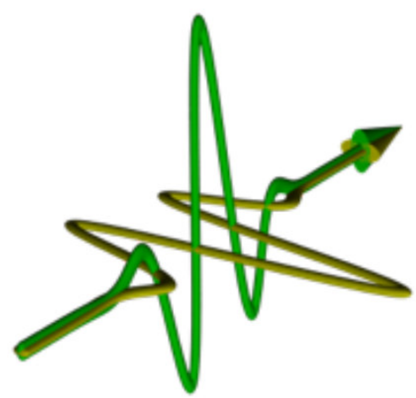
FREIA

SUFEL
STOCKHOLM-UPPSALA CENTRE FOR FREE ELECTRON LASER RESEARCH

UPPSALA UNIVERSITET

Towards GV/m single-cycle THz pulses from undulators



Vitaliy Goryashko

2016

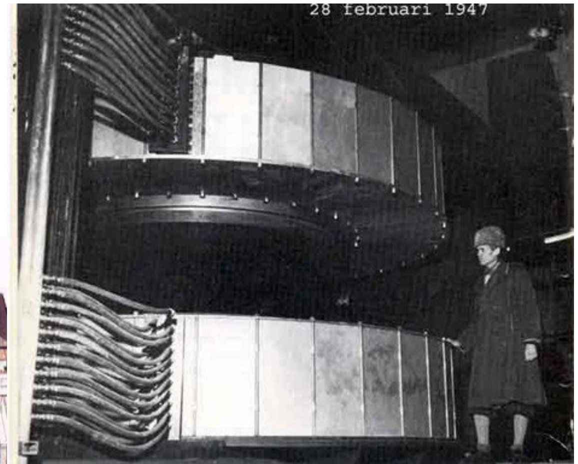
Outline

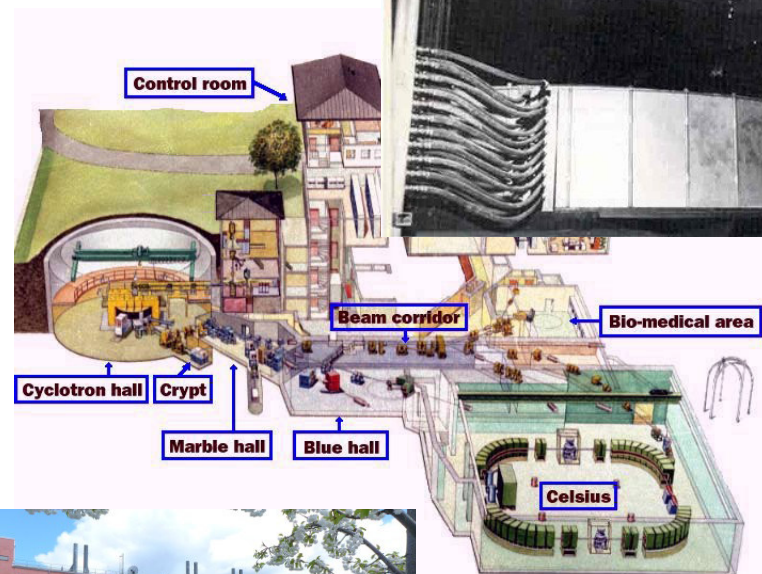
- Accelerator physics in Uppsala and FREIA Laboratory
- Work on a linac-based THz source
- Concept of generation of single-cycle pulses with undulators
- Optimal tapering
- Proposal for a THz Light at Uppsala

Background: accelerator physics in Uppsala

1940's: The(odore) Svedberg proposes to build a cyclotron

- Gustaf Werner synchro-cyclotron (1947 – present)
  - nuclear physics & cancer treatment
- CELSIUS ring (1984 – 2005)
  - nuclear physics
- External
  - CTF3/CLIC at CERN (since 2005)
  - FLASH/XFEL at DESY (since 2008)
  - ESS (since 2009)
- FREIA laboratory (since 2011)
- Skandion clinic (2015)
  - cancer treatment

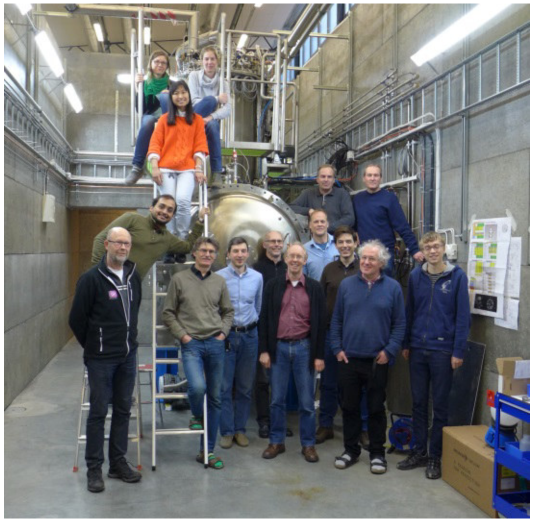




European Spallation Source (ESS), Sweden


FREIA

FREIA: Facility for Research Instrumentation & Accelerator Development

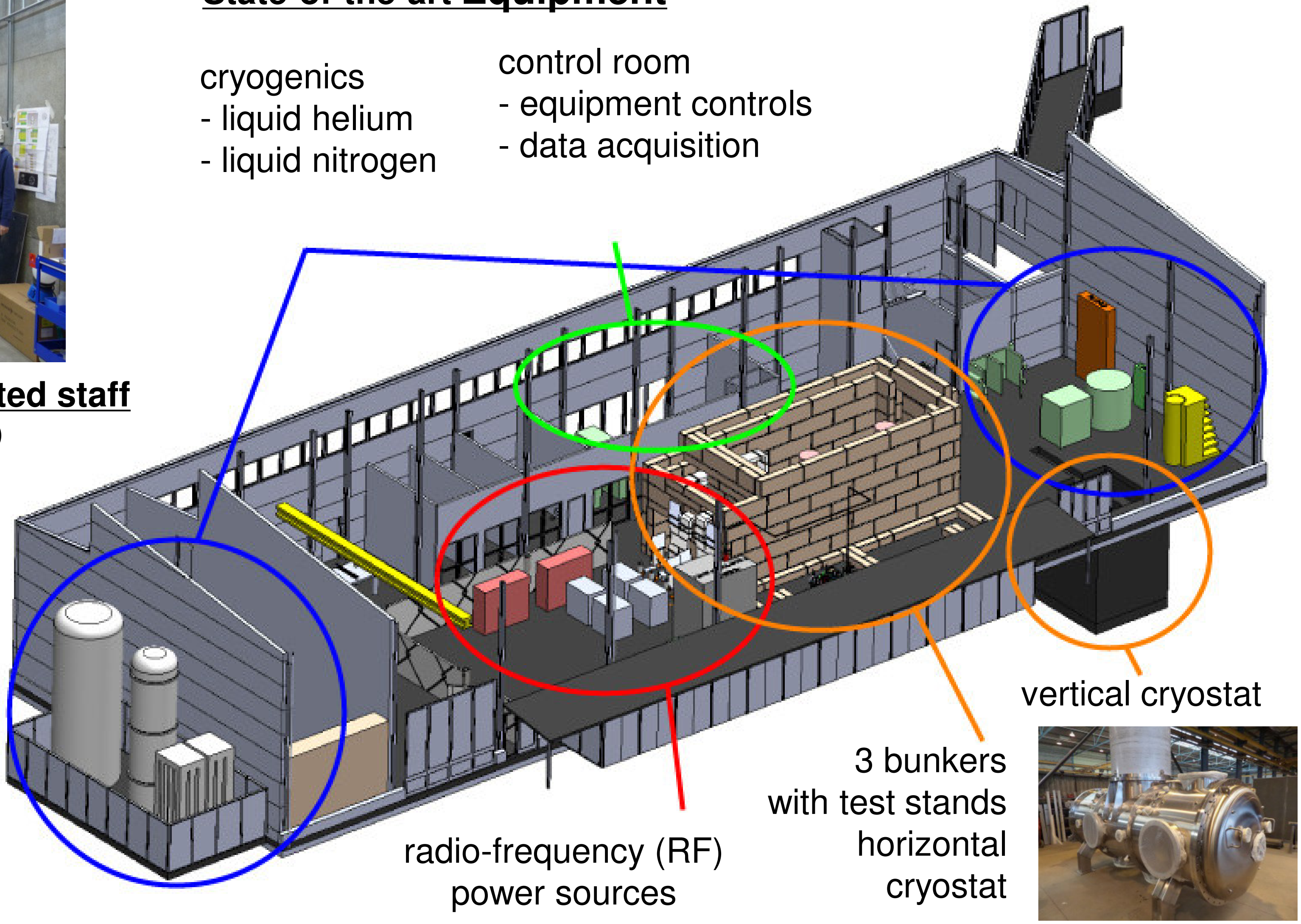


Competent and motivated staff

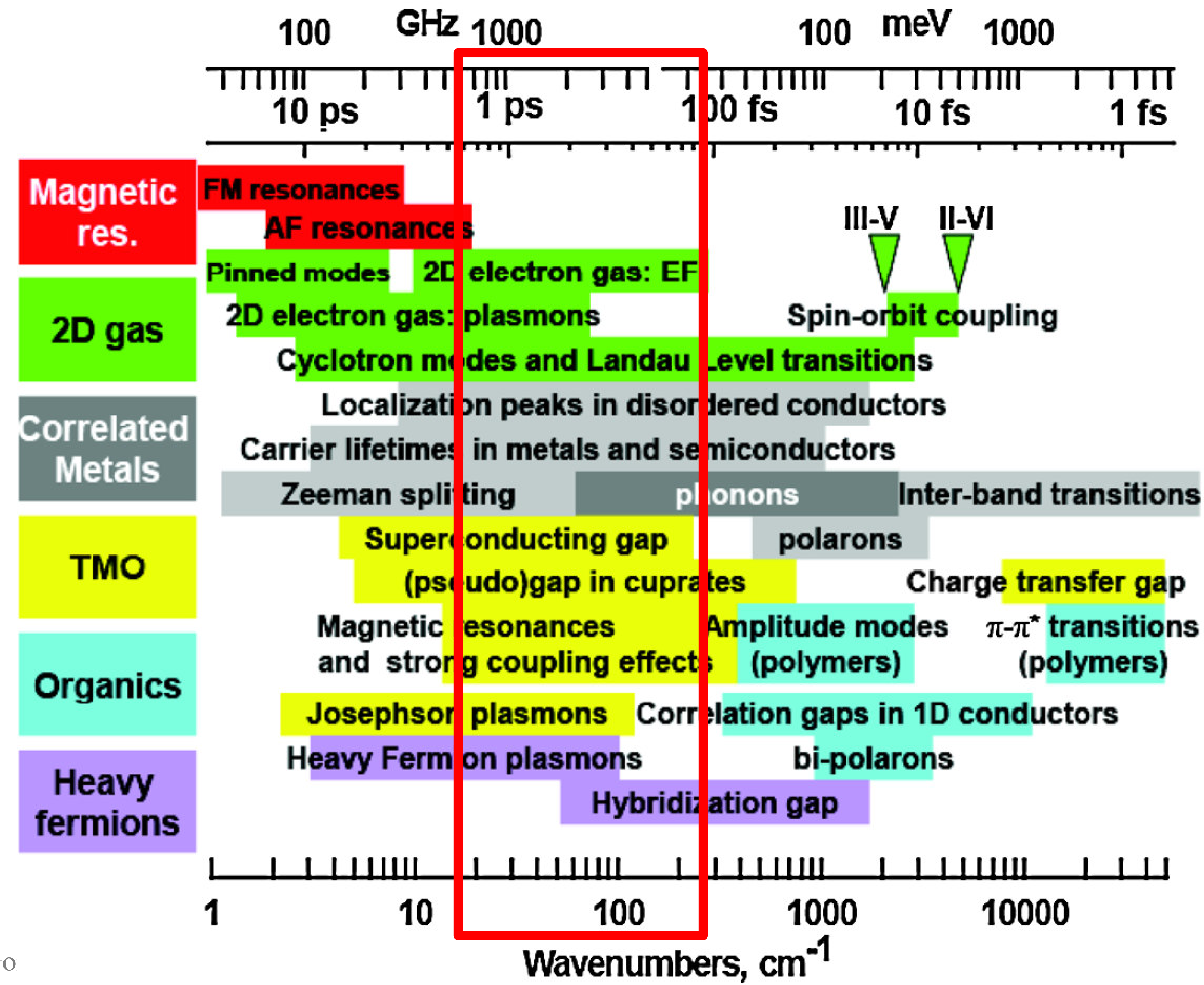
collaboration of physics (IFA)
and engineering (Teknikum).

Funded by
KAWS,
Government,
Uppsala Univ.

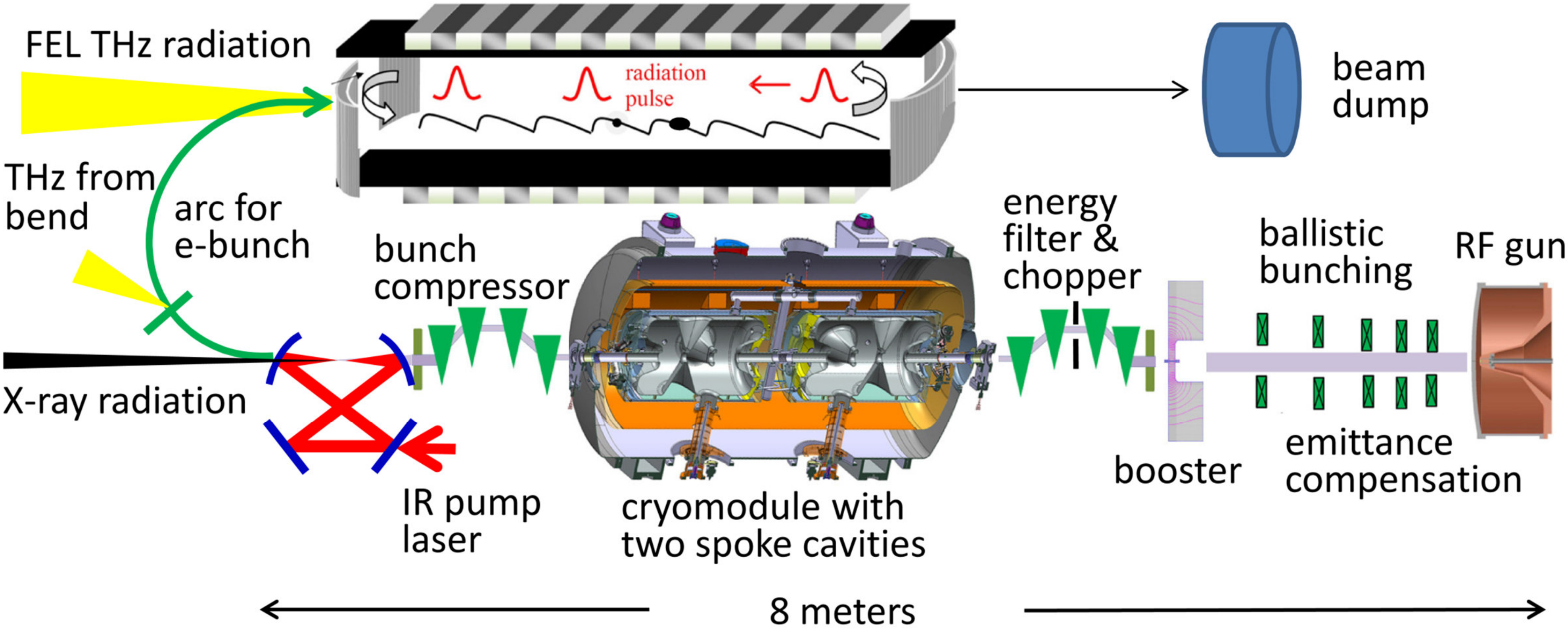
State-of-the-art Equipment



Low-energy excitations: *D. N. Basov et al., Rev. of Mod. Phys. 2011*



Combined THz/X-ray source: old design



Stockholm University

KTH VETENSKAP OCH KONST ROYAL INSTITUTE OF TECHNOLOGY

UPPSALA UNIVERSITET

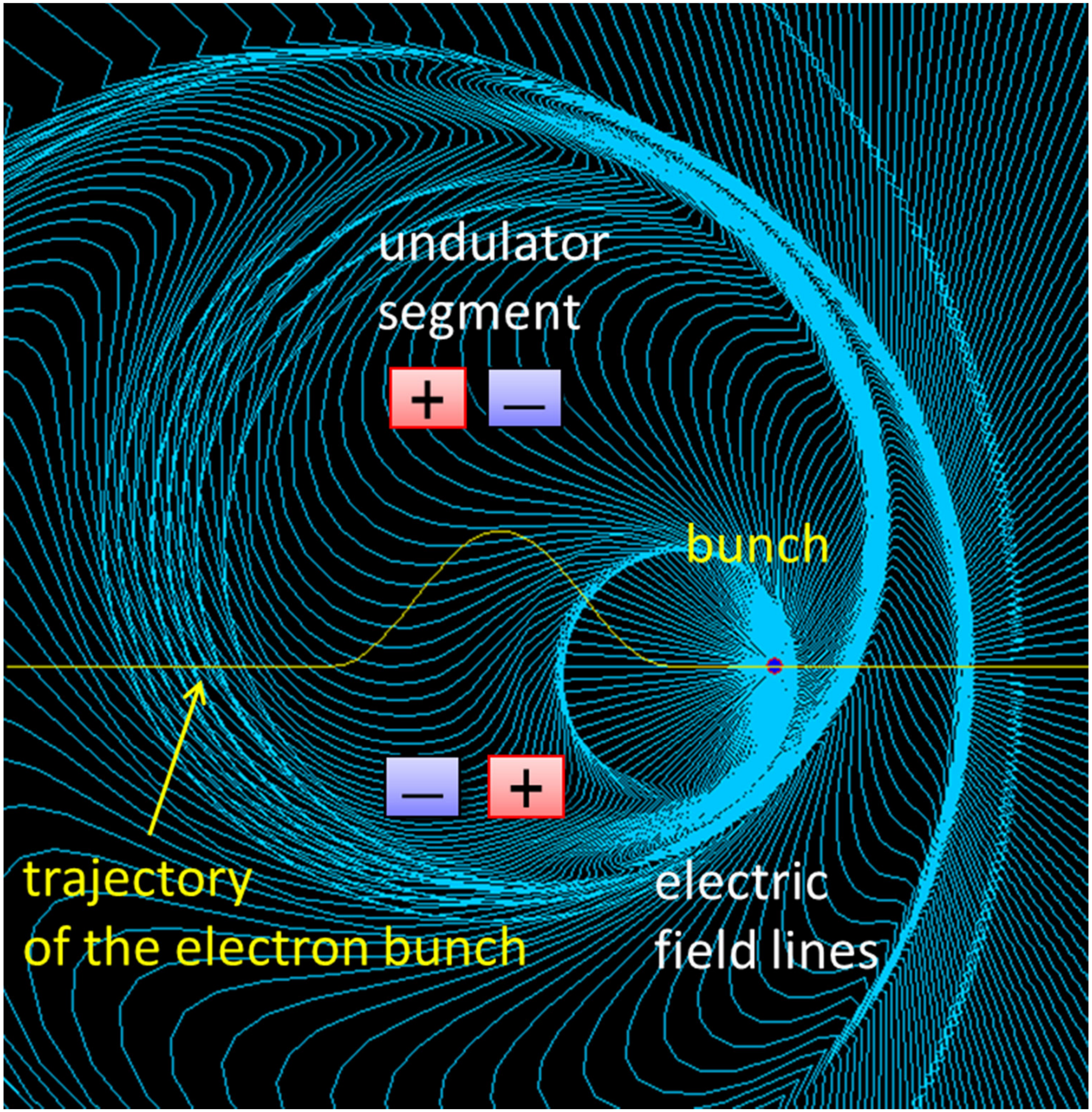
Workshop on the scientific opportunities of a THz-FEL in Sweden

24-25 November 2014

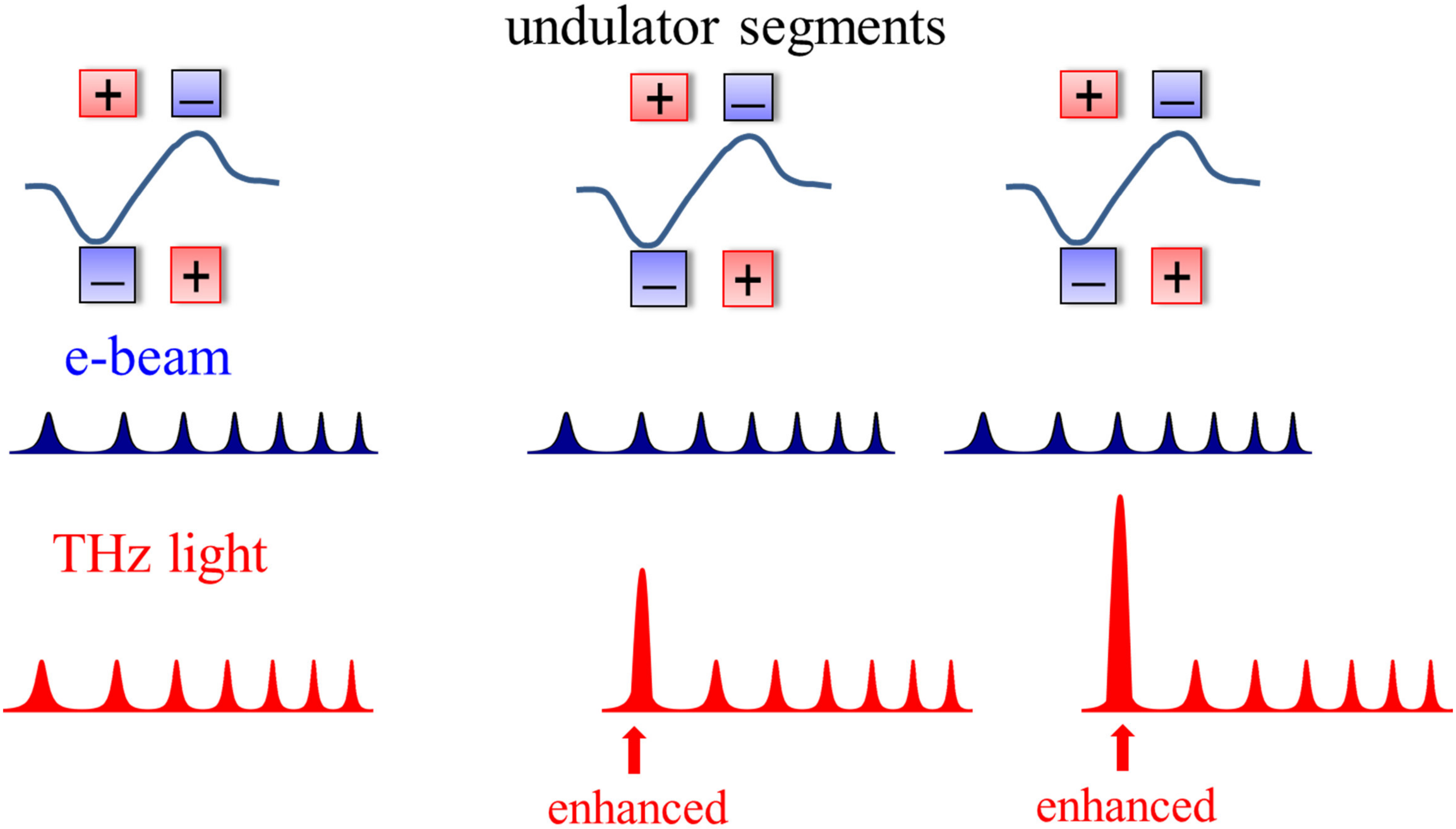
AlbaNova University Center Stockholm, Sweden

How to generate GV/m single-cycle pulses with MeV bunches?

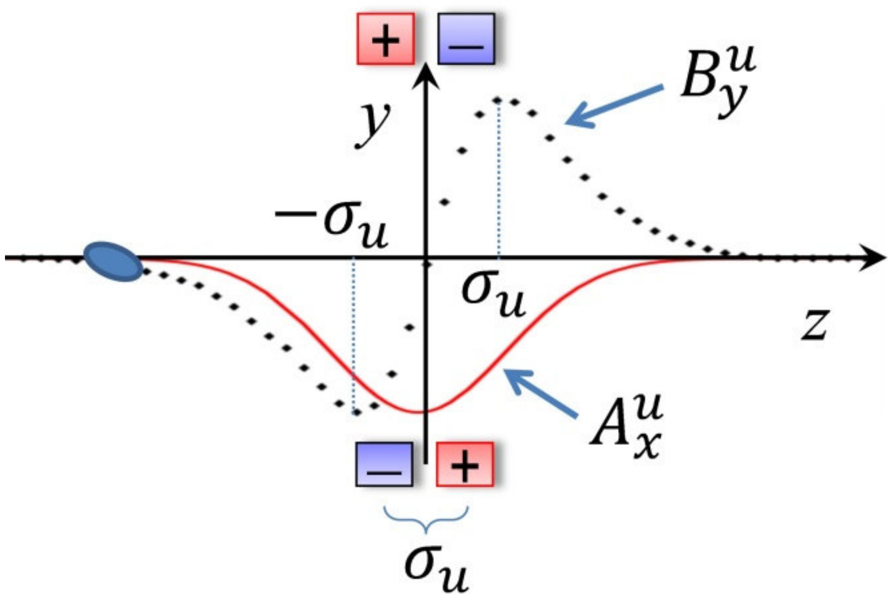
Single-cycle synchrotron radiation

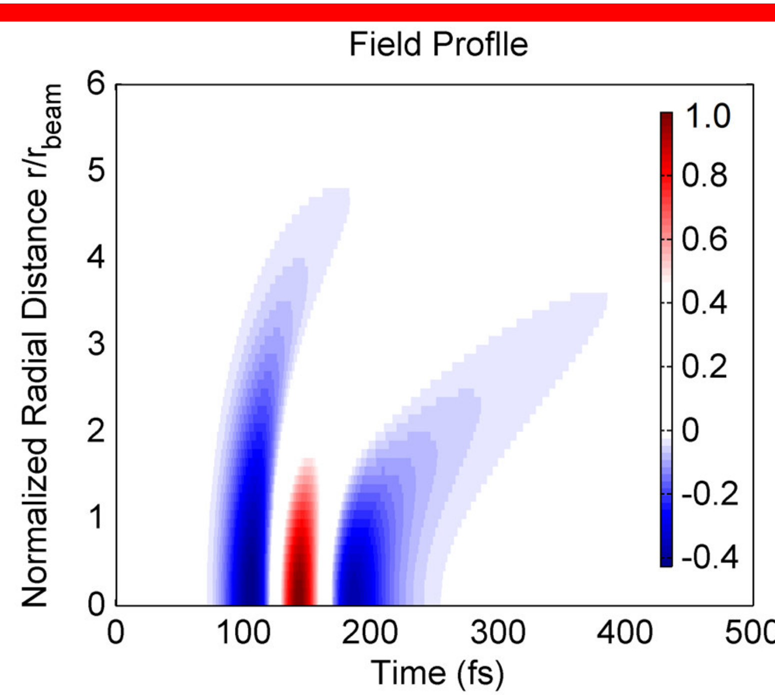


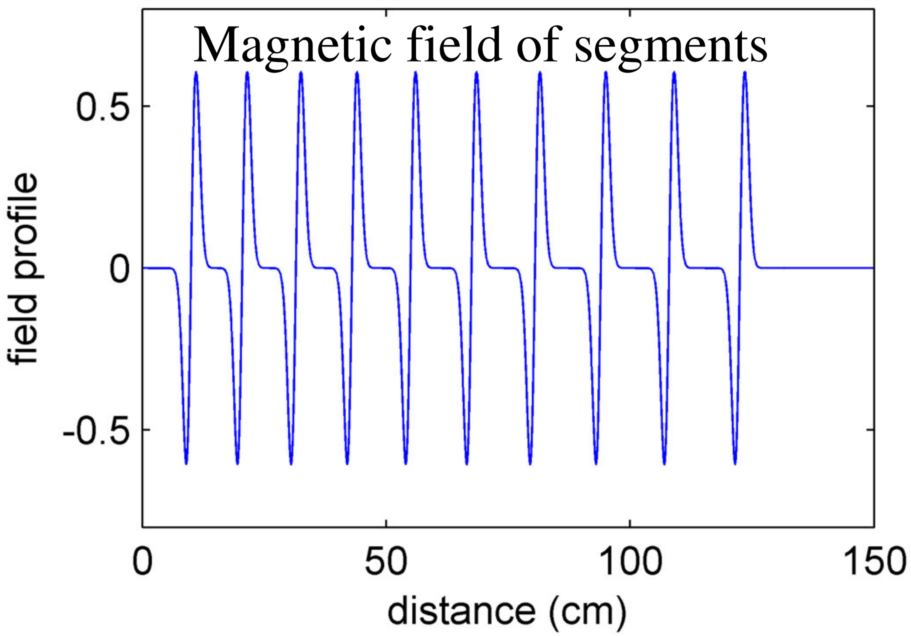
Single-cycle radiation from a segmented undulator

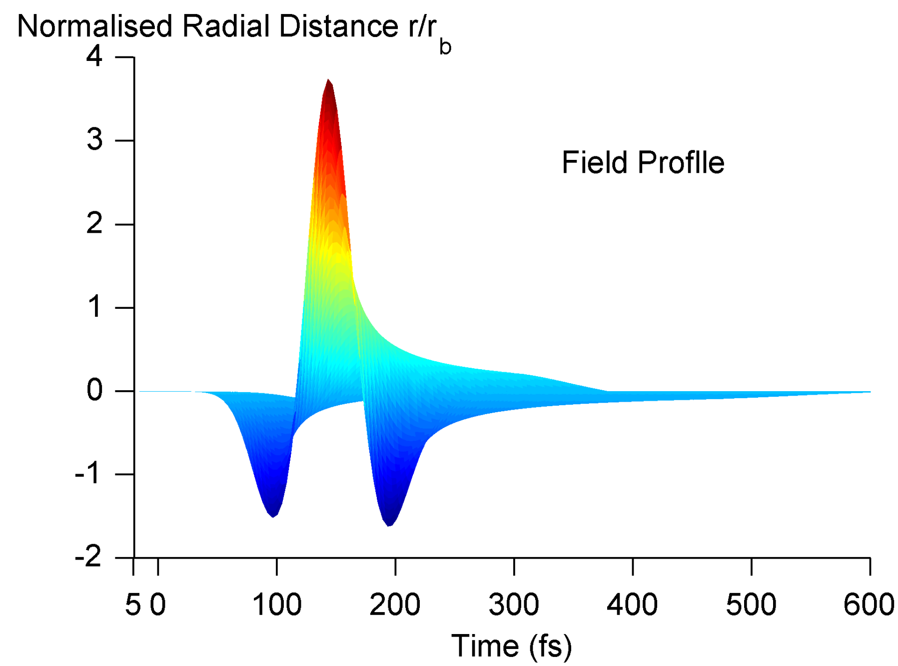


Single-cycle radiation from a segmented undulator: cont'd

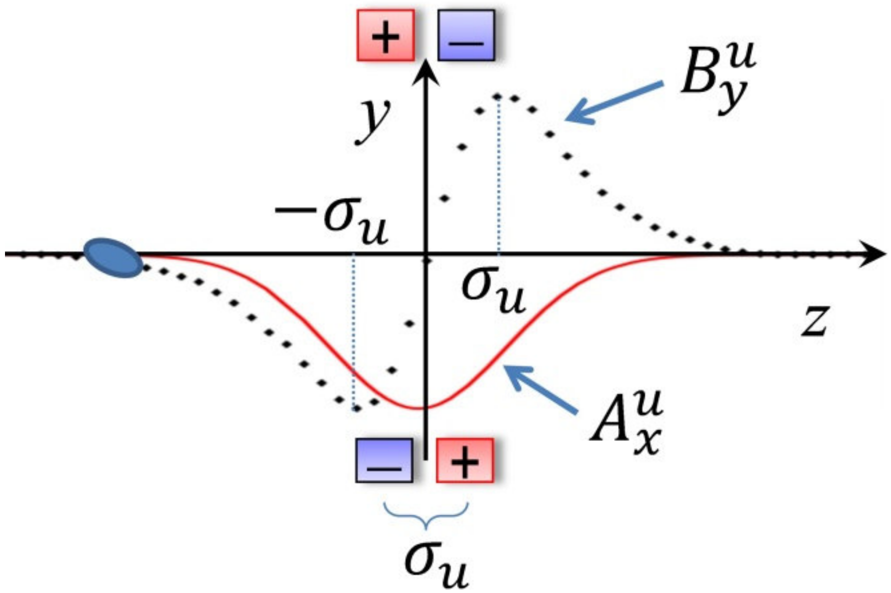


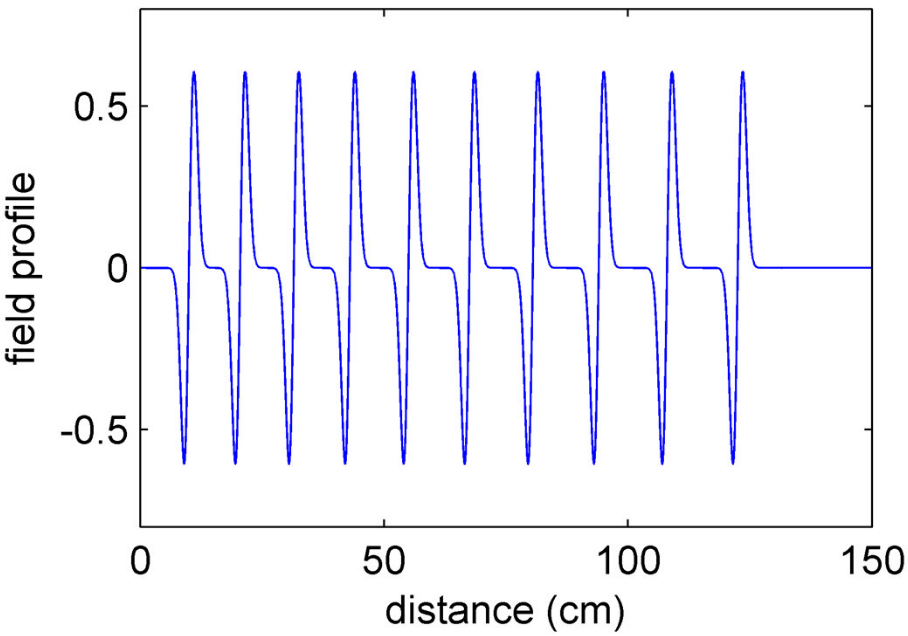




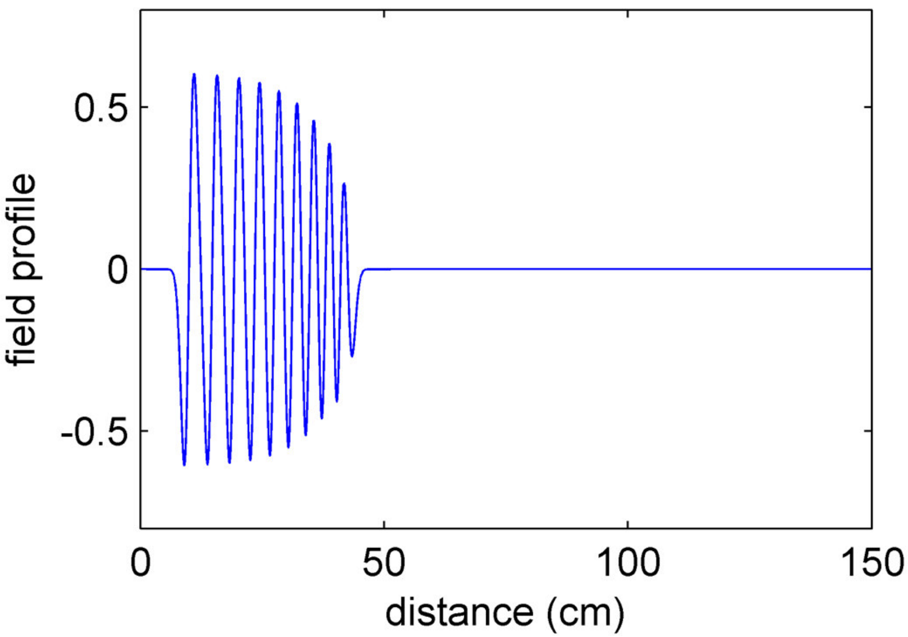


Single-cycle radiation from a segmented undulator



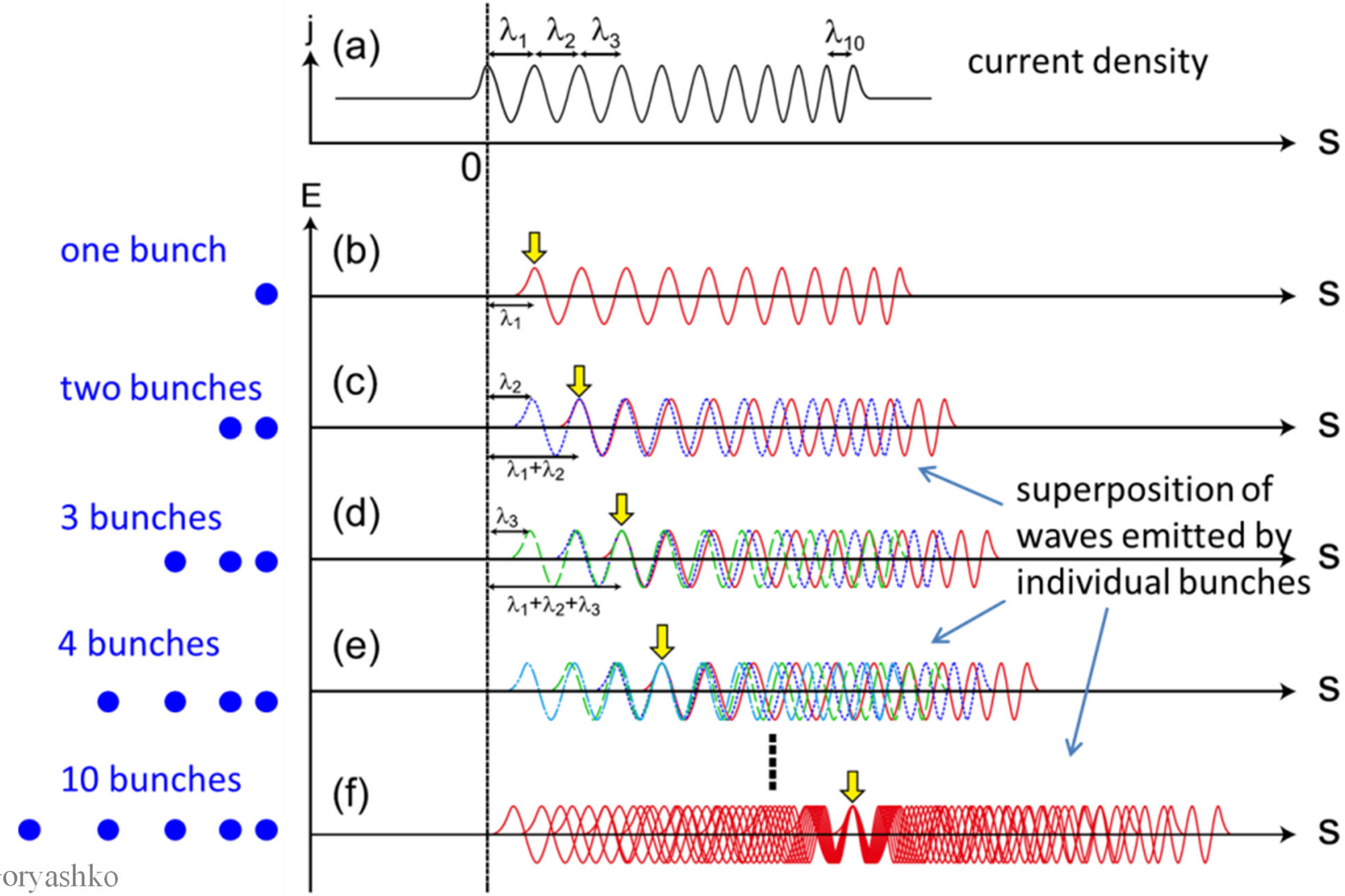


If instead of increasing the distance between the segments I will decrease it, I will recover Takashi's tapered undulator.



Proposal to Generate an Isolated Monocycle X-Ray Pulse by Counteracting the Slippage Effect in Free-Electron Lasers

Takashi Tanaka*



What is the optimum taper profile?
Can one generate just one cycle?

Simple reasoning from Takashi

$$E(t) = n(t) \otimes E_s(t),$$

total field is a convolution of the current density and the field of a single electron

$$n(t) = n_0[1 + bf(t)]$$

$$E_s(t) = E_0 g(t)$$

Suppose that the time profile of the current density is the same as the single-electron field profile

$$g(t) = f(T - t)$$

The convolution boils down to the inverse Fourier transform of the spectral power.

$$E(t) = bn_0E_0\mathcal{F}^{-1}[|\tilde{f}(\omega)|^2]$$

Let us optimize $\left|\tilde{f}(\omega)\right|^2$ via undulator tapering in order to get as few cycles as possible.

On-axis field in a tapered undulator

$$E_\omega(0,z) = -\frac{Q}{c2\pi\sigma_b^2}\frac{2\mathcal{K}}{\gamma}\, e^{-\frac{\omega^2\sigma_T^2}{2}} \int\limits_{-L_u/2}^{L_u/2} \frac{f_u(z')\sin[k_u z']}{1+i\,\frac{z-z'}{k\sigma_b^2}}\, e^{i\omega\,\Delta t_e(z')} dz'$$

$$E_\omega^+ = E_\omega^0 \int_{-L_u/2}^{L_u/2} g(z')\,\mathrm{e}^{i\Psi(z')}\mathrm{d}z'$$

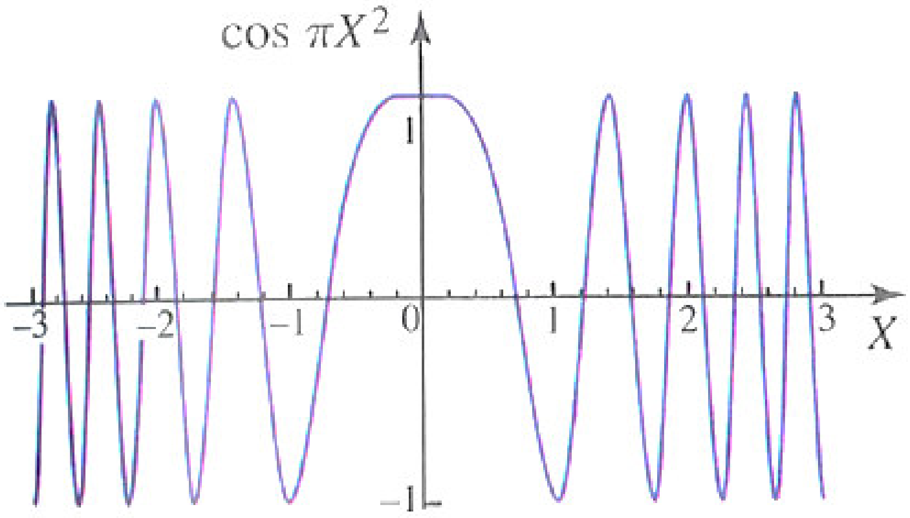
$$\Psi = \frac{2\pi}{\lambda_u \xi}\left[z(1-\xi) + \frac{\mathcal{K}^2}{2}\int_{-L_u/2}^{z} f_u^2(z')\mathrm{d}z'\right]$$

$$\xi = \frac{\lambda}{\lambda_0},$$

$$\lambda_0 = \frac{\lambda_u}{2\gamma^2}$$

E. Saldin et al. "A simple method for the determination of the structure of ultrashort relativistic electron bunches." NIMA 539.3 (2005): 499-526.

Stationary phase method



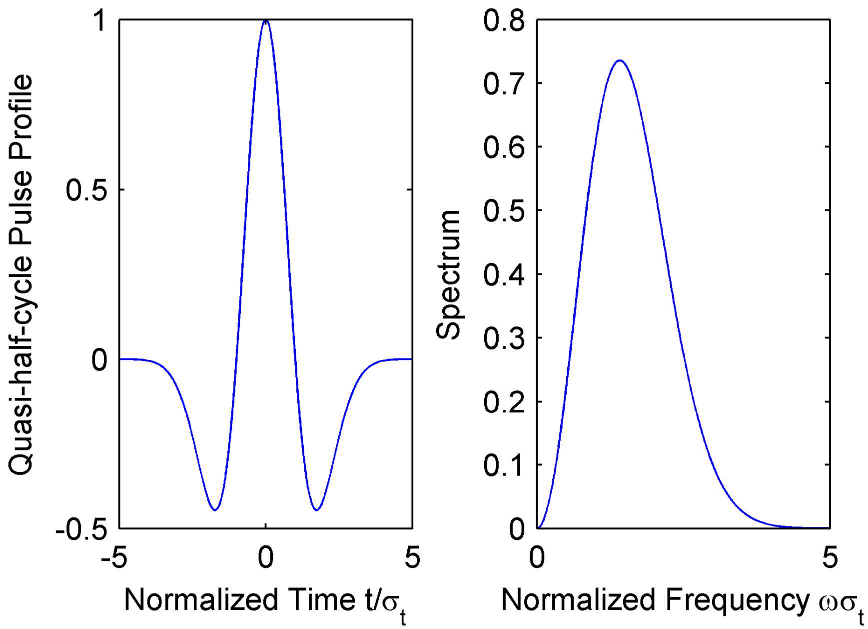
$$E_\omega^+ = E_\omega^0 \int_{-L_u/2}^{L_u/2} g(z')\, \mathrm{e}^{i\Psi(z')} \mathrm{d}z'$$

$\Psi'(z_0) = 0,$ stationary point

$$E_\omega(\xi) \approx \sum_j \sqrt{\frac{2\pi}{|\Psi''(z_{0,j})|}} E_\omega^0\, g(z_{0,j}) \exp\left[i\Psi(z_{0,j}) + i\frac{\pi}{4}\mathrm{sgn}\Psi''(z_{0,j})\right],$$

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{\mathcal{K}^2}{2} f_u^2(z_0)\right),$$

Optimal taper profile



Consider a quasi-half-cycle pulse of the form

$$A(t) = A_0 \left(1 - \frac{t^2}{\sigma_t^2}\right) \mathrm{e}^{-t^2/2\sigma_t^2},$$

whose Fourier-transform reads

$$A_\omega = A_0 \sqrt{\frac{2}{\pi}} \sigma_t^3 \omega^2 \mathrm{e}^{-\sigma_t^2 \omega^2/2}.$$

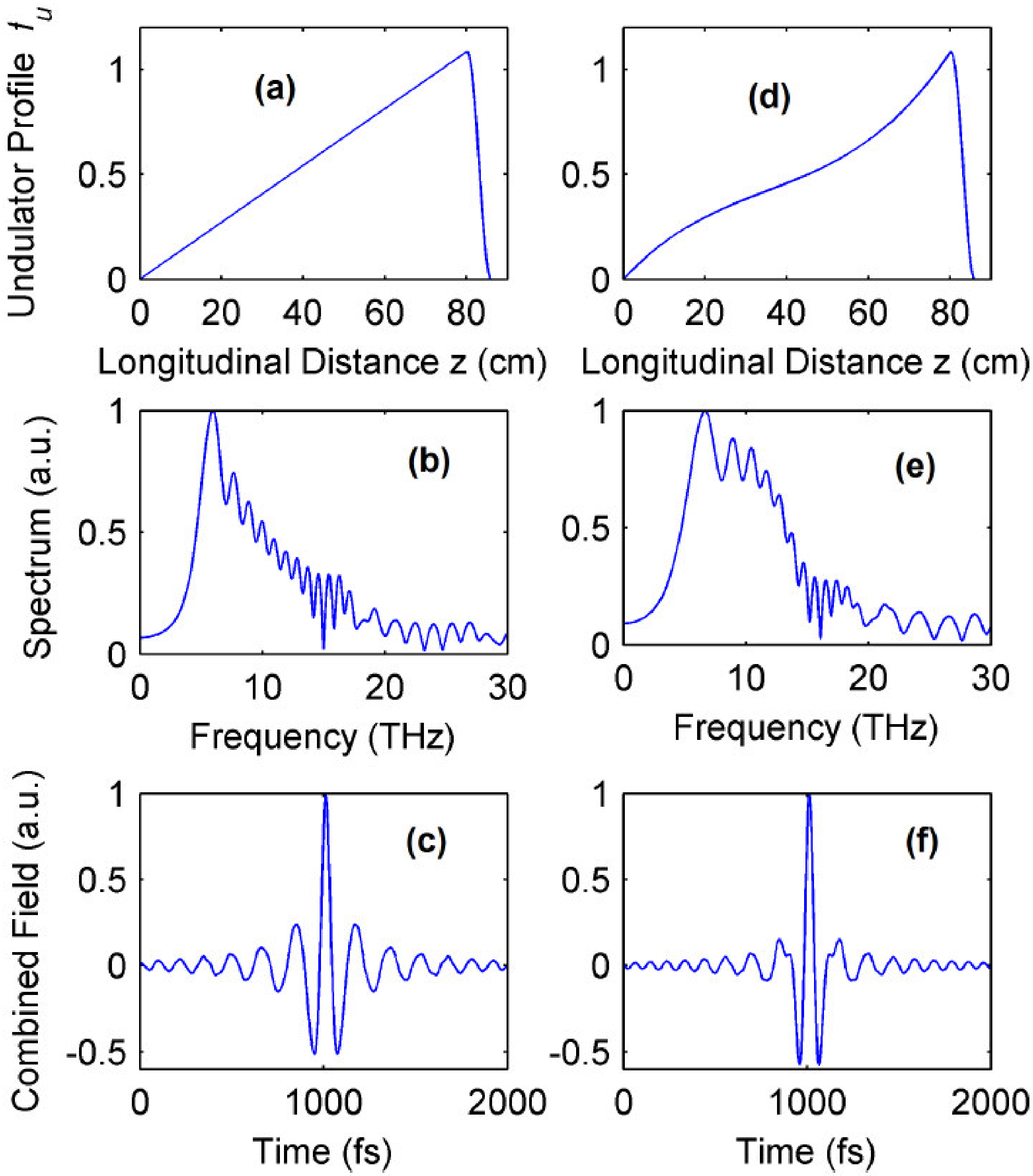
I equate the spectral power of radiation from a tapered undulator S_ω to that of the quasi-half-cycle pulse

$$S_\omega = |A_\omega|^2 \Rightarrow \frac{f_u \xi}{f_u'} = L_{\text{eff}}[1 - \alpha(\xi - \bar{\xi})^2], \quad \xi = 1 + \mathcal{K}^2 f_u^2(z_0)/2,$$

It turns out that the minimum number of cycles is 1.5.

$$\frac{z}{L_{\text{eff}}} = \frac{3}{2} \log\left[1 + \frac{f^2 \mathcal{K}^2}{2}\right] - \frac{f^2 \mathcal{K}^2}{4}.$$

Radiation from the optimally-tapered undulator



Parameter	Symbol	Value
bunch charge (pC)	Q_b	100
bunch duration (fs)	σ_τ	50
bunch radius (mm)	r_b	1
bunch energy (MeV)	U_b	20
undulator period (cm)	σ_u	6
number of periods	N_u	15
undulator parameter	$\mathcal{K}$	2
linear taper		
emitted energy (uJ)	$\mathcal{E}_r$	26
central frequency (THz)	f_c	7.25
relative bandwidth	$\Delta\omega/\omega$	95%
optimal taper		
emitted energy (uJ)	$\mathcal{E}_r$	25
central frequency (THz)	f_c	9
relative bandwidth	$\Delta\omega/\omega$	105%

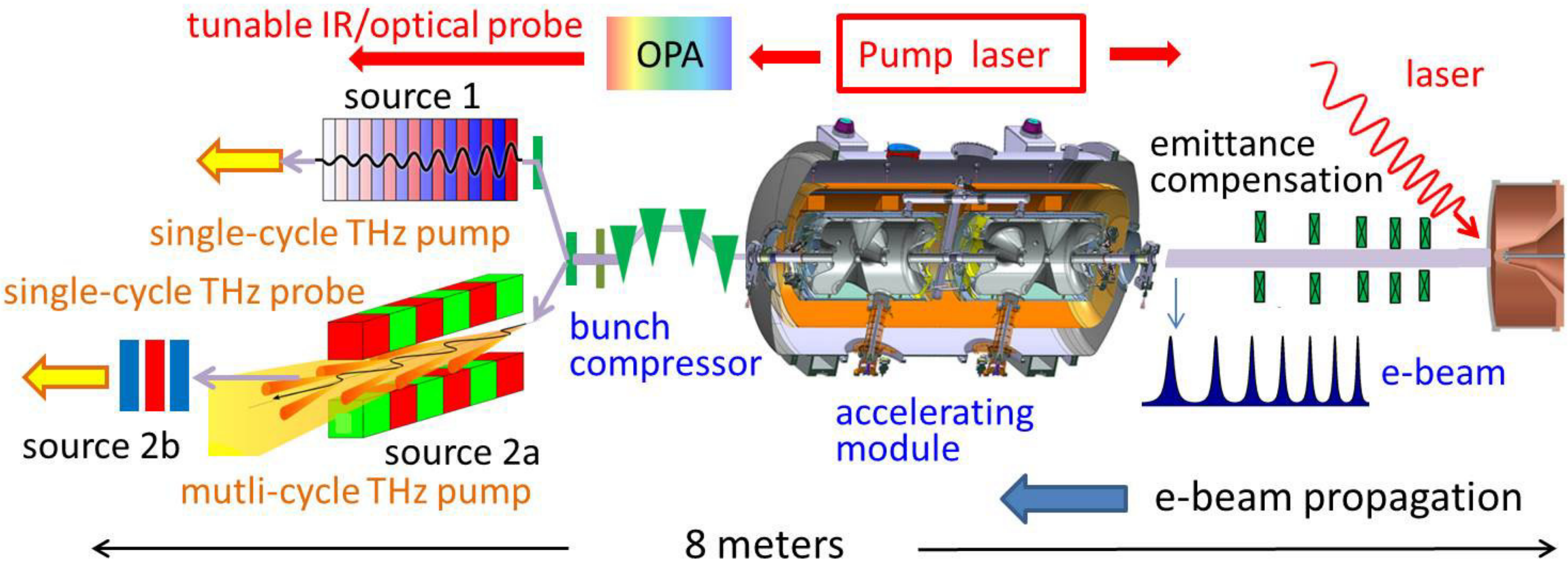
Proposal for a THz Light Source in Uppsala

Wish list for intense THz radiation.

Parameter	Quasi-half-cycle pulses for time-resolved experiments	Narrowband pulses for frequency-resolved experiments
Spectral range (THz)	1.5-15	1.5-15
Pulse duration (ps)	0.1-1	1-10
Pulse energy (mJ)	1000	100
Peak electric field (GV/m)	1	0.1
Relative bandwidth FWHM	100%	10%
Repetition rate (kHz)	1-100	1-100

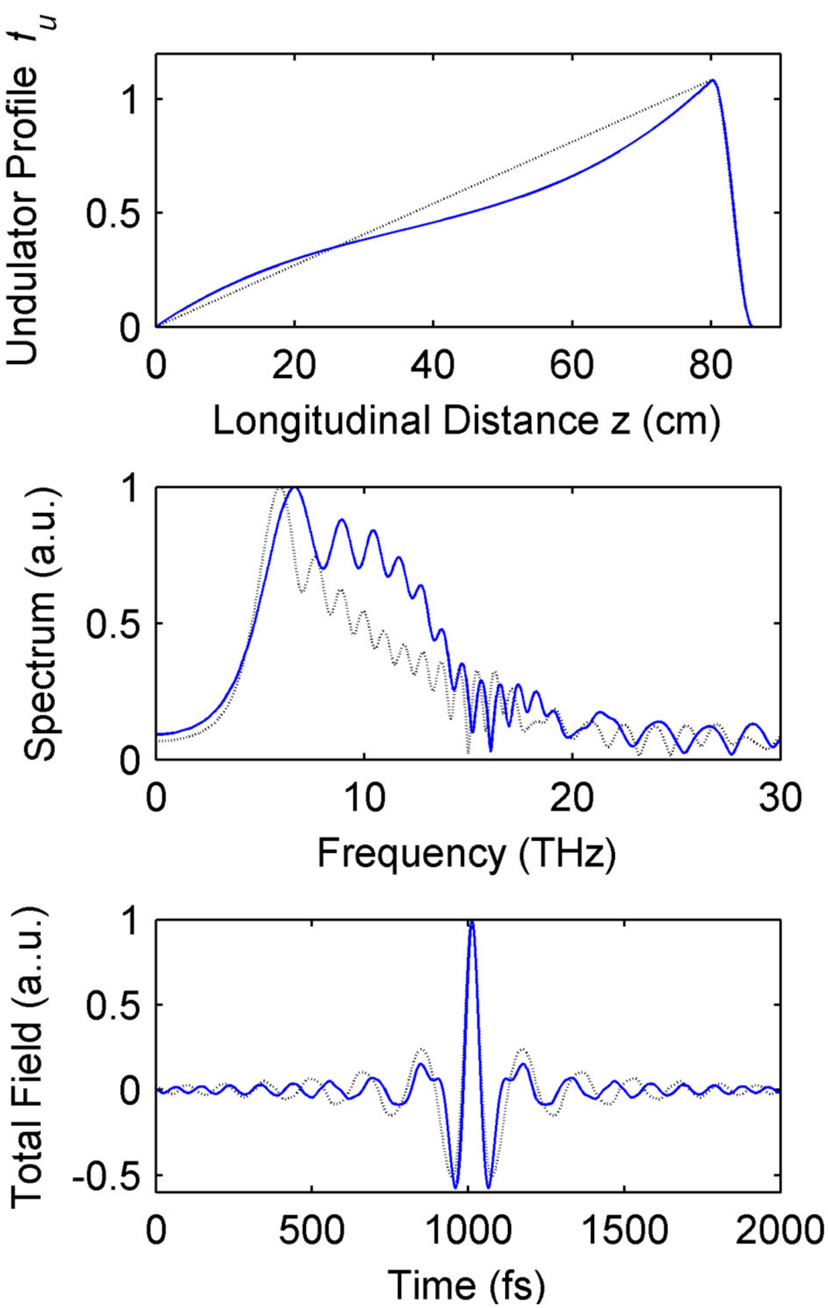
+ Polarization control, pump-probe configuration

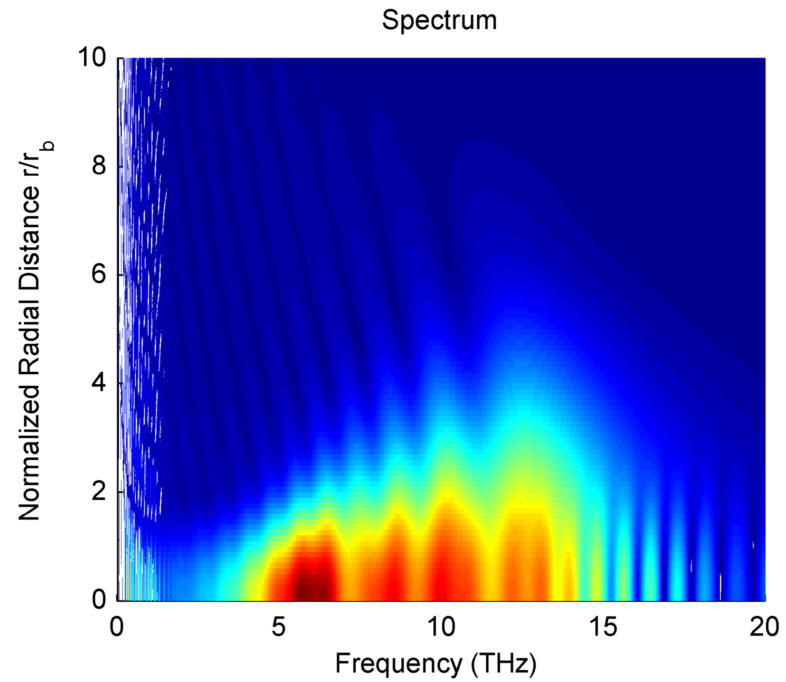
The source

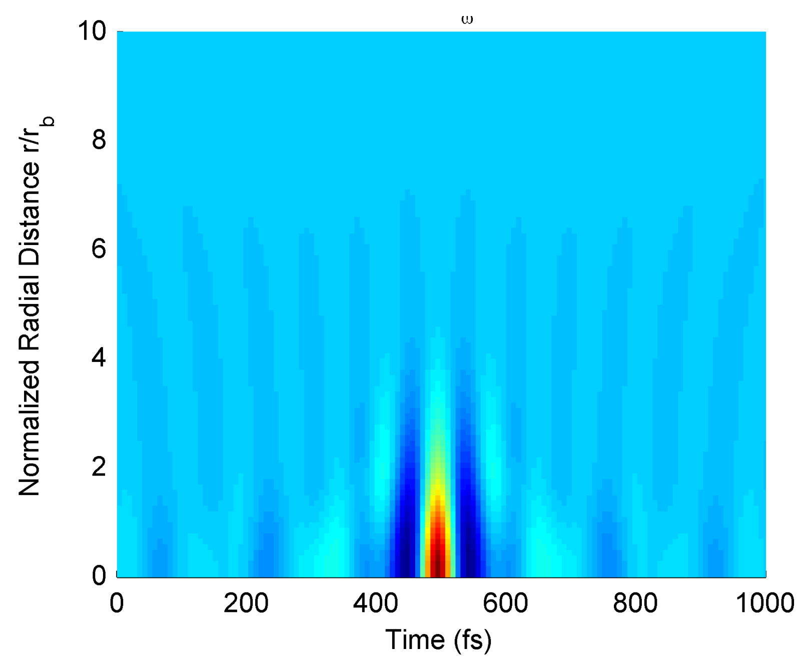


- it covers the spectral range from 5 to 15 THz, exceeding that of laser-based sources;
- polarization variable from linear to circular or elliptical;
- tunability of the central frequency and bandwidth;
- mutli-kilohertz repetition rate;
- light carrying orbital angular momentum.

Source 1: quasi-half-cycle pulses

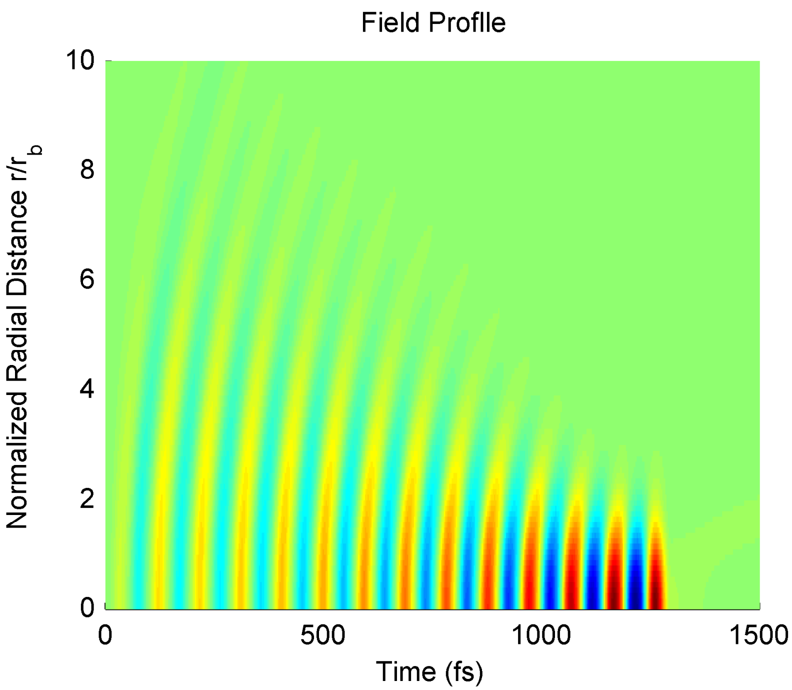


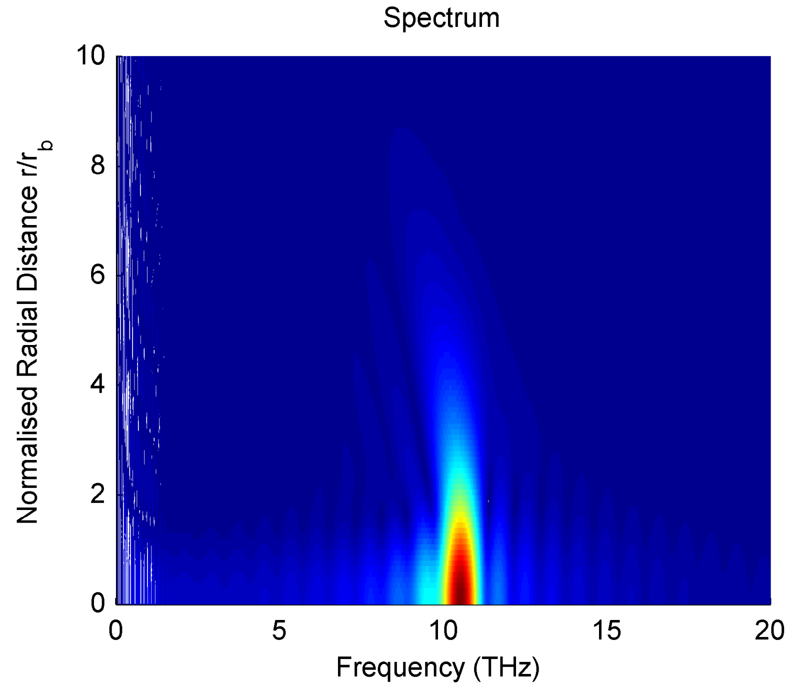




Source 2: multi-cycle pump and single-cycle probe

Source 2a





Source 2b