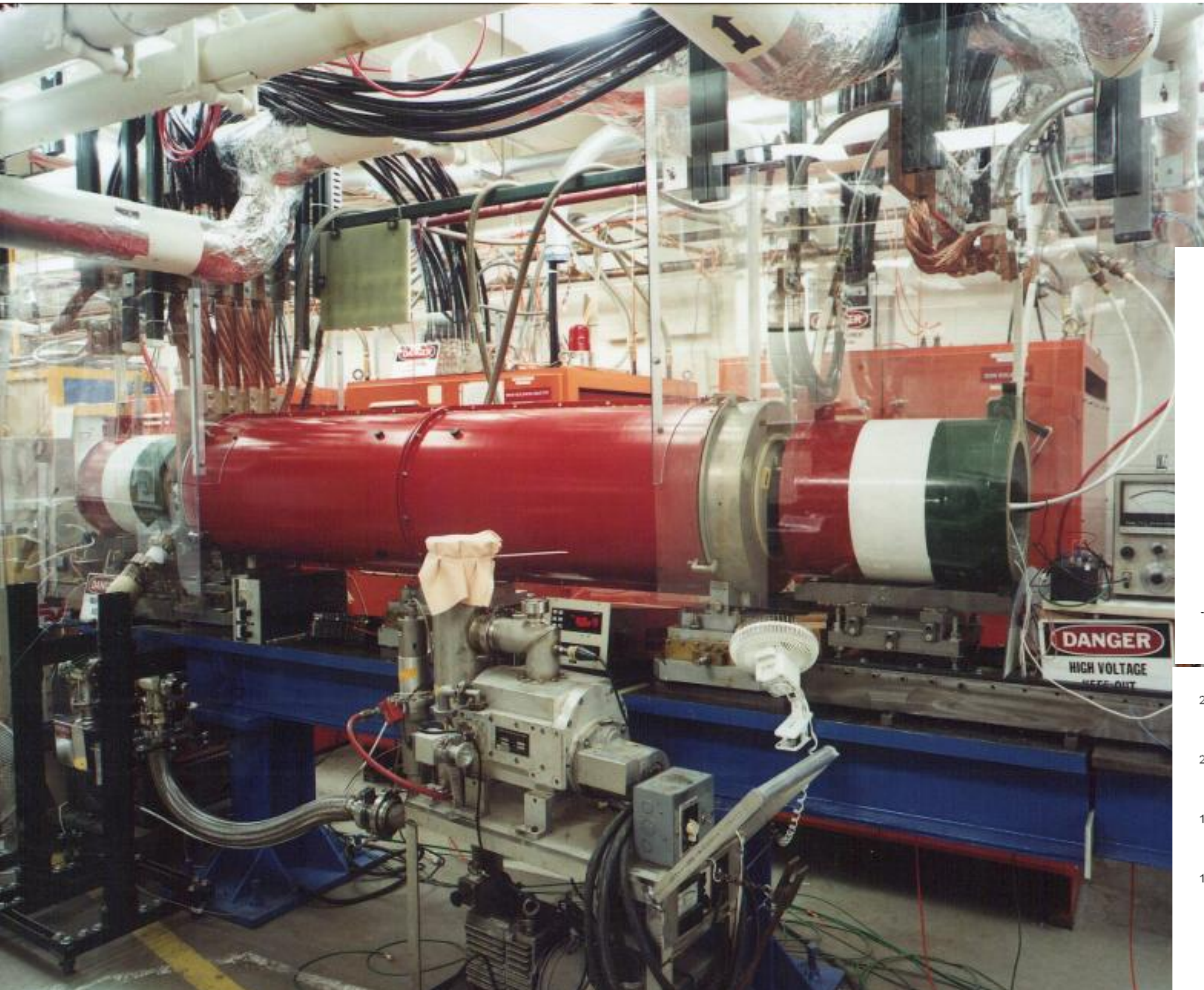
$$N_e = \frac{U[V]}{30\,(1+2\ln\frac{a}{\sigma})}\cdot\frac{L_{ec}}{ec} \approx 1.8\cdot10^{11}\cdot U[kV] \qquad (2)$$

The estimates above are valid under the assumption that the electron charge distribution follows the proton one as depicted in Fig.2.

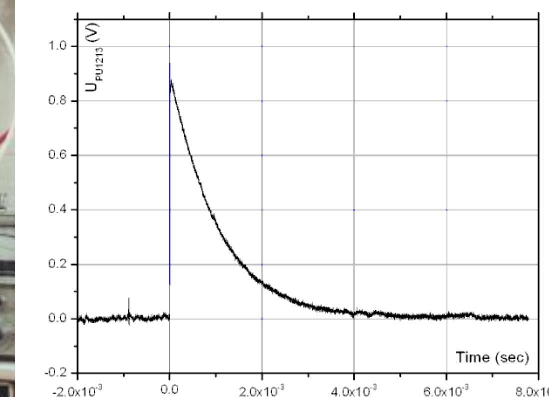
1. Tuneshift of upto +0.005 observed (!)
2. about ½ of expected
3. Coherent instability - ?

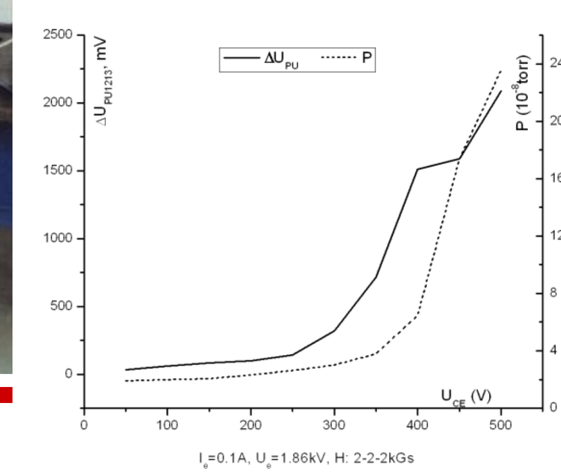


Moved studies to "Linac Lab" Setup



1. See significant charge accu-mulation in 4kG
2. In progress



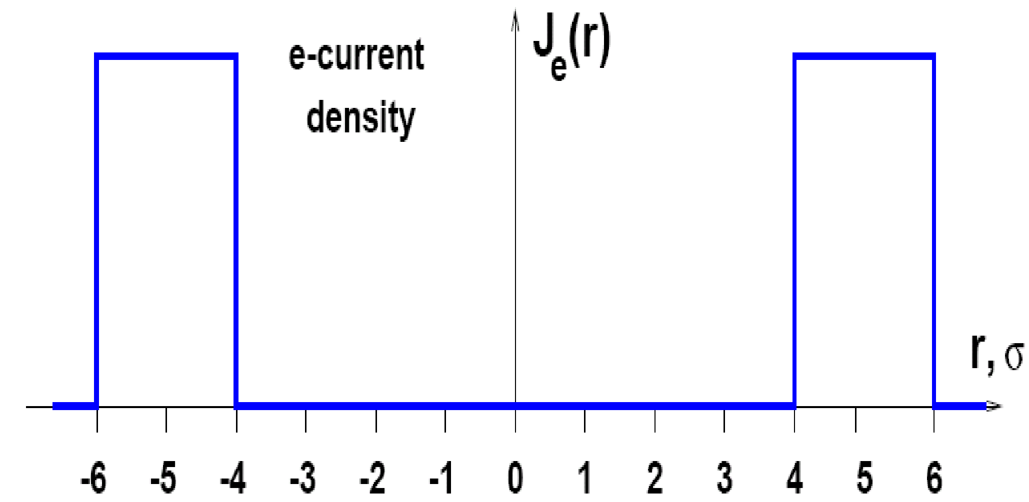


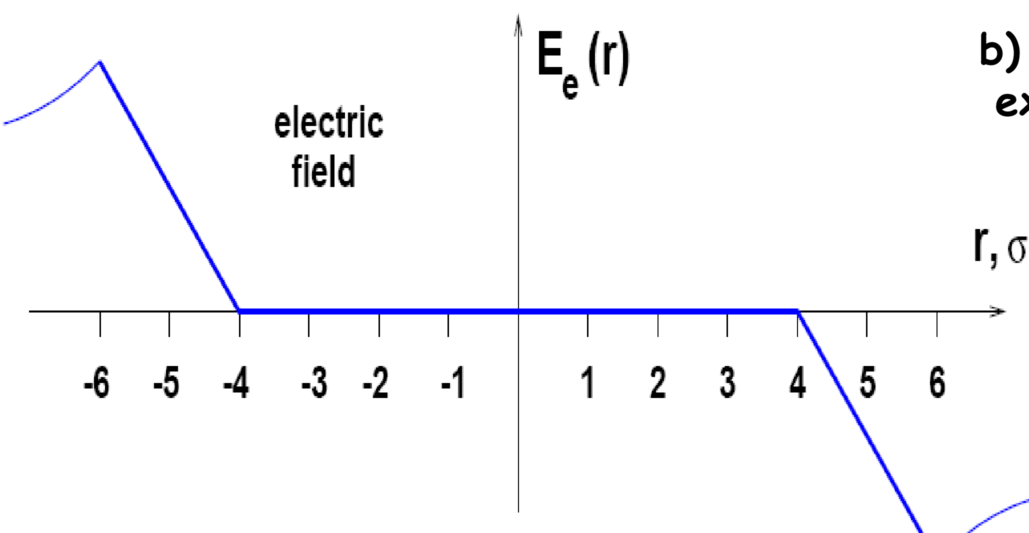
e-Lenses/e-Columns for SCC: R&D

- Technical goals :
  - Understand electron dynamics in e-columns (Linac Lab and TEL)
  - Simulate improvement of slow extraction from Debuncher with e-lenses/columns (mu2e)
  - Develop “stand-alone” SC solenoid technology for use in non-SC accelerators (cryocoolers)
  - Build an electron column or electron lens prototype for FNAL Main Injector and perform studies with highest available bunch intensity (max dQ_sc)

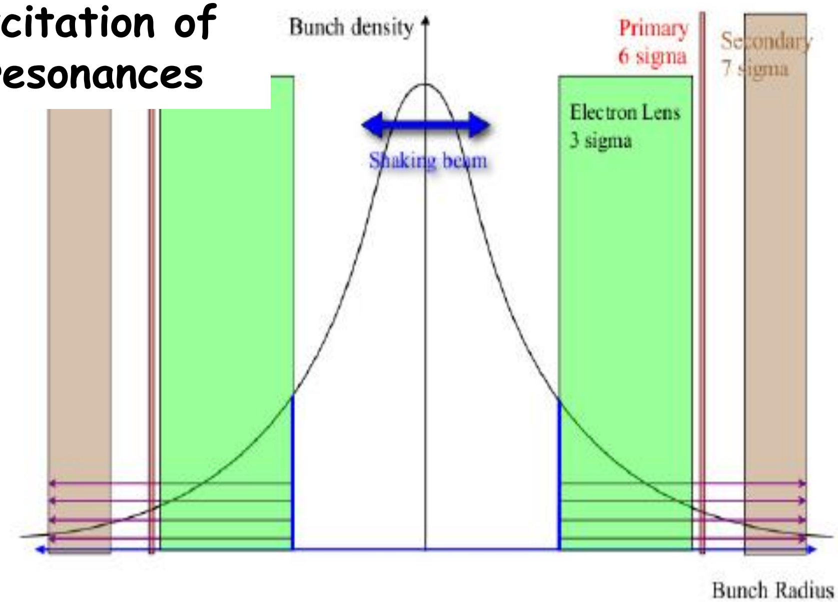
Hollow Electron Beam Collimator

no field inside

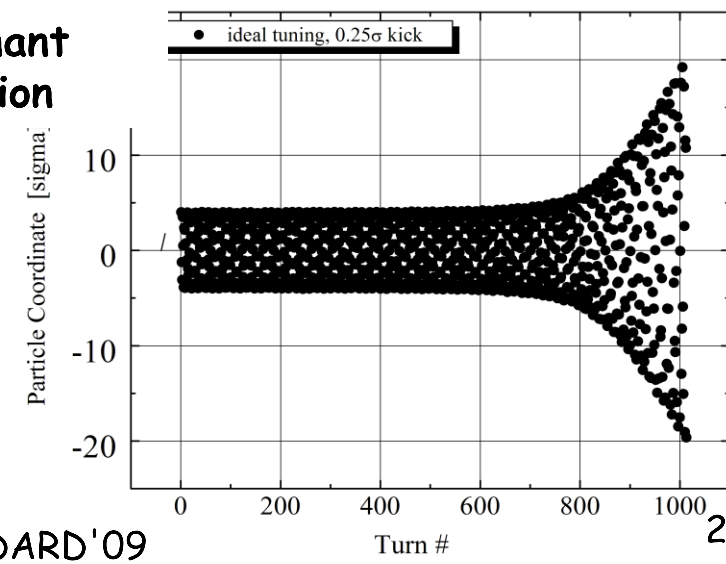




a) Excitation of NL resonances



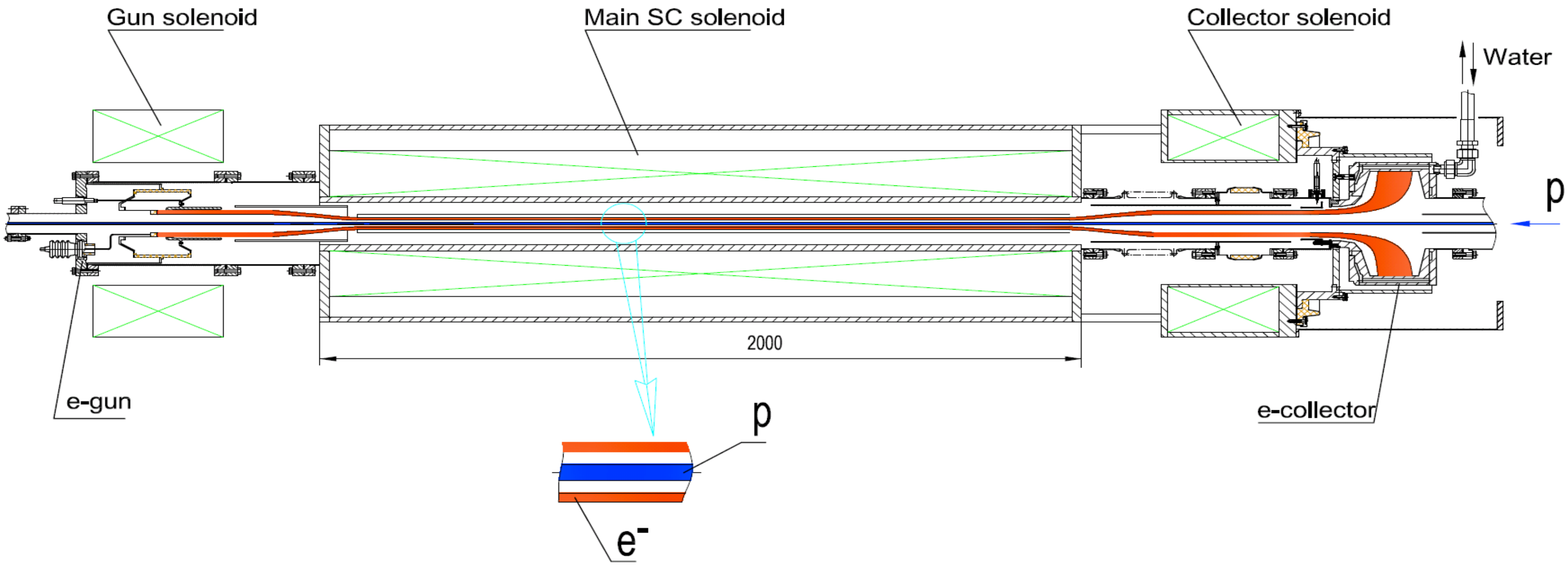
b) resonant excitation



Hollow e-Beam Advantages

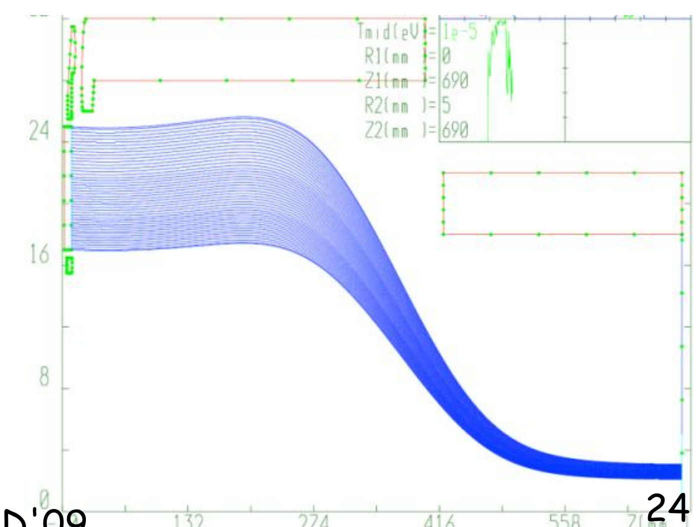
1. Halo particles as far in as 3 sigma could be effectively removed
2. The diffusion rate of halo particles would increase, which in turn would increase the impact parameter in the primary collimators (eff-cy)
3. The increase in the impact parameter would allow for the primaries (and secondaries) to be placed at greater sigma, decreasing the impedance contribution to the LHC.
4. Loss spikes in collimation system can be removed.
5. Since there is no matter-particle interaction, the e-scraper can be just as effective with ions.

Hollow E-Beam Collimator for LHC



Differencies from E-lens:

1. Straight
2. Ring cathode and collector
3. Larger compression (?)



Hollow e-scraper: R&D Plans

- Technical goals :
  - Develop a 10-15 mm hollow beam electron gun (suitablke for Tevatron E-lens), test it and measure its profile
  - Install in in TEL2 and operate (beam studies) in DC regime
  - Design TEL2 modification with hollow cathode/collector and straight configuration → for possible test at the end of Run II
  - Build an electron scraper for LHC (→ mb test at RHIC→) install in the LHC

Summary

- New types of electron-beam based accelerator elements have been/are being developed:
  - Electron lenses for beam-beam compensation
  - E-lenses/columns for space-charge compensation
  - Hollow e-beams for proton /ion halo collimation
- Development of these tools is well in line with general trend (at FNAL) toward high intensity high power beams of protons (Project-X, mu2e, NF/MC front-end, etc) and thus has to be supported
- More applications possible
  - SC in linacs -?
  - Slow extraction out of the part of beam -?
  - "RF quadrupole" – fast focusing element -?