Development of A4 Compton Polarimeter Chicane

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Two main goals

- does not disturb the A4 main parity-violating experiment
- does handle the electron beam well to measure the electron polarization

Outline

- A4 experiment and Compton polarimeter
- chicane optimization with the simulations and wire scanners
- two Synchrotron radiation effects
- summary and outlook

A4 Parity-Violating Experiment

- the strangeness contribution to the proton ($F^s_{1,2}$ or $G^s_{E,M}$).
- the parity-violating asymmetry for elastic electron scattering off an unpolarized proton.

$$A_{\mathrm{measured}} = \frac{N^+ - N^-}{N^+ + N^-} = \mathbf{P} \cdot A_{\mathrm{phys}}.$$

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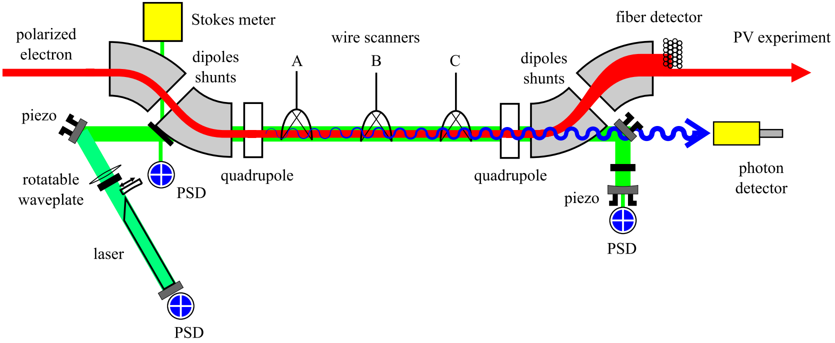
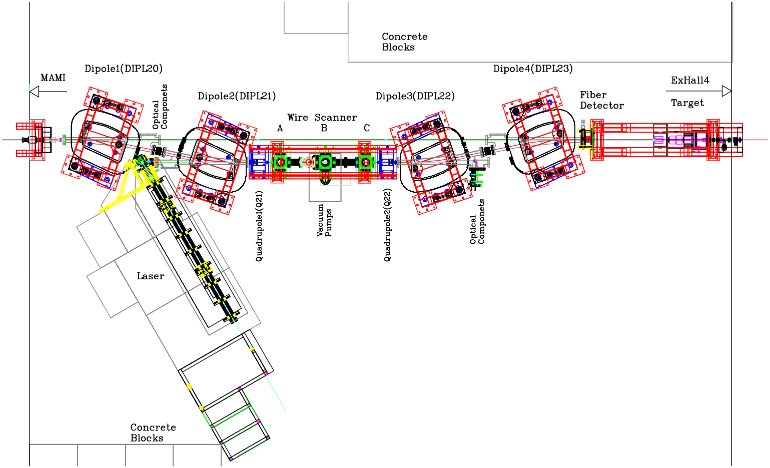
Compton Polarimeter



Back


Concrete Blocks
Dipole1(DIPL20)
MAMI
Optical Componets
Dipole2(DIPL21)
Wire Scanner
A
B
C
Dipole3(DIPL22)
Dipole4(DIPL23)
Fiber Detector
ExHall4
Target
Quadrupole1(Q21)
Vacuum Pumps
Quadrupole2(Q22)
Optical Componets
Laser
Concrete Blocks

Chicane Optimization

- to minimize the changing electron beam properties (size, angle, and dispersion)
- to make a good overlap between the electron beam and the laser

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- Wire scanner analysis ↔ TRANSPORT simulation

Simulation

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- How close to the real chicane is the simulation chicane?
  → As possible as we can!

dipole magnet - input

- effective length l_{eff} is used from the MIT collaborator
- TRANSPORT can handle the fringing field
  - measure the pole gap g
  - measure the entrance and exit pole-face rotation angle
  - assume that the dipole to be a square-edged non-saturating magnet
- measure the magnetic field strengths as a function of the applied current

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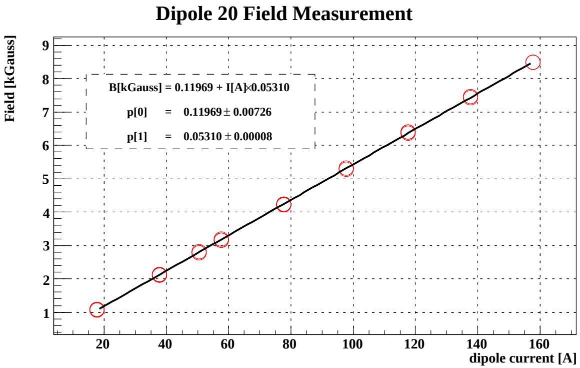

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  - assume that the dipole to be a square-edged non-saturating magnet
- measure the magnetic field strengths as a function of the applied current
- consider the current instabilities (below 3ppm)
  $\rightarrow$ magnetic field uncertainty per each dipole magnet
- shunt per each dipole is used to change magnetic field slightly

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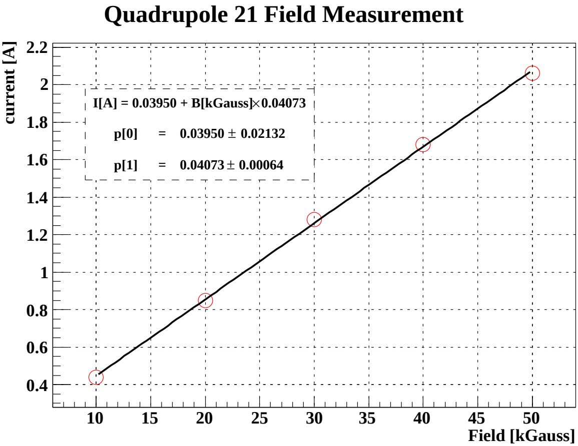

quadrupole magnet - input

- measure the magnetic field strengths as a function of the applied current (by J.Müller)
- measure the aperture radius a
- measure the mechanical length l_m
- effective length l_{eff}

$$l_{\text{eff}} = l_m + c \cdot a$$

, where c is a constant varying between 0.8 and 1.1. we use the average value 0.95.

initial beam properties(difficulties) - input

- no device to measure the beam position, direction, and size at the beginning of the chicane.
- one solution about the initial beam position and direction
- one assumption about beam size

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  → with wire scanner measurement and simulation
- one assumption about beam size

initial beam properties(difficulties) - input

- no device to measure the beam position, direction, and size at the beginning of the chicane.
- one solution about the initial beam position and direction
  → after wire scanner analysis
- one assumption about beam size
  → the chicane has a periodic structure (best condition)

periodic structure

- a region in phase space from the beginning to the end of the chicane with no first-order change in properties
- the same initial and final Twiss parameters (β, α)
- a waist condition in the middle of the chicane

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- the same initial and final Twiss parameters (β, α)
  $\rightarrow$ the initial Twiss parameters
- a waist condition in the middle of the chicane
  $\rightarrow$ Rayleigh length of the electron beam

initial Twiss parameters - periodic structure

The transfer matrix of the chicane by

$$M_{\text{chicane}} = M_{\text{dipole}_{23}} \cdot M_{\text{d}_4} \cdot M_{\text{dipole}_{22}} \cdot M_{\text{d}_3} \cdot M_{\text{quad}_{22}} \cdot M_{\text{d}_2} \cdot M_{\text{quad}_{21}} \cdot M_{\text{d}_1} \cdot M_{\text{dipole}_{21}} \cdot M_{\text{d}_0} \cdot M_{\text{dipole}_{20}}$$

initial Twiss parameters - periodic structure

The transfer matrix of the chicane by

$$M_{\text{chicane}} = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix}_{\text{components}}$$

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$$\equiv \begin{pmatrix} \cos\mu + \alpha\sin\mu & \beta\sin\mu \\ -\gamma\sin\mu & \cos\mu - \alpha\sin\mu \end{pmatrix}_{\text{periodic}}$$

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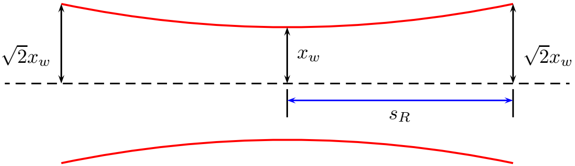
Thus

$$\mu = \cos^{-1}\left(\frac{R_{11}+R_{22}}{2}\right), \quad \alpha = \frac{R_{11}-R_{22}}{2\sin\mu}, \quad \beta = \frac{R_{12}}{\sin\mu}, \quad \text{and} \quad \gamma = -\frac{R_{21}}{\sin\mu}$$

With α and β, TRANSPORT calculates the beam size and the divergence along the chicane.

Rayleigh length - periodic structure



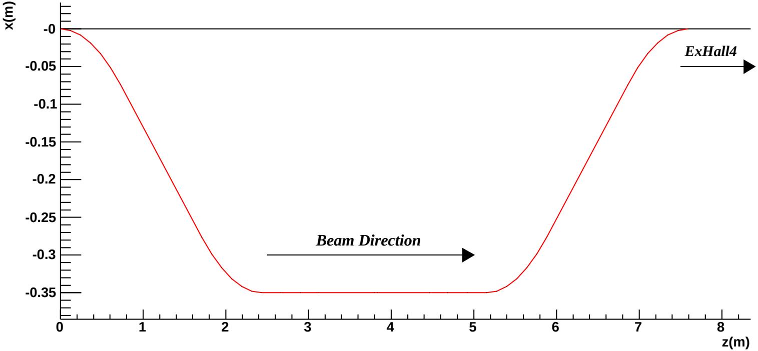
$x(s_R) = \sqrt{2}x_w$, where $x = \sqrt{\epsilon\beta}$ $\qquad$ $\beta(s) = \beta_0 - 2\alpha_0 s + \gamma_0 s^2$

$\beta_R = 2\beta_w$ $\qquad$ $\beta_R = \beta_w + \frac{s_R^2}{\beta_w}$

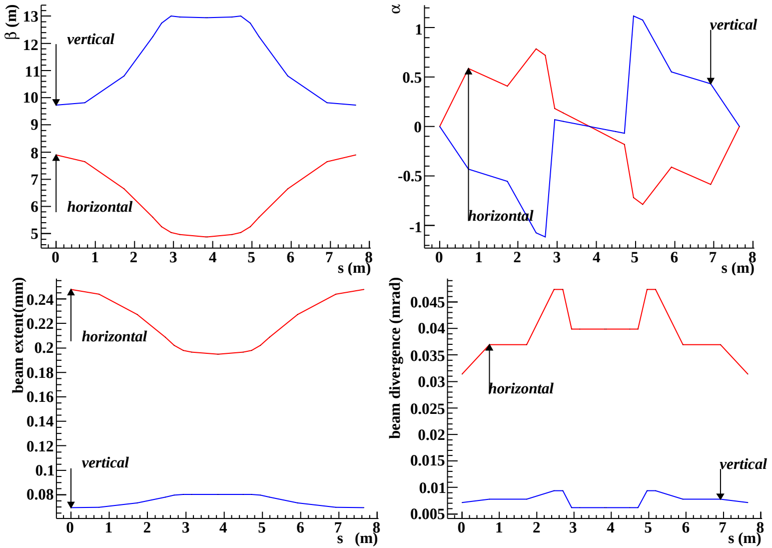
$$\therefore \quad s_R = \pm\beta_w$$

One result at 854.3 MeV

Ideal reference trajectory on the horizontal plane FL



Twiss parameters - periodic structure



dispersion D and D'

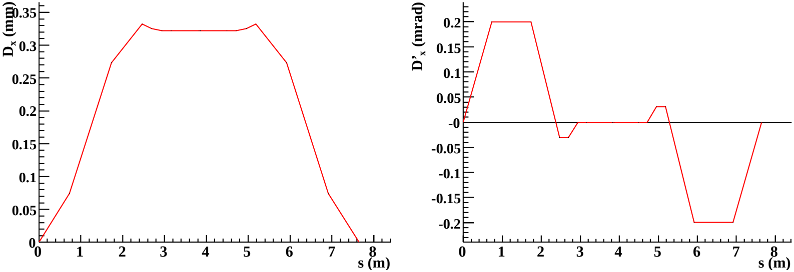
- Since the chicane has four dipole magnets, the position dispersion and the angular dispersion will be introduced.

$$\begin{pmatrix} x_f \\ x_f' \\ \delta \end{pmatrix}_{\text{end}} = \begin{pmatrix} R_{11} & R_{12} & \mathbf{D} \\ R_{21} & R_{22} & \mathbf{D'} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ \delta \end{pmatrix}_{\text{begin}}$$

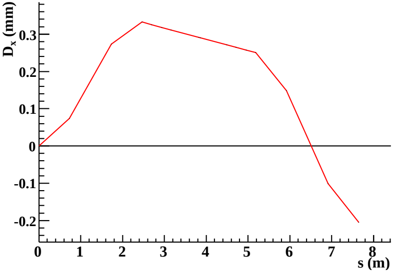
$$x_f = R_{11}x_0 + R_{12}x_0' + \mathbf{D}\delta, \qquad x_f' = R_{21}x_0 + R_{22}x_0' + \mathbf{D'}\delta$$

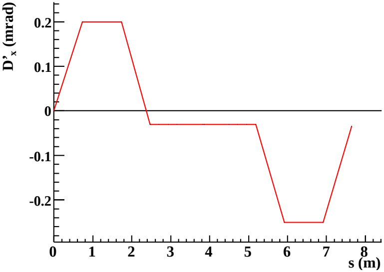
- We should minimize **D** and **D′** by two quadrupoles
- Quadrupole field strengths are one of simulation results

position and angular dispersion with quadrupoles

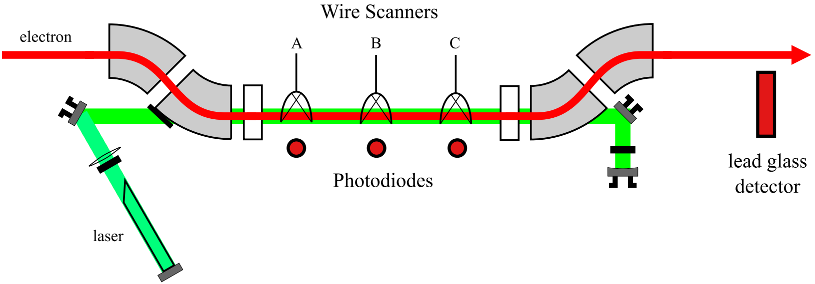


position and angular dispersion without quadrupoles





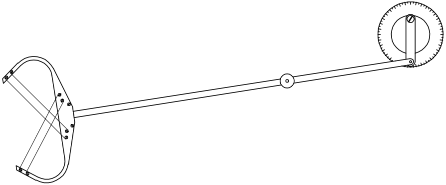
Wire Scanner Analysis



- to make good overlap
- electron and laser position measurement at the same time

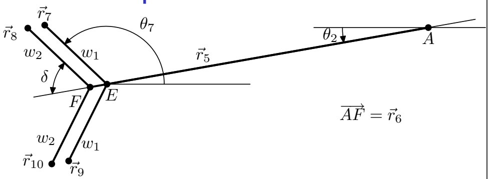
MAMI wire scanner

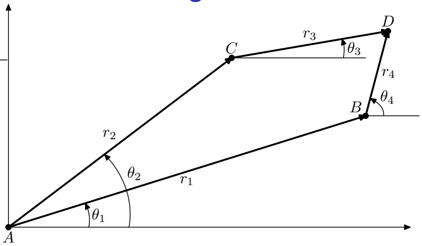
- Made in Germany by MAMI
- old analysis based on the geometry



four-bar linkage

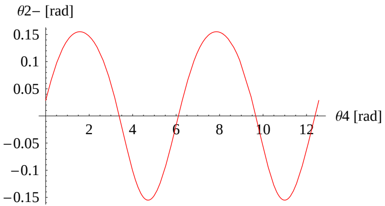
extended part

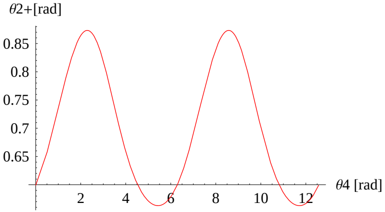


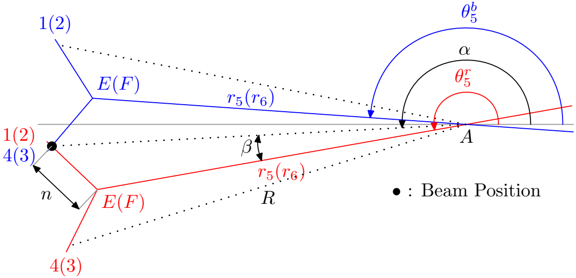


loop equation

From $\vec{r}_2 + \vec{r}_3 = \vec{r}_1 + \vec{r}_4$, we found $\theta_2(\theta_4)$ function Back





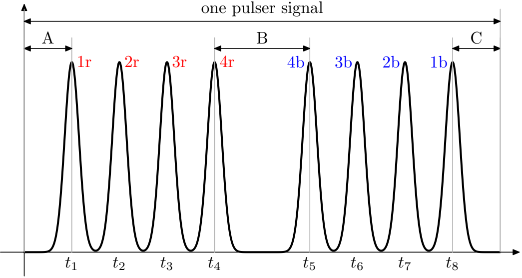


$$x = R\cos\alpha$$
$$y = R\sin\alpha$$
$$R = \frac{r_5(r_6)\sin\delta}{\sin(\delta-\beta)}$$
$$\alpha = \frac{\theta_5^r + \theta_5^b}{2}$$
$$\beta = \frac{\left|\theta_5^r - \theta_5^b\right|}{2}$$
$$\theta_5 = \theta_2 + \pi$$

Beam Position

$$x = -R\cos\gamma \qquad y = -R\sin\gamma$$
$$\gamma = (\theta_2^r + \theta_2^b)/2 \qquad \beta = \left|\theta_2^r - \theta_2^b\right|/2$$

Measured spectrum



- $\theta_4^{\rm raw}[t_i] = A\omega \cdot t_i$, where $A\omega = 2\pi / \left|\text{pulser}_0 - \text{pulser}_1\right|$
- $A + C > B$: up-motion θ_2
  $t_1 \to 1r, t_2 \to 2r, t_3 \to 3r, t_4 \to 4r \cdots$
- $A + C < B$: down-motion
  $t_1 \to 4b, t_2 \to 3b, t_3 \to 2b, t_4 \to 1b \cdots$

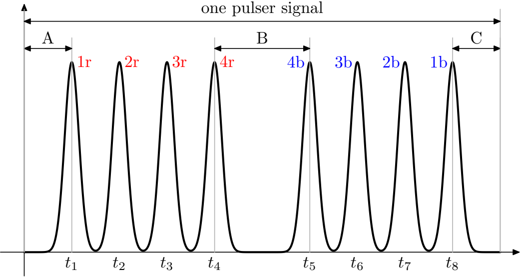
How to know the θ_4

wire	1	2	3	4
t_a	t_1	t_2	t_3	t_4
t_b	t_8	t_7	t_6	t_5

A wire goes into the beam twice with the same θ_2 and the different θ_4

$$\theta_4^{\rm raw}[t_i] = \theta_4[t_i] + \theta_{\rm offset}$$
$$\theta_4[t_b] = \theta_4[t_a] + \theta_4^{\rm raw}[t_b] - \theta_4^{\rm raw}[t_a]$$
$$\theta_2\left(\theta_4[t_a]\right) = \theta_2\left(\theta_4[t_a] + \theta_4^{\rm raw}[t_b] - \theta_4^{\rm raw}[t_a]\right)$$

Measured spectrum



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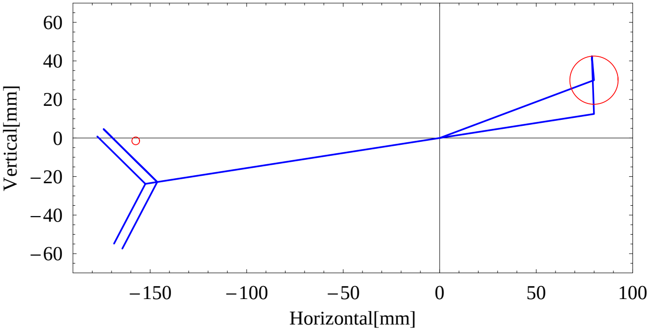
$$\theta_2\left(\theta_4[t_a]\right) = \theta_2\left(\theta_4[t_a] + \theta_4^{\mathrm{raw}}[t_b] - \theta_4^{\mathrm{raw}}[t_a]\right)$$

full motion of the wire scanner



initial position and angle

$$x_0, x_0', y_0, \text{ and } y_0' = ?$$

Using matrix formalism with wire scanner measurement,

$$\begin{pmatrix} x_B \\ x_B' \end{pmatrix} = M_{\mathrm{BA}} \cdot \begin{pmatrix} x_A \\ x_A' \end{pmatrix}$$

$$\begin{pmatrix} x_A \\ x_A' \end{pmatrix} = M_{\mathrm{A0}} \cdot \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}$$

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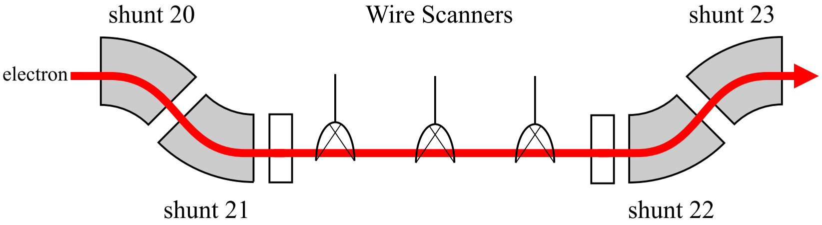
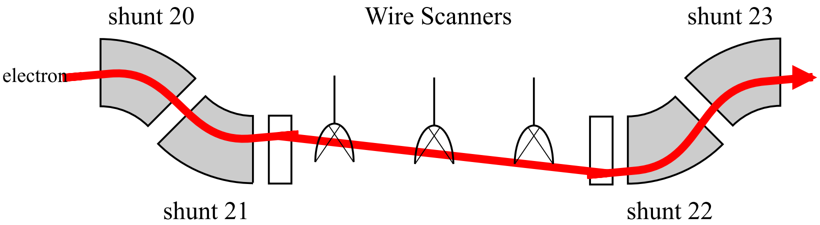
$x_0, x_0', y_0, \text{and} y_0'$ are the input parameters in the simulation

rotating electron beam



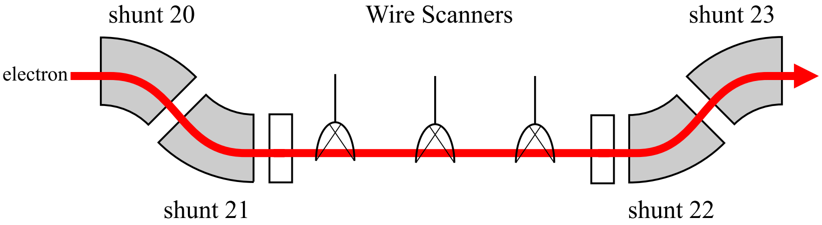
shunt	20	21	22	23
percent	50	50	50	50

rotating electron beam



shunt	20	21	22	23
percent	60	70	30	40
↻	$+\alpha$	$+2\alpha$	-2α	$-\alpha$

rotating electron beam



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↺	$-\alpha$	-2α	$+2\alpha$	$+\alpha$

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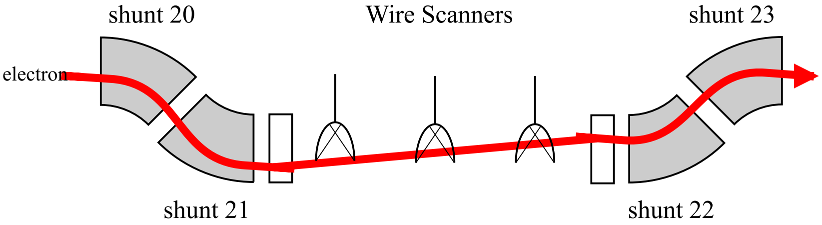

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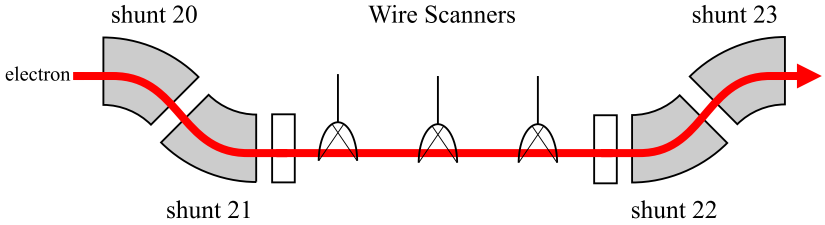

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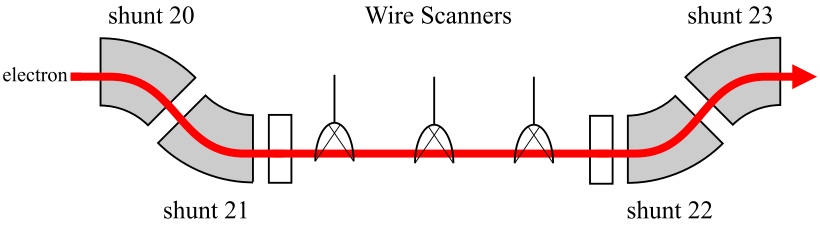
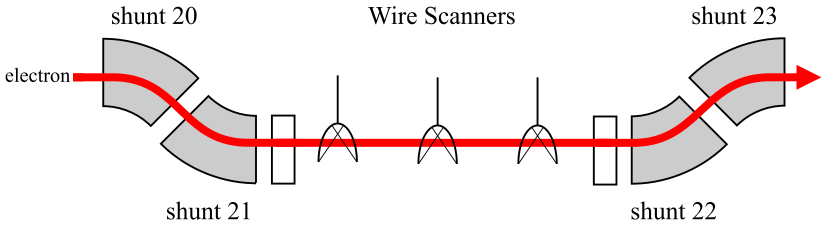
shifting electron beam



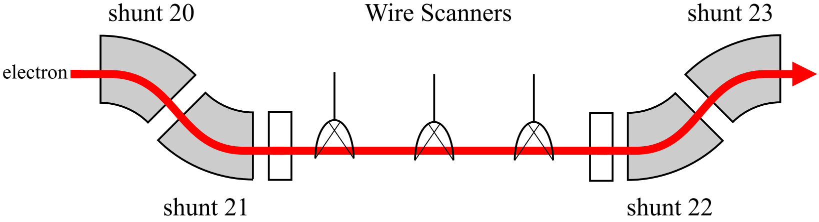
shunt	20	21	22	23
percent	50	50	50	50

shifting electron beam



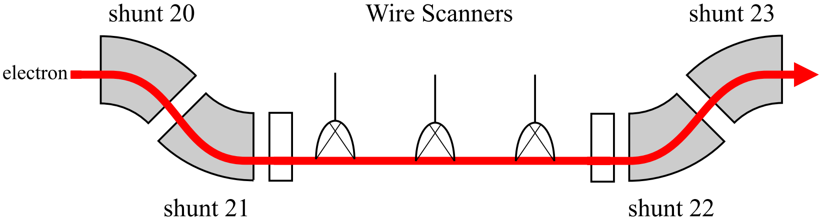
shunt	20	21	22	23
percent	60	60	60	60
$\uparrow$	$+\alpha$	$+\alpha$	$+\alpha$	$+\alpha$

shifting electron beam



shunt	20	21	22	23
percent	50	50	50	50
↓	$-\alpha$	$-\alpha$	$-\alpha$	$-\alpha$

shifting electron beam



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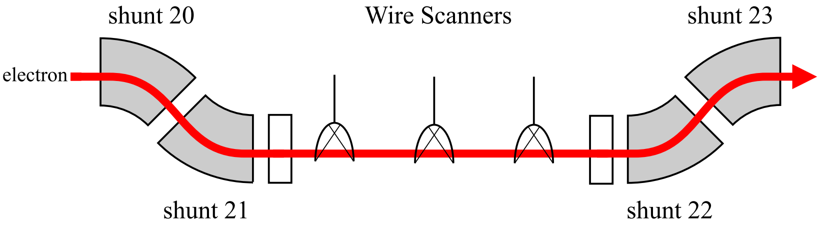
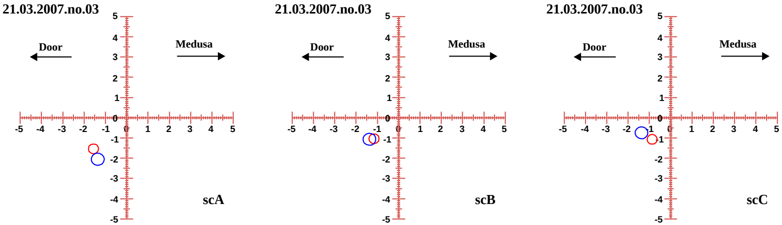


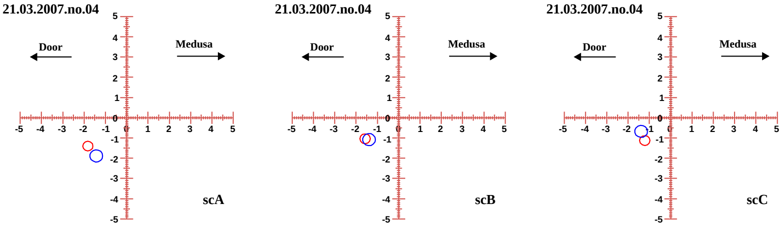
shunt	20	21	22	23
percent	50	50	50	50
$\uparrow$	$+\alpha$	$+\alpha$	$+\alpha$	$+\alpha$

Spatial overlap



- decide the good overlap or not
- TRANSPORT simulation (input: I_{main}, I_{shunt}, scA, scB)
- shunt and current optimization → ask MAMI operator

Spatial overlap



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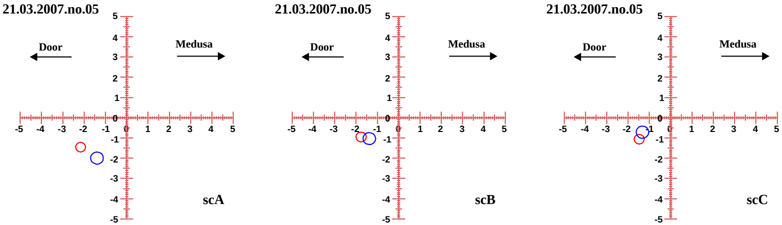

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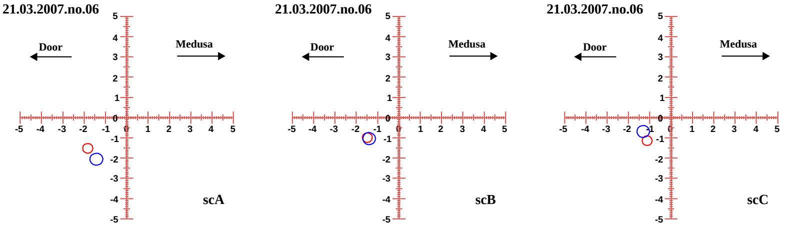
Spatial overlap



- the good overlap
- TRANSPORT simulation (input: I_{main}^{opt}, I_{shunt}^{opt}, scA, scB)
- two quadrupole field strengths → ask MAMI operator

Synchrotron Radiation

- motivation, aim, and assumptions
- overview of SR
- energy loss inside the chicane
- SR on the photon detector

Motivation

- One bending magnet is the most simply radiation source. And four bending magnets define the geometry of the electron chicane.
- A viewpoint of electron: How much will electron energy loss be inside the chicane? Is there some effect of the energy loss on PV experiment?
- A viewpoint of radiation: We estimated Synchrotron Radiation(SR) effect could be ignored or be too small. It would be better to know SR effect on the photon detector exactly.

Aim and Assumption

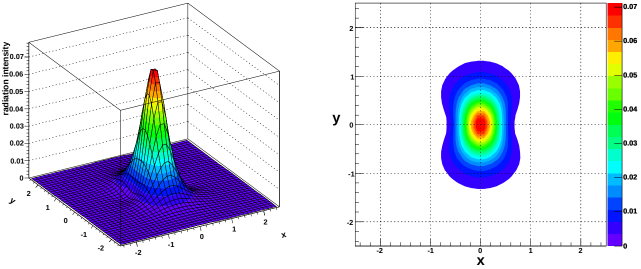
- To calculate the electron energy loss inside the Compton polarimeter chicane
- To determine that the effect on the photon detector will be crucial or not.
- no quadrupole effect, perfect vacuum condition, and midplane symmetry inside four dipole magnets.

Power radiated of an electron P_0

$$P_0 = \frac{2}{3} r_e m c^3 \frac{\gamma^4 \beta^4}{\rho^2}$$

Spatial Distribution $\frac{dP}{d\Omega}$

$$x = \gamma \sin\theta_\gamma \cos\phi \qquad y = \gamma \sin\theta_\gamma \sin\phi$$



Critical Photon Energy ε_c

- $\varepsilon_c = \hbar\omega_c = \hbar\frac{3c\gamma^3}{2\rho}$
- the upper bound for the synchrotron radiation spectrum

Photon or Quantum Distribution Function $\dot{n}(\varepsilon)$

- Number of quanta emitted per unit time at energy ε.
- $\dot{n}(\varepsilon) = \frac{P_0}{\varepsilon_c^2}F(\varepsilon/\varepsilon_c) = \frac{P_0}{\varepsilon\varepsilon_c}S(\varepsilon/\varepsilon_c)$.
- $S(\xi) = \frac{9\sqrt{3}}{8\pi}\xi\int_\xi^\infty K_{5/3}(s)\mathrm{d}s$, where $K_{5/3}(s)$ is a modified Bessel function of the second kind.

energy loss of an electron per a magnet

$$U_0 = \int P_0 \mathrm{d}t \approx \frac{C_0 E^4}{2\pi\rho^2} L_{\mathrm{eff}}$$

,where L_{eff} is the effective length of the dipole magnet and C_0 Sand's radiation constant.

energy loss of a chicane

energy lose due to SR is below 2 keV

Electron energy (MeV)	Energy loss of a dipole magnet (keV)	Energy loss of four dipole magnets (keV)	After chicane electron energy (MeV)
854.30(16)	0.42129(39)	1.6852(13)	854.29958(16000)
570.30(16)	0.083667(94)	0.33467(38)	570.29992(16000)
315.13(16)	0.007800(16)	0.0312000(63)	315.12999(16000)

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four-momentum transfer Q^2

$$Q^2 = 4EE' \sin^2\frac{\theta}{2}, \quad \delta Q^2 = Q^2\sqrt{\left(\frac{\delta E}{E}\right)^2 + \left(\frac{\delta E'}{E'}\right)^2}, \quad \text{and} \quad \delta E' = \frac{E'^2}{E^2}\delta E$$

E (GeV)	0.85430(16)	0.85430(16)
Energy Loss	NO	YES
θ_M (Ring 1)	39.22°	
E' (GeV)	0.70890(11)	0.70889(11)
$Q^2(\mathrm{GeV/c})^2$	0.272859(66)	0.272858(66)

all Q^2

four-momentum transfer Q^2

$$Q^2 = 4EE' \sin^2\frac{\theta}{2}, \quad \delta Q^2 = Q^2\sqrt{\left(\frac{\delta E}{E}\right)^2 + \left(\frac{\delta E'}{E'}\right)^2}, \quad \text{and} \quad \delta E' = \frac{E'^2}{E^2}\delta E$$

- However, after averaging Q^2 with two significant figures
  $\rightarrow$ the same Q^2 and the same δQ^2

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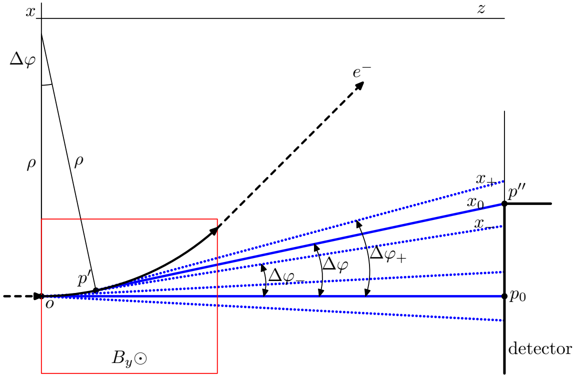
- However, after averaging Q^2 with two significant figures $\rightarrow$ the same Q^2 and the same δQ^2
- We can ignore the SR effect from the viewpoint of PV experiment.

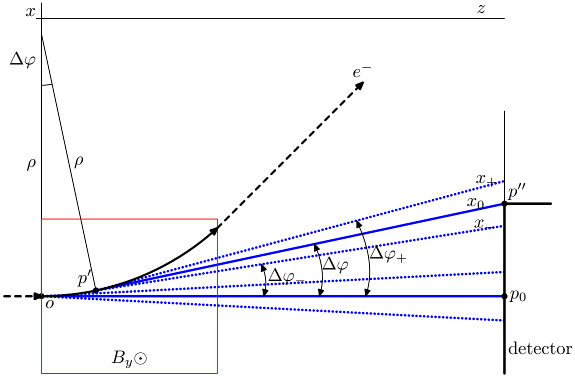
angle coverage $\Delta\varphi$



$$x_0 = z_0 \tan \Delta\varphi^{max} + \rho\,(1 - \sec \Delta\varphi^{max})$$

$$x_\pm = z_0 \tan \Delta\varphi^{max}_\pm + \rho\left(1 - \cos\theta_\gamma \sec \Delta\varphi^{max}_\pm\right)$$

angle coverage $\Delta\varphi$



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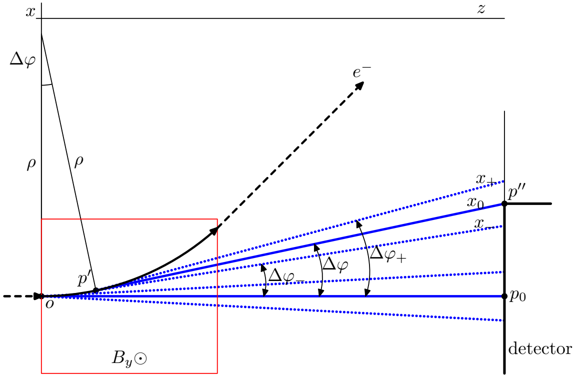


$$x_0 = z_0 \tan \Delta\varphi^{max} + \rho\,(1 - \sec \Delta\varphi^{max})$$

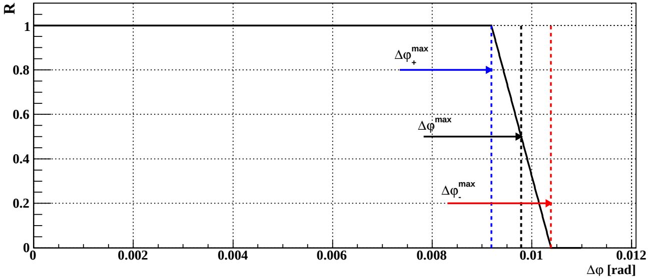
$$x_\pm = z_0 \tan \Delta\varphi_\pm^{max} + \rho\left(1 - \cos\theta_\gamma \sec \Delta\varphi_\pm^{max}\right)$$

Energy (GeV)	$\Delta\varphi_+^{max}$(mrad)	$\Delta\varphi^{max}$(mrad)	$\Delta\varphi_-^{max}$ (mrad)
0.85430	9.18775	9.78613	10.38405
0.57030	8.88958	9.78613	10.68162
0.31513	8.16285	9.78613	11.40595

$$R = \frac{\mathcal{A}}{|x_+ - x_-|}$$

,where

$$\mathcal{A} = \begin{cases} |x_+ - x_-| & 0 \leq \Delta\varphi < \Delta\varphi_+^{max} \\ |x_0 - x_-| & \Delta\varphi_+^{max} \leq \Delta\varphi < \Delta\varphi_-^{max} \\ 0 & \Delta\varphi_-^{max} \leq \Delta\varphi \end{cases}$$



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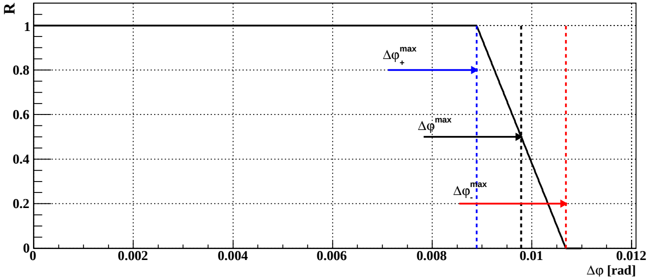

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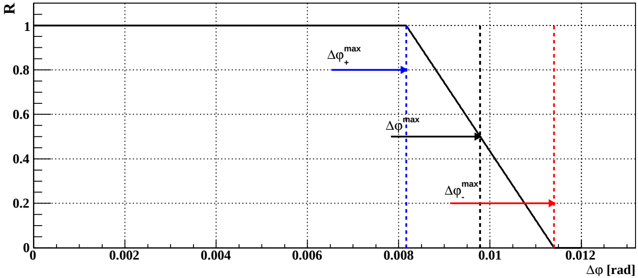


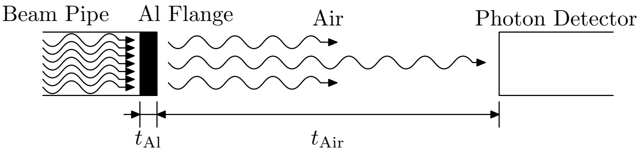
total emitted photon number

After integration over all SR photon energy,

$$\dot{N}^e_\varphi = \int_0^\infty \dot{n}^e_\varphi(\varepsilon)\mathrm{d}\varepsilon = \frac{15\sqrt{3}}{16\pi}\frac{P_0}{\varepsilon_c}\frac{I}{e}\Delta\varphi^{max}$$

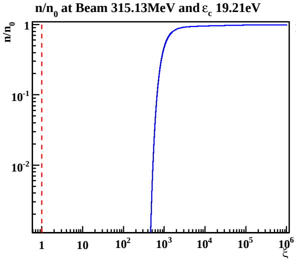
Beam [MeV]	ε_c (eV)	$\dot{N}^e_\varphi$ (rad/s)
854.30	382.74763	2.84211×10^{20}
570.30	113.86530	1.89729×10^{20}
315.13	19.21102	1.04838×10^{20}

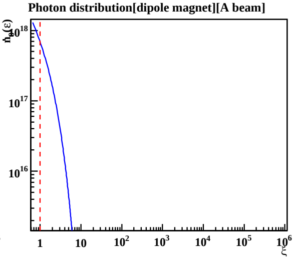
transmitted photon number with a certain energy ϵ

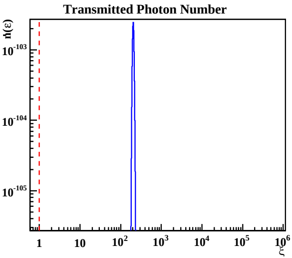


$$\dot{n}^e_\varphi(\epsilon) = \dot{n}^e_{\varphi 0}(\epsilon) \exp\left[\frac{\mu}{\rho}(\epsilon)_{\rm Al} \cdot x_{\rm Al} + \frac{\mu}{\rho}(\epsilon)_{\rm Air} \cdot x_{\rm Air}\right]$$

where $x = \rho t$ is the mass thickness and μ/ρ a mass attenuation coefficient.







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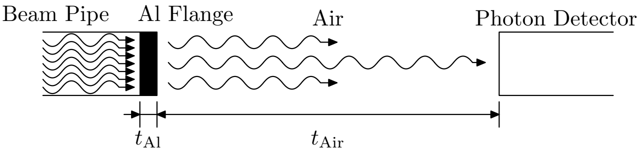

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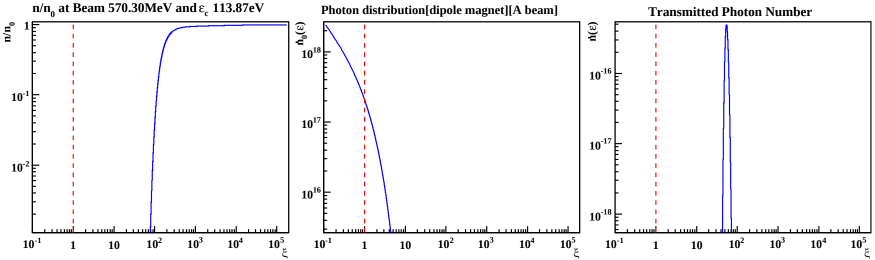

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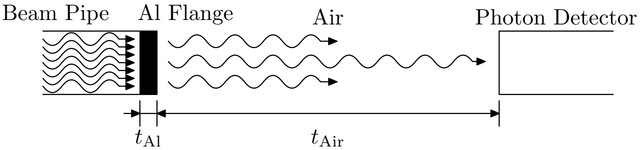

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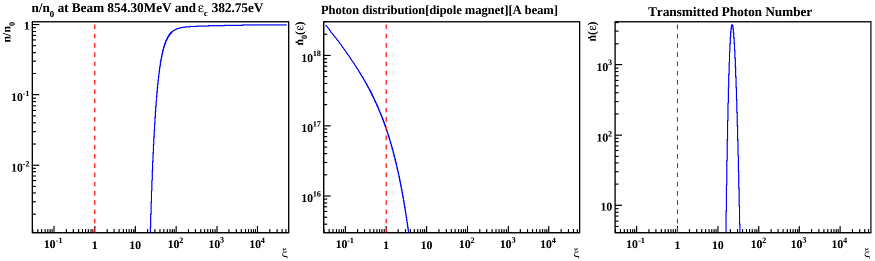
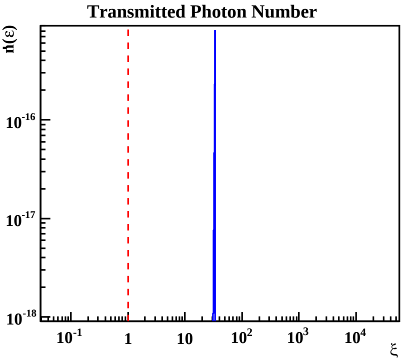
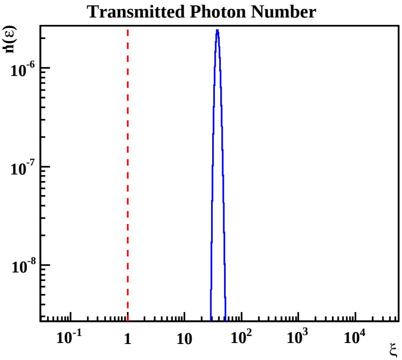


Al Thickness (mm)	0	1	2	3	4	10
$\dot{n}_{\varphi}^{e}$ (maximum)	$\sim 10^{3}$	$\sim 10^{0}$	$\sim 10^{-2}$	$\sim 10^{-4}$	$\sim 10^{-5}$	$\sim 10^{-10}$
Pb Thickness (mm)	0.5	1	1.5	2	2.5	10
$\dot{n}_{\varphi}^{e}$ (maximum)	$\sim 10^{-15}$	$\sim 10^{-31}$	$\sim 10^{-39}$	$\sim 10^{-43}$	$\sim 10^{-47}$	$\sim 10^{-76}$

0.5mm pb



5 mm aluminum



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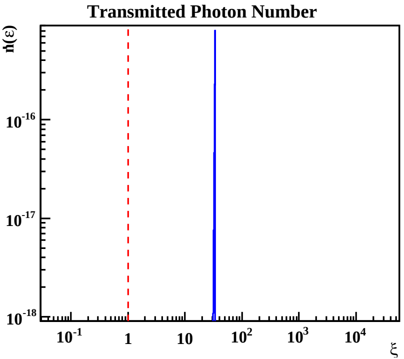
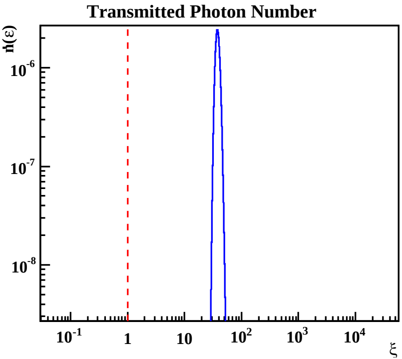


5 mm aluminum



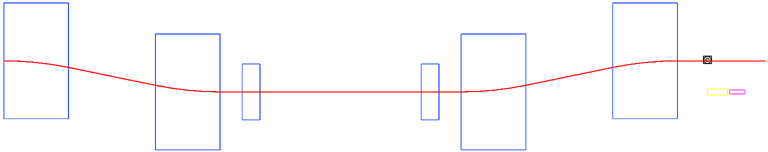
We can ignore the SR effect on the photon detector.

Summary

- more physically realistic beam line simulation
- wire scanner analysis to overlap two beams
- synchrotron radiation effects on the beam line and the detector

Outlook

- improvement realistic beam line simulation with TRANSPORT
  → more fancy way to tilt and shift the electron beam
- Using the results of TRANSPORT
  → beam line and detector simulation with GEANT4



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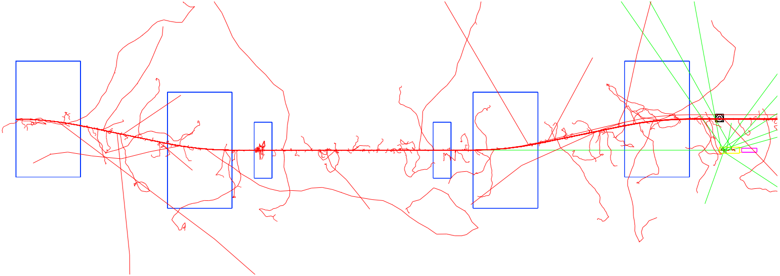
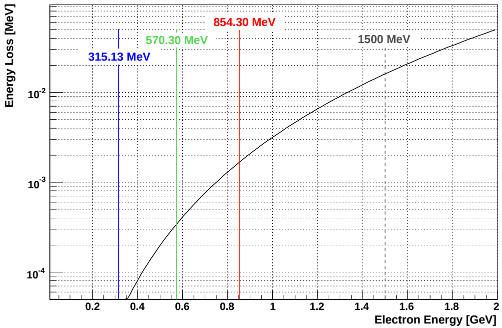


Energy loss

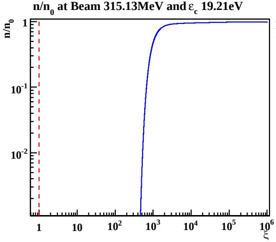


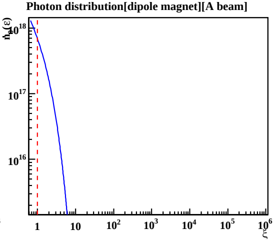
Electron energy (MeV)	Energy loss of a dipole magnet (keV)	Energy loss of four dipole magnets (keV)	After chicane electron energy (MeV)
1500.00(16)	4.0041(17)	16.0165(68)	1499.99600(16000)
854.30(16)	0.42129(39)	1.6852(13)	854.29958(16000)
570.30(16)	0.083667(94)	0.33467(38)	570.29992(16000)
315.13(16)	0.007800(16)	0.0312000(63)	315.12999(16000)

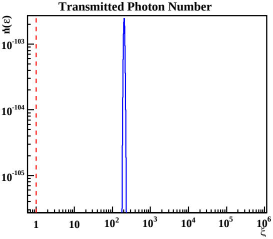
Q^2 Back

E (GeV) Energy Loss	0.85430(16) NO	0.85430(16) YES	0.57030(16) NO	0.57030(16) YES	0.31313(16) NO	0.31513(16) YES
θ_M (Ring 1)	39.22°		39.22°		140.78°	
E' (GeV)	*0.70890(11)*	*0.70889(11)*	0.50162(12)	0.50162(12)	0.197442(63)	0.197442(63)
$Q^2\,(\mathrm{GeV/c})^2$	*0.272859(66)*	*0.272858(66)*	0.128890(48)	0.128890(48)	0.22085(13)	0.22085(13)
θ_M (Ring 2)	37.69°		37.69°		142.31°	
E' (GeV)	0.71790(11)	0.71790(11)	0.50611(12)	0.50611(12)	0.196755(62)	0.196755(62)
$Q^2\,(\mathrm{GeV/c})^2$	0.255956(62)	0.255956(62)	0.120458(45)	0.120458(45)	0.22214(13)	0.22214(13)
θ_M (Ring 3)	36.20°		36.20°		143.80°	
E' (GeV)	0.72659(12)	0.72659(12)	0.51041(13)	0.51041(13)	0.196111(62)	0.196111(62)
$Q^2\,(\mathrm{GeV/c})^2$	0.239650(59)	0.239650(59)	0.112383(42)	0.112383(42)	0.22334(13)	0.22334(13)
θ_M (Ring 4)	34.77°		34.77°		145.23°	
E' (GeV)	0.73483(12)	0.73483(12)	0.51446(13)	0.51446(13)	0.195520(62)	0.195520(62)
$Q^2\,(\mathrm{GeV/c})^2$	0.224179(55)	0.224176(55)	0.104774(40)	0.104774(40)	0.22445(13)	0.22445(13)
θ_M (Ring 5)	33.39°		33.39°		146.61°	
E' (GeV)	0.74269(12)	0.74269(12)	0.51830(13)	0.51830(13)	0.194971(61)	0.194971(61)
$Q^2\,(\mathrm{GeV/c})^2$	0.209448(52)	0.209448(52)	0.097577(37)	0.097577(37)	0.22548(13)	0.22548(13)
θ_M (Ring 6)	32.06°		32.06°		147.94°	
E' (GeV)	0.75014(12)	0.75014(12)	0.52192(13)	0.52192(13)	0.194464(61)	0.194464(61)
$Q^2\,(\mathrm{GeV/c})^2$	0.195466(49)	0.195466(49)	0.090788(35)	0.090788(35)	0.22643(14)	0.22643(14)
θ_M (Ring 7)	30.77°		30.77°		149.23°	
E' (GeV)	0.75724(13)	0.75724(13)	0.52535(14)	0.52535(14)	0.193993(61)	0.193993(61)
$Q^2\,(\mathrm{GeV/c})^2$	0.182134(46)	0.182134(46)	0.084352(32)	0.084352(32)	0.22732(14)	0.22732(14)

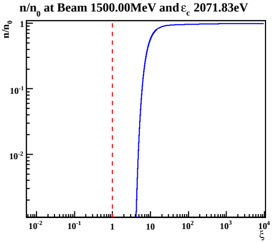
854.3 MeV

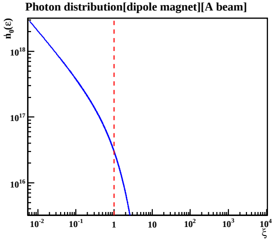


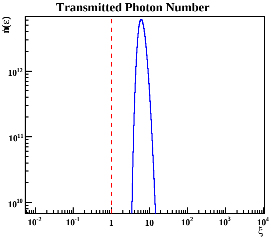




1.5 GeV







Current Stability Test from the manufacturer

$$I_{\mathrm{dipole}} = I_0 \pm \frac{I_0 \delta I_{\mathrm{FWHM}}}{2\sqrt{2\ln 2}} = I_0 \pm \delta I_0.$$

	design value	3 mins	30 mins	8 hours
δI_{FWHM} (ppm)	3	0.5	1	2

Beam ditribution and phase space with GEANT4