HFSS 核心算法技术全览

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ANSYS 首席研发专家

HFSS 的一些历史

1969年的电磁学

- **EM is textbook stuff （电磁只限于教课书）**
- **Computers were primitive（电脑还很原始）**
  - Punched card input (打孔卡输入）
  - Memory in KB （内存很少）
  - Limited to solving a 100 X 100 matrix （最多只能解100x100的矩阵）
- **CEM was in it's infancy（计算电磁才刚刚开始）**
  - Kane S. Yee, FDTD（时域有限差分）, IEEE AP-S, 1966
  - Roger F. Harrington, Field Computation by Moment Methods （ 矩量法 ）, 1968

一个行业的演化
第一阶段 – 研发

- **1967**
  - 第一篇应用在电磁的有限元文章 (P. Silvester)
- **1969**
  - 第一篇用有限元解非线性静磁(magnetostatic)问题(M. V. K. Chari and P. Silvester)
- **1970**
  - 发现寄生模（Spurious modes）(P. Daly and, separately, **Z. Cendes** and P. Silvester)

一个行业的演化
第一阶段 – 研发

- **Z. J. Cendes**, D. N. Shenton and H. Shahnasser, "Magnetic field computation using Delaunay triangulation and complementary finite element methods*", IEEE Transactions on Magnetics*, Vol. MAG-19, pp. 2551-2554, 1983.

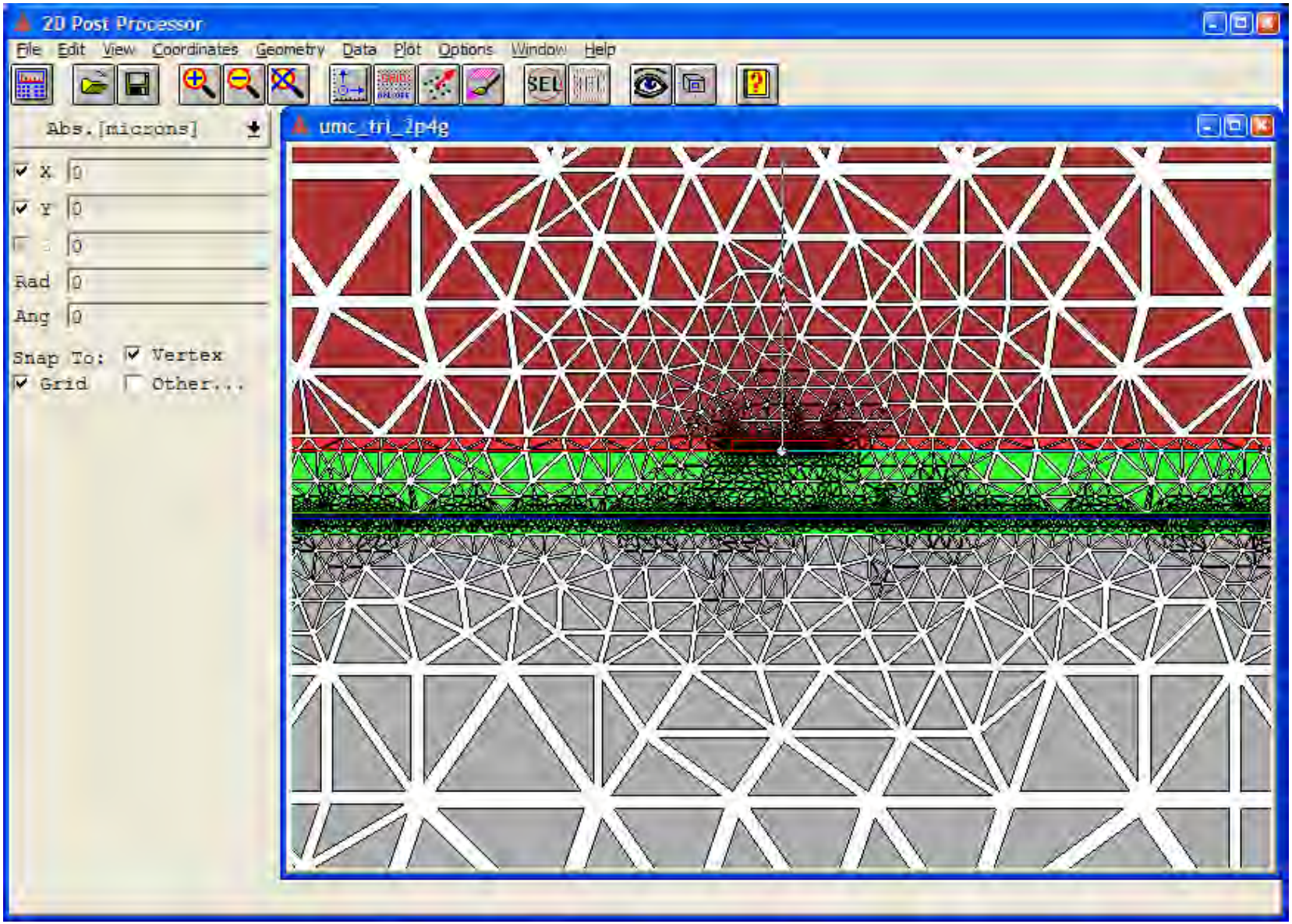
- M. L. Barton and **Z. J. Cendes,** "An improved method for magnetic flux density visualization using three‐dimensional edge finite element method *", J. Applied Phys*, 1987**.**

- *S.* H. Wong and **Z. J. Cendes**, "Combined Finite Element-Modal Solution of Three-Dimensional Eddy Current Problems," *IEEE Transactions on Magnetics*, pp, 21685-2687, 1988.

- J. F. Lee, D. K. Sun, and **Z. J. Cendes**, "Tangential vector finite elements for electromagnetic field computation", IEEE Transactions on Magnetics, Vol. 27, No. 5, pp. 4032-4035, 1991.

一个行业的演化
第二阶段– 创业

- **1979**
  - Infolytica
- **1984**
  - Ansoft
- **1985**
  - Vector Fields
  - Magsoft
  - IES
- **Others**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umc_tri_2p4g

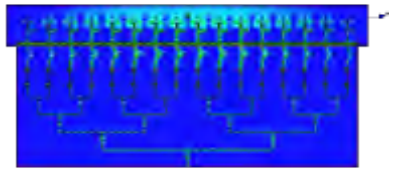
David Shenton & Meshmaker

Dr.Din Kow Sun & Prof. Jin-Fa Lee

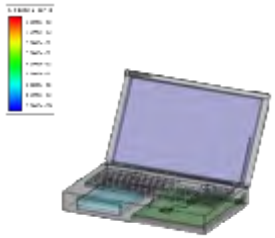
经典HFSS 的算法技术

HFSS 的算法

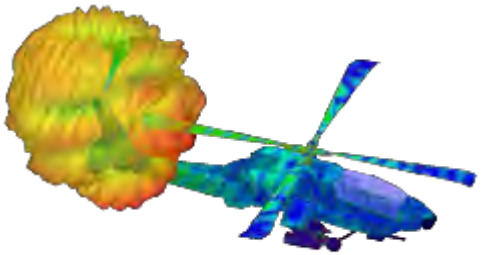
- **HFSS: Frequency domain finite element solver（频域有限元）**
  - ✓ 经典 FEM 求解器
  - ✓ 适用范围广



- **HFSS-Transient: Time domain finite element solver（时域有限元）**
  - ✓ v13 版本添加
  - ✓ 主要用于研究瞬变现象



- **HFSS-IE: Frequency domain integral equation solver（频域矩量法）**
  - ✓ v12 版本添加
  - ✓ 主要用于电大金属结构



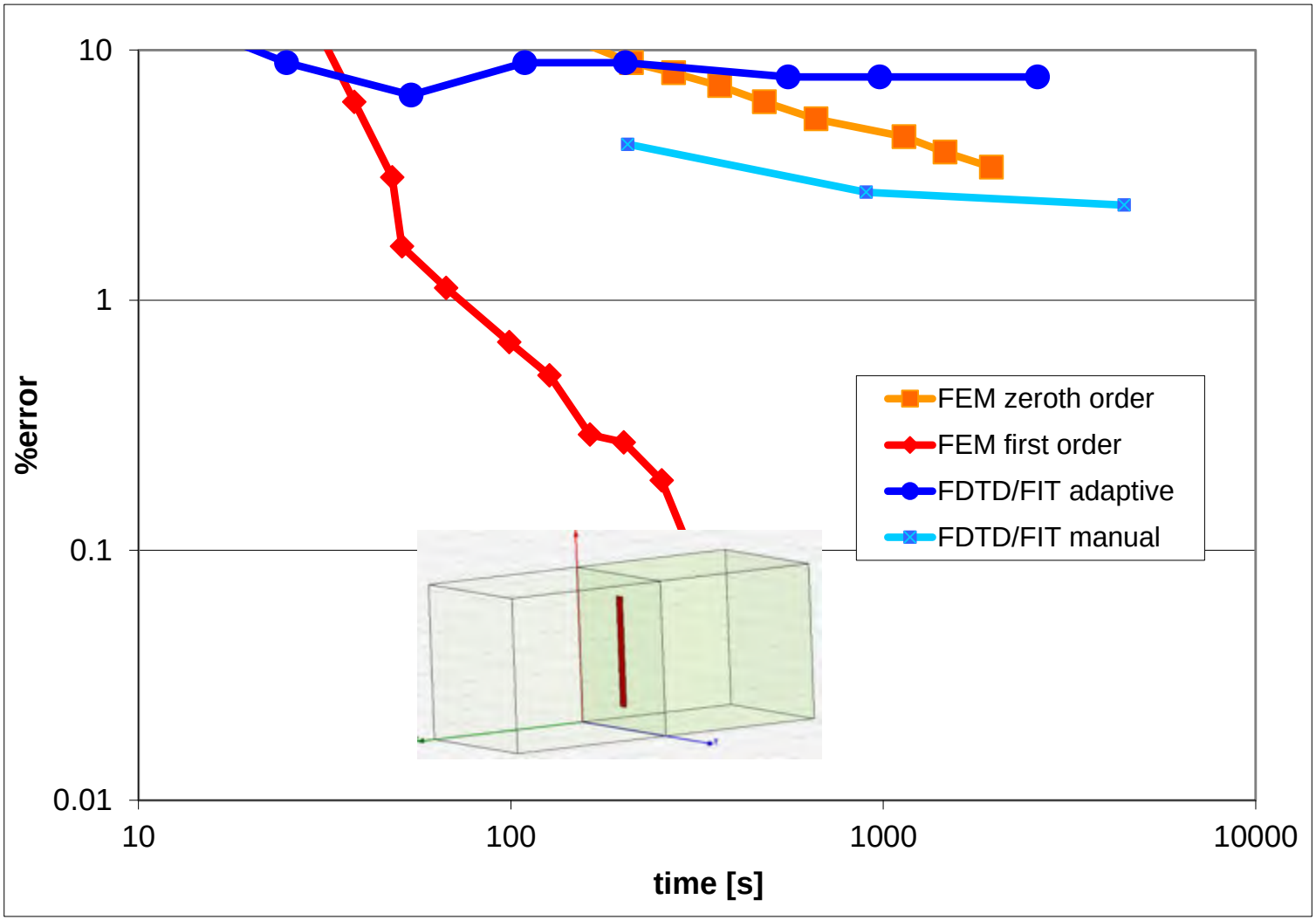
关键技术突破

- **Spurious Free Vector Basis Functions（物理化矢量基函数）**
  - 对Maxwell方程组提供可靠的解
- **Automatic Adaptive Meshing（准确高效的自动自适应网格剖分）**
  - “Physics defines the mesh not the other way around” “物理定义了网格，而非相反”
- **Transfinite Element Method（ 超限元法）**
  - 提供准确有效的端口网络的参数提取（S、Y 和 Z 参数）
- **Domain Decomposition Method（区域分解法）**
  - 实现分布式内存（集群）并行计算
  - 对于许多先进算法功能相当关键

其他重要技术

- **避免低频崩溃的一些特别处理技术**
  - ✓ 基于树-叉树分割 (Tree-cotree basis splitting) 实现更好的矩阵调整
  - ✓ 在低频段，特有的端口方程很稳定
  - ✓ 扩展精度 (Extended precision) 以充分利用这些特性
- **提升扫频速度**
  - ✓ 调优的宽带扫频技术（插值扫频）
  - ✓ 高效的窄带扫频技术（快速扫频）
- **对 SI 类问题采用终端模式 (Terminal Modes)**
  - ✓ 终端模式与本征模式 (Eigen Modes) 是线性组合
  - ✓ 确保模式的一致性（已获专利）

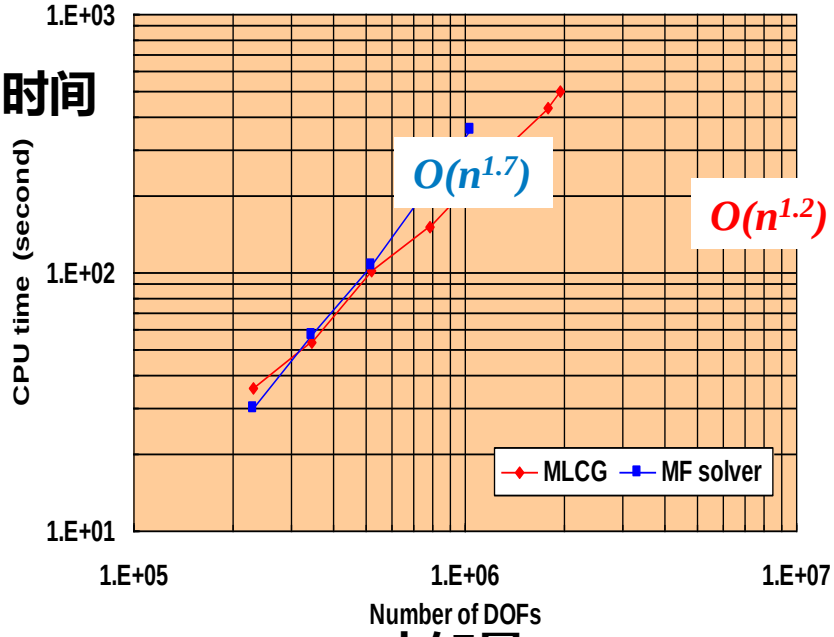
矢量基函数: 不同阶数和网格的效果对比



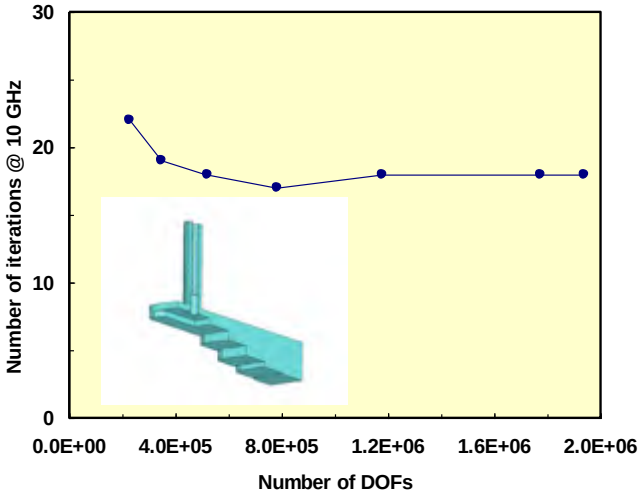
直接法 (Direct Solver) 和迭代法 (Iterative Solver)

复杂度

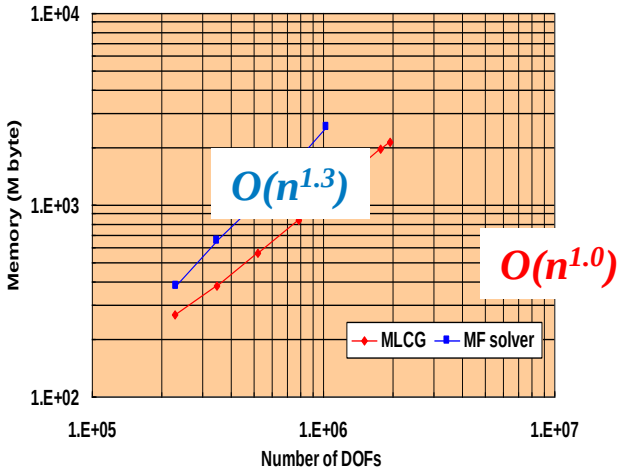
时间



未知量

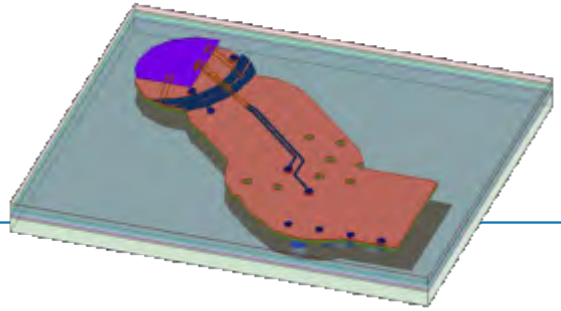


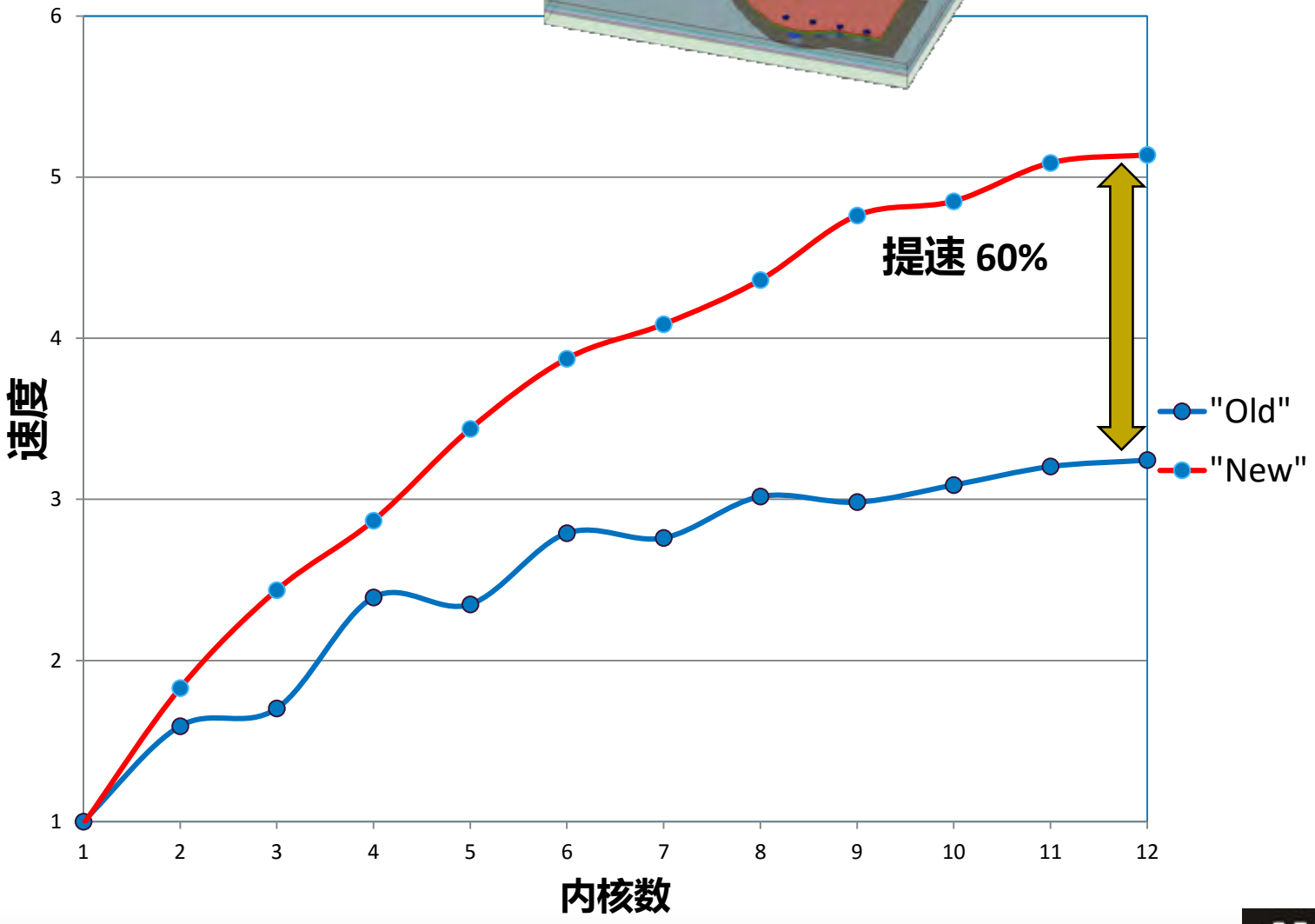
内存



未知量

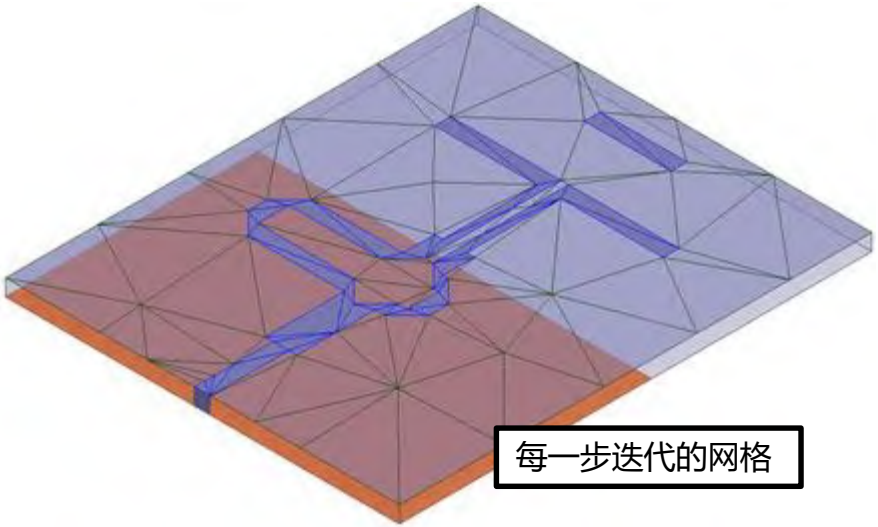
直接法的HPC 提速

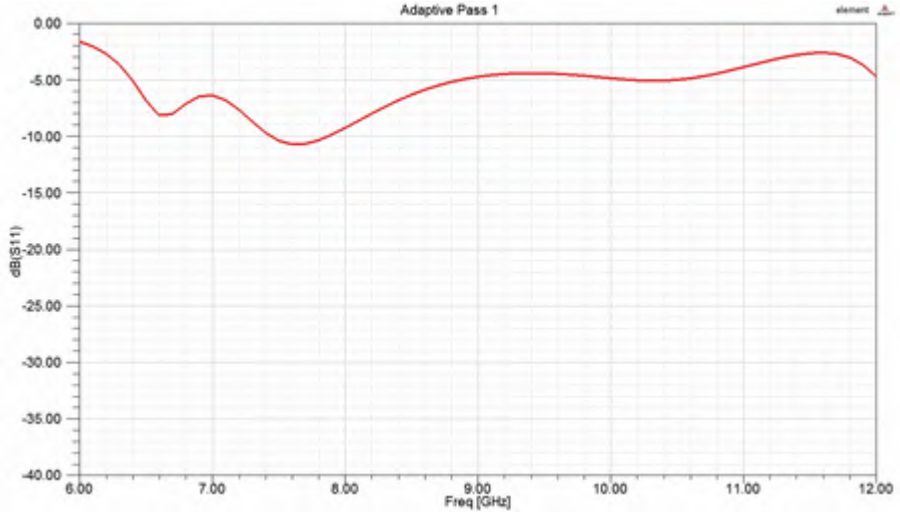




Automatic Adaptive Meshing
自动自适应网格剖分

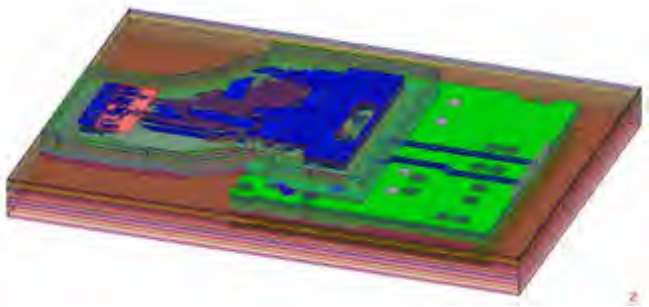
- 自适应剖分: 网格自动产生且精确





宽带扫频

- 采用 8X4 (HPC 32) 和 8X16 (HPC 128)

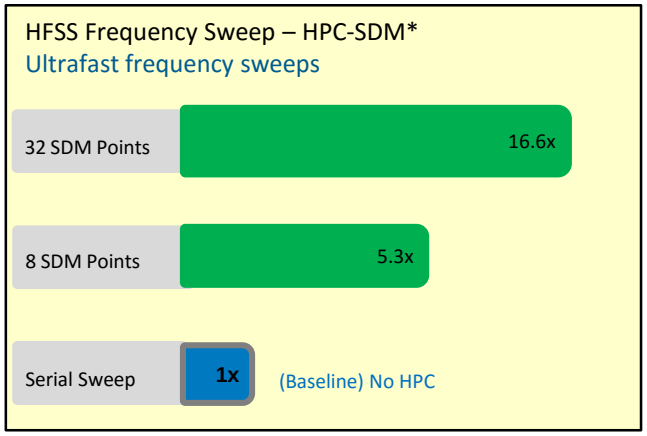


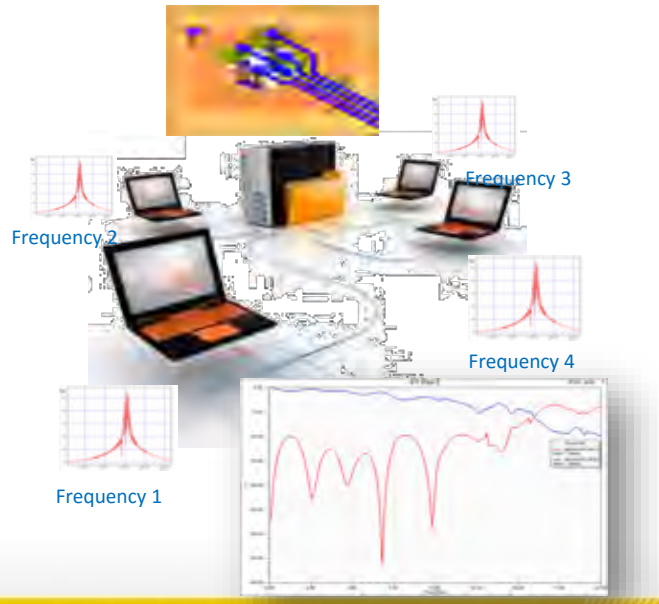
	HFSS 14	HFSS 15
矩阵求解时间 (8 cores)	19:34	14:25 **(35% faster)**
HPC 32 扫频效率	74%	98%
HPC 32 求解时间	25:04:40	14:48:15 **(70% faster)**
HPC 128 扫频效率	52%	95%
HPC 128 求解时间	08:50:08	03:50:14 **(130% FASTER!)**

v14 550% v15

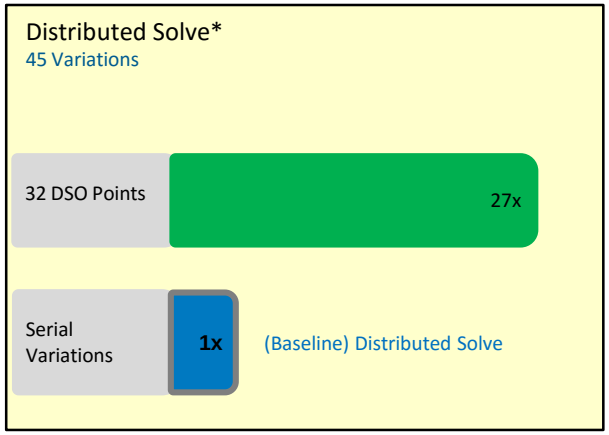
分布式并行求解

并行扫频

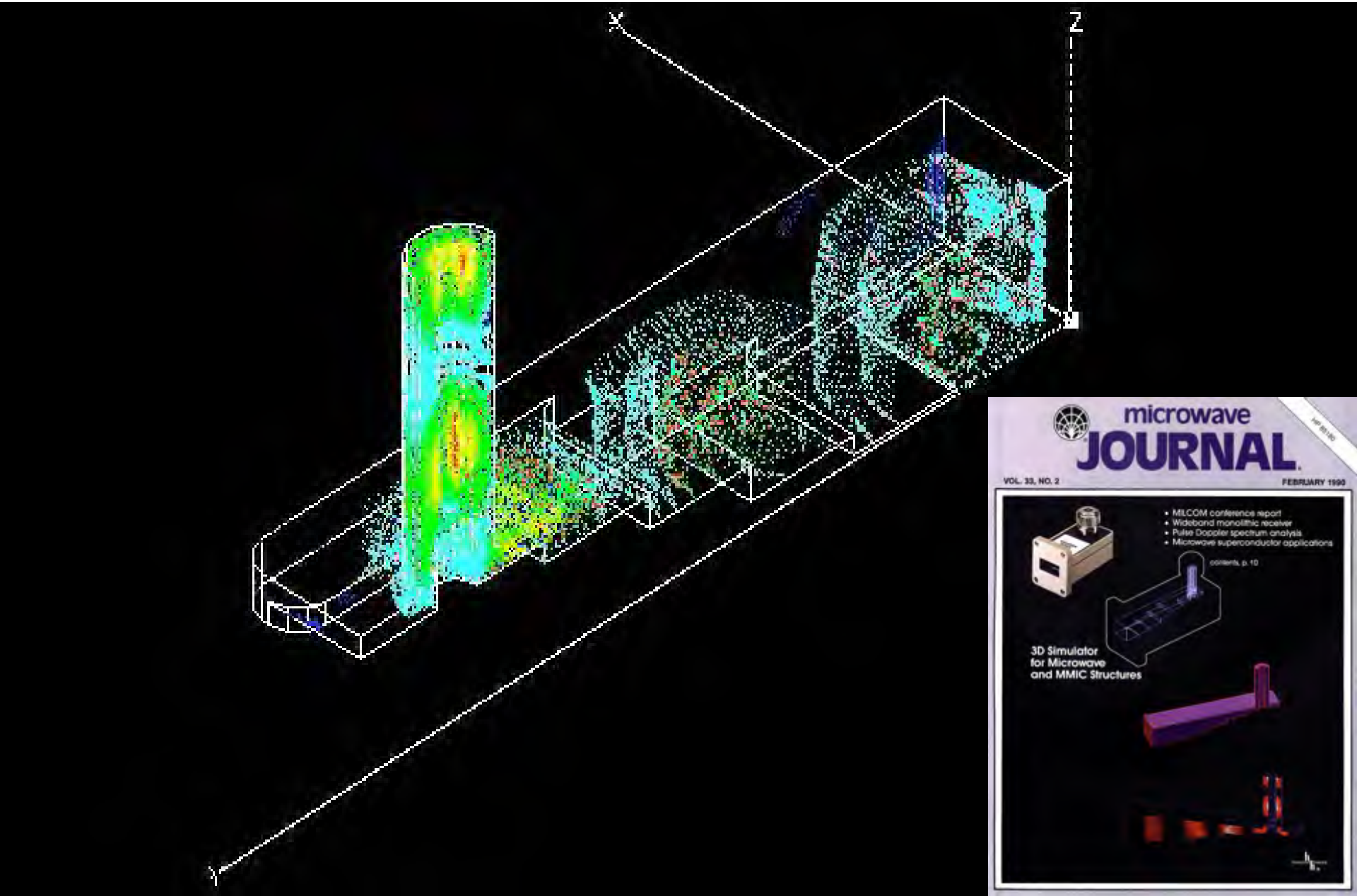




并行参数扫描

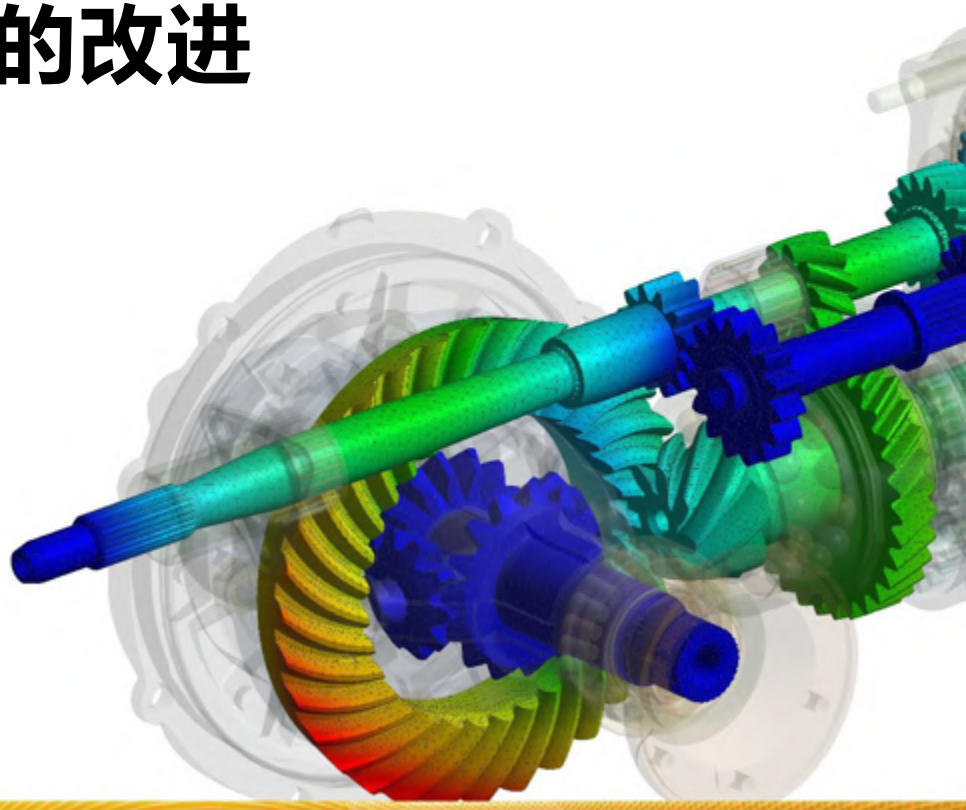


1990 16 小时， 2007 *3 秒*!



ANSYS

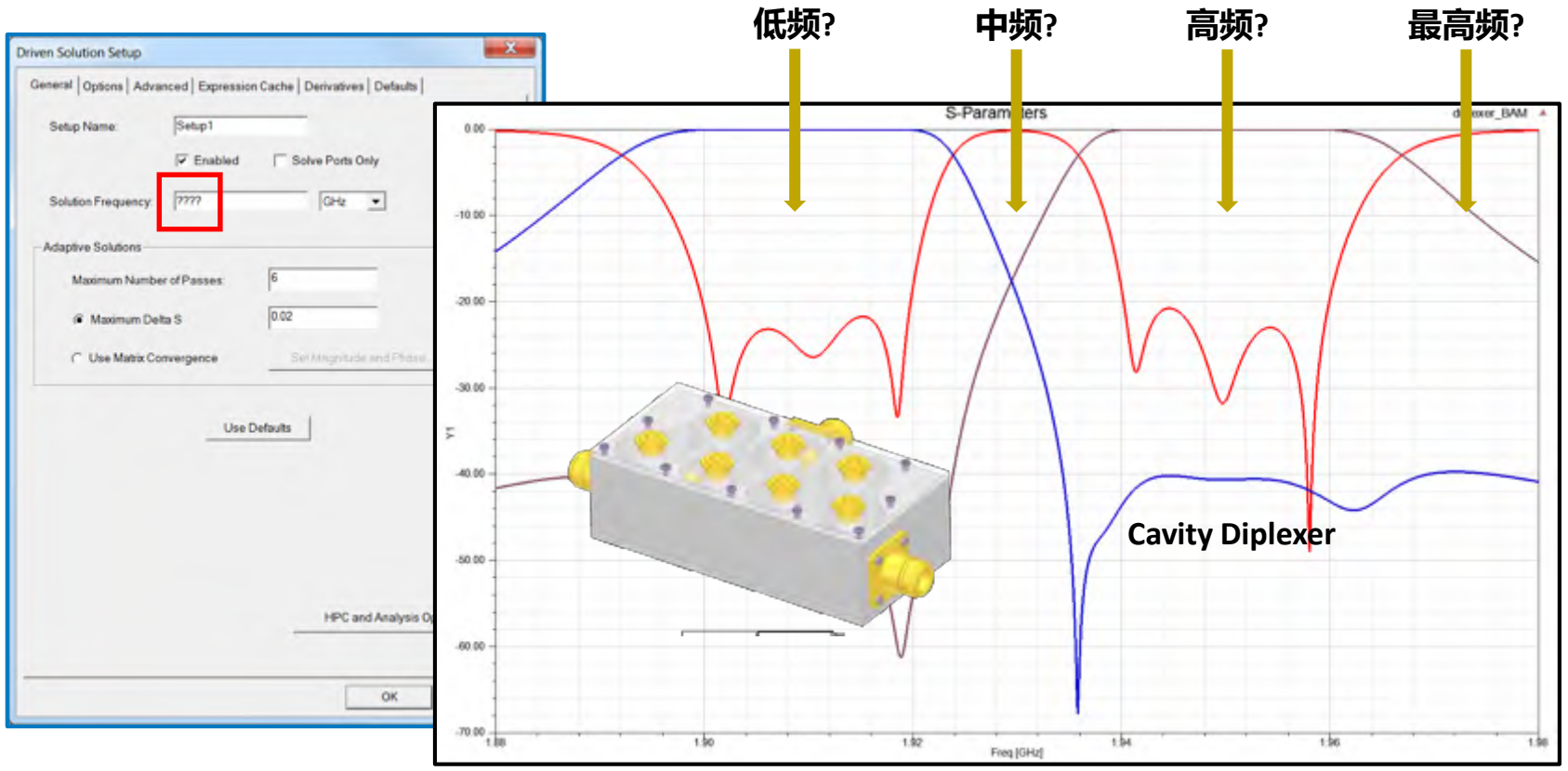
R18.x 的改进



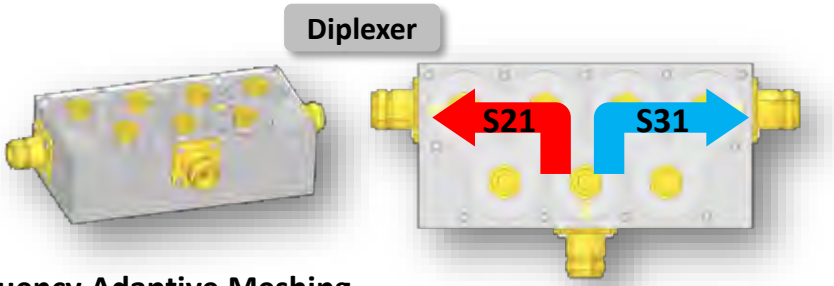
宽带自动自适应网格剖分

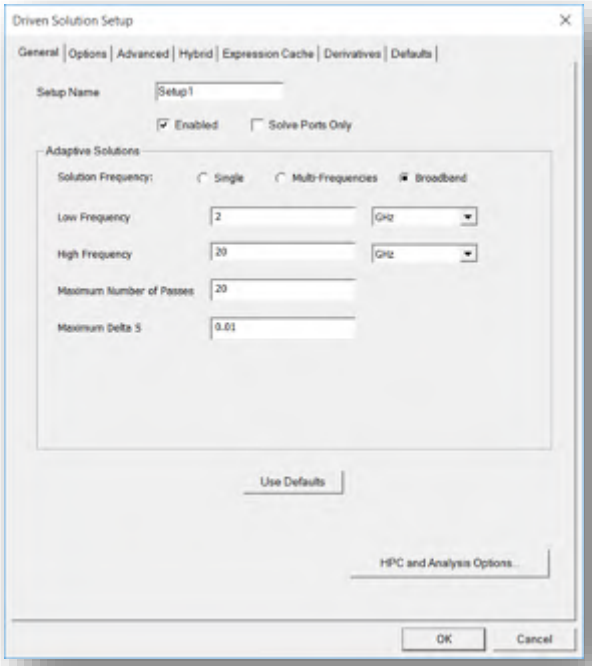
Broadband Adaptive Meshing

- 宽带扫频时要用哪个频率做网格剖分?

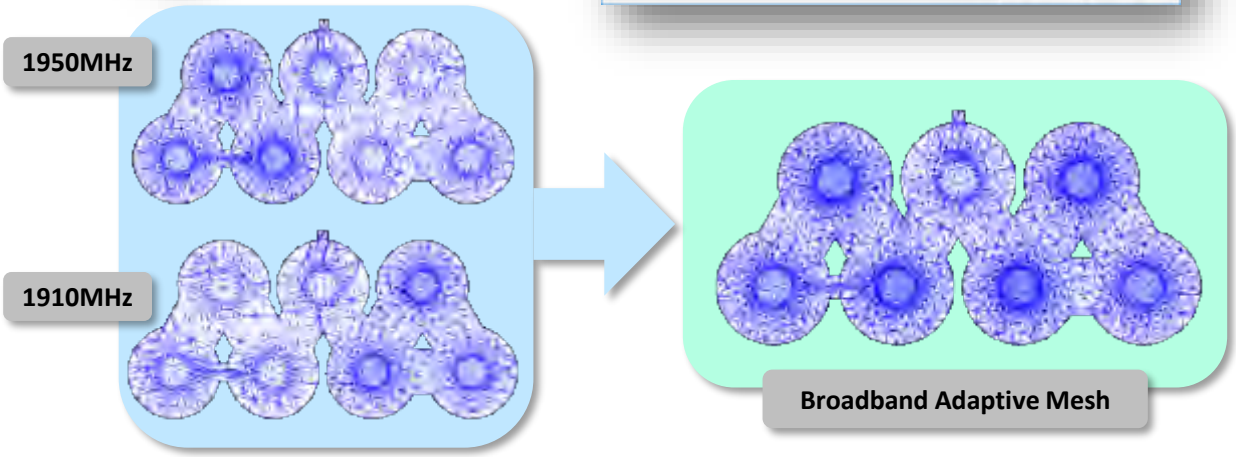


宽带自动自适应网格剖分
Broadband Adaptive Meshing

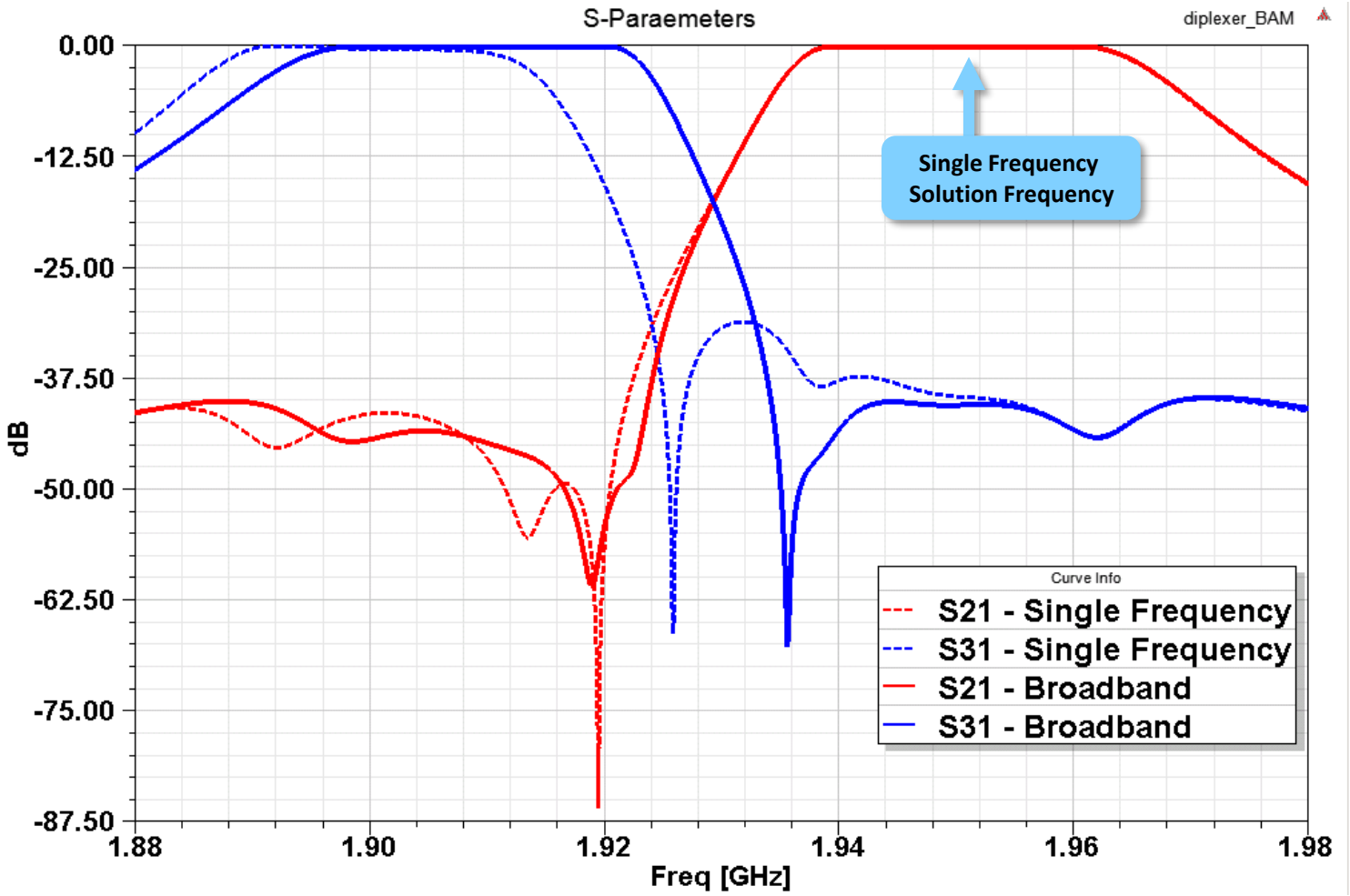




- **Single Frequency Adaptive Meshing**
  - Adaptive meshing is traditionally performed at a single solution frequency
    - Relies on user choosing the appropriate solution frequency
    - Some designs are sensitive to choice of solution frequency in delivering broadband accuracy
- **Diplexer Example**
    - Field behavior is significantly different depending on frequency of operation
    - Single frequency adaptive mesh is not ideal at across all frequency points



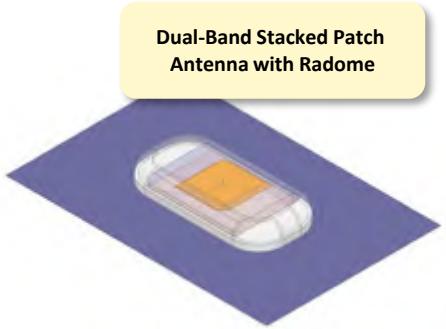
宽带自动自适应网格剖分结果比较



插值扫频的改进

S-Parameter Only Matrix Solve

- **插值扫频时只需解S参数**
- **矩阵分解时也只需解和存跟S参数有关的未知量**
  - 每个频率点10-20% 加速
  - 减少内存需求
    - HPC可以用相同的内存解更多频率点，以此更快



Adaptive Meshing Fr...				
Simulation Setup	00:00:02	00:00:02	88.4 M	Disk = 0 KBytes
Matrix Assembly	00:00:02	00:00:17	774 M	Disk = 0 KBytes, 41777 tetrahedra , 1: 112 triangles
Solver DCS16	00:00:11	00:01:30	1.84 G	Disk = 0 KBytes, matrix size 250785 , matrix bandwidth 2
Field Recovery	00:00:01	00:00:06	1.84 G	Disk = 11347 KBytes, 1 excitations
				Adaptive Passes converged

Saved Fields and S-Parameters

Frequency: 1.5GHz a...				
Simulation Setup	00:00:02	00:00:02	96.3 M	Disk = 0 KBytes, 41777 tetrahedra
Matrix Assembly	00:00:03	00:00:17	781 M	Disk = 0 KBytes, 41777 tetrahedra , 1: 112 triangles
Solver DCS16	00:00:09	00:01:06	1.04 G	Disk = 0 KBytes, matrix size 250785 , matrix bandwidth 2
Field Recovery	00:00:00	00:00:05	1.04 G	Disk = 1 KBytes, 1 excitations

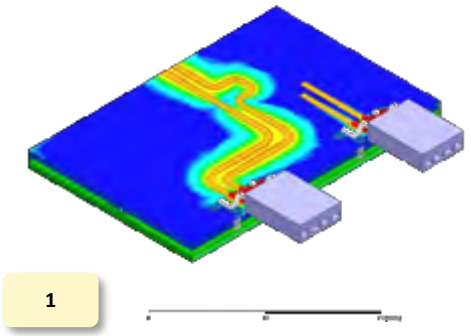
Saved Only S-Parameters

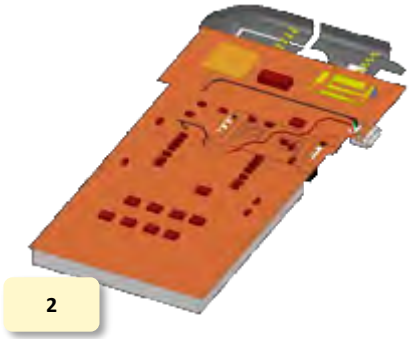
插值扫频的改进的案例

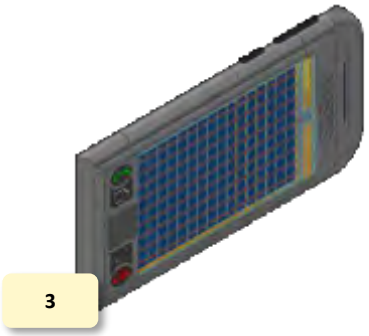
例子 #	R17	R18
1	13.5 GB	3.41 GB
2	39.4 GB	9.71 GB
3	188 GB	30.8 GB

4X 内存节省

256GB的电脑R17只能解1个频率点，R18能同时解8个频率点，最终R18总时间2X加速

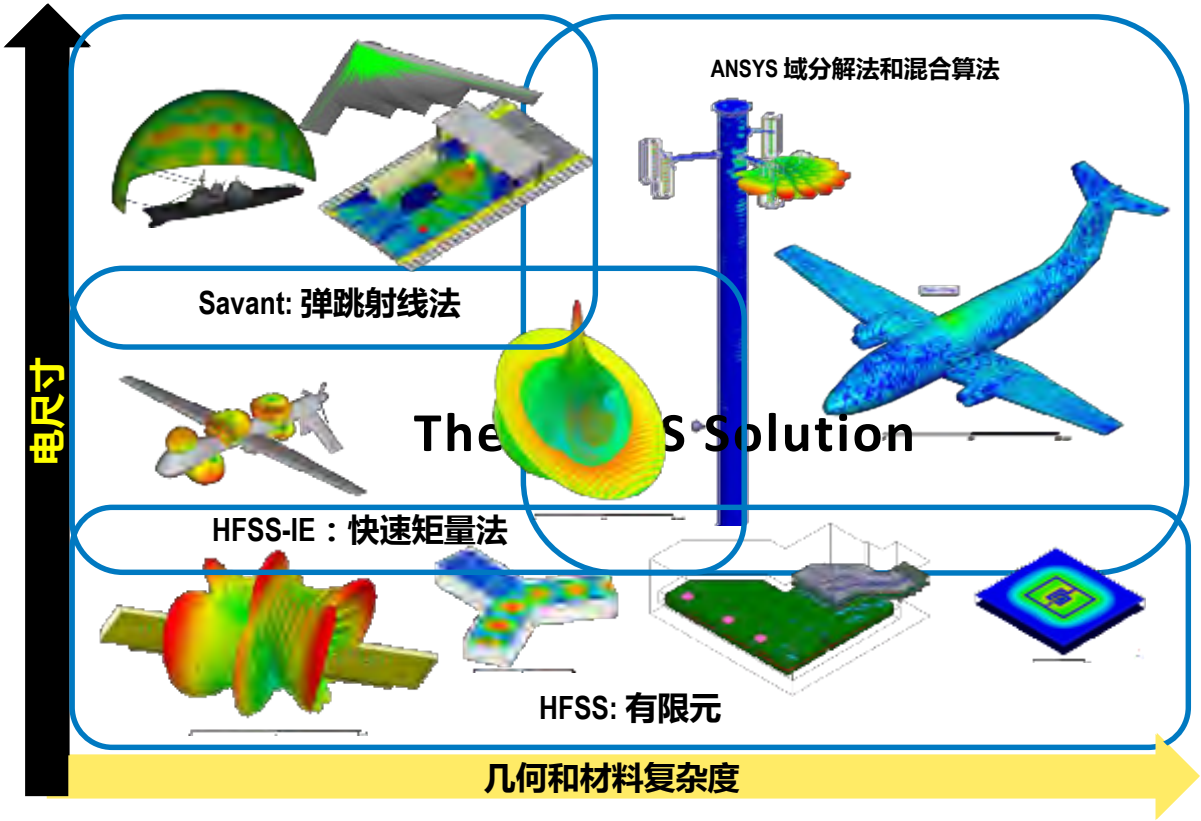






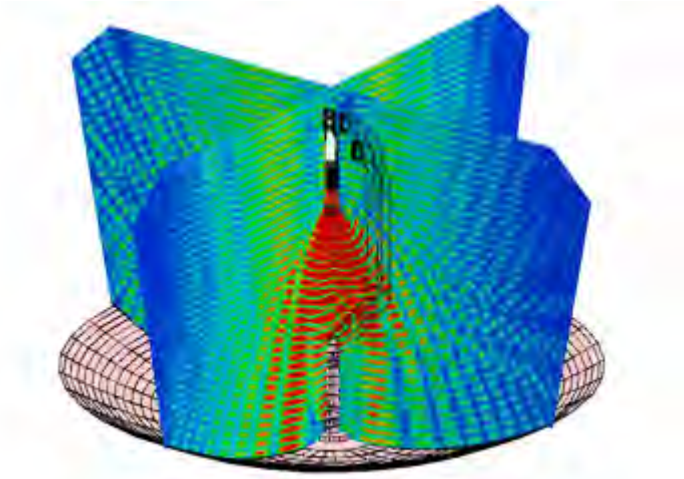
HFSS 先进的算法技术

HFSS算法体系


ANSYS 域分解法和混合算法
Savant: 弹跳射线法
The S Solution
HFSS-IE：快速矩量法
HFSS: 有限元
电尺寸
几何和材料复杂度

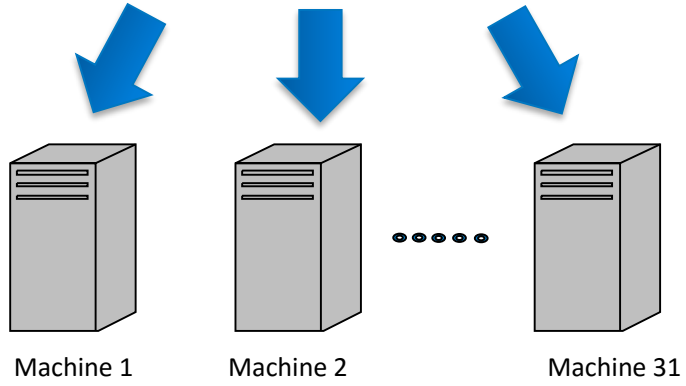
HFSS DDM (Domain Decomposition, 区域分解法)

- **区域分解求解器**
  - ✓ v12 版本首次引入
  - ✓ 可高效求解电大尺寸电磁问题



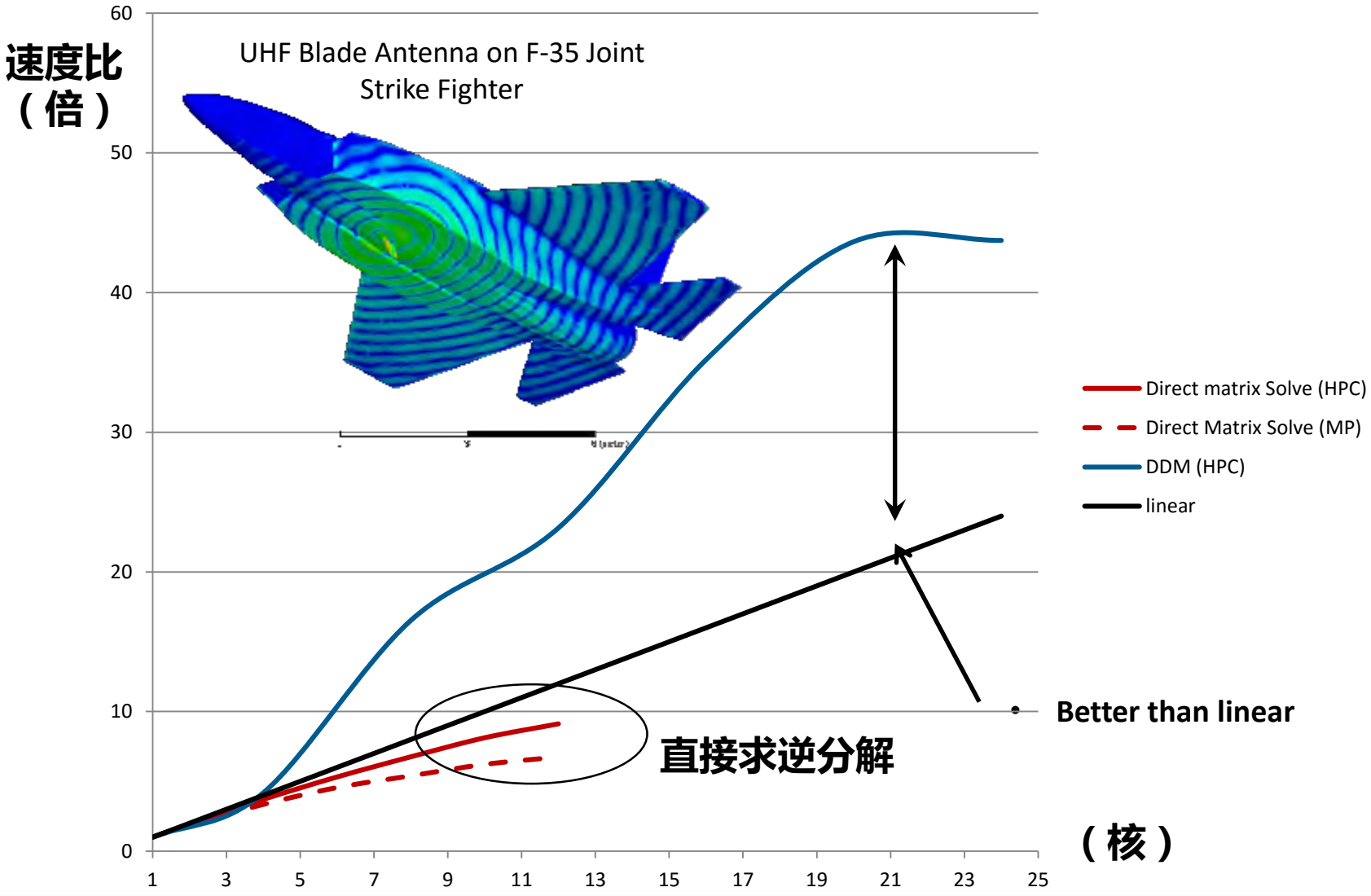
带有喇叭馈源和支撑结构的抛物面天线

- **根据网格自动分区域**
  - ✓ 易用性好
  - ✓ 负载均衡 (Load balance)



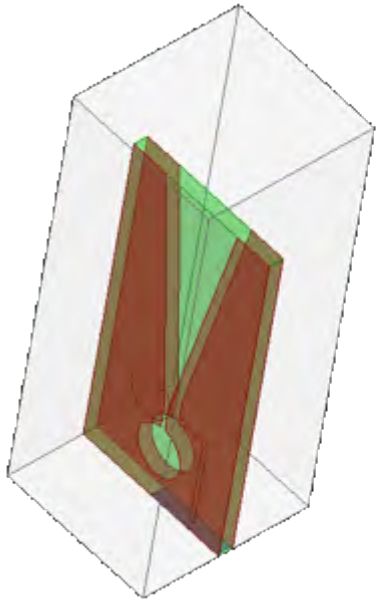
未知量:	12.5 Million
HFSS 11 计算时间:	17 hrs
HFSS 12 DDM 计算时间:	**2.5 hrs (6.8X)**

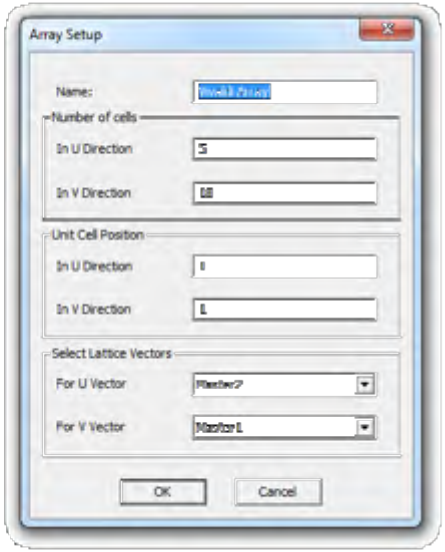
区域分解算法的并行加速比（Parallel Scalability）

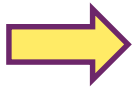


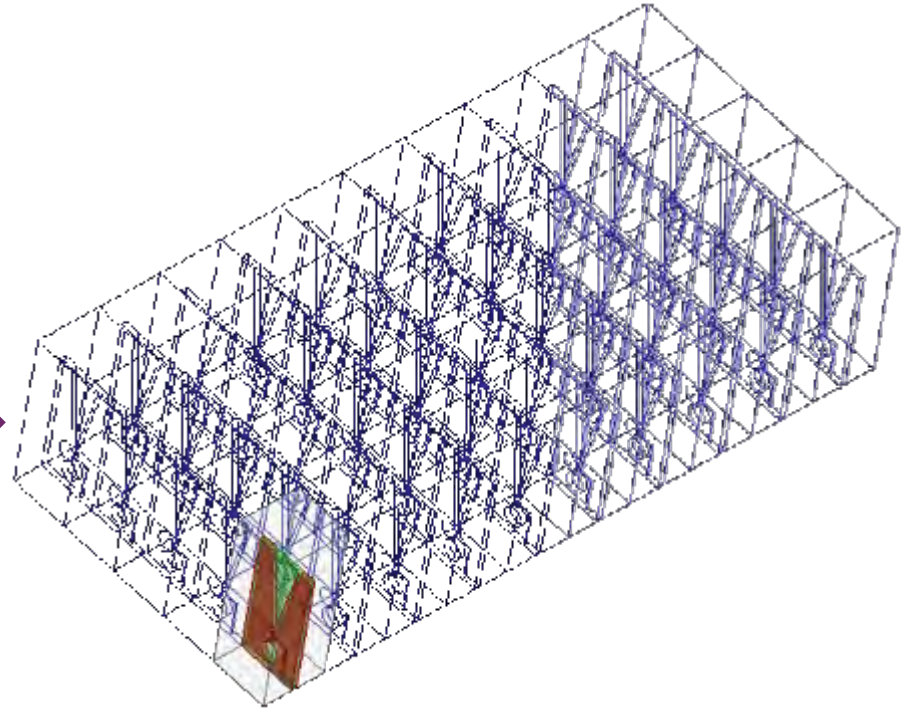
采用 DDM 技术的有限大阵列算法 (Finite Array Solver)

- **针对周期性结构的 DDM 技术** New in V14
  - ✓ 建模简便、网格剖分和算法高效
  - ✓ 特定的界面，专门用于阵列问题



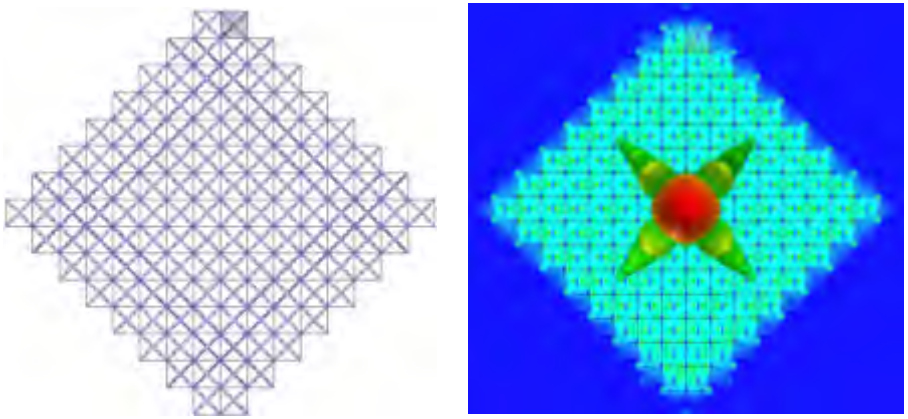




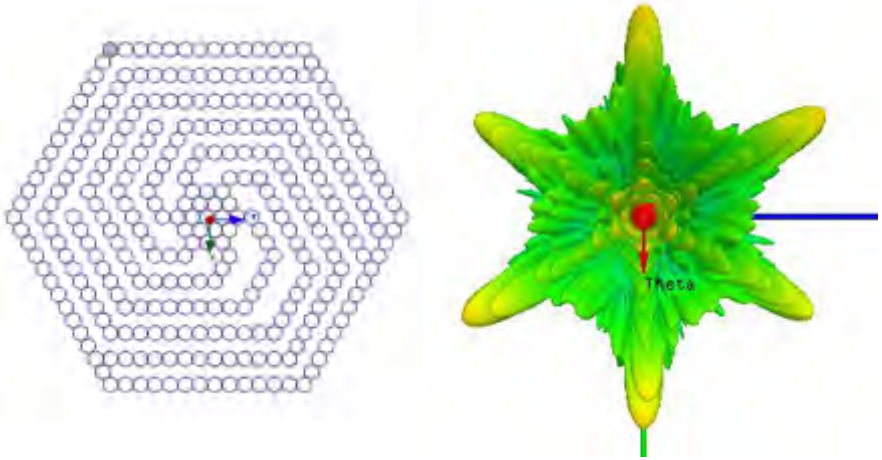


Flexibility（灵活性） – Shaped and Sparse Arrays

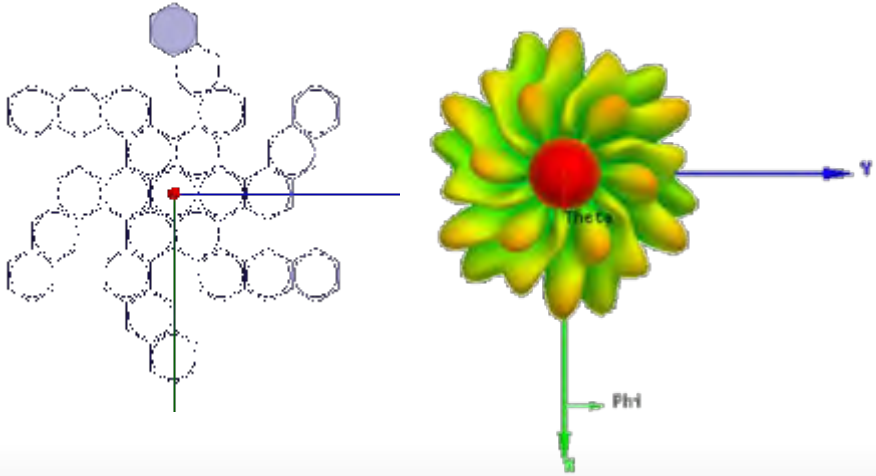
Diamond （钻石状）



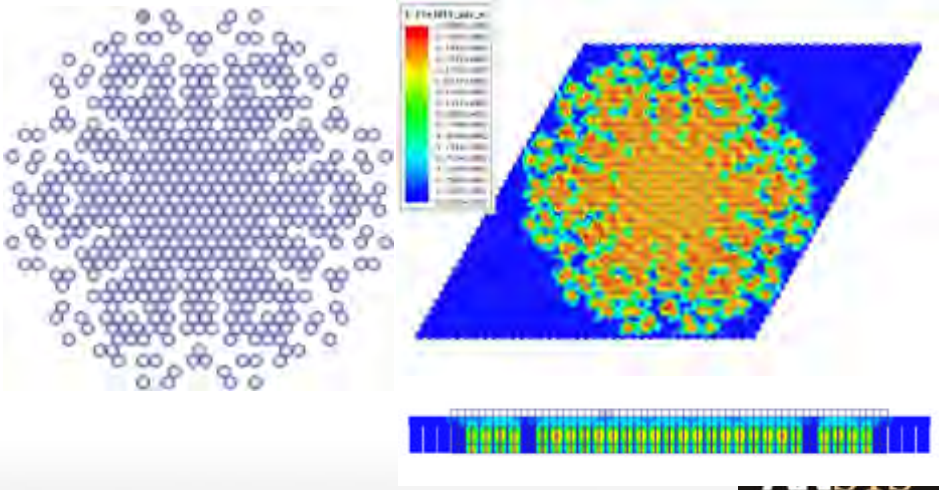
Asymmetric Spiral/Hex （ 螺旋状）



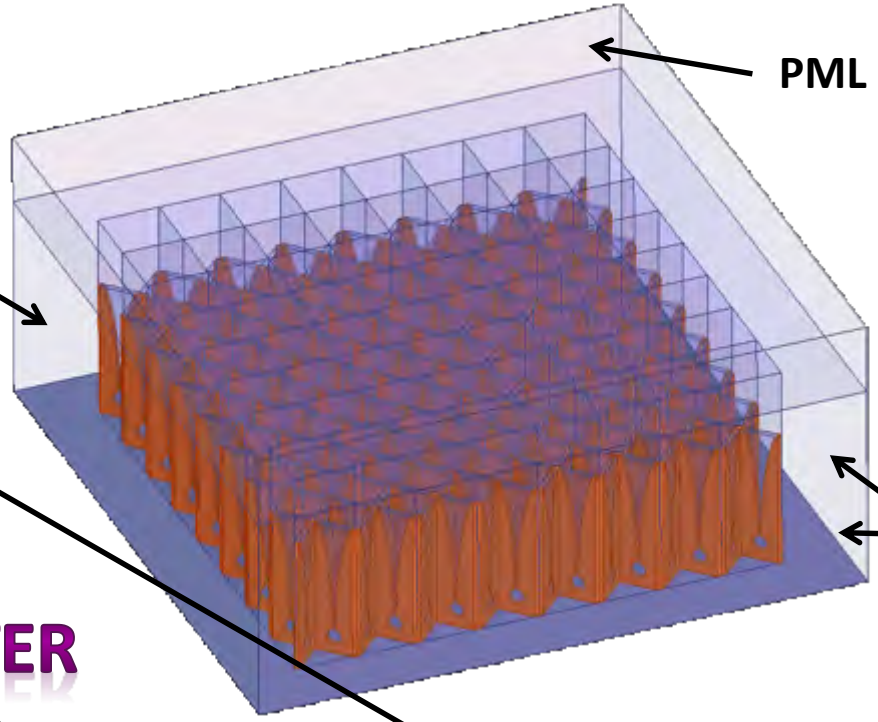
Small Spiral



Snowflake （ 雪花状）



域分解法对比经典算法



DDM USES 77% LESS RAM

DDM IS 4.1X FASTER

模型	# 激励	# 核	剖分时间	解时间	# 四面体	总需内存	节点最大内存	节点平均内存
8x8 DDM Array	256	13	0h:7m	30h:30m	11,242,700	48.2GB	6.0GB	4.0GB
256 Element Explicit Array	256	12	Total =	122h:18m	5,881,409	211GB	N/A	N/A

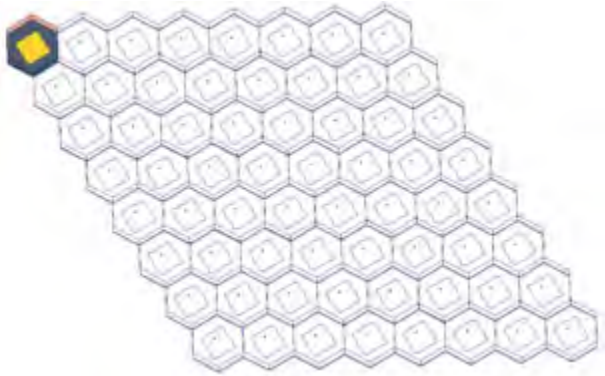
HFSS 区域分解法的发展

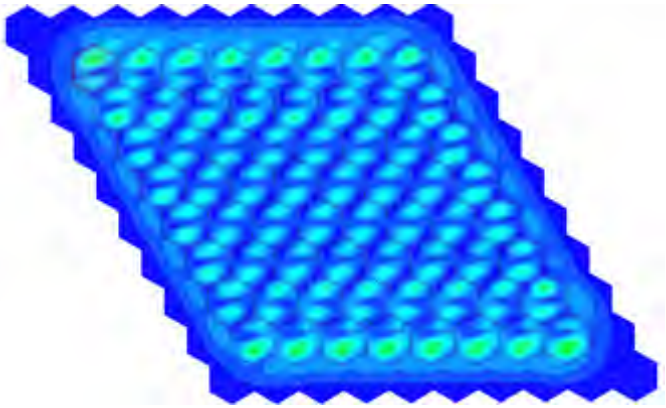
基本区域法取用一阶Robin传输条件 → 分布并行（distributed parallel）运用文件传输 → 区域法取用高阶Robin传输条件

3.2GB, 120 min

3.17GB, 74 min

8x8 Hex-Patch Array, 64 excitations





多右端项的 循环处理和重新回收

3.19GB, 51 min

取用数值格林函数

3.2GB, 29 min

MPI 内存并行

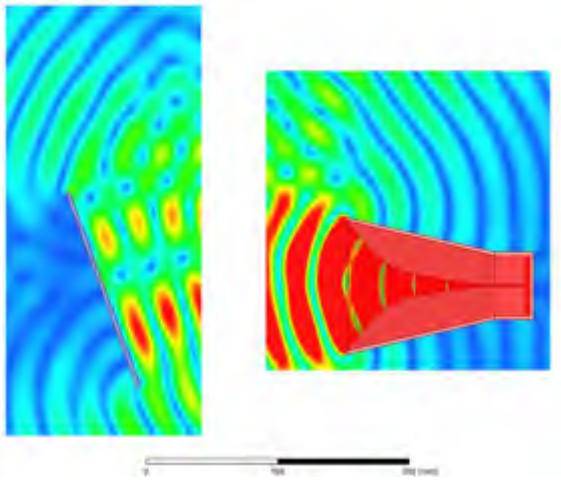
3.2GB, 9 min

8 个核

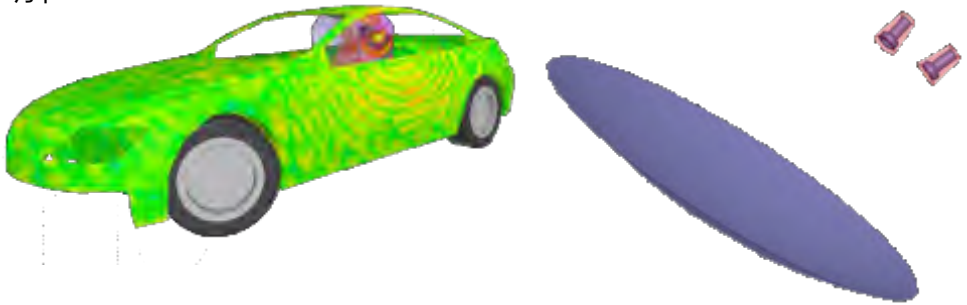
版本	未知数	内存	平均迭代步	运行时间
v14	5.17M	3.0G	19.2	54 min
v15	5.17M	3.0G	8.9	9 min

采用 DDM 技术的混合算法 (Hybrid Solver)

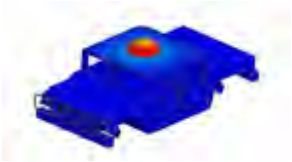
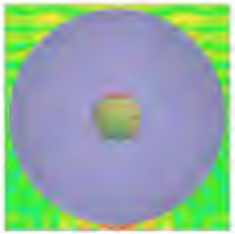
- **FE-BI 技术计算辐射和散射** New in v13
  - ✓ 内部区域采用 FEM (有限元法) 求解
  - ✓ 外部自由空间采用 IE (积分方程法) 求解
  - ✓ 高精度的同时实现高效率计算



- **IE Regions** New in v14
  - ✓ 开放空间的金属物体可直接用 IE 求解
  - ✓ 更多内部复杂结构采用 FE-BI 方法



采用 DDM 技术的混合算法 (Hybrid Solver)


FE-BI

IE Region

Dielectric Cavity

Linked Region

Domain Decomposition Based Hybrid Solver

SBR+ Region

PO Region

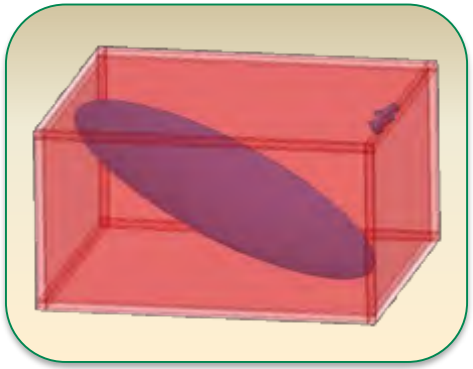
Dielectric PO

Dielectric IE Region



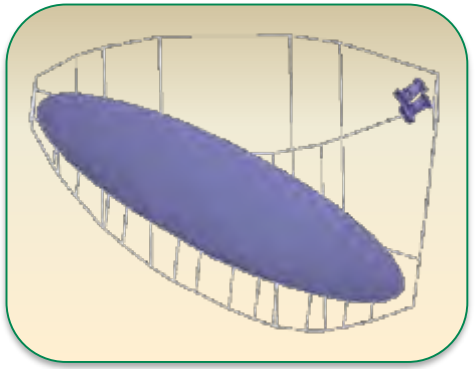
HFSS 求解器演化历程

FE-PML



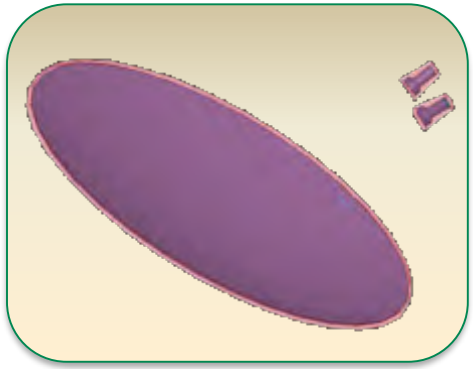
N=7.7M, 137GB, 136min

Hybrid FE-BI



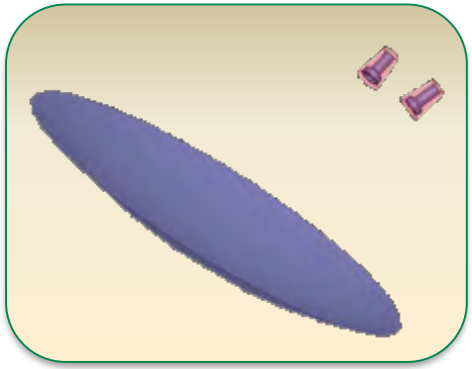
N=5.0M, 78GB, 101min

Disjoint FE-BIs



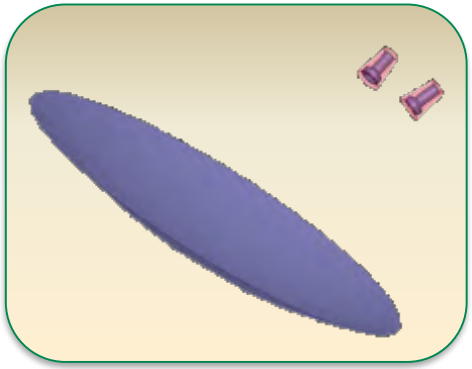
N=777K, 18GB, 29min

Hybrid FE-BI and IE Region



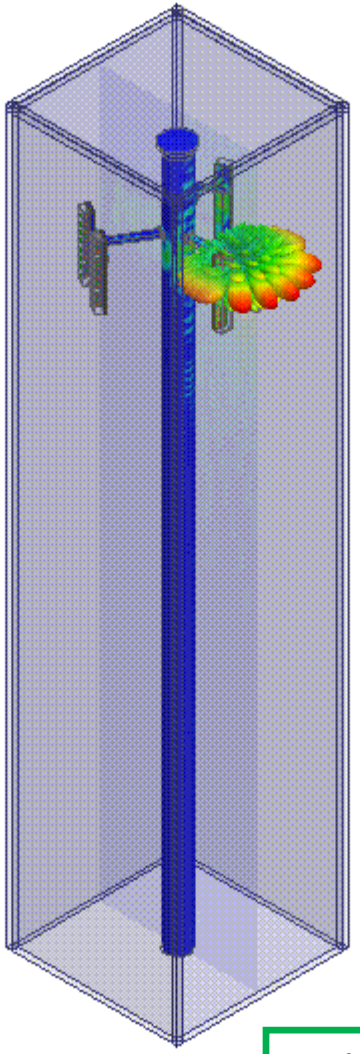
N=127K, 5GB, 6min

Hybrid FE-BI and PO Region

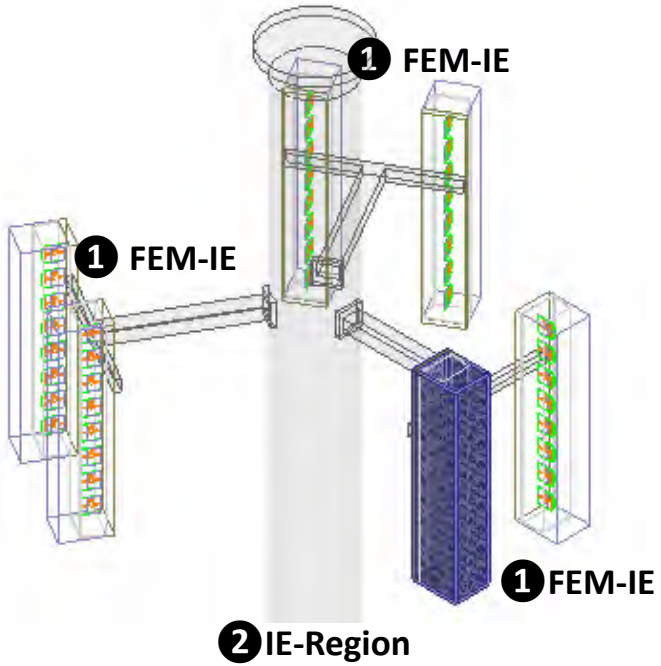


N=127K, 1.6GB, 1.5min

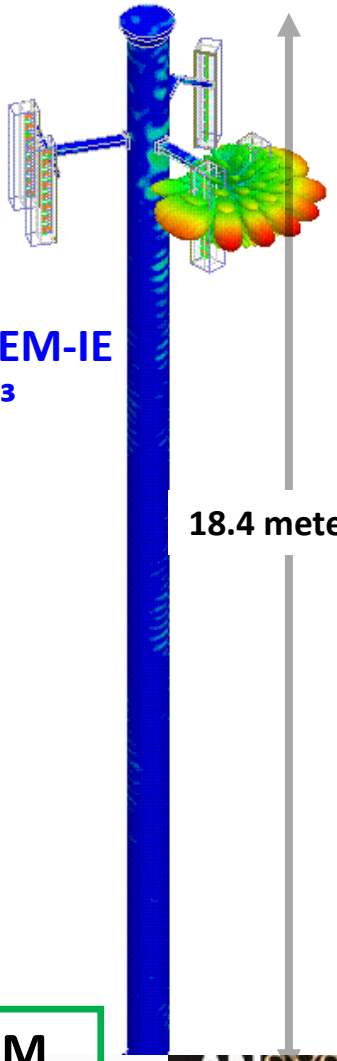
改善的 混合算法 IE-Regions (v15)



PML Setup
10625 λ³



Hybrid FEM-IE
37 λ³



算法	总内存	运行时间
FEM	98 GB	9.1 小时
Hybrid Solution	**23.7 GB**	**4.5 小时**

Hybrid IE-Regions shows 2x Speedup, and 76% **Less RAM**

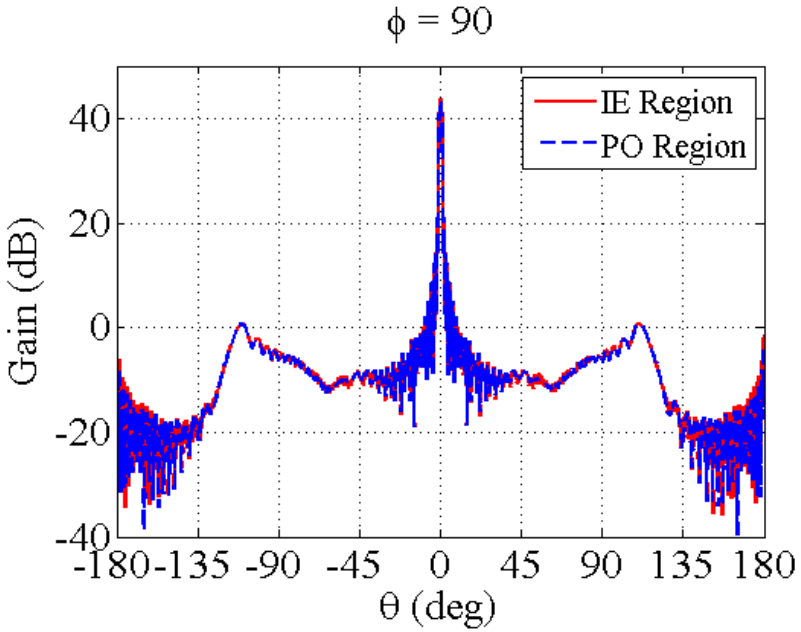
FEBI + IE/PO Region 案例：58λ 碟形反射面

IE Region

Freq	S:2:1	S:2:2	S:2:3
7.25 (GHz)	2:1 (0.4717, 92.6)	(0.0030895, -11.5)	(0.0021267, 157)
	2:2 (0.0030856, -11.5)	(0.12924, 67)	(0.00064122, -175)
	2:3 (0.0021208, 157)	(0.00064125, -175)	(0.12493, 69.9)

PO Region

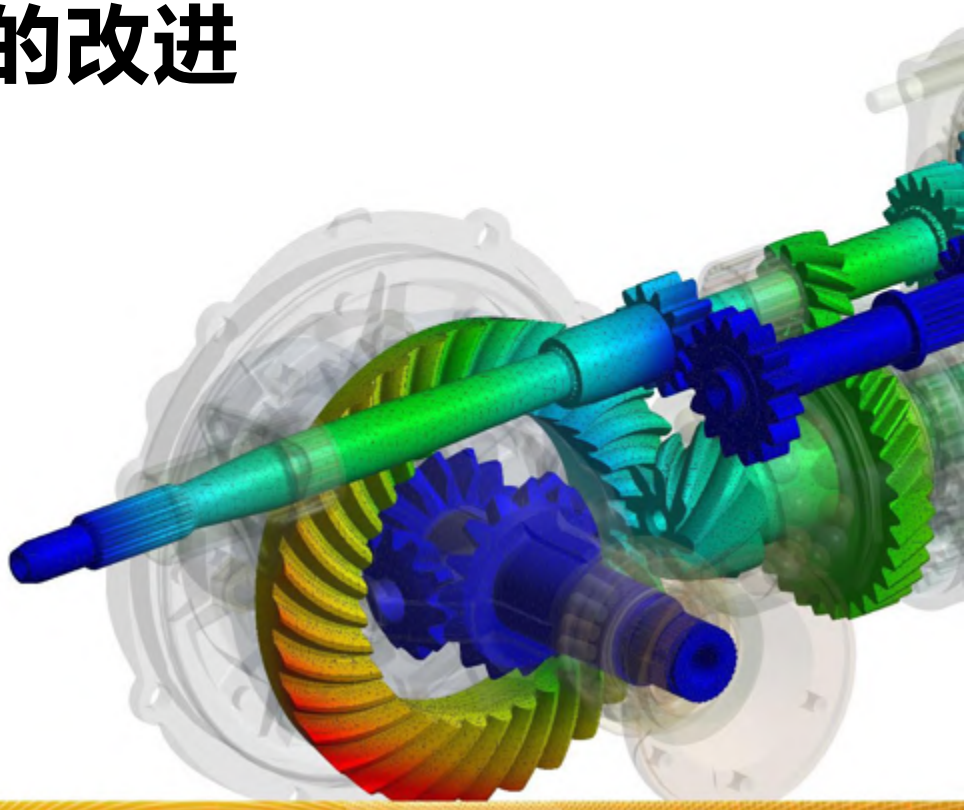
Freq	S:2:1	S:2:2	S:2:3
7.25 (GHz)	2:1 (0.4704, 92.6)	(0.0031269, -12)	(0.0021887, 159)
	2:2 (0.0031269, -12)	(0.12987, 67.2)	(0.00057552, -163)
	2:3 (0.0021888, 159)	(0.00057554, -163)	(0.12543, 70.1)



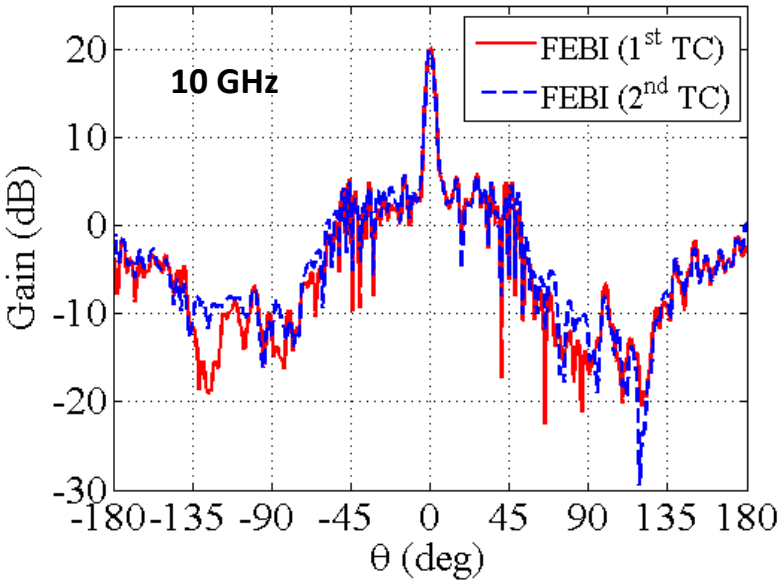
求解器	未知量	内存	迭代步数	仿真时间
IE Region	1,367,400	129 GB	10	160 min
PO Region	1,367,400	14 GB	10	9.5 min

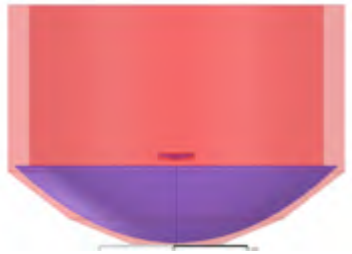
ANSYS

R18.x的改进



改善的 FE-BI



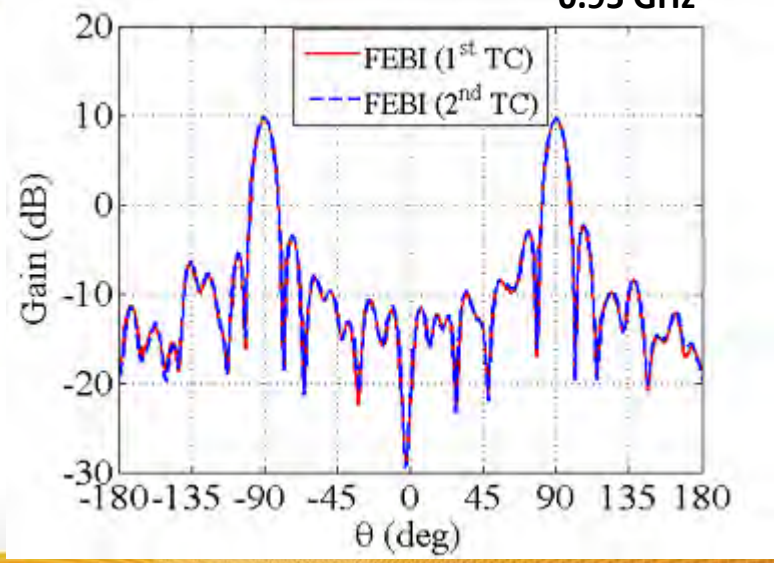


1 task 16 cores

求解器	未知量	内存	迭代步数	仿真时间
R17	1,398,461	27.2 GB	147	210 min
R18	1,398,461	15.6 GB	12	17 min

DDM residual 1.e-3

0.95 GHz

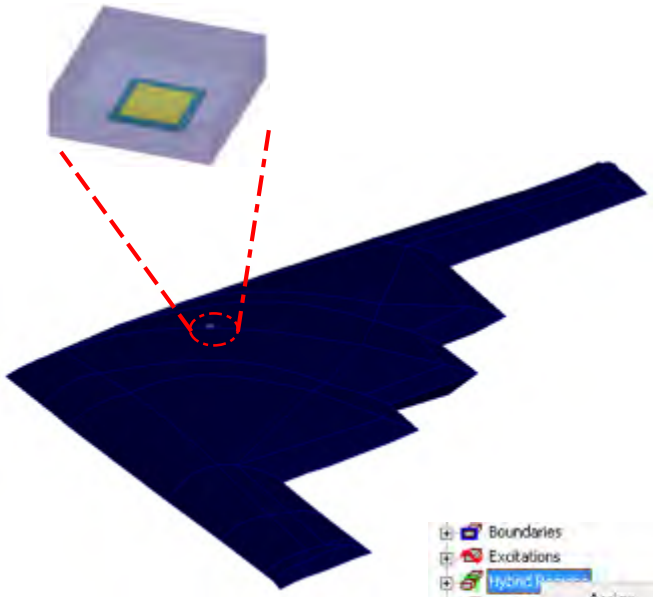


8 task 16 cores

求解器	未知量	内存	迭代步数	仿真时间
R17	804,937	25.6 GB	14	124 min
R18	804,937	24.5 GB	8	78 min

DDM residual 1.e-3

1way vs 2-way, B2 轰炸机 @ 1GHz

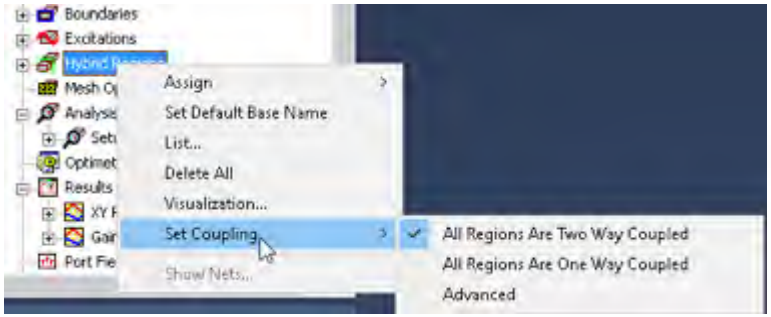


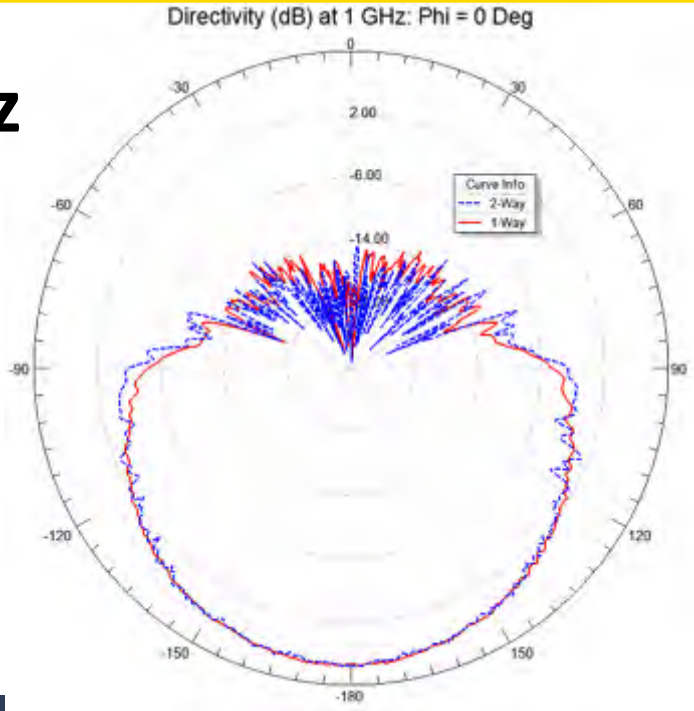
2-way

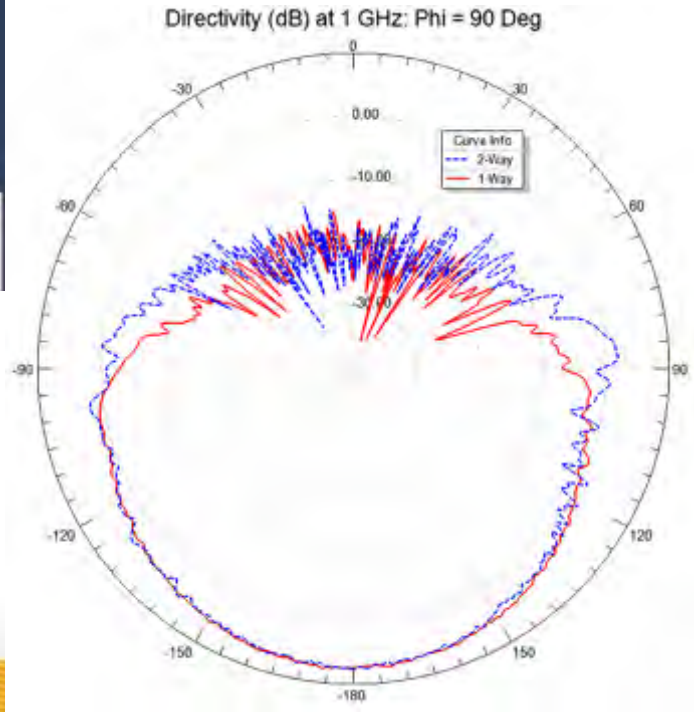
Freq		S:Pin_T1
1000 (MHz)	Pin_T1 (0.9203,	141)

1-way

Freq		S:Pin_T1
1000 (MHz)	Pin_T1 (0.92015,	141)



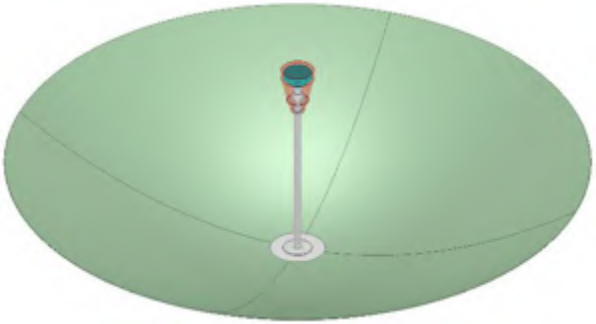


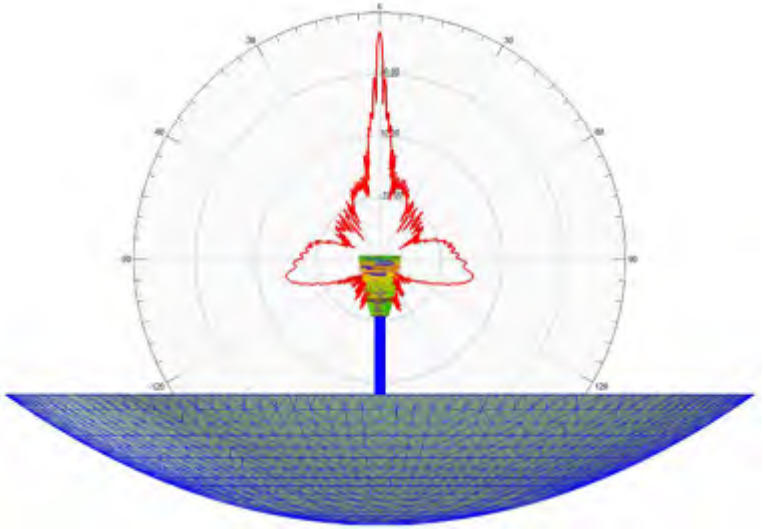


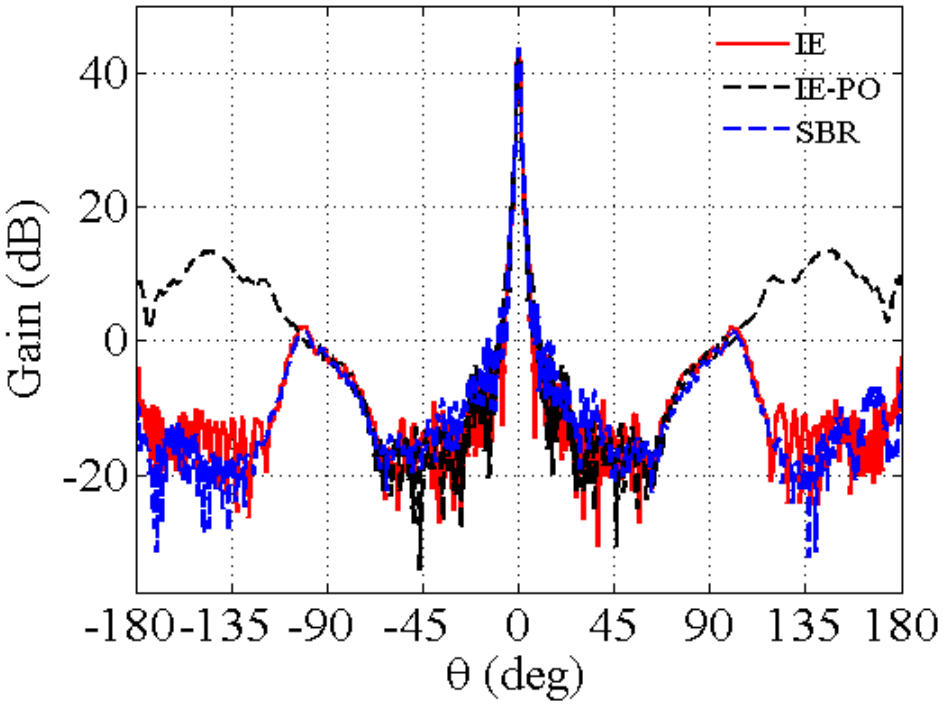
1 task 16 cores

求解器	未知量	内存	仿真时间
Two-Way	454,538	52.2 GB	67 min
One-Way	454,538	49.9 GB	38 min

SBR+ Region:碟形反射面@ 7.1GHz



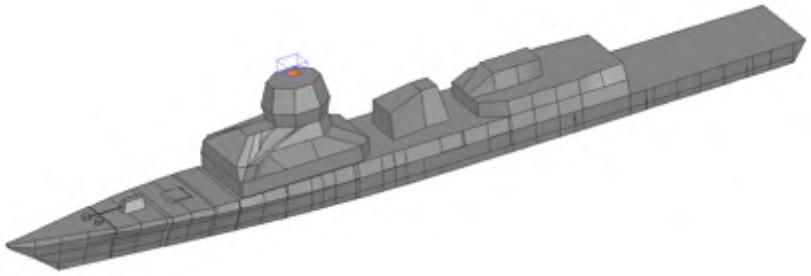


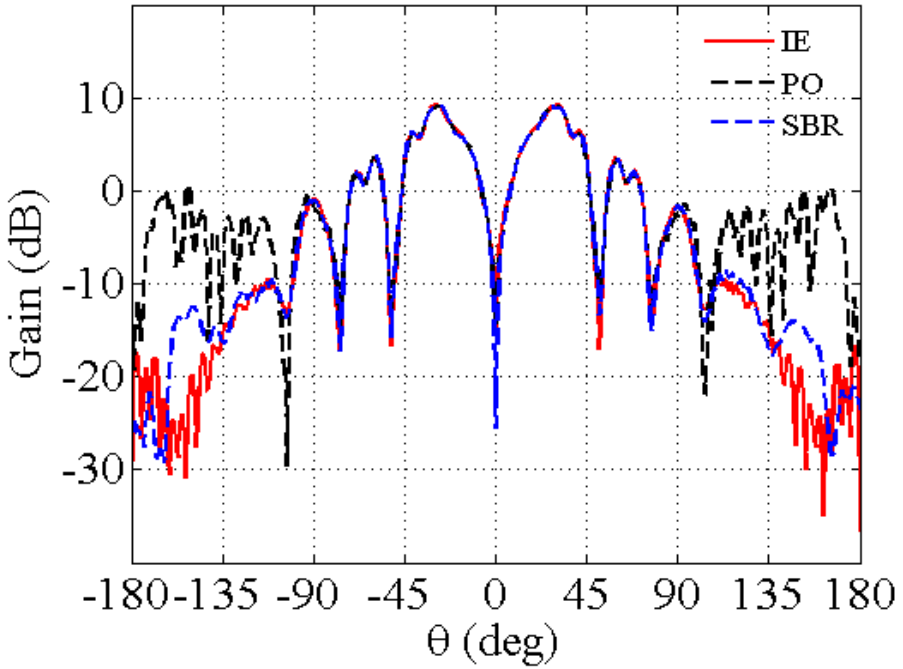


1 task 16 cores , 3 adaptive passes

算法	内存	运行时间
FEBI-IE	24.3 GB	56 min
FEBI-IE-PO	10.7 GB	16 min
FEBI-SBR	2.0 GB	6 min

SBR+ Region: 战舰 @ 0.5GHz





- **战舰长度250 波长.**
- **IE网格**剖分时间**12 分钟.**

1 task 16 cores

算法	内存	运行时间
FEBI-IE	366 GB	407分钟
FEBI-PO	39.8 GB	24分钟
FEBI-SBR	2.04 GB	3分钟

感谢聆听