Towards real-time S-parameter qualification and macromodeling

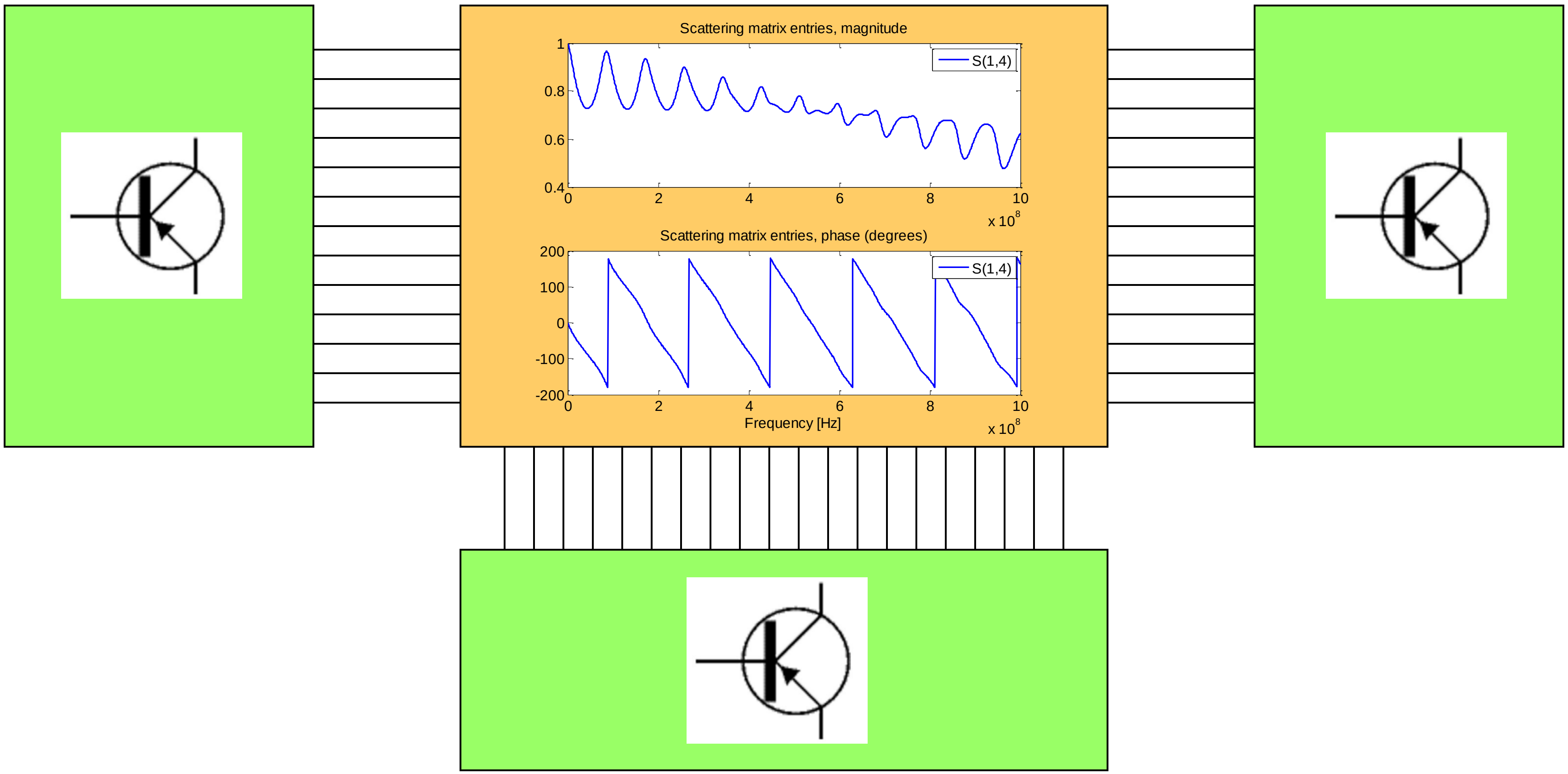
Stefano Grivet Talocia

Politecnico di Torino, Italy
stefano.grivet@polito.it

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

The objective

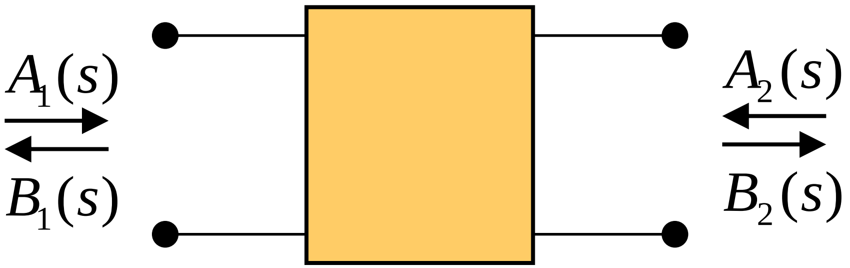
S-parameter block



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



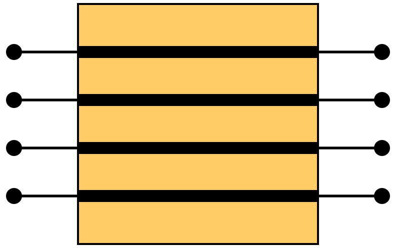
power waves

complex frequency

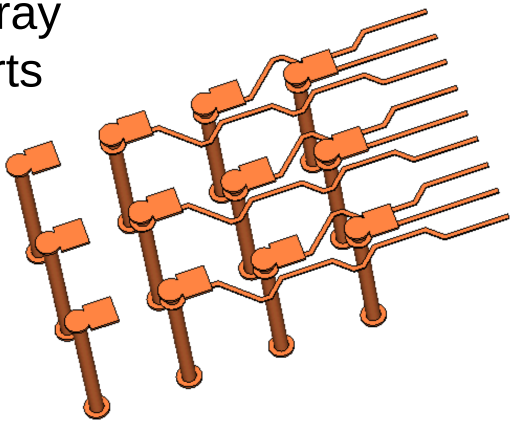
$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \underbrace{\begin{bmatrix} S_{11}(s) & S_{12}(s) \\ S_{21}(s) & S_{22}(s) \end{bmatrix}}_{\text{Scattering matrix}} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}$$

Scattering matrix

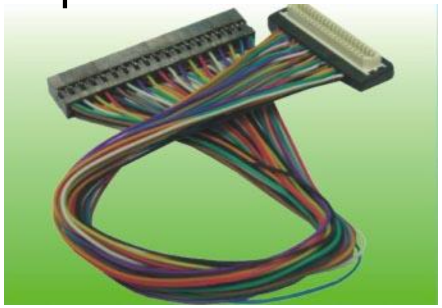
Examples of S-parameter data



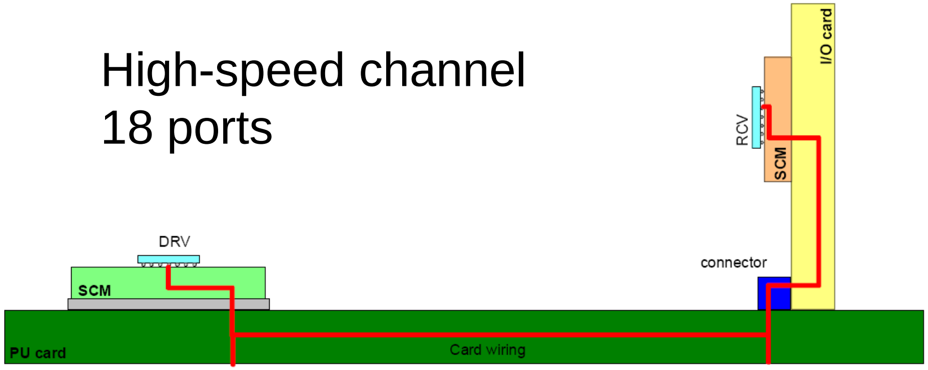
Via array
12 ports



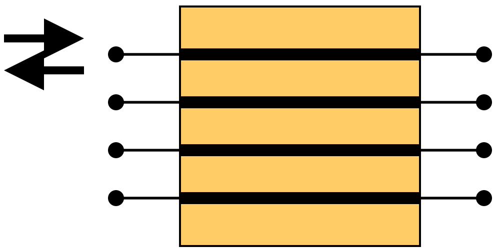
Wiring harness
8 ports

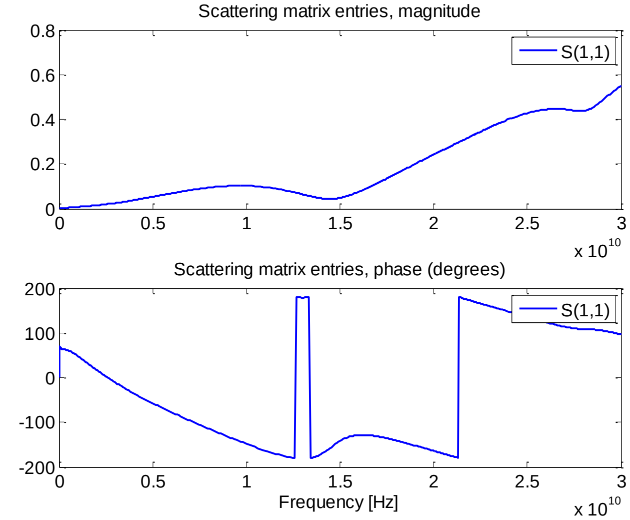


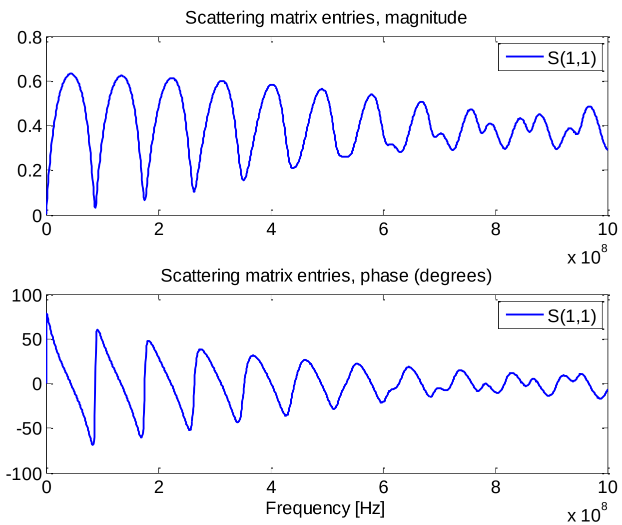
High-speed channel
18 ports

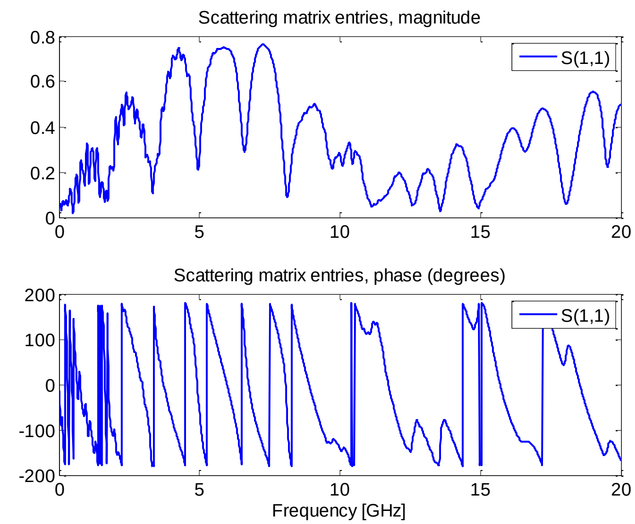


Examples of S-parameter data

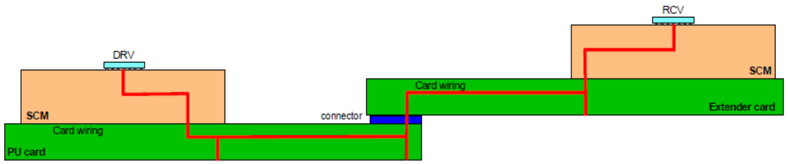








S-parameter modeling flow



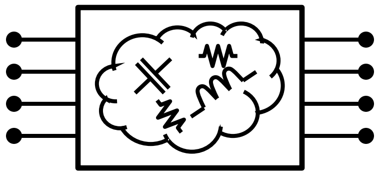
Measurement → **Frequency response**
Simulation

↓

Data qualification
Rational approximation
Passivity enforcement
Synthesis

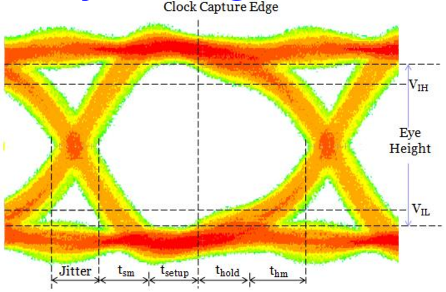
↓

Passive Causal
Macromodel



Circuit solver
←
Time domain simulation

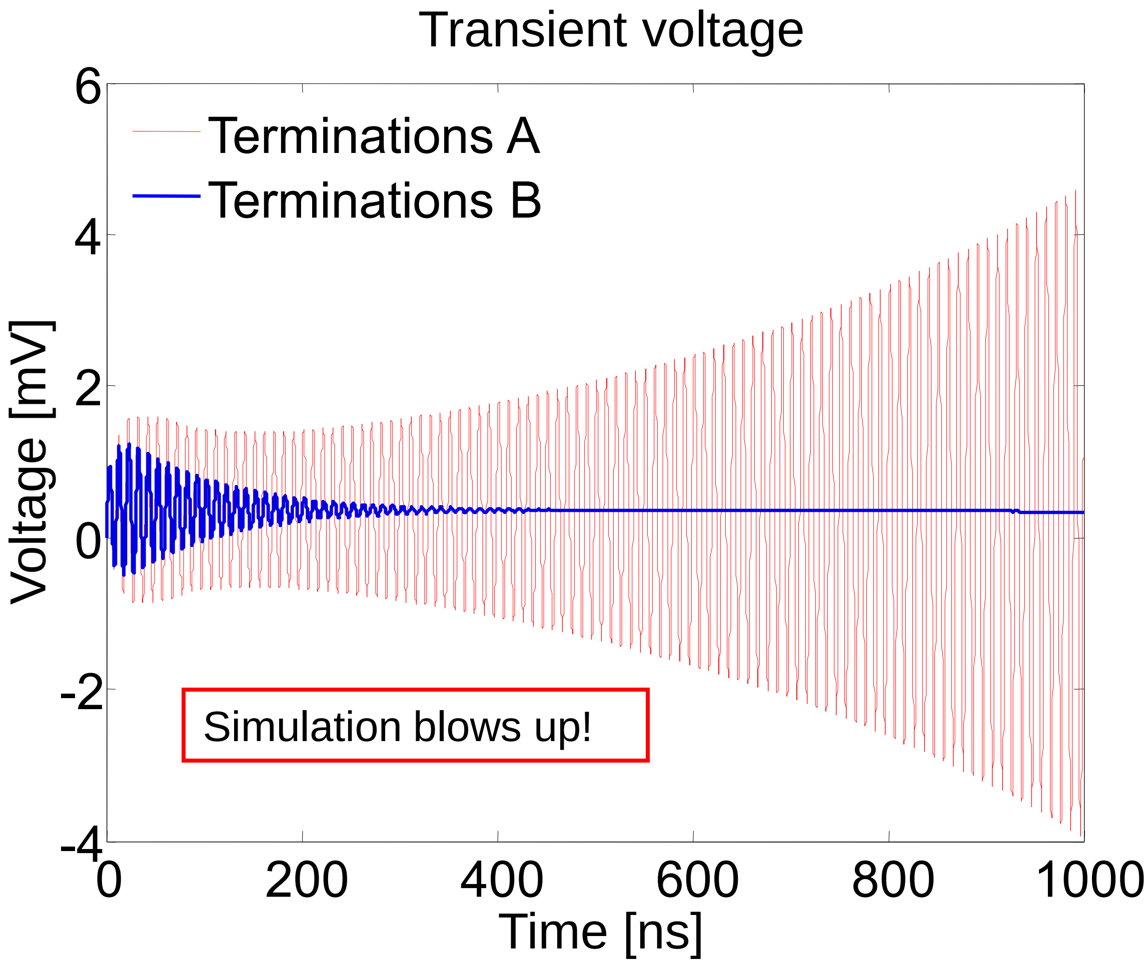
Eye diagram

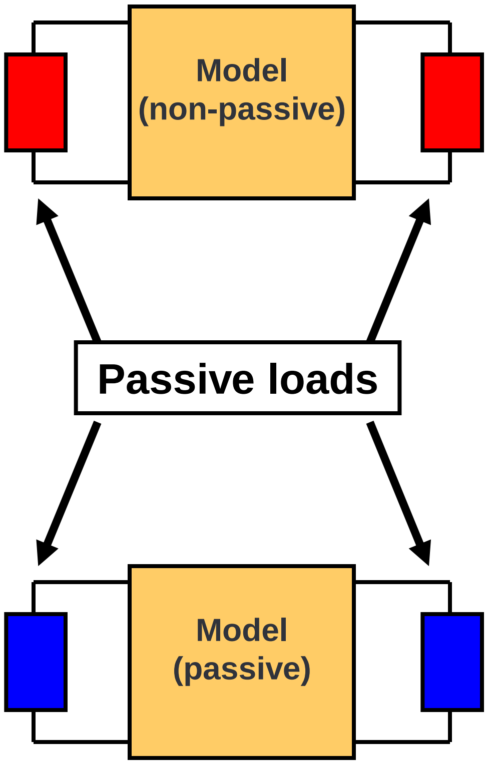


Part I: qualification

A quick overview

Passivity: why?





Passivity

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

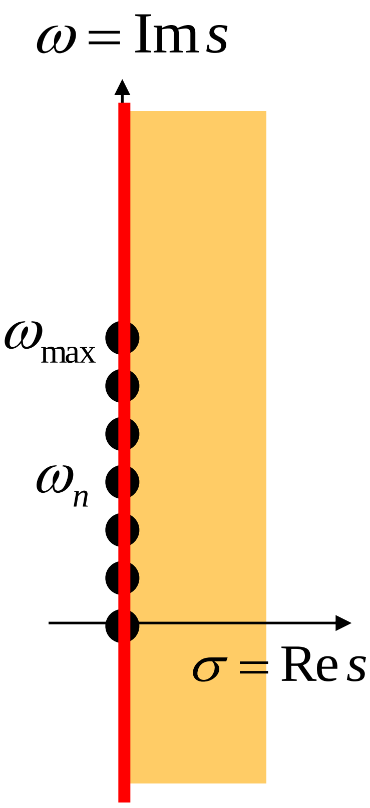
Guarantees real-valued impulse response.
Always assumed by construction

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

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

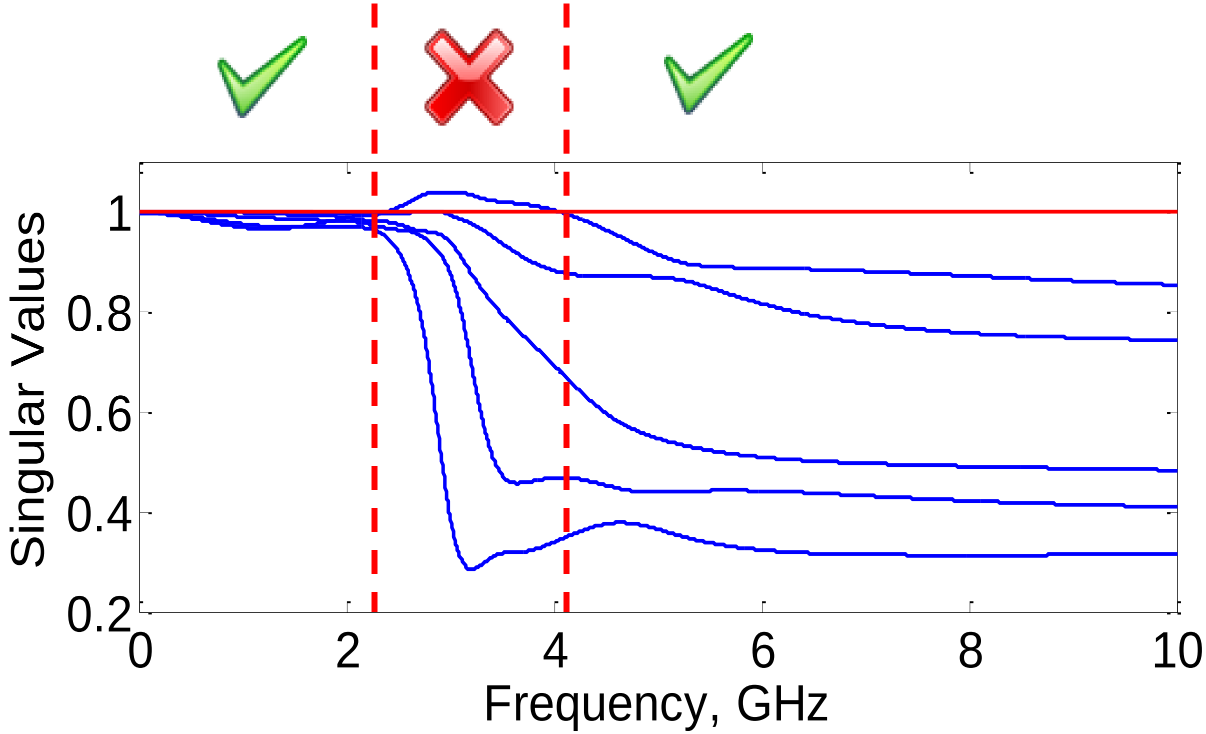
$$\mathbf{S}(j\omega) \text{ is causal}$$

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

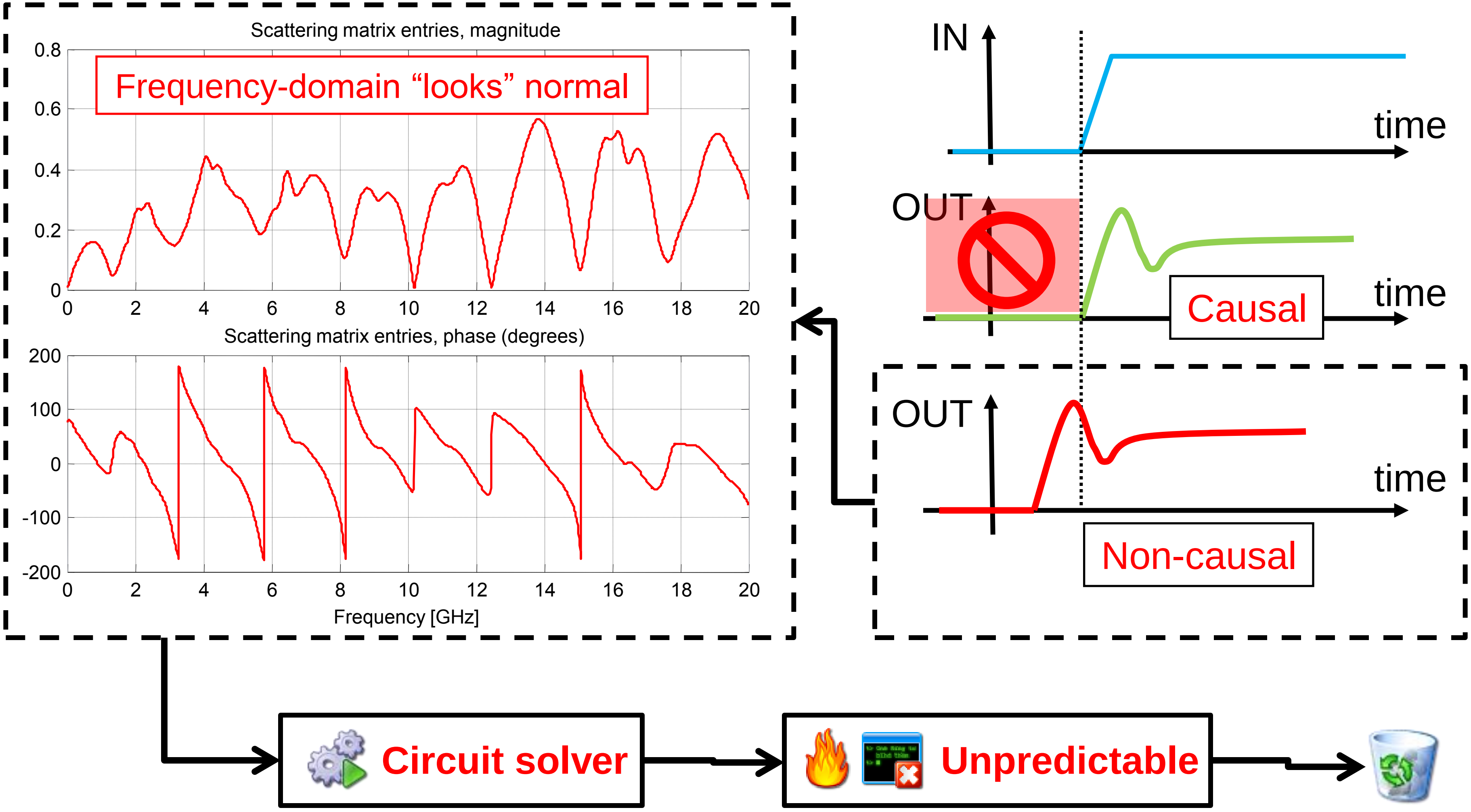


Passivity

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



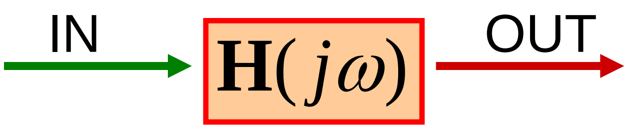
Causality

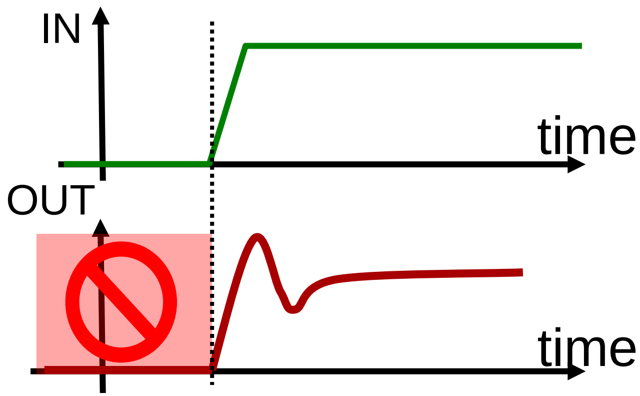


Scattering matrix entries, magnitude
Frequency-domain “looks” normal
Scattering matrix entries, phase (degrees)
Frequency [GHz]
IN
time
OUT
time
Causal
OUT
time
Non-causal
Circuit solver
Unpredictable

Causality: definitions

Time-domain





Note: no delay extraction here

Frequency-domain

Hilbert transform

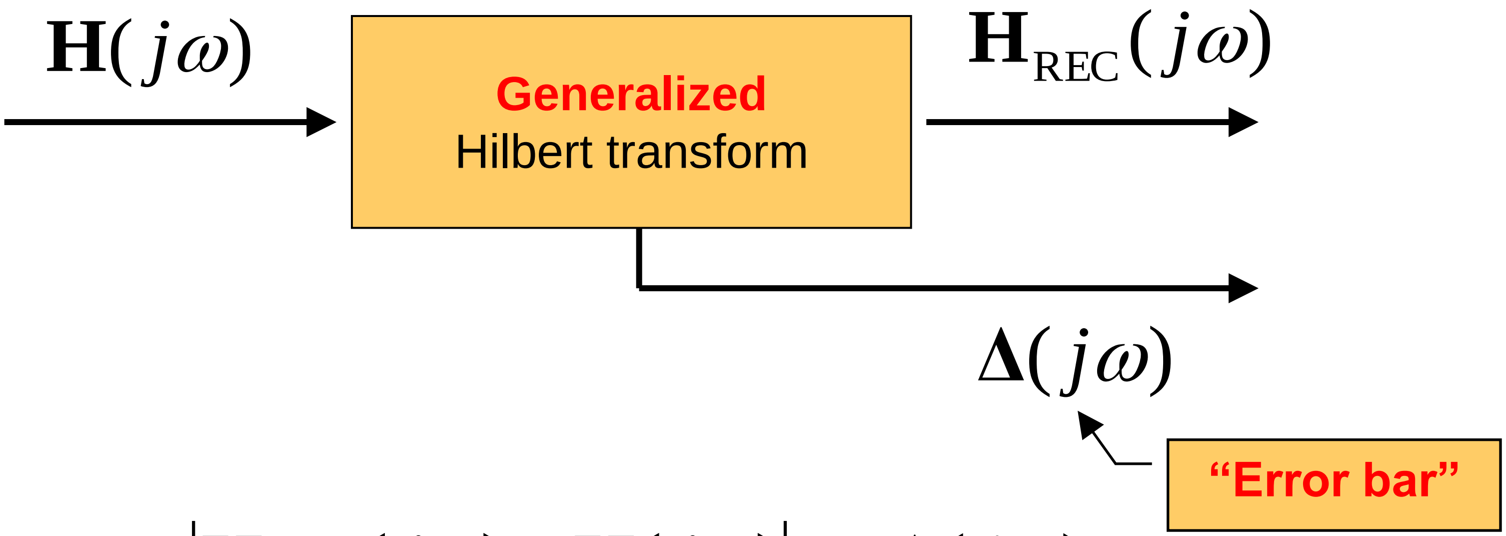
Kramers-Krönig dispersion relations

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

Self-consistency

All samples are strongly related

Causality check



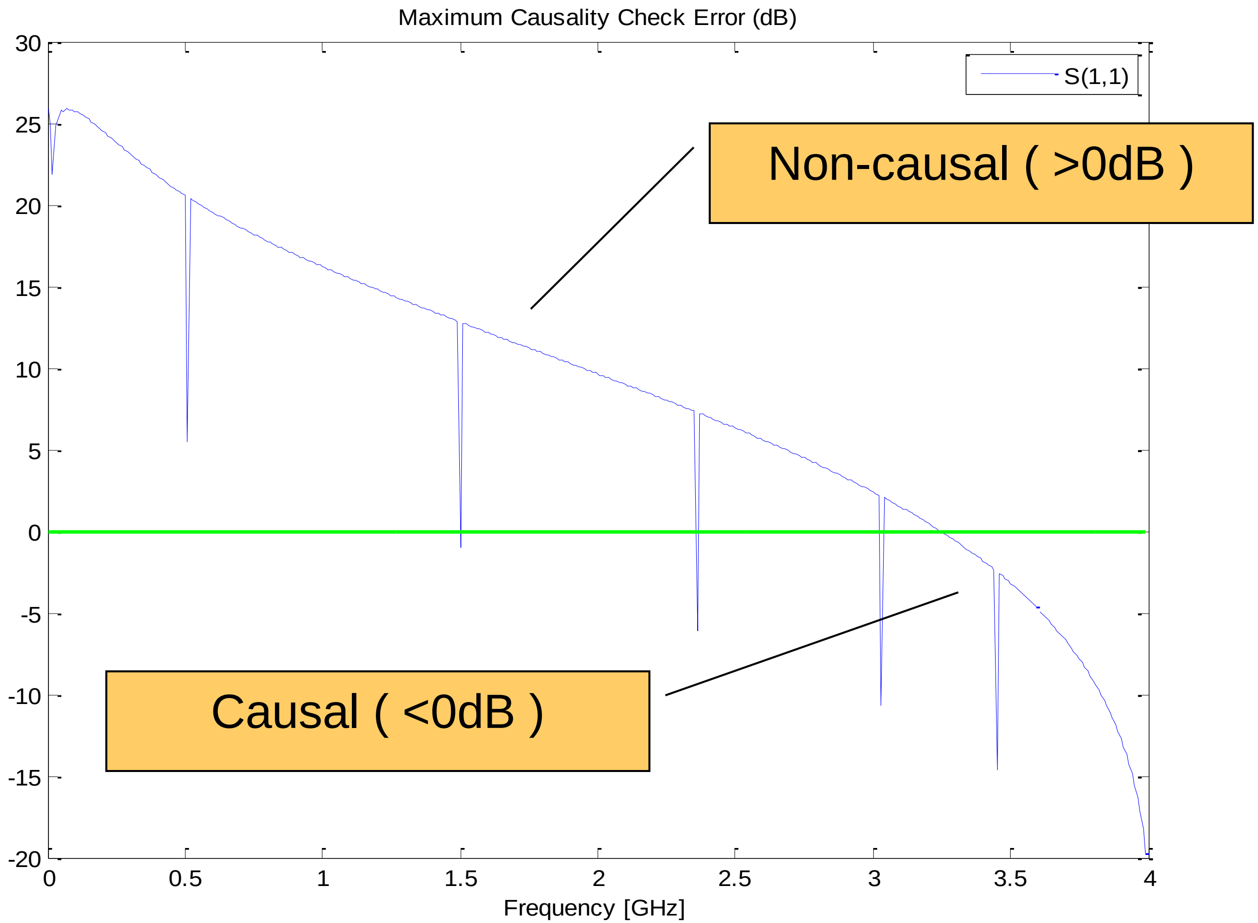
Causal $$\left|\mathbf{H}_{\mathrm{REC}}(j\omega)-\mathbf{H}(j\omega)\right| < \mathbf{\Delta}(j\omega)$$

Non-causal $$\left|\mathbf{H}_{\mathrm{REC}}(j\omega)-\mathbf{H}(j\omega)\right| > \mathbf{\Delta}(j\omega)$$

Causality check error

$$E_{dB}(j\omega) = 20\log_{10}\frac{\left|H_{\mathrm{REC}}(j\omega) - H(j\omega)\right|}{\Delta(j\omega)}$$

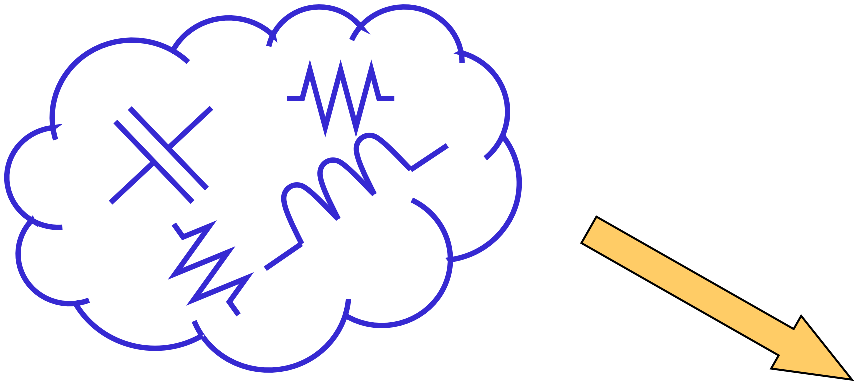
Computed (parallel) for each scattering response



Part II: macromodeling

An update on recent developments

Rational function fitting: why?



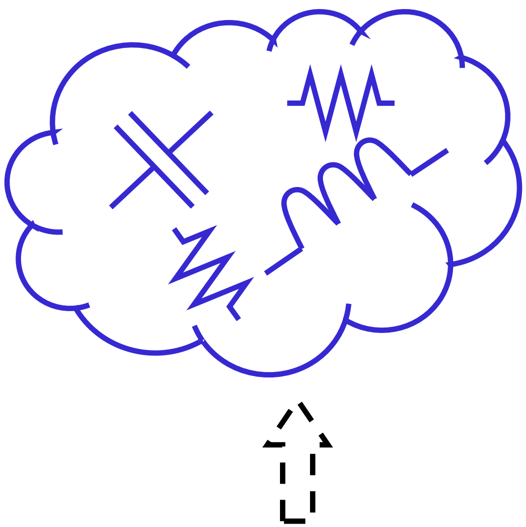
Circuit solvers understand circuits

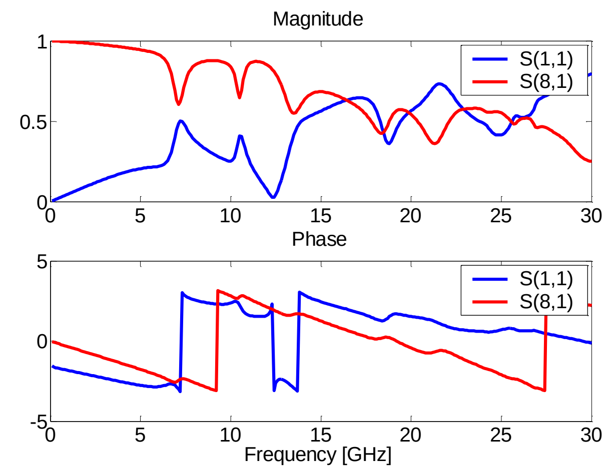
Any lumped circuit has rational frequency responses (poles-residues, poles-zeros, ratio of polynomials)

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

Impedance, admittance, scattering

Rational function fitting: why?





Circuit solvers understand circuits

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

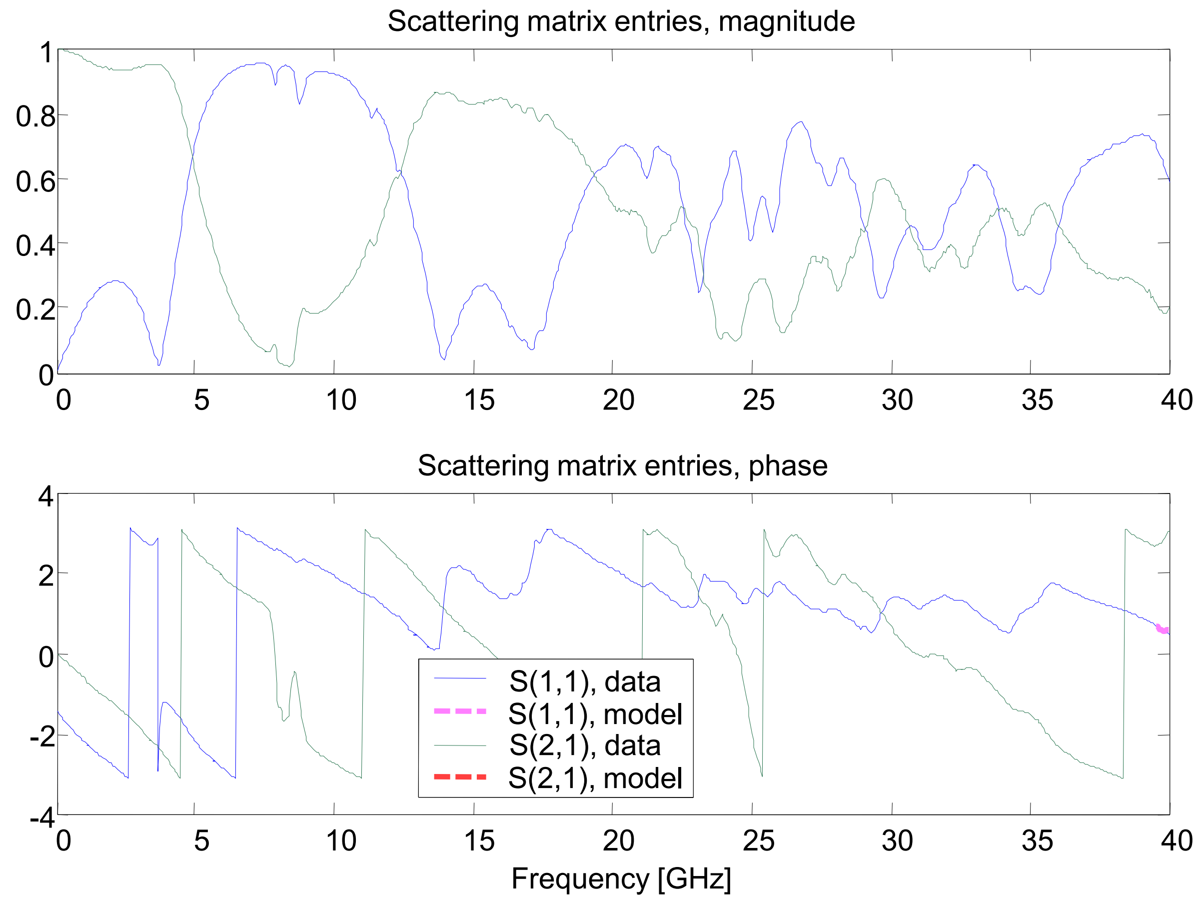
$$\mathbf{S}(s) \approx \sum_{n=1}^{N} \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty$$

Impedance, admittance, scattering

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

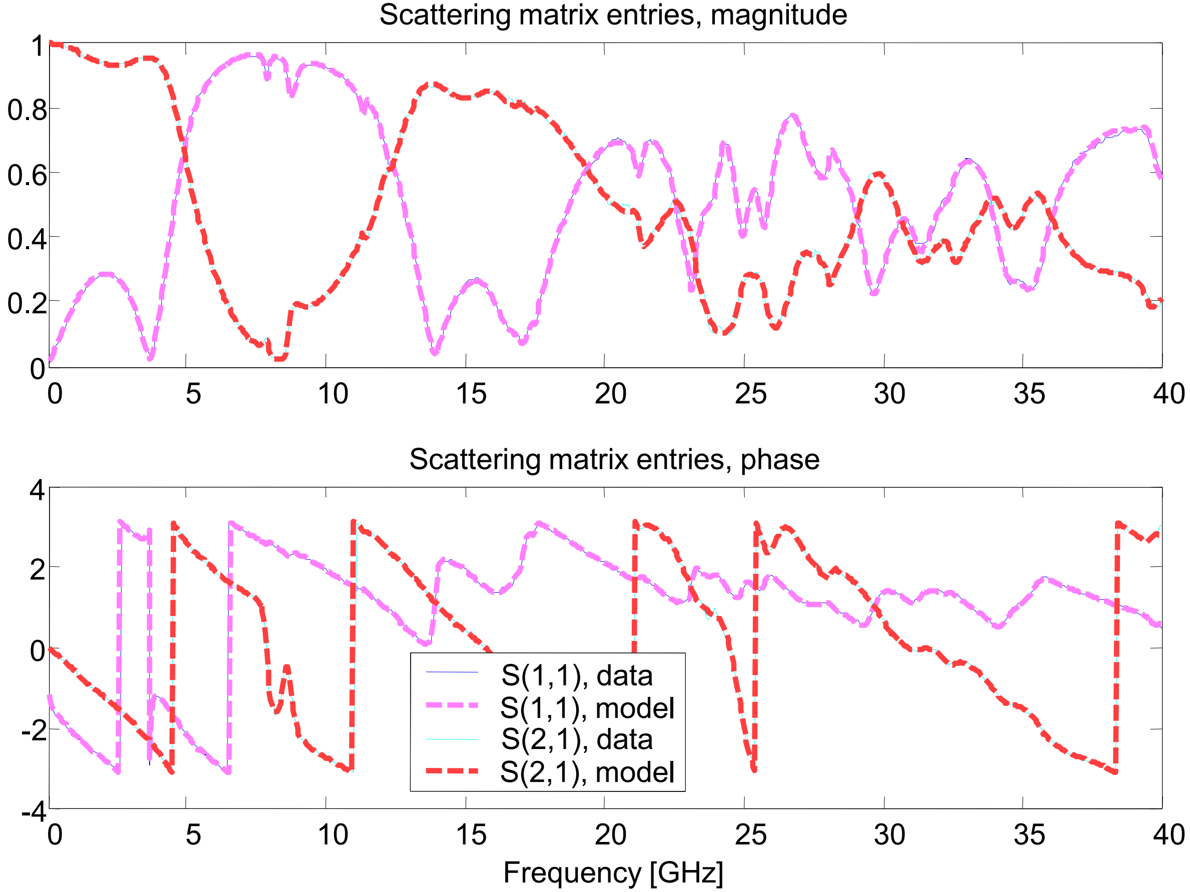
Stripline + launches

Data: measured S-parameters

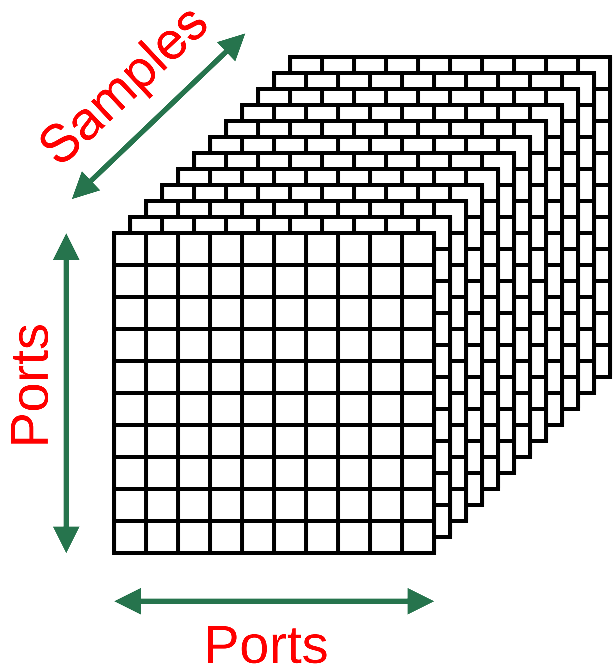


Stripline + launches

Macromodel: 60 poles



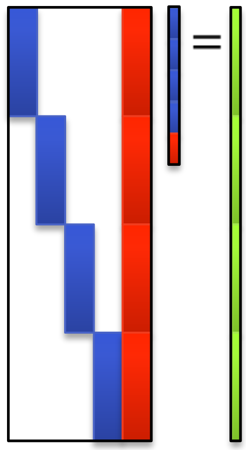
Handling many ports



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

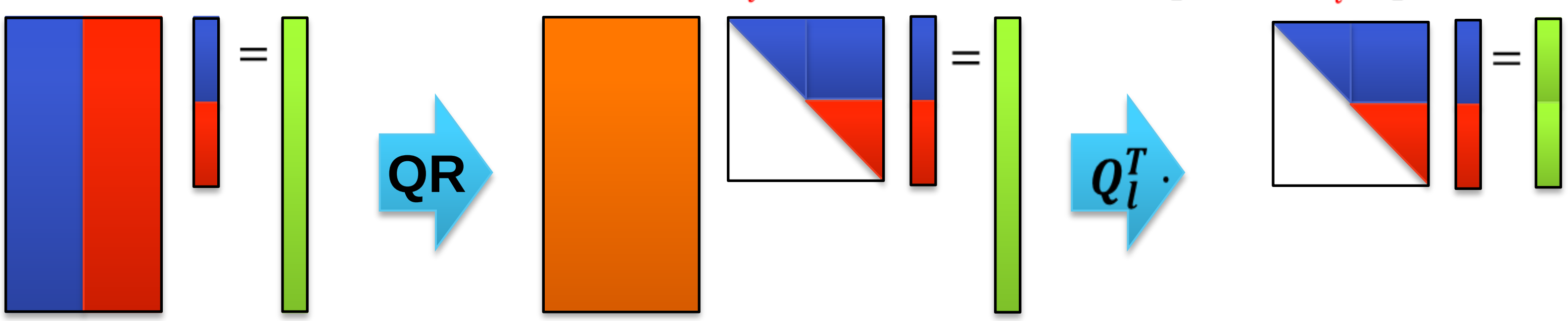
Processing **all** responses may lead to a **large** system!

Parallel Vector Fitting

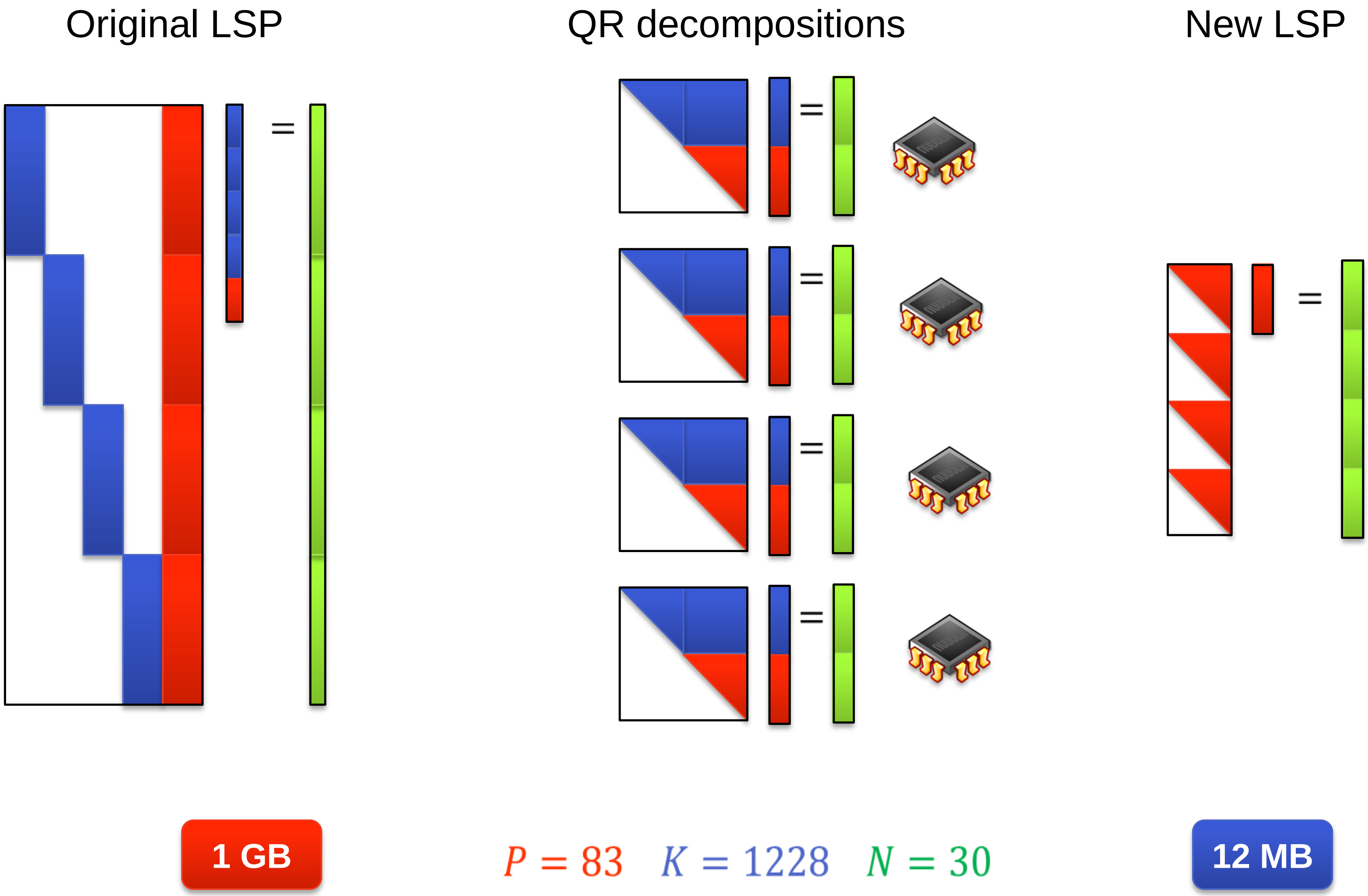


$$\begin{bmatrix} I_K & \varphi & 0 & 0 & \cdots & 0 & 0 & -S_1\varphi \\ 0 & 0 & I_K & \varphi & \cdots & 0 & 0 & -S_2\varphi \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & I_K & \varphi & -S_{P^2}\varphi \end{bmatrix} \begin{bmatrix} R_1 \\ R_2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

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



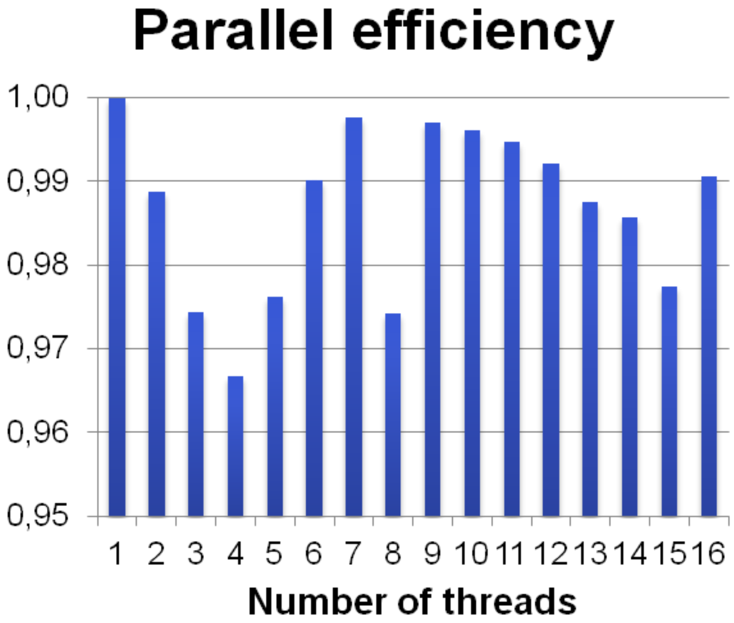
Parallel Vector Fitting

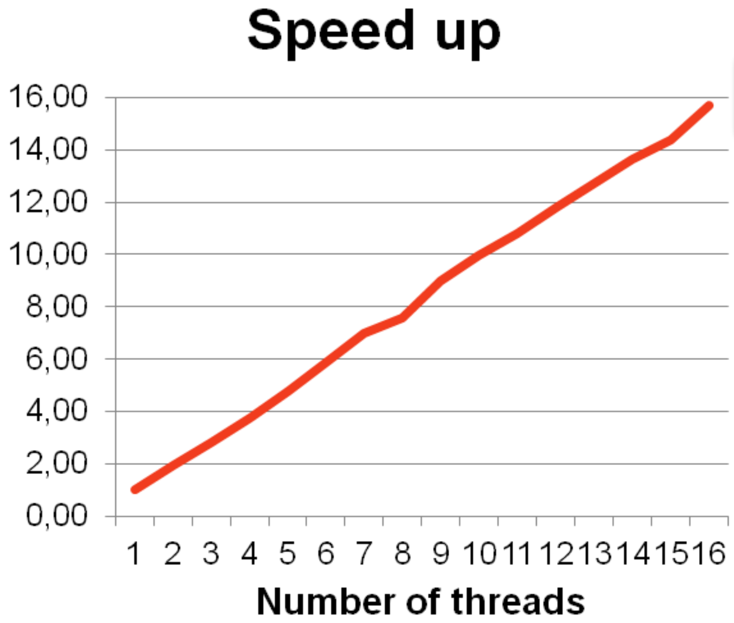


$P = 83 \quad K = 1228 \quad N = 30$

Parallel Vector Fitting

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

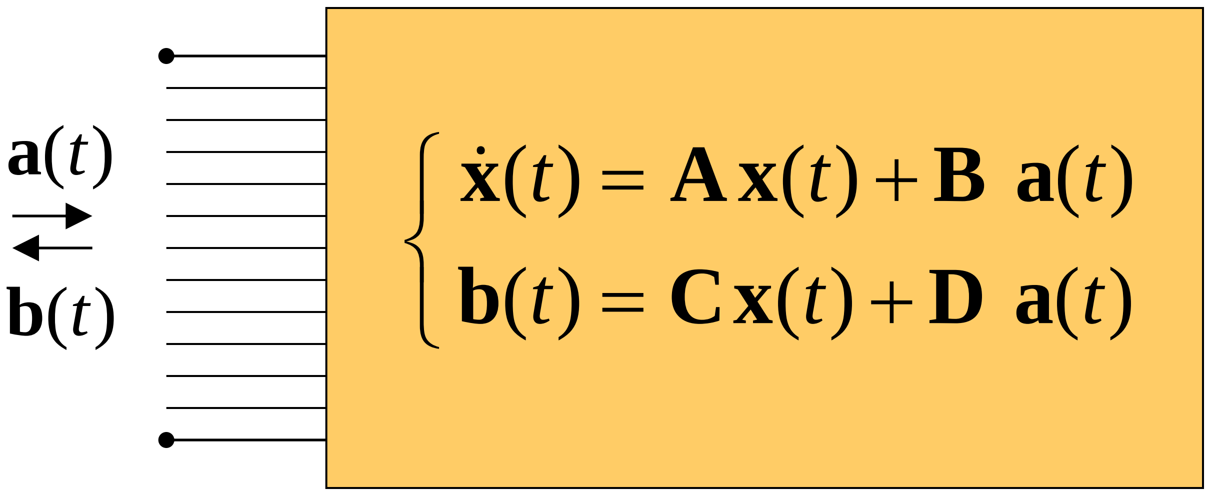




15.7 x

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

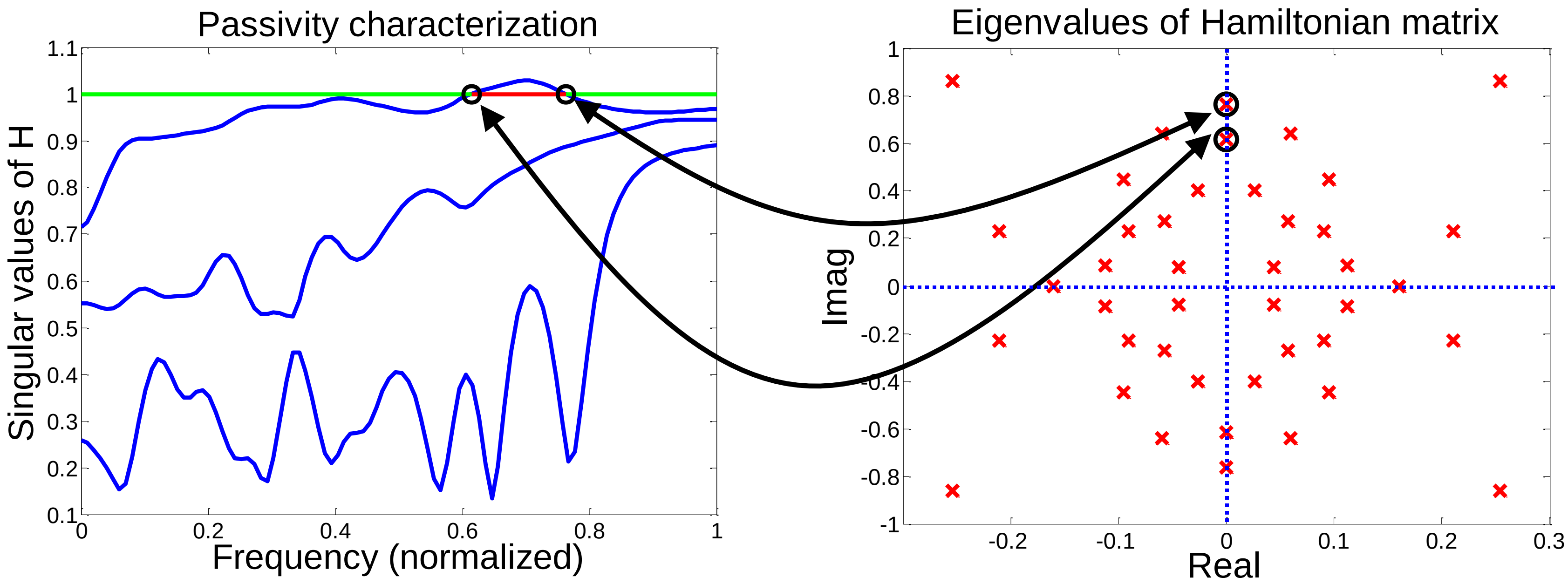
$$\left\{ \text{singular values of } \mathbf{S}(j\omega) \right\} \leq \mathbf{1}, \quad \forall \omega$$

Eigenvalues of Hamiltonian matrix

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

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

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

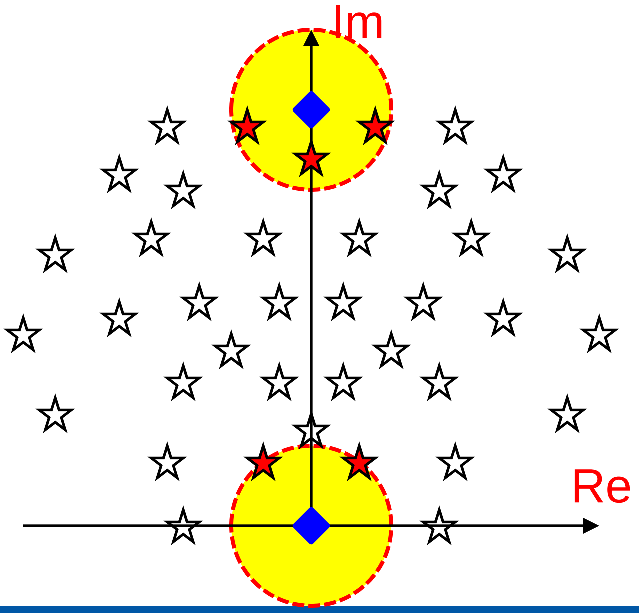
$$\Delta\mathbf{S} = \Delta\mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

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

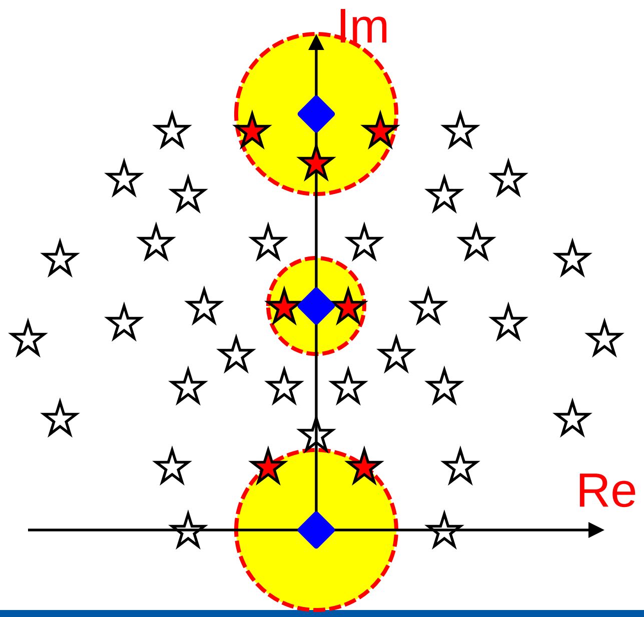


Passivity check: computing few eigenvalues

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



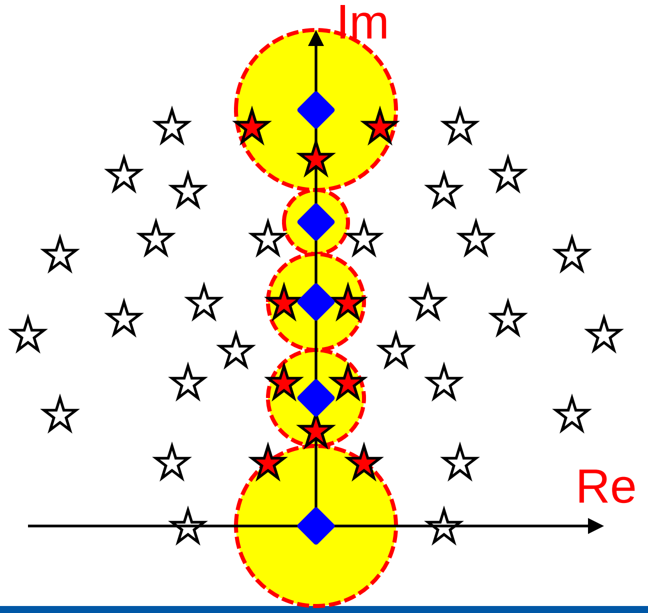
Bisection on imaginary axis

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”.

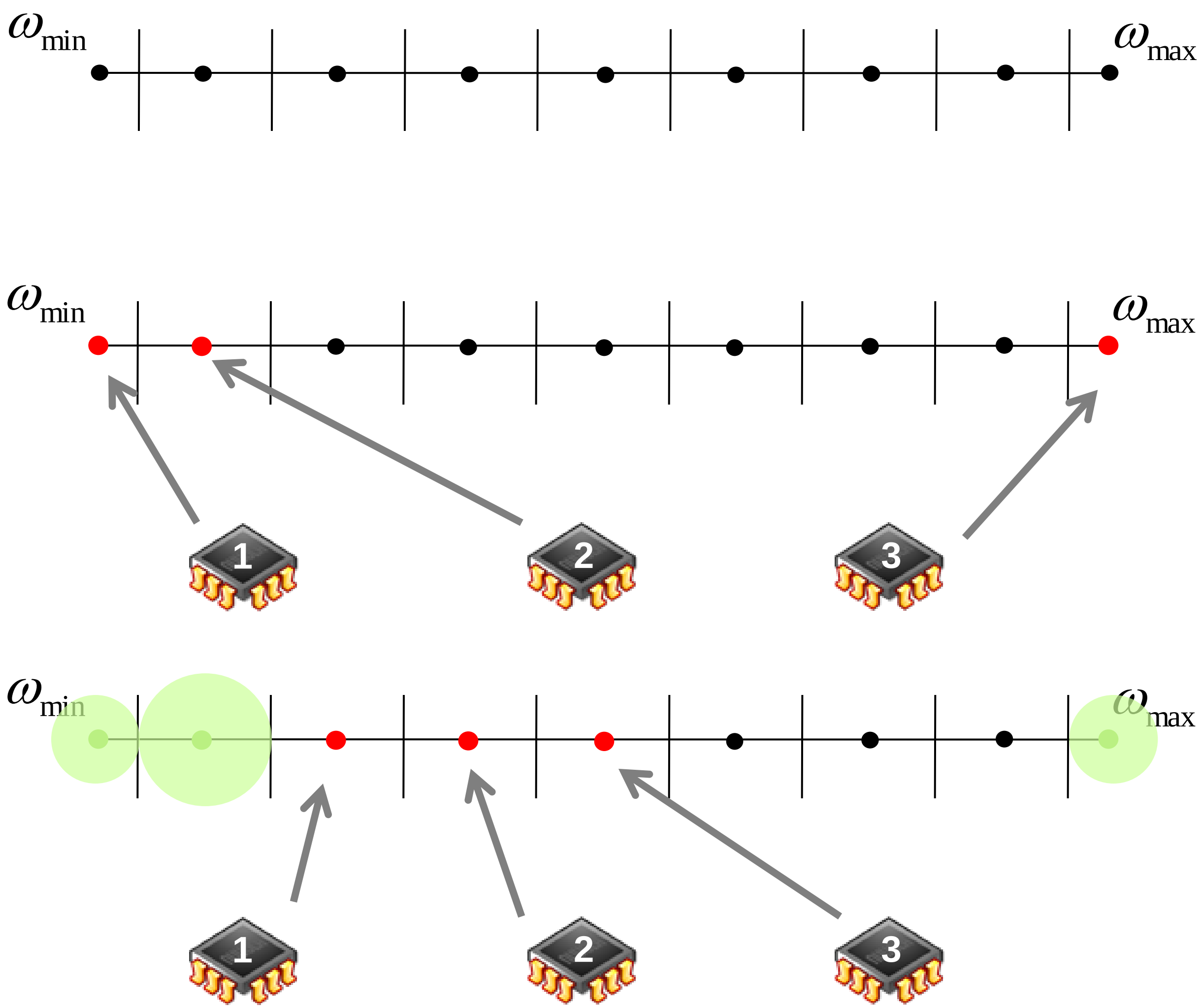
Pick initial shifts at ends of spectrum



Bisection on imaginary axis

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

Basic idea: single-shift ↔ single-thread



Split bandwidth into N subbands

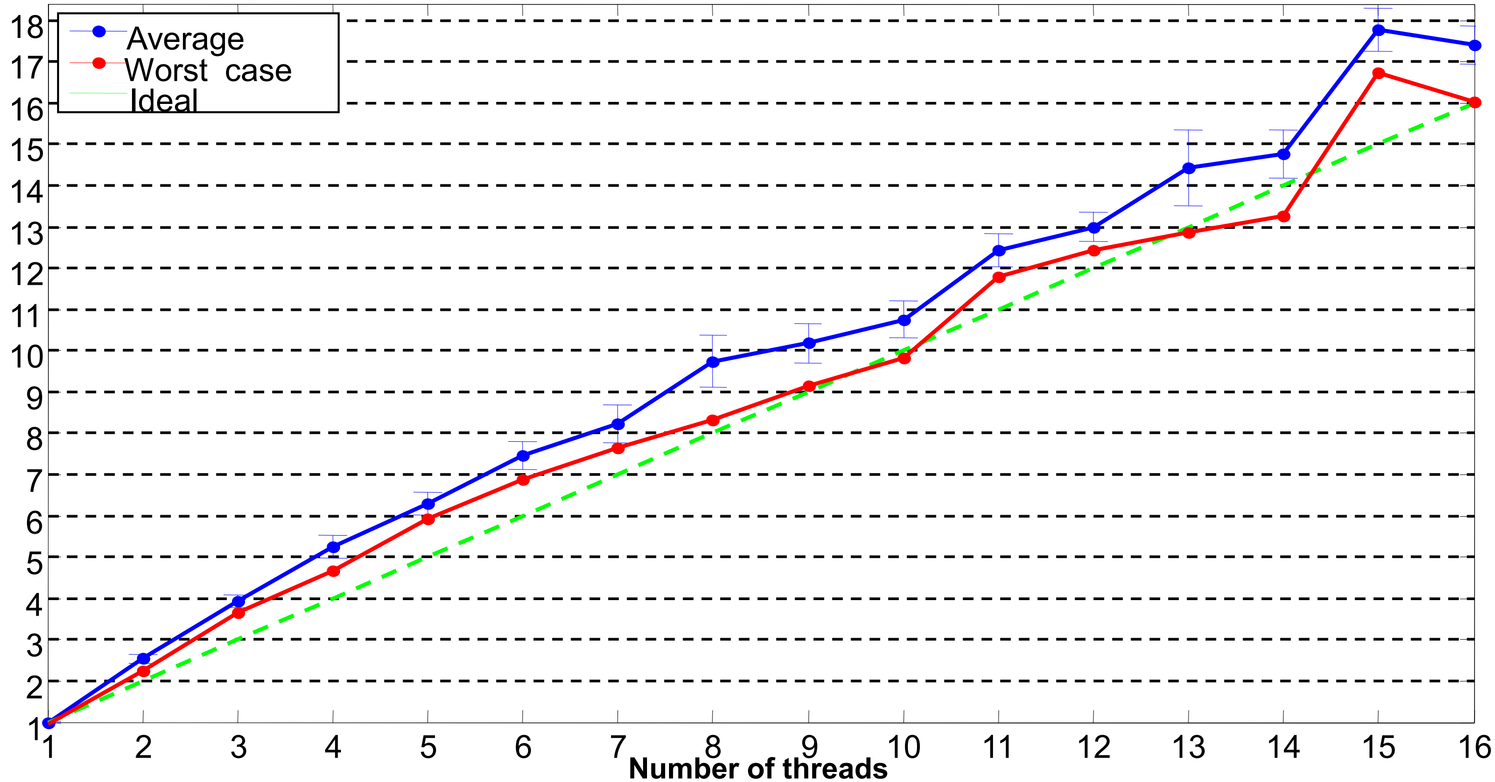
N = F(T)

T= threads

Startup phase

- **Ready**
- **In execution**
- **Completed**

Speedup (high-speed connector model)



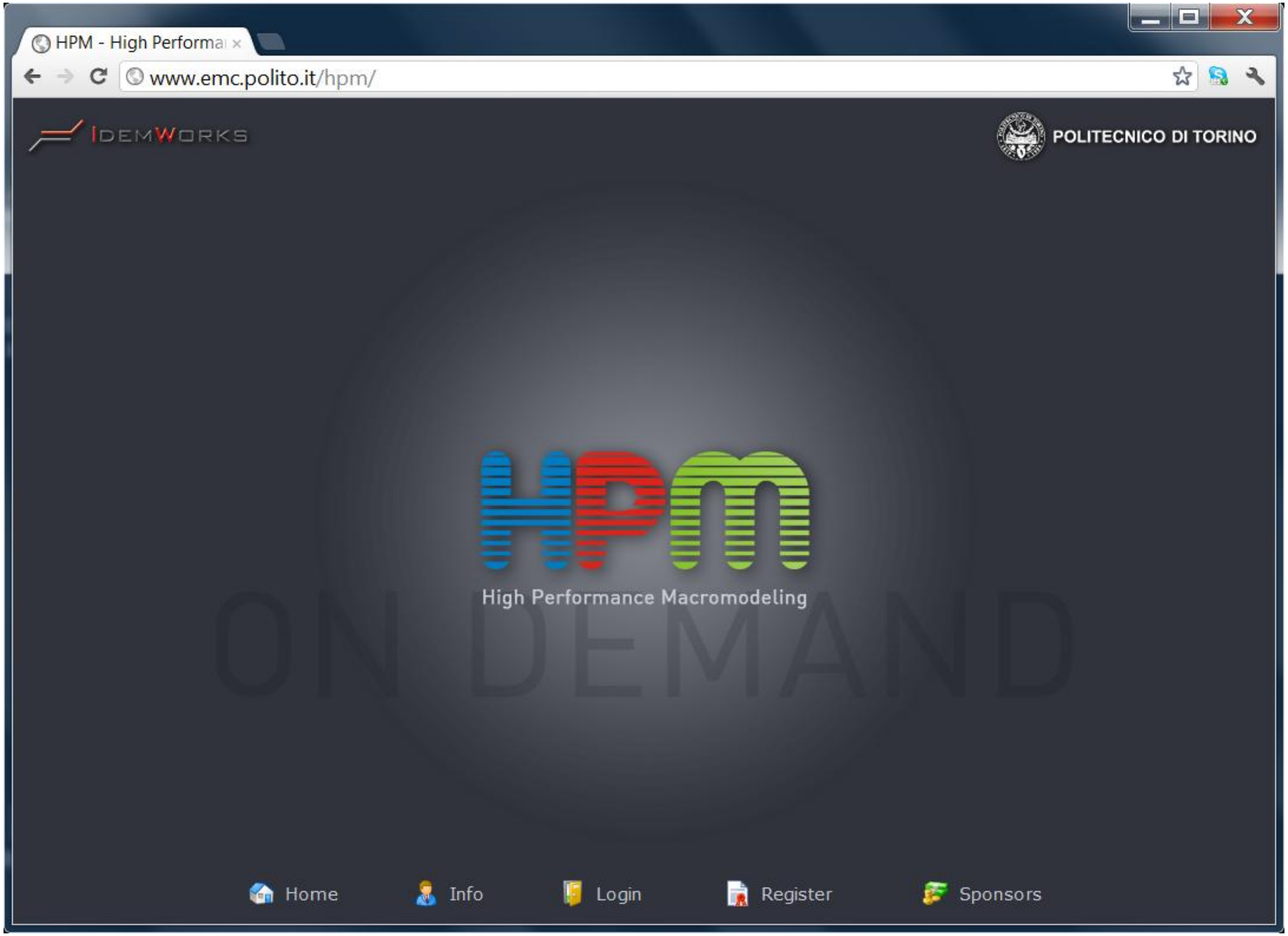
Order	2240
Ports	56
f_{min}	0 GHz
f_{max}	21 GHz
α	5
N λ_{imag}	22

Number of threads	1	2	8	16
Number of λ	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	**17.4 X**

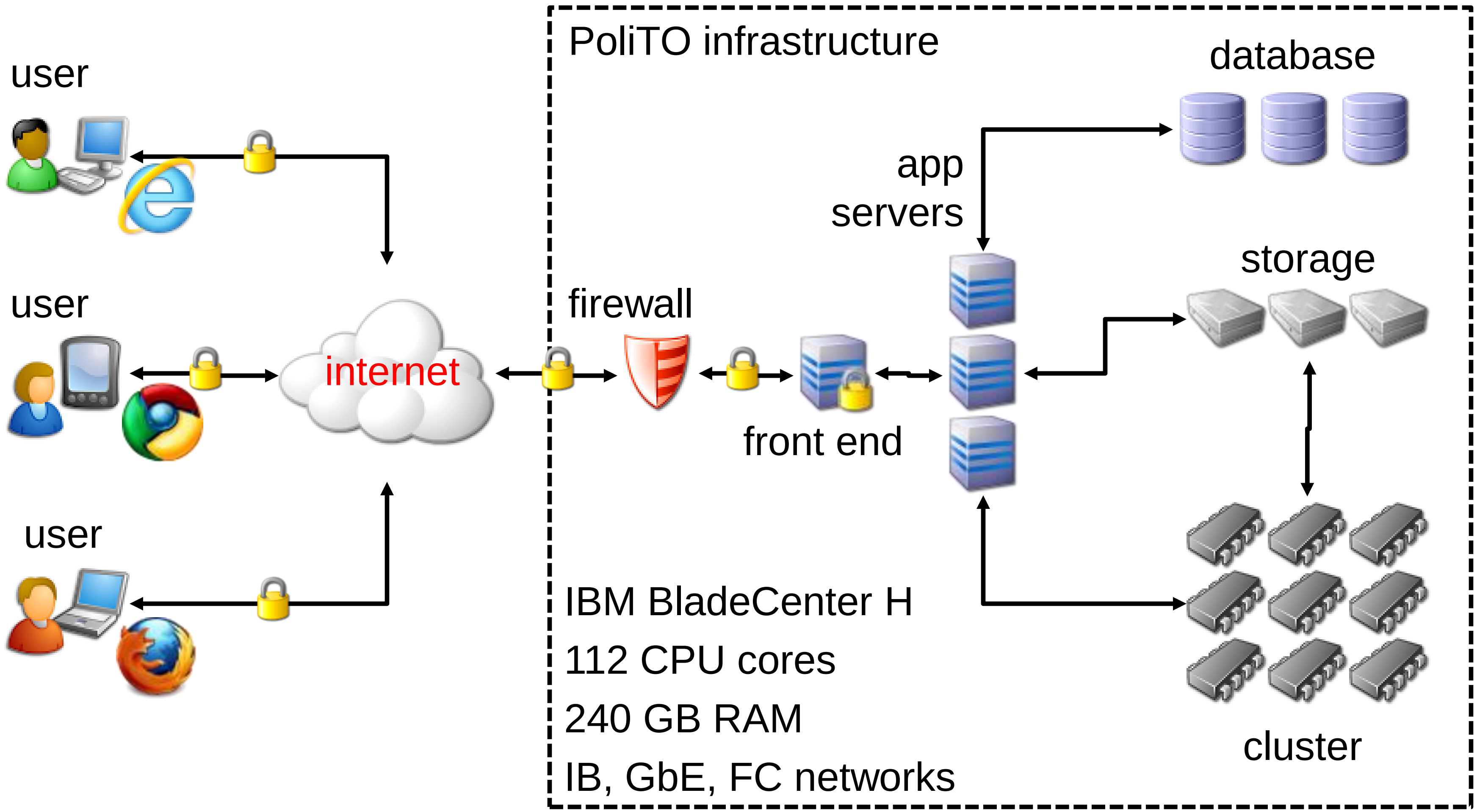
S-parameter modeling flow: a summary

- 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

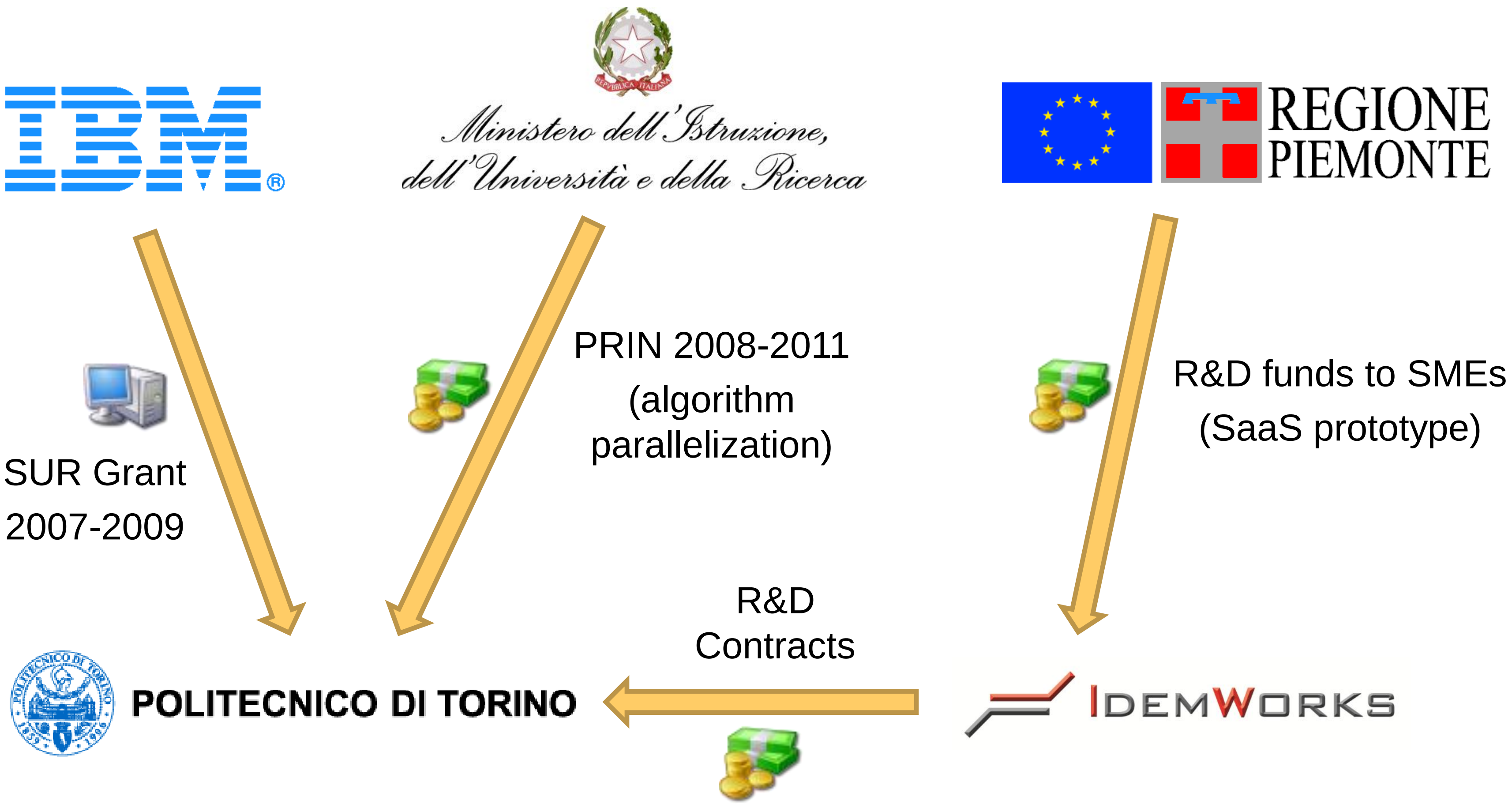
The HPM Service

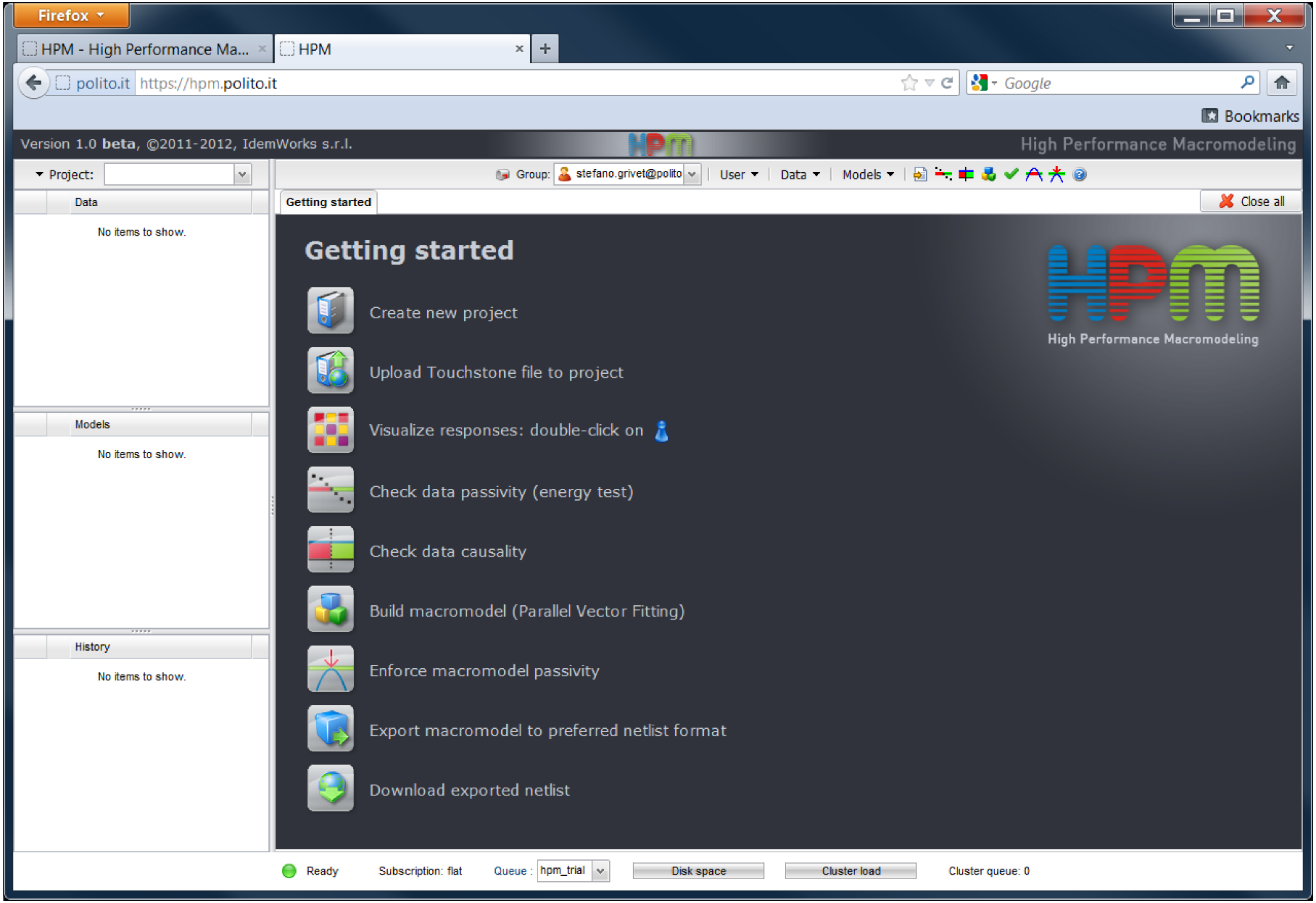


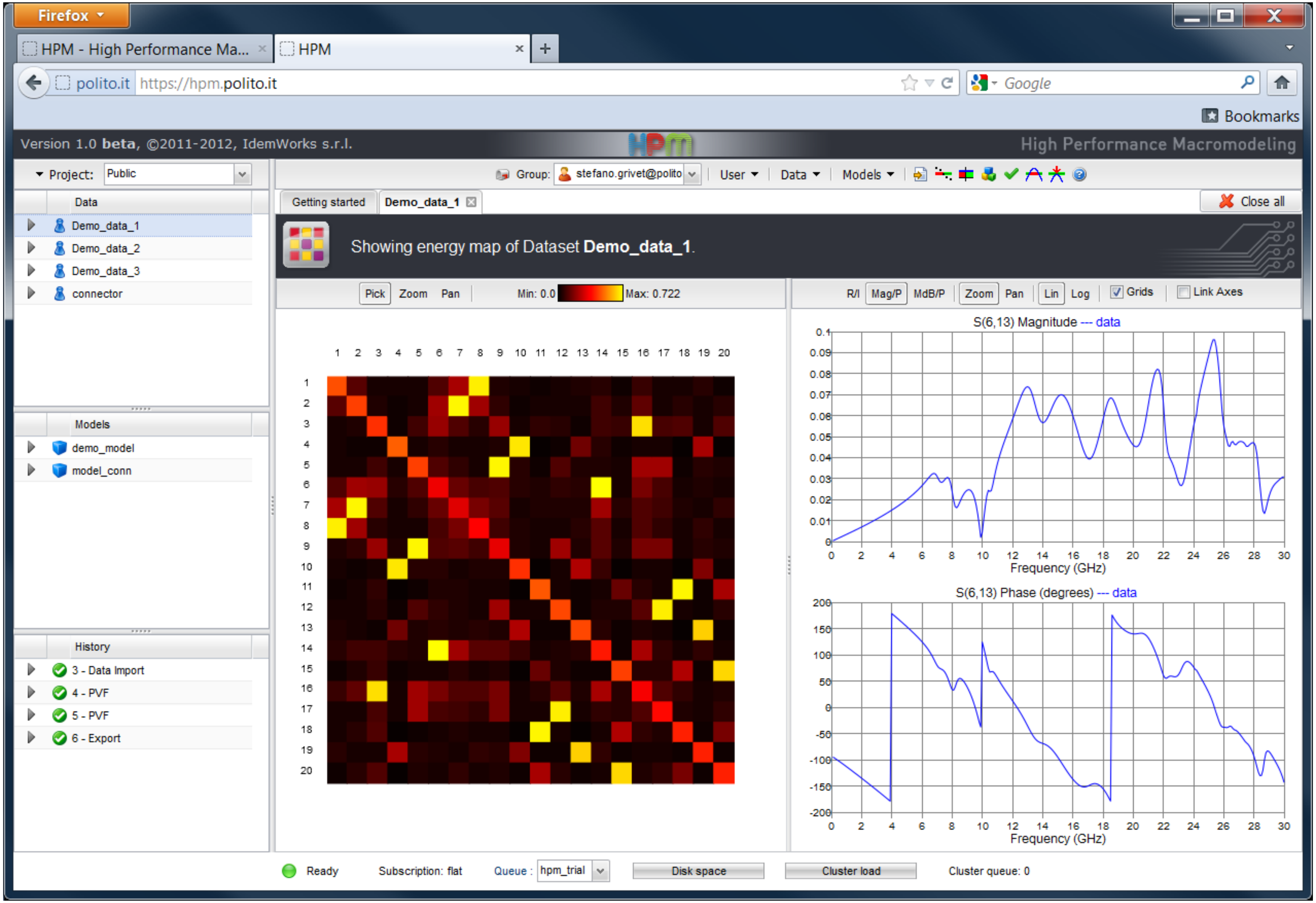
The HPM Service

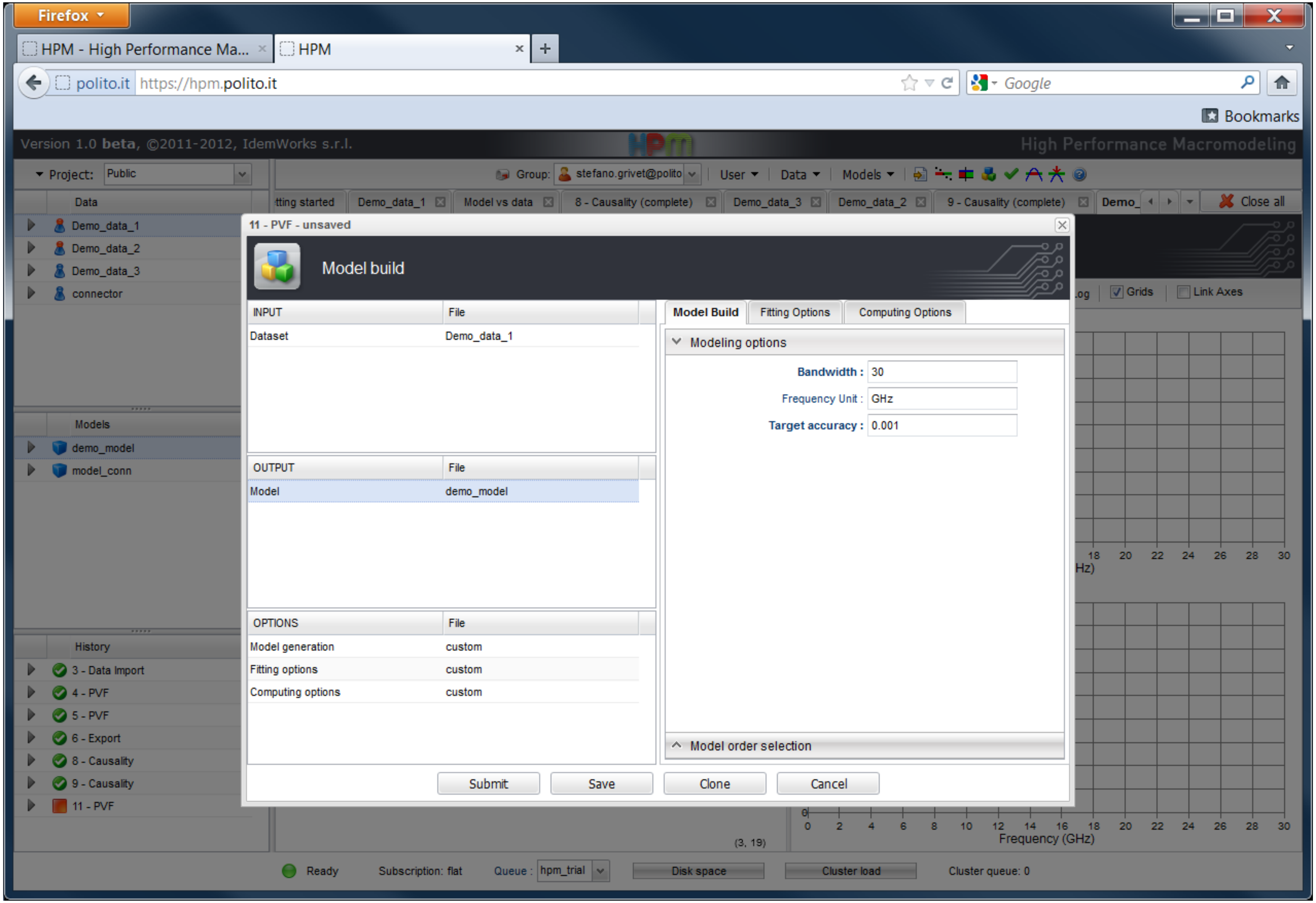


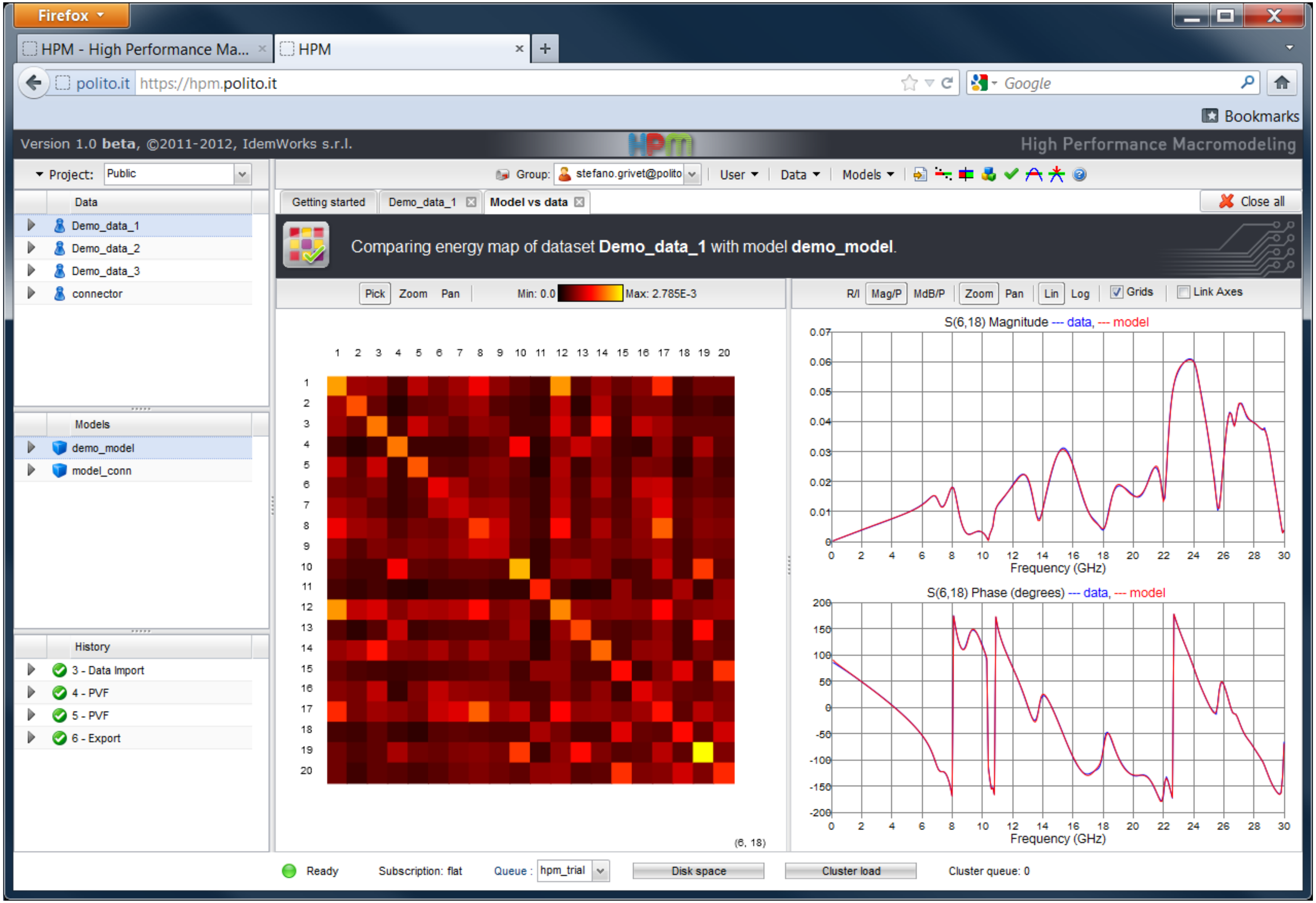
Sponsors

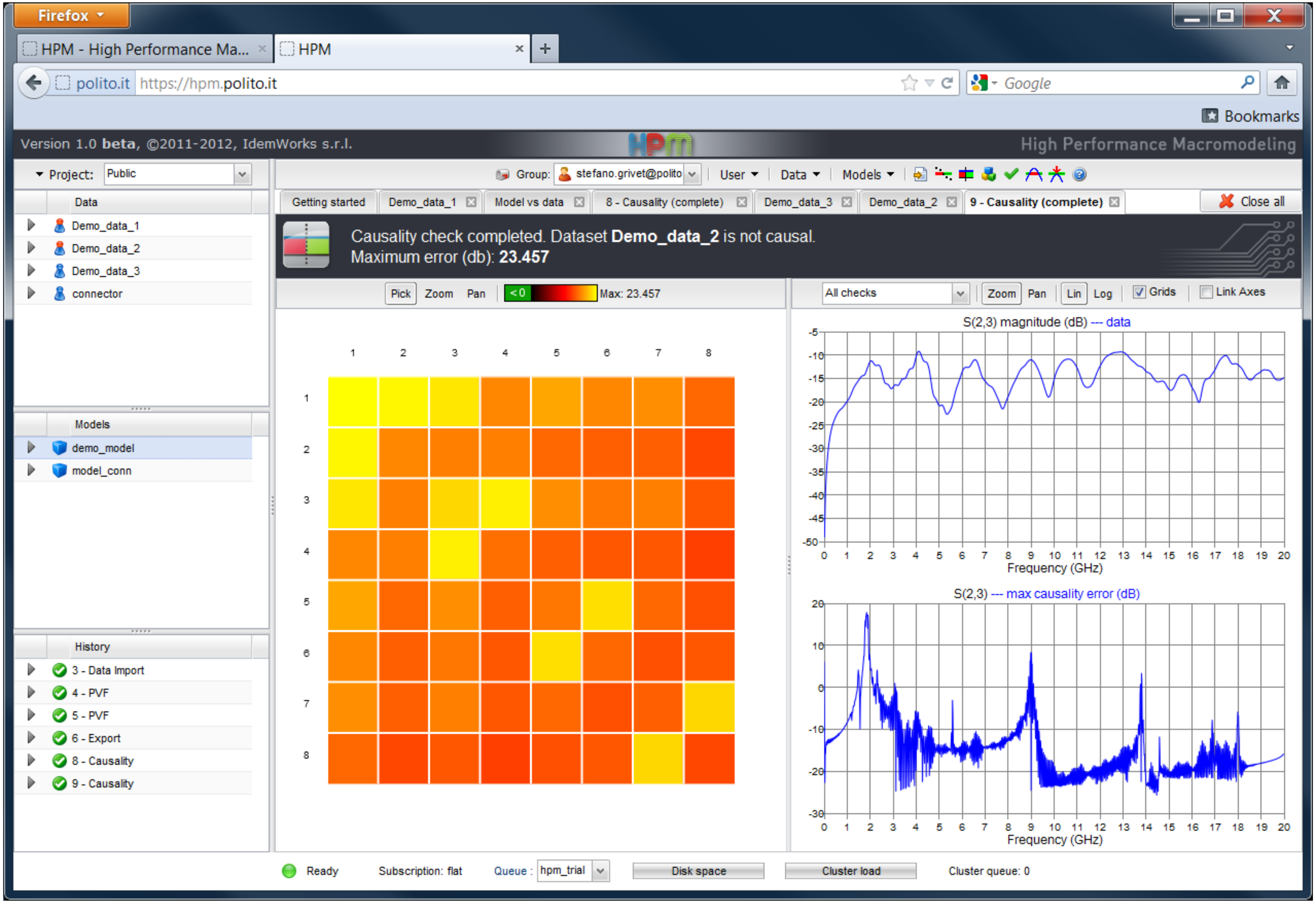

IBM
Ministero dell'Istruzione, dell'Università e della Ricerca
REGIONE PIEMONTE
SUR Grant
2007-2009
PRIN 2008-2011
(algorithm
parallelization)
R&D funds to SMEs
(SaaS prototype)
R&D
Contracts
POLITECNICO DI TORINO
IDEMWORKS


Firefox
HPM - High Performance Ma...
HPM
polito.it https://hpm.polito.it
Google
Bookmarks
Version 1.0 beta, ©2011-2012, IdemWorks s.r.l.
High Performance Macromodeling
Project:
Group: stefano.grivet@polito
User
Data
Models
Getting started
Close all
Data
No items to show.
Models
No items to show.
History
No items to show.
Getting started
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
HPM
High Performance Macromodeling
Ready
Subscription: flat
Queue : hpm_trial
Disk space
Cluster load
Cluster queue: 0

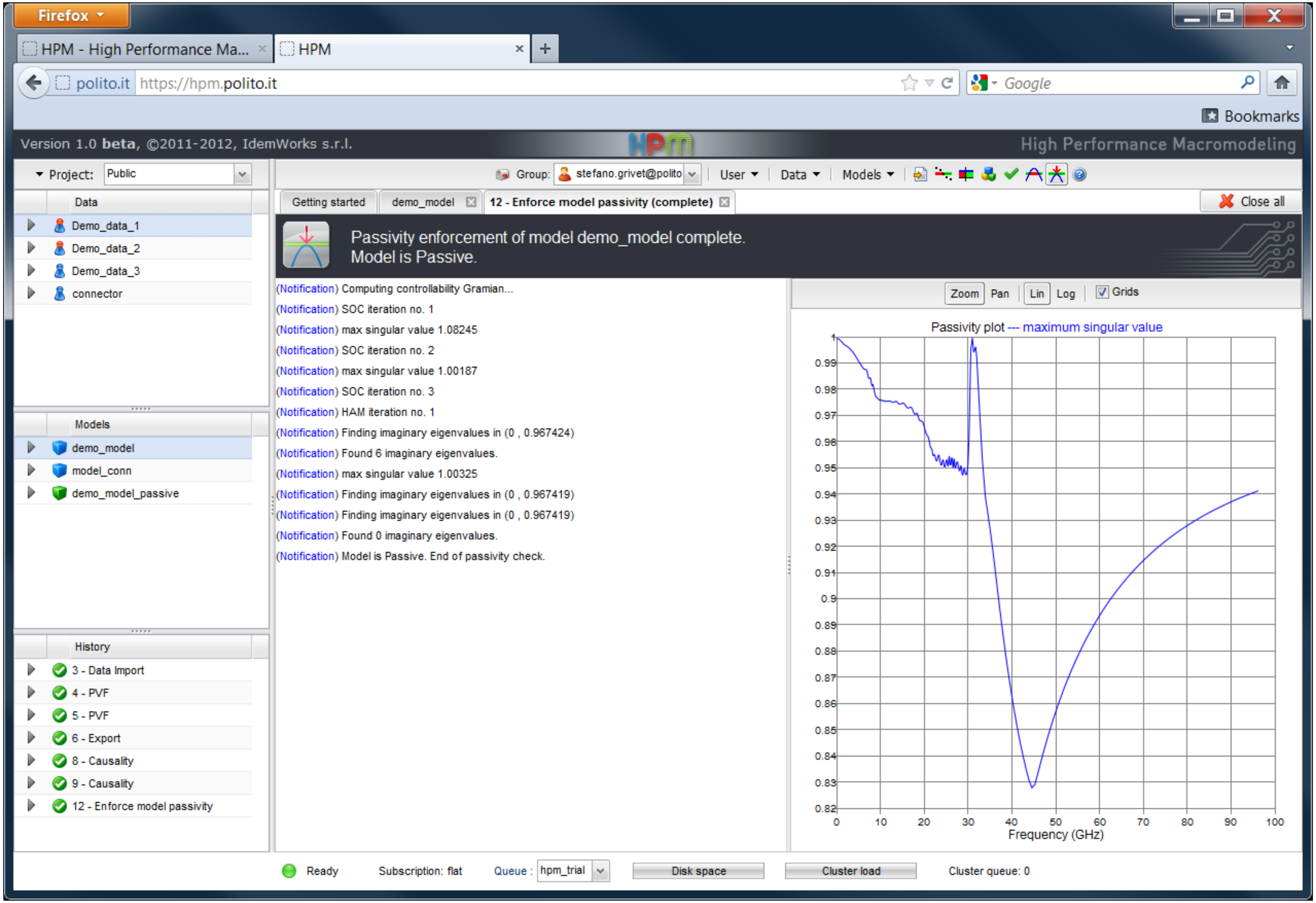

Firefox
HPM - High Performance Ma...
HPM
polito.it https://hpm.polito.it
Google
Bookmarks
Version 1.0 beta, ©2011-2012, IdemWorks s.r.l.
High Performance Macromodeling
Project: Public
Group: stefano.grivet@polito
User
Data
Models
Data
Demo_data_1
Demo_data_2
Demo_data_3
connector
Getting started
Demo_data_1
Close all
Showing energy map of Dataset Demo_data_1.
Pick Zoom Pan
Min: 0.0
Max: 0.722
R/I Mag/P MdB/P Zoom Pan Lin Log Grids Link Axes
S(6,13) Magnitude --- data
Frequency (GHz)
S(6,13) Phase (degrees) --- data
Frequency (GHz)
Models
demo_model
model_conn
History
3 - Data Import
4 - PVF
5 - PVF
6 - Export
Ready
Subscription: flat
Queue : hpm_trial
Disk space
Cluster load
Cluster queue: 0

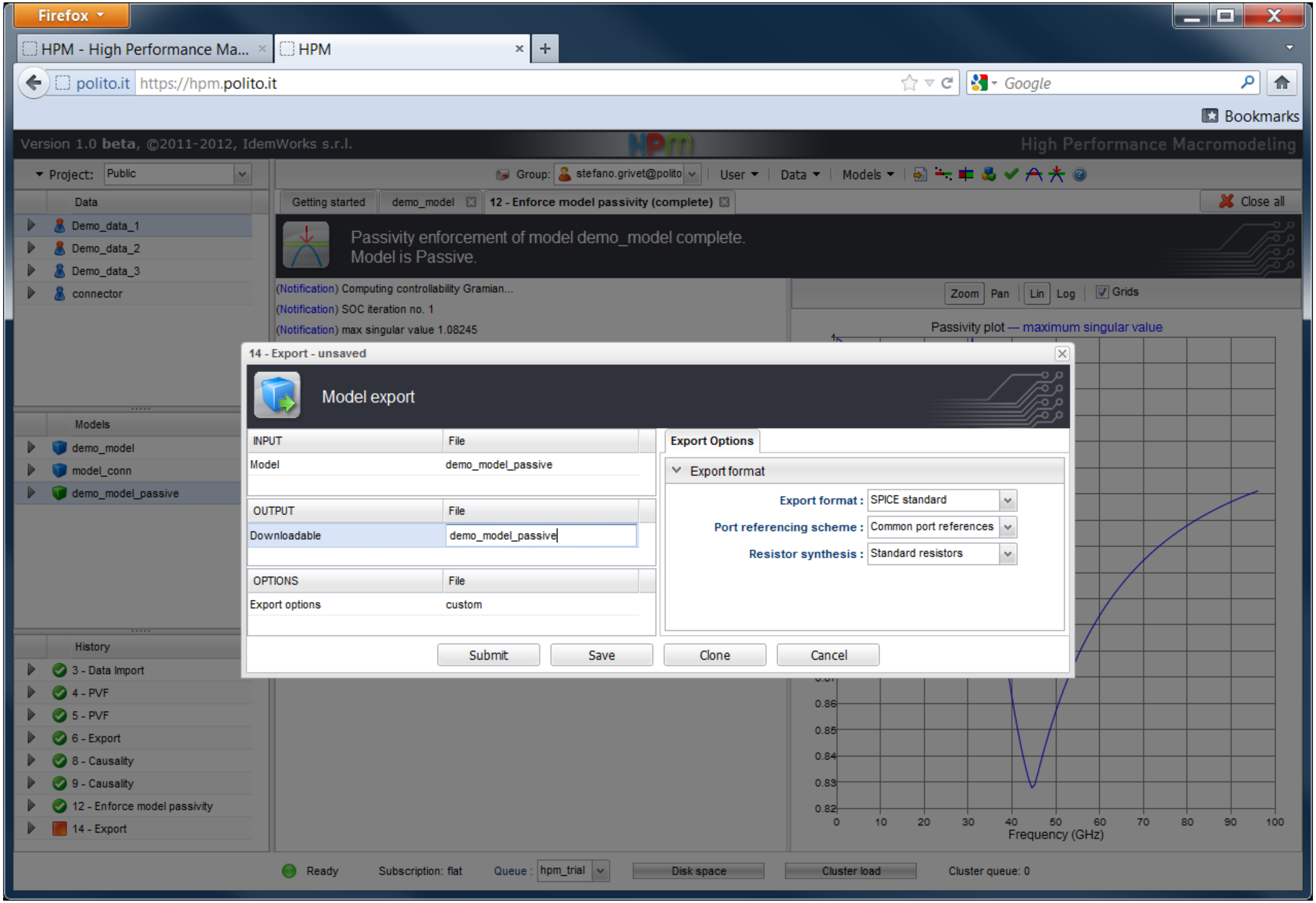

Firefox
HPM - High Performance Ma...
HPM
polito.it https://hpm.polito.it
Google
Bookmarks
Version 1.0 beta, ©2011-2012, IdemWorks s.r.l.
High Performance Macromodeling
Project: Public
Group: stefano.grivet@polito
User
Data
Models
Data
Demo_data_1
Demo_data_2
Demo_data_3
connector
Models
demo_model
model_conn
History
3 - Data Import
4 - PVF
5 - PVF
6 - Export
8 - Causality
9 - Causality
11 - PVF
11 - PVF - unsaved
Model build
INPUT File
Dataset Demo_data_1
OUTPUT File
Model demo_model
OPTIONS File
Model generation custom
Fitting options custom
Computing options custom
Model Build
Fitting Options
Computing Options
Modeling options
Bandwidth : 30
Frequency Unit : GHz
Target accuracy : 0.001
Model order selection
Submit
Save
Clone
Cancel
Close all
Grids
Link Axes
Frequency (GHz)
Ready
Subscription: flat
Queue : hpm_trial
Disk space
Cluster load
Cluster queue: 0

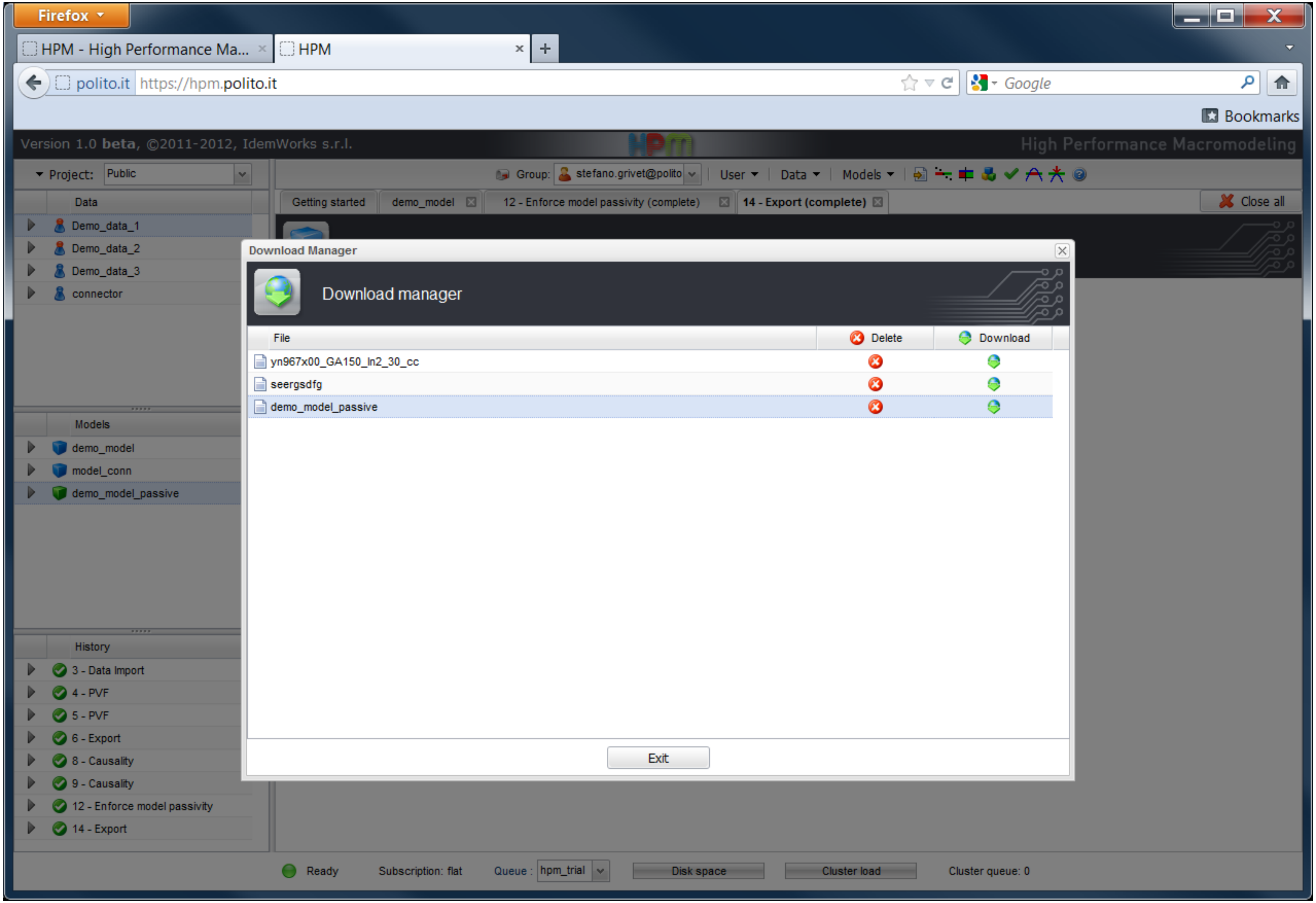

HPM - High Performance Ma...
HPM
https://hpm.polito.it
Version 1.0 beta, ©2011-2012, IdemWorks s.r.l.
High Performance Macromodeling
Project: Public
Group: stefano.grivet@polito
User
Data
Models
Data
Demo_data_1
Demo_data_2
Demo_data_3
connector
Models
demo_model
model_conn
History
3 - Data Import
4 - PVF
5 - PVF
6 - Export
Getting started
Demo_data_1
Model vs data
Close all
Comparing energy map of dataset Demo_data_1 with model demo_model.
Pick
Zoom
Pan
Min: 0.0
Max: 2.785E-3
(6, 18)
R/I
Mag/P
MdB/P
Lin
Log
Grids
Link Axes
S(6,18) Magnitude --- data, --- model
Frequency (GHz)
S(6,18) Phase (degrees) --- data, --- model
Frequency (GHz)
Ready
Subscription: flat
Queue : hpm_trial
Disk space
Cluster load
Cluster queue: 0

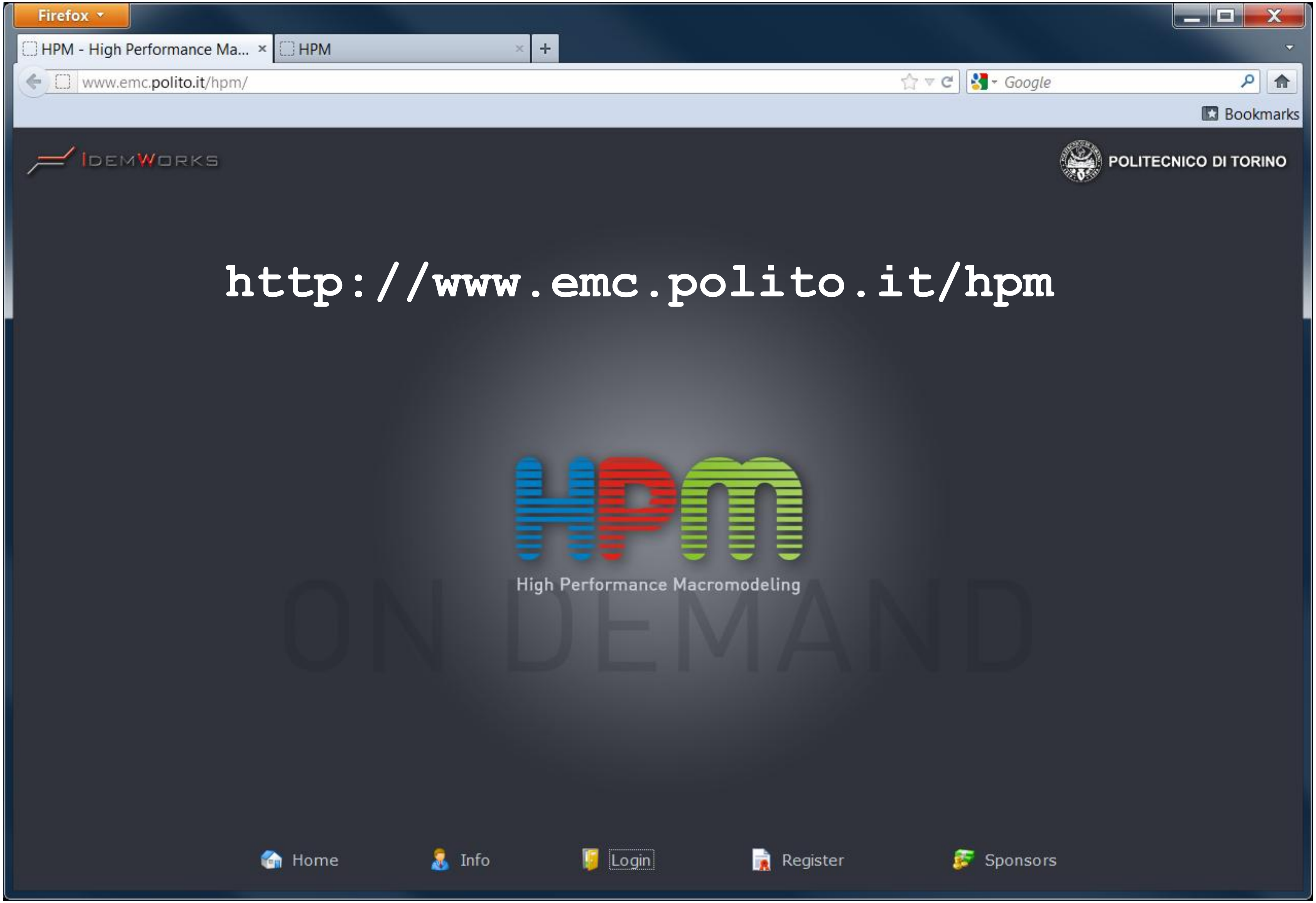


Firefox
HPM - High Performance Ma...
HPM
polito.it https://hpm.polito.it
Google
Bookmarks
Version 1.0 beta, ©2011-2012, IdemWorks s.r.l.
HPM
High Performance Macromodeling
Project: Public
Group: stefano.grivet@polito
User
Data
Models
Getting started
Demo_data_1
Model vs data
8 - Causality (complete)
Demo_data_3
Demo_data_2
9 - Causality (complete)
Close all
Data
Demo_data_1
Demo_data_2
Demo_data_3
connector
Causality check completed. Dataset Demo_data_2 is not causal.
Maximum error (db): 23.457
Pick
Zoom
Pan
< 0
Max: 23.457
All checks
Zoom
Pan
Lin
Log
Grids
Link Axes
S(2,3) magnitude (dB) --- data
Frequency (GHz)
S(2,3) --- max causality error (dB)
Frequency (GHz)
Models
demo_model
model_conn
History
3 - Data Import
4 - PVF
5 - PVF
6 - Export
8 - Causality
9 - Causality
Ready
Subscription: flat
Queue : hpm_trial
Disk space
Cluster load
Cluster queue: 0


Firefox
HPM - High Performance Ma...
HPM
polito.it https://hpm.polito.it
Google
Bookmarks
Version 1.0 beta, ©2011-2012, IdemWorks s.r.l.
High Performance Macromodeling
Project: Public
Group: stefano.grivet@polito
User
Data
Models
Data
Demo_data_1
Demo_data_2
Demo_data_3
connector
Models
demo_model
model_conn
demo_model_passive
History
3 - Data Import
4 - PVF
5 - PVF
6 - Export
8 - Causality
9 - Causality
12 - Enforce model passivity
Getting started
demo_model
12 - Enforce model passivity (complete)
Close all
Passivity enforcement of model demo_model complete.
Model is Passive.
(Notification) Computing controllability Gramian...
(Notification) SOC iteration no. 1
(Notification) max singular value 1.08245
(Notification) SOC iteration no. 2
(Notification) max singular value 1.00187
(Notification) SOC iteration no. 3
(Notification) HAM iteration no. 1
(Notification) Finding imaginary eigenvalues in (0 , 0.967424)
(Notification) Found 6 imaginary eigenvalues.
(Notification) max singular value 1.00325
(Notification) Finding imaginary eigenvalues in (0 , 0.967419)
(Notification) Finding imaginary eigenvalues in (0 , 0.967419)
(Notification) Found 0 imaginary eigenvalues.
(Notification) Model is Passive. End of passivity check.
Zoom
Pan
Lin
Log
Grids
Passivity plot --- maximum singular value
Frequency (GHz)
Ready
Subscription: flat
Queue : hpm_trial
Disk space
Cluster load
Cluster queue: 0


Firefox
HPM - High Performance Ma...
HPM
polito.it https://hpm.polito.it
Google
Bookmarks
Version 1.0 beta, ©2011-2012, IdemWorks s.r.l.
High Performance Macromodeling
Project: Public
Group: stefano.grivet@polito
User
Data
Models
Close all
Getting started
demo_model
12 - Enforce model passivity (complete)
Passivity enforcement of model demo_model complete.
Model is Passive.
(Notification) Computing controllability Gramian...
(Notification) SOC iteration no. 1
(Notification) max singular value 1.08245
Zoom
Pan
Lin
Log
Grids
Passivity plot — maximum singular value
Frequency (GHz)
Data
Demo_data_1
Demo_data_2
Demo_data_3
connector
Models
demo_model
model_conn
demo_model_passive
History
3 - Data Import
4 - PVF
5 - PVF
6 - Export
8 - Causality
9 - Causality
12 - Enforce model passivity
14 - Export
14 - Export - unsaved
Model export
INPUT
File
Model
demo_model_passive
OUTPUT
File
Downloadable
demo_model_passive
OPTIONS
File
Export options
custom
Export Options
Export format
Export format : SPICE standard
Port referencing scheme : Common port references
Resistor synthesis : Standard resistors
Submit
Save
Clone
Cancel
Ready
Subscription: flat
Queue : hpm_trial
Disk space
Cluster load
Cluster queue: 0


Firefox
HPM - High Performance Ma...
HPM
polito.it https://hpm.polito.it
Google
Bookmarks
Version 1.0 beta, ©2011-2012, IdemWorks s.r.l.
High Performance Macromodeling
Project: Public
Group: stefano.grivet@polito
User
Data
Models
Getting started
demo_model
12 - Enforce model passivity (complete)
14 - Export (complete)
Close all
Data
Demo_data_1
Demo_data_2
Demo_data_3
connector
Models
demo_model
model_conn
demo_model_passive
History
3 - Data Import
4 - PVF
5 - PVF
6 - Export
8 - Causality
9 - Causality
12 - Enforce model passivity
14 - Export
Download Manager
Download manager
File
Delete
Download
yn967x00_GA150_ln2_30_cc
seergsdfg
demo_model_passive
Exit
Ready
Subscription: flat
Queue : hpm_trial
Disk space
Cluster load
Cluster queue: 0


Firefox
HPM - High Performance Ma...
HPM
www.emc.polito.it/hpm/
Google
Bookmarks
IDEMWORKS
POLITECNICO DI TORINO
http://www.emc.polito.it/hpm
HPM
High Performance Macromodeling
ON DEMAND
Home
Info
Login
Register
Sponsors

Thank you

http://www.emc.polito.it

IDEMWORKS

http://www.idemworks.com

References

1. S. Grivet-Talocia, HPM: an interactive web service for high-performance macromodeling of passive interconnects in system-level verification flows, *University Booth, Design Automation and Test in Europe Conference (DATE12), Dresden (Germany)*, March 12-16, 2012.
2. HPM service. Available online: http://www.emc.polito.it/hpm
3. P. Triverio, S. Grivet-Talocia, M.S. Nakhla, F. Canavero, R. Achar, "Stability, Causality, and Passivity in Electrical Interconnect Models" , *IEEE Transactions on Advanced Packaging, vol. 30, n. 4*, pp. 795-808, November, 2007
4. A. Chinea, S. Grivet-Talocia, "On the Parallelization of Vector Fitting Algorithms" , *IEEE Transactions on Components, Packaging, and Manufacturing Technology, Vol. 1 , n. 11*, pp. 1761-1773, November 2011, 2011
5. L. Gobbato, A. Chinea, S. Grivet-Talocia, "A Parallel Hamiltonian Eigensolver for Passivity Characterization and Enforcement of Large Interconnect Macromodels" , *Design, Automation and Test in Europe Conference (DATE11), Grenoble (France),* pp. 26-31, March 14-18, 2011