Compact Charged Particle Accelerator for Applications

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Seong Hee Park

Kitae Lee, Jaehoon Kim

Department of Accelerator Science
Korea University

KAERI

KERI

Laser-Plasma Acceleration vs RF Acceleration

Energy = acceleration field strength x channel length
Current ~ input power x efficiency

Conventional RF acceleration

Acceleration by a RF field in an acceleration tube

Acceleration field strength limited by a vacuum discharge: < 100 MV/m

Long channel (km) and high input power (GW)

Laser - Plasma acceleration

Acceleration by ES field formed in a plasma due to space charge separation induced by a laser field

Acceleration field: >100 GV/m

Channel length limited by a sheath length (μm)

Low input power (100 W)

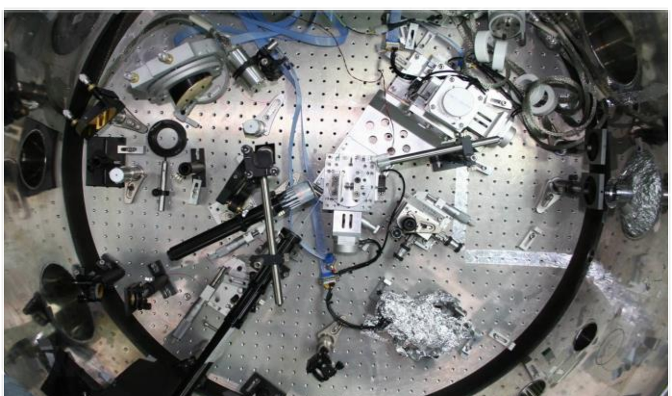
Low current, but, COMPACT & Ultrashort pulse

Lab of Laser-Plasma based Radiation at KAERI

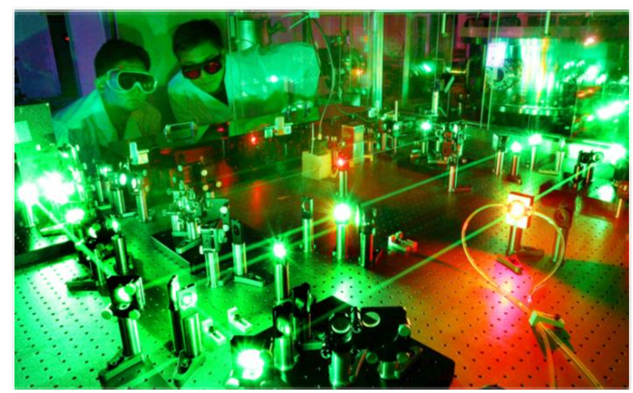
Facility on Laser Plasma-based Radiation

Laser acceleration Lab.

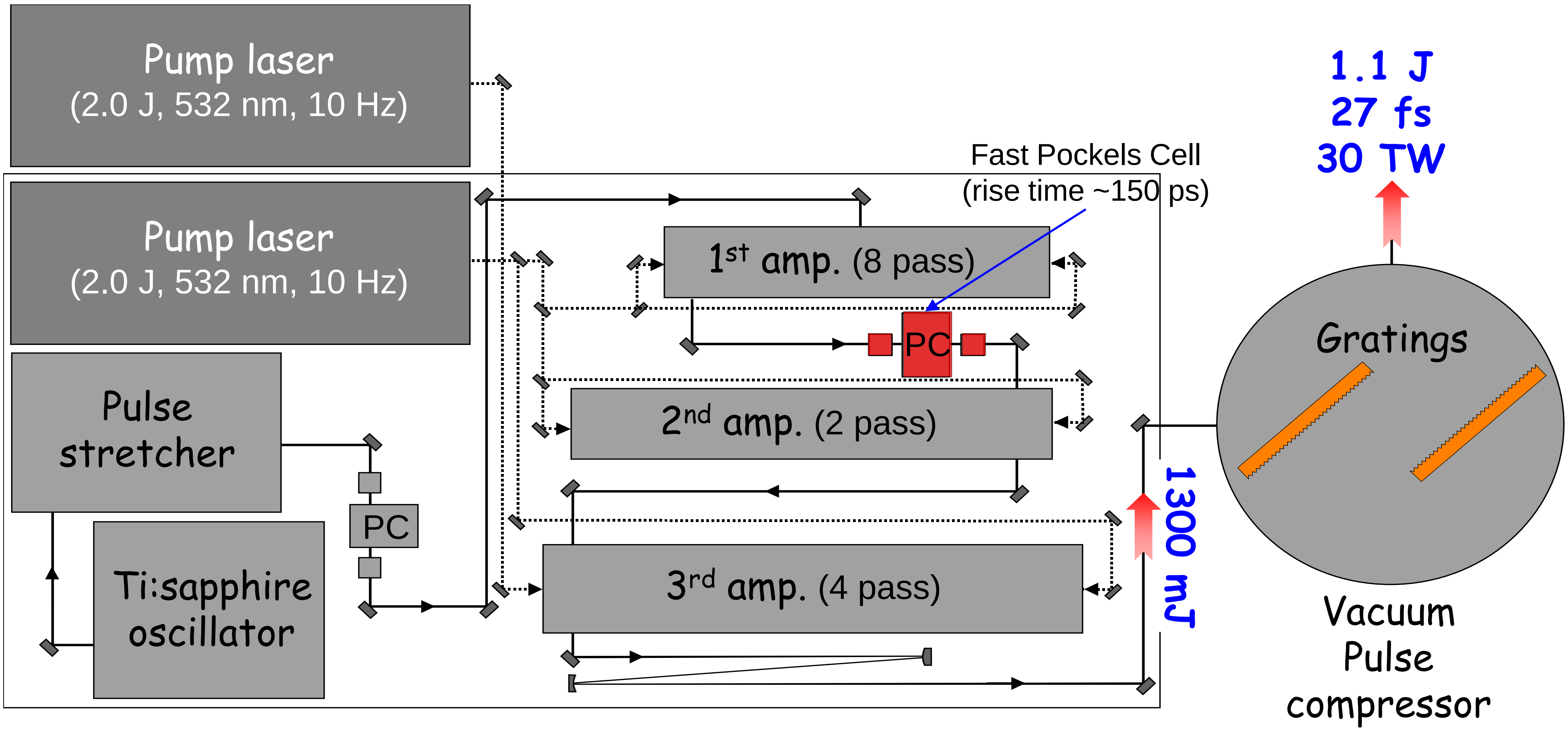
30 TW Laser Lab.



Laser Electron Accelerator
Laser Proton Accelerator
Laser Plasma-based X-ray laser

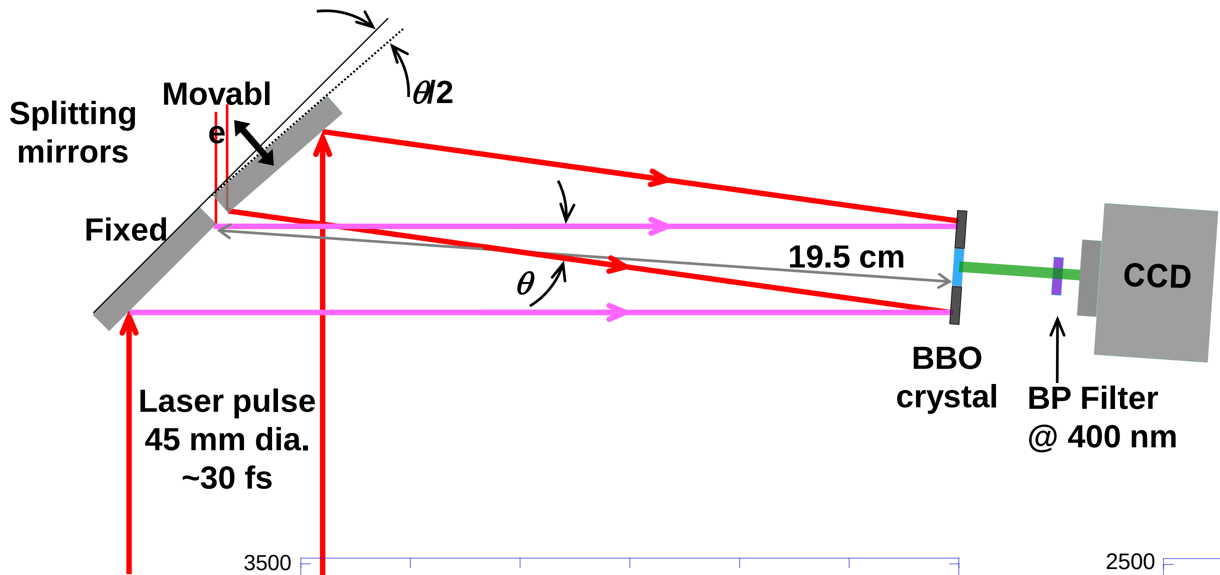


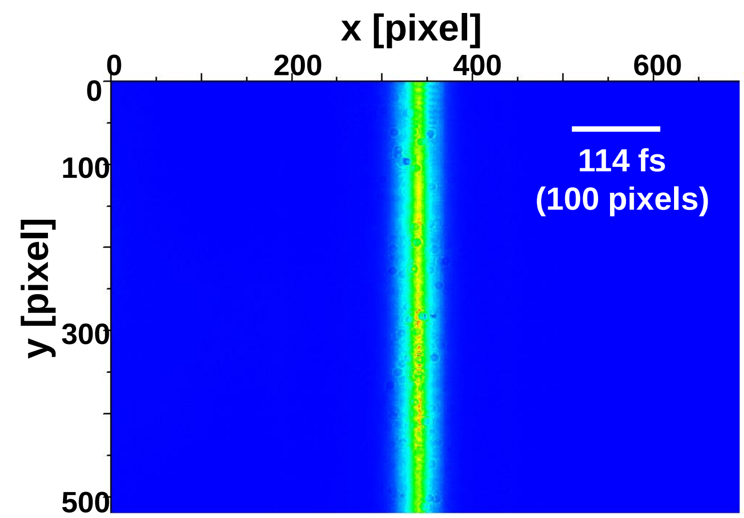
30 TW Ti:Sapphire Laser at KAERI

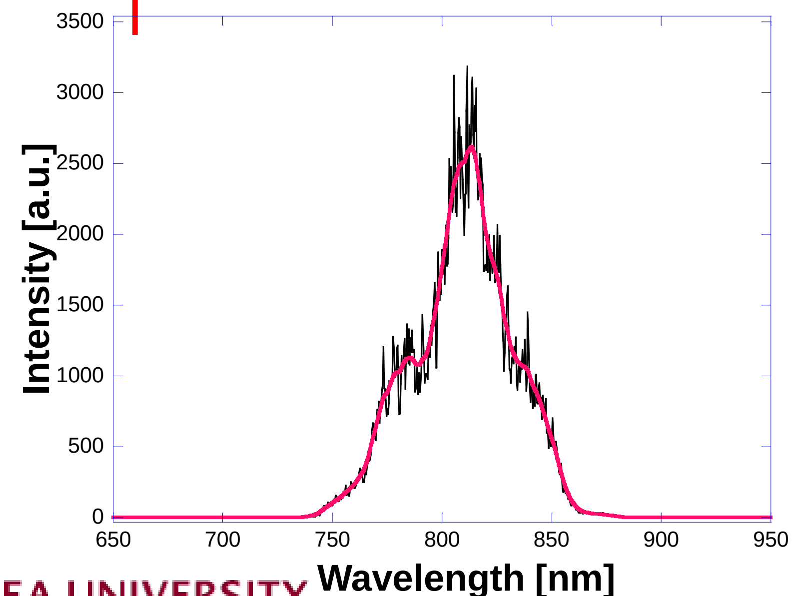


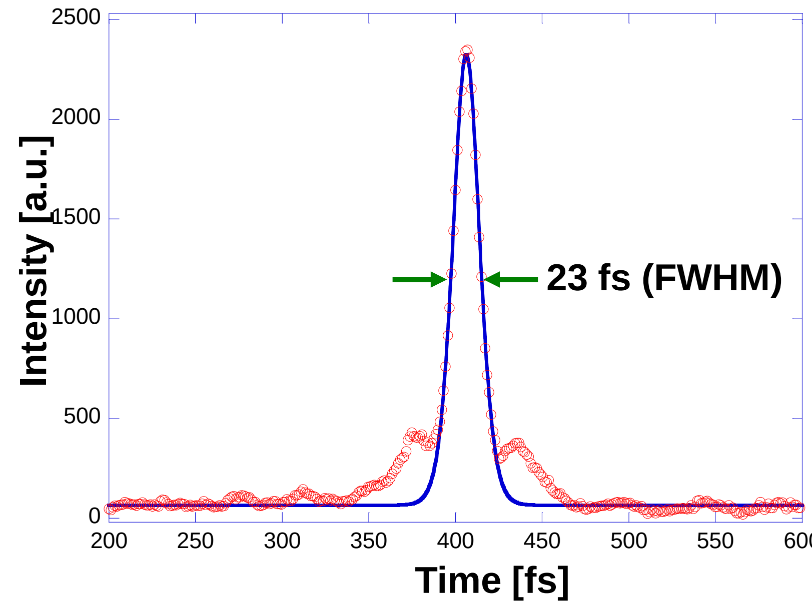
- Main pulse: 10 TW/ 30 TW
- ASE ratio : 10^{-7} - 10^{-8} in 200-300 psec
  <10^{-10} over nsec

KAERI TW Laser: Temporal/Spatial width & ASE



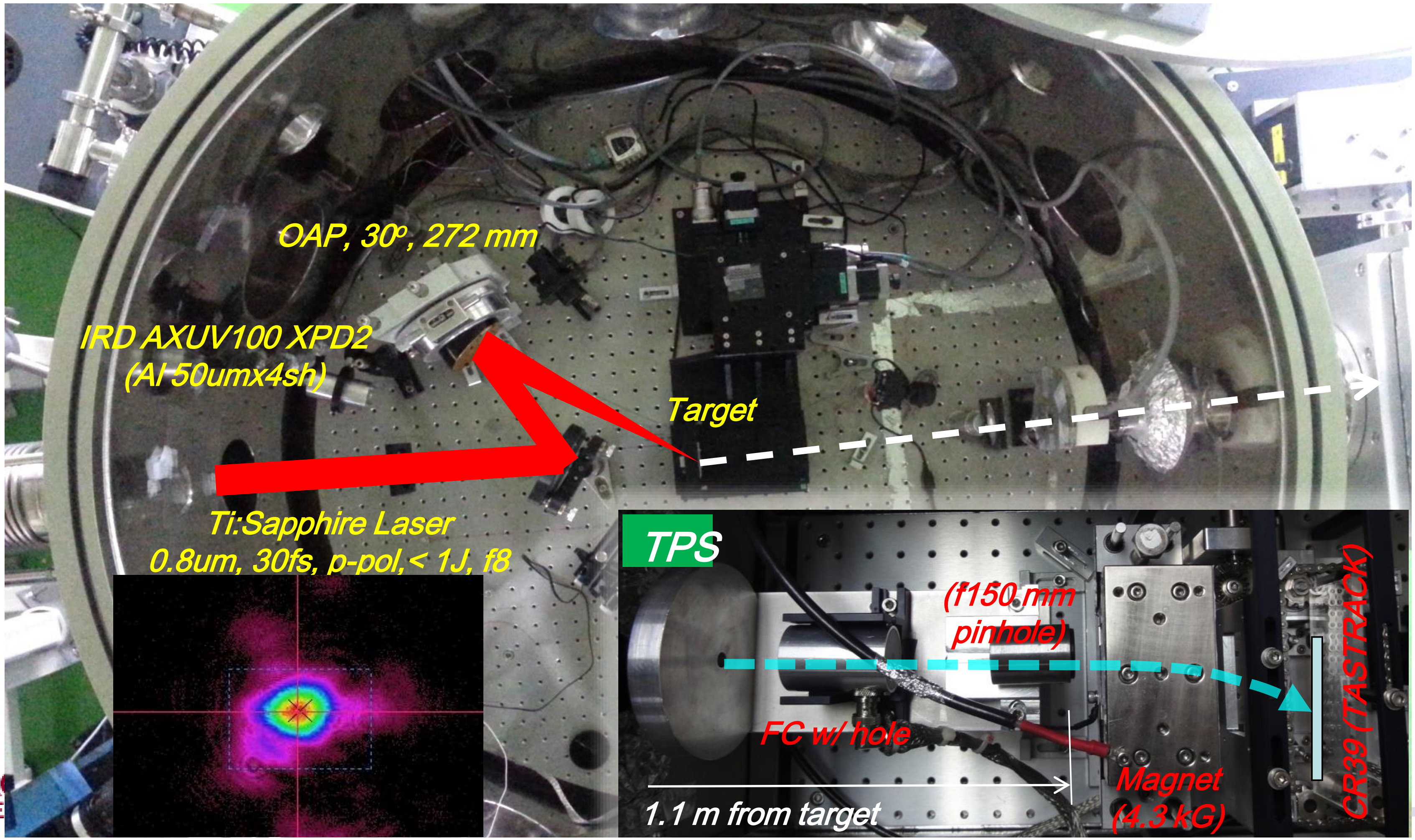






Laser-Plasma Proton Acceleration

Conversion Efficiency
→ ILEA target – New Acceleration Scheme

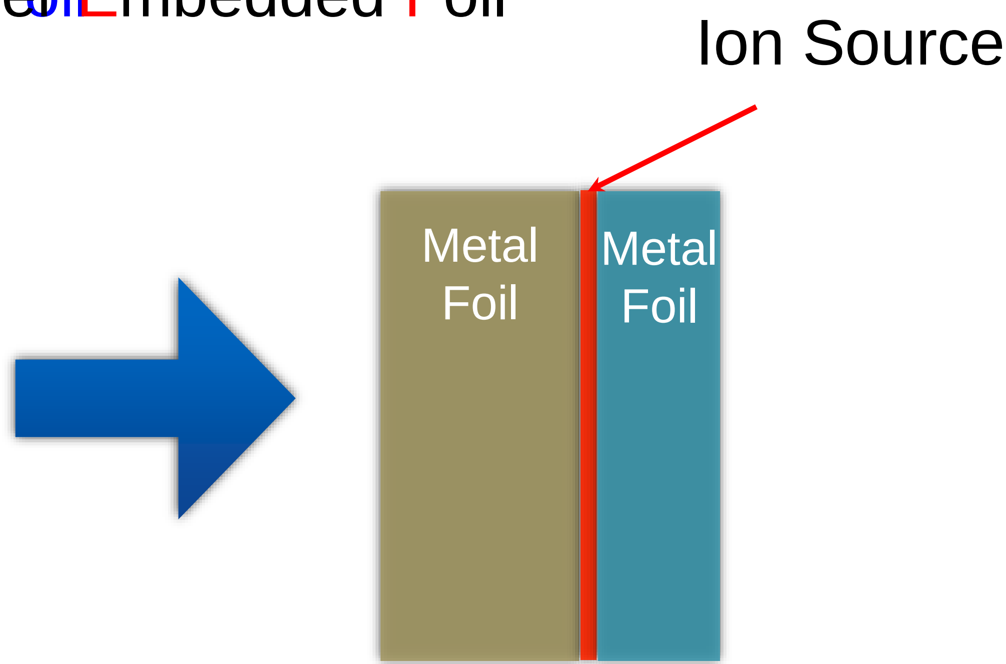


Ion Acceleration: ILEF Target

K. N. Kim et al., POP 23, 033119 (2016)

Single Foil

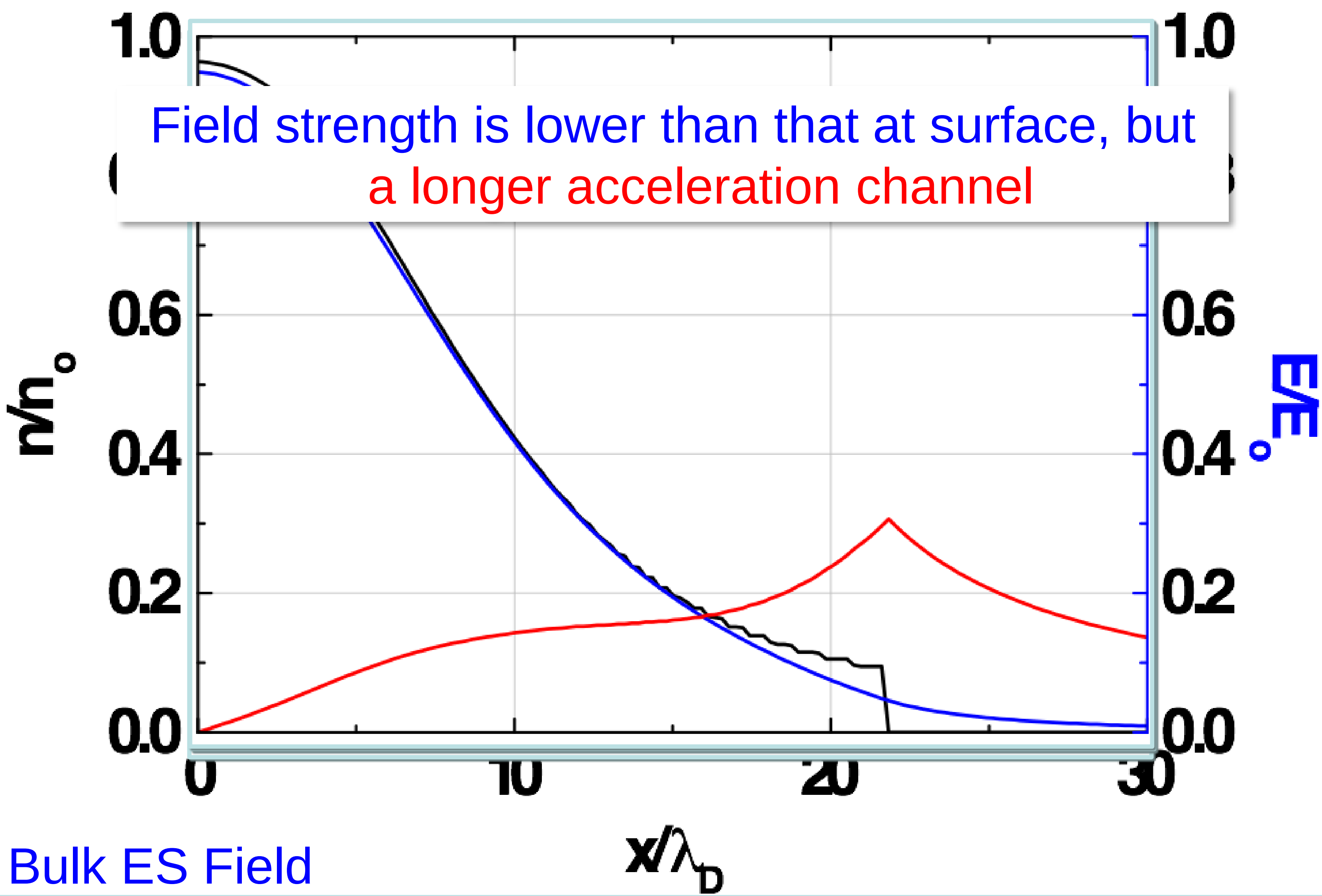
Ion Layer Embedded Foil



Ion Acceleration: ILEF Target – 1D fluid simulation

$\omega t =$ 4

Field strength is lower than that at surface, but a longer acceleration channel



Bulk ES Field

Courtesy by Kitae Lee at KAERI

Ion Acceleration: ILEF Target – 2D PIC simulation

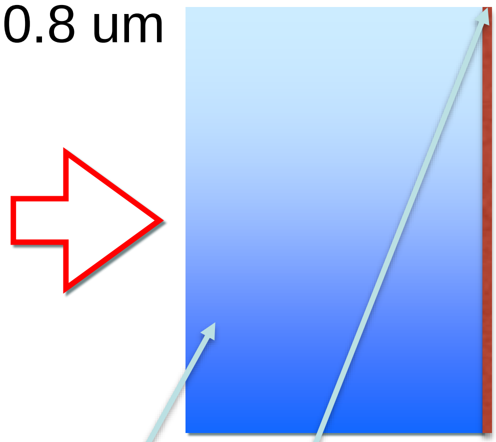
Energy Spectrum
on *layer position*

2×10^{19} W/cm^2

27 fs

0.4 um

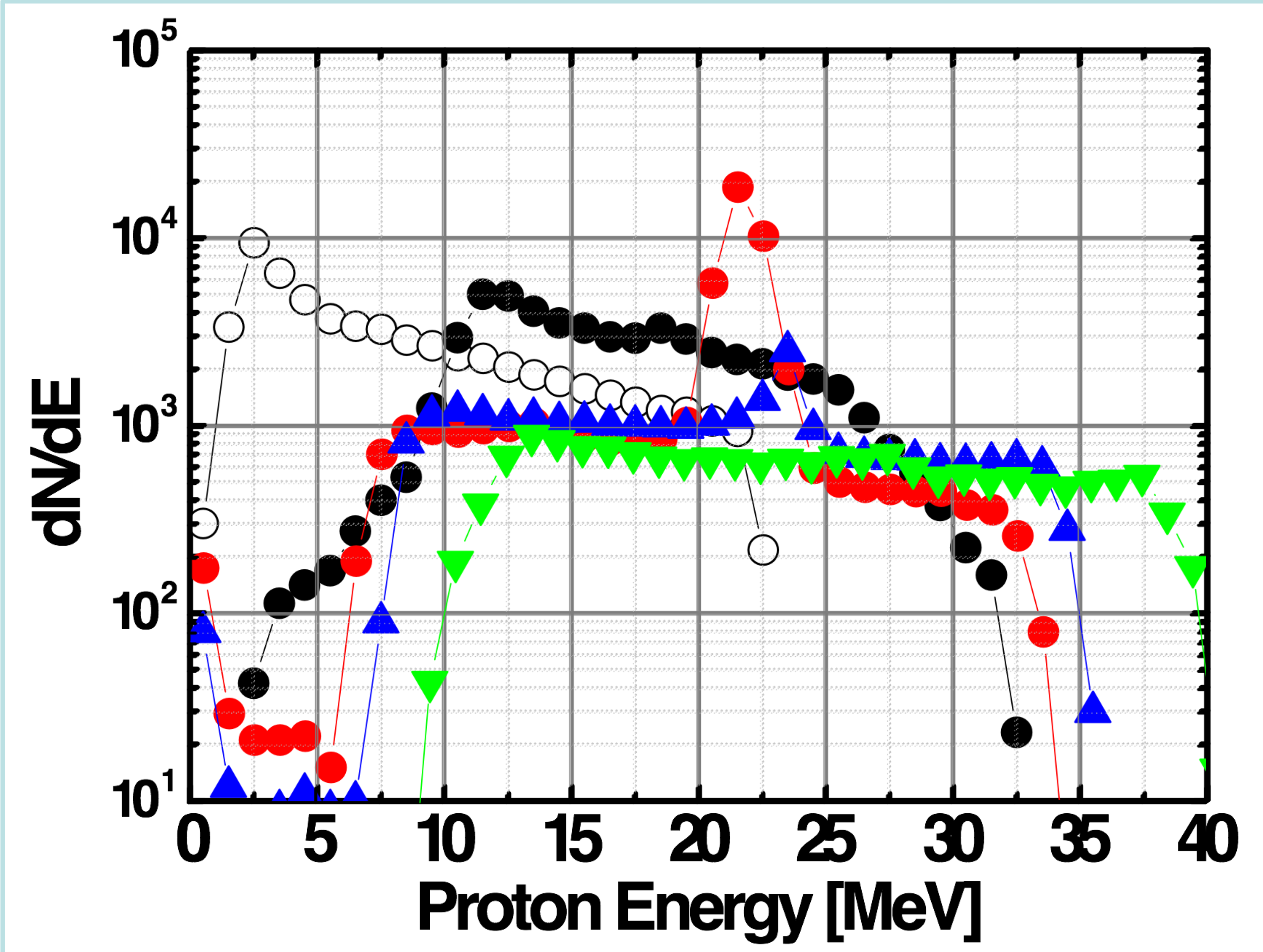
0.8 um



Cu 3+, 2.4 um

Proton Layer 30 nm

$n_e = 147\ n_c$



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Courtesy by Kirae Lee at KAERI

Neutron Generation

IAEA-TECHDOC-1223, "Current status of neutron capture therapy", May 2001

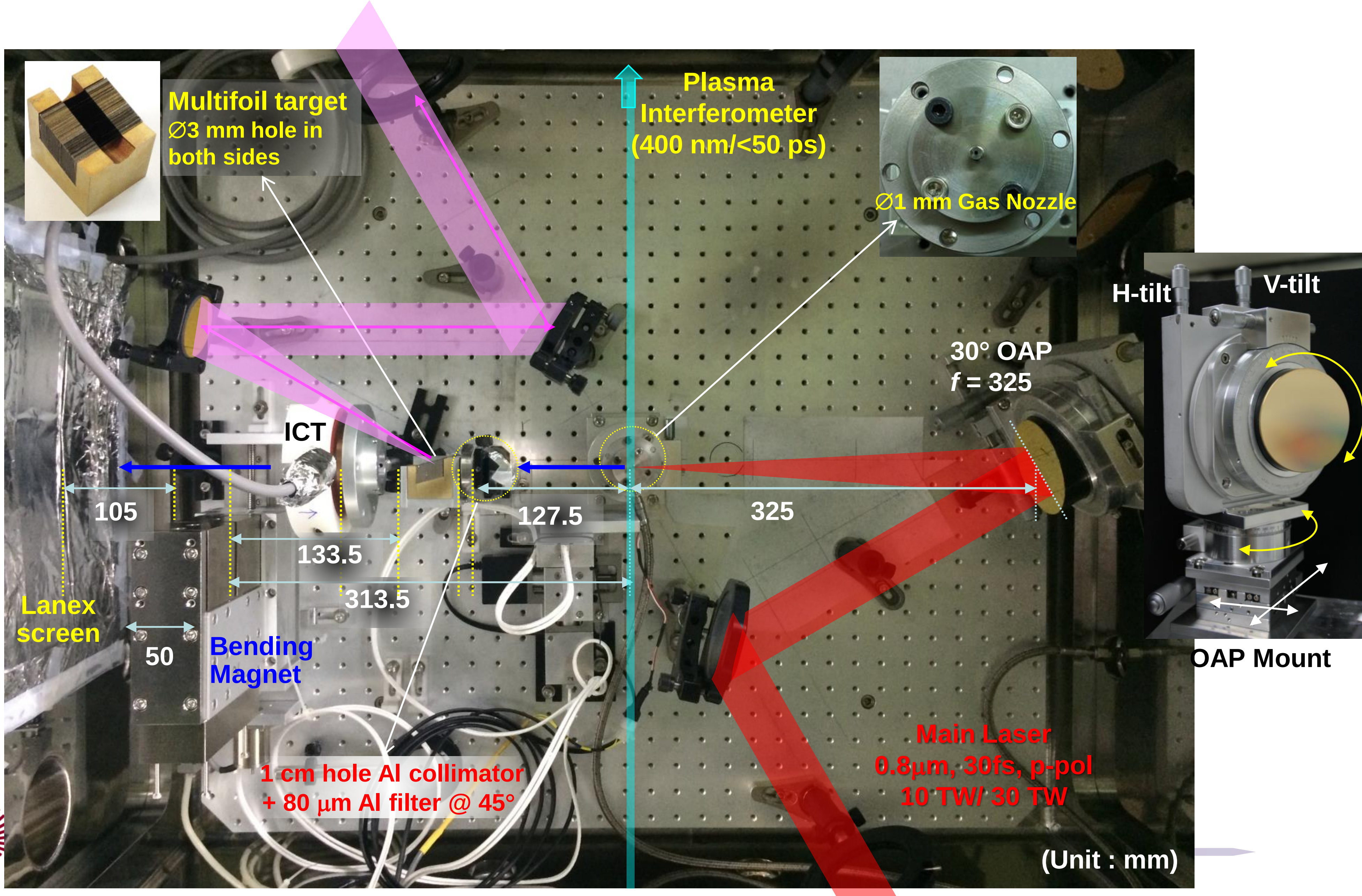
IAEA Guideline for therapy

Neutron Energy range	0.5 eV ~ 10 keV	
Epithermal n flux	$> 1\times10^{11}$ n/cm^2/s	
Harmful fast neutrons	$< 2\times10^{-13}$ Gy·cm^2/n	
Harmful γ-rays	$< 2\times10^{-13}$ Gy·cm^2/n	

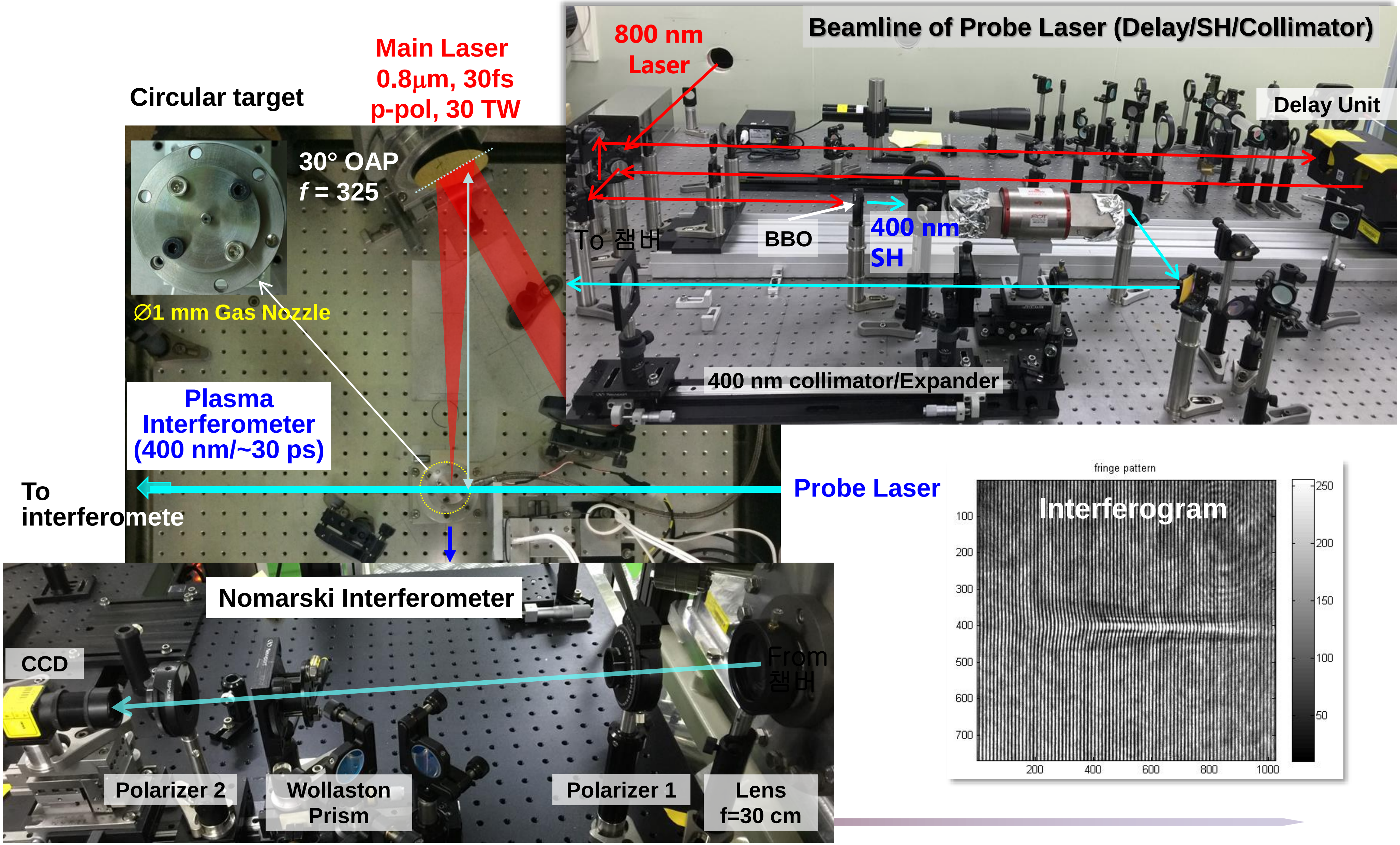
Neutron Flux from different targets

Isotope	Threshold energy [MeV]	Accelerated energy [MeV]	Neutron yield [#/sec/mA]	Maximum n energy [MeV]	Target
^{7}Li(p,n) ^{7}Be	1.88	2.5	9×10^{11}	0.8	Radioactive ^{7}Be (53 d), oxidization, T_{mp} 180°
^{9}Be(p,n) ^{9}Be	2.06	4.0	9×10^{11}	2.2	Stable ^{9}Be, T_{mp} 1287°
^{9}Be(p,xn) ^{9}Be	-	30	2×10^{14}	30	fast n
Spallation W	-	70	1×10^{15}	72	

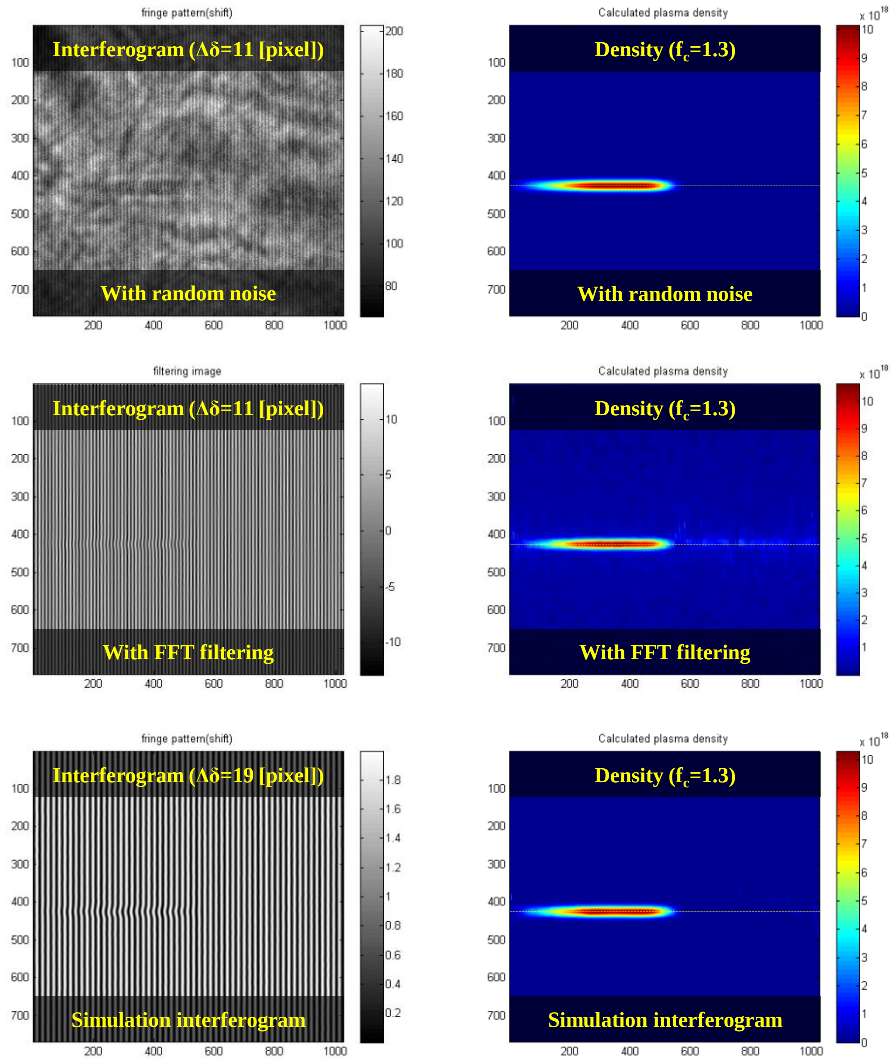
Laser-Plasma Electron Acceleration



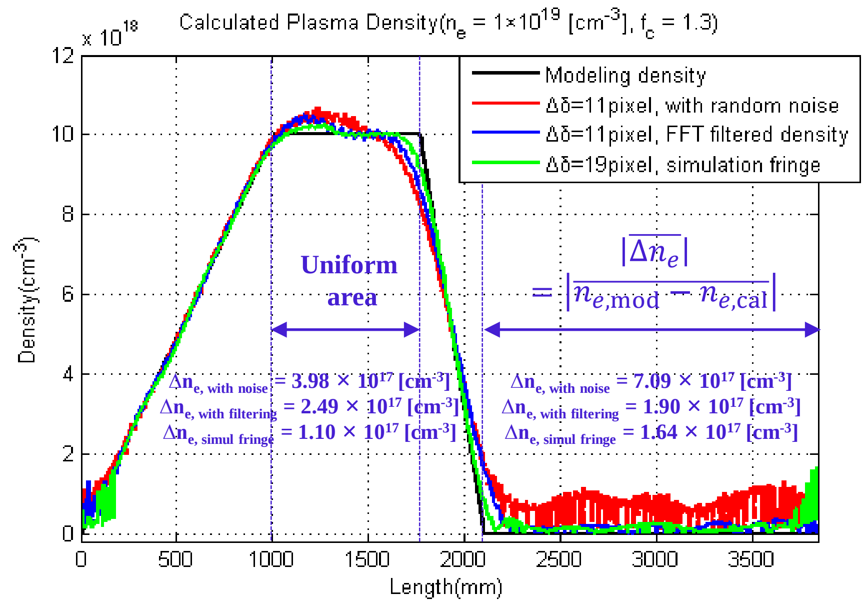
Plasma Diagnostics : Nomarski Interferometer



Plasma Density : Nomarski interferometer



Line-profile of calculated plasma densities

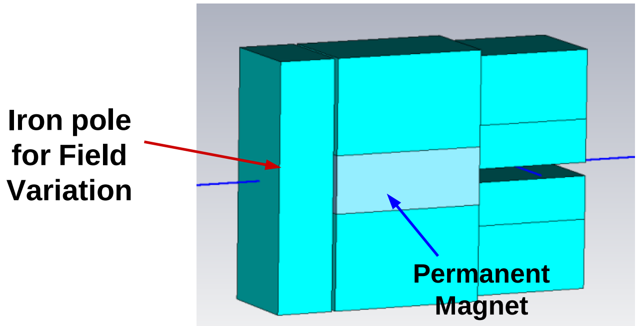


Optimal condition of plasma density calculation

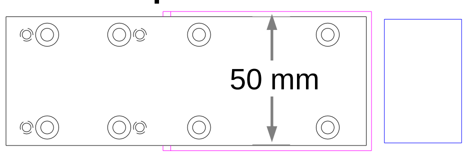
	Distance (x_1, [mm])	Fringe spacing ([pixel])	Center frequency (f_c)	Wavelet scale	Error(%) (Uniform)
With noise	x_1 = 60 , x_2 = 240	11 (42.64[㎛])	$\Psi(x) = \frac{1}{\sqrt{\pi f_b}} e^{2i\pi f_c x} e^{-\frac{x^2}{f_b}}$		3.98
FFT filtering					2.49
Modified fringe	x_1 = 40 , x_2 = 260	19 (69.29[㎛])	1.3	35	1.10

Energy spectrometer : Bending magnet

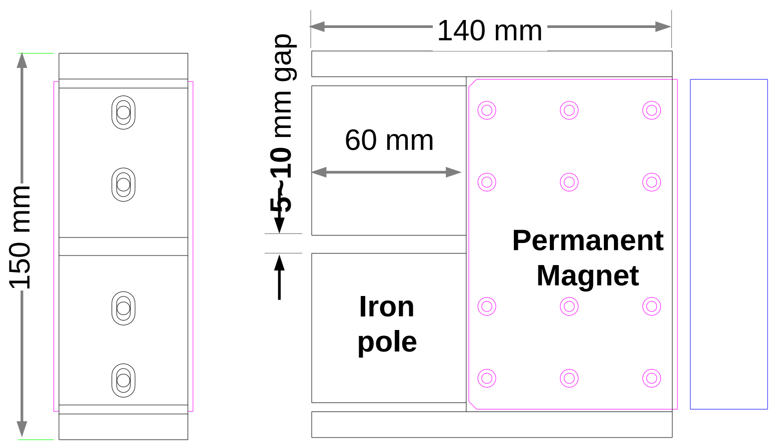
B-field Area: 60x50x10c :



Top View



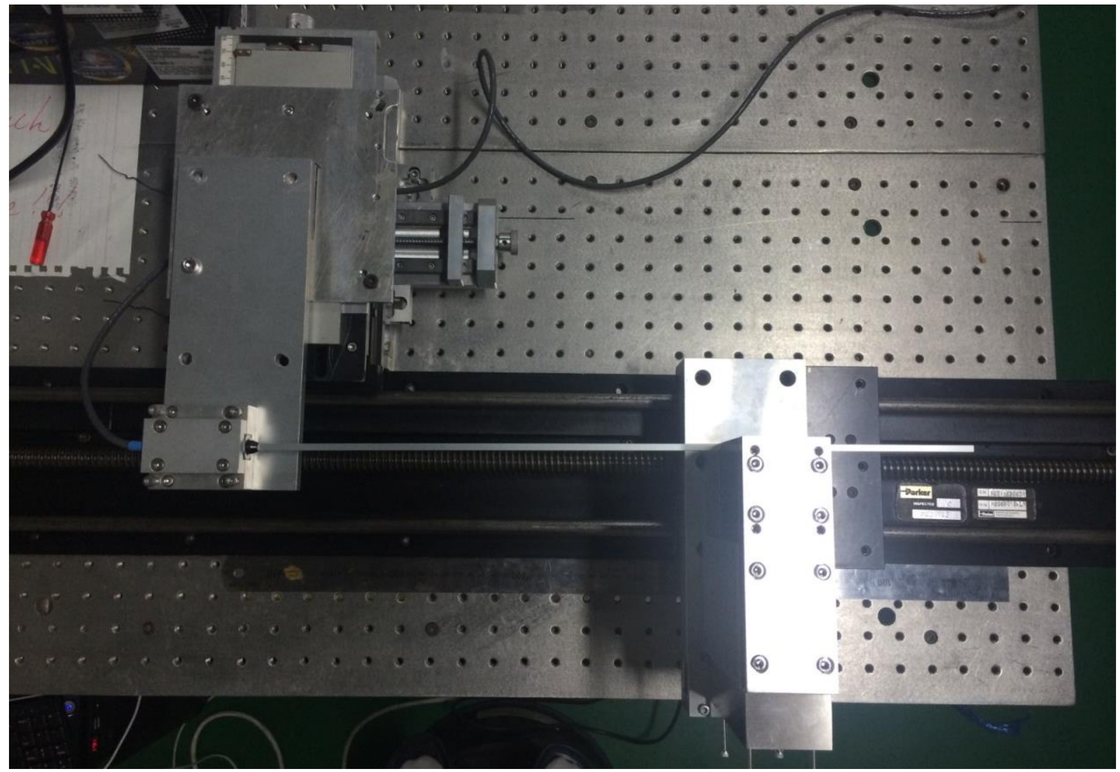
Gap : 5~10 mm
Area : 60×50 mm^2
B field : 0.3~0.8 Tesla



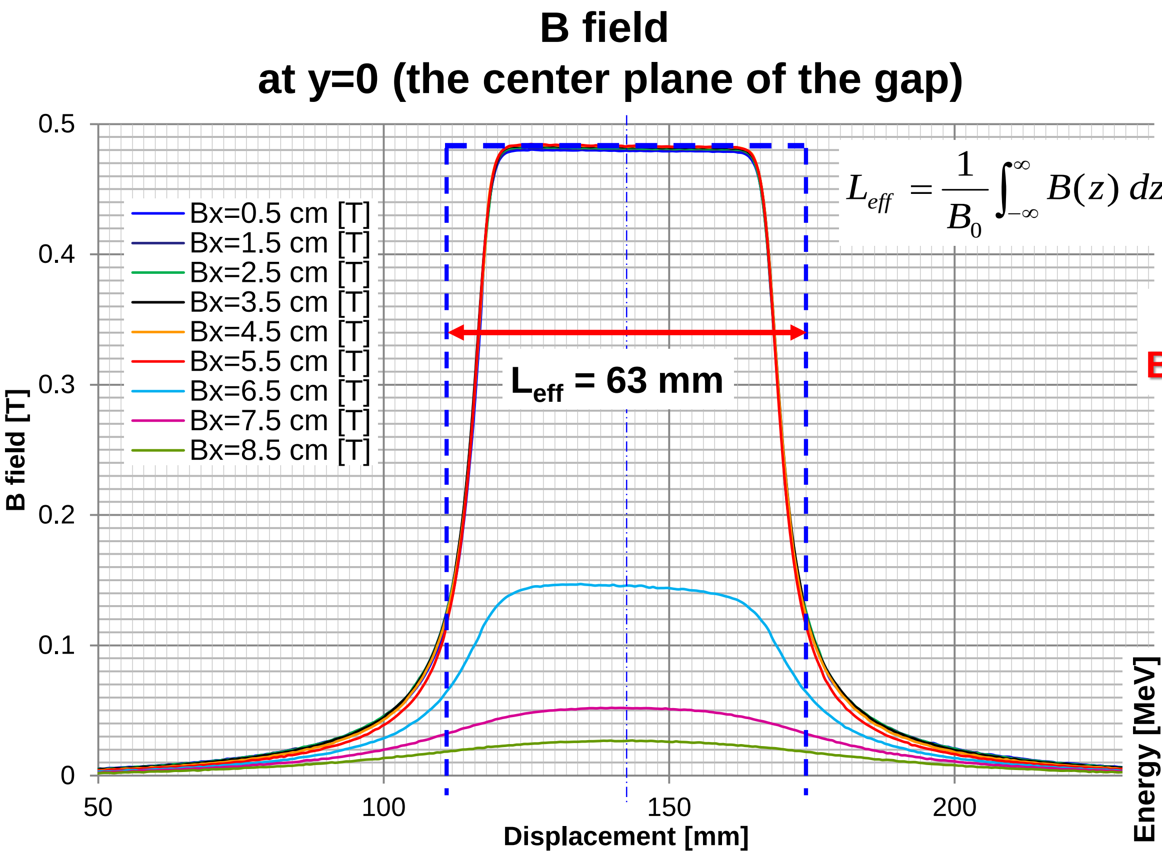
Side View

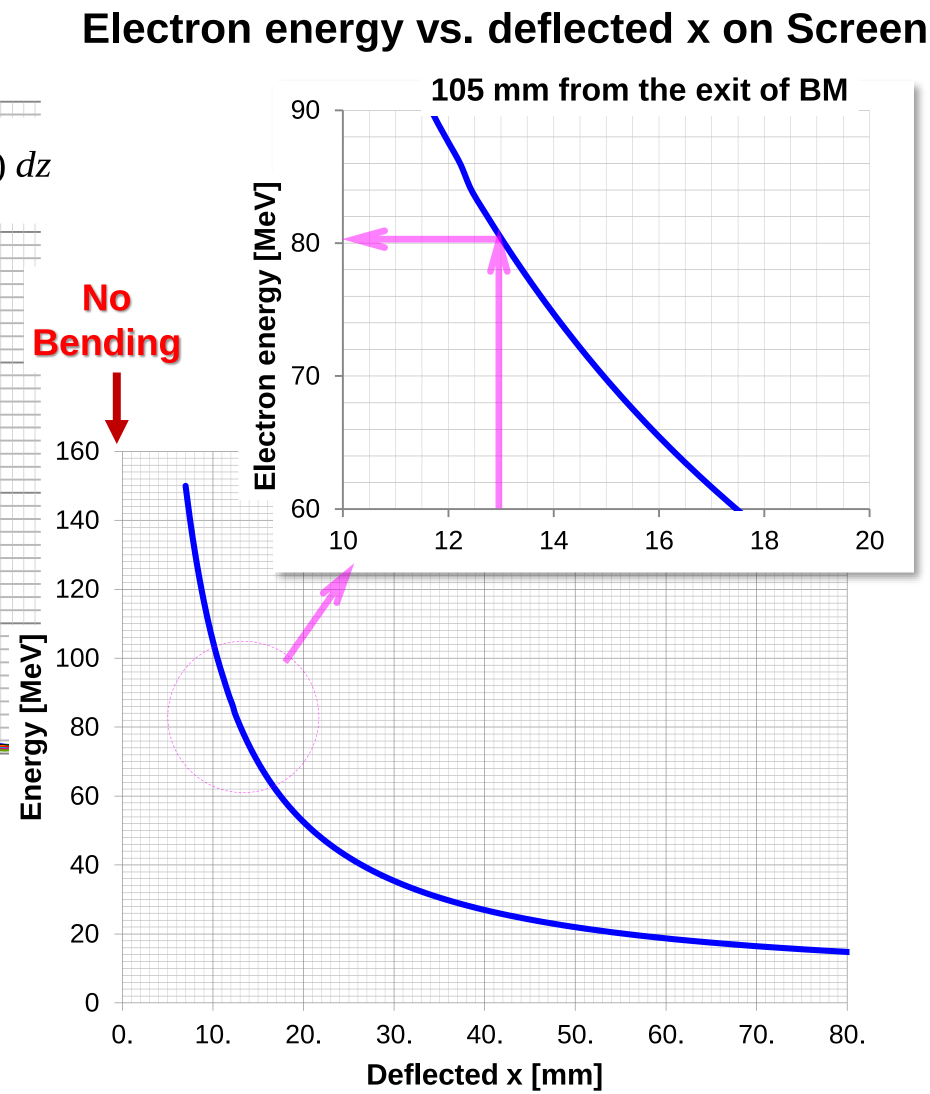
Front View

B Field Measurement Set-up



Energy spectrometer : B_0 & L_{eff} :, E_e vs x





B_0 = 0.483 T ± 0.0015

L_{eff} = 63 mm

E_e = 70 MeV for x = 14.95 mm

E_e = 80 MeV for x = 13.06 mm

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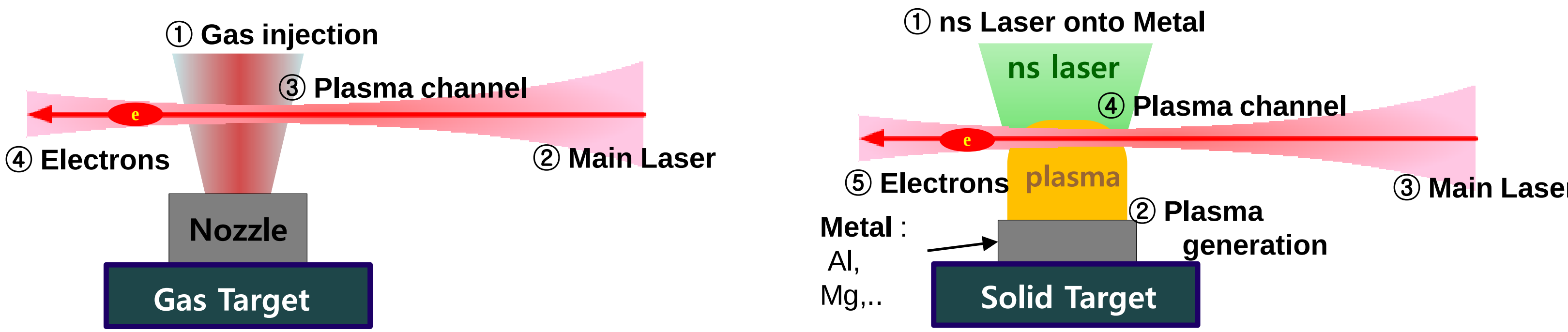
Gas & Metallic target

Collaboration with J. Kim (KERI)

- **To answer whether the laser accelerated e-beam can be used as conventional e-beam injector but very compact size**
  - **Vacuum can be manageable**
  - **Not easy to control the plasma density, but the plasma channel shape.**
    - elongated plasma channel, plasma channel with density gradient
  - **High rep. operation or number of shots limited by target size**

⇨ **Experimental set-up was moved from KERI to KAERI in March, 2015**

Interaction Process for different targets



Laser-Plasma Electron Acceleration : He gas

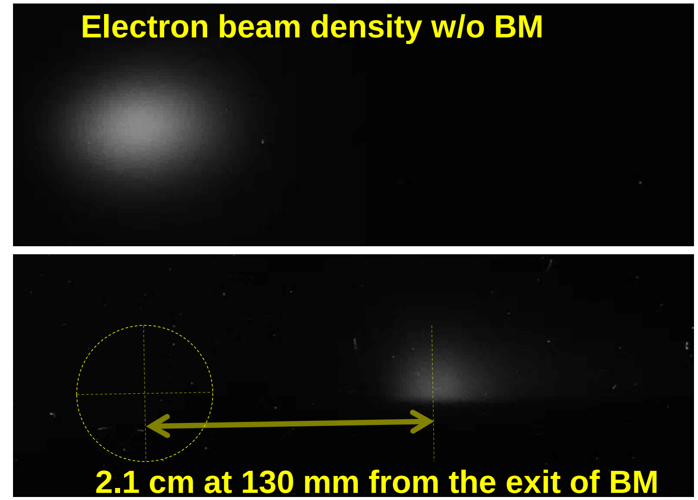
Parameters of Laser accelerated Electron Beam

Laser :20 TW, 27 fs, 800 nm (ϕ40 mm)
Focal spot : 9.0 μm_{FWHM},
Rayleigh range : Z_R ~ 170 μm
Gas jet target : He, 1 mm dia. nozzle,
distance from nozzle Δl= 4 mm
650 psi backing pressure
Plasma:density n ~ <1 x10^{19} cm^{-3}
wavelength λ_p ~ 8.5 μm
dephasing length, λ_{deph} ~ 800 μm

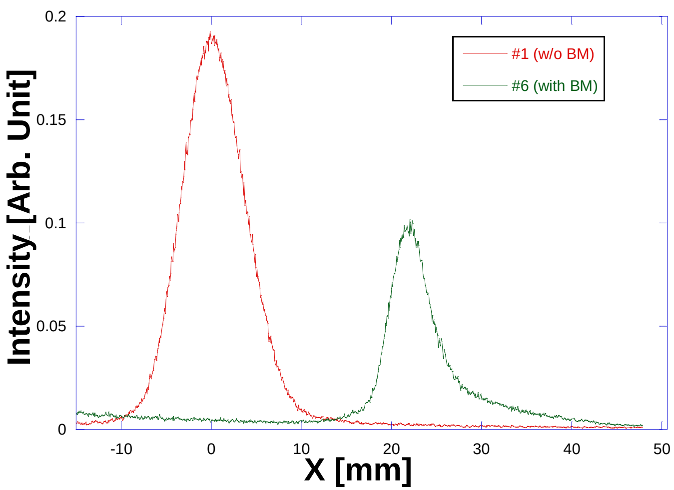
Electron beam:

Energy : ~62 MeV
Energy spread : ~ 23%
Charge : < 200 pC
Divergence : ~ 4 mrad

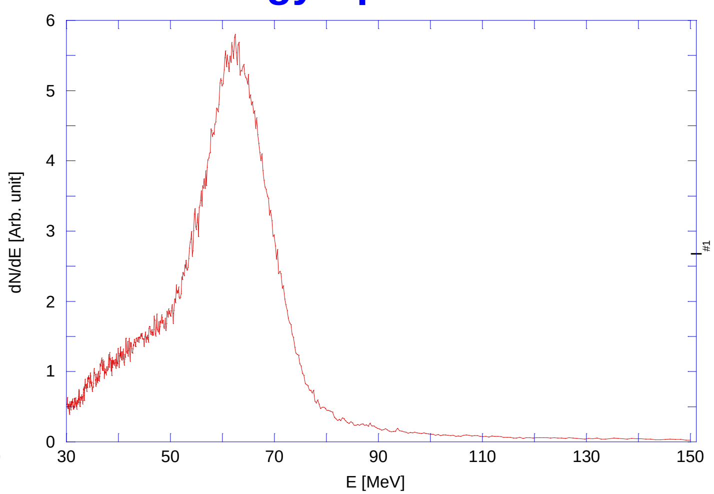
Images in Lanex screen



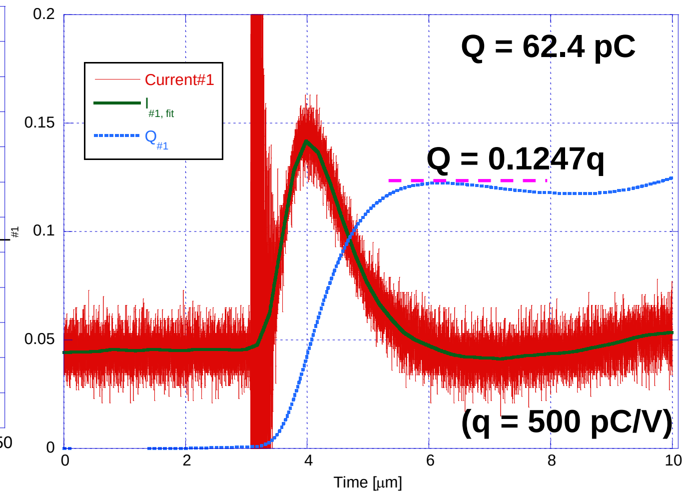
Density distribution



Energy Spectrum



Electron Beam Charge



Laser-Plasma Electron Acceleration : He gas

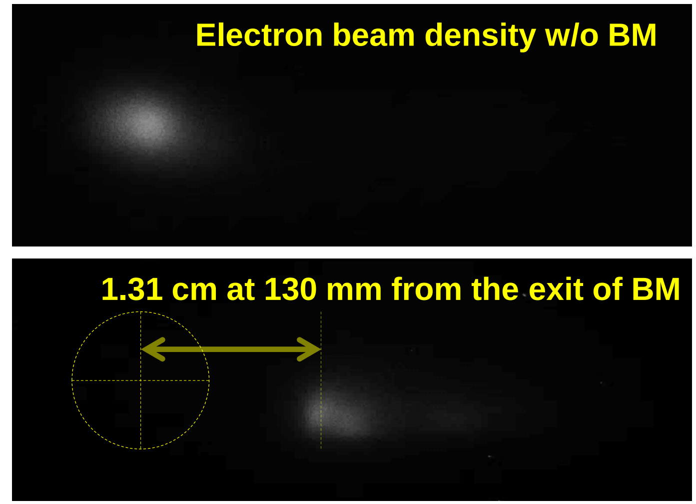
Parameters of Laser accelerated Electron Beam

Laser : 20 TW, 27 fs, 800 nm (ϕ40 mm)
Focal spot : 7.5 μm$_{FWHM}$,
Rayleigh range : Z_R ~ 170 μm
Gas jet target: He, 2x3 mm rectangular nozzle,
distance from nozzle Δl= 4 mm
900 psi backing pressure
Plasma: density n ~ 1 x10^{19} cm^{-3}
wavelength λ_p ~ 8.5 μm
dephasing length, λ_{deph} ~ 1 mm

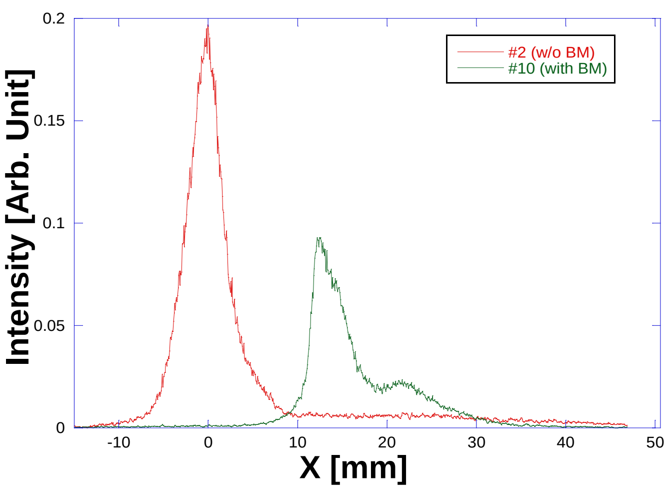
Electron beam:

Energy : ~110 MeV
Energy spread : ~ 30%
Charge : ~ 50 pC
Divergence : ~ 4 mrad

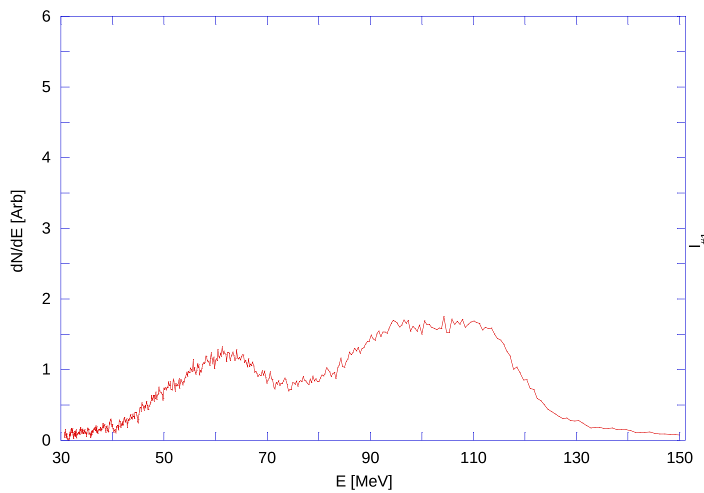
Images in Lanex screen



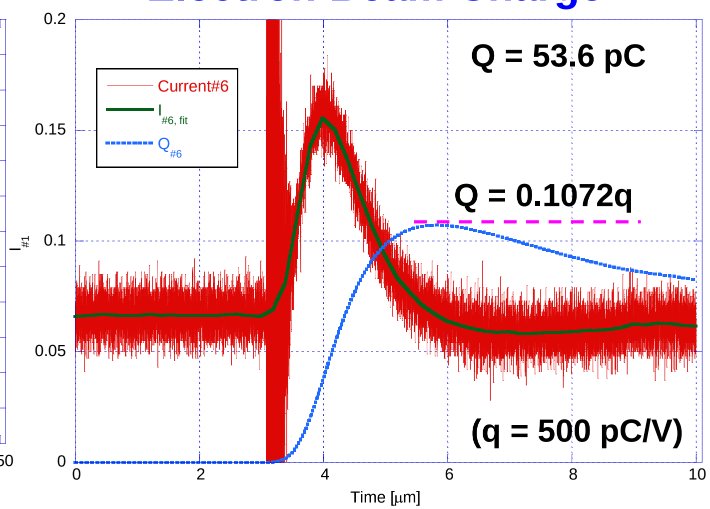
Density distribution



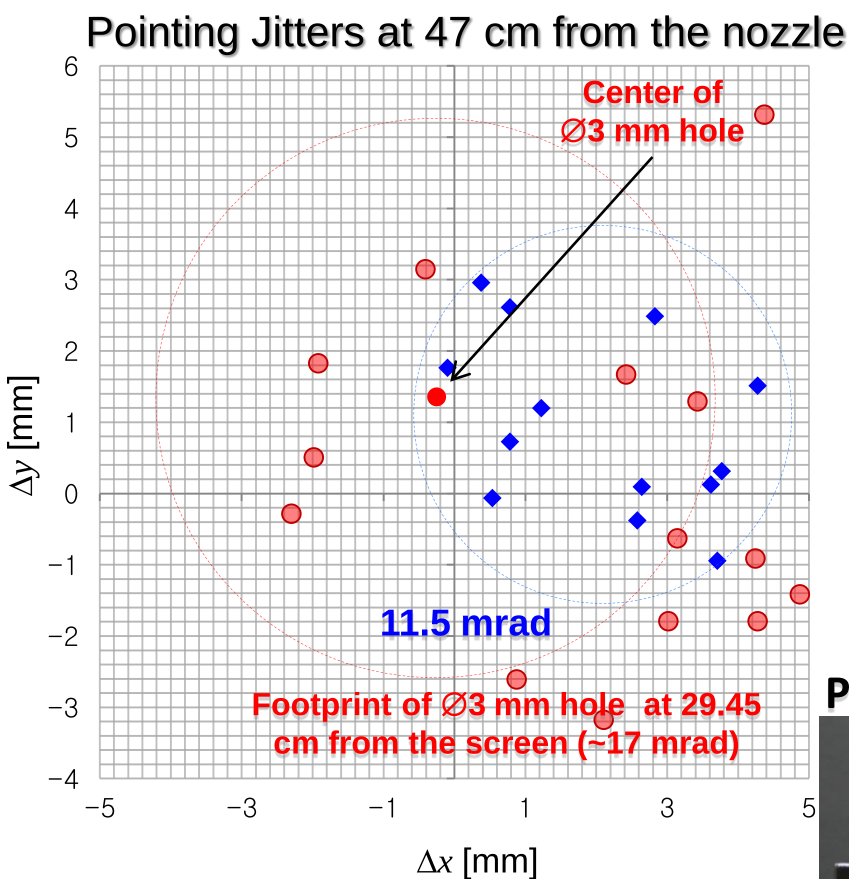
Energy Spectrum



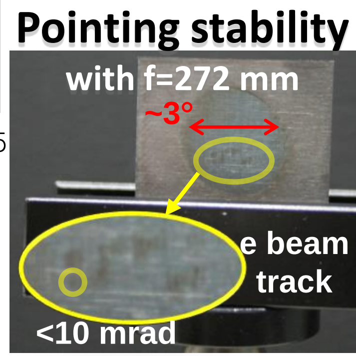
Electron Beam Charge

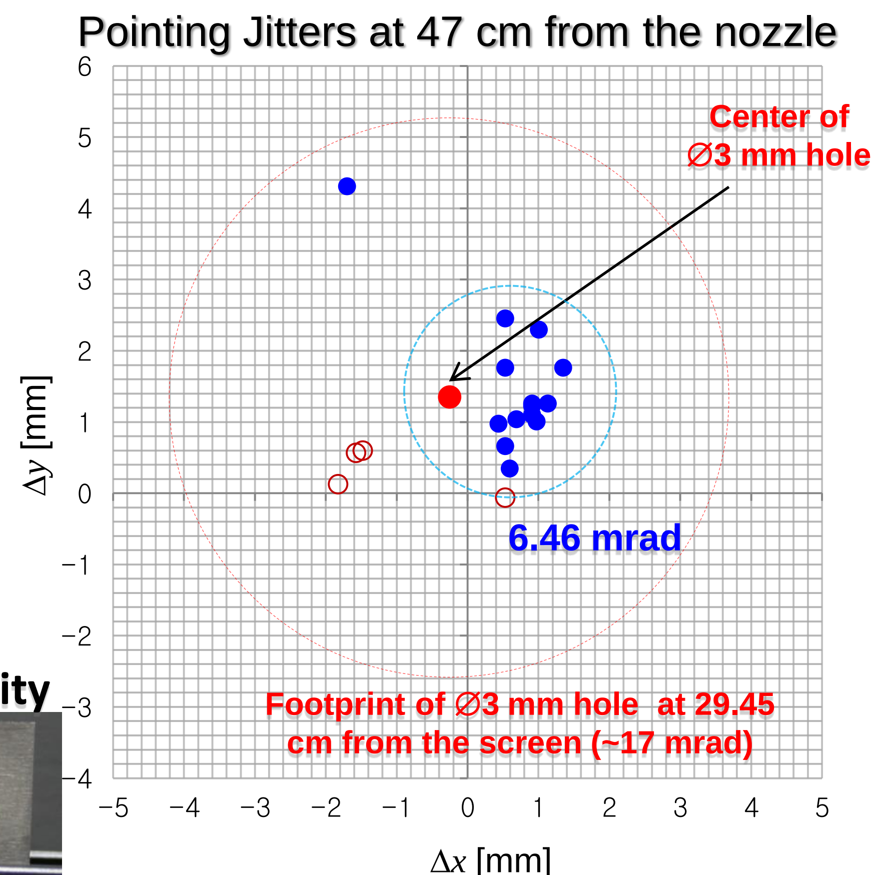


Shot-to-Shot Variation : Pointing Jitter



Alignment laser position : (0, 0)
Open red circle at h = 3.0 mm
Solid blue disk at h = 3.0 mm





Alignment laser position : (0, 0)
Open red circle at h = 3.98 mm
Solid blue disk at h = 4.0 mm

Laser Pointing & Power jitter ➔ Peak energy jitter in electron beam ➔ More reduction needed!

Gas & Metallic target

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- To answer whether the laser accelerated e-beam can be used as conventional e-beam injector but very compact size
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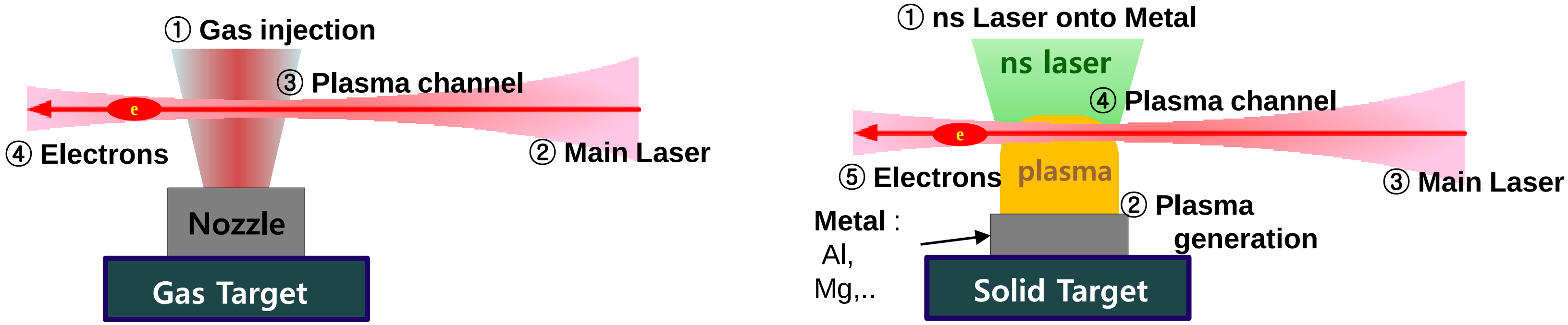
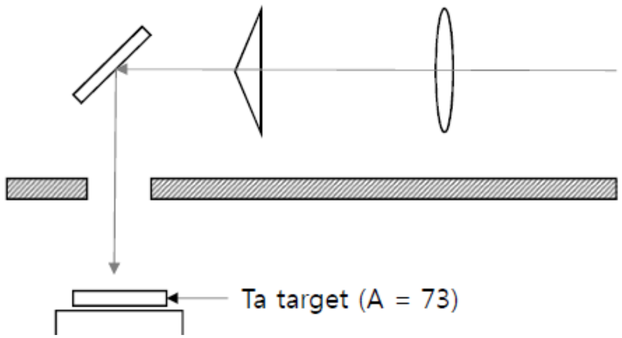
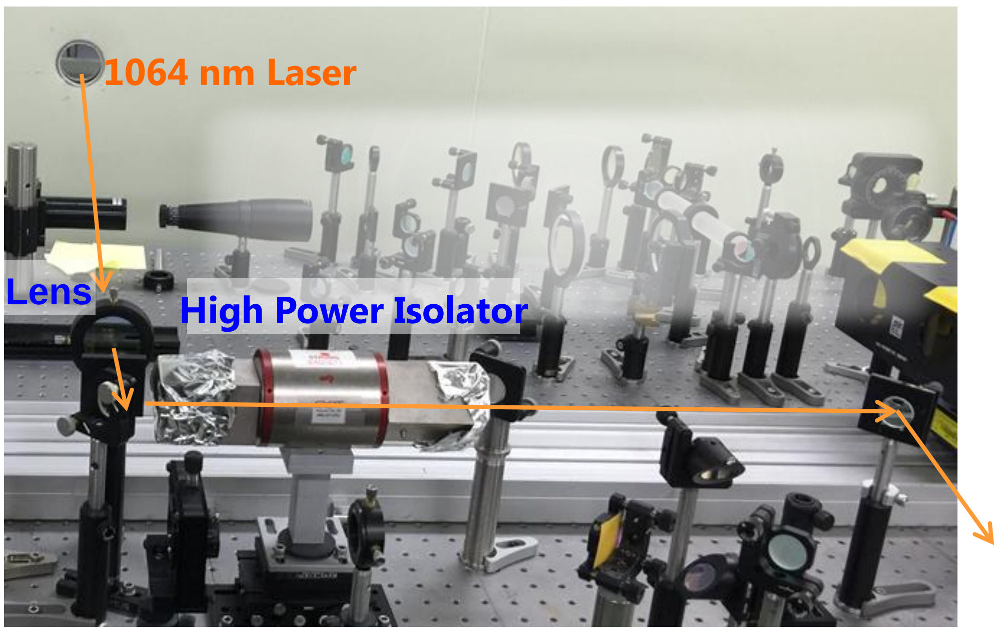


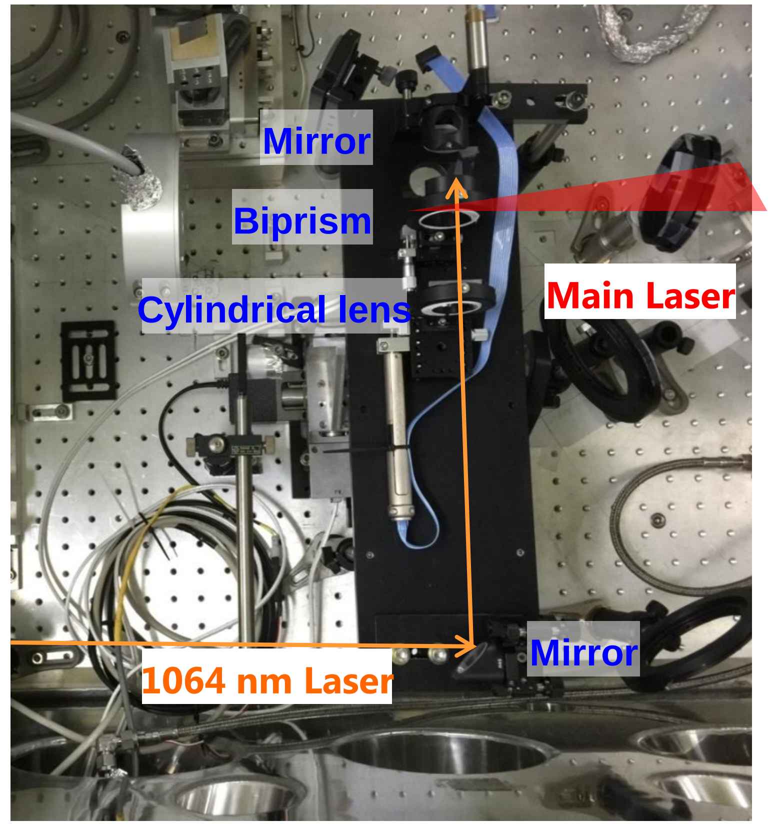
IR Beamline for Metallic Plasma

H.P. IR Laser Beamline for Metallic Plasma Generation





ns Nd:YAG Laser Beamline for Metallic Plasma

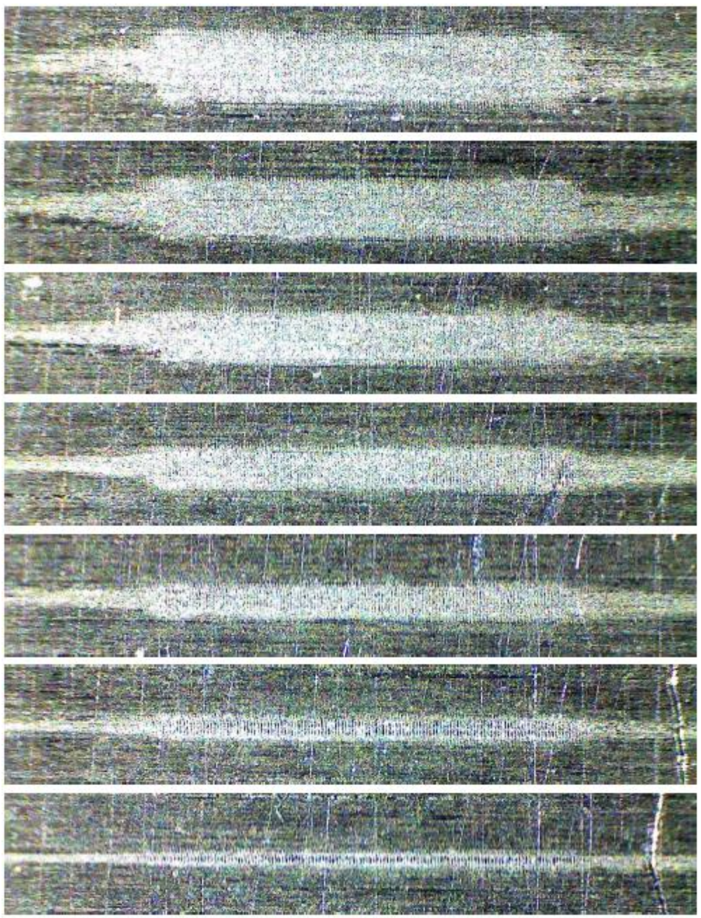


Laser Beam Shaping Optics

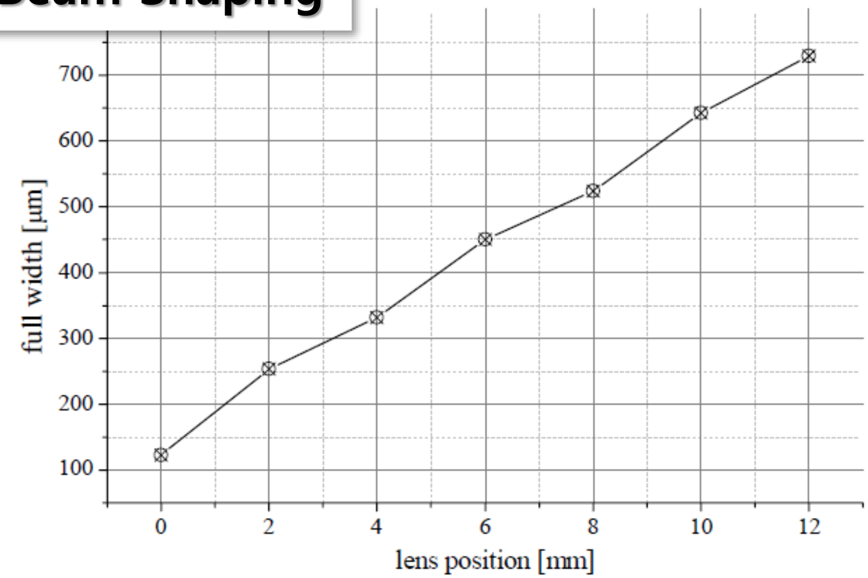
Laser Beam Shaping and Plasma Density

J. Kim (KERI)

Pre-Plasma Analysis depending to Laser Beam Shaping



Variation of Laser Beam Shape at the metal surface



Laser Beam Size vs Position of Focal Point

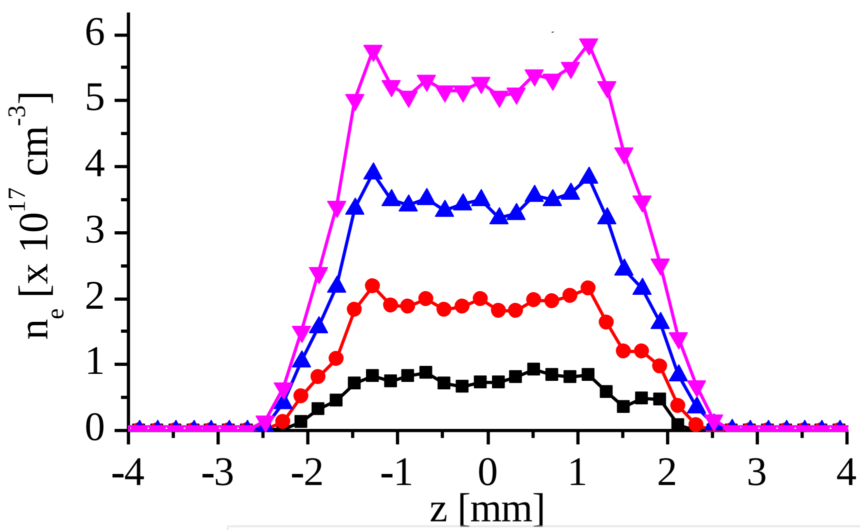
Density of Pre-plasma depending on the Beam size

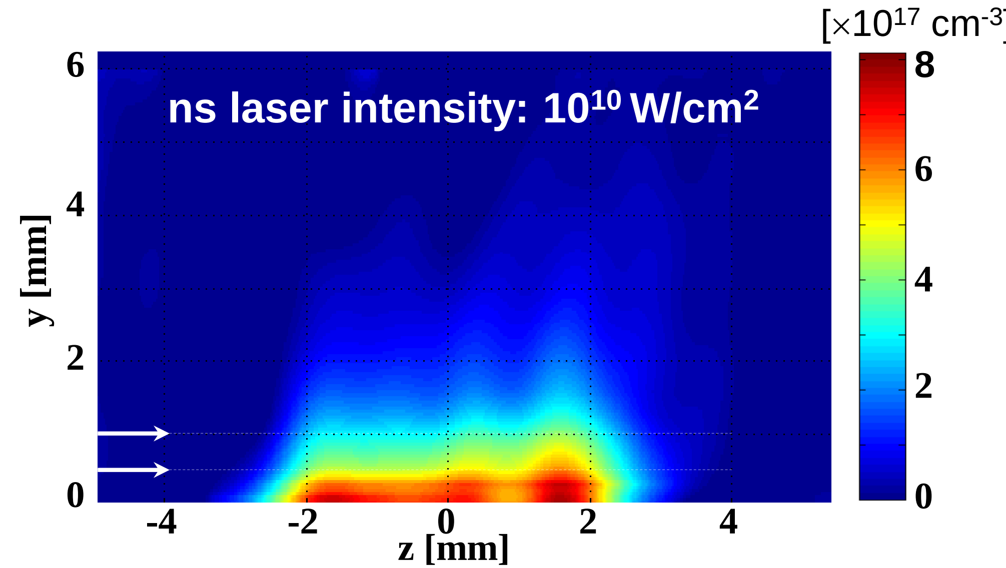
Lens [mm]	Line width [μm]	Phase at 0.65 mm	Density @0.65 mm ($x10^{17}$ cm^{-3})
0	122	0.57	2.5
2	253	1.65	7.2
4	332	1.38	6.0
6	450	1.85	8.1
8	524	2.80	12
10	642	4.33	19
12	730	4.2	18

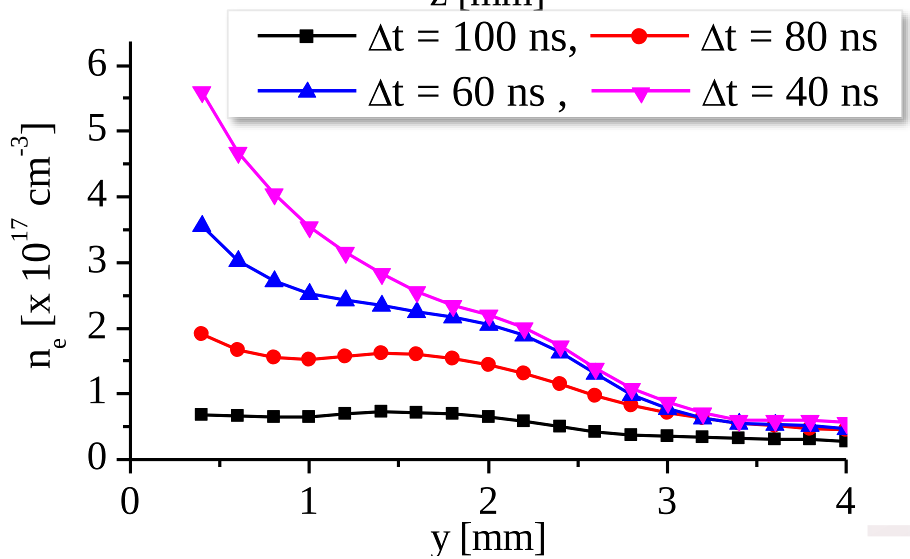
Plasma Density : Al target

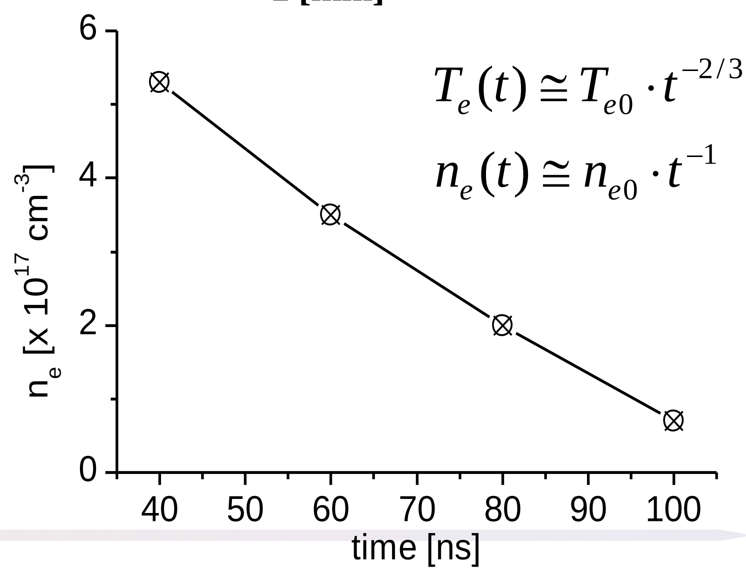
J. Kim (KERI)

Control of Plasma density: Laser Intensity, Time delay, Distance from the target surface









Applications : Radiotherapy

Gamma/X-ray radiotherapy : 6 - 18 MV photons

- Widely used
- Multiple-angle irradiation

Low energy electron radiotherapy : 5 - 20 MeV electrons

- Superficial tumour , skin cancers
- Well-defined cut-off point in a few cm

Hadron therapy : 100 – 300 MeV/u protons, heavy ions

- Well-defined cut-off range in matter
- Spread-out Bragg peaks

High Energy Electron Beam Therapy : 50 – 250 MeV Electrons

- Reach to deep-seated tumour
- High dose rate (compared to photons) : VHEE vs. VMRT
- More reliable beam delivery around inhomogeneous media
- Multiple-angle irradiation

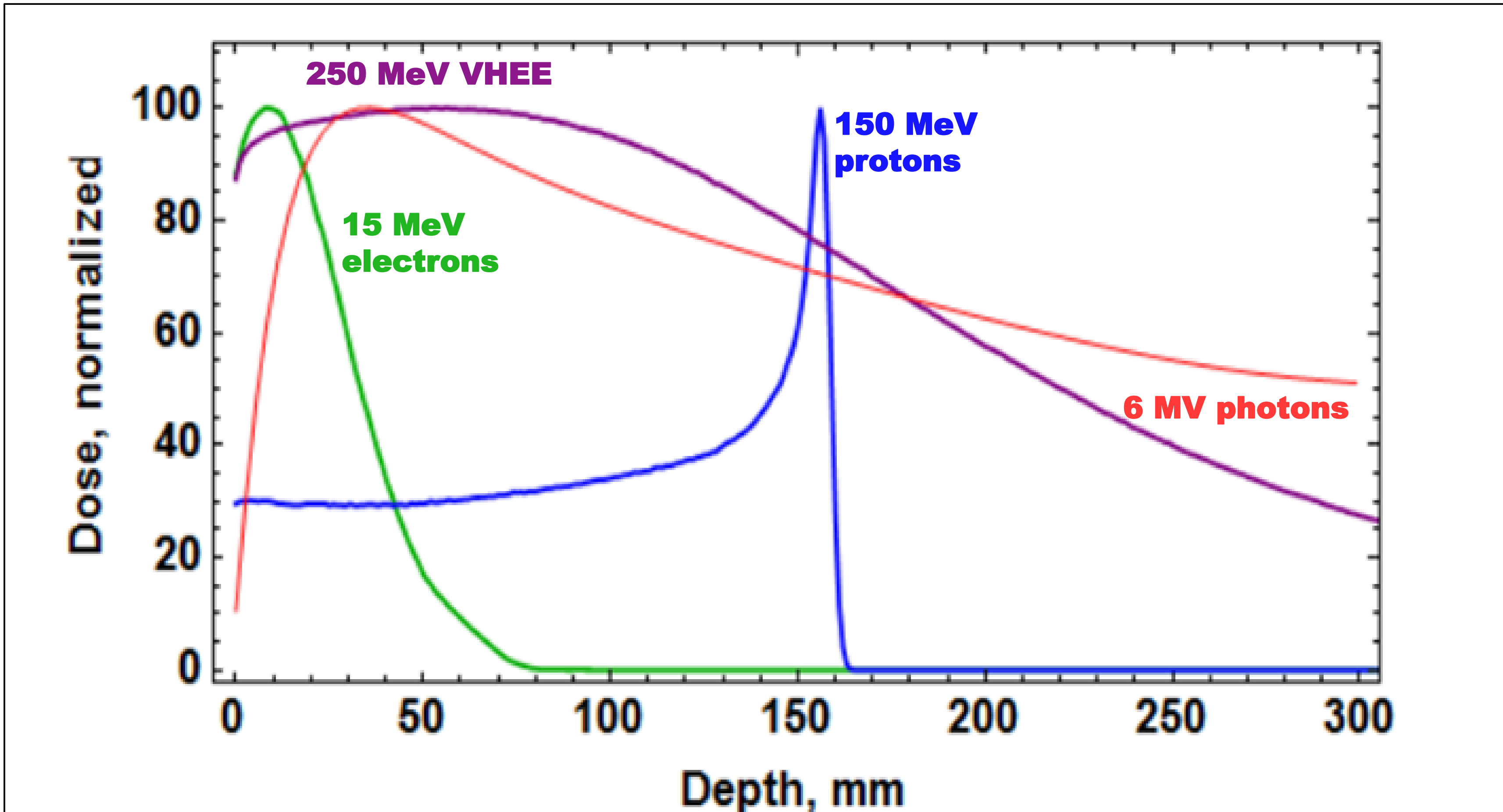
Boron Neutron Capture Therapy: Epithermal neutrons + Boron : Proton → Neutron

- Head and neck tumour, Brain, …..

Absorbed dose along penetration depth

Current radiotherapy methods

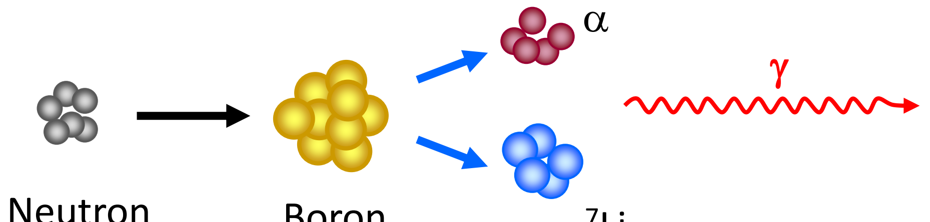
- 6 - 18 MV photons
- 5 - 20 MeV electrons
- 50 - 300 MeV/u hadrons (p, ^{12}C)



Dose profiles for various particle beams in water (beam widths r=0.5 cm)

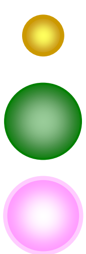
Boron Capture Neutron Therapy

- **High LET (Linear Energy Transfer) : ^{7}Li – 175 keV/μm and α – 150 keV/μm:**



$$^{10}B + n_{th} \rightarrow {}^{11}B^{*} \begin{cases} \xrightarrow{6\%} {}^{4}He + {}^{7}Li + 2.79\ MeV \\ \xrightarrow{94\%} {}^{4}He + {}^{7}Li^{*} + 2.31\ MeV \end{cases}$$

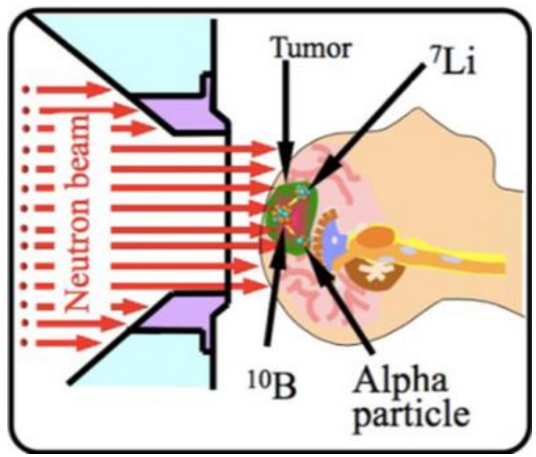
$$^{7}Li^{*} \rightarrow {}^{7}Li + \gamma + 0.48\ MeV$$



Boron compound

Cancer Cell

Healthy Cell



Short path length in tissue of ^{4}He and ^{7}Li : 6~10 μm

Neutron Generation

IAEA-TECHDOC-1223, "Current status of neutron capture therapy", May 2001

IAEA Guideline for therapy

Neutron Energy range	0.5 eV ~ 10 keV	
Epithermal n flux	$> 1\times10^{11}$ n/cm^2/s	
Harmful fast neutrons	$< 2\times10^{-13}$ Gy·cm^2/n	
Harmful γ-rays	$< 2\times10^{-13}$ Gy·cm^2/n	

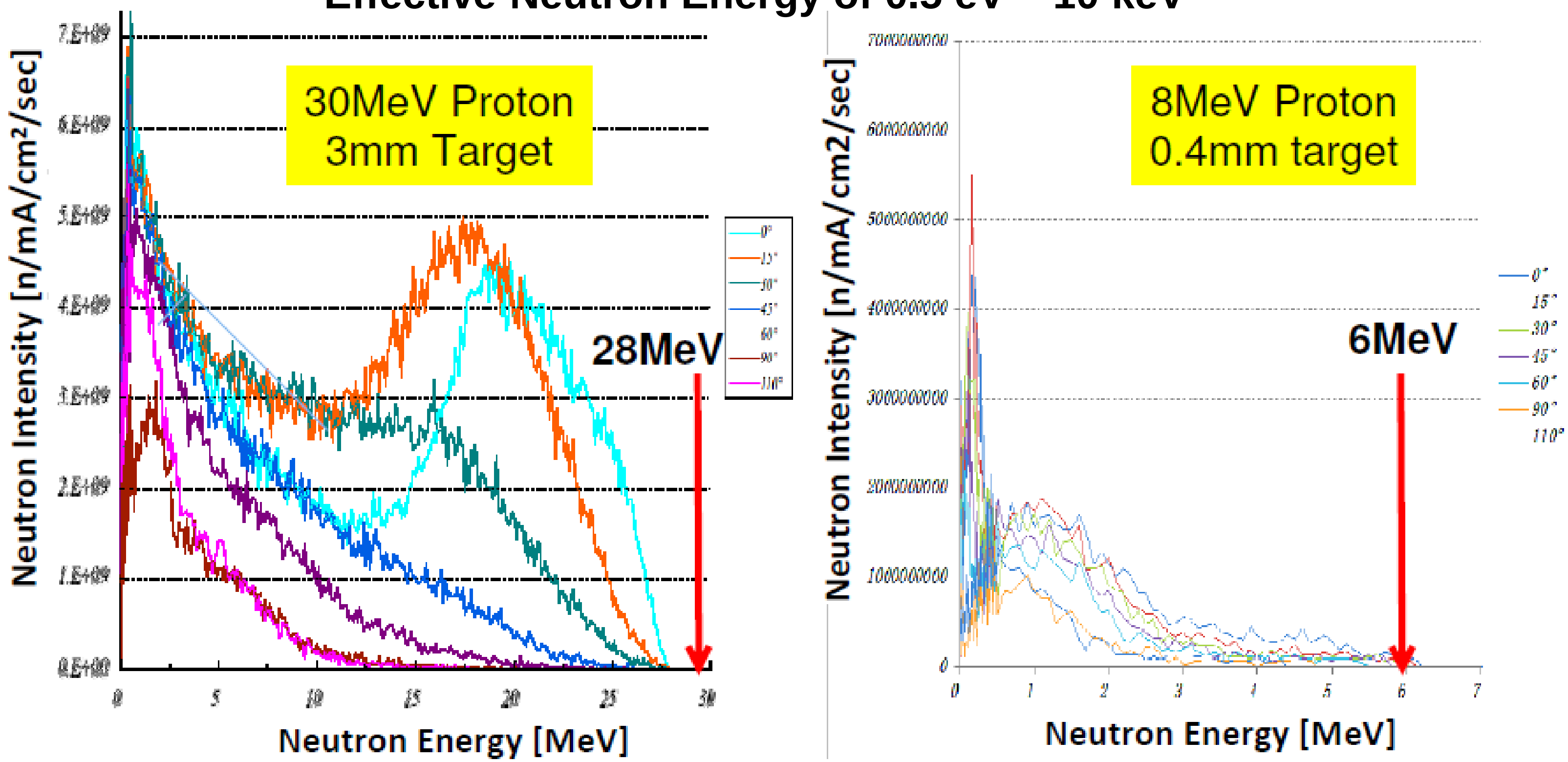
Neutron Flux from different targets

Isotope	Threshold energy [MeV]	Accelerated energy [MeV]	Neutron yield [#/sec/mA]	Maximum n energy [MeV]	Target
^{7}Li(p,n) ^{7}Be	1.88	2.5	9×10^{11}	0.8	Radioactive ^{7}Be (53 d), oxidization, T_{mp} 180°
^{9}Be(p,n) ^{9}Be	2.06	4.0	9×10^{11}	2.2	Stable ^{9}Be, T_{mp} 1287°
^{9}Be(p,xn) ^{9}Be	-	30	2×10^{14}	30	fast n
Spallation W	-	70	1×10^{15}	72	

Neutron Generation : Epithermal neutrons

- **Neutron generation : 10^9 n/cm²/s, 0.5 eV ~ 10 keV**
  - **Target : Be – $^9Be(p,n)^9B$**

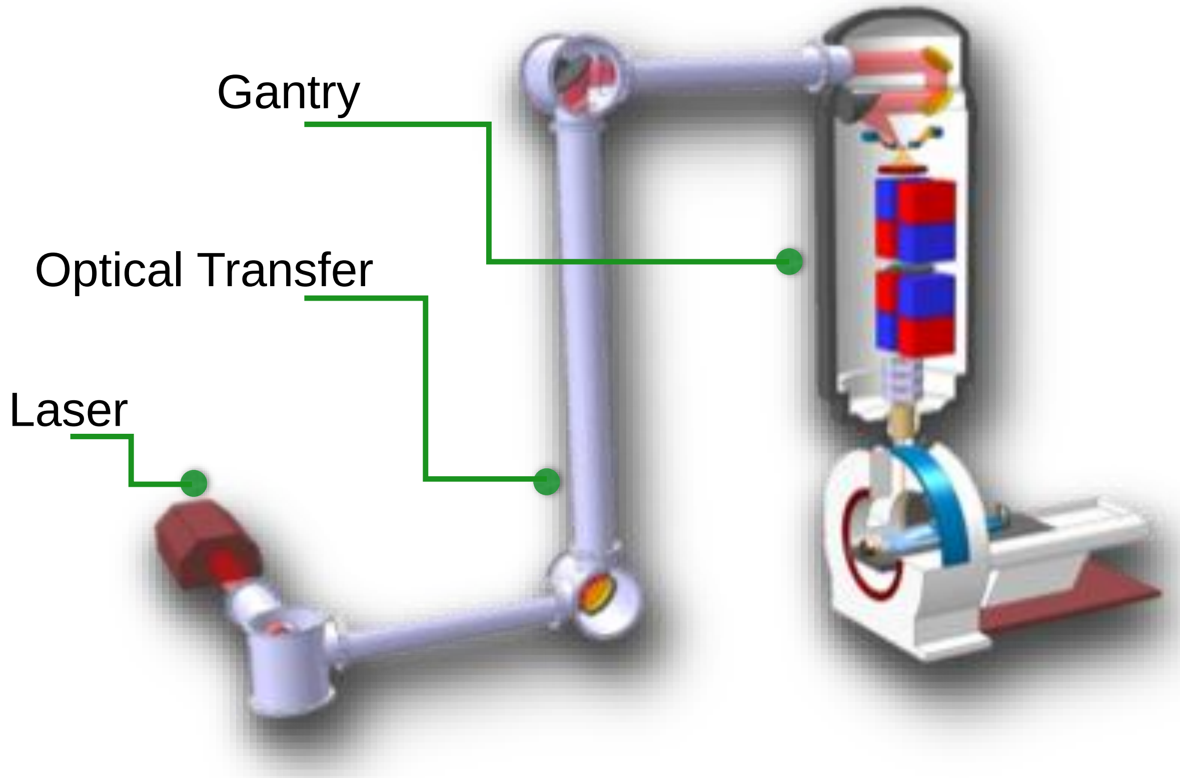
Effective Neutron Energy of 0.5 eV ~ 10 keV



Thermal neutrons: 3~4 cm
Epithermal neutrons: ~8 cm

Ref. ICABU2015,Hiroshi Matsumoto (KEK)

Realistically – VHEE, BNCT



Accelerator	Laser acceleration
	Energy: 250 MeV e^- 3~10 MeV p Current: ~? nA Pulsed Size: 5 x 5 m^2
Gantry	Isocentric gantry
	Size : Diameter: ~ 1m Length: ~1 m Weight: <a few ton
Cost	Low

- Energy : ⇒ Possible!
- Energy spread: < 1% ⇒ Needs improvements
- Current: ⇒ Need more R&Ds! Total dose vs. Peak Dose
- Stability ⇒ Getting better with real-time beam diagnosis

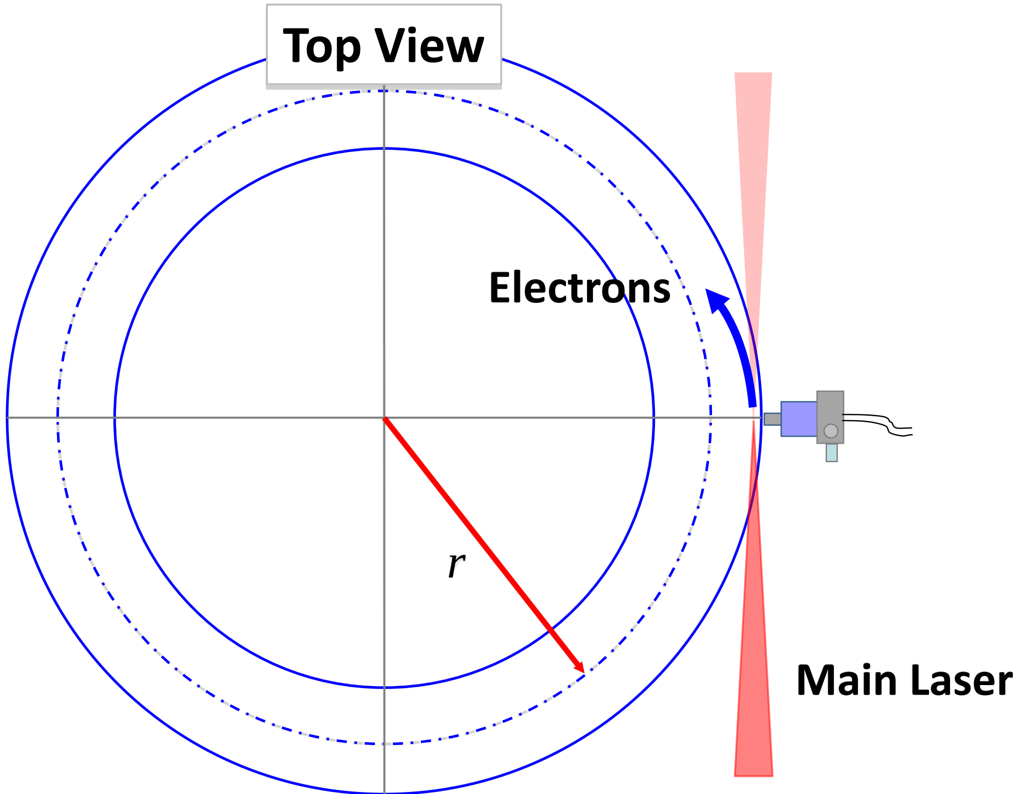
Courtesy by Kitae Lee at KAERI

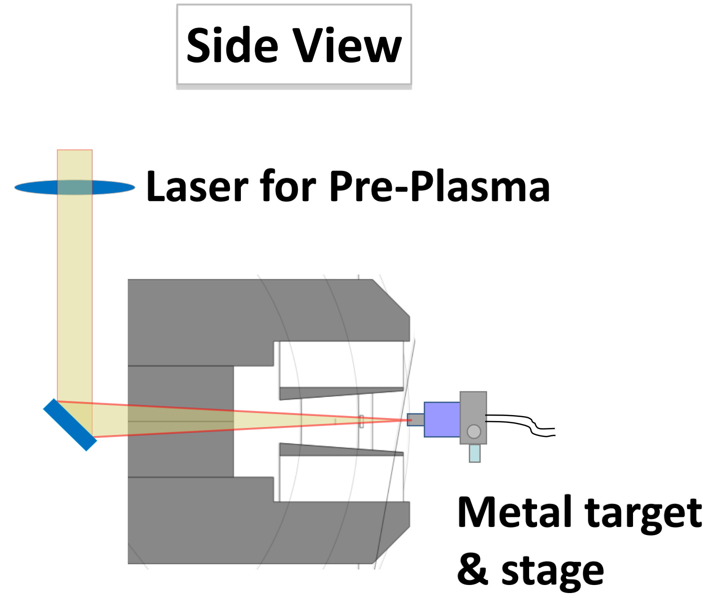
Applications : Radiation sources

- **Compact Storage Ring**
- **Gamma ray generation**

Scheme for Compact Storage ring

All-in-one Compact Storage Ring





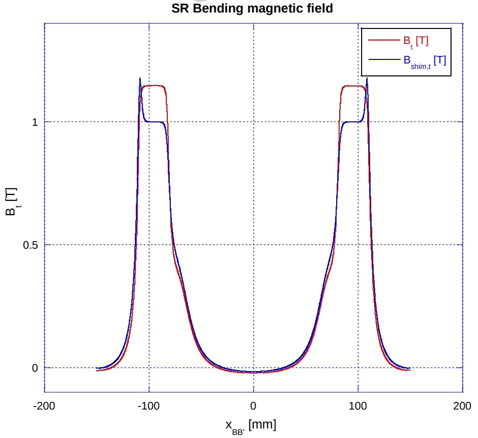
Critical Issues :

- E-beam energy: < 100 MeV at 0.5~1 T for Compactness
- Control of beam quality : Beam pointing, Energy spread, Divergence
- Need to study Pre-plasma density under Magnetic field

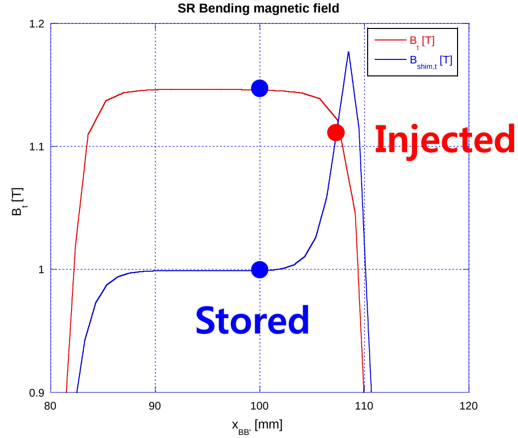
Design for Compact SR using permanent magnet

B-fields

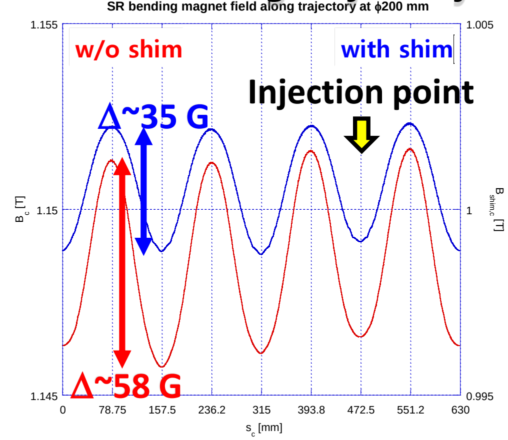
B-field along section xx′ or yy′



B-field along section xx′



B-field along trajectory



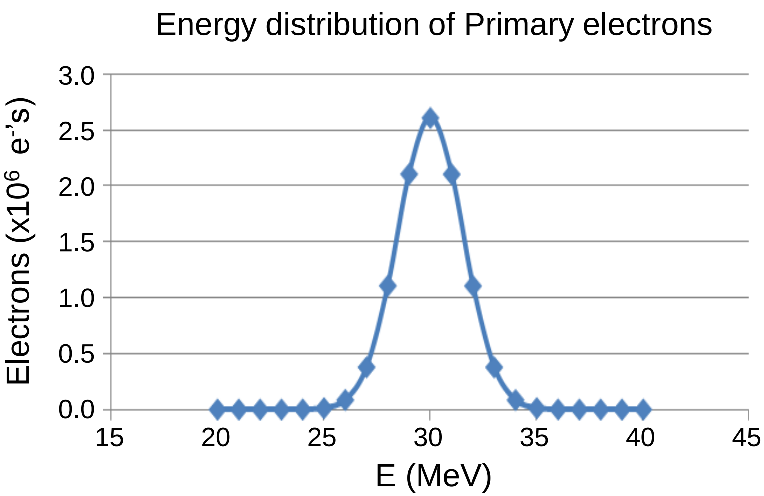
Design for Compact SR using permanent

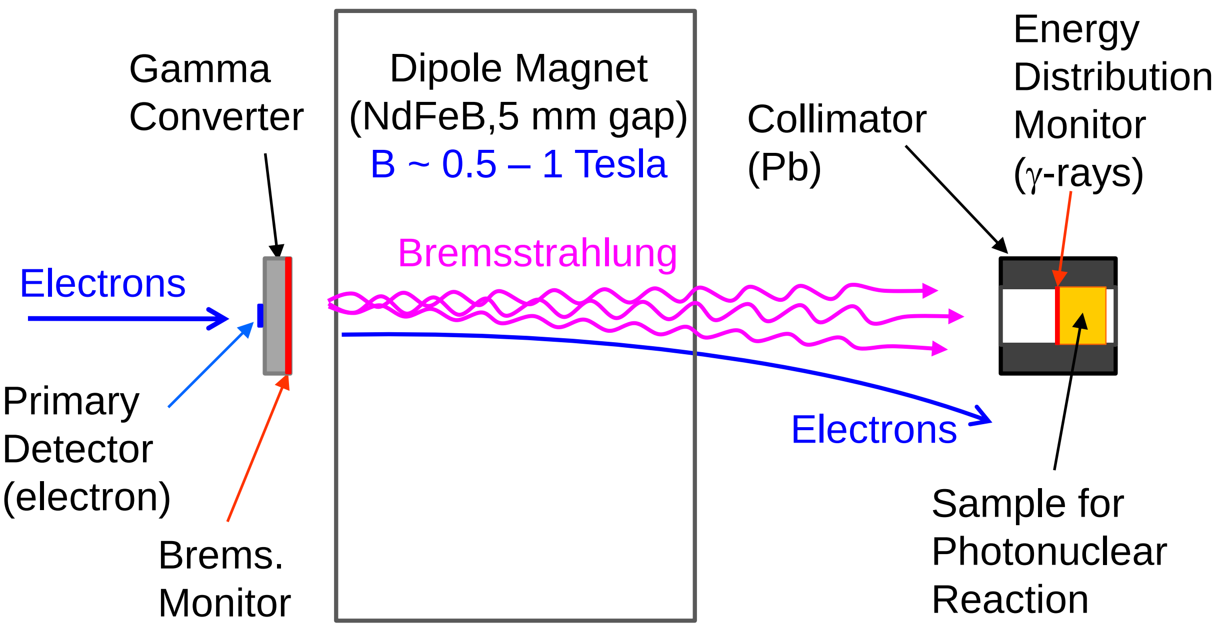
Bending radius & Radiation losses for different energy of electron beam at 1 Tesla Bending Magnet

Electron Beam	**E**	[MeV]	**150**	**100**	**80**	**50**	**30**
	γ		293.5	195.7	156.6	97.8	58.7
Bending Magnet	**B**	[Tesla]	1	1	1	1	1
	Bρ	mag. rigidity	0.500	0.334	0.267	0.167	0.100
	ρ	[cm]	50.034	33.356	26.685	16.677	10.005
rev. time	T_0	[ns]	10.486	6.991	5.593	3.495	2.097
Energy loss/turn	U_0	[eV]	89.566	26.538	13.587	3.317	0.717
Damping time	τ	[ms]	17.562	26.343	32.929	52.6878	87.632
Radiation at Bend	ε_c	[eV]	**14.96**	**6.65**	**4.26**	**1.66**	**0.60**
	λ_c	[nm]	**82.87**	**186.45**	**291.33**	**745.80**	**2071.66**

Bending Magnet	**B**	[Tesla]	0.483	0.483	0.483	0.483	0.483
	Bρ	mag. rigidity	0.500	0.334	0.267	0.167	0.100
	ρ	[cm]	103.591	69.060	55.248	34.529	20.715
rev. time	T_0	[ns]	21.711	14.474	11.579	7.237	4.342
Energy loss/turn	U_0	[eV]	43.260	12.818	6.563	1.602	0.346
Damping time	τ	[ms]	75.280	112.920	141.149	225.831	376.350
Radiation at Bend	ε_c	[eV]	**7.23**	**3.21**	**2.06**	**0.80**	**0.29**
	λ_c	[nm]	**171.57**	**386.02**	**603.16**	**1544.10**	**4289.16**

Gamma-ray generation: Geometry

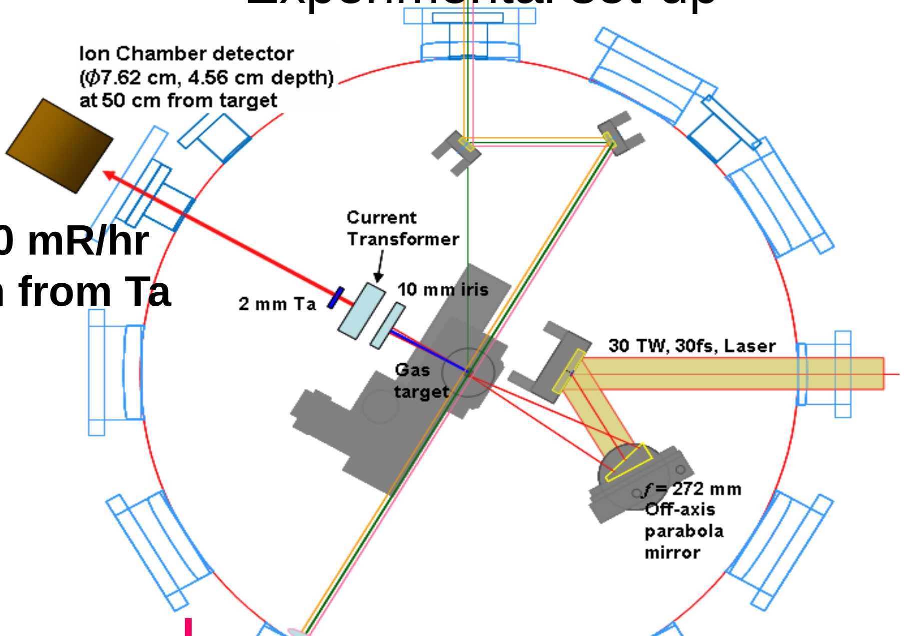




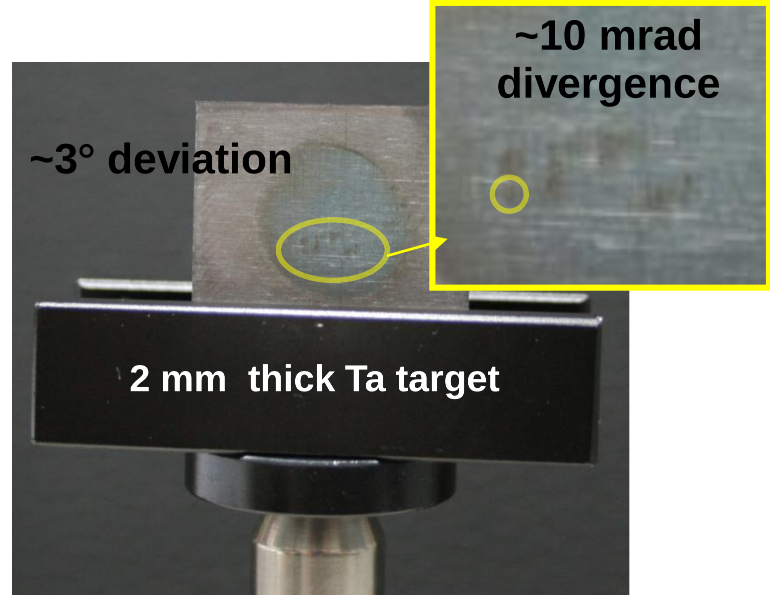
- $N_e = 10^7$
- $E_{e,\,peak}$ = 30MeV
- $\Delta E/E =$ 5% or 10 %
- Gaussian distribution

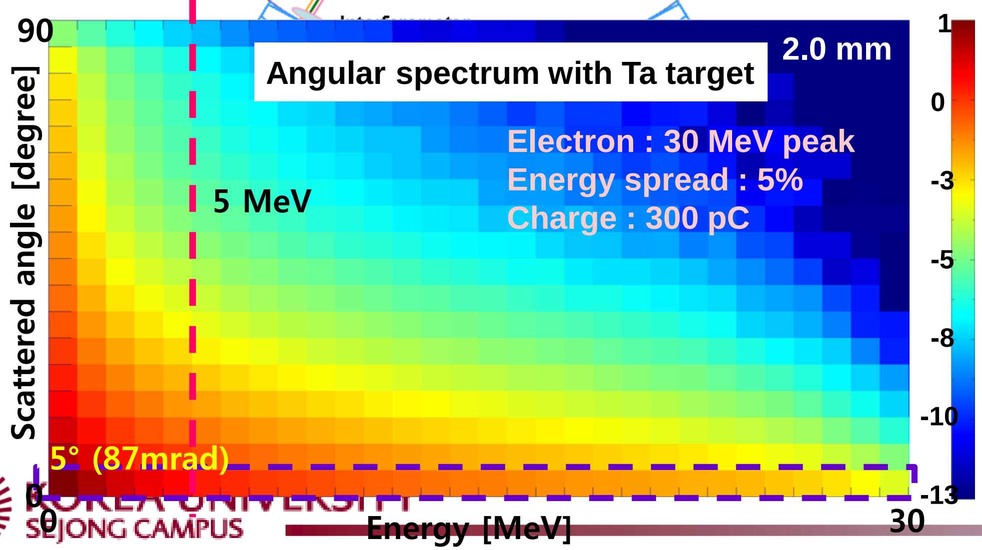
Bremsstralung generation : preliminary test

Experimental set-up



≥ 5000 mR/hr
50 cm from Ta





5000 mR/hr

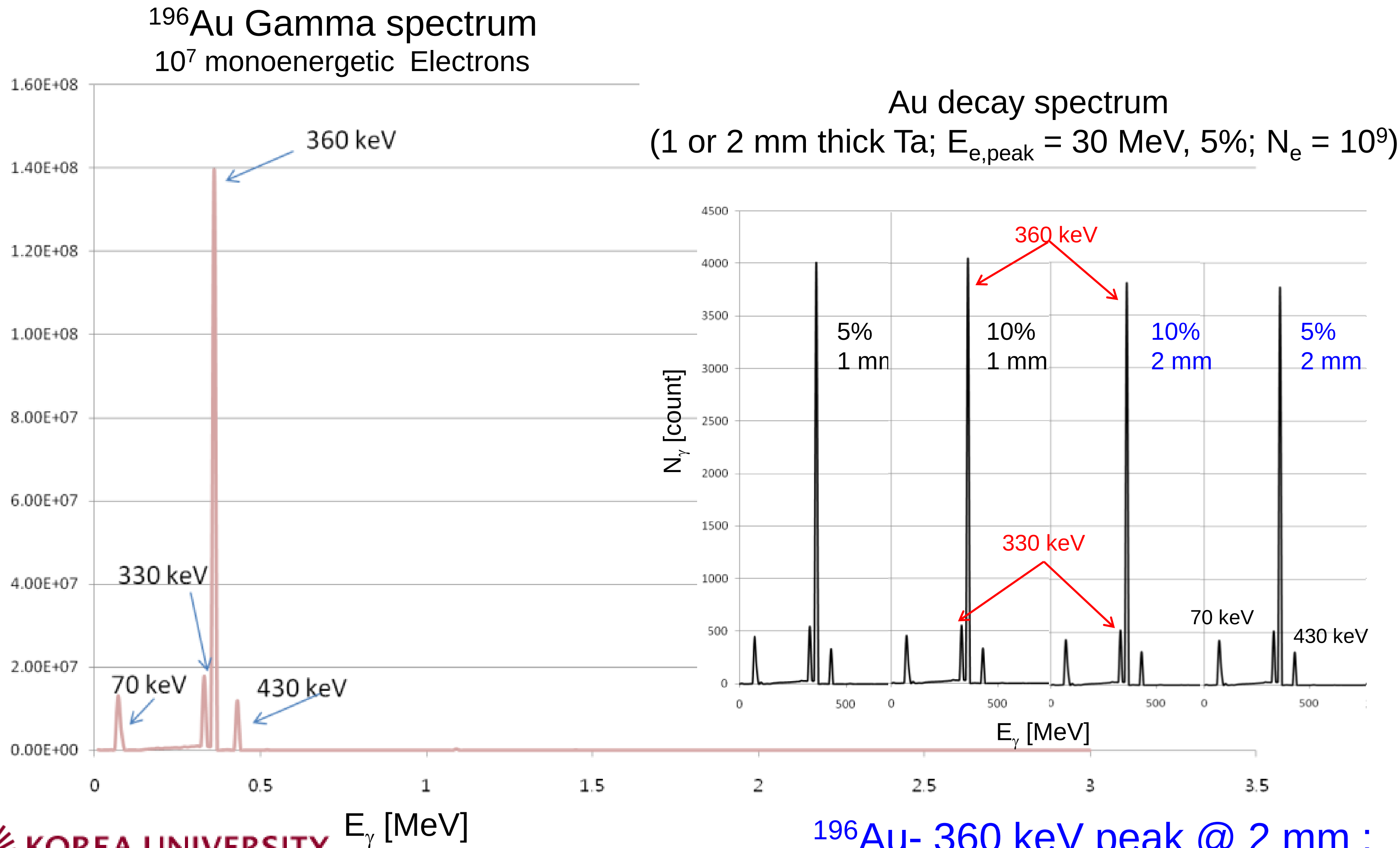
➔ > 6x10^7 ph/cm^2 @ 50 cm

Specification of Detector

- Response time to 90% : 5 sec
- Detectable energy : ≤7 MeV
- Detectable volume : 208 cm^3
  (∅72.6 mm dia. → 72.6 mrad)

cf. 1 mR = 2.083×10^6 ion pairs/cm^3

Gamma spectrum of activated ^{197}Au, i.e., ^{196}Au

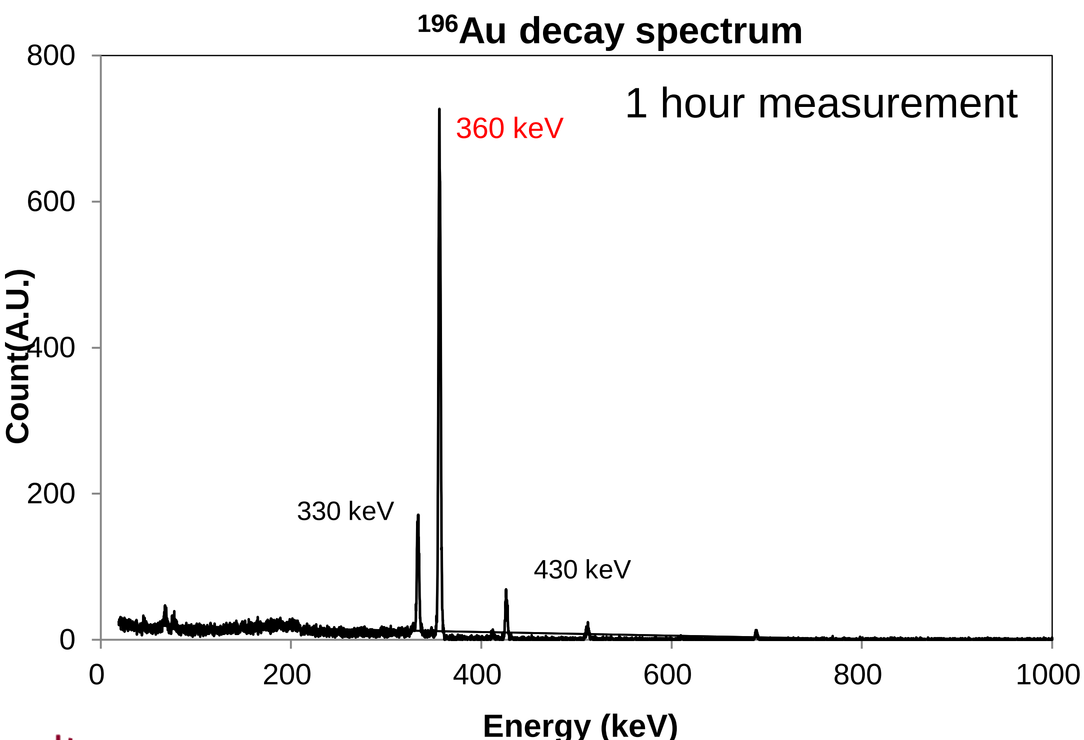


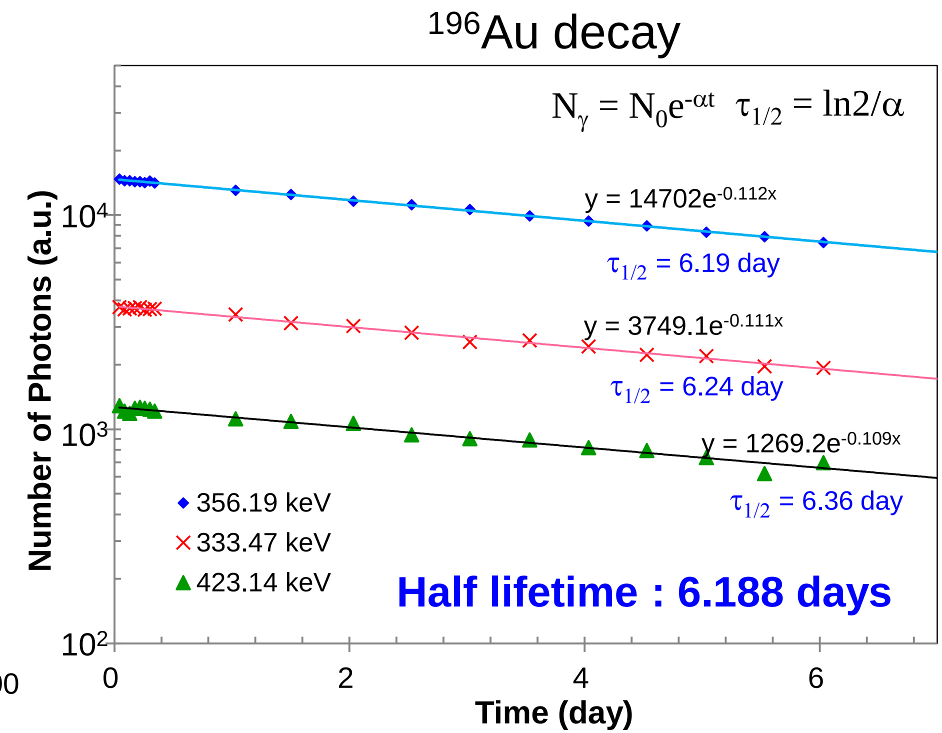
^{196}Au- 360 keV peak @ 2 mm :

➔ 2375 #/100pC/3°/1 mm thick Au

Decay spectrum of $^{197}Au(\gamma,n)^{196}Au$ reaction

- Laser : 650 mJ, ~8 μm spot size (FWHM) with 35 mm dia. iris
- Gas target : He, 1 cm dia., 650 psi, 1.35 mm from nozzle
- Electron : 25~30 MeV
- Bremsstrahlung : 2 mm Ta converter
- Activation : Gold (1 cm dia.x 4 mm), 2000 shots





➔ < 65 pC per shot

Estimation of Compton γ-rays

With RF Linac

LASER	Wavelength [nm]	800
	Average Power [Watt]	0.25
	Wavelength bandwidth [%]	~10
	Rep. rate [Hz]	100
	Rayleigh range [cm]	~20
ELECTRON	Energy [MeV]	20 ~ 30
	Charge [pC]/pulse	~200
	Energy spread [%]	~ 1
	Norm. emittance [mm·mrad]	2π
	Rep. rate [Hz]	100
γ-ray	**Energy [keV]**	**9.5 – 21.3**
	Flux [#/sec]	**> 10^5**
	Energy spread [%]	**~10%**

With Laser Accelerator

LASER	Wavelength [nm]	400
	Average Power [Watt]	0.1
	Wavelength bandwidth [%]	~1
	Rep. rate [Hz]	10
	Rayleigh range [cm]	3
ELECTRON	Energy [MeV]	200-300
	Charge [pC]/pulse	~100
	Energy spread [%]	< 5
	Norm. emittance [mm·mrad]	5π
	Rep. rate [Hz]	10
γ-ray	**Energy [MeV]**	**1.8 – 4.2**
	Flux [#/pulse]	**> 10^5**
	Energy spread [%]	**~ 5%**

Total Flux of scattered beam

$$\dot{N}_{scatt} = \frac{1}{e \cdot f_r} I_e[A] \cdot \frac{\sigma_{tot}}{A_{eff}} \cdot \dot{N}_{ph}$$

f_r: rep. rate

A_{eff} : Effective area

Summary

- Laser Plasma Acceleration : Proton
- Laser Electron Acceleration : Electron
- Compact Storage Ring
- Gamma ray generation

Thank you for attention!