MARS - a project of the diffraction-limited fourth generation X-ray source.

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ICFA Workshop on Future Light Sources
Argonne National Laboratory
April 6 - 9, 1999

Creation of SR sources was always aimed to solve two major problems:

- an increase of the spectral brightness;
- an extension of the available spectral range.

The design of an SR source is a compromise between users, machine and economic requirements.

Important task for the future generation of the X-ray source is providing:

• full spatial coherence;

• as high as possible temporal coherence.

In this case the increase of spectral brightness take place without increasing of the total photon flux for minimization of the problems with X-ray optics and the sample degradation.

$$B_{\lambda} = \frac{N_{ph}}{\Delta t} \bullet \frac{1}{\Delta S \bullet \Delta\Omega} \bullet \frac{1}{\Delta\lambda / \lambda}$$

Diffraction limit of optical source phase volume ("mode" volume)

$$\Delta S \bullet \Delta\Omega \sim \varepsilon_{\chi}\varepsilon_{y} \sim \lambda^{2}$$

The emittance of electron beam must be small enough.

$$\varepsilon_{x} = \sigma_{x} \bullet \sigma_{x'} \leq \frac{\lambda}{4\pi}$$

In this case source provide full spatial co-herence radiation:

$$\overset{\circ}{N}_{coh} = B_{\lambda} \bullet \lambda^{2} \bullet \frac{\Delta\lambda}{\lambda} = \frac{N_{ph}}{\Delta t}$$

- The temporal coherence of source is determined by monochromatisity of radiation

$$l_{coh} = \frac{\lambda^2}{2\Delta\lambda}$$

- Linewidth of undulator radiation is determined by number of undulator periods and energy spread of electron beam

$$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{N_u}; N_u < \left(\frac{\sigma_E}{E}\right)^{-1}$$

- Fundamental limit of energy spread is determined by quantum fluctuation of undulator radiation

$$\left(\frac{\sigma_E}{E}\right)^2 \sim 180 \bullet r_0 \bullet \lambda_c \bullet \gamma^3 \bullet \left(\frac{K}{\lambda_u}\right)^3 \bullet Z$$

r_0 and λ_c - classical radius and Compton wavelength of electron

K - undulator parameter

Z - distance from the undulator entrance

Main way of increasing the brightness of 4th generation X-ray source:

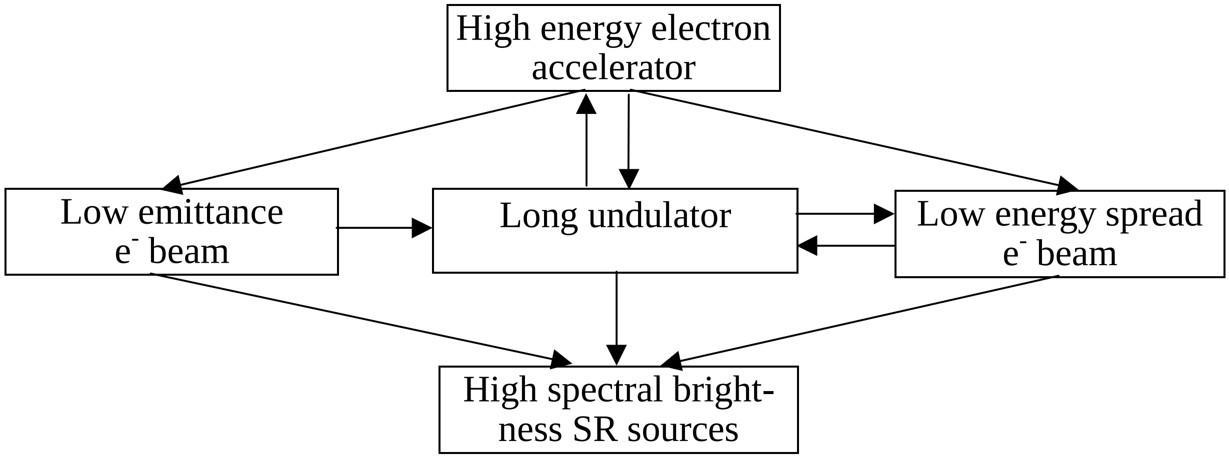
- decreasing the electron beam emittance down to diffraction limit

$$\varepsilon_x < \frac{\lambda}{4\pi} \sim 10^{-11} mrad \left(\lambda \sim 1 \mathring{A} \right)$$

- decreasing the electron beam energy spread down to fundamental limit due to quantum fluctuation of undulator radiation ($\sigma_E/E<10^{-4}$)

- using long undulator with number periods, determined by the fundamental limit due to quantum fluctuation of undulator radiation ($N_u \sim 10^4$)

Long undulator with 10^4 periods provides the radiation with narrow-peak spectrum and large length of the temporal coherence without additional monochromatization. This radiation can be successfully used for X-ray holography, X-ray microprobe and other experiments without using of monochromator.



1980	$\varepsilon \sim 10^3$ nmrad	$N_u \sim 10$	$\sigma_E/E \sim 10^{-3}$
1990	$\varepsilon \sim 10^2$ nmrad	$N_u \sim 10^2$	$\sigma_E/E \sim 10^{-3}$
2000	$\varepsilon \sim 1$ nmrad	$N_u \sim 10^3$	$\sigma_E/E \sim 10^{-3}$
2010	$\varepsilon \sim 10^{-2}$ nmrad	$N_u \sim 10^4$	$\sigma_E/E < 10^{-4}$

Three different kinds of SR sources are considered for last years:

- long undulators installed on the advanced storage rings;

- long undulators installed on the electron linear accelerators;

- long undulators installed on the MARS (Multiturn Accelerator-Recuperator Source);

- Electron beam emittance and energy spread in a storage ring is determined by equilibrium between radiation damping and two main diffusion processes: quantum fluctuation of the SR and the intrabeam scattering.

- There is no a solution to decrease the emittance in storage ring $\varepsilon_x < 10^{-10}$ mrad and energy spread $\sigma_E/E < 10^{-3}$.

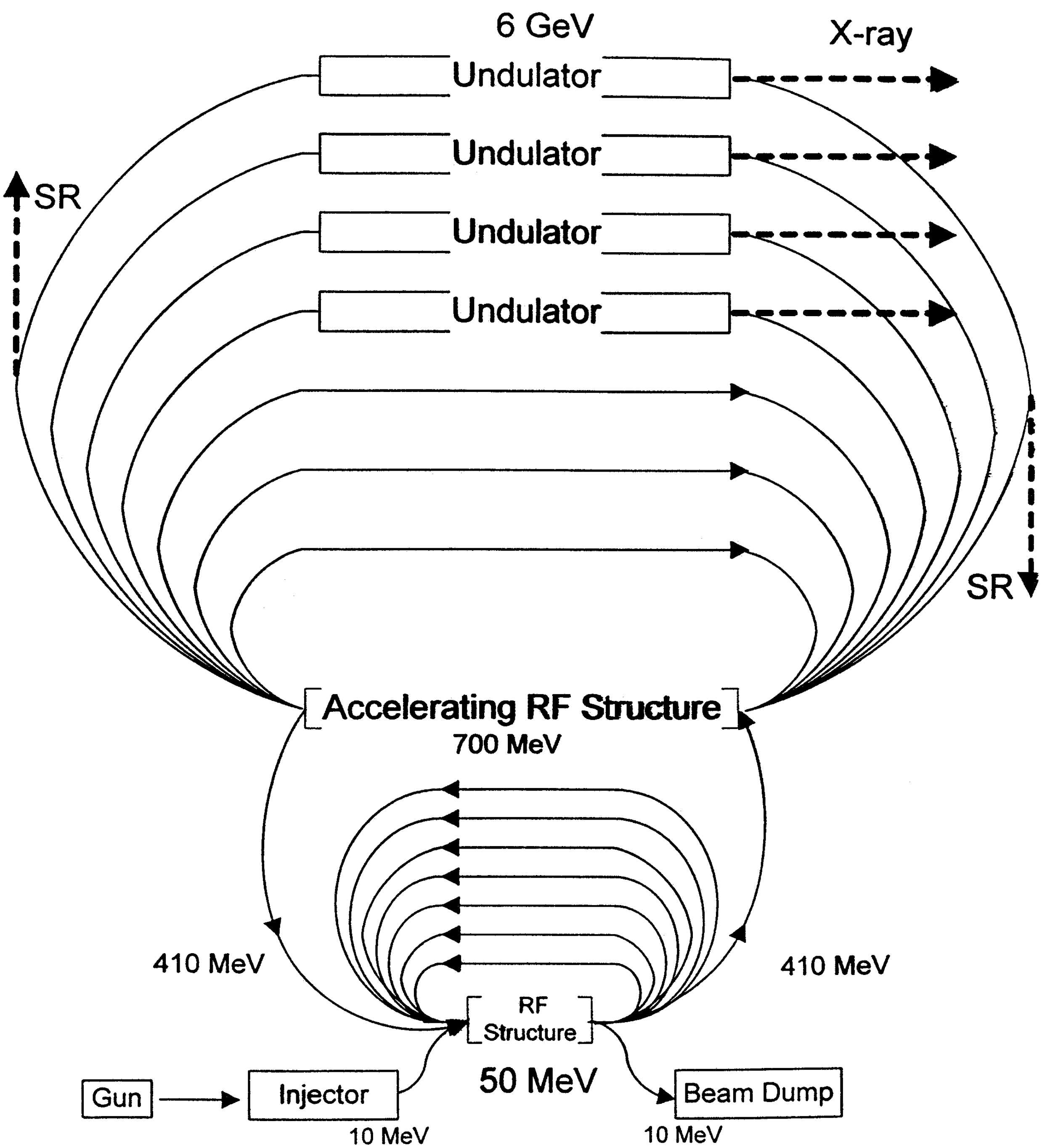
In the linear accelerator normalized emittance can be conserved during the acceleration process. Due to the adiabatic damping on energy E > 5 GeV emittance $\varepsilon_x \sim 10^{-11}$ mrad and energy spread $\sigma_E/E \sim 10^{-4}$ is possible.

Main disadvantages: low average current ($< 10^{-7}$ A) in case of pulsed conventional linac; high cost in case of superconducting linac.

For both kinds of linacs the radiation hazard is a very serious problem.

New approach to the 4th generation X-ray source was proposed recently (G. Kulipanov, N. Vinokurov, A. Skrinsky 1997 SRI-97).

The main motivation for MARS (Multi-pass Accelerator-Recuperator Source) was to combine the advantages of storage ring and linac.


6 GeV
X-ray
Undulator
Undulator
Undulator
Undulator
SR
SR
Accelerating RF Structure
700 MeV
410 MeV
410 MeV
RF
Structure
50 MeV
Gun
Injector
Beam Dump
10 MeV
10 MeV

MARS LAYOUT

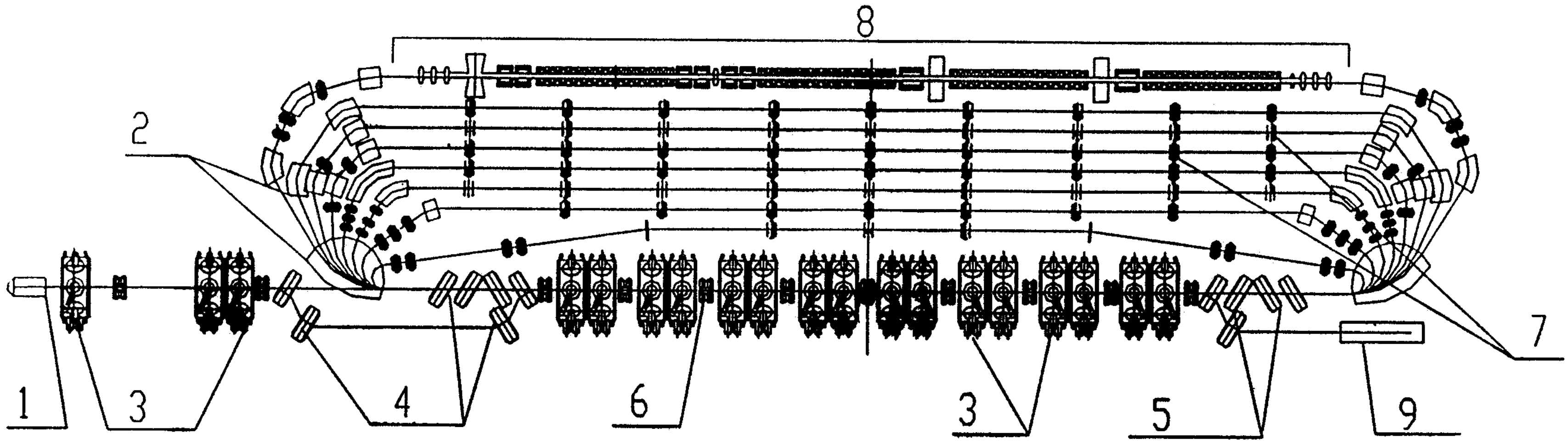
- The general scheme of MARS is shown in Fig. 1.
- Electron bunches from the RF gun (E ~ 300 keV) are accelerated in the RF linac up to the energy of 10 MeV.
- After the linac electrons are injected to the booster racetrack microtron-recuperator, they pass 8 times through the accelerating RF resonators and are accelerated up to the energy of 410 MeV.
- Then electrons are injected into the MARS, and additionally they pass 8 times through its RF resonators, and accelerating to 6 GeV.

- The “exhaust” beam delayed on 1/2 RF wavelength is decelerated in the MARS down to 410 MeV, and after that it is decelerated in the booster down to 10 MeV, giving the power back to the RF resonators.
- The electrons are absorbed in the beam dump with energy of 10 MeV. Due to this, problems with the radiation hazard and induced radioactivity will be eliminated.

- Main radiation sources of the MARS are:

  – four 150 m long undulators installed in straight sections, where electrons have energy 6; 5.3; 4.6 and 3.9 GeV.
  – many of bending magnets in the last arcs, where in the center of magnet, lattice functions are optimized to have a small beam size: $\sigma_x \sim 3\ \mu m$, $\sigma_z \sim 6\ \mu m$.

- Additionally to the accelerating-decelerating RF resonators in the long straight sections of the MARS and booster following magnetic elements where installed:
  - set of quadrupole magnets that provide focusing for the beam of any energy from injection energy to maximum energy;
  - injection and ejection magnetic system;
  - separating magnets to separate the beams with different energies;
- The example of the detailed scheme of the straight section is shown in Fig.2 for similar, but lower energy (100 MeV) accelerator - recuperator for high power IR FEL being constructed in Novosibirsk now.



Scheme of the microtron-recuperator (1 - electron gun, 2 - bending magnets; 3 - RF resonators; 4,5 - injection and outcoupling magnets; 6 - focusing solenoids; 7 -straight sections with the quadrupole lenses; 8 - FEL magnetic system; 9 - beam dump).

For users MARS based SR facility is similar to storage ring based SR source, but MARS uses "fresh" electron beam with low emittance
($\varepsilon_x \sim 10^{-11}$ mrad) and energy spread
($\sigma_E/E \sim 10^{-4}$).

As in MARS the time of the acceleration is small in comparison with the radiation damping time in storage ring (factor 10^3) main diffusion processes (quantum fluctuation of the SR in arc and intrabeam scattering) can not "spoil" emittance and energy spread.

In the MARS normalized emittance can be conserved during the acceleration process similar to linac. But due to multipass acceleration the cost of accelerating RF structure can be reduced. Due to energy recovery radiation hazard can be eliminated and cost of the RF power system and cost of building will be reduced.

Magnetic lattice

- The quantum fluctuation induced growth of energy spread in the 180-degree bend must be less, than the acceptable energy spread, therefore bending radius R must be large:

$$R > \frac{r_0}{\delta\gamma/\gamma}\sqrt{\frac{55\pi}{24\sqrt{3}\alpha}\gamma^5}$$

for $\delta\gamma/\gamma = 2 \cdot 10^{-5}$ $R > 40$m

- Emittance growth in the arcs can be reduced to acceptable value by the focusing lattice optimization.

- Arc cell consists of one gradient dipole magnet and one quadrupole magnet, arc lattice functions are shown in Fig. 3.

- Quadrupole magnets arrangement in the accelerating sections provides focusing for the beam of all energy set from energy injection to maximum energy.

- The behavior of the lattice functions has bilateral symmetry to get focusing both for accelerating and decelerating beams.

- An arrangement of the matching quadrupoles both adjust the lattice functions between the RF sections and arc and provides optimal lattice functions in rather strong (1,5 T) separating magnet (that separate the beams with different energies). The emittance growth in this magnet is very sensitive to the lattice functions behavior.

The undulator:

- undulator gap will be limited mainly by radiation losses in the walls of vacuum chamber- g=0.5 cm seems reasonable

- for K ~ l and g = 0.5 cm λ_W = l.5 cm;

- maximum length of undulator is determined by the increase of energy spread in undulator due to quantum fluctuation of undulator radiation

$$\left(\frac{\delta\gamma}{\gamma}\right)^2 \approx F(K)\frac{\Delta E_u \varepsilon_u}{E^2}$$

ΔE_u - total energy losses in undulator;
ε_u - energy of photons from undulator;

$$L\max(m) < 9\times 10^7 \sqrt[3]{\frac{\lambda_W^5(m)}{\gamma^2 K}}$$

L=150 m (N=10^4) $\delta\gamma/\gamma \sim 2\times 10^{-5}$

- Undulator must be segmented in sections of L ~ 5 m with 1 m straight section in between. Each straight section contains 3-pole phase adjuster, triplet, steering magnets and beam position monitor.

- Triplets between the undulator sections must be used for providing the equal and almost constant (inside undulators) beta functions $\beta_x \sim \beta_z$

- For tuning of the photon energy from undulators superconducting technology or combination electromagnet and permanent magnet technology (equipotential-bus electro-magnetic undulator) may be more appropriate for very long undulator.

- Photon beam monitors and monochromator for spectral measurements have to be install on beamline for feedback to the steering coils and phase adjusters.

RF photocathode Gun

- minimum possible normalized emittance, determined initial thermal energy spread, is fundamental and uncorrectable

$$\varepsilon_n \sim 3 \times 10^{-4}\, r_c$$

- distortion of phase space and emittance growth due to RF time dependent effects and space charge induced effects could be corrected (long RF wave length small transverse size of electron beam, small peak current and high accelerating gradient,...)

- example:

$r_c = 10^{-1}$ mm;
$\varepsilon_n = 3 \cdot 10^{-8}$ mrad;
I_{peak} 200 mA;
($J_c \sim 600$ A/cm^2)

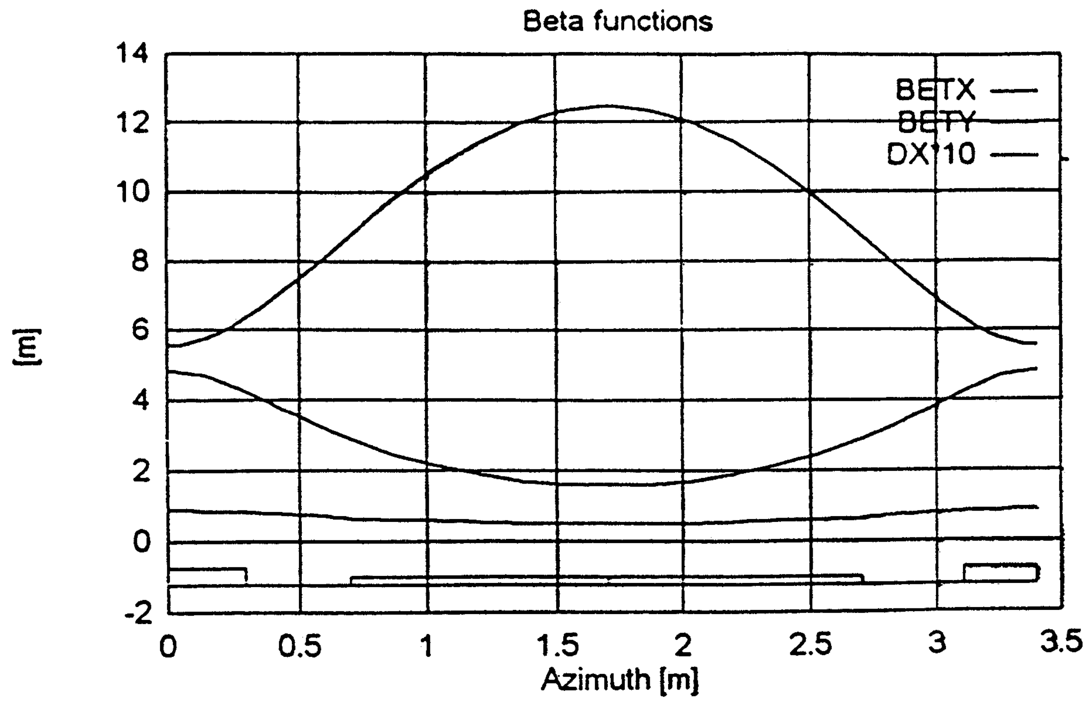


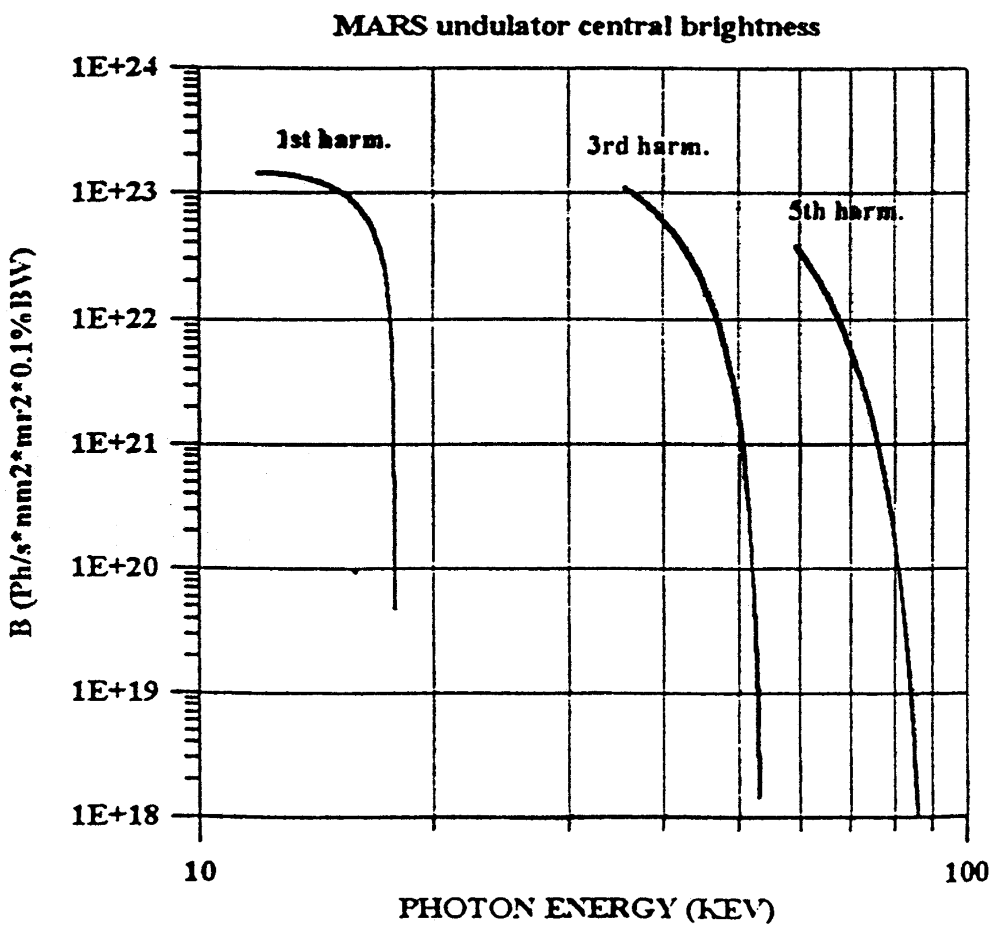
Fig.3 Lattice functions for the low-emittance arc cell.

Table 6: MARS source parameters.

		Undulator	Bend. magnet
β_x	m	75	1.5
β_z	m	75	12
η	m	0	0.05
σ_x	μm	18	2.8
σ_z	μm	11	6.9
σ'_x	μrad	0.9	1.9
σ'_z	μrad	0.8	0.6

Table 5: Accelerator parameters.

Energy	GeV	6
Electron current	mA	1.
Horizontal emittance	nm-rad	5.3×10^{-3}
Vertical emittance	nm-rad	4×10^{-3}
Relative energy spread		2.4×10^{-5}



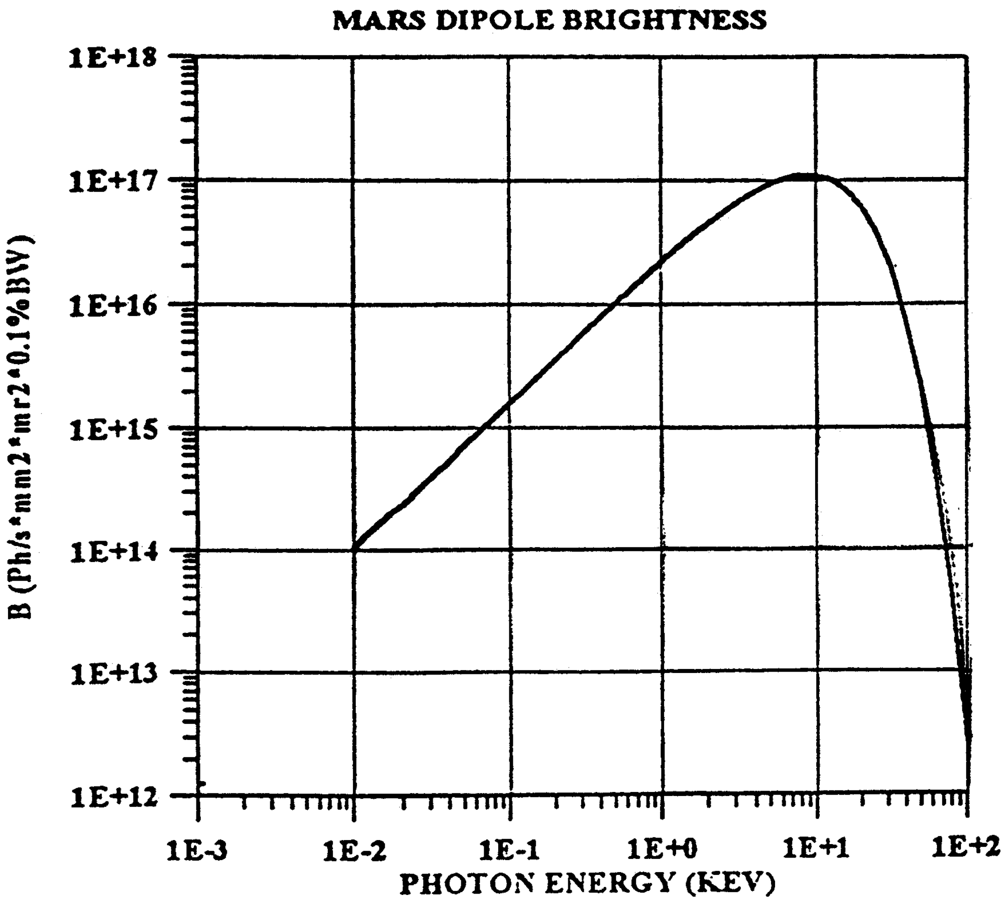


Fig.4: MARS bending magnet radiation brightness.

Comparison of various types of the coherent X-ray sources:

	ESRF storage ring	LCLS linac	MARS
Wavelength, nm	.1	.15	.1
Electron energy, GeV	6	14	5.4
Average current, A	.2	3×10^{-8}	10^{-3}
Peak current, A		3.4×10^{3}	1
Relative energy spread		2×10^{-4}	1×10^{-5}
Emittance, nm εx εz	4 2.5×10^{-2}	3×10^{-2}	3×10^{-3}
Undulator period, cm	4.2	3	1.5
Undulator length, m	5	100	150
Coherent flux, photon/s	6×10^{12}	6×10^{14}	7×10^{13}
Bandwidth	10^{-2}	10^{-3}	10^{-4}
Average brightness, $ph/s/mm^2/mrad^2/0.1\%BW$	10^{20}	6×10^{22}	3×10^{23}
Peak brightness, --//--		5×10^{33}	3×10^{26}
Transverse size of source (standard deviation), μm	σ_x 350 σ_y 8	9	10
Radiation transverse divergence (standard deviation), μrad	$\sigma_{x'}$ 13 $\sigma_{y'}$ 3	2	1

Conclusion

- In this talk a rough conceptual design of MARS (Multiturn Accelerator-Recuperator Source) is presented.

- No clear physical obstacles for MARS approach.

- Accelerator scheme and the most of the key systems, used here, were already tested at other facilities (Budker INP, CEBAF, MAMI, LEP).

- 4th generation light source, based on MARS, is mainly the issue of funding.

- The very rough cost estimations indicate, that scale of the cost is the same as for the existing large third-generation facilities (ESRF, APS, SPring-8).