Design of Photon Masks for the ILC Positron Helical Undulator

Khaled Alharbi, Sabine Riemann, Gudrid Moortgat-Pick, Andriy Ushakov, Ayash Alrashdi

LCWS 2021

15 - 19 March 2019

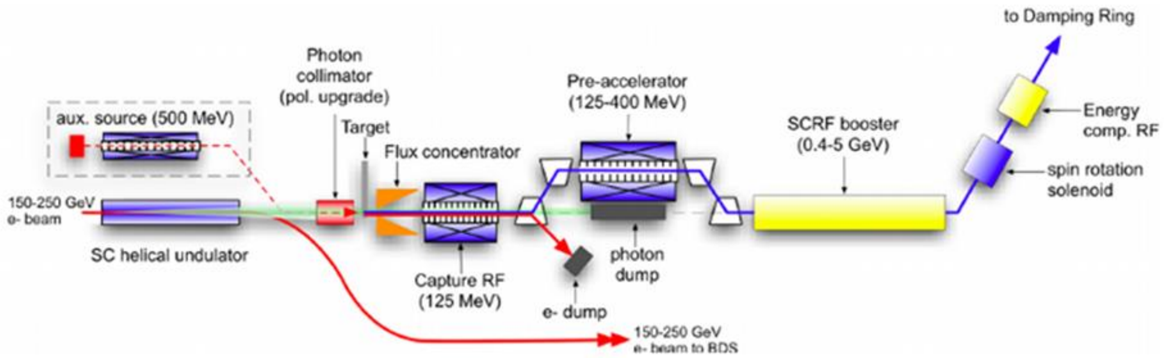
Content

- ILC Helical Undulator Structure
- Energy Deposited at the Mask
  - Simulation: PEDD and Temperature at the mask
- Polarization of the Photon Beam
- Conclusion

Helical Undulator based Positron Source for the ILC

ILC: use the high-energy e- beam to generate a multi-MeV photon beam to produce positrons.

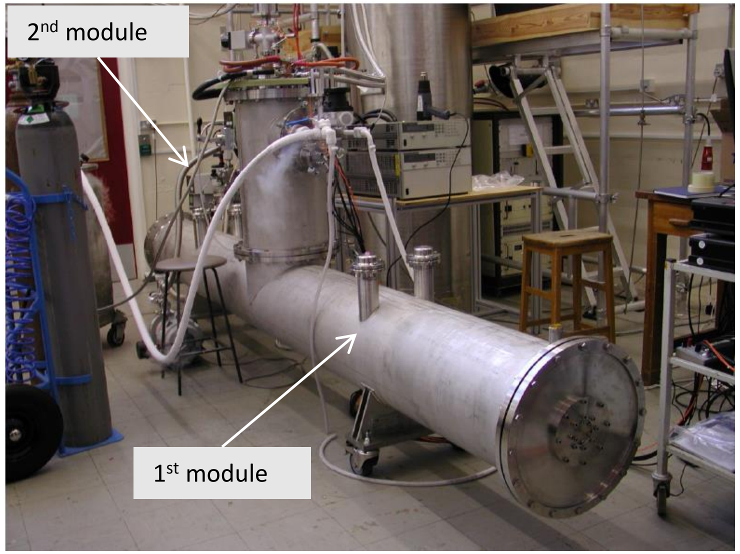
- After main linac, electrons pass a long superconducting Helical Undulator and produce a circularly polarized photon beam.



- photons hit spinning thin Ti6Al4V target and produce electrons-positron pairs
- e+ are captured and accelerated up to 5GeV and sent to positron damping ring

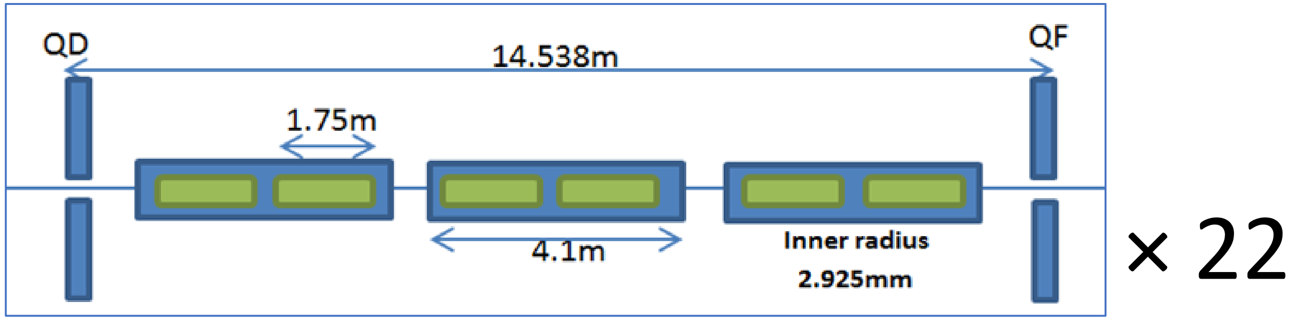
ILC Undulator structure

Helical Undulator Prototype
D.Scott et al.,
https://link.aps.org/pdf/10.1103/PhysRevLett.107.174803



- Two undulator modules with 1.75m each inserted in one cryomodule with 4m.
- 132 modules = 66 cryomodules
- Quadrupoles are located after each three cryomodules in total 23 quads
- Maximum 231m active undulator length,

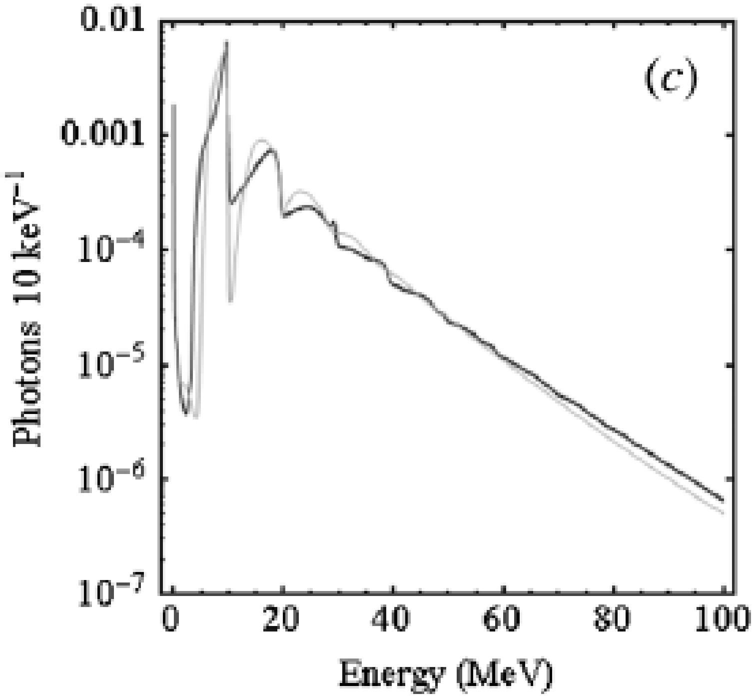
  320 m total undulator length
- Undulator aperture 5.85mm



Ideal and Real undulator

- Undulator prototype in the UK (details see: D.Scott et al., PRL 107(2011)1784803)
- Photon Spectra measured for the 2 modules of the undulator prototype
- B field in undulator prototype measured with Hall probe: ΔB= ± 10 %.

- The realistic photon spectra of the ILC undulator calculated by introducing the realistic error size into the magnetic field strength.
- HUSR can do that:
  - HUSR: **H**elical **U**ndulator **S**ynchrotron **R**adiation
    - **Developed at Cockcroft Institute by David Newton.**
    - Can simulate photon spectra produced by a Helical Undulator
    - **B field with errors**
    - Errors measured: randomly introduced into the period and field.
    - HUSR can calculate the photon polarization



Parameters

Three center-of-mass energies are considered for running the ILC:

- 250GeV: to produce Higgs bosons.
- 350GeV: to study the threshold of top-quark pair production.
- 500GeV: to study interesting processes of the Standard Model and beyond.

Center-of-mass-energy	250 GeV	350 GeV	500 GeV
Electron beam energy (GeV)	128	177.6	252
Bunches per pulse	1312	1312	1312
Photon energy (first harmonic) (MeV)	7.8	16.2	42.8
Undulator Active length (m)	231	147	147
Active undulator module number	132	84	84
Required undulator field (T)	0.79	0.7	0.42
undulator period length (cm)	1.15	1.15	1.15
undulator K	0.85	0.75	0.45
Electron energy loss in undulator (GeV)	3	2.6	2

ILC Undulator

- Superconducting undulator Problem: power deposition on the wall of the 320m long undulator.
  - To achieve Vacuum requirements (e.g. see **O. Malyshev EuroTeV** https://avs.scitation.org/doi/10.1116/1.2746876

- **Power deposition on the wall from synchrotron radiation must be ≤1W/m**
  (see also **Duncan Scott, 2008)**
  https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.490620

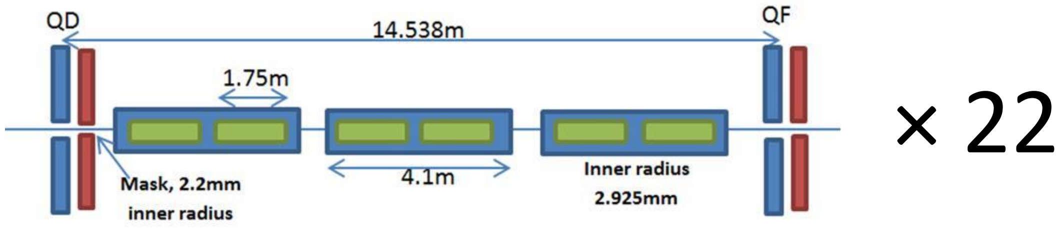
- We already studied the **IDEAL** power deposition on the wall from synchrotron radiation for ILC250 and 22 photon masks with 0.22 cm aperture radius are required to keep the energy deposited on the wall below the limit.

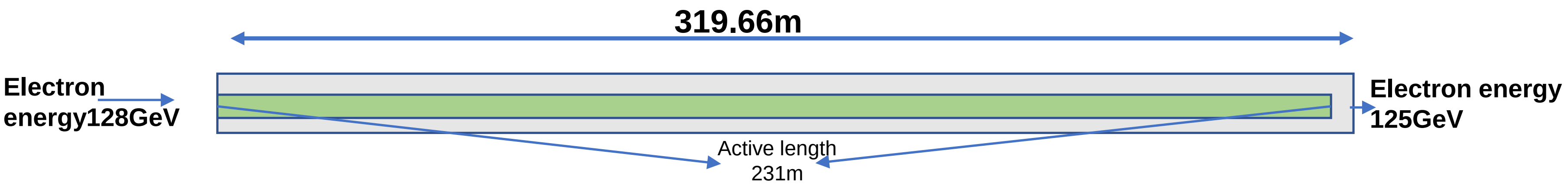
  For more details: https://arxiv.org/pdf/2001.08024.pdf

- The aim of this talk:
  - To study the non-ideal energy deposited at the photon masks for three different energies (250GeV, 350GeV and 500GeV center-of-mass energy)
  - A possible design of photon masks for the ILC Positron Helical Undulator
  - The photon polarization

Three undulators (E_{cm}= 250GeV, 350GeV and 500GeV)

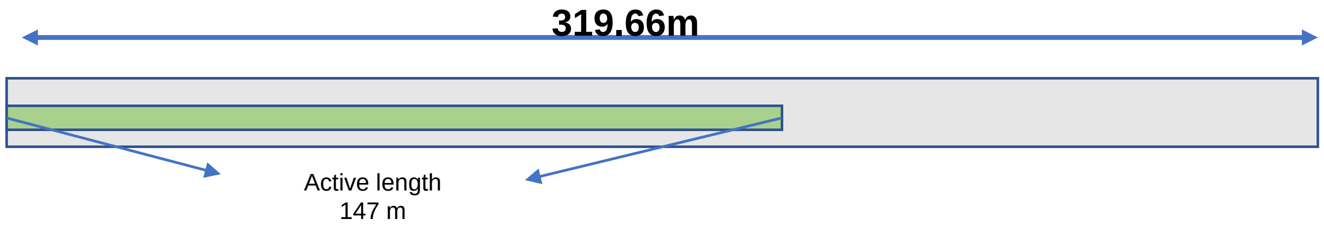
The Undulator total length reaches 319.66m including the undulator cryomodules, Quadrupoles and masks.





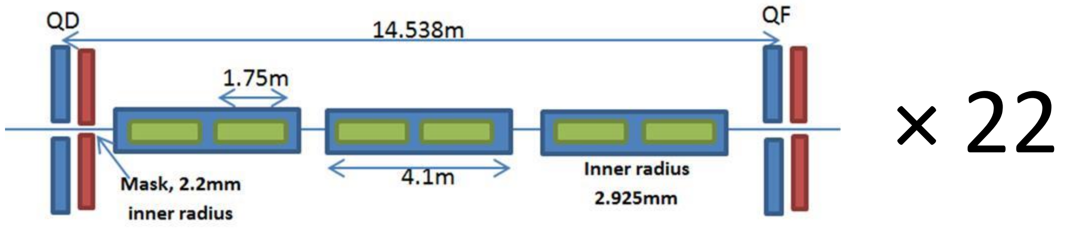
E_{cm}= 250GeV

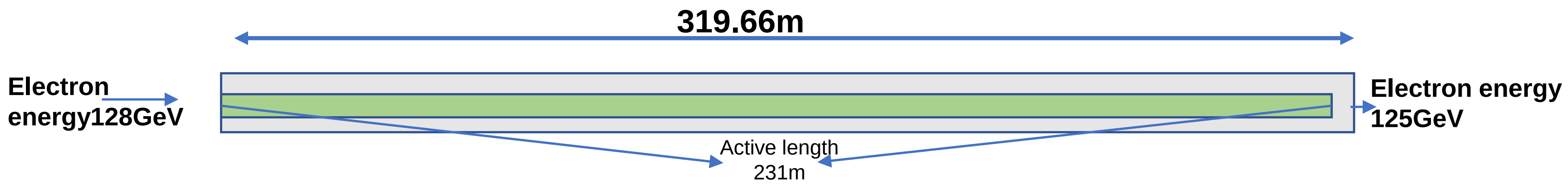
When Upgraded energy to 350GeV or 500GeV: only 147m active length is needed



Three undulators (E_{cm}= 250GeV, 350GeV and 500GeV)

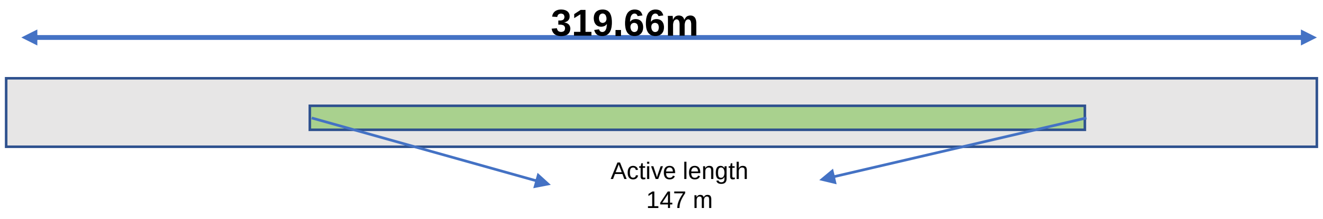
The Undulator total length reaches 319.66m including the undulator cryomodules, Quadrupoles and masks.





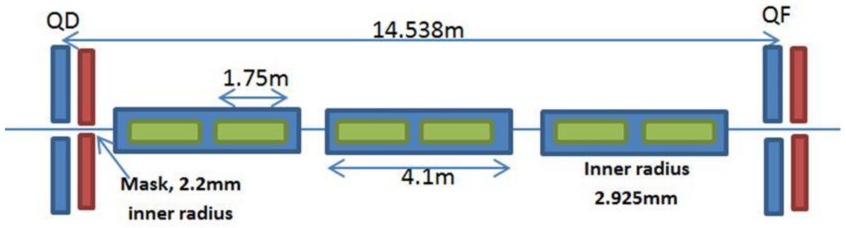
E_{cm}= 250GeV

When Upgraded energy to 350GeV or 500GeV: only 147m active length is needed

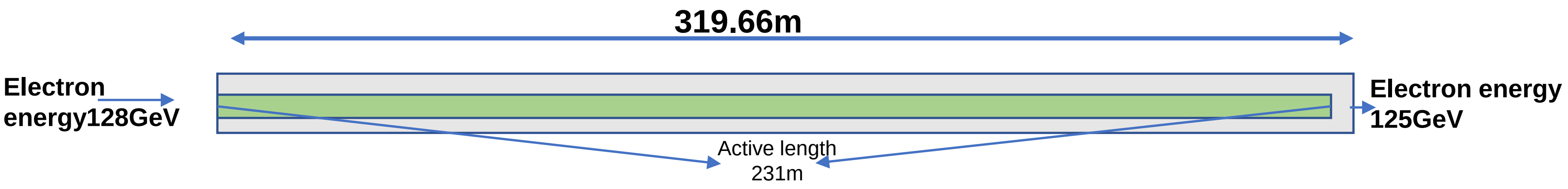


Three undulators (E_{cm}= 250GeV, 350GeV and 500GeV)

The Undulator total length reaches 319.66m including the undulator cryomodules, Quadrupoles and masks.

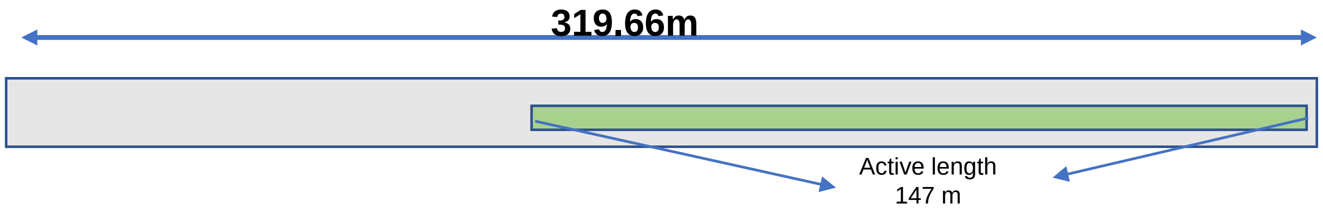


× 22



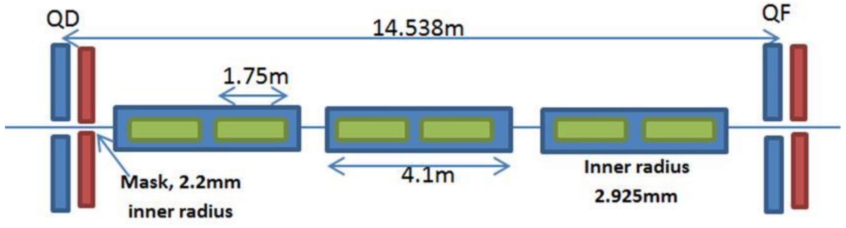
E_{cm}= 250GeV

When Upgraded energy to 350GeV or 500GeV: only 147m active length is needed

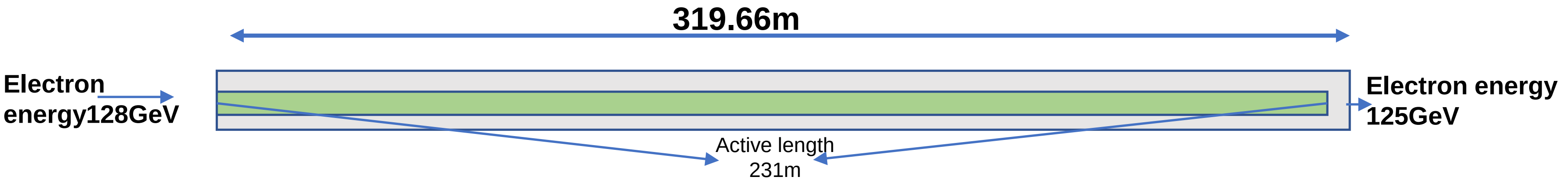


Three undulators (E_{cm}= 250GeV, 350GeV and 500GeV)

The Undulator total length reaches 319.66m including the undulator cryomodules, Quadrupoles and masks.

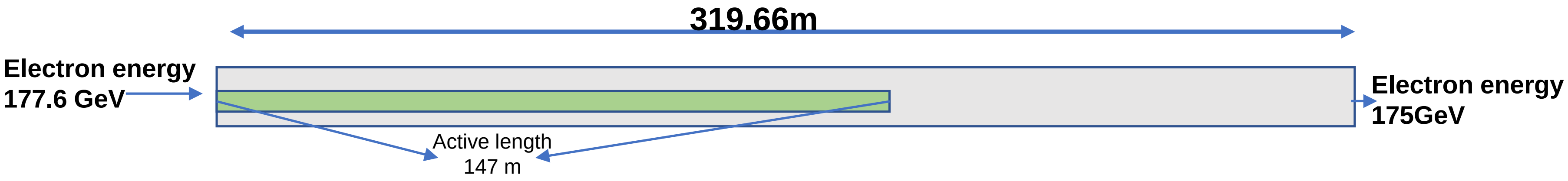


× 22

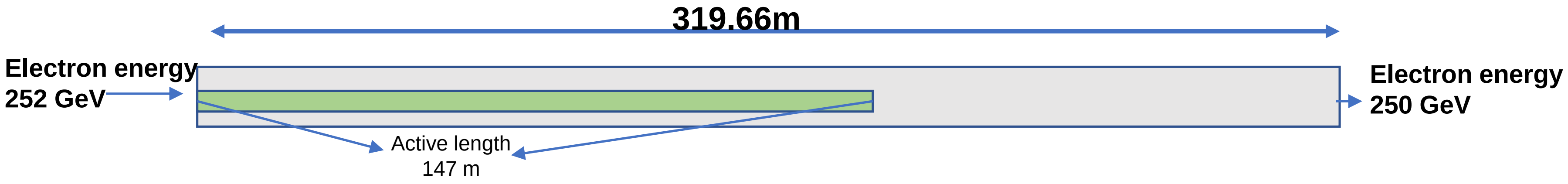


E_{cm}= 250GeV

In this study, first part was considered as in this scenario the mask will be received the highest among of energy deposited

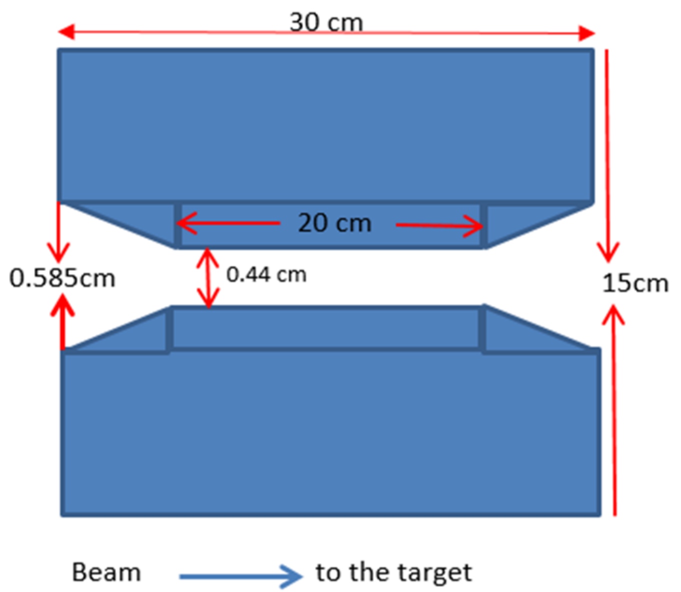


E_{cm}= 350GeV



E_{cm}= 500GeV

Photon Mask Design



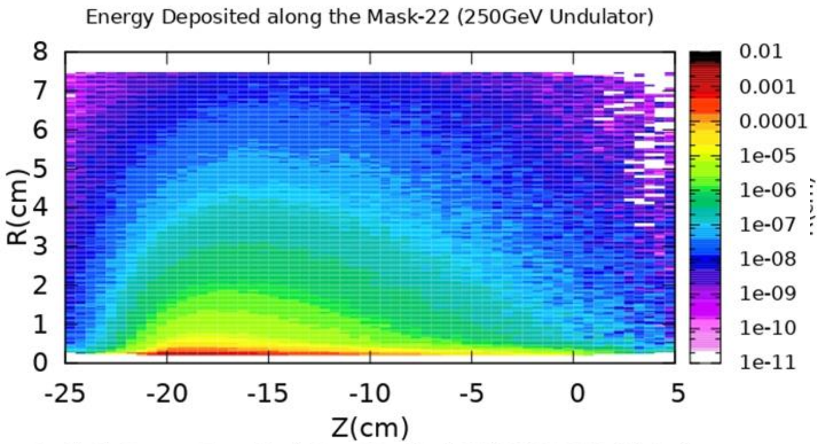
- Mask Design depends on:
  - The average incident photon energy (Ideal and Realistic)
  - The available area reserved for helical undulator (319.66m)
- A possible mask design:
  - cylinder
  - 30 cm length (cannot be longer since the limited area reserved 319.66m).
  - 7.5 cm outer radius.
  - 0.22 cm radius.
  - Taper in the 1st 5 cm and last 5 cm.
- Masks receive high energies in few MeV.
- Material: High Z-materials, large density and small radiation length are needed.
  - Material is Copper:

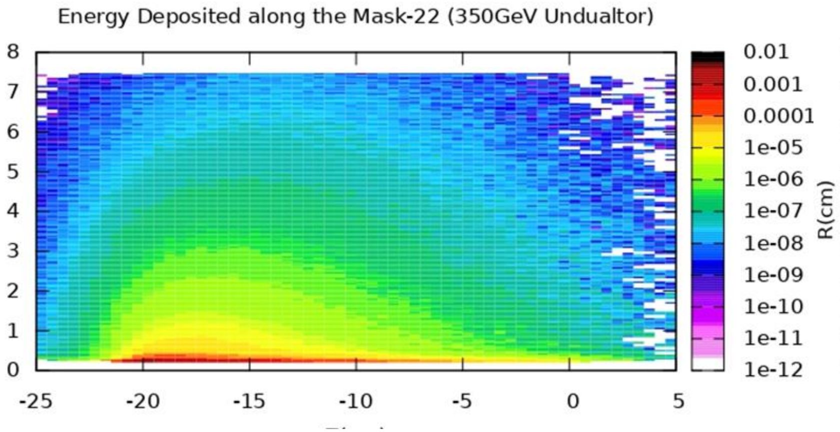
  (Different materials for masks (in case of Ideal Undulator) were studied: copper, iron and tungsten for more details : https://arxiv.org/pdf/2001.08024.pdf)

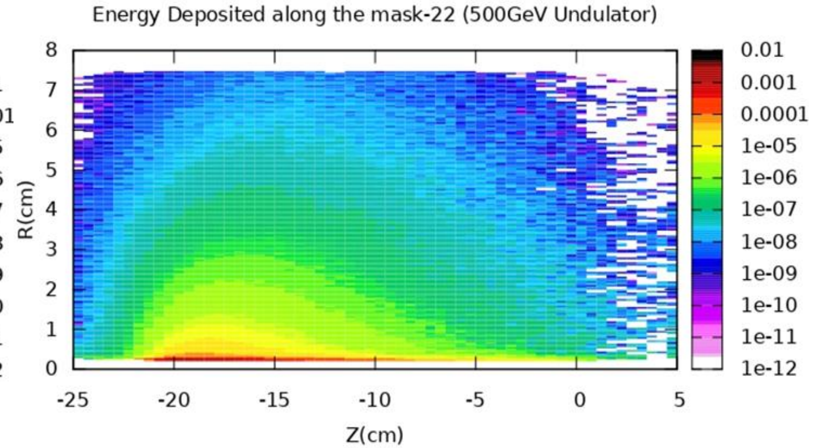
Parameter	Copper
atomic number	29
Density ($\frac{g}{cm^2}$)	8.96
Thermal conductivity (W/m.K)	358
heat capacity (J/g/K)	0.385
melting point (K)	1357.77
radiation length (cm)	1.436

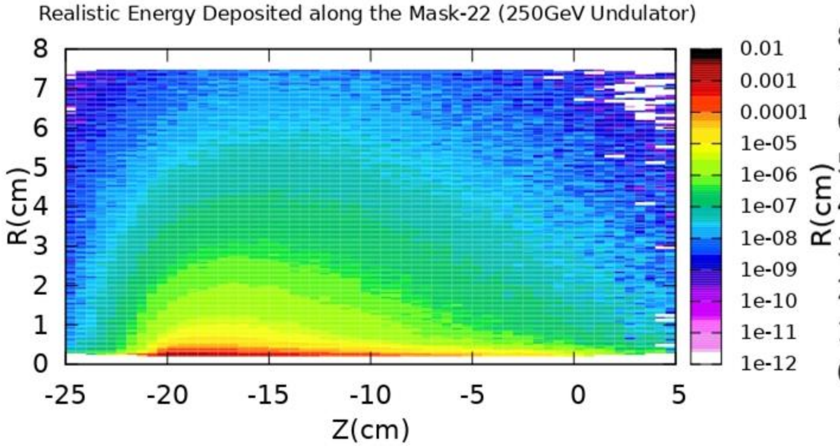
FLUKA Simulation

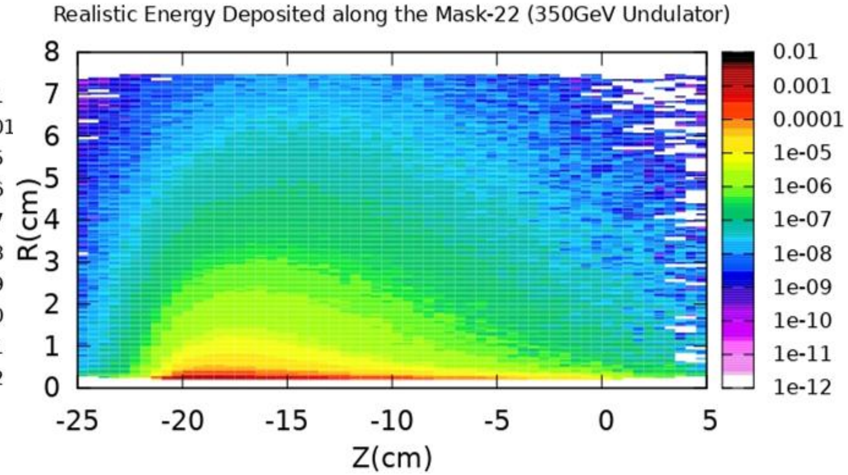
- Ideal and Realistic Energy Deposited along the mask-22 for three different energies (E_{cm}= 250GeV, 350GeV and 500GeV)

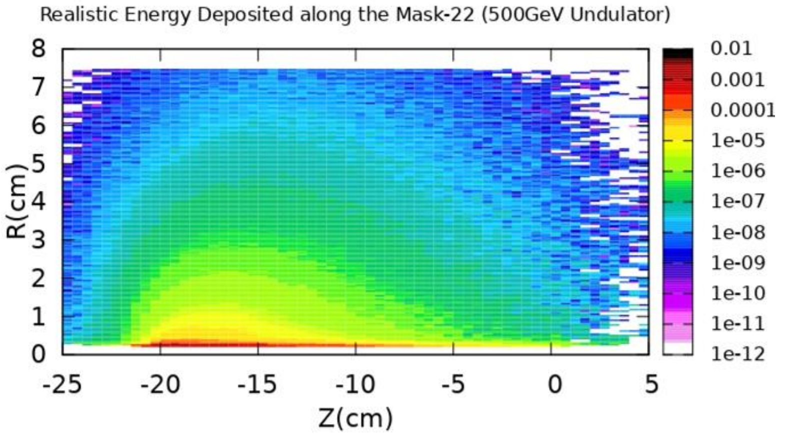




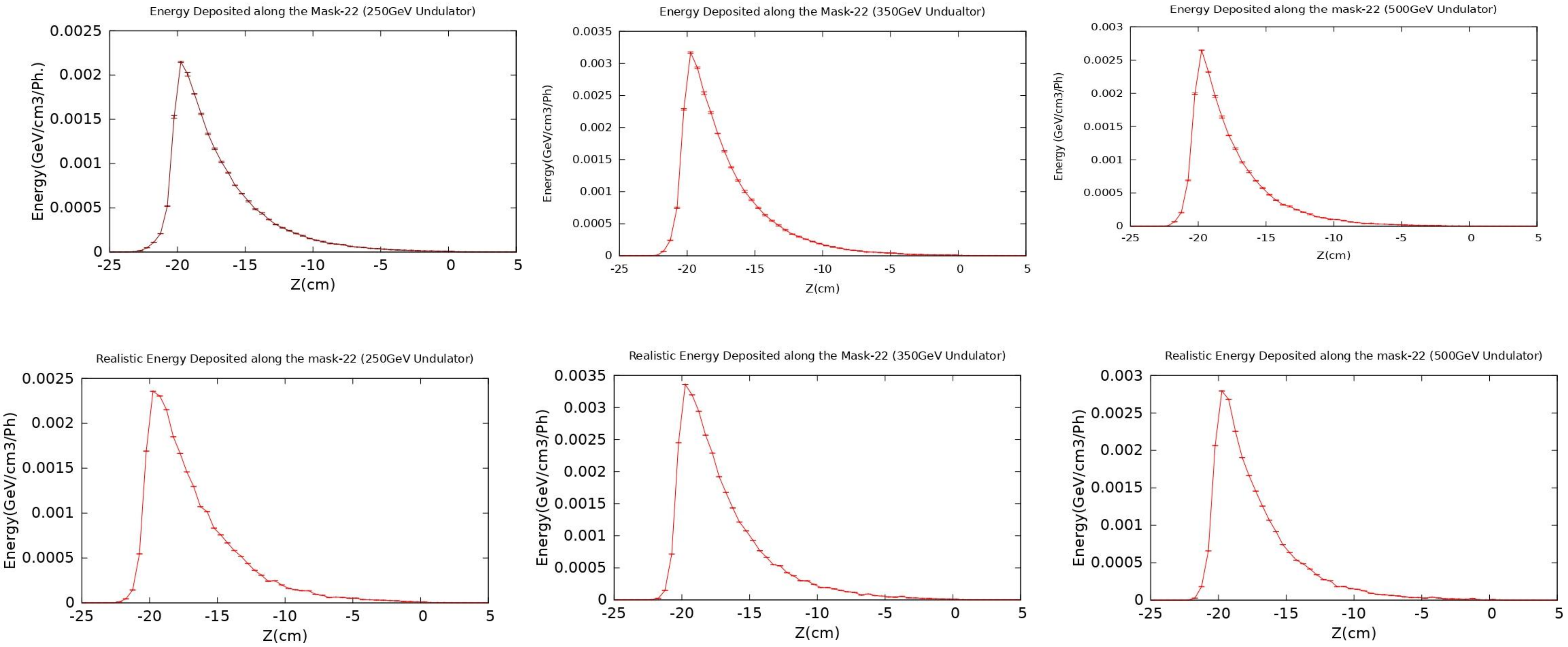








Ideal and Realistic Maximum Energy Deposited along the mask-22 for three different energies (E_{cm}= 250GeV, 350GeV and 500GeV)



Ideal Max Energy Deposited :

- 250GeV Undulator: 0.00214 (GeV/cm3/Ph)
- 350GeV undulator: 0.00316 (GeV/cm3/Ph)
- 500GeV undulator: 0.00264 (GeV/cm3/Ph)

Realistic Max Energy Deposited :

- 250GeV Undulator: 0.0024 (GeV/cm3/Ph)
- 350GeV undulator: 0.0033 (GeV/cm3/Ph)
- 500GeV undulator: 0.00275 (GeV/cm3/Ph)

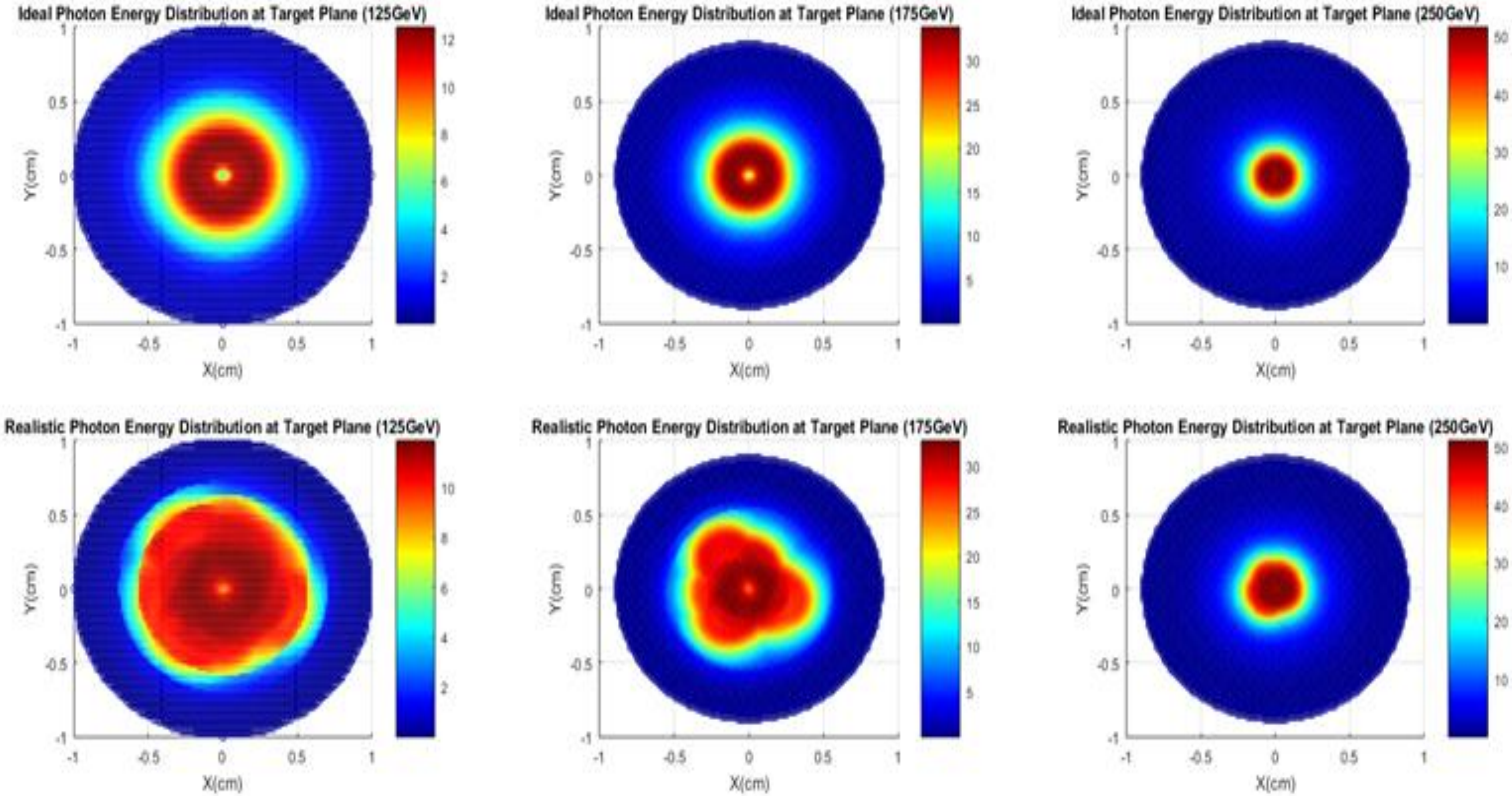
Average Incident Photon Energy (MeV) and PEDD at Last Mask

Table shows the average incident energy and power deposited at the last mask, #22
The last mask, 22, receives the highest power.
The opening angle of the photon beam is $\theta \sim \frac{1}{\gamma}(1 + K^2)^{1/2}, \gamma\ is\ lorantze\ factor.$
The Peak Energy Deposited Density (PEDD)
Photon Masks have to avoid PEDD values that could damage the material and cause failure of Photon Masks.
The results of calculation and simulation are shown in this table:

E_{cm}		Average Incident Photon Energy (MeV)	Power Deposited at Last Mask (W)	Max Energy (GeV/cm3/Ph)	Incident photon $(x10^{13})$/Pulse	PEDD (J/g/Pulse)	Max Temperate (K/Pulse)
250GeV	Ideal	2.01	336	0.0022	22	8.07	21
	Realistic	2.14	361	0.0024	21	9.03	24
350GeV	Ideal	2.54	186	0.00316	9	5.16	13
	Realistic	2.74	205	0.0033	10	5.50	14
500GeV	Ideal	1.75	21	0.00264	1.4	0.70	1.80
	Realistic	1.86	23	0.00275	1.6	0.76	2

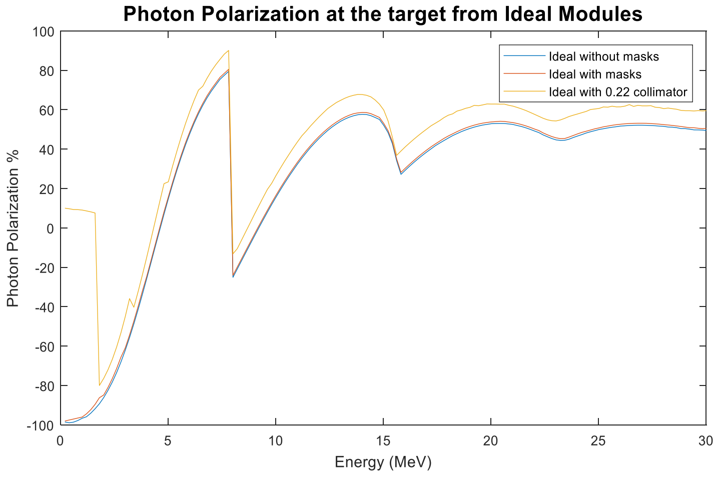
The Max PEDD for copper is 12 J/g/Pulse at room temperature
https://inis.iaea.org/collection/NCLCollectionStore/_Public/38/027/38027945.pdf?r=1

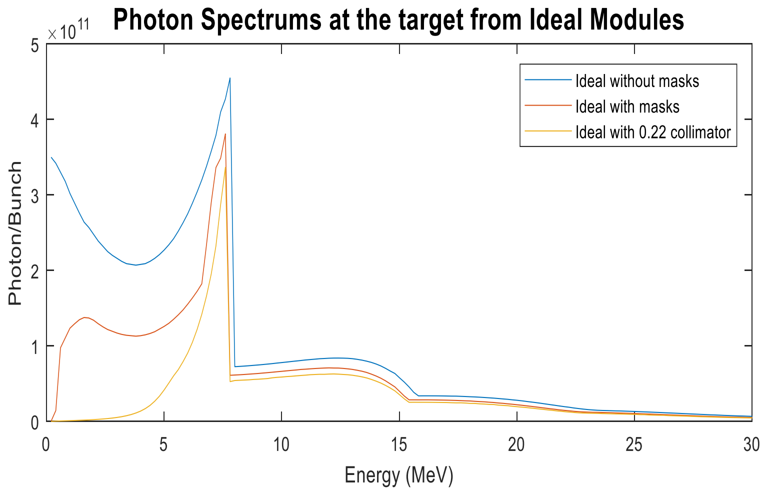
Ideal and Realistic Energy Distribution at Target for Three Different Energies (E_{cm}= 250GeV, 350GeV and 500GeV)

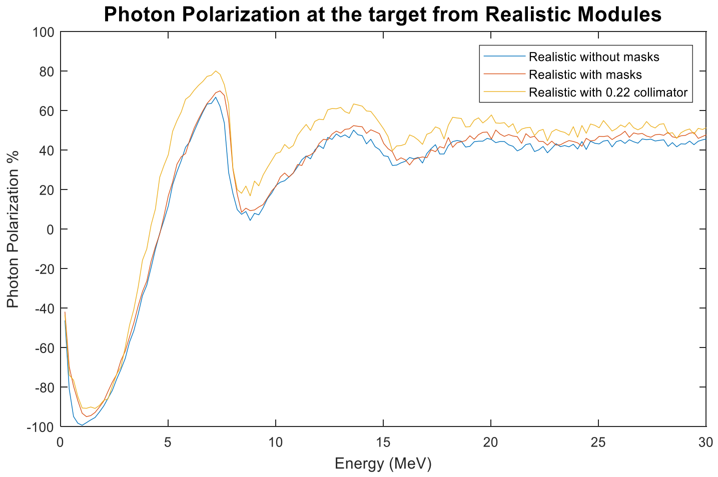


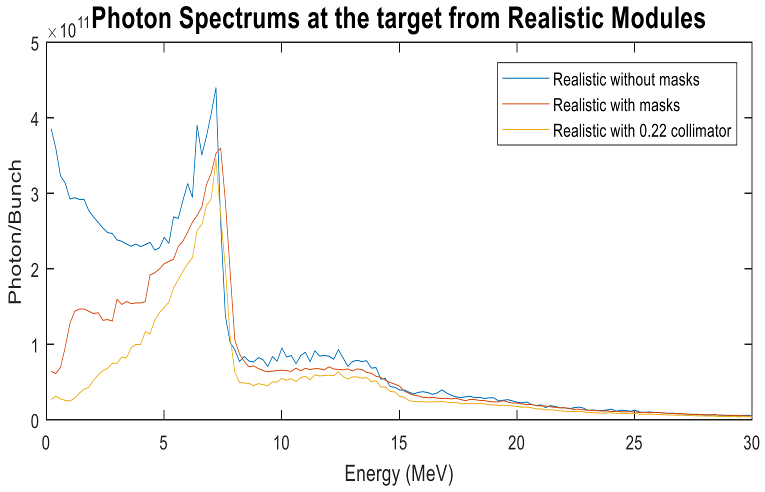
Influences of placing masks on photon power and polarization at the target for E_{cm}= 250GeV.

- Plots show photon spectrum and polarization at target for ideal and realistic undulator.
  1) Without masks. 2) With masks. 3) with Beam Spot radius 0.22cm.





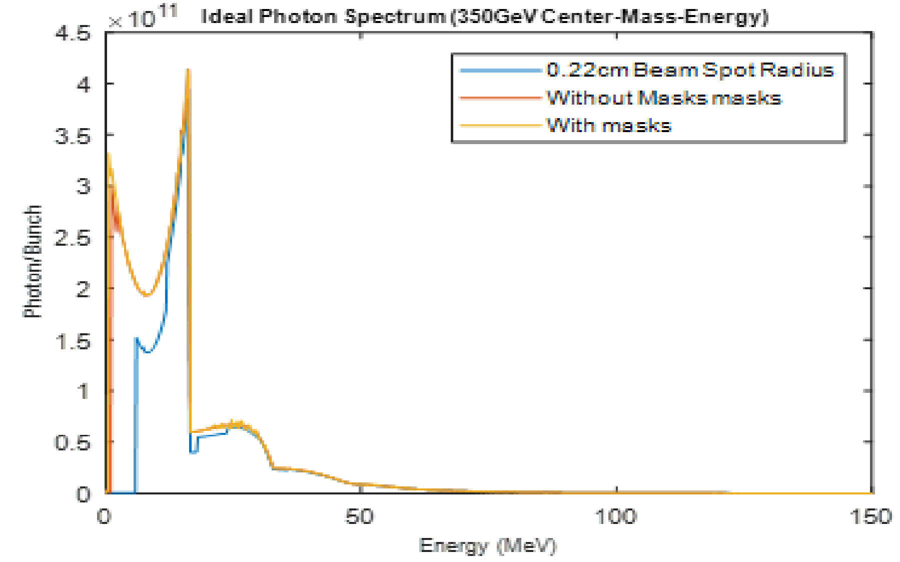


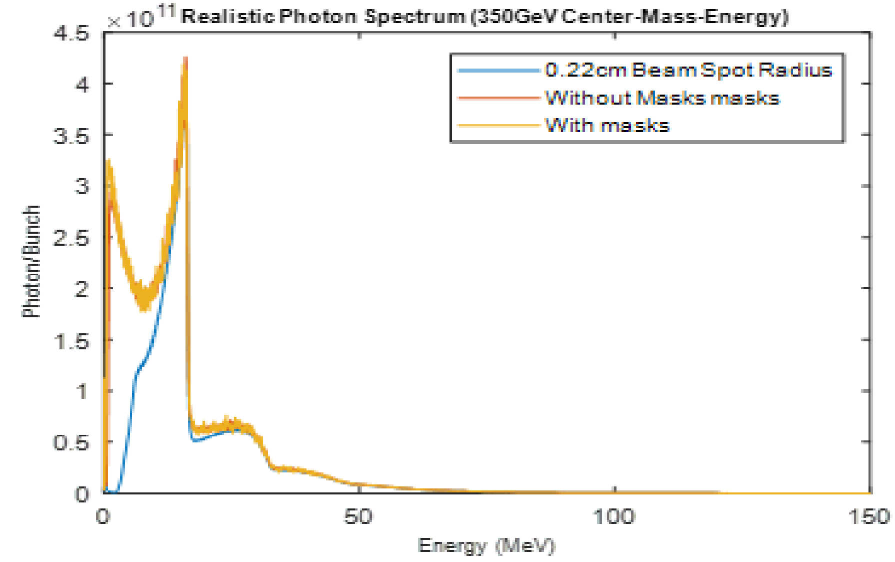


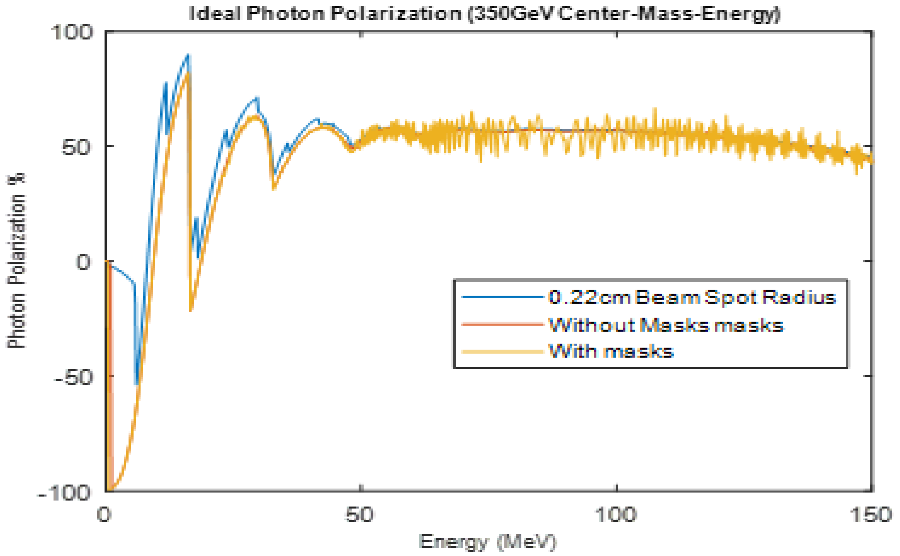
Influences of placing masks on photon power and polarization at the target for E_{cm}= 350GeV.

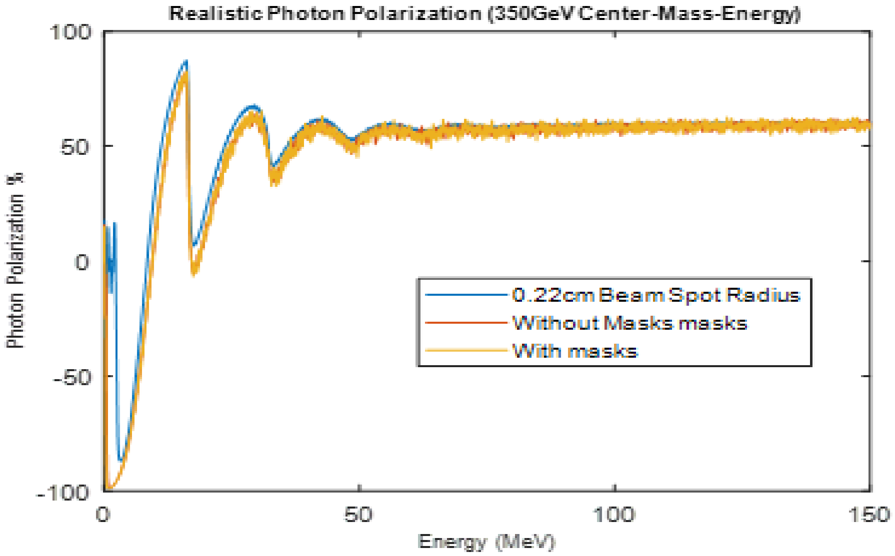
- Plots show photon spectrum and polarization at target for ideal and realistic undulator.

1) Without masks. 2) With masks. 3) with Beam Spot radius 0.22cm.





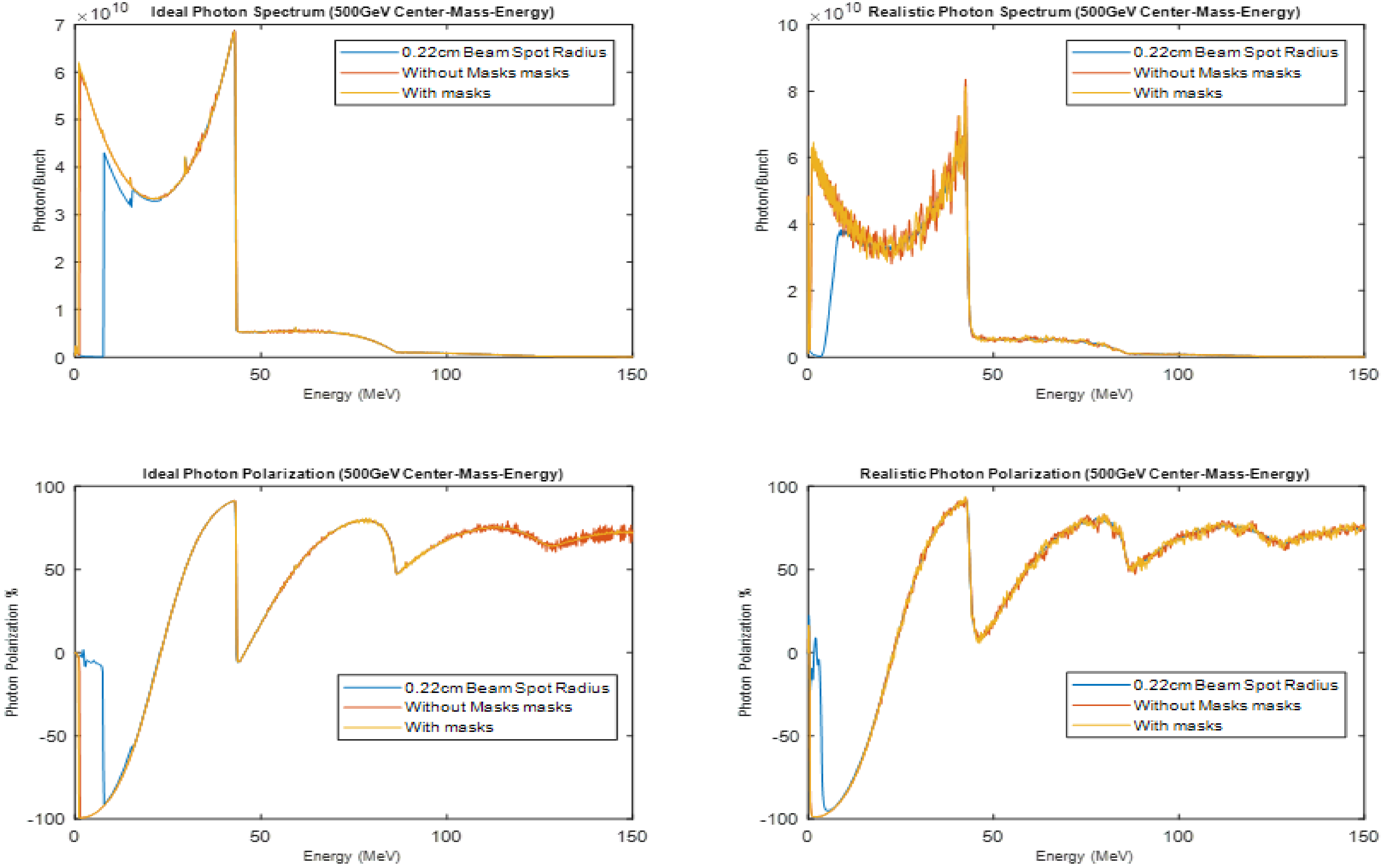




Influences of placing masks on photon power and polarization at the target for E_{cm}= 500GeV.

- Plots show photon spectrum and polarization at target for ideal and realistic undulator.

  1) Without masks. 2) With masks. 3) with Beam Spot radius 0.22cm.



Influences of placing masks on photon power and polarization at the target for E_{cm}= 250GeV..

- Masks increase:
  - Ideal: Polarization by 3.22% (from 38.1 to 41.32 %), Average photon energy increases average energy 7.68 to 7.97 MeV.
  - Realistic: Polarization by 1.6 % (from 37.14 to 38.69%), Average photon energy increases 7.59 to 7.87 MeV.
- 0.22 cm Beam Spot radius increase photon polarization to
  - 73.76 % but power decreases to 43.08 W (Ideal).
  - 66.1 % but power decreases to 42.38 W (Realistic).

	Ideal			Realistic		
	Average Energy (MeV)	Power (W)	Photon Polarization %	Average Energy (MeV)	Power (W)	Photon Polarization %
Without masks	7.68	62.5	38.1	7.59	61.56	37.14
With masks	7.97	60.1	41.32	7.87	59.32	38.69
With 0.4cm photon collimator radius	9.42	58.26	43.47	9.04	57.53	42.55
With 0.22cm photon collimator radius	10.65	43.08	73.76	10.26	42.38	66.1

Photon Polarization At the Target (250GeV, 350GeV and 500GeV)

- Adding Masks
  - 250GeV: increases photon polarization from 38.1 % to 41.32 %.
  - Almost no change in photon polarization in case of 350GeV and 500GeV.
- With 0.22cm Beam Spot radius:
  - 250GeV: photon polarization 73.76% (ideal) and 66.1% (realistic).
  - 350GeV: photon polarization 56.46% (ideal) and 54.27% (realistic). (primarily result).
  - 500GeV: photon polarization 49.61% (ideal) and 48.51% (realistic). (primarily result).

	250GeV Polarization%		350GeV Polarization%		500GeV Polarization %	
	Ideal	Realistic	Ideal	Realstic	Ideal	Realstic
Without Mask	38.1	37.14	39.05	38.52	44.87	44.78
With Mask	41.32	38.69	39.12	38.70	44.87	44.82
0.22cm Beam Spot radius	73.76	66.1	56.46	54.27	49.61	48.51

Conclusion

- Masks are needed to protect undulator wall from synchrotron radiation (limit 1 W/m).
- A possible photon mask geometry with a high photon absorption efficiency has been modelled with copper.
- Copper mask absorbs ~98.5%.
- Energy deposition and temperature increase studies proved that for these particular beam parameters (E_{cm}=250, 350 and 500GeV), the masks are SAFE. For example, the PEDD at copper mask are 8.18 and 9.03 J/(g*pulse) for Ideal and realistic 250GeV center-of-mass-energy, respectively. Also, maximum temperatures rise are 21 and 24 K/pulse for Ideal and realistic 250GeV center-of-mass-energy, respectively.
- Masks increase slightly average photon energy (4% ideal and 3.5 % realistic) for E_{cm}= 250GeV.
- Masks increase photon polarization (a small fraction) for E_{cm}= 250GeV, but no changes for for E_{cm}= 350 and 500GeV.
- To increase the photon polarization for $\mathrm{E_{cm}}$= 350 and 500GeV, a photon collimator system with radius less than 0.22cm. Conditionally essential, e+ yield must NOT below 1.5e+/e-

Thank you for your attention

Questions