11-13 March 2024
AWAKE Collaboration meeting, University of Liverpool, Liverpool, UK

Betatron radiation in AWAKE Run 2 and beyond

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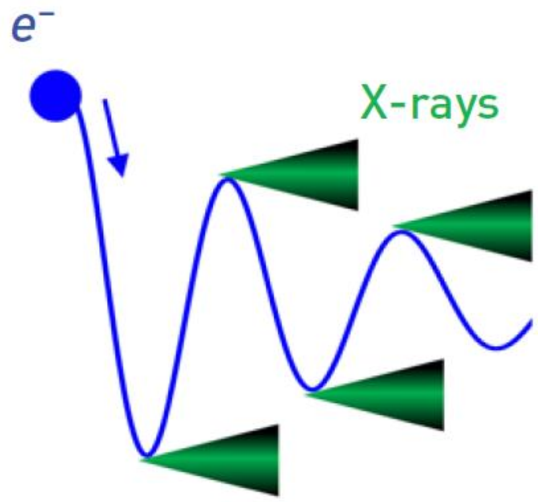
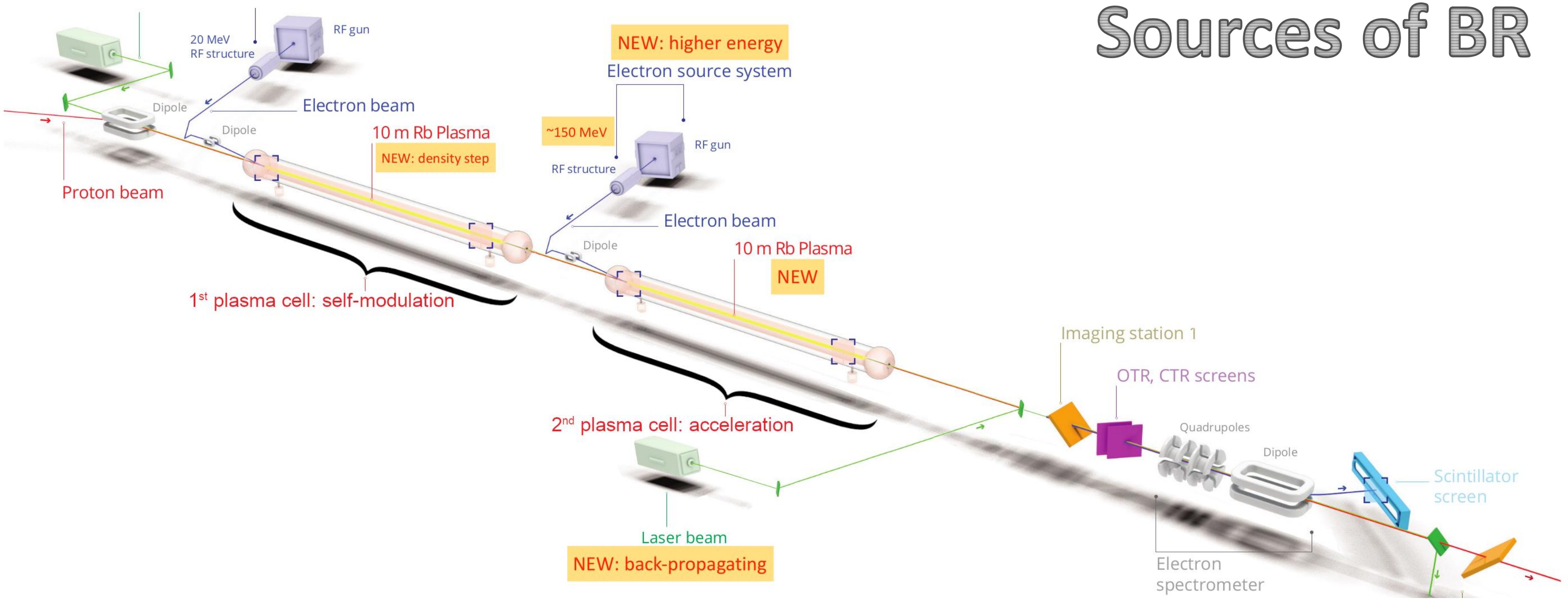
Betatron radiation

- ❑ Plasma accelerators exhibit very strong accelerating and focusing fields.
- ❑ The wiggling electrons emit radiation known as betatron radiation.
- ❑ Advanced X-ray photon source for imaging applications.
- ❑ BR is of interest for non-invasive beam diagnostic
  - LWFA in several labs
  - PWFA at FACET experiment
  - AWAKE



Betatron radiation in AWAKE Run 2

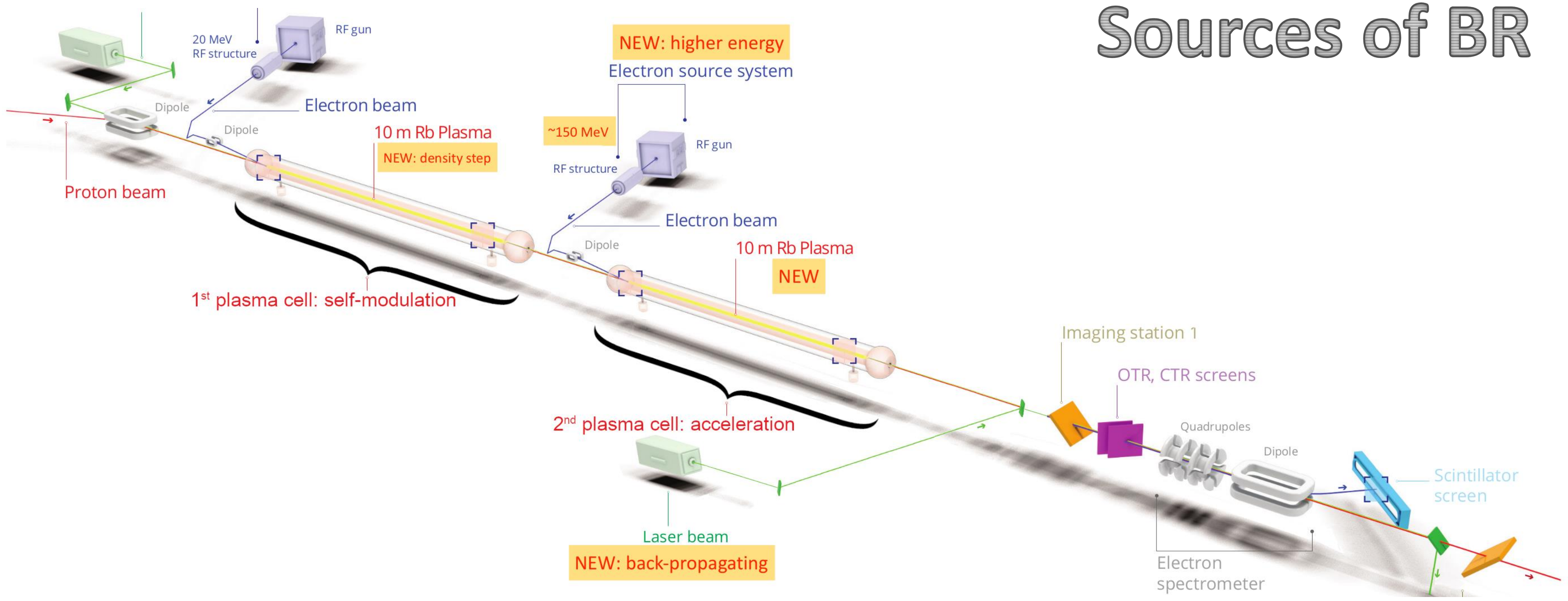
Sources of BR



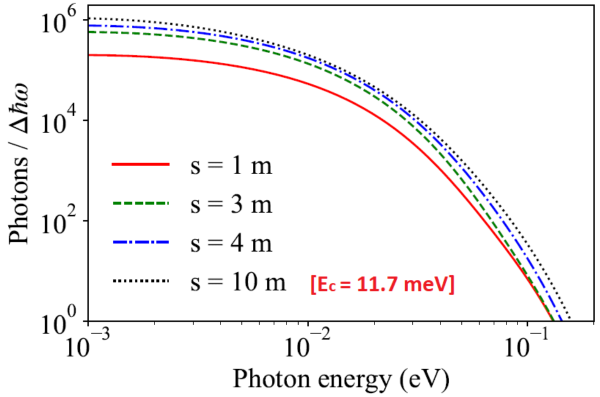
1) Witness electron beam
2) Seeding electron beam
3) Proton beam (~meV) 🤔

- ❑ Protons may oscillate in their wakefields, emitting betatron radiation.
- ❑ Maximum critical energy of a single proton is estimated: 73 meV

Sources of BR

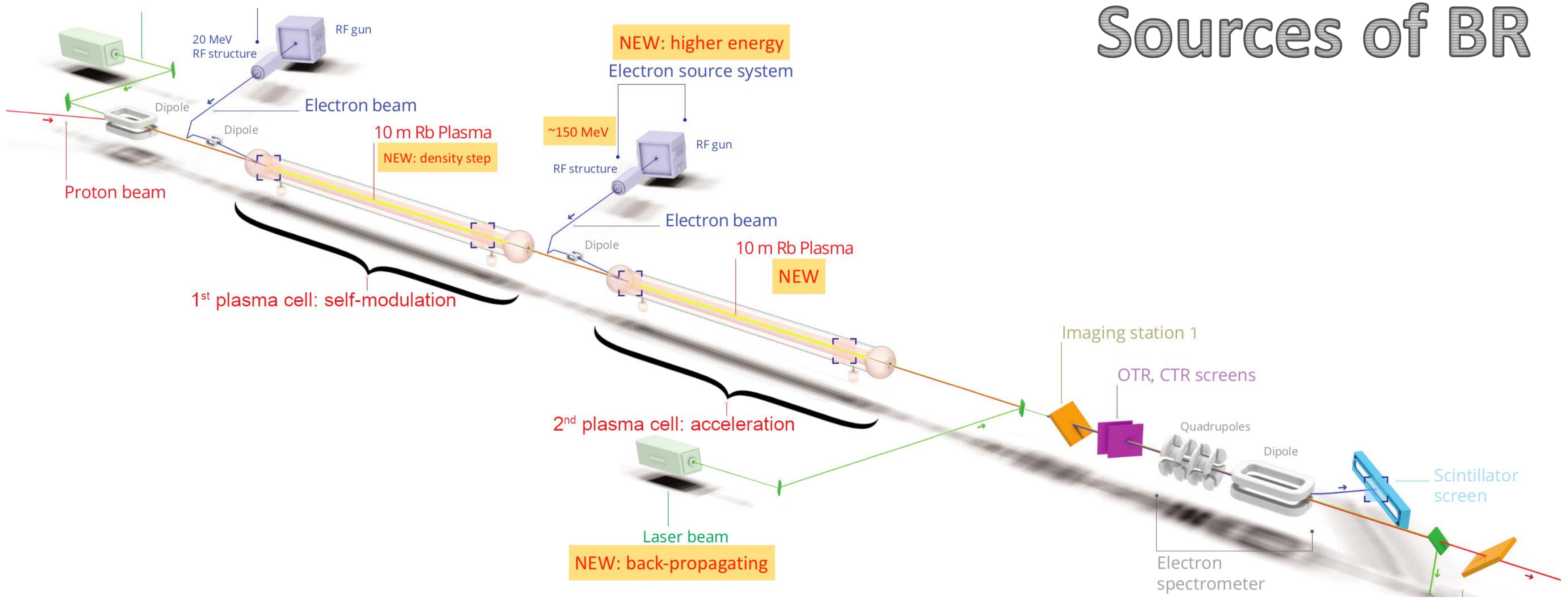


1) Witness electron beam
2) Seeding electron beam (meV)
3) Proton beam (~meV)

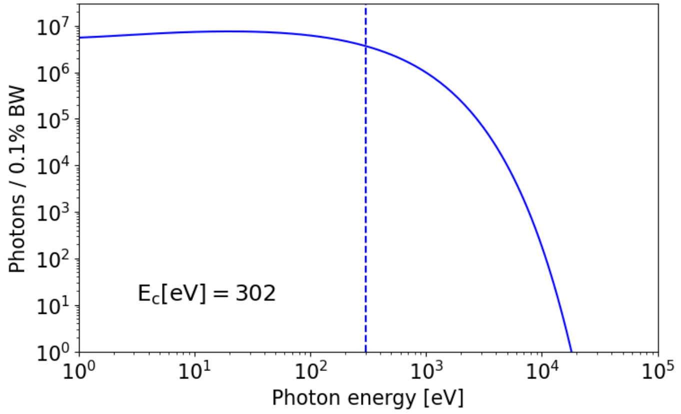


L. Liang- et al, J Plasma Phys. 89, 965890301(2023)

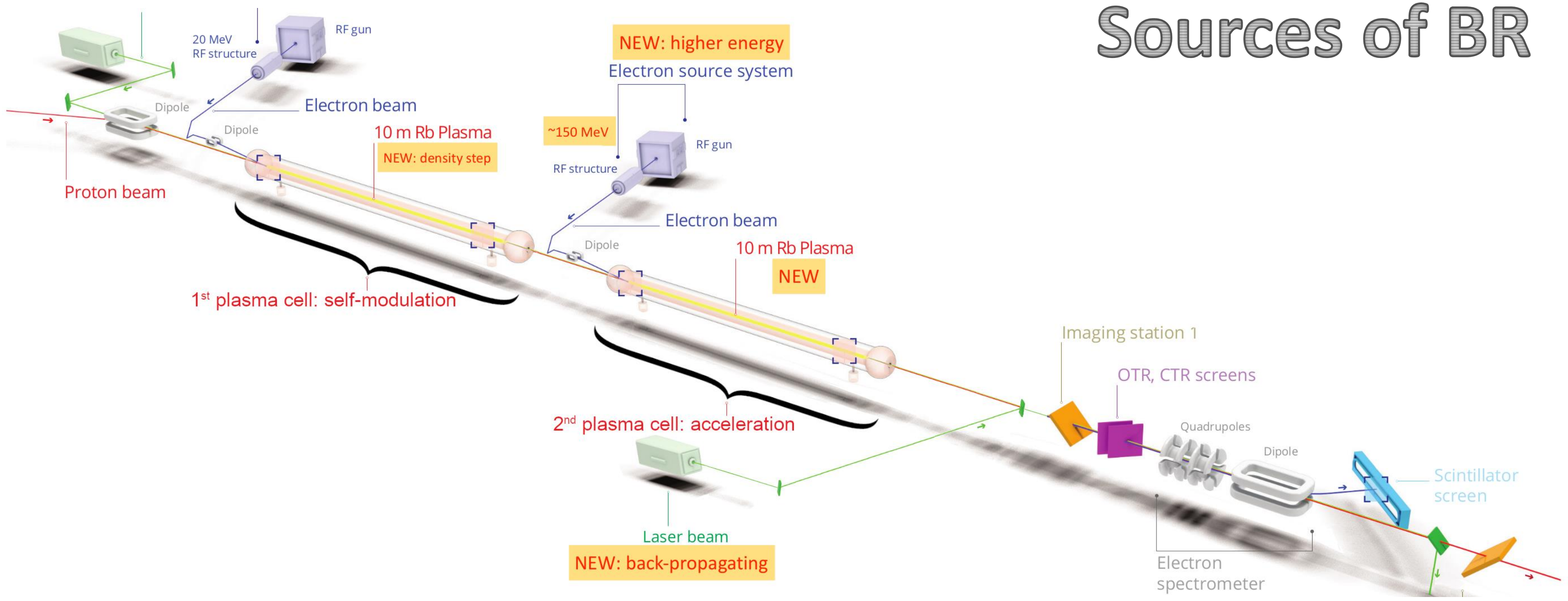
Sources of BR



1) Witness electron beam (~keV)
2) Seeding electron beam (meV) 🤔
3) Proton beam (~meV) 🤔



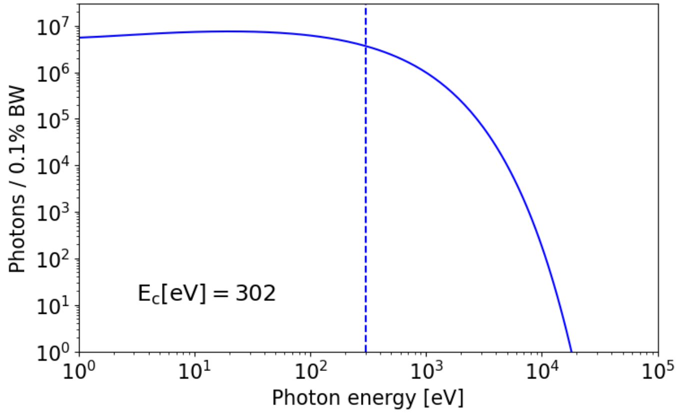
Sources of BR



1) Witness electron beam (~keV)

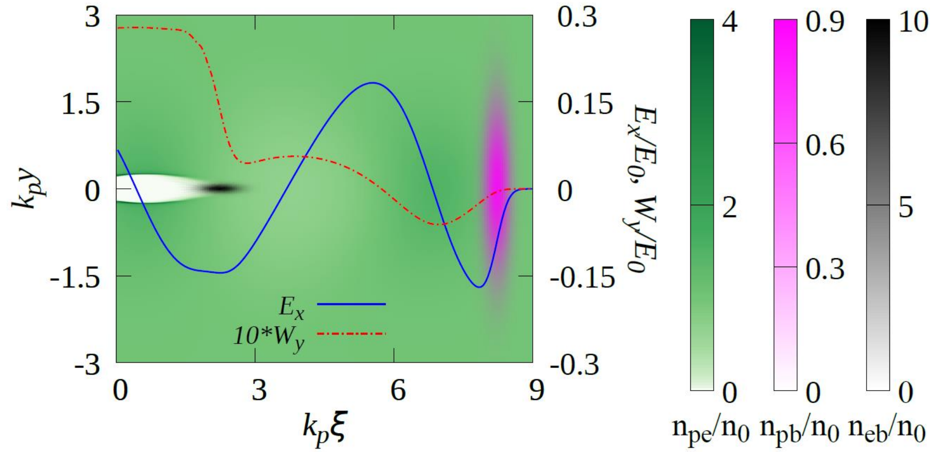
~~2) Seeding electron beam (meV)~~

~~3) Proton beam (~meV)~~



Due to its practicality, the witness beam radiation is regarded as AWAKE betatron radiation.

PIC simulation

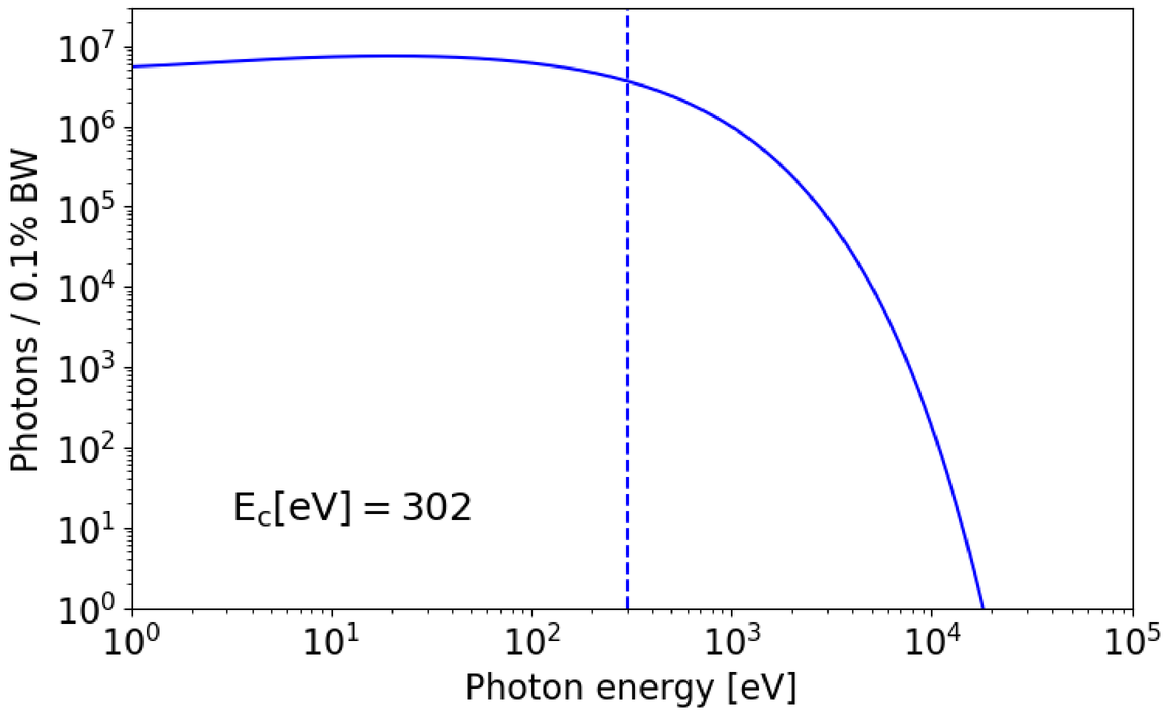


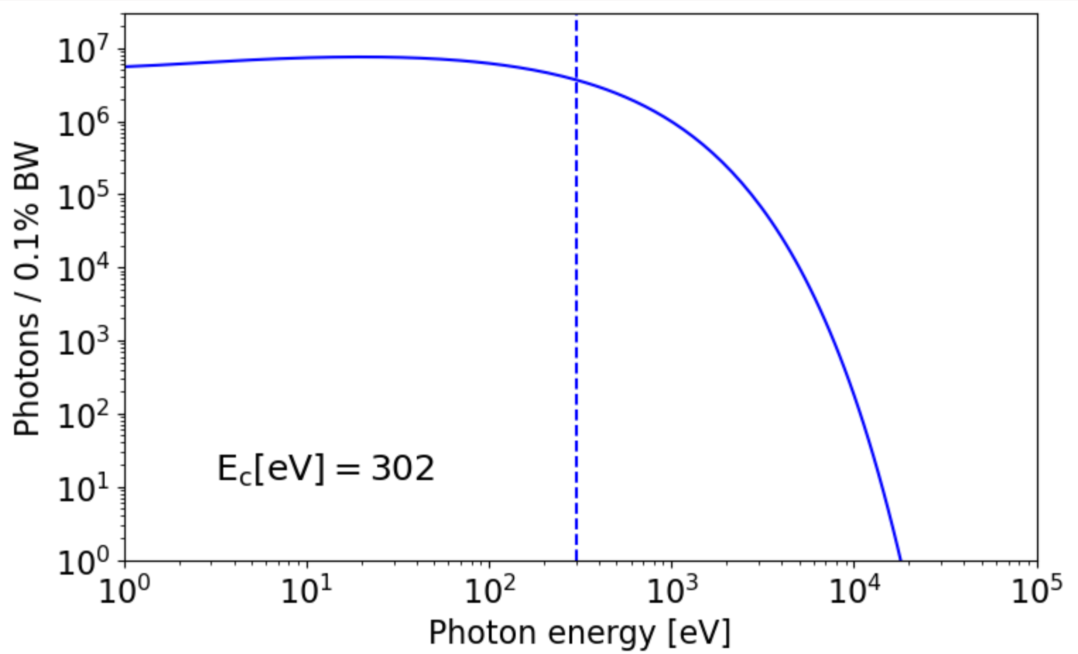
- ❑ QV3D PIC code
  - ❖ Build-in module to calculate synchrotron radiation
- ❑ Simulation model (V. Olsen et al, PRAB 2018)
  - ❖ Uses a dummy driver such that it replicates the wakefield of real proton driver
- ❑ AWAKE Run 2 baseline parameters.

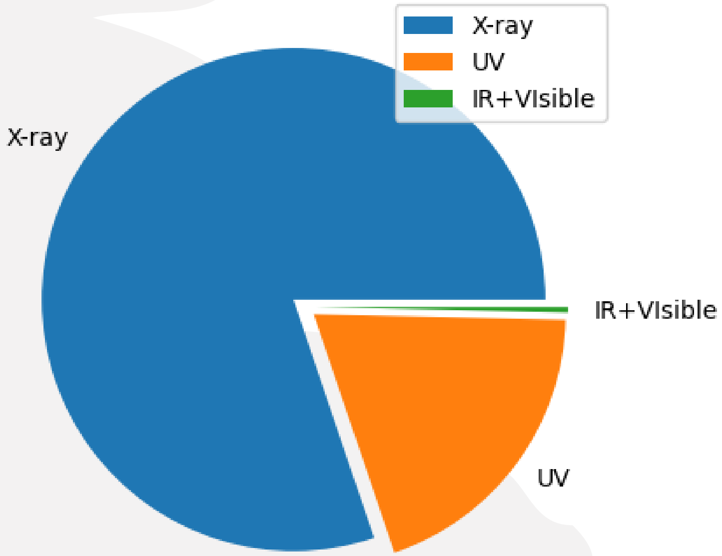
Parameter	Symbol [Unit]	AWAKE baseline
Plasma		
Density	n_0 [cm^{-3}]	7×10^{14}
Wavelength	λ_p [mm]	1.26
Length	[m]	10
Dummy Driver		
Energy	E_P [GeV]	400
Charge	Q_P [nC]	2.34
Density	n_P/n_0	0.83
Bunch Length	$\sigma_{\xi P}$ [μm]	40
Bunch Radius[a]	σ_{rP} [μm]	200
Electron Witness		
Density	n_e/n_0	34.1
Charge[b]	Q_e	120
Bunch Length[c]	$\sigma_{\xi e}$ [μm]	60
Bunch Radius[d]	σ_{re} [μm]	5.75
Energy	E_e [MeV]	150
Energy Spread	$\delta\gamma_e$	0.1%
Normalized Emittance	ε_{ne} [mm mrad]	2

Characteristics of AWAKE betatron radiation

- ❑ High energy radiation in the UV to X-ray range.
- ❑ Highly collimated radiation: focused into a narrow angle (~ mrad).
- ❑ Short pulse duration on the order of ~100 fs.
- ❑ Total photon numbers ~ 1E9.



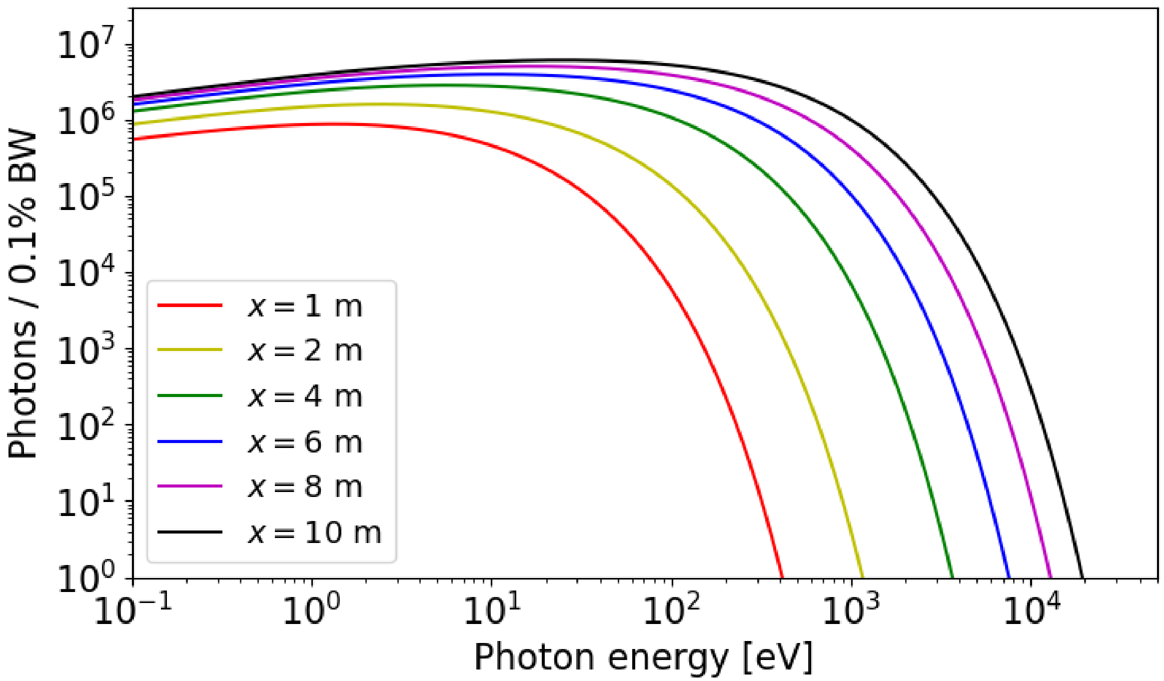


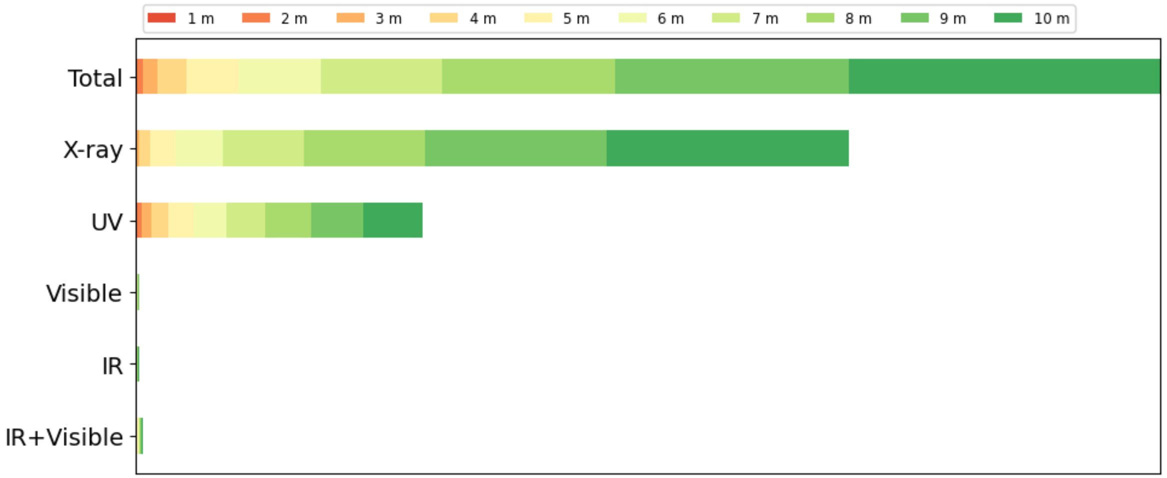


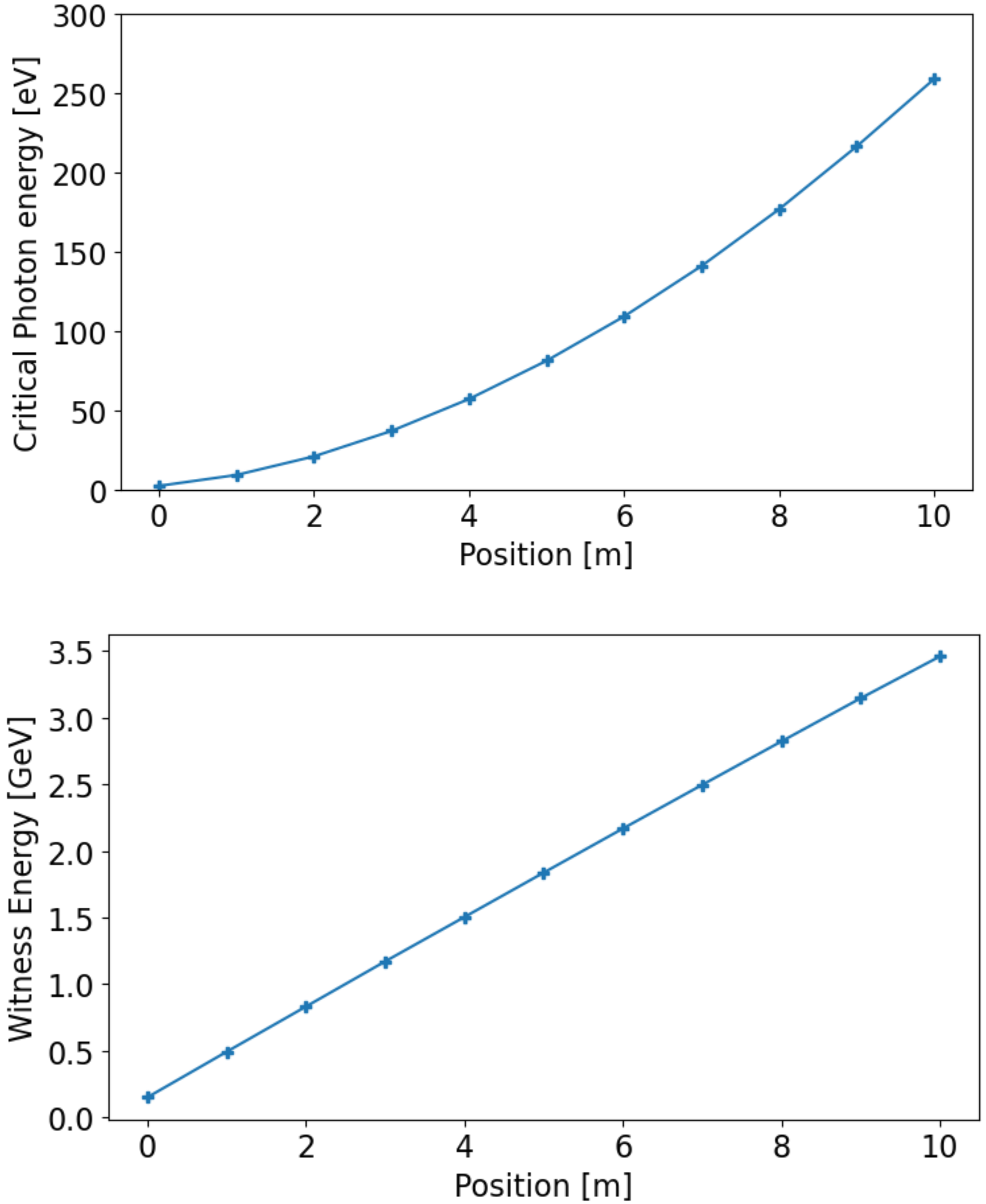
Photon	Energy range
X-ray	> 124 eV
UV	3.1-124 eV
Others	< 3.1 eV

Distribution of Photon Frequencies Across the Total Spectrum

Radiation along the plasma cell

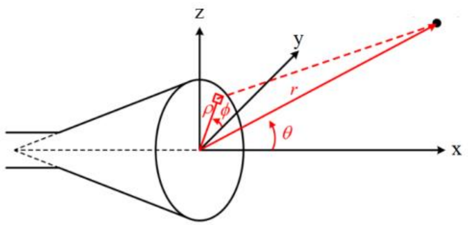


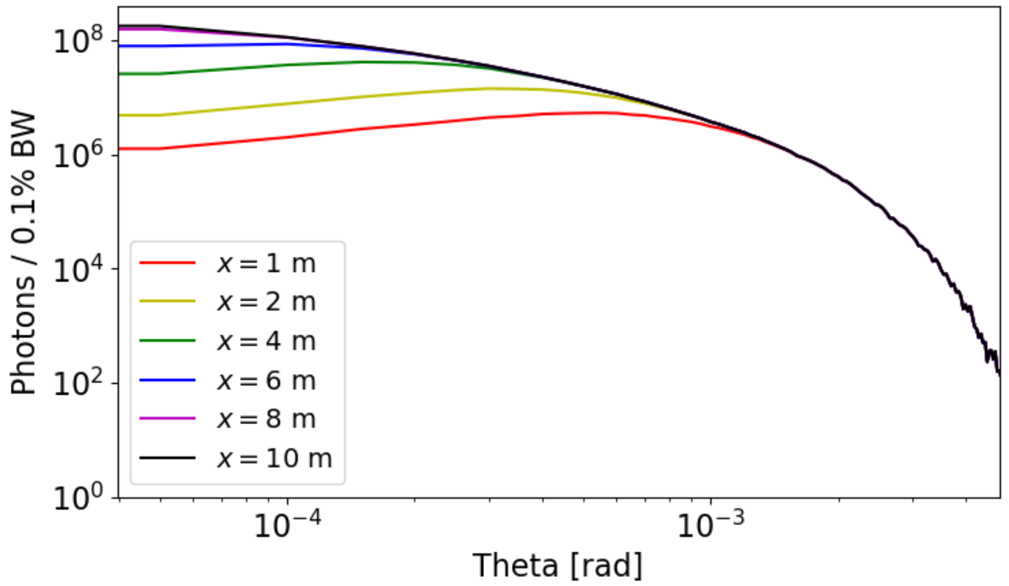




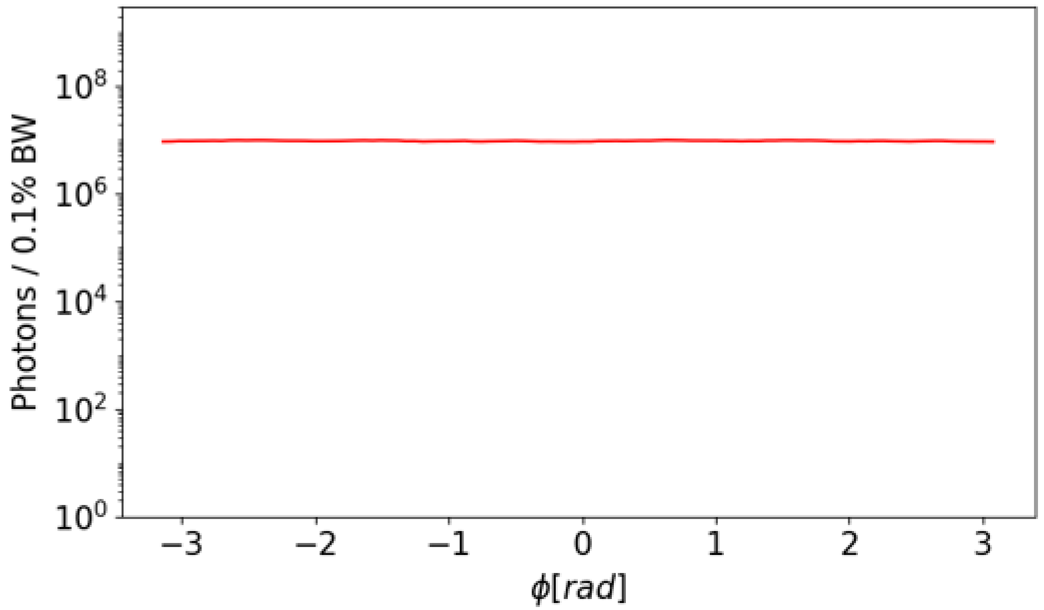
Along the plasma cell

Radiation spatial distribution





- Photons are inside a small angle: < few mrad
- Most photons below 1 mrad
- Photons emitted within 8-10 meters of the plasma cell exhibit divergence within 0.1 mrad.



- Photons are distributed with azimuthal symmetry.

Betatron diagnostic:
In experiment

AIP Conference Proceedings

Low-emittance electron bunches from a laser-plasma accelerator measured using single-shot X-ray spectroscopy

C. G. R. Geddes, G. R. Plateau, D. B. Thorn, M. Chen, C. B. Benedetti, E. Esarey, A. J. Gonsalves, N. H. Matlis, K. Nakamura, S. Rykovanov, C. B. Schroeder, S. Shiraishi, T. Sokollik, J. van Tilborg, Cs. Toth, S. Trotsenko, T. S. Kim, M. Battaglia, Th. Stöhlker, and W. P. Leemans

Citation: AIP Conference Proceedings **1507**, 278 (2012); doi: 10.1063/1.4773707
View online: http://dx.doi.org/10.1063/1.4773707
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1507?ver=pdfcov
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First experimental results of beam driven plasma wakefield acceleration at FACET-II: beam matching and gamma-ray radiation

P. San Miguel Claveria[1], E. Adli[2], R. Ariniello[3], S. Corde[1], C. Doss[3], H. Ekerfelt[4], C. Emma[4], H. Fujii[5], S. Gessner[4], M.Gilljohann[1], M. Hogan[4], K. Hunt-Stone[3], C. Joshi[5], A. Knetsch[1], O. Kononenko[1], V. Lee[3], M. Litos[3], Y. Mankovska[1], K. Marsh[5], A. Matheron[1], W. Mori[5], B. O'Shea[4], D. Storey[4], N. Vafaei-Najafabadi[6], Y. Wu[5], X. Xu[4], V. Yakimenko[4], J. Yan[6], N. Zan[5], C. Zhang[5]

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Research

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One contribution of 10 to a Theo Murphy meeting issue 'Directions in particle beam-driven plasma wakefield acceleration'.

Subject Areas:
plasma physics

Keywords:
plasma, accelerators, particle beams, radiation, gamma-rays

Betatron radiation and emittance growth in plasma wakefield accelerators

P. San Miguel Claveria[1], E. Adli[2], L. D. Amorim[3], W. An[4], C. E. Clayton[4], S. Corde[1], S. Gessner[5], M. J. Hogan[6], C. Joshi[4], O. Kononenko[1], M. Litos[7], W. Lu[8], K. A. Marsh[4], W. B. Mori[4], B. O'Shea[6], G. Raj[1], D. Storey[6], N. Vafaei-Najafabadi[3], G. White[6], Xinlu Xu[4,6] and V. Yakimenko[6]

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AIP Conference Proceedings

Betatron radiation from a beam driven plasma source

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Published Online: 21 December 2012

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Betatron radiation based diagnostics for plasma wakefield accelerated electron beams at the SPARC_LAB test facility

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V. Shpakov[a,*], M.P. Anania[a], A. Biagioni[a], E. Chiadroni[a], A. Cianchi[a,b], A. Curcio[a], S. Dabagov[a,c,d], M. Ferrario[a], F. Filippi[a], A. Marocchino[e], B. Paroli[f], R. Pompili[a], A.R. Rossi[f], A. Zigler[g]

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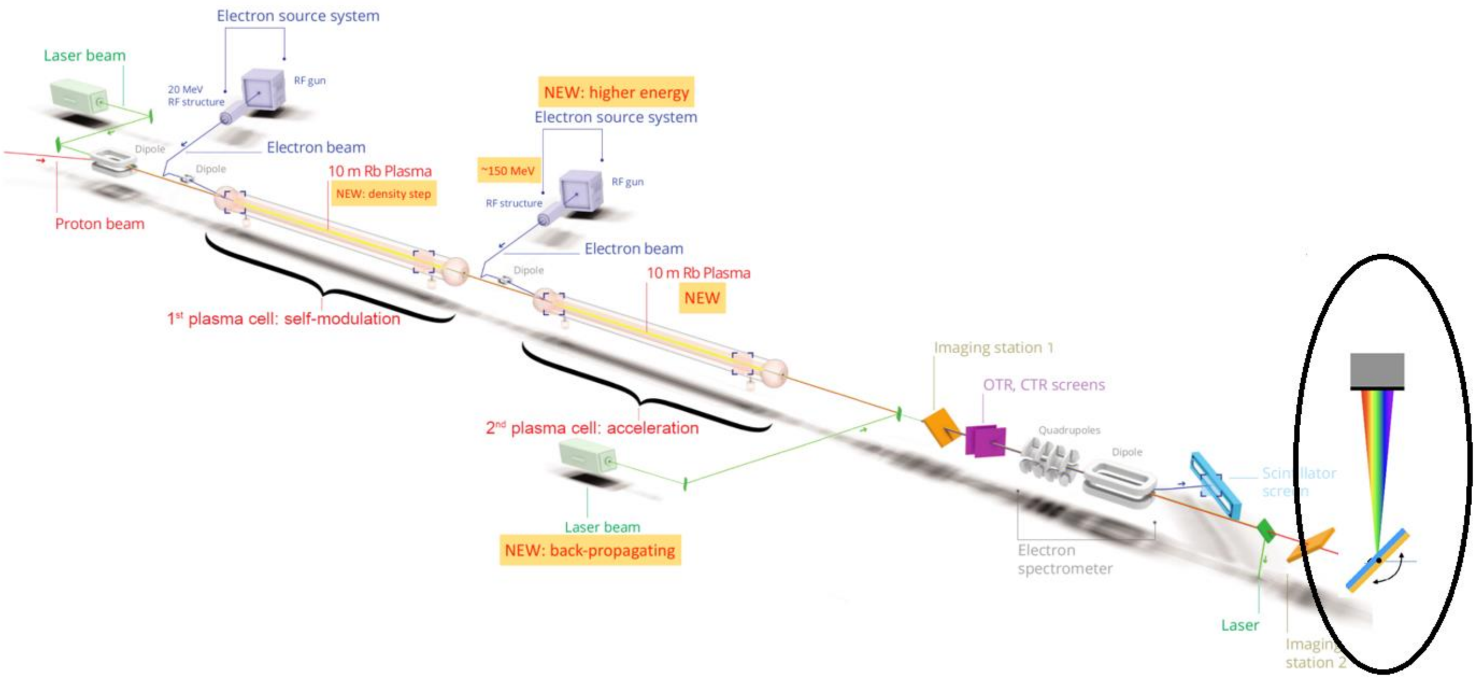
Research and application of Betatron diagnostics in BELLA, FACET, SPARC_LAB …

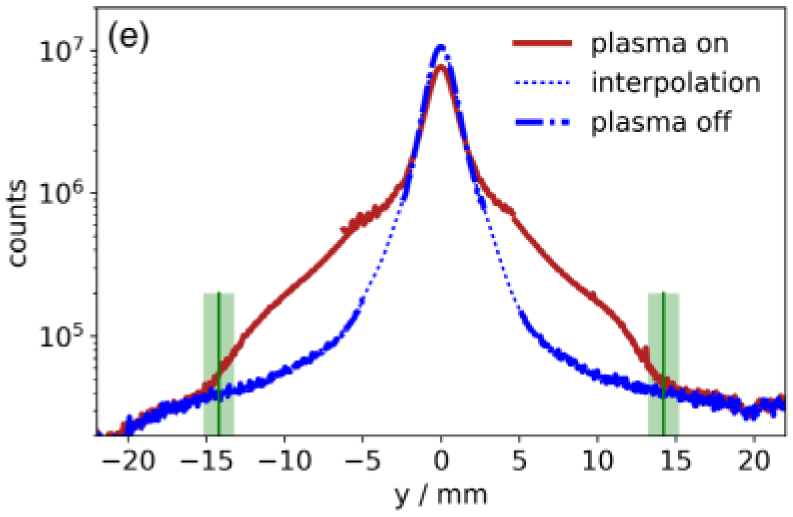
Propose betatron diagnostics in AWAKE

- Diagnose injection misalignment (e.g., beam phase-matching; beam off-axis injection)
  - L. Liang- et al, 'Characteristics of betatron radiation in AWAKE Run 2 experiment' J Plasma Phys. 89, 965890301(2023)

- Experimental proposal for betatron spectroscopy in AWAKE
  - B. Williamson, et al. NIMA **971**, 64076 (2020)

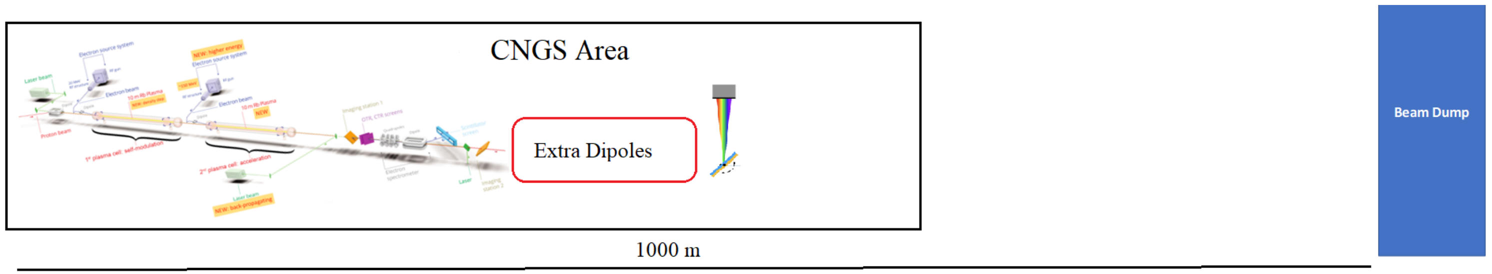


M. Turner (AWAKE Collaboration), PRL 122, 054801 (2019)



- The proton beam diverges to a radius of 15 mm after traveling 10 meters beyond the plasma cell.

- In case of CNGS dismantling, there would be room to divert the proton beam.



- Three dipoles, similar to the Run1 spectrometer, may be necessary to deflect the proton beam by more than 15 mm over a distance of 10 meters.

$$\theta = \frac{\mathrm{L[m]B[T]c}}{\mathrm{E[eV]}}$$

X-ray detector

- The primary radiation will be in the X-ray spectrum.
- Various types of X-ray detectors exist, encompassing gas detectors etc.
- Based on factors such as spectral coverage, energy resolution, spatial resolution, sensitivity, and price, we can select a suitable X-ray detector for procurement in the future.

Betatron radiation beyond AWAKE Run 2

What if we utilize higher plasma densities?

Elevating electron energy gain and betatron X-ray emission in proton-driven wakefield acceleration

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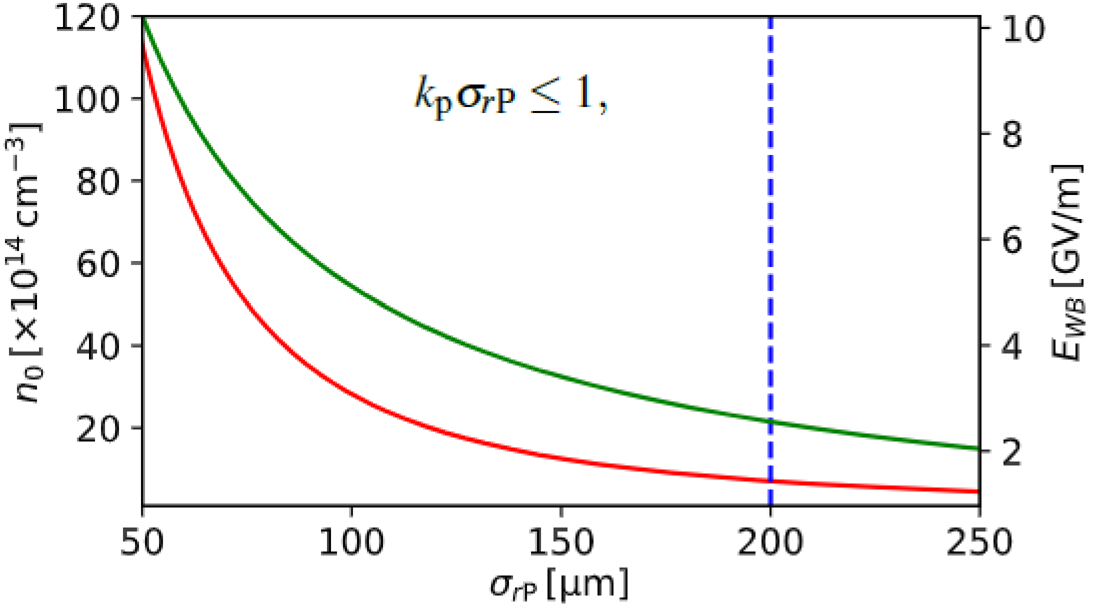
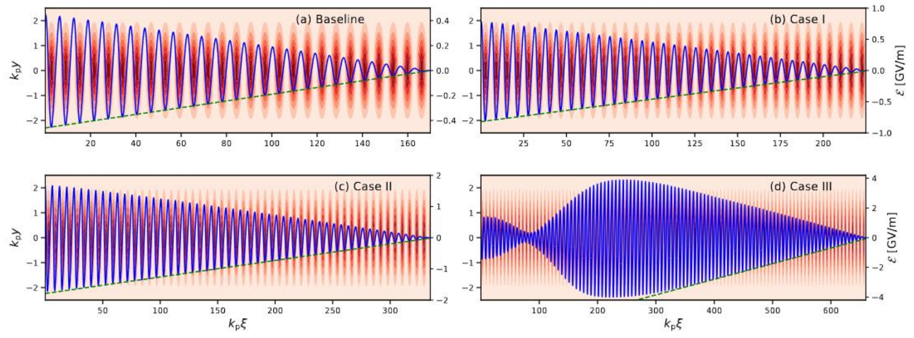
(*Electronic mail: hossein.saberi@manchester.ac.uk.)

(Dated: 6 March 2024)

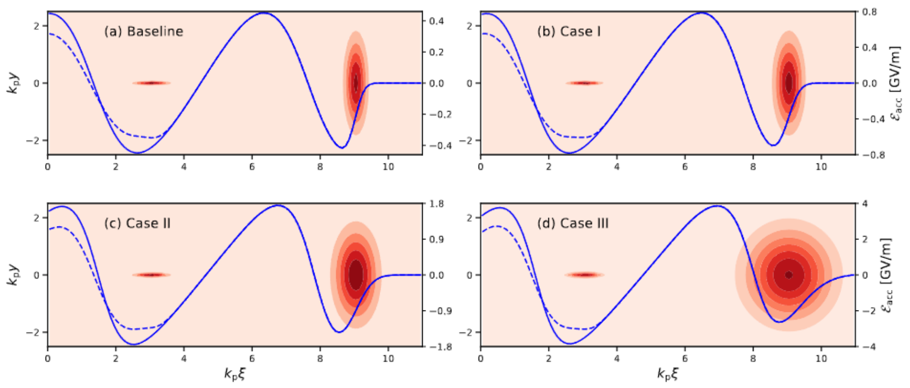


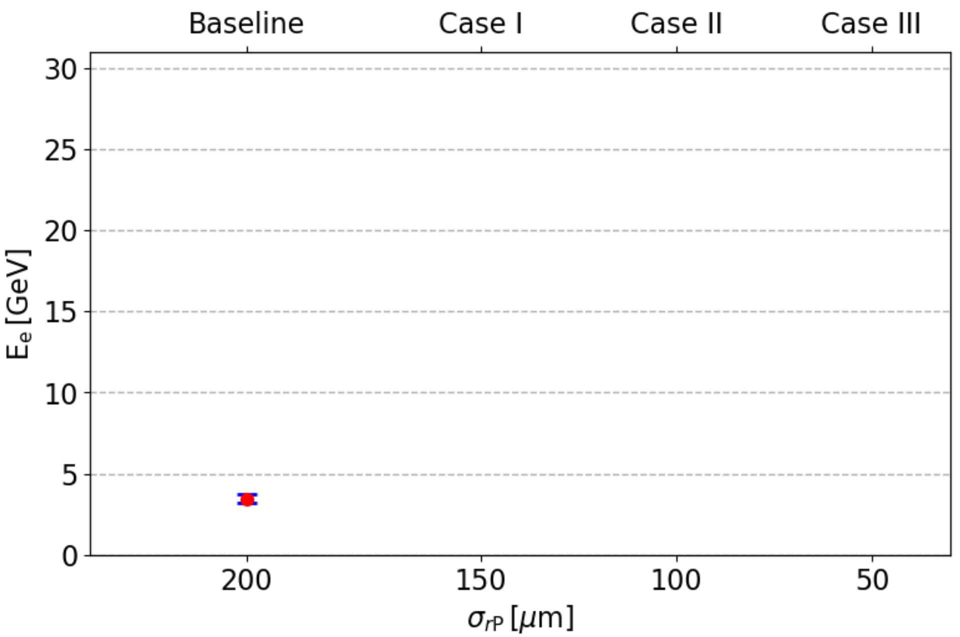
Plasma parameter	Symbol [Unit]	Baseline	Case I	Case II	Case III
Skin depth	[μm]	200	150	100	50
Density	$n_0\,[\mathrm{cm}^{-3}]$	7×10^{14}	1.25×10^{15}	2.80×10^{15}	1.13×10^{16}
Wavelength	λ_p [mm]	1.26	0.94	0.63	0.31
Length	[m]	10	10	10	10

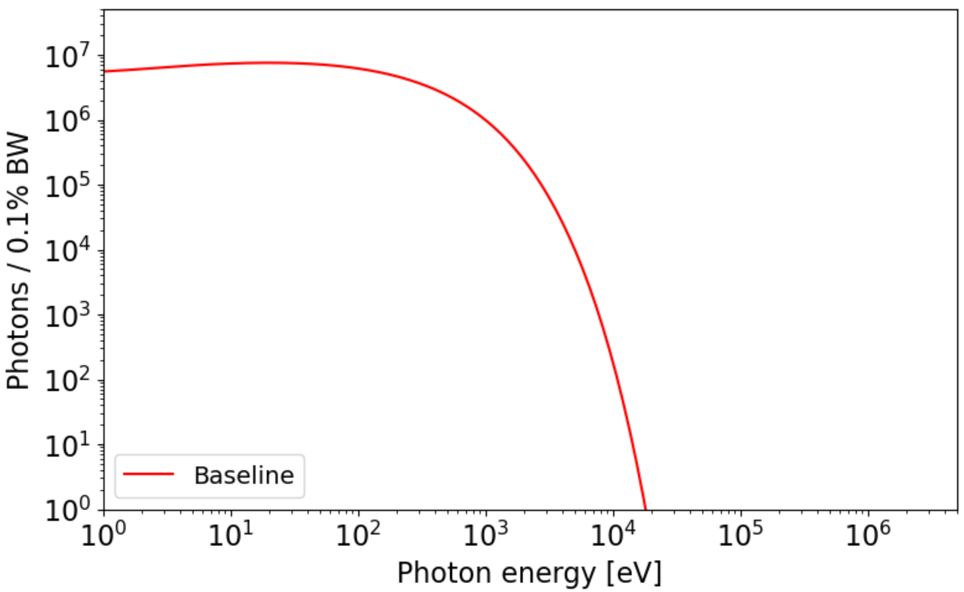
- Step 1. Calculate the peak wakefield by considering a fixed current and length of periodic train of bunches

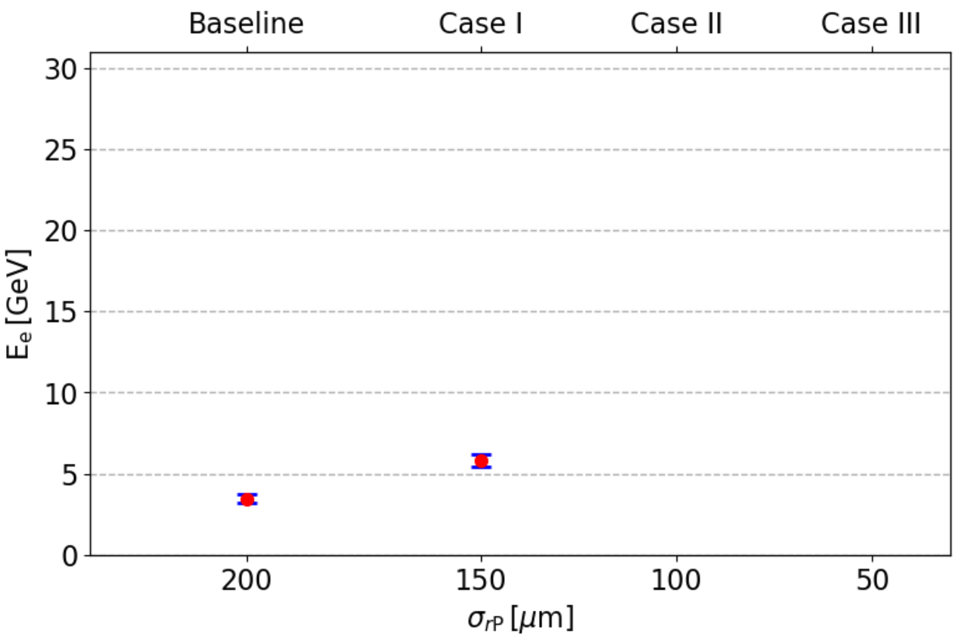


- Step 2. Study witness beam acceleration and radiation within the toy model simulation




Baseline
Case I
Case II
Case III
30
25
20
15
10
5
0
E_e [GeV]
200
150
100
50
σ_{rP} [μm]


10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Photons / 0.1% BW
Baseline
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Photon energy [eV]


Baseline
Case I
Case II
Case III
30
25
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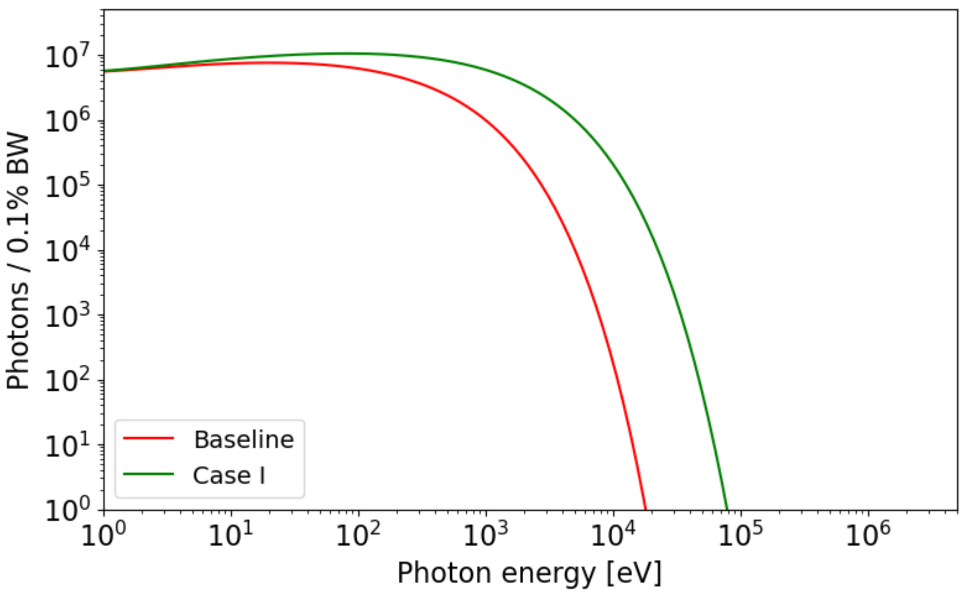
15
10
5
0
E_e [GeV]
200
150
100
50
σ_{rP} [μm]


10^7
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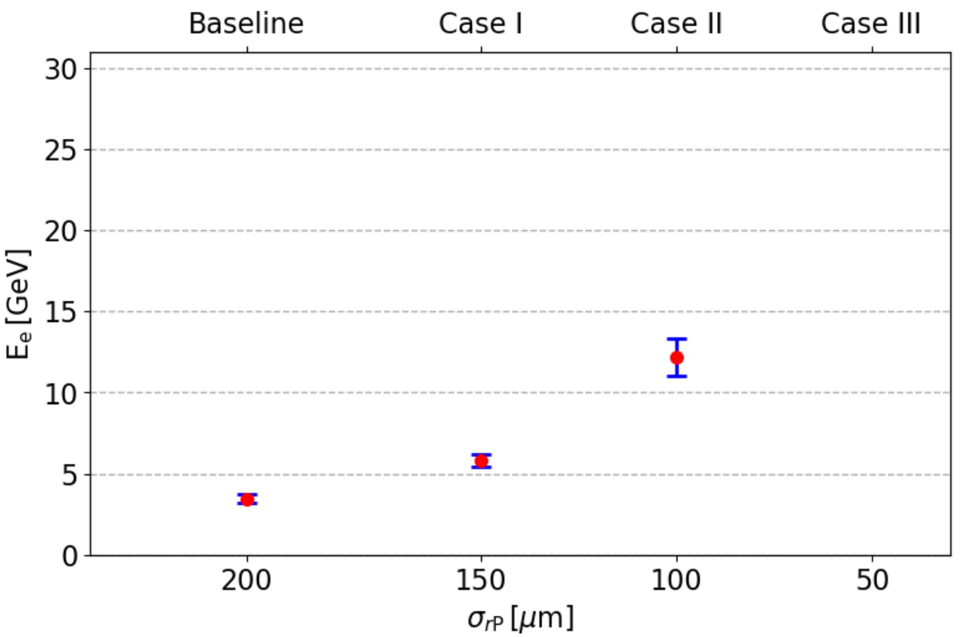
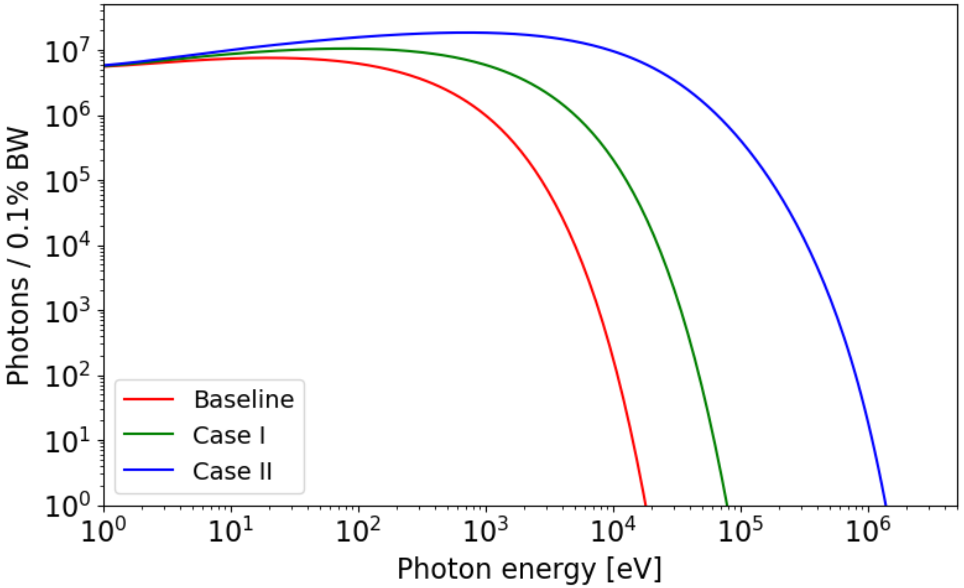
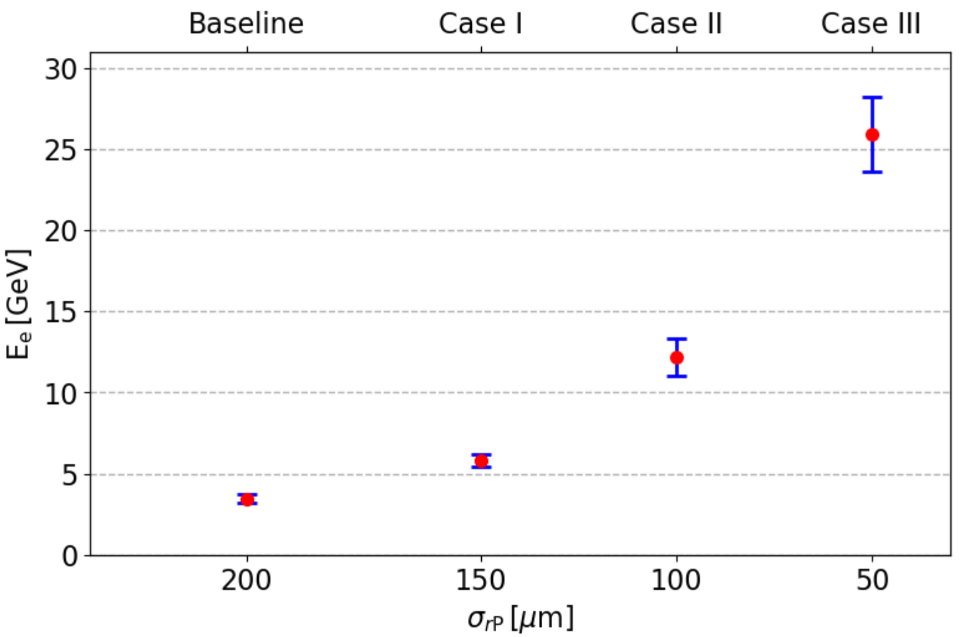
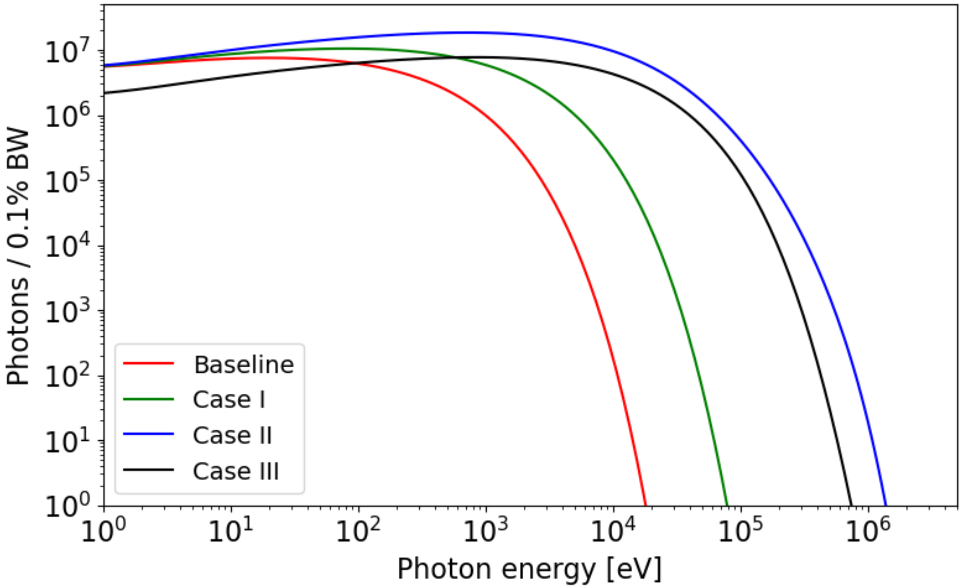
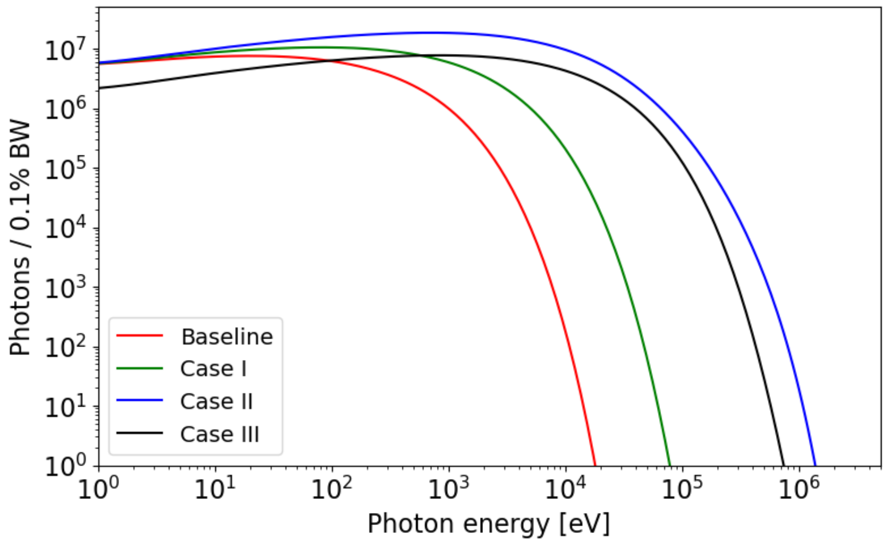
10^3
10^2
10^1
10^0
Photons / 0.1% BW
Baseline
Case I
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Photon energy [eV]


Baseline
Case I
Case II
Case III
E_e [GeV]
σ_{rP} [μm]


Photons / 0.1% BW
Photon energy [eV]
Baseline
Case I
Case II


Baseline
Case I
Case II
Case III
30
25
20
15
10
5
0
E_e [GeV]
200
150
100
50
σ_{rP} [μm]


10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Photons / 0.1% BW
Baseline
Case I
Case II
Case III
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Photon energy [eV]



We may seek the unexpected pattern in Case III in its lower charge and radius which has root in non-linear effects of wakefield decay.

Electron Witness					
Density	n_e/n_0	34.1	32.7	32.3	18.5
Charge[b]	Q_e [pC]	120	115	113	65
Bunch Length[c]	$\sigma_{\xi e}$ [μm]	60	45	30	15
Bunch Radius[d]	σ_{re} [μm]	5.75	4.98	4.07	2.87

Conclusion

Summary

- ❖ Explore betatron radiation characteristics in-depth.
- ❖ Propose potential applications of betatron diagnostics at AWAKE.
- ❖ Conduct a preliminary design study for betatron spectroscopy at AWAKE, addressing associated concerns.
- ❖ Perform a simulation study on utilizing a shorter proton beam driver and consequently higher plasma density.

Moving Forward: The Next Step

- Develop the models for electron beam reconstruction from the radiation.
- Conduct a detailed study on experimental design, including potential procurement of necessary tools.
- Initiate collaborations with laboratories such as CLARA, CLEAR, and SPARC_LAB for preliminary testing.
- Ultimately, construct and deploy diagnostics applications for the AWAKE Run 2c.

Backup slides

Periodic train driver

- For all scenarios, we consider a non-evolving beam comprising 1.62e10 particles, with a length of 65.6 mm, organized as a periodic train of microbunches.

- This periodic train driver has a period of plasma wavelength.

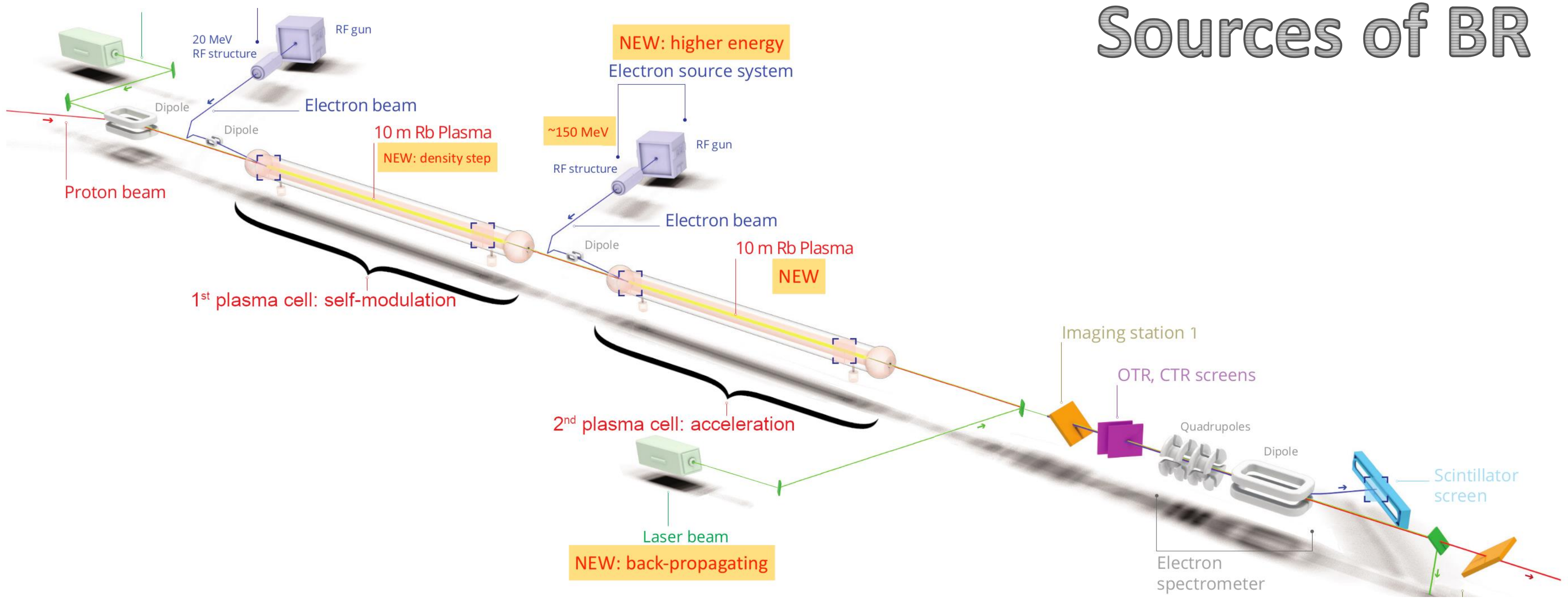
$$k_p \sigma_{rP} \leq 1,$$

$$k_p \sigma_{\xi mb} = \sqrt{2},$$

TABLE II. Microbunch parameters in the periodic train driver.

Parameter [Unit]	Baseline	Case I	Case II	Case III
No. Microbunch	26	35	52	104
Length [μm]	283	213	142	71
Radius [μm]	200	150	100	50
Charge [pC]	100	75	50	25

Sources of BR



1) Witness electron beam
2) Seeding electron beam
3) Proton beam
4) Background plasma electrons

Beam emittance and the radiation spectrum