Antiproton sources

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26 October 2006

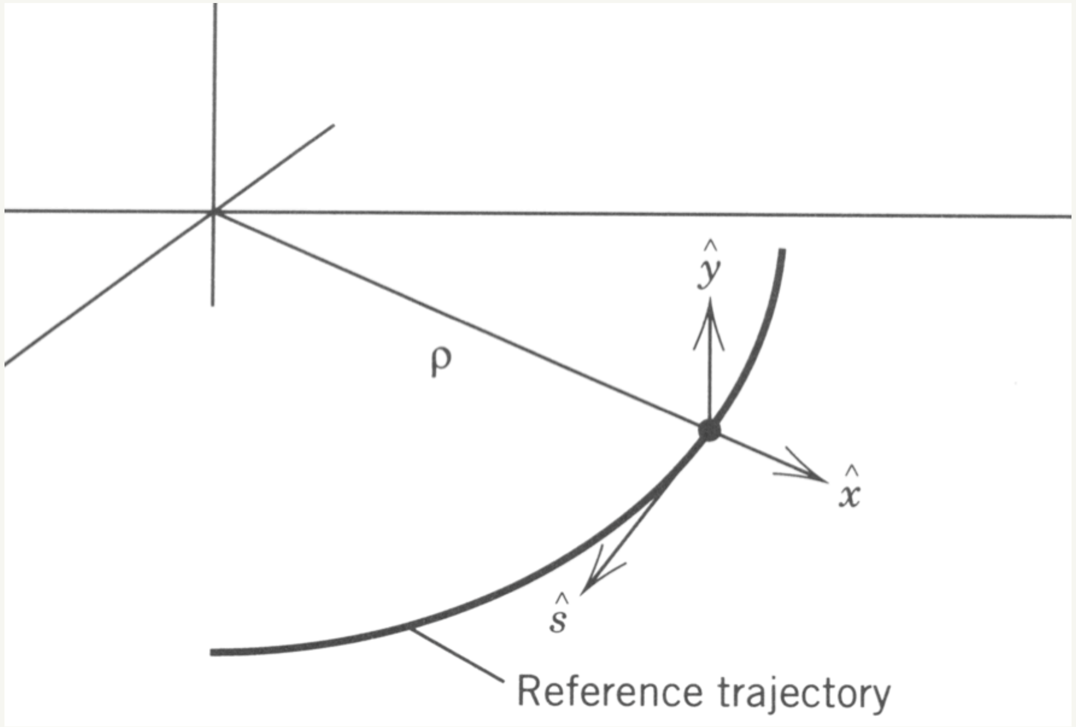
Motivation

- Relatively easy conversion of high-energy p synchrotrons (SPS at CERN and Tevatron at FNAL) to pbar-p colliding-beam storage rings
- Physics output: W e Z bosons, antihydrogen, charmonium spectroscopy, ...
- Low production yields (10^{-5} pbar/p) require beam cooling and accumulation
- Drawbacks: lower intensities, long stacking periods, expensive to build and operate

Essential timeline

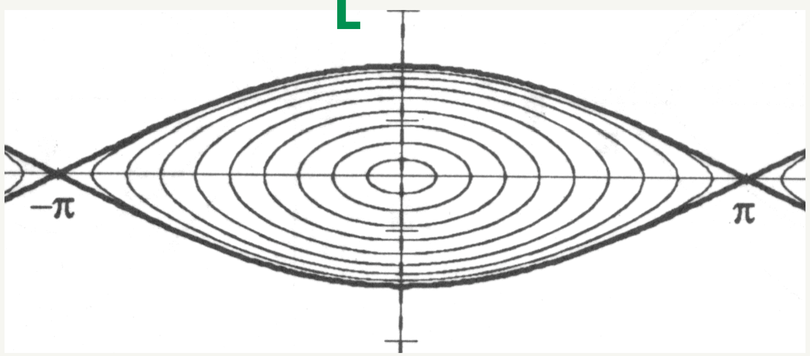
- 1972: van der Meer discusses stochastic cooling
- 1975: stochastic cooling demonstrated at ISR
- 1976: Rubbia, McIntyre and Clive propose use of counter-propagating pbars
- 1980: AA commissioned at CERN
- 1985: FNAL source commissioned
- 1996: AA, AC, LEAR shutdown at CERN
- 2000: AD (modified AC) operational at CERN

Coordinate system

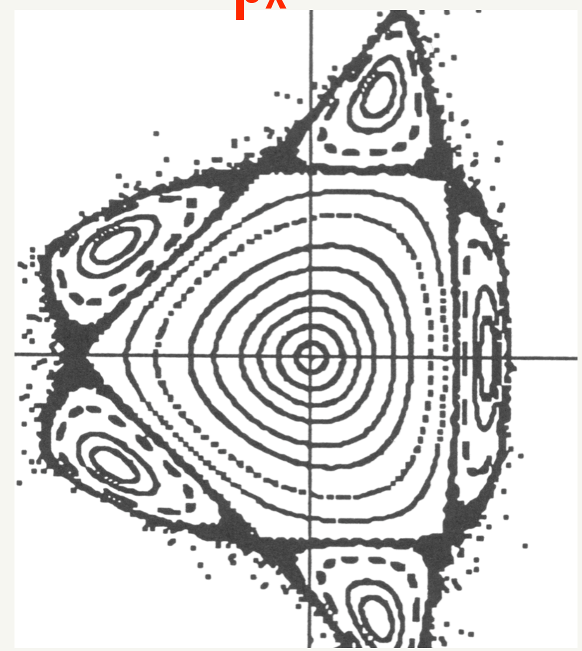


Beam phase space

Longitudinal



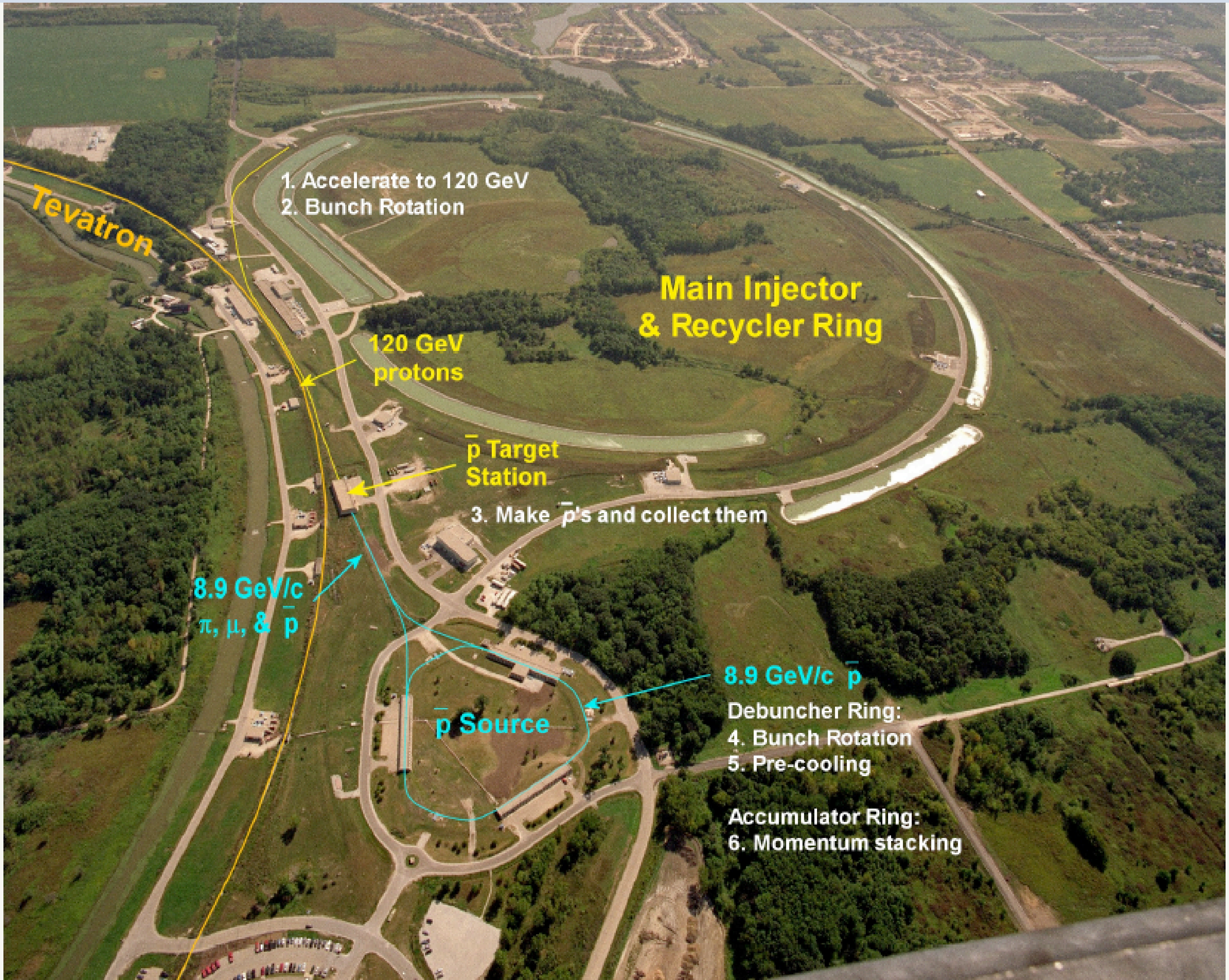
Transverse



Harmonic oscillations → ellipses

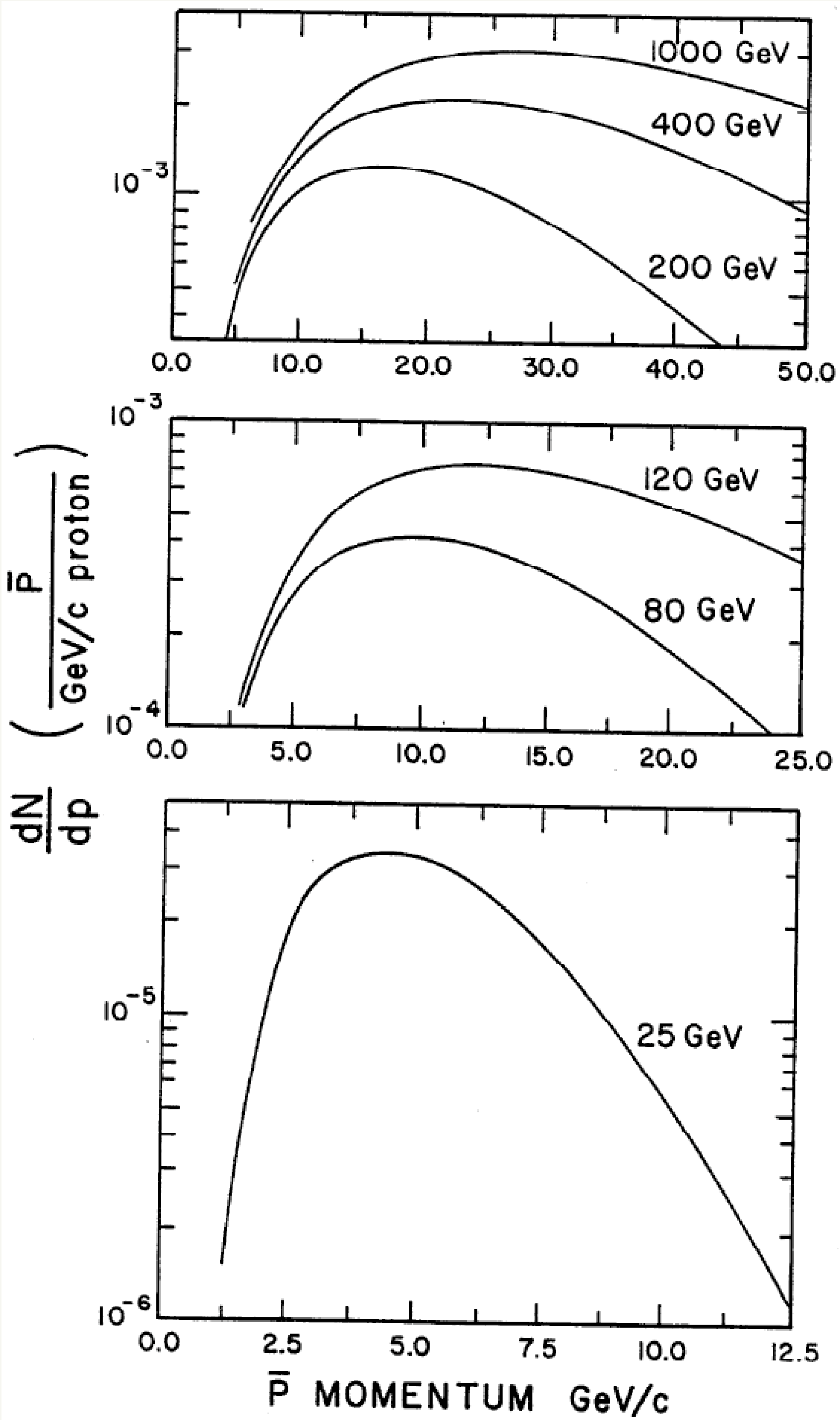
Energy conservation + Liouville's theorem:
conservative forces → constant area/volume (<u>emittance</u>)
and density (temperature)

The CERN/FNAL paradigm

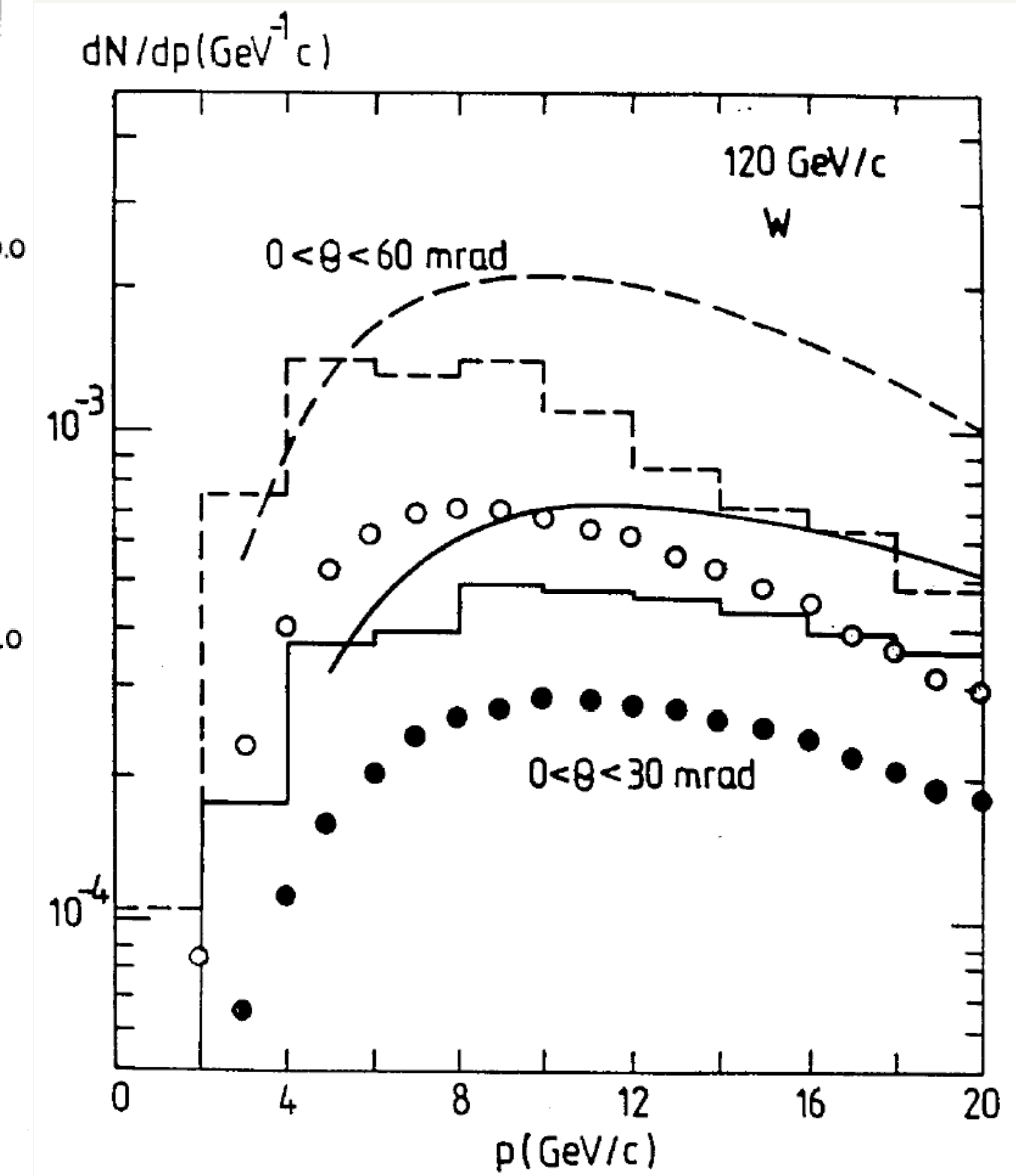


Production yields

- Considering process p + N → pbar + X
- Need to maximize yield within Debuncher phase-space acceptance
- See Hojvat and van Ginneken, NIM **206**, 67 (1983) and Azhgirev, Mokov, and Striganov, FERMILAB-TM-1730 for details



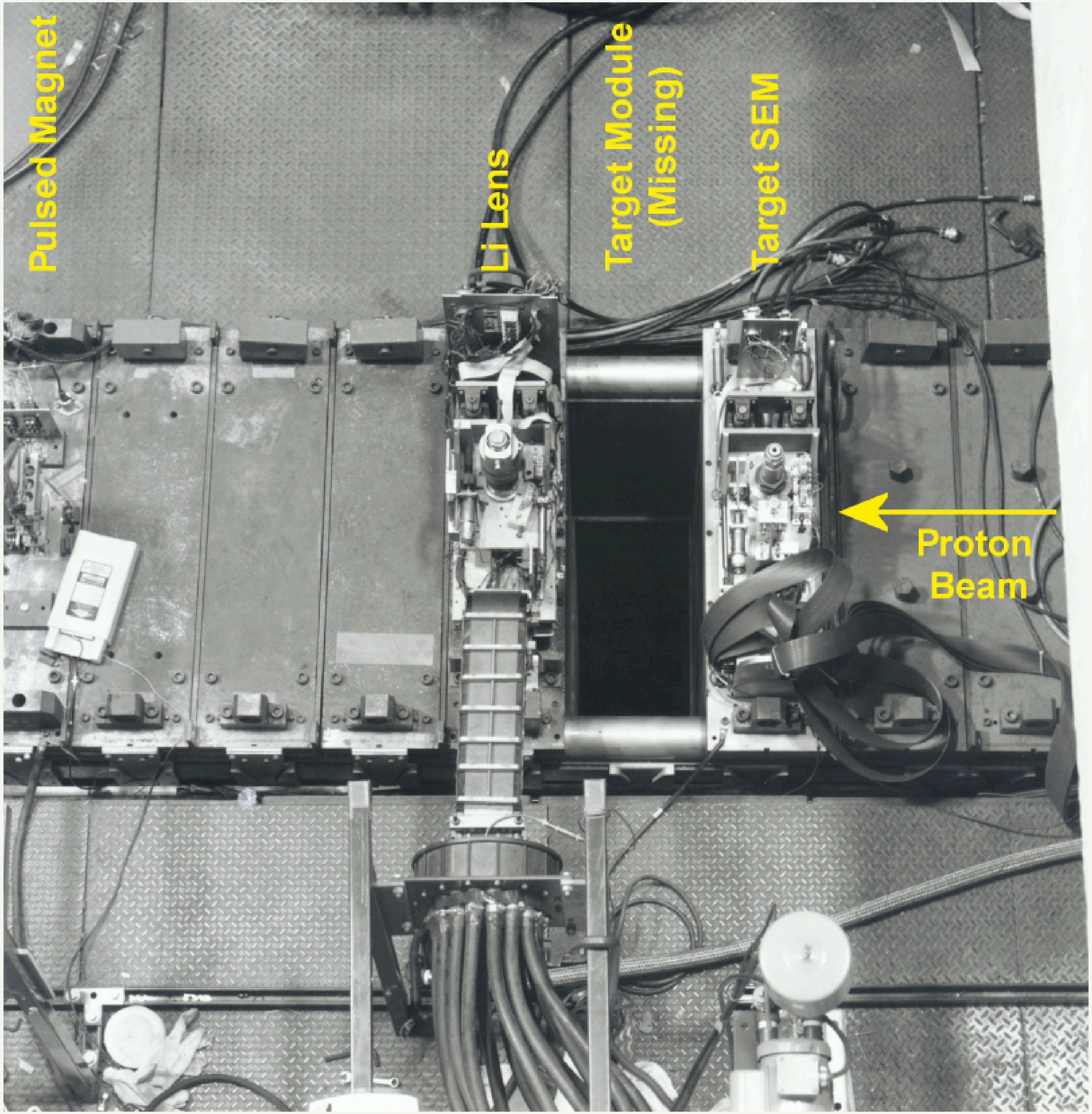
1000 GeV
400 GeV
200 GeV
10^-3
0.0
10.0
20.0
30.0
40.0
50.0
10^-3
120 GeV
80 GeV
10^-4
0.0
5.0
10.0
15.0
20.0
25.0
10^-5
25 GeV
10^-6
0.0
2.5
5.0
7.5
10.0
12.5
dN/dp (P̄ / GeV/c proton)
P̄ MOMENTUM GeV/c



dN/dp (GeV^-1 c)
120 GeV/c
W
0 < θ < 60 mrad
10^-3
0 < θ < 30 mrad
10^-4
0
4
8
12
16
20
p (GeV/c)

Primary beam

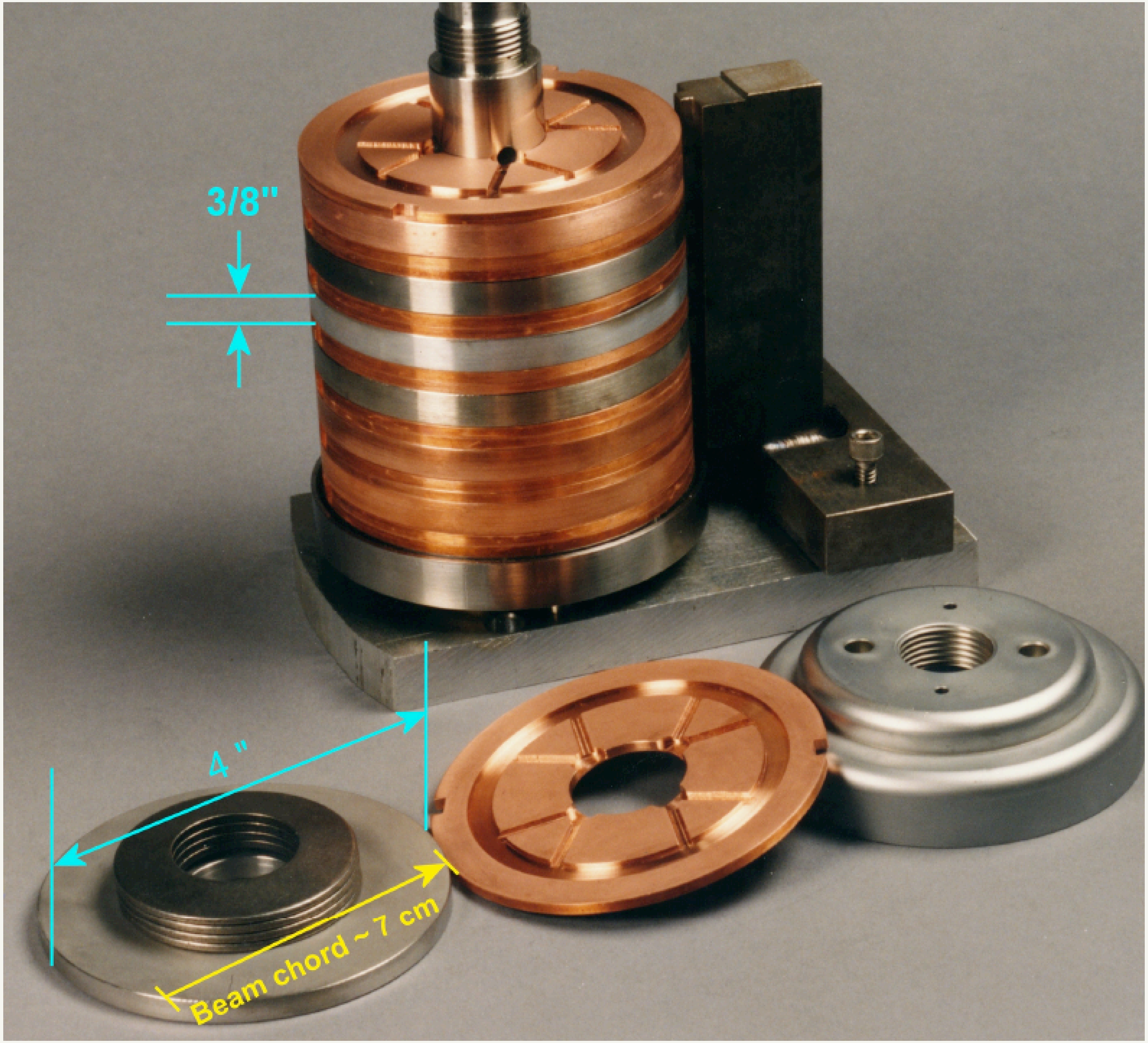
- 120 GeV protons from Main Injector
- 82 bunches every 1.5 s, 8 x 10^{12} p/pulse
- momentum spread 0.15%
- transverse size (rms) 0.2 mm



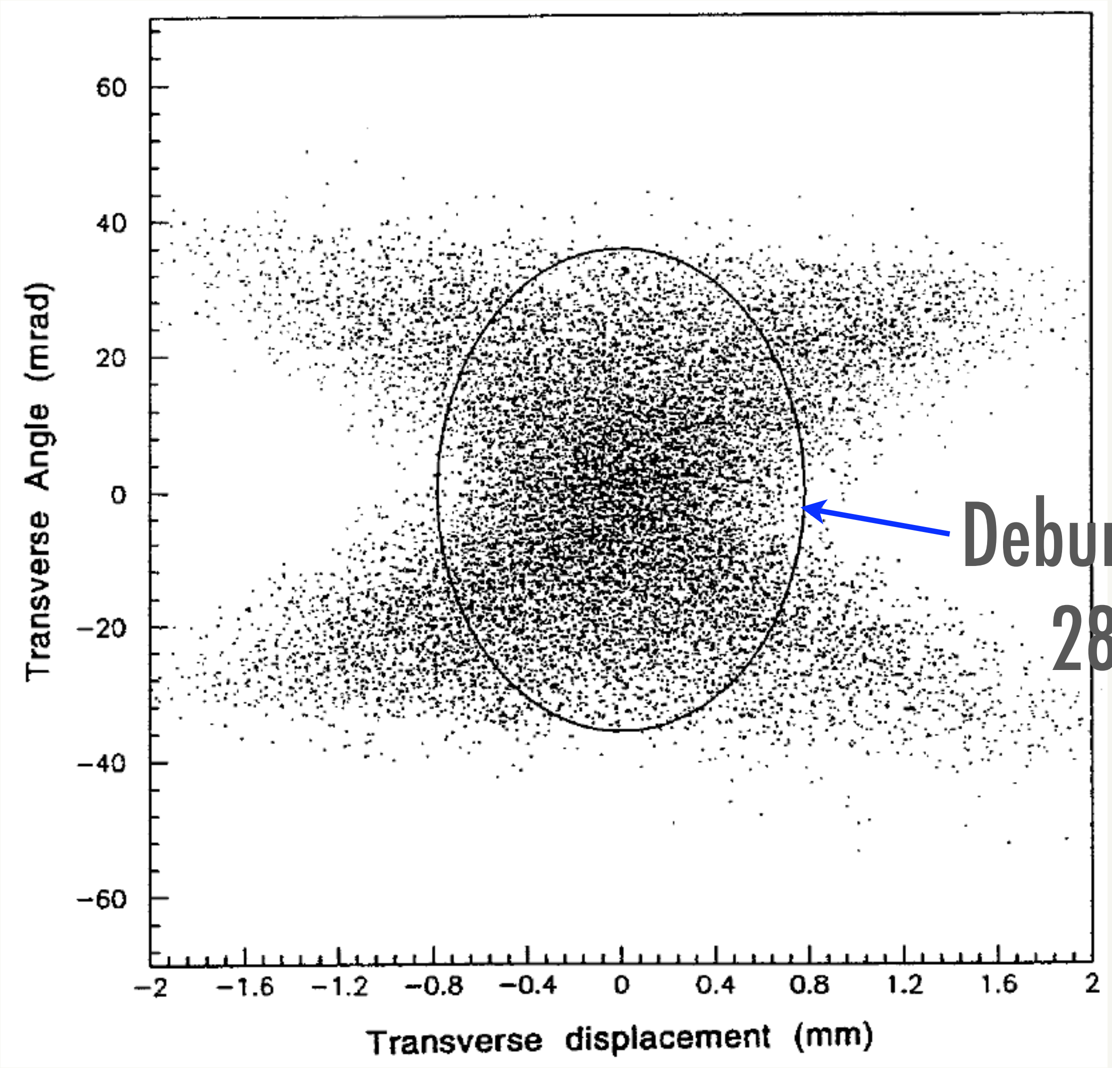
Pulsed Magnet
Li Lens
Target Module (Missing)
Target SEM
Proton Beam

Target station

- Beam power 0.4 kW deposited over small target volume
- Compromise between energy density and beam emittance
- High Z for high phase-space density
- Consider thermal capacities and melting points
- Pressure variations due to shock waves (Gruneison's constant)
- FNAL: copper or nickel in a rotating stack to change material and thickness


3/8"
4 "
Beam chord ~ 7 cm

Transverse phase space of produced pbars

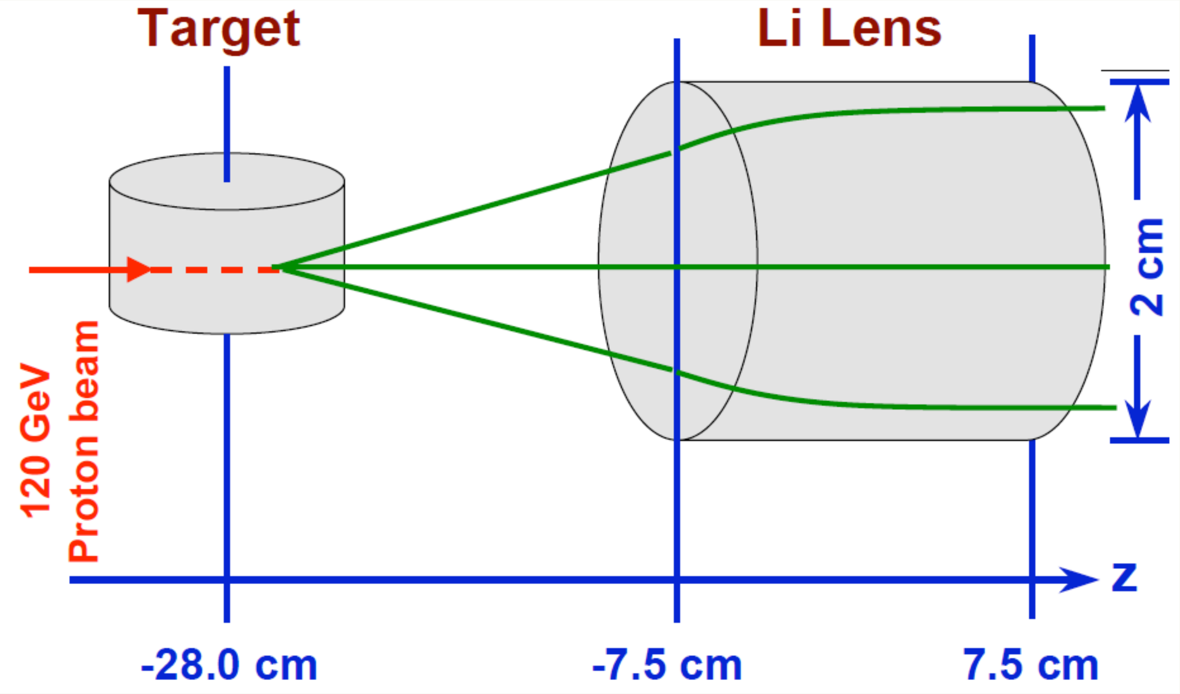


Debuncher acceptance
28 π mm mrad

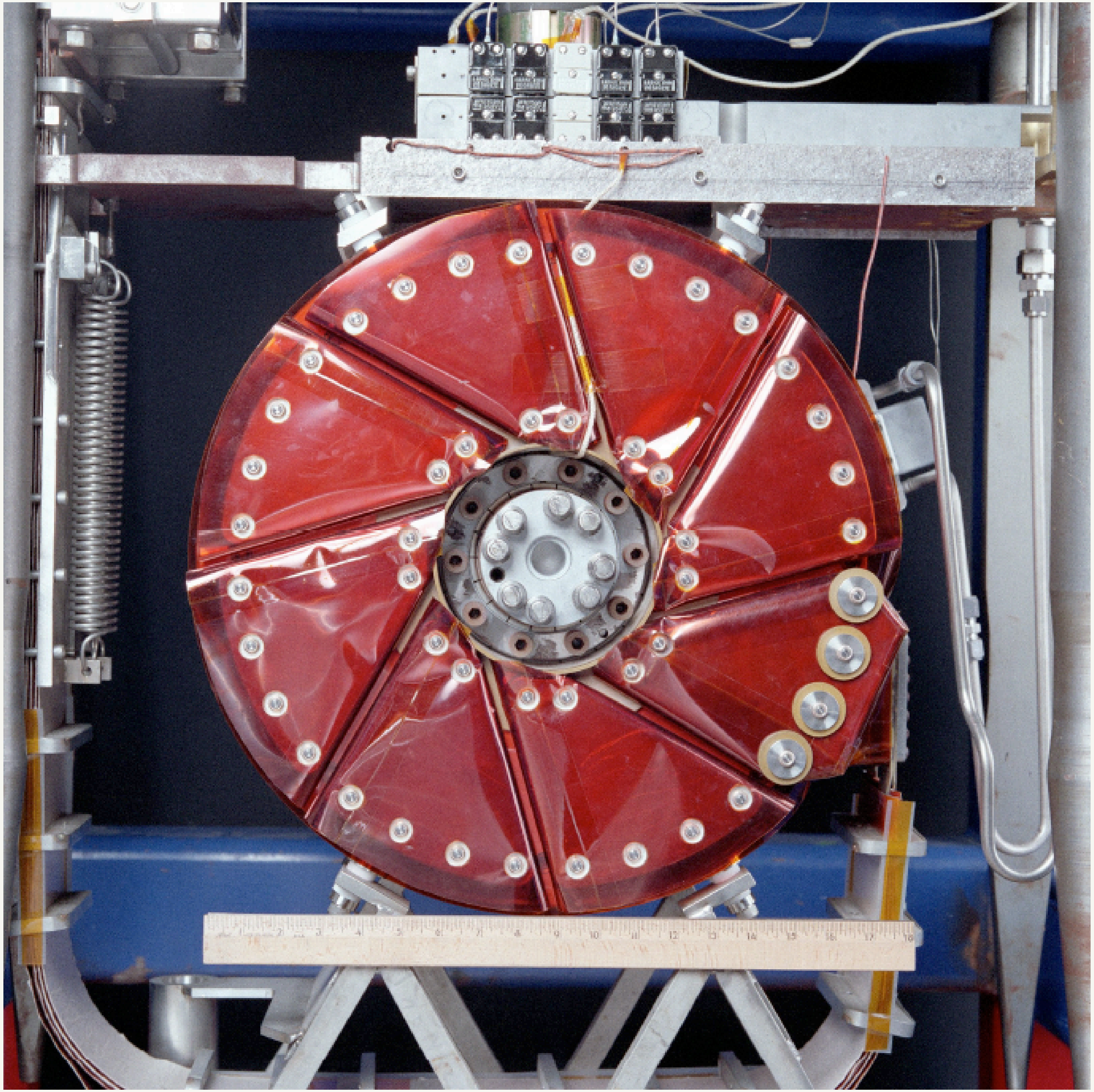
Need special focusing device: <u>the lithium lens</u>

Lithium lens

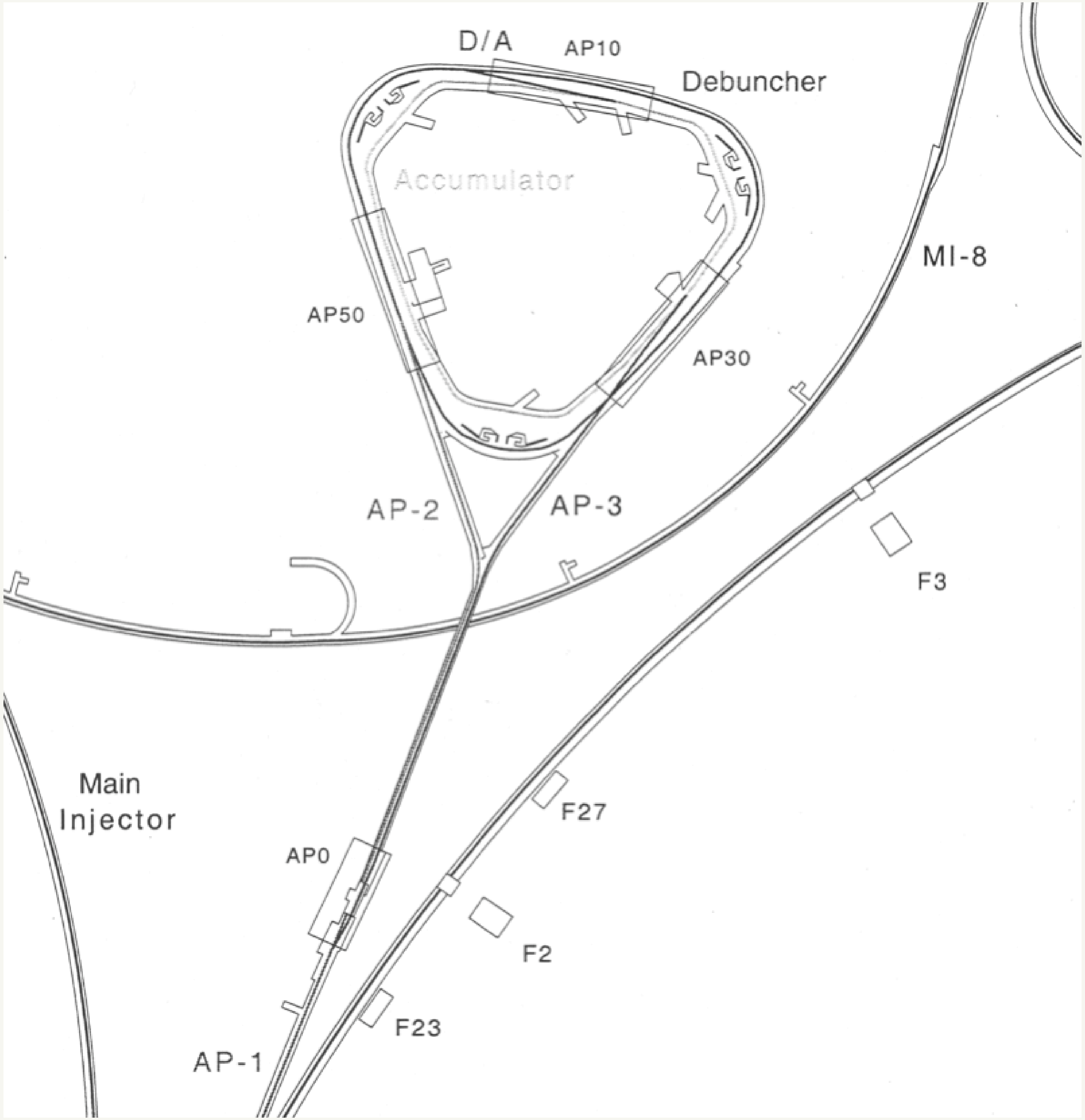
- 1-cm-radius, 15-cm-long, cylindrical piece of lithium with large axial current
- 0.4 MA current in 0.33 ms pulse



- Can match beam phase space
- Focuses in both planes, since $B_\theta = (\mu_0 J / 2) r$
- Beam losses and emittance growth due to passage through material
- Nuclear, mechanical, and electrical requirements make lithium only choice
- Requires cooling jacket to insulate from cooling water (titanium at FNAL)



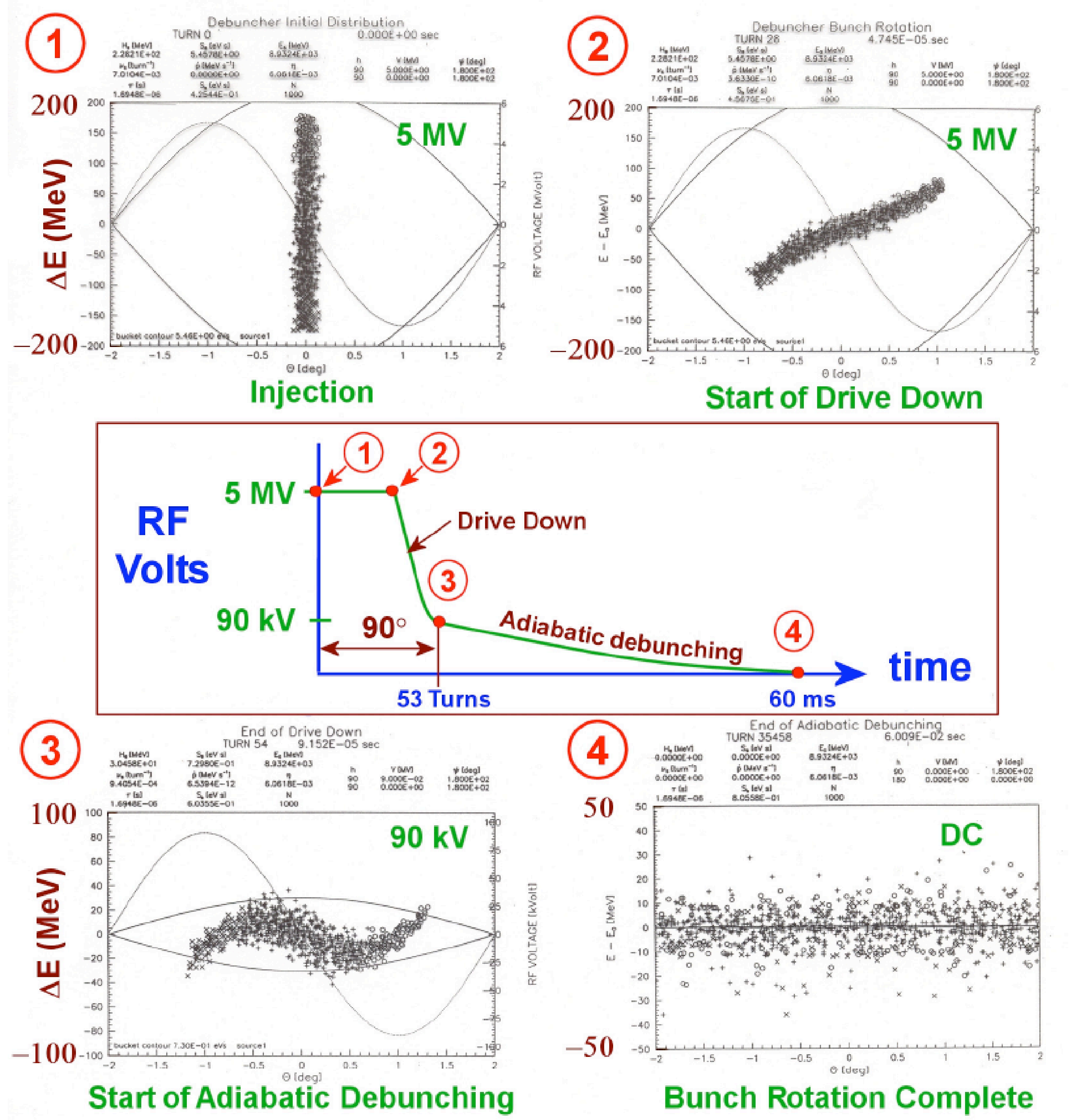
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18



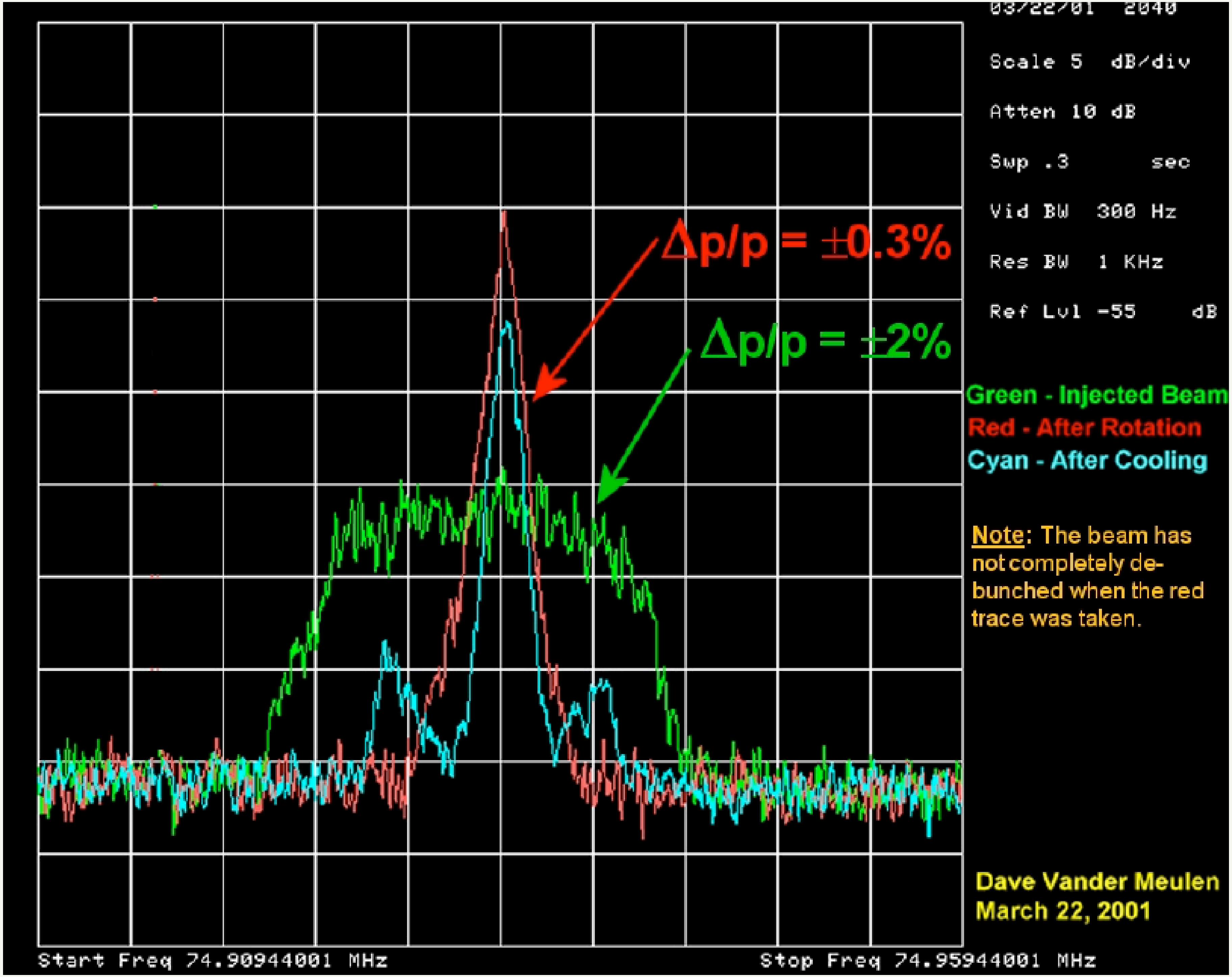
D/A
AP10
Debuncher
Accumulator
MI-8
AP50
AP30
AP-2
AP-3
F3
Main
Injector
F27
AP0
F2
F23
AP-1

Debuncher ring

- Acceptance: 28 π mm mrad transversely, ±2% longitudinally
- Reduce momentum spread by bunch rotation
- Perform stochastic pre-cooling

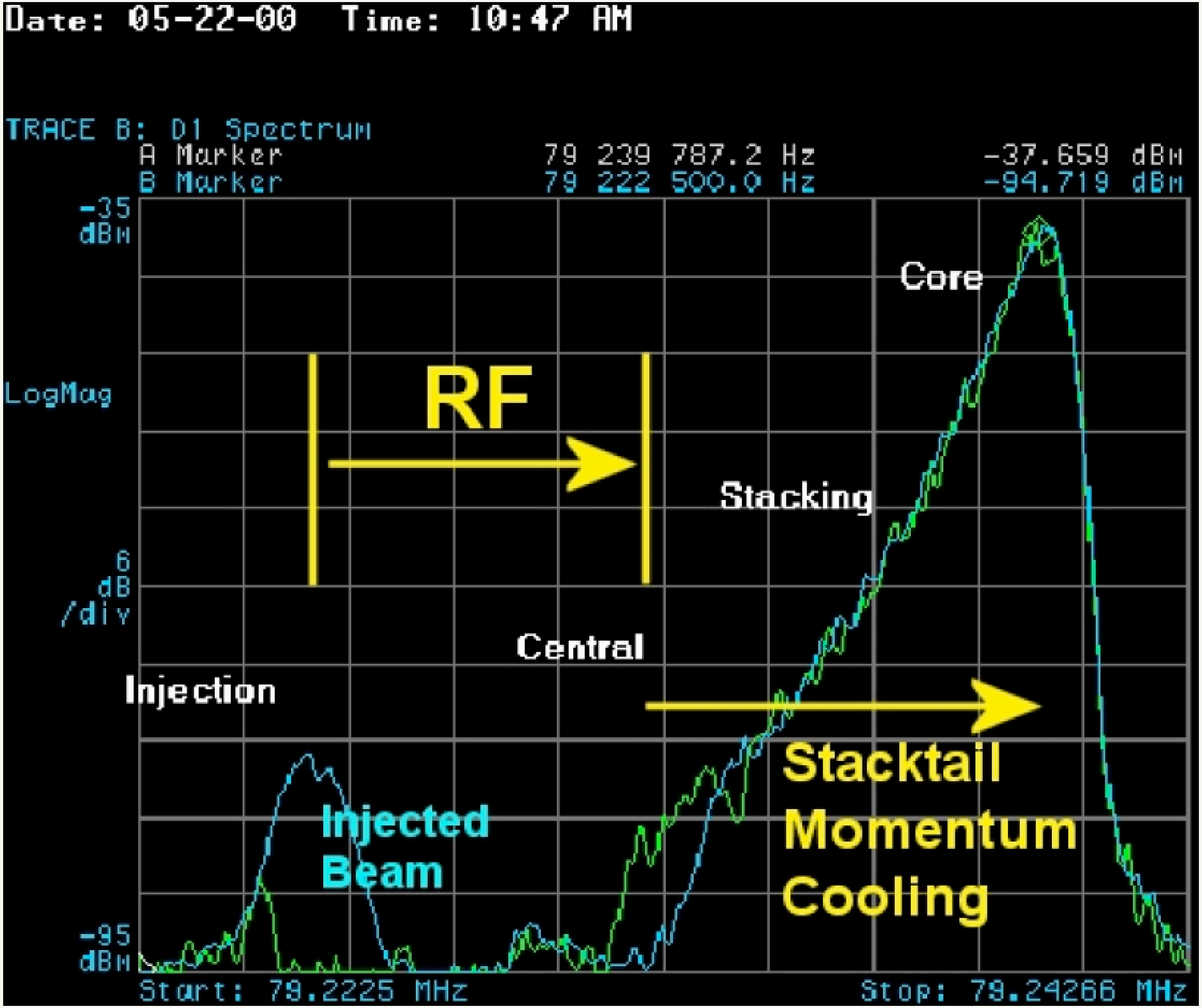


1
Debuncher Initial Distribution
TURN 0
0.000E+00 sec
5 MV
ΔE (MeV)
Θ [deg]
Injection
2
Debuncher Bunch Rotation
TURN 26
4.745E-05 sec
5 MV
Θ [deg]
Start of Drive Down
RF Volts
5 MV
90 kV
Drive Down
90°
Adiabatic debunching
time
53 Turns
60 ms
3
End of Drive Down
TURN 54
9.152E-05 sec
90 kV
ΔE (MeV)
Θ [deg]
Start of Adiabatic Debunching
4
End of Adiabatic Debunching
TURN 35458
6.009E-02 sec
DC
Θ [deg]
Bunch Rotation Complete


03/22/01 2040
Scale 5 dB/div
Atten 10 dB
Swp .3 sec
Vid BW 300 Hz
Res BW 1 KHz
Ref Lvl -55 dB
Δp/p = ±0.3%
Δp/p = ±2%
Green - Injected Beam
Red - After Rotation
Cyan - After Cooling
Note: The beam has not completely de-bunched when the red trace was taken.
Dave Vander Meulen
March 22, 2001
Start Freq 74.90944001 MHz
Stop Freq 74.95944001 MHz

Accumulator ring

- Perform stochastic stacking
- Cool both longitudinally and transversely
- Max. stack size of about 250×10^{10} pbars
- Send beam to Main Injector / Tevatron for acceleration to 1 TeV for CDF and D0 or perform internal experiments (charmonium spectroscopy, antihydrogen formation, antiproton decay searches, ...)
- Return to stacking mode



Date: 05-22-00 Time: 10:47 AM
TRACE B: D1 Spectrum
A Marker 79 239 787.2 Hz -37.659 dBm
B Marker 79 222 500.0 Hz -94.719 dBm
-35 dBm
LogMag
6 dB /div
-95 dBm
Start: 79.2225 MHz
Stop: 79.24266 MHz
RF
Core
Stacking
Central
Injection
Injected Beam
Stacktail Momentum Cooling

Stacking rate

- The figure of merit for the antiproton source is the stacking rate
- Estimate:

$$\left(8 \times 10^{12}\,\frac{\mathrm{p}}{\mathrm{pulse}}\right)\left(0.6\,\frac{\mathrm{pulses}}{\mathrm{s}}\right)\left(2 \times 10^{-5}\,\frac{\bar{\mathrm{p}}}{\mathrm{p}}\right)\left(3600\,\frac{\mathrm{s}}{\mathrm{h}}\right) = 35 \times 10^{10}\,\frac{\bar{\mathrm{p}}}{\mathrm{h}}$$

- FNAL reached 20 x 10^{10} pbars/h in February 2006 (was 3 x 10^{10} pbars/h in 2000 for E835)

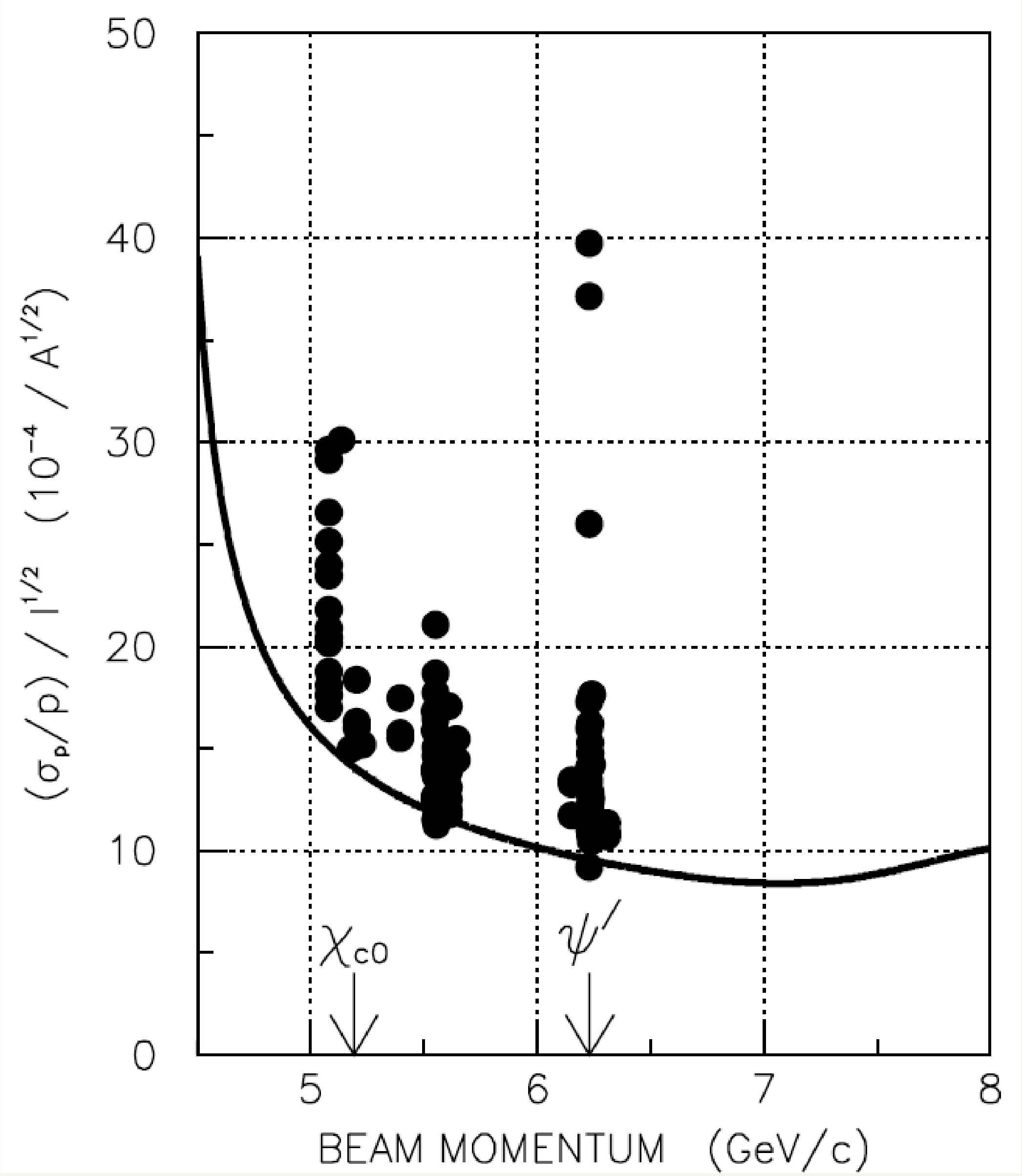
Intensity limitations

- Intrabeam scattering
- Residual-gas scattering
- Magnet power supply ripple
- Wall impedances
- Trapped ions

Wall impedances - longitudinal

Stability criterion (Ruggiero and Vaccaro, Keil and Schnell)

$$\left|\frac{Z}{h}\right| < \frac{2\pi F \beta^2 E |\eta|}{qI} \left(\frac{\Delta p}{p}\right)^2$$



D. P. McGinnis, G. Stancari, and S. J. Werkema, NIM A **506**, 205 (2003)

Diagnostics

- Pbars are too precious. You can’t save money on diagnostics
- Possibility of forward and reverse protons: apertures, tunes, steering, kicker timing, rf manipulations, cooling parameters
- Schottky pickups: single most useful device
- Beam current transformers, position monitors, profile monitors
- Scrapers

Bibliography

- M. D. Church and J. P. Marriner, "The antiproton sources: design and operation," Annu. Rev. Nucl. Part. Sci. **43**, 253 (1993)
- J. Morgan, "The antiproton source rookie book," August 1999, <http://www-bdnew.fnal.gov/pbar/documents/PBAR_Rookie_Book.pdf>
- Contributions by J. Peoples, J. Marriner and G. Dugan in "Handbook of Accelerator Physics and Engineering," A. W. Chao and M. Tigner (eds.) (World Scientific, 1999)