Development for End-to-End Modeling of Accelerators

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Why end-to-end modeling of accelerator?

- Provides a virtual machine prototype
  - direct diagnostic of machine design
  - training application software
- Provides global machine design parameter optimization
- On-line beam dynamics tuning/optimization

What are needed for end-to-end modeling

- Necessary beam physics models
  - beam generation
  - beam acceleration and transport
  - …
- Efficient computational methods
  - particle pusher
  - field solver
  - …
- Advanced computer hardware and software
  - multi-processor computer

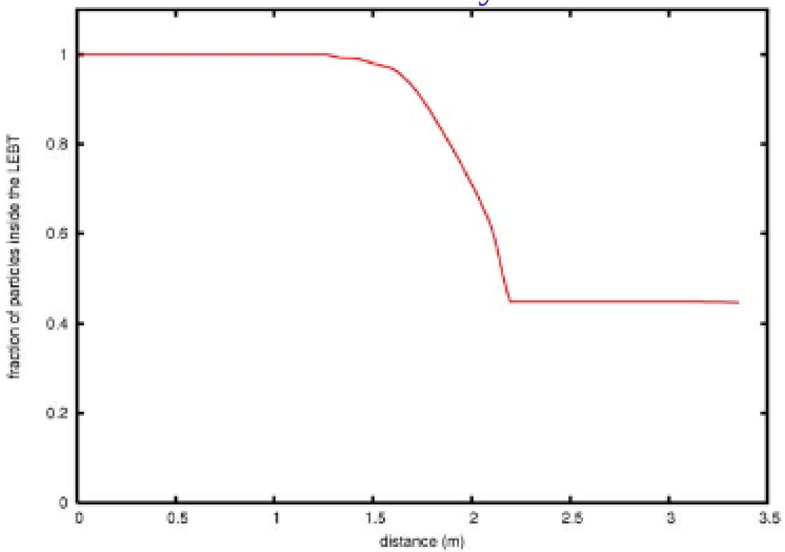
Some Beam Physics Models

- Ion beam formation model
- RF linac beam dynamics model
- Ring beam dynamics model
- Beam beam model for colliders

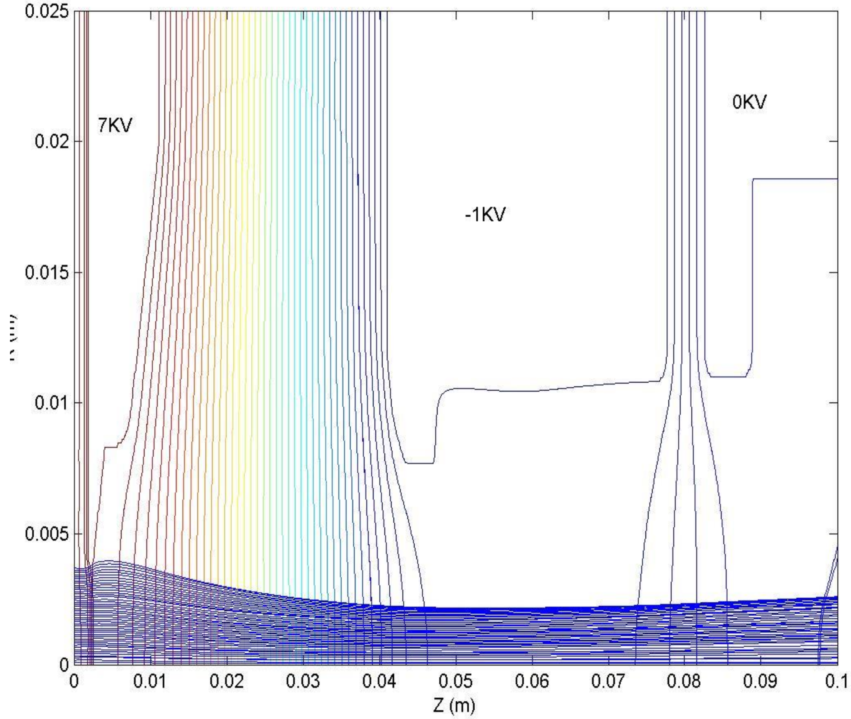
Simulation of Ion Beam Formation

- Model of electrode shape and voltage
- Model of external focusing magnets:
  - Dipole, quadrupole, solenoid, …
- Fully 3D space-charge model with complex geometry
- Plasma sheath model
- Multi-charge state
- …

Fraction of Ion beam as a Function of the VENUS LEBT System Distance



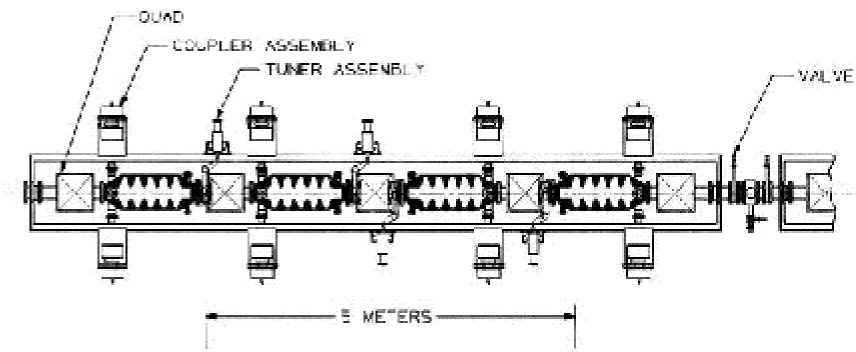
Ion Trajectories and Equal Potential Lines in a Simulation of Ion Beam Formation from VENUS Ion Source



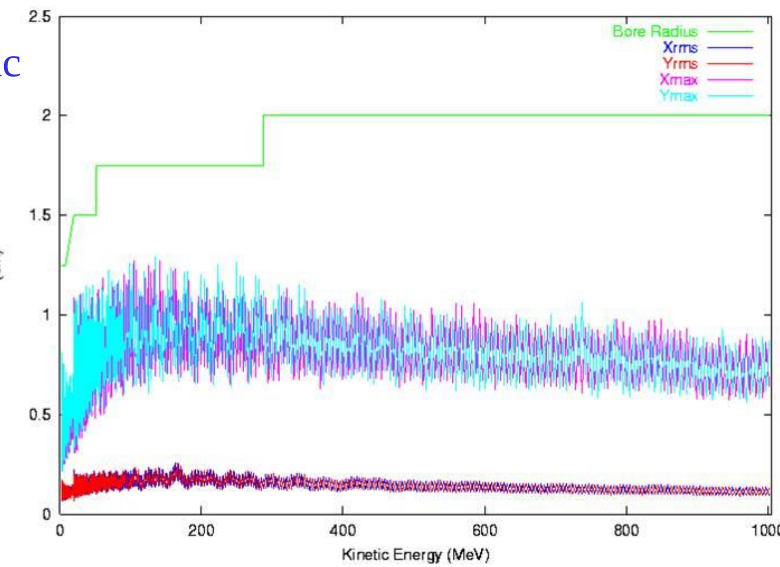
J. Qiang, D. Todd, D. Leitner, Comput. Phys. Comm. 175. p. 416 (2006).

Linac Beam Dynamics Model

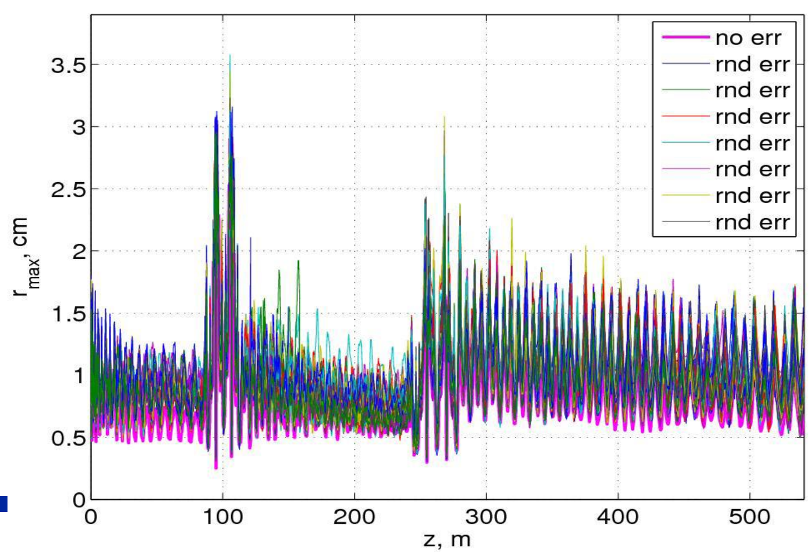
- Model of RF cavity
  - Transfer map
  - Direct integration
- Model of external focusing magnets:
  - Dipole, quadrupole, solenoid, …
- Space charge model
- Longitudinal and transverse wakefields
- Coherent Synchrotron radiation (CSR)/ISR
- Multi-charge state
- Stripper
- …



Transverse RMS Sizes and Maximum Amplitude Evolution in an SNS Linac

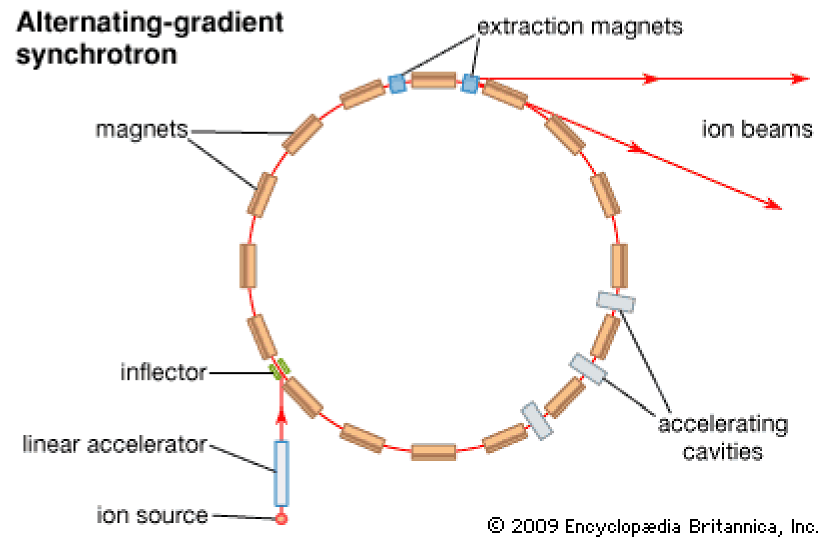


Maximum Radius Evolution with 100 Random Machine Errors in a RIA Linac

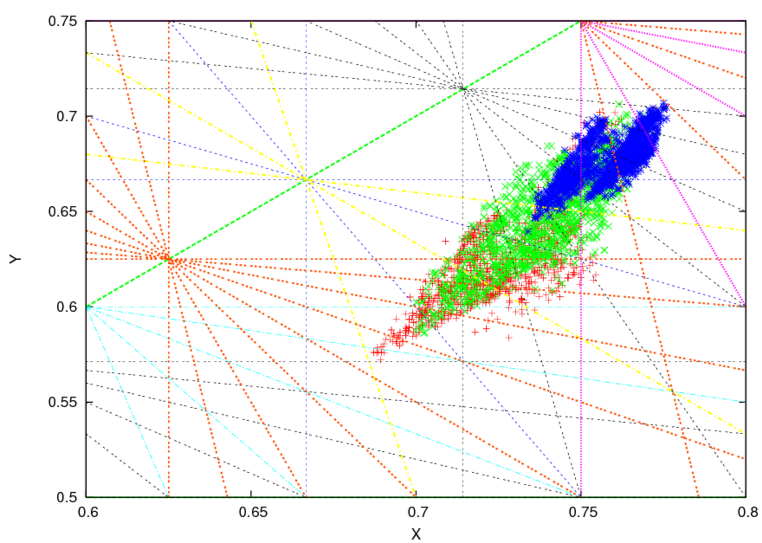


Ring Accelerator Beam Dynamics Model

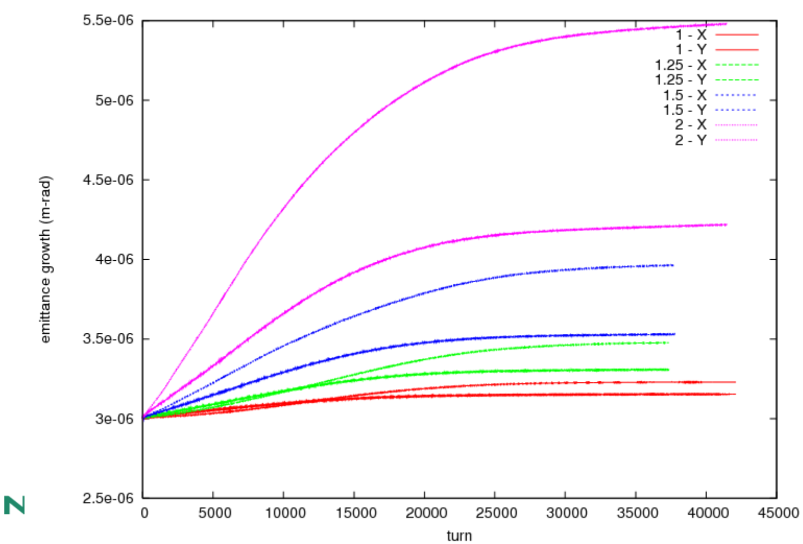
- Injection painting
- Accelerating cavity model
- External focusing magnets:
  - Dipole, quadrupole, sextupole, …
- Space charge model
- Longitudinal and transverse wakefields
- Coherent Synchrotron radiation (CSR)/ISR
- Electron cloud model
- Multi-turn
- …



Tune Footprint
4 GeV, 6 GeV and 8 GeV Energy

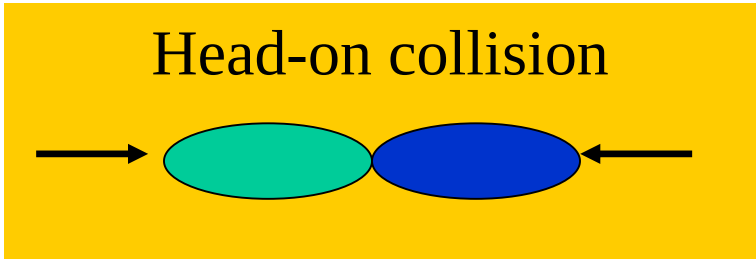


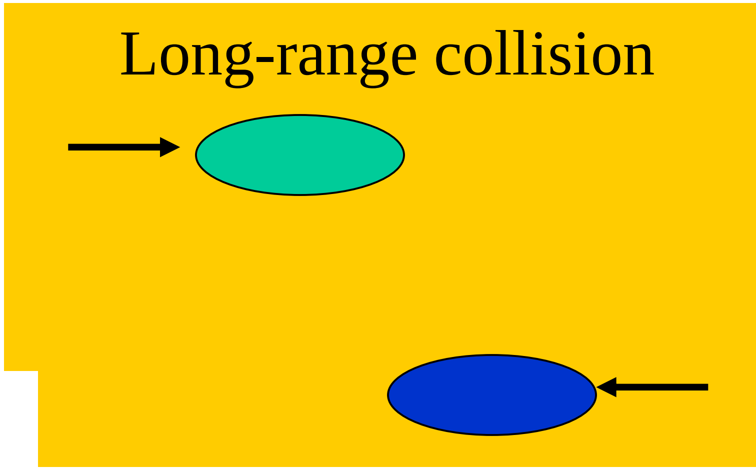
Transverse Emittance Evolution
with Different Proton Intensity

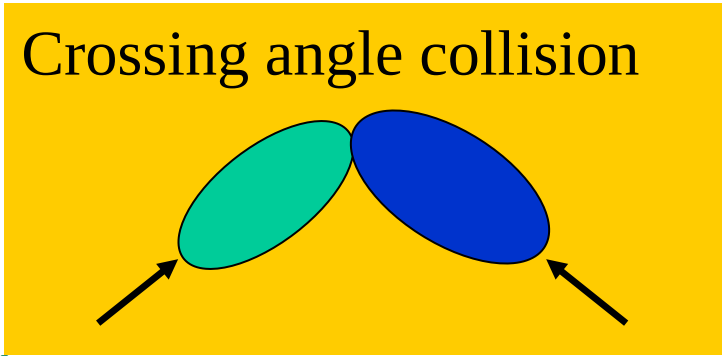


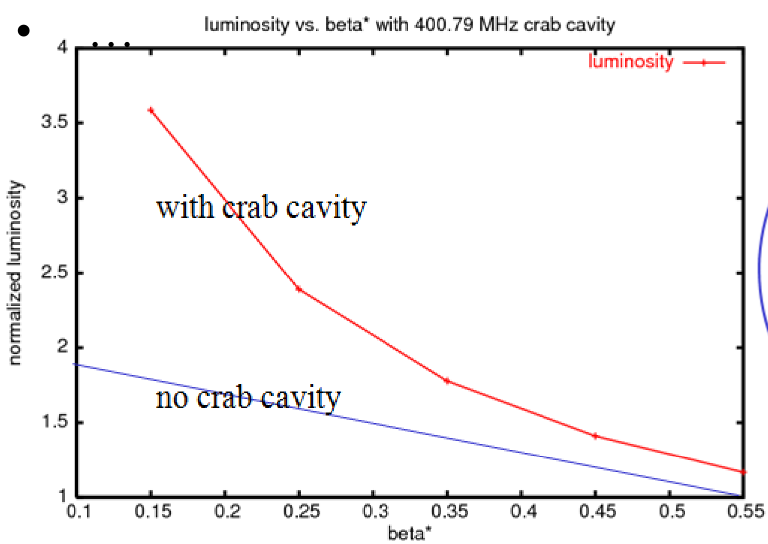
Beam Beam Model for Colliders

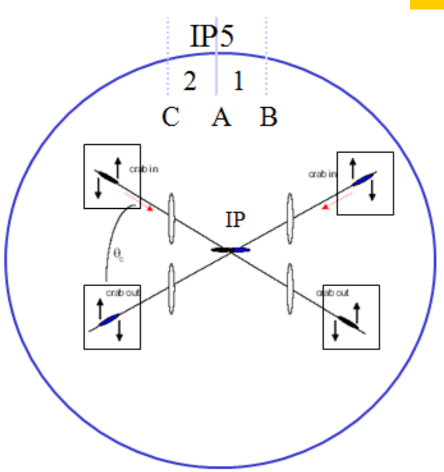
- Different collision geometries
- Multiple-slice for finite bunch length effect
- Multiple bunches
- Multiple collision points
- Wakefield
- Feed back model
- Different compensation schemes:
  - Conducting wire
  - Electron lens
  - Crab cavity
- …







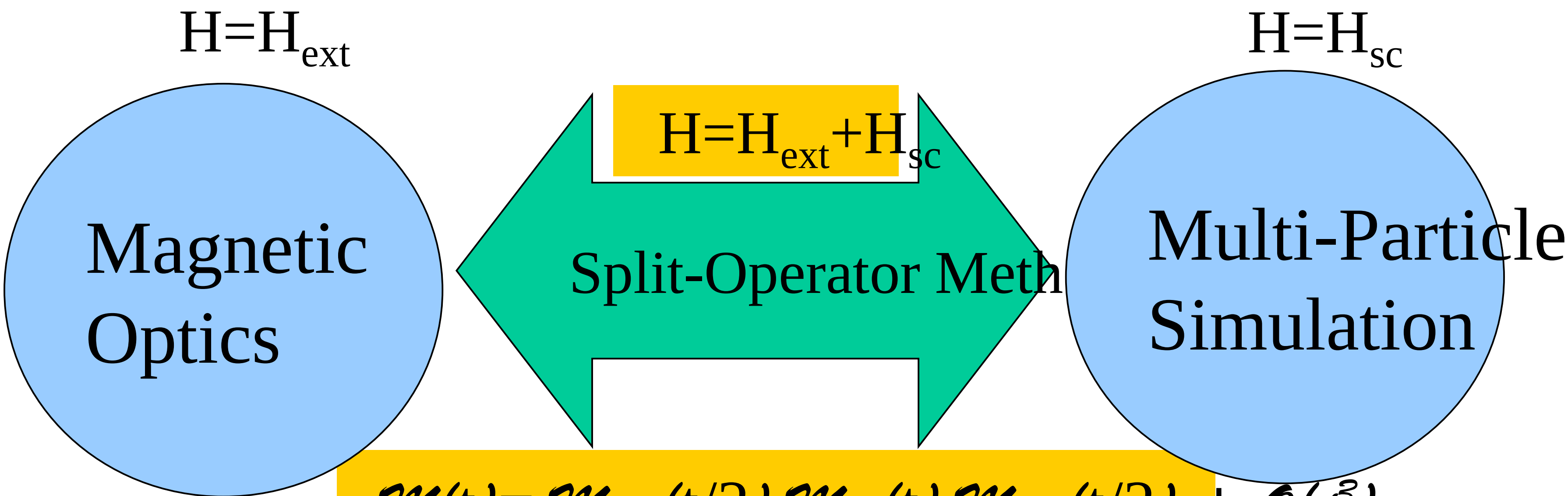




Efficient Numerical Methods

- Split-Operator method
- Efficient Space-Charge Solvers

Split-Operator Method



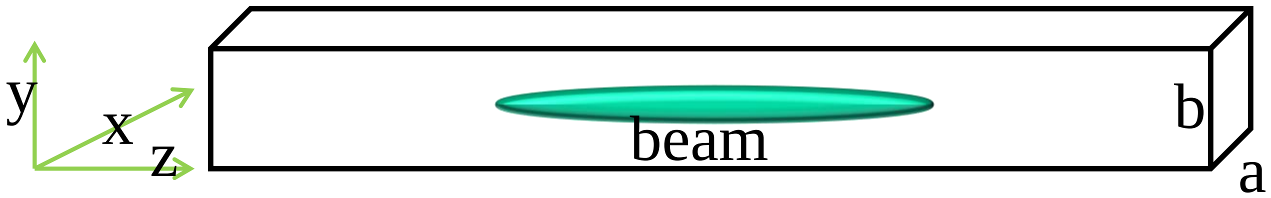
$$\mathcal{M}(t)=\mathcal{M}_{ext}(t/2)\,\mathcal{M}_{sc}(t)\,\mathcal{M}_{ext}(t/2)+\mathcal{O}(t^3)$$

$\mathcal{M}=\mathcal{M}_{ext}$ $\qquad$ $\mathcal{M}=\mathcal{M}_{sc}$

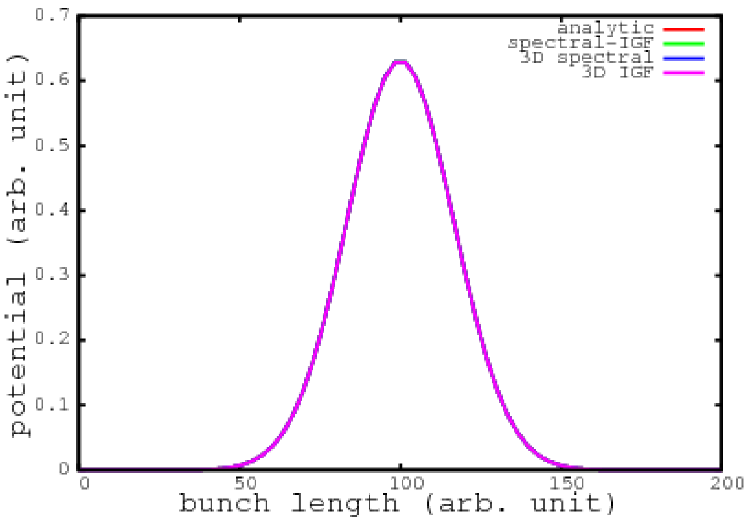
(arbitrary order possible via Yoshida)

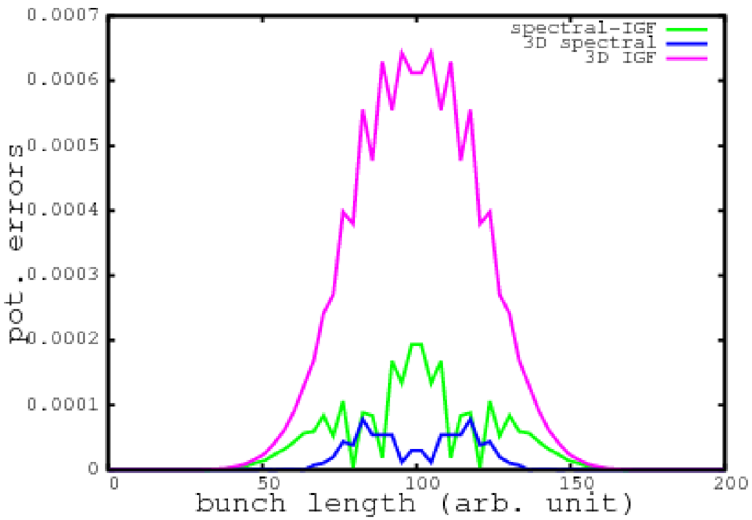
- Rapidly varying s-dependence of external fields is decoupled from slowly varying space charge fields
- Leads to very efficient particle advance:
  - Do not take tiny steps to push millions - billions of particles
  - Do take tiny steps to compute maps; then push particles w/ maps

Efficient Space-Charge Solvers (Nlog(N))



- FFT based integrated Green's function method
- Spectral-Integrated Green's function method
- 3D Spectral method





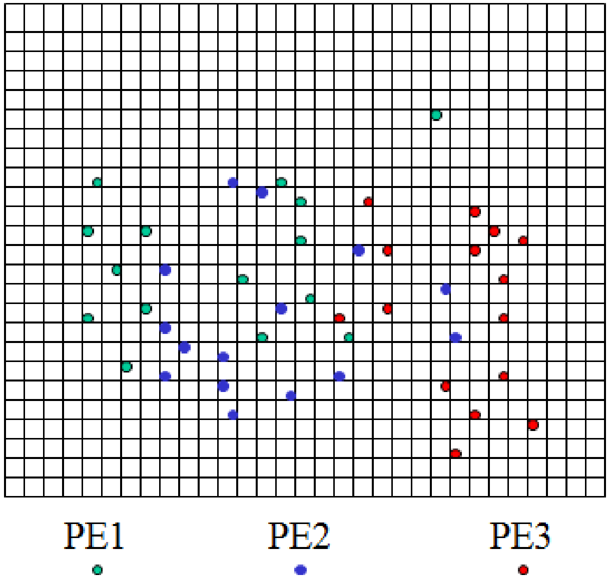
J. Qiang, in these proceedings.

Reduce Computing Time with Parallel Computers

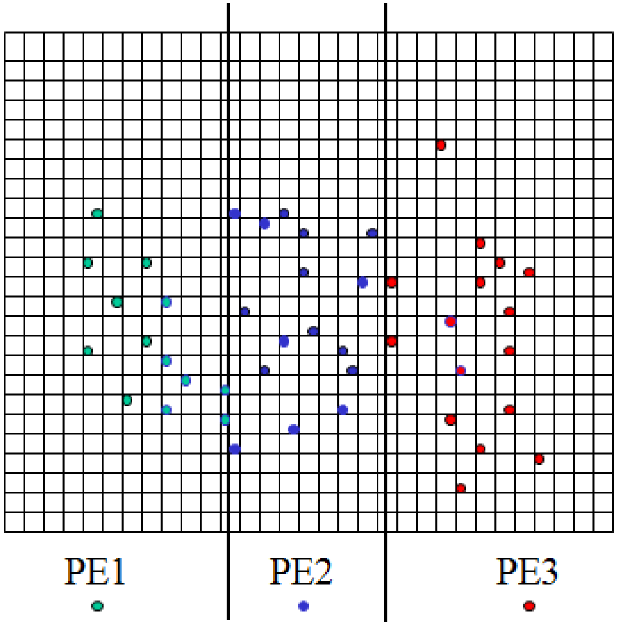
Berkeley Lab

Three Parallelization Methods:

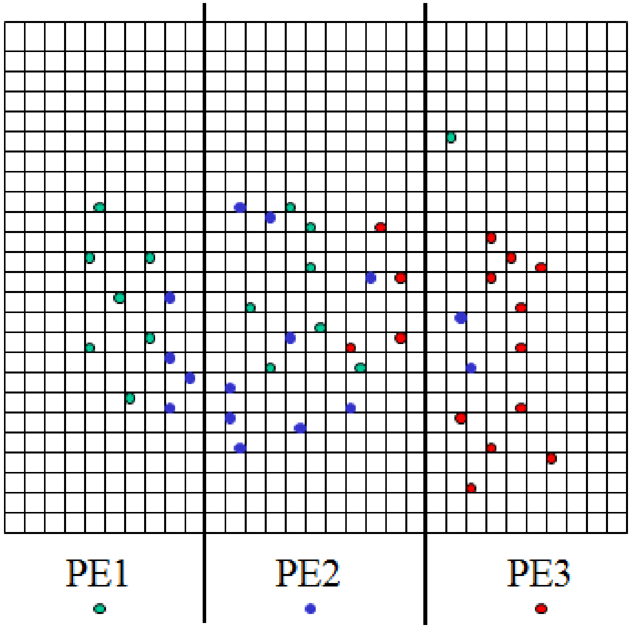
Particle Decomposition



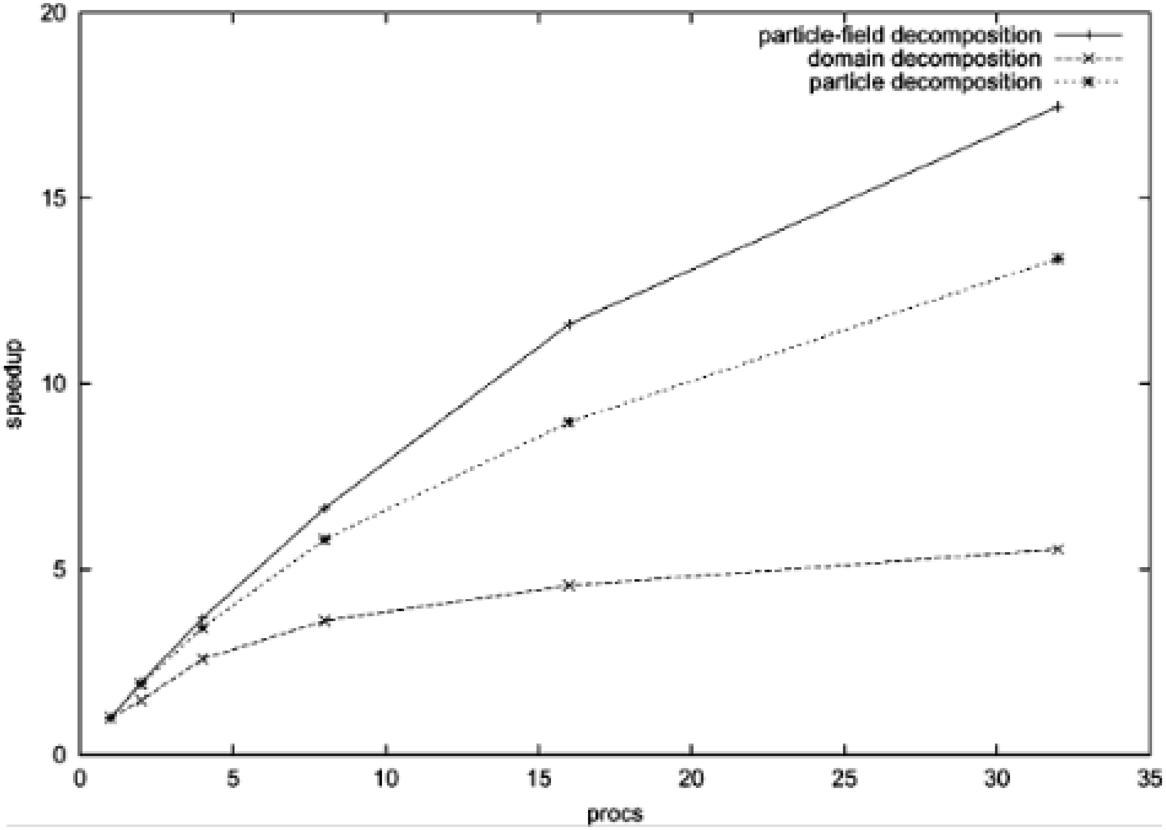
Domain Decomposition



Particle-Field Decomposition



Parallel Implementation Matters!



Speedup as a function of number of processors on IBM SP3 with particle-field decomposition, particle decomposition and domain decomposition

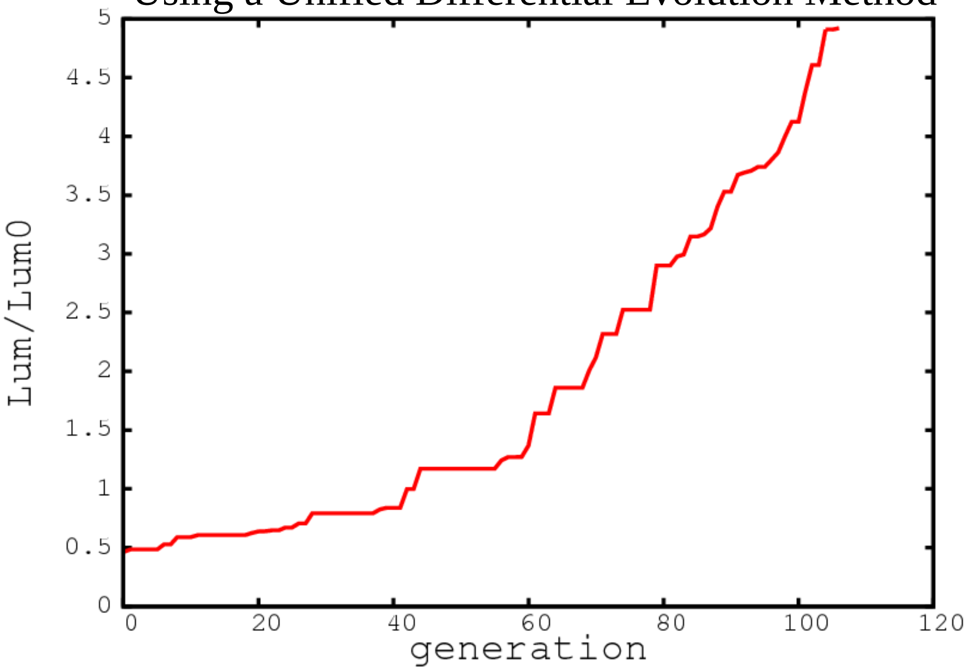
J. Qiang et al., J. Comp. Phys. 198, 278 (2004).

Multi-Level Parallelization

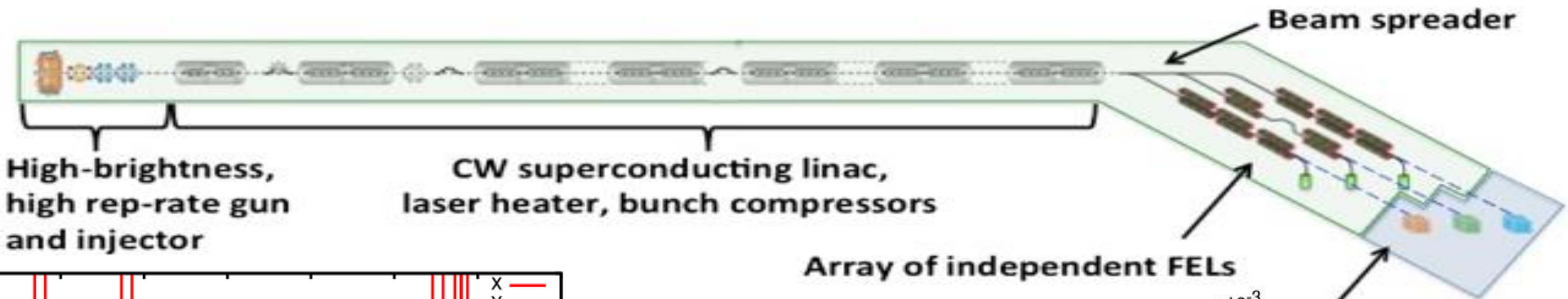
Table 1: Weak Scaling Test on Cray XT-5

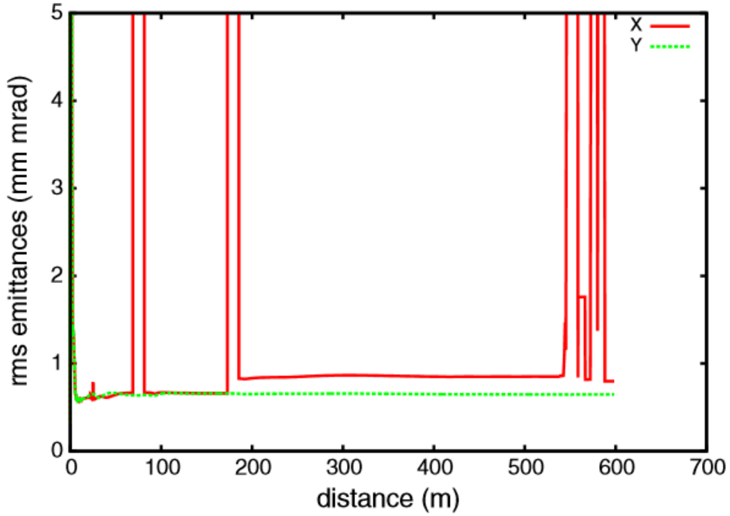
processors	time (sec)	problem size	efficiency
6400	2522	100	1
12800	2611	200	0.97
25600	2700	400	0.93
51200	2890	800	0.87
102400	2710	1600	0.93

Parallel Optimization of the LHC Luminoisty
Using a Unified Differential Evolution Method

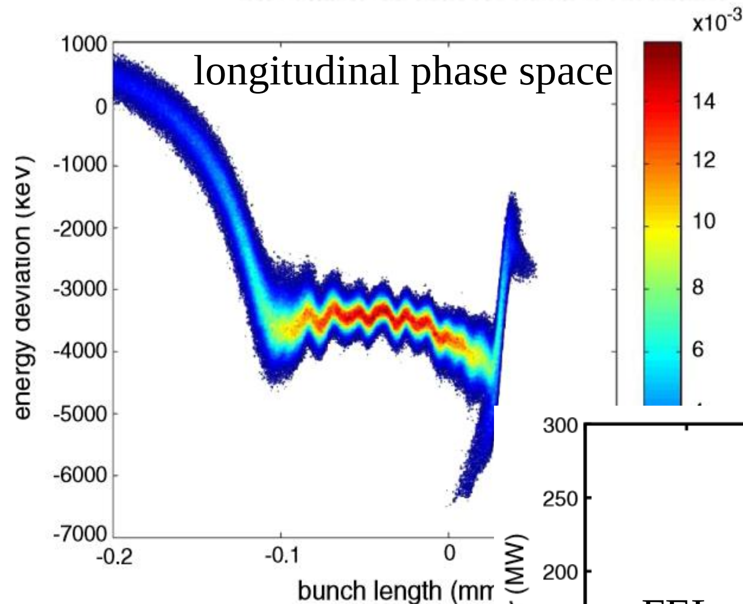


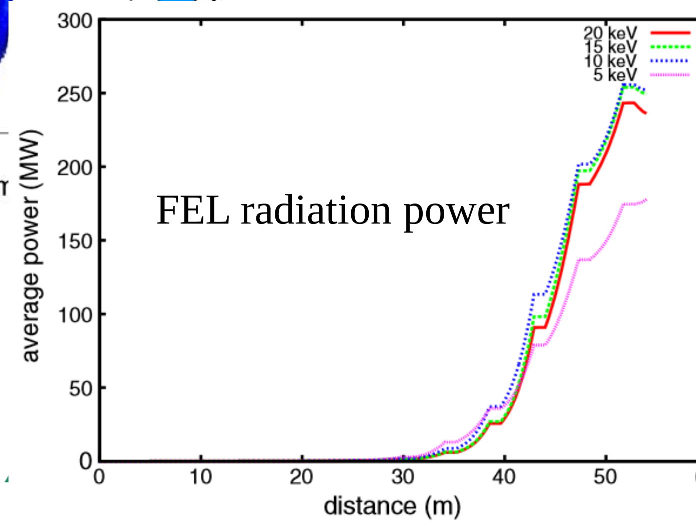
An Example of End-to-End Simulation:
(A Next Generation X-Ray FEL Light Source)





transverse emittance evolution

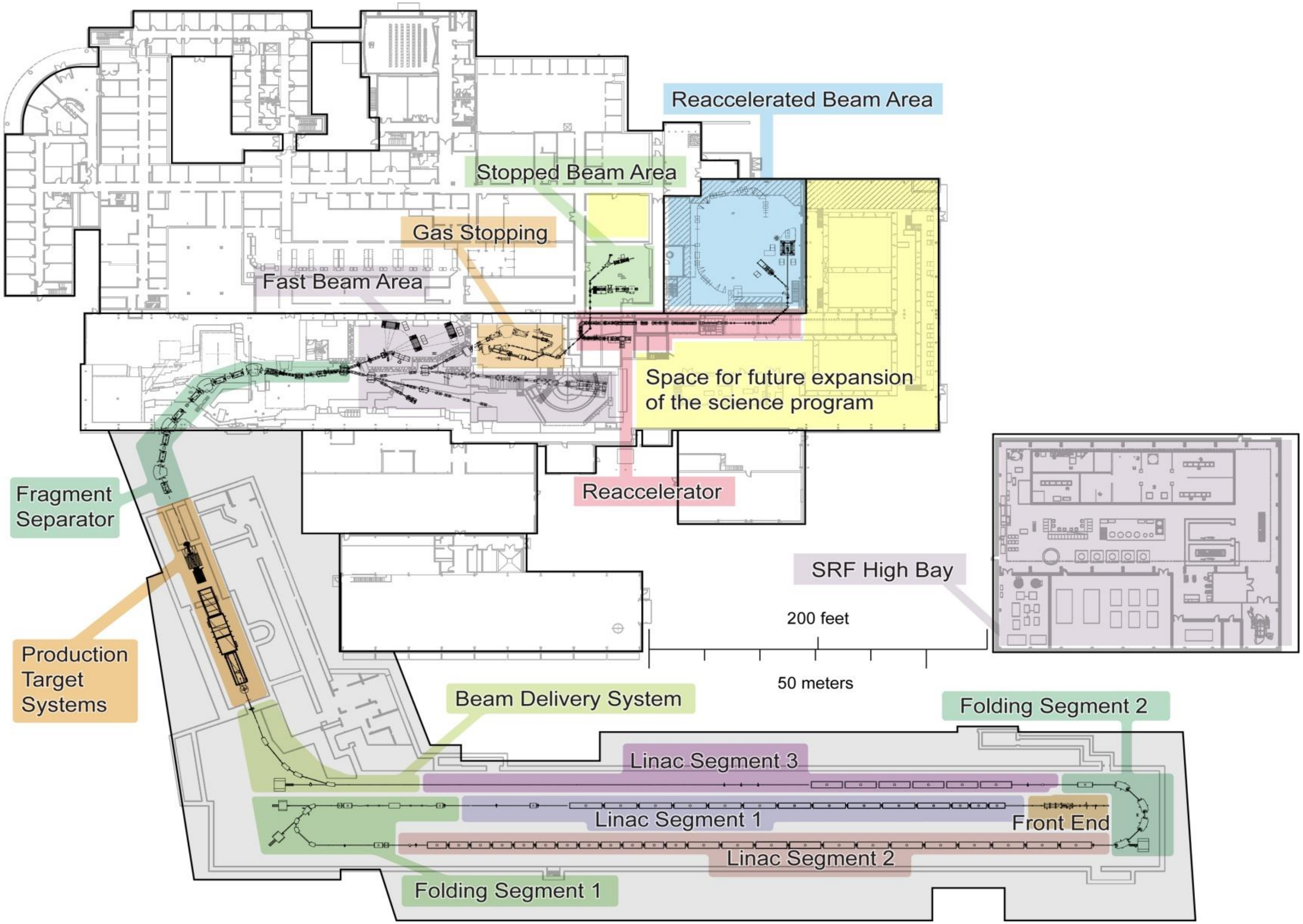




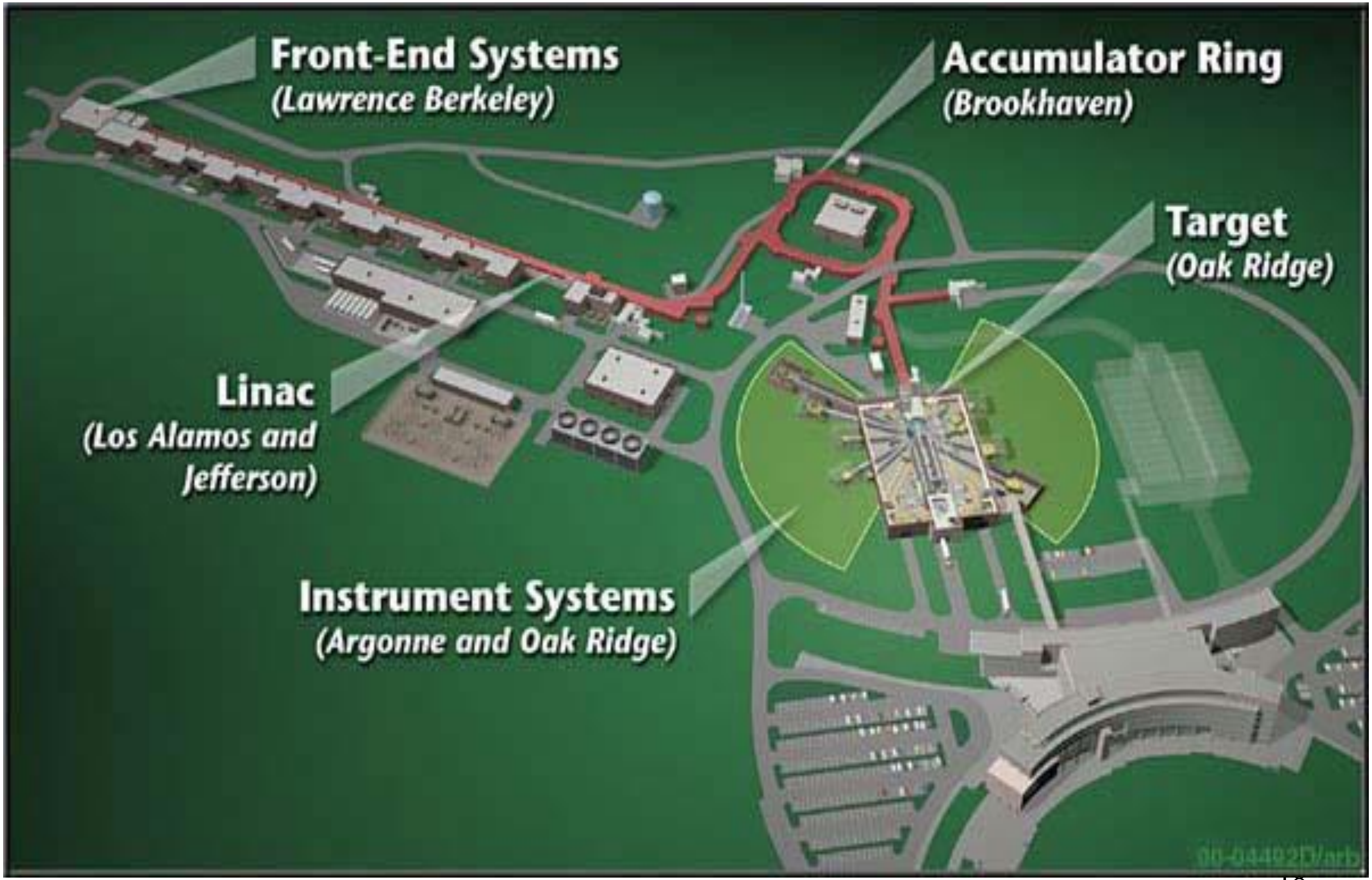
J. Qiang et al., PRST-AB 17, 030701, 2014.

Potential End-to-End Simulation
for Existing/Construction Accelerators

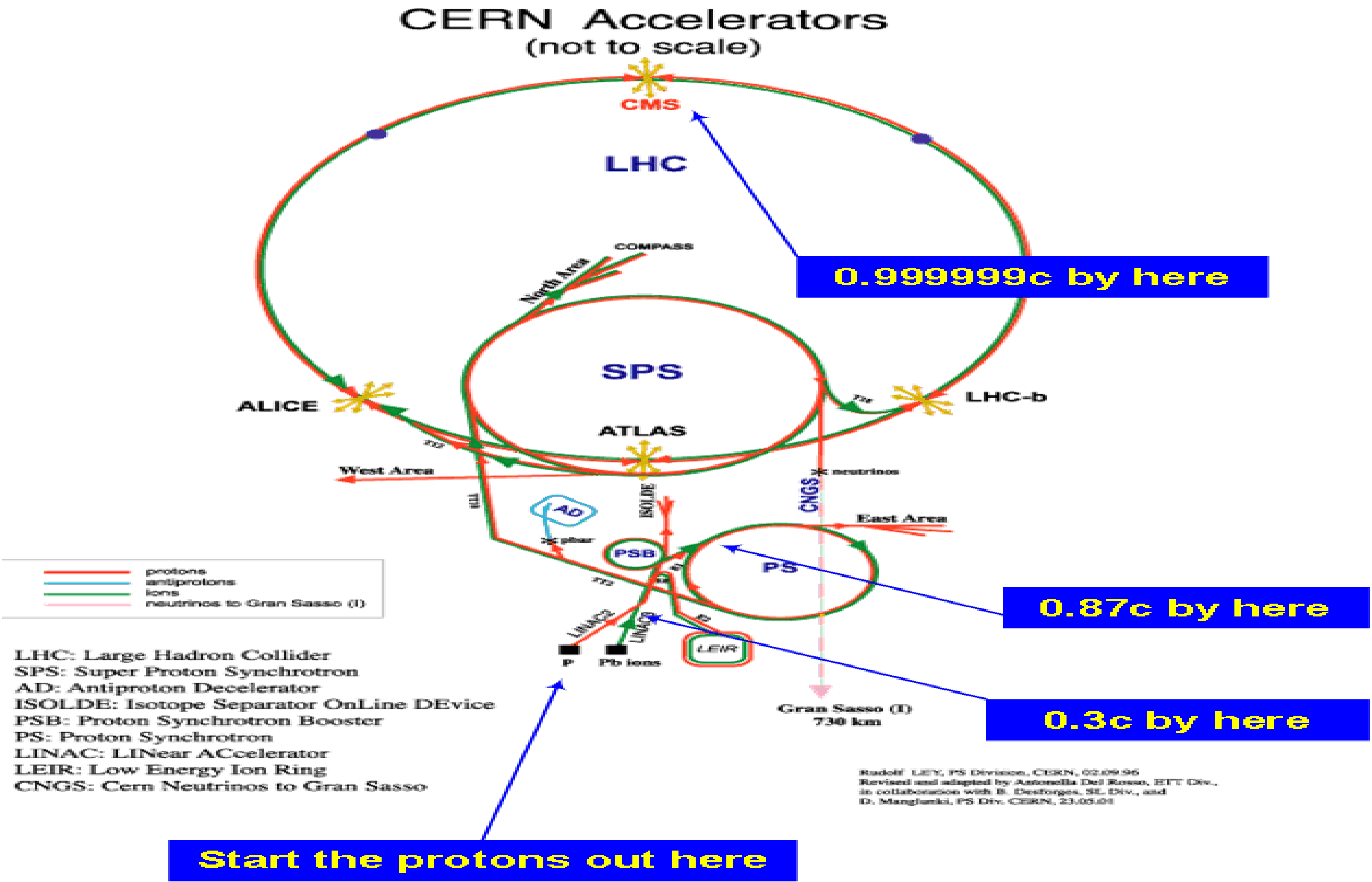
FRIB: Doable with Current Computing Capabilities



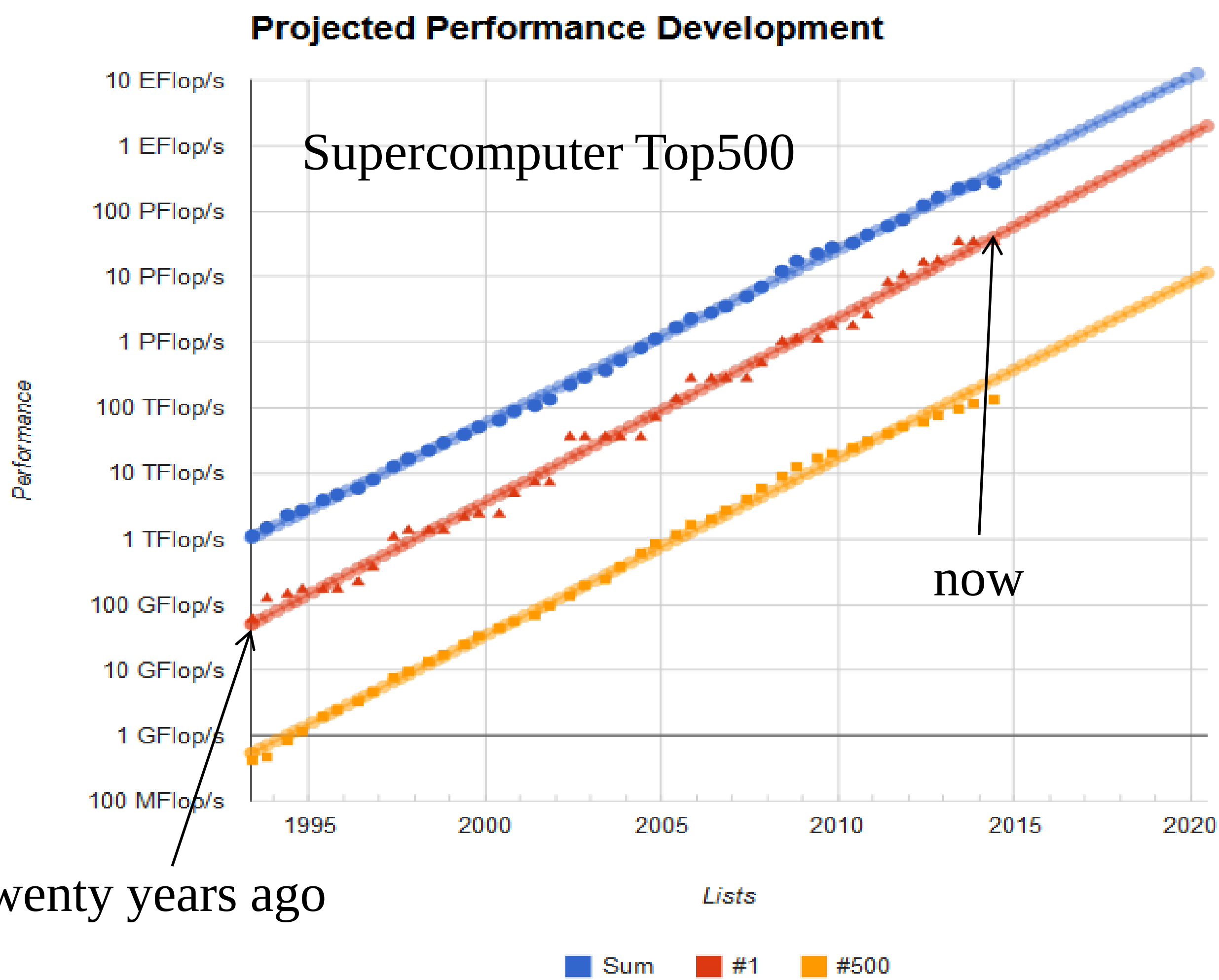
Spallation Neutron Source: Challenge but within the Reach of Current Computing Capabilities



LHC: Can We Do It?

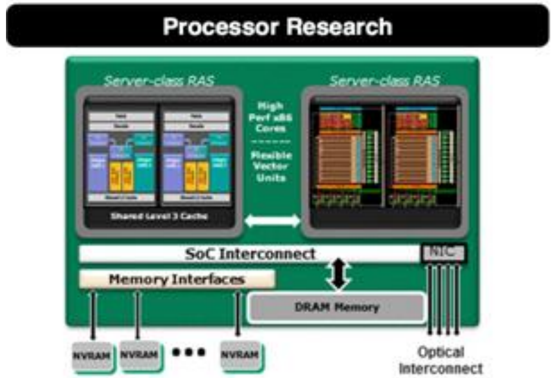


Advancement of Computers



AMD Next Generation Processor

Target Requirement	Target Value (per node)
System-Level Energy Utilization	50 GFLOPS/Watt
Compute Performance	10 TFLOPS
Network Data Rate	400 GB/sec
Memory Data Rate	4 TB/sec
Memory Capacity	1 TB



- Heterogeneous Processors, Energy Utilization, Resiliency and Reliability, Efficient Data Movement, Programmability

> Five orders of magnitude increase of computing power within last 20 years!

Thank You!