EUROfusion

Design Alternative Vertical Speed Observer in case of Magnetic Probe failure

G.Artaserse

JET

ENEA AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

Fusion Unit EUROfusion

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Outline

- NJOC activities
- JET PPCC System
  - Vertical Stabilization (VS) System : ERFA circuit
  - VS Observer (estimator of plasma vertical position velocity)
- Motivation
  - J1D intervention
  - Design alternative observer
- Test cases
- Magnetic signal failure (effect on VSEL)
- Procedure to design alternative VS observer
- Results
- Conclusion
  - Designed alternative observer due impossibility of J1T intervention
  - Tested during restart

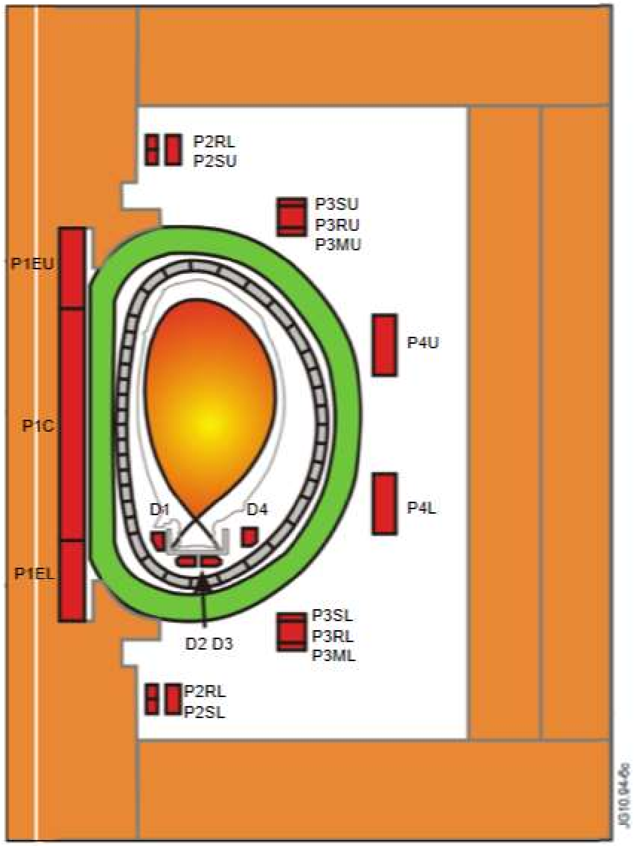
NJOC activity

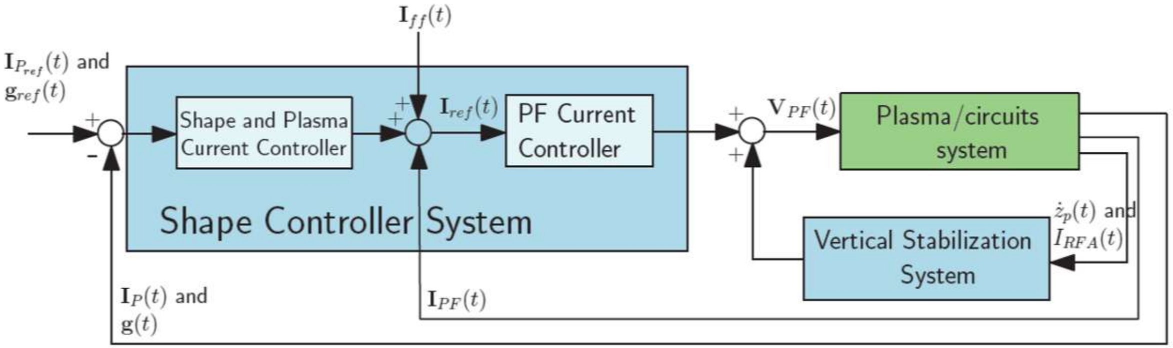
- Skills: Data analysis, control theory, magnetic and thermal modelling, numerical techniques (FEM, DFM),real time process (MARTe framework)
- Joined JET Plasma Operation Group (POG) in September 2014
- Equilibrium reconstruction codes (**Matlab,Python**,C++,Fortran)
  - CREATE NL/L,EFIT,MAXFEA,PROTEUS,XLOC
  - Mesh generator in Matlab (tokamak independent) for FEM,DFM
  - Design magnetic configurations
  - Linearized models for plasma control and predictions
- DRO for WALLS (RT PFC monitoring temperatures, limiter and divertor) :Numerical solving of diffusion problems FEM,DF
- RO for XSC (alternative JET SC, linearized model based)
- SL trainee with more than 60 session
- Since 2016 DRO for magnetics (having the responsibility to monitor the status of about 600 sensors (pick up coils, saddle loops, flux loops,…), maintaining the database of magnetics (geometrical info's, positioning, calibration factors, electrical tests, data acquisition specifications, cubicles maintenance,...), running and designing algorithms to check daily acquired magnetics signals (watchdog, toroidal field compensation, running equilibrium reconstruction codes for analysis – EFIT), integration with plasma control system (shape and vertical position). Beryllium worker trained with pressurized suit
- Since 2019 RO for JET disruption database
- Support to JET experimental campaigns

* DRO = Deputy responsible Officer
* RO = responsible Officer

JET PPCC system

- The JET poloidal field coils system (**PFCs**) is used to control the plasma shape, position and current.
- The overall poloidal system is divided into 10 circuits, each powered by a separate amplifier.
- The control system responsible to control the currents in each circuit is the Plasma Position and Current Control system (**PPCC**) using a *frequency separation approach*
  - Shape Controller system (**SC**) controlling the plasma shape and current in the low frequency domain (500Hz,2ms)
  - VS system (**VS**): stabilizing the plasma vertical position in the high frequency range (20kHz).

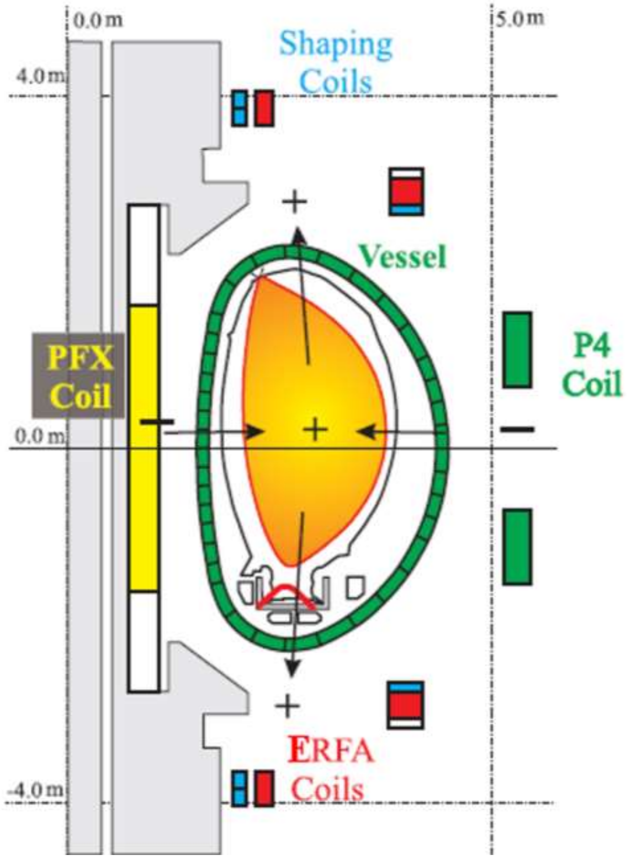




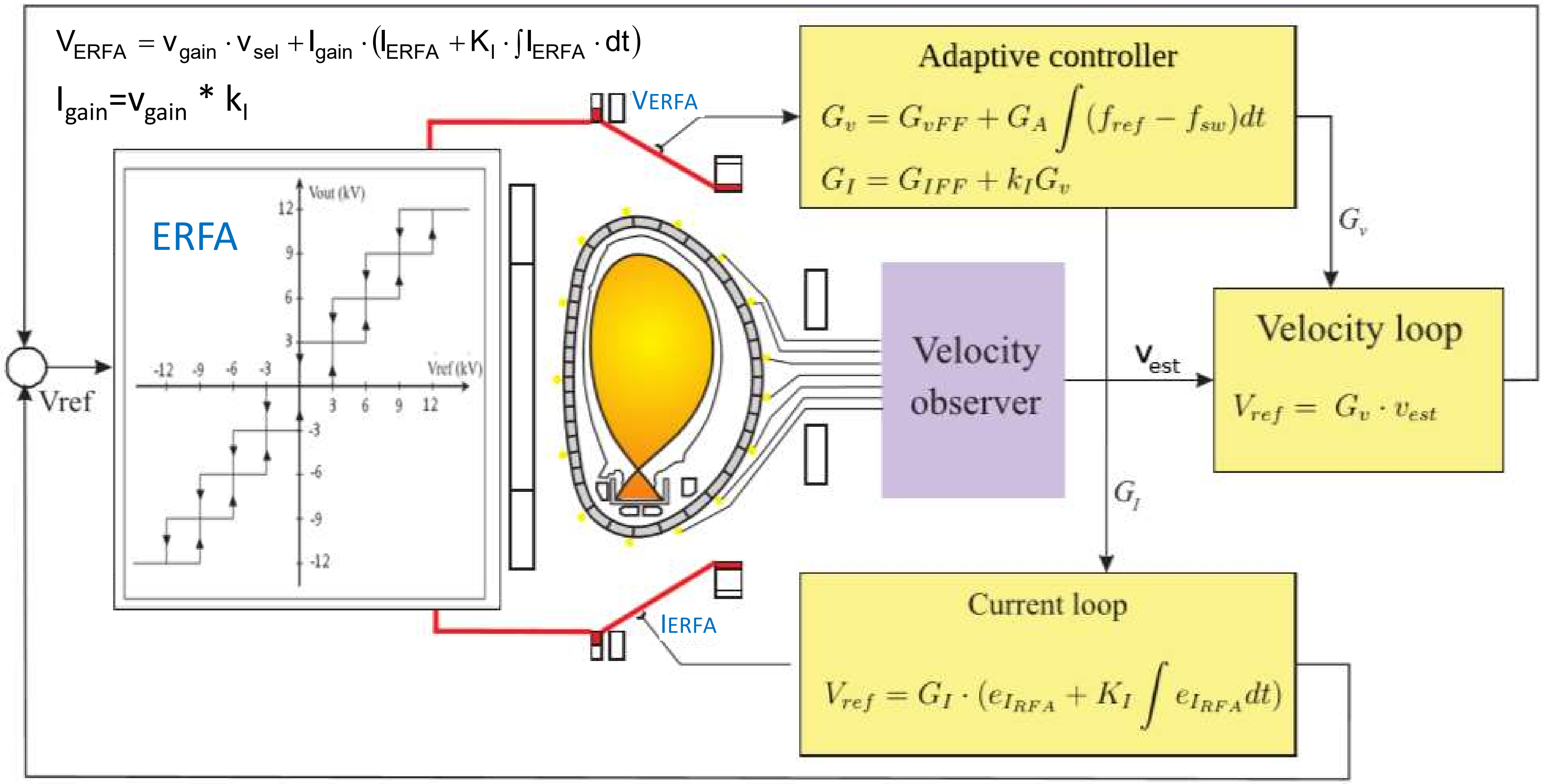
Simplified block diagram of the JET PPCC system.

JET VS

- **Elongated plasmas**, such as those experienced at JET, present a vertical instability that can lead to a sudden termination of the plasma experiment and could cause significant damage to the vacuum vessel and supporting structures.
- This event is normally referred to as a **Vertical Displacement Event (VDE)** and it is the task of the VS system to avoid its occurrence.
- The instability growth rate changes depending on the plasma elongation, where more elongated plasmas present a higher instability time constant.
- The overall effect of the poloidal field circuits is to create currents of the same sign as the plasma current on the top and bottom of the plasma (Shaping circuit) and of the opposite sign on the inner and outer sides of the plasma (PFX and P4 circuits), so modifying the **plasma elongation** (ratio between vertical and horizontal dimension of the cross section) and **triangularity** (geometric parameter for D-shaped plasmas)
- The attraction forces between the upper (or the lower) shaping coils and the plasma increase as the distance decreases. Therefore, a vertical movement of the plasma in either direction increases the attraction force (in the same direction), hence triggering a vertical instability.
- The **vertical stabilization system** uses the **ERFA** (Enhanced Radial Field Amplifier) circuit to **counteract the plasma movement by keeping the average of the estimated plasma vertical speed to zero** $\dot{z}_p = 0$ (*not used to control the plasma vertical position*).
- IERFA constant, **IERFA = Iref**
- ERFA: connect in series some turns of the P2 and P3 coils, namely P2R and P3R, which are connected to create a mainly radial field. The radial field circuit is powered by a 5 kA-12kV IGBT amplifier.



JET VS (ERFA)



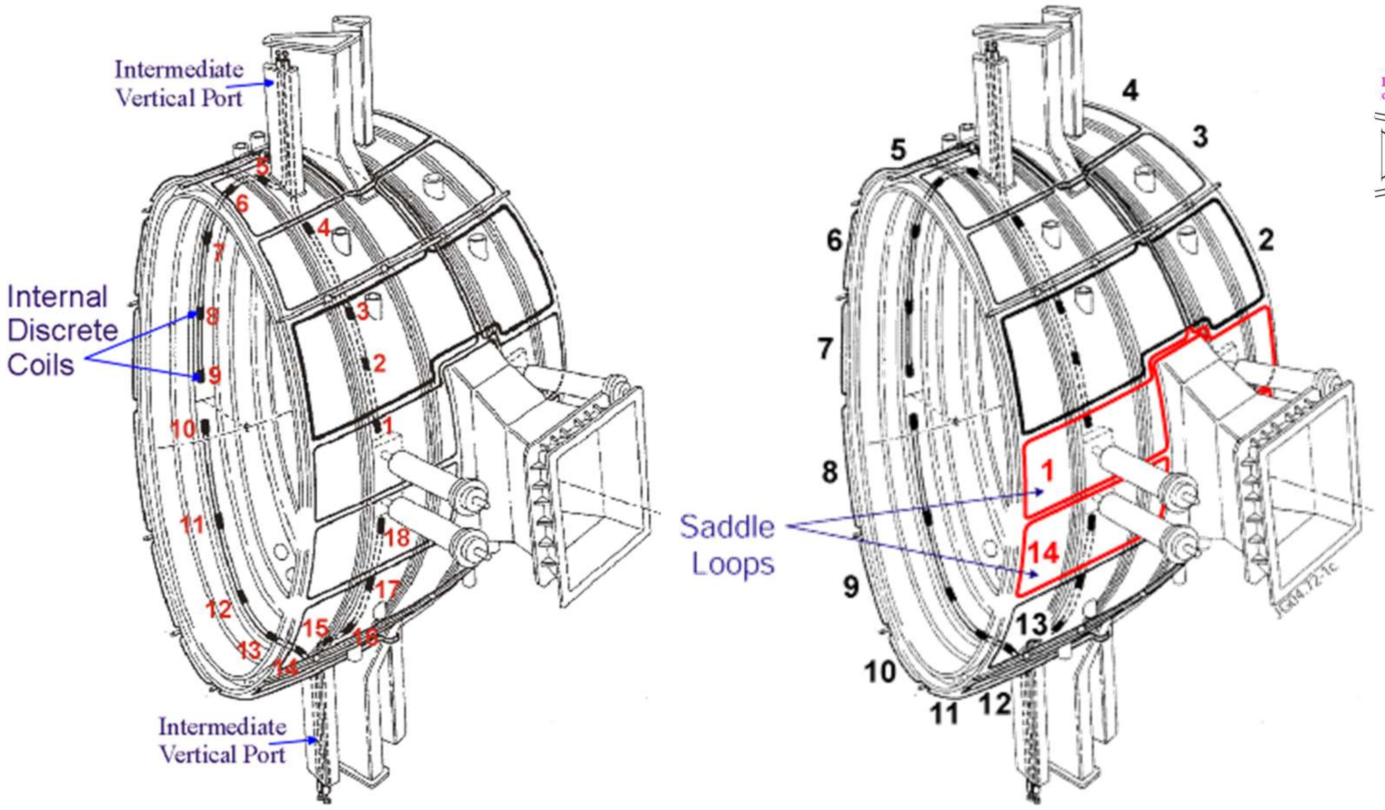
- The information about the plasma position and his velocity v_{est} (and shape) also known as **Velocity Observer** (VSEL) used as **feedback quantity by the stabilization system**, is obtained by using a set of magnetic measurements located at different toroidal and poloidal positions.
- Depending on the quantity to be estimated, the magnetic measurements are integrated over time to produce a local measurement of the magnetic field and magnetic flux, or used non-integrated to measure the time derivatives of the magnetic field and flux.

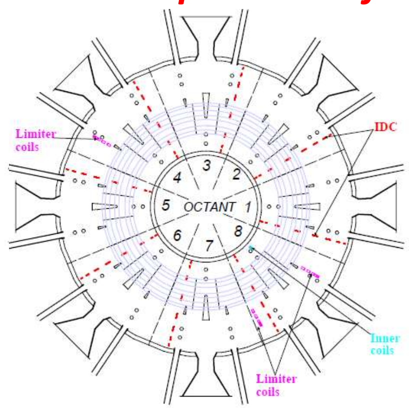
VS Observer (VSEL)

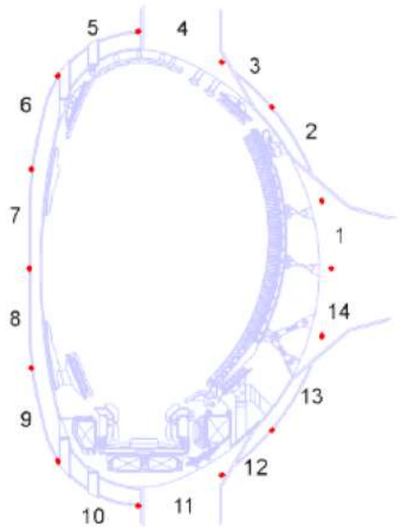
VS use 32 magnetics signals to estimate VSEL

- 18 pick up coils [Mirnov Coils](oct. 1,3,5,7)
- 14 saddle loops (oct. 1,3,5,7)

Data digitized @ 2MHz, JPF @ 20kHz
Voltages (not integrated signals)
Contains already NA and n=2 compensation factor







JET

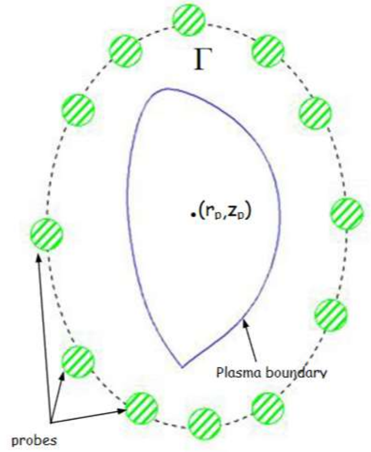
VS Observer (VSEL)

- The VS system uses **18** poloidal field measurements provided by the IDC tangential, situated inside the vacuum vessel, and **14** saddle loops measuring the average normal field to estimate the **plasma vertical speed** (correlated to the unstable mode), which is used as the feedback quantity by the stabilization system.
- The technique that is used to compute the plasma vertical speed is derived from the **current moment method** initially by Zakharov and later revised by Aikawa and Ogata

$$\frac{d(Z_c I_\phi)}{dt} = \frac{1}{\mu}\oint_l \left[z\frac{dB_t(r,z)}{dt} - r\log\left(\frac{r}{R_0}\right)\frac{dB_n(r,z)}{dt}\right] dl$$

$$\frac{d(z_p)}{dt} I_p \approx \sum_{i=1}^{18} a_i \frac{dB_t(r,z)}{dt} + \sum_{i=1}^{14} b_i \frac{dB_t(r,z)}{dt} - \frac{d(I_p)}{dt} z_p - z_{pass}\frac{d(I_{pass})}{dt}$$

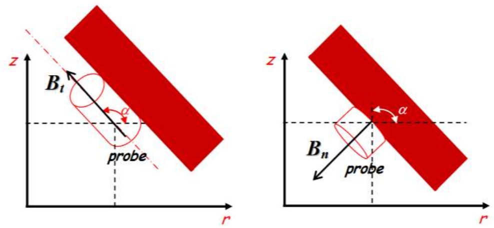
$$z_{pass}\frac{d(I_{pass})}{dt} = \sum_{i=1}^{4} z_D(i)\frac{d(I_D(i))}{dt} - z_{rr}\frac{d(I_{rr})}{dt} - z_{mkII}\frac{d(I_{mkII})}{dt}$$



VSEL

$$\frac{dI_P}{dt} = \frac{1}{\mu}\oint \frac{dB_t}{dt} ds \approx \sum_{k=1}^{Nmag} w_{0k} m_k$$

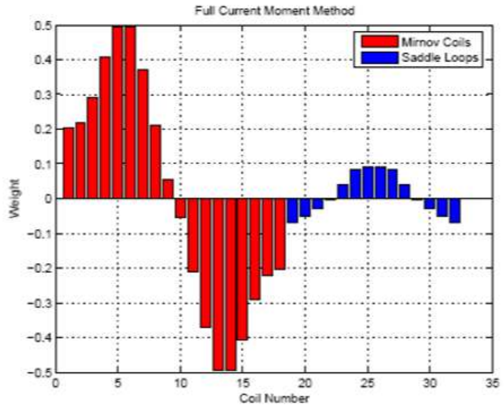
$$\frac{d(Z_P I_P)}{dt} = \frac{1}{\mu}\oint \left[Z\frac{dB_t}{dt} - R\log\left(\frac{R}{R_0}\right)\frac{dB_n}{dt}\right] ds \approx \sum_{k=1}^{Nmag} w_k m_k$$

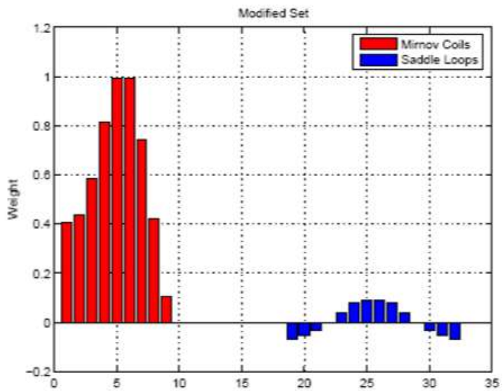


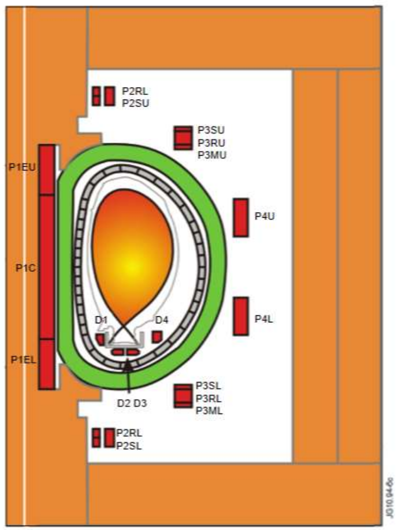
- The observer (VSEL) is a linear combination of magnetics m_k by suitable weights w_k

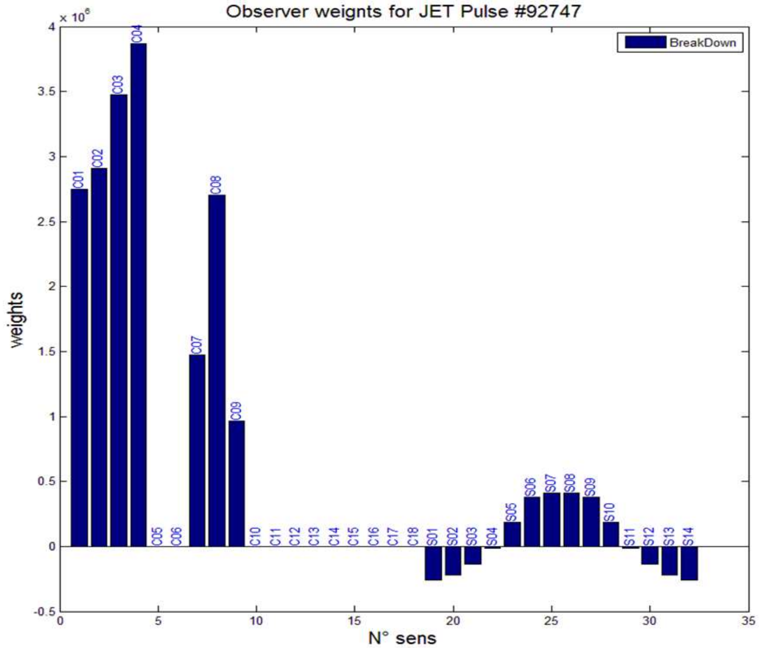
VS Observer (VSEL)

- After installation of D1-D4 divertor currents and MKII conducting structure inside the vessel, the magnetic signals in the lower part of the machine were significantly affected not only by the passive currents but also by the noise amplifiers, so the weights were readjusted
- VSEL inaccurate but still correlated with the unstable mode
- For ITER-like wall (ILW) was required better design to cope with:
  - **VDE** (same sensitivity to the unstable mode),
  - Insensitive as much as possible to the **ELMs**





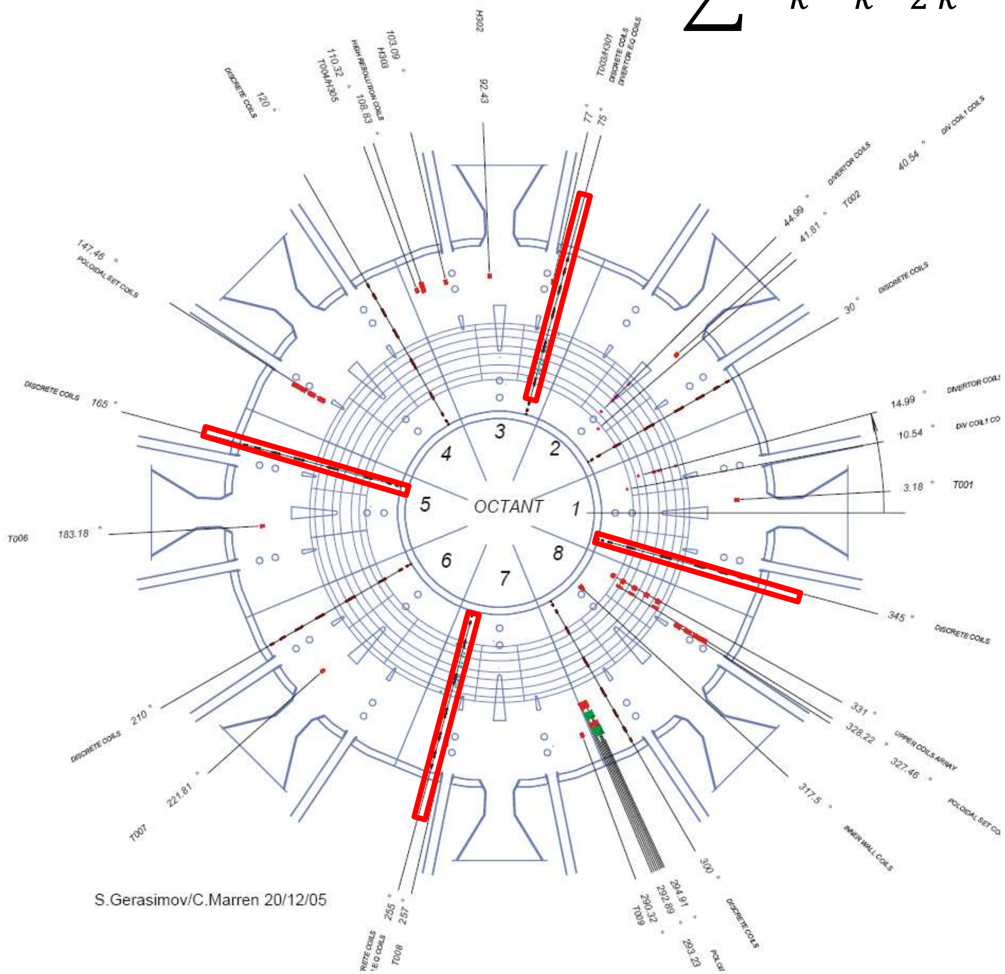


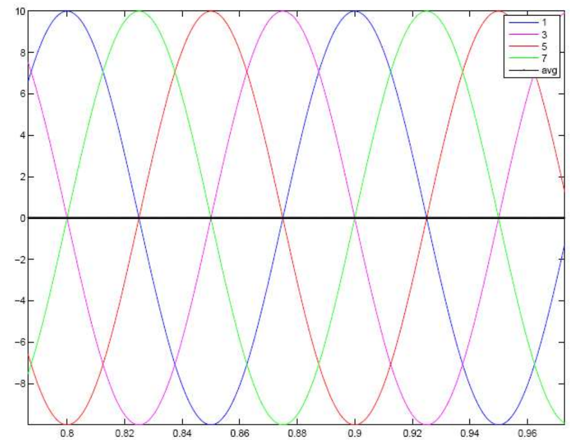


$$VSEL = \sum_{i=1}^{N_{sens}} w_i M_i$$

VS Observer (VSEL)

- N2 geometrical compensation by ***N2k*** coefficients (less than 1° of correction to respect the ideal location) $\sum w_k m_k N_{2\,k}$





ideal case, sin waveform phase shifted by 90°

A generic MHD DISTURBANCE can be Modelled as additional component to magnetic measurements

$$D_{m,n} = Re\left\{A\, e^{j2\pi f t}\, e^{jn\varphi}\, e^{jm\theta}\right\}$$

φ : TOROIDAL ANGLE

θ : POLOIDAL ANGLE

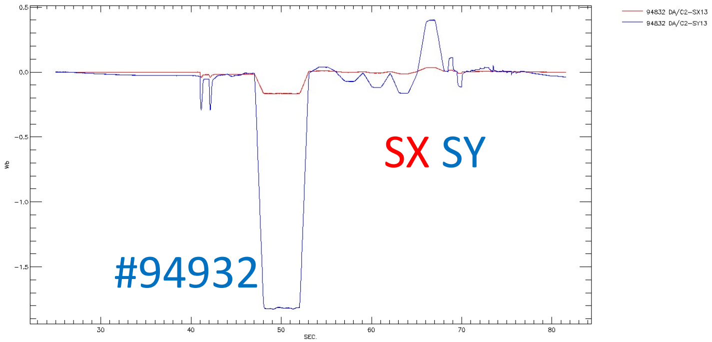
To eliminate n=2 components on measurements apply AVERAGE in 4 IDENTICAL POLOIDAL LOCATION DISPLACED TOROIDALLY BY 90°

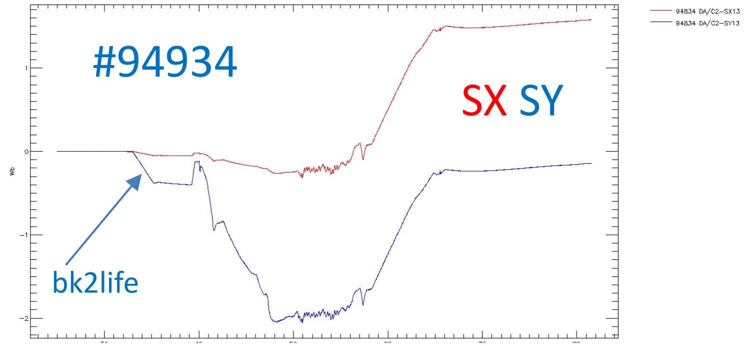
The RESULTING MHD NOISE CAN BE MODELLED AS:

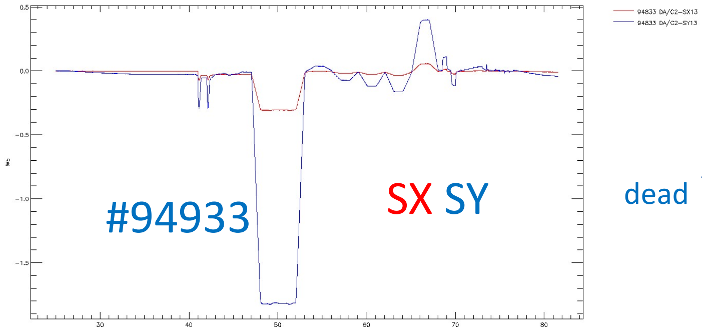
$$D_{m,n} = Re\left\{A\, e^{j(2\pi f t + m\theta)} \cdot \underbrace{\left[1 + e^{jn\pi/2} + e^{jn\pi} + e^{jn\frac{3}{2}\pi}\right]}_{0}\right\}$$

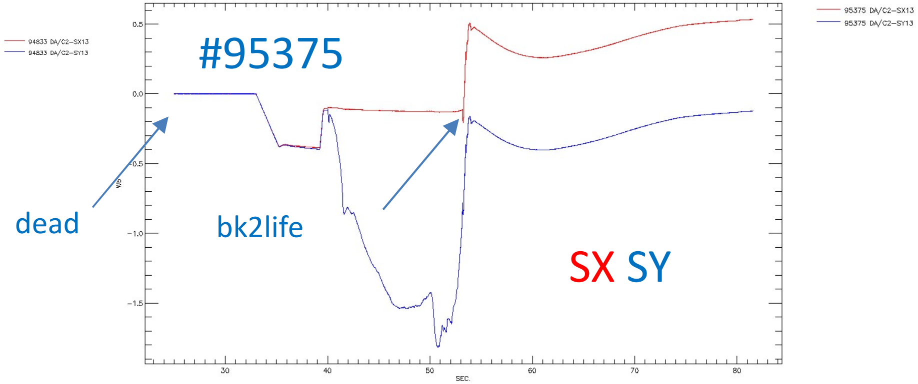
Motivation

- #94932:34 **KC1D symmetry check** between C2-SX13(oct.3) and C2-SY13(oct.7) failed due failure of signal from saddle #13 from oct.3 [#94932,33 dry run, #92934 plasma run]
- Back to life in #92934 @50s but failed again in the middle of #95375 (plasma run)









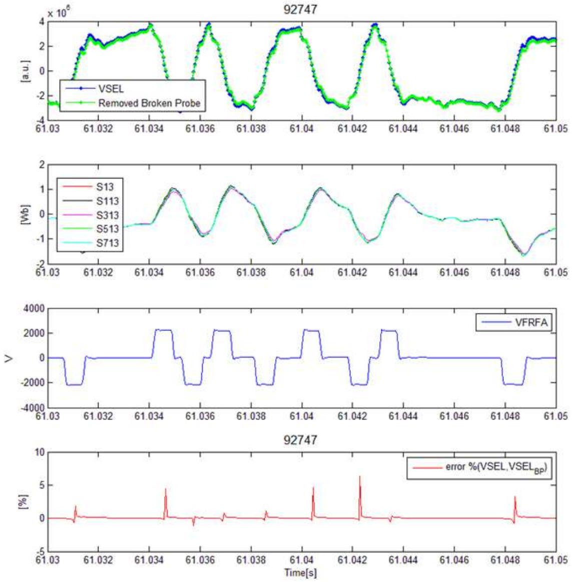
Because saddle loop #13 is used by the VS to compute the plasma vertical position velocity (observer VSEL), is **recommended to find an alternative solution in case of future failure**….

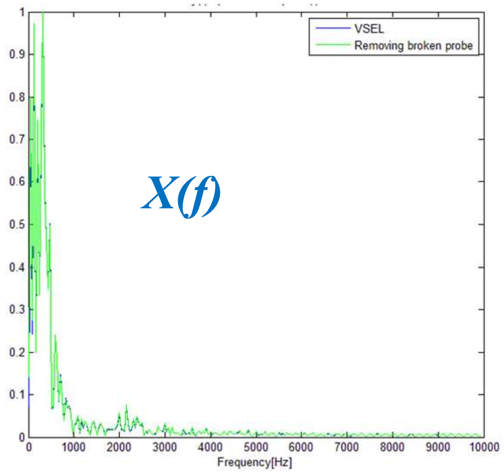
- **Study effects** on observer computation excluding a signal from broken magnetic
- **Design** a new observer with a reduced set of magnetics (**due lack of torus hall intervention time**)

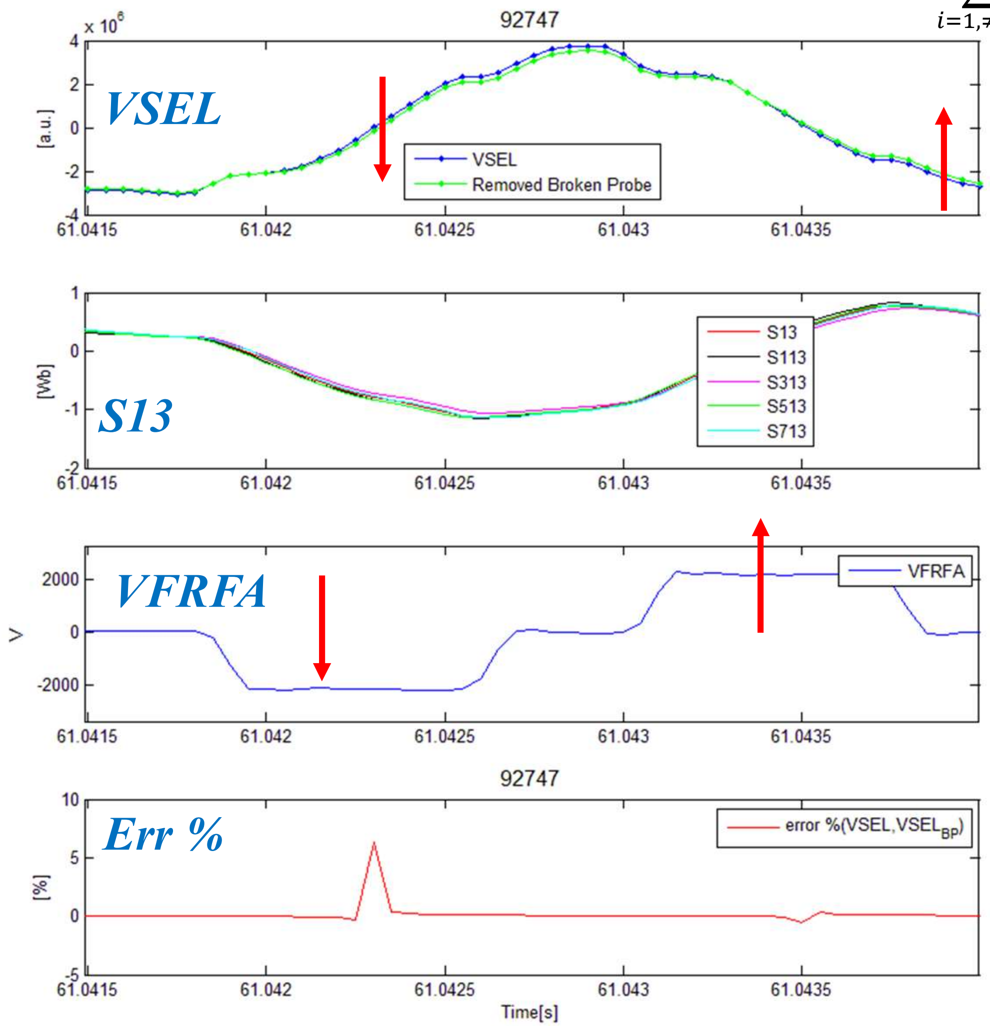
Failure of magnetic signal (effect on VSEL)

#92747,V5 commissioning 2018,Mode D, very high growth rate γ=1400 1/s

$$VSEL = \sum_{i=1,\neq BP}^{N_{sens}} w_i M_i$$



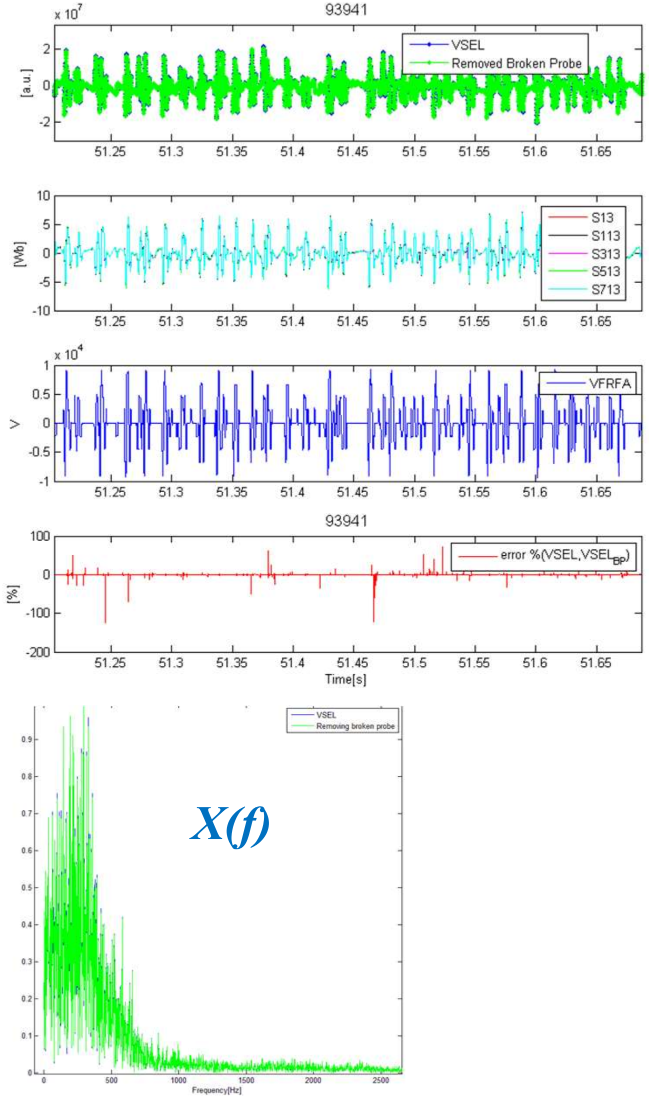


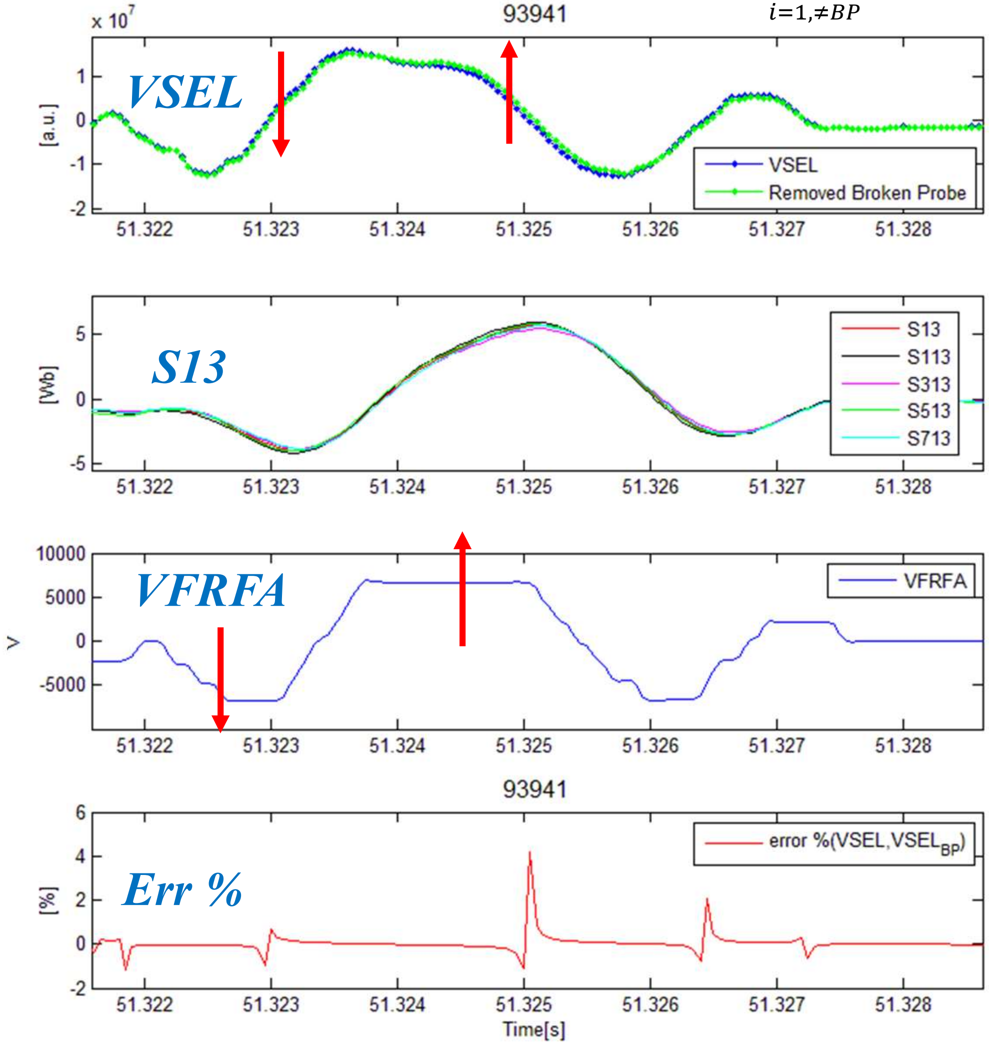


Failure of magnetic signal (effect on VSEL)

#93941,V5 commissioning 2019,Mode D, ERFA kicks

$$VSEL = \sum_{i=1,\neq BP}^{N_{sens}} w_i M_i$$





Procedure to design alternative VS observer

Constrained Least Square Problem (Lagrange Method)

$$\begin{cases} min_w \; \|M_R w - VSEL\|^2 \\ s.t. \quad Cw = w_R \end{cases}$$

where: $M_R(m \times n), w(n \times 1), VSEL(N_T \equiv m \times 1), C(p \times n), w_R(p \times 1), N_T \equiv m >> n$

$$M_R = \begin{bmatrix} & \dots & \dots & \end{bmatrix}, w_R = \begin{bmatrix} \vdots \\ \vdots \end{bmatrix}, R = \{1{:}n \equiv N_{MAG}, n \neq i_{BP}\}, C = \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & \ddots & \\ & & & 0 \end{bmatrix}$$

Row to penalize to Spread optimization error (on S12 and S14 the S13 surroundings)

Via Lagrange Multiplier

$$\mathcal{L}(w,\lambda) = \|M_R w - VSEL\|^2 + \lambda^T(Cw - w_R) =$$
$$= (M_R w - VSEL)^T(M_R w - VSEL) + \lambda^T(Cw - w_R) =$$
$$= w^T M_R^T M_R w - 2VSEL^T M_R w + w^T C^T \lambda - \lambda w_R^T$$

where: $\lambda(p \times 1)$

Solution comes from solving a set of linear equations (optimal conditions) solved by QR regularization

$$\begin{cases} \left.\dfrac{\partial \mathcal{L}}{\partial w}\right|_{(\hat{w},\hat{\lambda})} = 2M_R^T M_R \hat{w} - 2M_R^T VSEL + C^T \hat{\lambda} = 0 \\ \left.\dfrac{\partial \mathcal{L}}{\partial \lambda}\right|_{(\hat{w},\hat{\lambda})} = C\hat{w} - w_R = 0 \end{cases}$$

Procedure to design alternative VS observer

Matricial form of *(n+p)* linear equations

$$\begin{bmatrix} 2M_R^T M_R & C^T \\ C & 0 \end{bmatrix} \begin{bmatrix} \widehat{w} \\ \hat{\lambda} \end{bmatrix} = \begin{bmatrix} 2M_R^T VSEL \\ w_R \end{bmatrix}$$

$$\begin{bmatrix} \widehat{w} \\ \hat{\lambda} \end{bmatrix} = \underbrace{\begin{bmatrix} 2M_R^T M_R & C^T \\ C & 0 \end{bmatrix}^{-1}}_{KKT\ matrix} \begin{bmatrix} 2M_R^T VSEL \\ w_R \end{bmatrix}$$

If $\xi = \hat{\lambda} - 2d$

$$\begin{cases} 2(M_R^T M_R + C^T C)\widehat{w} + C^T \xi = 2M_R^T VSEL \\ C\widehat{w} = w_R \end{cases}$$

Via QR factorization

$$\begin{bmatrix} M_R \\ C \end{bmatrix} = QR = \begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} R \qquad \Rightarrow M_R = Q_1 R, C = Q_2 R$$

$$(M_R^T M_R + C^T C) = R^T R$$

JET

Procedure to design alternative VS observer

$$\begin{cases} R\hat{w} + \dfrac{Q_2^T}{2}\xi = Q_1^T VSEL \\ Q_2 Q_2^T \xi = 2 Q_2 Q_1^T VSEL - 2 w_R \end{cases}$$

Via Q_2^T QR factorization $Q_2^T = \tilde{Q}\tilde{R} \Longrightarrow \tilde{R}\xi = 2\tilde{Q}^T Q_1^T VSEL - 2\tilde{R}^T w_R$
$\tilde{R}$ not invertible (is a rectangular matrix) $\Longrightarrow W = \tilde{R}^T\tilde{R}$ became square matrix and is invertible

$$\xi = 2W^{-1}\tilde{R}^T \underbrace{\tilde{Q}^T Q_1^T}_{Q_2} VSEL - 2W^{-1} w_R$$

$$\xi \Longrightarrow \hat{\lambda} \Longrightarrow \hat{w}$$

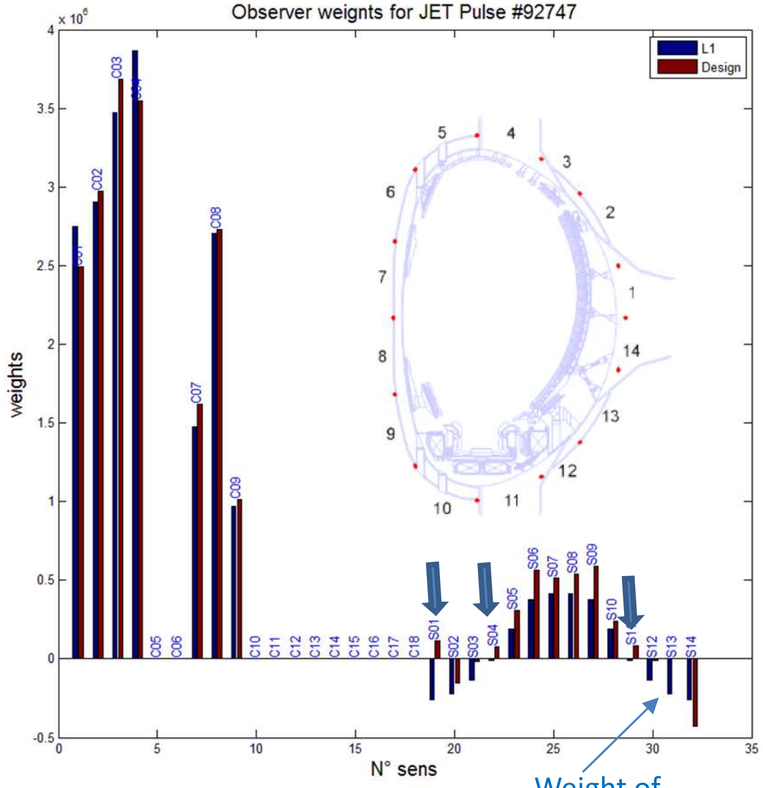
$$\begin{cases} \hat{\lambda} = \xi + 2d \\ \hat{w} = -\dfrac{1}{2}(M_R^T M_R)^{-1} C^T \hat{\lambda} + (M_R^T M_R)^{-1} M_R^T VSEL \end{cases}$$

Results

- New weights designed (MatLab procedure easily can be exported to Python) with Lagrange Multiplier method using experimental data (magnetic signals) from shot #92747

	x1e6		x1e6
C01	2.74941207450000		2.49169834050850
C02	2.90651026120000		2.97310778948487
C03	3.47238882900000		3.68410965449707
C04	3.86704936800000		3.54867602955755
C05	0		0
C06	0		0
C07	1.47583286760000		1.61897813373165
C08	2.70328563960000		2.73207517541790
C09	0.96777456230000		1.01083296961210
C10	0		0
C11	0		0
C12	0		0
C13	0		0
C14	0		0
C15	0		0
C16	0		0
C17	0		0
C18	0		0
S01	-0.25668536687430	**S01** →	0.11467600026557
S02	-0.22305792521740		-0.15185337011154
S03	-0.13783188055000		-0.01370280609752
S04	-0.01253017220000	**S04** →	0.07992642642762
S05	0.18795256025000		0.30891295027728
S06	0.37590512050000		0.56440443443960
S07	0.41349563710000		0.51335652806887
S08	0.41349563710000		0.54165904611145
S09	0.37590512050000		0.59124959298708
S10	0.18795256025000		0.24186559600010
S11	-0.01253017220000	**S11** →	0.08129901487507
S12	-0.13783188055000		-0.01037795275183
S13	-0.22305792521740	**S13** → Imposed to be 0	0
S14	-0.25668536687430		-0.42511215668902

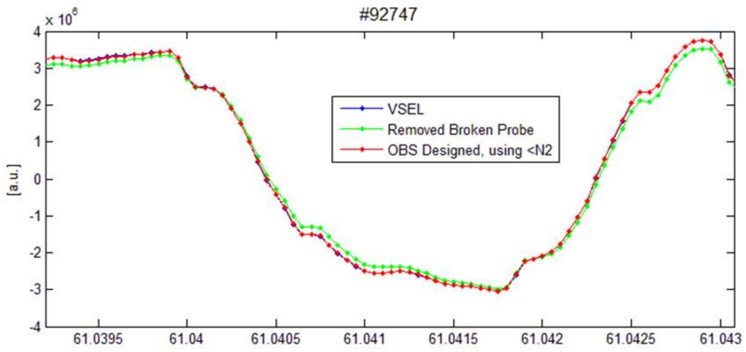
Original Weights — Designed Weights

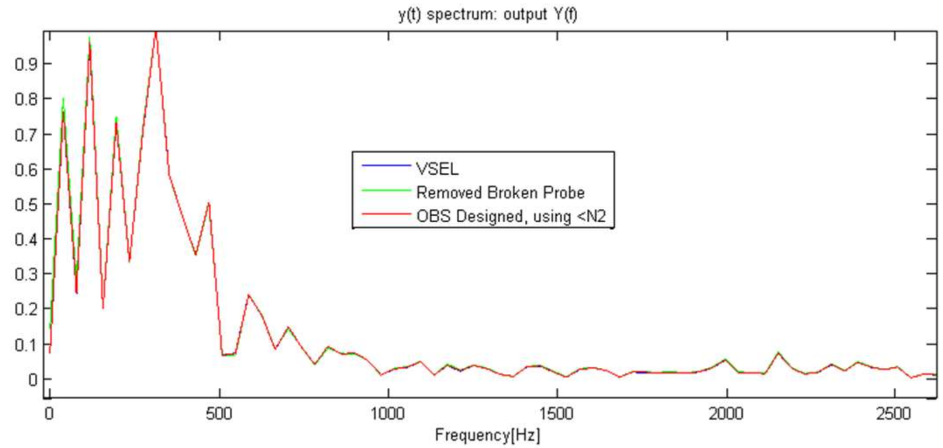


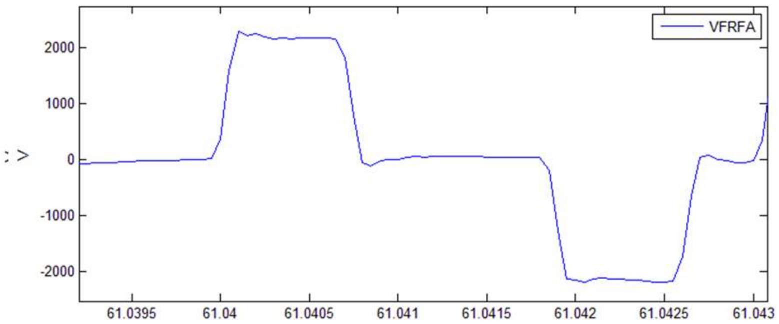
Weight of S13 imposed 0

Results

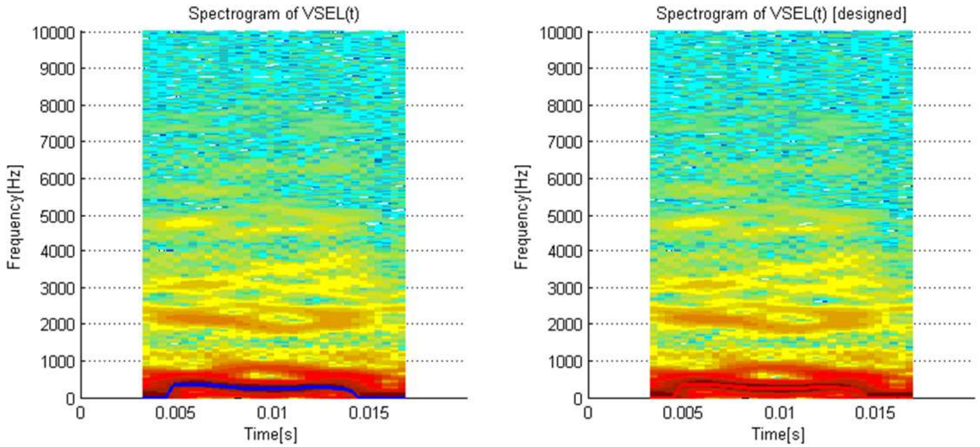
#92747,V5 commissioning 2018,Mode D, very high growth rate γ=1400 1/s







PSD(power spectral density)



In bold periodgram (estimation of PSD)

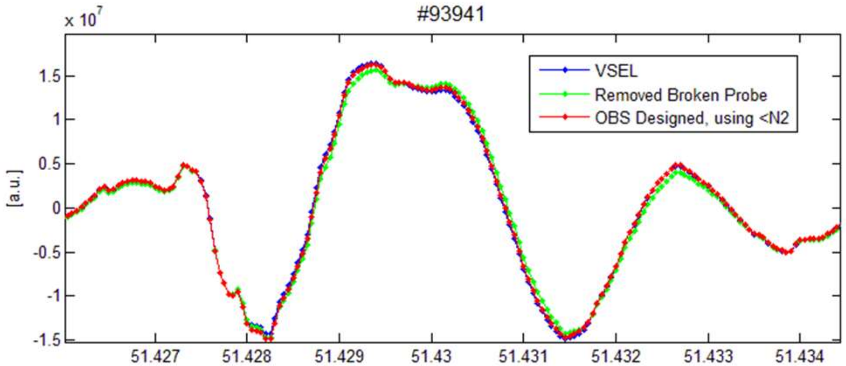
$$\left\|VSEL_{BP} - VSEL\right\|_2 = 3.0986 * 1e6$$

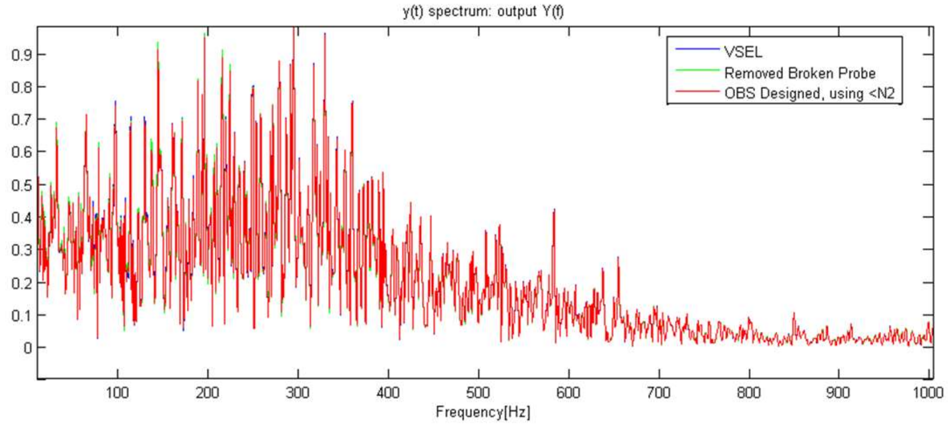
$$\left\|VSEL_{L} - VSEL\right\|_2 = 0.1234 * 1e6$$

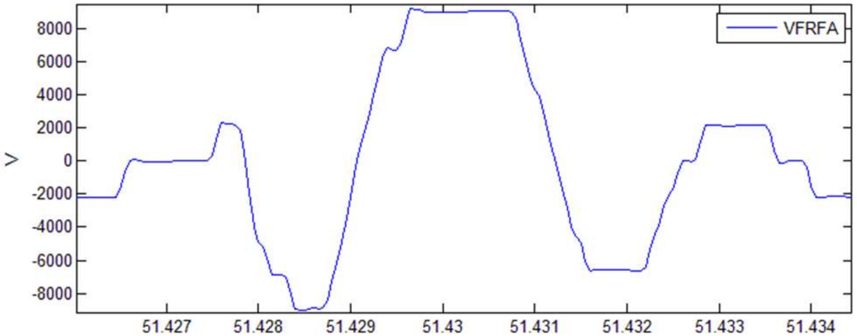
$$\left\|VSEL_{BP} - VSEL\right\|_2 > \left\|VSEL_{L} - VSEL\right\|_2$$

Results

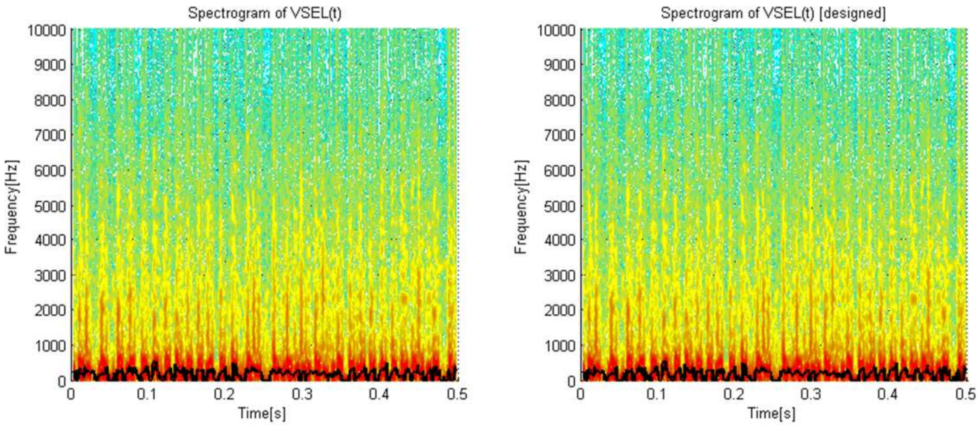
#93941,V5 commissioning 2019,Mode D, ERFA kicks







PSD(power spectral density)



In black periodgram (estimation of PSD)

$$\left\| VSEL_{BP} - VSEL \right\|_2 = 4.3758 * 1e6$$

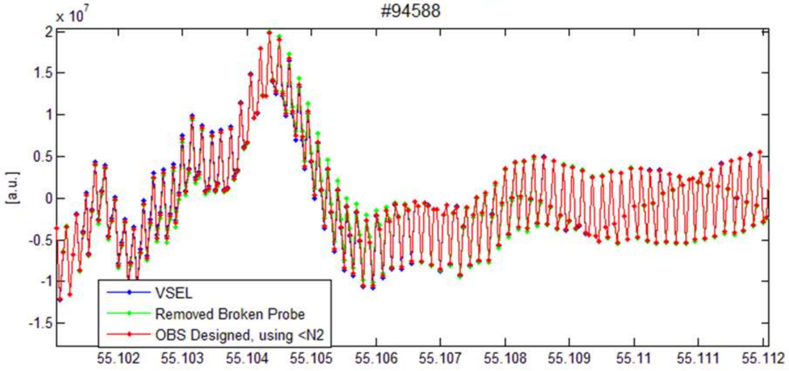
$$\left\| VSEL_{L} - VSEL \right\|_2 = 1.6495 * 1e6$$

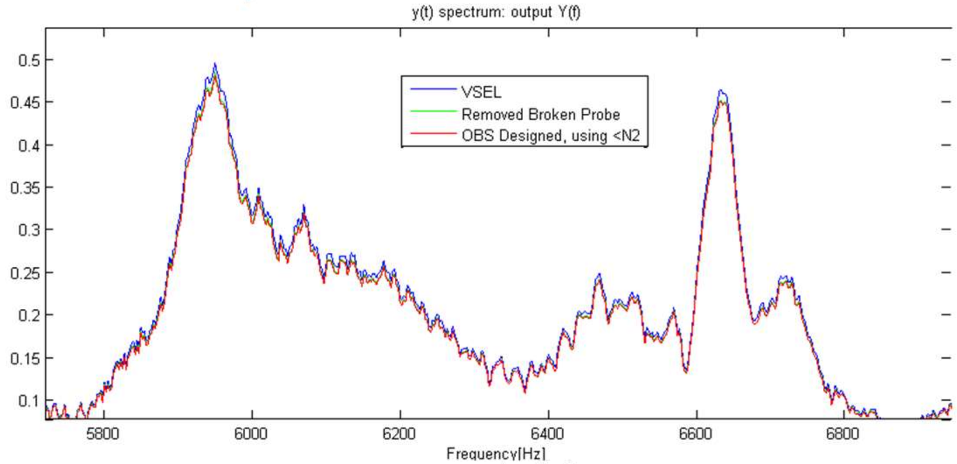
$$\left\| VSEL_{BP} - VSEL \right\|_2 > \left\| VSEL_{L} - VSEL \right\|_2$$

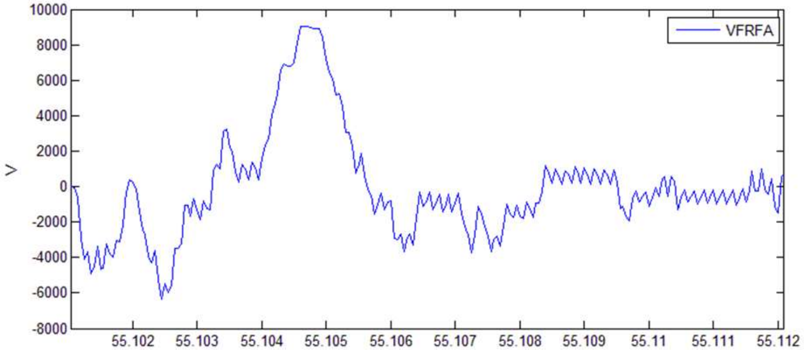
JET

Results

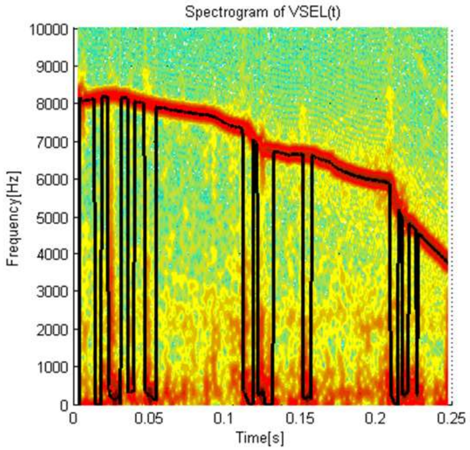
#94588, high n=2 mode @53.92 -> disruption @56.16s

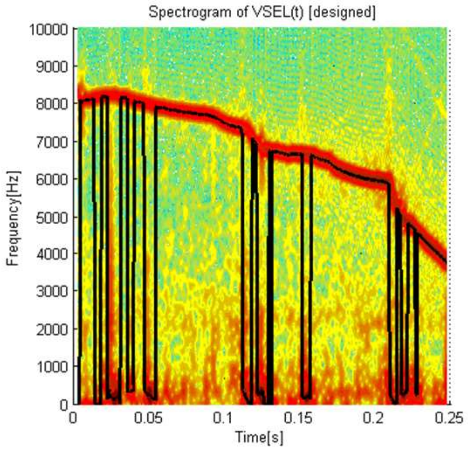






PSD(power spectral density)





In black periodgram (estimation of PSD)

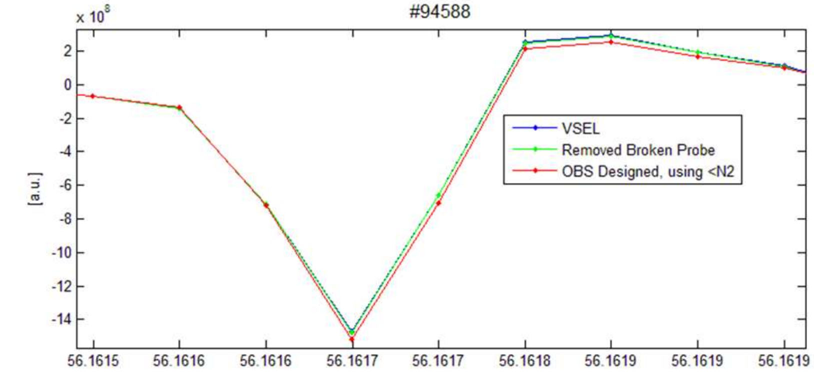
$$\|VSEL_{BP} - VSEL\|_2 = 1.9664 * 1e7$$

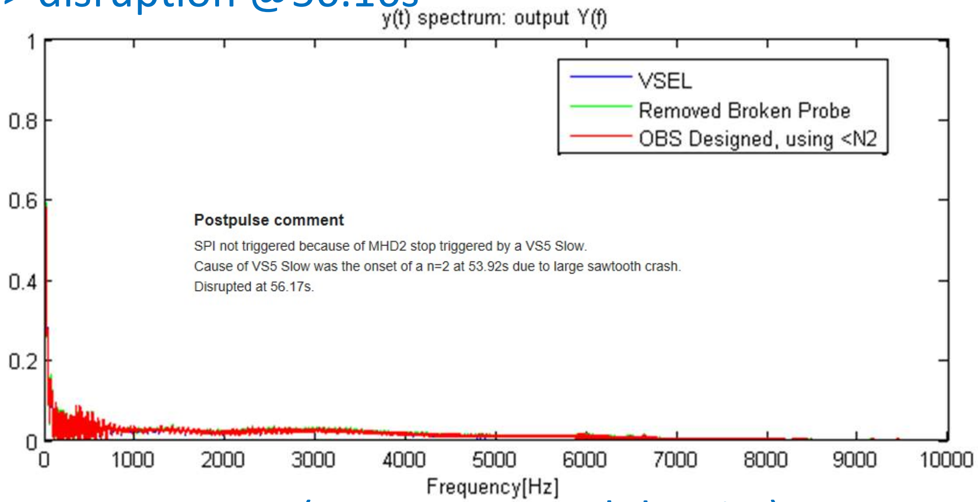
$$\|VSEL_{L} - VSEL\|_2 = 1.0624 * 1e7$$

$$\|VSEL_{BP} - VSEL\|_2 > \|VSEL_{L} - VSEL\|_2$$

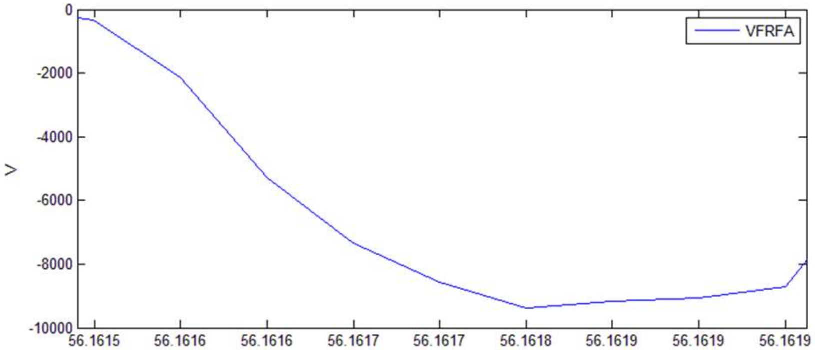
Results

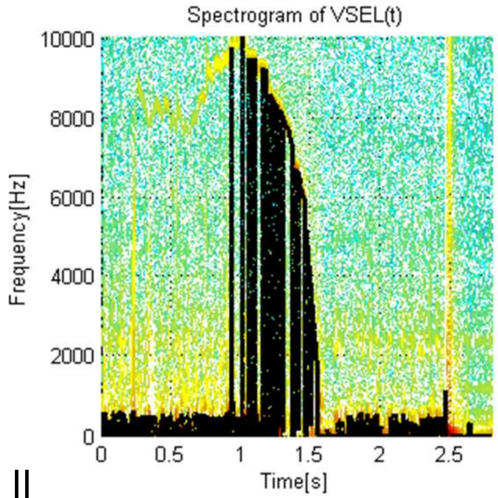
#94588, high n=2 mode -> disruption @56.16s

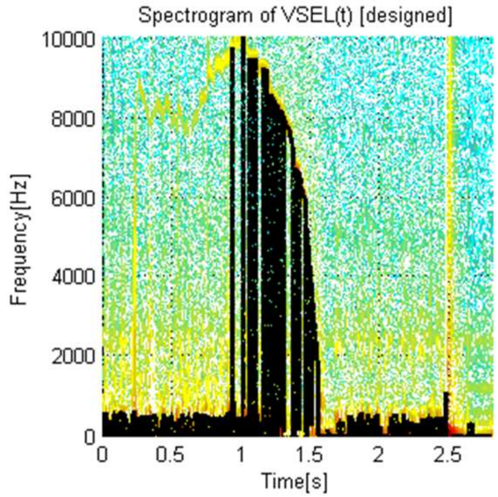




PSD(power spectral density)







$$\left\| VSEL_{BP} - VSEL \right\|_2 = 1.9975 * 1e8$$

$$\left\| VSEL_{L} - VSEL \right\|_2 = 1.1966 * 1e8$$

$$\left\| VSEL_{BP} - VSEL \right\|_2 > \left\| VSEL_{L} - VSEL \right\|_2$$

In black periodgram (estimation of PSD)

JET

Conclusions

- A failure of magnetic probe has impact on the estimation in real time of the vertical stabilization feedback quantity (observer)
  - Recommended a backup solution
  - Not feasible J1T (JET torus hall) intervention (substitution of LEMO cable at the feedthrough) which require scaffolding (1w)
- Designed alternative observer
  - Constrained Least Square Problem based on Lagrange multiplier
- Tested on various JPN, behaving similar to VSEL
  - Time domain
  - Frequency domain
- Alternative observer tested (in observation) during the restart (not in control loop) showing same behaviour of the real-time ones
- In progress: Apply same procedure for others observers (RE, BD)