Case 4 – Compact ERL for THz Radiation

• Goal: *Design a facility to provide high-rep THz radiation in the range of 1 to 20 THz with either single cycle emission or a bandwidth below 2%*

Results of group 8
Jörn Boedewadt, Raimund Kammering (DESY)
Ben Ledroit (Johannes Gutenberg-Universitaet Mainz)
Alberto Petralia (ENEA Frascati)
Angela Saa-Hernanddez (PSI)
Martin Schmeisser (Helmholtz-Zentrum Berlin)
General layout of the ERL THz facility

SRF photon injection at 2.5 MeV, 200 pC (650 kW)

Rf-frequency 1.3 GHz

acceleration/de-acceleration 41.5 MeV

Beam energy: 44 MeV, 200 pC (260 mA)
Virtual beam power: 7.8 MW

R_{56} = 100 mm range

single cycle CSR

1-20 THz @ 2 % bandwidth

e^- extraction at low energy
Design consideration for the FEL

• FEL for low bandwidth (2%)
• high gain FEL would require very short bunch length and peak current
  • low gain FEL oscillator → compact
  • fixed (ERL) beam energy and constrain on wavelength 1 – 20 THz
  • Use permanent magnet undulator with variable gap for wavelength tuning
    \[ \lambda_{FEL}(E, \lambda_u, K) = \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right) \]
    \[ K = 93.6 \ B[T] \ \lambda_u[m] \]
  • start with \( K > 1, \ B \) on axis < 1.0T, reasonable dimensions of gap/undulator
  • gap / vacuum chamber diameter > 30 mm (see next slide)
    \[ B_0 = 1.8 \ B_r \ \exp \left( -\pi \ \frac{gap}{\lambda_u} \right) \]
  • \( \rightarrow \lambda_u = 10 \) cm

\[ B_r = 1.4 \ \text{T} \]
Design consideration for the FEL

- Resonator cavity design
- What is the expected beam size?

Stability criterion

At waist:

At mirror:

1 THz

\[ \pi \sqrt{g_1(1 - g_1 g_2)} \]

Determines minimum gap of undulator
Tuning range and undulator give beam energy

Beam energy ~ 44 MeV

10 cm undulator period
Estimate on FEL peak power

Gain per turn:
\[ G_0 = \frac{(4\pi\rho N_u)^3}{\pi} \]

Saturation power:
\[ P_{\text{sat}} = P_0 (1 + G_{\text{net}})^m \]

\[ G_{\text{net}} = G_{\text{max}} - G_{\text{loss}} \]
\[ G_{\text{max}} = 0.85G_0 \cdot F + 0.19(G_0 \cdot F)^2 \]

Single pulse energy: 48 – 118 µJ
Optical beam power: 150 kW

B. Qin et al., Design considerations of a planar undulator applied in a tera hertz FEL oscillator, NIM A 727 (2013) 90–96
Compression

- initial bunch length 20 ps (needed for FEL oscillator)
- final bunch length to get reasonable CSR in THz needs 0.5 ps
- this gives a compression factor of 40 which is challenging using a single compression stage
- other alternatives to get a short radiating pulse: foil, corrugated structure... not possible with ERL design
  - use non linear compression schema – use “spike mode”

\[
E(s) = E_0 + eV_{RF} \cos(ks + \varphi_{RF}) = E_0 + eV_{RF}[\cos(\varphi_{RF}) - k \sin(\varphi_{RF})s - k^2 \cos(\varphi_{RF}) s^2 + \ldots]
\]

\[
s_f = s_i + \frac{R_{56}}{E_0} (-ke_{RF} \sin(\varphi_{RF}) s_i - k^2 e_{RF} \cos(\varphi_{RF}) s_i^2)
\]
Compression
single cycle CSR

Incoherent synchrotron radiation flux

\[
\frac{d\dot{N}_{ph}}{d\phi} = \frac{4\alpha}{9} \frac{I}{e} \frac{\Delta \omega}{\omega} S \left( \frac{\omega}{\omega_c} \right)
\]

\[
S \left( \frac{\omega}{\omega_c} \right) = \frac{9\sqrt{3}}{8\pi} \frac{\omega}{\omega_c} \int_{\omega_c/\omega}^{\infty} K_{5/3}(\bar{x}) \, d\bar{x}
\]

Coherent radiation governed by form factor

\[
g_{\lambda} = |\int n(z) e^{2\pi iz/\lambda} \, dz|^2
\]

\[
P_{\lambda coh} = N_{\lambda inc} P_{\lambda coh}
\]

At 30 MeV, 100pC, R=10m bend

S. Di Mitri, G. Wüstefeld
single cycle CSR
Summary of determined parameters

• Machine parameters:
  • 260 mA average beam current
  • 200 pC @ 1.3 GHz
  • 20 ps bunch length (uncompressed down to 500 fs compressed)
  • Beam energy 44 MeV

• Undulator parameters:
  • gap 30 mm, 10 cm undulator period
  • $B = 0.16 \ldots 1.0$ T ($K = 1.5 \ldots 9.3$)