Fermilab

Tevatron Collider Run II:

A Cinderella Story

…or The Art of Collider Commissioning

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Fermilab

Abstract

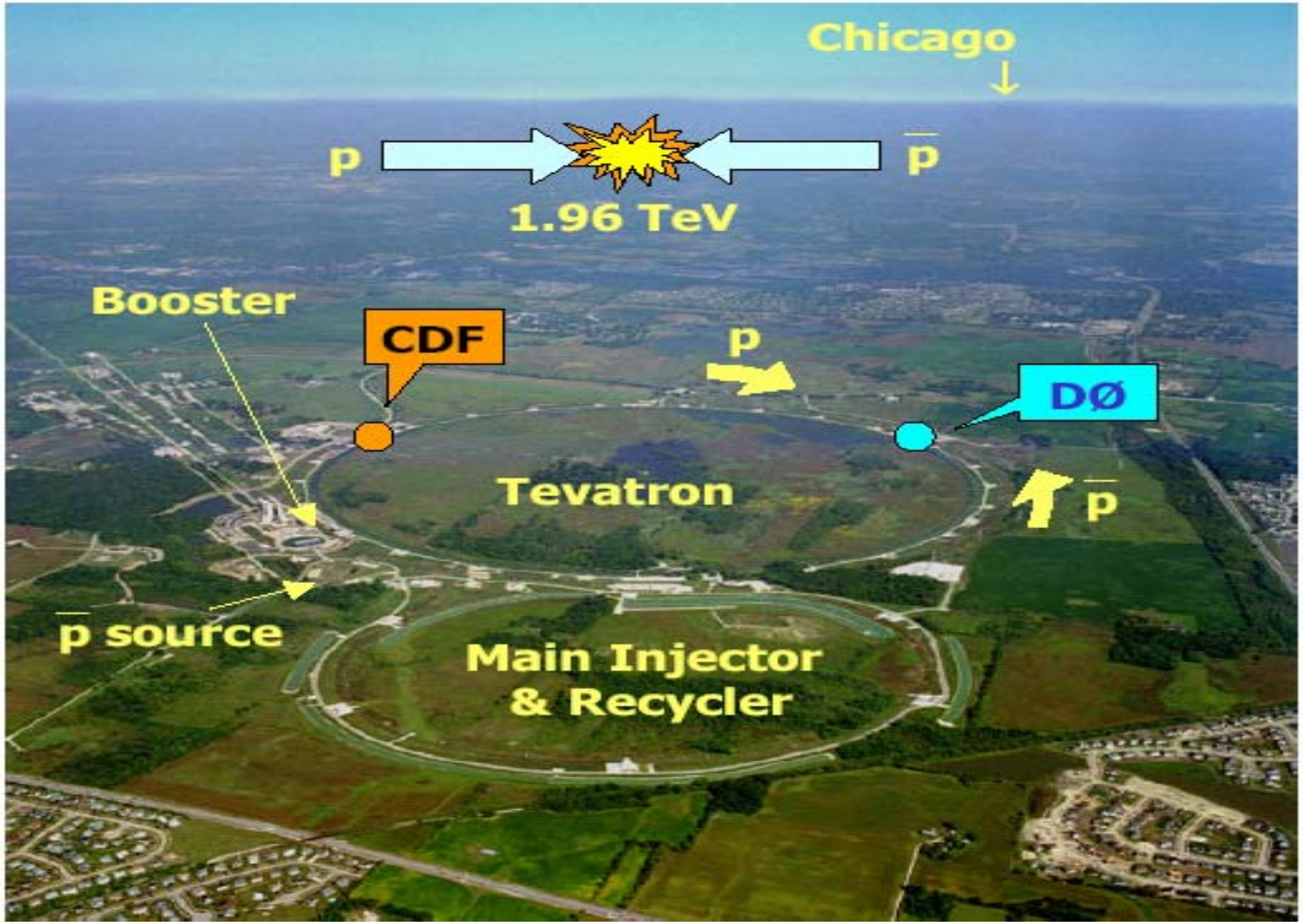
2007-08 ACADEMIC TRAINING PROGRAMME LECTURE SERIES

- 01, 03, 04, 05 October 2007
- Main Auditorium, bldg. 500, 11:00-12:00
- ***Tevatron: The Cinderella Story or The Art Of Collider Commissioning V. SHILTSEV / Fermi National Accelerator Laboratory, Batavia IL, USA***
- The Tevatron Collider at Fermilab (Batavia, IL, USA) is the world's highest energy particle collider at 1.8TeV c.m.e. The machine was a centerpiece of the US and world's High Energy Physics for many years. Currently, the Tevatron is in the last years of its operation in so-called Run II which started 2001 and is tentatively scheduled to end in 2010. In this lecture series, we'll try to learn from the exciting story of the Tevatron Collider Run II: the story of long preparations, great expectations, initial difficulties, years of "blood and sweat", continuous upgrades, exceeding its goals, high emotions, tune-up of accelerator organization for "combat fighting". The lectures will cover Introduction to the Tevatron, its history and Run II; "Plumbing" Issues; Beam Physics Issues; Luminosity Progress; Organization of Troops and Lessons for LHC.

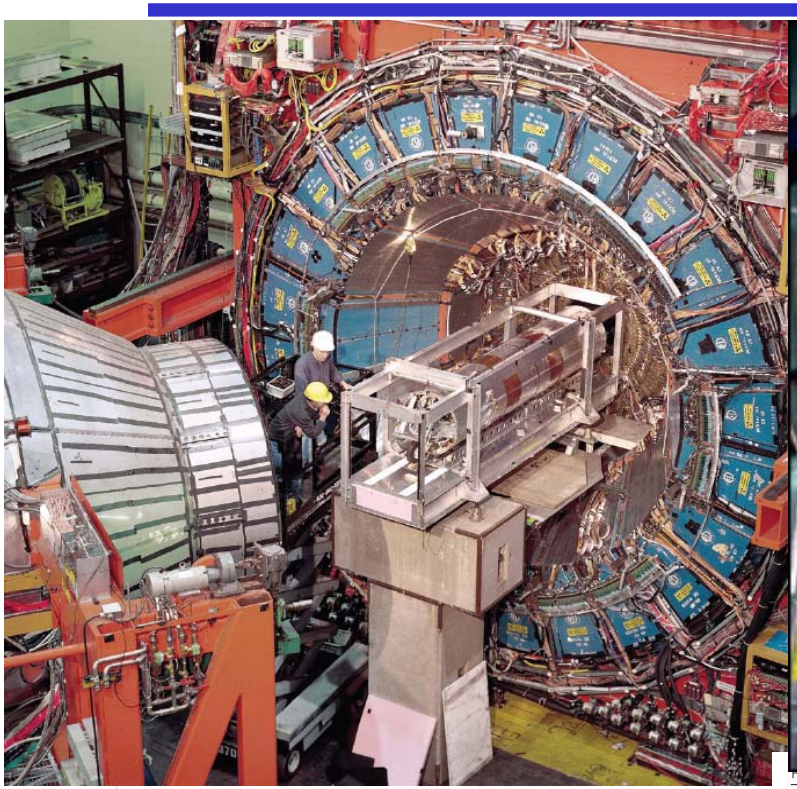
Content

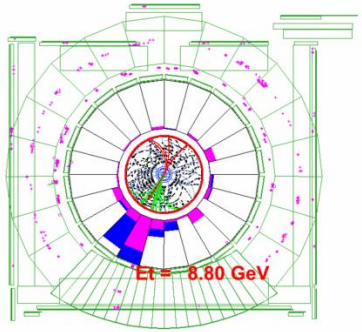
- Monday Lecture 1: Introduction
  - what is Tevatron Collider?
  - why Cinderella?
- Wednesday Lecture 2: "Plumbing" of Accelerators
  - Hardware (no beam): magnets, vacuum, RF, etc
  - Hard-soft-ware (beam): diagnostics, controls, etc
- Thursday Lecture 3: Physics of Accelerators
  - High intensity issues
  - High luminosity issues
- Friday Lecture 4: Lessons
  - Tevatron vs other accelerators
  - Will LHC be different?

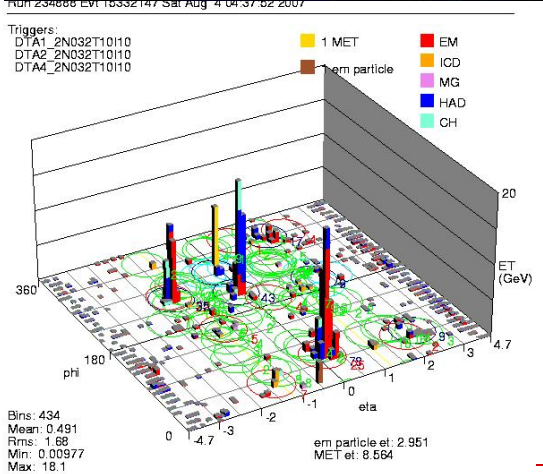
Scenery: Tevatron Collider Run II



Detectors: CDF and D0







For the purpose of these lectures:

Fascinating apparata

Great people (~700 in each team)

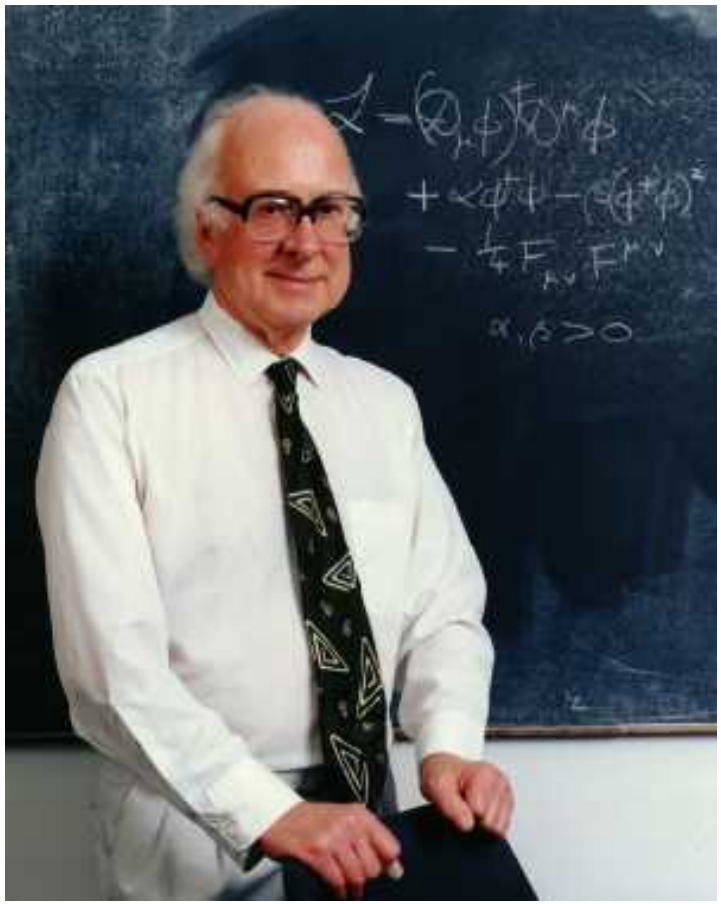
Tons of great results

Unfortunately - they need Collider (very demanding - with good Luminosity@ 1.96TeV)

Have some systems affecting beam

Very instrumental and can be a great beam diagnostics

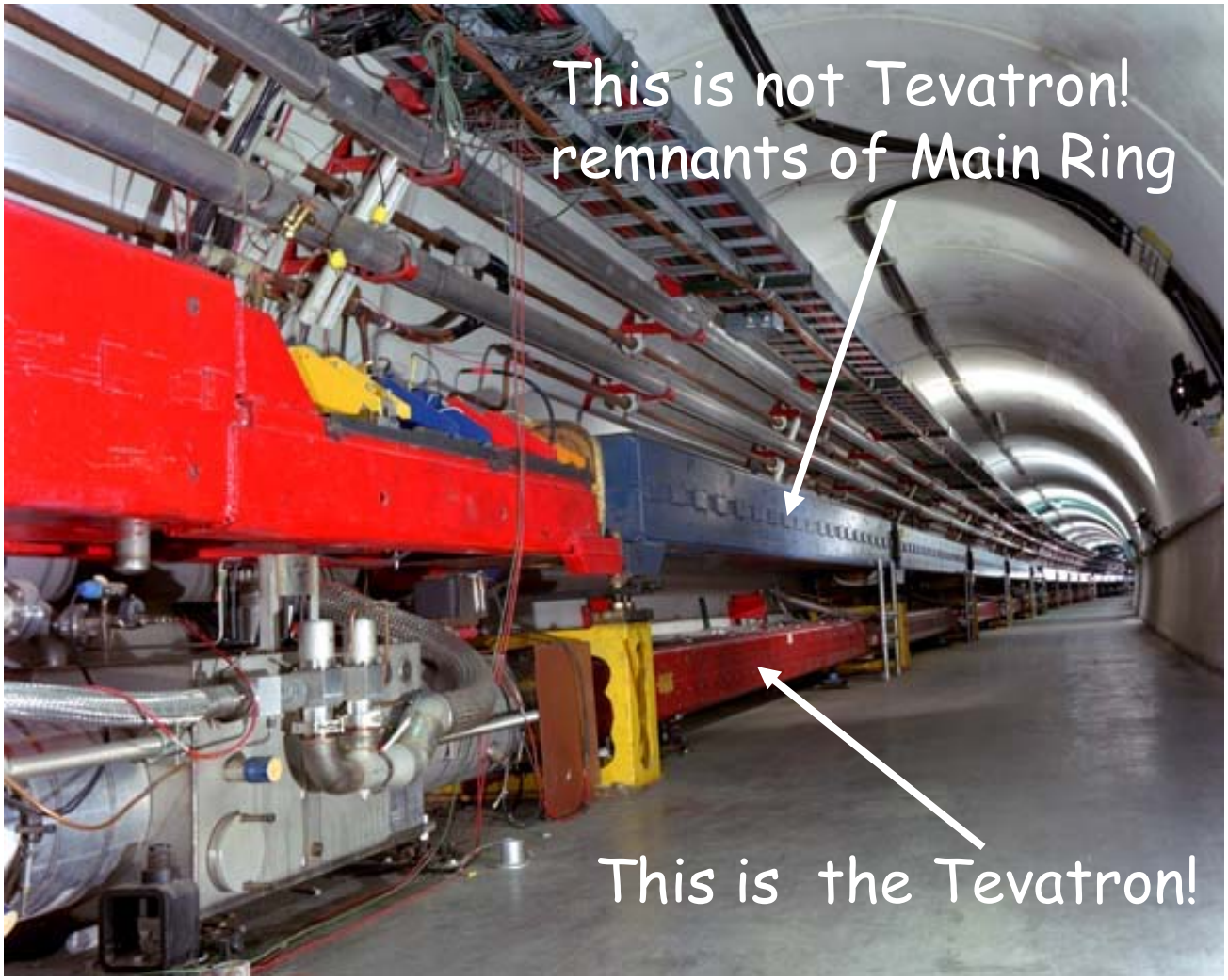
Their role: Prince Charming?



Higgs…

not here yet (expct '09 ?)

Tevatron



C=6.28km
~800 SC Magnets (4d+q)
B_max=4.5T
E=980GeV
E_inj=150 GeV
Proton clockws
Pbars counter
36+36 bunches
Same aperture
26 HV separators
2 Low-beta insertions

It's a COLLIDER

Tevatron's Role: Cinderella

… you'll see later that's not that simple but…

Main Injector

C=3.32km

Room temperature magnets (<2T)

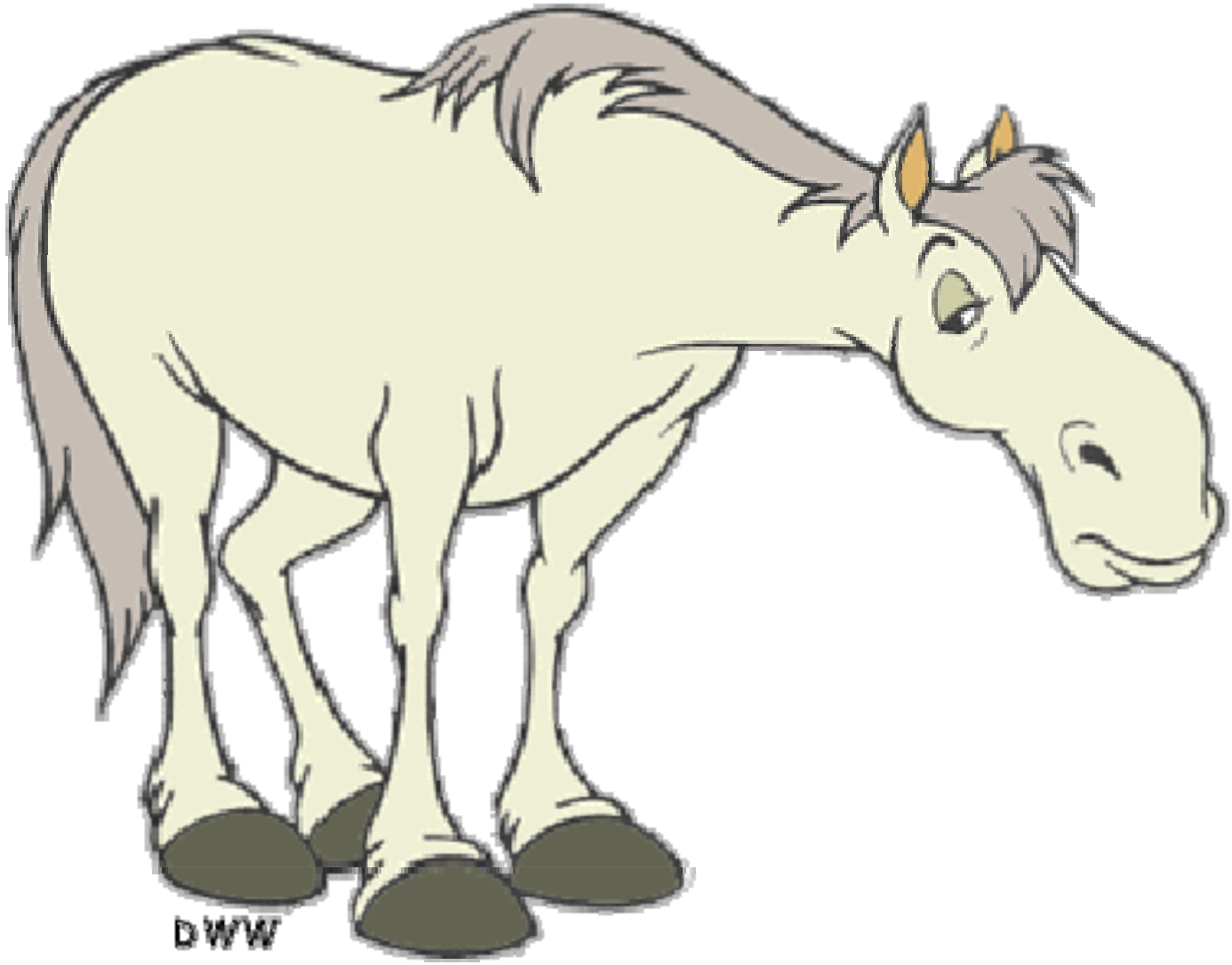
E_max=150GeV
E_inj=8 GeV

Min cycle time 1.4s

Accelerates protons and Pbars to 150GeV for Tevatron

Accelerates protons to 120 GeV for pbar production and NuMI

Main Injectors's Role: Workhorse



Recycler Ring

Shares tunnel with Main Injector

C=3.32km

Permanent magnets (344, 1.45T, Sr-Fe combined function)

E_kin=8 GeV fixed

Stores and cools antiprotons (originally – from Tevatron, now-from Antiproton Accu-mulator only)

Recycler's Role: Magic Wand

… not that simple… but played well at the end

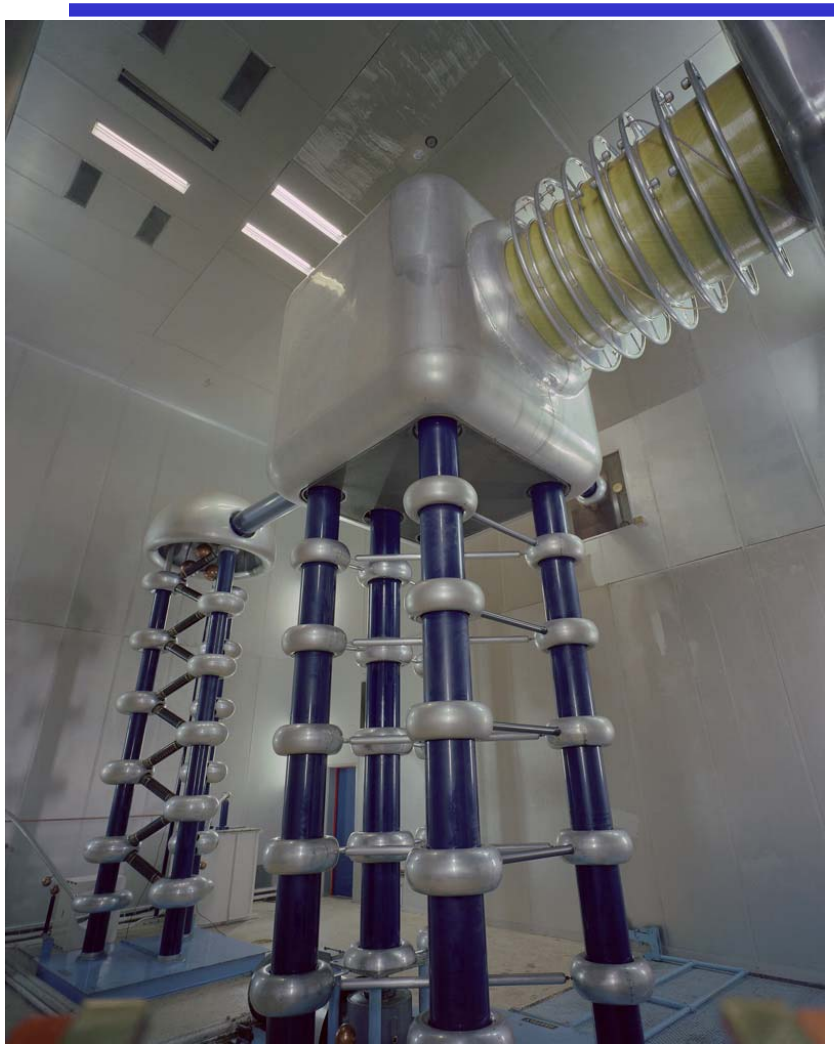
Booster, Debuncher and Antiproton Accumulator

Two 8 GeV pbar rings for stochastic cooling in one Δ-shape tunnel
Debuncher (fast cool)
Accumulator (deep cooling with stacking).. aperture

Booster: C=480m
15 Hz synchtron
E_inj=400 MeV H-
E_max=8GeV protons
~5e12 p/pulse max
Space charge dominated

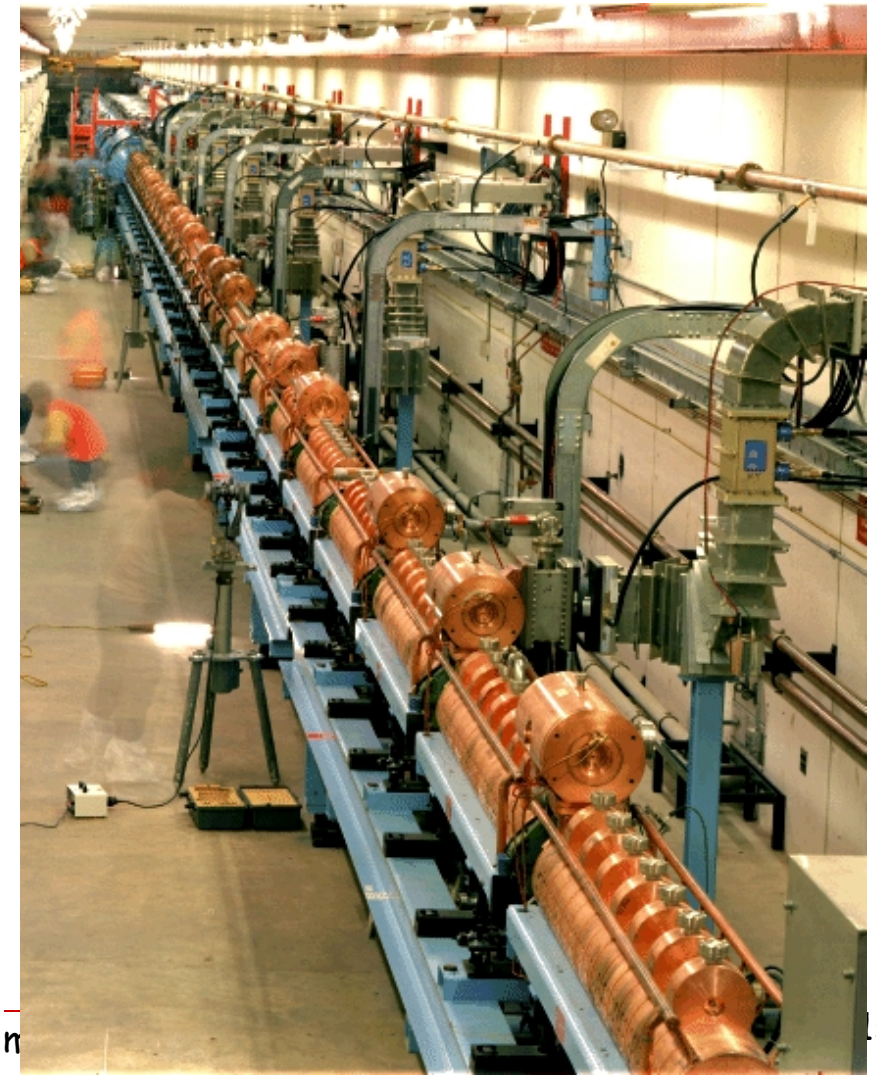
Booster, AA and Debuncher: Horses

Proton Source



H- ion source and 750keV Cockcroft-Walton accelerator, sends beam to Linac

E_kin=400MeV H- to Booster room temperature RF linac 400MHz



Proton Source: Coach

…and Finally

Funding agencies

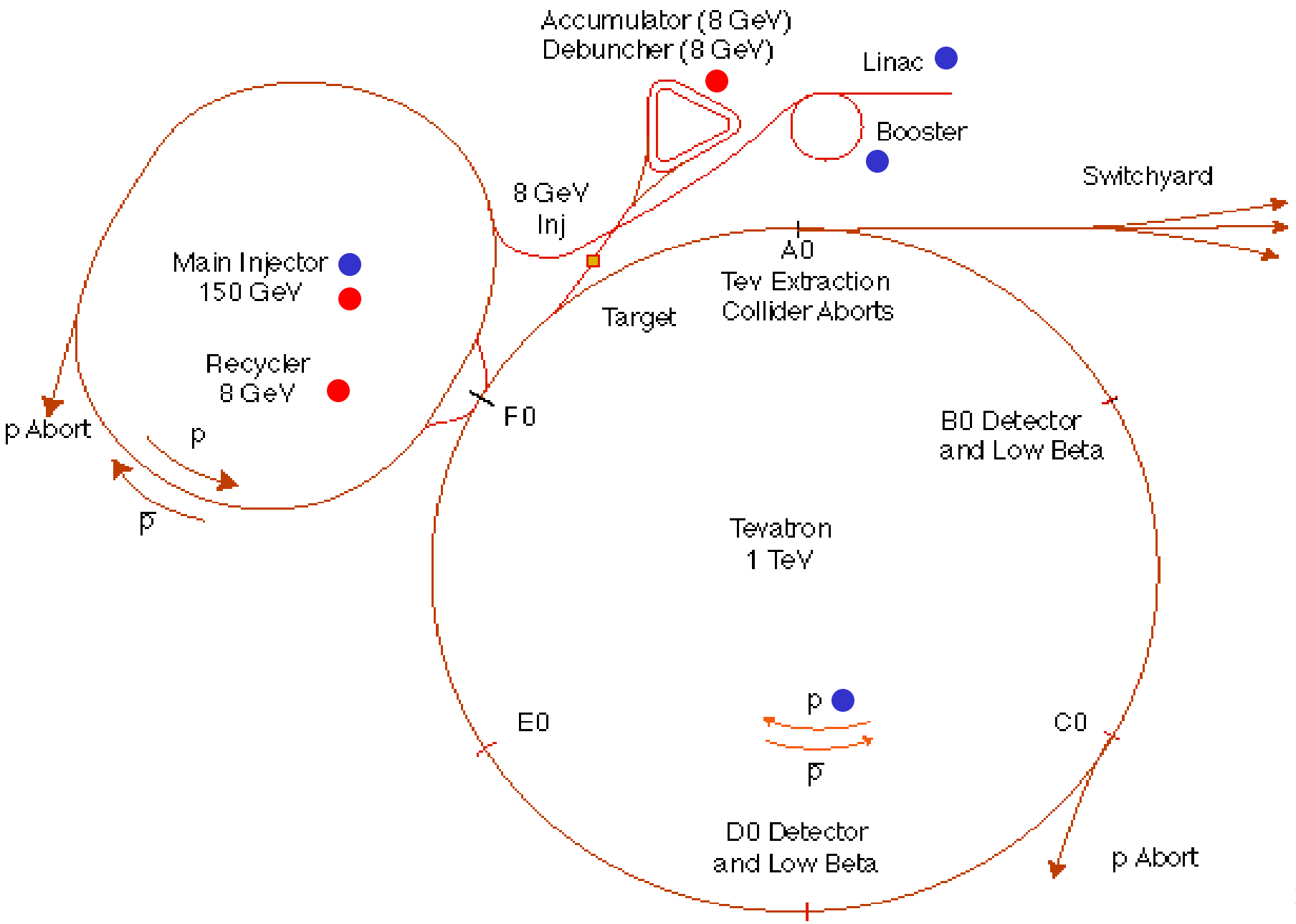
Entire Lab

US labs

CERN et al

Tevatron Run II Team

FermilabTevatron Accelerator With Main Injector

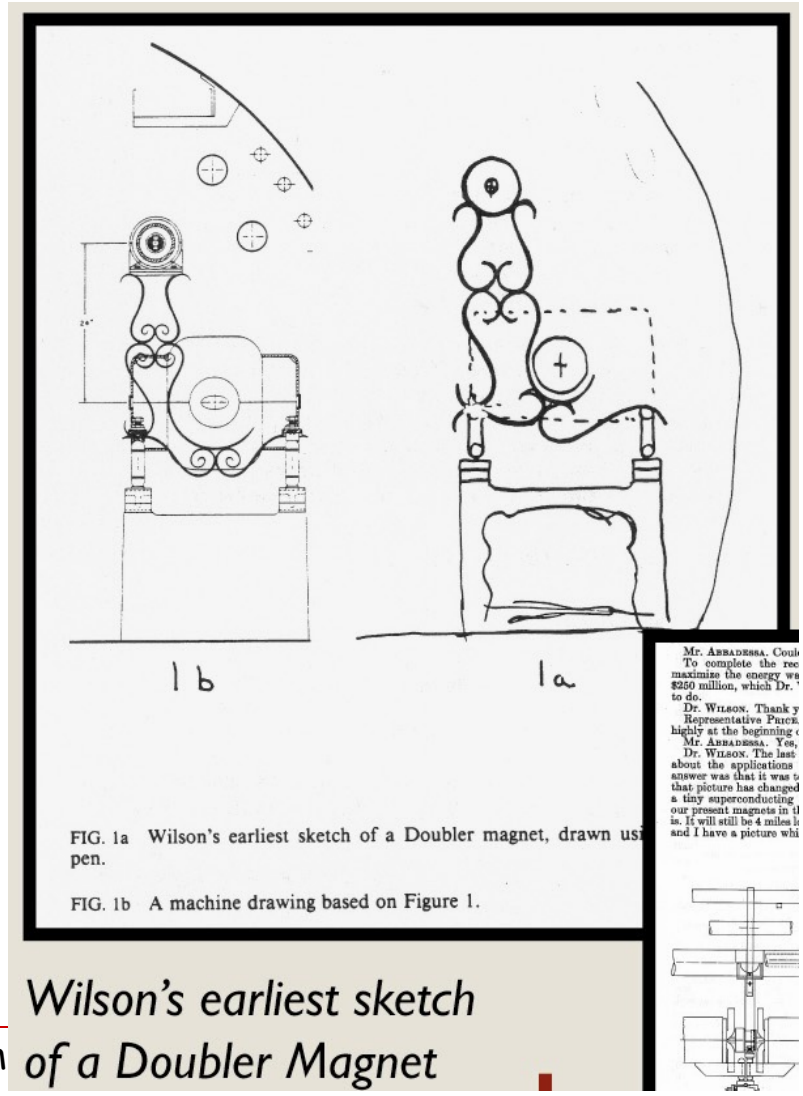


A Bit of History

Robert Wilson

"father-founder"

March 1971: R.R. Wilson announces intention to request authorization to build the Energy Doubler/Saver



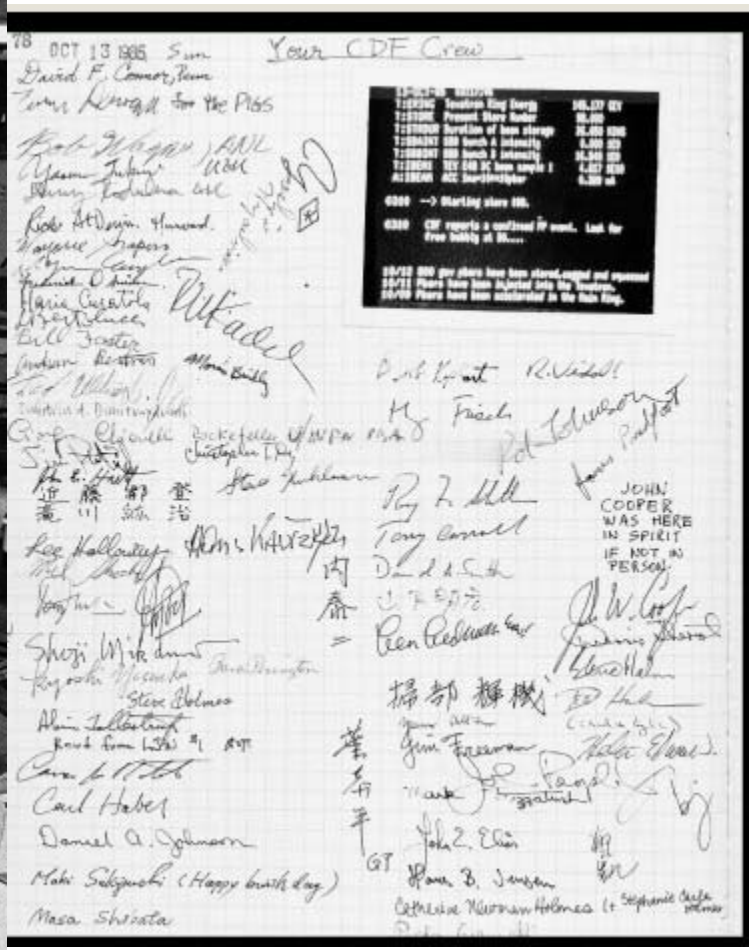
Wilson's earliest sketch of a Doubler Magnet

More History

July 5, 1979: US Department of Energy authorization of Tevatron project (after magnet R&D done)

March 18, 1983: Installation of the last of 774 superconducting dipole magnets in the Tevatron

Success!



July 3,1983: Tevatron achieves world-record proton beam energy 512 GeV

Tevatron as p-pbar Collider: 1985 -

October 13, 1985: 1st observation of pbar-p collisions by CDF at 1.6 TeV

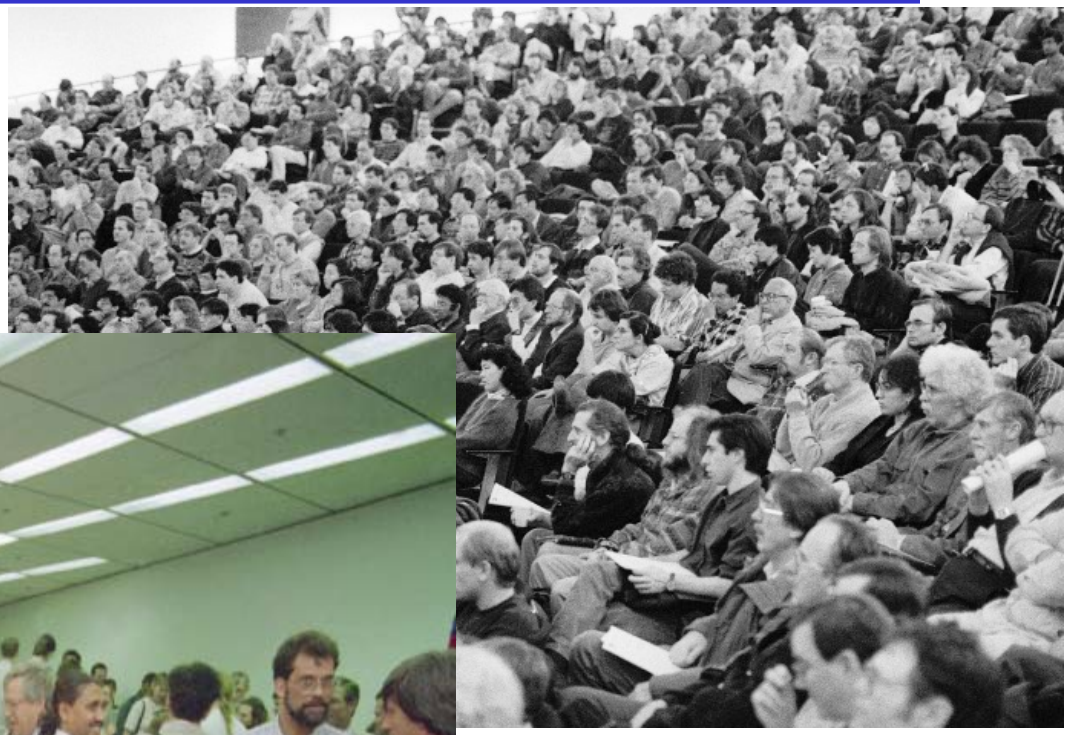
June 20, 1988: First Collider run begins

Mar.22,1993: Main Injector groundbreaking

Sep.4,1993: New 400 MeV Linac 1st beam

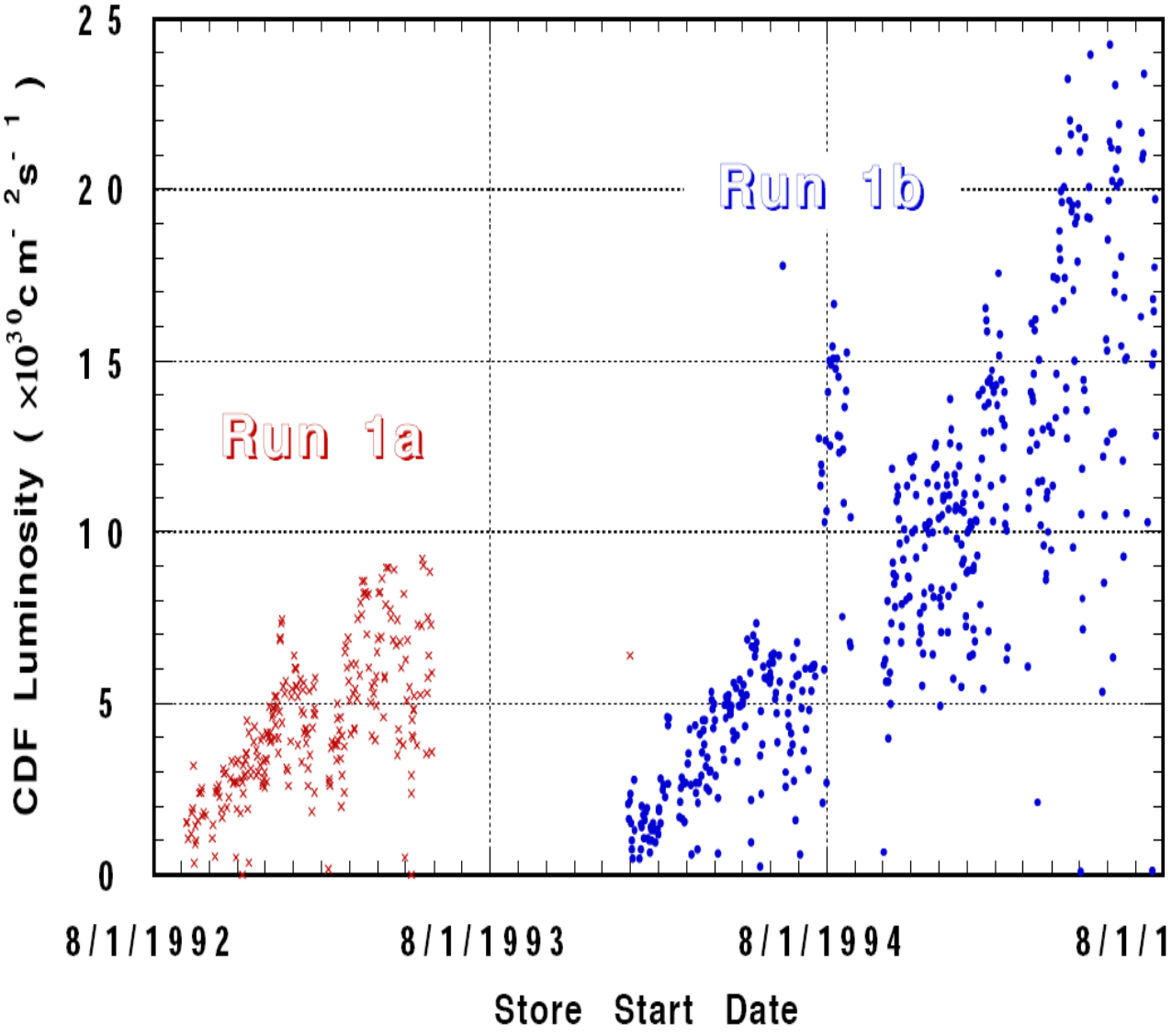
Smashing Success!!

March 2, 1995: CDF and D0 announce the discovery of the top quark.



Feb.19,1996: End of Run I and start of shutdown to complete Main Injector

Tevatron Run I: 1.8 TeV com



Peak L=25e30

Typ. L=16e30

Avg. 2 pb-1/wk

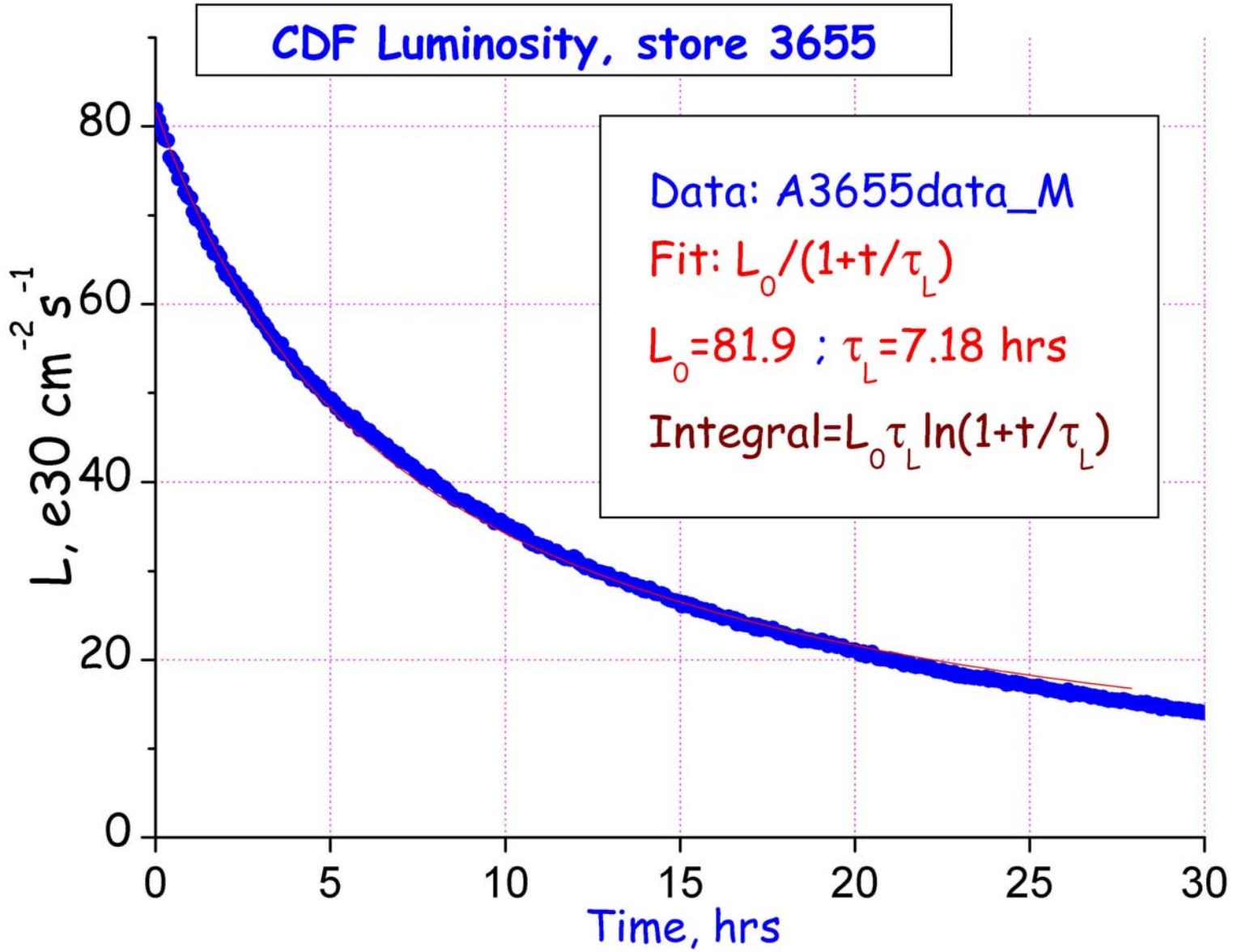
Best 18pb-1/m

Total delivered

0.15 fb^{-1}/detector

Pbar stacking rate 5e10/hr (weekly avg)

Luminosity, Lifetime and Integral



Luminosity and Luminosity Integral

$$L = \gamma f_0 \frac{(B N_{\bar{p}}) N_p}{2\pi\beta^* \left(\varepsilon_p + \varepsilon_{\bar{p}}\right)} H\left(\sigma_l / \beta^*\right)$$

$$I = \int L dt \approx N_{stores} \tau_L L_0 \ln(1 + T / \tau_L)$$

- Luminosity Integral: primary factors
  - Beta* at IP and bunchlength: H(x)/beta^*
  - Emittances ε_p ε_{pbar}
  - Number of protons: N_p
  - Number of antiprotons: BN_{pbar}
  - Lumi-lifetime: τ_L
  - Number Stores: N_{stores}

What people thought in 1996

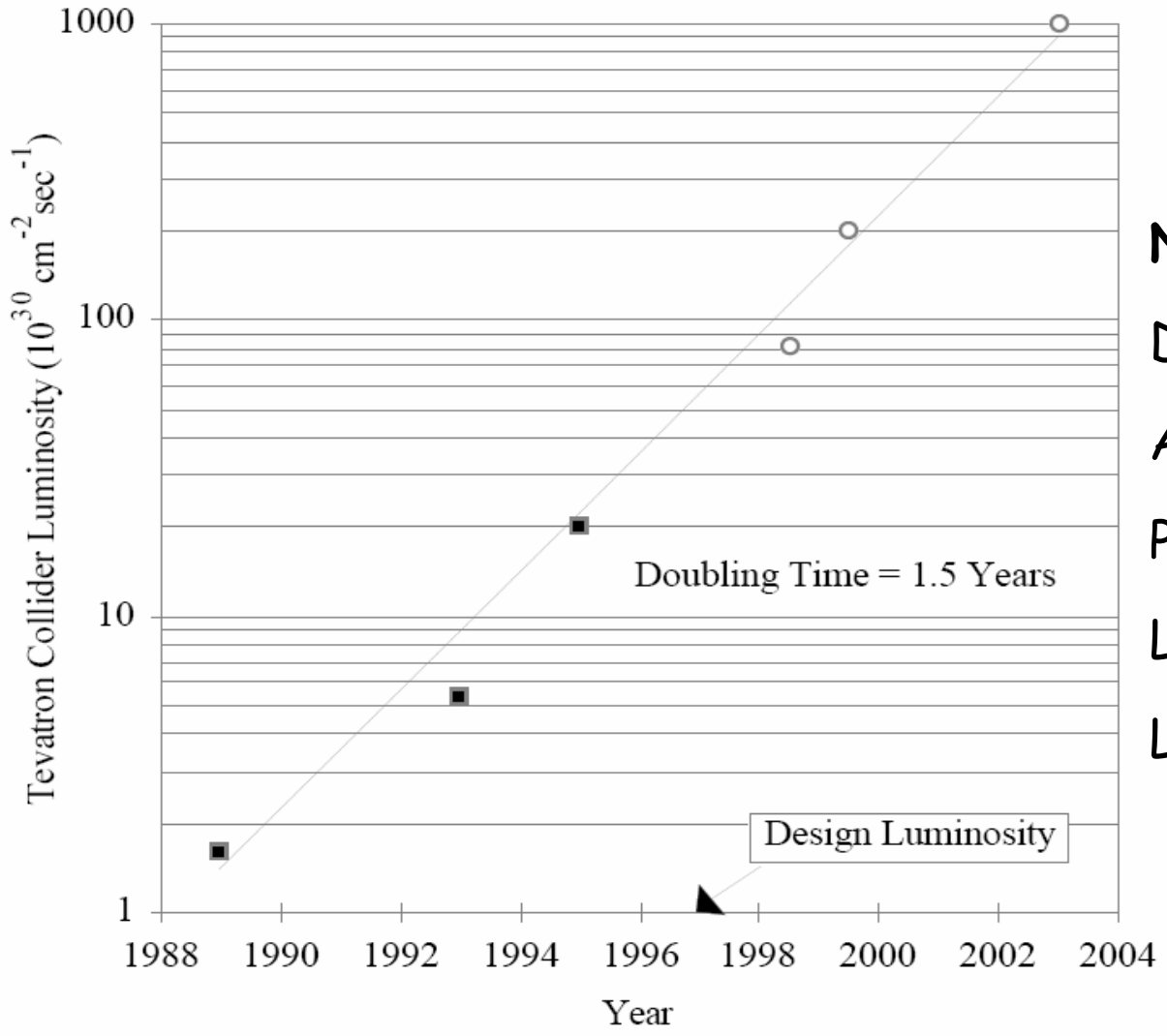


Figure 1.1: Tevatron Collider luminosity as a function of time. The filled circles are measured "best typical" peak luminosities, the line is an exponential fit to the data, and the open points represent goals for the future.

Recycler TDR
FNAL TM-1991

Note:

Design luminosity

Achieved luminosity

Projected luminosity

LHC design 10000xe30

Log-Lin scale

What people thought in 1999

ICFA Seminar:
"Future Perspectives in High Energy Physics"
October 5, 1999

The **Main Injector** is designed to support:

- a three-fold increase in the antiproton production rate.
- good antiproton transmission efficiency from the Re
- a m int

The **Recycler** is designed to:

- relieve the Antiproton Source of responsibility for maintaining high stacking rate at high stacks
- double the effective stacking rate via antiproton recovery
- prov enha

The **Antiproton Source** is being reconfigured to:

- Achieve a factor of three increase in the achievable antiproton production rate.
- A ac

The **Tevatron** has been reconfigured to:

- Accommodate 36 bunch operations.
- Achieve collider operations at 2000 GeV in the center-of-mass.

The initial Run II goal is to deliver an integrated luminosity of >2 fb^{-1} by about the end of 2002.

What people thought in 2001

FNAL-AD
Beams-doc-2385

- The luminosity goal for Run IIa is 2 fb^{-1} **X10 Run I**
  - Peak luminosity up to $2x10^{32}$ $cm^{-2}sec^{-1}$ **X10 Run I**
  - Switch to 103 bunches at $1x10^{32}$ $cm^{-2}sec^{-1}$
  - Length of Run IIa is about 2 years

X100 Run I
in the pre-LHC Era

- The luminosity goal for Run IIa+Run IIb is 15 fb^{-1}
  - Increase antiproton intensity by 2-3
  - Peak luminosity up to $5x10^{32}$ $cm^{-2}sec^{-1}$ **X25 Run I**
  - 103 bunch operation
  - Length of Run IIb is about 4 years

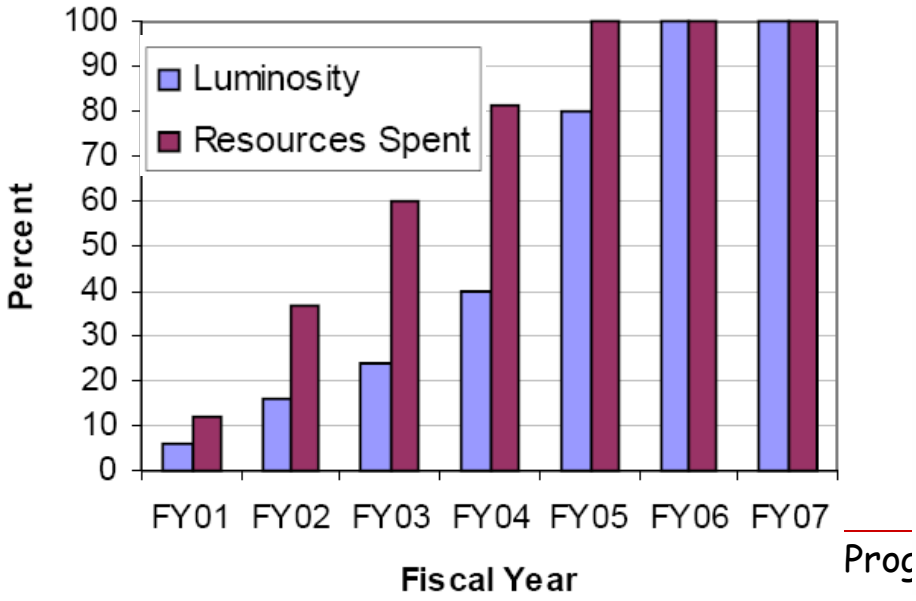
A Well Laid Plan for Collider Run II

RUN	Ib (1993-95) (6x6)	Run IIa (36x36)	Run IIa (140x105)	Run IIb (140x105)	
Protons/bunch	2.3×10^{11}	2.7×10^{11}	2.7×10^{11}	2.7×10^{11}	
Antiprotons/bunch*	5.5×10^{10}	3.0×10^{10}	4.0×10^{10}	1.0×10^{11}	
Total Antiprotons	3.3×10^{11}	1.1×10^{12}	4.2×10^{12}	1.1×10^{13}	
Pbar Production Rate	6.0×10^{10}	1.0×10^{11}	2.1×10^{11}	5.2×10^{11}	hr^{-1}
Proton emittance	23π	20π	20π	20π	mm-mrad
Antiproton emittance	13π	15π	15π	15π	mm-mrad
β^*	35	35	35	35	cm
Energy	900	1000	1000	1000	GeV
Antiproton Bunches	6	36	103	103	
Bunch length (rms)	0.60	0.37	0.37	0.37	m
Crossing Angle	0	0	136	136	μrad
Typical Luminosity	0.16×10^{31}	0.86×10^{32}	2.1×10^{32}	5.2×10^{32}	$cm^{-2}sec^{-1}$
Integrated Luminosity†	3.2	17.3	42	105	pb^{-1}/week
Bunch Spacing	~3500	396	132	132	nsec
Interactions/crossing	2.5	2.3	1.9	4.8	

What people thought in 2001: Upgrades

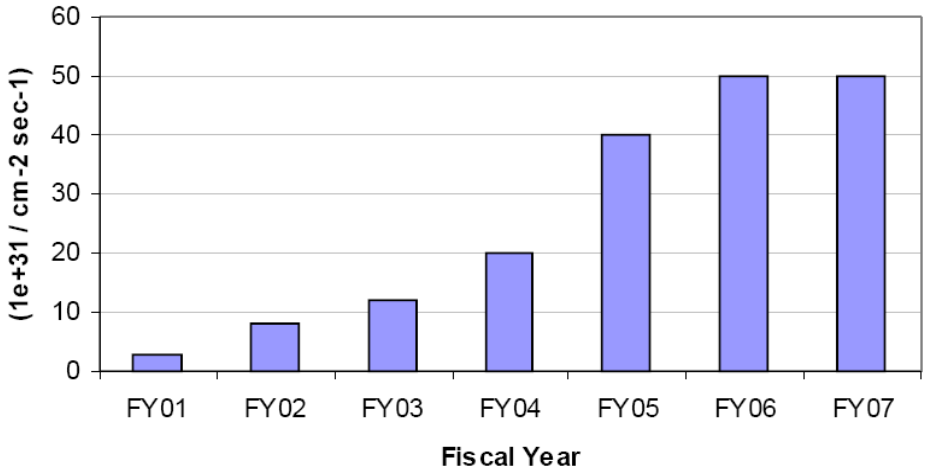
R&D projects

- Improved antiproton availability
  - Electron cooling
  - Slip-stacking
  - Liquid lithium lens
  - Aperture improvements
- Controlling the antiproton (long-range) beam-beam interaction.
  - Electron beam compensation

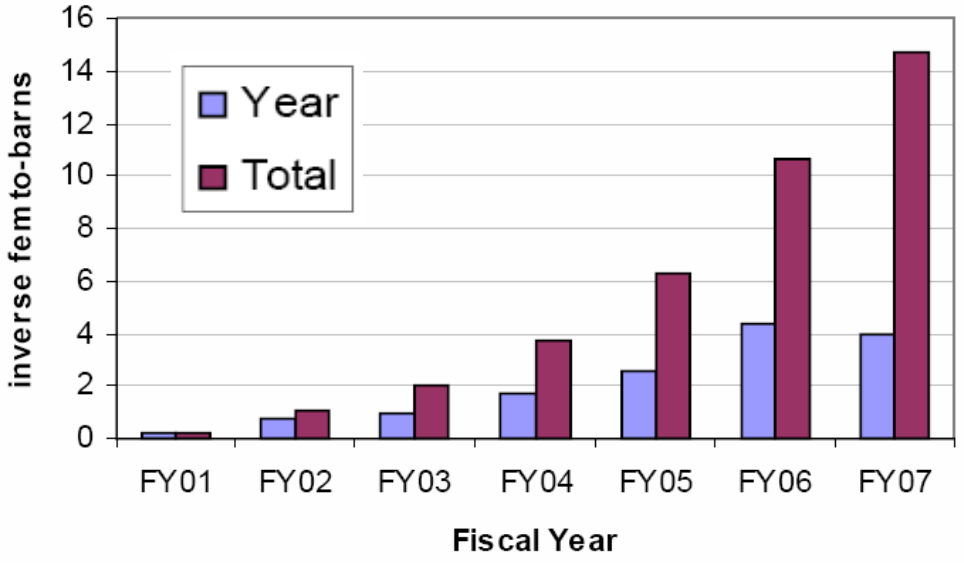


Prog

Initial Store Luminosity



Integrated Luminosity



So, March 1, 2001 comes…

READY?!

SET…

GO !!!

Luminosity Progress 2001-03

	FY'01	FY'02	FY'03
▪ Total integral/yr	20 pb^{-1}	80 pb^{-1}	236 pb^{-1}
expected in '01	*200*	*1800*	*800*
goal set prev. year	200	300	230
▪ Peak Luminosity (record)	7e30	49e30	103e30
expected in '01	*25*	*80*	*120*
(typical)			

WWW: What Went Wrong -?

- Let's go over L-factors (as we understand now)
  - Beta* at IP and bunchlength: H(x)/beta^*
    - Beta*~60cm instead of 35,optics was not controlled, lattice measurements were hard due to old BPMs, etc
    - Bunchlength was 60-70cm instead of 37, coalescing was not tuned up, strange "dancing bunches" observed
  - Emittances ε_p ε_{pbar}
    - Larger from sources: p(Booster – orbit and machine control) and AA(pbar – very large IBS)
    - blown up at each transfer, also in collissions
    - Factors 2-3 larger than design, awful diagnostics
  - Number of protons: N_p
    - Low trsf eff in MI and Tev due to large emm., optics
    - Bad lifetime in Tev at Inj due to high chromaticity
    - Intentionally limited due to pbar lifetime in Tevatron

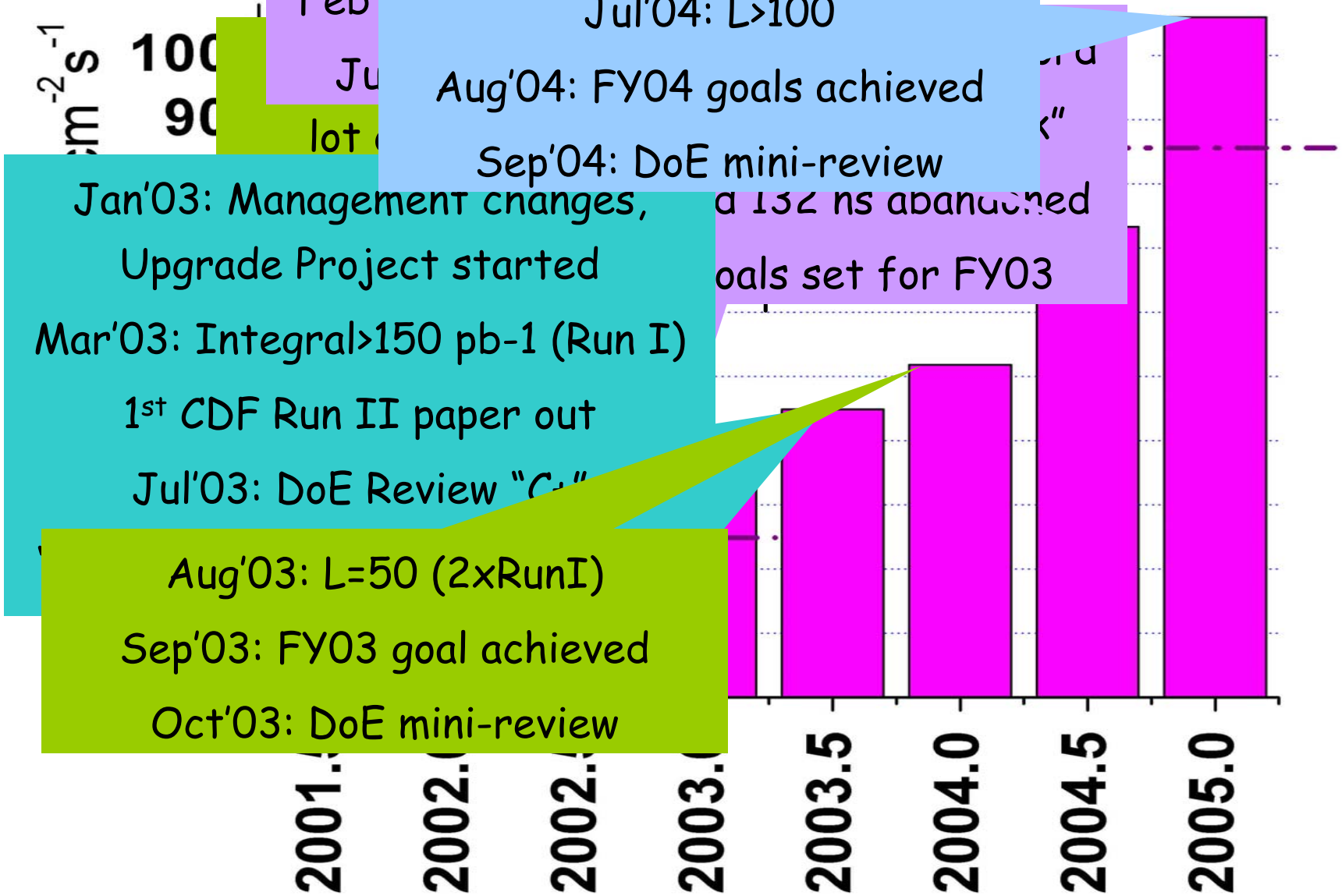
WWW: What Went Wrong -?

- Number of antiprotons: BN_{pbar}
  - Transfer eff as low as 30% (source to low-beta) – losses all along the chain, incl. beam-beam in Tevatron
  - Stacking rate low due to losses in beamlines, slower than expected stochastic cooling, low production eff
  - Short Tevatron stores limited the max pbar stack size
- Lumi-lifetime: τ_L
  - The only parameter that was decent – but because of low luminosity and intensities
- Number Stores: N_{stores}
  - periods when every other store ended prematurely
  - …even every beam abort resulted in a quench (4-6 hrs)
  - 60-80 stores/week were normal, toll of beam studies
  - Even that was waisted as detectors eff was ~50-75%

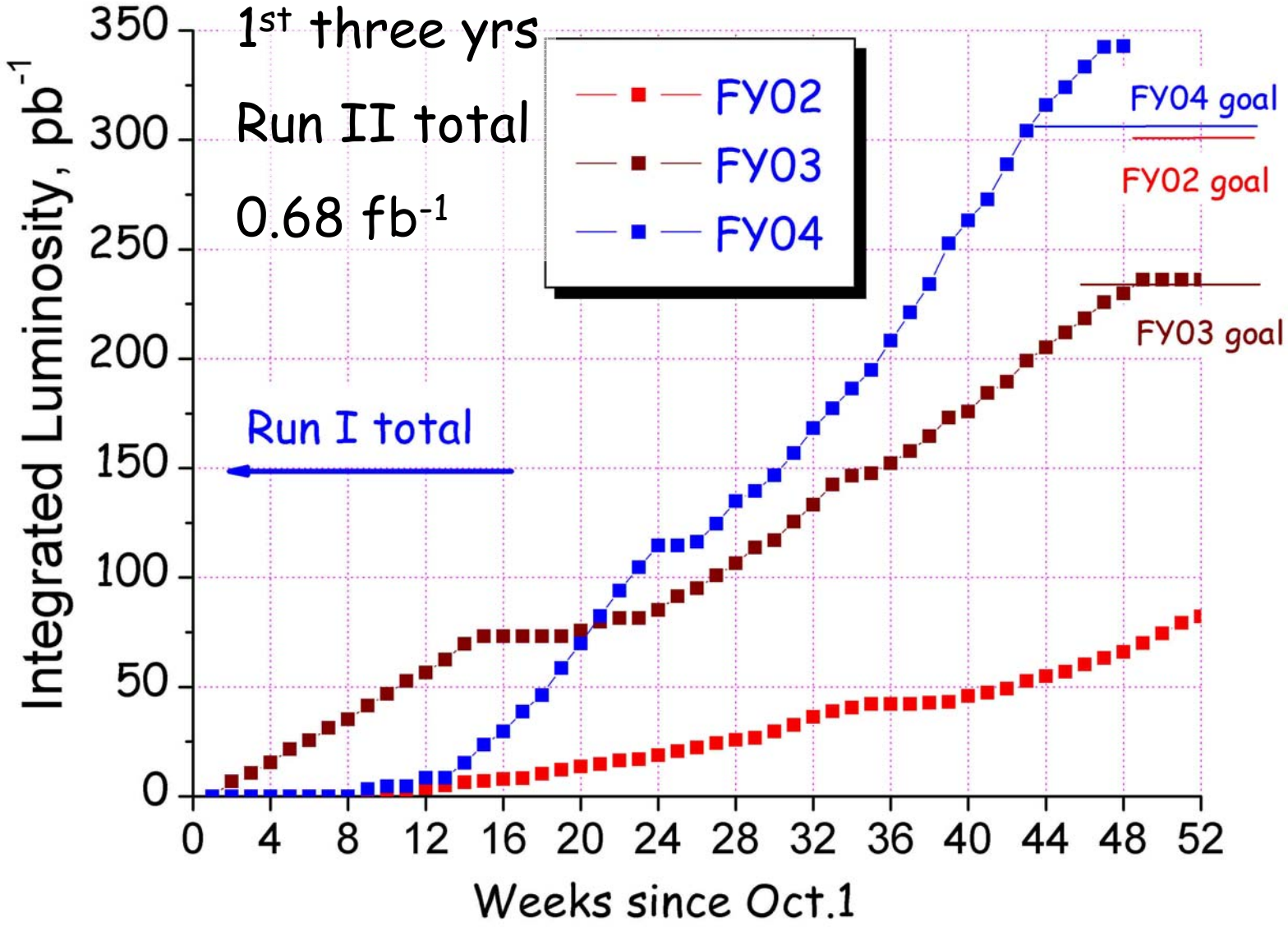
Mother Nature – Stepmother?

The team was sent back to blackboards, labs, control room… "trenches"

Tevatron Run II : The Battle Begins



Integrated Luminosity



Facing The Reality

- Get realistic!
- Attention to Basics
- Understand Physics
- Get into R&D and Upgrades

All that simultaneously!!

Collider Run II had become a complex campaign of operation, beam studies and continuous upgrades

Get Realistic!

- "Get realistic!":
  - goals adjusted to understanding
    - yearly goals were set between "base" (low) and "design" (high) numbers
    - No Run IIa and Run IIb , Run II only
  - several projects abandoned as their outcome was found doubtful:
    - Liquid Lithium Lens
    - 140x105 bunches
    - Crossing angle in Tevatron
    - Recycling of antiprotons (RR never rec'd)
    - Luminosity leveling

Attention to Basics ("plumbing")

- Get machines clean and orderly
  - Alignment of magnets, field control
  - Address vacuum issues
- Understand your machine
  - get better beam diagnostics
- Machine protection
  - to reduce # of quenches, failures
- Uptime
  - Reduce tuneup time, transfer, etc

Understand Physics

- Effects which caught us by surprize:
  - Strong Pbar Intra-Beam Scattering
  - Slow Pbar stacking with stochastic cooling
  - Instabilities in MI and Tevatron
  - DC beam generation in Tevatron
  - Very strong beam-beam effects

R&D and Upgrades

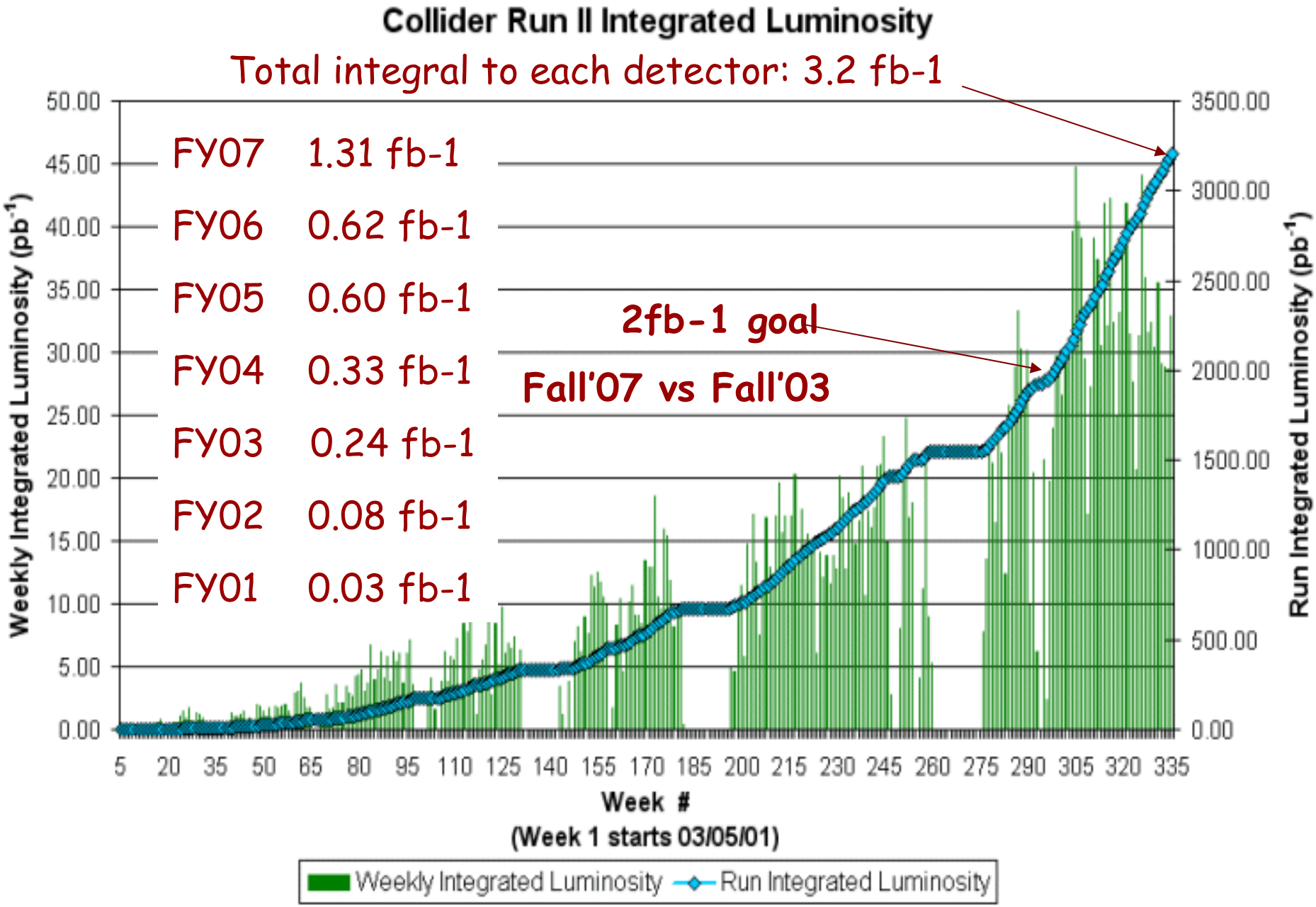
- Tevatron Luminosity Upgrade project started (3 yrs, ~45M$):
  - Support major R&D toward higher L
  - Suport operational gains
- R&D projects paid off:
  - Electron cooling in Recycler
  - Slip-stacking in Main Injector
  - Digital feedback systems in MI
  - Tevatron electron lenses

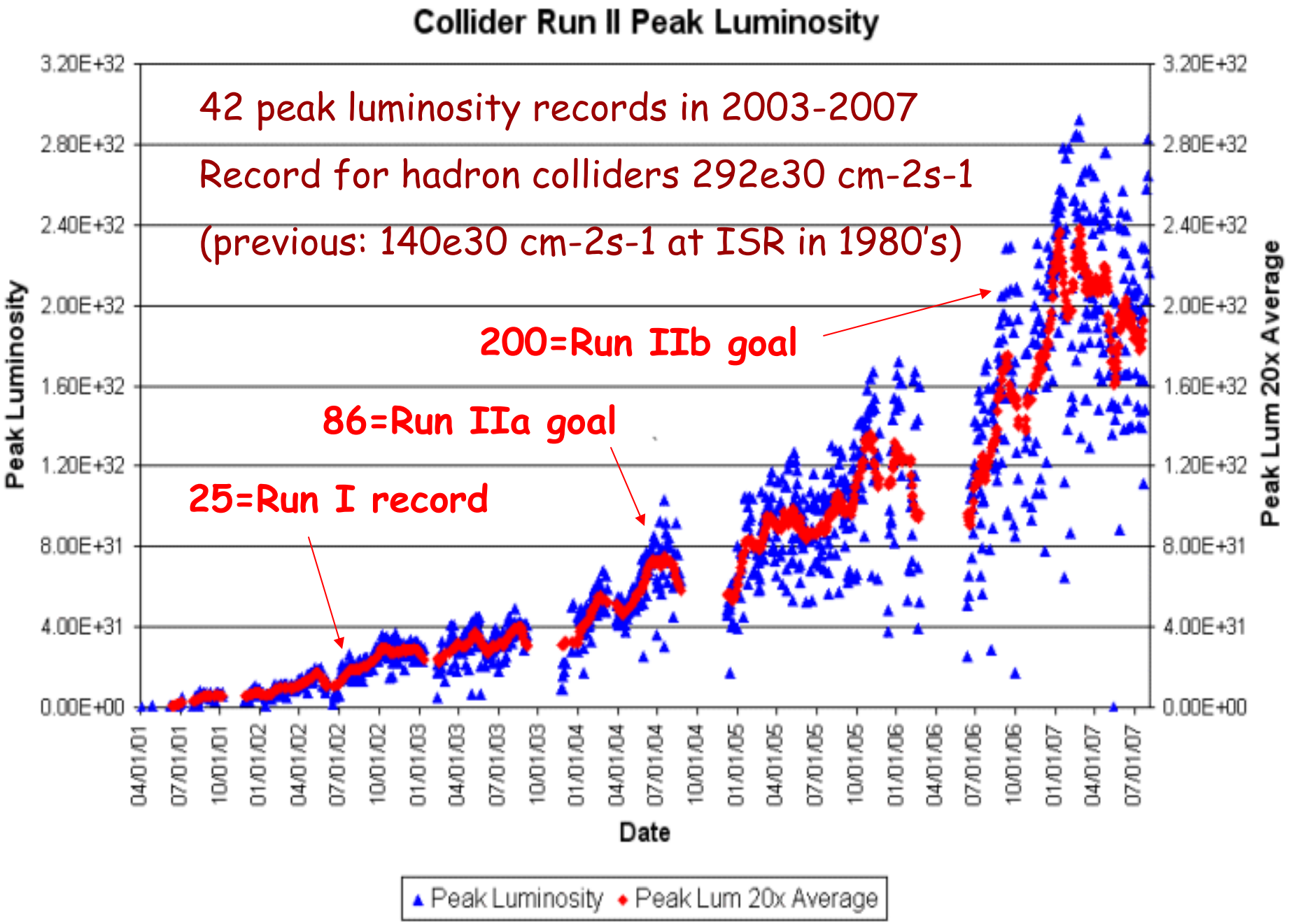
Long Campaign, Many Battles

1.	Optics AA->MI lines fixed	Dec'01	~25 %
2.	DC beam cleaned by TEL-1	Feb'02	uptime
3.	New LB squeeze helix	Mar'02	~40 %
4.	"New-new" injection helix	May'02	~15 %
5.	AA Shot lattice vs IBS	July'02	~40 %
6.	Tev BLT/inst.dampers at injection	Sep'02	~10 %
7.	Pbar coalescing improved in MI	Oct'02	~5 %
8.	C0 Lambertsons Removed	Feb'03	~15 %
9.	S6 cuircuit tuned/SEMs removed	June'03	~10 %
10.	"5 star" helix on ramp	Aug'03	~2 %
11.	Reshimming/Alignment	Nov'03	~12 %
12.	Longer Stores/ MI dampers	Feb'04	~19 %
13.	2.5MHz AA→MI trnsf/Cool shots	April'04	~8 %
14.	Reduction of beta* to 35 cm	May'04	~26 %
15.	Shots from Recycler	July'04	~18%

Improvements in 2005-2007

16. Slip Stacking in MI	Mar'05	~20%
17. Tev Octupoles at 150 GeV	April'05	~5%
18. Reduction of beta* to 28 cm	Sep'05	~10 %
19. RR Electron Cooling operational	2006	~30%
20. Pbar production task force	Feb'06	~10 %
21. Tev 150 GeV helix→ more p's	June'06	~10 %
22. Tev collision helix → lifetime	July'06	~15 %
23. New RR WP →emittances	Sep'06	~25 %
24. Fast AA→RR trsfers (60→15min)	End'06	~15%
25. New Pbar target/higher gradient	Jan'07	~10%
26. Accumulator stack-tail gain correct	Spring'07	~12%
27. Tevatron sextupoles for new WP	(ongoing)	~10?%


Collider Run II Integrated Luminosity
Total integral to each detector: 3.2 fb-1
FY07 1.31 fb-1
FY06 0.62 fb-1
FY05 0.60 fb-1
FY04 0.33 fb-1
FY03 0.24 fb-1
FY02 0.08 fb-1
FY01 0.03 fb-1
2fb-1 goal
Fall'07 vs Fall'03
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
5 20 35 50 65 80 95 110 125 140 155 170 185 200 215 230 245 260 275 290 305 320 335
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity


Collider Run II Peak Luminosity
42 peak luminosity records in 2003-2007
Record for hadron colliders 292e30 cm-2s-1
(previous: 140e30 cm-2s-1 at ISR in 1980's)
200=Run IIb goal
86=Run IIa goal
25=Run I record
Peak Luminosity
Peak Lum 20x Average
Date
3.20E+32
2.80E+32
2.40E+32
2.00E+32
1.60E+32
1.20E+32
8.00E+31
4.00E+31
0.00E+00
04/01/01
07/01/01
10/01/01
01/01/02
04/01/02
07/01/02
10/01/02
01/01/03
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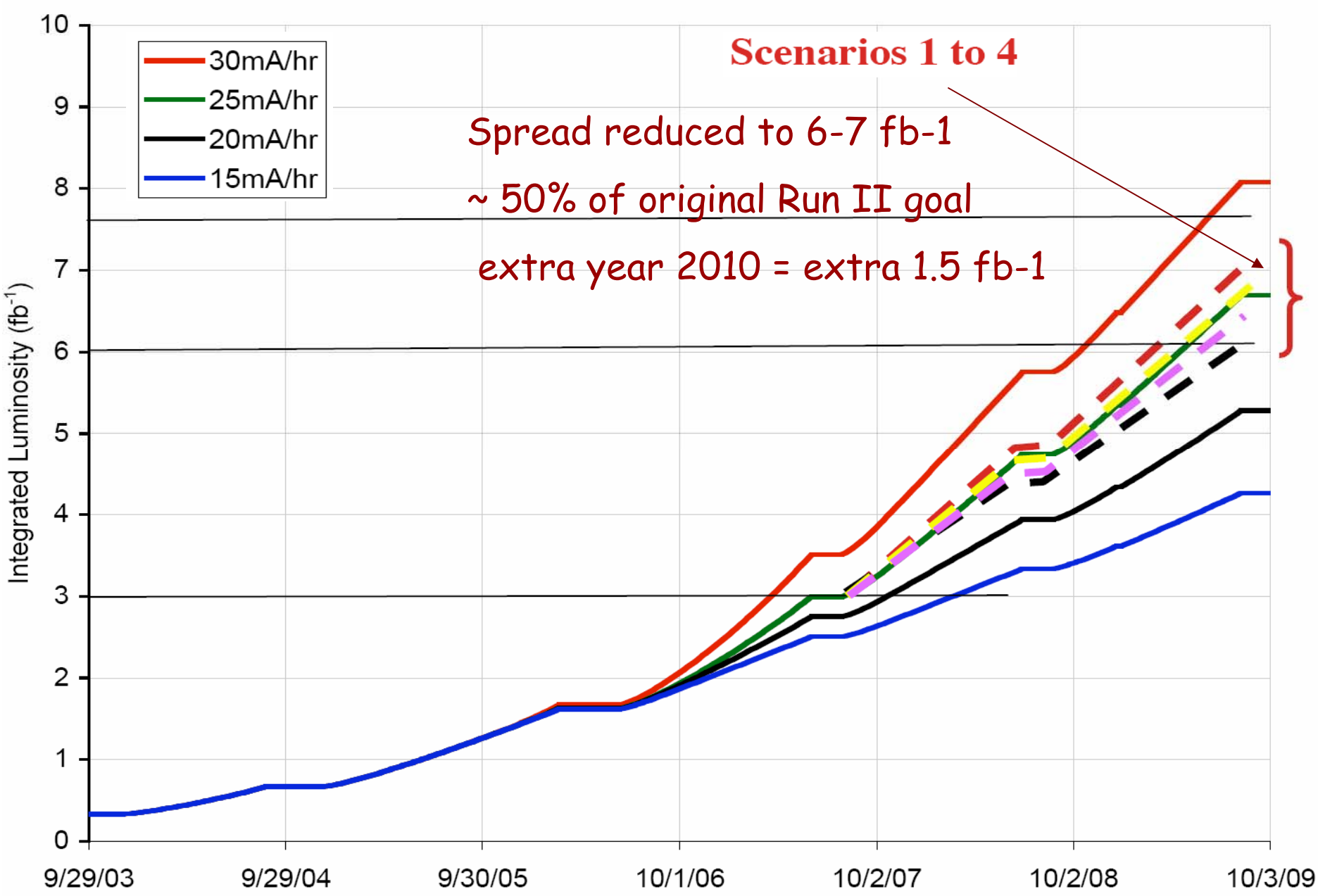
01/01/07
04/01/07
07/01/07
Peak Luminosity
Peak Lum 20x Average

Current Run II Projections



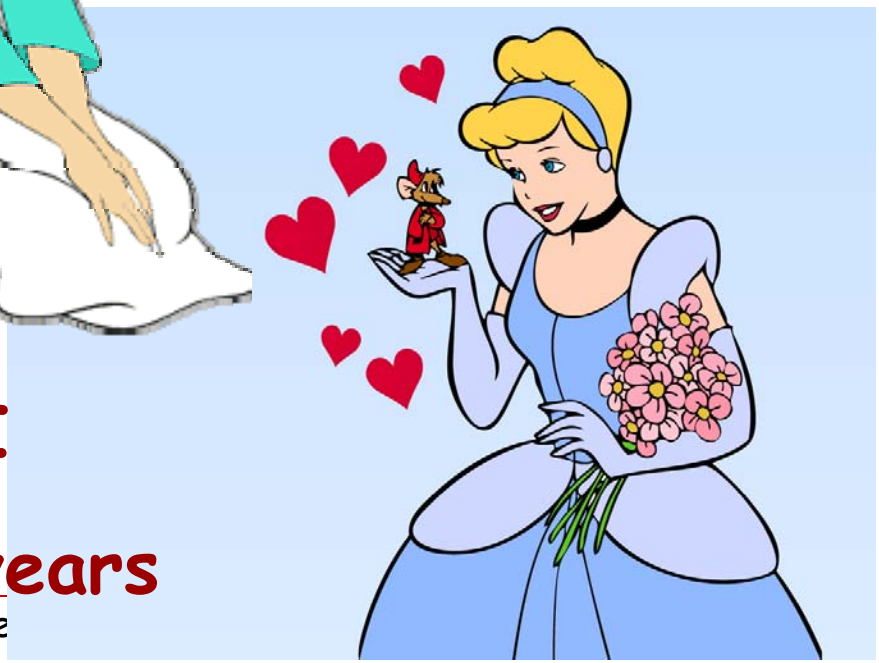
Thus, the real story of Tevatron is

Run I

Run II

troubled years

we deserve some luck ?



Thank You for Your Attention!

Lecture 2 Wed: Plumbing “show and tell”

Luminosity 2002-2004: $1.16^{16} = 10$

First 9 months	Mar-Nov'01	
Optics AA->MI lines fixed	Dec'01	~25 %
Quenches on abort fixed by TEL-1	Feb'02	uptime
Pbar loss in LB squeeze fixed	Apr'02	~40 %
"New-new" injection helix	May'02	~15 %
Shot lattice, AA cooling reduces IBS	July'02	~40 %
Tev BLT/inst.dampers help at injection	Sep'02	~10 %
Pbar coalescing improved in MI	Oct'02	~5 %
C0 Lambertsons Removed	Feb'03	~15 %
S6 cuircuit tuned/SEMs removed	June'03	~10 %
"5 star" helix on ramp	Aug'03	~2 %
Reshimming/Alignment	Nov'03	~18 %
Longer Stores/ MI dampers	Feb'04	~18 %
2.5MHz AA → MI transfer/Cool shots	April'04	~7 %
Reduction of beta^* to 35 cm	May'04	~26 %
Shots from Recycler	July'04	~18 %

What people thought in 2001

Possible Accumulation of Luminosity in the pre-LHC Era

2001	Main Injector and Recycler	0.6 fb^{-1}
2002	Initiate antiproton recycling	1.2 fb^{-1}
2003	6 month shutdown to install e-cool, 132 nsec, and other intensity improvements	0.8 fb^{-1}
2004	Achieve $2x10^{32}$ $cm^{-2}sec^{-1}$	2.0 fb^{-1}
2005	Achieve $3.5x10^{32}$ $cm^{-2}sec^{-1}$	3.5 fb^{-1}
2006	Achieve $5x10^{32}$ $cm^{-2}sec^{-1}$ 6 month shutdown to install C-0.	2.3 fb^{-1}
2007	Achieve $5x10^{32}$ $cm^{-2}sec^{-1}$ Initiate Kaon program	3.8 fb^{-1}
TOTAL		**~15 fb^{-1}**

Introduction

- Tevatron Collider Run I:
  - 1992-1995, discovery of top-quark
  - Integral 150 pb-1, peak $\mathcal{L}$=25e30 cm-1 s-1
  - 6(proton)x6(antiproton) bunches, 900 GeV/beam
- Original Run II Plan:
  - 2001-2007, Higgs and supersymmetry
  - 11-15 fb-1, peak $\mathcal{L}$~86e30… with Recycler → 300-500
- Major Changes (1996-2000):
  - High intensity 150 GeV Main Injector
  - Antiproton Source Upgrade
  - 36x36 bunches in Tevatron, 980 GeV/beam
  - Recycler Ring with e-Cooling - for Run IIb

Recycler Ring

Shares tunnel with Main Injector

C=3.32km

Permanent magnets (344, 1.45T, Sr-Fe combined function)

E_kin=8 GeV fixed

Stores and cools antiprotons (originally – from Tevatron, now-from Antiproton Accu-mulator only)