RFA Experiments on the T2R RFP

Open loop control experiments

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Open loop control experiments in EXTRAP T2R RFP

Outline

The theme of the workshop is back to the basics.

Topics aimed at in this talk are:

- Assumption of mode rigidity
- Applicability of the linear model

Data shown:

- "Open loop" constant resonant control harmonic
  (qualitative information)
- "Open loop" pulsed resonant control harmonic
  (quantitative estimates of transfer functions, mode growth rates and mode damping rates)

Basics - Resistive- wall mode stability in the RFP

Cylindrical plasma bounded by a thin wall: radius $\boldsymbol{r_w}$ and (long) penetration time $\boldsymbol{\tau_w}$.

Natural growth rate, $\boldsymbol{\gamma_{m,n}}$, of a non-rotating m=1 RWM is then defined by the stability index given by the discontinuity in the logarithmic derivative of the perturbed field at r_w.
[ref C G Gimblett, Nuc Fus 26 (1986) p 617].

$$\mathbf{2\gamma_{m,n}\tau_w = r_w\Delta_{m,n}'.}$$

An important assumption is that the mode structure in the plasma is **rigid**.

Therefore the plasma can be specified by the single parameter, the growth rate, $\gamma_{m,n}$, of the RWM.

Resistive- wall mode stability in the RFP

An externally produced **control field** <u>**or**</u> **a field error**, at $r_f > r_w$, modifies $\Delta_{m,n}'$
and thereby the growth rate for that (m,n)-harmonic.

To compare experiment and theory, examine the time dependence of the **RWM radial field** perturbation evaluated on the inside surface of the thin wall, **which is the location of the sensor coils in the experiment**.

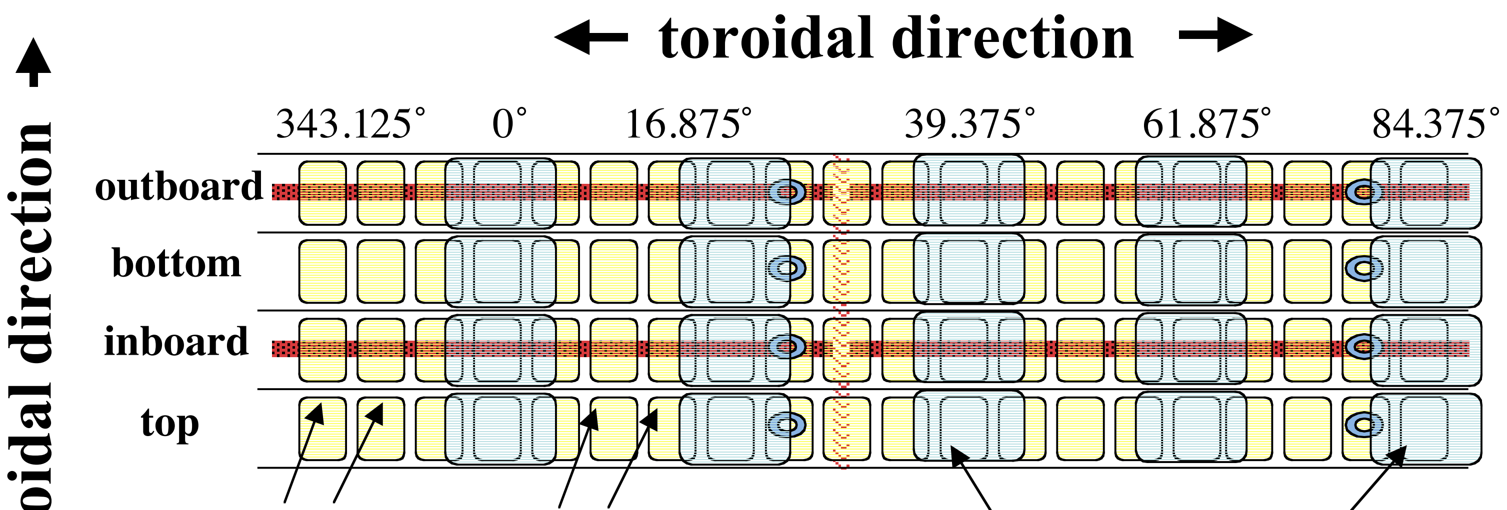
Linear model for the (m,n)-harmonic of the RWM including external error and control field harmonics

$$d_t b_{m,n} = \gamma_{m,n} b_{m,n} - \gamma_{m,n,w}(M_{m,n}\, I_{m,n} + b_{m,n}^{error})$$

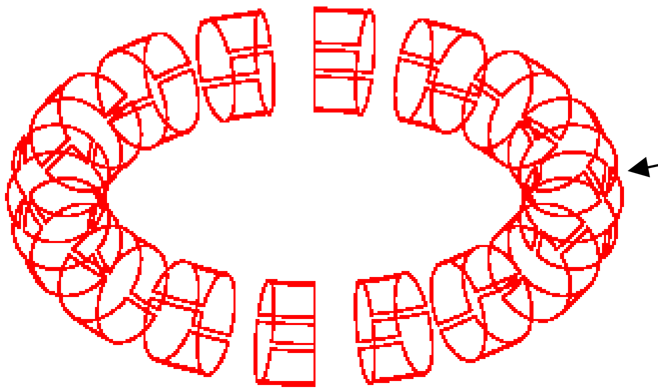
where,

- $\mathbf{b_{m,n}}$ is the perturbed field measured at the sensor coil.
- $\boldsymbol{\gamma}_{\mathbf{m,n}}$ is the growth rate of the mode.
- $\boldsymbol{\gamma}_{\mathbf{m,n,w}}=(\boldsymbol{\tau}_{\mathbf{m.n,w}})^{-1}$ describes the diffusion rate of the harmonic at the thin wall and is determined only by the mode number and the wall parameters.
- $\mathbf{b_{m.n}^{error}}$ is that part due to an external inherent field error.
- $\mathbf{M_{m,n}I_{m,n}}$ is the saddle-coil-produced control field ($I_{m,n}$=current & $M_{m,n}$=ratio field to current, [*Tesla/Amp*])

T2R Coil system(s)



Br sensor coils
4 (poloidal) x 64 (toroidal) positions
full surface coverage (limited acquisition)



Active coils:
twice the width of the sensor coils
4 (poloidal) x 16 (toroidal) positions
50% surface coverage

Control system

Sensors

- 32x2 one-turn, m=1 flux loops measure radial magnetic flux through shell
- 16x2 saddle-coil current measurements

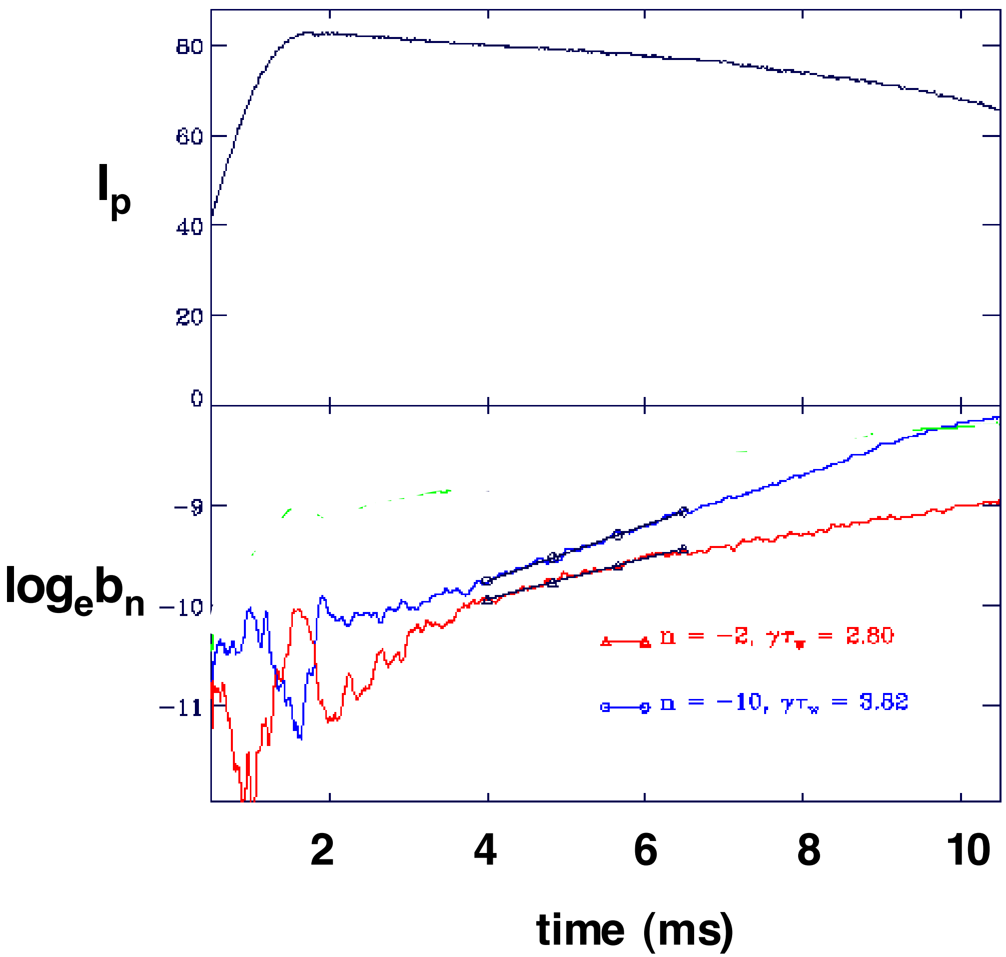
Controller

- digital controller, 64 sensor inputs, 32 coil current inputs
- real-time spatial FFT for toroidal harmonics
- Input feedback laws in the form of a matrix of complex gains
- 16x2= 32 **preprogrammed** control voltage outputs drive the saddle coil currents

Actuators

- m=1 connected saddle coils, L/R time constant 1 ms
- coil current 20 A, magnetic field 1 mT (1% of equil. poloidal field)
- high-bandwidth audio amplifiers, output power 700 Watt

”Natural” mode amplitude and phase traces for standard discharge



- **"Error field" mode (e.g. n=-2):**
  - Linear growth
  - Wall locked
  - Reproducible phase

- **RWM (e.g. n=-10):**
  - Exponential growth
  - Wall locked
  - Reproducible phase

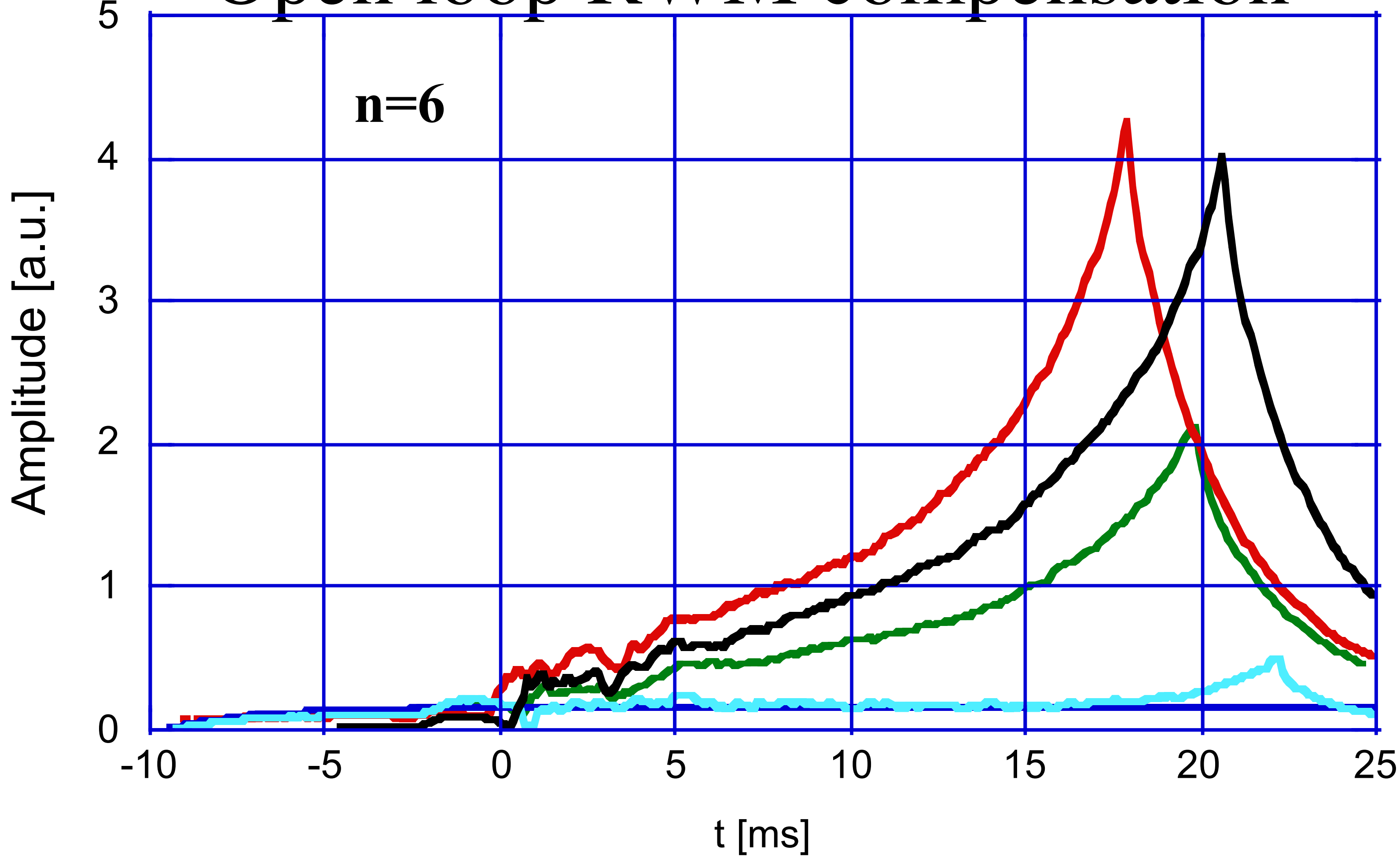
Open loop preprogrammed constant external control field harmonic applied to n=6 unstable mode

What happens if a constant control harmonic is applied

- in phase with the natural mode (i.e. positive feedback orientation)?
- 180 degrees phase difference relative to the natural mode (i.e. negative feedback orientation)?

The data qualitatively demonstrates mode rigidity.

Open loop RWM compensation



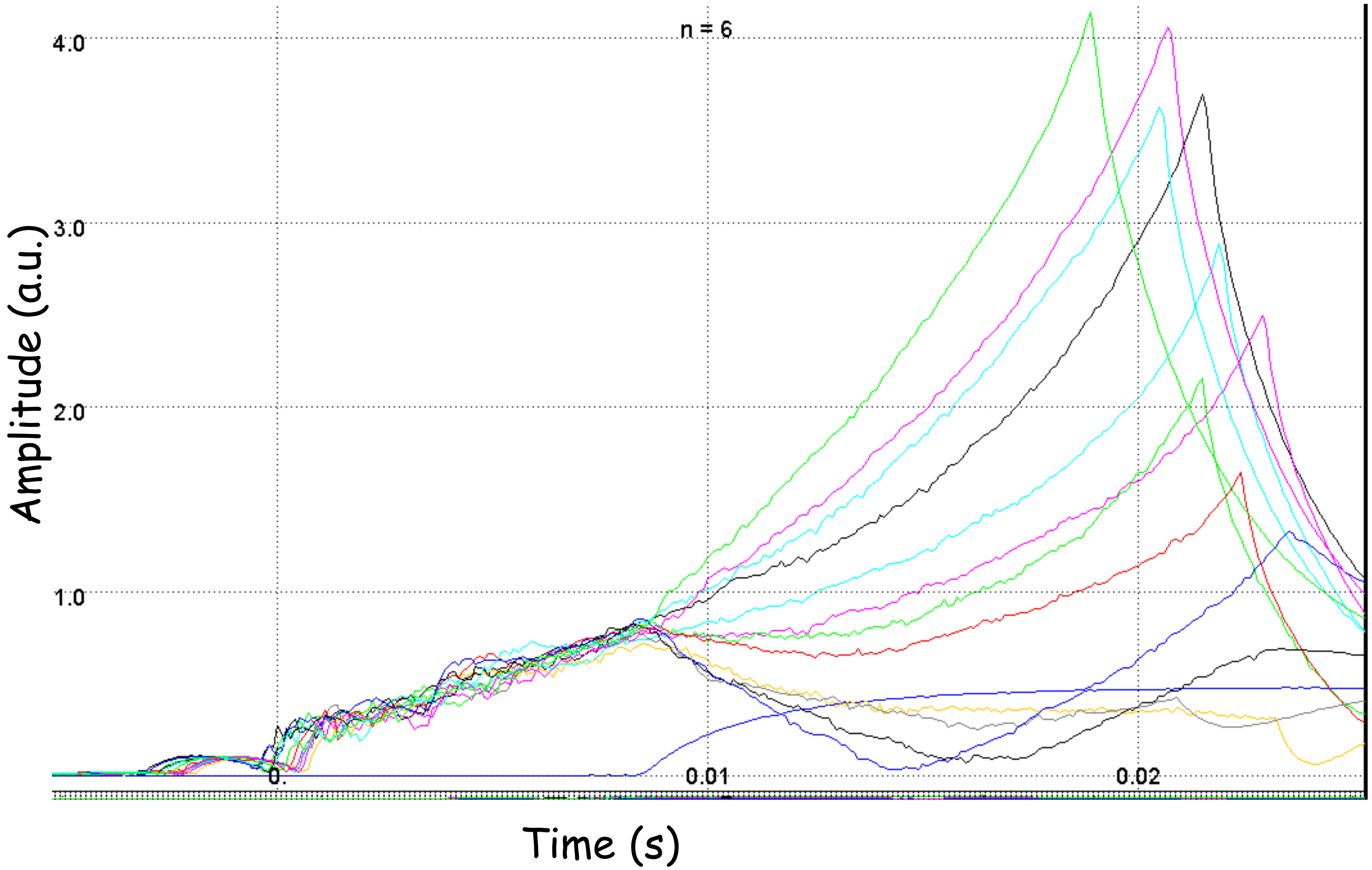
Amplitude of the mode is ≈ 1.0 mT; a. of the external perturbation is ≈ 0.02mT

Open loop preprogrammed constant external control field harmonic applied to n=6 unstable mode

What happens if the control harmonic is turned on at a later time when the mode amplitude is larger ?

- **The data qualitatively demonstrates mode rigidity.**

Open loop RWM studies



Compensation can be obtained with a perturbation starting in the middle of the discharge but at the price of a higher amplitude.

This case can be compared with feedback operations

Open loop pre-programmed *pulsed* external control field harmonics applied to different modes:

- unstable modes
- marginally unstable modes
- marginally stable modes
- robustly stable

Resonant field error amplification?

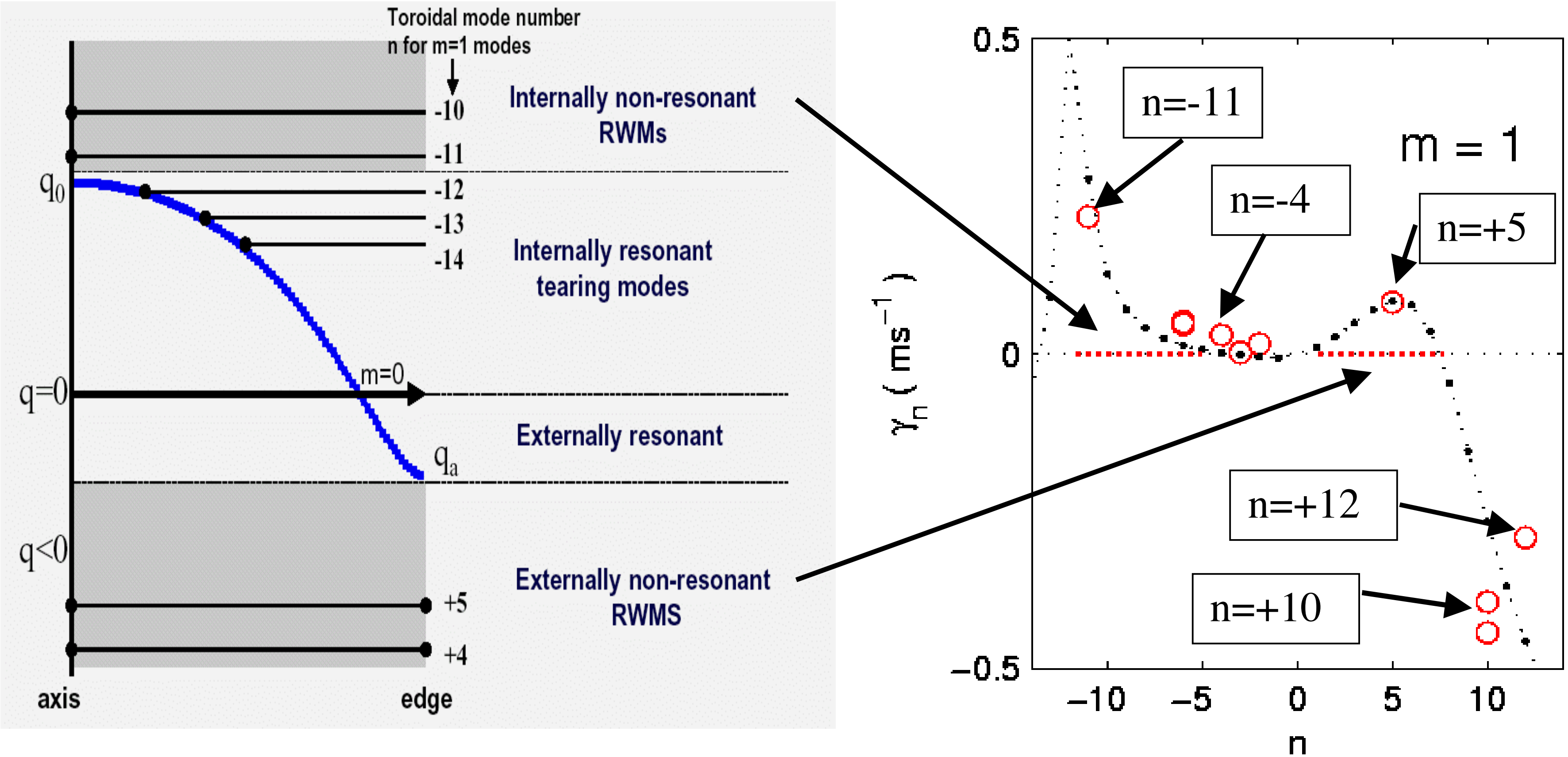
Measure growth and damping rates.

Give indication of applicability of linear model.

Analyze resonant field error amplification.

Open loop experiments with a pre-programmed *pulsed* external control harmonic

Comment on the spectrum of unstable modes in an RFP

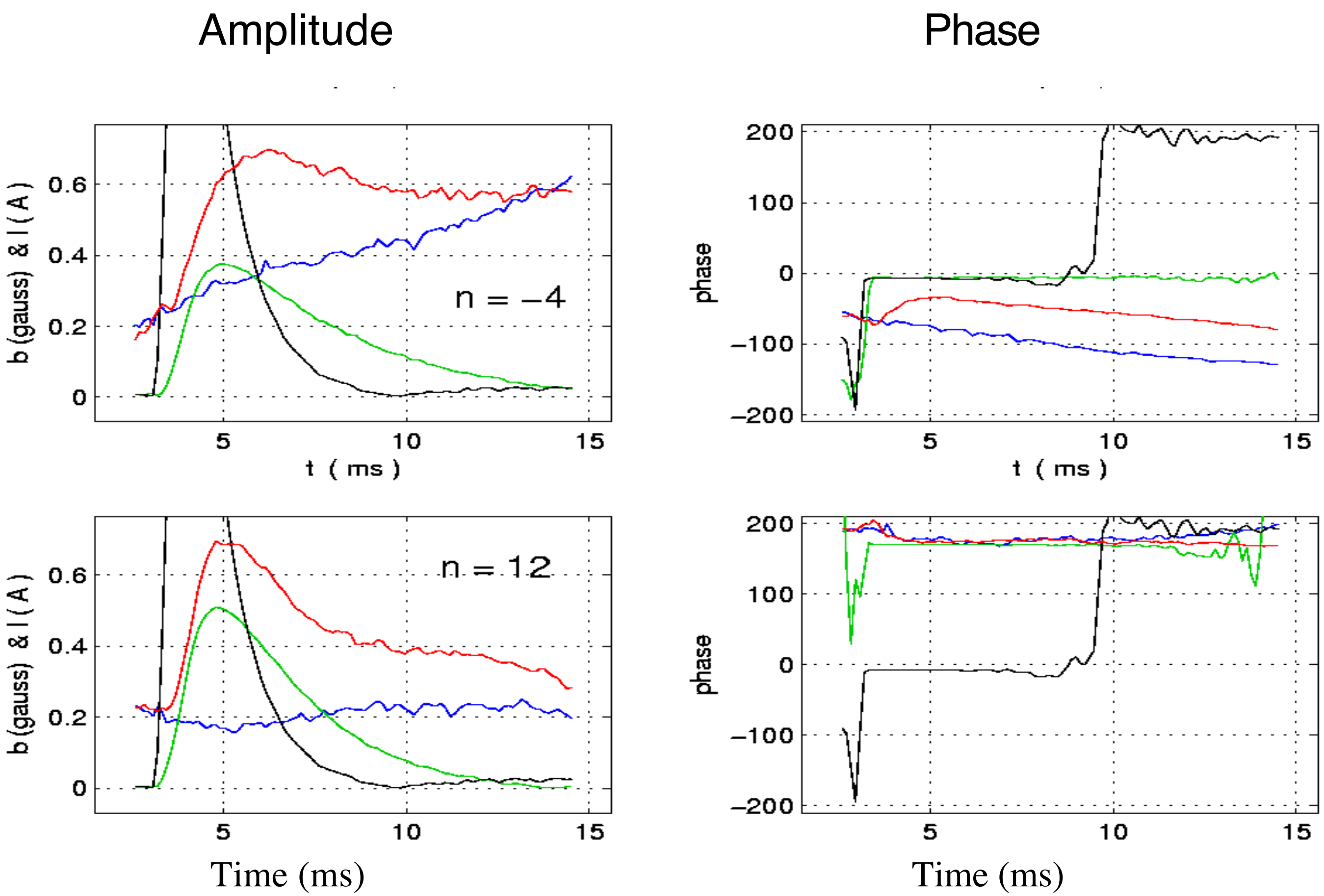


Open loop preprogrammed *pulsed* external control field harmonics applied to different modes.

Harmonics for two modes are shown:

n=-4 (marginally unstable)

n=+12 (stable)



Black = current pulse to external saddle coil (Short pulse with constant phase)

Green = b-external harmonic pulse measured by sensor coil.

Blue = b-plasma harmonic for a reproducible reference discharge

Red = b-plasma harmonic for a discharge with external perturbation applied.

Open loop preprogrammed *pulsed* external control field harmonics applied to different modes.

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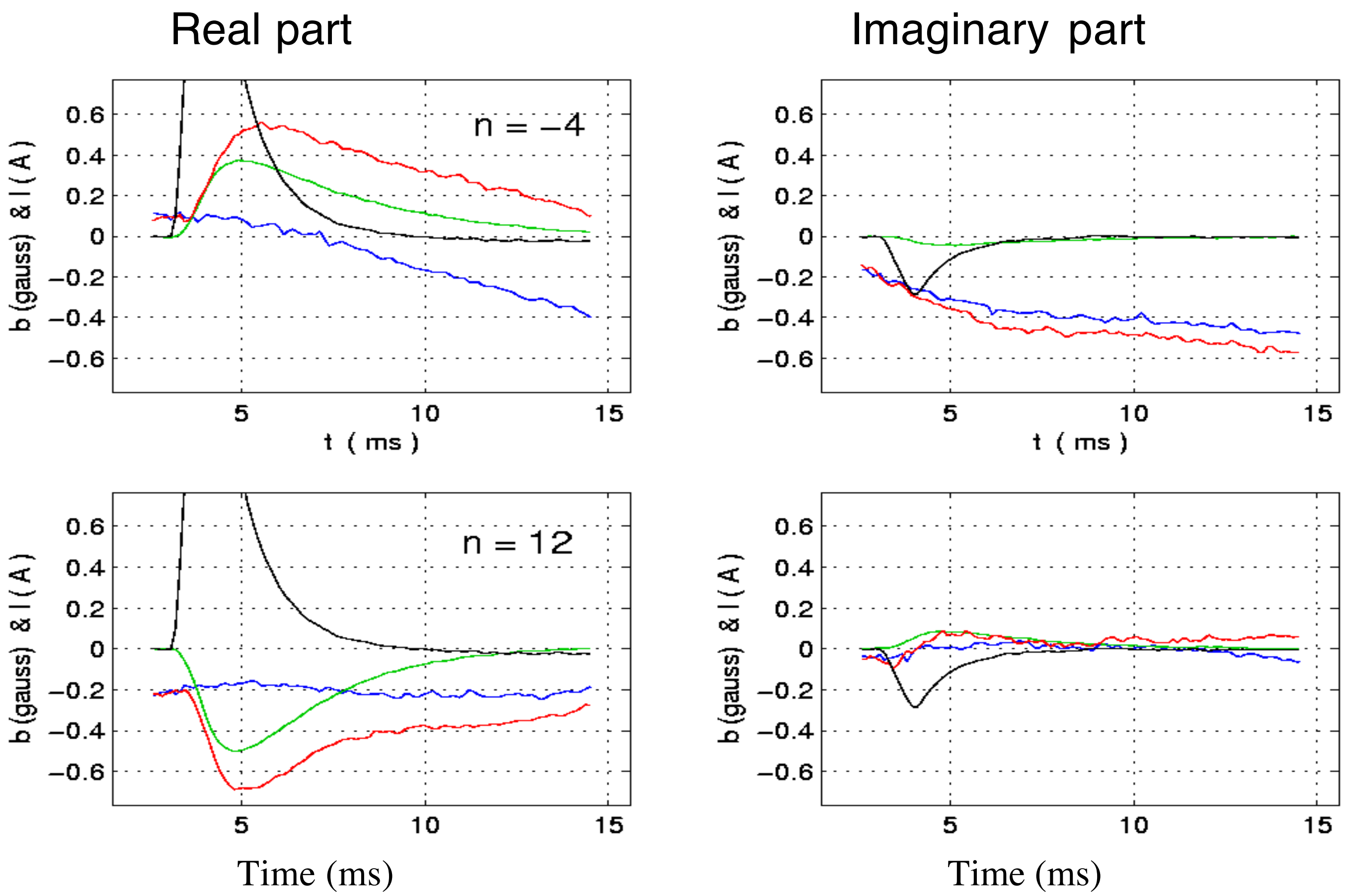

Green = b-external harmonic pulse in *vacuum* measured by sensor coil.

Blue = b-plasma harmonic for a *reference* discharge

Red = b-plasma harmonic for a discharge *with* external perturbation applied.

Open loop preprogrammed *pulsed* external control field harmonics applied to different modes.

Harmonics for two modes are shown:

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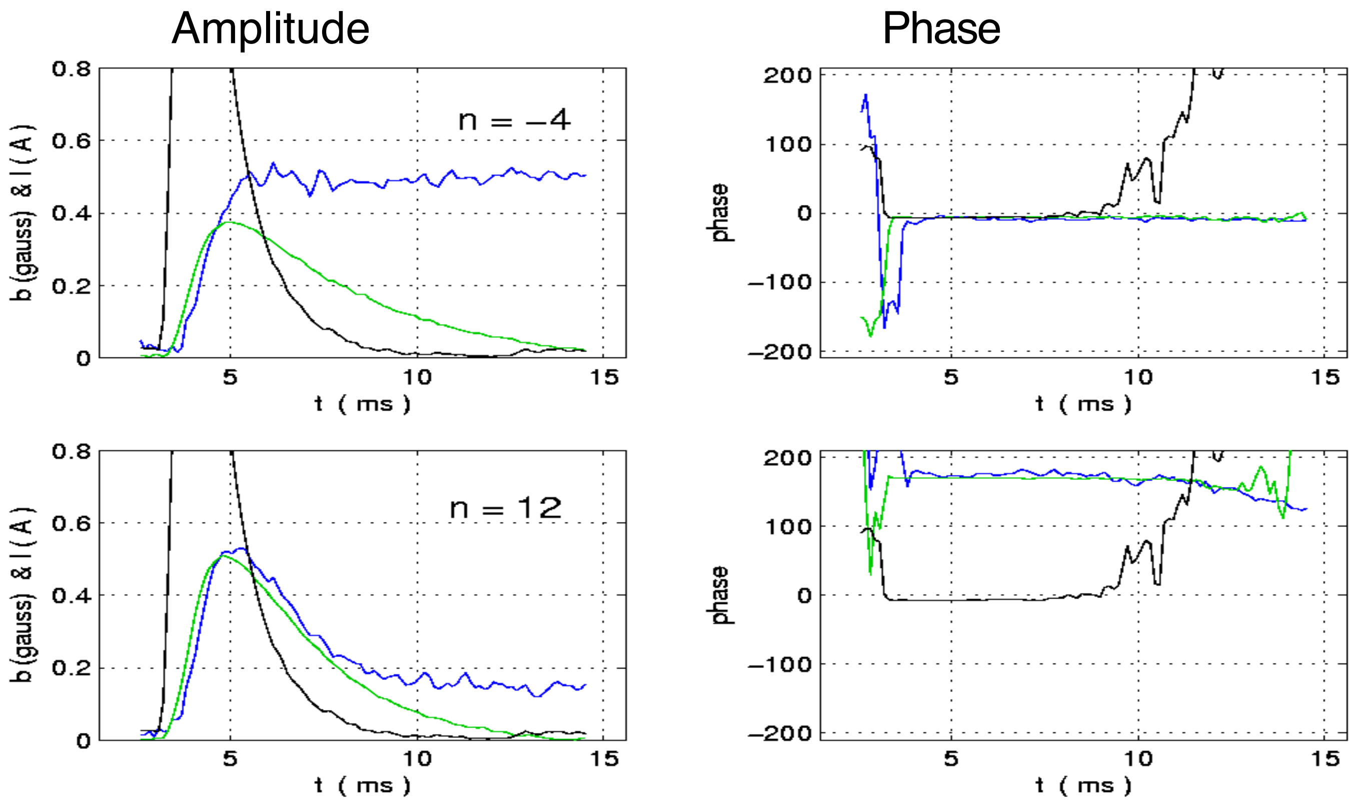


Time (ms)　　Time (ms)

Green = external perturbation (Short pulse with constant phase)

Blue = (discharge with external perturbation applied) *minus* (reference discharge)

Open loop experiments

Vacuum shots →

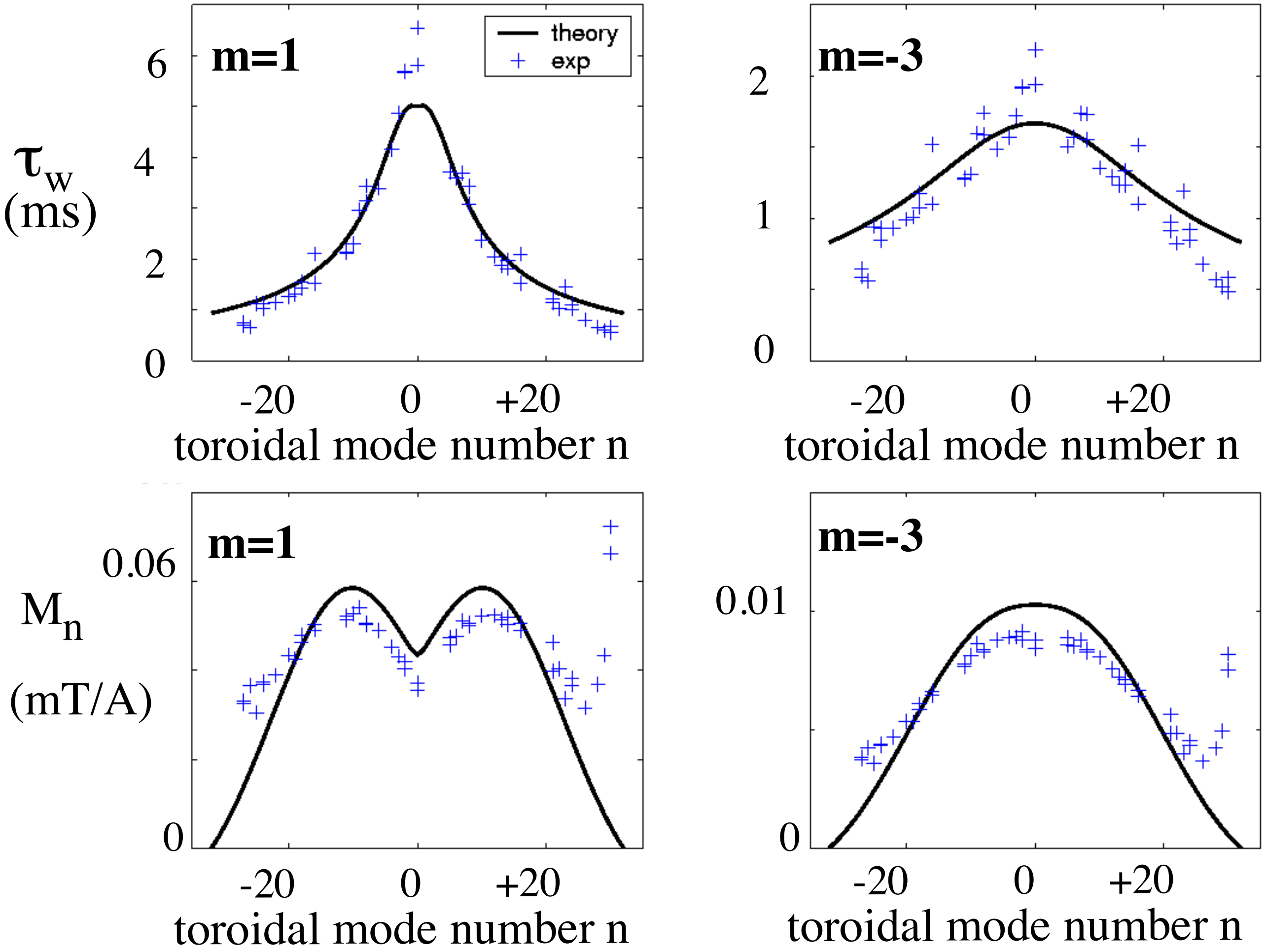
- Resistive wall diffusion rate, $\gamma_{m,n,w} = 1/\tau_{m,n,w}$
- Ratio M = field / current

Plasma shots (Reproducible mode $\gamma_{n,o}$) →

- Growth & damping rates of RWM
- External Error field
- Resonant field amplification (RFA) studies

RWM linear model

$$d_t b_{m,n} = \gamma_{m,n} b_{m,n} - \gamma_{m,n,w}(\underbrace{M_{m,n} I_{m,n}}_{\text{Control field}} + b_{m,n}^{error})$$



Open loop:
Vacuum wall diffusion time, τ_w
&
Ratio $M_{m,n}$, $\dfrac{b_{m,n}^{ex}}{I_{m,n}^{sc}}$

Theory: Calculations for a thin, smooth resistive cylinder

Experiment(+): Measurements in vacuum using pre-programmed current waveforms for saddle coil currents.

Open loop preprogrammed *pulsed* external control field harmonics applied to different modes.

Vacuum shots →
- Shell diffusion time of (m=1, n) harmonics
- Ratio M = field / current (harmonics)

Plasma shots (Reproducible mode $\gamma_{n,o}$) →
- Growth & damping rates of RWM
- External Error field
- Resonant field amplification (RFA) studies

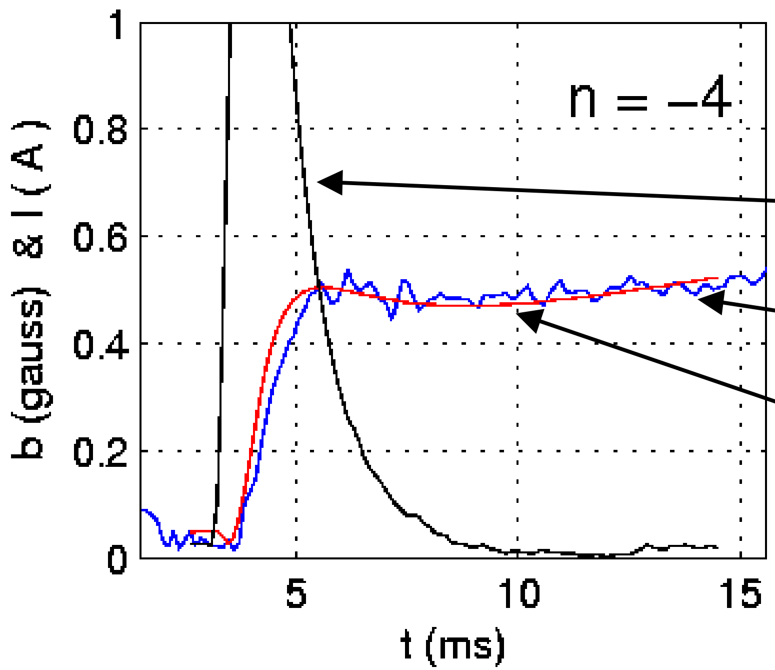
RWM linear model

$$d_t b_{m,n} = \gamma_{m,n} b_{m,n} - \gamma_{m,n,w}(\underbrace{M_{m,n} I_{m,n}}_{\text{Control field}} + b_{m,n}^{error})$$

Open loop preprogrammed *pulsed* external control field harmonics applied to different modes.

Resonant field error amplifcation can be studied by subtracting the reference plasma shot from the plasma shot with the external resonant perturbation.

- **Use the linear model.**
- **Make a best fit to the data where the fitting parameters are the plasma growth (damping) rates and the ratio $M = b_n / I_n$.**



$$d[b_{n,with} - b_{n,ref}]/dt = \gamma_n [b_{n,with} - b_{n,ref}] - \gamma_{n,w} M_n I_n$$

black is I_n

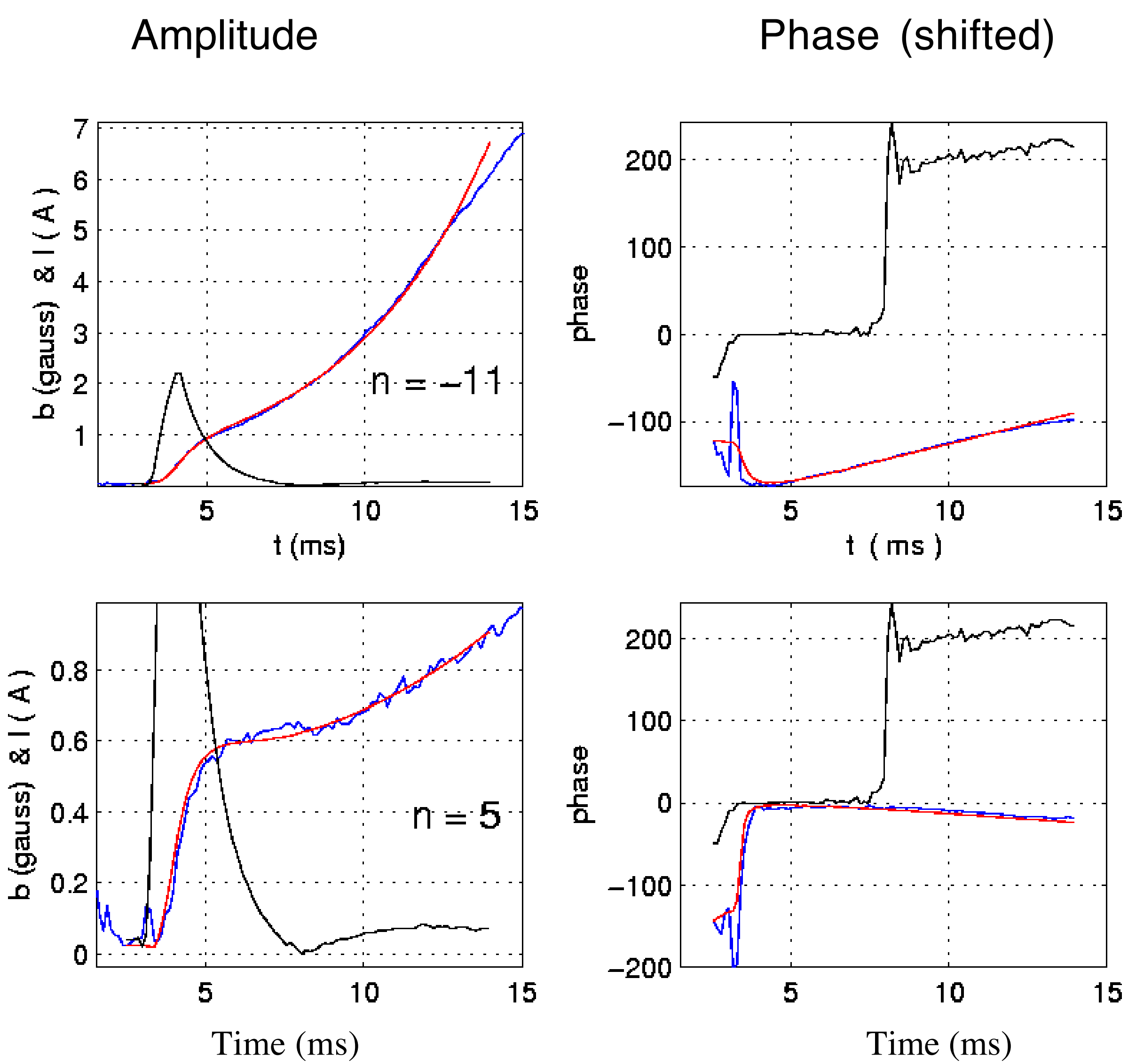
blue is $[b_{n,with} - b_{n,ref}]_{(measured)}$

red $[b_{n,with} - b_{n,ref}]_{(simulation)}$

γ_n & M_n are fitting parameters

Preprogrammed ***pulsed*** external control harmonics applied to different modes.

Harmonics for two *unstable* modes: n= -11 & n=+5

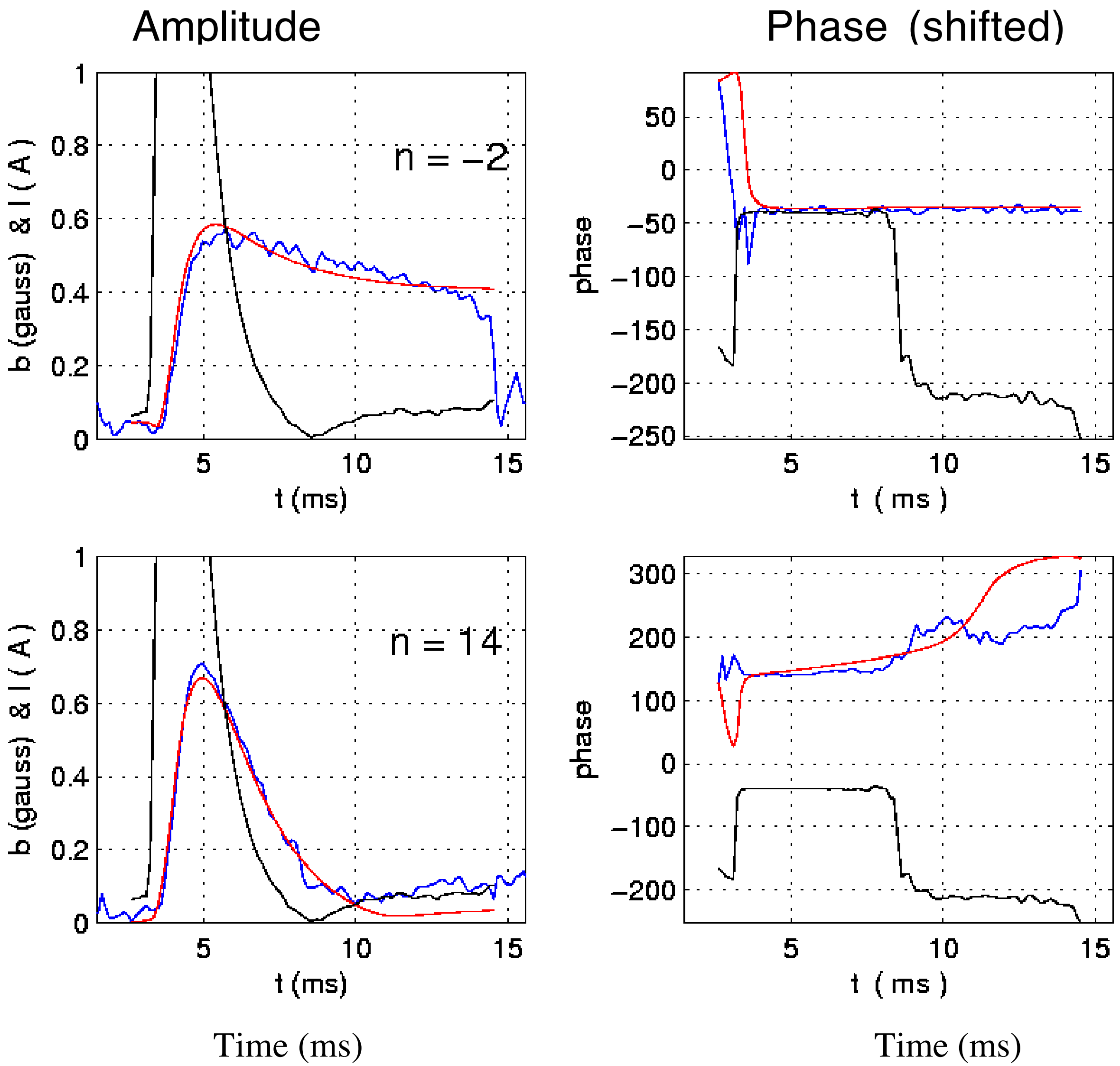


Red =
Best fit simulation with γ_n & M_n *as fitting parameters*

Blue =
(discharge with external perturbation applied)
minus
(reference discharge)

Preprogrammed *pulsed* external control harmonics applied to different modes.

Harmonics for a *marginally stable* mode (n= -2) & a stable mode (n=+14)



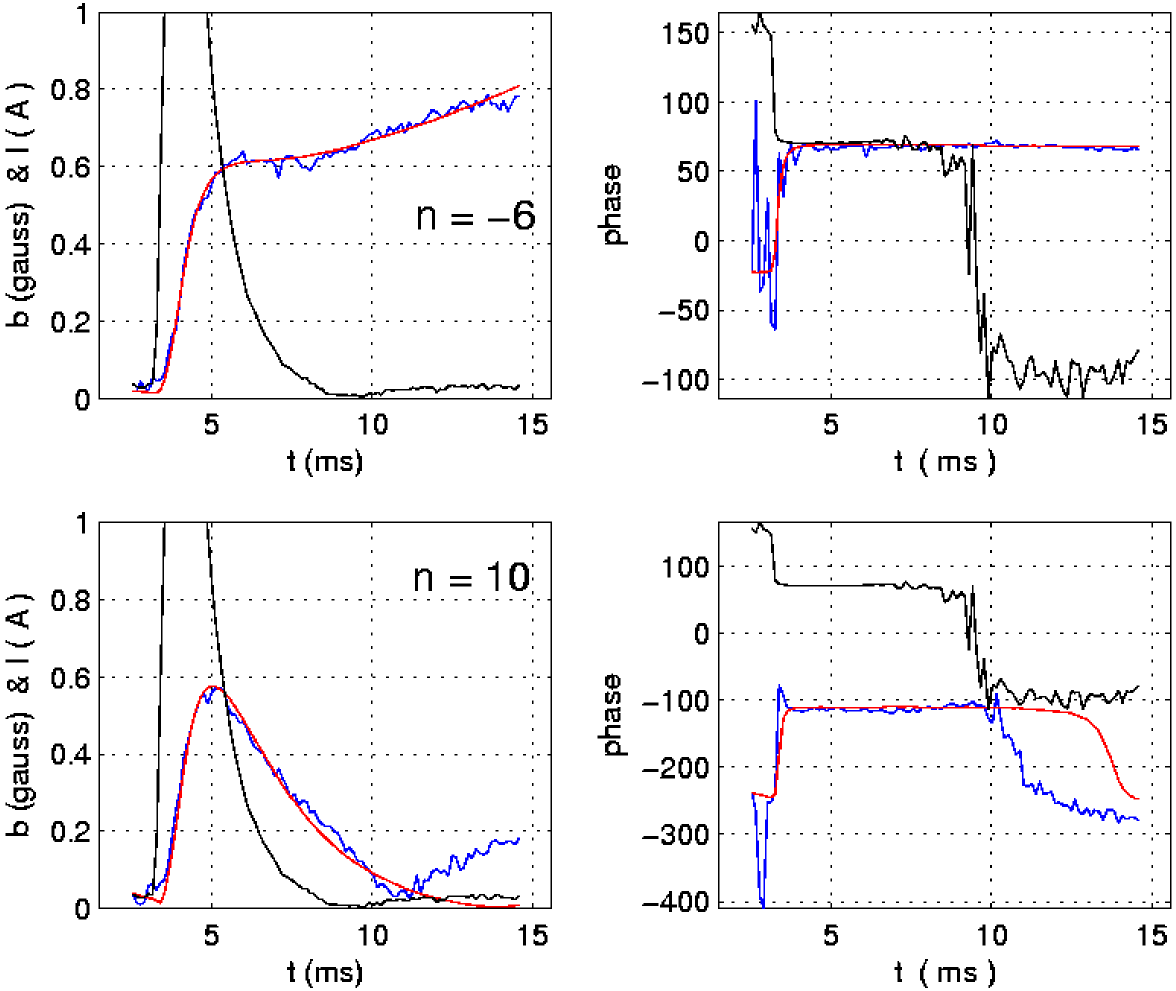
Red =
Best fit simulation with γ_n & M_n *as fitting parameters*

Blue =
(discharge with external perturbation applied)
minus
(reference discharge)

Preprogrammed *pulsed* external control harmonics applied to different modes.

Harmonics for another *unstable* mode (n= -6) & a stable mode (n=+10)

Amplitude Phase (shifted)



Time (ms) Time (ms)

Red = Best fit simulation with γ_n **&** M_n ***as fitting parameters***

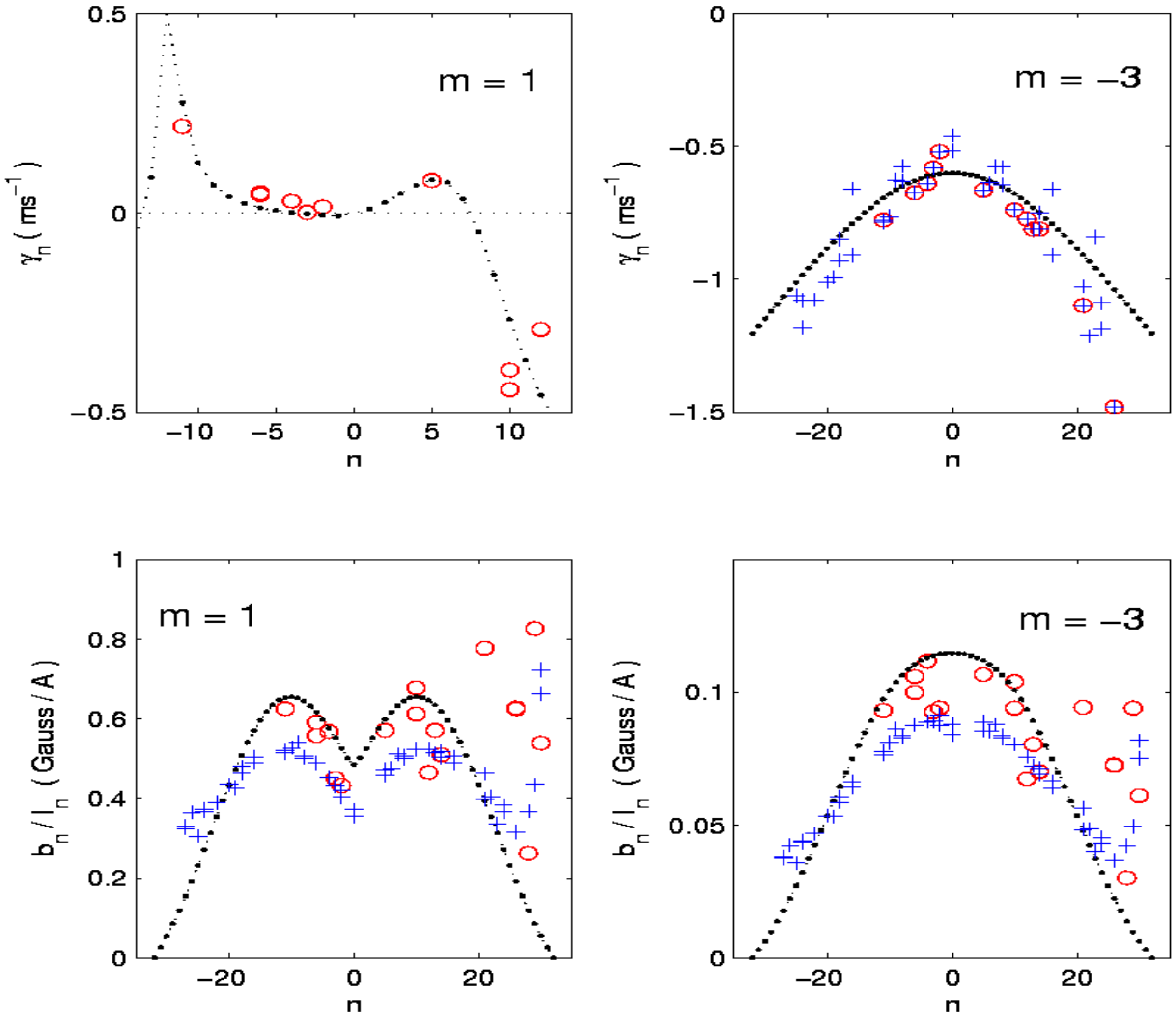
Blue = (discharge with external perturbation applied)

minus

(reference discharge)

Preprogrammed *pulsed* external control harmonics applied to different modes.

Summary of growth (damping) rates and ratio $M = b_n/I_n$ determined from best fit to measured data.



Note!

Red "o" are values for cases with plasma & control harmonic

Blue "+" are values for control harmonic in vacuum

The mutuals,
$M_n = b_n/I_n$,
should be the same for best fit to vacuum data and to plasma data.

(Higher m numbers must be included to model current in saddle coils.)

Summary

Modeling of open loop control experiments in EXTRAP T2R RFP using the well known form:

$$d_t b_{m,n} = \gamma_{m,n} b_{m,n} - \gamma_{m,n,w}(M_{m,n}\, I_{m,n} + b_{m,n}^{error})$$

With fitting parameters:

- Growth (damping rates)
- Mutuals (field at sensor coil/current in saddle coil

Give the following values for growth (damping) and inherent error fields:

n	-11	-6	-4	-3	-2	+5
γ(ms^{-1})	0.22+i0.15	0.05	>0.02	<0.01	<0.02	0.08+i0.03
b_{err} (mT)		0.013	0.02	<0.01	0.1	
b_{err} (phase)		0°	-145°		45°	