Overview on advanced diagnostics for High Brightness Beams

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2nd European Advanced Accelerator Concepts Workshop 2015 La Biodola, Isola d'Elba
Outline

• Brightness
• Emittance
• Incoming and outcoming beam measurements
• State of the art
• Conclusion
Definitions of Brightness

\[ B = \frac{dI}{dSd\Omega} \]

For particle distribution whose boundary in 4D trace space is defined by an hyperellipsoid

\[ \bar{B} = \frac{2I}{\pi^2 \varepsilon_x \varepsilon_y} \]

\[ [\text{A}/(\text{m-rad})^2] \]

Normalized Brightness

\[ \bar{B}_n = \frac{2I}{\pi^2 \varepsilon_{nx} \varepsilon_{ny}} \]

From diagnostics point of view what does it mean high brightness?
Some references

Parameters to measure

- Charge
- Energy
- Energy spread
- Transverse and longitudinal profile
- **Emittance**
- 6D
Geometrical vs Normalized

\[ \varepsilon_n^2 = \langle x^2 \rangle \langle \beta^2 \gamma^2 x'^2 \rangle - \langle x \beta \gamma x' \rangle \]

\[ \sigma_E^2 = \frac{\langle \beta^2 \gamma^2 \rangle - \langle \beta \gamma \rangle^2}{\langle \gamma \rangle^2} \]

\[ \varepsilon_n^2 = \langle \gamma \rangle^2 \sigma_E^2 \langle x^2 \rangle \langle x'^2 \rangle + \langle \beta \gamma \rangle^2 \left( \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2 \right) \]

M. Migliorati et al, Physical Review Special Topics, Accelerators and Beams 16, 011302 (2013)

K. Floettmann, PRSTAB, 6, 034202 (2003)
For the accelerator community the normalized emittance is one of the main parameters because it is constant.

For such a beam, due to the large energy spread and huge angular divergence, it is not true anymore.
Two main scenarios

- **LWA**: Diagnostics of the output beam

- **PWFA**: Diagnostics of both input (hopefully not intercepting) and output beam
We need at least 3 measurements in 3 different positions to evaluate the emittance.
Main limitations

- Multi shots
- Intercepting
- Chromaticity

\[ \varepsilon_1^2 = \left< x_1^2 \right> \left< x_1' \right> - \left< x_1 x_1' \right>^2 = \varepsilon_0^2 + (kl)^2 \sigma_x^4 \sigma_y^2 = f(\varepsilon_0, \sigma_y, \sigma_x) \]
Train of bunches

- COMB-like electron bunches are injected inside the preformed plasma. The first bunches create the wakefield, which is then seen from the last bunch (witness) which will be then accelerated.
- Challenge: creation and manipulation of driver bunches and matching all the bunches with the plasma.
- In order to fulfil this requirement a diagnostic of the single bunch is needed.
Time separation

\[ \sigma_y = \sqrt{\sigma_{y_{RFD}}^2 + \sigma_{y_{beam}}^2} \]

Paul Emma, Josef Frisch, Patrick Krejcik, A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics, LCLS-TN-00-12
Christopher Behrens, Measurement and Control of the Longitudinal Phase Space at High-Gain Free-Electron Lasers, FEL 2011, Shanghai

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Longitudinal phase space

<table>
<thead>
<tr>
<th>Bunch</th>
<th>Beam Energy (MeV)</th>
<th>Energy Spread (%)</th>
<th>Position (ps)</th>
<th>Bunch Length (ps)</th>
<th>Long. Emit (keV mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>117.12 (0.02)</td>
<td>0.067 (0.002)</td>
<td>6.39 (0.02)</td>
<td>0.19 (0.03)</td>
<td>4.0 (0.2)</td>
</tr>
<tr>
<td>D1</td>
<td>116.65 (0.02)</td>
<td>0.158 (0.005)</td>
<td>5.02 (0.02)</td>
<td>0.12 (0.02)</td>
<td>5.6 (0.2)</td>
</tr>
<tr>
<td>D2</td>
<td>116.82 (0.02)</td>
<td>0.175 (0.009)</td>
<td>4.19 (0.02)</td>
<td>0.08 (0.02)</td>
<td>4.6 (0.4)</td>
</tr>
<tr>
<td>Whole</td>
<td>116.80 (0.02)</td>
<td>0.210 (0.005)</td>
<td>4.92 (0.02)</td>
<td>7.67 (0.02)</td>
<td>53.4 (1.2)</td>
</tr>
</tbody>
</table>
Single bunch test

- Transverse size with RFD on/off
Quad scan comb beam
Results


<table>
<thead>
<tr>
<th>Bunch</th>
<th>Emittance (mm-mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver #1</td>
<td>1.38 (0.04)</td>
</tr>
<tr>
<td>Driver #2</td>
<td>1.61 (0.07)</td>
</tr>
<tr>
<td>Witness</td>
<td>1.22 (0.06)</td>
</tr>
</tbody>
</table>

\[ \sigma_x \times 10^{-5} \]

\[ \text{Current [A]} \]

\[ \text{\[m\]} \]
5 bunches
Not intercepting but multi shot

Steven J. Russell, Emittance measurements of the Sub-Picosecond Accelerator electron beam using beam position monitors, Review of Scientific Instruments 70, 2, February 1999


L. J. Nevay et al, Laserwire at the Accelerator Test Facility 2 with submicrometer resolution, Physical Review Special Topics Accelerators and Beams 17, 072802 (2014)
EOS encoding

- Laser crosses the crystal with an incident angle
- One side of the laser pulse arrives earlier on EO crystal with respect the other by a time difference $\Delta t$
- Columb field inducing birefringence is encoded in the spatial profile of laser pulse

EOS setup
A comblike beam

• $\sigma_1 = (375\pm10)$ fs
• $\sigma_2 = (344\pm10)$ fs
• dist = (879±9) fs


Pyro-electric line detector 30 channels @ room temperature no window, works in vacuum fast read out sensitivity
Single shot CTR measurements II


KRS-5 (thallium bromoiodide) prism based spectrometer developed

Images OTR from foil onto 128 lead zirconate titanate pyroelectric elements with 100 μm spacing line array

Also double prism (ZnSe), S. Wunderlich et al., Proceedings of IBIC2014
Summary input beam

• There are well established solution for
  – Emittance measurement
    • Quad scan
  – Longitudinal phase space
    • Eos, dipole, RFD, CTR etc

• Not all of them are single shot or not intercepting
Multiple OTR monitors

- C. Thomas, N. Delerue and R. Bartolini “Single shot transverse emittance measurement from OTR screens in a drift transport section”, 2011 JINST 6 P07004

\[ \theta_0 = \frac{13.6 \text{MeV}}{\beta c p} \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln \frac{x}{X_0}\right) \]

- In their case (3GeV) the multiple scattering is not a factor for thin (5 μm) screens
- It is possible to produce even 1 μm aluminum screen
- This system seems not feasible for beams with energy in the range of hundreds of MeV
- A waist is a must

P. Castro, “Monte Carlo simulations of emittance measurements at TTF2”, Desy Technical-Note-03-03
To measure the emittance for a space charge dominated beam the used technique is the well known 1-D pepper-pot.

The emittance can be reconstructed from the second momentum of the distribution

\[ \varepsilon = \sqrt{\langle x'^2 \rangle \langle x^2 \rangle - \langle xx' \rangle^2} \]

The contribution of the slit width to the size of the beamlet profile should be negligible.

The material thickness (usually tungsten) must be long enough to stop or heavily scatter beam at large angle (critical issue at high energy).

The angular acceptance of the slit cannot be smaller of the expected angular divergence of the beam.

\[ \sigma = \sqrt{(L \cdot \sigma')^2 + \left(\frac{d^2}{12}\right)} \]

\[ L \gg \frac{d}{\sigma' \cdot \sqrt{12}} \]

\[ l < \frac{d}{2\sigma'} \]
Holes machining

- Holes array have been successfully produced.
- The thickness of the material can be as large as 100 times the hole diameter

High energy pepper pot

- In principle can operate also at moderate to high energy (500 MeV - 1 Gev)
- Length 50 mm, slit 500 μm, spaced 2 mm

Emittance Measurements of a Laser-Wakefield-Accelerated Electron Beam

S. Fritzler,1 E. Lefebvre,2 V. Malka,1 F. Burgy,1 A. E. Dangor,3 K. Krushelnick,3 S. P. D. Mangles,3 Z. Najmudin,3 J.-P. Rousseau,1 and B. Walton3

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 092803 (2010)

Emittance and divergence of laser wakefield accelerated electrons

Christopher M. S. Sears,1,* Alexander Buck,1,2 Karl Schmid,1 Julia Mikhailova,1 Ferenc Krausz,1,2 and Laszlo Veisz1,

1Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
2Fakultät für Physik, Ludwig-Maximilians-Universität München, 85748 Garching, Germany
(Received 31 May 2010; published 22 September 2010)

PRL 105, 215007 (2010)

Low Emittance, High Brilliance Relativistic Electron Beams from a Laser-Plasma Accelerator


Physics Department, University of Strathclyde, Glasgow G4 QNG, United Kingdom
(Received 31 August 2010; published 19 November 2010)
Intrinsic limit for LWFA beams

• No considerations about
  – S/N ratio
  – Detector
  – Multiple scattering
  – Background
• Mask thickness neglected
• All beams have $\varepsilon_n = 1$ mm-mrad
• $z = 0.6$ m
• $\beta = 0.1$ m means $10 \ \mu$m on the source
• $\beta = 0.001$ m means $1 \ \mu$m on the source
No problems

- Everything roughly optimized in to minimize the error and to use all the particles

\[ D_2 = 0.5 \text{ m} \]
\[ \text{%error} \approx 1\% \]
5 slits
50 \( \mu \text{m} \) size
500 \( \mu \text{m} \) distance
\[ D_1 = 0.6 \text{ m} \]

\[ D_2 = 2 \text{ m} \]
\[ \text{%error} = 37\% \]
11 slits
25 \( \mu \text{m} \) size
50 \( \mu \text{m} \) distance
\[ D_1 = 0.6 \text{ m} \]

5 MeV \( \beta = 1 \text{ m} \)
500 MeV \( \beta = 0.1 \text{ m} \)

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No chances for $\beta=0.001$ m

- The phase space is so thin that the sampling is very inefficient especially in angle


$D_2=2$ m
%error>1000%
31 slits
50 $\mu$m size
100 $\mu$m distance
$D_1$ 0.6 m
Quantization error


\[ \mathcal{E}_{err} = \frac{2}{\pi} \left( x_{\text{max}} \Delta x' + x'_{\text{max}} \Delta x \right) \]

\[ \lambda_b = \lambda_p \sqrt{2\gamma} \propto \sqrt{1/n_e} \]

Betatron spectroscopy


- 400 MeV energy with a rms energy spread of less than 5% and 1 mrad divergence from a plasma density of $5 \times 10^{18} \text{cm}^3$
\( \sigma \sigma' \gamma \Delta \gamma \) at the same time

- S. Kneip and al., PRST-AB 15, 021302 (2012)

Source size by Fresnel diffraction

Energy, energy spread and divergence behind the dipole
A new kind of Quadscan

- R. Weingartner and al., PRST-AB 15, 111302 (2012)
Transition radiation

Electron beam

Metallic screen

Beam splitter

Beam imaging system

angular distribution

Transition radiation
• C. Couillaud, A. Loulergue, G. Haouat, “ELECTRON BEAM TRANSVERSE EMITTANCE MEASUREMENT USING OPTICAL TRANSITION RADIATION INTERFEROMETRY”, Proceedings of Epac96, Spain
Further improvement

Electron beam → Metallic screen

Beam imaging system

Beam splitter

Image plane + mask

angular distribution
With a mask

Conclusions

• High brightness beam diagnostics is very challenging especially for emittance measurements
• Well established methods are available for input beams even in case of comb like structure
• A lot of work must be dedicated for output beams
• It is not ancillary part because as the saying goes: «an accelerator is just as good as its diagnostics». 
It is over, finally!!

Thank you for your attention