Improvements in Antiproton Cooling and Stacking

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Contents

Accelerator physics seminar

FNAL

January 24, 2008

Introduction

Performance Expectations at September of 2006

- By summer 2007
  - Zero stacking rate ~30 mA/hour
    - ⇒ 27.5 achieved at Nov. 30, 2007
  - …

Plan of actions as it was at September of 2006

- Introducing equalizers (done)
  - …
  - we can gain factor of ~1.5 in stacking rate
    - 20 mA/hour -> 30 mA/hour
- Upgrading stack-tail to 2-6 GHz band should yield further improvement by ~1.5 times resulting the stacking rate above 45 mA/hour

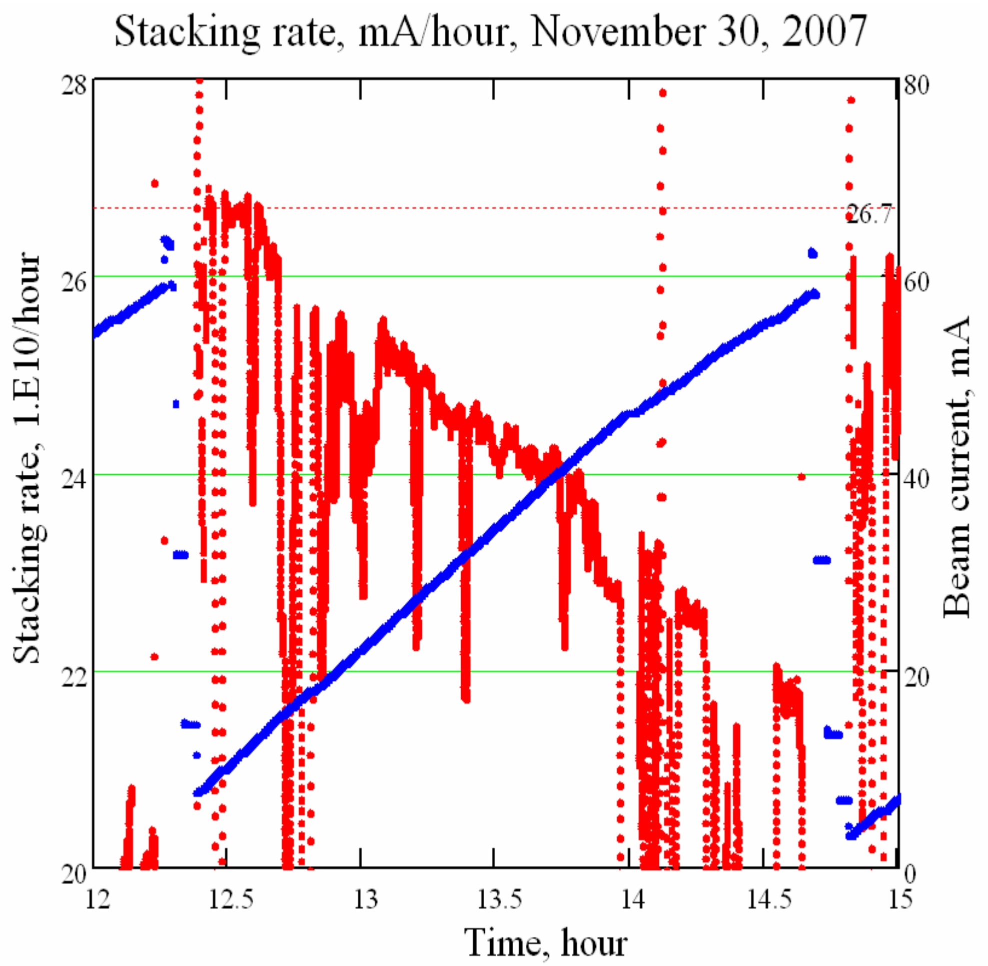
  Decision to cancel it was taken shortly after. OK in today's judgment
  - …

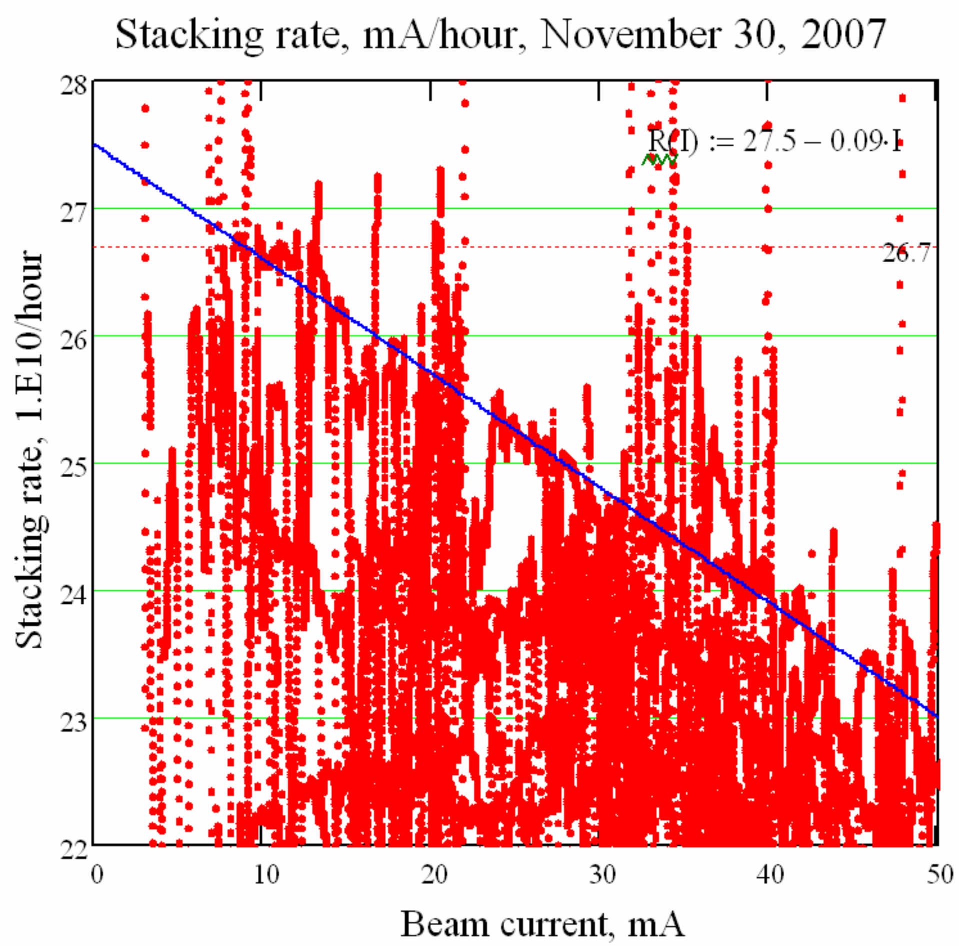
Present vision of 2006 expectation

- Large underestimate of what actually has to be done
  - 1.5 years later we are still not there

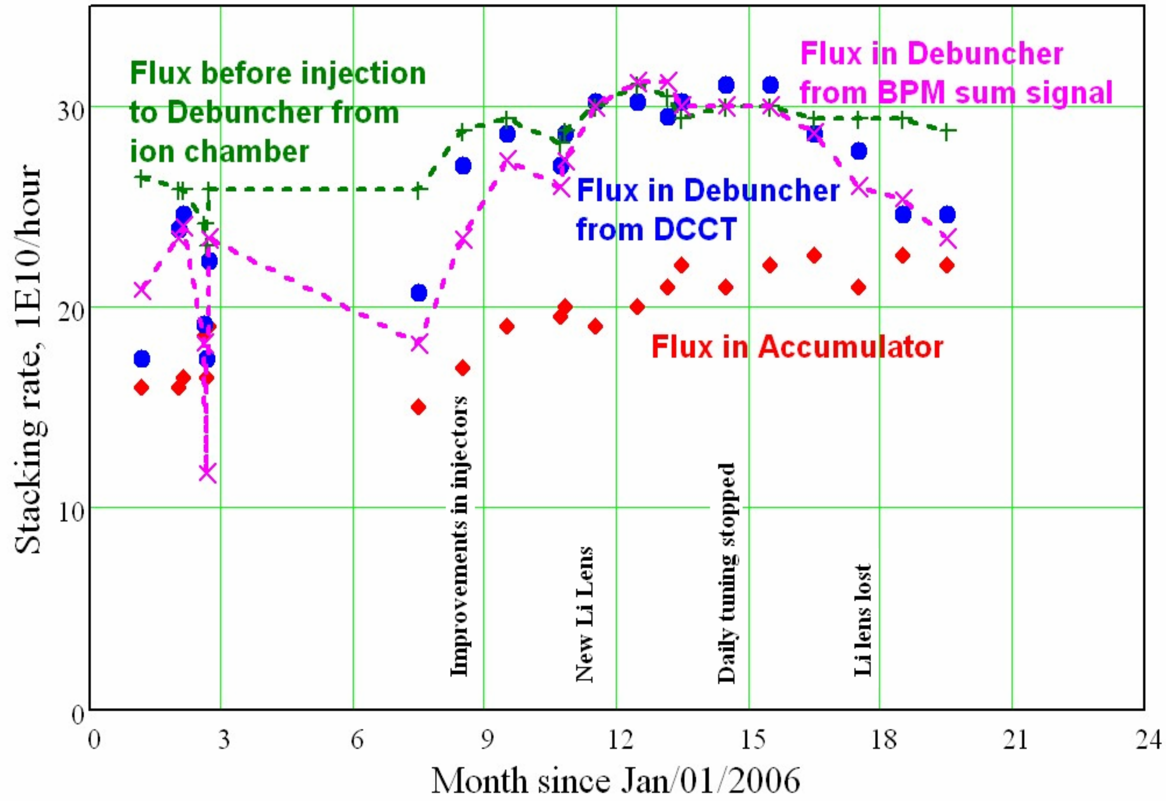
Stacking Definitions and Stacking Results

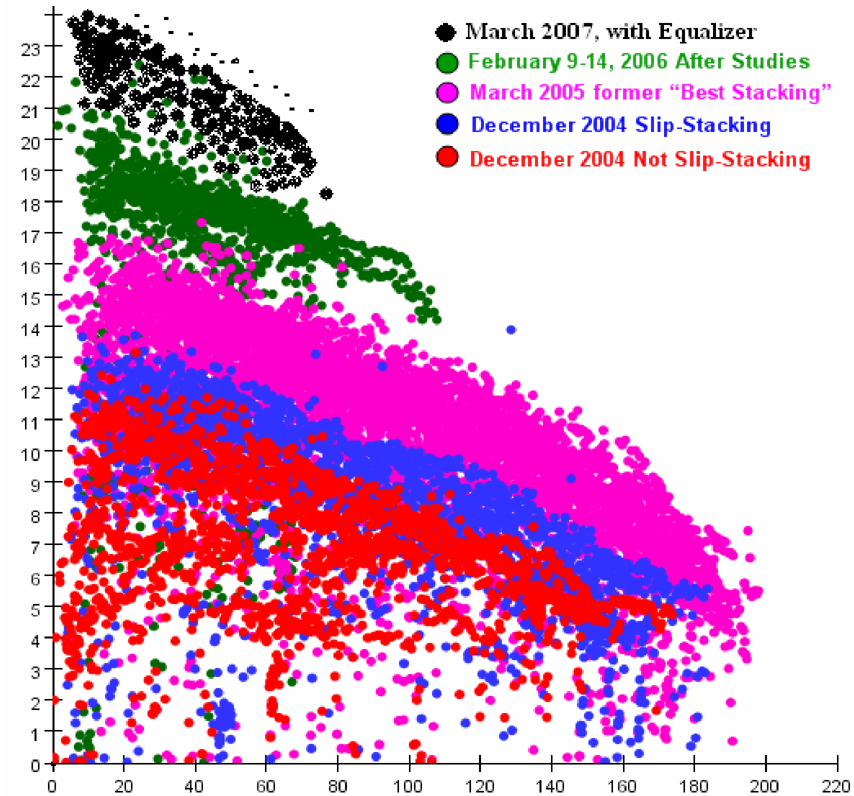
- Zero stack stacking rate – 27.5 mA/hour (Nov. 30, 2007)
- Peak stacking rate – 26.7 mA/hour (Nov. 30, 2007)
- Maximum in 1 hour – 24.7 mA/hour (Jan.9, 2008)
  - Expected 25.5 mA/hour with 10 mA initial stack size





FY'07 stacking improvements and upgrades

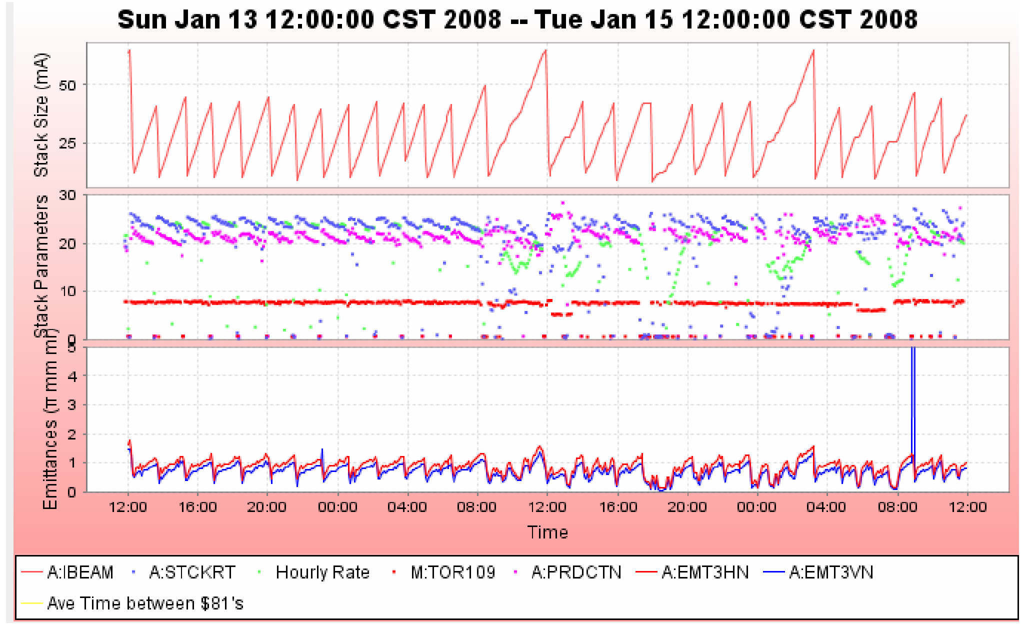




- Dec'05-Deb. optics and steering
- Feb'06 – Larger gain for 4-8 long. core cooling; 18->20 mA/hour
- July–Aug/06 - Tuning injector chain - pre-shutdown parameters restored
- Oct. 1 - Stacktail polarity flip ⇒ peak stacking rate: 20 ⇒ 22 mA/hour
- Dec. - New Li-lens
- March: Equalizer prototype for stacktail: 22 ⇒ 24 mA/hour
- May: Accumulator optics change (increased slip factor, reduced IBS)
- June: Final Equalizer for stacktail
- July – Notch filter #3: BAW (Bulk Acoustic Wave) ⇒ SC (superconducting)

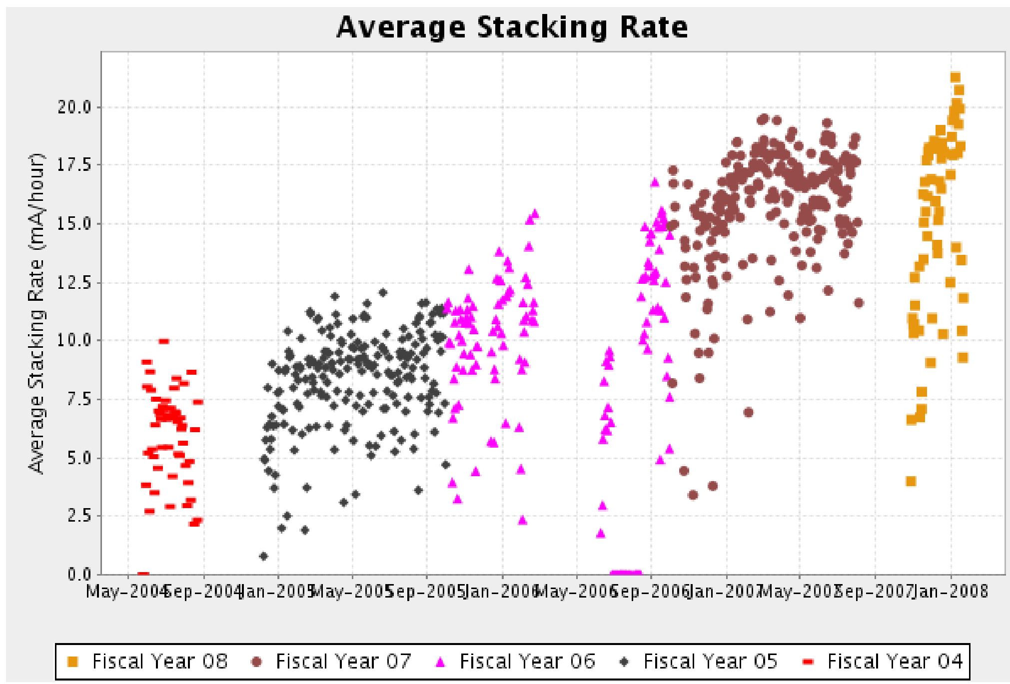
FY'08 stacking improvements and upgrades

- Summer 2007 shutdown
  - Li-lens repair
  - Equalizer for longitudinal core cooling
- Shortening core cooling cycle from 2.4 to 2.2 s
  - It compensated ~15% loss of p-on-target
    - 8.7E12 → 7.5 E12
  - For 8E10 p-on-target the flux in Debuncher is ~33 mA/hour
- Reduction of Acc.-to-MI transfer time allowed reduction of maximum stack size to 40 mA

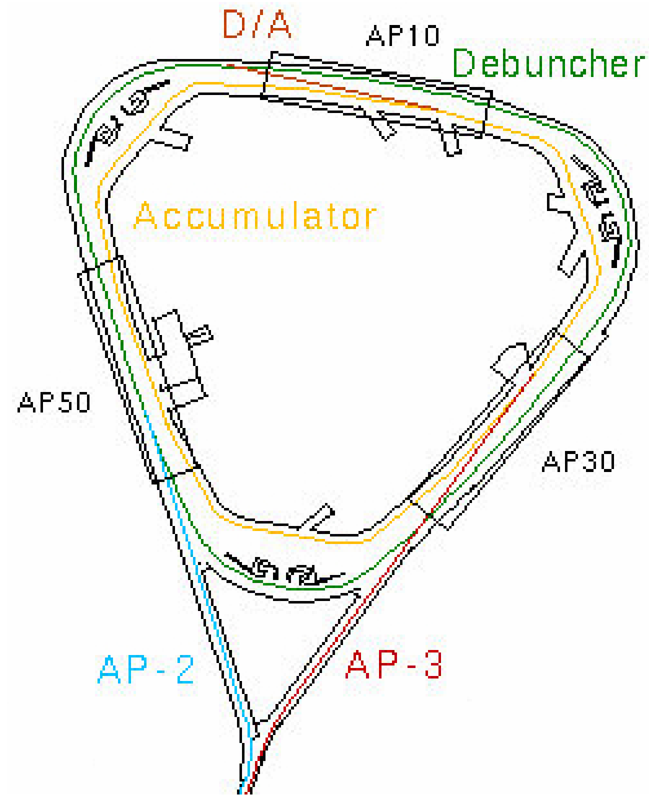


48 hours of good stacking,

2 day average - 18.8 mA/hour



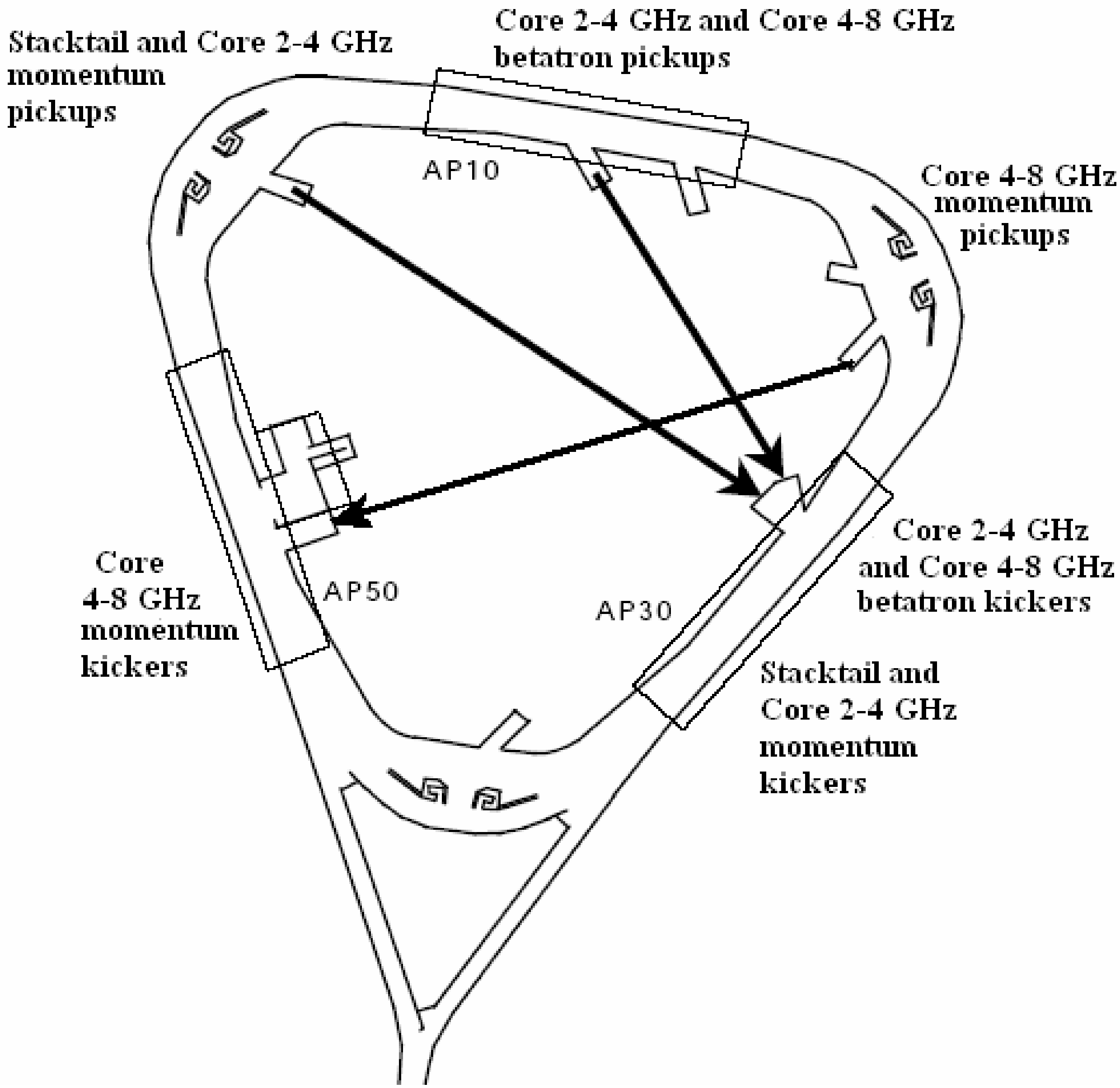
Simplified Review of Operations



- Every 2.2 s ~$8\cdot10^{12}$ protons at 120 GeV from MI sent to the target
- LI lens located at ~30 cm from target (center-to-center) reduces initially large angular spread
- 8 GeV (±2.5%) antiprotons and other secondaries (μ^-, π^-, …) are transported to Debuncher, N_{pbar}~$2\cdot10^8$, acceptance $\varepsilon \approx$35 mm mrad (not normalized)
- After 6D stochastic cooling in Debuncher antiprotons are sent to Accumulator
  - Three cooling systems (H, V, L). Each system has 4 bands.
- After storing ~$40\cdot10^{10}$ antiprotons in Accumulator (~1.5 hour) ~$30\cdot10^{10}$ are sent to Recycler
  - 4 stochastic cooling systems (stacking, long. core, H and V) are used to stack and cool antiprotons
- ~$430\cdot10^{10}$ antiprotons are stored in Recycler (~24 hour) and then sent to Tevatron (18.8 mA/hour, 95% transfer efficiency)

Cooling and Stacking in Accumulator

- 5 cooling systems
  - Core cooling
    - H & V – 4-8 GHz
    - Longitudinal: 2-4 GHz and 4-8 GHz
  - Stacktail - 2-4 GHz
- Stacktail system moves injected antiprotons to the core

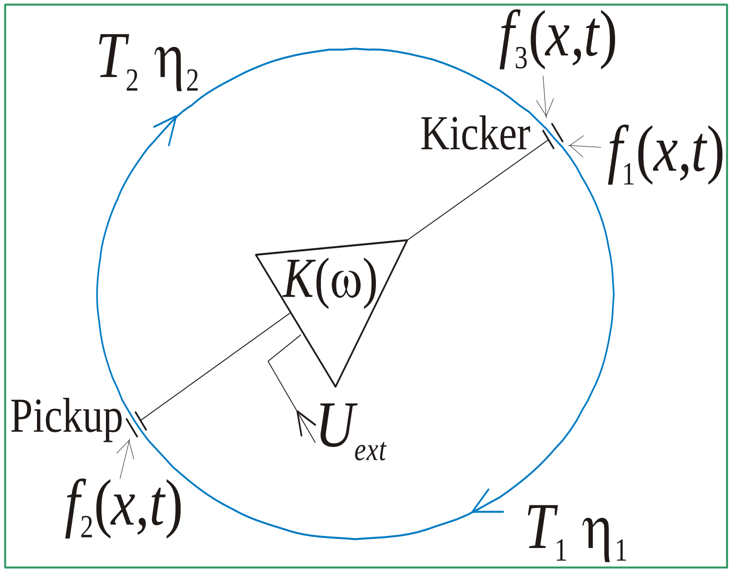


Problems and actions

- It has been known for long time that there are three problems determining the stacking rate
  - Stacking rate limitation due to stacktail itself (inverse flux)
  - Transverse core emittance blowup
  - Longitudinal core emittance blowup
- In Sep. 2006 it was clear that the first problem has to be addressed
  - The work carried out proved that the two other are problems are the same important
- The following actions were done
  - Stacktail bandwidth increase with equalizer increased the maximum stacktail flux
  - Accumulator optics change reduced the transverse core emittance blowup and increased maximum stacktail flux
  - SC notch filter improved longitudinal coherent stability of the stack
  - Equalizer in the longitudinal core system increased its damping and, consequently, reduced the longitudinal core emittance blowup

Stacktail Model

Fokker-Planck equation for longitudinal motion



$$\frac{\partial \psi}{\partial t}+\frac{\partial}{\partial x}\left(F(x)\psi\right)=\frac{1}{2}\frac{\partial}{\partial x}\left(D(x)\frac{\partial \psi}{\partial x}\right).$$

$$F(x)=f_0\sum_{n=-\infty}^{\infty}\frac{G_1(x,\omega_n)}{\varepsilon(\omega_n)}\left(1-A(\omega_n)e^{-i\omega_n T_0}\right)e^{i\omega_n T_2\eta_2 x}$$

$$D(x)=\sum_{n=-\infty}^{\infty}\frac{1}{\left|\varepsilon(\omega_n)\right|^2}\left[\frac{2\pi e^2 P_{Unoise}(\omega_n)}{T_0^{\,2}\left(\gamma\beta^2 mc^2\right)^2}\left|\frac{Z_k(\omega_n)}{Z_{ampl}}\right|^2+f_0\left|G_1(x,\omega_n)\left(1-A(\omega_n)e^{-i\omega_n T_0}\right)\right|^2\frac{\psi(x)}{|n\eta|}\right].$$

$$\varepsilon(\omega)=1+\left(1-A(\omega)e^{-i\omega T_0}\right)\int_{\delta\to 0_+}\frac{d\psi(x)}{dx}\frac{G_1(x,\omega)e^{i\omega T_2\eta_2 x}}{e^{i\omega T_0(1+\eta x)}-(1-\delta)}dx\ ,$$

Here: $\int \psi(x)dx=N\quad,\quad \omega_n=n\omega_0(1-\eta x),\quad \frac{\Delta p}{p}\equiv x$

term $\left(1-A(\omega_n)e^{-i\omega_n T_0}\right)$ describes notch filter (three notch filters are used in the stacktail making Eqs. even more complicated)

Van der Meer solution

- To get to the Van der Meer solution
  - We factorize cooling force and diffusion
    $$G(x,\omega)\left(1-A(\omega)e^{-i\omega T_0}\right)=G_x(x)G_\omega(\omega)$$
  - We neglect pickup-to-kicker delay
  - We neglect particle screening
  - We neglect thermal noise
  - Replace sum by integral
- Then, we arrive to

$$F(x)=2G_x(x)\int_0^\infty \mathrm{Re}\left(G_\omega(2\pi f)\right)df$$

$$D(x)=\frac{2N\psi(x)G_x(x)^2}{T_0|\eta|}\int_0^\infty \left|G_\omega(2\pi f)\right|^2\frac{df}{f}$$

- Rectangular gain function

$$G_\omega(2\pi f)=\begin{cases}G_0\,, & f\in[f_{\min}, f_{\max}]\\ 0\,, & otherwise\end{cases}$$

$$W=\frac{f_{\max}-f_{\min}}{\sqrt{\ln\left(f_{\max}/f_{\min}\right)}}$$

- Linearly growing gain

$$G_\omega(2\pi f)=\begin{cases}G_0 f/f_{\min}\,, & f\in[f_{\min}, f_{\max}]\\ 0\,, & otherwise\end{cases}$$

$$W=\sqrt{\frac{f_{\max}{}^2-f_{\min}{}^2}{2}}$$

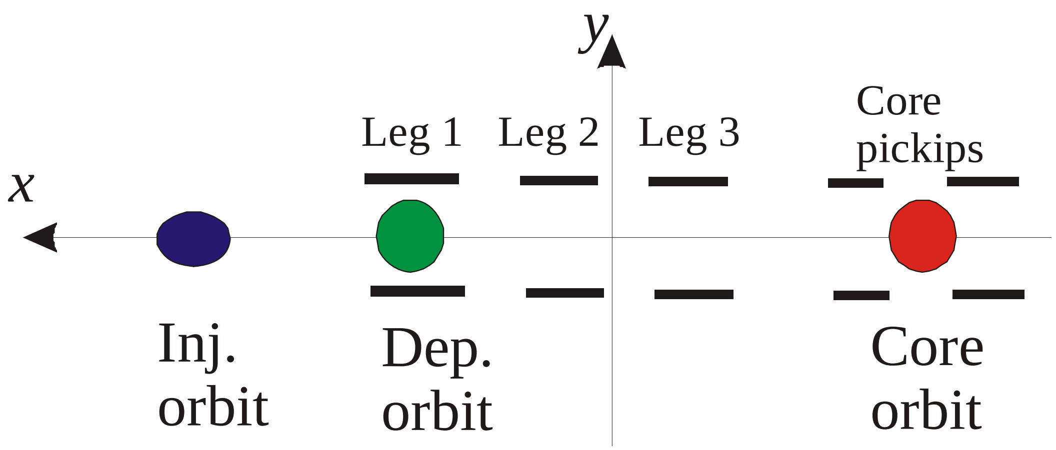
For one octave band, $f_{\max}/f_{\min}=2$, that results in 4% larger bandwidth

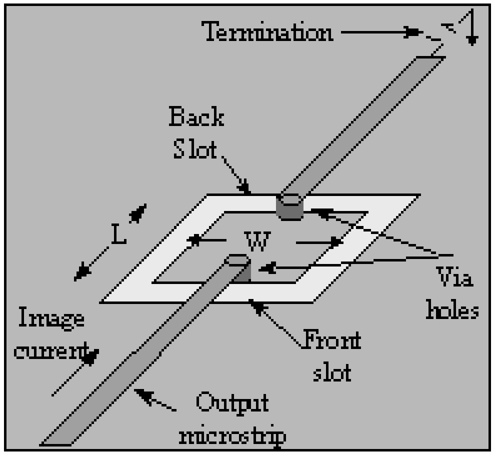
- Assuming that $G_x(x)=G_0\exp(-x/x_d)$ one can solve the Fokker-Planck equation. That results in the maximum flux:

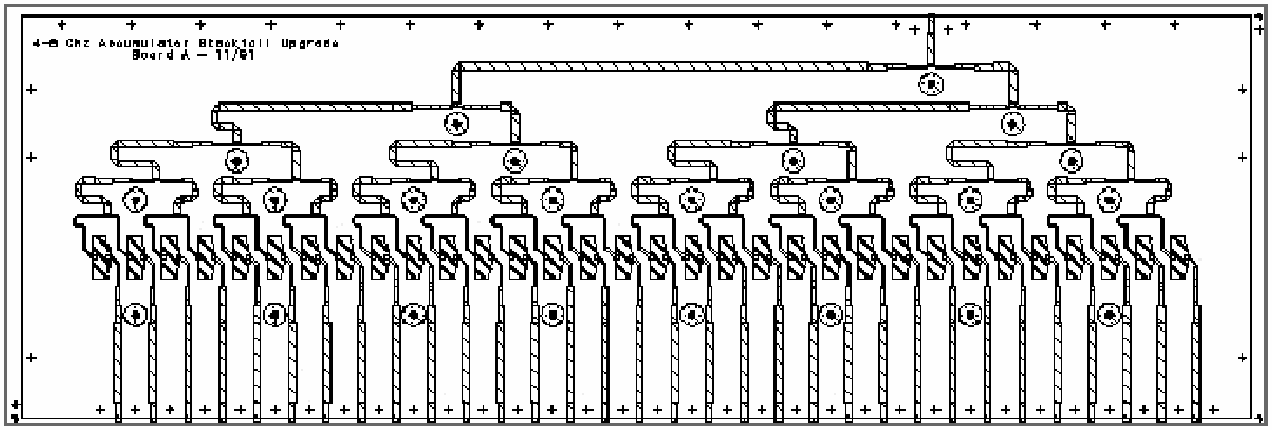
$$J_{\max}=|\eta|x_d T_0 W^2$$, where $$W=\sqrt{\frac{\left(\int_0^\infty \mathrm{Re}\left(G_\omega(2\pi f)\right)df\right)^2}{\int_0^\infty \left|G_\omega(2\pi f)\right|^2\frac{df}{f}}}$$

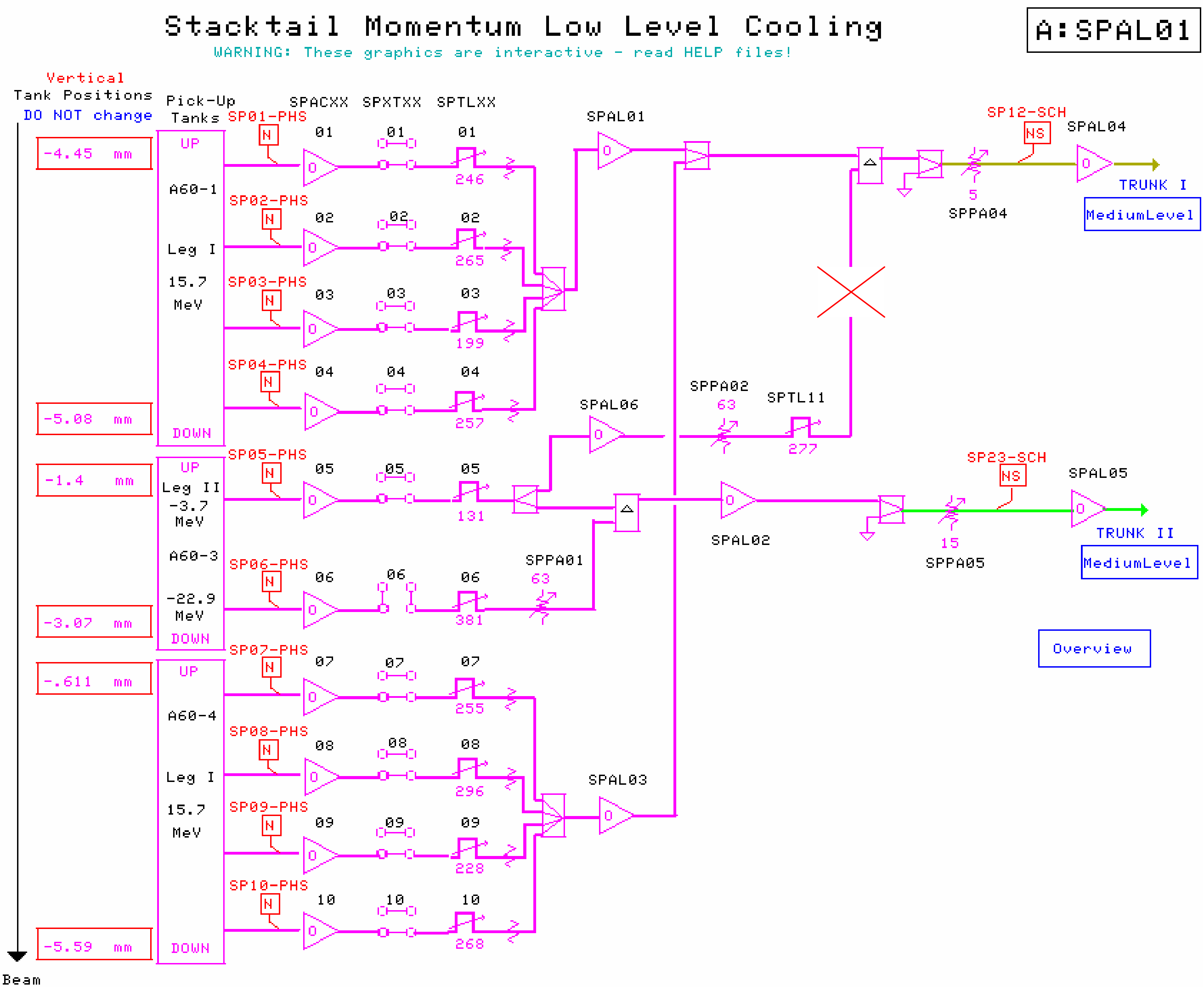
Stacktail hardware

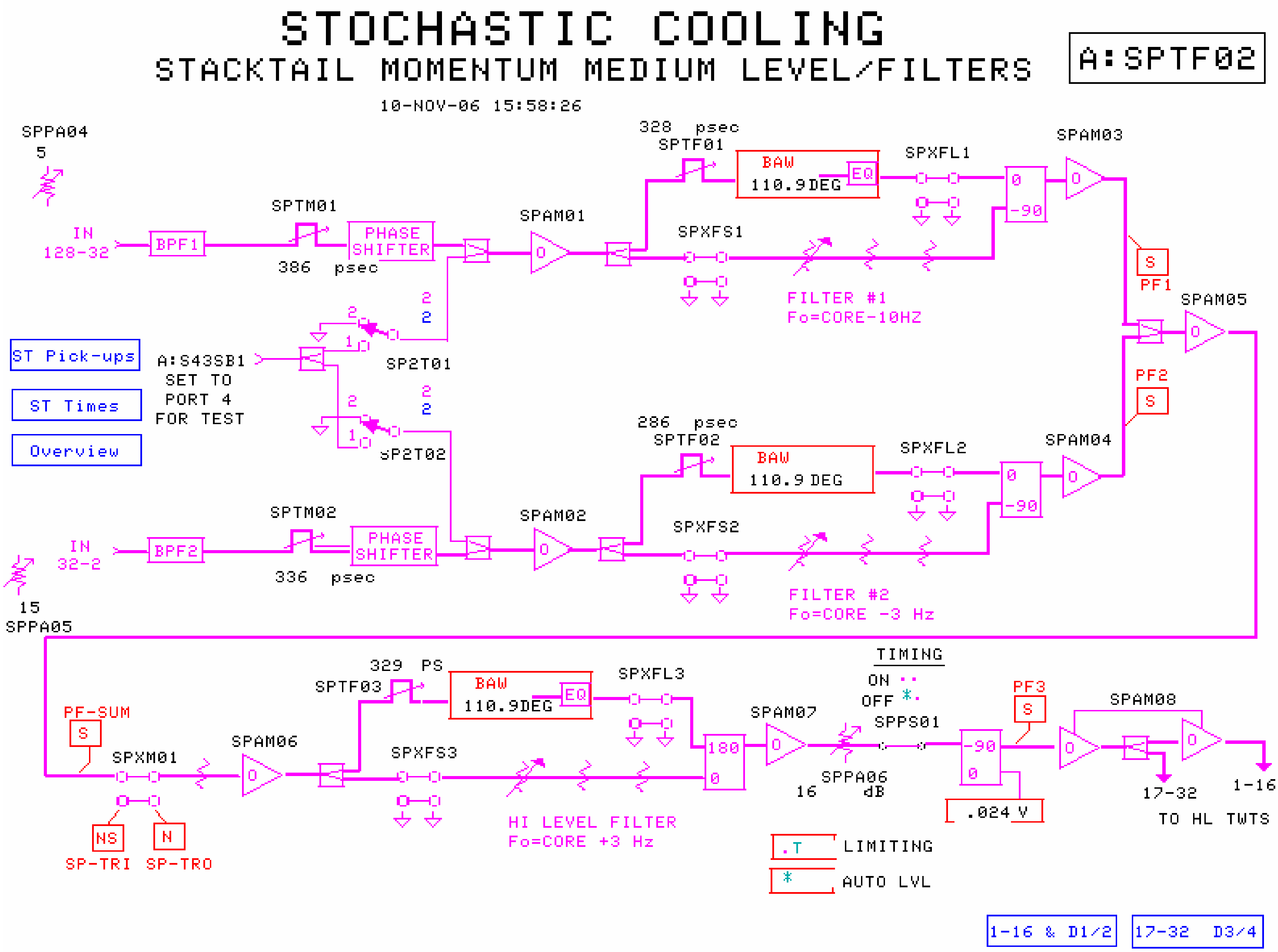
- Pickups are located at large dispersion (~9.1 m) while kickers are at zero dispersion (Palmer cooling)
- Stacktail has 3 pickups located at different radial positions to make desired dependence of gain on the momentum
- Pickups and kickers are built on the same technology
  - Planar loops
  - Printed circuit board technology
  - Works good at small frequencies (f≤4 GHz)
- Outside of pickup aperture its sensitivity drops exponentially. That allows one to form desired gain profile on particle position with small number of pickups
- Notch filters perform additional suppression of the gain on the core (~40 Db dynamic range)

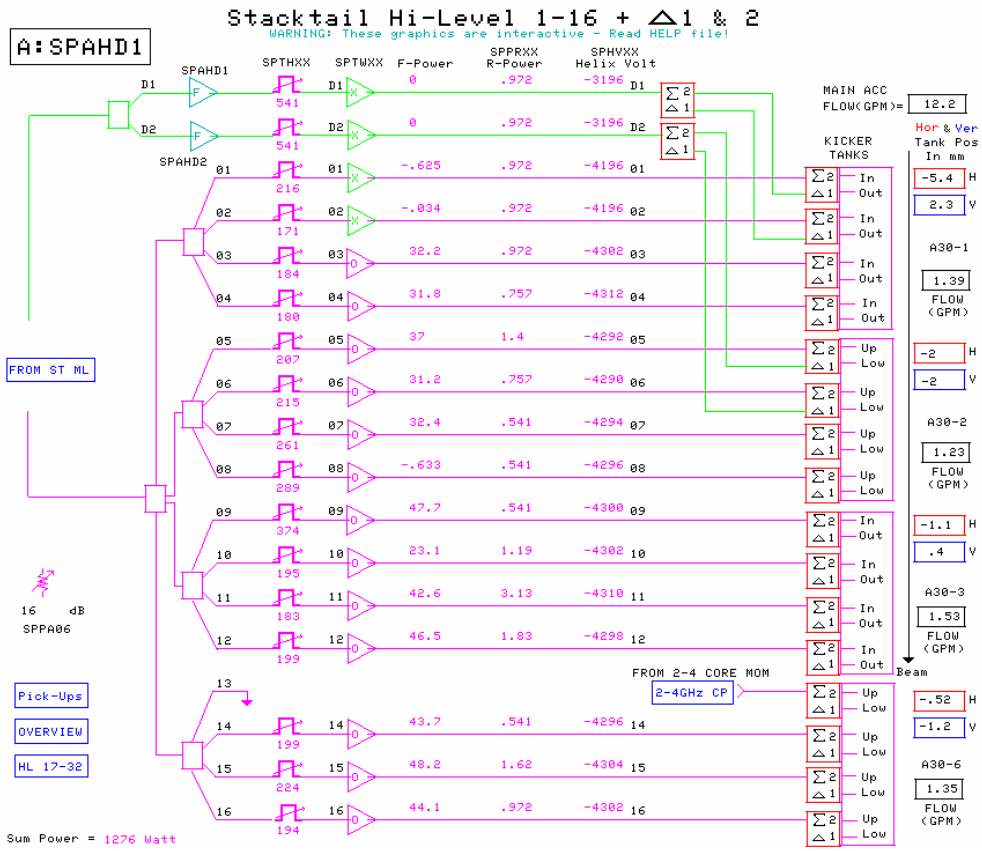


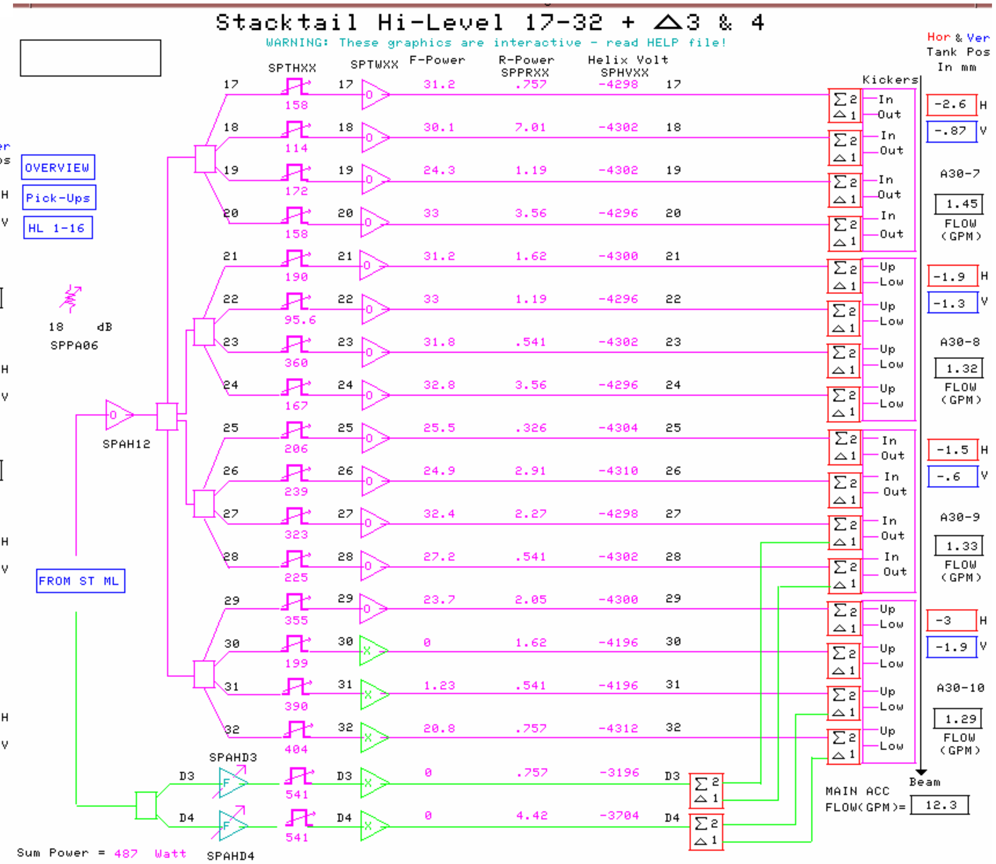





Stacktail Momentum Low Level Cooling
WARNING: These graphics are interactive - read HELP files!
A:SPAL01
Vertical
Tank Positions
DO NOT change
Pick-Up
Tanks
SPACXX SPXTXX SPTLXX
-4.45 mm
-5.08 mm
-1.4 mm
-3.07 mm
-.611 mm
-5.59 mm
UP
A60-1
Leg I
15.7
MeV
DOWN
UP
Leg II
-3.7
MeV
A60-3
-22.9
MeV
DOWN
UP
A60-4
Leg I
15.7
MeV
DOWN
SP01-PHS
SP02-PHS
SP03-PHS
SP04-PHS
SP05-PHS
SP06-PHS
SP07-PHS
SP08-PHS
SP09-PHS
SP10-PHS
246
265
199
257
131
381
255
296
228
268
SPAL01
SPAL06
SPAL03
SPAL02
SPPA01
63
SPPA02
63
SPTL11
277
SP12-SCH
NS
SPAL04
5
SPPA04
TRUNK I
MediumLevel
SP23-SCH
NS
SPAL05
15
SPPA05
TRUNK II
MediumLevel
Overview
Beam

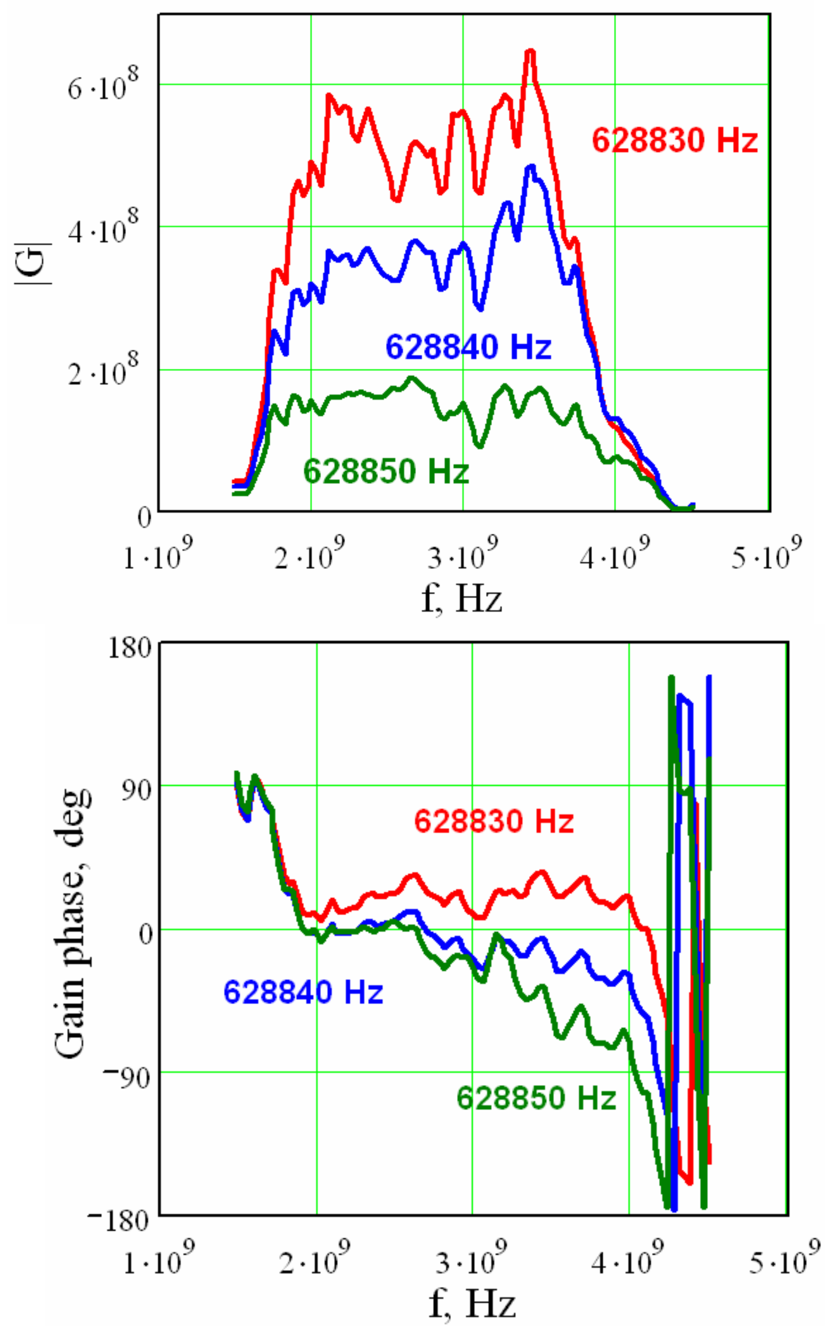

STOCHASTIC COOLING
STACKTAIL MOMENTUM MEDIUM LEVEL/FILTERS
A:SPTF02
10-NOV-06 15:58:26
SPPA04
5
IN
128-32
BPF1
SPTM01
386 psec
PHASE SHIFTER
SPAM01
328 psec
SPTF01
BAW
110.9DEG
EQ
SPXFL1
SPAM03
0
-90
SPXFS1
FILTER #1
Fo=CORE-10HZ
S
PF1
SPAM05
ST Pick-ups
ST Times
Overview
A:S43SB1
SET TO
PORT 4
FOR TEST
SP2T01
SP2T02
PF2
286 psec
SPTF02
BAW
110.9 DEG
SPXFL2
SPAM04
SPTM02
IN
32-2
BPF2
336 psec
PHASE SHIFTER
SPAM02
SPXFS2
FILTER #2
Fo=CORE -3 Hz
15
SPPA05
329 PS
SPTF03
BAW
110.9DEG
EQ
SPXFL3
TIMING
ON
OFF
PF-SUM
S
SPXM01
SPAM06
SPXFS3
HI LEVEL FILTER
Fo=CORE +3 Hz
NS
N
SP-TRI
SP-TRO
180
0
SPAM07
SPPS01
SPPA06
16
dB
PF3
-90
.024 V
SPAM08
17-32
1-16
TO HL TWTS
LIMITING
AUTO LVL
1-16 & D1/2
17-32 D3/4


A:SPAHD1
Stacktail Hi-Level 1-16 + △1 & 2
WARNING: These graphics are interactive - Read HELP file!
SPTHXX
SPTWXX
F-Power
SPPRXX R-Power
SPHVXX Helix Volt
MAIN ACC FLOW(GPM)= 12.2
KICKER TANKS
Hor & Ver Tank Pos In mm
OVERVIEW
Pick-Ups
HL 1-16
FROM ST ML
16 dB SPPA06
18 dB SPPA06
FROM 2-4 CORE MOM
2-4GHz CP
Pick-Ups
OVERVIEW
HL 17-32
Beam
Sum Power = 1276 Watt


Stacktail Hi-Level 17-32 + △3 & 4
WARNING: These graphics are interactive - read HELP file!
SPTHXX
SPTWXX
F-Power
R-Power SPPRXX
Helix Volt SPHVXX
Kickers
Hor & Ver Tank Pos In mm
SPAH12
FROM ST ML
SPAHD3
SPAHD4
MAIN ACC FLOW(GPM)= 12.3
Beam
Sum Power = 487 Watt

Numerical model

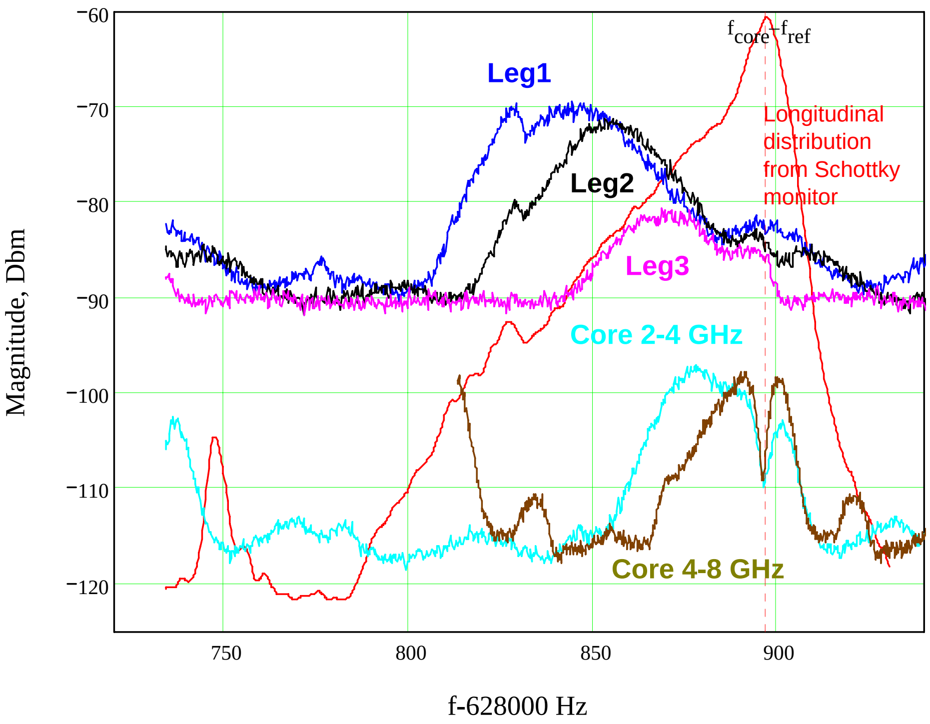
- Numerical model is based on the open loop BTF measurements
  - It took a while to determine Pencil beam intensity and Level of beam excitation
- Dependence of gain on frequency was measured on the revolution frequency harmonics in 1.5 – 5 GHz range with notch filters off
  - Notch filters were measured separately

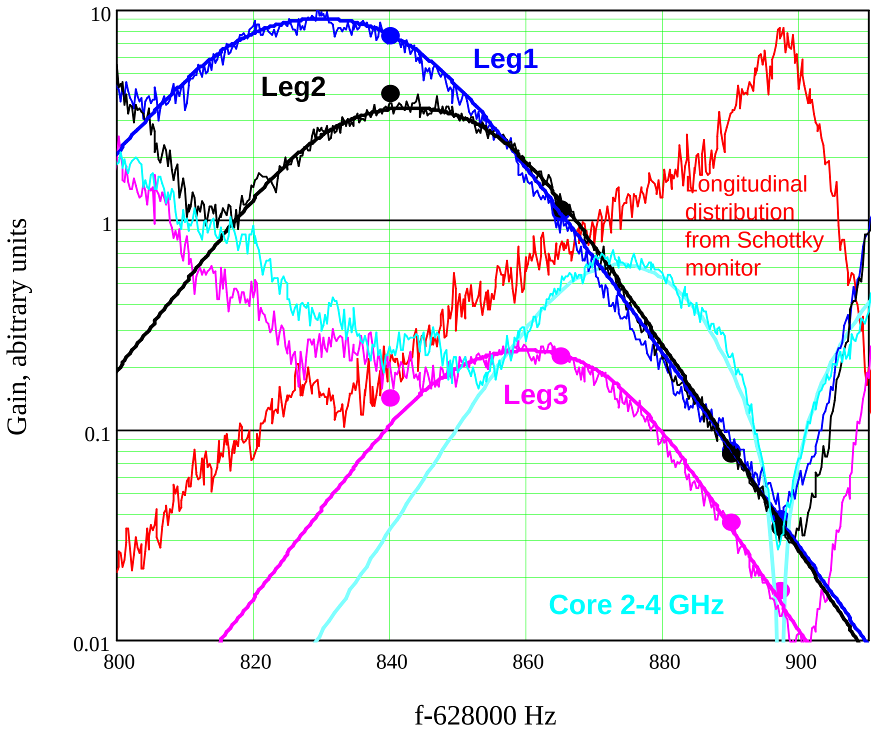


Total system gain after stacktail upgrade

Numerical model (continue)

- Pickup coordinate response
  - The response is obtained from a ratio of single band Schottky noise of each subsystem to the longitudinal Schottky monitor signal (D_x=0)
  - Results are close to the test-stand measurements
    - $\eta(x)$ variation (~15%) is accounted
    - Measurements are fitted to: $F(x)=\frac{1}{\pi}\left[\operatorname{atan}\left(\sinh\left(\frac{\pi}{h}\left(x-x_0+\frac{w}{2}\right)\right)\right)-\operatorname{atan}\left(\sinh\left(\frac{\pi}{h}\left(x-x_0-\frac{w}{2}\right)\right)\right)\right]$





Numerical model (continue)

Stacktail Pickup Coordinate Response

- Pickup coordinate response coincides well with following formula

$$F(x) = \frac{1}{\pi}\left[\operatorname{atan}\left(\sinh\left(\frac{\pi}{h}\left(x - x_0 + \frac{w}{2}\right)\right)\right) - \operatorname{atan}\left(\sinh\left(\frac{\pi}{h}\left(x - x_0 - \frac{w}{2}\right)\right)\right)\right]$$

- Parameters used in the fitting are

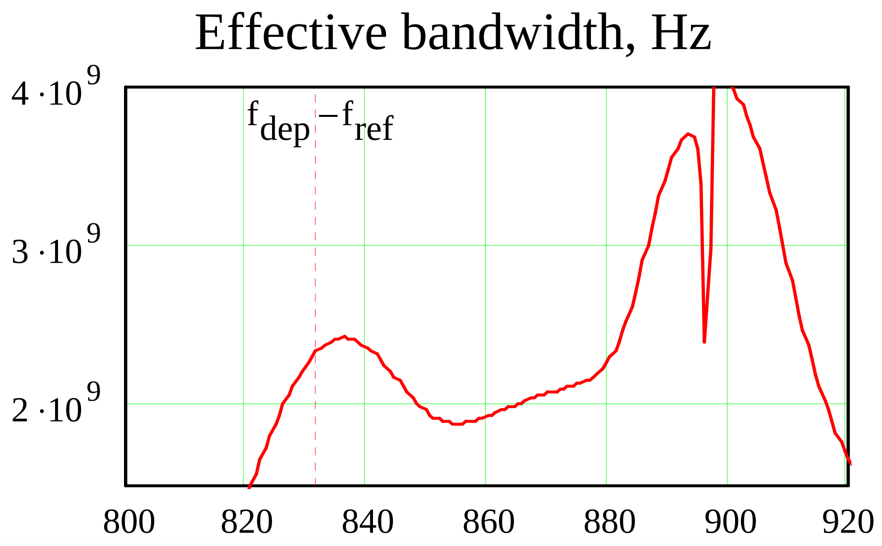
	x_0[cm]	h [cm]	w[cm]
Leg1	1.07	3.2	3.2
Leg2	-0.77	3.1	
Leg3	-2.4	3.1	
Core 2 - 4 outer	-3.5	3	2
Core 2 - 4 inner	-8.5		
Core 4 - 8 outer	-4.88	3.3	1
Core 4 - 8 inner	-7.08		

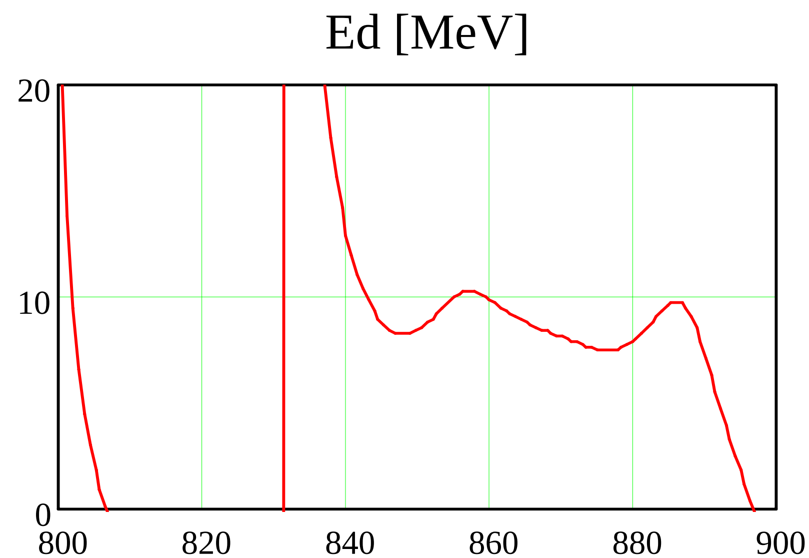
- Dispersion at pickup is 910 cm (nonlinearity of dispersion on momentum is neglected

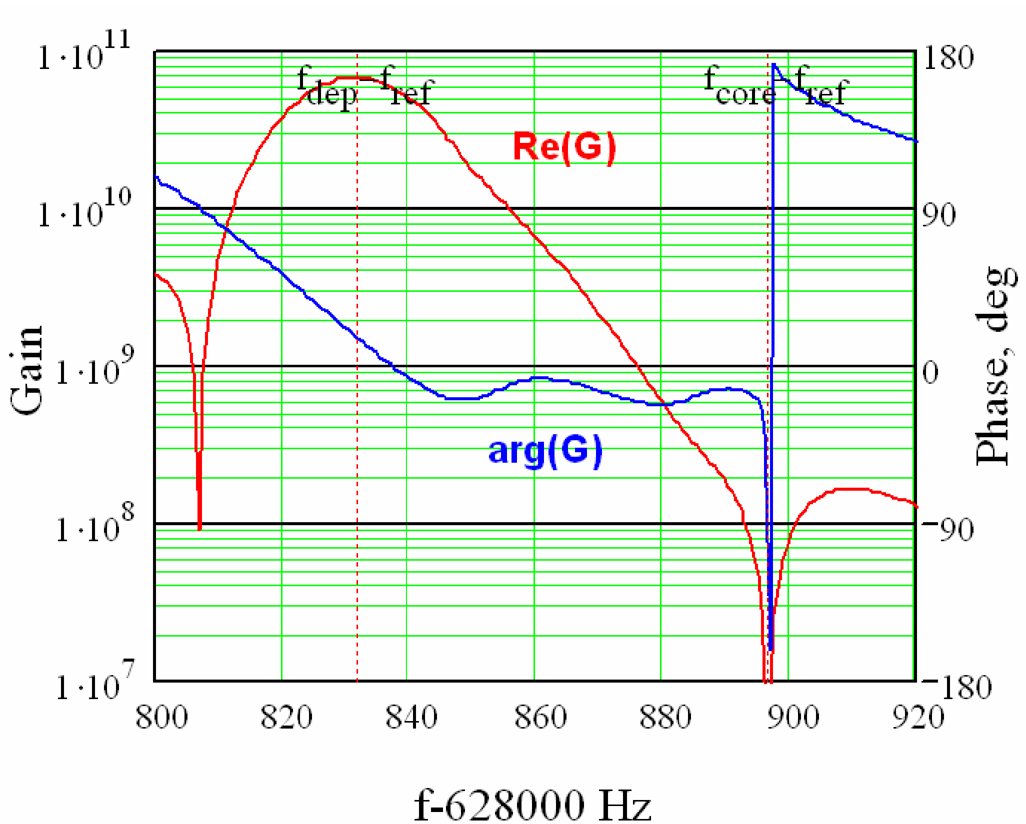
Numerical model (continue)

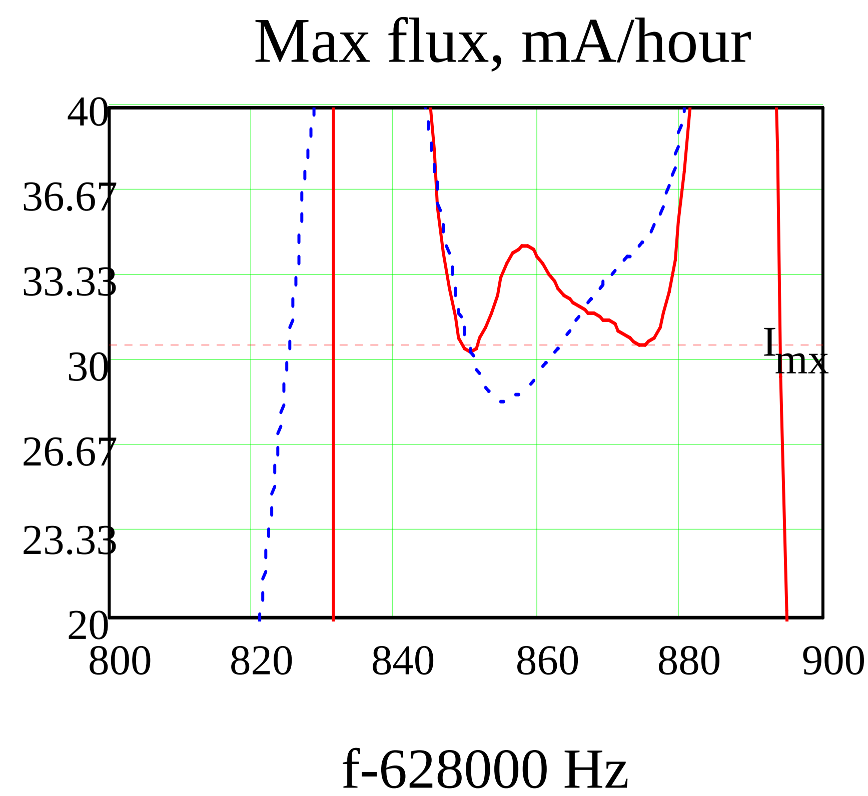
- Wiring all pieces together (including two core cooling systems) one obtains $G(x,\omega)$
- Static flux model computes
  - cooling force: $G(x)$
  - Inverse rate of cooling force change: $E_d \equiv p\, x_d$
  - Effective bandwidth
  - Van der Meer flux

Results of Static Model (for stacktail system after all upgrades)

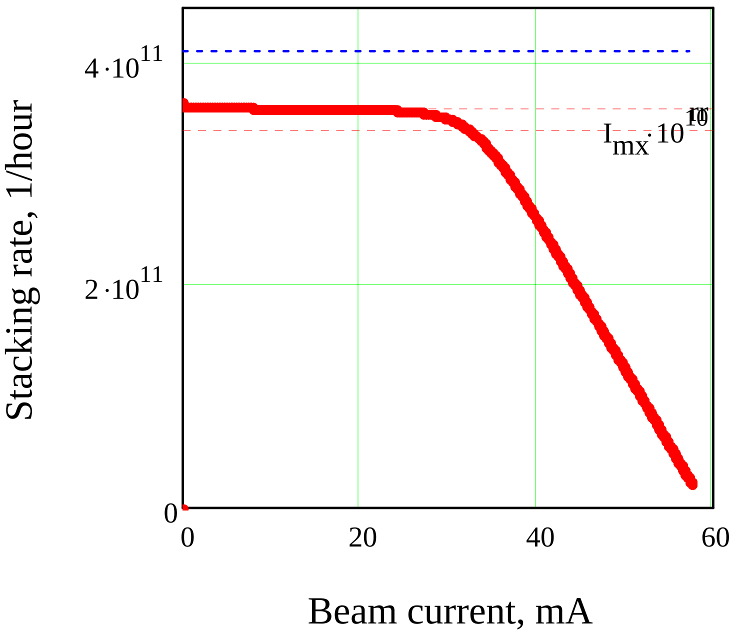




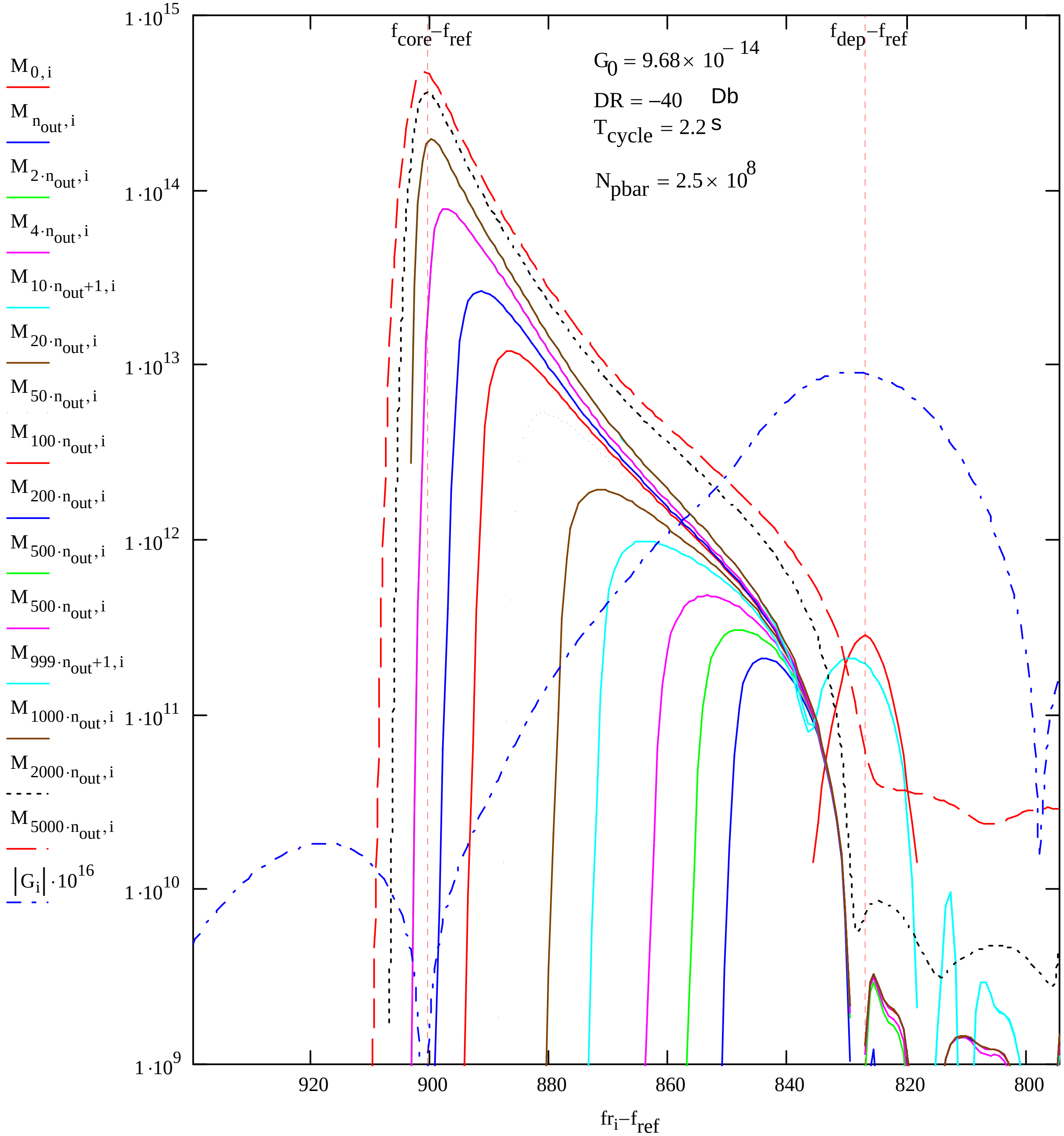




Dynamic Stacktail model predictions

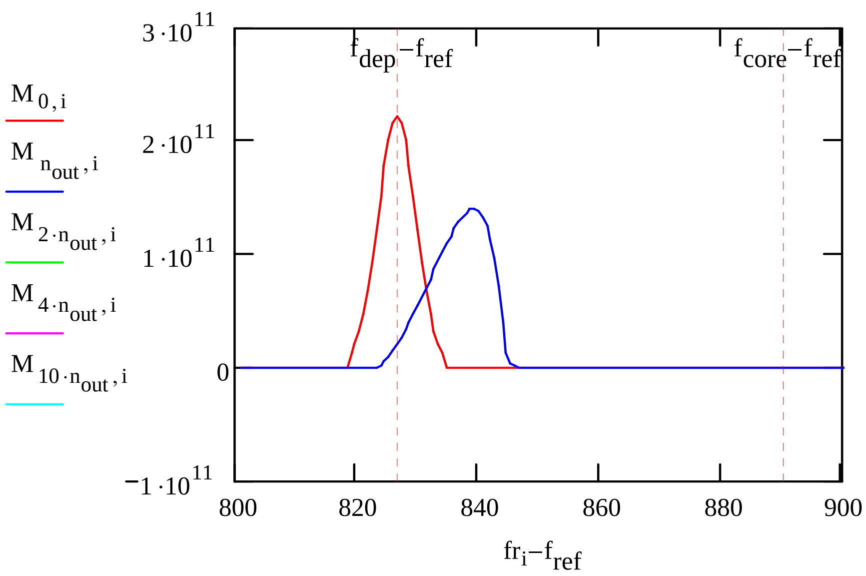


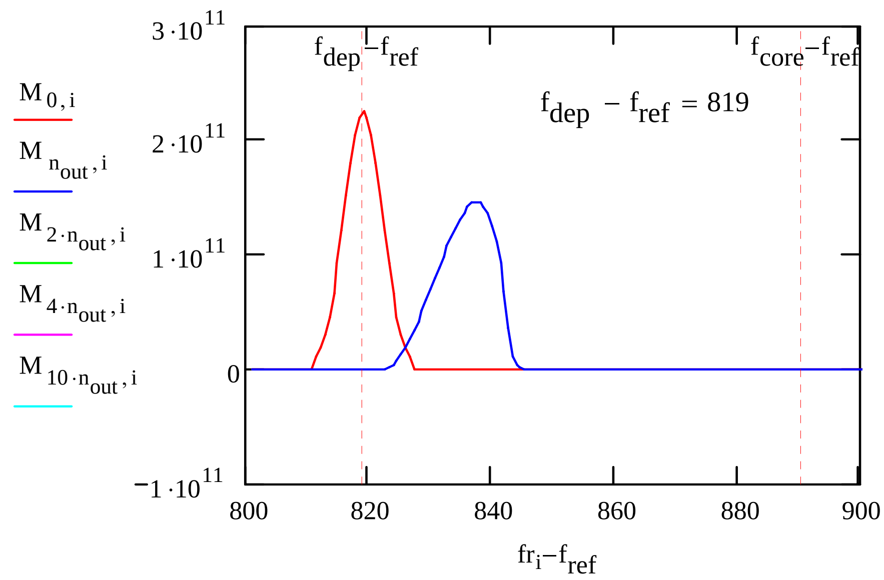
- $\varepsilon(\omega)$ is presently ignored in simulations to accelerate computations but it sets the gain of the system

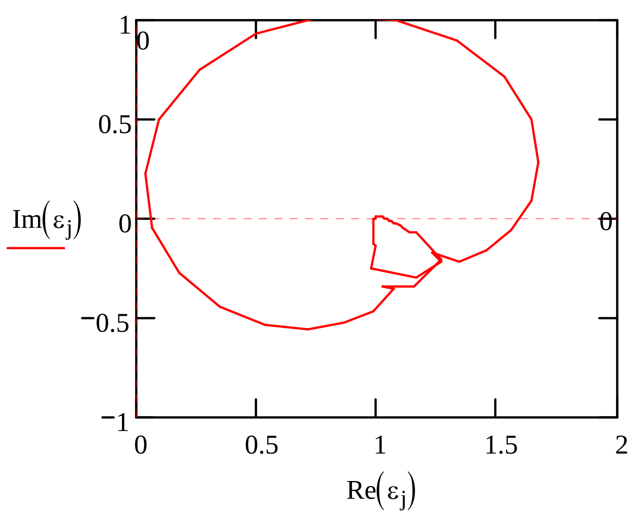


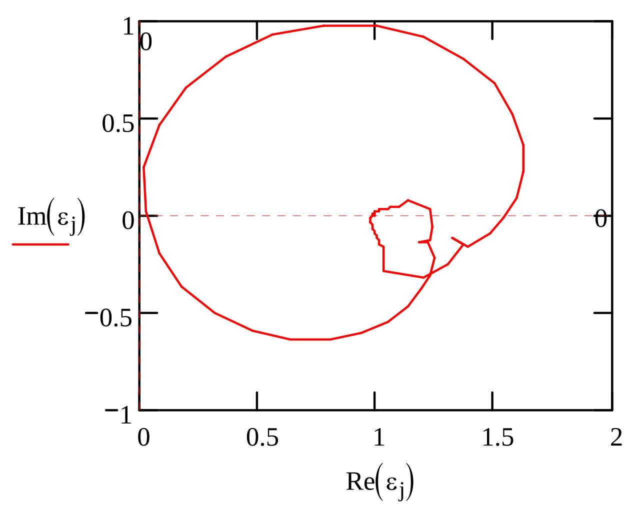
Dynamic Stacktail model predictions (continue)

Deposition orbit clearing is limited by the instability excited by stack-tail









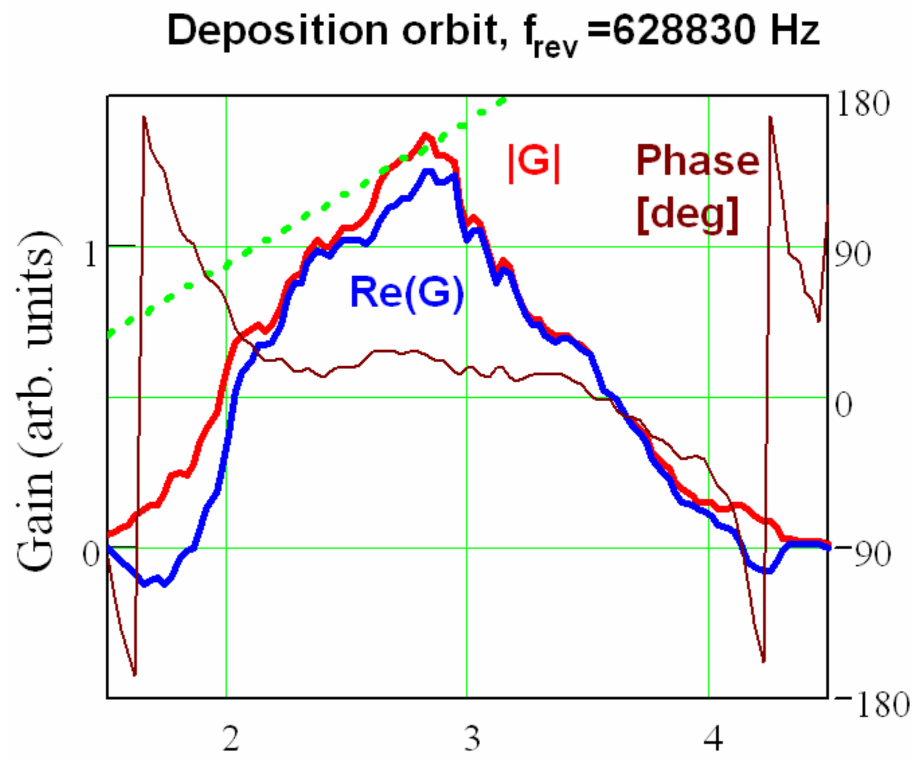
Present (f.=2.5 GHz) *Future (f.=3.5 GHz)*

Dielectric functions just after injection of the first antiproton pulse at fr. of maximum response

Stacktail Upgrade

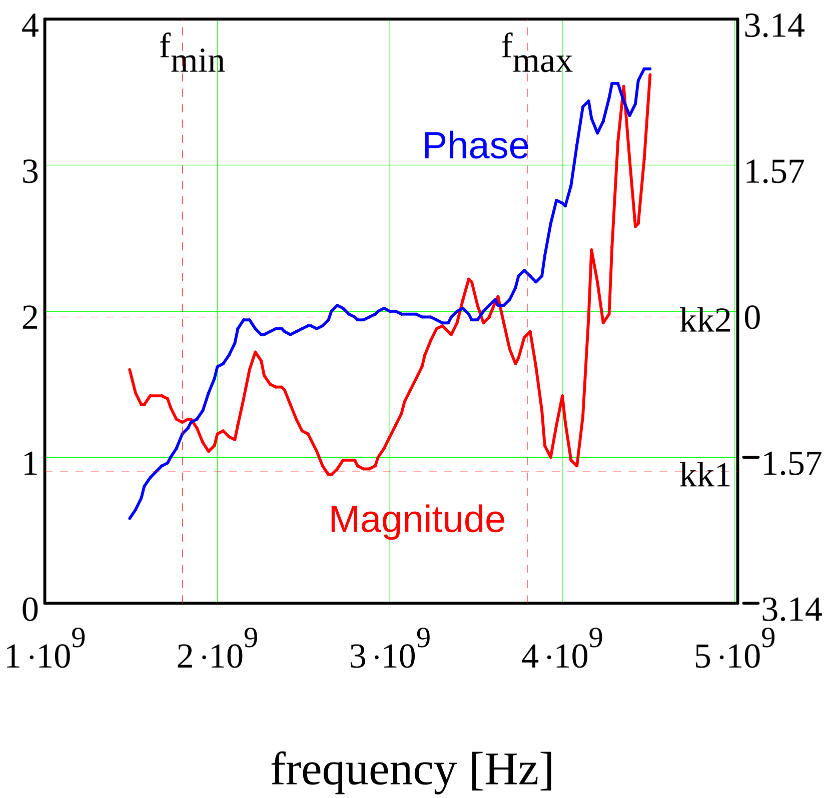
$$J_{\max} = T_0 |\eta| W^2 x_d$$

- Bandwidth increase, W
  - Gain is peaked in the band center
  - Large phase varations at band edges
  - 20 Db signal-to-noise ratio
  - 10 Db gain correction ⇒ increase of effective bandwidth by ~20% ⇒ 40% increase of stacking rate.
- Increase of x_d would require more power which we have not had
- Increase of the slip factor, η, by ~20% looked attractive
  - Further increase is limited by the band overlap at high frequencies
  - It required optics change in Accumulator
- Feb.'06 stacking rate (before equalizer) coincided with the model predictions
  - At the end of 2006 it looked very probable that $30{\cdot}10^{10}$/hour will be achieved by summer of 2007
    - Nevertheless, other complications were coming soon

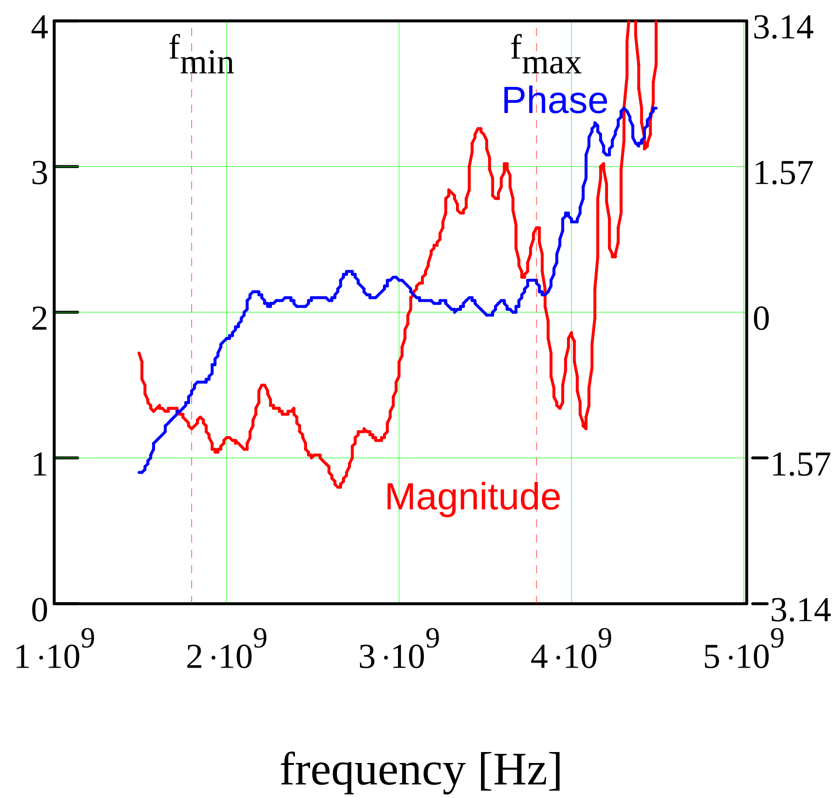


What Equalizer does?

- It corrects phase and magnitude of the gain so that to achieve maximum bandwidth



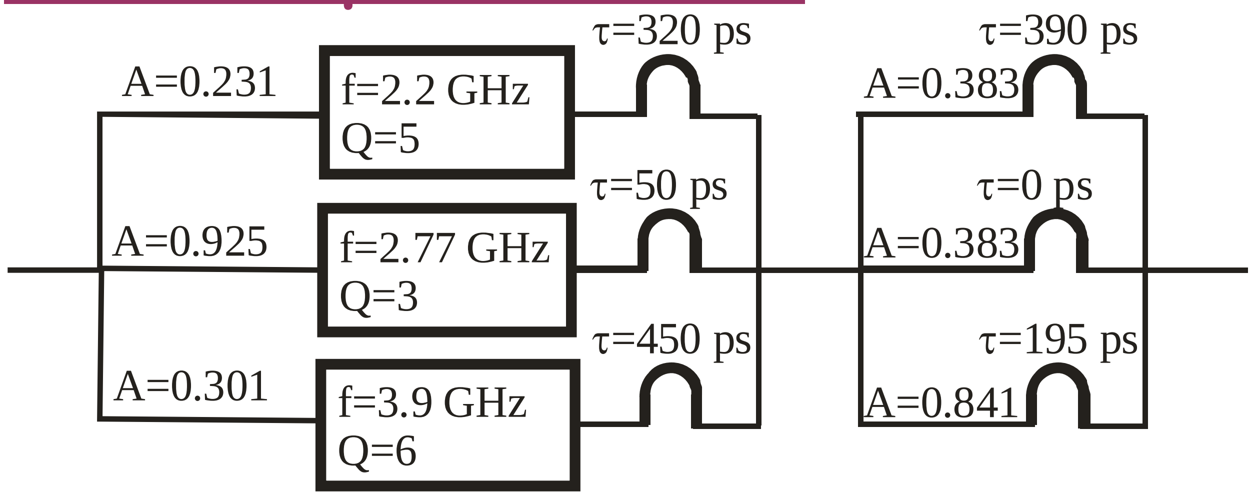
Equalizer with reduced gain at high frequency (equalizer prototype). It was tested first.

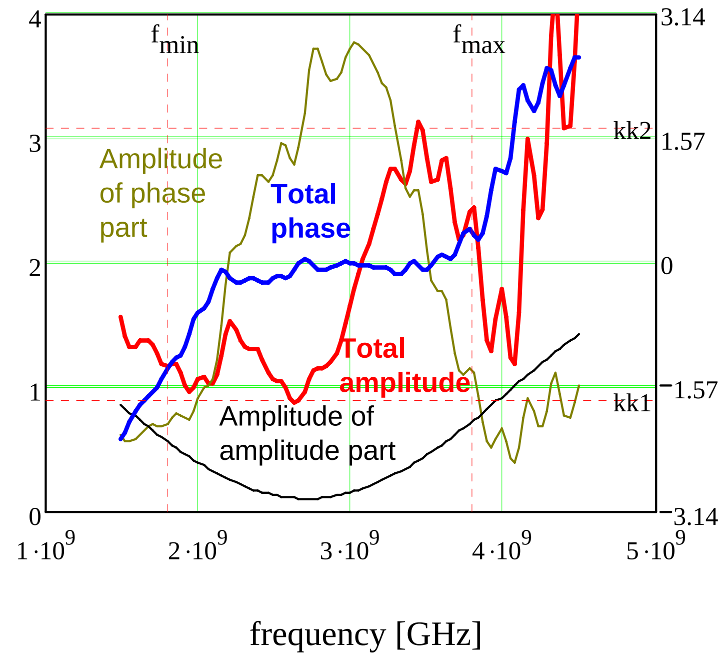


Present equalizer

Is causality violated ?

How the equalizer is built





Prototype Equalizer specifications

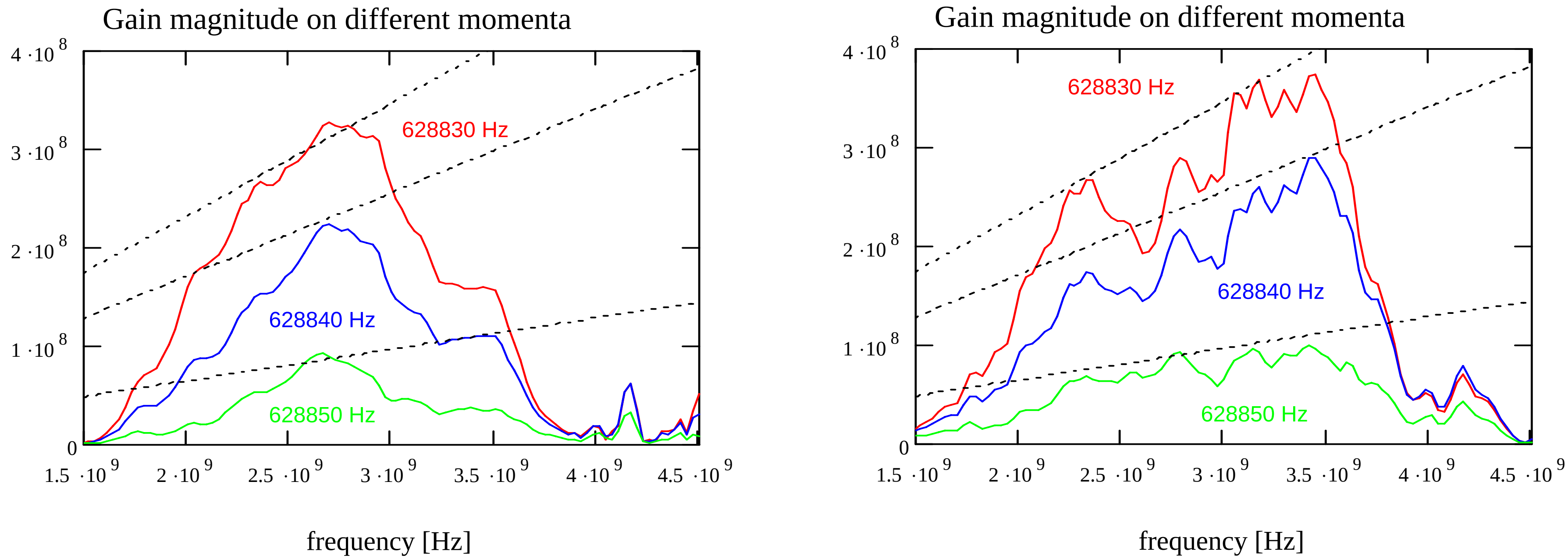
- Phase part corrects phase
- Amplitude part corrects amplitude so that to get the total amplitude as desired

$$K_i(\omega) = \frac{A_i}{1 + iQ_i \dfrac{\omega^2 - \omega_i^2}{\omega\omega_i}}, \quad i = 1,2,3$$

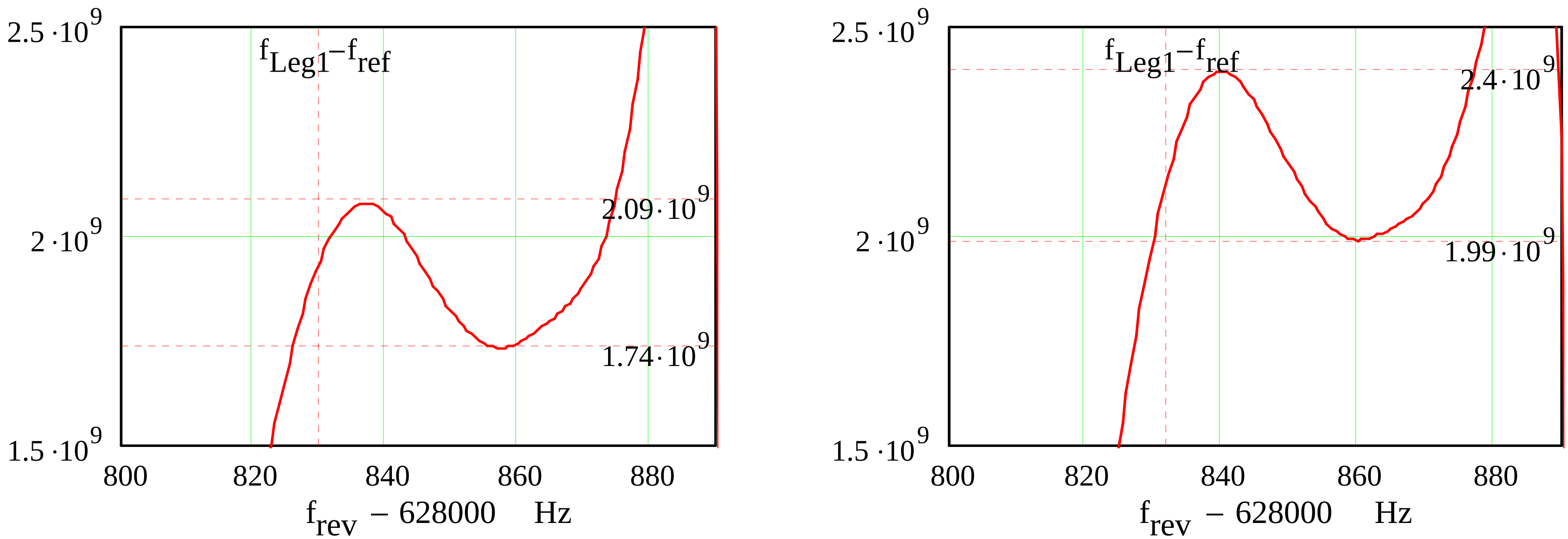
$$K_A(\omega) = 1 + 0.91\cos(\omega\tau), \quad \tau = 195\ ps$$

$$K_{tot}(\omega) = K_A(\omega)\left(K_1(\omega) + K_2(\omega) + K_3(\omega)\right)$$

- Final equalizer has 5 resonators and two-stage amplitude correction



Dependence of stacktail gain on frequency before and after installation of the equalizer



Dependence of effective bandwidth before and after installation of the equalizer (~15% growth)

What did we achieved after equalizer installation?

- With equalizer fully commissioned we found that we cannot run system with sufficiently high gain because of $\perp$ heating
  - Basically the same stacking rate but 2 times smaller power
    - $\Rightarrow$ 1.6 kW $\rightarrow$ 0.8 kW
  - Optics change in Accumulator addressed this problems

Transverse Heating and its Mitigation

- Transverse emittance growth is excited by the stacktail because of non-uniformity of longitudinal kick across the aperture

$$U(x,y)=U_0\left(1\pm\frac{x^2-y^2}{2a_{eff}{}^2}\right)\Rightarrow\begin{cases}E_x\propto\dfrac{dU(x,y)}{dx}=U_0\dfrac{x}{a_{eff}{}^2}\\E_y\propto\dfrac{dU(x,y)}{dx}=-U_0\dfrac{y}{a_{eff}{}^2}\end{cases}$$

$$a_{eff}\approx 1.87\text{ cm}$$

- Kicker offset
  - Average offsets are kept sufficiently small
  - But, electrical center position varies with frequency
- Parametric heating
  - Excited by noise at sidebands of doubled betatron tune, $2\nu_x+n$
- Non-zero dispersion at kicker location

Emittance growth due to parametric heating

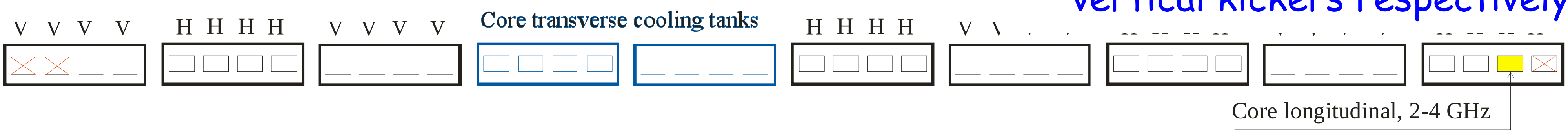
Transverse emittance growth can be expressed through stack-tail parameters, beta-functions at kicker positions and effective kicker aperture

$$\frac{1}{\varepsilon}\frac{d\varepsilon}{dt}=\frac{v_0^{\,2}\beta_{eff}^{\,2}}{4\pi\omega_0 a_{eff}^{\,4}}\sum_{k,m=-\infty}^{\infty}\frac{\psi(\tilde{p}_{km})}{\left|\eta k^3\right|}\left|G(\tilde{p}_{km},\tilde{\omega}_{km})\right|^2\left|\left(1-A(\tilde{\omega}_{km})e^{-i\omega_{km}T_0}\right)\right|^2 , \quad p\equiv\frac{\Delta P}{P}$$

$$\beta_{eff}^{\,2}=\frac{1}{\left(\sum_{i=1}^{N}|\kappa_i|\right)^2}\sum_{i,j=1}^{N}\kappa_i\kappa_j\left(\beta_0^{\,2}+2s_i's_j'+\frac{s_i'^2 s_j'^2}{\beta_0^{\,2}}-\left(s_i'-s_j'\right)^2\right)$$

s_i' - long. coordinate of *i*-th kicker relative to the point of minimum beta-function, β_0

$\kappa_i=\pm1$ for horizontal and for vertical kickers respectively



- Kicker rearrangement to reduce parametric heating
  - Core 2-4 GHz kicker is moved to the end
  - Two kickers at each end are off
- Effective β-function is reduced from 2.3 m to 0.6 m
  - 15 times reduction resulted negligible effect from parametric heating
- If we would go with 2-6 GHz system transverse heating would be a problem due to smaller a_{eff}

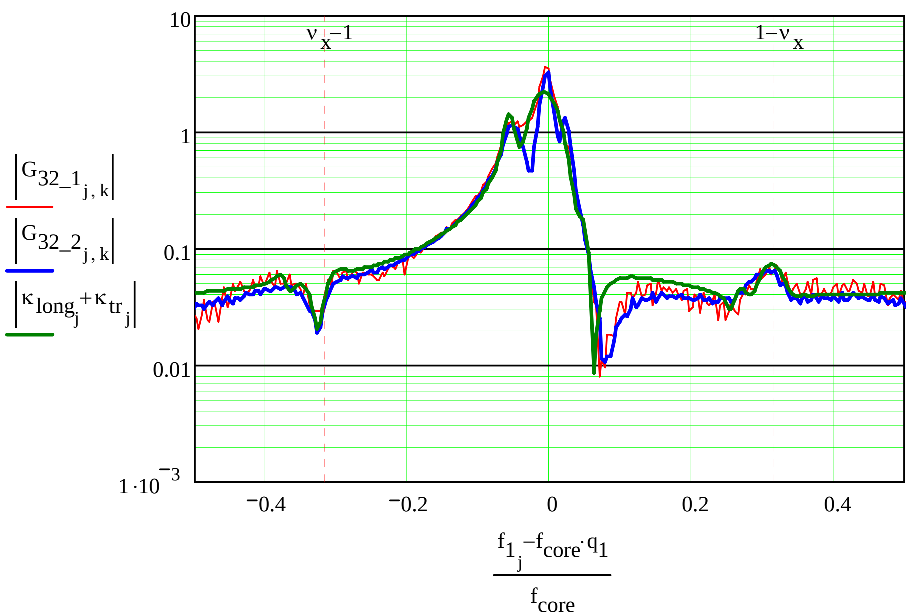
Emittance growth due to offset of kickers

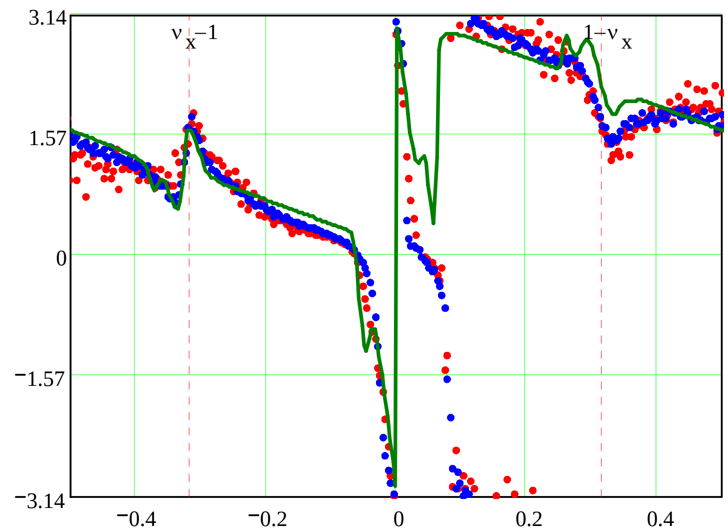
$$\frac{d\varepsilon(p)}{dt} = \frac{\omega_0 \beta_{kick}}{4\pi} \sum_{k,m=-\infty}^{\infty} \frac{\psi(p_{km})}{|\eta k|} \left|G(p_{km},\omega_{km})\right|^2 \left|D_{eff}(\omega_{km})\right|^2 \left|\left(1 - A(\omega_{km}) e^{-i\omega_{km}T_0}\right)\right|^2 ,$$

$$D_{eff}(\omega) = \frac{v_0 X(\omega)}{\omega a_{eff}}^2 + \frac{D'_{kick}\beta_{kick} + \alpha_{kick} D_{kick} - iD_{kick}}{\beta_{kick}}^2 .$$

$X(\omega)$ - position of kicker electrical center relative to the beam center

- Open loop stacktail measurements exhibited that the kicker electrical center depends on frequency
  - Resonance at 3.25 GHz, x_0=2 mm, Q=27,
- It results in emittance growth. It cannot be suppressed by kicker centering
  - Δ-kickers with correct amplitude and phase response will be used if required



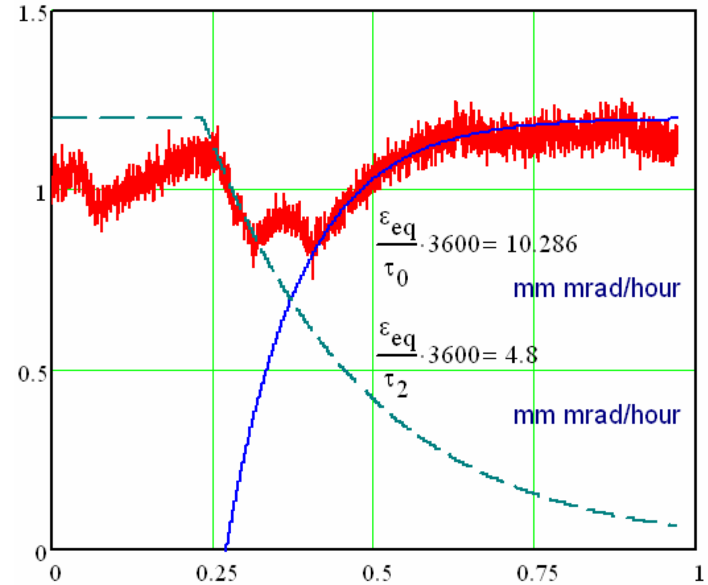


Narrow band open loop measurements of stacktail at 3.2 GHz (Apr. 10/2007)

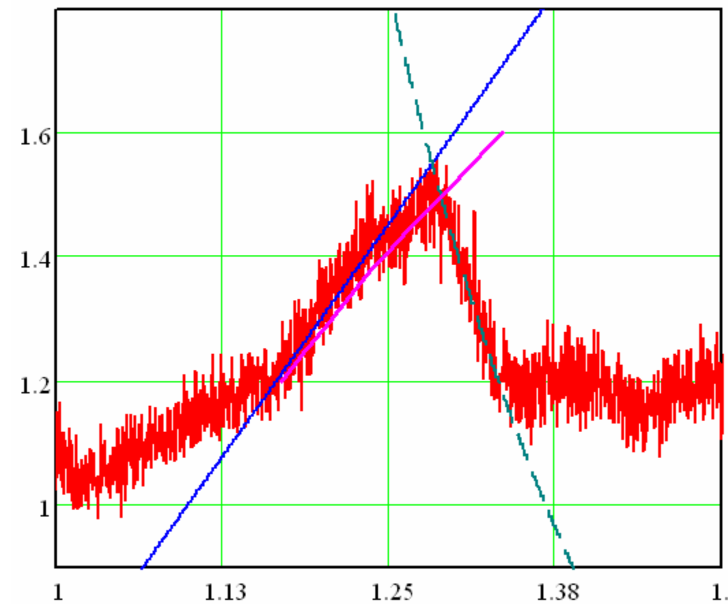
Directly Measured Heating Terms before Accumulator optics correction

- Analysis of H. emittance changes during stacking interruption and switching off all cooling systems results in
  - Core cooling time is 7 min
  - Direct measurements of heating terms before Accumulator optics correction

Heating mechanisms	mm mrad/hour
IBS heating at 50 mA	~3
Stacktail heating	5-6
Noise of core systems	~2
Total heating	~10



Data taken during stacking interruption

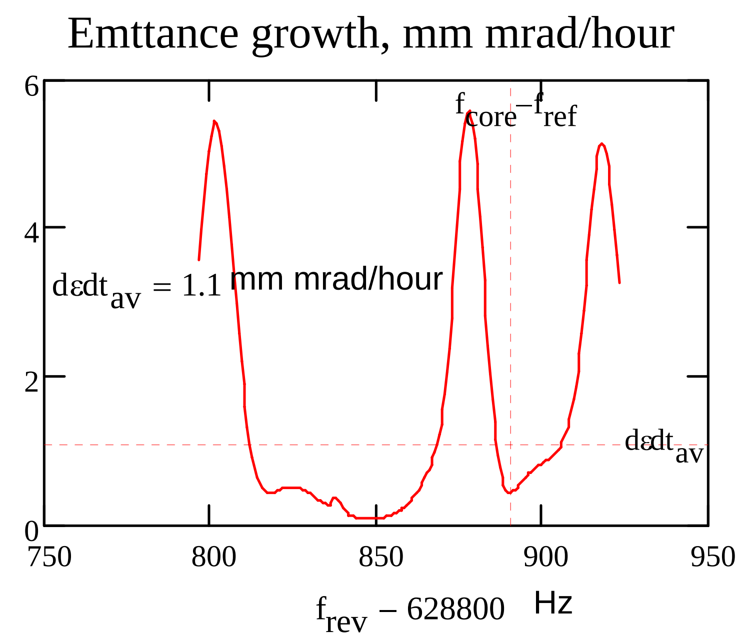


Data taken during stack-tail Schottky noise measurements; all cooling is off for ~10 min,

Estimate of Stacktail heating based on other measurements

Heating mechanisms	mm mrad/hour
Parametric heating	~0.25
Dispersion mismatch	~2.4
Kicker offset (res. at 3.25 GHz)	~1.2 - 2.2
Unaccounted*	~1.1 mm

* Most probably it is heating due to geometric kicker offset



Numerical simulation for measured kicker parameters:

x_0=2 mm, Q=27, $\omega_0/2\pi$ = 3.25 GHz

Accumulator Optics Change

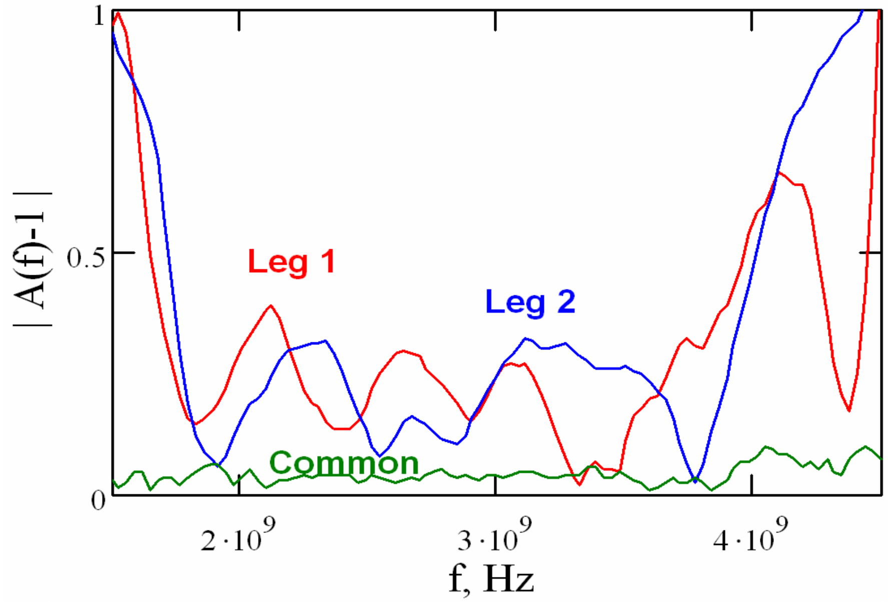
- Accumulator optics correction increased slip-factor, η, by ~20% and resulted in an acceptable $\perp$ emittances
- It reduced heating due to
  - IBS – smaller dispersion invariant
  - Dispersion match – smaller dispersion in kickers
  - Parametric heating
  - Kicker offset heating
    - the core sets between two peaks generated by Q and (1-Q) sidebands
- It also improved core cooling

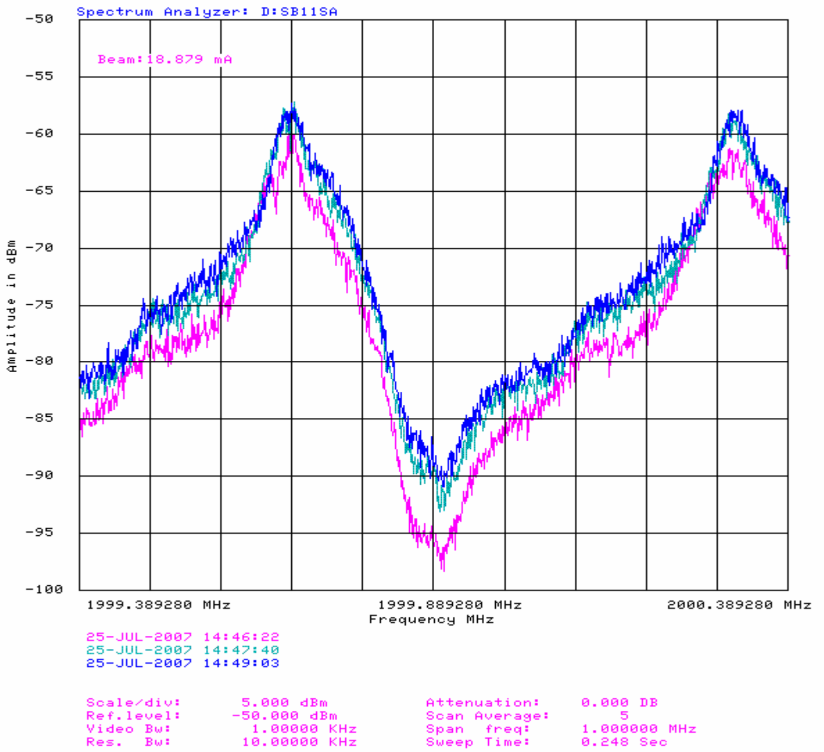
What did we achieved after fixing transverse blowup?

- But then the longitudinal heating set another limitation
  - Replacement of BAW (bulk-acoustic wave) notch filter 3 by SC notch filter addressed the longitudinal core stability but longitudinal heating still has been too large

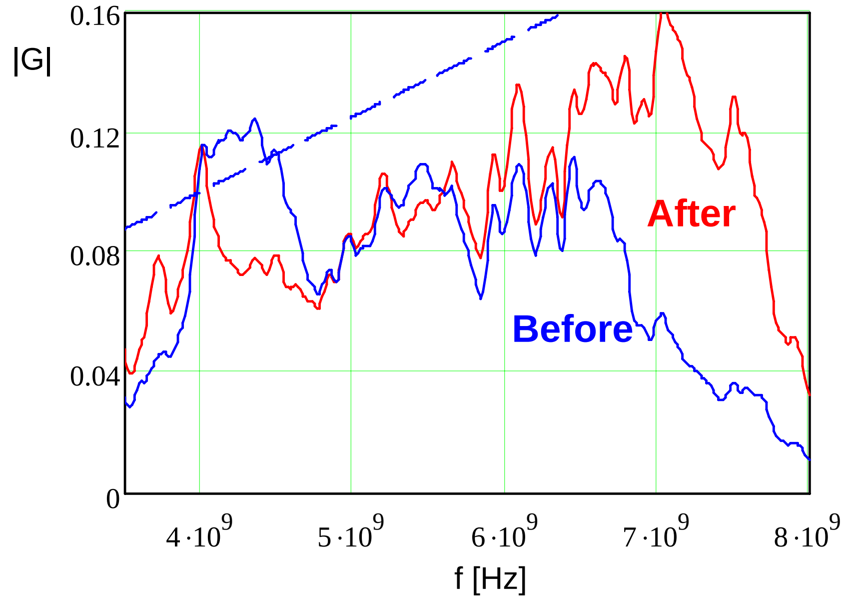
Longitudinal Heating and its Mitigation

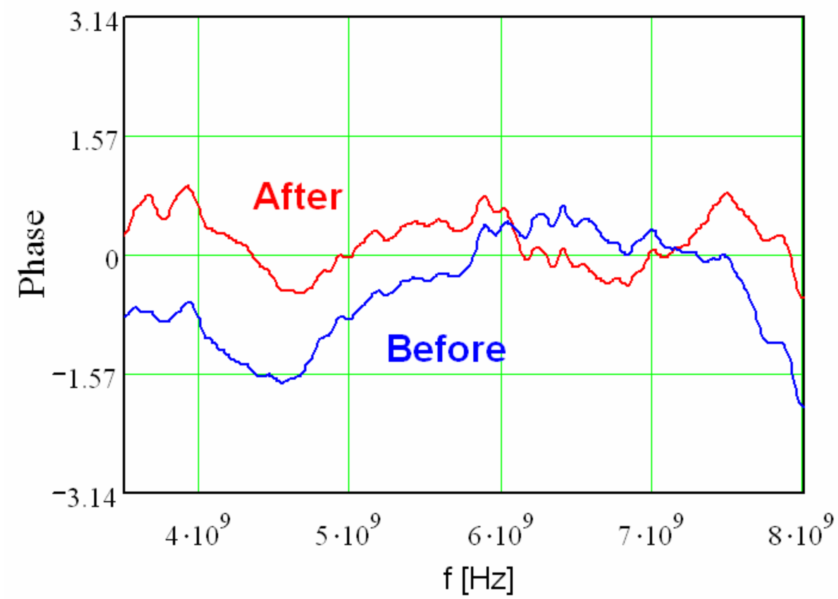
- Longitudinal core blowup is excited by Stacktail noise on harmonics of core revolution frequency
- Notch filters for additional suppression
  - ~35 Db dynamic range is set by noise of preamplifier
    - at high power by intermods
- Coherent Stability of the core at band edges was corrected by replacement of BA notch filter by SC one

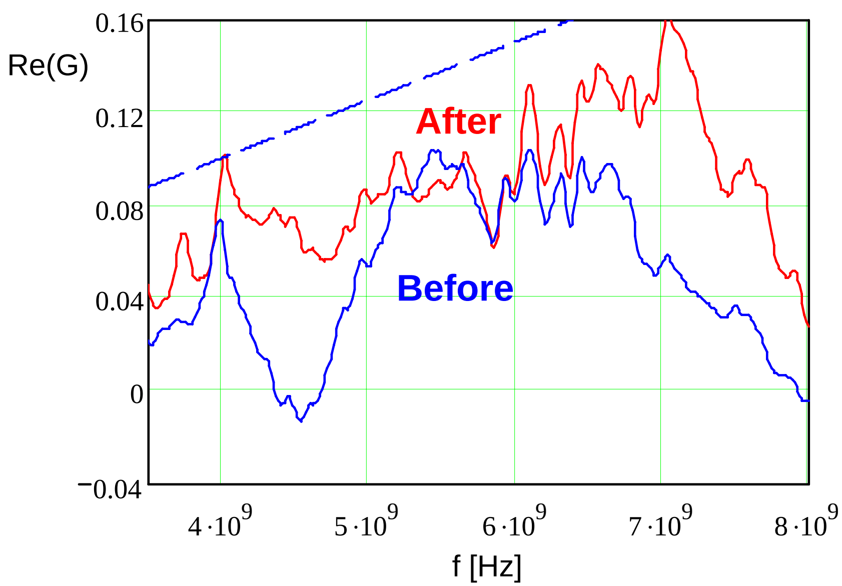




Longitudinal core cooling equalizer







Equalizer for 4-8 core cooling system resulted in the largest gain in the effective bandwidth

$$\frac{W_{new}}{W_{old}} = 1.77$$

That addressed problem of longitudinal core blowup

Conclusions and Further plans

- During last 1.5 years:
  - Zero stack stacking rate: $(20 \Rightarrow 27.5)\cdot 10^{10}$/hour
    - further increase to $\sim 30\cdot 10^{10}$/hour is expected in 2008
  - Average stacking rate (weekly peak): $(10.5 \Rightarrow 16.5)\cdot 10^{10}$/hour
    - further increase to $(20\text{-}22)\cdot 10^{10}$/hour is expected in 2008
- The work carried out during last 2 years resulted in
  - Much better understanding for operation of cooling systems
  - All important upgrades have been introduced
    - Few final ones will be finished during 2008
  - Installation of equalizers in all Recycler stochastic cooling systems is a byproduct of this work
- Optimal tuning of Antiproton source is a high priority for 2008
  - Gain ramping of the stacktail
  - Separate gain ramps for longitudinal Debuncher cooling
  - Two turn delay notch filter for L Debuncher cooling
  - Better transverse and longitudinal cooling in Debuncher
    - Fixing phasing and gain errors for pickup and kickers
    - Modification of band-pass filters so that to equalize the bandwidth

Sequence of major events for the Stacktail upgrade

Hybrid flip	– October 1, 2006
Equalizer prototype installation	
First attempt	- March 12, 2007
Installation wit reduced gain at high f	- March 19, 2007
Final installation	- March 23, 2007
Stacking record, 23.1 mA/hour	– March 22, 2007
Legs 2 & 3 pulled away	- April 3, 2007
Accumulator lattice upgrade	– May 16, 2007
Leg 3 is fully operational	- May 4, 2007
New lithium lens lost	– May 24, 2007
Final equalizer installation	- June 4 , 2007
SC notch filter 3 installed	- July 18, 2007
Longitudinal core cooling equalizer	- Shutdown 2007

Sequence of major events for the Debuncher cooling improvements

Notch filters installation for Debuncher $\perp$ cooling, bands 3&4	- Shutdown 2007
Debuncher lattice upgrade (pickup-to-kicker $\Delta\nu_y$ –correction)	– Nov. 20, 2007