Northern Illinois University

Electron Cooling for an Electron Ion Collider: Computational Methods and Code Development

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DOE-NP Accelerator R&D PI Meeting

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Main Goals

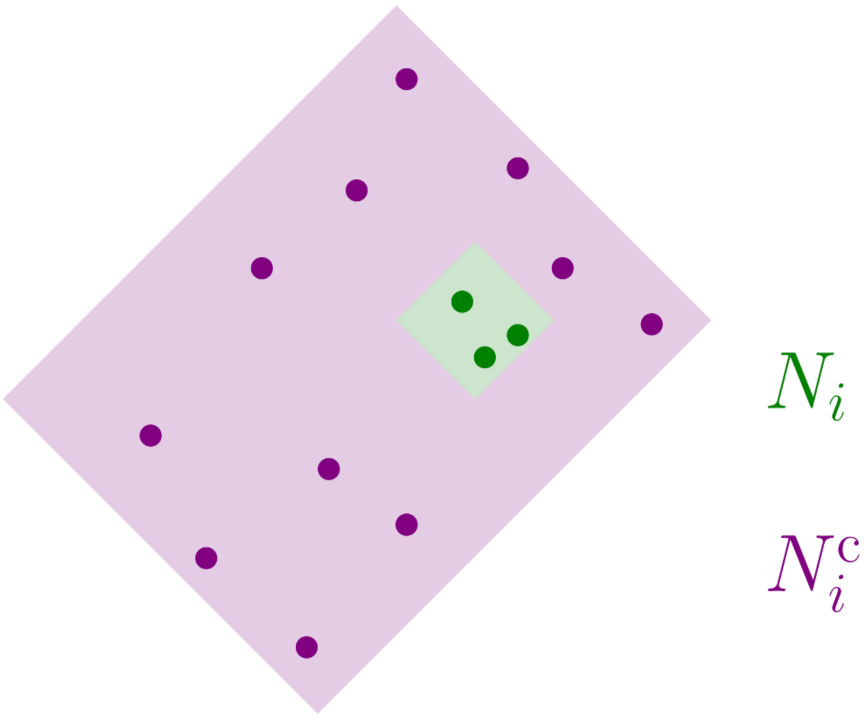
- Proof of principle **demonstration of electron cooling** with the **first particle-level detailed** simulations (Jones Report:: line 3: High, A)
- **Develop a high-performance code** with these capabilities, and other beam dynamics challenges beyond cooling (Jones Report:: line 4: High, A)
- **Applications** to electron-ion collider (JLEIC) modeling, design, and optimization (Jones Report:: line 39: High)

Expenditures and Milestones

	FY10+FY11	FY12+FY13	FY14+FY15	FY16+FY17	TOTALS
Funds Allocated	0+56	55+52=107	50+54=104	50+50=100	$367K
Actual Costs to Date	56	107	104	100	$367K

	FY17	FY18
Quarter 1	Shared memory parallelization of FMM data structures and integration with parallel FMM	Identification of speed and parallel efficiency bottlenecks in the current version of PHAD
Quarter 2	Variable order Picard integrator with automatic step size control parallelization	Amelioration of speed and efficiency bottlenecks in PHAD
Quarter 3	Binned time step implementation in parallel	DC electron cooling initial rate estimations for different ion species (charge states) at low energy
Quarter 4	Parallel PHAD integration, benchmarking and optimizations	Low energy electron cooling initial rate estimations for different initial distributions and external fields

PHAD Overview



- Accurate at expense of speed.
- No approximations (exact treatment).
- Algorithms employed are the most efficient available.

Main Outcomes

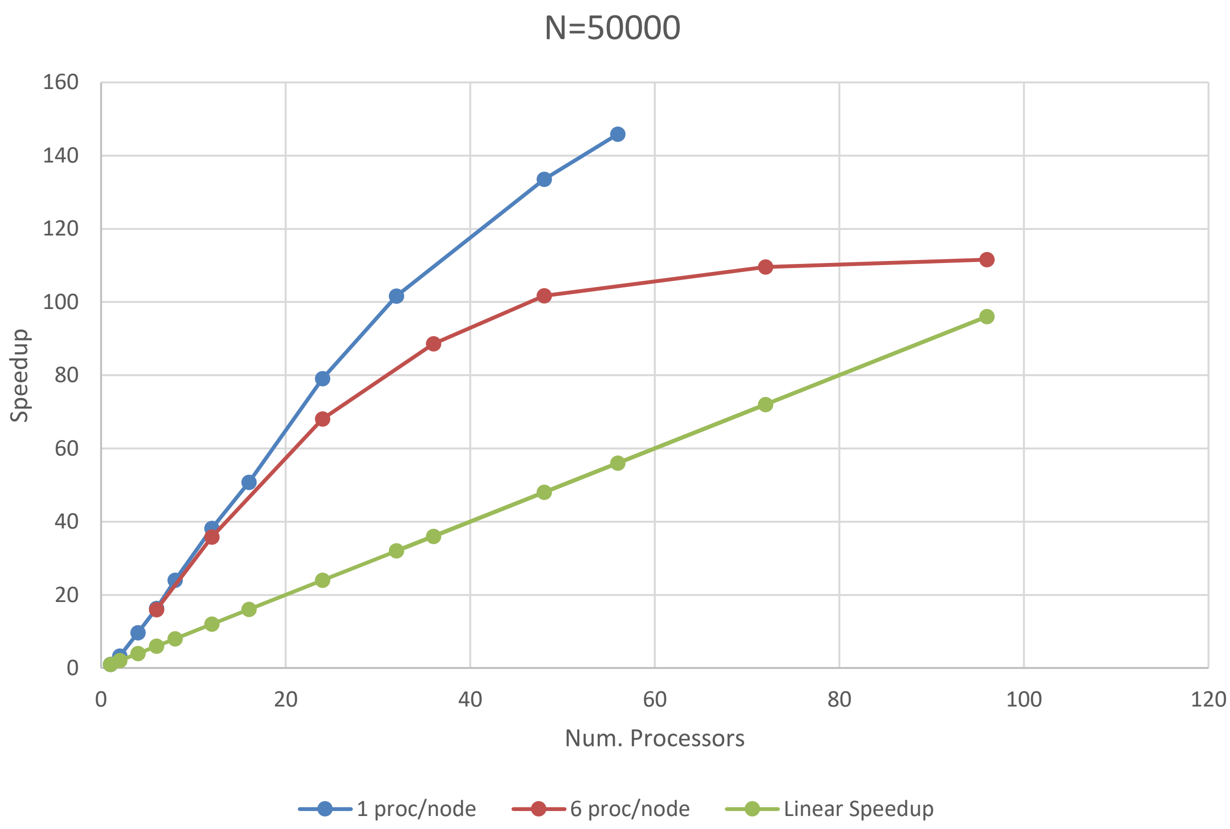
Stability & Performance

- Improved FMM.
- Improved local solver (Simo integrator).
- Memory improvements.
- Avoidance of digit cancelation.

User friendliness

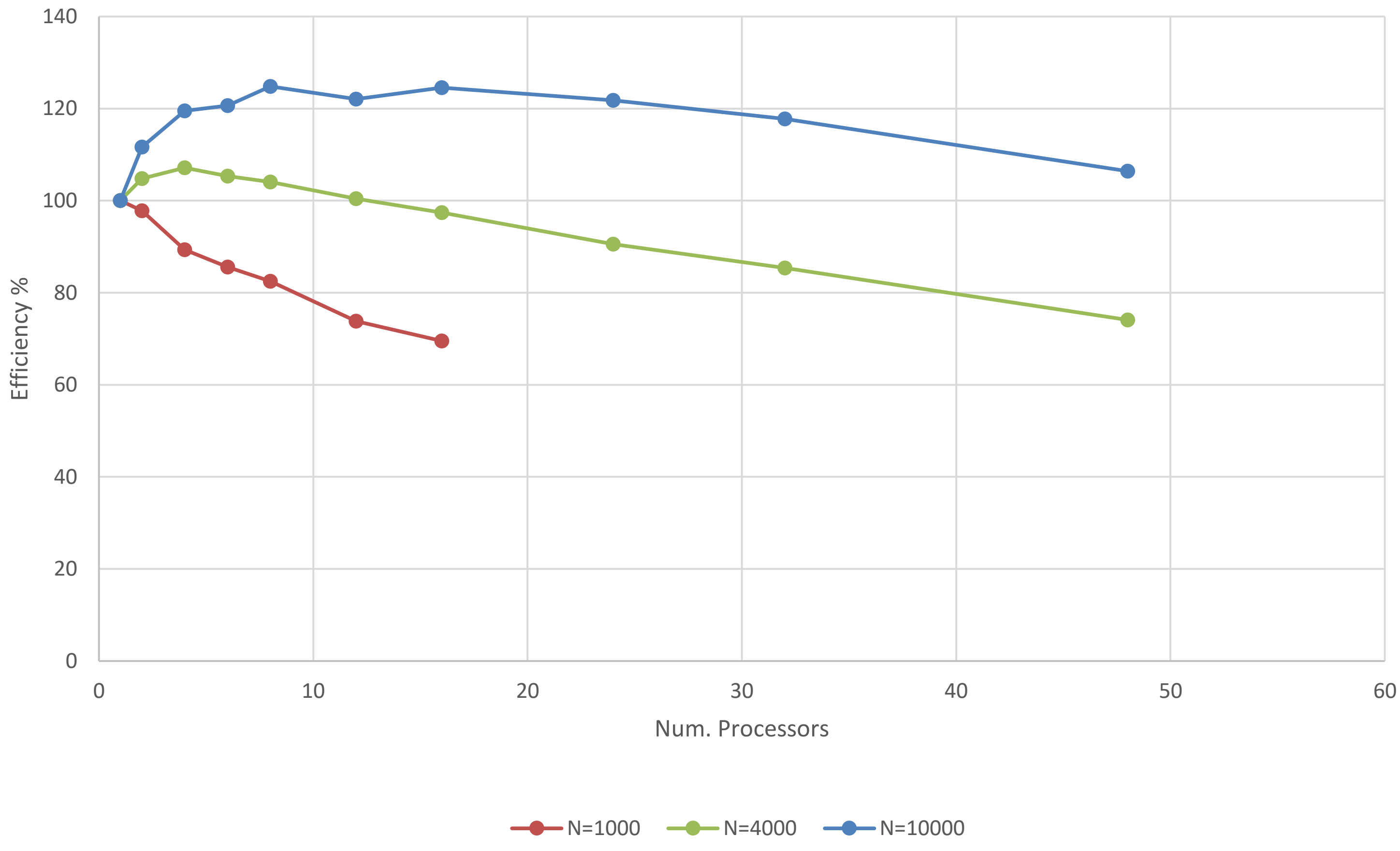
- Parameter tracking.
- Additional timers.
- Error messages.
- Relaunch capability.
- New example.

Parallel Simo Integrator



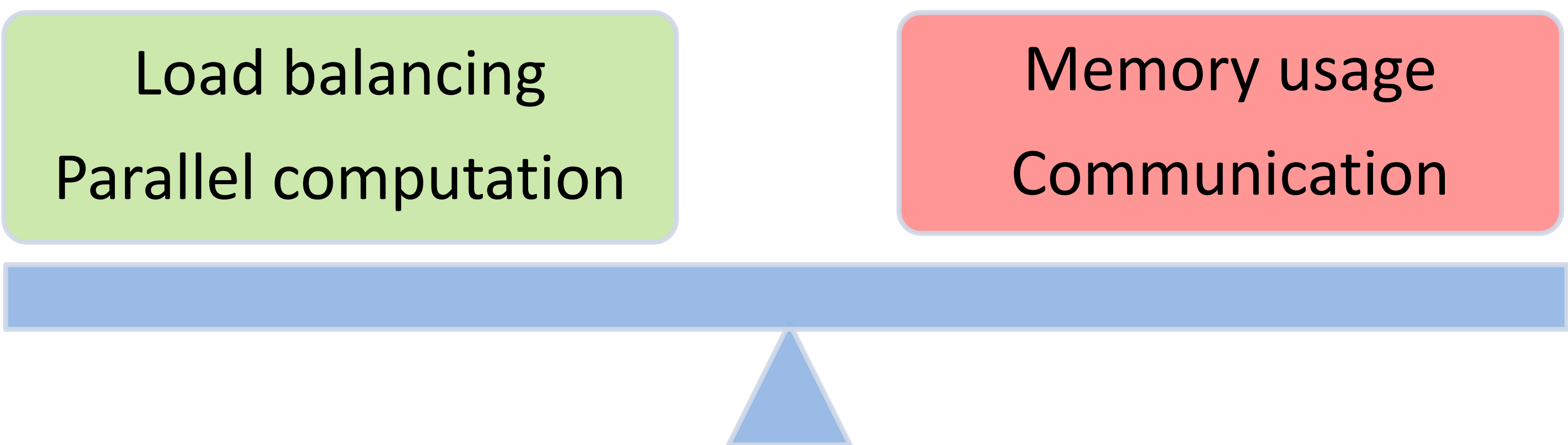
Superlinear speedup

Efficiency of weak scaling



Identifying Bottlenecks

- Implemented several different parallelization strategies.
- Strategies have competing benefits and costs.



PHAD Parallelization Strategies

$$N_1 \left\{ \begin{array}{c} \text{Process } 1 \\ \text{Process } 2 \\ \vdots \\ \text{Process } p \end{array} \right. \quad N_2 \left\{ \begin{array}{c} \text{Process } 1 \\ \text{Process } 2 \\ \vdots \\ \text{Process } p \end{array} \right. \quad \cdots \quad N_k \left\{ \begin{array}{c} \text{Process } 1 \\ \text{Process } 2 \\ \vdots \\ \text{Process } p \end{array} \right.$$

$$\left\{ \begin{array}{ccccccc} N_1 & N_{p+1} & N_{2p+1} & \cdots & & \text{Process } 1 \\ N_2 & N_{p+2} & N_{2p+2} & \cdots & \vdots & \text{Process } 2 \\ \vdots & \vdots & \vdots & & N_k & \vdots \\ N_p & N_{2p} & N_{3p} & \cdots & & \text{Process } p \end{array} \right.$$

$$\left\{ \begin{array}{ccccccc} N_{\sigma(1)} & N_{\sigma(p+1)} & N_{\sigma(2p+1)} & \cdots & & \text{Process } 1 \\ N_{\sigma(2)} & N_{\sigma(p+2)} & N_{\sigma(2p+2)} & \cdots & \vdots & \text{Process } 2 \\ \vdots & \vdots & \vdots & & N_{\sigma(k)} & \vdots \\ N_{\sigma(p)} & N_{\sigma(2p)} & N_{\sigma(3p)} & \cdots & & \text{Process } p \end{array} \right.$$

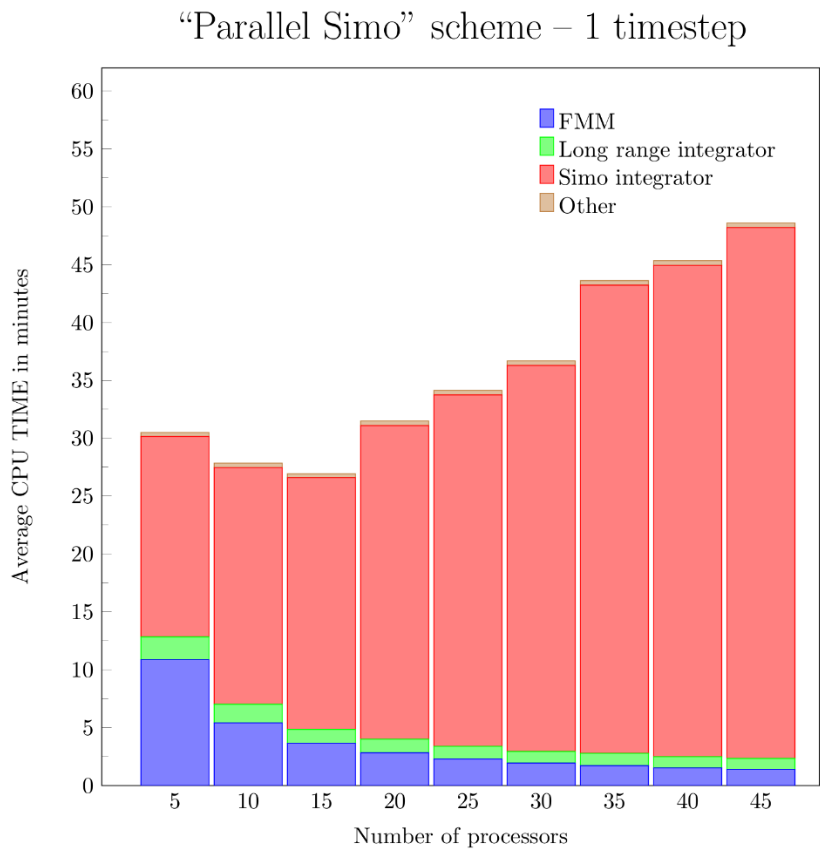
Balanced strategy

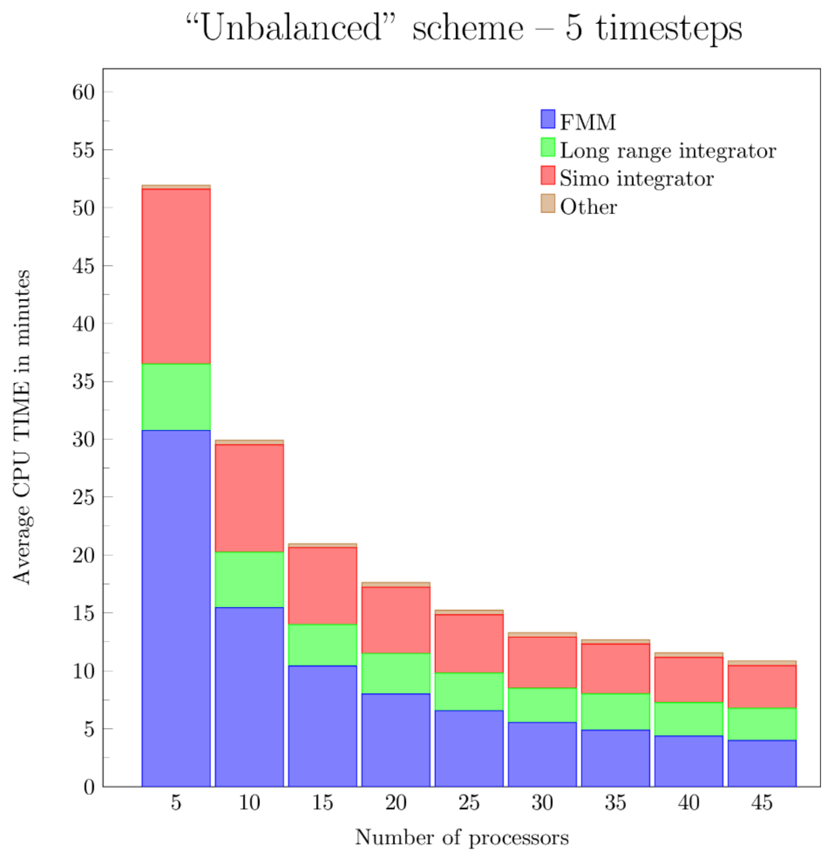
$$\left\{\begin{array}{ccccc} N_{\sigma(1)} & N_{\sigma(p+1)} & N_{\sigma(2p+1)} & \cdots & \text{Process } 1 \\ N_{\sigma(2)} & N_{\sigma(p+2)} & N_{\sigma(2p+2)} & \cdots & \text{Process } 2 \\ \vdots & \vdots & \vdots & & \vdots \\ N_{\sigma(p)} & N_{\sigma(2p)} & N_{\sigma(3p)} & \cdots & \text{Process } p \end{array}\right.$$

$$\begin{bmatrix} |N_1| & 1 \\ |N_2| & 2 \\ \vdots & \vdots \\ |N_k| & k \end{bmatrix} \xrightarrow{\text{indexed quicksort}} \begin{bmatrix} |N_{\sigma(1)}| & \sigma(1) \\ |N_{\sigma(2)}| & \sigma(2) \\ \vdots & \vdots \\ |N_{\sigma(k)}| & \sigma(k) \end{bmatrix}$$

$$|N_{\sigma(1)}| \leq |N_{\sigma(2)}| \leq \cdots \leq |N_{\sigma(k)}|$$

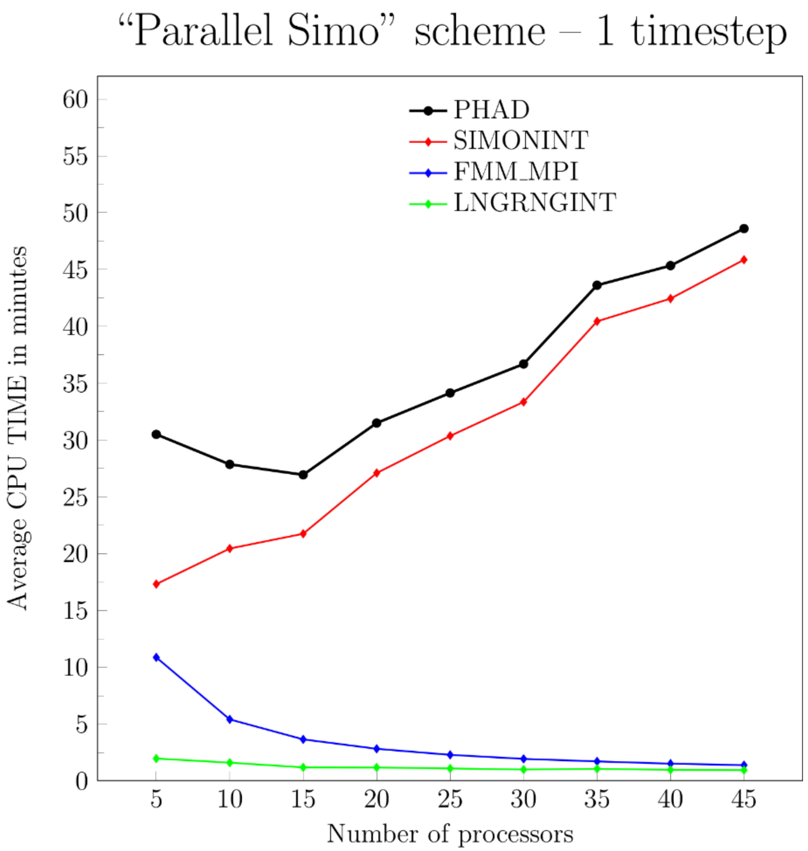
Parallel Simo Vs. Unbalanced

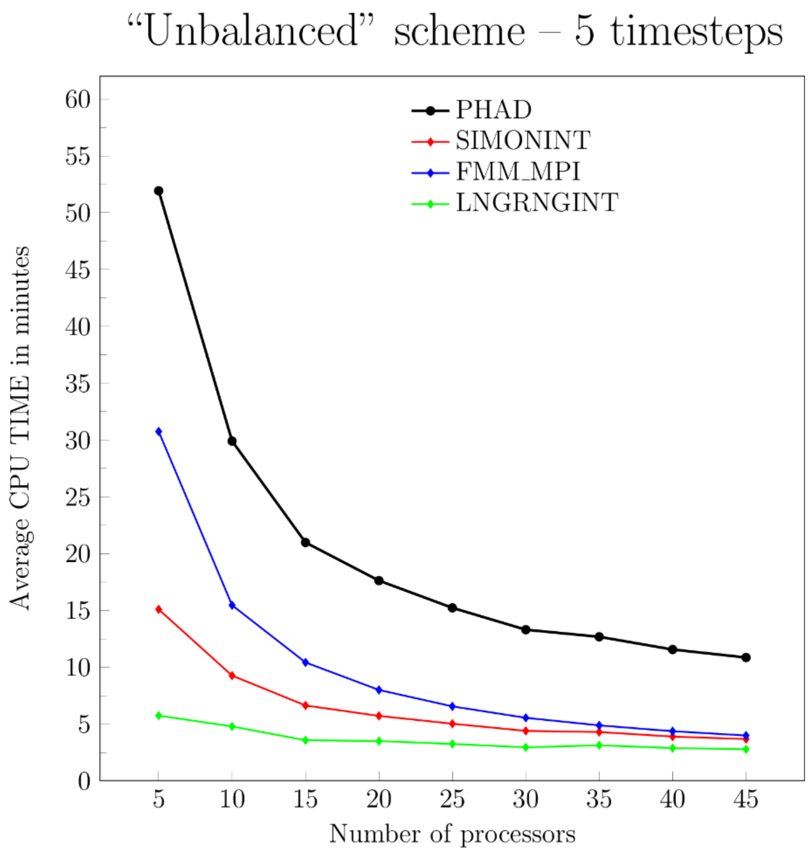




49.9K Particles, FMM order 6, q=60

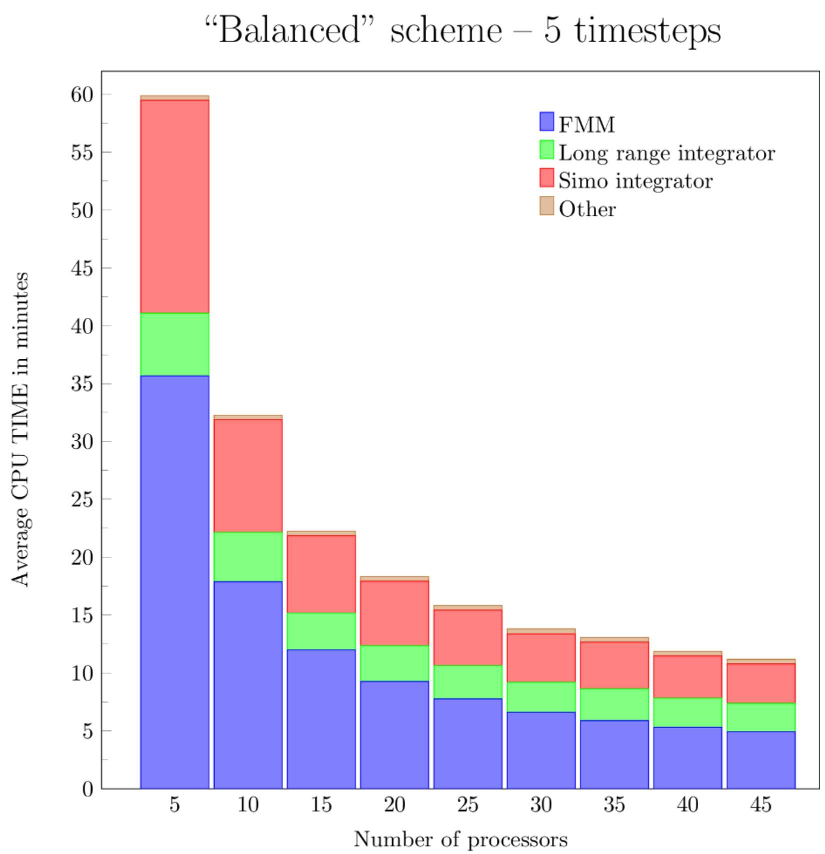
Subprocedure Breakdown

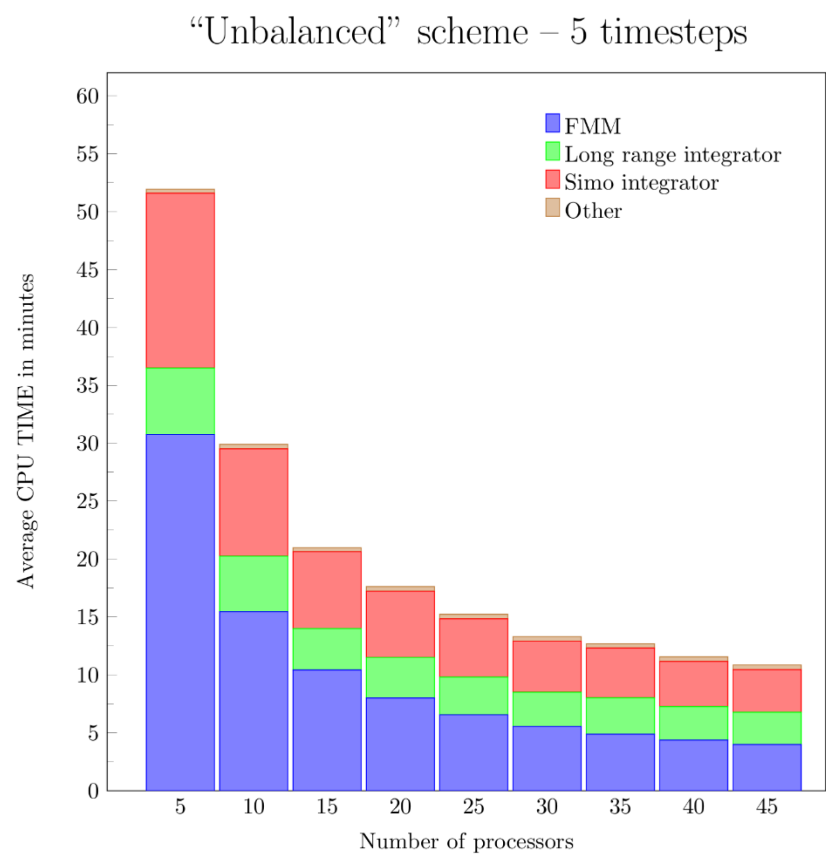




49.9K Particles, FMM order 6, q=60

Balanced Vs. Unbalanced





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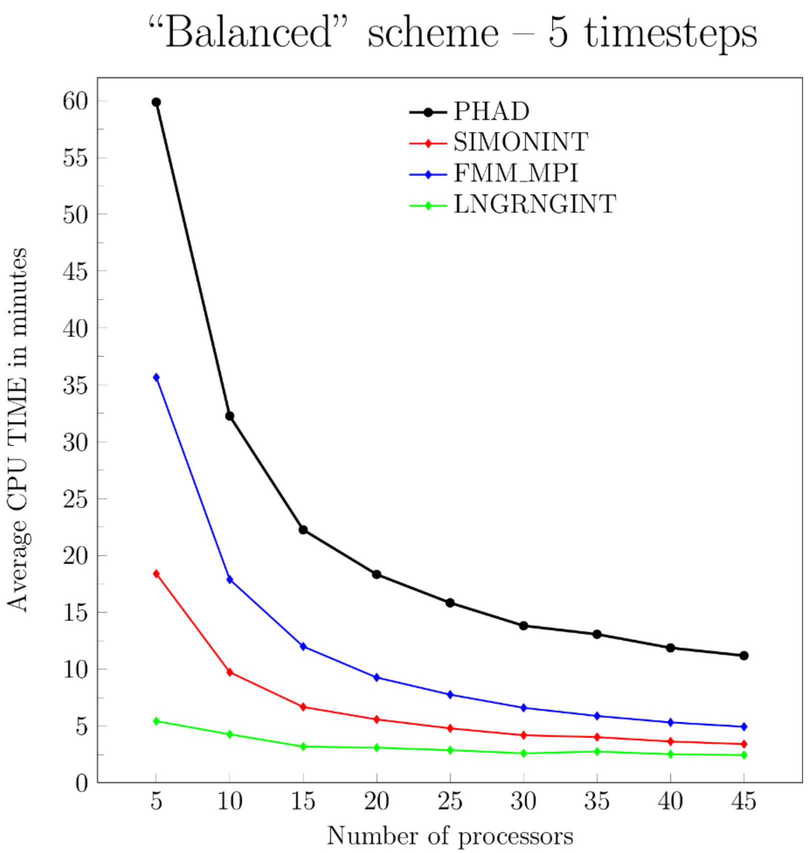
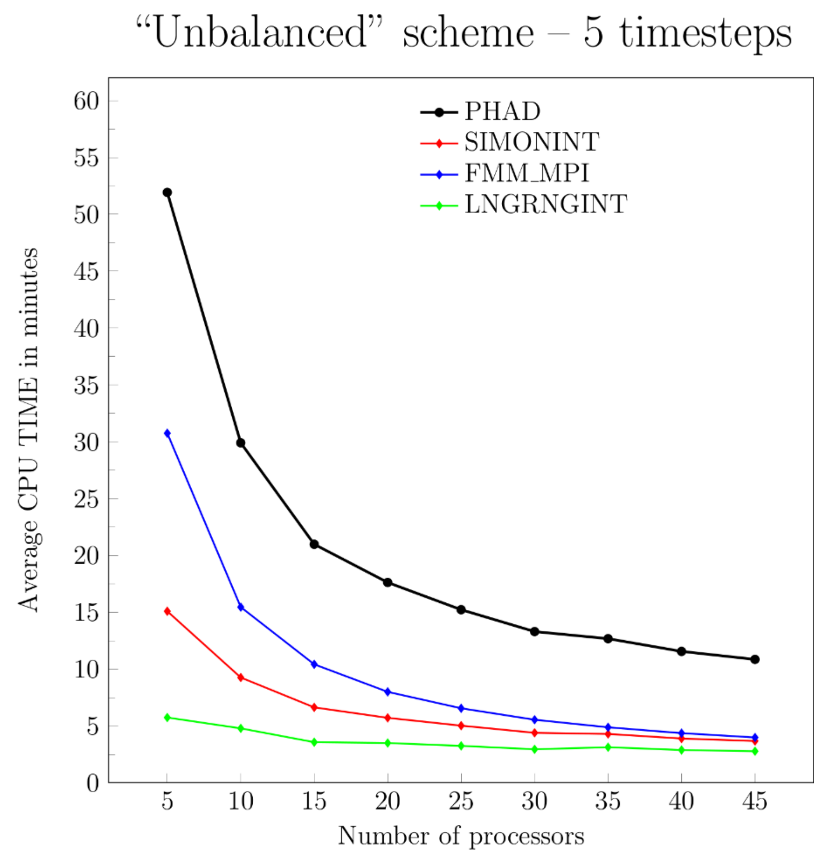
Subprocedure Breakdown





49.9K Particles, FMM order 6, q=60

Stability & Performance Improvements

- Simo integrator ensures large timesteps leading to nonphysical results are not taken.
- Relativistic gamma computed to avoid digit cancelation.
- Modification allows smaller Simo order for small PHAD timesteps.
- Several memory improvements.

Memory improvements

- FMM memory requirements do not scale with the number of processors.
- Memory for Taylor series in Simo integrator depends on q parameter instead of N.
- Memory improvement in indices storage.

Index Memory Improvements

$$
\begin{array}{c}
\text{number} \\ \text{of} \\ \text{neighborhoods}
\end{array}
\left\{
\begin{array}{cccccc}
\multicolumn{6}{c}{\overbrace{\hspace{20em}}^{q}} \\
n_{11} & n_{12} & \cdots & n_{1|N_1|} & \times & \times \\
n_{21} & n_{22} & \cdots & n_{2|N_2|} & \times & \times \\
 & & \vdots & & &
\end{array}
\right.
\quad \text{2D}
$$

$$
n_{11}\ n_{12}\ \cdots\ n_{1|N_1|}\ n_{21}\ n_{22}\ \cdots\ n_{2|N_2|}\ n_{31} \cdots \quad \text{1D}
$$

Bonuses: Communication efficiency.
Larger N with same RAM.

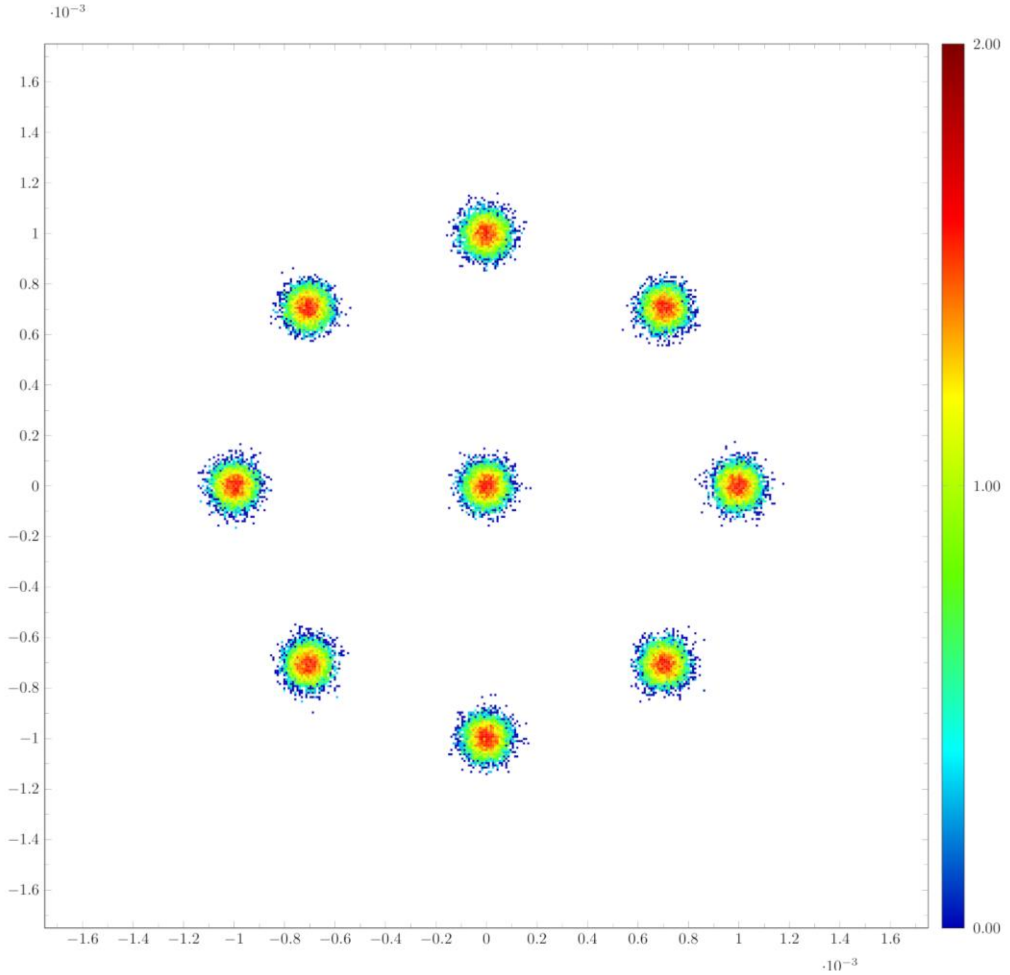
User friendliness

- Parameter tracking - Simo integrator largest order and minimum timestep used.
- Separate timers for read/write and some communications.
- Descriptive error messages.
- Relaunch capability.
- Website improvement (in progress).
- New example – beamlets.

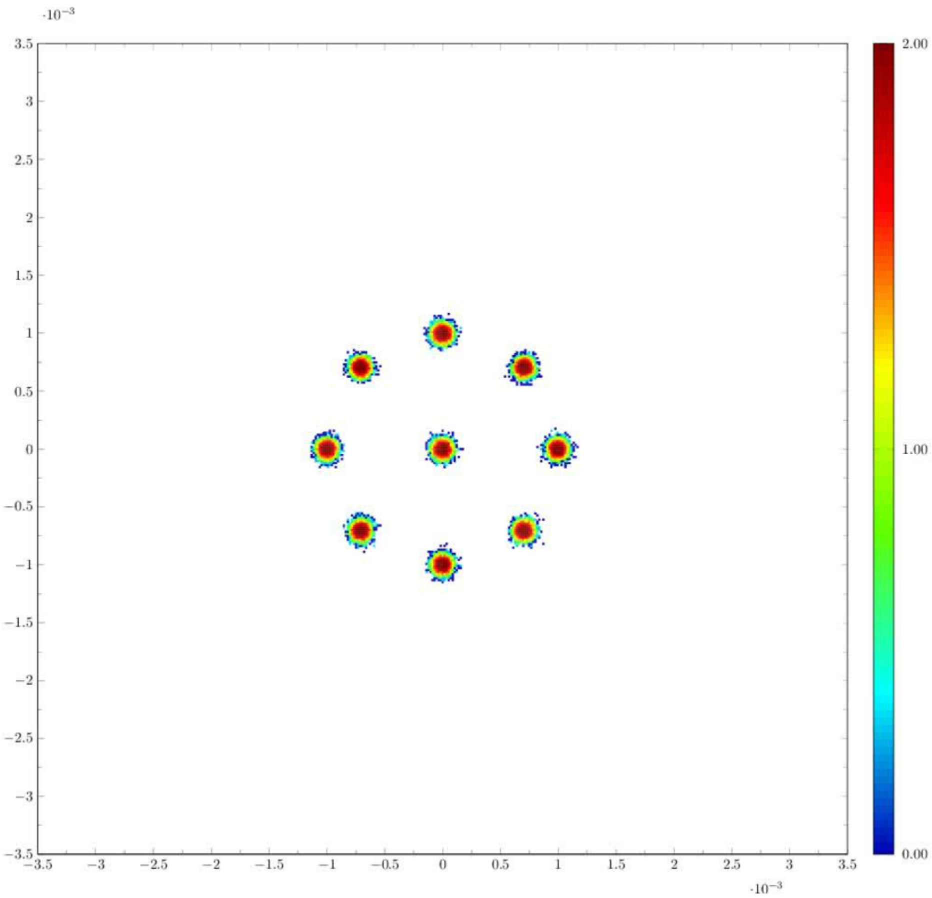
Beamlets example script

- Generates all PHAD input files.
- Positions generated using 2D Gaussian and uniform beam size.
- Momentum generated from Maxwell-Boltzmann distribution.
- Detailed documentation.

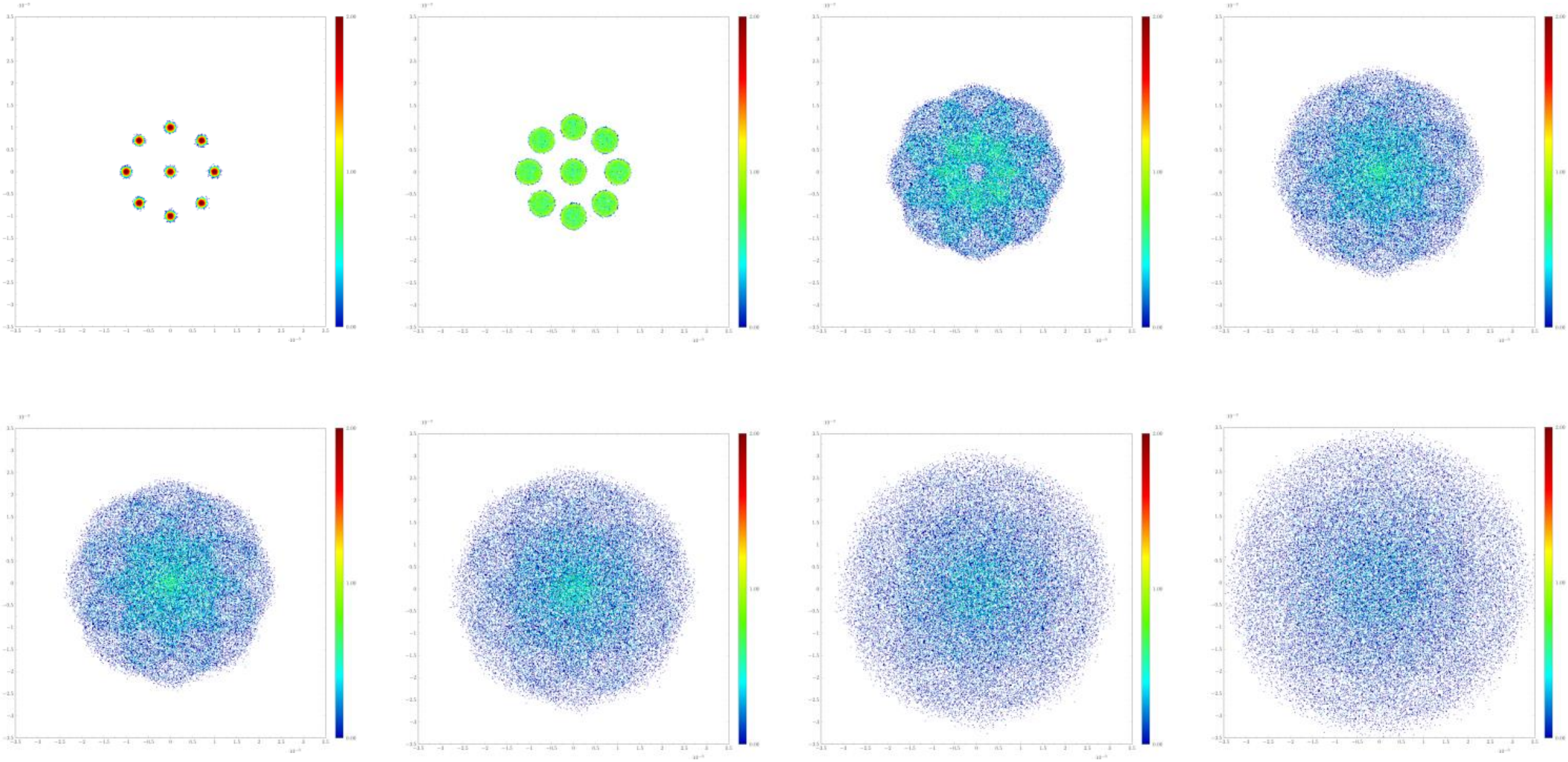
Beamlet Setup



Beamlet Simulation



Snapshots



Summary and Conclusions

- PHAD is stable.
- Improvements to the FMM have improved its performance.
- Among the three tried strategies for parallelizing PHAD, the unbalanced strategy seems to be the best.
- Overall memory requirements have been significantly reduced.
- Several user friendly capabilities have been added (Relaunch, error messages, additional timers, parameter tracking)
- Further electron cooling simulations have begun.
- Use our code; we are here to help.

https://niu.edu/beamphysicscode/