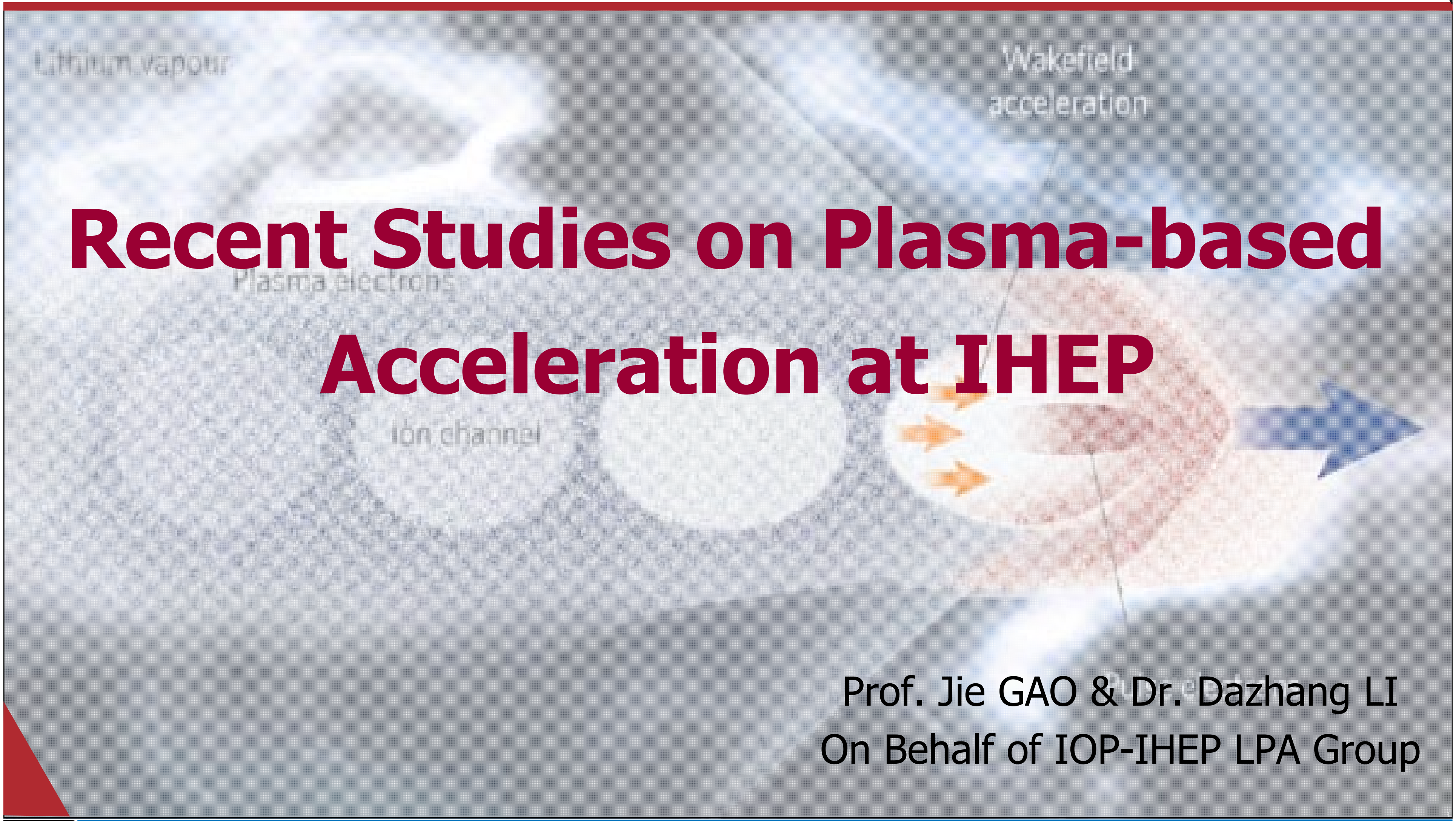
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

Recent Studies on Plasma-based Acceleration at IHEP



Prof. Jie GAO & Dr. Dazhang LI
On Behalf of IOP-IHEP LPA Group

OUTLINES

- Introduction
  - IOP-IHEP LPA&R collaborated team
  - What we do and what we have
- Plasma-based Acceleration Studies during the last 2 years
  - Studies on 20 TW laser @ IOP----Stable e- beam and application
  - Studies on 100 TW laser @ SJTU-----Enhancement of Betatron X-ray
  - Studies on 100J/1ps laser @ CAEP----High charge e- bunch and radiation
  - Studies on plasma-based CEPC injector design
- Summaries and Prospects

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IOP-IHEP collaborated group on LPA&R

Prof. L. M. Chen
Laser-cluster interaction, X-ray, Nuclear physics, plasma physics

Prof. J. Gao
Conventional acceleration physics and technology

Dr. D. Z. Li
LPA e- acceleration, e- bunch optimization, e- and X-ray parameter measurement, PIC simulation studies

Dr. K. Huang, Dr. M. H. Li
X-ray measurement, Kα X-ray, X-ray Laser, Ionization Injection

Dr. W. C. Yan, Dr. J. Y. Mao, Dr. Y. Ma
e- acceleration, laser evolution, Laser-solid interaction

Dr. J. R. Zhao, Dr. Y. F. LI
Neutron generation, simulation support

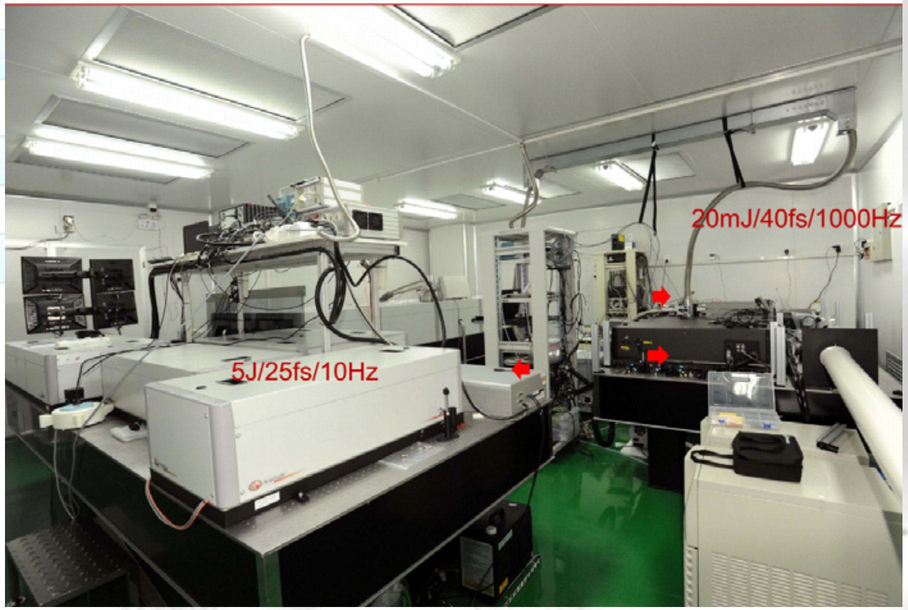
Dr. L. Zhang, Dr. M. Z. Tao
Laser-cluster interaction, laser propagation, laser-cluster e- acceleration

Since 2006, We are a young team…

But with a lot of help!! ☺

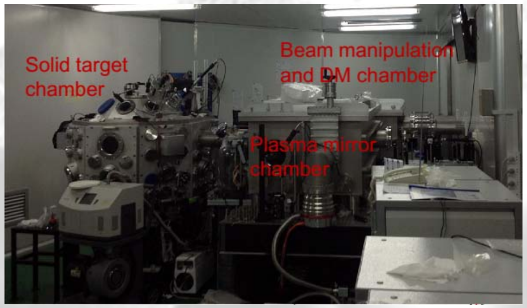
What we do and what we have

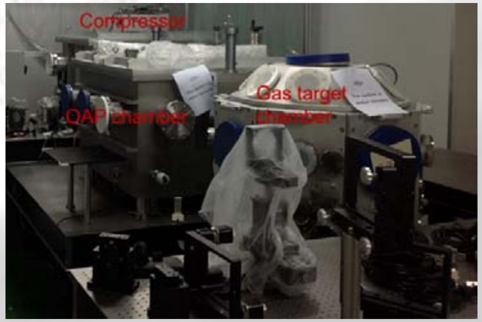
Layout of the IOP Laboratory



We are mainly interested in:

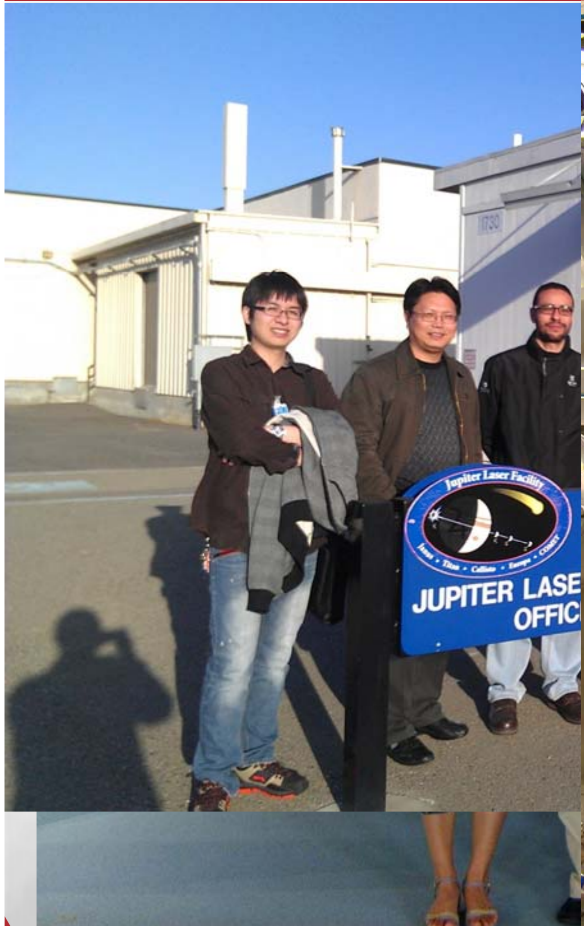
- *Laser-driven e- acceleration*
- *Laser-driven betatron radiation during the electron acceleration*
- *Kα X-ray source from laser-cluster/solid interactions*

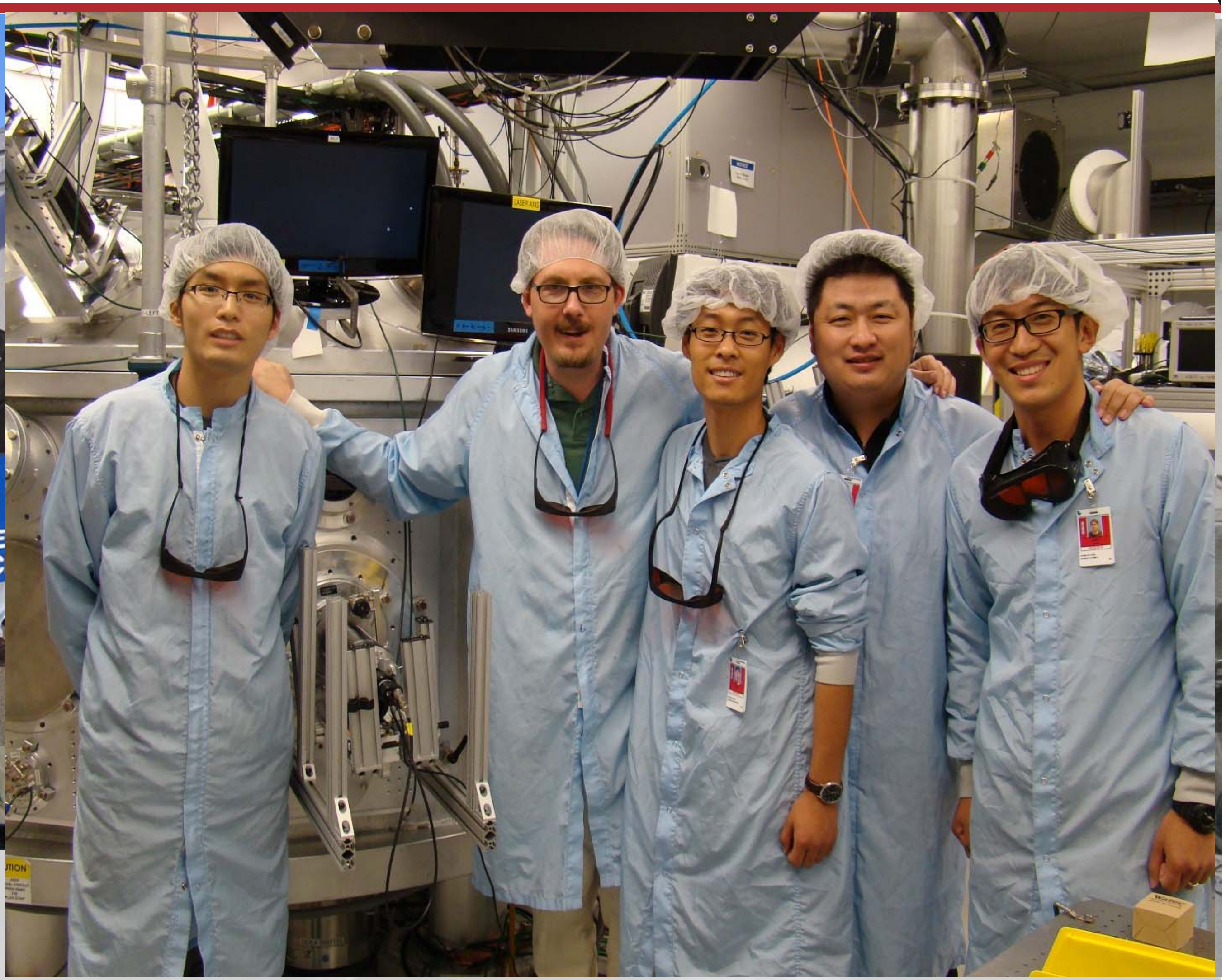




SJTU Laboratory for laser plasma physics

In the Collaborated Experiments





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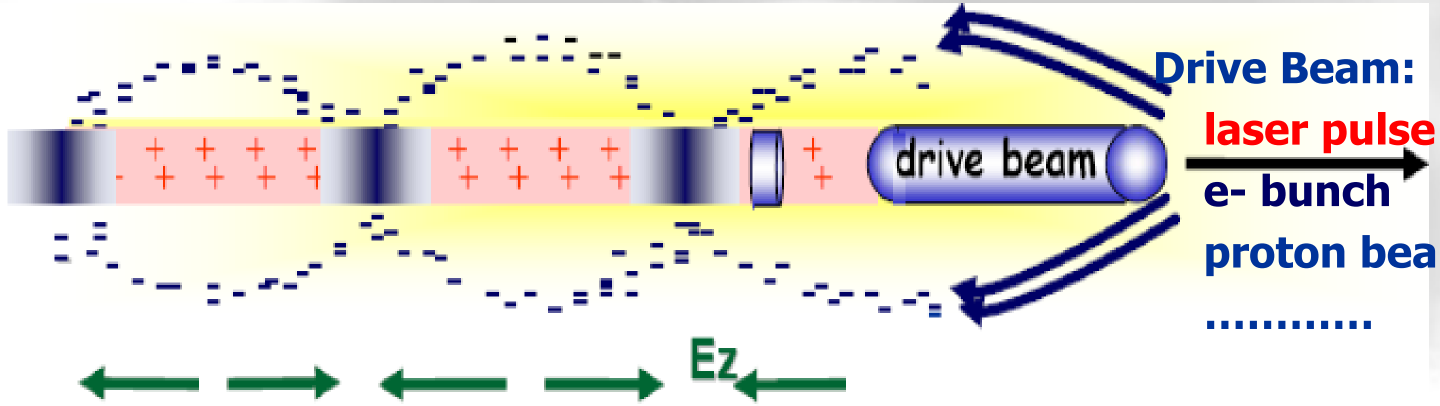
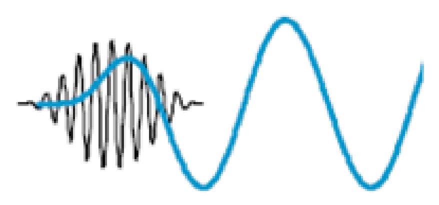
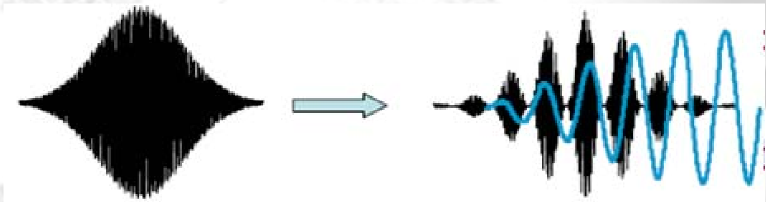
Principles of Plasma-Based Accelerators





Laser WakeField Accelerator
1 single short pulse

Plasma Beat Wave Accelerator
2 long pulses with small Δω



Self-Modulated Laser WakeField Accelerator
1 long pulses, modulated by plasma waves

Simply the best!

Require ultra-intense and ultra-short laser pulses

Achievable now due to Chirped Pulse Amplification

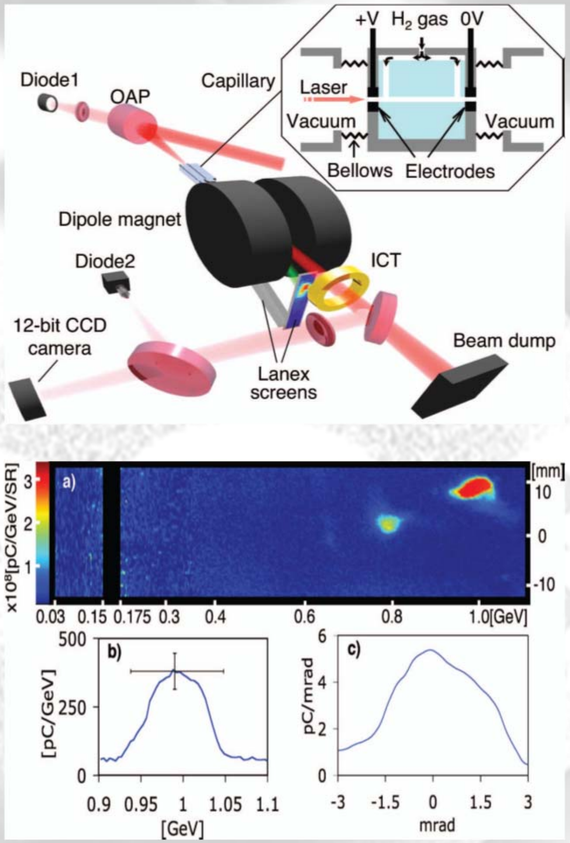
Proposed as an alternative way to LWFA

CAN'T generate high quality e- beams??

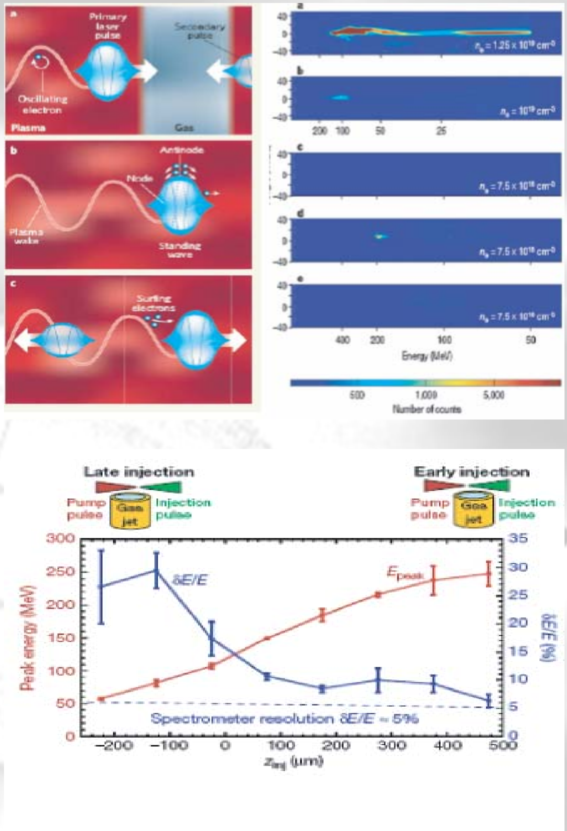
Need reappraised now!!

LPA Milestones in the last 15 years

2004-LBNL-LOA-RAL
"Dream Beam"

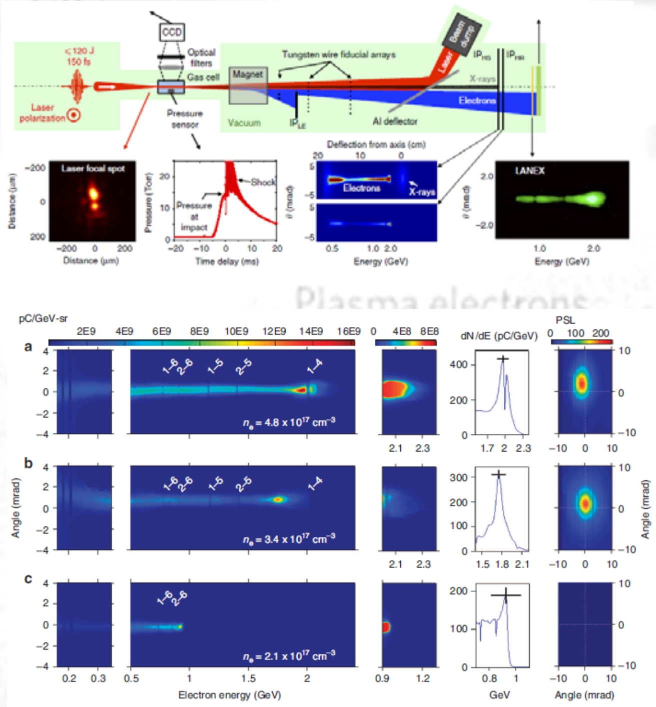


2006-LBNL-GeV bunch

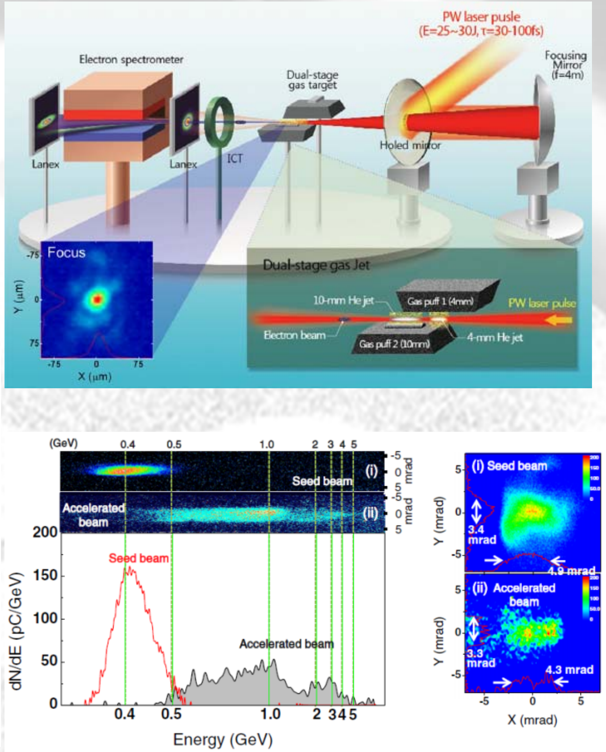


2006-LOA
Colliding Pulse Injection

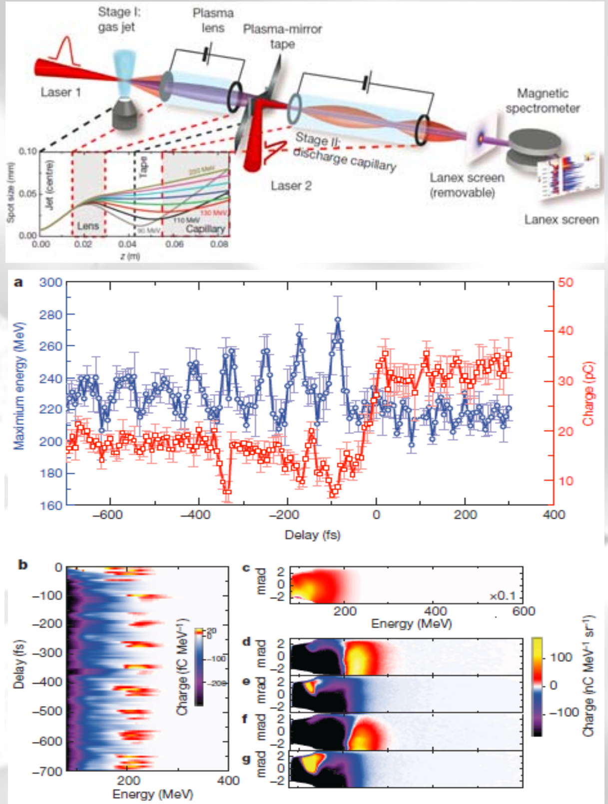
LPA Milestones in the last 15 years



2012-UT Austin
PW Laser, 2 GeV e- beam

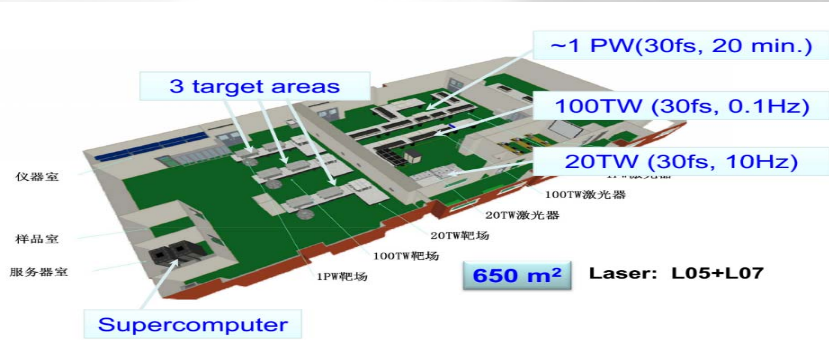


2013-GIST
PW Laser, dual-stage
3 GeV tail in 4+10 mm



2016-LBNL
Multi-Stage coupling

LPA studies at IOP (Since 2013)



Performances Summary Specified (S) / Expected (E)	Specified	Measured during OSAT
Repetition rate (Hz) (S)	10Hz	10Hz
Central wavelength (nm) (S)	800 nm +/- 10 nm	800nm
Spectral width (nm) (E)		79nm
Pulse duration (fs) (S)	< 25 fs	24 fs
Energy before compression (E)		702mJ
Compressor Transmission (E)		80%
Energy after compression (E)		561mJ
Peak Power (S)	>20 TW	23.4 TW
Energy stability (RMS) (S)	Short term : 2% Long term : 2%	Short term : 1.78% Long term : 1.86%
Beam quality (S)	M^2 < 1.5 on both axis	$M^2x = 1.48$ $M^2y = 1.42$
Pointing stability (S)	< 30 µrad	2.2 µrad
Polarization (S)	1:100	1:100
Contrast ns (S)	< 10^-8:1	4.3*10^-9
Contrast ASE < -300 ps (S)	< 10^-10:1	1.1*10^-10
Contrast ASE < -50 ps (S)	< 10^-9:1	5*10^-10
Contrast ps @ -20 ps (S)	< 10^-7:1	2*10^-8
Contrast ps @ -5 ps (S)	< 10^-5	6*10^-6
Contrast ps @ -1 ps (S)	< 10^-3	1*10^-4

LPA studies at IOP (Since 2013)

Laser Condition:

~ 500mJ/25fs/20TW

F/5, w_0~6μm, a_0~3

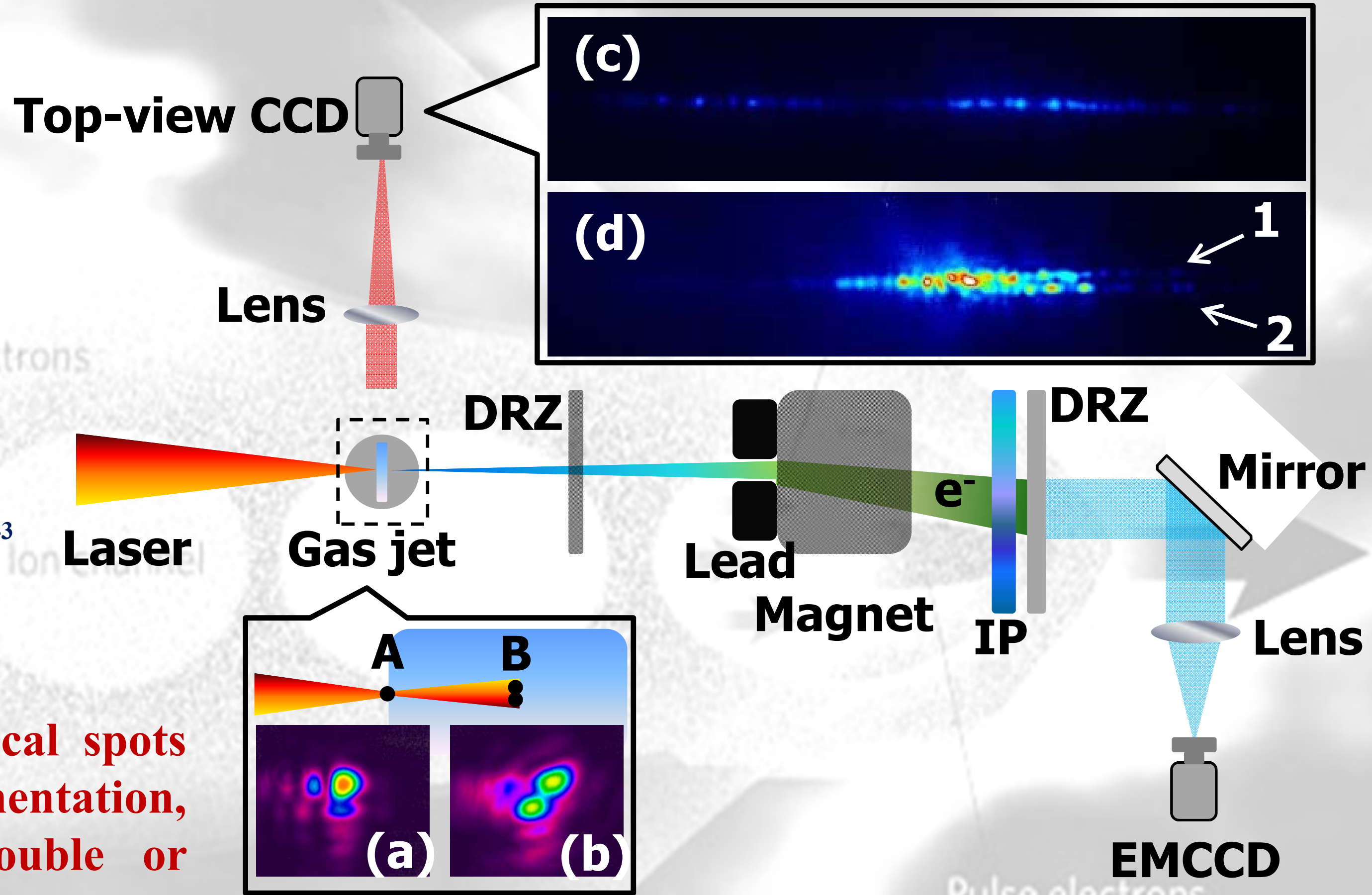
Nozzle:

1.2mm×4mm

Plasma Density:

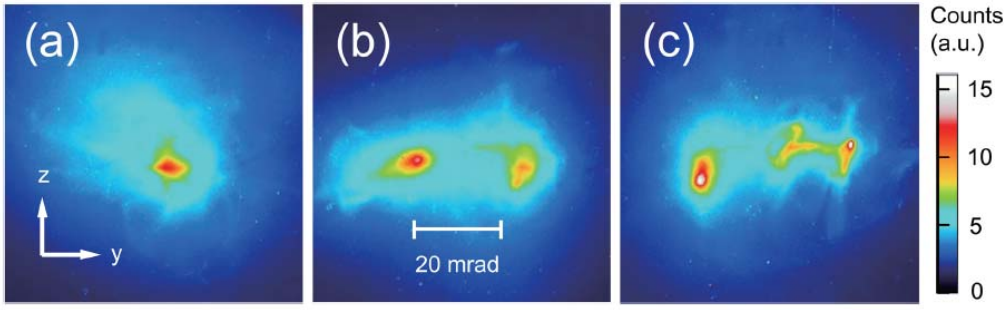
0.1~3×$10^{19}$$cm^{-3}$

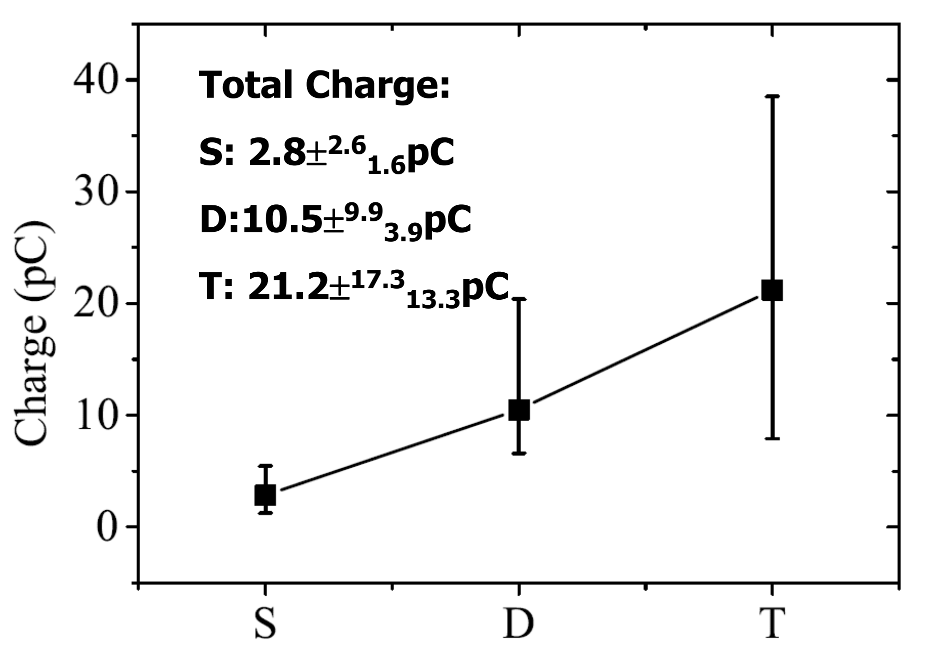
Optimized @ 6×$10^{18}$$cm^{-3}$

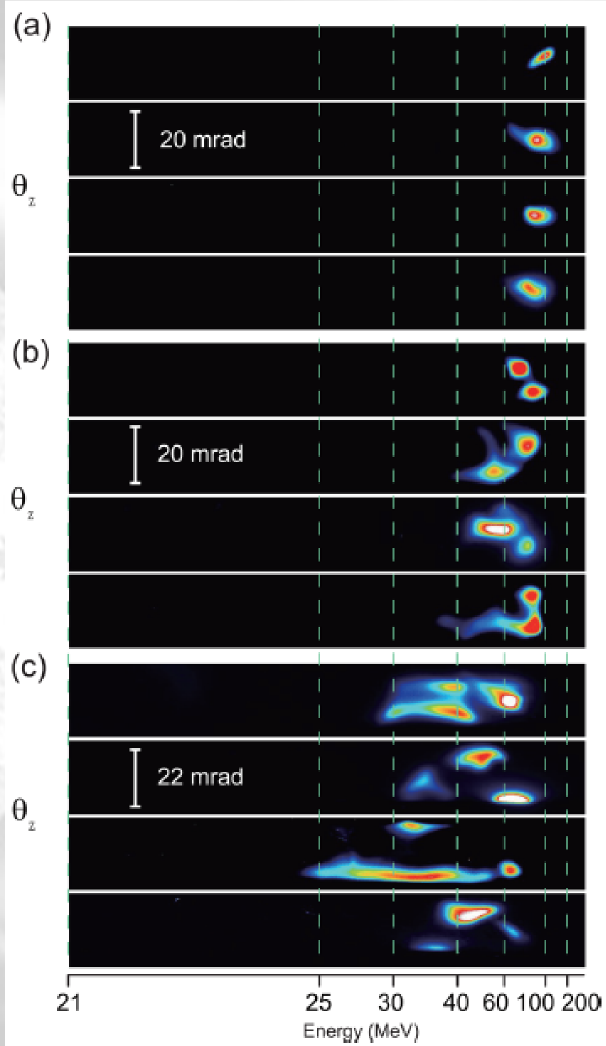


Double or triple focal spots appear due to filamentation, which leads to double or triple accelerated e- bunches

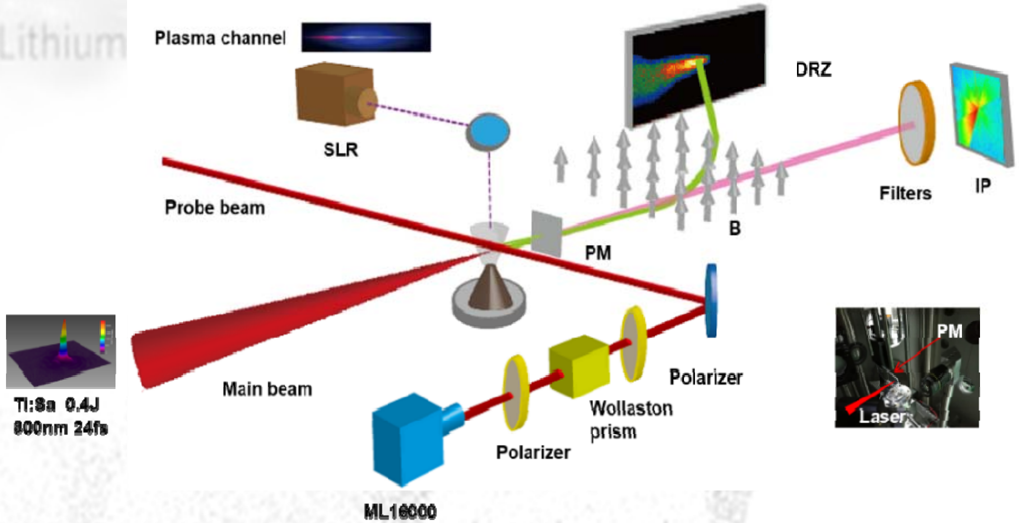
LPA studies at IOP (Since 2013)

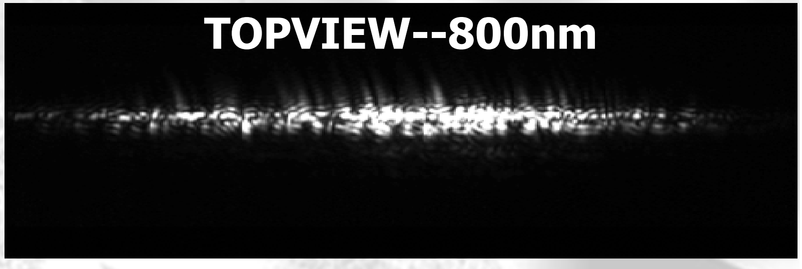


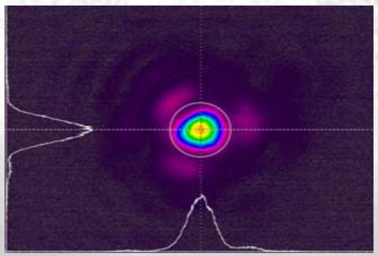




LPA studies at IOP in the last 2 years







Laser on target:

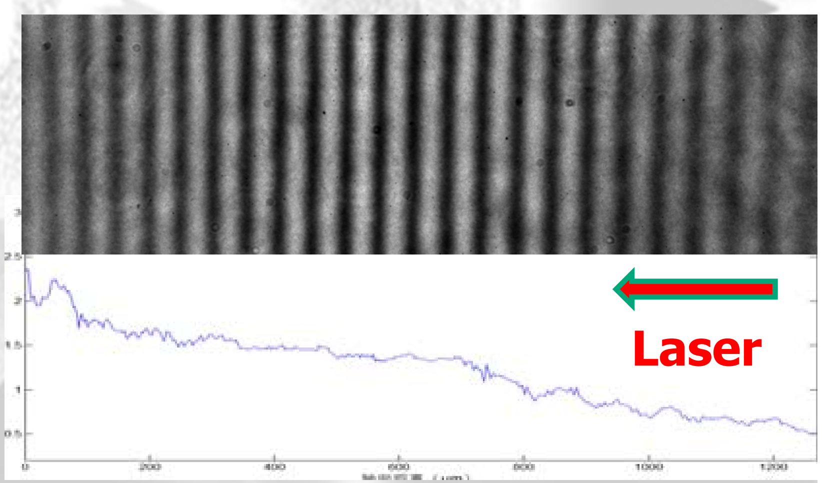
450mJ, 25fs @ 1.2mm×4mm nozzle

Focal Spot:

w_0=11μm, Z_R =470μm

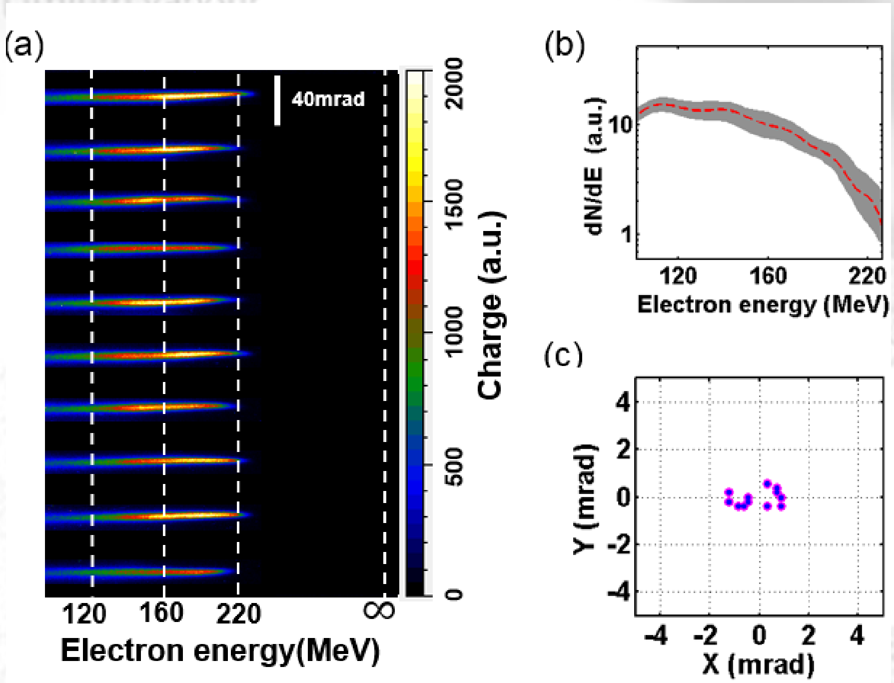
w_{FWHM}=11.2μm (31.4% Energy)

I=5*10^{18} W/cm^3 a_0=1.5



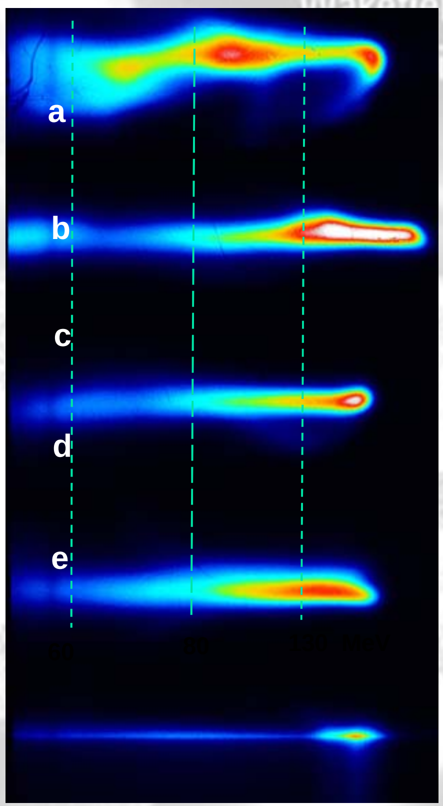
Stable electron generation from nitrogen gas

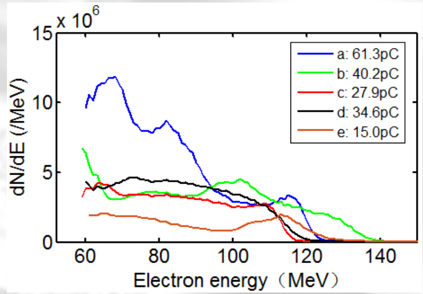
Pure Nitrogen gas



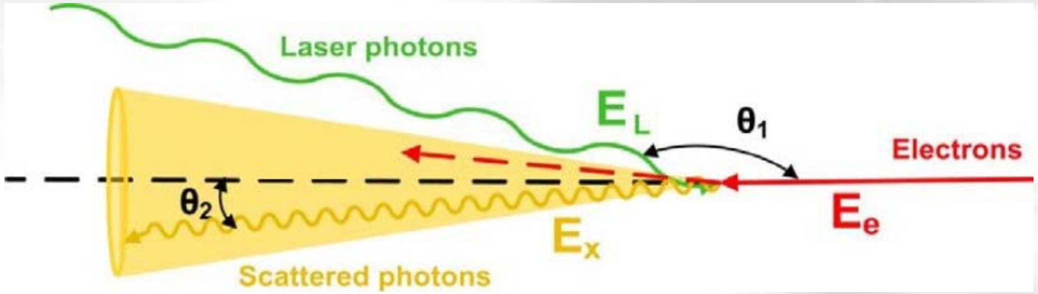
Divergence: 5.0 mrad
Pointing: 0.5 mrad (30 shots)

Pure Helium gas



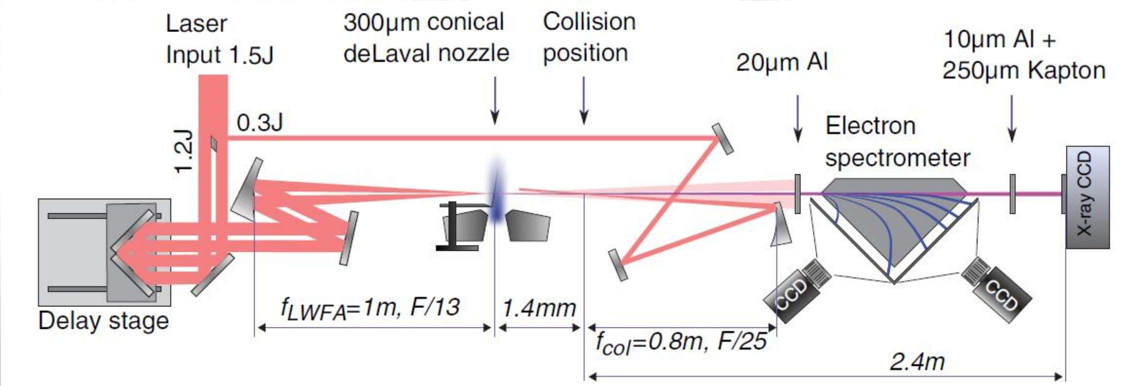


2 Methods of all-optical Thomson Scattering



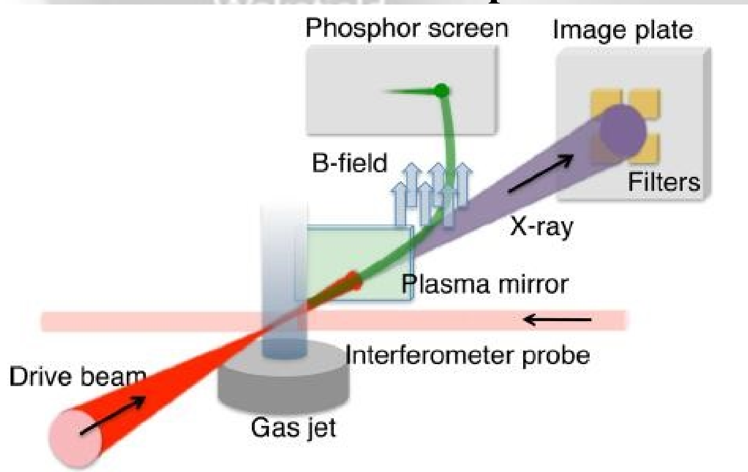
Thomson scattering scheme

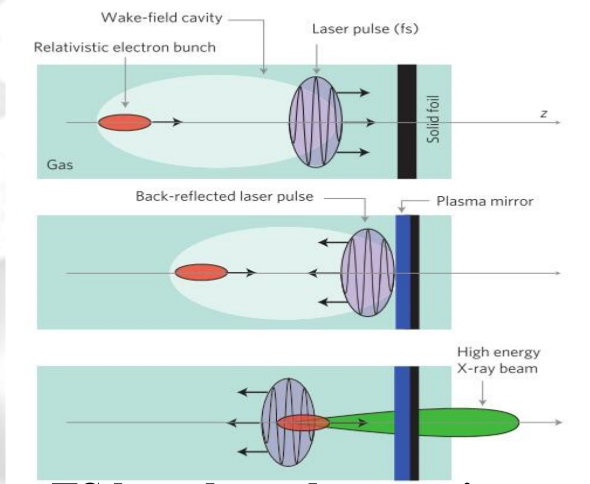
Method one: driven laser+ collision laser



TS based on two laser system

Method two: driven laser+ plasma mirror

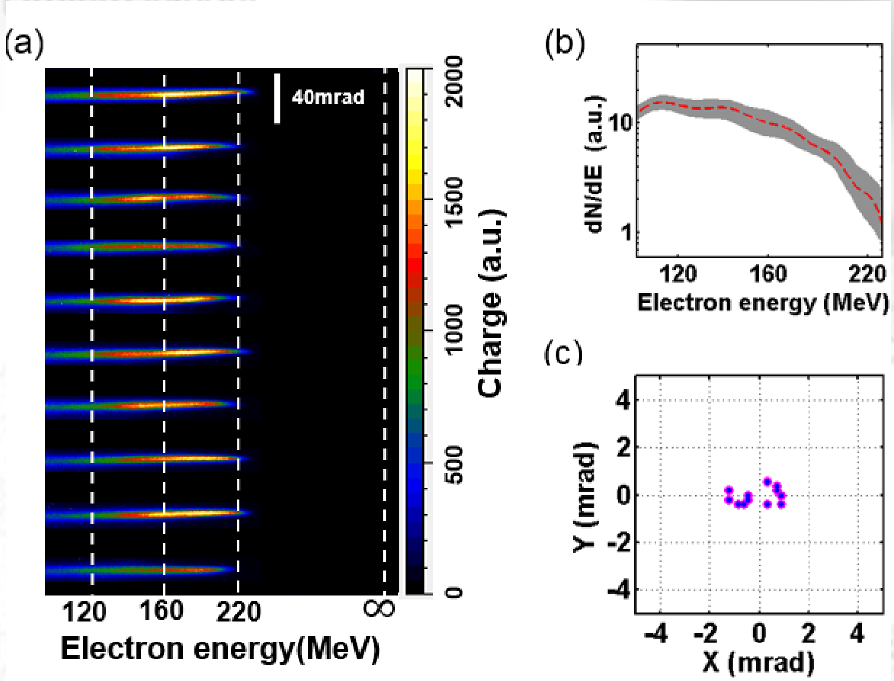




TS based on plasma mirror

More stable electrons and higher laser energy

Pure Nitrogen gas



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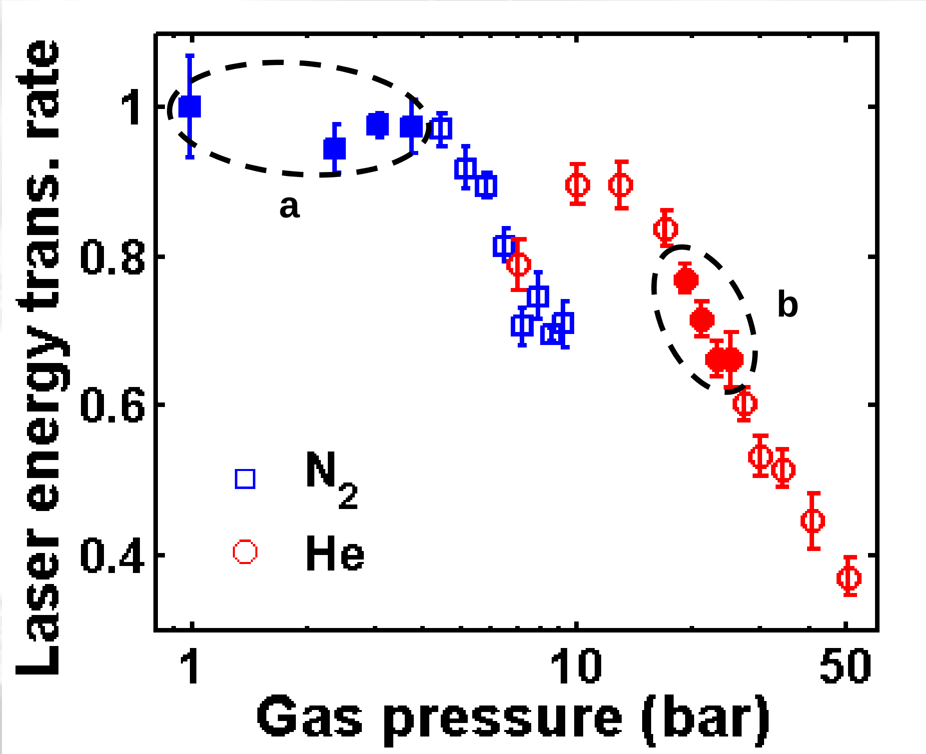
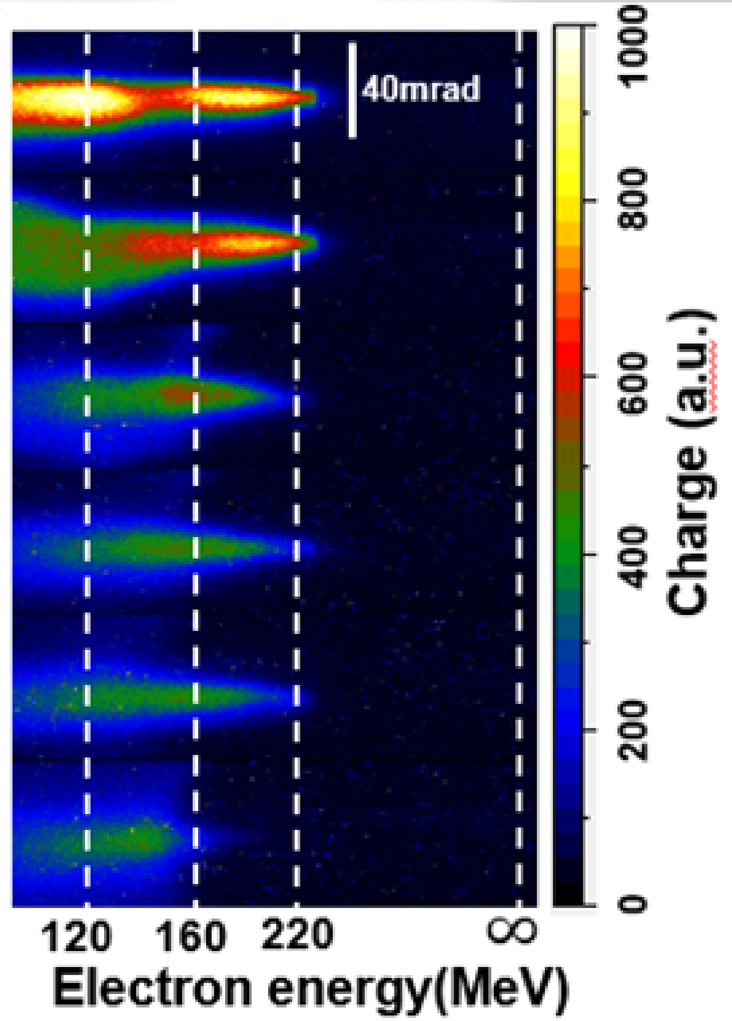
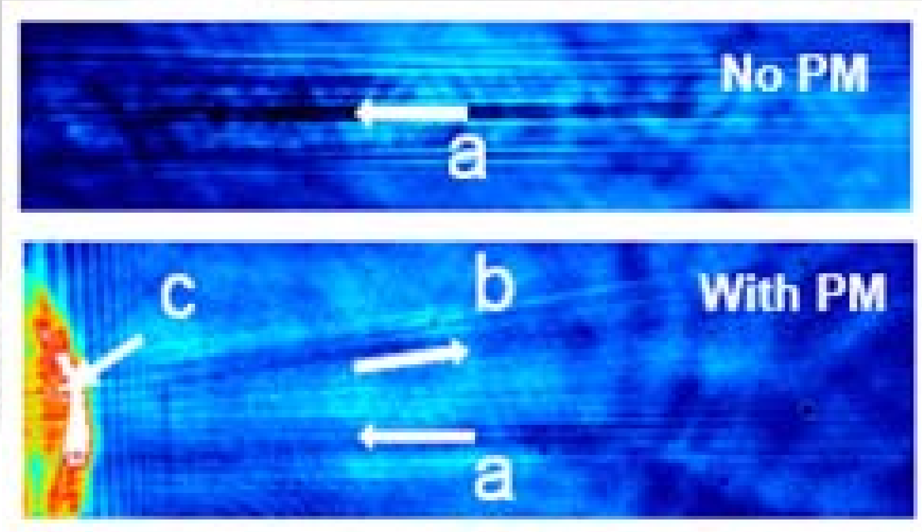
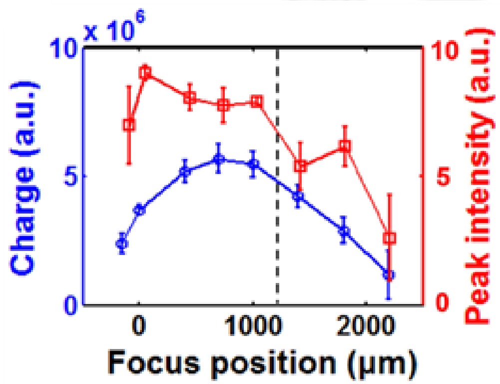
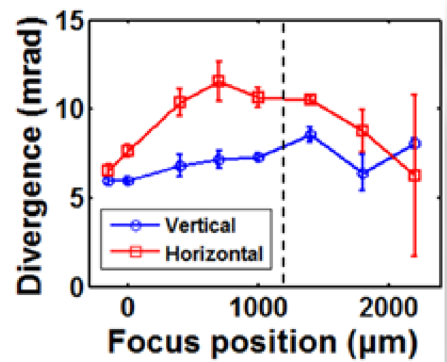


Thomson Scattering by using plasma mirror









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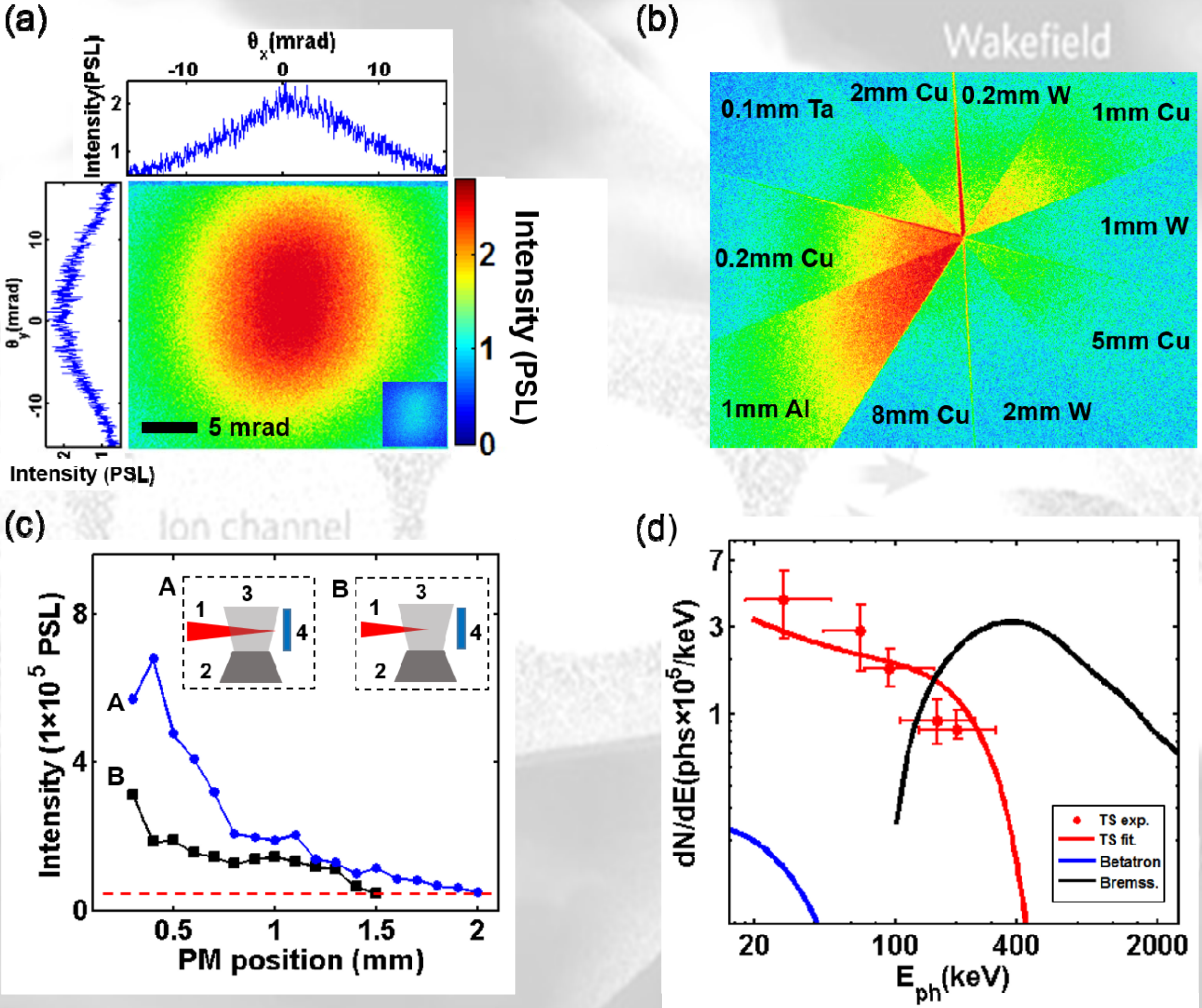
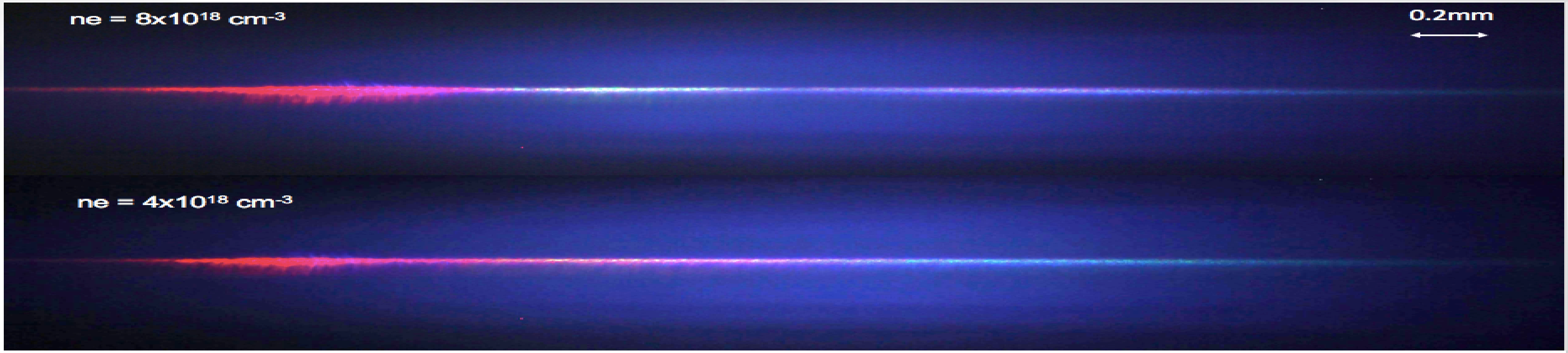
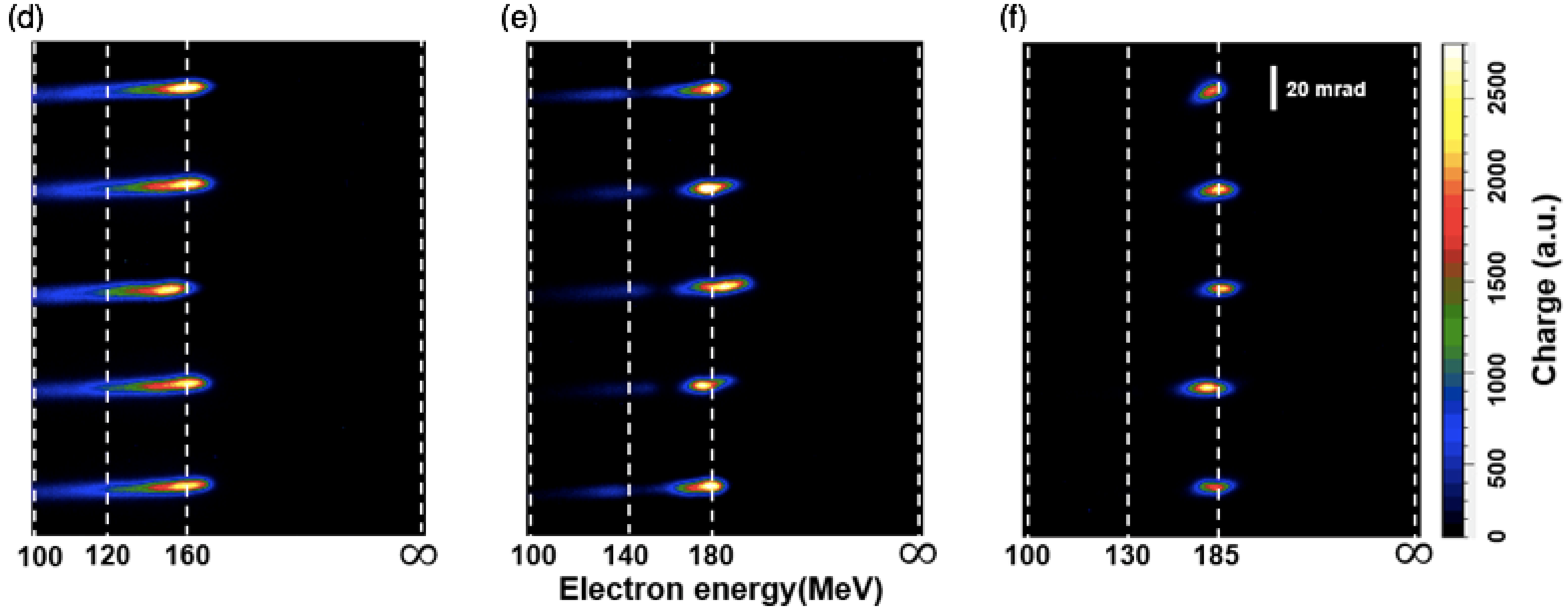


Small energy spread by self-evolved ionization





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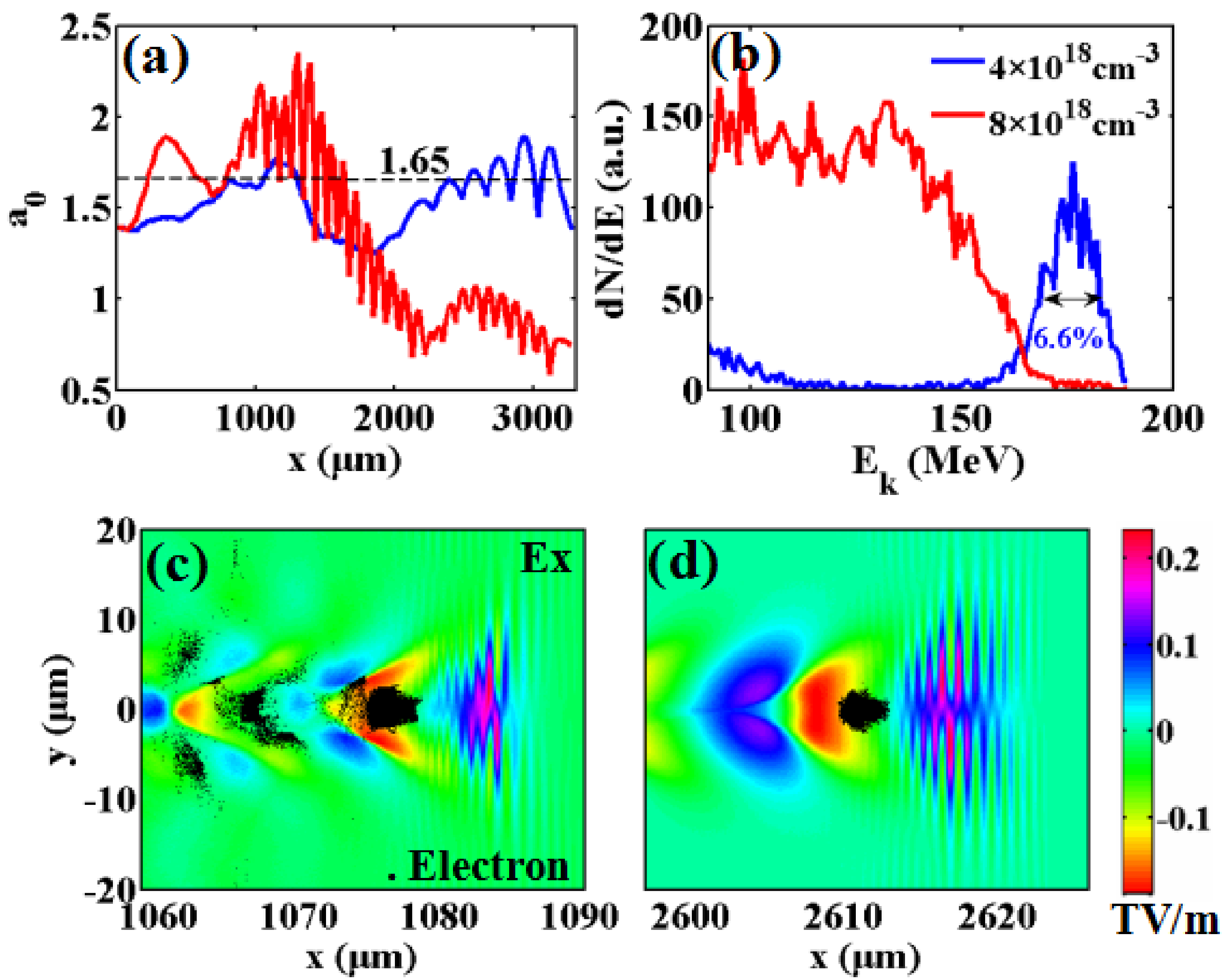
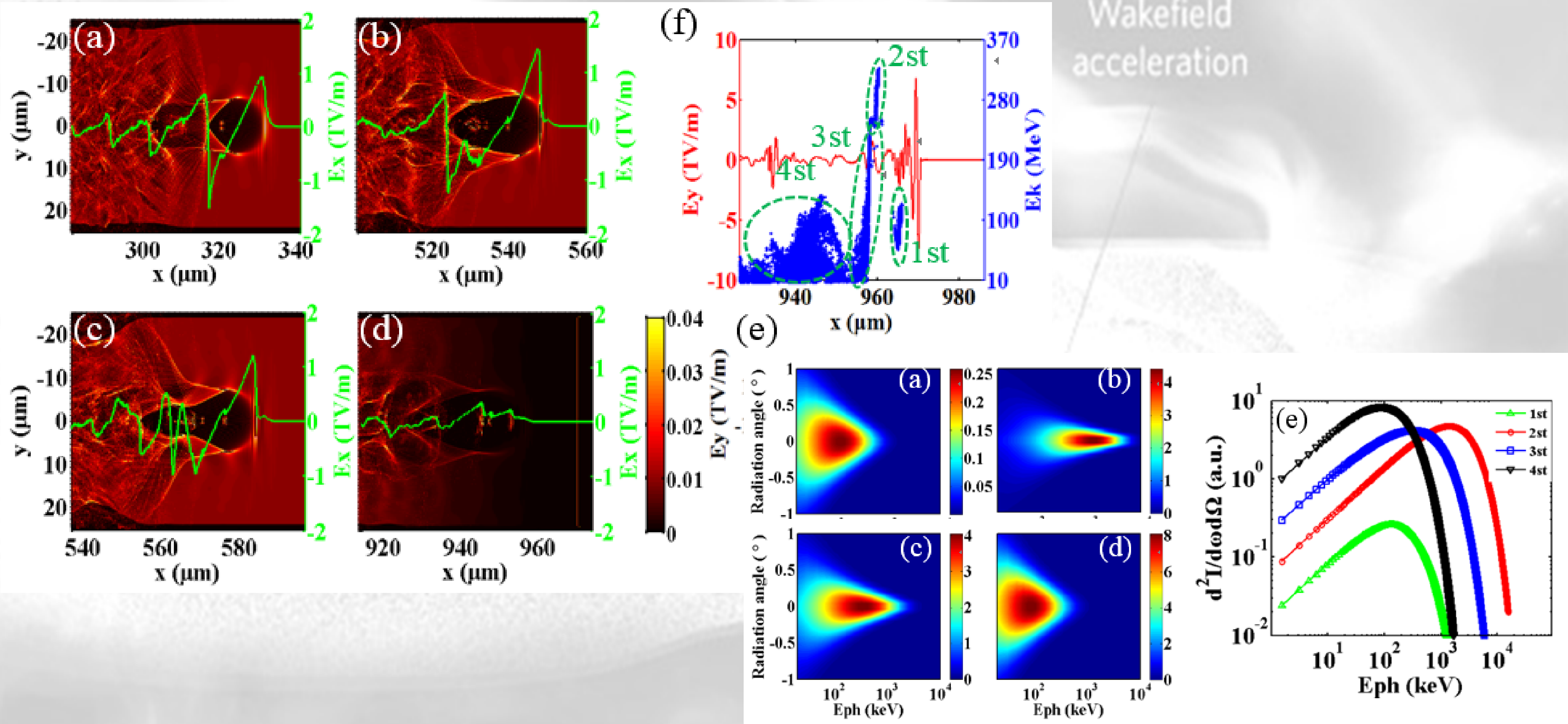
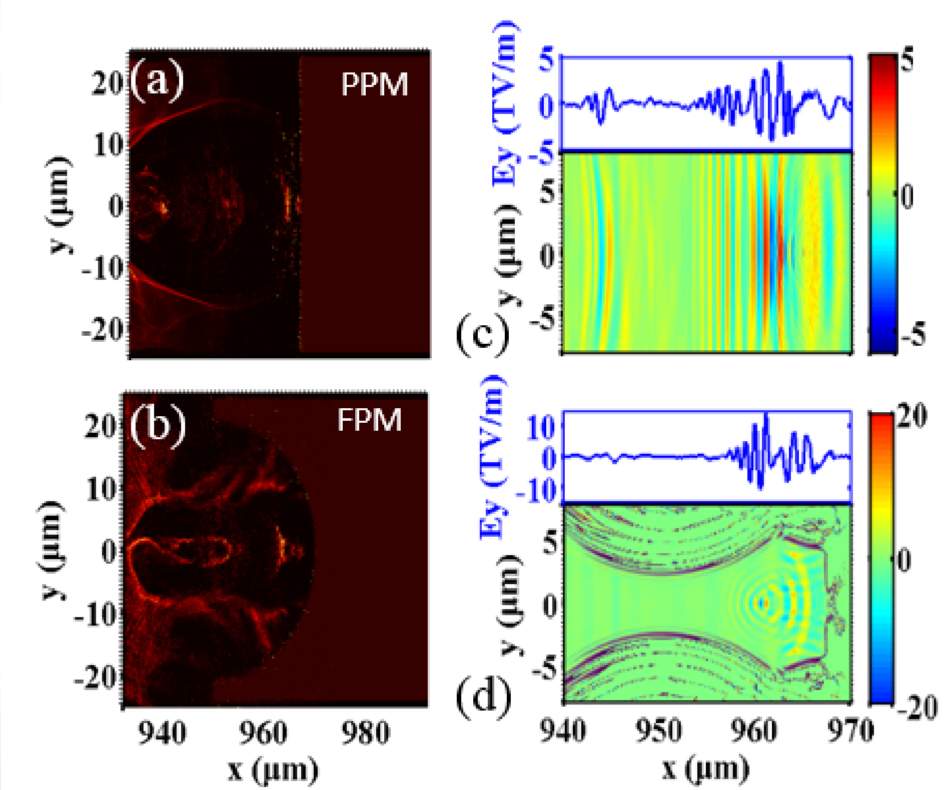


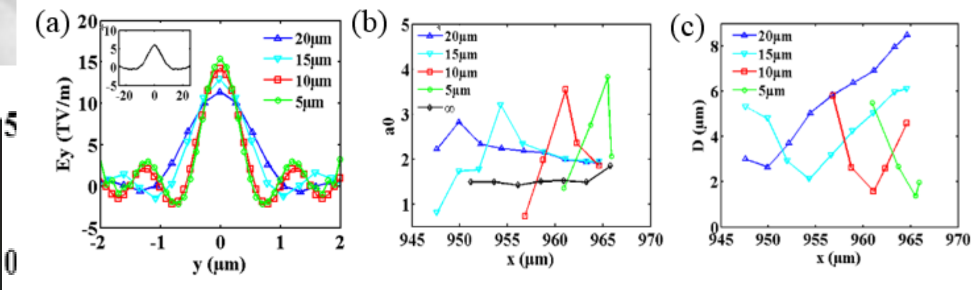
Enhance the radiation by using Focus PM

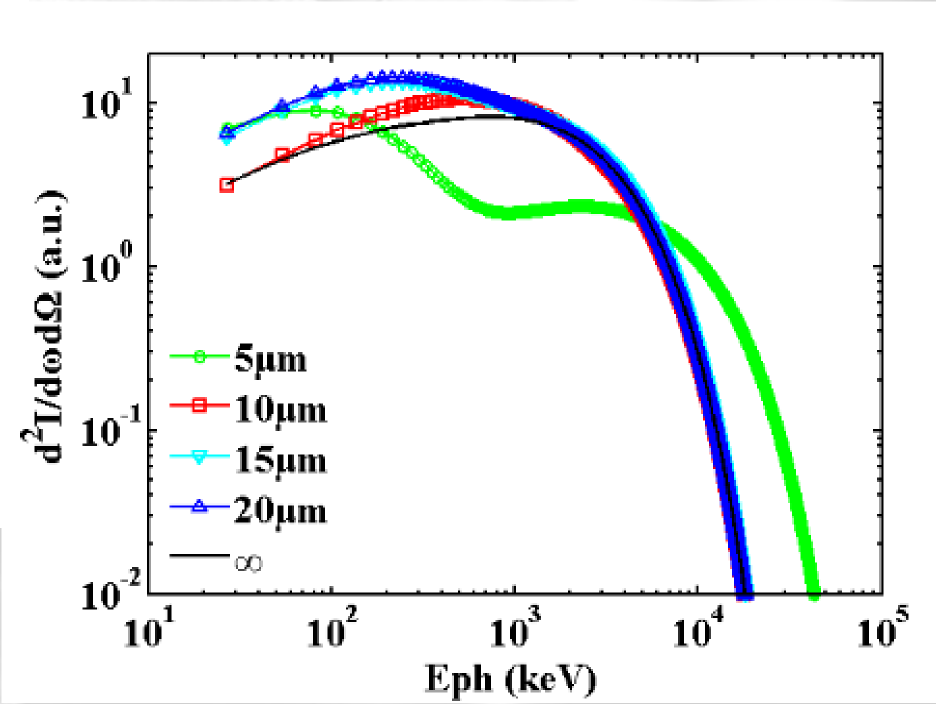


Wakefield acceleration

Enhance the radiation by using Focus PM







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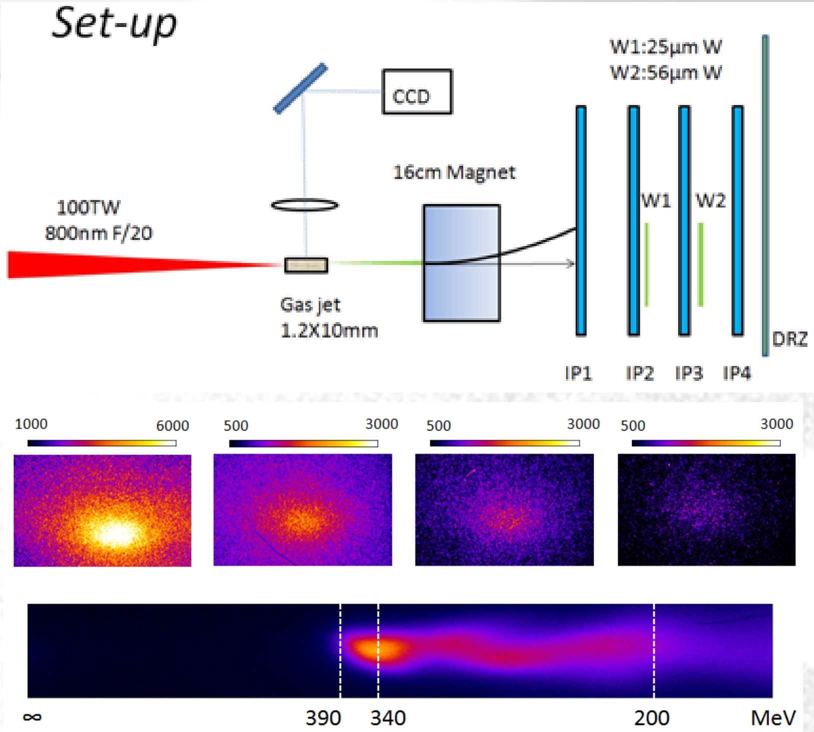
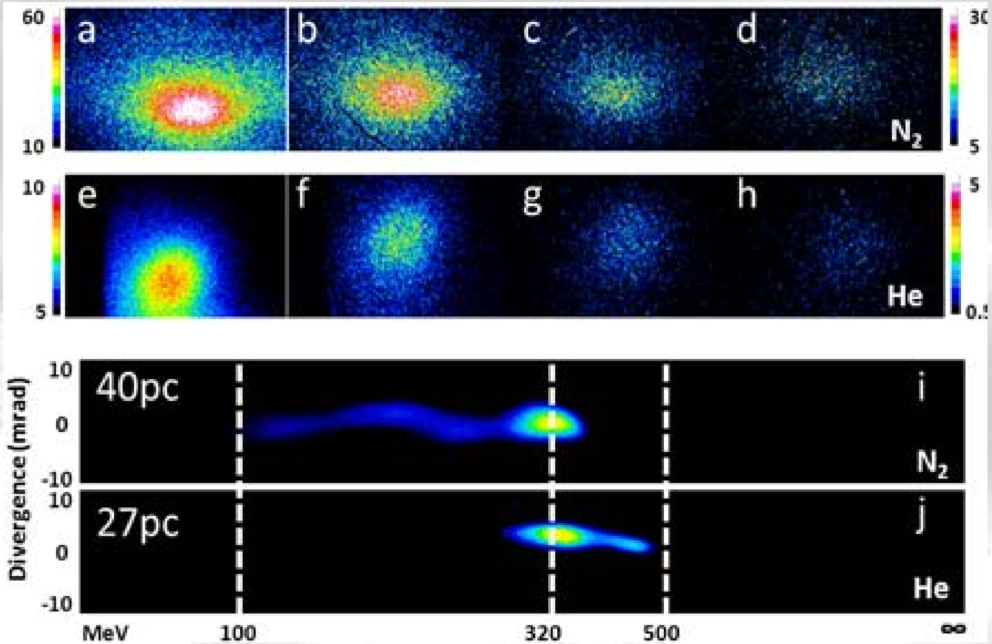
LPA studies at SJTU (since 2013)



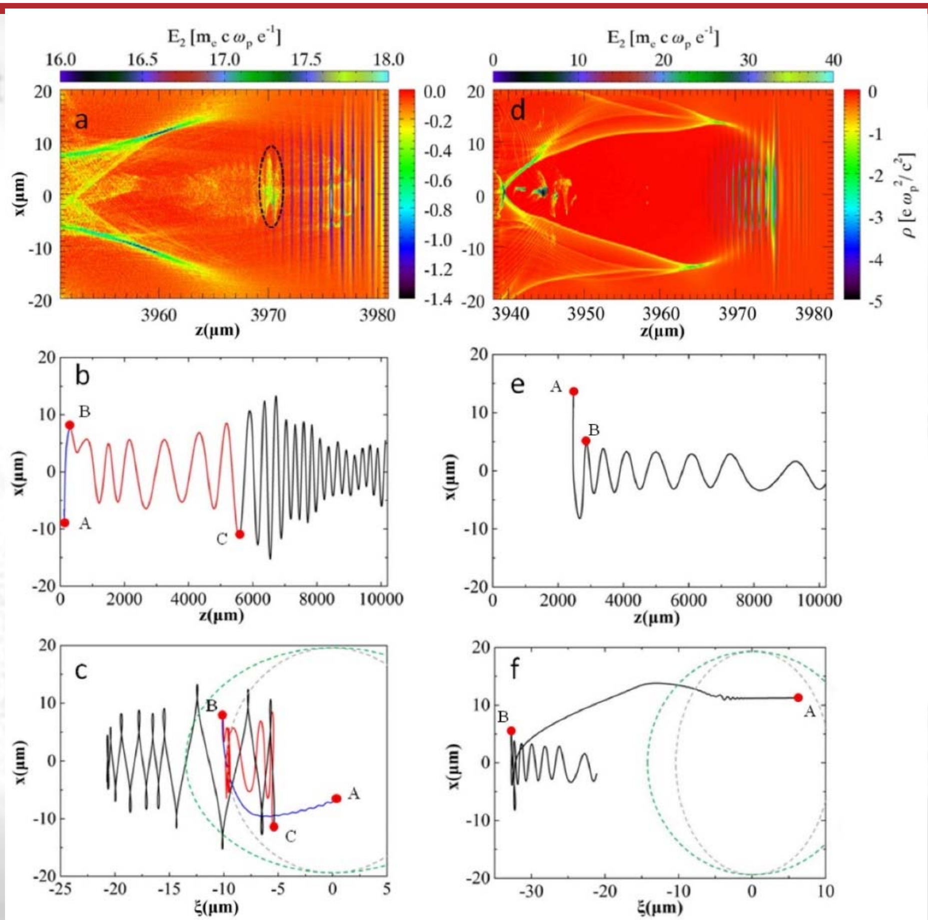
IP	1	2	3	4
Photon energy	>7keV	>36keV	>52keV	>110keV
Photon number	2.3×10^8	6.5×10^7	3.6×10^7	2.3×10^7



- ~10^9 hard x-rays with energy > 10 keV
- The critical energy is 75 keV
- 10^8 X-rays with **energy > 110 keV**.

K. Huang, D. Z. Li, L. M. Chen*, *Sci. Rep*, 6, 27633 (2016)

LPA studies at SJTU (since 2013)



Time needed for injection (A→B):

0.66ps（N_2）, 1.36ps （He）

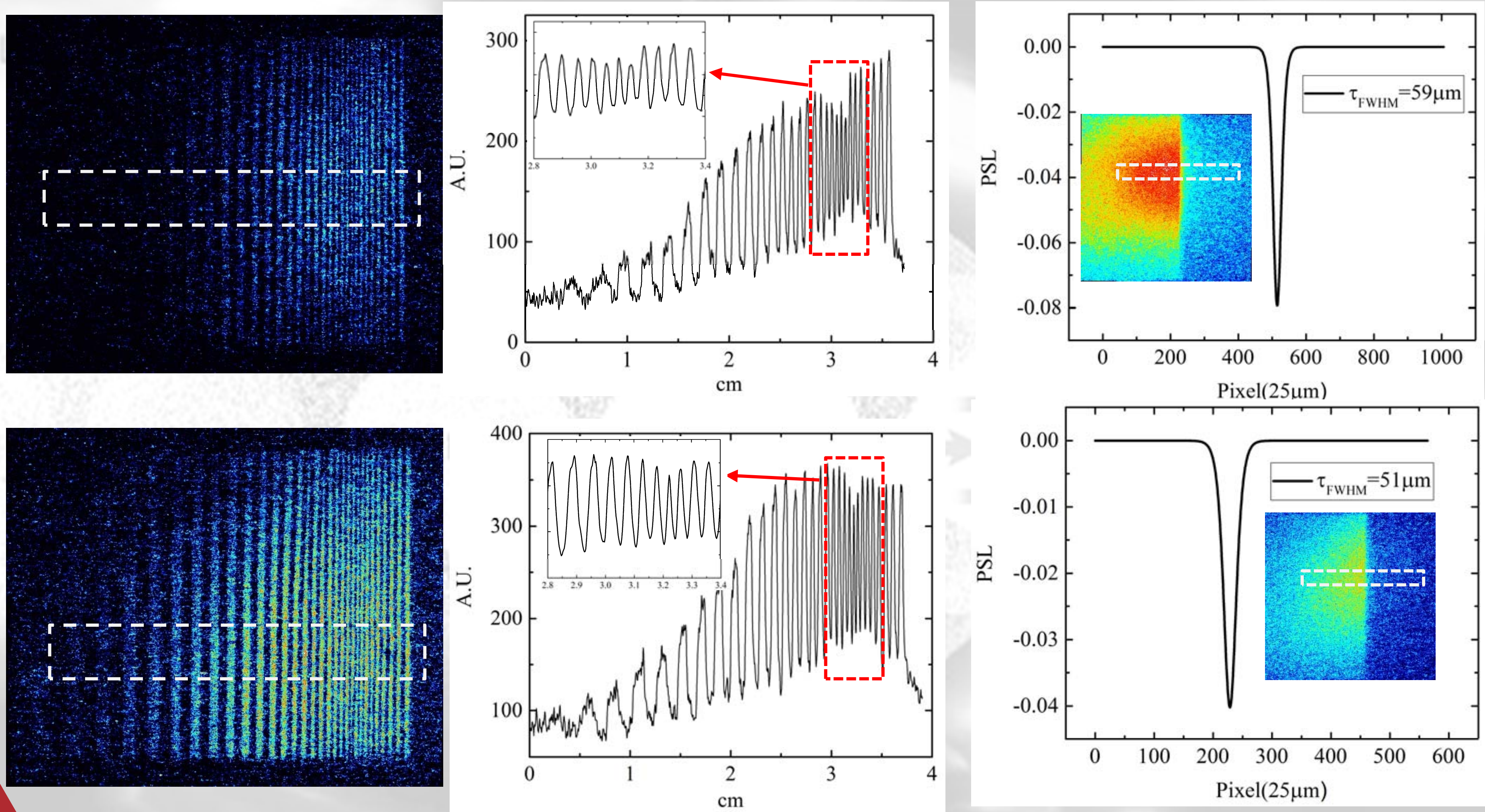
Born Position in Laser frame (Point A):

N_2: -10 μm, middle of bubble

He: -33 μm, tail of bubble

It is demonstrated that the ionization injection scheme stimulated by nitrogen gas shortens the time for the injected electrons to catch up with the laser pulse, which increases the probability of resonant betatron oscillations.

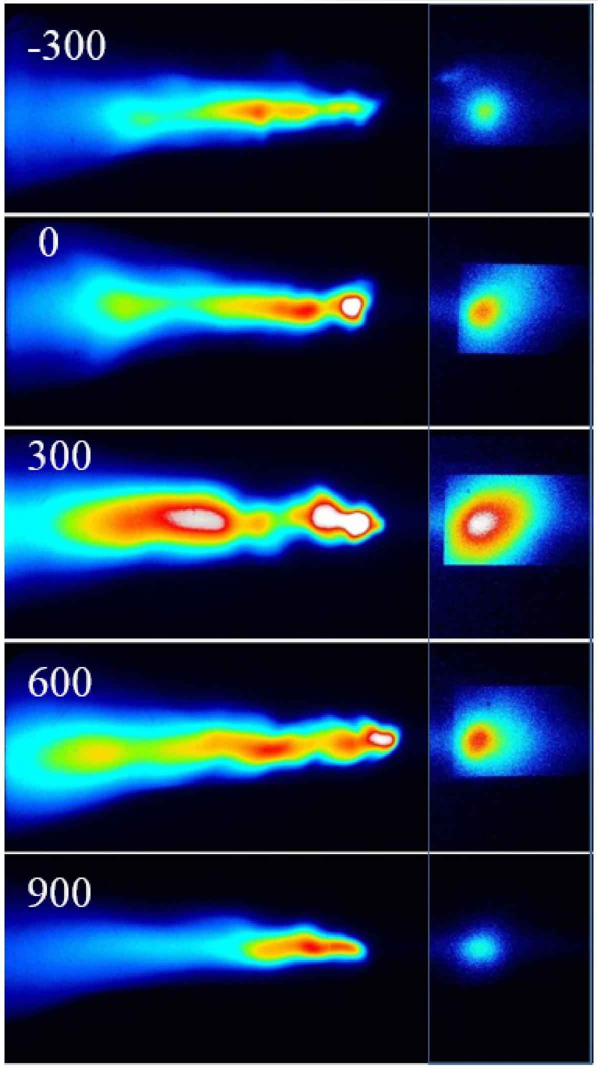
Betatron radiation source size measurement

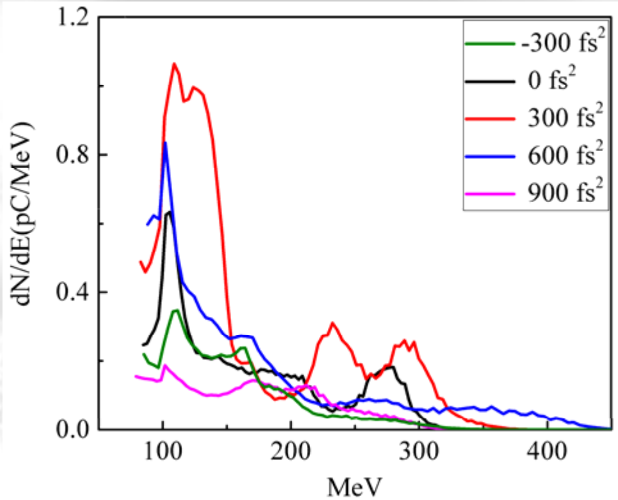


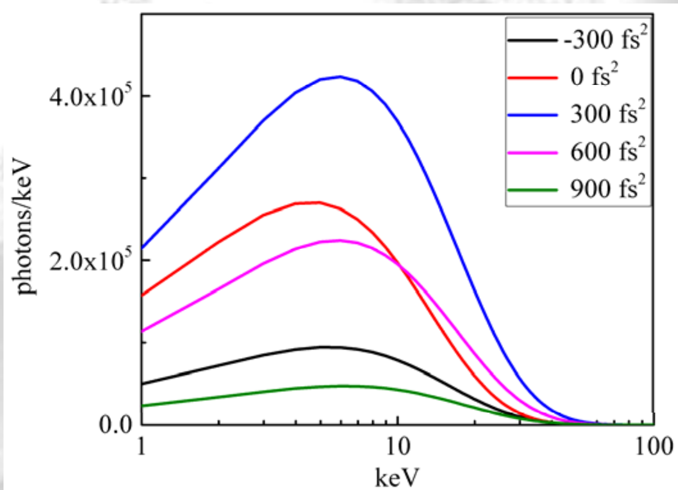
Line pair method: size ≤ 50 μm

Knife edge method: size ~ 50-70 μm

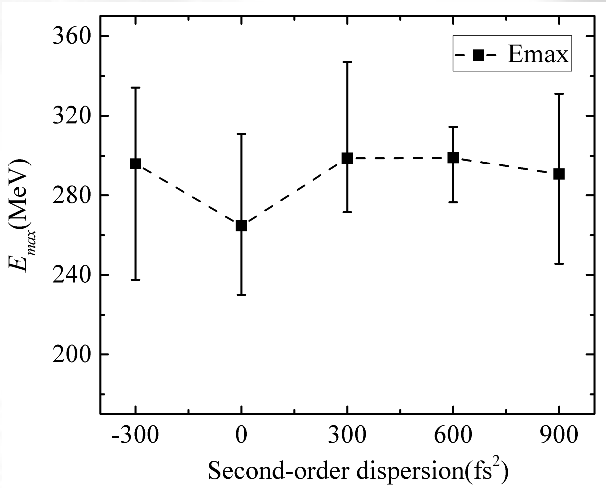
e- and X-ray evolving with the Chirp

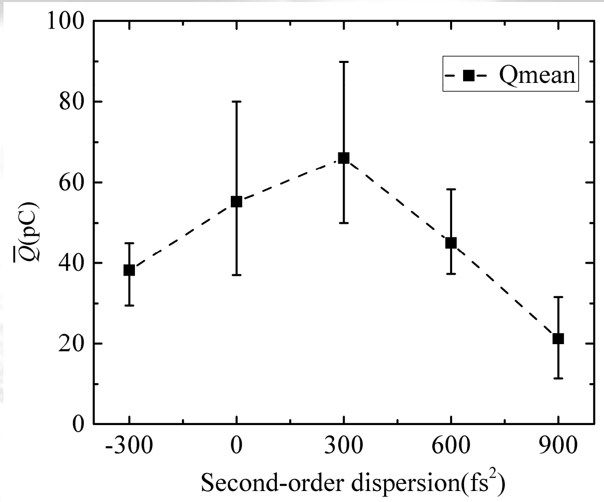


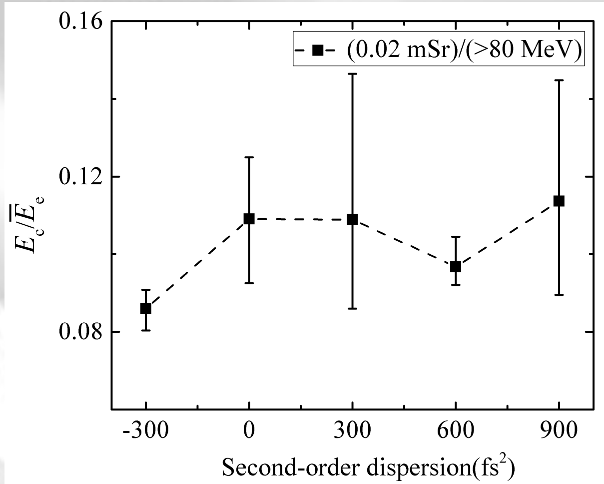


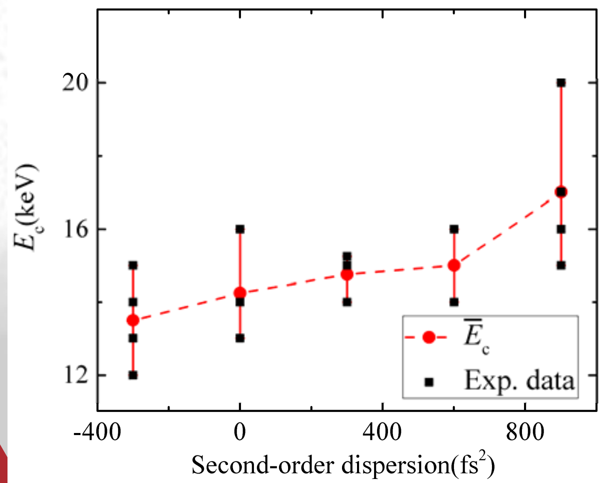


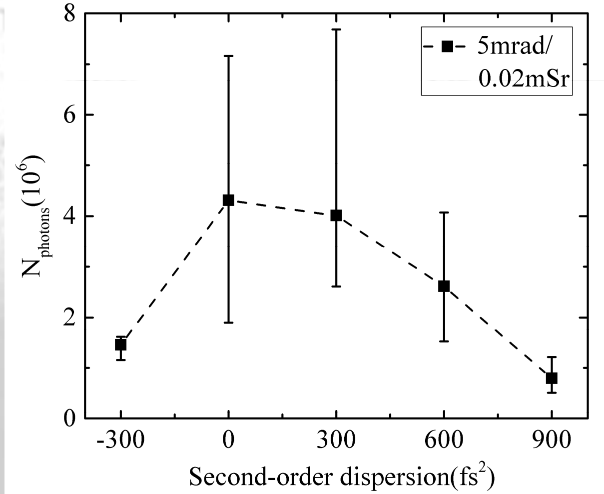
e- and X-ray evolving with the Chirp

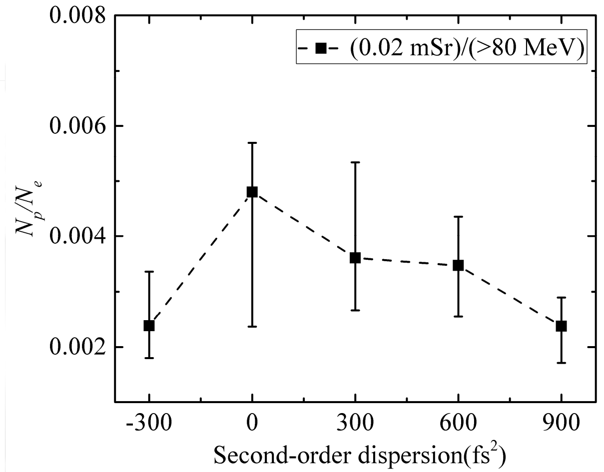




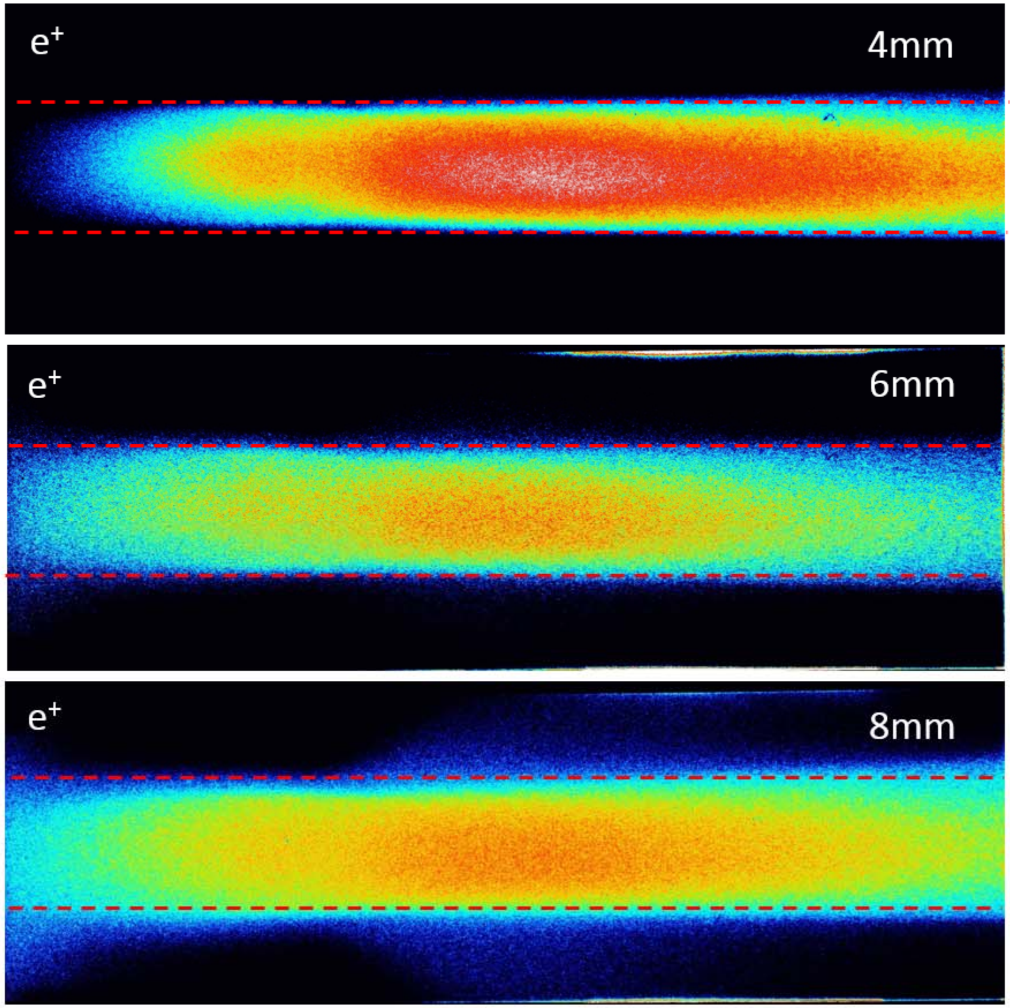


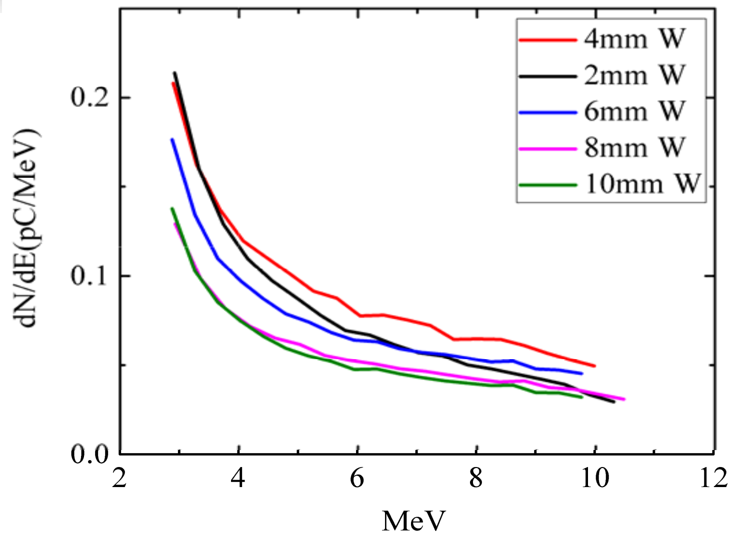


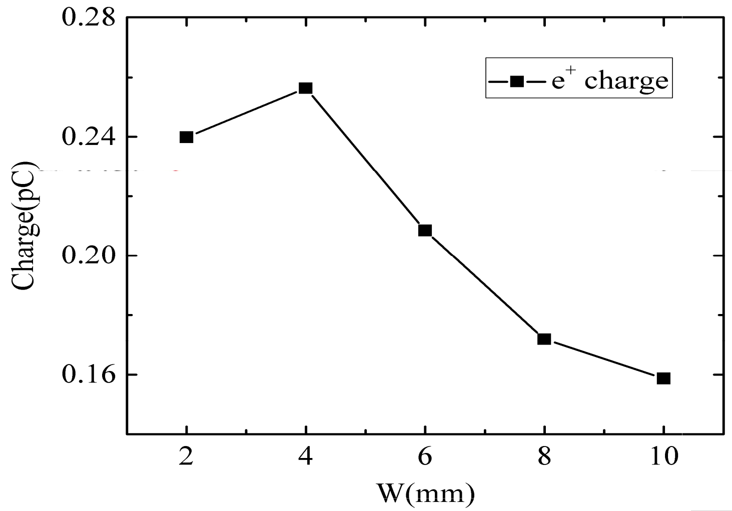




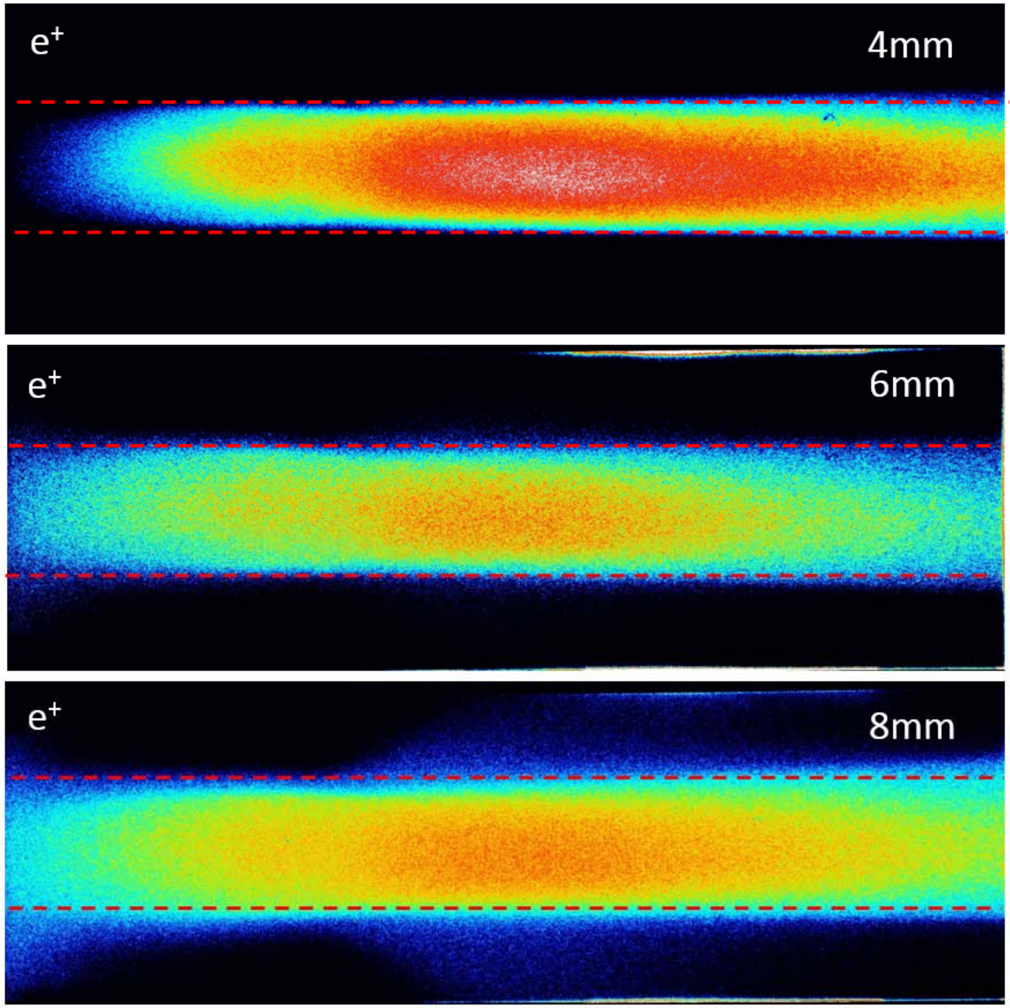
e+ generation e- tungsten interaction

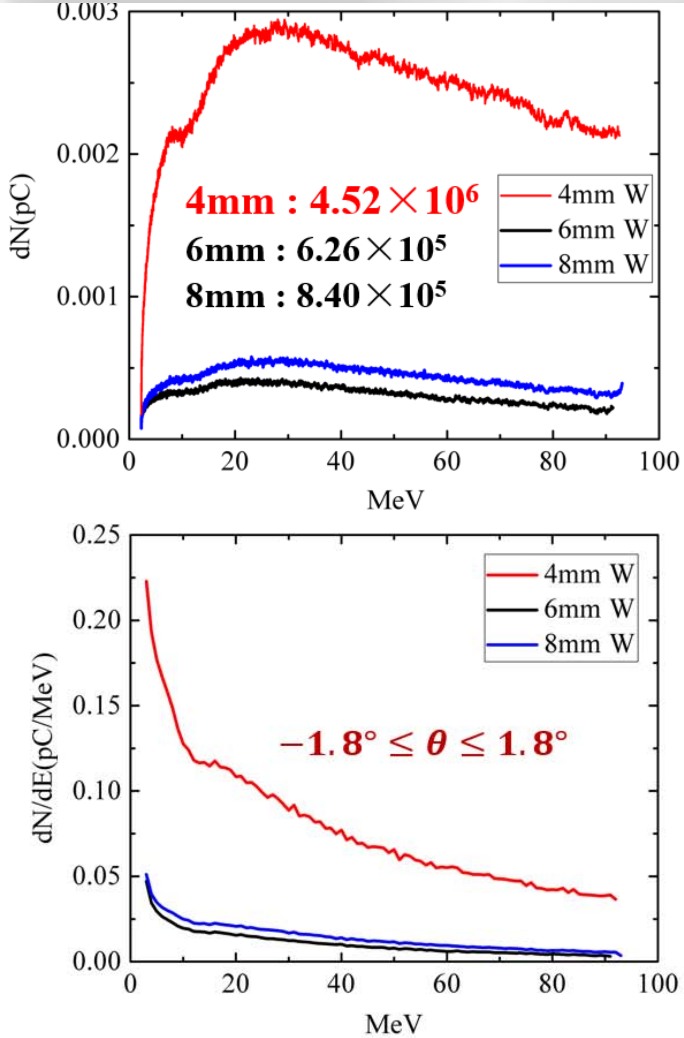






e+ generation e- tungsten interaction





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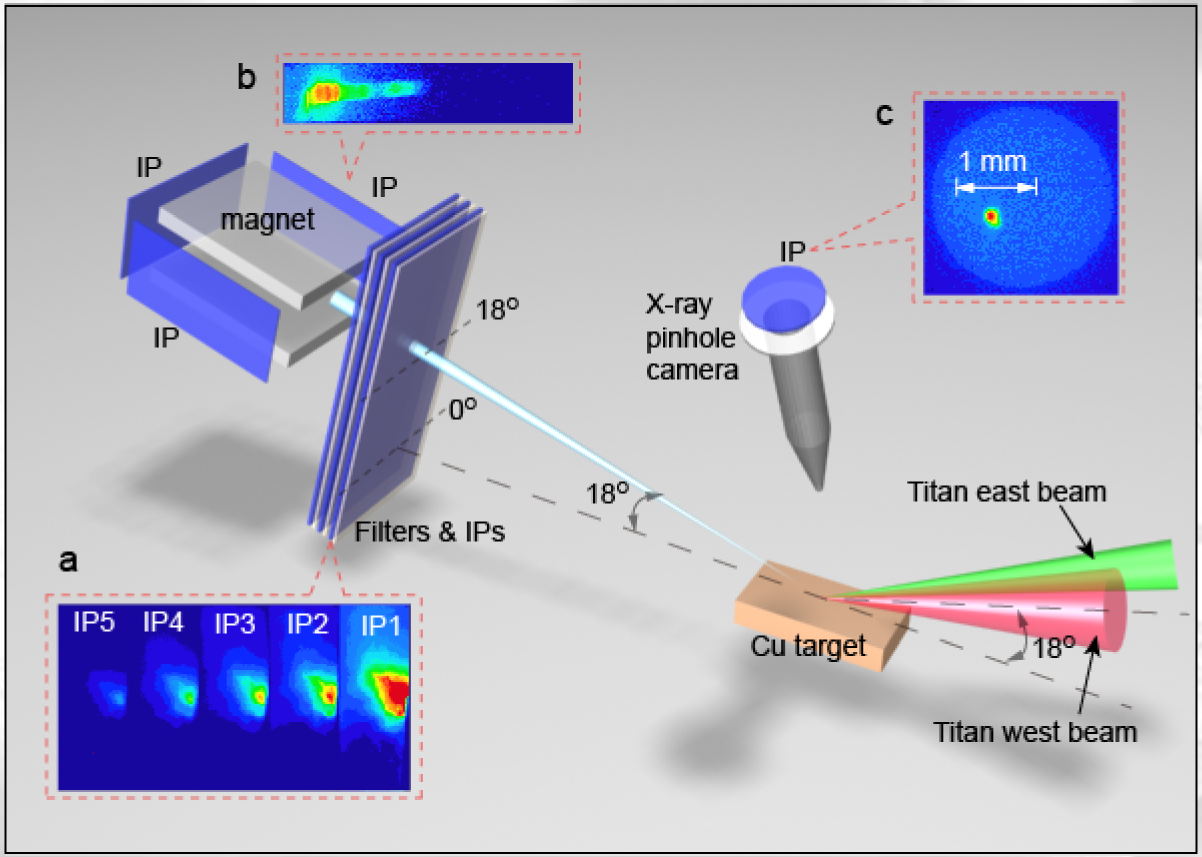
High charge bunch from 100J Titan laser



Titan Laser @ Jupiter laser facility, LLNL

Laser:

Titan west beam (Main)

E: 140J (1ω), 30J (2ω)

τ: 700fs

P: 200TW

w_0: 7um

I: 2.6×10^{20}W/cm^2 (a_0=14) (a_0=3.4)

E_{pre}: 5mJ (1×10^{16}W/cm^2)

E_{pre}: 0.2uJ (2ω) (4×10^{11}W/cm^2)

Titan east beam (2ω)

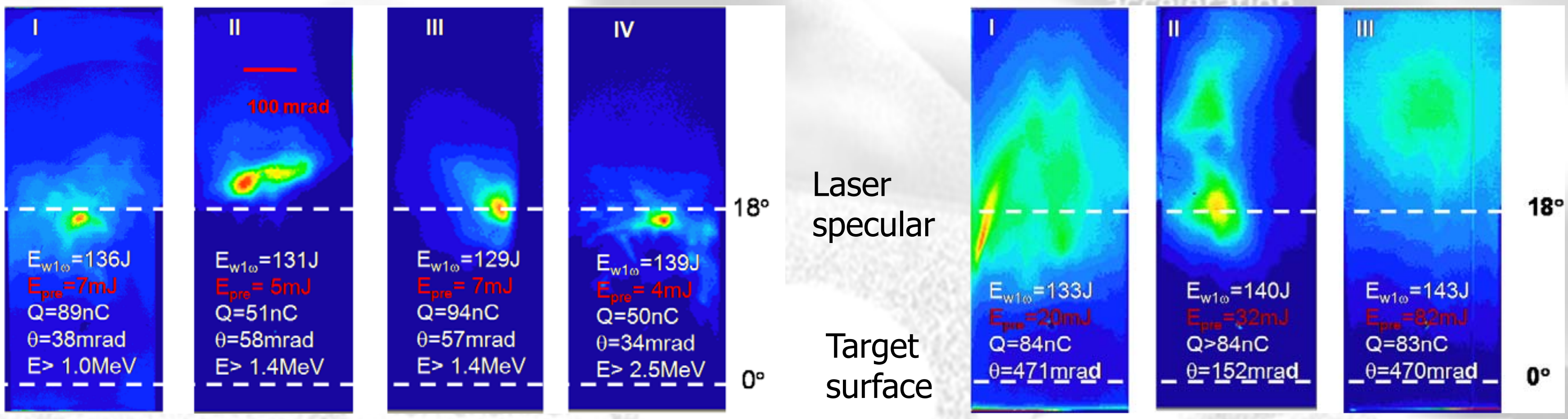
E: 220J, τ: 1ns, w_0: 38um

I: 1×10^{16}W/cm^2

Ultrahigh bunch charge was obtained

West 1ω only
E_{pre}: ~5 mJ

Increase the prepulse energy



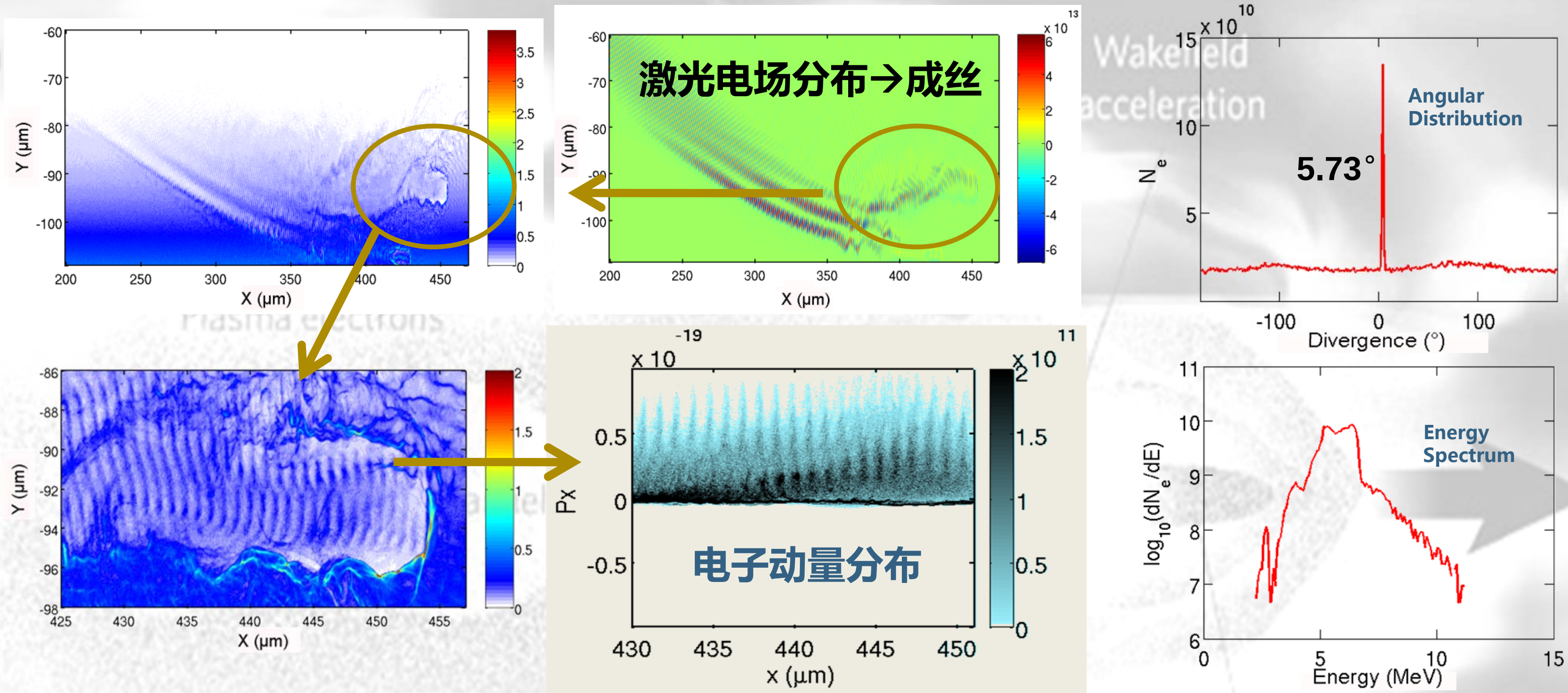
Main results：

- **Tightly Focused: 2-3°**
- **Well collimated: laser specular not target surface**
- **Ultrahigh bunch charge: 50~94 nC, Energy conversion efficiency ~10^{-3}**

We may set a record!!!

- **The bunch divergence increase**
- **The pointing and charge doesn't change**

Simple simulation for this interaction



Laser filamentation

→ Strong focusing force

→ Collimated

Direct laser acceleration

→ Phase locking

→ Quasi-monoenergetic

Injection in several λp

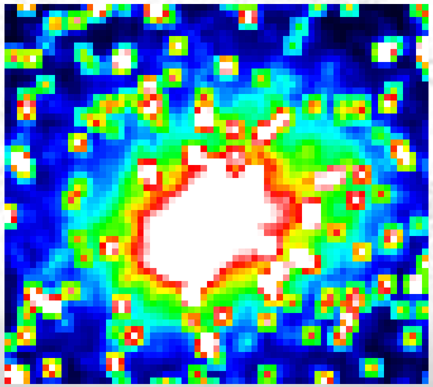
→ Less beam-loading effects

→ High bunch charge

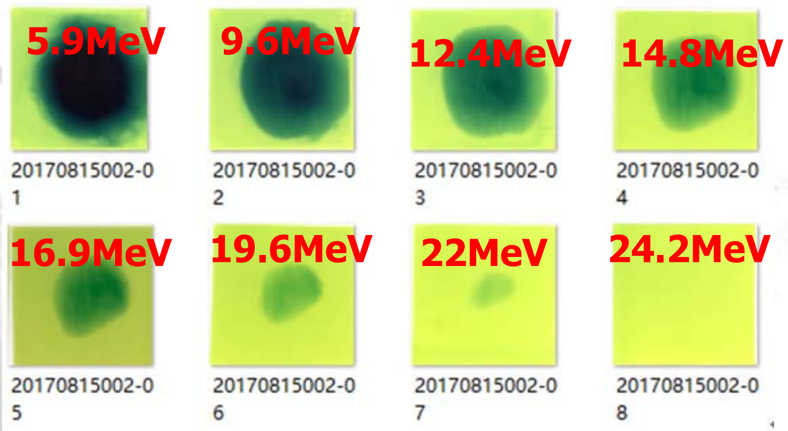
KEY POINT: the scale and density profile of the pre-plasmas

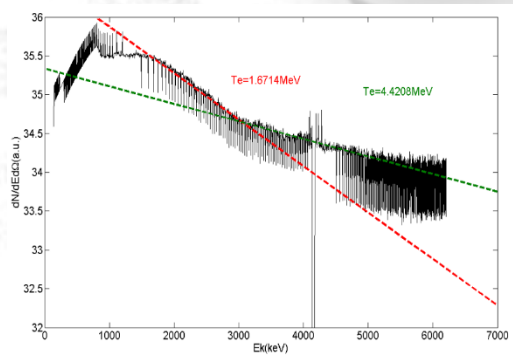
Experimental results at SILEX-III (test shots)

Shot No.	Laser Energy	Pulse Duration	Contrast	Focal Spot（FMHW, μm）	Electron temperature	Proton Energy
20170814001t	115 J	0.86 ps	8.0×10^7	N/A	T1=1.3 MeV T2=4.3 MeV	E_{max}>15MeV
20170815002t	110 J	0.95 ps	5.1×10^7	58.3×72.0	T1=2.1 MeV T2=3.8 MeV	E_{max}>22MeV
20170815003t	124 J	0.86 ps	8.5×10^7	58.2×62.8	T1=1.6 MeV T2=4.4 MeV	E_{max}>17MeV



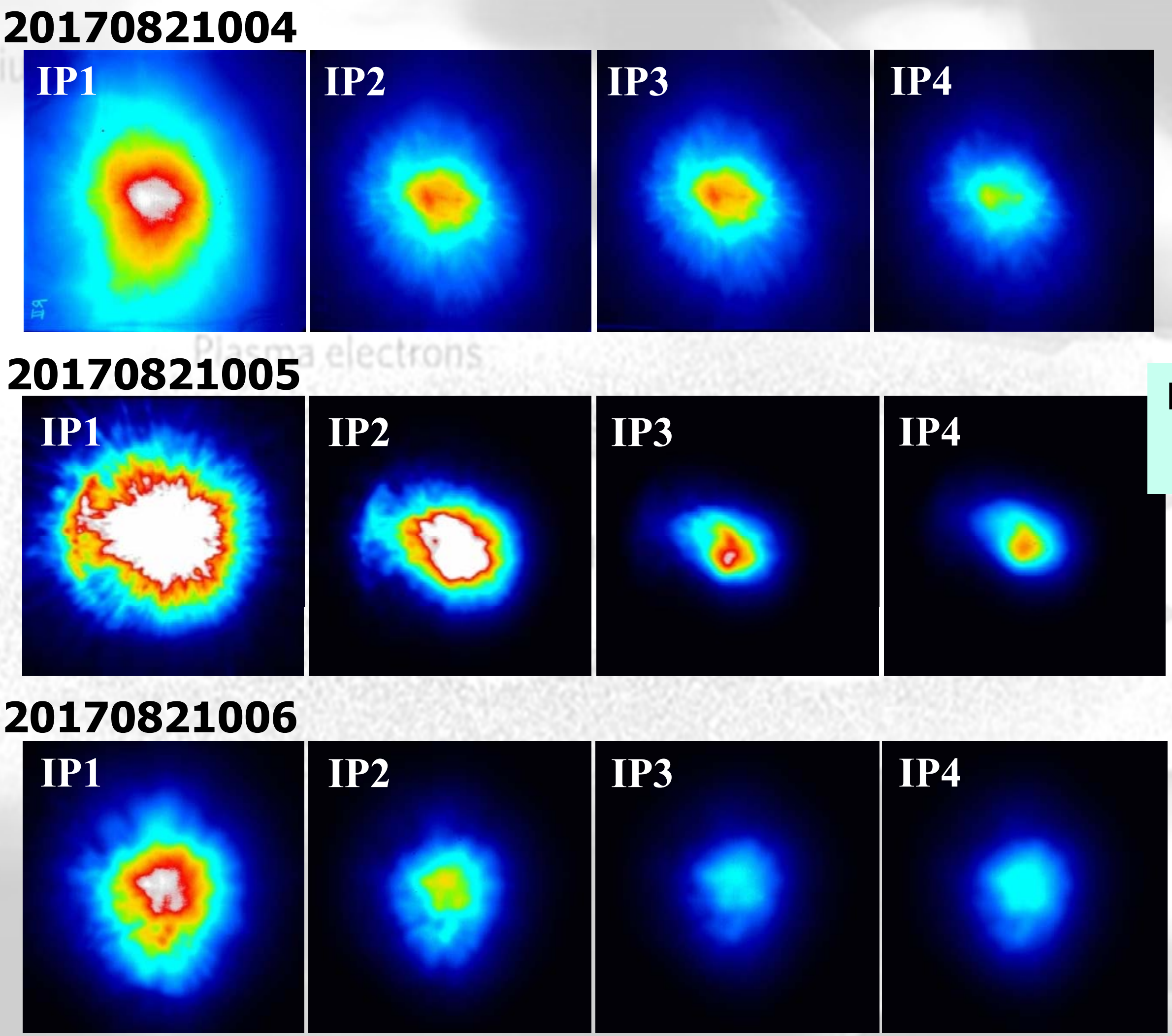
58.2μm x 62.8μm





Pulse electrons

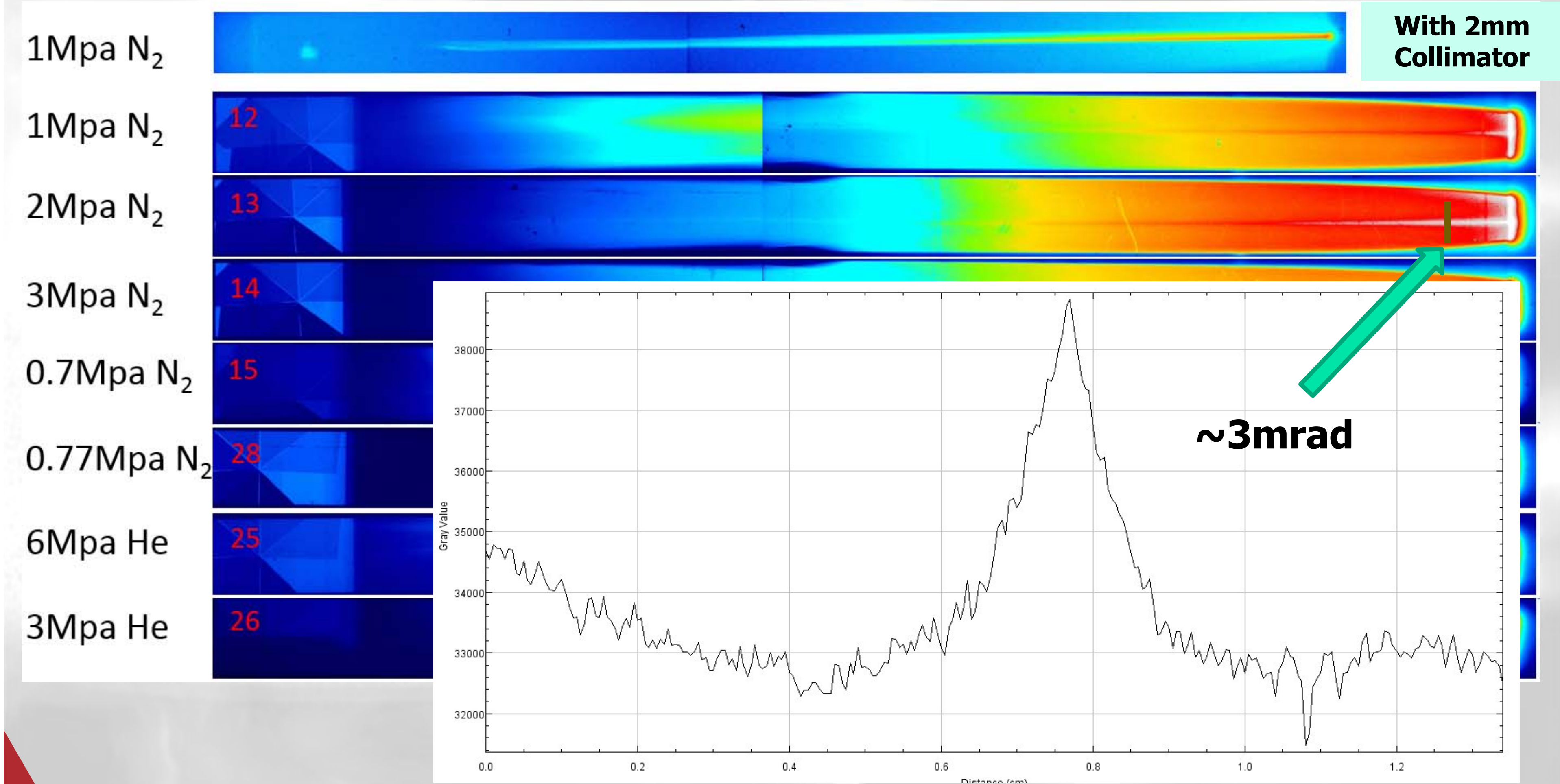
Electron profile measurement



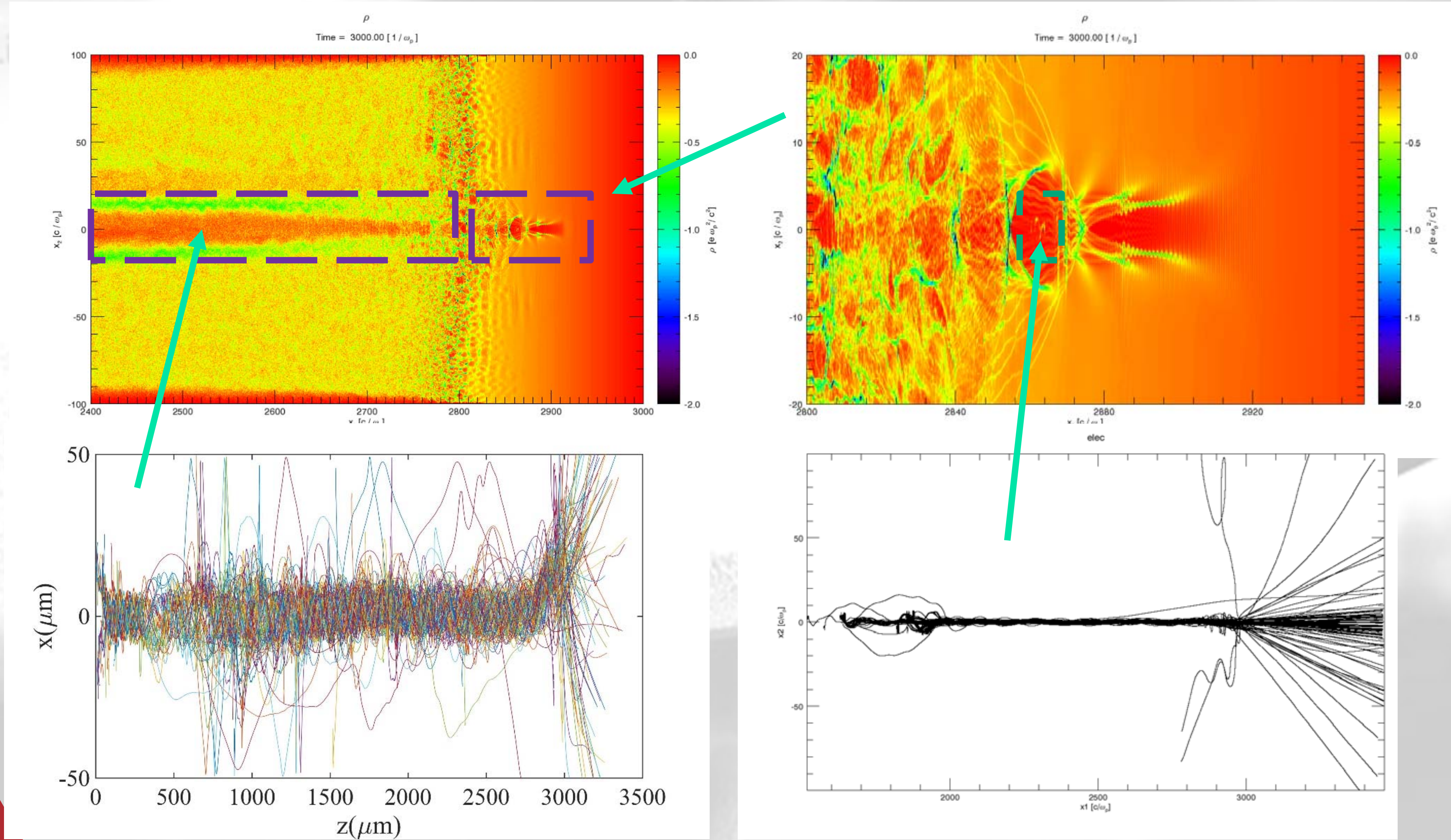
Bunch Charge (shot No.5):

Q~450pC (5MeV<Ee<5.5MeV)

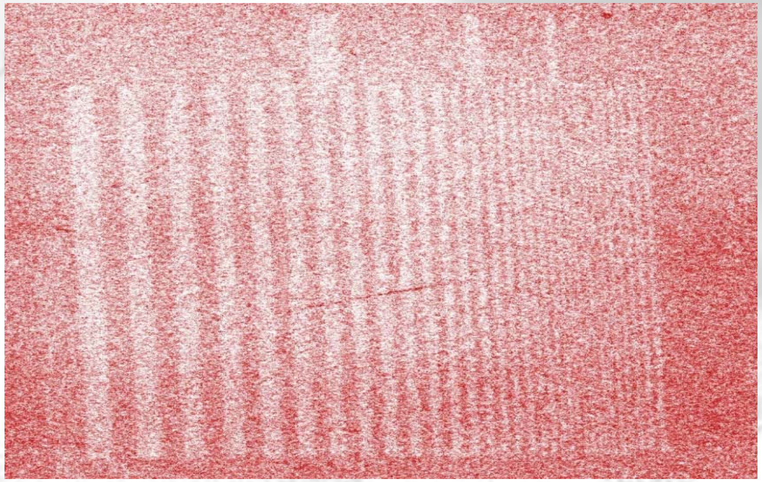
Electron energy spectrum measurement



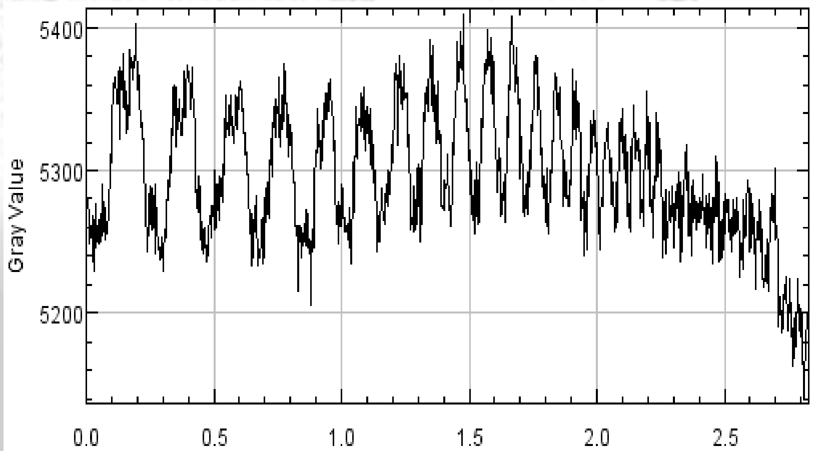
Simulation analysis for e- energy spectrum

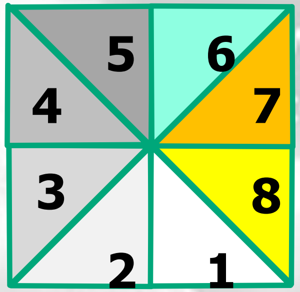


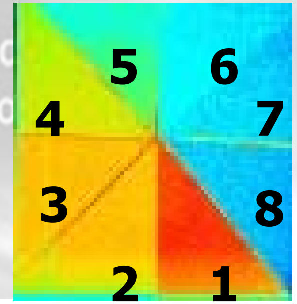
Radiation source size and spectrum measure

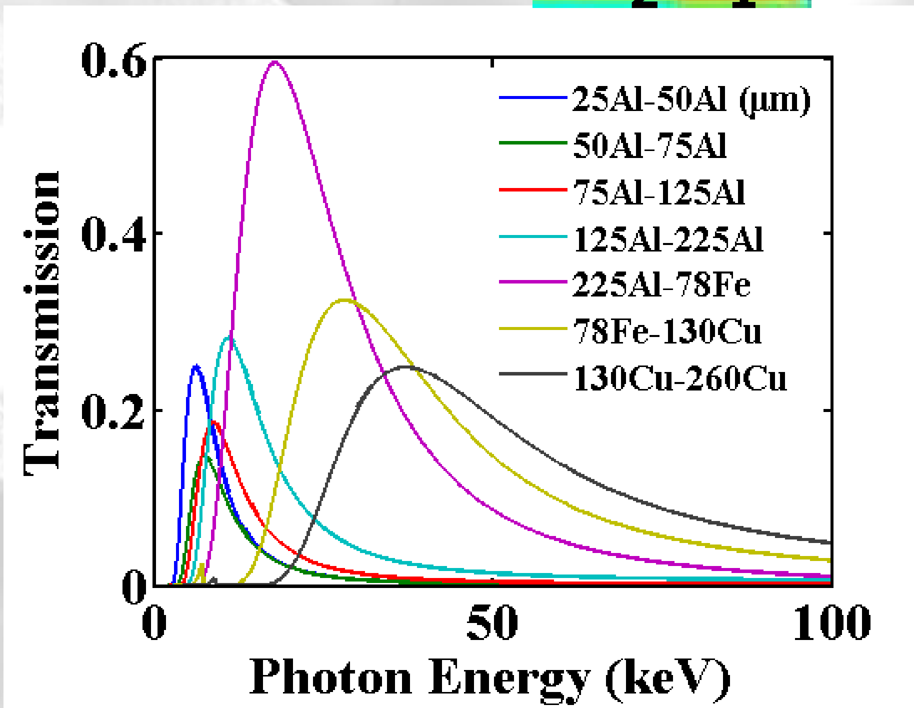


9.1/mm, < 62.5μm

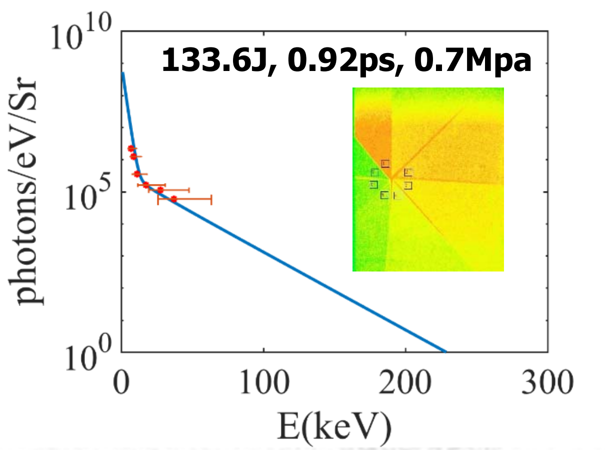




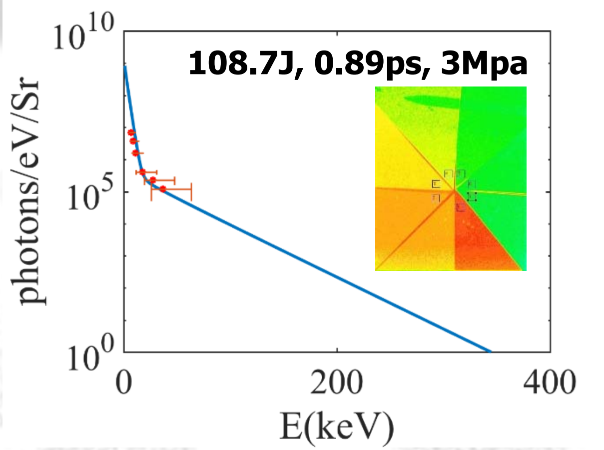




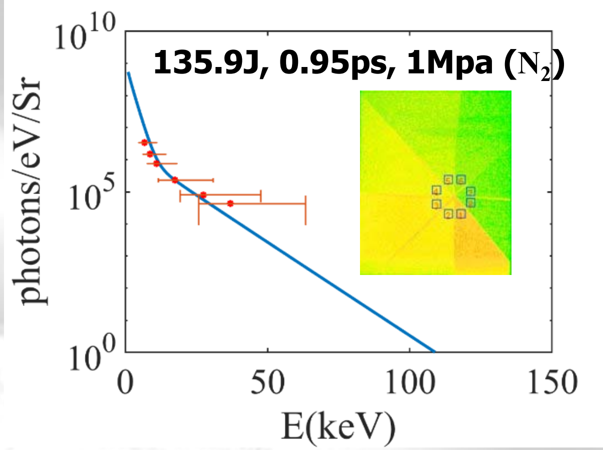
Betatron radiation spectrum measure



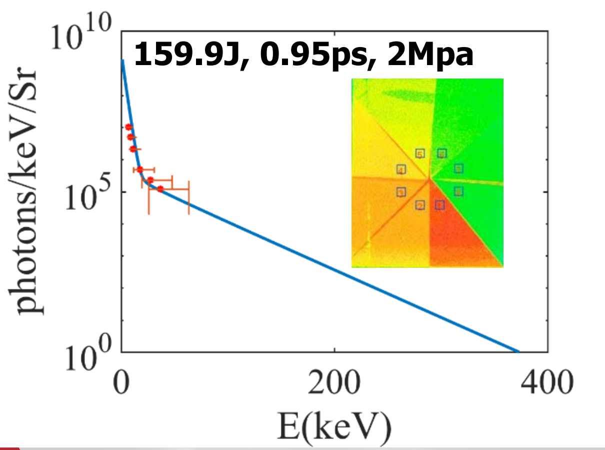
E_{c1}=3 keV, E_{c2}=36 keV



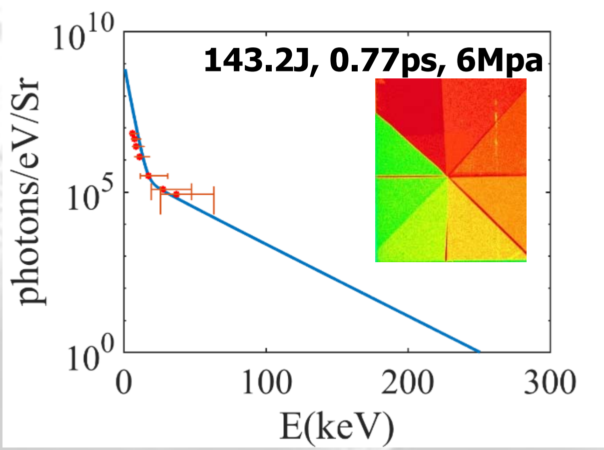
E_{c1}=4 keV, E_{c2}=52 keV



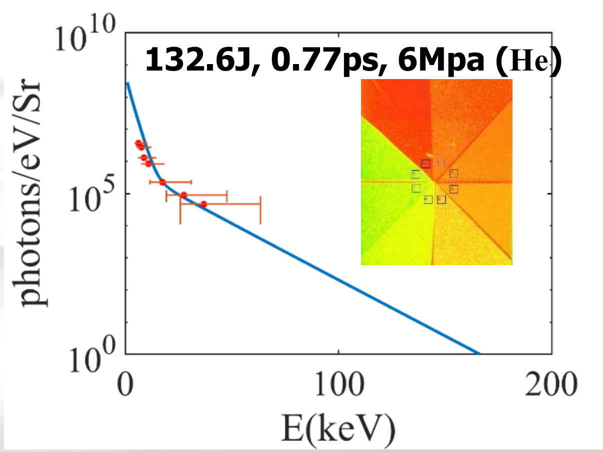
E_{c1}=3 keV, E_{c2}=15 keV



E_{c1}=4 keV, E_{c2}=59 keV



E_{c1}=4 keV, E_{c2}=39 keV



E_{c1}=4 keV, E_{c2}=25 keV

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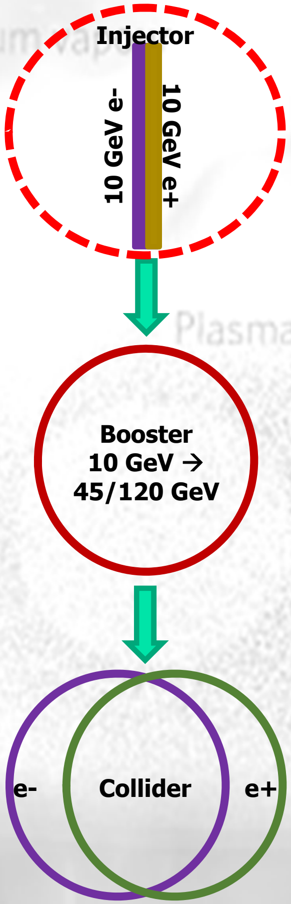
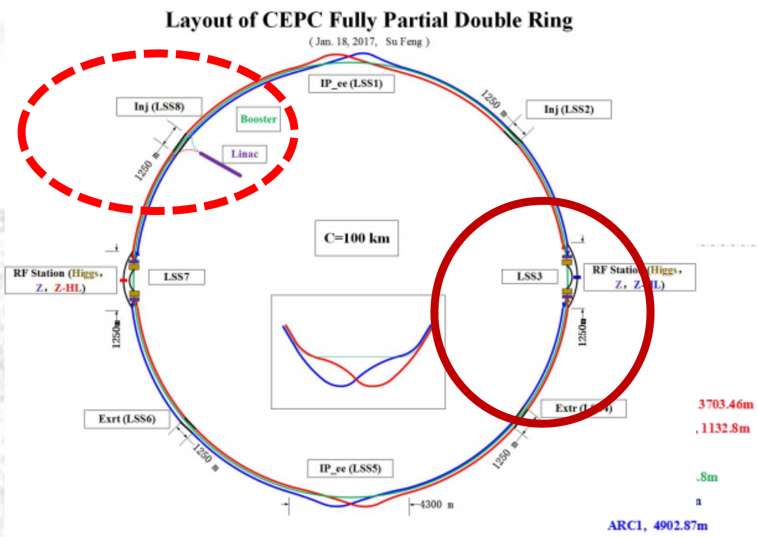
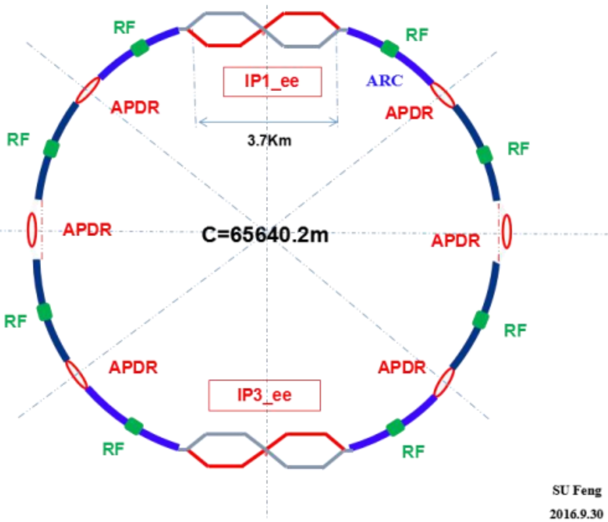
Conceptual design for CEPC





CEPC Advanced Partial Double Ring Option II



CEPC Baseline Design

Better performance for Higgs and Z compared with alternative scheme, without bottle neck problems, but with higher cost

CEPC Alternative Design

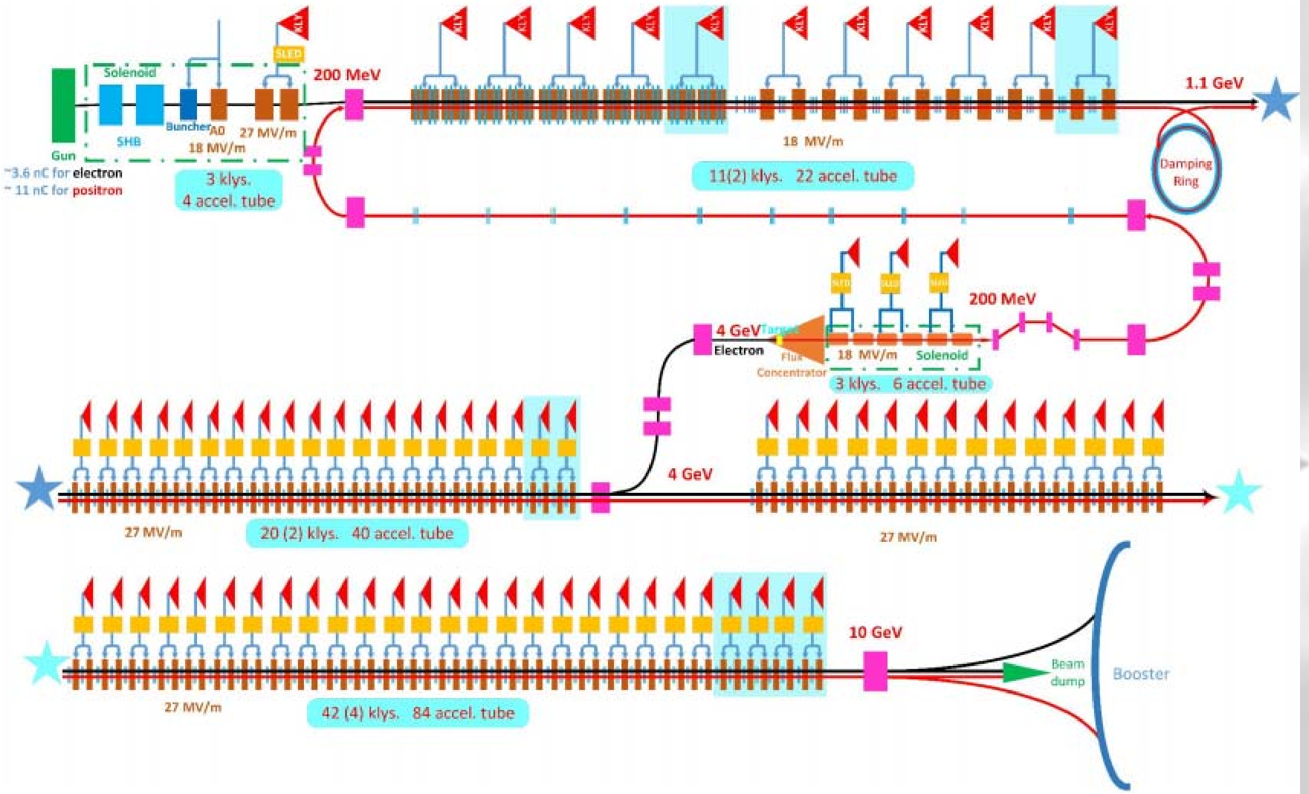
Lower cost and reaching the fundamental requirement for Higgs and Z luminosities, under the condition that sawtooth and beam loading effects be solved

CEPC CDR/Pre-CDR linac requirement

Parameter	Symbol	Unit	Pre-CDR	CDR
e^- /e^+ beam energy	E_{e-}/E_{e+}	GeV	6	10
Repetition rate	f_{rep}	Hz	50	50
e^- /e^+ bunch population	Ne- /Ne+		2×10^{10}	6.25×10^{9}
		nC	3.2	1.0
Energy spread (e^- /e^+)	σ_E		$<1\times10^{-3}$	$<2\times10^{-3}$
Emittance (e^- /e^+)	ε_r	mm·mrad	<0.3	<0.3
e^- beam energy on Target		GeV	4	4 (2)
e^- bunch charge on Target		nC	10	10

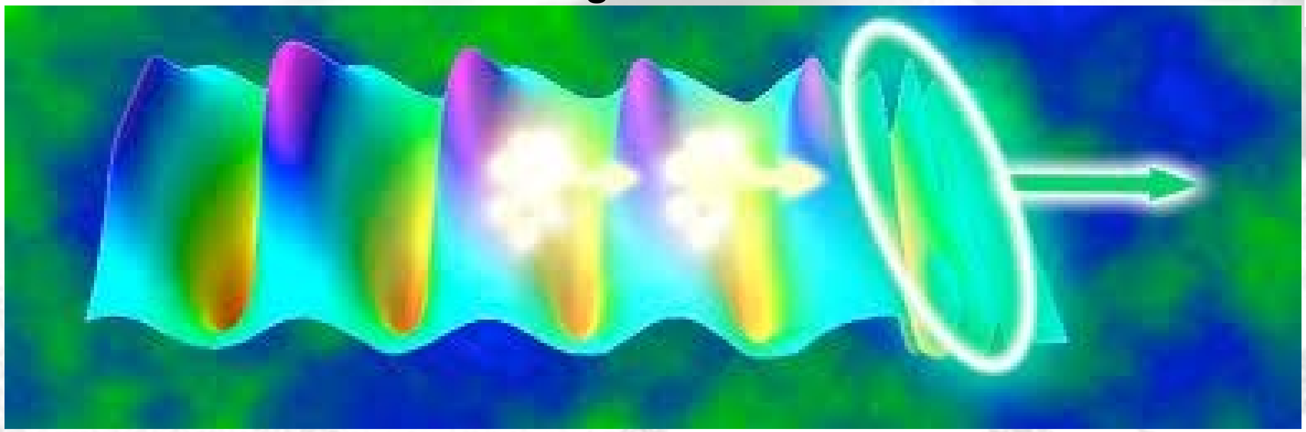
Layout of CEPC Linac Scheme

- 1.1 GeV damping ring
  - Positron
  - Time schedule
  - Emittance
- SLED (SLAC Energy Doubler):
  - 200 MeV~1.1GeV without SLED
  - 1.1 GeV~10 GeV with SLED
- Accelerating gradient:
  - 18 MV/m
  - 27 MV/m
- Frequency of Booster:
  - 1300 MHz=3.25MHz×400
- Frequency of Linac:
  - 2856.75 MHz=3.25MHz×879



Plasma-based Wakefield Acceleration

- Laser or beam Pulse
- Trailing beam



Wake

Huge gradient (~100GV/m) + Tiny structures (~10-100um)

T.Tajima and J.M. Dawson PRL (1979)
LWFA
P.Chen, J.M. Dawson et.al. PRL (1983)
PWFA

Understanding the physics on plasma-based acceleration

Theory

- Wake excitation and beam loading (PRL06, PRL 08)
- Electron hosing instability (PRL 07)
- Laser plasma matching and guiding (POP06, PRSTAB07)
- Phenomenological framework of LWFA in the blowout regime (PRSTAB07)
- Injection dynamics and high brightness beams (PRL 13, PRL 14, PRL 16b, PRAB 14, PPCF 16)
- Perfect staging using plasma structure (PRL 16a)
- Physics of radiation pressure ion acceleration instability (PRL 16c)

Simulation

- Development of the capability of large scale parallel PIC simulation
- 3D simulations of LWFA stage from GeV-100GeV
- 3D modeling of PWFA experiments and proposed TeV stages
- Boosted frame simulations (Nat. Phy. 2010, CPC 2011, 2013,2015)

Understanding the physics on plasma-based acceleration

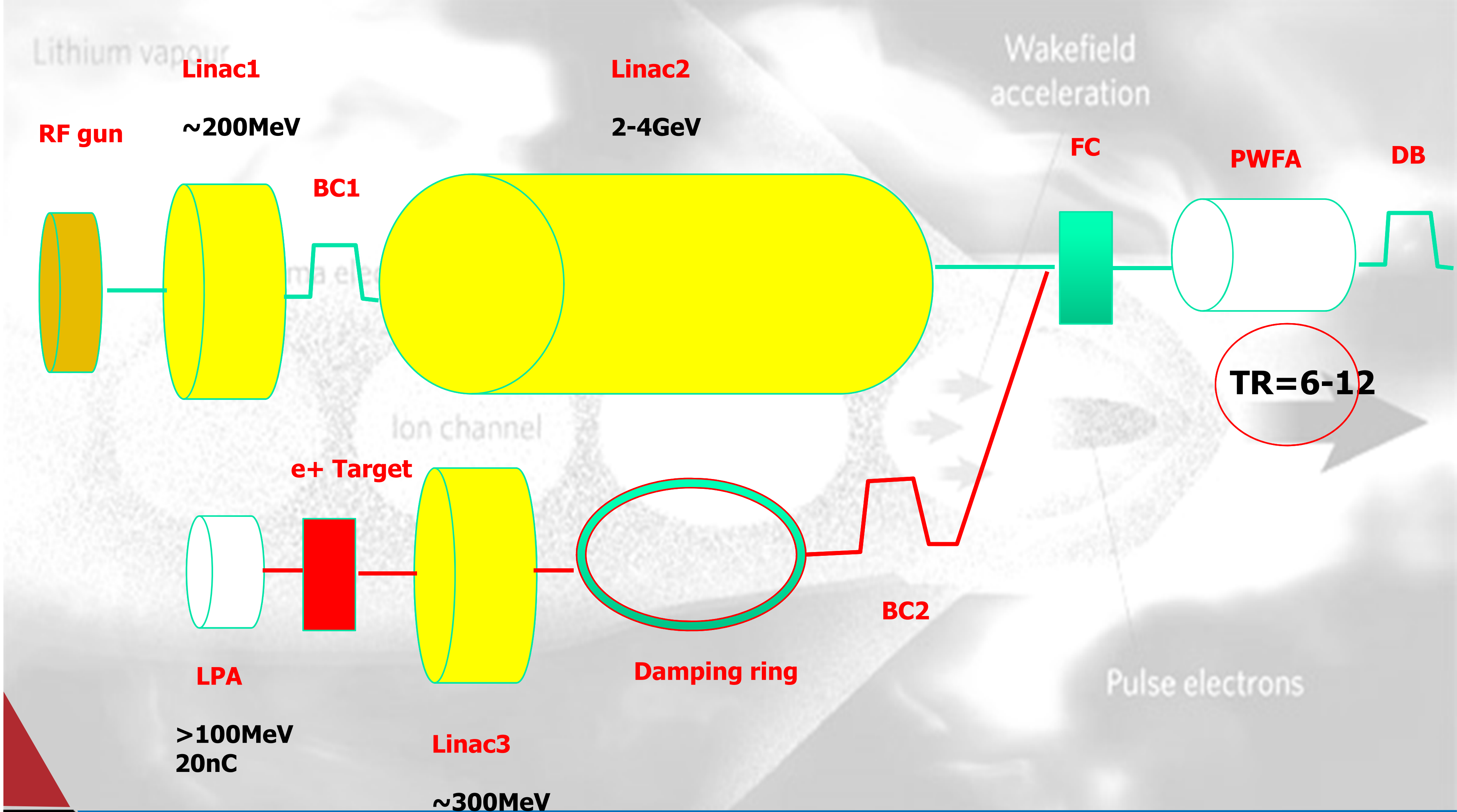
Experiment

- **1-100GeV level PWFA: acceleration and focusing (PRL05,Nature07)**
- **Betatron X-ray and positron production (PRL02, PRL08)**
- **Matched self-guiding of short pulse laser (PRL09a)**
- **GeV level self-guided LWFA with self-injection (PRL 09b)**
- **Ionization induced injection (PRL07, PRL10a)**
- **Self-guided LWFA with ionization injection beyond 1GeV (PRL10)**
- **Two stage LWFA (PRL 11)**
- **High efficiency acceleration of e+/e- (Nature 14,15, Nat. Comm. 16a, 16b, 16c)**
- **Wakefield imaging using electron snapshot (Sci. Rep.16 for theory)**
- **Controlled injection with very low energy spread (IPAC 14)**

Boundary condition for CEPC plasma linac

- **Beam average power (kW 100Hz)**
- **Beam charge per-bunch (nC)**
- **Beam energy spread (0.2-1%?)**
- **Beam geometric emittance (<0.3mm mrad)**
- **Positron generation**

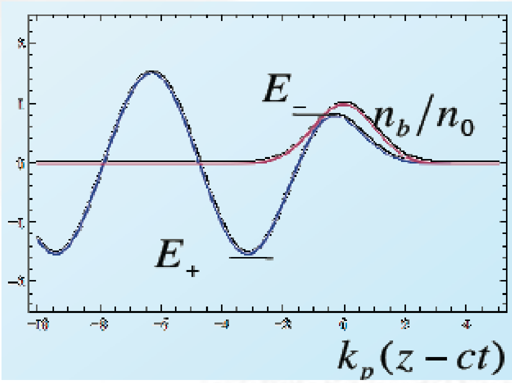
Conceptual design for CEPC plasma linac (Ver. 1.0)

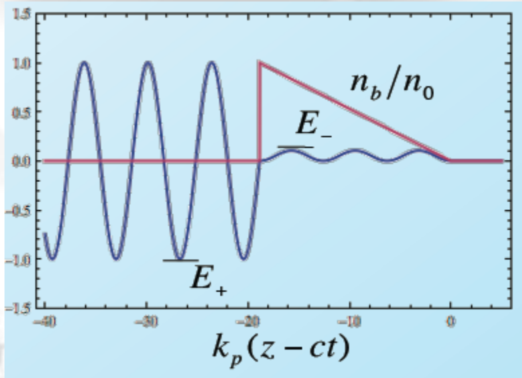


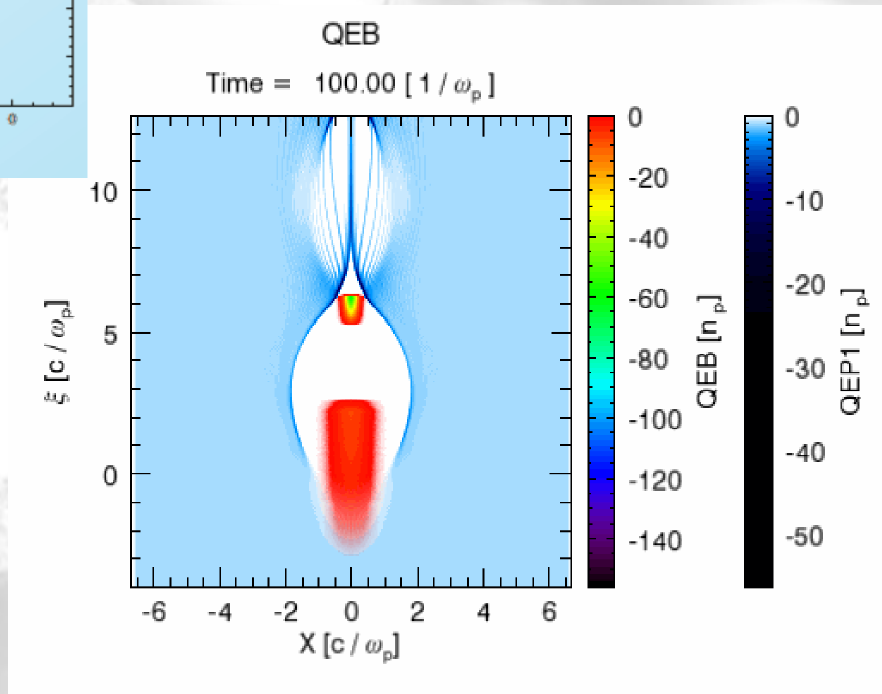
Conceptual design 1.0 ---- Cascaded HTR PWFA

- **The 1st stage**
  - Two shaped bunches (**5ps 25nC, 1ps 5nC**)
  - TR=2 or 3
  - Efficiency (**60%**)
- **The 2nd stage**
  - Controlled injection for e (**200fs 1nC or 2nC**)
  - TR=2 or 3
  - Single stage efficiency (**60%**)
  - Overall **TR=(1+TR1)*TR2**
- Overall efficiency **Q3(1+TR1)*TR2/(Q1+Q2)=40%**
- **The positron stage**
  - Combining e+ with e- (**200fs 1nC**)
  - TR=1 Single stage efficiency (**~50%**)
  - Overall efficiency for positron **20%**

Ideal high TR (~3) PWFA Stage for electrons





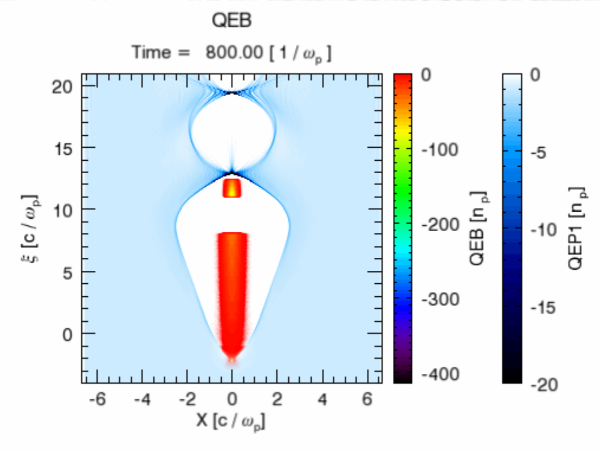


Driver pulse	5ps
Driver charge Q1	25nC
Driver energy	2GeV
Trailer pulse	0.5ps
Trailor charge Q2	5nC
Trailor energy	2GeV
Final energy	8GeV
Average TR	3
Efficiency	~60%

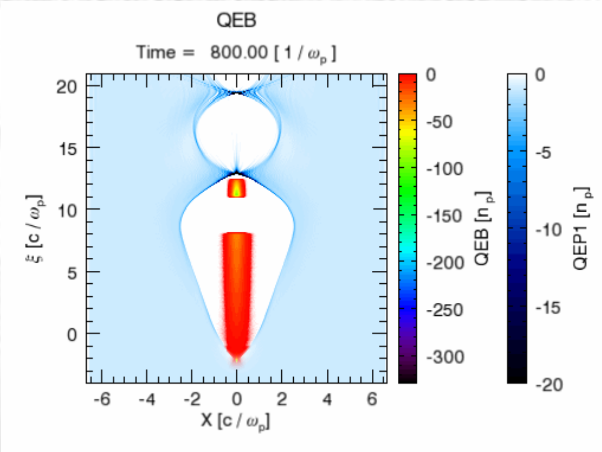
Parameters of Stage I

Conceptual design 2.0 -- Single stage HTR PWFA

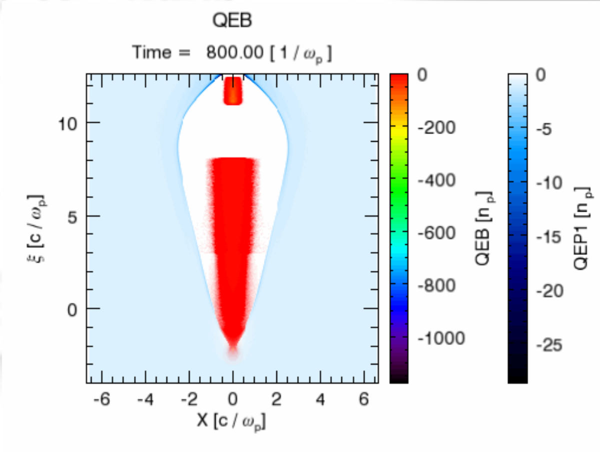
E_{driver}	$10GeV$
$E_{trailor}$	$2GeV \rightarrow 40.5GeV$
TR	3.8
Energy spread	1.8%
efficiency	58.8%



Without tilt, perfect injection



With 1μm tilt

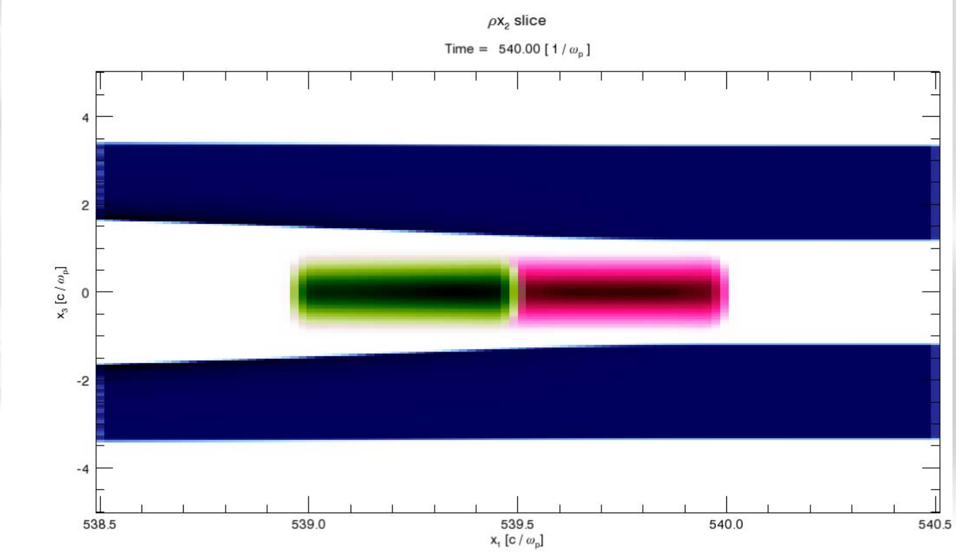


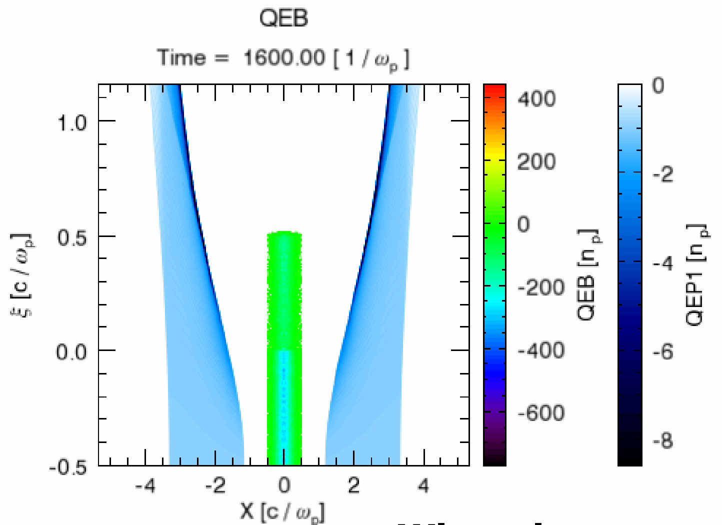
With 1μm tilt, wide beam

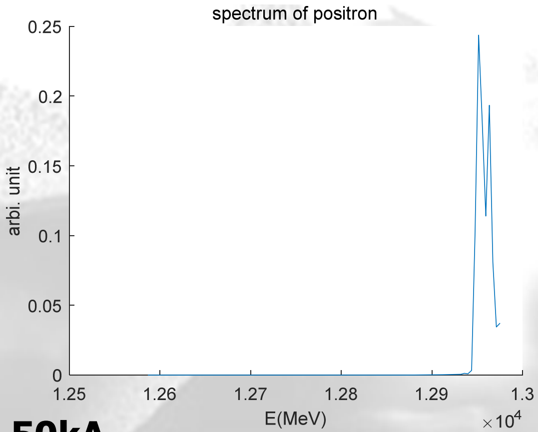
Conceptual design ---- Positron acceleration

Advantages

- Extremely low energy spread (~0.1%)
- Nearly 100% efficiency
- TR = 1
- The shortest electron + positron length







$$E_e = 15GeV$$

$$E_p = 3GeV$$

$$\Delta E_p = 9.9GeV$$

$$\eta = 19\%$$

$$\frac{\delta E}{E} = 0.07\%$$

When the current is 50kA

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Summaries and Prospects

- ***Stable e- beam and Thomson scattering X-ray generated from 20 TW laser @ IOP***
  - ✓

- ***Intense X-ray even γ-ray radiation needs 100TW to PW laser system***

- ***Hundreds J, sub-ps lasers generate extremely high Q (collimated) bunches***

- ***Studies on Plasma-based acceleration as an alternative method for CEPC injector***

Summaries and Prospects

- ***Stable e- beam and Thomson scattering X-ray generated from 20 TW laser @ IOP***
  - ✓ *Studies on ionization injection begins and will be continued (e.g. mixture gases)*
  - ✓ *Focusing Plasma mirror (plasma lens) may increase the scattering according to simulation*
  - ✓ *Try to fulfill and improve the beam measurement this year (Q, ε_n, $\sigma_{x, y, z}$ etc.)*

- ***Intense X-ray even γ-ray radiation needs 100TW to PW laser system***
  - ✓ *Further studies on Thomason or laser-Compton scattering at SJTU and SECUF (Huairou)*
  - ✓ *Chirp-dependent LPA e- quality needs more studies (Seems good for radiation)*

- ***Hundreds J, sub-ps lasers generate extremely high Q (collimated) bunches***
  - ✓ *NCD nozzle or clusters target may also be suitable (simulation under discussion)*
  - ✓ *Measurement for ultrahigh charge and large divergence e- and X-ray need to be improved*

- ***Studies on Plasma-based acceleration as an alternative method for CEPC injector***
  - ✓ *Single-stage high TR mode (TR~4) is preferred till now*
  - ✓ *More experimental studies are needed especially on positron acceleration and cascaded acceleration*

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Thank you !