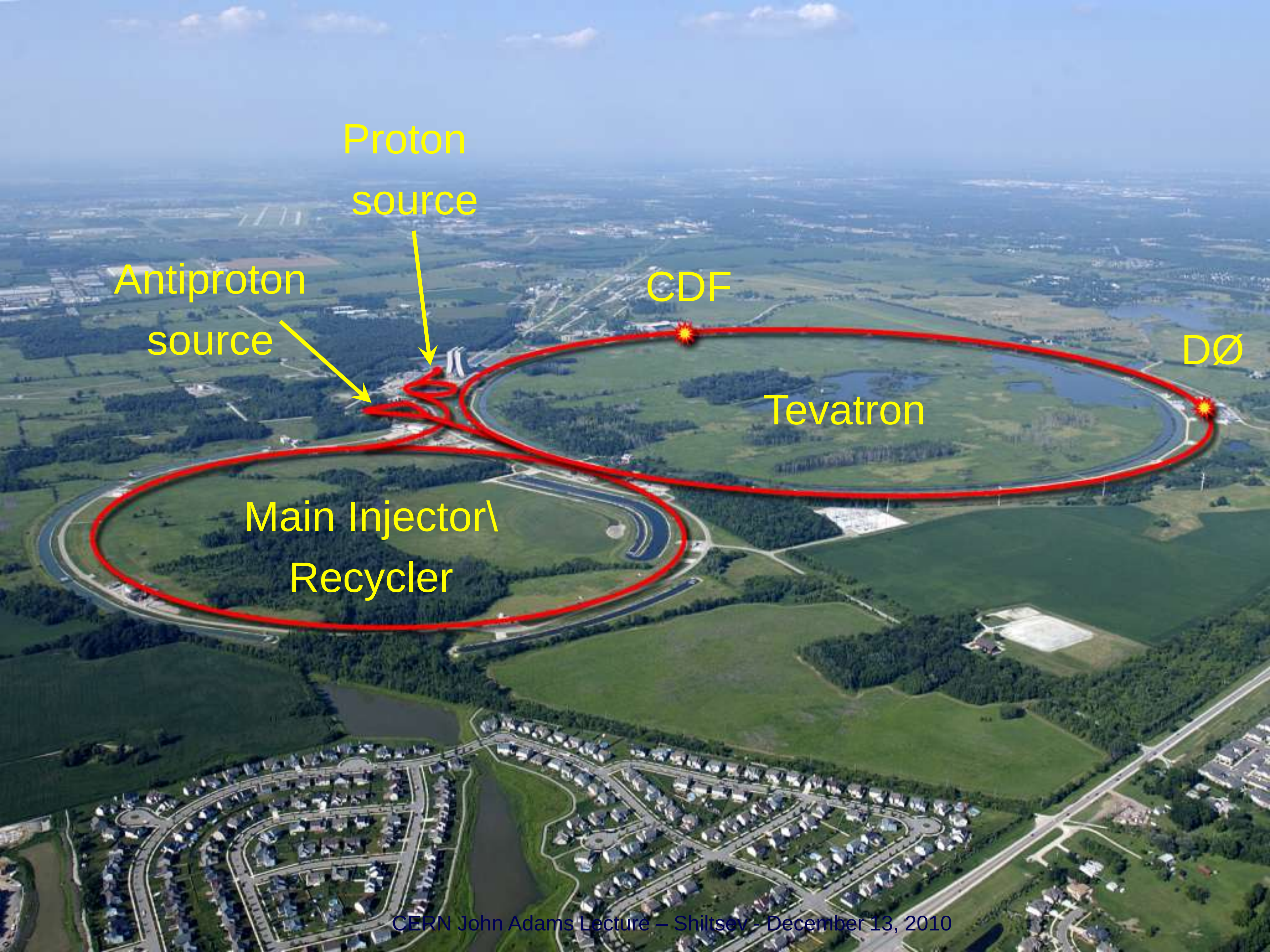

Proton
source
Antiproton
source
CDF
DØ
Tevatron
Main Injector\
Recycler

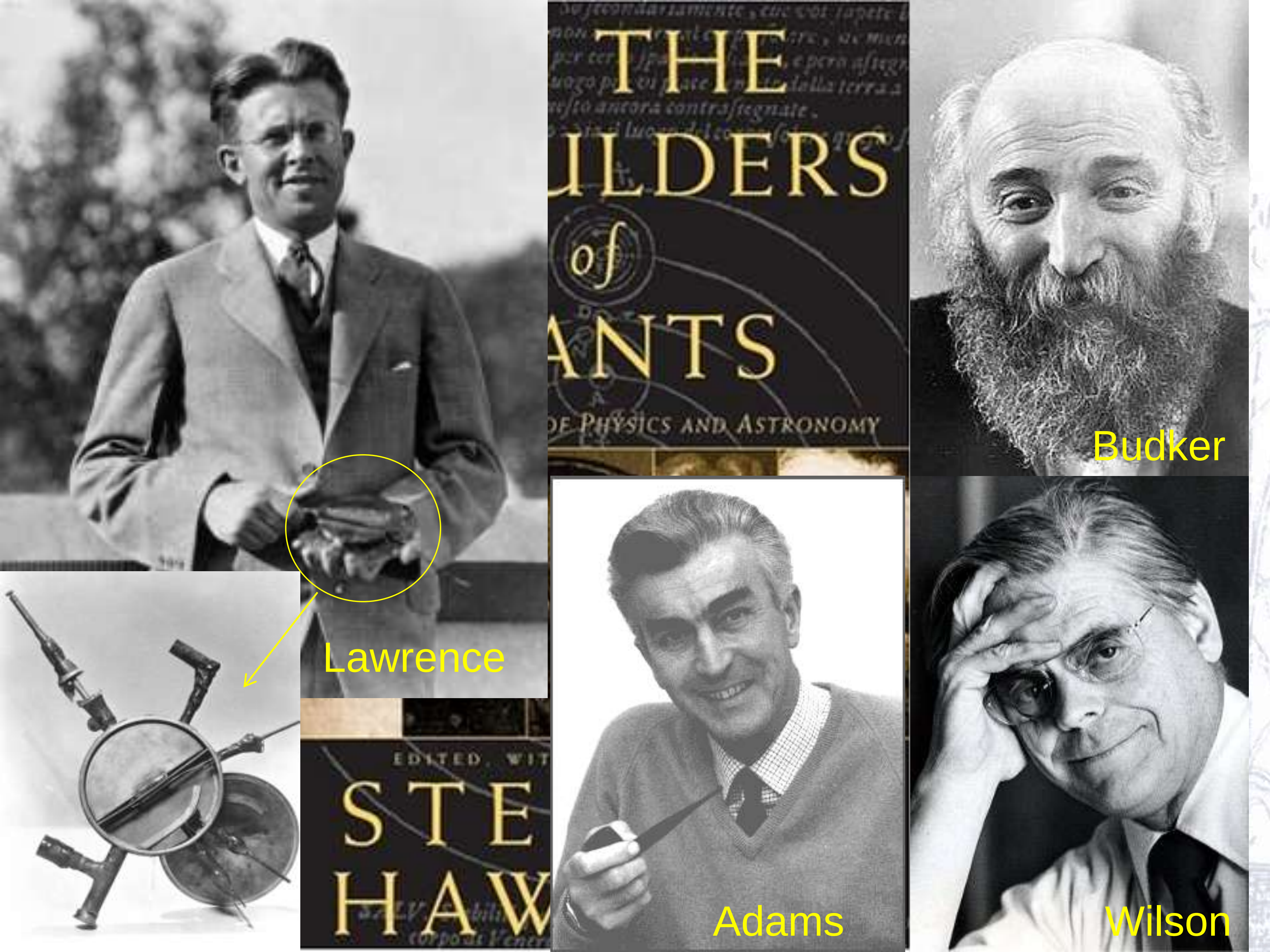
Accelerator Breakthroughs, Achievements and Lessons from the Tevatron Collider

Vladimir Shiltsev
Fermilab

John Adams Lecture
December 13, 2010, CERN

Content

- Intro:
  - History
  - Accelerators
- "Physics of Beams:
  - Stochastic cooling
  - Electron cooling
  - Slip stacking
  - RF barrier buckets
  - Beam-beam compensation
  - Hollow e-beam collimator
- Sociology
- Summary
- Technology
  - SC magnets
  - Cryoplant
  - Recycler magnets
- "Plumbing":
  - Magnet leads
  - Zebra mussels
  - Alignment
  - Black tape
- Performance/outlook
  - Achieved and plans
  - CPT theorem & LHC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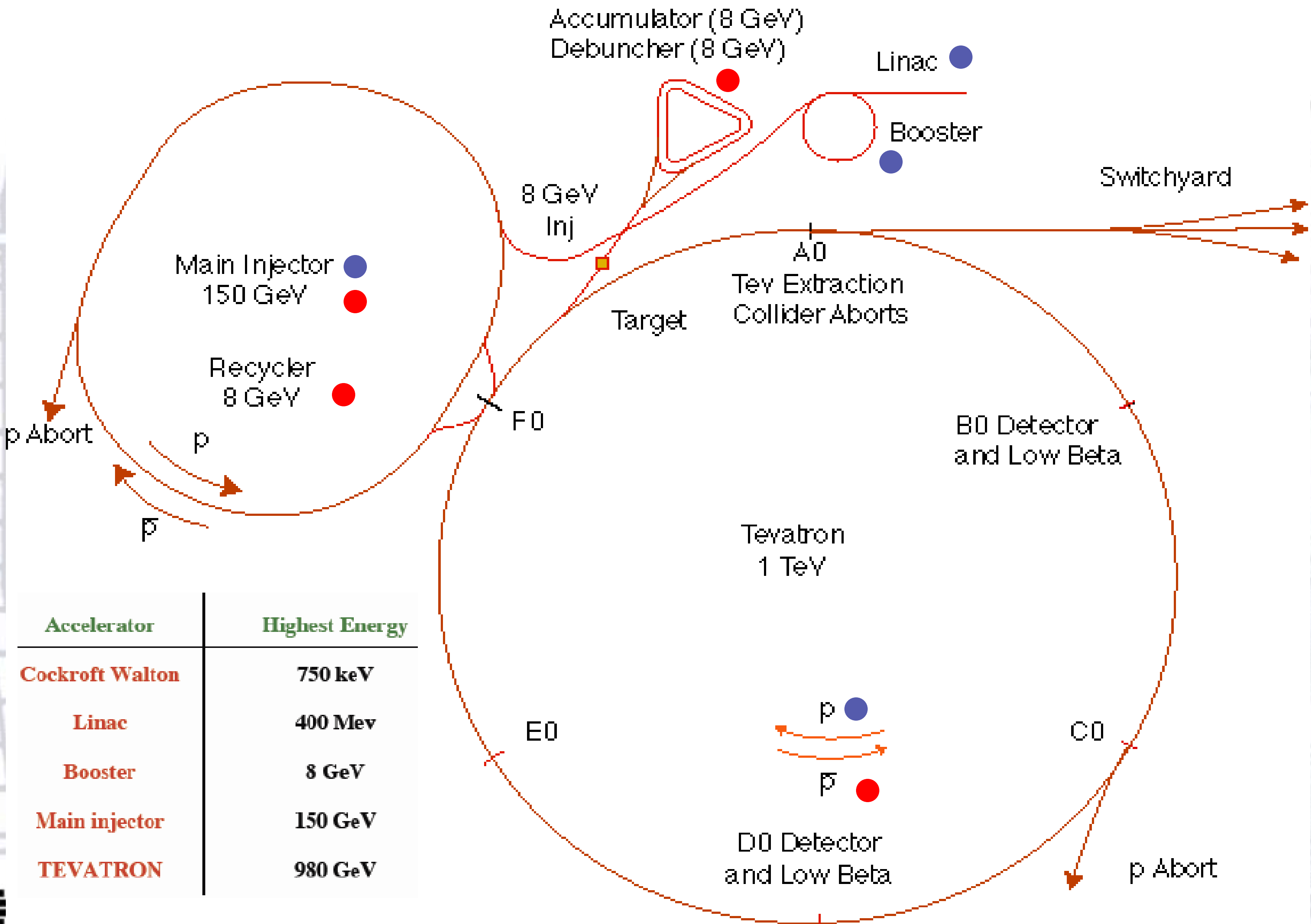
Budker
Adams
Wilson

Tevatron Collider Timeline

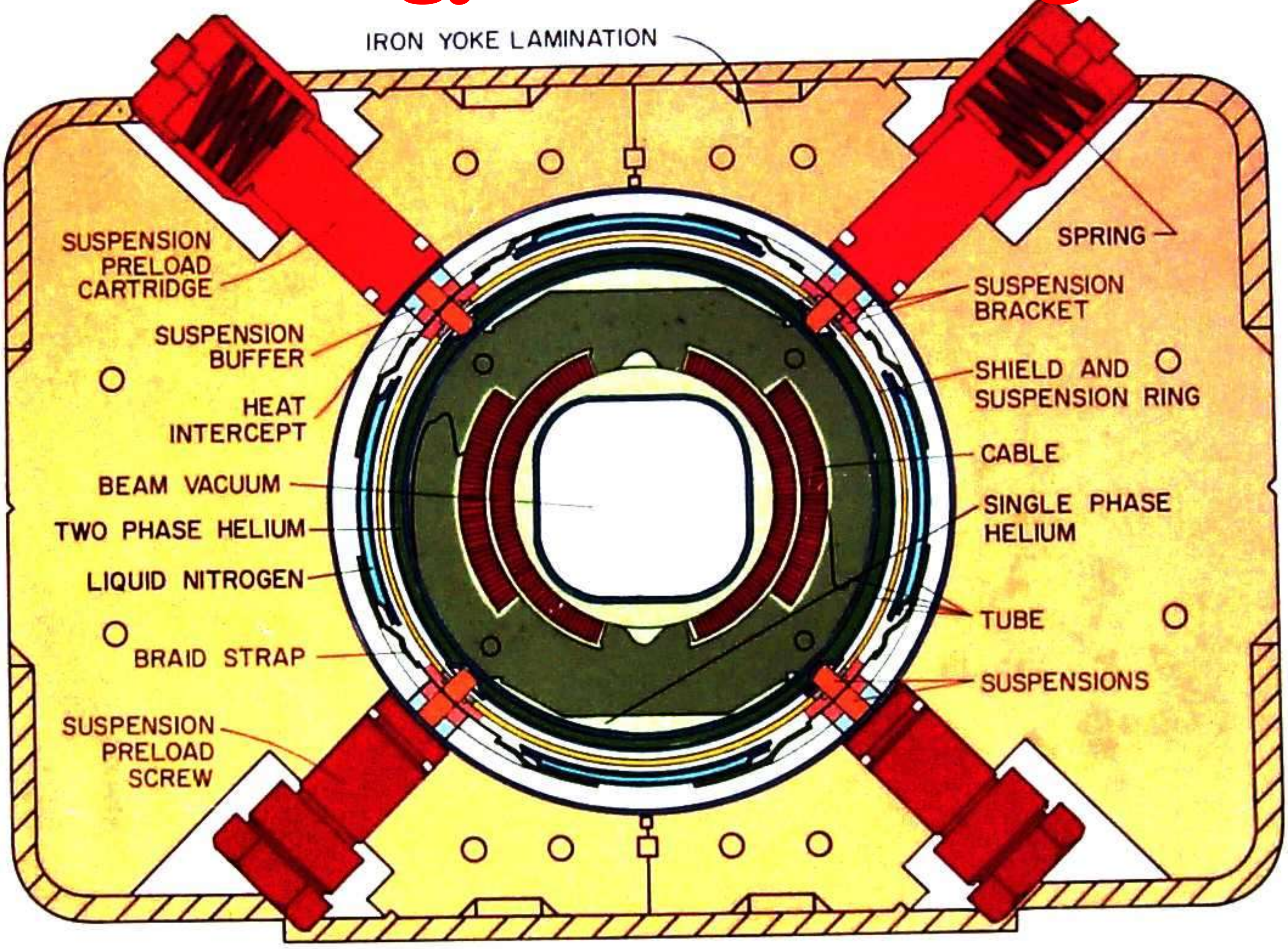
Jul 1983	Tevatron SC synchrotron commissioned, reached world record 512 GeV (protons)
1982-1985	Antiproton source construction & commissioning, installation of the B0 low beta insertion magnets
Oct 1985	First 1.6 TeV c.o.m. p-pbar collisions in CDF
1987-1989	Collider Run at 1.8TeV c.o.m., magnet leads fix
1990 -1992	HV separators installed, new low beta insertions at D0 and B0 interaction regions
1992 -1993	Collider Run Ia at 1.8 TeV c.o.m.,both CDF & D0
1992 -1993	400 MeV Linac construction and commissioning
1994 -1996	Collider Run Ib, top quark discovery
1993 -1999	Main Injector construction and commissioning
Mar 2001-(?)	Collider Run II, 1.96 TeV c.o.m.

FermilabTevatron Accelerator With Main Injector



Accelerator	Highest Energy
Cockroft Walton	750 keV
Linac	400 Mev
Booster	8 GeV
Main injector	150 GeV
TEVATRON	980 GeV

Technology: 4.5T SC Magnets

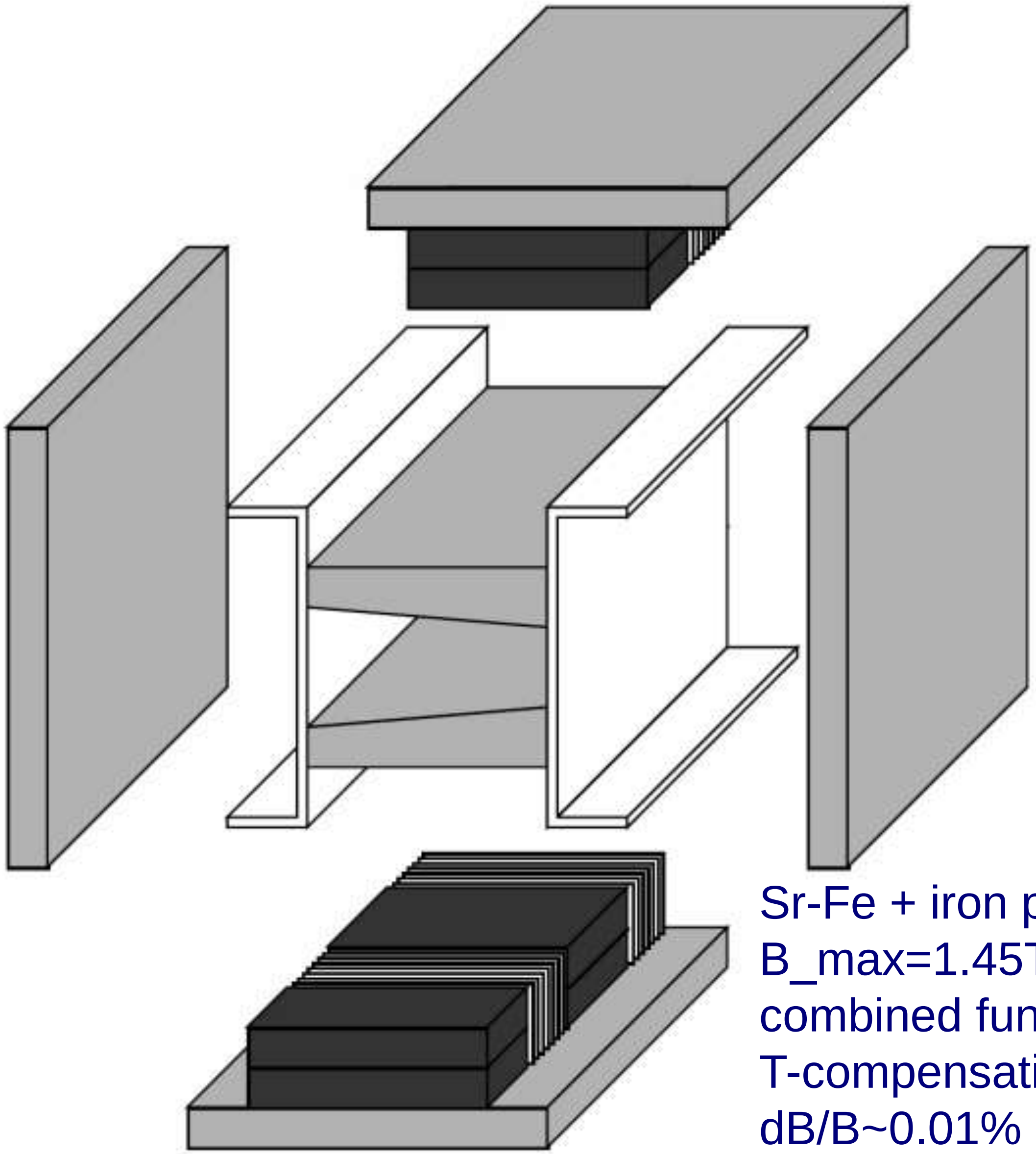


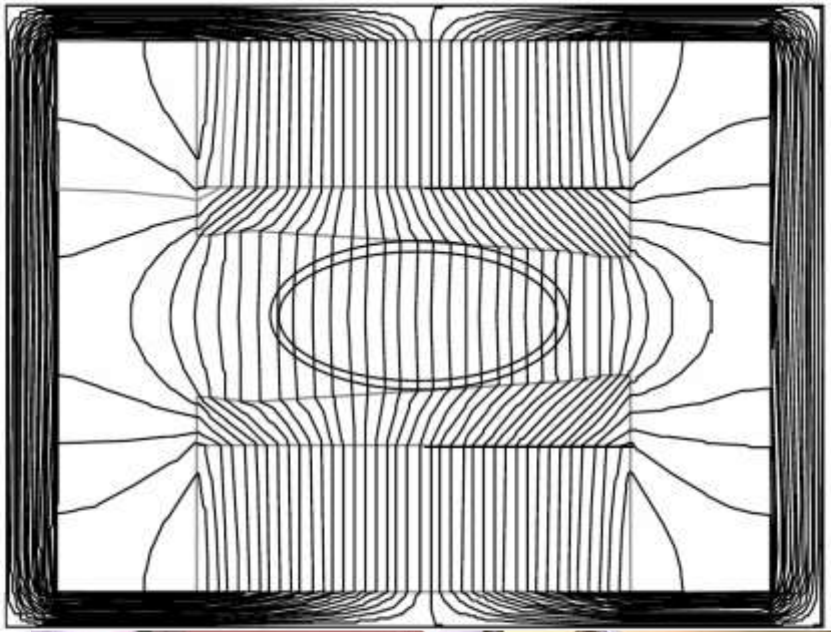
Tevatron Magnets

C=6.28km, ~800 SC magnets (4d+q) @ 4.2 K,
E_max/inj=980/150GeV, small size, quench protection

Technology: Cryoplant

Technology: Permanent Magnets





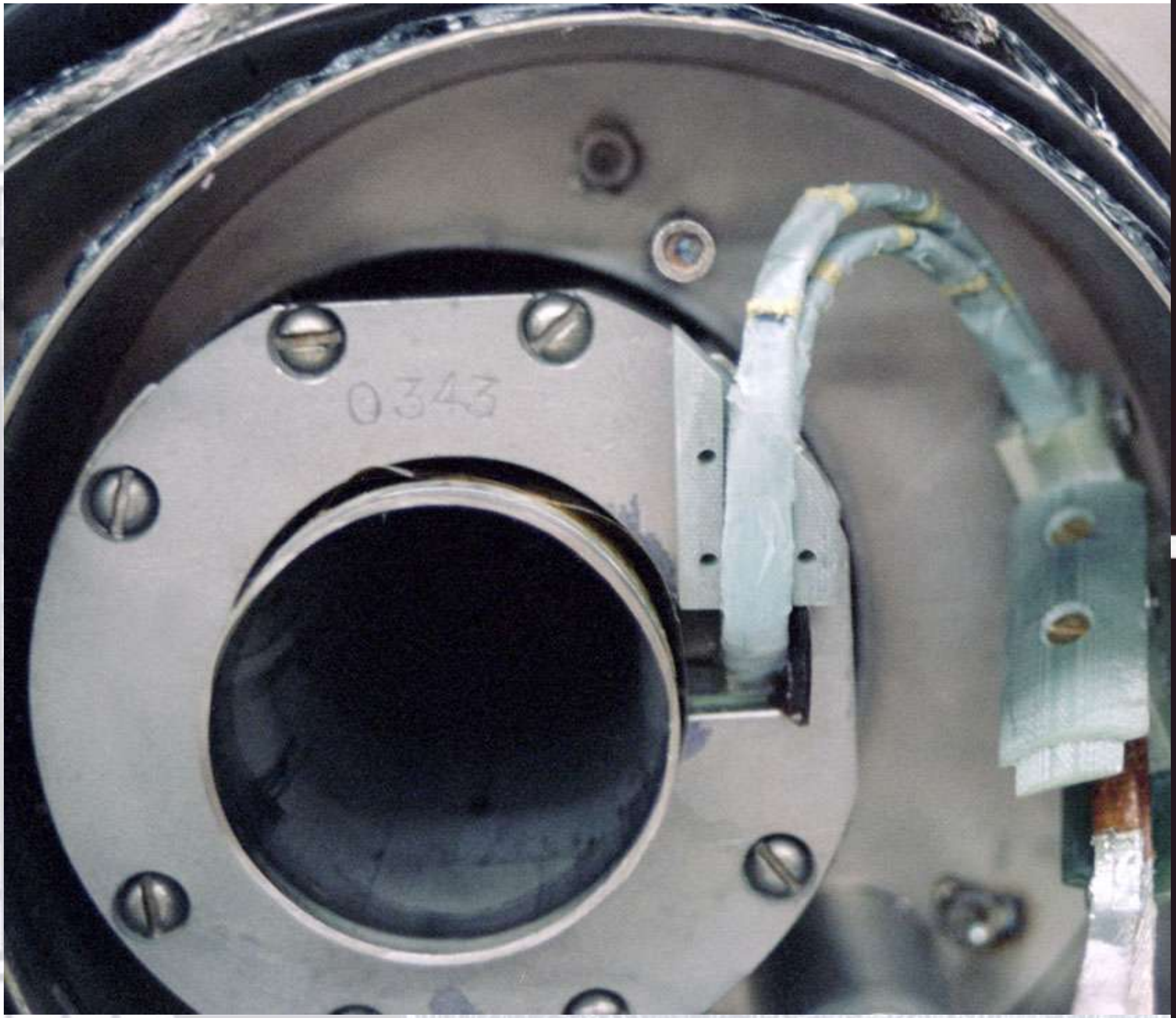
Sr-Fe + iron poles
B_max=1.45T
combined function
T-compensation
dB/B~0.01%

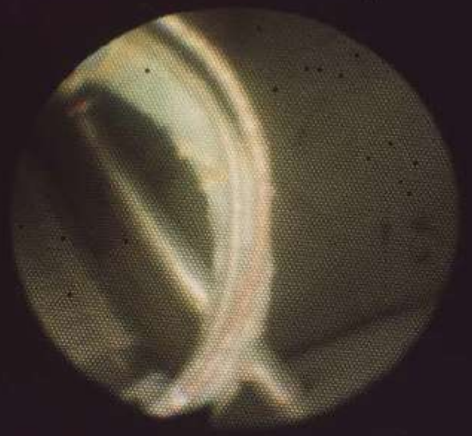
Recycler Ring

- E_kin=8 GeV fixed
- Shares tunnel with 150 GeV fast cycling Main Injector
- C=3.32km
- 344 Permanent magnets (344, 1.45T, Sr-Fe combined function)
- Stores and cools antiprotons
- **Build by the US Congressman**

"Plumbing": Magnet Leads

Current leads moving during ramps





every magnet X-ray and boroscoped

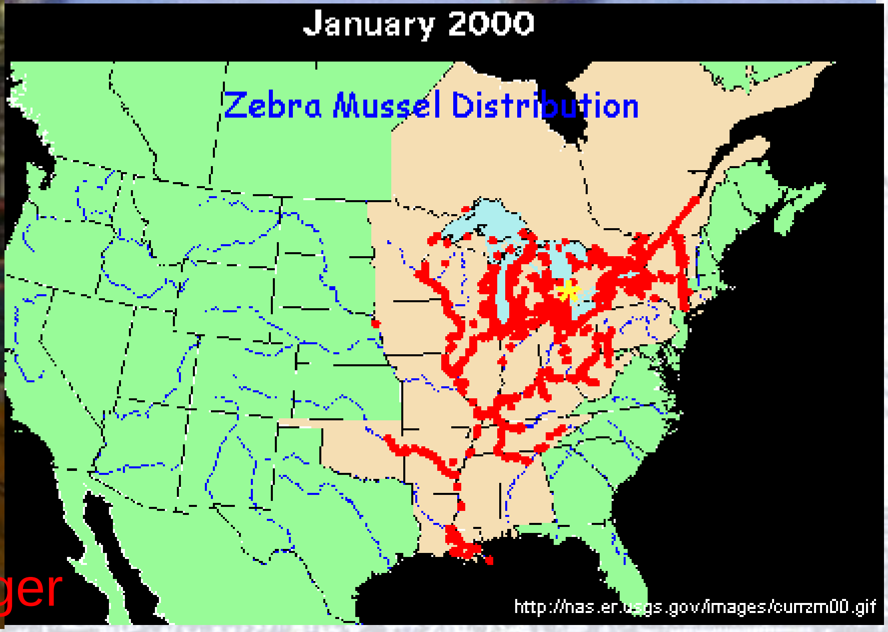
all opened in re-tied

“Plumbing”: Alignment

Example of the Tevatron magnet alignment (not common, but)

every year: survey and reset major offenders
to <0.2mm and <2mrad
every minute: orbit stabilization to <20 microns

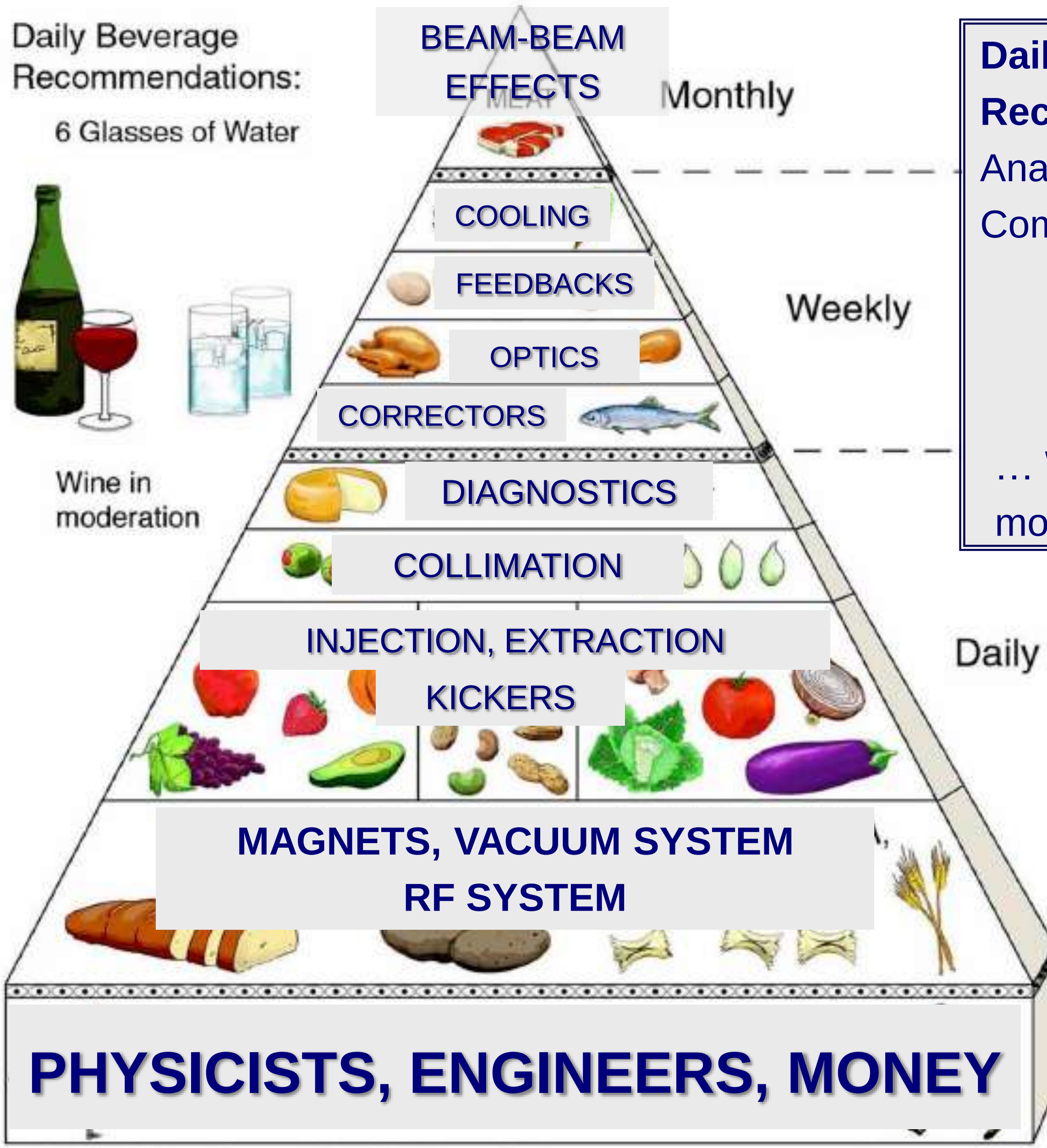
“Plumbing”: Zebra Mussels



“Plumbing”: Anecdotal Tape

Cryo-vacuum leak thru rubber O-ring

Healthy Life Recipe Modern Collider



Daily Action Recommendations:

Analysis

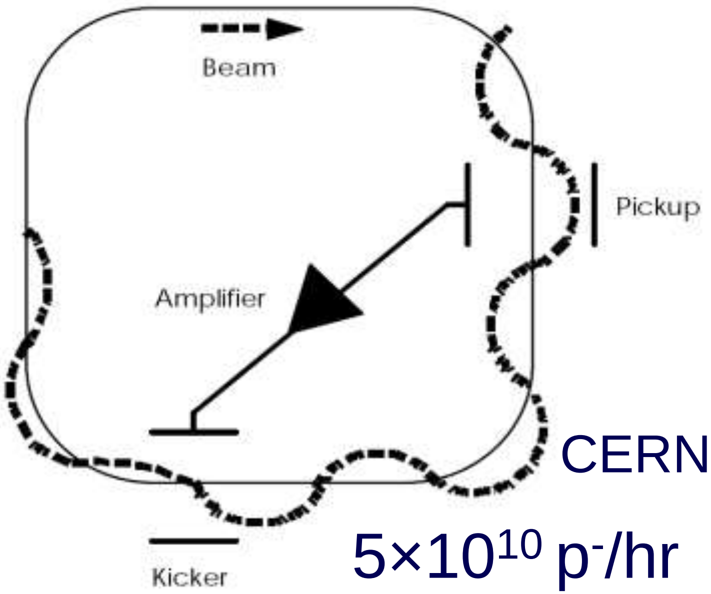
Communication

- Engineers
- Experiments
- Accelerator physicists

… Wine in moderation

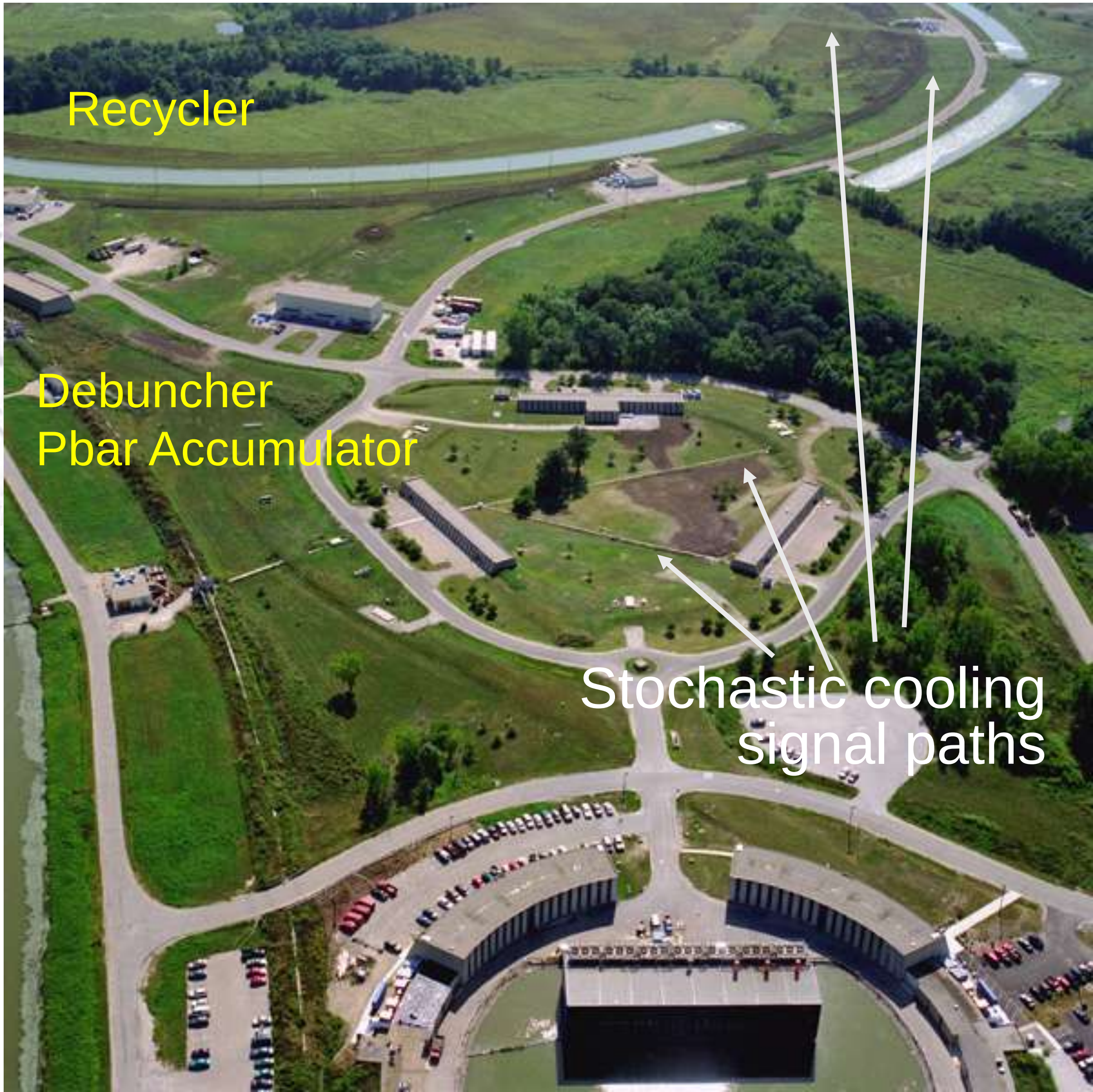
Fermilab

Beam Physics: Stochastic Cooling

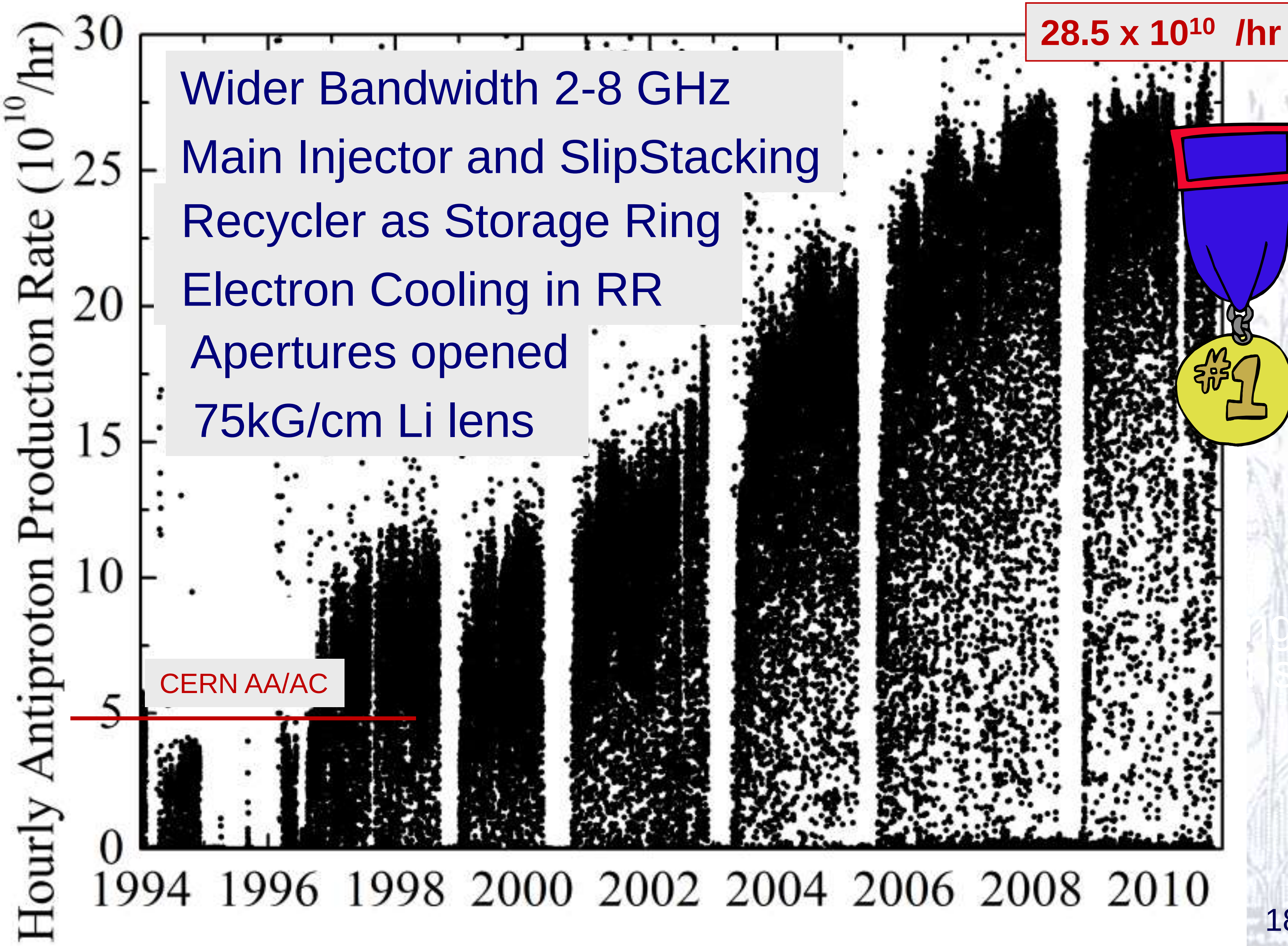


CERN

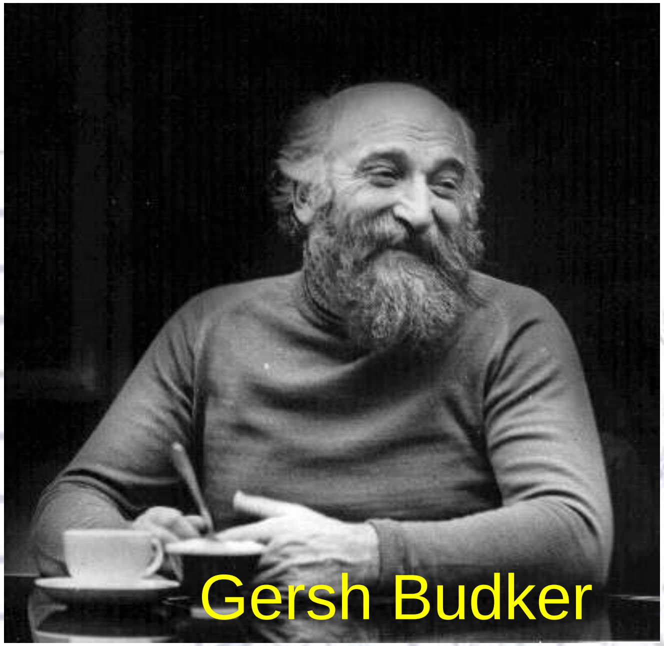
5×10^{10} p^-/hr



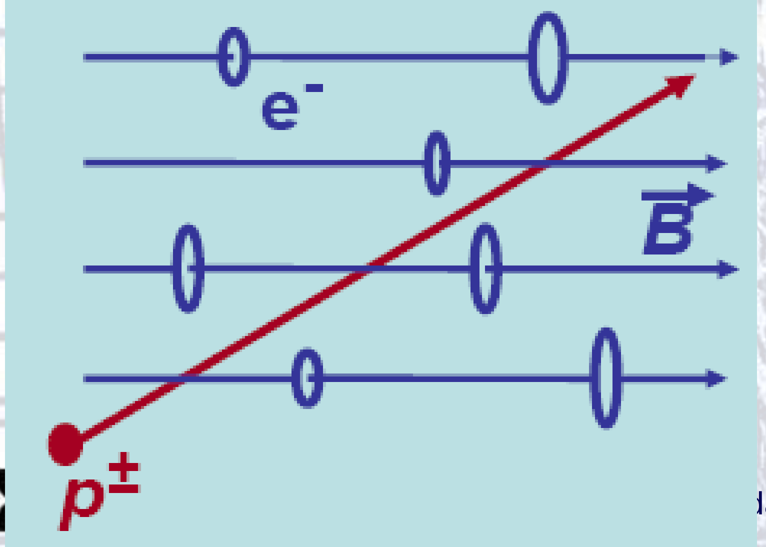
Antiproton Production Rate



Physics: Electron Cooling


Gersh Budker

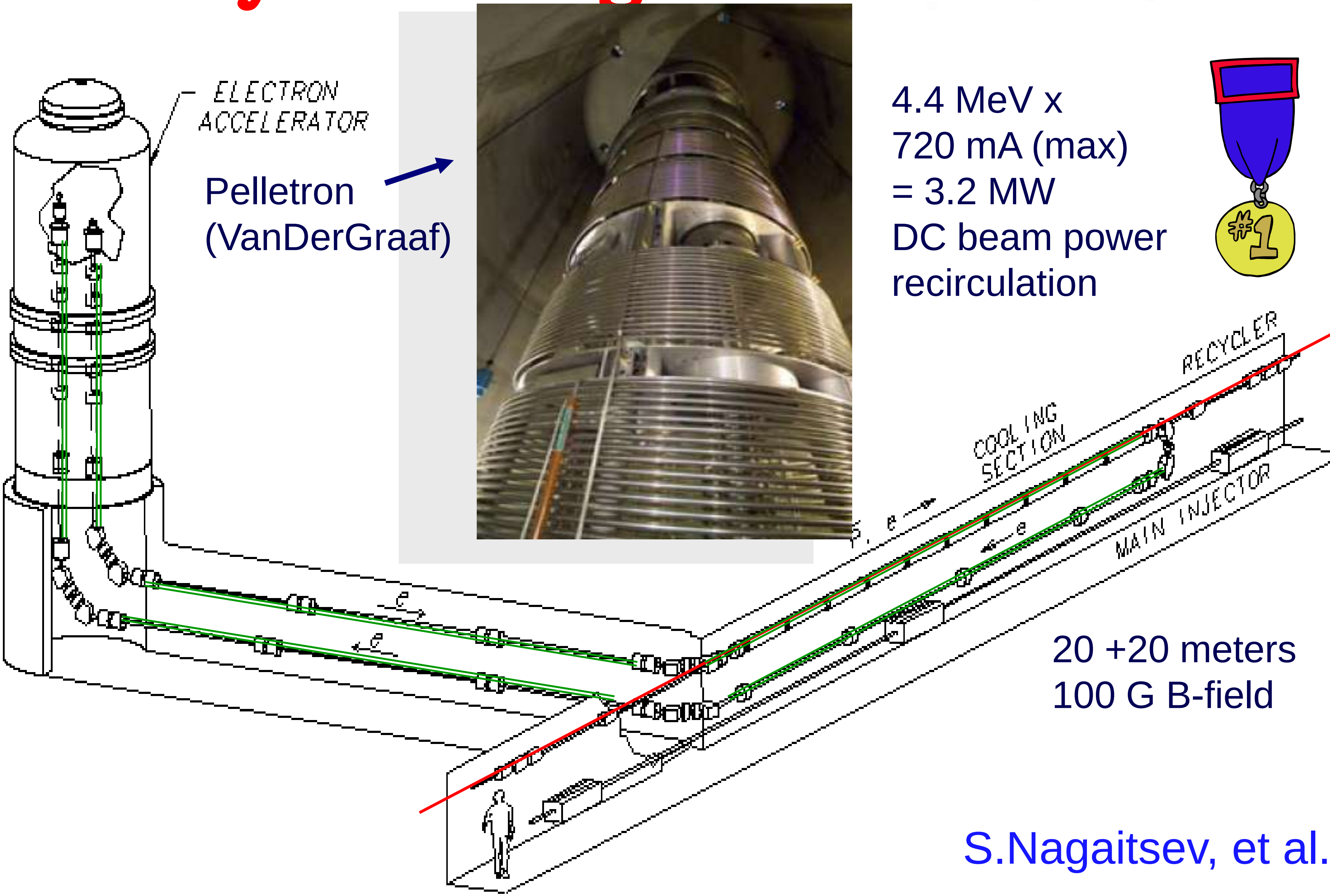
Ions in a bath of cold electrons



Condition#1 for effective heat transfer: V_e = V_antiproton

4.338 MeV e- for 8.89GeV pbar

Recycler Ring Electron Cooler



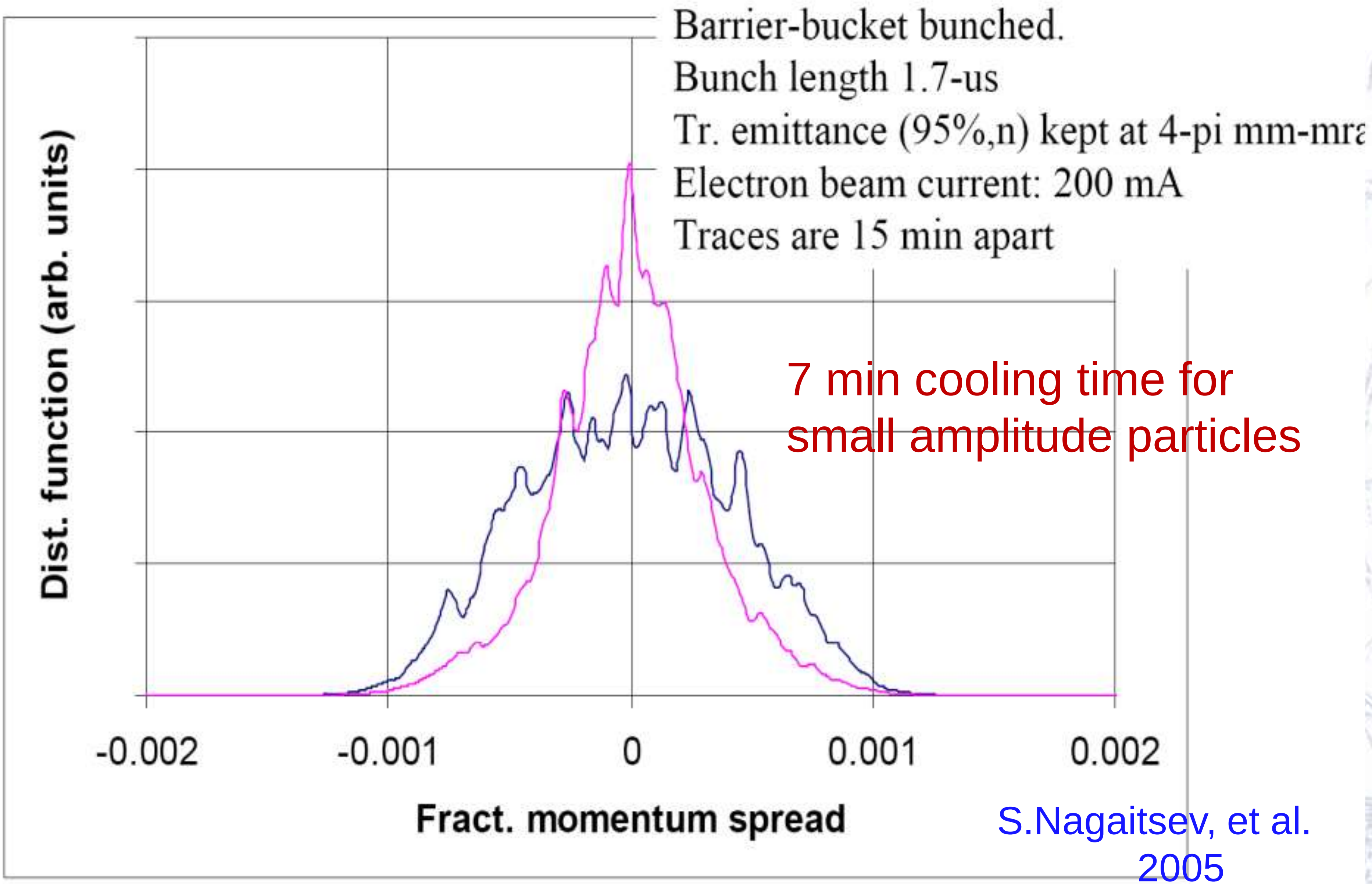
Pelletron
(VanDerGraaf)

4.4 MeV x
720 mA (max)
= 3.2 MW
DC beam power
recirculation

20 +20 meters
100 G B-field

S.Nagaitsev, et al.

Electron Cooling of Antiprotons



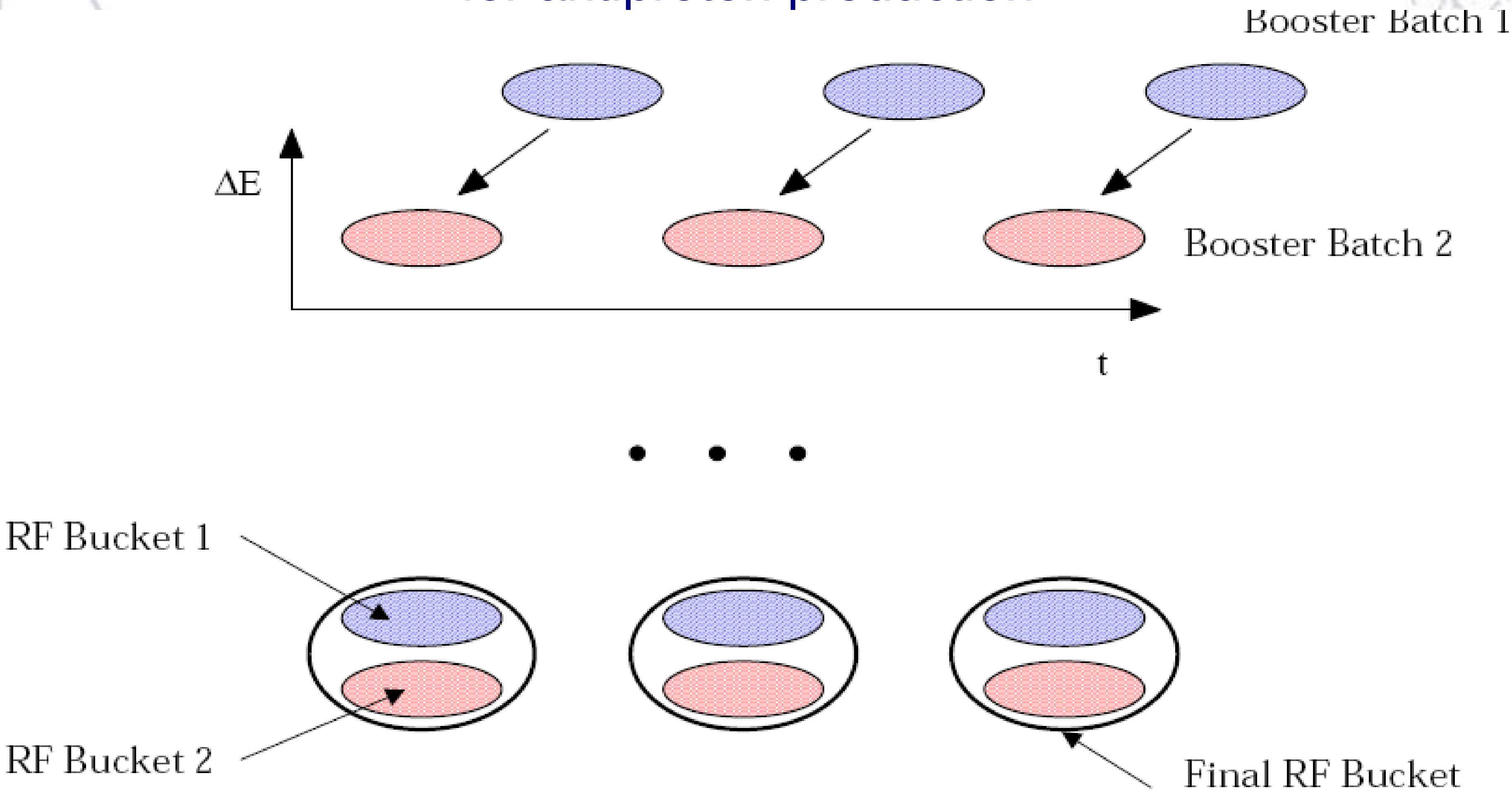
7 min cooling time for small amplitude particles

S.Nagaitsev, et al. 2005

Physics: “Slip-Stacking”

The technique to double single bunch intensity

for antiproton production

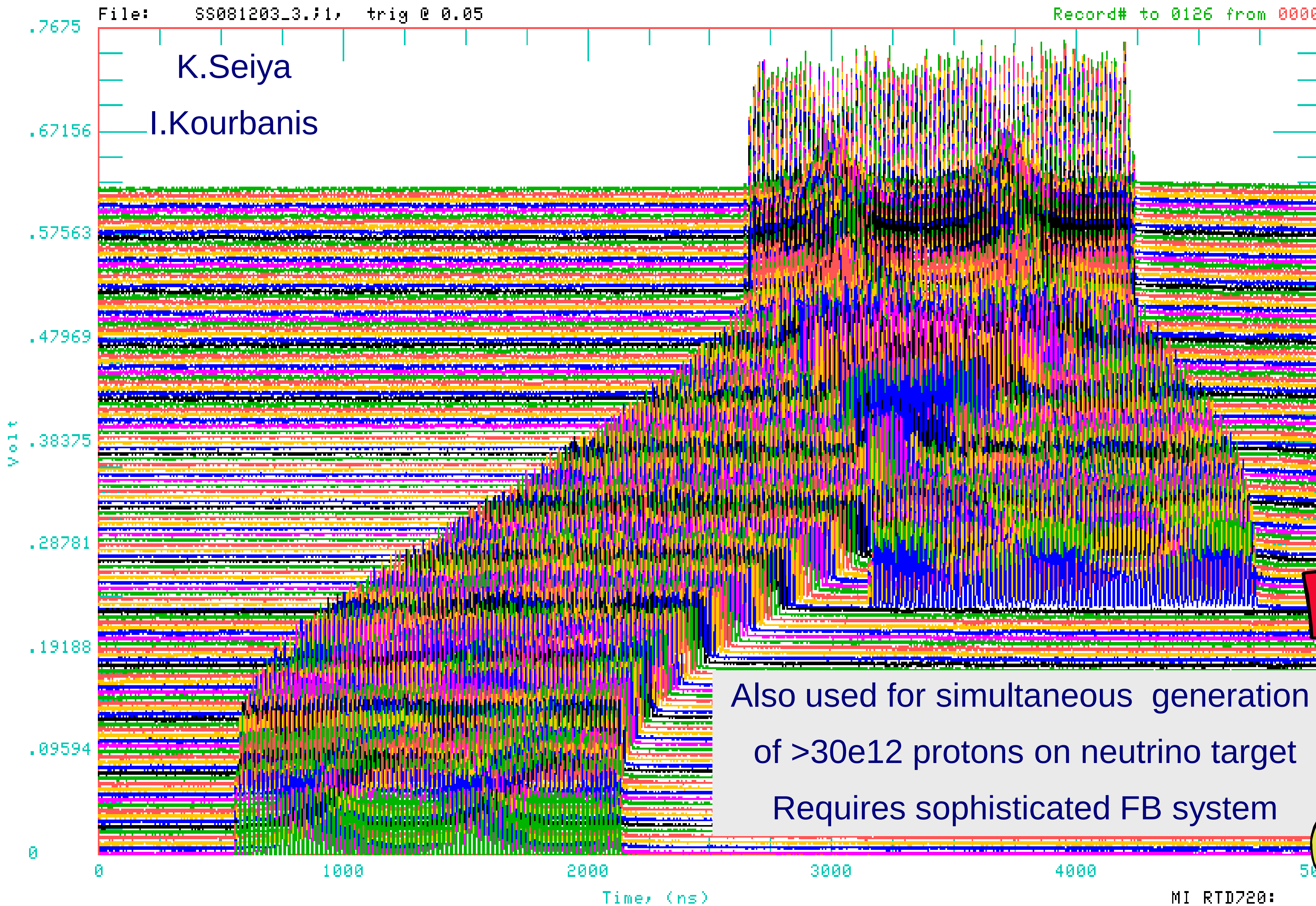


RF Phase Space Cartoon

F.Mills (BNL, 1971)

Slip-Stacking in Main Injector

4.1e12+4.1e12 =8.2 e12 protons on target per 2.2 s MI cycle



Also used for simultaneous generation of >30e12 protons on neutrino target

Requires sophisticated FB system

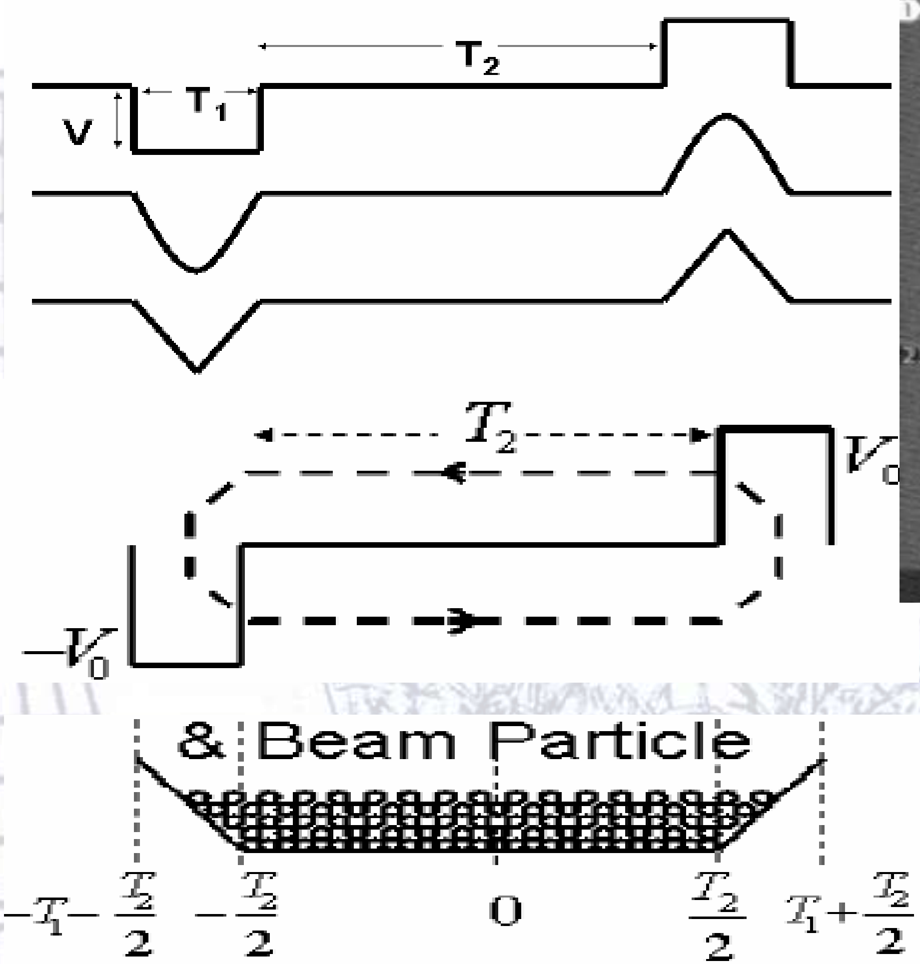
Physics: "RF Barrier Bucket"

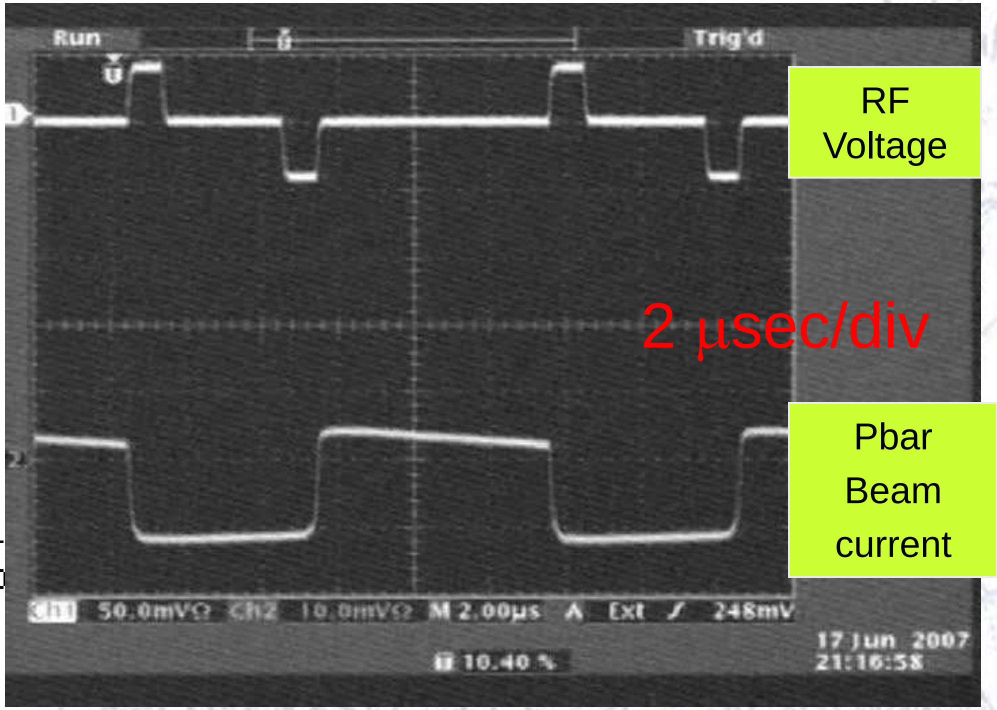
To manipulate with pbars in Recycler: create bunch structures, etc

C.Bhat

Broad band ~1kV RF, ferrite loaded

J.Griffin, FNAL 1983

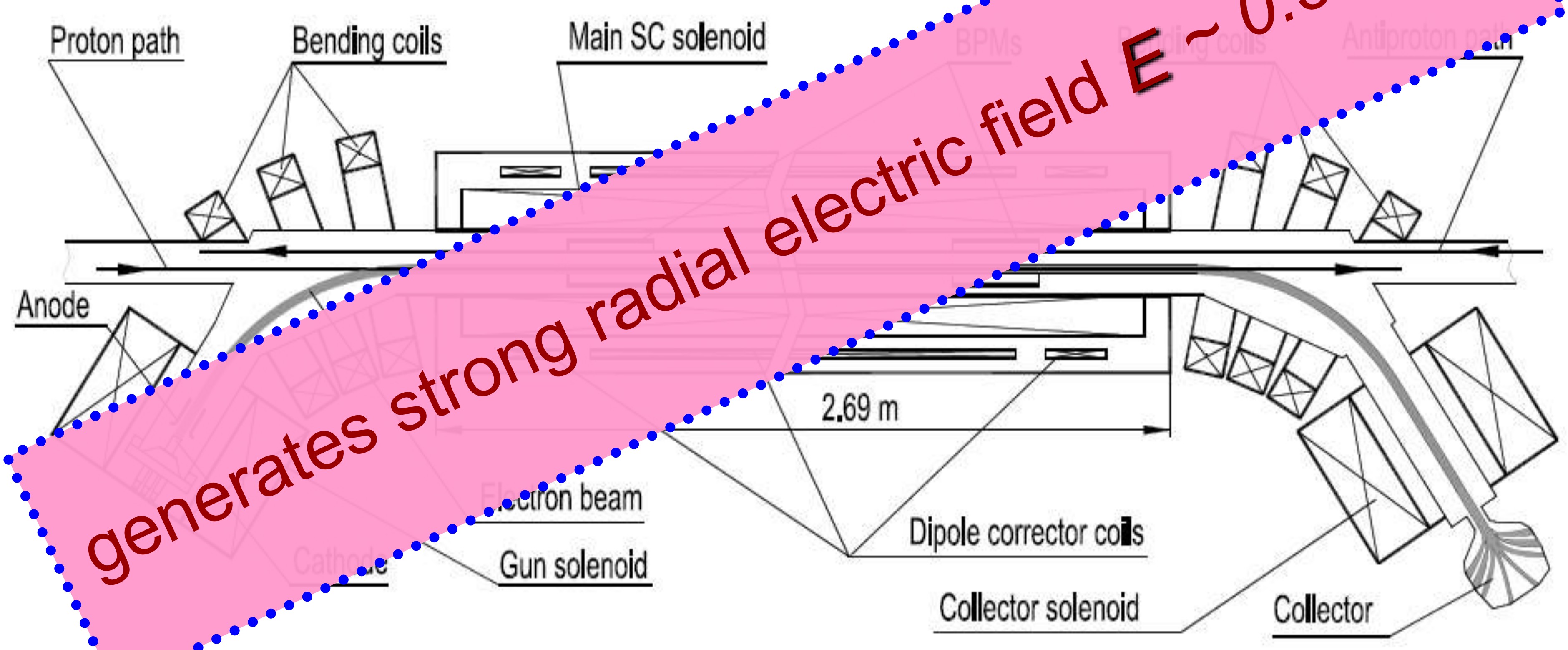




Longitudinal momentum mining in the Recycler to generate constant emittance, constant intensity pbar bunches for the Tevatron shots (since 2004)

Physics: Electron Lenses

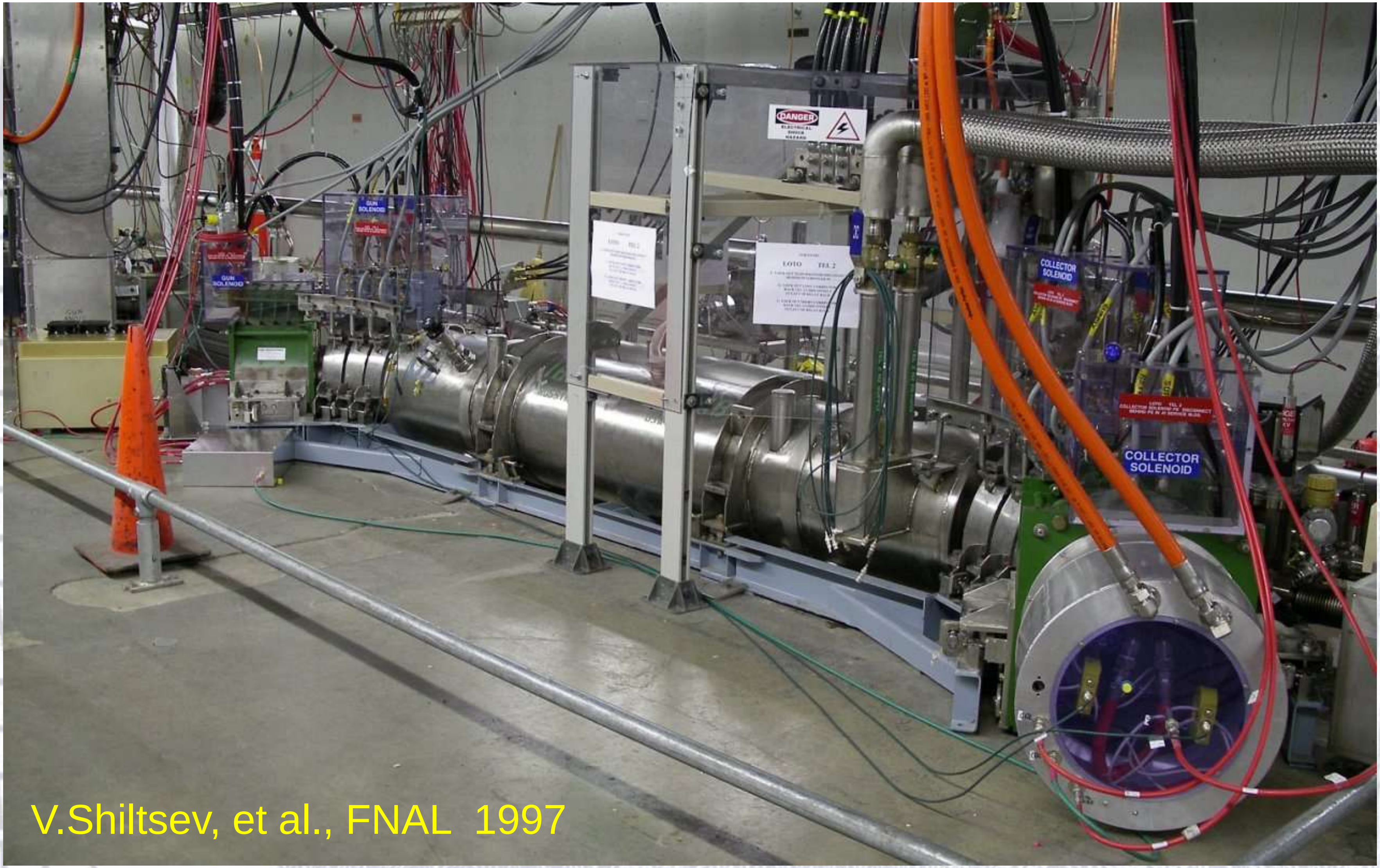
~4 mm dia 2 m long in 3T solenoid beam of ~10 kV ~1A electrons (~10^{12}) can turn on/off in ~0.5 usec



generates strong radial electric field *E* ~ 0.3MV/m

Tevatron Electron Lens

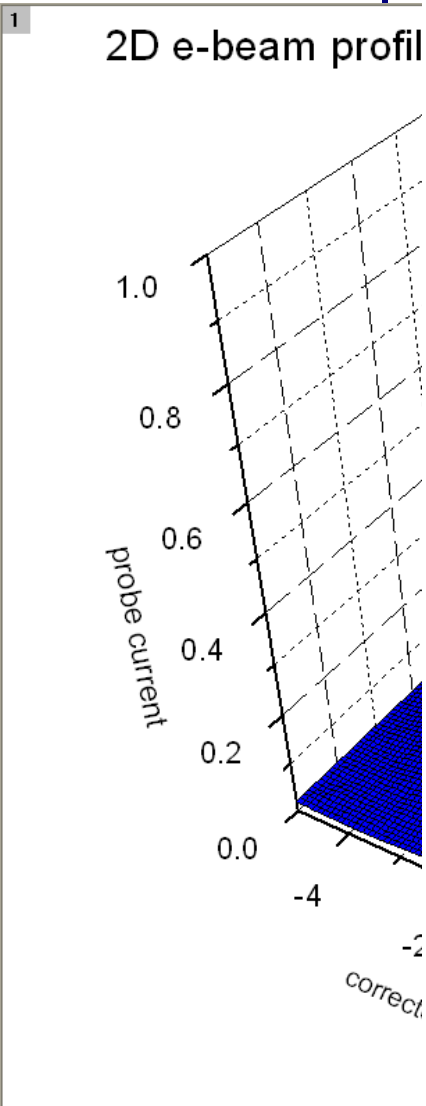
Two TELs installed in the Tevatron

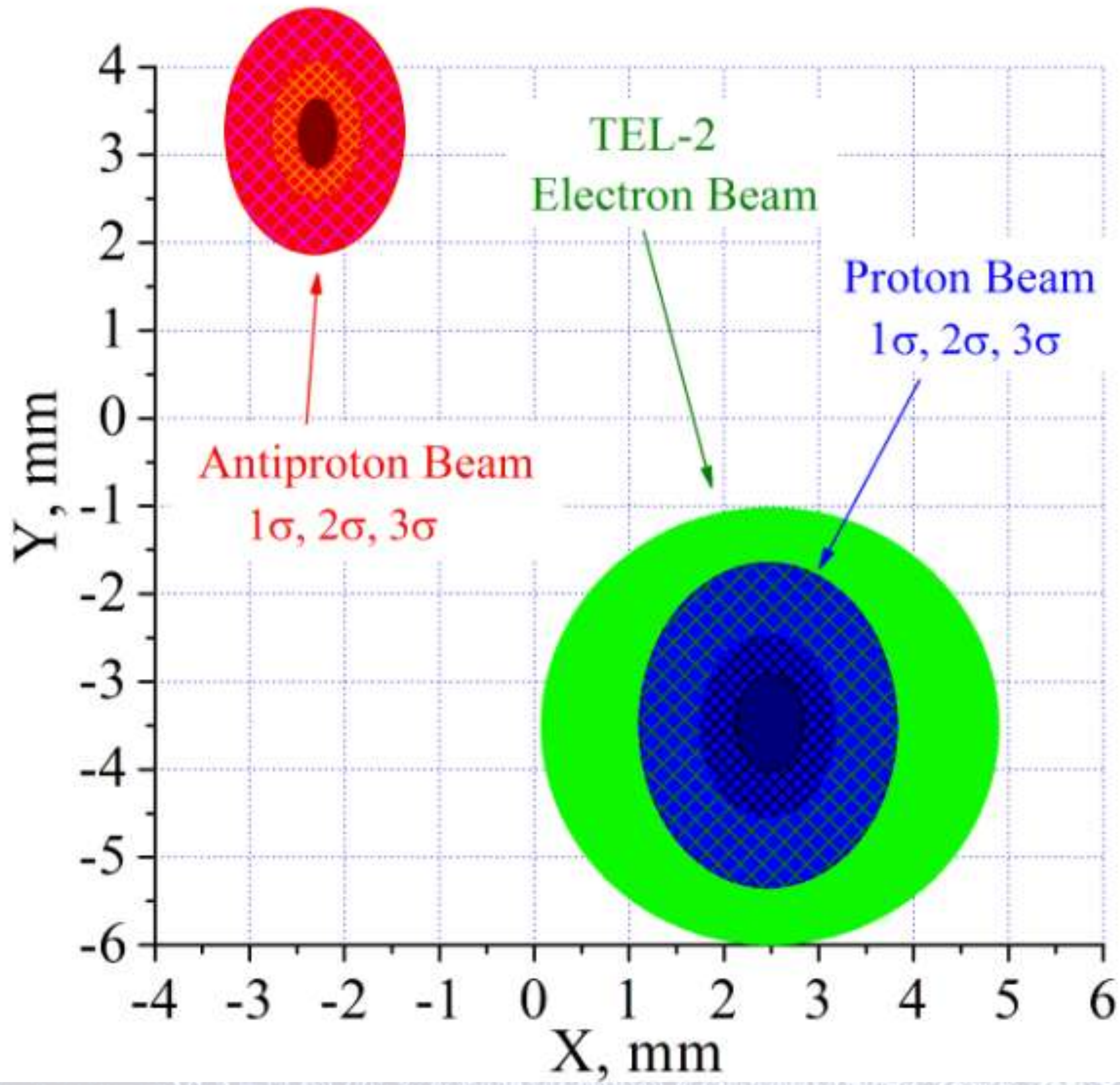


V.Shiltsev, et al., FNAL 1997

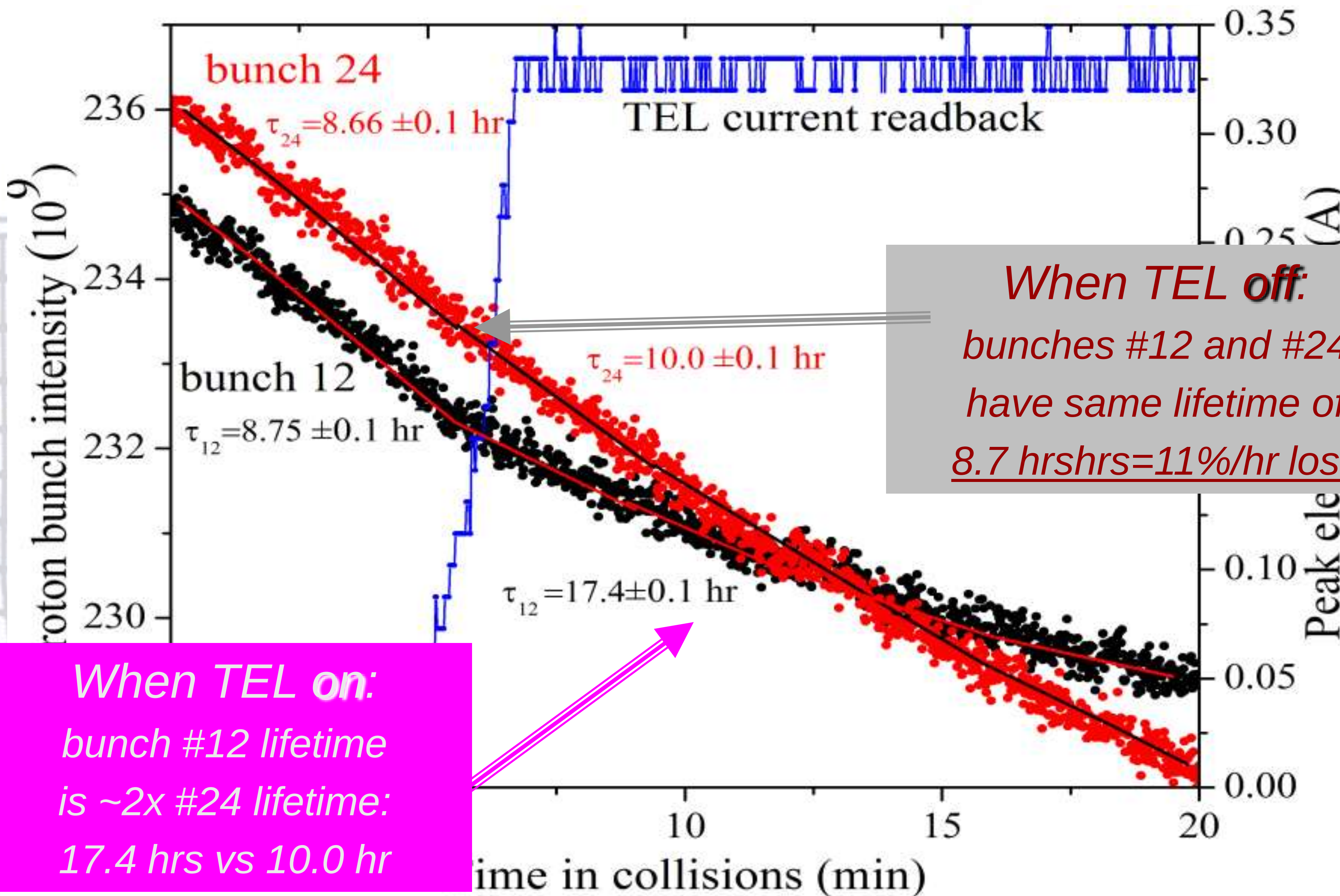
Beam-Beam Compensation

in Tevatron operation - TELs compensated of long range BB effects





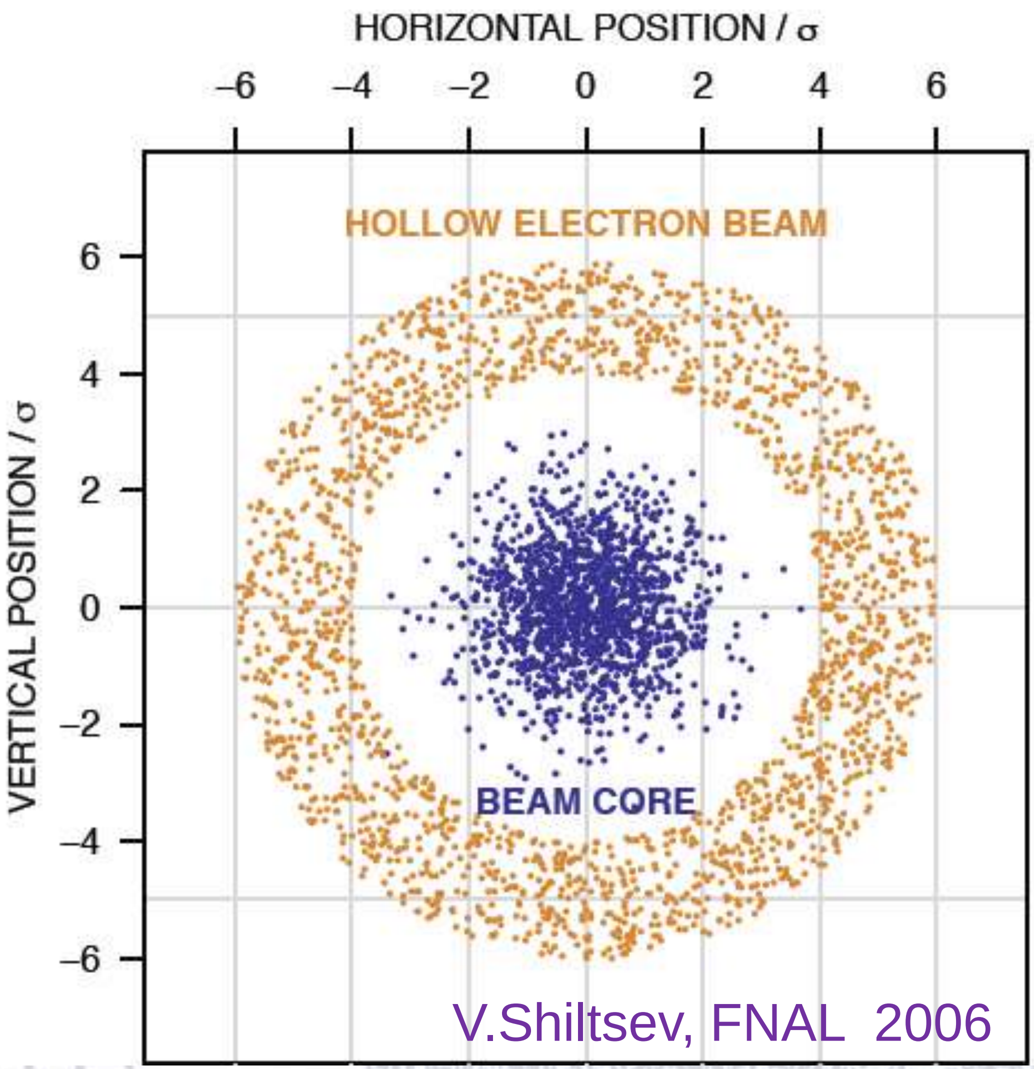
TEL2 on One "Bad" Bunch (P12)



*When TEL **off**:*
bunches #12 and #24
have same lifetime of
8.7 hrshrs=11%/hr loss

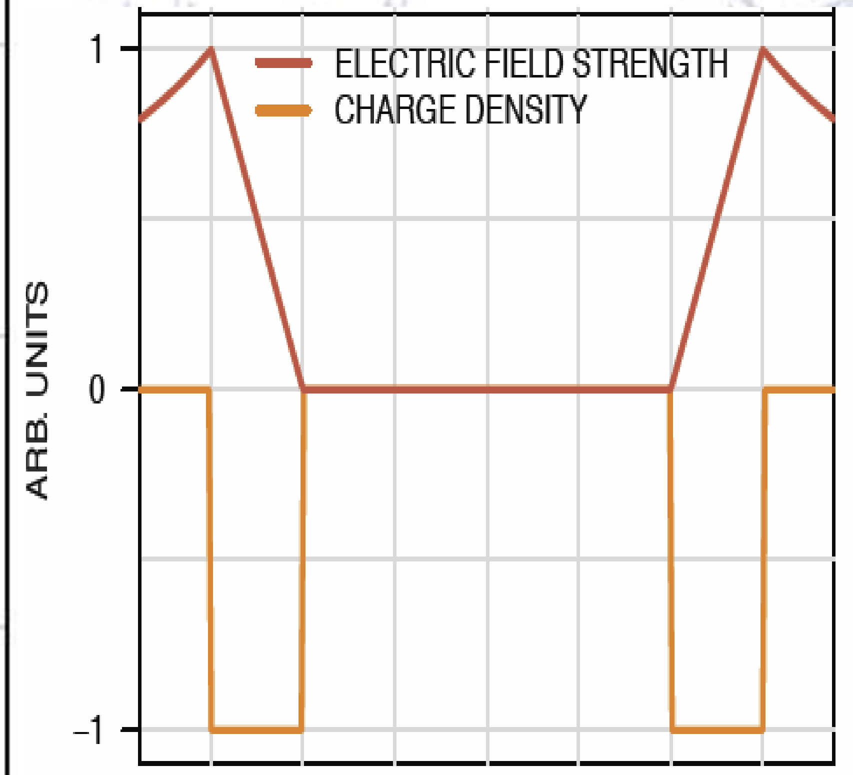
*When TEL **on**:*
bunch #12 lifetime
is ~2x #24 lifetime:
17.4 hrs vs 10.0 hr

Physics: Hollow Electron Beam

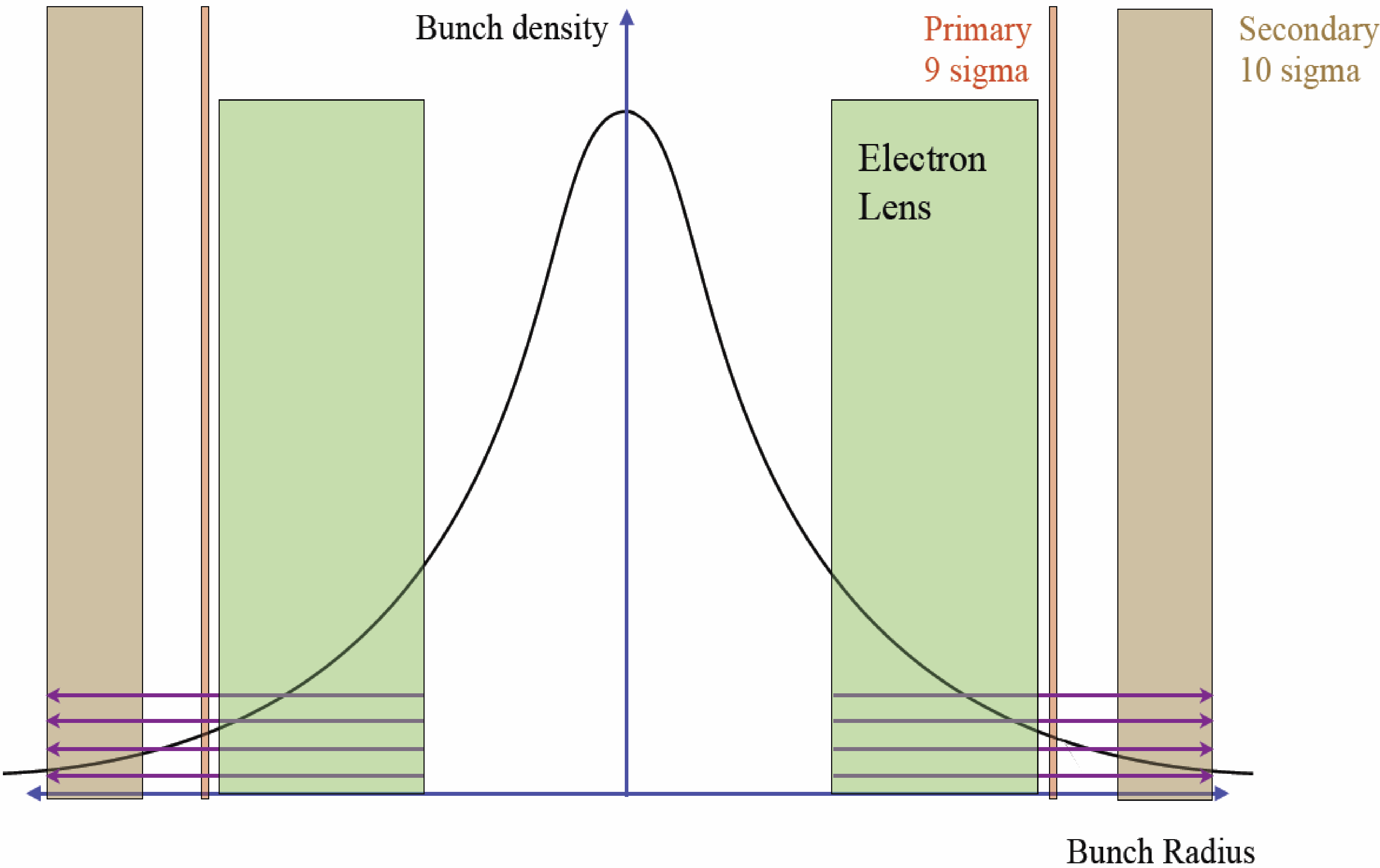


No EM field inside

Strong field outside



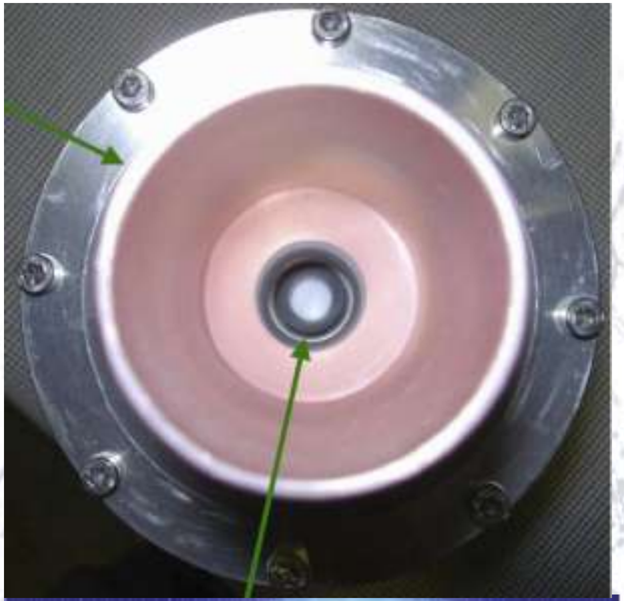
Collimation by Hollow e-Beam

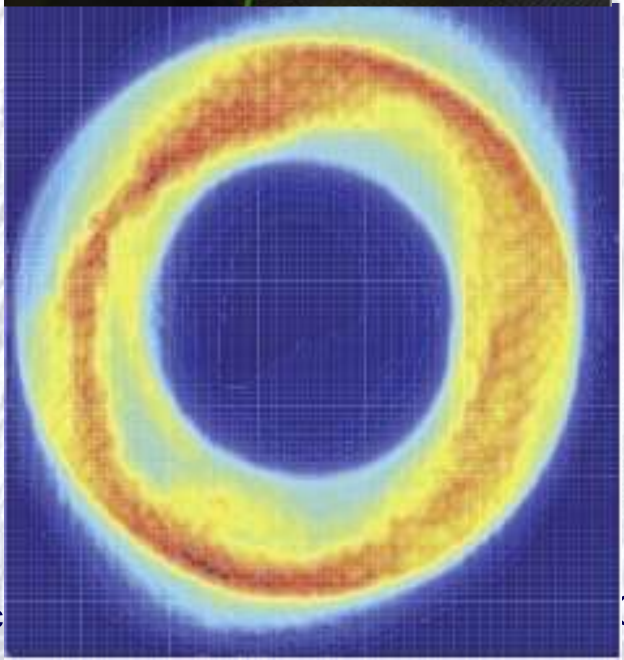


Tevatron HEB-Collimator

To explore advantages:

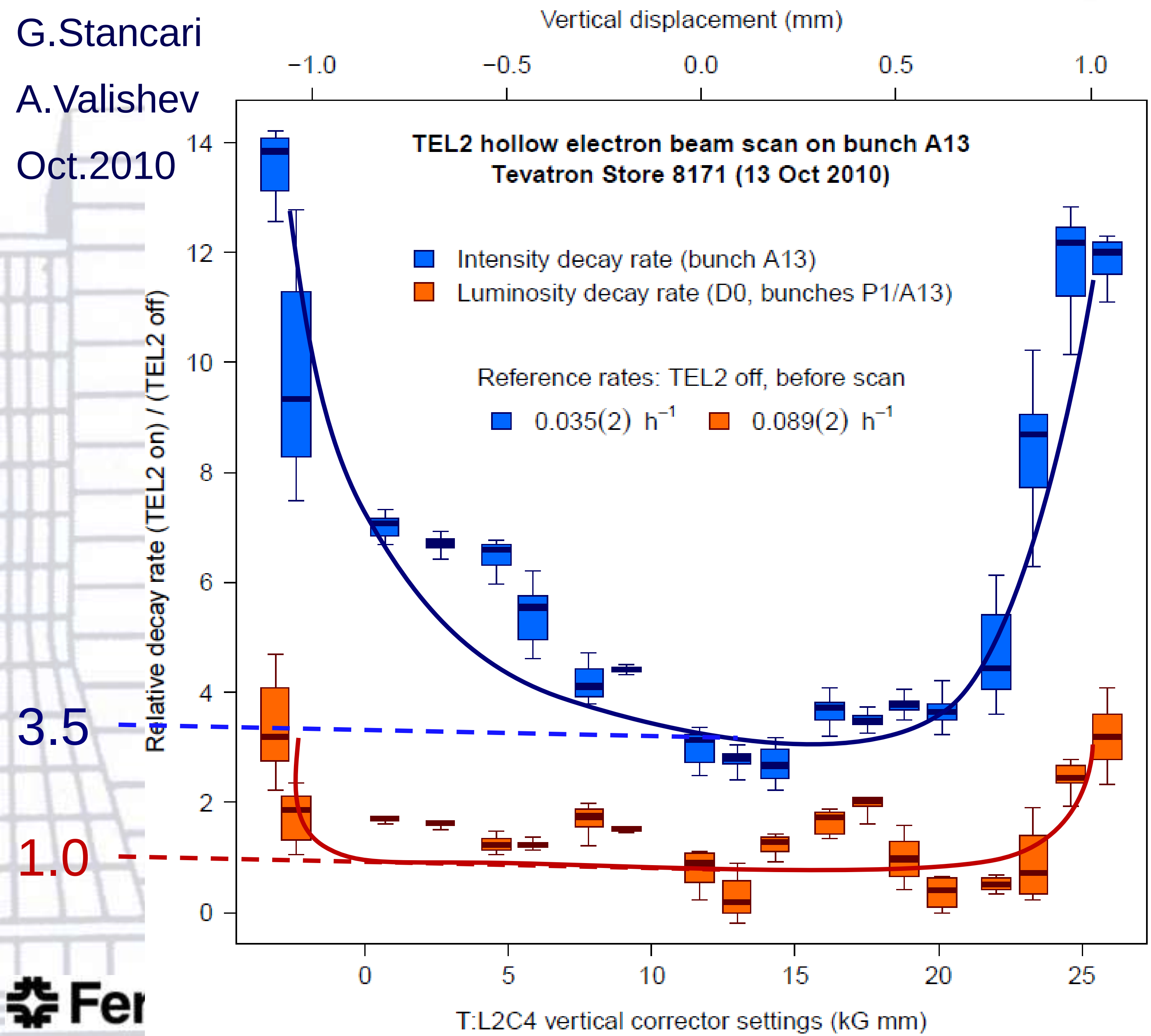
- Kicks are small but not random
- Halo diffusion enhancement ("smooth" scraper)
- Resonant excitation is possible (pulsed e-beam)
- No material damage
- No ion breakup
- Low impedance
- Position control by magnetic field (no motors or bellows)
- Established e-lens technology





Hollow eBeam in Tev Store

G.Stancari
A.Valishev
Oct.2010



Presented is **RATIO** of decay rates with TEL on/TEL off:

Intensity losses are **UP**

Luminosity **INTACT!!!**

That IS collimation!

Accelerator Science & Social "Stir"

29 PhD Theses in the Accelerator Physics made at the Tevatron since 1987

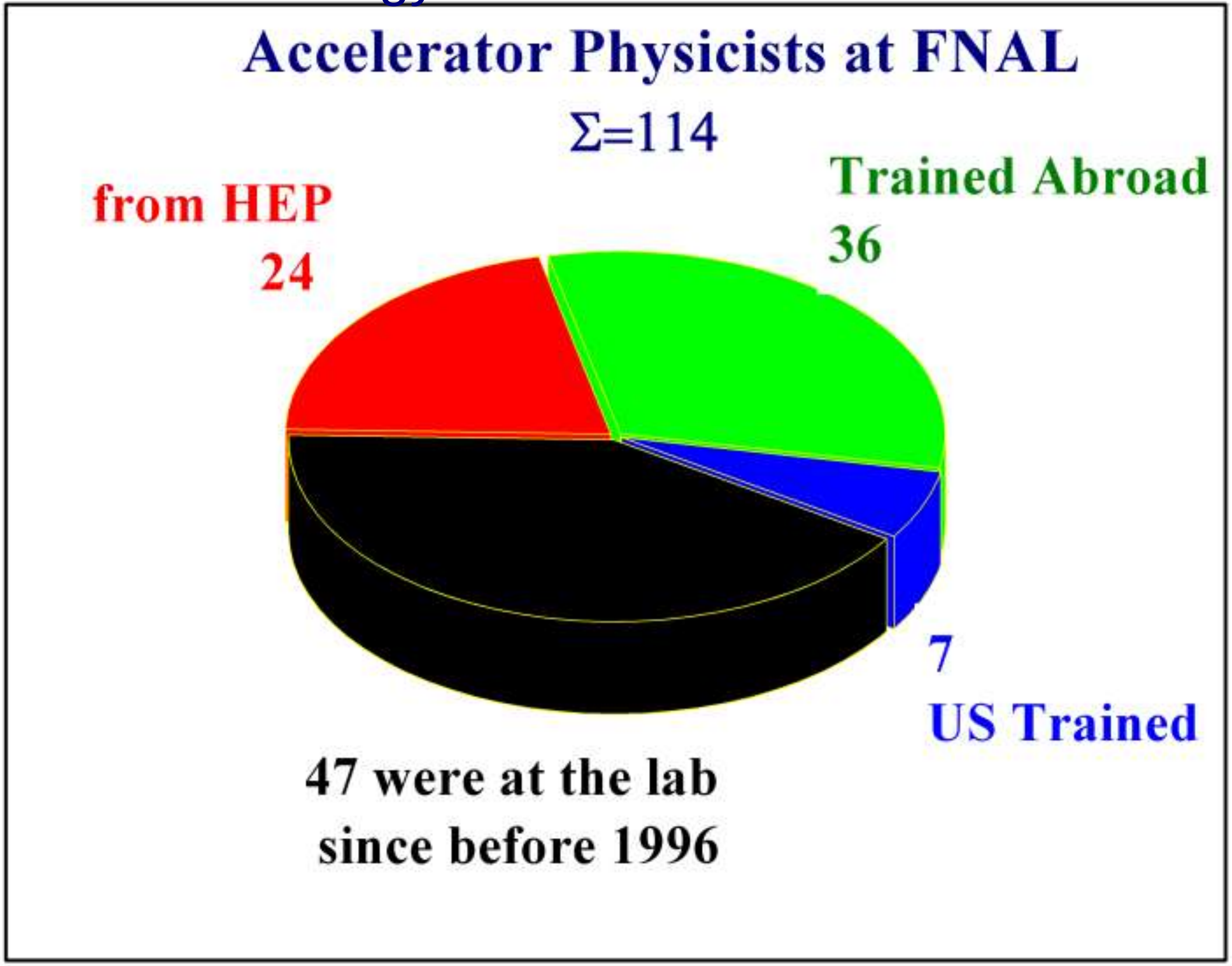
Over the past decade, some 140 operators worked in the MCR

33 of them moved to Machine Departments (charged with maintenance, operation & upgrades of 9 accelerators, beamlines)

Many of them got advanced degrees (MSc, PhD)

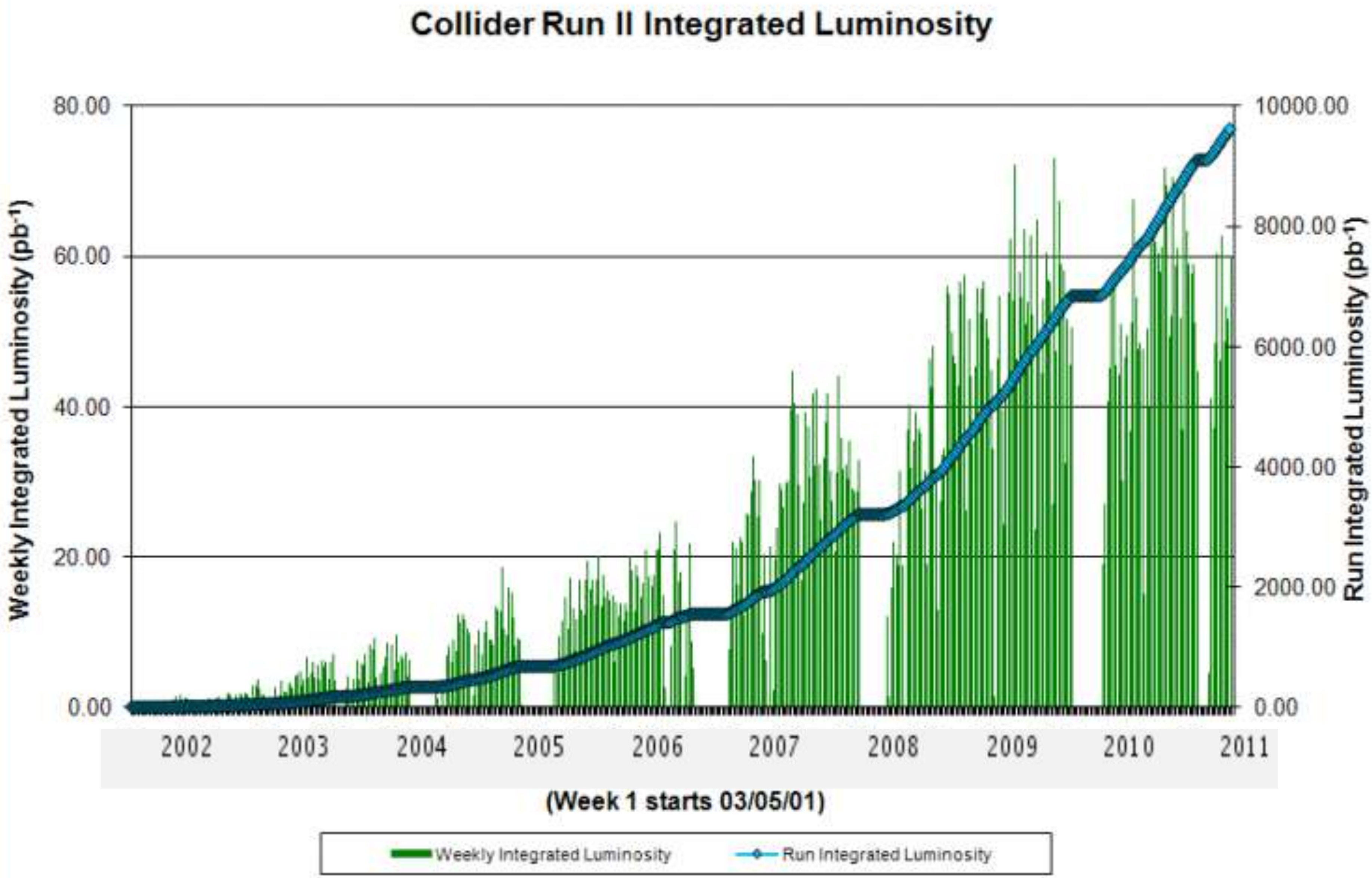
Tevatron Collider as a Melting Pot

Sociology of the Collider Run II Team



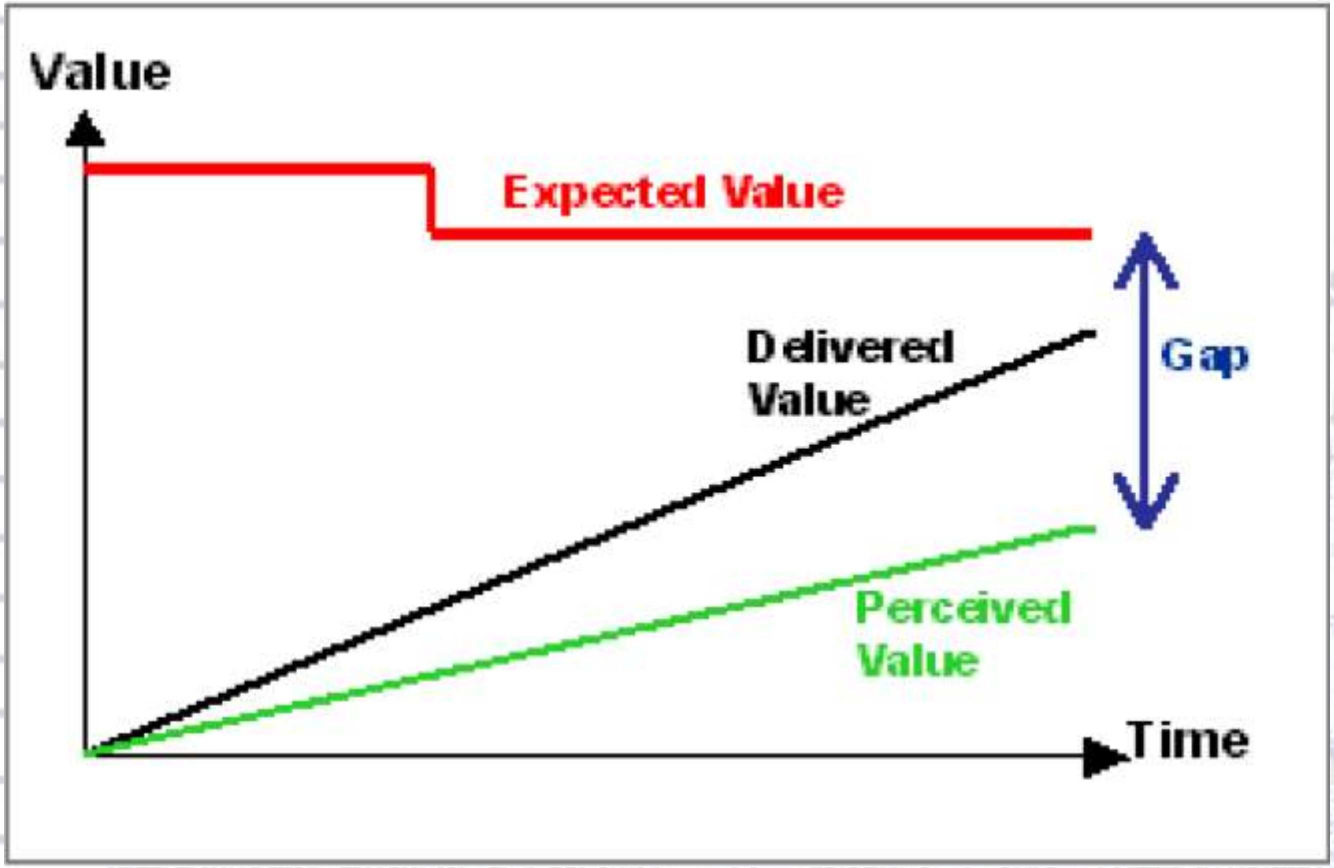
Tevatron Performance

As of Dec'2010: 9.4 fb^{-1} total; about 2.4 fb^{-1} /year; 60+ pb^{-1} /week



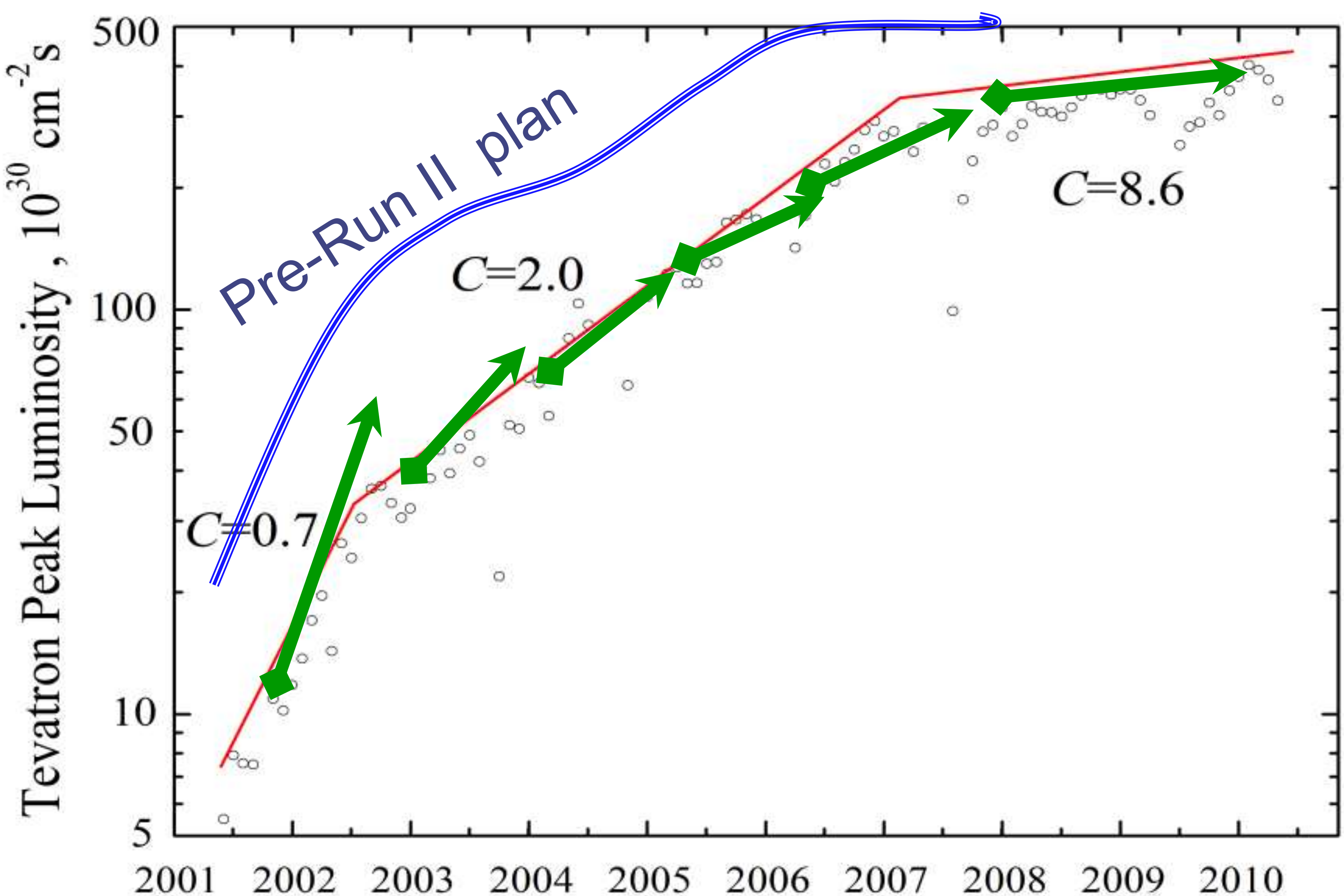
Lesson: Expectation Management

The road to superb Collider performance was not smooth: during the first 2 years of Run II we were way below the 2001 plan



" Expectations are a primary measure of your success"

Run II Luminosity Progress



Run II Luminosity Progress

Some 30 steps, no "silver bullet"

Improvement		Luminosity Increase
Pbar injection line AA → MI optics	12/2001	25%
Tevatron quenches on abort stopped by TEL-1	02/2002	0%, reliability
Pbar loss at Tevatron squeeze step 13 fixed	04/2002	40%
New Tevatron injection helix	05/2002	15%
New AA lattice reduces IBS, emittances	07/2002	40%
Tevatron injection lines tuned up (BLT)	09/2002	10%
Pbar coalescing improved in MI	10/2002	5%
Tevatron C0 Lambertson magnets removed	02/2003	15%
Tevatron sextupoles tuned/ SEMs taken out of pbar lines	06/2003	10%
New Tevatron helix on ramp, losses reduced	08/2003	2%
Tevatron magnets reshimming & realignment	12/2003	10%
MI dampers operations/ store length increased	02/2004	30%
2.5MHz AA → MI transfer improved/Cool shots	04/2004	8%
Reduction of β^* to 35 cm	05/2004	20%
Antiprotons shots from both RR and AA	07/2004	8%
RR e-cooling operational	01-07/2005	~25%
Slip Stacking in MI	03/2005	~20%
Tevatron octupoles optimized at 150 GeV	04/2005	~5%
Reduction of of β^* to 28 cm	09/2005	~10 %
"Pbar production task force"	02/2006	~10 %
Tevatron 150 GeV heliximproved, more protons	06/2006	~10 %
Tev collision helix improved, better lifetime	07/2006	~15 %
New RR WP, smaller pbar emittances	07/2006	~25 %
Fast transfers AA→RR (60→15min)	12/2006	~15%
New Pbar target/higher gradient	01/2007	~10%
Tevatron sextupoles for new WP	(2007?)	~10(?)%
Tevatron zero 2nd order chromaticity	2008	~5%?
Shot-setup time reduction/multi-bunch proton injection	2008-09	~5%?
Scraping protons in MI	2008	~10%?
Pbar size dilution at collisions/B0 aperture increased	2008	5%?
Booster proton emittances reduced /P,A1lines tuneup	Apr 2010	10%?

Overall factor of 30 luminosity increase

Fermilab

Tevatron Exponential Progress

….that makes an average ~12.5% increase per step

$$Gain\ after\ 8\ steps\ (1+0.125)^8 \approx e$$

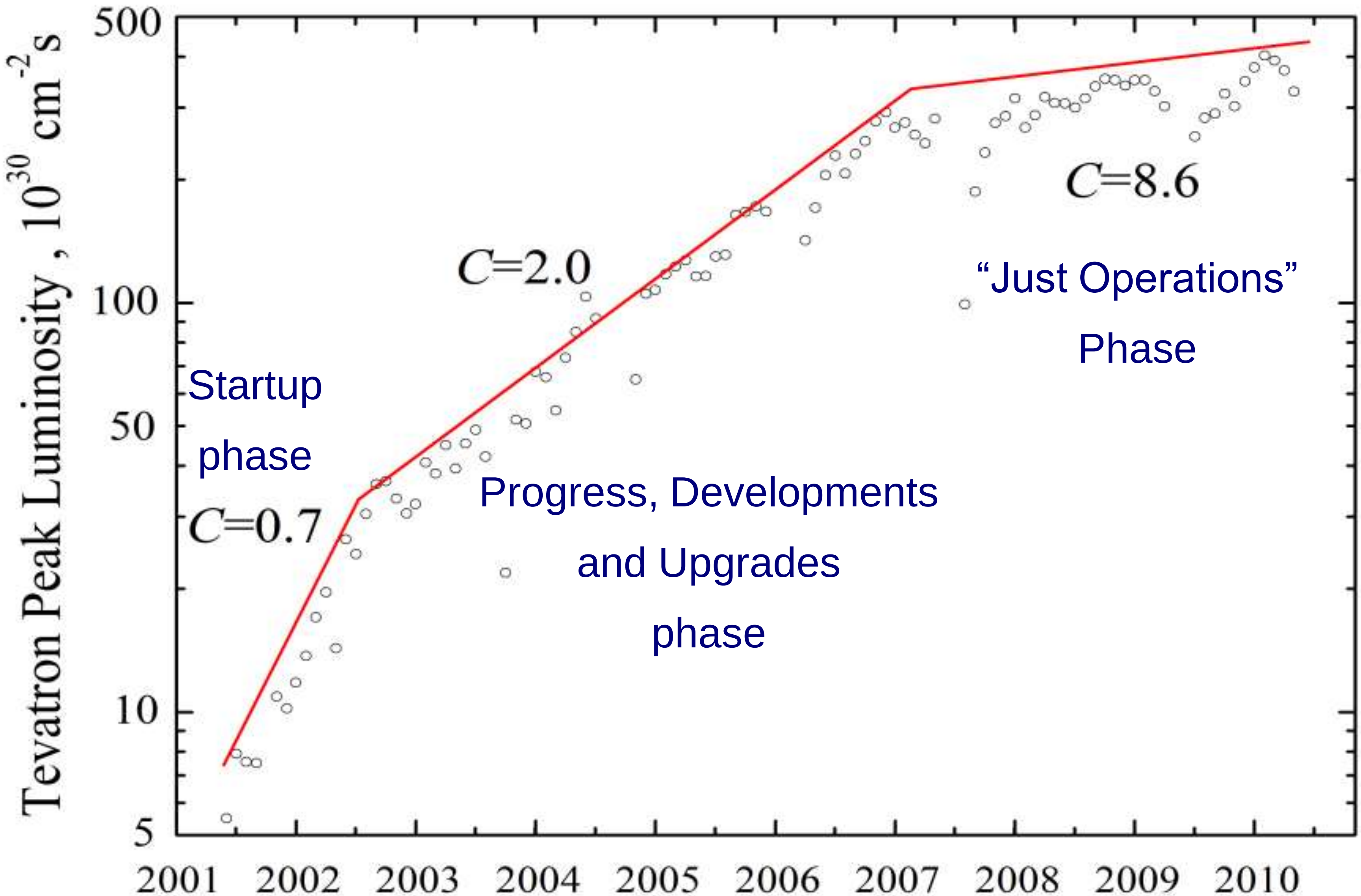
$$after\ 16\ steps\ (1+0.125)^{16} \approx e^2, \text{etc.}$$

So, due to regular improvements the evolution was

$$L(after\ \ time\,T) = L_0 \times \exp(T/C)$$

C (Complexity) = time [years] to **e**-fold

Tevatron Run II "Complexity"



Machine "Complexity" Table

Machine	Design *L*	T_f	*dT, yr*	L_f	L_i	*C*	*Ce*
APS (ANL)			0.5			0	0
MI (FNAL)			0.6			0	0
CESR, 1986-88 Run		01/1988	1	83	20	0.7	1
1990-92 Run		03/1992	1.33	250	50	0.8	1
1996-99 Run		02/1999	3	750	250	2.7	1
2000-01 Run		06/2001	1	1500	550	1.0	1
PEP-II 1999-2001	3000	01/2001	1.5	300	3000	0.7	1
2002-04	3000	06/2004	1.5	8200	4400	2.4	1
KEK-B	10000	06/2003	2.5	10400	2000	1.5	1
DAFNE	100	01/2005	5	143	5	1.5	1
LEP 45 GeV	16	1995	3	33	11	2.7	1
90 GeV	27	1998	2	102	34	1.8	1
SLC	6	1998	5	3	0.3	2.2	3
ISR I		1975	3	32	5	1.6	3
ISR II		1982	6	140	35	4.3	2
SppS	1	1990	7	5.5	0.18	2.0	2
HERA I	16	06/2000	5	18	4	3.6	2
Upgrade	75	07/2005	4.5	51	11	2.9	2
Tevatron Run Ib	15	09/1995	0.8	25	10	0.9	2
Run IIa	200	11/2006	4.0	232	25	2.1	2
RHIC	32, n-pair	2004	3	58	15	2.2	2

“CPT Theorem for Accelerators”

$$C \times P = T$$

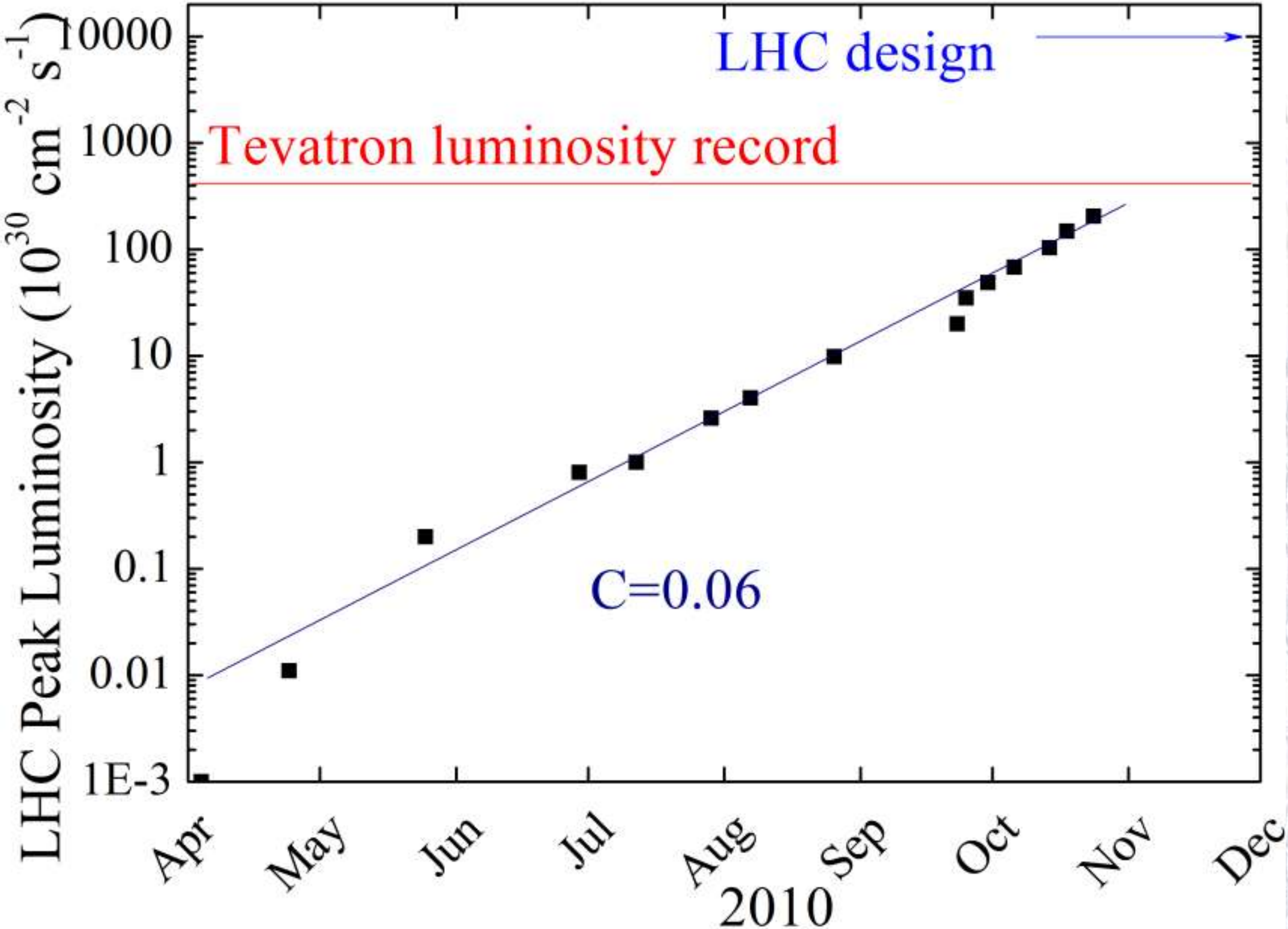
C = Complexity of the machine

P = Performance (or Challenge)

= ***ln*** (Luminosity Increase)

T = Time to reach ***P***

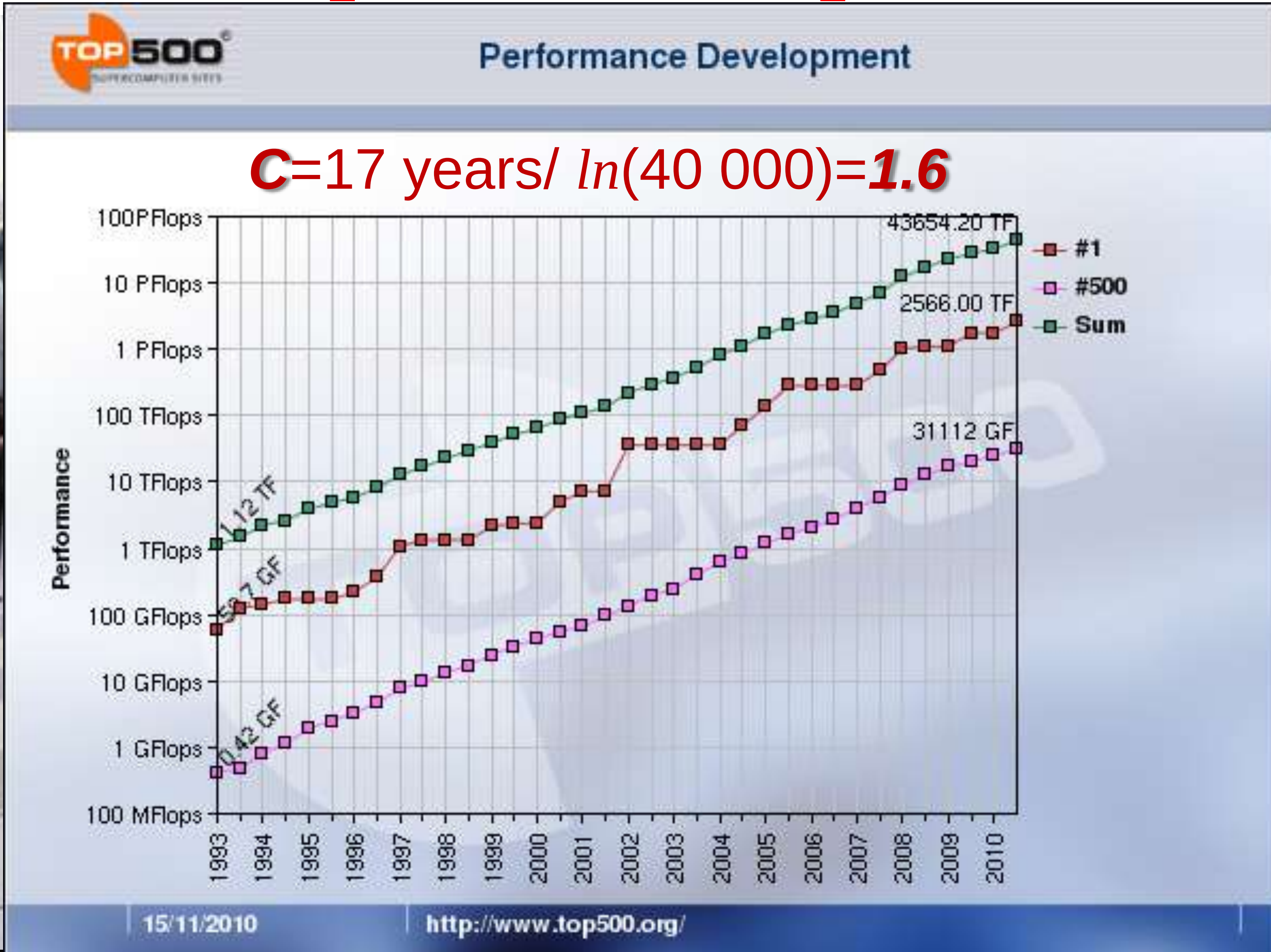
CPT at LHC



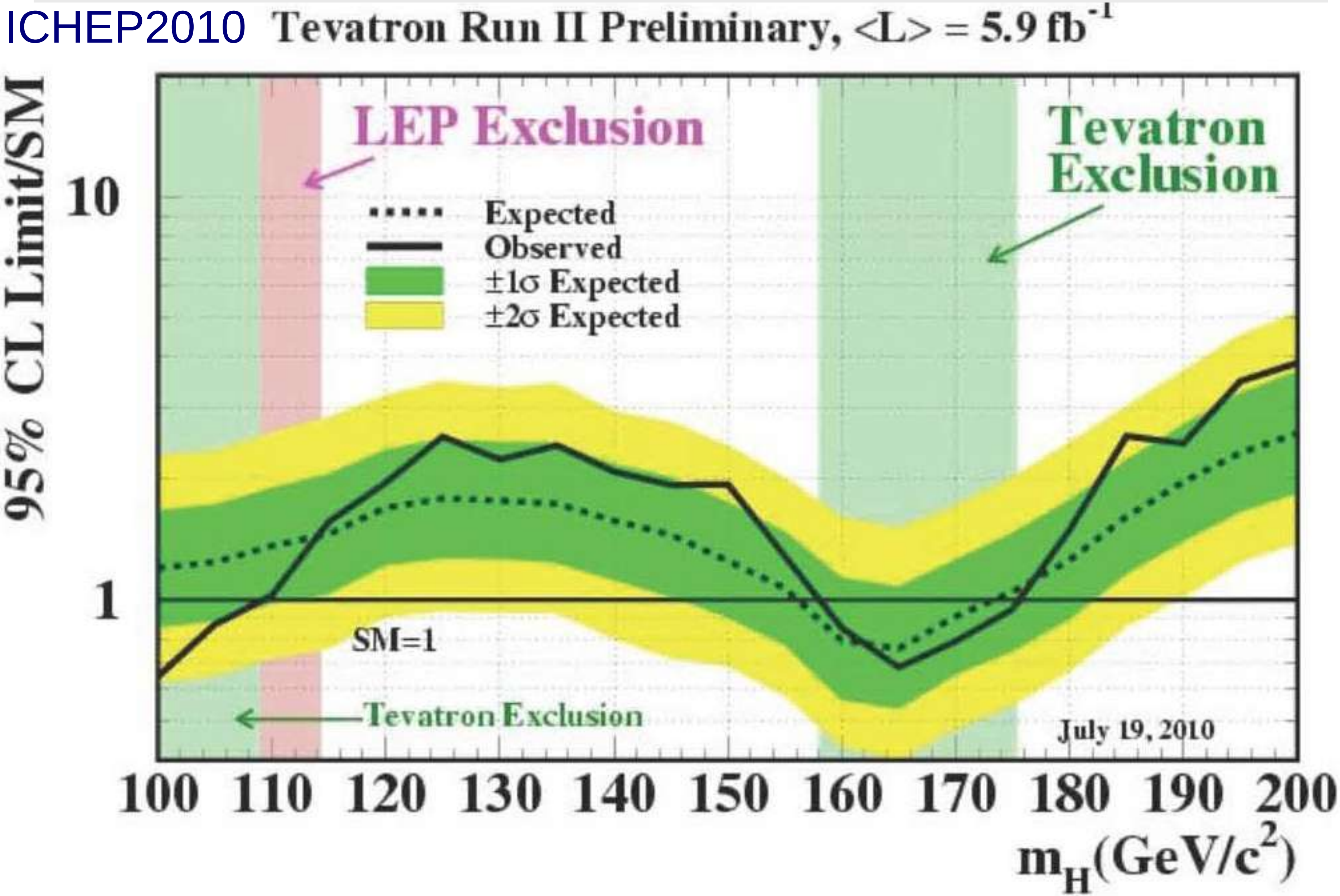
LHC design
Tevatron luminosity record
C=0.06
LHC Peak Luminosity (10^{30} cm^{-2} s^{-1})
10000
1000
100
10
1
0.1
0.01
1E-3
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2010

Computations Speed

C=17 years/ ln(40 000)=***1.6***

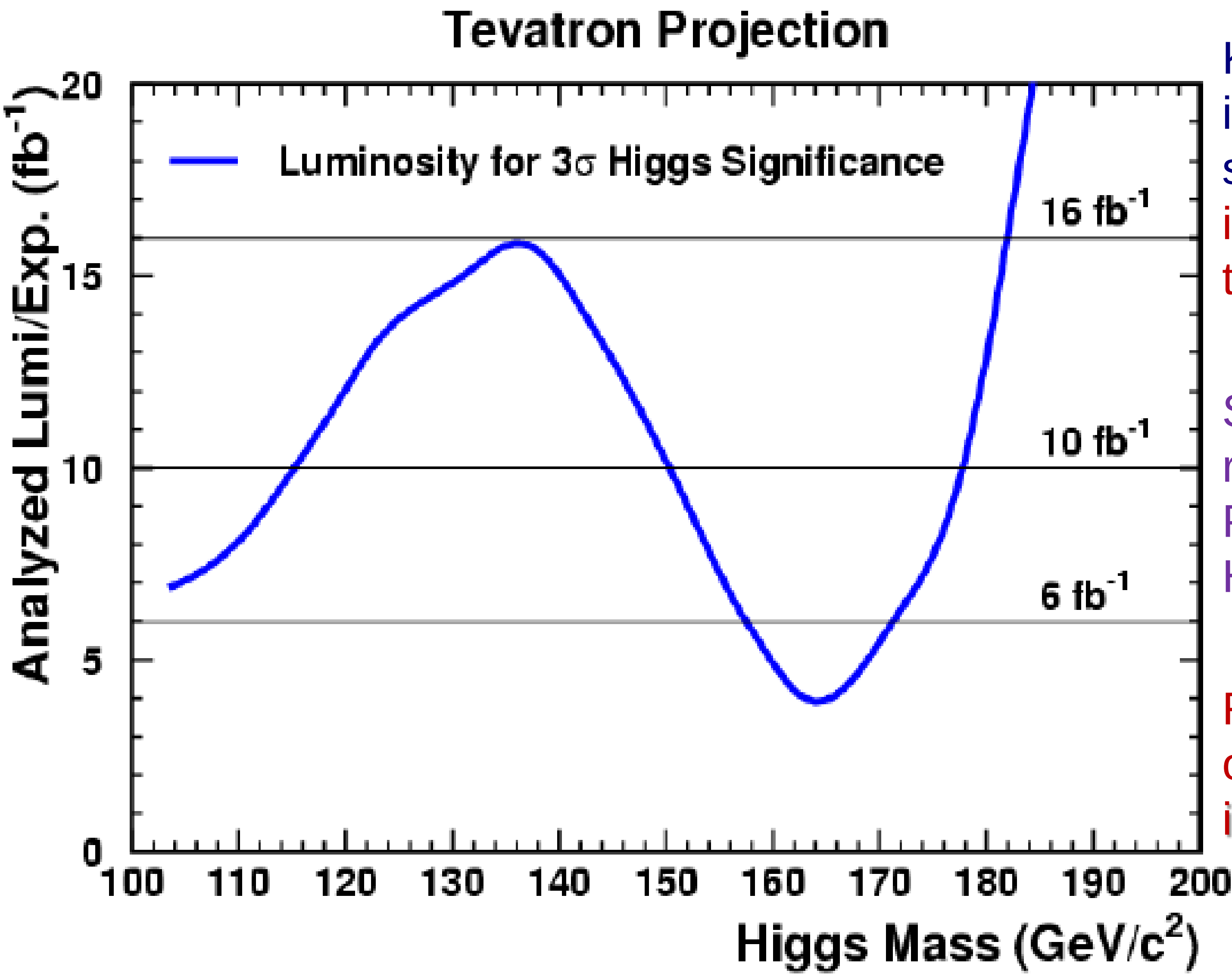


Physics Highlight: Higgs Search



Tevatron Run Extension →2014

Luminosity Delivered/Analyzed : 12/10→20/16 fb^{-1}



Key is the 60% increase in luminosity + continually improving analysis techniques

Strongly recommended by PAC, endorsed by HEPAP P5

Required funding of 35 M$/yr x 3 yrs is not secured yet

Summary

- The Tevatron Collider has worked extremely well for 25 years and is still working well.
- The Collider has greatly advanced accelerator technology and beam physics
- It has enabled CDF and D0 to discover the top quark and observe important features of the standard model for the first time.
- By the end of 2011 it will have delivered about 12 fb^{-1} to each detector. 3 extra years will make at least one more important discovery possible.
- Its success is a great tribute to the Fermilab staff

Thanks for your attention!