Recent Developments in QuickPIC Open Source

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Plasma Based Accelerator Research is at the Forefront of Science

Bella

AWAKE

FLASH

FACET

.....

Plasma simulation has greatly impacted on PBA research.

The Quasi-Static PIC code

Embeds a 2D PIC code inside a 3D PIC code

Quasi-Static Approximation*

$(x, y, z; t)$

⬇

$(x, y, \xi=ct-z, s=z)$

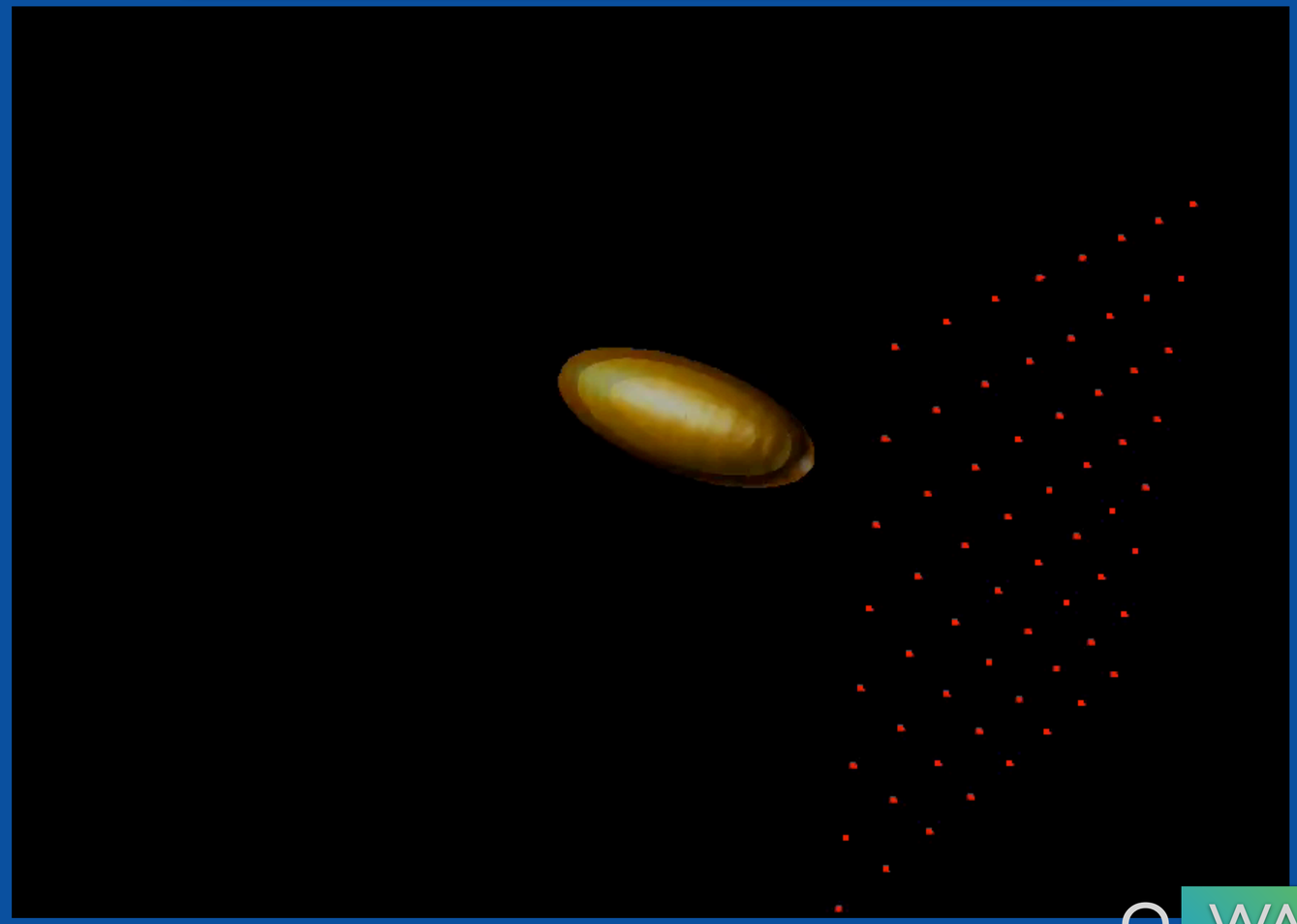
⬇

$\partial_s << \partial_\xi$

⬇

Plasma: $(x, y; \xi)$

Beam: (x, y, ξ, s)



QuickPIC is a 3D parallel Quasi-Static PIC code, which is developed based on the framework UPIC.

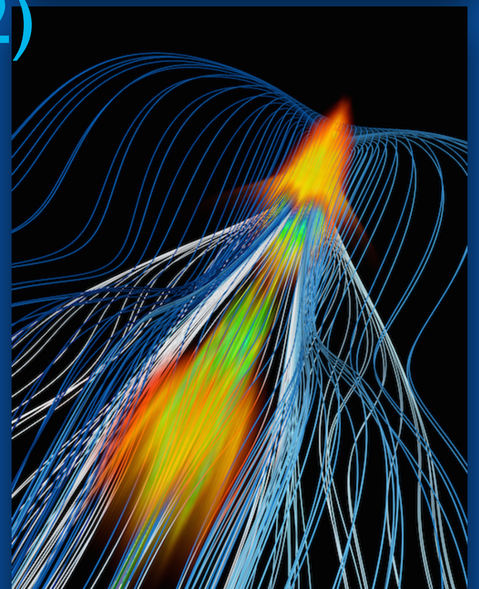
https://gitee.com/bnu-plasma-astrophysics-sg/quick-pic-open-source

Q S A WAKE LCODE HIPACE

QuickPIC @ FACET

(1)

(2)



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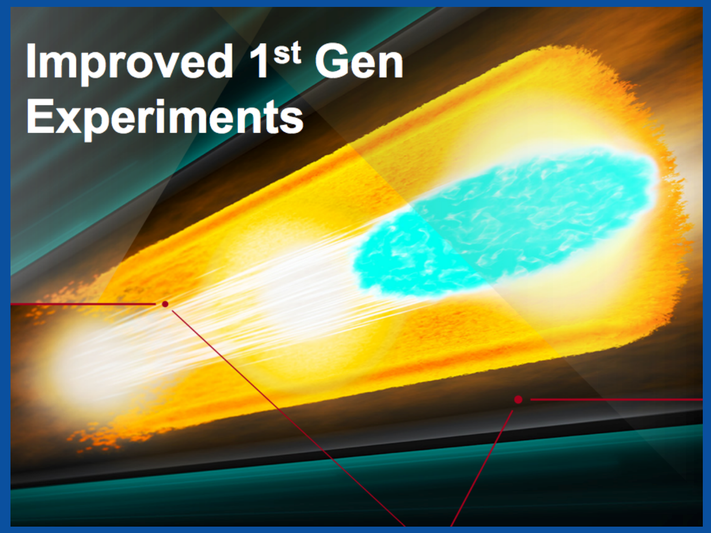

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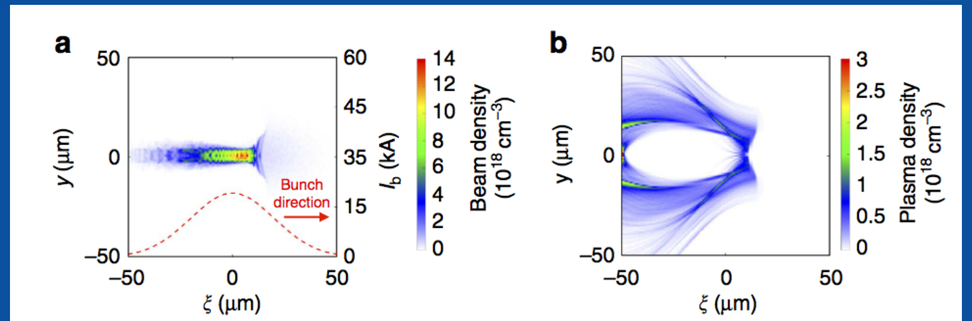

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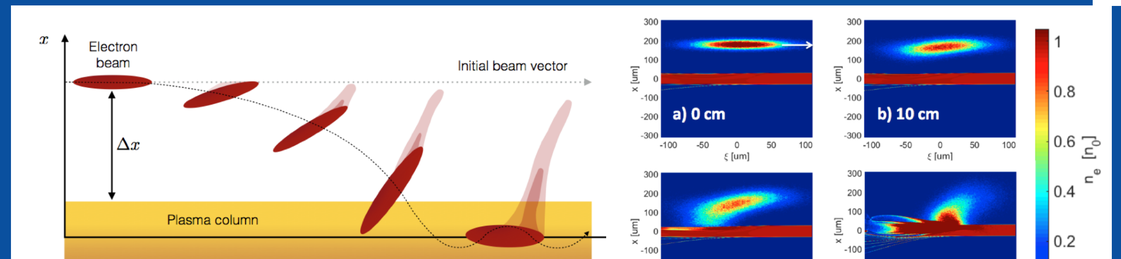

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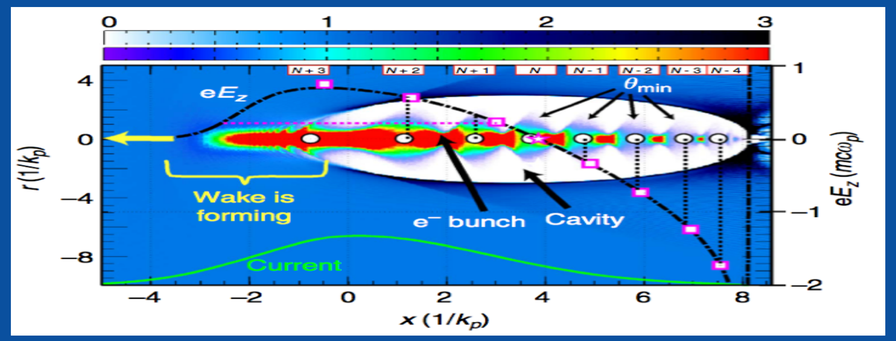

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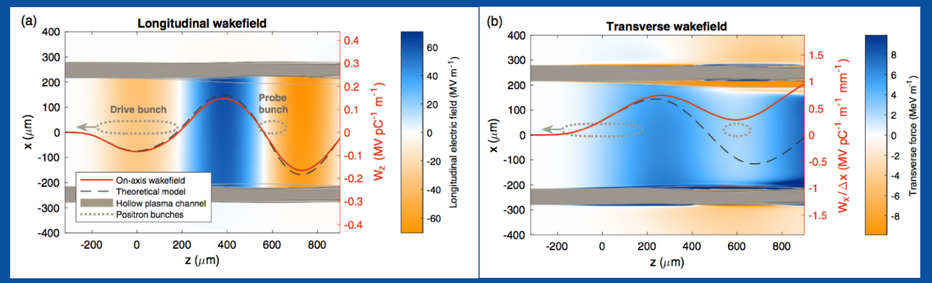

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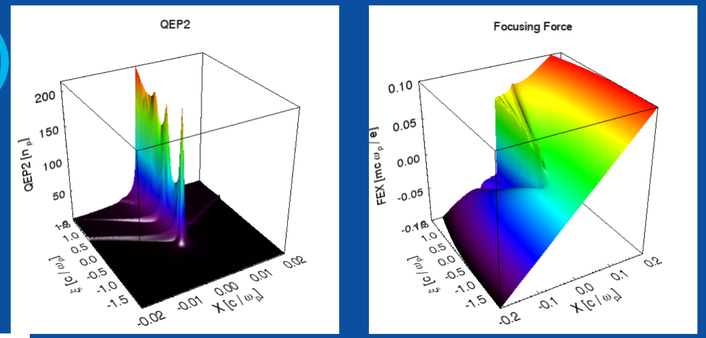
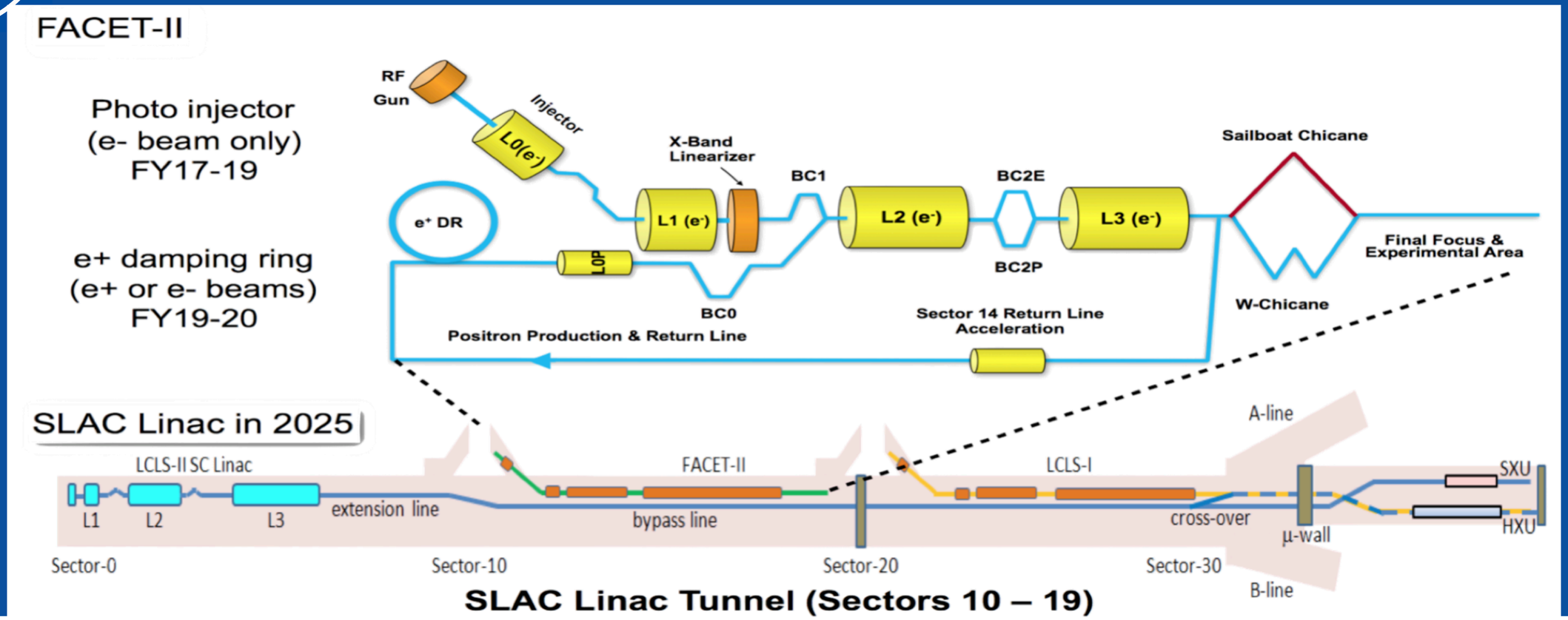
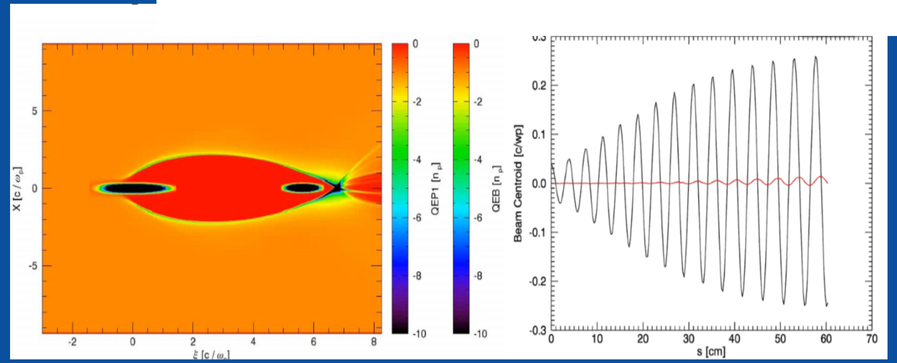
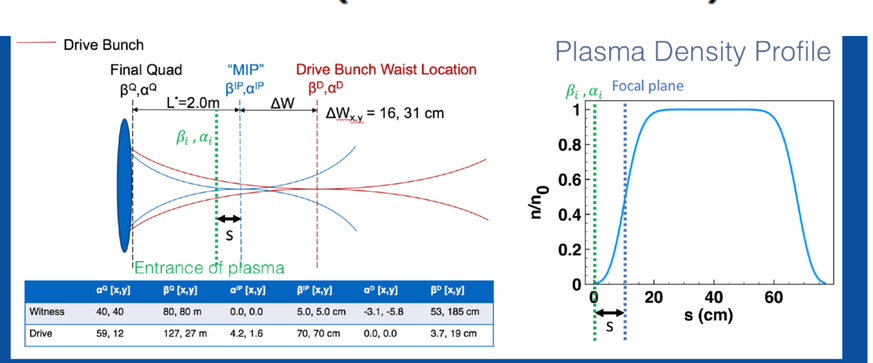


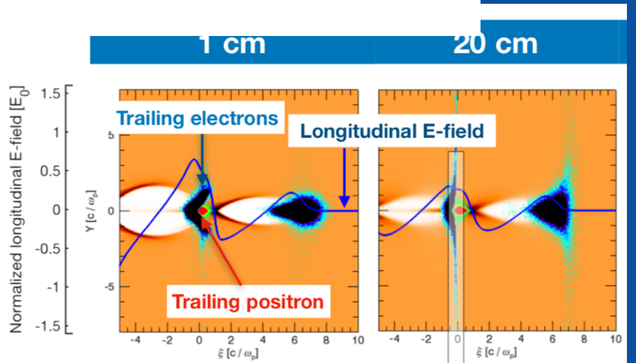
Highly Nonlinear
Nonuniform
Asymmetric
Field Ionization

QuickPIC @ FACET II



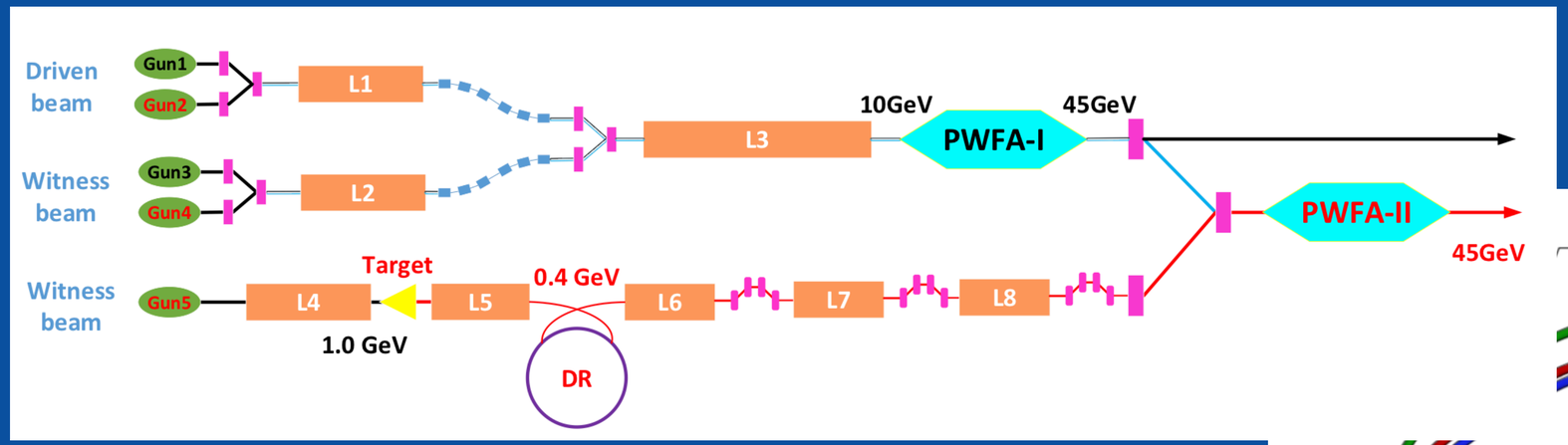






QuickPIC @ CEPC

Design CEPC Plasma Injector



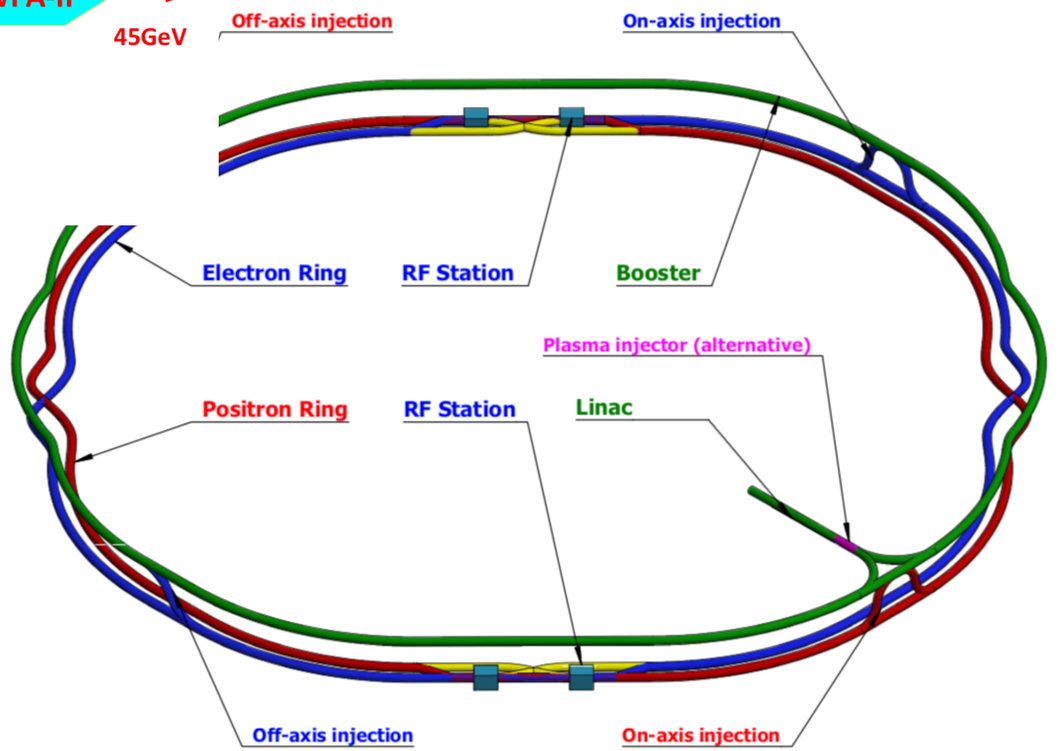


Fig. 1. CEPC layout. The blue one corresponds to the electron ring and the red one corresponds to the positron ring. There are two interaction regions, two RF regions and four injection regions in the collider.[1]

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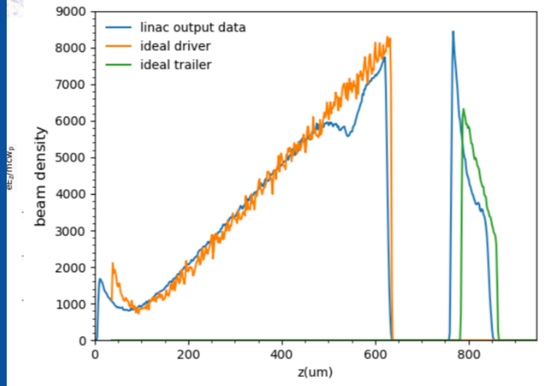
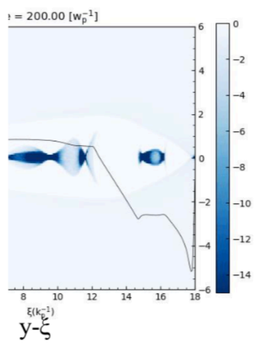
QuickPIC @ CEPC

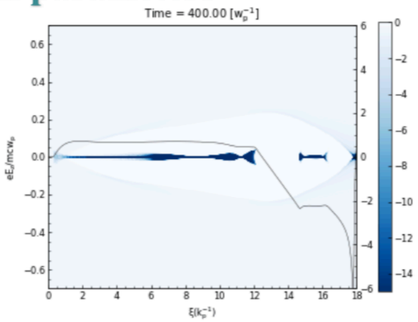
Electron Acceleration

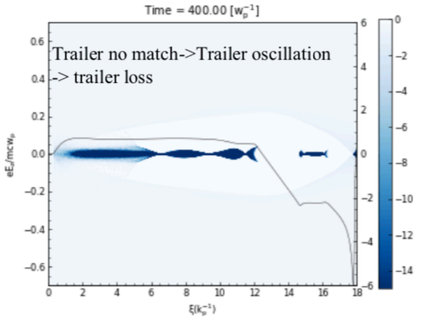
Start to end simulation

Rewrite beam parameters









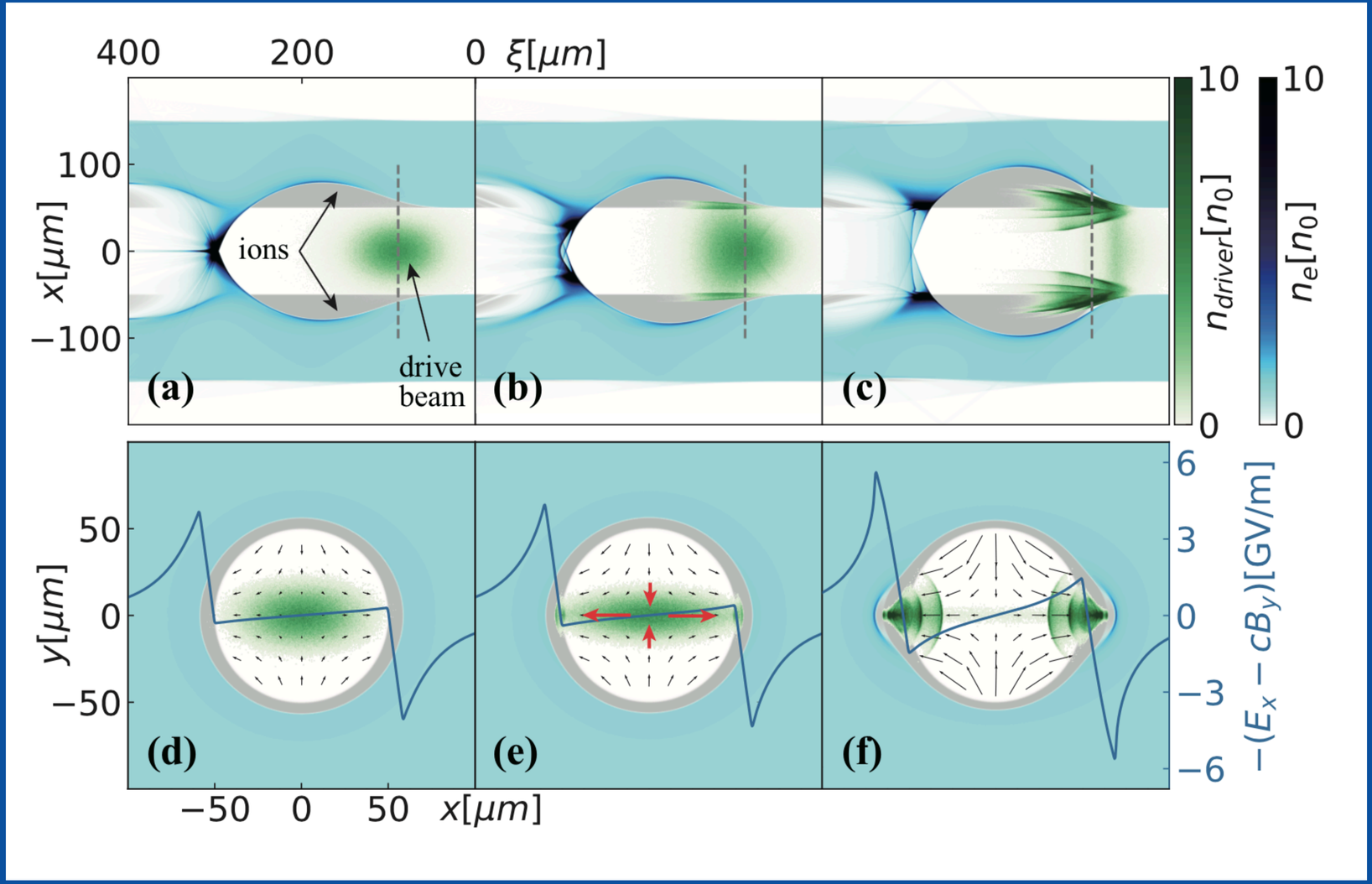
	Linac output	Linac output	Linac output	design
plasma density $n_p(\times 10^{16} cm^{-3})$	0.58	0.54	0.47	0.50334
Accelerating distance (m)	10.07	10.49	10.9	10.65
Driver energy $E(GeV)$	3.36	3.11	2.85	1.30
Trailer energy $E(GeV)$	40.6	39.15	35.8	45.5
Normalized emittance $\epsilon_n(mm\ mrad)$	3.01/9.65	2.13/10.0	0.87/6.6	98.44/98.44
Spot size(um)	7.42/13.68	6.46/13.88	4.45/12.07	5.92
Energy spread $\delta_E(\%)$	2.77	3.6	5.38	0.56
TR	4.61	4.2	3.61	4.08
Efficiency(%) (driver -> trailer)	79.50	72.93	60.0	59.1
Trailer loss(%)	10.24	3.7	0.14	0

1、beam profile->driver spreads out faster->Ez^-↑->trailer energy < 45.5GeV

2、 Ez^+ uneven ->Trailer energy spread↑

By courtesy of Xiaoning Wang (IHEP)

QuickPIC @ CEPC



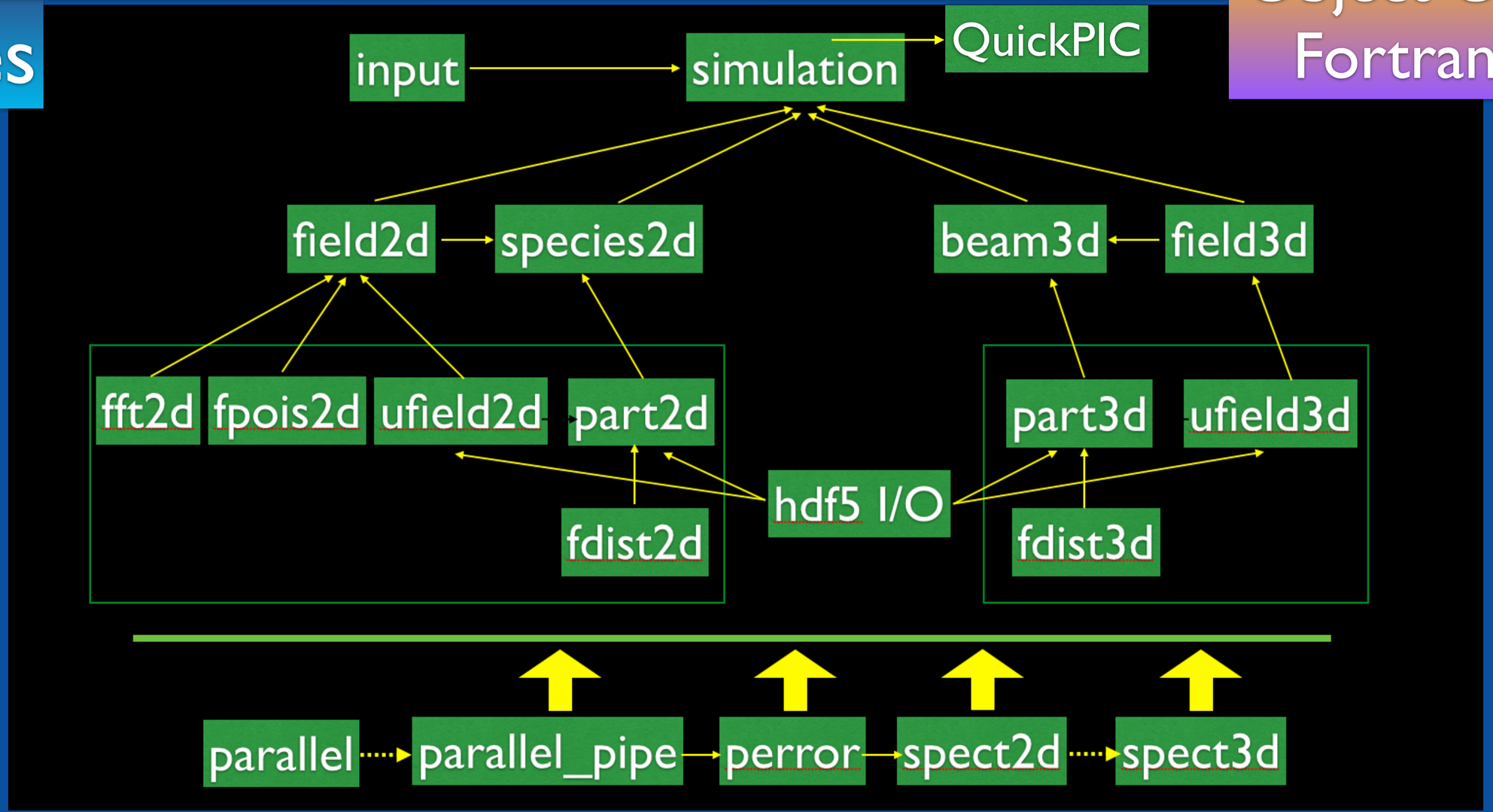
Shiyu Zhou, Jianfei Hua, Weiming An, Warren B. Mori and Chan Joshi, Gao Jie, and Wei Lu*, "High efficiency uniform wakefield acceleration of a positron beam using stable asymmetric mode in a hollow channel plasma", PRL 2021

QuickPIC Open Source

https://github.com/UCLA-Plasma-Simulation-Group/QuickPIC-OpenSource

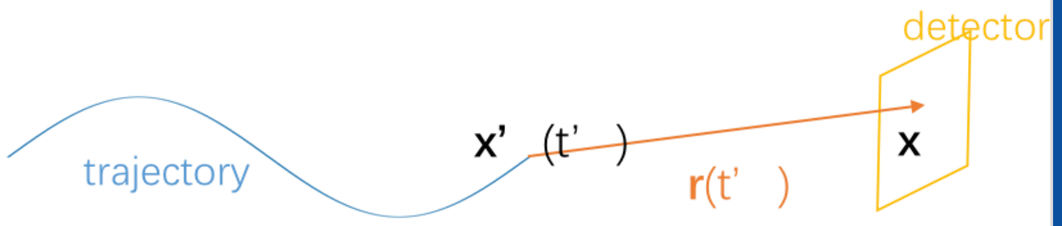
Object Oriented Fortran 2003

Classes



Recent Development: Betatron Radiation

Theoretical formula of betatron radiation*



- intensity :

$$\frac{dP(t')}{d\Omega} = \frac{q^2}{16\pi^2\varepsilon_0 c}\frac{\left|\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]\right|^2}{(1-\vec{\beta}\cdot\vec{n})^5} \xrightarrow{\text{time integration}} \frac{dW}{d\Omega} = \frac{q^2}{16\pi^2\varepsilon_0 c}\int_{t_0}^{t_1}\frac{\left|\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]\right|^2}{(1-\vec{\beta}\cdot\vec{n})^5}dt'$$

- spectrum :

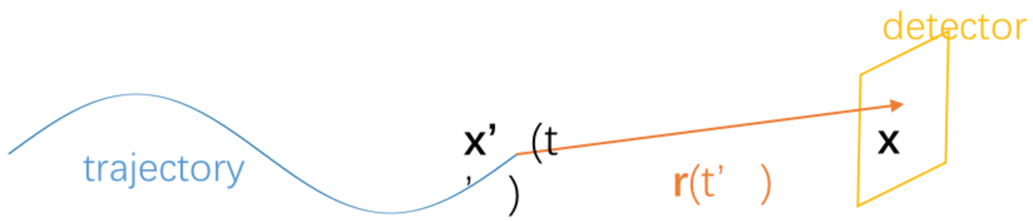
$$\frac{d^2I}{d\Omega d\omega} = \frac{q^2}{16\pi^3\varepsilon_0 c}\left|\int_{-\infty}^{\infty}\frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{\beta}\cdot\vec{n})^2}e^{i\omega(t+\frac{r(t)}{c})}dt\right|^2$$

What we need ?

- position, velocity and acceleration along the trajectory of each particle
- position of detector
- radiation frequency

*Jackson, J. D., Classical Electrodynamics[M]. 3rd ed. Wiley, 2001

Recent Development: Betatron Radiation



Radiation from a bunch of electrons

- intensity : summing the radiation of each particle
- spectrum: summing the contribution of each particle before taking the squared norm

$$\frac{d^2I}{d\omega d\Omega} = \frac{e^2}{16\pi^3\epsilon_0 c}\left|\sum_{j=1}^{N_e}\int_{-\infty}^{+\infty} e^{i\omega[t-\vec{n}\cdot\vec{r}_j(t)/c]} \times \frac{\vec{n}\times[(\vec{n}-\vec{\beta}_j)\times\dot{\vec{\beta}}_j]}{(1-\vec{\beta}_j\cdot\vec{n})^2}dt\right|^2.$$

Input File for Radiation

- detector information
  - position
  - grid numbers
- spectrum information
  - frequency range
  - grid numbers
- output
- diag

```
"radiation":
{
    "detector":{
        "x":[-1000,1000],
        "nx":100,
        "y":[-1000,1000],
        "ny":100,
        "z":400000
    },
    "time":[399990,400100],
    "nt": 1,
    "spectrum":{
        "frequence":[1e5,1.35e8],
        "nw":200,
        "in_n":5,
        "Nx":40,
        "Ny":40,
        "fsample":128
    },
    "ndump" : 10,
    "diag":["intensity","spectrum"]
}
```

Recent Development: Betatron Radiation

Drive Beam: E = 10 GeV

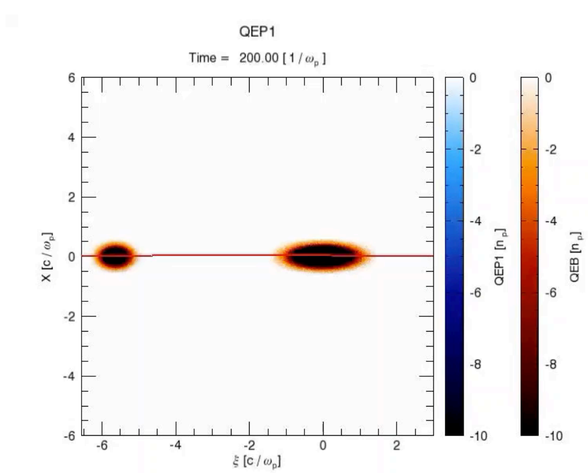
```
"gamma" : 19569,
"peak_density" :31.2,
"quiet_start" : true,
"center" : [0.0,0.0,1.88],
"sigmaz" : 0.24,
"sigma_vz" : 0,
"alpha" :[5.8776,1.92] ,
"beta" : [50239,34692],
"emittance": [0.12796,0.11290],
```

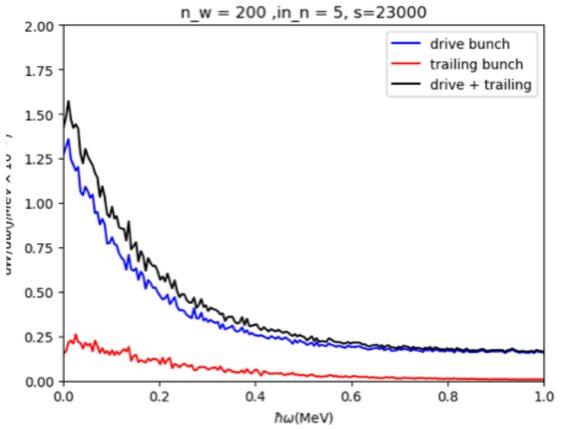
Trailing Beam: E = 10 GeV

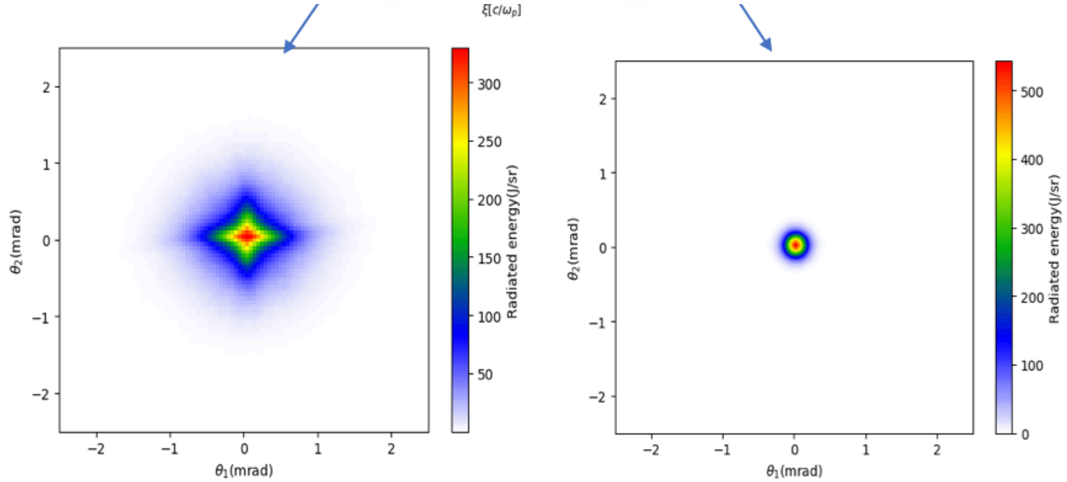
```
"gamma" : 19569,
"peak_density" : 83.5,
"quiet_start" : true,
"center" : [0.0,0.0,7.5175],
"sigmaz" : 0.1053 ,
"sigma_vz" : 0,
"alpha" : [1.26,1.26],
"beta" : [4869,4869],
"emittance" : [0.12043,0.12043],
```

Distance between two bunches: 150 μm

Plasma Density: 4.0 x 1016 cm-3 (with ramps)

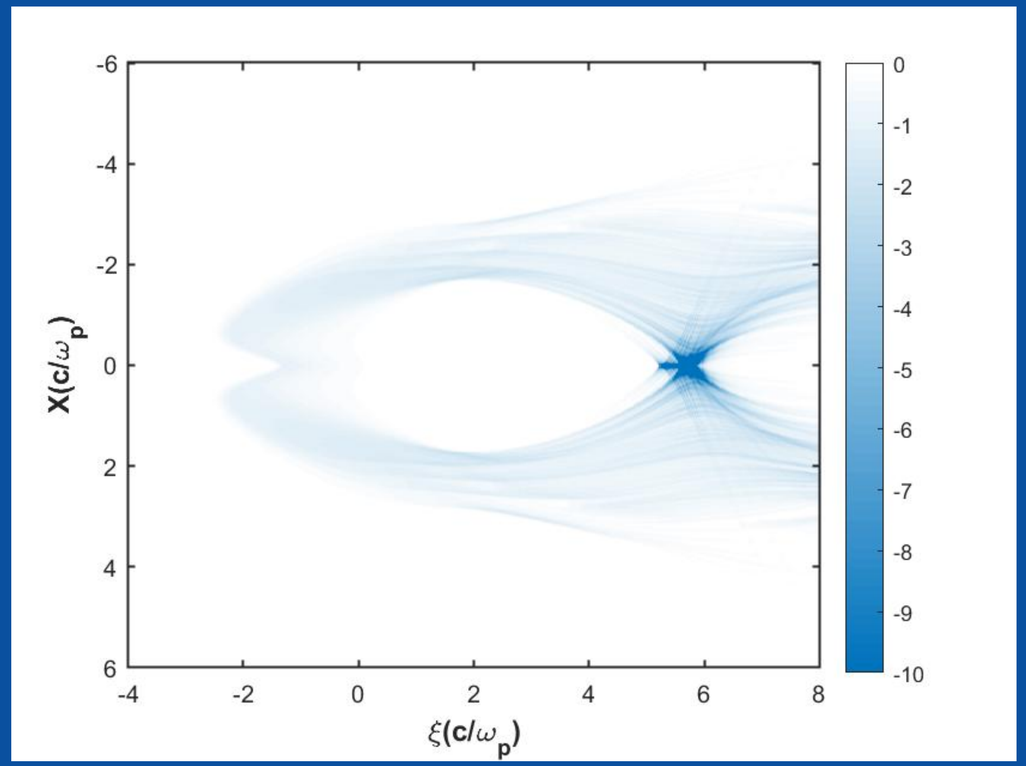


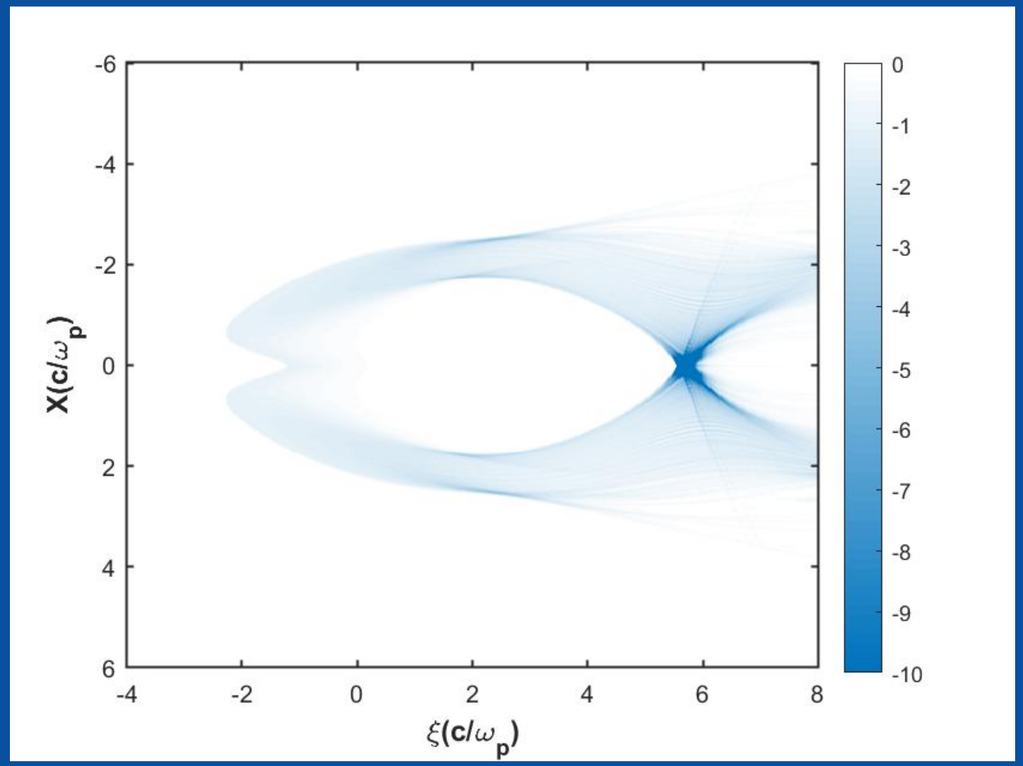




Recent Development: Field Ionization

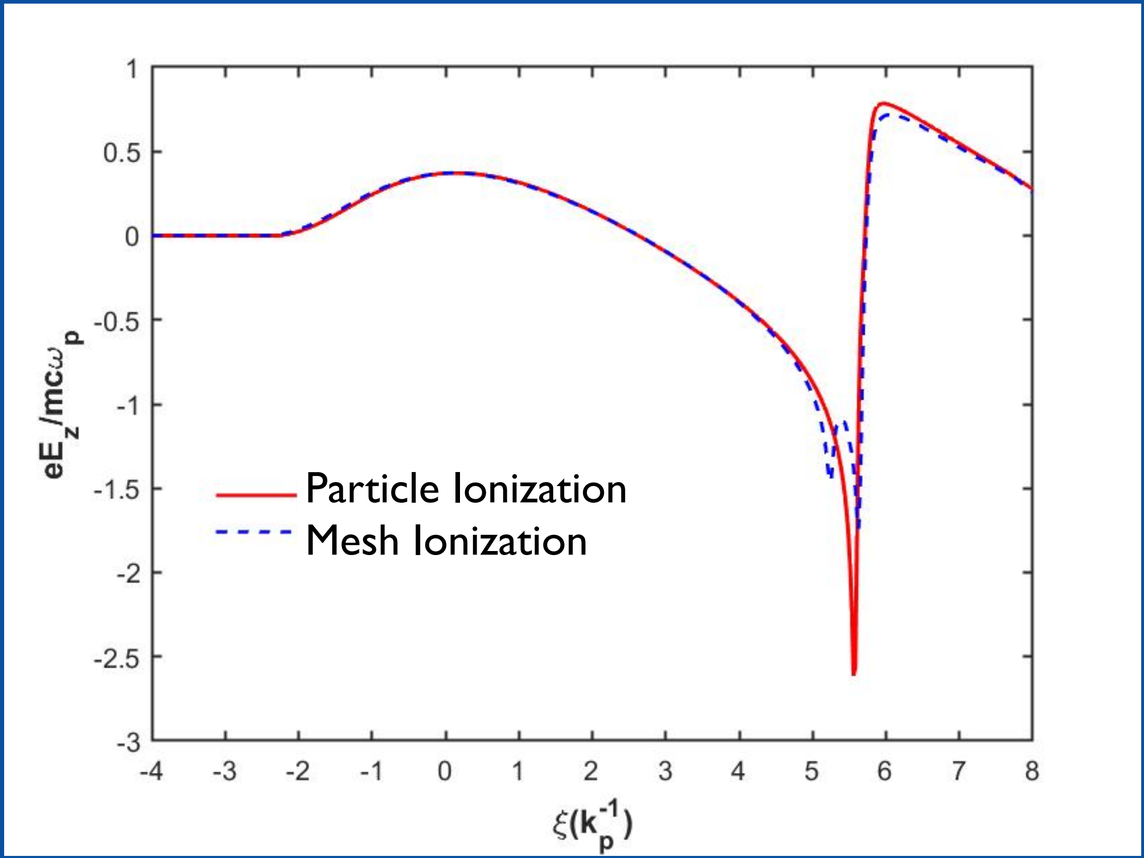
Mesh Ionization → Particle Ionization

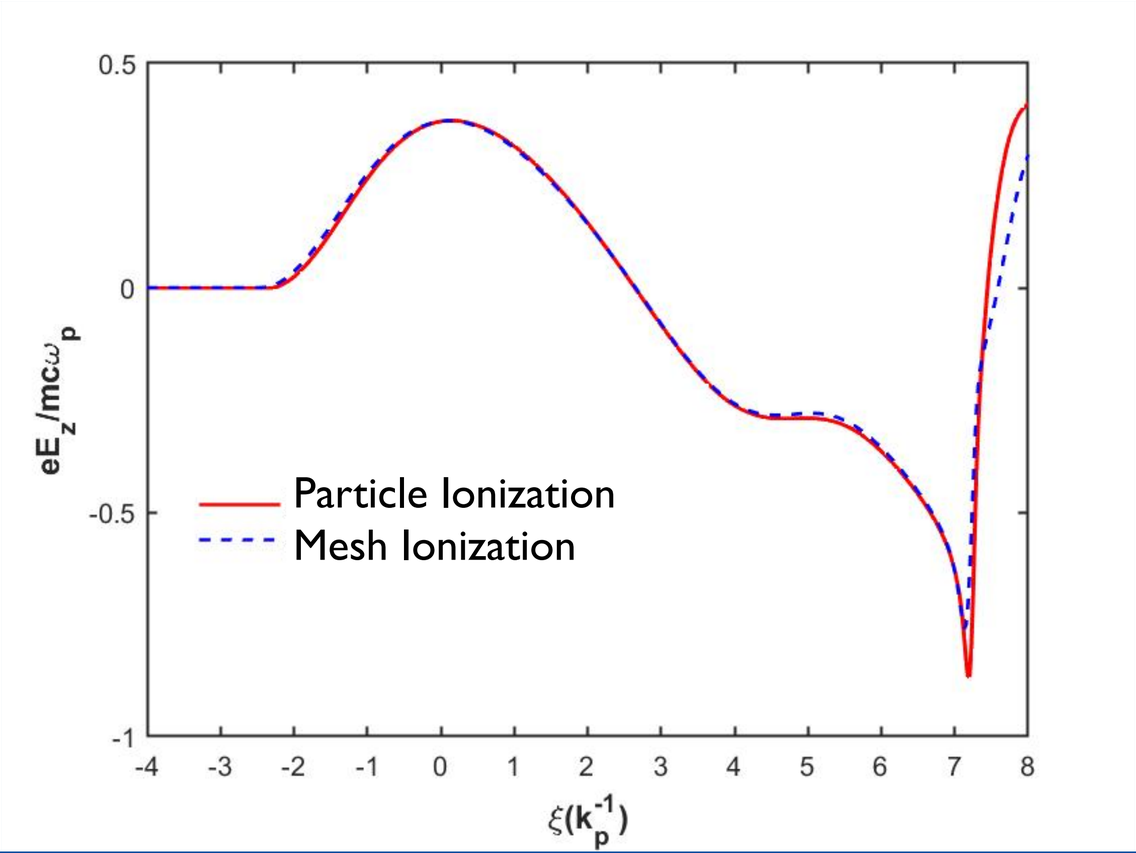




Neutral Class is composed of several Part2d objects

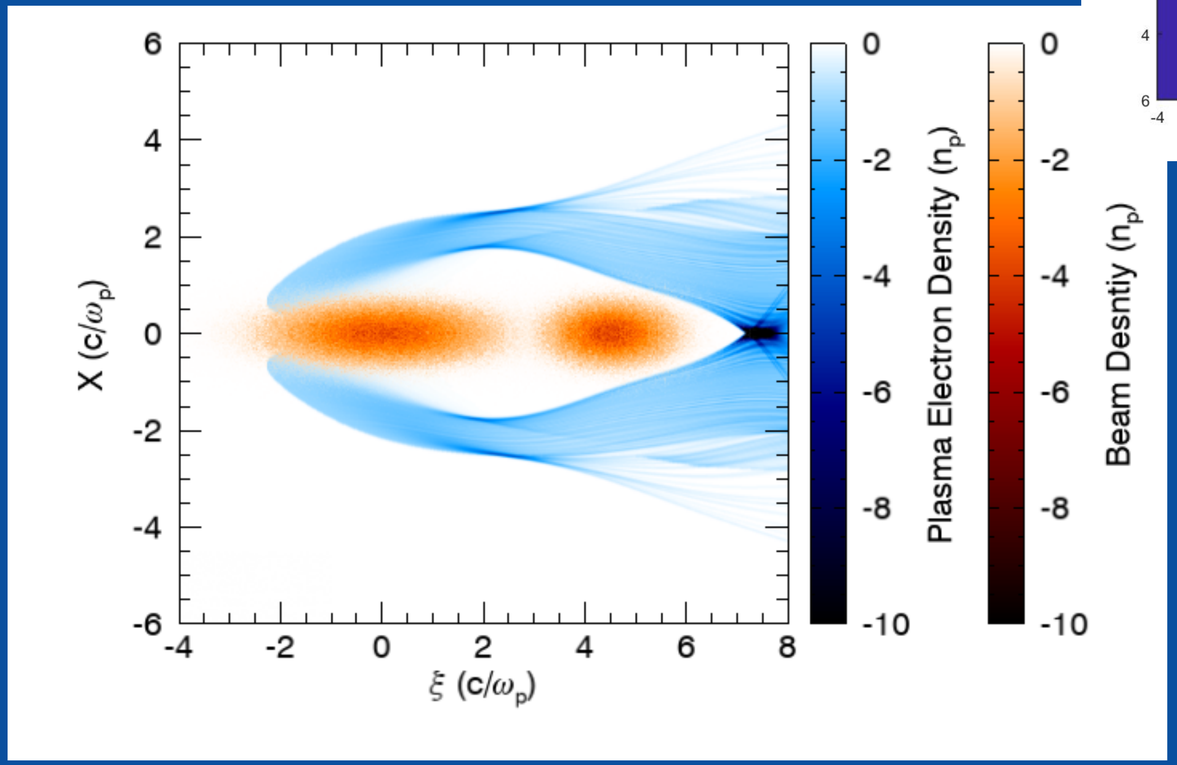
Recent Development: Field Ionization

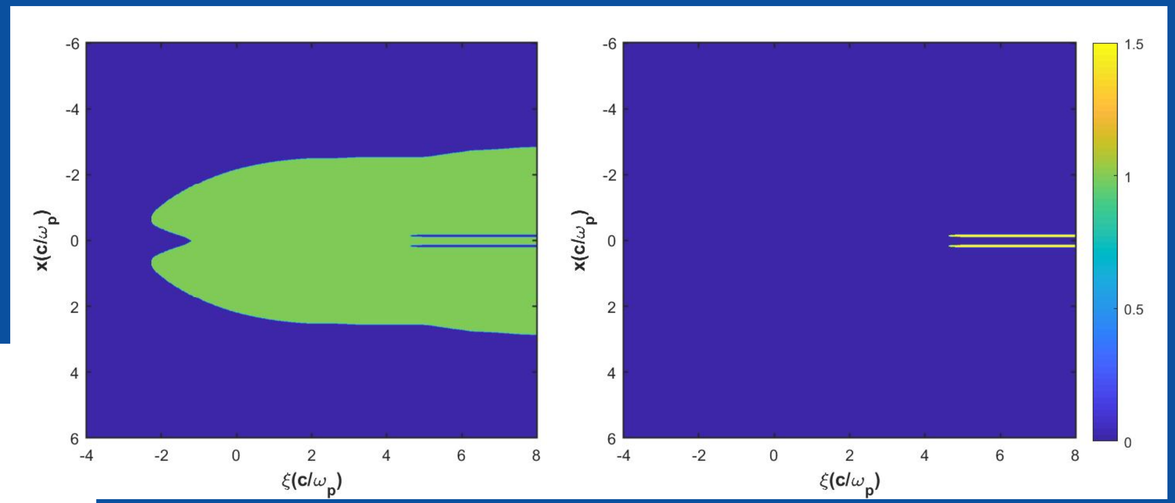


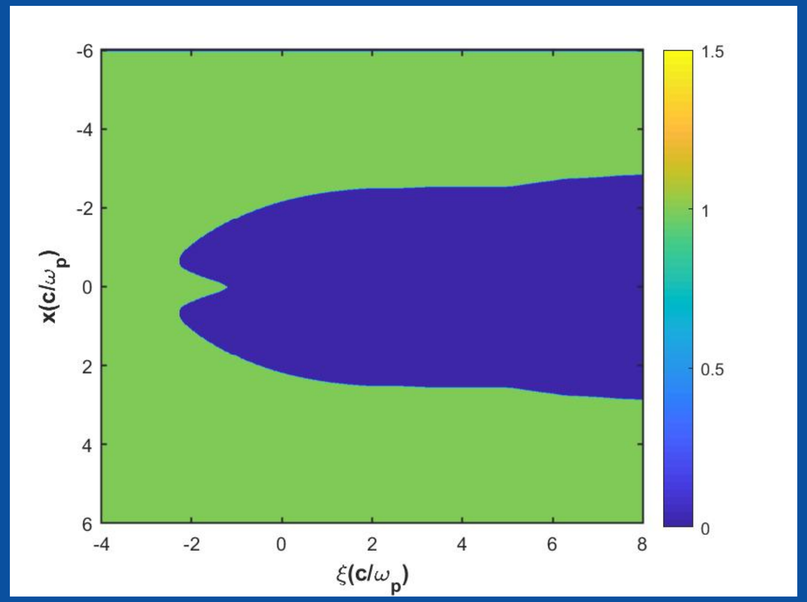


Recent Development: Field Ionization

Multiple Ionization for either Neutral Atoms or Ions





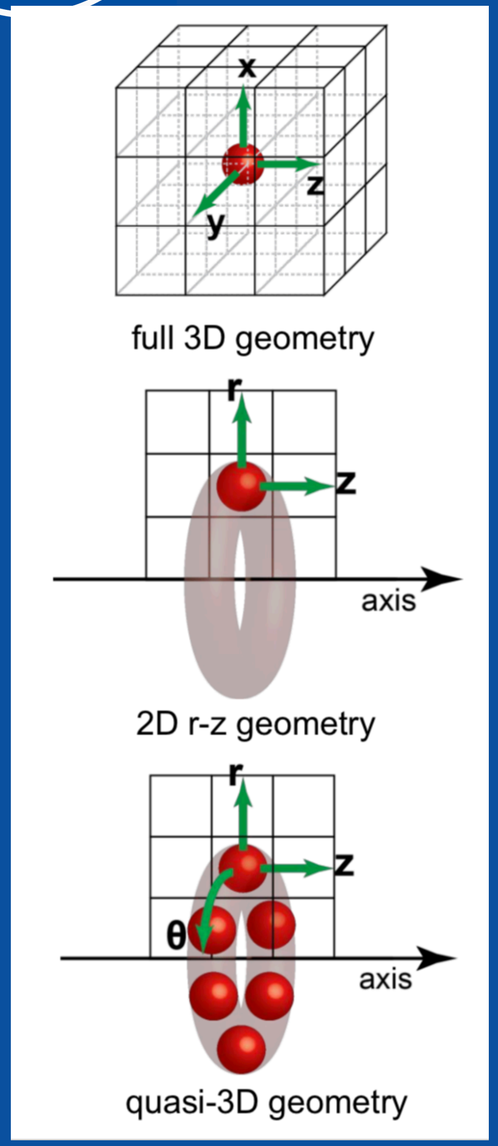


QPAD*: QuickPIC with Azimuthal Fourier Decomposition

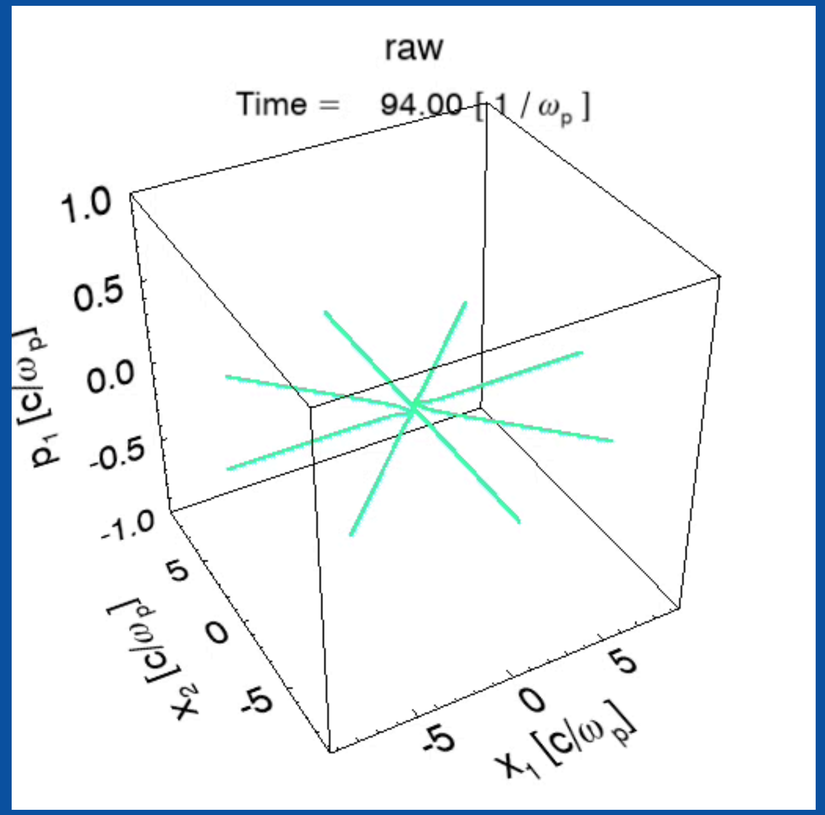
- Azimuthal decomposition is a technique to speed up the simulation without much loss of accuracy. Some explicit PIC codes (e.g. Calder, quasi-3D OSIRIS, FBPIC, PLARES-PIC) have employed this algorithm to achieve 100x ~ 1000x speed-up.
- None of current quasi-static PIC codes has this feature.
- QPAD is a newly developed code based on part of the frame work of open source QuickPIC.

Fei Li, Weiming An*, Viktor K. Decyk, Xinlu Xu, Mark J. Hogan, Warren B. Mori, et. al., "A quasi-static particle-in-cell algorithm based on an azimuthal Fourier decomposition for highly efficient simulations of plasma-based acceleration: QPAD", Computer Physics Communications 261, 107784 (2021).

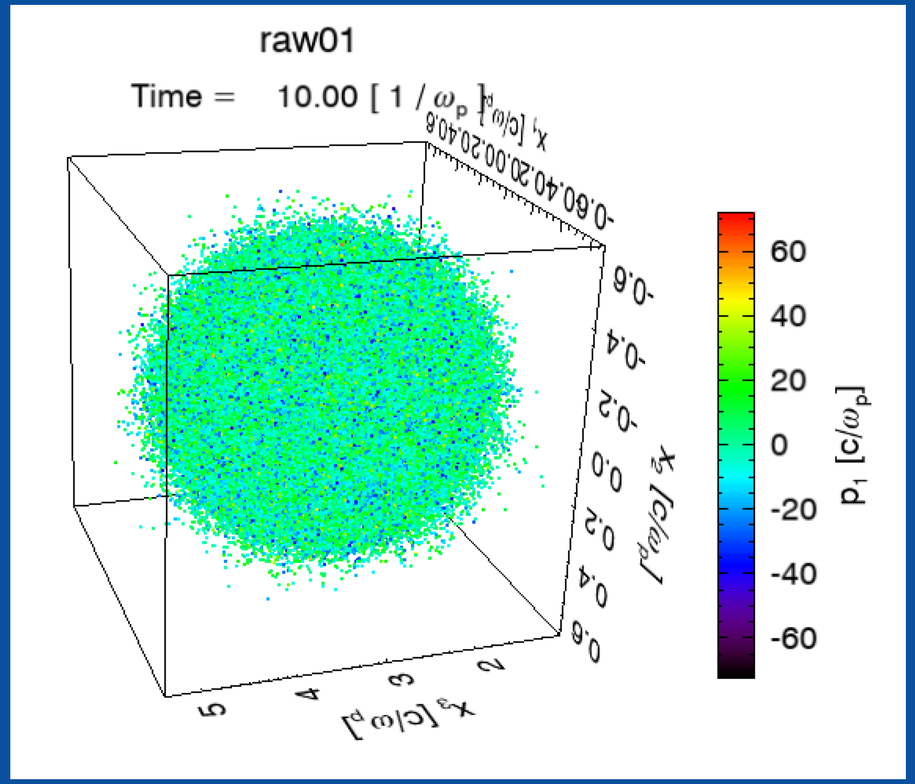
QPAD*: QuickPIC with Azimuthal Fourier Decomposition



Plasma Particle



Beam Particle (3D)

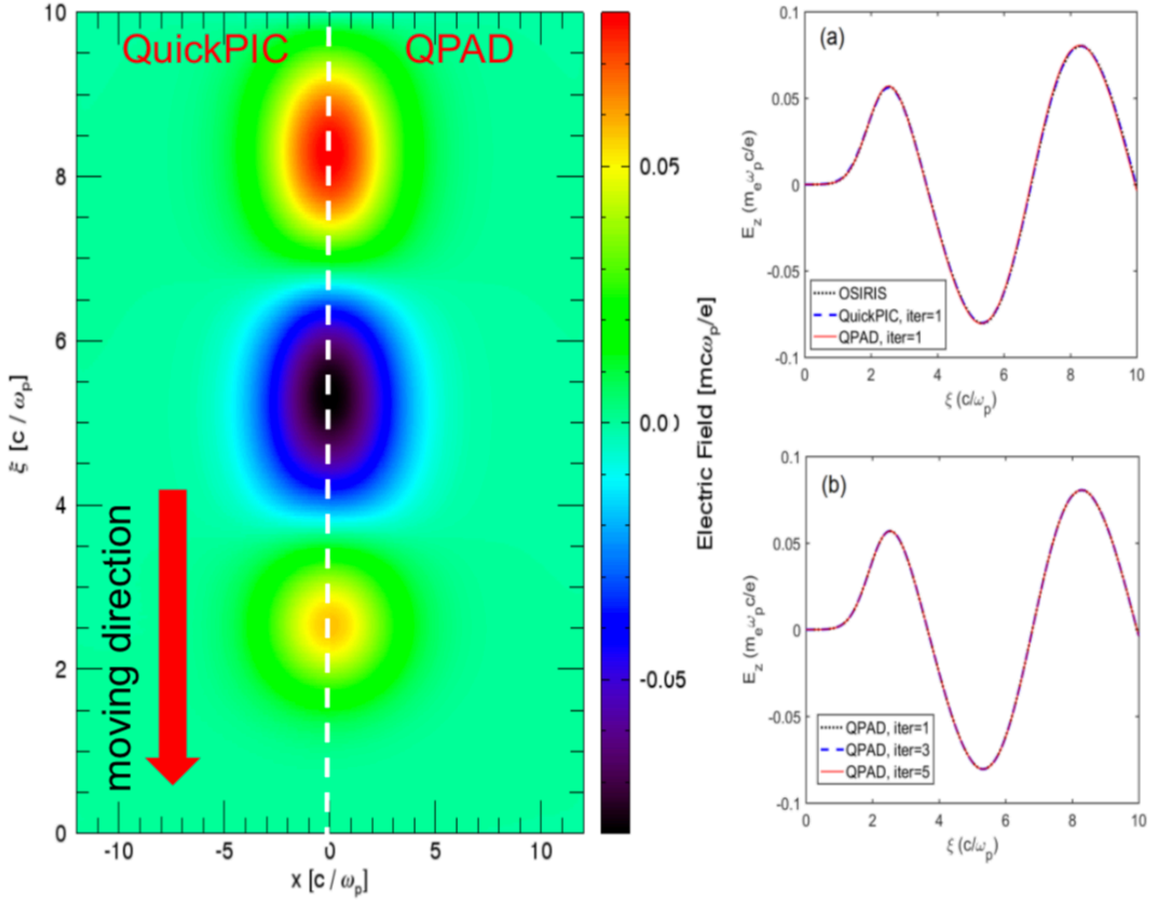


QPAD*: QuickPIC with Azimuthal Fourier Decomposition

Linear regime

$$k_p\sigma_r = 2.0, k_p\sigma_z = 0.5, n_b = 0.1n_p, \Lambda = 0.4$$

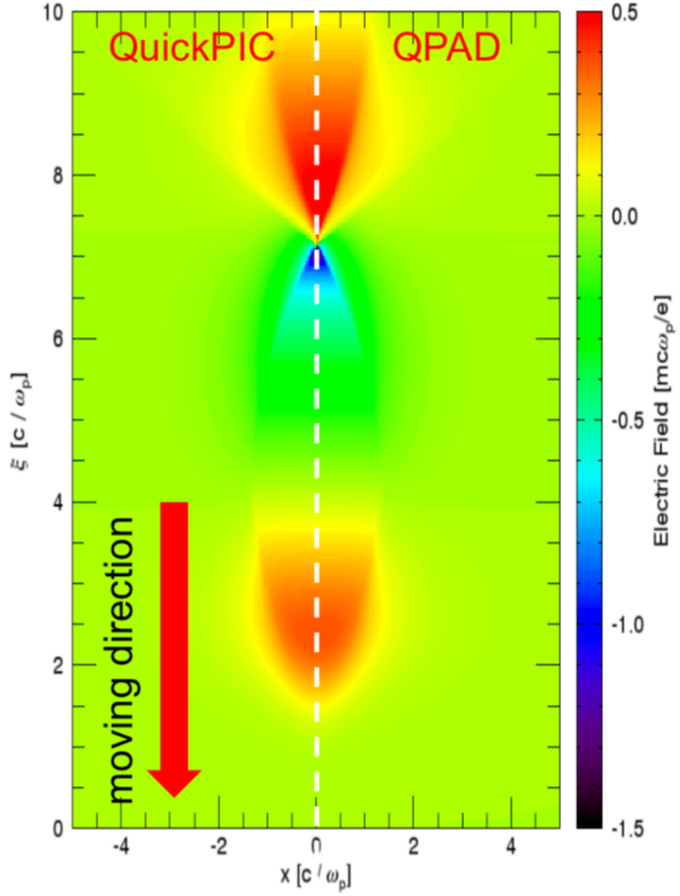
E_z (m=0 mode)

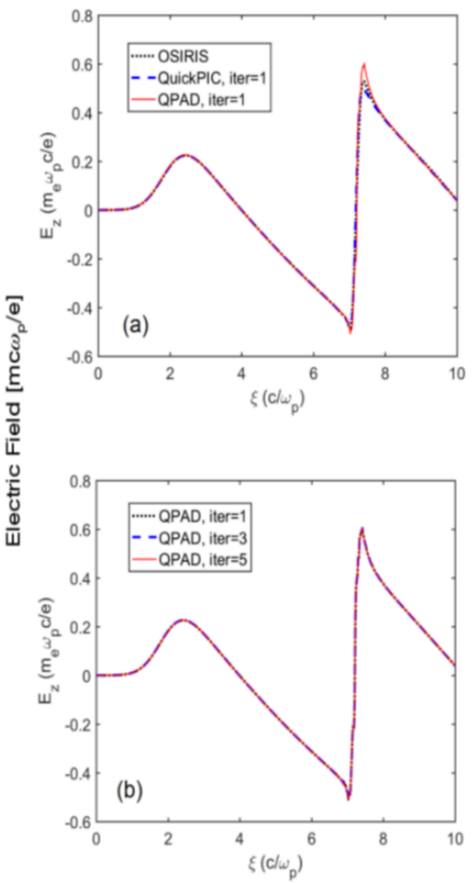


Nonlinear (Blowout) regime

$$k_p\sigma_r = 0.25, k_p\sigma_z = 0.5, n_b = 4n_p, \Lambda = 0.25$$

E_z (m=0 mode)

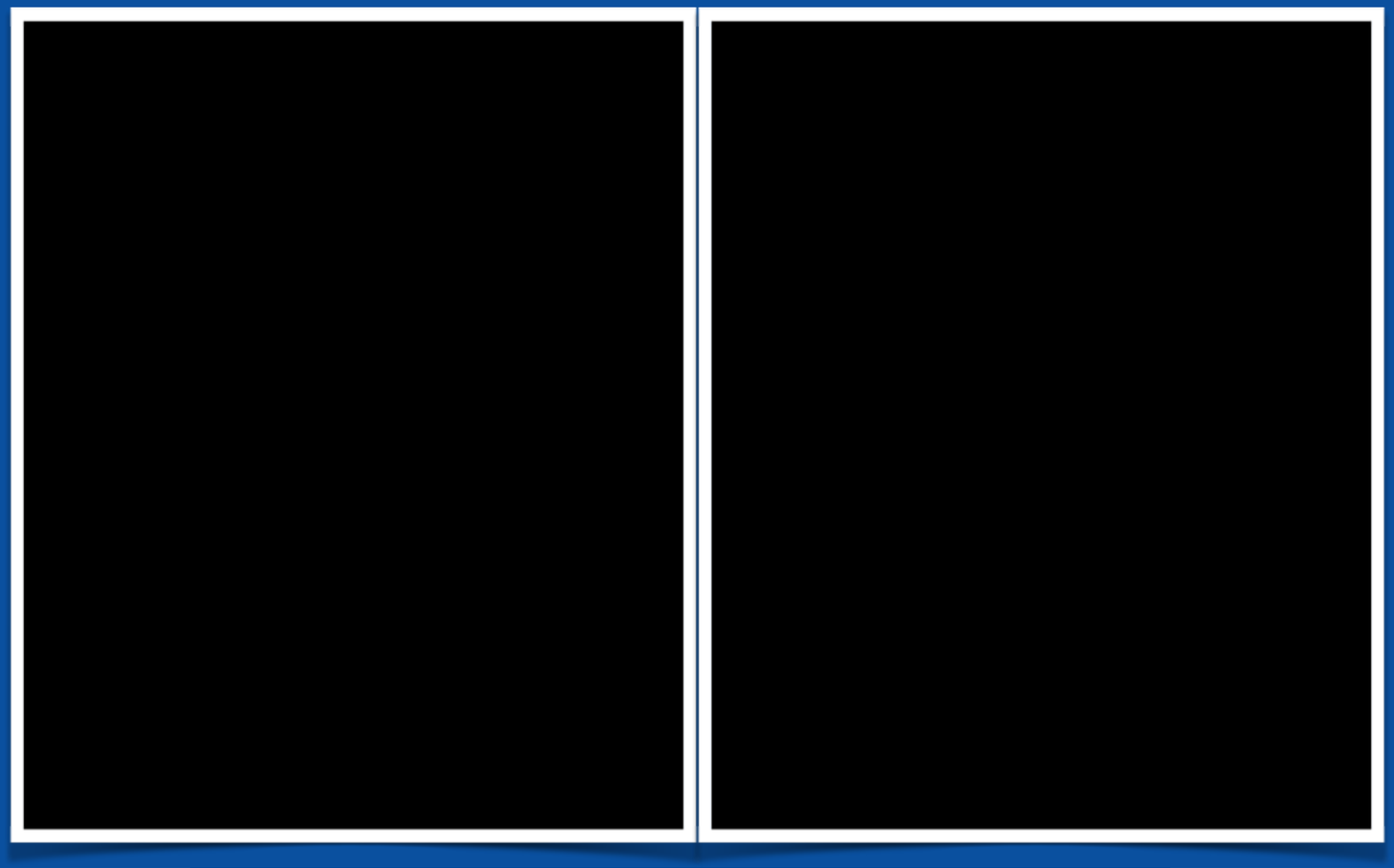


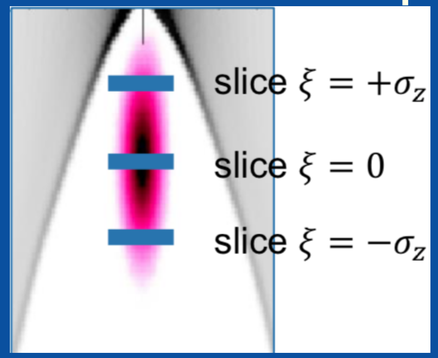


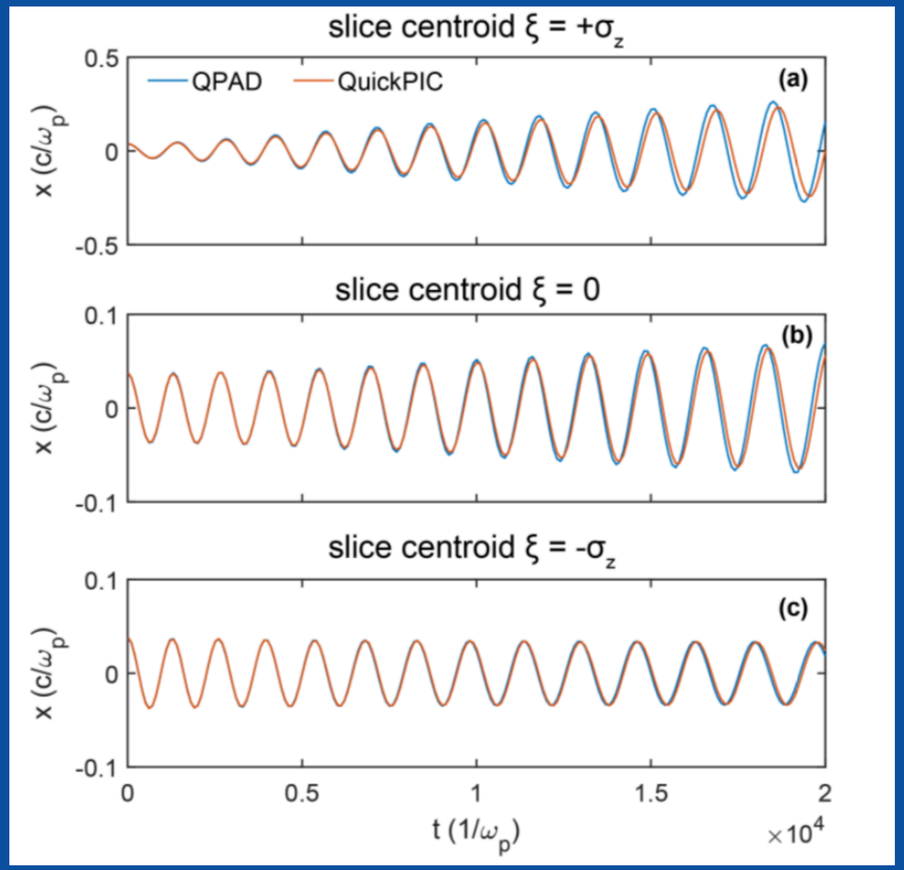
QPAD*: QuickPIC with Azimuthal Fourier Decomposition

QuickPIC

QPAD(4 modes)







drive beam: $k_p\sigma_r = 0.14, k_p\sigma_z = 0.48, \Lambda = 1.8, \gamma = 20000$

trailing beam: $k_p\sigma_r = 0.14, k_p\sigma_z = 0.24, \Lambda = 1.1\ \gamma = 20000, k_p\Delta_{\text{off}} = 0.0375$

Future Plan (QuickPIC and QPAD)

Laser Module

Beam and Plasma Particle Tracking

Adding Modules for Radiation Reaction

Adding Modules for Spin

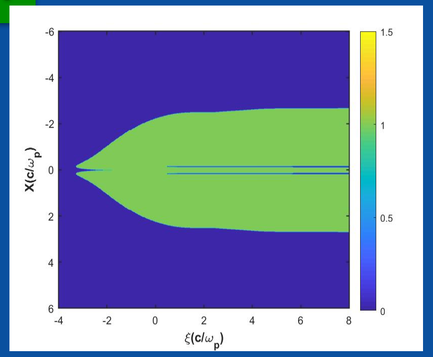
Adaptive 2d and 3d time steps

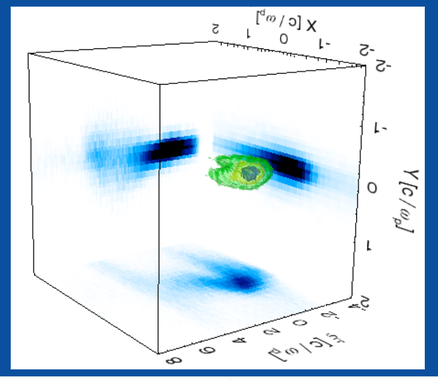
Impact Ionization

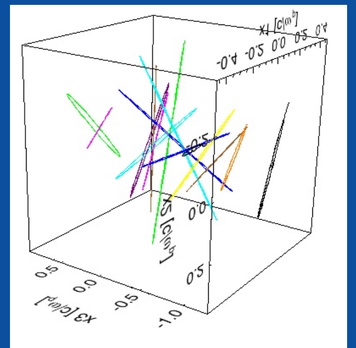
Dynamic load balancing

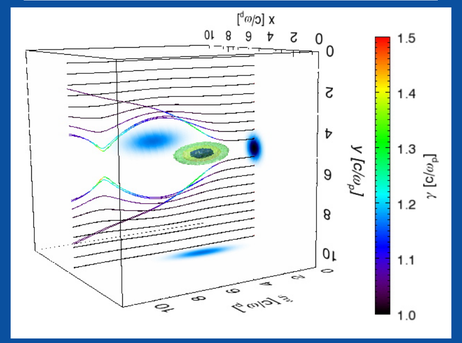
Adaptive mesh refinement

Existing Modules which will be ported into open source QuickPIC.









Thanks!

BNU & UCLA Collaboration

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