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Plasma physics simulations with PIC codes

Ivona Vasileska

LECAD laboratory, Faculty of mechanical engineering, University of Ljubljana

What is plasma?

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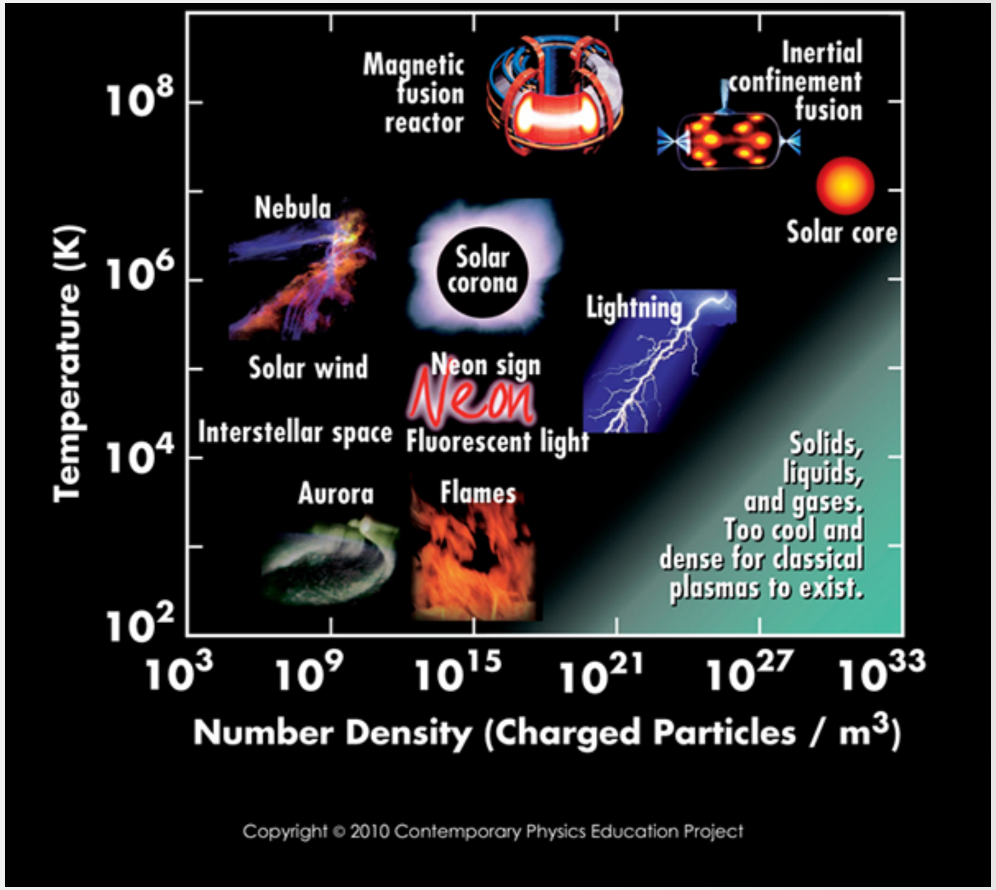
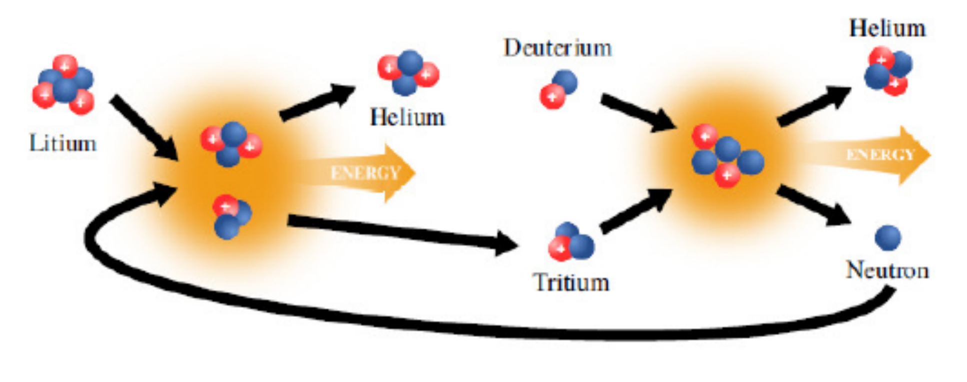
- A plasma is a quasineutral gas containing charged particles. In the most common case, the plasma consists of electrons and positively charged ions.
- The fundamental characteristics and properties of plasma are:
  - The quasineutrality (*Ne = Ni*).
  - The volume where the plasma quasineutrality is violated is characterized by the Debye length $\left(\lambda_D = \sqrt{\frac{\epsilon_0 k T_e}{n_0 e^2}}\right)$.
  - Plasma temperature $\left(T \gg \frac{e^2 n^{1/3}}{\epsilon_0 k}\right)$.
  - Plasma frequency $\left(\omega_{pe} = \sqrt{\frac{n e^2}{\epsilon_0 m_e}}\right)$.
  - Plasma density $\left(n \gg {}^1/_{\lambda_D}\right)$.



Nuclear fusion

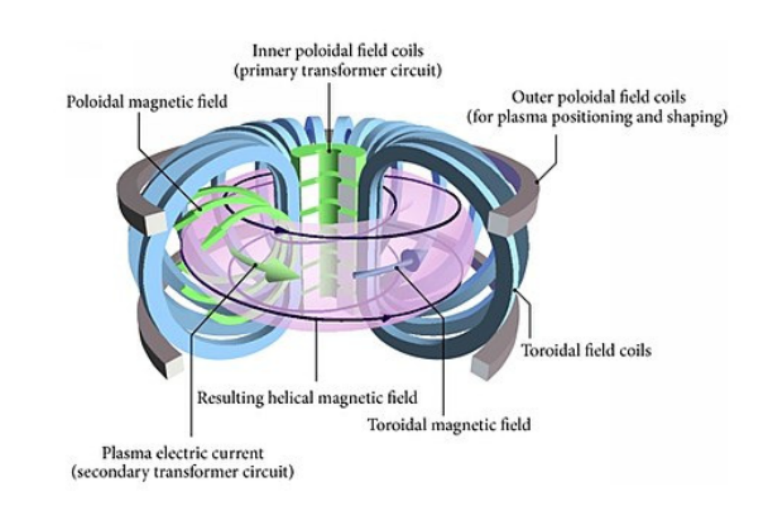
- Nuclear fusion - process of combining light atomic nucleus into heavier ones due to the kinetic energy of their thermal motion.
- The thermonuclear fusion energy occurs in the form of:
  - thermonuclear weapons (hydrogen bomb), where an uncontrolled nuclear reaction with a explosive nature takes place;
  - fusion reactors, where a controlled nuclear reaction takes place.

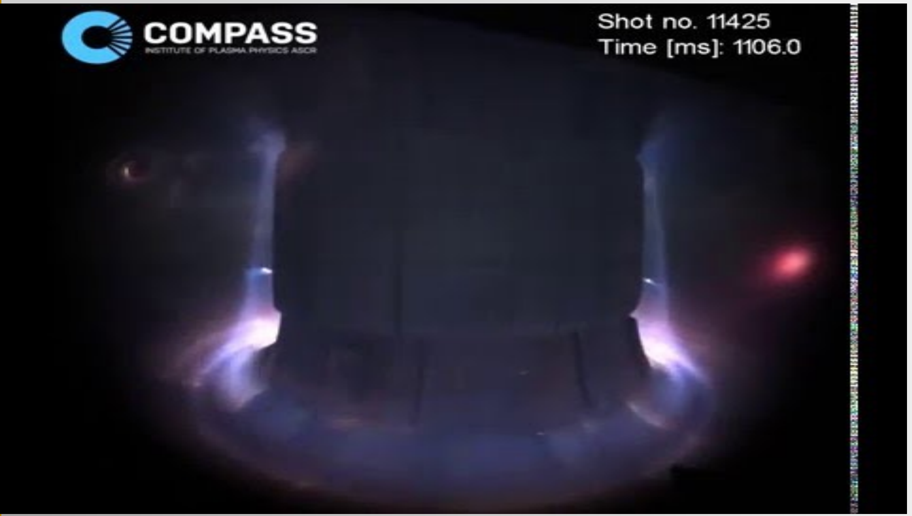


6Li + n →T + 4.8 MeV

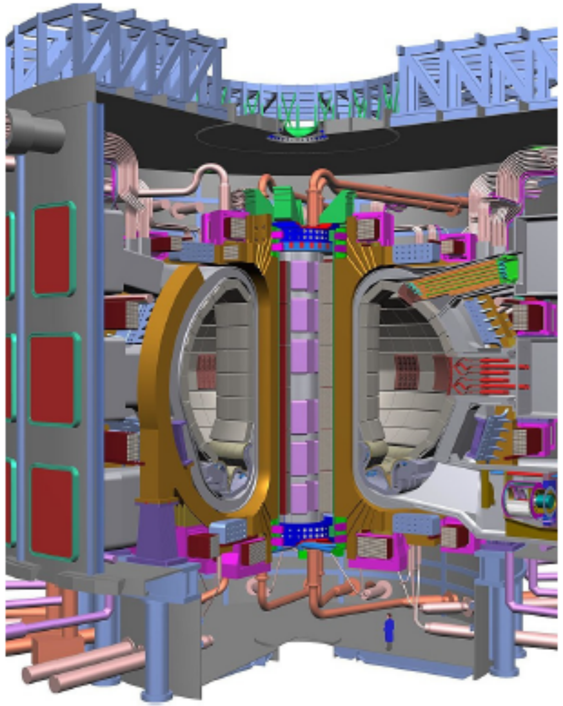
D+T→ 4He + n + 17.6 MeV

Fusion reactors - tokamak





- ITER parameters:
  - power 500 MW,
  - ratio of the fusion energy synthesis to heating energy not less than 10,
  - burning plasma time 400 s,
  - large and small radii torus 6.2 m and 2 m, respectively,
  - plasma volume 840 m3,
  - plasma current 15 MA. As a fuel it uses a mixture of deuterium with tritium.



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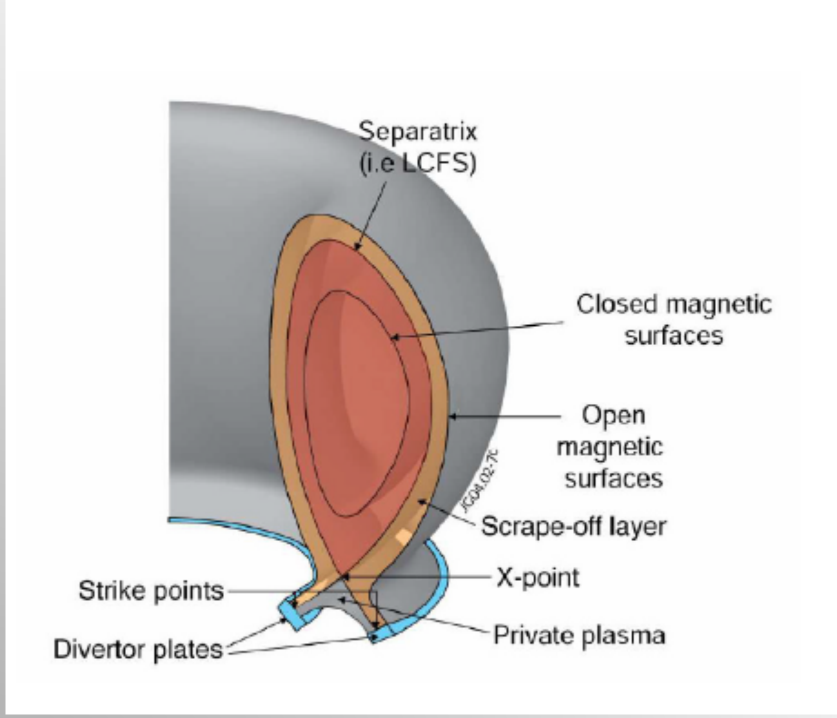
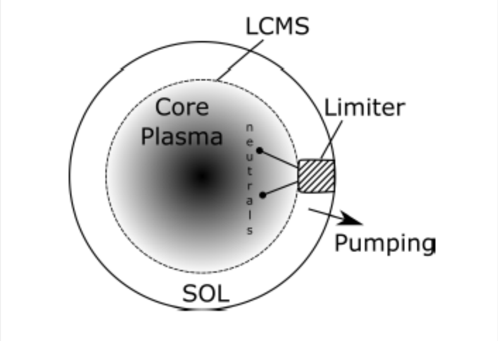
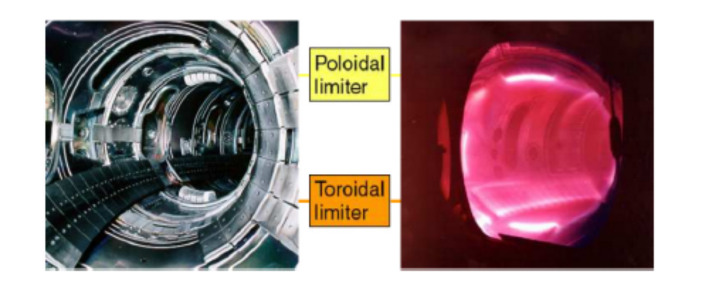
Plasma Scrape-Off Layer (SOL)

Field lines in tokamak

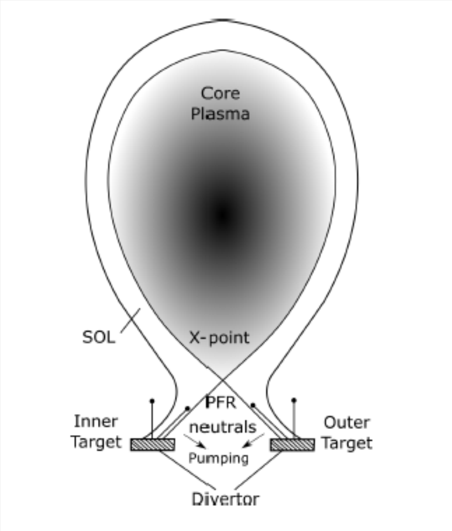


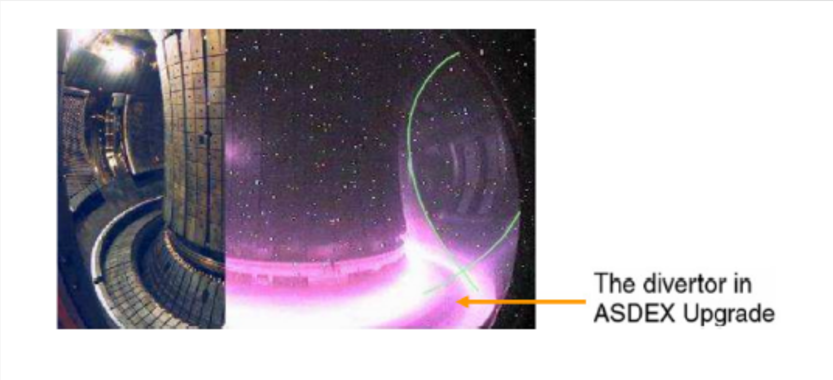
Limiter configuration



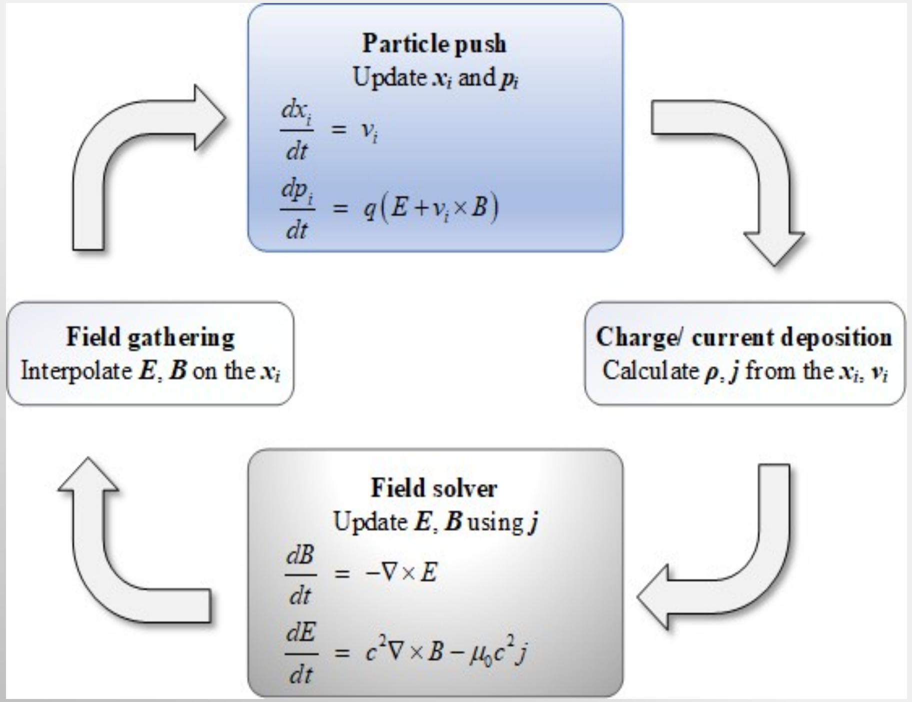


Divertor configuration





Kinetic modelling plasma tool - Particle-In-Cell (PIC) codes

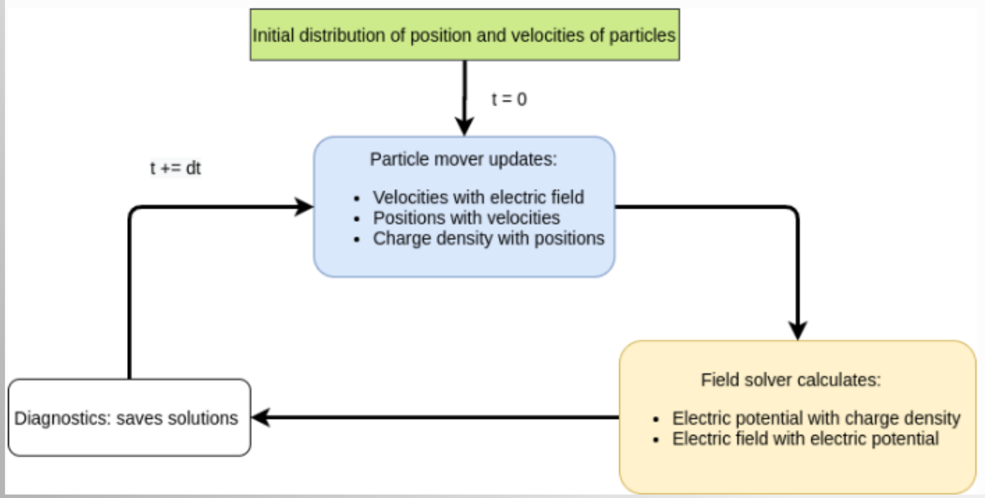


Main PIC code algorithm

- Features:
  - Calculates super-particles motion. Each super-particle represents many particles in the plasma (more particles → more accuracy). This feature is called particle mover.
  - Takes into account fields generated by the particles and external circuits, this feature is called field solver. Two types of description:
    - Electrostatic codes: Solves the Poisson's equation for the electric field.
    - Electromagnetic codes: Solves a set of Maxwell's equations.

Simple PIC code (SimPIC)

- Code documentation: https://lecad-peg.bitbucket.io/simpic/simpic.html?highligh
- SIMPIC workflow:



- Input variables in SIMPIC:

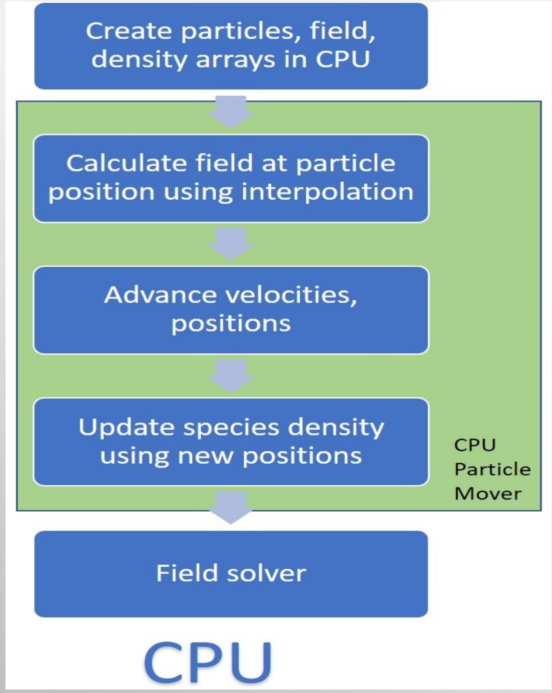
NT=200 *# of time steps*
PPC=100 *# of particles per cell*
CPP=64 *# of cell per process*
DTFACTOR=0.001 *#defines a fraction of dt vs. time steps from plasma frequency; #must be positive*
NPROC=4 *# of processors*
LHSV=25000 *#applied voltage on left-hand side; RHS is grounded;*

- Output results:

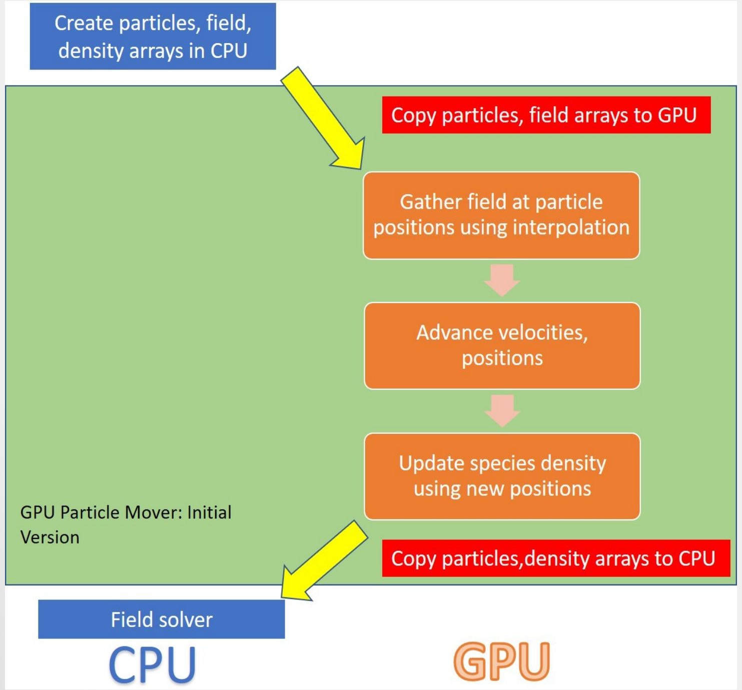
den *#density*
E *# electric field*
phi *# potential*
vxx *# phase space*
nt *# time evolution of number of particles per processor*

File format for each processor is:
time, relative_position, value

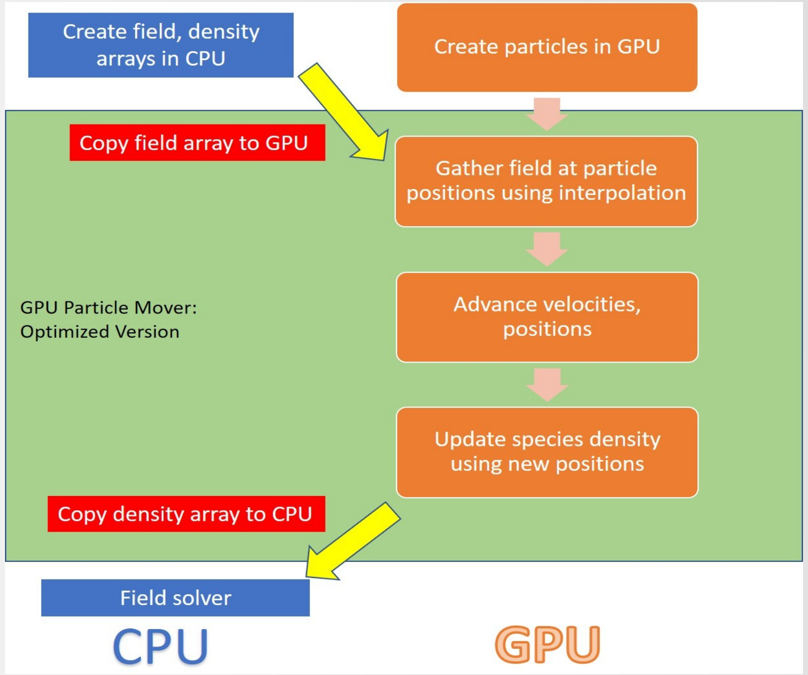
Comparing CPU vs GPU Particle Mover



CPU SIMPIC of the particle mover

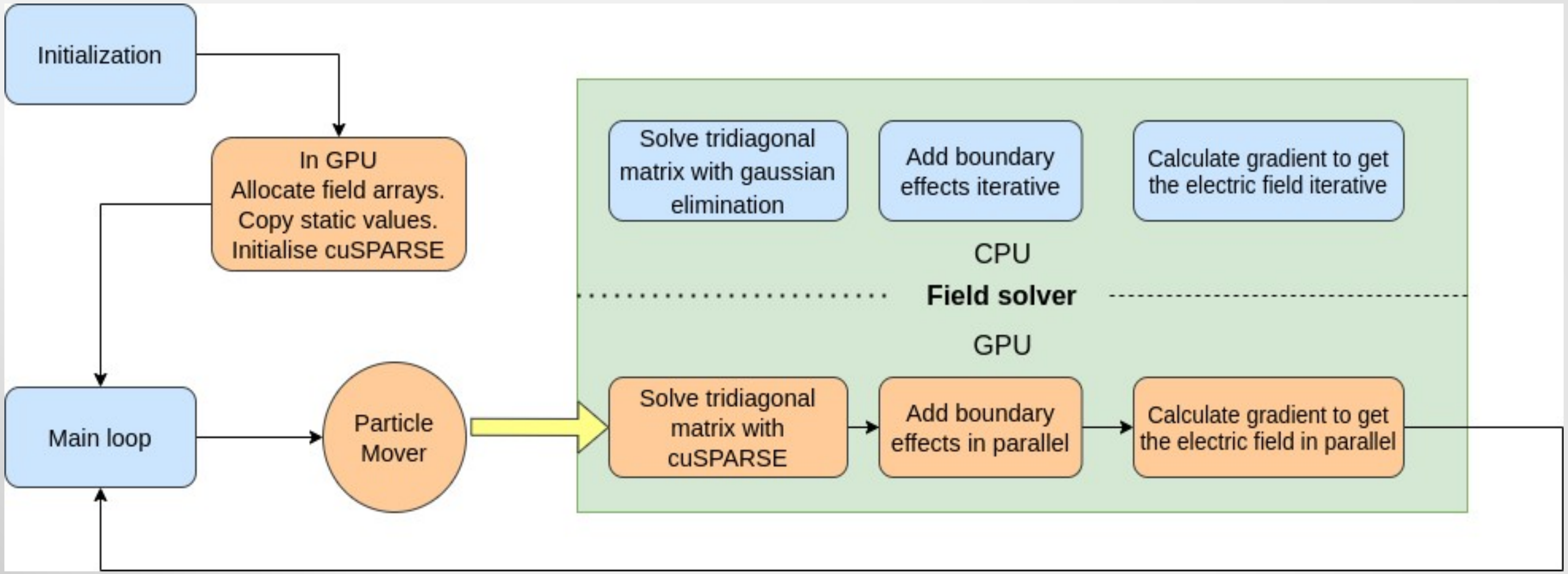


GPU SIMPIC of the particle mover: Initial Version



GPU SIMPIC of the particle mover: Optimized Version

GPU field solver



GPU of the filed solver

Heterogeneous Computing. Why StarPU?

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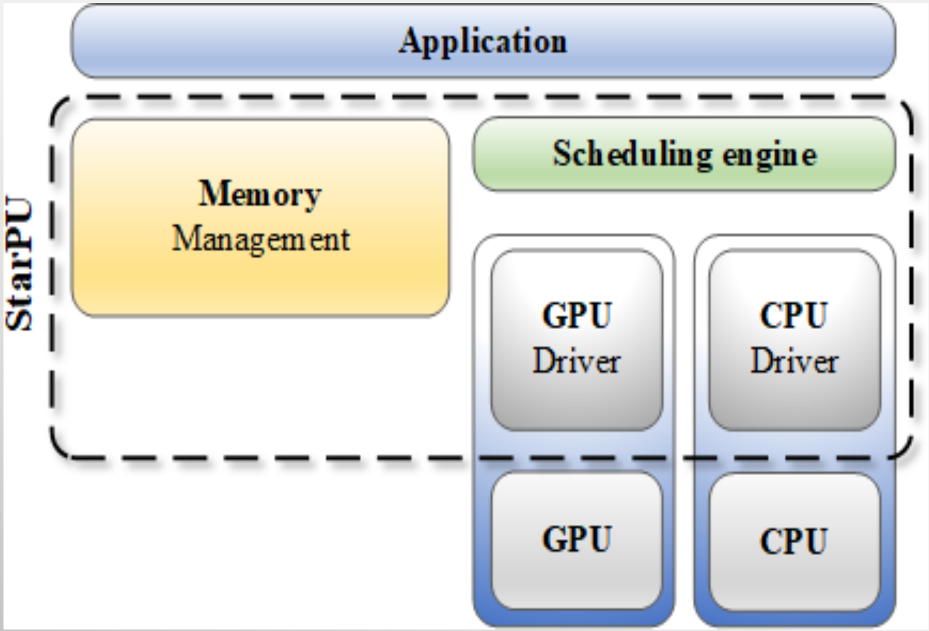
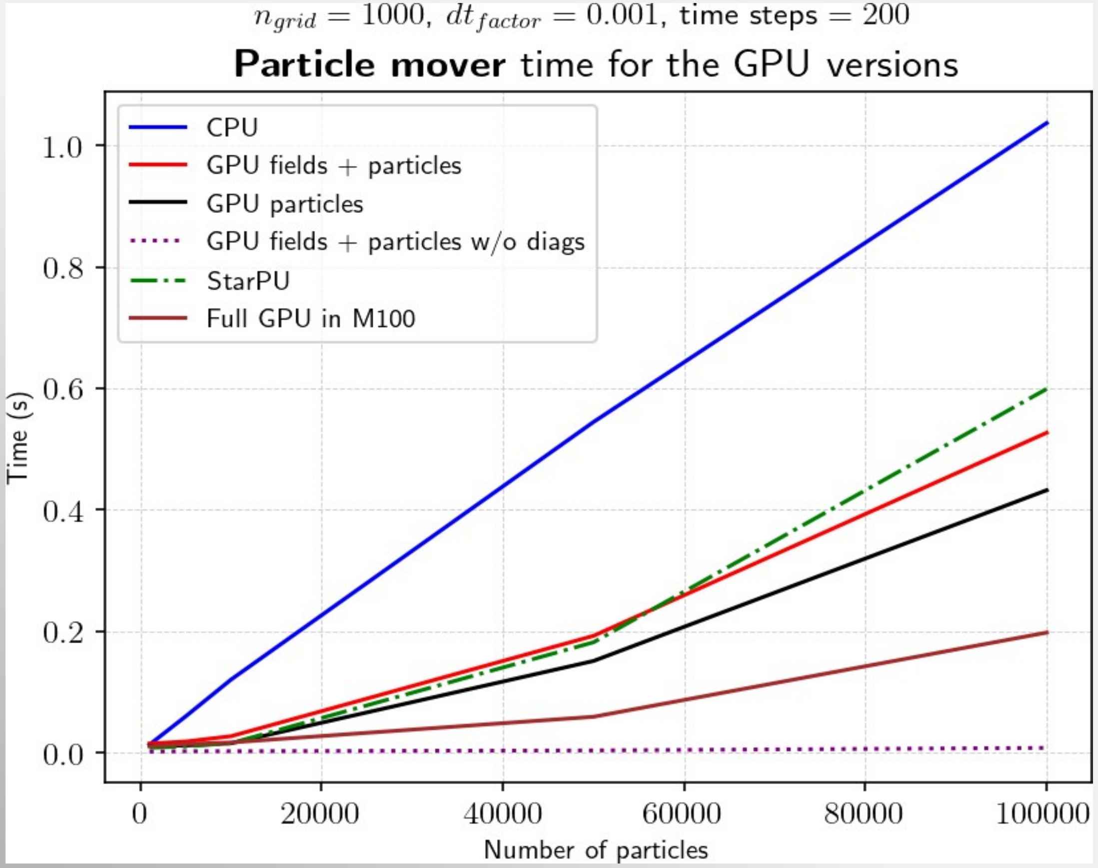
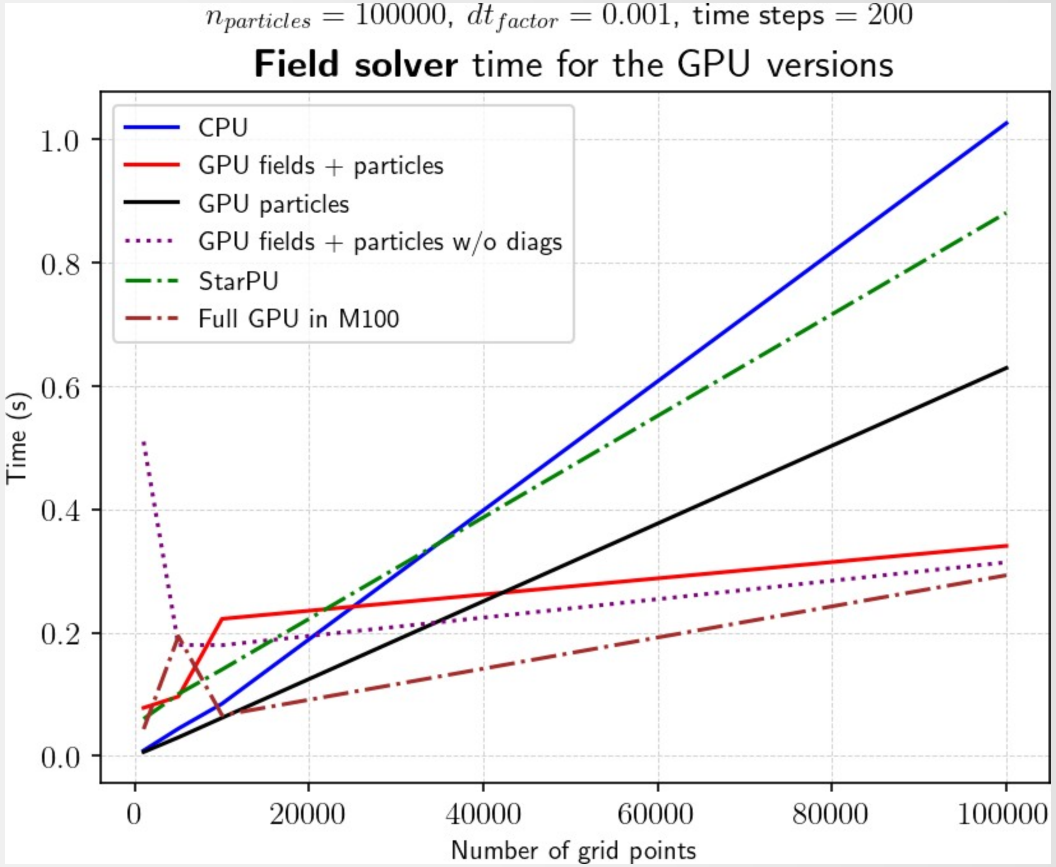


Function scheme of the StarPU run system

- Heterogeneous Computing uses all available processing units (CPUs,GPUs) for computation
- StarPU enables portability of code across various architectures and ensures interaction between different PUs
- StarPU implements task based parallelism. Each task could be a CPU function, CUDA kernel or OpenCL kernel.

Benchmarks for fully GPU version





Building SIMPIC on VIZ-HPC

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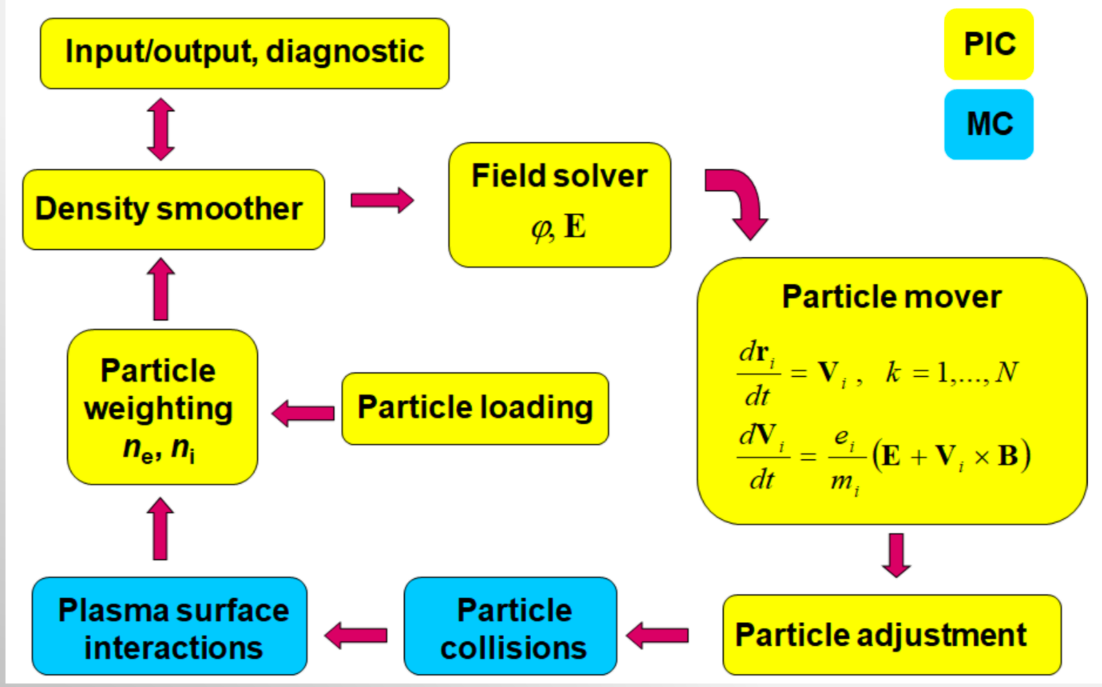
```
git clone https://bitbucket.org/lecad-peg/simpic.git
module load Python/3.7.4-GCCcore-8.3.0 #HOME DIRECTORY
module load OpenMPI/3.1.4-gcccuda-2019b #HOME DIRECTORY
python3 -m venv simpyenv #HOME DIRECTORY
source simpyenv/bin/activate #HOME DIRECTORY
python3 -m pip install --upgrade pip sphinx_rtd_theme #HOME DIRECTORY
pip install numpy scipy pandas matplotlib #HOME DIRECTORY
pip list #HOME DIRECTORY
cd simpic
cd GPU_mover_fields #GPU version
make
./runsimpic.sh 2> run.log

For CPU versions first is needed to install STARPU
wget https://files.inria.fr/starpu/starpu-1.3.4/starpu-1.3.4.tar.gz
tar xvf starpu-1.3.4.tar.gz
cd starpu-1.3.4
mkdir build
cd build
../configure --prefix=$HOME/starpu
make
make install
export PKG_CONFIG_PATH=$PKG_CONFIG_PATH:$HOME/starpu/lib/pkgconfig #IN SIMPIC
export LD_LIBRARY_PATH=$HOME/starpu/lib:$LD_LIBRARY_PATH #IN SIMPIC
export PATH=$PATH:$HOME/starpu/bin #IN SIMPIC
```

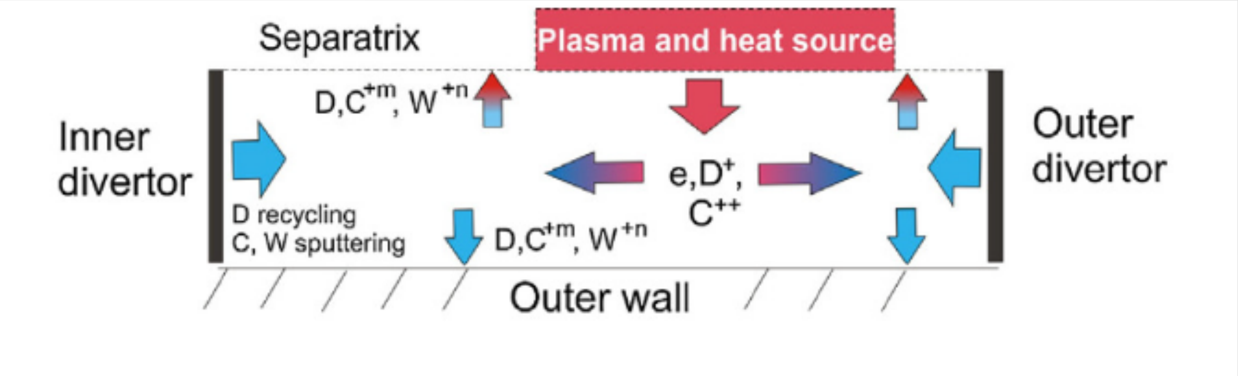
SIMPIC tasks:

- Run the code changing the input parameters (increasing and decreasing the number of cells, number of particles and applied voltage);
- Plot the plasma parameters with different input parameters;
- Do the same with GPU version of the code;
- With fixed input parameters run both codes CPU and GPU version and compare running time, plot graphs

OOPD1 and BIT1, PIC code



PIC/MC algorithm codes



Simulation geometry of tokamak in BIT1

Building OOPD1,PIC on VIZ-HPC

```
cp -r /home/ivasileska/test_oopd1 .
module load tk/8.6.8/intel-18.0.2-kzhkvu6
module load X11/20190717-GCCcore-8.3.0
module load OpenMPI/3.1.4-GCC-8.3.0
cd test_oopd1
cd xgrafix
nano run_conf.sh
IN run_conf.sh #CHANGE PLEASE PREFIX prefix=$HOME/opt/xgrafix
#SAVE
./run_conf.sh
make
make install
cd ..
cd oopd1
make
./pd1 -h

./pd1 -i inp/test.inp -s 1000 #SIMPLE CASE
./pd1 -i inp/argon_10mTorr_27MHz.inp -s 1000 #ARGON CASE
```

Building BIT1,PIC on VIZ-HPC

```
module load OpenMPI/3.1.3-GCC-8.2.0-2.31.1
cp /home/ivasileska/BIT1.tar.gz . #home directory
tar xzfv BIT1.tar.gz . #home directory
cd PTC
cd BIT1
tar xvzf bit1_n_18.tar.gz
cd BIT1_n_18
make
./BIT1
```

OOPD1 and BIT1 tasks:

- OOPD1 tasks:
  - Run first simple test.inp and than argon_10mTorr_27MHz.inp, compare both parameters.
  - Changing input parameters compare output plasma parameters;
- BIT1 tasks:
  - Input file and output results,
  - Tokamak simulations JET and ITER.
  - Compare all PIC results

THANK YOU FOR YOUR ATTENTION

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