Nuclear Excited Studied by proton scattering With a High-Resolution Magnetic Spectrometer

Lecture II

Experiment using High-Resolution Spectrometer Grand Raiden

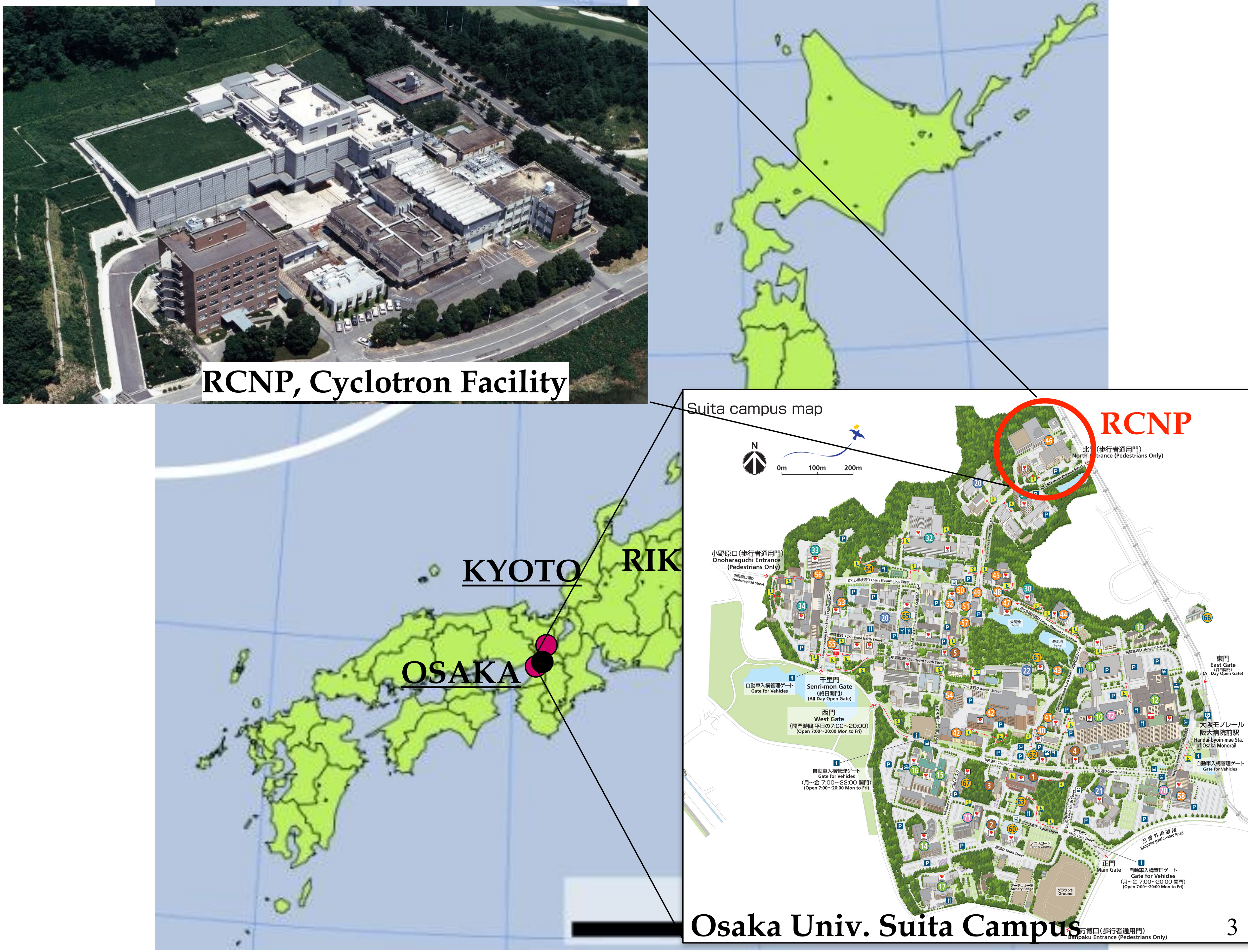
8242 0953 at https://menti.com

https://www.menti.com/al2r5brnmtdj

How to study the microword

light-ion (proton) scattering experiment

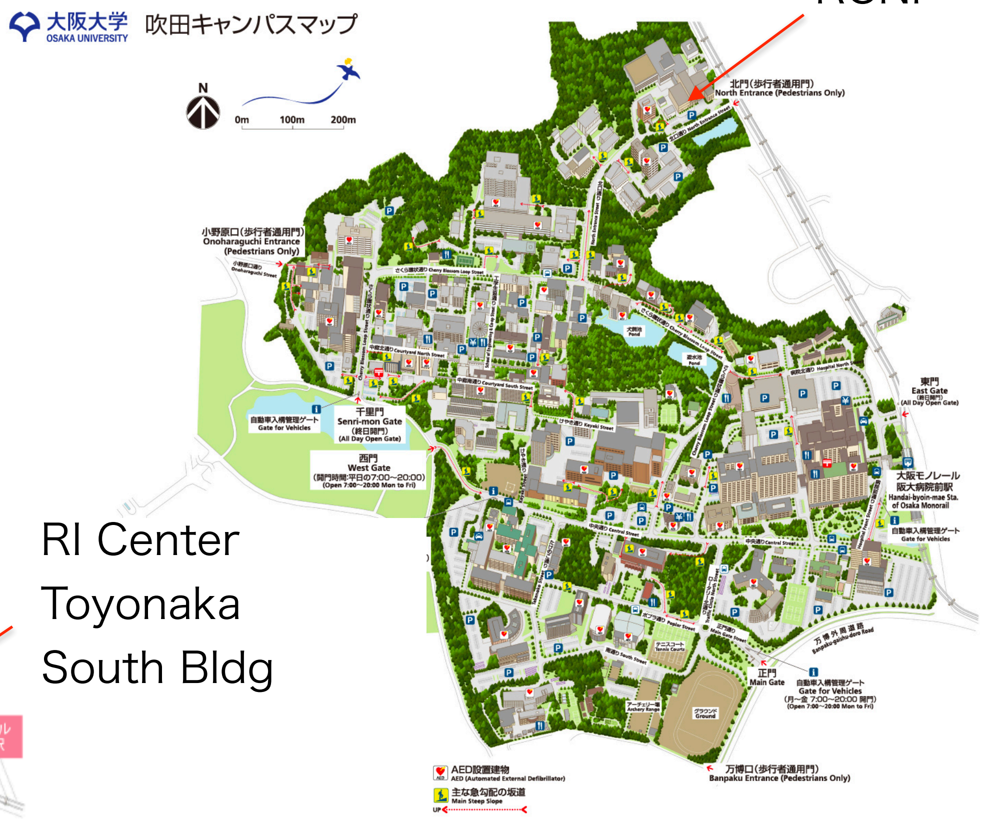
using an accelerator and a spectrometer


RCNP, Cyclotron Facility
KYOTO
OSAKA
RIK
Suita campus map
N
0m 100m 200m
RCNP
North Entrance (Pedestrians Only)
小野原口(歩行者通用門)
Onoharaguchi Entrance
(Pedestrians Only)
千里門
Senri-mon Gate
(終日開門)
(All Day Open Gate)
自動車入構管理ゲート
Gate for Vehicles
西門
West Gate
(開門時間:平日の7:00~20:00)
(Open 7:00~20:00 Mon to Fri)
東門
East Gate
大阪モノレール
阪大病院前駅
Handai-byoin-mae Sta.
of Osaka Monorail
正門
Main Gate
万博外周道路
グラウンド
Ground
万博口(歩行者通用門)
Banpaku Entrance (Pedestrians Only)
Osaka Univ. Suita Campus

Research Center for Nuclear Physics (RCNP), Osaka University

RI Center
Toyonaka
South Bldg

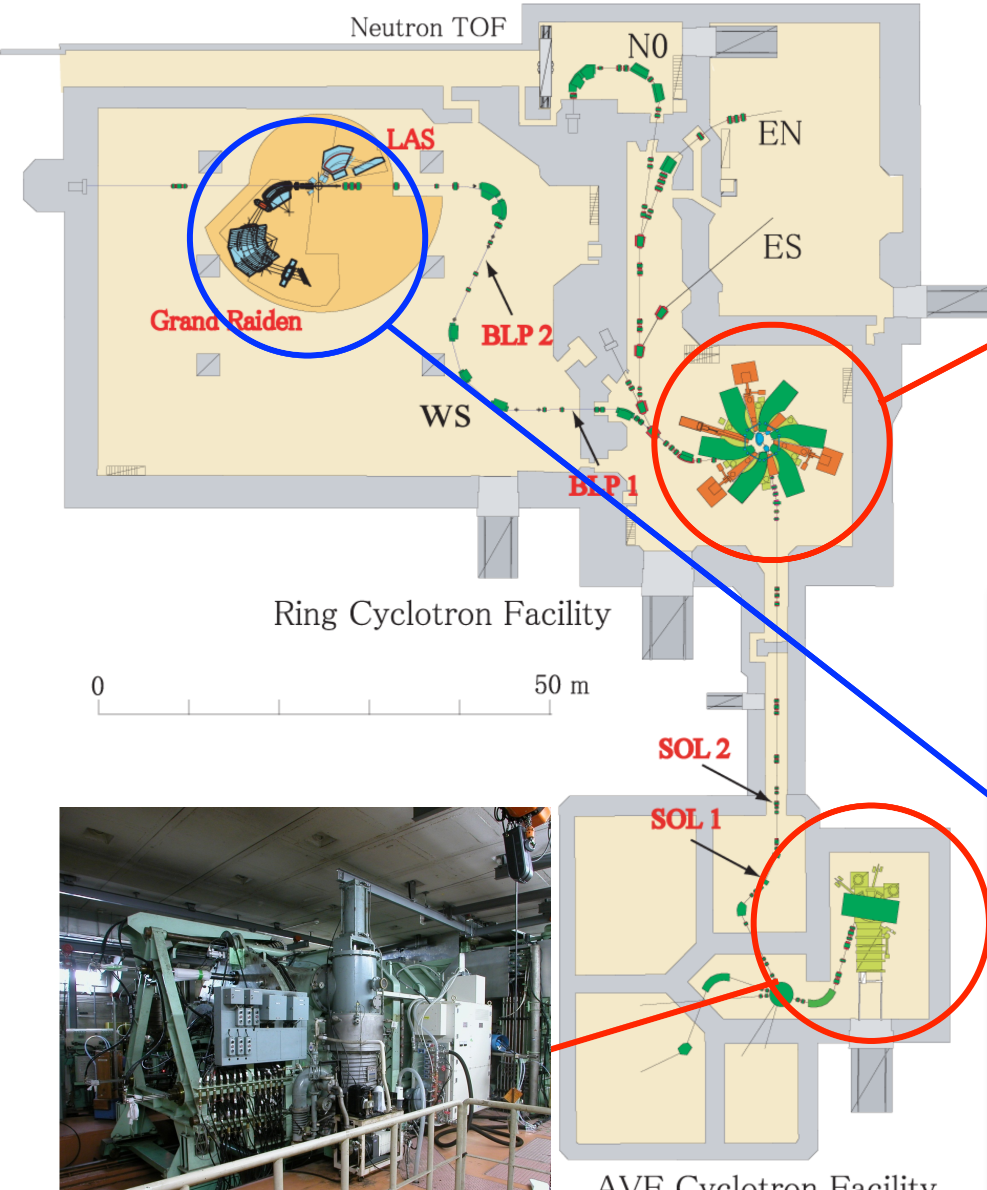
Toyonaka Campus

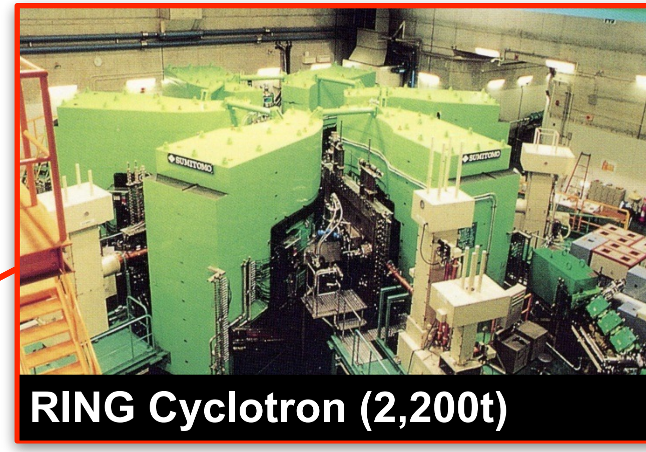


RCNP

Suita Campus

Research Center for Nuclear Physics





RING Cyclotron

Spectrometer Grand Raiden

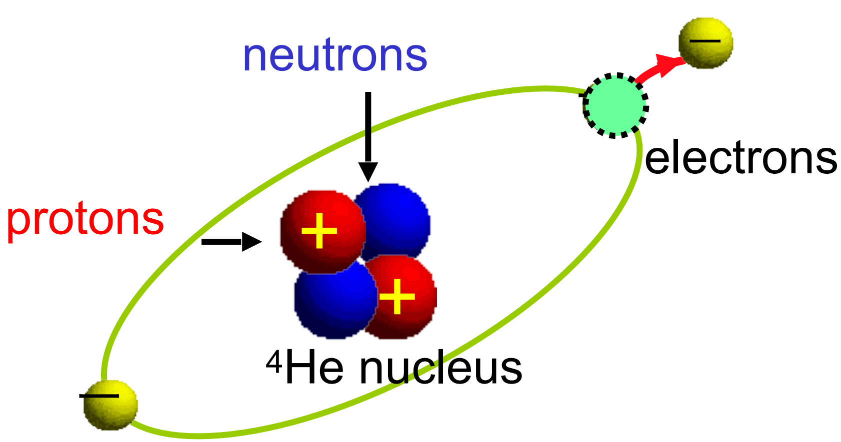
AVF Cyclotron

Ion-Beam Production

Production of an ion bem —ECR ion source

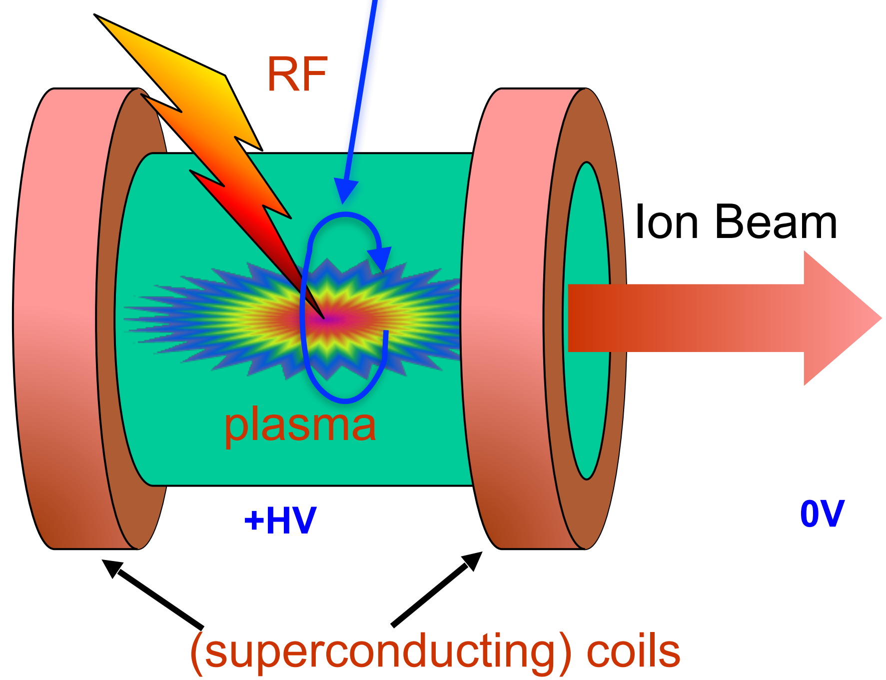
Ion Production

Electrons are removed by the hit of electron



ECR (Electron Cyclotron Resonance) Ionizer

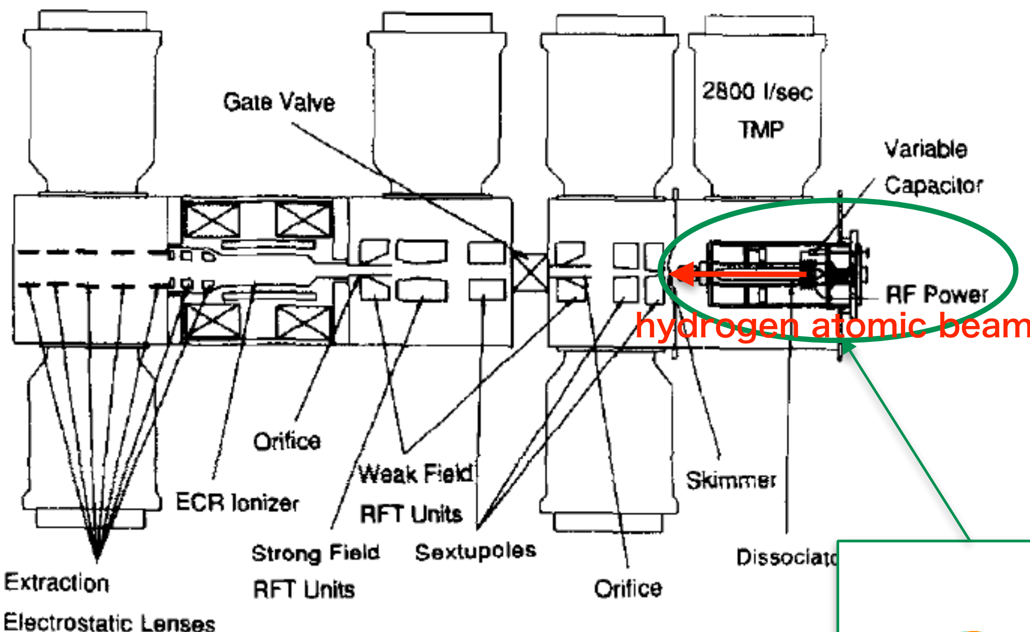
Electrons are accelerated by microwave (cyclotron motion)



Electrons are trapped between the strong magnetic fields. Ions are trapped by the attractive force with the electrons.

A polarized proton (deuteron) beam

HIPIS
atomic type

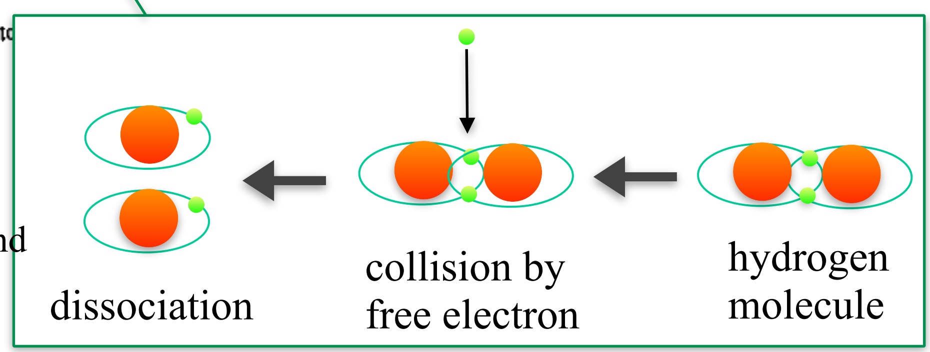


Outline

- produce hydrogen atomic gas (dissociator)
- Selection of electron spin with inhomogeneous magnetic field (Stern Gerlach)
- RF transfer of the electron spin to nuclear spin by RF (adiabatic fast passage)
- Remove electrons by ECR

Essences

- mag. field at ionization defines the nuclear spin-orientation
- spin follows the mag. field before that



TIPS

- 2.45 GHz is often used due to commercial availability and the law on electromagnetic wave
- A microwave oven often uses 2.45GHz even though it does not match the characteristic frequency of water

HIPIS@RCNP K. Hatanaka et al., NIMA 384, 575(1997)

原理の詳細についてはたとえば、久保・鹿取「スピンと偏極」培風館

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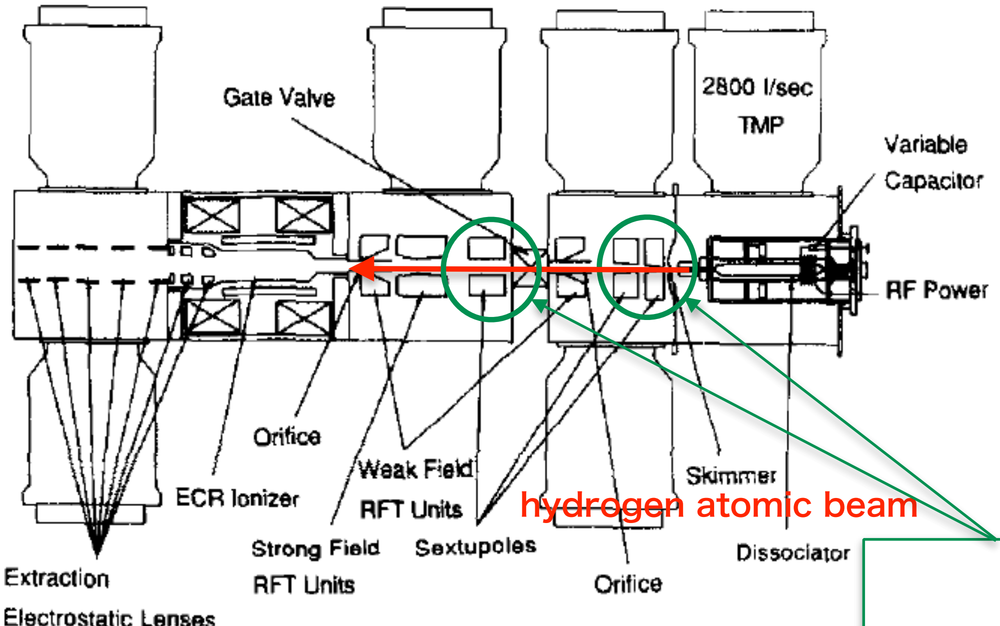
HIPIS

atomic type



※Two sets of sextupole magnet and RF-transition for deuteron polarization

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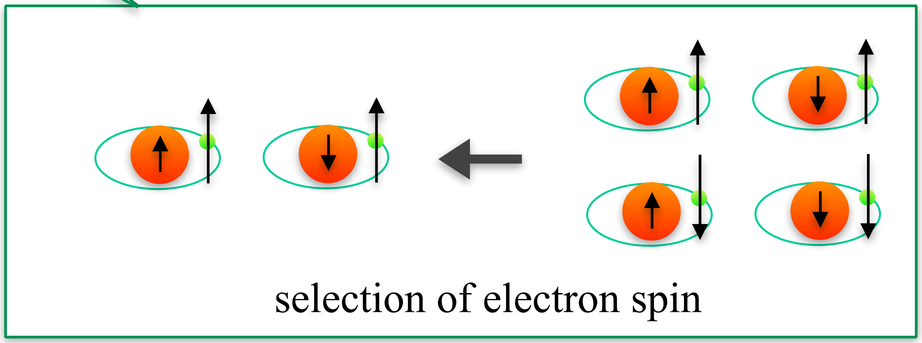

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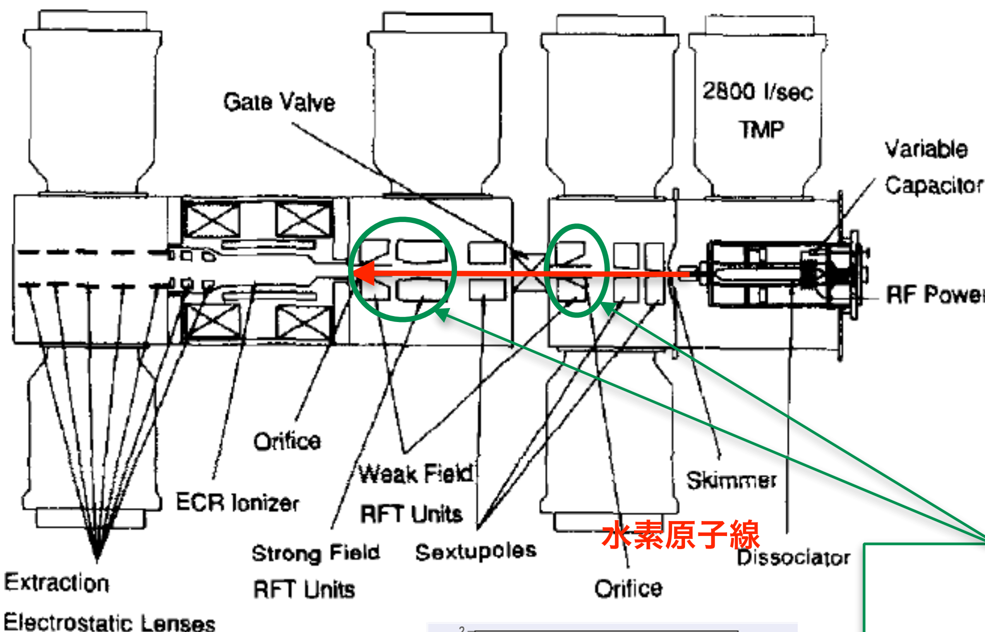

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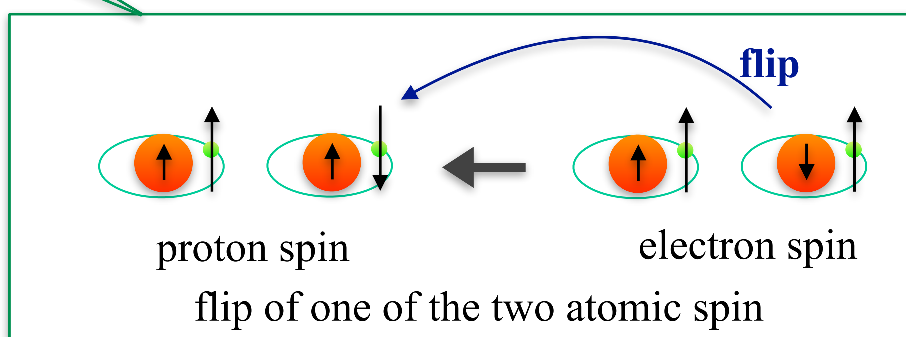
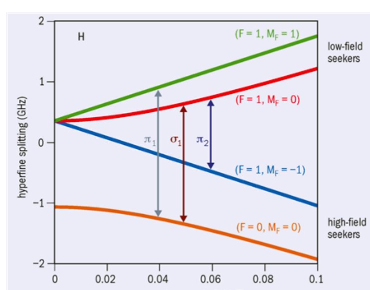


Energy diagram
of an hydrogen atom
in a magnetic field
(Breit-Rabi Diagram)



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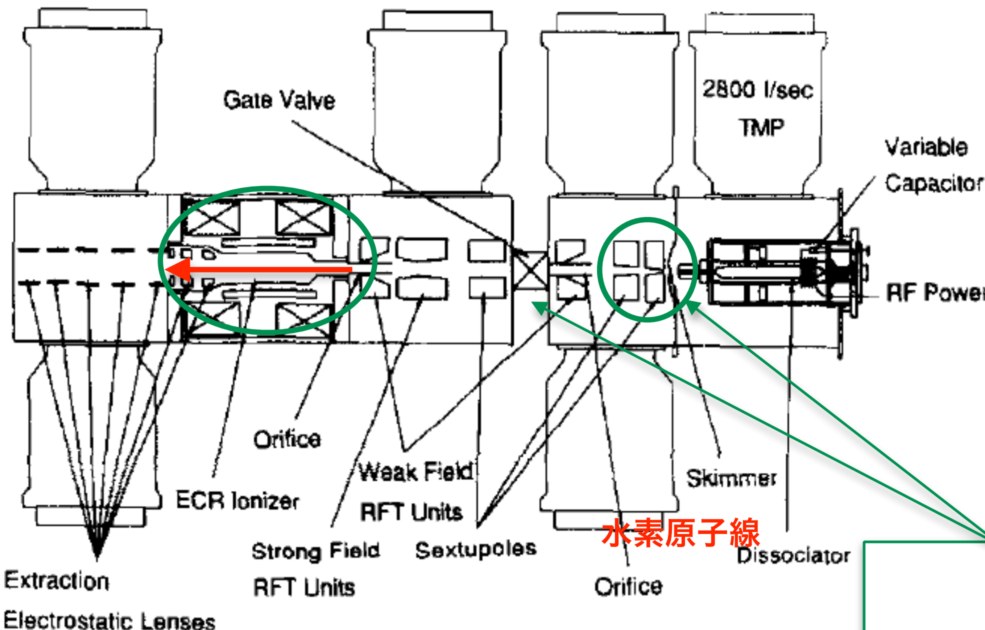

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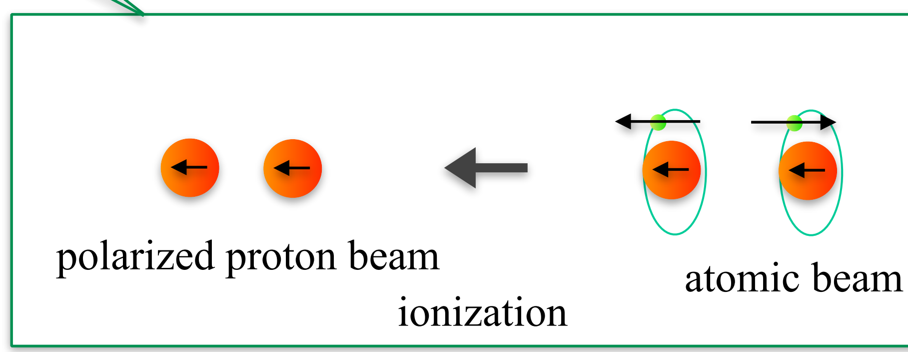

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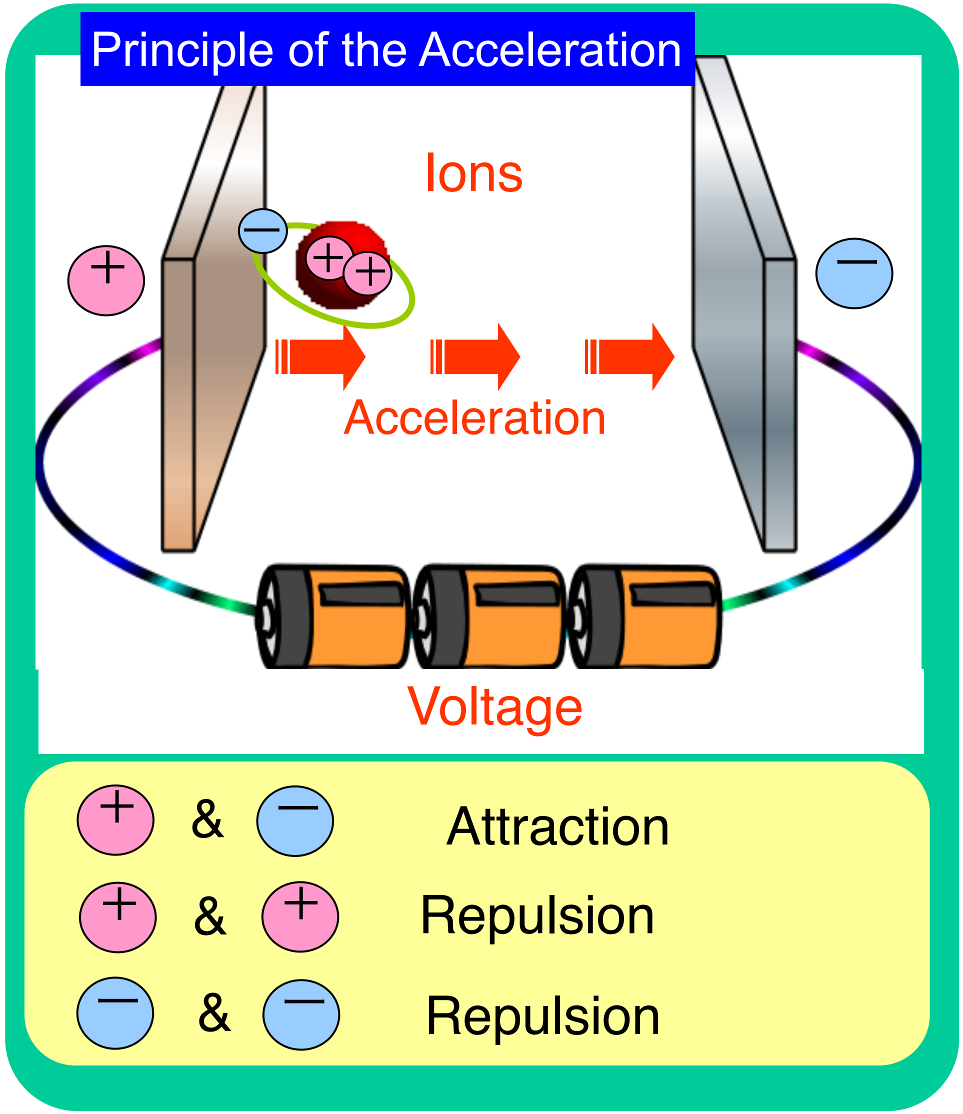
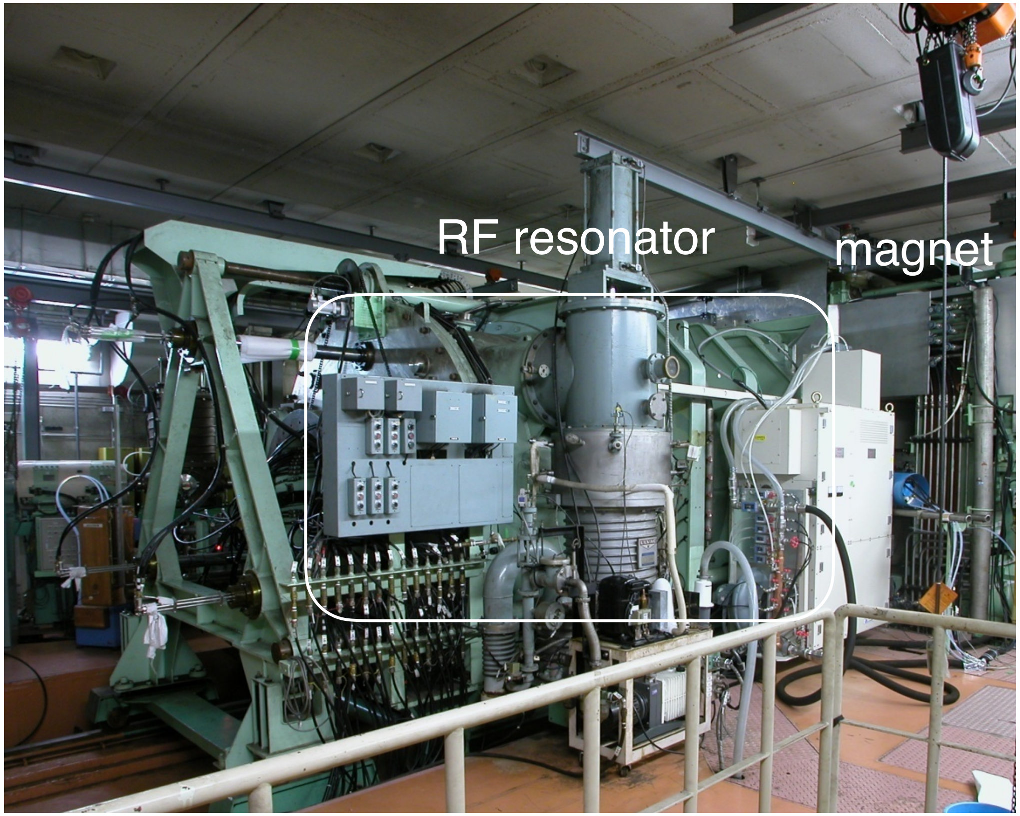
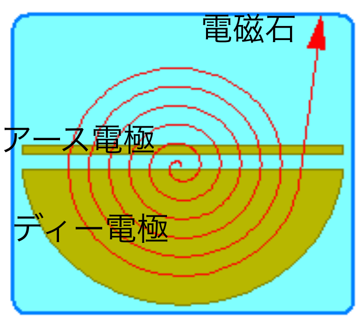
Acceleration of Ions



AVF(Azimuthally Varying Field) Cyclotron





1/4 モデル電磁石磁極部

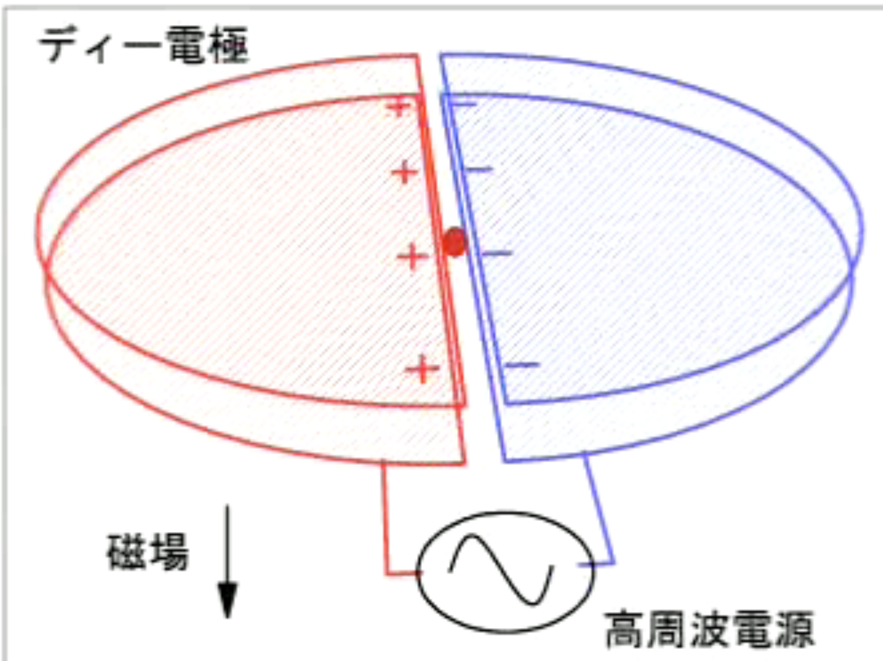
AVF Cyclotron

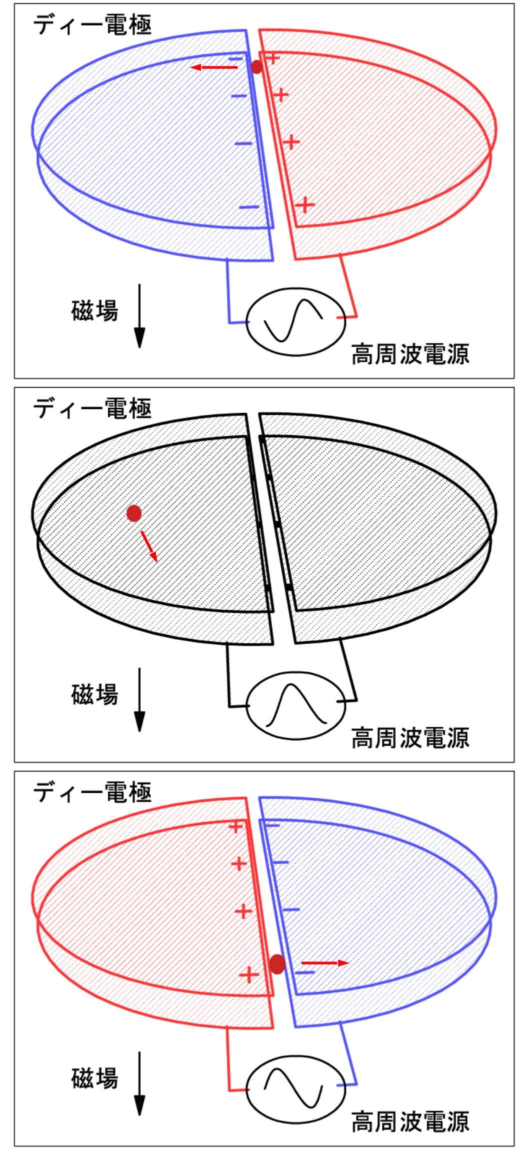
- Ions make rotation in a uniform magnetic field

  The rotation frequency is independent from the energy (isochronous)
- Ions are accelerated (twice in a turn) by the electric

  field between the two Dee electros

B

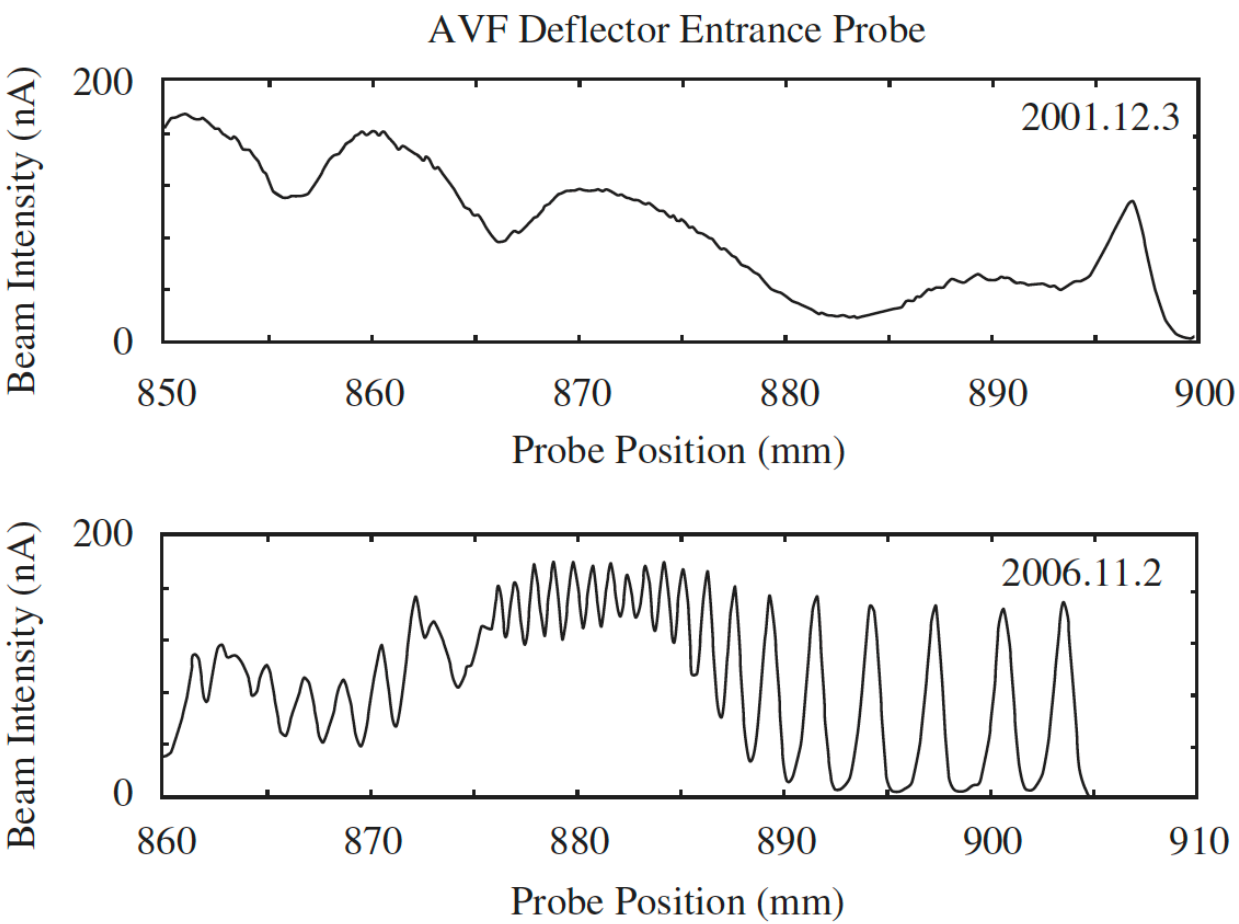




Essences

- uniform mag. filed for a a cyclotron
- time increasing mag. field for a synchrotron

AVF Cyclotron



AVFビームのターンセパレーションの向上

©任天堂

RING Cyclotron (K400)

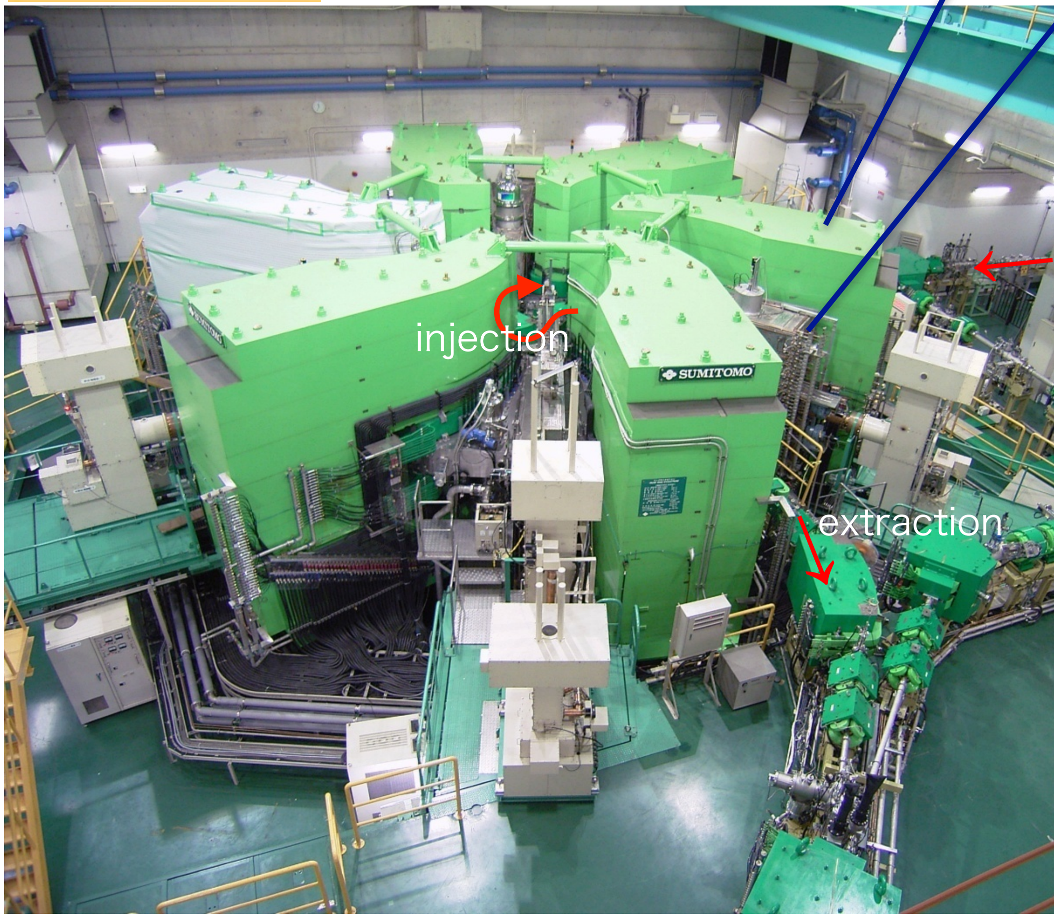
100,000 V

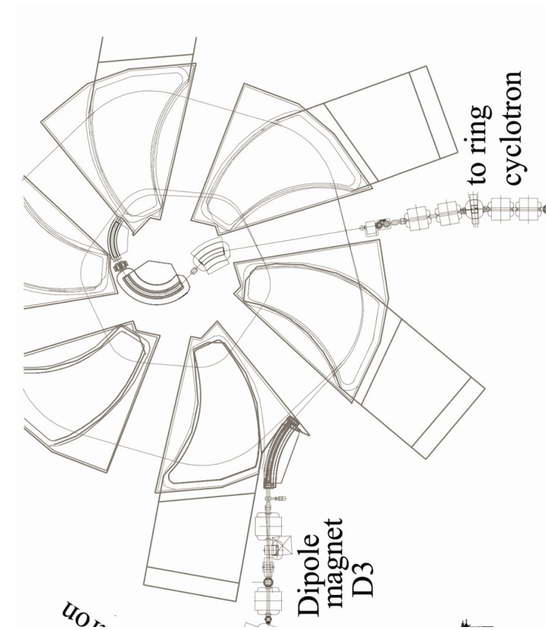
1 turn = 10 Pikachu

Magnets (green)

RF Cavity (gray)

injection





RF Cavity	Magnet (6)
Frequency：30〜52MHz	Weight：2200ton
Voltage：max500kV	Field：max 1.75T

One Piece

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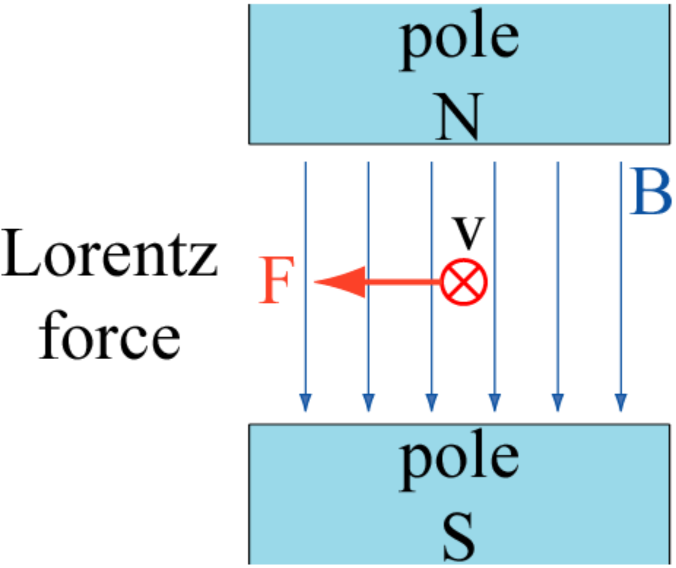
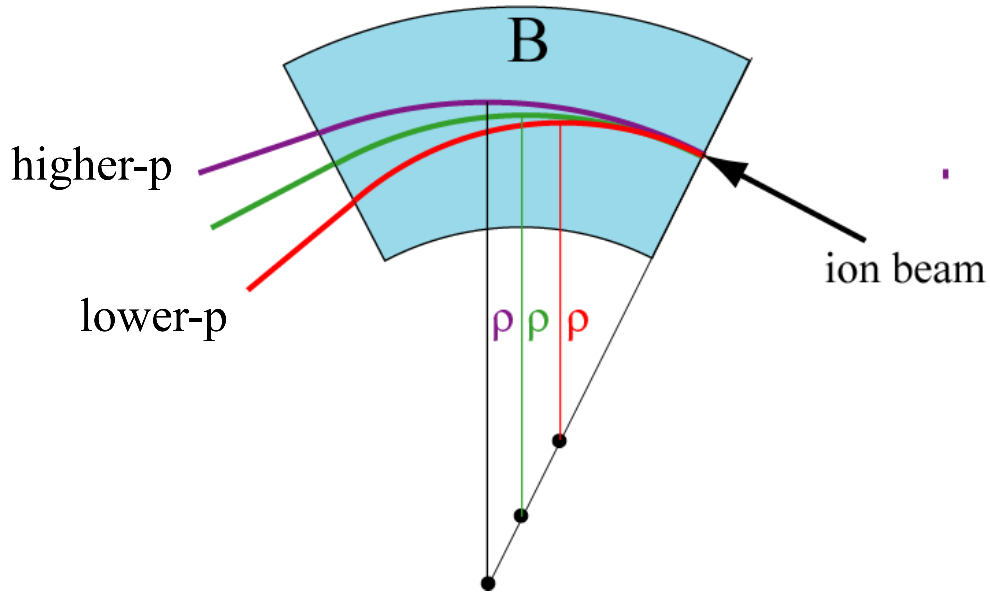
God Eneru: 200 MV

total accel. = 2 Eneru

Beam Lines

Dipole (Bending) Magnets





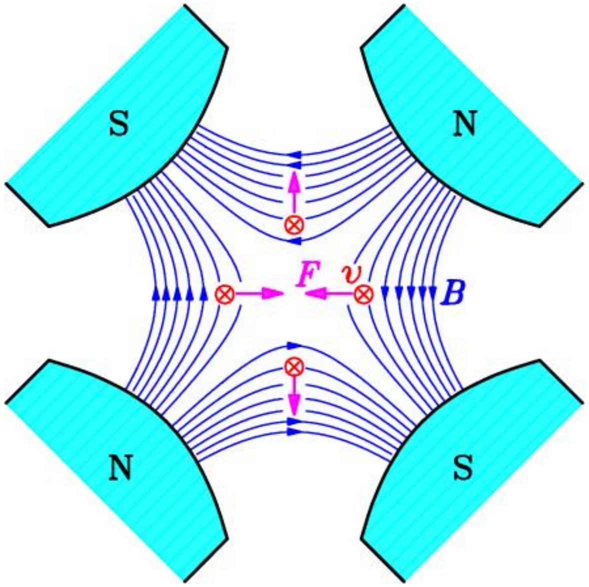
Bending magnet

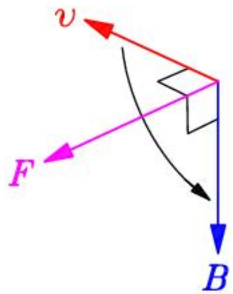
- Change the beam direction
- Analysis of the particle momentum

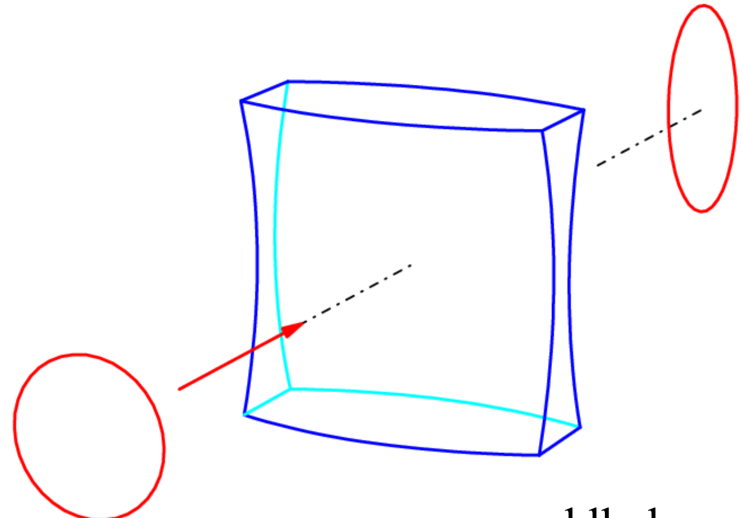
$$p = 0.3QB\rho$$

p (GeV/C)
q (e)
B (T)
r (m)

Quadrupole Magnets

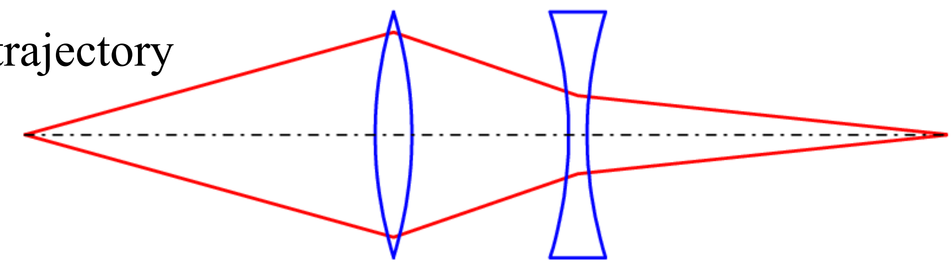




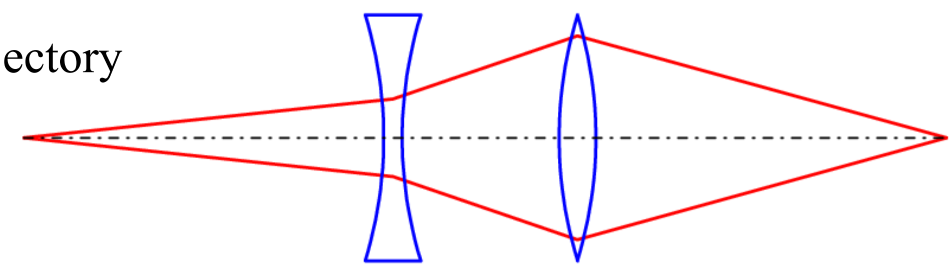


saddle lens

horizontal trajectory



vertical trajectory

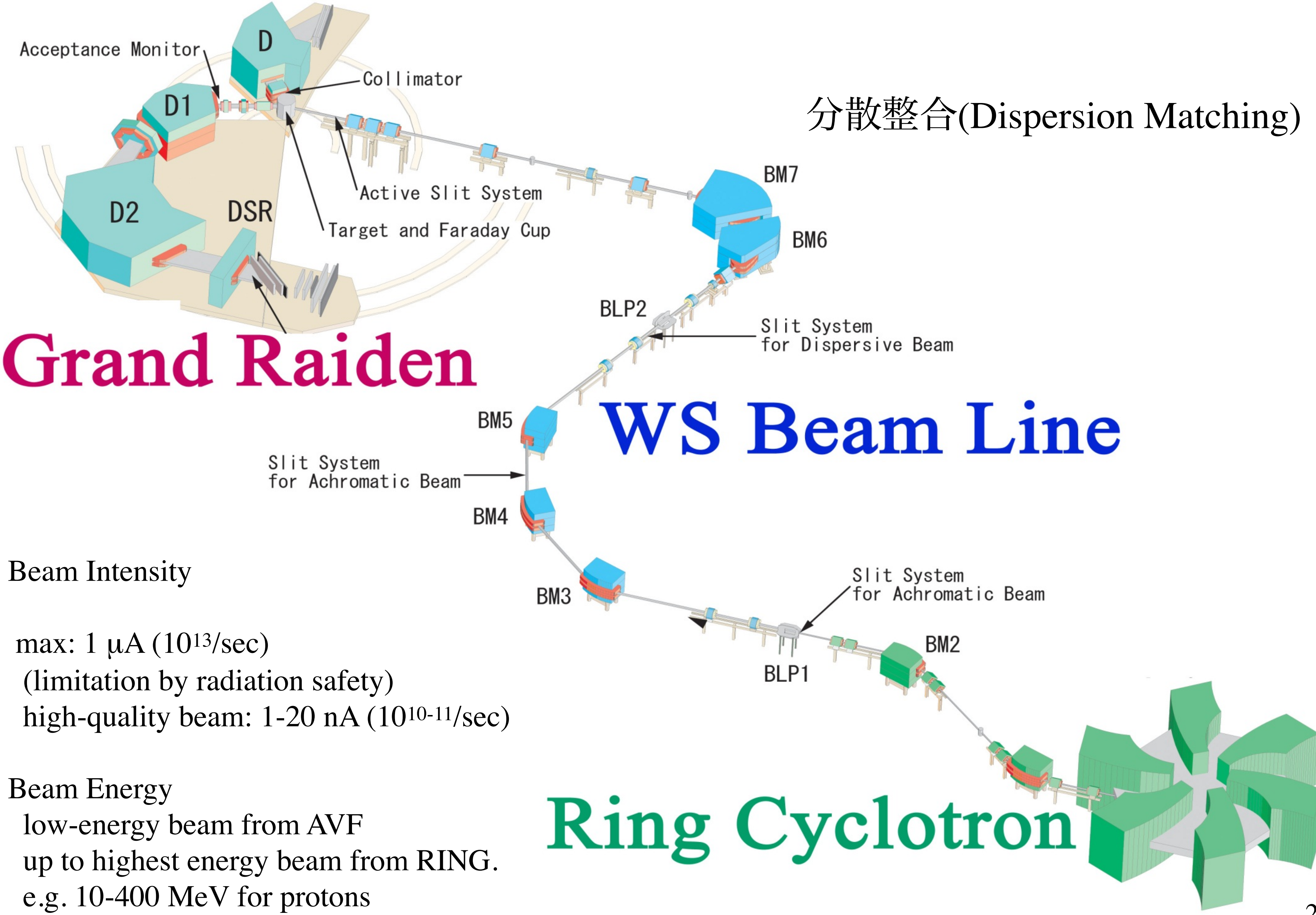


Combine two or three quadruple magnets

⇒ focuses the beam both for horizontal and vertical directions

High Resolution Beam-line (WS)

分散整合(Dispersion Matching)



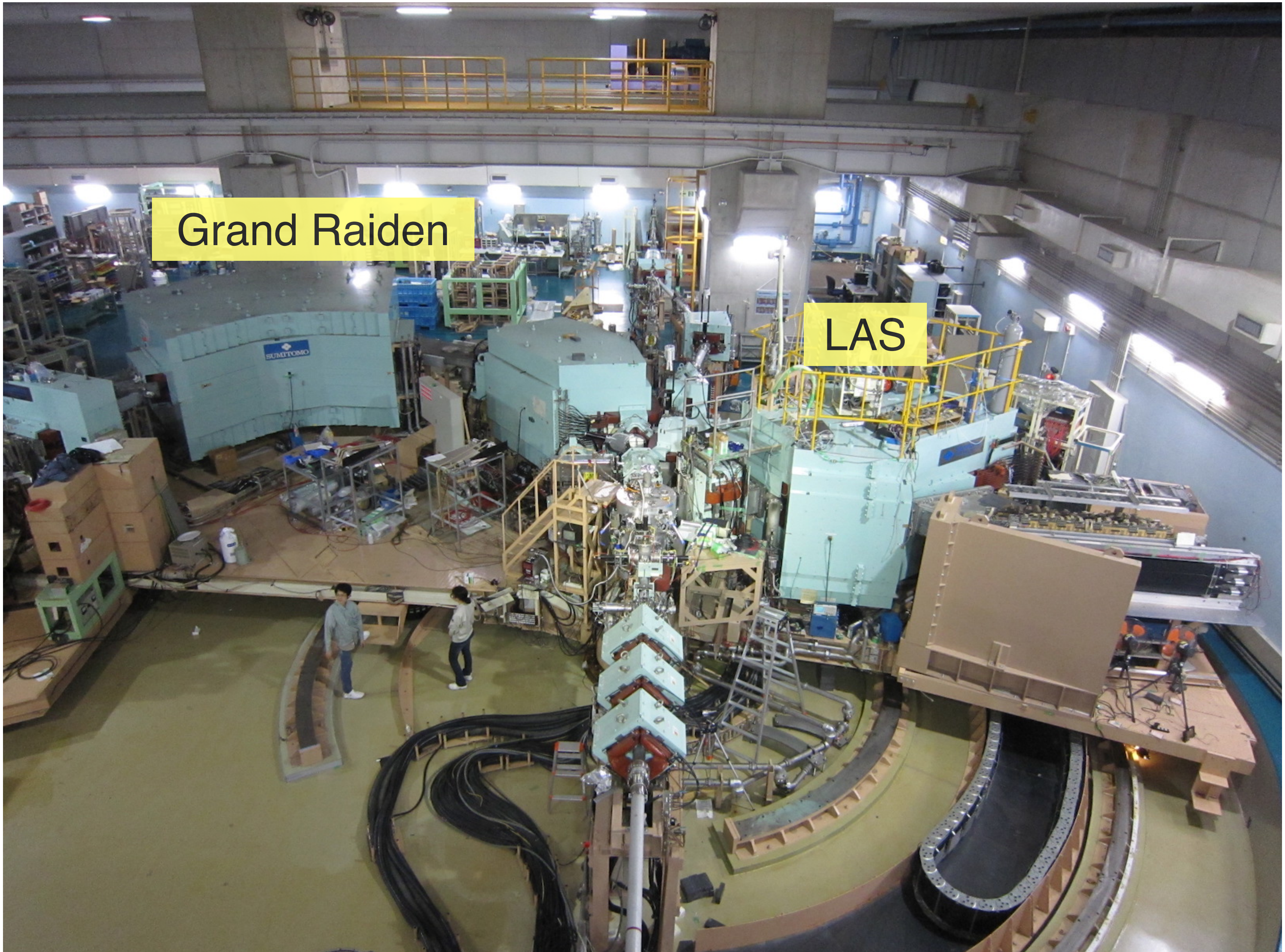
Beam Intensity

max: 1 μA (10^{13}/sec)
(limitation by radiation safety)
high-quality beam: 1-20 nA ($10^{10\text{-}11}$/sec)

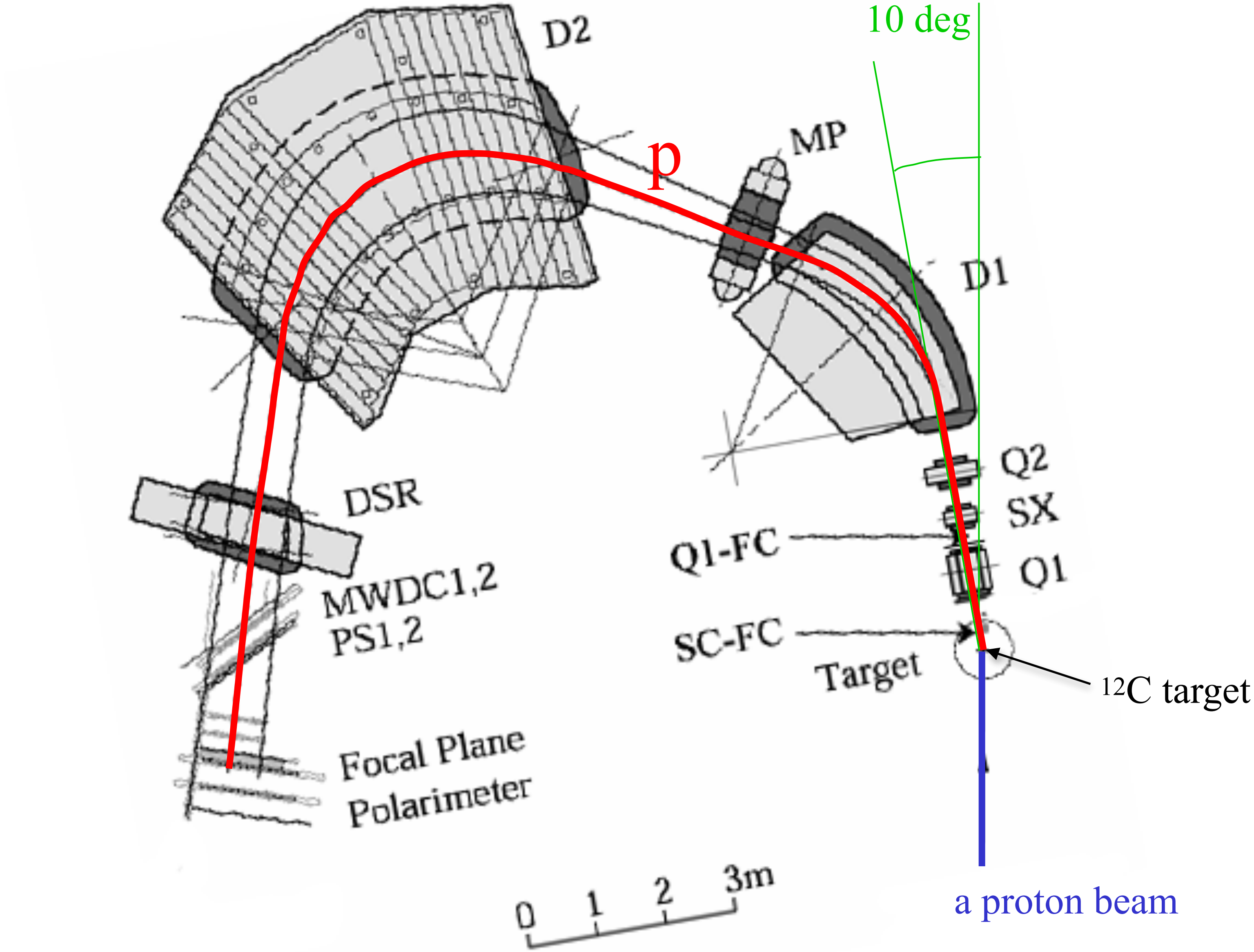
Beam Energy
low-energy beam from AVF
up to highest energy beam from RING.
e.g. 10-400 MeV for protons

Spectrometer

Spectrometer Grand Raiden and LAS

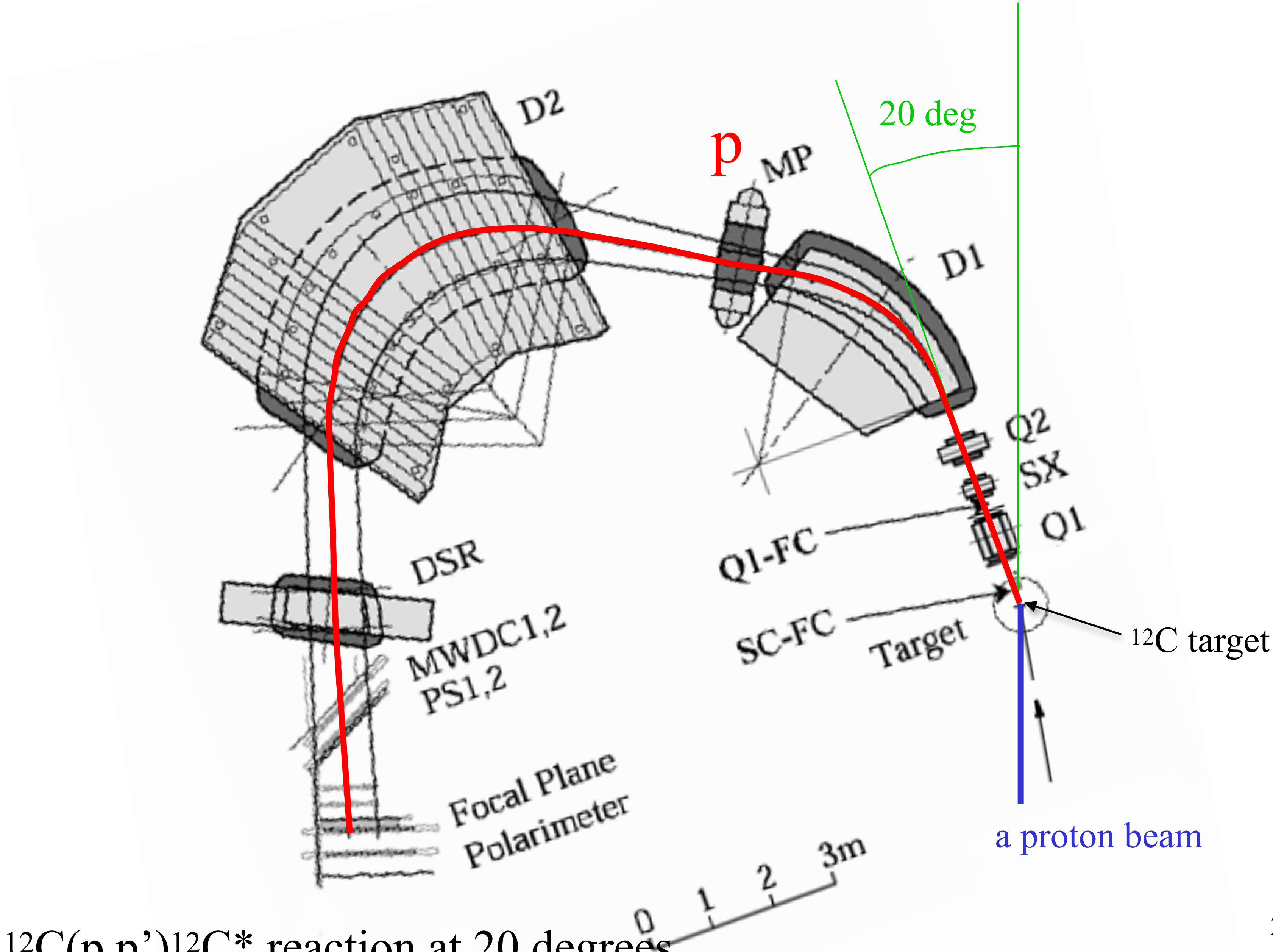


Grand Raiden Spectrometer



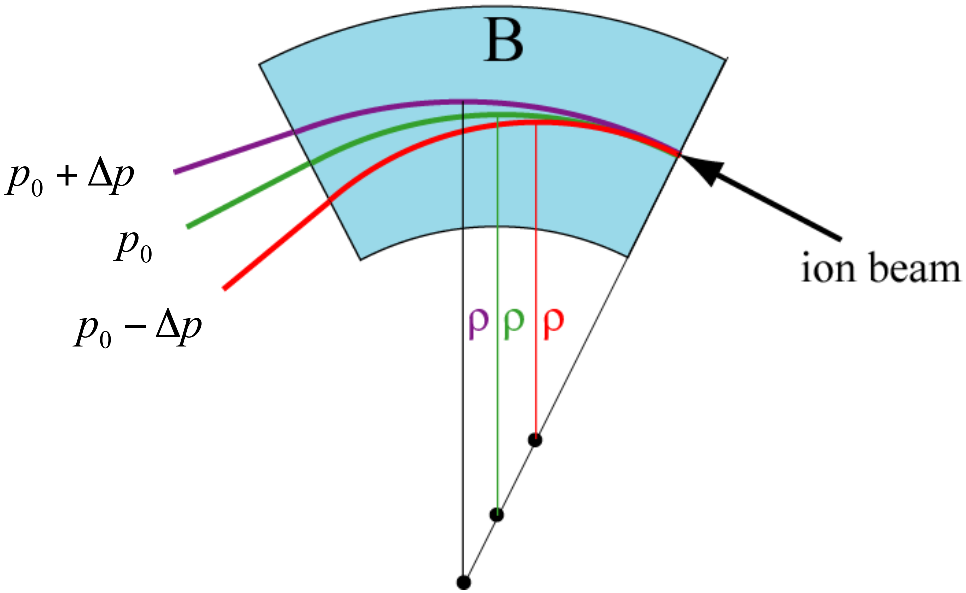
$^{12}C(p,p')^{12}C^*$ reaction at 10 degrees

Grand Raiden Spectrometer



$^{12}C(p,p')^{12}C^*$ reaction at 20 degrees

Dipole (Bending) Magnet



A spectrometer maps a momentum to a position

$$\text{momentum dispersion} = \frac{\Delta x}{\delta}$$

$$\delta \equiv \frac{\Delta p}{p_0}$$

$$\frac{p}{Q} = 0.3 B\rho$$

p : momentum [GeV/C]

Q: charge []

B: magnetic field [T]

ρ: bending radius [m]

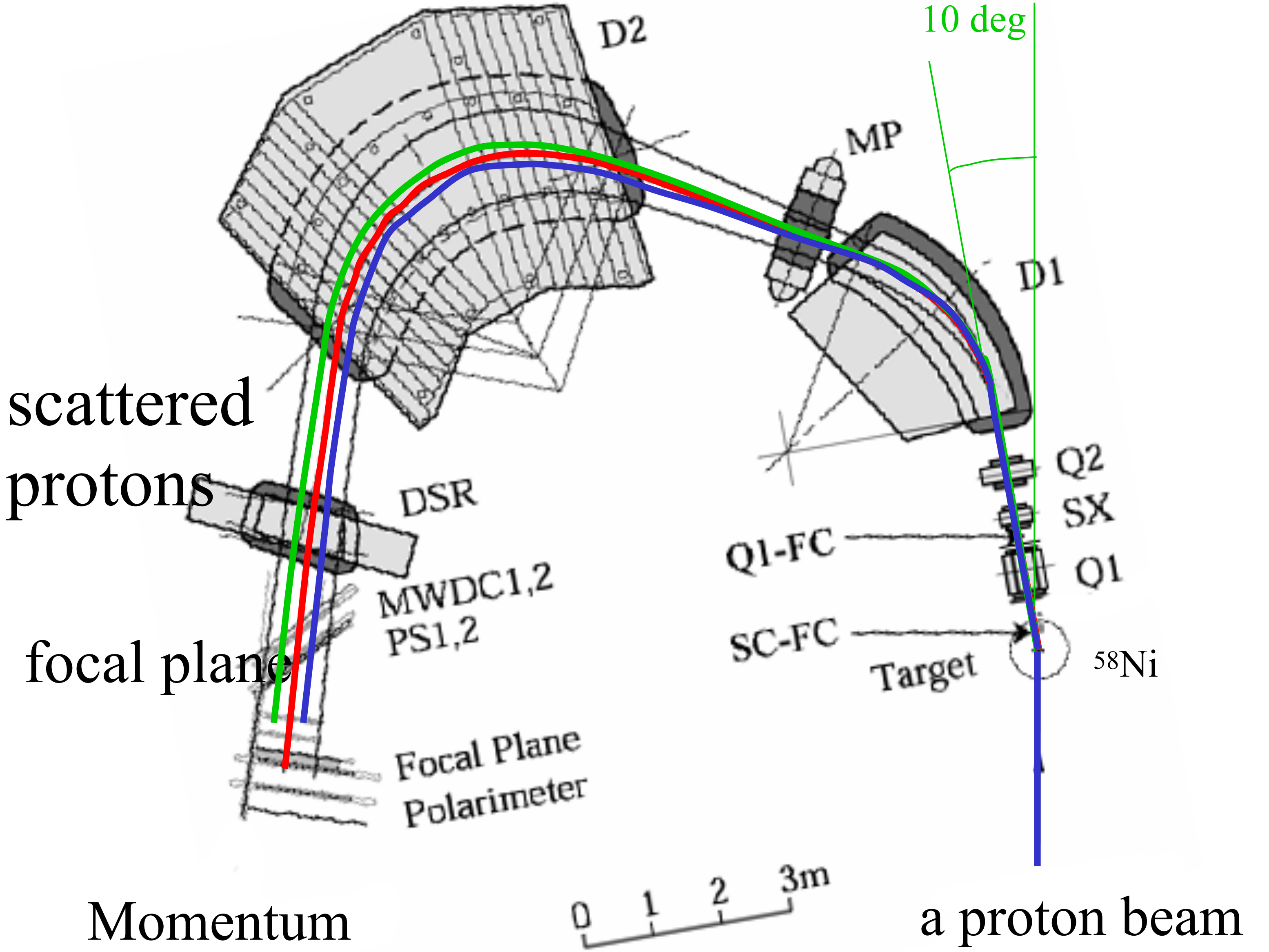
momentum dispersion of Grand Riden:15.4 m

When analyzing 295 MeV proton in 17 keV resolution
する場合

17 keV / 295 MeV = 6×10^{-5}

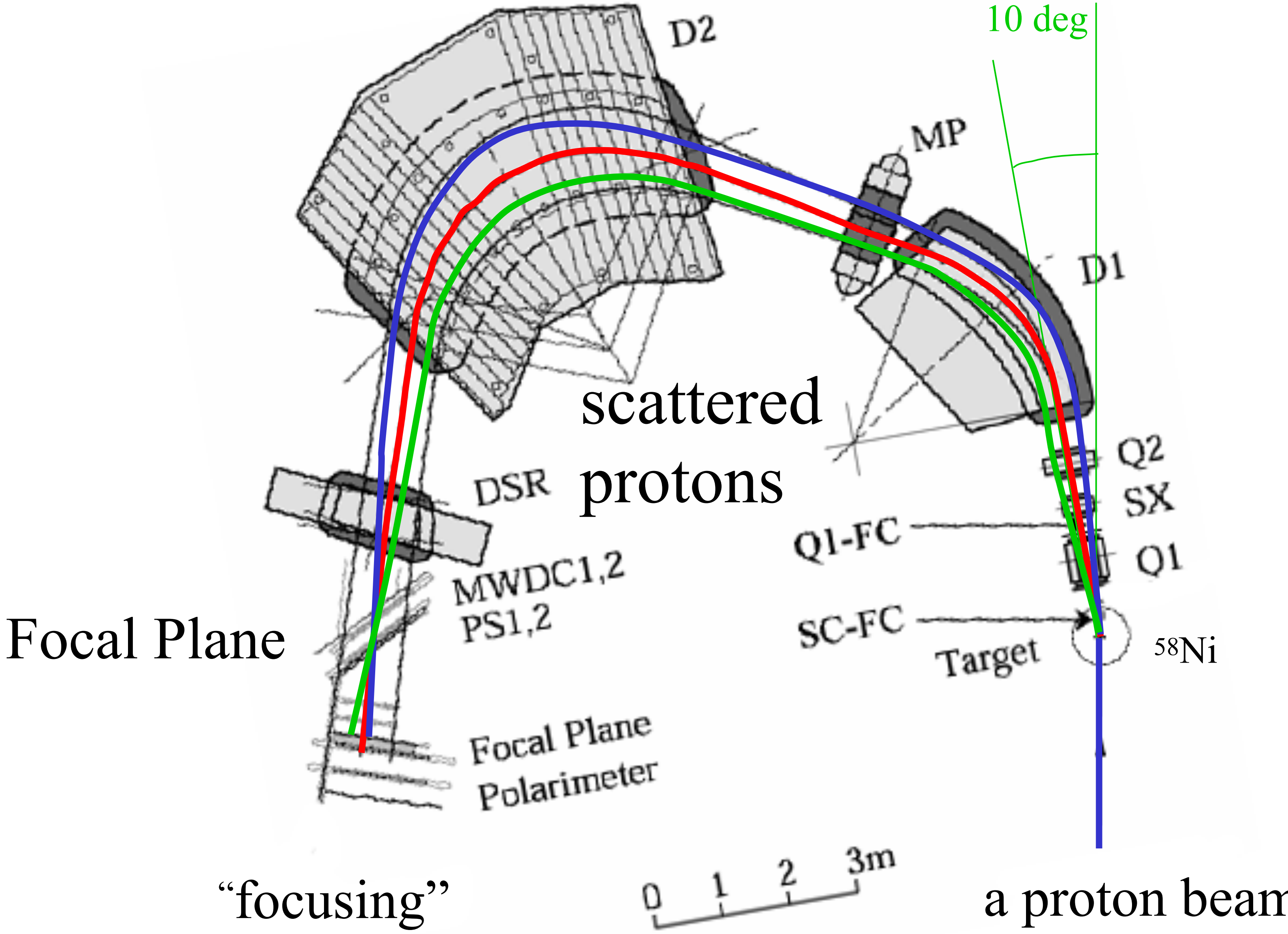
→ momenutm deviation $\delta = 3\times10^{-5}$
→ position difference Δx=0.5mm

Grand Raiden Spectrometer for different momentum

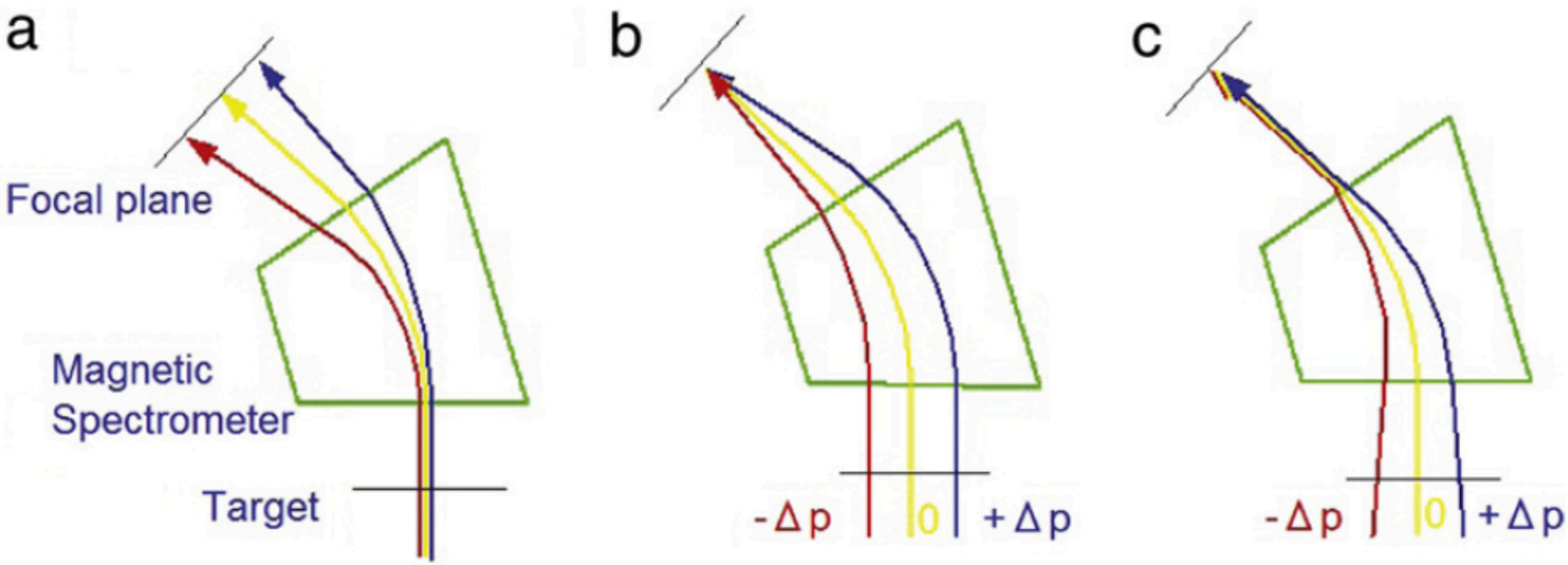


Momentum analysis

Grand Raiden Spectrometer for different incidence angle



Dispersion Matching
for high-resolution



Standard mode （achromatic）

A beam has an energy spread
→ The energy resolution is limited by the energy spread.

100 keV → 20 keV

momentum matching

momentum dispersion

The beam momentum is analyzed before the target point.
The momentum is mapped on the horizon position on target
→matched with the horizontal magnification of the spectrometer

good energy resolution

angular matching

momentum dispersion
angular dispersion

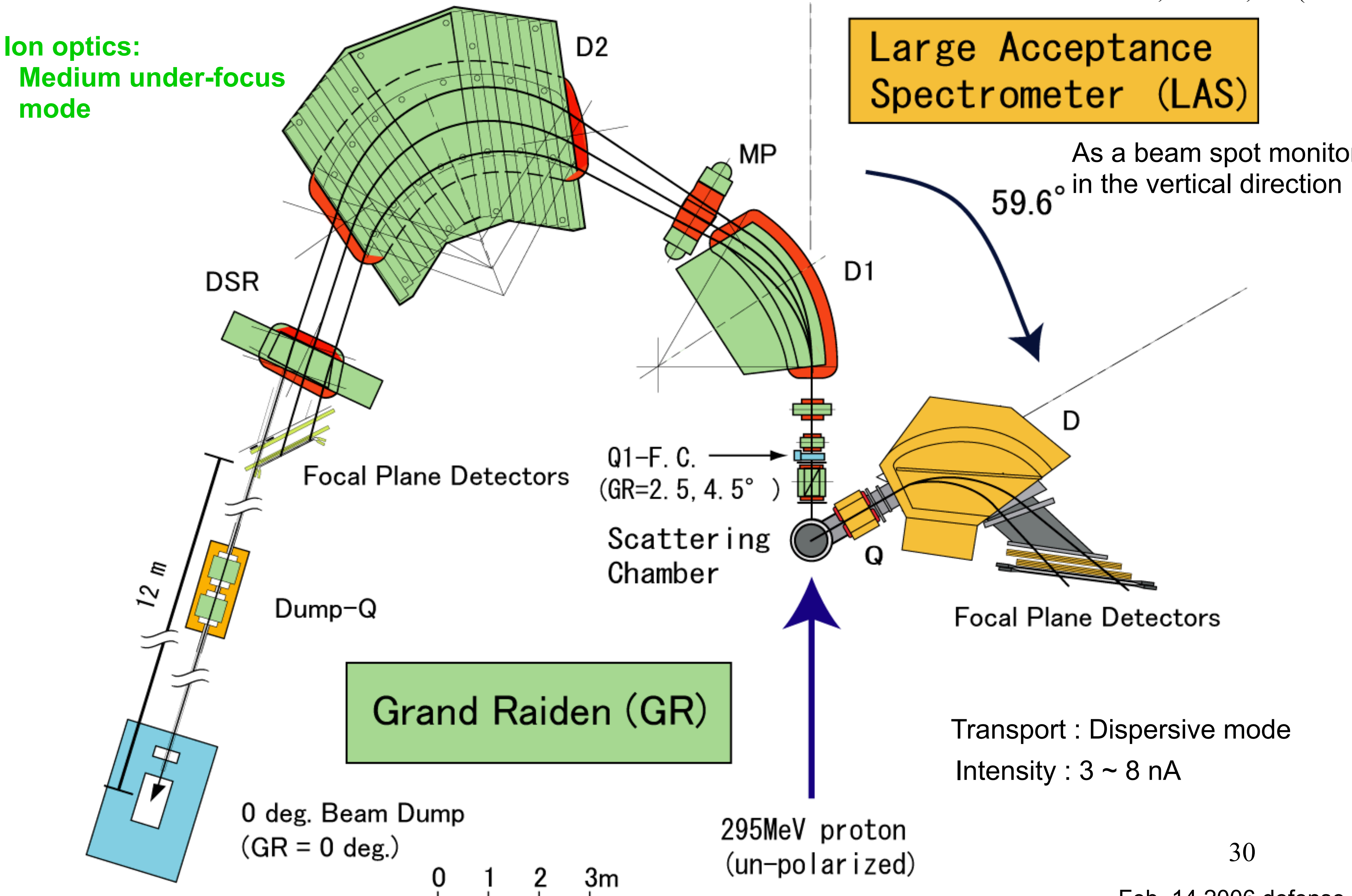
The incidence angle is matched with the momentum
→the angle is matched at the focal plane

good angular resolution
0.1 deg

0-degree proton scattering experiment setup

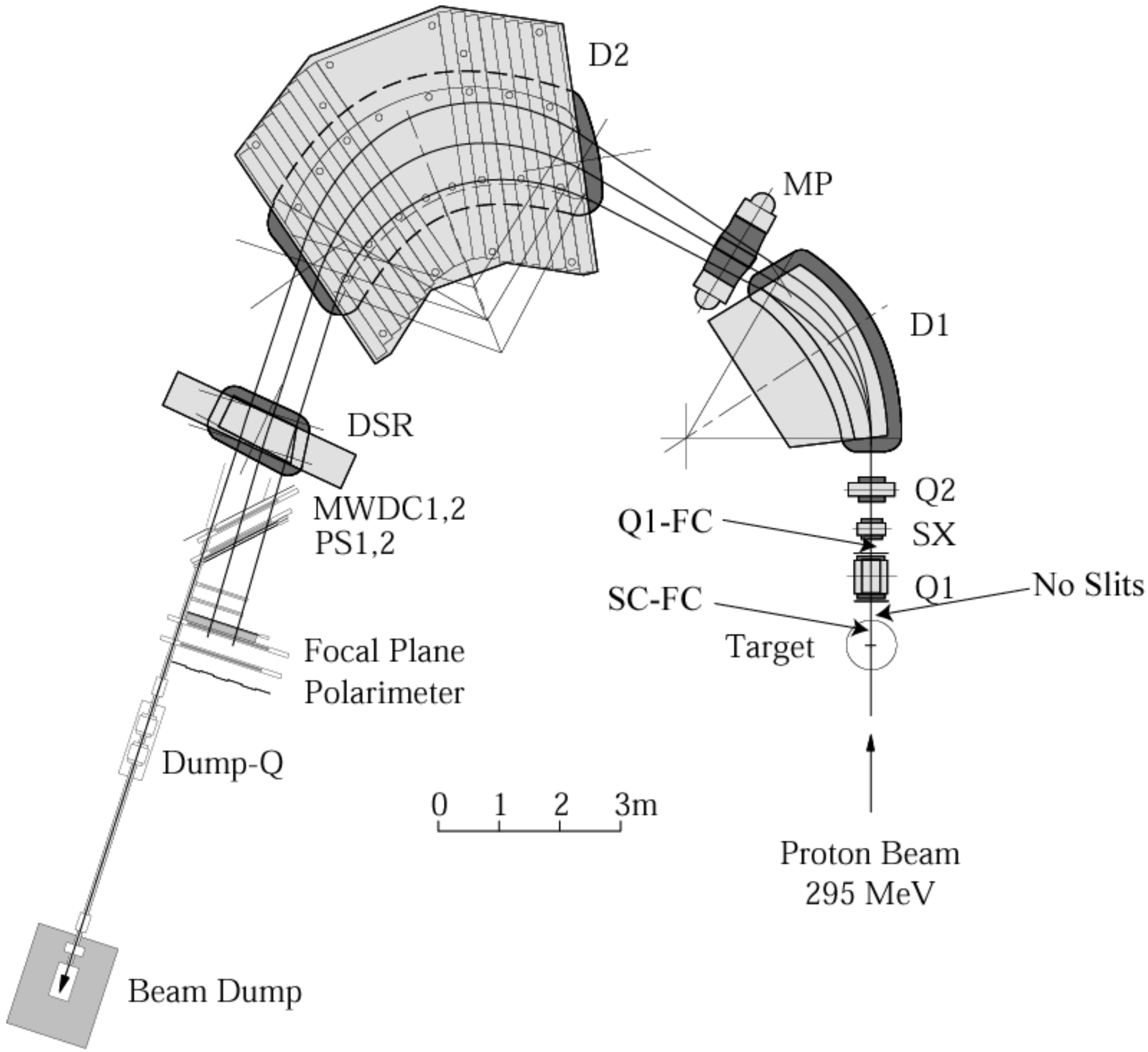
A. Tamii et al., NIMA **605**, 326 (2009)

P. von Neumann-Cosel and A. Tamii, EPJA**55**, 110 (2019).



Feb. 14 2006 defense

0-degree proton scattering experiment setup



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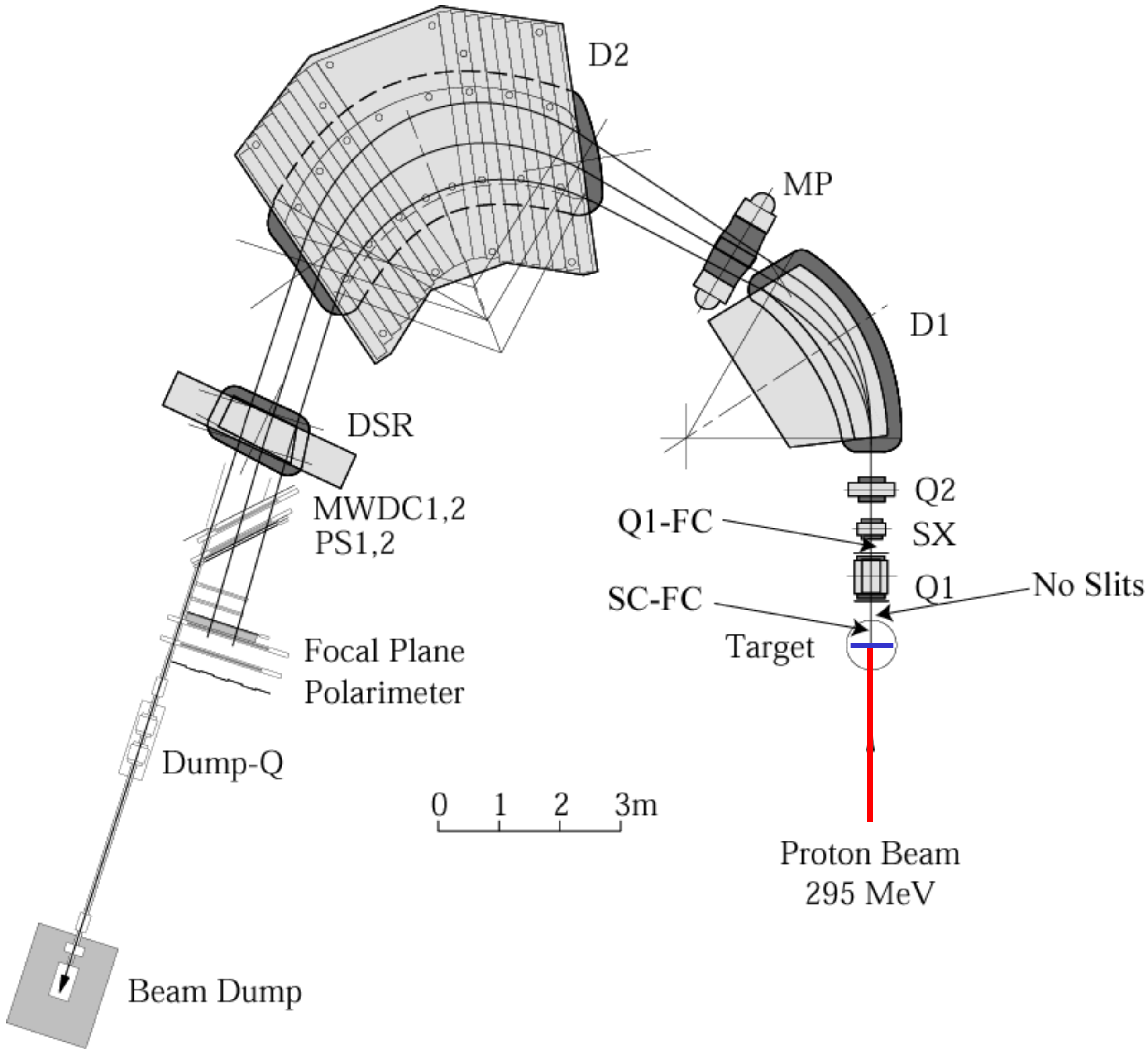

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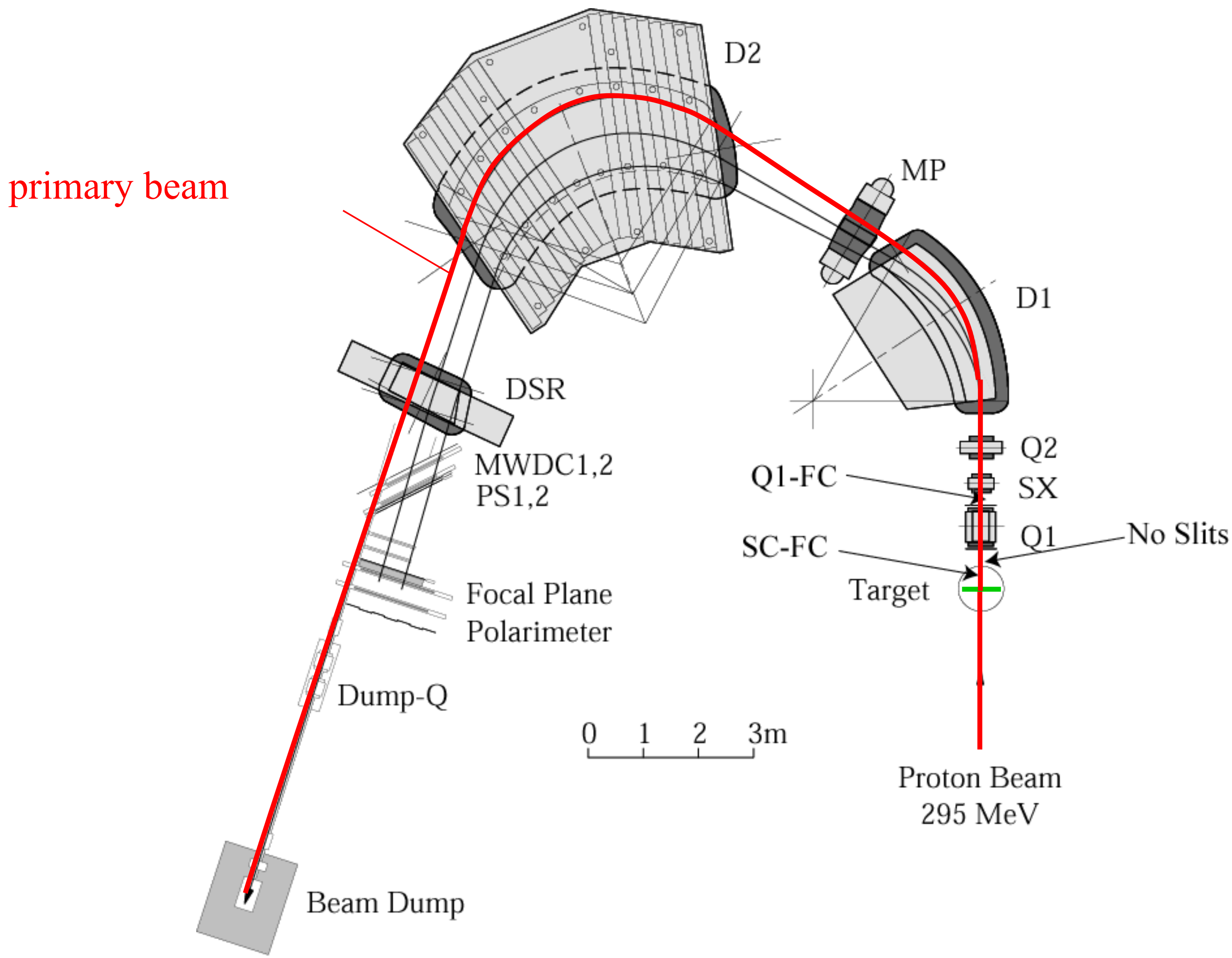

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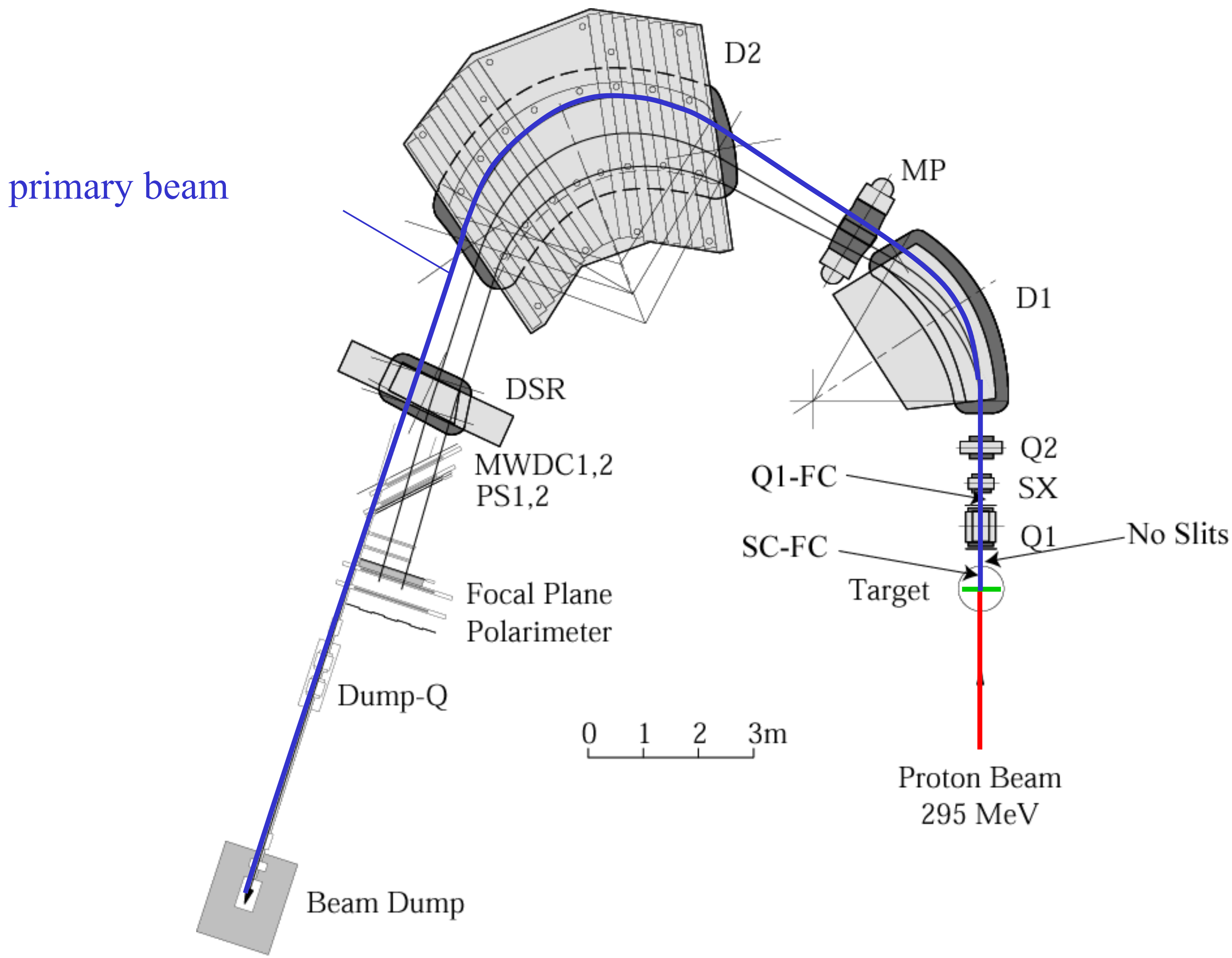

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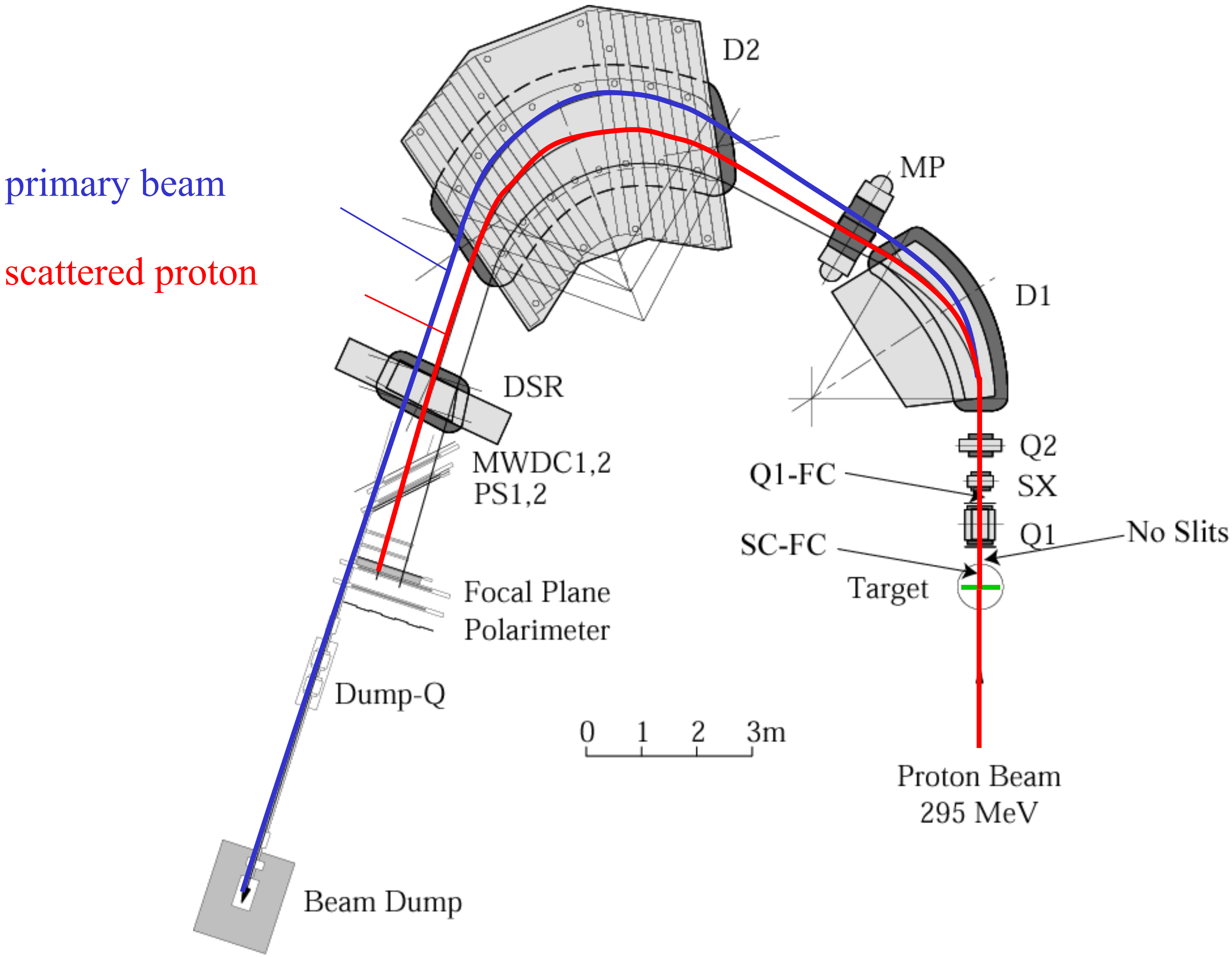

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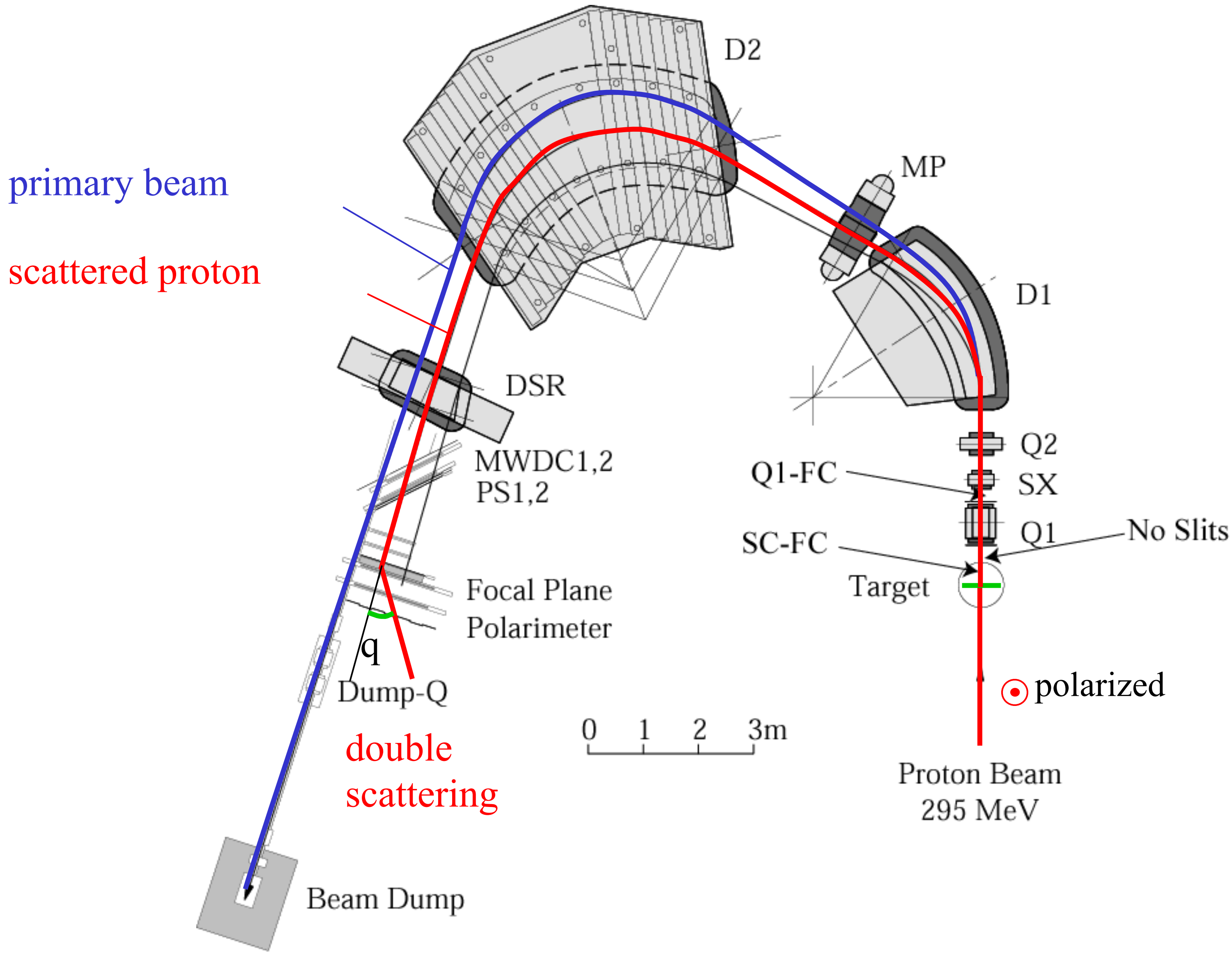
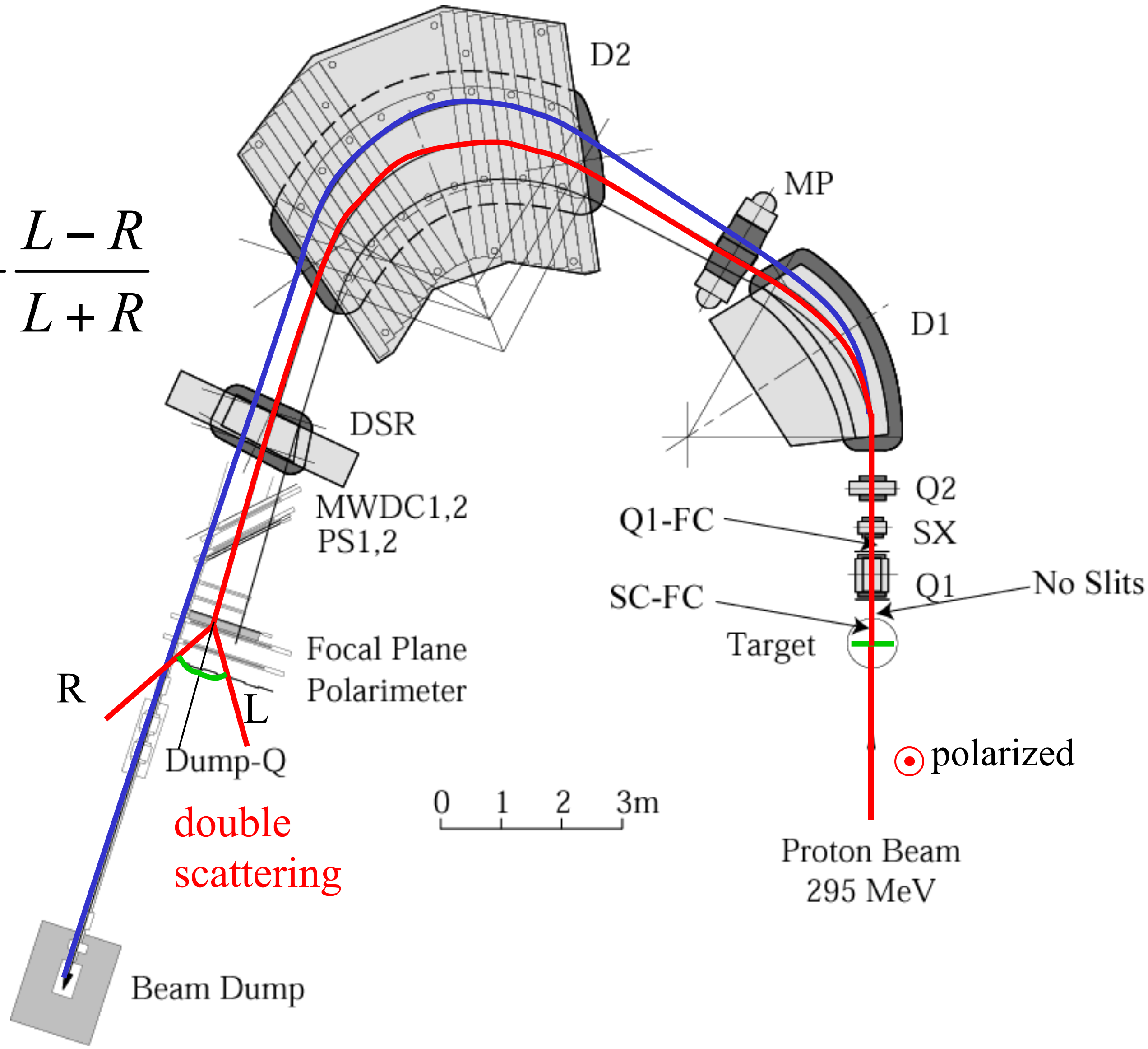


0-degree proton scattering experiment setup

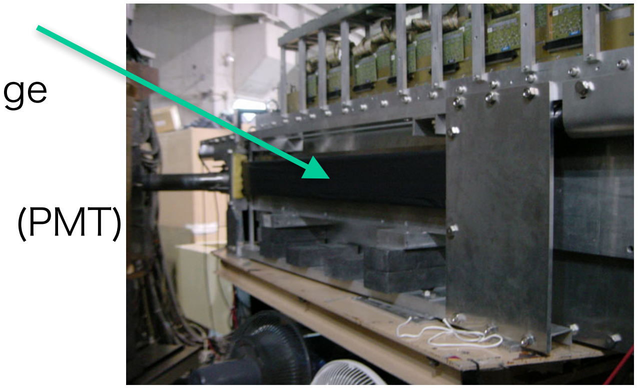
$$p_{y'} = \frac{1}{A_y}\frac{L-R}{L+R}$$



Detectors, Electronics

Plastic Scintillation Counter (PS)

(organic scintillator)

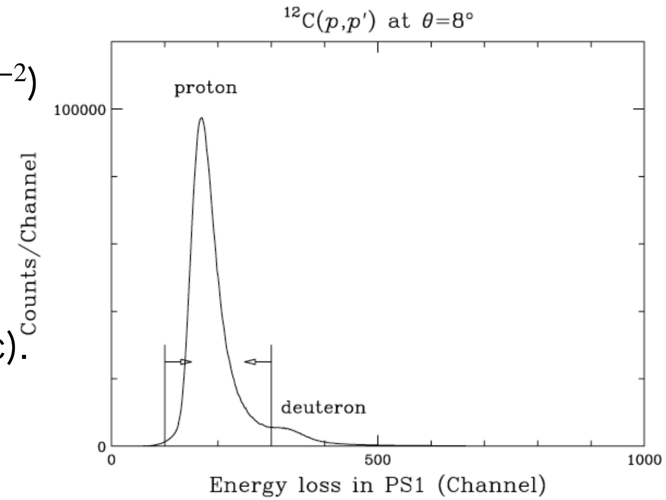


Mechanism

- Excite molecules in the scintillator by charged particle passage
- Emit light when de-excited (scintillation light)s
- Collect light, convert to electrons, and multiply the electrons (PMT)

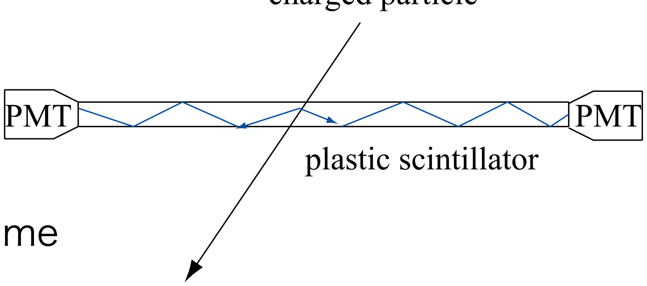
Essences

- The energy loss of a charged particle is proportional to the square of the incident particle charge and inversely proportional to the square of the particle velocity ($\Delta E \propto z^2 v^{-2}$)
- Good timing resolution(<100 ps). Energy resolution is not good (100-200 eV for an excitation)。
- Cheap, can be big, good for shaping
- Particle identification by the wave form analysis(n, γ ,p,d,etc). Exploiting the fact that longer-decay comonent is more excited for higher energy-loss density



Applications

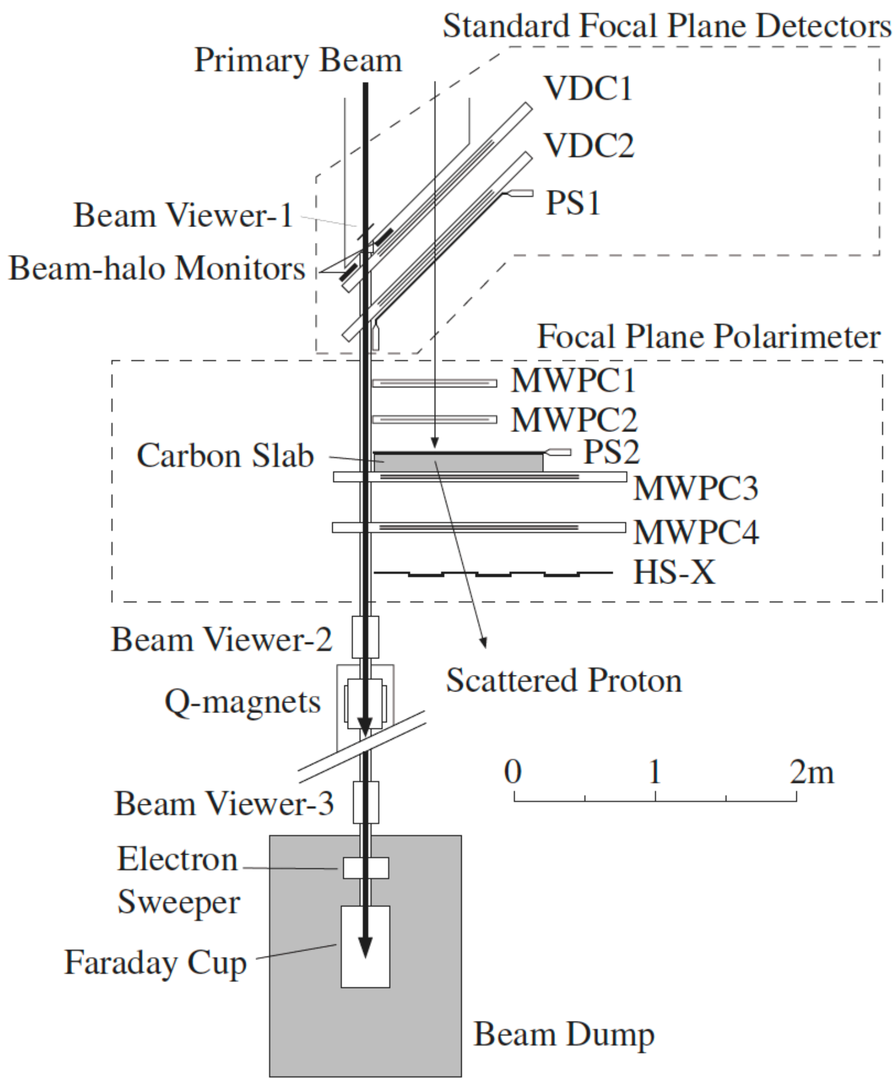
- Trigger detector
- Energy loss detector
- Neutron detector with large volume



Tips

- Alcohol is not good for plastic scintillators
- Some people insist that they can recognize the scintillation light in their eyes

Focal Plane Detectors



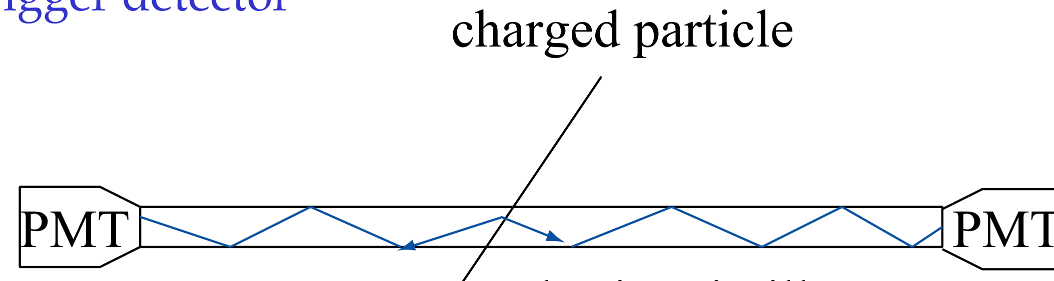
Vertical Drift Chamber (a kind of MWDC)

Plastic Scintilltor

Focal Plane Polarimeter (FPP) using MWPCs

Figure 2.5: The standard focal plane detectors and the Focal Plane Polarimeter (FPP) at the focal plane of the spectrometer in the setup of the 0° experiment.

Plastic Scintillator
energy loss detector, timing detector, and trigger detector



Behe-Block energy loss formula

$$\frac{dE}{dx} \propto \frac{Z}{A}\frac{z^2}{v^2}$$

particle

target material (plastic)

Plastic Scintillator:

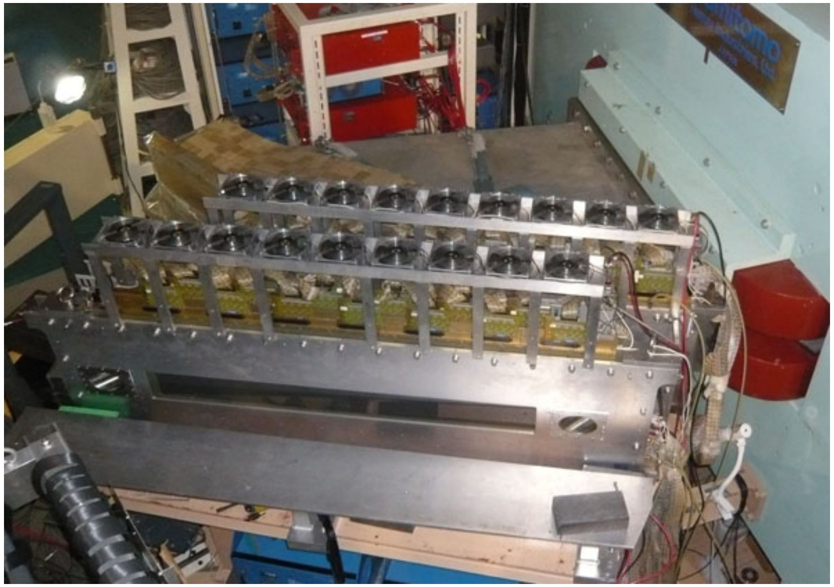
Quick response: ~10 nsec

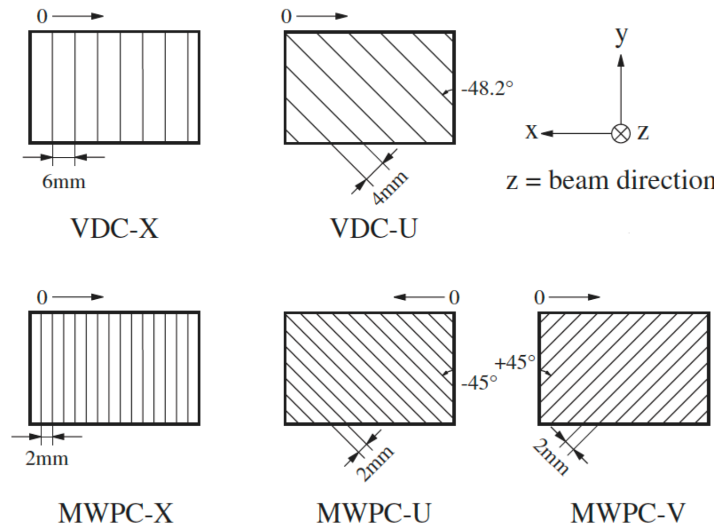
Good timing resolution: ~100 psec

Good (~100%) detection efficiency for charged particles

Inexpensive, can be thin (>=0.1mm), easy to shape

Vertical Drift Chamber (Muliti-Wire Drift Chamber)

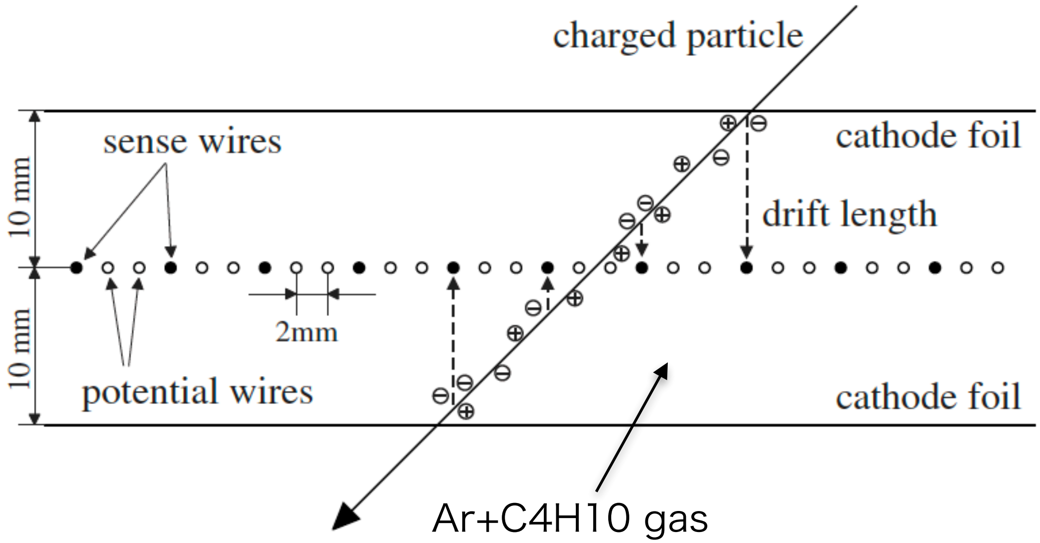




Wire configuration	X(0°), U(-48.2°)
Active area	$1150^{W} \times 120^{H}$ mm
Number of sense wires	192 (X), 208 (U)
Anode-cathode gap	10 mm
Anode wire spacing	2 mm
Sense wire spacing	6 mm (X), 4 mm (U)
Anode sense wires	20 $\mu m\phi$ gold-plated tungsten wire
Anode potential wires	50 $\mu m\phi$ gold-plated beryllium copper wire
Cathode film	10 μm carbon-aramid film
Applied voltage	-5600 V (cathode), -300 V (potential), 0 V (sense)
Gas mixture	argon:iso-butane:iso-propyl-alcohol = 70:30:*[1]
Pre-amplifier	LeCroy 2735DC
Digitizer	LeCroy 3377 drift chamber TDC

[1]Mixed with the argon gas in 2°C vapor pressure.

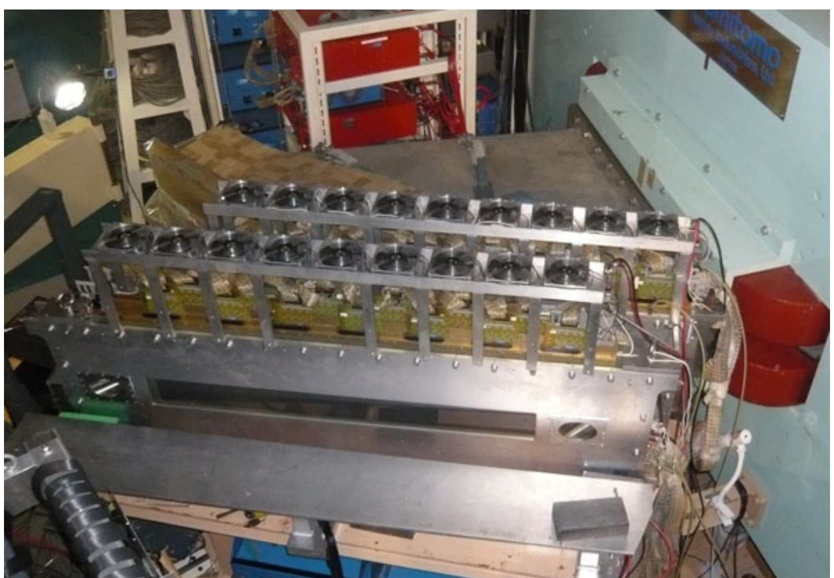
Multi-wire Drift Chambers

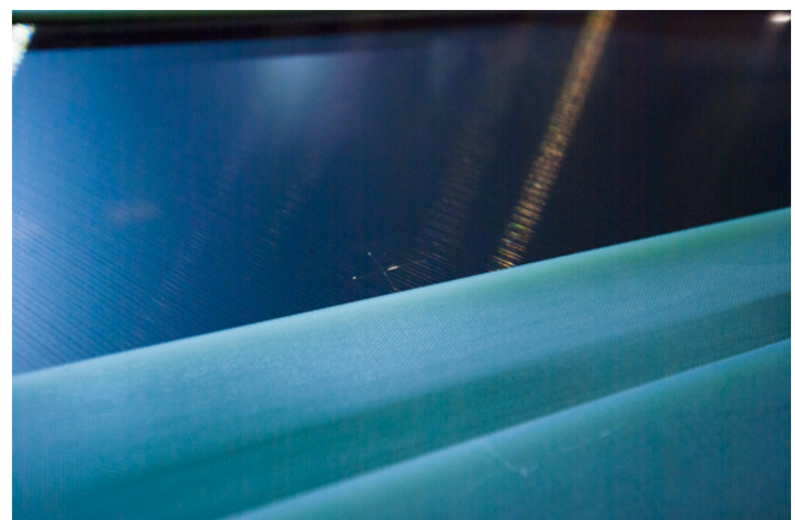


negative voltage (-5.6 kV)

0 V

negative voltage (-5.6 kV)





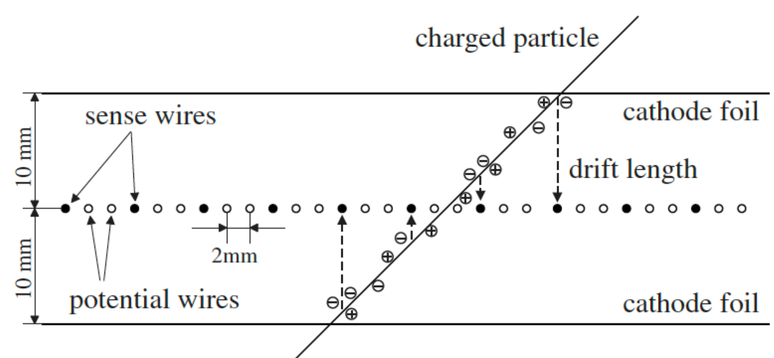
Multi-wire Drift Chambers

Mechanism

- Electron-ion pairs are produced along the trajectory of a charged particle
- Electrons drift to the anode wires with a nearly constant velocity (~50μm/nsec)
- Electrons are accelerated at close to an anode wire. —> Produce more electrons. —> Avalanche effect. ~$10^{5\text{-}6}$. Ions are also created.
- Ions move to a cathode foil, inducing the signal in the anode wires.
- The anode wire signals are pre-amplified, discriminated, and time-recorded.
- Timing signals are used for determination of the position and incidence angle of charged particles.

Essences

- High-position resolution (0.2-0.5mm) covering large area
- Gas material density is low. Charged particle go straight with negligible deflection by collision.
- Designed to have a nearly constant drift velocity of electrons.
- Signal size is proportional to the energy loss (proportional counter)

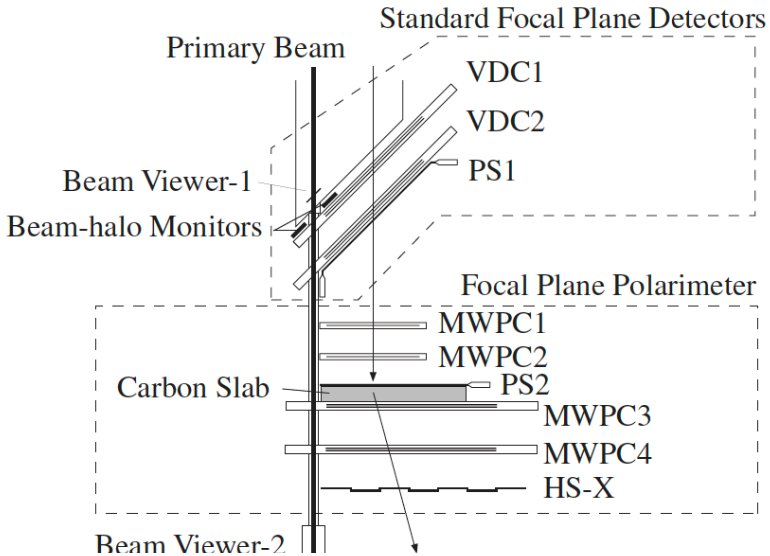


Multi-wire Drift Chambers

TIPS

- G. Charpak got a Nobel prize for developing MWDCs.
  A student Sauli was excellent. See Sauli's papers to learn MWPCs and MWDCs.
- A type of mixed gas is commonly used (magic gas)
  Inert gas is for producing electron seeds（no molecular oscillation of rotation to consume energy）.
- Quencher gas（e.g. isobutane: C4H10）absorb X-rays from the de-excitation of the inert gas. Efficient absorption of X-rays due to molecular oscillation of rotations.
- Without quenching gas, X-ray reaches to cathode an create photo-electrons. The electron drift to the anode wire and make signals. It can cause a positive-feedback to produce a very large signal that is not proportional to the energy loss (Geiger Mueller counter)
- A small amount of alcohol (iso-propyl alcohol) is mixed in the gas for longer life-time of the detector. The quencher gas is ionized and drift to the cathode and stack on the surface on the cathode by polymetrization. Alcohol quickly exchange electrons with the quencher gas ions and drift to the cathode but does not make polymetrization.

Focal Plane Polarimeter (FPP)



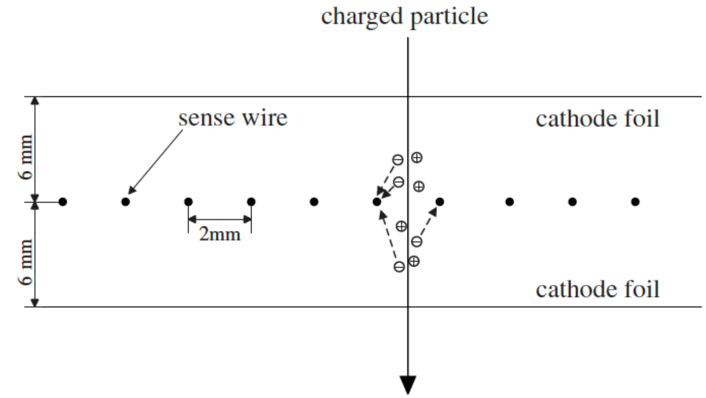
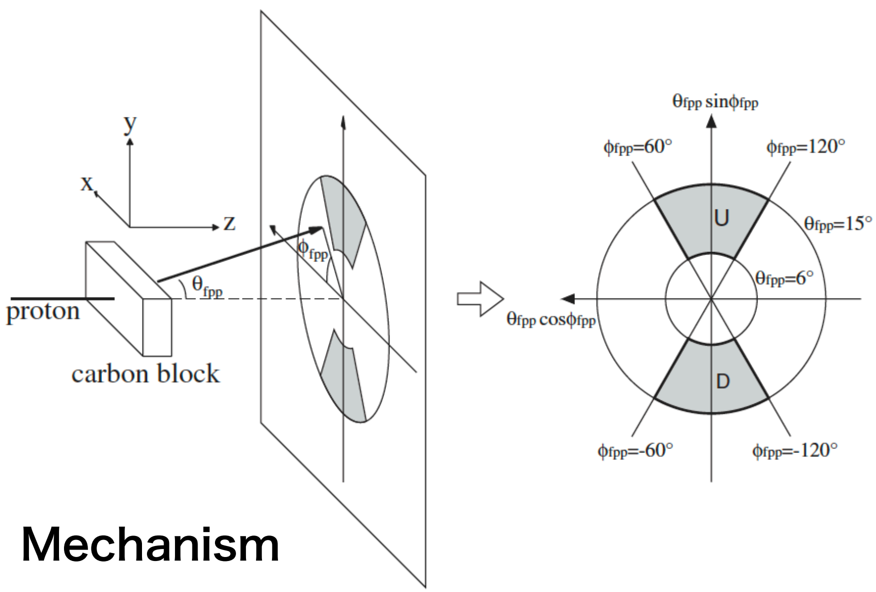


Figure 3.5: Structure of the MWPCs.

Table 2.3: Specification of the MWPCs.

	MWPC1,2	MWPC3	MWPC4
Wire configuration	X(0°)	X(0°), U(-45°), V(+45°)	
Active area	$760^W \times 200^H$ mm	$1400^W \times 418^H$ mm	$1400^W \times 600^H$ mm
Number of wires	384	704 (X), 640 (U,V)	704 (X,U,V)
Anode-cathode gap	6 mm		
Anode wire spacing	2 mm		
Anode wires	25 mmϕ gold-plated tungsten wire		
Cathode film	10 μm carbon-aramid		6 μm aluminized mylar
Cathode voltage	-4900 V	-4700 V	
Gas mixture	argon:iso-butane:freon:iso-propyl-alcohol = 66:33:0.3:[1]		
Pre-amplifier	LeCroy 2735PC and Nanometric N277-C3		
Digitizer	LeCroy PCOS III		

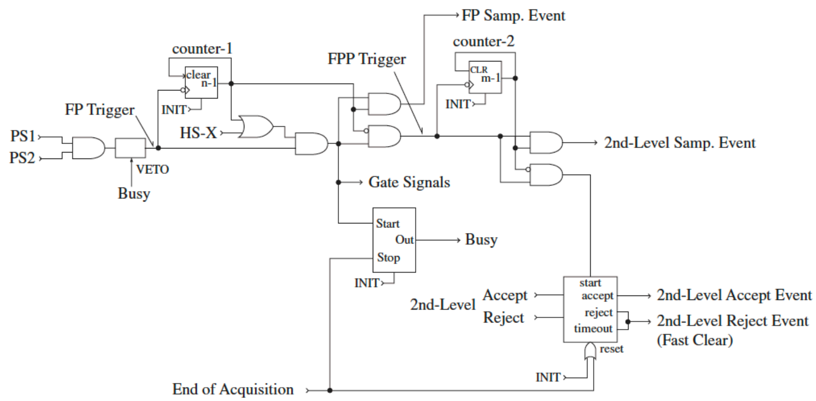
[1]Mixed with the argon gas in 2°C vapor pressure.



Mechanism

- Measure the second scattering angular distributions —-> measure polarization

Trigger Circuit, Data Acquisition System



Mechanism

- Decision of DAQ by a trigger created from fast detectors (PS)
- Aquire timing (TDC) and signal size (ADC) information

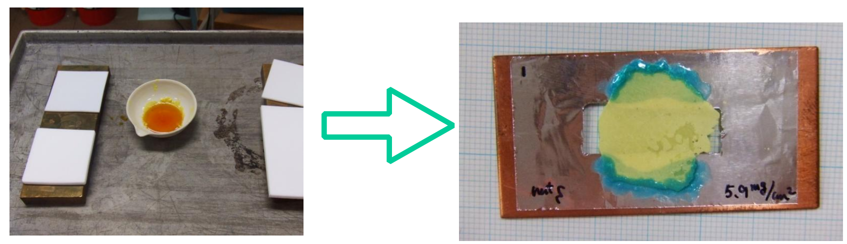
TIPS

- Recent digital acquisition system record a wave form a detector signal.
- The data size become much larger, more complicated analysis?
- At RCNP with Grand Raiden, 1TB of data are taken typically for a beam time of 3-7 days.

Targets

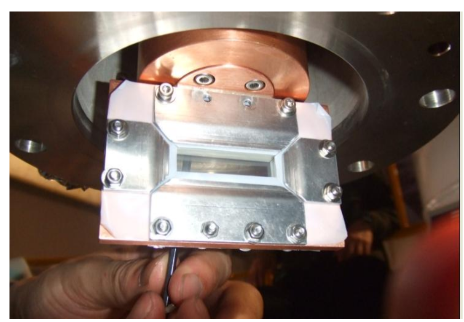
- pure foils with a thickness of 10-100 μm〜100 μm.
- a size of 1-2 cm
- isotopically enriched (expensive)
- various types of targets dep. on the material

Sulfur: H. Matsubara *et al.*, NIMB **267**, 3682 (2009)

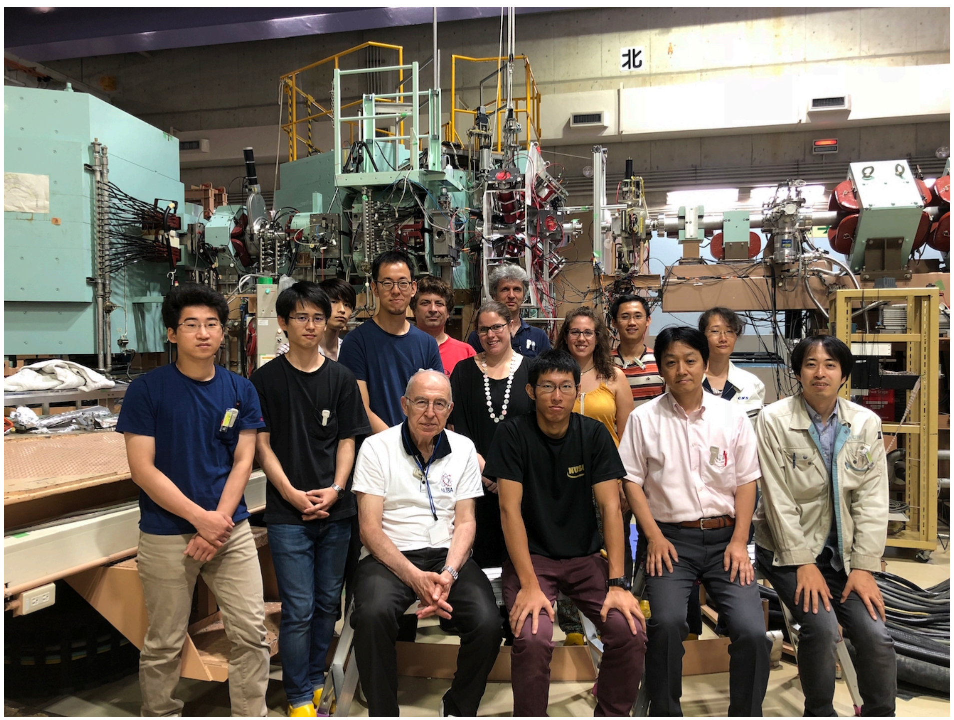


ice target: T. Kawabata *et al.*, NIMA 459 (2001) 171.

gas target : H. Matsubara *et al.*, NIMA **678**, 122 (2012)



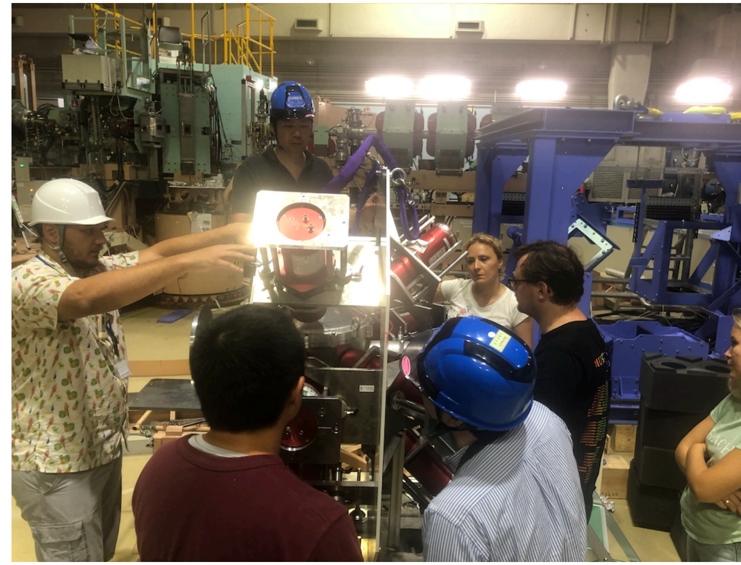
Perform Experiments

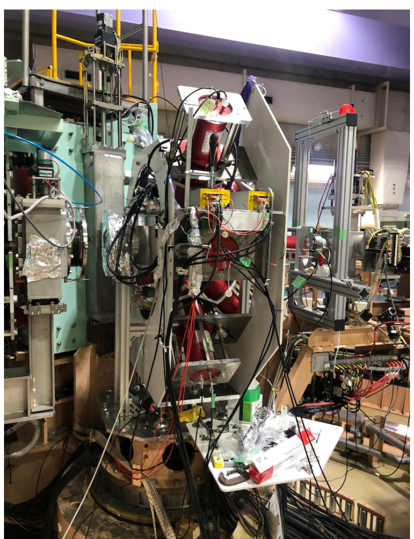


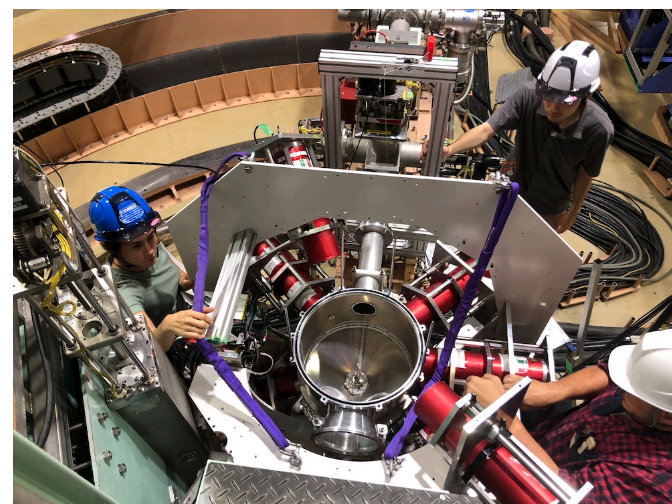
20-30 people, 2-10 days

A biggest experiment using Grand Raiden involved about 100 people

PANDORA exp. in October 2023)





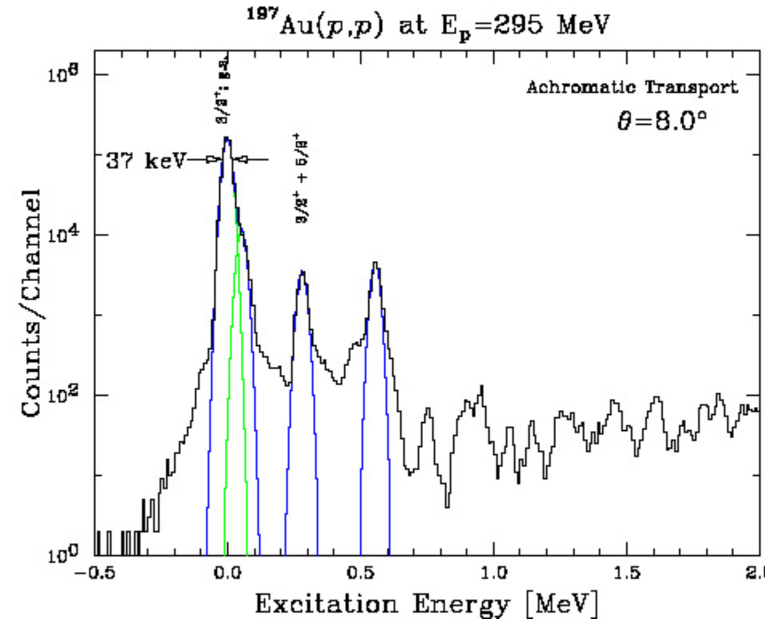


PANDORA exp. in October 2023)

Experimental setup trouble shootings

Beam Tuning, Calibrations

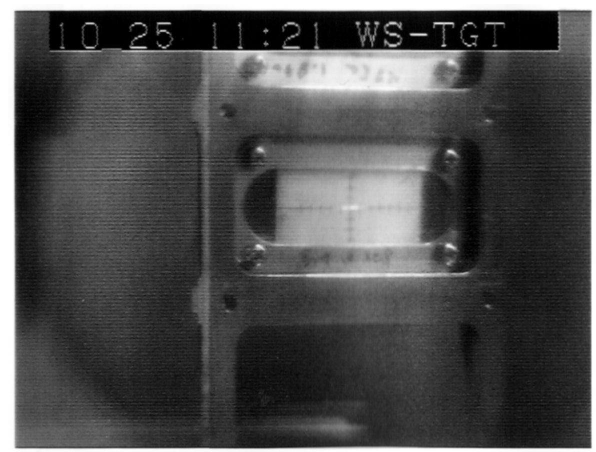
- It takes 1-2 days for tuning a high-quality high-resolutions beam
- Check all the detectors are working properly.
- Optimize measurement conditions, DAQ
- Online monitoring of data, trouble shooting
- Take data for calibrations
- Record everything in the logbook!



TIPS

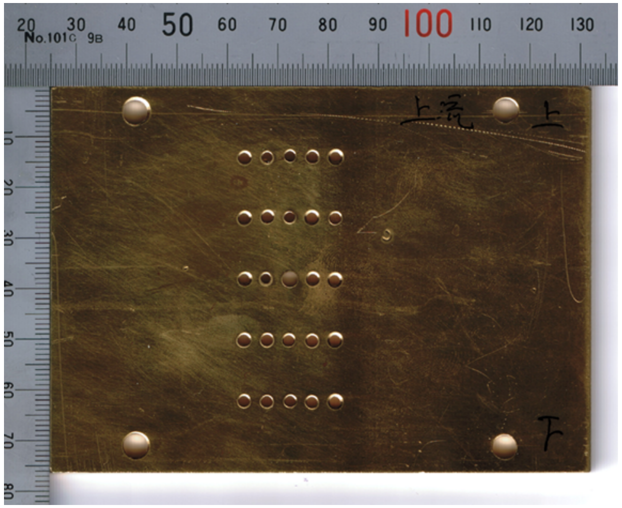
- Always troubles happen in experiments.
- In my feeling, a good experiment is suffered from more troubles
- Fixing problems are indispensable skill of experimentalists. It is a good chance for showing the skill when one a problem happens.

  finding a problem
  localizing the problem
  guess and prove the origin of the problem
  fixing the problem or alternative measure?



Beam spot in the dispersive mode

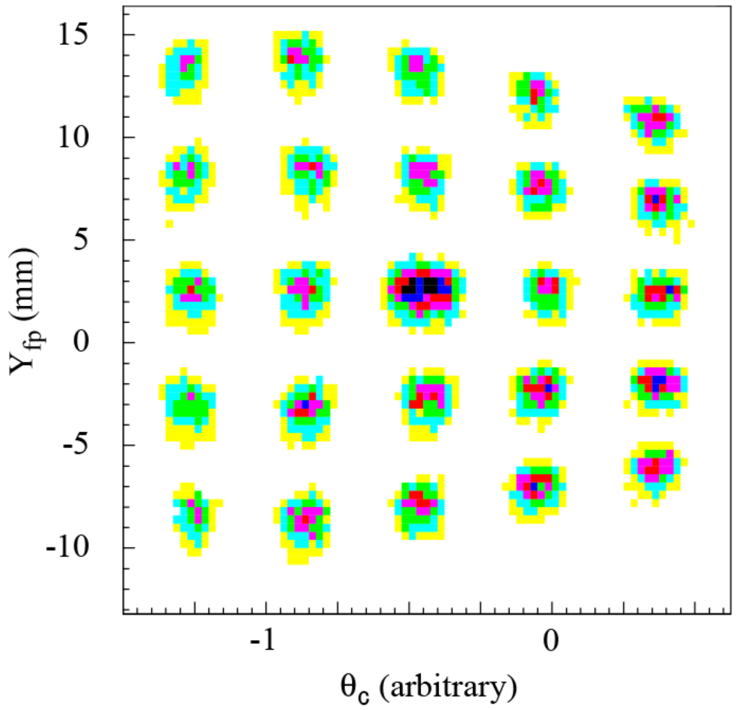
Data Analysis



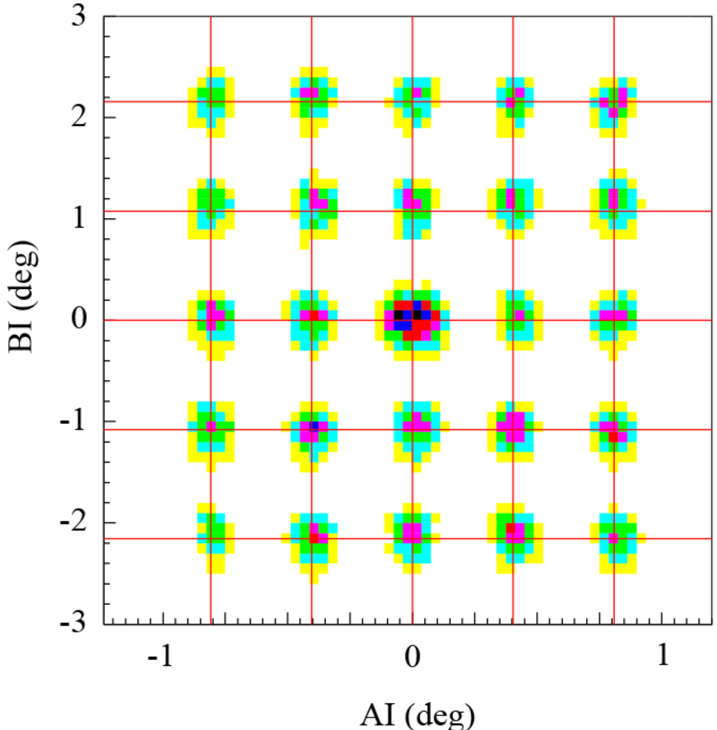
Calibration of the Scattering Angle using a sieve-slit

←
a sieve-slit was placed at the entrance of GR

Image at the focal plane



Reconstructed image



Sieve Slit Calibration (Scattering Angle)

Sieve slit data by using $^{58}Ni(p, p_0)$ reaction at 16°

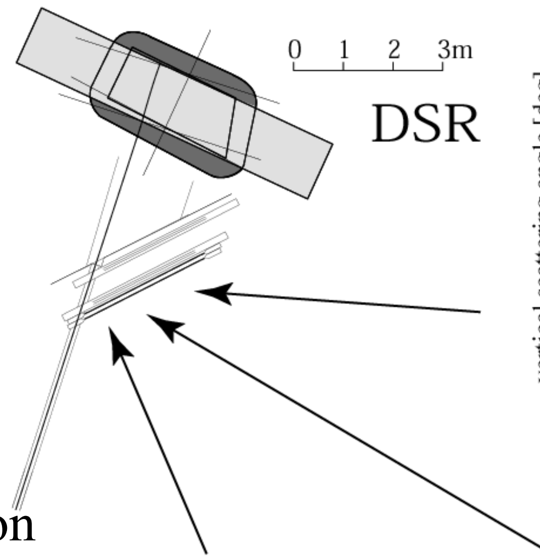
Horizontal scattering angle resolution:

$\Delta\theta = 0.15$ deg

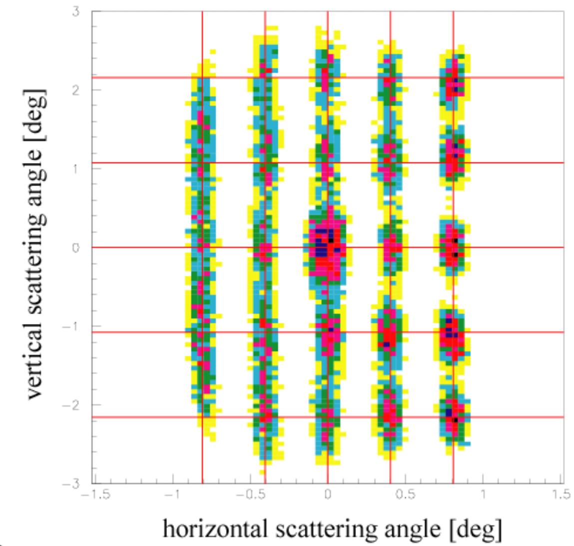
Vertical scattering angle resolution depends on the F.P. position

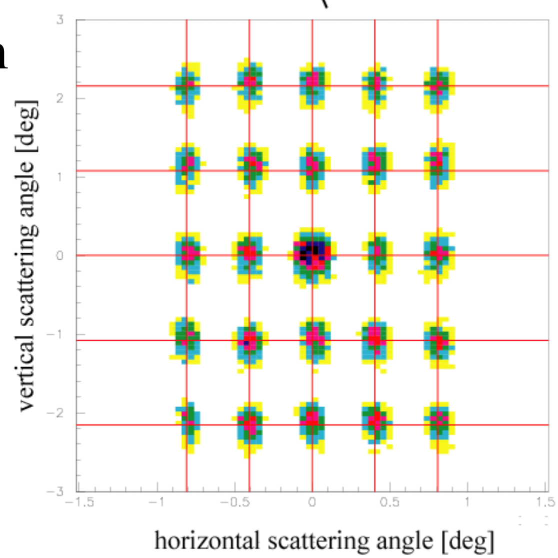
$\Delta\phi = 0.5$ deg at lower E_x.

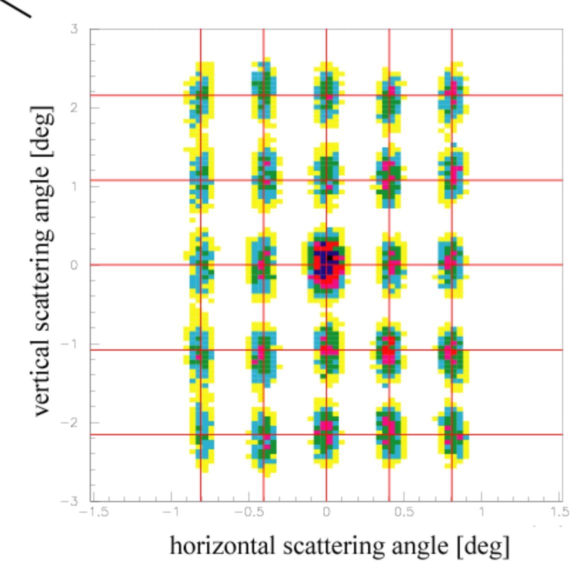
0.8 deg at higher E_x.



calib. by H. Matsubara

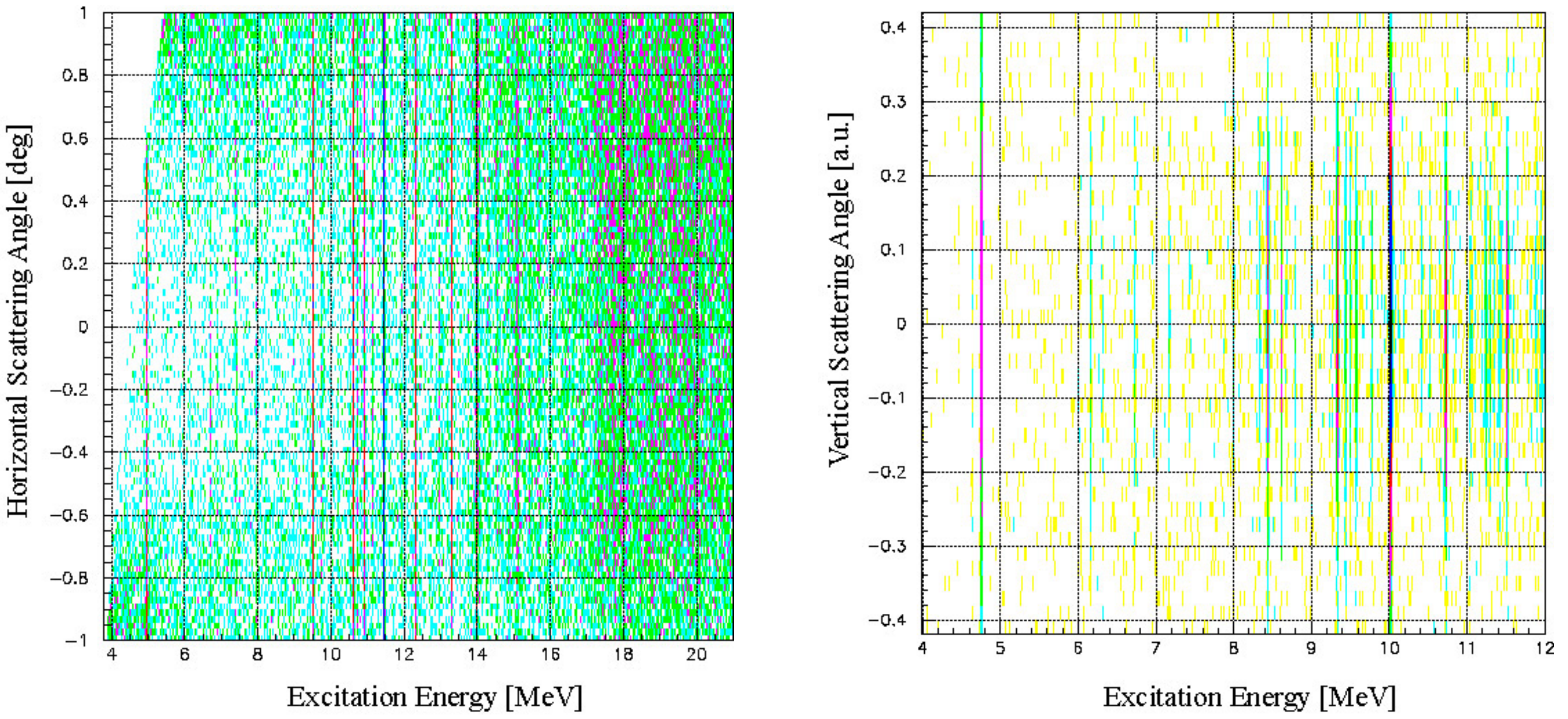




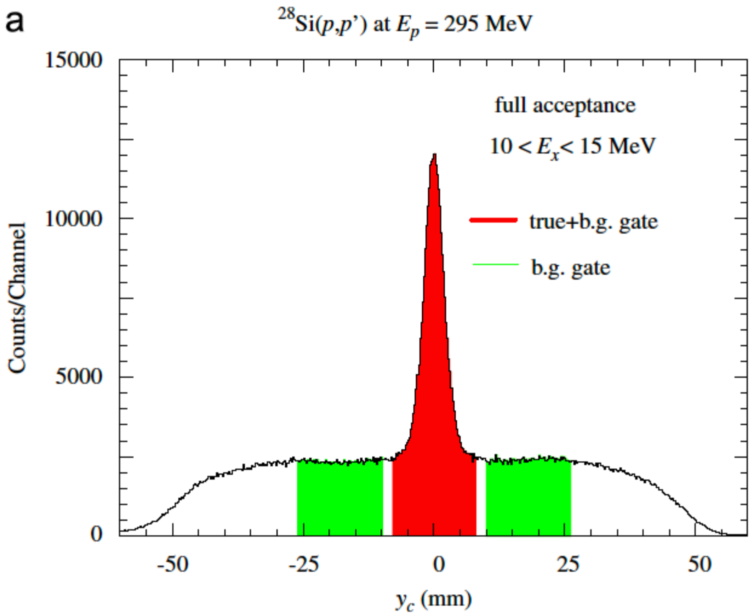


Higher-order corrections of the spectrometer ion-optics for high-resolution measurement

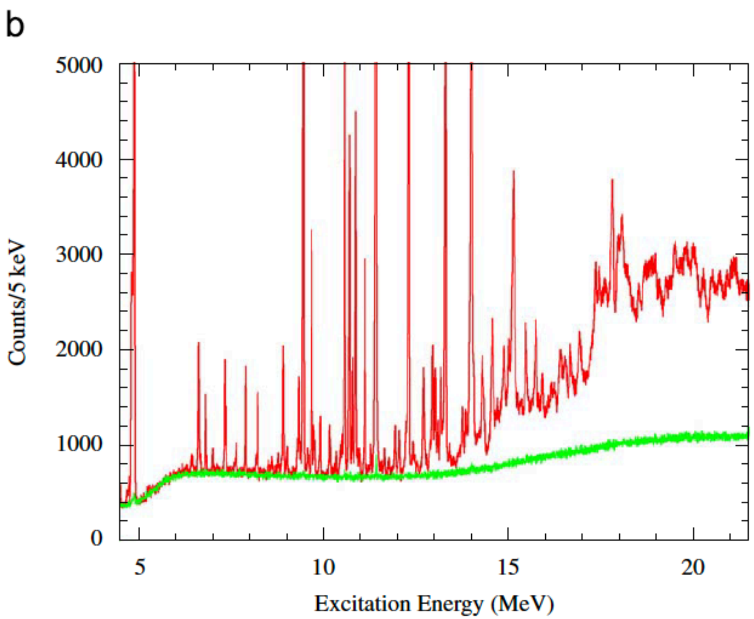
calib. by H. Matsubara

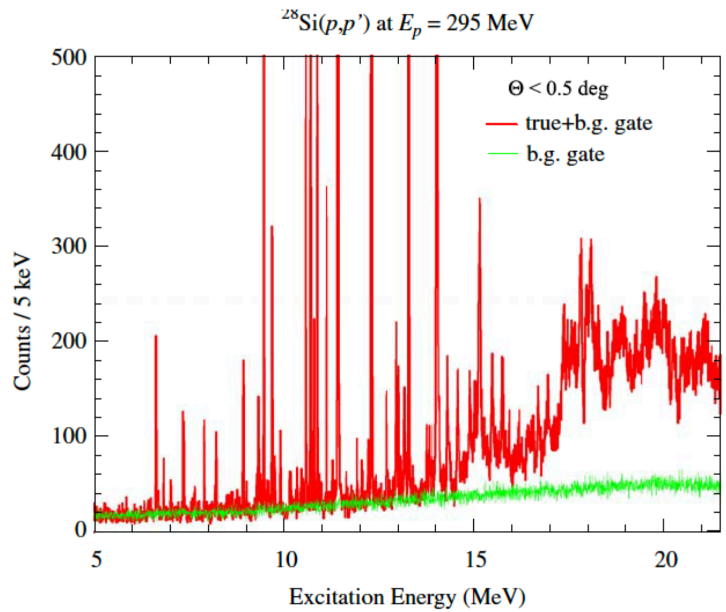


Background estimation, subtraction



simplified method

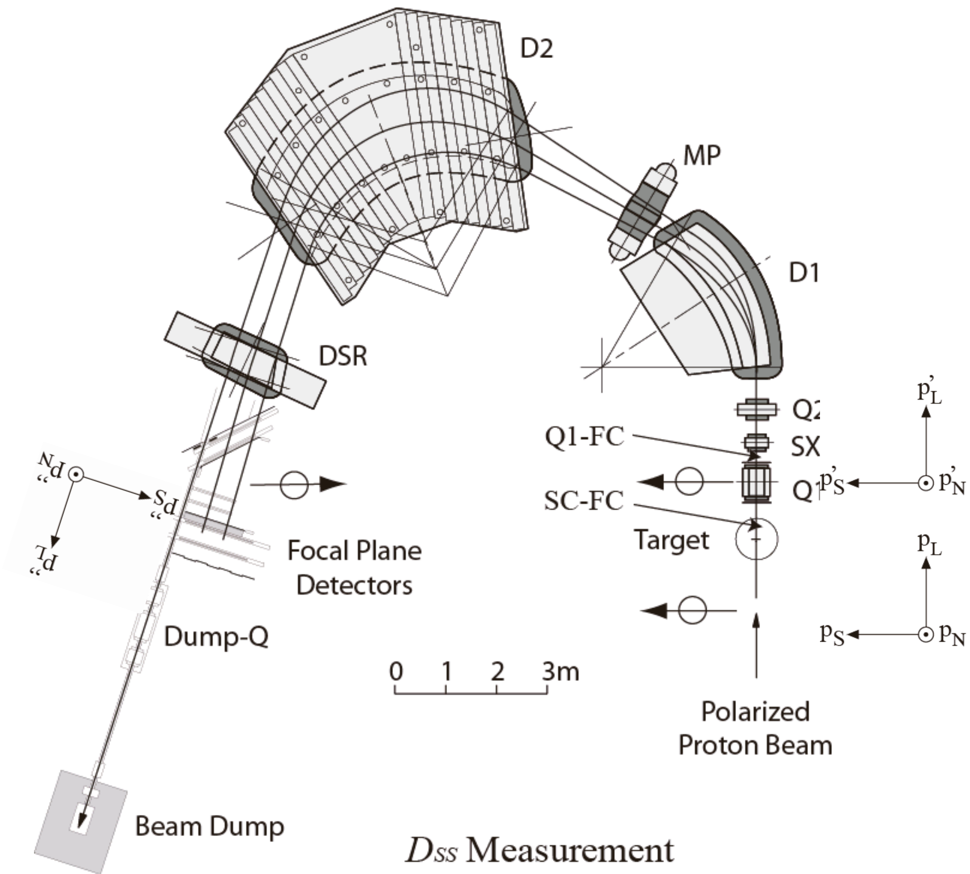




Correction of spin-rotation in the spectrometer

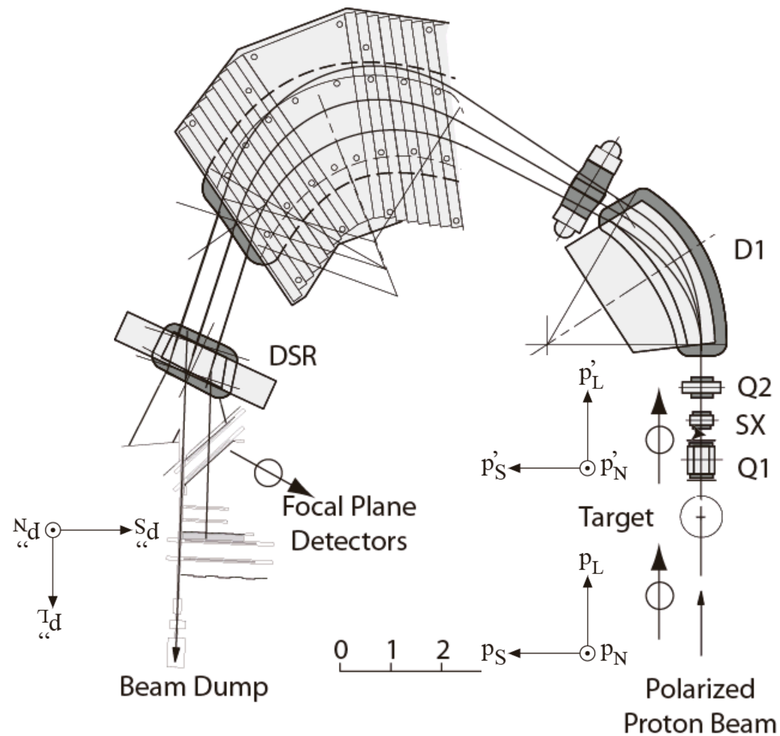
$$\theta_p = \gamma\left(\frac{g}{2} - 1\right)\theta_b$$

θ_p: precession angle with respect to the beam direction
θ_b: bending angle of the beam
g: Lande's g-factor
γ: gamma in special relativity



Dss Measurement

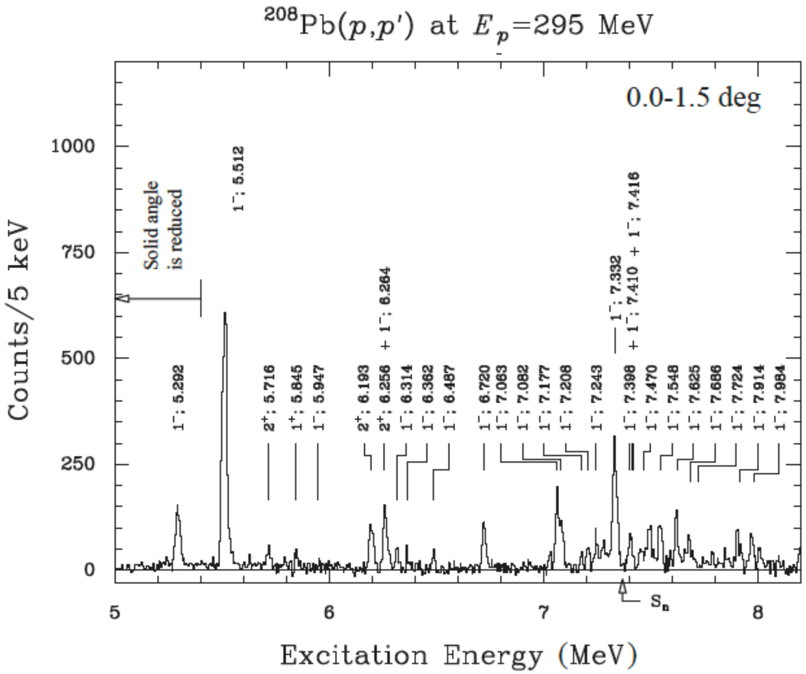
$\theta_b \cong 162°$



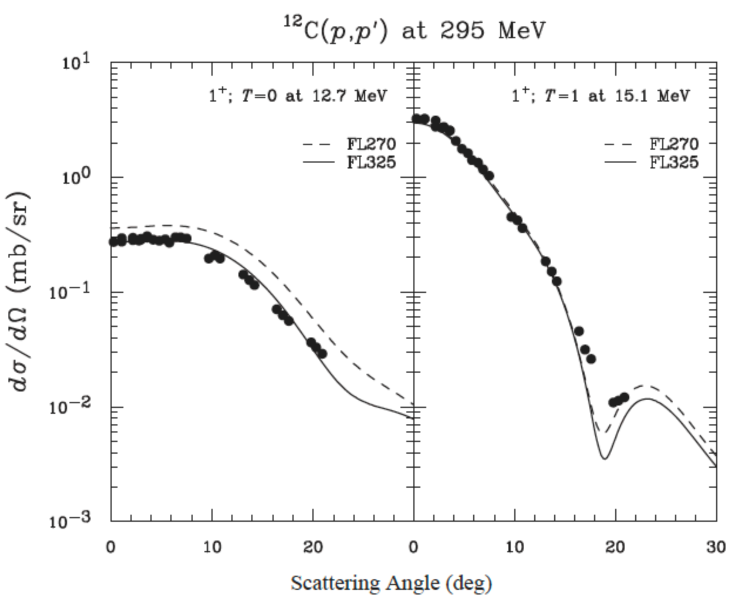
DLL Measurement

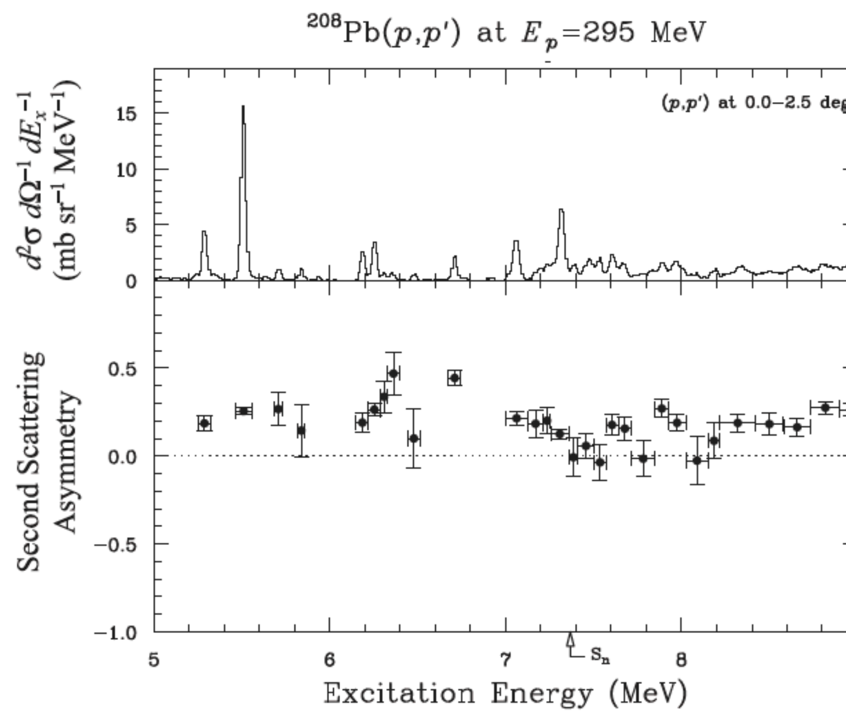
$\theta_b \cong 180°$

Data Analysis



- A. Tamii et al., Nucl. Inst. Meth. A **605**, 326 (2009).





High-resolution Excitation Energy Spectra