

ALGORITMI NUMERICI

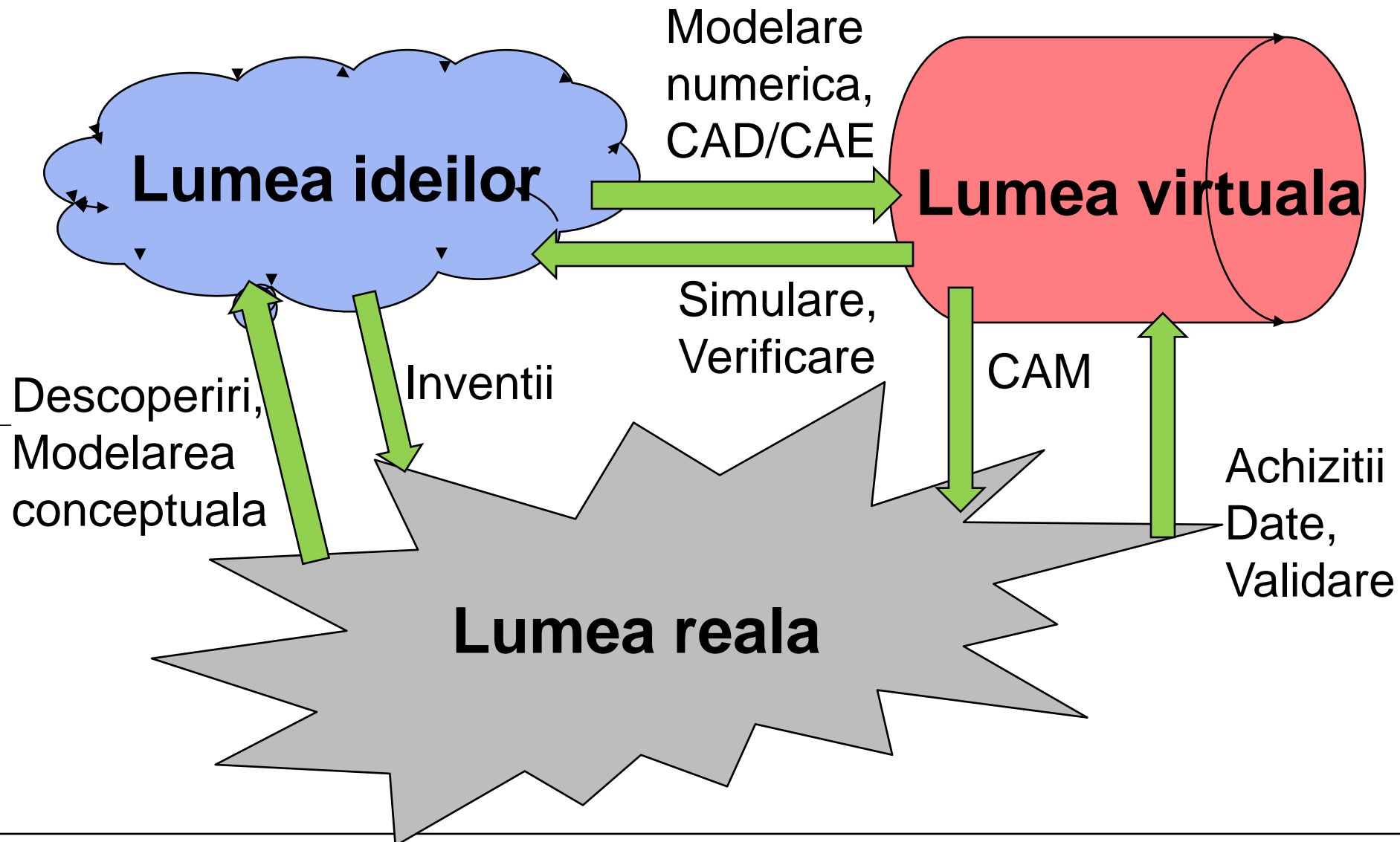
Aspecte motivationale pentru masteranzi

Daniel Ioan, cu ajutor de la
Gabriela Ciuprina, Dan Daniel, Sorin Lup
Universitatea Politehnica din Bucuresti –
PUB - CIEAC/LMN

<http://www.lmn.pub.ro/~daniel>

- **Introducere - context**
 - Modelare
 - LMN
 - Comunitate
- **Continut - 3 idei novatoare:**
 - dFIT
 - MEEC
 - ALROM
- **Aplicatii si proiecte**
 - Car radar pentru Philips
 - Electromagneti pentru FAIR
 - RF MEMS pentru IMT

Civilizatia dupa trei revolutii: stiintifica, industrialala si digitala



un concept fundamental

Reprezentarea in lumea ideilor si in cea virtuala a unor obiecte din lumea reala, la care fenomenele electromagnetice sunt esentiale.

Prin extensie se obtine modelarea multifizica.

Etapele modelarii (ACES)

1. Modelarea conceptuala

- a) fizica
- b) geometrica

2. Modelarea matematica

3. Modelarea analitica – aproximativa

4. Modelarea numerica

5. Modelarea algoritmica

6. Reducerea modelului

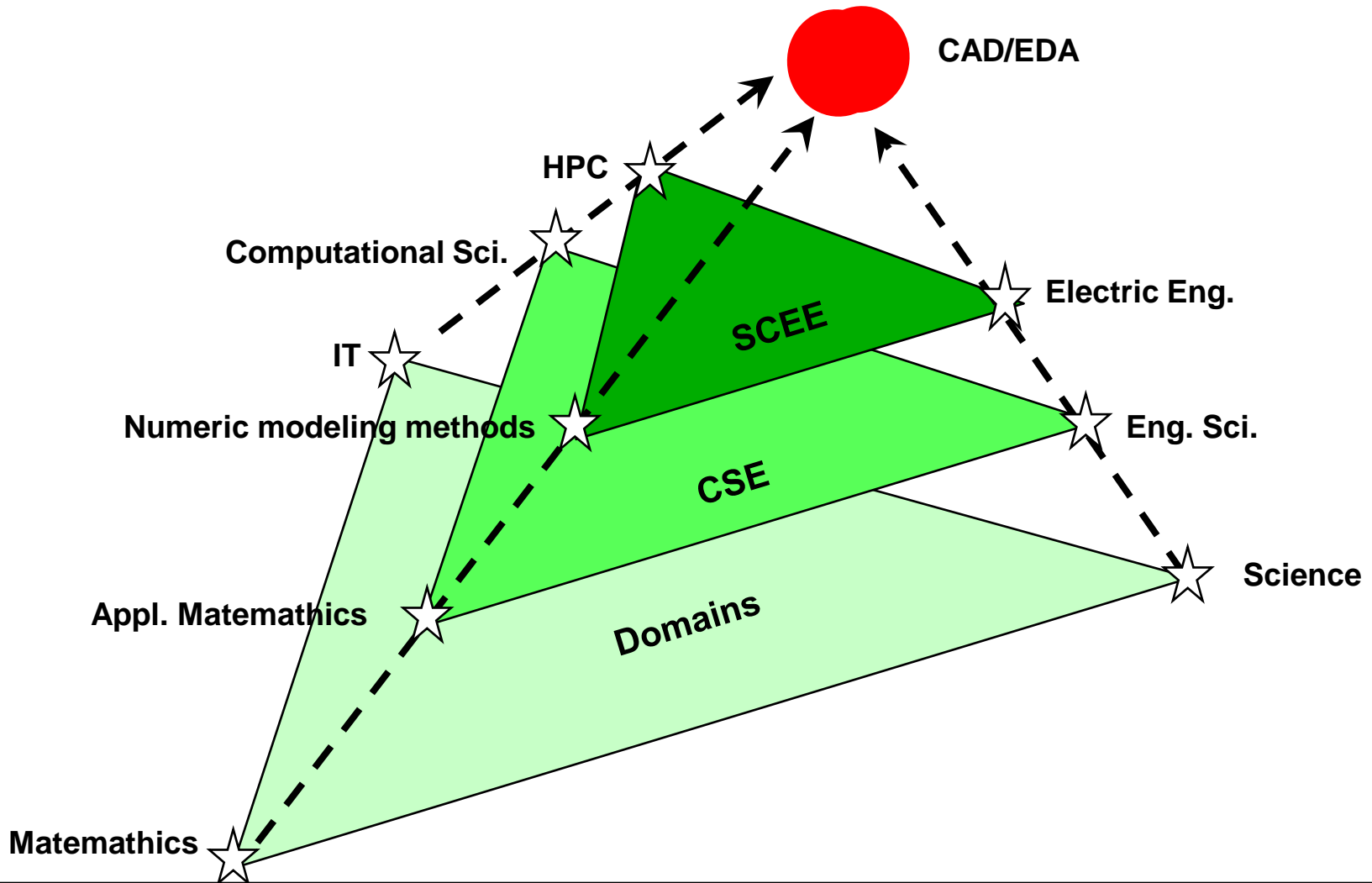
7. Verificarea si validarea

Detalii in *D. Ioan – Modelarea multifizica,*

la cerere: Daniel.Ioan@upb.ro

Piramida SCEE (Scientific Computing in EE)

Viziunea strategica a LMN: modelarea este interdisciplinara



Calcul de inalta performanta

HPC=High Performace Computing

- **Obiectiv:** Folosirea tehnicilor de calcul de inalta performanta in rezolvarea problemelor stiintifice si ingineresti
- **Tehnici de calcul de inalta performanta (HPC=High Performace Computing):** utilizarea eficienta a sistemelor de calcul avansate – care de regula au mai multe unitati de procesare (**multiprocesor**)
- Initial ele se foloseau pentru **supercalculatoare**, dar ulterior datorita dezvoltarii si ieftinirii procesoarelor avansate precum si a interconectarii, ele s-au “democratizat”, devenind populare in majoritatea proiectelor IT avansate, creative, referitoare la problemele complexe, de mari dimensiuni.



Calculul științific de înaltă performanță - HPSC

HPSC are un puternic caracter **interdisciplinar**, implicând cunoștințe:

- **Științifice** (în special de fizică) și ingineresti (electrice, electronice, mecanice, termice, hidro și aero-dinamice) dar și de Matematici aplicate,
- De **algoritmi numerici**, în special de **algebra liniară numerică**
- **Metodologii software**

Pentru implementarea eficientă a aplicațiilor sunt necesare și cunoștințe de

- **Arhitectura și caracteristicile calculatoarelor**, atât la nivel CPU cât și la cel al sistemelor paralele și
- Deprinderi specifice **ingineriei software**, în vederea managementului software profesional în dezvoltarea procedurilor și programelor de aplicații pentru sistemele de calcul multi-procesor

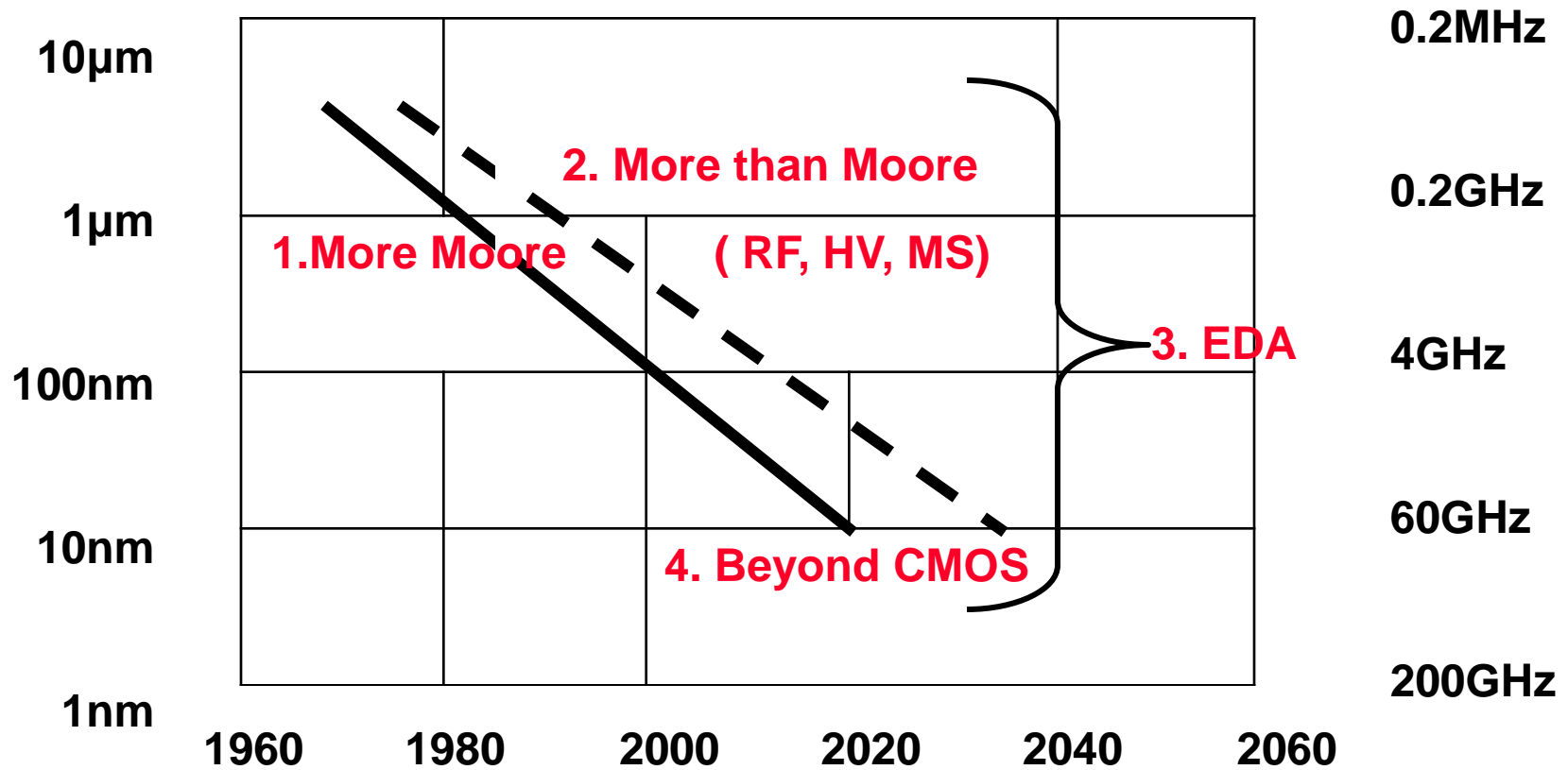
Disciplina HPSC (High Performance Scientific Computing) este deci o **punte între Metodele de Modelare Numerică și Tehnicile de calcul paralel și distribuit, în strânsă legătură cu CSE**. Scopul este de a dezvolta **Algoritmi Numerici** eficienți pentru rezolvarea problemelor de mari dimensiuni, ținând cont de structura reală a sistemelor de calcul, și nu doar pentru un calculator ipotetic, virtual.

COMPUMAG topics (**Bold = abordate in LMN**)

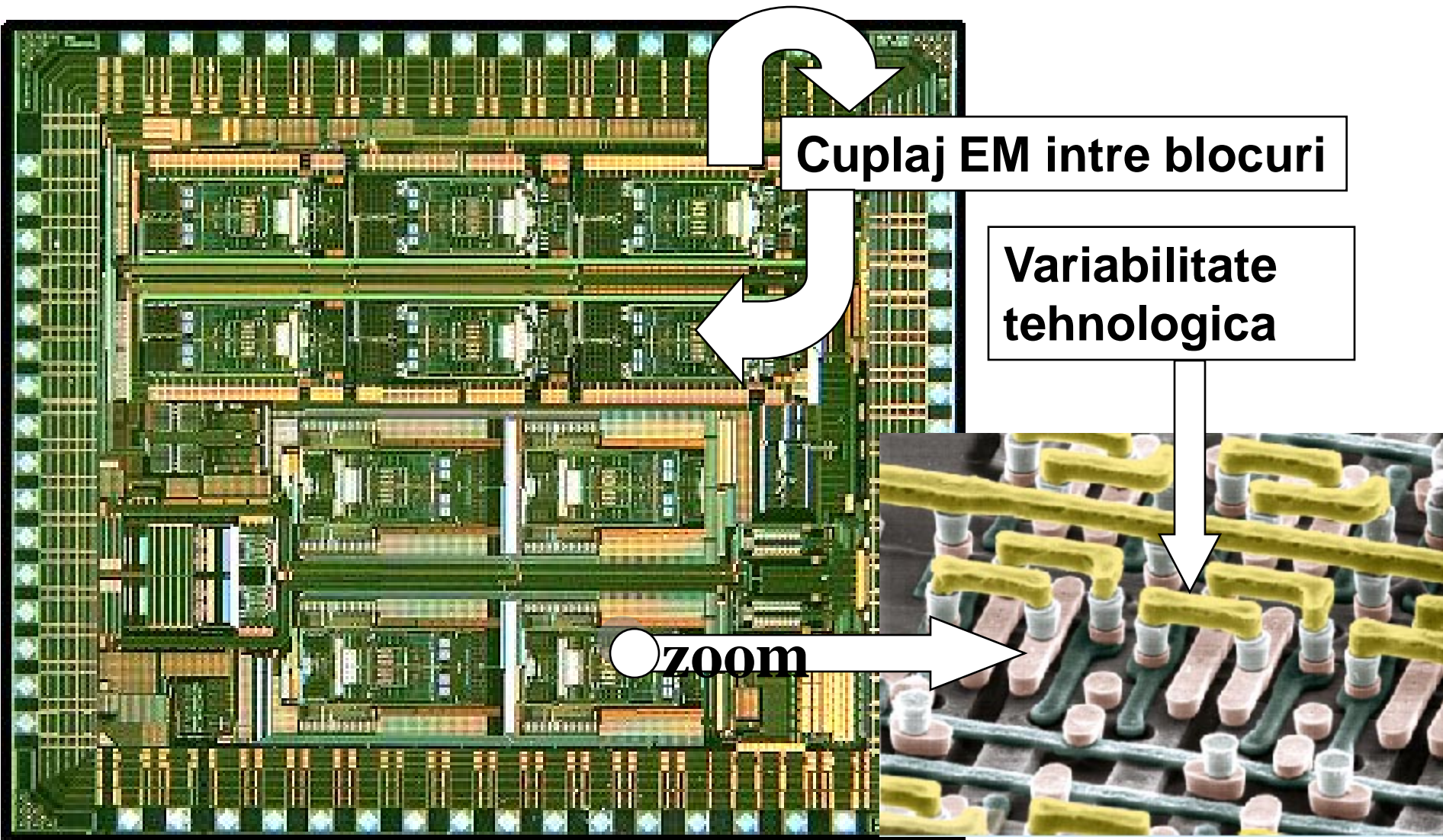
1. **Static and Quasi-Static Fields**
2. **Wave Propagation**
3. **Electromagnetic Compatibility**
4. **Nano-Electromagnetic Computation and Applications**
5. **Bio-Electromagnetic Computation and Applications**
6. **Non-destructive Electromagnetic Inspection and Applications**
7. Photonics and Optoelectronics
8. Material Modelling
9. **Coupled Multi-physics Problems**
10. **Optimization and Design**
11. **Numerical Techniques**
12. **Software Methodology**
13. Electric Machines and Drives
14. **Devices and Applications**
15. **Education**
16. **Benchmarking (TEAM)**

www.compumag.org

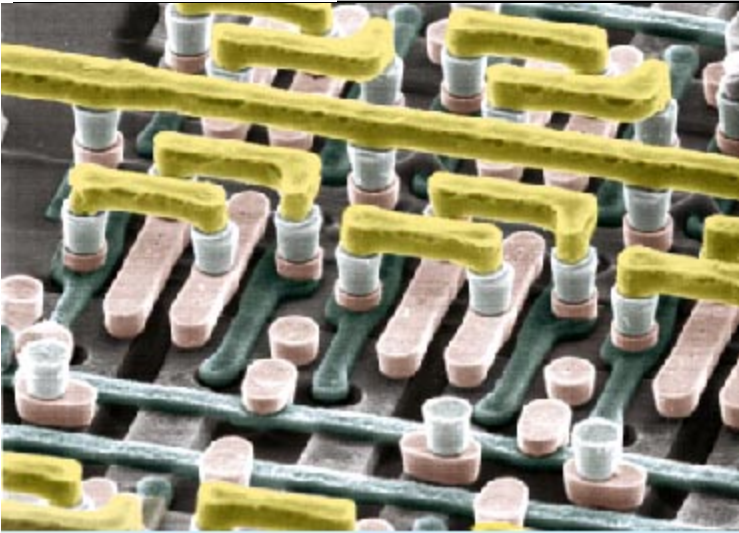
Directiile strategice de cercetare (SRA):



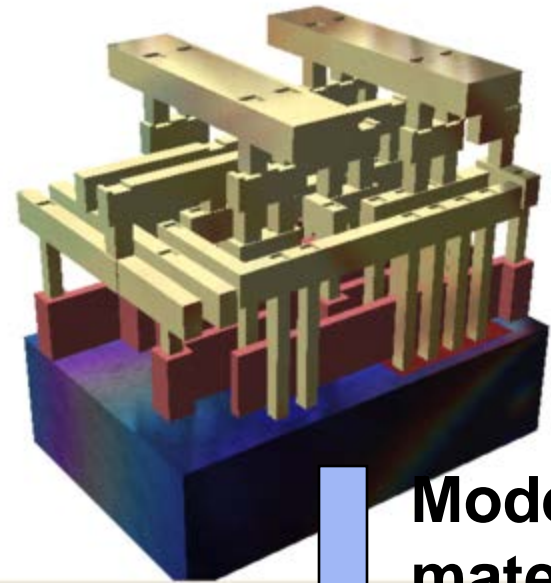
Complexitatea lumii reale



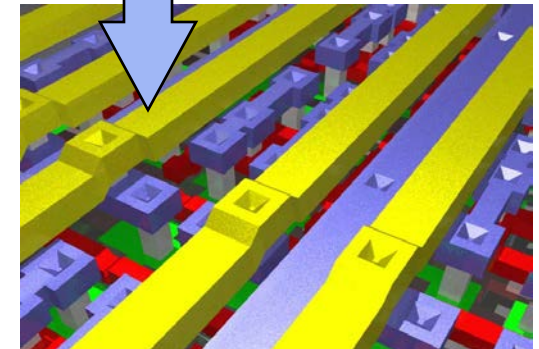
Calculul campului EM in abordarea clasica



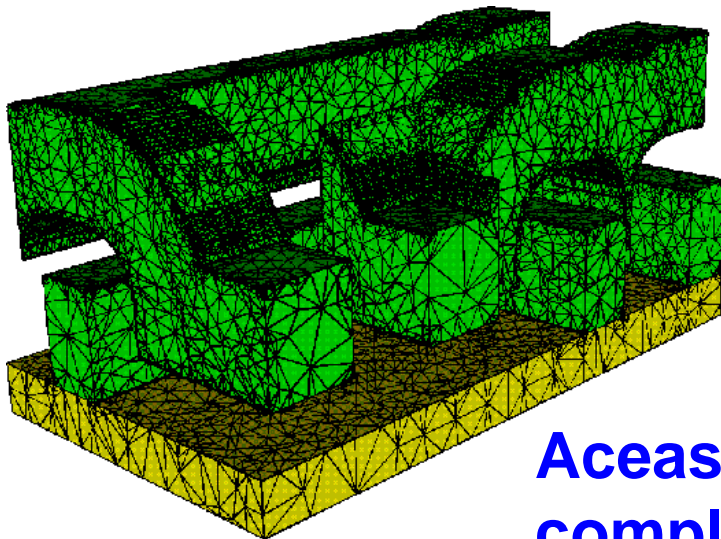
Modelarea
geometrica
idealizata



Modelarea
materialelor

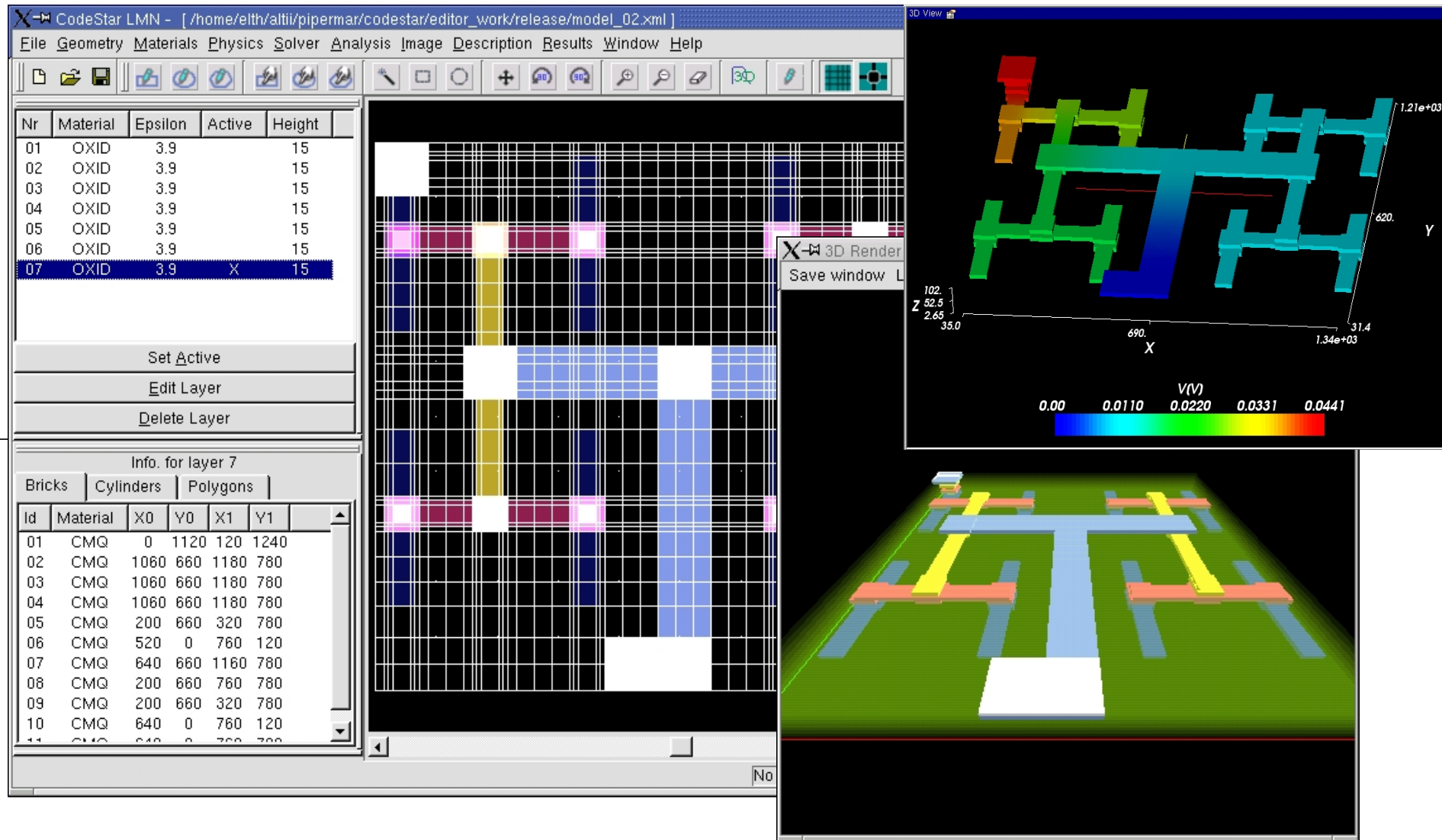


Retea BEM
sau FEM



**Aceast abordare nu poate face fata
complexitatii realitatii !**

Obiectivul Codestar: o punte de la masti (.cif ,.gds) la circuit (Spice)



The screenshot displays the CodeStar LMN software interface. The main window shows a 2D layout editor with a grid and various colored regions representing different materials and layers. A 3D render window is visible, showing a 3D perspective view of the circuit board with a color scale for voltage (V) ranging from 0.00 to 0.0441. The 3D view includes axes (X, Y, Z) and a color bar indicating voltage levels.

Table 1: Layer Properties

Nr	Material	Epsilon	Active	Height
01	OXID	3.9		15
02	OXID	3.9		15
03	OXID	3.9		15
04	OXID	3.9		15
05	OXID	3.9		15
06	OXID	3.9		15
07	OXID	3.9	X	15

Table 2: Layer 7 Bricks

Id	Material	X0	Y0	X1	Y1
01	CMQ	0	1120	120	1240
02	CMQ	1060	660	1180	780
03	CMQ	1060	660	1180	780
04	CMQ	1060	660	1180	780
05	CMQ	200	660	320	780
06	CMQ	520	0	760	120
07	CMQ	640	660	1160	780
08	CMQ	200	660	760	780
09	CMQ	200	660	320	780
10	CMQ	640	0	760	120
11	CMQ	640	0	760	120

Structura de invatamant superior si cercetare:

- **LMN:** Laboratorul de Metode Numerice (din Catedra de Electrotehnica a UPB, EA208): 1984
- **PS CAEE** (Computer Aided Electrical Engineering) TEMPUS Graduate School: 1992
- **CIEAC:** Centrul de Inginerie Electrica Asistata de Calculator din UPB: 1995
- **DS SCEE:** Marie Curie Doctoral School in Electrical Engineering and Computational Science: 2005
- **LMN:** Laboratorul de Modelare Numerica (din CIEAC, EAD01): 2008

Aceste structuri au fost infiintate si conduse de D. Ioan

1. TEMPUS JEP/JEN 2717 – **PS CAEE** coordonator de proiect: 1991-95
2. PECO – **CAEE '93** – initiator si coordonator proiect: 1992-93
3. TEMPUS JEP 2912 - **ACIT** - contractorul proiectului: 1995-1998
4. INCO-COPERNICUS/**EuroEast** – coordonator UPB: 1995-1998
5. FP5/Copernicus/**Manodet** - coordonator UPB: 1997-2000
6. JASAEM/JRJSAEM – coordonator UPB: 1996-98
7. JSAEM/**ENDE** - coordonator UPB: 1998-2002
8. WB/CNCSU/BCUM/**CoLaborator** - co-initiator proiect: 1998-2000
- 9. FP5/IST/**Codestar** - coordonator UPB: 2002 – 2004
10. FP6/IST/**Chameleon RF** - coordonator UPB: 2005 – 2008
11. FP6/EST/**EST3** - initiator si coordonator proiect: 2005-2009
12. FP6/RTN/**COMSON** - coordonator UPB: 2005 – 2009
13. FP6/ToK/**4nEDA** - initiator si coordonator proiect: 2006 – 2010
14. FP6/NMP/**Artic** - coordonator UPB: 2006 – 2010
15. COST/**EU-MORNET** – coordonator al subretelei RO-MORNET: 2012-18

Buget total: peste **3 milioane Euro** gestionati de UPB/CIEAC

Echipele de cercetare din LMN se alcatuiesc pe baza proiectelor. Din ele au facut parte in diferite proiecte mai multe persoane din tara si din strainatate:

- D. Ioan
- F.M.G. Tomescu
- C. Popeea
- Irina Munteanu
- Gabriela Ciuprina
- Alexandra Stefanescu
- B. Ionescu
- M. Lazarescu
- I.F. Hanitila
- M. Iordache
- M. Nitescu
- V. Ionita
- Al. Morega
- S. Kratochvil
- C. Stancu
- M. Rebican
- R. Popa
- M. Popescu
- A. Duca
- S. Gim
- S. Kula
- D. Niculae
- D. Isvoranu
- D. Mihalache
- I. Andrei
- D. Dan
- B. Dita
- S. Lup
- M. Platon
- Gh. Juncu
- M. Radulescu
- M. Piper
- M. Bodea
- S. Popescu
- S. Spanoche
- C. Dan
- R. Dogaru
- C.G. Constantin
- J.F. Villena
- I.A. Lazar
- C. Ciobotaru
- A. Szigeti
- C. Dumitrescu
- V. Beiu
- Mihaela Dumbrava
- H. Giuroiu,
- L. Jurubița
- R. Mărculescu
- D.M. Farini
- B. Vasiliu
- T. Chelcea
- S. Stanescu
- S.D. Grigorescu
- M. Albu
- Fl. Enache
- Z. Sheng
- J. Plata
- M. Dobrzinski
- Al. Vasenev
- si altii

Personalitati:

- A. Bossavit
- K. Richter
- K. Miya
- T. Weiland
- G. Molinari
- J. Tegopoulos
- T. Tsiboukis
- M. Silveira
- W. Schildes
- G. Rubinacci
- D. Rodger
- J. K. Sykulski
- J. Pavo
- O. Biro
- K. Preis
- D.A Lowther

Parteneri academici:

- TU/E
- Delft TU
- Ghent Univ.
- Groningen Univ.
- Bath Univ.
- Graz TU
- Darmstadt TU
- NTU Athens
- Budapest TU
- Catania Univ.
- Calabria Univ.
- Lisbon Univ.
- Univ. Wupertal
- Tokyo Univ.
- Torino Univ.
- EPFL ...

Parteneri industriali:

- Philips research
- NXP
- AustriaMicroSystems
- Infineon
- ST Microelectronics
- IMEC
- MAGWEL
- IMTEK Freiburg
- Liquids Research Ltd.
- IMT
- INCDFIT Iasi

Resurse LMN (Laboratorul de Modelare Numerica)

- 250 m² spatiu **birouri (20 persoane)**,
- Sala de **trainig 24 persoane**
- Copiator, **imprimare** alb/negru si color
- Centru de **documentare**
- **Internet**, wireless
- **Server HPC** - clusterul ATLAS cu 32 quad-64bits CPUs, adica 128 cores si 2 GPGPUs cu 500 stream processors, oferind o putere de calcul de peste 1 Teraflop/sec, 240 GB RAM si 10 TB disk-space
- **Software**: MATLAB PCT, DCS, COMSOL RF, AC/DC, Fedora OS, *Scientific software development kit*, din domeniul public



Resurse LMN, cea mai importanta este cea umana!

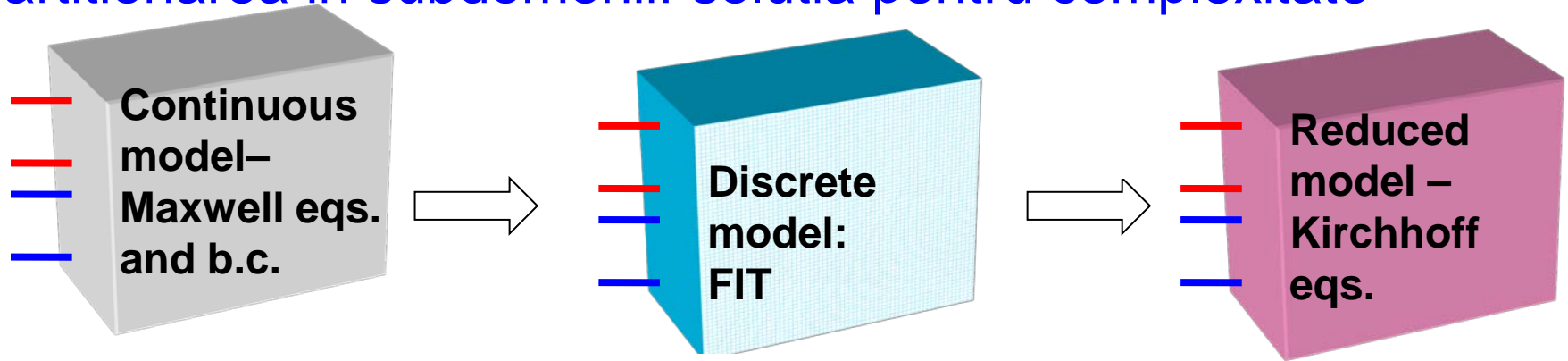


3 idei novatoare

- **dFIT – dual Finite Integration Technique (tehnica integralelor finite duale)**
- MEEC – Magneto-Electric Equivalent Circuits – model for inductive effects on chip level
- ALROM – All levels Reduced Order Modeling procedure

Extragerea modelelor reduse: de la Maxwell la Kirchhoff

Partitionarea in subdomenii: solutia pentru complexitate

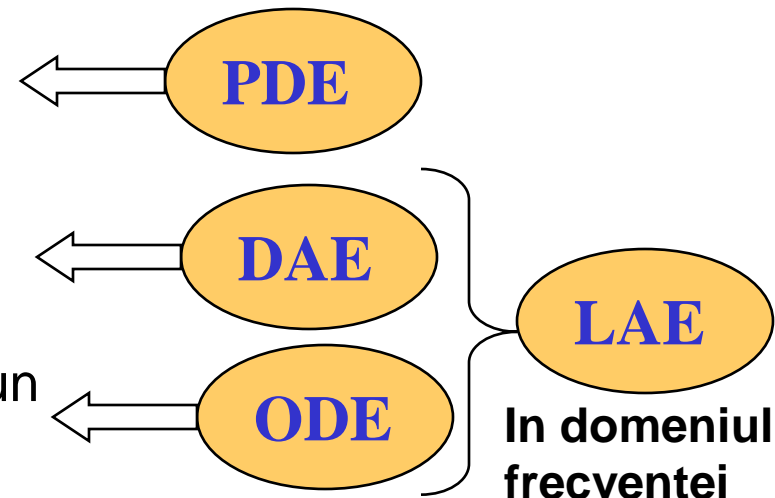


- **Problema de camp EM pentru componentele pasive:**

- Ecuatiile Maxwell cu conditii de frontiera potrivite pentru
- modelarea cuplajului EM

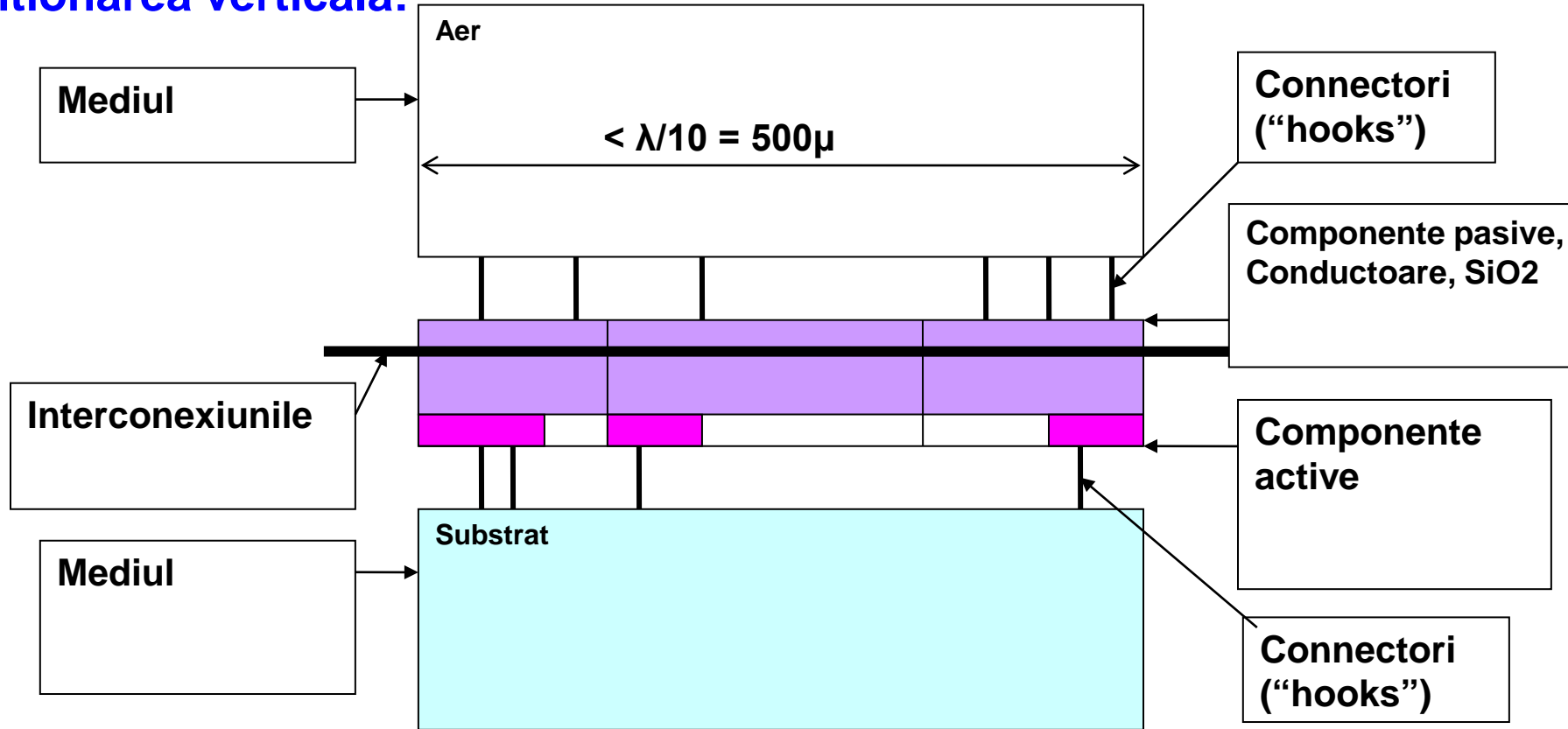
- **Dupa discretizare** (nu rezolvare!) este generat **modelul non-compact**

- Dupa **reducerea ordinului** este sintetizat un **circuit parametric redus**



Partitionarea tipica in subdomenii a CI

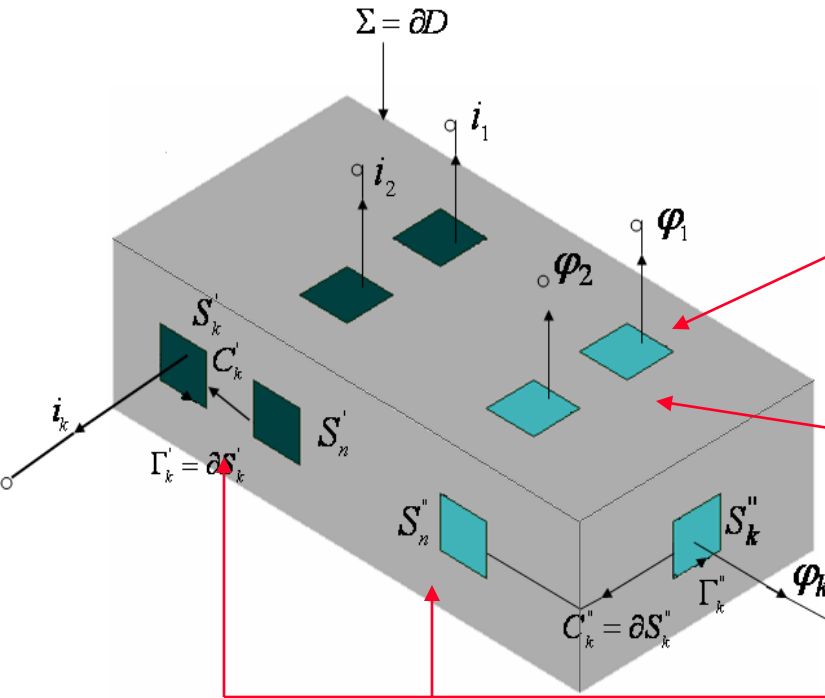
Partitionarea verticala:



Partitionarea planului orizontal:

Planurile mastilor chipului sunt partitionate in subdomenii 2D – componentele din schema circuitului. **EMCE: cea mai buna conditie de frontiera**

Formulara Matematica: EMCE-Elementul EM de Circuit



- Fluxul magnetic trece numai prin **terminalele magnetice**

$$\mathbf{n} \operatorname{curl} \mathbf{E}(P, t) = 0 \quad \forall P \in \Sigma - \cup S_k''$$

- Curentul electric trece doar prin **terminalele electrice**

$$\mathbf{n} \operatorname{curl} \mathbf{H}(P, t) = 0 \quad \forall P \in \Sigma - \cup S_k'$$

- Terminalele electrice sunt **echipotentiale electric**

$$\mathbf{n} \times \mathbf{E}(P, t) = \mathbf{0} \quad \forall P \in \cup S_k'$$

- Terminalele magnetice sunt **echipotentiale magnetic**

$$\mathbf{n} \times \mathbf{H}(P, t) = \mathbf{0} \quad \forall P \in \cup S_k''$$

Aceste conditii de frontiera permit **cuplarea cu circuite** electrice/magnetice exterioare.

Cuplarea Camp-Circuit

Componenta pasiva sau modelul ei redus (circuitul echivalent)

Puterea P

Mediul electric:
modelat de circuitul
electric echivalent:
RLC, surse
comandate,
tranzistoare, etc.

Mediul magnetic:
Modelat de circuitul
magnetic echivalent
alcatuit din
reluctantele R_m si
surse comandate

$$P = \sum_{k=1}^{n'-1} (v_k i_k) + \sum_{k=1}^{n''-1} u_k \frac{d\varphi_k}{dt}$$

Puterea

Pentru terminalele
electrice:

$$i_k(t) = \int_{\Gamma'_k} \mathbf{H} d\mathbf{r}$$

$$v_k(t) = \int_{C'_k} \mathbf{E} d\mathbf{r}$$

Pentru terminalele
magnetice:

$$\dot{\varphi}_k(t) = \int_{\Gamma''_k} \mathbf{E} d\mathbf{r}$$

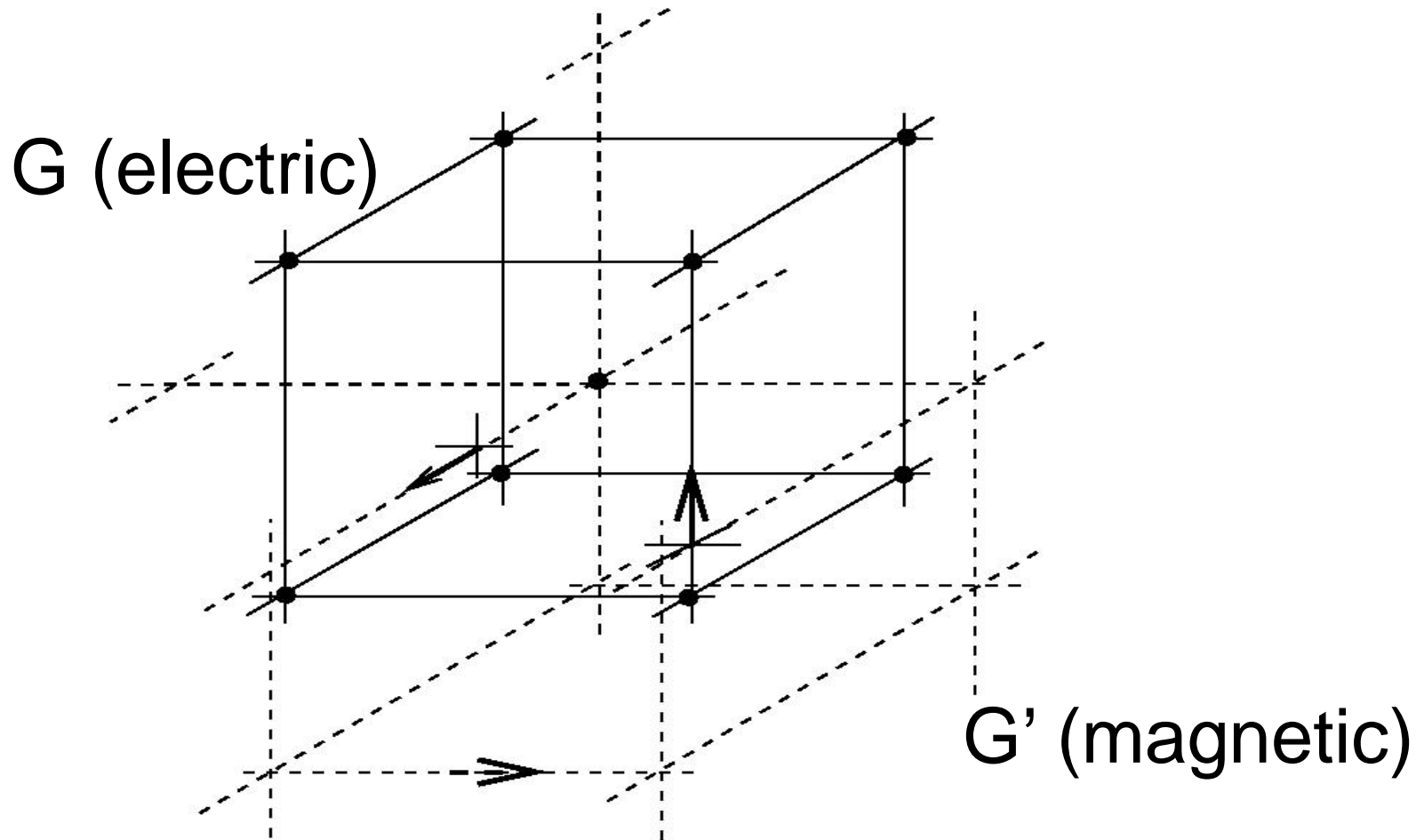
$$u_k(t) = \int_{C''_k} \mathbf{H} d\mathbf{r}$$

Abordarea numerica: FIT (Finite Integration Technique)

Tehnica Integralelor Finite (FIT) este o metoda numerica pentru rezolvarea problemelor de camp EM in regim general variabil (FW-EM) bazata pe discretizari spatiale “**fara functii de forma**”, folosind:

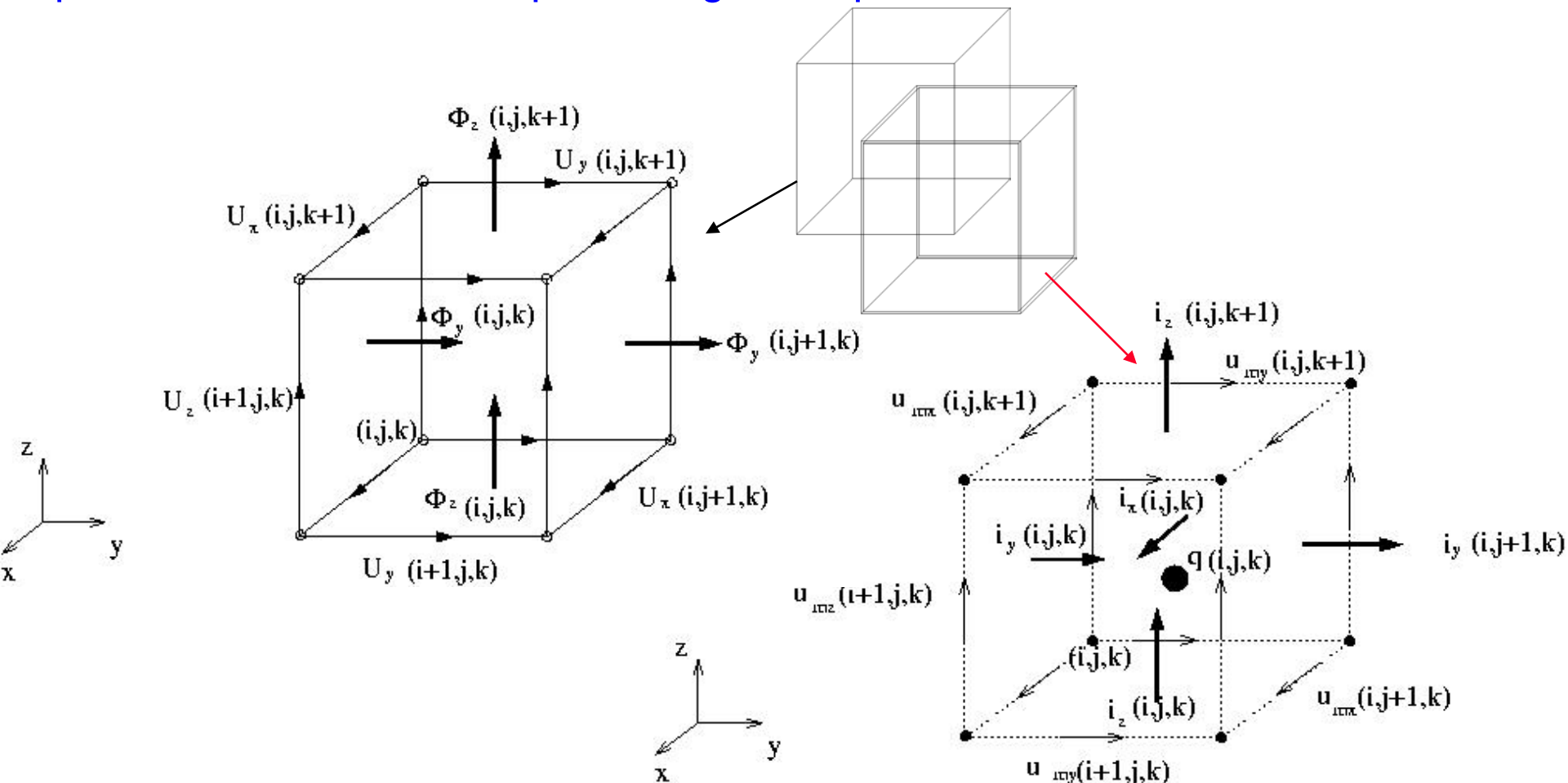
- **Forma globala a ecuatiilor campului** (nu cea diferentiaza folosita in MDF, nici cea slaba-variationala, folosita in MEF, nici cea a ecuatiilor integrale din BEM/MEI);
- **Marimi globale ca grade de liberate**: tensiuni si fluxuri pe laturile si fetele celulelor elementare ale retelei de discretizare (si nu componente vectorilor campului ca in FDTD);
- **Pereche de retele duale inlantuite**, de obicei ortogonale (de tip Yee = “complex de celule carteziane duale carteziane”), dar pot fi si griduri neortogonale de tip Delaunay/Veronoi

Retelele duale de tip Yee



Aceste rețele ortogonale sunt potrivite pentru modelarea circuitelor integrate, care au **“geometrie Manhattan”**

Legile generale ale campului EM in forma globala sunt satisfacute individual pe fiecare celula, deci si pe intreagul complex al retelei de celule



Ecuatiile lui Maxwell pe Grid (MGE)

$$\begin{cases} \text{curl} \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\ \Rightarrow \text{div} \mathbf{B} = 0 \end{cases} \Rightarrow \begin{cases} \oint \mathbf{E} = -\iint \frac{\partial \mathbf{B}}{\partial t} \\ \Rightarrow \oiint \mathbf{B} = 0 \end{cases} \Rightarrow \begin{cases} \mathbf{C} \mathbf{u} = -\frac{d\varphi}{dt} \\ \Rightarrow \mathbf{D}' \varphi = 0 \end{cases}$$

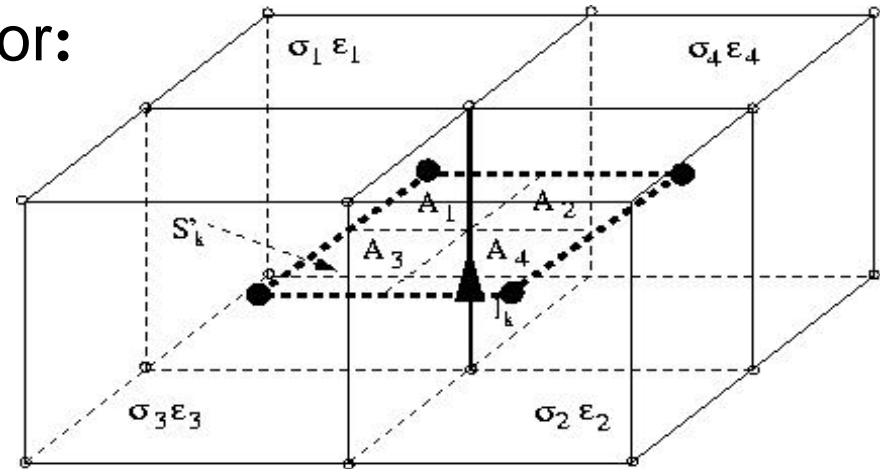
$$\begin{cases} \text{curl} \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \\ \Rightarrow \text{div} \mathbf{D} = \rho \end{cases} \Rightarrow \begin{cases} \oint \mathbf{H} = \iint (\mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}) \\ \Rightarrow \oiint \mathbf{D} = \iiint \rho \end{cases} \Rightarrow \begin{cases} \mathbf{C}' \mathbf{u}_m = -\frac{d\varphi}{dt} \\ \Rightarrow \mathbf{D} \psi = \mathbf{q} \end{cases}$$

$$\Rightarrow \text{div} \mathbf{J} = -\frac{\partial \rho}{\partial t} \Rightarrow \iint \mathbf{J} = -\iiint \frac{\partial \rho}{\partial t} \Rightarrow \mathbf{D} \mathbf{i} = -\frac{d\mathbf{q}}{dt}$$

- Ecuatiile fundamentale MGE **nu au erori de discretizare**
- Ele sunt DAE **topologice (metric-free), rare, mimetice si conservative, fara moduri false de oscilatie (spurious).**

Descriu comportarea materialelor:

$$\begin{cases} \mathbf{J} = \sigma \mathbf{E} \Rightarrow \mathbf{i} = \mathbf{M}_\sigma \mathbf{u} \\ \mathbf{D} = \varepsilon \mathbf{E} \Rightarrow \psi = \mathbf{M}_\varepsilon \mathbf{u} \\ \mathbf{H} = \nu \mathbf{B} \Rightarrow \mathbf{u}_m = \mathbf{M}_\nu \varphi \end{cases}$$

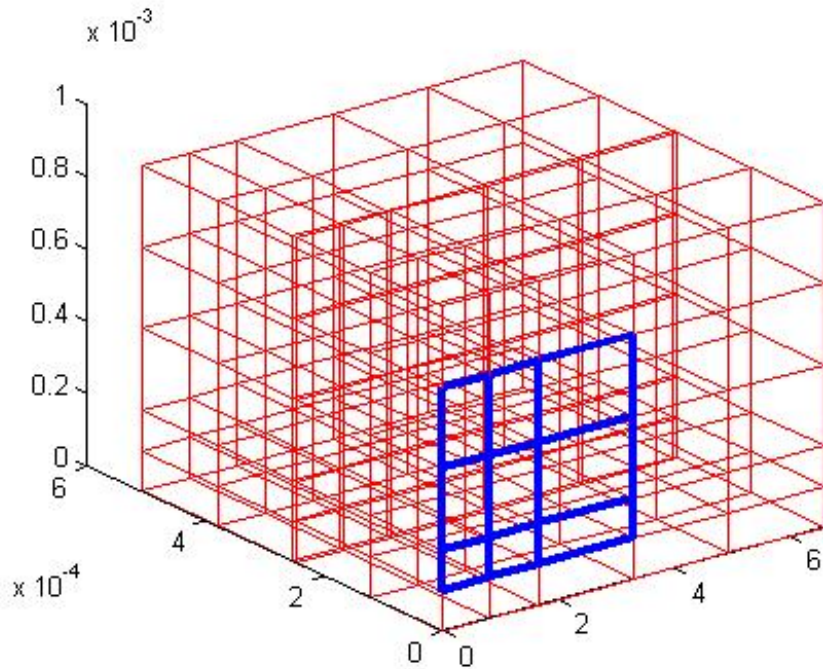


Au caracter metric si poarta erorile de discretizare.

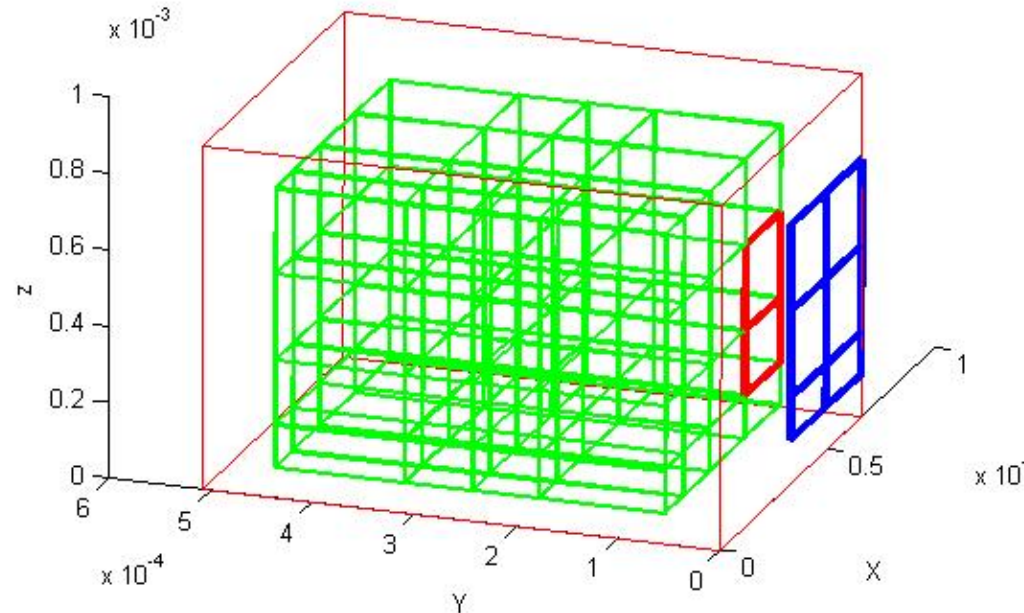
Abordarea FIT clasica (MGE+Hodge) a trebuit **imbunatatita si adaptata**, pentru a face fata angajamentelor proiectului Codestar.

Asta am facut!

Terminalele Electrice si Magnetice pe gridul FIT



Un **terminal electric** pe gridul electric



Un **terminal magnetic**, pe
gridul magnetic si umbra sa pe
gridul electric

TERMINAL = reuniune de fete ale celulelor gridului

Modelul MIMO in spatiul starilor generat de FIT

FIT equations: $\rightarrow \begin{bmatrix} \mathbf{C}_e & 0 \\ 0 & \mathbf{G}_m \end{bmatrix} \frac{d}{dt} \begin{bmatrix} \mathbf{v} \\ \mathbf{u} \end{bmatrix} + \begin{bmatrix} \mathbf{G}_e & -\mathbf{B}' \\ \mathbf{B} & 0 \end{bmatrix} \begin{bmatrix} \mathbf{v} \\ \mathbf{u} \end{bmatrix} = 0$

with boundary conditions $\rightarrow \begin{cases} \mathbf{C} \frac{d\mathbf{x}}{dt} + \mathbf{G} \mathbf{x} = \mathbf{z} \\ \mathbf{y} = \mathbf{L}\mathbf{x} \end{cases}$

in the frequency domain $\rightarrow \begin{cases} (s\mathbf{C} + \mathbf{G})\mathbf{x} = \mathbf{z} \\ \mathbf{y} = \mathbf{H}\mathbf{z} \end{cases}$

Electric/magnetic terminals may be excited in current/flux or in voltage:

State variables: electric and magnetic voltages of grid edge

Current



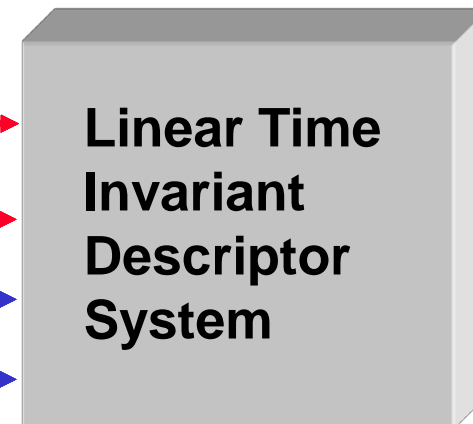
Voltage



Magn. Circ.



Flux



Linear Time Invariant Descriptor System



Voltage



Current



Flux



Magn. Circ.

dFIT - dual Finite Integration Technique

- FIT este aplicat de **doua ori**. Fiecare din cele doua retele duale inlantuite este folosita ca retea electrica si apoi ca una magnetica;
- Cel doua solutii numerice astfel obtinute ofera **marginii superioara si inferioara** ale solutiei exacte;
- Aceasta abordare duala (complementara) permite **controlul acuratetii** solutiei numerice, conferind astfel robustete si eficienta calculelor. Ea este folosita si pentru controlul global si local al **rafinarii retelei** de discretizare.
- Media celor doua solutii complementare este mai exacta si are o **rata superioara a convergentei** decat FTI.

Prin dFIT, numarul de noduri, si deci **efortul de calcul necesar obtinerii acuratetii dorite este redus drastic!**

Teorema incadrarii solutiei

Solutia primara C_p si cea secundara C_s sunt margini inferioare si superioare ale solutiei exacte C :

$$C_s \leq C \leq C_p$$

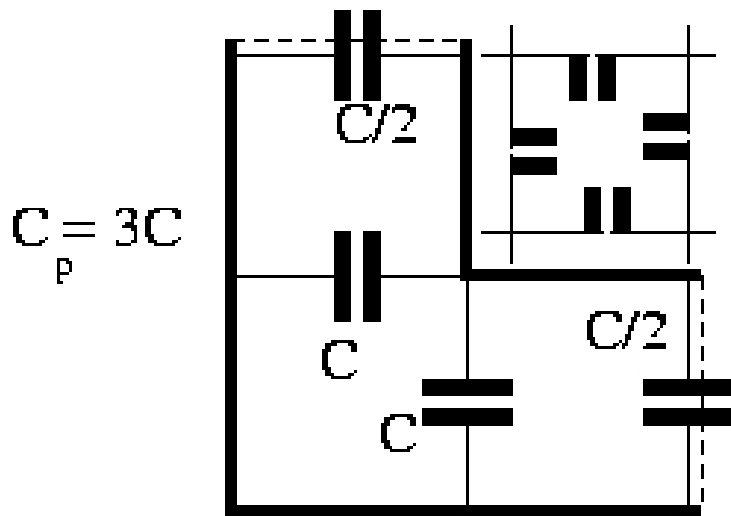
In consecinta

$$\varepsilon = \|C_d - C\| / \|C_d\| \leq \|C_p - C_s\| / \|C_d\|$$

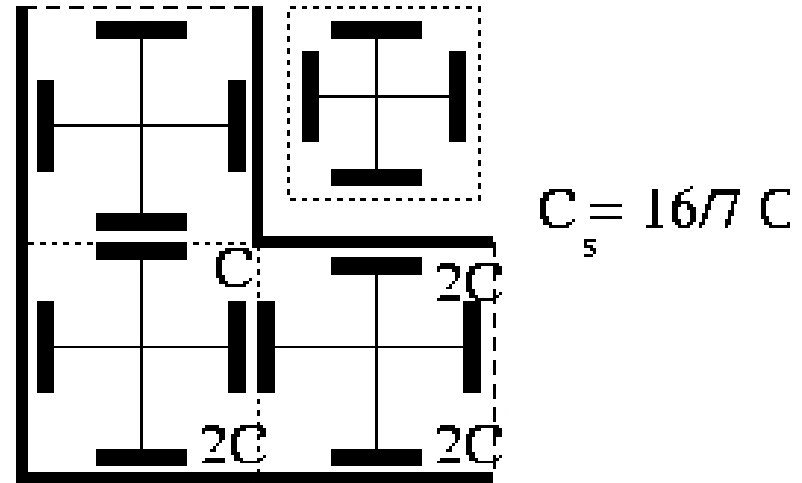
- Aici $\mathbf{A} \leq \mathbf{B}$ inseamna $\mathbf{x}^T(\mathbf{A}-\mathbf{B})\mathbf{x} \leq \mathbf{0}$ pentru orice vector \mathbf{x} .
- Energia exacta: $\mathbf{W} = \mathbf{v}^T \mathbf{C} \mathbf{v} / 2$
- $\mathbf{W} < \mathbf{v}^T \mathbf{C}_p \mathbf{v} / 2$ Energia solutie pFIT (rot-conforma)
- $\mathbf{W} > \mathbf{v}^T \mathbf{C}_s \mathbf{v} / 2$ Energia solutiei sFIT (div-conforma)

Stampilele primare si secundare pentru celulele dFIT

Capacitatea unui domeniu de forma literei L



Primary FIT - error 17%

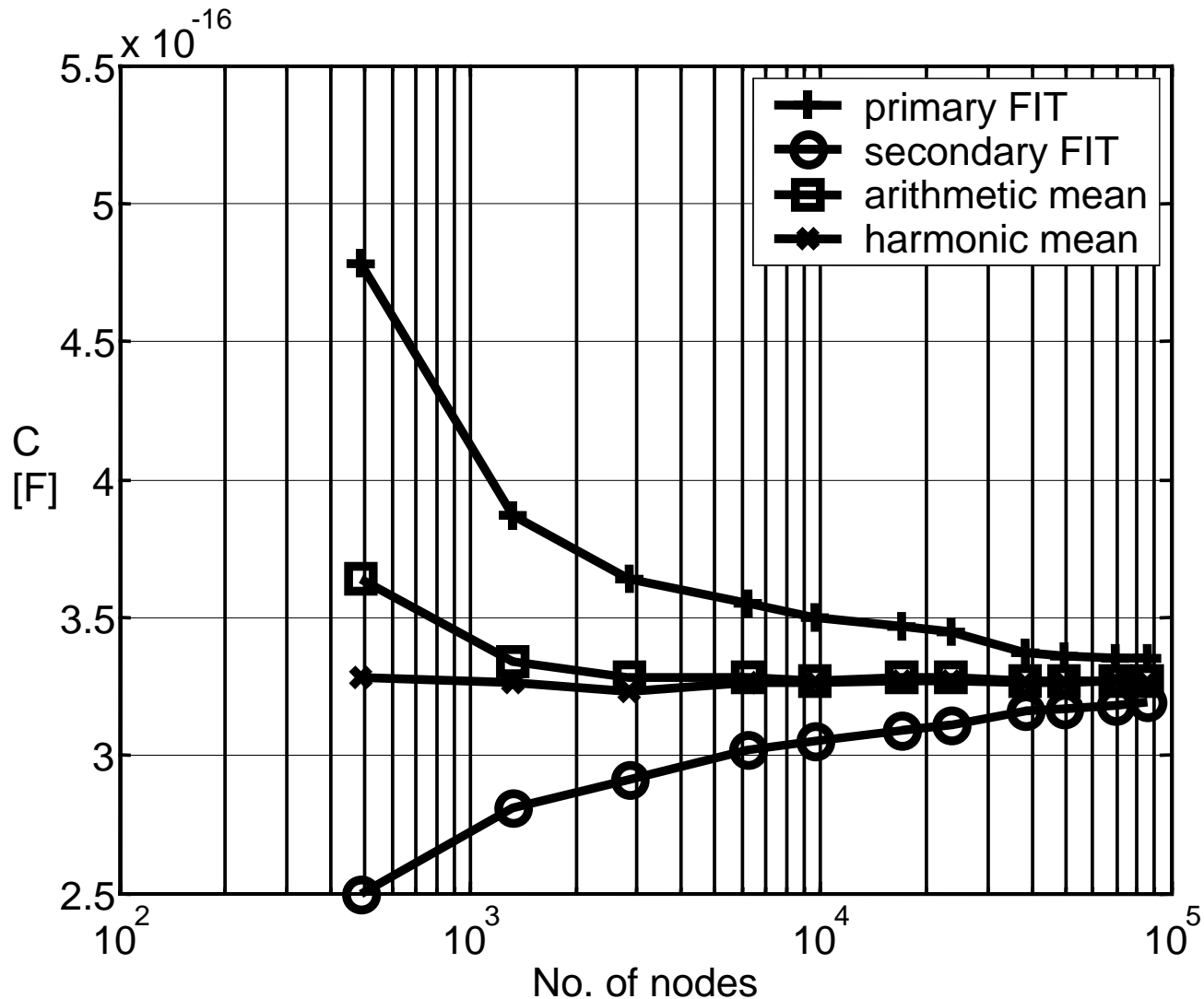


Secondary FIT - error: -7%

$$C_d = (C_p + C_s) / 2$$

dFIT - error: 3%

Marginile capacitatii vs nivelul multigrid, de rafinare



Concluzii privind dFIT

Accelerarea extragerii modelului - s-a dezvoltat o metodologie foarte eficienta pentru analiza numerica a campurilor stationare si s-a aplicat la modelarea si simularea structurilor pasive si interconexiunilor din circuitele integrate.

Controlul acuratetii solutiei – asigurand robustete calculelor - increderea in solutia numerica si folosirea eficienta a resurselor de calul (timp si memorie).

Scade dimensiunea problemei (nr. de grade de libertate), pentru o acuratete ceruta. In cazurile de test CODESTAR:

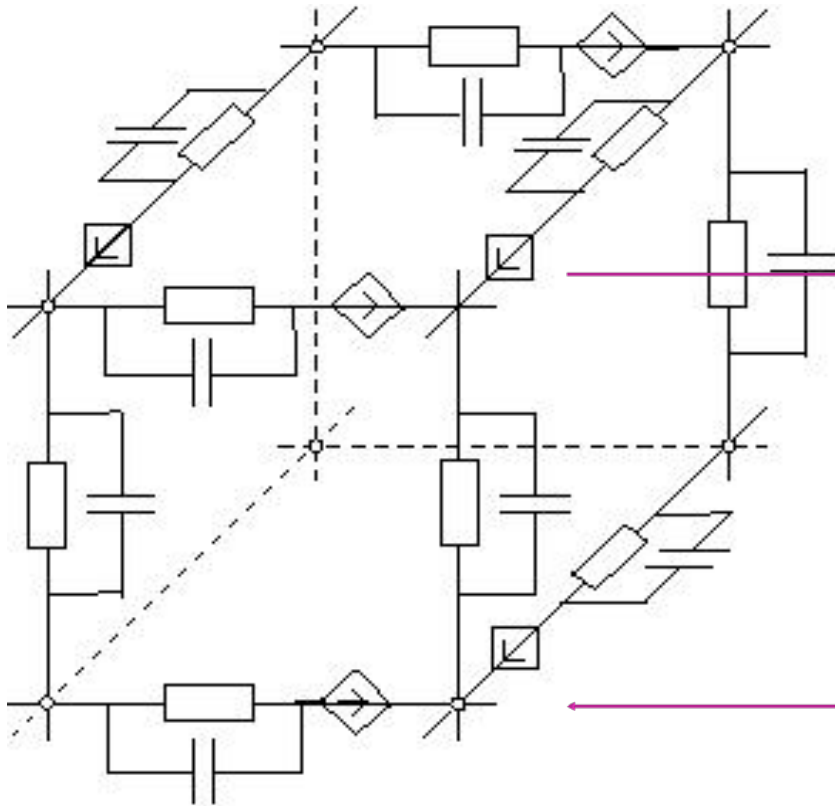
- *dFIT* - scadeea a fost de 33 ori, fata de FIT iar **timpul de extractie a scazut de >1000 ori!**

3 idei novatoare

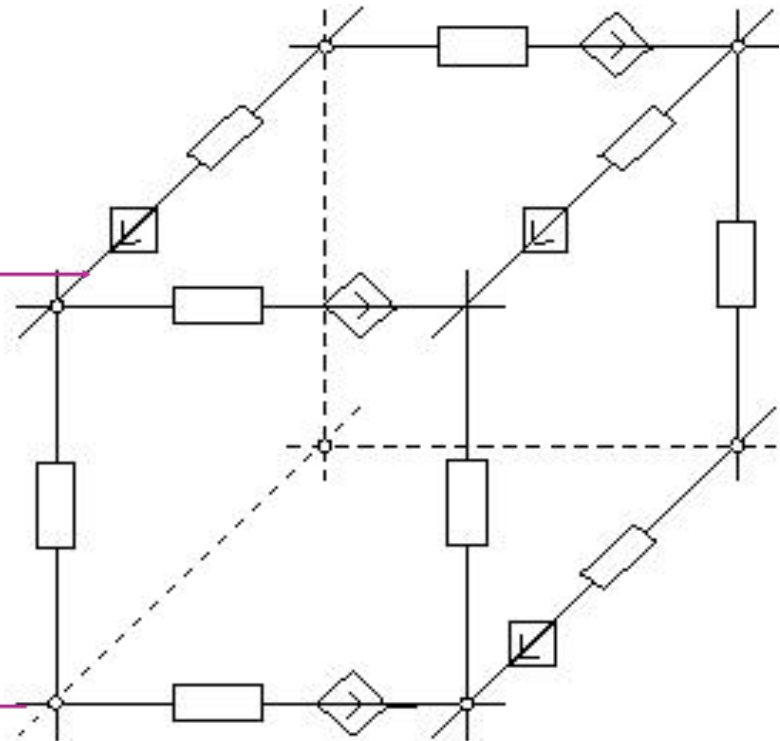
- dFIT – dual Finite Integrals Technique
- **MEEC – Magneto-Electric Equivalent Circuits (Circuitul Magneto-Electric Echivalent) – model pentru efectele inductive la nivel global in C.I.**
- ALROM – All levels Reduced Order Modeling procedure

Circuitul Magneto-Electric Equivalent (MEEC)

Circuitul Electric



Circuitul Magnetic



$$\mathbf{MGE} = \mathbf{CKL} + \mathbf{VKL}$$

Grafurile circuitelor electric/magnetic = gridurile duale FIT

Magneto-Electric Equivalent Circuits (MEEC)

Forma discreta a teoremei conservarii sarcinii \Rightarrow KCL pentru circuitul electric

$$\mathbf{D}\mathbf{i} = 0 \quad \Leftrightarrow \quad \mathbf{A}\mathbf{i} = 0;$$

$$\text{where } \mathbf{i} = \mathbf{j} + \frac{d\mathbf{d}}{dt} \quad \mathbf{i} = \mathbf{i}' + \mathbf{i}''$$

Forma discreta a legii fluxului magnetic \Rightarrow KCL pentru circuitul magnetic

$$\mathbf{D}'\mathbf{b} = 0 \quad \Leftrightarrow \quad \mathbf{A}'\boldsymbol{\varphi} = 0$$

Forma discreta a legii inductiei electromagnetice \Rightarrow KVL pentru circuitul

$$\mathbf{C}\mathbf{e} + \frac{d\mathbf{b}}{dt} = 0 \quad \Leftrightarrow \quad \mathbf{B}\mathbf{u} = 0$$

$$\mathbf{u} = \mathbf{u}' + \mathbf{F} \frac{d\boldsymbol{\varphi}}{dt}$$

Forma discreta a legii circuitului magnetic \Rightarrow KVL pentru circuitul magnetic

$$\mathbf{C}'\mathbf{h} - \mathbf{i} = 0 \quad \Leftrightarrow \quad \mathbf{B}'\mathbf{u}_m = 0$$

$$\mathbf{u}_m = \mathbf{u}'_m + \mathbf{S}\mathbf{i}$$

De la MGE la Ecuatiile lui Kirchhoff!

Circuitul Magneto-Electric Equivalent (MEEC)

Operatorii Hodge

\Rightarrow

Relatiile Constitutive ale laturilor

$$\mathbf{d} = \mathbf{M}_\varepsilon \mathbf{e} \quad \Leftrightarrow$$

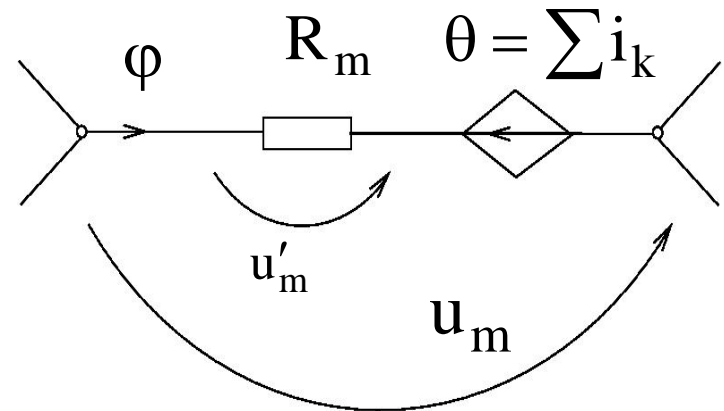
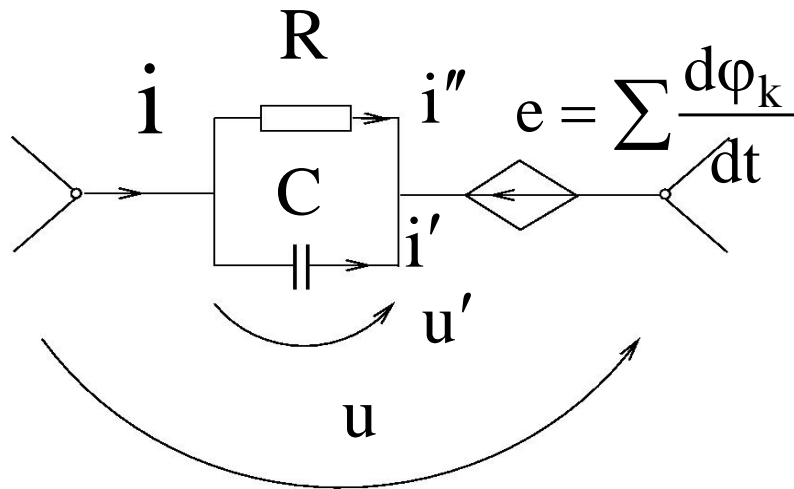
$$\mathbf{i}' = \mathbf{C} \frac{d\mathbf{u}}{dt}$$

$$\mathbf{b} = \mathbf{M}_\mu \mathbf{h} \quad \Leftrightarrow$$

$$\mathbf{u}'_m = \mathbf{R}_m \varphi$$

$$\mathbf{D} = \mathbf{M}_\sigma \mathbf{e} \quad \Leftrightarrow$$

$$\mathbf{i}'' = \mathbf{G} \mathbf{u}'$$



Latura tipica a circuitului electric

Latura circuitului magnetic

Circuitul Magneto-Electric Equivalent (MEEC)

Operatorii Hodge

⇒

Relatiile Constitutive ale laturilor

$$\mathbf{d} = \mathbf{M}_\varepsilon \mathbf{e}$$

⇔

$$\mathbf{i}' = \mathbf{C} \frac{d\mathbf{u}}{dt}$$

$$\mathbf{b} = \mathbf{M}_\mu \mathbf{h}$$

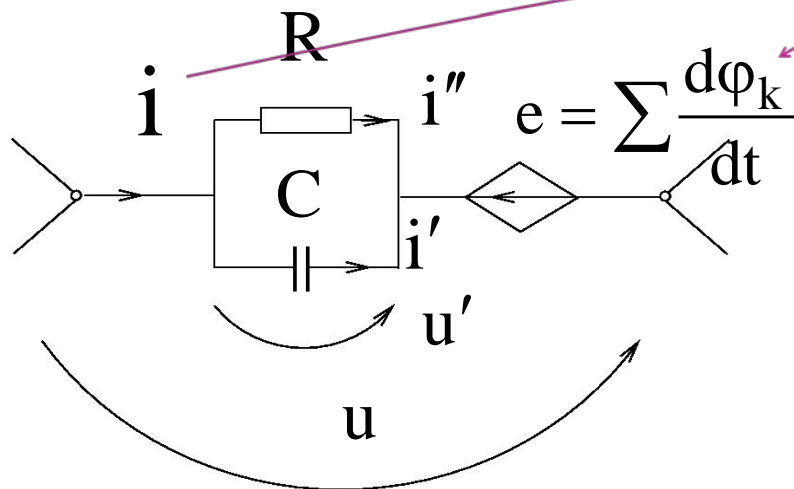
⇔

$$\mathbf{u}'_m = \mathbf{R}_m \varphi$$

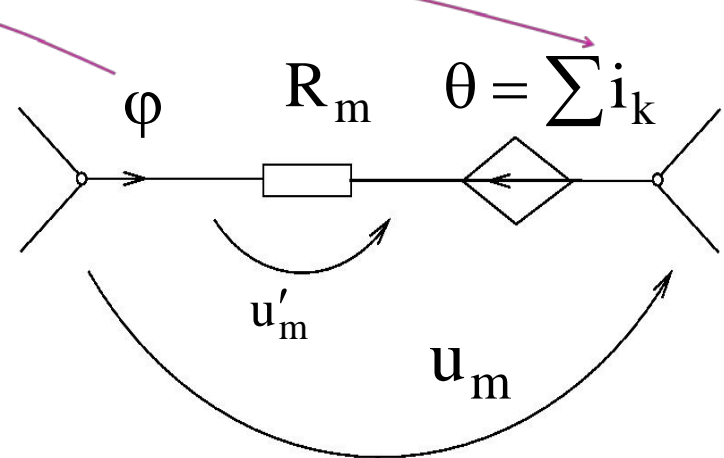
$$\mathbf{D} = \mathbf{M}_\sigma \mathbf{e}$$

⇔

$$\mathbf{i}'' = \mathbf{G} \mathbf{u}'$$



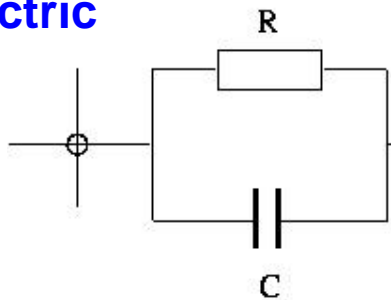
Latura tipica a circuitului electric



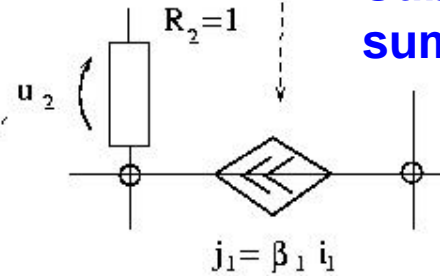
Latura circuitului magnetic

Circuitul Spice echivalent modelului FIT

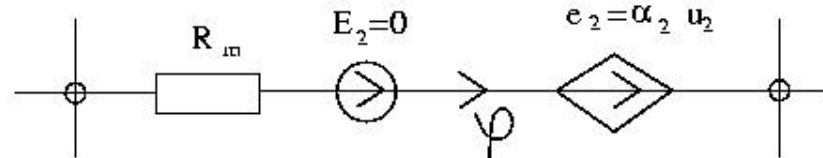
Subcircuitul electric



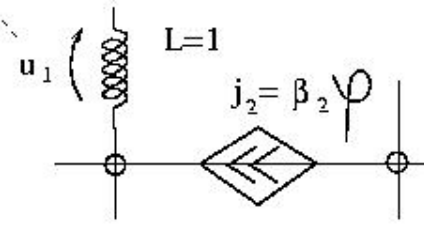
Subcircuitul de sumare



Subcircuitul magnetic



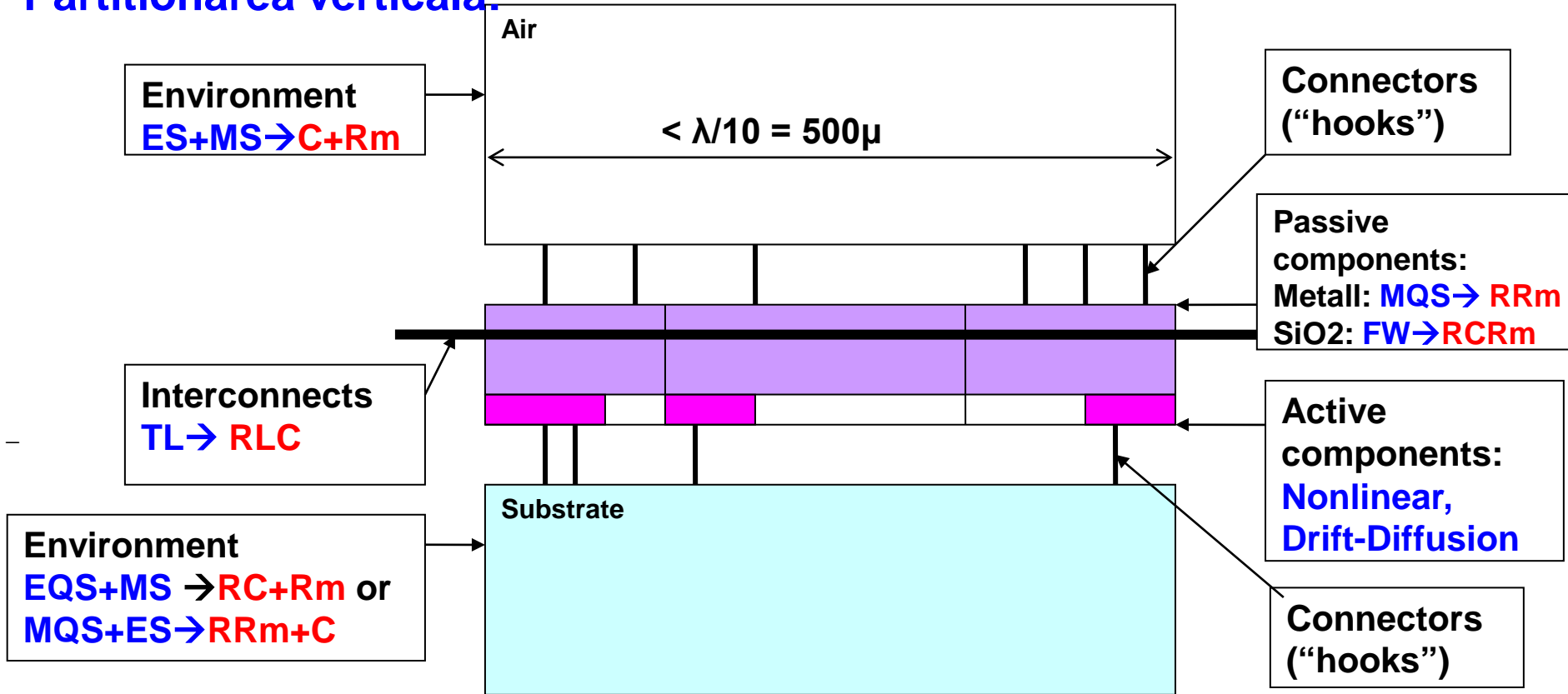
Subcircuitul de derivare



- Circuitul echivalent Spice consta din **patru subcircuite cuplate**
- El are o **complexitate liniara** fata de numarul de noduri FIT
- Chiar si asa dimensiunea sa este inacceptabil de mare. **Este necesara reducerea ordinului.** Am reusit aceasta prin partitionare in subdomenii (DP)

Partitionarea in subdomenii si regimurile campului EM

Partitionarea verticala:



Partitionarea orizonatala: subdomenii 2D, conform schemei.

Fiecare subdomeniu are alt regim al campului (se reduce MEEC)

Modelel MEEC **reduse** sunt extrase si interconectate → MEEC global

Interconectarea modelelor MEEC reduce

I/O signals of Electric Hooks:

$$i_k(t) = \int_{\Gamma_k} \mathbf{H} \cdot d\mathbf{r}$$

$$v_k(t) = \int_{C_k} \mathbf{E} \cdot d\mathbf{r}$$

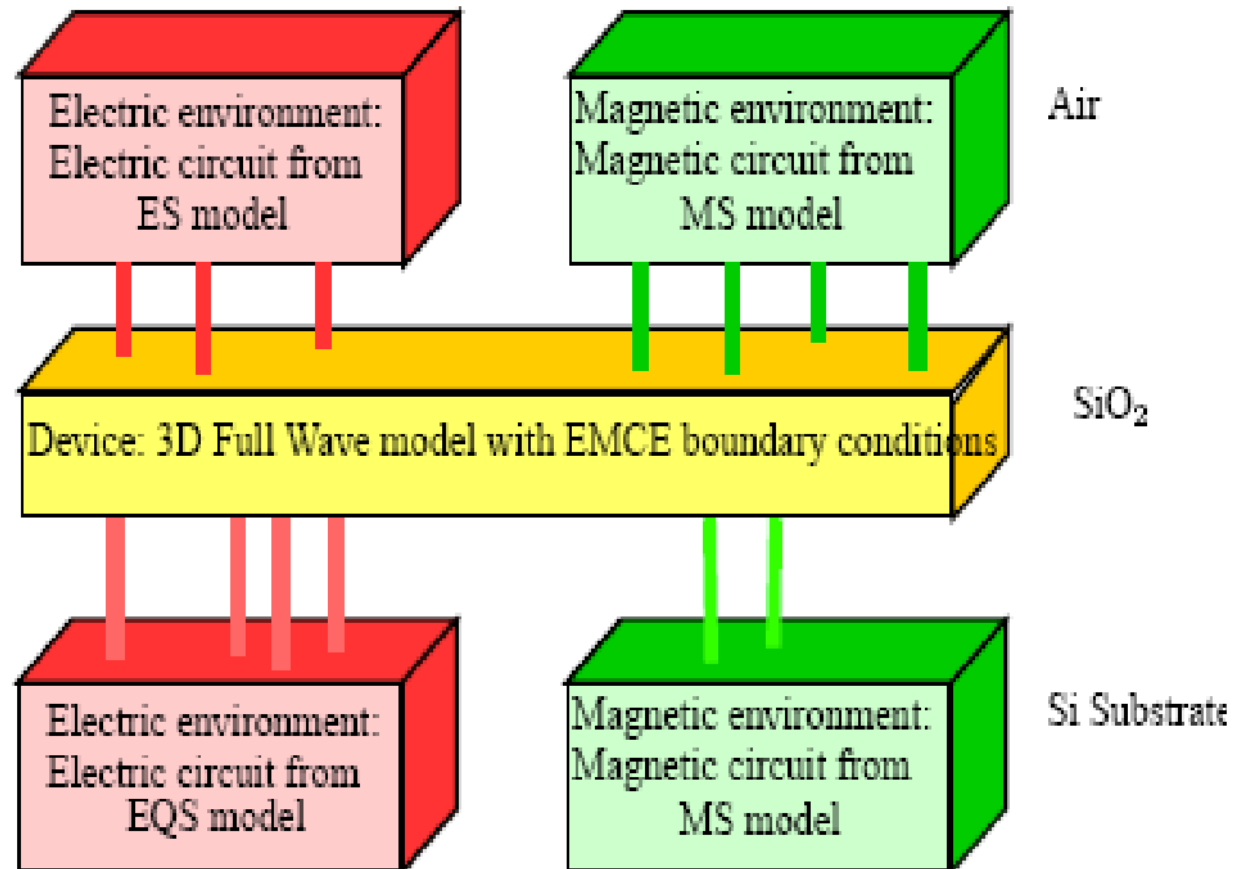
I/O signals of Mg. Hooks

$$\dot{\phi}_k(t) = \int_{\Gamma_k} \mathbf{E} \cdot d\mathbf{r}$$

$$u_k(t) = \int_{C_k} \mathbf{H} \cdot d\mathbf{r}$$

$$P = \sum_{k=1}^{n'-1} (v_k i_k) + \sum_{k=1}^{n''} u_k \frac{d\phi_k}{dt}$$

Different field formulations can be used



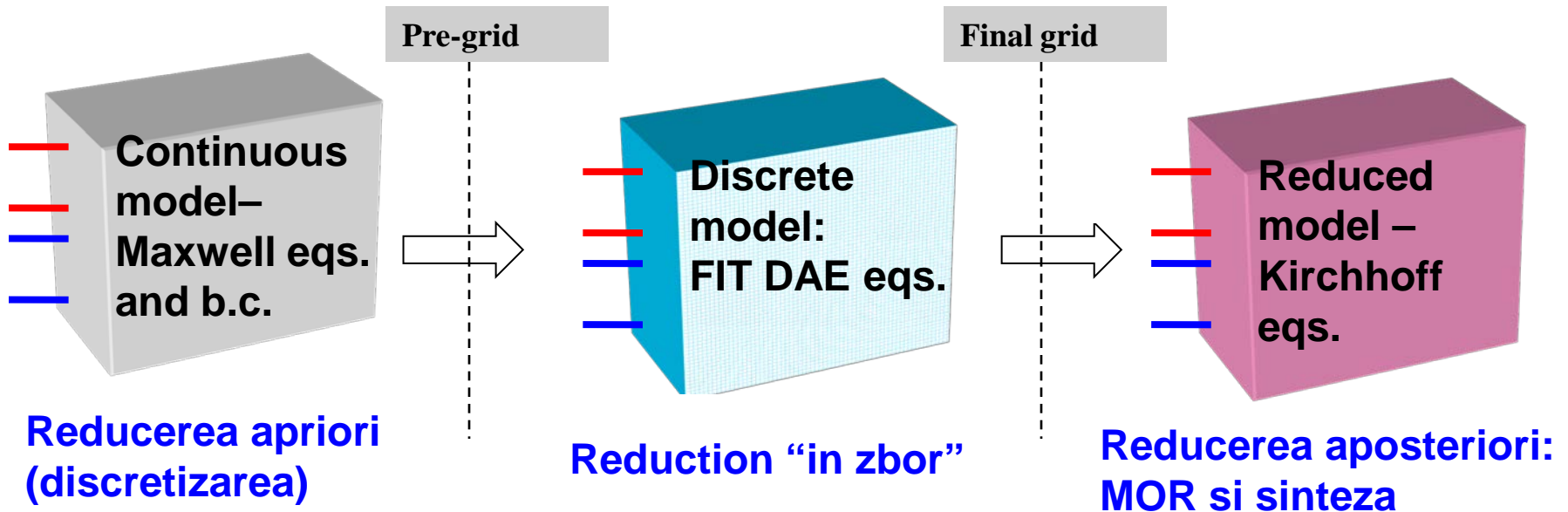
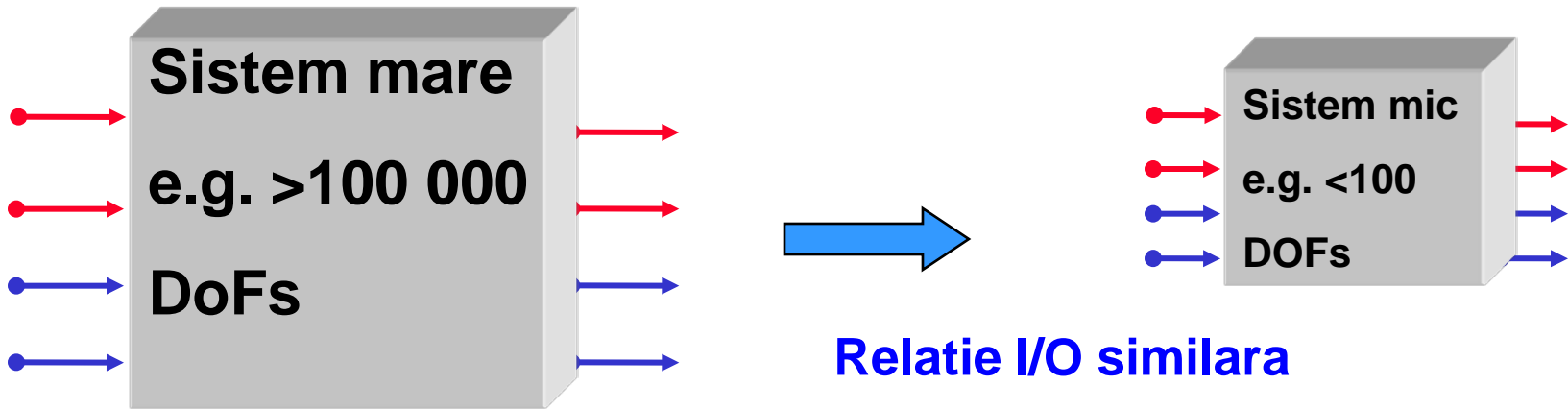
Avantajele abordarii MEEC global

- **Fundament teoretic solid: EMCE** (sursa raului: inductantele partiale au fost eliminate).
- Deoarece nu se realizeaza segmentarea din PEEC, ci descompunerea curentilor in bucle fundamentale, modelele extrase au **ordin mai mic**.
- **Nu este necesara inversarea** matricei inductantelor partiale L , ca in metodele K si $VPEC$.
- • Permite **rarefiera** robusta si eficienta, realizata atat pe criterii algebrice cat si geometrice, cat si **reducerea ordinului si a numarului de terminale**.
- Partitionarea in subdomenii permite **extragerea in paralel**.
- Modelul extras se poate simula direct in **SPICE standard**.
- **Flexibilitatea modelarii**: prin conectorii magnetici, modelul poate fi cuplat cu un numar necunoscut de surse exterioare de camp magnetic perturbator.

3 idei novatoare

- dFIT – dual Finite Integrals Technique
- MEEC – Magneto-Electric Equivalent Circuits – model for inductive effects on chip level
- **ALROM – All Levels Reduced Order Modeling procedure (Reducerea Ordinului la Toate Nivelele Modelarii)**

Reducerea Modelelor



ALROM: All Levels Reduced Order Modeling

Principiu: reducerea se face cat de curand posibil !

Etapele tehnologiei ALROM:

- **Descompunerea in subdomenii: ecuatii EM**

- Calibrarea gridului 3D cu dFIT

- Calibrarea frontierei virtuale cu dELOB

- Analiza in frecventa cu AFS

- Extragerea modelului parametric

- redus cu VF

- **Integrarea** modelelor reduse parametrica ale efectelor parazite, analiza variabilitatii si simularea Spice

Reducere a priori

Reducere din zbor

Reducerea a posteriori a ordinului

Model extraction

Etapele algoritmului de reducere a modelului

1. **Calibrarea gridului cu dFIT:** rețeaua este rafinată succesiv până la nivelul optim (acuratețe acceptabilă)
2. **Calibrarea Frontierei Virtuale cu dELOB:** domeniul de calcul este extins succesiv (în aer) până la o dimensiune optimă
3. **Analiza în frecvență cu esanționare adaptivă (AFS).** Pentru fiecare pulsație ω dintr-un set minimal se calculează **raspunsul sistemului**: $Y(\omega) = (Y_p(\omega) + Y_s(\omega))/2$, și **sensitivitatea** $S_Y(\omega)$:
 - $Y_p(\omega)$ - admitanță calculată cu FIT pe **gridul primar cu parametrii ELOB**: $\epsilon_r = M \gg 1$, $\mu_r = 1$;
 - $Y_s(\omega)$ - admitanță calculată cu FIT pe **gridul secundar** cu parametrii ELOB: $\epsilon_r = 1$, $\mu_r = M \gg 1$;
4. **Sinteza circuitului Spice** parametric, extras cu **AFT** și redus cu **VF+DEM**

PRINCIPIUL GENERAL: să se aplice ROM cât mai devreme posibil, la fiecare etapă a modelării

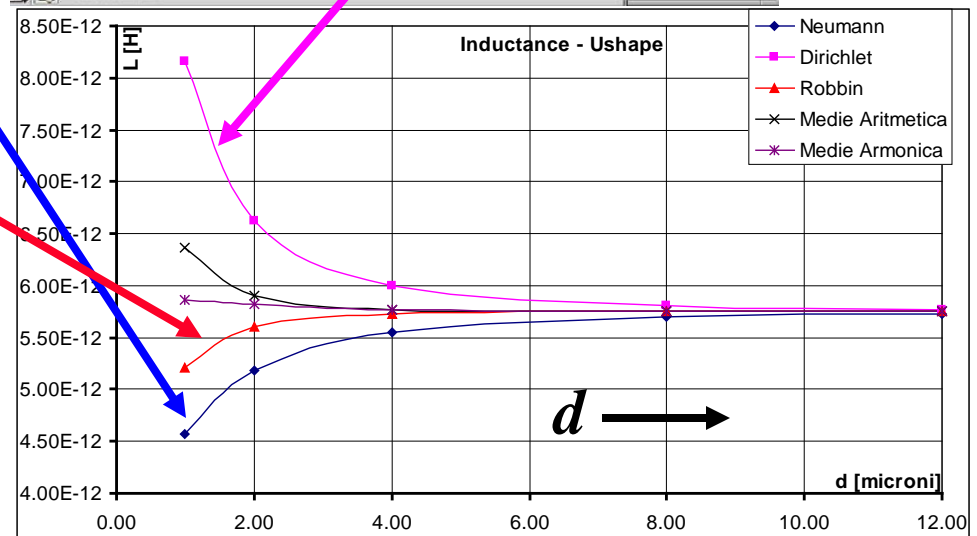
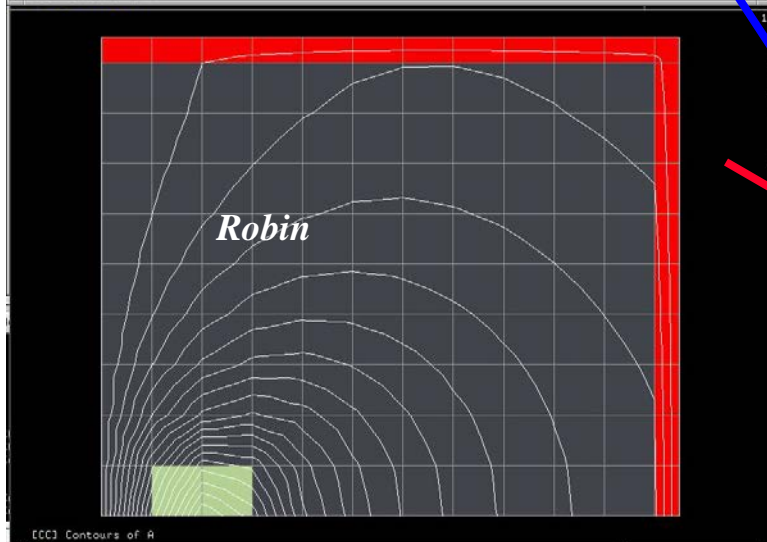
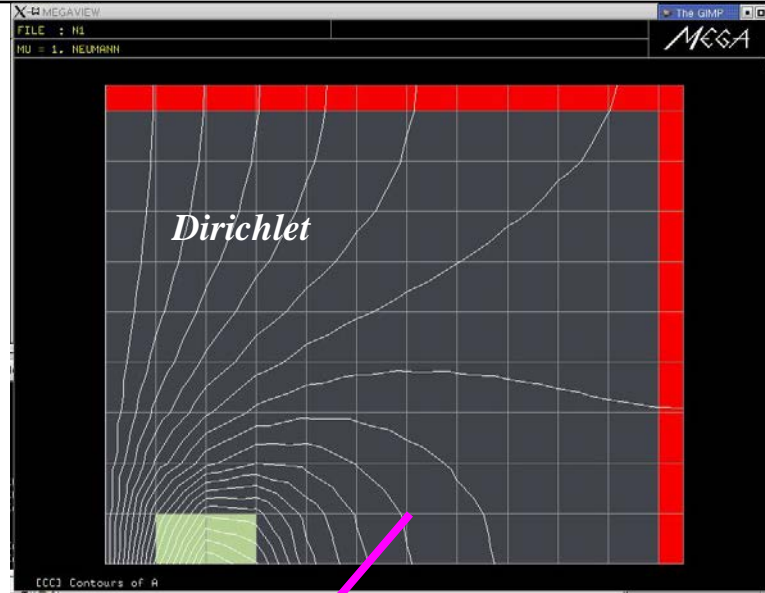
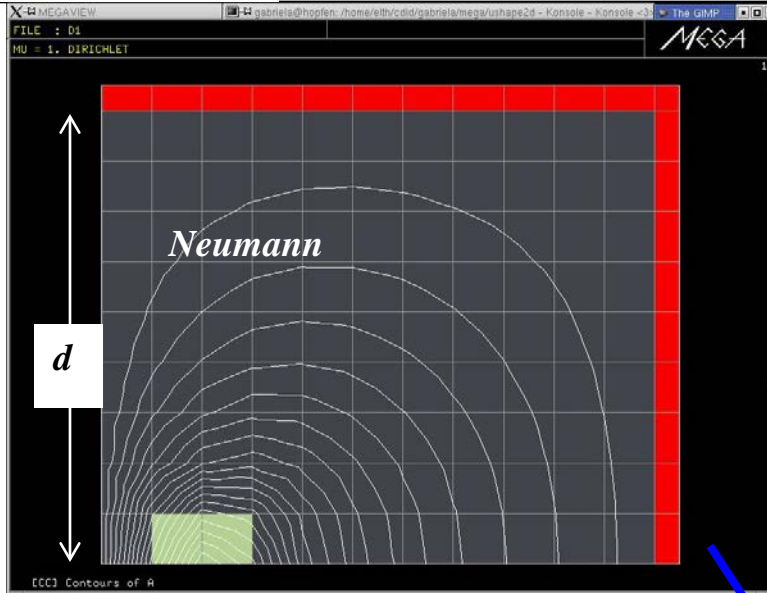
Tehnici de reducere folosite in tehnologia ALROM si eficienta lor

Nr.	ROM techniques	Modeling aspect	n - DOFs before	q - DOFs after	Efficiency n/q
1	CellHo = Cell Homogenisation	Non-Manhattan interfaces (poly., cyl., via)	$10 \cdot 10^6$	$8.3 \cdot 10^6$	1.2
2	ELOB = Equivalent Layer of Open Boundary condition	Boundary condition	$8.3 \cdot 10^6$	$8.5 \cdot 10^5$	9.8
3	dFIT = dual Finite Integration Technique	Optimal mesh step	$8.5 \cdot 10^5$	$1.9 \cdot 10^5$	4.2
4	PROM = Phenomenon based ROM based on suitable electromagnetic field regime (FW, LL, MQS, EQS, EMQS)	Displacement current and induced voltage	$1.9 \cdot 10^5$	10^5	1.9
5	TCR = Tree/Cotree Reduction	Gauge condition	10^5	71930	1.5

Tehnici de reducere folosite in tehnologia ALROM si eficienta lor

Nr.	ROM techniques	Modeling aspect	n - DOFs before	q - DOFs after	Efficiency n/q
6	FredHO = Frequency Dependent Hodge Operators	Skin effect	71930	11380	6.3
7	ASPEEC = Algebraic Sparsified Partial Equivalent Electric Circuit	SiO ₂ /Low k insulator modeling	11380	883	12.9
8	SSA = Successive Symbolic Approximation	Si substrate modeling	-	-	-
9	KROM = Krylov based ROM	Essential moments	883	10	88.3
10	VECTORFIT = Frequency Characteristic Fitting	Frequency behavior	6	1	6
	GLOBAL	ROM	10·10 ⁶	1	10·10⁶

Field lines for tested boundary conditions



Teorema incadrarii solutiei in domenii cu frontiera deschisa

Matricea inductantelor L_{NBC} calculata in conditii Neumann si L_{DBC} calculata cu conditii Dirichlet sunt margini inferioare si superioare ale matricei exacte L , dar si ale matricei L_{ELOB} , calculata cu conditii de frontiera de tip ELOB cu parametri pozitivi arbitrari:

$$L_{NBC} \leq L \leq L_{DBC} \quad L_{NBC} \leq L_{ELOB} \leq L_{DBC}$$

$$\varepsilon_a = \frac{\|L_a - L\|}{\|L_a\|} \leq \frac{\|L_{NBC} - L_{DBC}\|}{\|L_a\|}$$

$$\varepsilon_h = \frac{\|L_h - L\|}{\|L_h\|} \leq \frac{\|L_{NBC} - L_{DBC}\|}{\|L_h\|}$$

$$L_a = (L_{NBC} + L_{DBC})/2, \text{ or } L_h = 2((L_{NBC})^{-1} + (L_{DBC})^{-1})^{-1}$$

O distributie data de curent inmagazineaza o energie magnetica mai mare $i^T L' i / 2 \leq i^T L'' i / 2$ in materiale cu permeabilitate mai ridicata $\mu'(r) \leq \mu''(r)$.

- C. f. Neumann = conditia ELOB cu $\mu \rightarrow 0$
- C.f. Dirichlet = conditia ELOB cu $\mu \rightarrow \infty$

CellHo: Omogenizarea celulelor

Save window Lights Options

Minimal mesh: 43 264 nodes

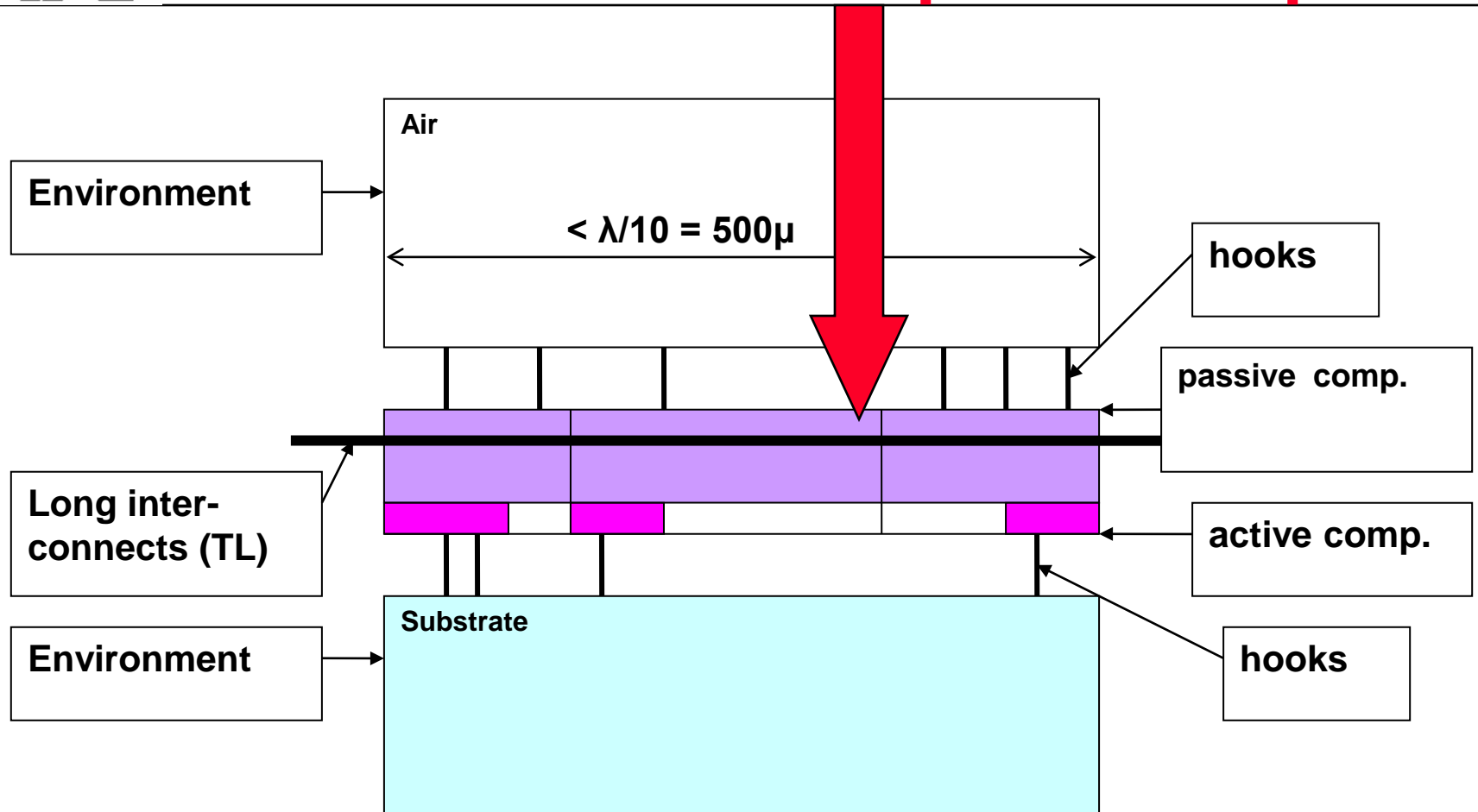
$$\bar{\varepsilon}(x,y), \bar{\sigma}(x,y)$$


Save window Lights Options

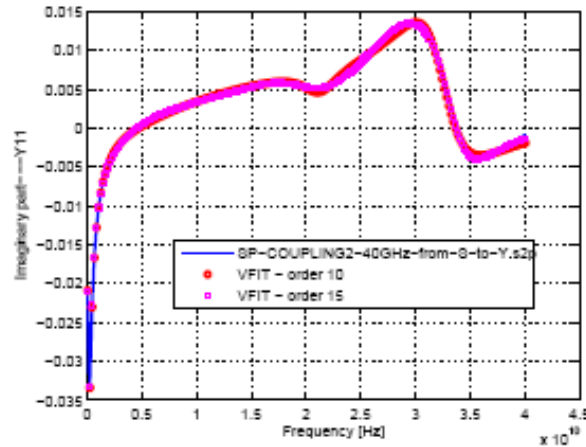
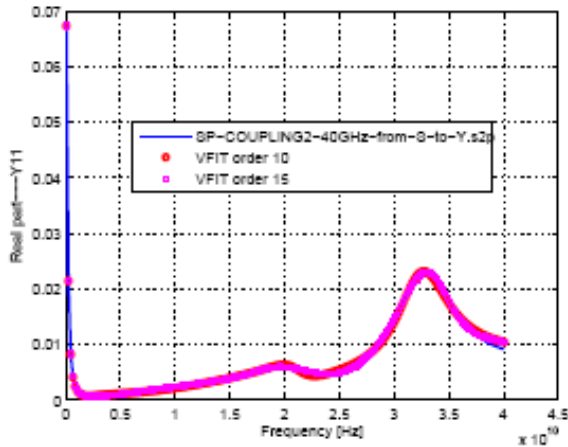
Minimal mesh: 144 nodes

$$\varepsilon_e = ct, \sigma_e = ct$$


Partitionarea in subdomenii: componentele pasive



CHRF-201 Y parameters



- ROM ord 10
- ROM ord 15
- Measured

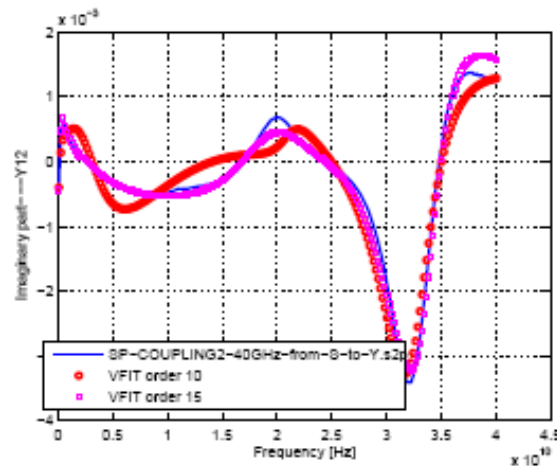
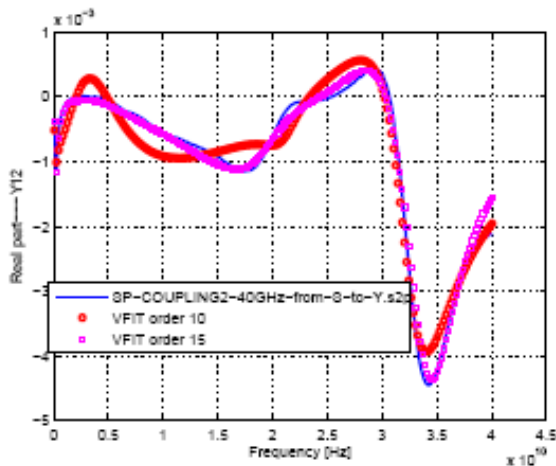
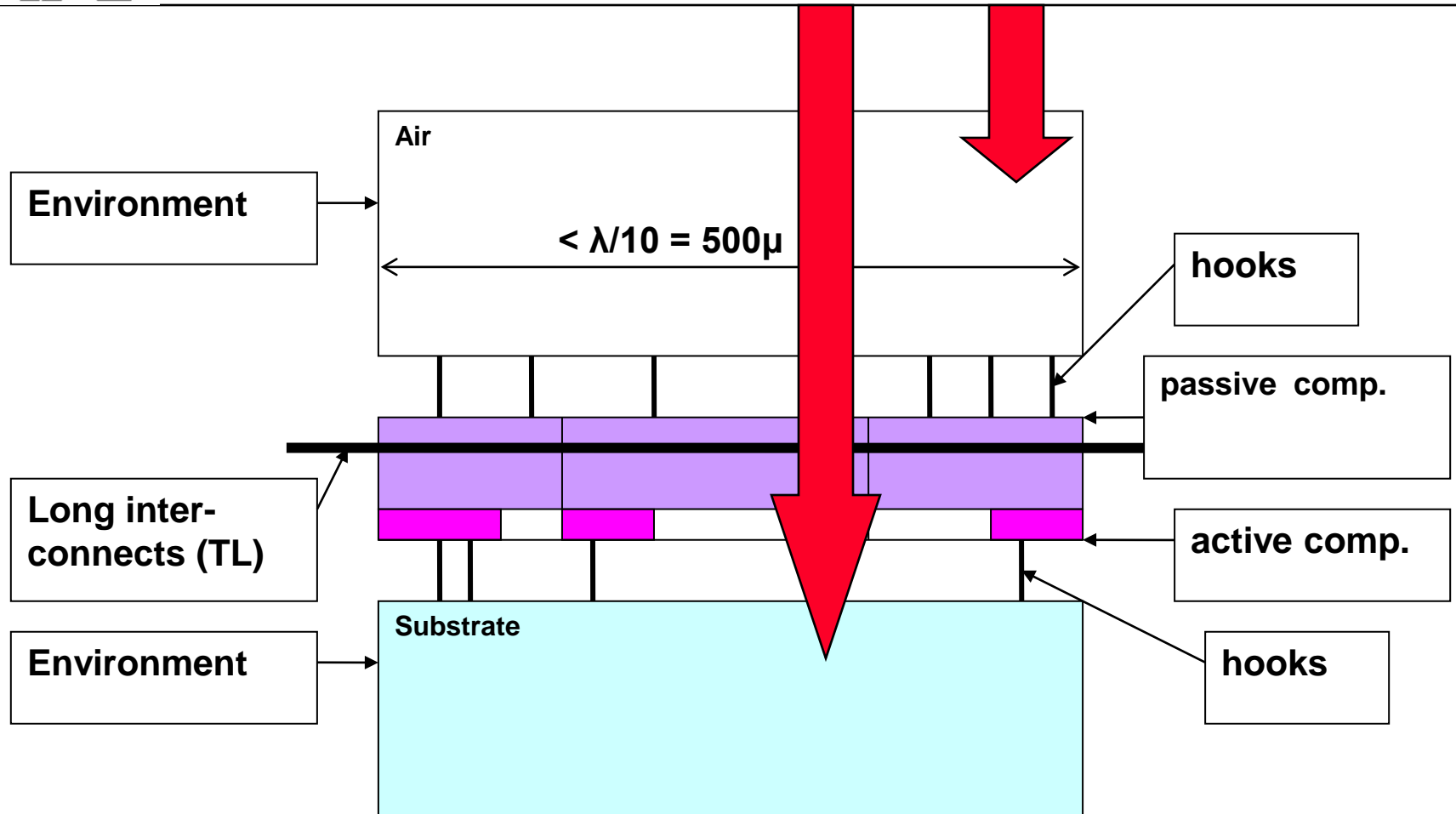
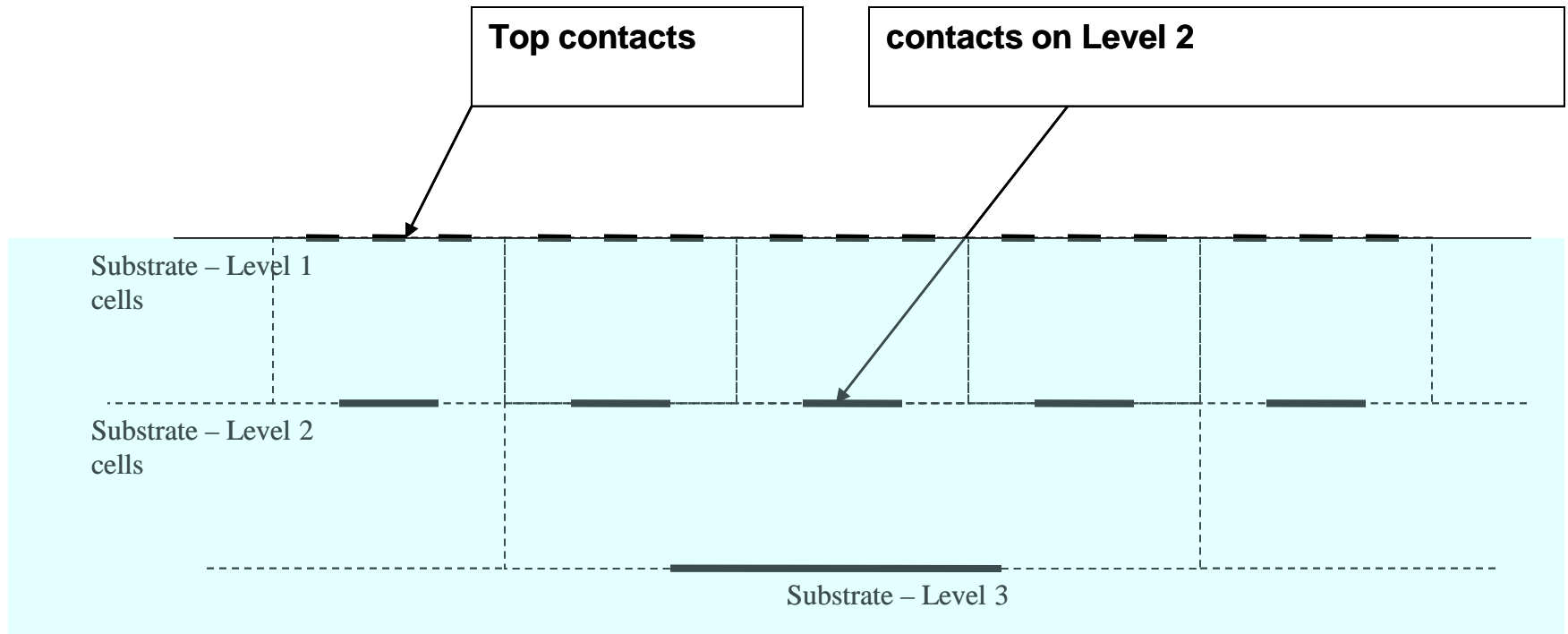


Figure 5.30: SP-Coupling / Y parameters / reduced models of order 10 and 15 obtained starting from the experimental results, using Vector fitting

Partitionarea in subdomenii: modelarea substratului

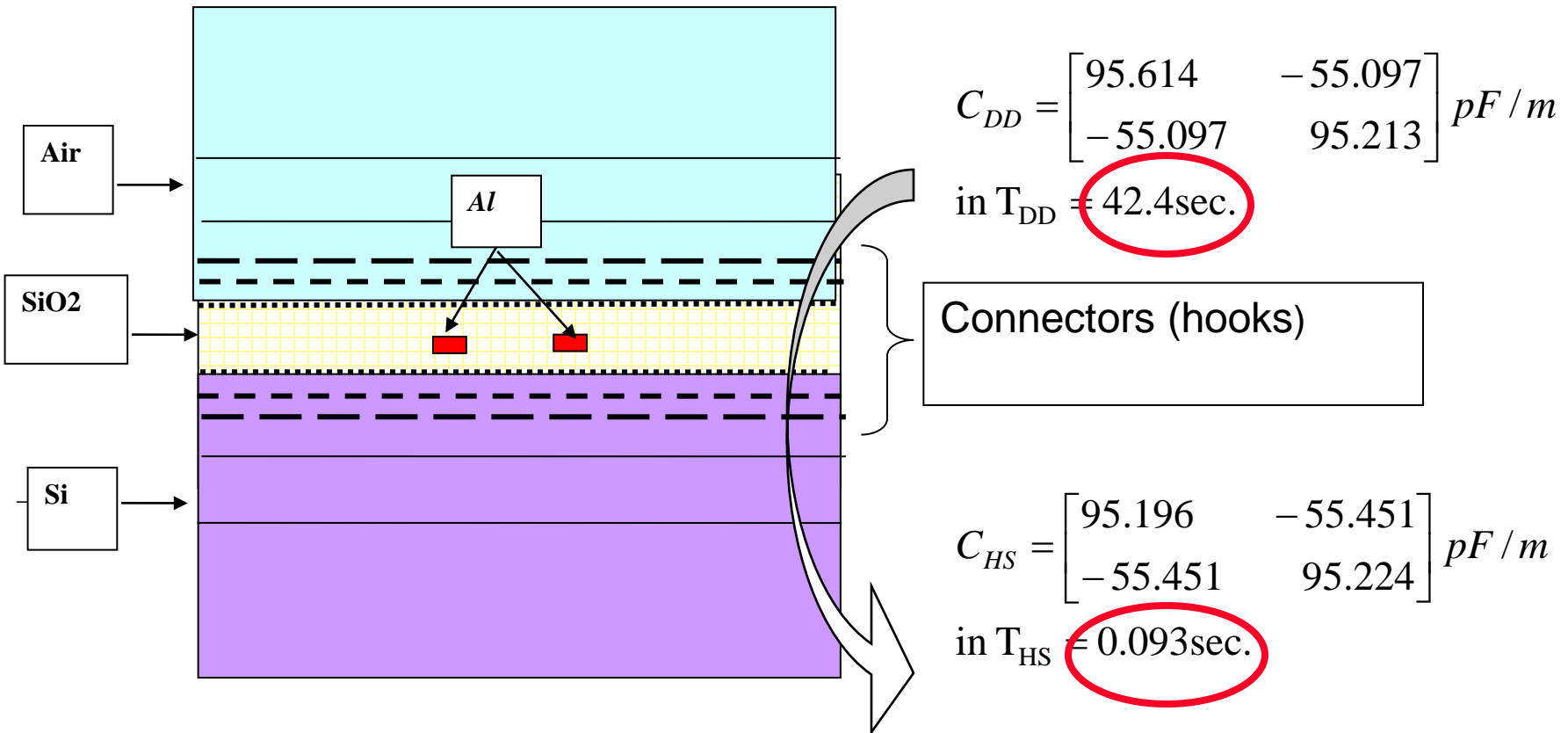


HSS: Hierarchical Structured Substrate Model

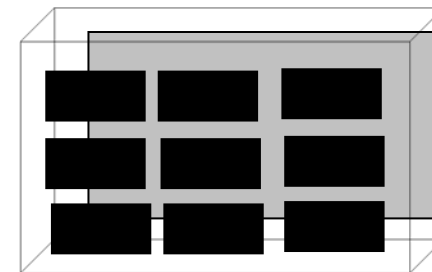


- Substratul de Si este structurat in straturi virtuale de grosime crescatoare in progresie geometrica
- Straturile sunt apoi structurate in macroelemente paralelipipedice
- Fiecare macroelement este un EEMC cu 10 terminale si cu o schema echivalenta cu 45 elemnte dipolare cu parametri concentrati.

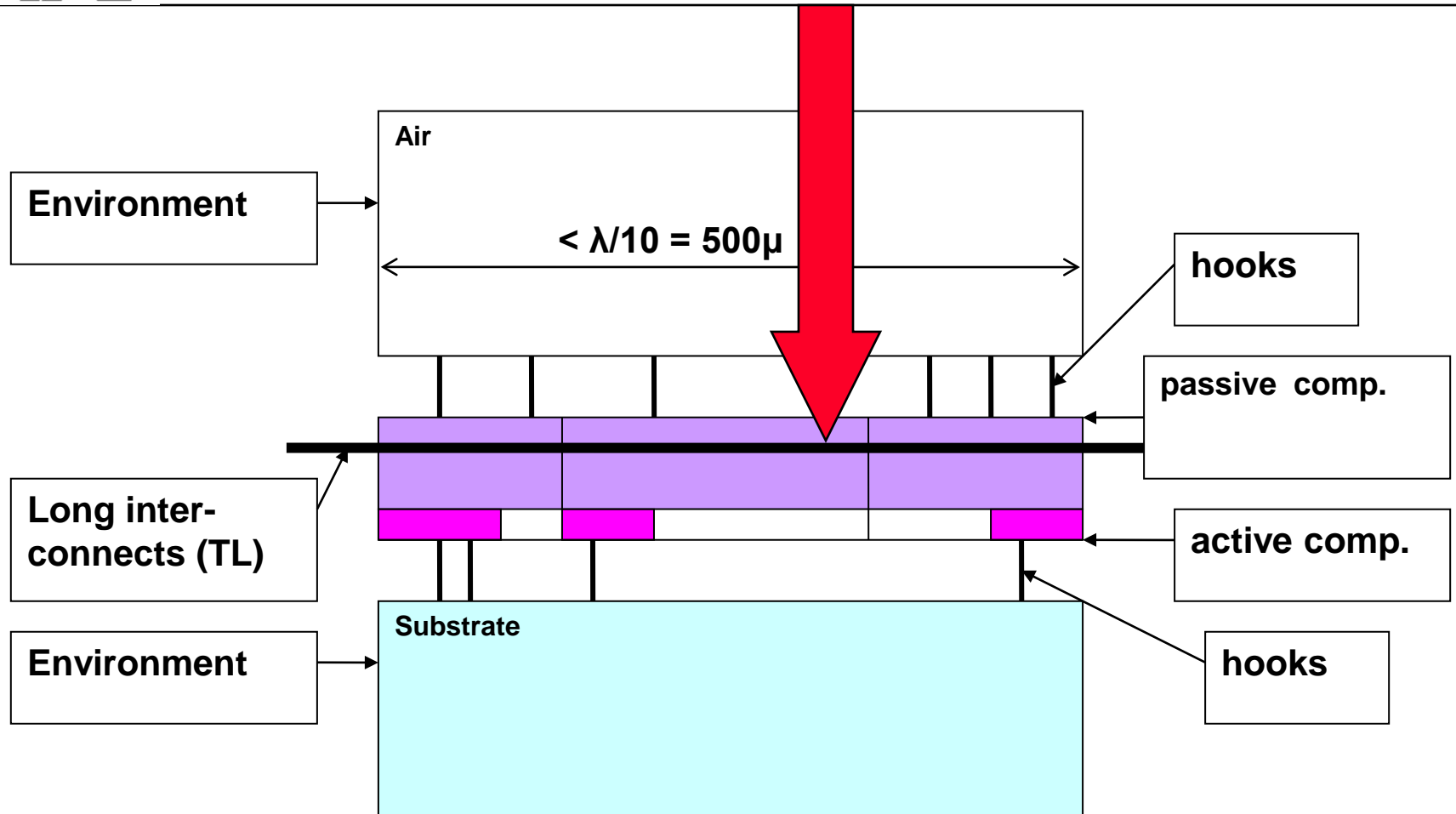
Aplicatia rarefierii ierarhice sparsification – Cazul de test TL2



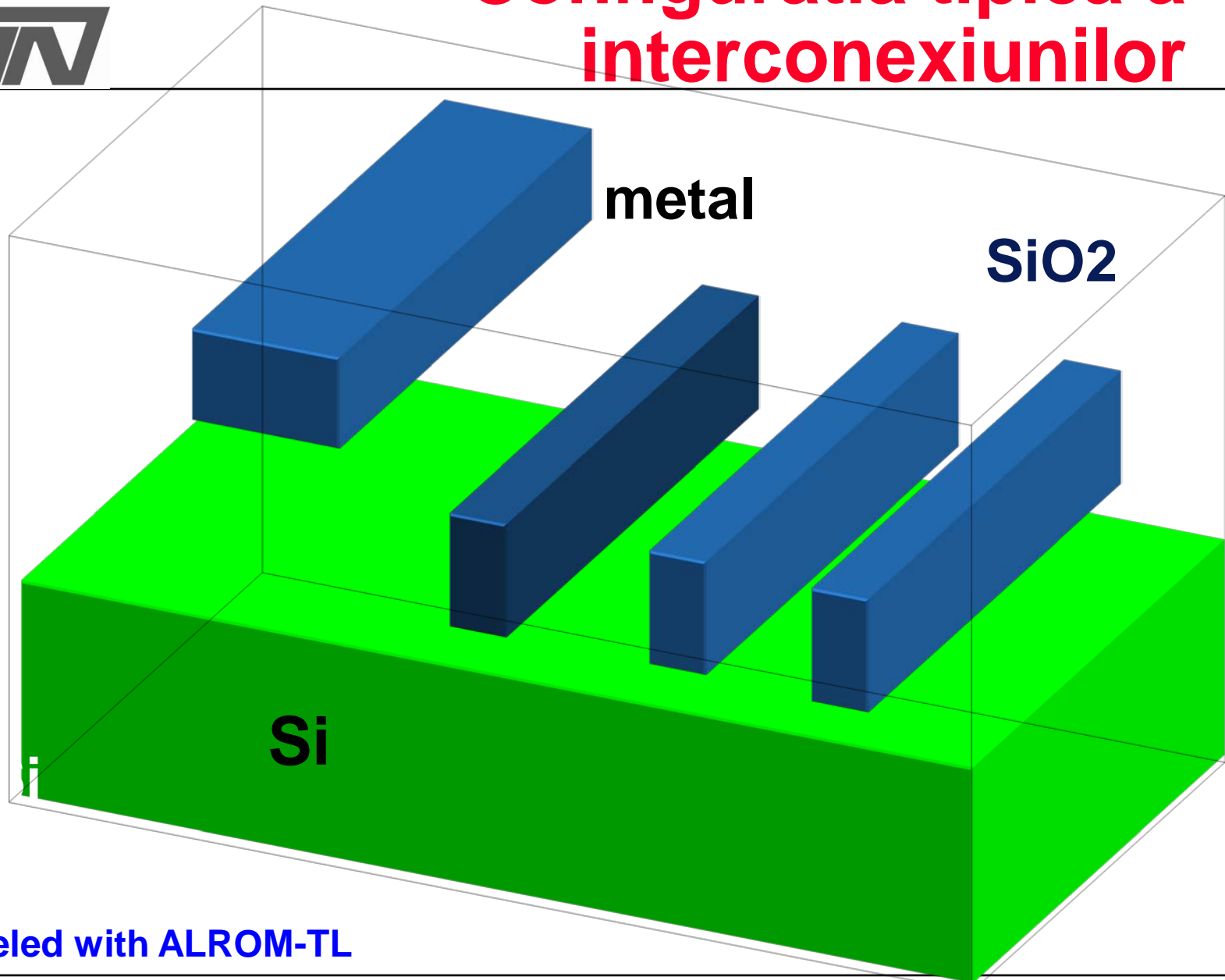
Problema de camp este redusa
la rezolvarea ecuatiei Laplace
intr-o macrocelula standard cu
10 terminale



Partitionarea in subdomenii: Interconexiuni

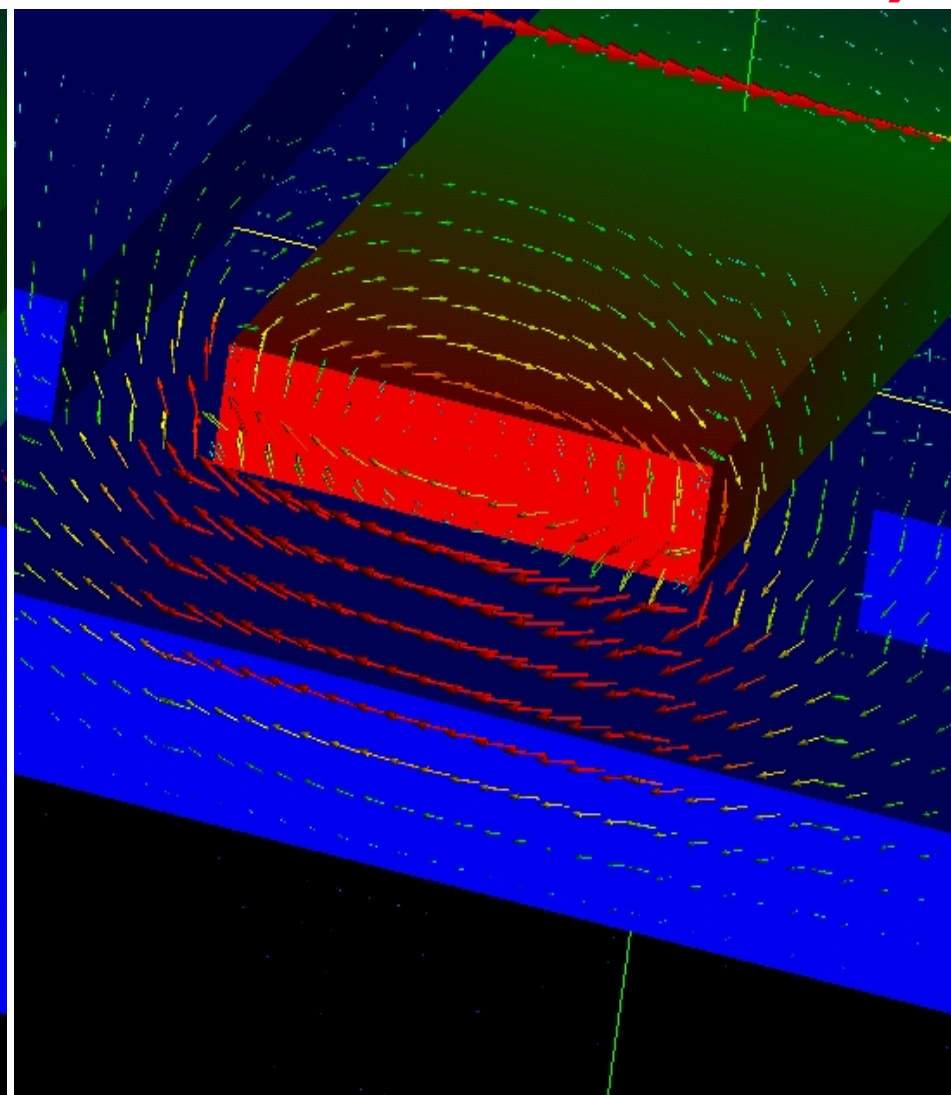
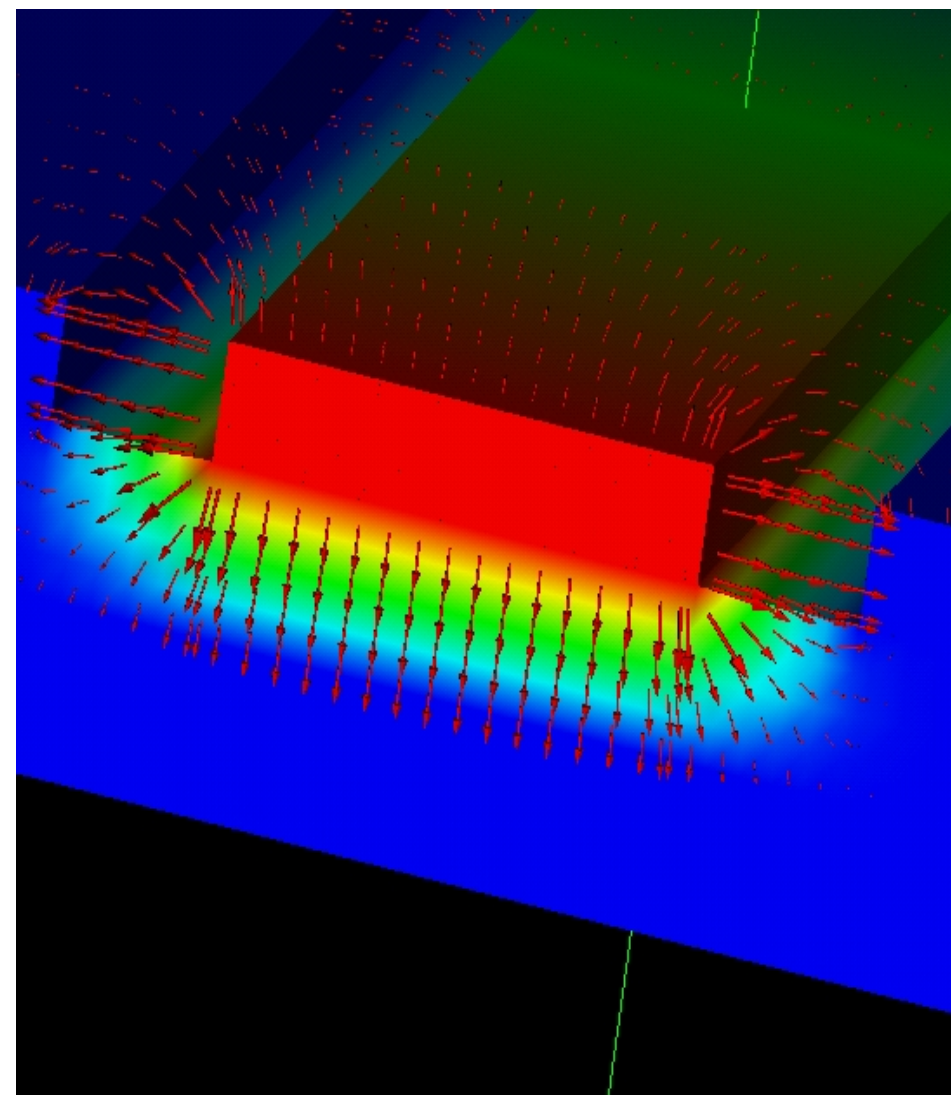


Configuratia tipica a interconexiunilor



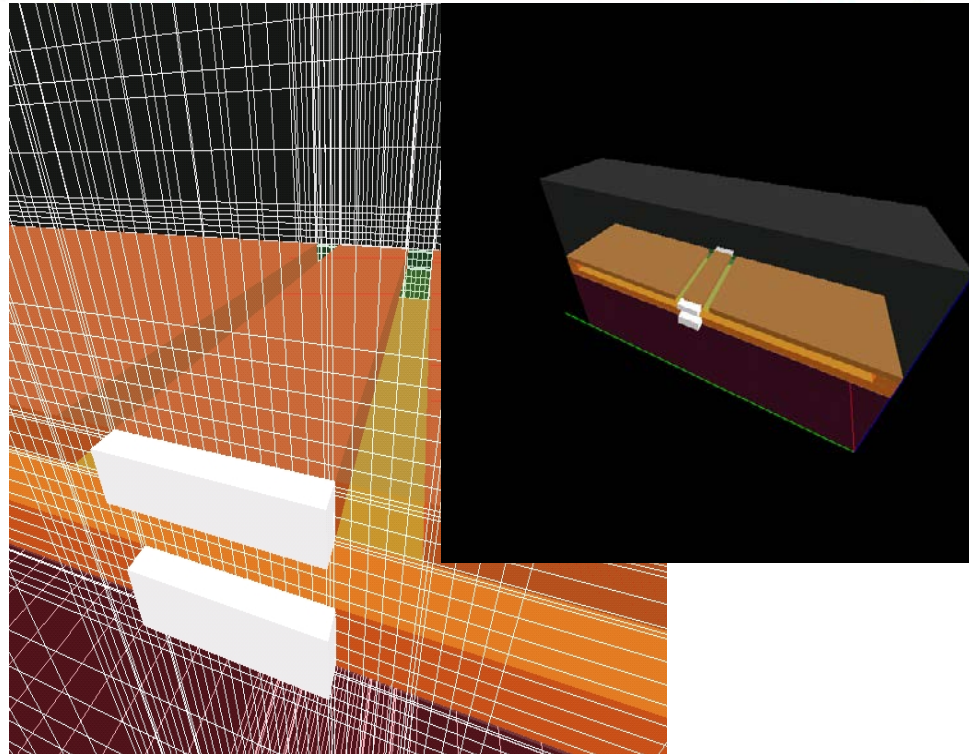
Modeled with ALROM-TL

Modelul TM (EQS for C,G + MQS for R,L)



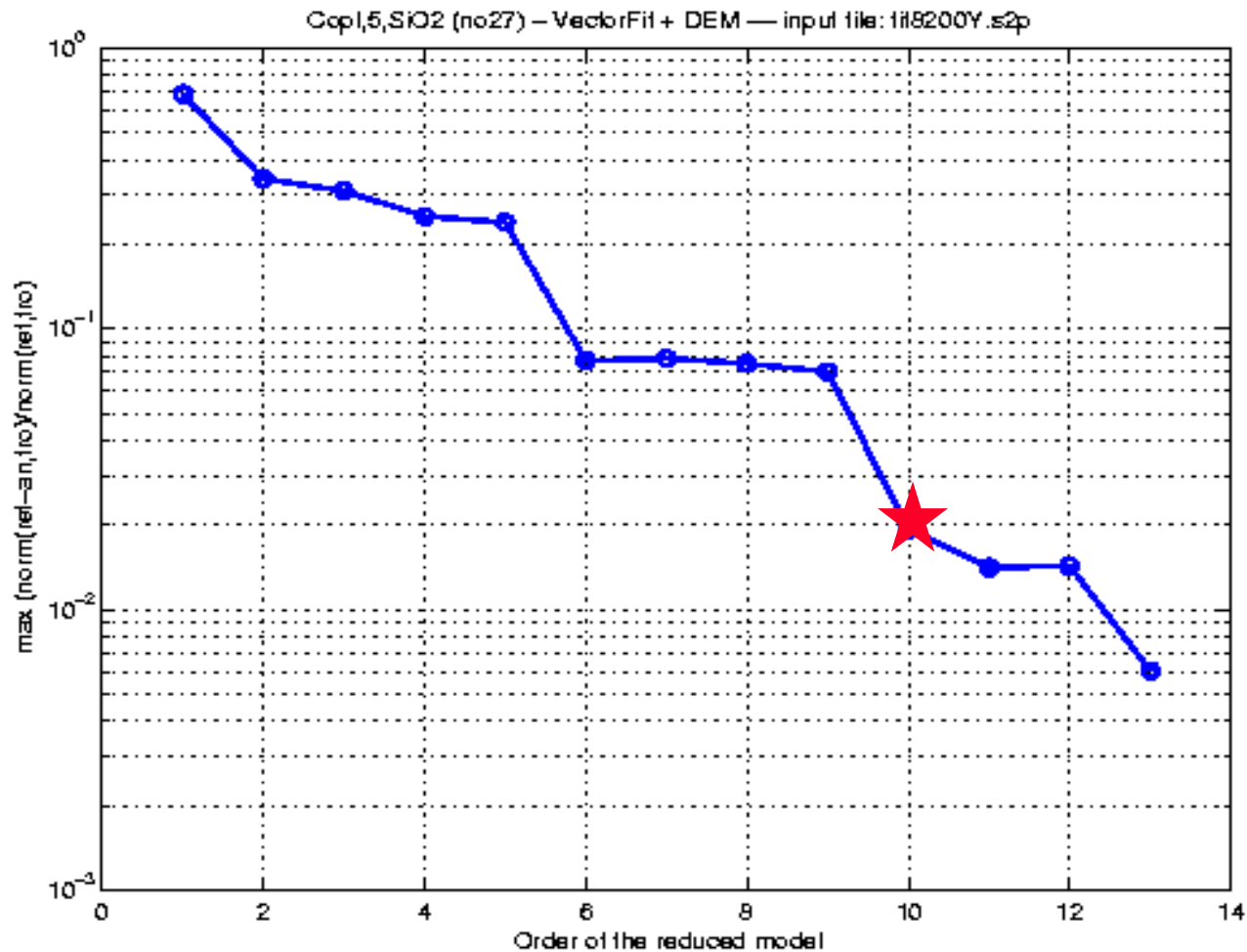
Structura de test Codestar #27

T=8200UM W=5UM S=4UM



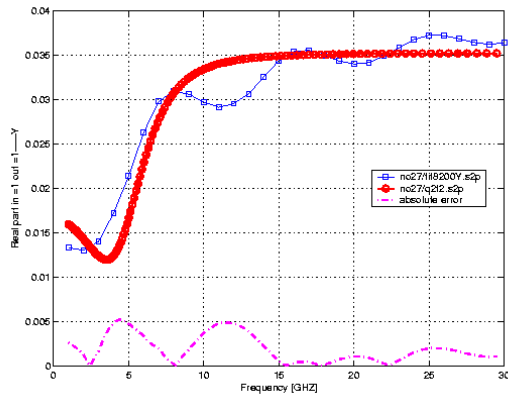
- Numarul de noduri in retea initiala = **2 866 441**
- Numarul initial de DOFs = **17,198,646**
- Domeniul redus de calcul: $200\mu \times 46.588\mu \times 17.74\mu$;
- Ordinul modelului redus = **10**
- Timpul CPU de extragere a modelului = **161 s**
- Eroarea relativa = **5.0 %**

Eroarea MOR vs ordinul redus q

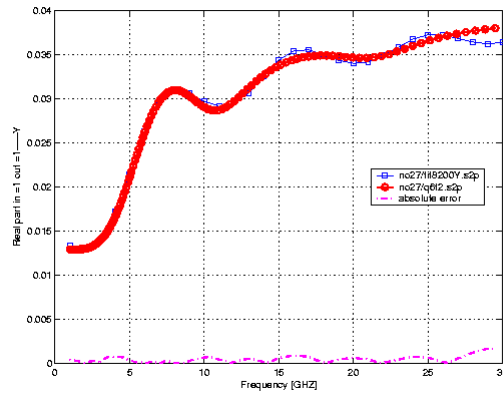


Modelul redus CDS#27

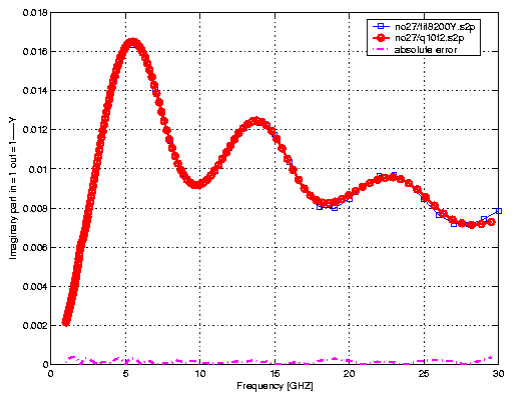
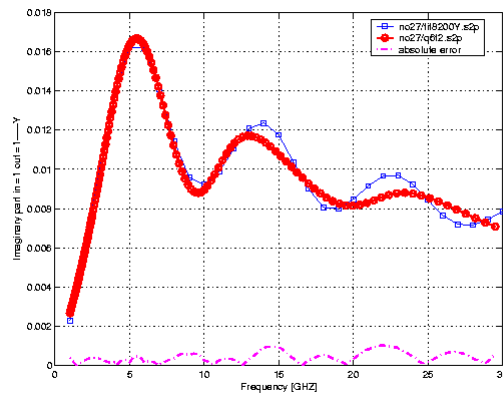
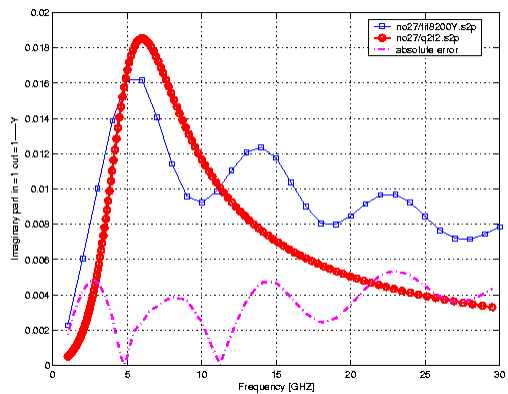
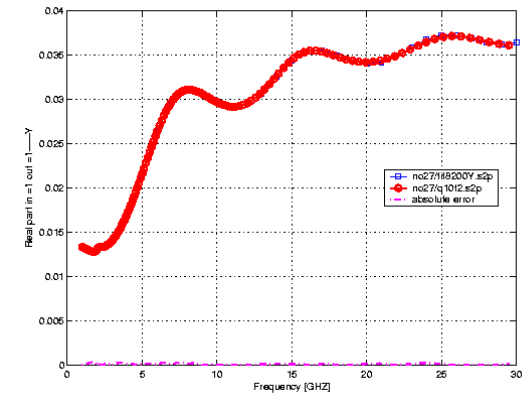
q = 2



q = 6



q = 10



Concluzii ALROM. Contributii LMN

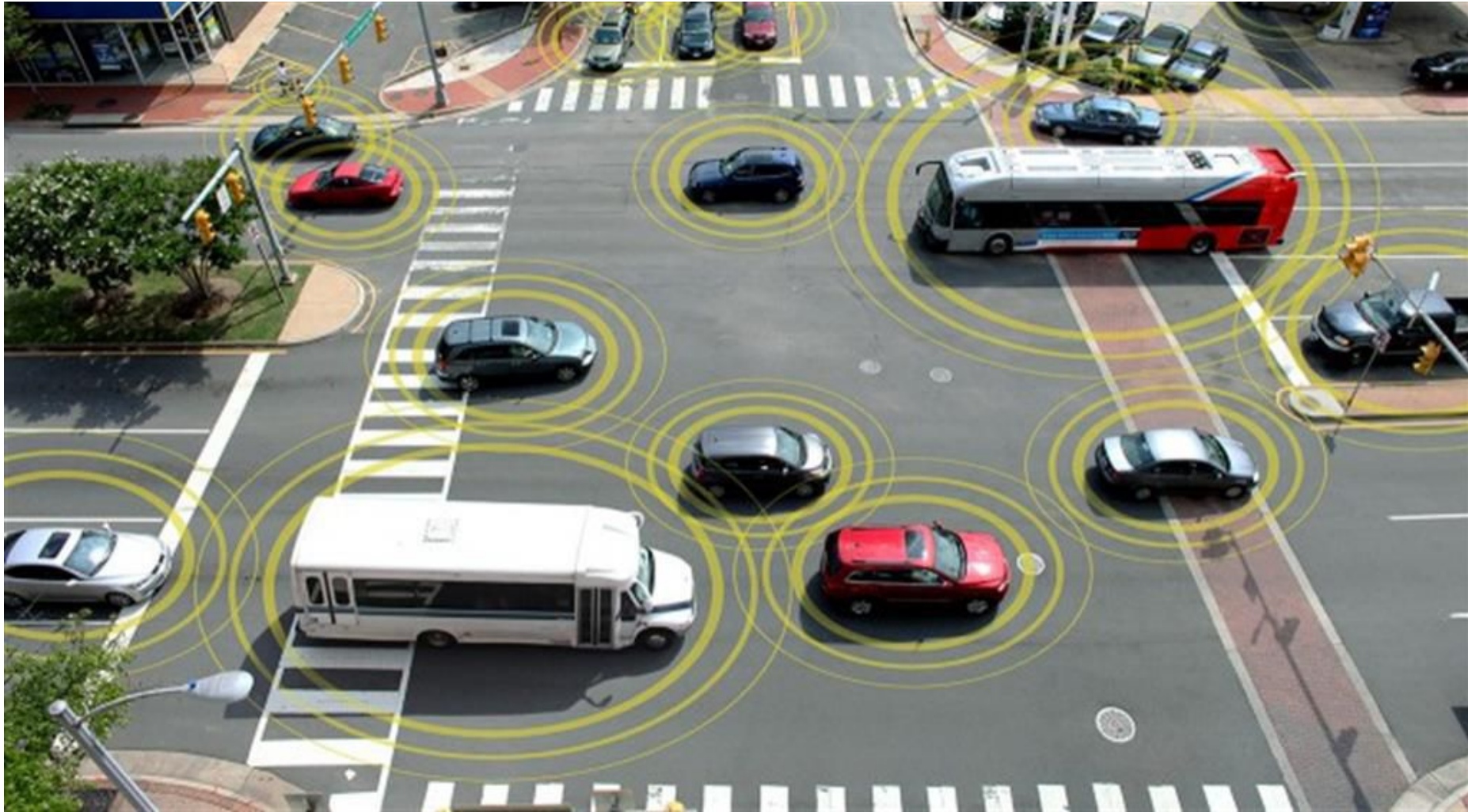
- O noua tehnologie eficienta **TCAD** pentru extragerea modelelor componentelor pasive din circuitele integrate de RF
- Reducerea trebuie aplicata **cat mai devreme posibil si in toate etapele** de modelare
- Fiecare subdomeniu are propriul **regim al campului EM**
- Conditii de frontiera sunt de tip **EMCE cu terminale alese optimal**
- **Reducere a priori**: discretizare si partitie optimale cu **dFIT, dELOB, HSS, TL**
- **Reducere "din zbor"**: **MEEC redus, FIT, CellHo, FredHO**
- **Reducerea (aposteriori)** a ordinului modelului: **AFS+VF**
- Extragerea modelului **parametric**: **AFT**
- In toate cazurile de test reducerea dimensiunii modelului s-a facut la un ordin **$q < 20$** , chiar daca s-a pornit de la peste un milion de grade de libertate, in conditiile in care **eroarea a fost sub 5%**

3 aplicatii - proiecte

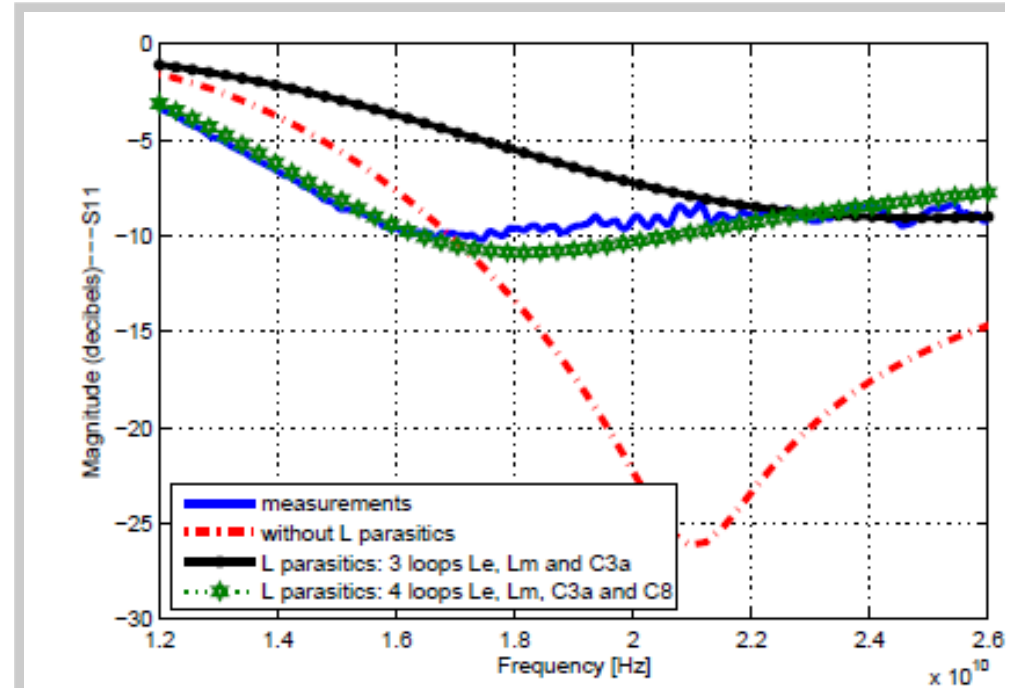
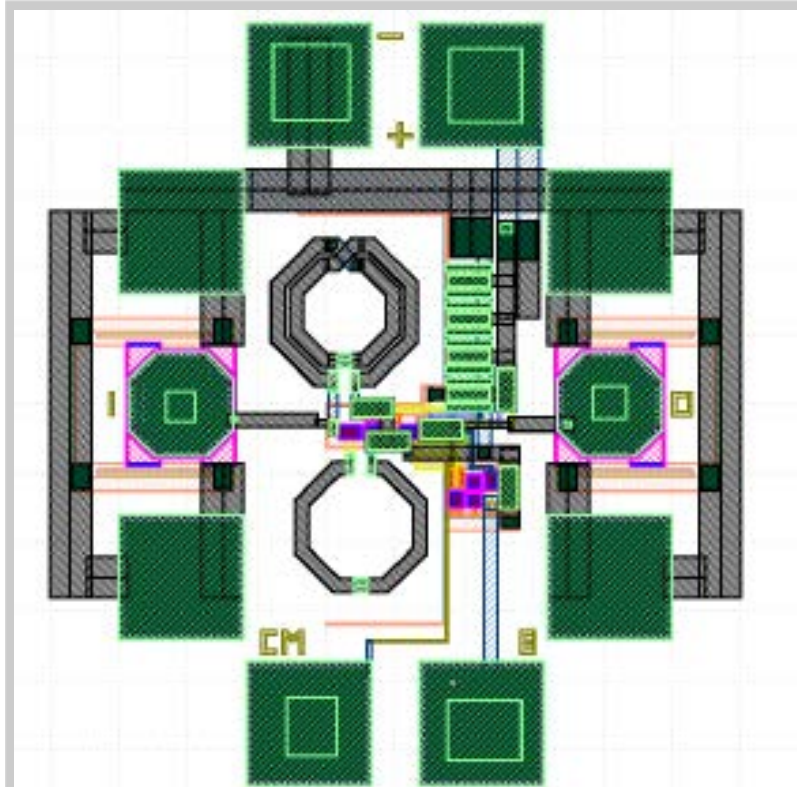
- **Proiectarea circuitului integrat pentru car-radar - Philips**
- **Optimizarea electromagnetilor pentru acceleratorului de particule – FAIR Darmstadt**
- **Comutator Micro-electro-mecanic de radiofrecventa - RF MEMS switch - IMT**

- **Proiectarea circuitului integrat pentru car-radar Philips - Olanda**
- Optimizarea electromagnetilor pentru acceleratorului de particule FAIR - Facility for Antiproton and Ion Research – Darmstadt
- Comutator Micro-electro-mecanic de radiofrecventa - RF MEMS switch - IMT

Car radar

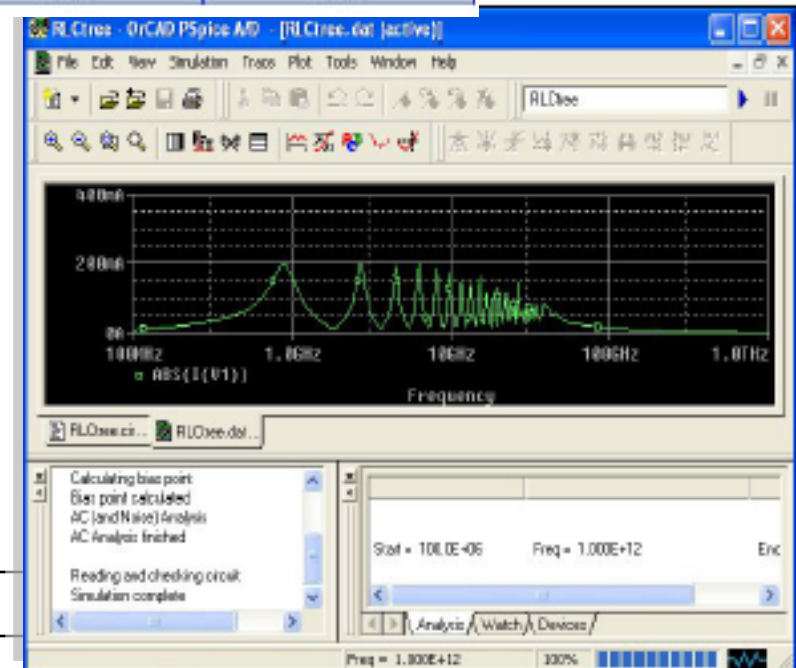
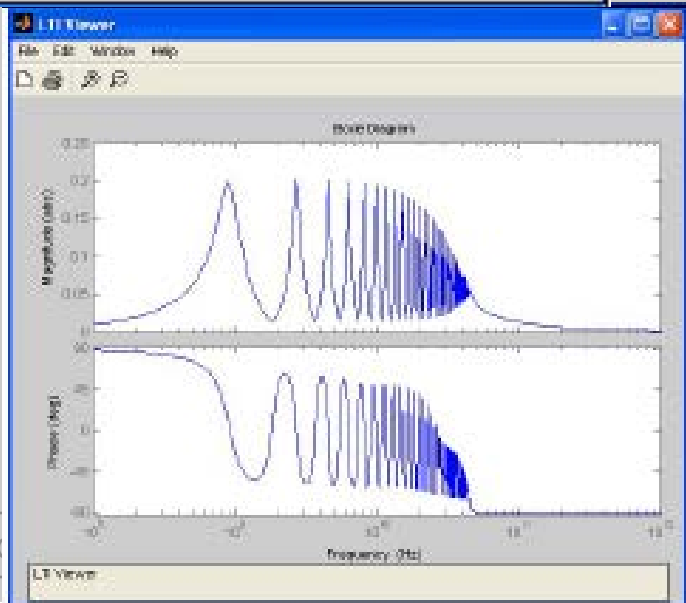
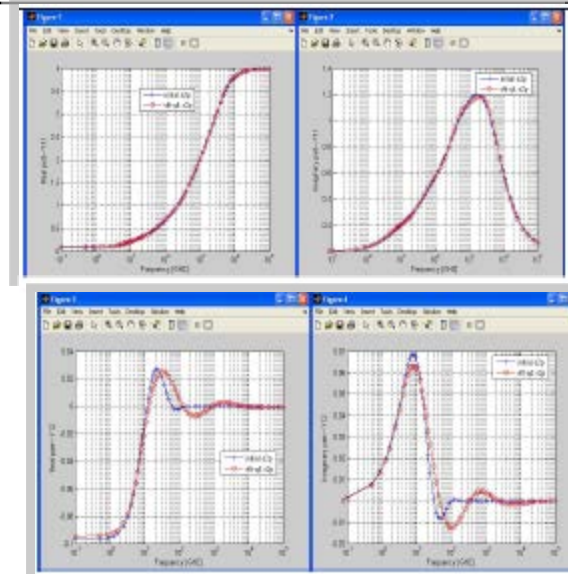
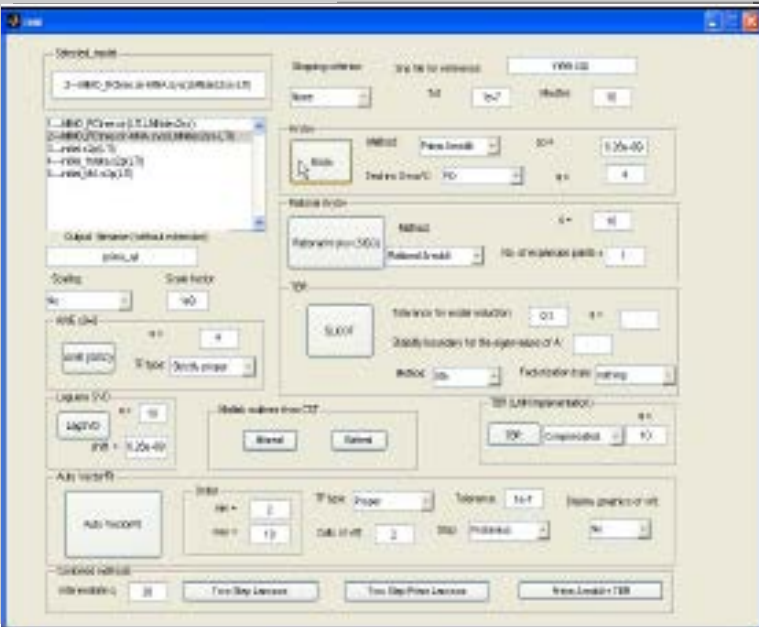


Car radar Philips, modelat cu FIT-MEEC



In perspectiva: dezvoltarea de noi algoritmi eficienți de extragere automată a modelelor reduse a circuitelor integrate de RF/microunde bazate pe tehnici HPC (sisteme de calcul multiprocesor)

Capturi de ecran cu software dezvoltat in LMN



On-Wafer RF Characterization of RF ICs (Philips)



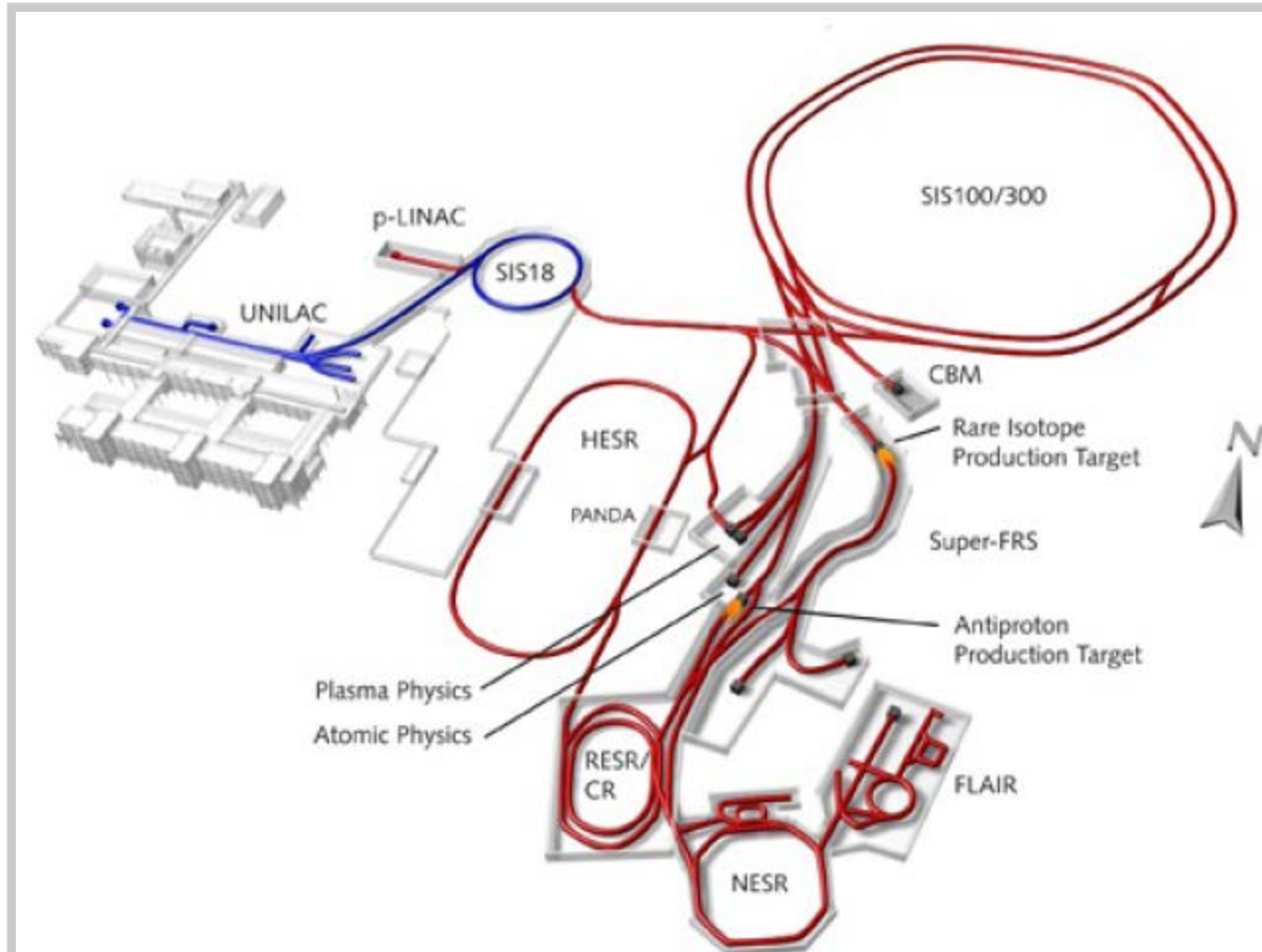
A doua aplicatie

- Proiectarea circuitului integrat pentru car-radar Philips
- **Optimizarea electromagnetilor pentru acceleratorului de particule FAIR – Darmstadt Germania**
- Comutator Micro-electro-mecanic de radiofrecventa - RF MEMS switch - IMT

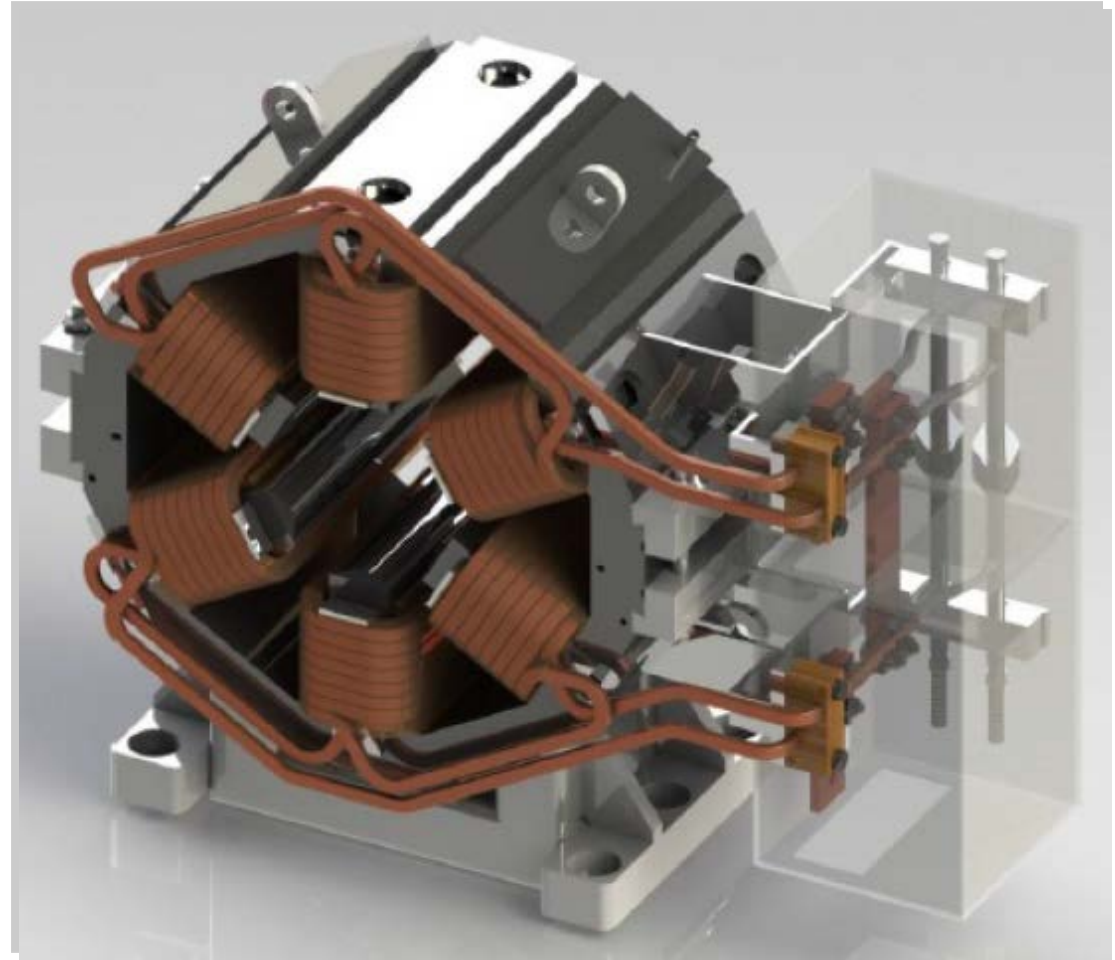
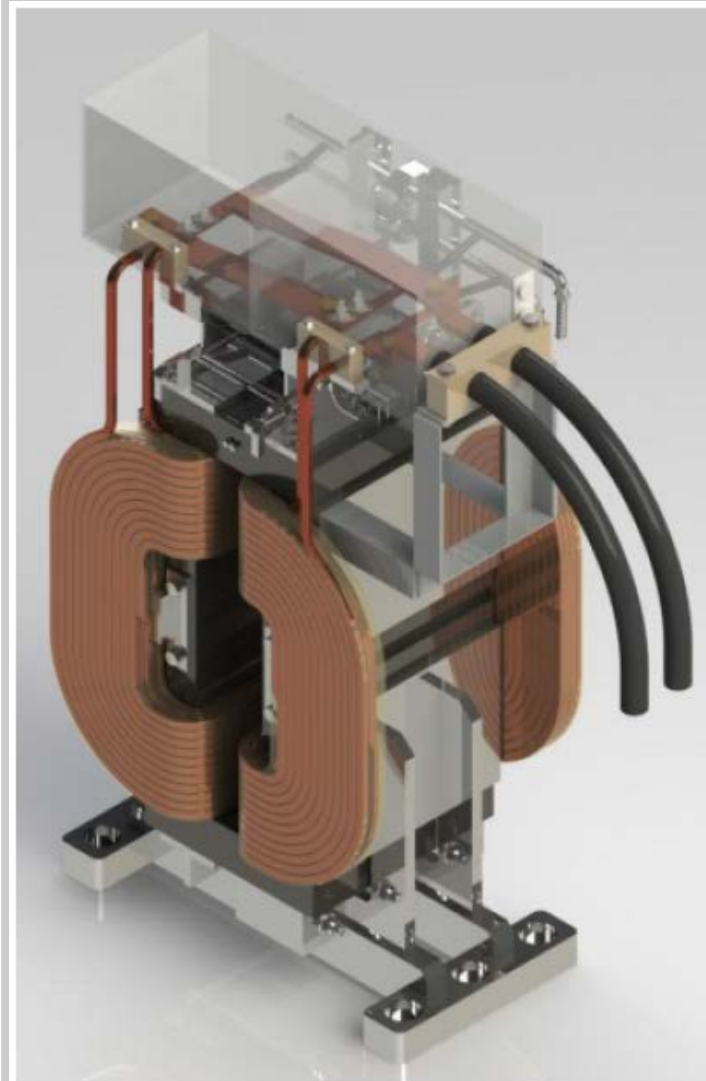
FAIR - Facility for Antiproton and Ion Research



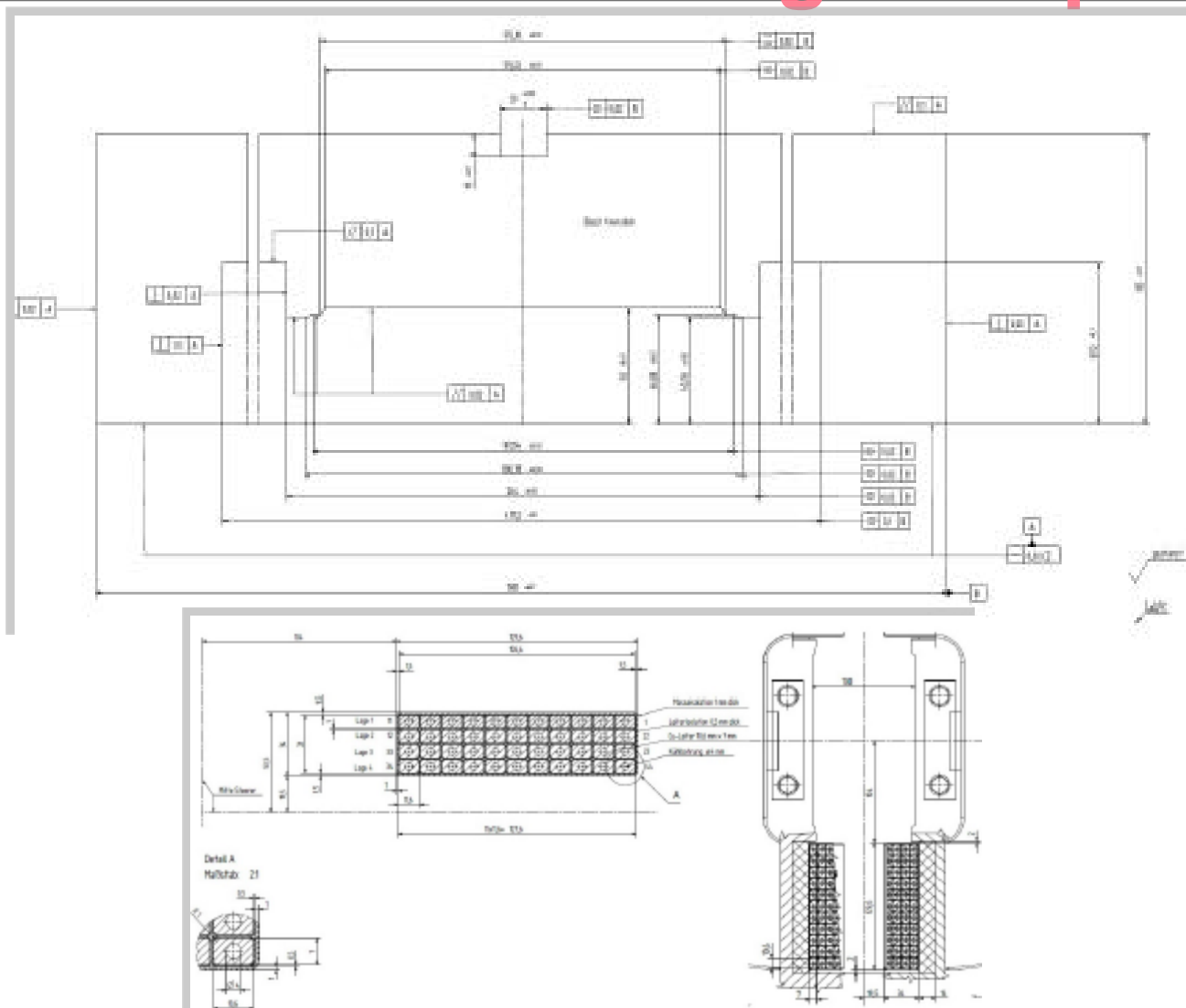
Buclele acceleratorului FAIR



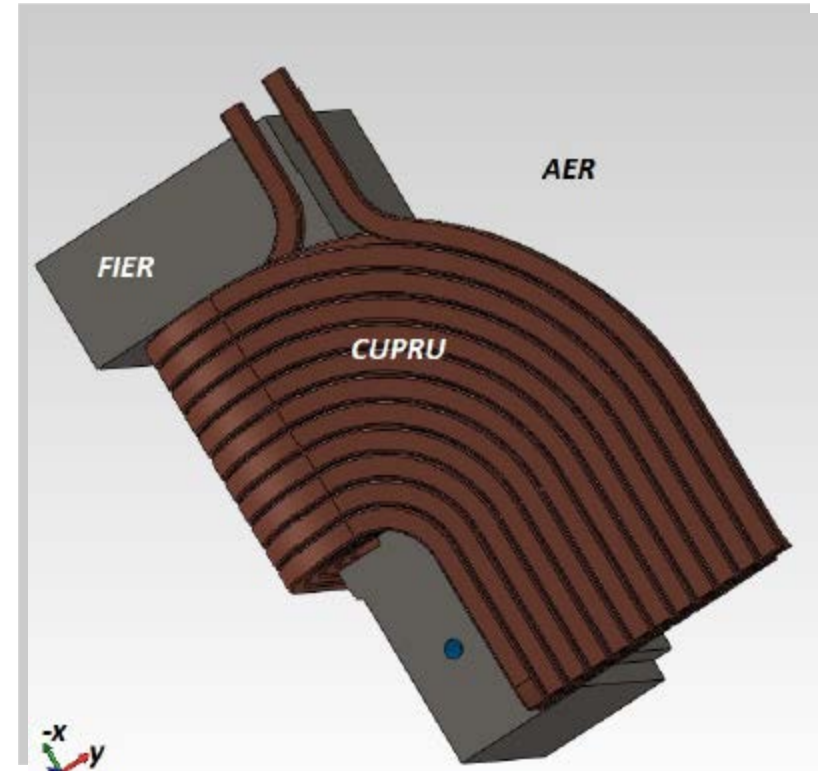
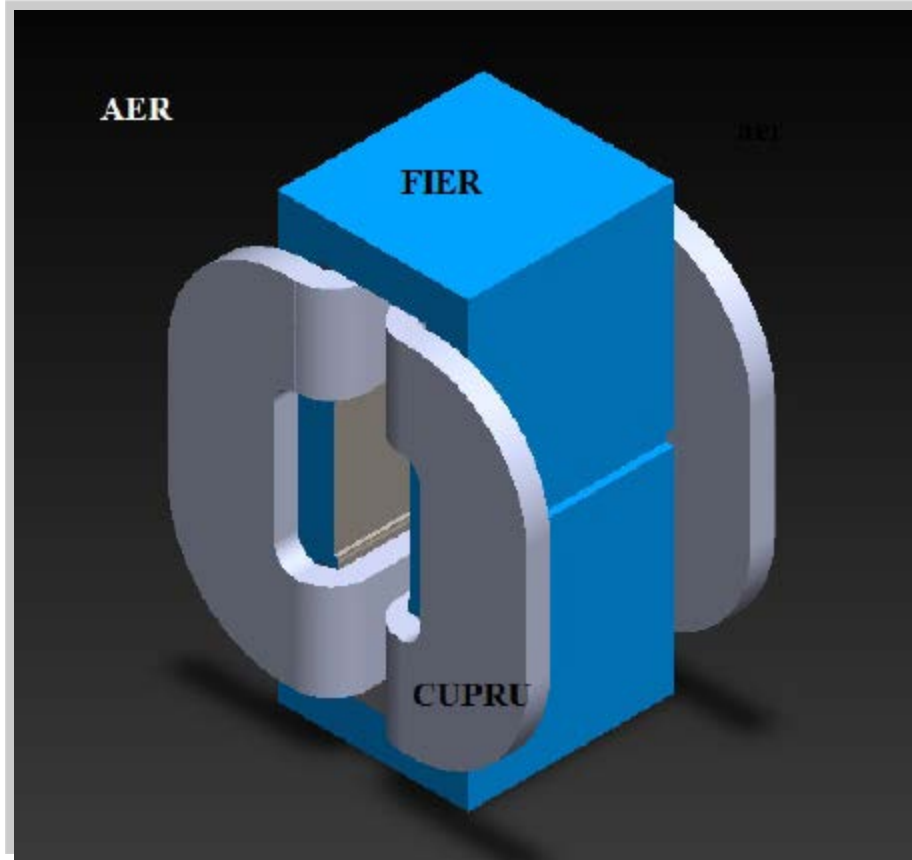
Electromagnetii dipolar si hexapolar pentru FAIR



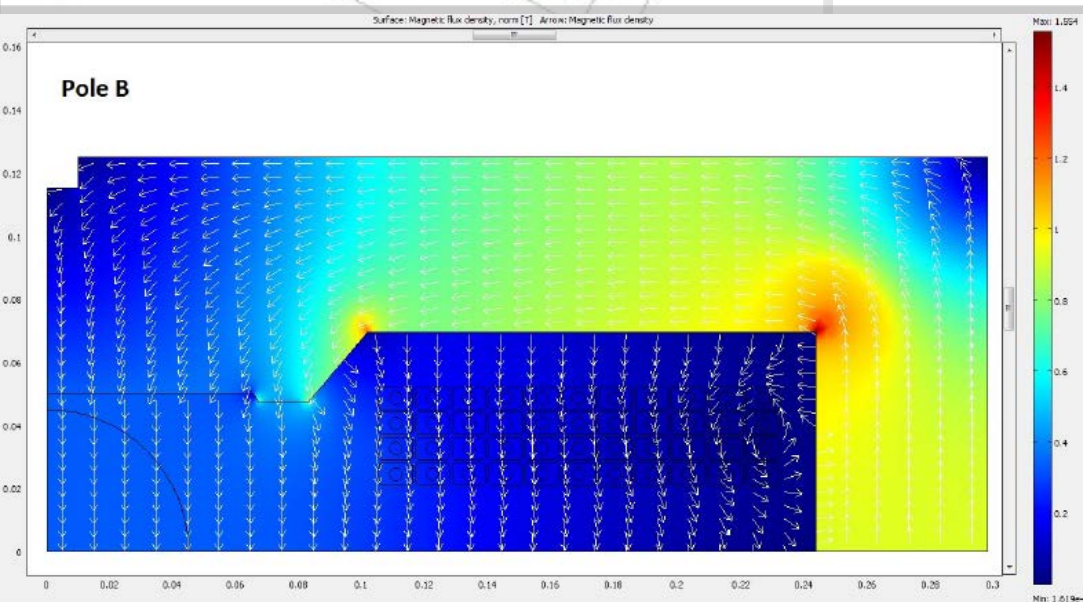
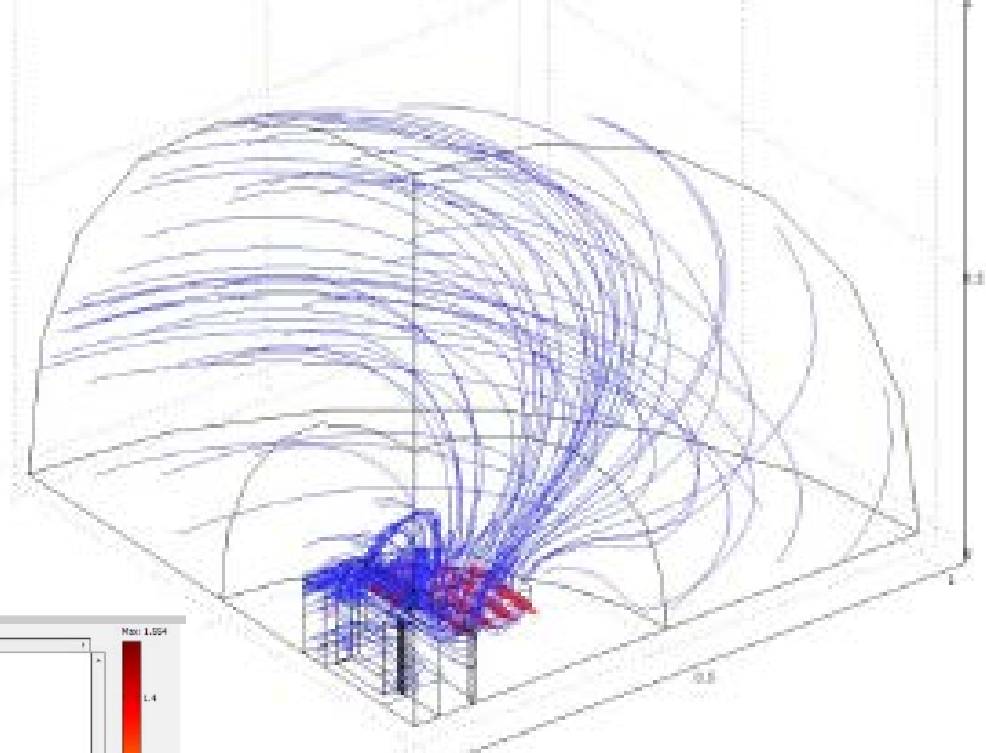
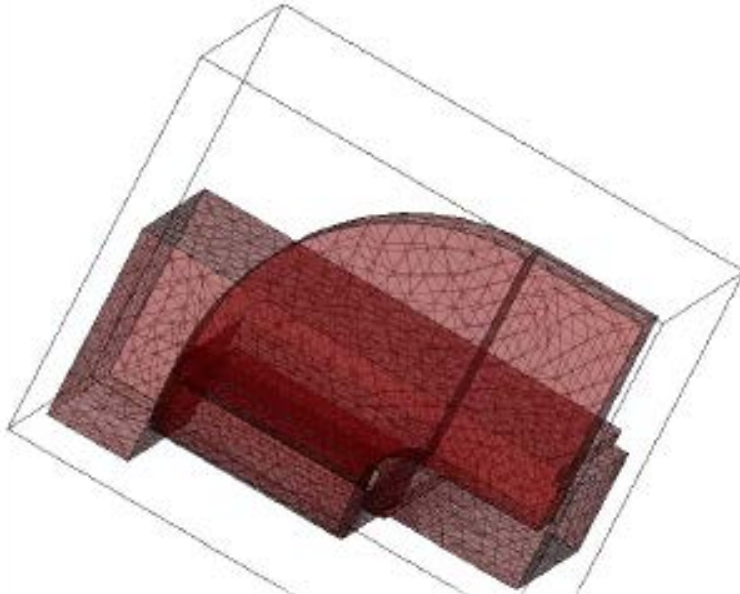
Miez si infasurare pentru electromagnet dipolar



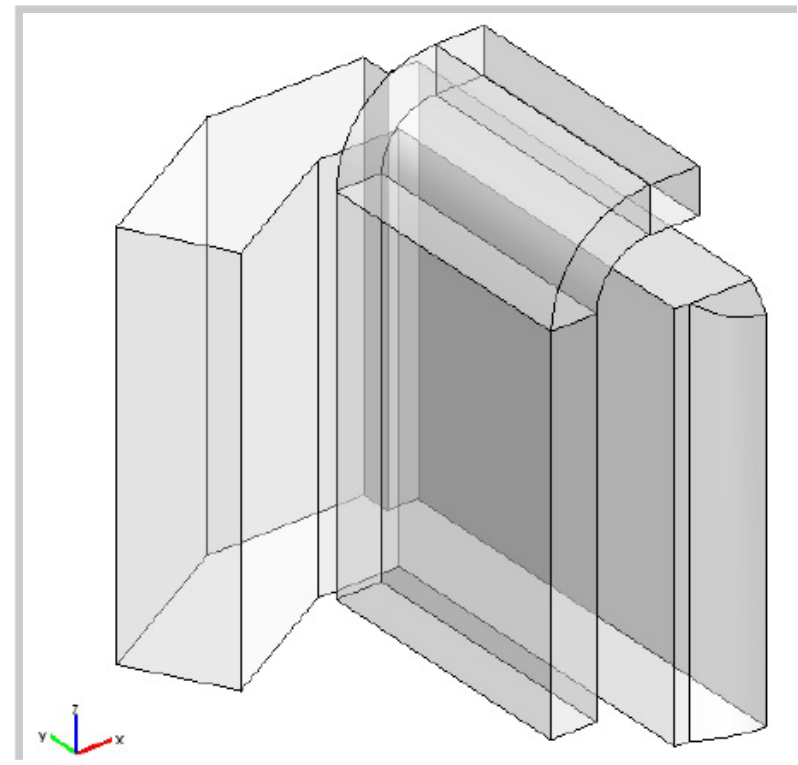
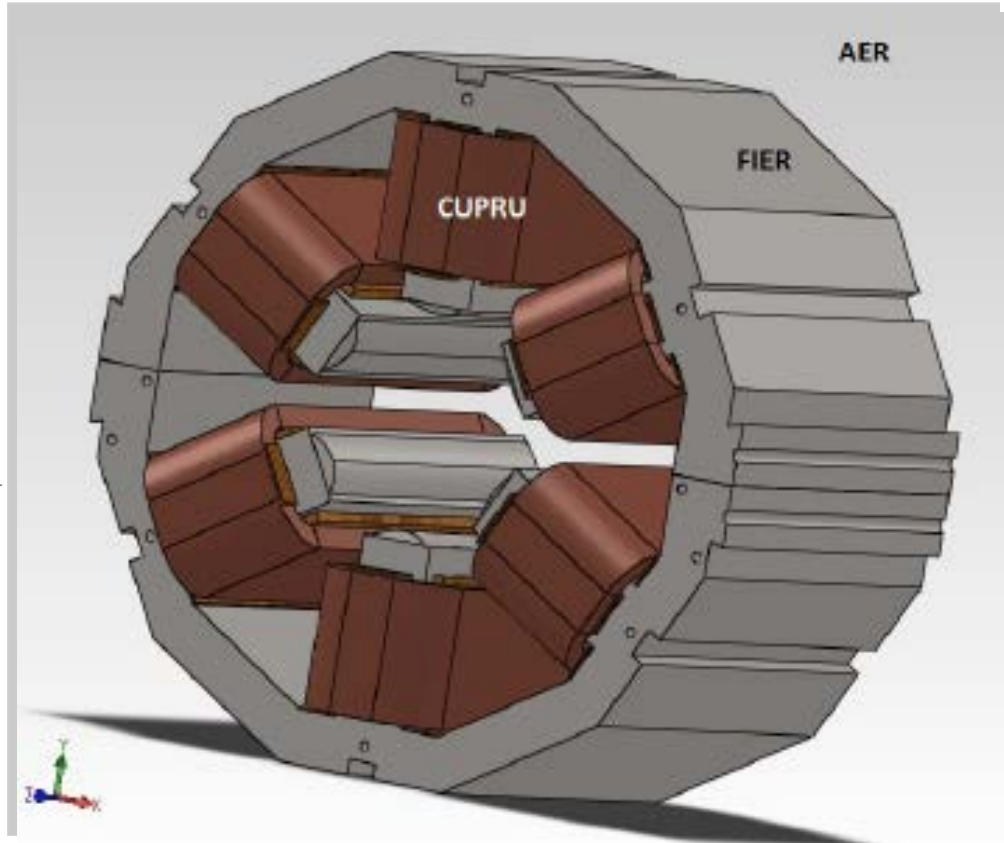
Modelul geometric 3D pentru dipol



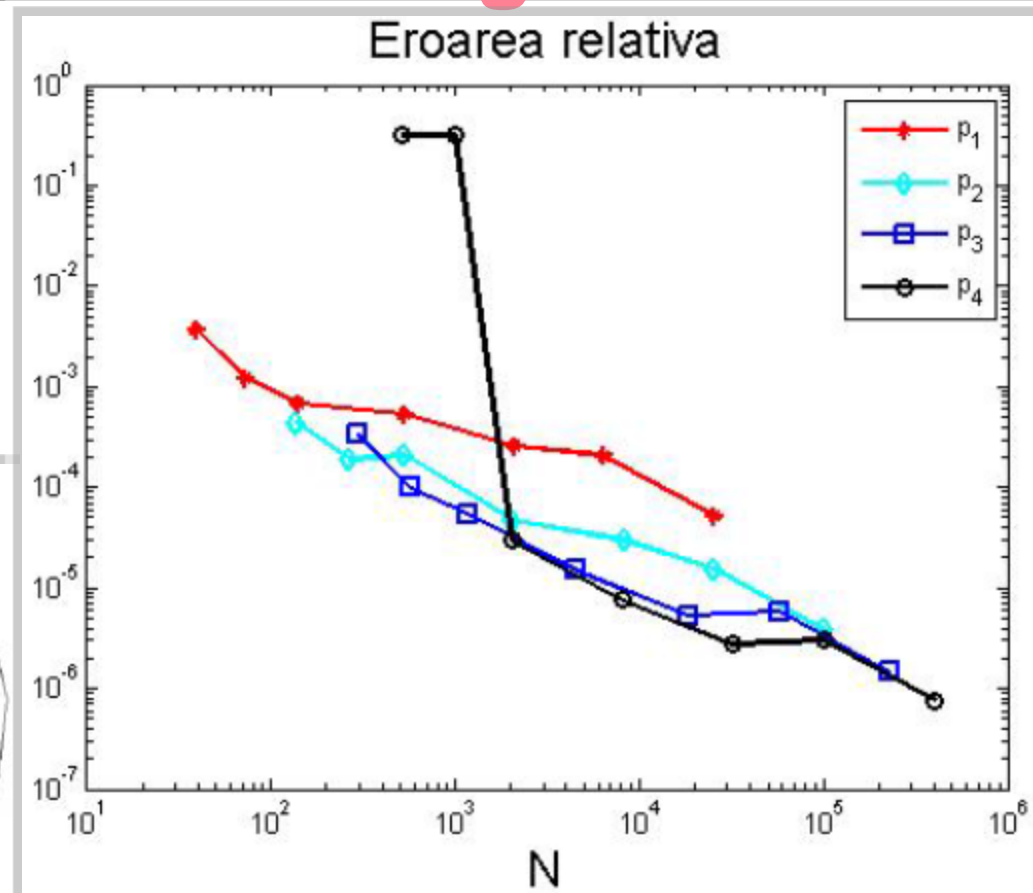
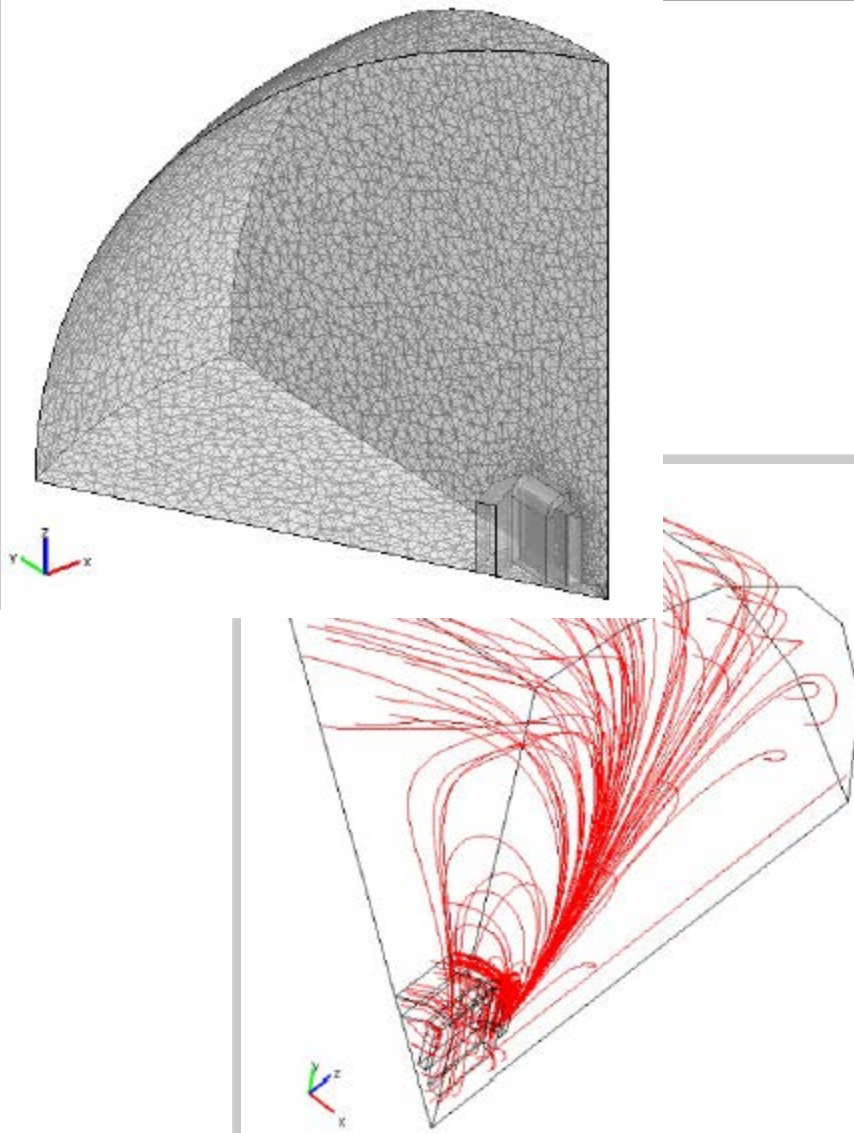
Modelul numeric (FEM) si solutia- spectrul campului



Modelul geometric 3D pentru hexapol



Model numeric (Comsol), solutia si convergenta sa



In perspectiva: dezvoltarea de noi algoritmi eficienti si robusti de optimizare bazati pe tehnici HPC

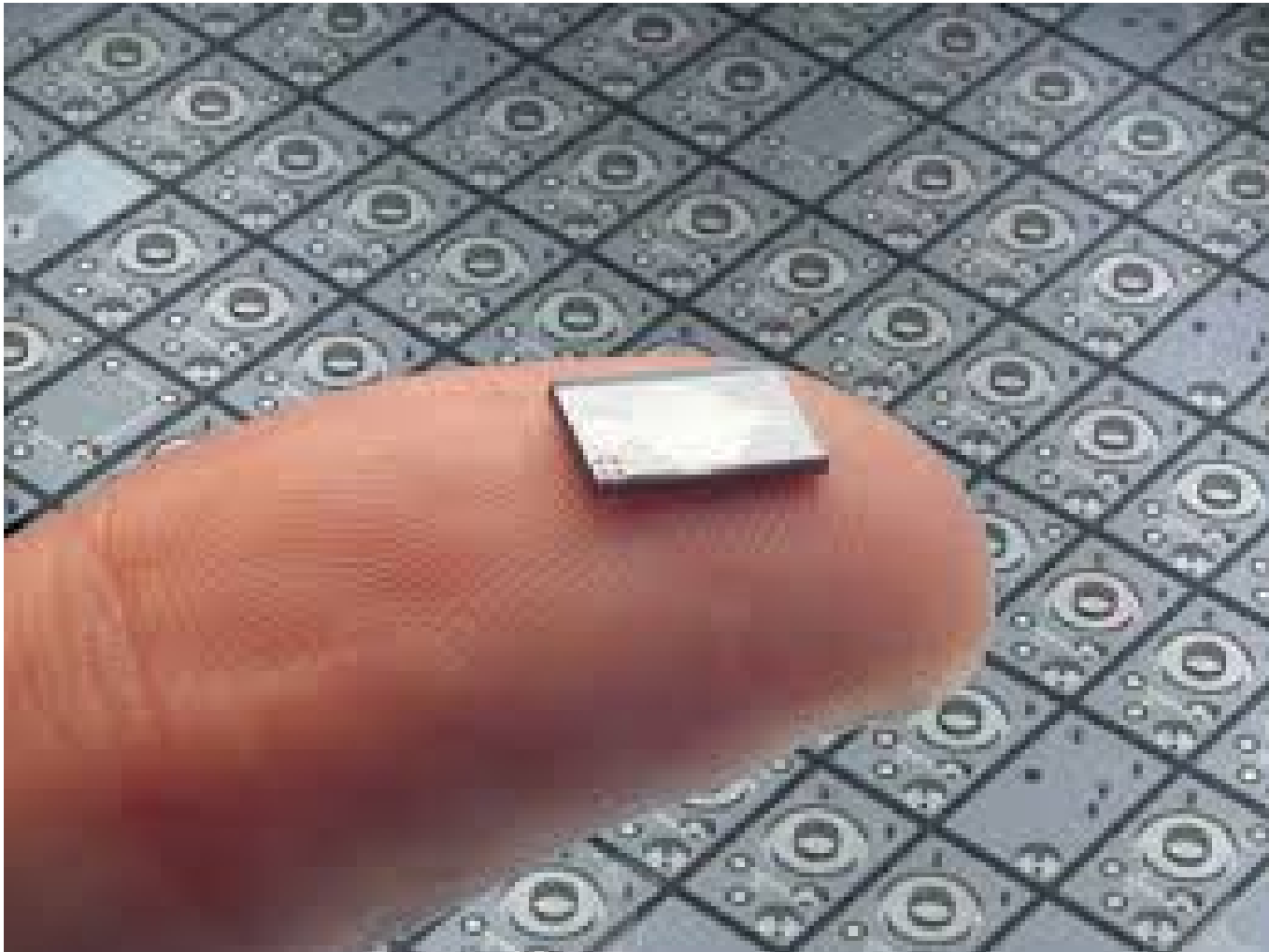
Standul de verificare electromagneti la CERN



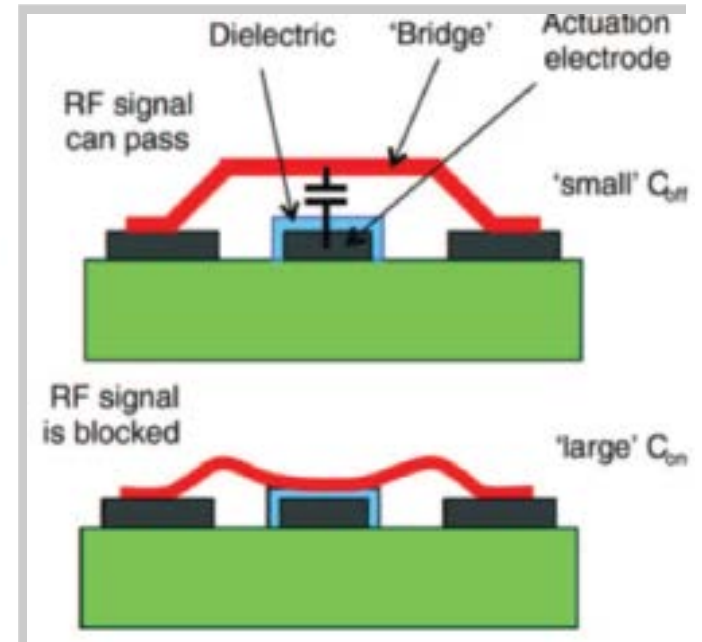
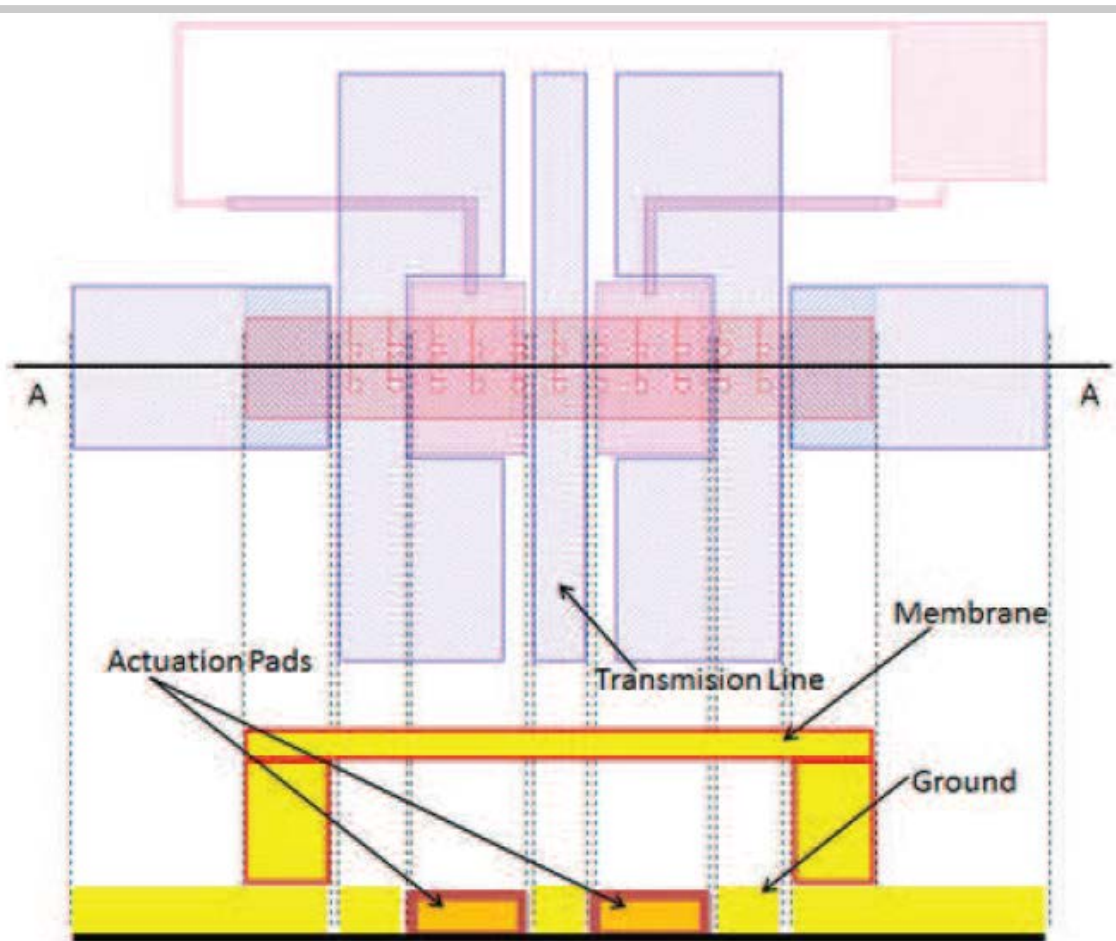
A treia aplicatie

- Proiectarea circuitului integrat pentru car-radar Philips
- Optimizarea electromagnetilor pentru acceleratorului de particule FAIR – Darmstadt
- **Comutator Micro-electro-mecanic de radiofrecventa - RF MEMS switch - IMT**

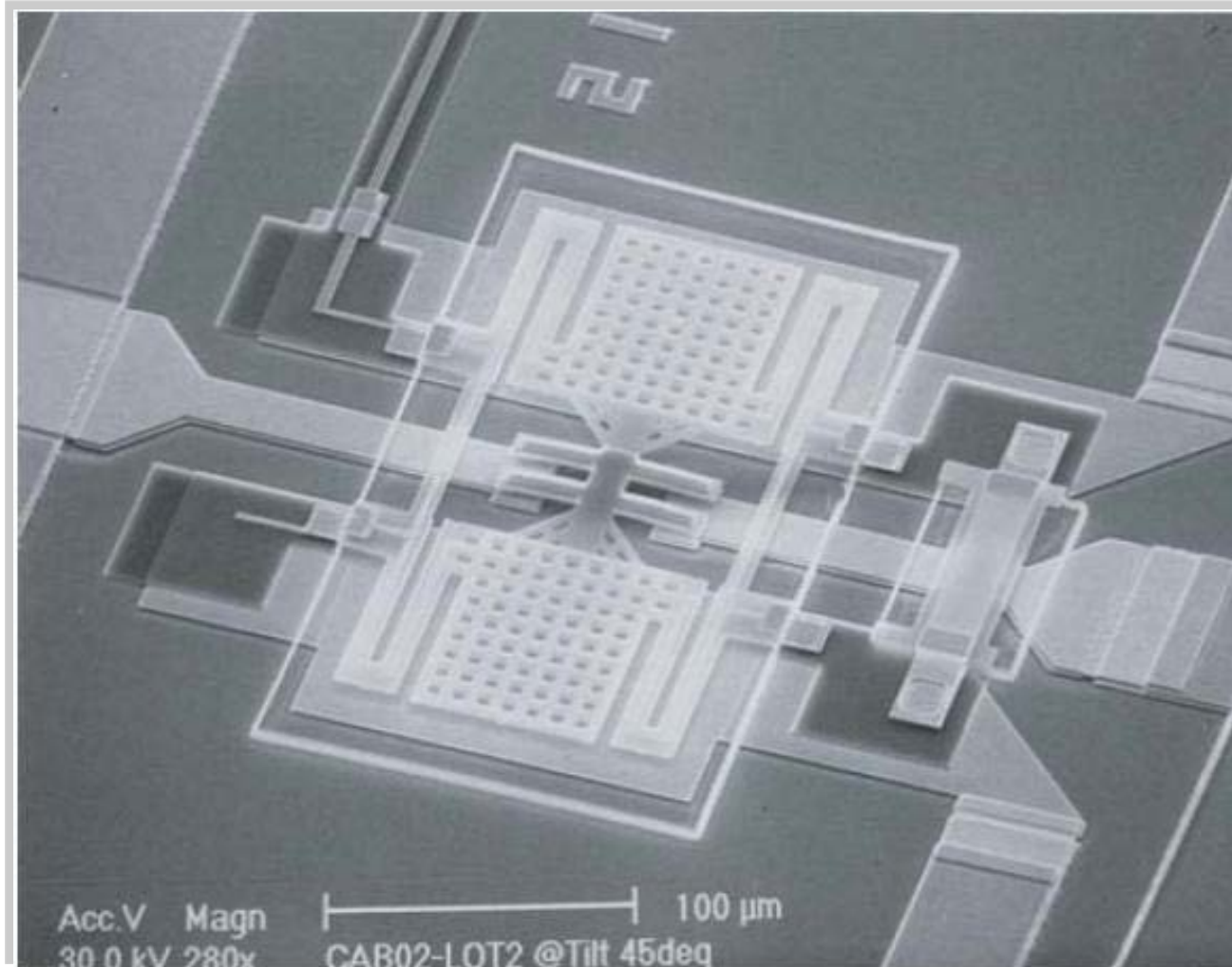
RF MEMS comutatoare micro- electro-mecanice de radiofrecventa



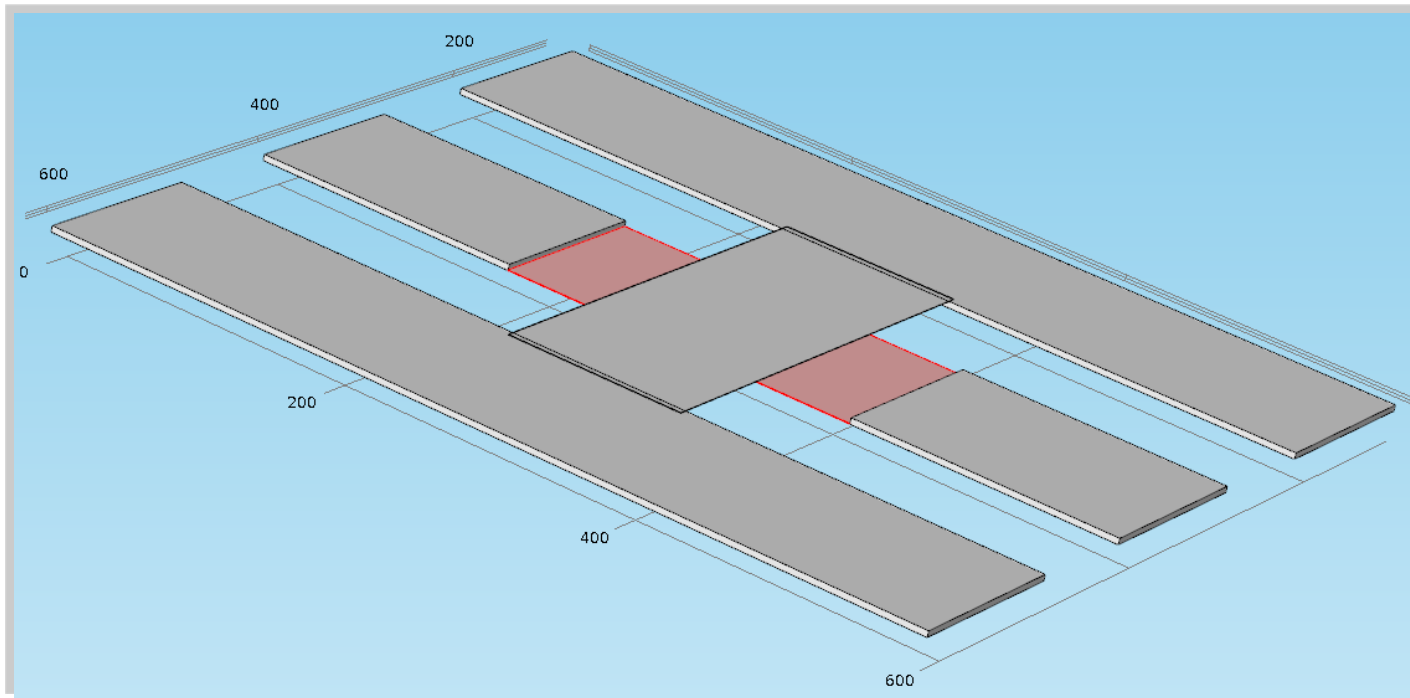
IMT RF MEMS Switch



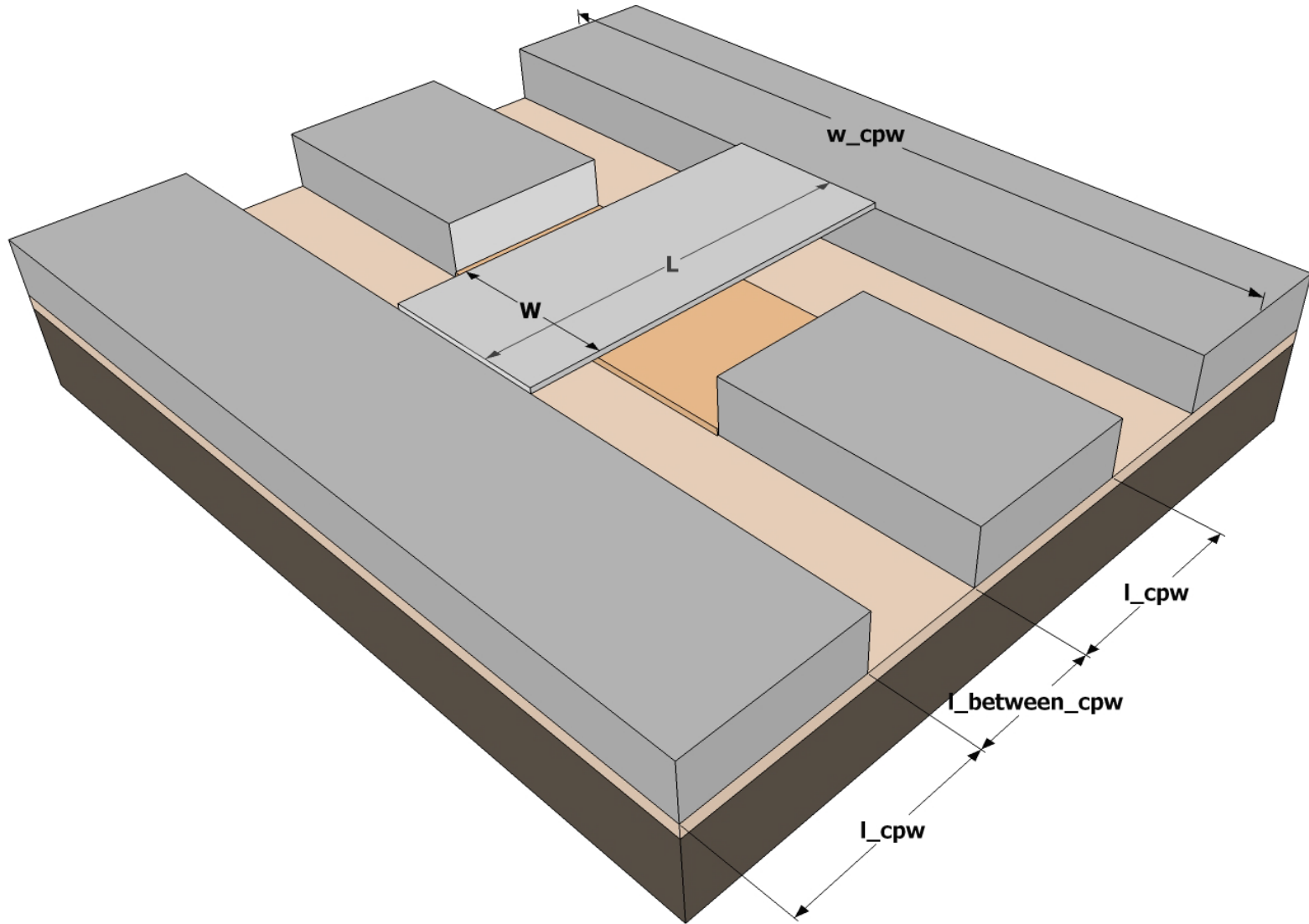
Imagine la microscop electronic a unui RF MEMS



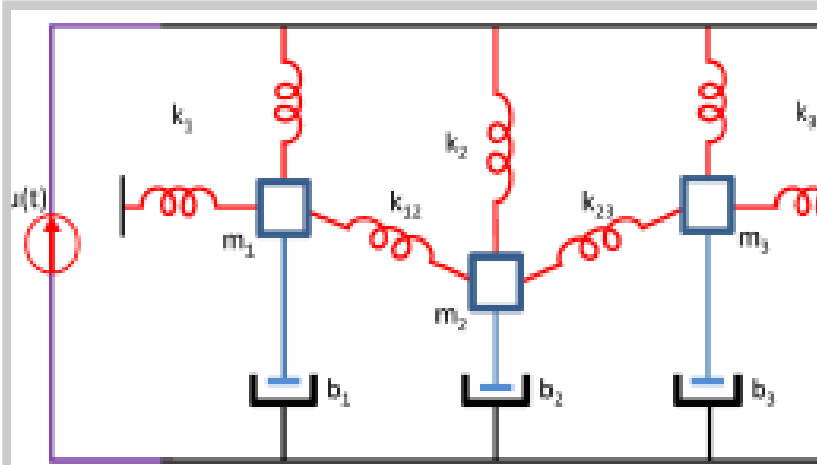
Modelul geometric al RF MEMS (chamy – software LMN)



Modelul geometric parametrizat



Reducerea modelelor: de la milioane la zeci de stari



$$k^{(1)} = \begin{bmatrix} k_{11}^{(1)} & k_{12}^{(1)} & 0 \\ k_{12}^{(1)} & k_{22}^{(1)} & k_{23}^{(1)} \\ 0 & k_{23}^{(1)} & k_{33}^{(1)} \end{bmatrix} \quad k^{(3)} = \begin{bmatrix} k_{11}^{(3)} & k_{12}^{(3)} & 0 \\ k_{12}^{(3)} & k_{22}^{(3)} & k_{23}^{(3)} \\ 0 & k_{23}^{(3)} & k_{33}^{(3)} \end{bmatrix}$$

$$m = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & 0 \\ 0 & 0 & m_{33} \end{bmatrix} \quad b = \begin{bmatrix} b_{11} & 0 & 0 \\ 0 & b_{22} & 0 \\ 0 & 0 & b_{33} \end{bmatrix}$$

$$m \frac{d^2 \mathbf{z}}{dt^2} + b \frac{d\mathbf{z}}{dt} + k_1 \mathbf{z} + k_3 \mathbf{z}^3 = F_{ES}(u, \mathbf{z})$$

Aspecte studiate: electromagnetice/multifizice; formulare matematica (marimi si ecuatii); algoritmi numerici de rezolvare

Instrumente folosite: MATLAB, COMSOL

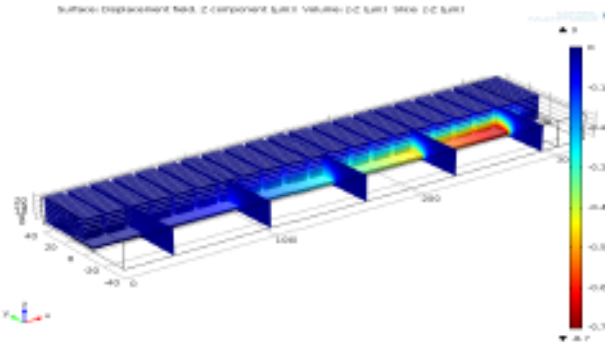
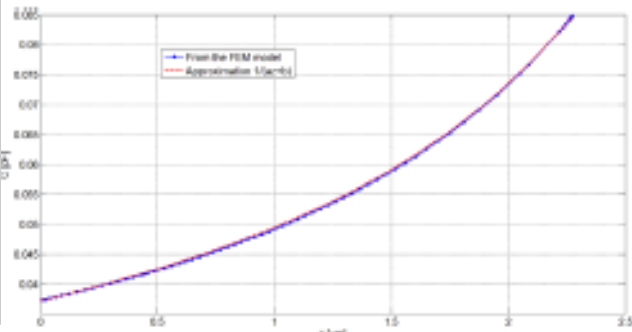
Tinta: dezvoltarea de noi instrumente software pentru proiectanti, in vederea (re)proiectarii optime

INGINERIA ELECTRICA High Tech are la baza: camp – circuite – sisteme si rezolvarea numerica a PDE-ODE. **Avem responsabilitatea corectitudinii!!**

Etapele algoritmului numeric de extragere a modelului redus

Step 1 Compute lumped electric forces from static simulation.

$$F_{ES}(u, z_j) = -\frac{c_{1,j}Z_j}{(c_{1,j}z_j + c_{2,j})^2}u^2$$



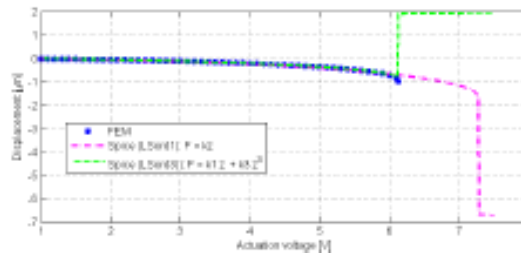
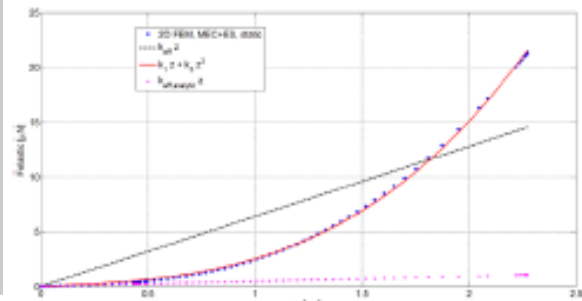
← Capacitance and its approximation

$$EI \frac{\partial^4 g}{\partial x^4} - S \frac{\partial^2 g}{\partial x^2} = f_{ES} + f_d - \rho l \frac{\partial^2 g}{\partial t^2}$$

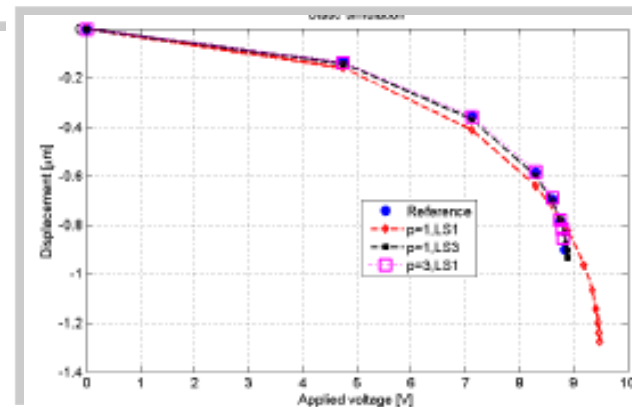
$$\text{div} \left(\left(1 + 6 \frac{\lambda}{g} \right) g^3 p(\text{grad}(p)) \right) = 12\mu \frac{\partial(pg)}{\partial t}$$

Ecuatii rezolvate cu algoritmi numerici proprii implementati in MATLAB si validati in Comsol

Step 2 Extract effective elastic coefficient matrices.



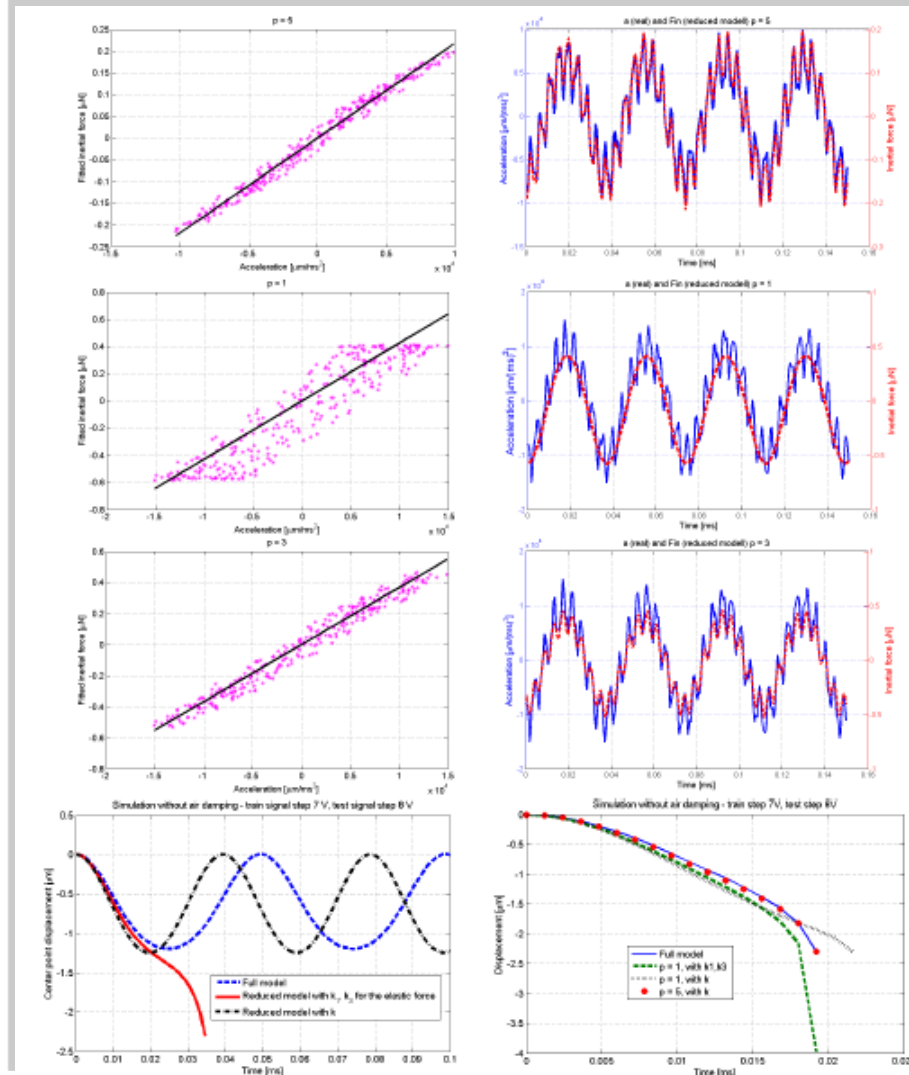
← Elastic force and its approximations.



Etapele algoritmului numeric de extragere a modelului redus

Step 3 Extract lumped mass matrix, from a time domain simulation without damping

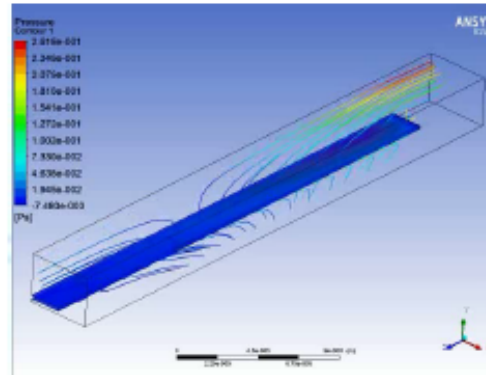
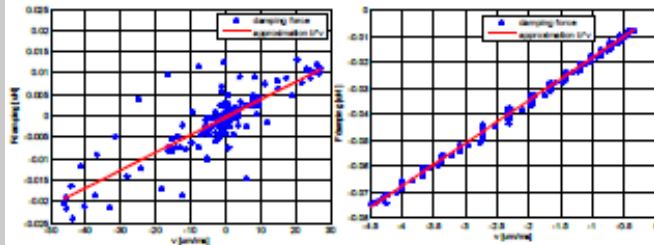
$$F_{in}(u, z) = F_{ES}(u, z) - k_1 z - k_3 z^3$$



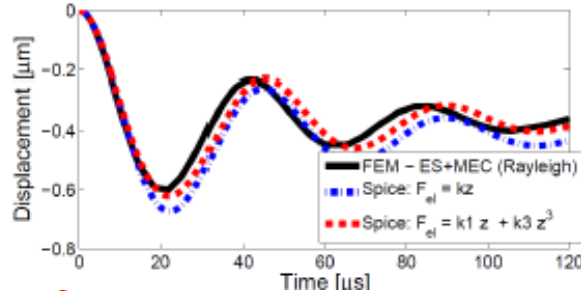
Etapele algoritmului numeric de extragere a modelului redus

Step 4 Extract lumped damping matrix, from a time domain simulation with damping

$$F_d(u, z) = F_{ES}(u, z) - k_1 z - k_3 z^3 - m \frac{d^2 z}{dt^2}$$

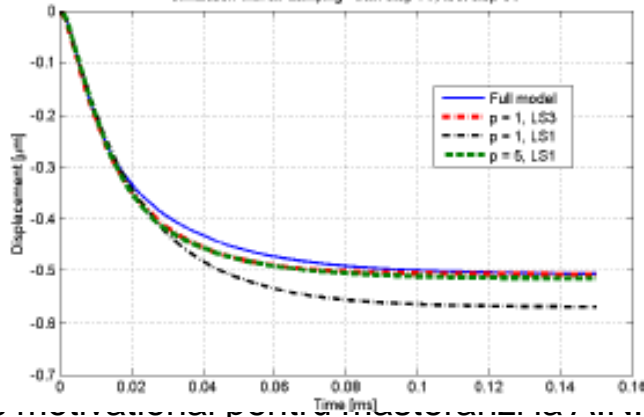


$\beta = 1.5e-6$ [s]

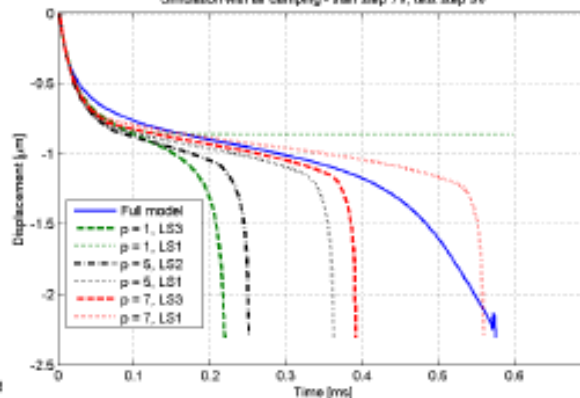


Imposed β_s [s]	Extracted β [s]	Rel. diff. [%]	Computed $b = \beta * k$ [g/s]	Rel.er. [%] FEM-SPICE use k, k_1, k_3
6.0e-5	7.1e-5	19.2	1.70e-2	1.2 0.082
6.0e-6	7.3e-6	21.5	1.73e-3	2.1 0.074
1.5e-6	1.8e-6	18.7	4.23e-4	12 0.55
6.0e-7	6.8e-7	13.0	1.61e-4	26 1.4

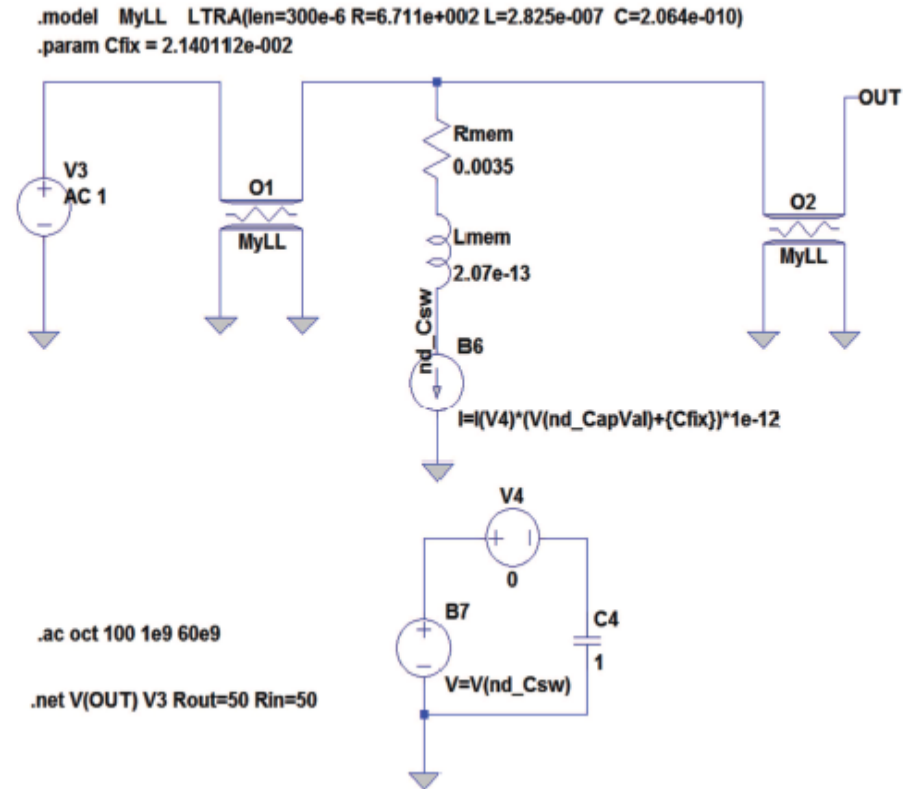
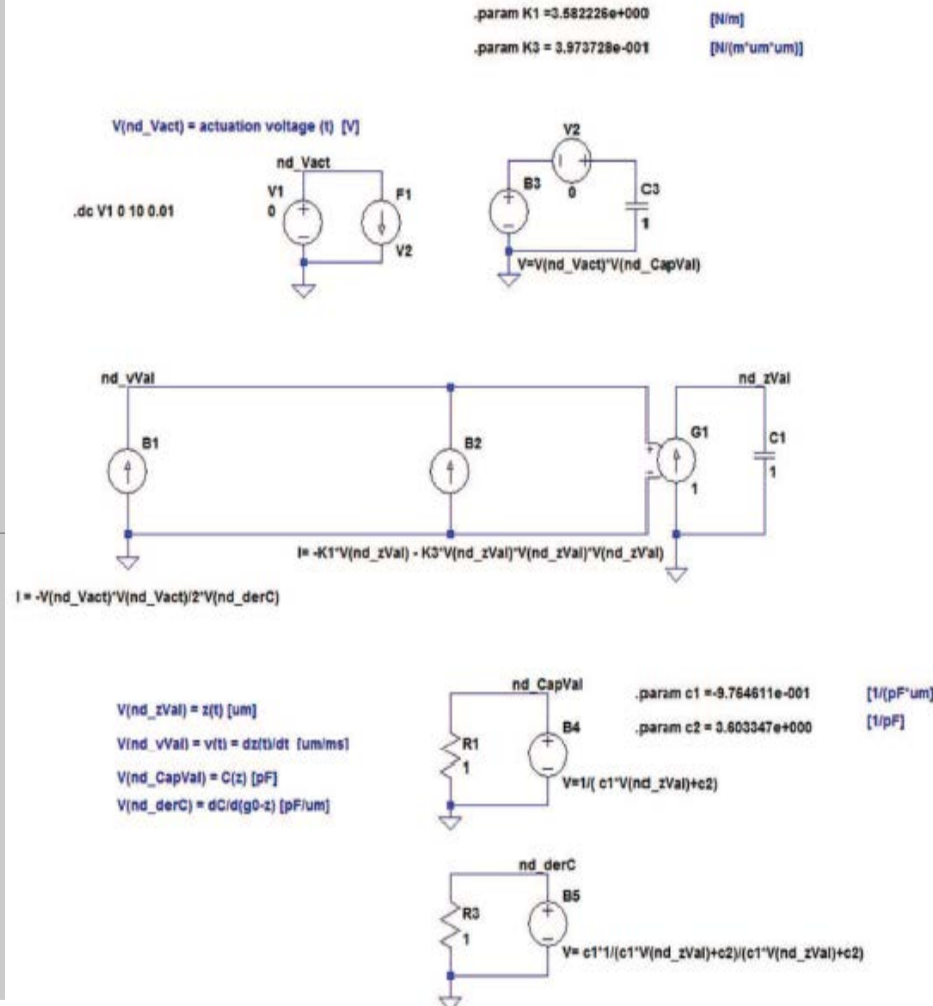
Simulation with air damping - train step 7V, test step 8V



Simulation with air damping - train step 7V, test step 9V

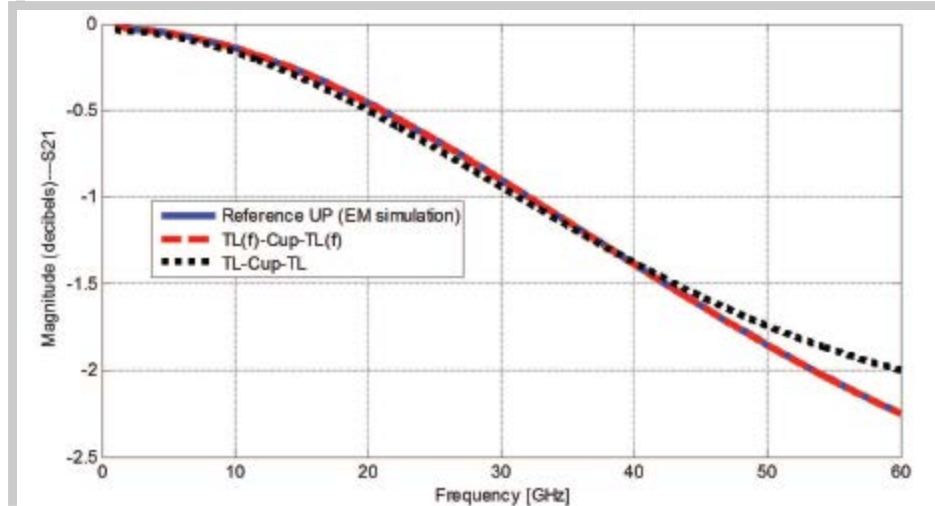
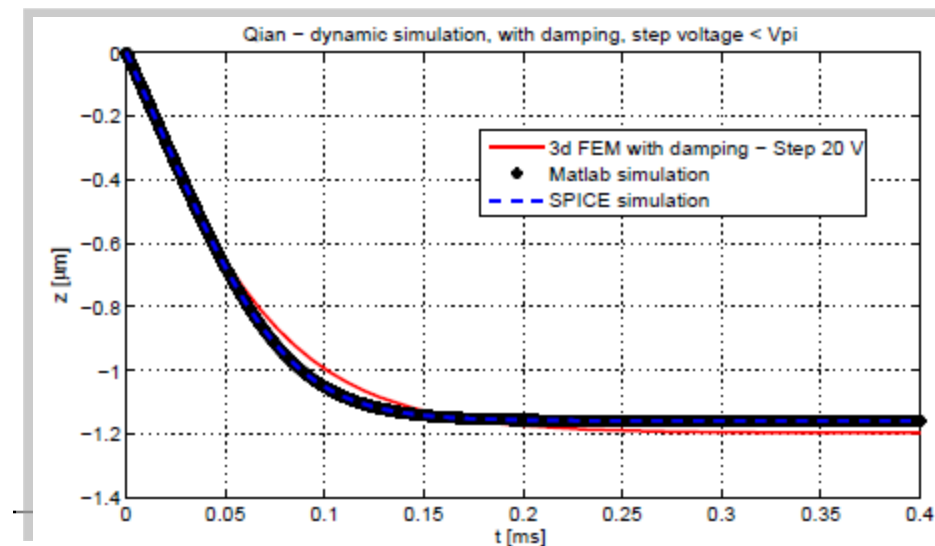
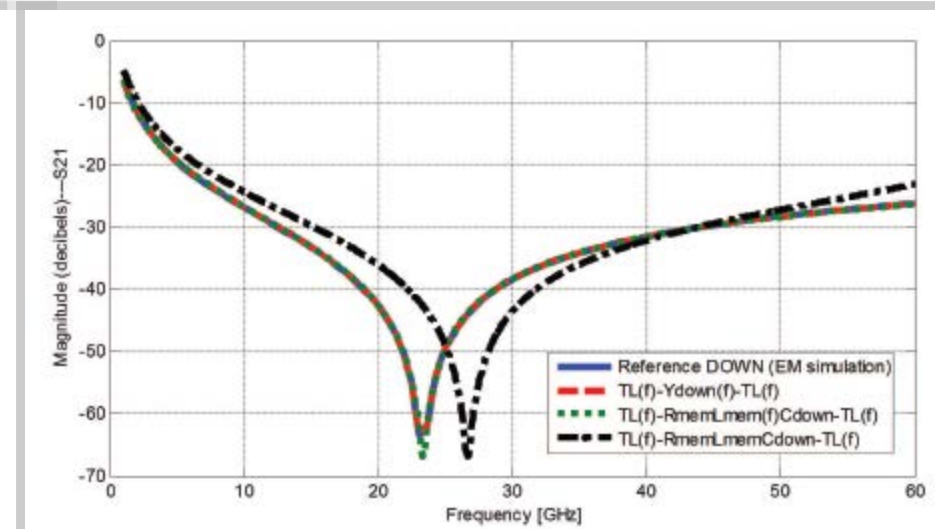
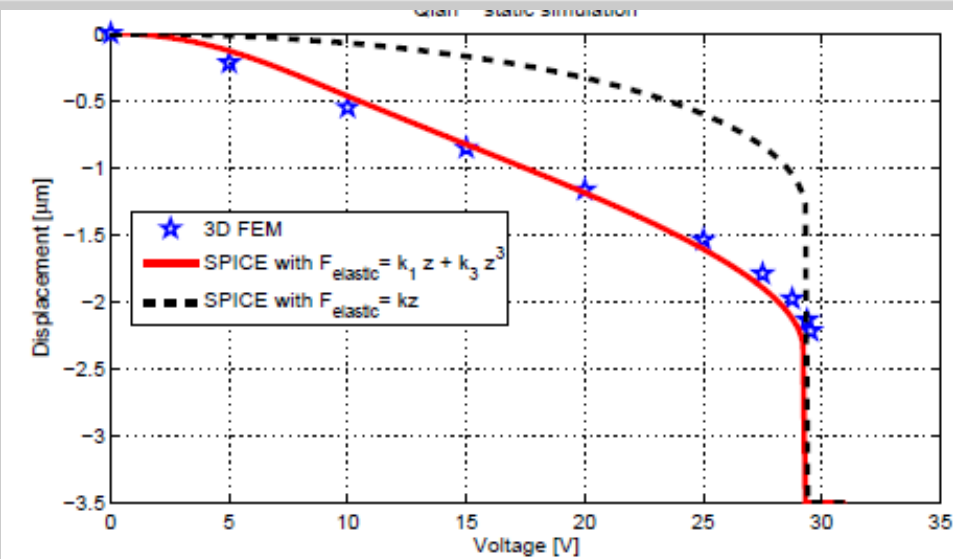


Modelul SPICE multifizic extras cu FEM/FIT: EI-mg, structural, fluidic



In perspectiva: extragerea unor modele Spice parametrice si folosirea lor pentru optimizarea produsului cu tehnici HPC

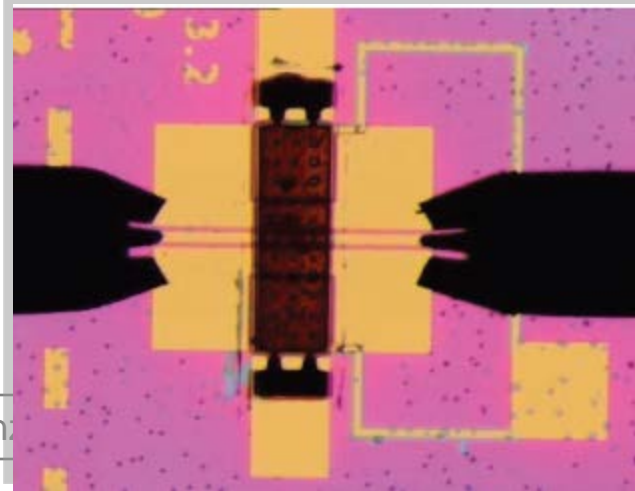
Verificarea si validarea rezultatelor



Camera alba a IMT unde au fost realizate comutatoarele

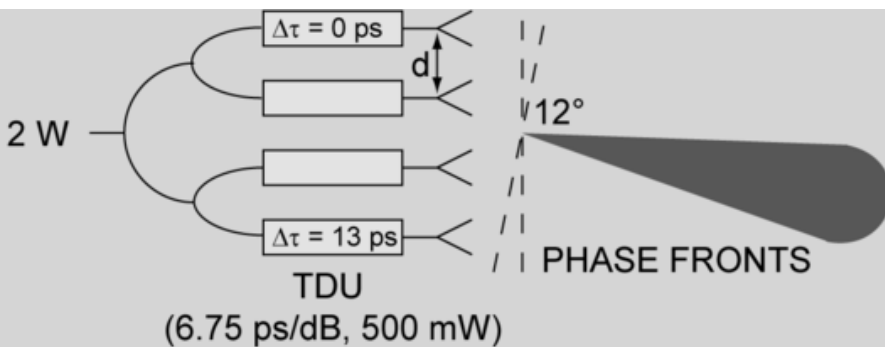
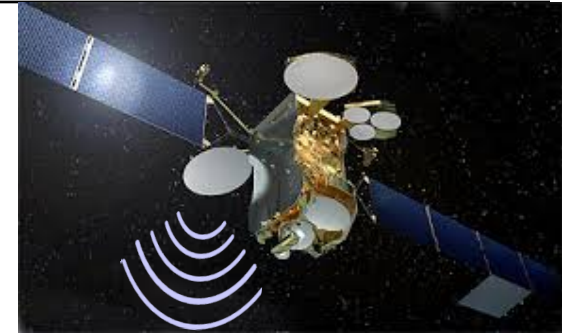


Platforma experimentală pentru caracterizare MEMS (IMT)



Aplicatii tinta ale RF MEMS Switch

- Sisteme de telecomunicatii fara fir, RF/microunde, inclusiv smartphon/TV
- Sisteme de anticoliziune vehicule
- Comunicatii prin satelit (ROSA-Romanian Space Agency – Agentia Spatiala Romana)
- Aplicatii militare (avioane de lupta, radar)
- Orientarea statica a antenelor:



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[Physical Review E 79 \(4\), 046304](#)

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[D Ioan, G Ciuprina, M Radulescu, E Seebacher](#)

[Magnetics, IEEE Transactions on 42 \(4\), 547-550](#)

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