Diagnostics for High Intensity Hadron Accelerators

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Examples of High Intensity Hadron Accelerators

Short pulse spallation neutron sources

H- linac plus accumulator ring(s) (e.g., SNS, ESNS, PSR)

H- linac plus rapid cycling synchrotrons (RCS) ring (e.g., ISIS, IPNS, AGS, NMI)

Long pulse spallation neutron sources (possible LANSCE application)

pulsed proton linac.

Tritium production (e.g., APT)

CW proton linac (e.g., 100 mA @ 1.7 GeV!!).

Waste transmutation (e.g., ATW)

CW proton linac.

Anti-proton production (for pbar – p colliders)(e.g., Tevatron)

H- linac plus synchrotrons.

Muon production (proton driver for muon collider)

H- linac plus RCS synchrotron.

Energy Amplifier (C. Rubbia)

FFAG Cyclotron?

Other (isotope production, radiation effects meas., neutral particle beams, etc.)

Diagnostics Uses

<u>Needs for beam diagnostics</u>

- Commissioning.
- Monitoring normal operation (machine protection, tuning).
- Identification of and recovery from off-normal operation.
- Machine development and improvement studies.

<u>Special needs for high intensity hadron machines.</u>

- Linacs (proton and H-)
  - emittance control (especially for H- injection)
  - halo control (especially for CW linacs)
  - steering
  - beam losses
  - component damage
  - activation
- Rings (synchrotrons and accumulator rings)
  - closed orbit
  - beam stability
  - transition crossing & resonances
  - emittance growth
  - Halo control

H^- Linacs

<u>H- Linacs</u>

•All the problems of proton linacs, plus the added problems of H- beams.

•Energy spread and bunch lengthening happen very quickly at low energies.

•Mismatches (transverse and longitudinal) lead to halo development & emittance growth.

•Losses must be controlled to roughly 1 watt per meter, independent of beam power.

•Mis-steered beam can destroy accelerator components very quickly, especially at low energies.

•H- stripping on residual gas is a major source of beam loss and activation (need good vacuum).

•Magnetic stripping is easily controlled below ~ 1.5 GeV (e.g., bend radius ρ >= 34 m for 1.5 GeV).

•Any H- beam that hits an interceptive diagnostic (e.g., wire scanner) gets stripped and lost.

Linacs -Beam Current Monitors

<u>Beam current monitors (BCMs: toroids, DCCTs)</u>

- Useful but not essential after initial commissioning (except for low β).
- Differential current measurement required for machine protection (low β).
- BCM does not require bunching structure, so can detect debunched beam.
- Differential current monitors cannot detect losses at the level required to prevent activation (<1 watt per meter at 1 GeV, corresponding to ~1 part per million/meter).

Linacs - Beam Position Monitors

Beam position monitors (BPMs)

Totally non-interceptive.
Needed for steering correction.
Can be used for synchronous phase measurement (required for setting phase and amplitude.
Can be used for energy measurement (time of flight; low β)
Sum (intensity) signal useful for commissioning.
Not much good for beam profile measurement (quadrupole moment).

Stripline type
Good sensitivity and dynamic range.

Buttons
Good for very short bunches (electrons), but lack sensitivity for longer proton bunches with less charge per bunch.

Linacs-Beam Profile Monitors

Beam profile monitors

Needed for transverse beam size measurement, transverse matching.
Generally good for rms profile, but not halo measurement (> 3 σ).

Wire scanners (stepping wires, flying wires)

Interceptive; requires low duty cycle operation, especially at low beam energies.
Flying wires may work at higher energies in CW linacs (lower dE/dx).
Wires strip H- beams, create large losses.
May interfere with superconducting cavity operation (beam losses, wire ablation).

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Laser wires (H- only).

Laser photo-detachment cross section ~40,000,000 barns at 1.5 eV photon energy.
(at 0.8 μm laser photon energy in H- rest frame).

Good non-interceptive technique, but needs development.

Laser Photo-Detachment Profile Monitor

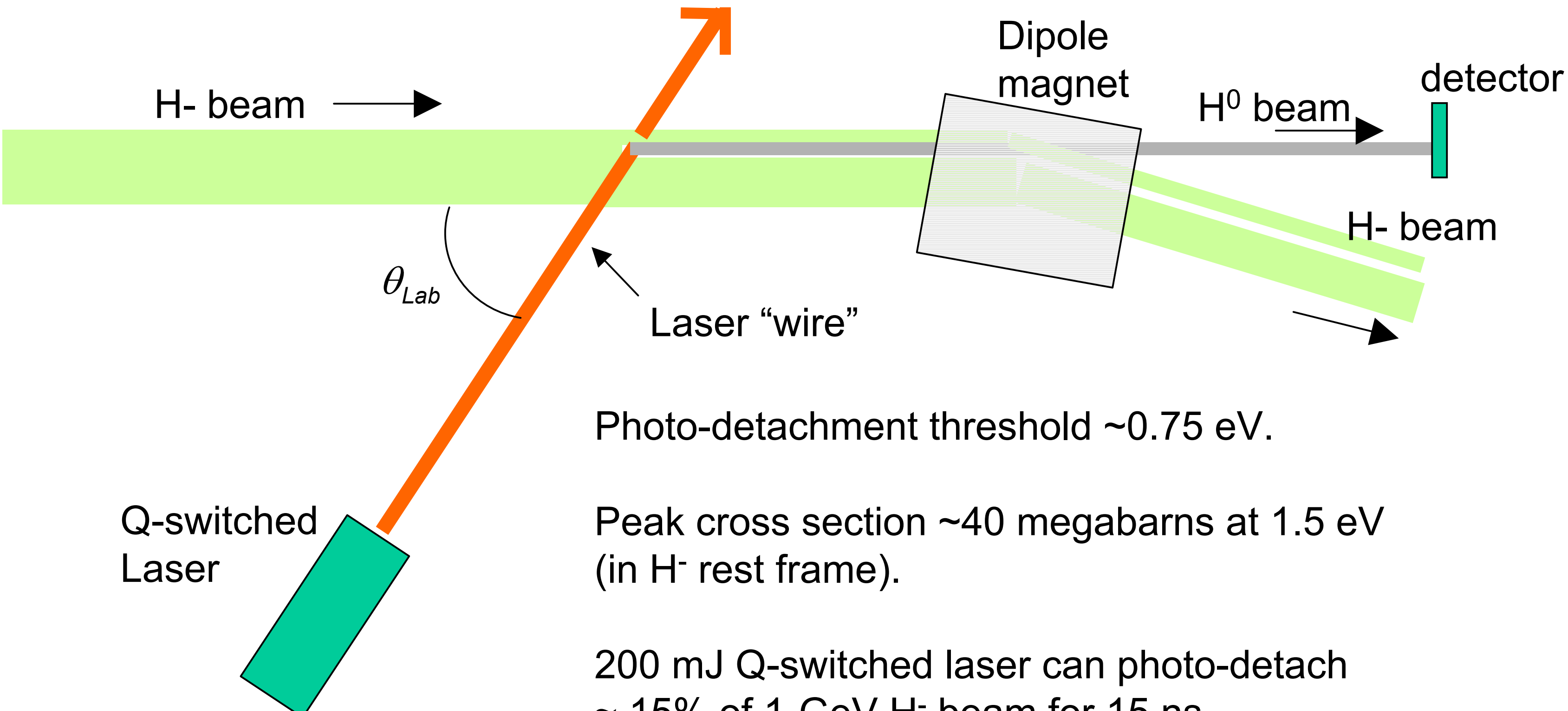


Photo-detachment threshold ~0.75 eV.

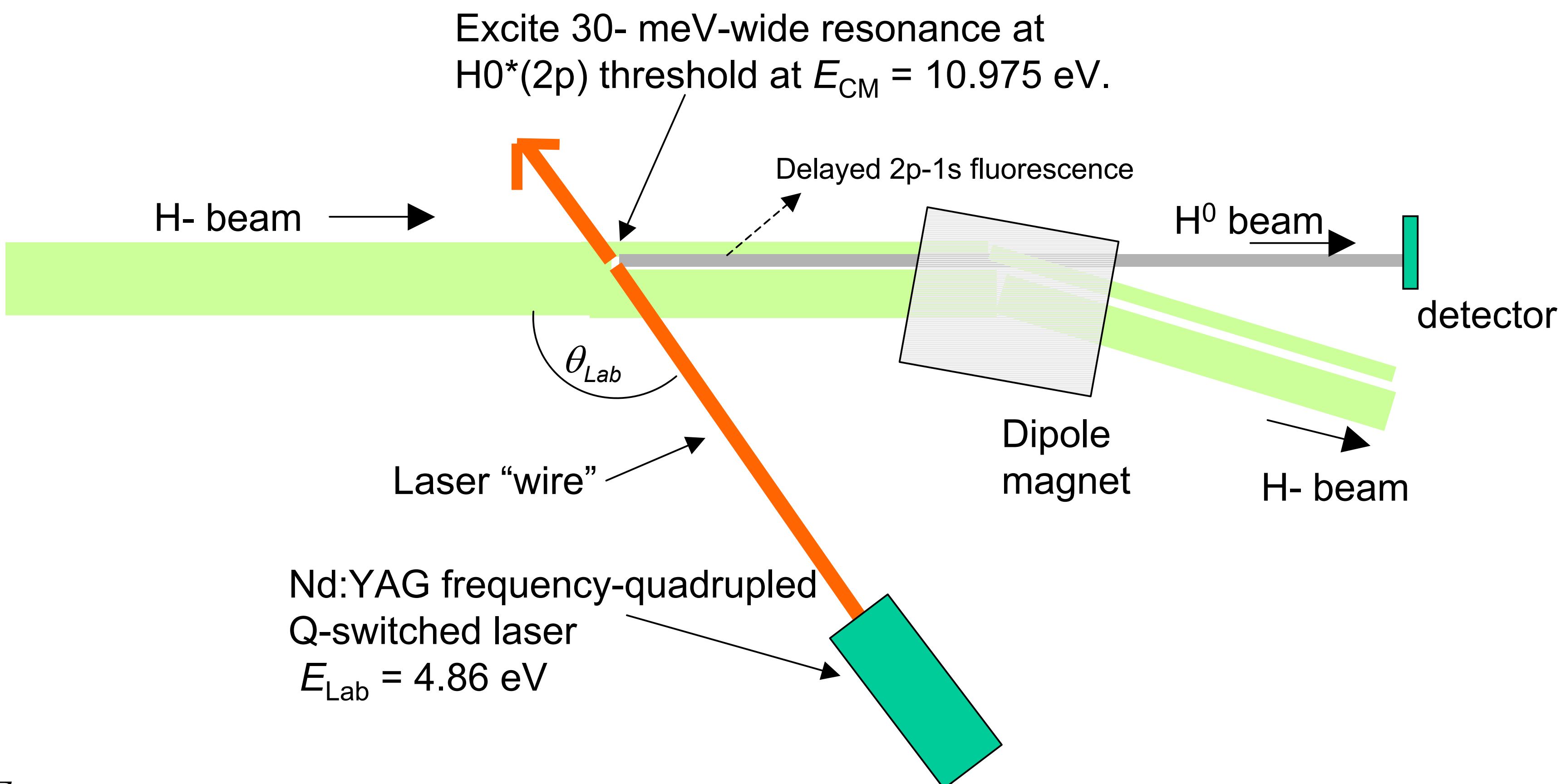
Peak cross section ~40 megabarns at 1.5 eV (in H^- rest frame).

200 mJ Q-switched laser can photo-detach ~ 15% of 1-GeV H^- beam for 15 ns.

$E_{CM} = \gamma E_{lab} \left[1 - \beta \cos\theta_{lab} \right]$ Photon energy Lorentz transformation to H- rest frame.

$$Yield \cong \frac{I_b N_{laser}}{\sqrt{2\pi} e \beta c} \frac{1 - \beta \cos\theta_{lab}}{\sin\theta_{lab}} \frac{\sigma_N \left(E_{CM} \right)}{\left(\sigma_{beam}^2 + \sigma_{laser}^2 \right)^{1/2}}$$

Laser Energy and Energy Spread Monitor



$$\frac{E_{CM}}{E_{lab}} = \gamma\left[1-\beta\cos\theta_{lab}\right] = 2.258$$ Photon "gamma" (energy) boost from Lorentz transformation.

$$Yield \cong \frac{I_b N_{laser}}{\sqrt{2\pi} e\beta c}\frac{1-\beta\cos\theta_{lab}}{\sin\theta_{lab}}\frac{\sigma_N\left(E_{CM}\right)}{\left(\sigma_{beam}^2+\sigma_{laser}^2\right)^{1/2}}$$

Linacs – Profile Monitors (cont)

Residual gas ionization

Expensive, requires lots of beamline space. Also requires E-field and B fields to counteract effects of beam potential.

Residual gas fluorescence.

Questionable usefulness (excited atomic state lifetimes & thermal drift velocities, photon yield & collection efficiency, gas stripping of H- beams).

BPM quadrupole moment measurement.

Will not work for round beams, only highly elliptical beams.
Proposed by Miller in 1983, but only one or two applications have been made to work.

Bunch length measurement

Witkover/Feshenko bunch length monitors (secondary emission electrons from wires).

Mode-locked laser (H- beam only).

Phase dependence of capture in RF buckets (DTL) (maybe).

Accumulator Rings

General comments

Very high beam currents- large space charge effects.

Coupling impedances of diagnostics pickups are important.

No (persistent) high-harmonic RF structure – only h=1 or h=2.

Poor signal response of derivative-coupled (d/dt-coupled) diagnostics at low frequencies (e.g., BPMs).

Long fill times – typically 1 millisecond. Plenty of time for instabilities to develop.

Accumulator Rings – Diagnostics Requirements

Beam Current Monitors (BCMs)

- Fill efficiency monitoring (what % of linac beam gets into ring, vs. turn number).
- Beam current losses due to instabilities.
- Beam envelope azimuthal shape (line current) evolution (synchrotron osc. freq. Is very low).
- Requires very high beam current dynamic range.
- Measure extraction efficiency (with BCM in extraction line).

Beam Position Monitors (BPMs)

- Closed orbit measurement
- Use low-*h* revolution frequency harmonic (no persistent high-*h* RF bunching).
- BPMs have derivative coupling, so poor low frequency response.
- Require very high amplitude dynamic range.
- Need to avoid harmonics that have zero Fourier transform (e.g., h=2 for half-filled ring).

- Transverse instability detection
- Must have very wide bandwidth response.
- Monitor revolution harmonic betatron sidebands up to 100's of MHz.
- Requires very high amplitude dynamic range.
- Very strong revolution harmonic signal from beam gap in electrode signals.
- Electrode sum signal similar to wide-band "wall current" monitor for line current density.

PSR Wide Band BPM Signals

Example wide-band BPM in Proton Storage Ring (PSR)

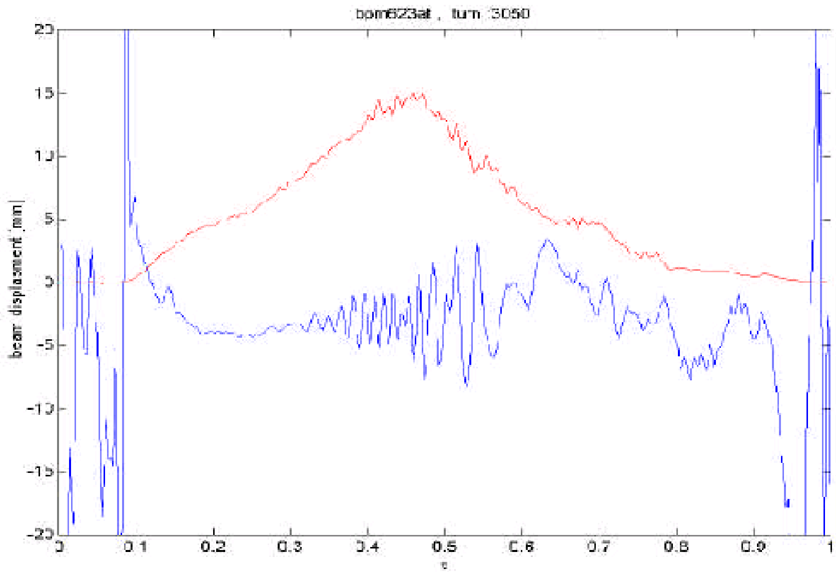


Figure 2. Beam displacements during one turn (blue line). Red curve is beam current profile.

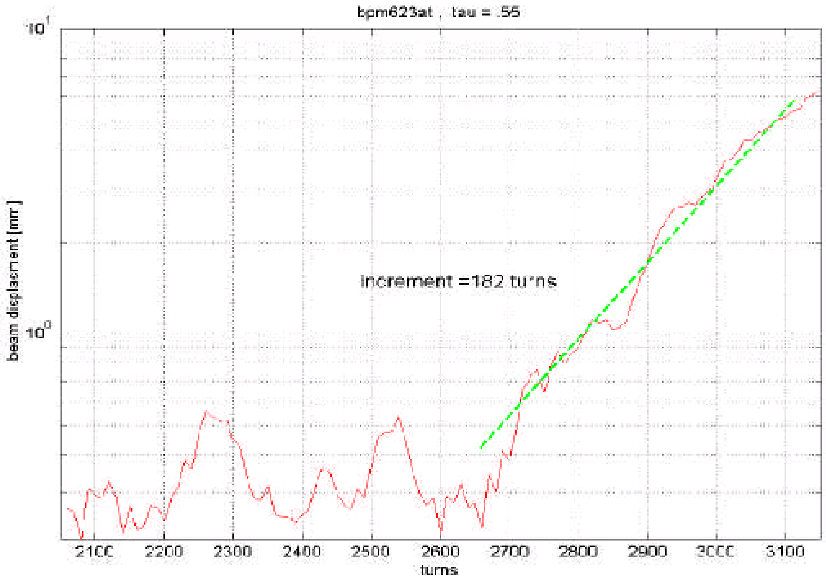


Figure 3. Amplitude of transverse oscillations versus number of turns.

Courtesy Sasha Aleksandrov

Beam current profile (line current density) and transverse beam oscillations during single turn.

Amplitude of transverse beam oscillations vs. turn number.

PSR Wide Band BPM Signals

Wideband BPM signal analysis from Proton Storage Ring.

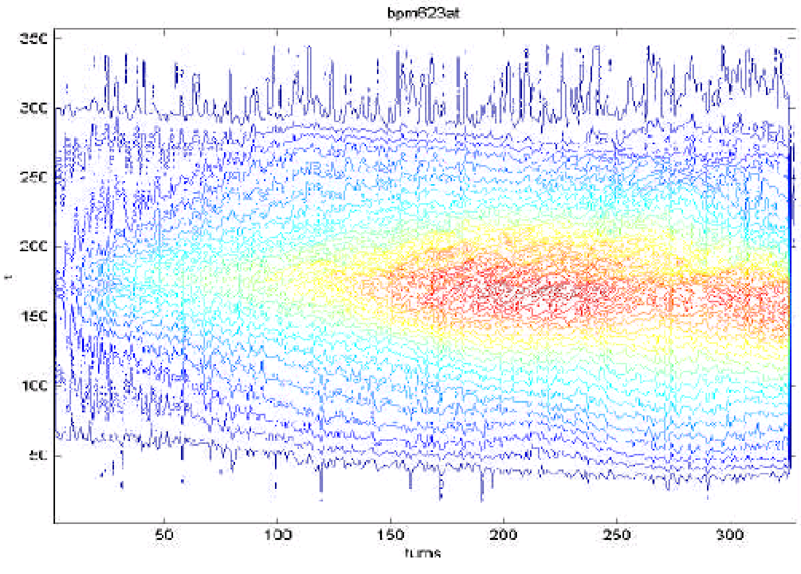


Figure 4. Contour plot of beam charge distribution in beam frame of reference in

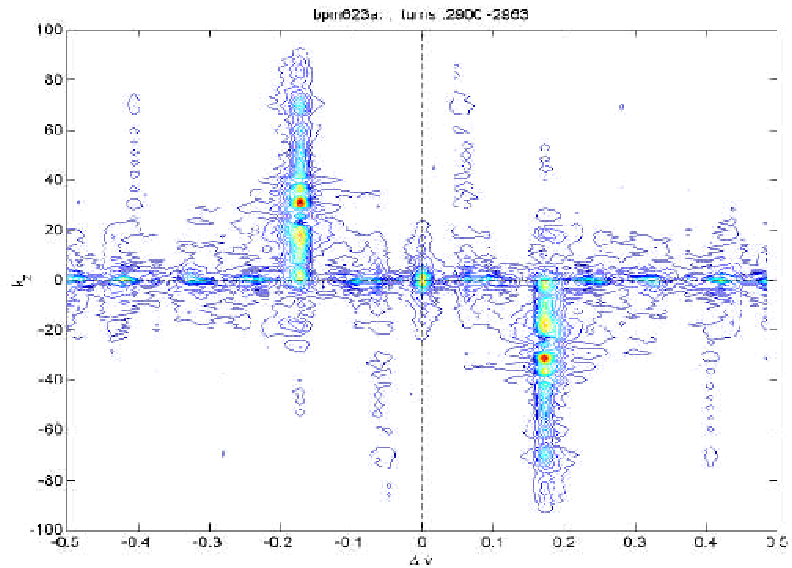


Figure 5. 2D Fourier spectrum of transverse beam oscillations.

Courtesy Sasha Aleksandrov

Charge (line current) distribution in ring vs. turn number. Vertical axis is azimuth in degrees, color is line current density, horizontal axis is turn number.

Fourier analysis of betatron sidebands in wideband transverse oscillation spectrum. The vertical axis is the revolution harmonic number, color is amplitude, and horizontal axis is fractional tune.

Accumulator Rings – Diagnostics Requirements(2)

<u>Beam profile measurement (painted beams)</u>

Avoid interceptive monitors (e.g., wire scanners) if possible.
Problems include wire heating, multiple scattering, nuclear scattering.

<u>Lasers don't work</u>
Proton Compton cross-section is too low.

<u>Gas ionization profile monitors</u>
Good choice if distortion from beam potential well can be corrected with large B and E fields.

<u>Gas fluorescence profile monitors.</u>
Maybe, but no real successful demonstration yet.
Poor photon collection efficiency compared to ion collection.

<u>Beam loss (ionization) monitors</u>
Similar to linac requirements.
Need to limit losses to ~ 1 watt/meter

<u>Halo monitors</u>
Difficult measurement. Halo hitting wall probably causes e-p instability.

RCS Diagnostics Requirements

General

Beam diagnostics is generally easier than for accumulator rings.

Much lower beam currents than accumulator rings.

Filling time is a few μs to 400 μs typically (H- charge-exchange injection).

Strong RF bunching generally reduces instabilities.

Beam current dynamic range requirement is lower than accumulator ring.

Strong RF bunching harmonic signal facilitates operation of BPMs.

Diagnostics must be frequency compliant (RF frequency changes during acceleration).

Resonances and transition crossing: Need mountain-range displays of bunch length.

RCS-Wall Current Monitor

Mountain range display of wide-band wall current monitor showing bunch phase oscillations in FNAL Booster synchrotron.

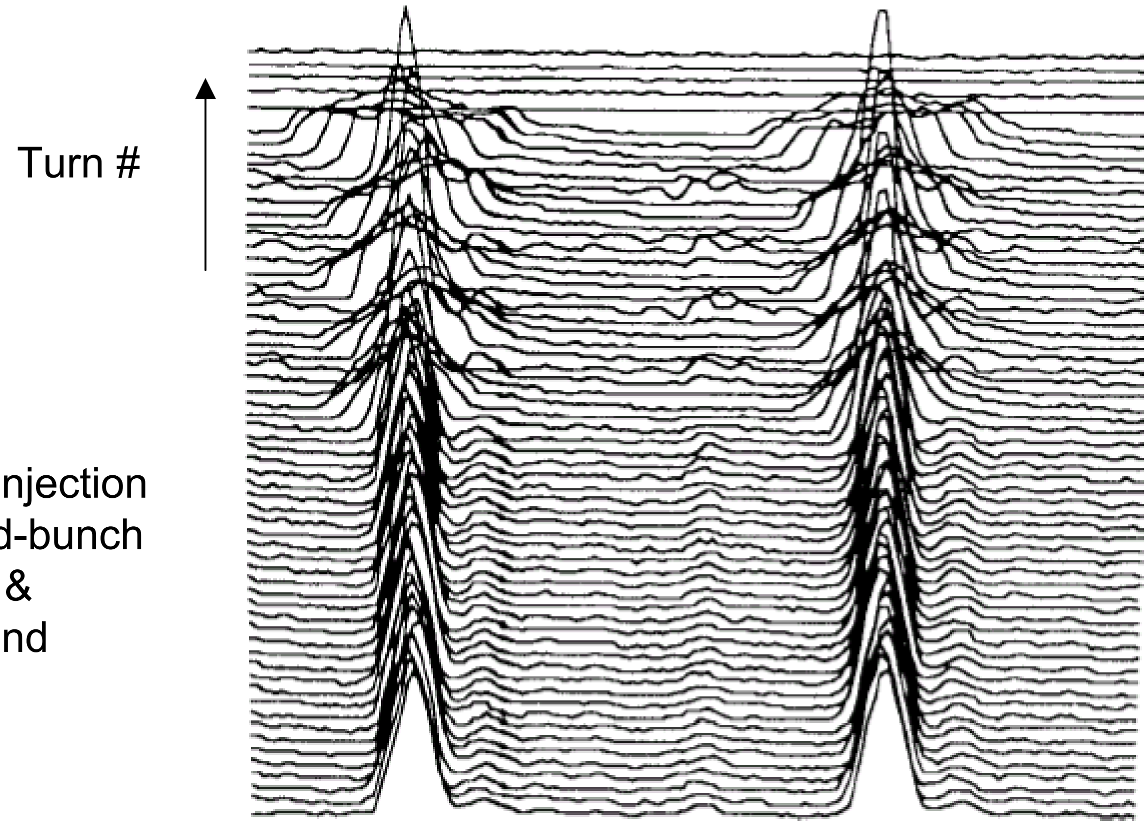


Figure 3. tumbling bunches in the Booster.

Courtesy Jim Griffin

Useful for observing injection phase errors, coupled-bunch effects, bunch dipole & quadrupole modes, and transition crossing.

RCS-Beam Position Monitors

Closed orbit measurement (BPMs)

Stripline type (not buttons) for protons.

Must have sufficient bandwidth for frequency change during acceleration.
use difference/sum or log ratio, not AM/PM processing.

Measure sum signal as well as difference (or ratio)- useful during commissioning.

Other BPM Measurements

Tune measurements (Fourier harmonic analysis of turn-by turn).
Dispersion
Beta functions
Chromaticity
x – x' phase space trajectories
x – y coupling
etc.

RCS - Other diagnostics

Profile
Need fast profile measurements, residual gas beam profile monitor may work.

Halo
Intercepting adjustable scrapers may work; produce betatron oscillations and energy loss, leading to interception by collimators.

Beam loss monitors
Need to control losses to about 1 watt per meter.
Gas ionization beam loss monitors are fast enough for most applications.