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Relativistic Thomson Scattering in Compact Linacs and Storage Rings: a Route to Tunable Laboratory-Scale X-ray Sources

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X-ray applications:

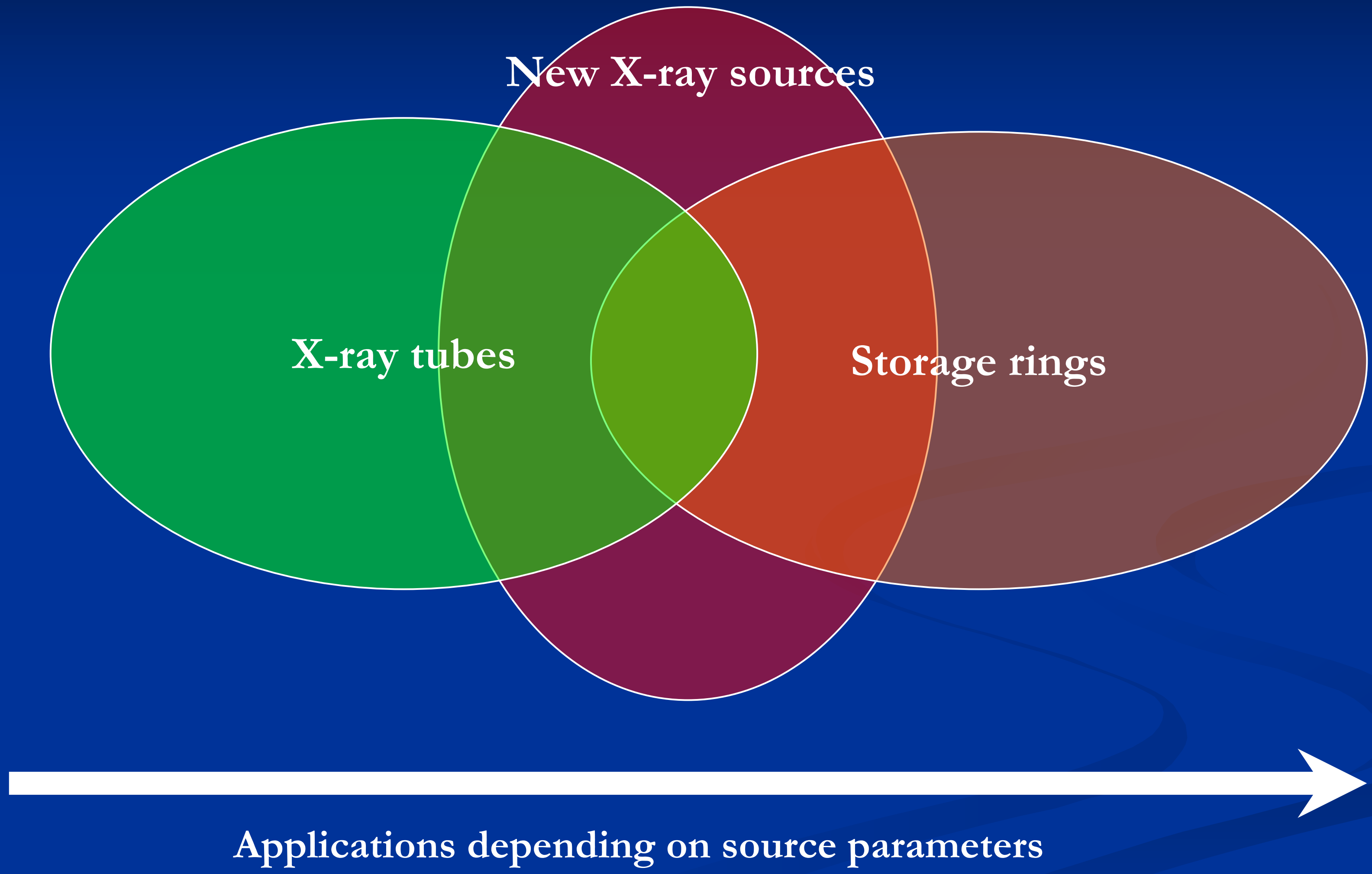
(~0.01–100nm, equivalent to ~120keV–12eV)

- medicine;
- safety systems;
- introscopy;
- radiation technologies;
- material science;
- etc.

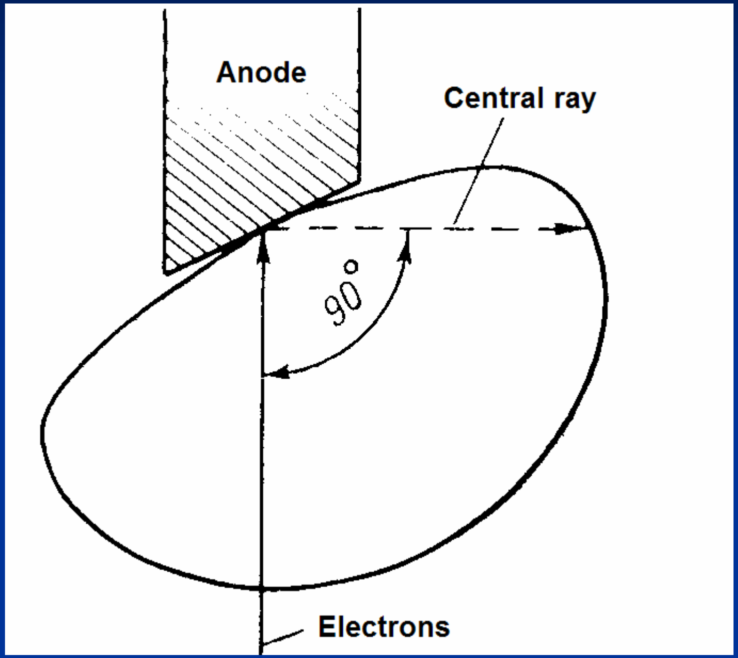
X-ray radiation and source parameters:

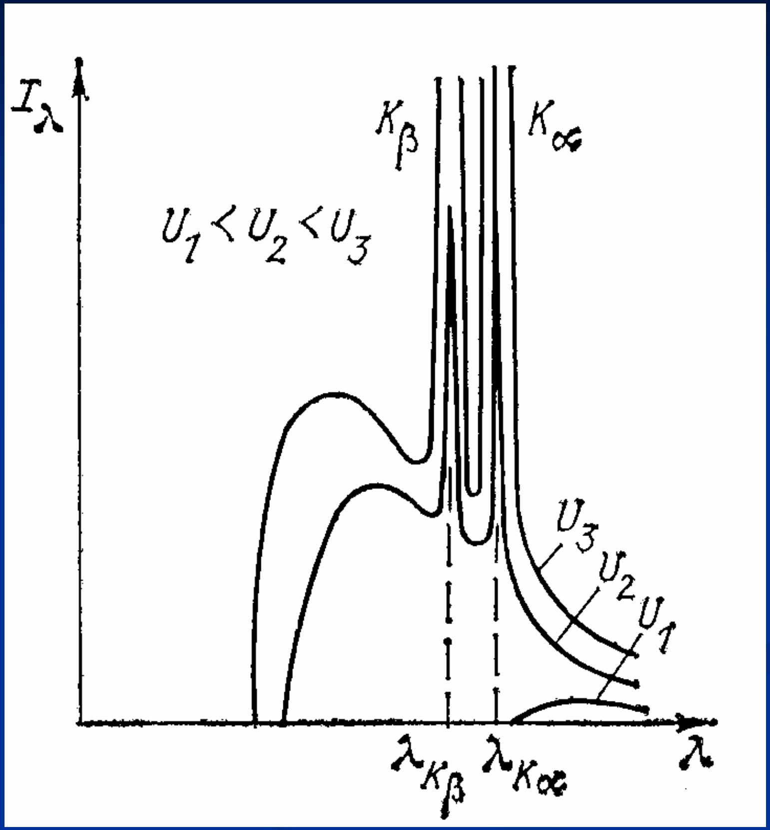
- energy and energy spectrum;
- total photon flux;
- brilliance;
- spatial distribution;
- temporal structure;
- source dimensions and consumed power;
- source cost;
- etc.

X-ray sources



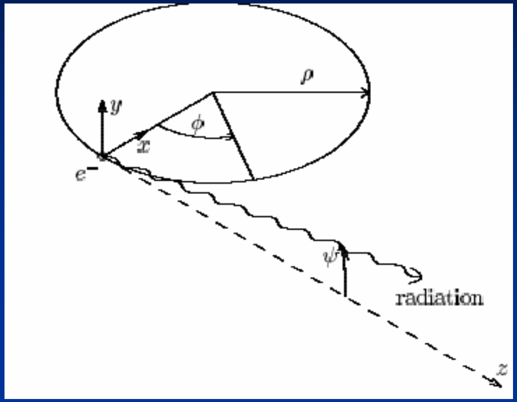
X-ray tubes

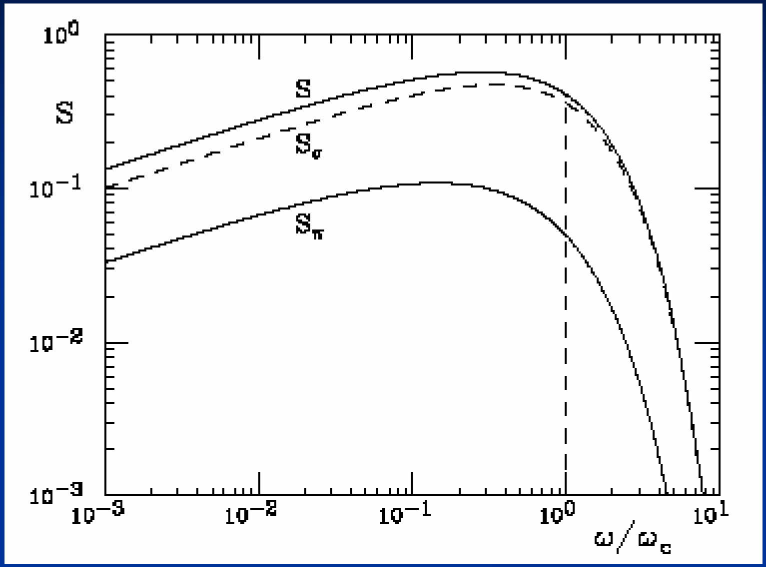




Since 1895. Compact, low cost, robust, but only less than 1% of electron beam energy is transformed to X-ray energy, which is ~uniformly distributed over angles. Energy spectrum is continuous. Heat loading limits attainable brightness. The maximum x-ray tube brilliance is achieved with a rotating anode microfocus x-ray generator at about 10^9 photons s^{-1} $mrad^{-2}$ mm^{-2}/0.1% BW.

Storage rings





Synchrotron radiation. Normalized power spectra for two polarizations

$$\omega_c = \frac{3c\gamma^3}{2\rho}$$

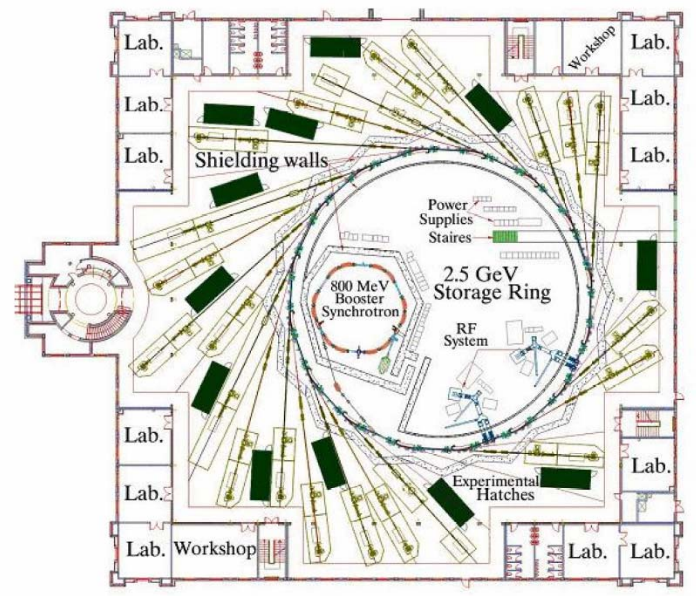
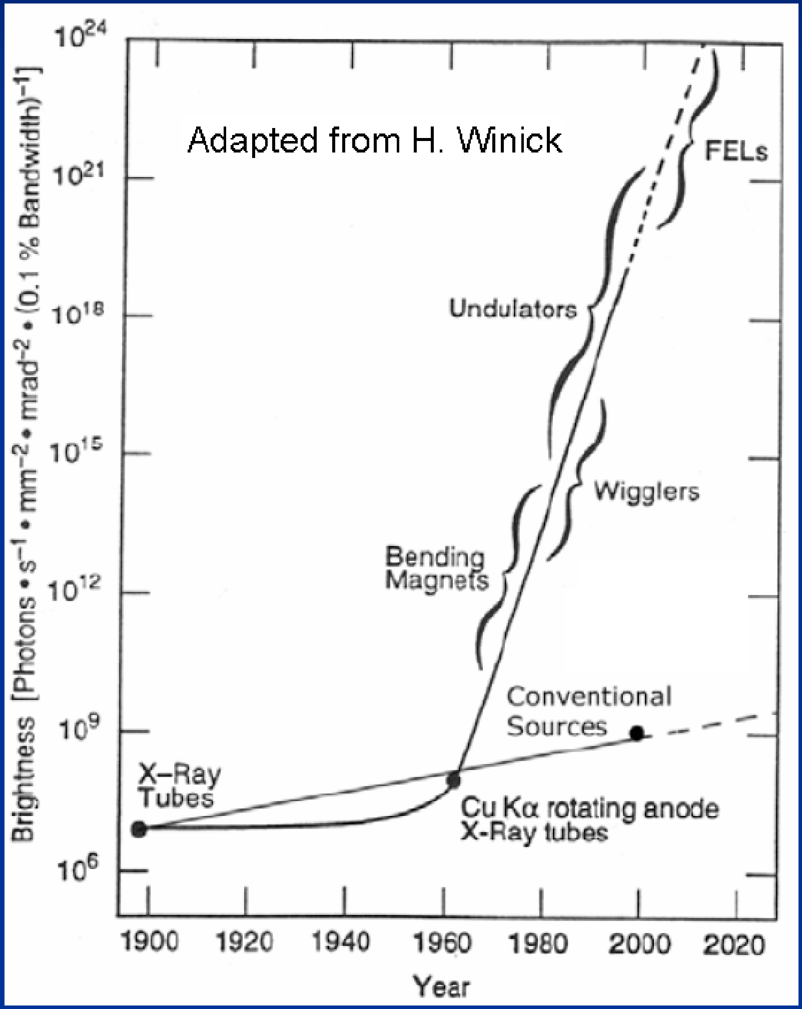


Figure 5.2: An overview of the SESAME machine and experimental hall.

To get 30 keV with storage ring 2.5 GeV beam and 7.5 T SC wiggler are necessary

http://www.sesame.org.jo/PDF/Chapter5.pdf

Wide unfilled gap between X-ray tubes and storage rings



	Tube/SR
Brightness	- 1 / >10^8
Tunability	- no / yes
Divergence	- 1 / 10^{-4}
Occupied area	- 1 / 50
Cost	- 1 / >10^3
Access facilities	- labs / user
Others	- running cost, stuff, power consumption etc.

New X-ray sources

European Cooperation
in the field of Scientific
and Technical Research
- COST -

Secretariat

Brussels, 5 December 2006

COST 321/06

MEMORANDUM OF UNDERSTANDING
FOR THE IMPLEMENTATION OF A EUROPEAN CONCERTED RESEARCH ACTION
DESIGNATED AS

COST ACTION MP0601

Short Wavelength Laboratory Sources

~0.01–100nm, equivalent to ~120keV–12eV

… expansion in [X-rays] application areas is due largely to modern synchrotron sources, many applications will not become widespread, and therefore routinely available as analytical tools, if they are confined to synchrotrons. This is because synchrotrons require enormous capital and infrastructure costs and are often, of necessity, national or international facilities. … Hence the need to develop bright but small and (relatively) cheap x-ray sources, not to replace synchrotrons but to complement them.

New X-ray sources

Requirements:

As compared with X-ray tubes:

Higher brilliance, directivity, monochromaticity, tunability, better time structure.

As compared with storage rings:

Less dimensions, energy consumption, staff, cost.

Destination :

Scientific laboratories.

Hospitals.

Factories.

New X-ray sources

Some methods:

Laser => harmonic generation

Laser => plasma

Z, X-pinch => plasma

Electron accelerator + target
=> Channeling etc.

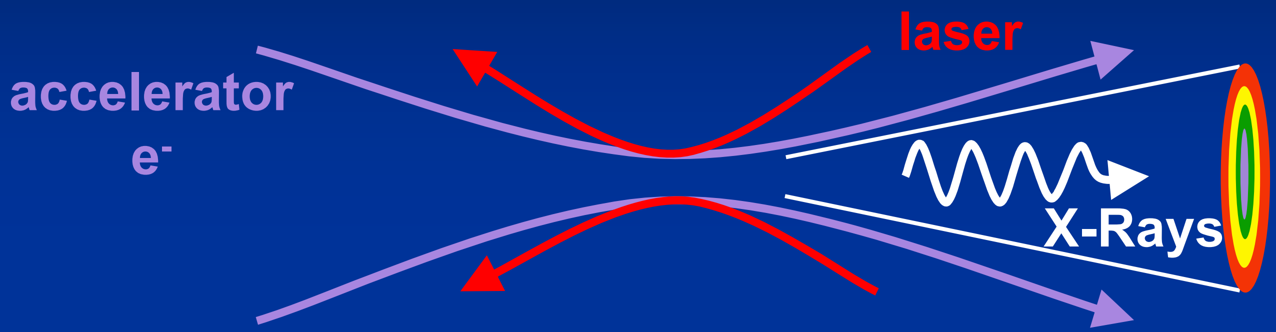
Laser + electron accelerator
$\Rightarrow$Relativistic Thompson scattering

Laser => plasma <= laser

Laser –Electron X-ray generator

Scattering of laser photons on relativistic electrons is one of promising methods for generation of quasi-monochromatic, tunable, highly directed, high brightness X-ray radiation with flexible time structure.

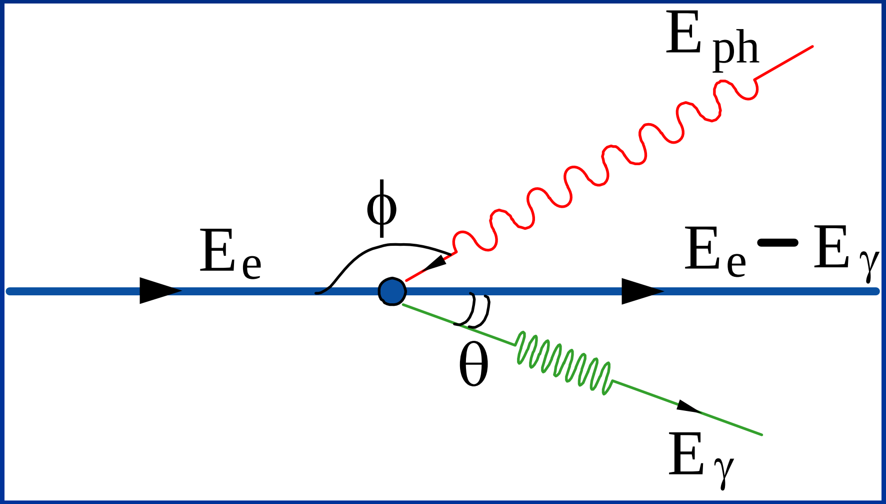
Laser + electron accelerator: relativistic Thompson scattering

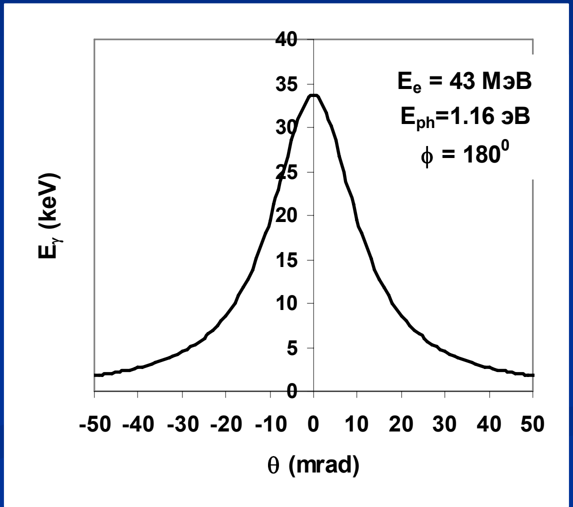


$$E = 4\gamma^2 E_L, \quad \gamma = E_e / mc^2$$

Laser photon, E_L	Electron energy, E_e	X-ray photon energy, E
1.16 eV λ=1.06μ	43 MeV γ=84	33keV Iodine K-edge

Scattering kinematics





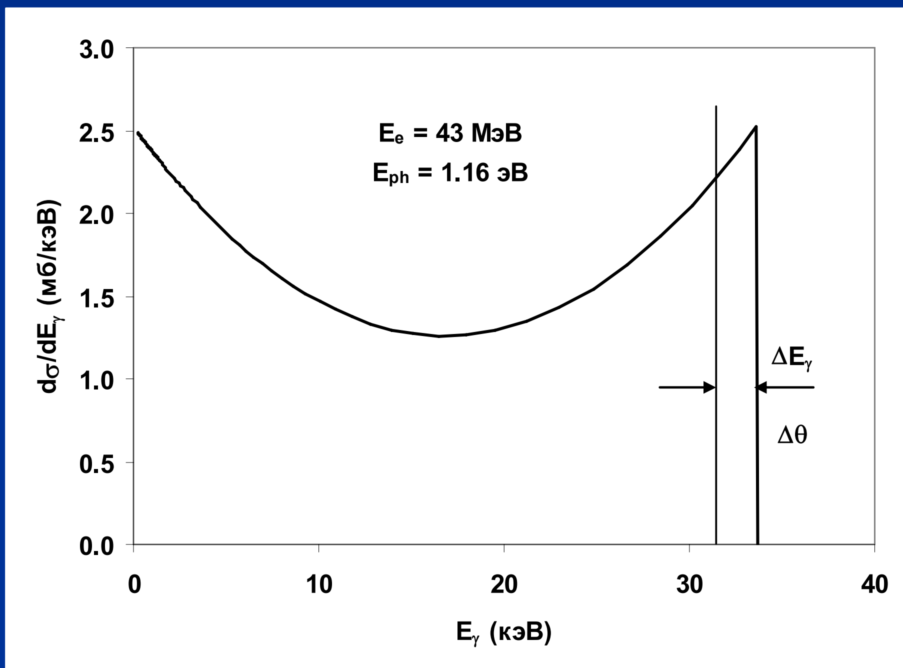
$$E_\gamma \approx \frac{2\gamma^2 E_{ph}}{1+\gamma^2\theta^2}(1-\cos\phi), \quad \gamma >> 1, \ \theta << 1$$

ϕ - collision angle

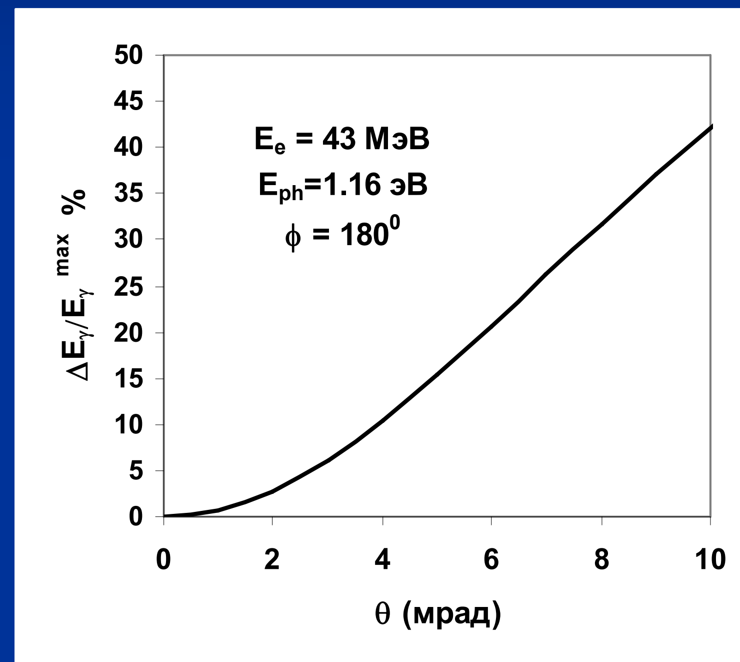
θ - scattering angle

Correlation between photon energy and scattering angle

Energy spectrum

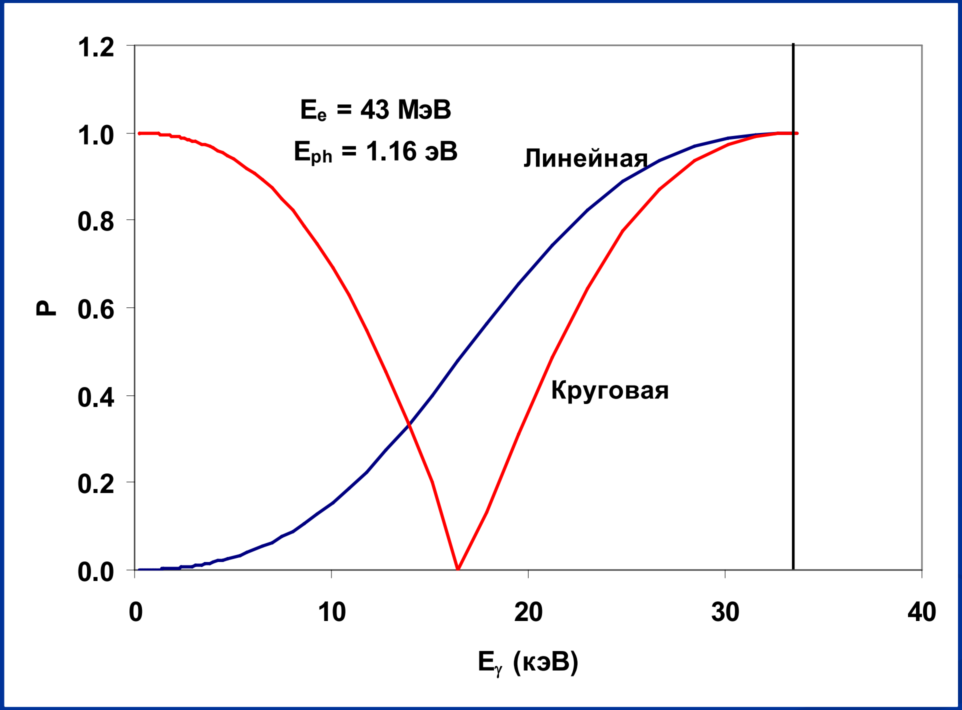


Scattering cross section. Selection of narrow spectrum by collimation.



Dependence of energy spectrum width on collimation angle

Polarization of the scattered photons for different polarization of laser radiation.



Number of X-ray photons per one interaction

$$N_\gamma = \sigma_{Th} \frac{N_e N_{ph}}{4\pi\sigma_r^2}$$

$\sigma_{Th} = 6.65 \times 10^{-29}$ ì ^{2} - Thompson scattering cross section,

N_e - number of electrons in bunch,

N_{ph} - number of photons in laser pulse,

σ_r - rms radii of the electron and photon beams.

Typical values:

$q_e = 1\,\text{nC},\ w_{ph} = 20\,\text{mJ},$

$N_e = 5 \times 10^{9},\ N_{ph} = 10^{17},$

$\sigma_r = 2 \times 10^{-5}\,\text{m},\ N_\gamma \approx 10^{7}$

Number of X-ray photons per unit time

$$\text{Peak}: \frac{dN_\gamma}{dt} = \frac{N_\gamma}{\tau}, \ \tau \text{ - pulse duration}$$

$$\tau = 100\ \text{fs}, \frac{dN_\gamma}{dt} \approx 10^{20}\ \text{s}^{-1}, \ \tau = 50\ \text{ps}, \frac{dN_\gamma}{dt} \approx 2\times 10^{17}\ \text{s}^{-1}$$

$$\text{Average}: \frac{d\overline{N}_\gamma}{dt} = N_\gamma f, \ f \text{ - collisions repetition rate}$$

$$f = 10\ \text{Hz}, \frac{d\overline{N}_\gamma}{dt} \approx 10^{8}\ \text{s}^{-1},$$

$$f = 100\ \text{kHz}, \frac{d\overline{N}_\gamma}{dt} \approx 10^{12}\ \text{s}^{-1},$$

$$f = 10\ \text{MHz}, \frac{dN_\gamma}{dt} \approx 10^{14}\ \text{s}^{-1}$$

The ways to get high average X-ray flux:

Increase number of electrons in bunch or photons in pulse or both at low repetition rate.

Limitations: electron beam emittance growth proportionally to charge, laser pulse energy growth.

Increase number of bunches and laser pulses generated per unit time.

Limitations: high average power of the electron and laser beams.

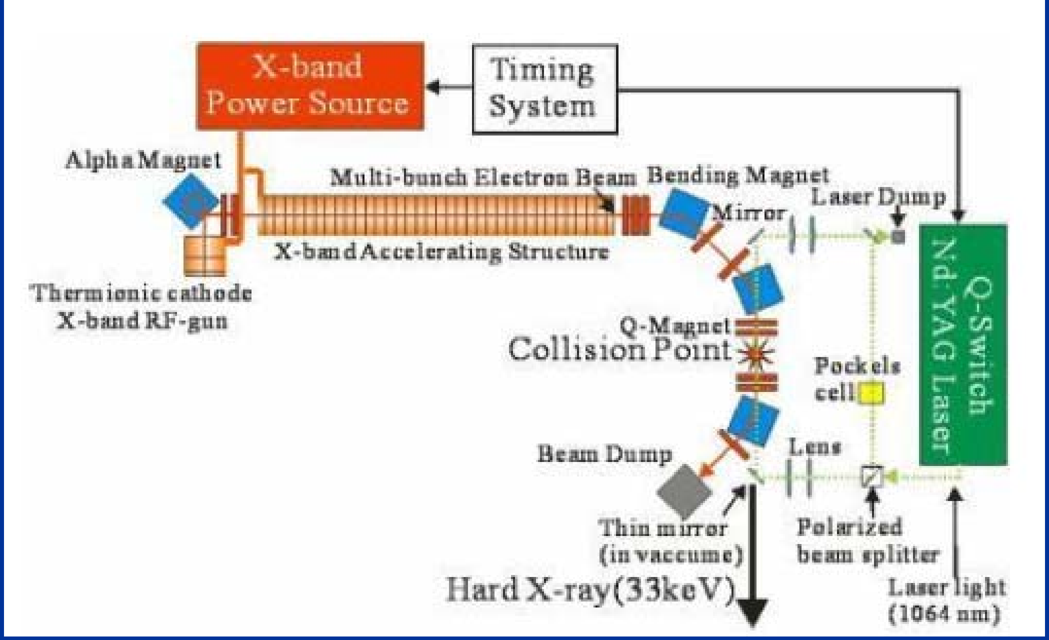
Multiple use of the same bunches and laser pulses with storage or recirculating electron rings and laser cavities.

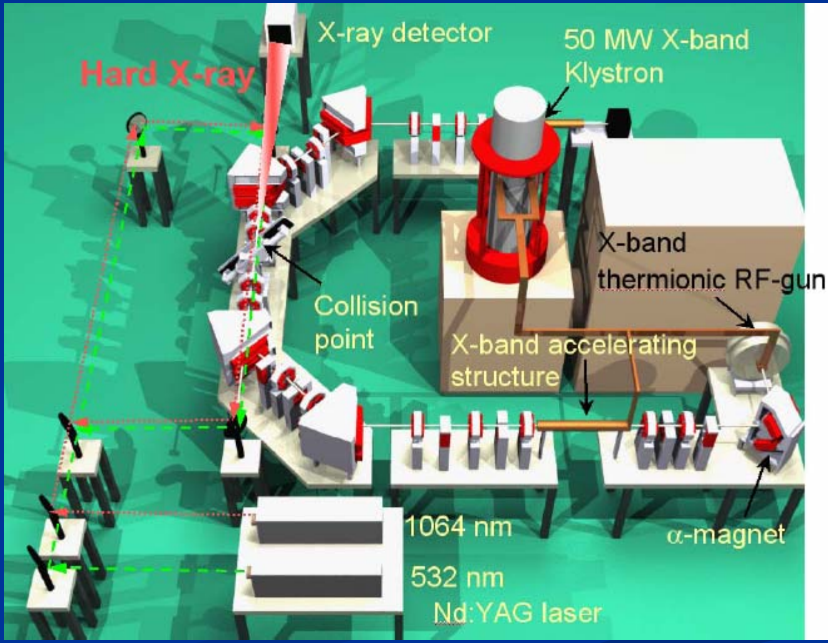
Limitations: Electron and laser beam quality degradation.

One of several Japanese projects

Proc. of 2005 Particle Accelerator Conference Proceedings

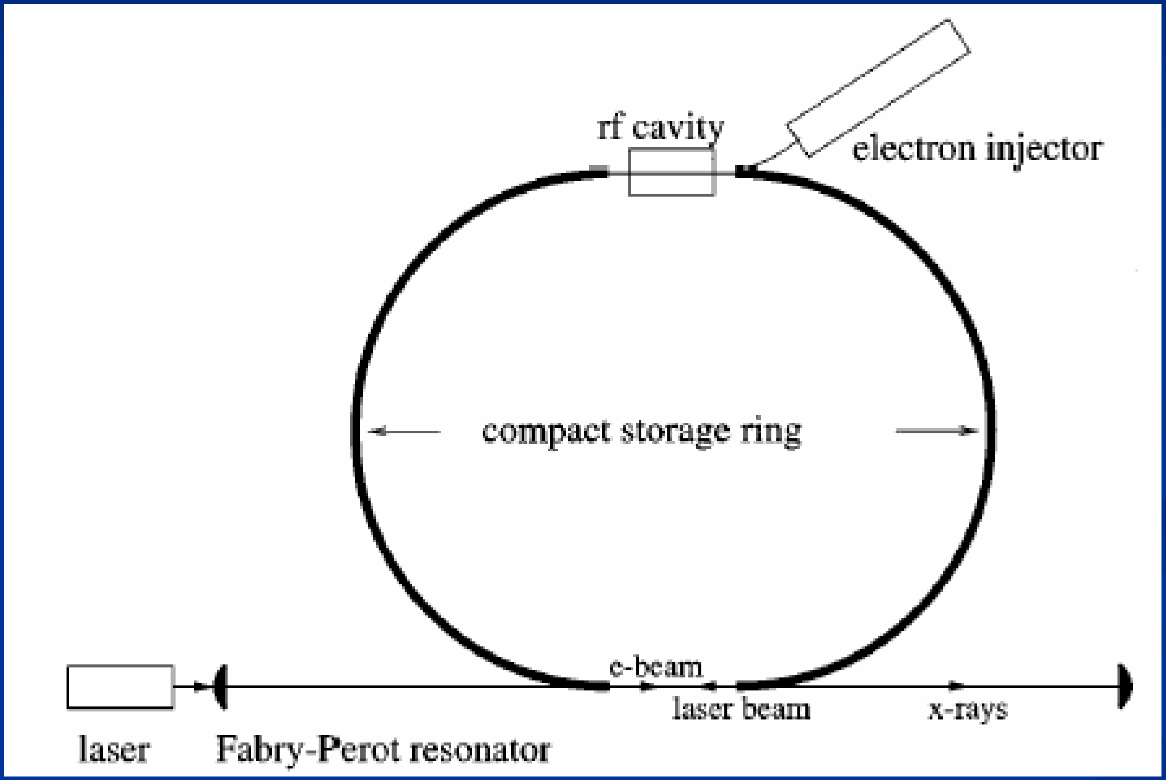
A. Fukasawa, T. Kaneyasu, F. Sakamoto, F. Ebina,
H. Ogino, M. Uesaka, UTNL, Naka, Ibaraki 319-1188 Japan





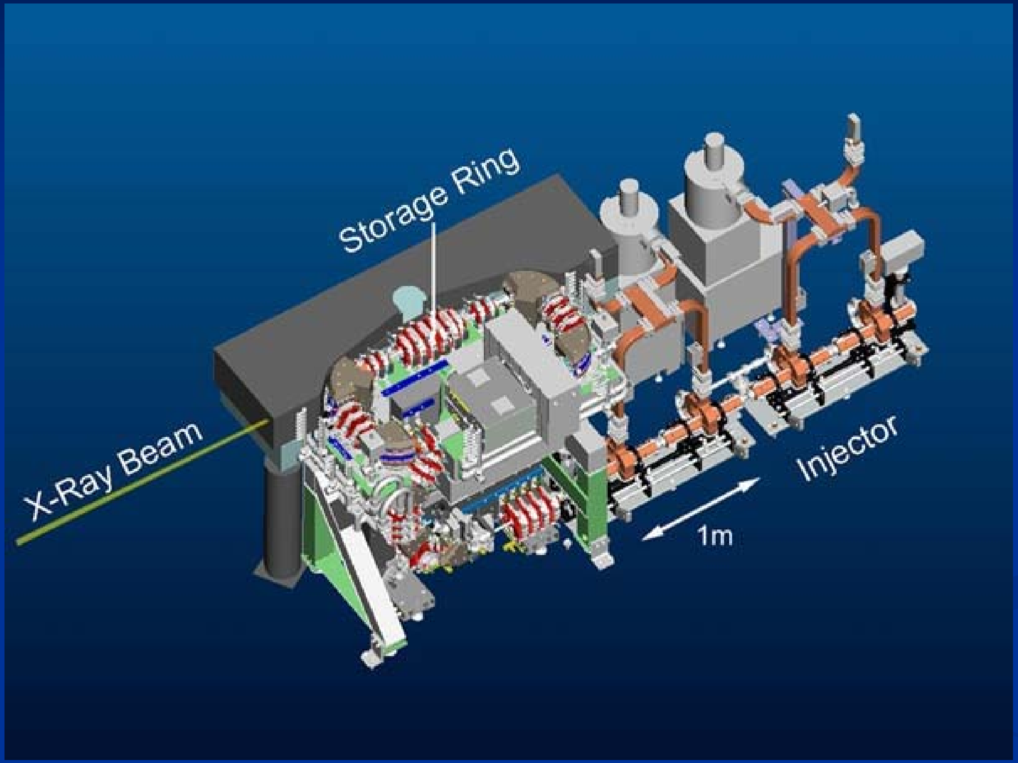
Average number of photons below 10^6 per second

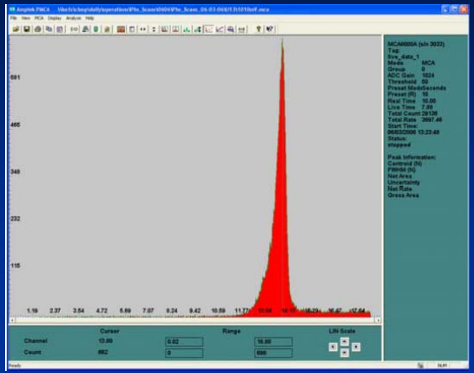
Laser-electron X-ray generator with multiple interaction

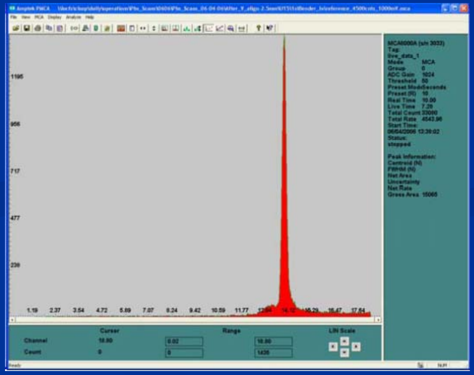


Zhirong Huang and Ronald D. Ruth, Volume 80, Number 5 Physical Review Letters 2 February 1998

Lyncean Technologies, Inc (USA)







Source layout (from Lyncean Technologies, Inc web site).
The main destination - protein crystallography.
Electron energy 25 MeV, photon energy 12 keV.
Average <u>project</u> brightness **10^{11} ph s^{-1} $mrad^{-2}$ mm^{-2}/0.1% BW**

Measured photon spectra without and with monochromator.

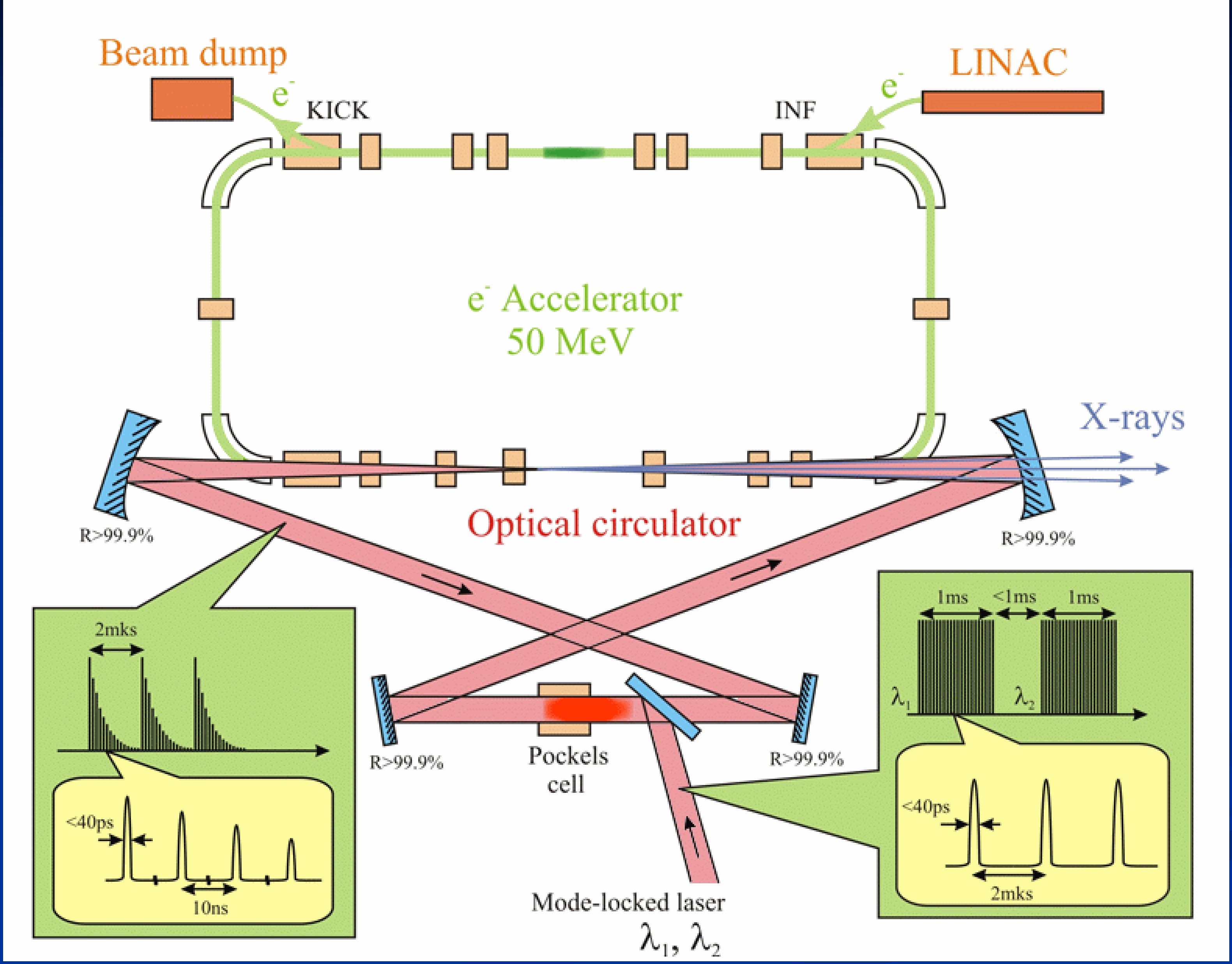
P.N. Lebedev Physical Institute and Moscow State University proposal for laser electron X-ray generator

Final goal:

$$E_\gamma = 12 - 45\,\mathrm{keV}$$

$$E_e = \gamma m_0 c^2 = 25 - 50\,\mathrm{MeV}$$

$$B_{av} > 10^{12}\ \mathrm{s^{-1}mm^{-2}mrad^{-2}(0.1\%BW)^{-1}}$$


Beam dump
LINAC
e⁻
e⁻
KICK
INF
e⁻ Accelerator
50 MeV
X-rays
R>99.9%
R>99.9%
Optical circulator
2mks
<40ps
10ns
1ms
<1ms
1ms
λ_1
λ_2
<40ps
2mks
R>99.9%
R>99.9%
Pockels
cell
Mode-locked laser
λ_1, λ_2

The main components of the laser-electron X-ray generator

Injector-

– compact electron linear accelerator with injection from RF gun with max. energy 50 MeV producing electron bunches with 1 nC charge, normalized emittance 1 mm mrad with repetition rate 50 Hz.

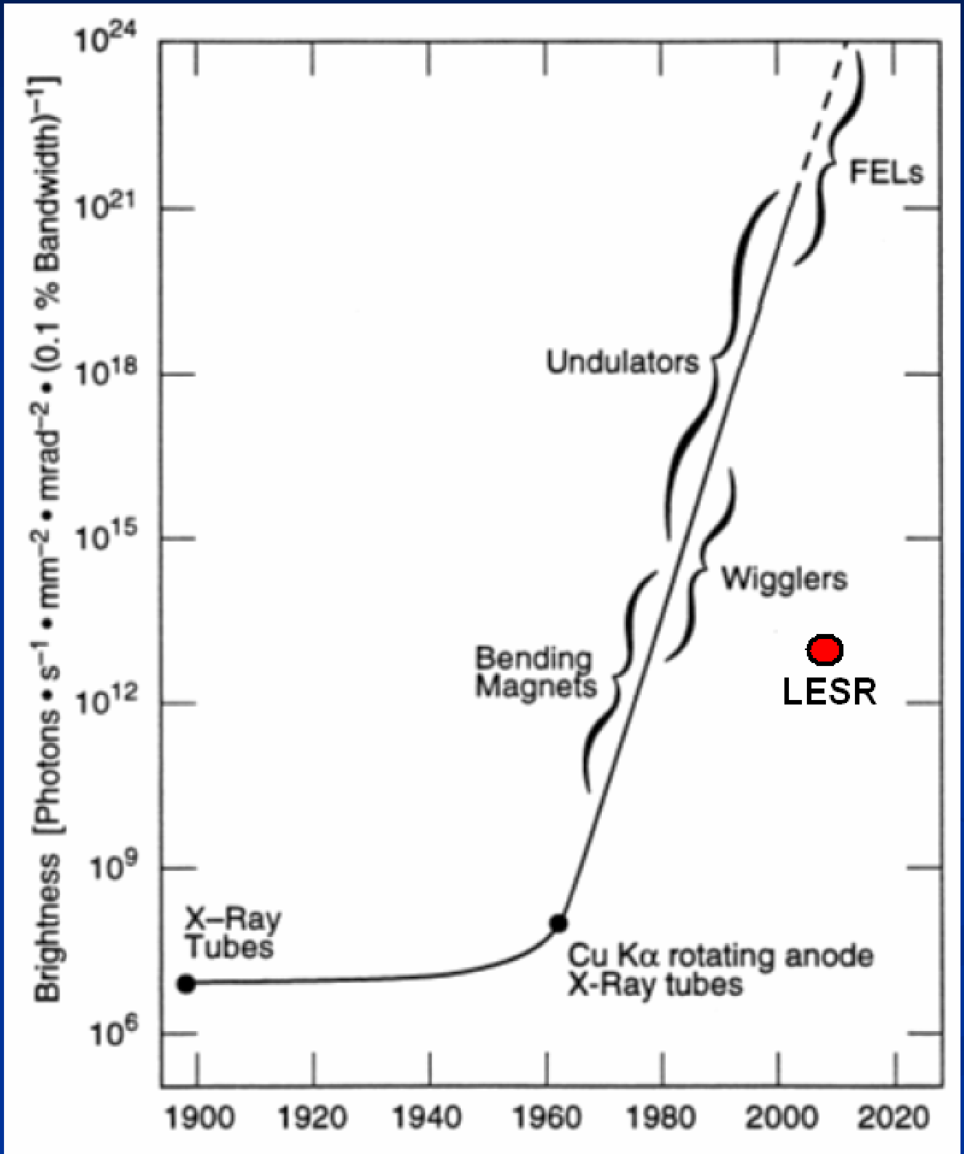
Electron beam recirculation system.

Laser-

- Wavelength 1064 nm, 10 J/pulse with duration 2 ms, consisting of 1000 micropulses 40 ps duration, pulse repetition rate 50 Hz.

Laser pulse recirculation system.

Average brightness in comparison with SR and X-ray tubes



The project milestones

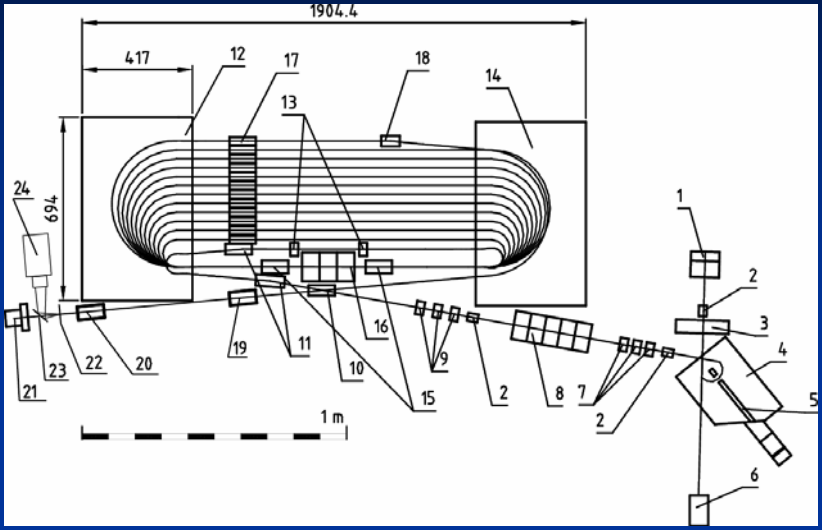
1. Modify laser system available at P.N. Lebedev Institute and conduct test experiments with RF gun available at SINP MSU. Get average flux up to 10^7 ph/s of 0.5 keV photons.

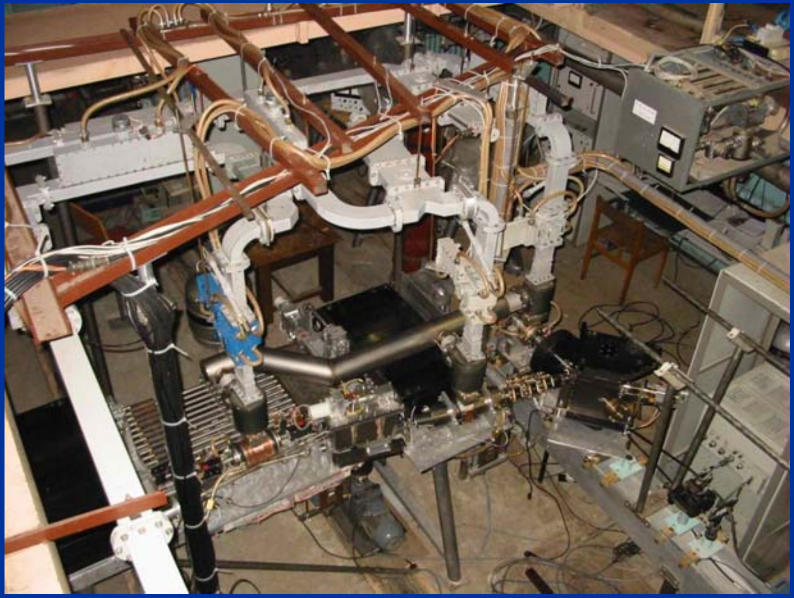
2. Build new RF gun with multiple bunches, higher bunch charge, higher repetition rate, lower emittance with new laser system for photocathode. Build laser pulse recirculation system. Get average flux from 10^9 to 10^{12} ph/s of 0.5 keV photons.

3. Build electron linac for energy 25-50 MeV. Get average flux from 10^9 to 10^{12} ph/s of 12-45 keV photons.

4. Build electron recirculating ring for energy 25-50 MeV. Get average flux up to 10^{12} ph/s of 12-45 keV photons.

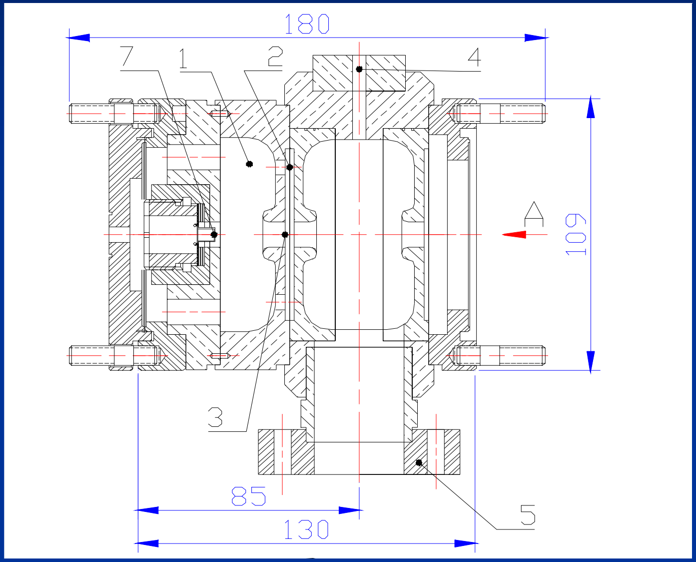
SINP MSU RACETRACK MICROTRON WITH HIGH BRIGHTNESS BEAMS

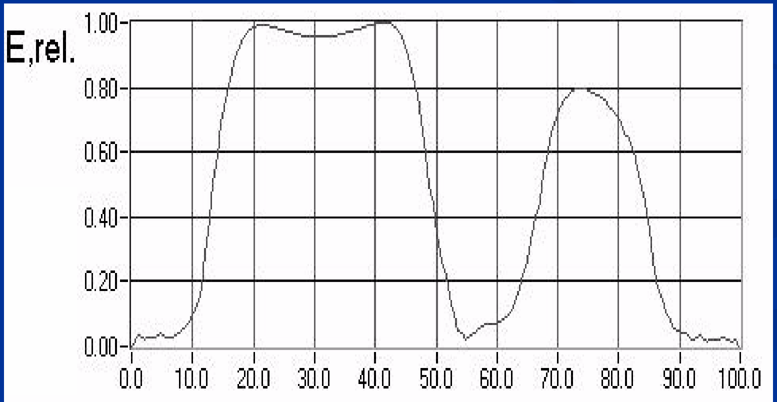




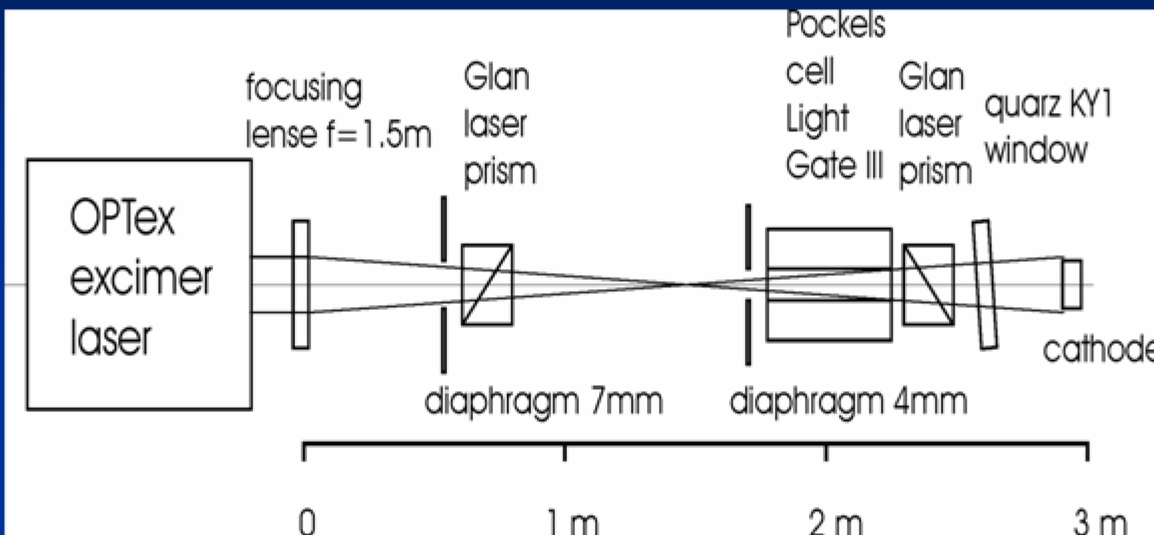
Injected beam energy	4.85 MeV
Energy gain per turn	2.43 MeV
Output beam energy	4.85-34.20 MeV
Normalized emittance	10 mm mrad
Longitudinal emittance	200 keV degree
Micro pulse length	5 ps
Pulse repetition rate	1-150 Hz
Micro charge	150 pC
RF frequency	2.856 GHz
Pulsed RF power	< 3 MW
End magnet field	0.486 T

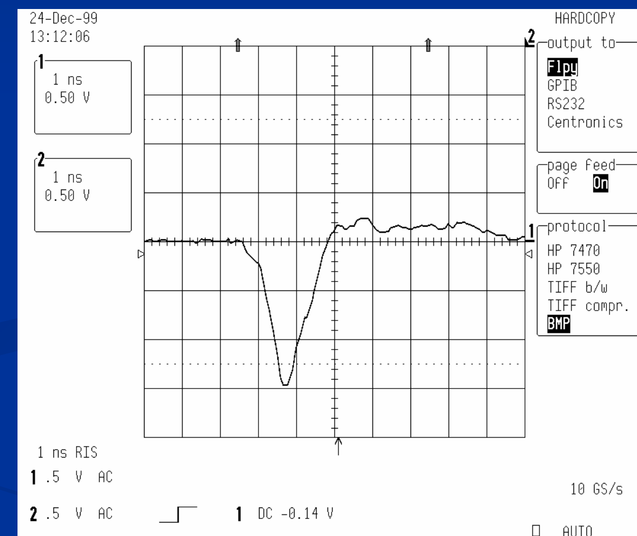
RF gun with photocathode





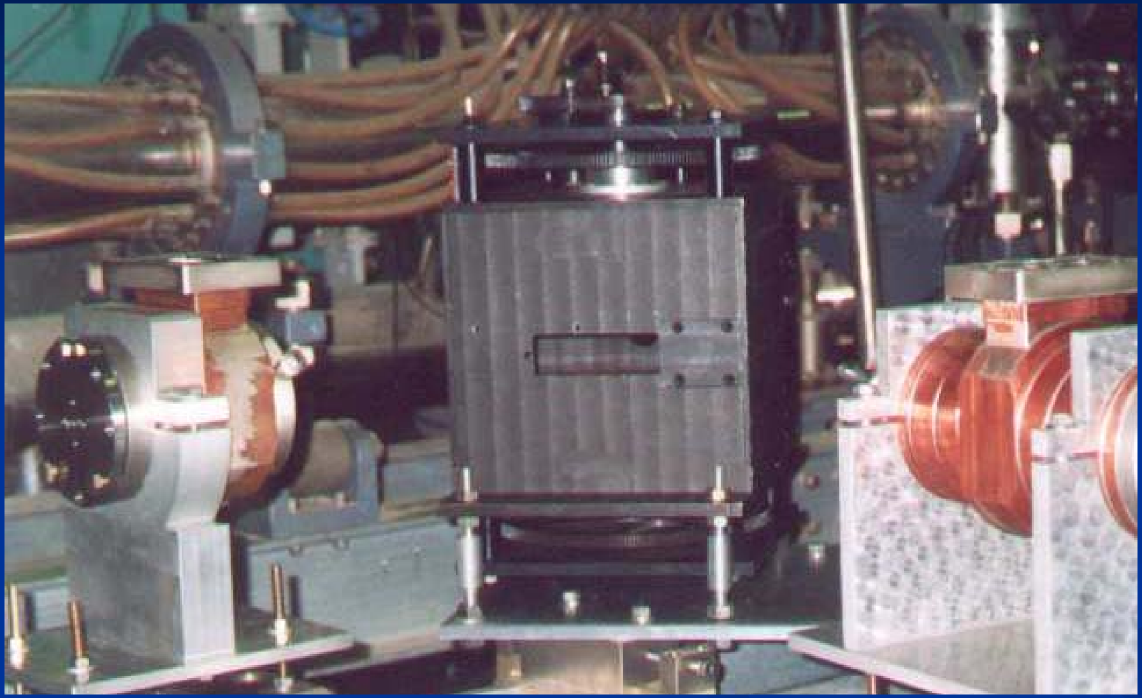
Laser system – schematic and photo

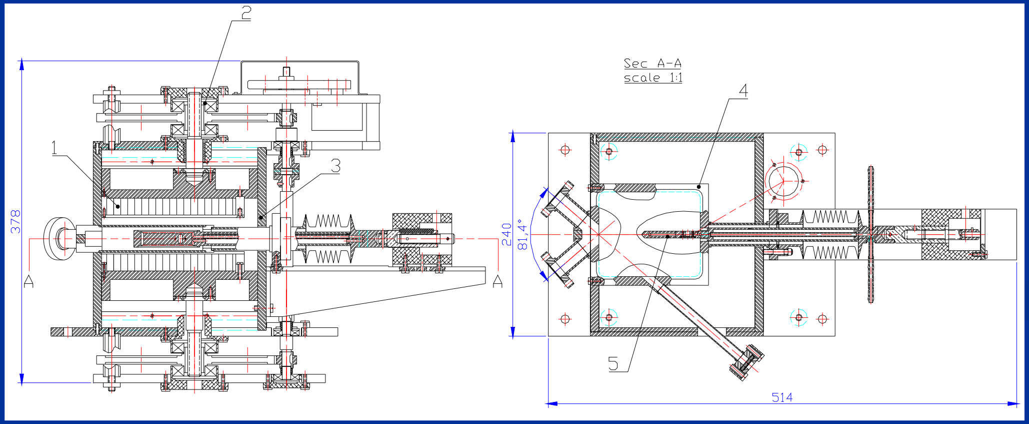


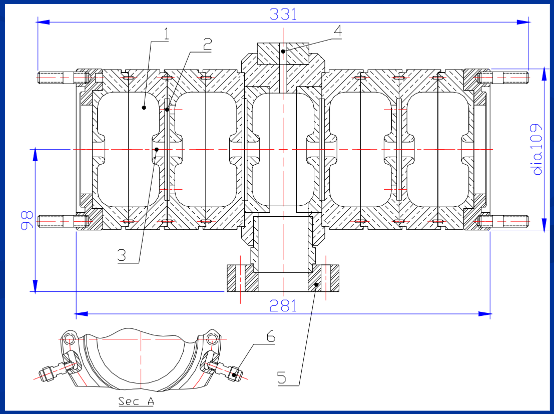


Laser pulse

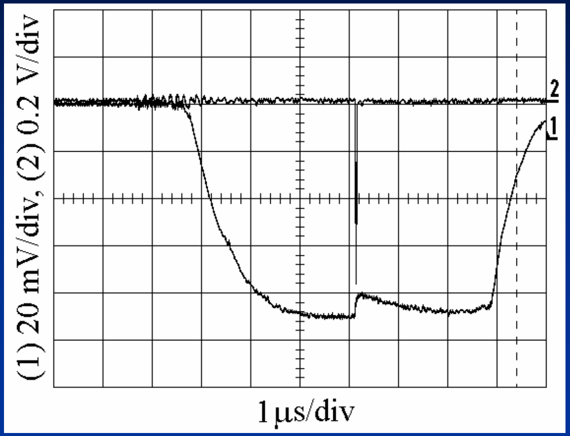
Alpha magnet and pre-accelerator

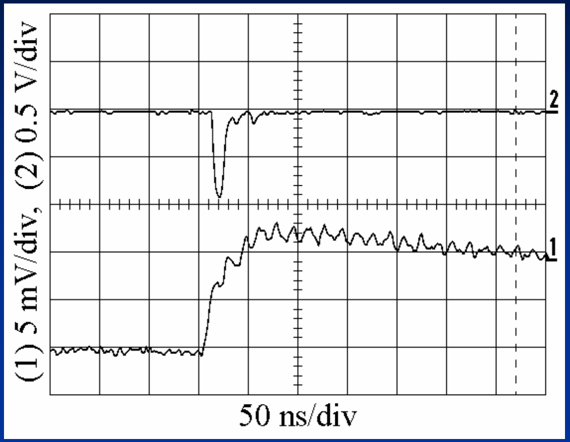






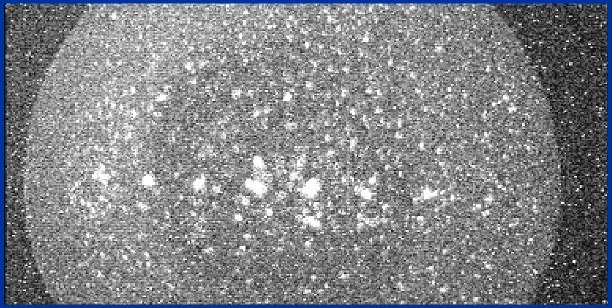
RF gun loading by 15 bunches. Total charge 24 nC.



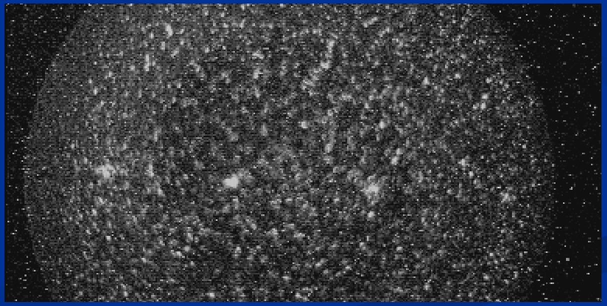


RF field envelope and Faraday cup signal

Bunches with streak camera

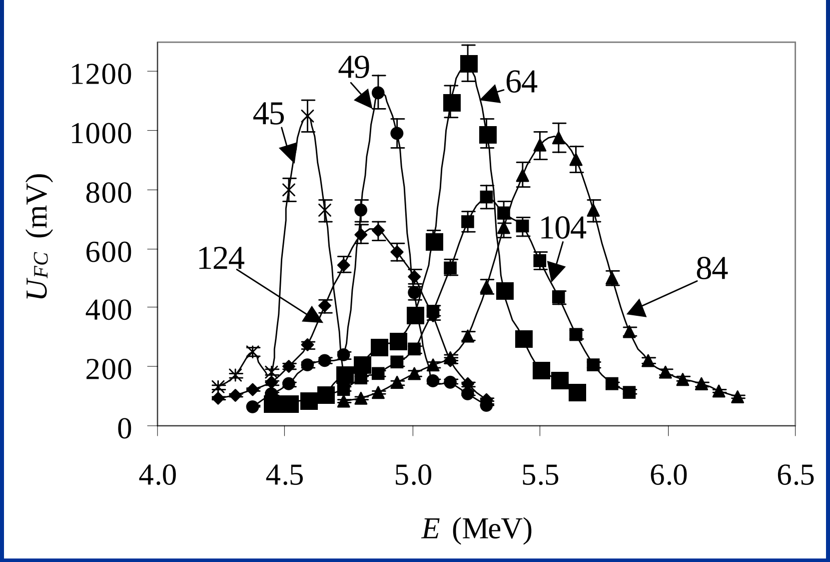


1 ns/cm

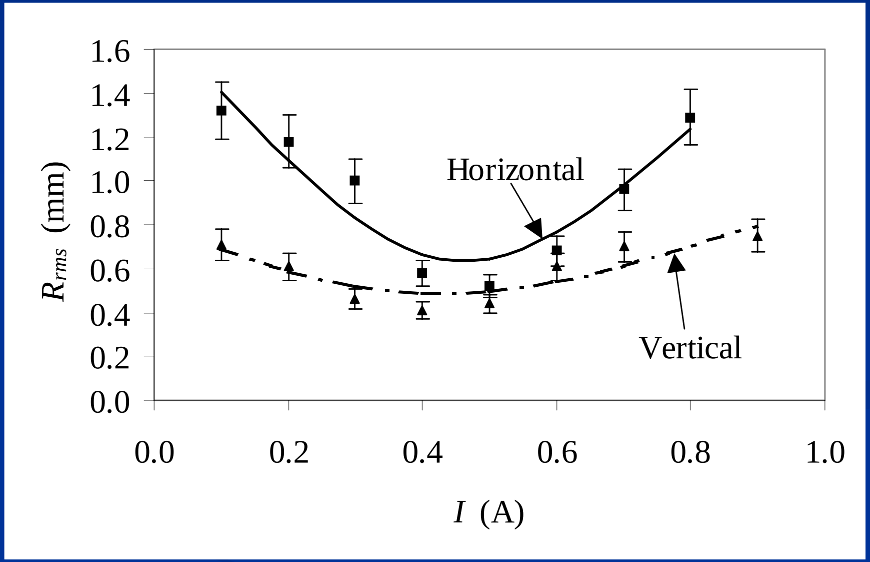


0.25 ns/cm

Energy spectra and emittance at injector exit



Energy spectra on phase difference between RF gun and pre-accelerator

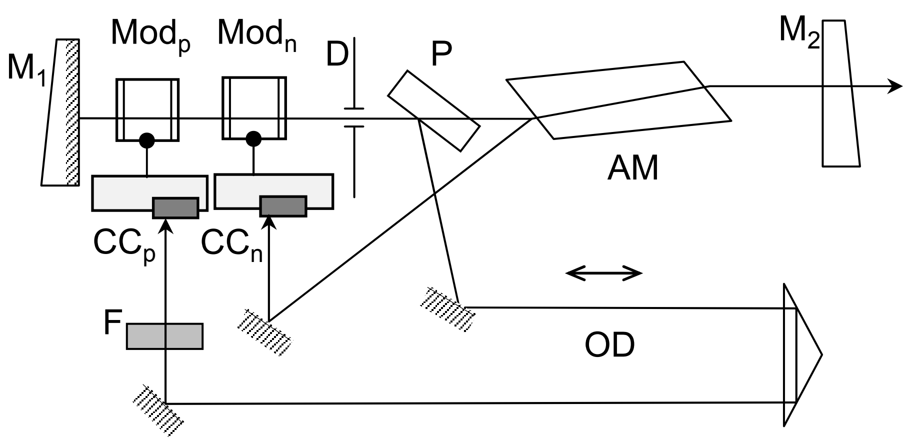


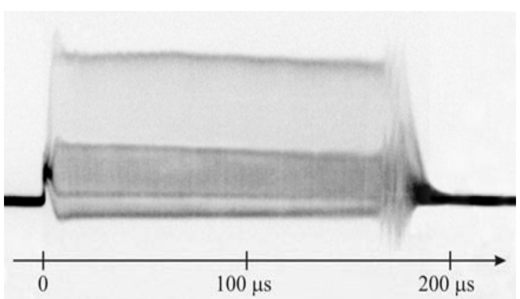
Rms beam radius on focusing lens current, normalized rms emittance, 8.2 ± 4 mm mrad

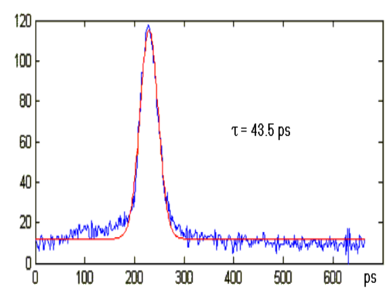
Optical source for laser-electron X-ray generator (Lebedev Physical Institute)

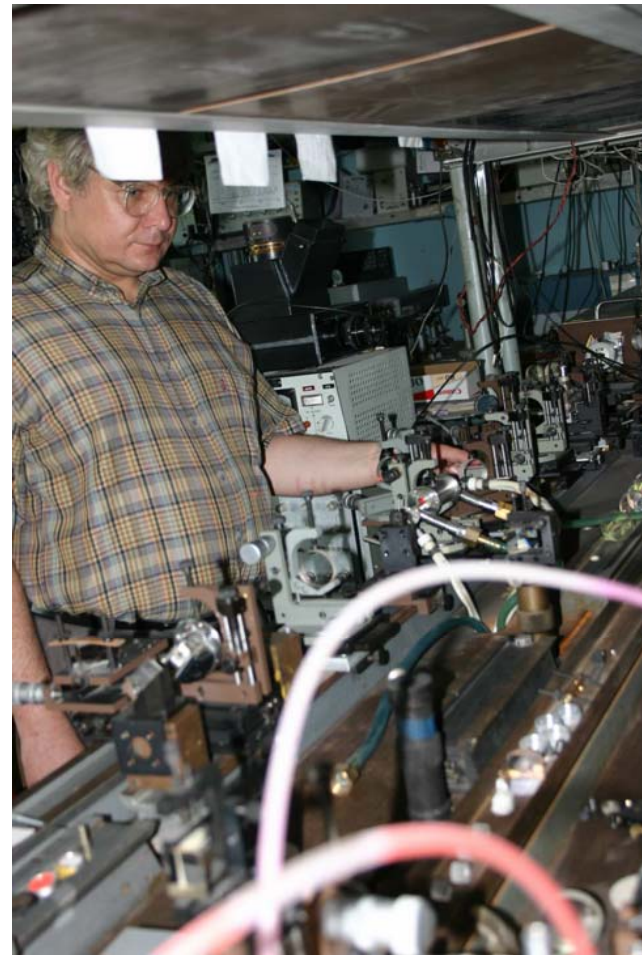
Nd:YAG laser generating stabilized

trains of picosecond pulses.









Further development: optical circulator.

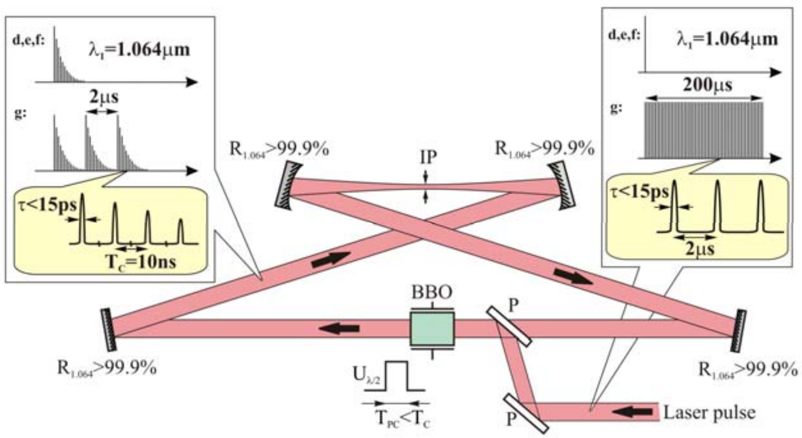


Fig. 1. Optical circulator based on intracavity Pockels cell.

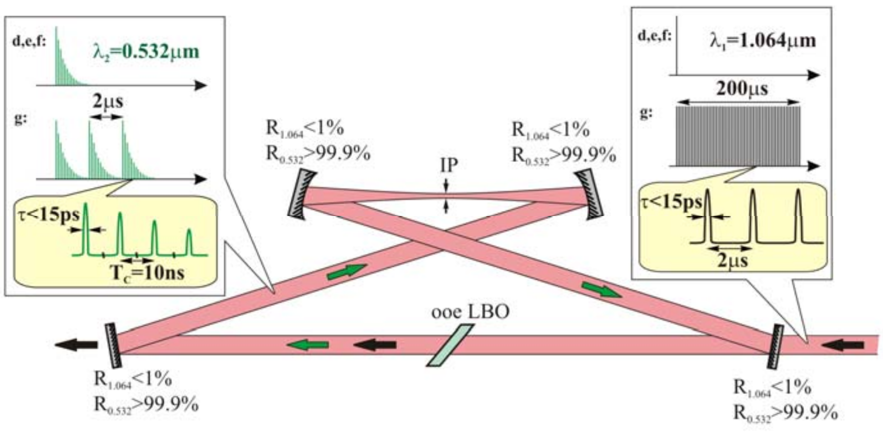
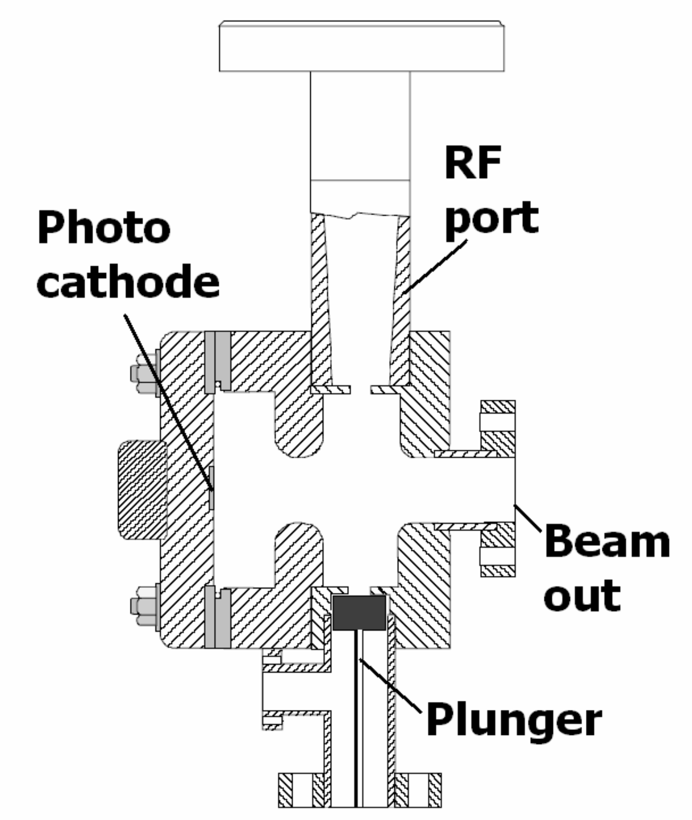
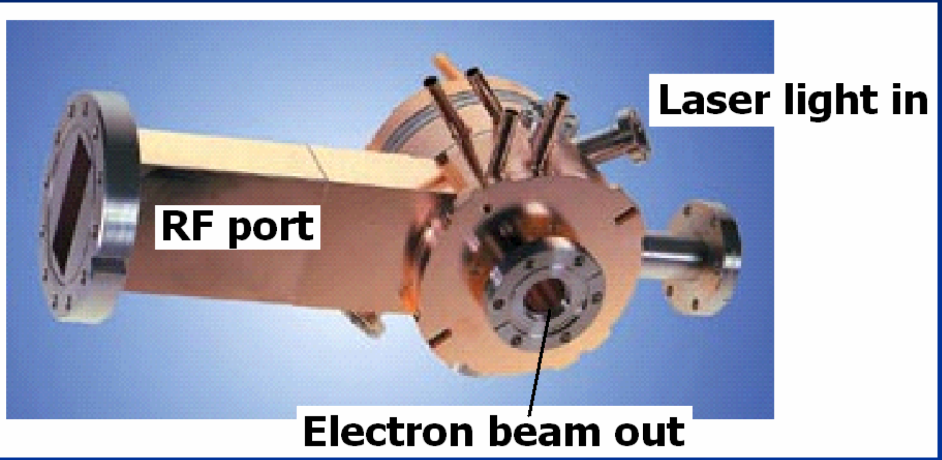


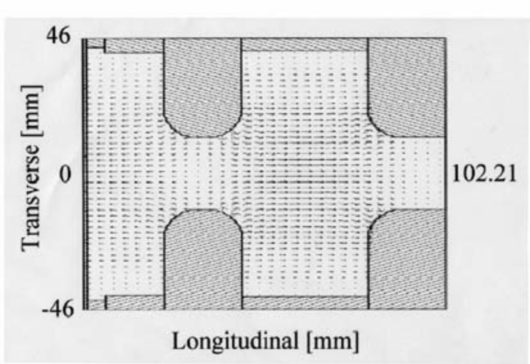
Fig. 2. Optical circulator based on intracavity second harmonic generation.

The important advantage of the circulator is the possibility to operate with phase non-coherent laser pulses.



Further development: low emittance 1 nC RF gun of BNL type



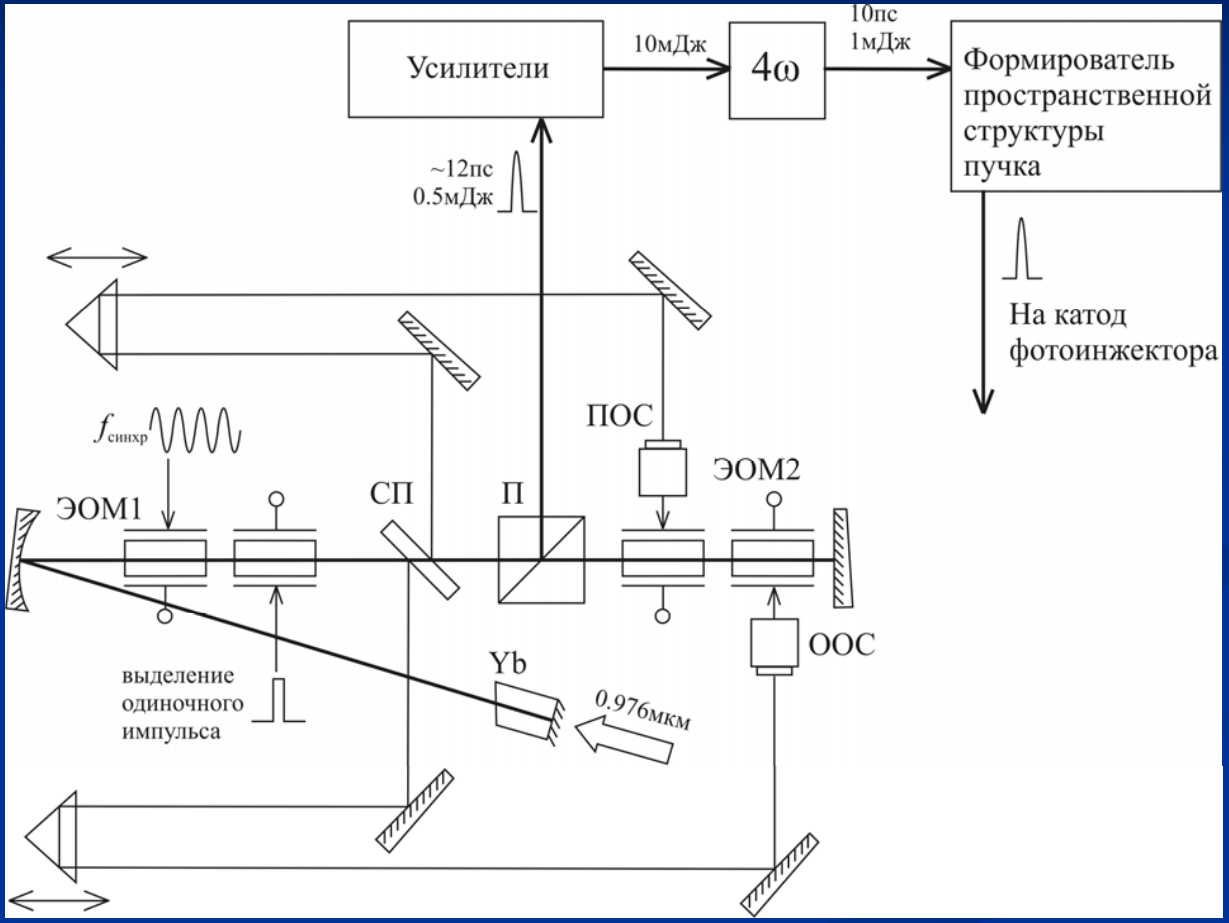


Calculated E-field distribution

BNL type 1.6-cell 2856-MHz photocathode rf gun

~25 μJ	laser energy
263 nm	wavelength
8 MW	RF power
102 MV/m	electric field
5.0 MeV	exit energy

Further development: RF gun laser system



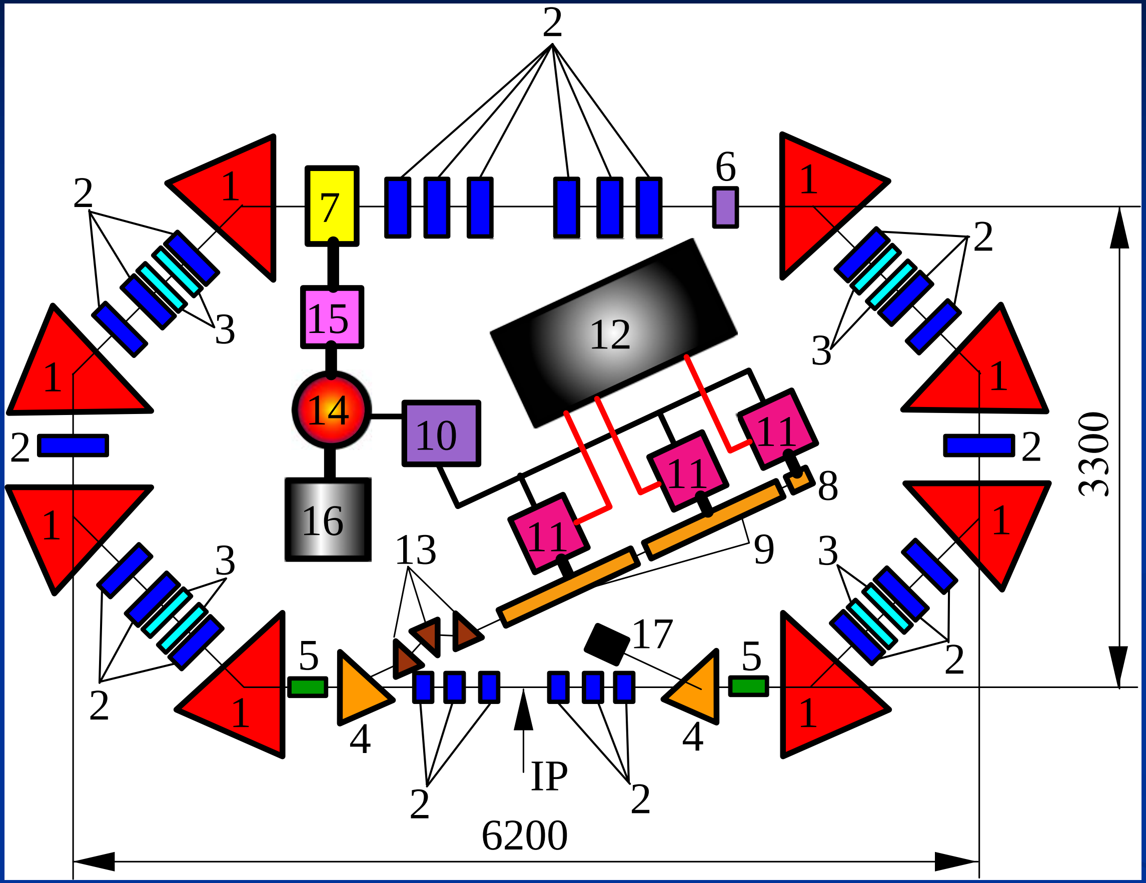
Further development: toward to higher energy

Accelerating structure for high energy

Klystron

High voltage modulator

Final step: electron beam recirculator



1 – dipole magnets, 2 - quadrupoles, 3 - sextupoles, 4 – septums, 5 – kickers, 6 - beam monitors, 7 – RF cavity, 8 – RF gun, 9 – accelerating structure, 10 – master oscillator, 11 –RF units, 12 – high voltage modulator, 13 – beam stretcher,14 – klystron, 15 – waveguide elements, 16 – high voltage power supply.

Conclusion

1. Proposal for laser-electron X-ray generator was initiated by P.N. Lebedev Physical Institute. Moscow State University is active collaborator.

2. X-ray generator has great potential for application in material science, medicine, biology, safety systems, etc

3. There are several stages with total duration 5 years.

4. Total cost estimations: 5 million €

5. Project status: yet not funded.

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