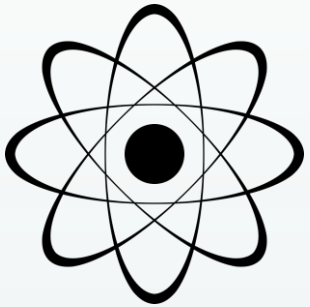


SMACD23
3-5 JULY • FUNCHAL • MADEIRA ISLAND • PORTUGAL

UNIVERSITY OF THESSALY
FOUNDED 1984

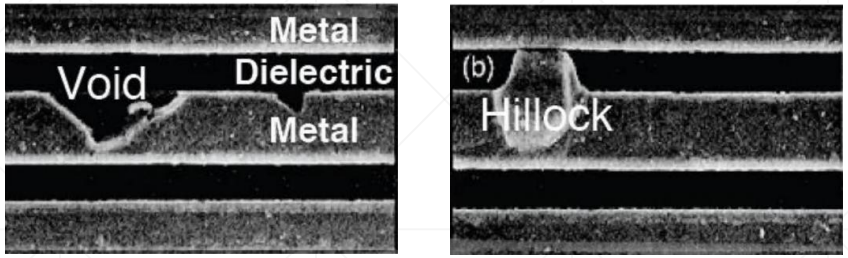
PROTON –

A Python Framework for Physics-Based Electromigration Assessment on Contemporary VLSI Power Grids

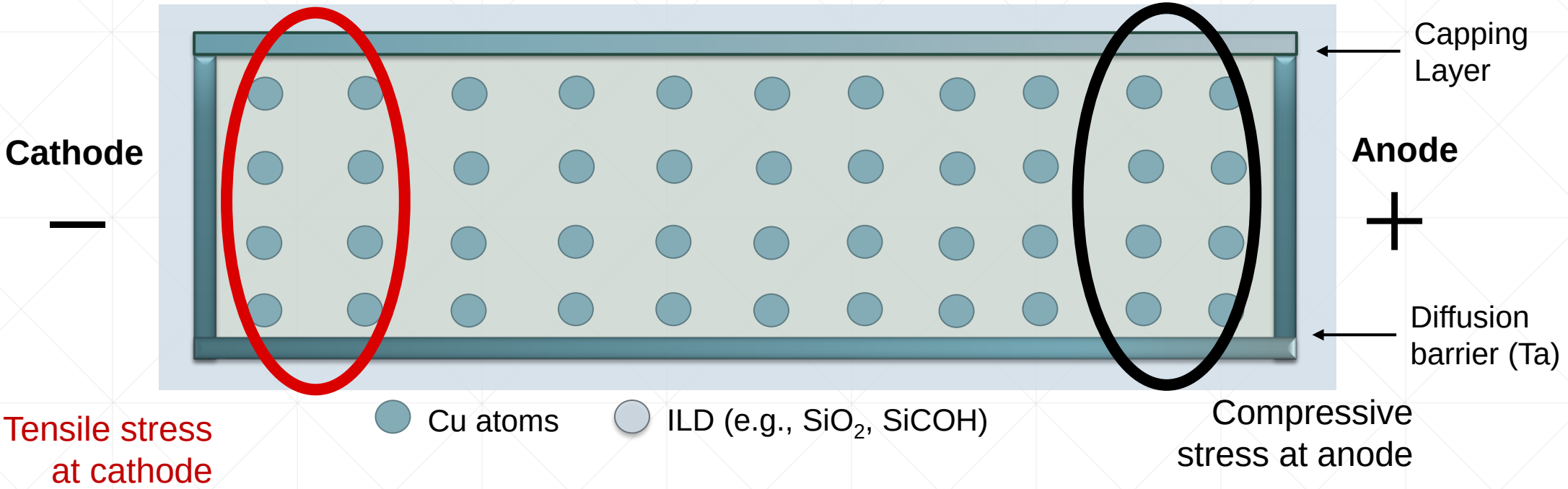
Olympia Axelou, Eleni Tselepi, George Floros, Nestor Evmorfopoulos, George Stamoulis
University of Thessaly, Greece

04/07/2023

Electromigration (EM) Stress



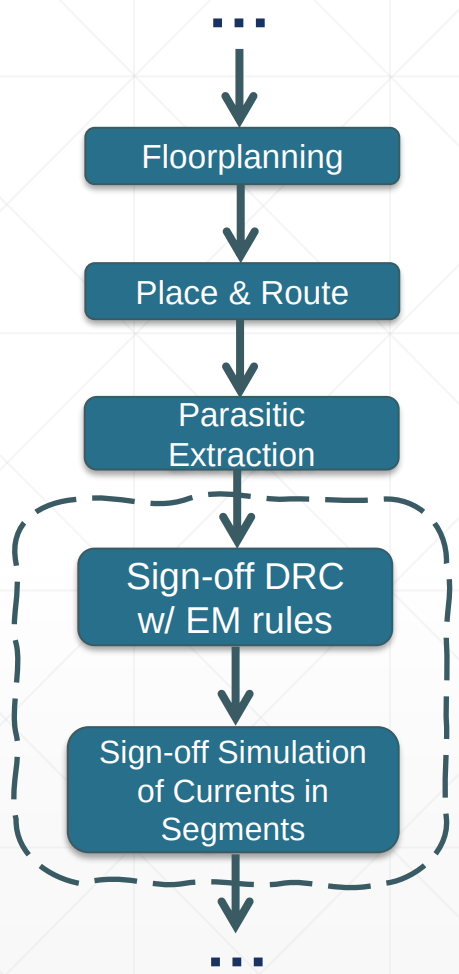
[1]



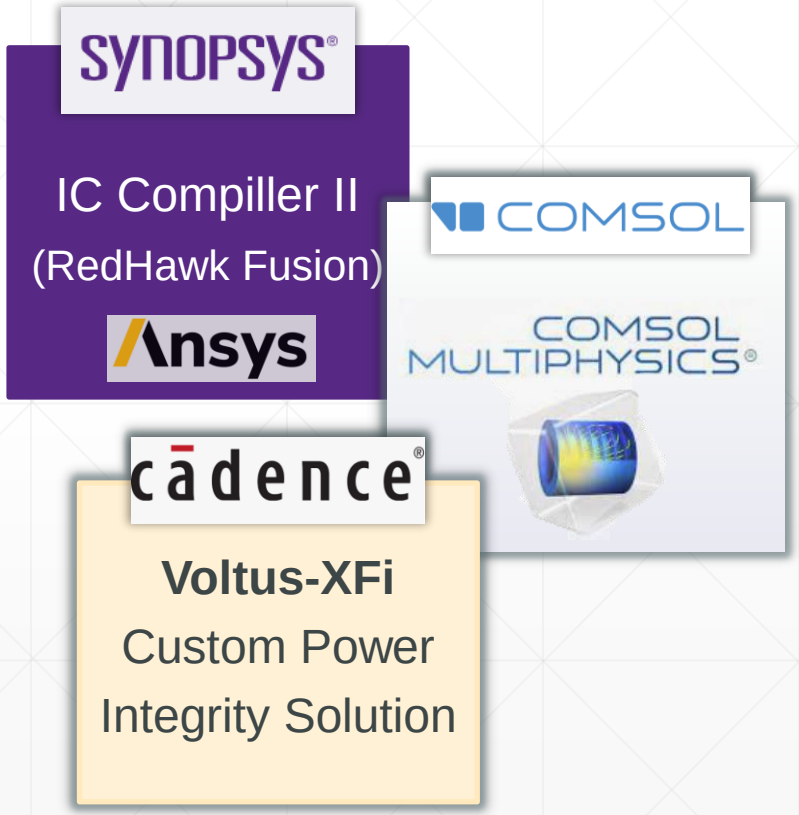
[1] J. Lienig and M. Thiele, Fundamentals of electromigration-aware integrated circuit design. Springer International Publishing, 2018.

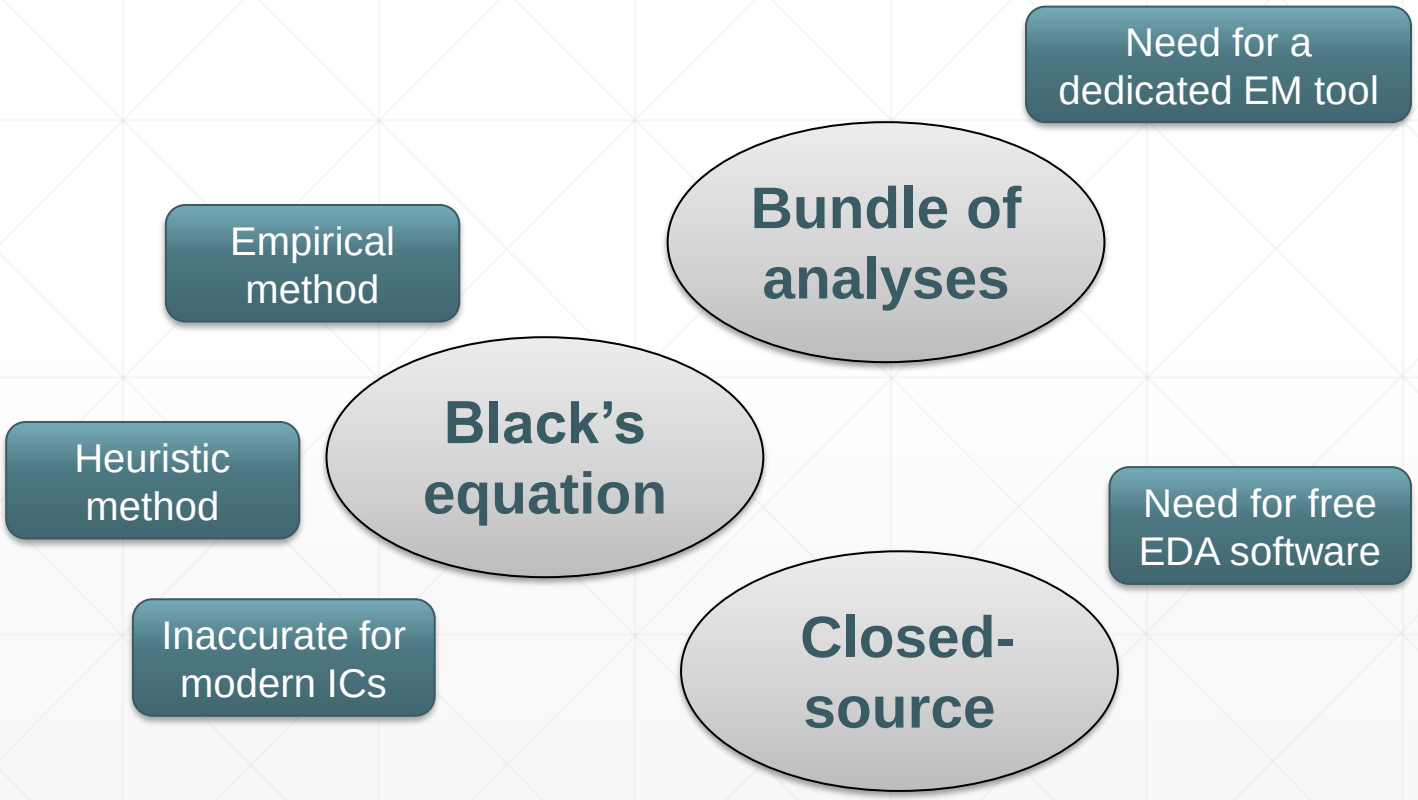
Long-term Reliability of Power Grids

- Phenomenon of EM
  - Caused by the continuous downscaling of the ICs and the simultaneous increase of currents
- Major concern for nanometer-scaled Integrated Circuits (IC)
  - Process variation in modern technology nodes
- Has been included in the IC design flow
  - Traditional methods are incorrect for modern interconnects (e.g., Black's equation and Blech's criterion)



Addressing the gap: A free physics-based EM tool





Democratizing EM Analysis

Bring down barriers to democratize HW design

- PROTON's goal aligns with **open-source strategies** from EU (e.g., EuroEXA, CONVOLVE) and large-scale EDA projects in US (e.g., OpenROAD)
- Enabling smaller design teams and individuals to benefit from cutting-edge EM analysis
  - Fostering innovation and collaboration within the EDA community
- **Open-source is the future of EDA…**

Open source software strategy

"The European Commission will further encourage and leverage the transformative, innovative and collaborative potential of open source."

EUROEXA

ExaNoDe

CONVOLVE

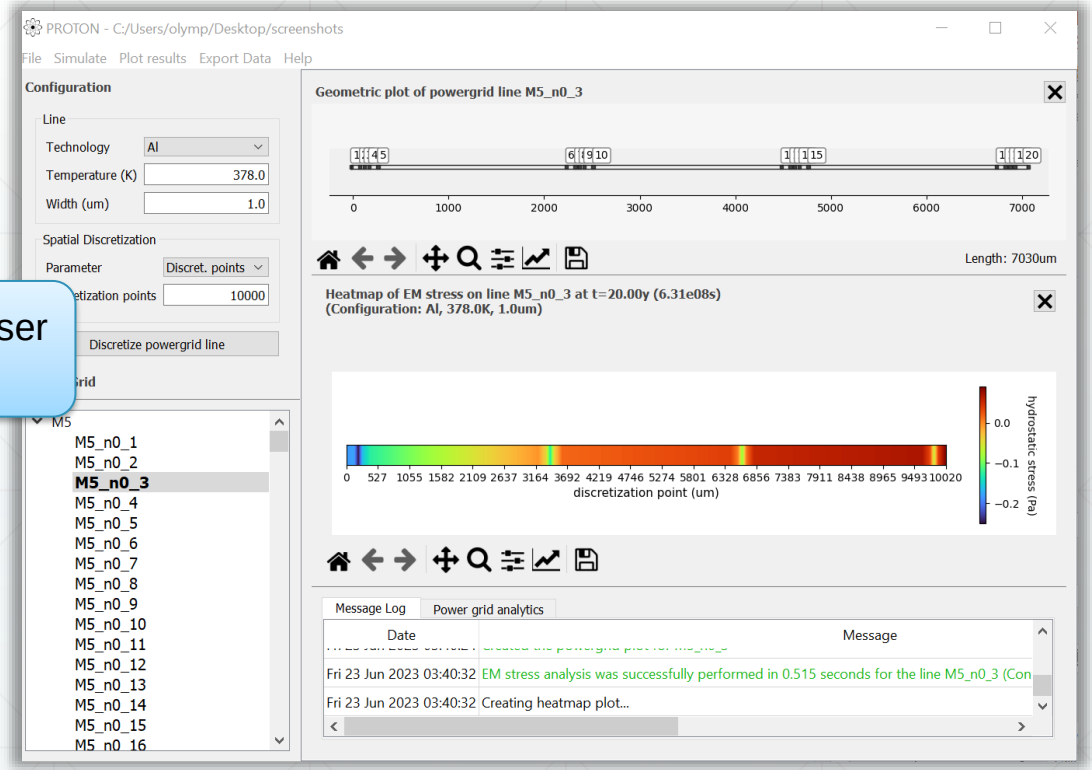
OpenROAD

Democratizing Hardware Design

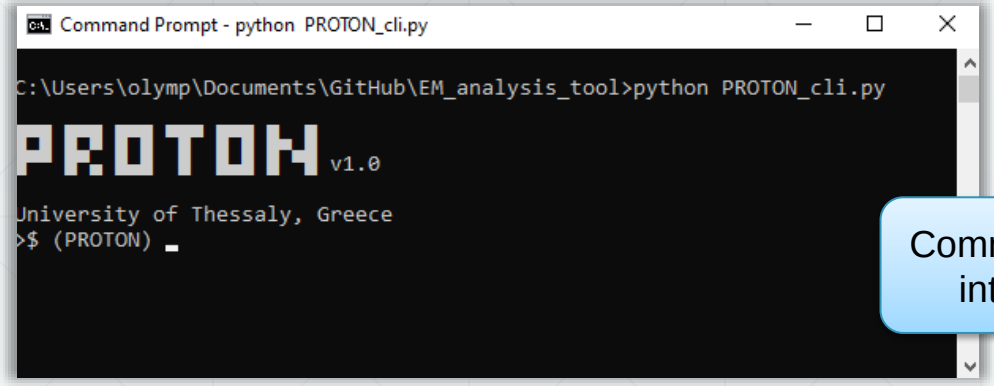
"The OpenROAD™ project attacks the barriers of Cost, Expertise and Uncertainty (i.e., Risk) that block the feasibility of hardware design in advanced technologies."

PROTON – Overview

- Very fast EM analysis
- Open-source
- Cross-platform
- Intuitive UI
- High level of integration



Graphical-user interface



Command-line interface

The core of the tool

✓ Low complexity

✓ Robust methods

Korhonen's equation w/ line boundary conditions + **FDM Discretization** into n discretization points

$$\dot{\boldsymbol{\sigma}}(t) = \mathbf{A}\boldsymbol{\sigma}(t) + \mathbf{B}\boldsymbol{j}$$

Line Analysis

$$\boldsymbol{L}(t) = diag(t, \frac{e^{\lambda_2 t} - 1}{\lambda_2}, \dots, \frac{e^{\lambda_n t} - 1}{\lambda_n})$$

$$\boldsymbol{\sigma}(t) = \boldsymbol{V}\boldsymbol{L}(t)\boldsymbol{V}^T\boldsymbol{B}\boldsymbol{j}$$ [1]

$$\boldsymbol{V}^T\boldsymbol{r} \Leftrightarrow DCT(\boldsymbol{r})$$
$$\boldsymbol{V}\boldsymbol{r} \Leftrightarrow IDCT(\boldsymbol{r})$$

$O(nlogn)$

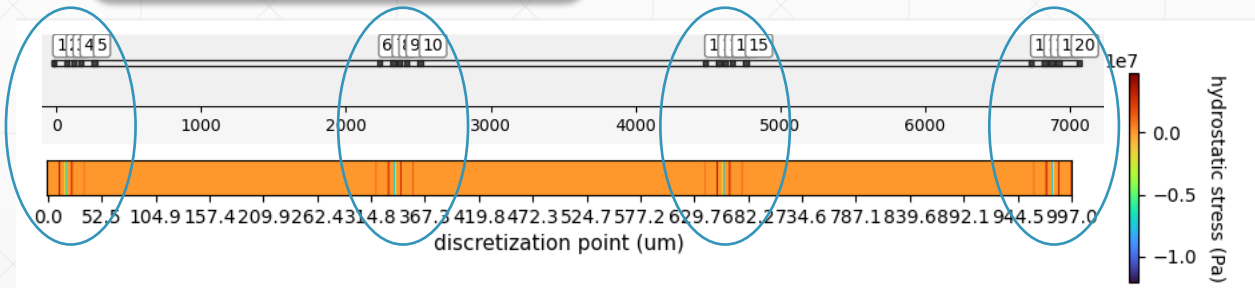
Completely **parallelizable** for different lines in the under-test power grid

State-space model

$$\dot{\boldsymbol{\sigma}}(t) = \mathbf{A}\boldsymbol{\sigma}(t) + \mathbf{B}\boldsymbol{j}$$ [2]
$$\boldsymbol{y}(t) = \boldsymbol{L}\boldsymbol{\sigma}(t)$$

Vias Transient Analysis

Stress is more pronounced at vias and endpoints



[1] O. Axelou et al., A Novel Semi-Analytical Approach for Fast Electromigration Stress Analysis in Multi-Segment Interconnects. ICCAD, 2022.

[2] O. Axelou et al., Fast Electromigration Stress Analysis Using Low-Rank Balanced Truncation for General Interconnect and Power Grid Structures. Integration Journal, 2023.

PROTON – C++ Kernels

✓ **Applicable** for all power-grid sizes

✓ **Robust**

sparse modules

Line Analysis

https://fftw.org/

Fast complete power grid analysis

Vias Transient Analysis

state-of-the-art direct solver

State-of-the-art libraries

Low-memory footprint

Fast sparse solvers

Suitable for large-scale problems

Accurate, fast and robust

PROTON Flowchart

✓ Easily Integratable

✓ Highly automated

SPICE file

```
R9833 n2_10366_7174 n2_10366_7178 2.539683e-03
R9834 n2_10366_7270 n2_10366_7329 3.746032e-02
R9835 n2_10366_7329 n2_10366_7362 2.095238e-02
R9836 n2_10366_7362 n2_10366_7376 8.888889e-03
R9837 n2_10366_7376 n2_10366_7399 1.460317e-02
R9838 n2_10366_7399 n2_10366_7545 9.269841e-02
R9839 n2_10366_7545 n2_10366_7578 2.095238e-02
R9840 n2_10366_7578 n2_10366_7761 1.161905e-01
R9841 n2_10366_7761 n2_10366_7794 2.095238e-02
R9842 n2_10366_7794 n2_10366_7977 1.161905e-01
R9843 n2_10366_7977 n2_10366_8010 2.095238e-02
```

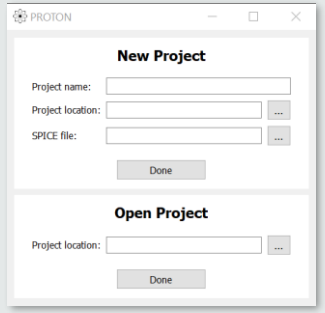
JSON configuration file

On *Open*

```
{
    "line": {
        "technology": "CuDD",
        "temperature": 378,
        "width": 10
    },
    "discretization": {
        "parameter": "points",
        "points": 10000
    },
    "analysis": {
        "time": 1e5,
        "method": "numerical",
        "numerical": {
            "mor": {
                "moments": 2,
                "reduced order": 20
            },
            "transient": {
                "point": 1,
                "timestep": 1e4
            }
        }
    }
}
```

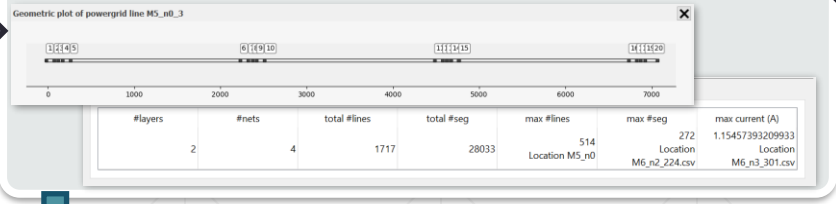
PROTON

IMPORT POWERGRID & CONFIGURATIONS



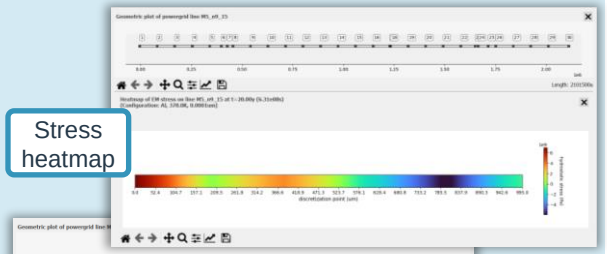
SPICE FILE PARSING & POWERGRID ANALYSIS

SPICE Parsing & Line extraction → Line visualization (e.g., vias, segments)

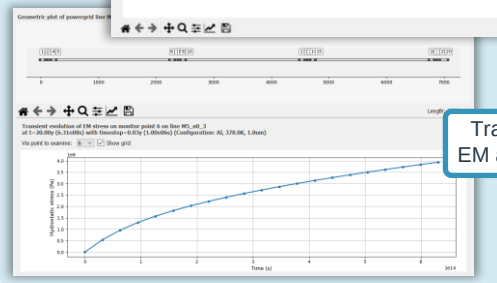


STRESS PLOTTING & RESULTS ANALYTICS

Stress heatmap



Transient EM analysis



LINE SPATIAL DISCRET.

Finite Difference Method

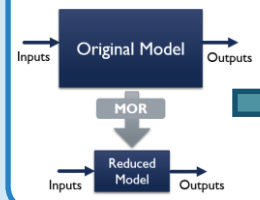
PROTON ENGINE (C++ Kernel)

LINE ANALYSIS

Eigendecomposition of system matrix & DCT-II Transform → EM stress calculation at all spatial points independently with near linear complexity

Choice from configuration

VIAS TRANSIENT ANALYSIS



Transient EM stress analysis on via and blocking points with an implicit Backward Euler formula

Segment currents

Closed-source

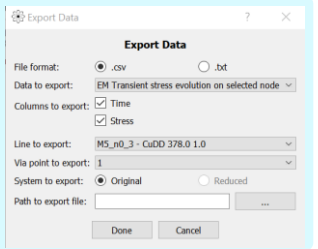
cadence Spectre

SYNOPSYS PrimeSim HSPICE

Open-source

XYCE

STRESS RESULTS EXPORT



Input/Output

User-driven act

Fully-automated act

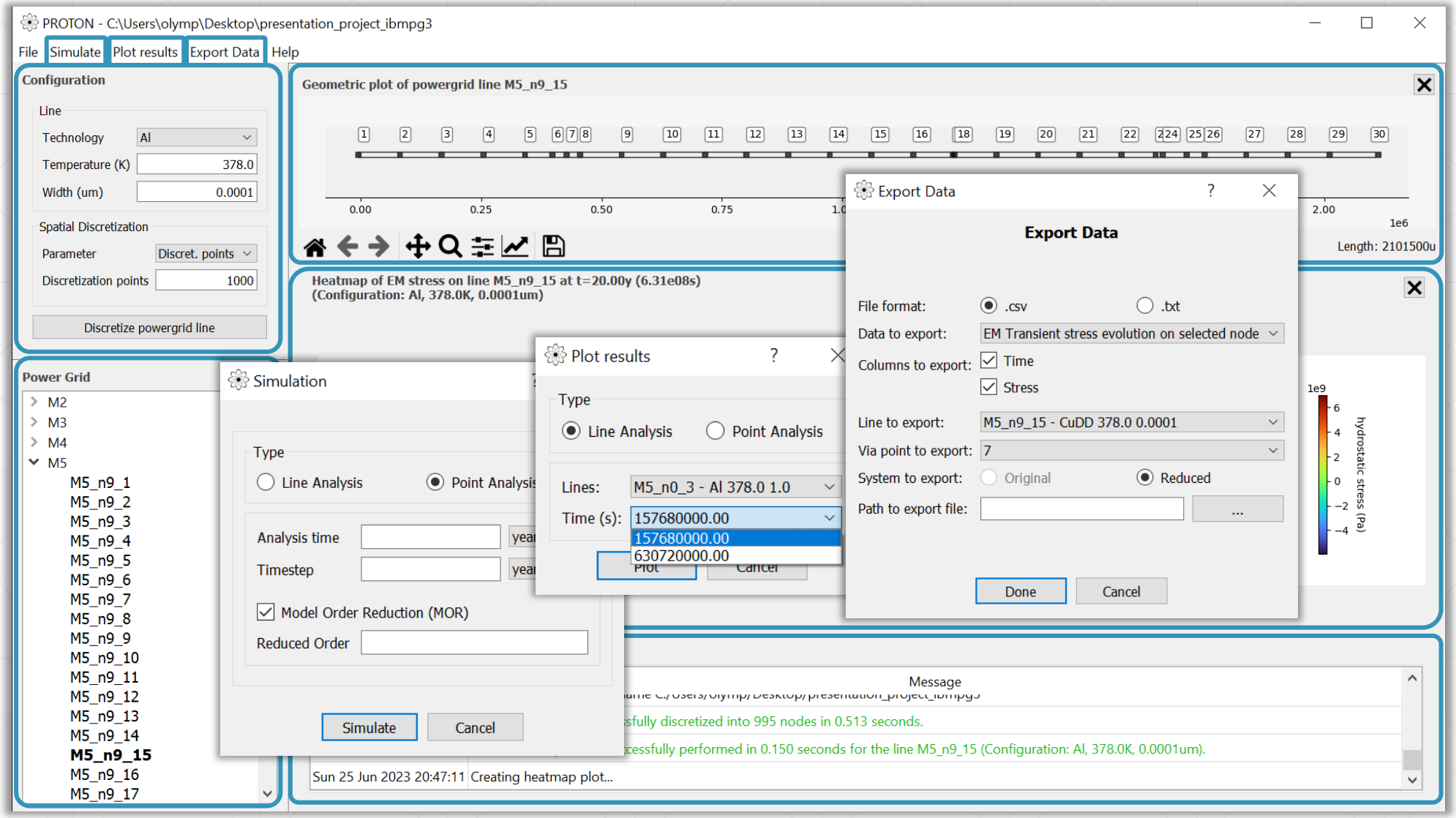
Interaction w/ external tools (Fully-automated)

PROTON – A Python Framework for Physics-Based Electromigration Assessment on Contemporary VLSI Power Grids

Olympia Axelou, University of Thessaly, Greece

User Interface

✓ Simple and intuitive UI



Analysis parameters

Selection of line to analyze

Visualization of selected line

Analysis results

Message log & power grid analytics

PROTON – A Python Framework for Physics-Based Electromigration Assessment on Contemporary VLSI Power Grids

Olympia Axelou, University of Thessaly, Greece

✓ Fully automated

Command-Line Version

powergrid_EM_analysis.tcl

```
...
#  An automated script that parses a SPICE powergrid file and performs
# Electromigration (EM) analysis on the complete powergrid at specific
# time (e.g. chip lifetime) and finds the EM-susceptible lines.
#  Then, some statistics on the parsed powergrid are reported as well
# as the line with the maximum stress.
#
# Author: Olympia Axelou
# Affiliation: University of Thessaly, Greece
# Date: 19/6/2023

# Create new project
set_powergrid C:\Users\olymp\Documents\GitHub\EM_analysis_tool\benchmarks\ibmpg1.
set_project_path C:\Users\olymp\Desktop
set_project_name automated_ibmpg1
parse_powergrid
# open_project C:\Users\olymp\Desktop\automated_ibmpg1

# Set technology, temperature, line width
set_technology CuDD
set_temperature 378
set_line_width 1

# Complete powergrid EM stress check at 20y (6.38e8s) for a random sample of 100
# and check for lines that exceed the critical stress of 10KPa
analyze 6.38e8 --sample 100 --critical 10000

# Export stats on the powergrid and EM stress results
report_powergrid_stats --file C:\Users\olymp\Desktop\powergrid_stats.txt
report_line_stress --maxstress --file C:\Users\olymp\Desktop\critical_line_stress.csv

# Quit
quit
```

source TCL scripts

Command Prompt - python PROTON_CLI.py

```
PROTON v1.0

University of Thessaly, Greece
>$ (PROTON) set_powergrid example.spice
>$ (PROTON) set_project_path C:/Users/olymp/Desktop
>$ (PROTON) set_project_name example_cli_project
>$ (PROTON) parse_powergrid
Found layer M3, net 1
Found layer M4, net 2
Found layer M5, net 5
Found layer M6, net 6
Found layer M3, net 0
Found layer M4, net 3
Found layer M5, net 4
Found layer M6, net 7
Spice file was successfully parsed in 1.921 seconds and the project has been created at C:\Users\o
lymp\Desktop\example_cli_project.
>$ (PROTON)
```

Simple command-line interface

Use Cases – Comparison with existing tool

Line analysis comparison between PROTON and COMSOL on different benchmarks at 20y

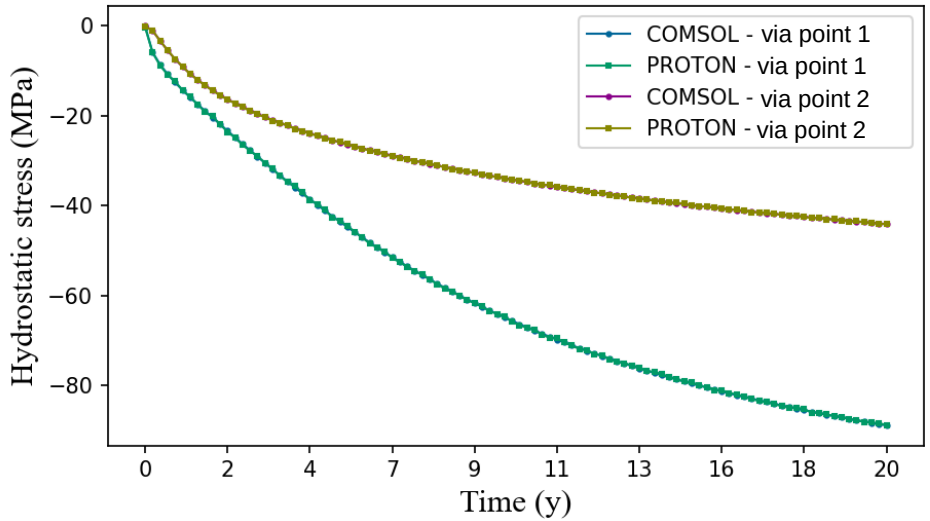
	IBMPG2			IBMPG6		
Tools	runtime (s)	speedup	rel. error	runtime (s)	speedup	rel. error
COMSOL	87.09	×279.3	3e-6	1921	×685	6e-7
PROTON	0.312			2.803		

Indistinguishable responses

Competitive and scalable runtimes

Very low relative error

Point analysis comparison between PROTON and COMSOL at 20y



We invite you to take a look!

- Installation guide
- Integration of custom kernels guide

https://github.com/oaxelou/PROTON

Demo

Olympia Axelou

oaxelou@e-ce.uth.gr

University of Thessaly, Greece

UNIVERSITY OF THESSALY

PROTON in a nutshell

- **PROTON** is a fast EM power grid assessment tool
  - **open-source**, **cross-platform**
  - **intuitive** GUI and **fully-automated** CLI version
  - **easily integratable** into any power grid design flow (SPICE input format)
- It employs **state-of-the-art** methodologies and libraries
  - very low computational complexity
  - **robust** methods
  - **applicable on any large-scale** power grid design (low-memory footprint)