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Towards real-time S-parameter qualification and macromodeling

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# Towards real-time S-parameter qualification and macromodeling

**Stefano Grivet Talocia**

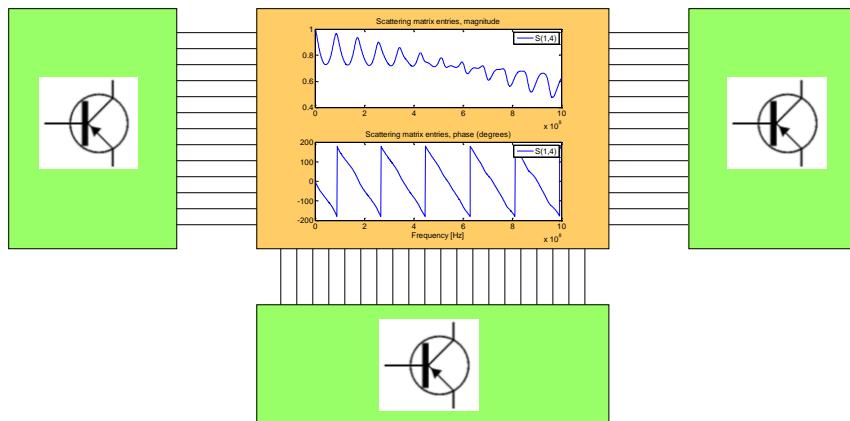
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16<sup>th</sup> IEEE Workshop on Signal and Power Integrity  
IBIS Summit, 16 May 2012, Sorrento, Italy



## The objective

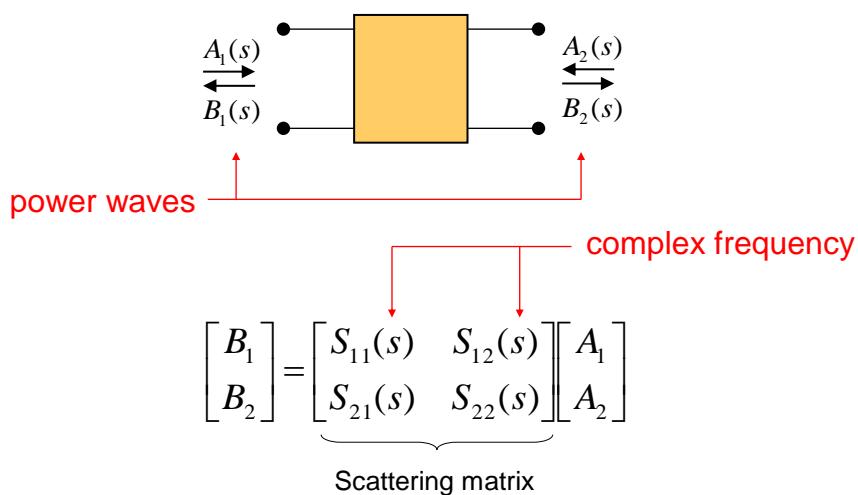
### S-parameter block



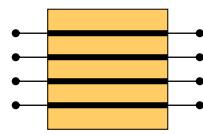
## Why S-parameters

- S-parameters are always defined
  - Impedance or admittance may not
- S-parameters are normalized
  - Good numerical properties in simulation
- S-parameters are easily measured
  - Even at very high frequency, good reliability
- Standard format for S-parameters
  - Touchstone files from measurement hardware
  - All field solvers provide S-parameters on output
- Tabulated frequency data
  - Intrinsic IP protection for vendors
  - Do not disclose design details, but only I/O electrical properties
- Best way to represent broadband EM/circuit interactions
  - The essence of Signal and Power Integrity

## Scattering network functions



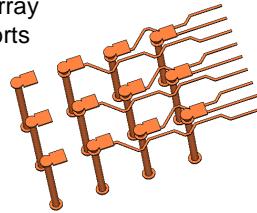
## Examples of S-parameter data



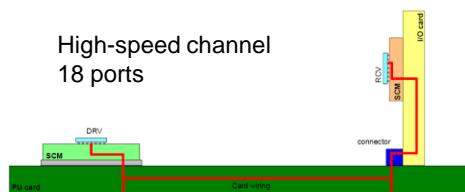
Wiring harness  
8 ports



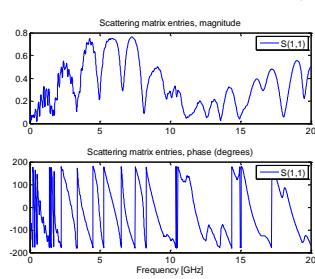
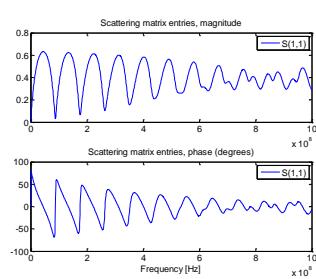
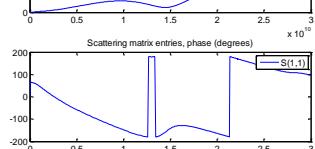
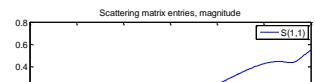
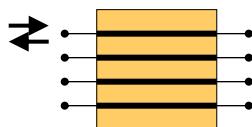
Via array  
12 ports

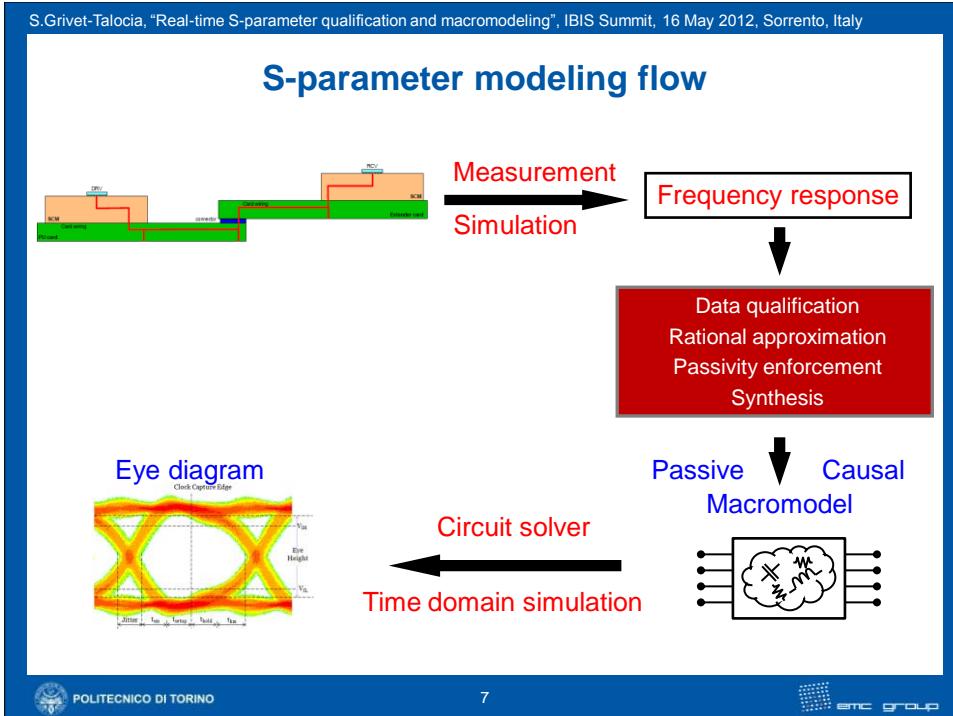


High-speed channel  
18 ports



## Examples of S-parameter data

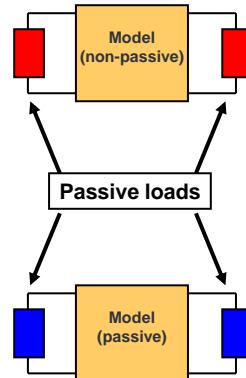
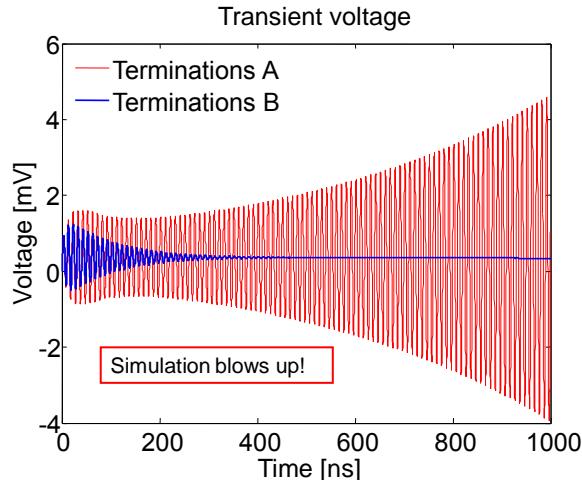




## Part I: qualification

A quick overview

## Passivity: why?



## Passivity

$$\mathbf{S}(-j\omega) = \mathbf{S}^*(j\omega)$$

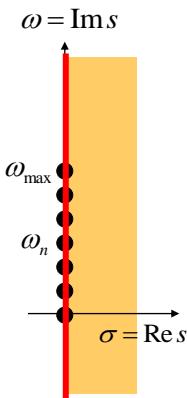
Guarantees real-valued impulse response.  
Always assumed by construction

$$\|\mathbf{S}(j\omega)\| \leq 1 \quad \text{or} \quad \max_i \sigma_i \{\mathbf{S}(j\omega)\} \leq 1$$

Energy condition: structure must not amplify signals.  
Sometimes called simply "passivity" condition

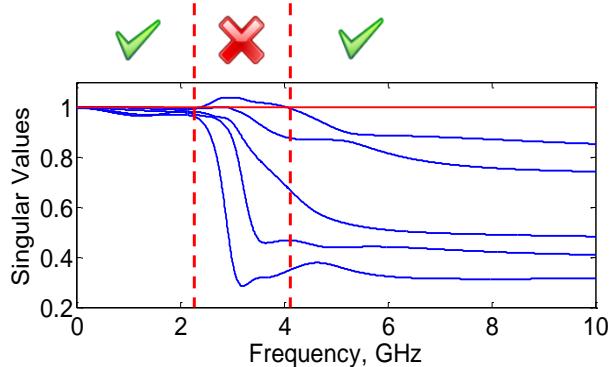
$\mathbf{S}(j\omega)$  is causal

No anticipatory behavior in time-domain.  
Note: causality is a prerequisite for passivity!

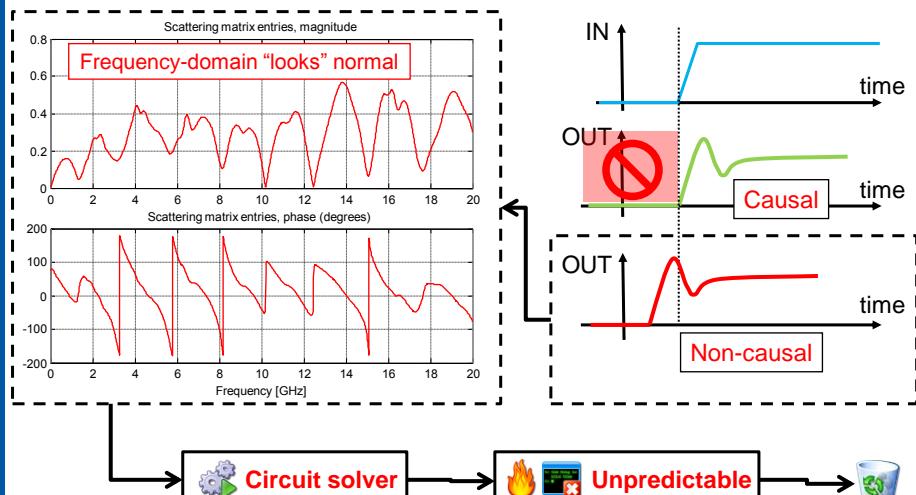


## Passivity

$\mathbf{S}(s)$  is passive  $\Rightarrow \{\text{singular values of } \mathbf{S}(j\omega)\} \leq 1, \forall \omega$

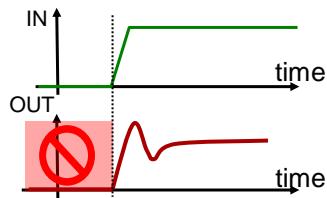


## Causality



## Causality: definitions

### Time-domain



Note: no delay extraction here

### Frequency-domain

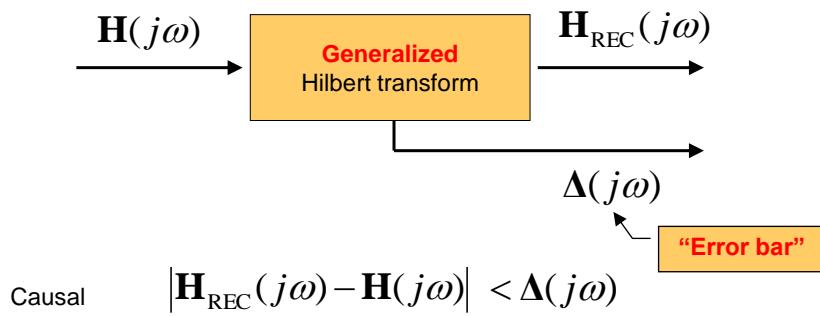
Hilbert transform  
Kramers-Krönig dispersion relations

$$H(j\omega) = \frac{1}{j\pi} \text{pv} \int_{-\infty}^{+\infty} H(j\omega') \frac{d\omega'}{\omega - \omega'}$$

Self-consistency

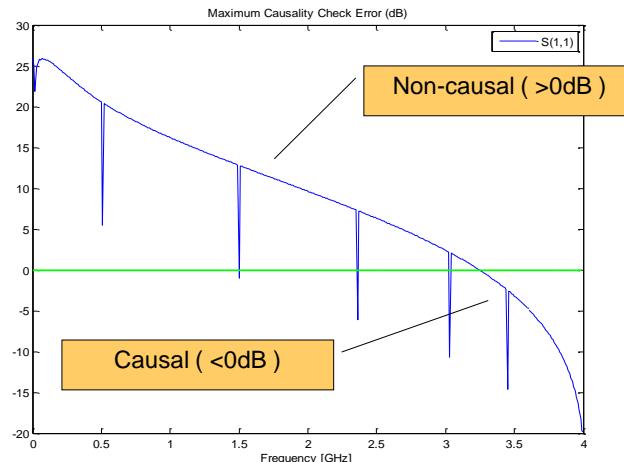
All samples are strongly related

## Causality check



## Causality check error

$$E_{dB}(j\omega) = 20 \log_{10} \frac{|H_{REC}(j\omega) - H(j\omega)|}{\Delta(j\omega)} \quad \text{Computed (parallel) for each scattering response}$$

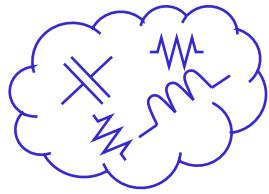


## Part II: macromodeling

An update on recent developments



## Rational function fitting: why?



Circuit solvers understand circuits

Any lumped circuit has rational frequency responses (poles-residues, poles-zeros, ratio of polynomials)

$$\mathbf{S}(s) \approx \sum_{n=1}^N \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_{\infty}$$

Impedance, admittance, scattering

## Rational function fitting: why?

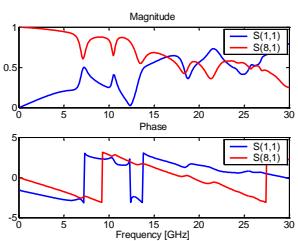


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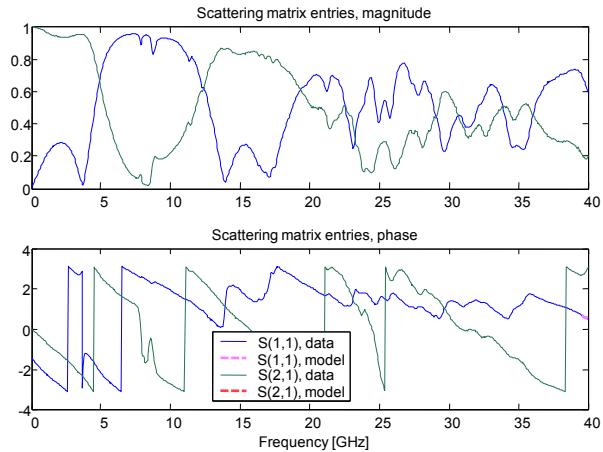
Impedance, admittance, scattering



Extraction of an equivalent circuit is an inverse problem (two-step)

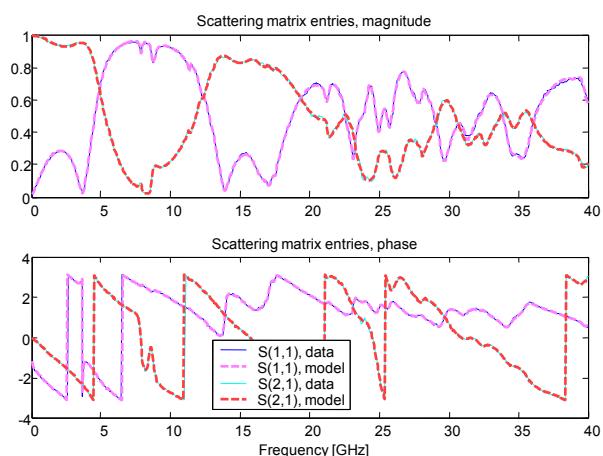
## Stripline + launches

### Data: measured S-parameters

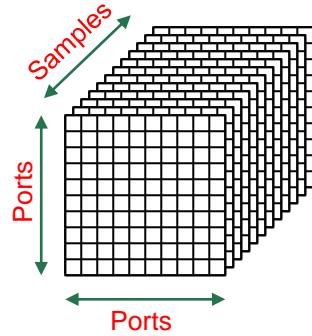


## Stripline + launches

### Macromodel: 60 poles



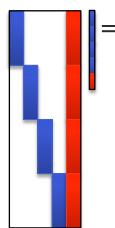
## Handling many ports



$$\hat{S}_{i,j}(s) \approx \sum_{n=1}^N \frac{R_n^{i,j}}{s - p_n} + S_\infty^{i,j}$$

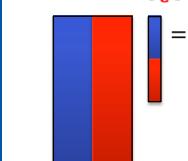
Processing **all** responses may lead to a **large** system!

## Parallel Vector Fitting



$$\begin{bmatrix} I_K & \varphi & 0 & 0 & \cdots & 0 & 0 & -S_1\varphi \\ 0 & 0 & I_K & \varphi & \cdots & 0 & 0 & -S_2\varphi \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & I_K & \varphi & -S_{P^2}\varphi \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_{P^2} \\ C \end{bmatrix} = \begin{bmatrix} S_1 I_K \\ S_2 I_K \\ \vdots \\ S_{P^2} I_K \end{bmatrix}$$

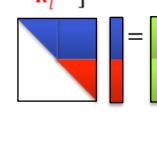
$$[I_K \quad \varphi \quad -S_1\varphi] [R_l] = S_l I_K$$



$$Q_l \begin{bmatrix} R_l^{(11)} & R_l^{(12)} \\ 0 & R_l^{(22)} \end{bmatrix} [R_l] = S_l I_K$$

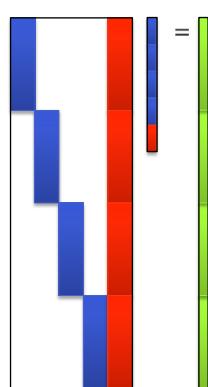


$$\begin{bmatrix} R_l^{(11)} & R_l^{(12)} \\ 0 & R_l^{(22)} \end{bmatrix} [R_l] = Q_l^T S_l I_K$$

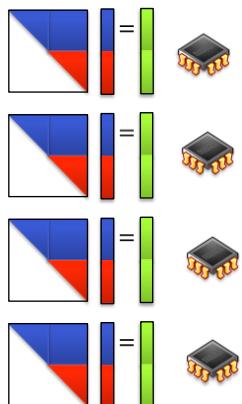


## Parallel Vector Fitting

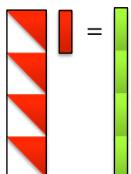
Original LSP



QR decompositions



New LSP



1 GB

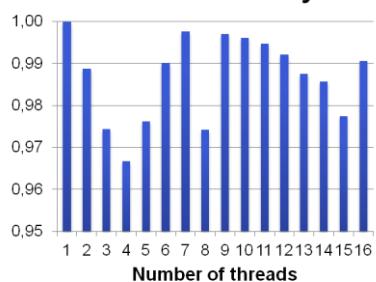
$P = 83 \quad K = 1228 \quad N = 30$

12 MB

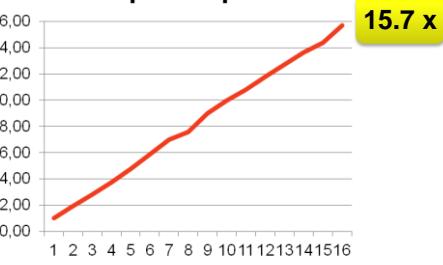
## Parallel Vector Fitting

$P = 83 \quad K = 1228 \quad N = 30$

Parallel efficiency



Speed up



15.7 x



From 193.33 to 12.23 seconds

## State-space macromodel realization

$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A} \mathbf{x}(t) + \mathbf{B} \mathbf{a}(t) \\ \mathbf{b}(t) = \mathbf{C} \mathbf{x}(t) + \mathbf{D} \mathbf{a}(t) \end{cases}$$

$$\mathbf{S}(s) \approx \sum_{n=1}^N \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_{\infty} = \mathbf{D} + \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

## Checking macromodel passivity

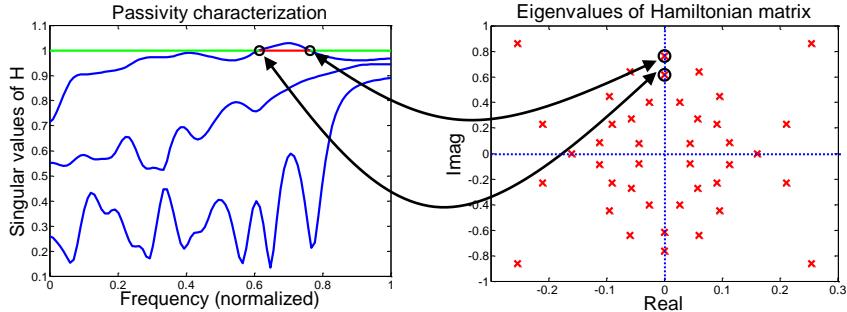
$$\{\text{singular values of } \mathbf{S}(j\omega)\} \leq 1, \quad \forall \omega$$

## Eigenvalues of Hamiltonian matrix

$$\mathbf{M} = \begin{pmatrix} \mathbf{A} - \mathbf{B}(\mathbf{D}^T \mathbf{D} - \mathbf{I})^{-1} \mathbf{D}^T \mathbf{C} & -\mathbf{B}(\mathbf{D}^T \mathbf{D} - \mathbf{I})^{-1} \mathbf{B}^T \\ \mathbf{C}^T (\mathbf{D} \mathbf{D}^T - \mathbf{I})^{-1} \mathbf{C} & -\mathbf{A}^T + \mathbf{C}^T \mathbf{D} (\mathbf{D}^T \mathbf{D} - \mathbf{I})^{-1} \mathbf{B}^T \end{pmatrix}$$

Real matrix  $\mathbf{M}$  must have no imaginary eigenvalues

## Checking macromodel passivity



### Theorem

$j\omega_0$  is an eigenvalue of  $\mathbf{M} \Leftrightarrow \sigma = 1$  is a singular value of  $\mathbf{S}(j\omega_0)$

## Passivity enforcement

- Generate a new passive macromodel
- Apply small correction to preserve accuracy through
  - iterative passivity check
  - solution of small-size optimization problems

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{a} \\ \mathbf{b} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{a} \end{cases} \quad \xrightarrow{\hspace{1cm}} \quad \begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{a} \\ \mathbf{b} = (\mathbf{C} + \Delta\mathbf{C})\mathbf{x} + \mathbf{D}\mathbf{a} \end{cases}$$

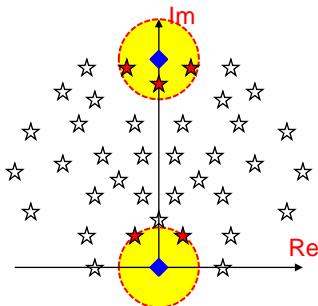
$$\Delta\mathbf{S} = \Delta\mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

## Passivity check: computing few eigenvalues

We need only all purely imaginary eigenvalues of  $\mathbf{M}$

Iterative single-shift Arnoldi iterations to find few eigenvalues "close" to imaginary "shift points".

Pick initial shifts at ends of spectrum



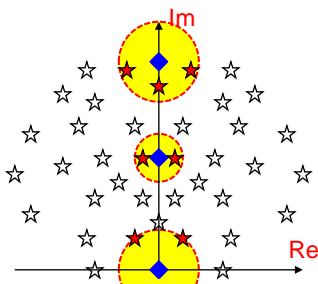
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Bisection on imaginary axis

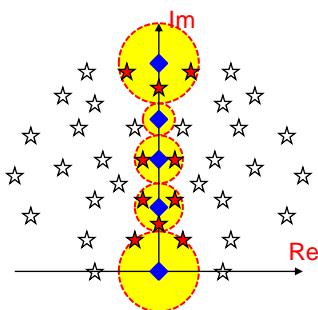


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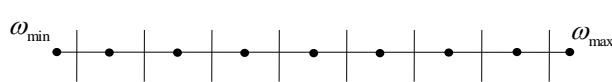


Bisection on imaginary axis

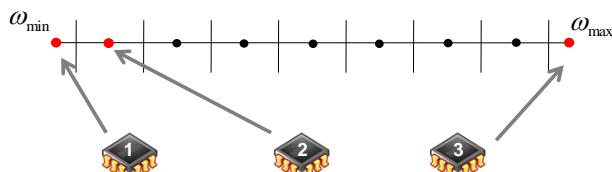
The union of all disks must have no “gaps”!



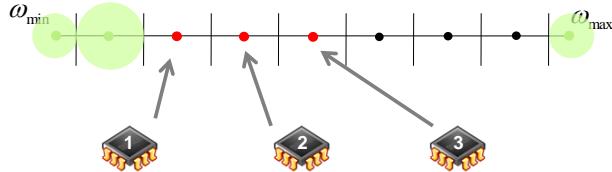
## Basic idea: single-shift $\leftrightarrow$ single-thread



Split bandwidth into N subbands  
 $N = F(T)$   
 $T = \text{threads}$



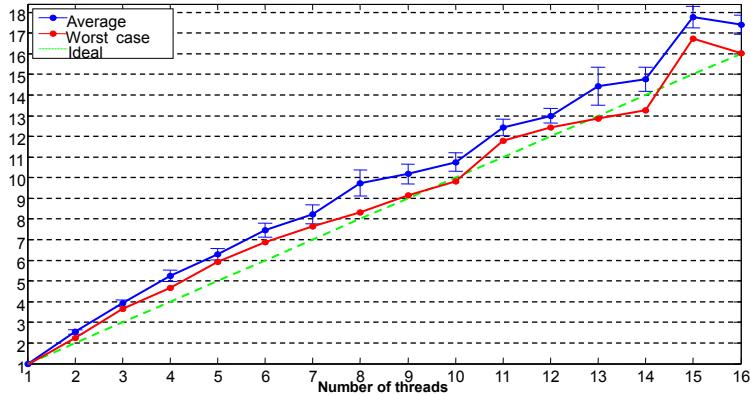
Startup phase



- Ready
- In execution
- Completed



## Speedup (high-speed connector model)



Order	2240
Ports	56
$f_{min}$	0 GHz
$f_{max}$	21 GHz
$\alpha$	5
$N \lambda_{imag}$	22

Number of threads	1	2	8	16
Number of $\lambda$	90	110	86	84
Analysis time [s]	33.778	13.259	3.369	1.830
Refine time [s]	0.096	0.039	0.021	0.019
Total time [s]	33.972	13.398	3.487	1.950
Speedup			2.5 X	9.7 X



## S-parameter modeling flow: a summary

### Input

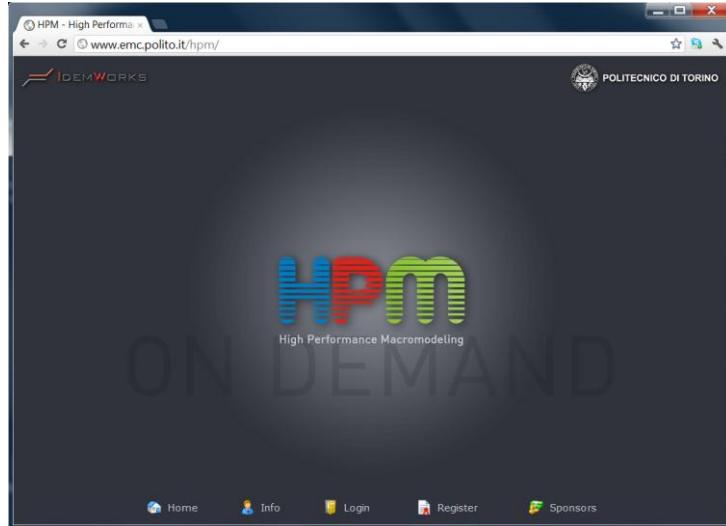
- Tabulated frequency responses ("numbers", "S-parameters")
  - From EM simulations (in-house or external tools)
  - From measurements
  - From vendors (connectors, filters, etc...)
- Standardized (Touchstone format)
- Small-size, compact files
- Hides IP (behavioral data)

### Output

- System-level simulation model ("equation", "netlist")
- Qualification certificate (WHY?)
  - Physical self-consistency (stability, causality, passivity)
  - Guaranteed performance in system-level analysis

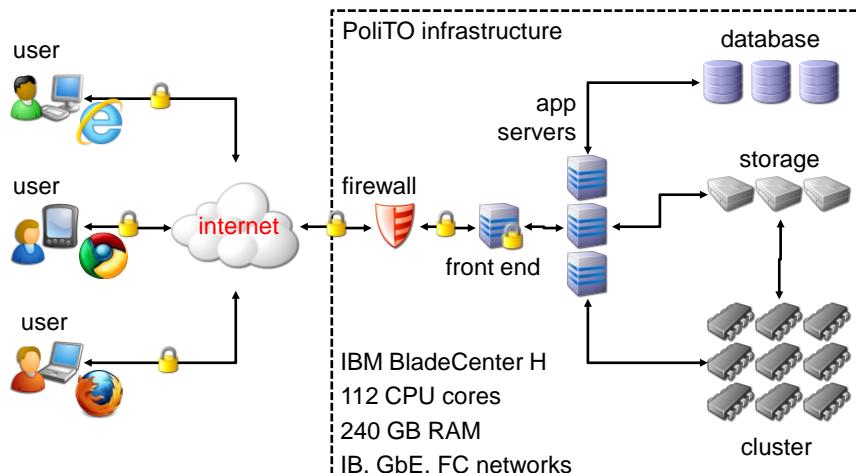


## The HPM Service



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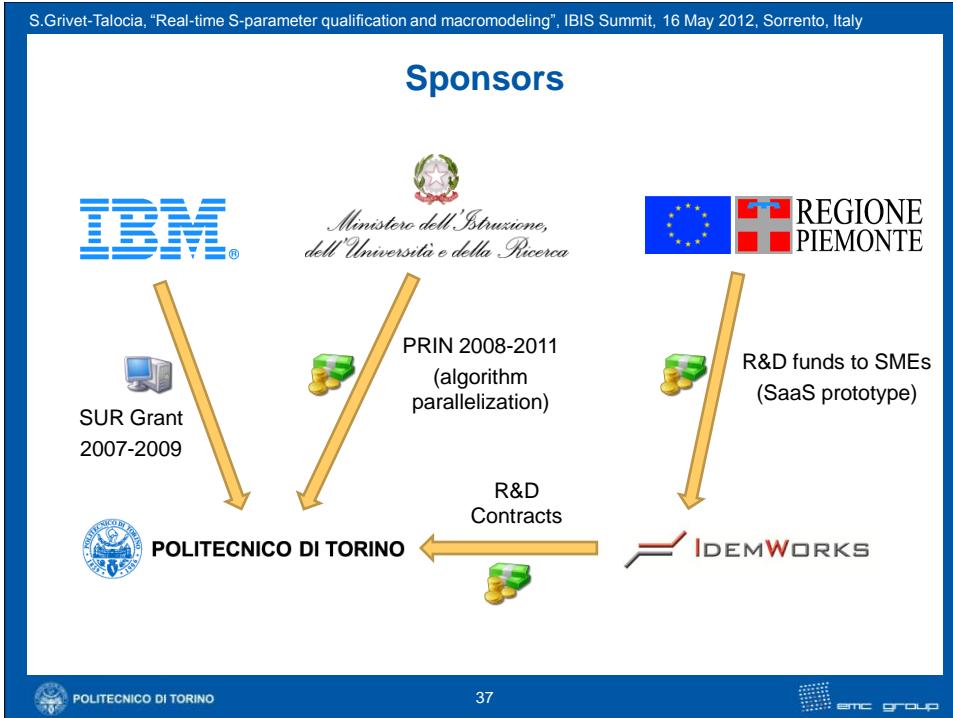
## The HPM Service



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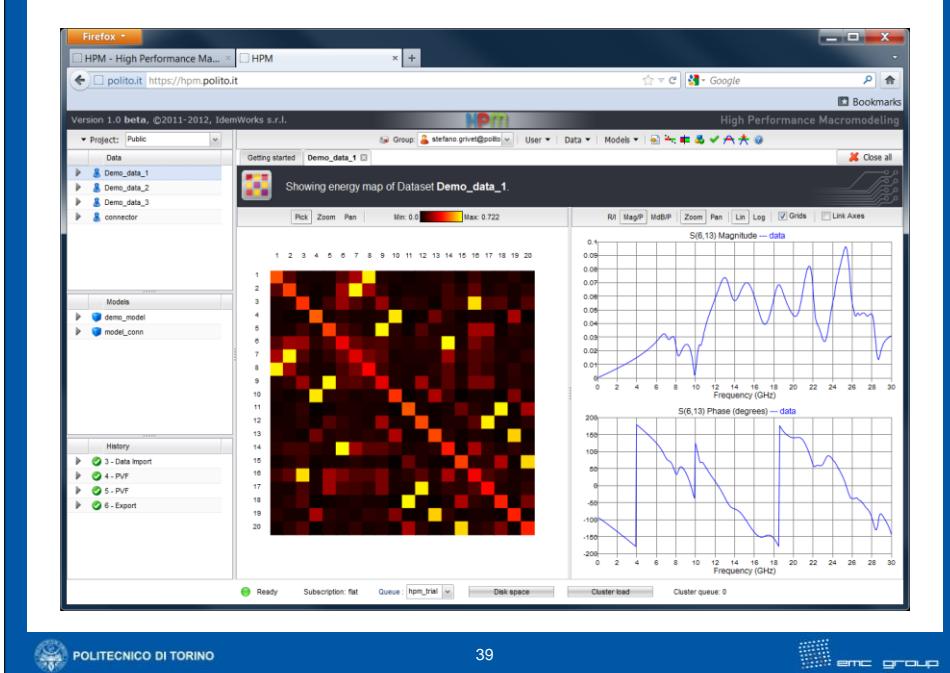
EMC group



The screenshot shows the HPM software interface running in a Firefox browser window. The title bar reads "Firefox - HPM - High Performance Ma...". The address bar shows "polito.it https://hpm.polito.it". The main window is titled "High Performance Macromodeling" and displays the "Getting started" screen. The sidebar on the left shows sections for "Data", "Models", and "History", all currently empty. The main content area lists "Getting started" tasks:

- Create new project
- Upload Touchstone file to project
- Visualize responses: double-click on
- Check data passivity (energy test)
- Check data causality
- Build macromodel (Parallel Vector Fitting)
- Enforce macromodel passivity
- Export macromodel to preferred netlist format
- Download exported netlist

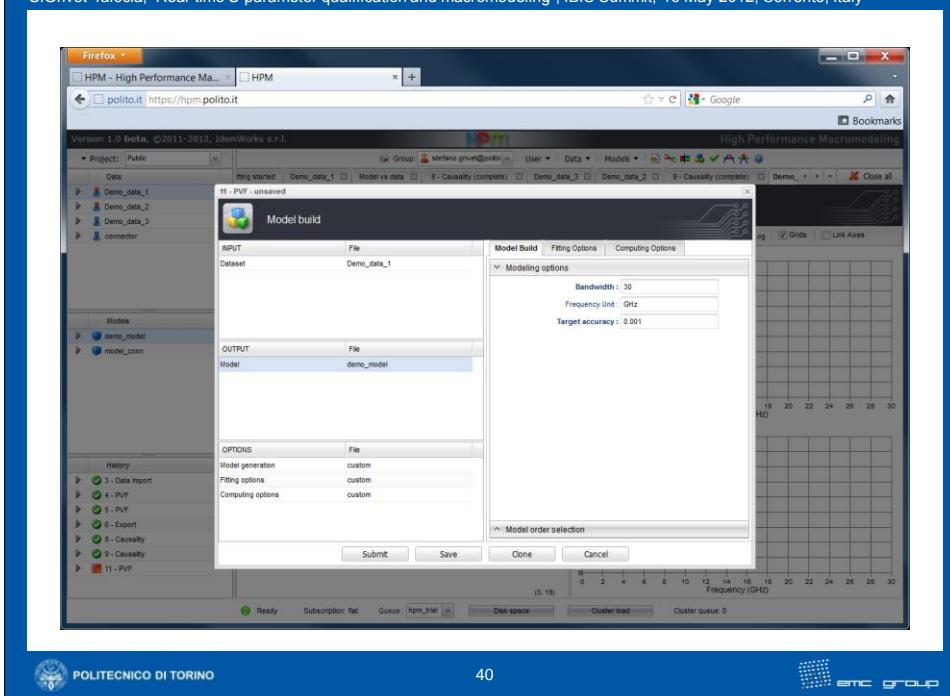
The bottom of the window shows system status: "Ready", "Subscription: fsl", "Queue: Norm\_trial", "Disk space", "Cluster load", and "Cluster queue: 0".



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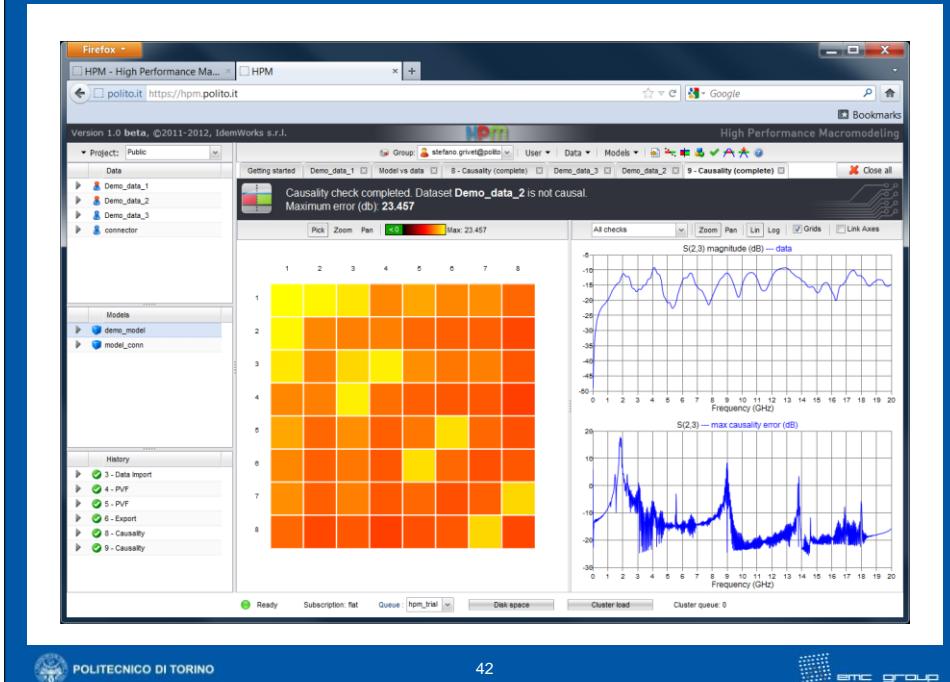
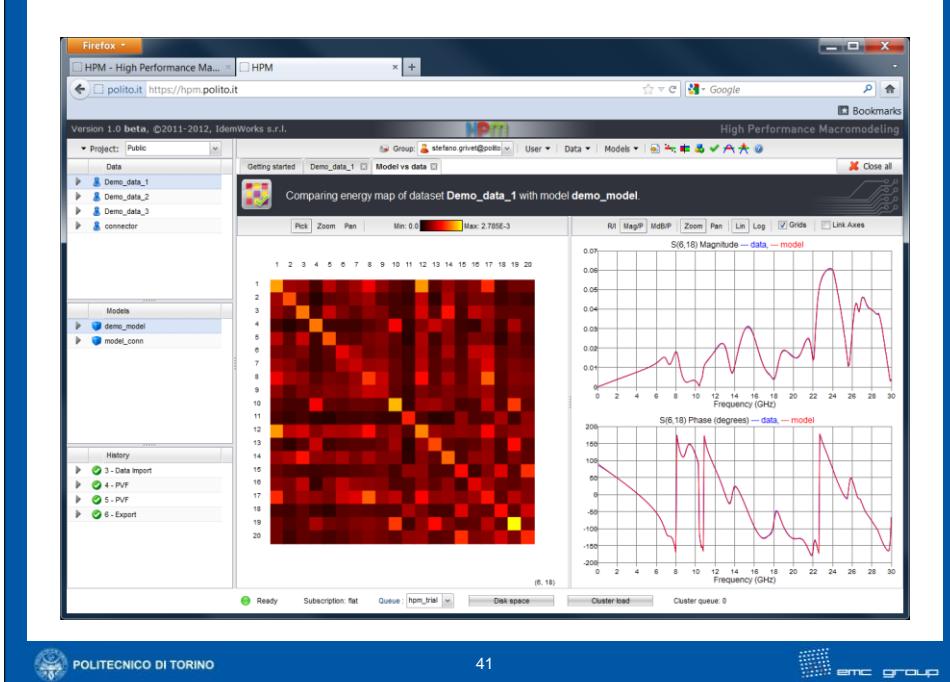
EMC group

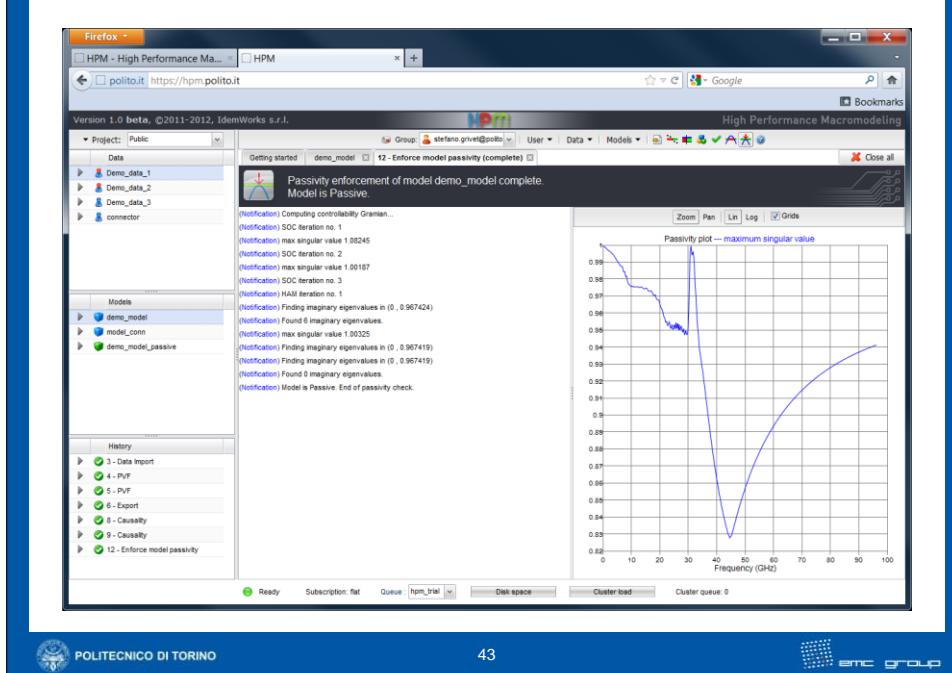


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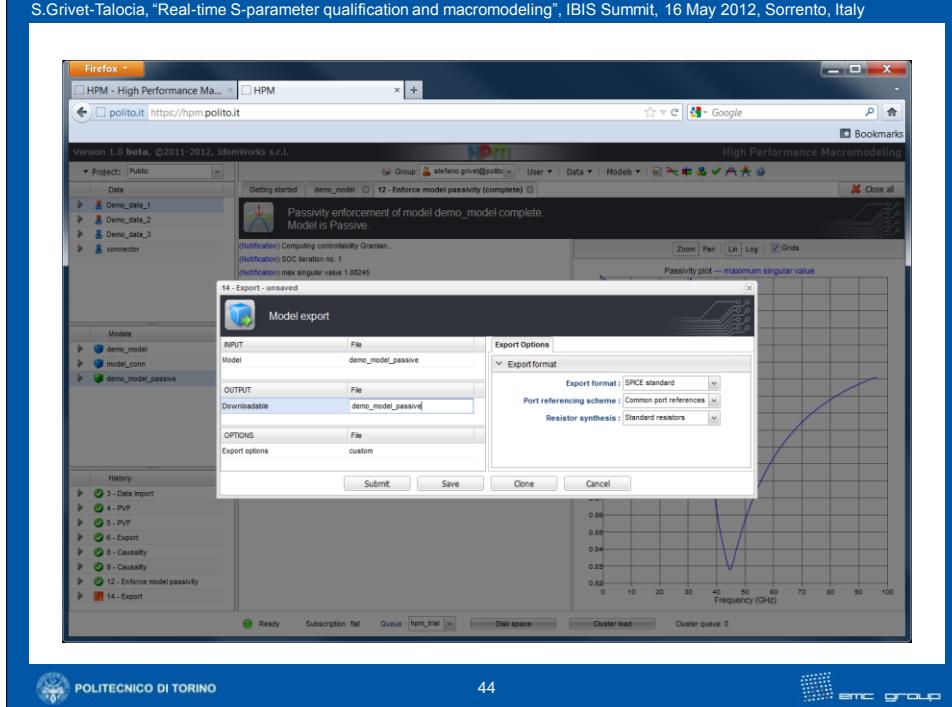
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EMC group



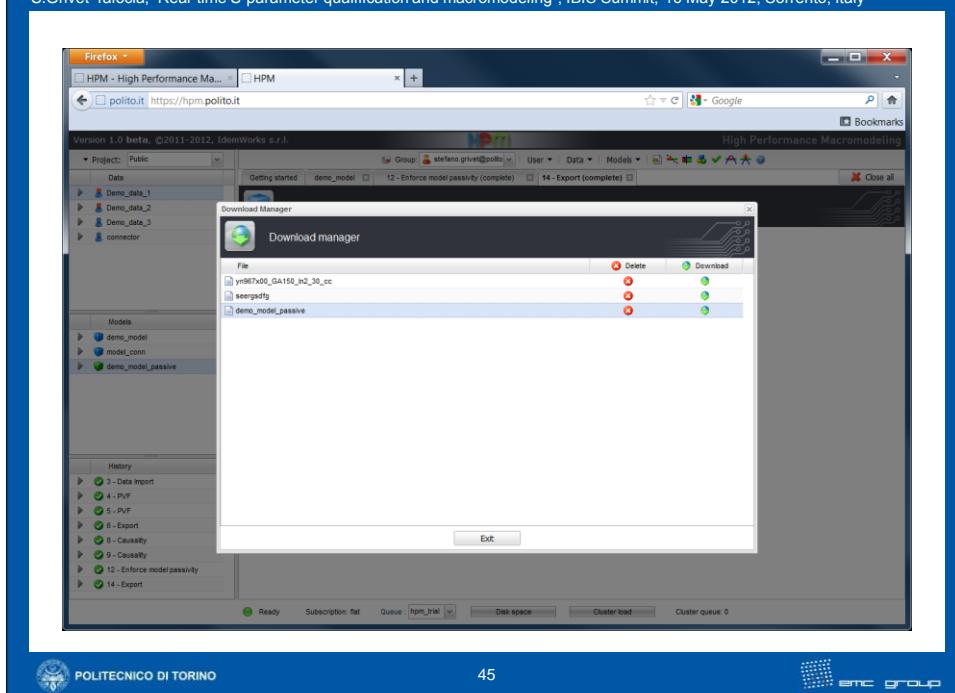


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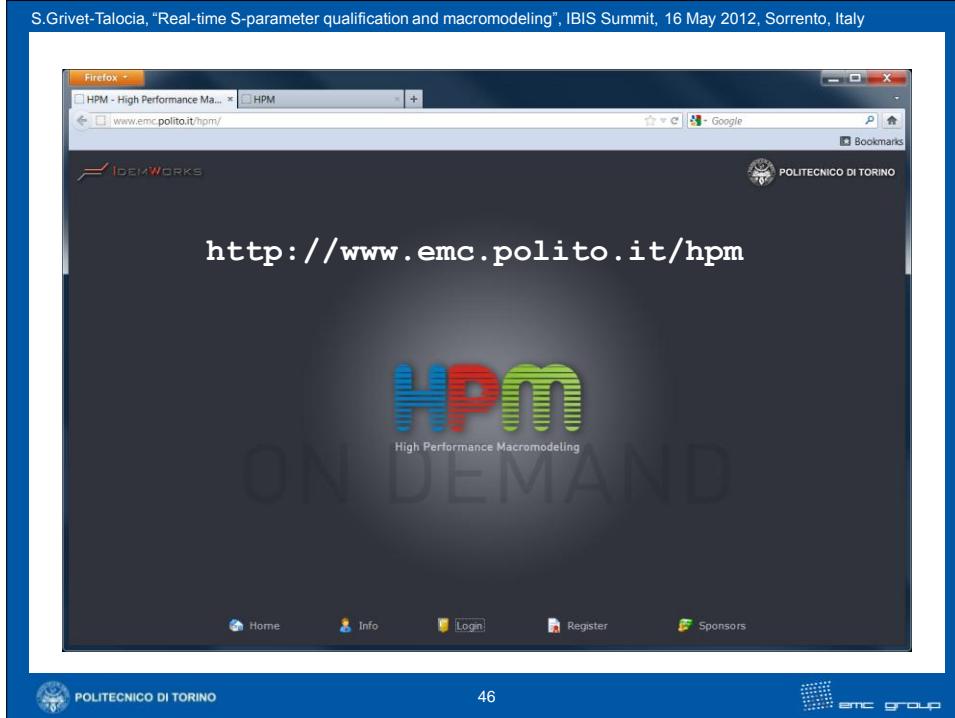


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Thank you



<http://www.emc.polito.it>



<http://www.idemworks.com>

## References

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2. HPM service. Available online: <http://www.emc.polito.it/hpm>
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