Design Considerations for Antiproton Stacking and Cooling

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Director's Review

Outline

- Parameter Goals
- Antiproton Stacking Process
- Issues
- Key Parameters
- Study Plan
- Summary

Parameter Goals

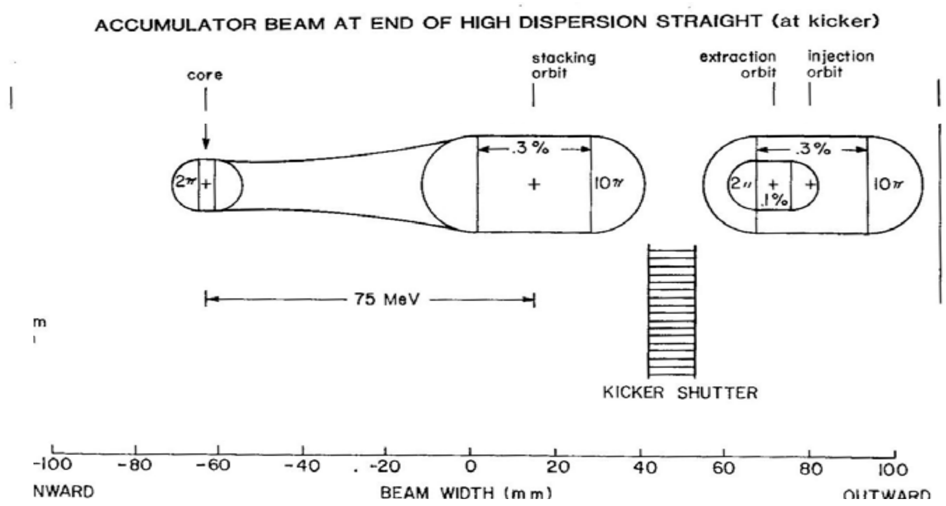
- Goals
  - Average Stacking Rate 40×10^{10} pbars/hour
  - Stack at this rate for at least 15 hours
  - Final Stack Parameters
    - Size = 625×10^{10} pbars
    - Transverse emittance < 15π-mm-mrad (95% normalized)
    - Longitudinal emittance < 50 eV-Sec
- Inputs
  - Collect 280×10^{6} antiprotons from the target every 2 seconds
    - Transverse emittance = 35π-mm-mrad (95% **un-normalized**)
    - Momentum Spread = 4%
    - Bunch lengths < 1.5 nS

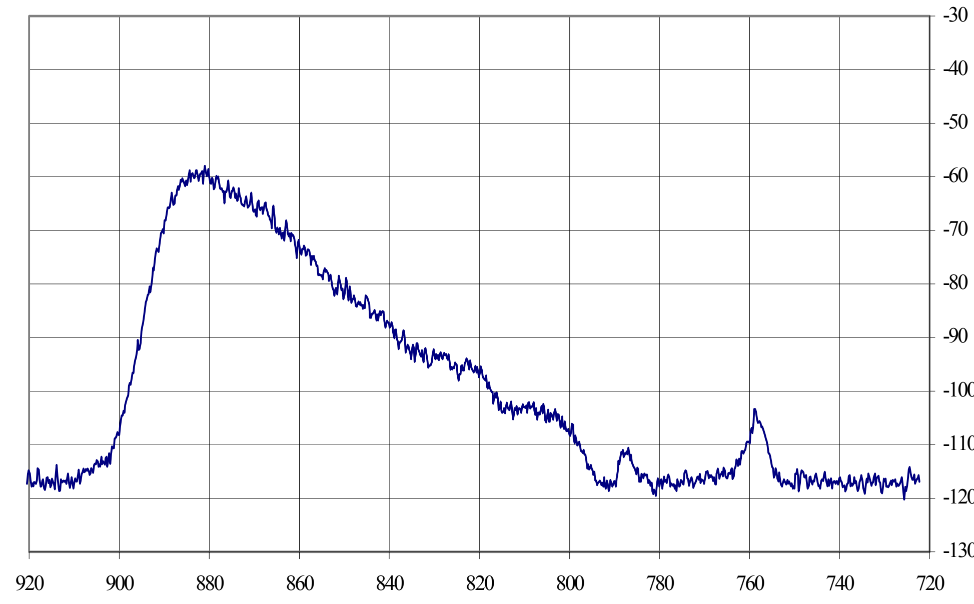
Antiproton Stacking Process

- Debuncher Bunch Rotation
  - Exchange
    - Large Momentum spread of 4% (360 MeV)
    - Short bunches < 1.5 nS (95%)
  - For
    - Small momentum spread of 0.4% (36 MeV)
    - Coasting beam
- Debuncher Cooling
  - System Configuration
    - Liquid Helium front end (T_{eff}=30K)
    - Bandwidth = 4-8 GHz Subdivided into 4 bands
    - Available kicker power
      - 2400 Watts/ plane (transverse)
      - 4800 Watts (momentum)
  - Cooling Rate Specs.
    - Momentum: 36 MeV to 6 MeV in 1.9 Seconds
    - Transverse: 35π-mm-mrad to 5 π-mm-mrad (95% un-normalized) in 1.9 seconds

Antiproton Stacking Process

- Accumulator Stacktail Cooling
  - Process
    - Beam is injected onto the Injection Orbit
    - Beam is
      - Bunched with RF
      - Moved with RF to the Stacking Orbit
      - Debunched on Stacking orbit
    - Stacktail pushes and compresses beam to the Core orbit
    - Core Momentum system gathers beam from the Stacktail
    - Accumulator Transverse Core Cooling system cools the beam transversely in the Stacktail and Core





Antiproton Stacking Process

- Accumulator Stacktail Cooling
  - Specifications
    - Injection pulse width: 6 MeV
    - Stacktail:
      - Bandwidth = 2-6 GHz
      - Width = 42 MeV
      - Gain slope = 8 MeV (can handle 90×10^{10} pbars/hr)
      - Power = 550W into 6400Ω
    - Core momentum
      - Bandwidth = 4-8 GHz
      - Aperture = 9.6 MeV
      - Gain slope = 5 MeV (can handle 90×10^{10} pbars/hr)
      - Stacksize = 34×10^{10} pbars
    - Extraction
      - Longitudinal emittance: 10eV-sec
      - Transverse emittance 1.0π-mm-mrad
      - Stacking interval: 30 minutes
      - Transfer size: 22.5×10^{10} pbars

Antiproton Stacking Process

- Recycler Electron Cooling
  - Every ½ hour an injected batch of 22×10^{10} pbars in 10 eV-Sec and 1.0 π-mm-mrad phase space is injected into the Recycler
    - Transfers between the Accumulator and the Recycler
      - Are done on "event"
        - ~instantaneously
        - No more mini-shot setup
      - A 50% dilution is assumed to occur on each transfer
        - 15 eV-Sec and 1.5 π-mm-mrad phase space
    - Transverse stochastic pre-cooling of the injected batch
      - To bring the transverse emittance of the injected batch within the reach of the electron cooling
      - The injected batch is kept separate from the main "core" by barrier buckets
      - Transverse stochastic cooling systems are "gain gated"
        - Low density injected batch – fast stochastic cooling
        - High density core – slow stochastic cooling

Antiproton Stacking Process

- Recycler Electron Cooling
  - Every ½ hour, the previous injected batch is merged into the core with barrier bucket manipulations to make room for the new injected batch
  - The Recycler Core
    - Is cooled mainly with electron cooling in all 3 planes
      - 55eV-Sec/hour
      - 0.24π-mm-mrad/hour
    - Weak transverse stochastic cooling for high amplitude particles
    - Intra-beam scattering (IBS) is "shut-off"
      - Recycler
        - » operates below transition
        - » has low dispersion
        - » has smooth lattice functions
      - The Core is squeezed with barrier buckets so that it occupies only 20% of the machine circumference
      - The transverse emittance is cooled to less than 0.3π-mm-mrad (95% un-normalized) so that the beam temperature in all 3 planes is equal

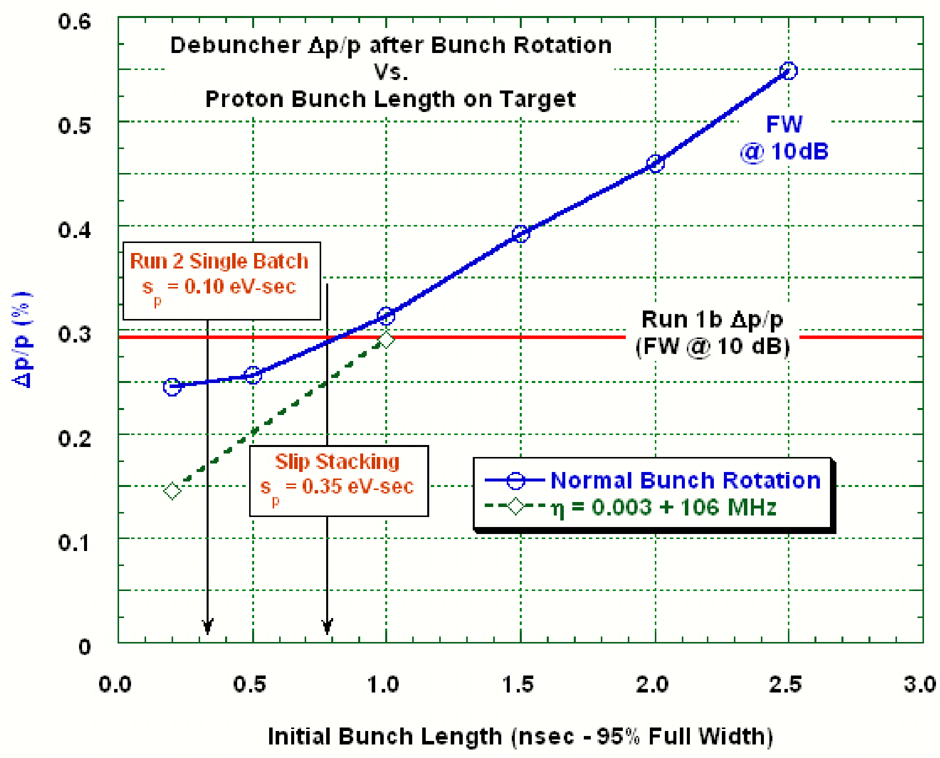
Debuncher Bunch Rotation Issues

- Momentum cooling aperture
  - Momentum Cooling rate is supposed to be very fast (0.2 Sec)
  - Momentum spread after bunch rotation must be less than the momentum aperture of the Debuncher Momentum Cooling system

$$\frac{\Delta pc}{pc} = \frac{x}{\eta}\frac{f_o}{f_{max}}$$

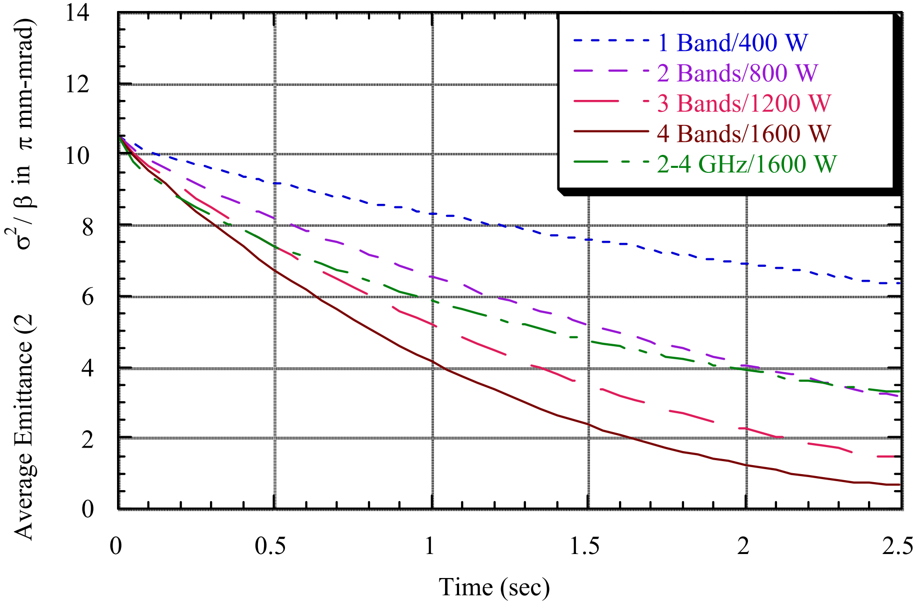
  - X=precentage spread of Schottky band
  - F_{max} = 8.2 GHz, x =1/3 requires Δp/p<0.4
  - Bunch length < 1.5 nS
- Main Injector Coupled Bunch modes

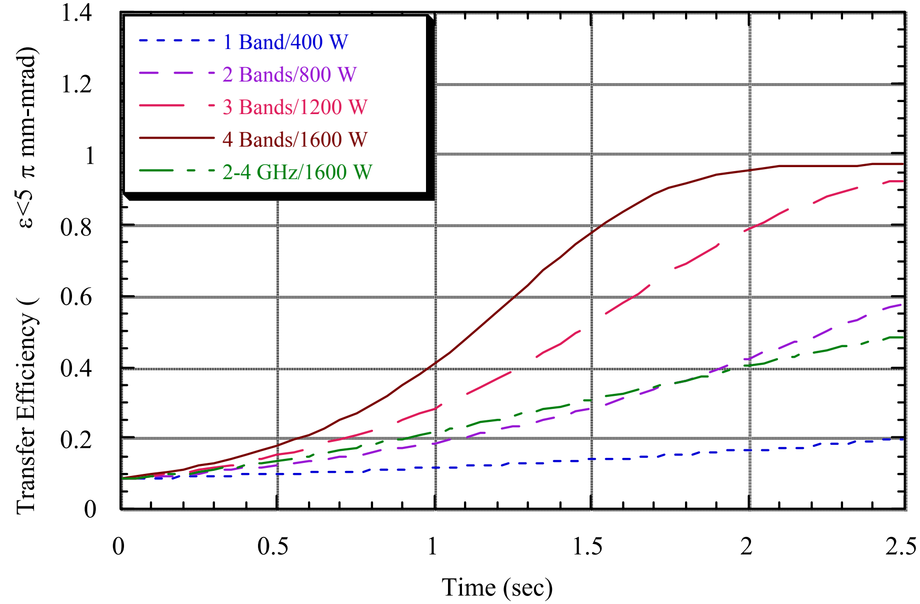
$$\tau_{95_{eff}} \approx 4\sqrt{\sigma^2_{bunch} + \sigma^2_{phase}}$$



Debuncher Transverse Cooling Issues

- Power Limited
- Cooling Rate
  - Calculations done for 400×10^6 pbars in 25π-mm-mrad give 1 sec cooling rate
  - Scaling (good signal/noise) give 1 sec cooling rate for 280×10^6 pbars in 35π-mm-mrad
  - Final emittance is 6π which gives 85% into 5π aperture.
  - Need 25% more power to get to 5π emittance





Debuncher Transverse Cooling Issues

- Power Leveling
  - Beam cools – power will drop – increase gain
  - Increase gain linearly by 25% in 2 seconds
    - Achieve 5π-mm-mrad
    - Final power level rises from 225W to 270W
- Common mode rejection
  - $P_{beta} > 10 \times P_{long}$
  - Alignment: d< 1.5 mm

$$\frac{P_\beta}{P_L} = \frac{\beta_{pu}\varepsilon_{95}}{12d^2}$$

  - Phase Imbalance θ<1.5 degrees

$$\frac{P_\beta}{P_L} = \frac{\varepsilon_{95}}{12A\sin^2(\theta)}$$

Debuncher Momentum Cooling Issues

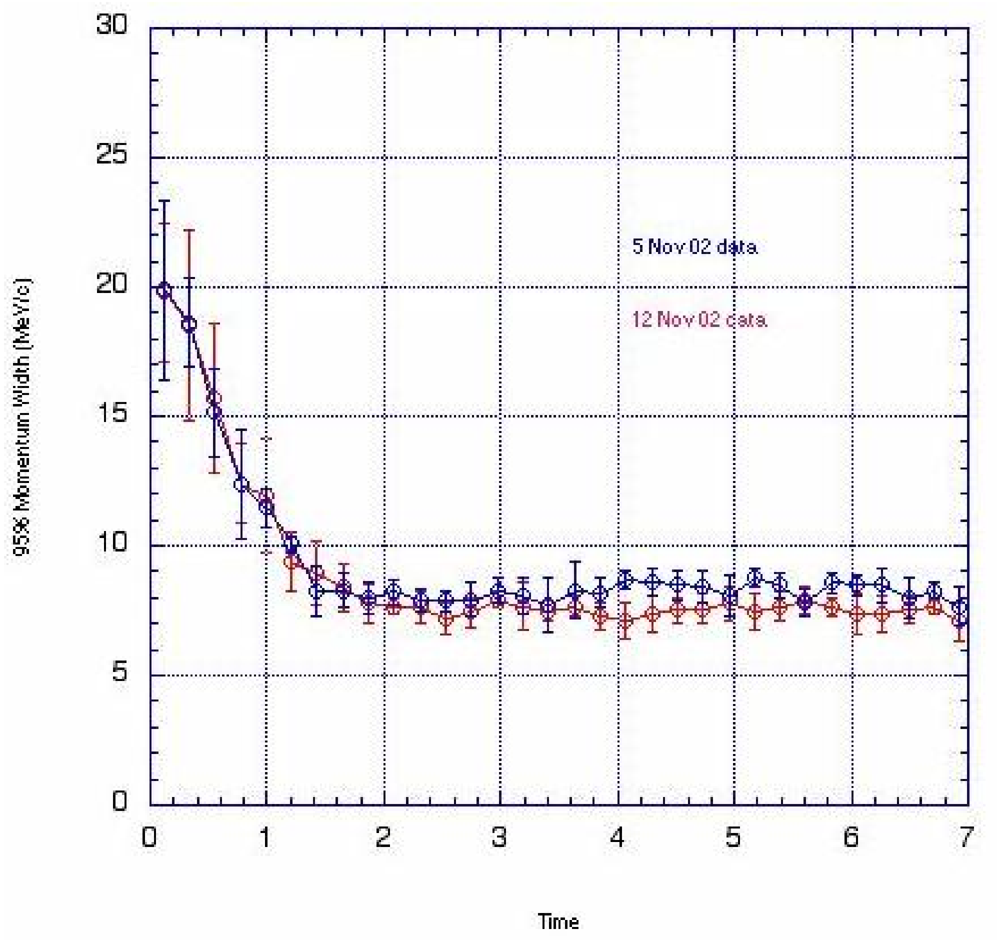
- Uses filter cooling
- Large asymptotic momentum spread
  - Good Signal/Noise
  - Band to Band alignment

$$\frac{\Delta pc}{pc} = \frac{1}{\eta} \Delta T_{notch} f_o$$

    - ΔT_{notch} < 1ps
  - Notch filter dispersion

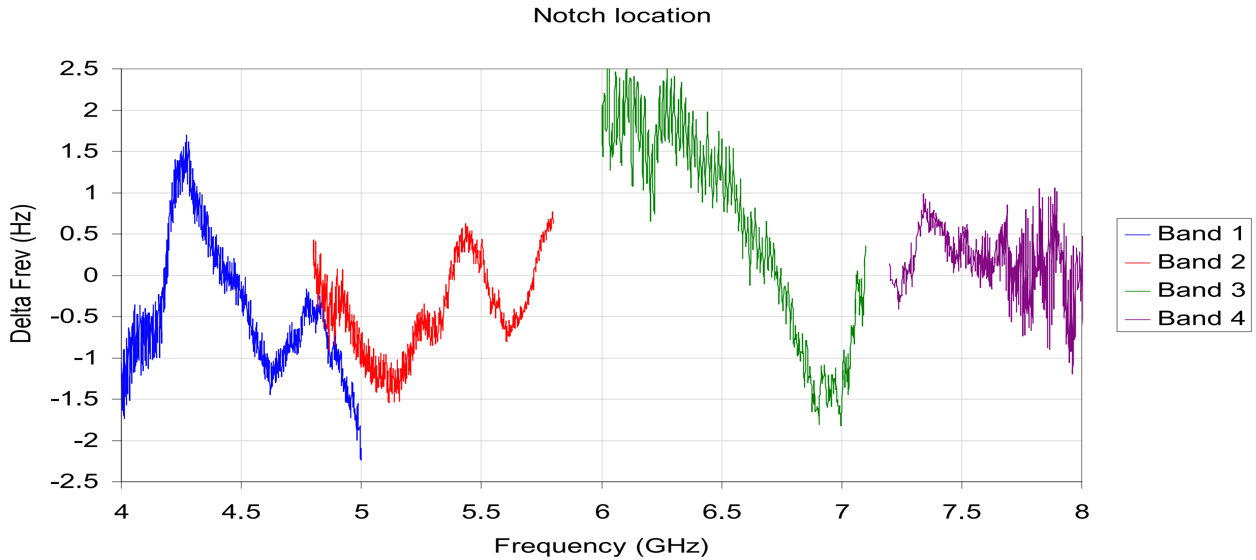
$$\frac{\Delta pc}{pc} = \frac{1}{\eta}\frac{1}{N}\sum_n \frac{\left|\theta_e(nf_o) - \langle\theta_e\rangle\right|}{2\pi n}$$

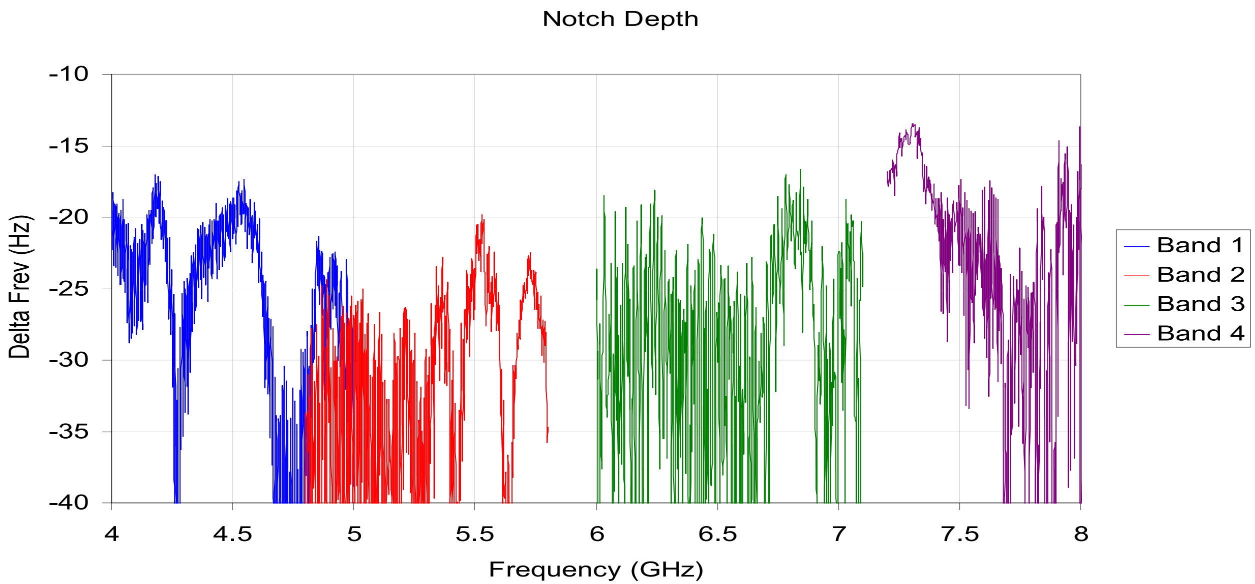
    - $\Delta\theta_{rms}$ < 2 degrees
    - Δf_{notch} < 0.4 Hz



Time (secs)

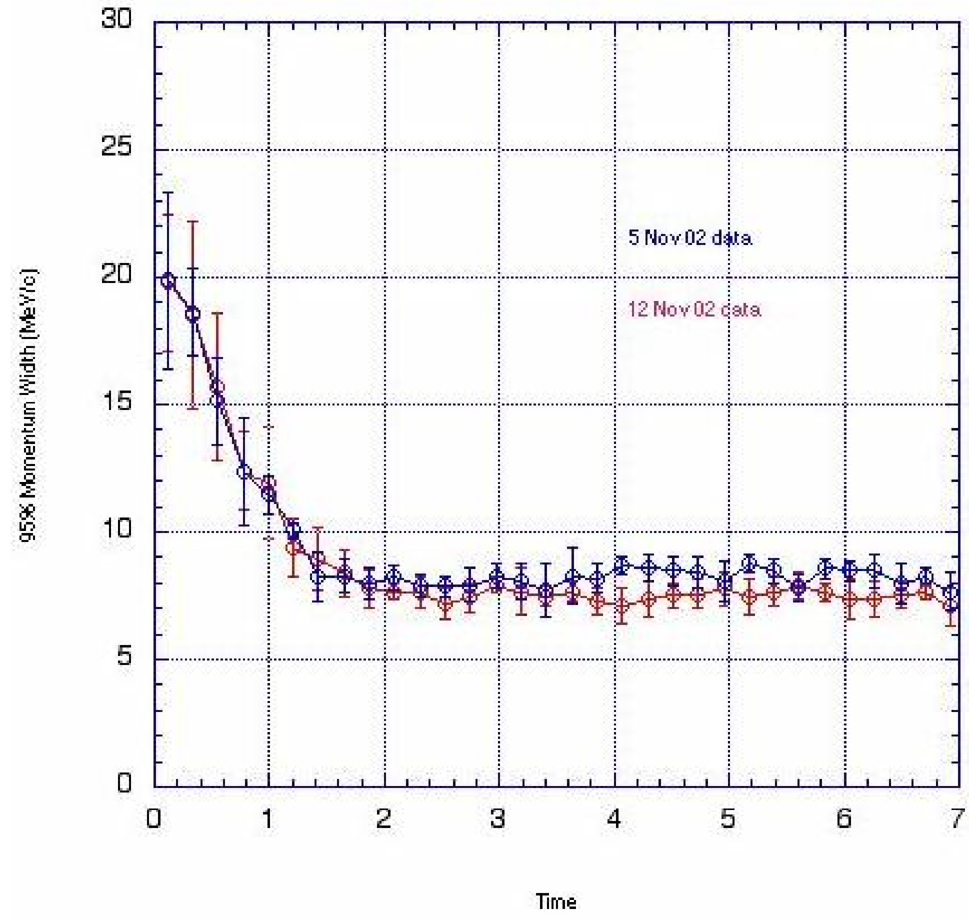
Debuncher Momentum Cooling Issues





Debuncher Momentum Cooling Issues

- Slow Cooling Rate
  - Calculated Cooling rate = 0.2 Sec
  - Necessary cooling rate = 0.85 sec
  - Measured cooling rate = 2 sec
    - Caused by notch filter Dispersion?
    - Need to develop model that includes dispersion.



Stacktail Momentum Cooling Issues

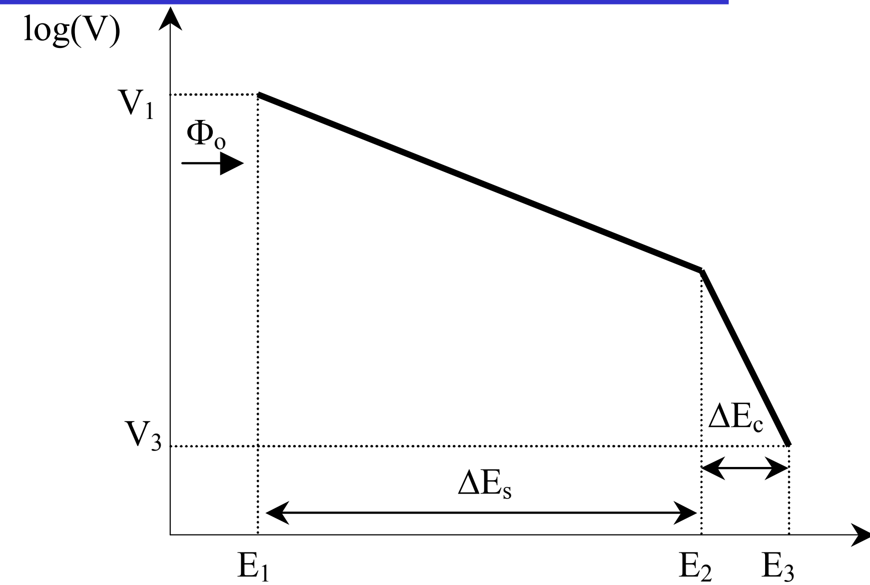
- Design margin for flux = 90×10^{10}pbars/hour
- Optimum profile that maximizes $d\psi/dE$ is exponential

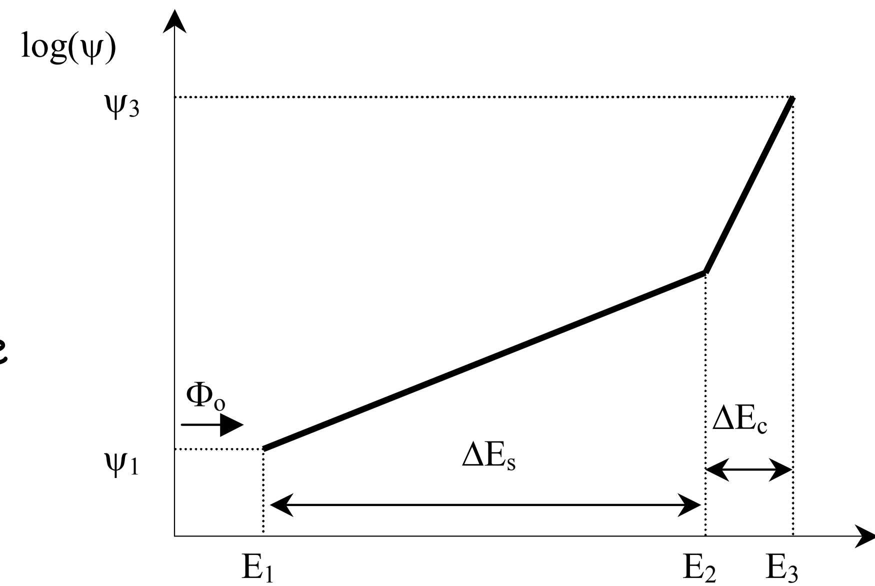
$$\psi(E) = -\frac{2\Phi_o}{f_o V(E)} = -\frac{2\Phi_o}{f_o V_i} e^{-\frac{E_i - E}{E_d}} = \psi_i e^{-\frac{E_i - E}{E_d}}$$

$$\psi_1 = \frac{\Phi_o T_{rep}}{\Delta E_{bD}}$$

$$\Phi_o = \frac{|\eta| W^2 E_d}{f_o \beta p c \ln\left(f_{max} / f_{min} \right)}$$

- Large E_d needs a large momentum aperture or results in a low final core density
- The best way to increase flux is to increase the bandwidth





Stacktail Momentum Cooling Issues

- Stacktail Momentum Cooling
  - Energy Aperture and Stability
    - Would like energy aperture as big as possible to get a large core density
    - Stacktail uses Notch Filters to shape gain near core
    - For system stability, operate at frequencies where Schottky bands do not overlap

$$f_{max\_stack} < \frac{f_o}{|\eta|} \frac{pc}{\Delta E_s + \Delta E_c + \Delta E_{bD}}$$

    - Strategies
      - Reduce η
        - Increases β functions – decreases aperture
        - Increases intra-beam scattering heating
      - Reduce momentum aperture of cooling system
      - Core Momentum system with higher bandwidth
        - Energy aperture of core is limited by "bad" mixing between pickup and kicker at high frequencies

$$\Delta E_c \leq \frac{1}{6\eta} \frac{f_o}{f_{max\_core}} pc$$

Stacktail Momentum Cooling Issues

- Core Density and Stacking Interval
  - Particles to be transferred must be inside desired Recycler longitudinal emittance

$$\Phi_o T_{stack} = \int_{E_3 - f_o A_{bc}}^{E_3} \psi_c(E)\, dE$$

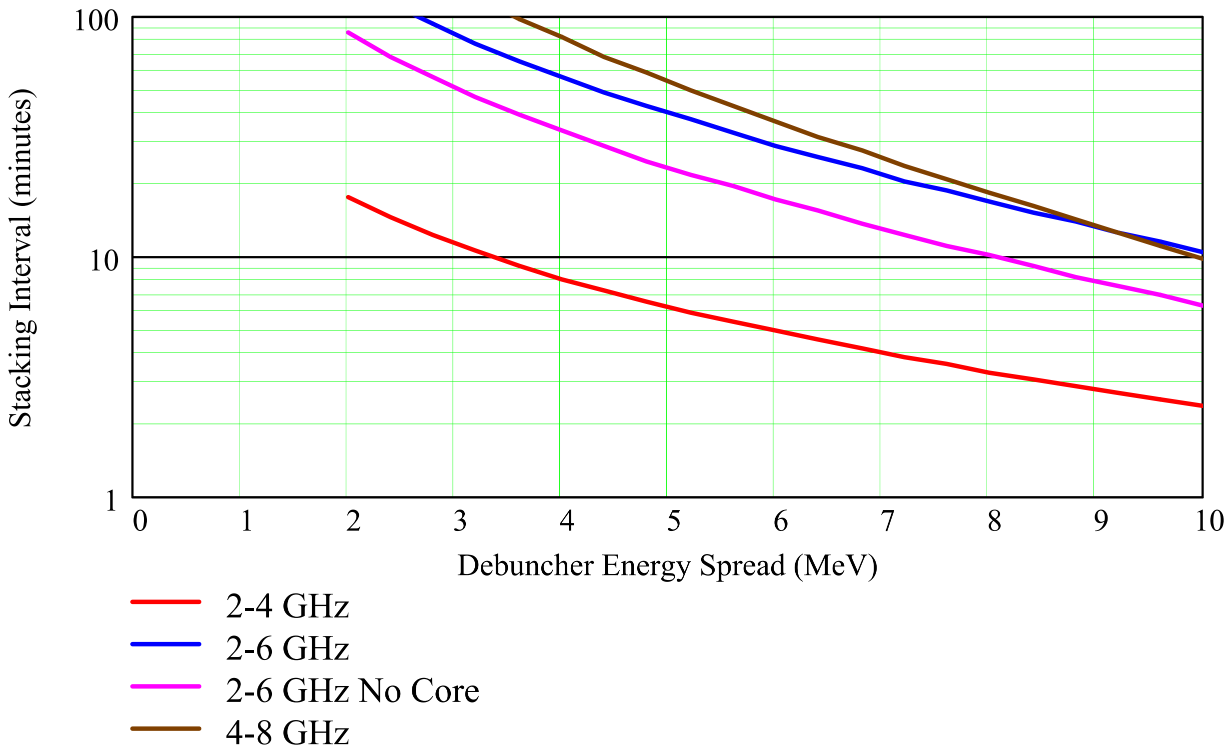
$$T_{stack} = T_{rep} \frac{E_{dc}}{\Delta E_{bd}} \left(1 - e^{-f_o A_{bc}/E_{dc}}\right) e^{\frac{\Delta E_s}{E_{ds}} + \frac{\Delta E_c}{E_{dc}}}$$

  - Desire long stacking interval
    - Small Debuncher energy spread ΔE_{bd}
    - Large energy aperture $\Delta E_s + \Delta E_c$
    - Small characteristic energy slope (E_d)
- Stacktail Power

$$P_{\Phi\, max} = 2 \frac{f_o}{W} \Phi_o T_{rep} \frac{1}{Z_k} \left(\frac{\Delta E_{bD}/q}{f_o T_{rep}} \right)^2 \frac{E_{ds}}{\Delta E_{bD}} e^{\Delta E_{bD}/E_{ds}}$$

Stacktail Momentum Cooling Design Examples

Stacktail Bandwidth	Core Bandwidth	E_{ds}	E_{dc}	$\Delta E_s + \Delta E_{bd}$	ΔE_c	Fraction Unstacked
(GHz)	(GHz)	(MeV)	(MeV)	(MeV)	(MeV)	(%)
2-4	4-8	20	5	77.4	9.6	50
2-6	4-8	8	5	48.4	9.6	66
2-6	2-6	8	8	45.2	12.8	55
4-8	4-8	5	5	33.9	9.6	72



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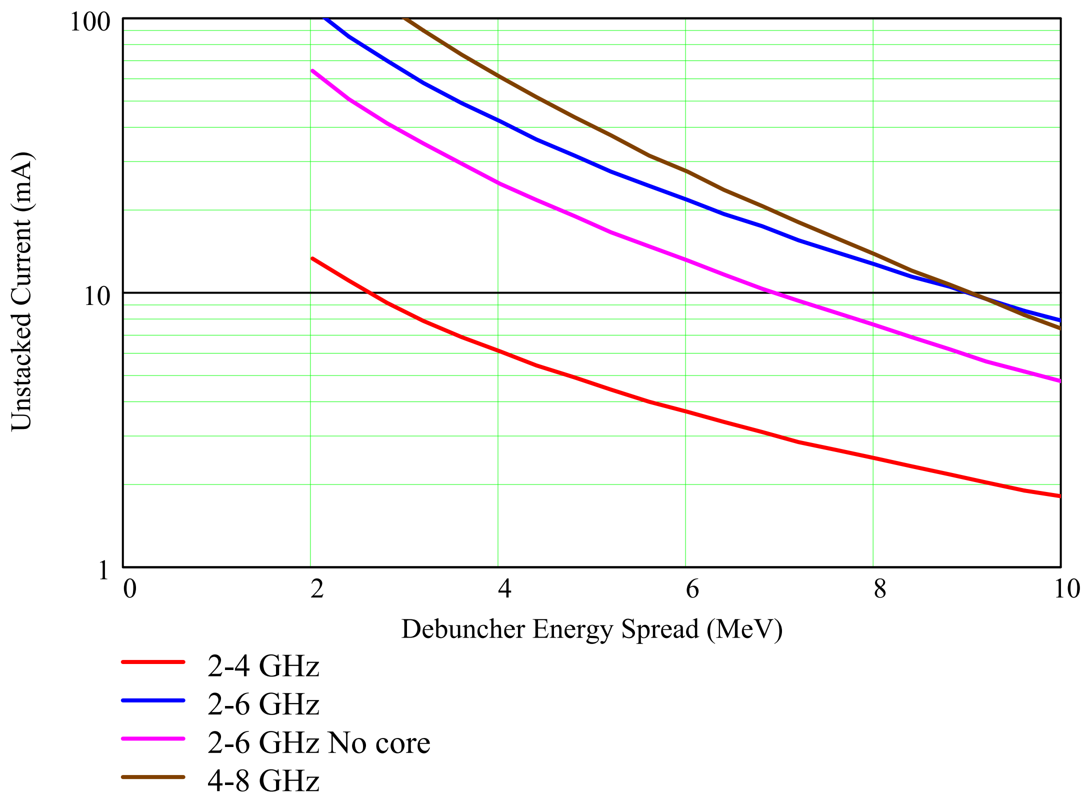

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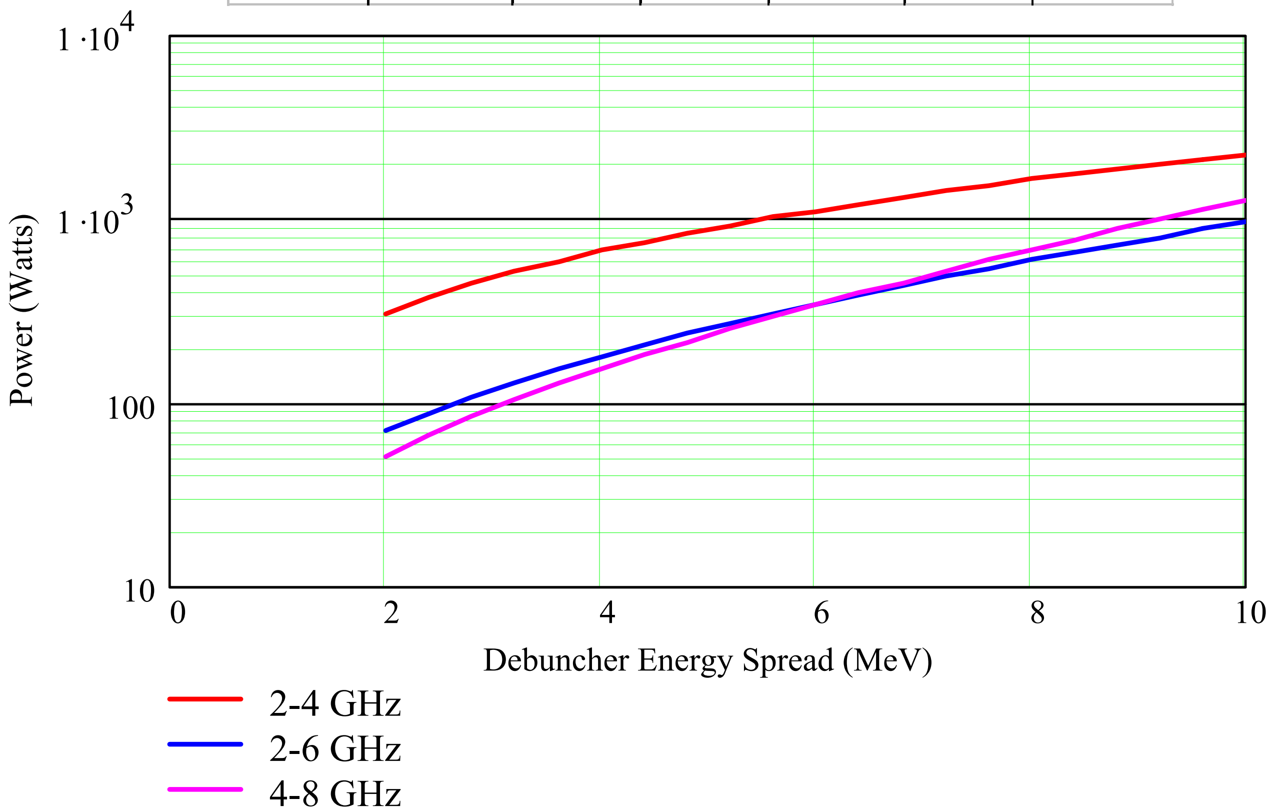


Stacktail Momentum Cooling Issues

- Design examples
  - 2-4 GHz
    - extremely short stacking intervals
    - Requires large amount of power
    - Proven design
  - 4-8 GHz
    - longest stacking intervals for small Debuncher momentum spreads
    - Small energy aperture
    - Difficult pickup design in high dispersion
  - 2-6 GHz system
    - Moderate stacking intervals for small Debuncher momentum spreads
      - 4-8 Core system makes substantially higher intervals and core densities
    - Moderate energy aperture
    - Proven pickup design in high dispersion
    - Large fractional bandwidth
      - Multi-band system

Accumulator Transverse Cooling Issues

- Cool 5π-mm-mrad beam at injection to 1.5π-mm-mrad beam at core
- Use present 3 band 4-8 GHz core system with bandwidth of 3.5 GHz

$$\frac{d\varepsilon}{dt} = -\frac{W}{2N}\left[2\,\mathrm{Re}\{g\} - |g|^2\left(\frac{1}{n_1}\sum_n \frac{f_o}{\Delta f_n}\right) - |g|^2 U\right]\varepsilon$$

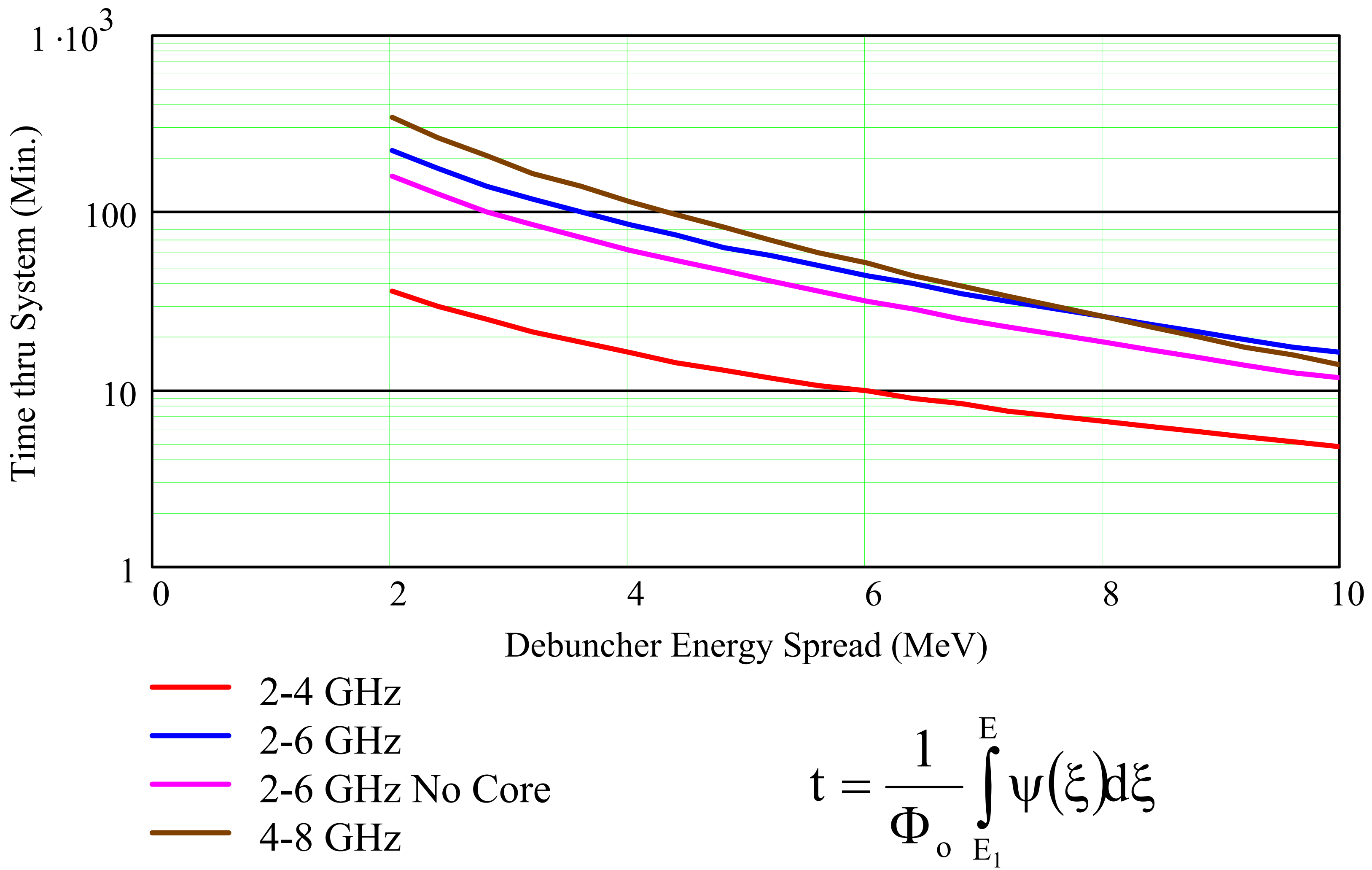
- Particles see wide range of densities on the way to the the Core

Cooling — Heating from other particles — Noise

$$\frac{d\varepsilon(t,E)}{dt} = -\frac{1}{\tau_c}\left(2\,\mathrm{Re}\{x\} - |x|^2\frac{M(E)}{M(E_c)}\right)\varepsilon(t,E) + \frac{|x|^2}{\tau_c}\frac{U_o}{M(E_c)}$$

$$M(E) \approx \frac{pc}{\eta}\psi(E)\frac{f_o}{f_c} \qquad \frac{1}{\tau_c} = \frac{W}{2M(E_c)}$$

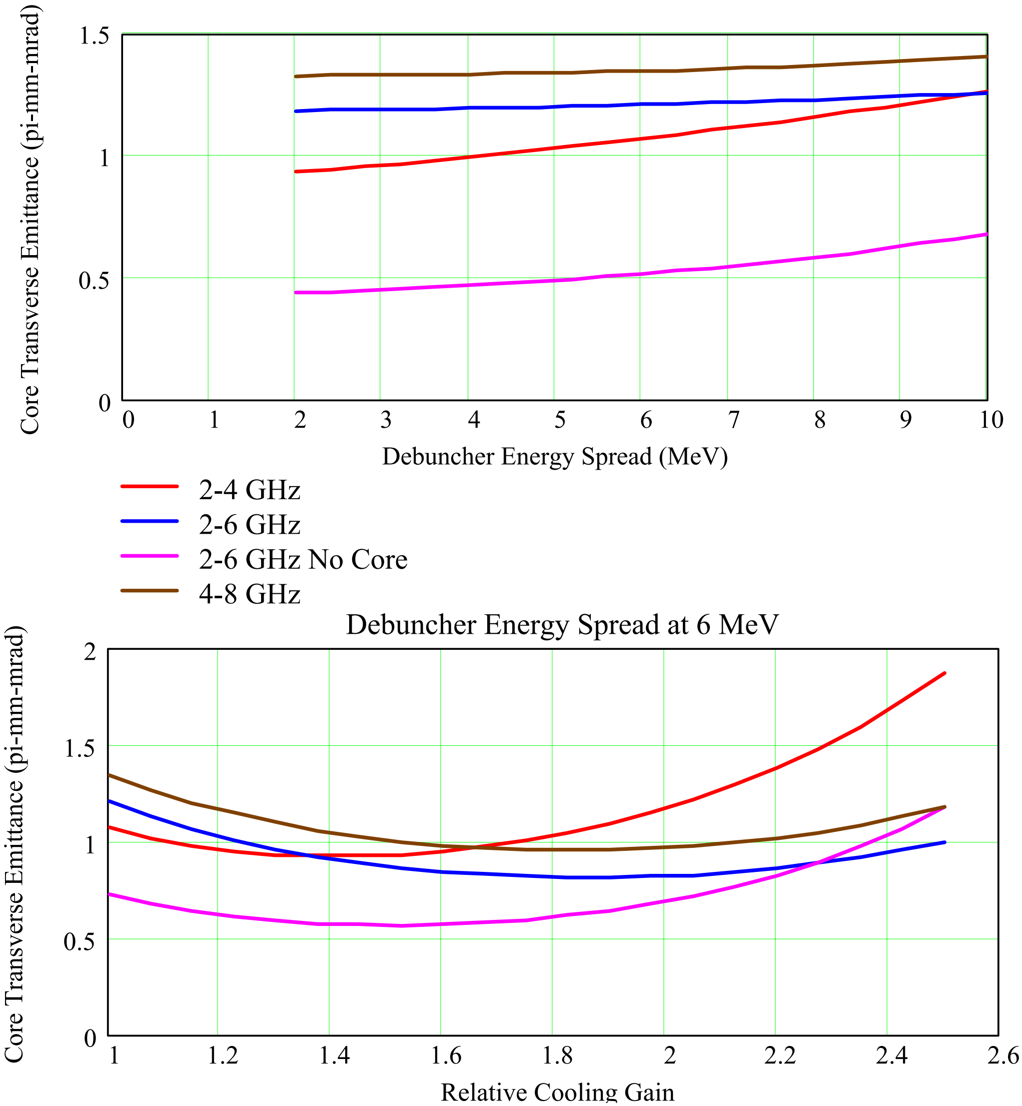
Accumulator Transverse Cooling Issues



$$t = \frac{1}{\Phi_o} \int_{E_1}^{E} \psi(\xi) d\xi$$

Accumulator Transverse Cooling Issues

- Gain > g_{opt} at core results in lower emittance because heating term is not important until particles arrive at the core.
- Emittance < 1.0π-mm-mrad at core
  - No heating in Stacktail assumed
  - No margin assumed on bandwidth



Recycler Electron Cooling Design Process

- Decide on whether to do longitudinal cooling and/or betatron cooling
  - Longitudinal cooling rate independent of β function
    - Important for the Recycler
  - Transverse cooling rate proportional to $\beta^{1/2}$
    - Not as important for the Recycler
- Design for minimum angular spread in electron beam
  - Cooling section solenoid field quality
  - Aberrations in the beamline
  - Stability of the antiproton orbit
  - Stability of the electron optics
  - Emittance and space charge
  - Stray magnetic fields
- Decide on reasonable emittance range for optimum cooling

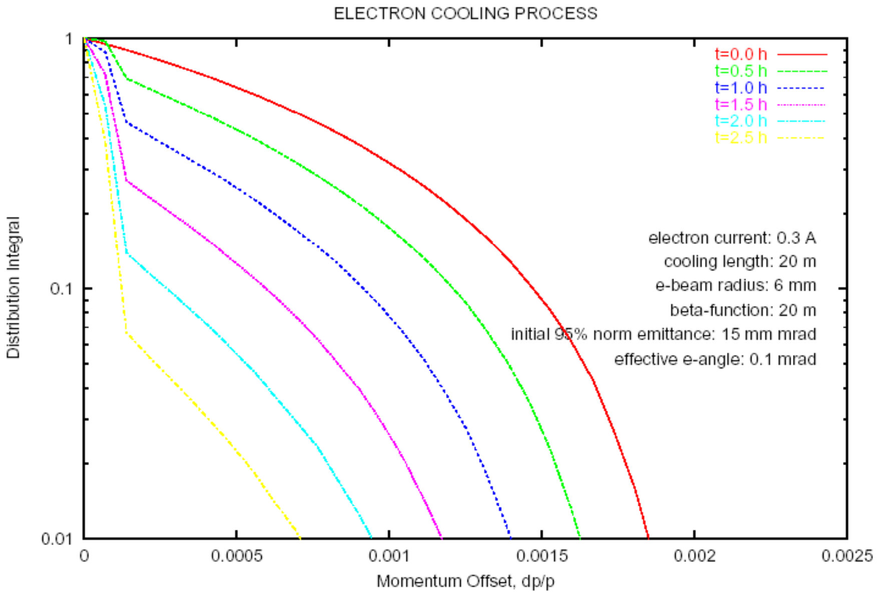
$$\sqrt{\frac{\varepsilon_{95\%}}{6\beta}} \approx \Delta\theta_{\mathrm{electron}_{\mathrm{spread}}}$$

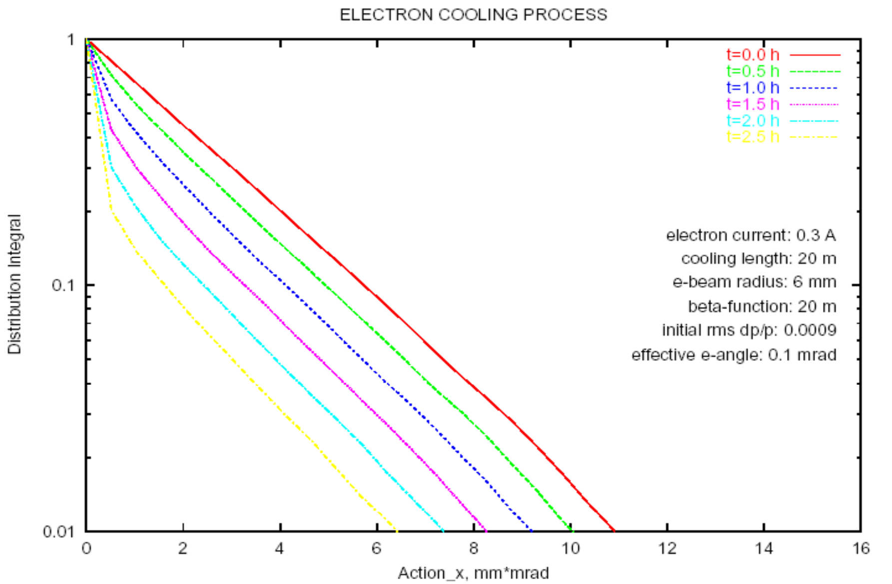
$$r^2 = \varepsilon_{95\%}\beta$$

- Design electron beam size

Recycler Electron Cooling Design Specs.

- Emphasis on longitudinal cooling
- Angular spread of electron beam = 0.1 mrad
- Design cooling for transverse emittance of 1.5π-mm-mrad with β=30m
- Electron beam size = 6 mm
- Cooling rate
  - 22 eV-s/hr per 100 mA of electron current
  - 0.12 π mm mrad/hr per 100 mA of electron current





Recycler Electron Cooling Issues

- The equilibrium emittance of the stack is determined by either electron beam misalignment or the pbar space charge limit.
  - For 6×10^{10} pbars inside 30 eVs and 0.3 πmm mrad of 95% emittance

$$\Delta \nu = \mathbf{0.08}$$

  - For conventional electron coolers, space charge limits at about

$$\Delta \nu = \mathbf{0.15}$$

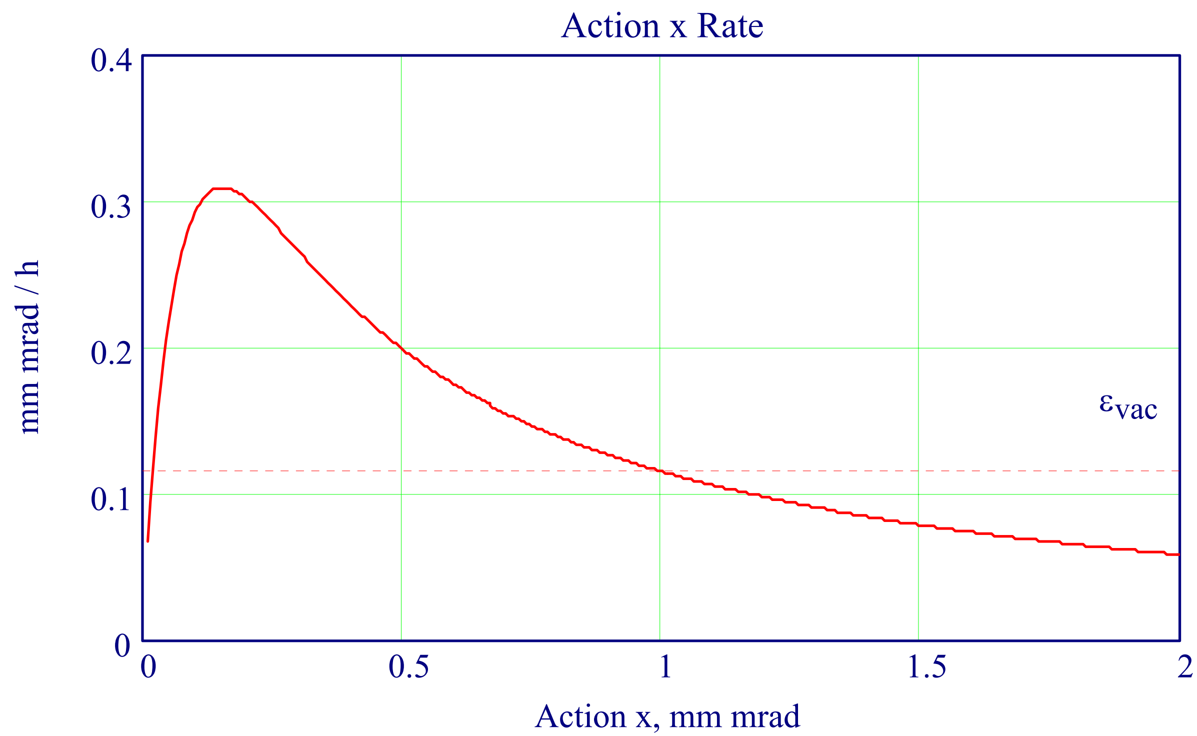
- Operating close to the space charge limit might induce a beam shape instability.
  - This can be prevented by regulating electron-beam angles at the entrance of the cooler.
  - Due to the high space charge tune shift, there is no Landau damping for transverse oscillations up to

$$f_{LD} \cong f_0 \frac{0.3\Delta \nu}{\eta \sigma_p} \cong 1 \text{ GHz}$$

- Thus, a transverse instability has to be expected.
  - The shortest growth time is at the resistive wall impedance at about 50 KHz : 300 turns.
  - Broadband feedback up to the space charge limit is required.

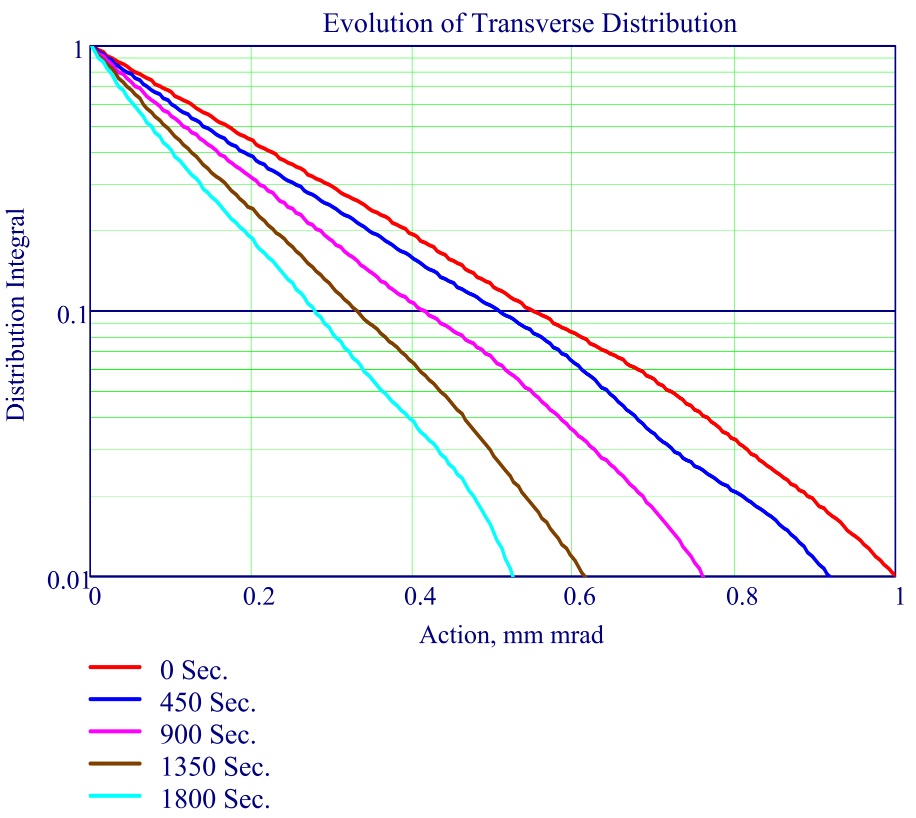
Recycler Stochastic Cooling Issues

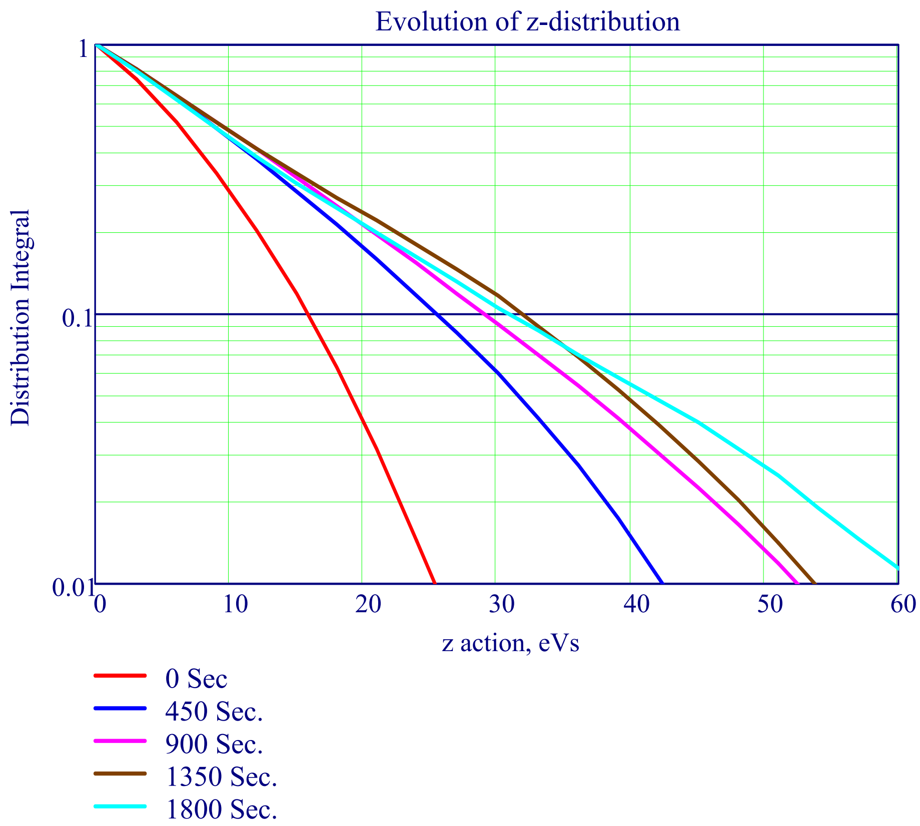
- Needed to transversely pre-cool $22x10^{10}$pbars injected from the Accumulator for ½ hour to bring the transverse emitance within reach of the electron cooling



Recycler Stochastic Cooling Issues

- Evolution of the injected batch with 22×10^{10} pbars using a Q=1 2-4 GHz Transverse Stochastic Cooling system, 0.7π-mm-mrad/hr vaccum growth rate





Key Parameters

Parameter	Value	Unit
Average Stacking rate	40	$x10^{10}$ per hour
Peak Stacking rate	45	$x10^{10}$ per hour
Number of particles injected into the Debuncher	280	$x10^{6}$
Debuncher transverse aperture	35	π-mm-mrad
Antiproton production cycle time	2	Secs
Maximum bunch length on target	1.5	nSecs.
Debuncher momentum aperture	4	%
Debuncher momentum cooling aperture	0.4	%
Debuncher final transverse emittance	5	π-mm-mrad
Debuncher final momentum spread	6	MeV
Debuncher transverse cooling common mode rejection	1.5	mm
Debuncher transverse cooling phase imbalance	3	degrees
Debuncher transverse cooling delay imbalance	1.4	pS
Debuncher momentum notch filter delay tolerance	1	pS
Debuncher momentum cooling notch filter dispersion	2.5	degrees
Debuncher to Accumulator transfer efficiency	95	%
Accumulator Stacktail Momentum bandwidth	2-6	GHz
Accumulator Core Momentum bandwidth	4-8	GHz
Accumulator Stacktail Momentum energy slope	8	MeV
Accumulator Stacktail Power	625	Watts
Accumulator Stacktail 2-6 GHz kicker impedance	6400	Ω
Accumulator Core Momentum energy slope	5	Mev
Accumulator Core Momentum cooling aperture	9.6	MeV
Accumulator Momentum cooling aperture	58	MeV

Key Parameters

Parameter	Value	Unit
Accumulator Momentum cooling aperture	58	MeV
Accumulator to Recycler transfer longitudinal emmitance	10	eV-Sec
Accumulator to Recycler transfer interval	30	minutes
Number of particles extracted from the Accumulator per trans	24	$x10^{10}$
Accumulator to Recycler transfer time	1	minutes
Accumulator to Recycler transfer efficiency	95	%
Accumulator core transverse emittance	1	π-mm-mrad
Recycler transverse emittance injection dilution	50	%
Recycler longitudinal emmittance injection dilution	50	%
Recycler transverse Stochastic Cooling Bandwidth	>1	GHz
Recycler Transverse Stochastic cooling Center Frequency	3	GHz
Maximum Recycler Transverse emittance Growth Rate	0.7	π-mm-mrad/hr
Peak Stack in Recycler	620	$x10^{10}$
Transverse emmitance of antiprotons extracted from Recycler	1	π-mm-mrad
Total Longitudinal emmitance of antiprotons extracted from Recycler	50	eV-Sec
Number of bunches extracted from the Recycler	36	
Minimum longitudinal cooling rate of Electron Cooling	55	eV-Sec/hour
Minimum Electron Cooling Current	250	mA
Electron Beam alignment tolerance	0.1	mrad
Transverse electron cooling rate per 100 mA	0.12	π-mm-mrad
Maximum transverse emittance for electron cooling	1.5	π-mm-mrad

FY03 Stacking Goals

- We need to provide 140 mA in 15 hours to for the FY03 goals
  - Average stacking rate of 9.3 mA/hr
- We have done:
  - Peak 13 mA/hr
  - Average 8.5 mA/hr
  - Stacked to 225 mA
  - Shoot routinely from 140-160 mA
- Minimum Goals
  - Peak stacking rate of 14.2mA/hr
  - Average stacking rate of 9.3 mA/hr
- We will strive to get 18 mA/hr peak
  - Reduce cycle time from 2.2 sec to 1.7 sec.
  - Increase protons on target from 4.7E12 to 5.0E+12

Key Parameter Comparison

Parameter	Value FY06	Value FY04	Value Now	Unit
Average Stacking rate	40	12	8.5	$x10^{10}$ per hour
Peak Stacking rate	45	18	13	$x10^{10}$ per hour
Beam on Target	8	5	4.7	$x10^{12}$
Number of particles injected into the Debuncher	280	100	90	$x10^{6}$
Debuncher transverse aperture	35	15	15	π-mm-mrad
Antiproton production cycle time	2	1.7	2.2	Secs
Maximum bunch length on target	1.5	1.3	1.3	nSecs.
Debuncher momentum aperture	4	3.7	3.7	%
Debuncher momentum cooling aperture	0.4	0.4	0.4	%
Debuncher final transverse emittance	5	5	5	π-mm-mrad
Debuncher final momentum spread	6	5	9	MeV
Debuncher transverse cooling common mode rejection	1.5	1	<1	mm
Debuncher transverse cooling phase imbalance	3	20	30	degrees
Debuncher transverse cooling delay imbalance	1.4	10	14	pS
Debuncher momentum notch filter delay tolerance	1	1	2-3	pS
Debuncher momentum cooling notch filter dispersion	8	10	20	degrees
Debuncher to Accumulator transfer efficiency	95	95	95	%
Accumulator Stacktail Momentum bandwidth	2-6	1.7-3.7	1.7-3.7	GHz

Key Parameter Comparison

Parameter	Value FY06	Value FY04	Value Now	Unit
Accumulator Core Momentum bandwidth	4-8	4-7	2-4	GHz
Accumulator Stacktail Momentum energy slope	8	11	11	MeV
Accumulator Stacktail Power	625	280	250	Watts
Accumulator Stacktail 2-6 GHz kicker impedance	6400	6400	6400	Ω
Accumulator Core Momentum energy slope	5	6	11	Mev
Accumulator Core Momentum cooling aperture	9.6	12	20	MeV
Accumulator Momentum cooling aperture	58	72	80	MeV
Accumulator to Recycler transfer longitudinal emmitance	10	15	15	eV-Sec
Accumulator to Recycler transfer interval	30	180	180	minutes
Number of particles extracted from the Accumulator per transfer	24	24	25	$x10^{10}$
Accumulator to Recycler transfer time	1	15	60	minutes
Accumulator to Recycler transfer efficiency	95	90	70	%
Accumulator core transverse emittance	1	1	1	π-mm-mrad
Recycler transverse emittance injection dilution	50	50	>100	%
Recyler longitudinal emmittance injection dilution	50	50	>100	%
Peak Stack in Recycler	620	200	80	$x10^{10}$
Transverse emmitance of antiprotons	1	1	-	π-mm-mrad
Total Longitudinal emmitance of antiprotons	50	50	100	eV-Sec
Transverse stochastic cooling time @ 100e10	0.7	0.7	-	hours

Cooling Upgrades

- FY03
  - Debuncher Momentum Notch Filter Equalizer Upgrade
  - Debuncher Transverse Notch filters for Bands 1 & 2
  - Accumulator Transverse Core Cooling Equalizers
  - Accumulator Stacktail Momentum Transverse Compensation Upgrade
  - Commission 4-8 GHz Accumulator Core Momentum system for stacking
- FY06
  - 4-6 GHz Band in Stacktail
  - Recycler Electron cooling
  - Accumulator Stacktail betatron cooling (subject to outcome of beam studies)

Beam Studies

- Debuncher Bunch Rotation
  - Experimentally verify the calculations of the final momentum spread as a function of proton bunch length
- Debuncher Transverse Stochastic Cooling
  - Document the cooling rate for a given starting emittance, power level, and number of particles for each band and all bands together.
  - Measure the signal to noise of each band for a given emittance and beam current and determine pickup impedance
  - Measure the common more rejection tolerances of each band
- Debuncher Momentum Stochastic Cooling
  - Develop Fokker-Plank Computer simulations to account for dispersion properties of notch filters
  - Measure cooling rate and dispersion for each band and compare to simulations
  - Measure the signal to noise of each band for a given momentum spread and beam current
  - Measure the momentum aperture of the cooling system

Beam Studies

- Accumulator Stacktail Momentum Stacking
  - Measure signal to noise and determine impedance of the Stacktail pickups, Core Momentum 2-4 GHz Pickups, and Core Momentum 4-8 GHz pickups
  - Characterize the beam transfer function as a function of energy for the Stacktail system, the Core 2-4 GHz
  - Develop detail Fokker-Plank model based on measurements
  - Measure Stacktail pulse evolution as a function of initial distribution intensity, width, and position. Compare to model
  - Measure zero stack Stacktail profile evolution as a function of initial distribution and pulse repetition rate. Compare to model

Beam Studies

- Accumulator Transverse Cooling
  - Measure signal to noise and determine impedance of core transverse pickups.
  - Document beam transfer function measurements at the core.
  - Measure cooling rate as a function of stack size and system gain. Measure and subtract natural emittance growth of the accelerator from cooling measurements.
- Recycler Stochastic Cooling
  - Measure signal to noise and determine impedance of transverse and longitudinal pickups.
  - Document beam transfer function measurements.
  - Measure cooling rate as a function of stack size and system gain. Measure and subtract natural emittance growth of the accelerator from cooling measurements.

Summary

- We have a design on paper in which all the parameters mesh
- In reality, we have a number of systems where we would like to improve the design margin
  - Debuncher Cooling
    - Momentum System
      - dominated with dispersion in filters
      - Momentum width is a key parameter for
        - Stacktail
        - Debuncher Bunch rotation
    - Transverse Systems have tight constraints on common mode rejection
  - Accumulator Transverse Cooling
    - Just meets spec.
    - No account of Stacktail heating
  - Electron Cooling
    - Design current dominated by recycling parameters
    - Hinges on performance of Recycler
- Upgrades identified
  - 4-6 GHz band for the Stacktail Momentum system
  - Low dispersion notch filters for the Debuncher Momentum system
  - Common mode rejection upgrade for the Debuncher transverse system
  - Stacktail betatron cooling