Applications of Beam-Driven Plasma Wakefield Accelerators

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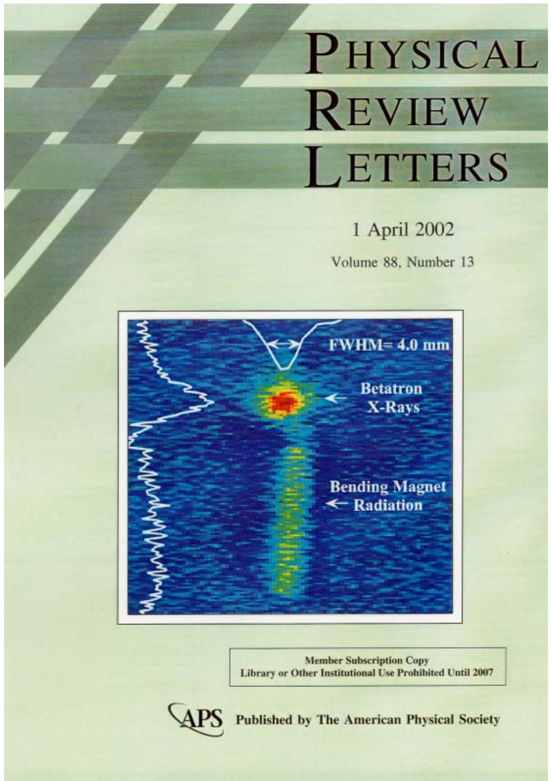
Overview

• Beam-Driven Plasma Wakefield Accelerators have demonstrated in meter-scale plasmas:

- Accelerating gradients E_z~50 GV/m
- Focusing gradients dB_θ/dr~10^6 T/m



Potential Applications

•"Afterburner" to significantly raise x-ray energy of an existing XFEL without a large-scale linac upgrade

• Ion Channel Laser (Whittum, Sessler & Dawson, 1990)

- •High-K regime: Hyper-spectral sources: THz (CTR) to Gamma Rays (Betatron Radiation)
  - ➔Early BD-PWFA experiments demonstrated x-ray production from betatron motion of mismatched beam in plasma
- •Low-K regime: plasma "undulator", more monochromatic
  - ➔FACET will study offset witness beam production of narrowband radiation as a variant of planned acceleration experiments

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Afterburner Case Study: FERMI@Elettra FEL

- FERMI@Elettra is a single-pass FEL user-facility located next to the third-generation synchrotron radiation facility ELETTRA in Trieste, Italy.
- Our Goal: Study using existing linac, undulators and civil footprint.
- Start from FEL-1 and find a self consistent set of parameters for beam and undulator that boost energy by two and get 20nm down to 5nm.

Parameter	FEL-1	Units
Wavelength	100-20	nm
Electron Beam Energy	1.2	GeV
Bunch Charge	0.8	nC
Peak Current	850	A
Bunch Length (FWHM)	400	fs
Norm. Emittance (slice)	0.8-1.2	mm-mrad
Energy Spread (slice)	150-250	keV
Repetition Rate	10-50	Hz

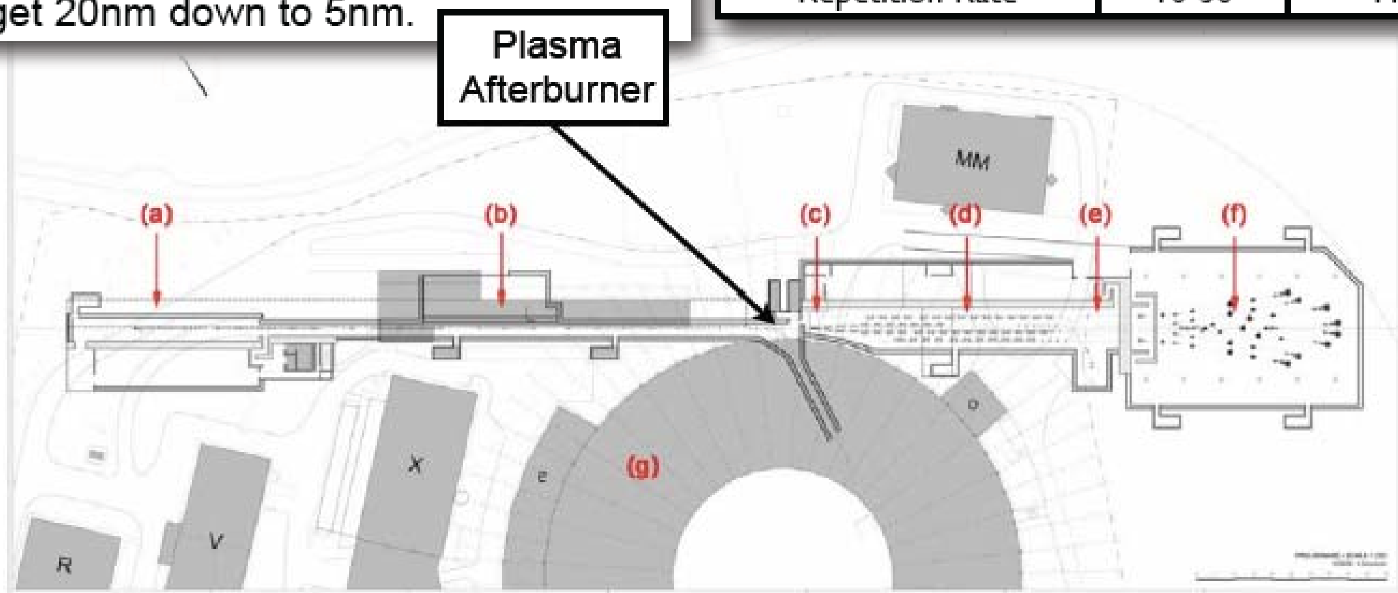


Figure 1: Schematic FERMI layout beside the ELETTRA storage ring building (g). See text for details.

Slide from Mark Hogan, SLAC

Afterburner Concept and Example

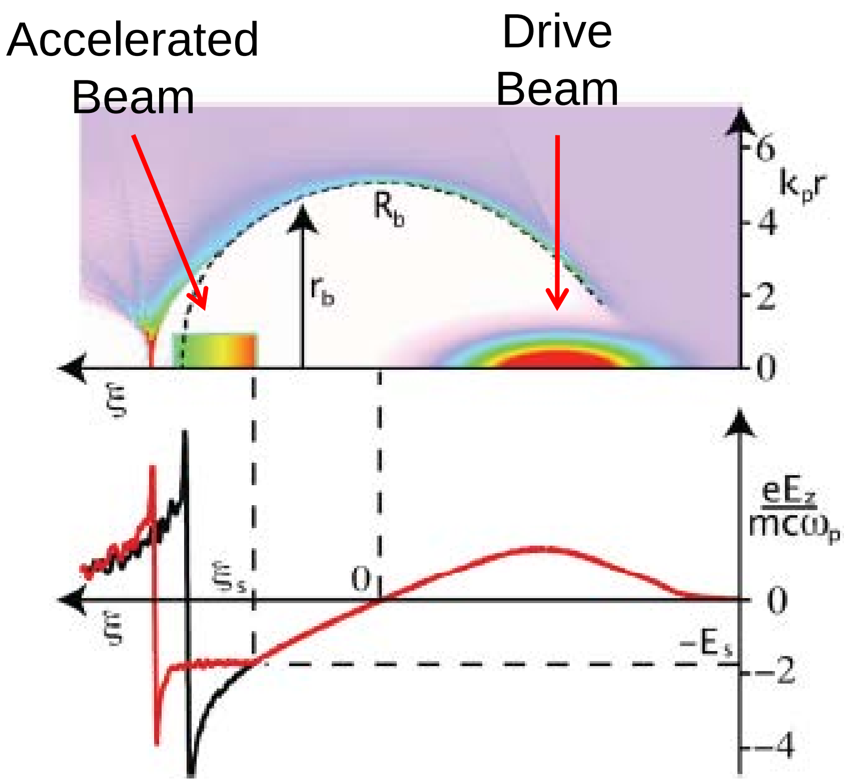
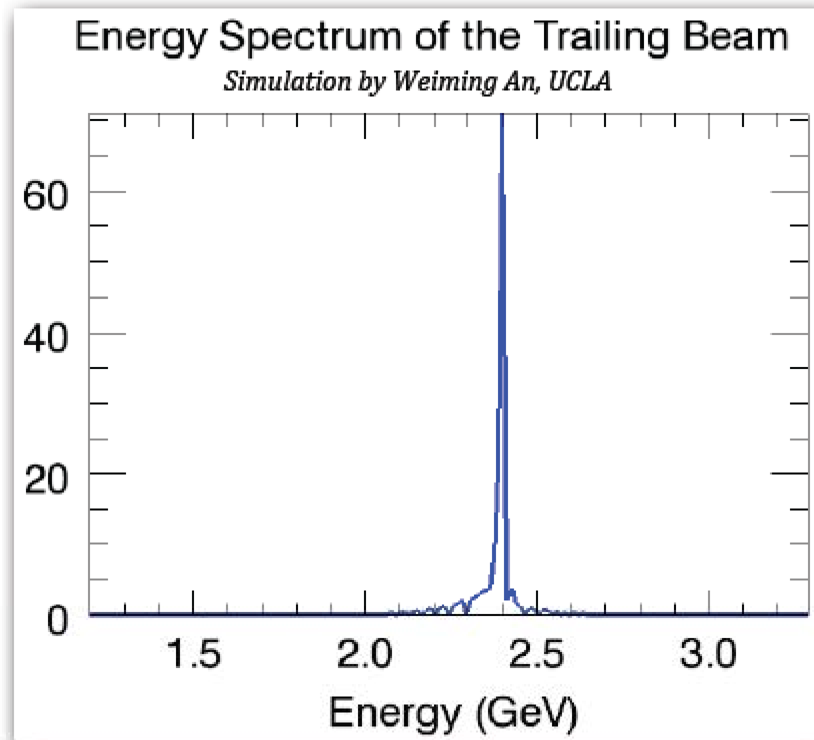


FIG. 1 (color online). The electron density from a PIC simulation with OSIRIS [19] for $k_p R_b = 5$ is presented. The beams move to the right. The broken black line traces the blowout radius in the absence of the load. On the bottom, the red (black) line is the lineout of the wakefield $E_z(\xi, r_b = 0)$ when the beam load is present (absent).

M. Tzoufras *et al*, *Phys. Plas*. **16**, 056705 (2009).

Preliminary simulation by Weiming An, UCLA

- Drive = 0.75 nC, witness= 0.25 nC
- Bunch lengths: 6 μm, 2 μm
- Plasma density 10^{18}/cc
- Drive/witness separation 32 microns
- $dE/E|_{rms}$ ~ 0.34%



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Parameters for an Afterburner for FERMI@Elletra

	Parameter	Units	Short Wavelength FEL I	Afterburner Upgrade
Upgrade	Energy Multiplication			2
	Witness Bunch Charge	nC		0.25
	Drive Bunch Charge	nC		0.75
	Witness Bunch Length	μm		1.7
	Drive Bunch Length	μm		7.5
	Bunch Separation	μm		32
Beam	Bunch Charge	nC	0.8	0.25
	Bunch Energy	GeV	1.2	2.4
	Projected Energy Spread	%	0.06	0.34
	Normalized Emittance	mm-mrad	0.8	1.47
	Peak Current	kA	0.85	17.65
Undulator (Planar NdFeB)	Period	cm	6.5	6.5
	Undulator K		2.4	2.4
	FODO Period	m	7.6	7.6
	Max Beta	m	9	5
	Undulator Length	m	22.8	22.8
Radiation Parameters	Wavelength	nm	20	5
Calculated Using	Saturation Length	m	23.15	18.5
PSI PARMS Spreadhseet	Gain Length	m	1.1	0.84
Incorporates Ming Xie	Photons per bunch		2.00E+14	5.00E+13
3D FEL Formalism	Output Power	GW	2.3	130
	Bandwidth	%	1.25	2.8

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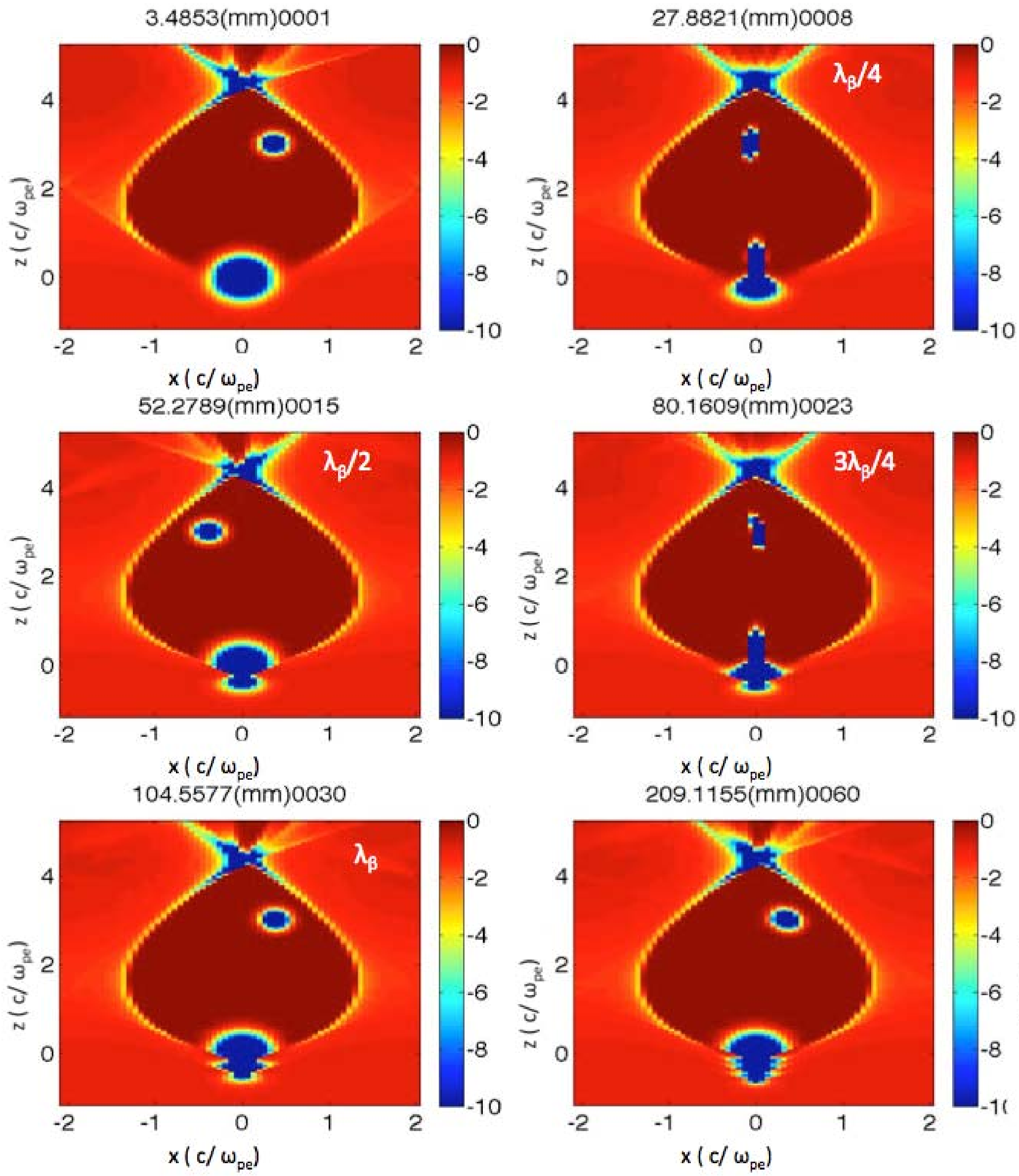
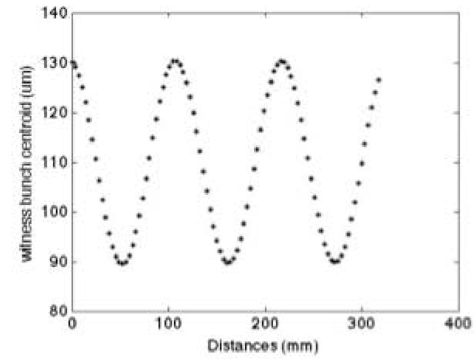
Radiation Generation from Offset Witness Beam

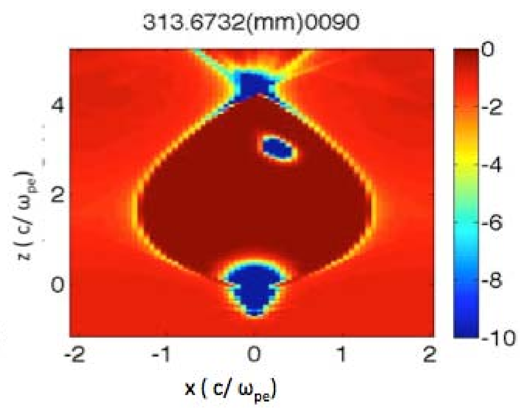
Yi Shi, USC student of Patrick Muggli





For the witness bunch:

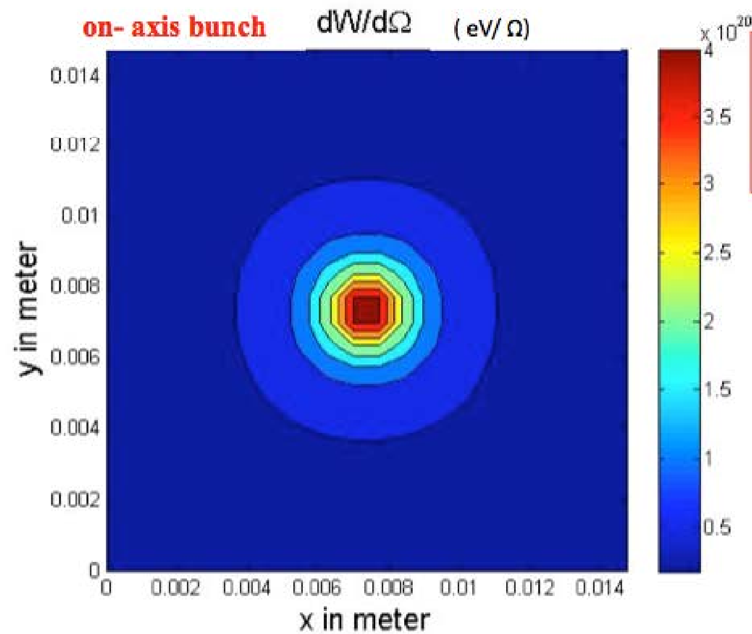
- oscillate like a “Macro” electron
- oscillate with betatron period, λ_β10.4 cm
- focused along betatron trajectory
- different numbers of betatron oscillations along the bunch $\omega_\beta = \frac{\omega_{pe}}{\sqrt{2\gamma}}$



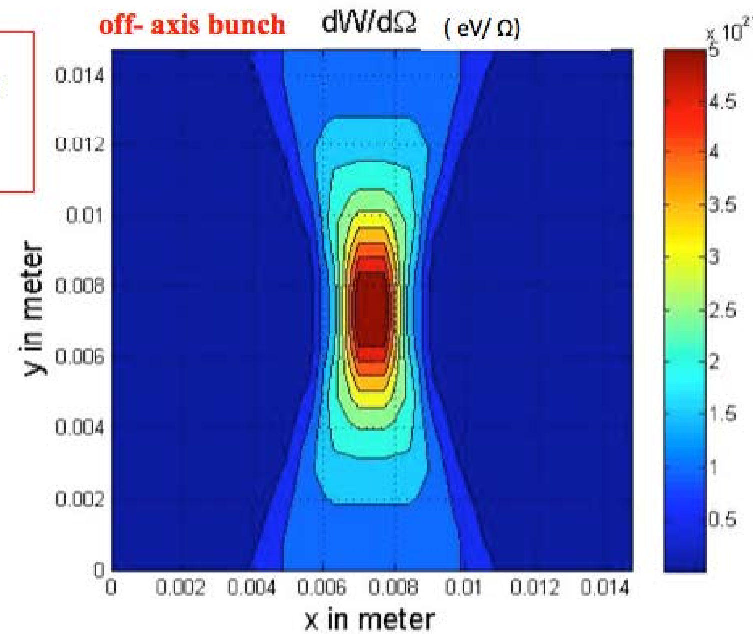
Saddle Point Calculation of Intensity

Yi Shi, USC student of Patrick Muggli

Radiation pattern (integrated in frequency)



E 28.5GeV
n_e 1e17 cm^{-3}
σ_r 5μm
r_c 10μm



- Saddle- point method, $\frac{d^2W}{d\omega d\Omega} = \frac{e^2\omega^2}{4\pi^2 c} \left| \int_{-\infty}^{\infty} \vec{n} \times (\vec{n} \times \overline{\beta(t)}) e^{i\omega(t - \vec{n}\cdot\vec{r}(t))} dt \right|^{2*}$ is simplified as

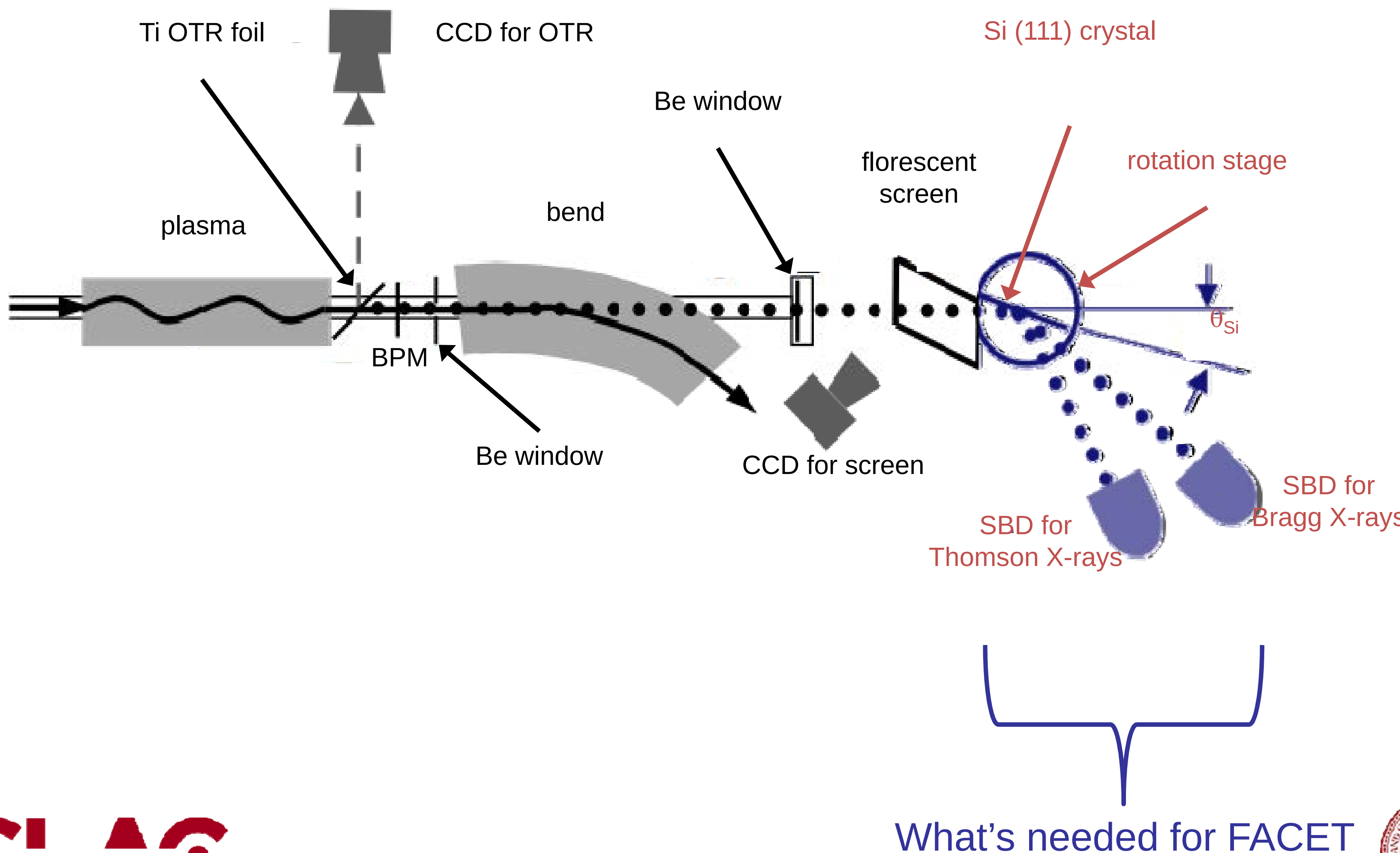
$$\frac{d^2W}{d\omega d\Omega} = 2N_0 \frac{e^2\eta^2\rho^2\chi^2}{3\pi^2 c}\left[\frac{\sin^2\theta\sin^2\phi}{\chi} K^2_{1/3}(q) + K^2_{2/3}(q)\right]^{**}$$, N_0 betatron oscillation number, $\rho = \sqrt{\frac{2\gamma_z}{p_x^2/\gamma_z^2 - \sin^2\theta\cos^2\phi}}$

$$\chi = \gamma_z^{-2} + \sin^2\theta\sin^2\phi, \quad q = \frac{1}{3}\eta\rho\chi^{3/2}$$

- Off-set pattern radiates more
- In future experiments, total power will be a combined radiation of on-axis drive bunch + off-axis witness bunch

* J. D. Jackson, *Classical Electrodynamics* 197 **I.Kostyukov, *Phys. Of Plasmas* 2003

Extending the FFTB Experiments to the Witness Bunch Case at FACET



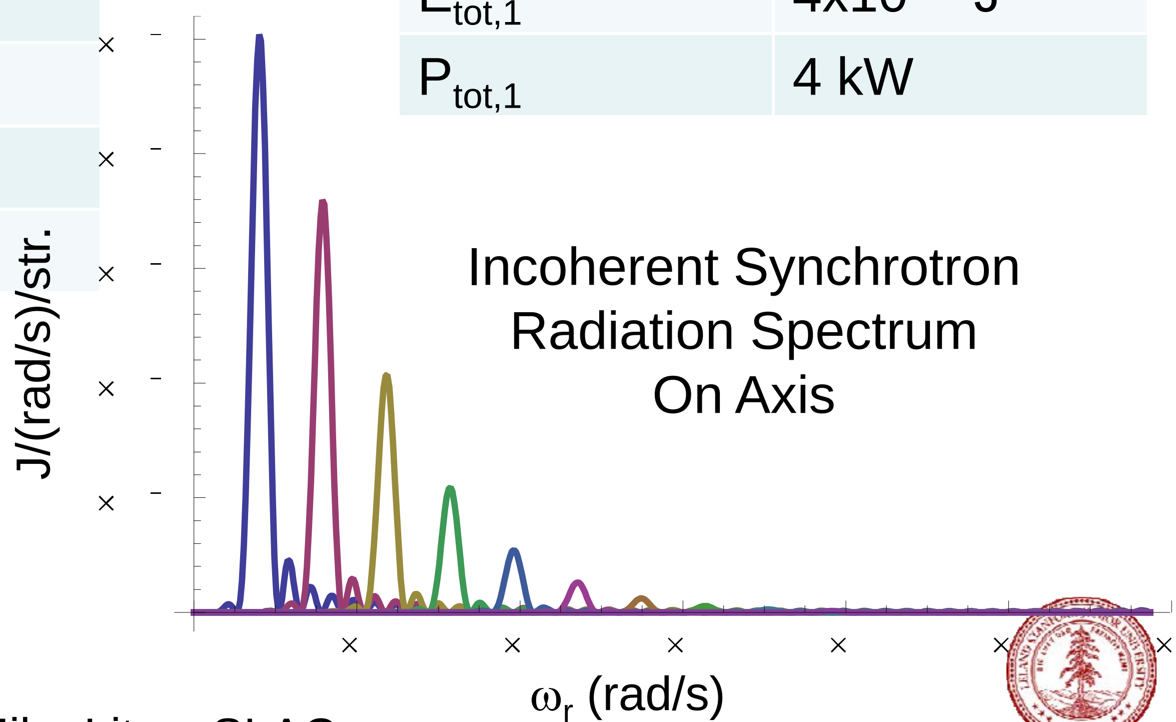
*S. Wang, et al., PRL **88**, 135004 (2002)*

Operation as an Undulator Requires a Different set of Operating Parameters

Parameter	Value
n_p	2×10^{13} cm^{-3}
σ_r	5 µm
N_e	10^9
γ	1000
r_0	50 µm
L_p	1 m
K	0.94
M_0	1.4×10^6

Parameter	Value
λ_1	240 nm
$\Delta\lambda_1$	80 nm
$N_{\gamma,1}$	5×10^8 photons
$E_{tot,1}$	4×10^{-10} J
$P_{tot,1}$	4 kW

$$\frac{d^2 I}{d\omega d\Omega}$$



Mike Litos, SLAC

Summary

- The performance requirements for High Energy Physics and Photon Science applications of Beam-Driven PWFA are compatible:
  - High peak current, small dE/E, low emittance, excellent stability, cost effectiveness…

- The demonstrated ability to sustain GV/m and MT/m gradients on the meter scale will enable novel x-ray and THz sources to be developed

- A BD-PWFA based afterburner offers a very compact upgrade path for linac XFELs to extend energy reach