Superconductive Undulators for Laser Wakefield Accelerators

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Outline

A Brief Introduction to Laser Wakefield Accelerators

Short Period Superconductive Undulators

Diagnostic Light Sources: Non-planar Undulators for Energy Spread Compensation

Conclusions

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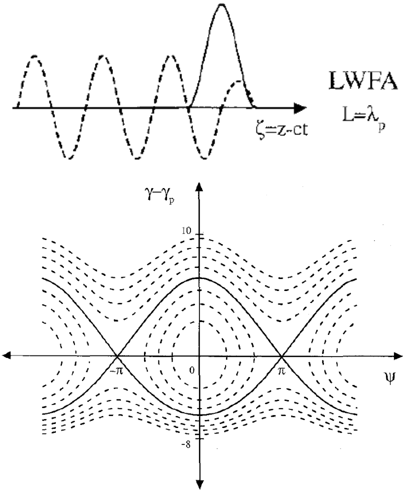
Laser Wakefield Acceleration

Principle



E. Esarey et al., IEEE Trans.Plas.Sci.24 (1996)

Figure: Linear plasma wake, single particle orbits in phase space of injected electrons

- high-power laser pulse travels through underdense plasma
- ponderomotive force causes plasma wake, most effectively with $L_{\mathrm{LP}} = \lambda_{\mathrm{p}}$
- longitudinal wake:

$$E_z = E_{\max} \sin\left(\omega_{\mathrm{p}}(z/v_p - t)\right)$$

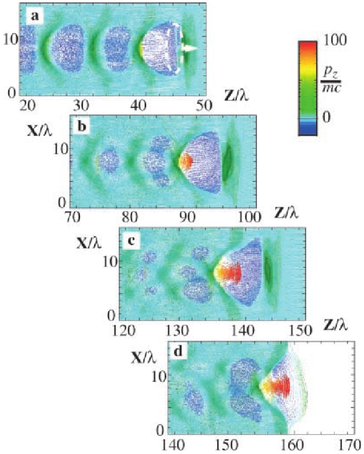
$$E_{\max} \leq E_0 := \frac{4\pi e n_0 c}{\omega_{\mathrm{p}}},$$

$$\omega_{\mathrm{p}} = \sqrt{\frac{4\pi n_0 e^2}{m_e}},$$

with $n_0 =$ ambient e^- density.

- $n_0 \sim 10^{18}\,\mathrm{cm}^{-3}$,
  $E_0 \sim 100\,\mathrm{GV/m}$

LWFA Wave-Breaking Regime



A.Pukhov,J.Meyer-ter-Vehn, Appl.Phys.B74 (2002)

Figure: Electron density (PIC-simulation)

Non-linear regime

$$v_e \to v_p : E_{\max} \to E_{WB}$$

$$E_{WB} = \sqrt{2(\gamma_p - 1)}\,E_0$$

non-relativistic wavebreaking limit:
⇒ wavebreaking, self-injection

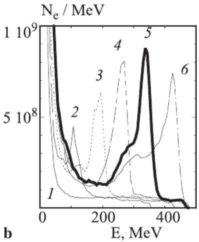
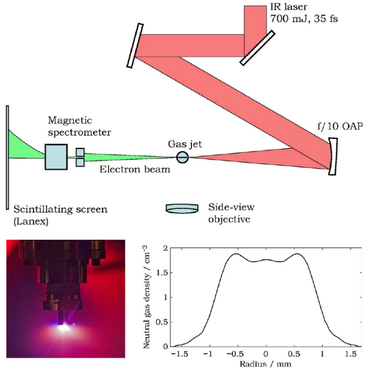


Figure: Electron energy spectrum @ $ct/\lambda = \{350, 450, ..., 850\}$

LWFA experimental setups

Gas jet

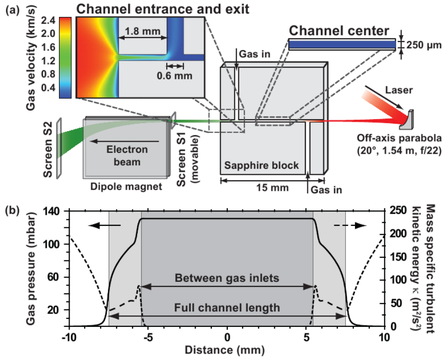


(a) (b)

F. Lindau et al.,IEEE Trans.Plas.Sci.36 (2008)

Figure: Schematic LWFA setup with supersonic gas jet, nozzle ($\oslash 2\,\mathrm{mm}$) during shot, gas density profile

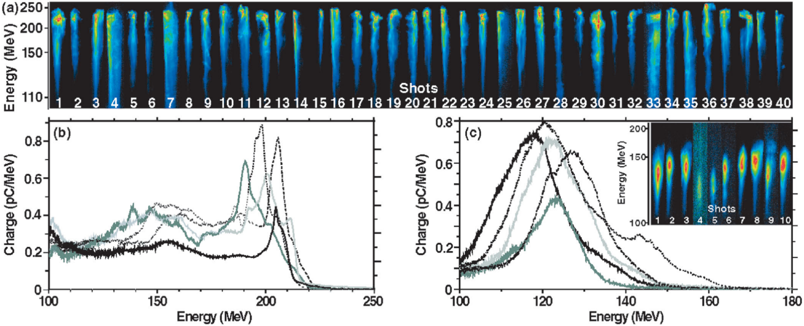
Capillary, plasma channel



J. Osterhoff et al., PRL 101 (2008)

Figure: Cross section of a capillary, magnified: gas flow in steady state, gas-pressure profile along central channel axis

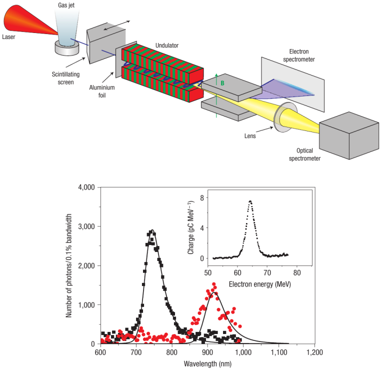
LWFA measured electron spectra



J. Osterhoff et al., PRL 101 (2008)

Figure: False-color images of 40 consecutive, spacially dispersed electron beams on S2 (cf. last slide)

LWFA-Driven Light Sources



H.-P. Schlenvoigt et al., nature physics 4 (2008)

Figure: Schematic setup of a LWFA-driven undulator light source, measured photon spectra @ $E_e = 64\,\mathrm{MeV}$ and $58\,\mathrm{MeV}$

TT-FELs

- Today's LWFAs provide end energies of 0.1...1 GeV.
- Tempting idea: table-top X-ray FELs could become feasible with short-period undulators.
- Possible solution: Nb_3Sn SCUs

Table: TT-FEL-SCU target parameters (Grüner et al., Appl. Phys. B 86)

λ_u [mm]	5
g [mm]	1.3
K	1
$\tilde{B}_y$ [T]	2.1
L_{sat} (VUV) [m]	0.8

Which needs do the undulators have to be tailored to?

- photon energy in X-ray range ⟹ very short periods ($\sim 5\,\mathrm{mm}, K \sim 1$)
- (low) pointing stability ⟹ large apertures preferred
- large energy spread ⟹ compensation schemes?
- heat load: probably not an issue

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- Maintaining K for shorter periods requires increasing the field

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- Permanent magnets:
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  - cryogenic PMUs

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- Permanent magnets:
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    - cryogenic PMUs
- Superconductive undulators
    - extremely high current densities required
    - Nb_3Sn (low field instabilities have to be overcome)
    - HTSC @ 4 K (not yet outperforming Nb-Ti)

Options for (very) short period undulators

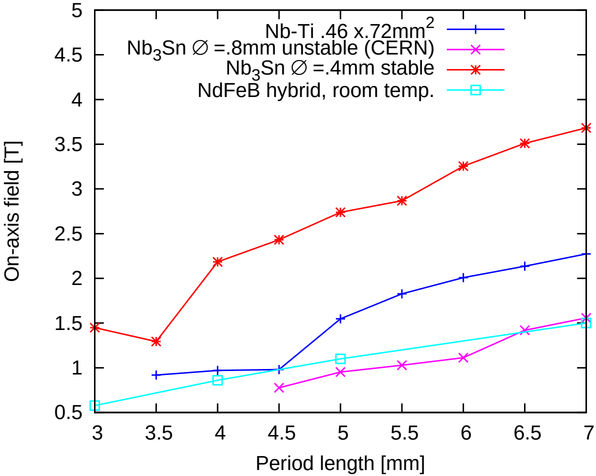

Figure: Simulated on-axis field as a function of period length for different particular sc wires @ 1.3 mm gap, 80%J_c and optimised winding configurations, as compared to a PMU. The indicated cross sections refer to the bare wire.

Nb_3Sn-Undulator for LMU Munich

Development steps

Despite of the low field instablities, Nb_3Sn involves mechanical challenges (heat treatment, brittleness).

1. transfer CERN/CLIC DW technique to short periods (2-period short model)
   - test and optimise heat treatment and mechanical stability
   - but: Nb-Ti will not be outperformed in this first step

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   - reduce wire and filament diameter
   - use process and heat treatment optimised for low fields (e.g. PiT)

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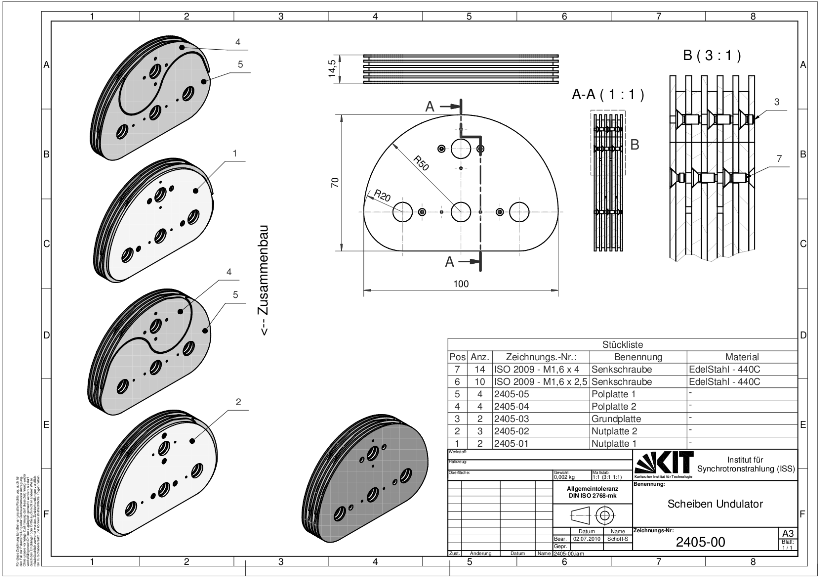
    - reduce wire and filament diameter
    - use process and heat treatment optimised for low fields (e.g. PiT)
3. construction and characterisation of 10-period short model using the optimum wire/process

Nb$_3$Sn-Undulator for LMU Munich



Stückliste

Pos	Anz.	Zeichnungs.-Nr.:	Benennung	Material
7	14	ISO 2009 - M1,6 x 4	Senkschraube	EdelStahl - 440C
6	10	ISO 2009 - M1,6 x 2,5	Senkschraube	EdelStahl - 440C
5	4	2405-05	Polplatte 1	-
4	4	2405-04	Polplatte 2	-
3	2	2405-03	Grundplatte	-
2	3	2405-02	Nutplatte 2	-
1	2	2405-01	Nutplatte 1	-

Werkstoff:
Halbzeug:
Oberfläche:
Gewicht: 0,002 kg
Maßstab: 1:1 (3:1 1:1)
Allgemeintoleranz DIN ISO 2768-mk
Institut für Synchrotronstrahlung (ISS)
Benennung: Scheiben Undulator
Zeichnungs-Nr: 2405-00
A3
Blatt: 1 / 1

	Datum	Name
Bear.	02.07.2010	Schott-S
Gepr.		

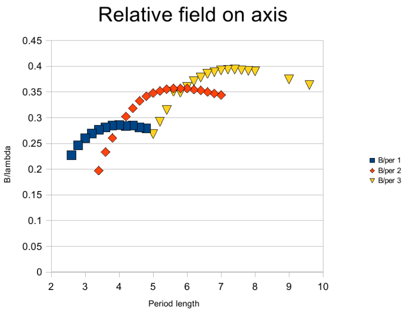
Zust. Änderung Datum Name 2405-00.iam

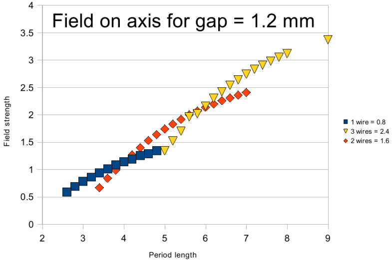
Nb_3Sn-Undulator for LMU Munich

Design approach

Use Nb_3Sn wire tested for CLIC damping wigglers:

diameter	0.8 mm
SC/Cu ratio	1.13
# filaments	60
filament diam.	80 μm





Conclusion

Optimum period length

- 4 mm for 1 wire per layer
- 5.4 mm for 2 wires per layer
- 7 mm for 3 wires per layer

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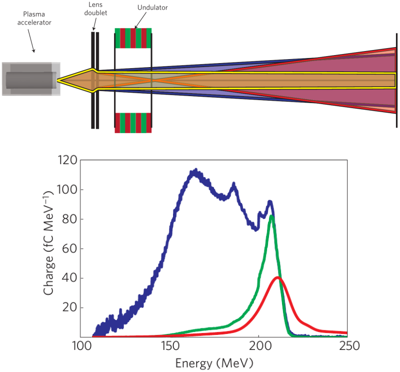
How to reduce the photon energy spread

Focusing



M. Fuchs et al., nature physics 5 (2009)

Figure: e-beam divergence after quad doublet for different energies, effective electron spectrum width “reduced bandwidth”

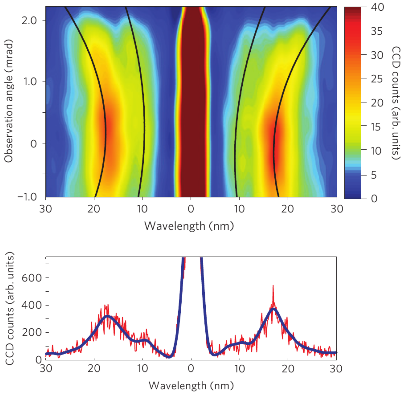


Figure: photon spectrum (0. and 1. diffraction order of grating). $E_e = 207\,\mathrm{MeV}$, $\lambda_{\text{fund.}} = 17\,\mathrm{nm}$

- Focusing rather hides than reduces the energy spread
- Diagnostic applications of undulator radiation relying on its monochromaticity require a different approach

Example: Emittance Measurement

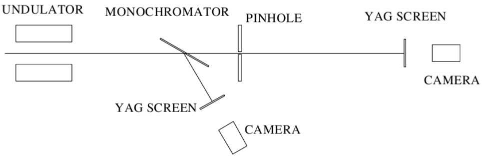


Figure: Possible setup for simultanous beam size and divergence measurements at SR sources

B.X. Yang, A.H.Lumpkin, PAC 1999

Measured (effective) monochromatic divergence

$$z_\mathrm{m}^2 \sigma_{x'\,eff}^2 = (z_\mathrm{m} - z_\mathrm{w})^2 \sigma_{x'}^2 + z_\mathrm{m}^2 \sigma_{r'}^2 + \sigma_{x0}^2$$

Imaged beam size:

$$\sigma_{x\,eff} = \frac{z_\mathrm{s}^2 \left(\sigma_{x'0}^2 + \sigma_r^2 + \frac{z_\mathrm{w}^2}{\beta_0^2} \sigma_r^2 \right)}{\sigma_{x'0}^2 (z_\mathrm{s} - z_\mathrm{w})^2 + \sigma_r^2 z_\mathrm{s}^2 + \sigma_{x0}^2} \sigma_{x0}^2$$

- z_m, z_w, z_s dist. of monochromator, beam waist, pinhole from undulator centre,
- σ_{x0}, $\sigma_{x'0}$, β_0 beam size, divergence, and beta function at beam waist, resp.,
- σ_r, $\sigma_{r'}$ diffraction limited source size and divergence.

Problem at LWFAs: The diffraction limited source size and divergence

$$\sigma_r = \sqrt{(\lambda L)/4\pi}, \quad \sigma_{r'} = \sqrt{\lambda/L}$$

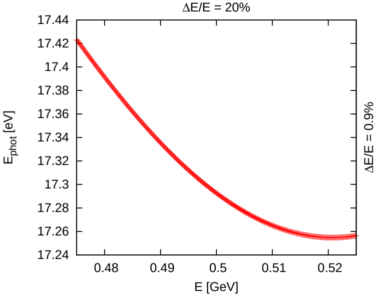
are not well defined due to the large energy spread $\frac{\sigma_\lambda}{\lambda}$!

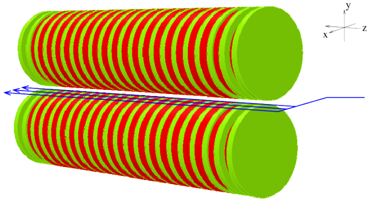
Energy Spread Compensation: Non-Planar SCUs

Concept

- disperse beam by chicane
- match laterally varying field strength to electron energy:

$$\lambda = \frac{\lambda_\mathrm{u}}{2\gamma^2(x)}\left(1 + \frac{K^2(x)}{2}\right) = const.$$



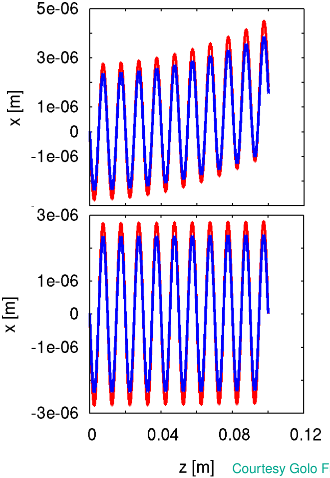


Courtesy Peter Peiffer

Example case

- cylindrical scu with $r_\mathrm{cyl} = 13\,\mathrm{mm}$
- $\lambda_\mathrm{u} = 10\,\mathrm{mm}$, $h_\mathrm{gap} = 1\,\mathrm{mm}$
- $E_e = 500\,\mathrm{MeV}$, $\frac{\sigma_E}{E} = 20\,\%$
- bandwidth reduced by 1 OM

Cyl. SCU: Trajectory Correction



Courtesy Golo Fuchert

Figure: Trajectory through the cylindrical undulator for the two extremal energies (shifted to $x = 0$) without and with sextupole correction field applied

Transverse Drift

- non-planar undulator half periods deflect the beam differently strong
- excentric sextupole correction field required:

$$B_{y\,\mathrm{corr}}(x) = g(x+e)^2 + d$$

- example case:

$$d = -0.5\,\mathrm{mT}$$

$$g = 34\,\frac{\mathrm{T}}{\mathrm{m}^2}$$

$$e = -3.5\,\mathrm{mm}$$

Non-planar SCUs: Agenda

3-year BMBF-funded joint project with University of Jena

- Theory and simulation tools

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- first measurements at JETI 9/2012

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- Laser wakefield accelerators in combination with short period superconductive undulators might open a path to compact X-ray undulator radiation sources and in far future even to table-top X-FELs.
- Very short periods require very large current densities and therefore sc materials beyond standard Nb-Ti technology
- Non-planar undulator geometries are an option for compensating the large energy spread of laser wakefield accelerators, thus making undulator radiation-based diagnostics for wakefield accelerators feasible
- A project of theoretically validating and expermentally testing and applying this concept is under way