Photon Energy Booster of X-ray Free Electron Lasers through Compact Beam-driven Plasma Wakefield Acceleration

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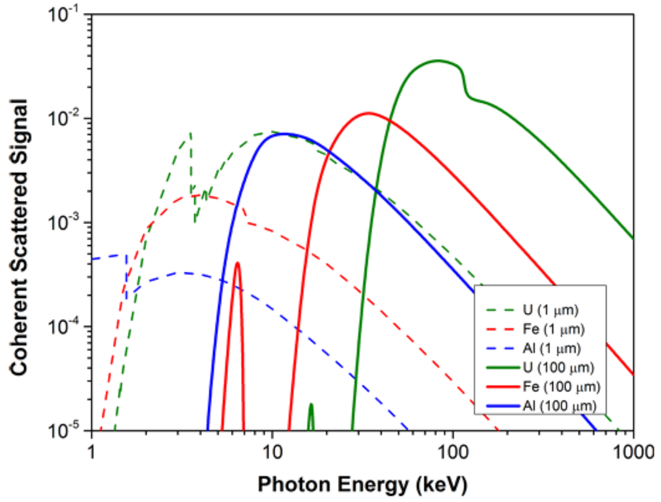
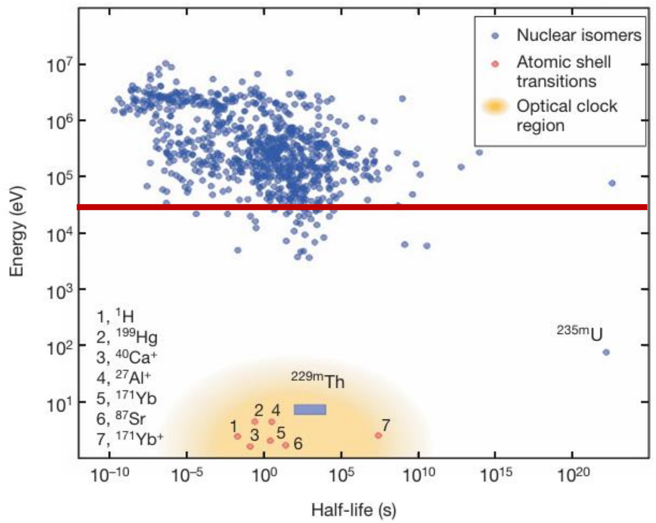
Why high-photon-energy XFEL?

- Laser: ~eV ⟹ XFEL: 0.1 keV to >20 keV
- >20 keV XFEL can do:
  - Coherent X-ray Diffraction Imaging (CXDI) on Mesoscale Materials
  - Nuclear Resonant Excitation (NRE) of suitable isomers…



CXDI: 100 μm Fe at 20 keV[1]



NRE: ^{73}Se (25 keV), ^{85}Y (20 keV)…[2]

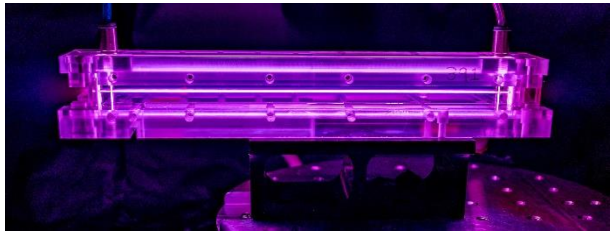
$$\hbar\omega_r \propto \gamma_e^2 \Longrightarrow$$ **Improve electron energy**

[1]Barber et al., Phys. Rev. B 89, 184105; [2]Wense et al., Nature 533, 47–51 (2016); Tuli, J. K. Nuclear Wallet Cards 8th edn (National Nuclear Data Center, Brookhaven National Laboratory, 2011).

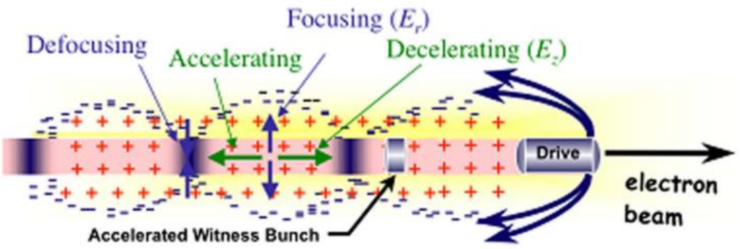
Plasma wakefield acceleration as a photon energy booster

lcls.slac.stanford.edu/overview

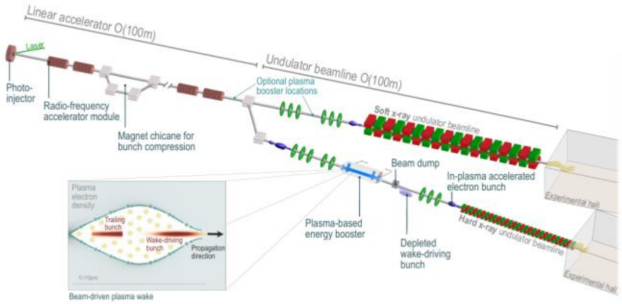
- RF Linac: limited to ~MV/cm, large size & high cost
- PWFA: High acceleration gradient ~GV/cm
- Two-bunch PWFA → embedded into XFEL facility as an energy booster[2]
- Demonstrate the feasibility of the scheme through detailed analysis and start-to-end simulations



LBNL: ~8 GeV in ~20 cm plasma[1]



Two-bunch PWFA



Schröder et al., arXiv: 2407.15583

[1]Gonsalves et al., Phys. Rev. Lett. 122, 084801 (2019); [2]Joshi et al., Plasma Phys. Control. Fusion 60(3), 034001;
[3]Schröder et al., arXiv: 2407.15583;

Two thresholds of FEL: $\varepsilon \lesssim \lambda_r/4\pi$ & $\Delta\gamma_e/\gamma_e < \rho$

$$\varepsilon \lesssim \lambda_r/4\pi$$

- ε_n is preserved by the linear focusing field in the plasma wake in PWFA

$$\Delta\gamma_e/\gamma_e < \rho \sim 10^{-4}$$

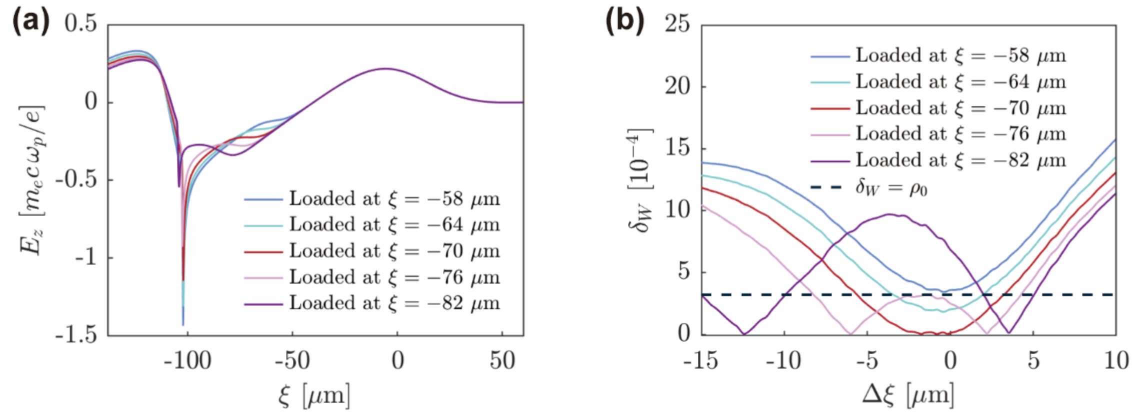
- Uniformity of E_z in the bubble
- Transverse: uniform
- Longitudinal:
  - Unloaded: $\mathrm{d}E_z/\mathrm{d}\xi \sim 1/2$

Can be flattened by beam loading[1]

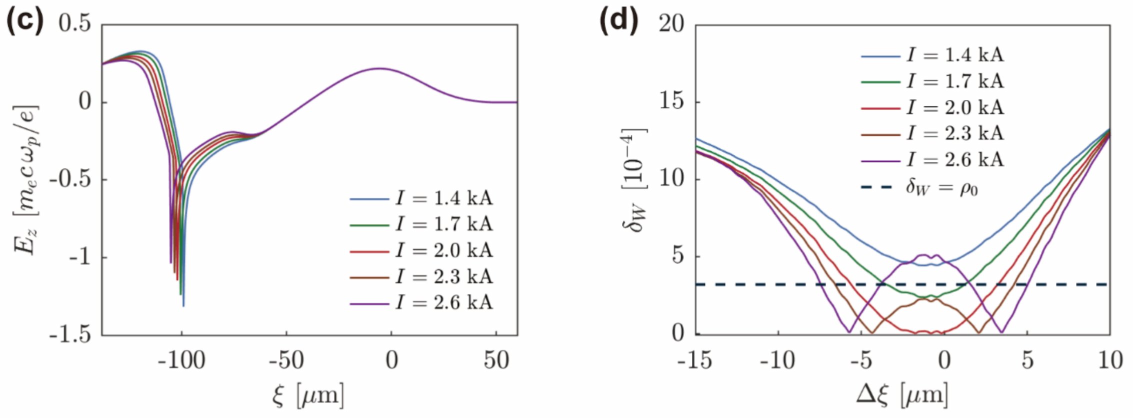
[1] Tzoufras et al., Phys. Rev. Lett. 101, 145002.

Find the optimum loading case

$\xi = z - ct, \quad \Delta\xi = \xi - \xi_w, \quad d_{slice} = 0.28\ \mu\text{m}$



Delay between Driver and Witness Δ from $58\ \mu\text{m}$ to $82\ \mu\text{m}$ ($I = 2\ \text{kA}$)



Peak current of Witness I from $1.4\ \text{kA}$ to $2.6\ \text{kA}$ ($\Delta = 70\ \mu\text{m}$)

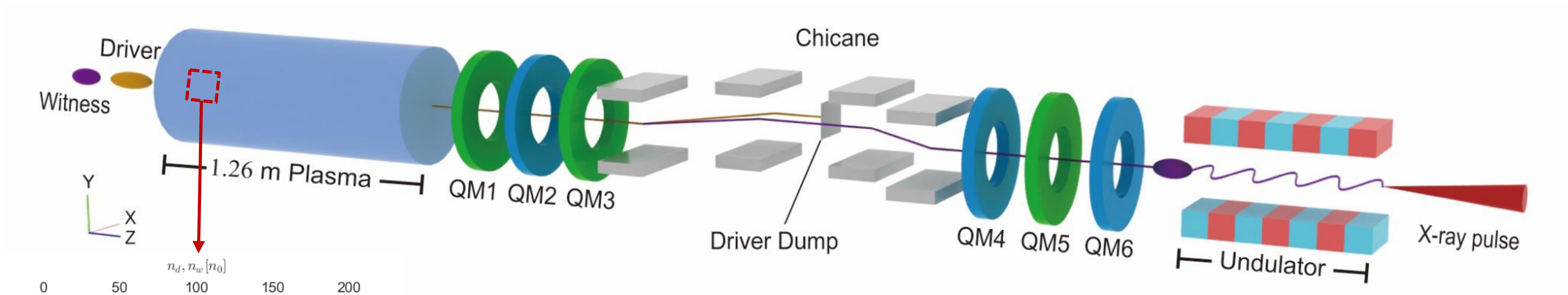
- E_z on axis from one-step PIC simulation by QuickPIC
- (b)(d) is calculated from (a)(c) using

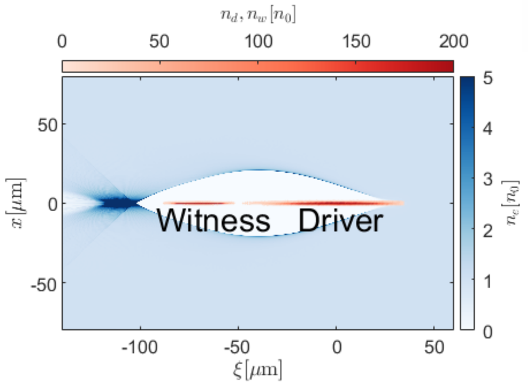
$$\delta_W = \frac{\Delta W}{W} = \frac{\Delta\gamma_e}{\gamma_e} = \left| \frac{1}{E_z}\frac{\mathrm{d}E_z}{\mathrm{d}\xi} d_{slice} \right| \cdot \frac{W - W_0}{W}$$

In case $\Delta = 70\ \mu\text{m}$ & $I = 2\ \text{kA}$ (red line), 53% (54 pC) of e^- meets $\delta_W < \rho_0$[1]

[1] ρ_0 represents the Pierce parameter ρ at peak current $I = 2\ \text{kA}$.

Start-to-End Simulation Setup





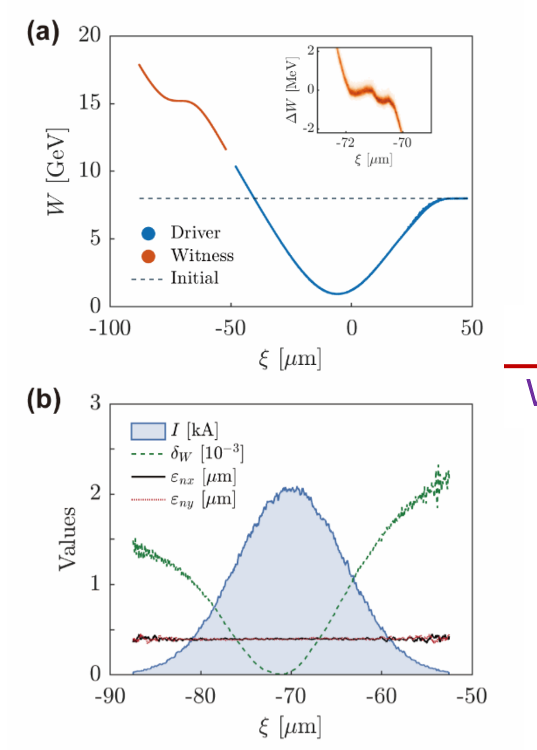
- Transport Line: ELEGANT
  - Chicane: dump the Driver
  - Match Witness to the undulator
- Undulator: GENESIS1.3
  - $\lambda_u = 2\ \text{cm}, B_0 = 1.5\ \text{T}\ (K = 2\sqrt{2})$
- PWFA Parameters：QuickPIC

	W[GeV]	σ_W[keV]	I[kA]	Q[pC]	ϵ_n[μm]	$\xi_{d,w}$[μm]	σ_r[μm]
Driver	8	80	2	269	1.2	0	0.52
Witness	8	80	2	103	0.4	70	0.3

Plasma (Li): $n_0 = 7 \times 10^{16}\ \text{cm}^{-3},\ L_{acc} = 1.26\ \text{m}$

Key Results

Witness at the exit of the plasma:

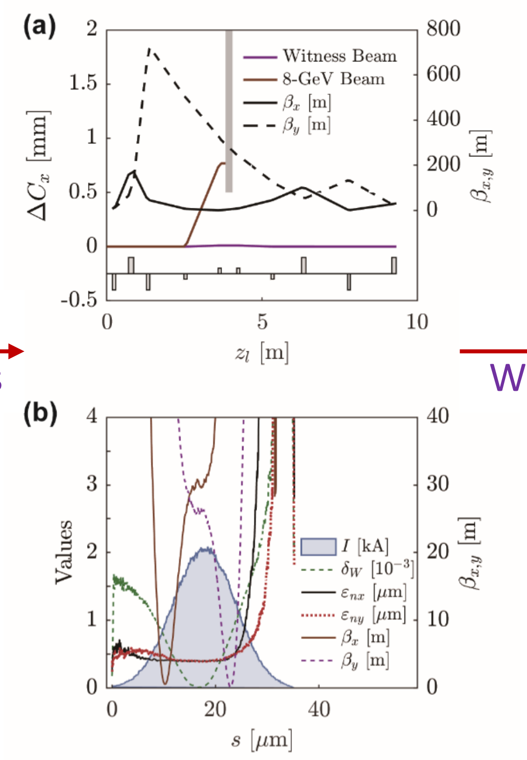


- Gain: 7.2 GeV in 1.26 m
- 49% of e^- meets $\delta_W < \rho$
- Positively chirped

Driver

Witness

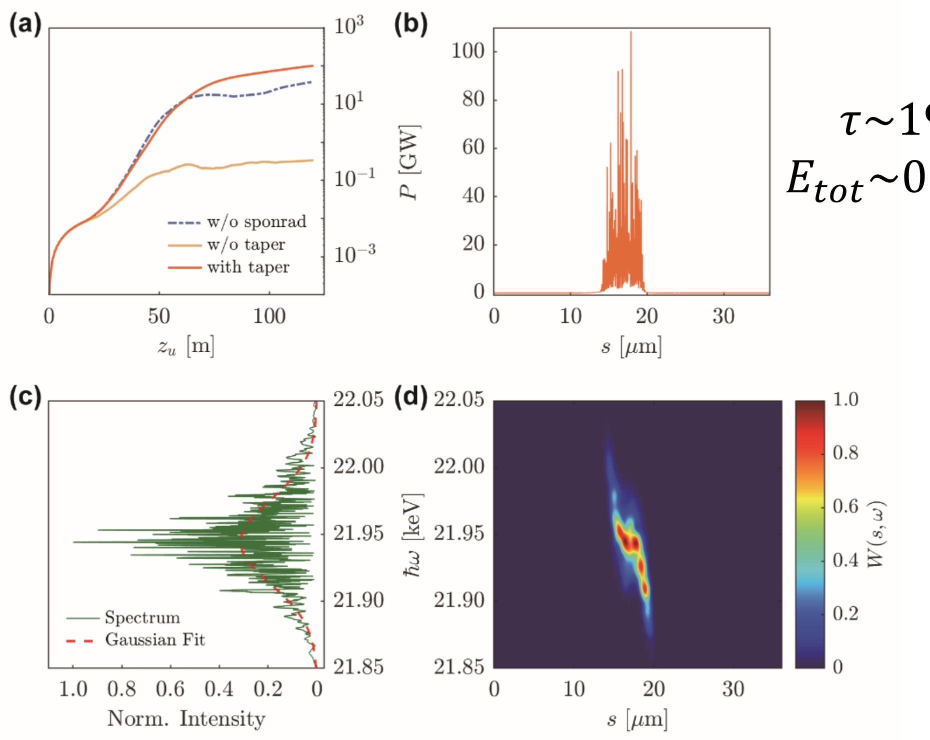
Transport Line & Driver dump



- $\Delta C_x \sim 0.7$ mm
- Well matched
- Quality preserved

Witness

Radiation in the undulator by Witness:



$\tau \sim 19$ fs

$E_{tot} \sim 0.25$ mJ

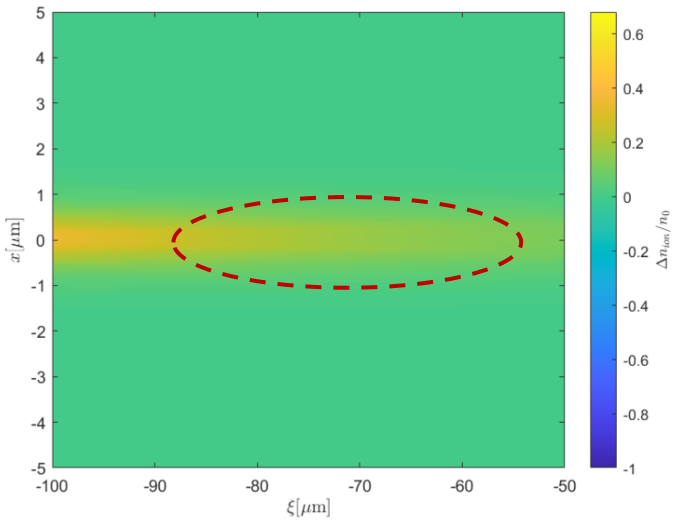
- A 22-keV pulse with 3.6 times boost in $\hbar\omega_r$
- $L_g \sim 5$ m, $P_{sat} \sim 100$ GW ($L_u \sim 120$ m)
- FWHW $= 0.3\% \longrightarrow$ Positively chirped

Conclusions

- Beam-driven Plasma Wakefield Acceleration can be utilized as a compact photon energy booster of X-ray Free Electron Lasers.
- Through optimization of the beam loading effects, nearly half of the electrons meet the two FEL thresholds.
- 7.2 GeV gain in the electron energy is achieved in a 1.26-m-long plasma, leading to a 3.6 times improvement in photon energy up to 22 keV, together with the saturation power over 100 GW.

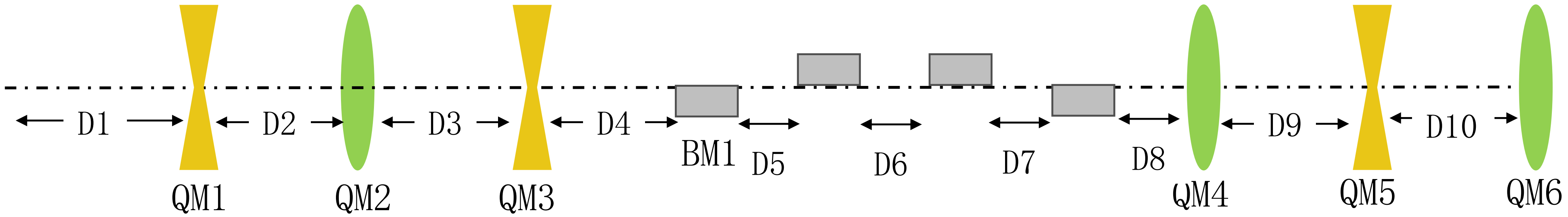
Thank you for listening!

Backup Slides-Ion Motion in PWFA



- The ion density changes due to the ultrahigh density of the Driver and Witness (~ 1000)
- It may cause:
  - Transverse: nonlinear focusing field $\rightarrow \ \varepsilon_n \uparrow$
  - Longitudinal:$\partial_z F_r = \partial_r F_z \rightarrow \delta W \uparrow$
- Critical density: $n_d/n_0 \gg m_i/m_e$
- Lithium is used to suppressed the ion motion
- $\varepsilon_n \uparrow$ and $\delta W \uparrow$ is negligible in our setup

Backup Slides-Transport Line



Quadrupole Magnet and drift

QM	QM1	QM2	QM3	QM4	QM5	QM6
l/m	0.11	0.16	0.11	0.13	0.08	0.13
k/m^{-2}	-13.1	15.1	-13.1	6.7	-7.7	6.7

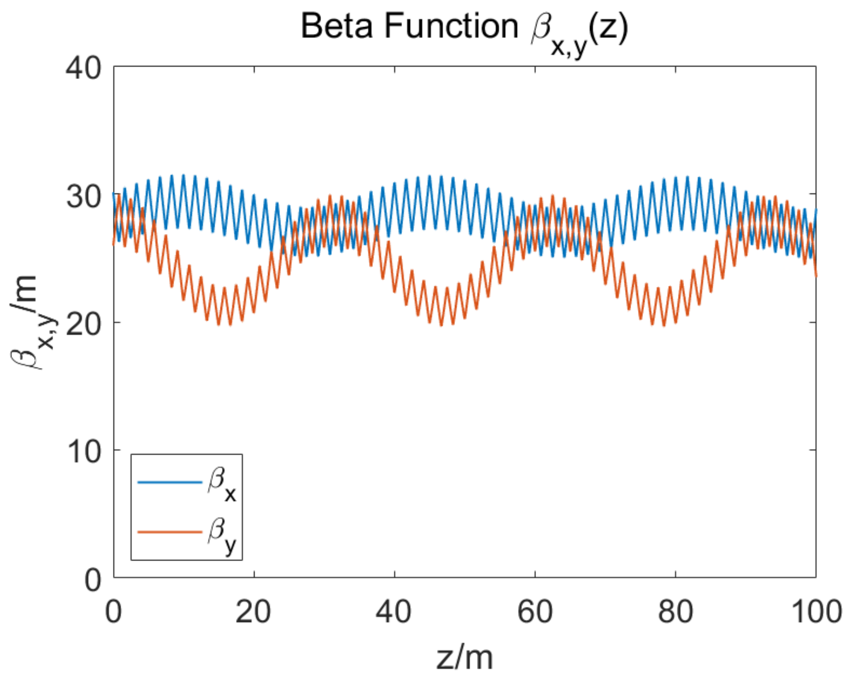
D	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
L/m	0.18	0.41	0.41	1.1	1	0.5	1	0.89	1.3	1.3

Dipole

BM	BM1	BM2	BM3	BM4
L/m	0.1	0.1	0.1	0.1
θ	-10^{-3}	10^{-3}	10^{-3}	-10^{-3}

Backup Slides-FODO lattice

- FODO lattice was designed with
  - $k = 1.79\ \mathrm{m}^{-2}$, $l = 0.04\ \mathrm{m}$, $L = 2\ \mathrm{m}$



Backup Slides-Tapering

- The spontaneous radiation will cause an average energy loss to the electron beams.
- Can be compensated via Tapering (In this setup, $a = -7.8 \times 10^{-5}\ \mathrm{m}^{-1}$)