Antiproton Production at Fermilab

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DPF-09, Detroit
Antiproton Production at Fermilab: Outline

- Introduction to the machine operation
- Overview of the machine development in last 5 years
- Current machine performance
- Experimental options with antiprotons
Introduction: Machine operation
Introduction: Antiproton Source

Antiproton Source:

- Accumulator
- Debuncher
- AP1 line
- AP3 line
- AP2 line
- D/A line
- Target station 🌟

~2.4 km of beam path
Introduction: Machine operation: MI-8 line

Booster to Main Injector
8 GeV protons
~8E12 protons for Pbar
Introduction: Machine operation: Main Injector

Main Injector:
Acceleration to 120 GeV
2.2 sec cycle
Introduction: Machine operation: P1-P2-AP1 line

Transport line (P1-P2-AP1) to the Target station

Target station: Ni (Inconel) target + Li collection lens + Pulsed magnet
Introduction: Machine operation: P1-P2-AP1 line

Transport line to the Target station

Target station: Ni (Inconel) target + Li collection lens + Pulsed magnet
Introduction: Machine operation: AP2 line

Antiproton transport to the Debuncher (AP2) 
( \( \bar{p} \) + ... )
Introduction: Machine operation: Debuncher

Debuncher ring:

~2e8 pbars/cycle
Large acceptance
Fast compression (2sec):
   Adiabatic debunching
   Stochastic cooling
~10x10x10
**Introduction:** Machine operation: Debuncher

Debuncher ring:

- ~2e8 pbars/cycle
- Large acceptance
- Fast compression (2sec):
  - Debunching
  - Stochastic cooling
  - ~10x10x10

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APD seminar, 05/17/07  
V.Nagaslaev, AD/Pbar
**Introduction:**

Machine operation: **Debuncher**

- Debuncher ring: ~$2 \times 10^8$ pbars/cycle
- Large acceptance
- Fast compression (2sec):
  - Debunching
  - **Stochastic cooling**
  - ~$10 \times 10 \times 10$
**Introduction:**

**Machine operation:** Accumulator

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**Accumulator ring:**

- Inject to +80 MeV
- RF move to deposition
- Moving to Core: -60 MeV
  - with Stochastic cooling
- RF unstack for extraction

**Stochastic cooling:**

- Stack-tail momentum
- Core momentum
- Core transverse
**Introduction:** Machine operation: Accumulator

**Accumulator ring:**

- Inject to +80 MeV
- RF move to deposition
- Moving to Core: -60 MeV with Stochastic cooling
- RF unstack for extraction

**Stochastic cooling:**
- Stack-tail
- Core momentum
- Core transverse

Cyan = After injection before RF capture
Green = After RF is turned off
Introduction: Machine operation: AP3-AP1-P2-P1

Antiproton transport

Accumulator->
Main Injector->
Recycler
### Antiproton Source parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam momentum</td>
<td>8.9 GeV/c</td>
</tr>
<tr>
<td>Peak stacking rate</td>
<td>27.6 $\times 10^{10}$/hr</td>
</tr>
<tr>
<td>Average stacking rate</td>
<td>24 $\times 10^{10}$/hr</td>
</tr>
<tr>
<td>Average production efficiency</td>
<td>22 $\times 10^{-6}$ $p / p$</td>
</tr>
<tr>
<td>Typical stack size</td>
<td>25 $\times 10^6$</td>
</tr>
<tr>
<td>Maximum stack size</td>
<td>310 $\times 10^6$</td>
</tr>
<tr>
<td>Stacking cycle</td>
<td>2.2 sec</td>
</tr>
<tr>
<td>Time between transfers</td>
<td>50 min</td>
</tr>
<tr>
<td>Total beam compression</td>
<td>$10^7$</td>
</tr>
<tr>
<td>Transfer to RR efficiency</td>
<td>96%</td>
</tr>
</tbody>
</table>

*(Terminology: “1mA” = $10^{10}$ pbars)*
Main machine developments since 2005

There’s been a remarkable progress with the Tevatron integrated luminosity since the beginning of Run-II. A crucial factor in this progress was the growth of antiproton production capability. Average weekly production has grown a factor of 3.5 since 2005.

Main improvements since 2005:

- Target and collection lens
- AP2/Debuncher acceptance
- Debuncher stochastic cooling
- Accumulator stochastic cooling
- Lattice (optics) modifications
- Rapid transfers
  (no luxury of incremental changes)
Production target

- Optimum yield with narrow beam spot, ~170u
- After implementing slip-stacking in MI - issues with target lifetime
- Engineering team working on the target design
- Eventually come up with a reliable solution, including the target, motion and cooling
- Beam sweeping
- Target is rotated by 15 degrees after each pulse

Previous design | Latest design-B | Latest design-C
Collection lens

- Li cylinder, $r=10\text{mm}$, $L=15\text{cm}$
- Focusing by axial current (600kA)
- Extreme heat and mechanical load
- Lifetime issues at high gradients
- New design developed:
  - Titanium body
  - Diffusion bonding
  - More efficient cooling
  - New transformer design
Run-II: goal – increasing AP2/Debuncher acceptance to $35\pi/35\pi$ (H/V)
March 2005 Debuncher acceptance $30\pi/25\pi$ (H/V)
A lot of work before 2005 to build new hardware and instrumentation
Requested 2 weeks of studies in December; Tevatron failure for 3 weeks:
  - studies in shifts around the clock (Study-O-Rama)
  - component centering, correcting orbits
  - aperture limitations searches (new method)
Got 2 more weeks in January 2006
  - searches continued
  - removed Debuncher Schottkys
  - installed new trims in AP2
  - lattice studies

Extraction kicker was modified to improve aperture
New lattice was developed shortly after, and that completed the goal
Design acceptance $\sim 40\pi/40\pi$, actual (measured) $35\pi/35\pi$
Debuncher Stochastic cooling

- Fast - 2 sec cycle time
- Wide acceptance in dP
- Very low signal - cryogenic
- 8 PU bands, 4 kicker bands, 4-8 GHz
- Total kicker power 10kW

- Run-II upgrade: bands 3&4 tanks added
- Main improvement after upgrade: Double turn notch filter
  - Switched in at 1 sec
  - 10% reduction of final energy spread
Accumulator stochastic cooling

- 4 systems:
  - StackTail Momentum 2-4 GHz
  - Core Momentum 2-4 GHz
  - Core Momentum 4-8 GHz
  - Core Betatron 4-8 GHz
- Main focus: StackTail
- 2006: switched focus from CM 2-4 to CM 4-8
- Detailed studying – numerical model developed
- Optimization, reconfiguration
  - Hybrid flip,
  - “Leg 3” resurrected
- 2007 – new equalizer
- Strong limitation: ST heating the Core
- Swapping 2 ST kicker tanks with 2 CM tanks
- Notch filter #3, BAW \(\rightarrow\) SC, increased depth
- Equalizer for Core momentum
- New optics (increased eta)

System gain versus frequency
before and after new equalizer installed
Lattice modifications

Accumulator:

- Slip factor increase by 15%:
- helps stochastic cooling

\[ J_{\text{max}} = T_0 |\eta| W^2 x_d \]

- dispersion variation in “wells”

- Address transverse heating:
  - Mitigate heating resonances
  - Suppress dispersion in straights
  - Lower beta-functions (IBS)

- Apertures:
  - Reduce beam size at tight locations

Debuncher:

- Increase machine acceptance
- Correct P-K phase advances for SC

2005: \(30\pi/25\pi\) mm·mrad
2006: \(35.3\pi/34.6\pi\) mm·mrad

Eliminated the need in replacing B4 cooling tanks
Rapid Transfers

Speeding up transfers:
• More time for stacking (13%)
• Smaller optimal stack size

Challenges:
• Thousands of devices involved
• Incremental changes
• Intelligent procedure
• Transfer efficiency

New hardware:
• BPM upgrade
• ramping magnets in AP1
• RF modifications – shorter bunches

Transfer efficiency:
• Orbit monitoring
• MI injections damper
• Optics modifications
• 2006: 75%-95%
• Now: routinely 96%
Antiproton source performance

- 2005 start combination shots to TeV
- 2006 only RR shots
- 2005-2006: AP2/Deb acceptance
- after 2006:
  - Stochastic cooling
  - Target
  - Lens
- 2006 also: start of Rapid Transfer effort
World’s antimatter production

<table>
<thead>
<tr>
<th></th>
<th>FNAL</th>
<th>CERN</th>
<th>GSI FAIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average production</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rate [e10/hr]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak production</td>
<td>27</td>
<td>7.5</td>
<td>3.5</td>
</tr>
<tr>
<td>rate [e10/hr]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ready to start</td>
<td>2011</td>
<td></td>
<td>2015</td>
</tr>
<tr>
<td>Experiments</td>
<td></td>
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</table>

What are we going to do with this facility when Run-II ends?

- Scope of this question spans beyond Fermilab
- We have not yet passed the decision point
- HEP community should think about it again – NOW!
Experimental options: In the past

E760 (1990-1991)
Charmonium experiments

Charmonium physics
and continuum cross-sections

*Precision measurements of number of parameters, still leading in PDG tables*

Detector pit is empty now!
Experimental options: In the past

APEX (T861/E868, 1995-1996)

Antiproton lifetime experiment

\[ p \rightarrow e + X \] (7 modes)

\[ p \rightarrow \mu + X \] (6 modes)
Experimental options: In the past

E862 (1996-1997)

Production of relativistic antihydrogen

Production and successful detection with no background has been demonstrated.

Experiment has been proposed to fine spectroscopic measurements including the Lamb shift (1-5% level)
Experimental options

What can be done now?

- Precision measurements with Charmonium
- Precision measurements of XYZ states
- Measurements of continuum
- Searches (excited C, exotics, glueballs)
- Asymmetries in Hyperon Decays (CP-violation)
- Rare hyperon decays
- Relativistic Antihydrogen (Lamb shift)
- Open Charm
- ...many others!

For details see Dan Kaplan’s talk at the parallel session “Hadron spectroscopy I”
Experimental options: $g$-2

- Using Fermilab beams to continue BNL $g$-2 experiments
- Valuable experiment at low cost and short time scale
- Potential: to improve experimental uncertainty from 0.54ppm to 0.14ppm

- Proposed to run parasitically with neutrino programs and before mu2e
- Use 8 GeV protons for 3.1 GeV pion production on the Pbar target
- Using Debuncher in a beam line mode
- Advantage of large Debuncher aperture and long decay path
  - Few technical challenges
  - Hardly compatible with antiproton program
  - Challenge to squeeze between Run-II and mu2e and low budget
Experimental options: mu2e

Charged Lepton Flavor Violation
- In 2 years running: $R_{\mu e} \sim 2 \times 10^{-17}$
- 4 orders lower than current limit
- Many models predict $e^{-15}$

Using Pbar Source:
- Natural time structure
- Slow spill extraction
  - Challenges of high intensity
  - High radiation issues
  - Extinction at $<10^{-9}$
  - End of the antiproton program

Options other than using the Pbar source are possible!
Conclusions

1. There has been a remarkable progress in antiproton production at Fermilab during Run-II
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Conclusions

1. There has been a remarkable progress in antiproton production at Fermilab during Run-II
2. Fermilab antiproton program is now and will be the world most powerful source of antiproton production for decades
3. Rich physics with antiprotons may become available, with plenty of opportunities for PhD research
4. Interest and input from physics community is important
Backup
**Experimental options: Alternatives**

**Project X, ICD-II (presented at NuFact-09)**

- **Pulsed 2 mA H- source, 5% duty factor**
- **MEBT consists of rebuncher cavities, beam chopper, focusing and transverse trims, and necessary instrumentation**
- **RFQ in each section to ~5 MeV**
- **10 mA DC p+ source**

**Diagram Details:**
- **2 GeV SC Linac**
- **Main Injector**
- 2-8 GeV section
  - An SC Linac?
  - A Rapid Cycling Synchrotron?
- **RF Splitter uses transverse RF cavity for beam splitting**