WHAT HAVE WE LEARNED FROM THE TEVATRON COLLIDER?

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IT WORKS!

Design: 2000 GeV @ 1×10^{30} $cm^{-2}sec^{-1}$
Operations: 1800 GeV @2×10^{31} $cm^{-2}sec^{-1}$

More specifically:

- Hadron colliders work as advertised
- Large scale superconducting magnet technology works
- Beam and lattice manipulations work
- Separated orbits work
- Emittance preservation requires eternal vigilance
- Hadron beams can survive the beam-beam encounter
- The experimenters care about beam characteristics
- Detectors can do "precision" measurements at a hadron collider.
- Antiprotons are hard to make

HADRON COLLIDERS WORK AS ADVERTISED

The Tevatron collider was not the first hadron collider--the ISR and the SPS at CERN were. The ISR consisted of two rings colliding 30 GeV unbunched beams with a crossing angle. The ISR still holds the record for the highest luminosity in a hadron collider, slightly in excess of 1×10^{32} $cm^{-2}sec^{-1}$. The SPS was the first bunched beam hadron collider in the world and operated at 315 GeV per beam. The luminosity was up to 6×10^{30} $cm^{-2}sec^{-1}$ by the time the accelerator ceased operation in 1991.

The Tevatron was originally specified to operate with a luminosity of 1×10^{30} $cm^{-2}sec^{-1}$ based on three proton and three antiproton bunches. This design luminosity was first achieved in 1989, with recent performance up to 2×10^{31} $cm^{-2}sec^{-1}$. Guess that Tevatron luminosity will poop out somewhere between $1\text{-}10\times10^{32}$ $cm^{-2}sec^{-1}$ following implementation of the Main Injector and Recycler.

Luminosity Evolution in the Tevatron

	Design	1989	IA (1992-93)	IB (1993-95)	
Protons/bunch	1.00E+11	7.00E+10	1.20E+11	2.32E+11	
Pbars/bunch	3.30E+10	2.90E+10	3.10E+10	5.50E+10	
Proton emittance	20	25	20	23	mm-mr
Pbar emittance	20	18	12	13	mm-mr
Beta @ IP	1	0.55	0.35	0.35	m
Energy	1000	900	900	900	GeV
Bunches	3	6	6	6	
Bunch length (rms)	0.65	0.65	0.55	0.6	m
Form Factor	0.86	0.71	0.62	0.59	
Typical Luminosity*	**1.0E+30**	**1.6E+30**	**5.4E+30**	**1.6E+31**	**cm-2sec-1**
Best Luminosity	2.1E+30	2.1E+30	9.2E+30	2.5E+31	cm-2sec-1
Integrated Luminosity	0.2	0.3	1.1	3.2	pb-1/week
Bunch Spacing	6000	3000	3000	3000	nsec
Interactions/crossing (@ 45 mb)	0.33	0.25	0.85	2.48	
Antiproton tune shift	0.022	0.025	0.009	0.015	
Proton tune shift	0.007	0.014	0.004	0.006	
What's New?			**Separators, Antiproton Source Improvements**	**Linac Upgrade**	

LARGE SCALE SUPERCONDUCTING MAGNET TECHNOLOGY WORKS

The Tevatron utilizes 774 superconducting dipoles and 216 superconducting quadrupoles.

- Design dipole field is 4.4 T (corresponds to 1 TeV)
- NbTi conductor at 4.5K carries up to 1800 A/mm^2
- Design based on warm iron (space constraint)
  - Consequence is relatively large heat leak (~2.5W/m)

Operational Experience

You're only as good as your weakest magnet

- Historically we have run approximately 3% below the quench current of the weakest magnet.
- Since the temperature profile is not uniform, position of the magnet relative to heat exchanger matters.

Active quench protection works.

- ~500KJ per magnet is dissipated with rare instances of equipment damage

Persistent currents and hysteresis are important and need to be controlled.

- 8.7 μm filament size
- Tevatron is ramped six times after store to reset field
- Sextupole ramps are played at the start of acceleration to compensate for persistent currents. Magnitude goes as log(t).

BEAM AND LATTICE MANIPULATION WORK

A number of beam manipulations were implemented in the Tevatron and the Main Ring specifically for collider operations:

- Longitudinal bunch coalescing
  - Up to nine bunches are coalesced into a single bunch with an efficiency typically exceeding 90%.

- Longitudinal differential beam cogging
  - “Orthogonal” rf systems are used to control the proton and antiproton beams.
  - Relative longitudinal position of the two beams can be controlled by running for a specified period of time with different momenta, i.e. “cogging”.

- Low beta squeezing can be negotiated with minimal beam loss.
  - The injection lattice can be run with a relatively large β^*, which can be subsequently adjusted downward with minimal beam loss (and without quenching the machine).

SEPARATED ORBITS WORK

Helical separated orbits were implemented in 1992. Collisions were still head on.

- An immediate factor of two in proton beam density was achieved.
- Differential tune and coupling control works and is necessary.
- Some indications that the allowable head-on beam-beam tune shift is reduced (see beam-beam discussion)
  - Attributable to long-range encounters?

EMITTANCE PRESERVATION IS VERY IMPORTANT
(and requires continuous vigilance)

Proton beam emittance in collision is about four times the beam emittance as it emerges from the linac.

- Degradation occurs at nearly every stage of the acceleration process

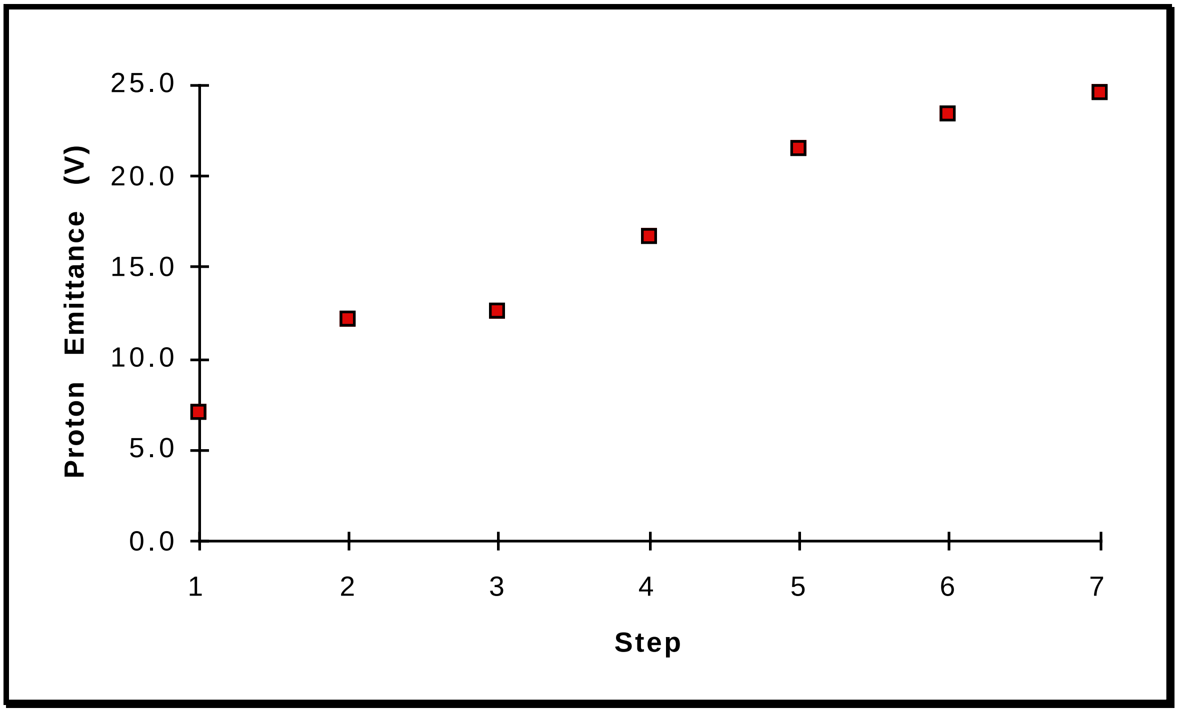
Intrabeam scattering sets ultimate limit on emittance growth in the collider

- Observed rate is ~0.5π mm-mr/hour
- Can be controlled somewhat through strong dependence on the momentum spread

Coupling is very important - even though beam is "round"

A stable machine can be designed without tracking thousands of turns.

- The Tevatron has sufficient dynamic aperture to allow storage of beams on separated orbits.
  - The large aperture of the magnets (75 mm, designed for slow extraction) clearly helps.
- No long term tracking was performed in the Tevatron design period. Only the beam extraction process, over several hundred turns, was simulated.
- Magnetic field specifications were based on slow extraction, chromaticities, tune vs. amplitude, and resonance widths.



Proton beam vertical emittance at various stages in the accelerate-to-collison process in the Tevatron. Data points represent average of all store between 7/24-94-7/23/95

1 Linac/400 MeV
2 Booster/8 GeV
3 MR @ 150 GeV after coalescing
4 Tevatron/150 GeV after proton injection
5 Tevatron/150 GeV after antiproton injection
6 Tevatron/900 GeV after squeeze
7 Tevatron/900 GeV in collision

HADRON BEAMS CAN SURVIVE THE BEAM-BEAM ENCOUNTER(S)

Prior to the operation of the Tevatron (and the SPS) a certain lore existed that said that the maximum beam-beam tune shift limit would be .003/interaction point.

The Tevatron and SPS showed that what appears to count is the total beam-beam tune shift summed over all encounters.

In the Tevatron the maximum tune shift limit (total) appeared to be .025 in the pre-separator era.

- Limited by the space between the 2/5 and 3/7 resonances.
- Proton beam was deliberately diluted during this era in order to stabilize antiprotons.
- 12th order resonance did not appear important.

In the post-separator era it was only near the end of Run Ib that the total beam-beam limit was being pushed.

- Indications that (total) beam-beam tune shift limit was being approached at ~.016.
  - Influence of long-range effects?

Instabilities

Very few beam instabilities have been observed in the Tevatron in collider mode:

- "Head-tail" instabilities are observed but largely controlled using the correction sextupole strings.
- Coupled bunch instabilities are not observed in collider mode, but are in fixed target at about 1.5×10^{13} total protons.
- A longitudinal mode 1 coupled bunch instability is observed in both Main Ring and Tevatron and is controlled via dampers.

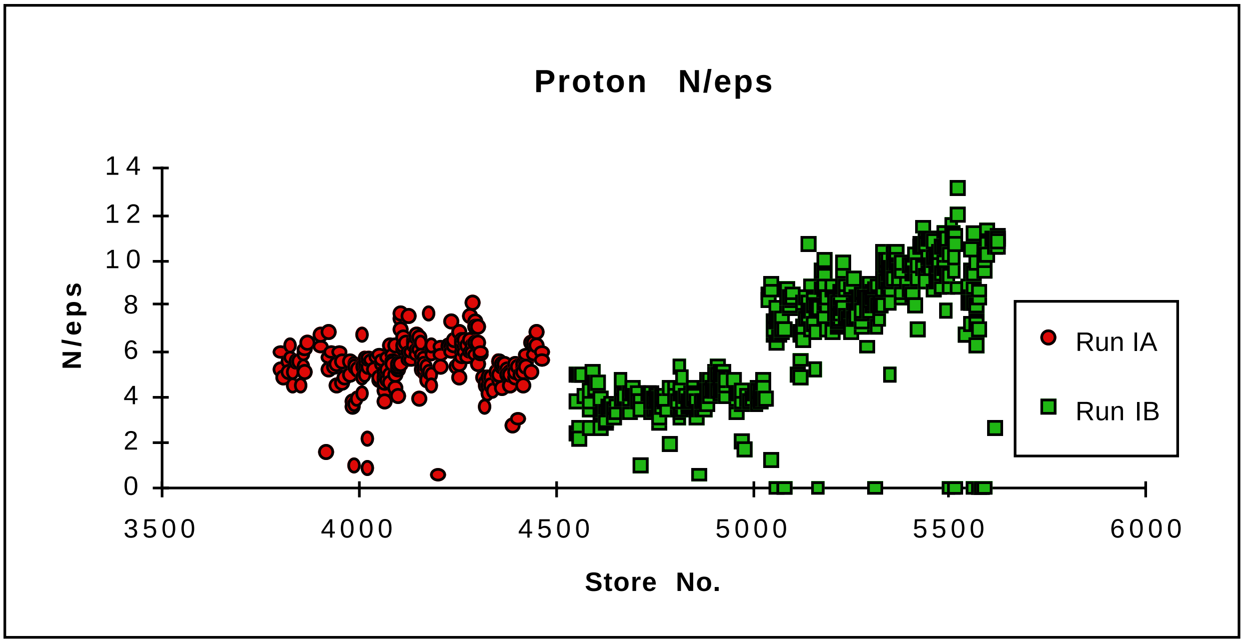
Poor performance is not always a result of subtle beam dynamics effects

- Early on anomalous emittance growth was traced to a (mechanical) vacuum pump resting on a dipole magnet.
- An severe, unexplained coupling in 1994 was discovered to be a result of a severe quench that rolled a quadrupole.

However,

Good diagnostics are essential

The Tevatron had the most extensive set of diagnostics (and correctors) of any accelerator constructed at Fermilab up to that time. As a result the commissioning of the machine proceeded relatively expeditiously.



Proton phase space density as observed in the Tevatron before (Run IA) and after (Run IB) the 400 MeV linac upgrade. The discontinuity midway through Run IB is related to solution of a severe coupling problem in the Tevatron.

EXPERIMENTERS CARE ABOUT THE BEAM

Successful operation of the Tevatron collider requires dialog between experimenters and the accelerator people.

Detectors are sensitive

- Minimization of beam halo is very important to quality data.
- Silicon detectors need to be protected

Experimenters like short bunches

This is primarily related to coverage by their silicon detectors.

- RMS bunch lengths in Run Ib were typically 55 cm
- Of course, what really matters is length of the luminous region.

  Will this trend continue as b-physics becomes a larger feature (and multiple events/crossing the norm)?

Experimenters prefer <3 interactions/crossing

We aren't allowed to package all our luminosity in a few bunches (as much as we would like to).

DETECTOR CAN DO "PRECISION" MEASUREMENTS AT A HADRON COLLIDER

The first measurement of W, Z, and top quark masses and widths came from hadron colliders.

The best measurement of the b-quark lifetime, and the first measurement of sin(2β) come from the Tevatron.

ANTIPROTONS ARE HARD TO MAKE

The design specification for the Fermilab Antiproton Source was 1×10^{11} antiprotons/hour

- Achieved rate is 0.7×10^{11} antiprotons/hour after 10 years operation.
  - Actual 120 GeV production cross section is 40% of design assumption.
- Recycling is worth it if it can be made to work.

SUMMARY

1. Hadron colliders work at high luminosity and can provide an environment that allows experimenters to carry out precision experiments.

2. Experimenters should be involved in the earliest stages of definition of parameters.

3. The design of large machines is going to require the consideration of some beam dynamics effects that were not confronted in the Tevatron (coupled bunch instabilities, ground motion, and crossing angles).

4. Stick with proton-proton.

5. Synchrotron radiation could change the rules of the game.

Figures

1. Histogram of quench currents (from Helen's article)

2. Emittance evolution plot (from IUCF talk)

3. Proton phase space vs. Run number in Ib (from IUCF)