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PETS Recirculation Theory and Data Analysis

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R. Ruber, V. Ziemann, *An alalytical model for PETS recirculation,* CTF3-Note-092
V. Ziemann, *Data analysis for PETS recirculation,* CTF3-Note-094

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Overview

- Simple Model
- Analytical solution with **constant** recirculation parameters (CRP) and constant bunch intensity
- Numerical solution with CRP with real data
- **Varying** recirculation parameters (VRP)
  - fit the gain and phase
  - recover coupling to beam and phase to detector
- Detector non-linearities and Breakdown
- Software

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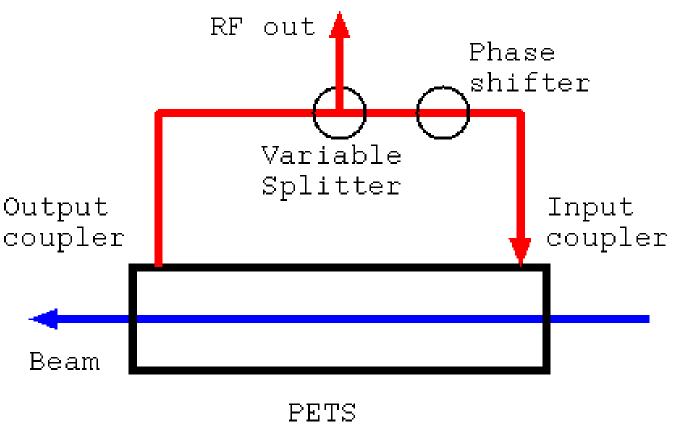
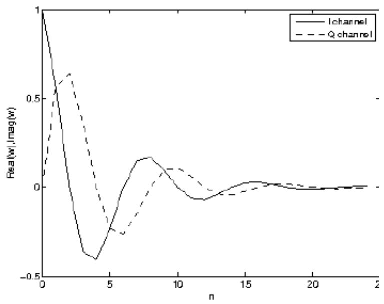
Simple Recirculation Model

- When an electron bunch passes through PETS it generates a field burst
- that shows up in the PETS again after a round-trip time τ and
  - is attenuated by factor $g=e^{-\alpha}$
  - returns with a phase shift ϕ

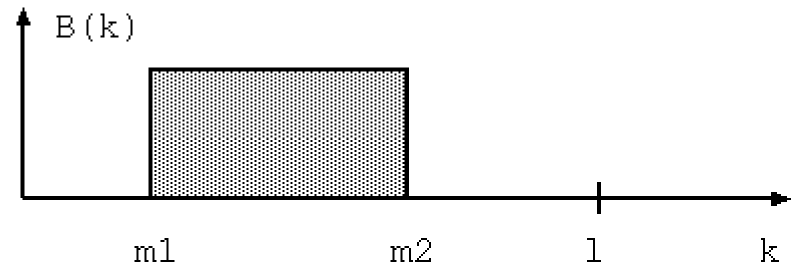


- After one turn $q=e^{i(\phi+i\alpha)}$
- 'Wake' or field in PETS of single bunch after n turns (Greens function, impulse response)

$$w(n) = g^n e^{in\phi} = e^{in(\phi+i\alpha)} = q^n$$



Wake function from bunch train



- Assume box-like bunch distribution
- Field after time 'l' (in units of round-trip-time)
  - convolution

$$f(l) = \sum_{k=m_1}^{l} w(l-k)B(k) = B\sum_{k=0}^{l-m_1} e^{ik(\phi+i\alpha)} = B\sum_{k=0}^{l-m_1} q^k$$

- just geometric sums
  - within bunch-train

$$f(l) = B\frac{1-q^{l-m_1+1}}{1-q} \quad \text{for } m_1 \le l \le m_2$$

  - after bunch-train

$$f(l) = B\sum_{k=m_1}^{m_2} w(l-k) = Bq^{l-m_2}\frac{1-q^{m_2-m_1+1}}{1-q} \quad \text{for } m_2 < l$$

- Simplify with

$$|\sin(\phi+i\alpha)|^2 = \sin^2\phi + \sinh^2\alpha$$

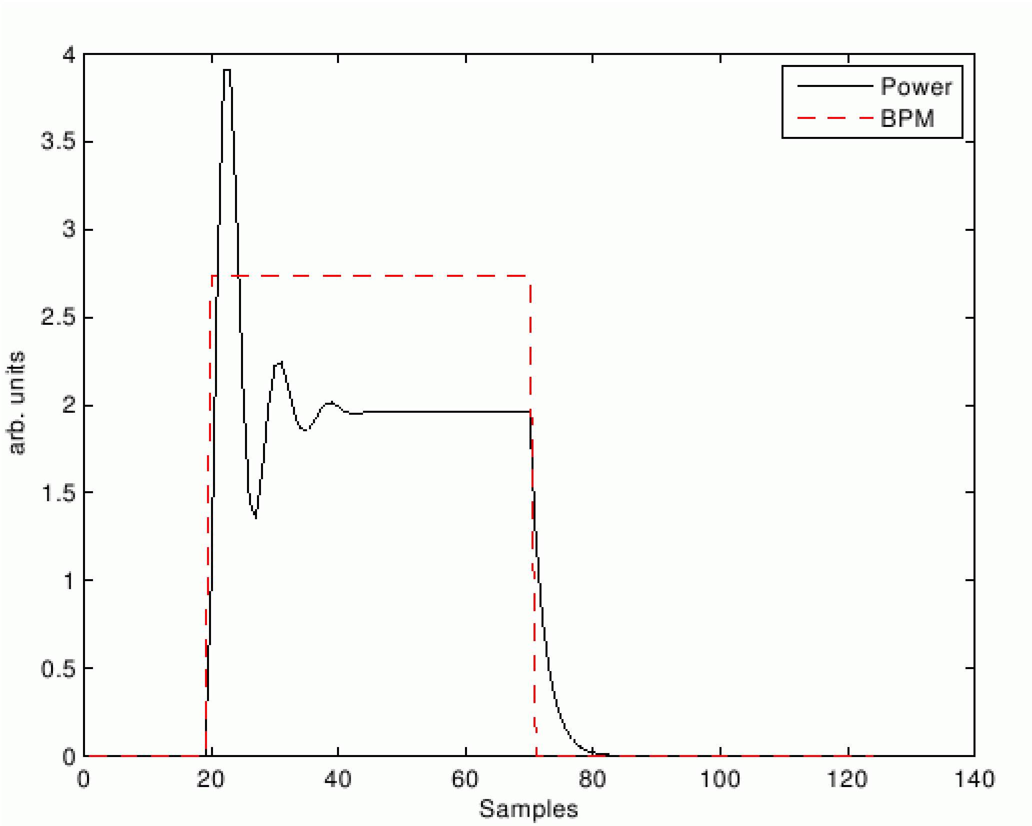
- Power = $|f|^2$

$$p(l) = B^2 e^{-(l-m_1)\alpha}\frac{\sin((l-m_1+1)\phi/2)^2 + \sinh((l-m_1+1)\alpha/2)^2}{\sin(\phi/2)^2 + \sinh(\alpha/2)^2}$$

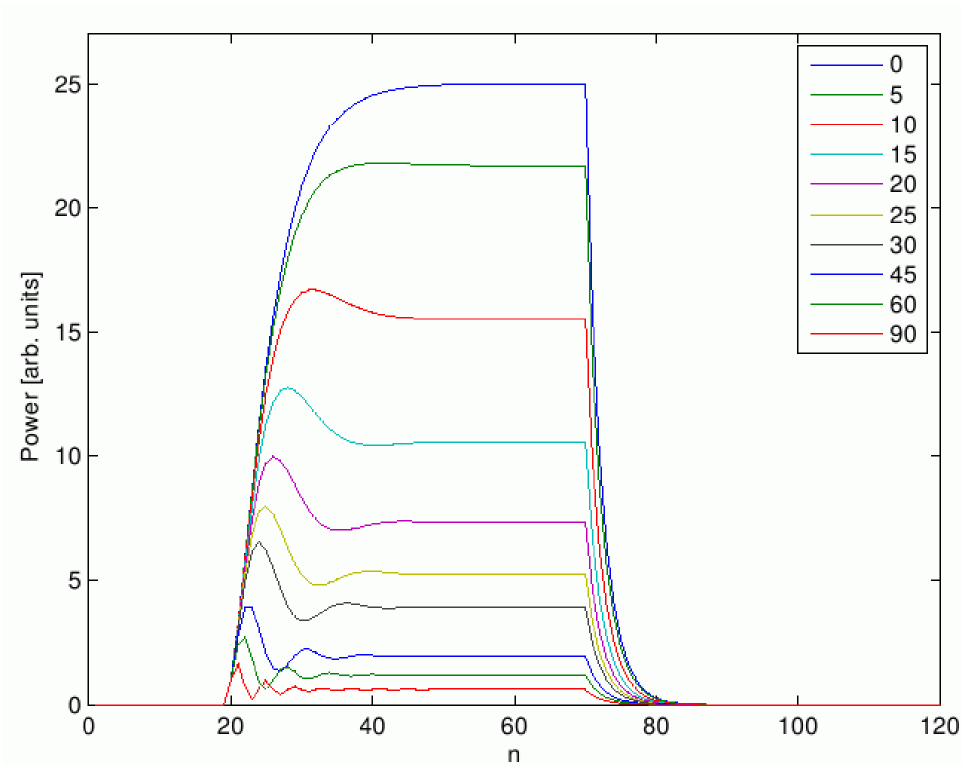
- in and behind

$$p(l) = p(m_2)e^{-2(l-m_2)\alpha} \quad \text{for } m_2 < l$$

Example



- Varying the phase with g=0.8



- g=0.8, ϕ=45 degree

Numerical model

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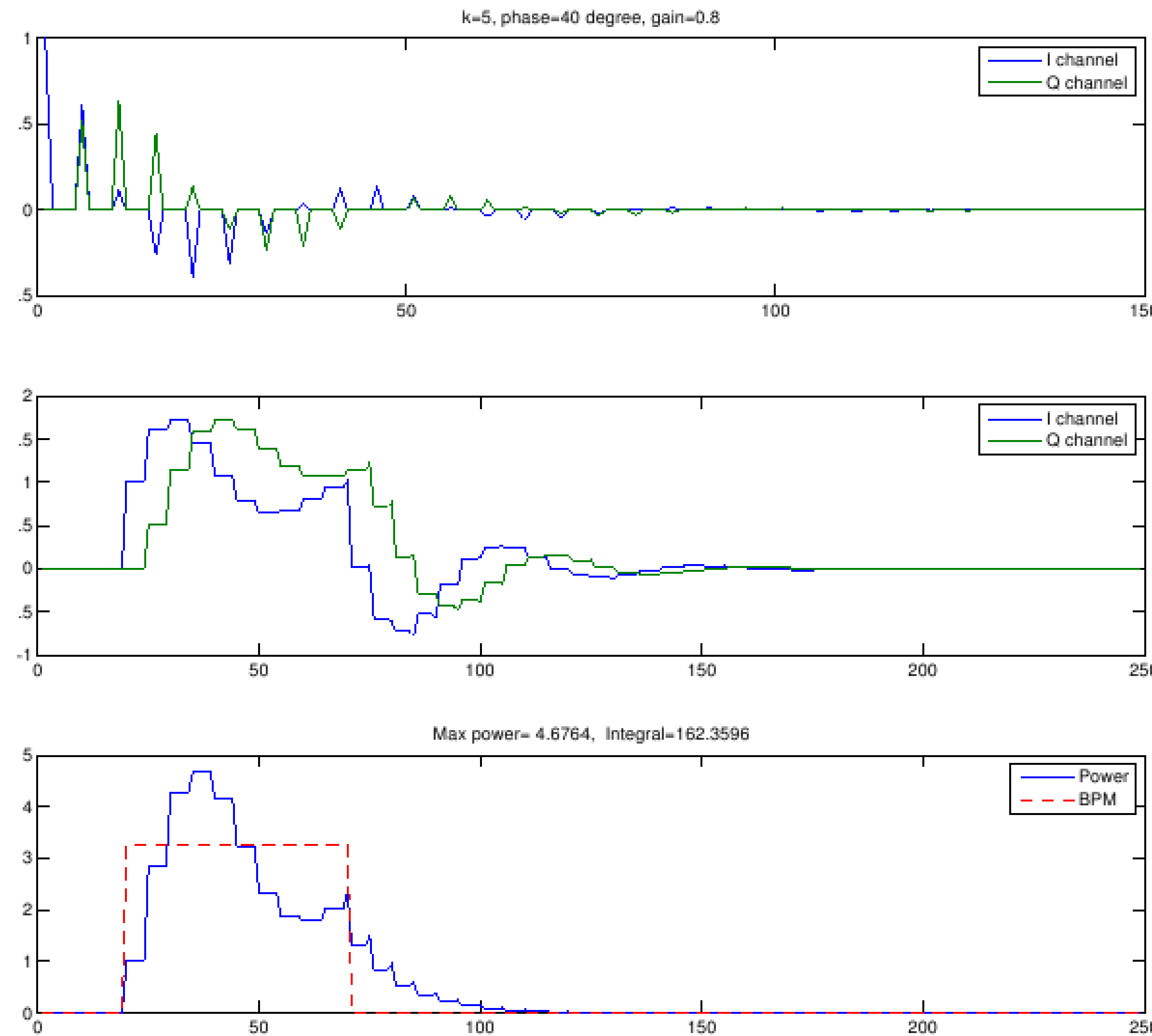
- Wake with round trip time

$$w(n) = \begin{cases} e^{in(\phi + i\alpha)/k} & \text{if } n = 0, k, 2k, \ldots \\ 0 & \text{else} \end{cases}$$

- c=Real(w)
- s=Imag(w)
- Matlab code

```
realf = conv(bpm,c);
imagf = conv(bpm,s);
power=realf.^2+imagf.^2;
```



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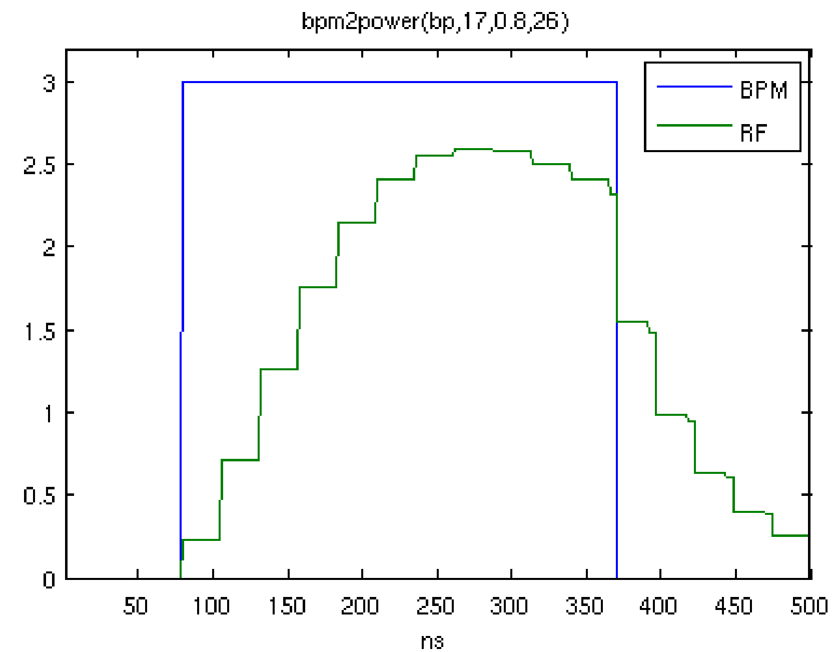
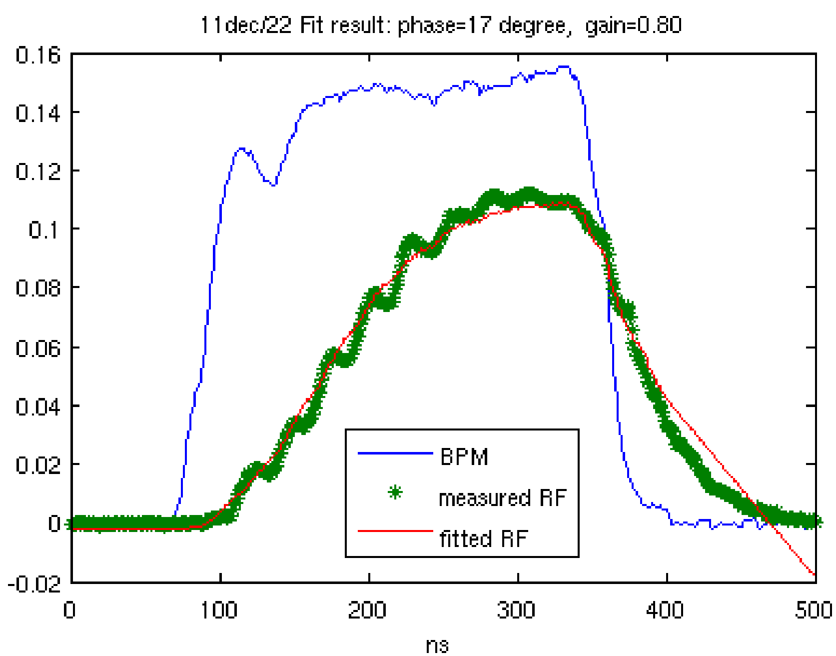
Steps

- Finite round-trip time causes steps in the recorded power
- Not properly reproduced

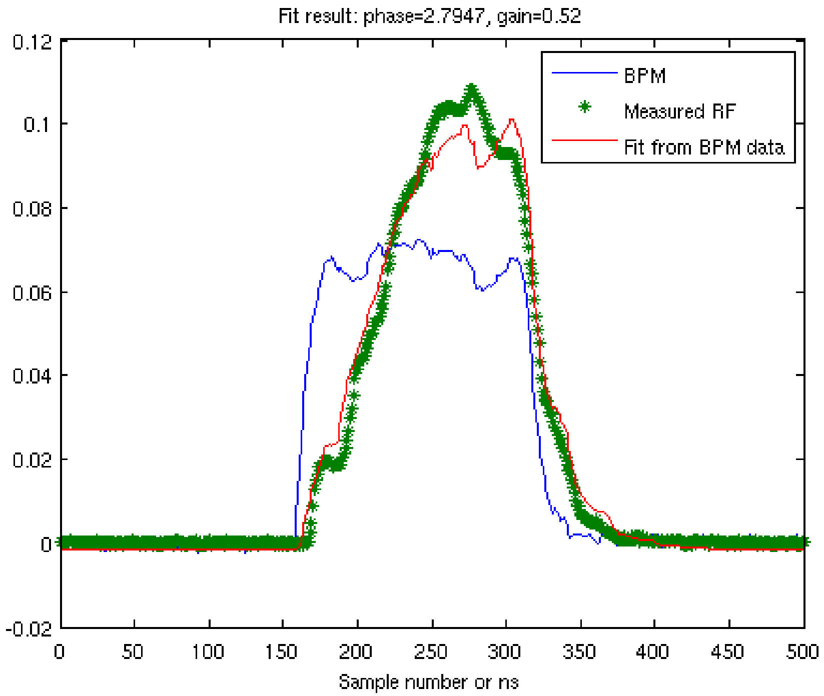




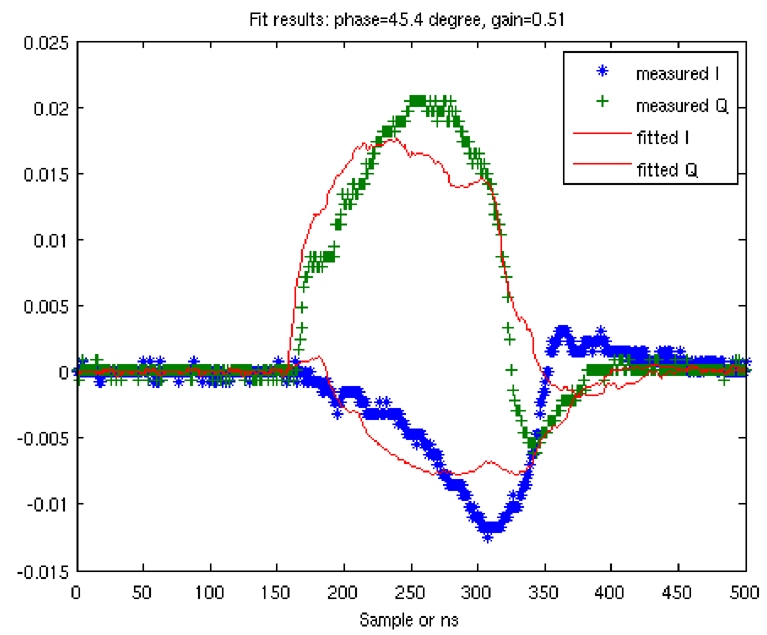
- But the simulation is OK for sharp BPM
- Limited bandwidth of the BPM smoothes out step-like features.

Fit real data from Nov 28, 2008

- Fit Power profile from BPM data (26 ns rt)
  - offset, amplitude, phase, gain, delay



- Fit I-Q profile from BPM data
  - phase, gain, amplitude, extra phase
- Unsatisfactory IQ-fit



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Variable Recirculation Parameters

- What's wrong with the IQ fit?
- What information can be extracted from the IQ data? Some sort of phase? If so, what phase?
- How do the recirculation parameters change when a discharge/breakdown occurs?
- Idea: Make the recirculation parameter $q=e^{i(\phi+i\alpha)}$ variable, i.e. $q_m=e^{i(\phi_m+i\alpha_m)}$ for DAQ-sample *m*.
- Now use the following equivalent representation

$$E_m = a\, I_m + q_m\, E_{m-1}$$ (*m-1* means one rt-time back)

where I_m = BPM signal, E_m = complex field in PETS

Determining the q_m

- If we measure E_m and I_m we can calculate q_m

$$q_m = \frac{E_m - aI_m}{E_{m-1}}$$

- But we measure E in the IQ detector, not E in the PETS with $\bar{E}=e^{i\psi}E$
- Rewrite q_m in terms of the measureable $\bar{E}$

$$q_m = \frac{e^{-i\psi}\bar{E}_m - aI_m}{e^{-i\psi}\bar{E}_{m-1}} = \frac{\bar{E}_m - ae^{i\psi}I_m}{\bar{E}_{m-1}}$$

- with unknown coupling a and phase ψ

Finding the coupling *a* and ψ

- The generalized coupling $c=ae^{i\psi}$ should be rather more slowly varying than the q_m.
- Minimize the variation X^2 of the q_m

$$\chi^2 = \frac{1}{M}\sum_{m=1}^{M}(q_m - \bar{q})^2$$

- with

$$\bar{q} = \frac{1}{M}\sum_{m=1}^{M} q_m$$

- with respect to a and ψ

Testing the Algorithm

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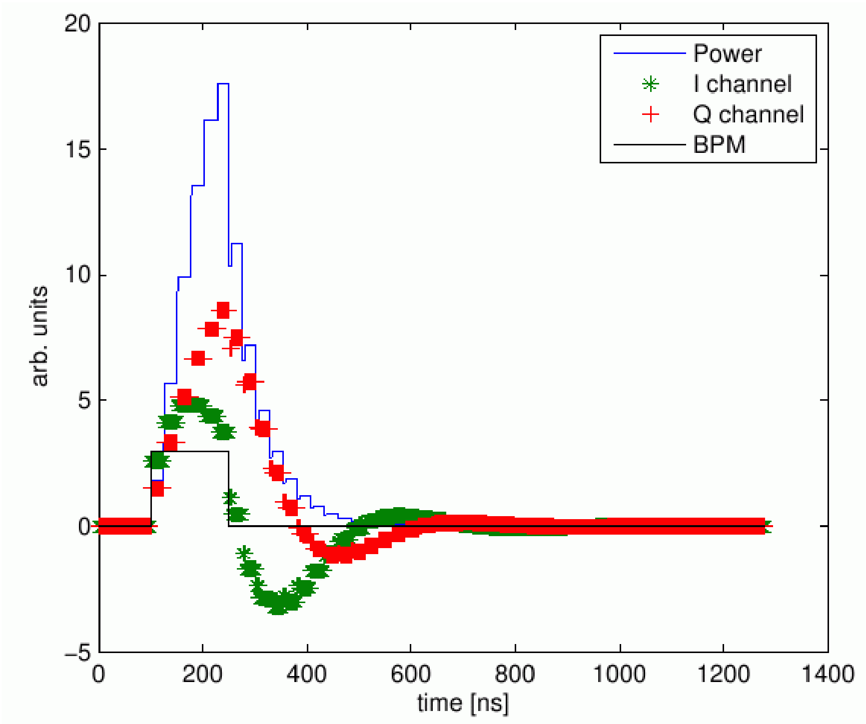
- Synthetic data
  - 26 ns, g=0.8, ϕ=20°
  - a=1, ψ=30°




```
Ebar=chI+ichQ;
c=x(1)+i*x(2);
cut=0.1*max(abs(Ebar));
q=zeros(1,length(Ebar));
for j=ktime+1:length(Ebar)
   if abs(Ebar(j-ktime))>cut
      q(j)=(Ebar(j)-c*II(j))/Ebar(j-ktime);
   end
end
```

- Matlab code
  - chI/chQ: measured data
  - $c=ae^{i\psi} = x_1+x_2$ = fit param'
  - ignore values with small $\bar{E}$
- and then minimize the rms variation of the q

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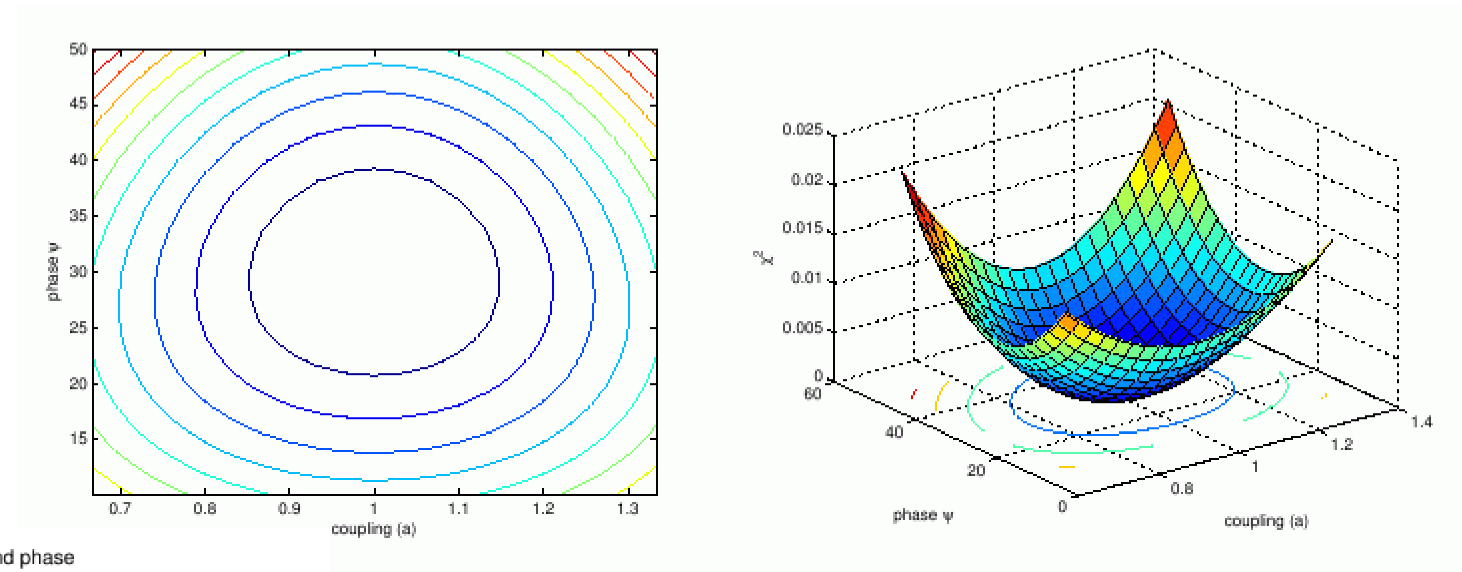
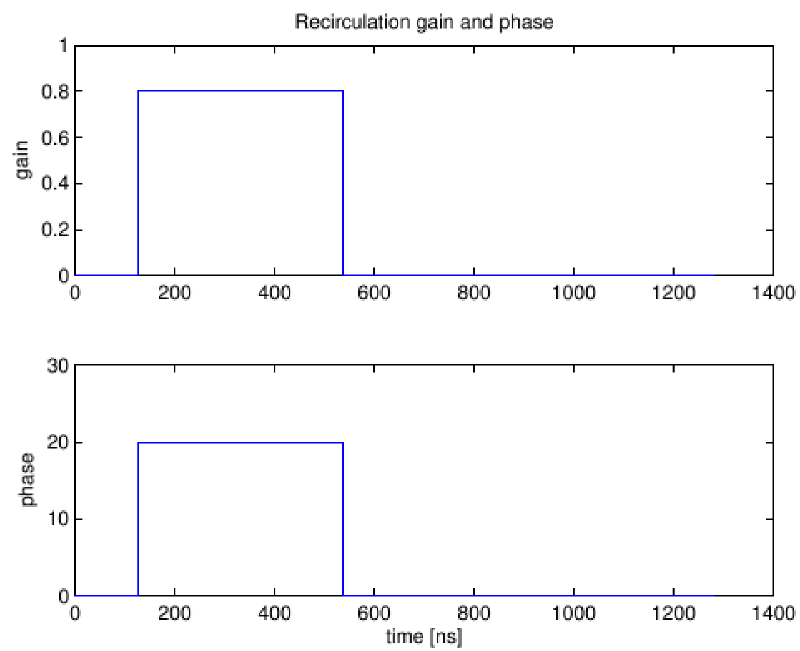
Test Results with clean data





- The X^2 minimization yields coupling a and ψ
- and the perfectly reconstructed g and ϕ within the pulse

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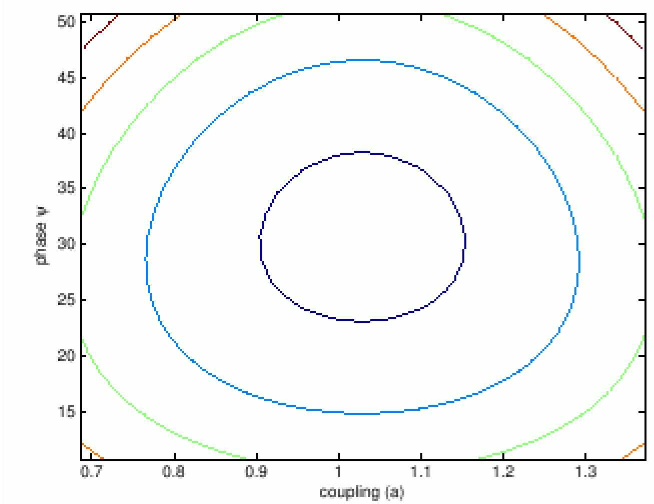
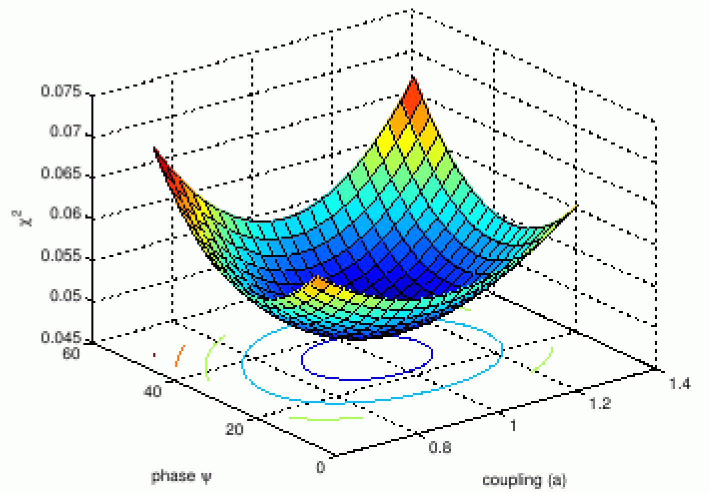
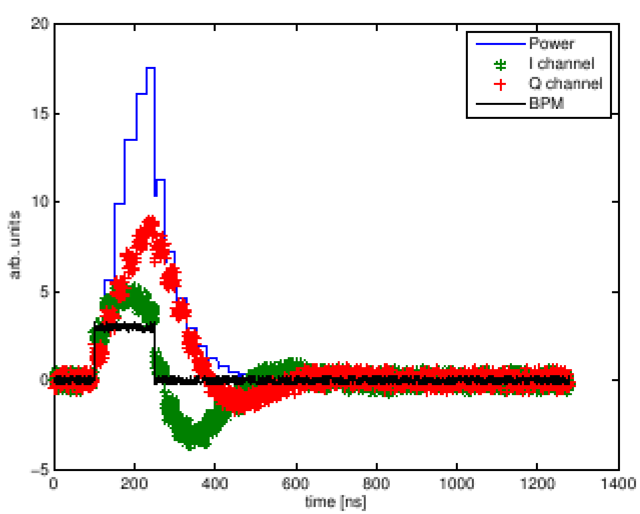
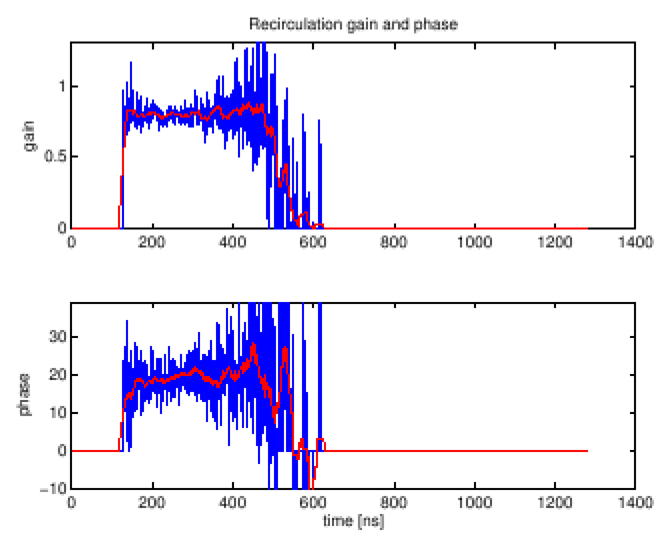
Noisy data





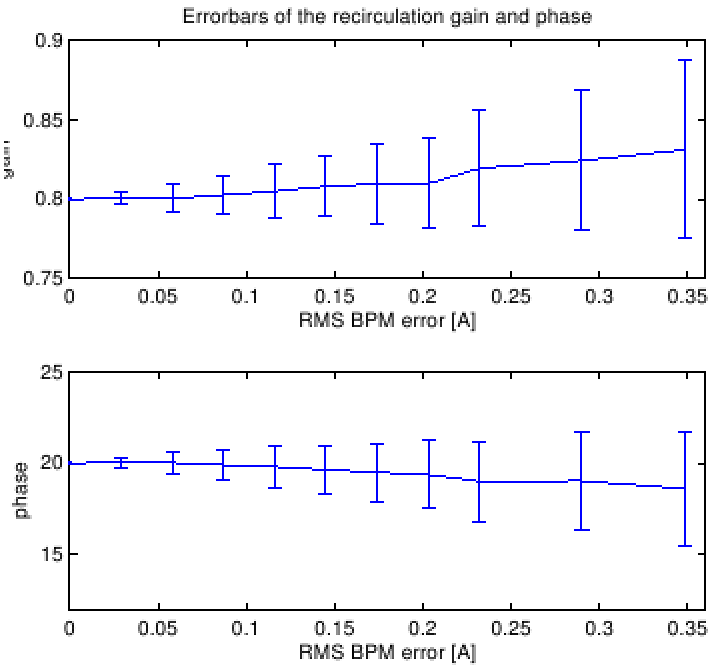


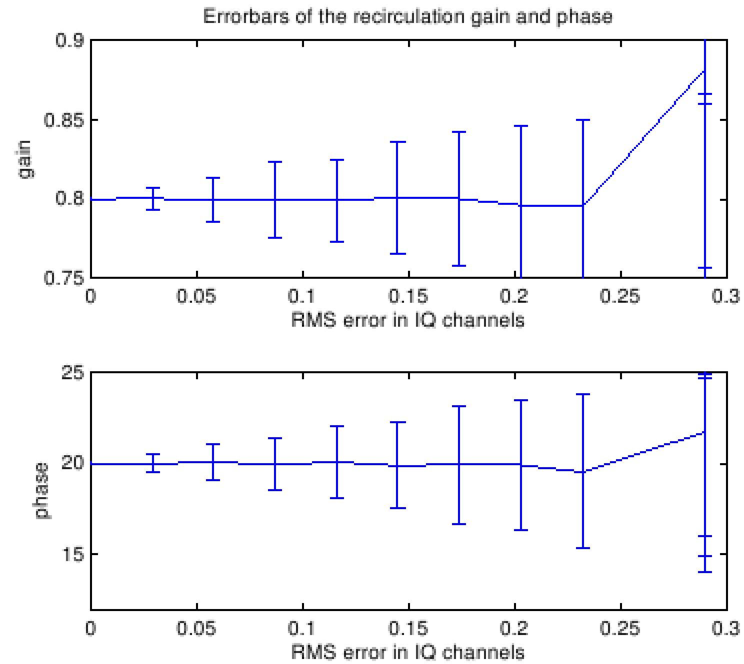


- BPM=±0.25
- IQ=±0.5
- hard-edge
- a=1.04 (1)
- ψ=30.7° (30)

- phase and gain roughly correct
- very noisy after bpm pulse

Noise scaling

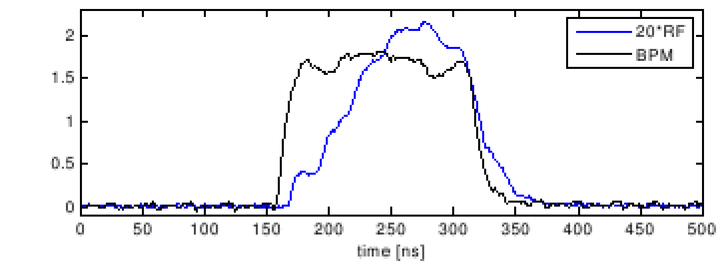


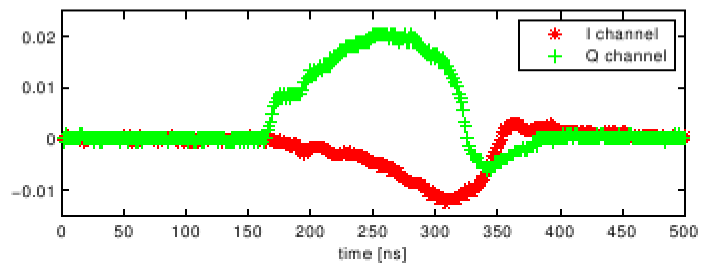


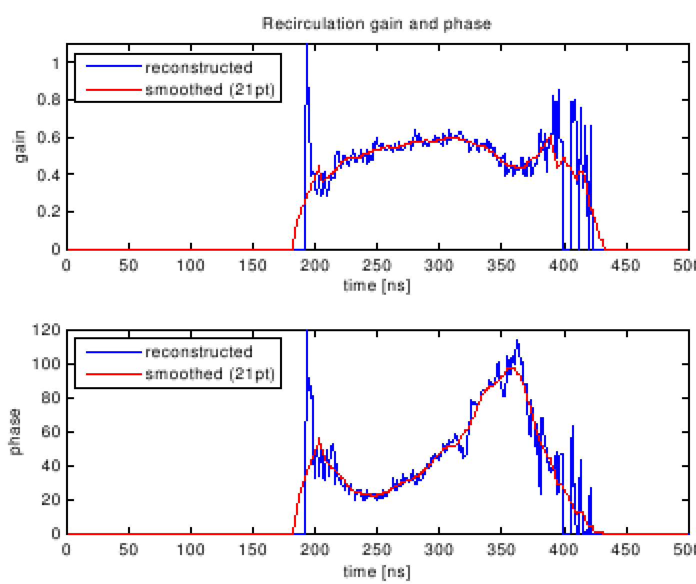
- BPM RMS-errors on the order of 0.1 A/3A
- few percent

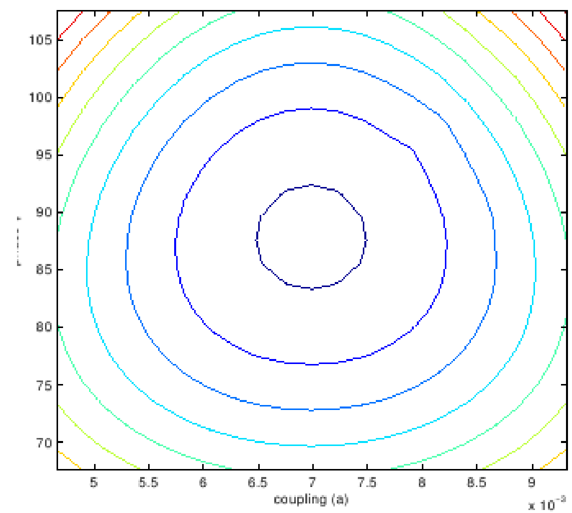
- IQ RMS-errors on the order of 0.1/10
- few percent

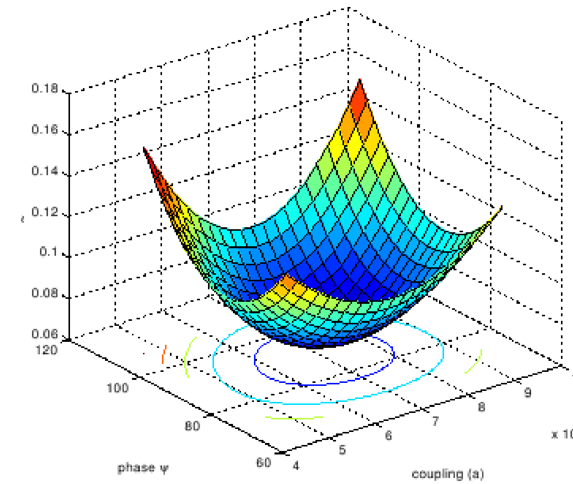
Measurements (28.11)

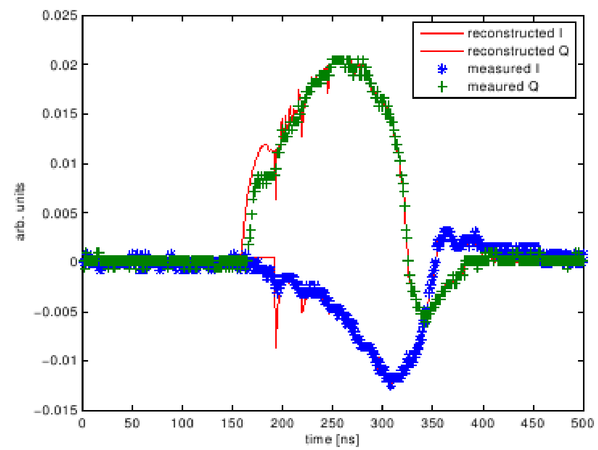


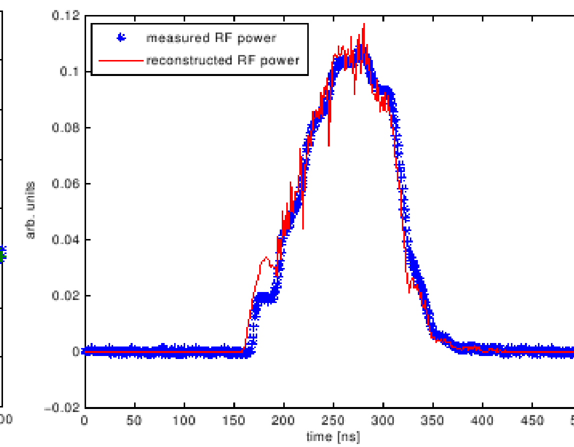












well-fitted I and Q

fitted I/Q and measured power

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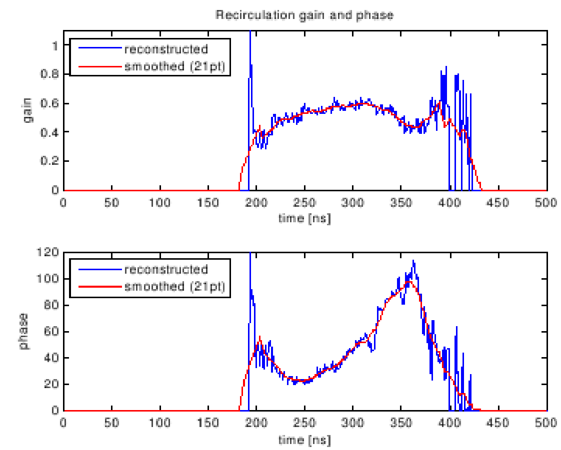
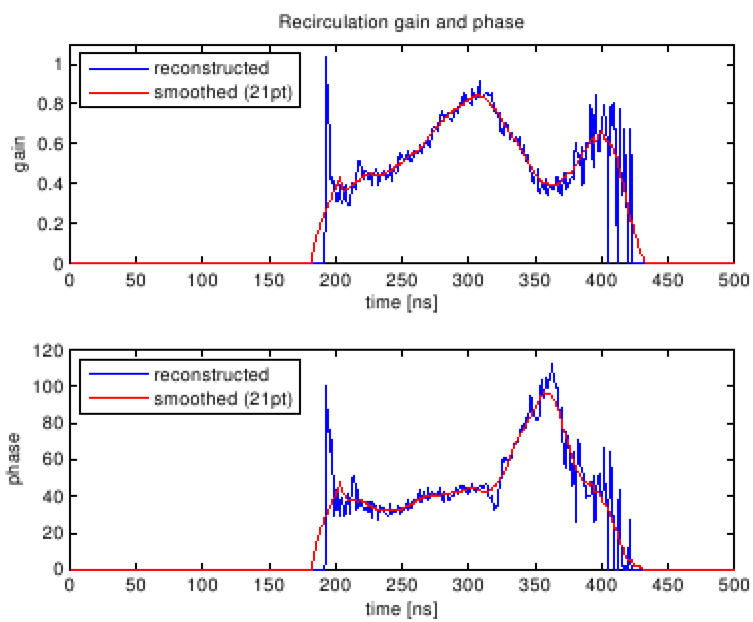
Non-linearity of the IQ detector

- Introduce curvature in IQ
- Trade flat gain vs flat phase

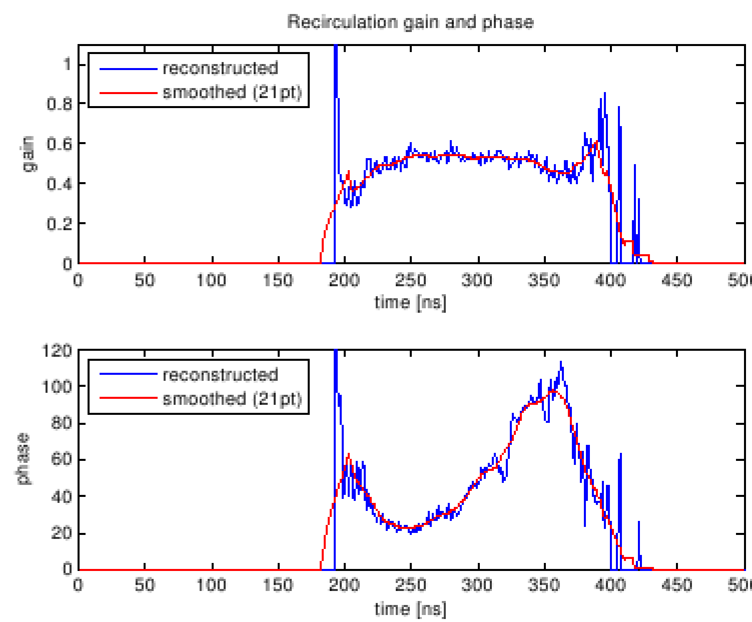
```
fudge=8;    % parameter for non-linearity
chI=chI-fudge*(chI+0.03).^2+fudge*0.03^2;
chQ=chQ-fudge*(chQ+0.03).^2+fudge*0.03^2;
```



0

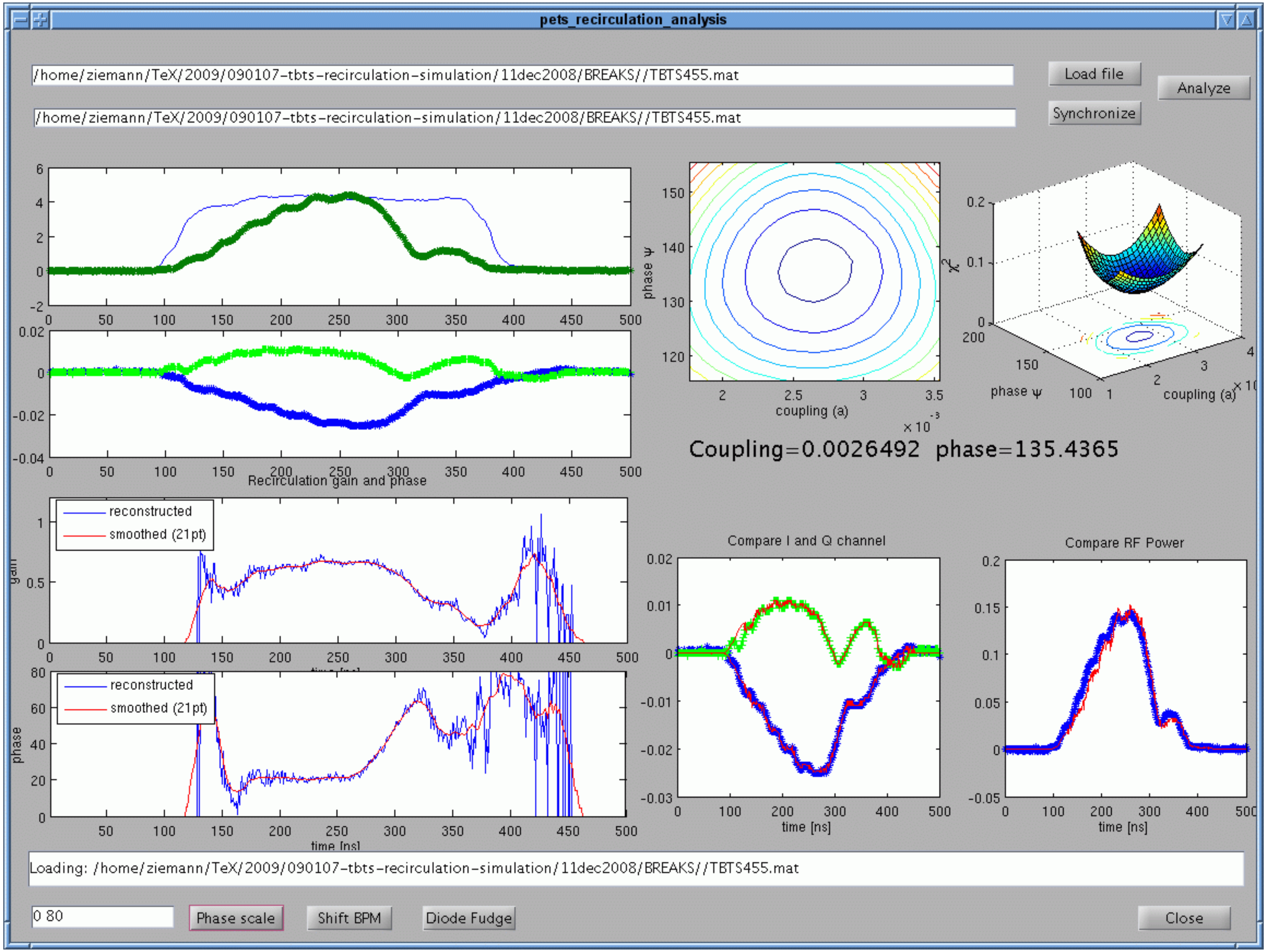


+8



-8

Software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Load file
Synchronize
Analyze
Recirculation gain and phase
reconstructed
smoothed (21pt)
gain
phase
time [ns]
phase ψ
coupling (a)
Coupling=0.0026492 phase=135.4365
Compare I and Q channel
Compare RF Power
Loading: /home/ziemann/TeX/2009/090107-tbts-recirculation-simulation/11dec2008/BREAKS//TBTS455.mat
0 80
Phase scale
Shift BPM
Diode Fudge
Close

Breakdown

- The event on the previous slide shows
  - shortened RF-pulse
  - gain-drop
  - phase shift
- Interpretation attempt
  - free electrons absorb RF power, thus the gain drop
  - and change the dielectric properties and therefore the refractive index, thus the phase shift

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Conclusion

- Simple model for PETS recirculation
  - with constant recirculation parameters
  - Works well for power, poor for IQ
- Extension for varying parameters: can reconstruct the phase and gain along the pulse
  - now both power and IQ signals fit well
- Breakdown
- Software

Another data set