Fermilab

Electron Lenses in Tevatron, RHIC and LHC

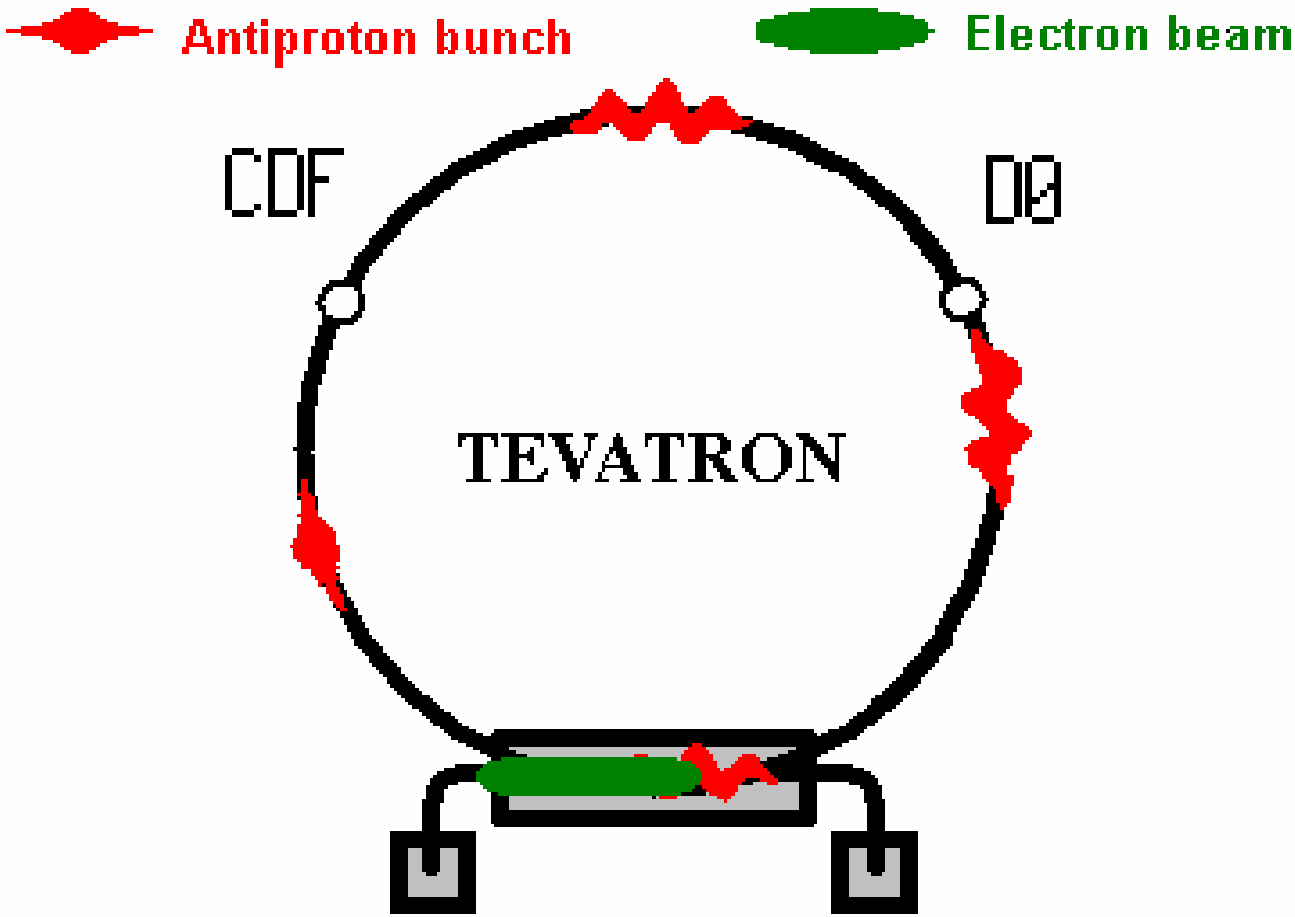
November 11, 2005

Vladimir Shiltsev

Content:

- TEL-1 / TEL-2 in Tevatron
- TELs in RHIC
- TELs in LHC

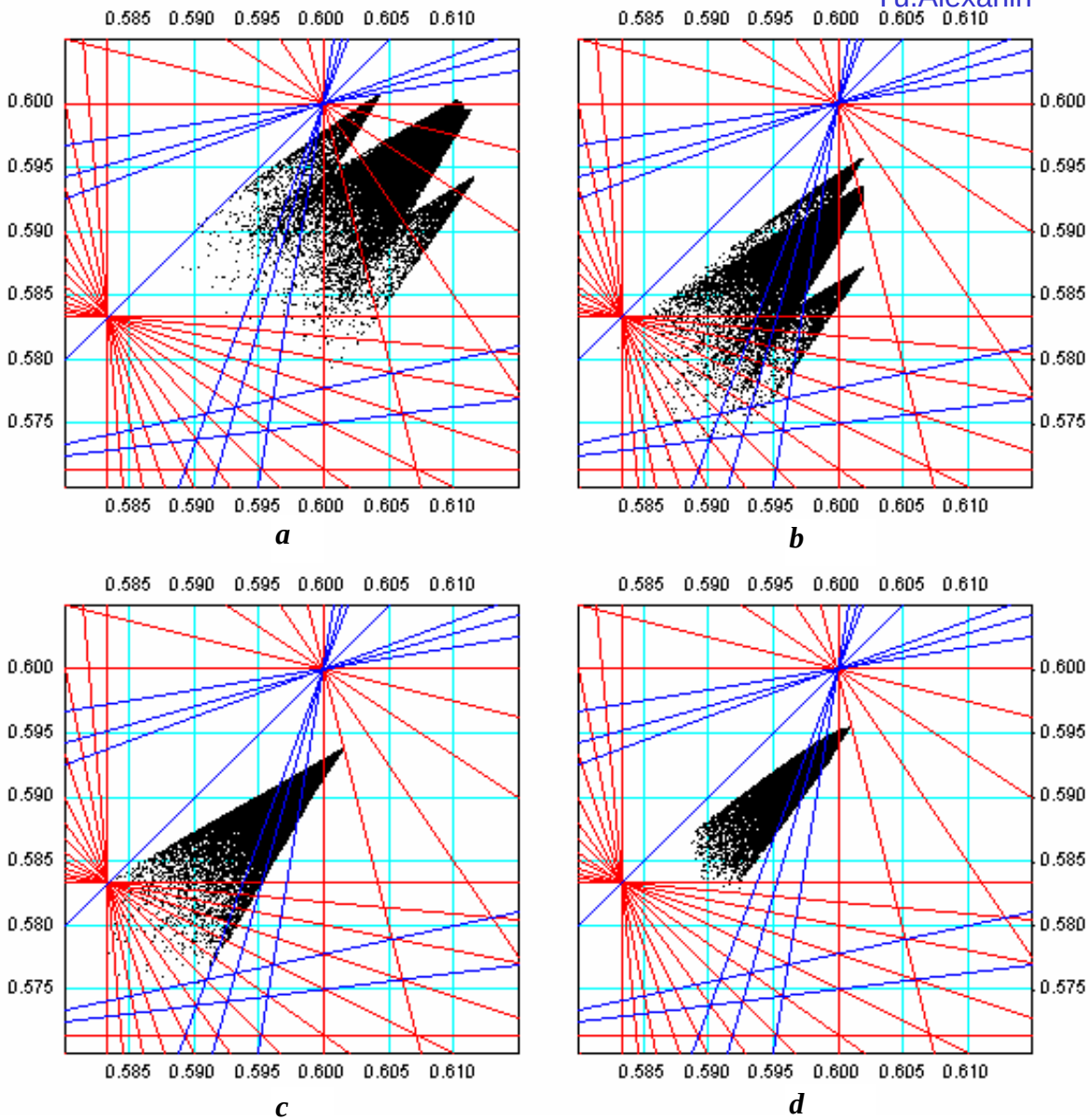
Original Idea Was…



"…to compensate (in average) space charge forces of positevely charged protons acting on antiprotons in the Tevatron by interaction with a negative charge of a low energy high-current electron beam " (1997)

Compensation with Two TELs (ca 2000)

Yu.Alexahin



Tev Run II: 36x36 bunches in 3 trains

compensate beam-beam tune shifts

- a) Run II Goal
- b) one TEL
- c) two TELs
- d) 2 nonlinear TELs

requires

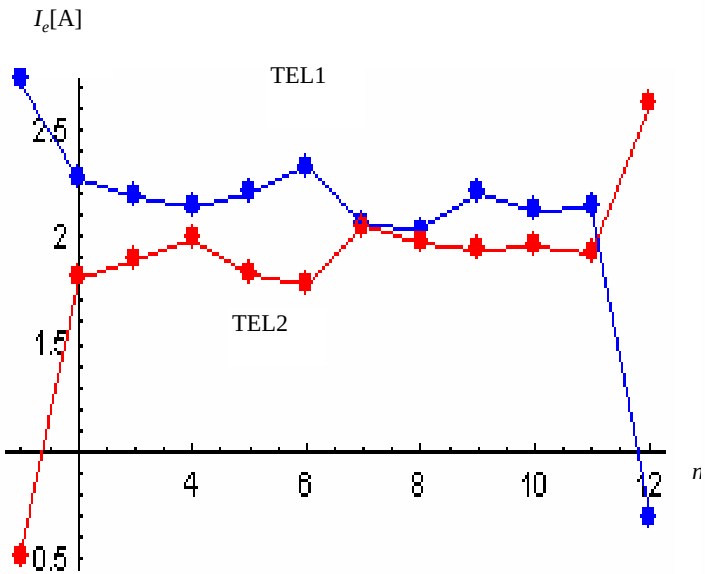
- 1-3A electron current
- stability dJ/J<0.1%
- e-pbar centering
- e-beam shaping

v

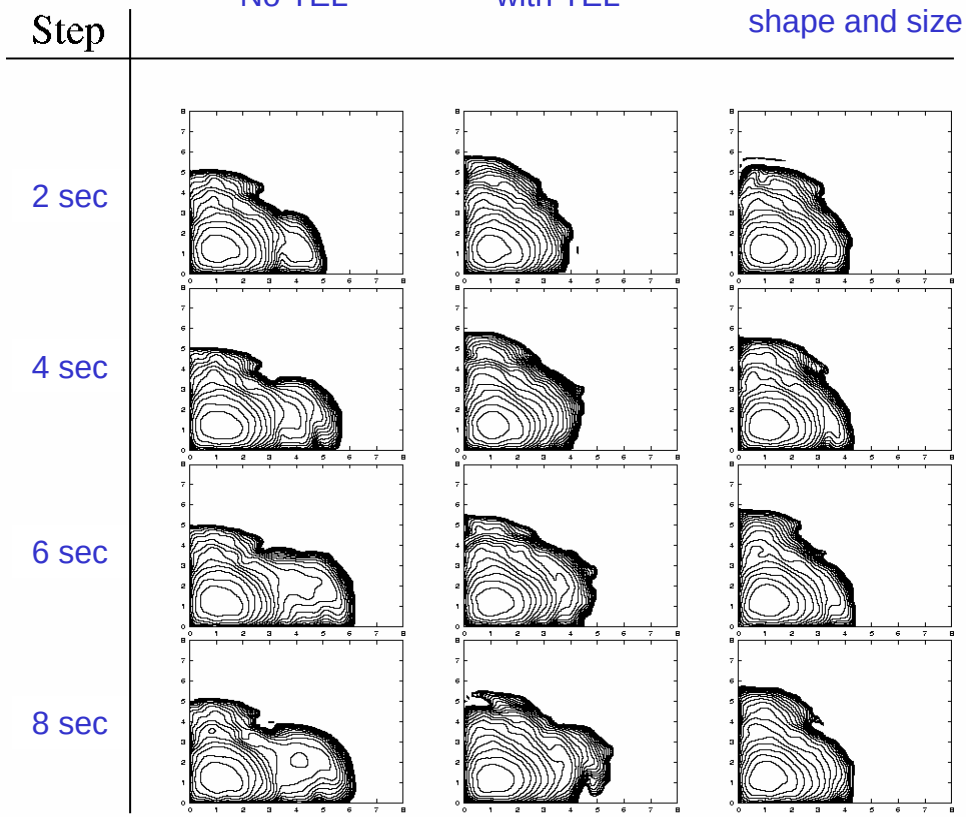
Ultimate Expectations (circa 1998-2000)

Better lifetime and smaller emittance growth of 6 out 36 bunches → ~5-10% in integrated luminosity

V.Shiltsev, Yu.Alexahin , D.Shatilov

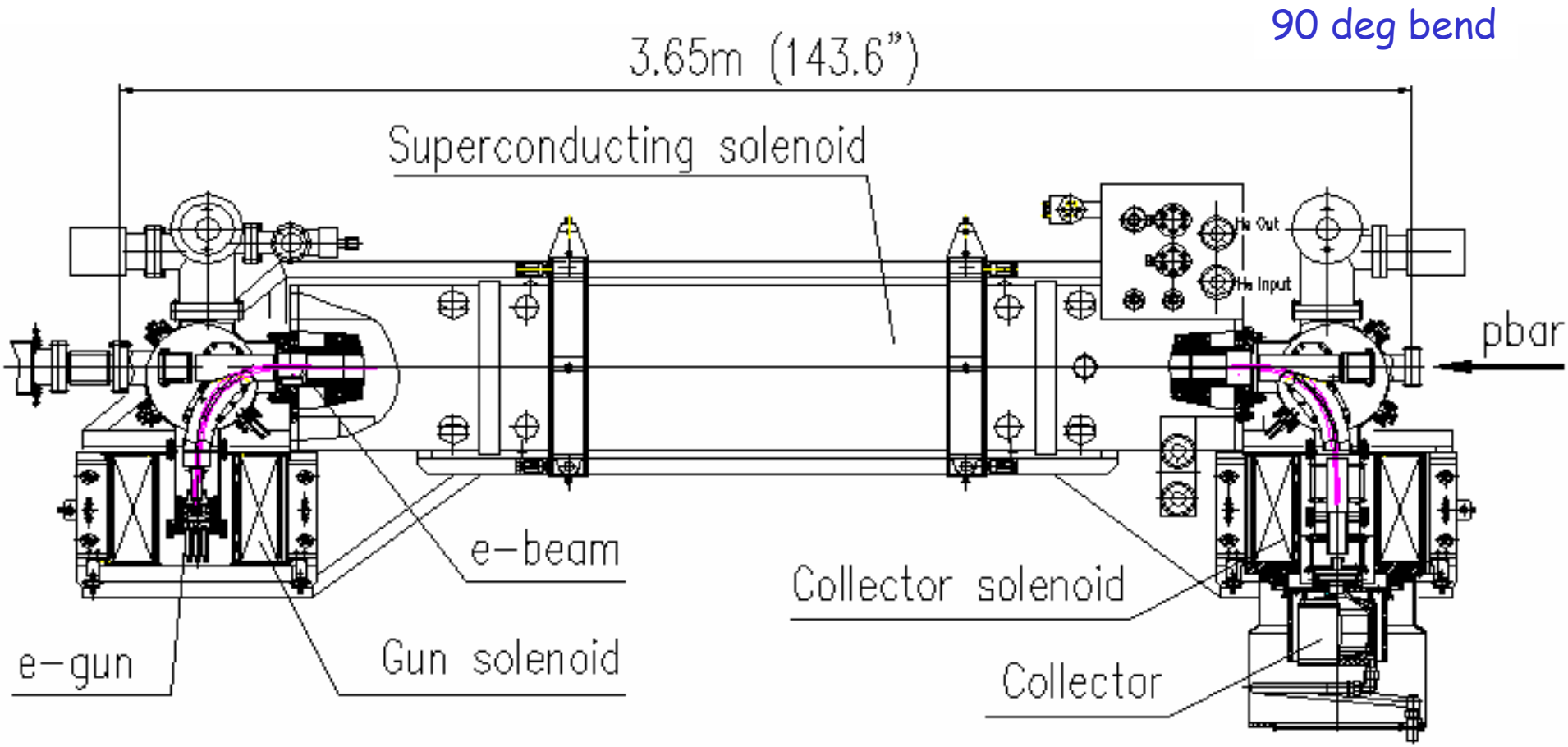


Electron currents in the two TELs as seen by different antiproton bunches #1 to #12



prototyping started in '98 →

Tevatron Electron Lens #1 (TEL-1)



+ HV Modulator, HV+HC PSs, Cryo, QPs, Vacuum, Controls, Diagnostics, Cables

Tevatron Electron Lens in the Tevatron Tunnel, sector F48

Things Upstairs : HV+HC PSs, CQPs, Controls, etc

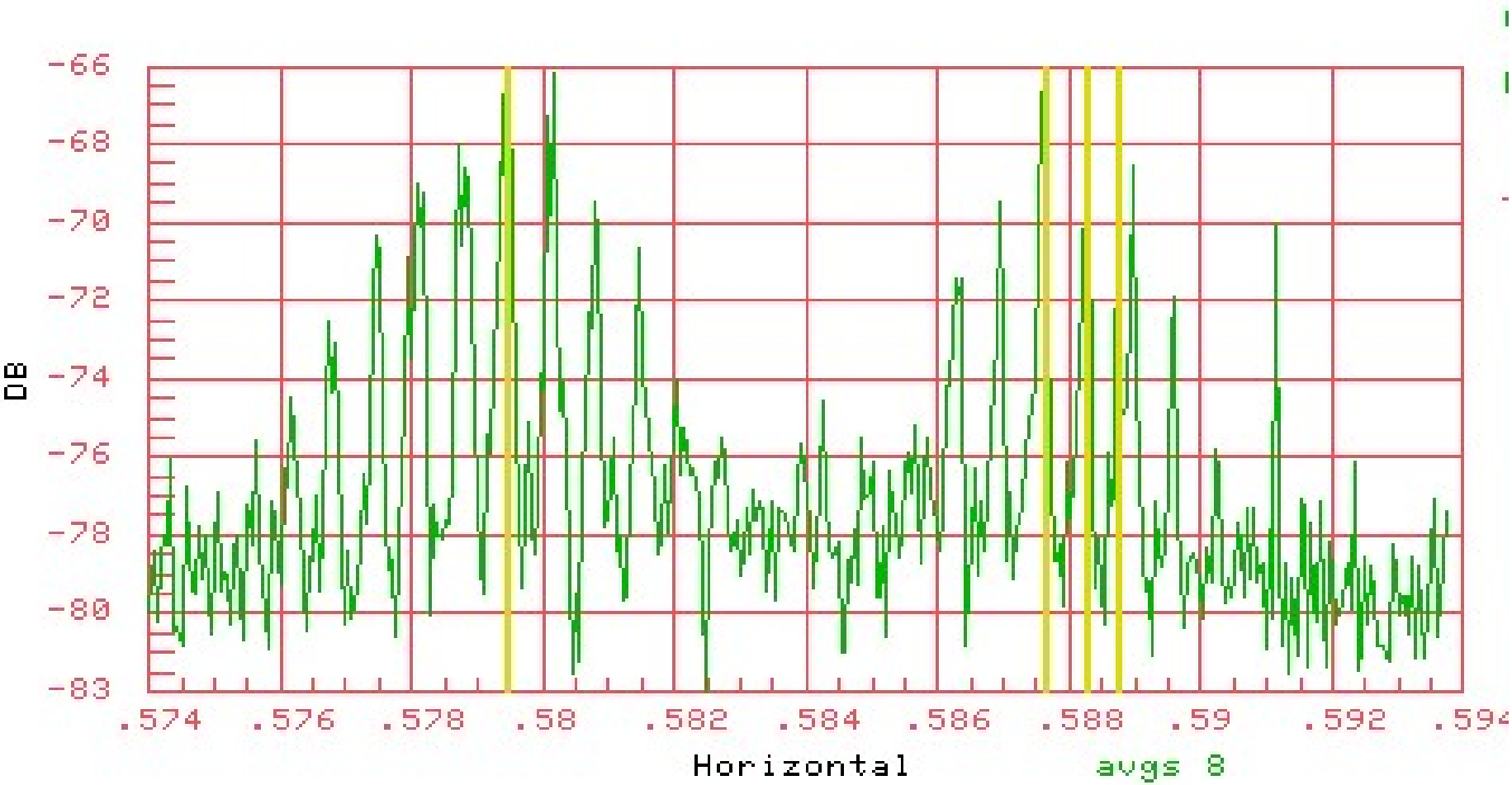
Total ~10 racks of electronics and PSs (e.g. 2kA 0V and 5A 10kV)

Cost of the fully loaded system ~600k$

Installation in the tunnel took 2 days + 5 days of baking (not count cable pulls and cryo preparations)

Installation /checkup upstairs took about 8 weeks

Tuneshift dQ_{hor}=+0.009 by TEL

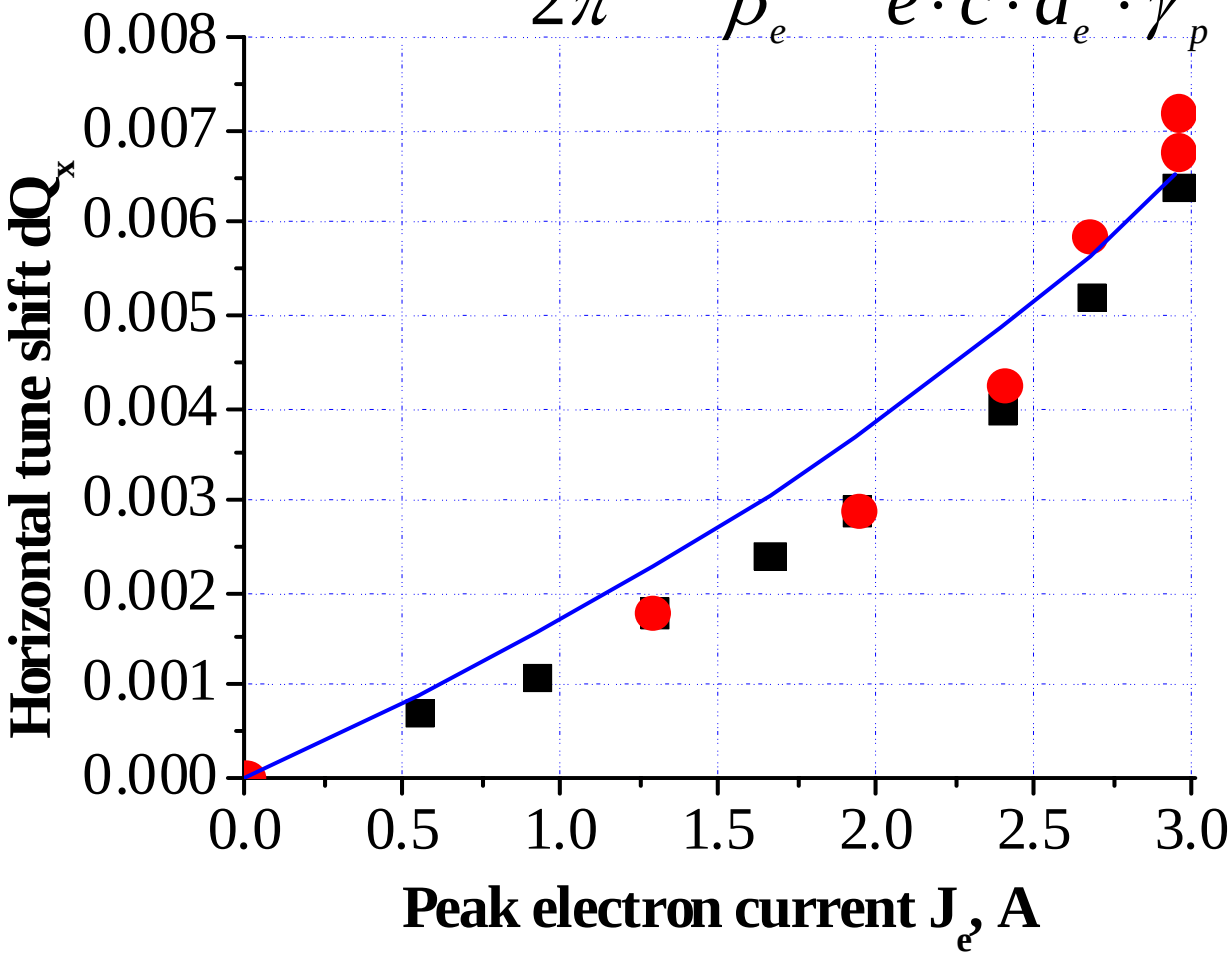


- Three p-bunches in the Tevatron, the TEL acts on one of them

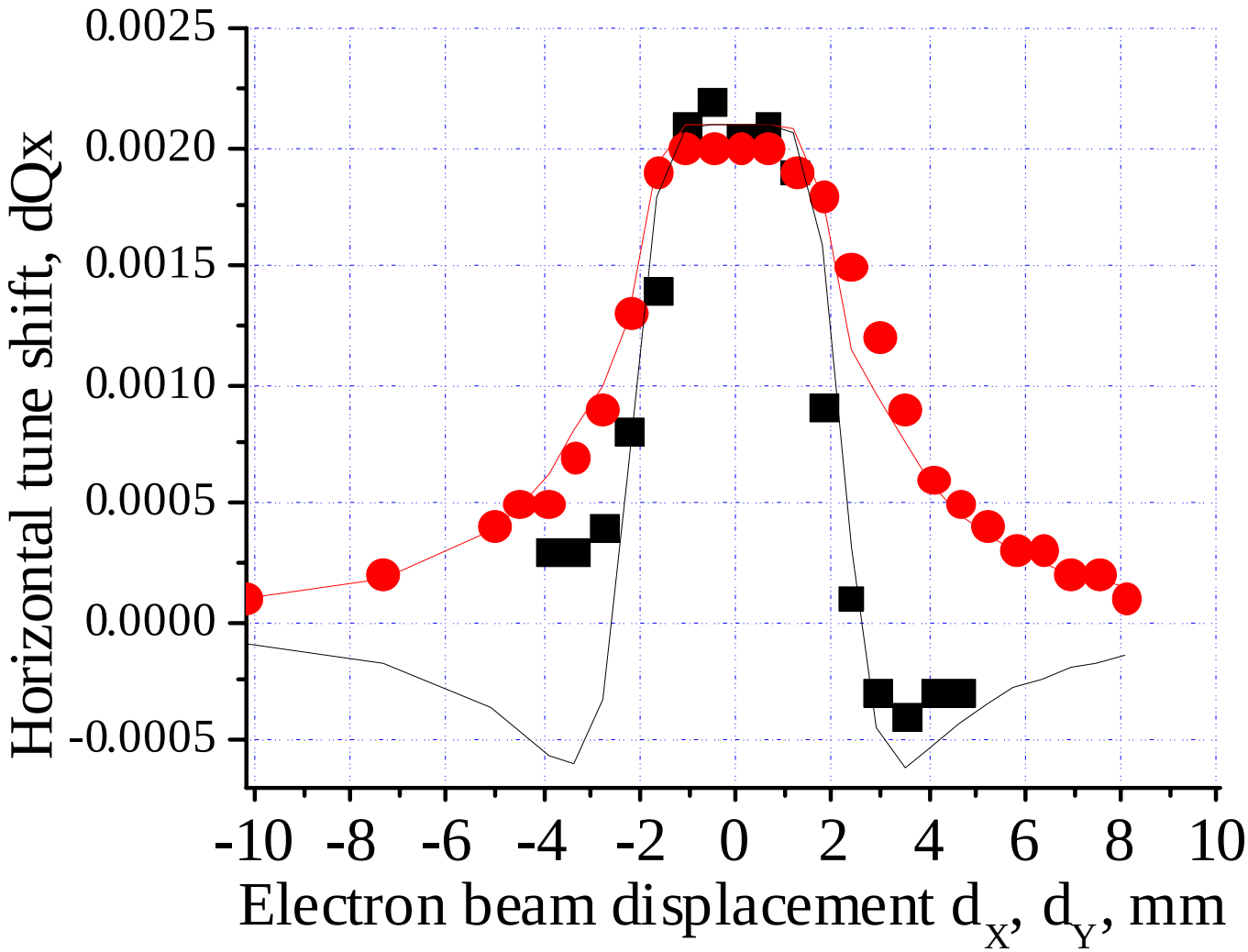
TEL in Tevatron: tuneshift as predicted

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

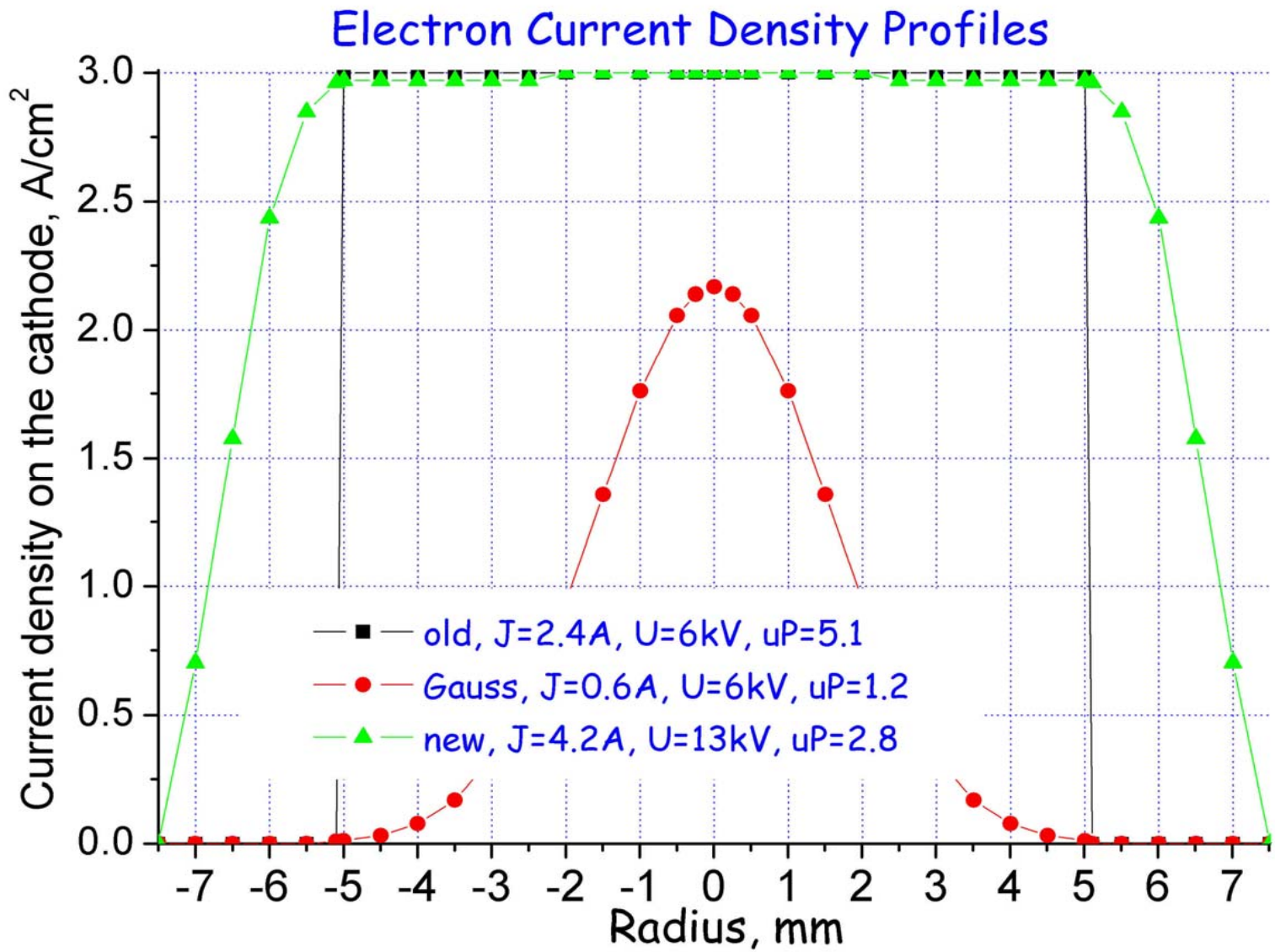
a=1.7mm
L=2m
E=980GeV
beta_e=0.2



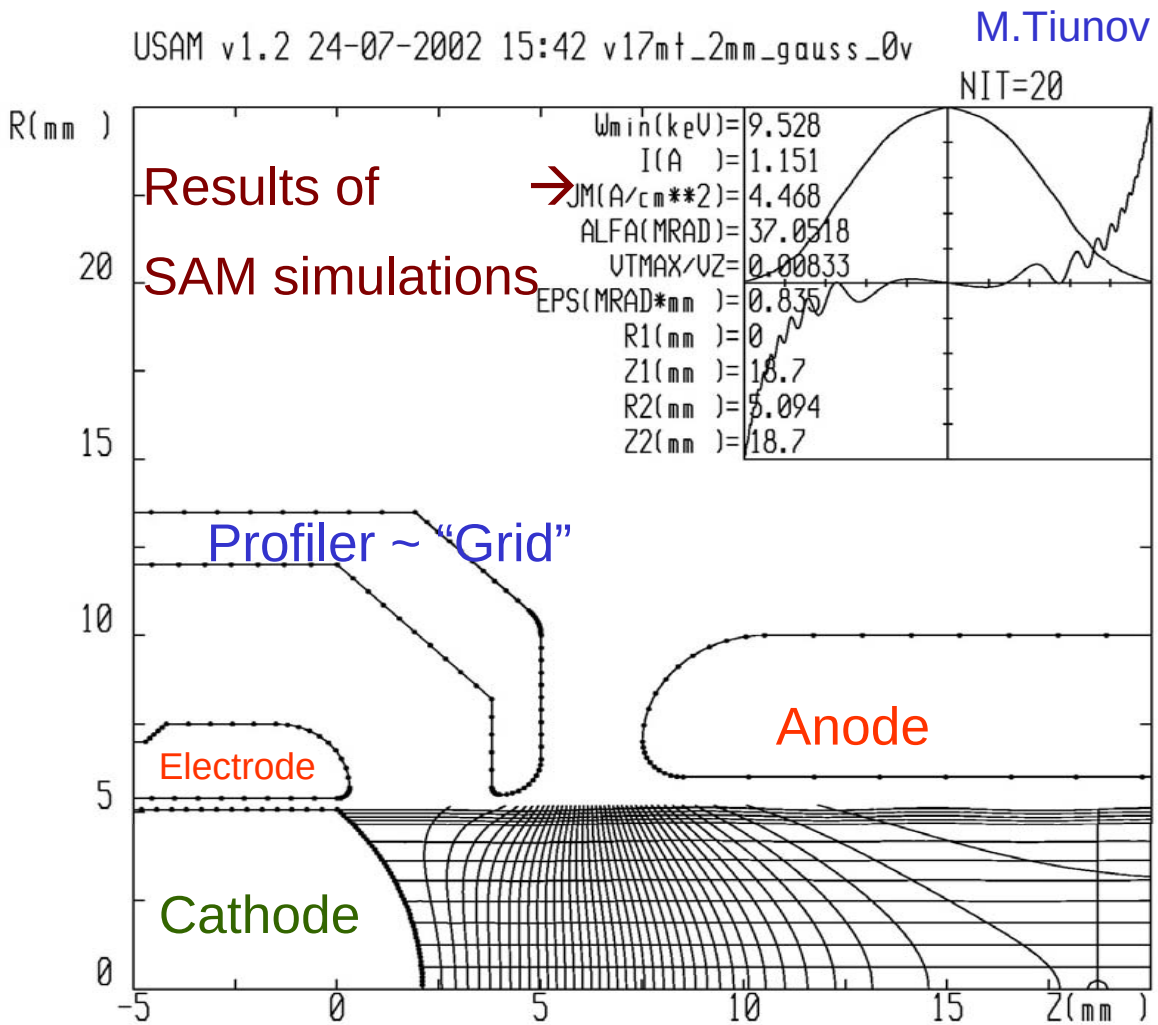
TEL : tuneshift vs e-position – gun #1



We can create beam profile we want

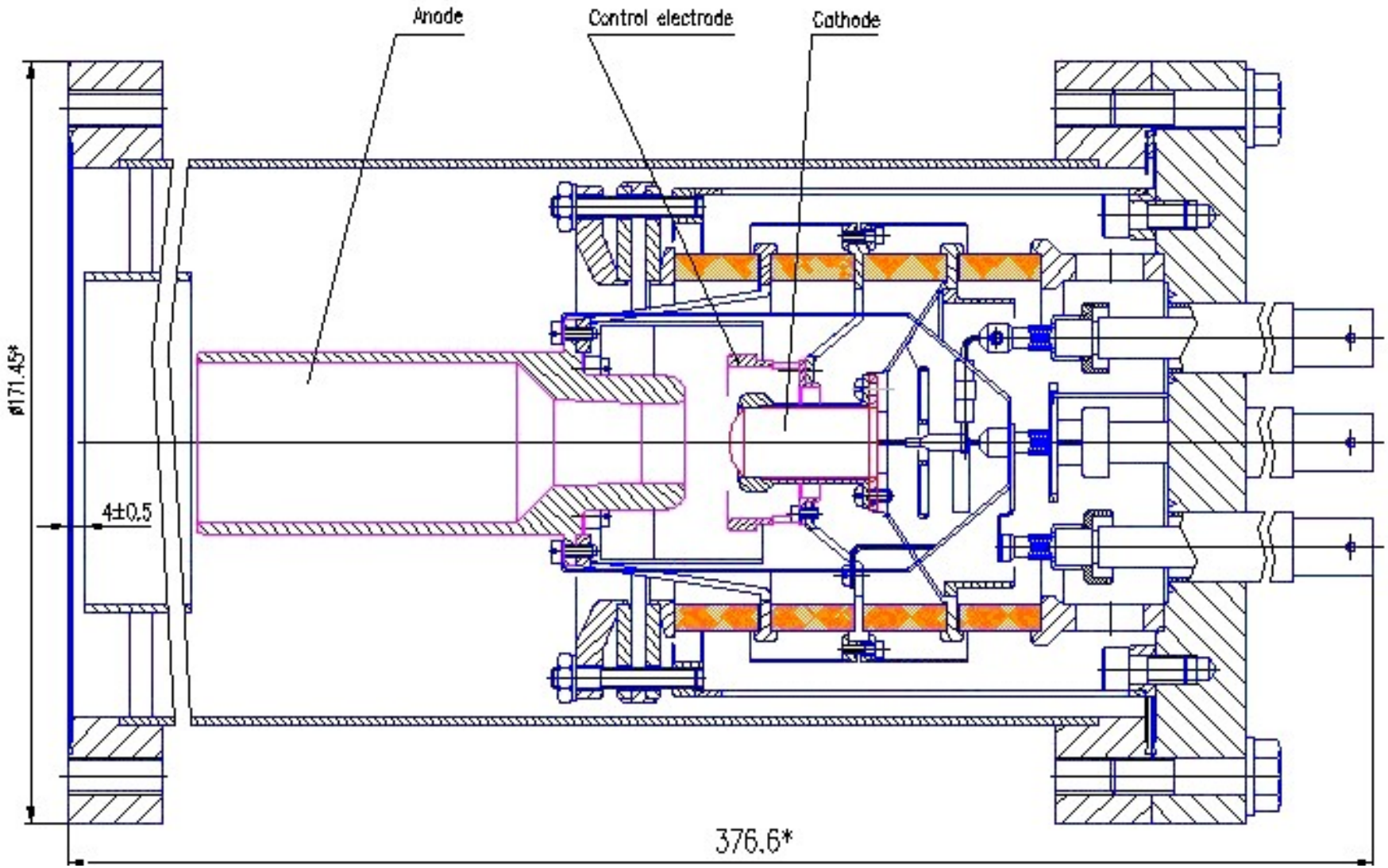


Need of Smooth Edges → Gaussian Gun



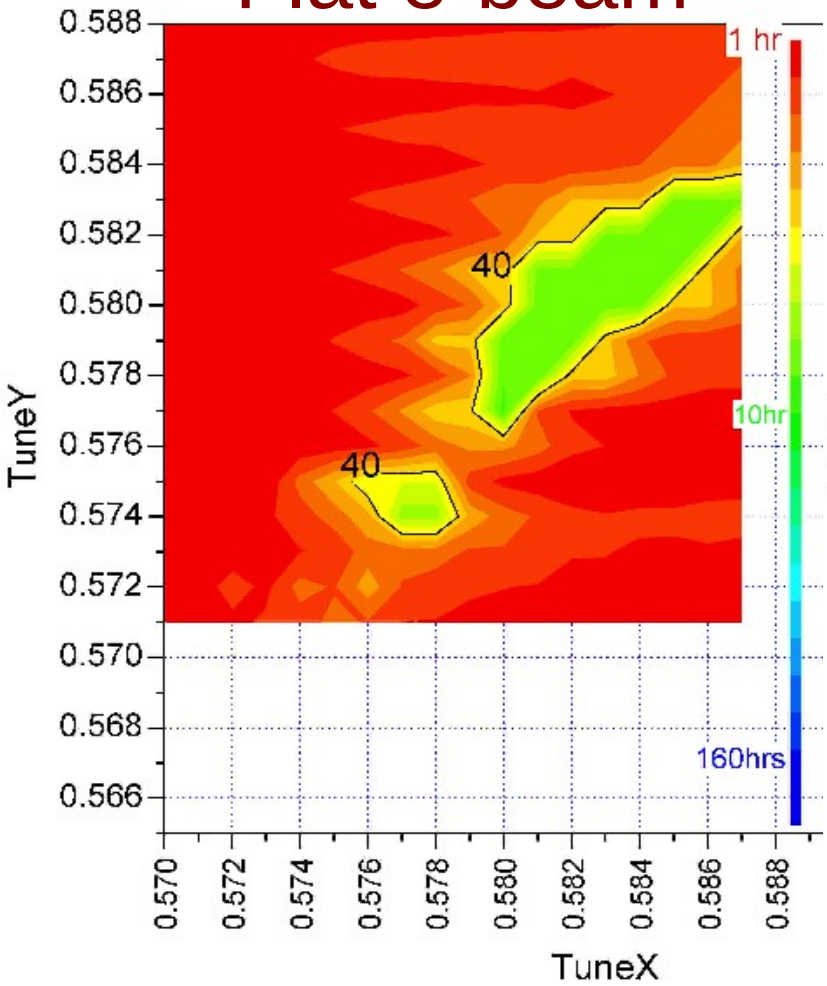
- Beam profile controlled by special electrode
- Somewhat reduced current density in the center → need of higher voltage
- Installed in Jan'2003

Beam-Shape control by near cathode electrodes and anode shape

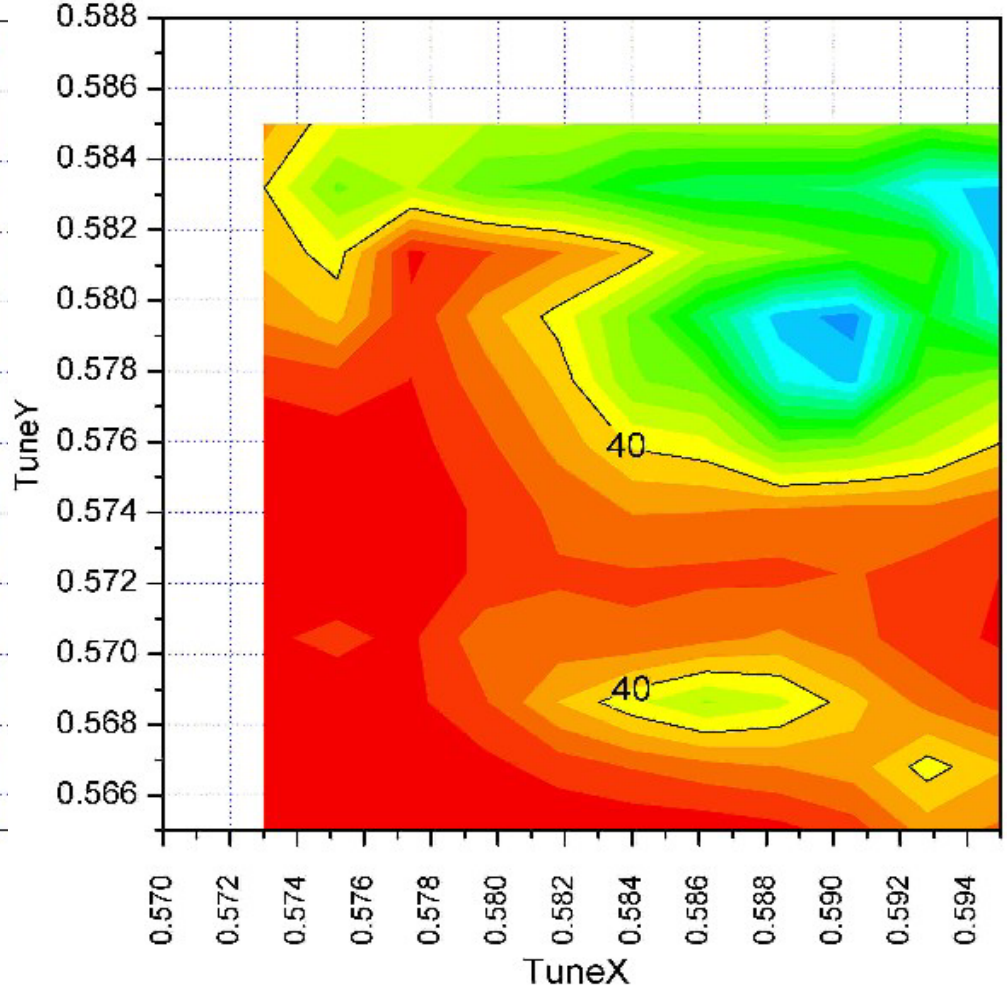


Lifetime vs WP with dQ_{TEL}~0.004

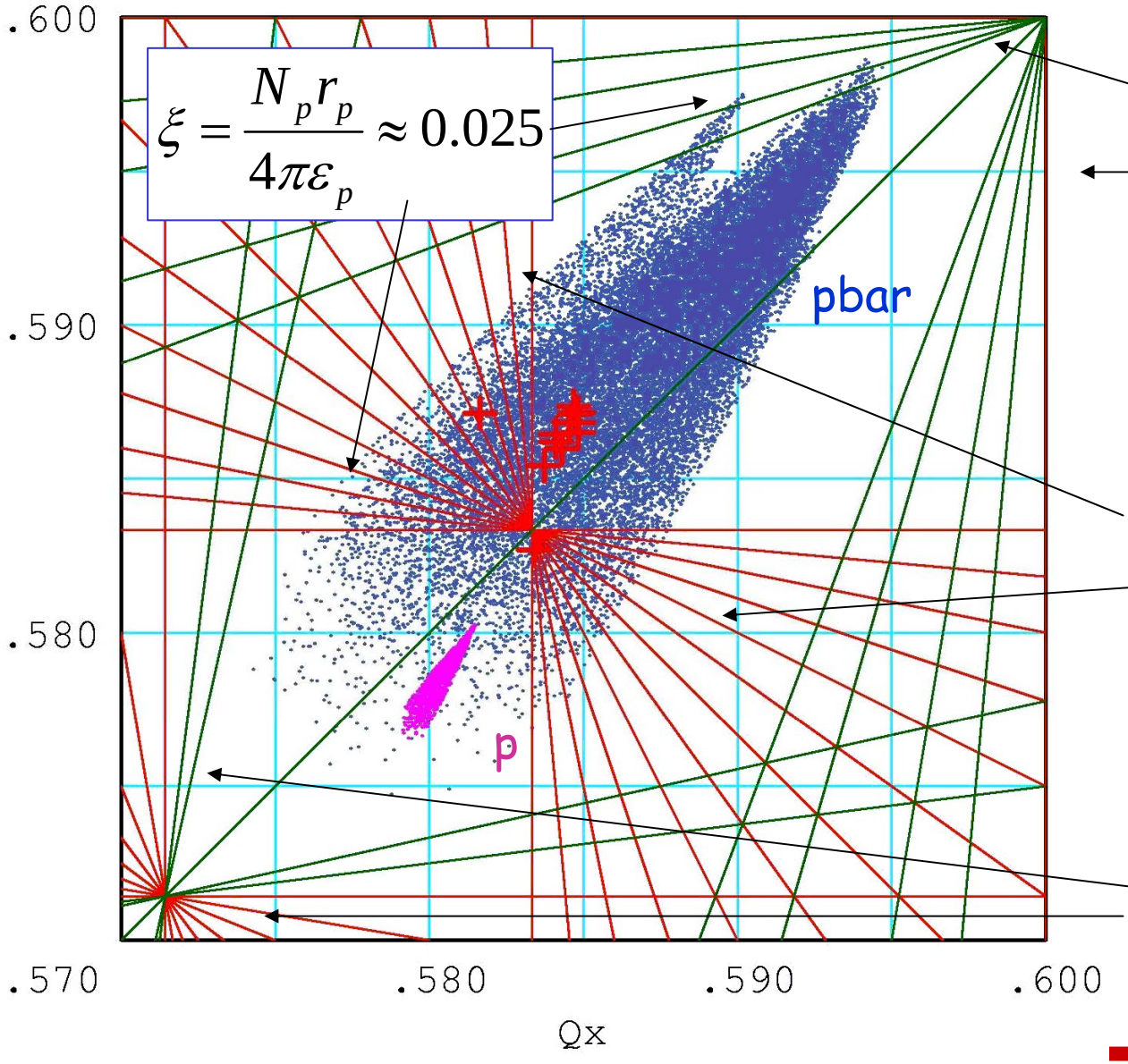
Flat e-beam



Gaussian e-beam



Beam-Beam at Low-beta Now: Confined



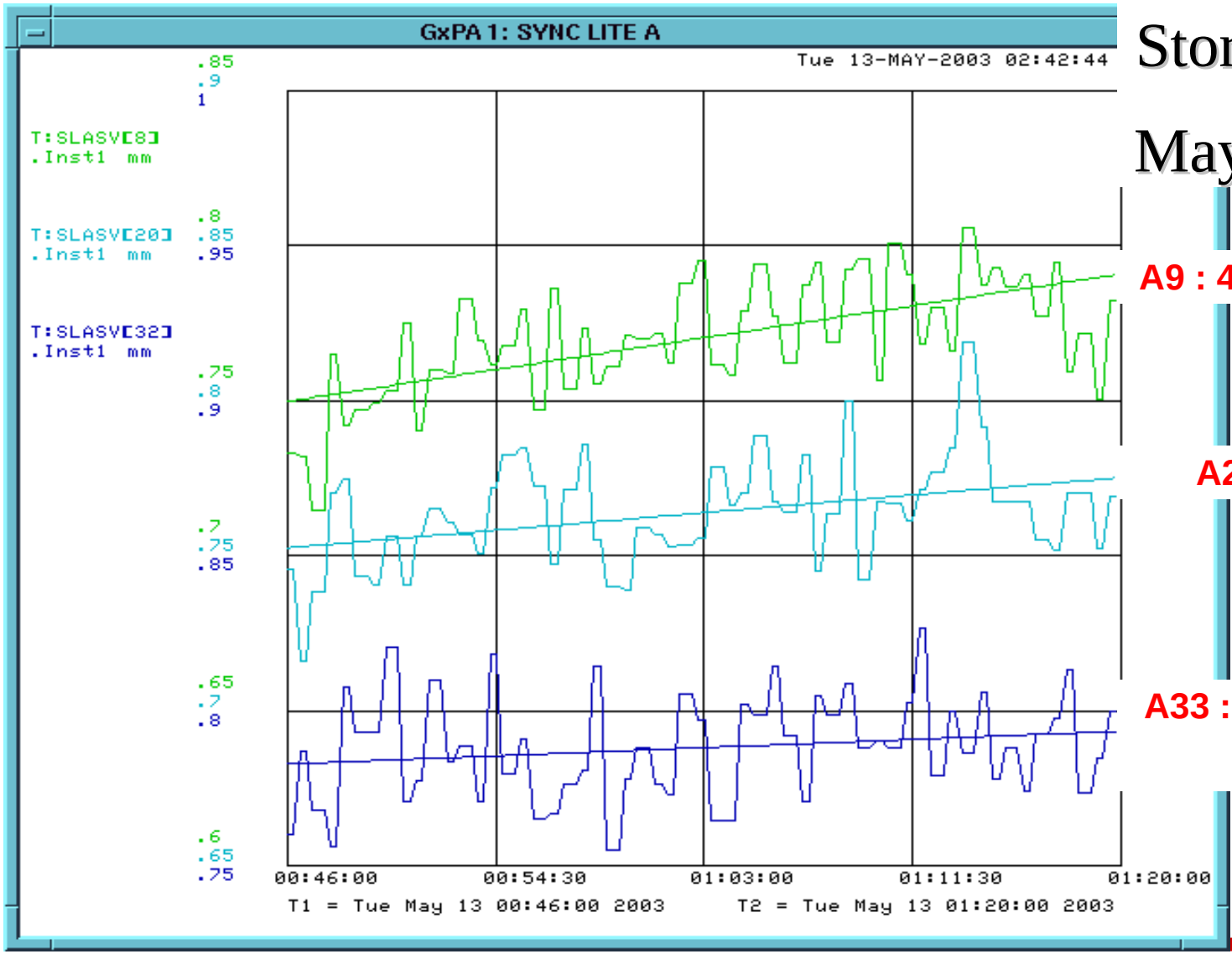
$$\xi = \frac{N_p r_p}{4\pi\varepsilon_p} \approx 0.025$$

5th order resonances:
Q=3/5=0.600 -
EMITTANCE BLOWUP

12th order resonances:
Q=7/12=0.583 -
Bad lifetime

7th order resonances:
Q=4/7=0.571 -
HIGH LOSSES

Pbar V-Sizes 34 min after p-pbar collisions initiated



Store #2540

May 12, '03

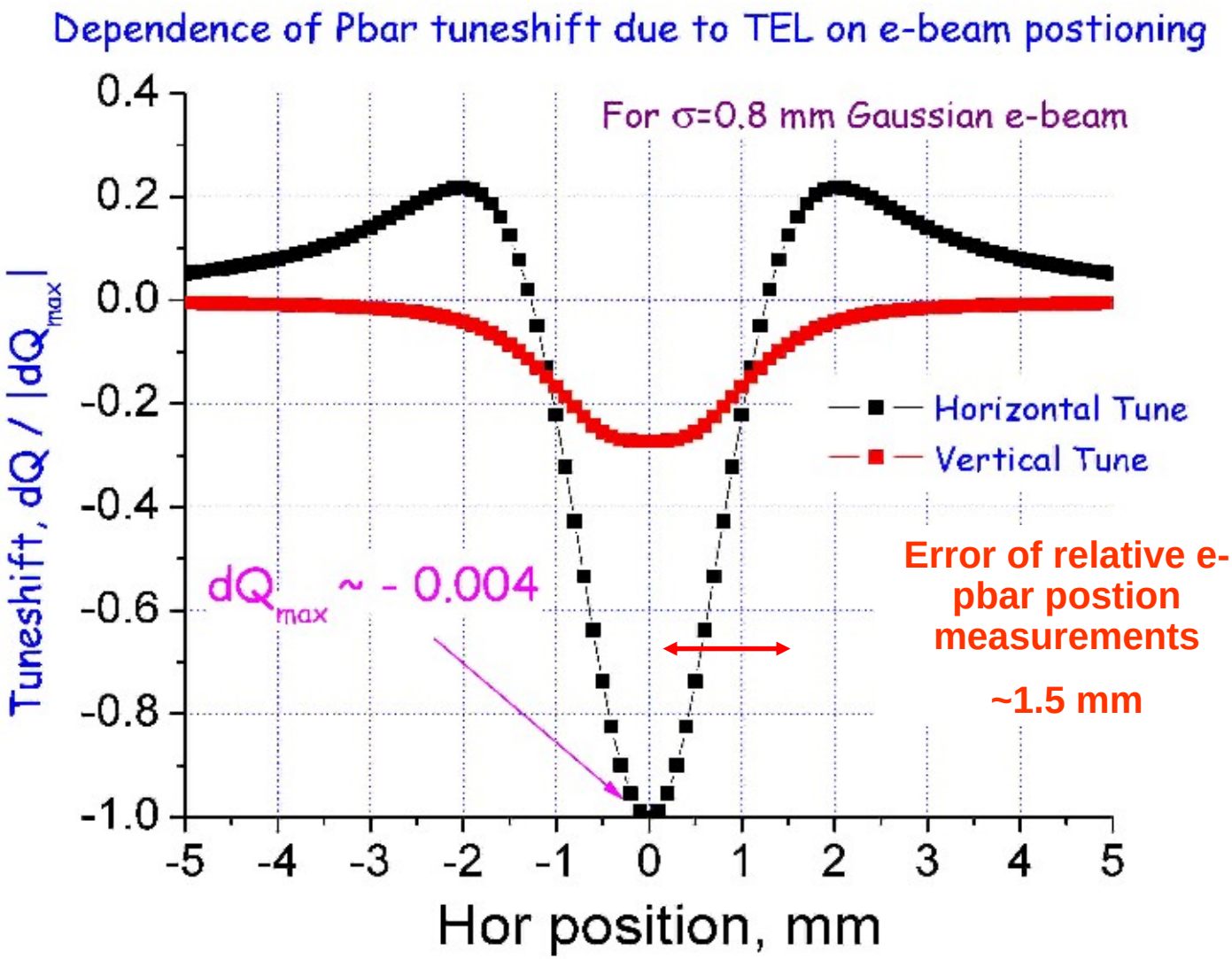
A9 : 4.1 □ mm mrad/hr

A21 : 2.2 □ mm mrad/hr

A33 : 1 □ mm mrad/hr

-TEL on it

e-Pbar Alignment is Crucial



E-lenses in RHIC and LHC

- In Tevatron TELs to compensate bunch-by-bunch tune shift parasitic beam-beam interactions →
  - Requires pulsed e-beam (~400-800ns)=expensive HV modulator
  - Need 2 lenses – one vert and one horizontal at unequal and large beta's
  - Better have much wider e-beam than p-beam + ~uniform j(r)
  - Needed dQ~0.006 ; max tuneshift dQ~0.009 achieved
- RHIC and LHC can benefit from head-on beam-beam compensation →
  - Electrons compensate prtons – that's good!
  - DC beam = no HV pulsers! (even better)
  - Need 2 lenses – one per beam; at equal beta's
  - Large beta is ~OK (at least better than in Tevatron as sigma_z/beta* is not as big as in Tev where it is ~2)
  - E-beam j(r) should be Gaussian to match protons at IPs – easy!
  - Need dQ_max~0.01 which is achievable → see next slide

E-lenses in RHIC and LHC: General Considerations

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

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

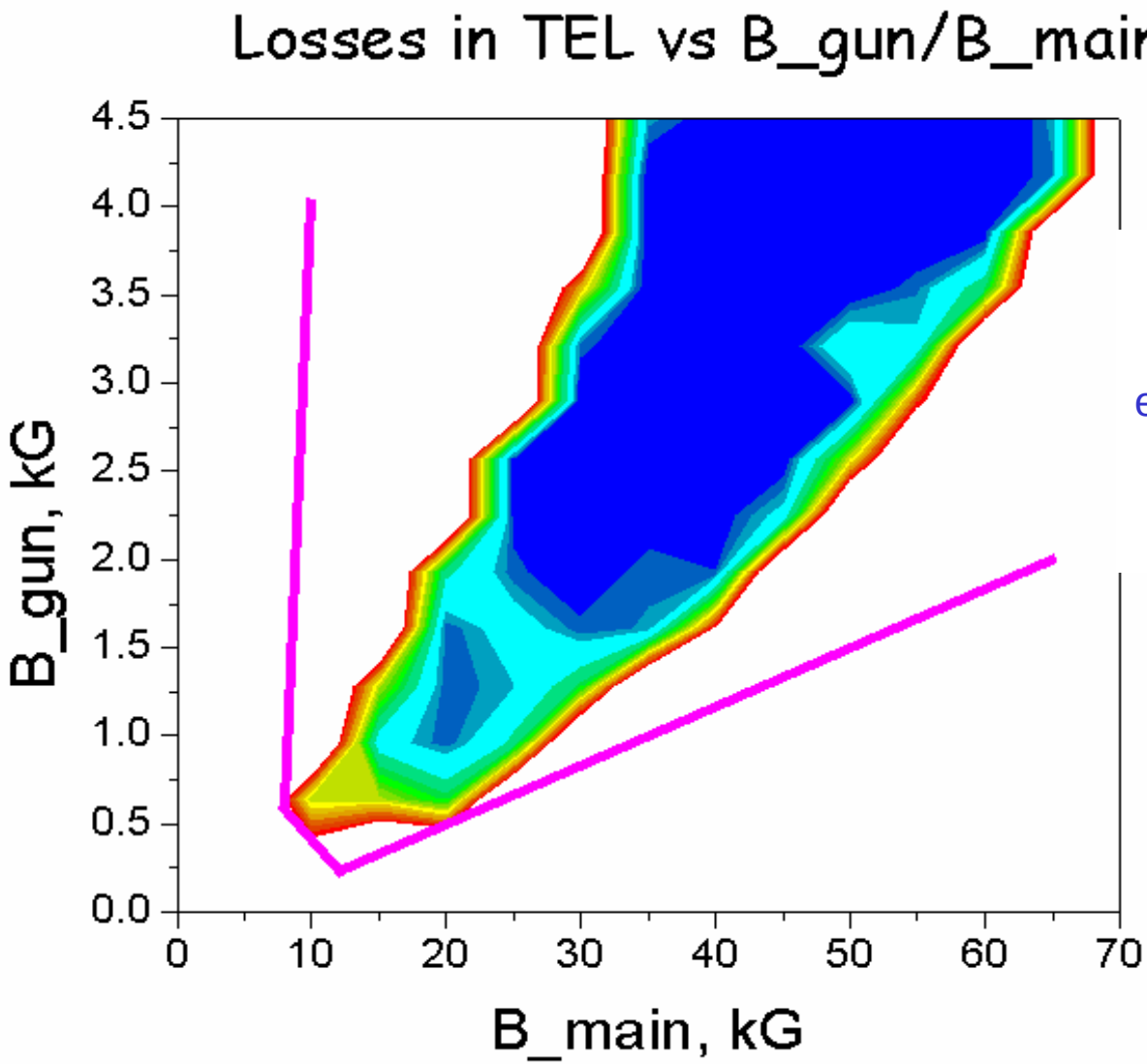
Scaling: need a_e = a_p and about same dQ~0.01
Two factors:

$$a_e^2 = a_{cathode}^2 \left(\frac{B_{cathode}}{B_{main}} \right) \qquad a_e^2 = \frac{\varepsilon_n \beta_{x,y}}{\gamma_p}$$

For RHIC: beta_x = 20 m for Tev: beta_x=100
gamma=250 gamma=1000
Thus (B_c/B_main)=4/5 x (B/B)_Tevatron → easy!

For LHC: beta_x = 200 m for Tev: beta_x=100
gamma=7000 gamma=1000
Thus (B_c/B_main)=1/3.5 x (B/B)_Tevatron → not easy, but doable

Transmission region of the TEL-1 and TEL-2



Determined by bending part

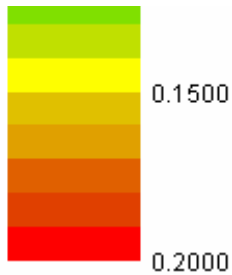
Larger ratio B_gun/B_main

→Possibility to change e-radius

e.g. TEL-1: 4/35 kG → 1.7 mm max

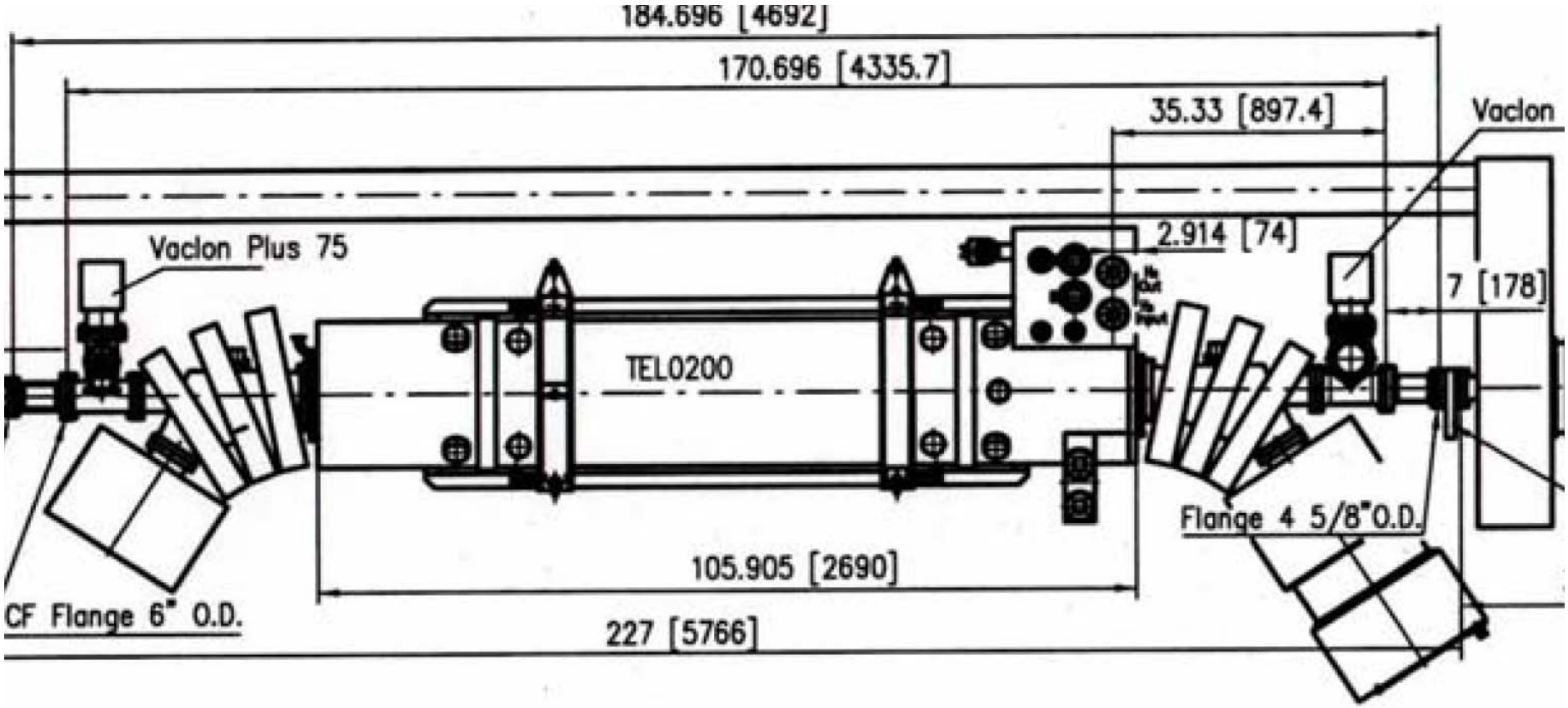
TEL-2: 4/16 kG → 2.4 mm max

(for 10 mm cathode)



Tevatron Electron Lens #2 (TEL-2)

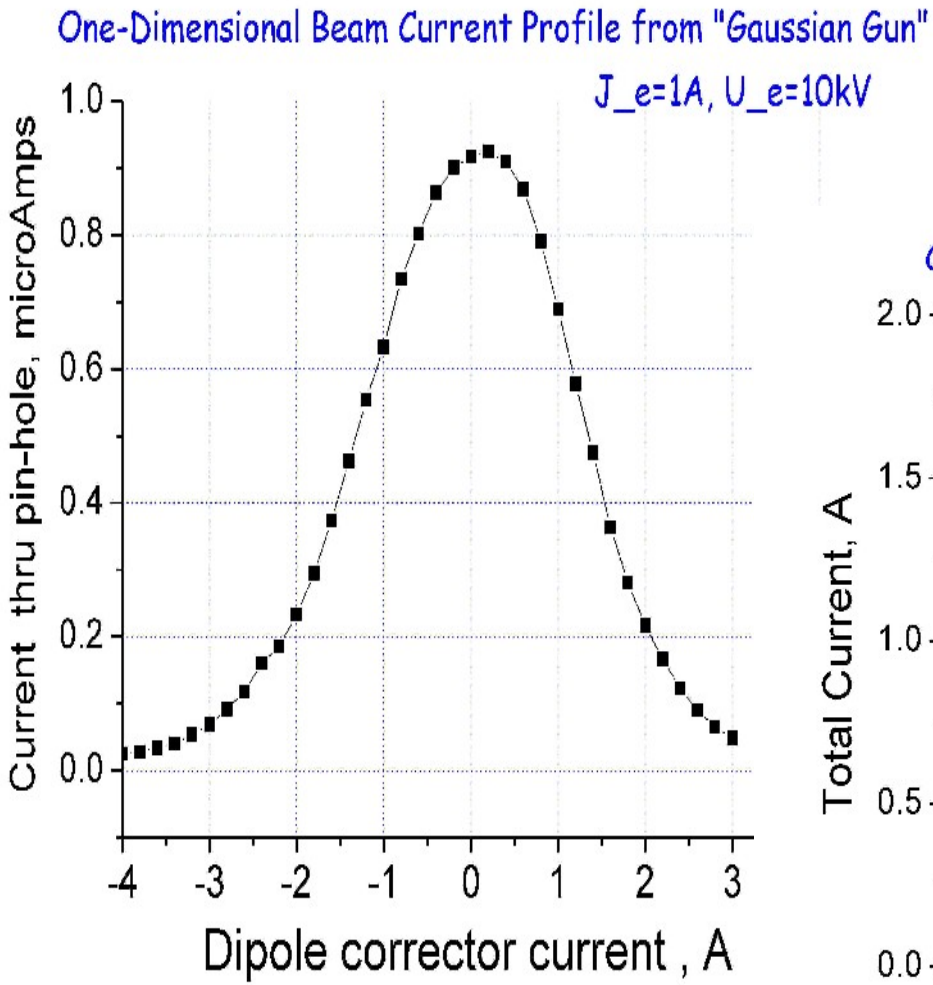
57 deg bend



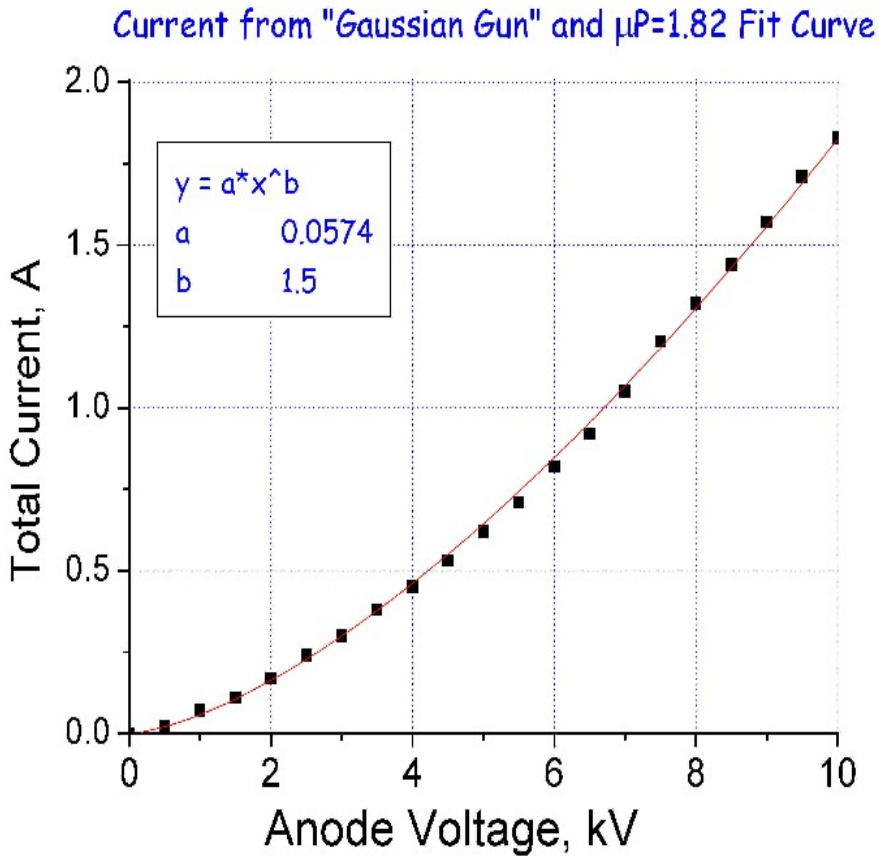
+ Marx HV Modulator, SEFT gun, 2 Cryo bypasses, new 4-plate BPMs & Cables

Back-Up Slides

TEL Gaussian Gun - Installed Jan'03

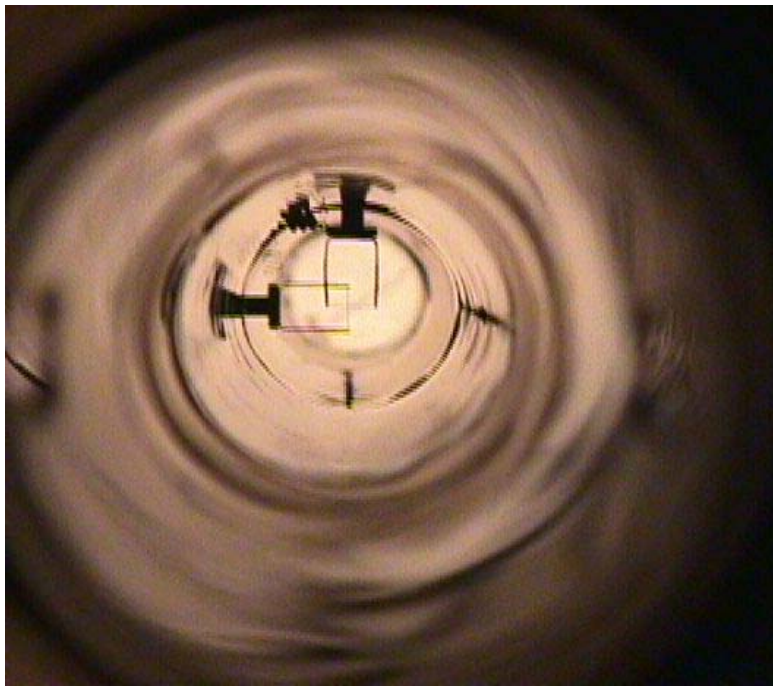


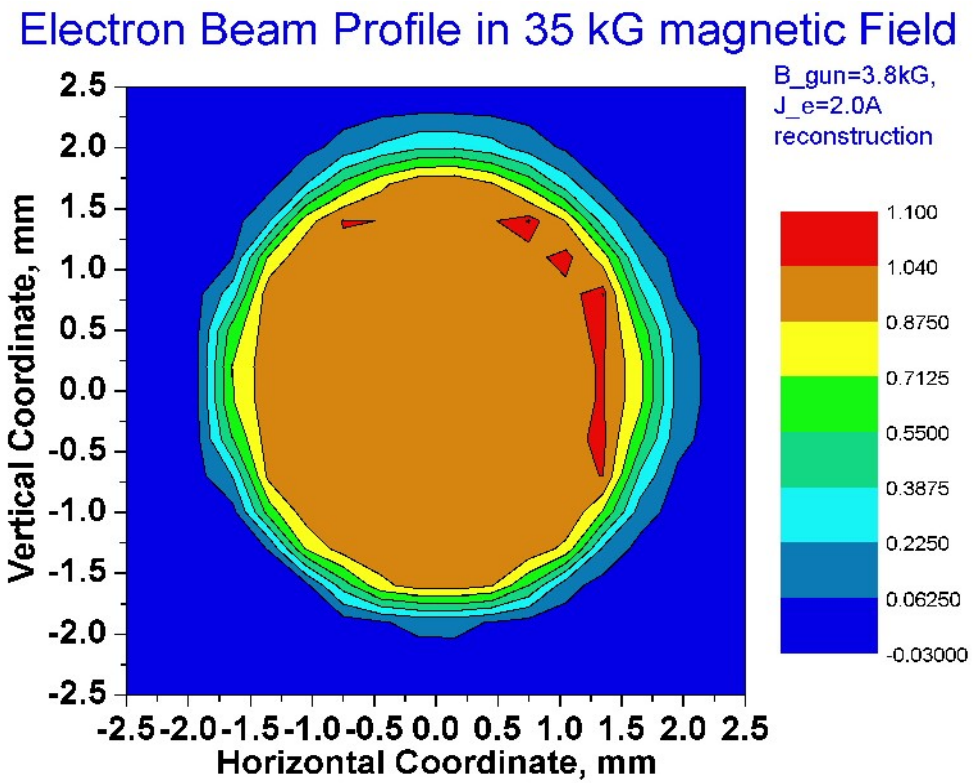
G.Kuznetsov,
K.Bishofberger
N.Solyak



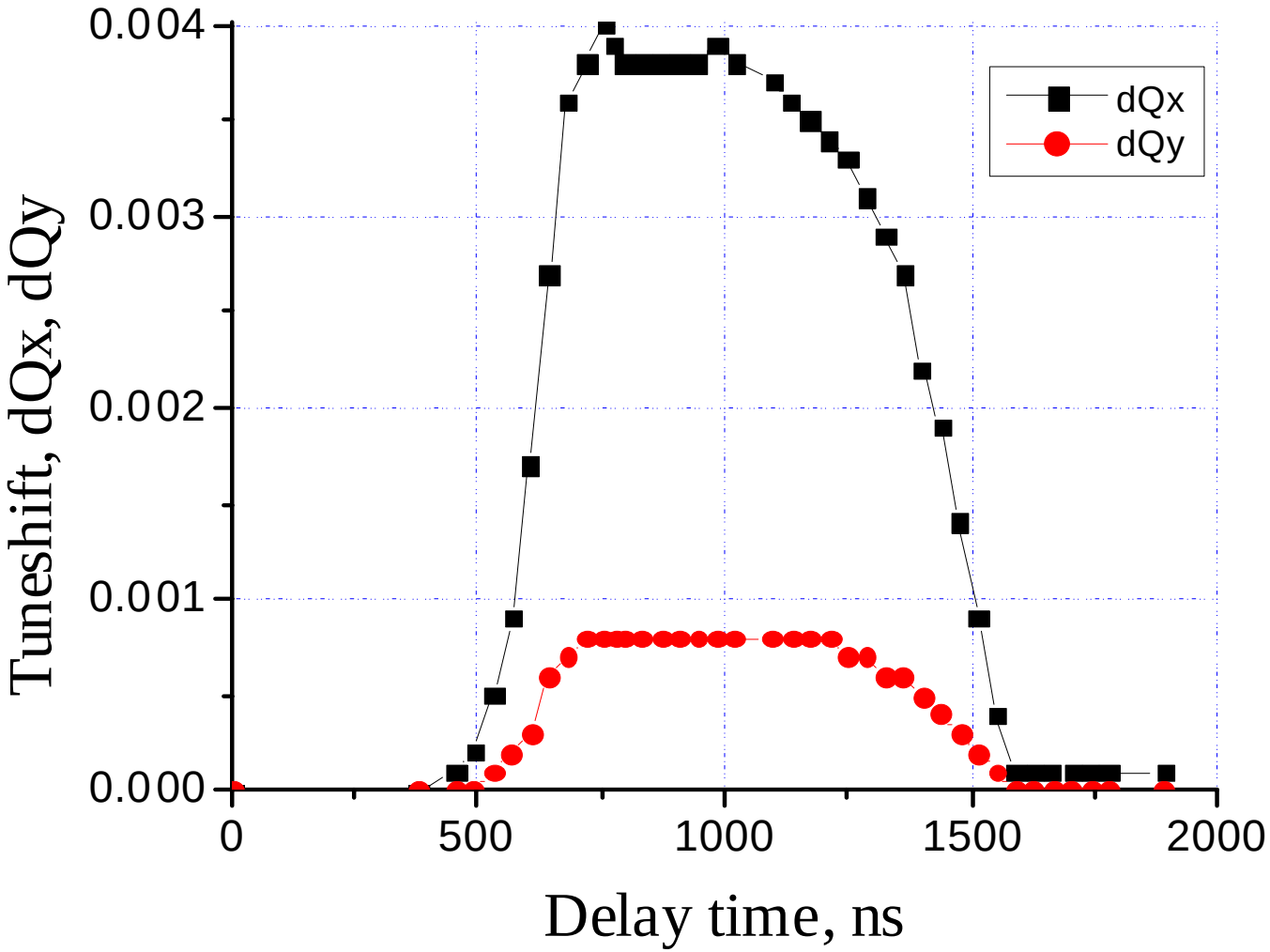
Electron Beam in Main Solenoid

- "flat" e-current density distribution +-5% over 3.4 mm diameter





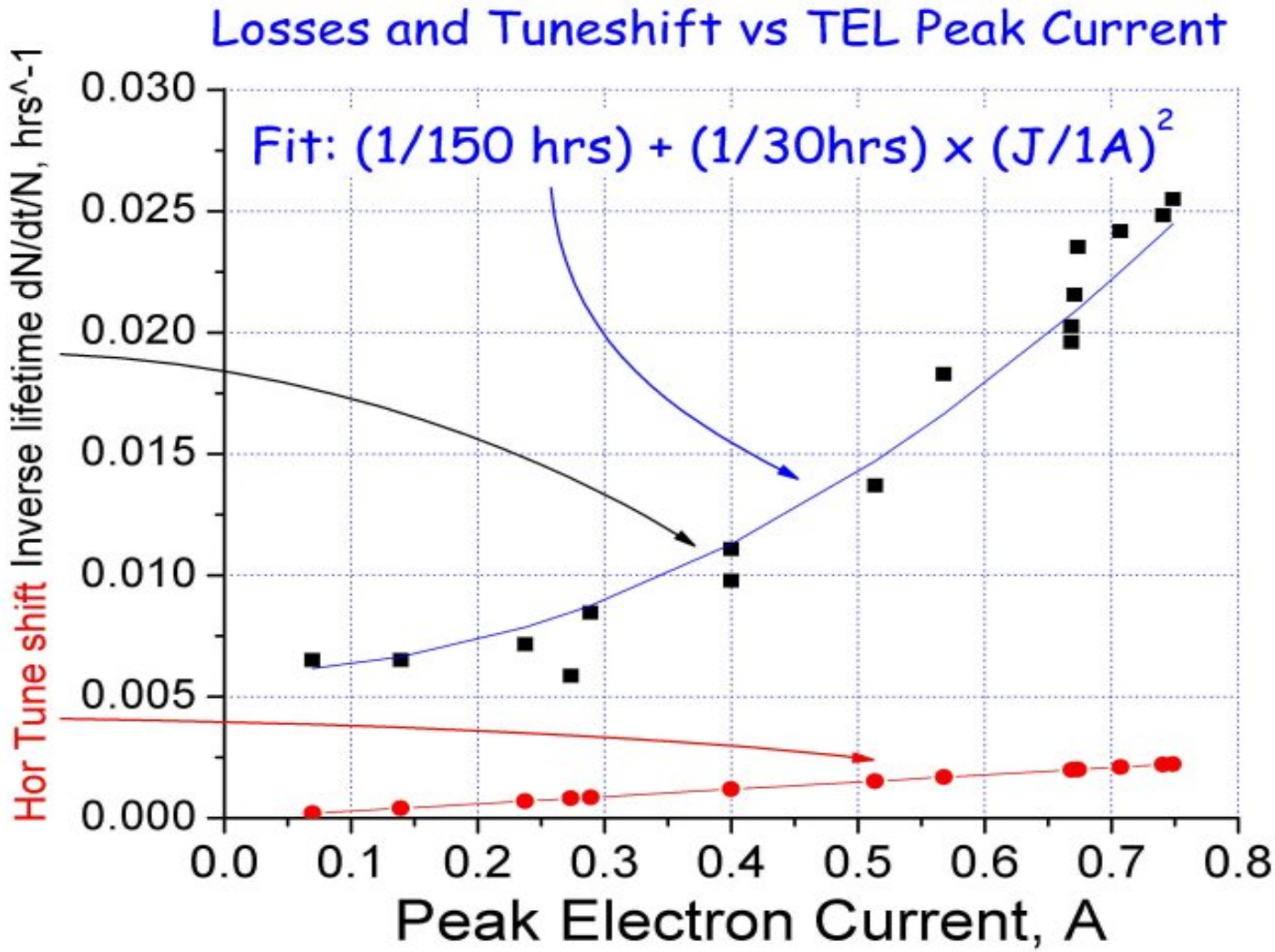
TEL : short pulses, bunch-by-bunch



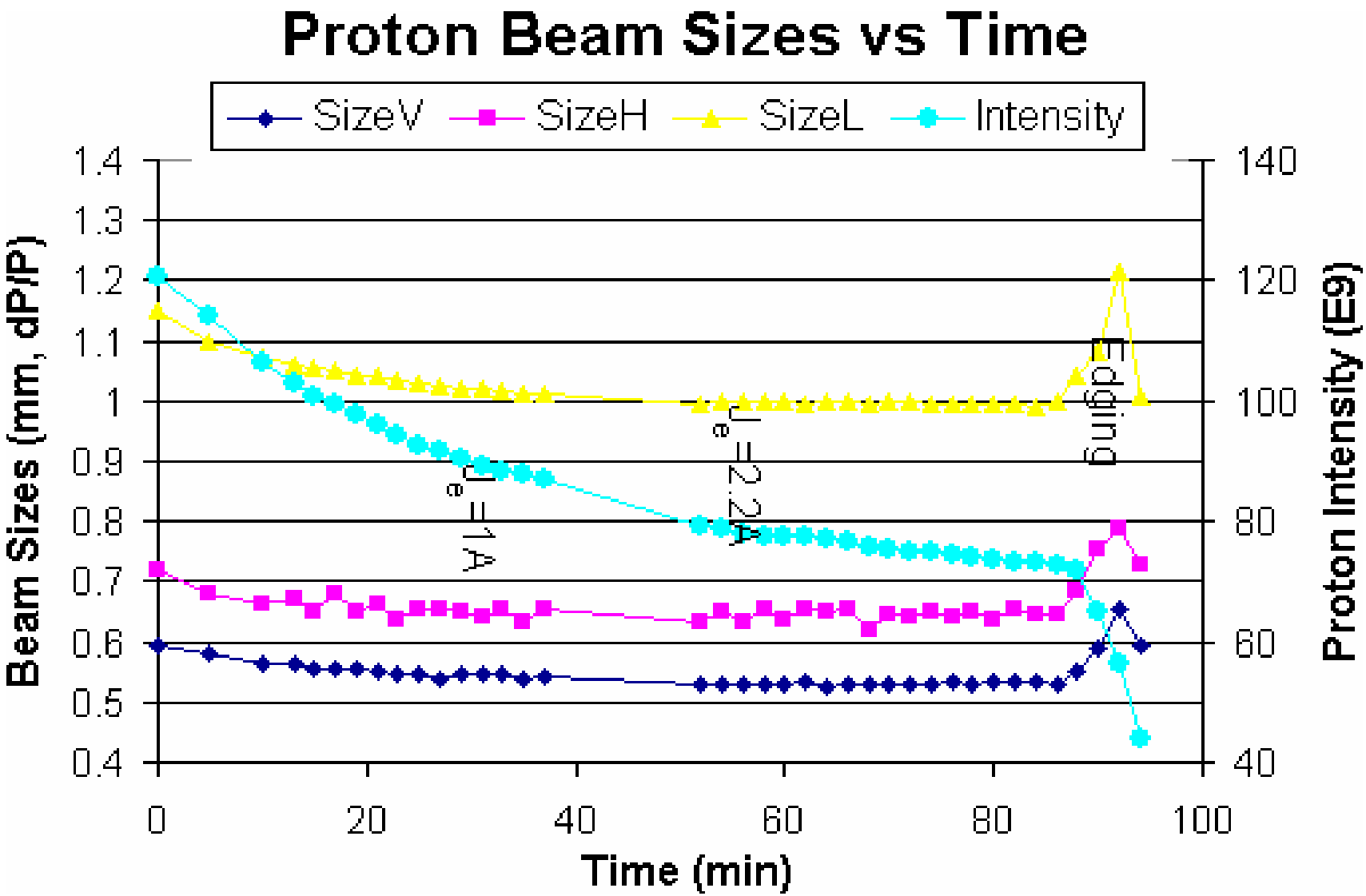
Content

- Sequence of events:
  - TEL-1 installed in 2001
  - max tuneshift dQ~0.009 achieved in 2001-02
  - TEL-1 operational for abort gap cleaning since Jan'02
- Lifetime Issues with TEL → resolved
- First indication of successful B-B-Compensation
- Next steps

Outstanding Issue with BBC in '01-'02 – limited lifetime



e-beam edge = "donut collimator" A~20□ ❍mrad



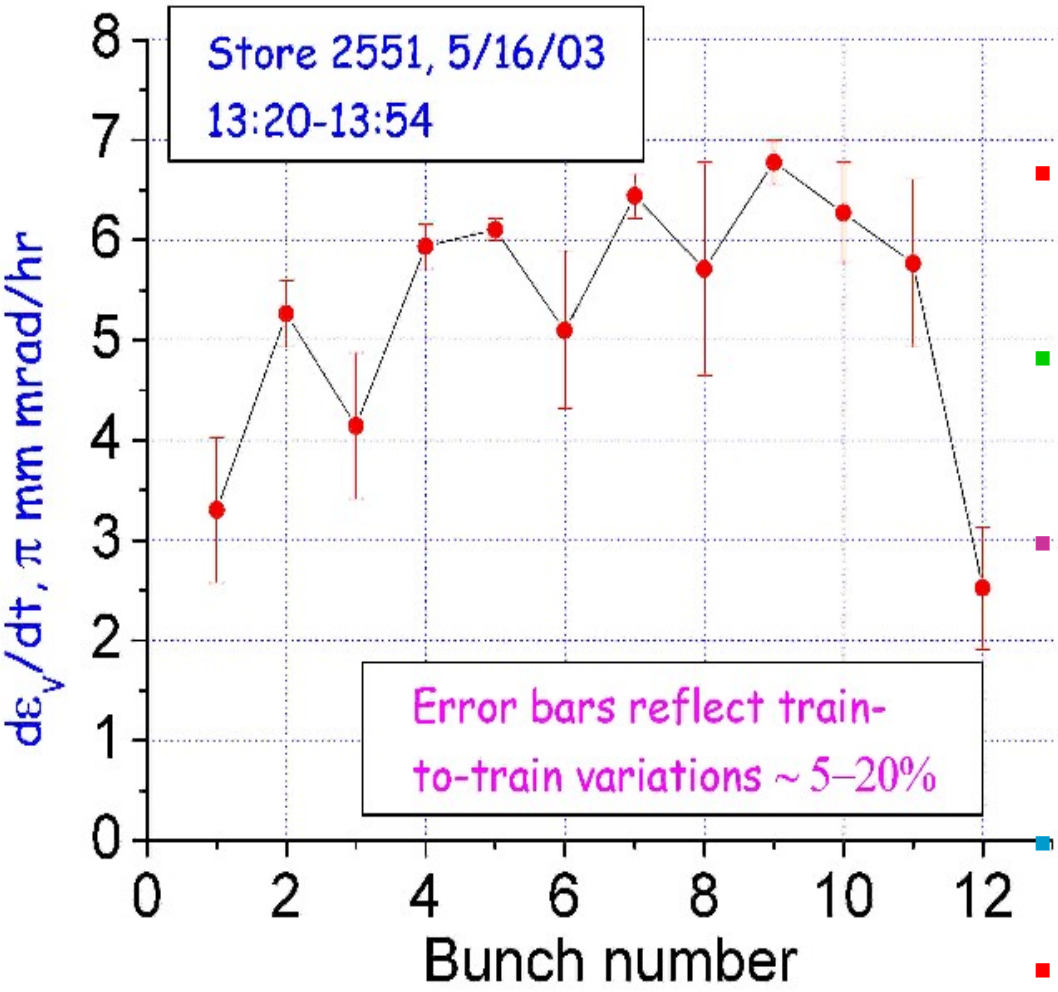
Successful Attempt of BBC with TEL

- first, the lifetime improvements with Gaussian gun made sense of the use of the TEL in HEP stores:

  $\blacklozenge_{TEL}$ ~ 100-160 hrs > $\blacklozenge_{pbar}$ ~ 30-50 hrs

- second, it was demonstrated that the TEL can be transferred from DC beam removal regime to BBC regime (includes still manual changes of U_cath, P_fil, triggering from 3/7 to 1/1, timing and pulse width, and use of strong dipole correctors to move e-beam on pbars) and back – with no significant effect on colliding beams or detector backgrounds
  - after that the TEL with some 0.6A of current was timed on single pbar bunch at the beginning of the Tevatron stores and **it was observed that the TEL can slower vertical emittance growth of antiprotons ("reduce scallops")**

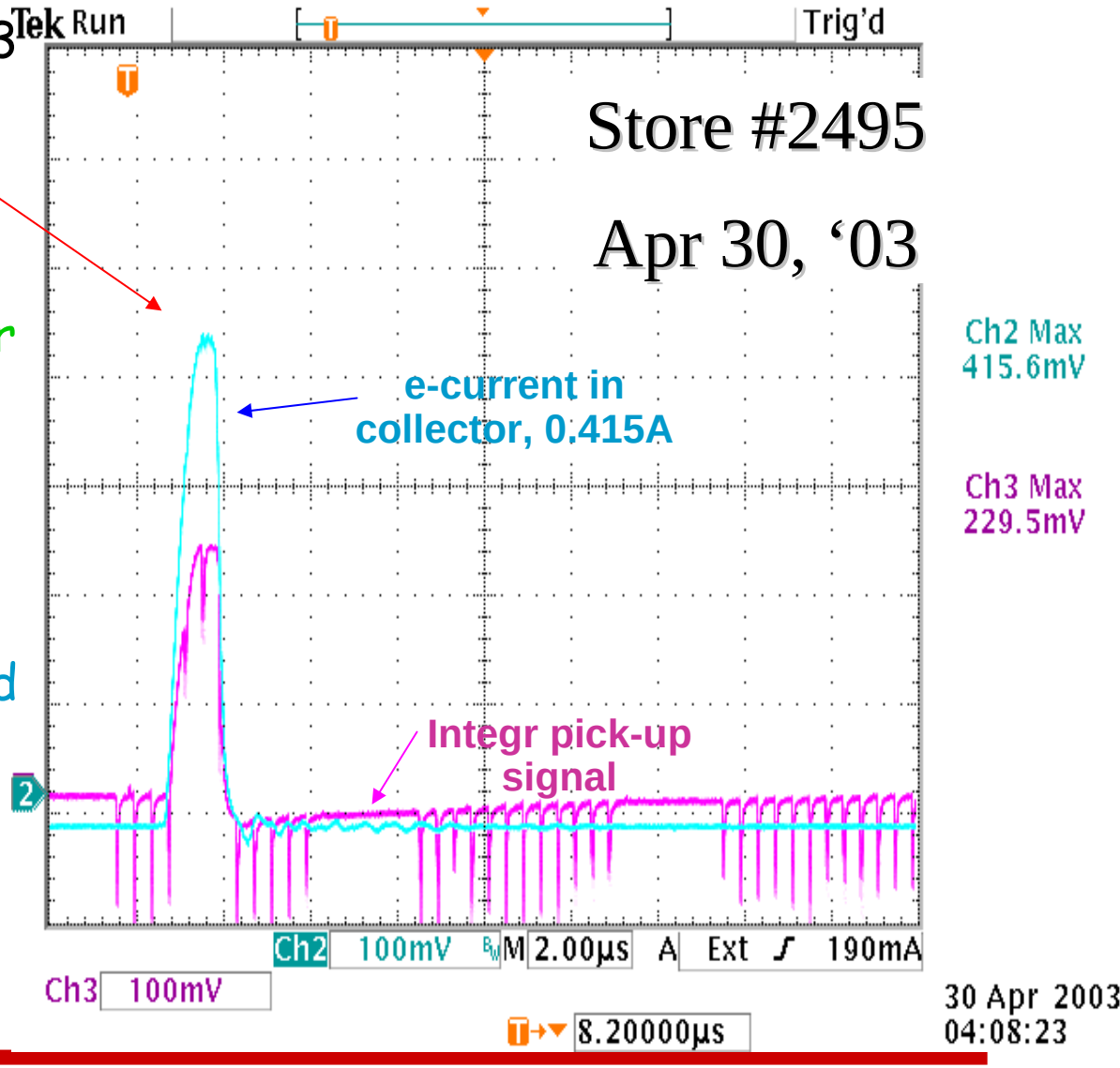
Pbar Vert Emittance Growth Rate



- "Scallops" is beam-beam phenomena, they started to occur after Nprotons exceeded 180e9/bunch
- "Scallops" do not take place in every store even with N_p >180e9/bunch
- "Scallops" occur in both planes, but often more prominent in vertical
- "Scallops" seem to be dependent on tunes , e.g. vertical tune change – 0.002 can significantly reduce scallops
- Small "scallops" are seen in protons
- Scallops are the same in all three trains of bunches (variations <20%)

Statistics of TEL used for BBC

- 8 attempts since 5/20/03
- Neutral or slightly negative effect in two stores #2546, #2549 – but "scallops" occur
- No effect in three earlier stores #2445, #2490, #2495 – no "scallops"
- Positive effect in one store #2540 – "scallops" suppressed
- Faulty pulse generator led to loss of 2 pbar bunches in two stores #2487, #2502



Pbar V-emittance growth rates (□ mm mrad/hr)

store	#A9	#A21	#A33
# 2536 (40 min)	9.9	9.2	9.3
#2538 (35 min)	1.9	1.7	2.8
#2540 (34 min)	4.1	2.2	1.0
#2546 (30 min)	3.9	1.9	4.0
#2549 (26 min)	4.5	3.6	7.1
#2551 (34 min)	6.7	6.6	7.0

Summary

- Status:
  - max dQ~0.009 tuneshift achieved
  - p(bar) lifetime deterioration proved to be due non-linear beam-beam force at the e-beam edges ("soft collimator")
  - after installation of Gaussian e-gun, p-beam lifetime of ~160hrs has been achieved (compare with 40 hrs in stores)
  - TEL was used in several stores recently and we've got first indications of successful beam-beam compensation : vertical emittance growth rate was reduced for pbar bunch #33 early in store #2540
- Work to do:
  - continue to explore BBC at 150, ramp, LB for both pbar and p
  - improve diagnostics (TEL BPM, Pbar Schottky tunemeter, etc)
  - wider e-beam , better beam current and position stabilization
  - the second TEL is under construction but the BBC is not the major motivation (← spare for the DC beam removal)
  - new HV pulser (~ 15kV instead of 7kV, shorter pulse)
- R&D review Mar'04, TEL-2 decision in Dec'04

Beam-Beam Compensation:

- the first *indication* of the BBC in store #2540
- later attempts in #2546 and #2549 show that the TEL effect can be neutral or even slightly negative
- the attempts will continue
- conditions to claim *demonstration* of the BBComp:
  - scallops or other "bad" effects without BBComp
  - the "bad" effects suppressed by TEL
  - on systematic basis

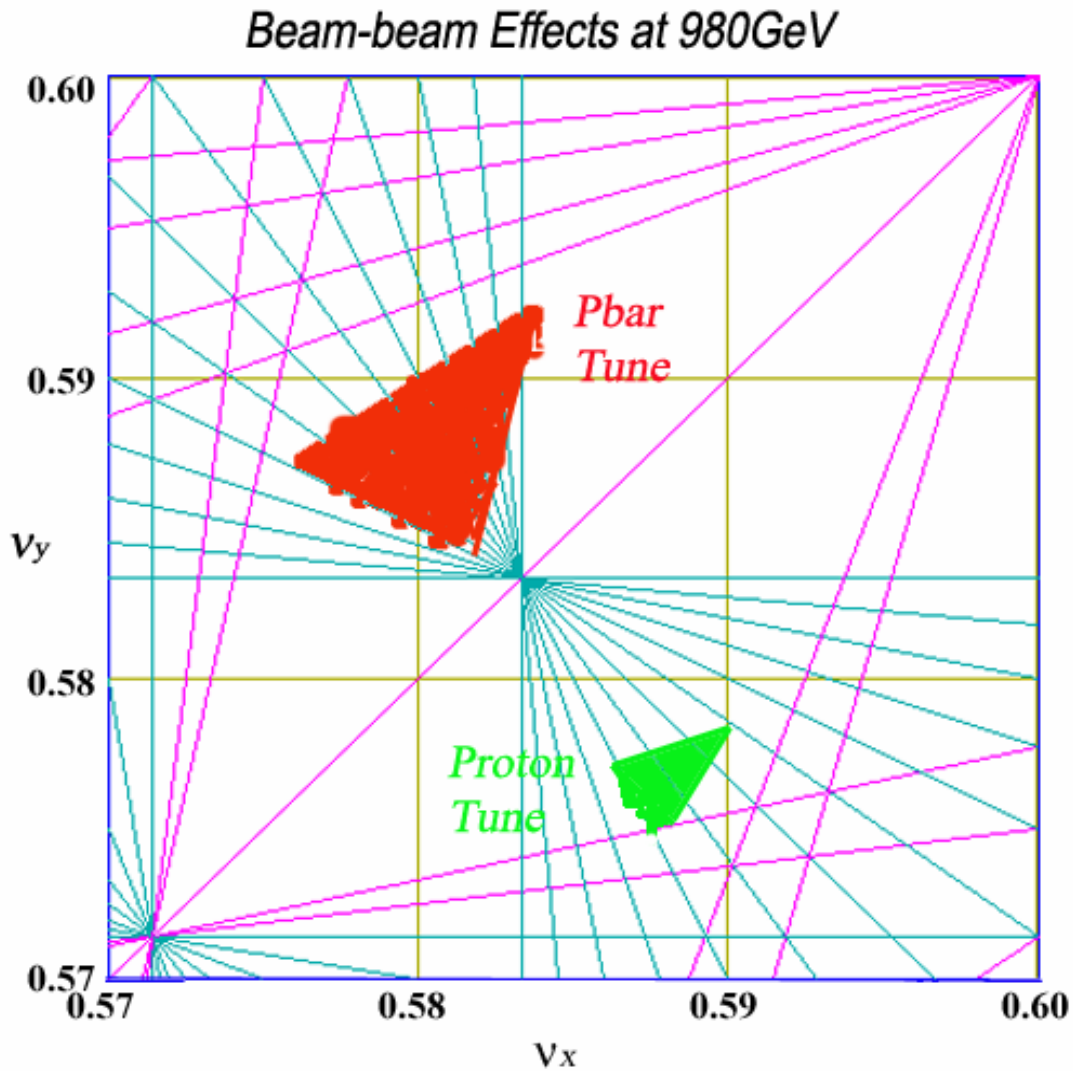
What is important for the BBComp?:

- following issues need to be resolved before the Beam-Beam Compensation will be used operationally :
  - better understand beam-beam effects in the Tevatron and parametrize them (see talks of T.Sen and Y.Alexahin)
  - improve e-pbar-p position measurements < 0.1 mm
  - single pbar bunch tune diagnostics (1.7GHz Schottky)
  - do we need wider e-beam or different shape?

What to compensate?

- Beam-beam interaction in the Tev leads to
  - Pbar losses at injection energy 150 GeV
    - 15% → 3%
    - Long-range BB
  - Pbar losses on ramp
    - 5-15%
    - Long-range BB
  - Pbar and proton losses during LB squeeze
    - 1-3% for pbars , of the order of 1% for protons
    - Long-range BB
  - Pbar and proton emittance growth in collisions
    - Vary from 1 to 20 pi mm mrad/hr for pbars (1/10th for p's)
    - Head-on and Long-range
  - High proton and pbar losses (poor lifetime) in stores
    - Can be as small as 20 hrs for both beams → detector bckgrnd
    - Head-on and Long-range

Tevatron Working Points



- with current parameters

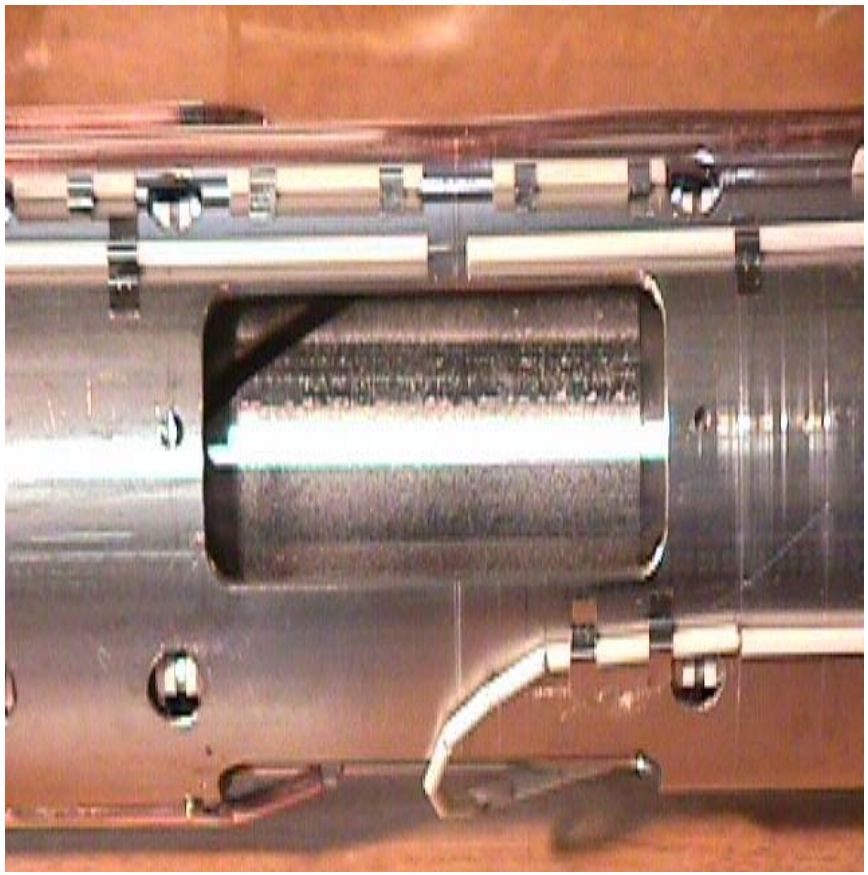
N_p ~ 250e9/bunch ,
emittance ~ 20
mmmrad

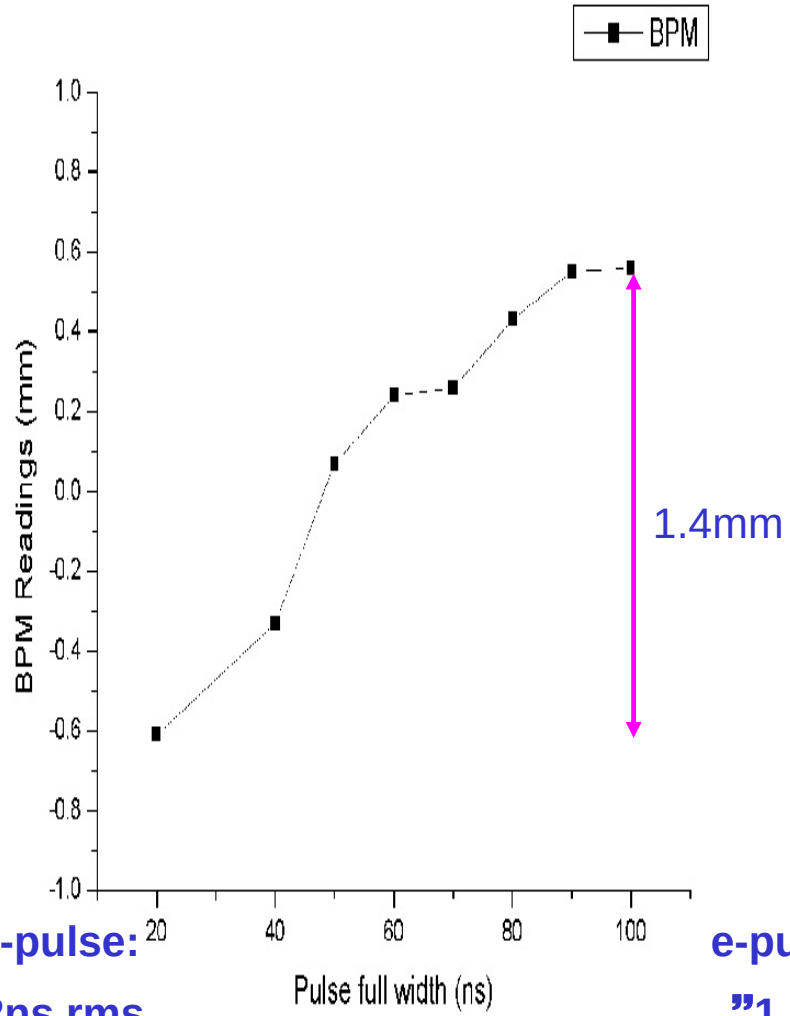
Head-on tuneshift is
~ 0.015

Bunch-by-bunch tune spread
dQ ~ 0.003-0.005

B-B dynamics dominated by 5^{th}, 7^{th}, and 12^{th} order resonances

TEL BPMs – Need to Be Improved



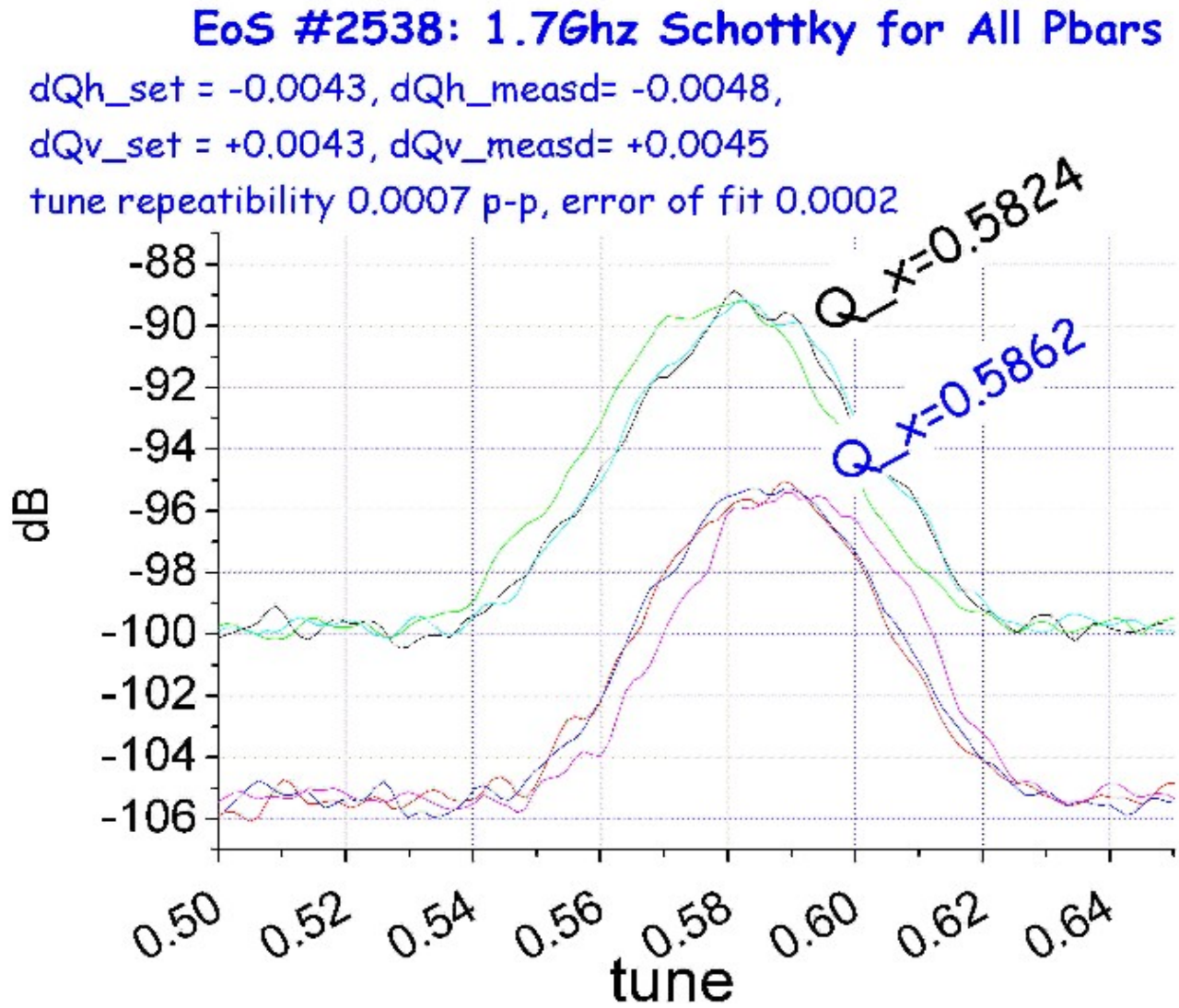


- *Calibrate BPMs X(f) in the tunnel with variable pulse generator - need access*
- *Calibrate BPMs using longitudinal waves in e-beam excited by protons - need study time*
- *Install new BPMs – already designed, tested – need shutdown*

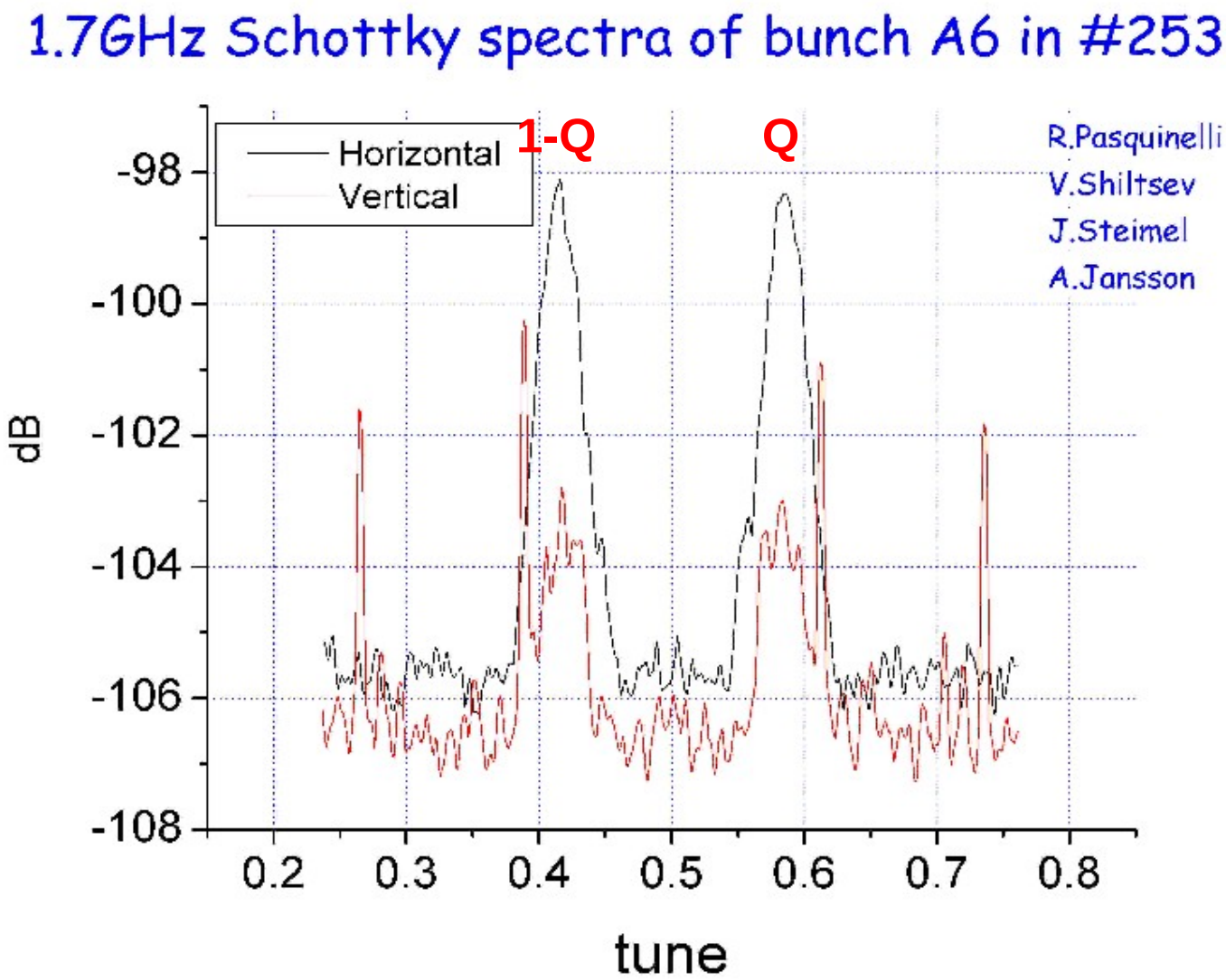
p-pulse: 2ns rms

e-pulse: ”1 Os

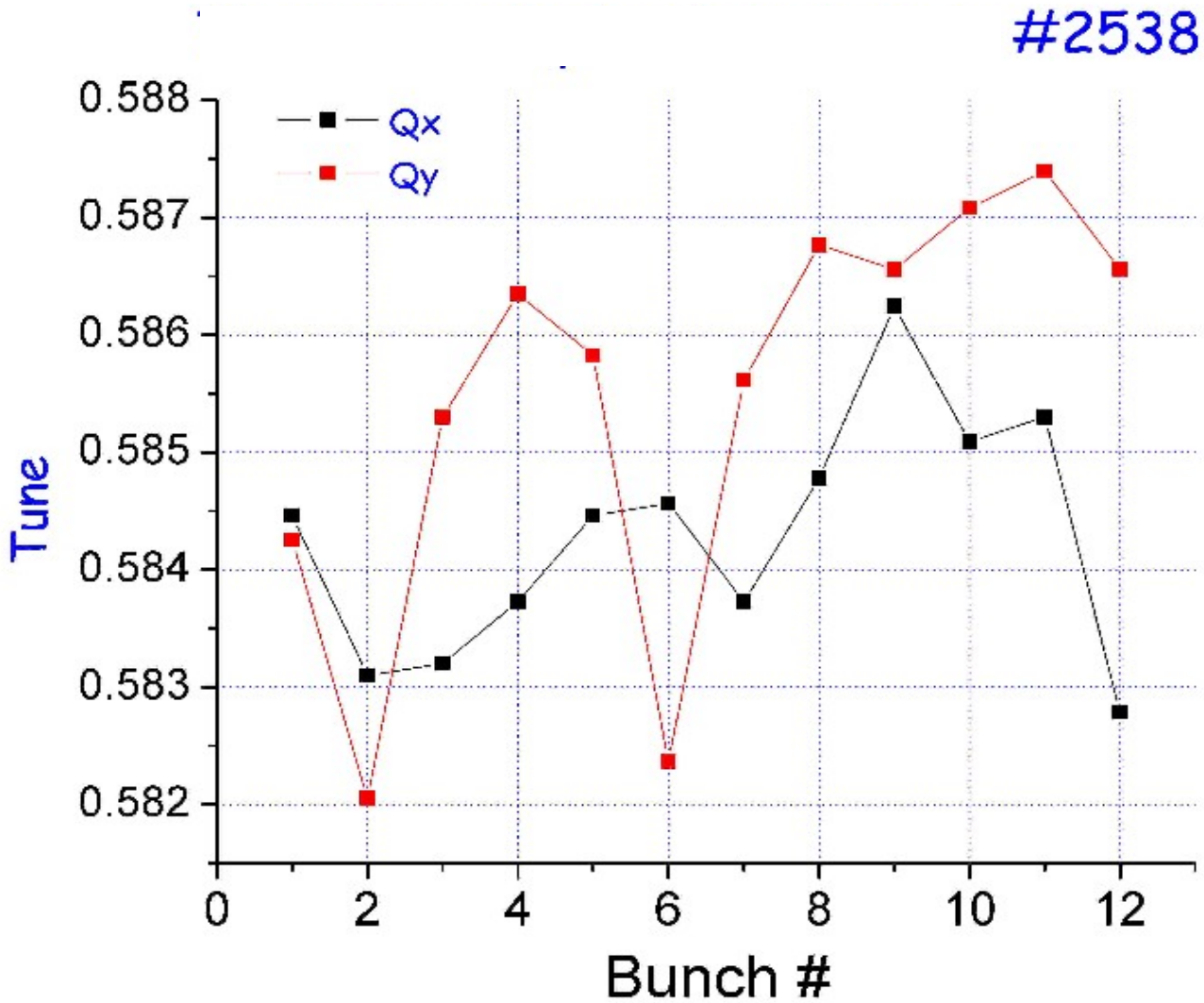
1.7GHz Schottky Spectra



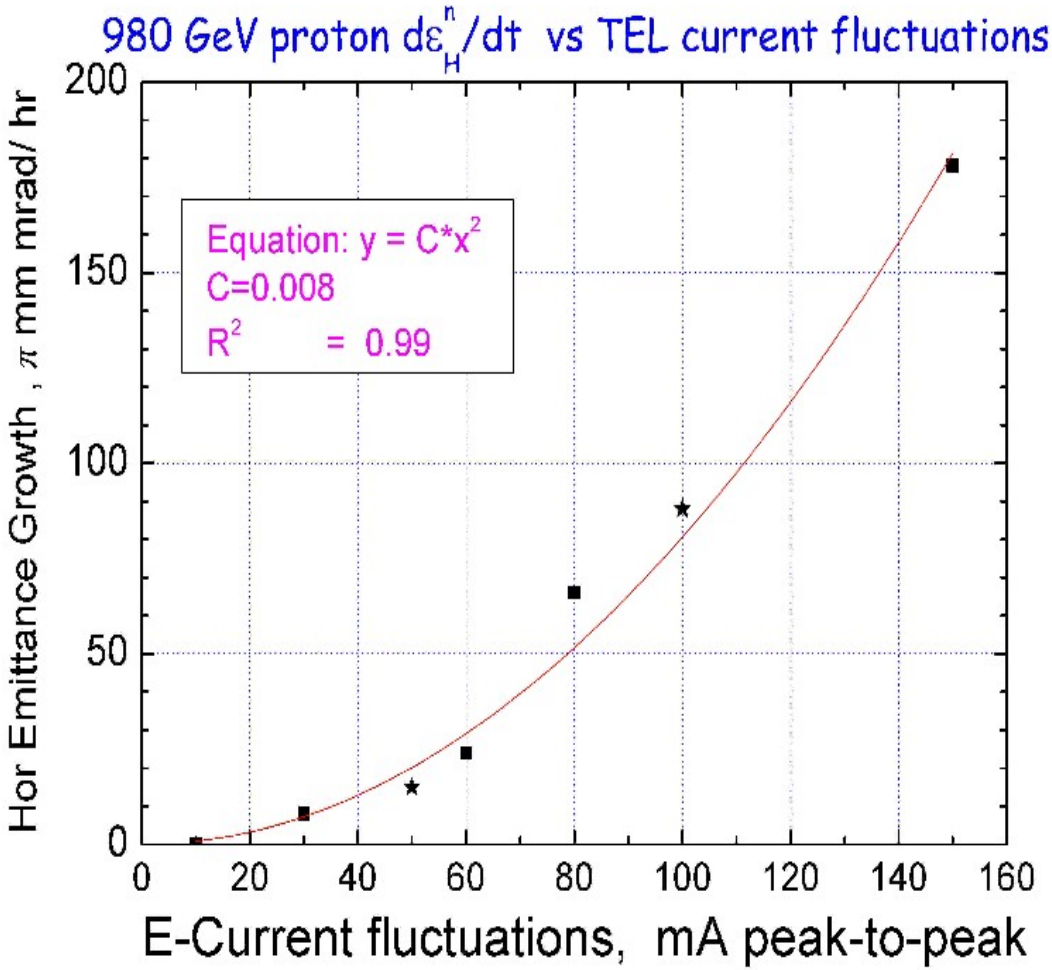
Tevatron 1.7GHz Schottky Spectra



Pbar Bunch Tunes Measured by 1.7GHz Schottky detector



Other Issues: e-Stabilization (needed?)

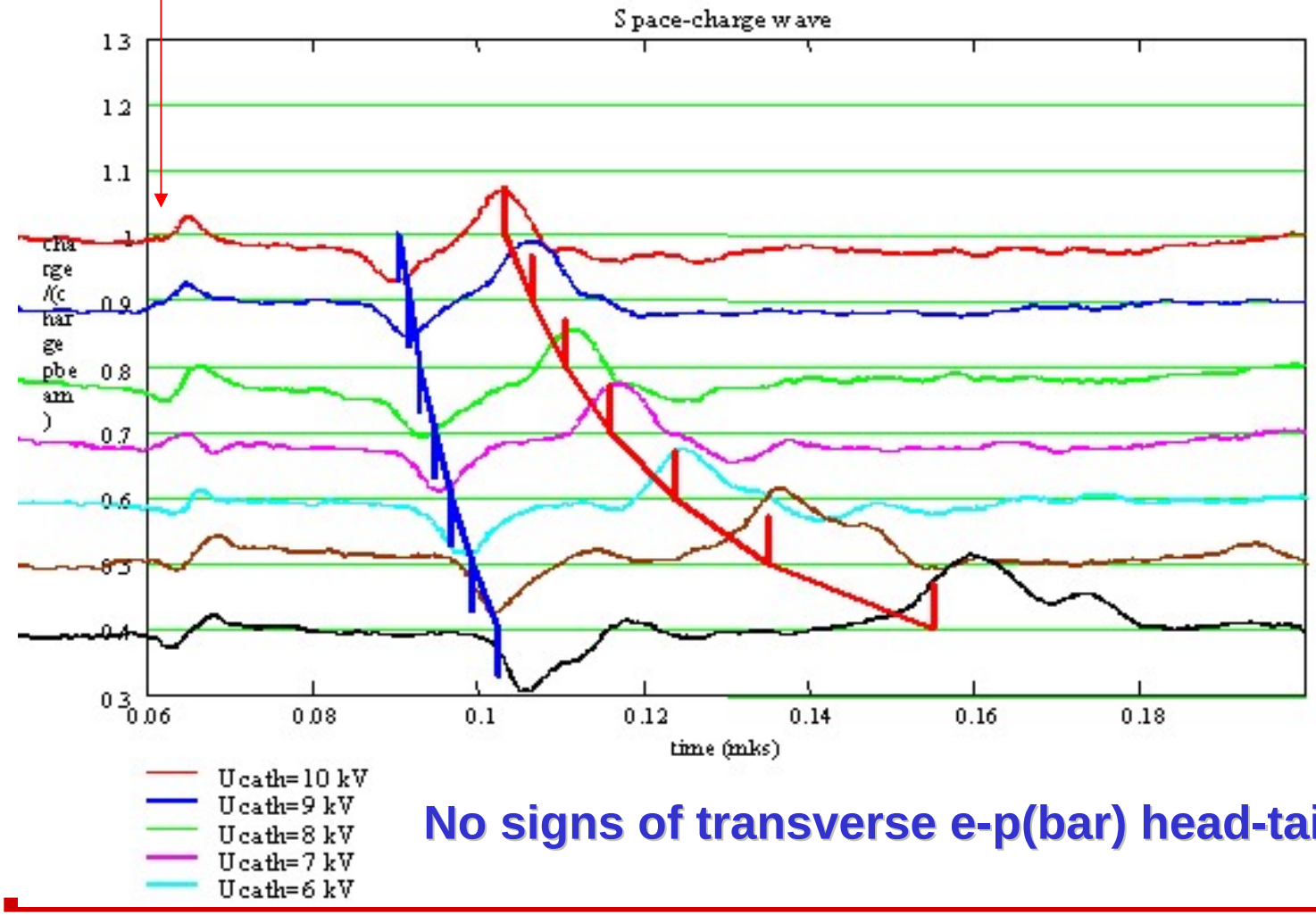


- TEL e-current turn-by-turn noise amplitude dJ_e ~3-5mA p-p
  while operating for BBC
  with dQ > 0.005
  → 0.1-0.2 □/hr
- That is less though comparable with "natural" emittance growth of 0.2-0.5 □/hr
- → we plan to consider possibilities for dJ_e and dX_e stabilization

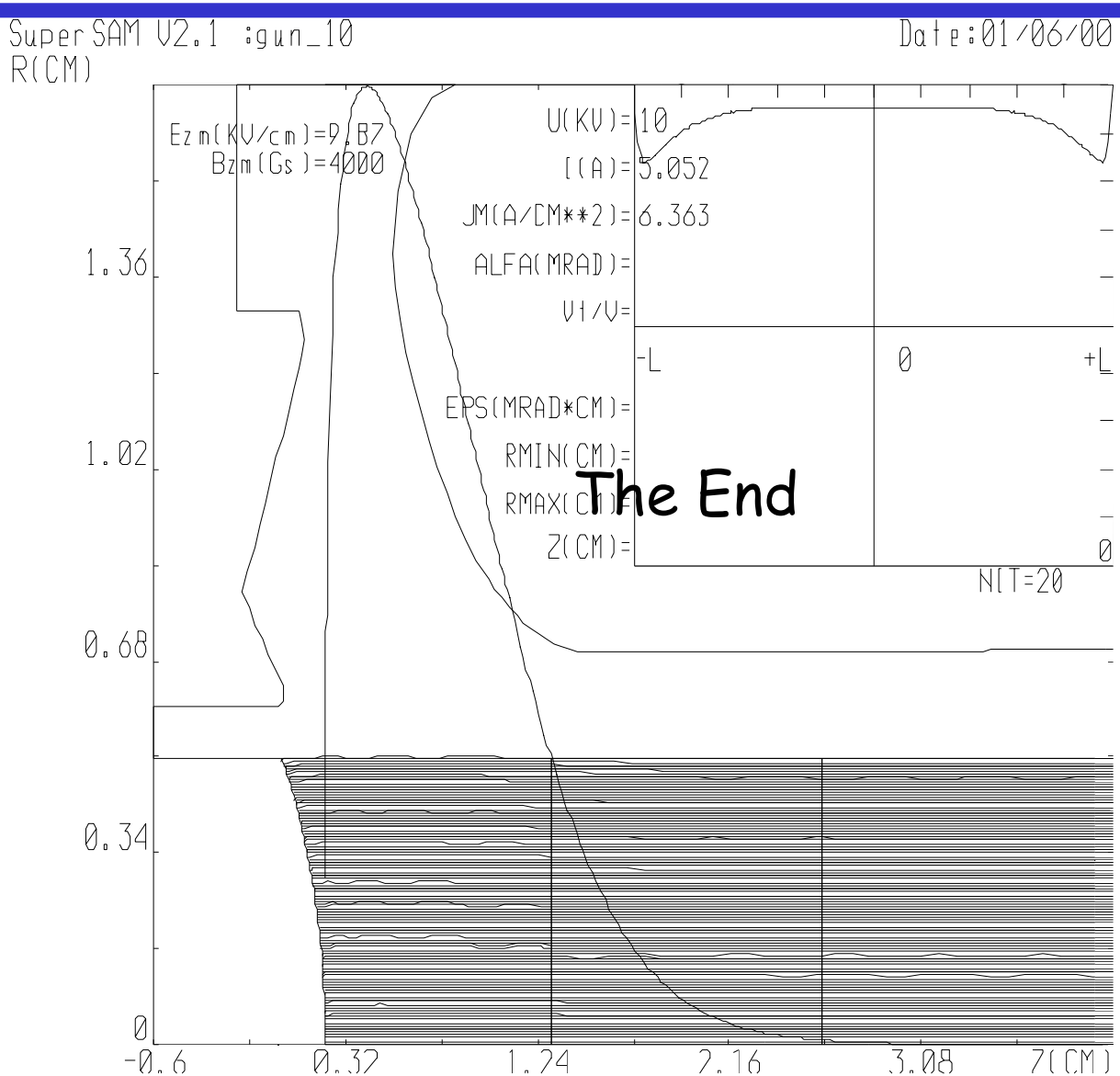
Electron SC Waves Excited by Protons

Passage of protons

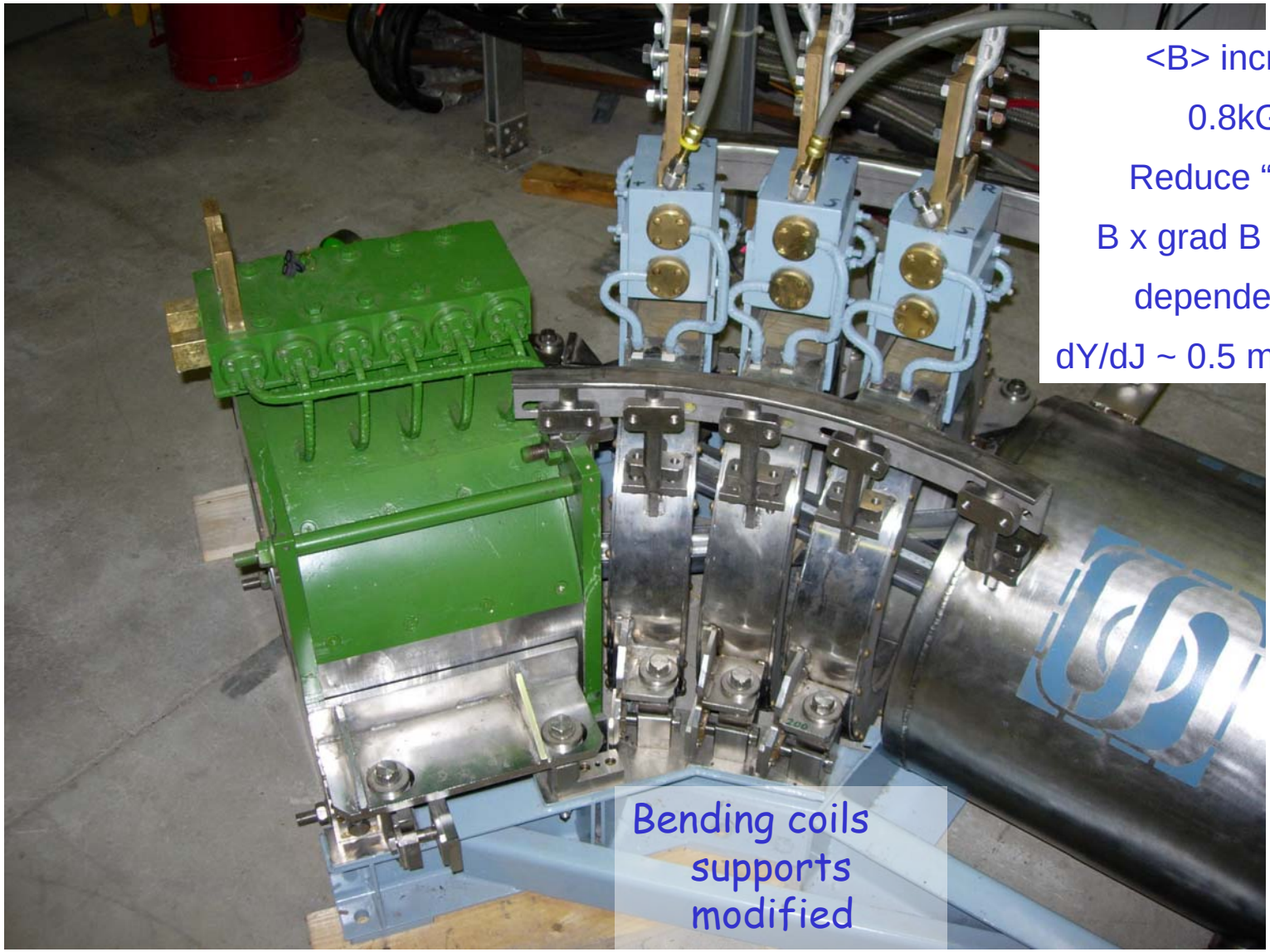
V.Parkhomchuk, V.Reva, V.Shiltsev



No signs of transverse e-p(bar) head-tail instability


Super SAM V2.1 :gun_10
Date:01/06/00
R(CM)
Ezm(KV/cm)=9.87
Bzm(Gs)=4000
U(KV)=10
I(A)=5.052
JM(A/CM**2)=6.363
ALFA(MRAD)=
Vt/V=
-L
0
+L
EPS(MRAD*CM)=
RMIN(CM)=
RMAX(CM)=
Z(CM)=
0
NIT=20
1.36
1.02
0.68
0.34
0
-0.6
0.32
1.24
2.16
3.08
Z(CM)
The End

Bending Section



<B> increased from

0.8kG → ~2kG

Reduce “gradient” drift

B x grad B and it’s current

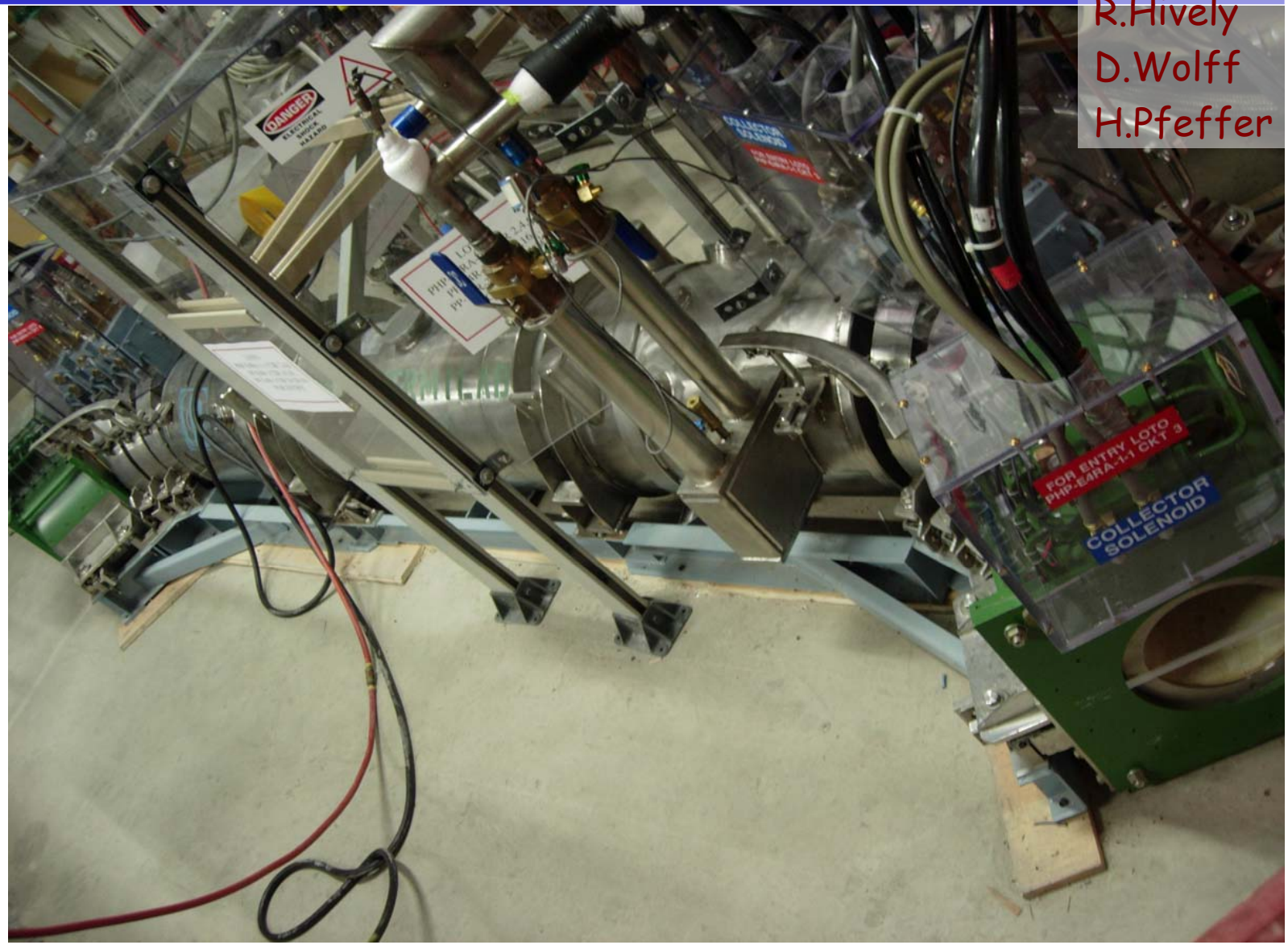
depended component

dY/dJ ~ 0.5 mm/A → 0.1 mm/A

Status: TEL-2

Magnets	delivered, tested - OK
Cryo	byspasses built - OK
PSs	installed, commiss'd - OK
HV pulser	waiting for MARX (Nov)
e-gun	SEFT tests underway
Collector	will use spare
Vacuum	to be tested
BPMs/Diagn	tests underway

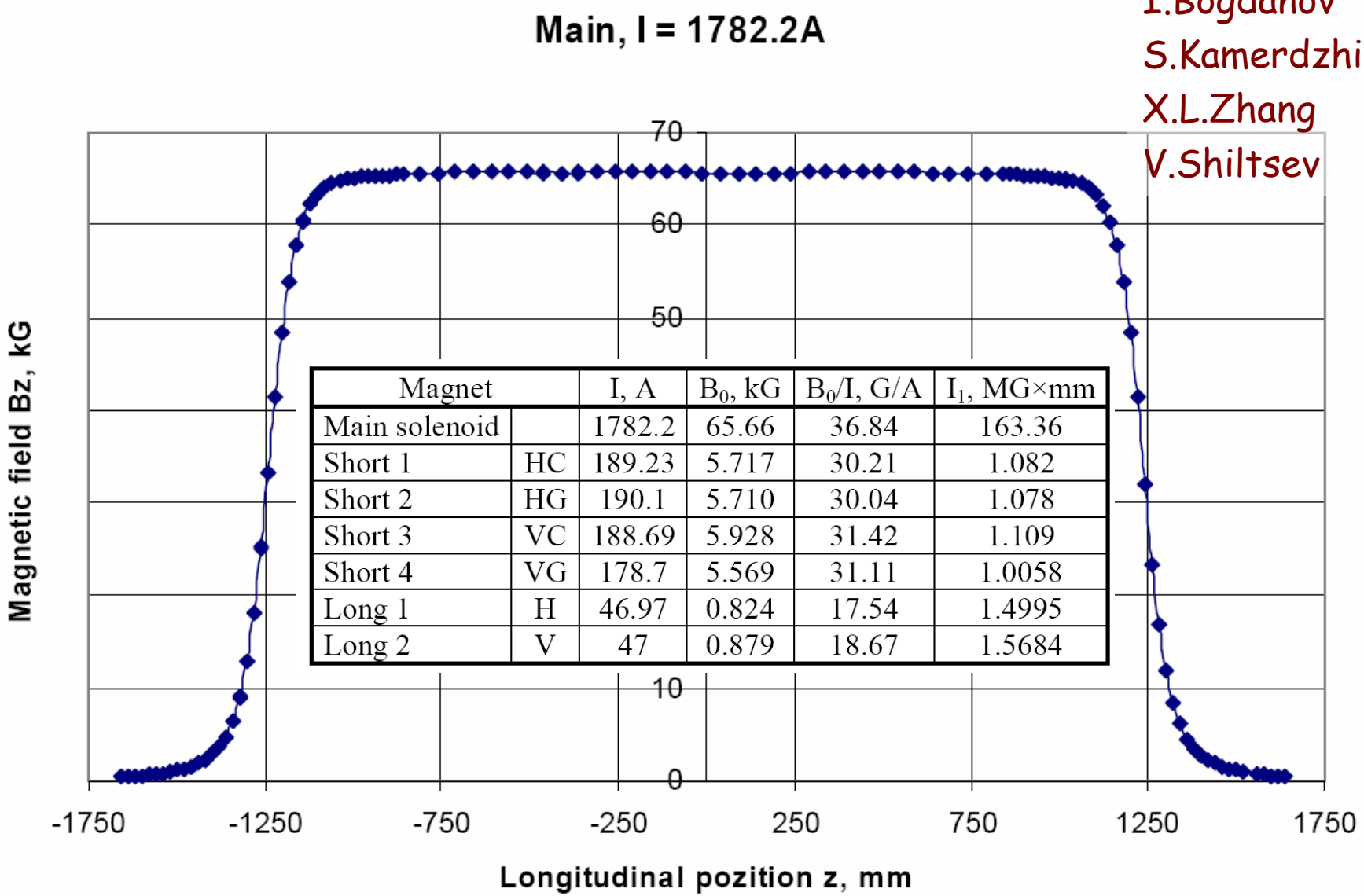
TEL-2 at E4R (note safety)



R.Hively
D.Wolff
H.Pfeffer

TEL-2 at E4R: 6.5T Achieved, Magn Measmnts

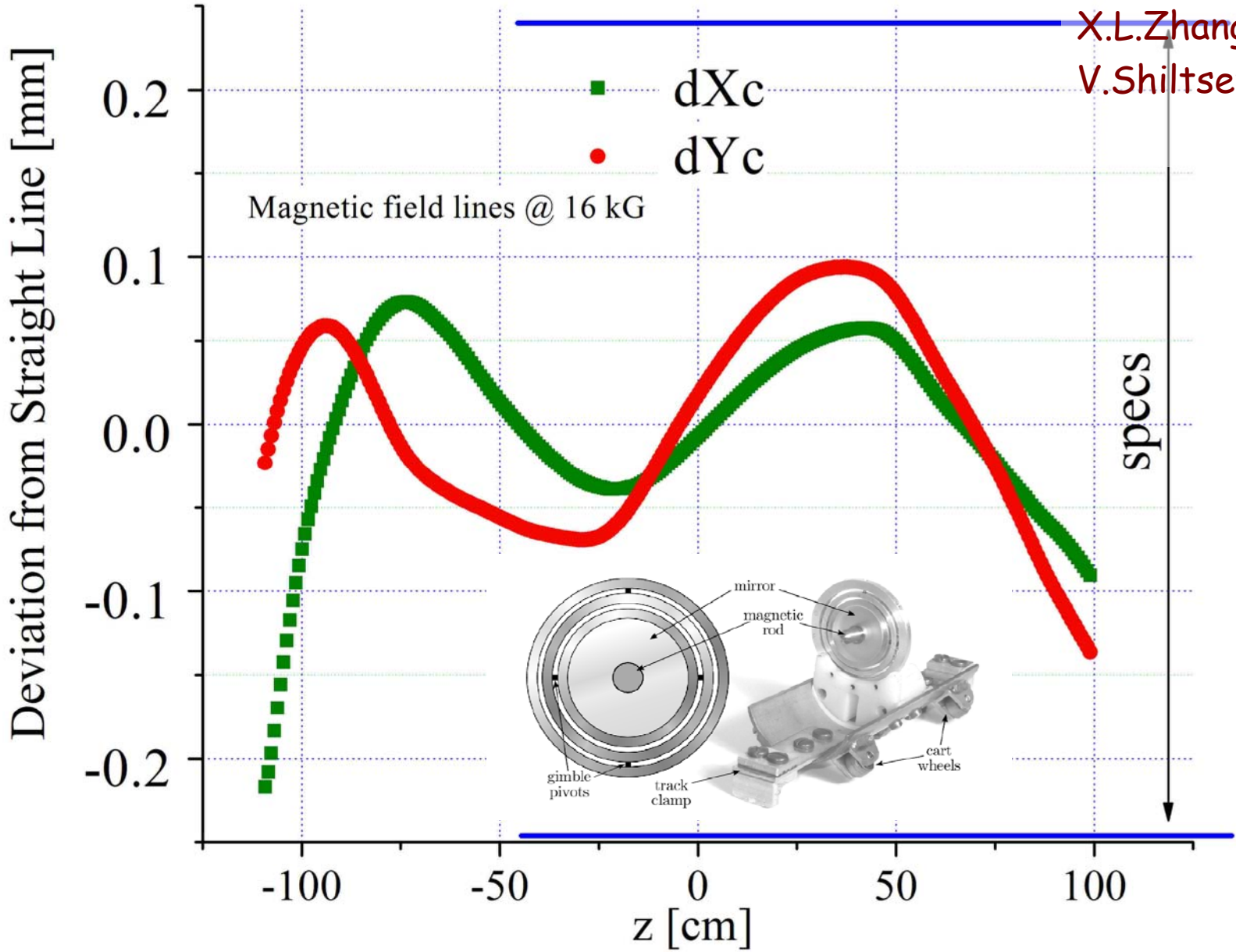
I.Bogdanov
S.Kamerdzhiev
X.L.Zhang
V.Shiltsev



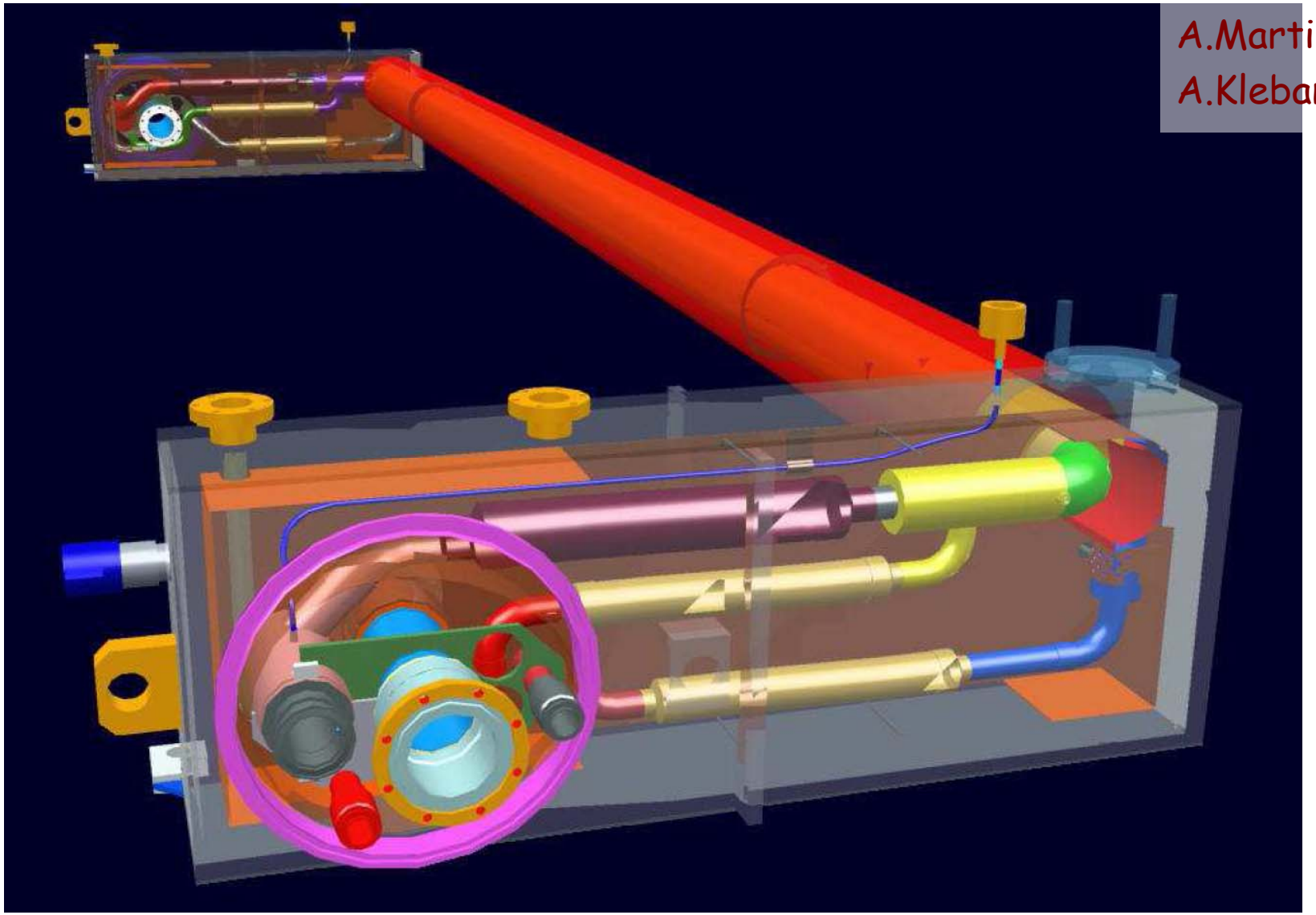
Magnet		I, A	B_0, kG	B_0/I, G/A	I_1, MG×mm
Main solenoid		1782.2	65.66	36.84	163.36
Short 1	HC	189.23	5.717	30.21	1.082
Short 2	HG	190.1	5.710	30.04	1.078
Short 3	VC	188.69	5.928	31.42	1.109
Short 4	VG	178.7	5.569	31.11	1.0058
Long 1	H	46.97	0.824	17.54	1.4995
Long 2	V	47	0.879	18.67	1.5684

Measurements with Magnetic Arrow

S.Kamerdzhiev
X.L.Zhang
V.Shiltsev

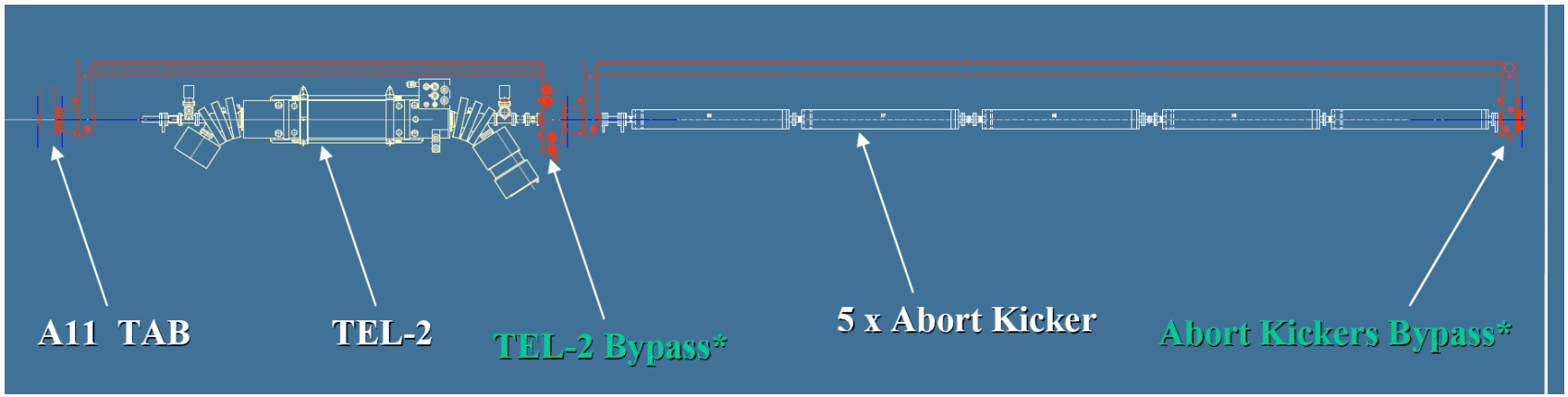


Cryo: Abort Kicker Bypass and TEL-2 Bypass

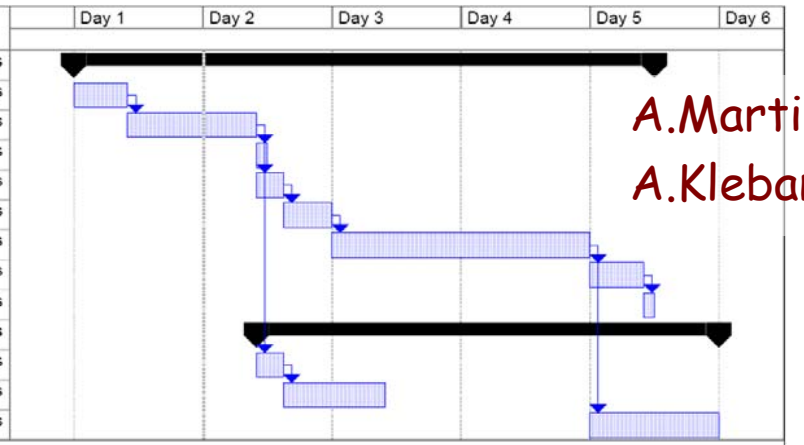


A.Martinez
A.Klebaner

Plan for Cryo Work in the Tunnel



ID	Task Name	Duration
1	**Mechanical**	**4.5 days**
2	Finalize U-tubes	2 hrs
3	Connect cooldown lines	8 hrs
4	Cap an existing cooldown lines	2 hrs
5	Connect Anderson Greenwood relief valves	4 hrs
6	Extend 1ph Kautzky valve control pressure line	2 hrs
7	Run 4 x ¼" OD lines for TEL 2 power leads to A1 frig	16 hrs
8	Install U-tubes	2 hrs
9	Safety walkthrough	2 hrs
10	**Electrical**	**3.75 days**
11	Connect TAB instrumentation	4 hrs
12	Install and calibrate valve actuators	4 hrs
13	Install power leads and KV leak indicator thermometers	8 hrs



A.Martinez
A.Klebaner

Project: TEL2 Installation Cryogenics \
Date: Tue 10/18/05

Task
Split
Progress
Milestone
Summary
Project Summary
External Tasks
External Milestone
Deadline

Page 1

Installation at A0

From: Jim Volk
Subj.: Tel II status
Date: Oct 20, 2005

Alex Martinez, John Featherstone, Terry Anderson, Ron Moore, Vladimir Shiltsev, Xialong, Gerry Annala, Scott McCormick

Overall things are in good shape. Cryo is ready with by pass, it has been certified and is ready to be installed. All vacuum parts for the TEL are built and ready to be installed. The TEL should be ready by January 1st 2006. This leaves 8 weeks to take care of any details. There are 3 cables that need to be pulled. These are signal cables and present no problem. Power supplies are installed upstairs. There will need to be a LOTO written for this but that can be a copy of the LOTO for the TEL I.

A fair amount of time was spent in estimating the installation time. The Cryo bypass will have to go in via the D0 drop hatch and be transported around the ring. Jim Volk and John Featherstone will coordinate the move so as not to interfere with other work in the tunnel. The pbar kickers will have to be moved in station by 5 inches. This will require AMG to as found the kickers before moving and then re-align them afterward. As a precaution the kickers will be disconnected before the move to protect the ceramic beam tubes. Installation time for the bypass, moving the kickers, moving a turn around box and installing the TEL will be 3 weeks. This will be 3 mechanical techs and help from the Tevatron department. There will be 1 more week to certify the vacuum and cool down A-1 house.

There is a desire to change out the existing spool for a HTS spool. This could add an extra week onto the task. The decision will wait until we know the work load for other jobs. Cryo will also need 5 days to move the turn around box and pull new instrumentation cables.

To protect the TEL during abort shielding will be needed around the beam pipe. This could be lead packed close to the beam pipe. Shiltsev and Xialong will investigate the use of steel instead of lead. If lead is used a hazard analysis will need to be generated and a plan for wrapping the lead and installing the shielding. Terry Anderson will work up a design for the shielding to get it around the beam pipe above and below.

There is a leak in the heat exchanger; to repair this would require the TEL II going back to Russia. The leak can be over powered with a turbo pump. If it gets worse the TEL will become a very good beam pipe.

To install the by pass the supports for the 120 GeV extraction line will have to be removed and the beam pipe temporarily support. Terry Anderson will look into making permanent supports hung form the ceiling for this beam line. Jim Volk will put in job requests for as founds of the p bar kickers and the 120 GeV extraction line and re survey of both. There are steel plates on the floor that need to be removed these can be done during a one day shutdown. Scott McCormick will take care of this. One more inspection of the area by Terry Anderson would be good before the start of the shutdown

3 weeks — MechSupport (incl 5 days of Cryo work)

1 week — checkup A1 (D.Plant)

Moving AAKs 5" to install bypass (!)

Cryo work will make A1 colder (reduce # of quenches there)

TEL-2 has small cold leak He to insulation vacuum and will have turbo pump on it

If needed, Tel can be easily taken out of Cryo circuits (with U-tubes) in 4-8 hrs (then TEL will be just a very good pipe)

Undesired: Fix of Cold Leak

Date: Wed, 26 Oct 2005 19:15:24 +0400
From: Kozub S.S. <Sergey.Kozub@ihep.ru>
To: Vladimir Shiltsev <shiltsev@fnal.gov>
Subject: TEL repair
Volodya, zdravstvui. Soobshaju ocenku stoimisti i vremeni remonta gelievogo sosuda i kriostata TEL2 s holodnimi ispitaniyami gelievogo sosuda posle remonta, a takzhe posle sborki v kriostate 1. Bez izgotovleniya novogo helievogo sosuda: 44 k$ i 7 mesyacev 2. V sluchae izgotovleniya novogo helievogo sosuda: 60 k$ i 8 mesyacev. Nadeemsy, chto udastsya oboitis' bez izgotovleniya novogo gelievogo sosuda, no tochnii otvet mozhno dat' posle razborki kriostata i nahozhdeniya techi. Mi ochen' zagruzheni do Maya sledujushego goda, potom osvobodimsya. V ocenku ne vhodit stoimost' perevozki. Pishi, esli nuzhna dopolnitel'naya informaciya i soobshi o prinyatih Vami resheniyah.

Sergey

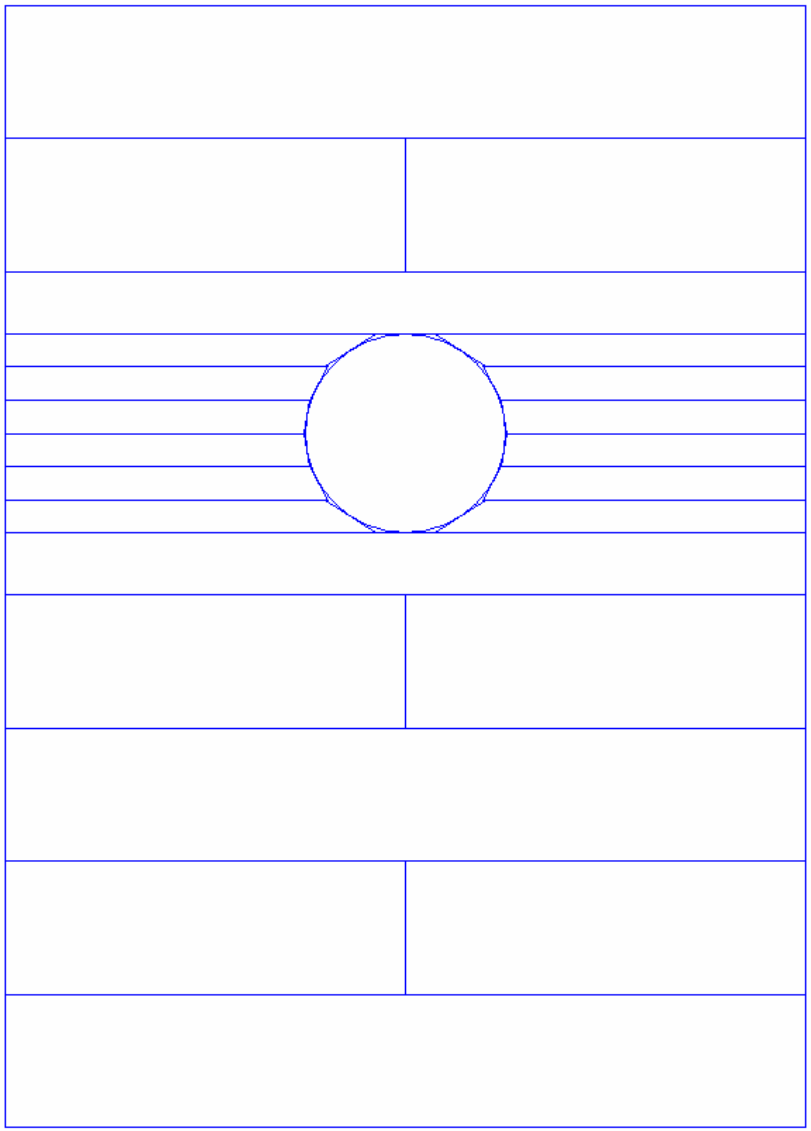
8 months and 60k$

Only after May '06 (IHEP shop booked by LHC order)

No need unless turbopump can not control the insulating vacuum (not the case now)

Transportation of SC coils block is undesired, too

Shielding: Cheap Solution (T.Anderson)

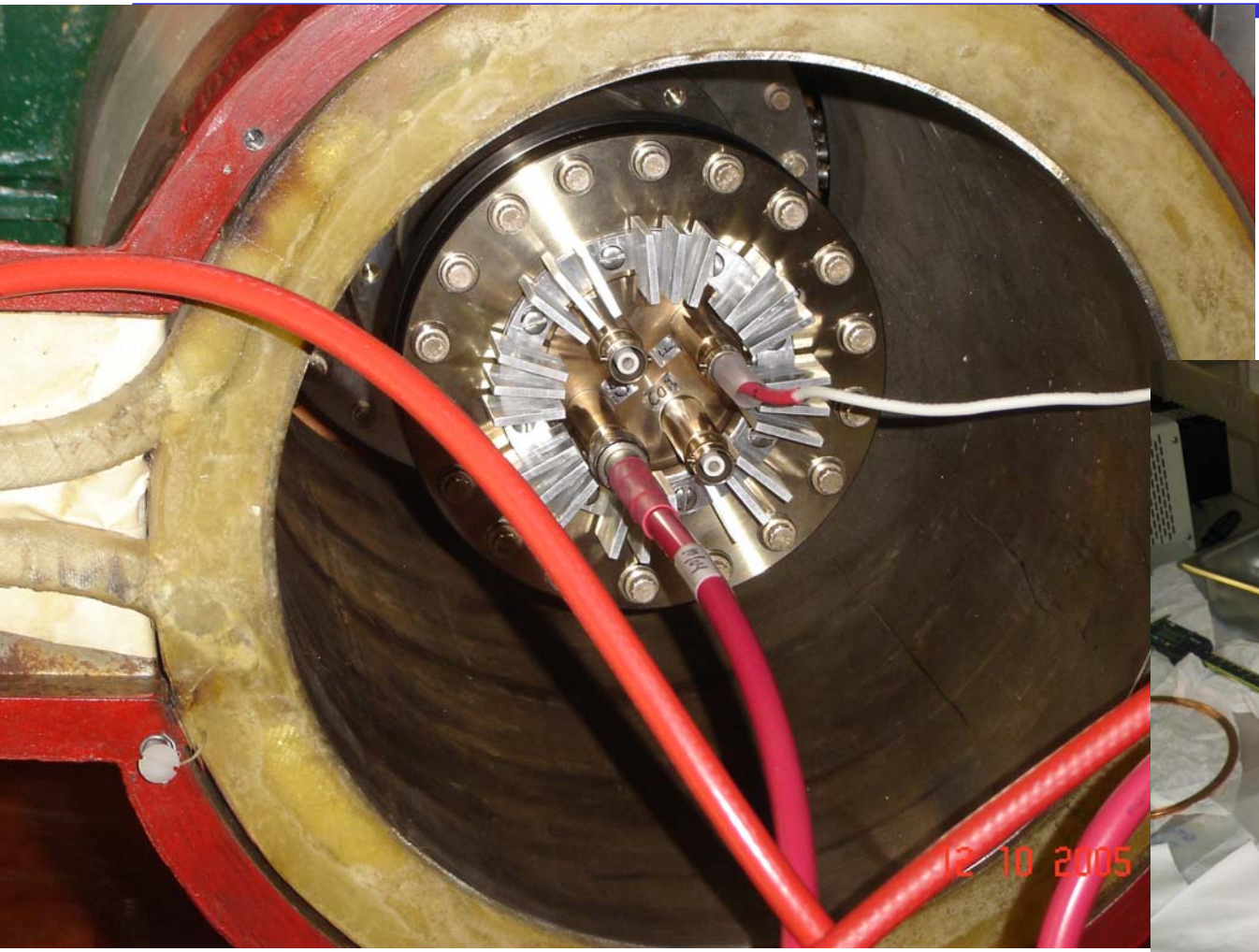


According to doc-1543 (M.Kostin, 2005), TEL-2 will quench on every abort of 10^13 protons (torchlight from abort block)

10 cm of iron from abort block to TEL-2 (all around beam pipe) should reduce the dose 100-fold.

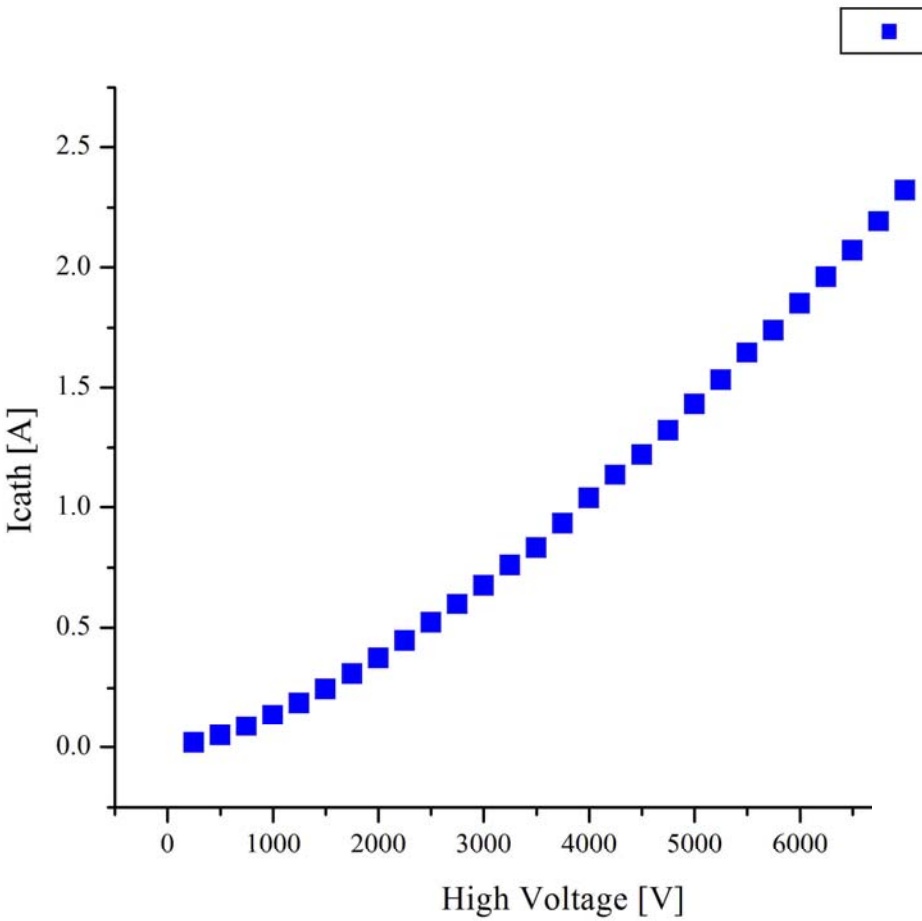
SEFT (Smooth Edge Flat Top) Gun

M.Tiunov
S.Kamerdzhiev
G.Kuznetsov

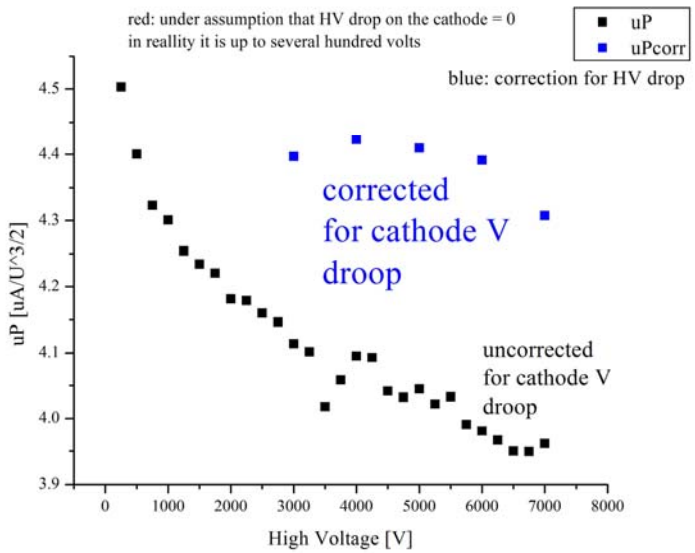


14 mm cathode Installed for tests in the Linac lab setup; initial corona problems overcome

SEFT Gun Microperveance

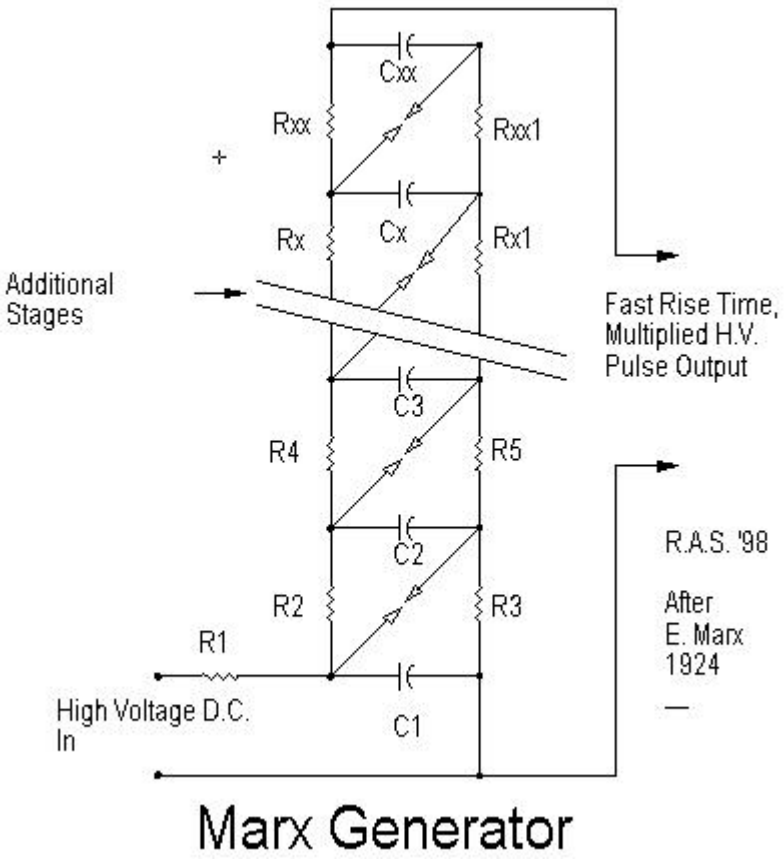


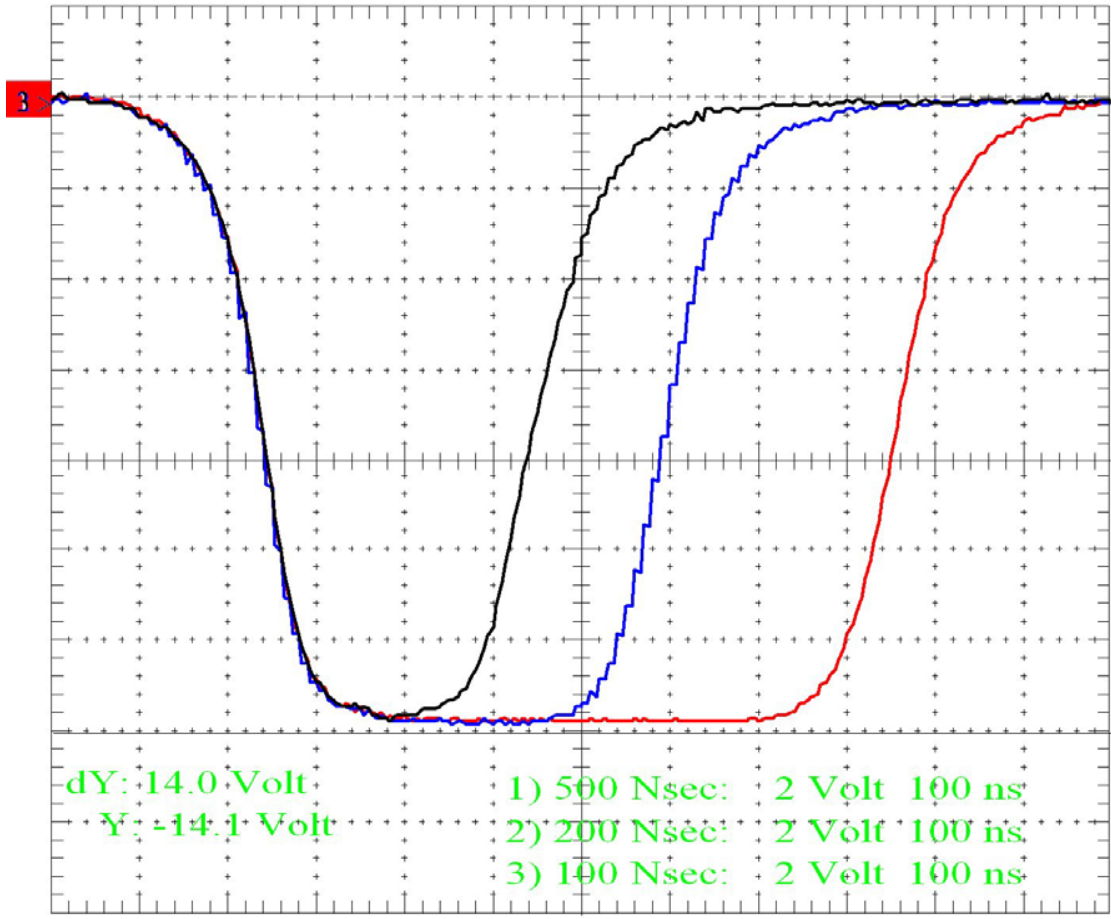
S.Kamerdzhiev
G.Kuznetsov



uP=4.3 as predicted by SuperSAM simulations

Marx Generator from Stangene Inc. (CA)





Expect Delivery in November; 2nd Generator ordered (adjustable pulse A)

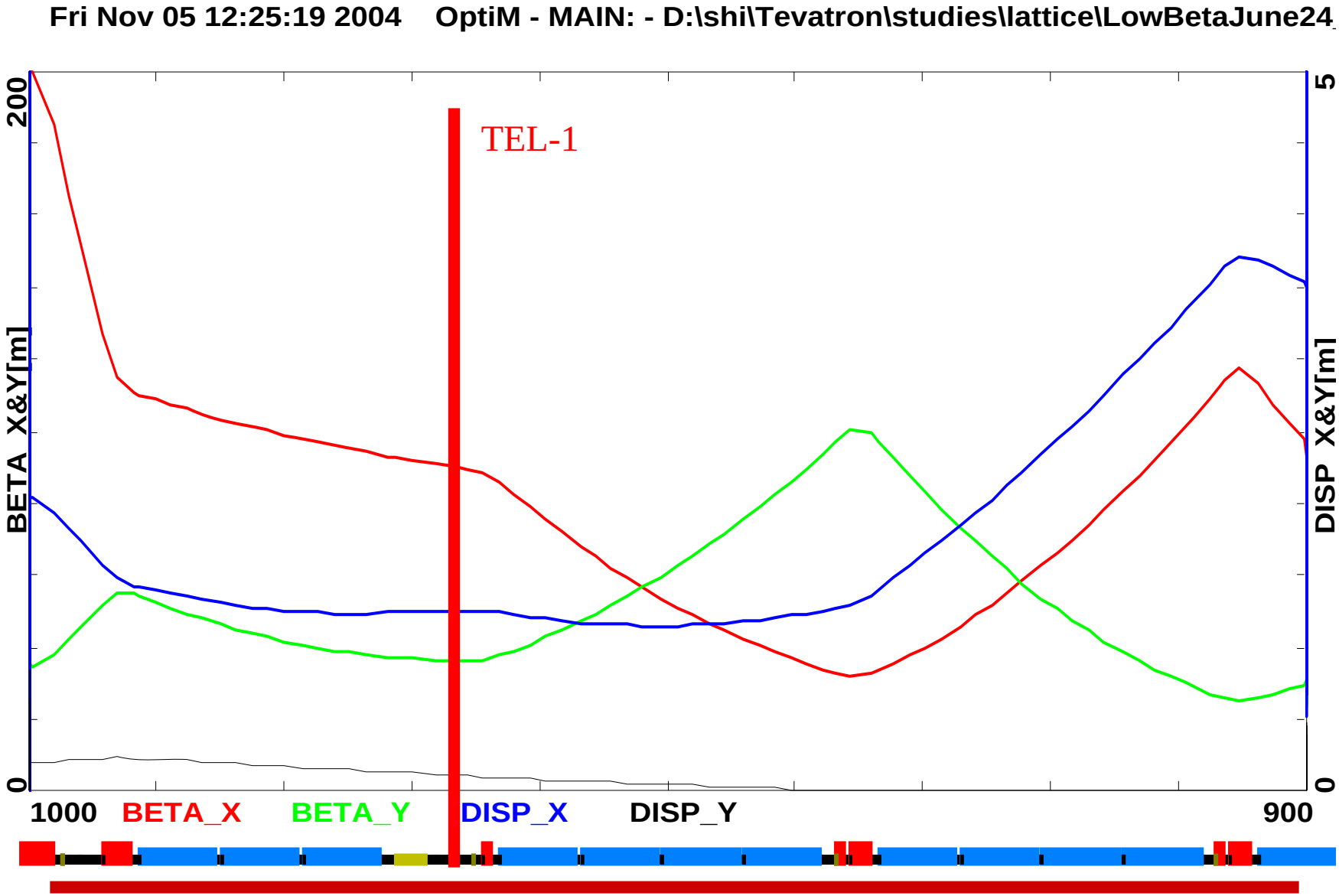
Action Plan

- Calibrate TEL-2 BPMs with stretch wire (Vic, Seva, Brian)
- Measure SEFT profile (Seva)
- Assemble TEL-2 vacuum system and bake (Gennady & John F)
- Perform EoS and SoS studies with TEL-1 (ZXL, VS, Seva)
- Get the current, study transmission vs B_gun/B_main (Seva, XL)
- Study e-beam orbit vs current (same)
- Tracking studies with LIFETRAC (Sasha Valishev)
- Calibrate TEL-2 BPMs with short e-pulses (Vic and Seva)
- Measure TEL-2 e-beam profile (Seva, Vic)
- Commission MARX generator pulser (Howie & we)
- Move & install TEL-2 FY06 during shtdn (Gennady, MSupp, et al)
- Commission TEL-2 with 980 GeV p-beam, studies with 2 TELs (all)
- Build parts for TEL-1 modification (Gennady, Seva, VS)
- Modify TEL-1 in FY07 shutdown (as in FY06)

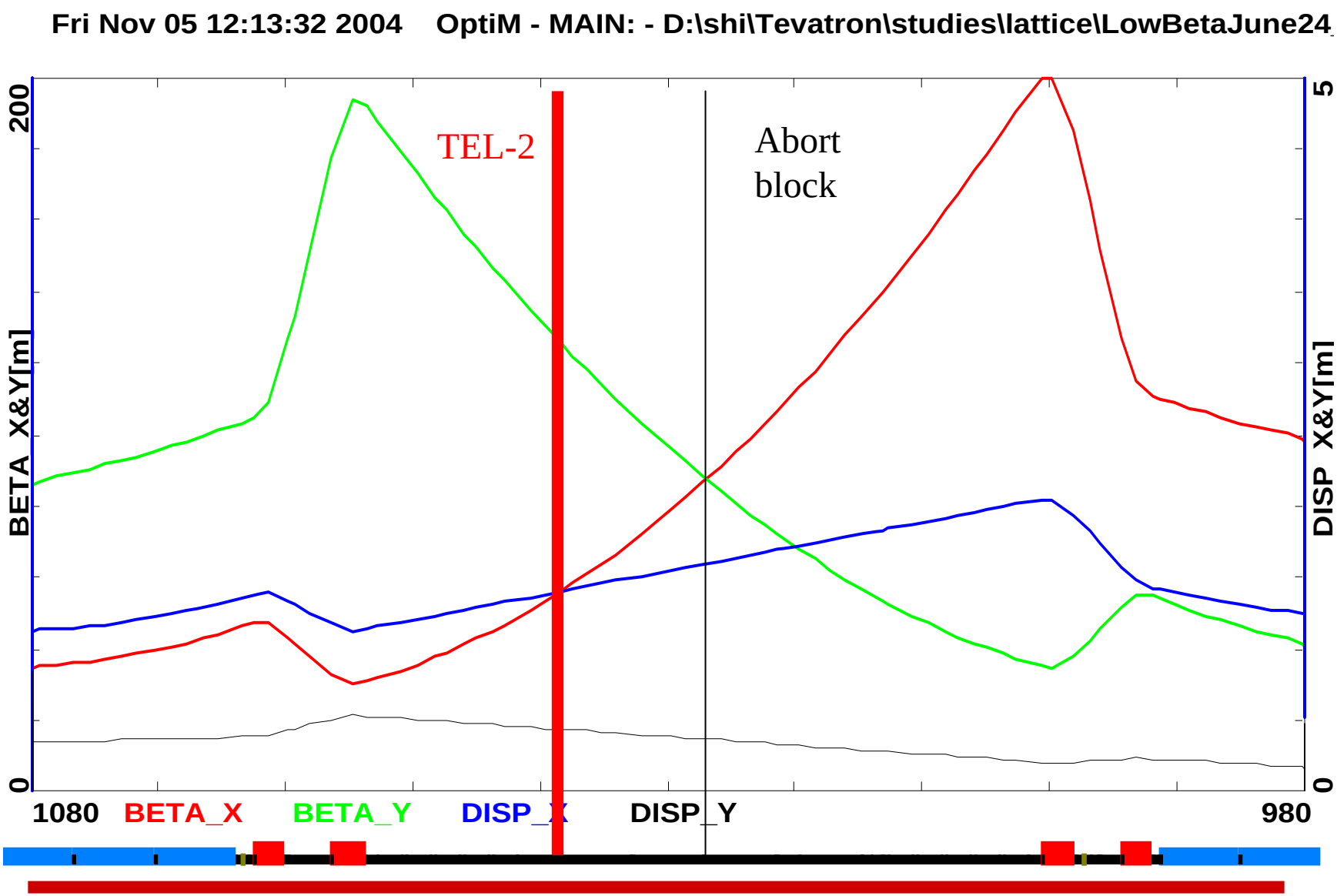
Budget FY06

- No need in TEL-3……..-600k$
  - TEL-3 was supposed to be a spare for operational TEL-1 and TEL-2
    - TEL-1 has shown good reliability over 4 yrs
    - Run II will end in 4 years
    - the system is not *operational* yet (till after FY07 ?)
- TEL-1 modifications, TEL-2 and spares:
  - Frame and bending coils 80k$
  - TEL-2 50kW collector 50k$
  - spare SETF gun 20k$
  - TEL-1 modified vacuum parts and BPMs 80k$
  - Contingency 30k$
- Total……260k$

Lattice Functions at TEL-1 (F48)



Lattice Functions at TEL-2 (A0)



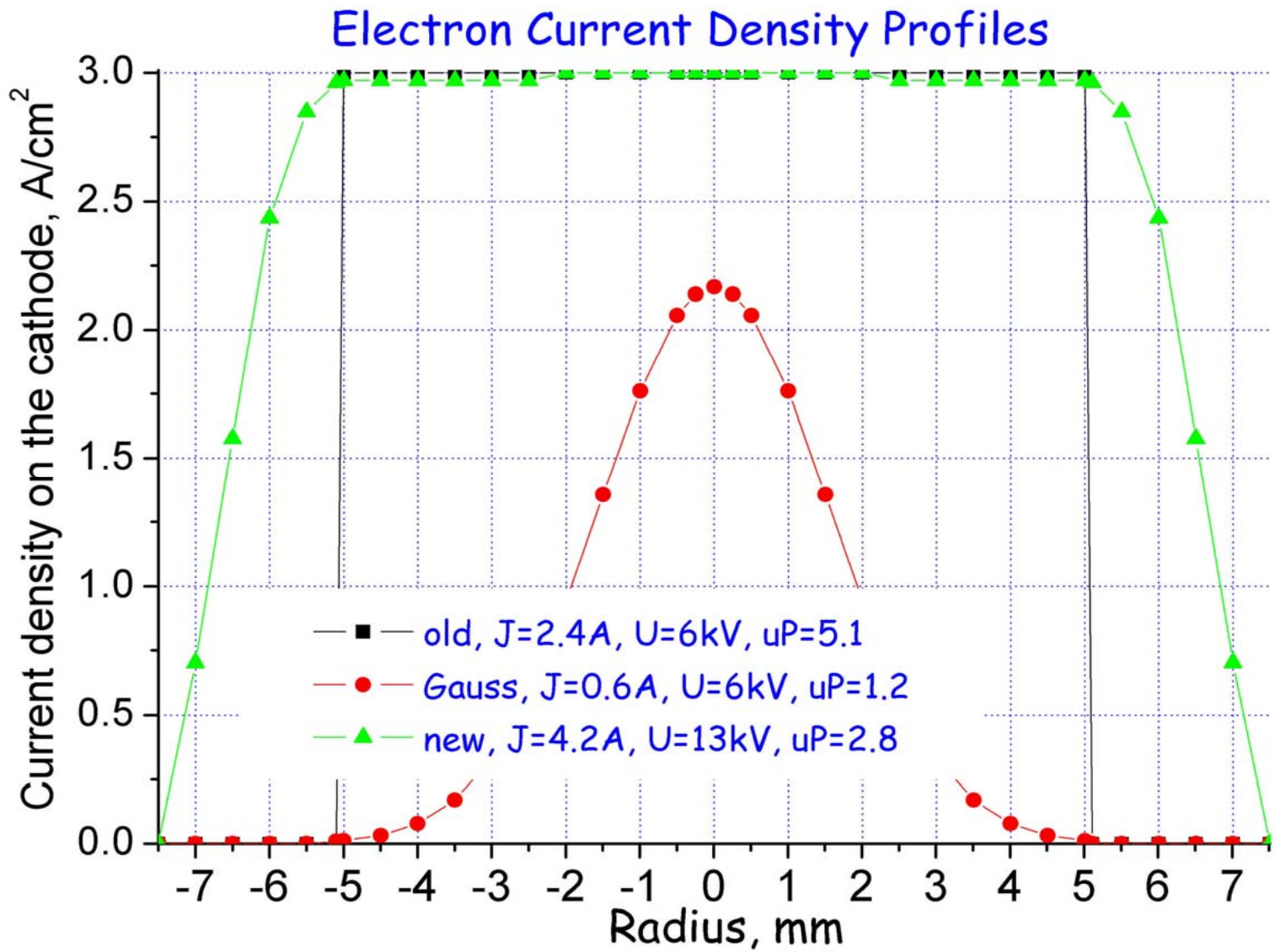
Summary of Two TELs

	Tel-1	Tel-2
β_x, m	100	49
β_y, m	30	136
D_x, m	1.8	2.1
dX_{co},mm	5.8	5.2
dY_{co},mm	1.4	-5.6
σ_x, mm	0.63	0.49
σ_y, mm	0.31	0.67

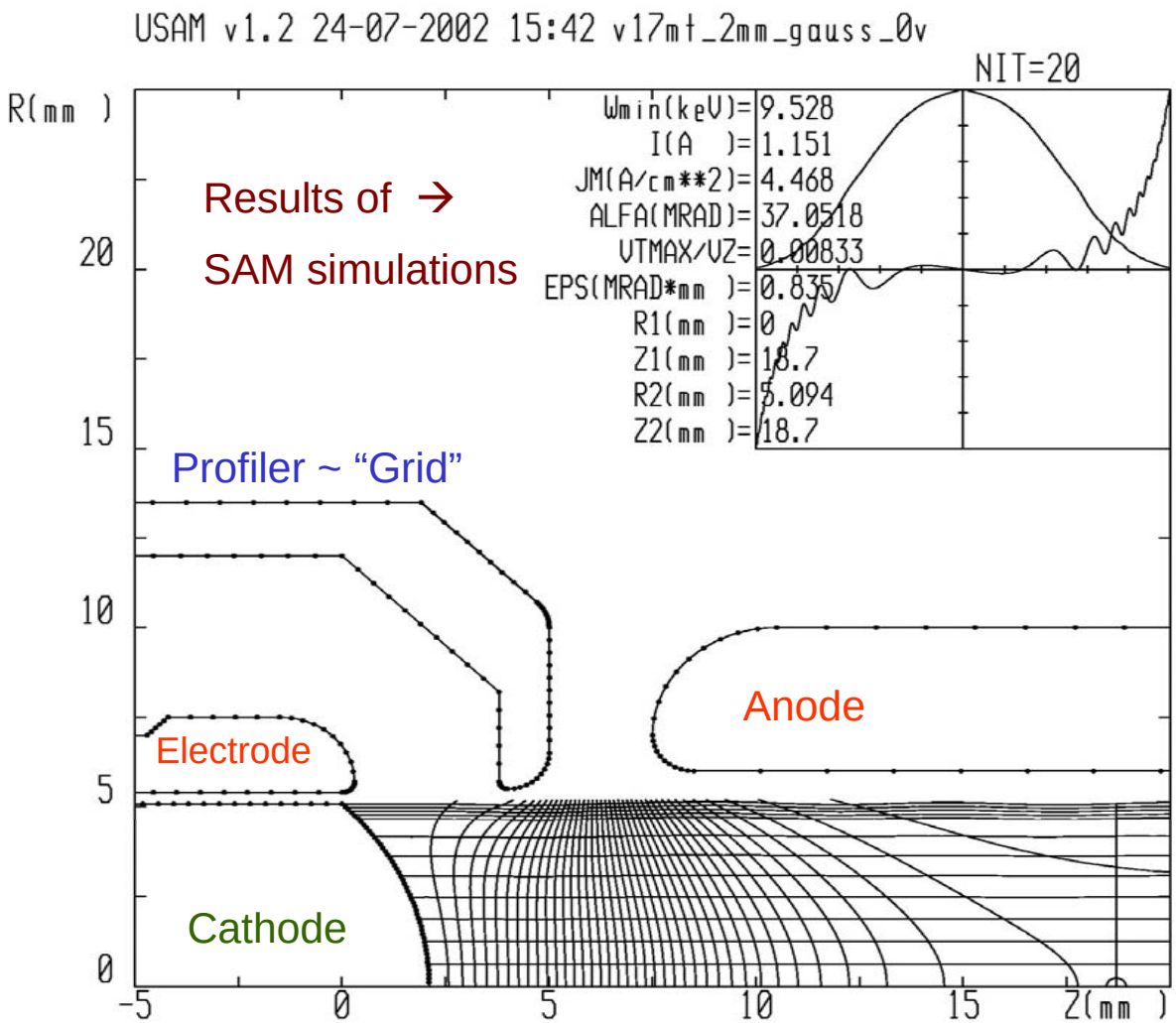
Check-up List

	#1	#2	spares	comm.
Magnets	√	√	no	later
Cryo	√	no	no	will build
PSs	√	~	√	
HV pulser	√	no	√	will use spare
e-gun	√	~	√	under design
Collector	√	no	~	will use spare
Vacuum	√	~	no	

Need wider beam => new HV modulator



Need of Smooth Edges → Gaussian Gun

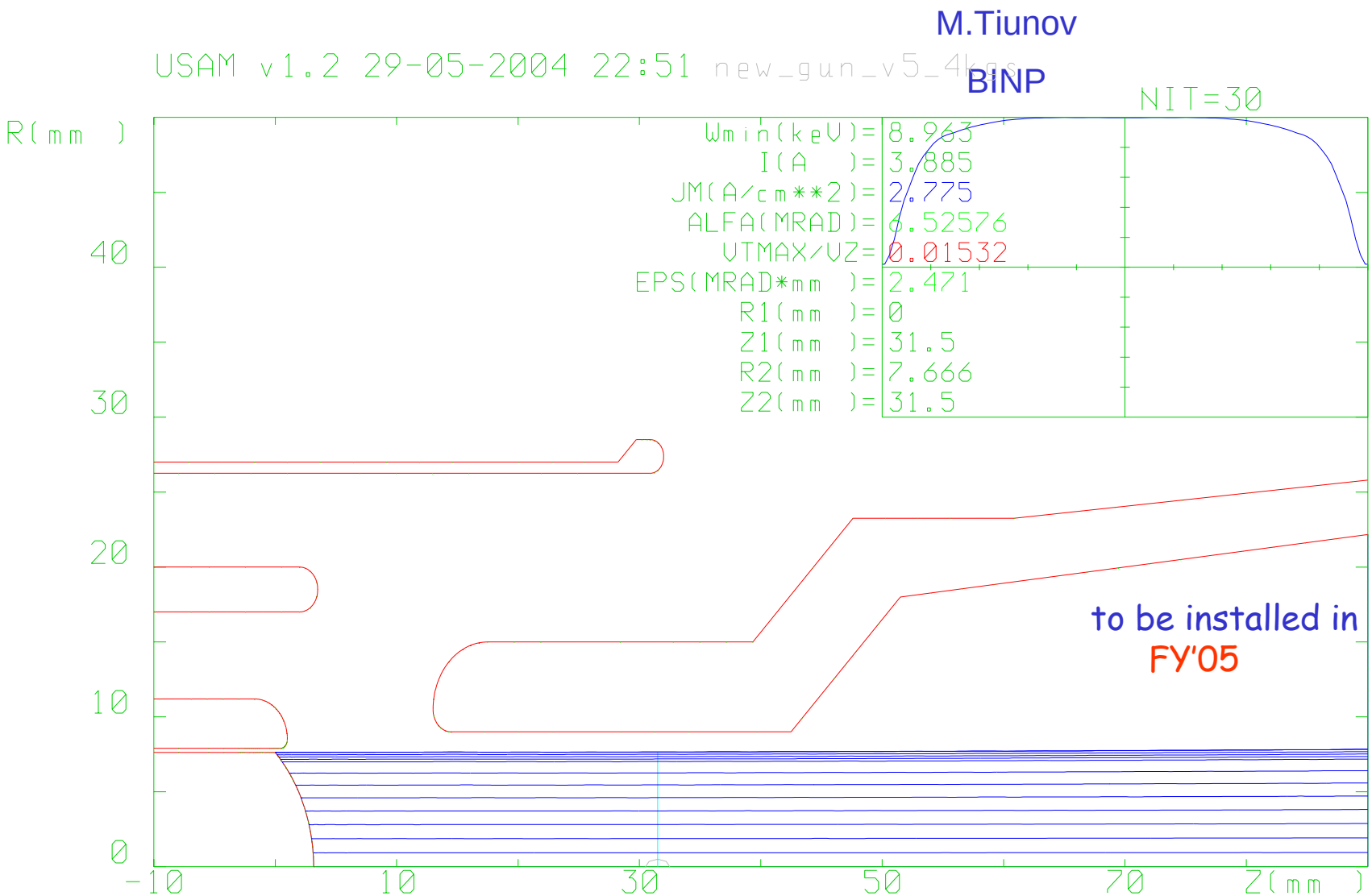


M.Tiunov

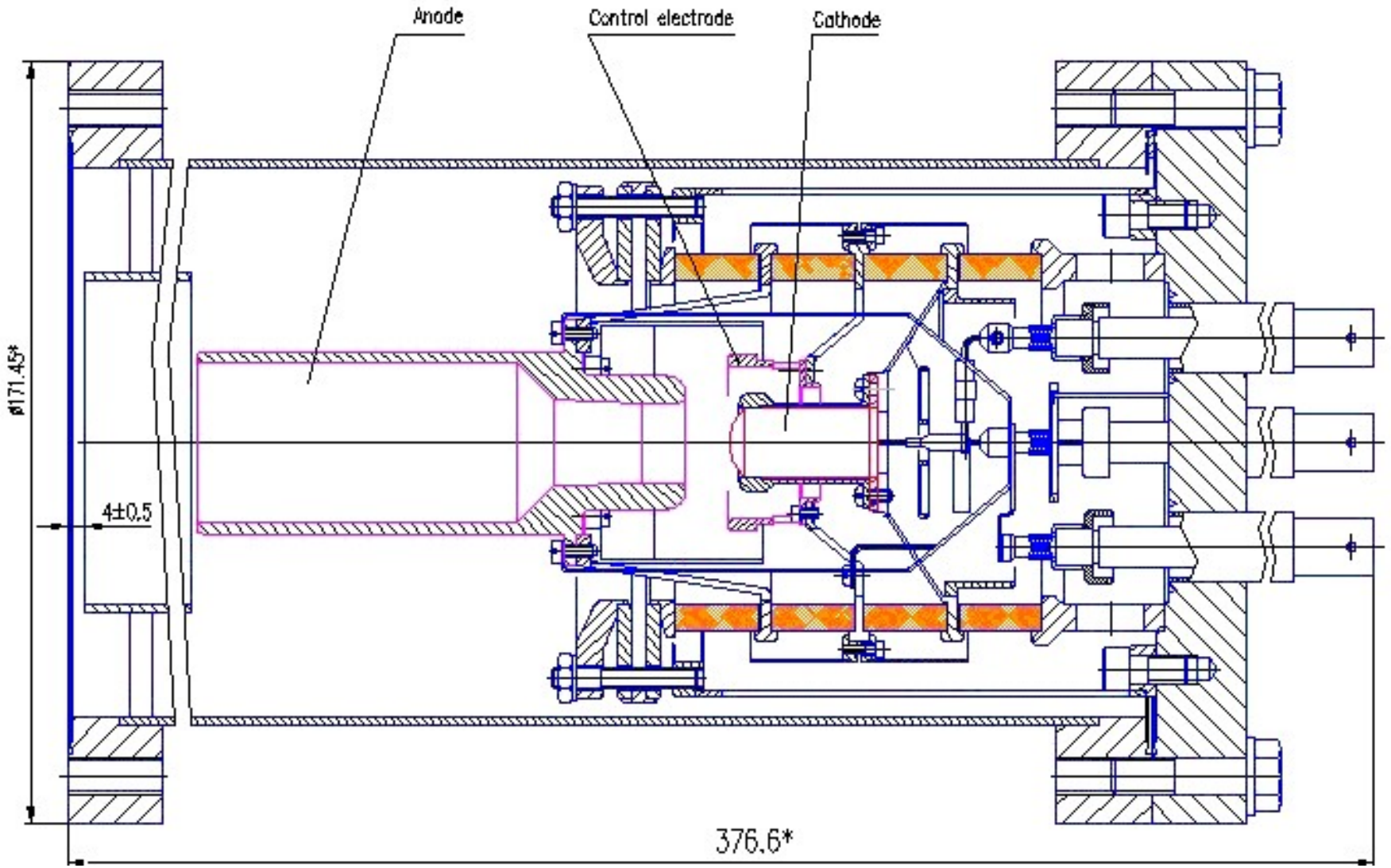
BINP

Installed in Jan'2003

Need of Flat Top → SEFT e-Gun



SEFT e-Gun "Smooth Edge+Flat Top"

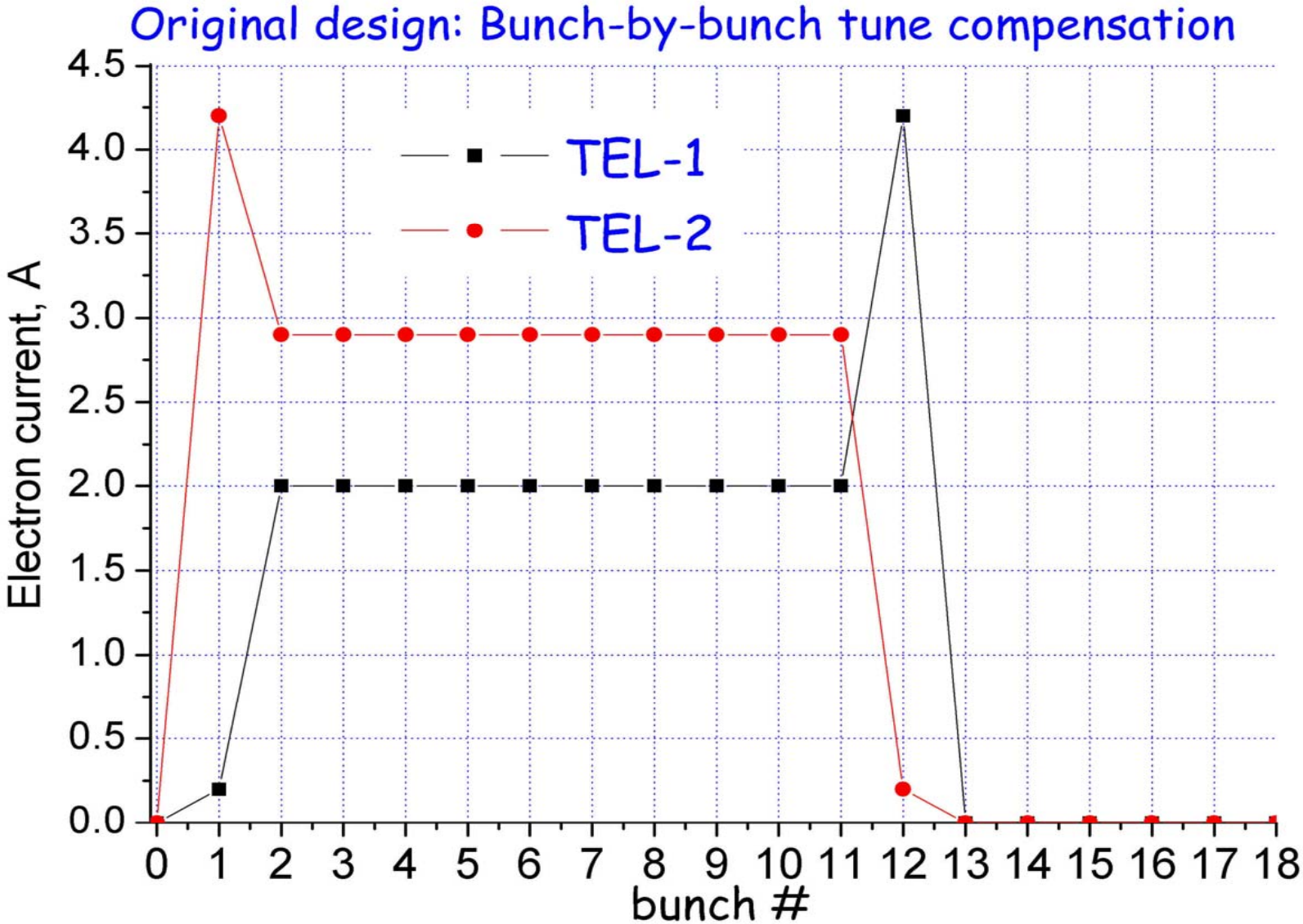


Summary of TEL e-Guns

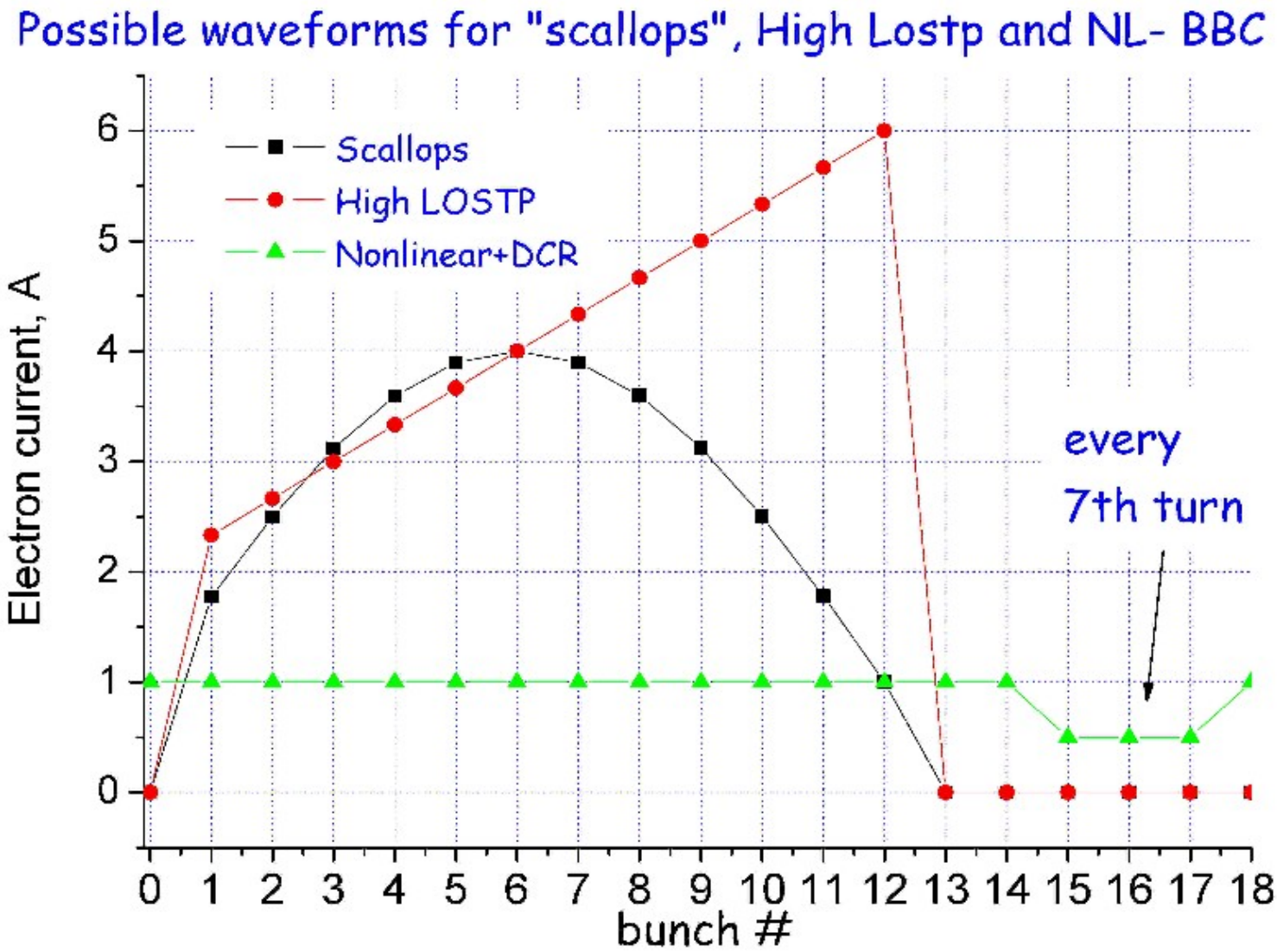
	Flat	Gauss	SEFT
μP	5.1	1.15	3.9
j_{max}, A/mm (at Va=10kV)	6.4	4.5	2.9
V_a, kV (for dQ=0.005 TEL-1 Ue=7kV)	5.0	6.3	8.6
V_a, kV (for dQ=0.01)	7.9	10.0	13.7

... currently we get Va ~ 6 kV

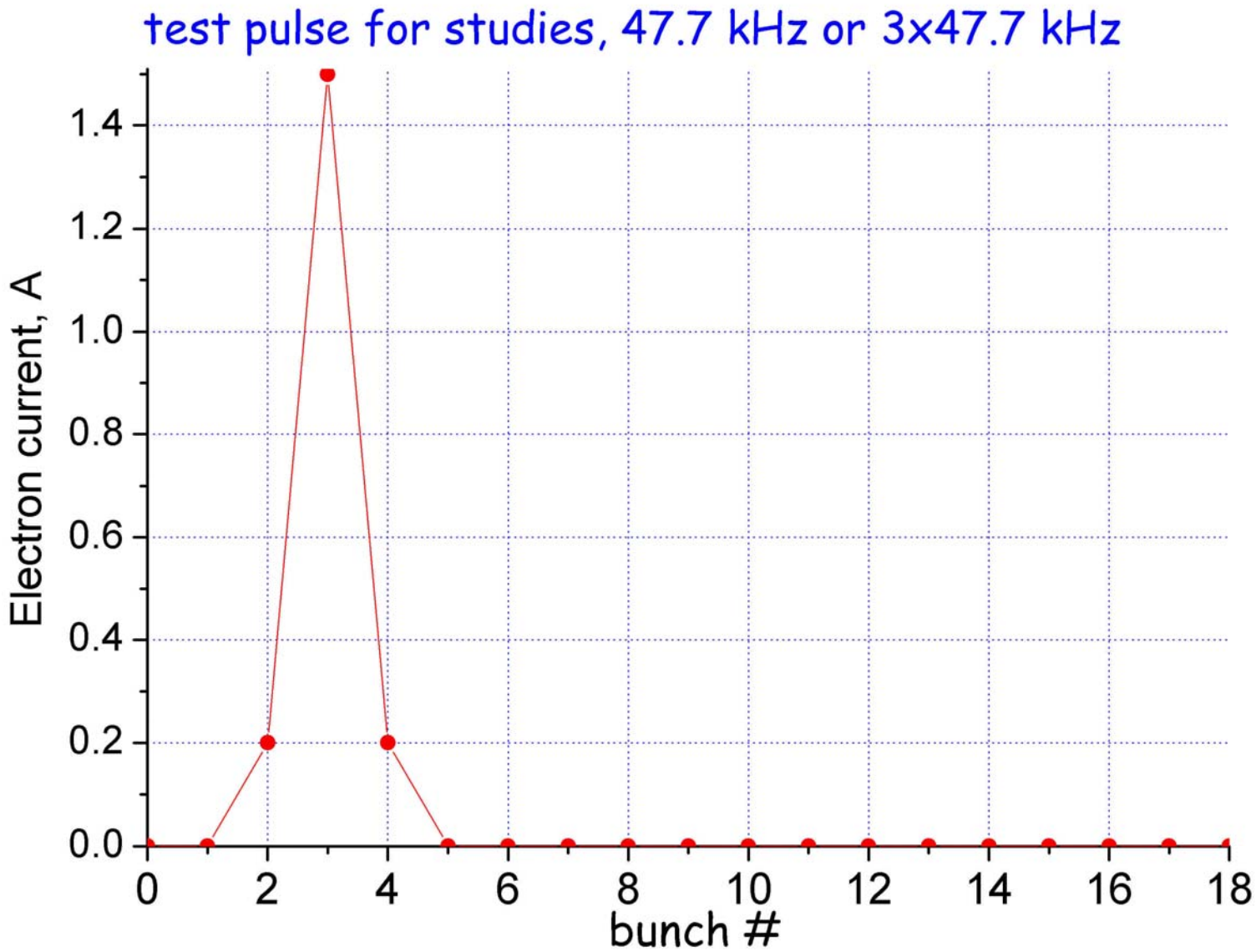
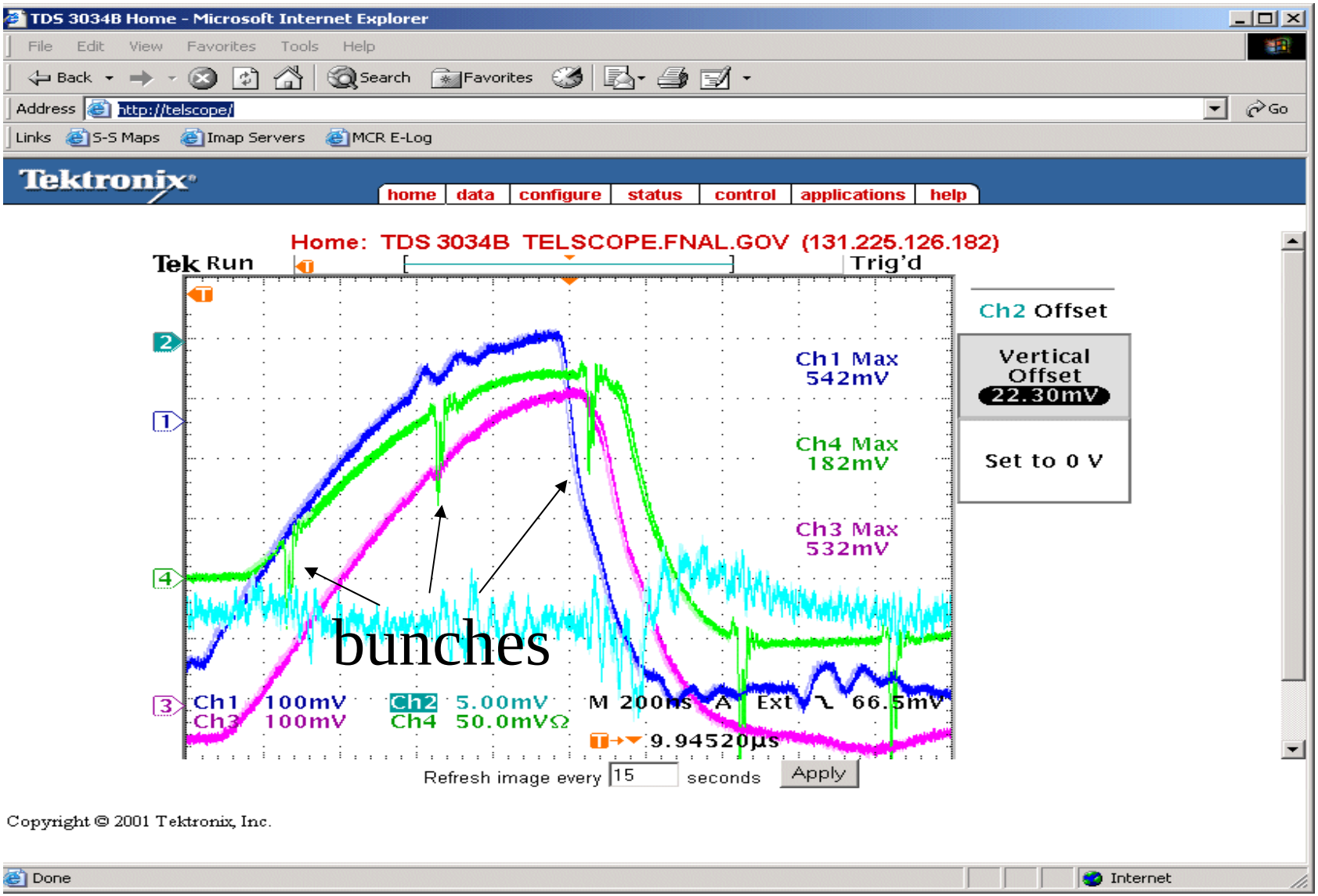
HV Output Waveform depends on what to BBC



or like that… ?


Possible waveforms for "scallops", High Lostp and NL- BBC
Scallops
High LOSTP
Nonlinear+DCR
every
7th turn
Electron current, A
bunch #
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

For single bunch studies during store



e-Pulse Affects 2 Bunches Now