Betatron radiation as bright hard x-ray source and effective diagnostic for plasma acceleration experiments

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Summary

Betatron Radiation: Generalities

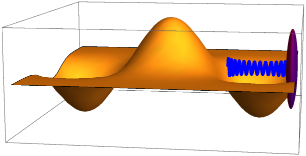
Compact Plasma Undulators

Experimental activity at Sparc-Lab

Conclusions

Plasma acceleration

Linear/Quasi linear regime

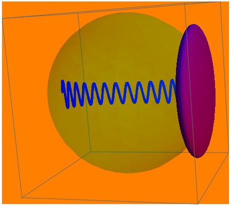


Plasma Wakefields:

$$E_z(r,\zeta) = \frac{\sqrt{\pi}}{4} a_0^2 k_p c\tau_0 E_0 \exp\left[\frac{2r^2}{w_0^2} - \frac{k_p^2 c^2 \tau_0^2}{4}\right] \cos k_p\zeta$$

$$E_r(r,\zeta) = -\sqrt{\pi} a_0^2 \frac{c\tau_0 r}{w_0^2} E_0 \exp\left[\frac{2r^2}{w_0^2} - \frac{k_p^2 c^2 \tau_0^2}{4}\right] \sin k_p\zeta$$

Bubble regime



Plasma Wakefields:

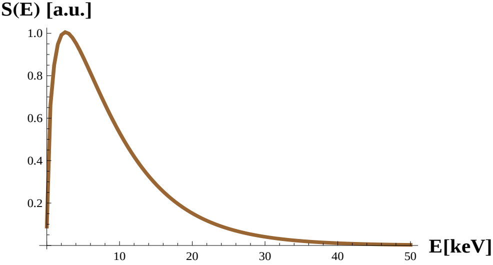
$$E_z(r,\zeta) = \frac{m}{3e}\omega_p^2 \zeta \cos k_p\zeta$$

$$E_r(r,\zeta) = \frac{m}{3e}\omega_p^2 r \sin k_p\zeta$$

Example of Betatron Radiation

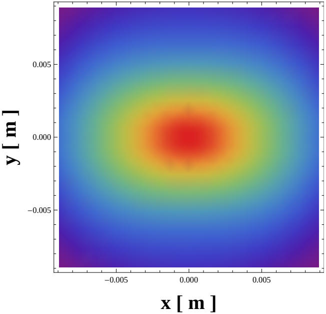
$I_0 \sim \times 10^{18} W/cm^2,\ \gamma_{max} \sim 1000,\ n_e = 5 \times 10^{17}/cm^3$

Betatron spectrum



Critical energy $E_c \sim 10\ keV$

Spatial distribution of the radiation



Radiation collected at 1 meter

Divergence

$\theta_\beta \sim \sigma k_\beta \sim 3\ mrad$

σ =bunch radius

Betatron oscillations/1

Electron dynamics: linear energy gain

$\gamma(z) \sim \gamma_0 + \frac{eE_z}{mc^2} z$

$r(z) \sim r_0(\frac{\gamma_0}{\gamma})^{\frac{1}{4}} \cos[\frac{\sqrt{2}E_0}{E_z}(\sqrt{\gamma} - \sqrt{\gamma_0})]$

$\omega_\beta \sim \frac{\omega_p}{\sqrt{2\gamma}}$

$E_0 = \frac{mc\omega_p}{e}$

Electron dynamics: quadratic energy gain

$\gamma(t) \sim \gamma_{max}[1 - \varepsilon(\frac{t}{t_{deph}} - 1)^2]$

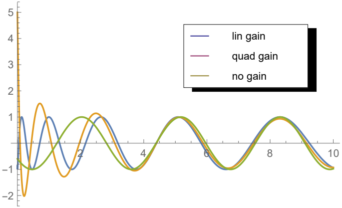
$r(t) \sim \frac{r_0}{P_\nu(-\varepsilon)} P_\nu(\frac{\varepsilon t}{t_{deph}} - \varepsilon)$

$\gamma_{max}(1 - \varepsilon) = \gamma_{min} = \frac{\omega_0}{\omega_p}$

$\nu \sim \frac{\omega_p}{\sqrt{2\gamma_{max}}} t_{deph}$

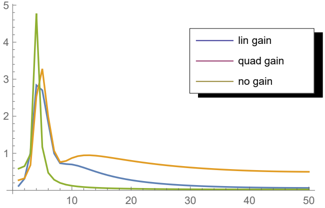
Betatron oscillations/2

Betatron oscillations



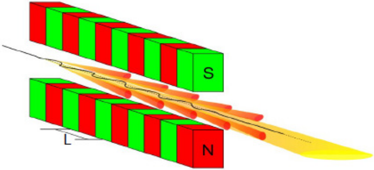
The betatron oscillations for an electron undergoing no energy gain, linear gain and quadratic gain

Betatron oscillations: Fourier transform



The Fourier transform of the betatron oscillations for an electron undergoing no energy gain, linear gain and quadratic gain

Characteristics of the Betatron Radiation: wiggler analogy



The difference between a wiggler and an undulator resides in the anharmonic motion of the oscillating particles, due to high transverse velocities, which mirrors in a broadband spectrum, while the spectrum of an undulator is narrowband.

Wiggler parameters:

$$\lambda_W = \frac{L}{2\gamma_0^2}\left(1 + \frac{K_W^2}{2} + \gamma_0^2\theta^2\right)$$

$$K_W = 0.934 B[T] L[cm]$$

$$E_c = 3\gamma_0^2 K_W \hbar\omega_W$$

Plasma wiggler parameters:

$$\lambda_b = \frac{\lambda_\beta}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

$$K = \gamma k_\beta r_0$$

$$E_c = 3\gamma_0^2 K \hbar\omega_b$$

Towards a plasma undulator?

PROBLEMS:

1⋆ Broadening due to acceleration

2⋆ Inhomogeneous broadening due to K-distribution

3⋆ Wiggler-like motion

4⋆ Bunch energy-spread

POSSIBLE SOLUTIONS:

1⋆ External injection in non-accelerating phase and/or in low density plasma wakefields

2⋆ External injection of anular electron bunches and other similar schemes

3⋆ External injection of small radius, low energy bunches in low density plasma wakefields

4⋆ External injection of monoenergetic electron bunches in plasma wakefields

EXTERNAL INJECTION SEEMS TO BE NECESSARY!

Betatron oscillations without acceleration

Electron dynamics without energy gain

$\gamma(z) \sim \gamma_0$

$r(z) \sim r_0 \cos[k_\beta z]$

$\omega_\beta \sim \frac{\omega_p}{\sqrt{2\gamma_0}}$

Undulator-like motion provided that $K = \gamma_0 k_\beta r_0$ is smaller than one !!!

But also are needed:

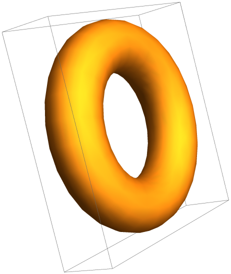
$\sigma_z << \lambda_p$ which ensures that all the particles of the bunch don't experience accelerating phases

And/or

$\frac{eE_z}{mc^2} L_{acc} << 1$ which ensures that the energy gain is not significant for each electron of the bunch

About the anular bunches

In order to reduce the inhomogeneous broadening due to the r_0 dependence of the strength parameter K anular shapes or similar for the externally injected electron bunches can be tought.



PROBLEM 1: how to generate this bunch shape? Shaping of the photocatode laser profile, cutting the electron profile at the center with a solid element on the beam line

PROBLEM 2: how to transport up to the injection point this bunch shape? Practical and reasonable values for the bunch sizes at the injection point are on the microscale, simulations are needed to check if a hollow structure can be preserved after the final focusing of the electron bunch inside the plasma undulator.

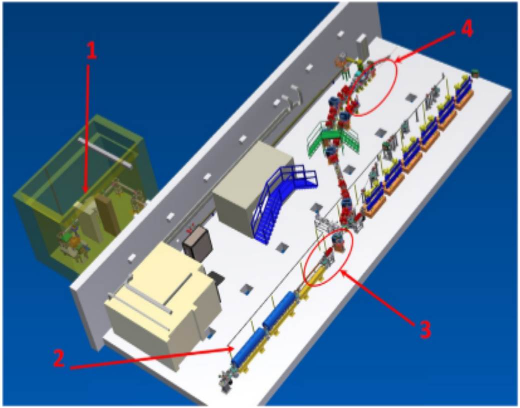
Why small radius bunches?

The appealing feature of a plasma undulator would be its compactness, on the millimeter/centimeter scale.

If X-ray radiation is sought, hundreds *MeV* electrons are needed.

To keep $K = \gamma k_\beta r_0 < 1$,micrometric bunches are required!!!!

Sparc Lab



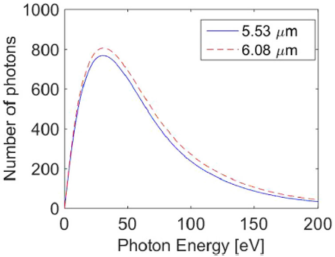
1 FLAME laser: ultrashort (30 fs) laser pulse, 20 μm spot size, with 3-4 J energy on a target.

2 SPARC photoinjector: photo-cathode assisted electron RF gun (UCLA/BNL/SLAC type, 1.6cells, S-band) and three S-band traveling wave (TW) accelerating sections to boost the energy of a HBEB up to 170 MeV

3 PWFA experiment site

4 LWFA experiment site

Forthcoming external injection PWFA experiment



*On-axis radiation, courtesy of V. Shpakov

From the knowledge of the plasma density, the electron energy and the betatron spectrum we can retrieve the bunch radius, so characterizing in a non-intercepting way the electron bunch inside the accelerating structure.

Bunch charge: 20 pC

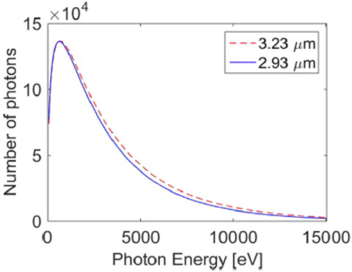
Bunch initial energy: 110 MeV.

The beam will be injected into a 3 cm length preformed plasma with density $n_e = 10^{16} cm^{-3}$.

Bunch final energy: 150 MeV.

Bunch transverse size: $\sim 5.5\ \mu m$.

Forthcoming external injection LWFA experiment



*On-axis radiation, courtesy of V. Shpakov

From the knowledge of the plasma density, the electron energy and the betatron spectrum we can retrieve the bunch radius, so characterizing in a non-intercepting way the electron bunch inside the accelerating structure.

Bunch charge: 20 pC

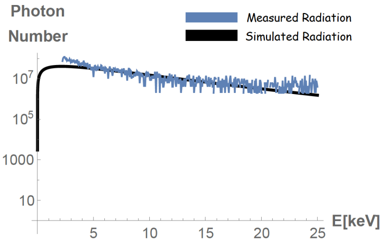
Bunch initial energy: 77 MeV.

The beam will be injected into a 3 cm length preformed plasma with density $n_e = 10^{17} cm^{-3}$.

Bunch final energy: 650 MeV.

Bunch transverse size: $\sim 3\ \mu m$.

Ongoing self-injection LWFA experiment/1



The aim is to retrieve both the bunch radius and divergence together with the electron energy in order to perform a single shot measurement of the electron beam inside the plasma cavity.

Bunch charge: 20-30 pC

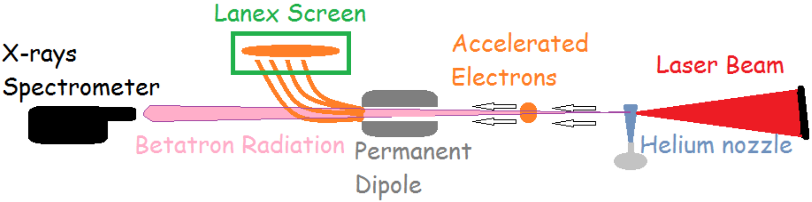
Bunch initial energy: 8 MeV.

The beam is self-injected into a 0.1 cm length laser-produced plasma with density $n_e = 6 \times 10^{18} cm^{-3}$.

Bunch maximum final energy: 200 MeV.

Bunch transverse size: $\sim 2\ \mu m$.

Ongoing self-injection LWFA experiment/2



Laser Parameters:

Energy in the focus: 1.5 J

Pulse duration: $35-40$ fs

Focus radius: 10 μm

Electron Parameters:

Max Energy: 200 MeV

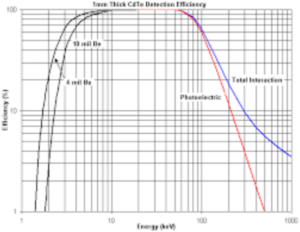
Energy Spread: $\sim$ down to 30%

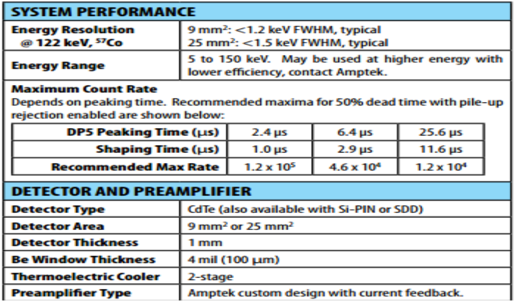
Divergence: $\sim$ down to 10 $mrad$

Charge: 10-100 pC

About diagnostics: Spectrometer for X-rays

Ampetex X-123 CdTe





SYSTEM PERFORMANCE	
Energy Resolution @ 122 keV, ^{57}Co	9 mm^2: <1.2 keV FWHM, typical 25 mm^2: <1.5 keV FWHM, typical
Energy Range	5 to 150 keV. May be used at higher energy with lower efficiency, contact Amptek.

Maximum Count Rate
Depends on peaking time. Recommended maxima for 50% dead time with pile-up rejection enabled are shown below:

DP5 Peaking Time (μs)	2.4 μs	6.4 μs	25.6 μs
Shaping Time (μs)	1.0 μs	2.9 μs	11.6 μs
Recommended Max Rate	1.2×10^5	4.6×10^4	1.2×10^4

DETECTOR AND PREAMPLIFIER	
Detector Type	CdTe (also available with Si-PIN or SDD)
Detector Area	9 mm^2 or 25 mm^2
Detector Thickness	1 mm
Be Window Thickness	4 mil (100 μm)
Thermoelectric Cooler	2-stage
Preamplifier Type	Amptek custom design with current feedback.

Conclusions

⋆ We summarized typical features of betatron radiation

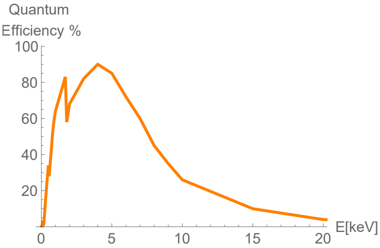
⋆ We discussed some problems and relative possible solutions in order to realize a plasma undulator based on betatron radiation

⋆ We presented the current and forthcoming activity on betatron radiation at Sparc-Lab in Frascati

Thanks for your attention

About diagnostics: CCD camera for X-rays

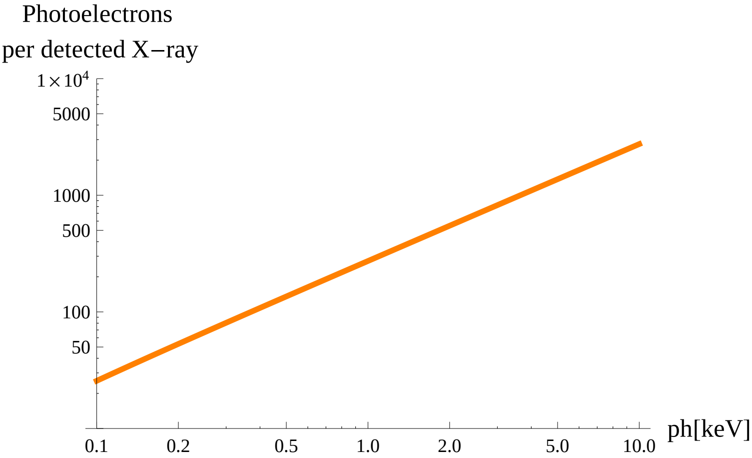
Andor DX 434 BR DD



Specifications Summary

Sensor type	20	20 ‘DD’	40	34
Active pixels	1024 x 255	1024 x 256	2048 x 512	1024 x 1024
Pixel size (W x H)	26 x 26 µm	26 x 26 µm	13.5 x 13.5 µm	13 x 13 µm
Image area	26.6 x 6.7 mm	26.6 x 6.7 mm	27.6 x 6.9 mm	13.3 x 13.3 mm
Register well depth	1,000,000 e^-	1,400,000 e^-	600,000 e^-	200,000 e^-
Maximum cooling	-100°C			
Maximum Spectra Per Sec @ 1MHz Maximum Frame Per Sec @ 1MHz	166 -	166 -	90 -	- 0.9
Read noise @ 1 MHz	18	18	7	7.5
Vacuum compatible	10^{-5} millibar and below			

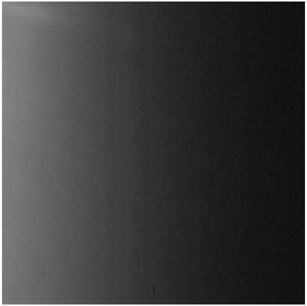
About diagnostics: X-ray Single Photon Spectroscopy



$y = 274.891\ x - 1.845$

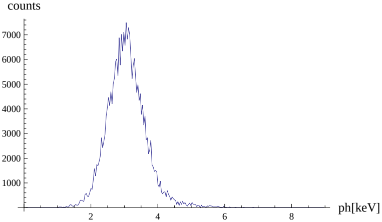
Test of X-ray Single Photon Spectroscopy

How the signal looks like

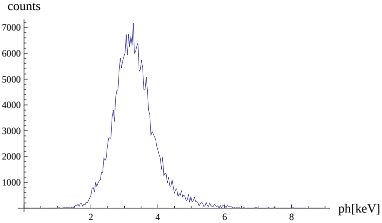


In this case we were detecting X-ray bremsstrahlung from a laser produced plasma in atmosphere. The histogram of the pixel values corresponds directly to a detected spectrum.

Target Position : 630μm
Laser energy : 7mJ
Target : Cu
Filters : 50μm Al + 25μm Be + 100μm kapton



Target Position : 605μm
Laser energy : 7mJ
Target : Cu
Filters : 50μm Al + 25μm Be + 100μm kapton



About diagnostics: high-flux measurements

Transmission law

$I_{t,j} = I_0 \int dES(E)e^{-\alpha(E)\delta_j}$

X-ray spectrum parametrization

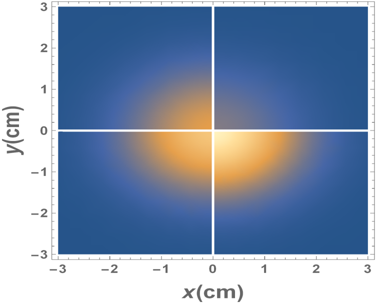
$\sum_{n=1}^{4} c_n E^n$

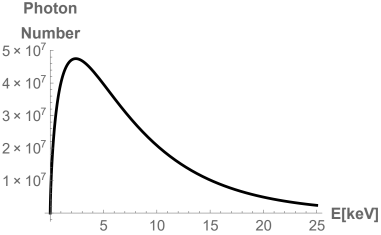
X-ray spectrum model

$\frac{dI}{dE} = \frac{2\alpha}{\sqrt{\pi}} \int_0^{t_d} \frac{dt}{\gamma^2(t)} [\frac{\Phi'(u)}{u} + \frac{1}{2} \int_{-\infty}^{+\infty} du\Phi(u)]$

$u = \frac{2cE}{\hbar\omega_p^2 r(t)\gamma^2(t)}$

Expected result





Test of high X-ray flux diagnostics

In this case we were detecting the bremsstrahlung from a high-energy laser produced plasma in vacuum.

Transmission law

$I_{t,j} = I_0 \int d\lambda S(\lambda) e^{-\alpha(\lambda)\delta_j}$

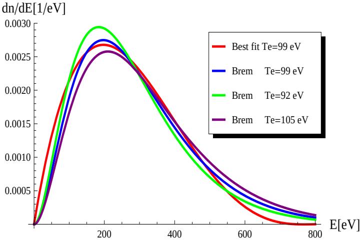
X-ray spectrum parametrization

$S(\lambda) = c_1\lambda + c_2\lambda^2 + c_3\lambda^3 + c_4\lambda^4$

X-ray spectrum model

$S(\lambda) \propto \lambda^2 Exp[-\frac{hc}{\lambda k T_e}]$

Experimental result

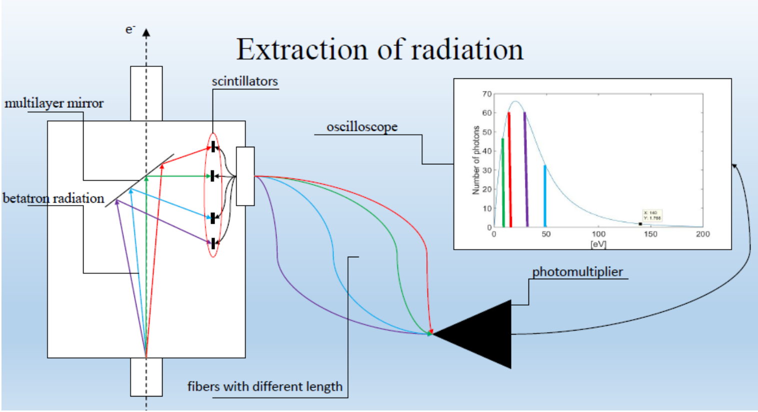


$T_e = (99 \pm 6) eV$

Scanned Image

About diagnostics: UV detection

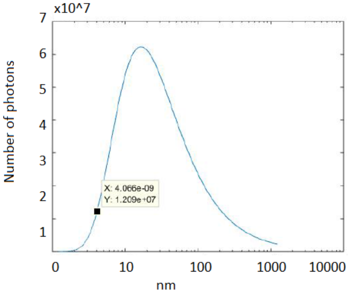
To measure the spectrum of betatron radiation in PWFA experiments a multi-layer mirror can be used.

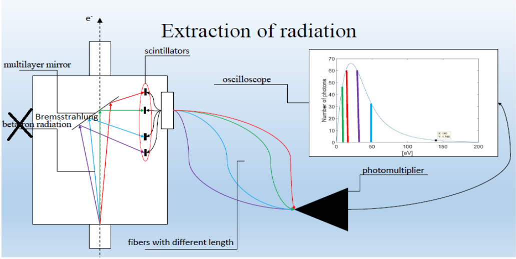


Test of UV diagnostics

In order to test this diagnostic bremsstrahlung radiation will be produced through the interaction of a mJ femtosecond class laser with a solid target, inducing UV radiation from the laser-produced plasma.

The expected spectrum:





Conclusions

- ⋆ We summarized typical features of betatron radiation
- ⋆ We discussed some problems and relative possible solutions in order to realize a plasma undulator based on betatron radiation
- ⋆ We presented the current and forthcoming activity on betatron radiation at Sparc-Lab in Frascati
- ⋆ We exposed some diagnostic strategies, most of them already tested, which and are going to be exploited for the betatron radiation detection

Thanks for your attention