Energy Scale Calibration of UHECR for the TA Experiment with ELS

BK Shin

2015/Dec/11th

Keywords

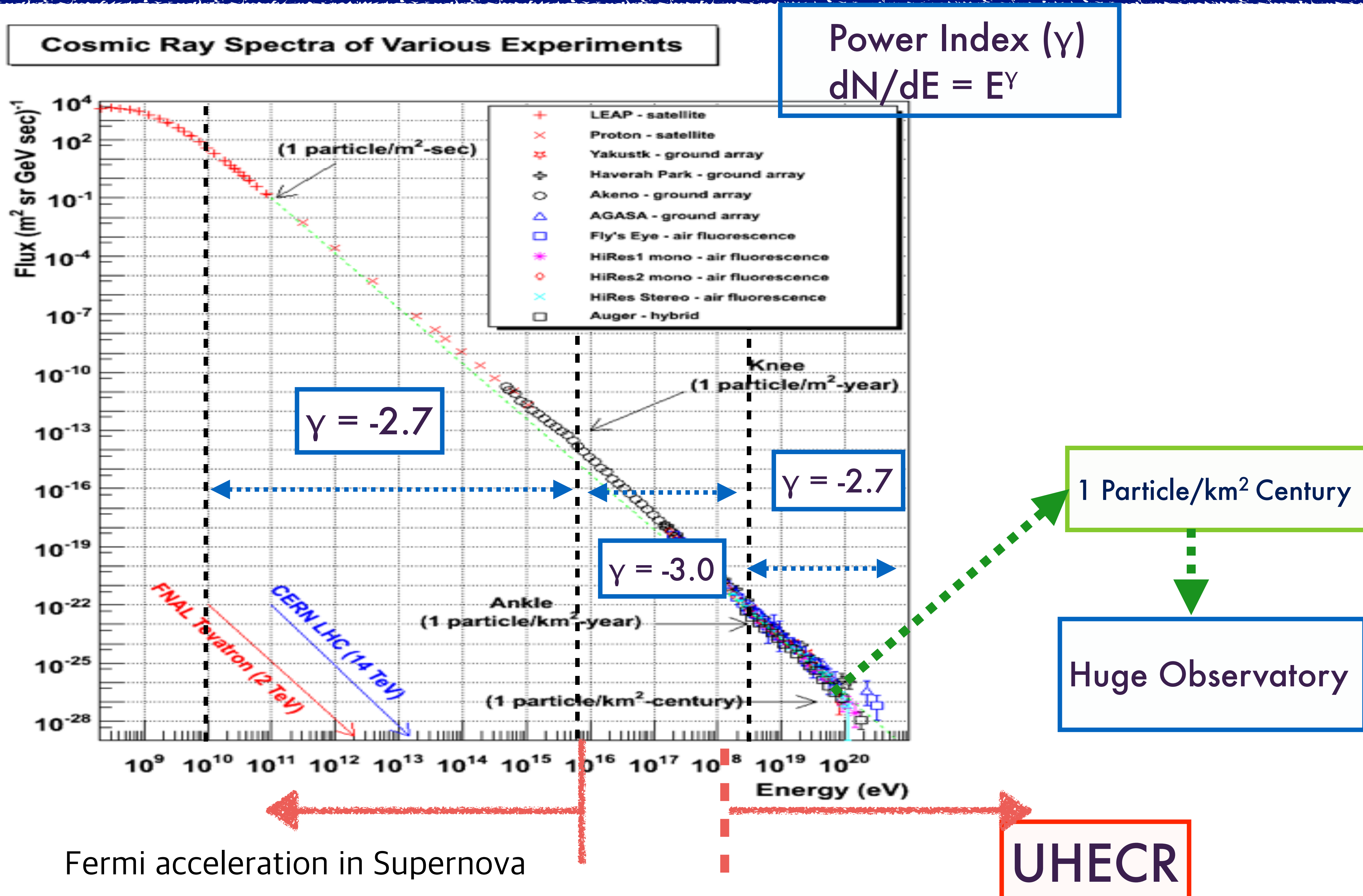
- **Ultra High Energy Cosmic Rays**
  - Energetic particle from the Universe ($E > 10^{18}$ eV)
  - Origin, Acceleration Mechanism?

- **Telescope Array**
  - A huge observatory for UHECR in northern hemisphere
  - Surface detector array(SDs), Fluorescence Detector (FD)

- **Electron Light Source (ELS)**
  - Injection electron beam into air
  - Energy calibration source for FD.

UHECR

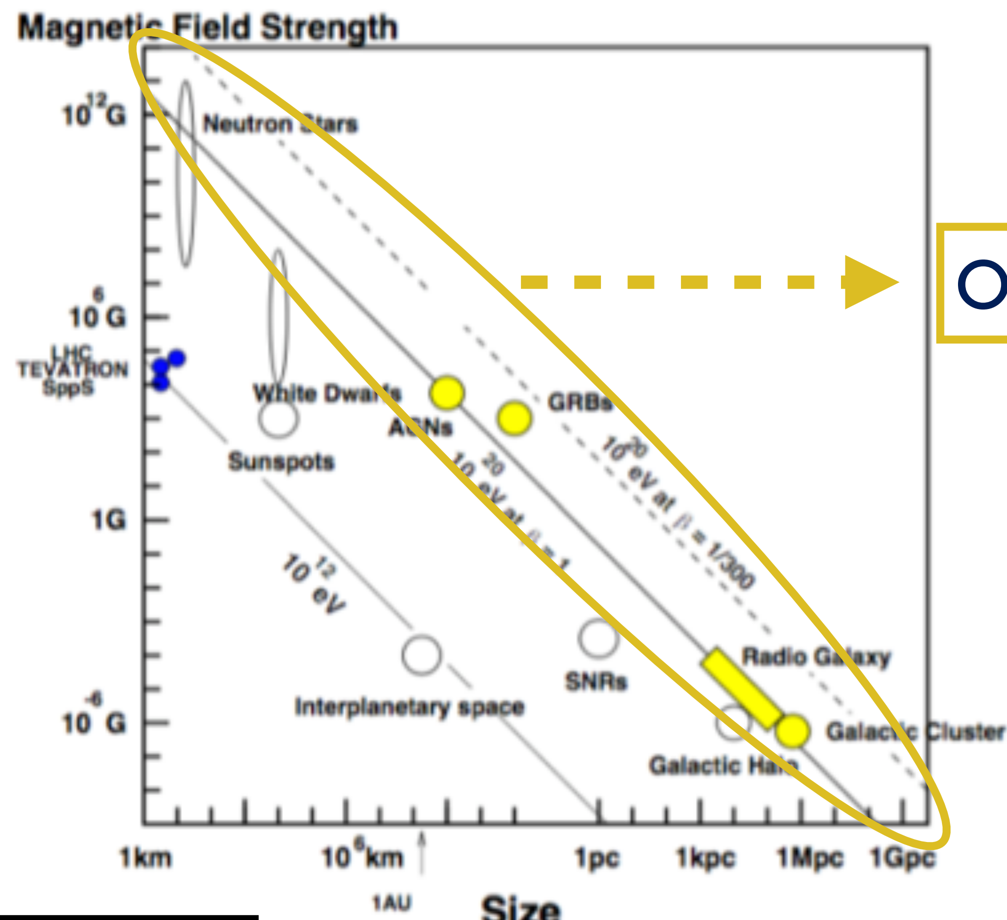
Cosmic Rays Energy Spectrum



Source of UHECR?

Source & acceleration mechanism of UHECR are still unknown.

Bottom-Up Model : Low energy → Acceleration → UHE



Hillas plot

$$E_{max} = \gamma e Z B R,$$

Origin?

Mass composition, Arrival direction

Top-Down Model
Super energy → Interaction → UHE

- Super heavy particle acceleration
- Super energy neutrino → Interaction with CMBR

GZK cutoff

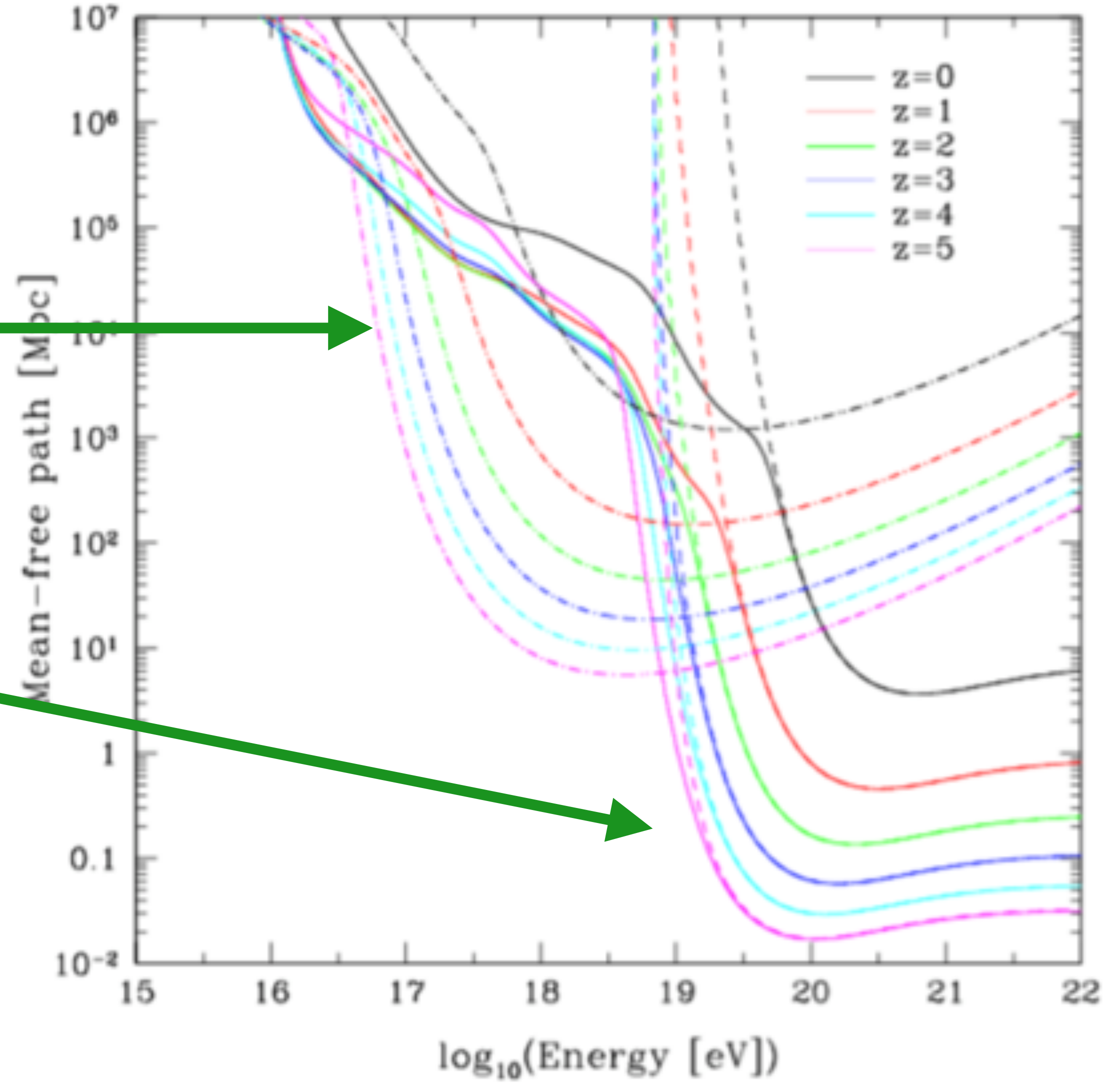
- GZK Cutoff
  - The limit of CR energy by Greisen, Zatsepin and Kuzmin in 1966

Bethe-Heitler process

$\gamma(CMBR) + p(> 10^{16}\ \text{eV}) \rightarrow e^{+} + e^{-} + p$

photo-meson process

$\gamma(CMBR) + p(> 10^{19}\ \text{eV}) \rightarrow p + \pi^{0}$ or $n + \pi^{+}$



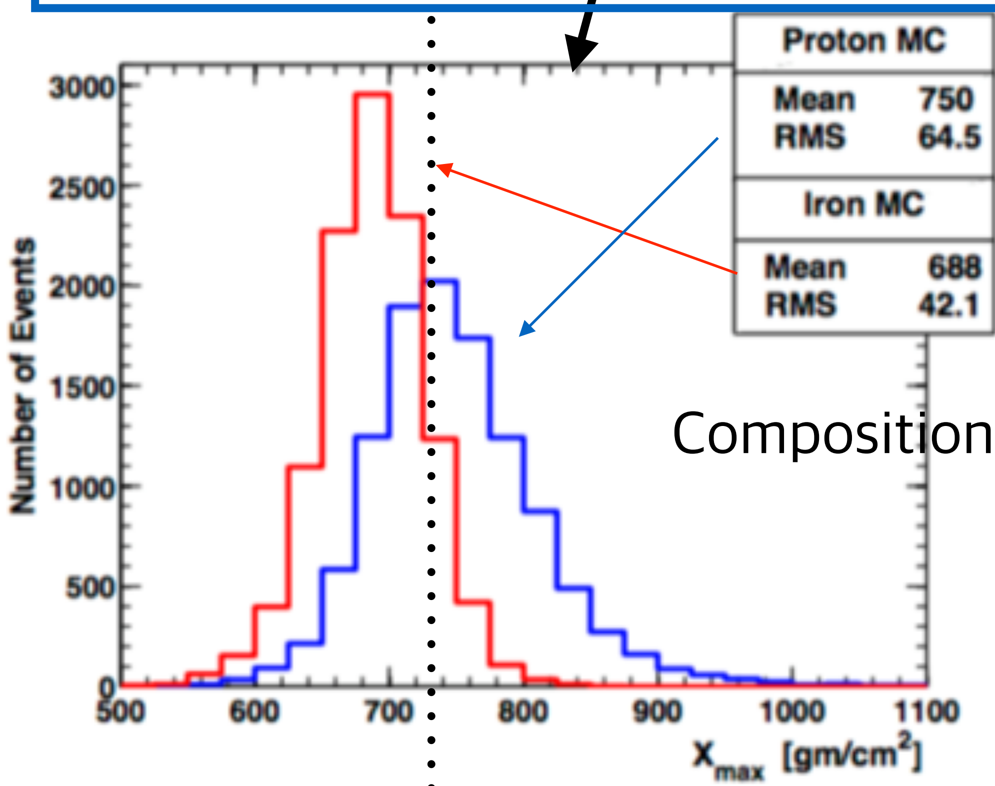
Origin of observed UHECR are in range of 100 Mpc.

UHECR Observation

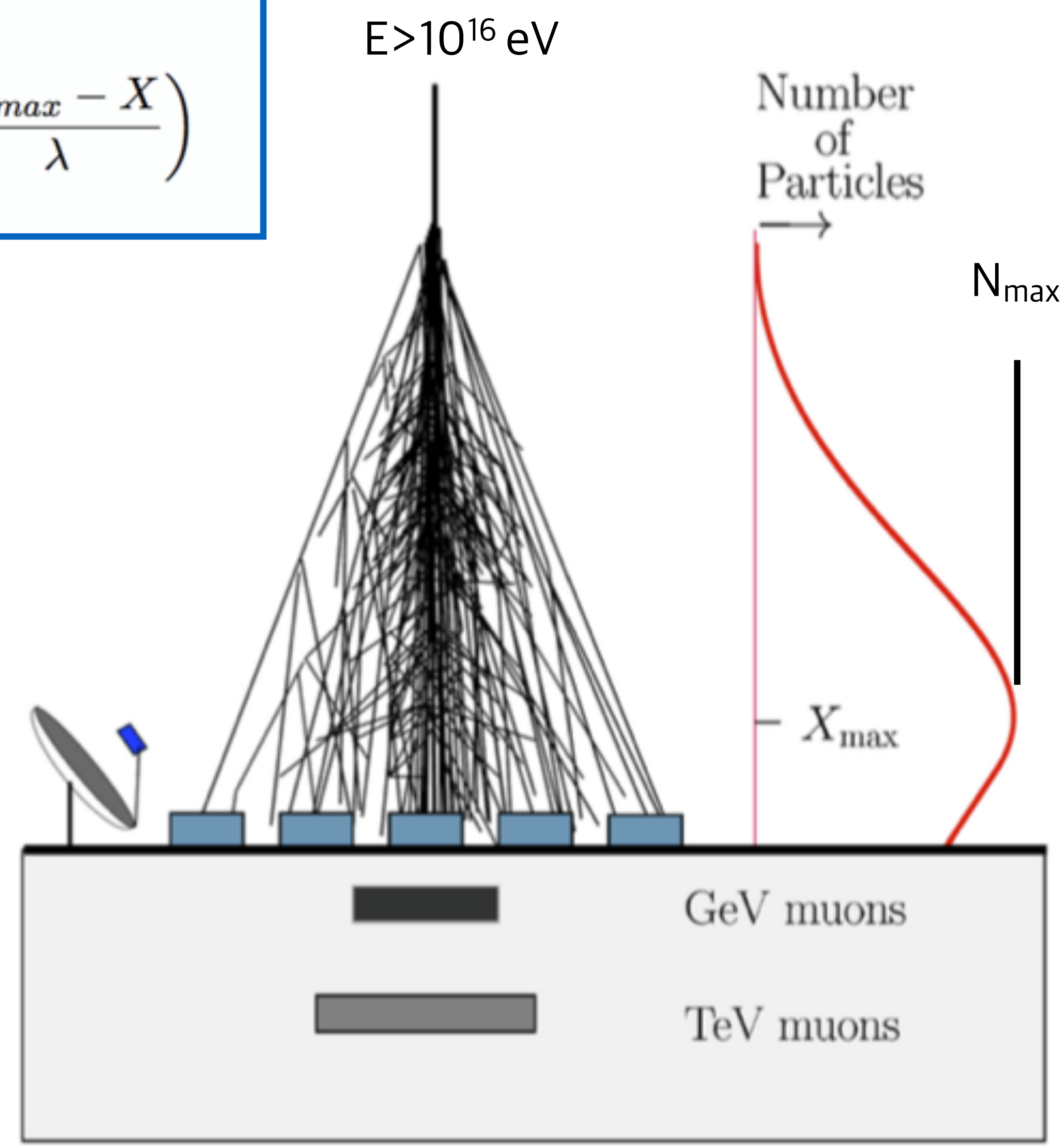
Extensive Air Shower (EAS)

Gaisser-Hillas (G-H) formula

$$N(X) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max}-X_0}{\lambda}} exp\left(\frac{X_{max} - X}{\lambda}\right)$$



Composition study

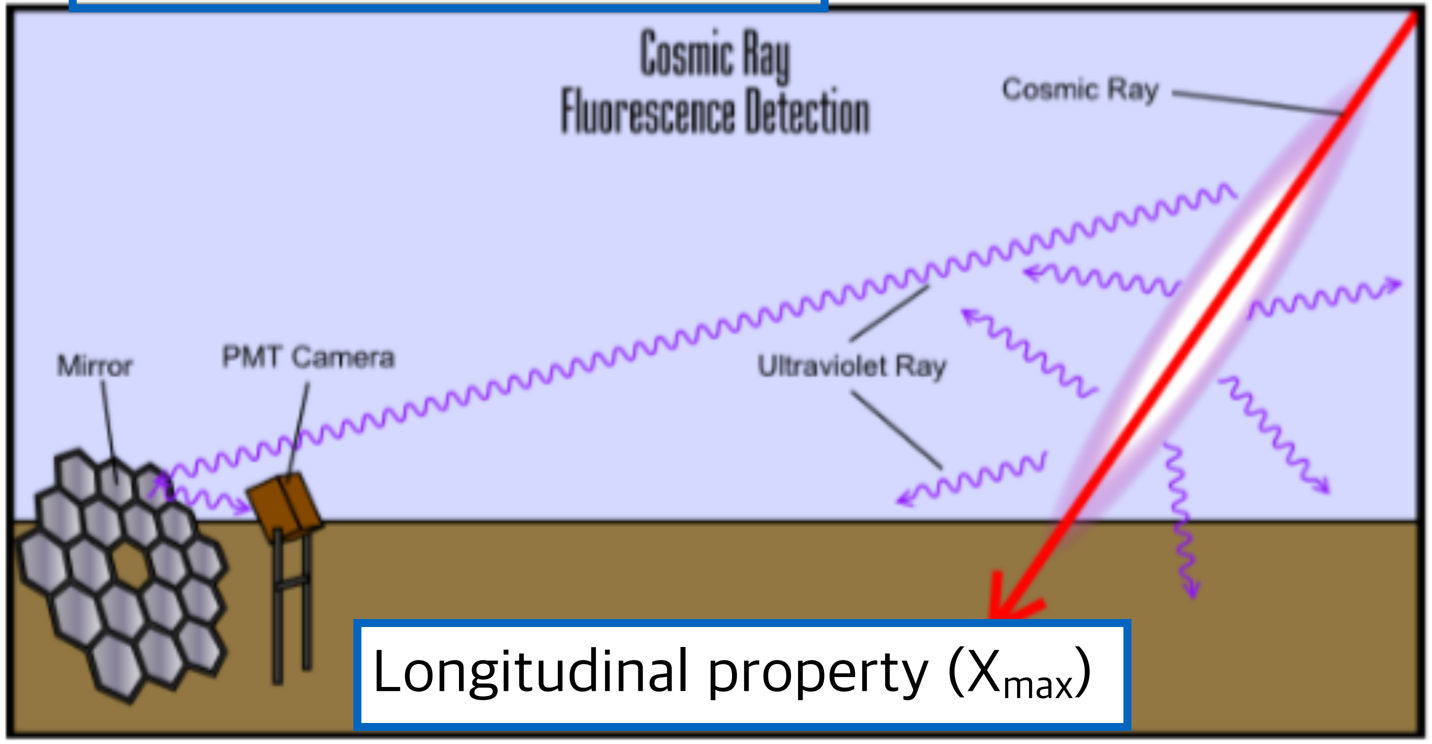


Energy Reconstruction

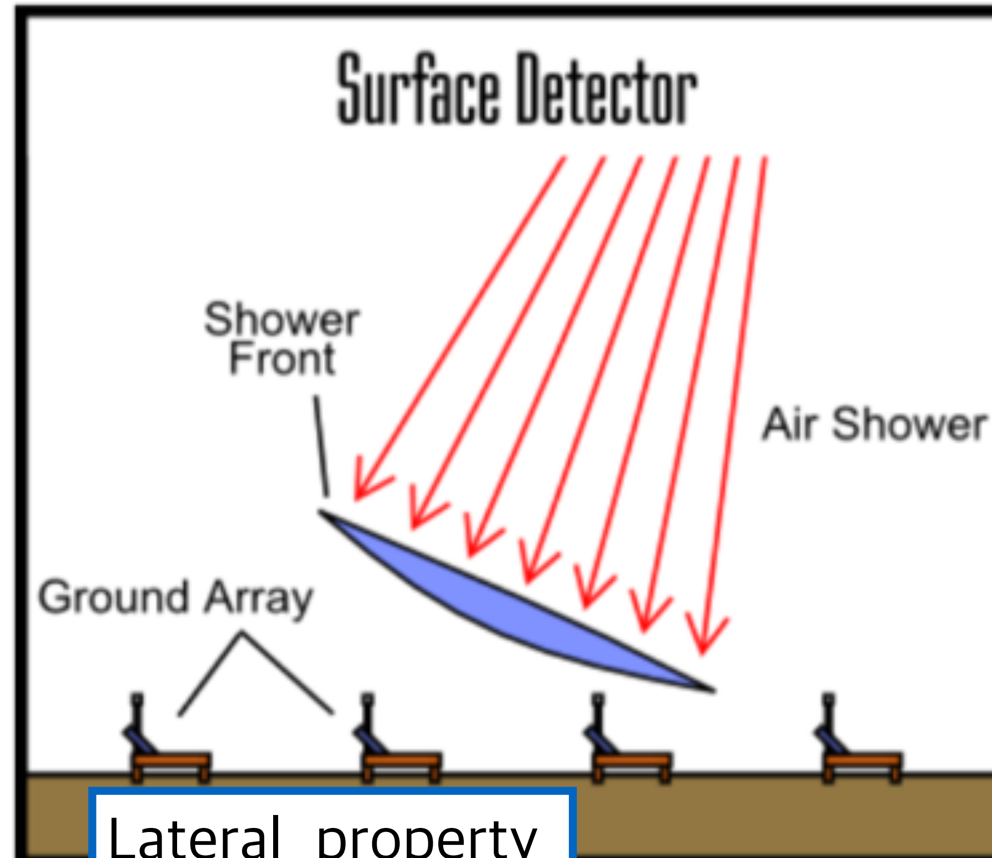
$$E = \lambda N_{max}\frac{d\bar{E}}{dX}\left(\frac{e}{\epsilon}\right)^{\epsilon}\Gamma(\epsilon + 1)$$

EAS Detection Methods

Fluorescence detection

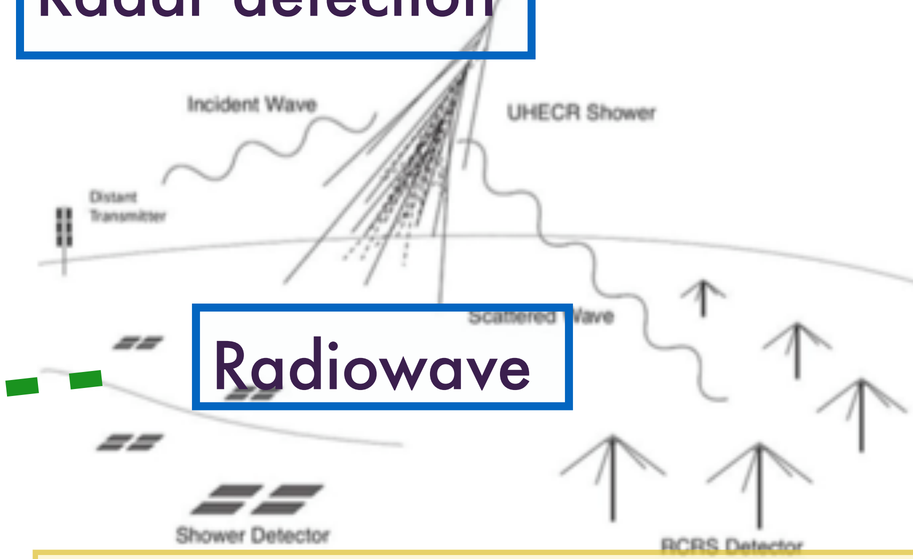


Longitudinal property (X_{max})



Lateral property

Radar detection



Radiowave

Under Study

Telescope Array (TA):

700 km^2, Northern hemisphere

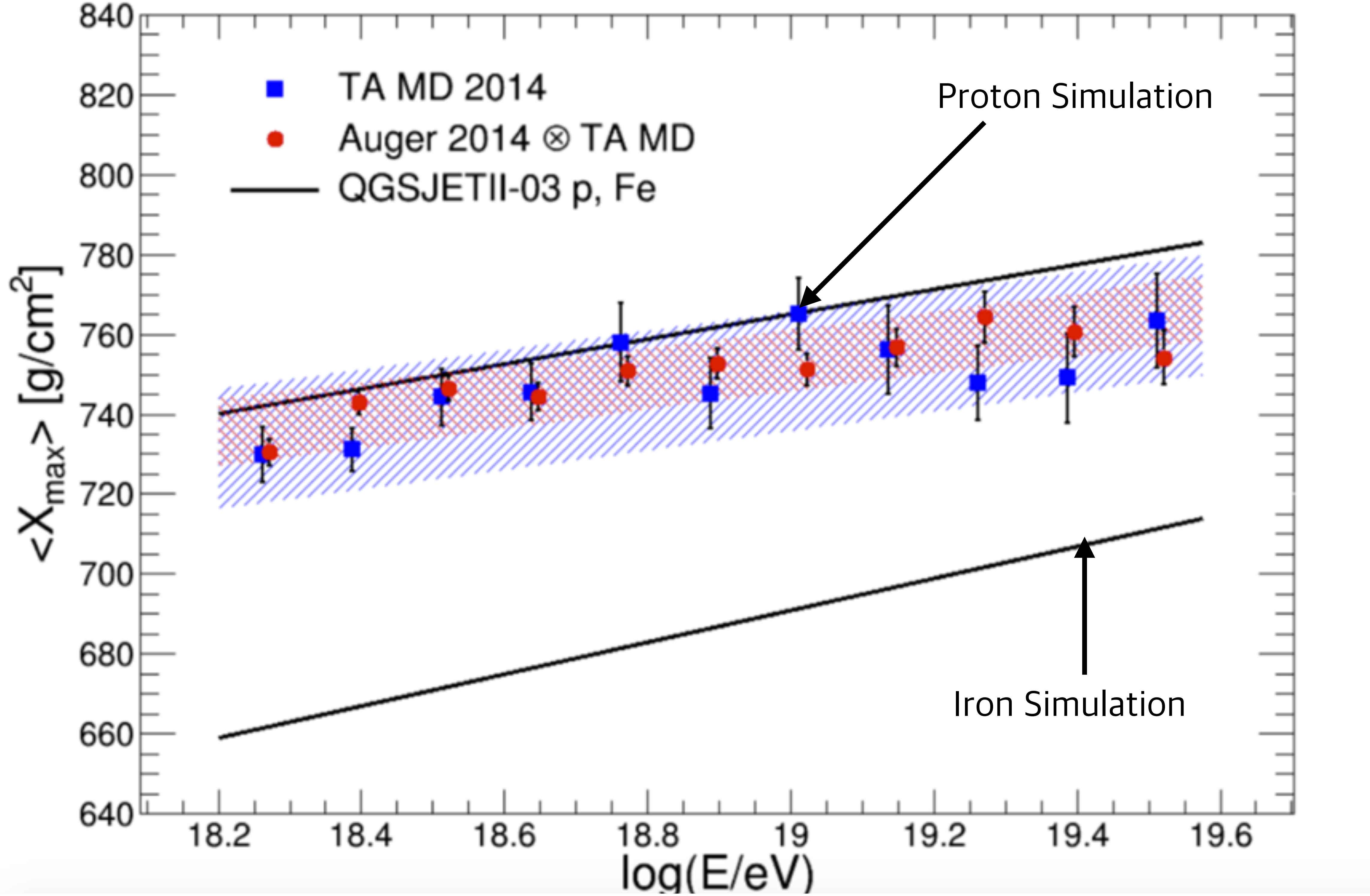
Pierre Auger Observatory(PAO) :

3000 km^2, Southern hemisphere

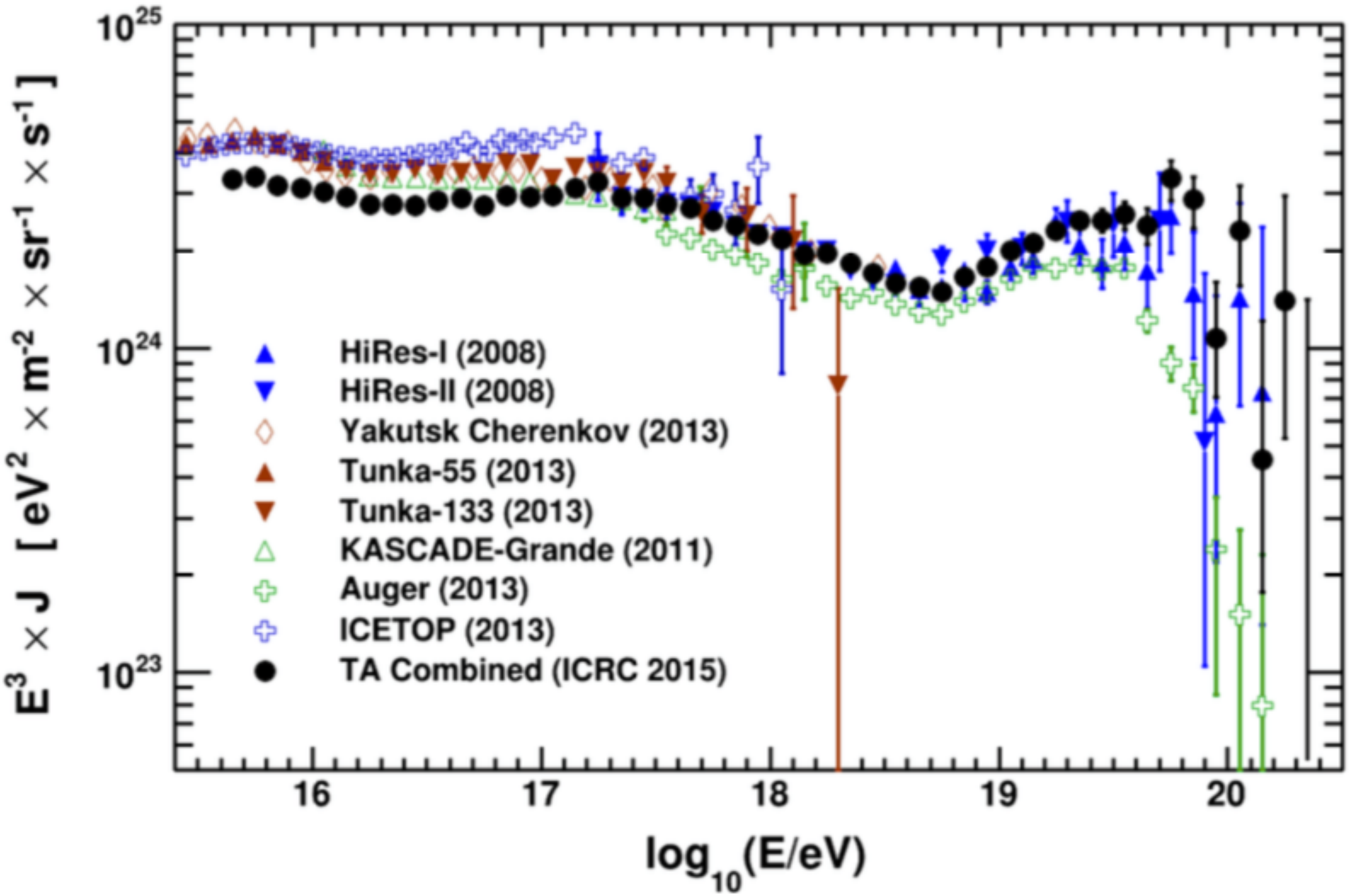
Current Results

Mass composition, Spectrum, Anisotropy

Mass composition



Spectrum



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GZK Cutoff

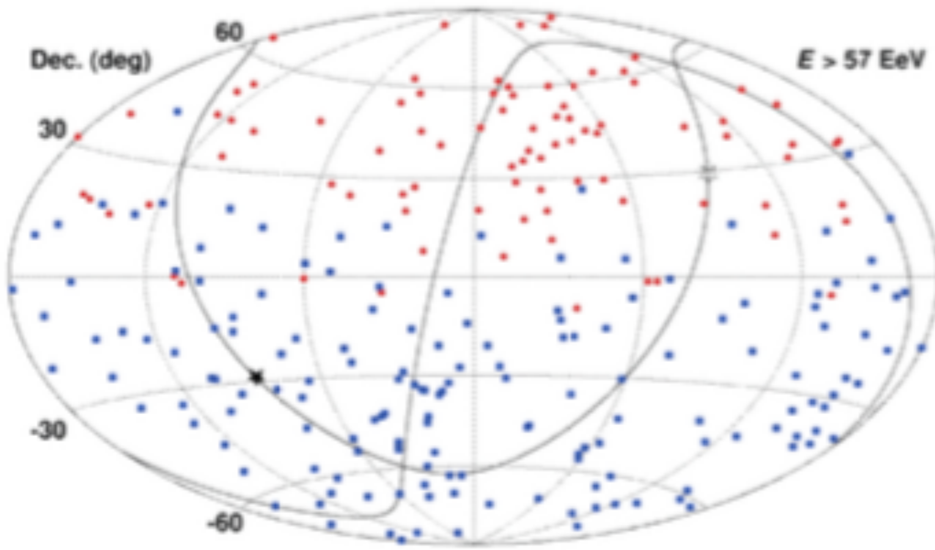
Anisotropy

Anisotropy of cosmic rays (E > 57 EeV) measured by TA and Auger

Point like source?

$10^{19.7}$ eV

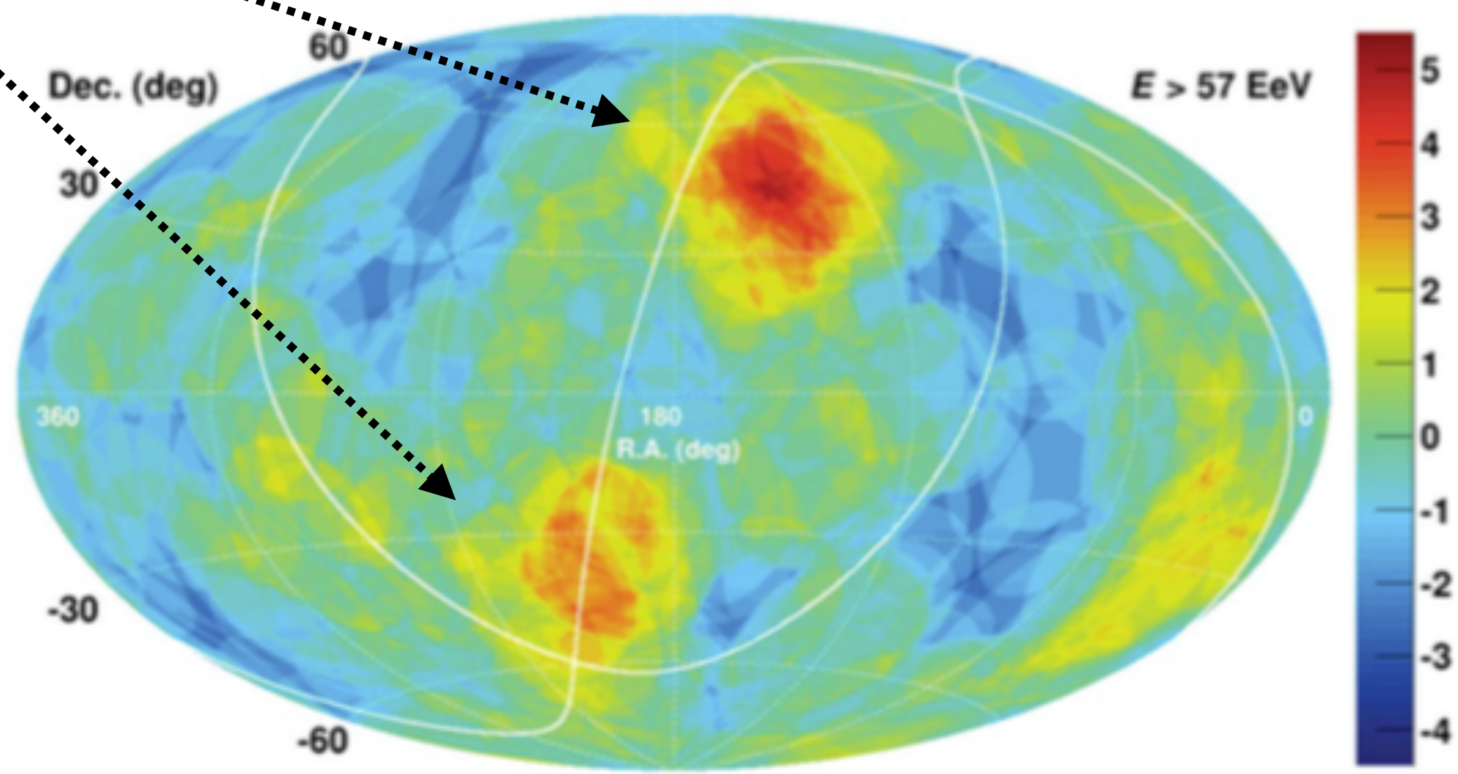
6years of TA data



10 years of Auger data
A. Aab et al., ApJ 804: 15 (2015)

Combined significance map

oversampling with 20-degree-radius circles



Maximum pretrial significance

TA: 5.2σ near Ursa Major 20 Mpc

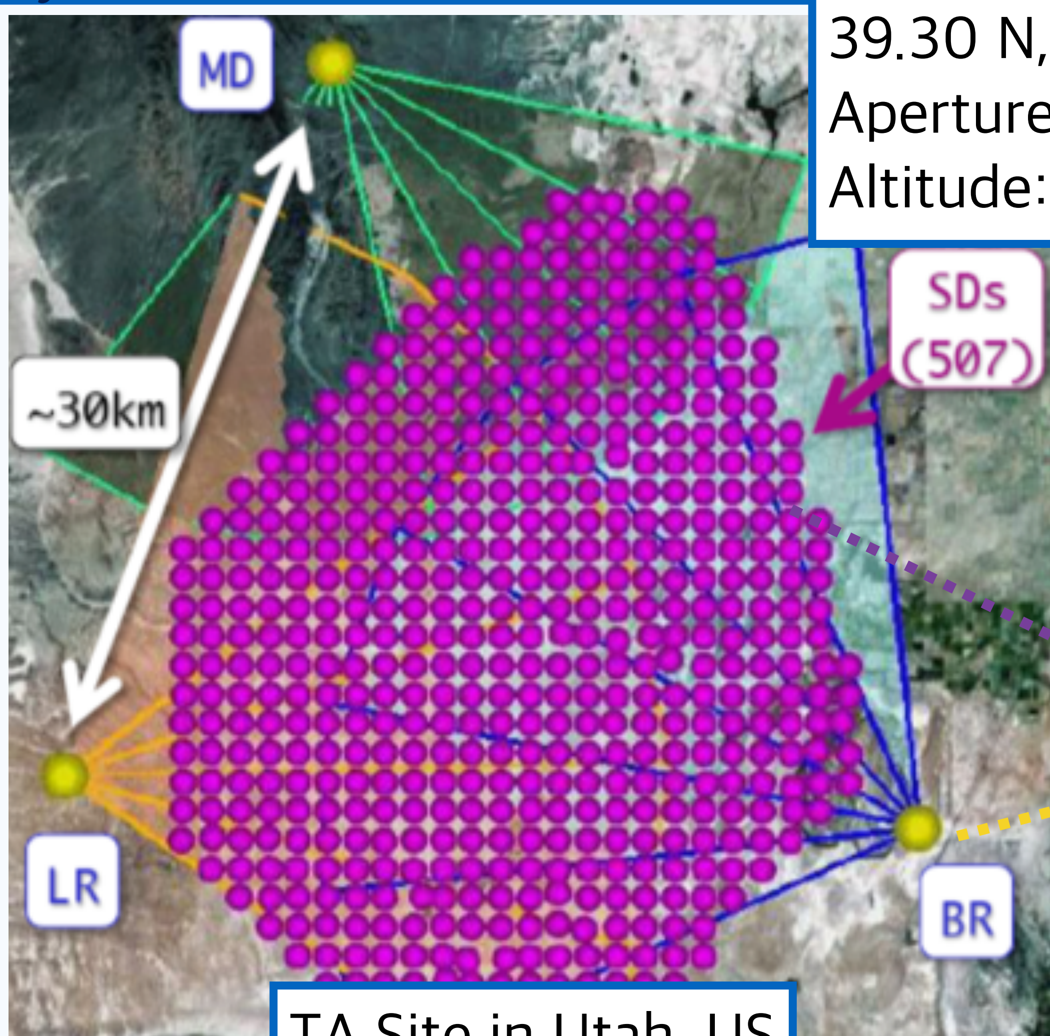
Auger: 3.6σ near Cen-A 5 Mpc

Telescope Array

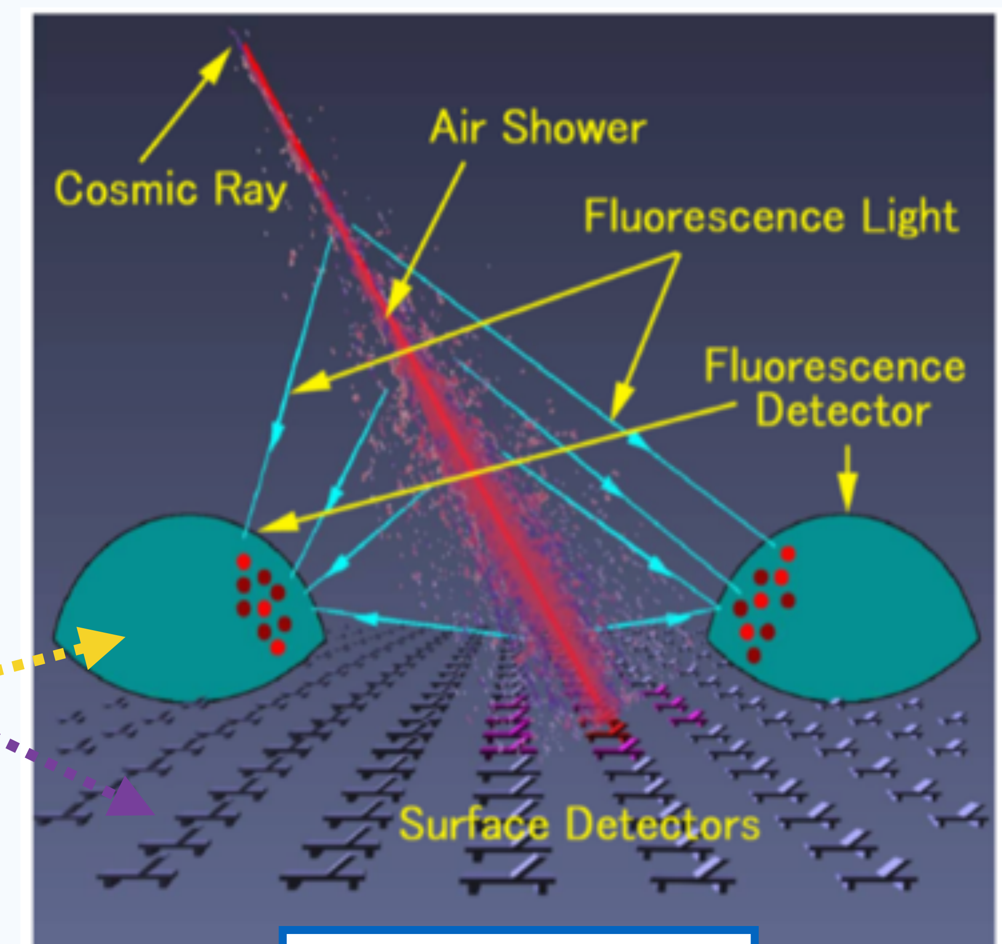
Overview

- **Physics goal : Search for UHECR**
  - Precise measurement: Energy spectrum, Mass composition, Anisotropy
- Site : Utah, USA
- Hybrid detection : 3 FD stations, an array with 507 SDs.

39.30 N,−112.91 W
Aperture: 700 km^2
Altitude: 1400 m



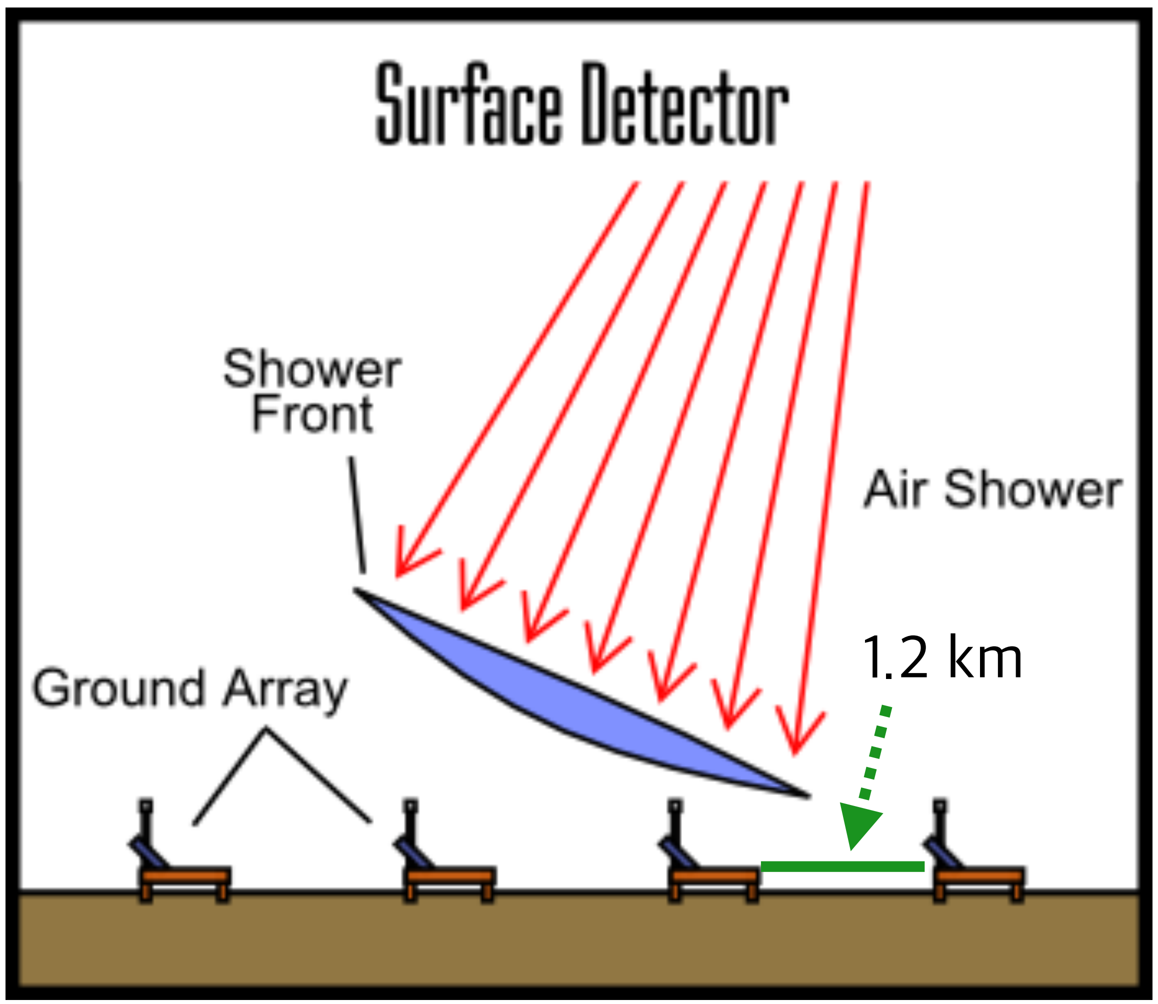
TA Site in Utah, US

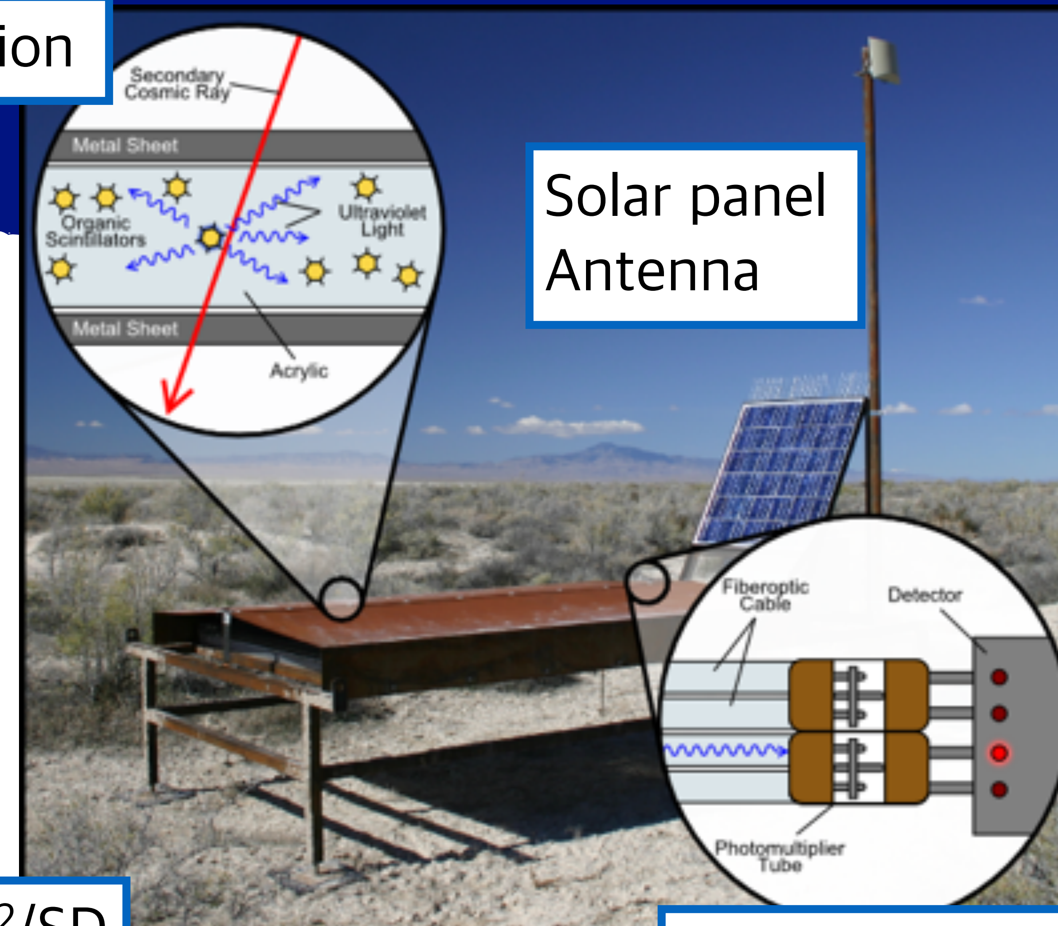


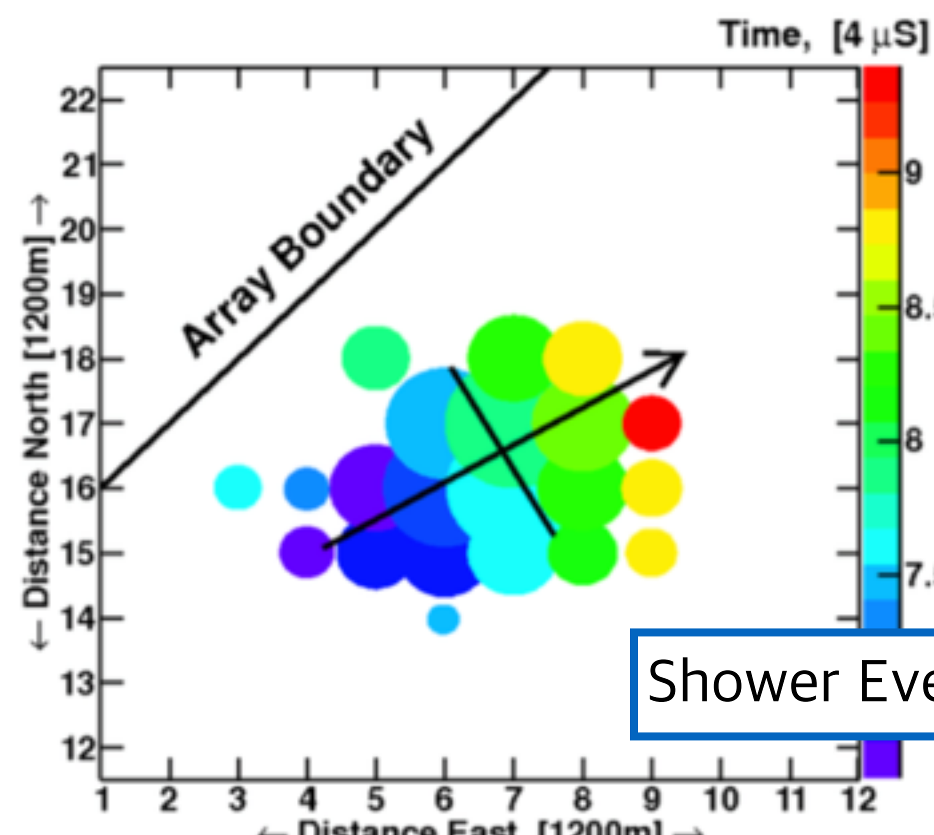
Hybrid Detection

Array of SD

- 507 SDs, 1.2 km space grid
- Lateral distribution.
- 100% of duty cycle.

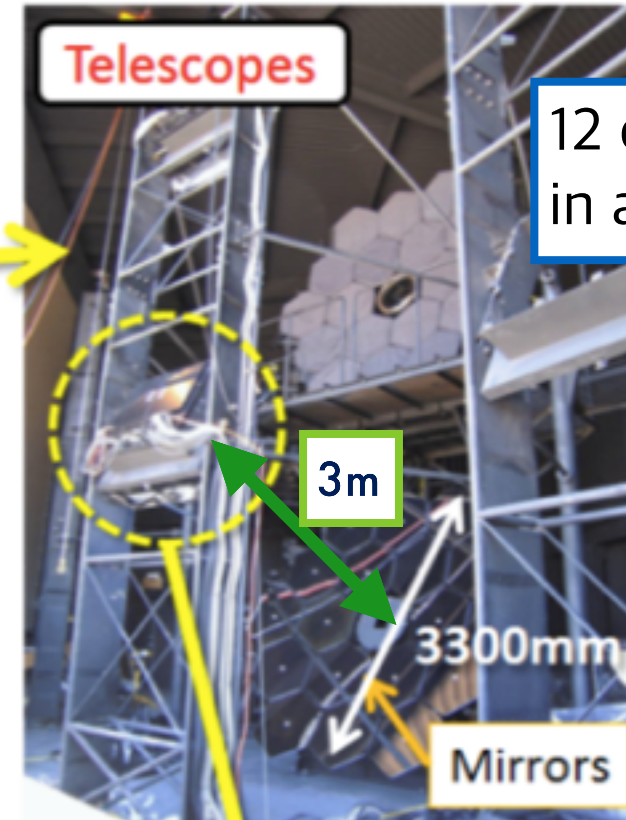






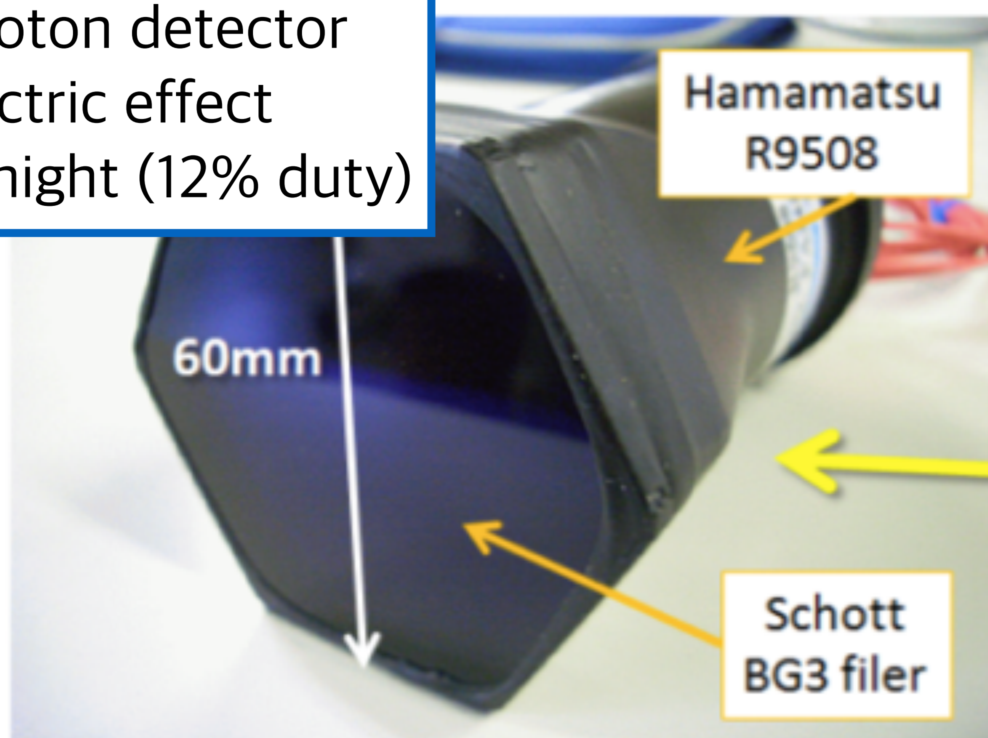
FD Station

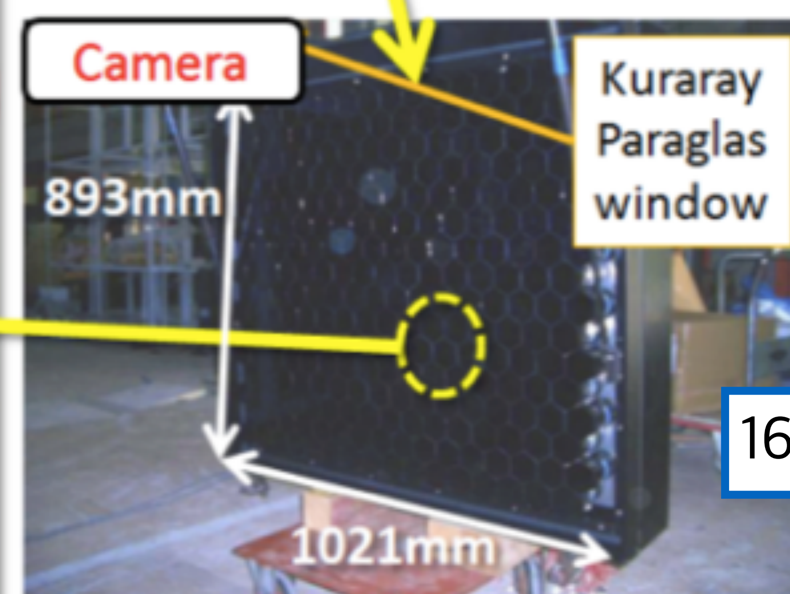
3 stations in TA site



12 or 14 telescopes in a station

PMT
- Sensitive photon detector with photoelectric effect
  - Moonless night (12% duty)





16 × 16 PMTs

FD Analysis

1. Shower Geometry
2. Energy Analysis

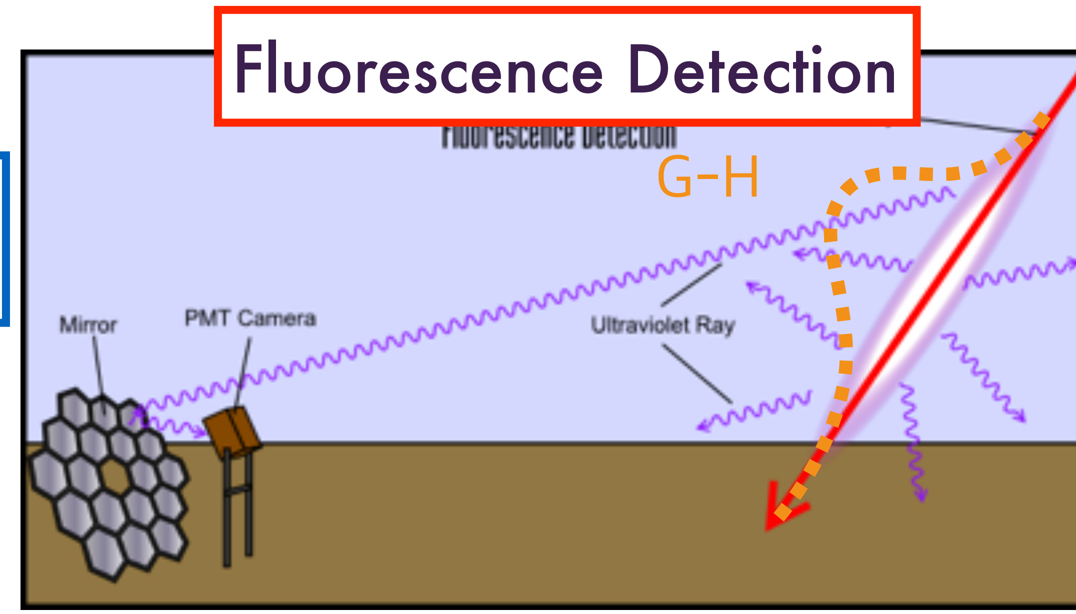
FD Detection Process

FD Detection Process

$$N(X) \times dE \times Y \times T_{AIR} \times G = F(X)$$

Analysis

Data(F) → Axis (X) → Profile (N) → Energy

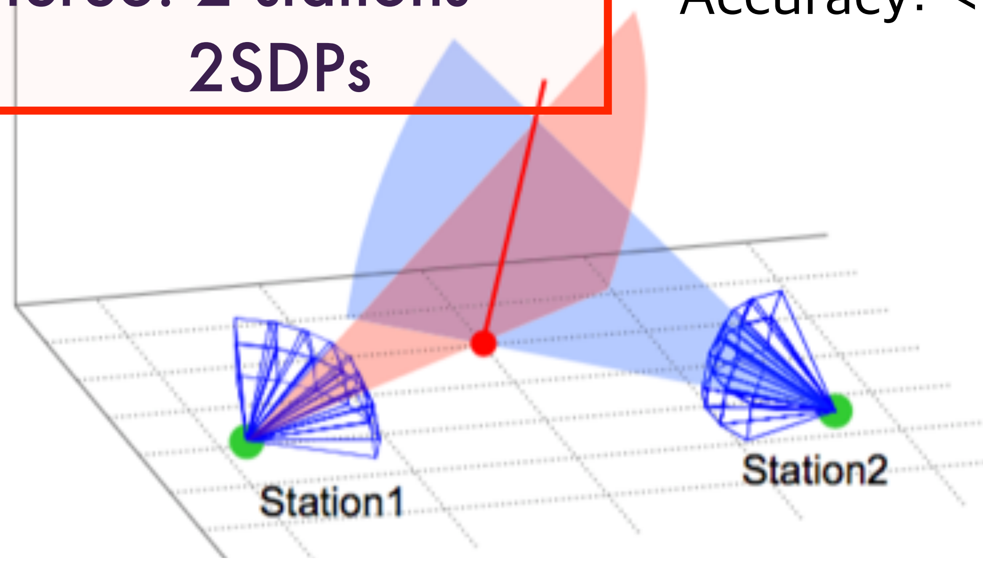


	Definition	Source	Value
N (X)	Number of Particles	G-H formula	
X	Slant depth	$X = \int d(h)\, dh \cos(\theta)$	
dE	Energy deposit	Simulation	~2 MeV/(g/cm^2)
Y	Air fluorescence Yield	with Beam	16 N_p/MeV
T_{AIR}	Air Transmittance	LIDAR	0.34 /km @ ground
G	FD Gain	CRAYS and so on.	0.442 F/N_p

Shower Geometry (2)

Stereo: 2 stations
2SDPs

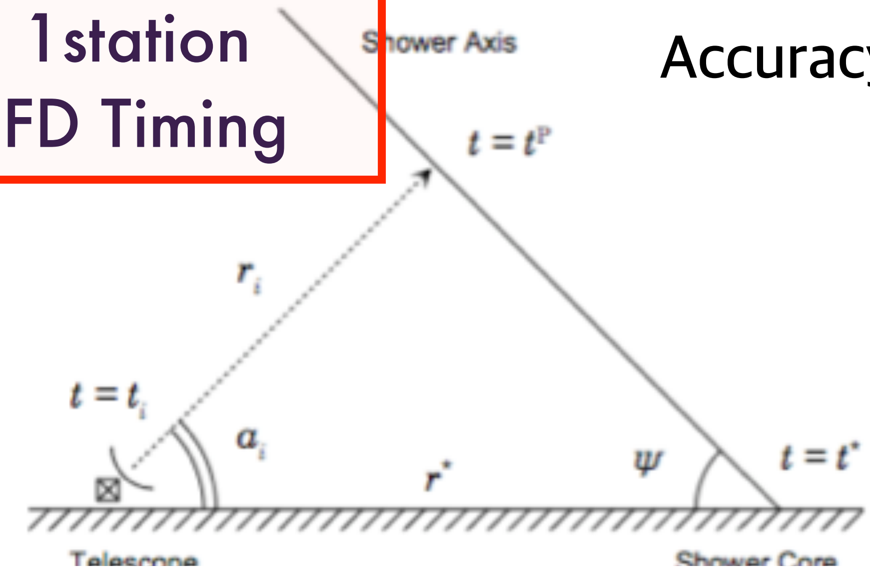
Accuracy: < 1○



$$\mathbf{s} = \mathbf{n_1} \times \mathbf{n_2}$$

Mono: 1station
2SDP, FD Timing

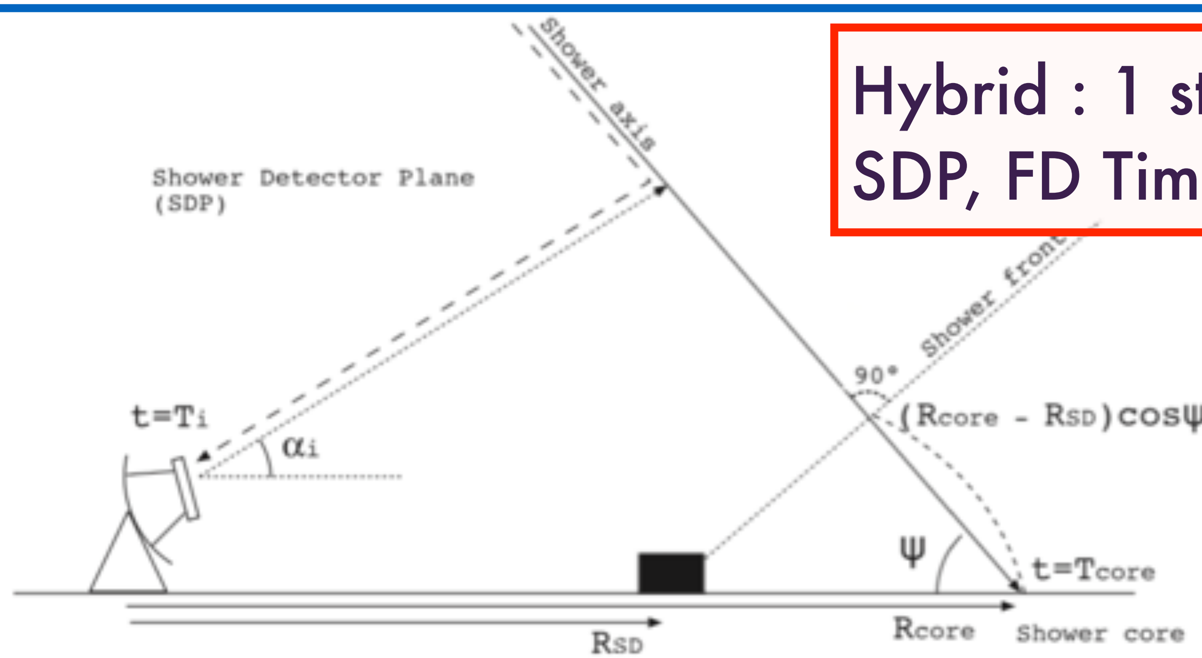
Accuracy: 10○



$$\chi^2 = \sum_i \left[t_i - t^* - \frac{1}{c} \frac{sin\psi - sin\alpha_i}{sin(\psi + \alpha_i)} r^* / \sigma_i^2 \right]$$

Hybrid : 1 station and 1 SD
SDP, FD Timing, SD Timing

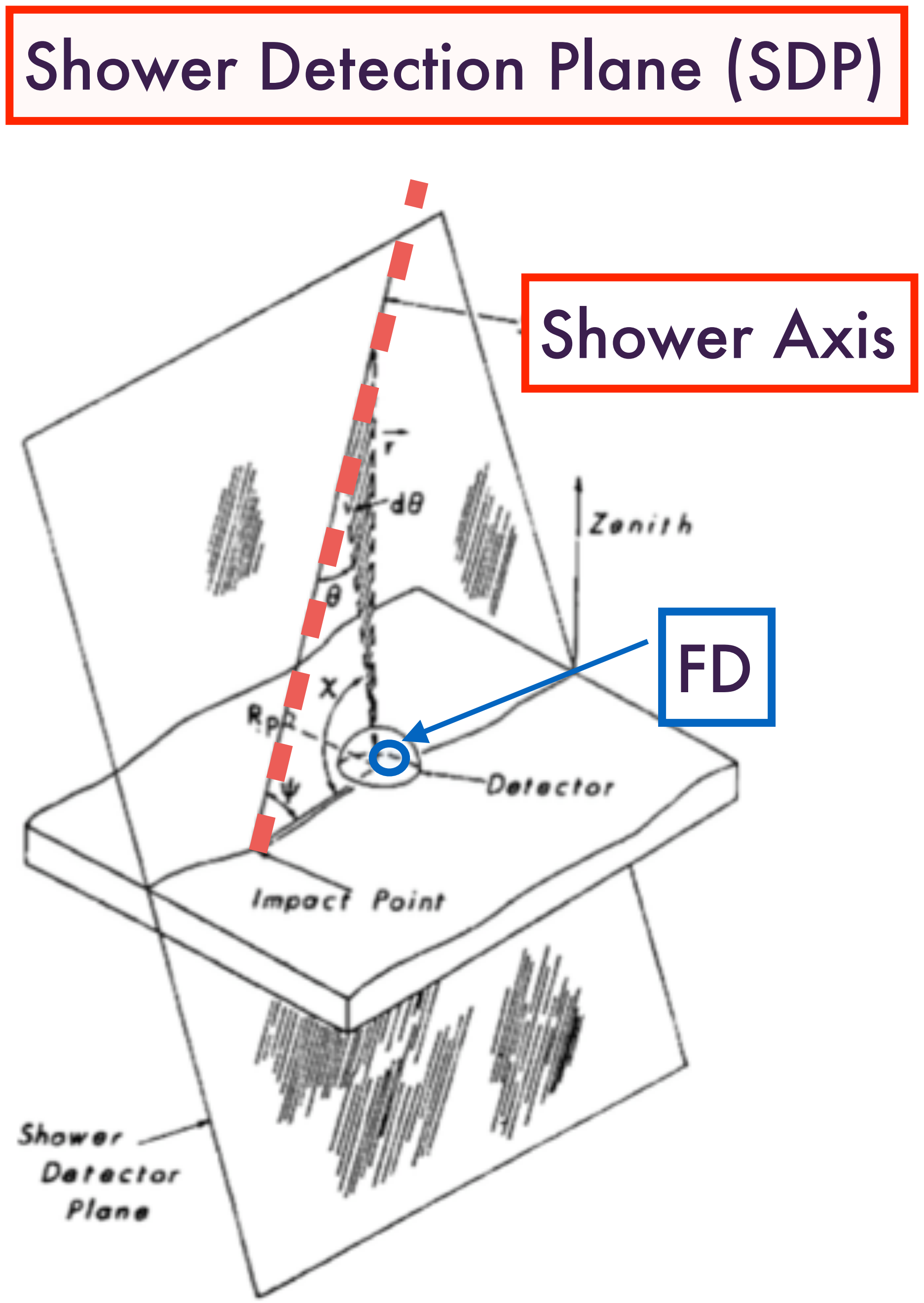
Accuracy: ~1○

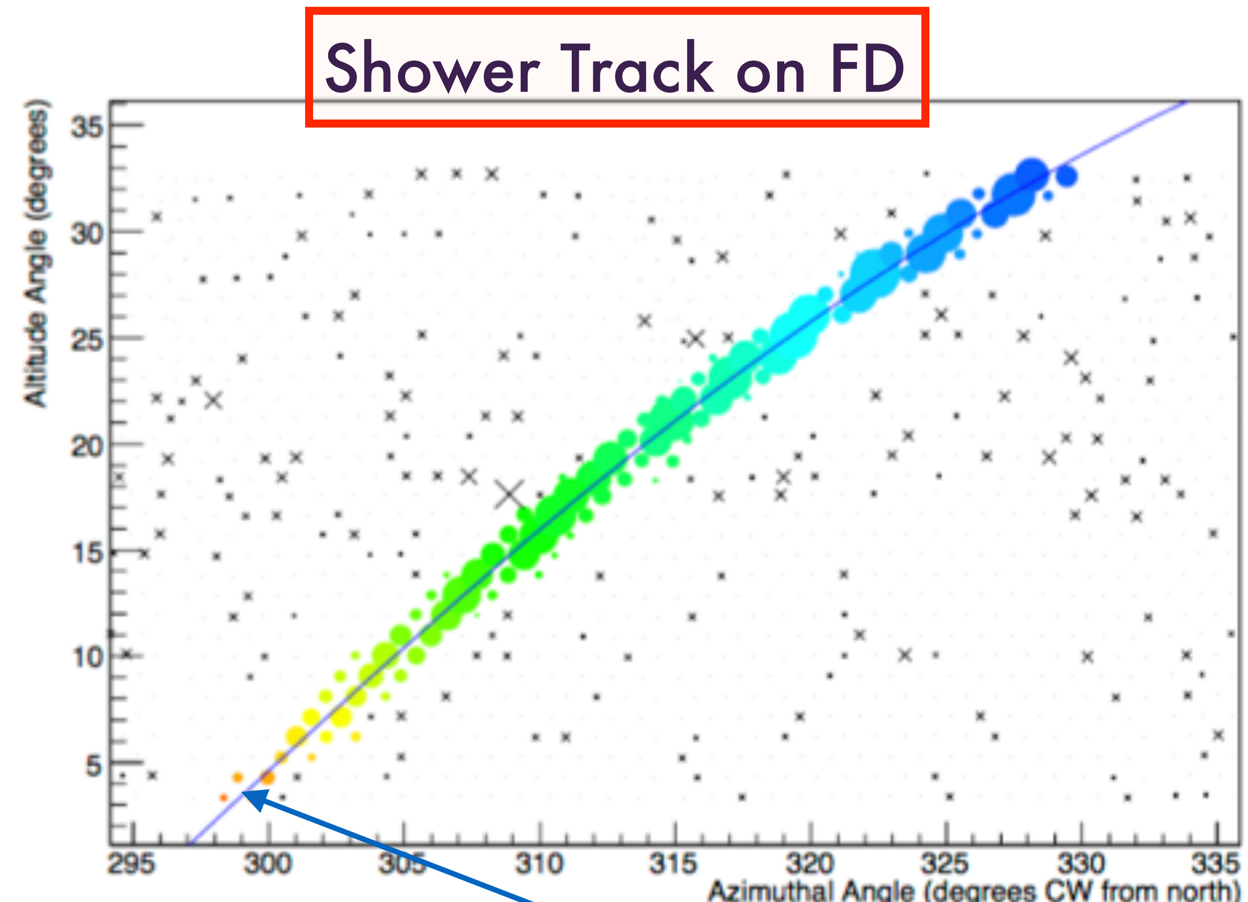


$$T_{core} = T'_{SD} + \frac{1}{c}(R_{core} - R_{SD})\cos\psi,$$

$$T'_{SD} = T_{SD} - \frac{1}{c}\{(\vec{P}'_{SD} - \vec{P}_{SD}) \cdot \vec{P}\},$$

Shower Geometry (1)





SDP

F

PMT FoV

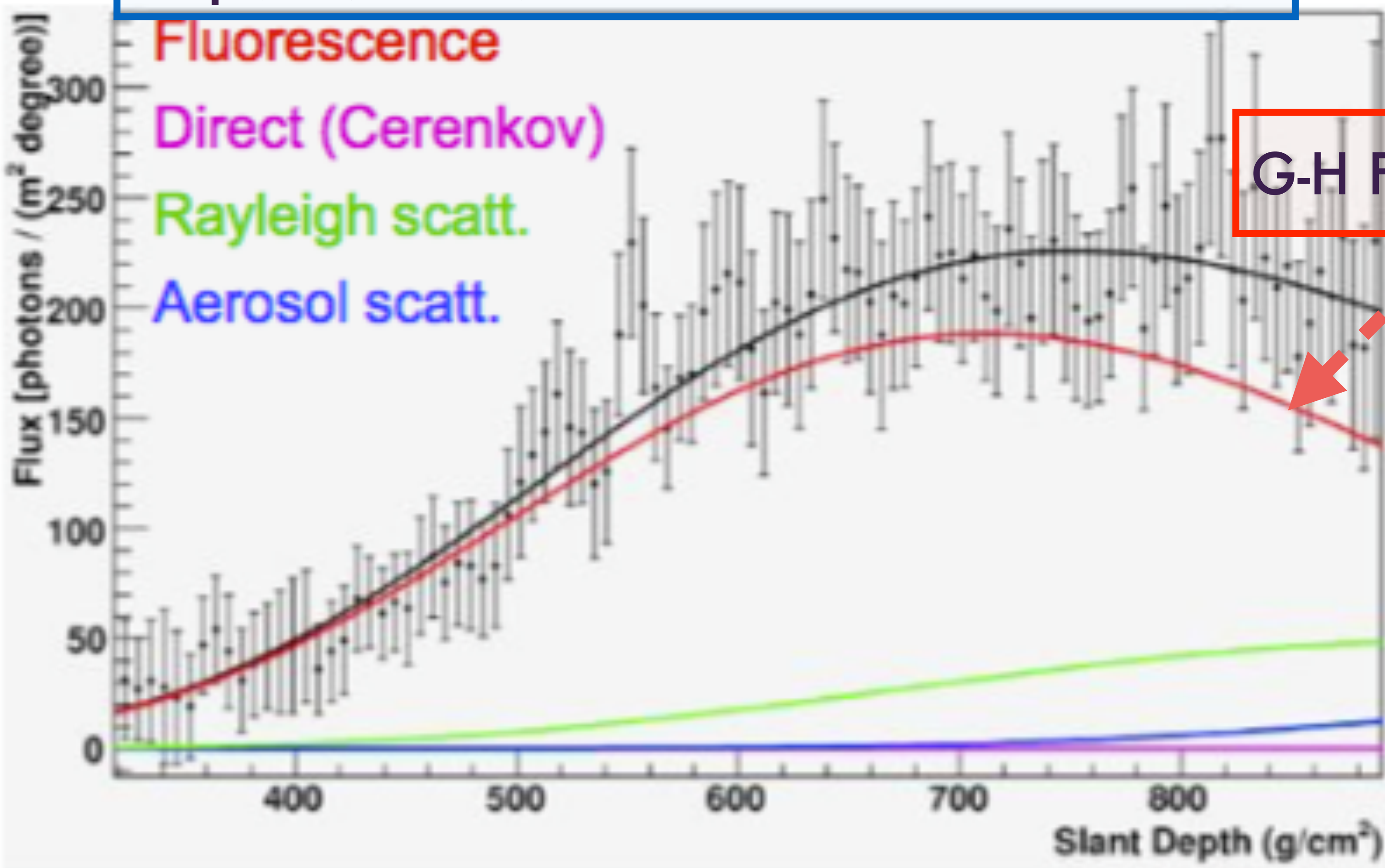
$$\chi^2 = \sum_i \frac{w_i(\mathbf{n}\cdot\mathbf{K^i})}{\sigma_i^2}$$

PMT ID

FoV uncertainty

Profile reconstruction

$N_p(X) = F(X)/(Y \times T_{AIR} \times G)$



G-H Formula

$$E = \lambda N_{max} \frac{d\bar{E}}{dX} \left(\frac{e}{\epsilon}\right)^{\epsilon} \Gamma(\epsilon + 1)$$

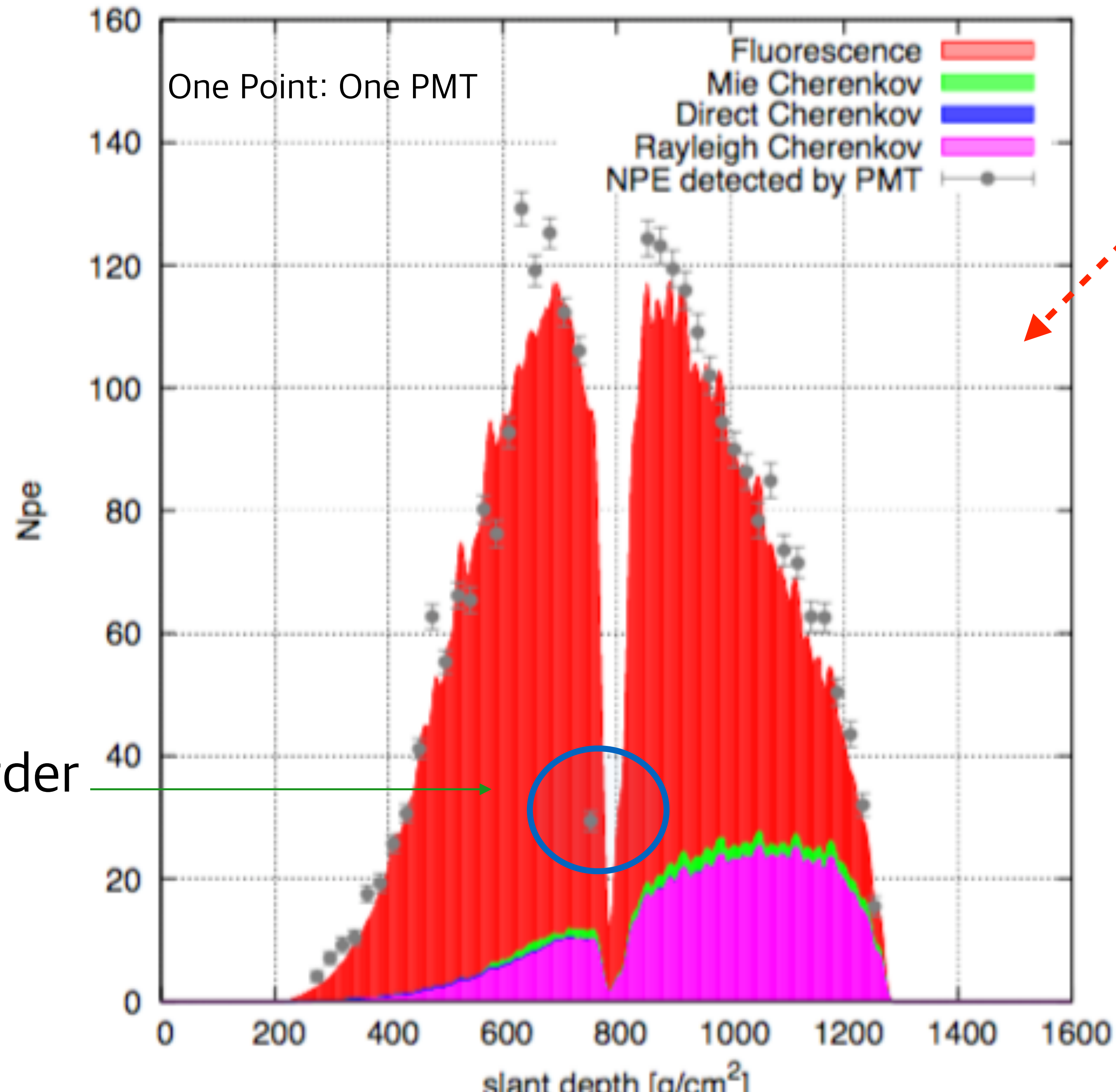
$$t = \frac{X - X_0}{\lambda}$$

$$\epsilon = \frac{X_{max} - X_0}{\lambda}$$

Energy reconstruction (IMC)

Inverse Monte Carlo (IMC)

PMT hit photon



Telescope boarder

Filled plot:
Hit photon MC

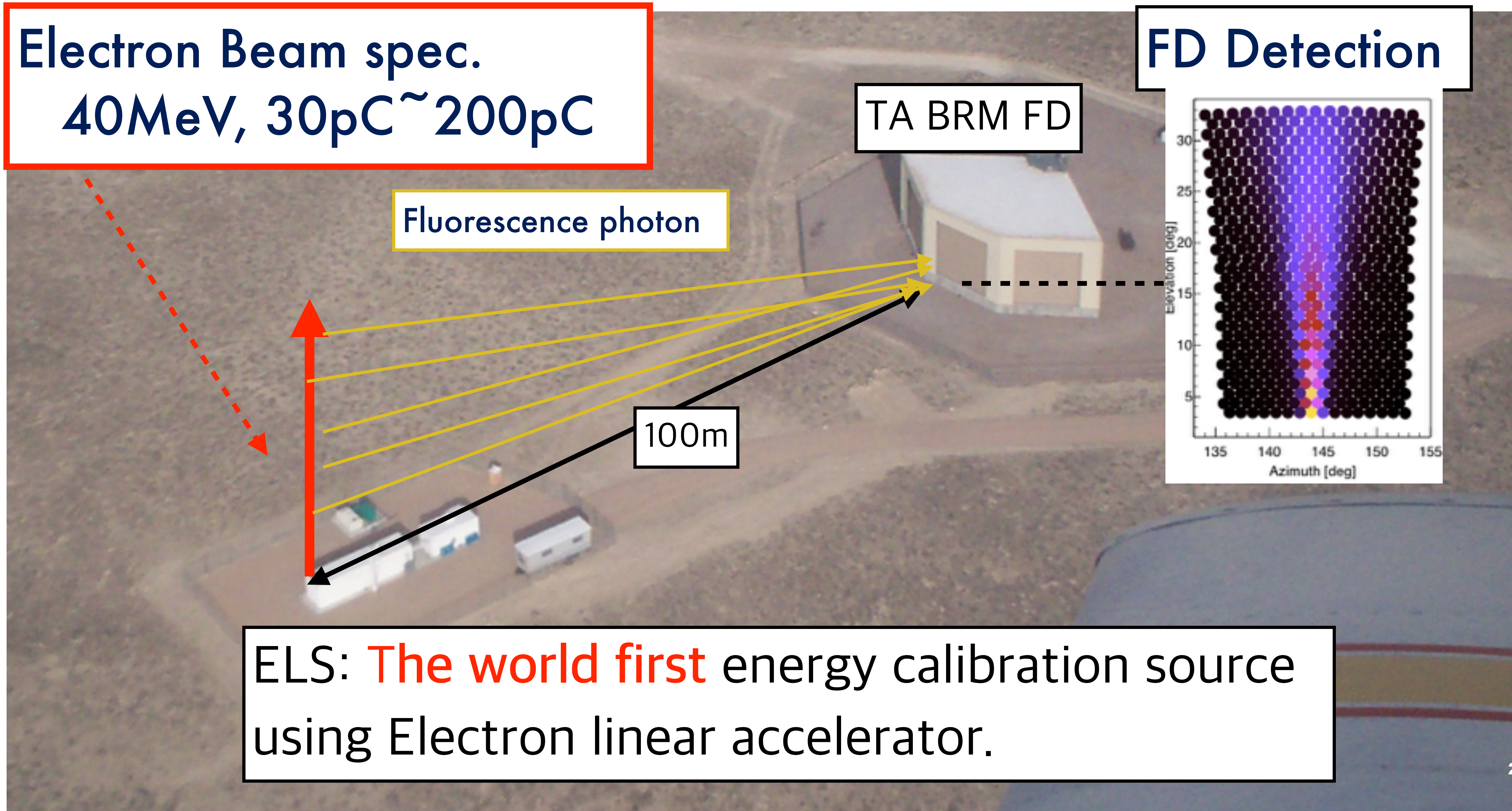
Simulation result with G-H formula and Cherenkov

Electron Light Source(ELS)

Electron Light Source(ELS)

Purpose : FD calibration by ELS electrons beam like as Air shower

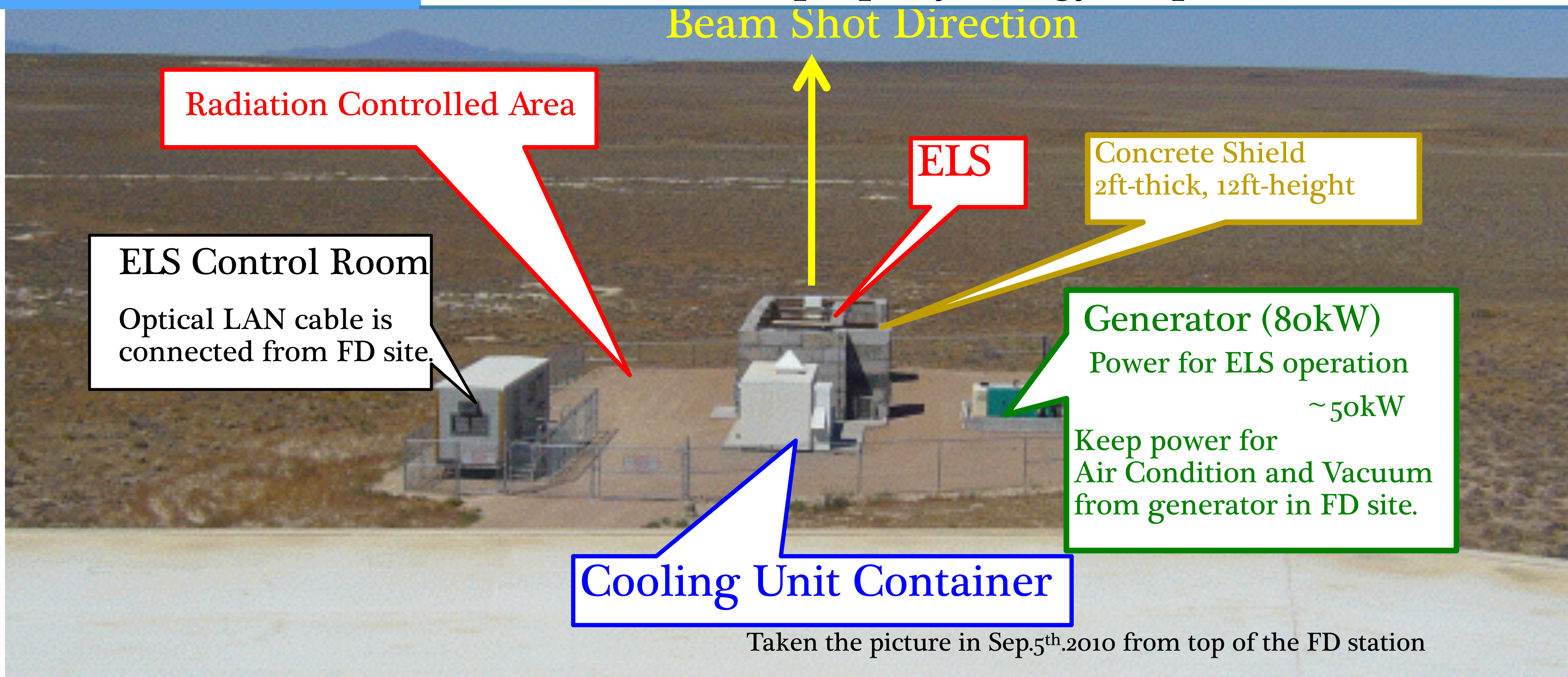
Electron Beam spec.
40MeV, 30pC~200pC



ELS: The world first energy calibration source using Electron linear accelerator.

ELS History & Components

2005~2008	Developed at KEK
2009 Mar	Installed at TA site
2010 Sep	First Operation & FD Detection
2013 Mar	**Beam Charge (Q) measured**
2014 Mar	**Beam property energy & spread measured**



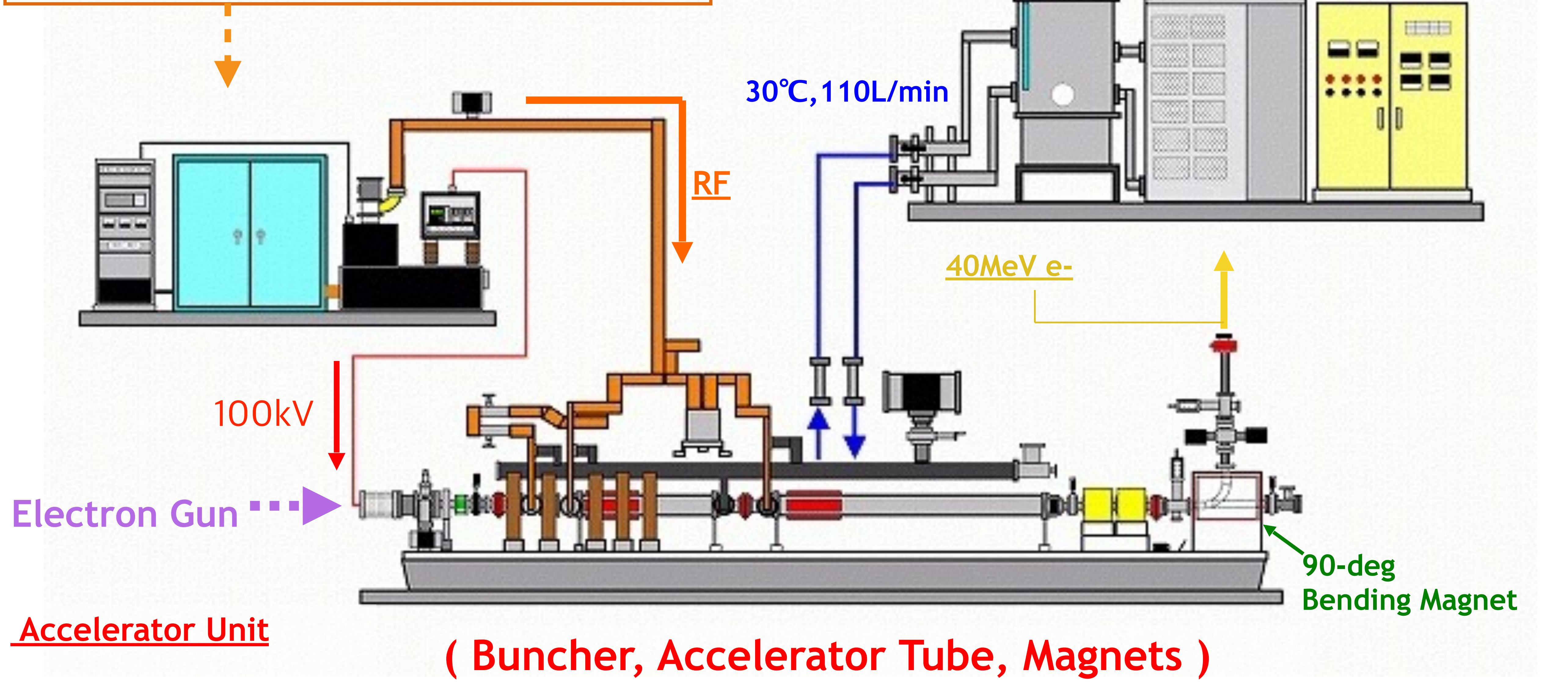
Overview of Components

RF System

Frequency=2856MHz Output Power～20MW

Power source for acceleration

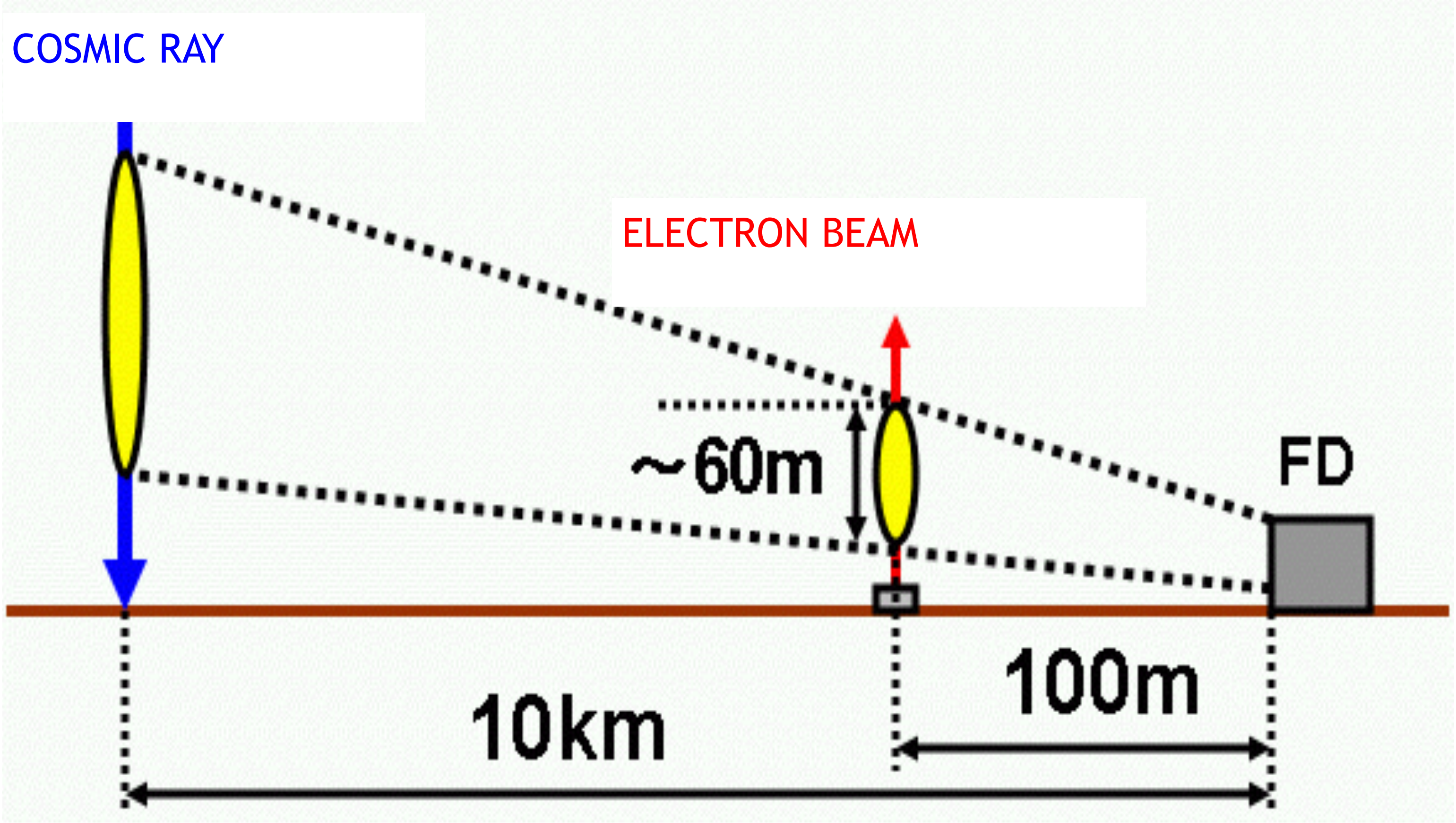
Use Non Frozen water For Acc, Magnets



Energy Calibration

Detection process

$$N_e \times dE(E) \times Y \times T_{AIR}(D) \times G = F$$



One source calibration from dE to FD detection

→ Improving systematic uncertainty

ELS Analysis Overview

Data/MC

$$C_{ELS} = \frac{F_{Data}/Q_{Data}}{F_{MC}/Q_{MC}}$$

E_{ELS}= 40 MeV
D = 100 m

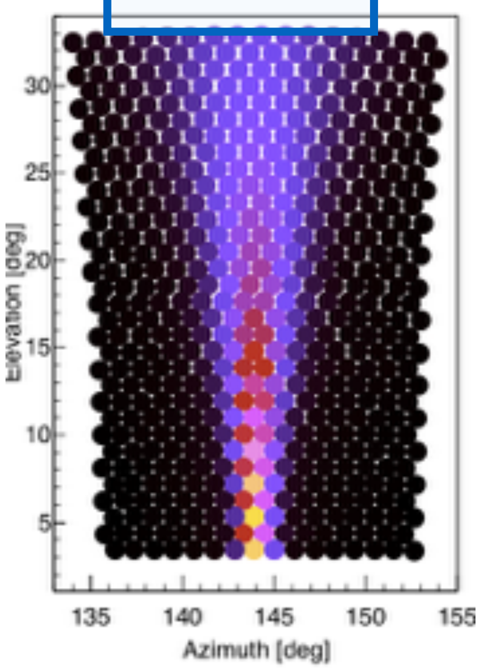
MC process

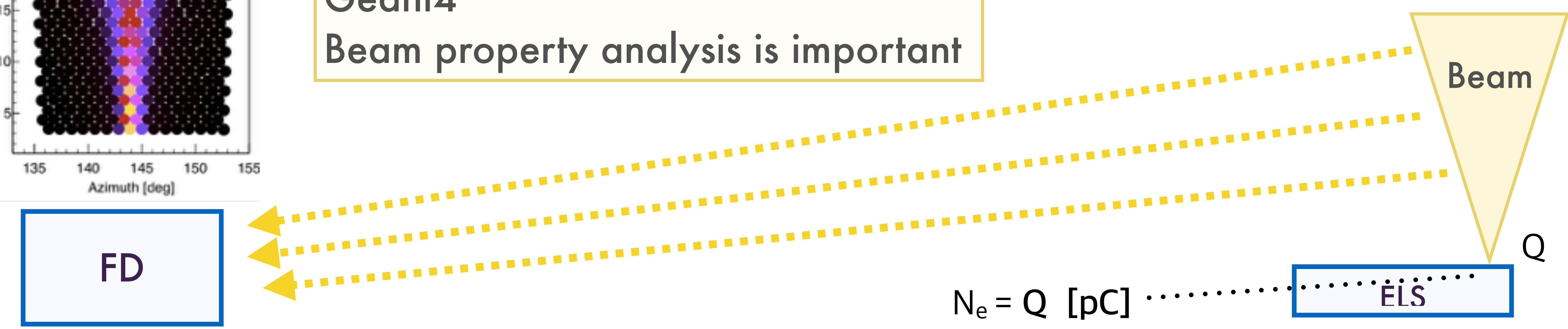
$$Q_{MC} \times dE(E) \times Y \times T_{AIR}(D) \times G = F_{MC}$$

Geant4
Beam property analysis is important

TA software for UHECR analysis

F MAP



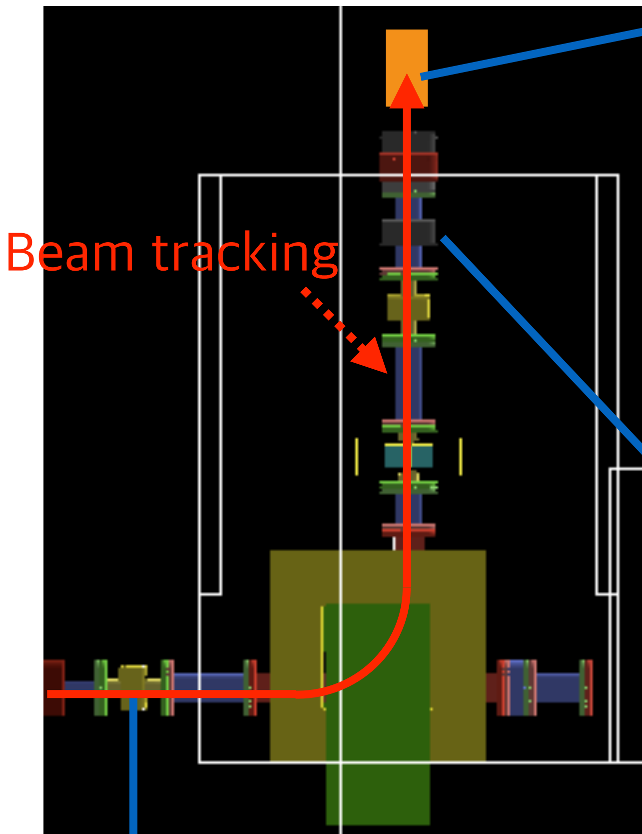


Beam Properties

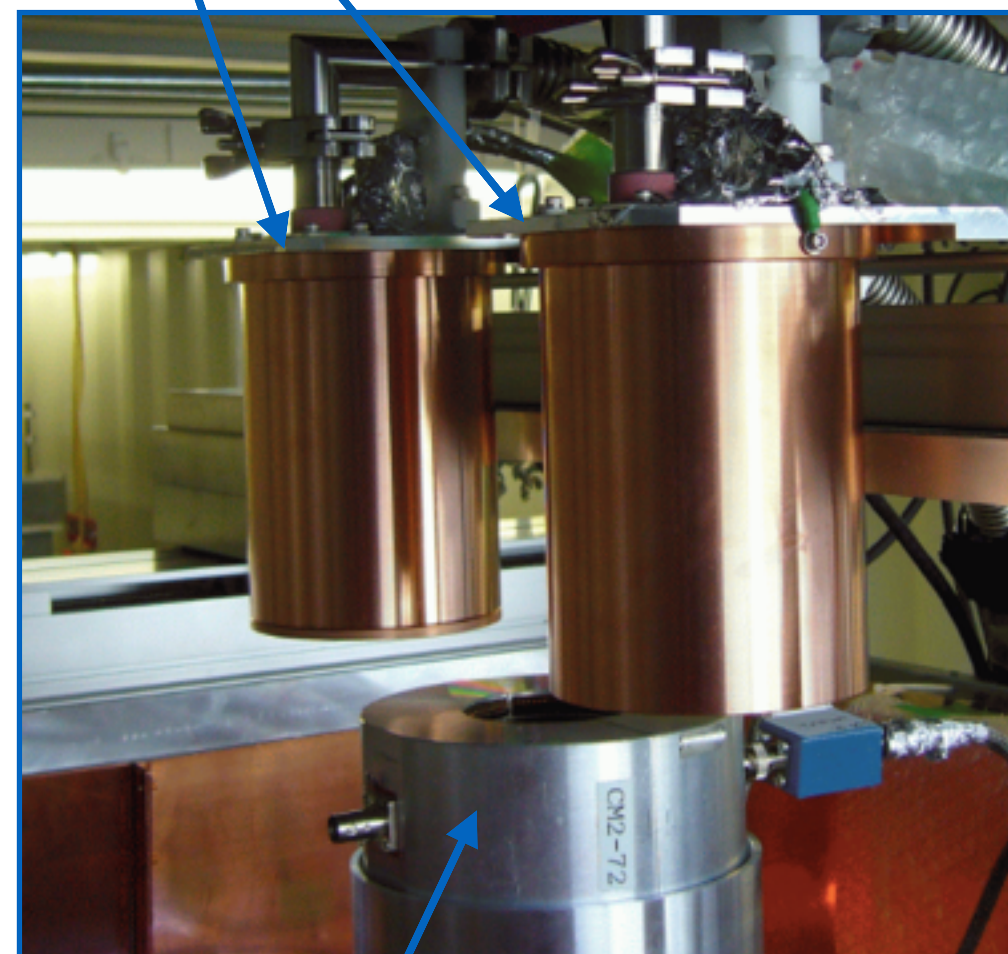
Beam Energy, Spread, Charge(Q)

Beam Measurement devices

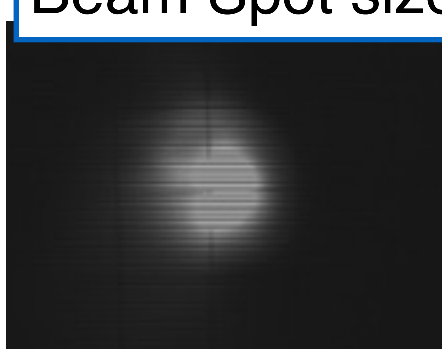
Beam Line Geometry



2 Faraday-cups
- Direct Charge
- Absorb beam



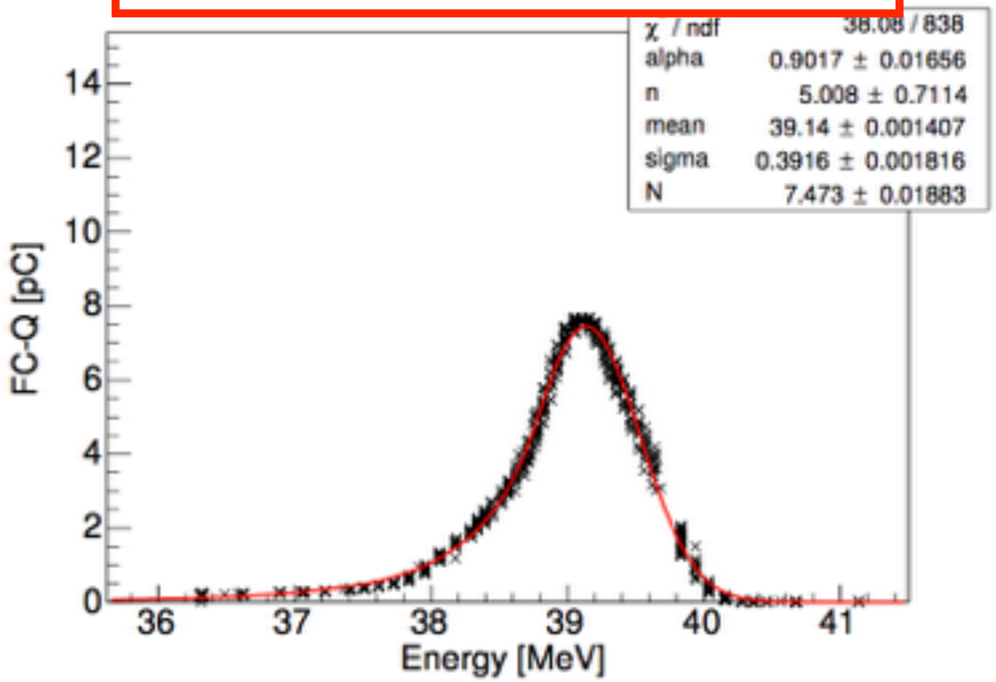
Screen monitor
Beam Spot size



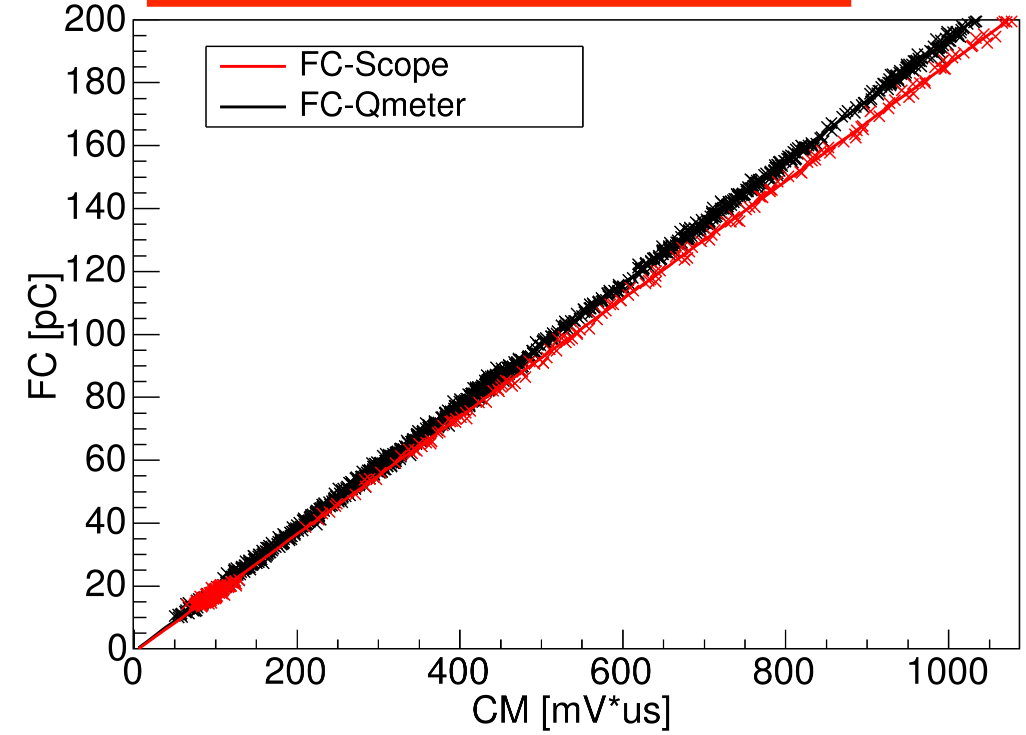
Core-monitor
- Incoherent Charge
- induced current by coils

Measurement of Beam Properties

Beam Energy Distribution.

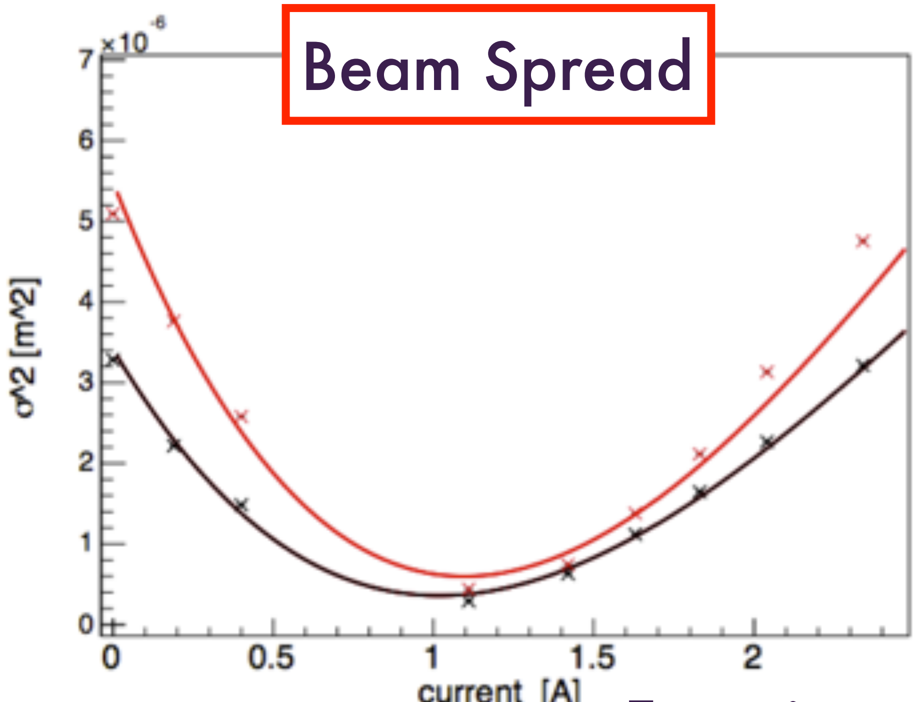


Beam Charge Linearity



Beam Spread

Beam Size



Focusing manget

After measurement of beam properties @ 2014, we could succeed to analyze beam line simulation using Geant4

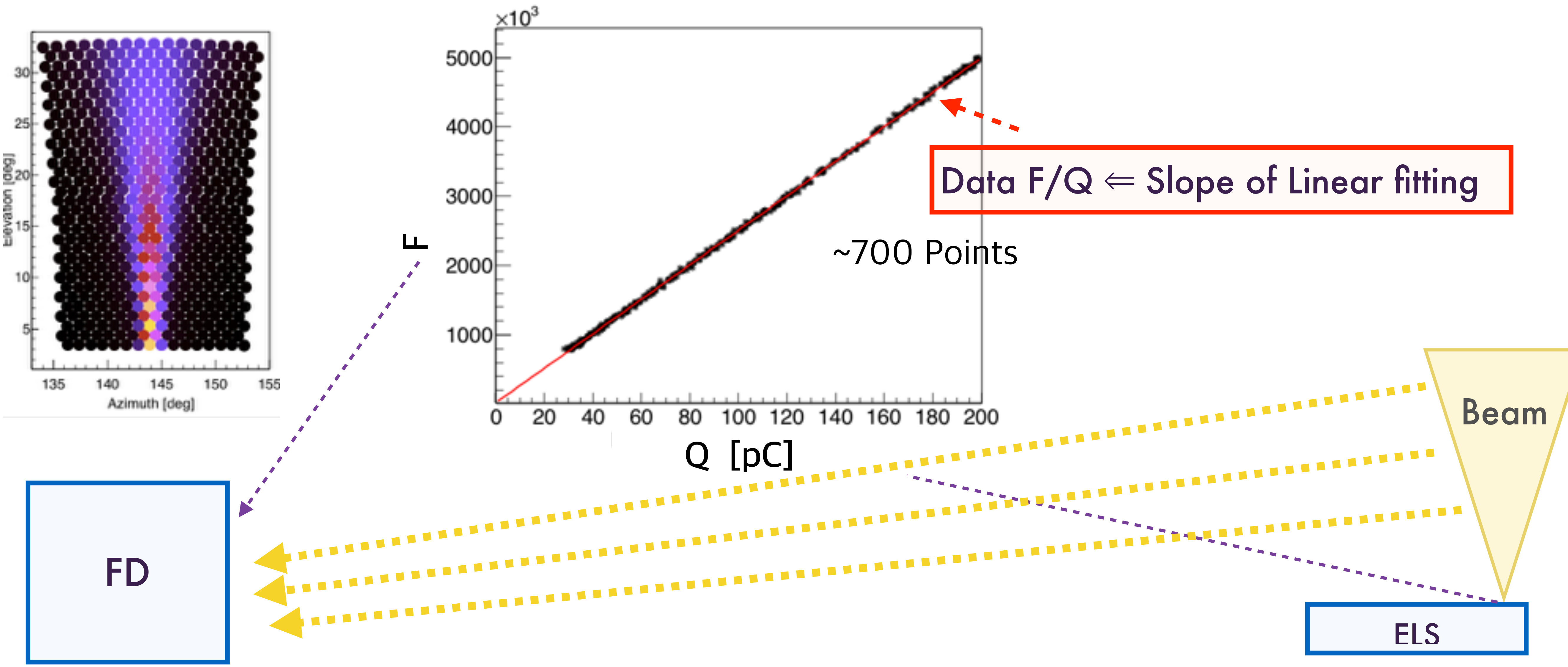
Uncertainty 20%(2013) → 8%(2014)

ELS Analysis

ELS Data Analysis

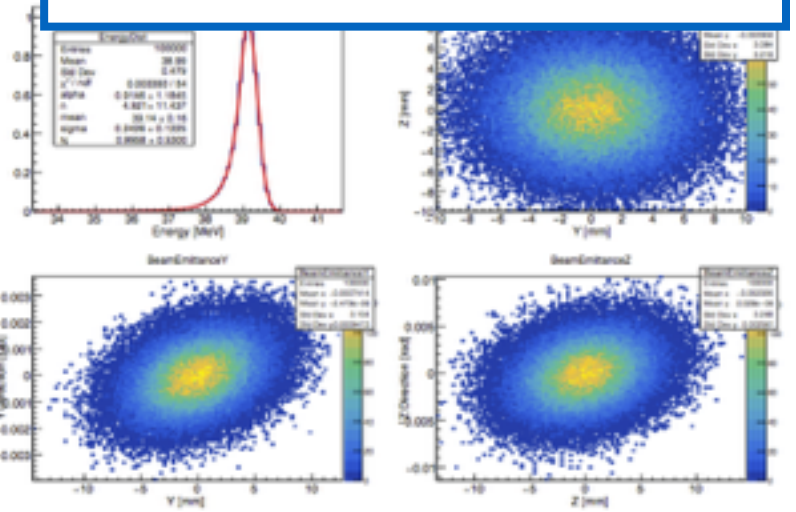
Data/MC

$$C_{ELS} = \frac{F/Q}{F_{MC}/Q_{MC}}$$

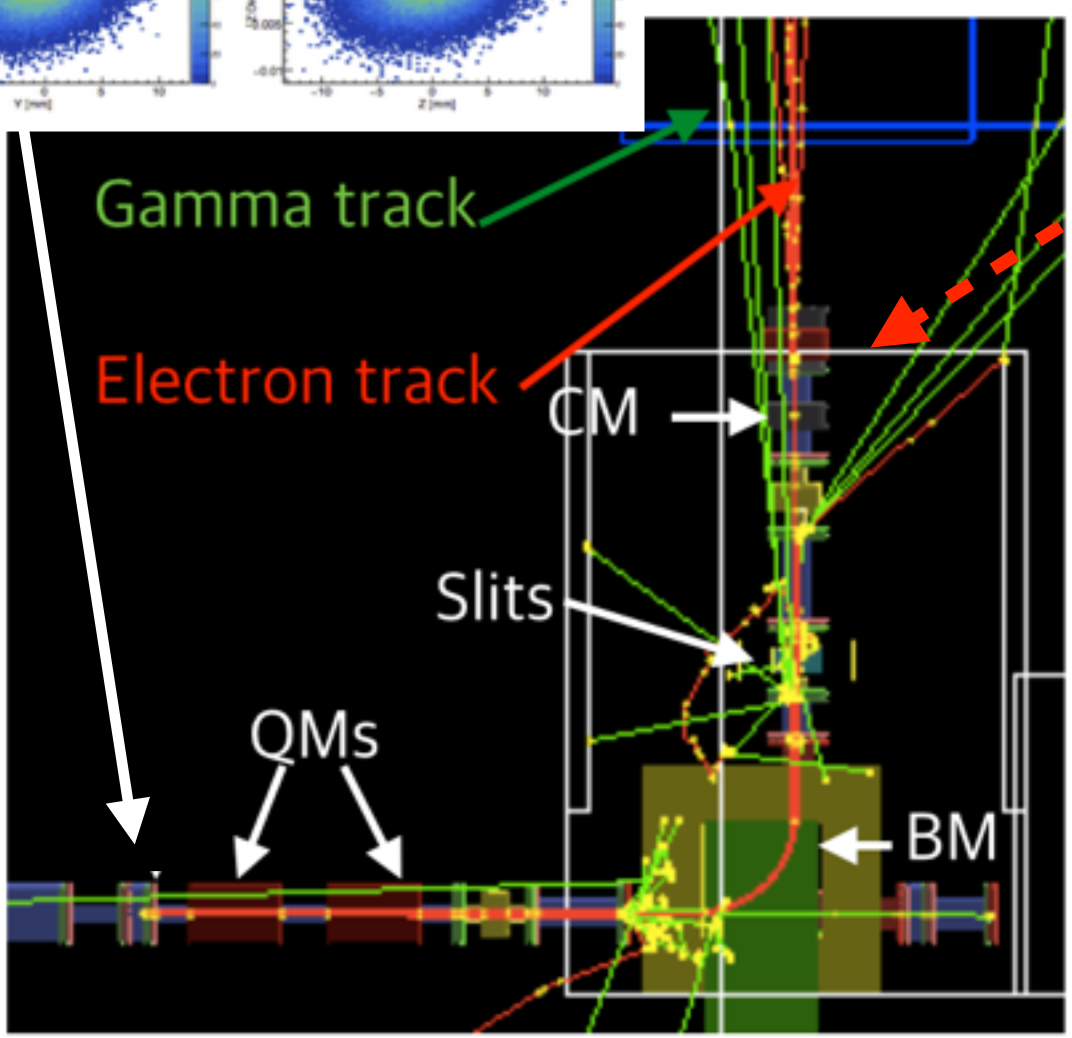


Shower Simulation by Geant4

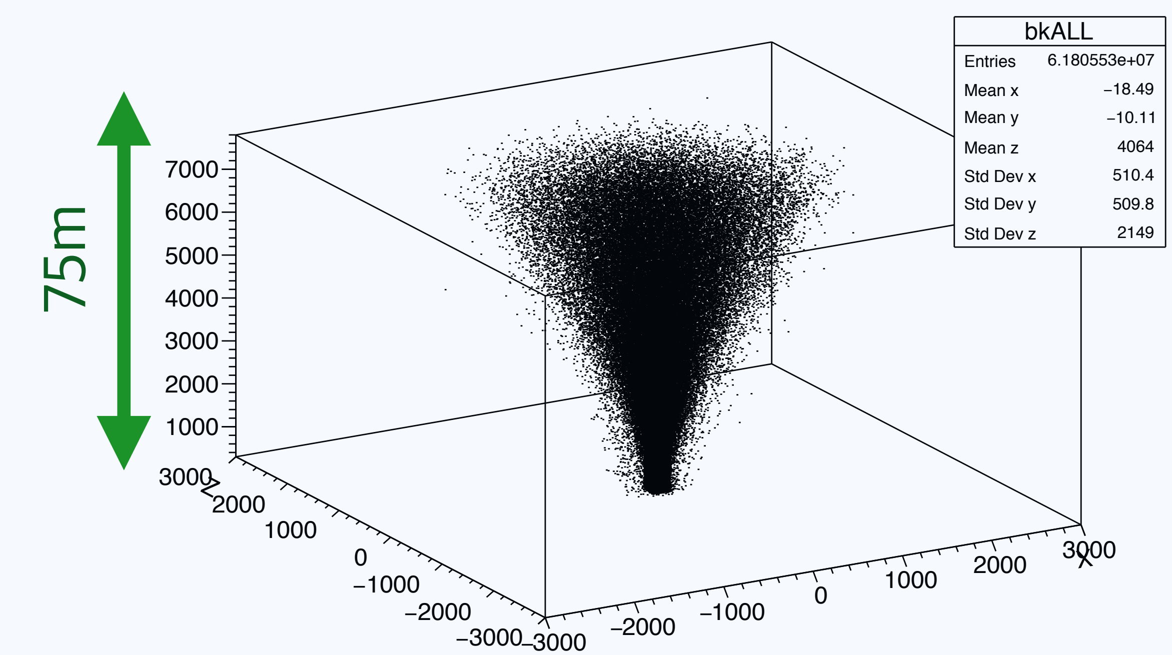
Measured Beam Properties



$$F_{MC}/Q_{MC} = G \times T_{AIR} \times Y \times dE_{MC}/Q_{MC}$$

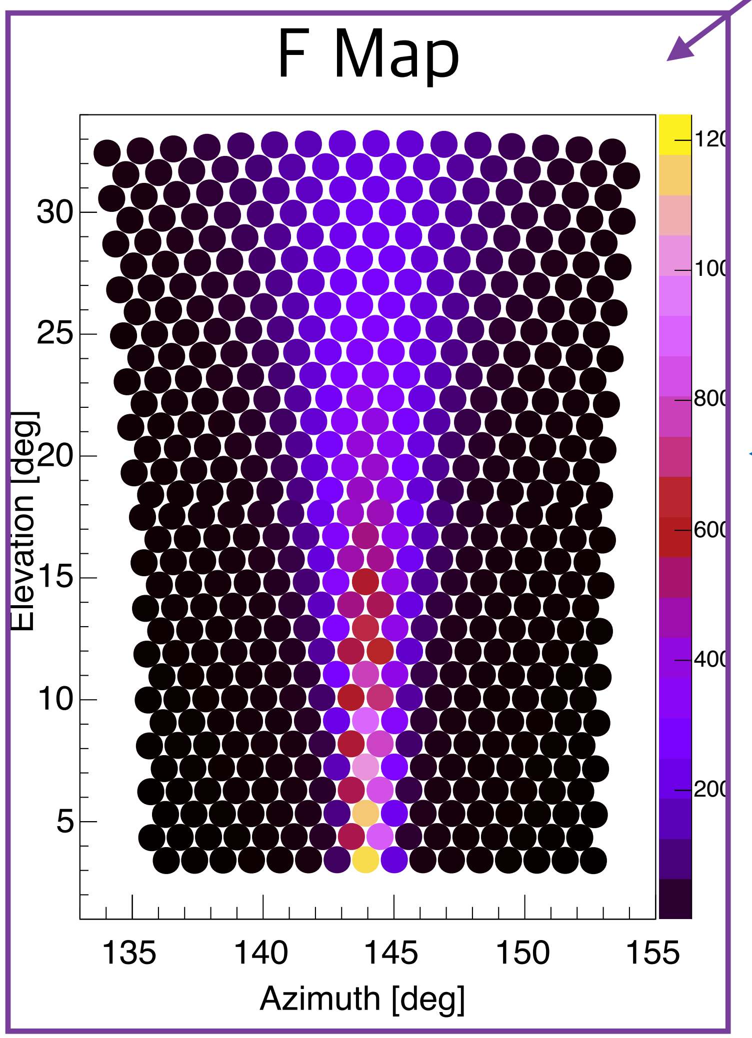


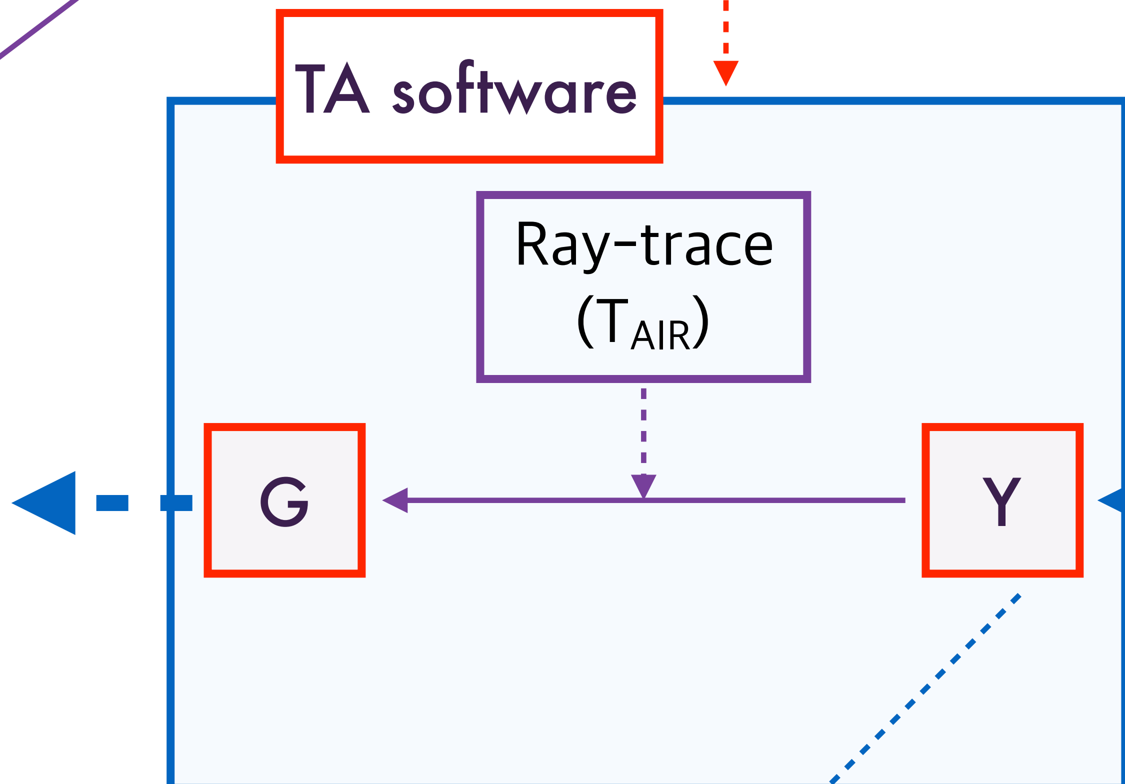
3D dE Map above ELS

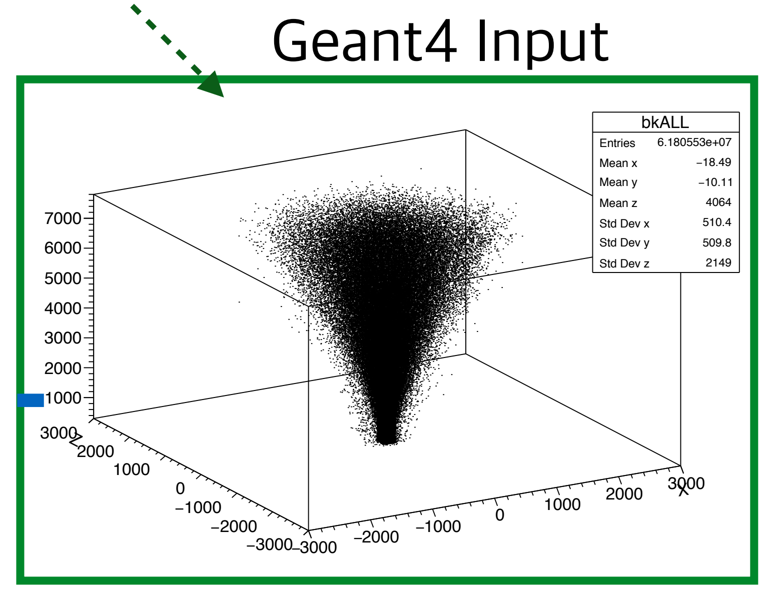


Detector Simulation by TA-soft

$F_{MC}/Q_{MC} = G \times T_{air} \times Y \times dE_{MC}/Q_{MC}$







Y Model	Yield [Np/MeV]	Uncertainty
Y^K (1996) (TA)	15.9	10%
Y^F (2008)	20.8	7%
T^A (2013)	20.6	4%

Result

$$C_{ELS} = \frac{F/Q}{G \times Y \times dE_{MC}/Q_{MC}}$$

Uncertainty 8%

- 6 operation dataset @ 2014

Current TA

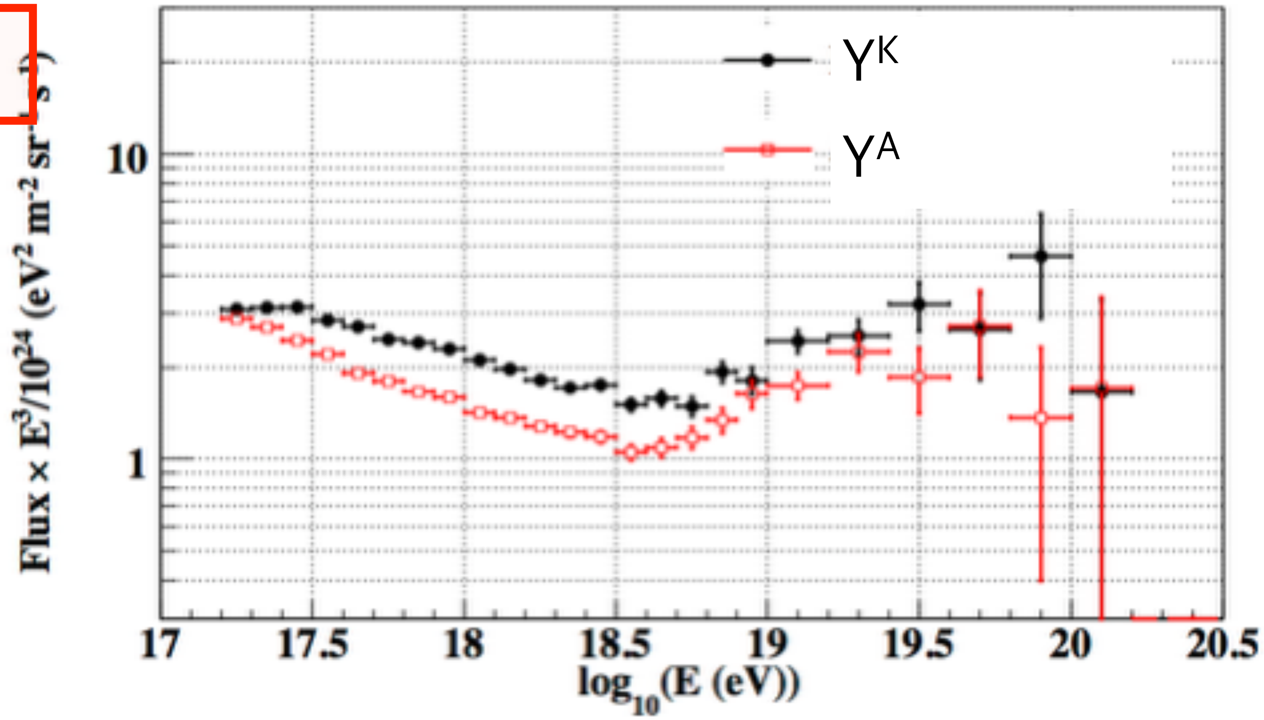
Run	Atmospheric condition			C_{ELS}		
	T [°C]	p [hPa]	H [%]	Y^F	Y^K	Y^A
1	7.3	855.1	29.2	0.998	1.245	1.002
2	6.8	861.8	16.8	0.996	1.245	0.991
3	0.0	865.1	47.9	1.004	1.264	1.016
4	0.4	864.2	47.5	1.010	1.248	1.025
5	-1.5	864.6	63.1	1.025	1.275	1.041
6	-5.0	864.3	71.3	1.017	1.267	1.037
Average				1.008	1.257	1.019

C_{ELS} with Y^A, Y^f agree within uncertainty
C_{ELS} with Y^k is out range of uncertainty

Current TA Energy (Y^K) is ~20% over estimated

Energy Scale Update with ELS

Energy Spectrum



C_{ELS} with Y^A = 1.02

Uncertainty

		Current TA	2016	Future?
ELS	σG	11%	8%	3%
	σAFY	11%		
σT_{AIR}		11%	11%	5~10%
σE_{recon}		10%	10%	5~10%
$\sigma Total$		21%	17%	7~14%

Summary

- ELS: The world first energy calibration source.
  - Calibration from electron to FD detection by one source

- ELS Data/MC C_{ELS} Analysis with data
  - $C^A_{ELS} = 1.02$, $C^F_{ELS} = 1.01$ ← Agree within uncertainty
  - $C^K_{ELS} = 1.26$ (Current TA) ← Disagree
  - TA energy scale is 20% over-estimated

TA Energy Scale meeting:
2015/Sep.~Dec

- **TA should use ELS calibration**

TA Energy reconstruction uncertainty 21% → 17%

To be updated @ TA Meeting 2015 Dec/18th~20th

ELS Applications

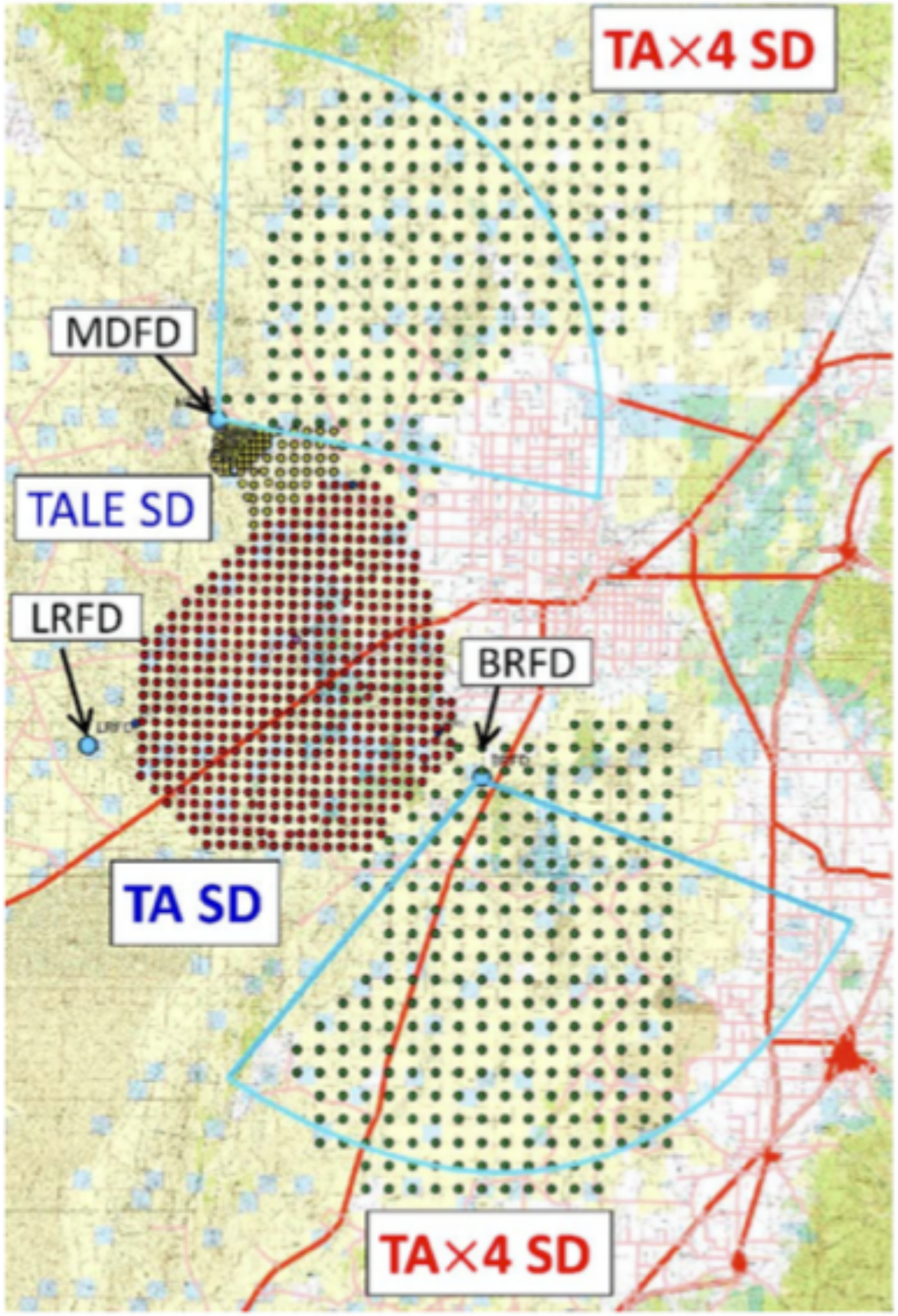
To be world standard calibration source

for future observatory

Future Observatory

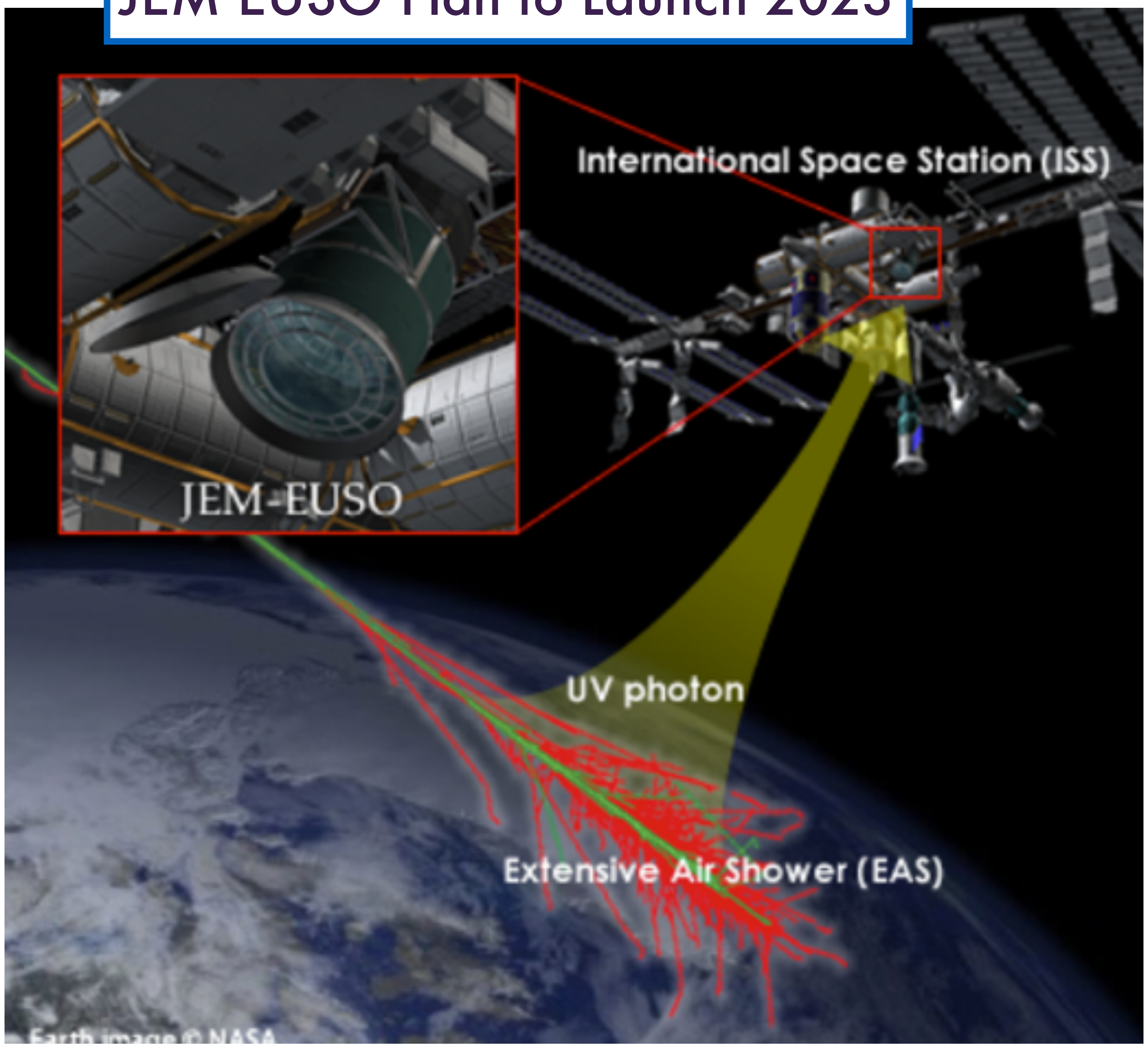
TA×4

- Quadrule TA SD (~3000 km²)
  - 500 scintillator SDs
    2.08 km spacing
- 2 FD stations
- Proposals
  - SD: approved in Japan in April 2015
  - FD: submit in US in October 2015
- Get 19 TA years of SD data by 2010
- Get 16.3 TA years of hybrid data
  - 2.7-year construction
    - TA in operation
  - 2.3-year observation



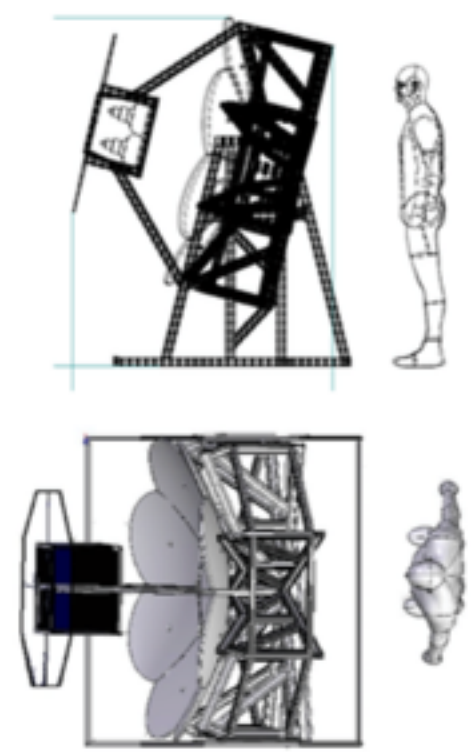
Future FD type Detectors

JEM EUSO Plan to Launch 2023



Aperture: TA × 100~500

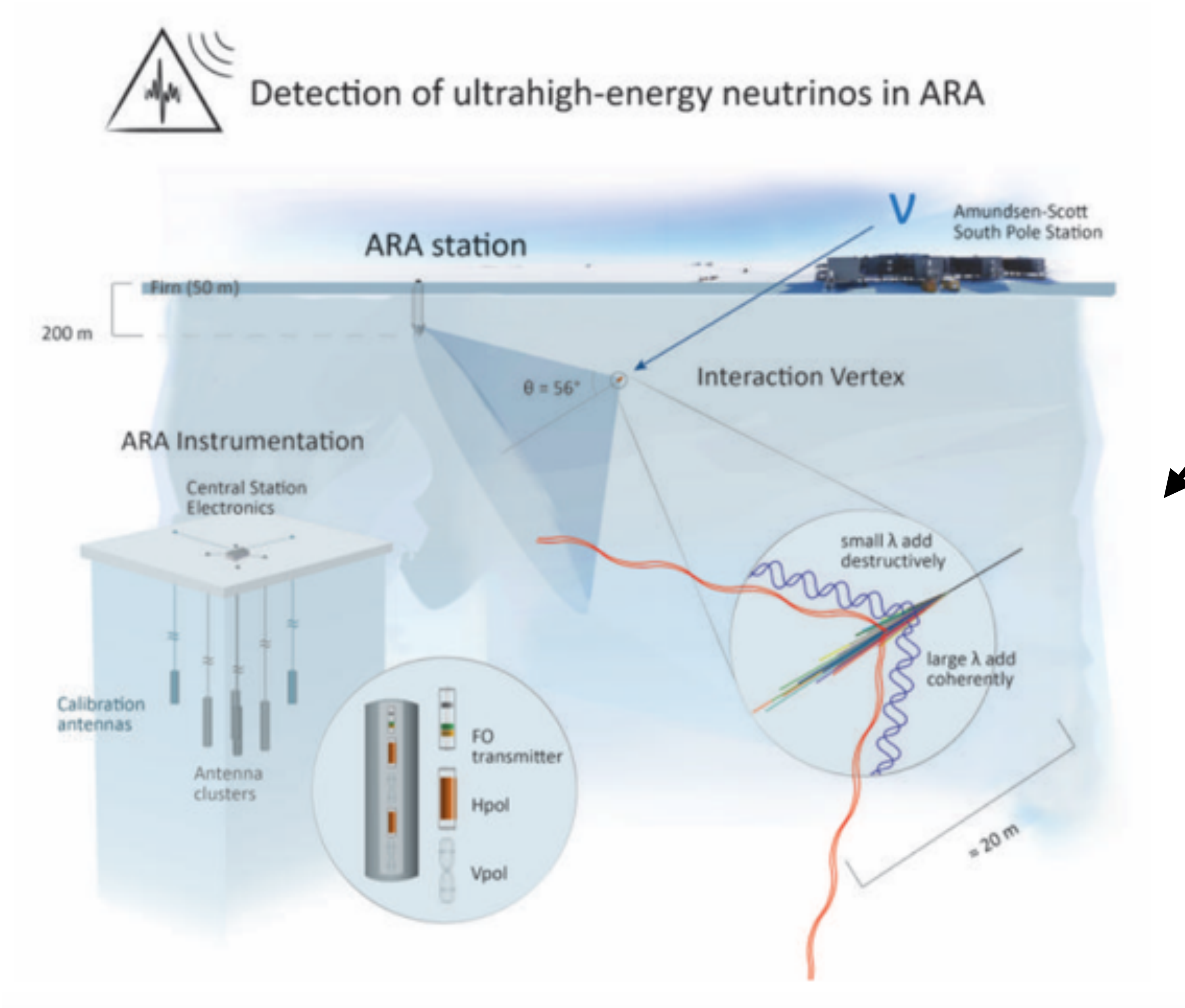
FAST



TA: 256 Pixels/T ,total 38T
FAST: 4 Pixels/T, many telescope

Askaryan Radio Array

- ARA (branch of ICE-CUBE)
- Neutrino Detector with Antenna



ICE-Cube

ELS collaboration

Energy calibration for FD detector

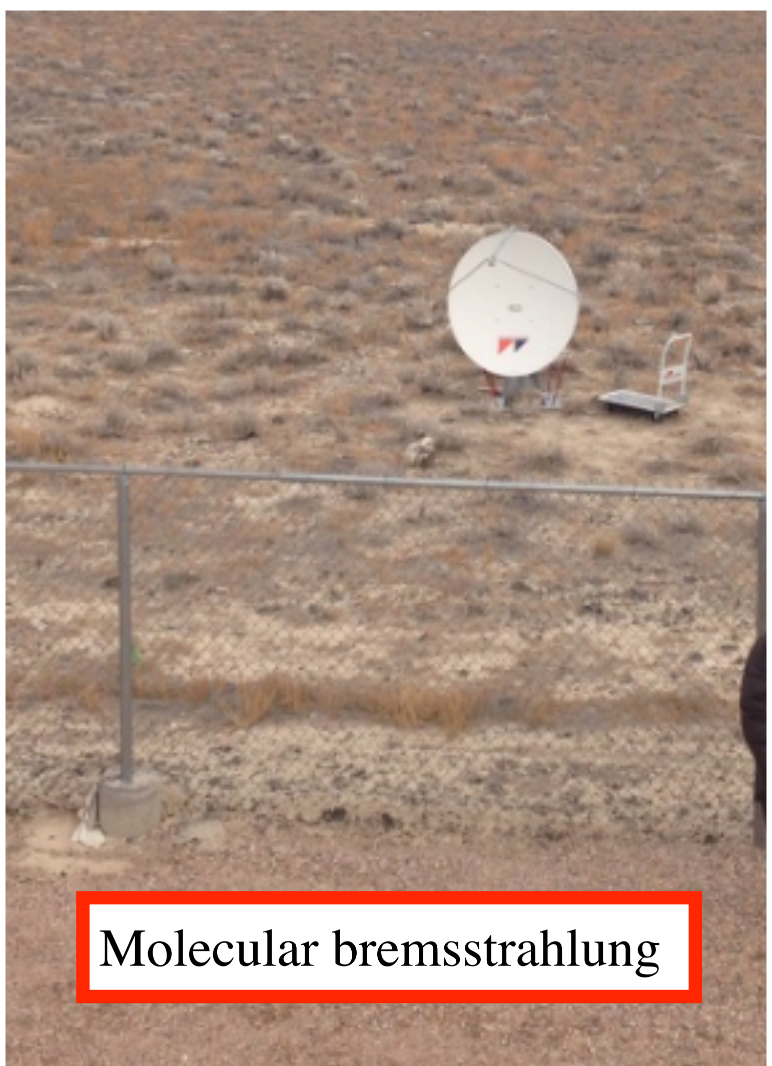
TA-EUSO House
EUSO telescope installed at 2015 & Aim ELS
UHECR obs rate of EUSO is 1/month
ELS is important crosscheck source

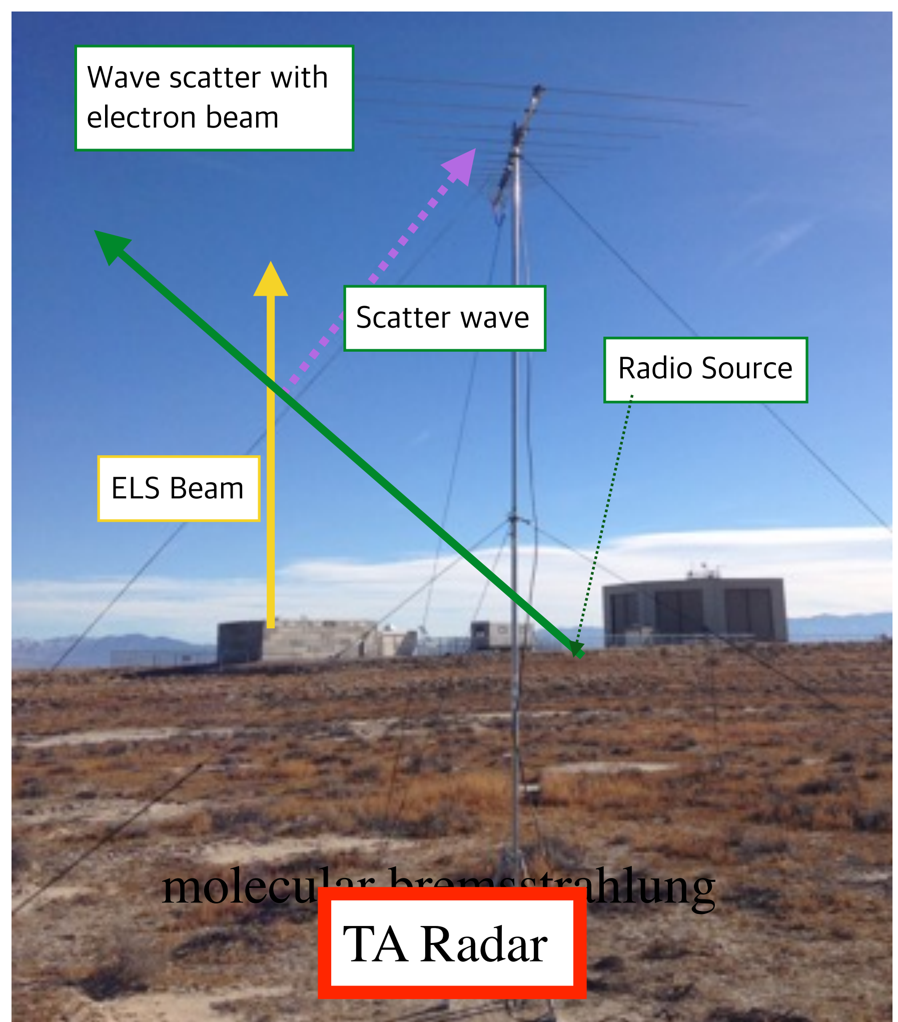
After finishing TA-EUSO test, FAST will crosscheck with ELS

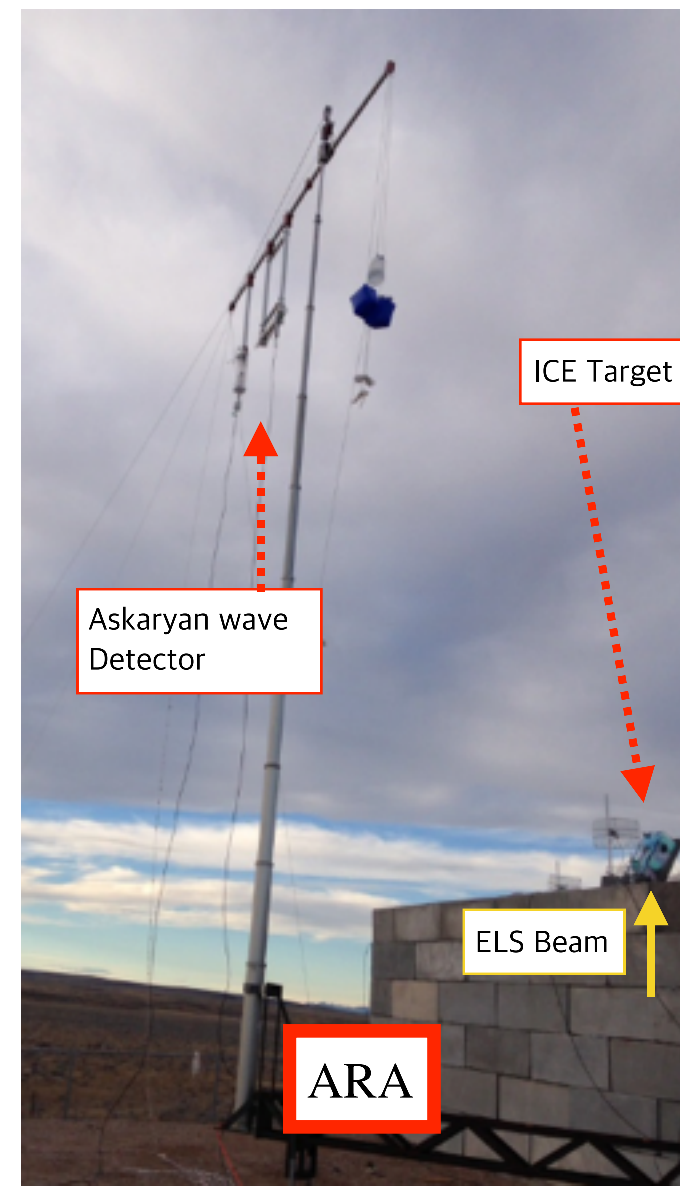
Radar Detector Calibration

ELS is unique source to inject beam into air.

Now ELS collaborate with 3 Radar detection R&D groups







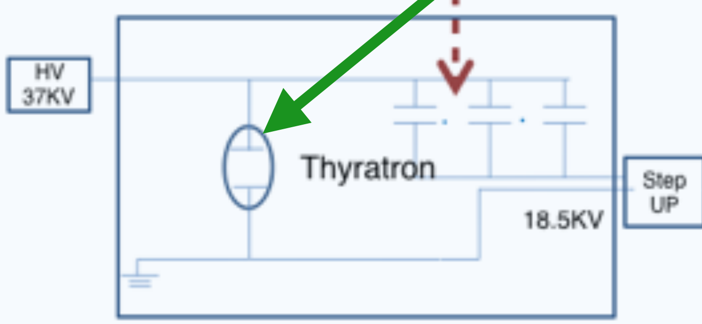
Back up

Radio Frequency Unit

High power pulse modulator

Source for RF amplification, electrons emission

18 condensers



Thyratron
Switch for high voltage

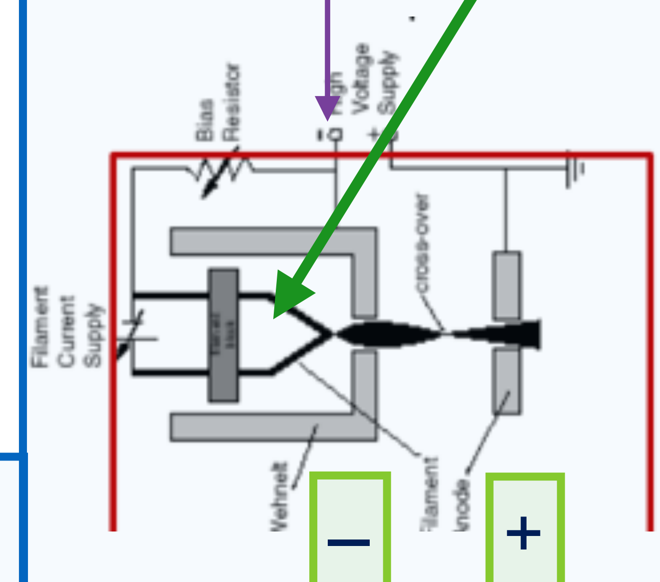
repetition rate of 0.5 Hz

300kV

E-gun

Filament:
Thermal electrons

100kV



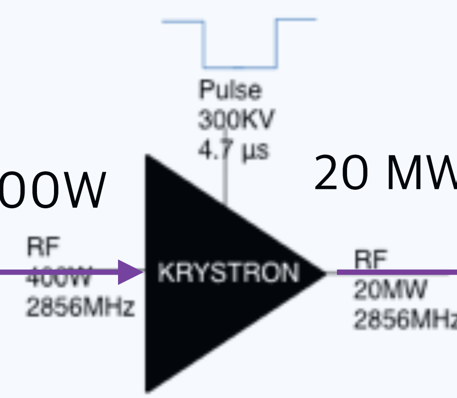
RF module

RF 2856MHz

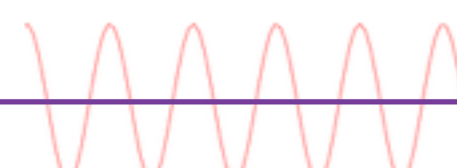
2 µs

400W

20 MW

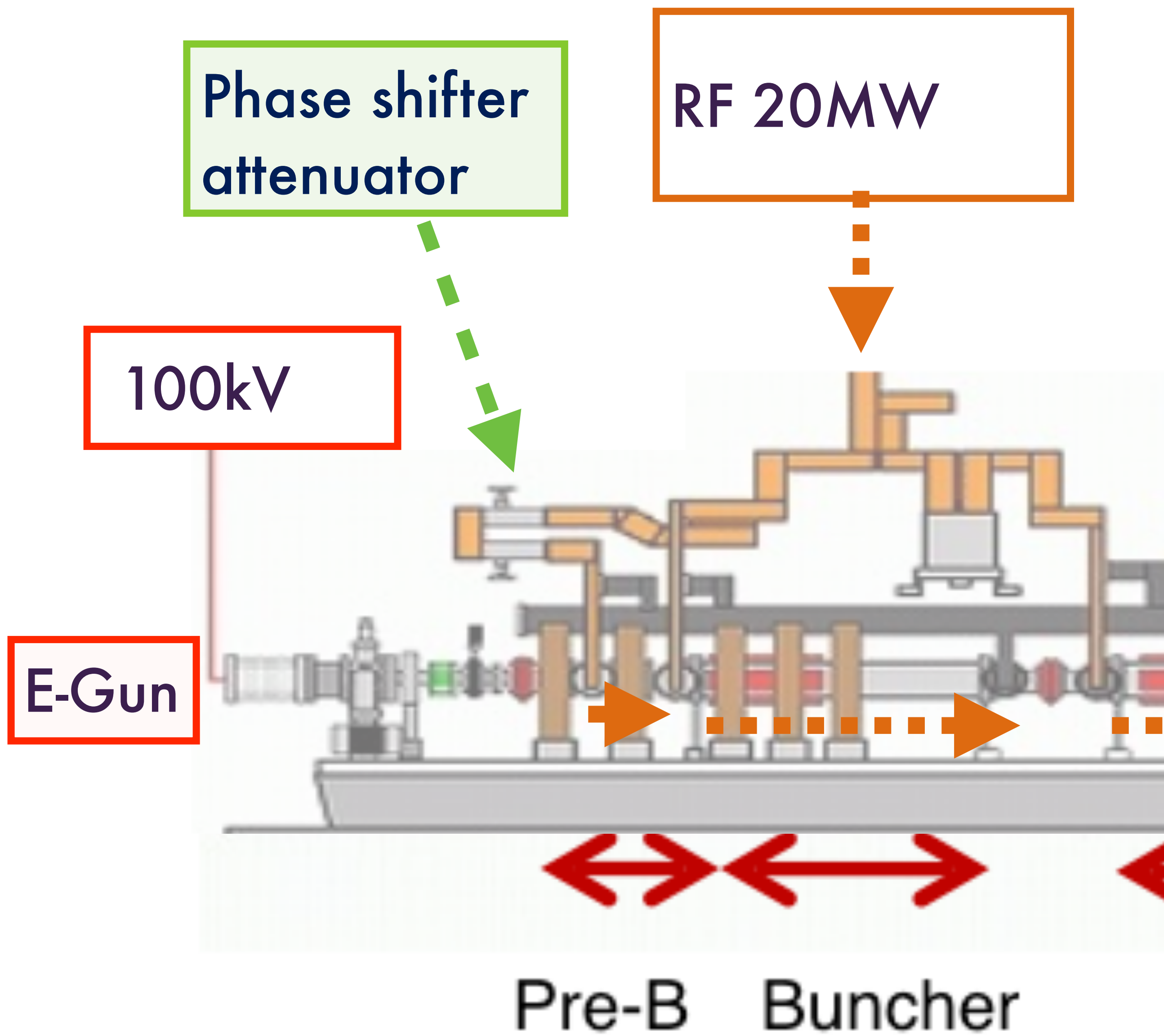


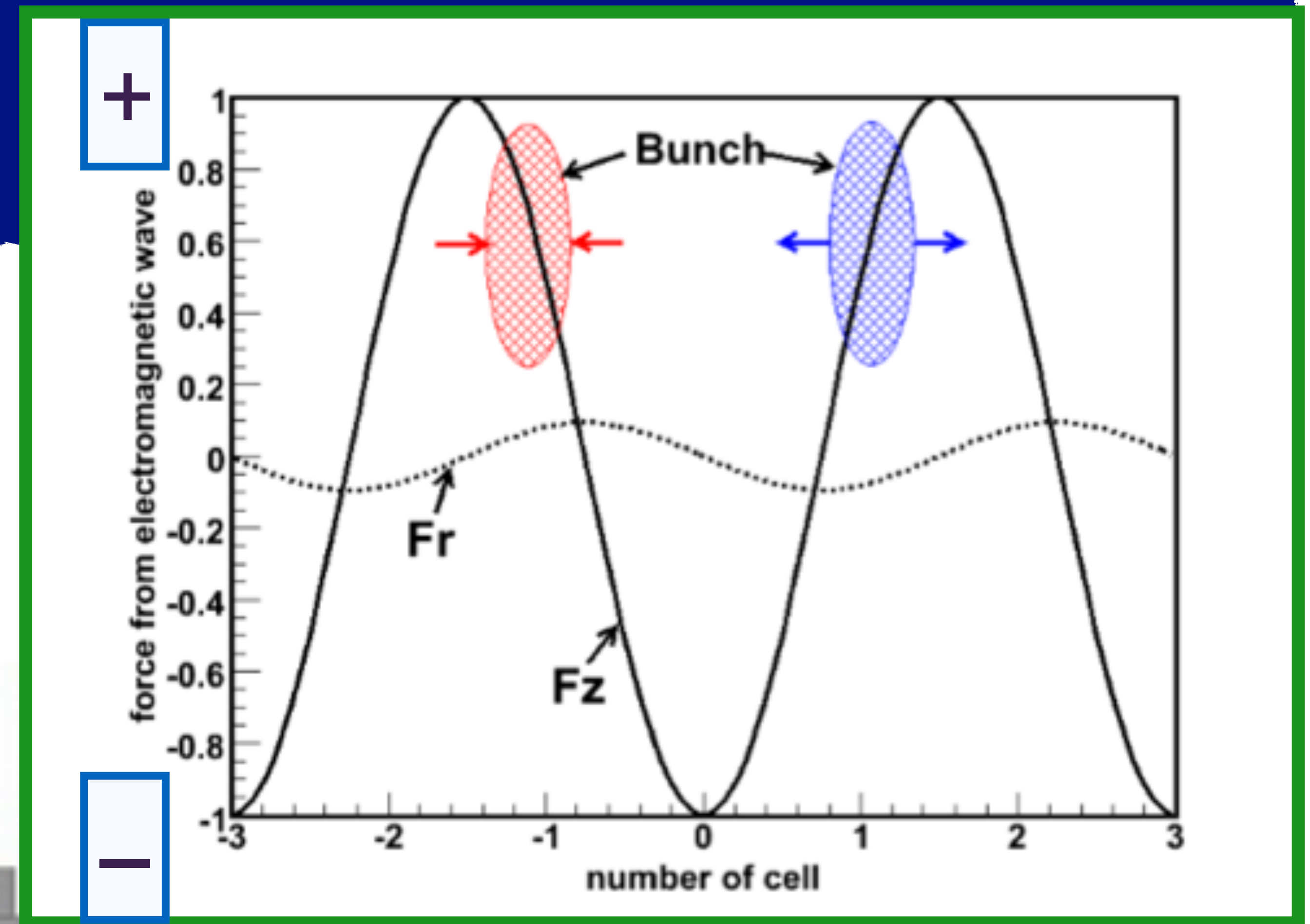
KRYSTRON

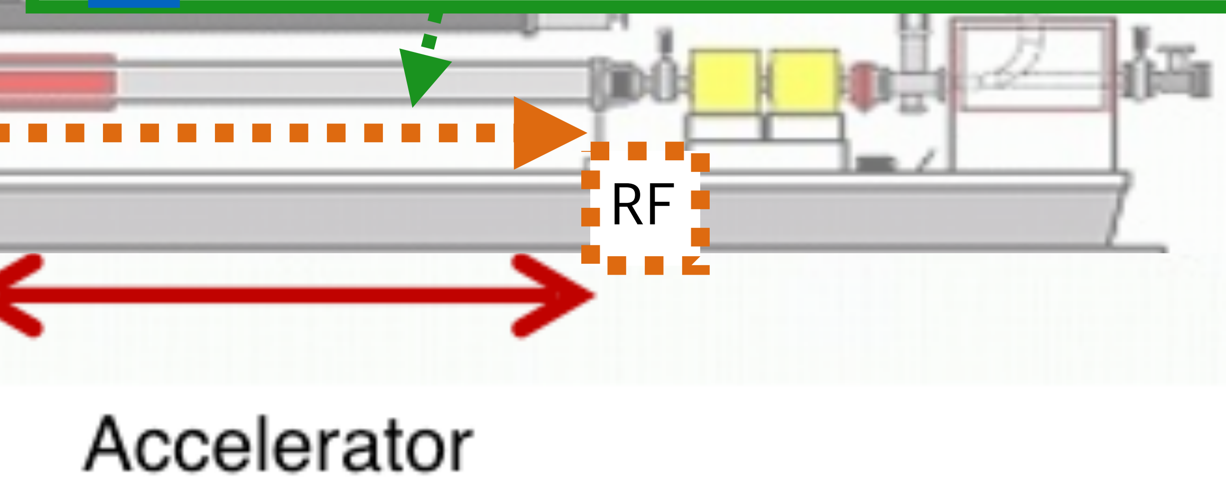


Accelerator

Accelerator Unit







Pre-B: Phase adjust
Buncher: bunch divider
Accelerator: Energy accelerator 40 MeV

Safety

Must Operate with RSO: Radiation Safety Officer (=faculty)

Radiation Protection

0.1 mrem/op = 1μSv/op

Interlock System

3step interlock system

Safety Running

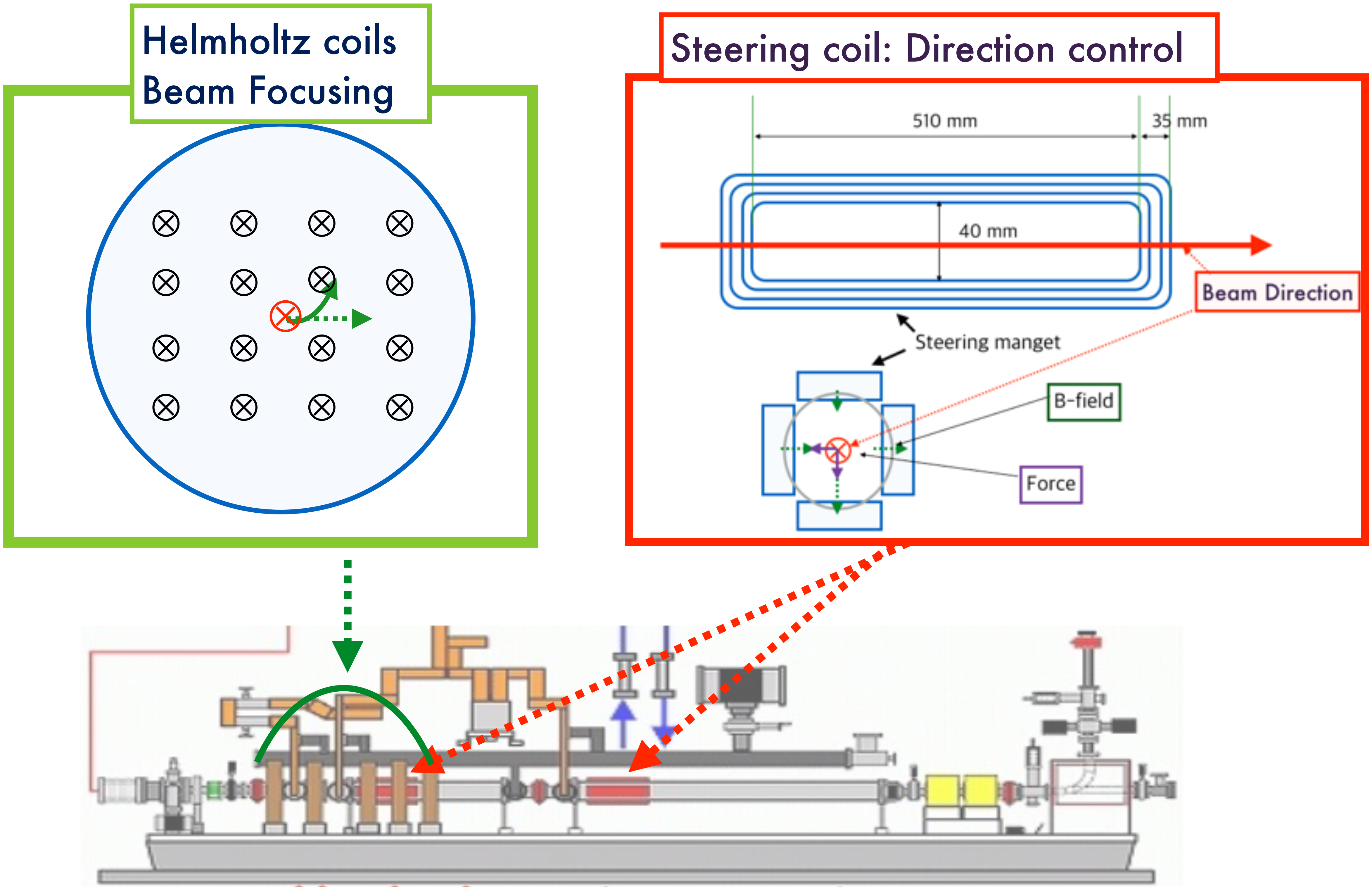
Magnets

Focusing: Helmholtz coils, Quadruple Magnets

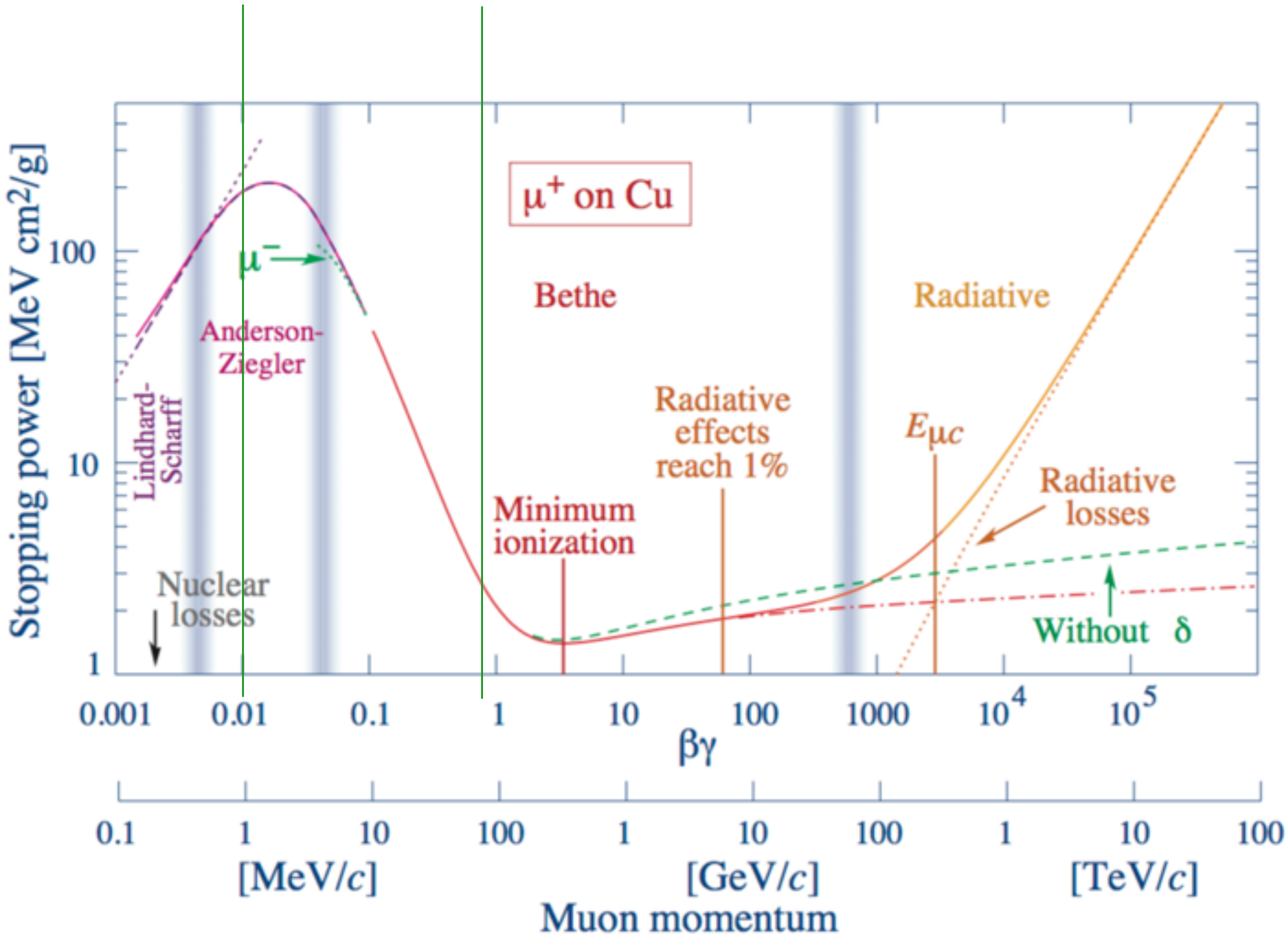
Steering : Steering coils

90° Bending: Bending manget

Magnets(1)


Helmholtz coils
Beam Focusing
Steering coil: Direction control
510 mm
35 mm
40 mm
Beam Direction
Steering manget
B-field
Force

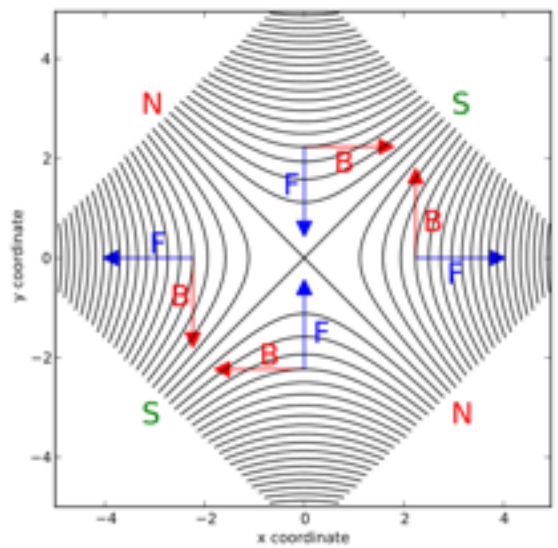
Plan2



μ⁺ on Cu
Stopping power [MeV cm2/g]
100
10
1
Lindhard-Scharff
Anderson-Ziegler
μ⁻
Nuclear losses
Bethe
Radiative
Radiative effects reach 1%
Minimum ionization
Eμc
Radiative losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

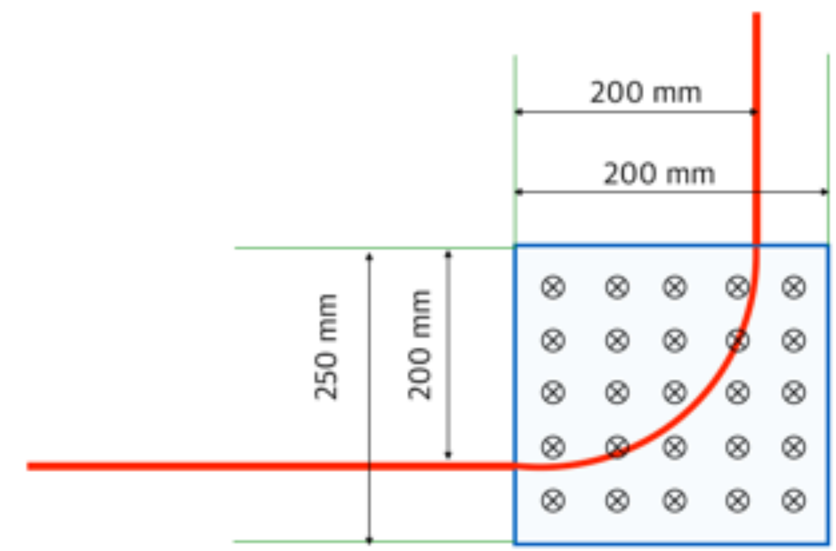
Magnet(2)

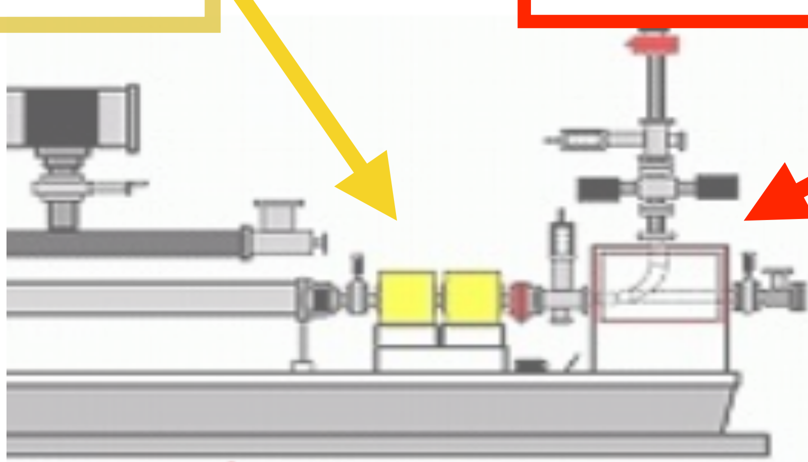
Helmholtz coils
Beam Focusing

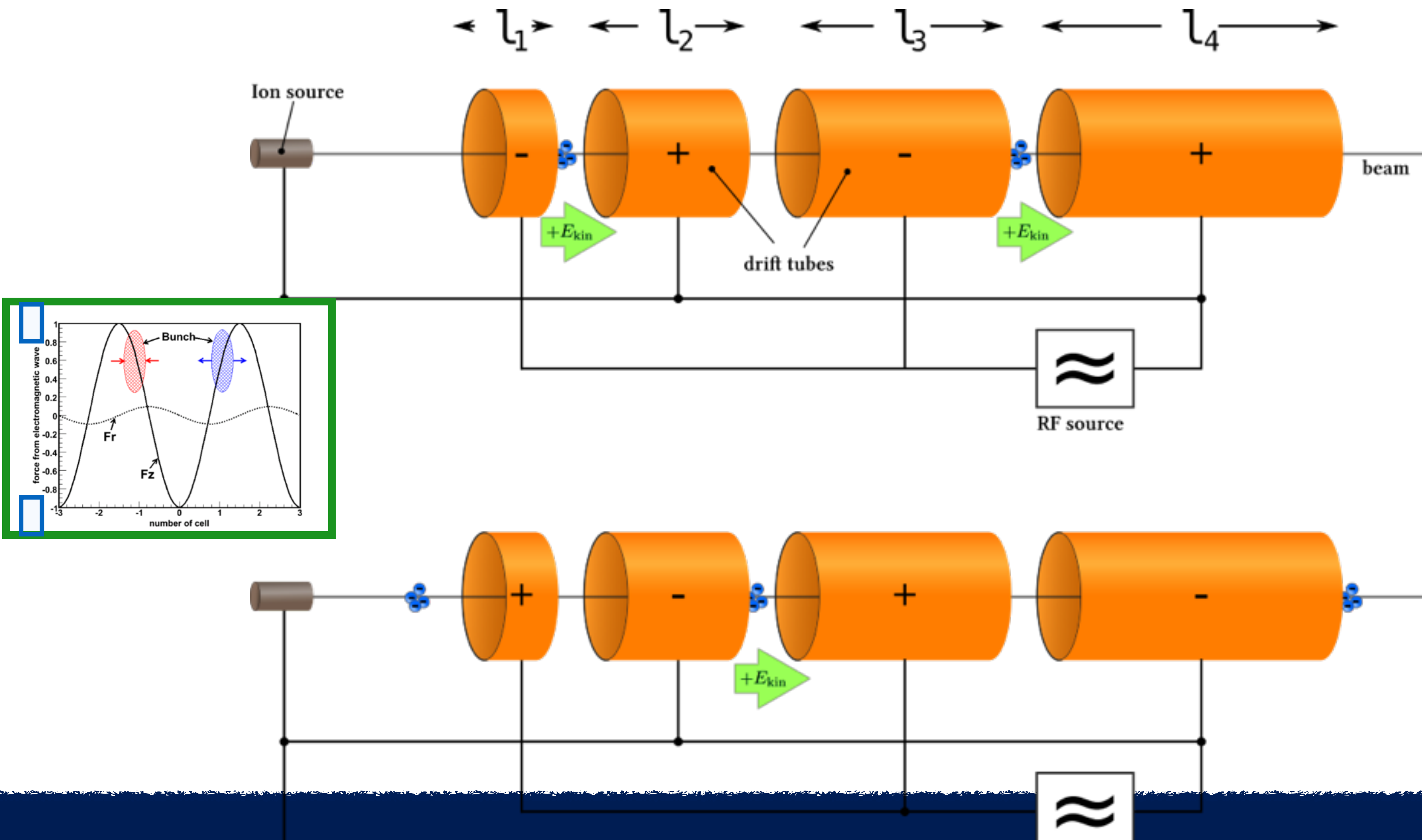


QM1 : Vertical focusing
QM2 :Horizontal focusing

Bending magnet: Direction control



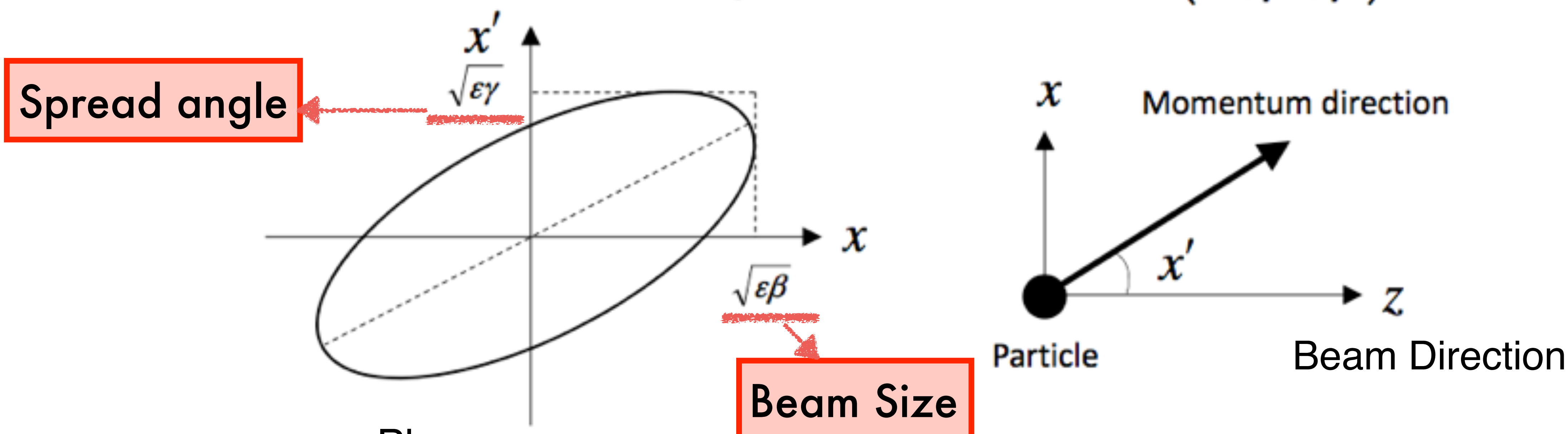




l_1
l_2
l_3
l_4
Ion source
beam
drift tubes
RF source
$+E_{kin}$
Bunch
Fr
Fz
force from electromagnetic wave
number of cell

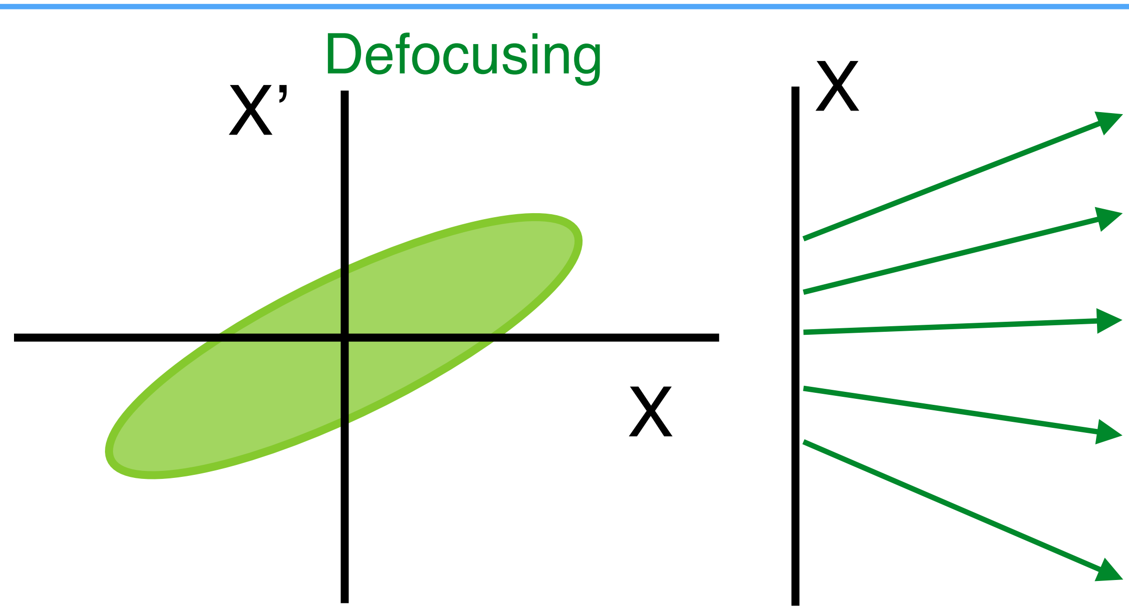
Twiss parameter & emittance

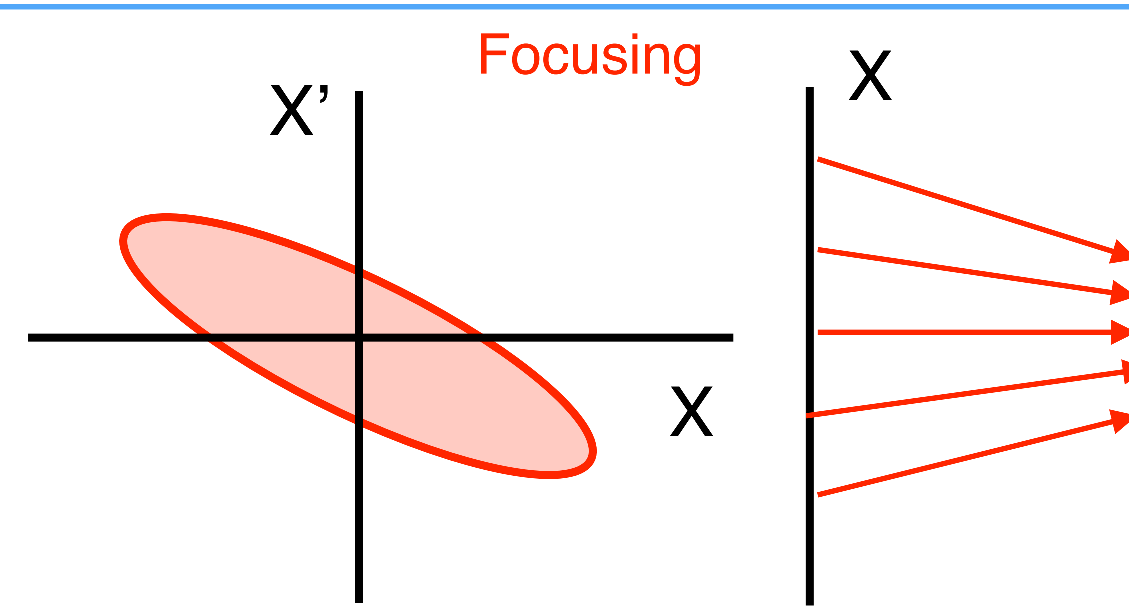
Emittance is defined by **Twiss Parameters** (α, β, γ)



Phase space

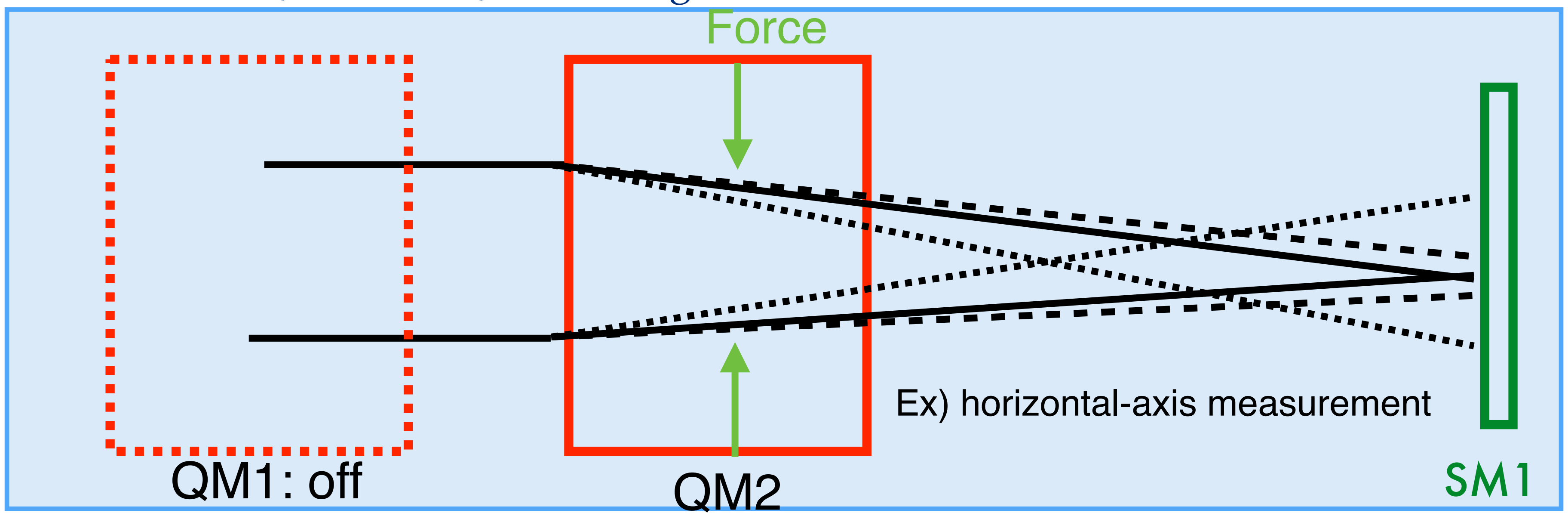
$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon$$





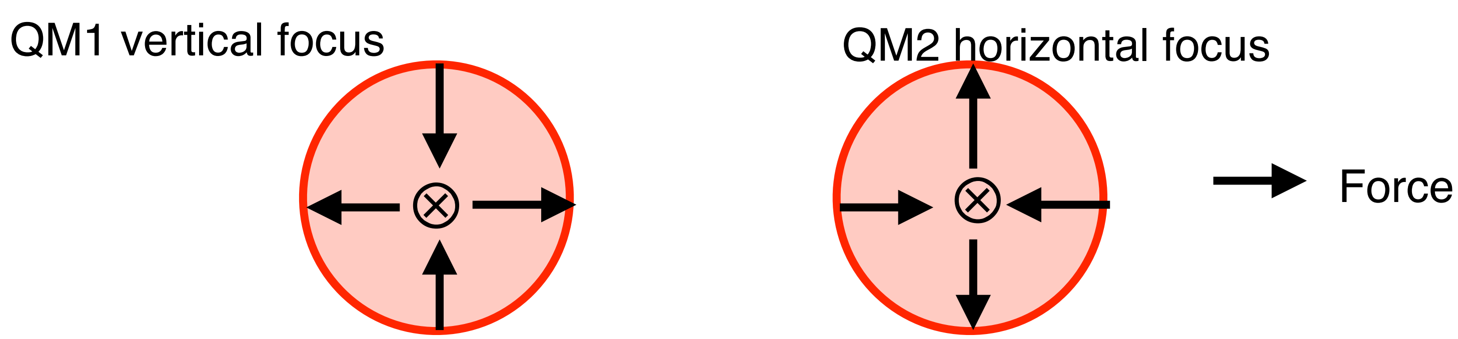
Twiss & Emittance Mesurement

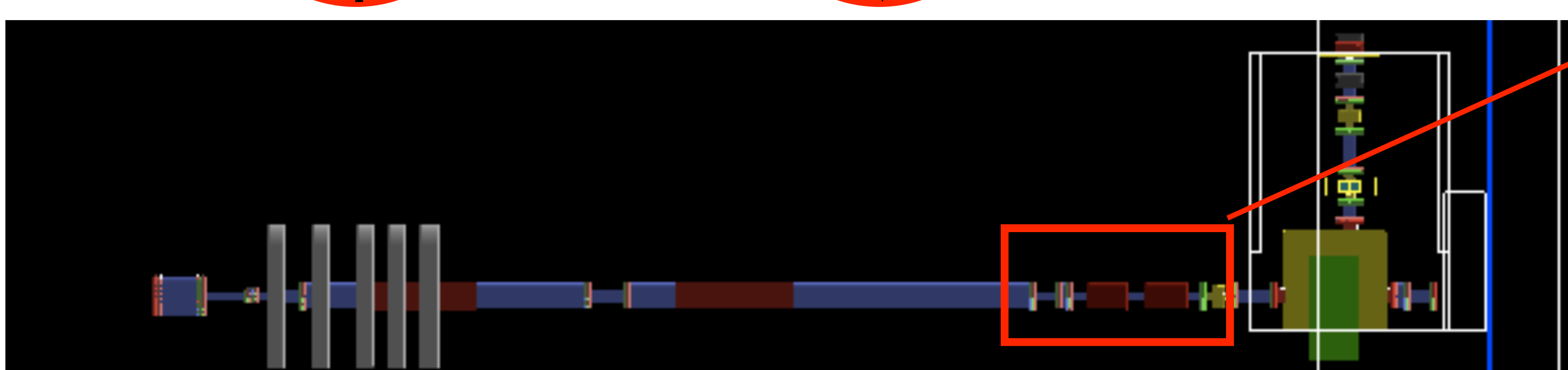
- Q-Scan : Using QuadrupoleMagnet(QM) , Screen Monitor (SM)
  - Vertical-axis : QM1 : change force, QM2 : off
  - Horizontal-axis : QM1 : off, QM2 : change force

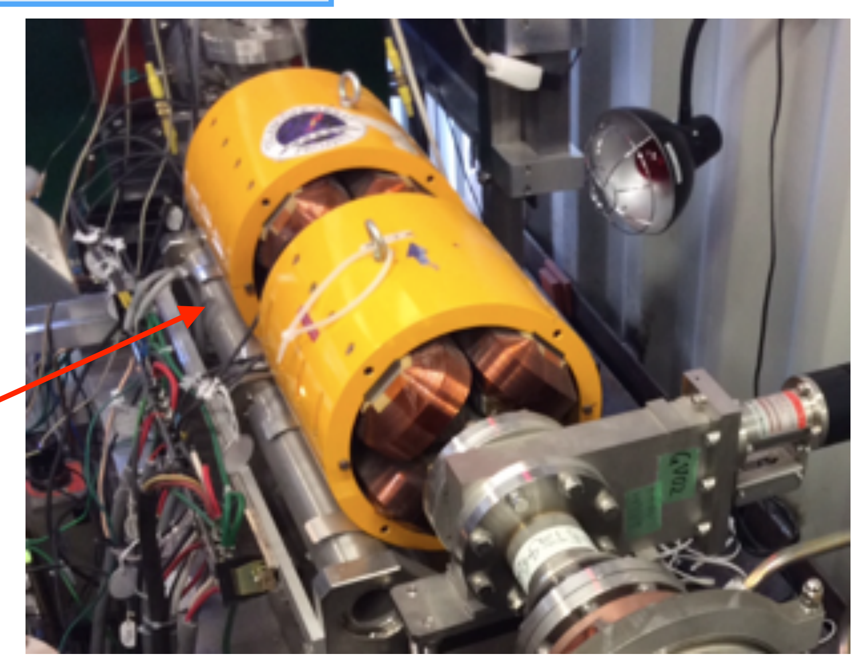


$\sigma^2 = \varepsilon\beta_1$

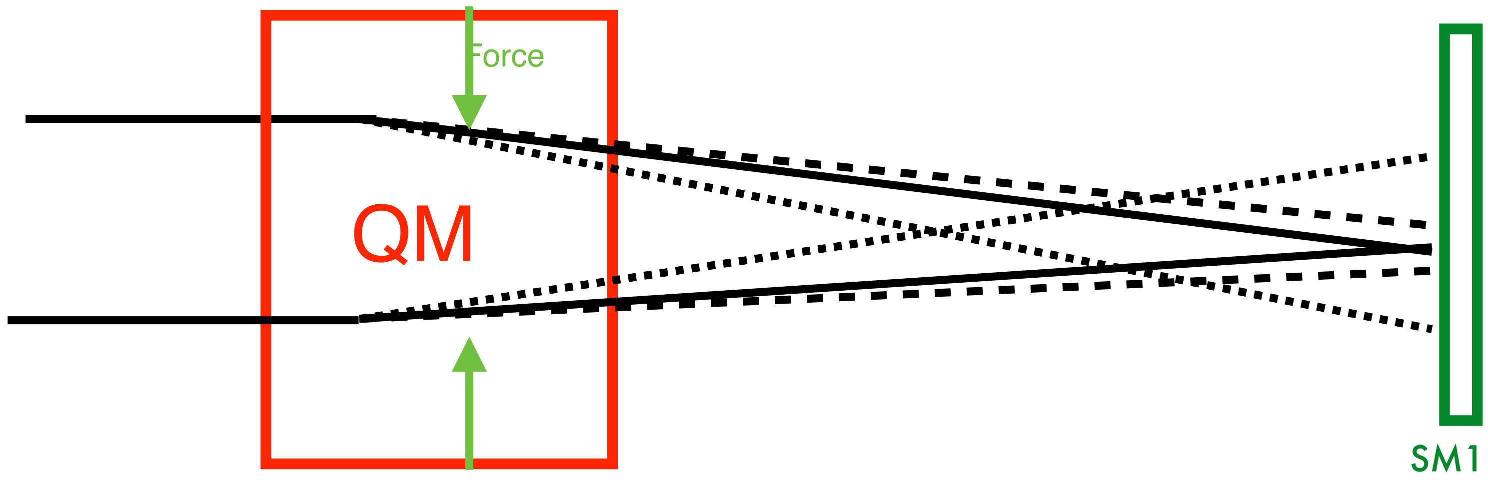
σ : Beam size







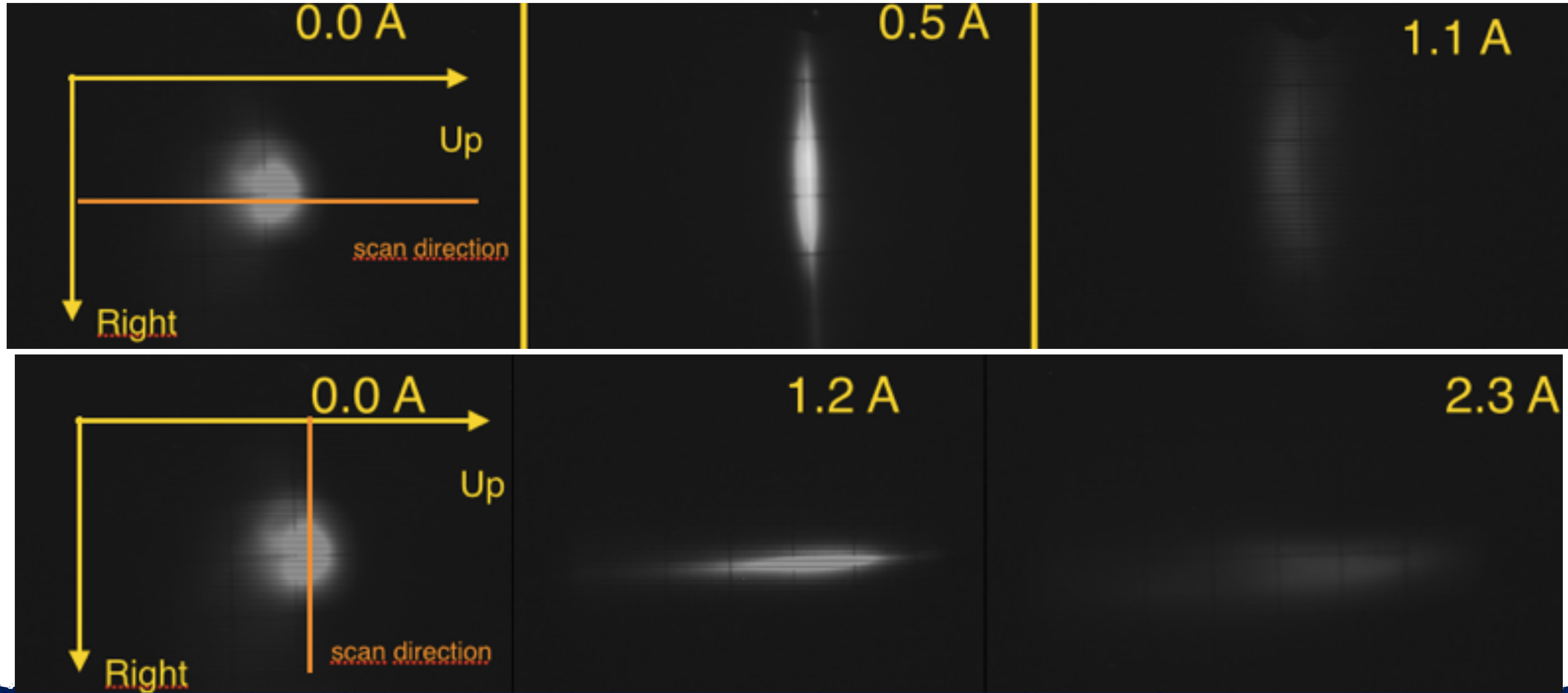
Example Q-Scan



Vertical emittance : Using QM1 (QM2 off)
Horizontal emittance : Using QM2 (QM1 off)

QM1(V)

QM2(H)

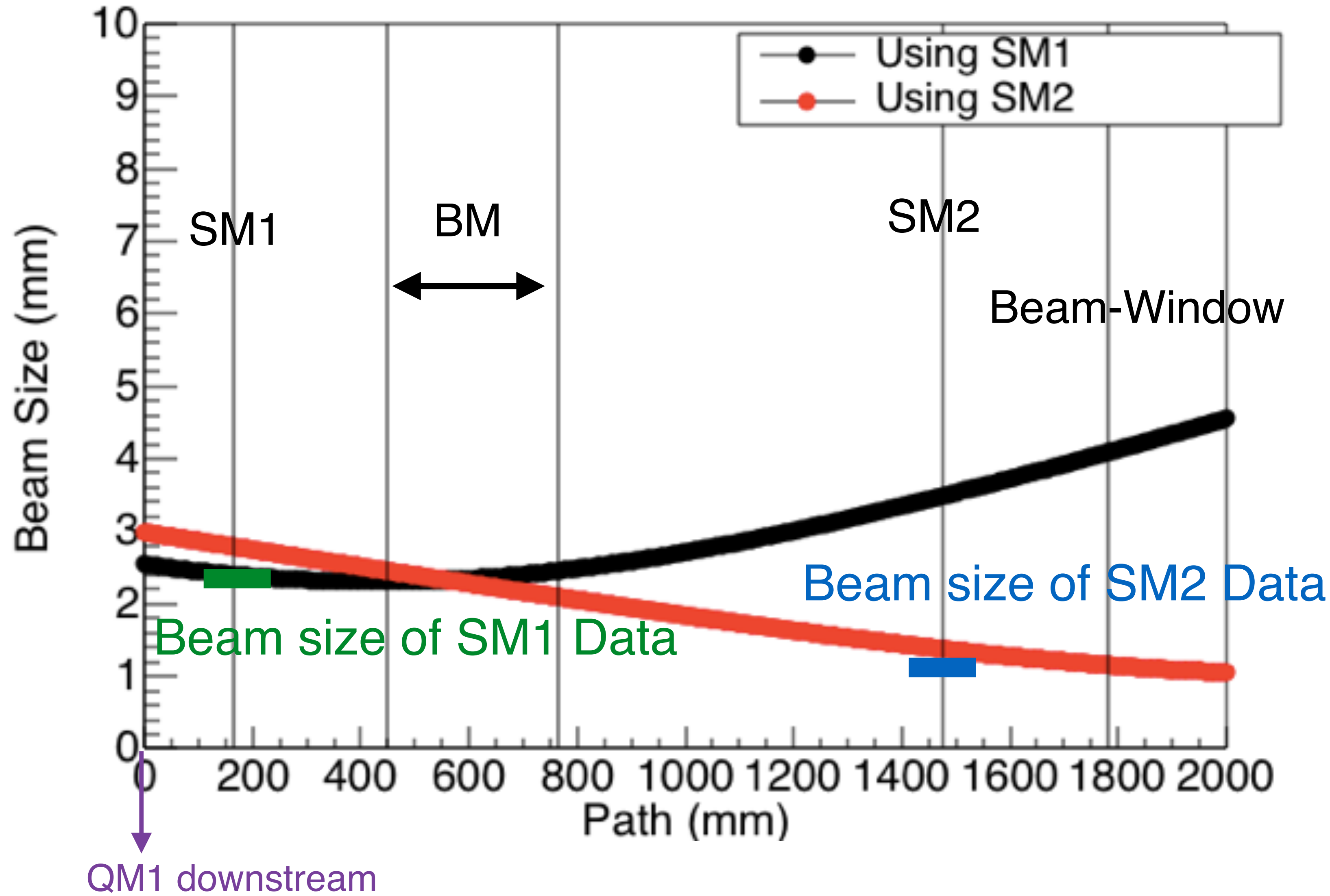


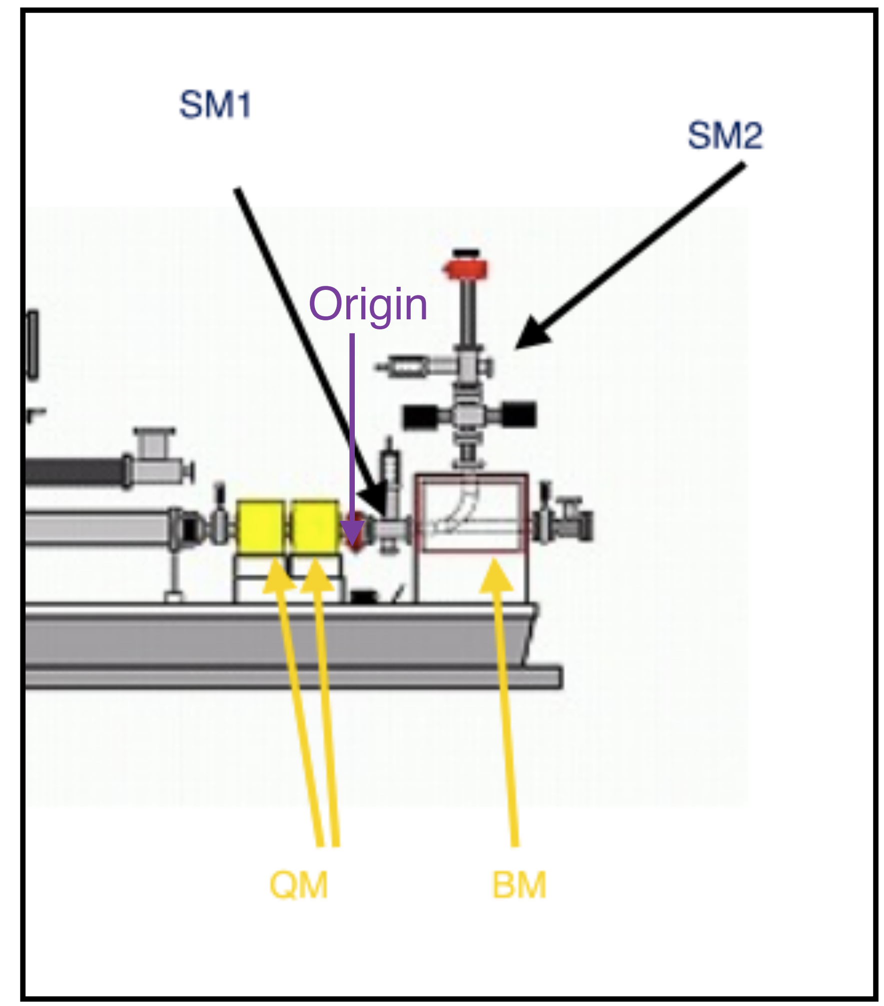
QScan result

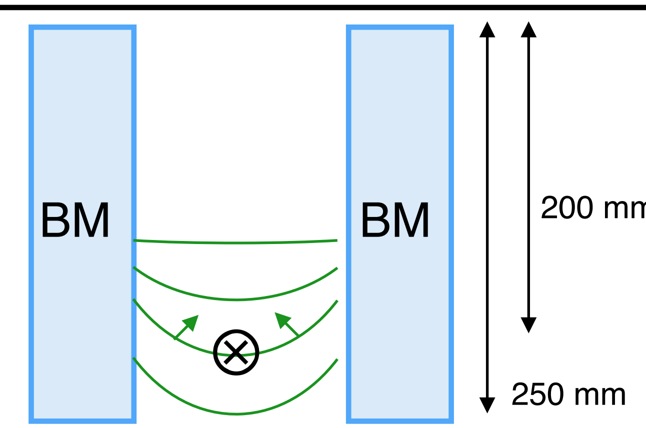
		Alpha (1/(m rad))	Beta (m/rad)	Gamma (rad/m)	Emittance (m rad)
SM1	Horizontal (W)	0.572	1.033	1.285	3.756E-06
	Vertical (W)	-0.262	1.950	0.548	2.242E-06
	Horizontal (N)	0.492	0.842	1.475	5.756E-06
	vertical (N)	0.151	1.045	0.979	1.141E-06
SM2	Horizontal (W)	-0.836	2.419	0.702	1.152E-06
	Horizontal (N)	-1.085	3.087	0.706	1.311E-06

Horizontal axis @SM2

Calculation using twiss parameter (Horiozntal = Non bending direction)







Beam-Window radius is 17.5 mm

Both case, beam size is less then Ti-window radius.

Discrepancy, because of vertical component of bending magnet.

Update

$$C^{\mathrm{K}}_{\mathrm{ELS}} = \frac{\mathrm{FADC}/Q_{\mathrm{CM}}}{G\,Y^{\mathrm{K}}\,E_{\mathrm{dep}}/Q_{\mathrm{MC}}}$$

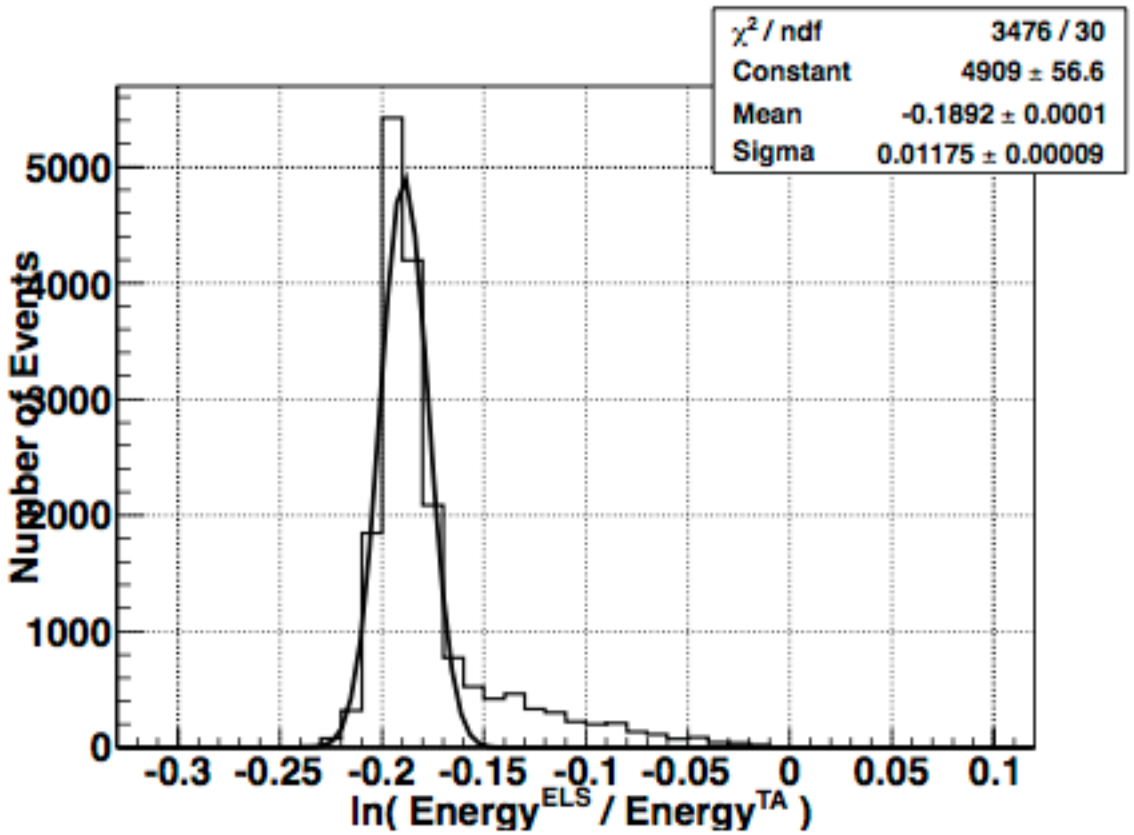
$$= 1.26 \pm \sigma \; = 1.26 \pm 0.20$$

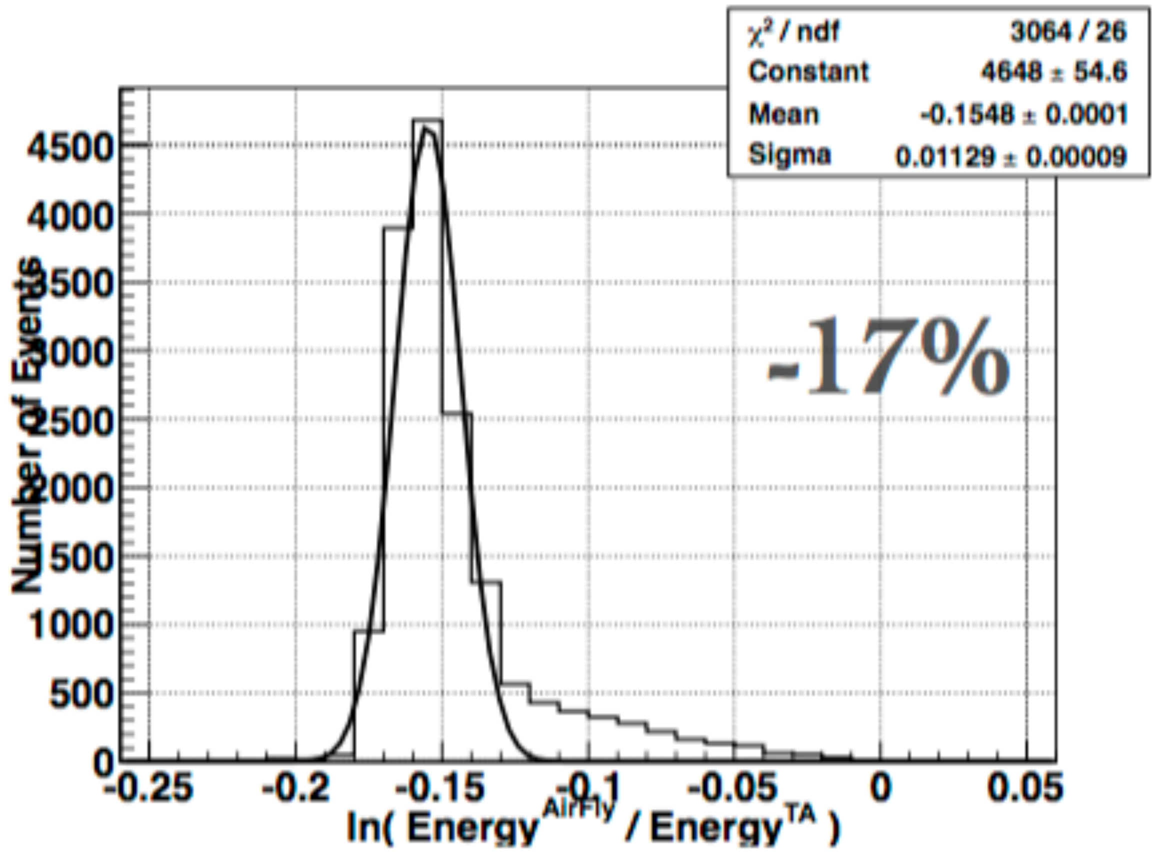
$$\sigma^2 = \sigma^2_{\mathrm{ELS}} + \sigma^2_G + \sigma^2_Y$$

σ_{ELS}					σ_{G}	σ_{Y}	**Total**
ELS (or FD) Geometry	Beam Q Measurement	γ contribution	Run-by-run difference	MC GEANT/Jana - FLUKA/TRUMP	FD calibration	Kakimoto yield	
5.5%	3.3%	1.6%	1.6%	4%	10%	10%	
8%					10%	10%	16%

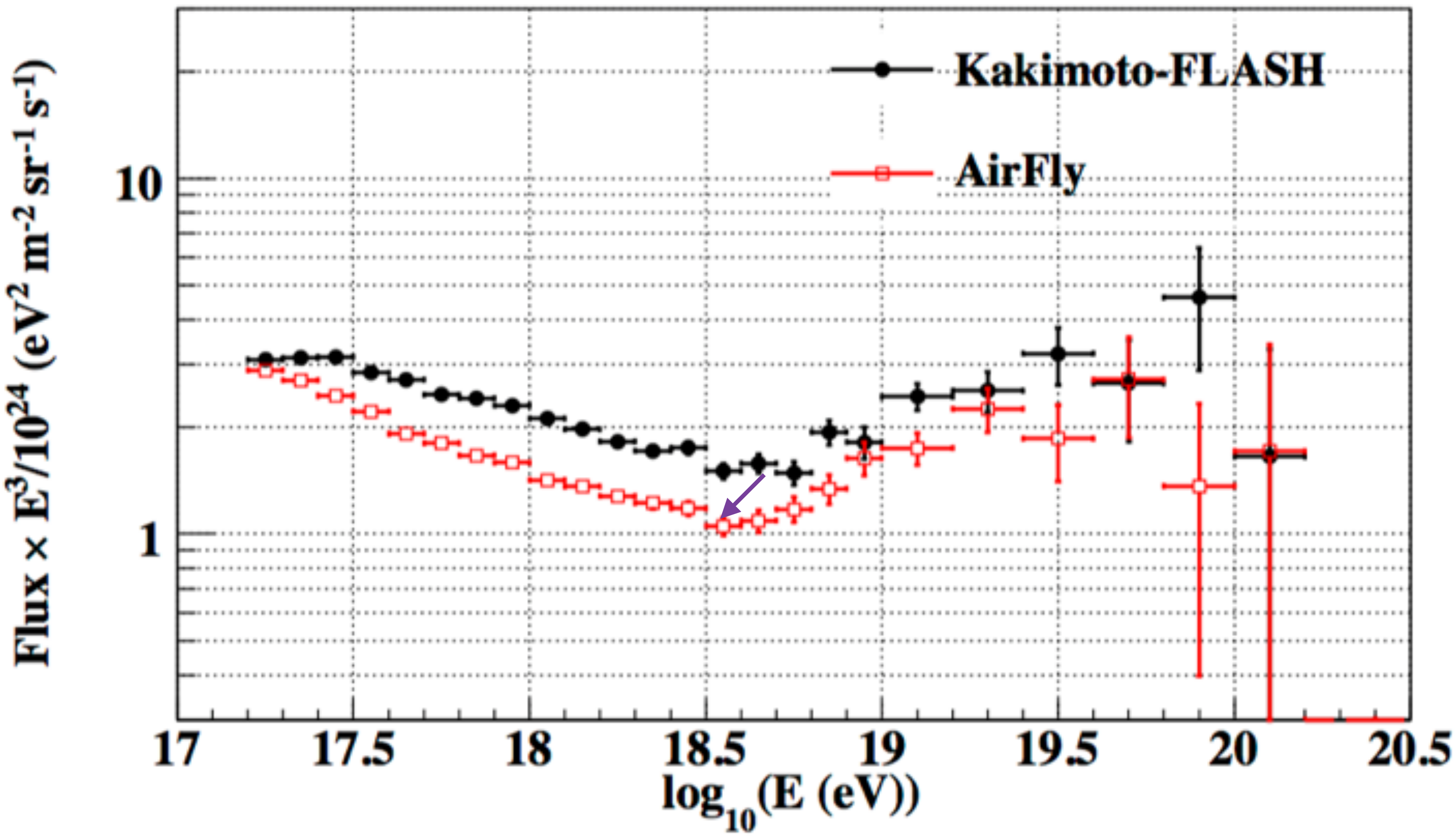
3

Energy Reconstruction with ELS





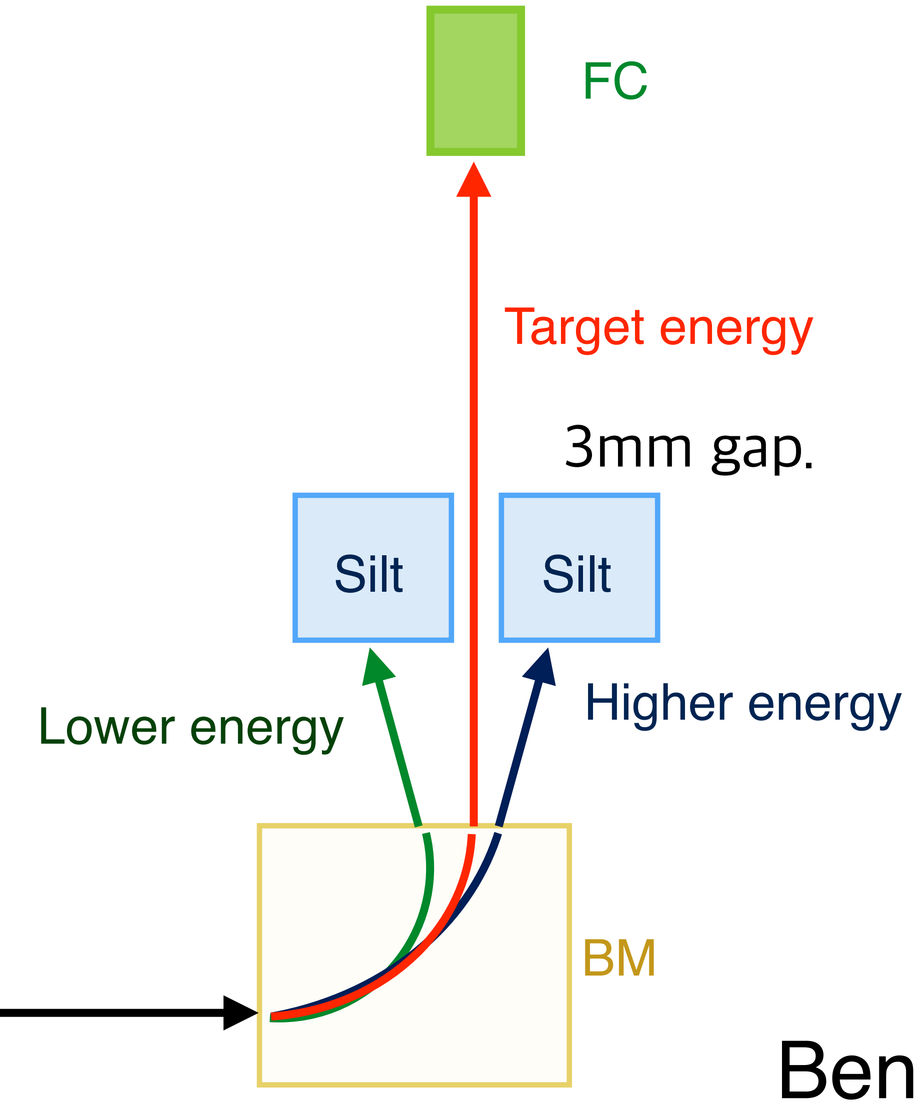
Expectation of Spectrum with ELS

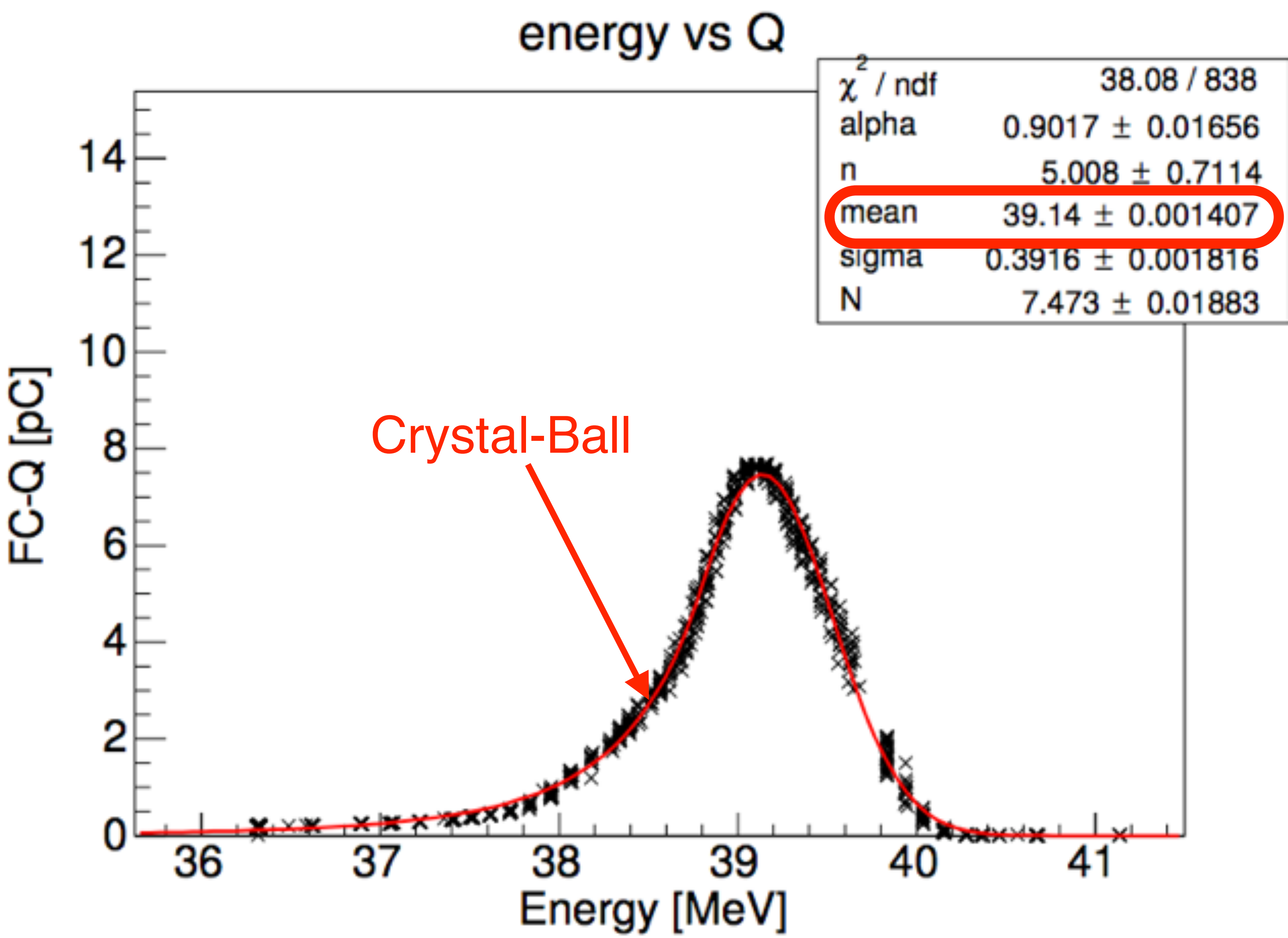


Second knee : 18.7 → 18.5 (Log E)

Bent Energy

Target energy selected by BM + slit





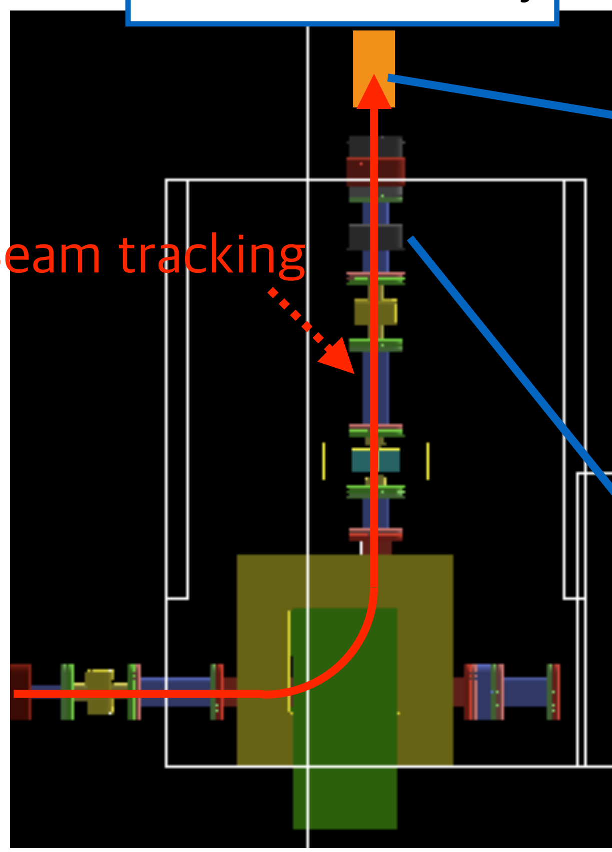
= BM Magnet

Bent energy ~ 40 MeV

$E_k \sim RBc$, R=0.22 m, B=0.6T, c = speed of light

Beam Charge

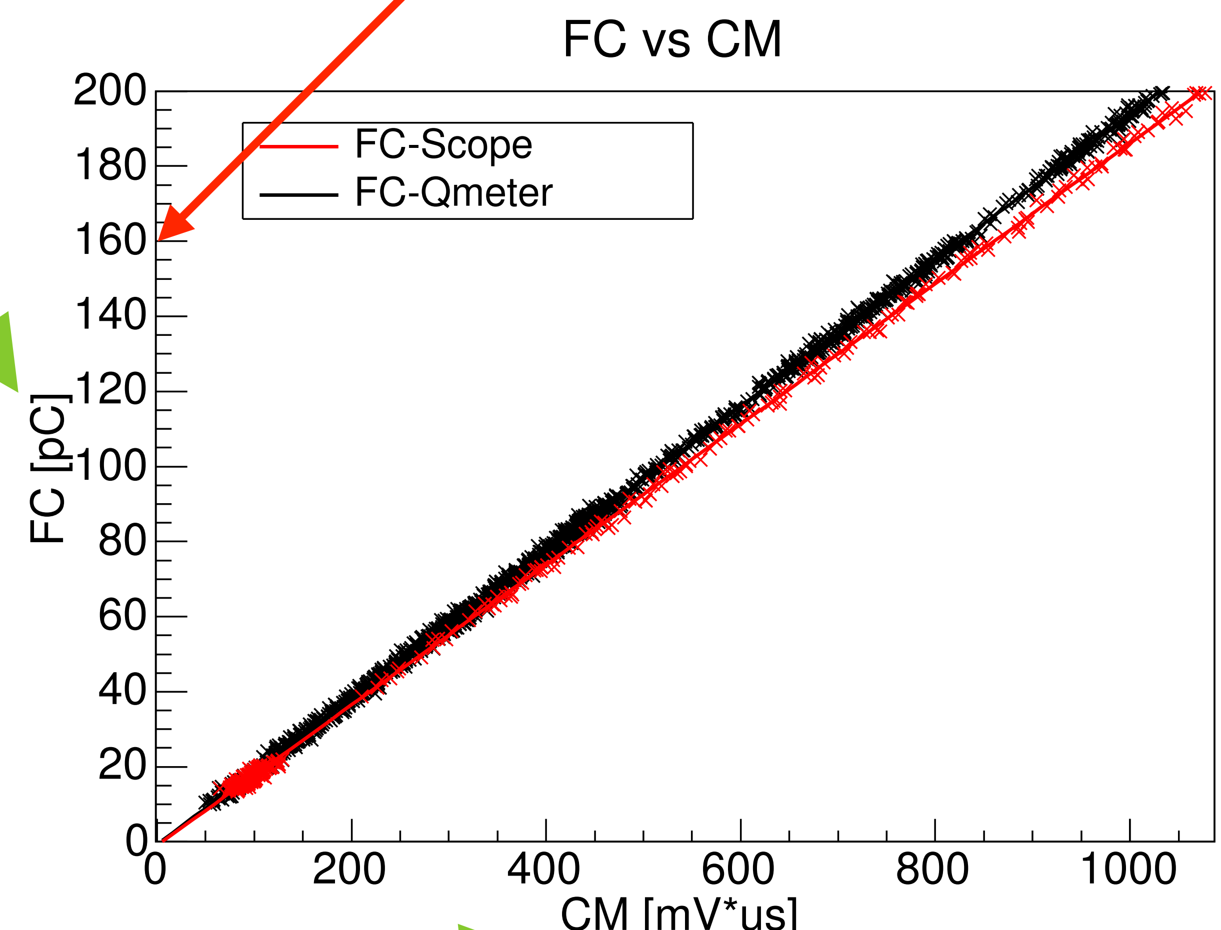
Beam Line Geometry



Faraday-cup
- Direct Charge
- Movable

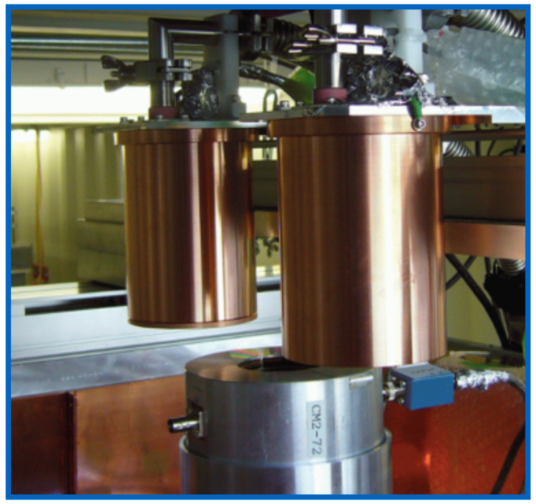
Core-monitor
-Incoherent Charge

10^9 electrons

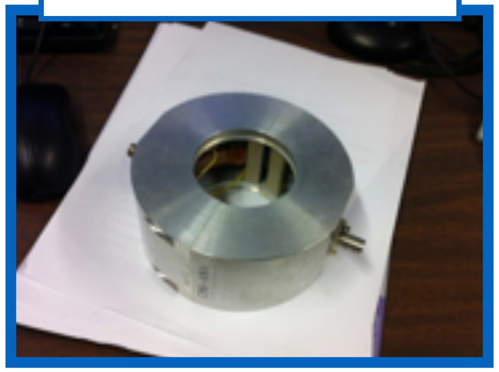


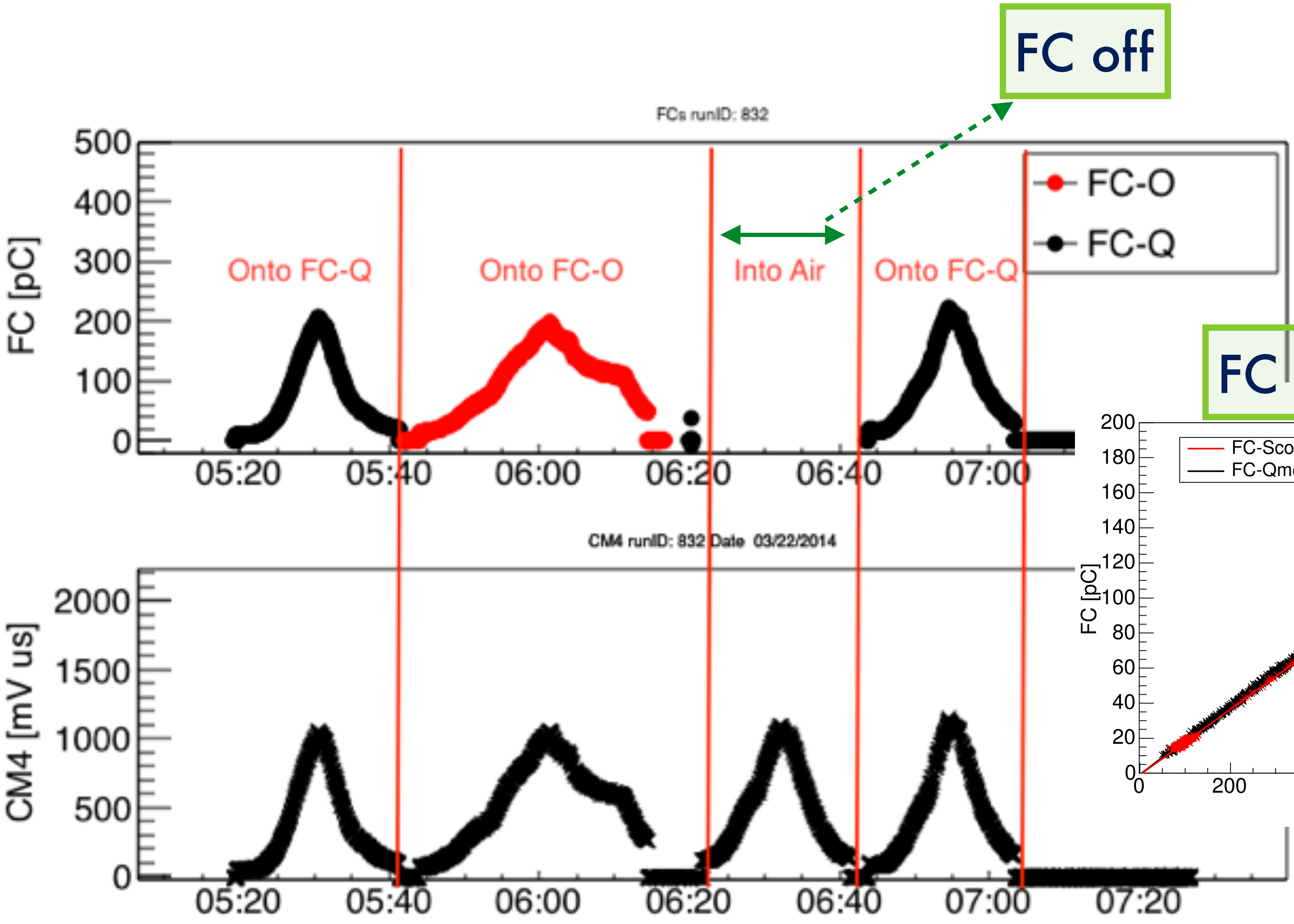
ELS Operation

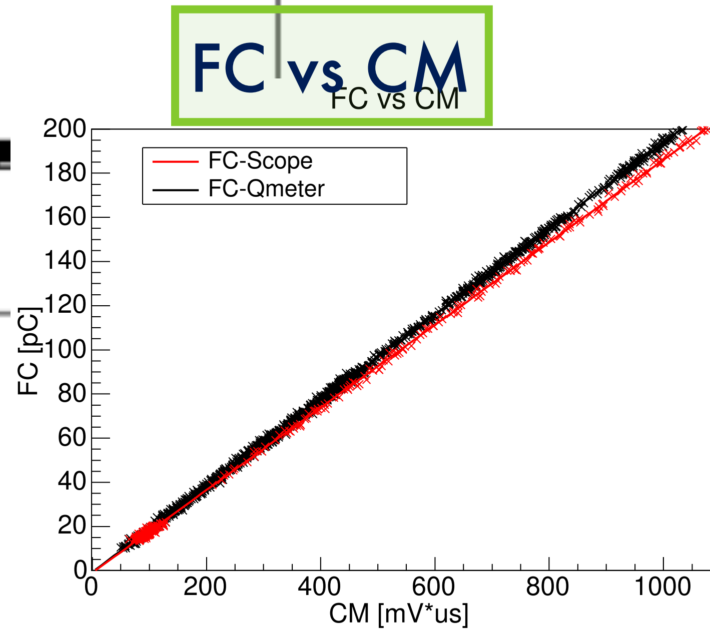
Faraday-cup
- Beam dumped



Core-monitor

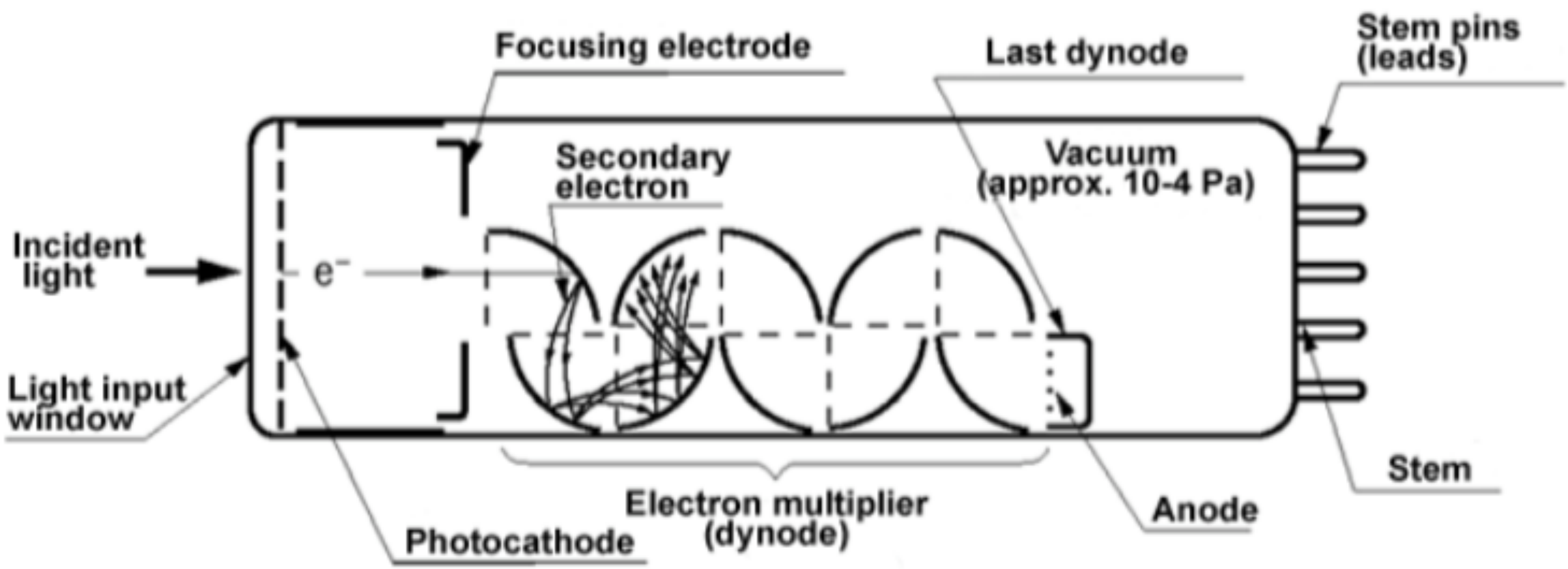






2 hours = ~3000 points

Photomultiplier tube



$$QE \times CE \times G = I \text{ (electric current)}$$

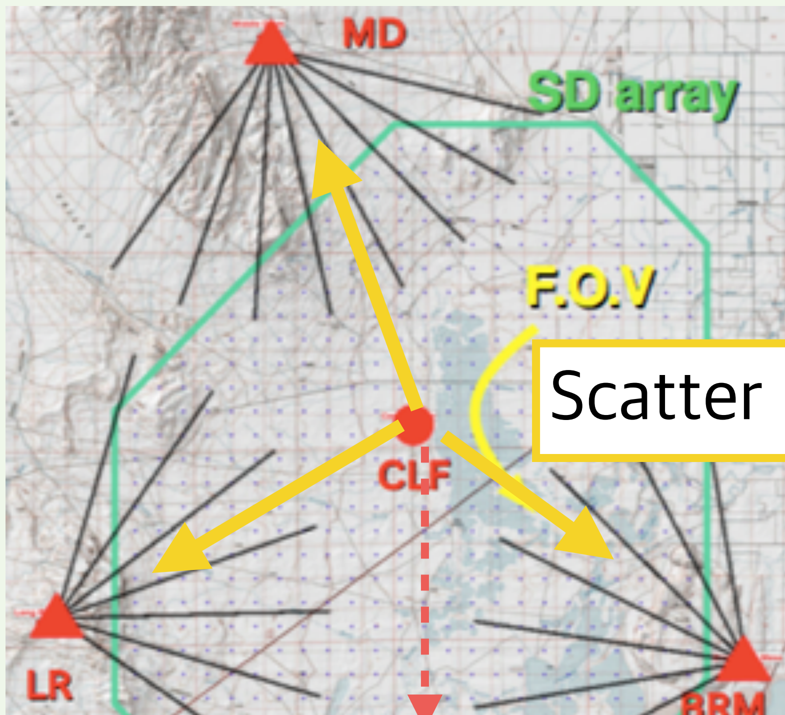
QE : Quantum efficiency: Ne / Np = 0.27

CE : Collecting efficiency: 0.9

G: 60000

Atmospheric Parameter.

CLF: Relative G_{ST}, Transmittance



Scatter photon

Vertical Shoot

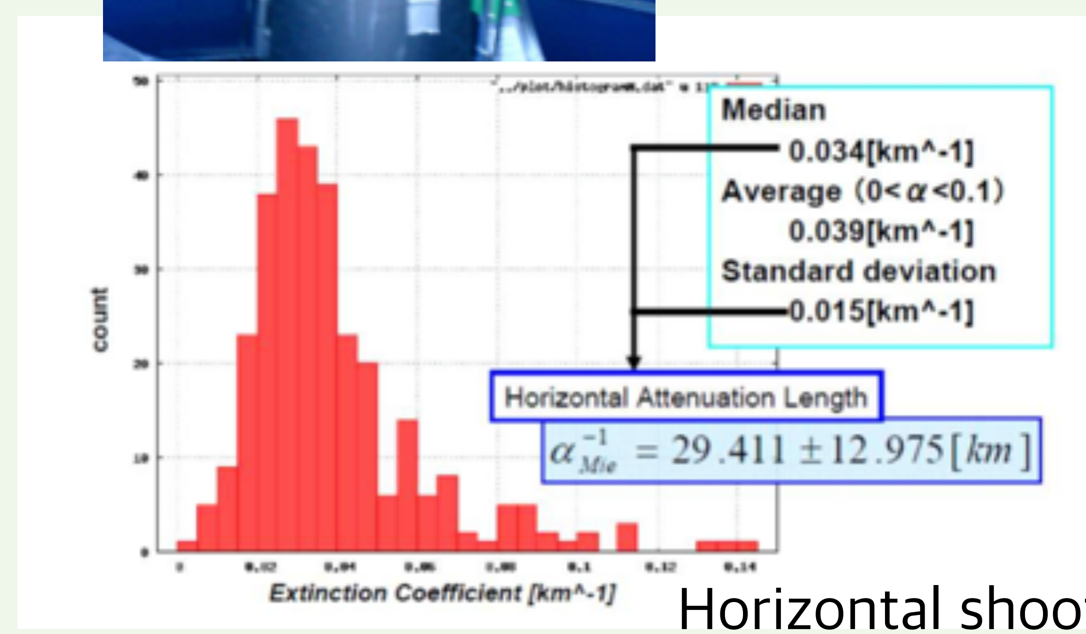
Under studying

LIDAR: Air Transmittance

Laser

Telescope to detect back scatter photon

Vertical, horizontal shoot



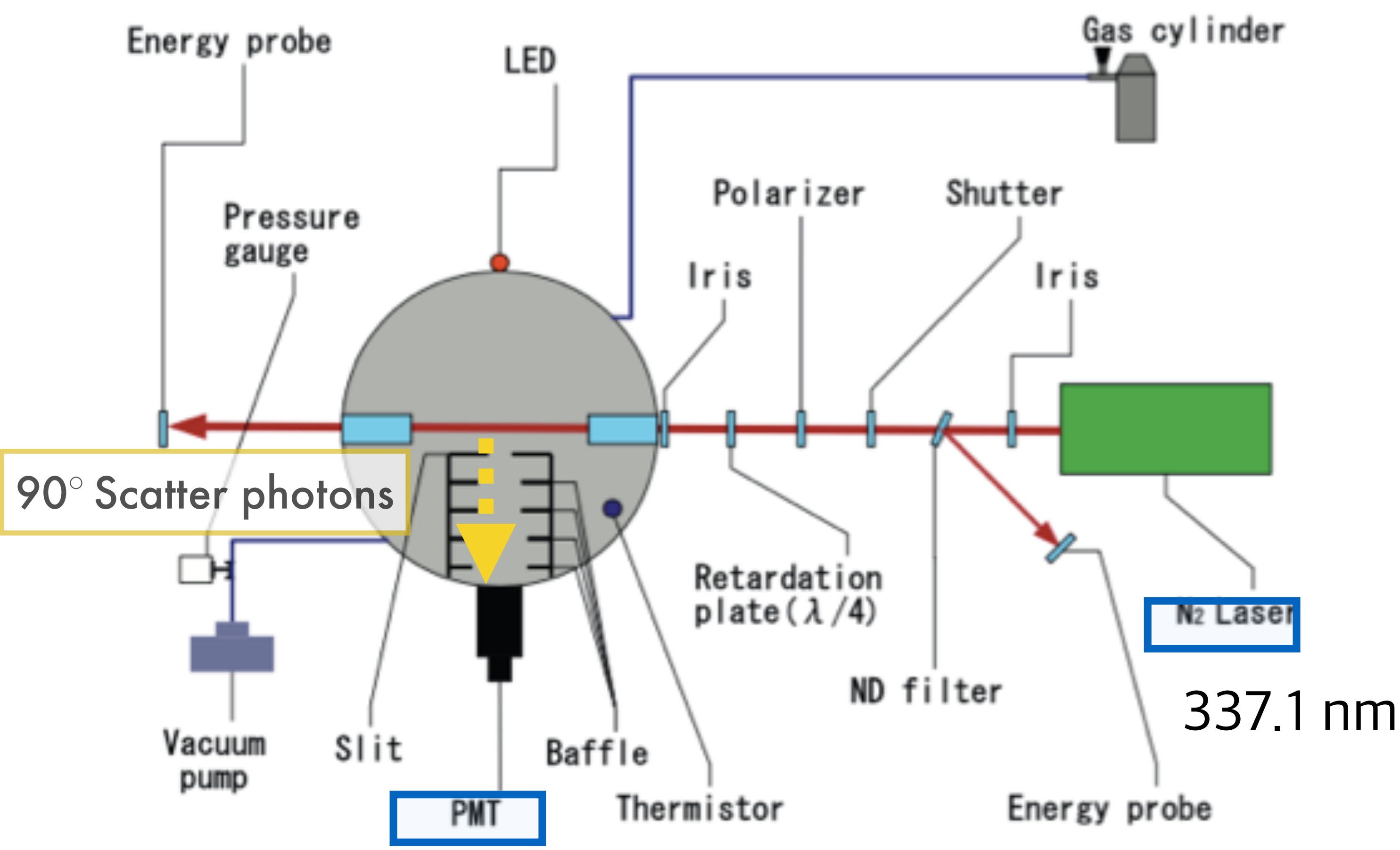
Horizontal shoot

0.034/km @ Air density of ground(1400m)

FD Calibration(1)

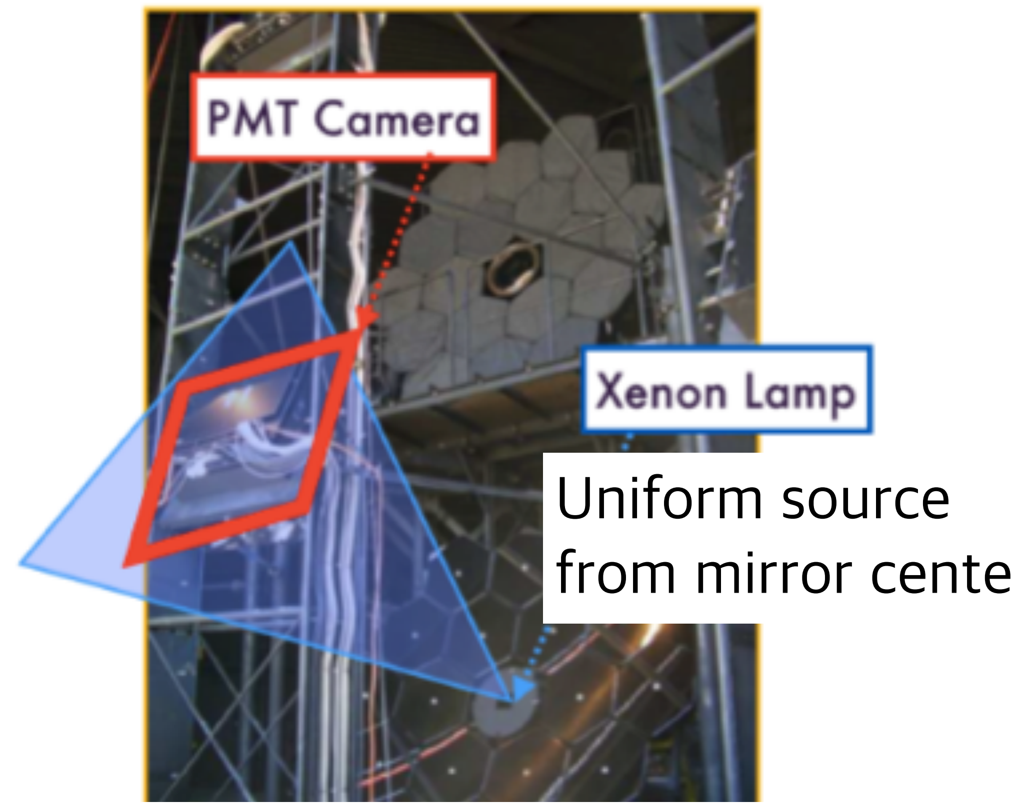
- G [FADC/Np]
  - FADC count: Digital number for electronics, Np : number of hit photon
  - $G = G_0 \times G_1 \times G_2 \times G_3 \times G_{mirror}$

G0: Absolute calibration with CRAYS



0.442 FADC counts/photon

G1: Relative calibration



2 or 3 CRAYS PMT in a camera

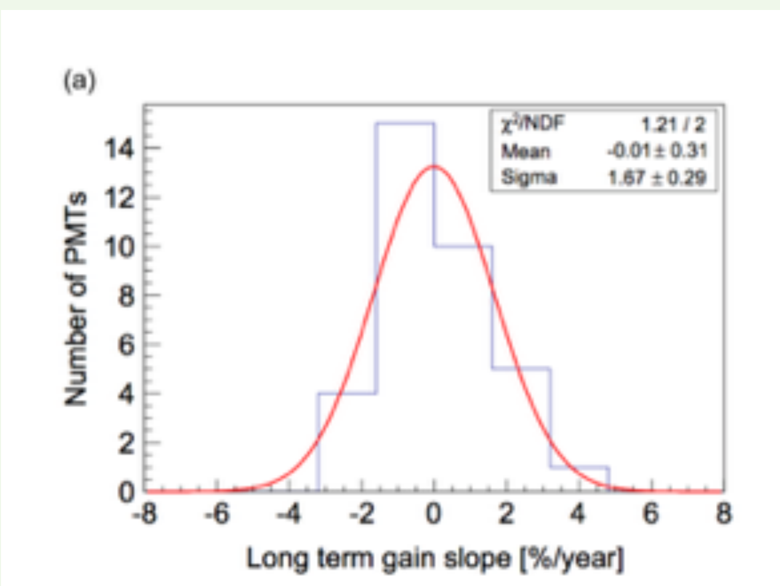
$R_{TXF} = S_{TXF} / A_{TXF}$

FD Calibration(2)

- $G = G_0 \times G_1 \times G_2 \times G_3 \times G_{mirror}$

G2: Long tern gain stability

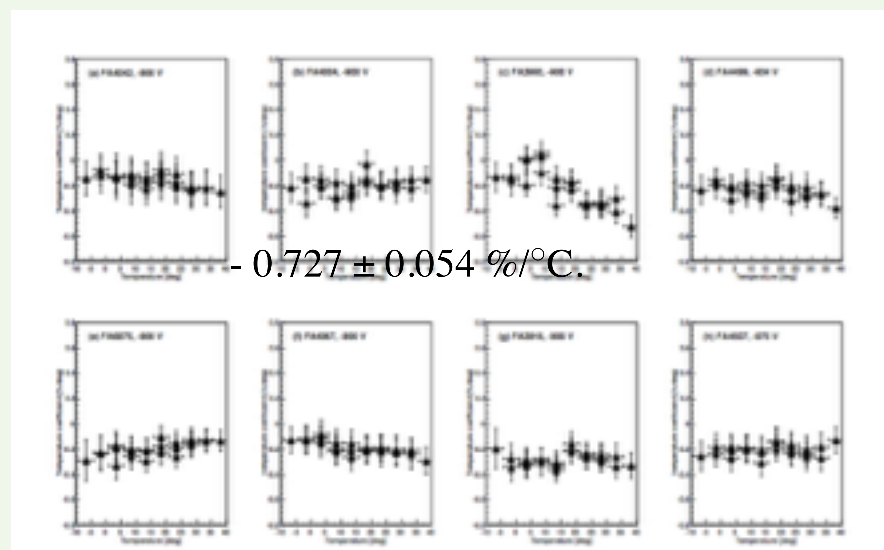
by YAP



-0.01 %/year

G3: Temperature coefficient

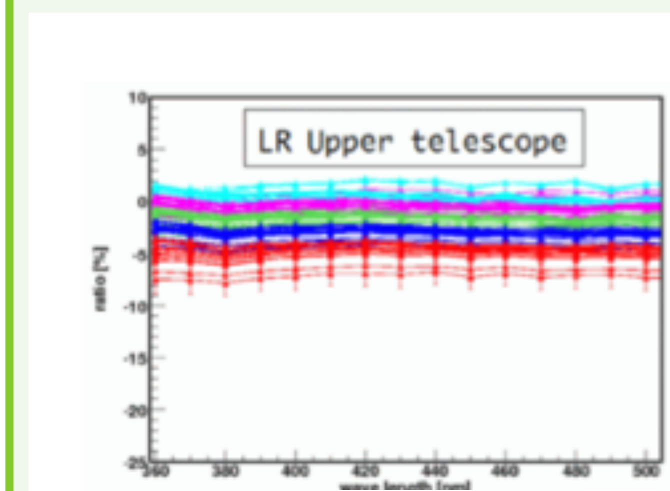
by YAP



-0.727 %/ ℃

G_{Mirror}: Reflectance

Measure every month
wash every year



Definition

$$t = \frac{X - X_0}{\lambda}$$

$$\epsilon = \frac{X_{max} - X_0}{\lambda}$$

$$E = \lambda N_{max} \frac{d\bar{E}}{dX} \left(\frac{e}{\epsilon}\right)^{\epsilon} \Gamma(\epsilon + 1)$$

Γ= Gamma func.

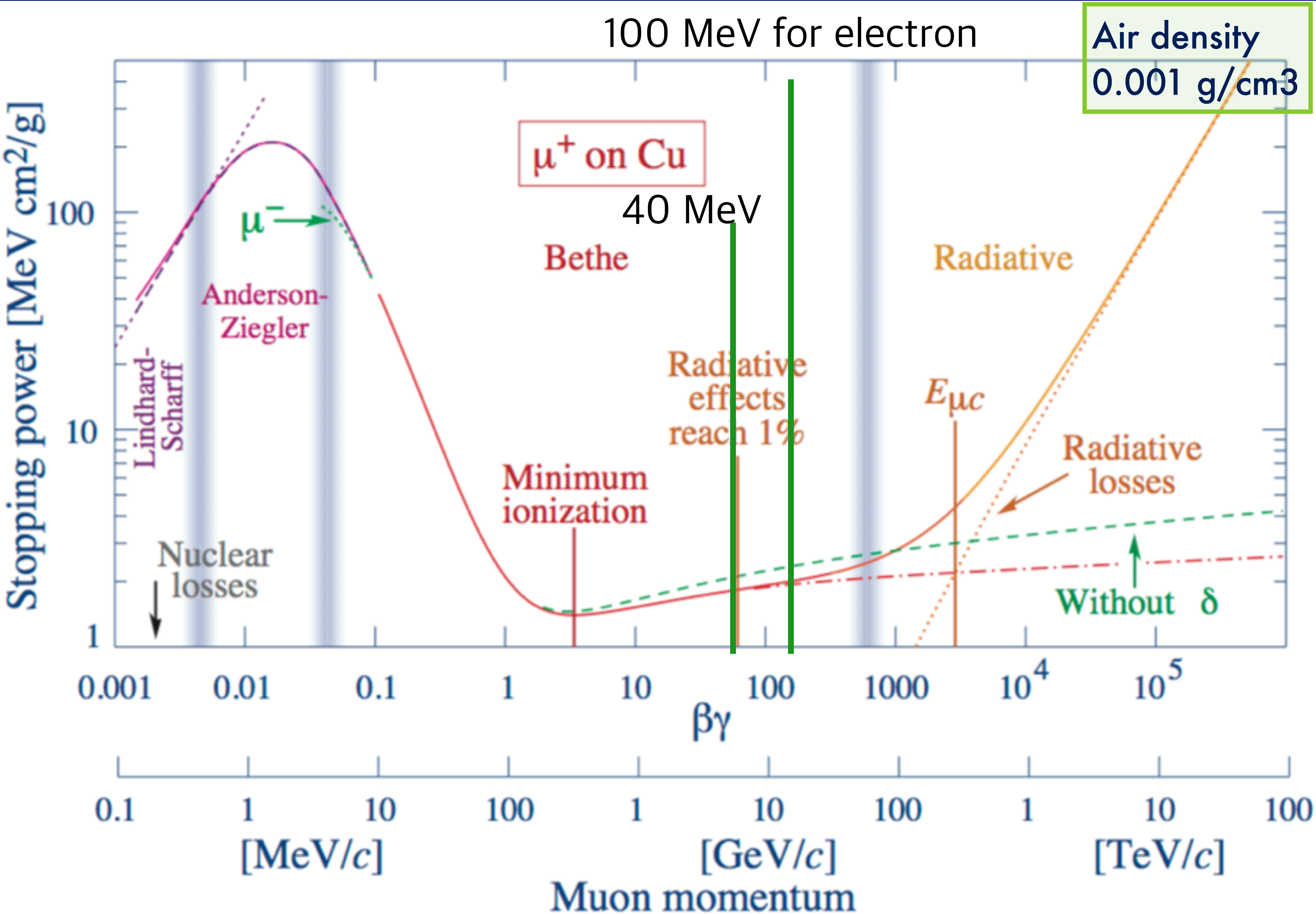
Slant Depth x

Slant depth = ∫ d(h) cos(θ)dh

d: density [g/cm^3]

θ: incident angle of CR in zenith

ex: Depth 800 g/cm^2 @ 1400m , θ=0


100 MeV for electron
Air density
0.001 g/cm3
40 MeV
μ+ on Cu
μ−
Bethe
Radiative
Anderson-
Ziegler
Lindhard-
Scharff
Radiative
effects
reach 1%
Eμc
Minimum
ionization
Radiative
losses
Nuclear
losses
Without δ
Stopping power [MeV cm2/g]
100
10
1
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
βγ
0.1
1
10
100
1
10
100
1
10
100
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

Extensive Air Shower (1)

E > 10^{16} eV

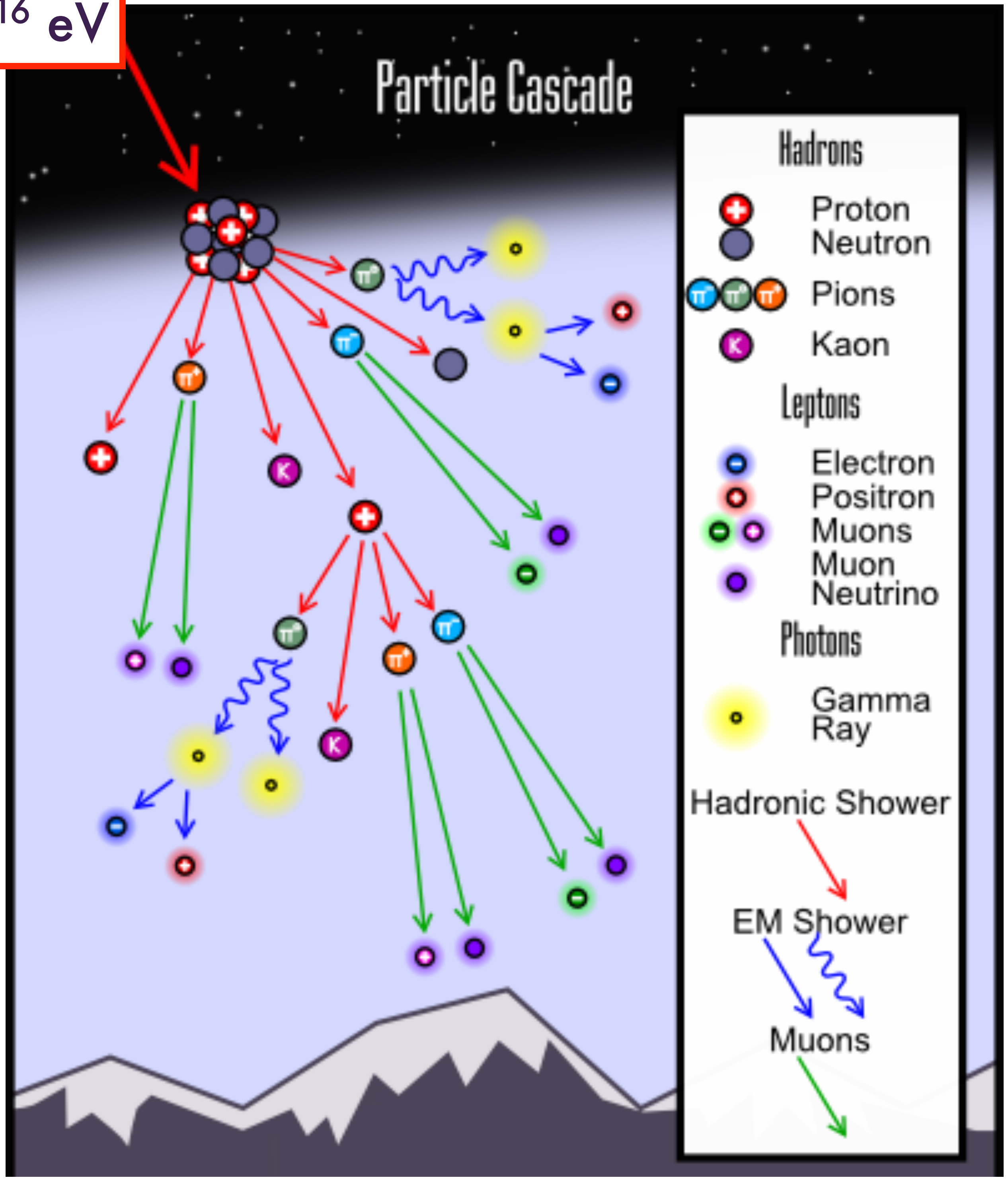
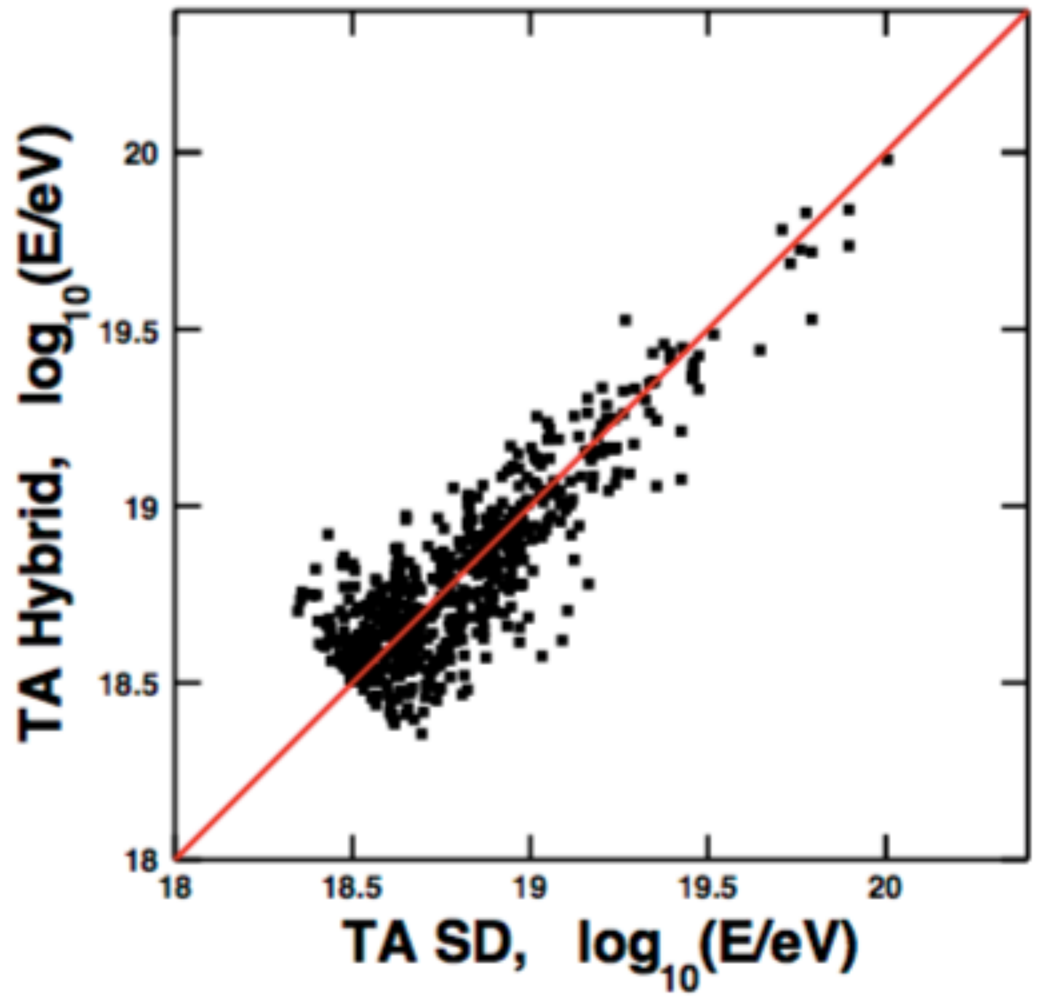


Figure 1 shows mean free paths / energy-loss lengths (attenuation lengths) of these processes. The energy-loss lengths of Bethe-Heitler process are $\sim$ Gpc because inelasticity is the order of $m_e/m_N \sim 10^{-3}$. For protons the mean free path of photomeson production is a few Mpc above 10^{20} eV in local universe ($z = 0$). Since the inelasticity of photomeson production is roughly 20%, observed UHE protons above 10^{20} eV arrive only from nearby universe, typically within 100 Mpc, and therefore the suppression of flux is predicted at $\sim 10^{20}$ eV (Greisen-Zatsepin-Kuz'min [GZK] effect) [8]. A similar effect is expected even for nuclei, but energies where it appears are generally different among nuclear species.

Energy SD vs FD



TA SD reconstructed energies normalized by 1/1.27 and compared to the TA Hybrid results of BR, LR, and MD simultaneously. Superimposed 45o line shows no significant non-linearities.

After ELS-calibration
SD/FD scale factor 1.27 → 1.60

Uncertainty

1.	Q in ELS data	3.3%	Difference in two FC measurements
2.	Soft photon background	1.5%	Dependence in ELS beam parameters
3.	Cherenkov photon background	0.4%	Estimated and not subtracted
4.	FADC of simulation	4.0%	Difference by simulation package
5.	P, T and h at BRM	0.5%	Difference of R by ambiguity of P,T and h
6.	$\Sigma FADC$ in ELS MC	5.5%	Difference by pixel summation region
7.	Telescope parameters	1.6%	Time, temperature dependence and others
	TOTAL	7.9%	quadratic sum of 1-7