Application of the CEPTRE Code to Cable SGEMP Problems

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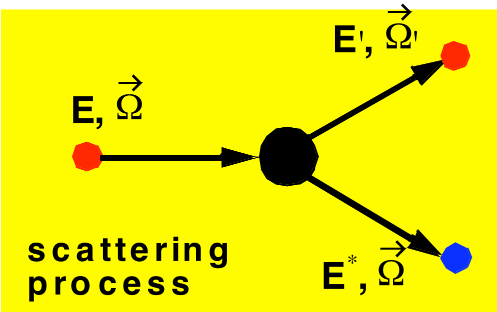
Outline

- Overview of CEPTRE
- Introduction to Cable SGEMP Simulations
- CEPTRE Numerical Difficulties
- CEPTRE Strategies for Speed-Up
- Results for RG402 Simulation
- Summary

CEPTRE Code

(**C**oupled **E**lectron **P**hoton **T**ransport for **R**adiation **E**ffects)

- Time-independent, deterministic, coupled electron-photon transport code on unstructured mesh
- Numerical solutions to the Boltzmann transport equation which describes the particle distribution in phase space (r, E, Ω)
- Physics of particle-media interactions properly characterized by cross sections
- Discretization of Phase Space
  - *Multigroup* approximation in energy along with Legendre expansion of scattering cross sections
  - *Discrete-Ordinates* approximation in direction
  - *Finite-Element* approximation in space



CEPTRE Features

- Multigroup energy discretization
- Discrete ordinates angular discretization
- Arbitrary order of anisotropic scattering
- Unstructured-mesh Galerkin finite elements
- Second-order forms of the transport equation
  - **S**elf-**A**djoint **A**ngular **F**lux (SAAF)
  - **E**ven-**O**dd **P**arity **F**lux (EOPF)
- Parallel implementation with spatial domain decomposition
- Object-oriented program design with C++
- Integrated into an architectural framework (Nevada)
- Build on parallel Krylov solver libraries (Trilinos, AztecOO)
- Simultaneous space-direction solve

Properties of Second-Order Form

$$\left[-\hat{\Omega}\cdot\nabla\Re^{-1}\hat{\Omega}\cdot\nabla+\Re\right]\psi\left(\vec{r},\hat{\Omega}\right)=Q\left(\vec{r},\hat{\Omega}\right)-\hat{\Omega}\cdot\nabla\left[\Re^{-1}Q\left(\vec{r},\hat{\Omega}\right)\right]$$

- Transport operator on left is self-adjoint
- Removal operator is an effective cross section – inverse appears
- Scattering included in transport operator
- Right side is fixed within an energy group

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CEPTRE Employs a Unique Solution Strategy

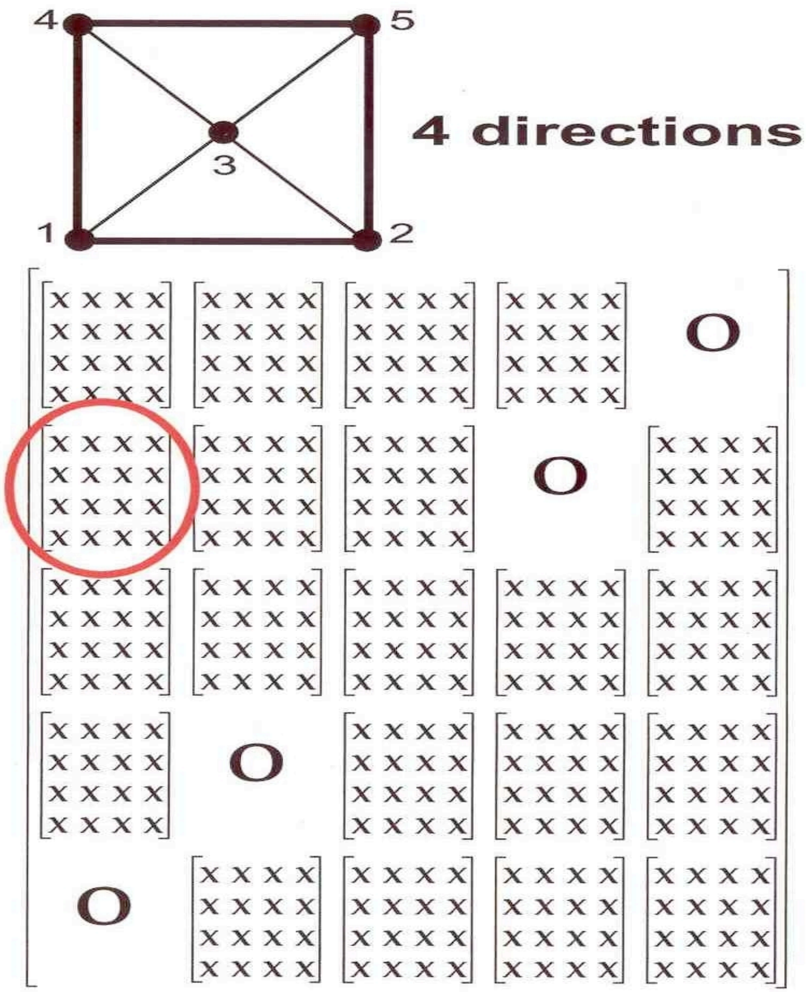
- Slow convergence rate for electron transport
- Low parallel efficiency due to coupling in directions from scattering

Conventional Source Iteration

- Fast convergence rate for electron transport
- Good parallel efficiency
- Large storage requirement

CEPTRE

Simultaneous Space-Direction Solution Algorithm



- Sparse block matrix
- Symmetric Positive Definite System
- Number of block rows:
  - N_{nodes}
- Block size
  - $N_{directions} x N_{directions}$
- Blocks are full due to coupling from scattering
- Tailor-made for VBR data format
- Storage $\sim(N_{directions})^2 x N_{nodes}$
- Run time $\sim(N_{directions})^2 x (N_{nodes})^{1.5}$

Parallel Iterative Algorithm

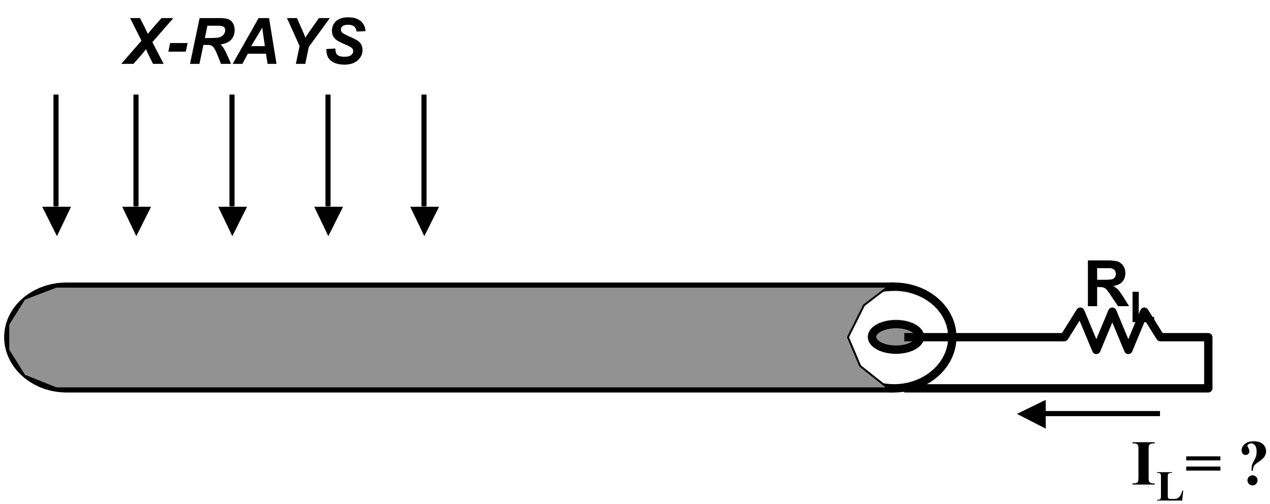
- Preconditioned Conjugate-Gradient method with domain decomposition
- Extensive use of existing parallel iterative-solution libraries (Trilinos, AztecOO)
- Fast convergence rate for electrons
- Slow convergence rate for photons on FE meshes with refined cells (90% of run time)

Cable SGEMP Analysis

- Will electronics be disrupted/damaged by an incident x-ray source that will cause photo/Compton-emission electrons from material surfaces and energy and charge deposition within its materials?
- Generates electrical fields on cable shields and conductors within cables, a phenomenon referred to as cable System Generated Electromagnetic Pulse (SGEMP)

Cable SGEMP Simulation Process

- Computational capability developed for cable SGEMP simulations consists of two distinct calculations:
    - CEPTRE performs radiation transport simulation
    - CABANA performs electrical response simulation
- CEPTRE provides energy deposition, current and charge profiles induced by radiation to CABANA



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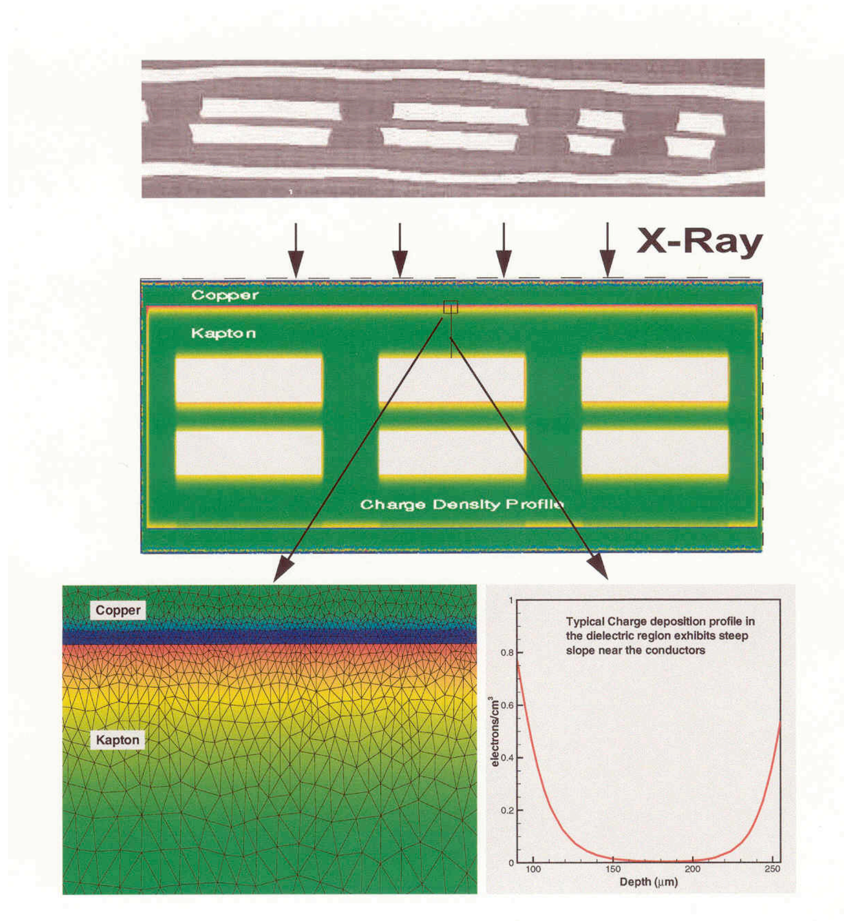
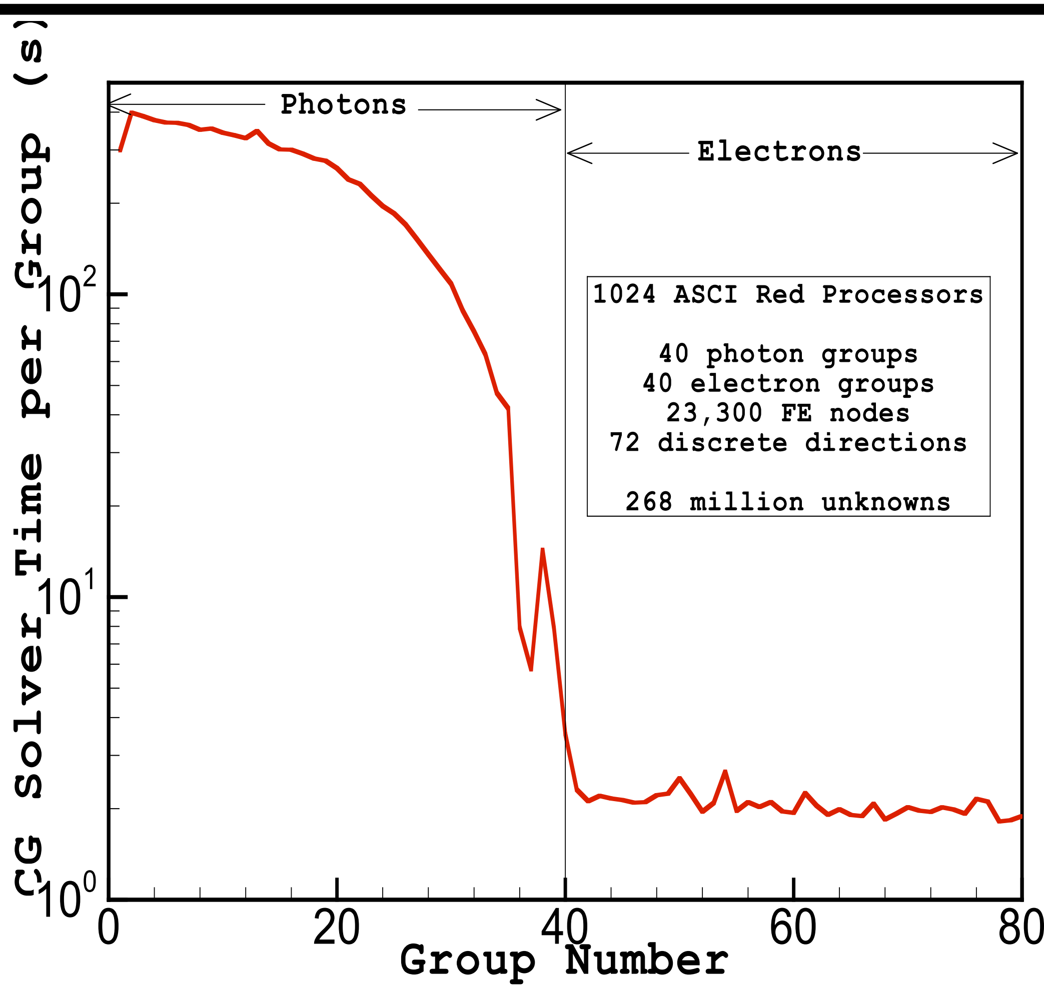
Cable SGEMP Simulation Needs

- Requires accurate resolution of dose-enhancement and charge profiles near conductor/dielectric interfaces
  - Results in extremely small mesh cells near the material interfaces
  - Use of higher-order finite elements
  - Ill-conditioned matrix for photon-transport



CEPTRE Numerical Difficulties



- Small mesh nearly transparent to photons
- Matrix extremely ill conditioned
- Slow CG convergence
- Effective preconditioning essential

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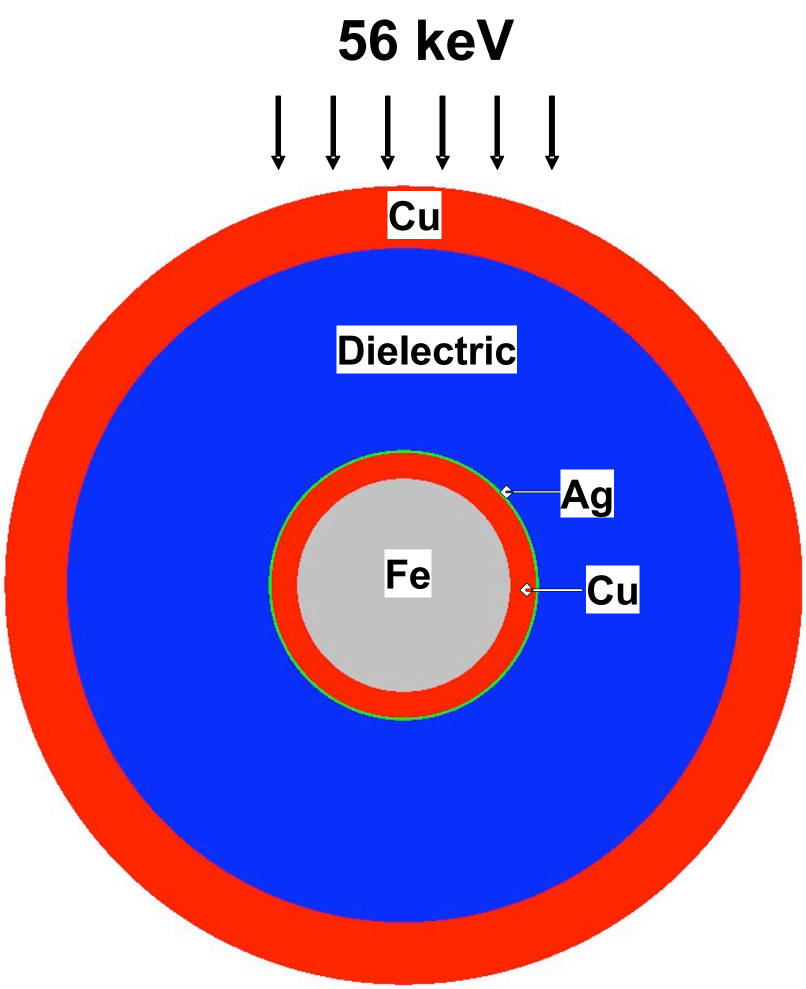
CEPTRE Speed-Up Strategies

- Solve photons on linear FEM and electrons on quadratic FEM (different mean free paths/ranges)
- Lower order quadrature and Legendre expansion of cross-sections for photons (scattering is more isotropic than electrons)
- Employ a block diagonal preconditioner
- Employ 1st order Sn transport for photons
- Will speed-up cost accuracy?
  - In radiation transport (knock-on charge at conductor/dielectric interfaces)
  - In electrical response (final load charge)

Consider the RG402 Coaxial Cable



- Average Energy of the Incident Spectra is 56 keV
- S8 Quadrature
- P5 Legendre Expansion of Scattering Cross-Sections

Material	Outer Radius (cm)
Steel	0.04780
Copper	0.05940
Silver	0.06060
Dielectric	0.15113
Copper	0.17907

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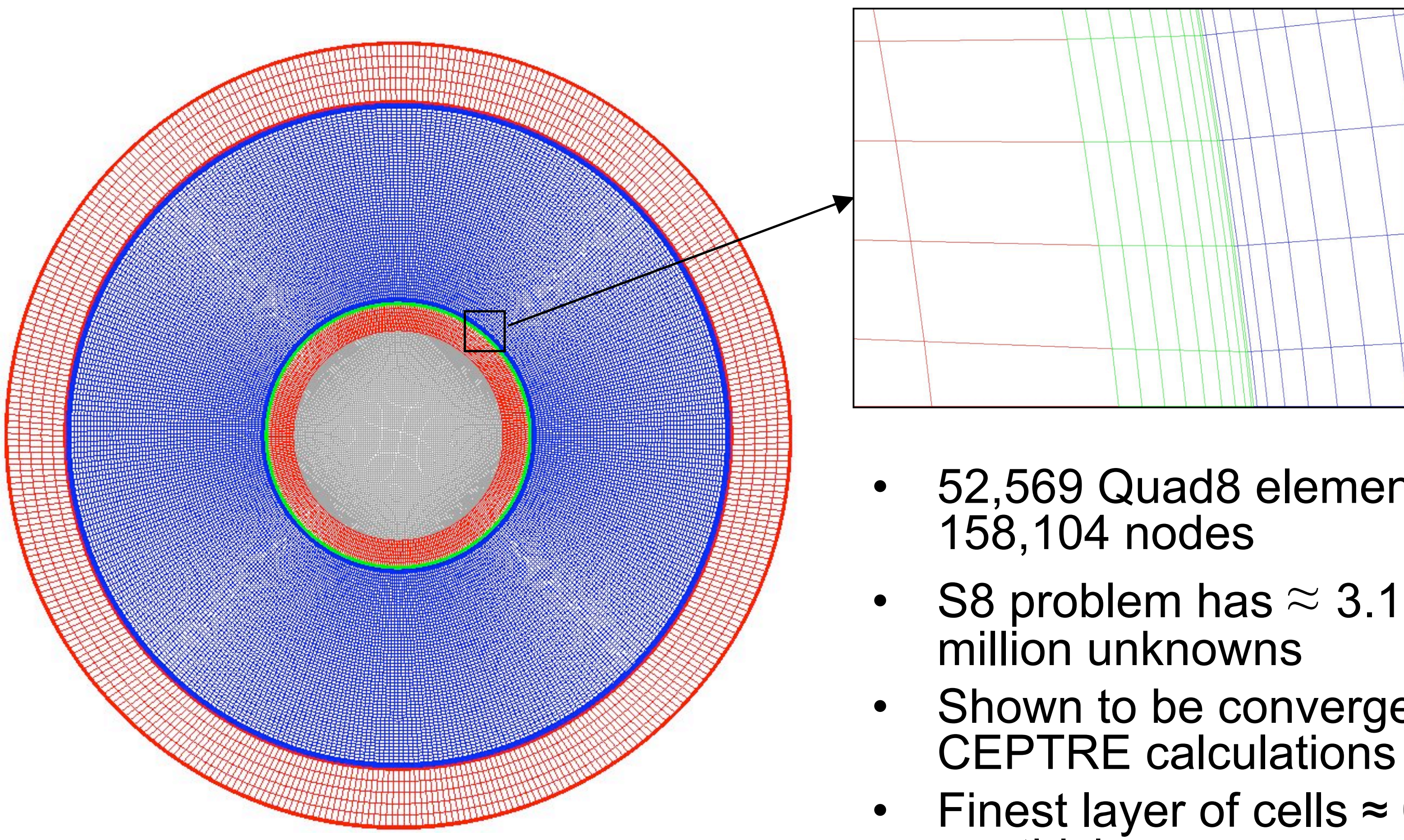
Refined RG402 Mesh



- 52,569 Quad8 elements and 158,104 nodes
- S8 problem has ≈ 3.16 million unknowns
- Shown to be converged for CEPTRE calculations
- Finest layer of cells ≈ 0.18 µm thick

Speed-Up of Photon Solve

- 32 processors on ICC
- Electron Solve Employs S8, P5 Legendre Expansion on quadratic FEM

Photon Sn / PL	Q knock-off (electrons/cm)	SGEMP (nC/cm)	Photon Solver Time (hrs)	Photon Finite Element Mesh Type
S8 / P5	3.39e-04	6.57e-17	65.75	QUADRATIC
S8 / P5	3.47e-04	8.14e-17	5.21	LINEAR
S8 / P3	3.04e-04	8.25e-17	5.33	LINEAR
S4 / P3	3.04e-04	8.07e-17	0.88	LINEAR

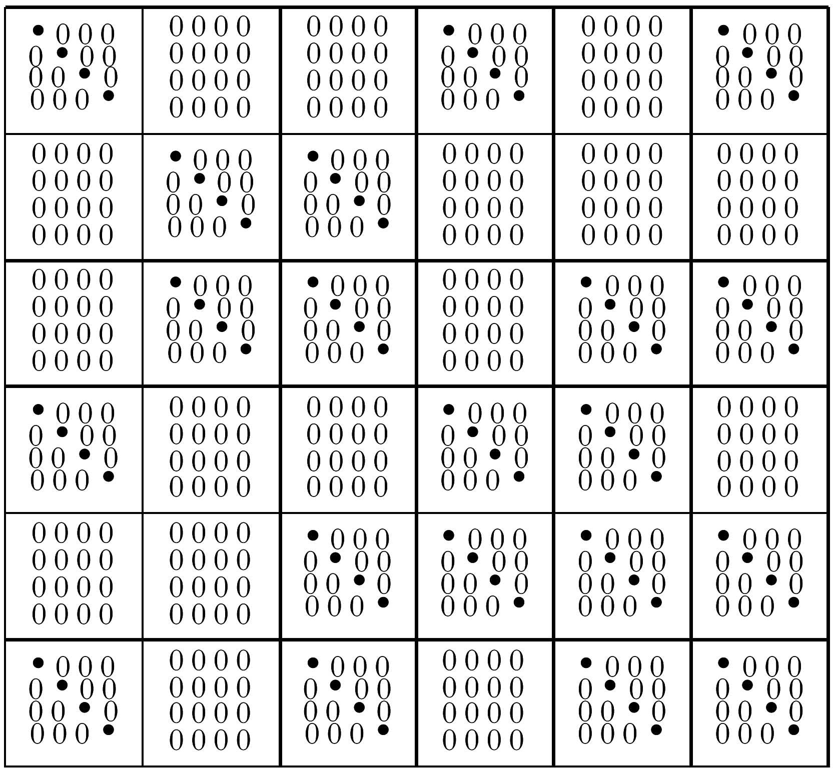
Accuracy and Speed-Up compared with S8, P5 Photon Solve on Quadratic Mesh:

Sn/PL	Ceptre Results	SGEMP Response	Speed-Up
S8/P5	2.3 %	24 %	12.6
S8/P3	10.3 %	26 %	12.3
S4/P3	10.3 %	23 %	74.7

Block Diagonal Preconditioner

Preconditioned linear system $M^{-1}Ax=M^{-1}b$

M=



- Transport equation *without* scattering
- Sparse-block structure
- Number of block rows:
  - N_{nodes}
- Block size:
  - $N_{directions} x N_{directions}$
  - Diagonal blocks
- Directions decoupled
- Symmetric
- Much easier to solve than original transport equation

Block Diagonal Preconditioner Speed-Up

- Outside of Nevada framework and using a special modified version of Aztec the block diagonal preconditioner has shown speed-ups on the RG402:
  - S8 speed-up of 4.3 observed
  - S16 speed-up of 8.0 observed
  - 80 ASCI-Red Processors
- We are in the process of implementing this preconditioner in the Nevada Framework version of Ceptre which uses Trilinos and AztecOO
- Using the preconditioner should not affect a cable's electrical response

First Order Sn Transport for Photons

- First order Sn transport of photons is efficient
  - Parallel multidimensional implementation is complex due to introduction of cycles in “sweeps”
  - Development is underway to implement this using new techniques to handle these parallel sweeps
- Allow solution of photons on same FE mesh as electrons
- Coupled with second order Sn transport of electrons

Summary

- Cable SGEMP analysis requires very accurate resolution of dose-enhancement and charge at material interfaces
- Refined mesh necessary to meet this criterion makes the photon transport with the 2^{nd} order form very expensive
- Speed-up can be obtained with minimal effect on radiation transport results
- Electrical response of a cable is very sensitive in radiation transport results
  - Change of 2.3% in radiation transport yields change of 30% in cable response
- Future work is very promising for reducing CEPTRE run-times