Single- and Multi-Stage Laser Wakefield Plasma Acceleration of Electrons .

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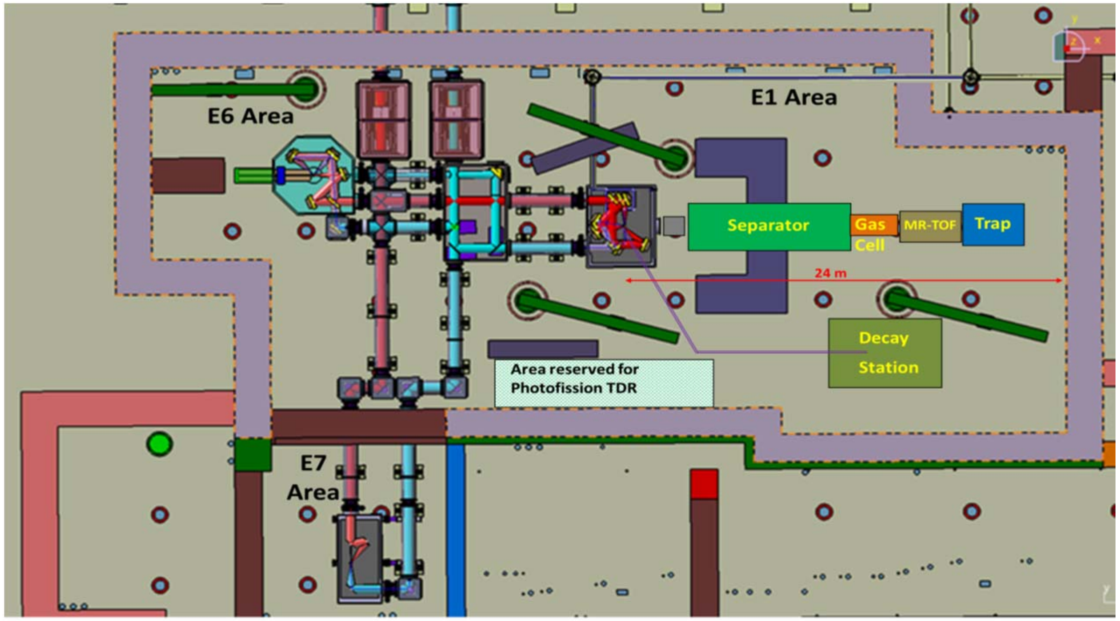
Summary

- High Fields QED Physics experiments proposed at E6.
- Single stage, Laser Wakefield Plasma Acceleration at the “High Fields QED physics” area at ELI-NP .
- Vorpal calculations of the optimum plasma density for 1PW, 5PW and 10PW.
- Proposal for the experimental layout for a double staged LWFA of electrons.
- Geometry of the tapered capillary plasma cells.
- Conclusion.

The three 10 PW experimental areas at ELI-NP

The "E1", "E6" and "E7" experimental areas with 2x10 PW Laser beams.



High Field QED Physics experiments at E6 area

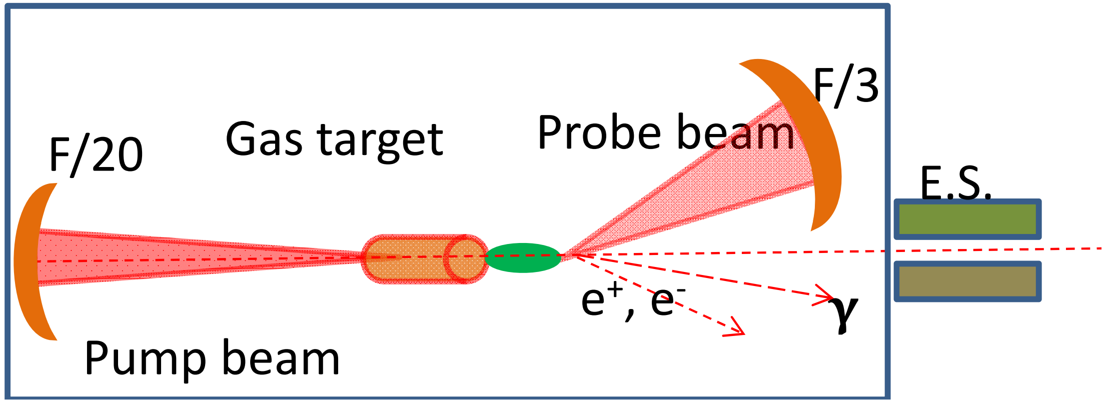
1. Radiation reaction physics in the classical and quantum regimes: gas cell
2. Linear and non-linear Compton and Thomson Scattering: gas cell
3. Electron beam cooling : gas cell
4. Emission of synchrotron radiation ($\eta \rightarrow 1$): solid target
5. High Harmonics generation (solid target)

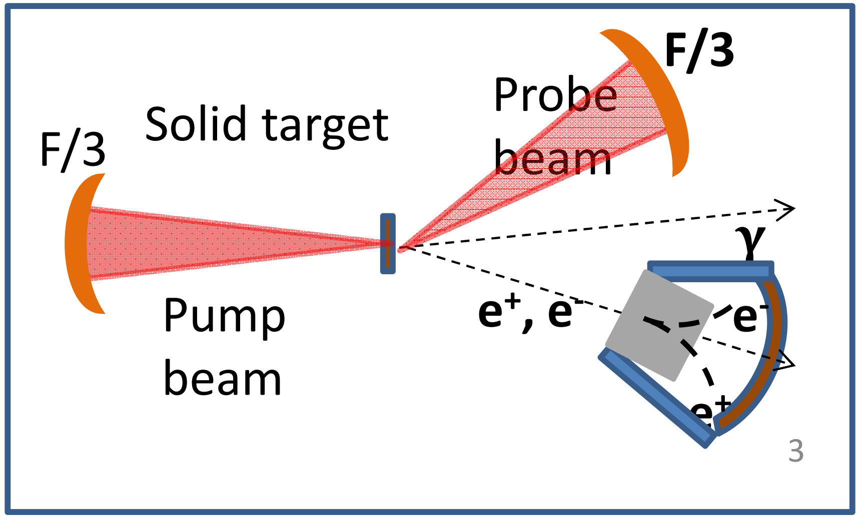
$$\eta = \gamma\, \Theta \sqrt{\frac{I_L}{I_S}}$$

γ electron Lorentz factor

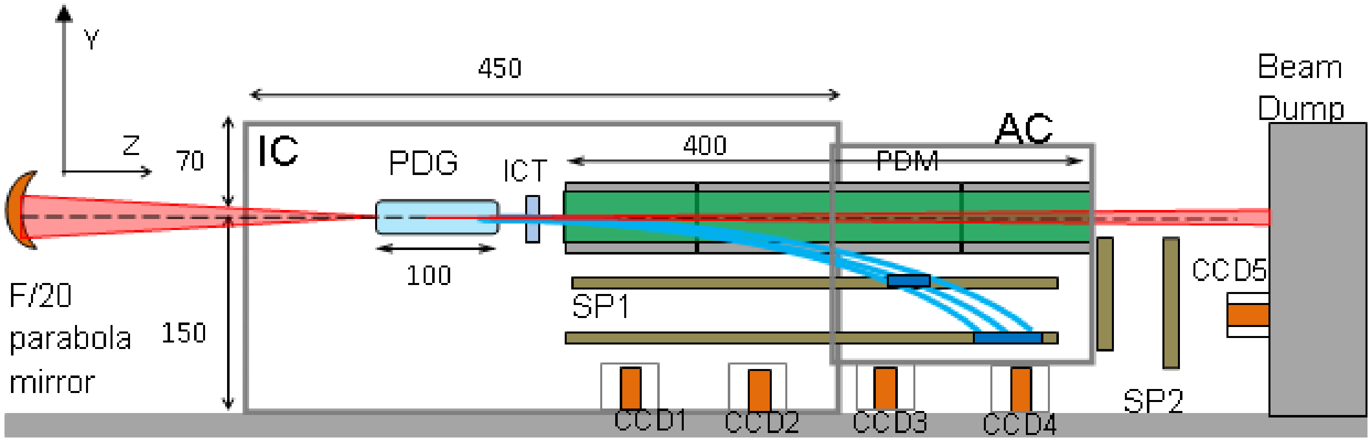
Θ=geometrical factor

I_L=Laser intensity $I_s = 2 \times 10^{29}$ W/cm^2





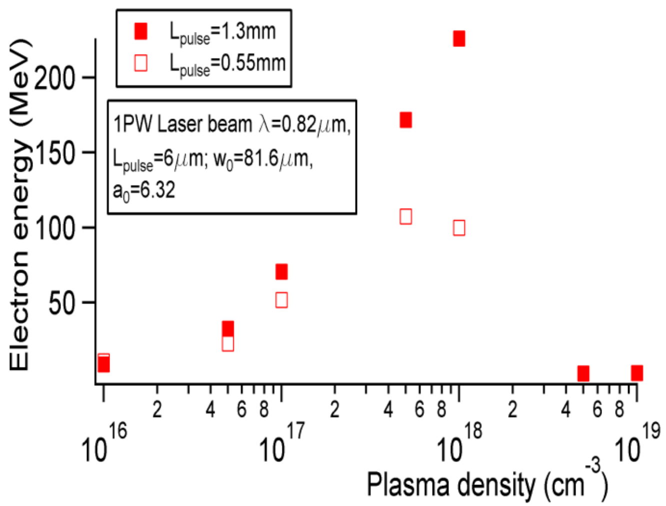
Single-stage LWFA of electrons

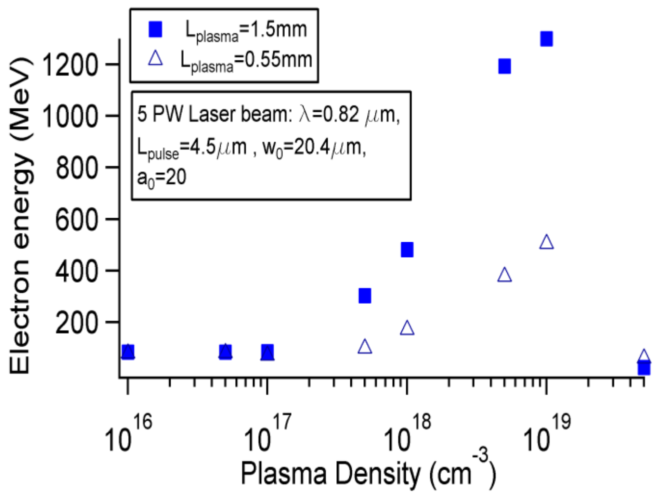


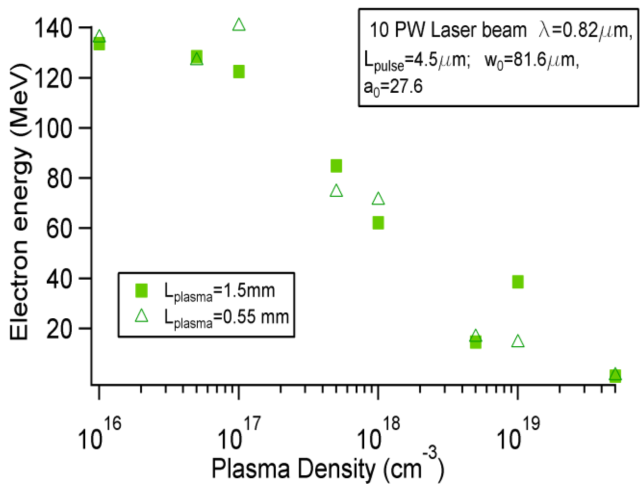
PDM : Permanent Dipole Magnet
IC: Main Interaction Chamber
AC: Auxiliary Chamber

PDG : Plasma Discharge Guide
ICT: Integrating Charge Transformer
SP1, SP2: Scintillating Plates
CCD1…CCD5: CCD cameras

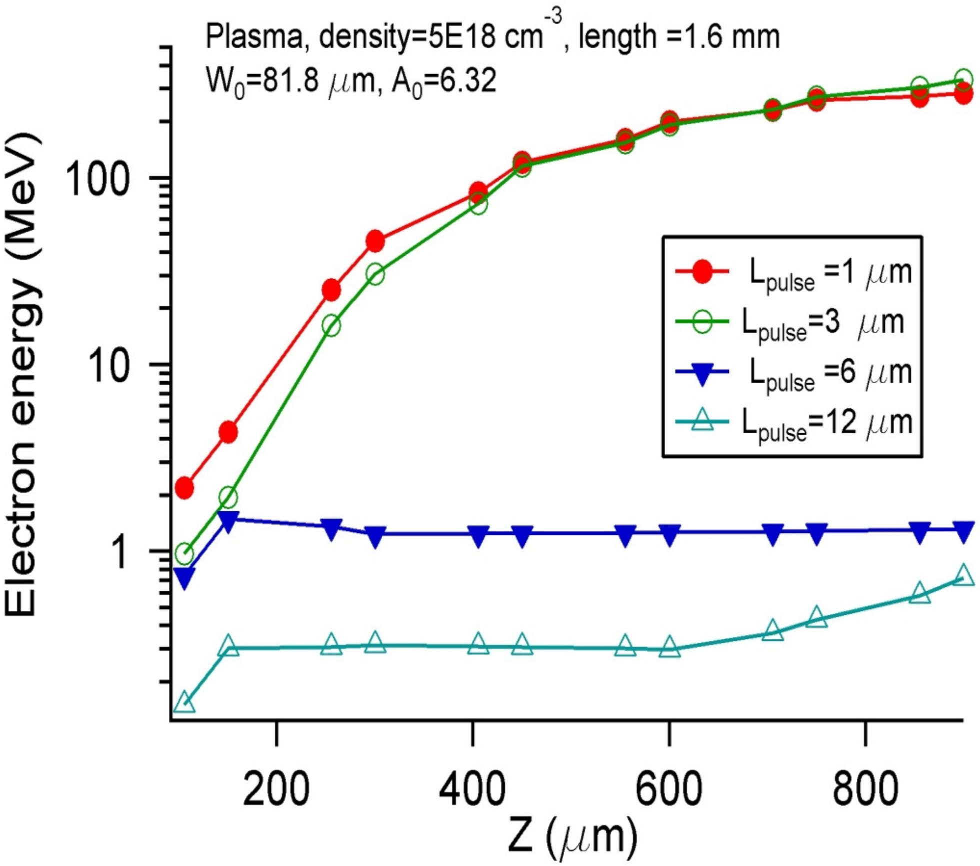
Vorpal 1D calculations : optimum plasma density for 1 PW, 5PW and 10 PW beam

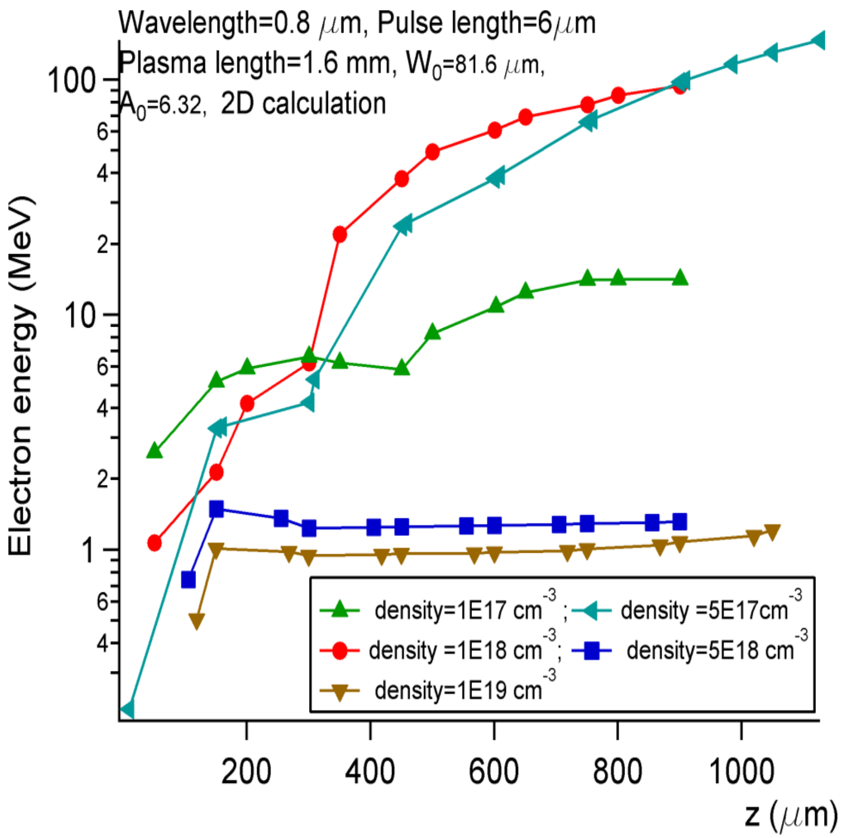






Vorpal 2D calculations of electron kinetic energy for 1PW Laser beam

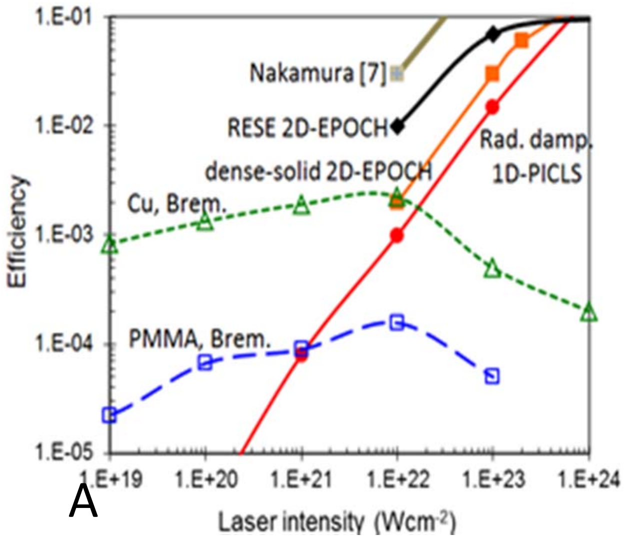




Electron energy versus the distance from the entrance face of plasma cell, computed for 1 ,3, 6 and 12 μm long plasma cells.

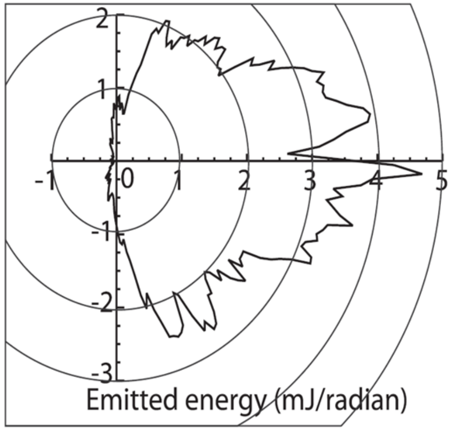
Electron energy versus the distance from the entrance face of plasma cell, computed for two plasma densities.

Investigation of High Harmonics Generation in the quantum radiation regime at ELI-NP

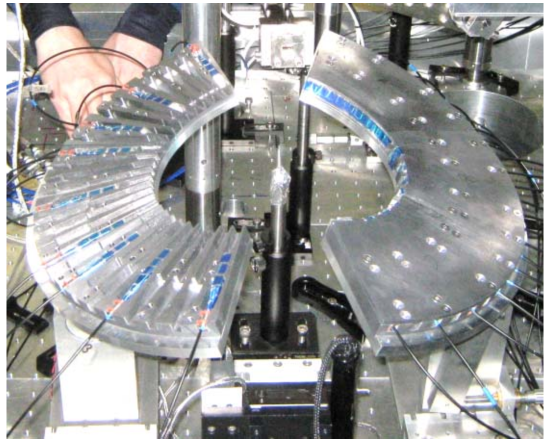


A

Efficiency of gamma rays production with the laser intensity up to 10^{23} Wcm^{-2}



B



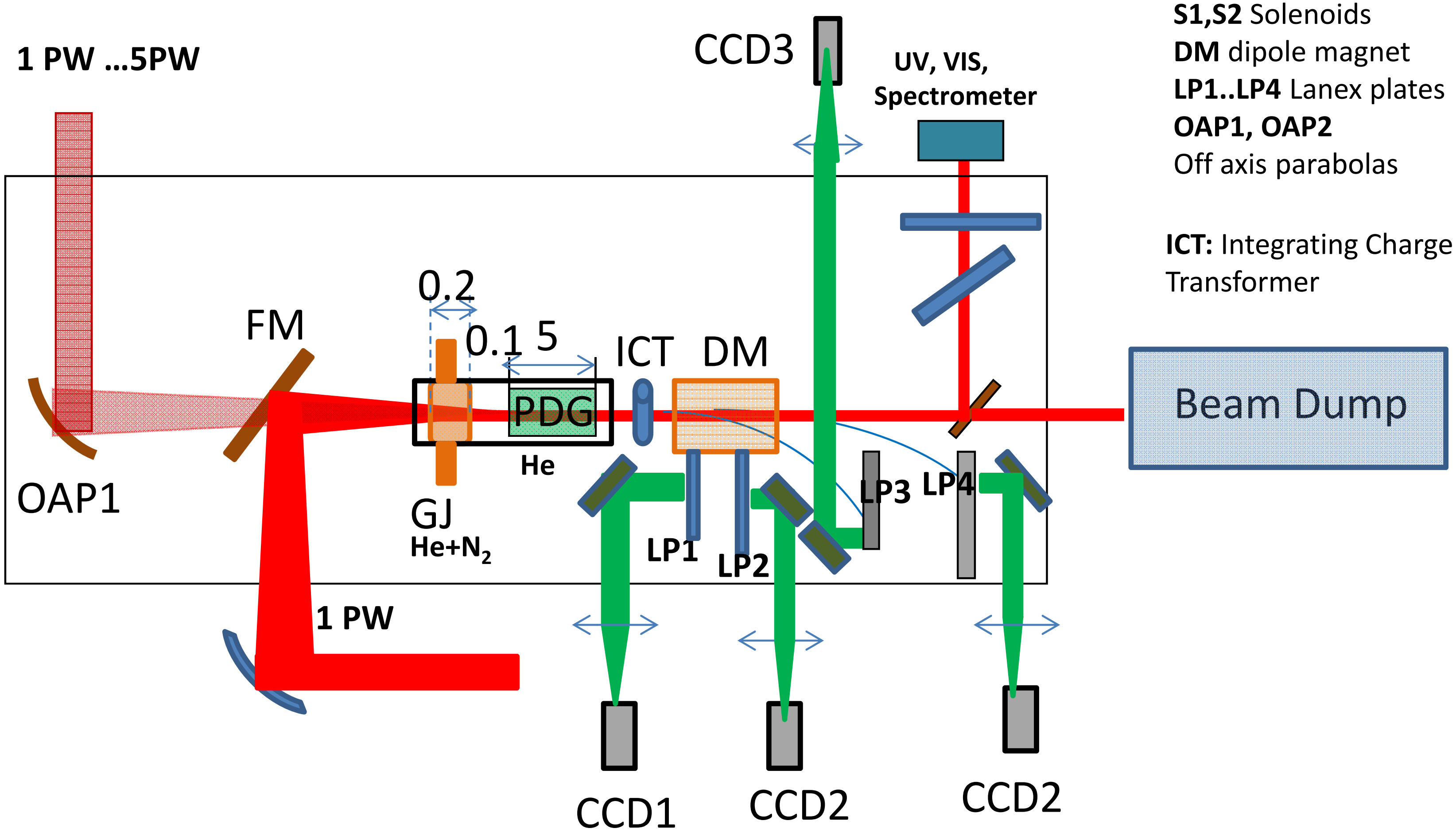
C

The calculated angular distribution of the emitted photons (B) The angular array of gamma ray detectors (in construction at Univ. Strathclyde) (D)

Laser used: 1X 10 PW, later 2X 10 PW (pump- probe). Polarization: linear and circular.
Target: thin foils, thickness 0.1 to 5 mm , CH_2, Al,Cu, foam.

Detection: Gamma-ray emission, wrap-around imaging platem array of scintillators, Positron and Electron Spectrometer, double Thomson Parabola for ion energy measures

Proposed experimental set-up for double-staged LWFA of electrons with gas-jet cell (He+N_2) and plasma discharge guide (He)

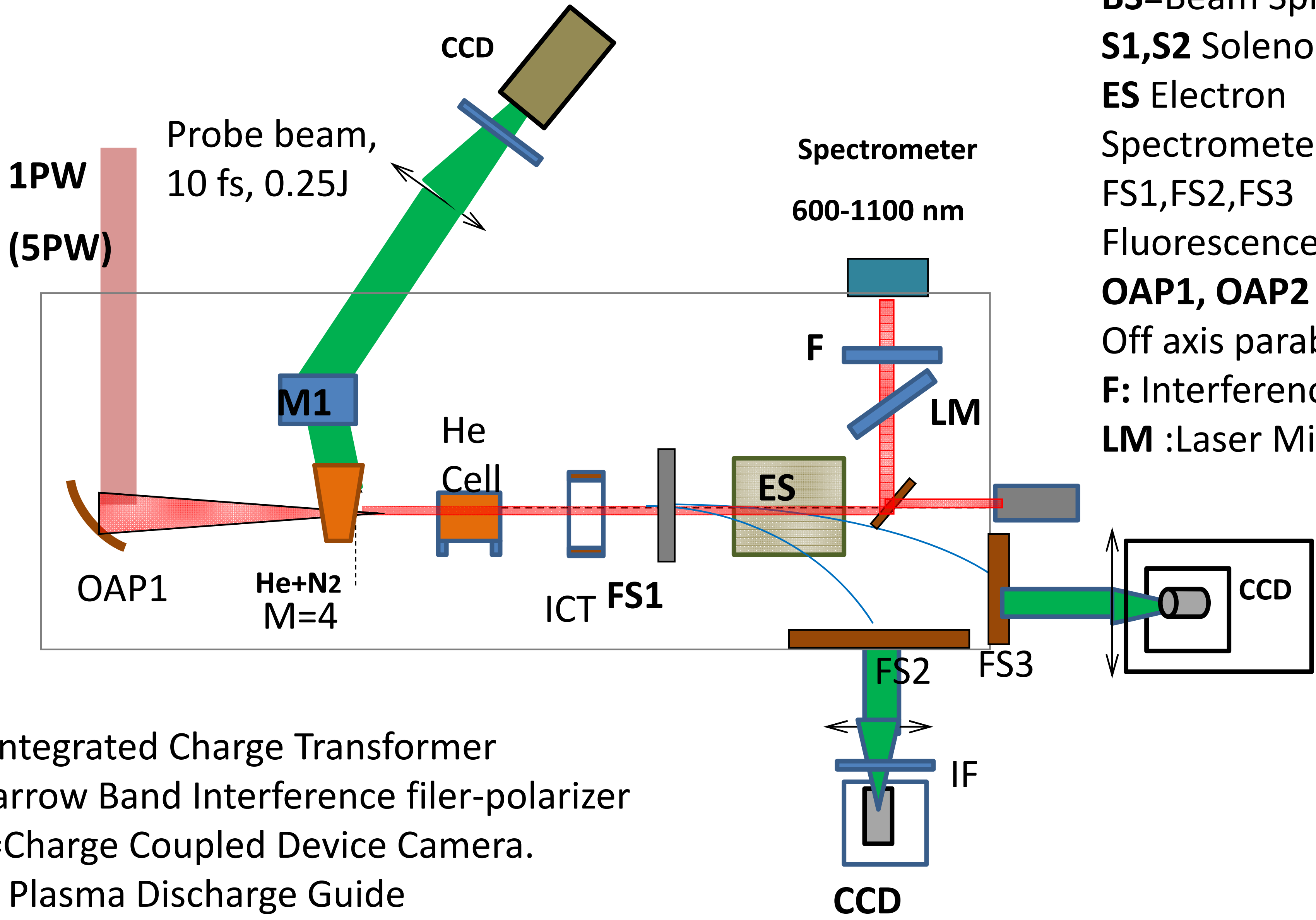


BS=Beam Splitter
S1,S2 Solenoids
DM dipole magnet
LP1..LP4 Lanex plates
OAP1, OAP2
Off axis parabolas

ICT: Integrating Charge Transformer

GJ: gas jet cell (He+1%N2)
PDG: plasma discharge guide

Proposed double-stage experiment with Ionization Injection in He+N_2 and He gas jets

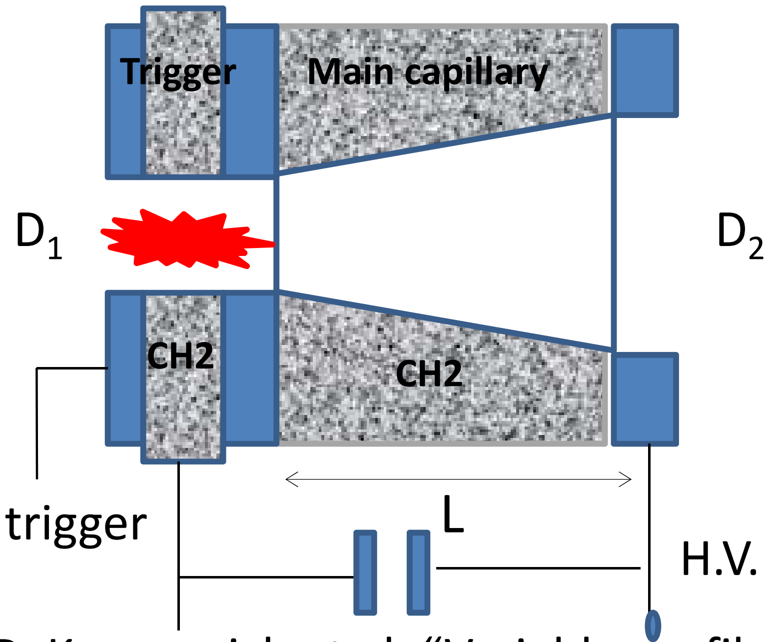


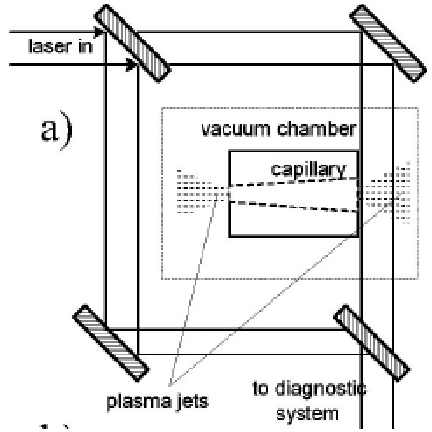
BS=Beam Splitter
S1,S2 Solenoids
ES Electron Spectrometer
FS1,FS2,FS3 Fluorescence screens
OAP1, OAP2 Off axis parabolas
F: Interference filter
LM :Laser Mirror

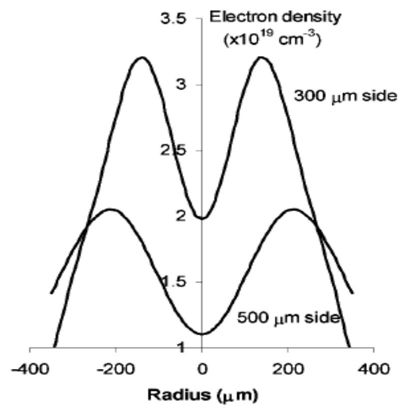
ICT= Integrated Charge Transformer
IF =Narrow Band Interference filer-polarizer
CCD =Charge Coupled Device Camera.
PDG= Plasma Discharge Guide
He+0.5%N2 , with density= 5E18 .... 1E20 cm^{-3}
Laser Intensity in the GJ cell =1E17 ...1E18 W/cm^2

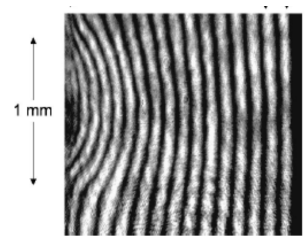
Variable profile capillary discharge for improved phase matching[1]

The dephasing distance is extended, by controlling the group velocity of the pump beam.



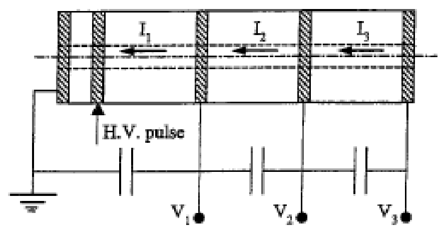




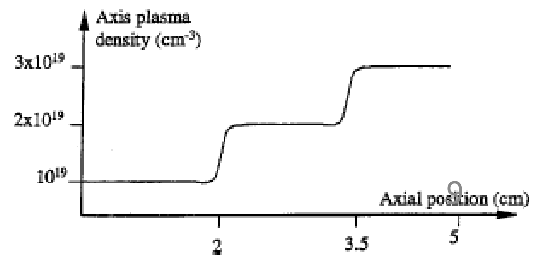


[1] D. Kaganovich et al, "Variable profile capillary discharge for improved phase matching in a laser wakefield accelerator", Applied Physics Letters. 75, 772, 1999

a)L=2 cm, D1=300 um, D2=500 μ m, n1/n2=2 ;b) L=2 cm, D1=500 um , D2=1400 μm, n1/n2=10



A segmented capillary discharge that produces an axial variation in plasma density .



List of Equipment

- Three CCD cameras; Integrated Charge Transformer Fluorescence screens
- Quad- RF plasma generator; Rectangular Electron and Positron Spectrometer.; Laser Mirror. Color glass filer (>600 nm). Narrow band interference filter, polarizing filter; All Reflective Achromatic Telescope
- Beam Splitter. Plasma Discharge Guide (tapered profile), Gas Jet Cell.

Work plan:

1) Single-stage acceleration of electrons at CETAL (2016-2018)
2) Double-stage acceleration of electrons , done in collaboration with the « Laser Plasma Acceleration group » from CNRS and Universite Paris Sud (2017-2018)

The goals:

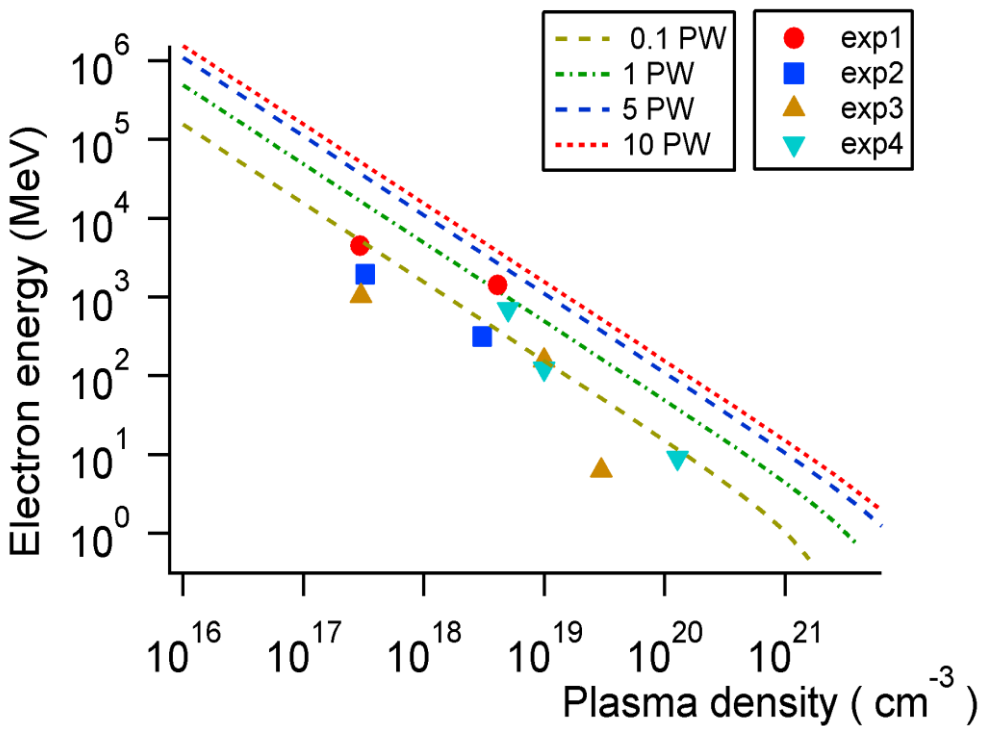
1. To study the feasibility of the laser plasma accelerators for multiple stages and high particle energies.
2. To implement the diagnostics, to construct the equipment needed for laser plasma acceleration and to enhance the colaboration between ELI-NP and Apollon.
3. The development of a reliable relativistic electron source for applications.

Conclusion

- Optimum plasma density is correlated with laser pulse length and can be calculated for best quality electron beam.
- The two stage Laser acceleration of electrons allows to control independently the production and acceleration stages of electron beams.
- Tapered plasma channels (with a variable density plasma profile) were proven to increase the dephasing length of the LWFA electron beams.
- Different construction schemes of such plasma channels are available.

The END

Electron beam energy and plasma density in single stage LWFA of electrons



$$I\left[\frac{W}{cm^2}\right]=\frac{2P}{\pi w_0^2}$$

$w_0 = 20.4\ \mu m$

$\lambda_0 = 0.82\ \mu m$

$$a_0 = 8.6\cdot 10^{-10}\cdot \lambda(\mu m)\sqrt{I\left(\frac{W}{cm^2}\right)}$$

$$\gamma_g = \frac{\omega_0}{\omega_p} \qquad \gamma_{\max} = \frac{2a_0}{3}\gamma_g^2$$

$$T(MeV) = (\gamma_{\max} - 1)\cdot m_e c^2$$

The electron energy versus the plasma density, is computed (dotted lines) and measured in practice (marks).

The pump detuning length L_d and pump depletion length L_{pd} are calculated according to:

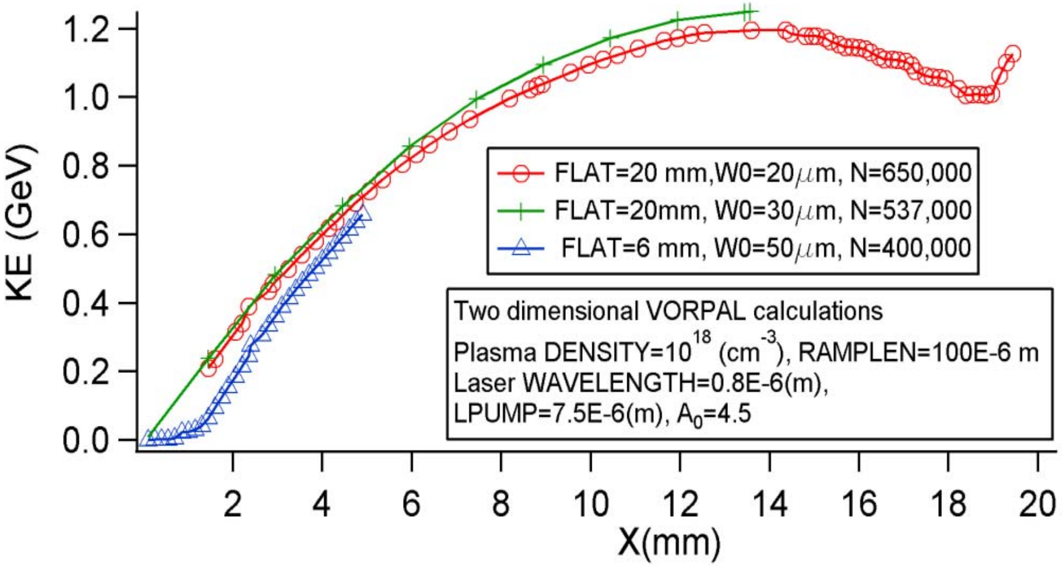
$$L_d = \frac{\omega^2}{\omega_p^2}\cdot\lambda_p\cdot\frac{2a_0^2}{\pi} \qquad a_0>>1$$

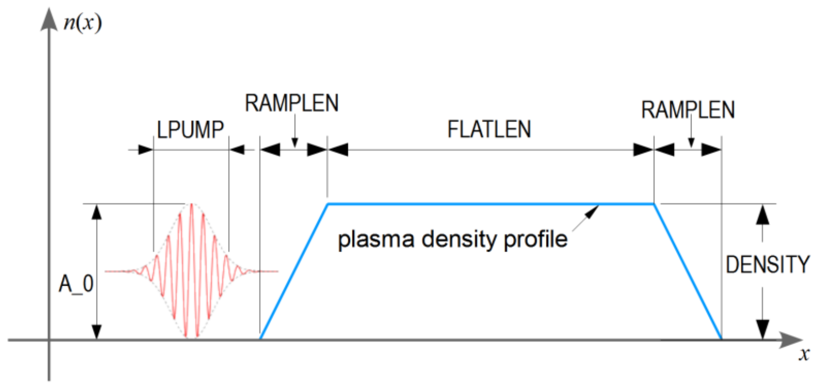
$$L_d = \frac{\omega^2}{\omega_p^2}\cdot\lambda_p\cdot\frac{a_0}{3\pi} \qquad a_0>>1$$

Laser plasma instabilities: stimulated forward/backward Ramman, self modulation, laser-house

Vorpal two dimensional simulation of Laser Wakefield acceleration of electrons in capillary plasma

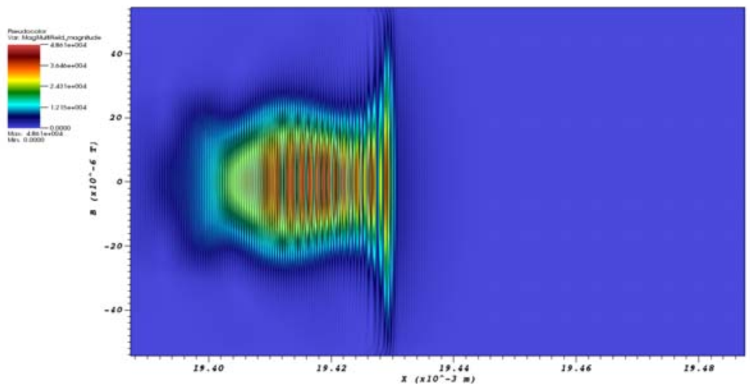
$$E(x,y,z) = E_0 \exp\left(-\frac{x^2}{2L_{RMS}^2}\right)\exp\left(-\frac{(y^2+z^2)}{W_0^2}\right)$$





Electron kinetic energy versus the acceleration length in plasma X(mm) for 20 mm and 6 mm long capillary , three diameters of the Laser beam spot W0=20 μm, 30 μm and 50 μm

Plasma density (cm^{-3})	X (mm)	KE (MeV)
$1.0 \cdot 10^{18}$	0.66	0.376
$0.8 \cdot 10^{18}$	0.74	0.263
$0.6 \cdot 10^{18}$	0.86	0.420
$0.4 \cdot 10^{18}$	1.05	0.232
$0.2 \cdot 10^{18}$	1.49	0.236



Laser parameters: A_0=4.5, LPUMP=7.5 μm, wavelength 0.8E-6 (m). Plasma density 10^{18} cm^{-3}, RAMPLEN = 100 μm. The Grid parameters were: N_LAMBDA_X=24, N_LAMBDA_T=3. Particles per cell PPCX_2=1 , PPCY_2=1. Grid steps: DX=0.8 μm /24 , DY=0.8 μm /3

Exploring strong-field QED with ultra-intense lasers

C.D. Murphy, S.P.D. Mangles, C.P. Ridgers, J.G. Kirk, A.G.R. Thomas, et al.

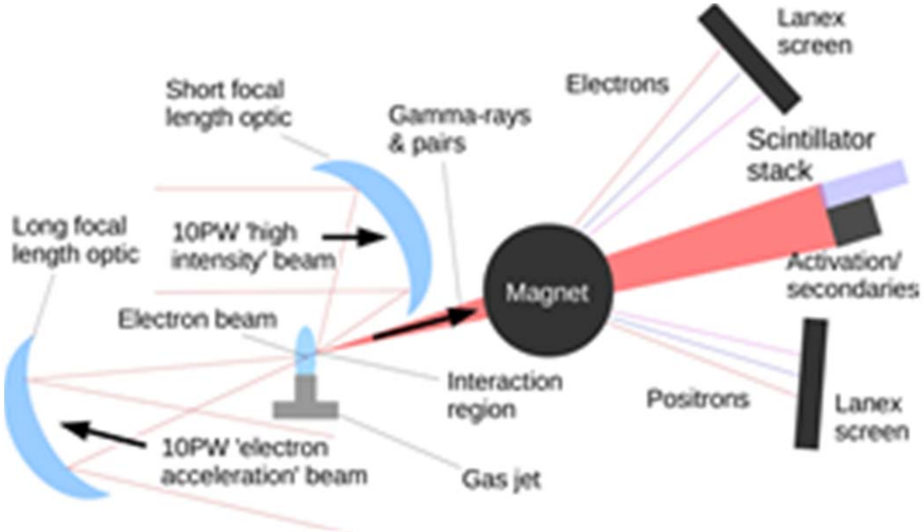
Nuclear Physics

Objectives

- Observe transition to nonlinear Compton scattering regime
- Radiation reaction: transition from a deterministic to a stochastic force
- Measure strongly-nonlinear Breit-Wheeler pair production cross section

Experiment

- LWFA: 10PW laser pulse focused into gas-jet – generate >1 GeV electrons
- Second 10PW laser pulse counter-propagating ($I \sim 10^{22}$ W/cm^2)
- Spectrum of γ-rays and pairs measured (scintillators, high-Z materials)



Expected outcomes

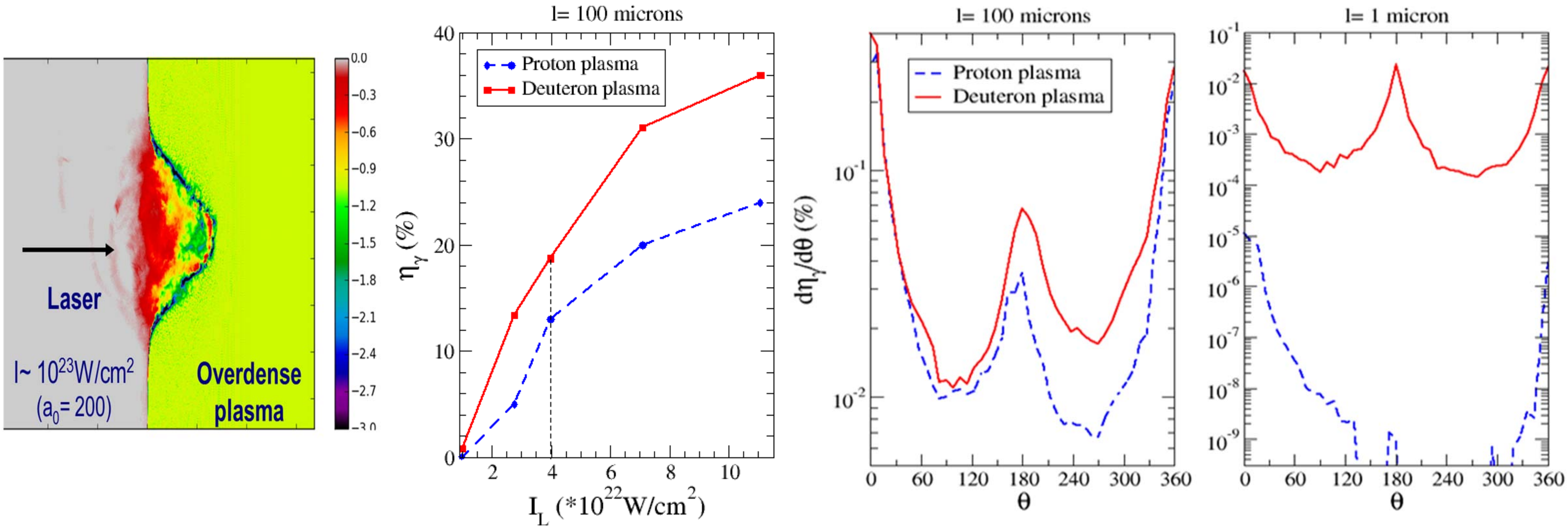
- Several GeV electrons and $I > 10^{21}$ W/cm^2
- Reach very nonlinear Compton and $\eta = E/E_S \sim 0.1$–1 quantum regime
- Substantial energy loss and spectrum broadened by quantum effects
- Order of magnitude reduction in RR compared to classical prediction
- Breit-Wheeler: order 10^6–10^7 pairs per interaction

Enhancement of the synchrotron radiation production by collective plasma effects

R. Capdessus, E. D'Humieres, P. McKenna et al (solid targets)

Nuclear Physics

For the first time: observe the predicted ion mass effect on radiation reaction physics and the corresponding changes to the collective plasma dynamics (via electrostatic field).



Laser: 1x10 PW Lasers Tight-focus mid-10^{22} Wcm^{-2}. Polarization control. Ultrahigh Intensity Contrast

Targets: Foil target C-H and C-D initially. Cryogenic D_2 and H_2 Target technology developed at STFC-RAL.

Detection: Gamma ray emission: wrap-around imaging plate detector pack, angular array of scintillators. Detector in development for Gamma energy > 400keV.

- Electron spectrum: large spectrometer or smaller spectrometers
- Ion energy spectrum and spatial distribution: two Thomson Parabolas with MCP detectors