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JG|U

High-level layout and tentative performance of the X-ray source

Vitaliy Goryashko, Anatoliy Opanasenko, Kevin Pepitone, Akira Miyazaki, Peter Salen, Zoltan Tibai, Roger Ruber, Gerd Schönhense, Hermann Durr

SAC meeting, Uppsala

Outline

- Design goals and strategies
- Conceptual layout of the X-ray source
- Performance of the X-ray source

High-level design goals and strategy

Design goals:

- 1-4 keV; 10^2-10^4 ph/shot & photon flux > 10^7 ph/sec
- Evenly spaced photon pulses at 1-100 kHz
- Sub-ps X-ray pulses synchronized with optical laser pulses
- Compact solution (preferably fits into 25 meters)

Design strategy

- Superconducting (SC) accelerator (~10 MeV) in CW mode
- Normal conducting CW RF gun (some analogy with LCLS-II)
- IR laser undulator
- Phase I: single-pass incoherent undulator (Compton) X-ray source
- Phase II: coherent undulator X-ray source

Our inhouse strength/base

- SC accelerator technology
- RF power sources
- Competence in beam physics, FEL physics, X-ray beamlines

Technical challenges and strategies

Design challenges:

- Beam emittance at the nm scale
- Beam bunching at the nanometer (nm) scale [for coherent X-rays]
- Beam focusing of laser and electron beams at the um scale
- Spatial overlap and temporal synchronization

Design strategies for ultralow emittance:

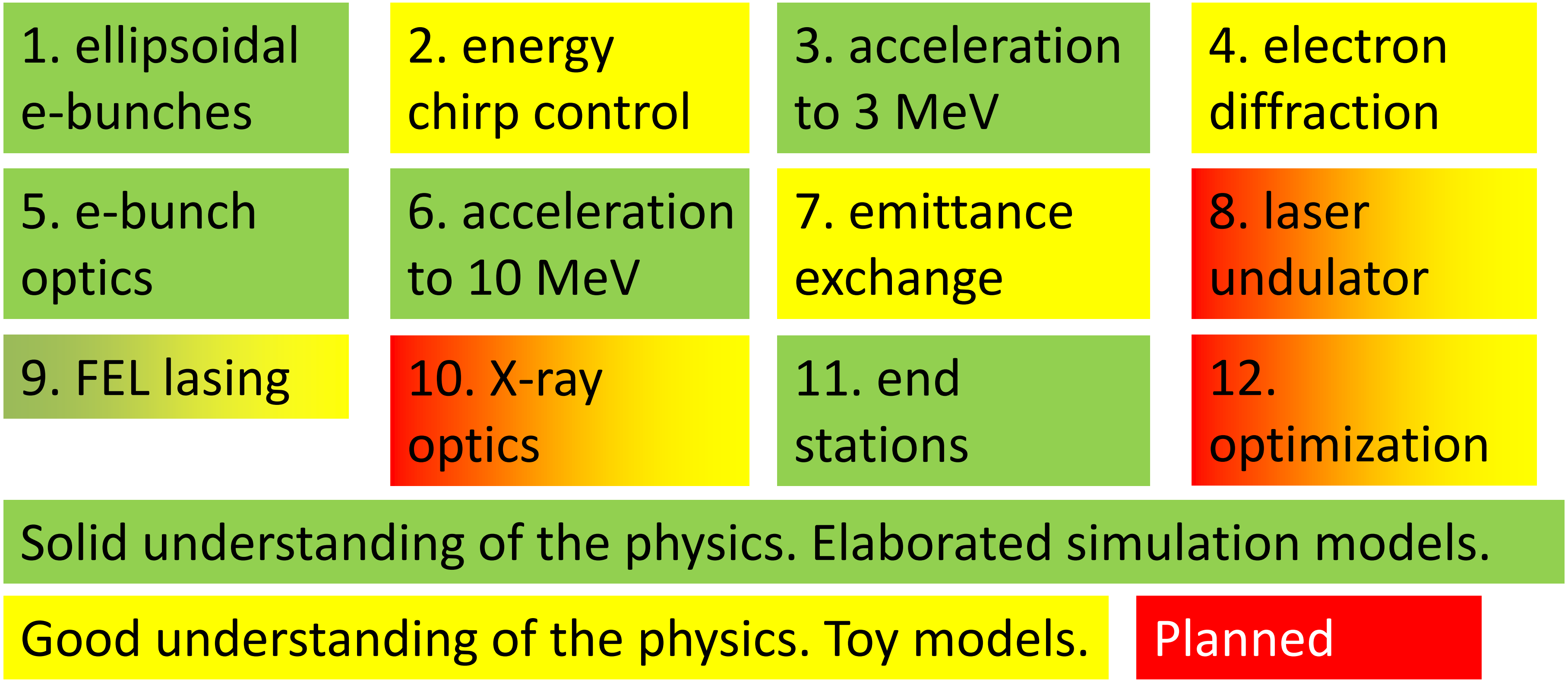
- Blow-out beam generation
- Collimation of a high-emittance beam
- Field emitters

Design strategies for beam structuring (nanobunching):

- Beam structuring via electron diffraction + emittance exchange
- Beam structuring using plasmonic cathodes + emittance exchange
- Modulated beam from a cold electron source

We started the design with a more general case of the coherent source to make sure that it can be accommodated in the Phase II.

Conceptual layout of the X-ray source

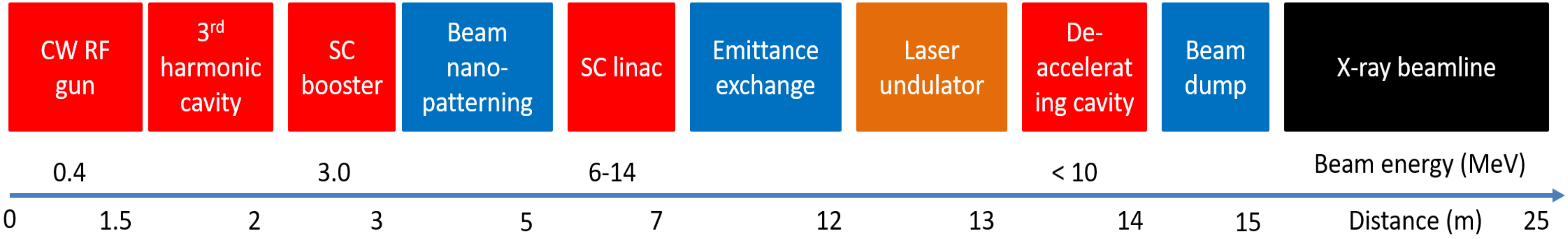


1. ellipsoidal e-bunches
2. energy chirp control
3. acceleration to 3 MeV
4. electron diffraction
5. e-bunch optics
6. acceleration to 10 MeV
7. emittance exchange
8. laser undulator
9. FEL lasing
10. X-ray optics
11. end stations
12. optimization

🟩 Solid understanding of the physics. Elaborated simulation models.

🟨 Good understanding of the physics. Toy models.

🟥 Planned



CW RF gun | 3rd harmonic cavity | SC booster | Beam nano-patterning | SC linac | Emittance exchange | Laser undulator | De-accelerating cavity | Beam dump | X-ray beamline

Beam energy (MeV): 0.4, 3.0, 6-14, < 10

Distance (m): 0, 1.5, 2, 3, 5, 7, 12, 13, 14, 15, 25

Conceptual layout: 1

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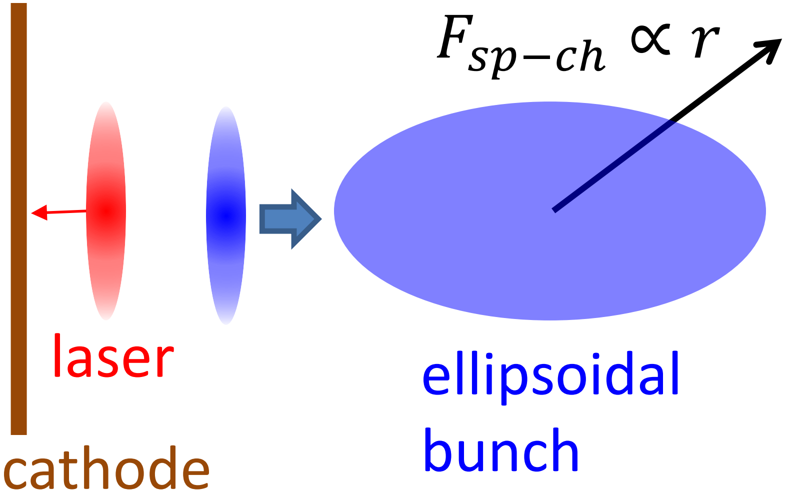

- Linear space-charge force of a uniform ellipsoidal electron bunch.
- A flat charged disk can blow out into a fully fledged ellipsoidal bunch, O.J. Luiten, PRL 094802 (2004).
- $\rho(r,z) = \sigma_0\sqrt{1-(r/R)^2}\delta(z)$
- Density is limited by the image charge.

Conceptual layout: 1

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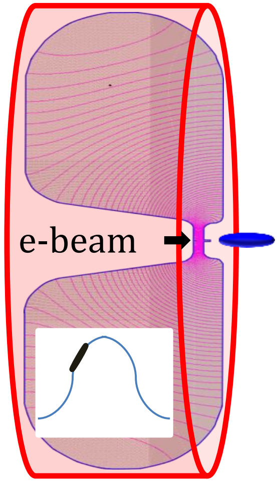
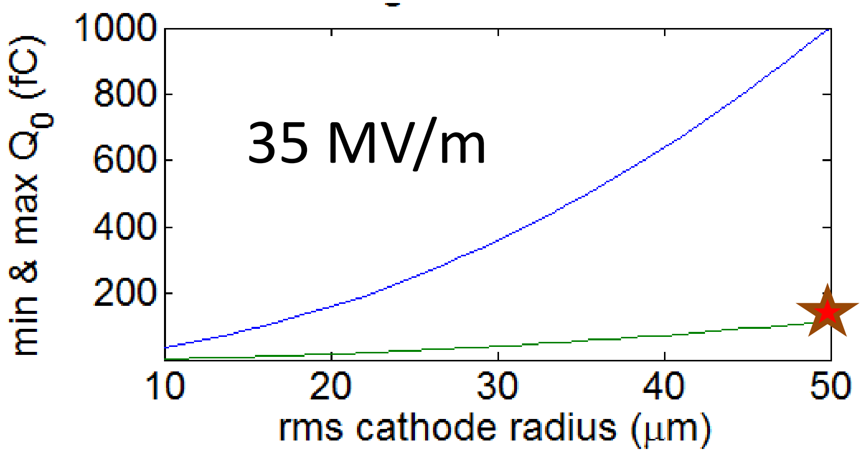
CW RF gun



325 MHz
CW, ~ 25 kW
420 keV



Initial beam:

- 50 um
- 100 fs
- 160 fC
- 20 nm emittance
- half-circular density distribution

Conceptual layout: 2

- 1. ellipsoidal e-bunches
- **2. energy chirp control**
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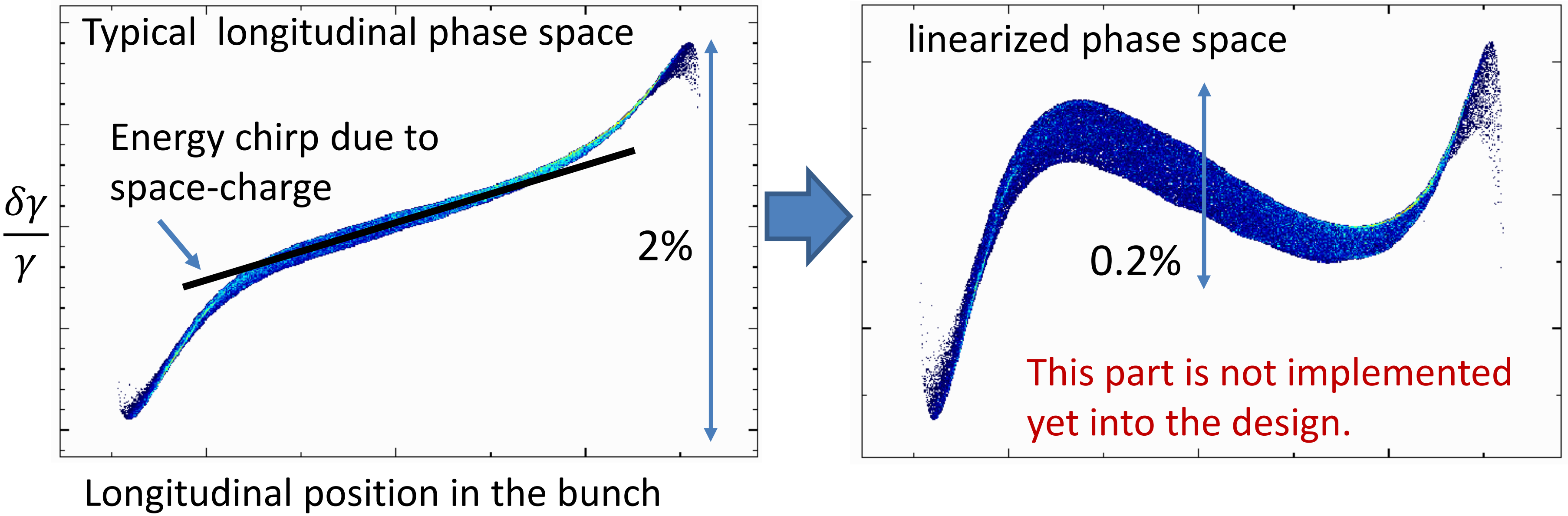

This part is not implemented yet into the design.

Conceptual layout: 3

1. ellipsoidal e-bunches	2. energy chirp control	3. acceleration to 3 MeV	4. electron diffraction
5. e-bunch optics	6. acceleration to 10 MeV	7. emittance exchange	8. laser undulator
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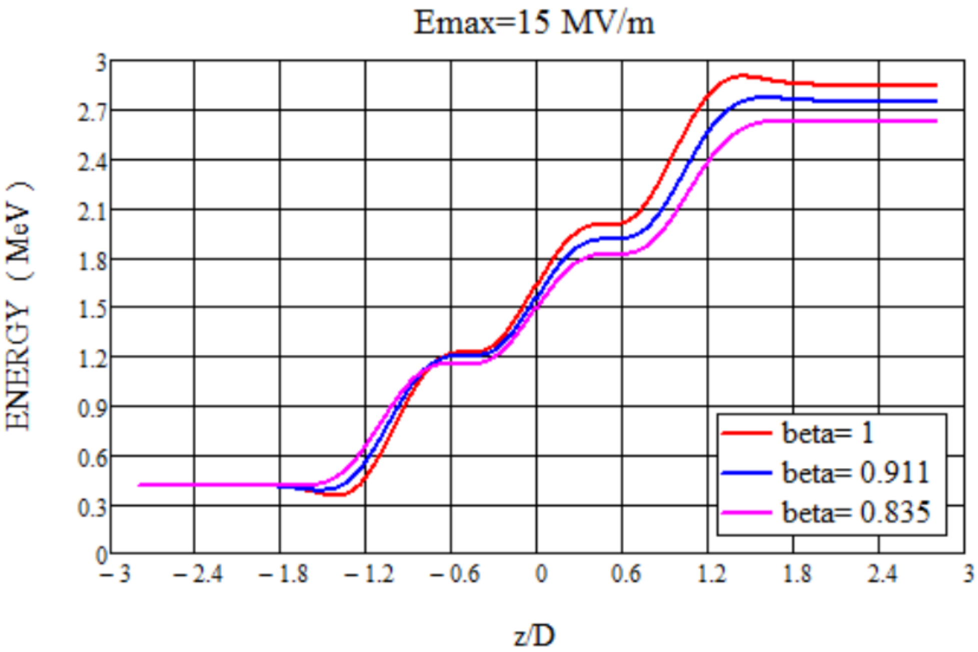
SC booster

1.3 GHz, SC
CW, ~1 W RF
3 MeV



Conceptual layout: 4

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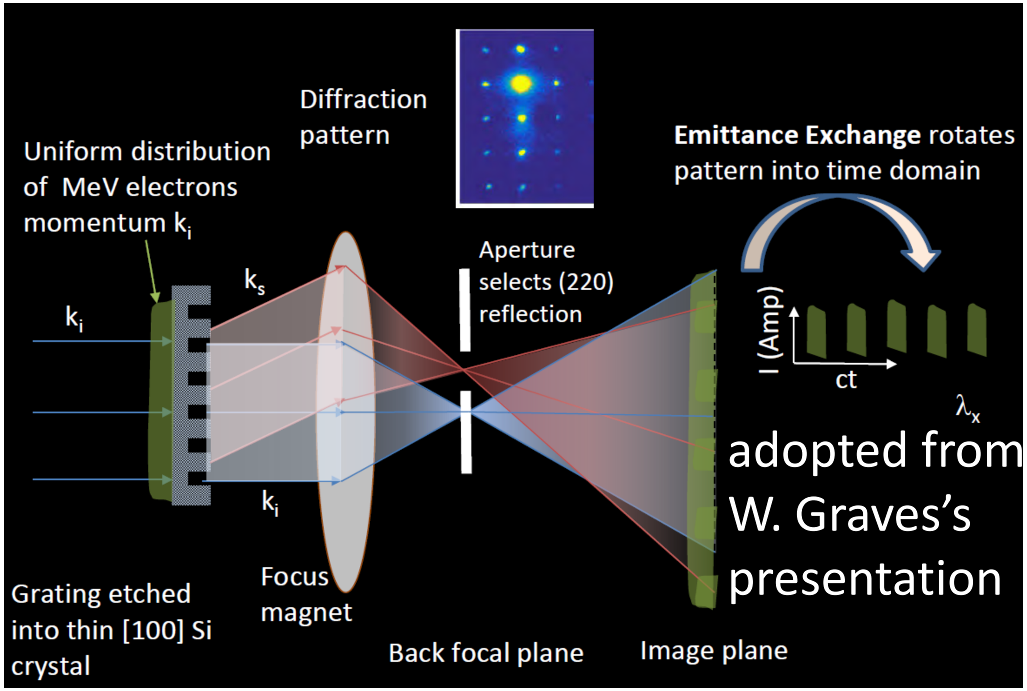

adopted from W. Graves's presentation

- Availability of strong local expertise in quantum simulations of electron diffractions on various structures
- Simulations are computationally heavy (energy spread, beam emittance, multiple scattering)
- When the modelling of beam dynamics is more solid, accurate quantum simulations of e-diffraction will be performed

Conceptual layout: 5

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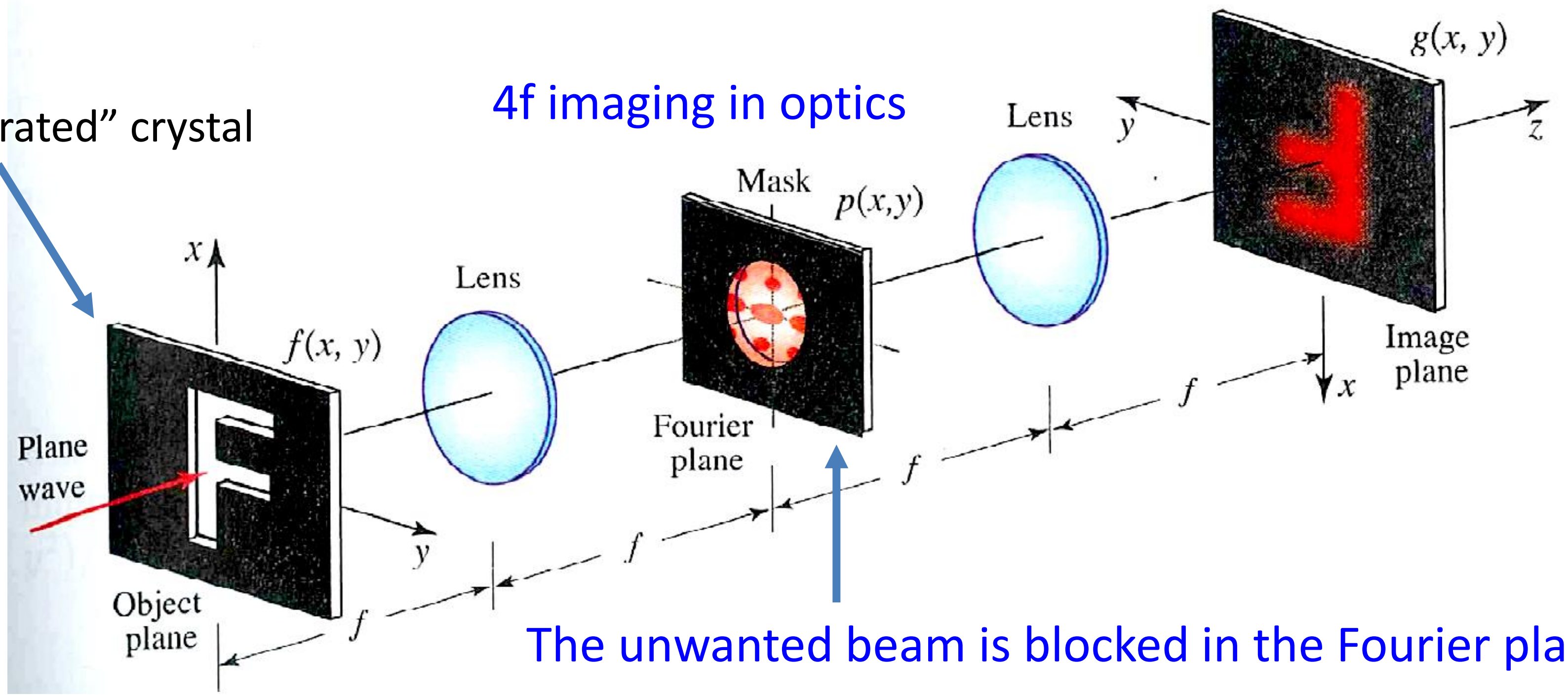

“Perforated” crystal

4f imaging in optics

The unwanted beam is blocked in the Fourier plane.

Conceptual layout: 6

1. ellipsoidal e-bunches

2. energy chirp control

3. acceleration to 3 MeV

4. electron diffraction

5. e-bunch optics

6. acceleration to 10 MeV

7. emittance exchange

8. laser undulator

9. FEL lasing

10. X-ray optics

11. end stations

12. optimization

SC main accelerator

1.3 GHz, SC CW, ~ 100 W, 7-14 MeV

Conceptual layout: 7

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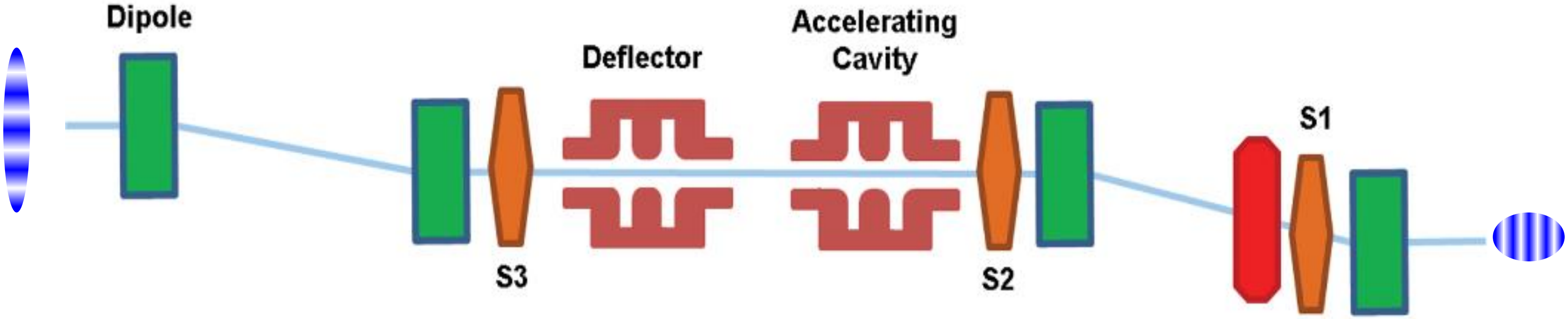

E. Nanni, and W. S. Graves. "Aberration corrected emittance exchange." *PRAB* (2015): 084401.

Conceptual layout: 8

1. ellipsoidal e-bunches	2. energy chirp control	3. acceleration to 3 MeV	4. electron diffraction
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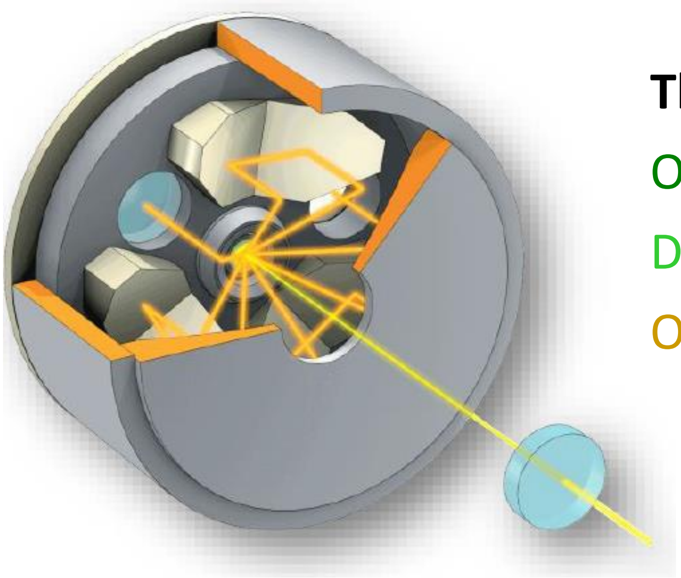

Tom Metzger,
TRUMPF Scientific Lasers

Thin-disk Yb:YAG lasers from TRUMPF at 1 um:

Off-the-shelf: 0.75 kW, 20-100 kHz, up to 150 mJ, < 1 ps

Demonstrated: 1.9 kW, 20 kHz, up to 95 mJ, < 1 ps

On special order: 5 kW, 100 kHz, 50 mJ, < 1 ps (M2 ?)

Conceptual layout: 9

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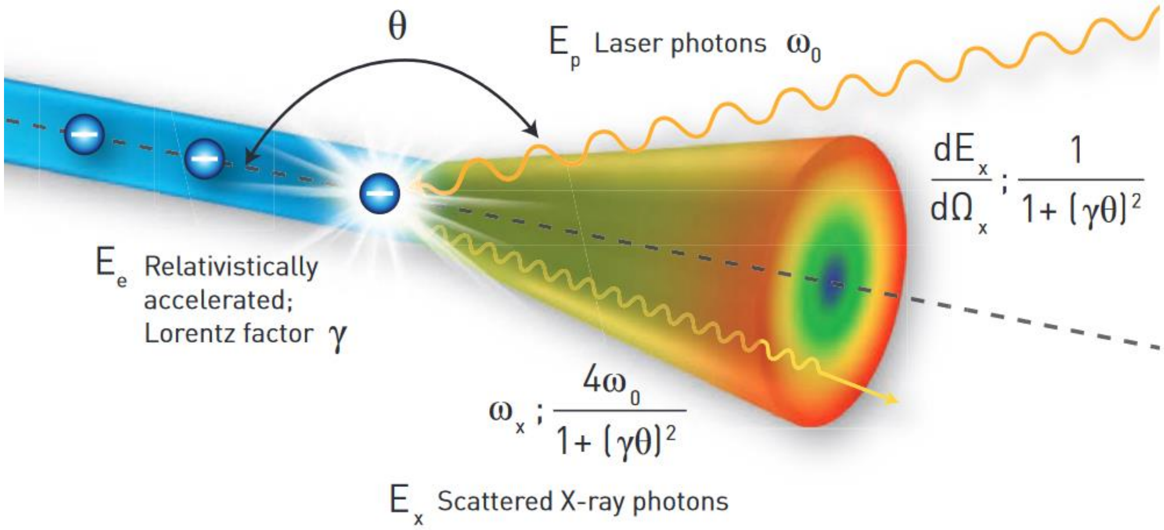
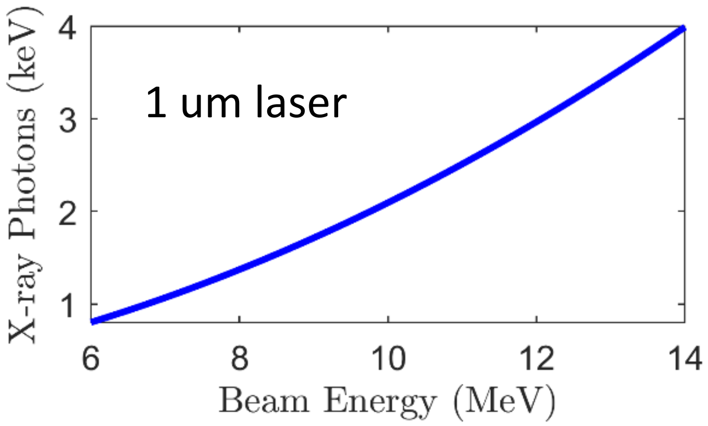


L. Assoufid *et al*. Optics and Photonics News (2015).



We will discuss this part in all details just in a few minutes!

Conceptual layout: 10

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- 9. FEL lasing
- **10. X-ray optics**
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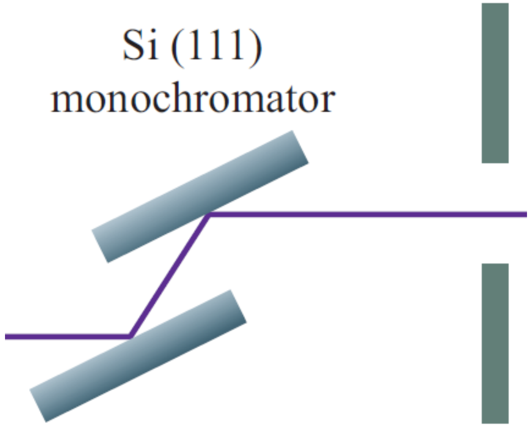
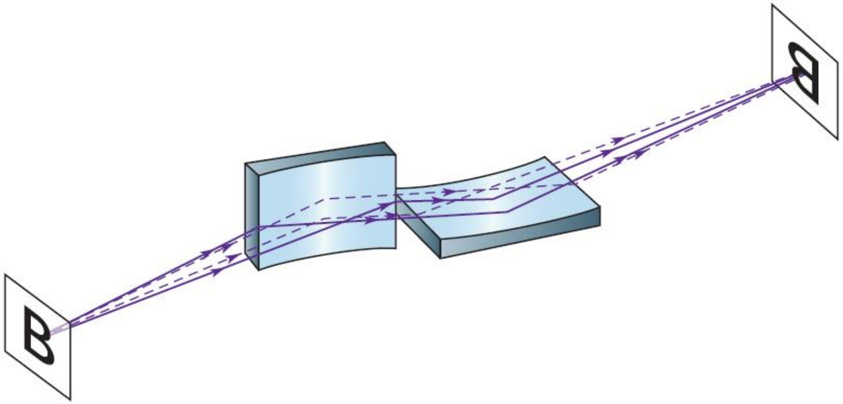
- The photon beam divergence is large
- We have experience with X-ray optics design
- Current solution is a KB set and a double-crystal monochromator





Conceptual layout: 11

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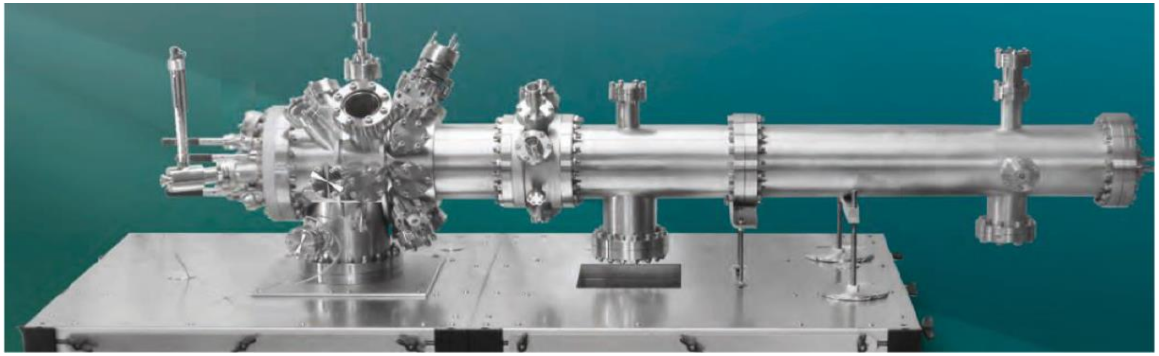

Momentum Microscope. Gerd Schönhense

Conceptual layout: 12

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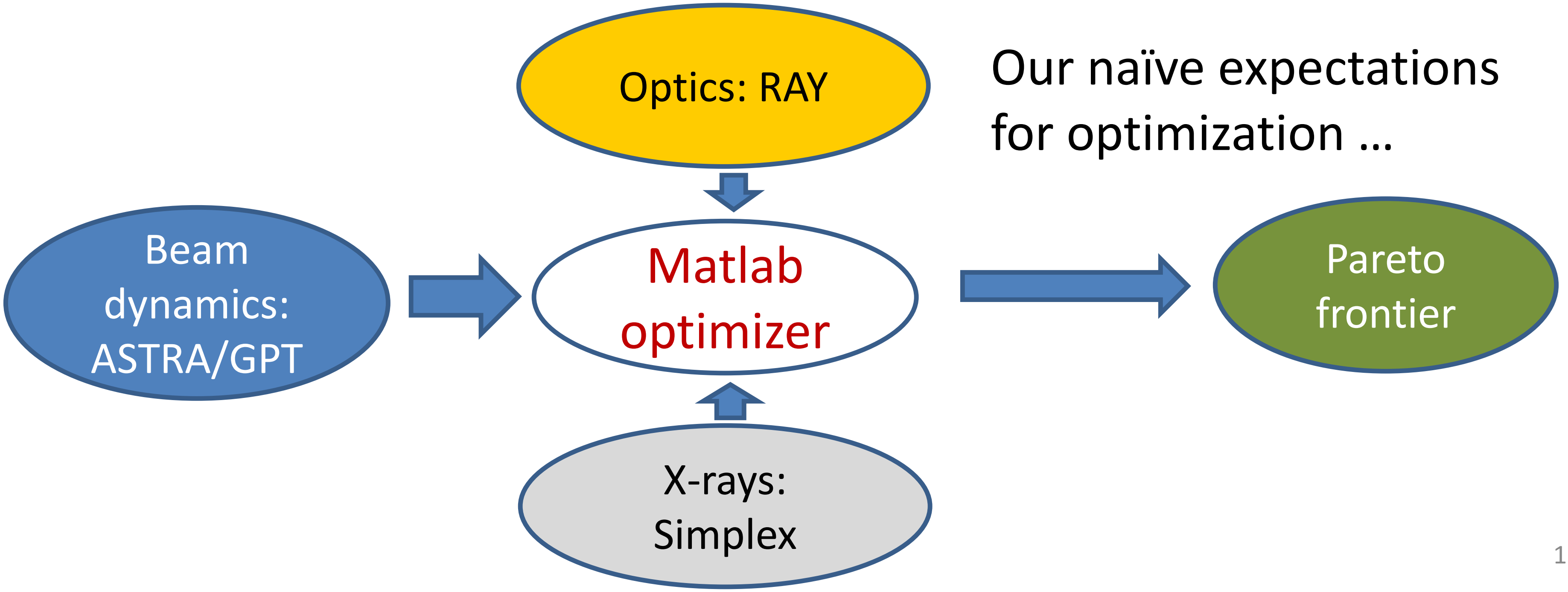
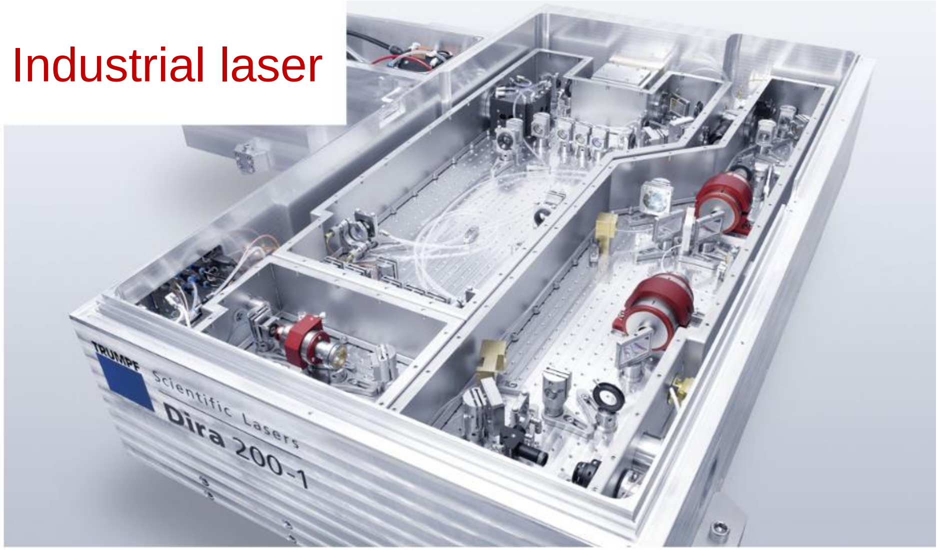
- **12. optimization**

Our naïve expectations for optimization …



X-ray source performance

Laser undulator options



Industrial laser

Thin-disk technology, for example, Trumpf Dira:
1 um, < ps, up to ~ 0.1 J,
high rep. rate and high power.

BNL (monster) $C0_2$ laser:
10 um, ~ 5 ps, ~ 1 J, low rep. rate.

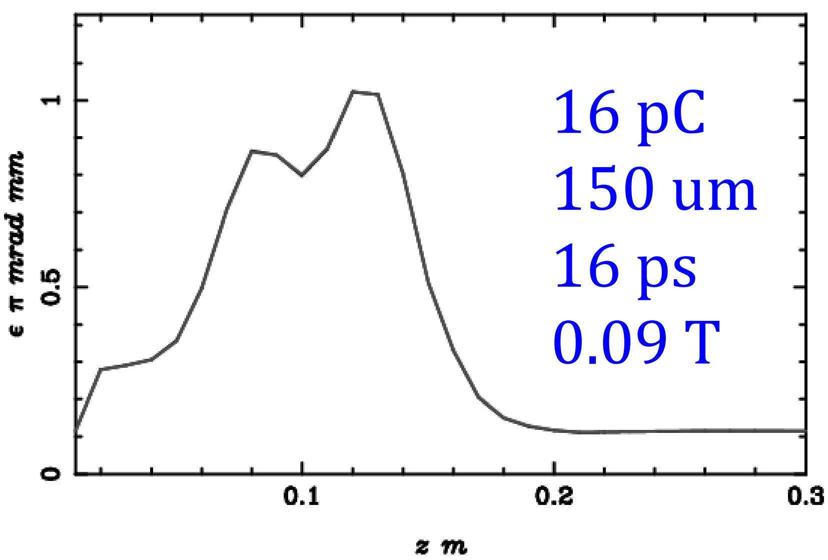
Comments on calculation of Compton radiation

- Earliest publications on Compton sources date back to the 60s [first experiment: C. Bemporad et al. Phys. Rev. 21 (1965); detailed theory: R. Coisson, Phys. Rev. A 20, 524 (1979)].
- Over 100 theoretical studies but no closed-form analytical solution taking into account all broadening effects.
- Work by W. Brown and F. Hartemann, PRST AB **7**, 060703 (2004) is probably the most detailed analysis in the literature.
- In our work, we estimate the total number of emitted X-ray photons using the model of spontaneous undulator radiation and calculate the spectrum broadening from Hartemann's publication.
- The intrinsic bandwidth is ~0.3% ($N_u \approx 300$).
- The ponderomotive broadening due to the varying amplitude of the laser pulse is assumed to be compensated for by the proper chirp of the pulse.
- The spatial profile is assumed to be flattened $\Delta E(r = \sigma_b)/E(0)$ < 8%.
- The broadening effect from the electron and photon beam divergence are calculated from Hartemann's publication, Eq. (63), and amounts to 0.42%.
- Simulations with Simplex are done for cross-checking.

Target parameters of incoherent X-ray source

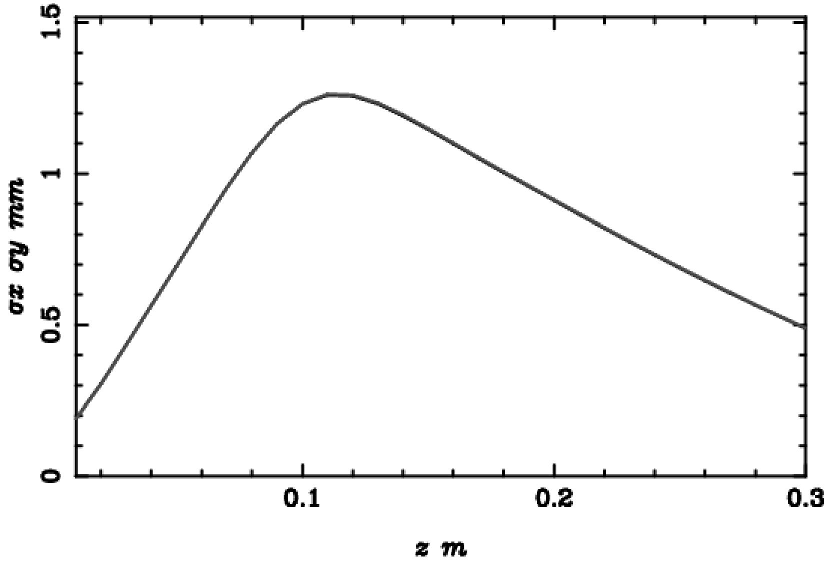
Electron beam parameters	electron bunch charge	Q_b	16	pC
	number of electrons	N_b	10^8	
	bunch energy	U_b	7.6	MeV
	relative energy spread	δ_γ	10^{-4}	
	rms bunch duration	τ_b	0.25	ps
	bunch emittance	ϵ_n	0.1	mm mrad
	rms bunch size	σ_b	3.5	um
	geometrical beta-function	β_g	2	mm
Laser beam parameters	laser wavelength	λ_L	1.0	um
	rms laser pulse duration	τ_L	1	ps
	rms laser beam size	σ_L	4.9	um
	Rayleigh length	z_R	0.3	mm
	laser pulse energy	$\mathcal{E}_L$	50	mJ
	undulator parameter	$\mathcal{K}$	0.14	
	laser rep. rate	f_L	100	kHz
X-ray yield	radiation wavelength	λ_r	1	nm
	rms X-ray pulse duration	τ_X	0.25	ps
	rms X-ray beam size	σ_X	3.5	um
	rms X-ray beam divergence	$\sigma_{X'}$	0.4	mrad
	X-ray photons/shot/0.01%BW	$N_{ph,0.01\%}$	780	
	X-ray photons/second/0.01%BW	$\mathcal{F}_{0.01\%}$	7.8 10^7	

Quick test of the RF gun performance

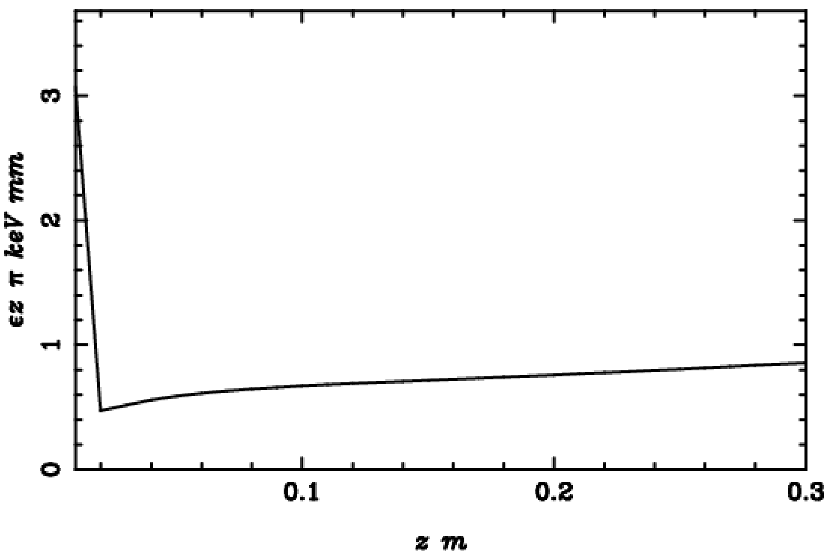


Transverse Emittance

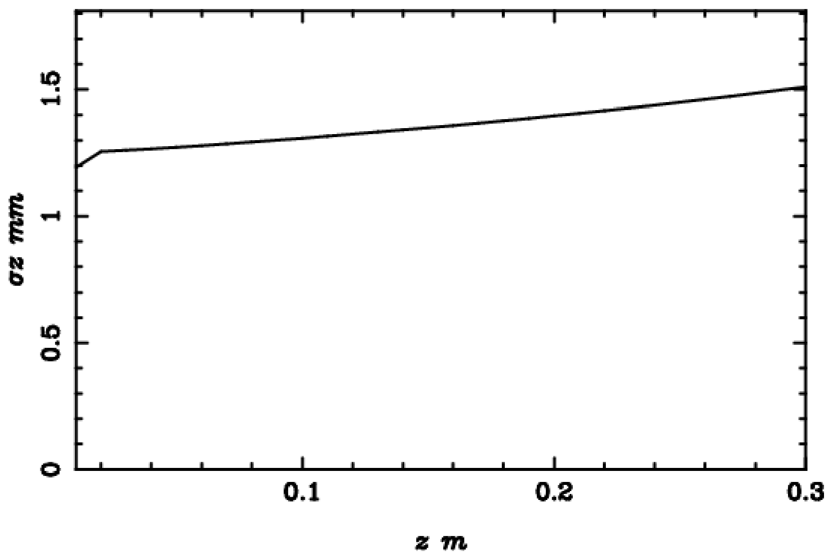
16 pC
150 um
16 ps
0.09 T



Beam Size



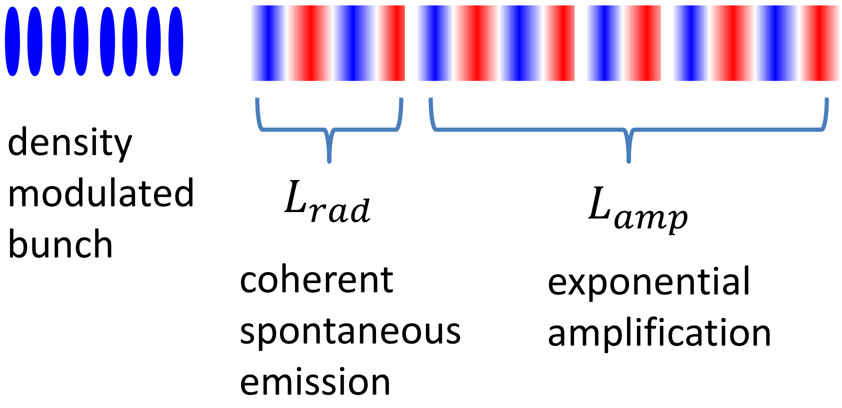
Longitudinal Emittance



Bunch Length

Coherent X-ray source

Self-**A**mplifier **C**oherent **S**pontaneous **E**mission (SACSE)



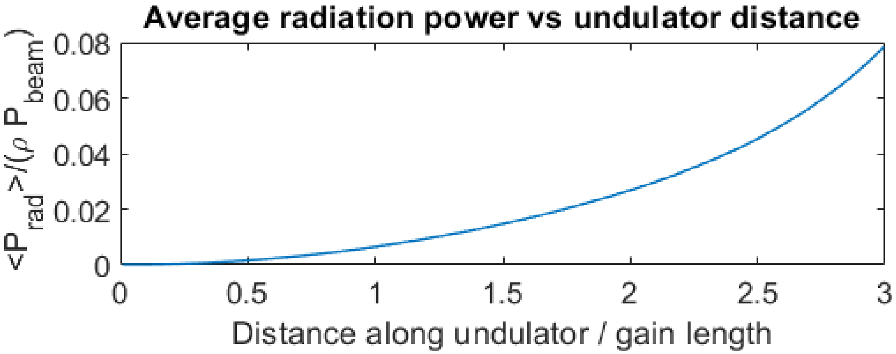
density modulated bunch

L_{rad}

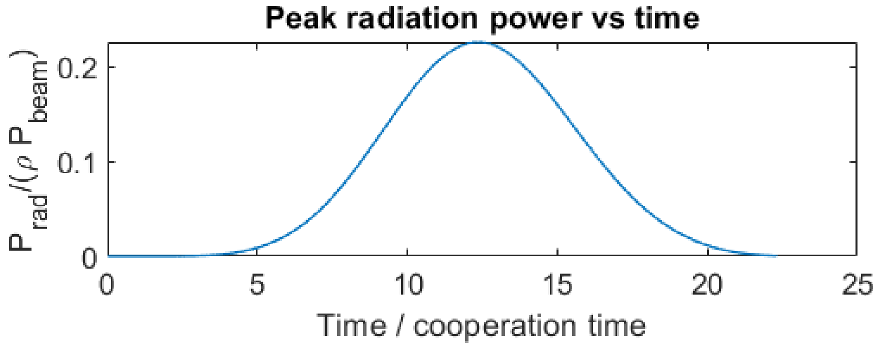
coherent spontaneous emission

L_{amp}

exponential amplification



Average radiation power vs undulator distance



Peak radiation power vs time

$\mathcal{E}_{\mathrm{rad}}^{\mathrm{sat}} \approx \varrho U_b Q_B$ radiated energy

bunch current

undulator period

undulator parameter

$$\varrho = \frac{1}{4\gamma_r}\left[\frac{1}{\pi^2}\frac{I_b}{I_\alpha}\frac{\lambda_u^2}{\sigma_b^2}K^2\right]^{1/3}$$

resonant bunch energy

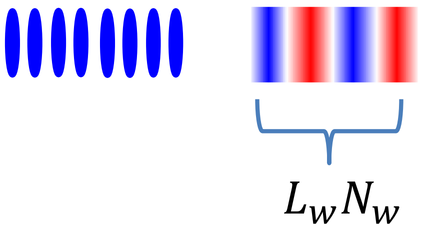
beam size

Alphen current, 17 kA

For a compact FEL, $\varrho \sim 10^{-5}$ - 10^{-4}.

$\boldsymbol{\mathcal{E}_{rad}^{sat}} \sim$ **1 – 10 nJ** for $Q_b \sim 1$ pC and $U_b \sim$ 10 MeV.

Coherent **S**pontaneous **E**mission



coherent
spontaneous
emission

Classical FEL vs compact FEL:

$\sigma_b = 10$ um, $\lambda_w = 10$ mm,
$\lambda_r = 1$ nm, $N_w = 100$
$N_F = 0.63$, D = 0.23

$\sigma_b = 1$ um, $\lambda_w = 1$ um,
$\lambda_r = 1$ nm, $N_w = 100$
$N_F = 63, D = 0.0025$

Coherent emission is very weak for a short period undulator.

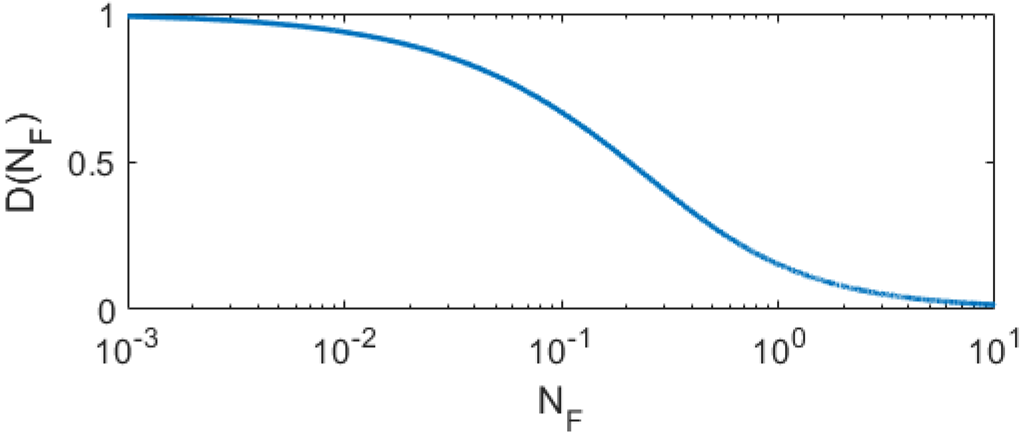
$\mathcal{E}_{rad} = D(N_F)\mathcal{E}_0$ - emitted energy

Energy emitted by an ultrathin electron beam:

$$\mathcal{E}_0 = \left[\frac{\pi^2 a_{\text{in}}^2}{2}\frac{I}{\gamma I_\alpha}\frac{K^2}{2+K^2}A_{\text{jj}}^2 N_w\right]U_b Q_b$$

$D(N_F)$ is the diffraction function with

$N_F = \frac{k\sigma_b^2}{N_w \lambda_w} \gg 1$ - electrons Fresnel number



E.L. Saldin et al. NIMA 539 (2005).

Coherent X-ray source

Electron beam parameters	electron bunch charge	Q_b	0.8	pC
	number of electrons	N_b	$5\ 10^6$	
	bunch energy	U_b	7.6	MeV
	relative energy spread	δ_γ	10^{-4}	
	rms bunch duration	τ_b	50	fs
	bunch emittance	ϵ_n	0.03	mm mrad
	rms bunch size	σ_b	2	um
	geometrical beta-function	β_g	2	mm
Laser beam parameters	laser wavelength	λ_L	1.0	um
	rms laser pulse duration	τ_L	1000	fs
	rms laser beam size	σ_L	4.9	um
	Rayleigh length	z_R	0.3	mm
	laser pulse energy	$\mathcal{E}_L$	50	mJ
	undulator parameter	$\mathcal{K}$	0.14	
	laser rep. rate	f_L	100	kHz
X-ray yield	radiation wavelength	λ_r	1	nm
	X-ray pulse duration	τ_X	50	fs
	rms X-ray beam size	σ_X	1.5	um
	rms X-ray beam divergence	$\sigma_{X'}$	75	urad
	X-ray photons/shot/0.01%BW	$N_{ph,0.01\%}$	$3\ 10^4$	
	X-ray photons/second/0.01%BW	$\mathcal{F}_{0.01\%}$	$3\ 10^9$	

Summary

- Recent development of very high-power ps lasers opened the door to high repetition rate, high-flux compact X-ray sources
- We envision a two-stage approach based on
  - (i) an incoherent X-ray source based on spontaneous undulator radiation from a laser undulator
  - (ii) a coherent source employing self-amplified coherent spontaneous emission from a pre-bunched electron beam
- The design of a SC accelerator is underway with the main focus on an emittance exchange line at the moment
- Design of an optical system is the next big goal.

Questions/Comments ?

Back-up slides

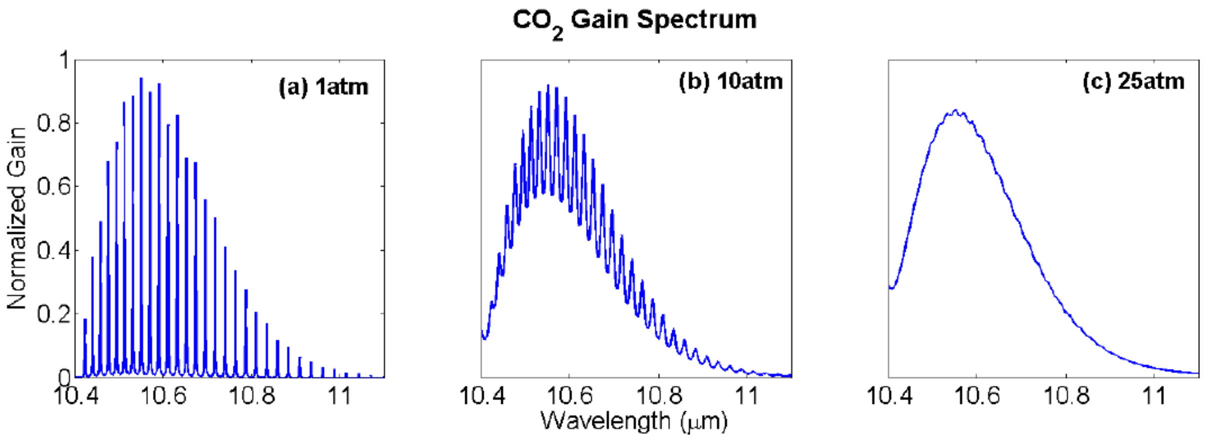
Carbone dioxide (CO2) lasers

There are only two groups in the world working on short-pulse CO2 lasers:

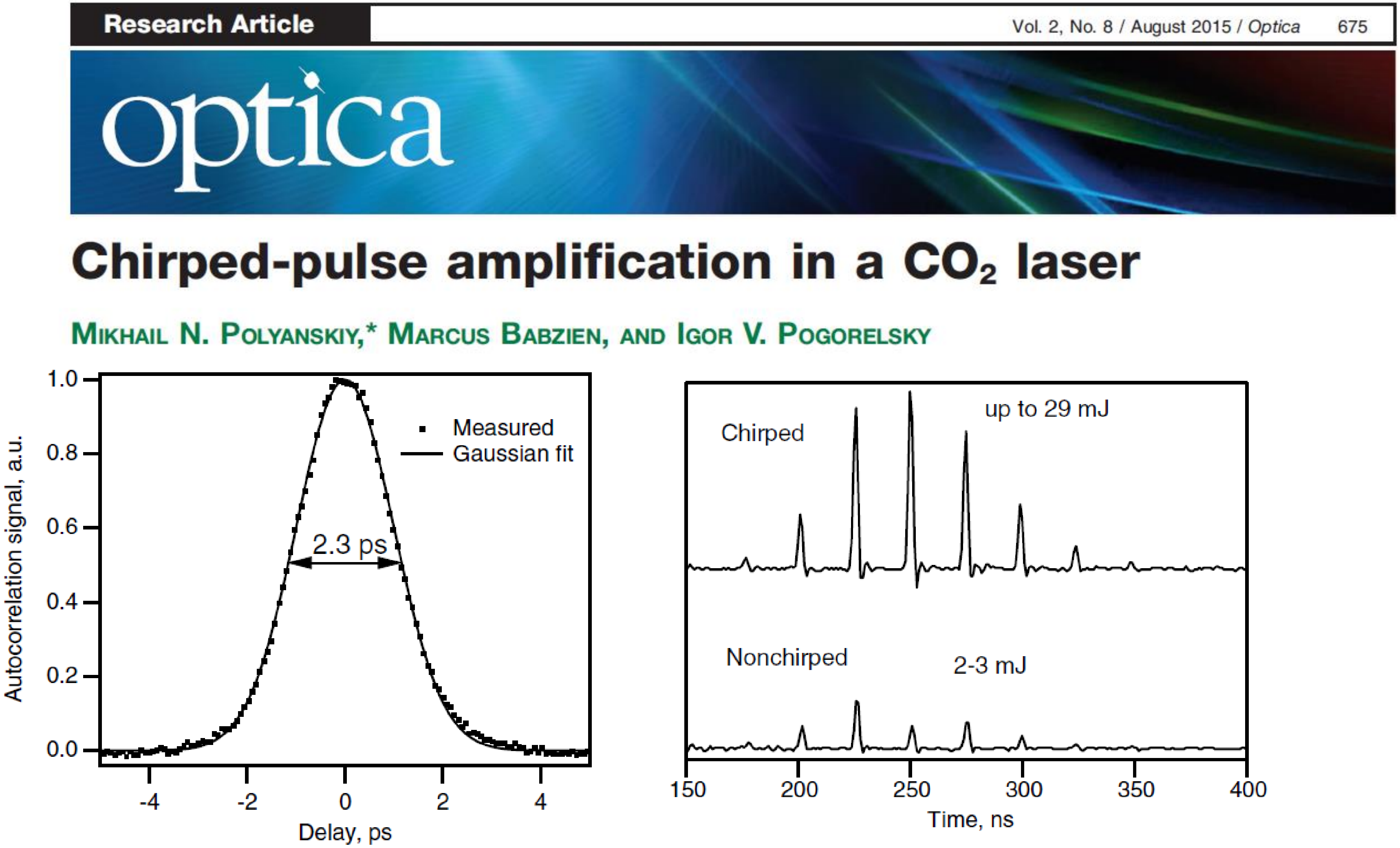
- Brookhaven Lab, US
- Neptune Lab, UCLA,US

C02 laser

- One of the first gas lasers in the world
- High pump efficiency ~20%
- Operated at around 10 um
- CW power up to 100 kW
- Widely used in industry for cutting and welding
- Very narrow transition line: typical pulse duration ~ ns
- To shorten the pulse duration, the gas must be pressurized to a few atmospheres to broaden the emission line



CO2 lasers at Brookhaven



Research Article

Vol. 2, No. 8 / August 2015 / *Optica* 675

optica

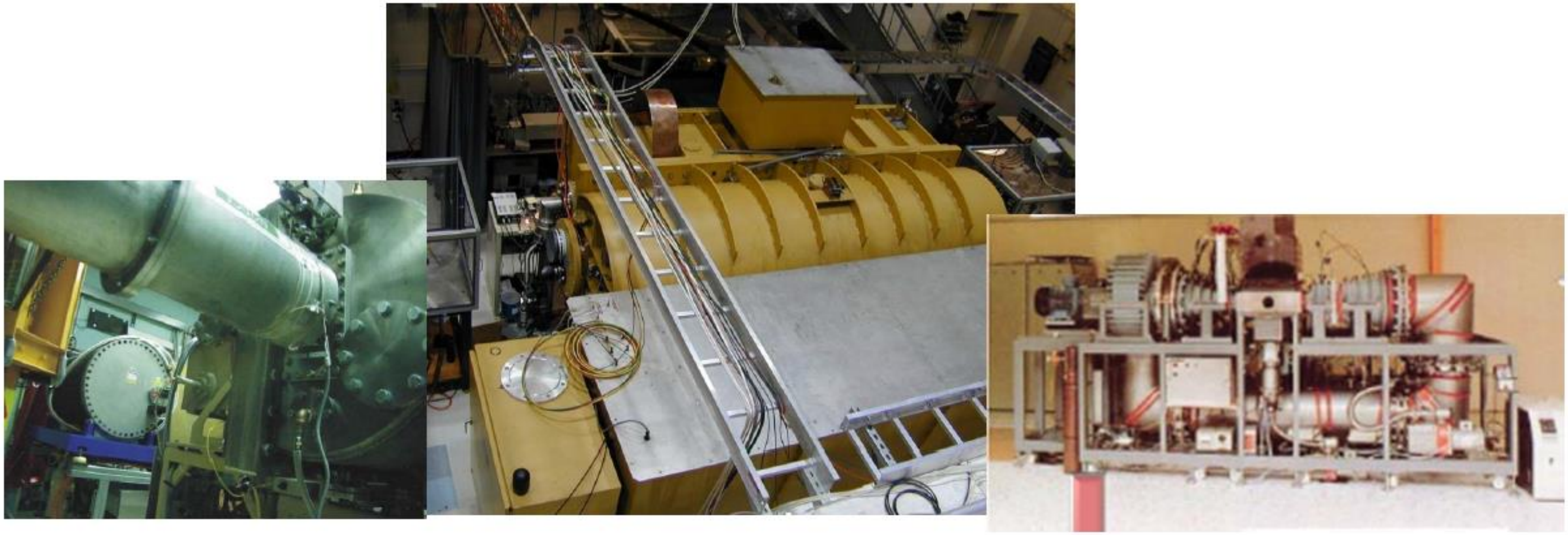
Chirped-pulse amplification in a CO_2 laser

MIKHAIL N. POLYANSKIY,* MARCUS BABZIEN, AND IGOR V. POGORELSKY

Short pulses are possible but the rep rate is low (~10 Hz) but laser output has a quasi-burst structure.

CO2 laser as wiggler

- ATF CO2 laser generates 5J / 3ps /~0.5% BW (upgrade pass to ~10-15J /~2% BW)
- UCLA Laser 150J in train of 3 3ps pulses
- Commercial Sopra laser is capable of ~10J /~2%BW at ~100Hz.



Vitaly Yakimenko ” Practical solutions for compact X ray FEL laser based undulator”