Petavac

Boson-Boson Collisions at 100 TeV

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Hadron colliders are the only tools that can directly discover gauge particles beyond TeV

- Predicting the energy for discovery is perilous.
- Example: for a decade after discovery of the b quark, we ‘knew’ there should be a companion t quark. But we couldn’t predict its mass. Predictions over that decade grew (with the limits) 20 → 40 → 80 → 120 GeV
- 4 e^+e^- colliders were built with top discovery as a goal.
- Finally top was discovered at Tevatron – 175 GeV!
- In the search for Higgs and SUSY, will history repeat?
Mass reach for new physics

*Tevatron* accessed new physics through $q\bar{q}$ annihilation.

*LHC* will access new physics through gluon fusion:

*Petavac* will access new physics through boson fusion

7x the collision energy $\rightarrow$ 3x the mass reach
A new vision for the future of high-energy discovery beyond LHC

• Hadron colliding beams in the SSC tunnel
• 16 T dipole ring provides 100 TeV collision energy
• Use $\bar{p}p$ so only one magnet ring is needed
• Superferric injector located in the same tunnel

Four developments make this possible to conceive:

- Recent success maturing Nb$_3$Sn dipole technology
- Commercialization of Nb$_3$Sn wire for ITER
- Spectacular performance of Fermilab $\bar{p}$ source
- 84 km SSC tunnel is nearly complete, waits for use
We need a new superconductor for 16 T: \( \text{Nb}_3\text{Sn} \)

**Cost today:**
- NbTi: \$150/kg
- \( \text{Nb}_3\text{Sn} \): \$1,000/kg
- Bi-2212: \$2,000/kg
16 Tesla dipoles have been built and tested.

LBNL HD1

4m-long racetrack coils using Nb$_3$Sn have been built and tested.

LARP LRS


- Nb$_3$Sn superconducting wire with the necessary performance is developed and commercialized.
- 3,000 A/mm$^2$ @ 12 T, 4.2 K in the superconductor

- ITER will use 400 tons of high-performance Nb$_3$Sn wire; it will drive the production capacity to what would be needed for Petavac.

*Transition to volume manufacture is predicted to drop Nb$_3$Sn wire price by half.*
Fermilab has matured antiproton source technology and electron cooling

- $3 \times 10^{11} \overline{p}$ /hr stacked, capacity for 10x more from target (adjacent $\Delta p$ windows)
- E-cooling in recycler has capacity for $\sim 10^{14} \overline{p}$

Lebedev 2008
New magnet technology makes it possible to develop 16 T collider dipoles

- **Block coil geometry**
  Arrange coil in rectangular blocks so that forces can be controlled.

- **Stress management**
  Intercept stress within the coil so that it cannot accumulate.

- **Optimized conductor**
  Separate the copper for quench protection into pure-Cu strands.

- **Suppress persistent-current multipoles**
  Use close-coupled steel boundary to naturally suppress p.c. multipoles.
Nb$_3$Sn dipole technology at Texas A&M: stress management, flux plate, bladder preload
Stress management
Horizontal steel flux plate redistributes flux to suppress multipoles

Suppress snap-back x5, relax requirements on filament size in Nb$_3$Sn.
**Nb$_3$Sn Magnets for Petavac**

16.5 T dipole

450 T/m quadrupole

6 cm aperture provides ample room for pretzel separated beams
Ring Dipole

16.8 T central field (short-sample limit), 6 cm bore

\[ J_{\text{non-Cu}} = 3000 \ \text{A/mm}^2 \ @ 12 \ \text{T}, 4.2 \ \text{K} \]

Cryogenics 4-6 K supercritical He

Total superconductor cross-section = 80 cm\(^2\) (LHC dual dipole 68 cm\(^2\))

Max coil stress 117 MPa.
Collider layout

\[ \sqrt{s} = 100 \text{ TeV}, \quad \mathcal{L} = 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \]

Main tunnel:
- 16 T single ring \( 5 \rightarrow 50 \text{ TeV} \)
- 1.6 T superferric injector \( 1 \rightarrow 5 \text{ TeV} \)

Medium-energy booster:
- 4 T \( \cos \theta \) booster \( 0.15 \rightarrow 1 \text{ TeV} \)
- 0.1 T permanent magnet freezer \( 8 \text{ GeV} \)

Low-energy booster:
- 1.5 T rapid-cycling booster \( 8 \rightarrow 150 \text{ GeV} \)

Superconducting linac:
- 0.01 \( \rightarrow \) 8 GeV
SSC tunnel ~70% bored, 35% lined
Petavac Lattice

$\beta^* = 0.5 \text{ m}$

$\beta_{\text{max}} = 9.6 \text{ km}$
## Comparison of Parameters

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>SSC</th>
<th>LHC</th>
<th>100TeV</th>
<th>100TeV</th>
<th>7 TeV in Tevatron</th>
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<td>1.6</td>
<td>27.9 h</td>
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</table>
Superferric High-Energy Injector shares the same tunnel
How much would an 86 km ring of Nb$_3$Sn dipoles cost?

• No one can know until we develop the technology and transfer it to industry, but…
• ‘the collared coils represent about 60% of the assembly cost and more than 70% of the total value of a dipole (mainly because of the superconducting cable cost)’…Lucio Rossi, LHC magnet leader
• Single Petavac ring requires 10,000 tons of wire
• Wire price today $1,000/kg, ÷3 in volume
• $3 billion superconductor → ~$5 billion for ring

A $pp$ collider would require two of these rings

That is the premium to use $\bar{pp}$ colliding beams.
New magnet design, New materials, Dramatic Performance
Accelerator Challenges for Petavac

- **Synchrotron light:** 6 W/magnet @ LHC, 1600 W/magnet @ Pentavac!

  *Solution:* room-temp photon stop between successive dipoles

  0.7 m long water-cooled blade is inserted/retracted so that it absorbs the entire fan of synchrotron light emitted in the flanking dipoles

  Total cryogenic heat load: 6 W/dipole

  Synchrotron light gives damping in all dimensions of phase space: 45 minutes in Petavac (24 hours in LHC)

  Helps to counteract mechanisms of slow emittance growth.
Avoid beam-beam tune shift from subsidiary crossings of bunches:

This issue is complicated by our need for close bunch spacing:
20 ns bunch spacing
@ 10 luminosity yields
85 interactions/crossing!

Solution: Separate beams on a vertical pretzel, so that beams only cross @ IPs, separation ~1 cm elsewhere minimizes tune issues.
Vertical orientation preserves small horizontal spread.
Suppress electron cloud effect:

- Beam protons ionize electrons from gas atoms
- Electrons are born with ~eV kinetic energy, so can’t reach wall before next bunch passes
- Electric field of next bunch accelerates electrons to ~kV energy
- Energetic electrons strike wall and liberate secondaries…

Poses serious challenge to reach even $10^{34}$ luminosity, much less $10^{35}$

Solution: Install continuous strip electrode on side wall of vacuum tube around entire ring. Bias ~50 V clears all charge in <20ns
Correct bunch-bunch tune spread to preserve luminosity: Successive bunches have different tune shifts due to a multitude of phenomena (injection, circulating charge, bunch intensity variations, chromaticity). The machine can be tuned to keep any one bunch happy, but the others…

Solution:
Use AC dipole to measure tunes of each bunch, use electron lens to correct tunes of each bunch dynamically during store.

Shiltsev et al., New Journal of Physics 10 (2008) 043042
Miyamoto et al., PRST-AB (2008)
Antiproton Production & Damping

We need \( \sim 100 \times \overline{p} \) stacking to support \( 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \)

- x10:
  ten debunchers fed from each \( \overline{p} \) target

- x2: separate mixing regions in stochastic cooling:
  max good mixing, min bad mixing (Wang COOL 2007)
  twice accumulation rate in each accumulator wrt Tevatron

- x5: five target stations fed from proton driver.
How to get from here to there?

- LHC plans to operate at reduced energy: 3-4 TeV/beam
- Build a single-ring 14 T $\bar{p}p$ collider in Tevatron tunnel:
  - 3.5 TeV/beam
- Upgrade antiproton source and recycler
  - $3 \times 10^{11} / \text{hr} \rightarrow 3 \times 10^{12} / \text{hr}$; stack $3 \times 10^{12} \rightarrow 2 \times 10^{13}$
- Build new half-tunnel to stretch 2 B0, D0 straight sections
- **Result:** 7 TeV $\bar{p}p$ colliding beams @ $3 \times 10^{33}$ luminosity
Implement features that build the foundation for the Petavac

- Nb$_3$Sn ring magnets, warm/cold transitions, $\gamma$ stops
- Separate beams using magnetic septum, crossing angle to accommodate close bunch spacing
- Upgrade $\bar{p}$ source with goal x10 faster accumulation
- Integrate ac dipole measurement and e-lens correction of tunes bunch by bunch
- Improve high-energy e-cooling for x10 stack, reduced emittance
- Coalesce CDF, D0 collaborations, upgrade one detector for 7 TeV, $10^{34}$ luminosity, 30 interactions/bunch crossing
So Fermilab could develop an LHC-competitive collider program:

- 7 TeV \(10^{34}\) luminosity

*and at the same time*

develop and prove the key technical challenges to substantiate a design for an ultimate hadron collider:

- 100 TeV \(10^{35}\) luminosity

Build upon all the assets that are here and planned to make 2 new generations of hadron collider.
AARD: Skunk Works for the Future of HEP

**HEP lives at the edge!** At any given time:

New discovery requires more energy/luminosity than we have today!

We have to find a way to build a next discovery machine for the same cost as the last one!

AARD is *the place in HEP* that supports long-term development of technologies that can make this possible.
Acknowledgements

It is a pleasure to acknowledge fruitful discussion with Chuck Ankenbrandt, Bill Foster, Gerry Jackson, Dave Johnson, Milorad Popovich, Al McInturff, Bruce Strauss, and Mike Syphers.

I would like to form a collaboration to develop serious studies of the 7-Tevatron and the Petavac

Fermilab has been the home of $\bar{p}p$ colliding beams for the past 30 years. Now is the time to renew its leadership and push for this new generation.