GREEN ILC

Plasma Wakefield And Beam Dumps

ALCW, Fukuoka May, 28 2018

Denis Perret-Gallix
LAPP/IN2P3/CNRS-KEK

Green-ILC Objectives

started Oct. 2013

ILC : lower running cost, better operational flexibility, environment friendly

Revisiting all ILC components:

1. Energy Saving: improving efficiency
   90% lost as heat waste +10% to Beam Dumps
2. Operational saving
3. Energy Recovery and Recycling

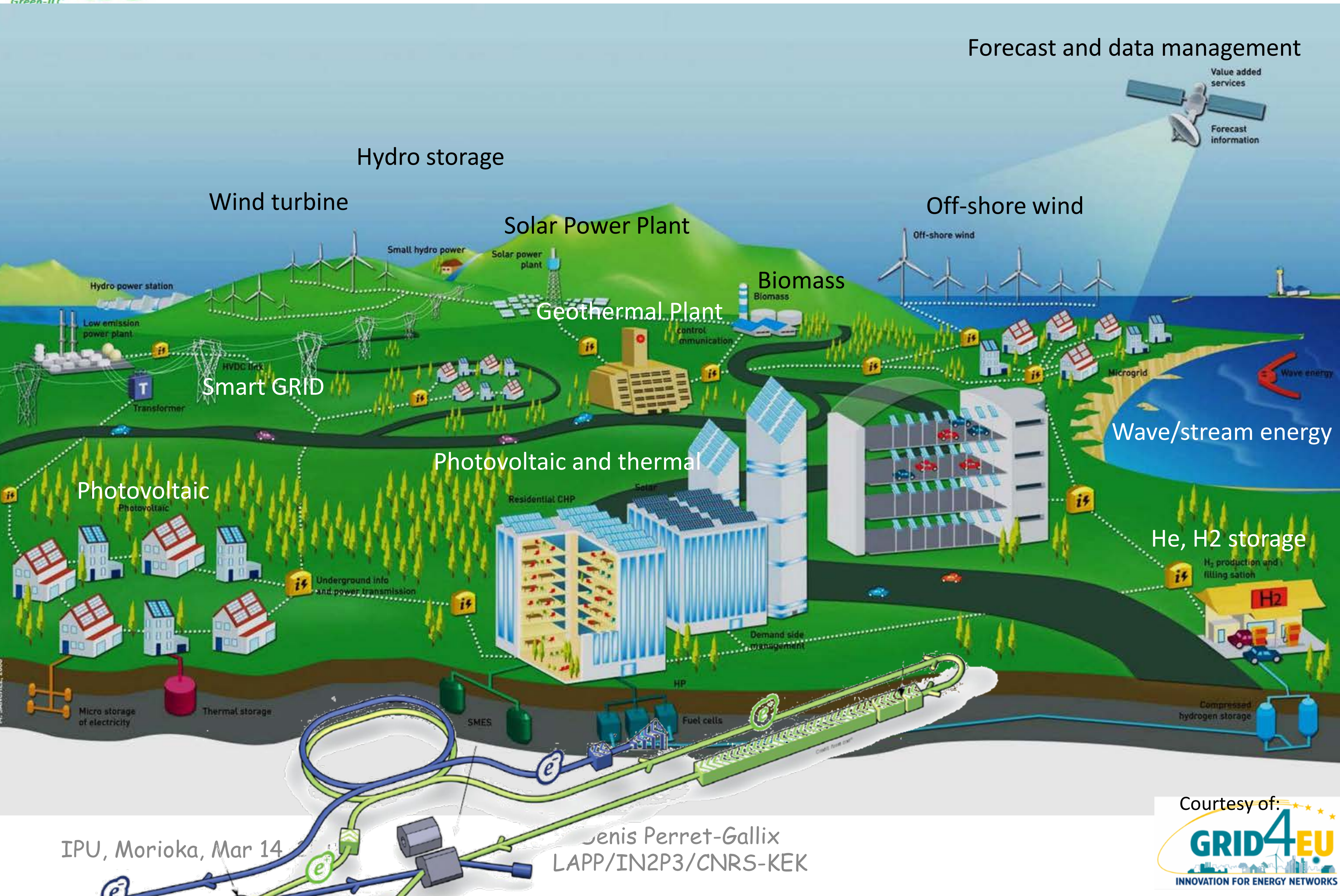
Renewable energies:

1. Renewable energy production, best mix for ILC and ILC site
2. Energy Storage (for energy recovery and intermittency)
3. Distribution and Management: Smart Grid

Energy for: societal needs and world economy,

1. Basic Research
2. Synergies: SC, magnets, beams, computing, photon, neutron factories, plasma acc.
3. Technology innovation
4. ILC as a test bench: e.g. pilot power plants for ILC

ILC "Energy Research Center" with its dedicated energy production



Courtesy of: GRID4EU INNOVATION FOR ENERGY NETWORKS

Beam Dumps

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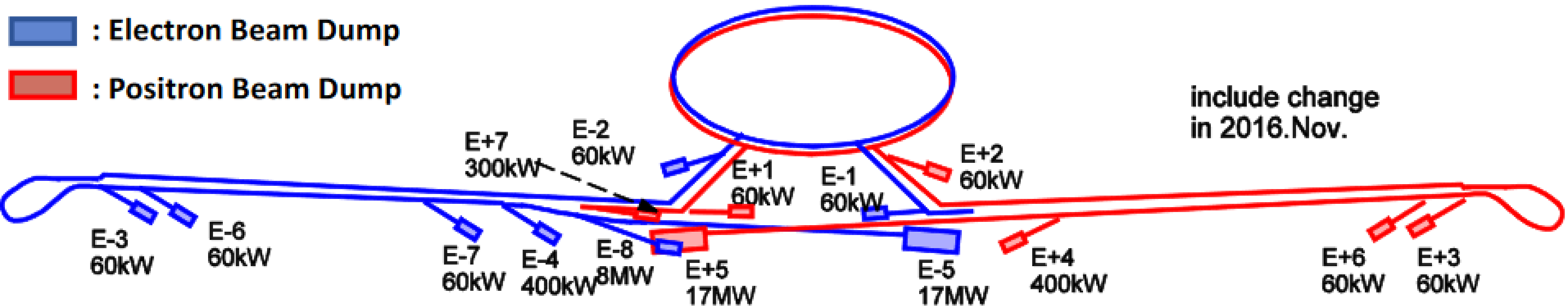
15 ILC Beam Dumps

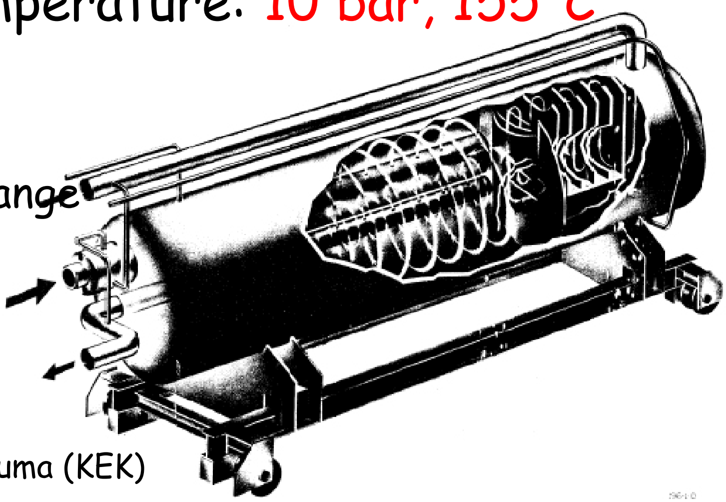
N. Terunuma (KEK)



Purpose	N	Beam Power	Absorber	
Commissioning	9	60 kW	Solid	at the end of sub-systems
Commissioning & MPS	2	400 kW	Solid	at the end of main LINAC ref. Euro-XFEL (300kW)
Photon Dump	1	300 kW	Gas, water?	downstream of the positron target Photon beam can not be deflected/swept. Hits at same point of under discussing in the ILC positron collaboration
5 + 5 Hz Operation for positron generation below e-beam 125 GeV	1	8 MW	Water	near the main beam dump
Main Beam-Dump	2	17 MW	Water	300 m downstream of IP 20% margin is included.

ILC Beam Dumps
Water absorber

- 500 GeV beam power ~17 MW
- 10 m long, Ø 1.5m, water tank, 18 m^3
- Based on SLAC 2.2 MW (only run at 0.8 MW)
- Radioactivation
  - Radiolysis: Hydrogen/Oxygen gas production: needs recombiner
  - Radionuclides A_{10y}=240TBq~6.4 10^3Ci; ^{7}Be (β), ^{3}H(γ); legal drain 5Mbq/m^3
  - Radiation handling: water, air, concrete, window, structural materials
    - Water and Air filtering
  - Emergency: Manage water/vapor leaks or possible window/vessel breaking
- Technological issues: High pressure and temperature: 10 bar, 155°C
  - 2 water cooling loops: primary and secondary
  - Pressure wave due to energy deposit in ps
  - Window (1mm Cu) stress: cooling and remote exchange
- Particle production
  - Muons (700m), Neutrons difficult to contain
- Decommissioning ?
  - 2 beam dumps proposal see: BD and Decommissioning: N. Terunuma (KEK)



See also M. Schmitz:
http://www.desy.de/d3/docs/ilc/ILC-dump-talk_22jun05.pdf

ILC Beam Dumps
Gas Dump

Rob Appleby, Daresbury Laboratory Sep. 2005

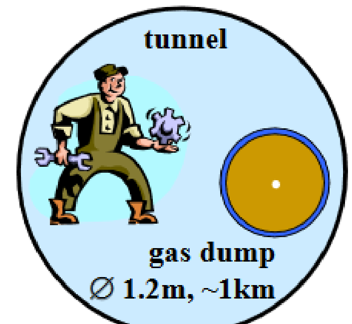
ASTeC Accelerator Science and Technology Centre

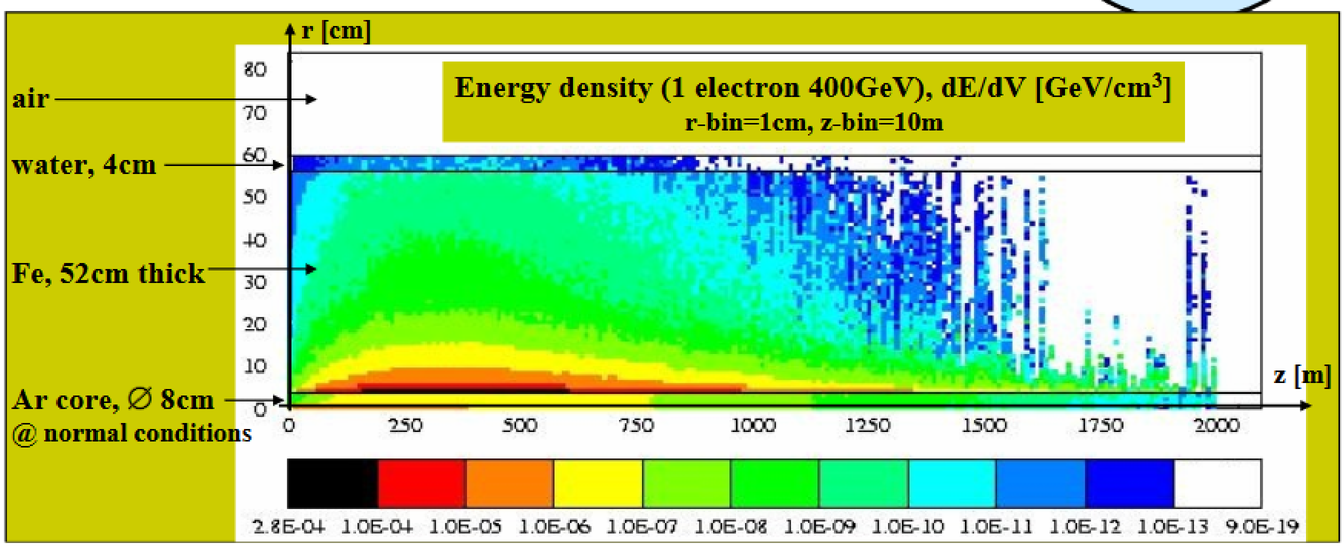
The gas dump

8740 tons iron

<u>**One atomic noble gas core (Ar, Xe) is surrounded by solid material (Fe)**</u>

gas core acts as scattering target (only small amount of energy deposition) and distributes energy longitudinally over ~ 1km into surrounding material. See Ilya's talk at this meeting





N.Terunuma and Yu Morikawa

NRI Report

Technology Survey contracted by MEXT

It pointed out issues about the main dumps ...

- **No prototype exists (17 MW)**
  - the performance not validated
  - SLAC 2 MW dump is not considered to be a prototype.
- **Erosion/corrosion of the window**
  - by the cooling water flow under high radiation level
- **Measure in case of accidents of breaking windov**
  - Can happen, for example, if the beam sweep system is
- **Treatment of radioactive material**
  - Tritium by the water dump

A real-scale prototyping with beam is impossible but a and a controllable design should be established.

What's Needed

- **Simulation of heat and radiation**
  - Within our expertise though lack of manpower now
  - Detailed studies have done for ILC and CLIC
  - Improvement is needed but can be done in the construction stage
- **Window**
  - Material study
  - Experiment is presumably hard
- **Safety issues**
  - Maintenance by remote handling system
  - Accident study
    - What happens if the window is broken (however stiff the window is)?
    - Repair by robotics
  - Engineering design of the dump hall and the surface facility
- **We need help from institutes (in particular CERN), universities and industries**

Plasma Wakefield

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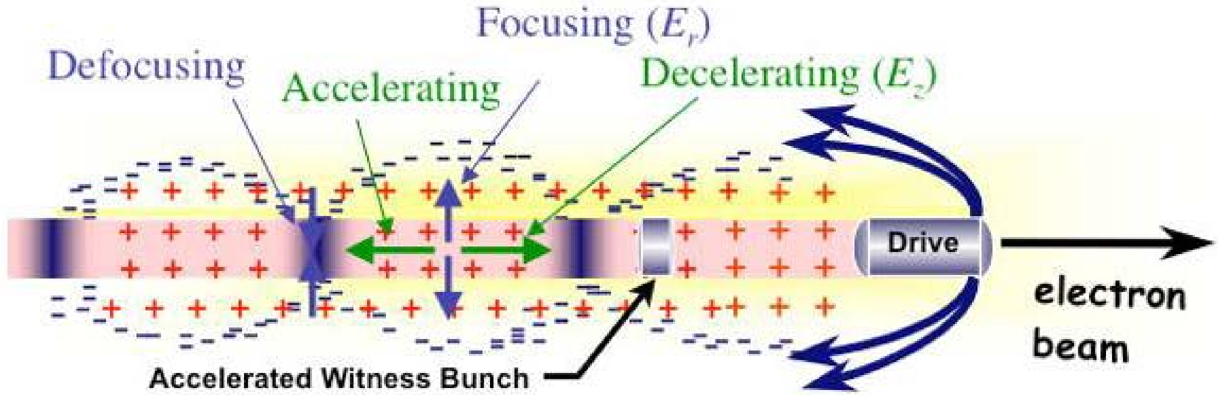
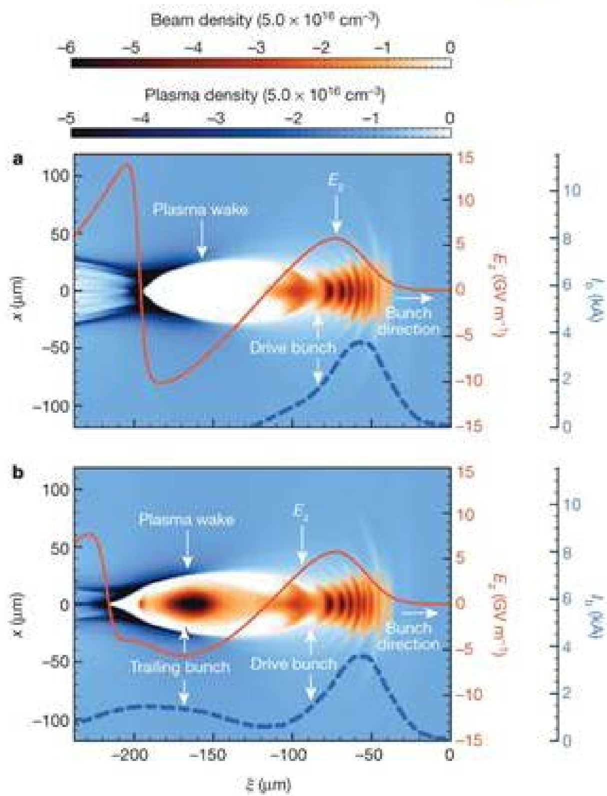
Plasma Acceleration, wakefield acceleration

Green-ILC



FACET (SLAC)

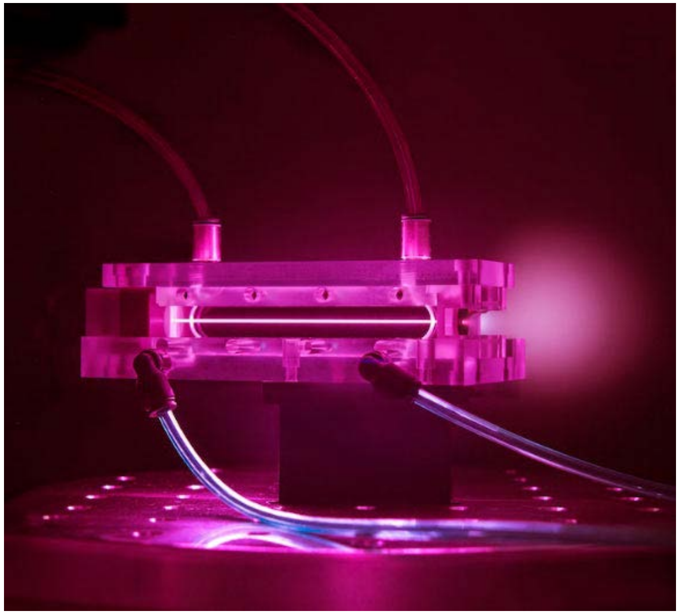
$$
\begin{aligned}
\omega_{\mathrm{pe}} &= \sqrt{\frac{n_{\mathrm{e}}e^2}{m^*\varepsilon_0}}\,[\mathrm{rad/s}] \\
N_e &= 3.10^{21}\,[\mathrm{m}^{-3}] \\
\lambda &= 610\,[\mu m] \\
f &= 490\,[GHz]
\end{aligned}
$$



Wakefield Beam Acceleration

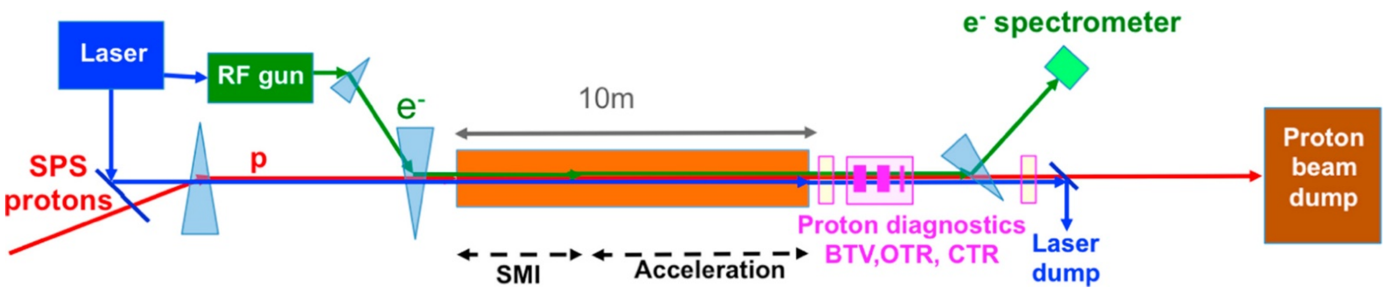
- First proposed by Tajima, T.; Dawson, J. M. (1979) "Laser Electron Accelerator". Phys. Rev. Lett. **43**: 267–270
- Accelerating Gradients 30-40 GV/m, 10^3 larger than SC RF
  - 30 GV/m , 1 GeV on 3.3 cm: laser
    Leemans; et al. (2006). "GeV electron beams from a cm-scale accelerator". Nature Physics. **418**: 696–699.
  - 47 GV/m : 42-> 82 GeV on 0.85 m : electron beam
    Blumenfeld; et al. (2007). "Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator". Nature. **445**: 741–744.
  - 48 GV/m: 4.25 GeV on 9 cm: laser
    Physical Review Letters. **113** (25): 245002 BELLA(Berkley) 2014
    - 6% rms ener. spread, 6pC, 3.7e7 e-, 0.3 mrad rms divergence

A disruptive technology



BELLA, credit: Roy Kaltschmidt.

- But Bunch density, higher energy, energy spread, emittance...
- AWAKE 400 GeV proton beam (CERN)



Denis Perret-Gallix
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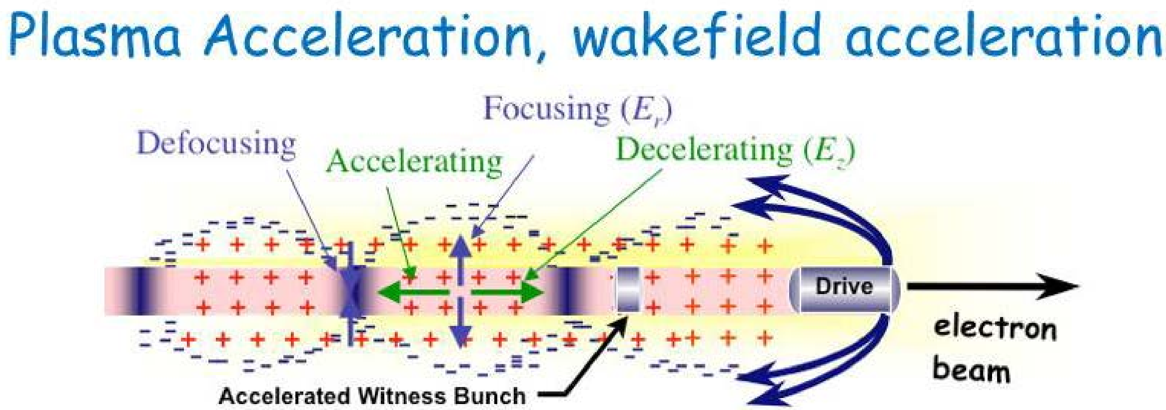
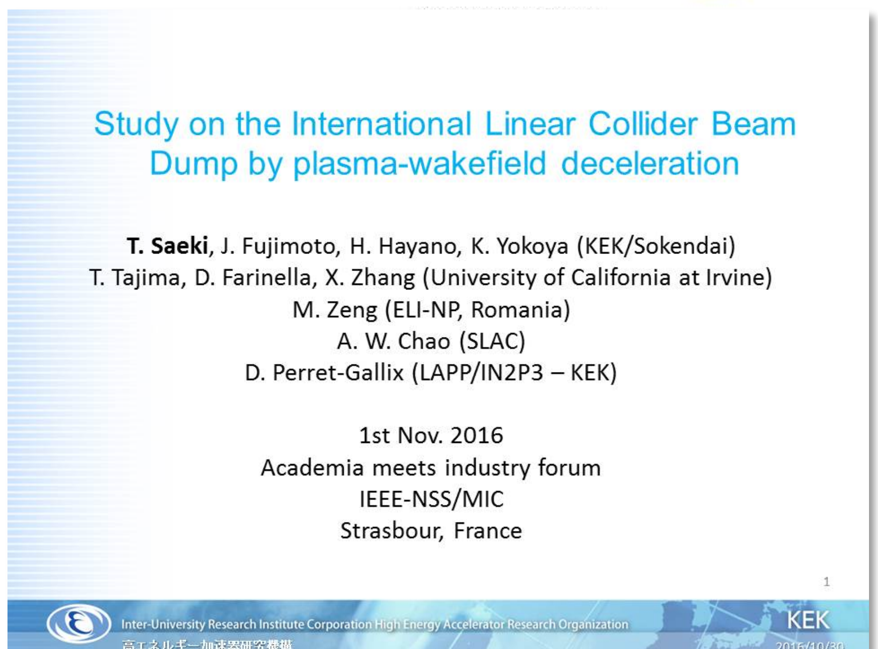
Plasma cell tube AWAKE

Fig. 9: Prototype of 10 m long rubidium vapour plasma cell for AWAKE

Wakefield Deceleration: Beam Dump





Study on the International Linear Collider Beam Dump by plasma-wakefield deceleration

T. Saeki, J. Fujimoto, H. Hayano, K. Yokoya (KEK/Sokendai)
T. Tajima, D. Farinella, X. Zhang (University of California at Irvine)
M. Zeng (ELI-NP, Romania)
A. W. Chao (SLAC)
D. Perret-Gallix (LAPP/IN2P3 – KEK)

1st Nov. 2016
Academia meets industry forum
IEEE-NSS/MIC
Strasbour, France

1

Inter-University Research Institute Corporation High Energy Accelerator Research Organization
高エネルギー加速器研究機構
KEK
2016/10/30

Deceleration by plasma collective effect

- Deceleration already observed at plasma accelerator experiments (FACET)
- Shorter beam dump compared to a gas dump.
- No Window
- Very little radioactive wastes, no ^{3}H, ^{7}Be, ...
  no muons (if final E_b <80 MeV), almost no neutrons
- Betatron radiation << bremstralhung for beam $\gamma < 10^7$ (10 TeV)
- Possible electrical/RF energy recovery from plasma oscillations
- Thermal heat removal issue

Needs conventional simple beam dump for backup, low energy particles and security

Wakefield deceleration

1. Collective deceleration: Toward a compact beam dump
   H.-C. Wu,T. Tajima,D. Habs,A. W. Chao,and J. Meyer-ter-Vehn
   Phys.Rev Accelerators and Beams 13, 101303 (2010)

2. Passive and active plasma deceleration for the compact disposal of electron beams
   A. Bonatto, C.B. Schroeder, J.-L. Vay, C.G.R. Geddes, C. Benedetti, E.Esarey and W.P. Leemans; https://aip.scitation.org/doi/am-pdf/10.1063/1.4928379

3. Simulation study of a passive plasma beam dump using varying plasma density
   Kieran Hanahoe, Guoxing Xia, Mohammad Islam, Yangmei Li, Oznur Mete-Apsimon, Bernhard Hidding and Jonathan Sm; https://arxiv.org/pdf/1701.01008.pdf

4. Collective Deceleration of Laser-Driven Electron Bunches
   S. Chou, J. Xu, K. Khrennikov, D. E. Cardenas, J. Wenz, M. Heigoldt, L. Hofmann, L. Veisz and S. Karsch; PRL 117, 144801 (2016)

5. Long-range attraction of an ultrarelativistic electron beam by a column of neutral plasma
   E Adli, C A Lindstrøm, J Allen, C I Clarke, J Frederico, S J Gessner, S Z Green, M J Hogan, M D Litos, B O'Shea, V Yakimenko, W An, C E Clayton, K A Marsh, W B Mori, C Joshi, N Vafaei-Najafabadi, S Corde and W Lu; New J. Phys.18(2016) 103013

Very preliminary simulation studies

- PIC (Particle in Cell) simulation, plasma physics simulation
- Used in most plasma physics: from diluted plasma to fusion and space plasma
- Pseudo particles (PP) representing group of particles: local densities
    1. Solving Maxwell's field equations (E,B) on a grid from charges generated by the PP's.
    2. Update PP's velocities and position, and back to 1.
- 3 PP species: beam, plasma electron, plasma ion

EPOCH
An open source PIC code for high energy density physics

This work was in part supported by the UK EPSRC funded Collaborative Computational Project in Plasma Physics grant reference number EP/M022463/1

- EPOCH (UK, EPSRC) Extendable PIC Open Collaboration
- VisIt (LLNL,DOE) Visualization
- GDL (IDL, Harris) Gnu/Interactive Data Language

- See following 2-D simulation but Epoch is 3-D enabled

- Other PIC: Osiris, QuickPIC, PIConGPU, WARP, INF&RNO

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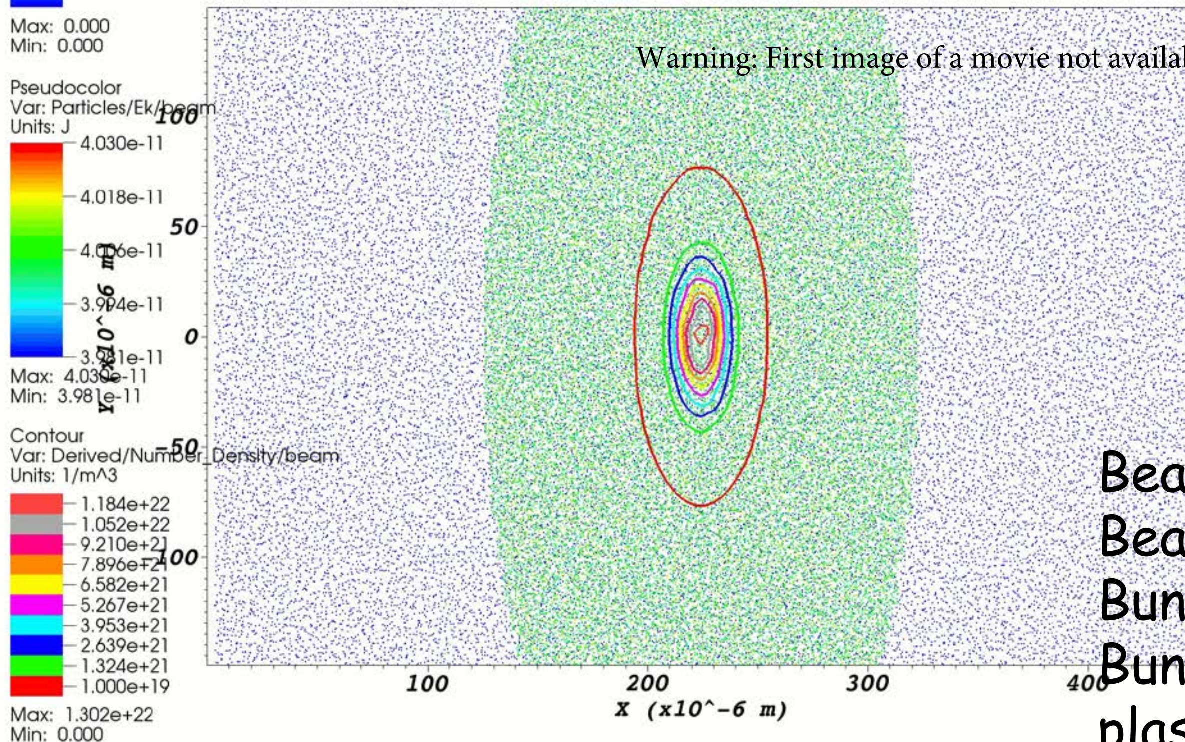
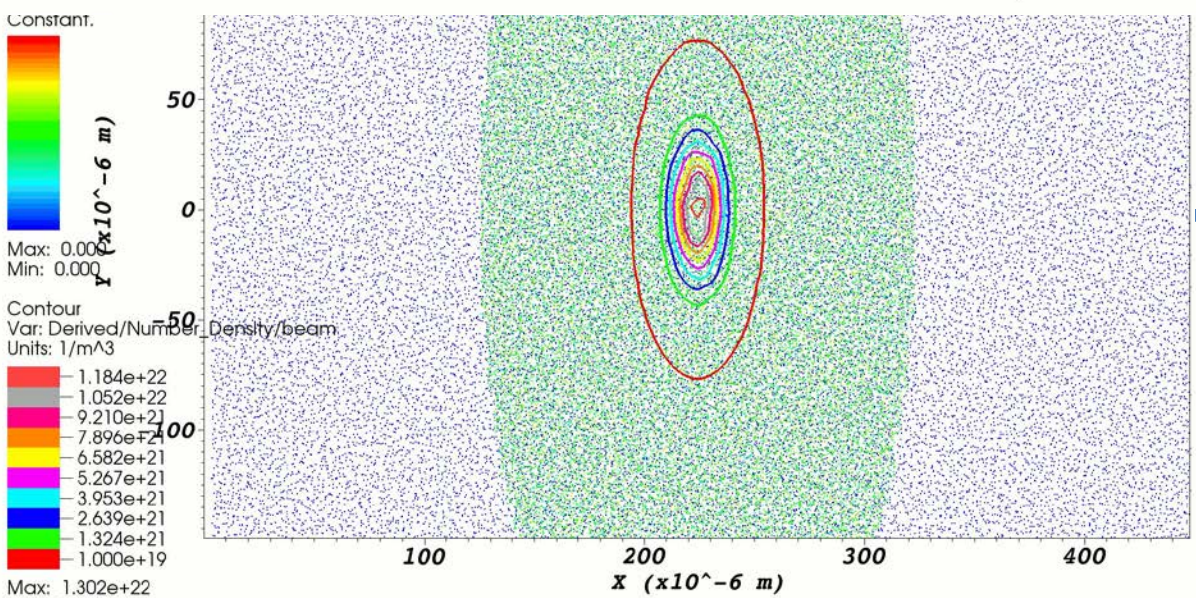
Beam and Plasma only



Electron beam

Beam energy: 250 MeV
Beam part.: 0.065 e^{10}
Bunch length: 7.5 μm
Bunch radius : 20 μm
plasma density :2 e^{23} m^{-3}



Positron beam

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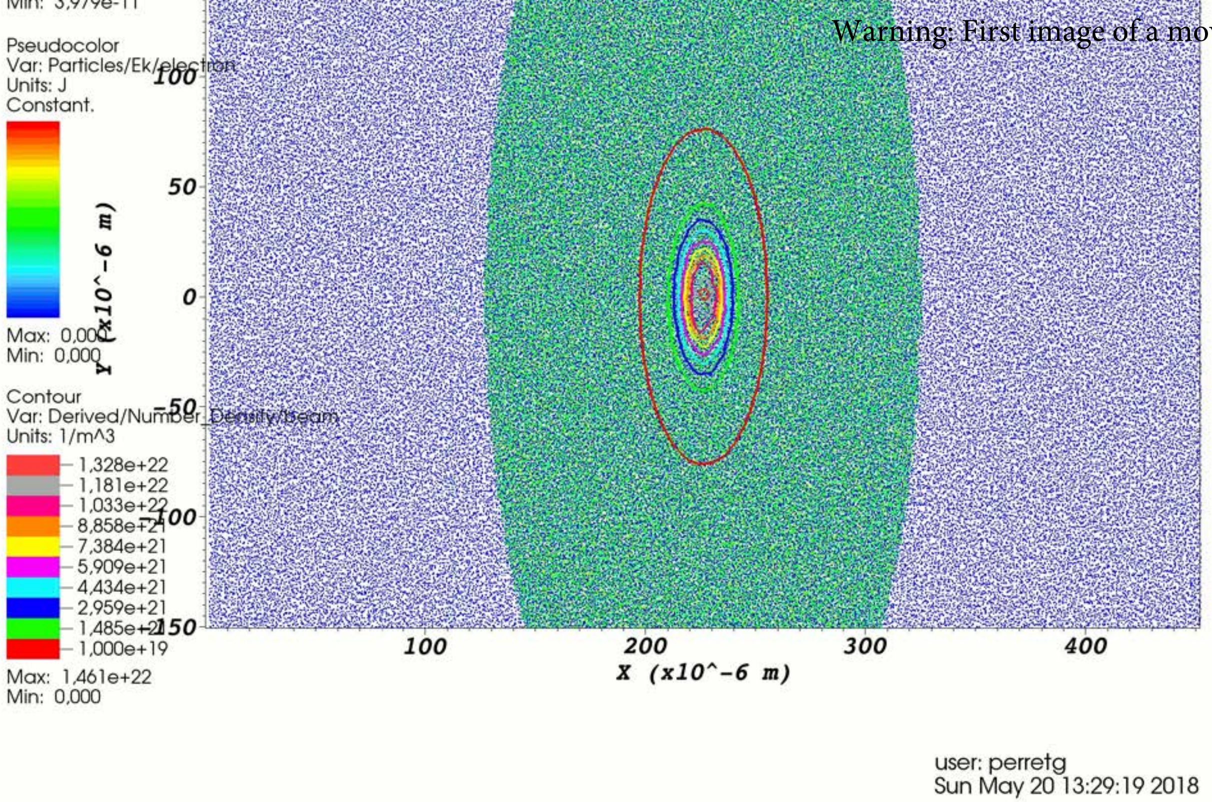
Plasma electron

+

Plasma proton



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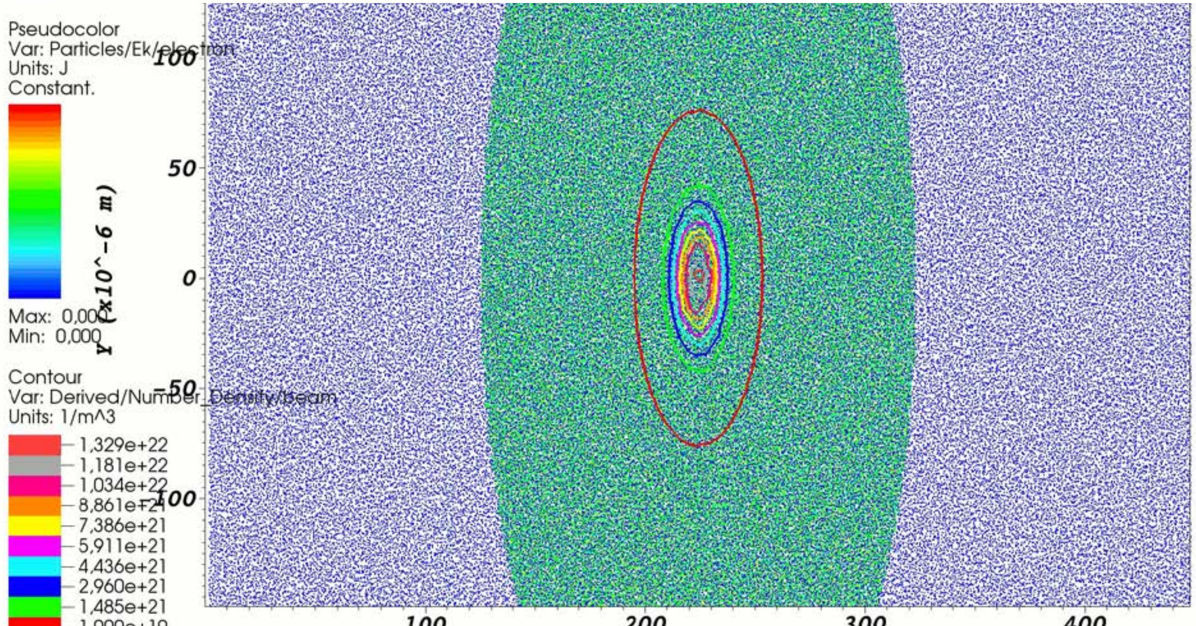
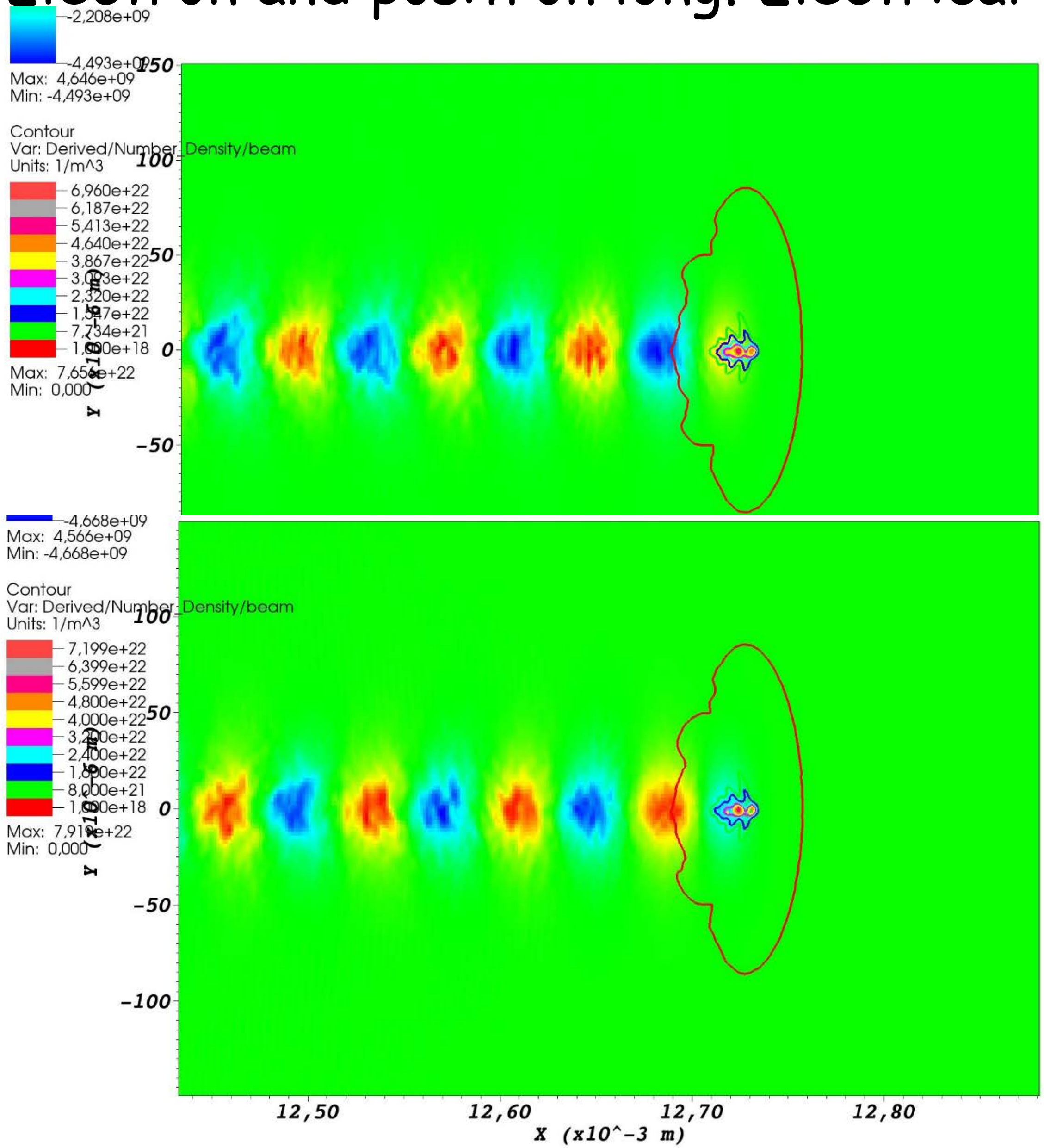


Positron beam

Electron and positron long. Electrical field



Electron Beam

Positron Beam

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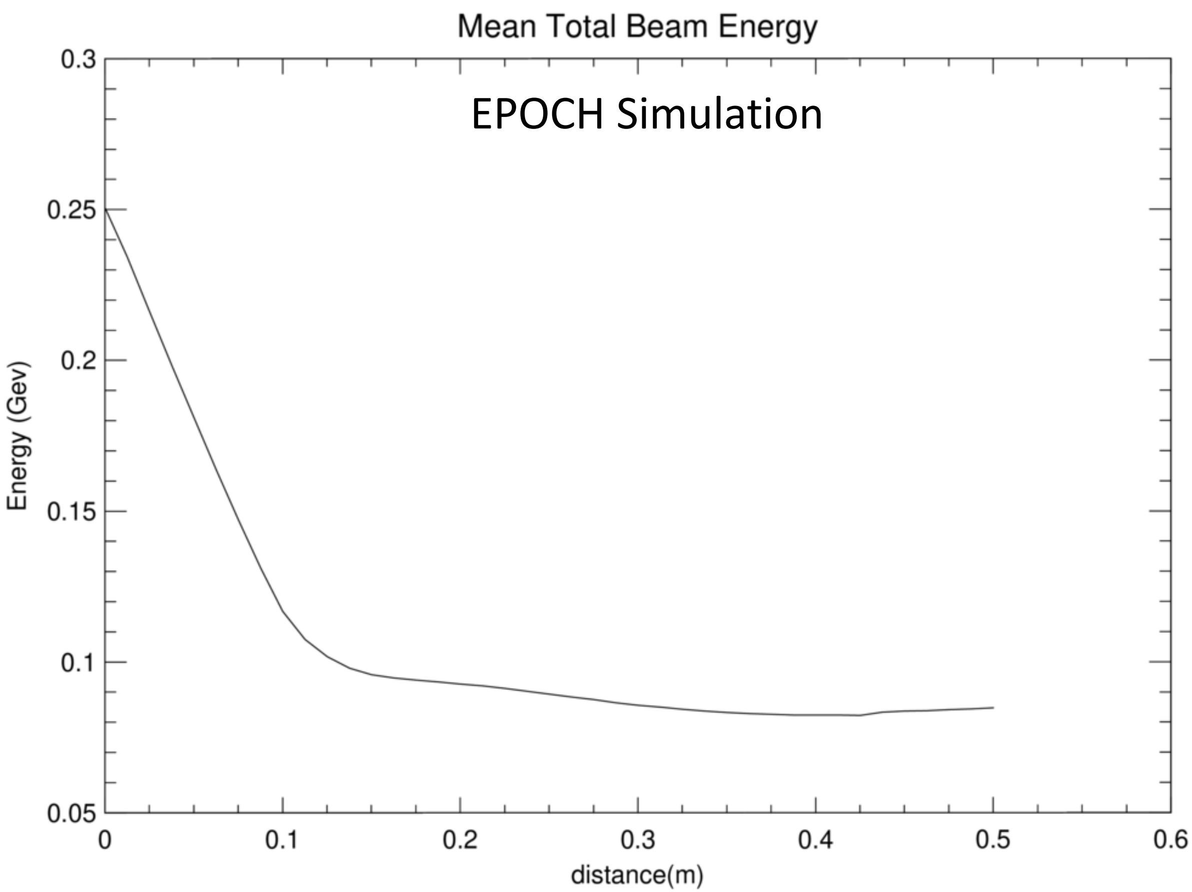
Low energy, short and thin beam



Beam energy: 250 MeV
Beam part.: 0.065 e^{10}
Bunch length: 7.5 μm
Bunch radius : 20 μm
plasma density :2 e^{23} m^{-3}

40% deceleration on 12 cm

1.25 GV/m

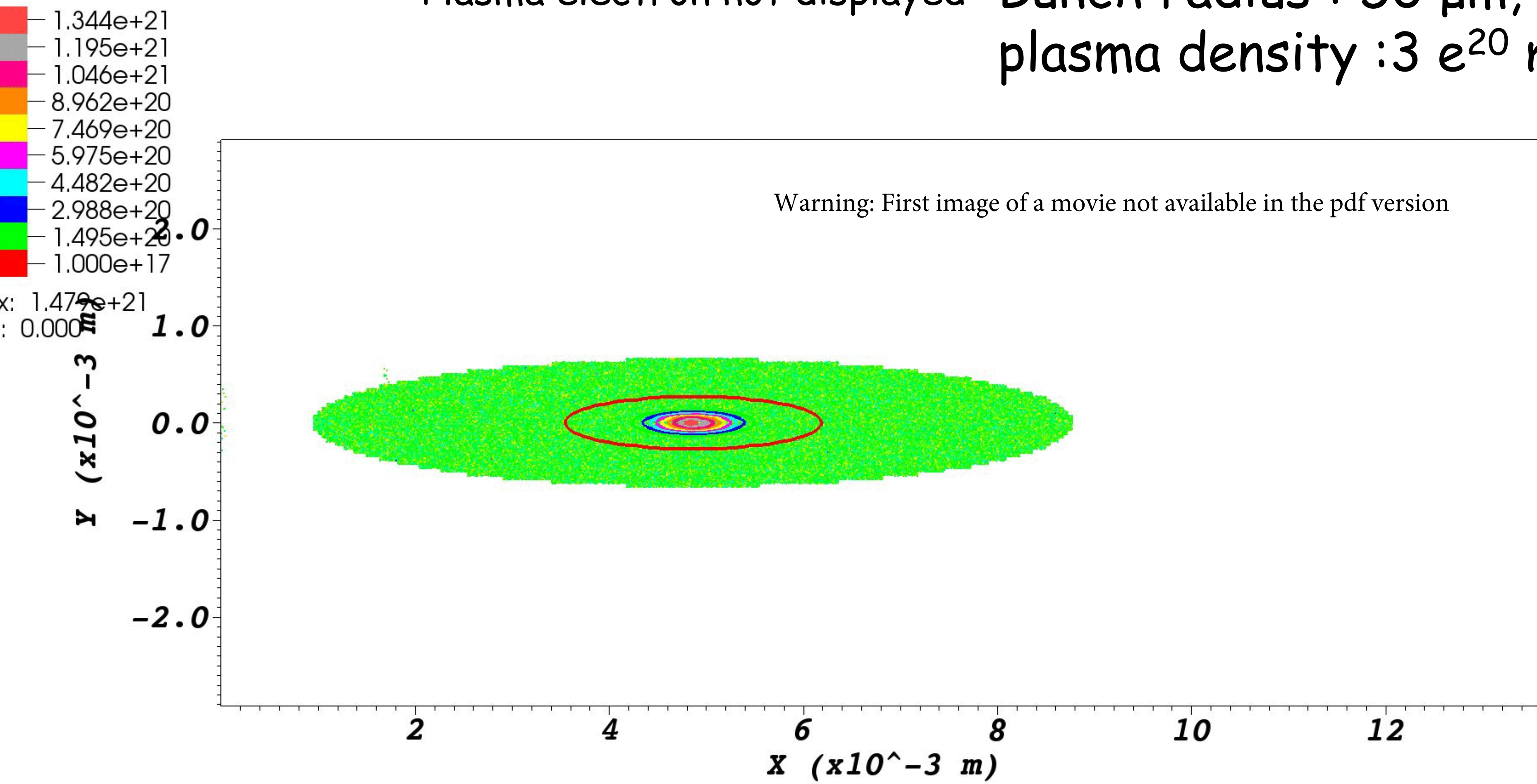
4.005e-08
x: 4.006e-08
: 4.005e-08

ntour
: Derived/Number_Density/beam
s: 1/m^3

Bunch in plasma

Plasma electron not displayed

Beam energy: 250 GeV,
Bunch length: 300 µm,
Bunch radius : 50 µm,
plasma density :3 e^{20} m^{-3}



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user: perretg
Sat May 12 16:57:16 2018

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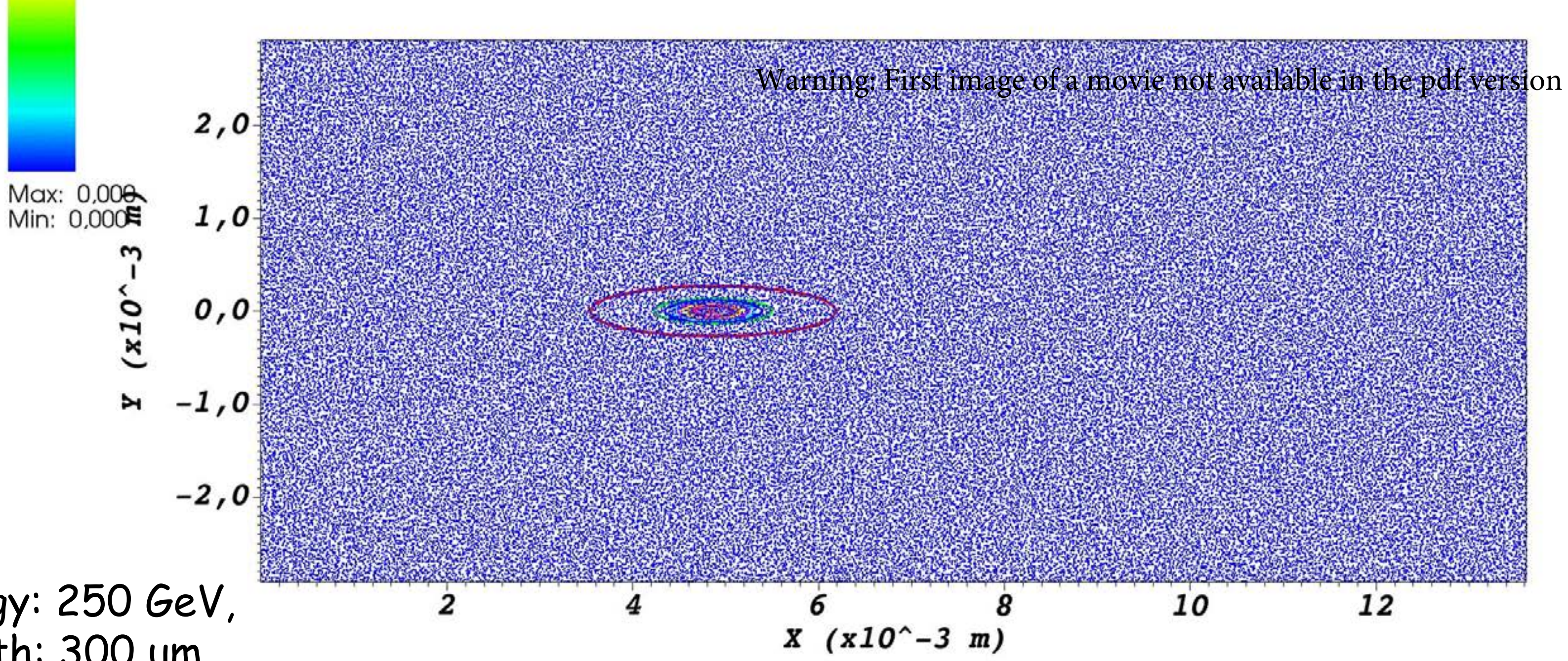
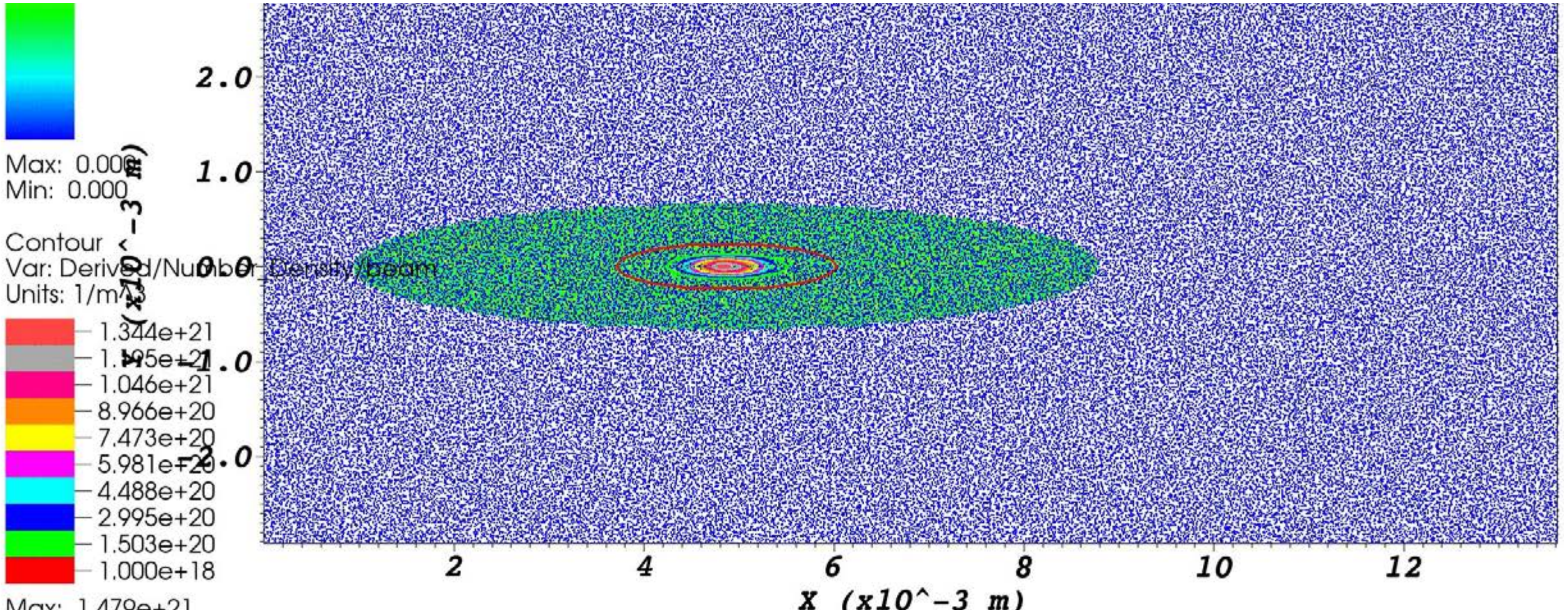
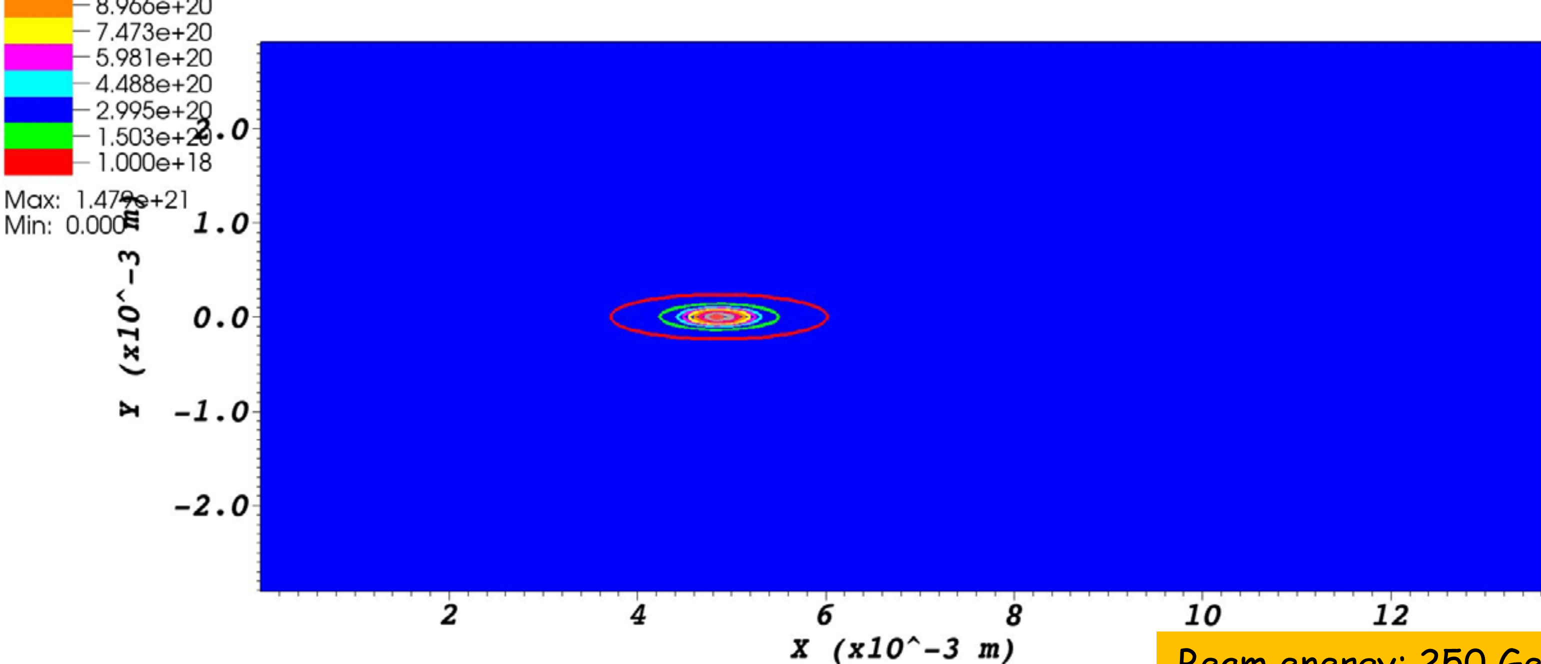


Beam energy: 250 GeV,
Bunch length: 300 μm,
Bunch radius : 50 μm,
plasma density :3 e^{20} m^{-3}

Bunch + plasma electron

user: perretg
Sat May 12 16:42:44 2018





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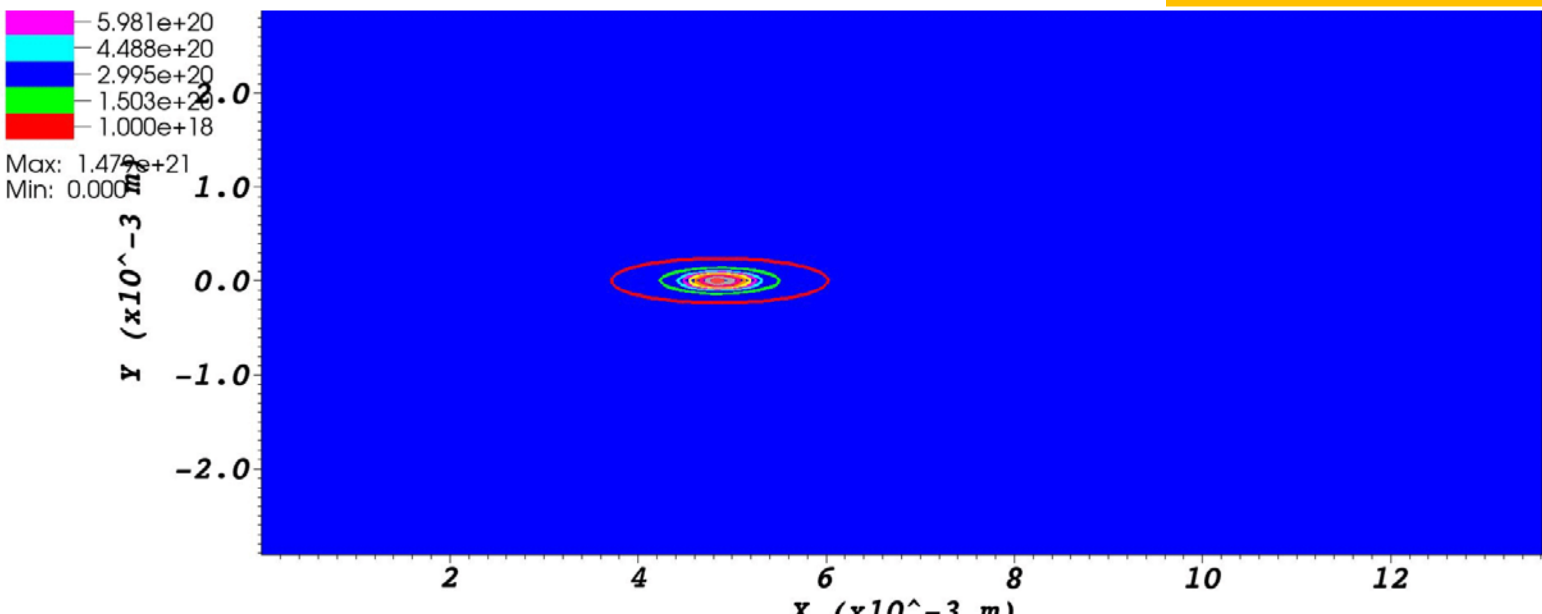
Electric field in plasma

Beam energy: 250 GeV,
Bunch length: 300 µm,
Bunch radius : 50 µm,
plasma density :3 e^{20} m^{-3}



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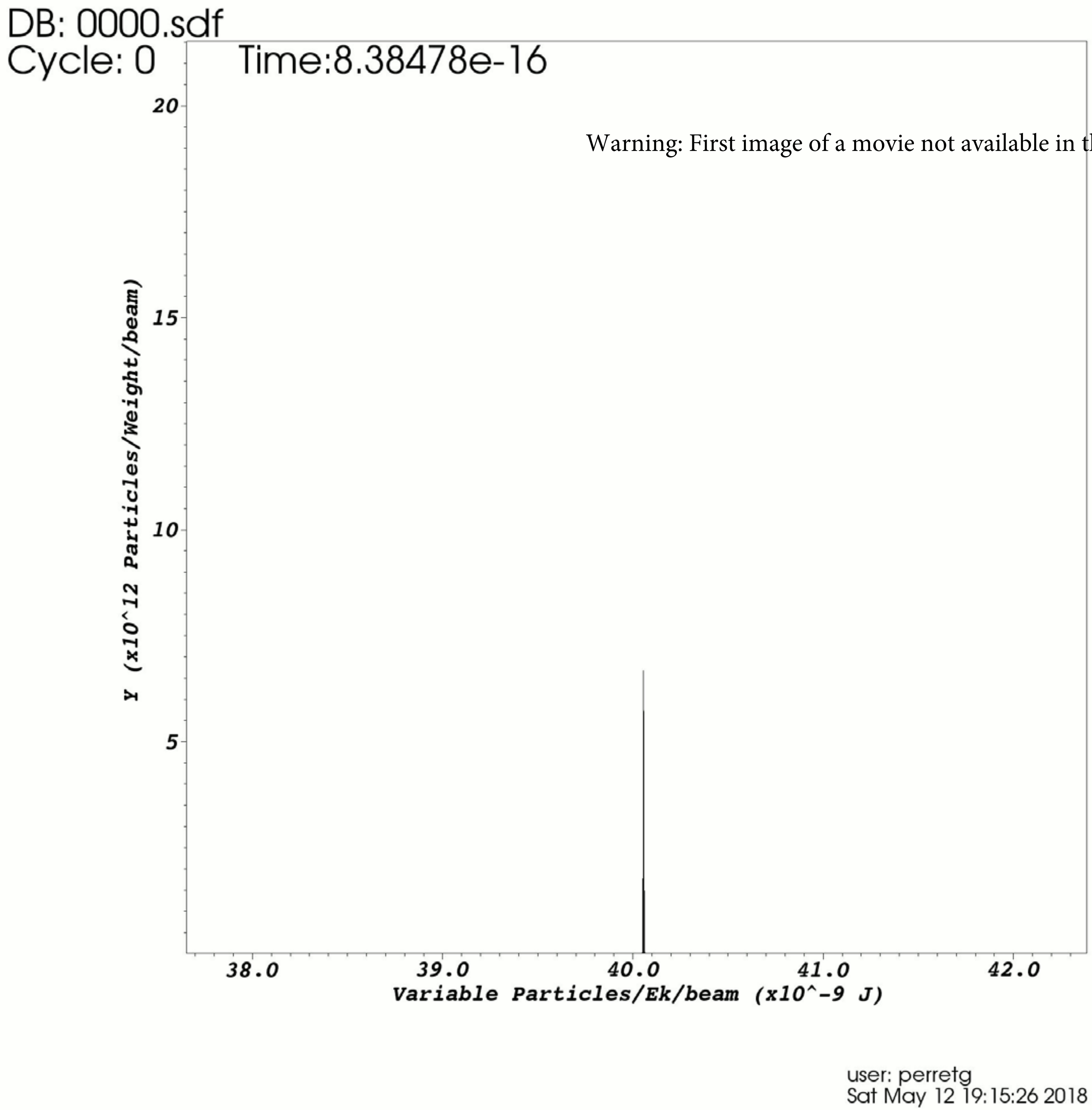
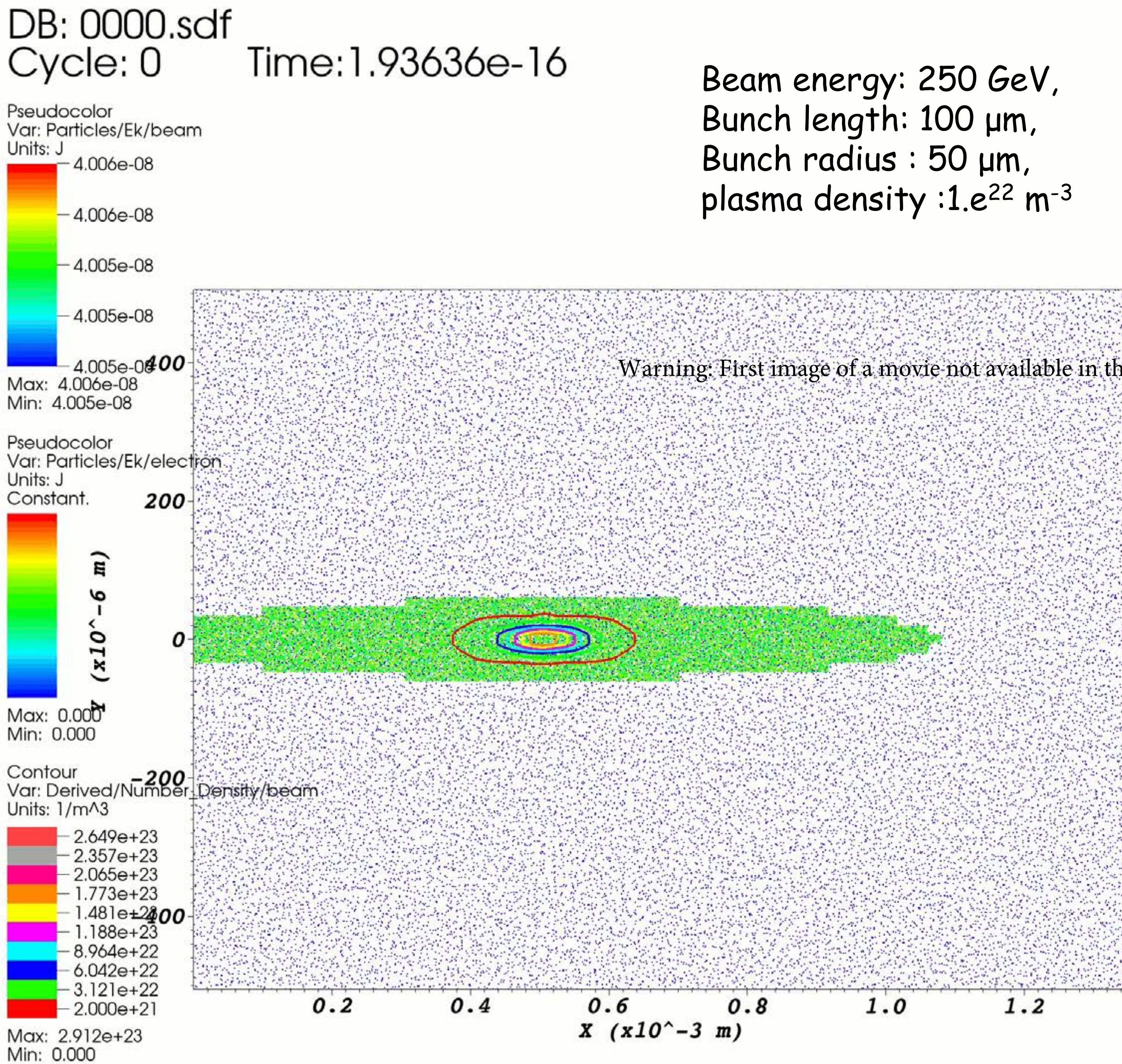


Beam energy: 250 GeV,
Bunch length: 100 μm,
Bunch radius : 50 μm,
plasma density :1.e^{22} m^{-3}



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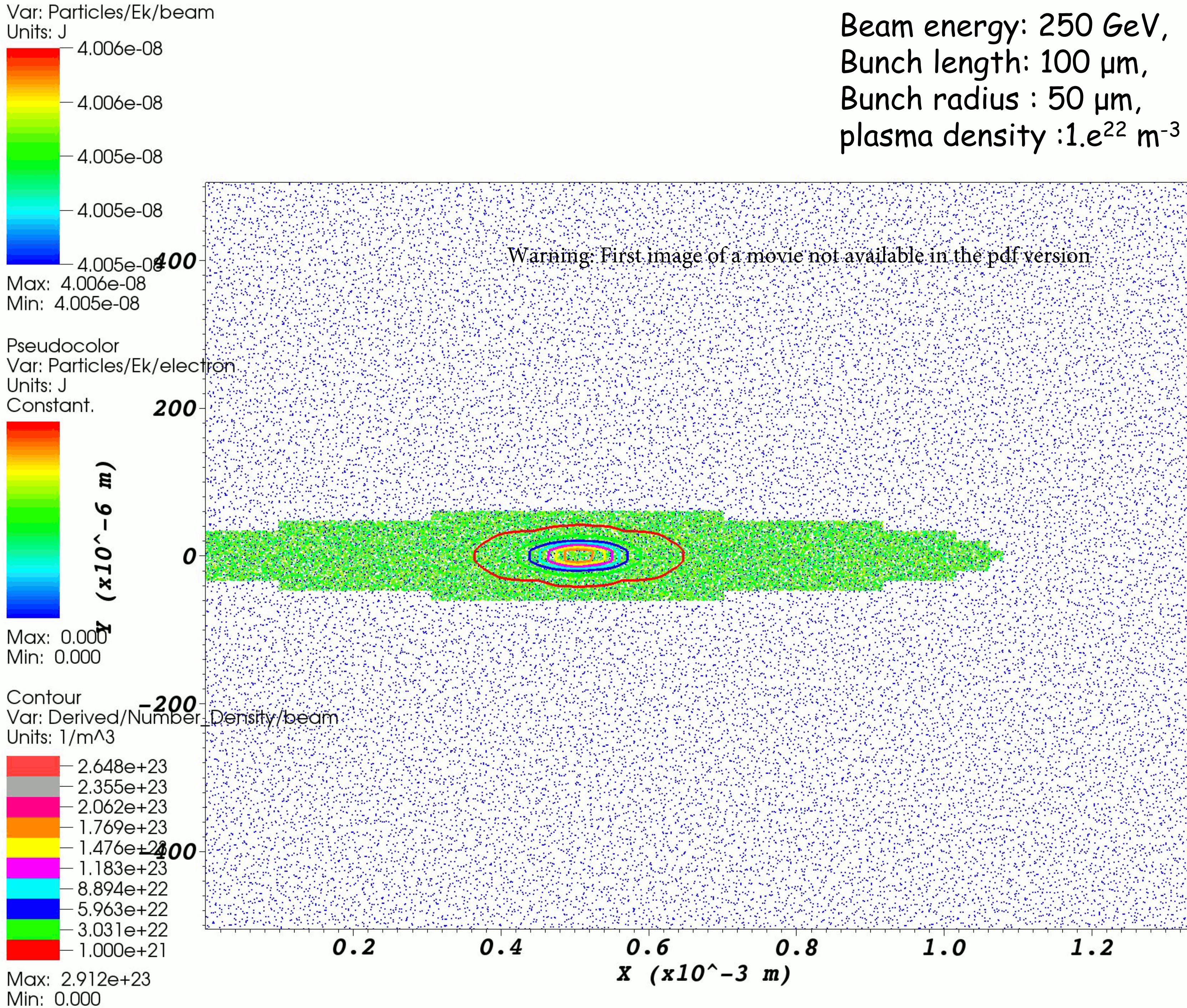
Beam energy: 250 GeV,
Bunch length: 100 μm,
Bunch radius : 50 μm,
plasma density :$1.e^{22}$ m^{-3}



Green-ILC

Passive mode effects

- Very strong effects, but needs short and high density bunches
  - Revisit the extraction beamline to create strong wakefield
- Plasma reshapes the beam
  - Focusing and defocusing effects.
  - Could be beneficial for BD

Plasma-Based Adiabatic Focuser,
P. Chen et al. PRL 64, 11, 1231, 1990

- Plasma breaks the bunch
  - Microbunching (recently demonstrated by AWAKE on long proton bunches (SMI: Self Modulation Instabilities)
- The head of the bunch is not decelerated
  - Conventional BD needed
- But beam head erosion effects may dissolve all of it
- Saturation effects from particle re-acceleration
  - Expulsing decelerated beam particles
- Positron beams similar to electron beams
- Ions no much dependence

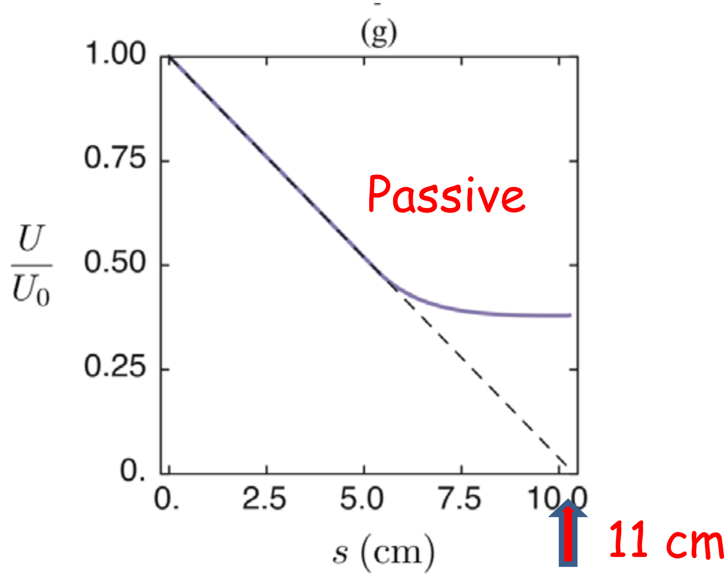
Further developments

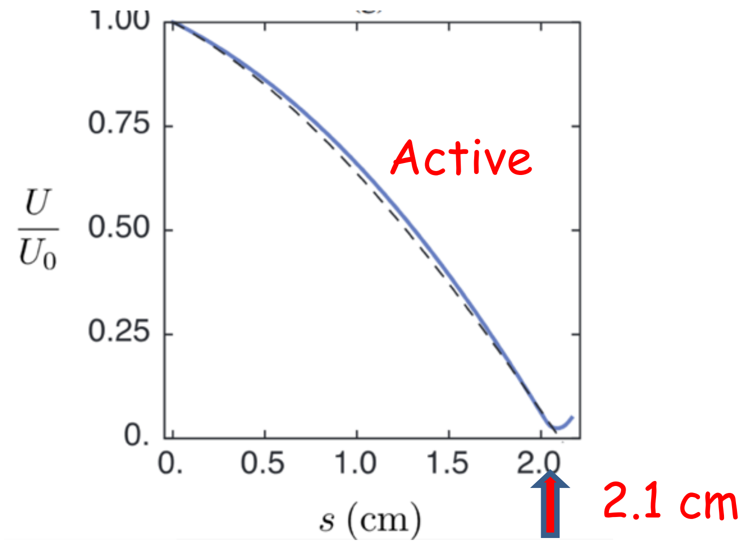
- Active wakefield using a laser drive
- Plasma density variation or sectioned plasma
  - To match the decelerated beam parameters
- Multi-stage plasma BD
  - Each element tuned to the beam conditions:
    - Pre-stage: beam shaping: plasma focusing and microbunching, close to IP
    - Several elements further away, each tuned to the local beam conditions
    - A final low power absorption BP for non-relativistic + BD for security
  - The AWAKE 10 m long plasma tube as a BP "prototype" ?
    - 2-3 aligned beams: e+- beam, ionization laser, drive laser
    - Ionized gas jets, electrical discharges,
- Simulation with realistic ILC beam parameters
  - both for non-colliding and disrupted beams
  - Ionization effects, electron collision, …

Active Mode

Passive and active plasma deceleration for the compact disposal of electron beams, A. Bonatto et al.

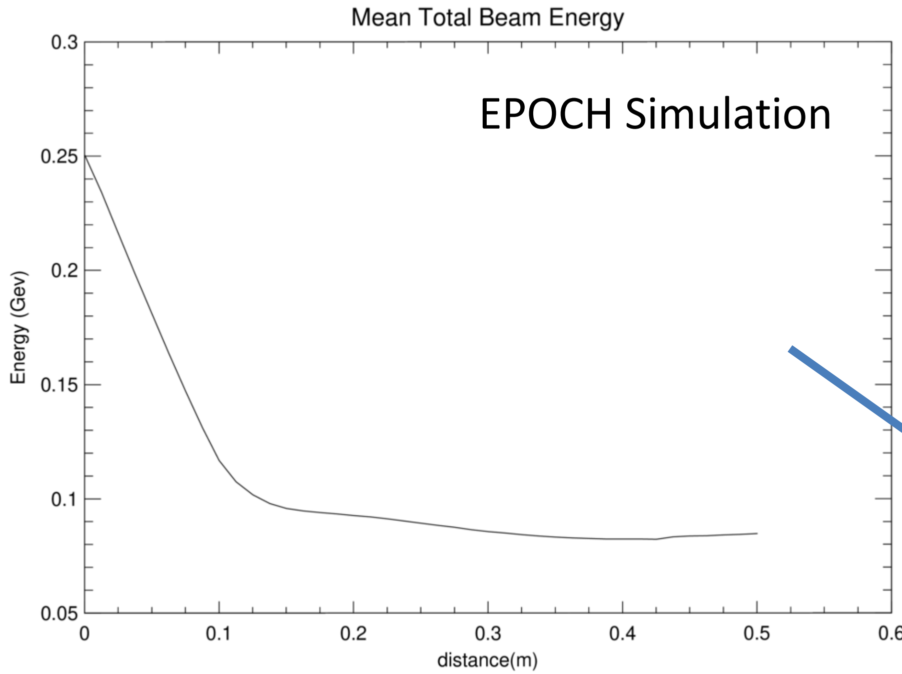
- A laser creates the wakefield adapted to the beam parameters
- Low energy: E=0.5 GeV (γ=1000) , short bunch ~ 2.7 micron
- Simulation in blue based on INF&RNO. Doted line analytic expressions
- Rely on a perfect synchronization laser/beam



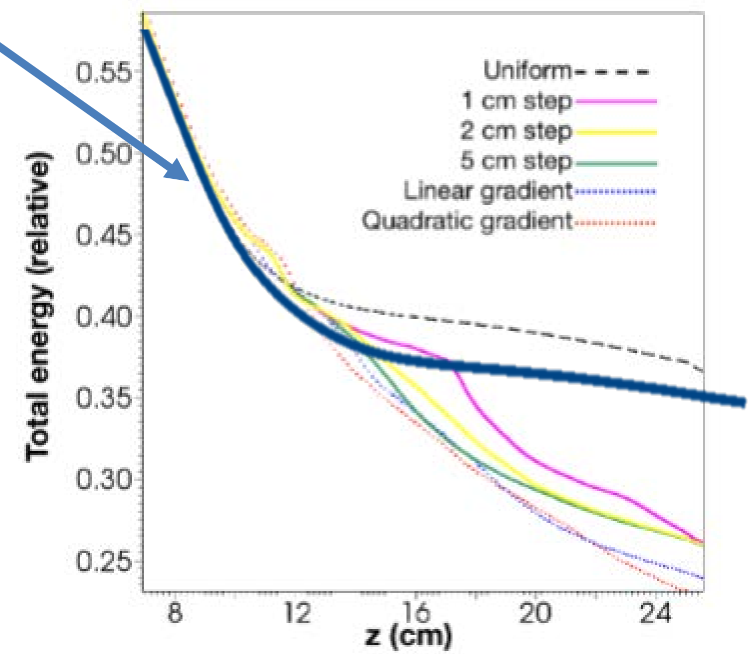


- Limited to short plasma cells ~10-20 cm due to laser power and pulse rate
- More works needed for ILC energy and beam structure.

Plasma density variation
Low energy short and thin beam



Beam part.: 0.065 e^{10}
Beam energy: 250 MeV,
Bunch length: 7.5 μm,
Bunch radius : 20 μm,
plasma density :2 e^{23} m^{-3}



Simulation study of a passive plasma beam dump using varying plasma density

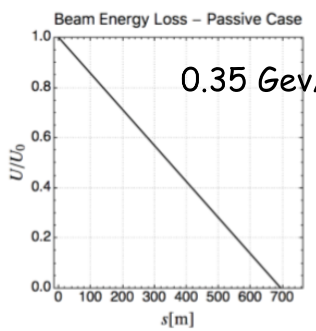
Kieran Hanahoe, Guoxing Xia, Mohammad Islam, Yangmei Li, Oznur Mete-Apsimon, Bernhard Hidding and Jonathan Sm;

https://arxiv.org/pdf/1701.01008.pdf

ILC Analytical studies (very preliminary)
A. Bonatto, CAPES (BR)

PASSIVE CASE

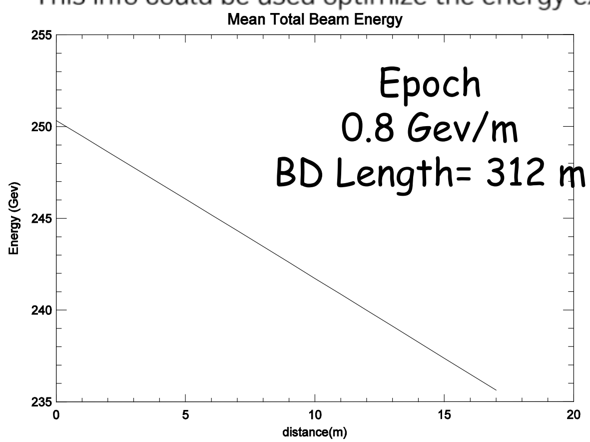
→ $L \simeq 750\,\mu m$, $r_b \simeq 75\,\mu m$, $n_0 \simeq 5 \times 10^{20} m^{-3}$,



→ $S_{\max} \simeq 700m$ is a theoretical estimate, never achieved in the passive case (particles from the beam "head" do not experience descelerating field).

→ Previous PIC simulations show good agreement with analytical energy loss while $\gamma \gg 1$.

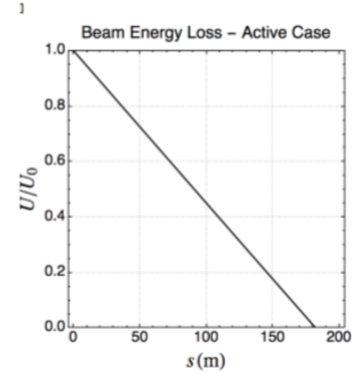
→ *Question*: What ranges are allowed for the given set of parameters (plasma density, beam size and charge, etc.)? This info could be used optimize the energy extraction.



Beam profile not Gaussian (like in simulation)
HSP (Half sine long/parabolic transverse
Roughly correspond to Gaussian:
σ_L =300μ, σ_r =50μ

ACTIVE CASE

→ $L \simeq 750\,\mu m$, $r_b \simeq 75\,\mu m$, $n_0 \simeq 5 \times 10^{20} m^{-3}$,, $a_0 = 1$, $\psi_0 = 0$, $\gamma_g^{\text{channel}} \simeq 1600$.



→ $S_{\max} \simeq 180m$.

→ Previous PIC simulations also show good agreement with analytical energy loss (while $\gamma \gg 1$).

→ Need to be done more carefully, checking dephasing length, γ_g, $w_0 \gg r_b$ condition (not attended here), laser power, PPc, etc.

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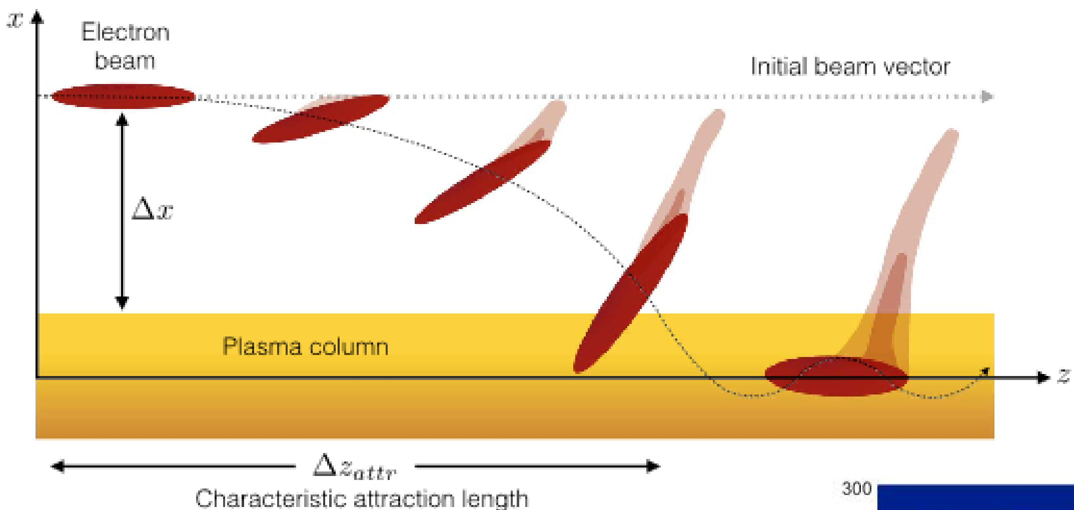
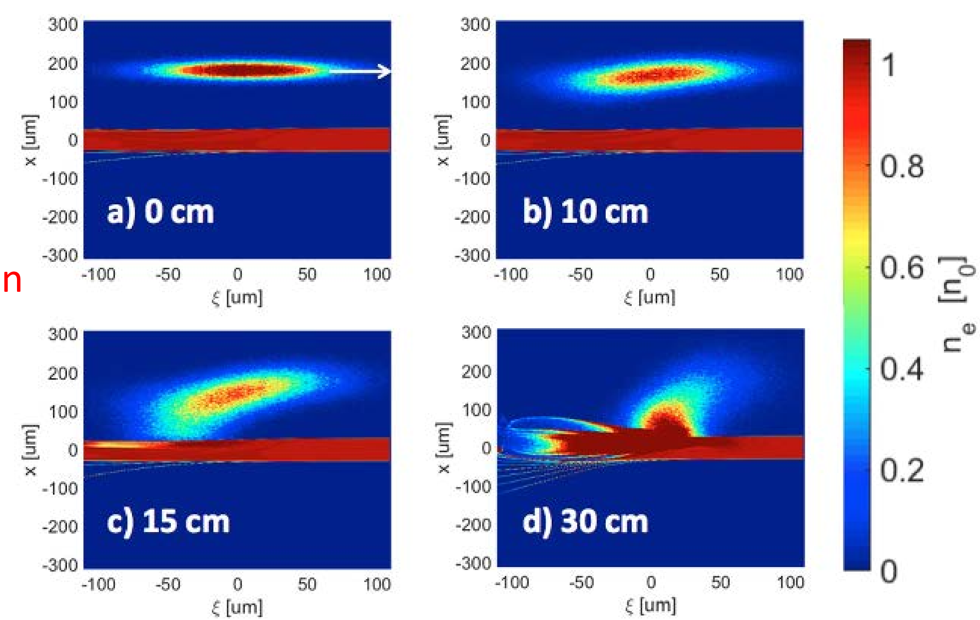
More studies, tuning needed !

Recently discovered effect
Bunch attraction by a neutral plasma column



Should stabilize the beam in the plasma column



Long-range attraction of an ultrarelativistic electron beam by a column of neutral plasma
E Adli et al. New J. Phys.18(2016) 103013

Heating and Radiation

- Heating the plasma
  - At the GeV scale and low frequency bunches, electron collisions are similar to laser plasma accelerator (LPA): no specific cooling needed, even better it sustains ionization
  - But at 250-500 GeV and 5-4 Hz 1312-2625 bunches, the heating of the plasma is quite large: a serious issue
- Radiation
  - Electron betatron oscillation in the transverse plane (x-ray) smaller than bremstralhung
  - 10–30 MeV thresholds for gamma-neutron reactions in typical shielding materials (< 10TeV) not reached for ILC/CLICC energies

Needs to be quantitative

Energy recovery ?

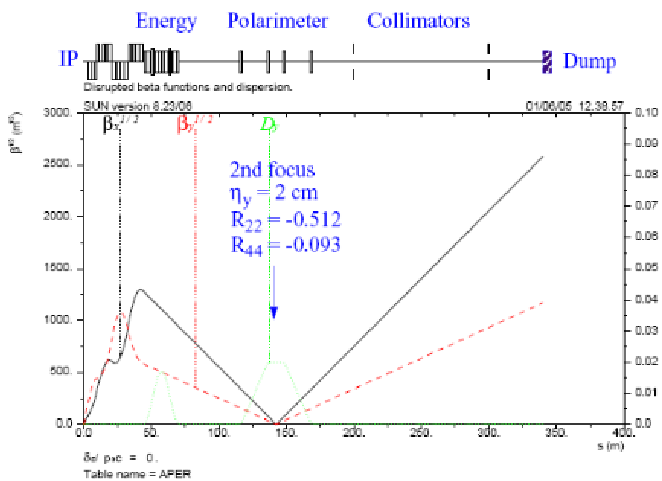
- Electrical recovery
  - Pickup the plasma oscillation, difficult as it is a pure electrostatic effect, no magnetic field variation: needs to have a transverse magnetic field.
  - Very high frequency: 500 GHz is edging transistor performances
- RF recovery
  - How to pickup the RF ? Micro Cavities ??
  - Photon accelerator:
    Increase laser photon frequency: UV laser, X-rays ?

ILC beam extraction line tuning

Rob Appleby, Daresbury Laboratory Sep. 2005

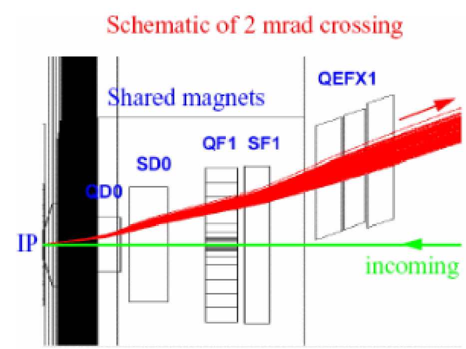
ASTeC Accelerator Science and Technology Centre

Beam dump context – 2/20mrad extraction lines



Nominal beam sizes on dump:

E_{CM}	Option	$\sigma_x \sigma_y$ (mm^2)
0.5 TeV	nominal (c11)	3.16 x 0.28 = 0.88
	high-L (c15)	4.57 x 0.34 = 1.55
1 TeV	nominal (c21)	1.87 x 0.63 = 1.18
	high-L (c25)	3.23 x 0.62 = 2.00
	high-L (c26)	1.87 x 0.61 = 1.14
	high-L (c27)	2.20 x 0.61 = 1.34



Common e+/e- and g dump for 20mrad and a separate g dump for 2mrad. Note optics can be adjusted to allow beam growth

Forecoming events and Acknowledgement

- Beam dump test at VELA/CLARA, Daresbury
- Plasma beam Dump Workshop Sept. 2018, Manchester
  - Guoxing Xia, organizer
- French GDR on plasma acceleration (in preparation)

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- Pisin Chen (Taiwan)
- Alex Bonatto (CAPES, Brazil)
- Guoxing Xia (Daresbury)
- Edda Gschwendtner (CERN, AWAKE)

Thanks to IN2P3 Computing Center (France) support

All mistakes are mine

Very reliminary Conclusions

- Great advantages of plasma wakefield deceleration: disruptive
- Many possible schemes to study
  - passive, active modes, segmented plasma, varying density and more to come
- Study new extraction lines for wakefield BD to achieve shorter, thinner and higher density bunches: needs Acc. Physicists involved
- Very serious heating effects for short BD, must investigate…
- No provision for beamstrahlung photons: dedicated BD as in current design
- Multi stage practical design studies, hybrid system ?
- Energy recycling and reuse, possible but no practical scheme yet, more to come
- Needs lot of simulations and beam tests
- Check with CLIC parameters

From a complex technology burden to an exciting basic physics

May become a unique test beam for wakefield acceleration physics,
For a Very High Energy ILC beyond 500 GeV or 1 TeV

Call for a larger collaboration

Thank you

Plasma Beam Dump Workshop
Manchester Sept. 2018
topics

- Plasma beam dump, theoretical studies
  - passive beam dump, active beam dump, hybrid scheme, plasma density tailoring,
  - electron, positron, muon and heavy ion beam dump, etc.
- Plasma beam dump, numerical studies
  - laser and beam parameter optimizations, new modelling tools, code benchmarking-VSim, EPOCH and other codes,, machine learning or AI to be used to optimize the parameters etc.
- Plasma beam dump, experiment studies
  - e- beams from conventional accelerators such as VELA/CLARA, KEK ATF, EuPRAXIA, ELI, etc., determine the plasma beam dump design for each specific facility, plasma sources and configurations, beam lines, diagnostics, possible implementation to the ILC beam, etc.
- Plasma beam dump as the test bench
  - for high energy density physics, compact radiation sources etc;
- Energy recovery from plasma dump
  - for LWFA generated beam, laser might pick up energy via blue shift after beam dump, for e- beam from conventional accelerators, how do we extract the energy from plasma?
- Collaboration and grant application
  - kick off the collaboration, fix the task forces, seek the grant from H2020, ERC or other sources