White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	
• Interactions of plasmas and waves	P
• Plasma self-organization	
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	
Will not attend	X

Title:	Intense Ion Beam for Innovative Science and Inertial Fusion Science
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)

Abstract Intense ion beam provides a unique tool to investigate innovative physics in dynamic instability stabilization and in High Energy Density Physics, and also provides a promising driver to study science in ion beam inertial fusion energy as our reliable future energy source. Beam ions deposit their energy inside a material, and so a warm or a high-energy area is created inside a material. One good example of the ion beam applications is an ion beam cancer therapy, in which a cancer inside a human body is directly illuminated without a serious damage of normal cells. The ion beam also has another unique feature of a precise controllability of the particle energy, the beam direction, the beam pulse duration, the beam pulse shape and also a wobbling capability by the ion beam axis precise rotation or oscillation. The wobbling capability of the ion beam presents an innovative tool to stabilize instabilities dynamically in plasmas and fluids. For example, the Rayleigh-Taylor instability growth would be controlled and stabilized significantly by the ion beam wobbling. This white paper shows a new wide range of an innovative science based on the intense ion beam.

- ***Describe the research frontier*** **and importance of the scientific challenge.**

After pioneers including Earnest Rutherford, John D. Cockcroft, Ernest Walton, Robert Van de Graaff, Earnest O. Lawrence, Rolf Videroe, and others in particle accelerator physics in the early 20th century [1], electron and ion beams have been employed to study various physics in elementary particle physics, high-energy physics, material sciences, bio-science applications, etc.

Recently it was discovered that an "intense" ion beam would have a remarkable capability as an innovative scientific tool:

1) An ion accelerator has an extraordinary precise controllability to define a clear energy deposition inside a material. The ion beam axis direction, the pulse length, the pulse shape, the particle energy and the routinely high-repetitive operation are precisely controlled as well as the wobbling capability with a high frequency [2]. The energy deposition of the ion beam in a material is well defined and predictable.
2) The wobbling ion beam would open a new control method of instabilities in plasmas and fluids [3]. This is a new general and robust method for the dynamic instability stabilization [4]. (see an example in Figure 1)
3) The energy deposition of an intense ion beam creates a high-energy area inside the matter.
4) The high-energy region inside a material provides an efficient acceleration of a payload material.
5) Therefore, the intense ion beams would provide an appropriate energy driver for a future inertial fusion energy (IFE) system [5].
6) The high-energy region inside a material would also supply a unique tool for high energy density (HED) plasmas. A volume, not a surface, is heated up, is confined inside the matter and would provide a new scientific tool for material science and plasmas.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

So far, the focus of accelerator research has not been sufficiently on the ion beam "intensity". The present ion accelerators provide a higher energy range with a relatively lower current for the present research purposes in high-energy physics and particle physics, compared with the higher current (~kA or more) and the lower particle energy (5-10MeV/nucleon) needed in the ion beam IFE Science and HED plasmas [6]. The "intense" ion accelerator is a challenge in accelerator science and plasmas, and would bring us new innovative scientific results in the next decade.

For example, if NDCX II at LBNL, Berkeley is enhanced to meet the requirements for the ion beam current and the particle energy toward the innovative science in the plasma instability stabilization and the future stable inertial fusion energy release, the "intense" ion beam will be available for the innovative scientific activities. Outside U. S. A., one can also find FAIR in GSI, Germany and also HIAF, a huge plan in China for the "intense" ion beam accelerator. When these facilities will be available, science initiated by the intense ion beam will be intensively explored.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

So far the control of the plasma instability in unstable plasma and fluid systems has not been focused well. Therefore, the growth rate of instability is examined well. On the other hand, the control theory has been developed intensively and applied to various controllable systems, for instance, various vehicles, machines, etc. For plasmas and fluids, the "intense" ion beam would provide a new tool to introduce the control theory for the dynamic stabilization of unstable plasmas [3, 4] (see also Fig. 1). The intense ion beam has the high controllability with the wobbling or oscillating or rotating beam axis motion, which creates the oscillating pressure force and the wobbling acceleration in plasmas. In addition, the ion beam energy is deposited inside a matter. The ion beam cancer therapy has been realized by using the ion beam controllability and its preferable energy deposition property. The ion energy deposition itself is well understood and controlled. The new scientific challenge of the control of the unstable plasmas would be opened by the "intense" ion beam controllability [3, 4].

In addition, the inertial fusion energy would be available for our human society as an unexhausted energy resource, if the fusion fuel target is compressed stably [7-9]. This is one of our dreams as plasma scientists.

Combining the preferable characteristics of the "intense" ion beam and its controllability with the societal requirement for the unexhausted energy resource of the fusion energy, the "intense" ion beam would also provide our future inertial fusion energy [5-9].

In conclusion, the "intense" ion beam is opening innovative sciences in the plasma instability control and in the ion beam inertial fusion science.

References

[1] for example, "Early Particle Accelerators", http:// www.aip.org/histor/lawrence/ epa.htm

[2] H. Qin, R. C. Davidson, et al., "Centroid and envelope dynamics of high-intensity charged particle beams in an external focusing lattice and oscillating wobbler", Phys. Rev. Lett. 104, 254801 (2010).

[3] S. Kawata, Phys. Plasmas, "Dynamic instability mitigation" 19, 024503 (2012).

[4] S. Kawata and T. Karino, "Robust dynamic mitigation of instabilities", Phys. Plasmas, 22, 042106 (2015).

[5] S. Kawata, "Fuel Target Implosion in Ion beam Inertial Confinement Fusion", arXiv: 1504.01831 (2015).

[6] for example, J.J. Barnard, et al., "NDCX-II target experiments and simulations", Nuclear Instruments Methods Phys. Res. A, 733, 45 (2014); S. Kawata, et al., "Laser ion acceleration toward future ion beam cancer therapy", Laser Therapy, 22, 103 (2013) and References therein.

[7] O. A. Hurricane, D. A. CALLAHAN, et al., "Fuel gain exceeding unity in an inertially confined fusion implosion. Nature 506, 343 (2014).

[8] H.-S. Park, O. A. Hurricane, D. A. Callahan, et al., "High-Adiabat High-Foot Inertial Confinement Fusion Implosion Experiments on the National Ignition Facility", Phys. Rev. Lett. 112, 055001 (2014).

[9] S. Kawata and K. Niu, "Effect of Nonuniform Implosion of Target on Fusion Parameters", J. Phys. Soc. Jpn. 53, 3416 (1984).

Figures (maximum 1 page)

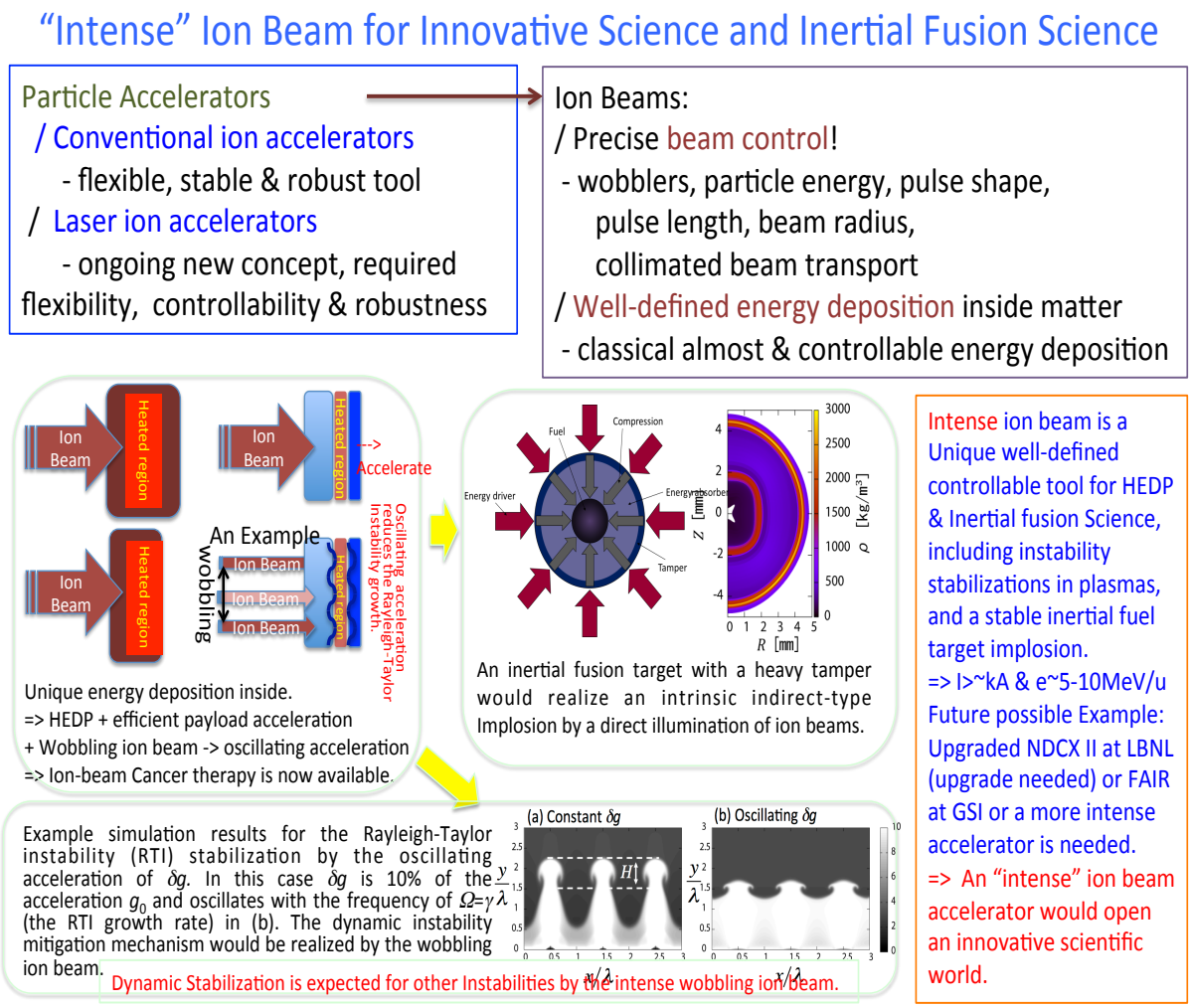

Figure 1. The "intense" ion beam accelerators provide a unique controllable well-defined tool for scientific innovation and for inertial fusion science. Beam ions deposit their energy inside a material, and so a warm or a high-energy density area is created inside a material. One good example of the ion beam applications is an ion beam cancer therapy, in which a cancer inside a human body is directly illuminated without a serious damage of normal cells. The ion beam also has another unique feature of a precise controllability of the particle energy, the beam direction, the beam pulse duration, the beam pulse shape and also a wobbling capability by the ion beam axis precise rotation or oscillation. The wobbling capability of the ion beam presents an innovative tool to stabilize instabilities dynamically in plasmas and fluids. For example, the Rayleigh-Taylor instability growth would be controlled and stabilized significantly by the ion beam wobbling. The wobbling beam also has a potential to stabilize other plasma instabilities.