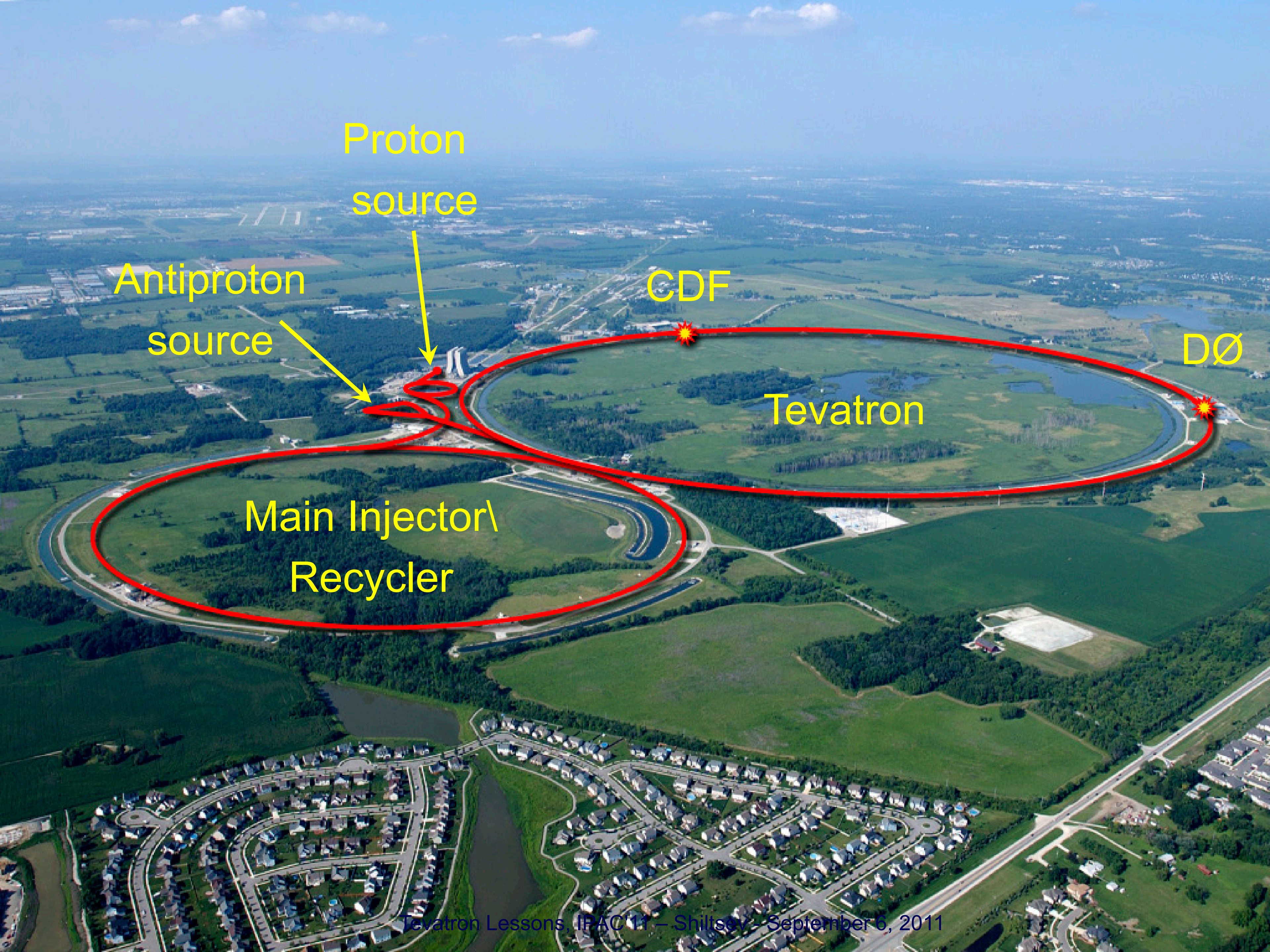


Proton
source
Antiproton
source
CDF
DØ
Tevatron
Main Injector\
Recycler

Achievements and Lessons from Tevatron

Vladimir Shiltsev
Fermilab

2nd International Particle Accelerator Conference

September 6, 2011, San-Sebastian Spain

Content

- History, Accelerator Complex and Performance
- Tevatron Accelerator Technologies
- Advances on Beam Physics
- Summary and Lessons

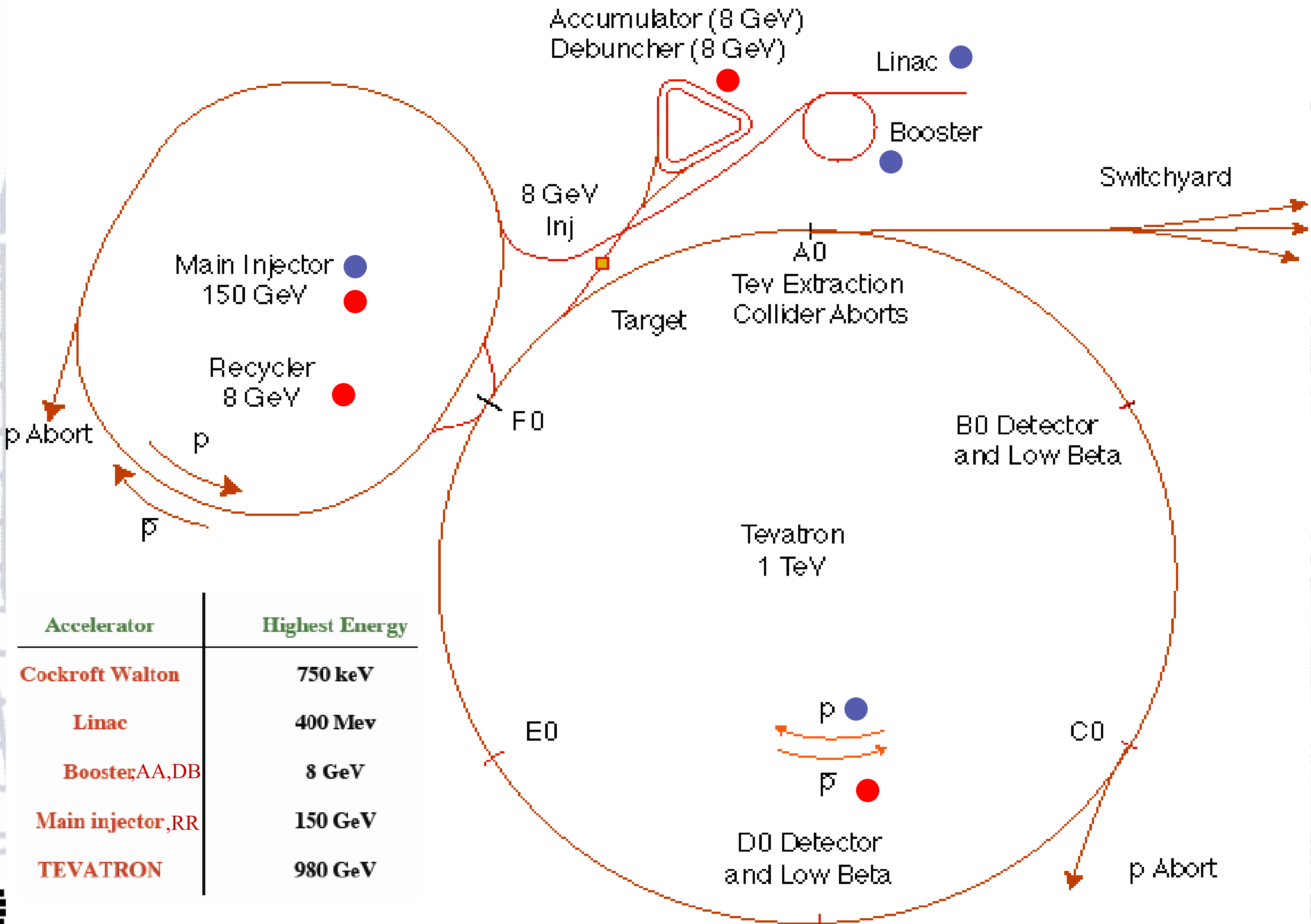
… once in 25 years…

Tevatron 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

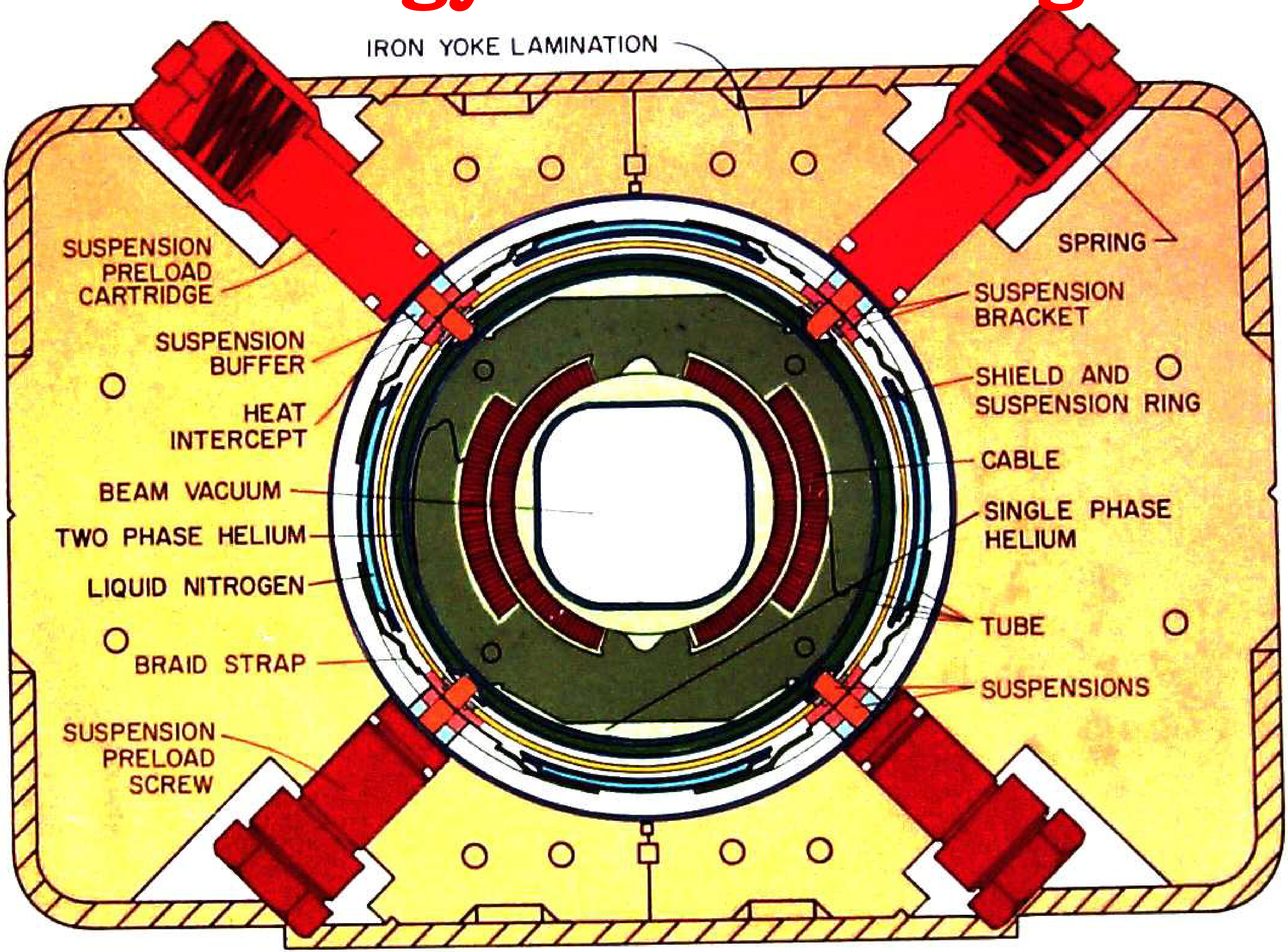
Mar 1 2001- Sep 30 2011 Collider Run II, 1.96 TeV c.o.m.

FermilabTevatron Accelerator With Main Injector

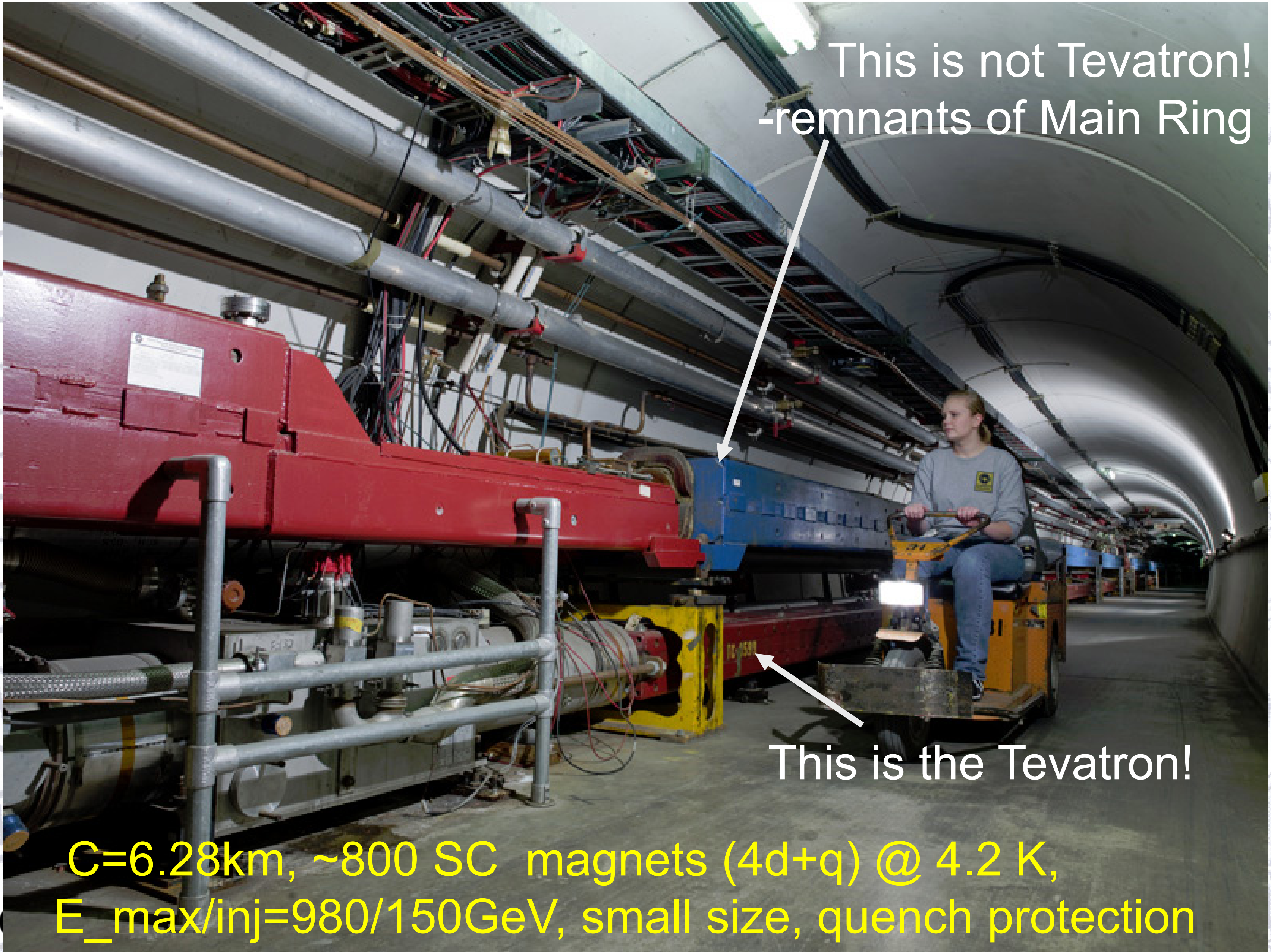


Accelerator	Highest Energy
Cockroft Walton	750 keV
Linac	400 Mev
Booster,AA,DB	8 GeV
Main injector,RR	150 GeV
TEVATRON	980 GeV

Technology: 4.5T SC Magnets



Tevatron Magnets

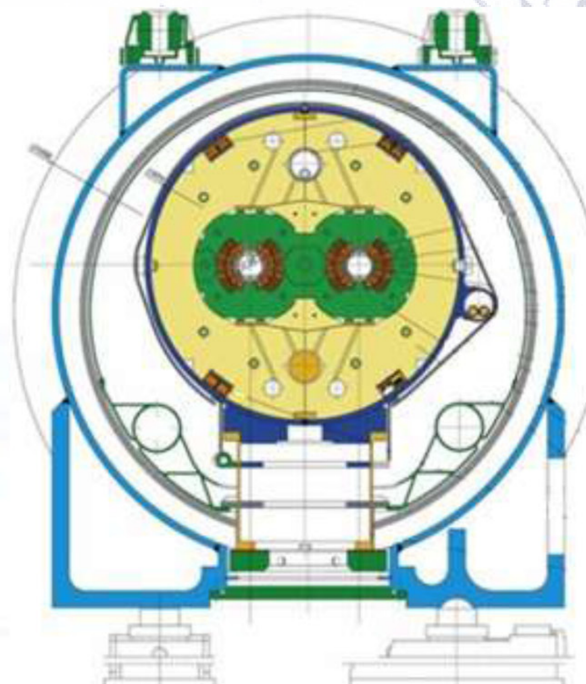


Accelerator SC Magnets

Tevatron paved the way for HERA, RHIC and LHC **8.3T**

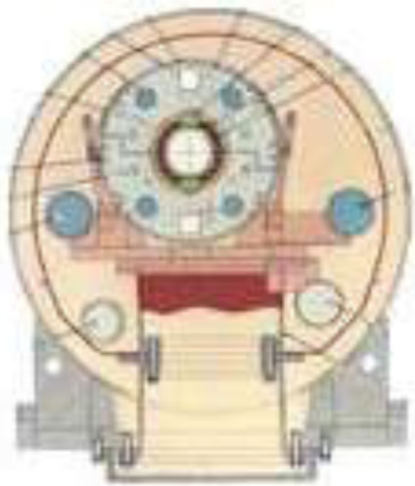
4.5T **5.3T** **3.5T**

LHC,
15 m, 56 mm
1276 dipoles



HERA,
9 m, 75 mm
416 dipoles

RHIC,
9 m, 80 mm
264 dipoles



Tevatron,
6 m, 76 mm
774 dipoles

warm iron
small He-plant

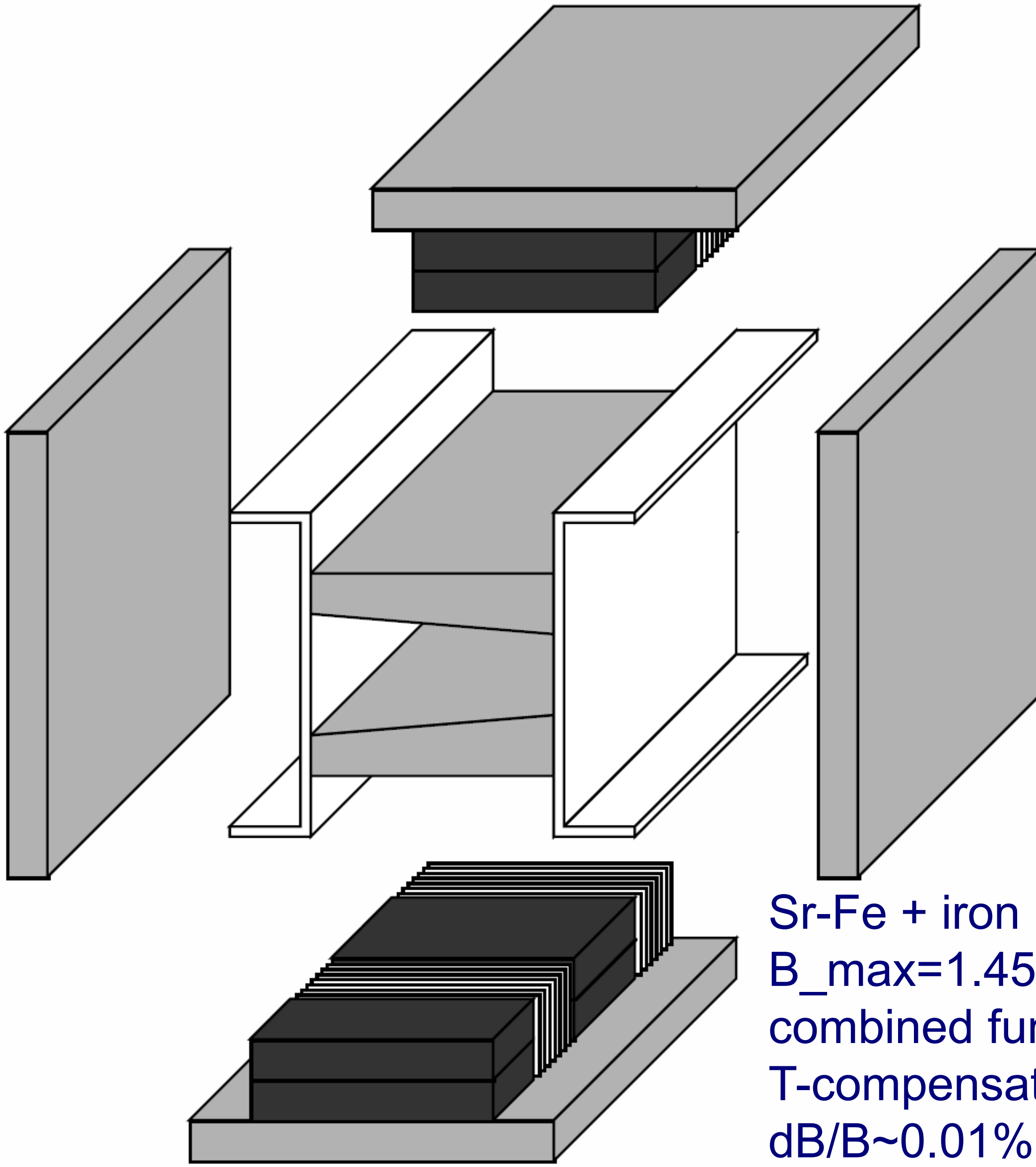
cold iron
Al collar

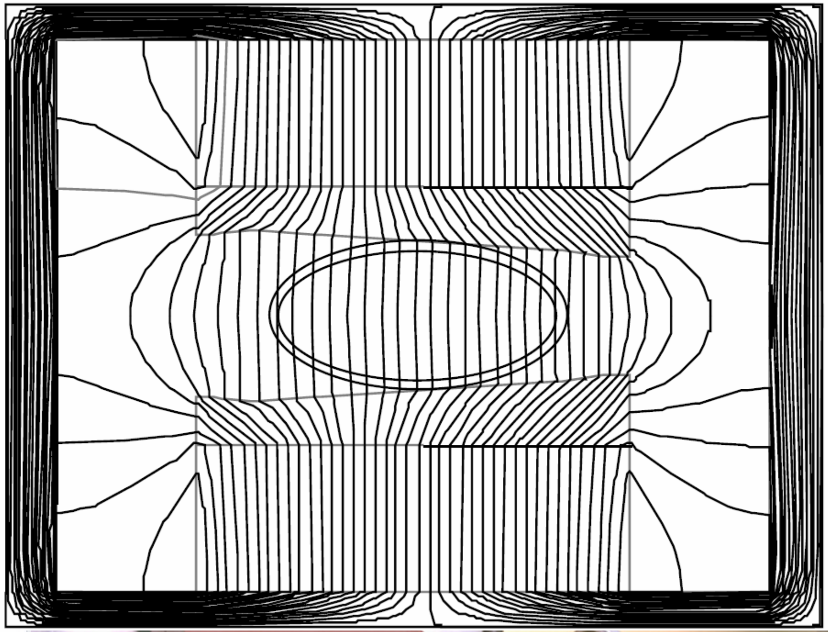
simple &
cheap

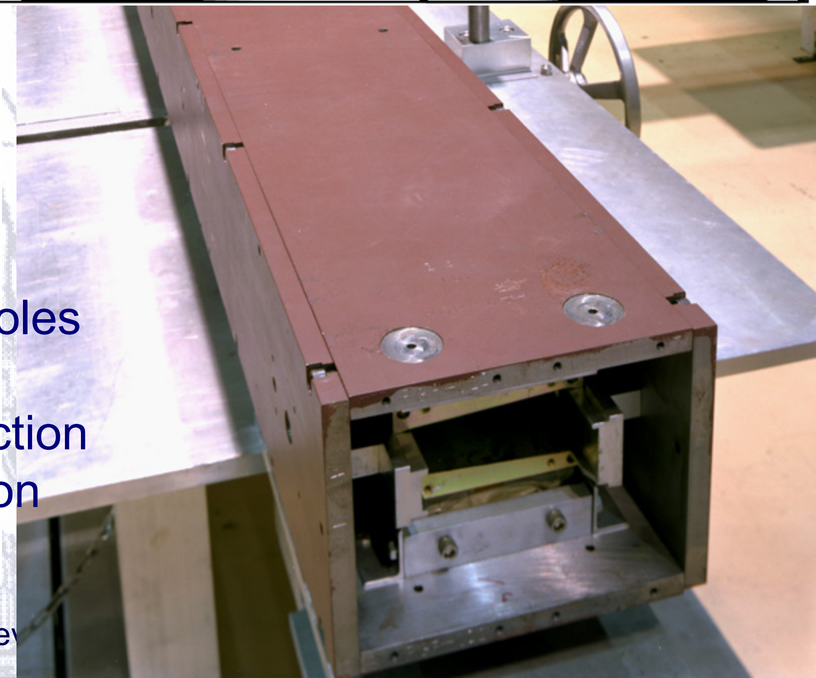
2K He
two bores

Technology: Cryoplant

Technology: Permanent Magnets





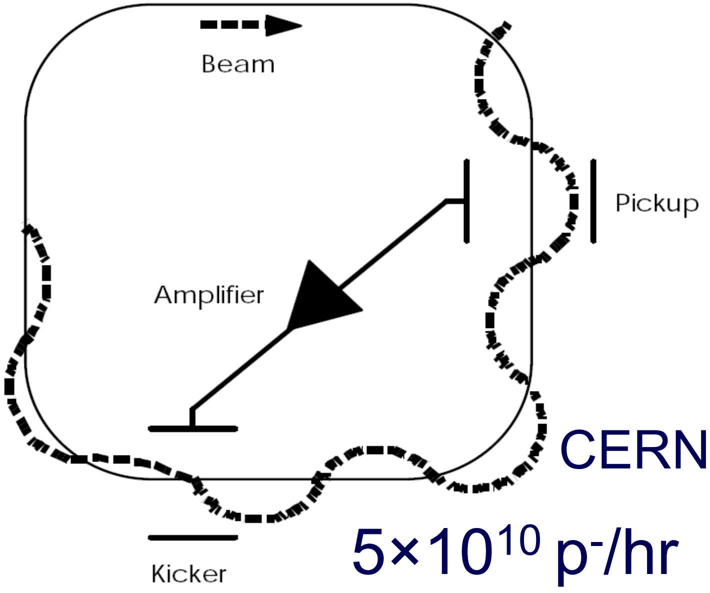


Sr-Fe + iron poles
B_max=1.45T
combined function
T-compensation
dB/B~0.01%

Recycler Ring

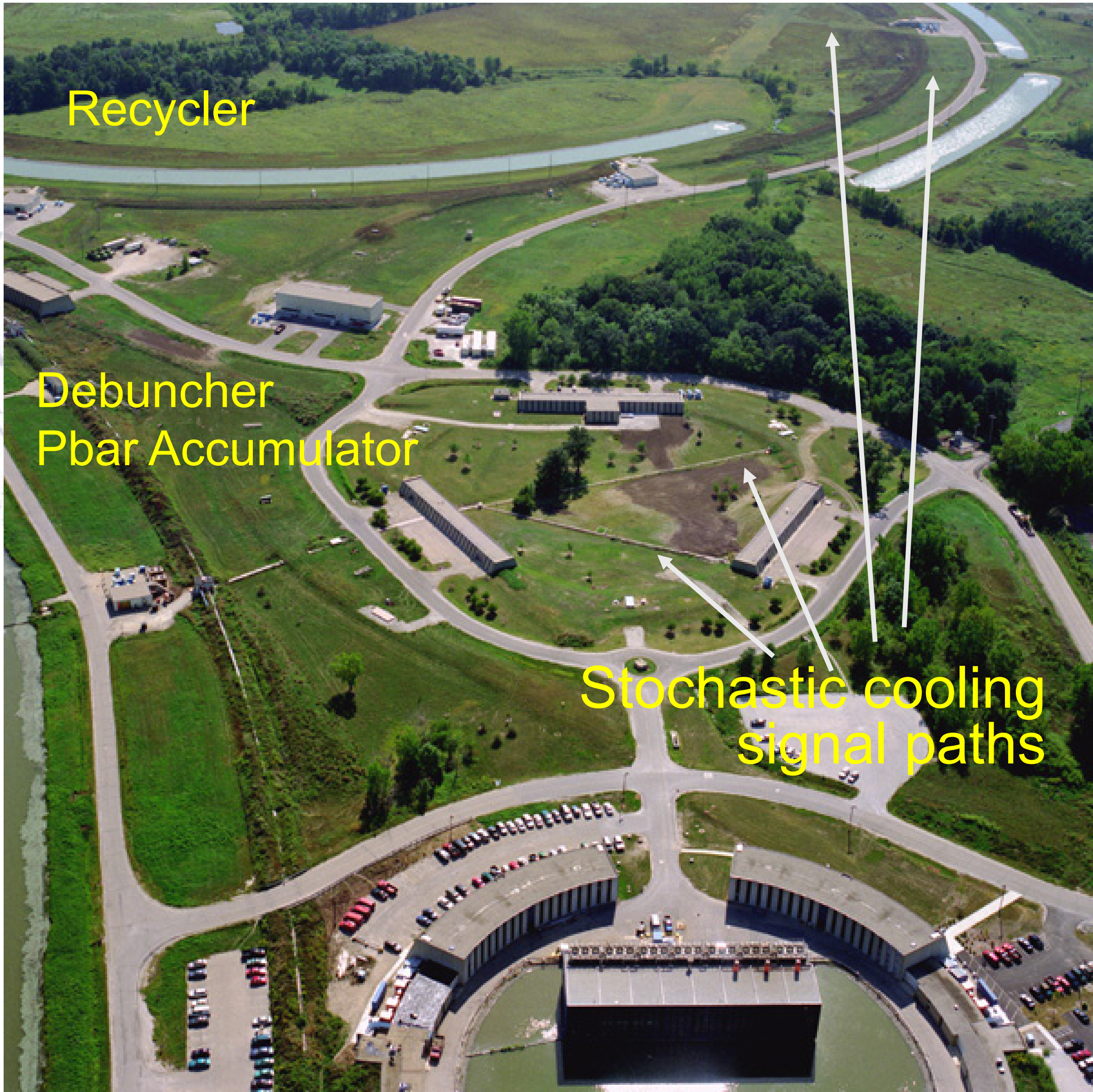
- E_kin=8 GeV fixed
- Shares tunnel with 150 GeV fast cycling Main Injector
- C=3.32km
- 344 Permanent magnets (344, 1.45T, Sr-Fe combined function)
- Stores and cools antiprotons
- **Build by the US Congressman**

Beam Physics: Stochastic Cooling



CERN

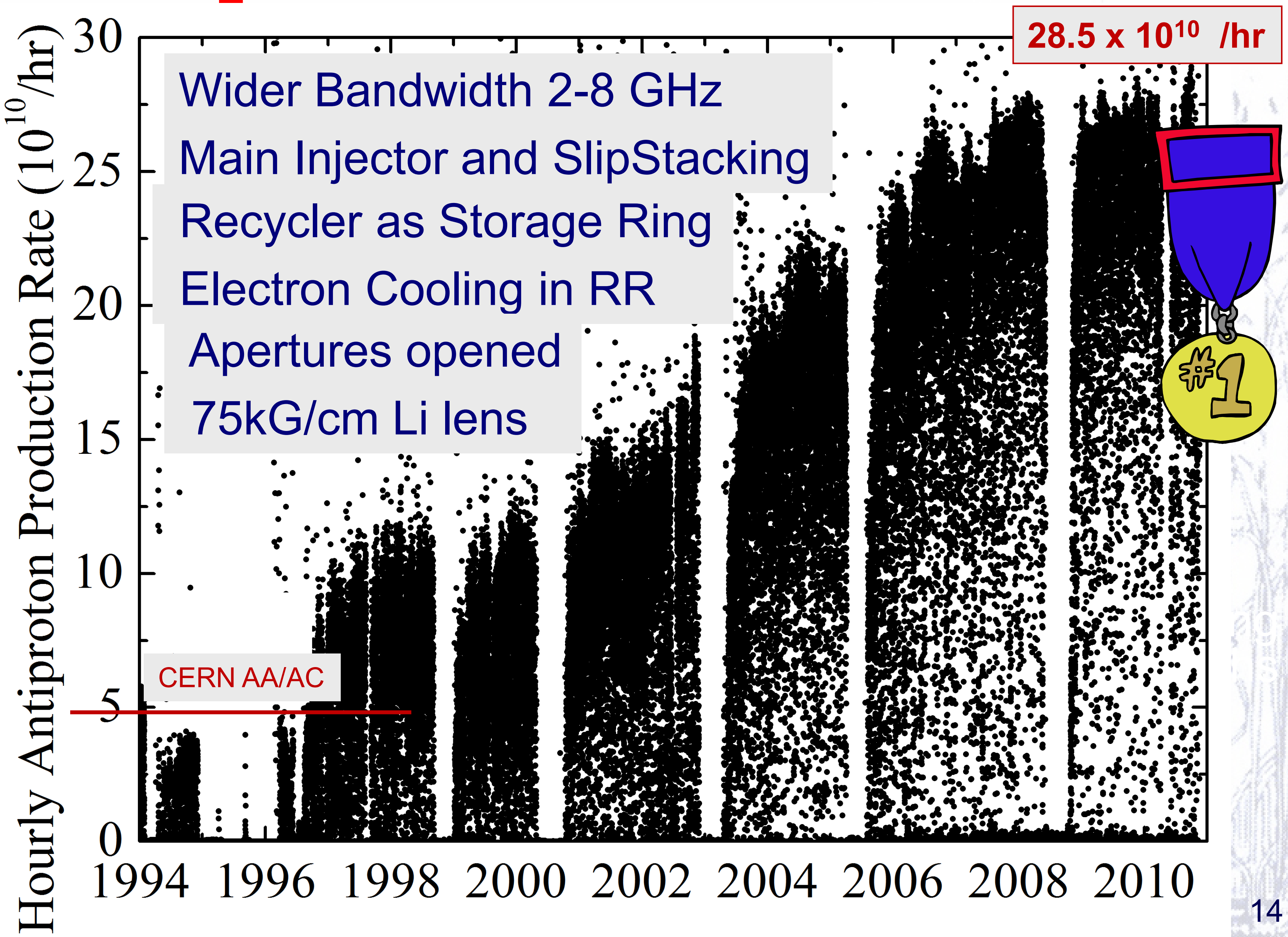
5×10^{10} p^-/hr



Stochastic Cooling Technology

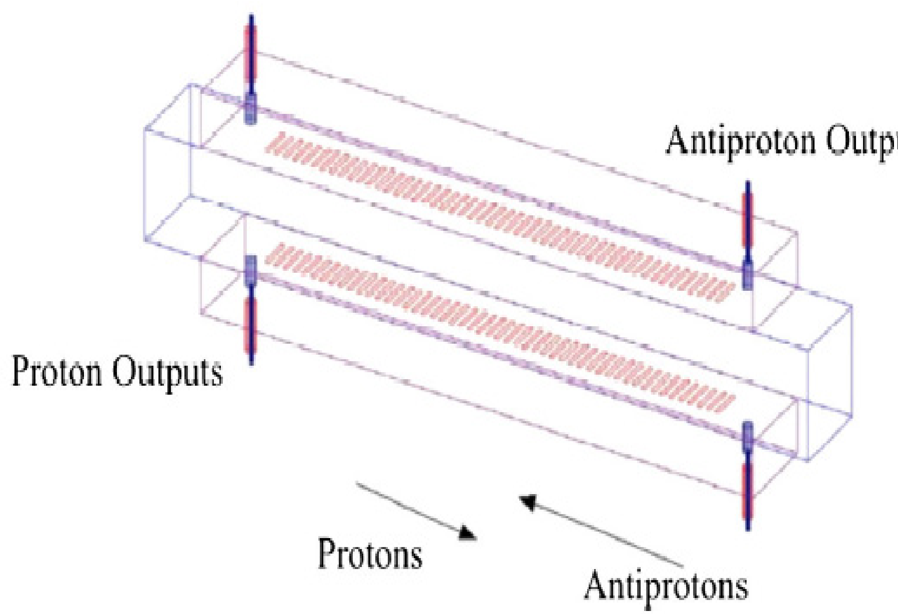
- Learned from **CERN**, greatly improved by:
  - Upto 8 GHz bandwidth, He-cooled pickup and kickers, preamps, power amps, recursive notch filters, signal transmission and equalizers
- A total of 25 independent cooling systems *V,H,L* are utilized in three 8 GeV Fermilab antiproton rings: Accumulator, Debuncher, and Recycler.
- Contributed to world-record high stacking rates of antiprotons in excess of 28×10^{10} per hour
- Tevatron bunched beam stochastic cooling system sent to Brookhaven, modified and expanded and is now successfully implemented at **RHIC** for cooling heavy ions

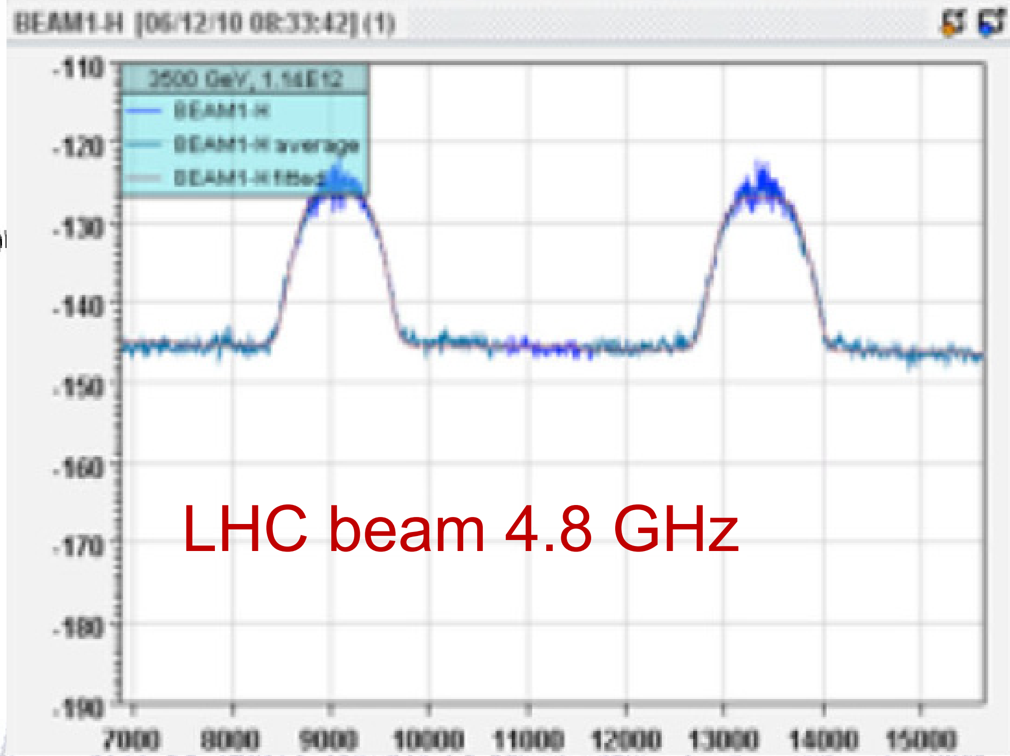
Antiproton Production Rate



Byproduct: multi-GHz Schottky

Tevatron array 1.7 GHz



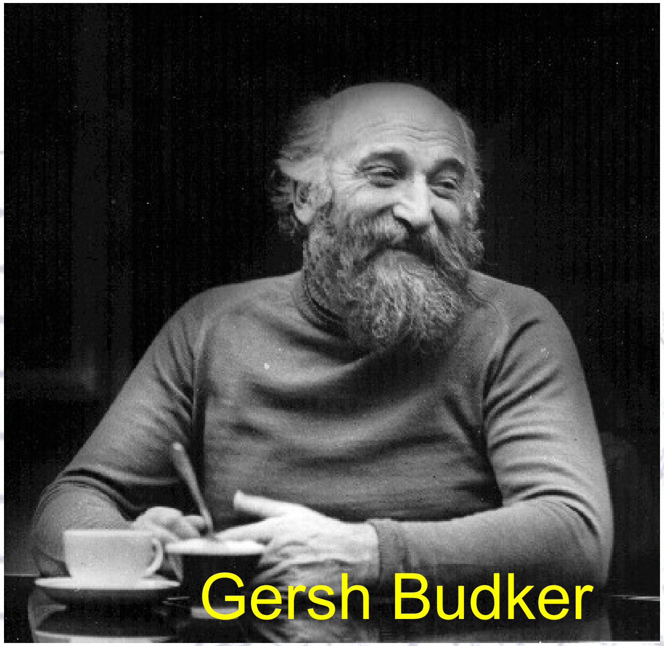


LHC beam 4.8 GHz

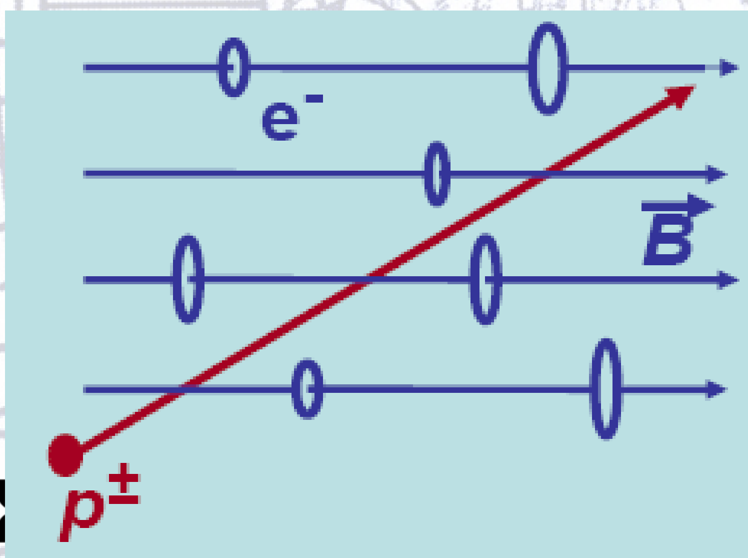
- multi-GHz Schottky monitors successfully employed for multi-bunch non-invasive diagnostics of beam parameters Tevatron, Recycler and **LHC**:
  - Q, Q', Emmittances, dP/P

R.Pasquinelli, et al, PRSTAB 2011

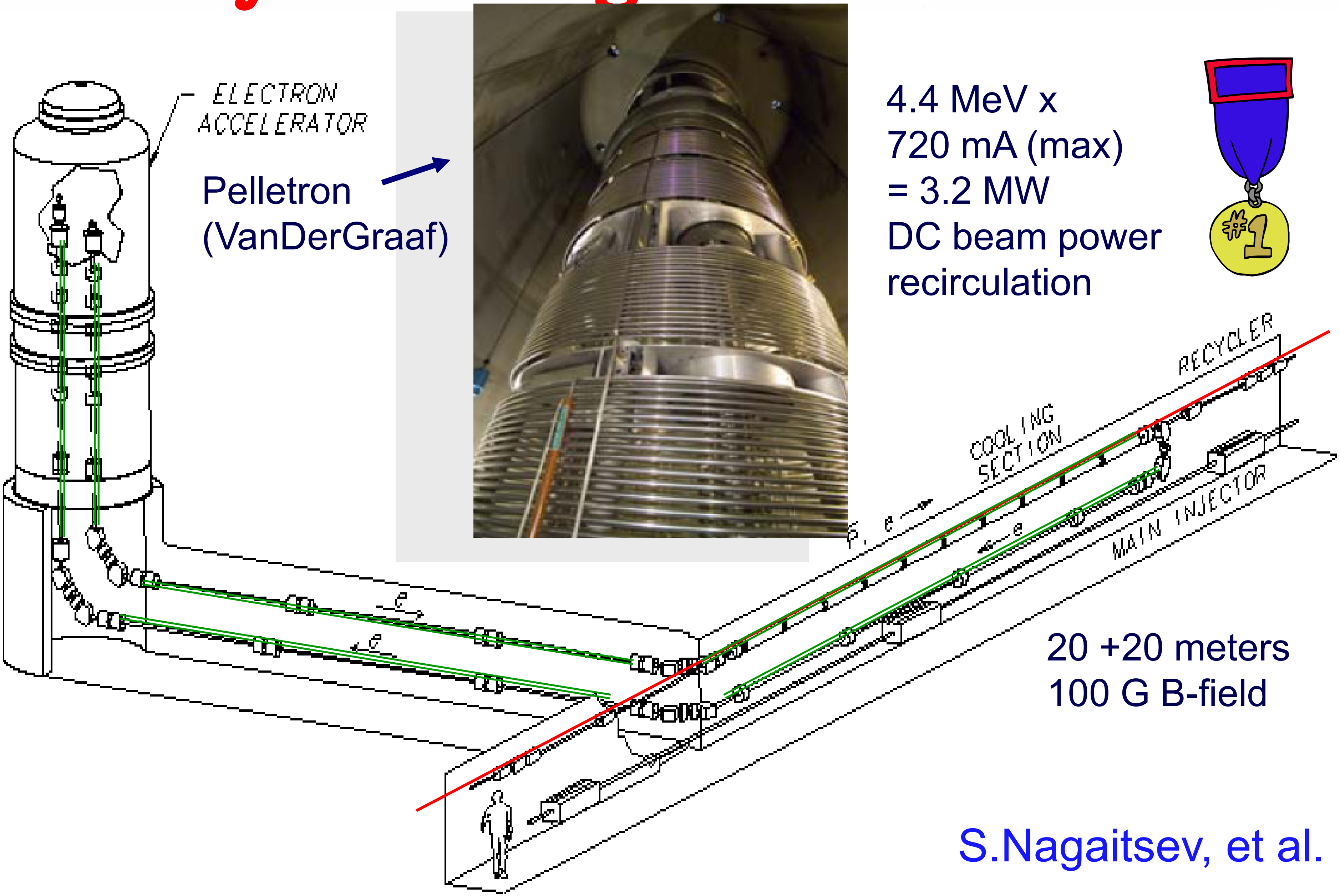
Physics: Electron Cooling



Ions in a bath of cold electrons



Recycler Ring Electron Cooler



Pelletron
(VanDerGraaf)

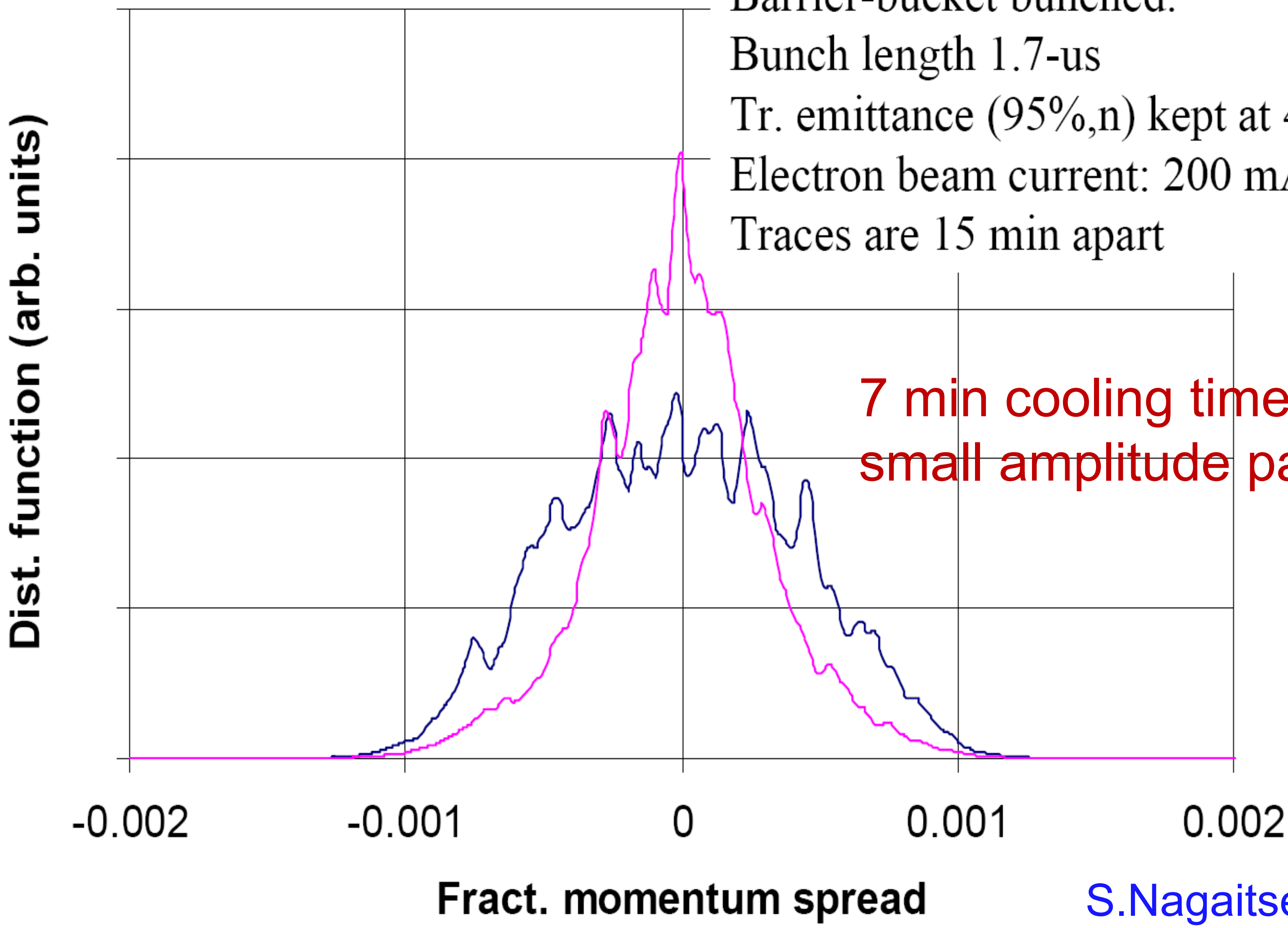
4.4 MeV x
720 mA (max)
= 3.2 MW
DC beam power
recirculation

20 +20 meters
100 G B-field

S.Nagaitsev, et al.

Electron Cooling of Antiprotons

Barrier-bucket bunched.
Bunch length 1.7-us
Tr. emittance (95%,n) kept at 4-pi mm-mra
Electron beam current: 200 mA
Traces are 15 min apart



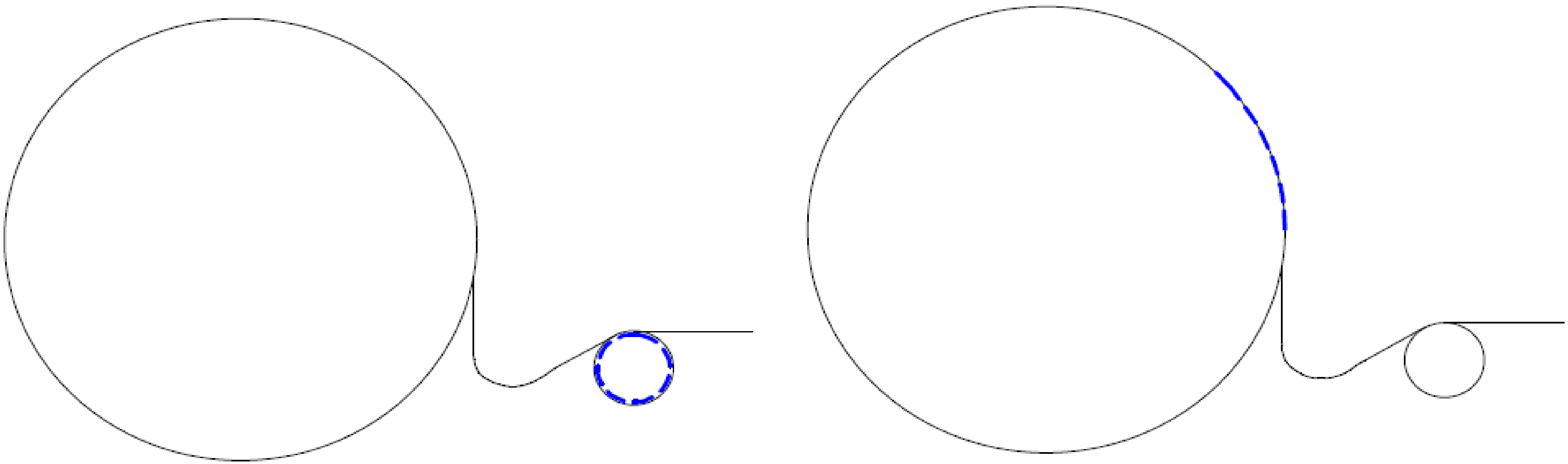
7 min cooling time for small amplitude particles

S.Nagaitsev, et al. PRL 2005

Physics: “Slip-Stacking”

The technique to double single bunch intensity

for antiproton production

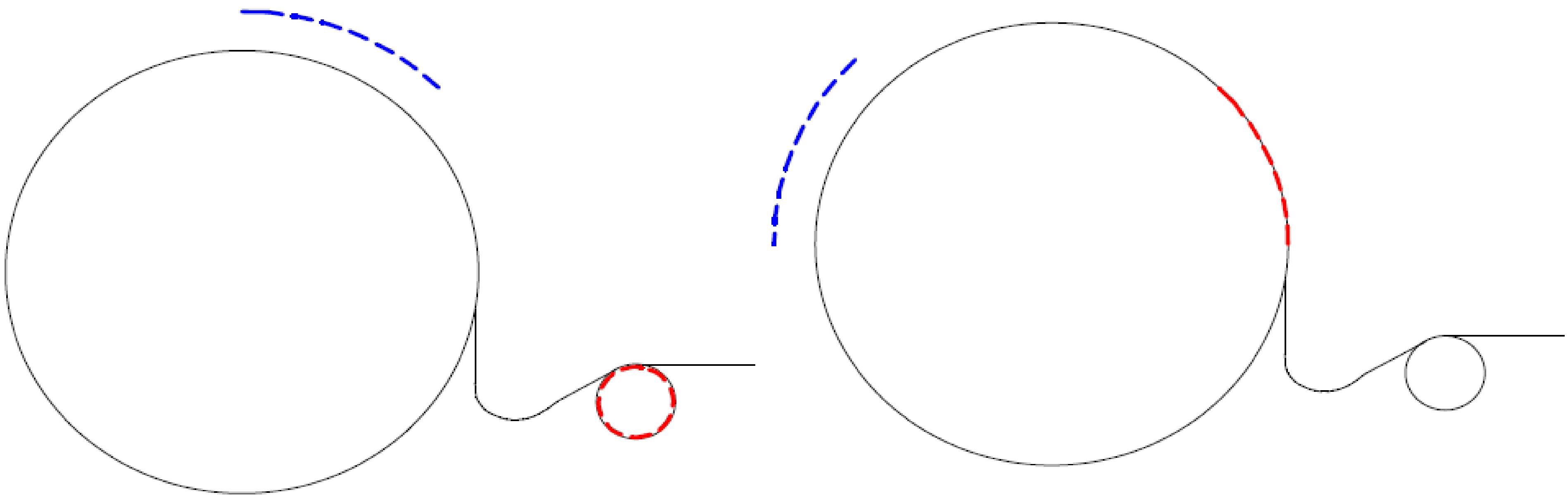


- First Booster Batch accelerated in Booster
- First Booster Batch injected onto MI central orbit with RF system A

Physics: “Slip-Stacking”

The technique to double single bunch intensity

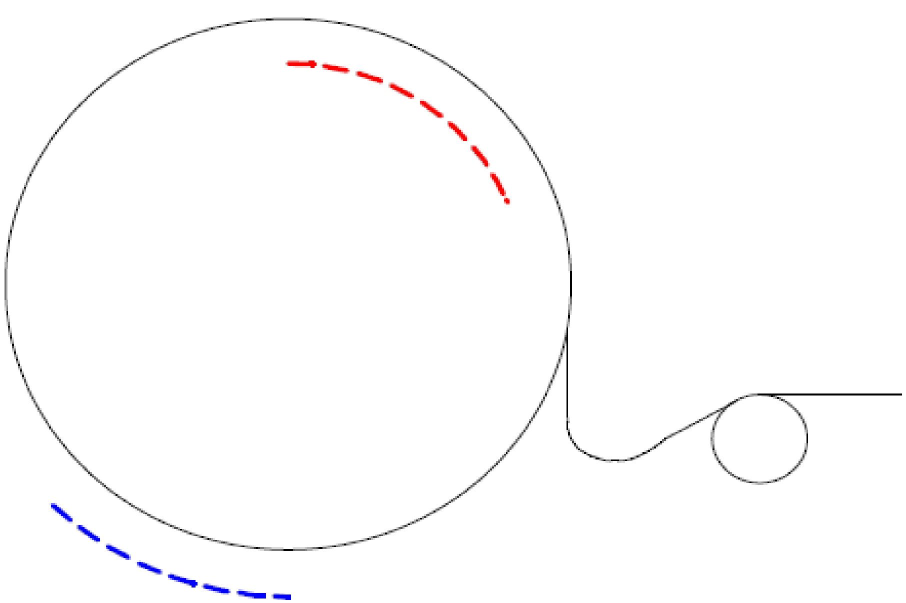
for antiproton production



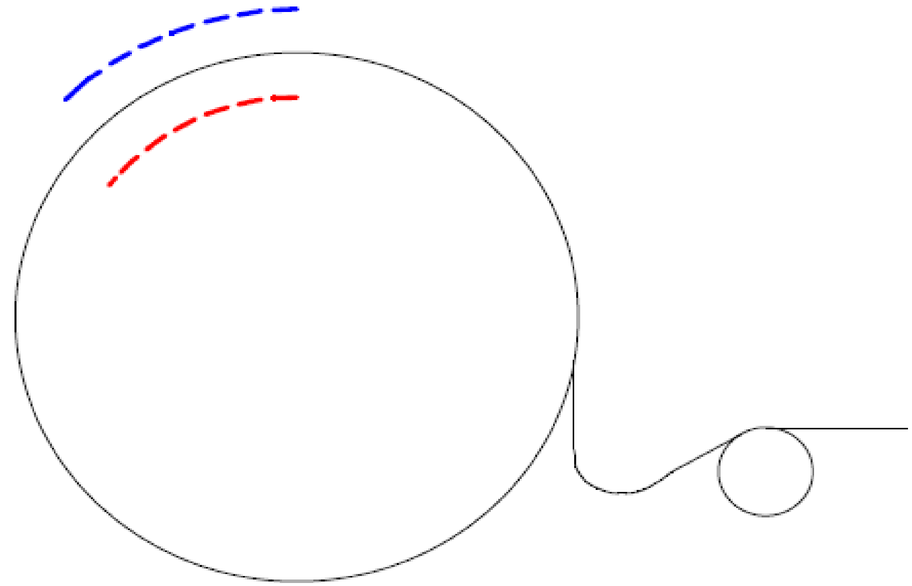
- First Booster Batch slightly accelerated in MI with RF System A
- Second Booster Batch accelerated in Booster
- Second Booster Batch injected onto MI central orbit with RF system B

Physics: “Slip-Stacking”

The technique to double single bunch intensity for antiproton production



- Second Booster Batch slightly decelerated in MI with RF System B

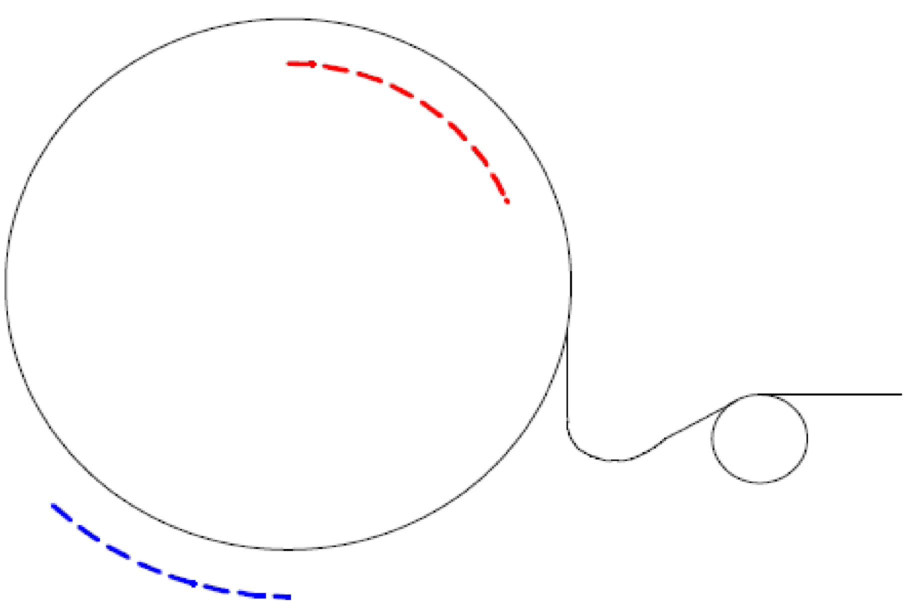


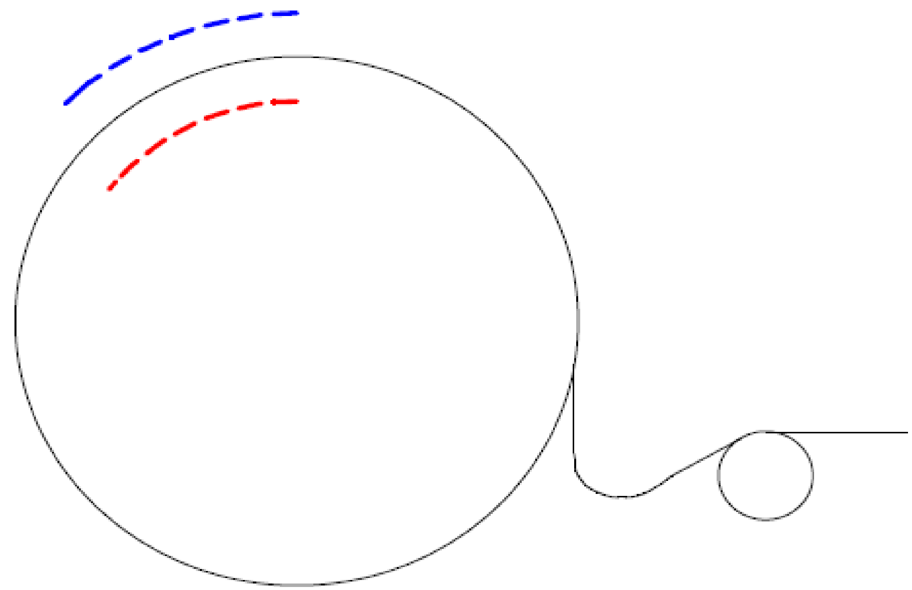
- Wait till batches line up and snap on RF system C while turning of RF systems A & B

accelerated in Booster

Physics: “Slip-Stacking”

The technique to double single bunch intensity for antiproton production

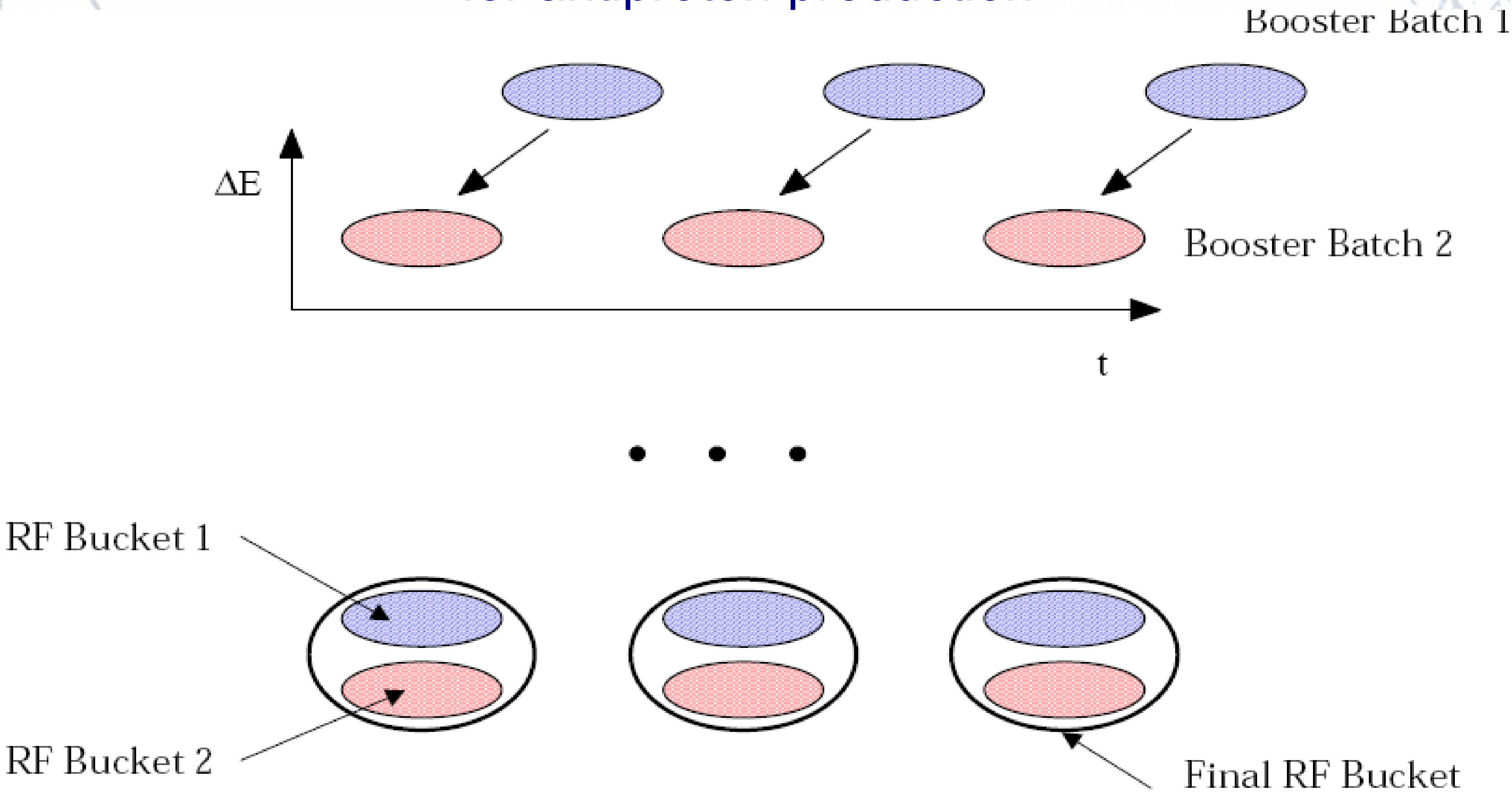




- Second Booster Batch slightly decelerated in MI with RF System B
- Wait till batches line up and snap on RF system C while turning of RF systems A & B

Physics: "Slip-Stacking"

The technique to double single bunch intensity for antiproton production



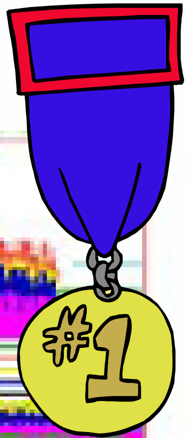
F.Mills (BNL, 1971)

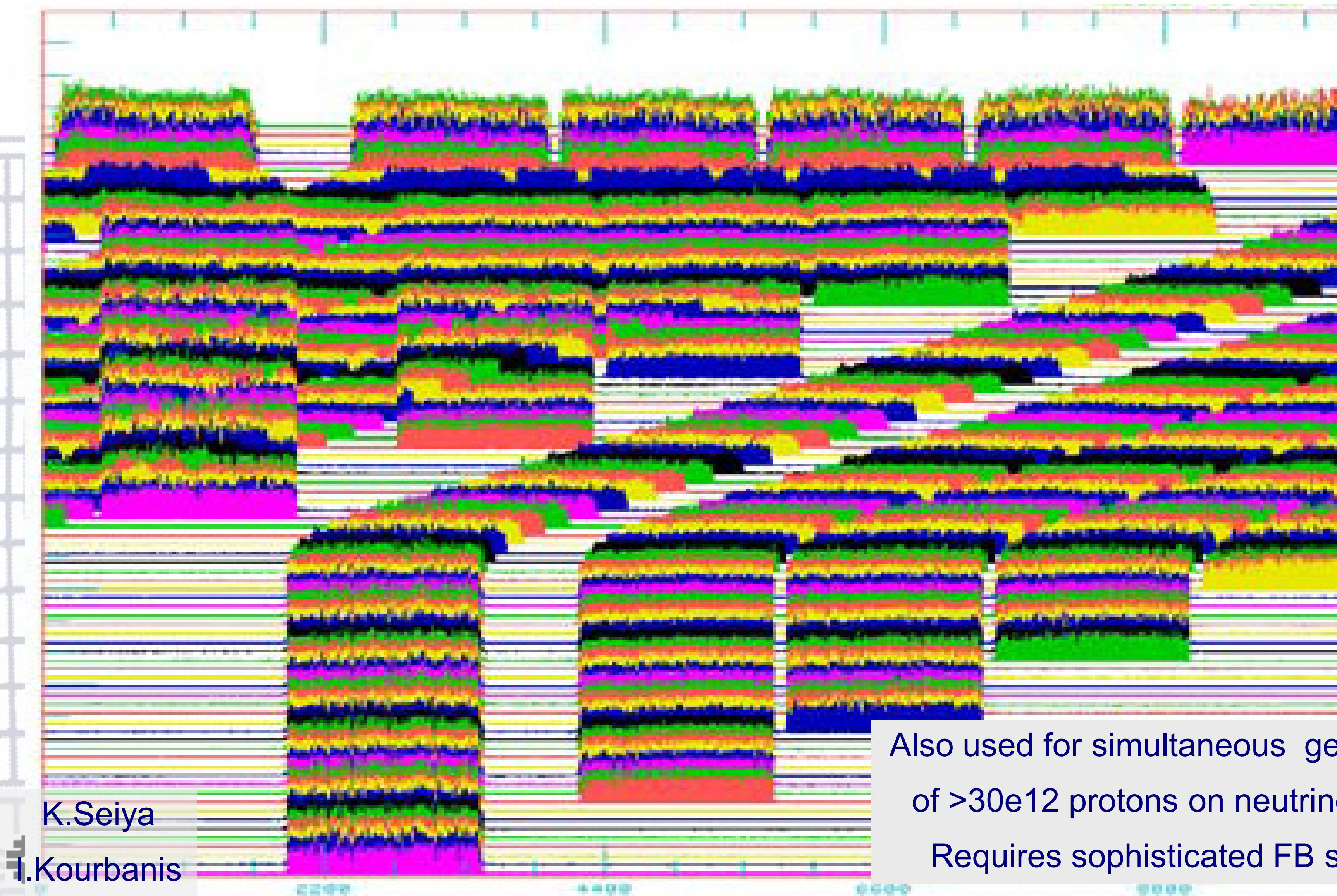
RF Phase Space Cartoon

I.Kourbanis, K.Seiya

Slip-Stacking in Main Injector

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





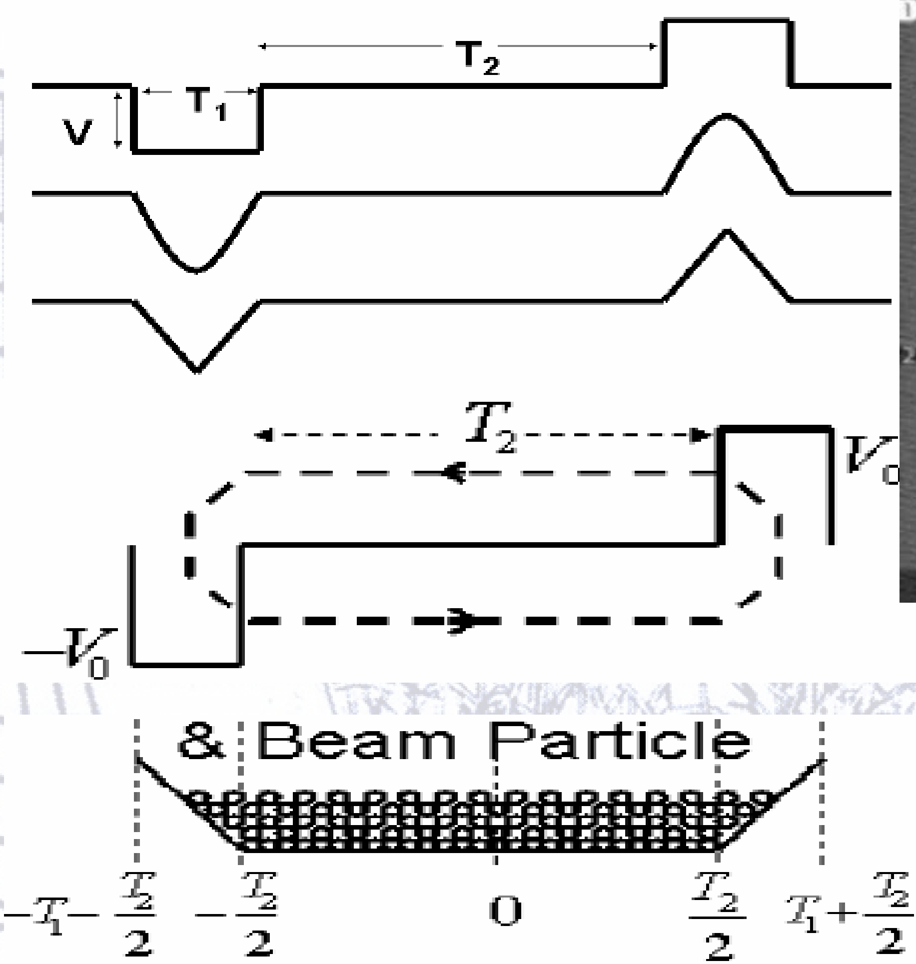
K.Seiya
I.Kourbanis

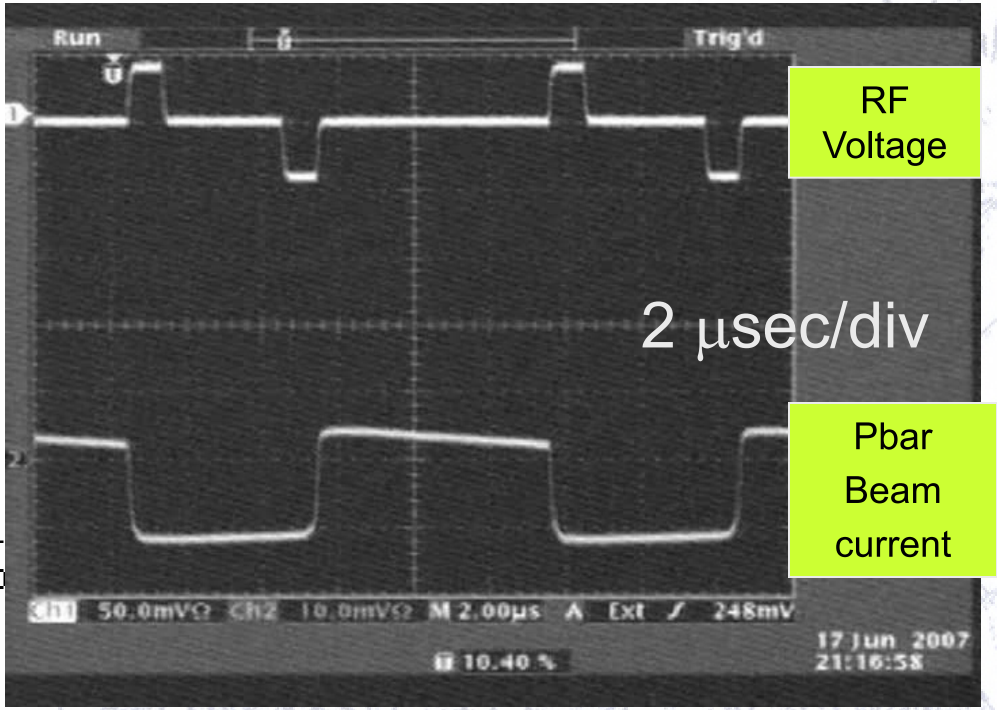
Also used for simultaneous generation of >30e12 protons on neutrino target
Requires sophisticated FB system

Physics: "RF Barrier Bucket"

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

Broad band ~1kV RF, ferrite loaded
J.Griffin, FNAL 1983



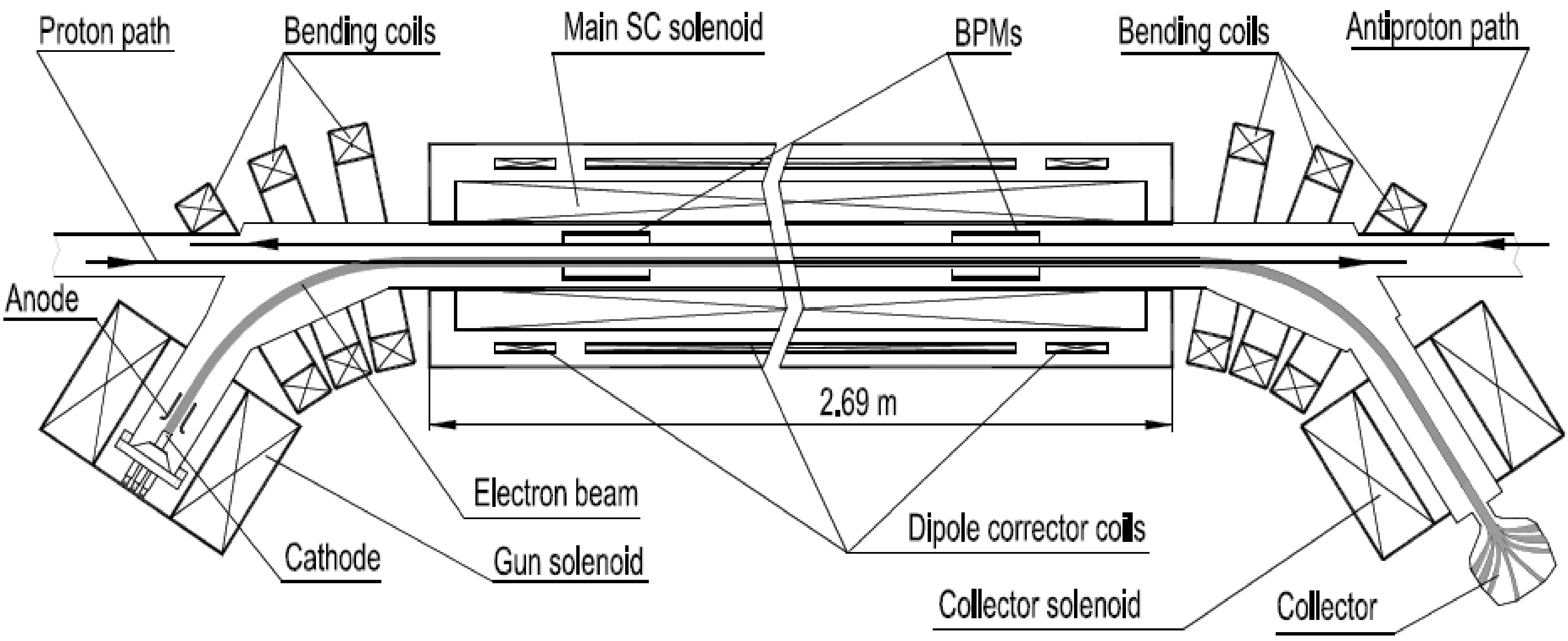


Longitudinal momentum mining in the Recycler to generate constant emittance, constant intensity pbar bunches for the Tevatron shots (since 2004)

C.Bhat, Phys Lett A (2004)

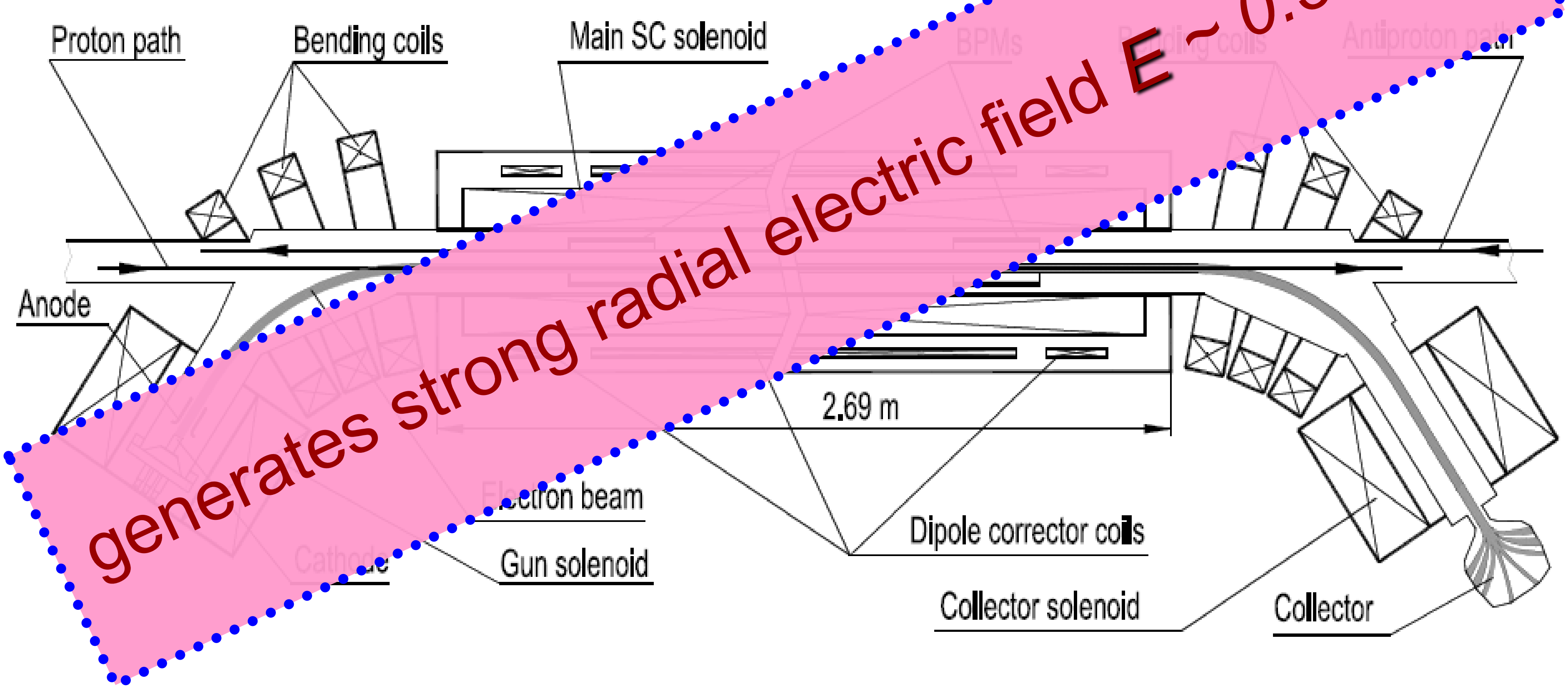
Physics: Electron Lenses

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



Physics: Electron Lenses

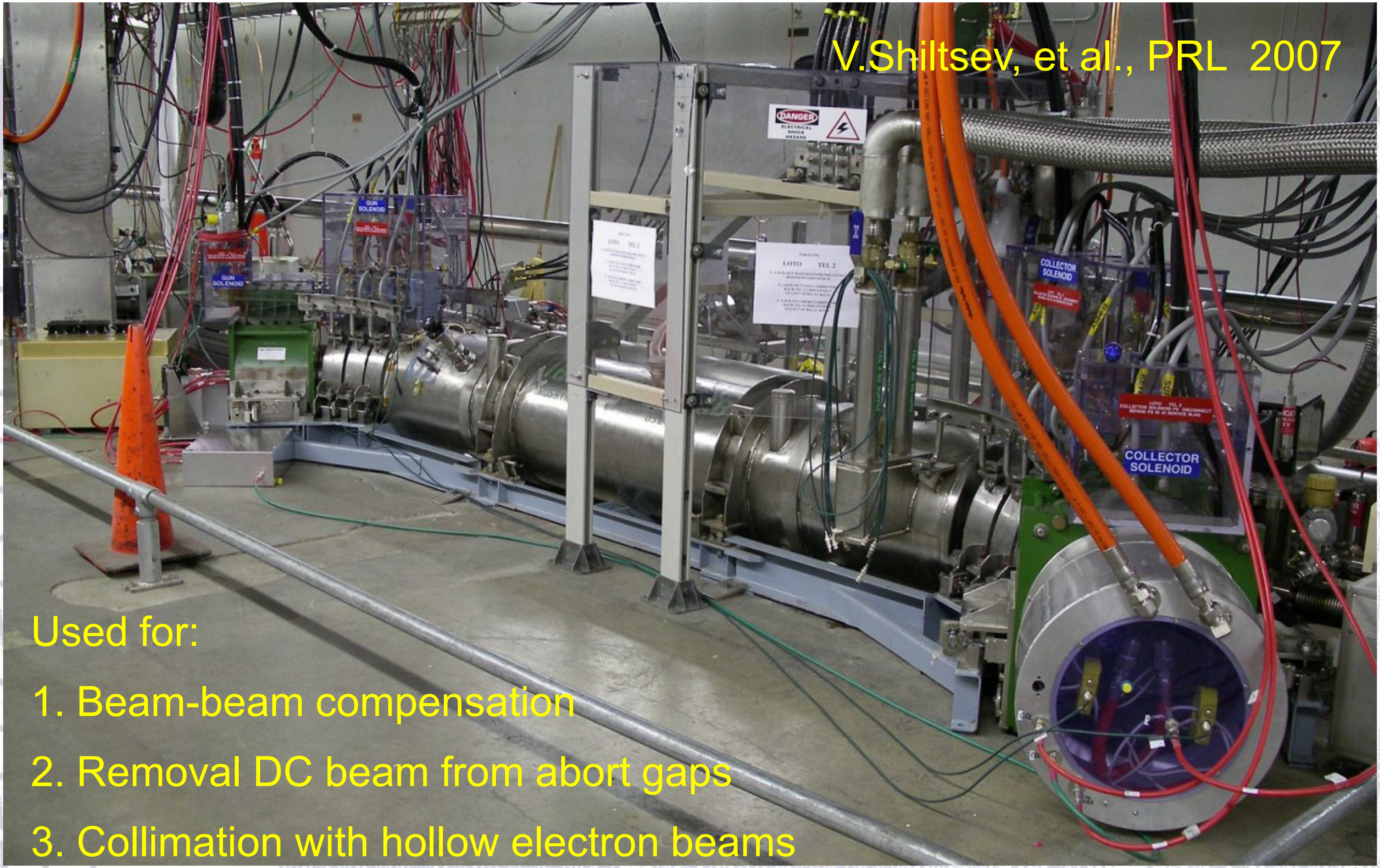
~4 mm dia 2 m long in 3T solenoid beam of ~10 kV
~1A electrons (~10^{12}) can turn on/off in 0.5 usec



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

Tevatron Electron Lens

Two TELs installed in the Tevatron



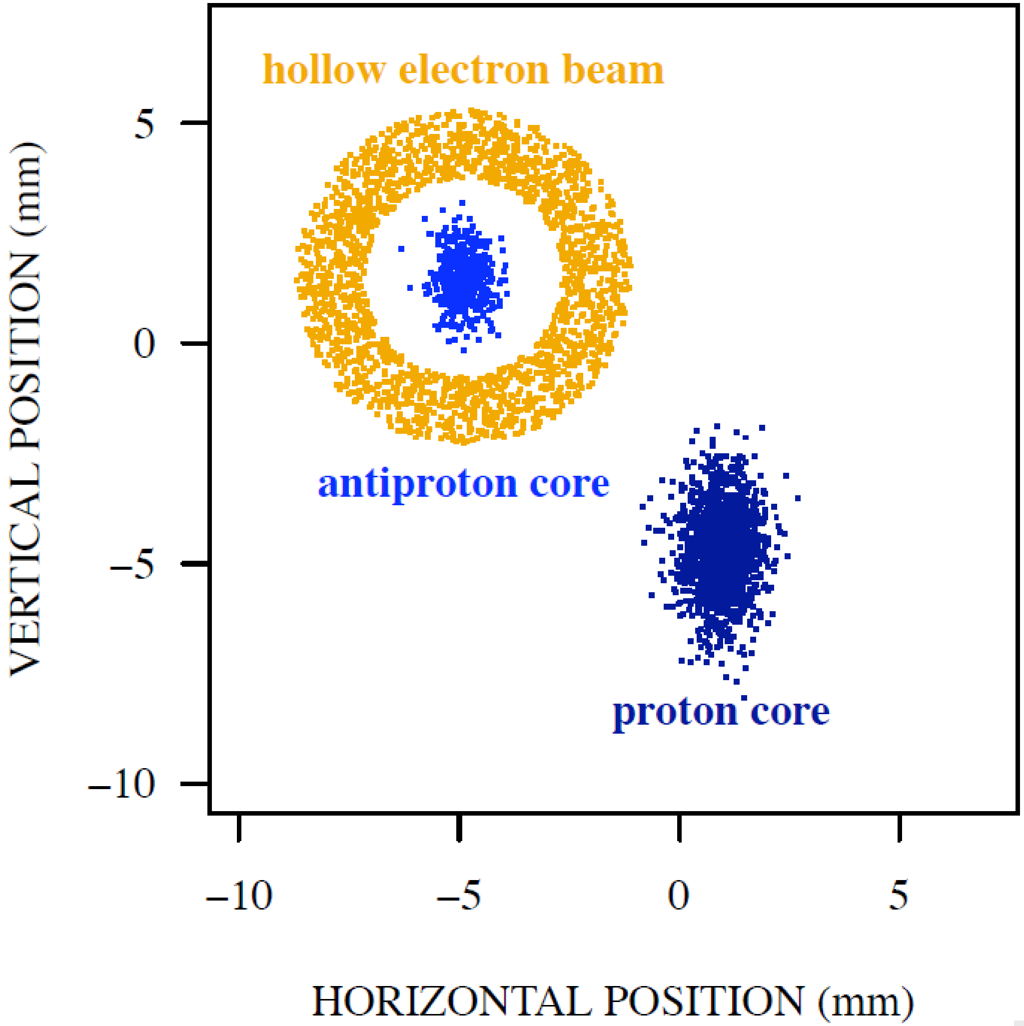
V.Shiltsev, et al., PRL 2007

Used for:

1. Beam-beam compensation
2. Removal DC beam from abort gaps
3. Collimation with hollow electron beams

Physics: Hollow Electron Beam

V.Shiltsev, 2006

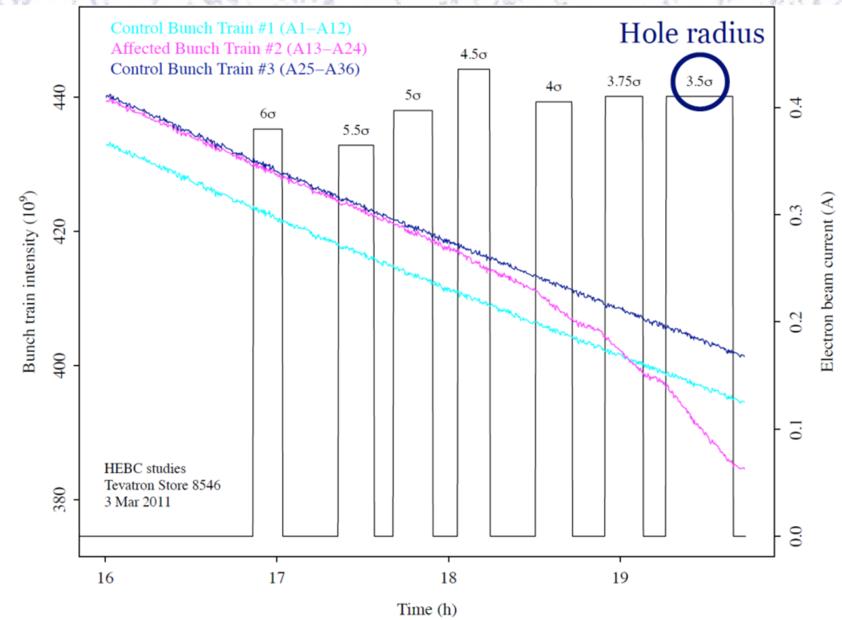


No EM field inside

Strong field outside

Halo dies while

Core stays intact!



G.Stancari, et al., PRL 2011

G.Stancari's talk Thur. PM

Tevatron Accelerator Physics: Special Issue of *JINST*

Journal of Instrumentation
an IOP and SISSA journal

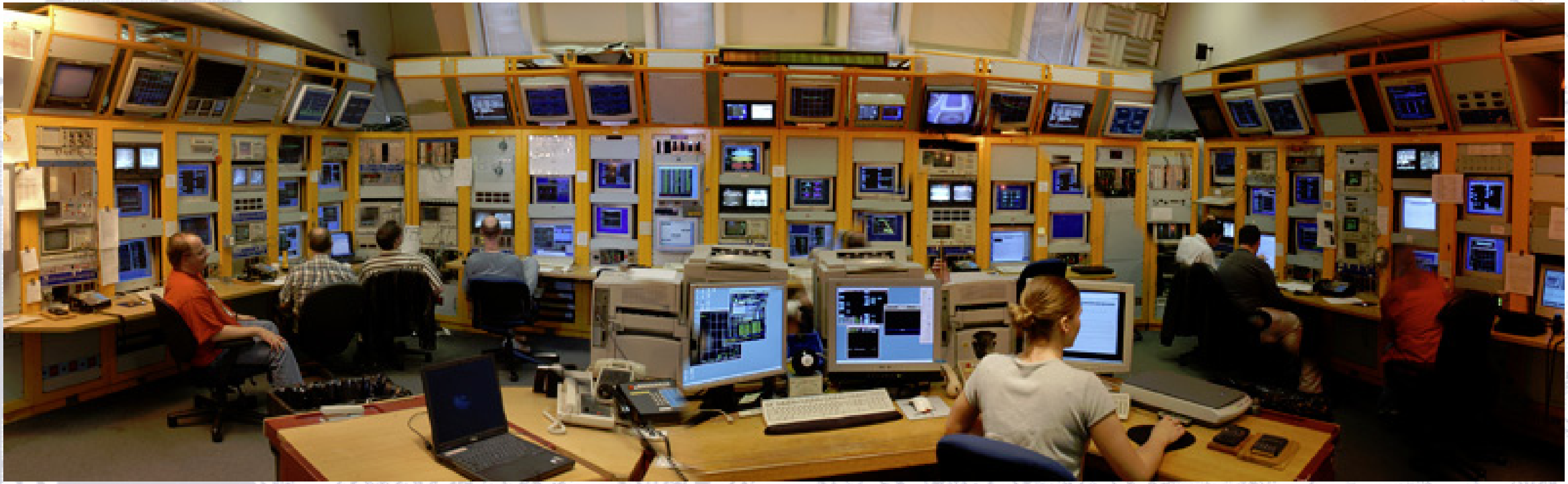
Accelerator Physics and Technology at the Tevatron Collider Run II - Tevatron Accelerators

For almost 25 years, the Tevatron proton-antiproton collider was the world's highest energy collider - since it began operation in December 1985 until it has been overtaken by the LHC in 2009. The aim aim of this unique scientific instrument was to explore the elementary particle physics phenomena with center of mass collision energies of up to 1.96 TeV. The initial design luminosity of the Tevatron was 1e30 cm−2 s−1, however due to many upgrades, the accelerator has been able to deliver luminosities up to L = 4e32 cm−2 s−1 to each of two high luminosity experiments, CDF and D0. It is scheduled to be shut off at the end of September 2011. The collider is one of the most complex accelerator ever to reach the operation stage and recognized by its achievements at the frontier of several technologies. In this special issue of JINST, we present technical papers that reflect the work carried out by the Tevatron Accelerator Team over the past decades in the field of beam physics and technology.

JINST is pleased to announce the 2010 Impact Factor: 3.148

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

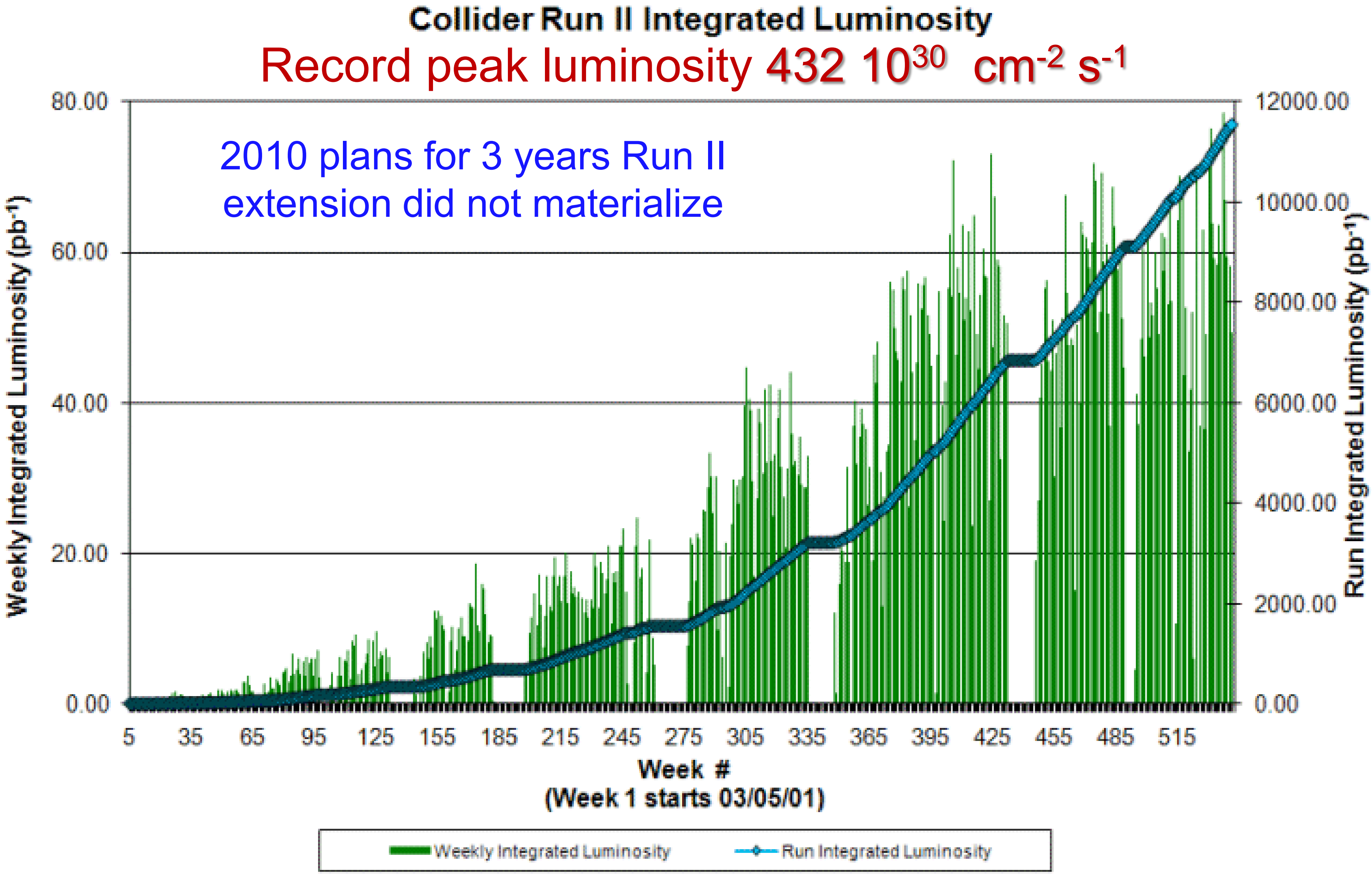
33 of them moved to Machine Departments (charged with maintenance, operation & upgrades of 9 accelerators, beamlines)

Many of them got advanced degrees (MSc, PhD)

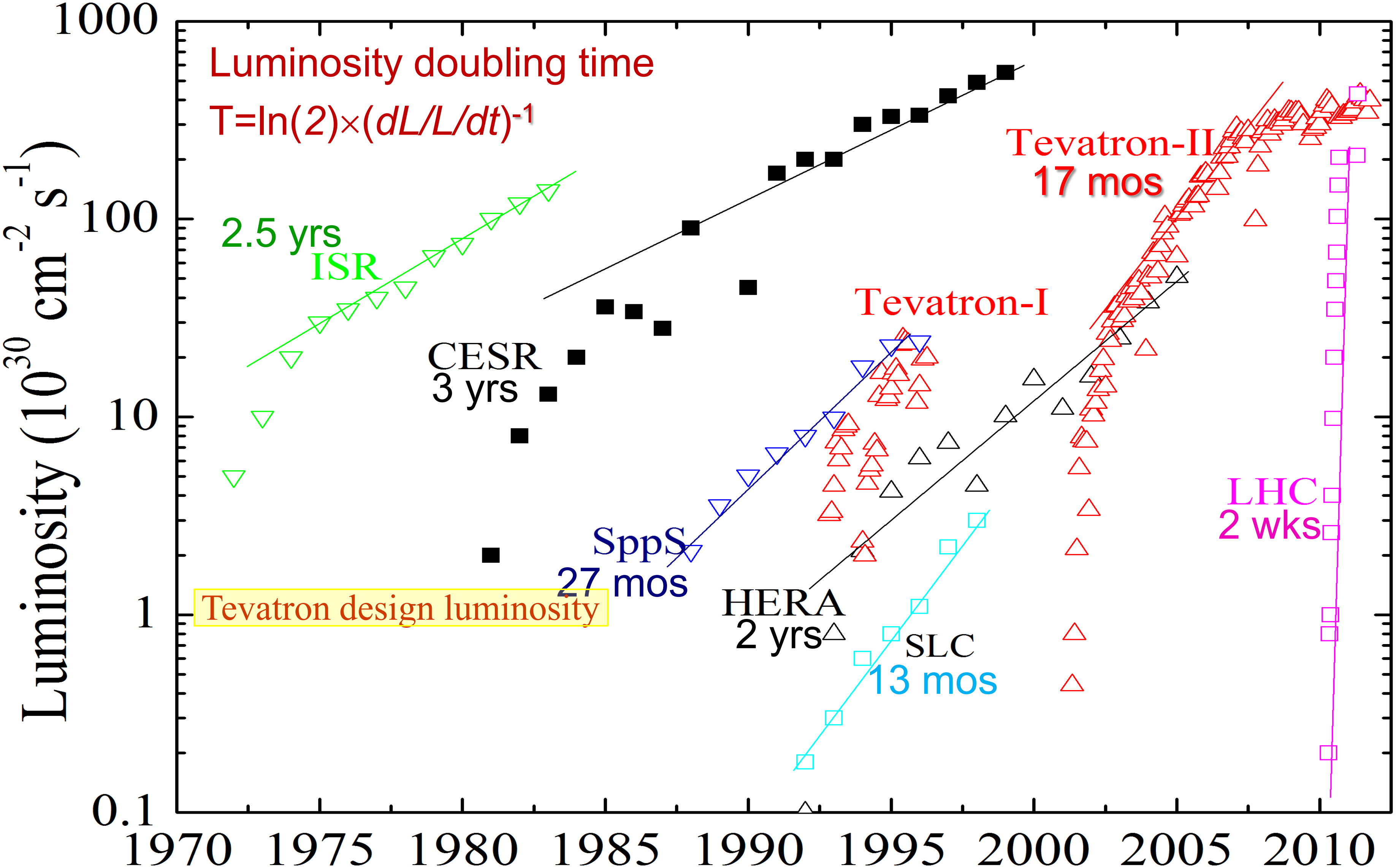
Tevatron Performance

Run II 2001-11: 11.9 fb^{-1} total; about 2.4 fb^{-1} /year; 60+ pb^{-1} /week

Record peak luminosity 432 10^{30} cm^{-2} s^{-1}



Luminosity Progress Pace



V.Shiltsev, CPT theorem, Mod Phys Lett A (2011)

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 Sep.30, 2011 it will have delivered about 12 fb^{-1} to each detector.
- Success of the Tevatron is a great tribute to the Fermilab staff

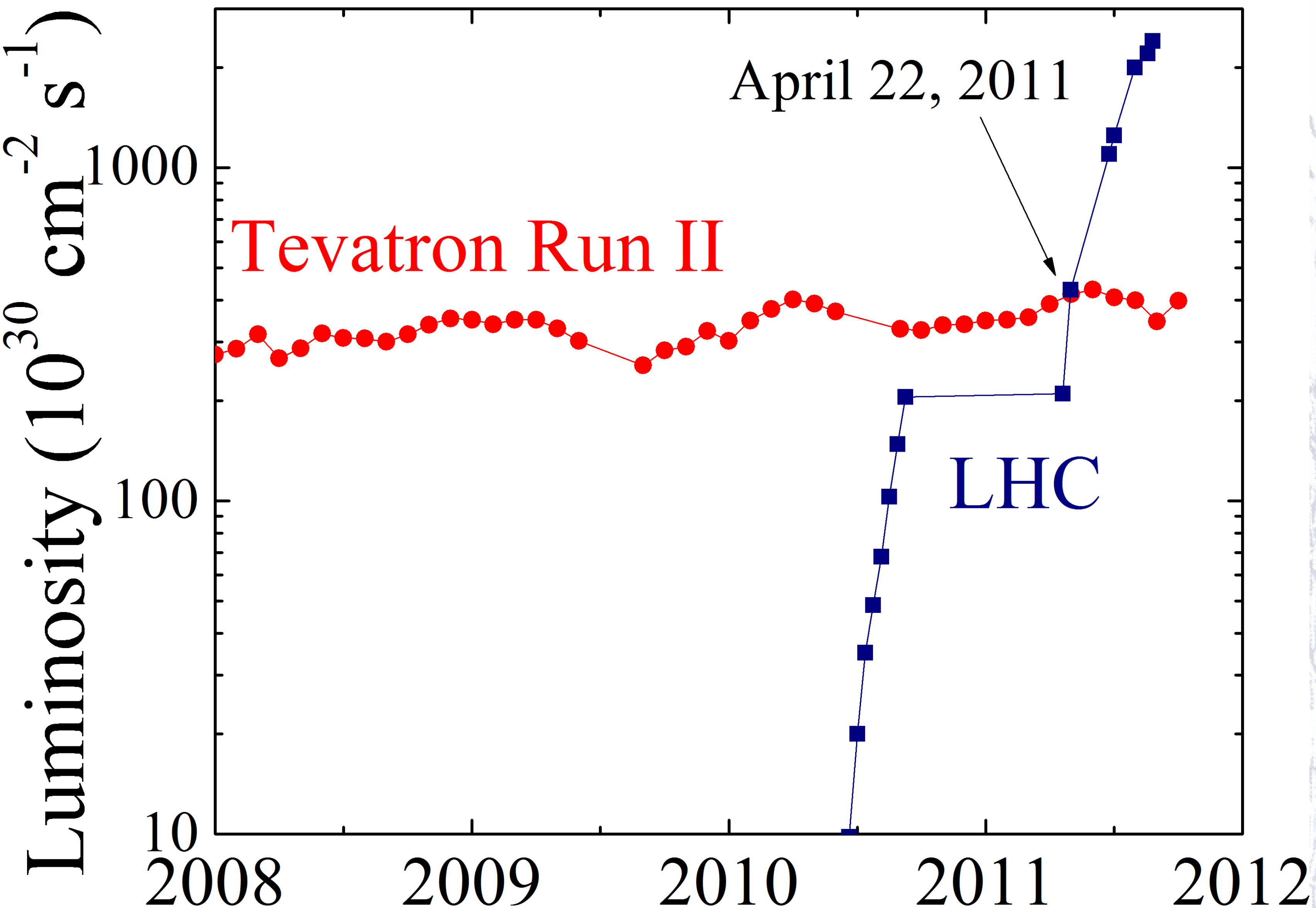
Lessons

- Exchange of ideas and technology transfer helps our field : from ISR & SPS to Tevatron, from Tevatron to HERA, RHIC and LHC, etc
- Be persistent and stubborn, attention to details is very important when working with highly complex systems such as SC hadron colliders, ~no "silver bullets"
- Be flexible, look for all possibilities to increase performance and not be afraid to change plans if experience shows their prospects diminishing
- Expectations management is very important
- Challenges not only create difficulties but also inspire staff and exalt creativity… "*it's the best time of my life*"

Thanks for your attention!

… but that's not all…

“Energy Frontier”



Energy Frontier Baton