Fermilab

Antiproton Stacking

Valeri Lebedev

December 21, 2006
Fermilab

Contents

- Present status
- Stack-tail hardware
- Stack-tail model
- Measurements of Stack-tail parameters
- Stack-tail upgrade
- Conclusions

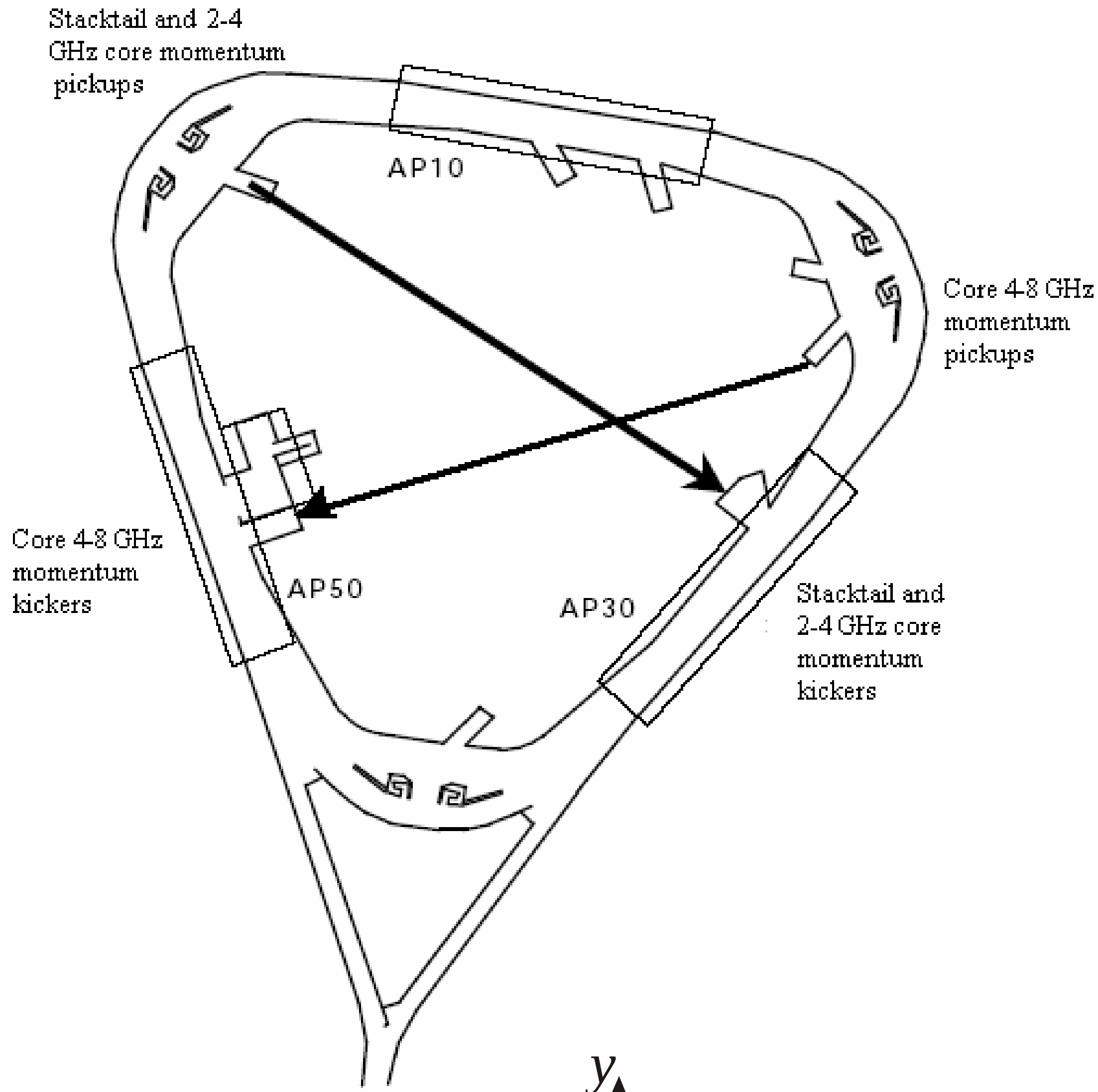
Present Status

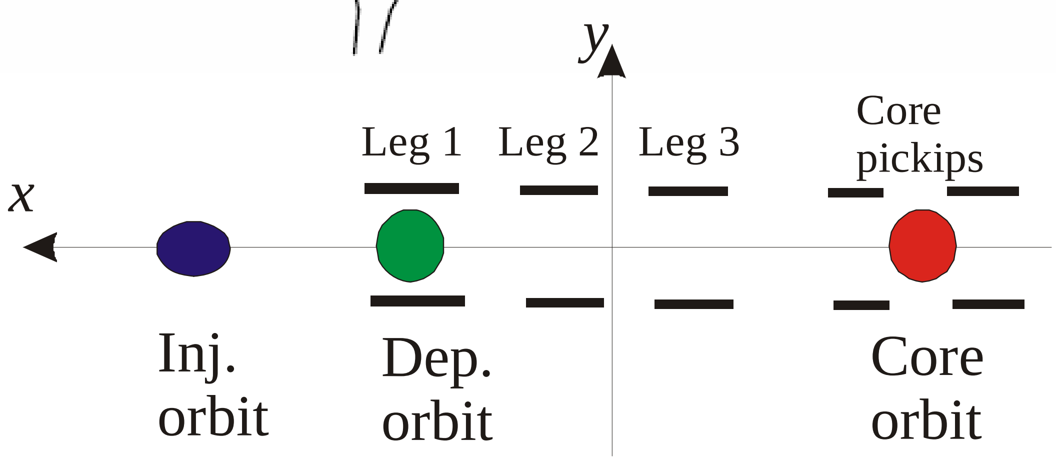
- Presently, most of the time, we inject and cool ~$2\cdot10^8$ antiprotons in Debuncher for each 2.4 cycle.
  - That corresponds to the flux of 30 mA/hour
  - Major fraction of these antiprotons is transferred to Accumulator;
- Nevertheless the best stacking rate we observed is ~21 mA/hour
  - All data we have point out that the performance is limited by the stack-tail
- The stack-tail model has been gradually improving during last 3 months and presently yields very close number of ~22 mA/hour. It also shows that the stacking rate is limited by 2 problems:
  - the throughput of the stack-tail which is set by
    - the effective bandwidth and
    - the gain profile on the beam momentum
  - and by clearing the deposition orbit which is set by
    - the effective bandwidth only

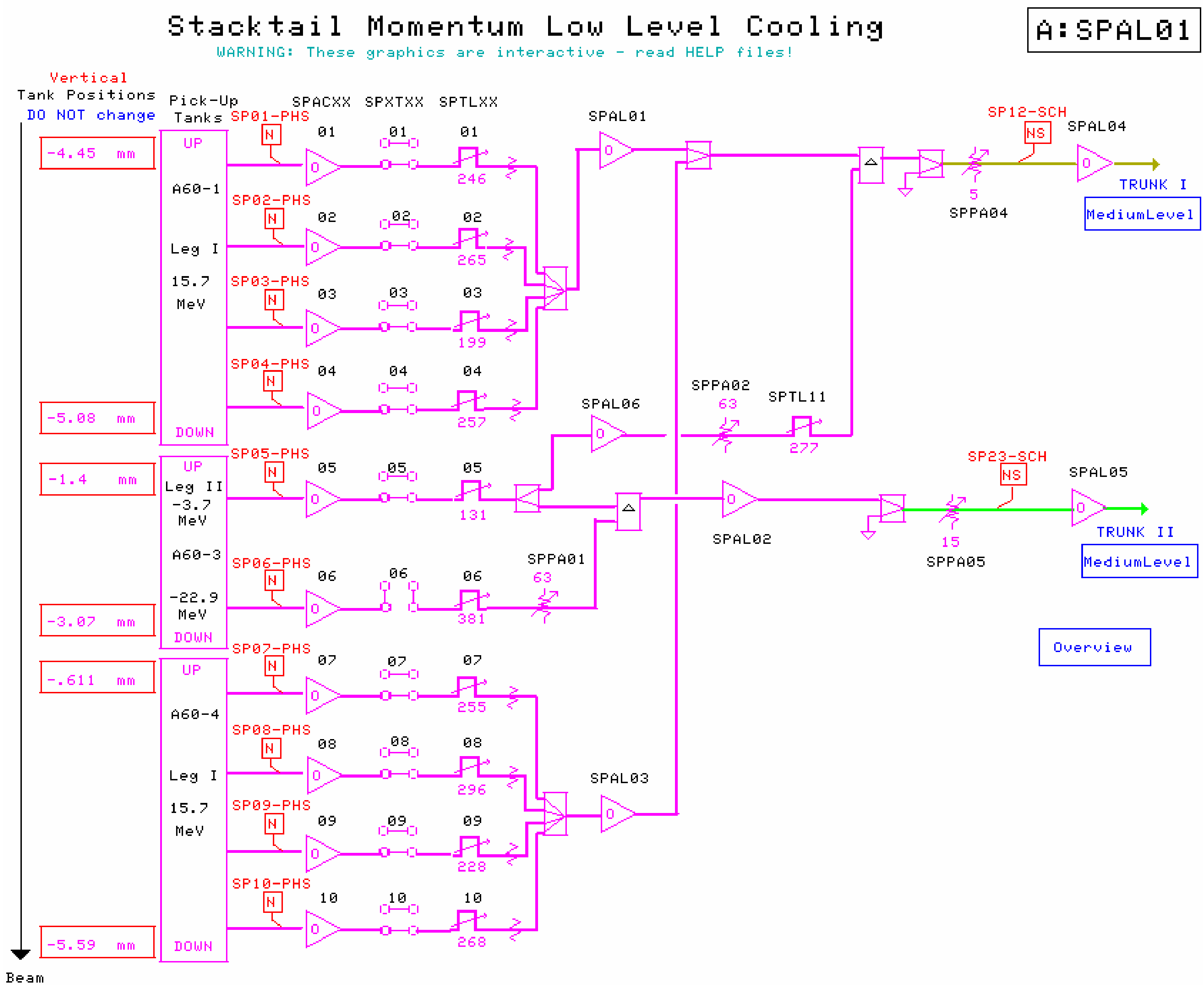
- There are two other problems which are just behind the corner and need to be addressed in the near future
  - The horizontal emittance grows fast with stack-tail gain/power. That is believed to be due to parametric heating at $2Q_x$
  - Excessive power in the stack-tail causes blow up of the core longitudinal emittance due to inter-modulation distortions in TWTs
- ♦ Better longitudinal cooling in the Debuncher should reduce the total stack-tail power and should alleviate both of these problems

Stack-tail Hardware

- Pickups are located at large dispersion (~9.1 m) while kickers are at zero dispersion
- Stack-tail has 3 pickups located at different radial positions to make desired dependence of gain on the momentum
- Outside of pickup aperture its sensitivity drops exponentially. That allows one to form desired gain profile on particle position with small number of pickups





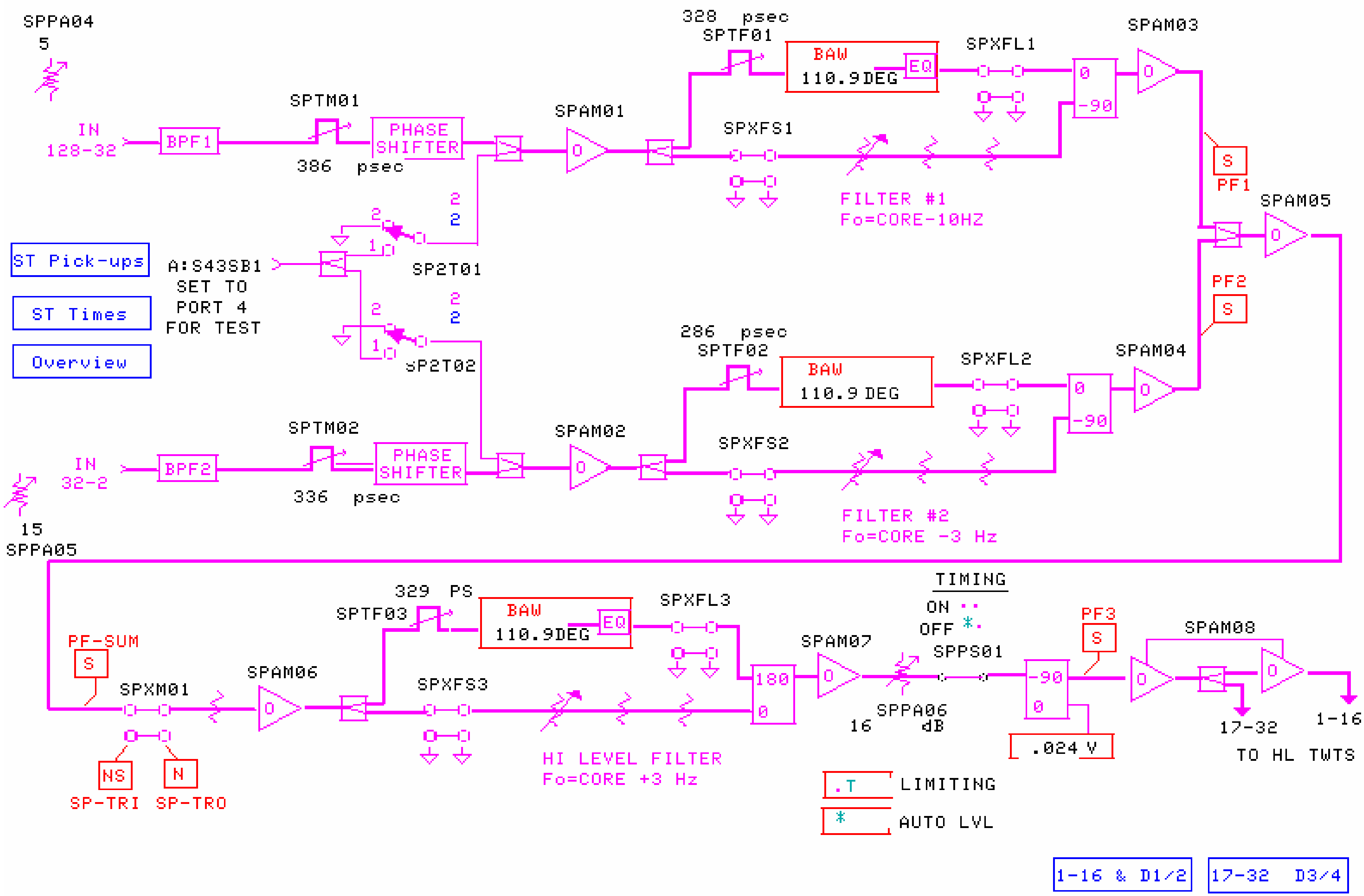

Stacktail Momentum Low Level Cooling
WARNING: These graphics are interactive - read HELP files!
A:SPAL01
Vertical
Tank Positions
DO NOT change
-4.45 mm
-5.08 mm
-1.4 mm
-3.07 mm
-.611 mm
-5.59 mm
Beam
Pick-Up
Tanks
UP
A60-1
Leg I
15.7
MeV
DOWN
UP
Leg II
-3.7
MeV
A60-3
-22.9
MeV
DOWN
UP
A60-4
Leg I
15.7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

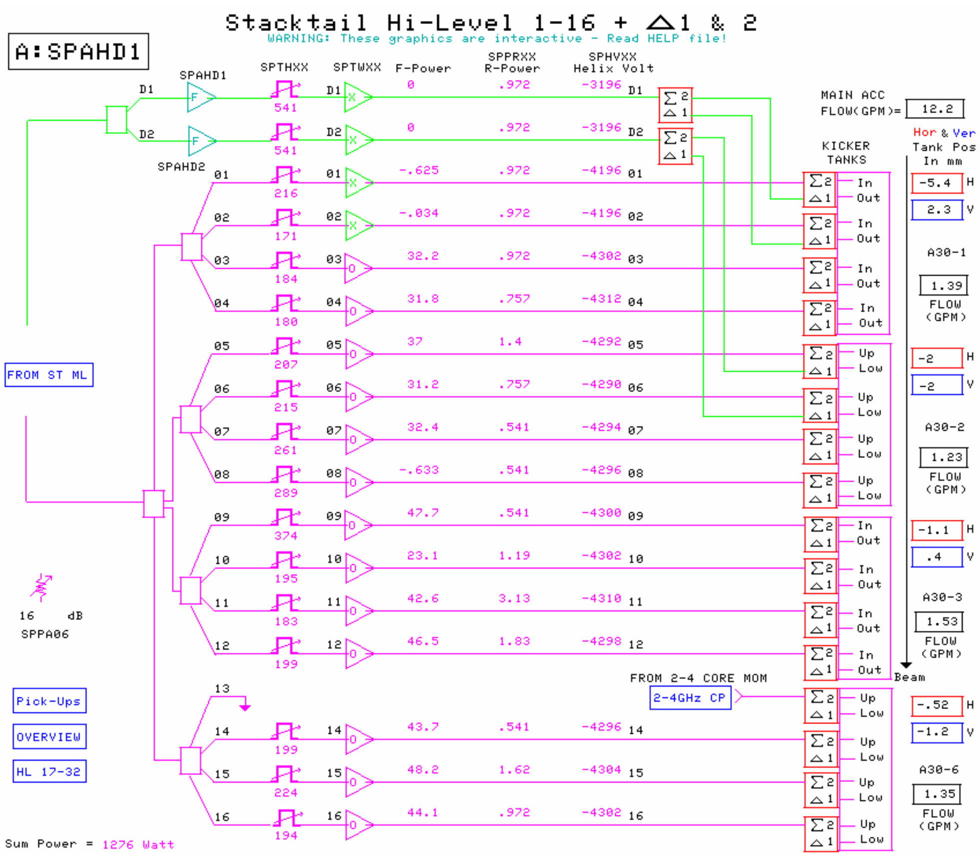
STOCHASTIC COOLING

STACKTAIL MOMENTUM MEDIUM LEVEL/FILTERS

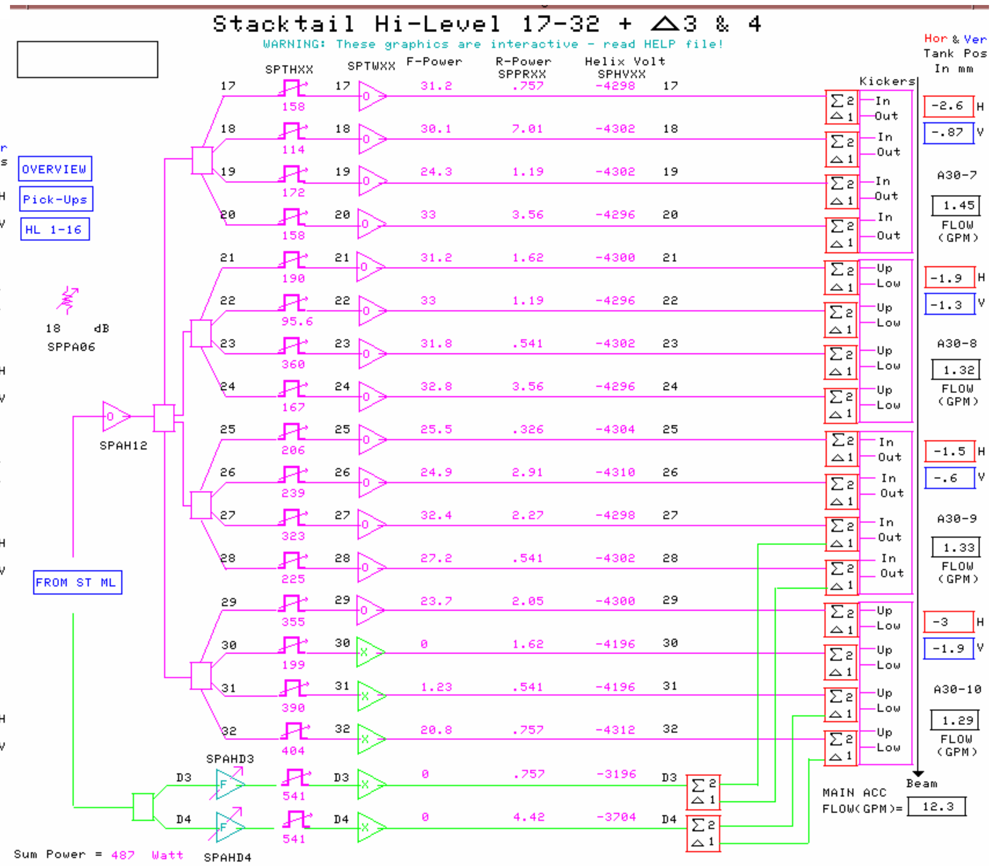
A:SPTF02

10-NOV-06 15:58:26



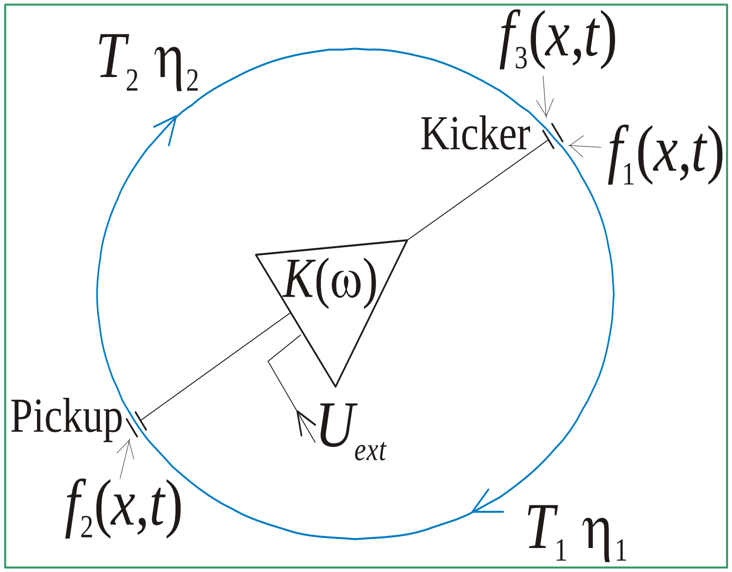


A:SPAHD1
Stacktail Hi-Level 1-16 + △1 & 2
WARNING: These graphics are interactive - Read HELP file!
SPTHXX
SPTWXX
F-Power
SPPRXX R-Power
SPHVXX Helix Volt
SPAHD1
SPAHD2
MAIN ACC FLOW(GPM)= 12.2
KICKER TANKS
Hor & Ver Tank Pos In mm
A30-1
A30-2
A30-3
A30-6
FLOW (GPM)
FROM ST ML
16 dB SPPA06
FROM 2-4 CORE 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
OVERVIEW
Pick-Ups
HL 1-16
18 dB SPPA06
SPAH12
FROM ST ML
SPAHD3
SPAHD4
A30-7
A30-8
A30-9
A30-10
FLOW (GPM)
MAIN ACC FLOW(GPM)= 12.3
Beam
Sum Power = 487 Watt

Stack-tail Model



- Evolution of particle distribution is described by Fokker-Planck equation

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

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

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

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

where: $\int \psi(x)dx = N$, $\omega_n = n\omega_0(1-\eta x)$

- Taking into account that the betatron size in the pickup is much smaller than the synchrotron size we can factorize the gain for each system or leg:

$G_1(x,\omega) = G_x(x)G_\omega(\omega)$, so that $\mathrm{Im}(G_x(x)) = 0$

- Neglecting particle screening, $\varepsilon(\omega)=1$, and thermal noise (normally signal to noise 15 – 20 Db)
  - allows one to eliminate the dependence of force and diffusion on the distribution function
- That yields:

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

$$F(x)=2f_0 G_x(x)\mathrm{Re}\left\{\sum_{n=0}^{\infty}\tilde{G}(x,\omega_n)\right\},\quad \tilde{D}(x)=2f_0 G_x(x)^2\sum_{n=0}^{\infty}\left|\tilde{G}(x,\omega_n)\right|^2\frac{1}{|n\eta|},\quad \omega_n=n\omega_0(1-\eta x)$$

where: $\tilde{G}(x,\omega)=G_\omega(\omega)\left(1-A(\omega)e^{-i\omega T_0}\right)e^{i\omega T_2\eta_2 x}$

  - Note that
    - in the general case $\tilde{G}(x,\omega_n)$ cannot be factorized – meaning system band is different at different momenta; and
    - in the case of stack-tail we have 5 systems working together and their contributions have to be properly summed.
    - Finally one arrives to

$$F(x)=2f_0\,\mathrm{Re}\left\{\sum_{n=0}^{\infty}\hat{G}_n(x)\right\}\quad,\quad \tilde{D}(x)=2f_0\sum_{n=0}^{\infty}\left|\hat{G}_n(x)\right|^2\frac{1}{|n\eta|}$$

Van der Meer solution

- Assuming that the total gain of the system can be factorized

$$G(x,\omega) = G_x(x) G_\omega(\omega) \quad , \quad G_x(x) = G_0 \exp(-x/x_d)$$

- and looking for a static solution with constant flux one arrives that the maximum flux is

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

where the effective bandwidth is:

$$W = \sqrt{\frac{\left(\int_0^\infty \mathrm{Re}(G_\omega(2\pi f)) df \right)^2}{\int_0^\infty |G_\omega(2\pi f)|^2 \frac{df}{f}}}$$

- For the rectangular gain function

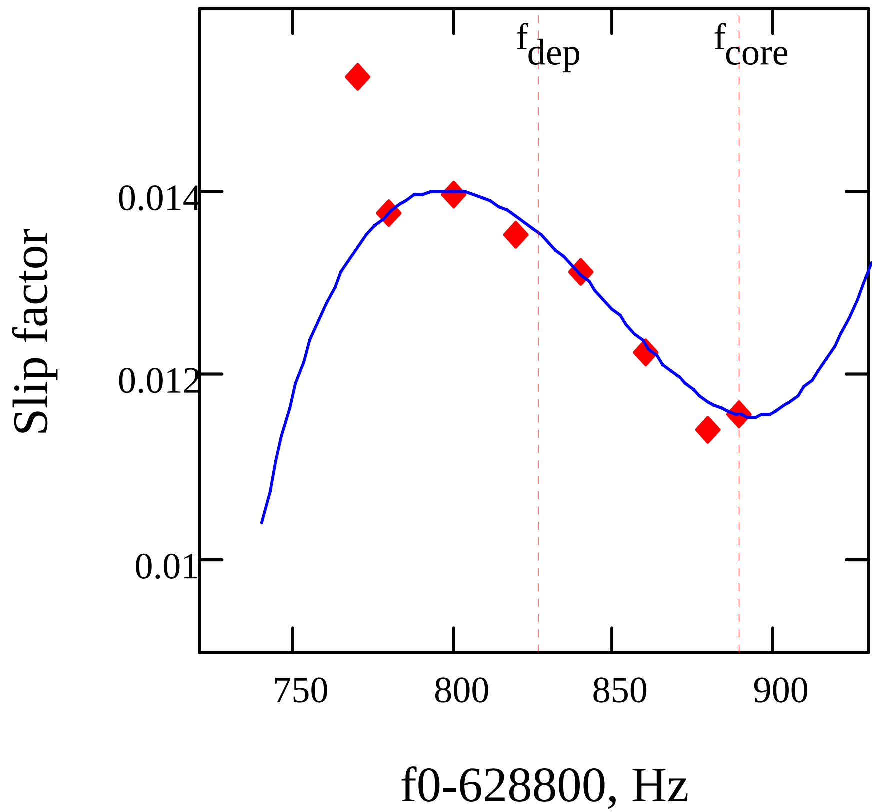
$$G_\omega(2\pi f) = \begin{cases} G_{opt} \ , & f \in [f_{\min}, f_{\max}] \\ 0 \ , & otherwise \end{cases}$$

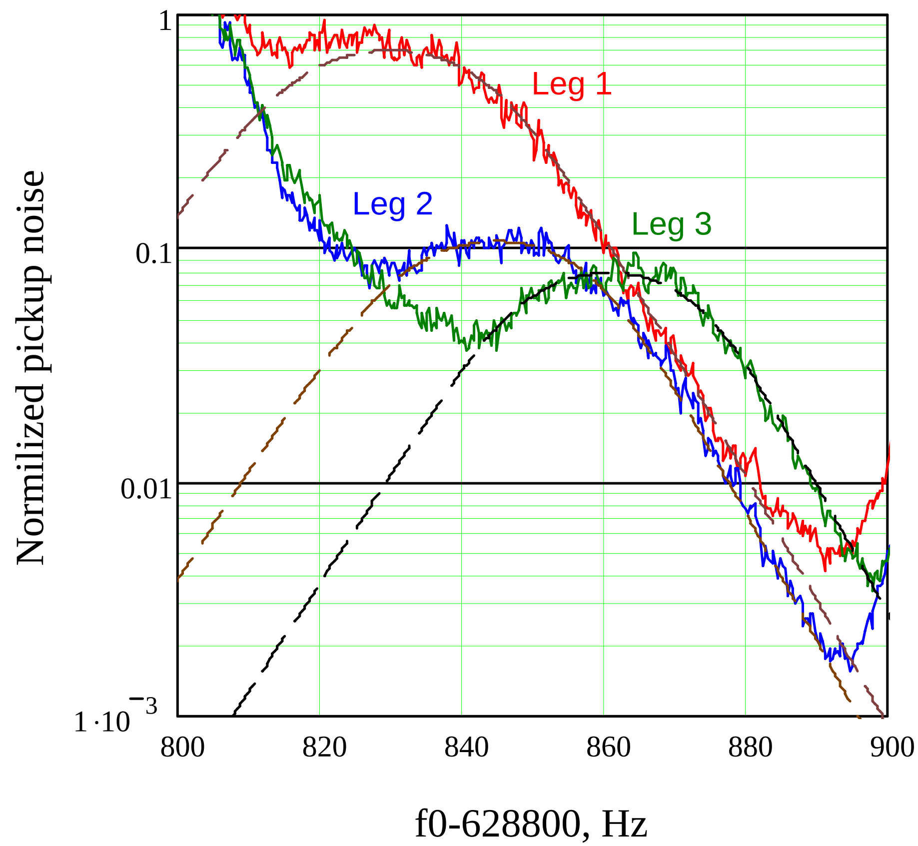
that yields

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

- The gain of real system cannot be factorized and is not exponential through entire stack-tail region
  - ♦ Solving complete Fokker-Plank equation is required to understand the system and to predict its behavior

Measurements of Stack-tail parameters





- Measured dependence of slip factor on the momentum is fitted by polynomial
  - Decent coincidence with Accumulator optics model
  - Non-linearity of η is amplified by ~2 times due to proximity to γ_{tr}
- Dependence of pickup sensitivity on the beam coordinate corresponds to the earlier measurements

Pickup coordinate response

- Pickup coordinate response coincides well with following formula

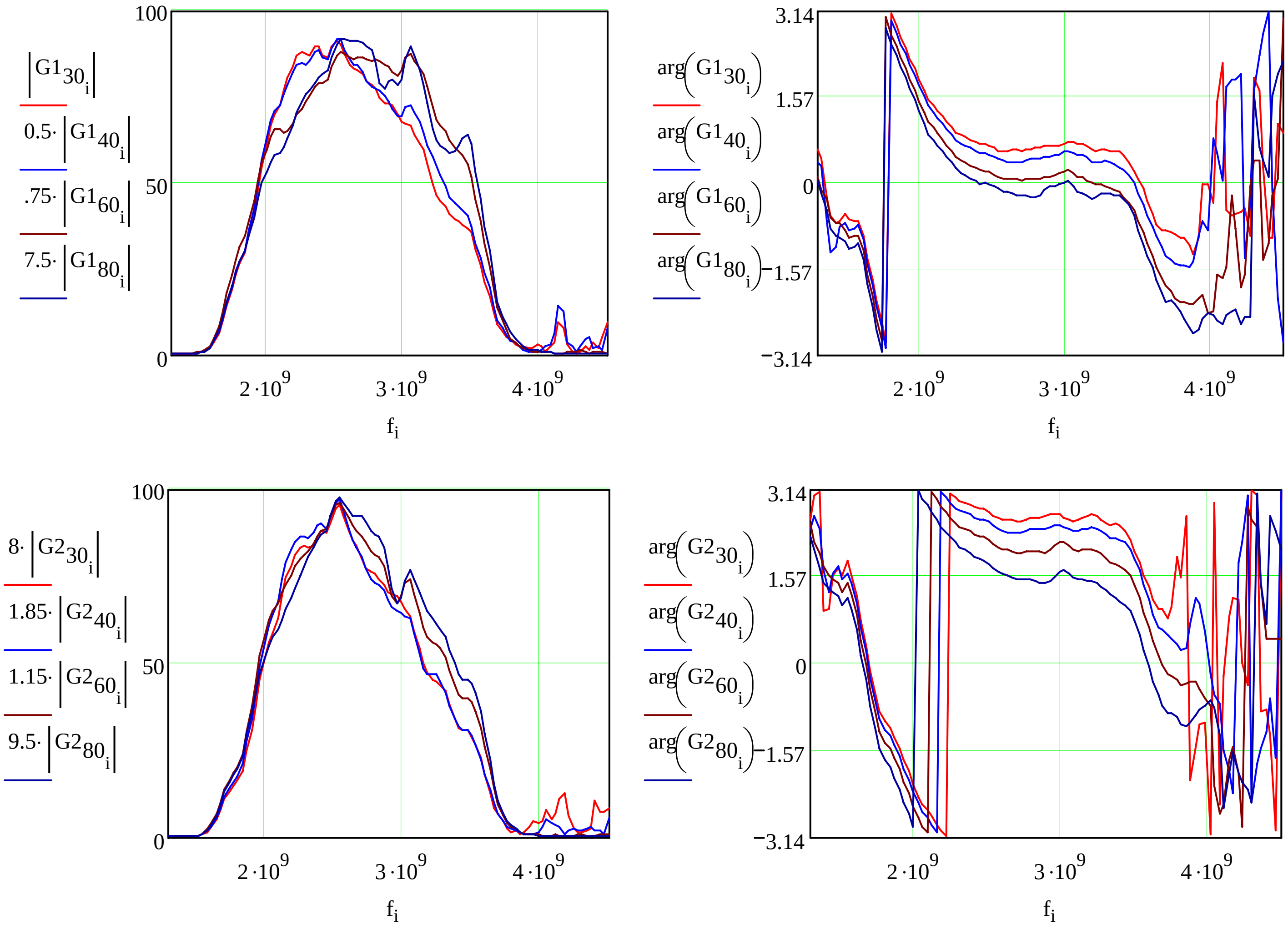
$$F(x) = \frac{1}{\pi}\left[\operatorname{atan}\left(\sinh\left(\frac{\pi}{h}\left(x - x_0 + \frac{w}{2}\right)\right)\right) - \operatorname{atan}\left(\sinh\left(\frac{\pi}{h}\left(x - x_0 - \frac{w}{2}\right)\right)\right)\right]$$

- Parameters used in the fitting are

	x_0[cm]	h [cm]	w[cm]
Leg1	1.07	3.2	3.4
Leg2	-0.57	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	-4.87	4.4	0.76
Core 4 - 8 inner	-7.02		

- Dispersion at pickup is 910 cm (nonlinearity of dispersion on momentum is neglected, no reliable measurements due to poor BPM calibration)

System gain was measured by open loop measurements for narrow beam at beam revolution harmonics without notch filters



Leg 1 frequency response depends on beam position in pickup (summing of 2 pickups or too many loops?)

Leg 2 shows this feature in much smaller scale

Phase shift with beam momentum is only 0.82 of expected for perfectly symmetric lattice

$$\Delta t = T_0 \eta_0 \frac{\Delta p}{p_0}, \quad \Delta t_{pk} = T_{pk} \eta_{pk} \frac{\Delta p}{p_0}, \quad \Delta t_{kp} = T_{kp} \eta_{kp} \frac{\Delta p}{p_0}$$

$$T_0 \eta_0 = T_{pk} \eta_{pk} + T_{kp} \eta_{kp}$$

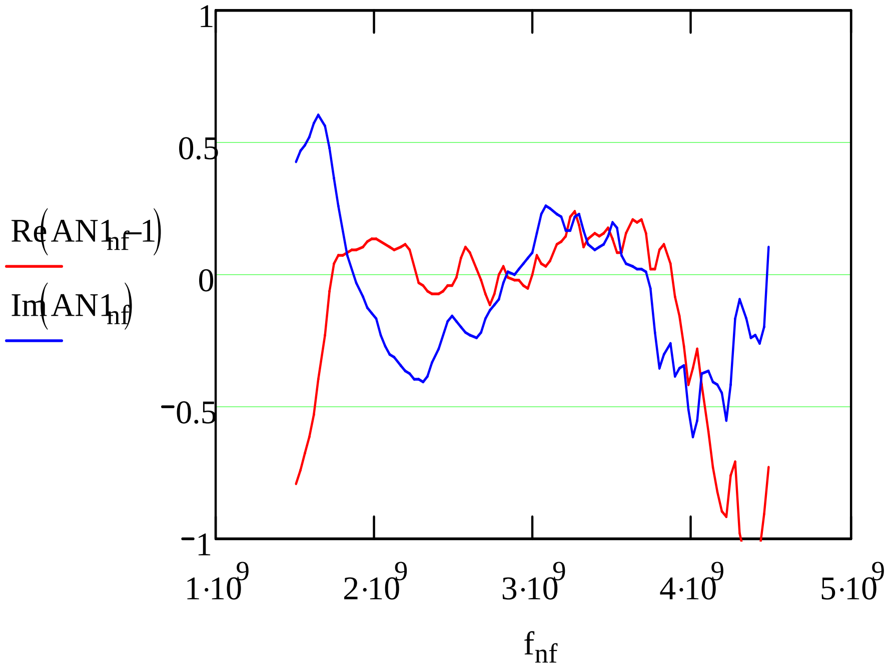
η_{pk}=0.82, η_{kp}=1.18 – pickup data

η_{pk}=0.86, η_{kp}=1.14 – OptiM

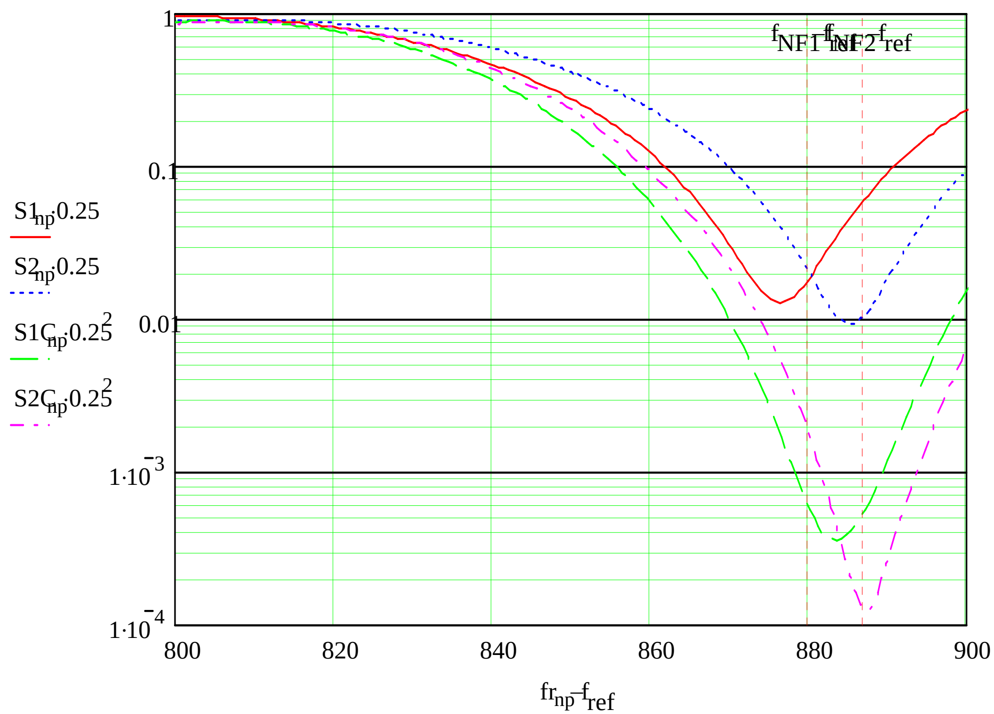
$T_{pk} = T_{kp} = T_0/2$

Each notch filter was individually measured

	Design (P. Derwent)	Dec, 2005 (P. Derwent)	Present guidance Nov. 14, 2006
Filter 1	628882	628890	628888
Filter 2	628886	628895	628906
Filter3	628886	628895	628895
Core	628884	628890	628890



Diffusion suppression by notch filters



- Two notch filters are required because of small depth and desire to widen the bottom to fit the entire core

Stack-tail Upgrade

Parts to be upgraded

- Displacement of stack-tail pickups and switching-on the legs 3 pickup
- Installation of equalizer to optimize the gain profile (present band-pass filters need to be removed)

Pickup displacements and changes to the gains

present/upgrade	Leg 1	Leg 2	Leg 3	Core cooling 2-4 GHz	Core cooling 2-4 GHz
f_0-628000, Hz	830/823	845/836	NA/852	890	890
Position, mm	10.7/18.4	-5.7/4.4	-23.9*/-13.8	-60.0	-60.0
Gain rel. to Leg 1	1/1	0.25/0.48	NA/0.1	0.010/0.006	0.030/0.019
Number of loops	256	48	16	0.010/0.006	0.030/0.019
Electronics gain relative to Leg 1	1/1	0.58/1.11	NA/0.4	NA	NA
Maximum stacking rate, mA/hour	**22 / 30†**				

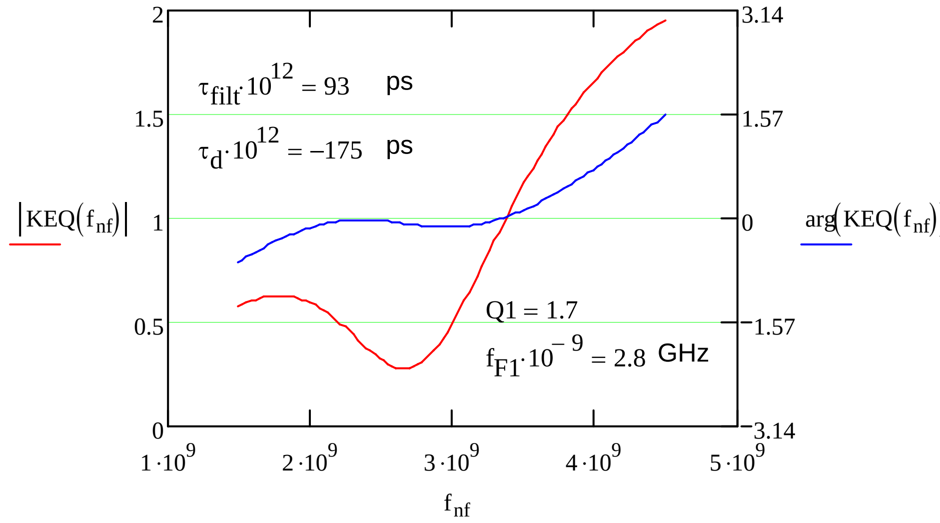
* It is not used presently. Bound up to the Leg2

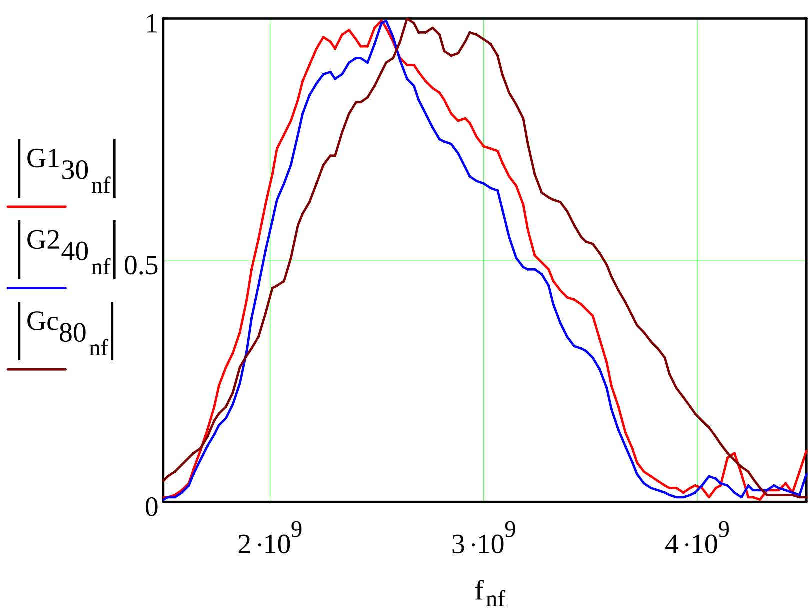
† This number is expected to be better after equalizer design will be complete

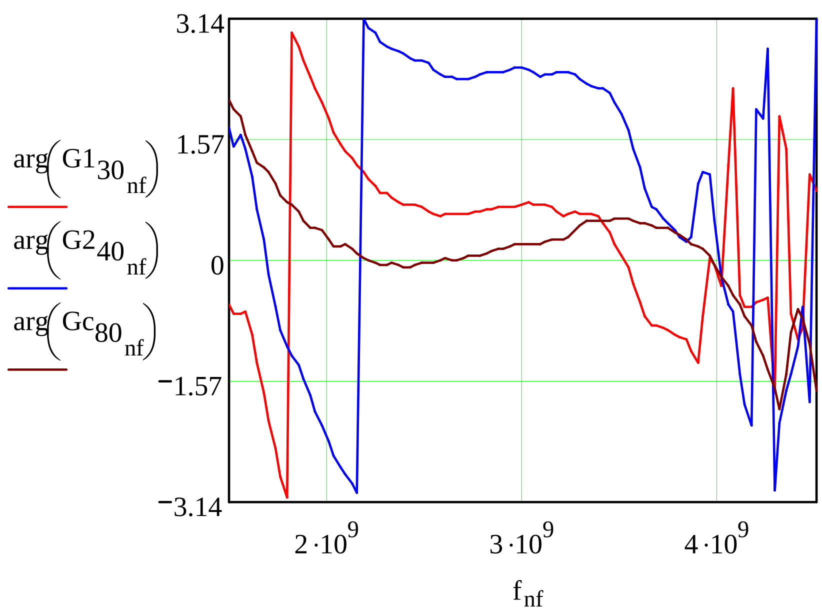
Parts to be upgraded (continue)

- Equalizer corrects the gain and phase of the system
- To demonstrate a possibility to correct phase and amplitude the equalizer prototype is designed as a sequence of two oscillators and a two modified notch filters
- Real microwave design still needs to be done

$$KEQ(f) := 14\cdot\left(\frac{1}{1 + i\cdot Q1\cdot\frac{f^2 - f_{F1}^2}{f\cdot f_{F1}}}\cdot\exp(-2i\cdot\pi\cdot f\cdot\tau_d)\right)^2\cdot\left(1.02 - \sin(2\cdot\pi\cdot f\cdot\tau_{filt})\right)$$

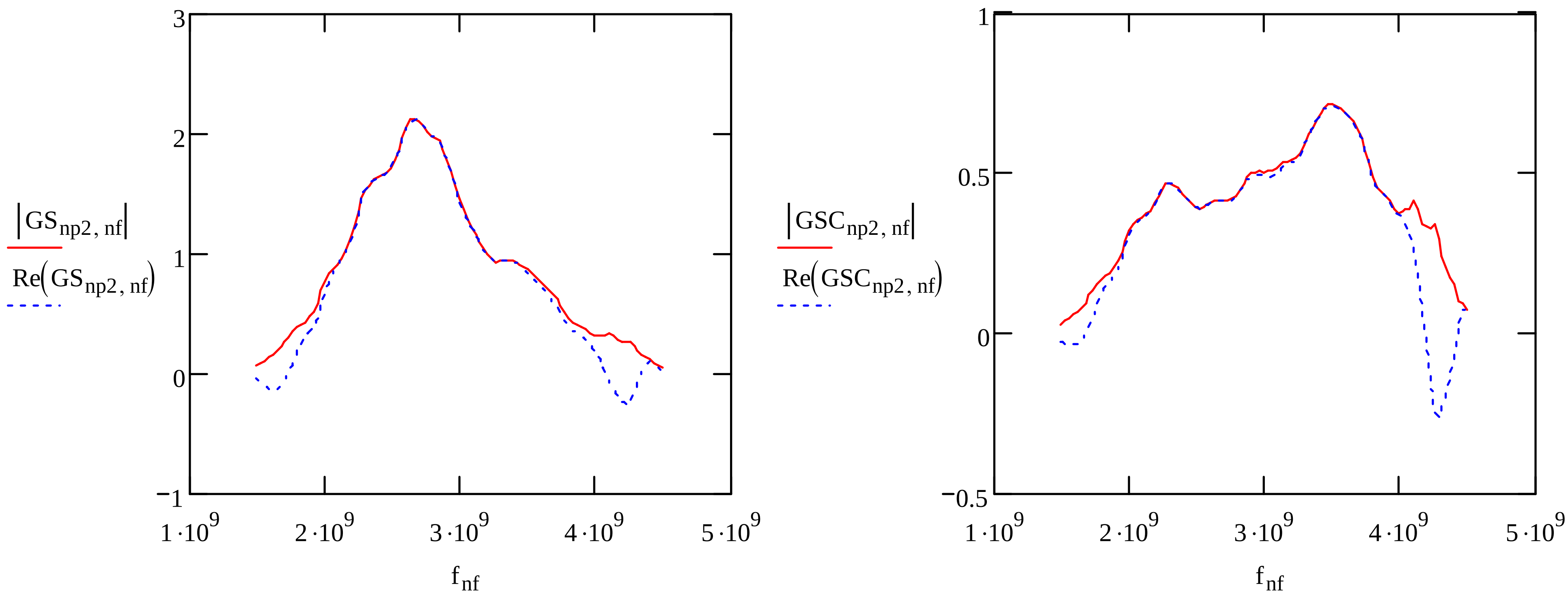






Measured gain in the stack-tail (no band pass filters, no notch filters) and core systems

Effect of gain correction

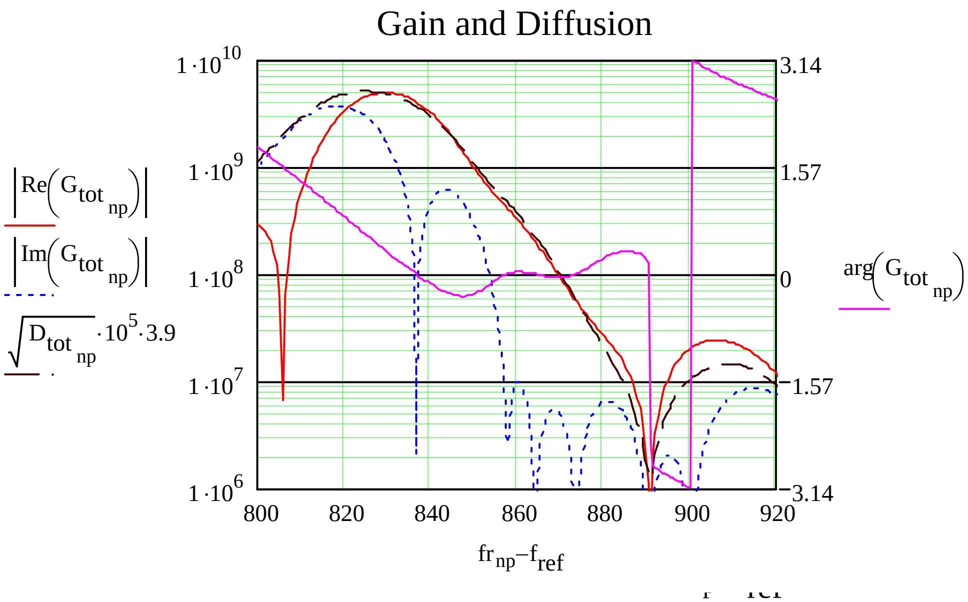


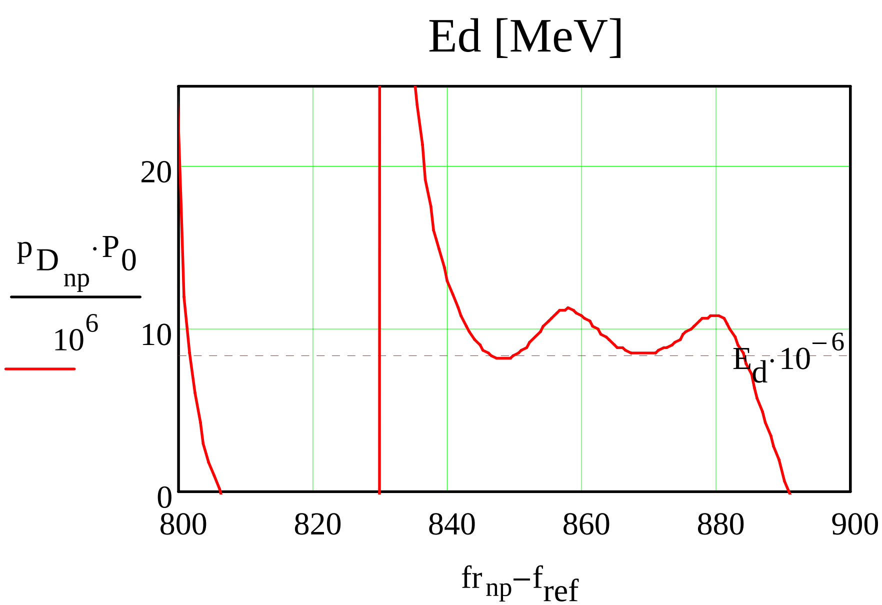
System gain before and after correction at 628830 Hz revolution frequency

- Further phase correction is desirable
- Because of the notch filters and the dependence of pickup-to-kicker time on the energy the dependence of system gain on frequency depends also on the energy (the gain cannot be factorized to the product of functions on the frequency and the momentum)

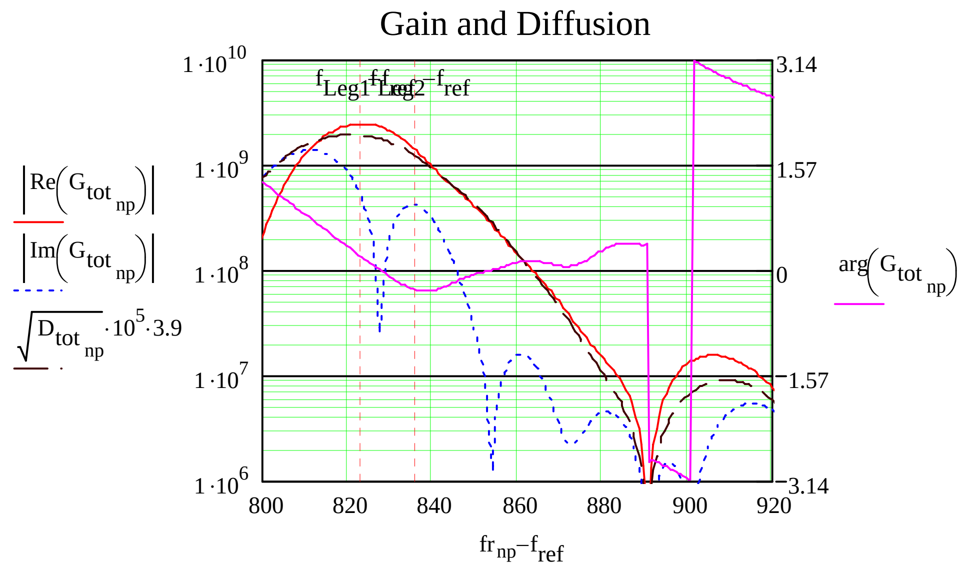
Correcting the Gain Profile on the Beam energy

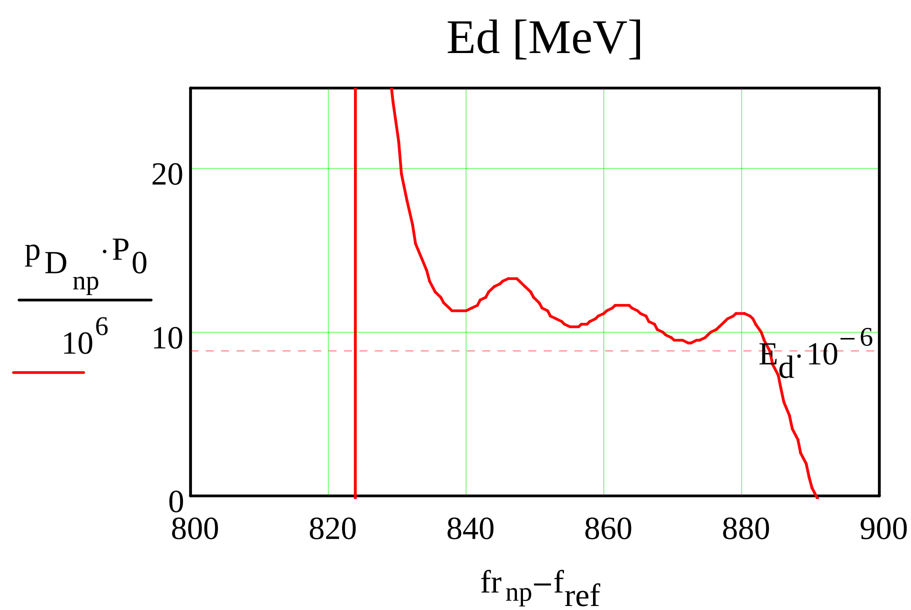
Present





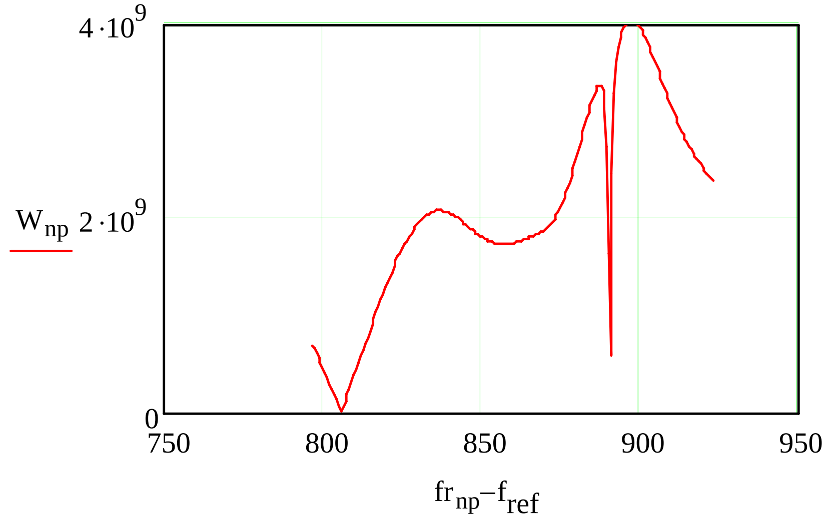
Future



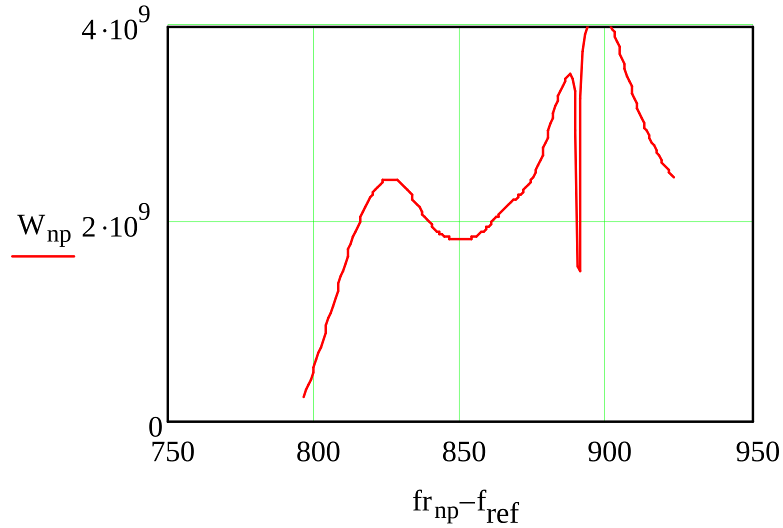


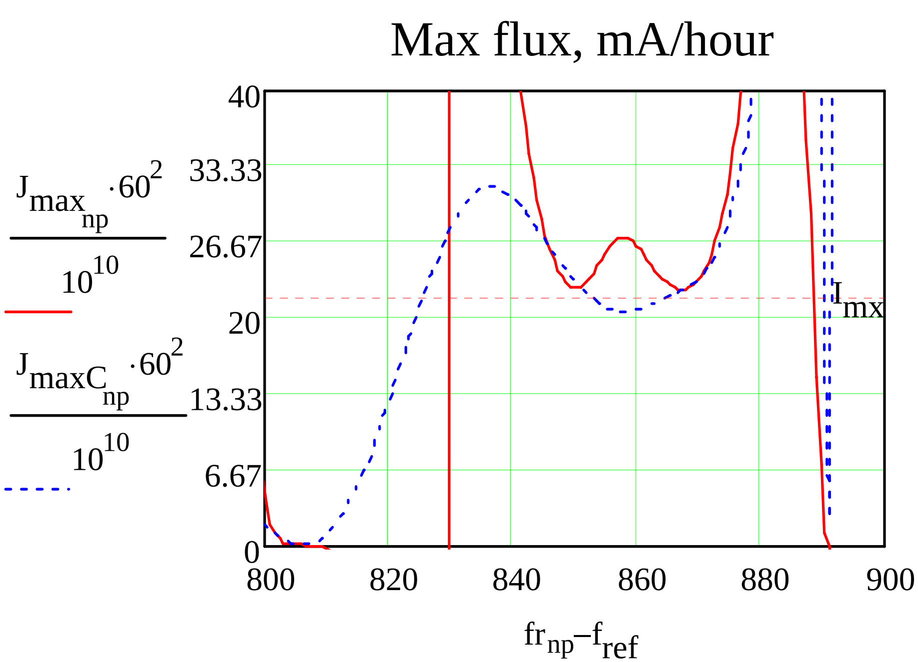
Effective Bandwidth and Flux

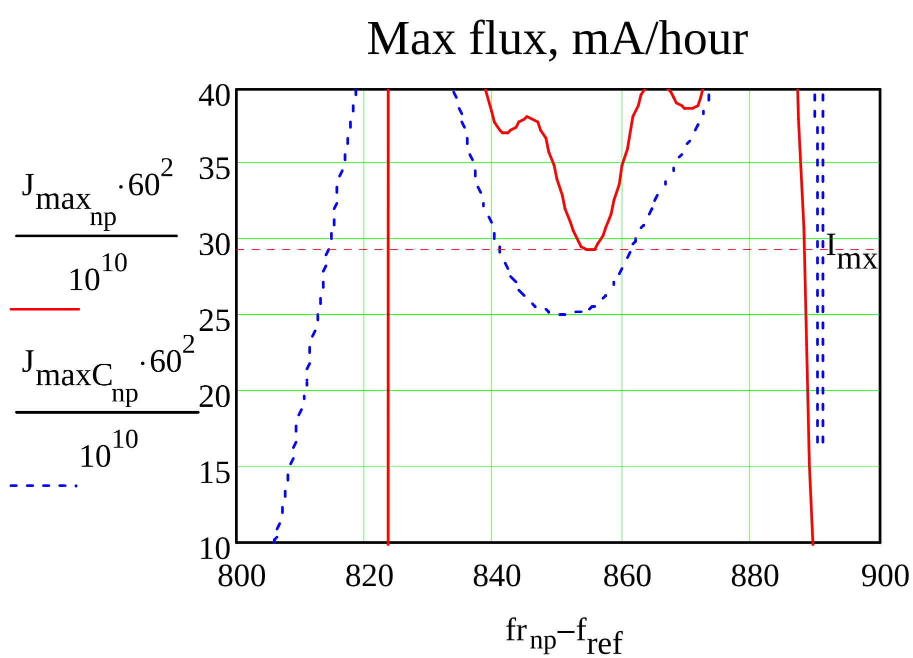
Present



Future

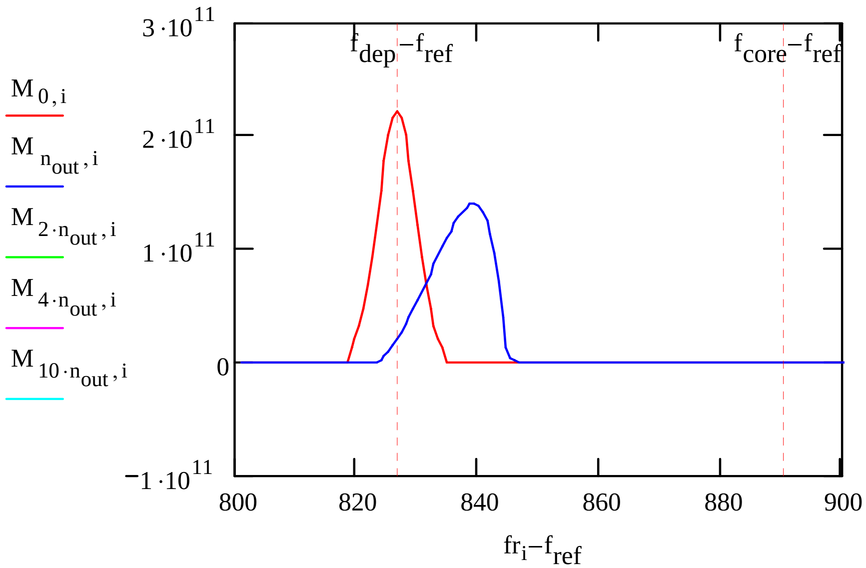


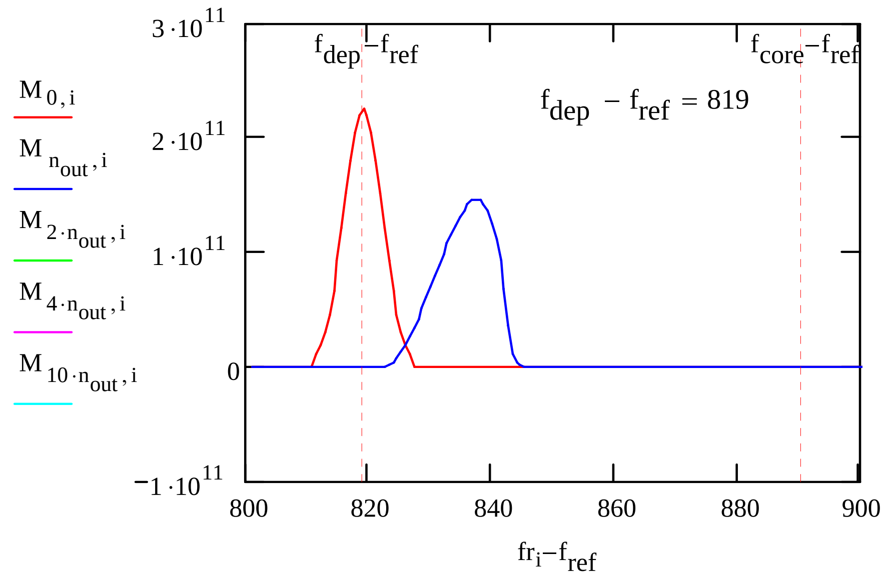


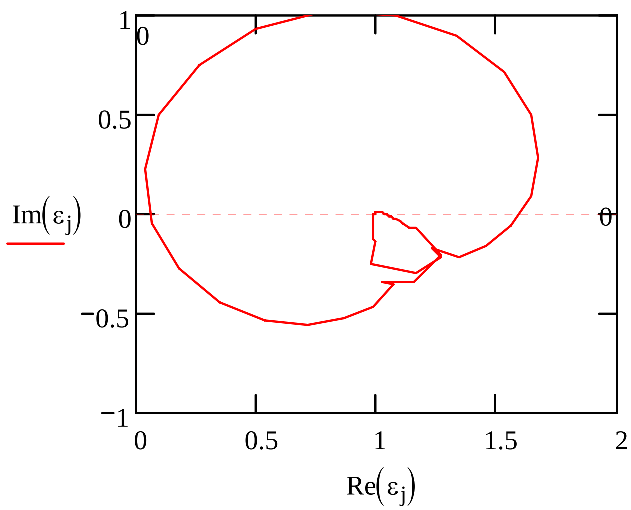


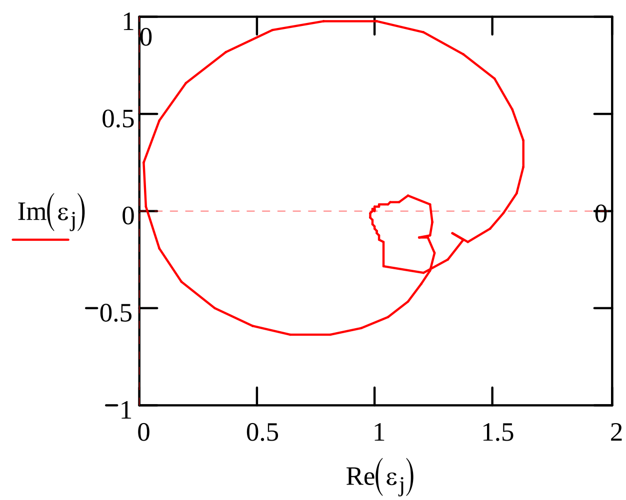
Time domain simulation of the stack-tail

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





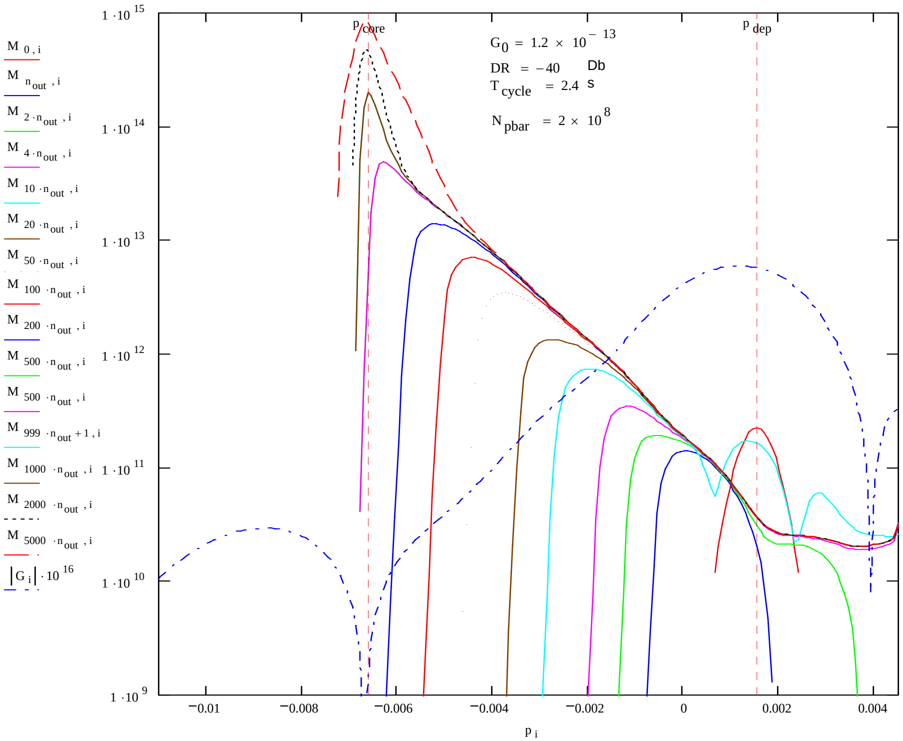


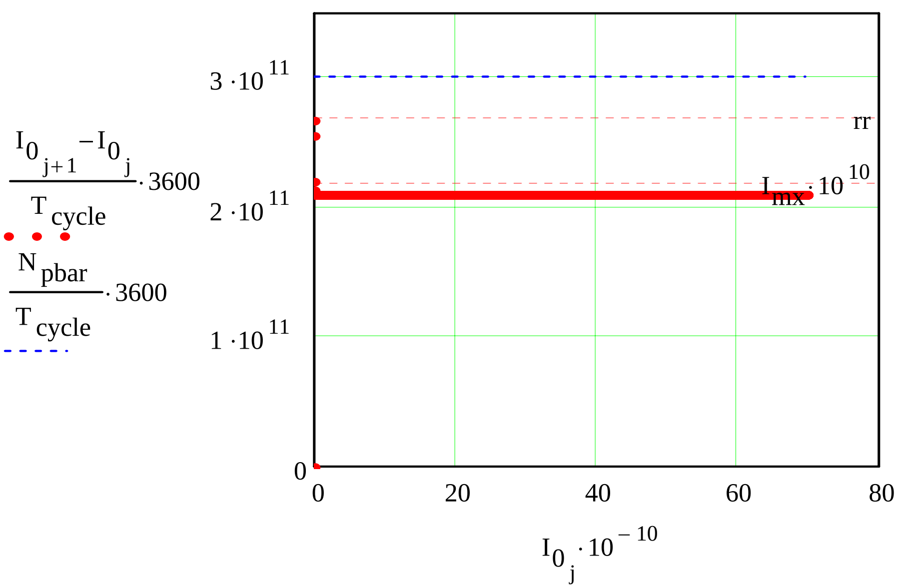


Present (f.=2.5 GHz) *Future (f.=3.5 GHz)*

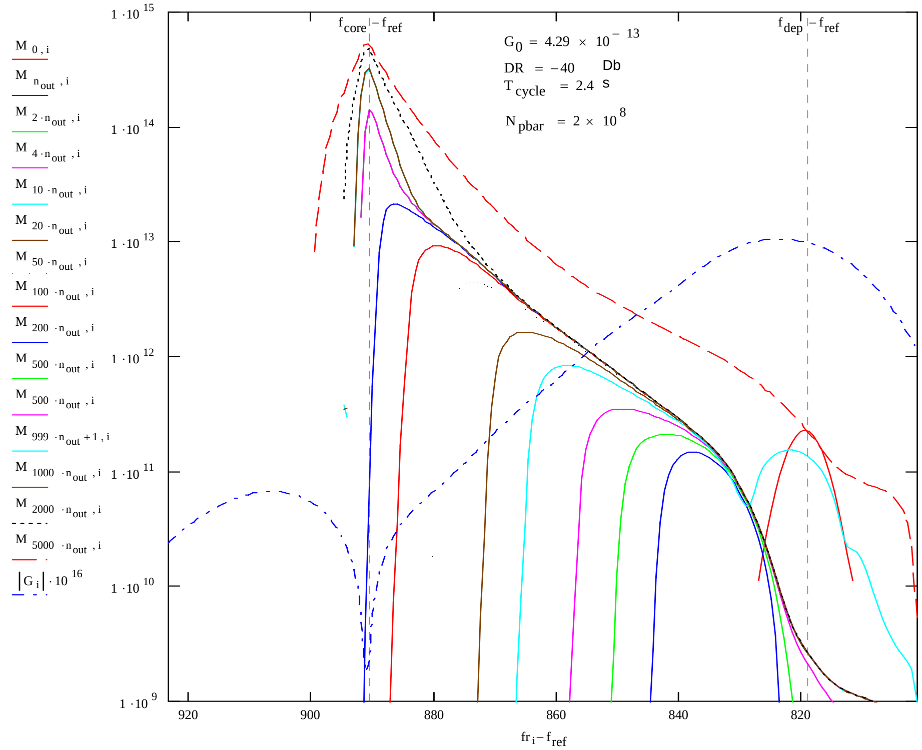
Dielectric functions just after injection of the first antiproton pulse at fr. of maximum response

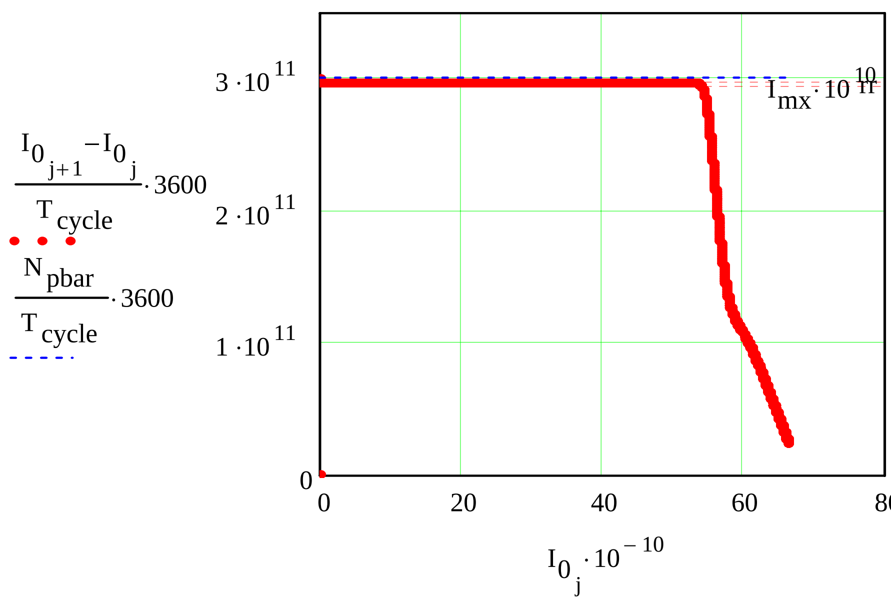
Present



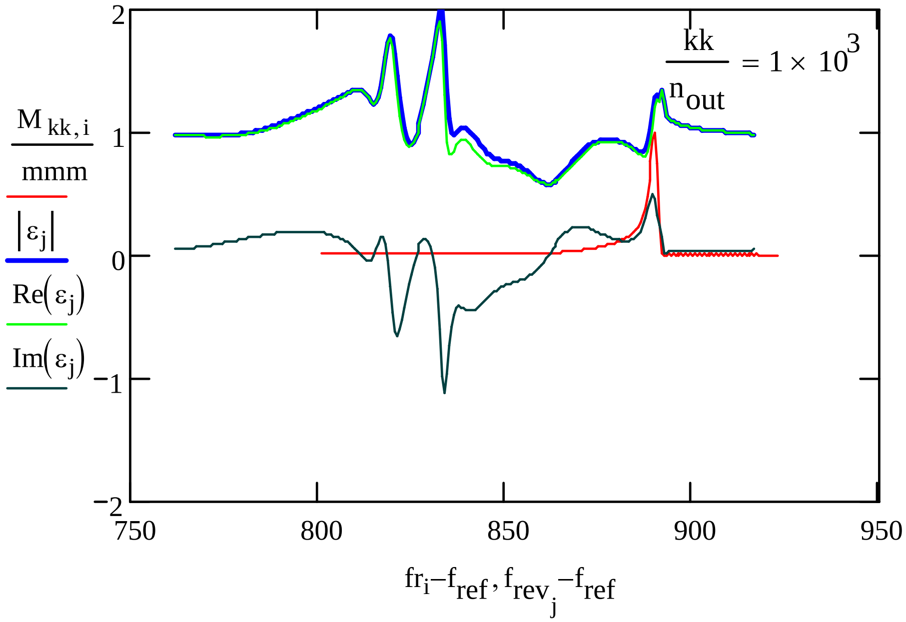


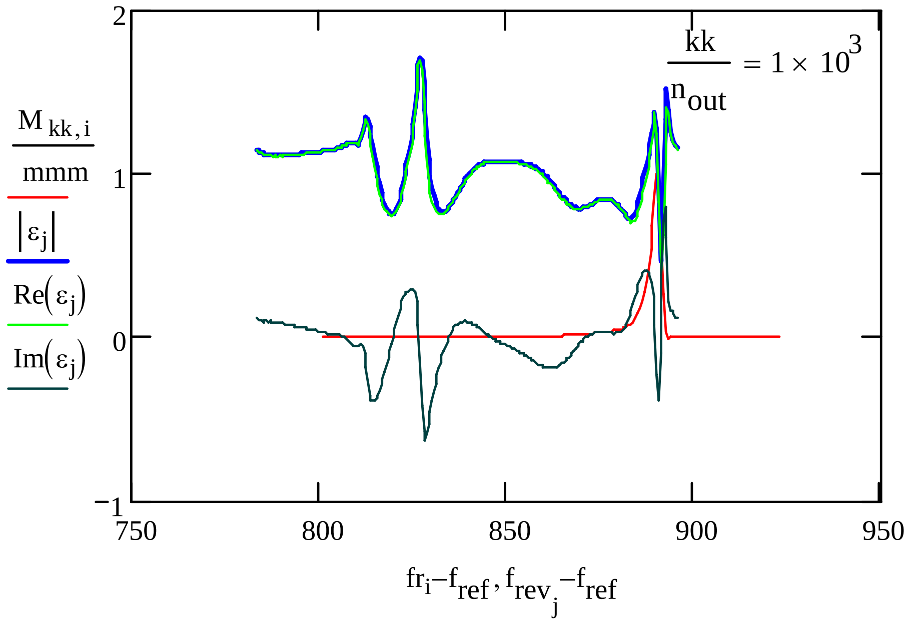
Future





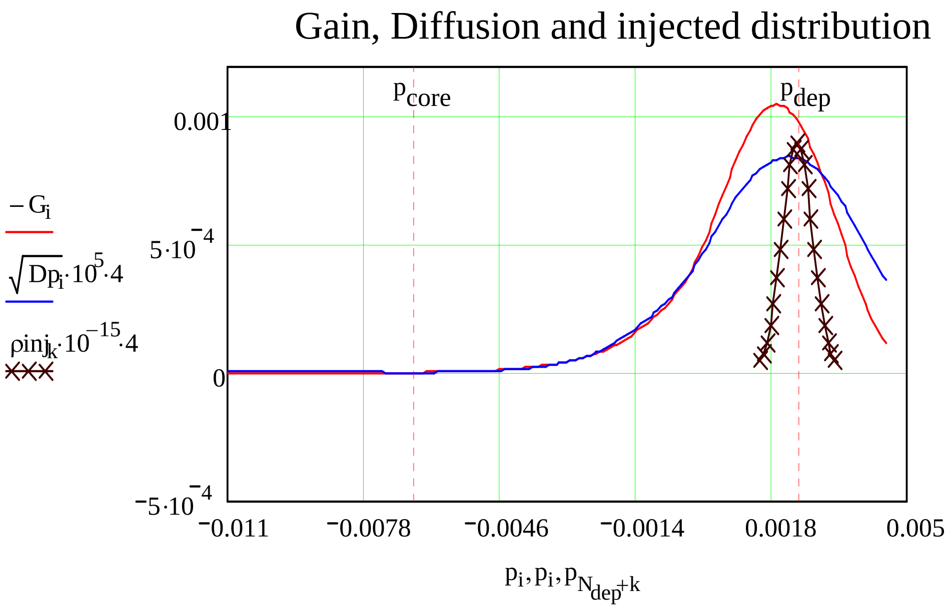
Presence of stack reduces particle interaction for injected particles

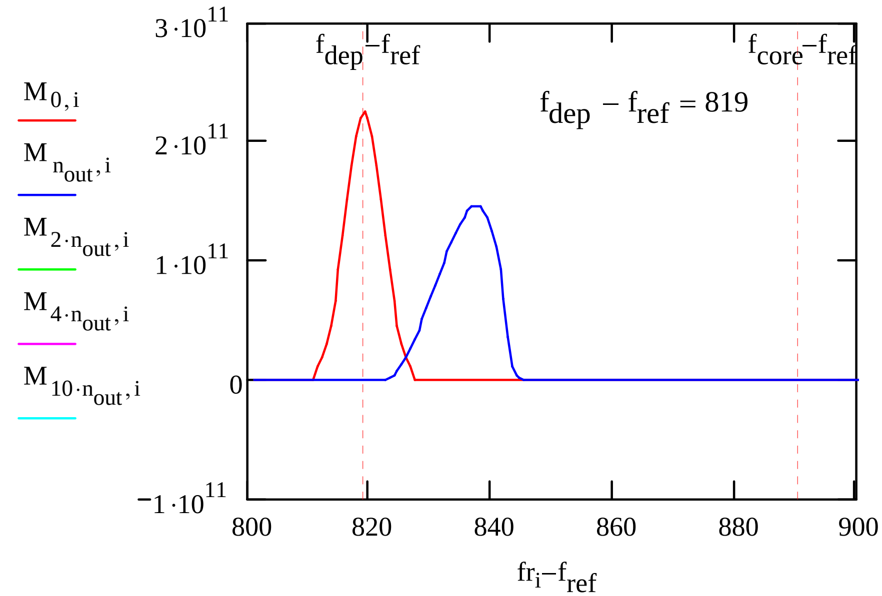


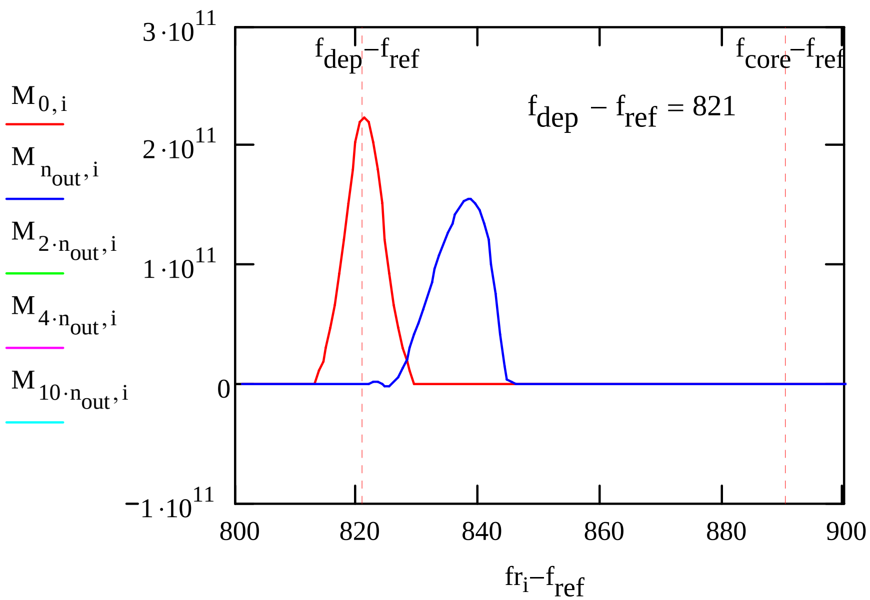


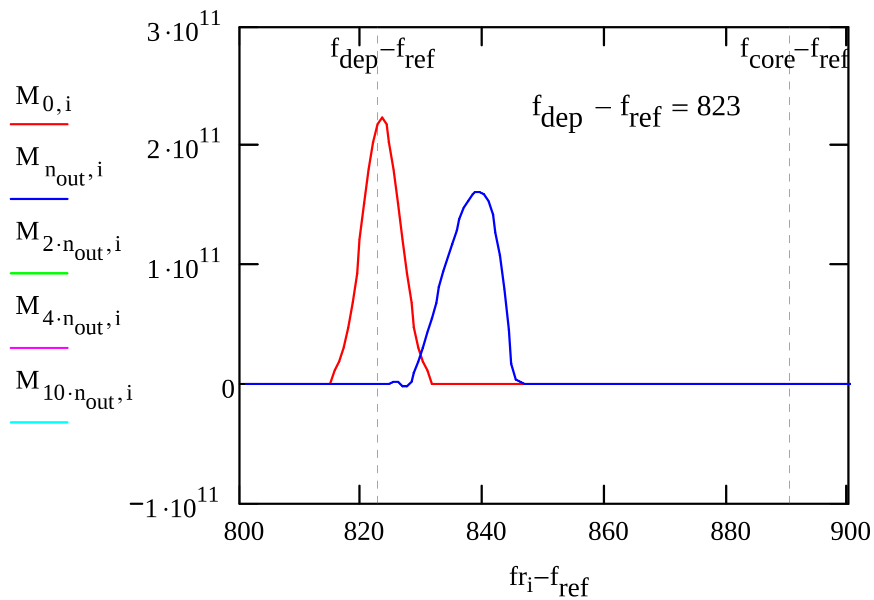
Present (f.=2.5 GHz) *Future (f.=3.5 GHz)*

Dielectric functions just after injection of the 1000-th antiproton pulse at the frequency of maximum response









Stacking is better if the deposition orbit is at outer side of force peak

Conclusions

- Next 2 months action plan includes (expected completion – March 1)
  - Design and built equalizers.
  - Move pickup legs and start using Leg 3 before equalizers are built
    - It will require additional studies and measurements and will take a while
  - Next step in simulations will be aimed to incorporate signal suppression factor: MathCAD -> C program
    - We also need to extend the model so that it would predict the transverse core heating by the stack-tail noise
  - Study how longitudinal cooling in Debuncher could be improved
- If successful this work should bring us close to 30 mA/hour in March
- Further growth requires an extension of stack-tail band to 2-6 GHz
  - Details can be clarified before summer shutdown
  - Installation cannot happen before January 2008
  - Minor improvements in Debuncher should support the stacking rate of 40 mA/hour
  - The band extension has to allow 40 mA/hour in Accumulator
    - The decision has to be supported by progress with improvement of present system performance