Detection of γ-ray from laser plasma using nuclear emulsion

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Outline

1. Introduction
- Reactions in plasma induced by high-intensity lasers
- Nuclear Reactions in Laser Plasmas
- Our Goal
- Challenges

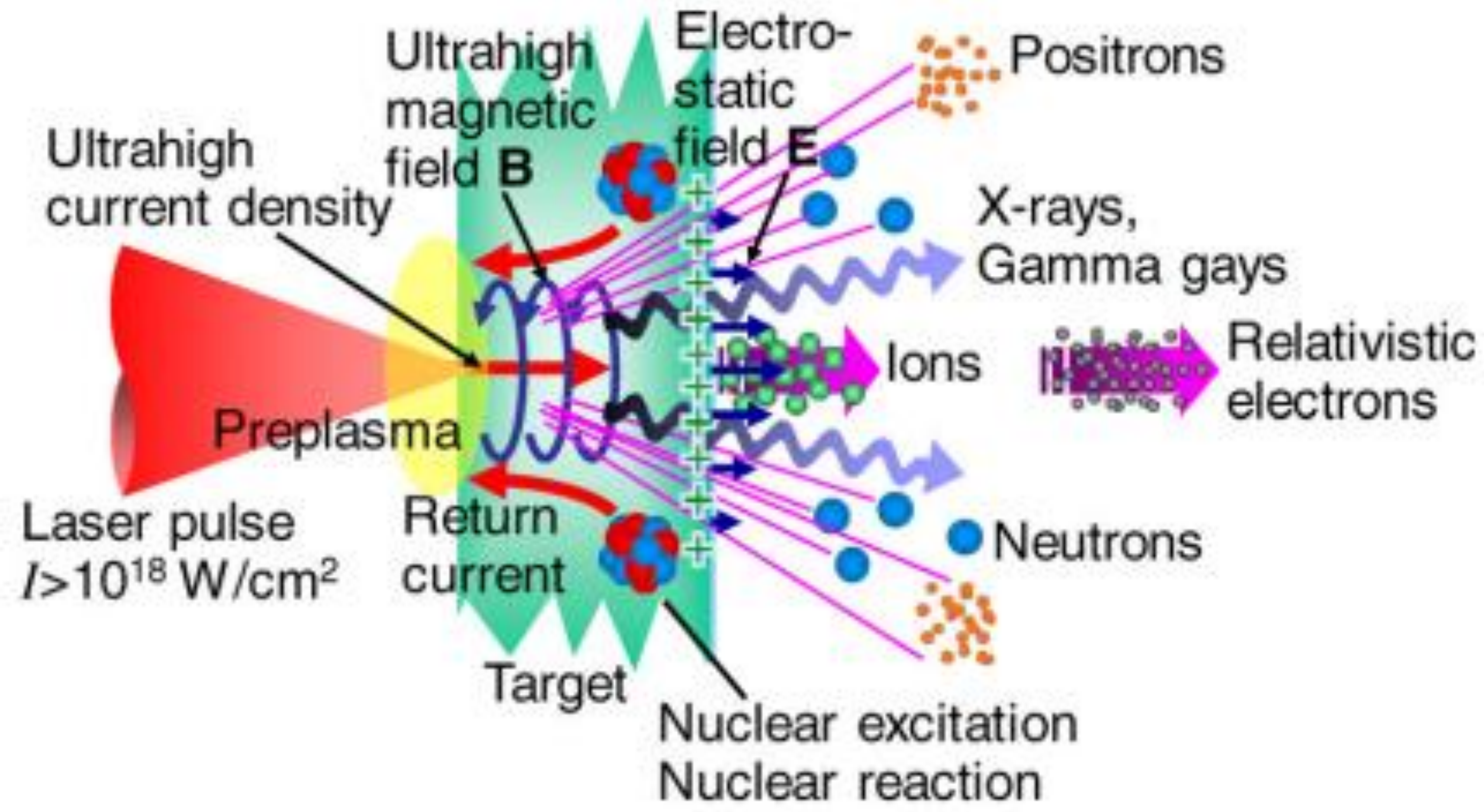
2. Experiment
- Facility
- Setup

3. Detector Detail
- What is Emulsion?

4. Analysis
- Event selection
- Result
- BG fit & true event calculation
- Flux calculation

5. Summary

Introduction(1/4) : Reactions in plasma induced by high-intensity lasers



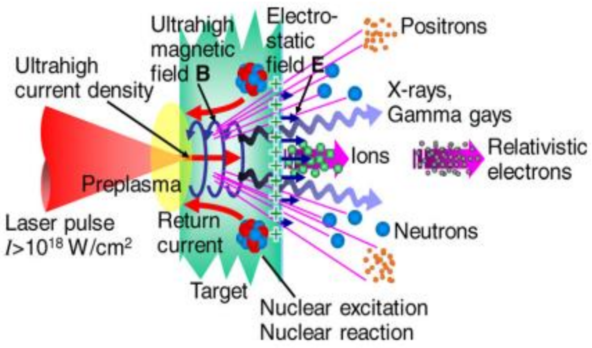
"Review of laser-driven ion sources and their applications "
Hiroyuki Daido, Mamiko Nishiuchi and Alexander S Pirozhkov

→ Diverse and complex phenomena are occurring

Introduction(2/4) : Nuclear Reactions in Laser Plasmas

Known facts：In

Focusing Intencity
$I = 10^{22}\ \mathrm{W/cm^2},\ E \approx 43.1\ \mathrm{MeV}$



Known facts：Out

Observation of electrons at the tens MeV

➢Nuclear reactions are expected to occur within the laser plasma

Why laser-driven nuclear reactions are significant

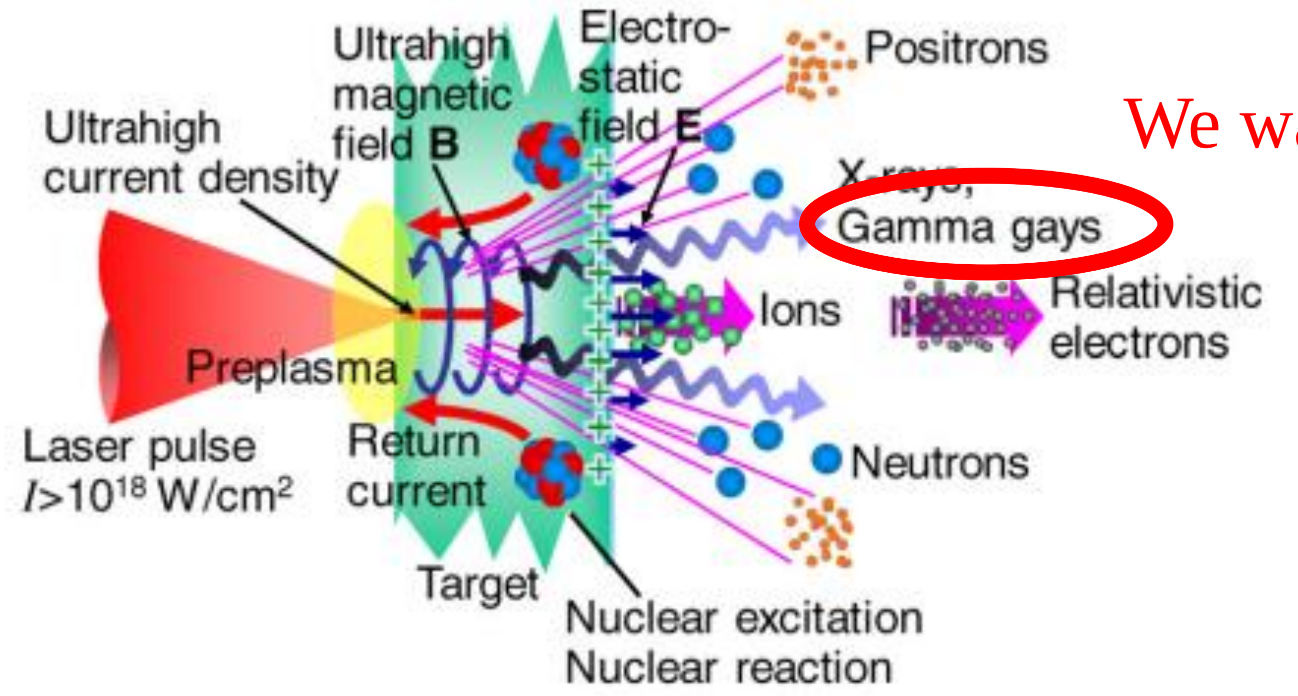
- A unique approach compared to accelerator-based experiments

Accelerator
Collide **high-energy** particle at **low-density** ⟷ Laser
Collide **low-energy** photons at **high-density**

- Observation of nuclear reactions in **ultra-high electromagnetic fields**

Introduction(3/4) : Our Goal

Goal： Clarify the mechanism of laser-driven nuclear reactions through precise analysis of γ-rays emitted from laser plasma.



We want to Measure!

Introduction(4/4) ：Challenges, Our approach

However, direct measurements of γ-rays emitted from laser plasma have not yet been achieved.

Challenges in γ-ray measurements

- **Signal pile-up** due to a lot of radiations emitted in an extremely short time
  $(10^7 \sim/cm^2)$ (~ ns)
- **Limited number of laser shots** per day, making it difficult to obtain sufficient statistics
- Shot-to-shot **variations** in laser characteristics

Our approach

- **Using nuclear emulsion :** A detector with **excellent spatial resolution**.
- **Record all radiation tracks** from a **single shot** without **pile-up**.

Precisely **detect** γ-rays in emulsion

⇒ Measure γ-ray **energy**, **direction**, and **flux** directly

Experiment (1/2): Facility

Kansai Photon Science Institute (KPSI)

Laser：J-KAREN-P

Wavelength：810 nm
Pulse energy：10 J
Pulse time length：30 fs
Focus size : ϕ= 1 µm
Focusing intensity：$10^{22} W/cm^2$
Repetition frequency：0.1 Hz

Experiment (1/2): Facility

Kansai Photon Science Institute , QST , Japan

Laser：J-KAREN-P

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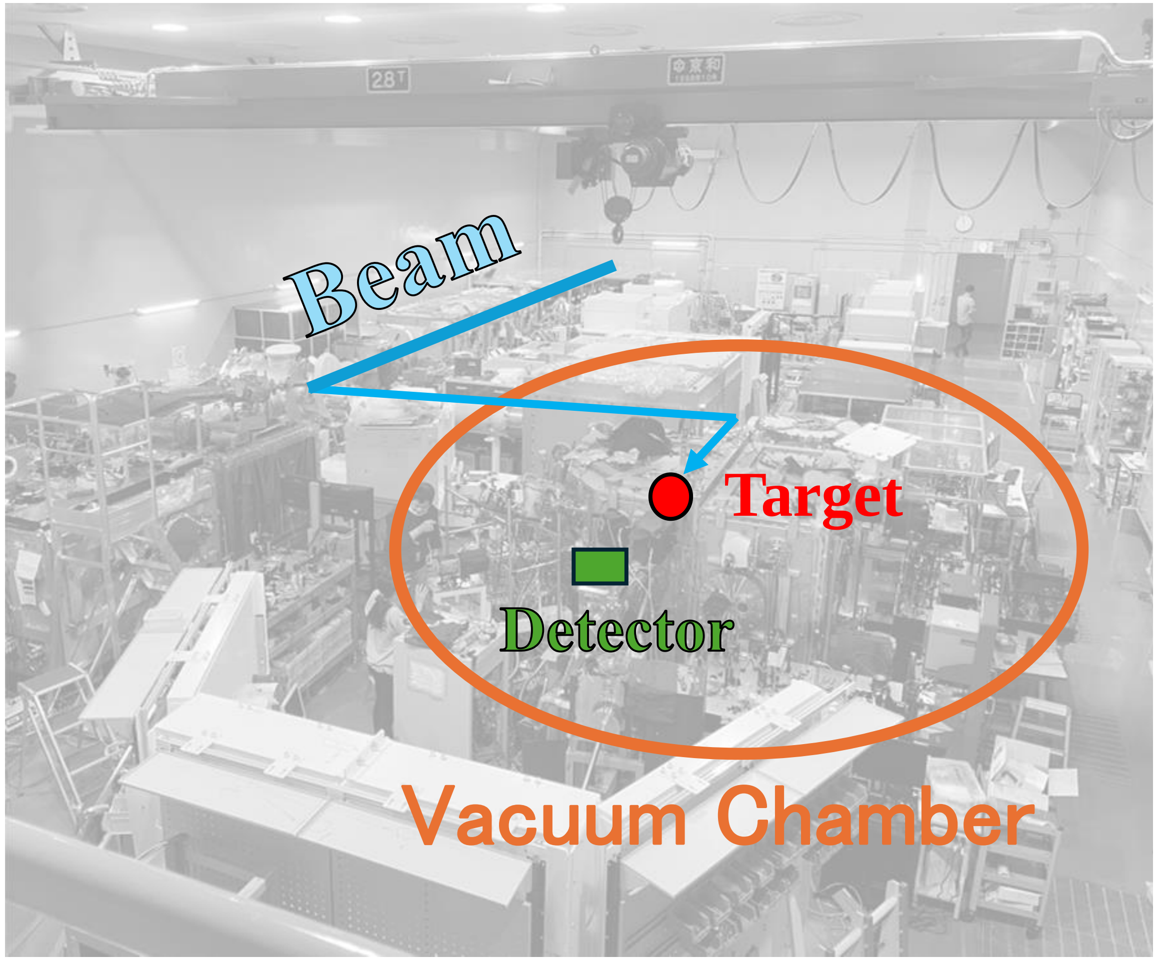


Experiment (2/2): Setup

Laser shot : 1 shot

Target : Ag 5μm

Detector : Emulsion Stack

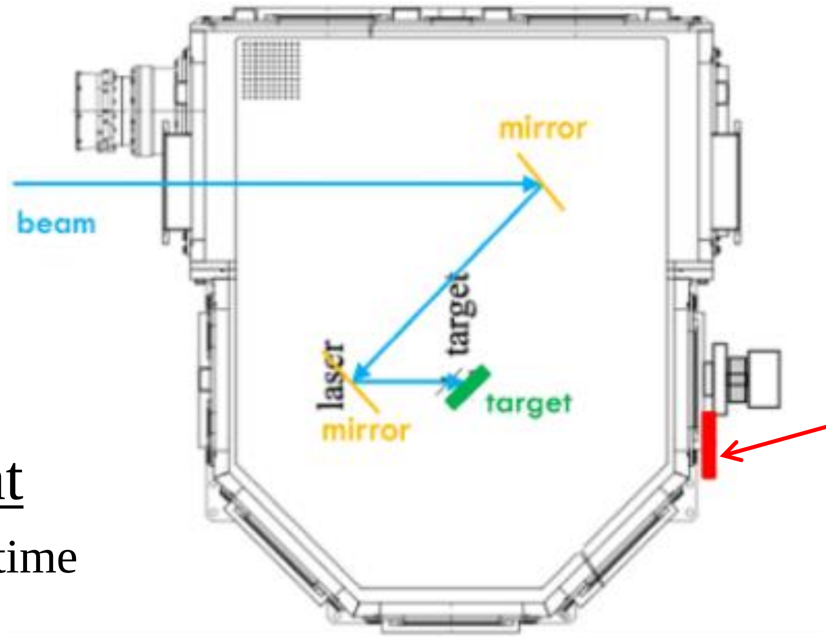
30 layers＋2 Changeable Seat

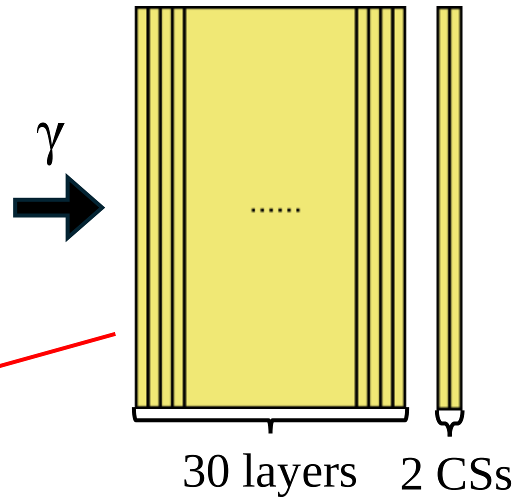
Put only experiment time

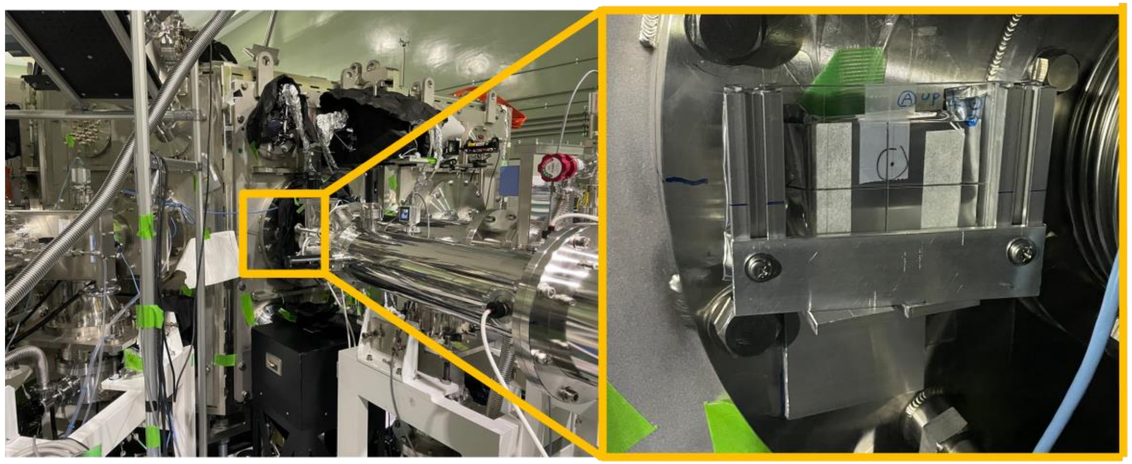
Size : 50 mm × 60 mm

Location : On the outer surface of the vacuum chamber (20 mm SUS wall),　positioned at 0°

Distance from target : 1023.9 mm



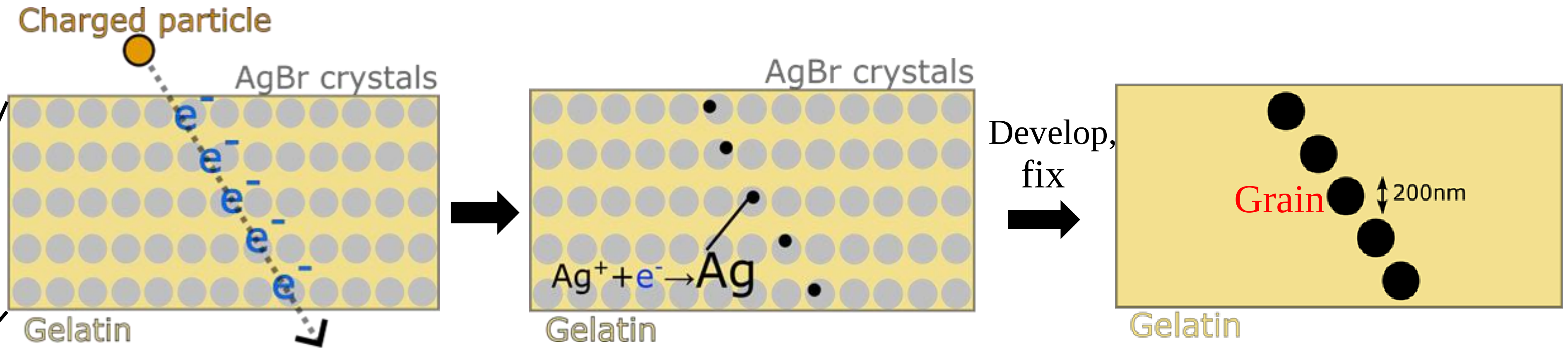


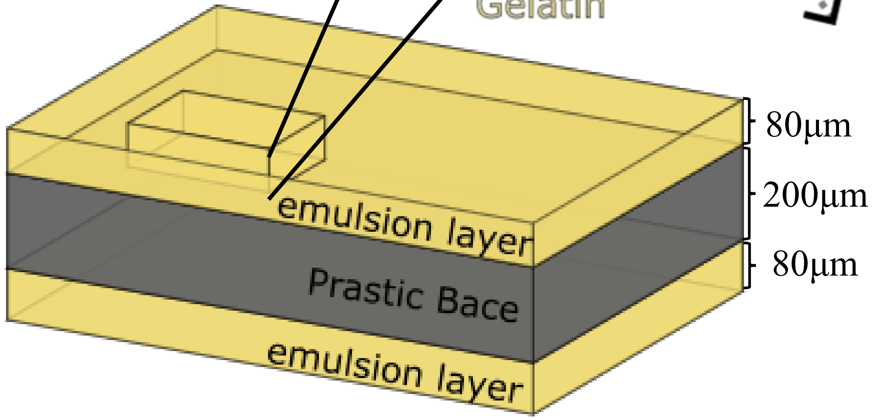


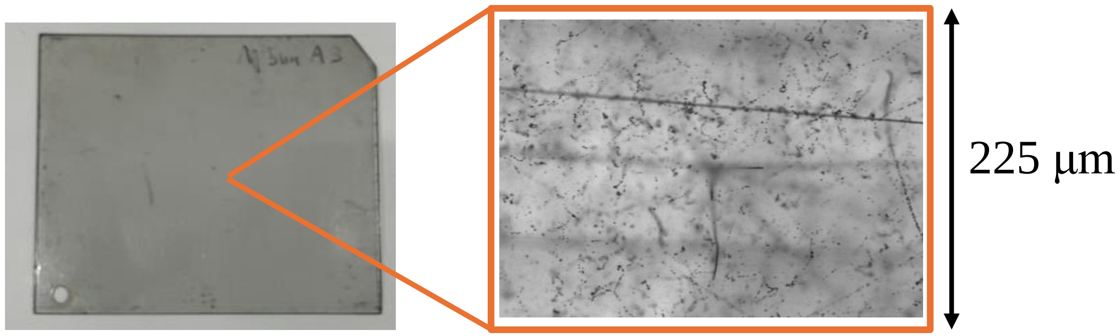
Detector Details : What is Nuclear Emulsion ?

Nuclear Emulsion： 3D Track Detector
that records charged-particle trajectories with **“high spatial resolution”**

High spatial resolution ：≈ 1 μm (The size of the AgBr crystals ：200 nm) , 10^{14}channels/cm^3
→ Can clearly separate individual tracks even in ultra-high radiation environments.



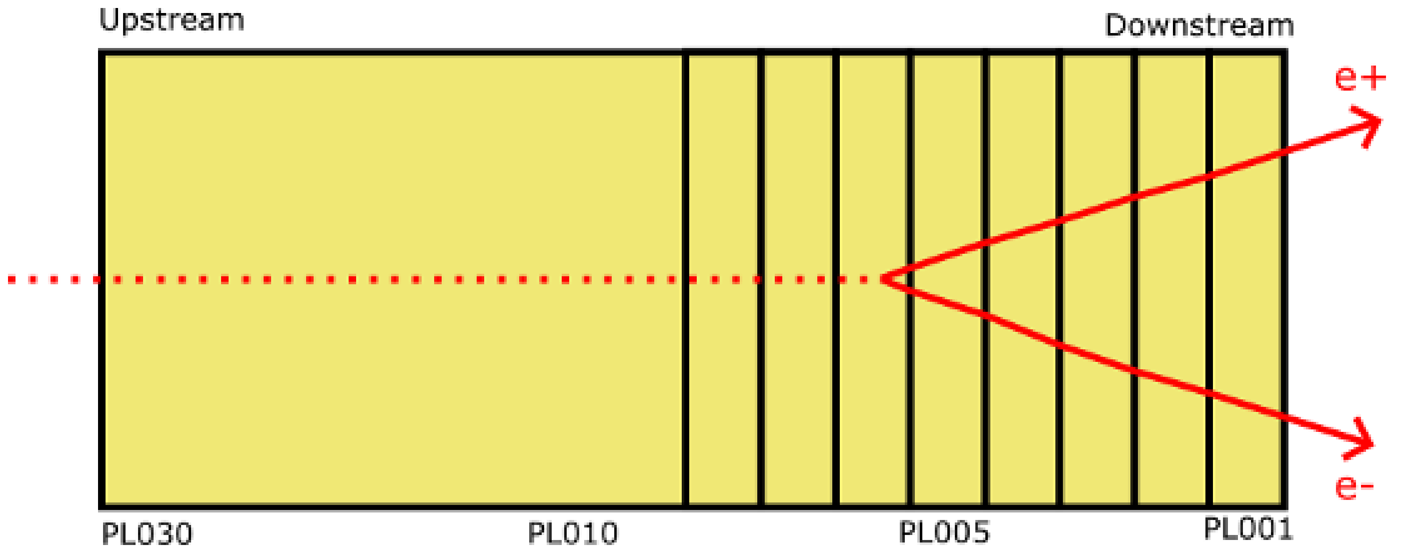




Real emulsion tracks

→Scan & digitized tracks

Analysis(1/4): Event selection

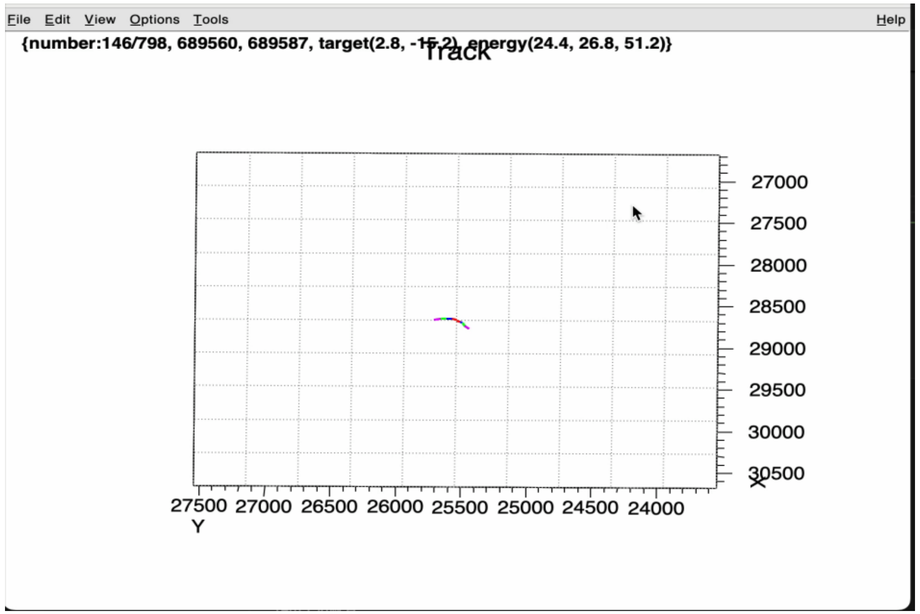


(1) No upstream tracks

(2) Track connected through 5 downstream layers

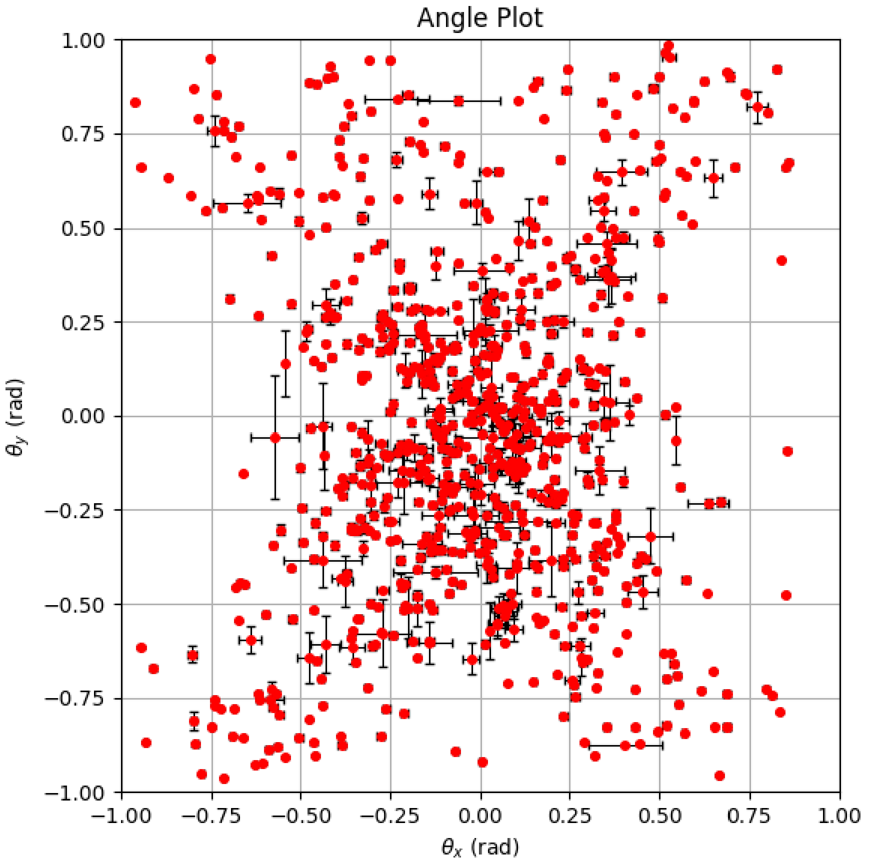
(3) There are pair tracks within 5 μm

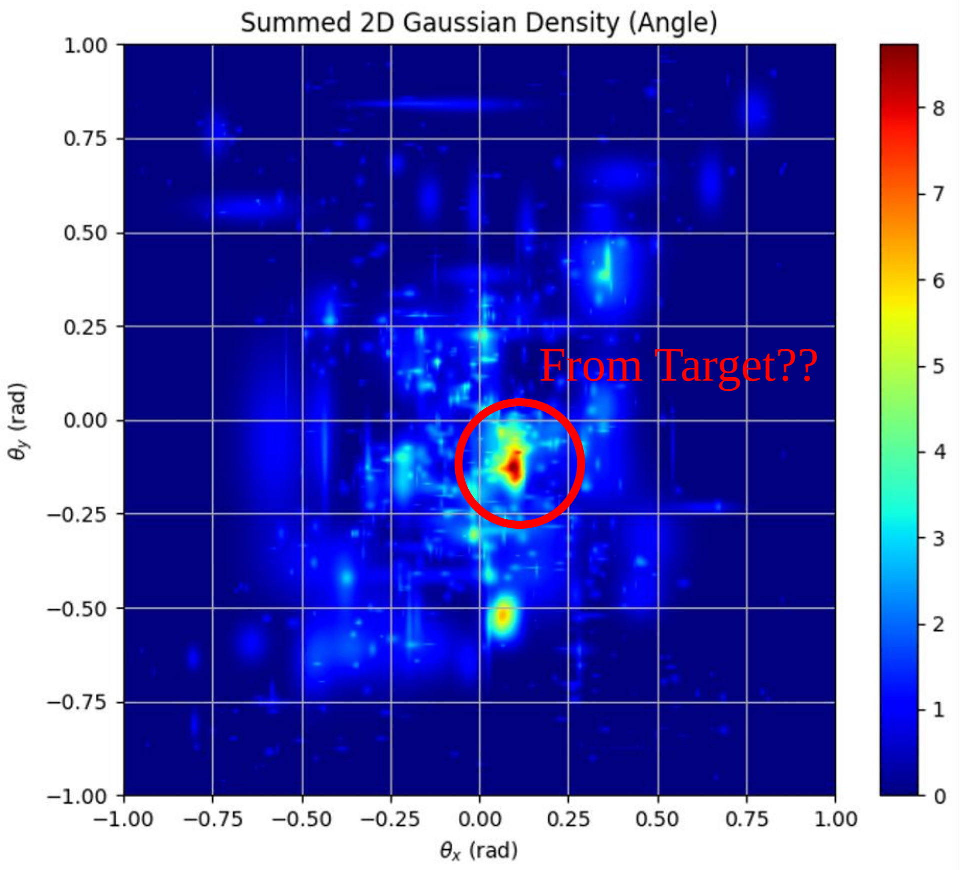
(4) The distance between the pair tracks is increasing



Analysis(2/4): Result (Angle)

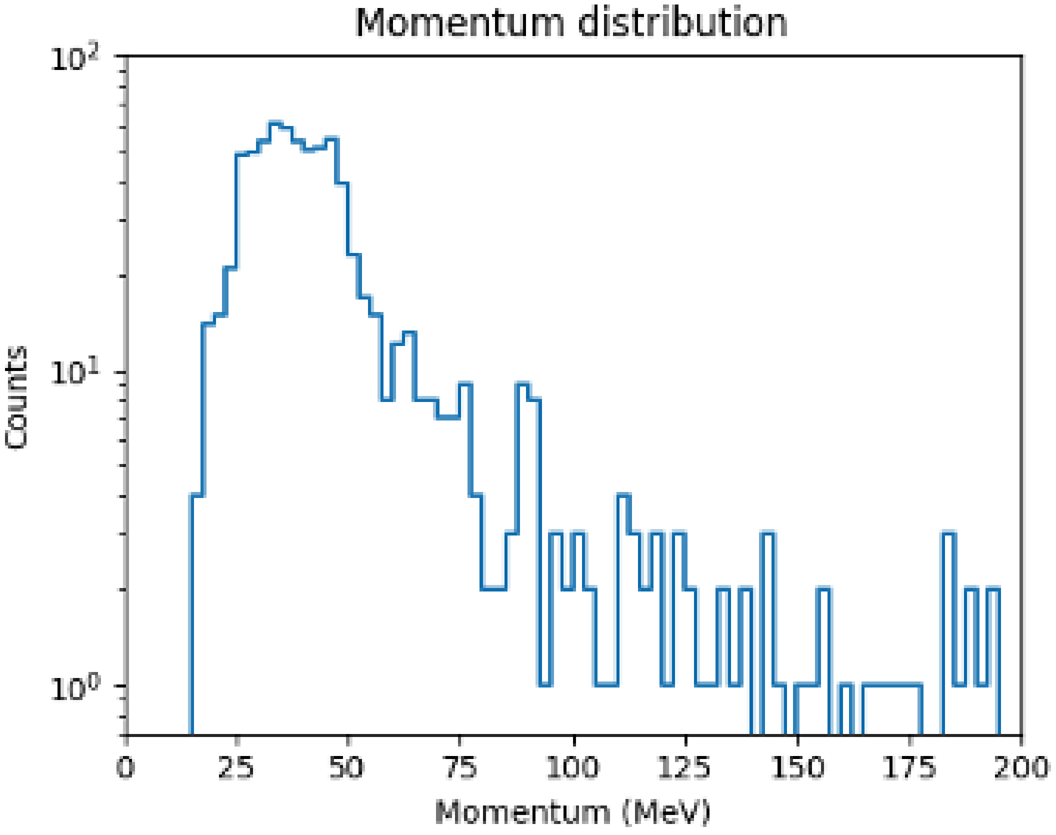
A total of 798 γ-ray events were identified



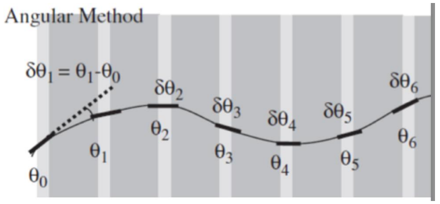


Observed a peak structure near the target direction in the angular distribution

Analysis(2/4): Result (Momentum)



Calculating method



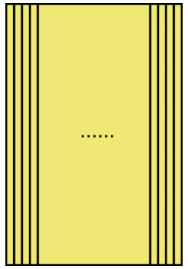
$$p = \frac{13.6\ \mathrm{MeV}}{\beta c\ \delta\theta_{rms}}\ z \sqrt{\frac{x}{X_0}}\left[1 + 0.038\ \ln\left(\frac{xz^2}{X_0\beta}\right)\right]$$

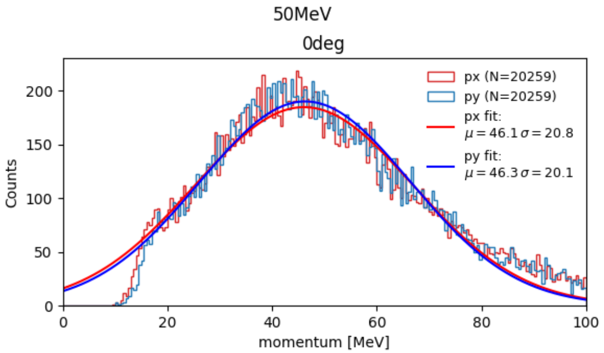
- Observe gamma rays in the tens of MeV range
- As the energy increased, they disappeared rapidly

Calibration search

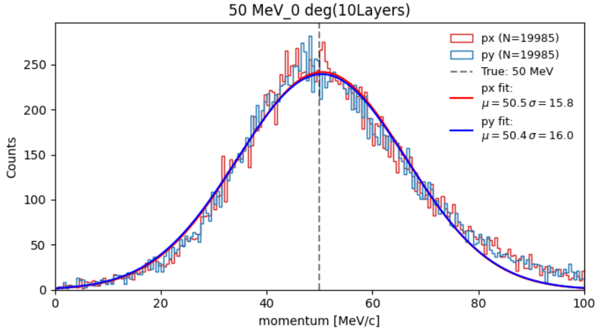
Constant momentum electrons

Emulsion stack





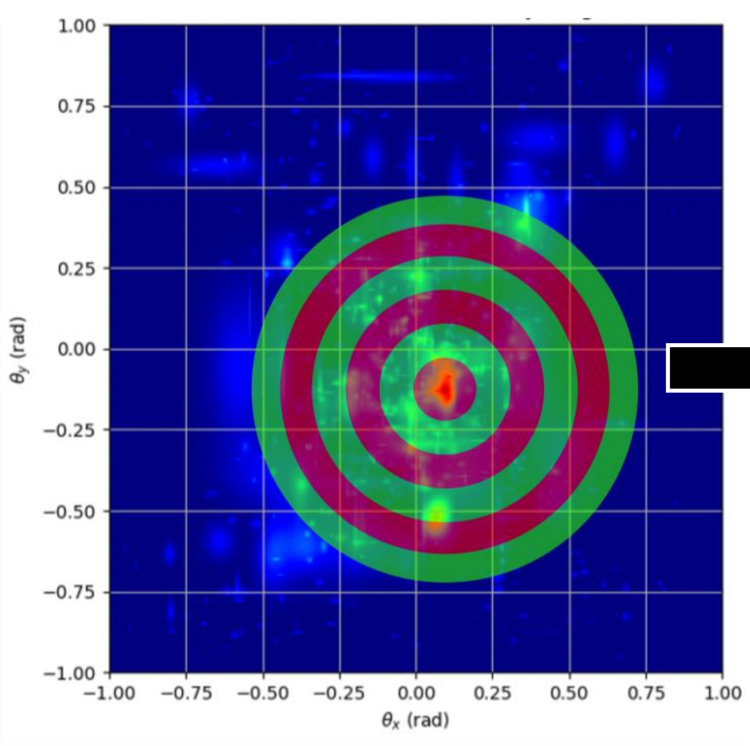
Experimental data

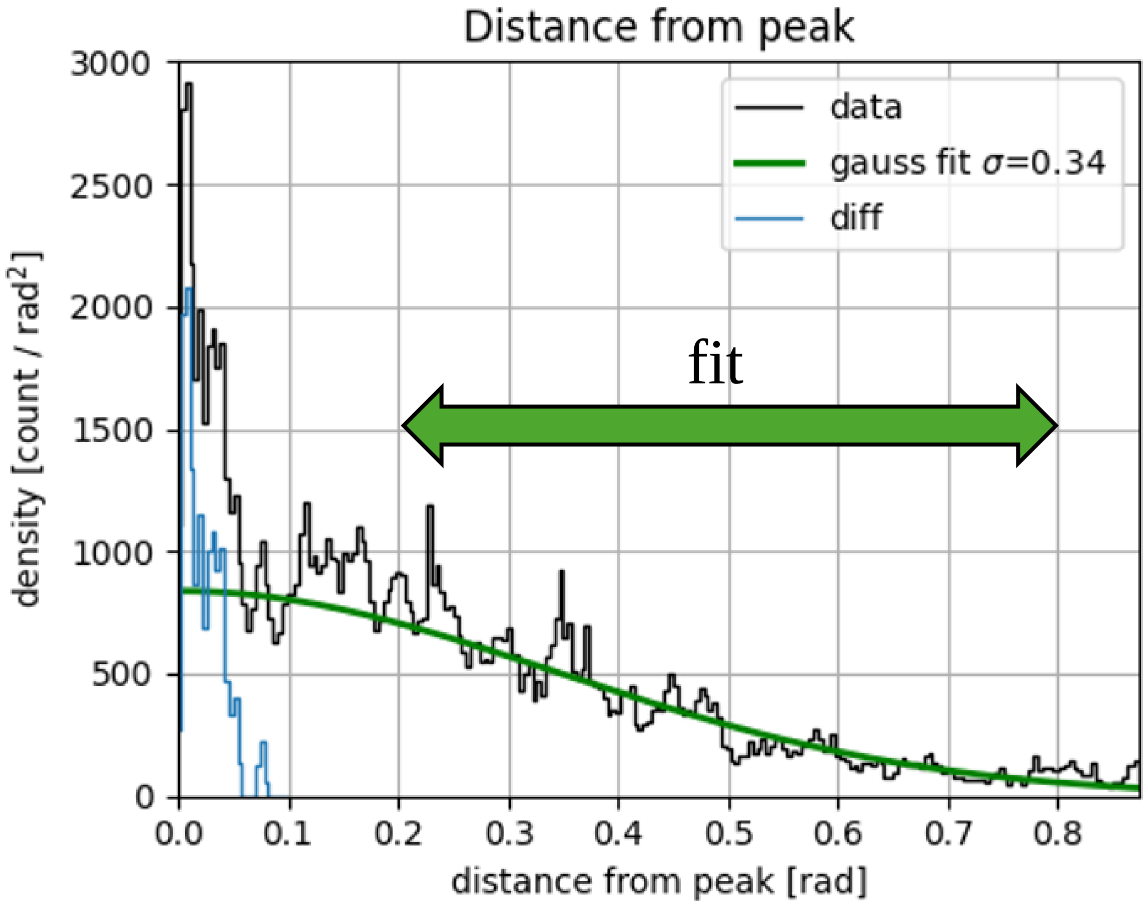


Simulation data

Analysis(3/4): BG fit & true event calculation

Fit the background assuming a Gaussian distribution





True event = 8.90 ± 2.98 [count]

Analysis(4/4): Flux calculation

The γ-ray flux Φ from the target,
assuming that γ-rays are emitted isotropically from the target

$$\Phi = \frac{Event}{\epsilon \times P_{AgBr} \times S \times n}$$

$$\approx 4.68 \times 10^{7} \pm 1.5 \times 10^{7}\ [\mathrm{counts/(sr \cdot shot)}]$$

$Event$: Number of true event (8.899 ± 2.98 count)

ϵ : The probability of a track being recorded through 5 emulsion layers (0.86^{5*2})

P_{AgBr} : Probability of $e^{+}e^{-}$pair production within 4 emulsion layers (4.5×10^{-4})

S : Area of the γ-ray search region on the emulsion ($20cm^2$ ÷ (102.39 cm)^2 [sr])

n : Number of laser shots (1 shot)

Summary , Future Works

- Aiming for direct measurement of γ-rays from laser-produced plasma using emulsion.

- Conducted experiments using J-KAREN-P and successfully observed 798 γ-rays events.

- The γ-ray flux per laser shot for the Ag 5 μm target was $4.68 \times 10^{7} \pm 1.6 \times 10^{7}$ [count/ sr · shot].

Future Works

・Evaluate the validity of the observed flux through comparisons with simulations.

Detector Details (2/2) : How to get particle tracks

Scanning device ： HTS-2 (Hyper-track selector 2)

The world's fastest emulsion scanning device (F Lab ,Nagoya University)

How to scan

- Capture a series of images while shifting the focal plane through the emulsion depth

⇩

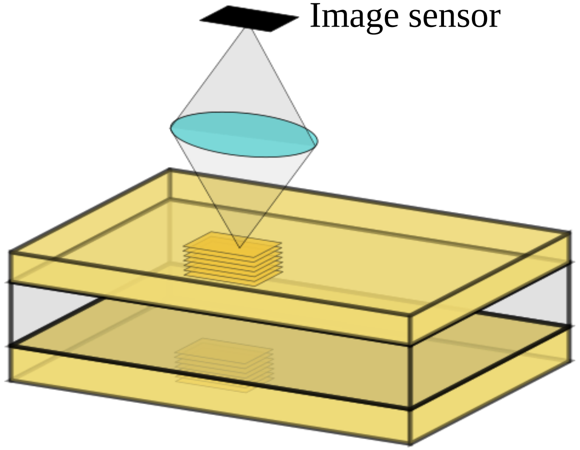
- Obtain positions(x,y,z) of Grains (silver crystals) through binarization

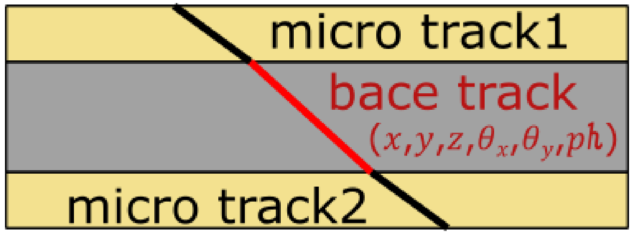
⇩

- Link Grains to create microtracks

⇩

- Connect the two microtracks (front and back) to form a **base track**



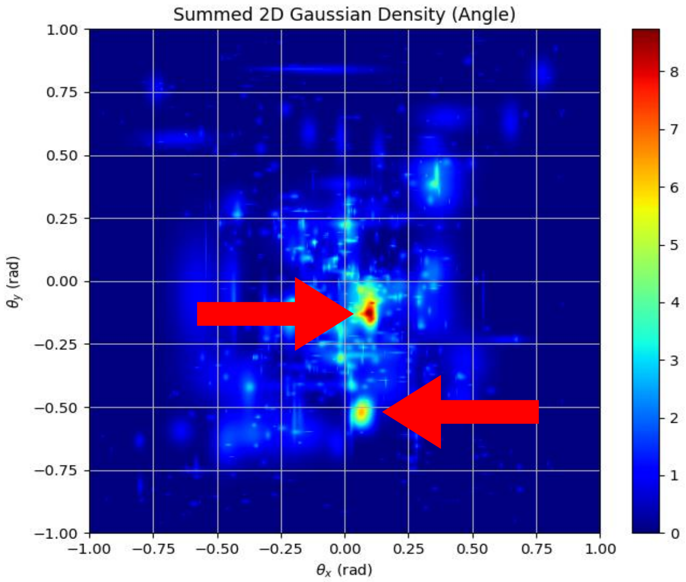


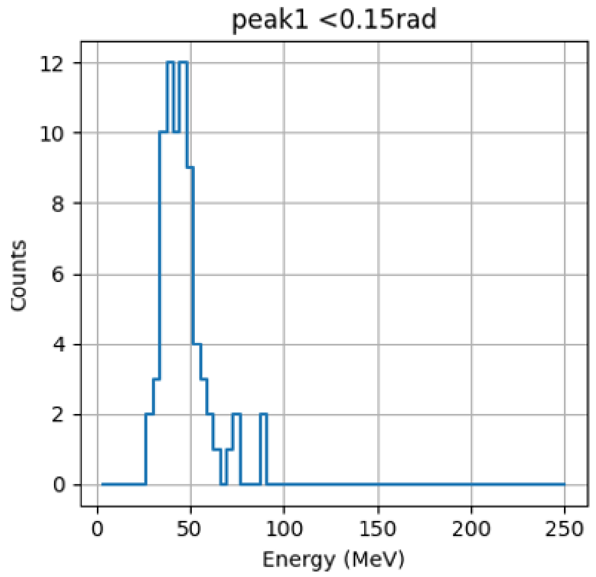
The **base track** contains information such as **position**, **angle**, and **pulse height**.

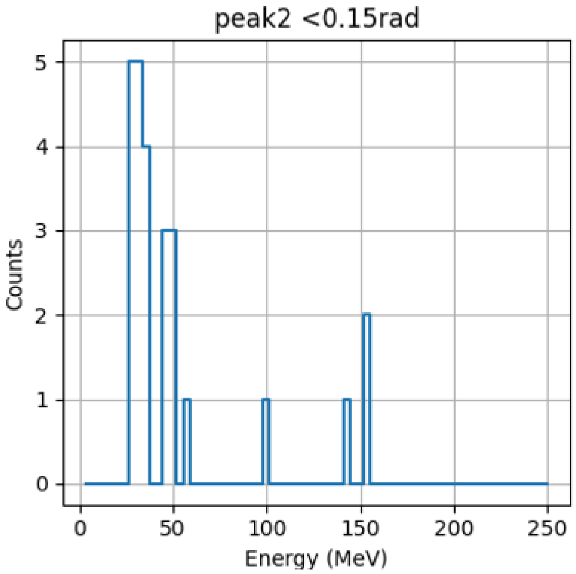
how many Grains are connected

Connecting **30 base tracks** (30 emulsion layers), we can reconstruct **3D particle trajectories**.

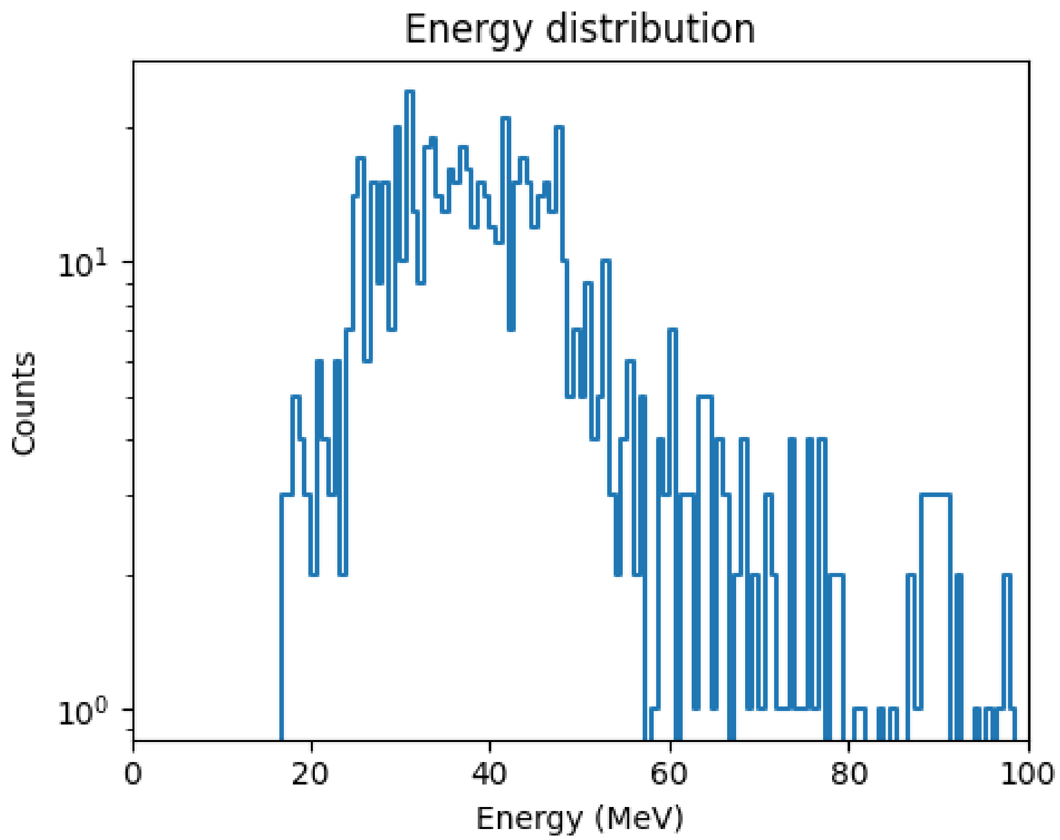
Experiment in 2021

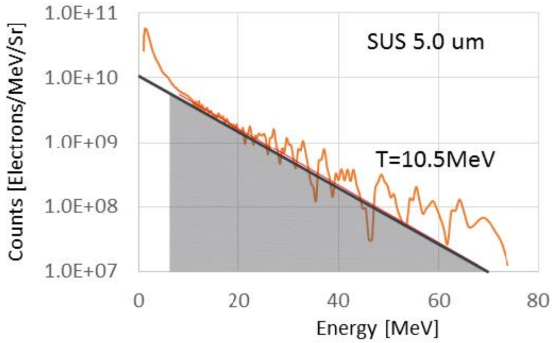






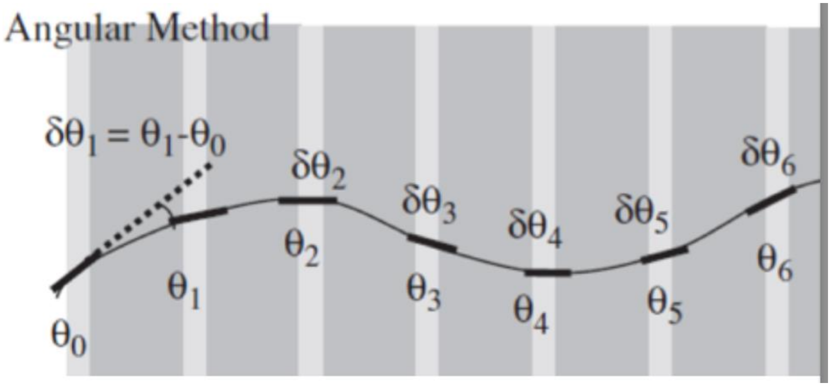
Analysis(2/4): Result (Energy)





キャリブレーション実験(3/4)：角度ずれを利用した運動量計算

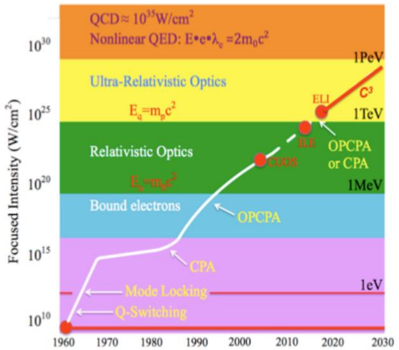
Trackにはレイヤーをまたぐときの角度ずれが記録されている



1 trackにおける$\delta\theta$のRMSを計算することでそのtrackの運動量が計算できる

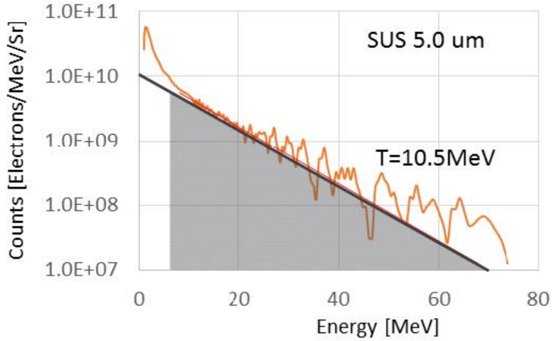
$$p = \frac{13.6\ \mathrm{MeV}}{\beta c\ \delta\theta_{rms}}\ z\sqrt{\frac{x}{X_0}}\left[1 + 0.038\ \ln\left(\frac{xz^2}{X_0\beta}\right)\right]$$

β：飛跡の速度 $\cong 1$， z：荷電粒子の電荷，
X_0：散乱体の放射長 $= 3.35\ cm$，x：散乱体1つの厚み$= 70 \times 2\ \mu m$



Exawatt-Zettawatt pulse generation and applications

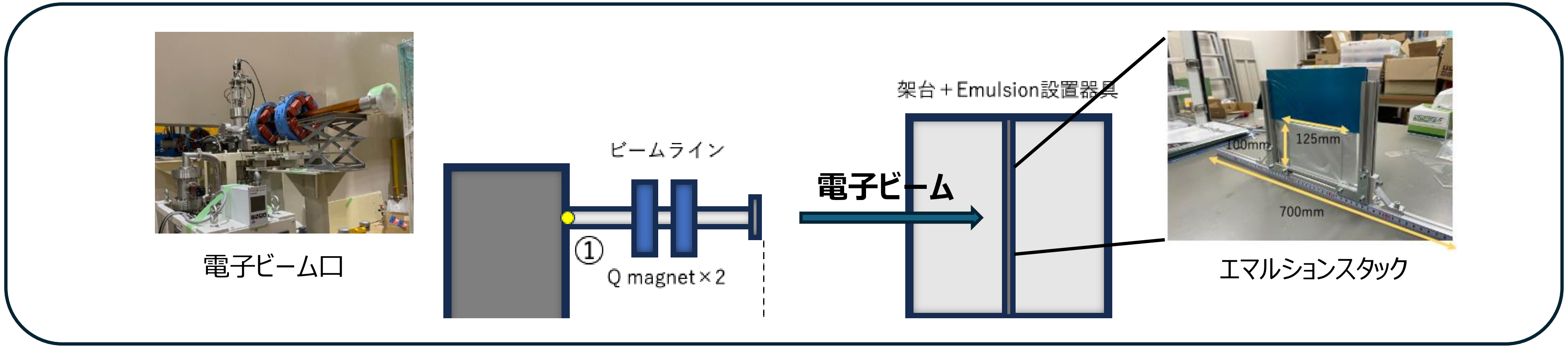
G.A. Mourou , N.J. Fisch , V.M. Malkin , Z. Toroker , E.A. Khazanov , A.M. Sergeev , T. Tajima , B. Le Garrec



キャリブレーション実験(1/4)：実験セットアップ

プラズマから発生するγ線は数十MeV
数十MeVという低エネルギー領域では検出効率や運動量分解能が著しく劣化する可能性がある

→一定エネルギーの電子を入射させてefficiencyと運動量分解能を決定する

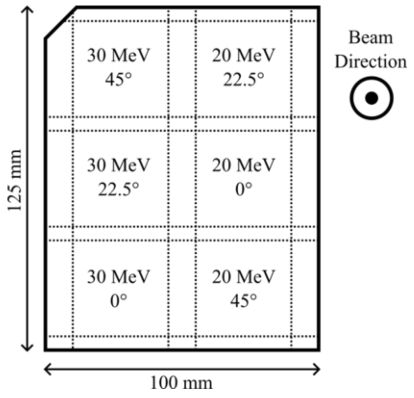


Facility：線形加速器 (KAKEN,KyotoUni)

20,30,40,50 MeVの電子ビームを0,22.5deg,45degに傾けたエマルションに照射

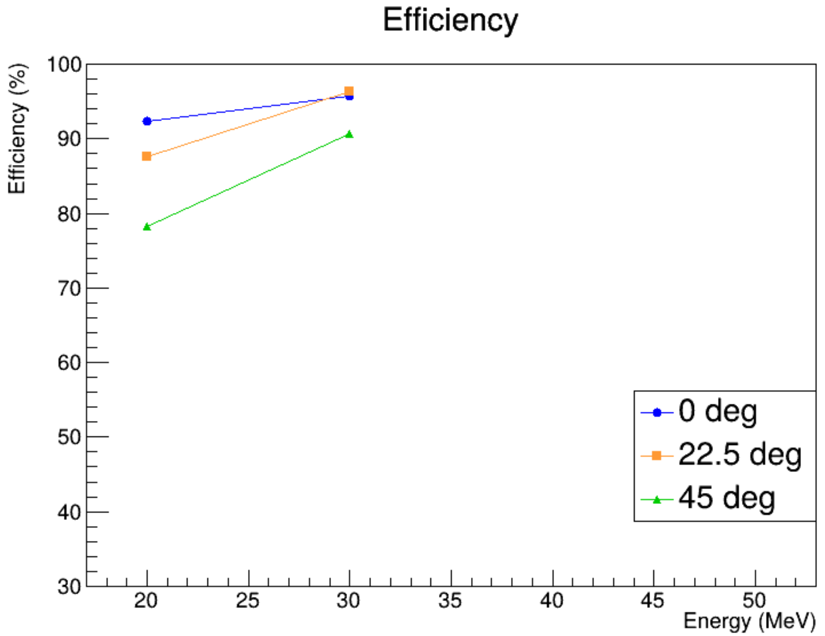
Emulsion stack：100 mm × 125 mm × 16 layers × 2 stack

→ 35 mm四方の範囲で６つに区分けして使う



キャリブレーション実験(2/4)：Calculate efficiency

$$\mathrm{Efficiency}_{(i\ \mathrm{th\ layer})} = \frac{(i-1), i, (i+1)\text{のすべてで繋がったトラック数}}{(i-1), (i+1)\text{で繋がったトラック数}}$$



それぞれの角度・エネルギーで上流2枚目のefficiencyの計算を行った

0degではスキャン装置の故障により正確な値が出なかった

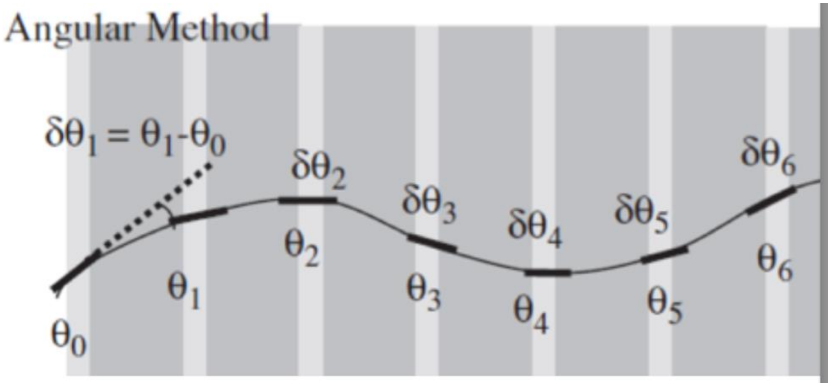
→エネルギーが小さいほど、角度がきついほど
efficiencyは低くなる傾向がある

→低エネルギーの粒子が斜めに入射すると電磁散乱によってトラックが曲がりすぎて飛跡検出がうまく行われない可能性がある

→フィットして関数を作る（40,50MeVがまだ．．．）

キャリブレーション実験(3/4)：角度ずれを利用した運動量計算

Trackにはレイヤーをまたぐときの角度ずれが記録されている



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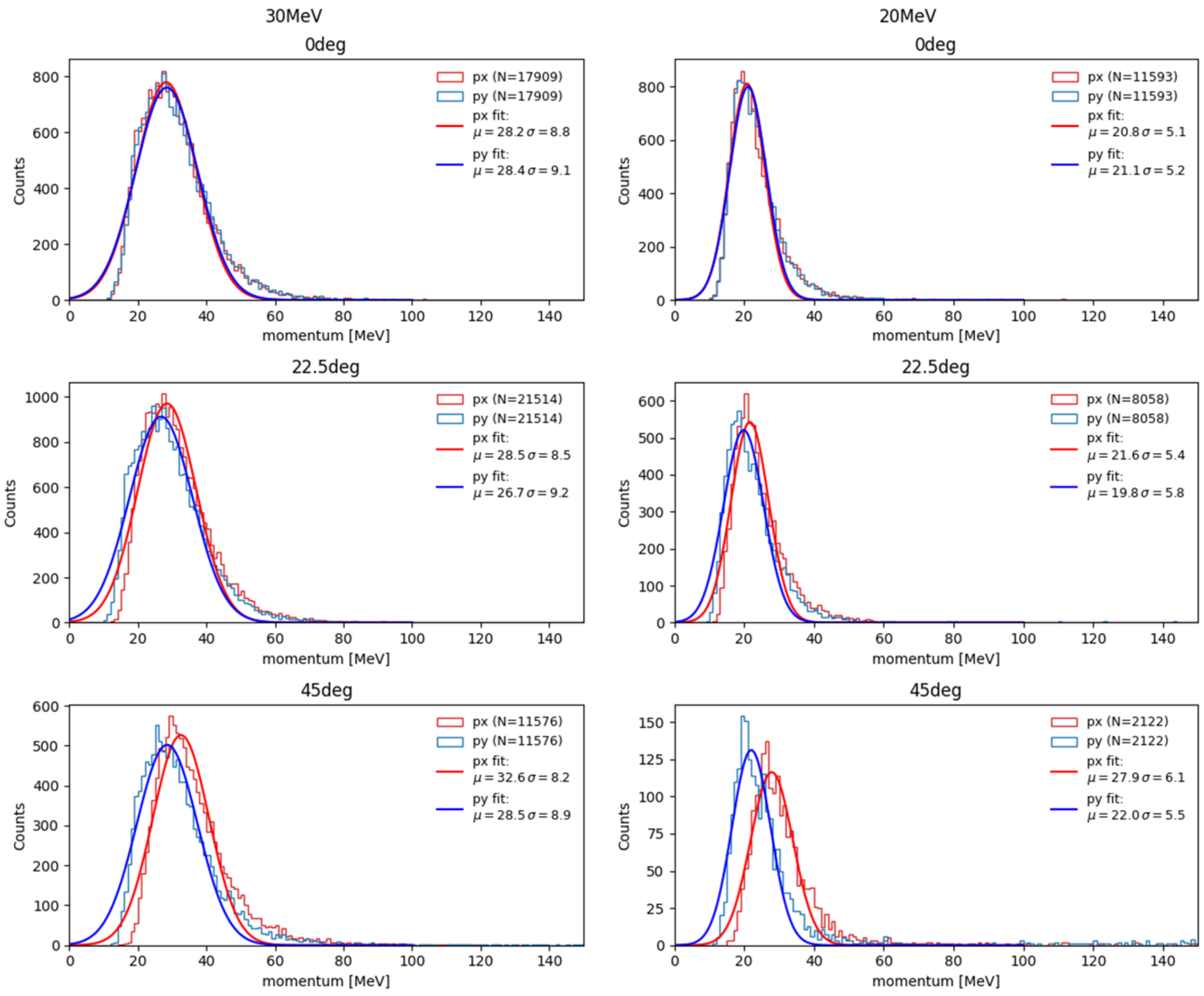
キャリブレーション実験(4/4)：角度ずれを利用した運動量計算



20,30MeVの入射ビームに対しての運動量分解能をx,y方向で計算した

入射ビームの運動量のばらつきは十分に小さい

入射角度が大きくなると同じはずのx,y方向の分布が異なってくる

→考慮できていない誤差の可能性

0deg入射においては

$\Delta p/p \approx 0.25$ほどであった

→40MeV,50MeVでも解析を進める

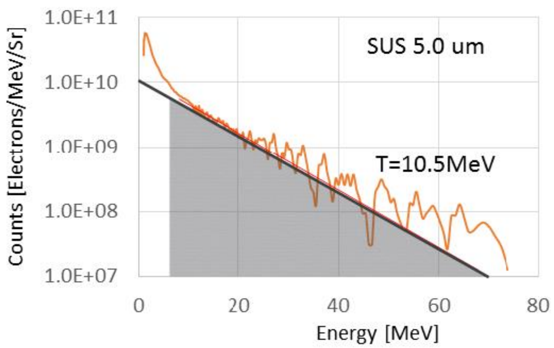
→0degでエネルギーにフィットした関数を作る

45degとかはおかしくなるのできる

Calibration experiment

- プラズマから発生するγ線は数十MeV
- Emulsionは高エネルギーの観測で使われるためこの領域の性能がわからない

→一定エネルギーの電子を入射させてefficiencyと運動量分解能を測定する必要がある



入射粒子： 20,30,40,50 MeVの電子ビーム by linac(KAKEN,Kyoto,JAPAN)

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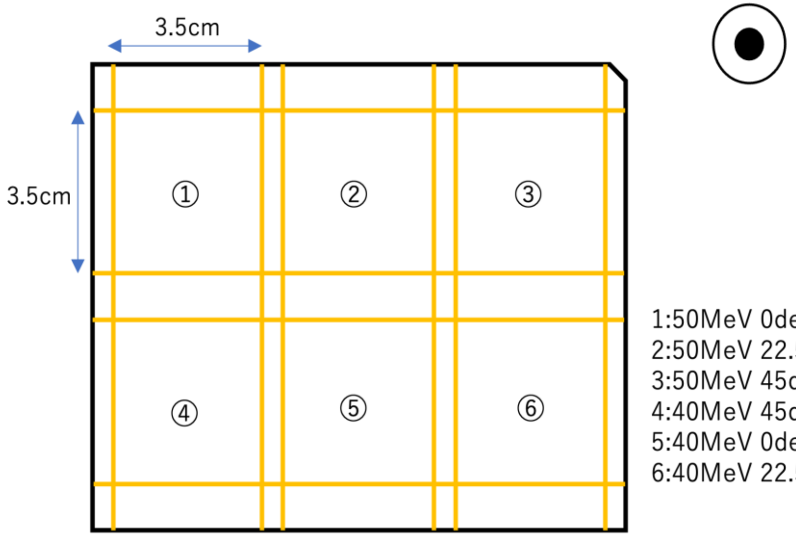
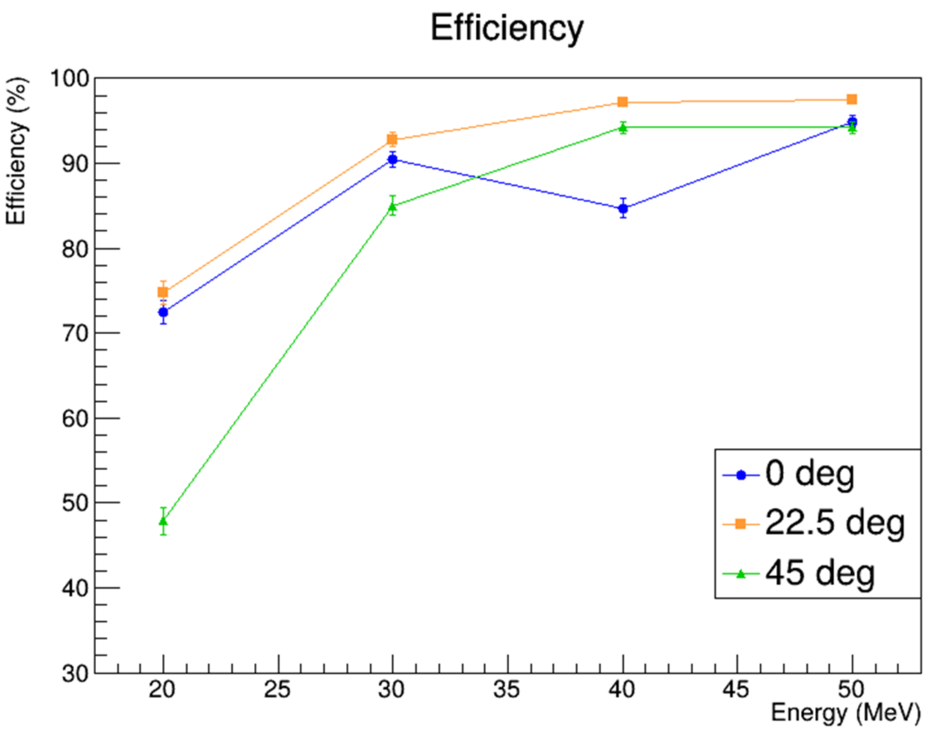
→ 35 mm四方の範囲で６つに区分けして使う



Emulsion stackを２つ使用して0,22.5deg,45degに傾けた各エネルギーの電子ビームを計12区画に照射する

Calculate efficiency

$$\mathrm{Efficiency}_{(i\ \mathrm{th\ layer})} = \frac{\text{Number of linked tracks between the } (i-1), \mathrm{i}, \text{and} (i+1) \text{ layers}}{\text{Number of linked tracks between the } (i-1) \text{ and } (i+1) \text{ layers}}$$



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Abstract

・Laserプラズマ由来のγ線の直接測定を目指している

・位置分解能に優れたemulsionを使用するアプローチをとっている

・QSTのペタワットレーザーを使用して実験を行った

→emulsionのスキャンを行おうとしている

Abstract

・We aim to direct measure of γ-rays from laser-produced plasmas.

・We take an approach using **nuclear emulsion detectors**

・Conducted experiments using the **PW laser system at QST**

→Now working on **emulsion scanning and data analysis**

Why detection of γ-ray from laser plasma?

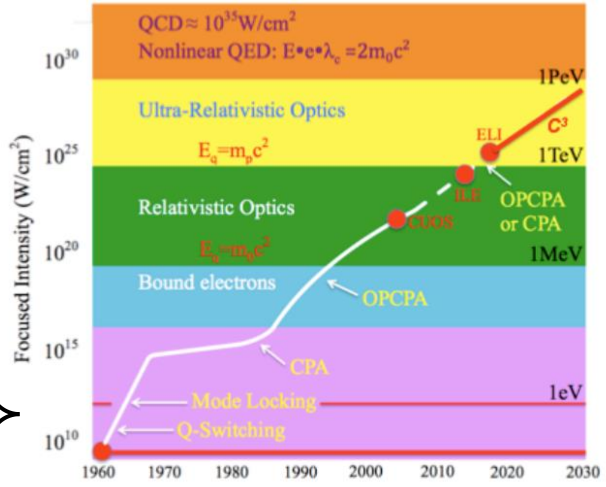
Achievable focusing intensity of laser is increasing

→ Nuclear reactions may occur in the laser plasma!

Why laser-driven nuclear reactions are significant

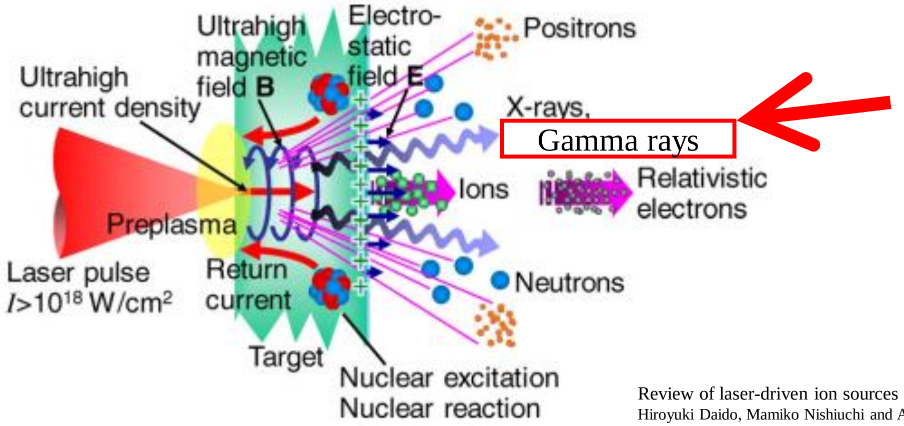
・Potential to discover new physics by observing nuclear reactions in ultra-high electromagnetic field environments

Accelerator		Laser
Collide **high-energy** particle at **low-density**	⟷	Collide **low-energy** photons at **high-density**



Exawatt-Zettawatt pulse generation and applications
G.A. Mourou , N.J. Fisch , V.M. Malkin , Z. Toroker , E.A. Khazanov , A.M. Sergeev , T. Tajima , B. Le Garrec

Goal： Clarify the structure of laser-driven nuclear reactions through precise analysis of γ-rays emitted from laser plasma.



Review of laser-driven ion sources and their applications
Hiroyuki Daido, Mamiko Nishiuchi and Alexander S Pirozhkov

Why use nuclear emulsion?

However, direct measurements of γ-rays emitted from laser plasma have not yet been achieved.

Challenges in γ-ray measurements

- **Signal pile-up** due to a lot of radiations emitted in an extremely short time
- **Limited number of laser shots** per day, making it difficult to obtain sufficient statistics
- Shot-to-shot **variations** in laser characteristics

Our approach

- **Use nuclear emulsion** ,to record a lot of radiations **without pile-up**
- Furthermore, it can simultaneously detect particles at various positions in a **single laser shot**.

Precisely **detect electron–positron pairs** produced by γ-rays in emulsion

⇒ Measure γ-ray **energy**, **direction**, and **flux** directly

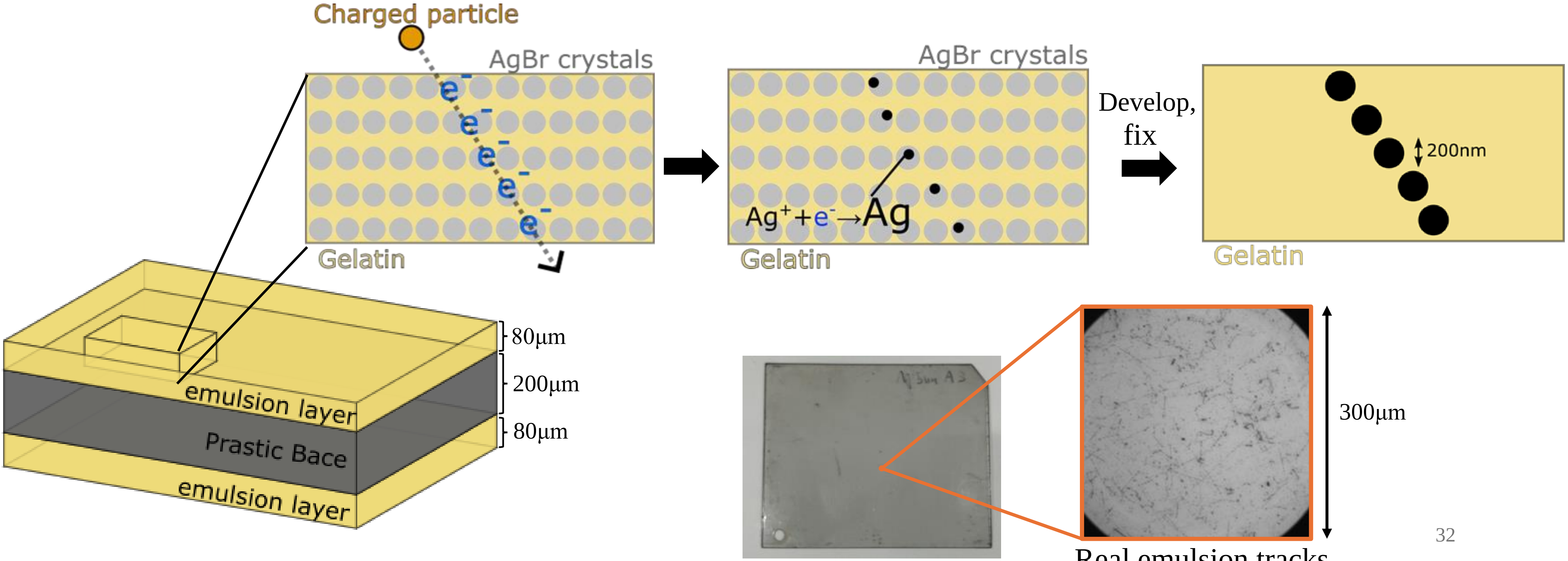
What is nuclear emulsion?

Nuclear Emulsion：A type of photographic film、used for particle measurement a long time

Strong Point

・Ultra-high spatial resolution：≈200 nm (The size of the AgBr crystals)

→ Can clearly separate individual tracks even in ultra-high radiation environments.



Real emulsion tracks

Emulsion scan in NAGOYA UNIVERSITY

The emulsion must be scanned and digitized for analysis.

Scanning device：HTS-2(Hyper-track selector nuclear emulsion readout system 2)

The world‘s fastest emulsion scanning device (F Lab ,Nagoya University)

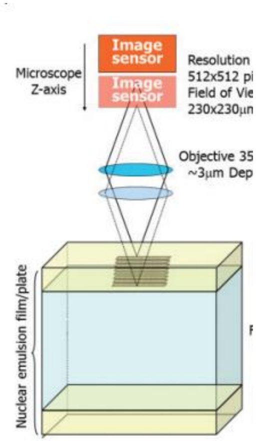
ピントの合う位置を深さ方向に変えながらエマルションを撮影

2値化によってGRAIN (銀の粒)を取得

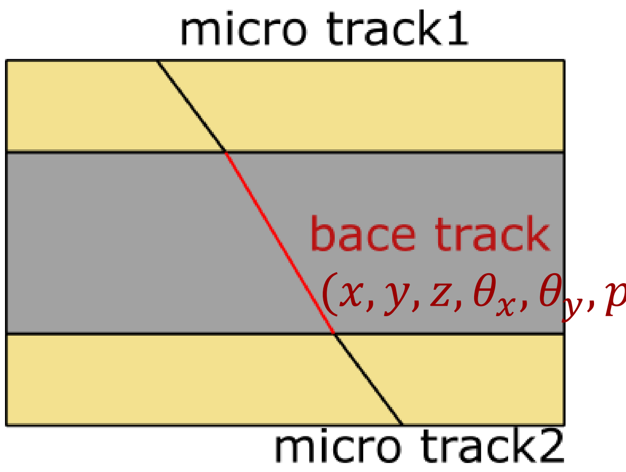
GRAINをつなぎ合わせマイクロトラックを作る

エマルションの表裏二つのマイクロトラックをつなぎ合わせてベーストラックを生成する

ベーストラックには位置、角度、パルスハイト（何個のGrainがつながっているか）といった情報が入っている



Hyper-track selector nuclear emulsion readout system aimed at scanning an area of one thousand square meters
Masahiro Yoshimoto1,2,∗, Toshiyuki Nakano1 , Ryosuke Komatani1 , and Hiroaki Kawahara



→base trackをトラックの基本単位としてエマルションを重ねることで粒子の軌跡の変化を追える

→このようにデータ化したトラックにアルゴリズムでカットをかける事で目的のトラックのみを選び出す

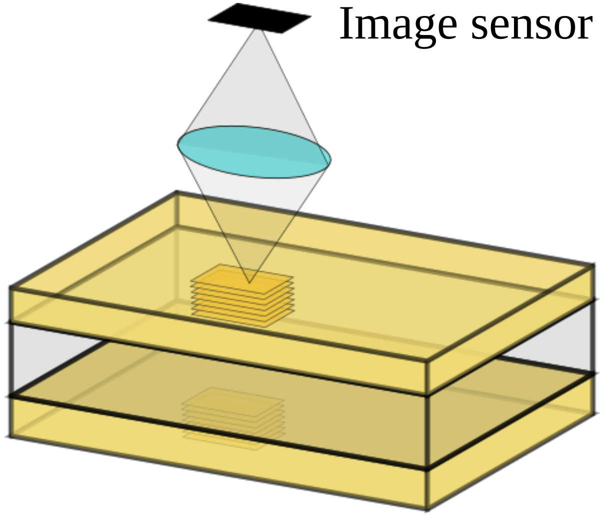
Emulsion scan in NAGOYA UNIVERSITY

The emulsion must be scanned and digitized for analysis.

Scanning device：HTS-2 (Hyper-track selector 2)

The world‘s fastest emulsion scanning device (F Lab ,Nagoya University)

How to scan



- ・Capture a series of images while shifting the focal plane through the emulsion depth

⇩

- ・Obtain GRAINs (silver crystals) through binarization

⇩

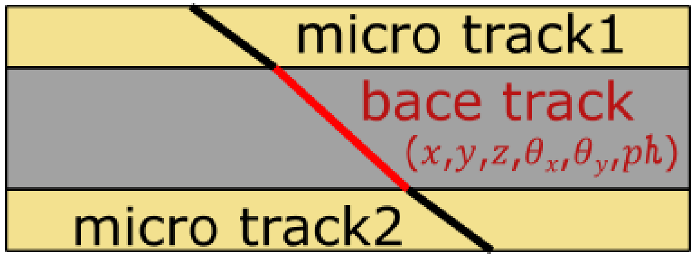
- ・Link GRAINs to create **microtracks**

⇩

- ・Connect the two **microtracks** (front and back) to form a **base track**

The **base track** contains information such as position, angle, and pulse height.

pulse height: how many GRAINs are connected



Stacking multiple emulsion layers and connecting base tracks,
we can reconstruct **3D particle trajectories**.

→By applying cuts to the digitized tracks, we extract only the desired particle tracks.

Summary, Future works

Summary

・We aim to **directly measure γ-rays** generated from laser-produced plasmas.

・We employ **nuclear emulsion detectors** with high spatial resolution to overcome pile-up and track identification challenges.

Future works

・Scan the emulsions used in the experiment to identify **electron–positron pair production events**

・Calibrate the **efficiency** and **momentum resolution** for low-momentum electrons

→ Improve the precision of γ-ray **energy** and **flux** measurements