Feasibility study of fusion plasma heating by relativistic high-current electron beams

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Motivation

The goal of this research will be to study the feasibility fusion plasma heating using ultra short high intensity electron beam by dissipating energy of excited wakes either in linear or nonlinear regimes

The mainstream magnetic confinement designs (ex. tokamak, stellarator, …) planned with plasma densities that support up to GV/m PWFA gradients. This opens a possibility for a highly compressed intense electron beam to efficiently deposit its energy into plasma

The requirement for a fusion plasma heating system is to provide tens of megawatts of external power with very high wall plug efficiency

In the past, electron beams of much lower energy (in the range of MeV) and much longer duration (10s and 100s of ns) were utilized. In this range of parameters, the mechanism of plasma heating is based on beam-plasma instabilities and plasma turbulence, and is relatively inefficient

The development of ultra-relativistic and extremely short electron bunches for PWFA application opens up a new possibility for plasma heating, where the beam energy is deposited through a new, highly nonlinear mechanism

Schematic diagram for a PWFA heating using ERL beam

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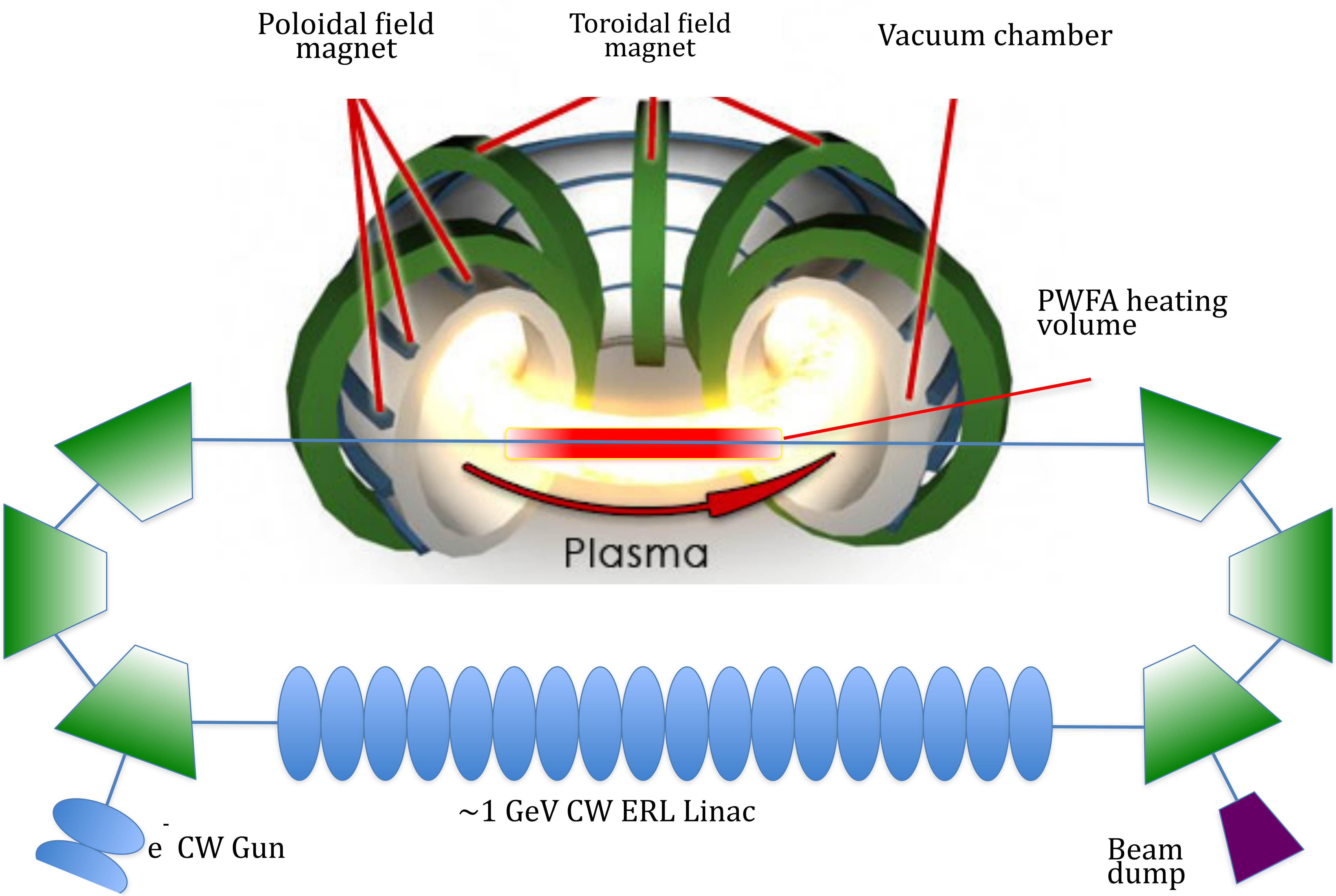


Few Numbers

Fusion plasma:

Heating power requirement	>10 MW
Plasma density	10^{14}-10^{15} cm^{-3}
Magnetic confident field	3-10 T

Heating beam:

Electron beam energy	~1 GeV
Average current	~100 mA
Reactive power	100 MW
Average energy deposition	~10 %

Longitudinal phase space rotation:

Acceleration:	0.1 MeV x 1 ps
Final compression:	3 MeV x 0.03 ps
PWFA energy deposition:	100 MeV x 0.03 ps
Energy recovery:	1 MeV x 3 ps

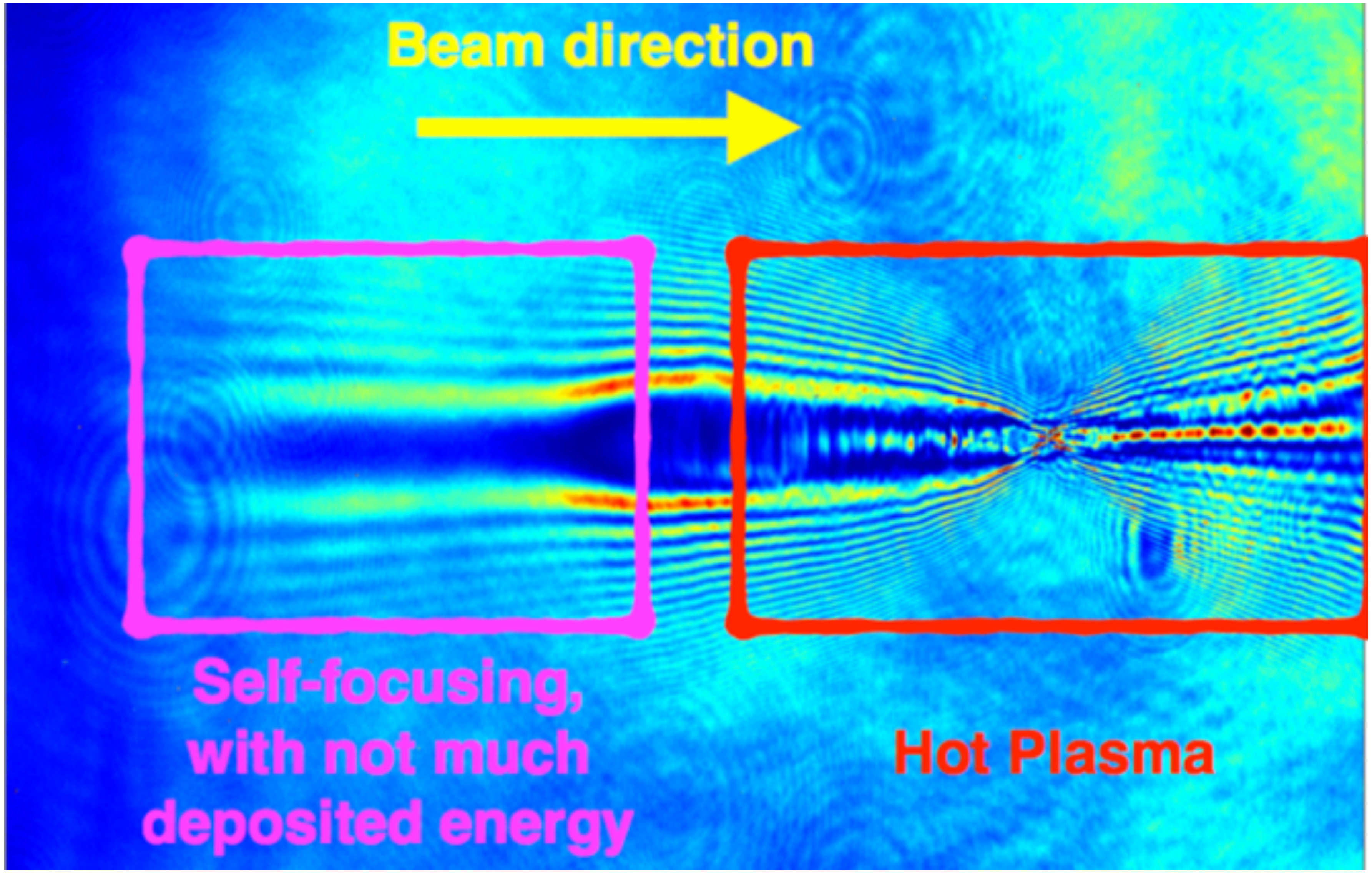
Non-linear VS. Linear wakes

The studies of plasma heating for a collider PWFA shows that non-linear ultra-relativistic electron wakefields interacting with the plasma ions lead to the excitation of a non-linear ion-wake

The phases of the oscillating radial electric fields of the slowly-propagating electron bubble is asymmetric in time and excites time-averaged inertial ion motion radially

In the linear electron wake regime, on the other hand, the wakefields are symmetric so they average out over the electron oscillation period and only the second-order ponderomotive force drives the ion-motion

Experimental interferogram of the plasma channel



Experimental interferogram of the plasma channel in the lithium vapor that was captured at FACET as part of E200 and E224 experiments that show transition from “cold” to “hot” plasmas after the drive electron beam

Questions to study:

Details of the energy deposition into plasma where PWFA drive beam interacts mostly with plasma electrons

How the heat is propagated through the plasma volume if the drive beam interacts with a small volume of the plasma?

Can one contain and efficiently recover the energy of the beam with a large energy spread after it interacted with the plasma and the magnetic confinement system?

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