Multiturn ERL X-ray Source (MARS)
Feasibility Study

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- The SR sources of the 3rd generation available and those under construction (APS, ESRF, Spring-8, SLS, ELETTRA, DIAMOND, SOLEIL, PETRA-III, ALBA …) are the efficient factories for generation of the new knowledge, new technologies and new materials.

- In the last two decades, there were active discussions on the development of SR sources of the 4^{th} generation. The world's physical community worked out the requirements to these sources and suggested several ways for the development of such sources.

List of requirements for future generation of X-ray sources:

- full spatial coherence;
- the highest temporal coherence ($\Delta\lambda/\lambda<10^{-4}$) without additional monochromatization;
- the averaged brightness of the sources is to exceed 10^{23}-10^{24} photons $s^{-1}mm^{-2}mrad^{-2}(0.1\%\ bandwidh)^{-1}$;
- the full photon flux for the 4th generation sources must be at the level of the 3rd generation SR sources;
- high peak brightness of the order of 10^{33} photons $s^{-1}mm^{-2}mrad^{-2}$ $(0.1\%\ bandwidh)^{-1}$ is important for some experiments;
- electron bunch length up to 1 ps; and if a specialized technique is used, the X-ray pulses become smaller than 100 fs;
- high long-term stability; generation of linear, left-right circular polarized radiation with fast switching of the polarization type and sign; constant heat load on chambers and optics, etc.
- servicing the multi-user community.

Further reading

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Scientific Needs for Future X-Ray Sources in the U.S.

A White Paper

Based on a study group co-chaired by Roger Falcone and Joachim Stöhr, and members: Uwe Bergmann, John Corlett, John Galayda, Jerry Hastings, Robert Hettel, Zahid Hussain, Janos Kirz, Bill McCurdy, Tor Raubenheimer, Fernando Sannibale, John Seeman, Z.-X. Shen, Robert Schoenlein, and Alexander Zholents.

Lawrence Berkeley National Laboratory
SLAC National Accelerator Laboratory

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- During the last 30 years, the brightness of the X-ray SR sources based on storage rings increased by a factor of 10^{9}.

- Nevertheless, on the modern sources, the flux of coherent quanta is only 10^{-3} of the total flux. Therefore, in spite of successful demonstrating X-ray holography, it has not become an efficient technique for structural studies of real objects of mostly noncrystalline structure. Even for crystalline structures, the speckle spectroscopy, which is accessible only in coherent light, is very important.

- Therefore, obtaining a fully spatially coherent flux of quanta with full photon flux at the level of the 3rd generation SR sourcesis is the most important from all the requirements to SR sources of the 4th generation.

- A possibility of obtaining undulator radiation with a monochromaticity of $10^{-3} \div 10^{-4}$ without using monochromators, which as a rule spoil the beam spatial coherence, is also of great importance.

Main ways of creation of 4^{th} generation X-ray sources:

1. Decreasing the electron beam emittance down to the diffraction limit

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

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

3. Using a long undulator with a number of periods determined by the fundamental limit due to quantum fluctuation of undulator radiation ($N_u \sim 10^4$).

- For realization of a fully spatially coherent X-ray source Kulipanov G., Skrinsky A., Vinokurov N. proposed using of accelerators-recirculators with energy recuperation (SRI-97)

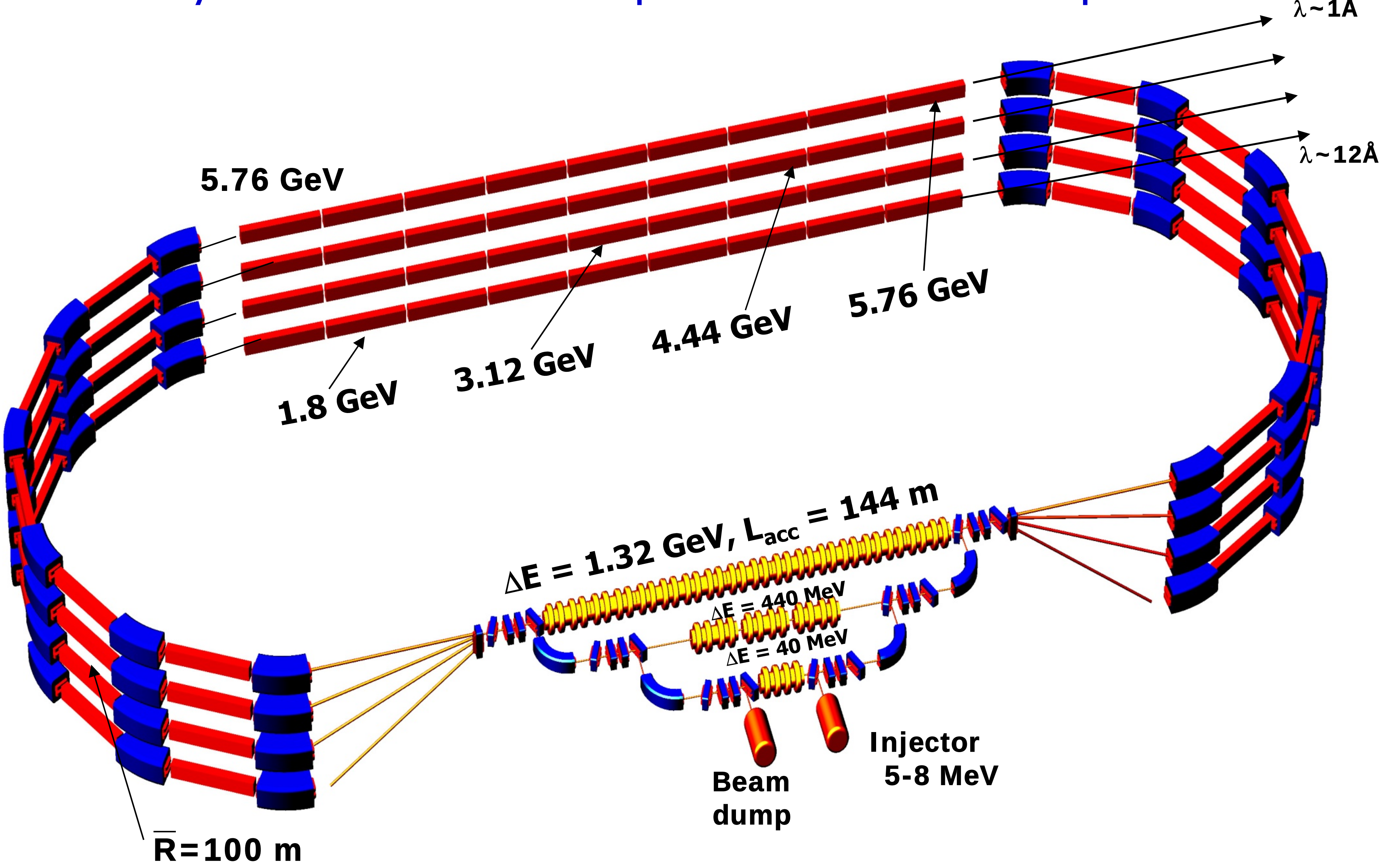
See: [1] *MARS - recirculator-based diffraction limited X-ray source. // Budker INP preprint No 97-103 (1997);*

[2] *Kulipanov G., Skrinsky A., Vinokurov N. Synchorton light sources and recent development of accelerator technology. // J. of Synchrotron Radiation –1998 V.5 pt.3 P.176*).

- MARS, a recuperator-based diffraction-limited X-ray source, was presented and discussed at the ICFA workshop on future light sources (ANL, USA, July 1999) and SRI-2000 (Berlin), "ERLSYN-2002" (Erlangen, Germany, 2002), "SR-2004" (Novosibirsk, Russia, 2004); "RUPAC-2005" (Dubna, Russia, 2005); "Nano-Beam 2005" (Kyoto, Japan, 2005).

- After SRI-2000, the idea of using the accelerators-recuperators for creation of 4th generation of SR sources has been actively discussed at Jefferson Lab, Cornell Uni., KEK, BNL, LBL, Erlangen Uni., Daresbury Lab.

Layout of 5.7 GeV four-pass accelerator-recuperator



- Main motivation for accelerator-recuperator:

combination of the advantages of storage ring (high reactive power in beam and low radiation hazard) and linac (normalized emittance and energy spread can be conserved during the acceleration process);

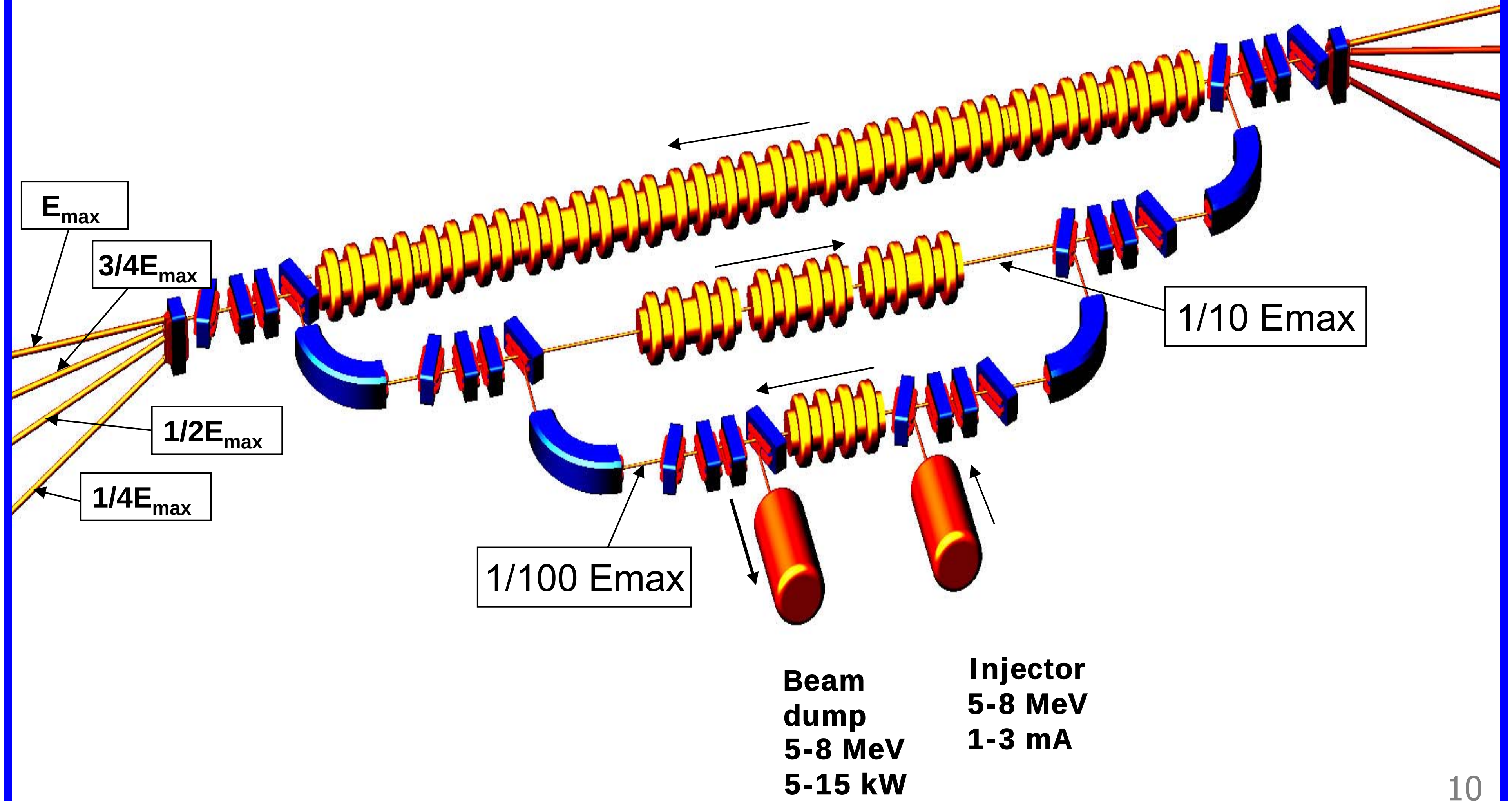
radiation hazard can be eliminated owing to energy recovery and the cost of construction will be reduced.

- Main motivation for multi-pass accelerator-recuperator:

the cost of the accelerating RF system can be reduced owing to multipass acceleration.

Cascade injection – effective solution of important problems of ERL

First linac has 5-8 MeV energy and does not use energy recovery.
For booster linacs (30 MeV and 330 MeV energy gain) energy recovery is used.



Cascade scheme of injection provides effective and economical solution to the following problems:

- Decrease in radiation hazard and limitation of induced radioactivity due to low energy of electrons at dump (5-8 MeV).

- Reduction in the cost of construction and RF power system for the injector.

- Simplification the problem of focusing particles of different energies traveling simultaneously in the accelerating structure, because the cascade scheme enables injection of electrons into all accelerating structures with energies of no less than $E_{max}/10$ (E_{max} is the maximum energy of electrons traveling in the accelerating structure).

The maximum value of electron current

- In order to achieve full spatial coherence of the source we suggest that the charge in one bunch be no more than

$$Q = 7.7 \cdot 10^{-12} \text{ Coul}$$

For F_{RF}=1.3 GHz that corresponds to a current value of 10 mA for a single-turn accelerator, 5 mA for two turn accelerator and 2.5 mA for a four-turn accelerator.

- The version suggested for some single-turn ERL projects - using current up to 100 mA for keeping the photon flux - seems to be far from optimum, since with such an increase in current the brightness does not increase and even decreases sometimes.

- To compensate the decrease in the current value compared with that of the 3rd generation SR sources, we shall use radiation only from three types of undulators with N_{u1}=100, N_{u2}=1000, N_{u3}=10 000, not from bending magnets. In this case, we solve the problem of full spatial coherence and at the same time keep the photon flux at the level of the 3rd generation sources.

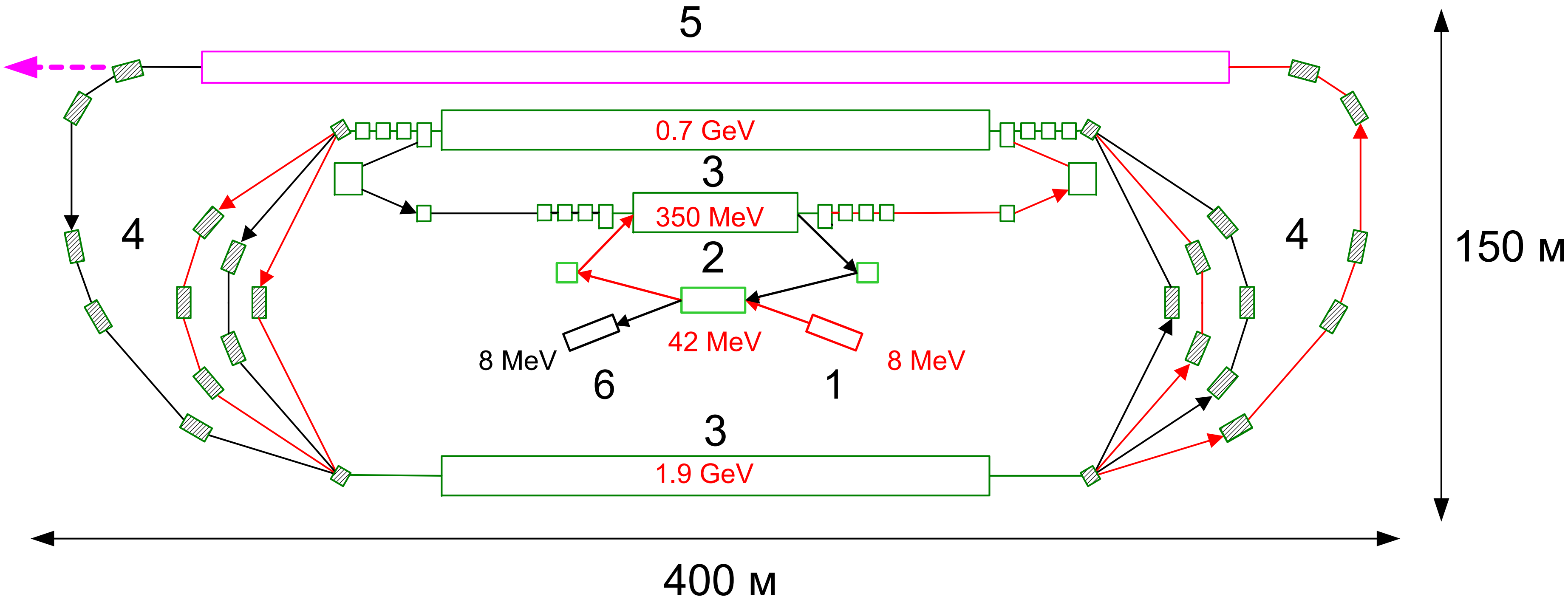
- Due to using small bunch charge (Q=8 pC) and relatively long bunch length (2 ps) we hope do not observe effects of growth of transverse and longitudinal emittance and beam loss due to:
  - coherent synchrotron radiation.
  - intrabeam scattering (Touschek)
  - disturbance from ions.

ERL with separated tracks for accelerated and decelerated beams

The initial scheme of the accelerator-recuperator MARS suffers from a number of shortcomings. The main one is that two beams – under acceleration and deceleration – are circulating simultaneously on all the tracks, which creates two sources of radiation from undulators on those tracks.

For this reason it was suggested recently to turn to an accelerator-recuperator scheme with two acceleration sections, similar to the scheme of the US accelerator CEBAF. Such schemes are considered below.

The simplest scheme of ERL (for understanding) with separated tracks

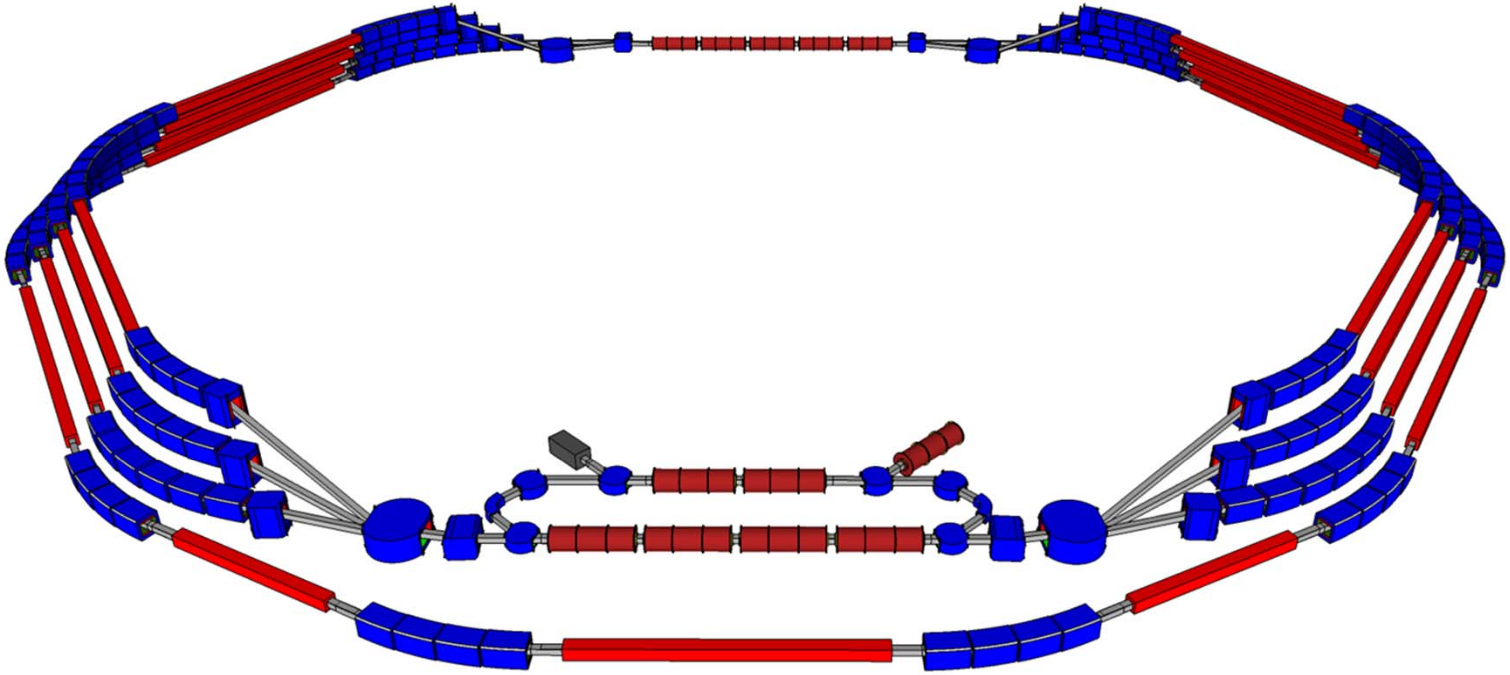


1 – injector, 2 – preliminary accelerating system, 3 – main accelerating RF structure, 4 – magnets, 5 – undulator, 6 – dump.

red arrows – accelerating bunch

black arrows – used decelerating bunch

Multy-pass Accelerator-Recuperator Source (MARS)



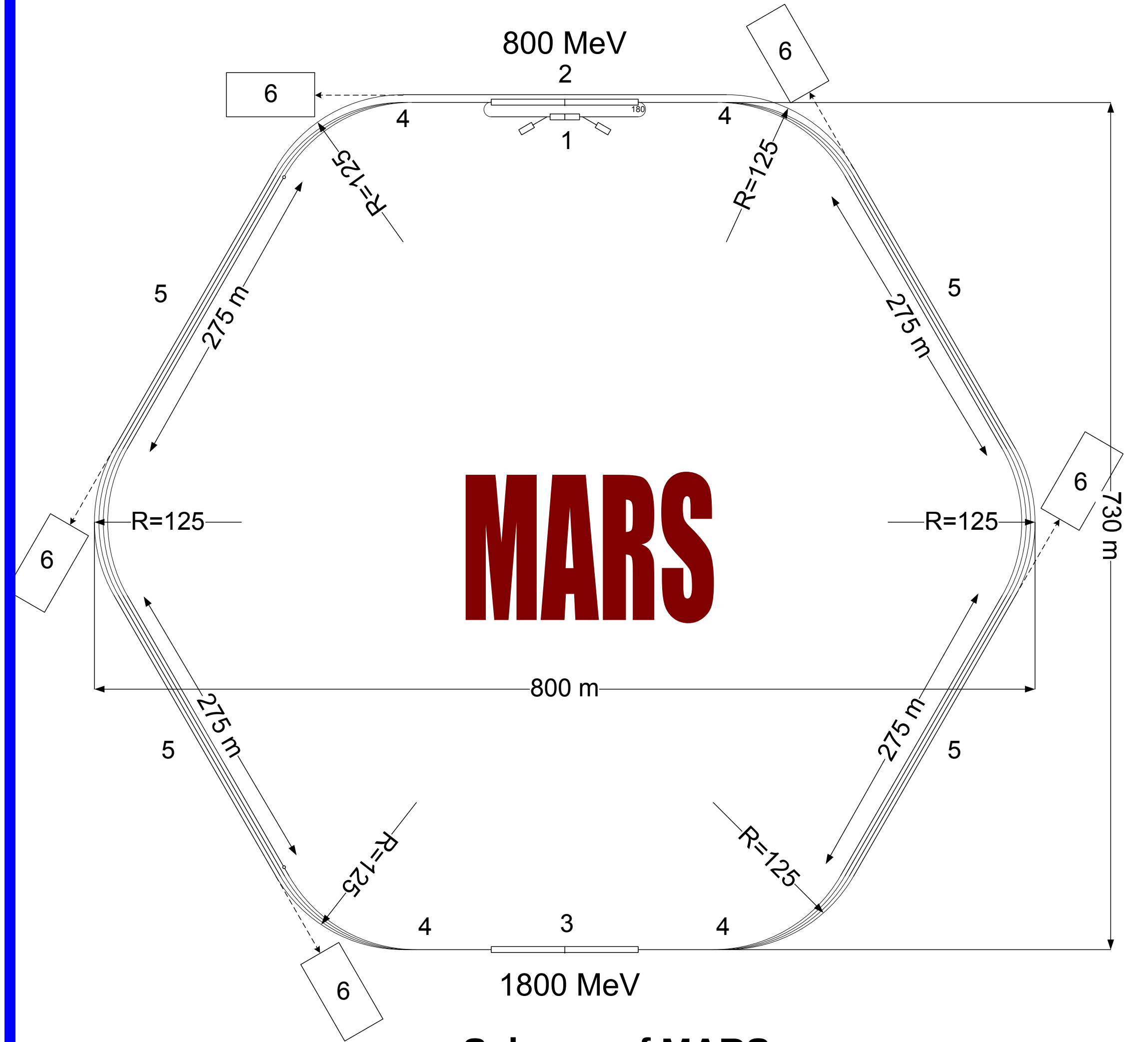
Energy range *5.6, 3.8, 3, 1.2 GeV*

Emittance: $\xi_n < 10^{-7}\, m \cdot rad$

Bunch Charge: $Q \leq 10^{-11}\, Cl$

- 7 undulators for 5.6 GeV
- 4 undulators for 3.8 GeV
- 4 undulators for 3 GeV
- 4 undulators for 1.2 GeV

Multy-pass Accelerator-Recuperator with two linacs



Scheme of MARS

1-injector, 2-1-st linac, 3 -2-d linac, 4 – spreders & recombiners, 5 – undulators, 6 – user stations

Supposed parameters

Energy range *5.6, 3.8, 3, 1.2 GeV*

Emittance: $\xi_n < 10^{-7} m \cdot rad$

Bunch Charge: $Q \leq 10^{-11} Cl$

Users stations:

- 7 undulators for 5.6 GeV
- 4 undulators for 3.8 GeV
- 4 undulators for 3 GeV
- 4 undulators for 1.2 GeV

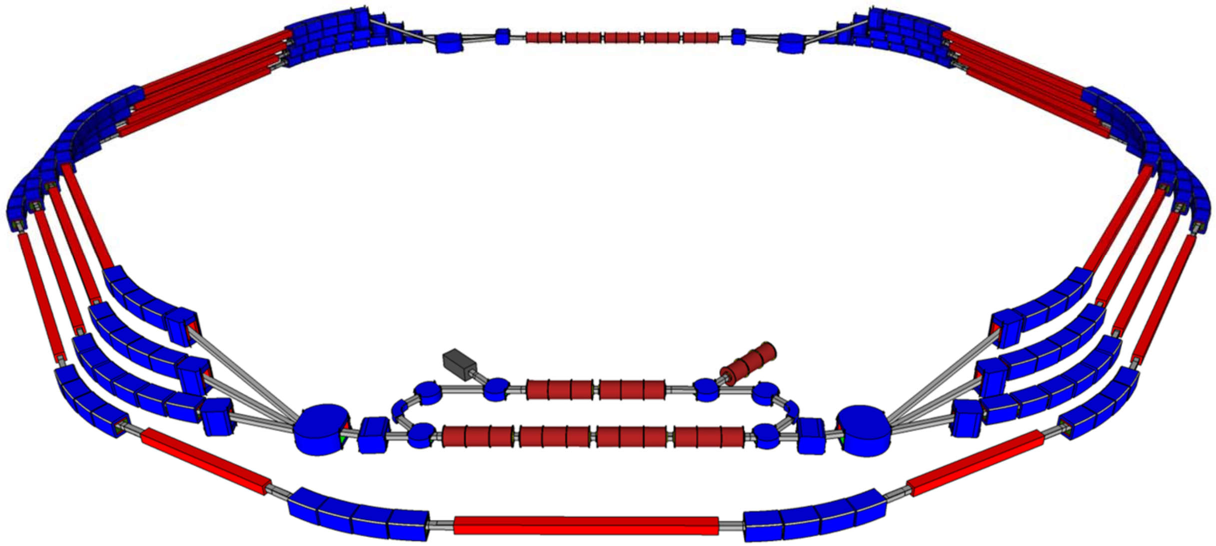
Conclusion

- All the requirements to X-ray radiation sources of the 4th generation cannot be satisfied with the use of only one kind of a source. The high peak brightness and femtosecond duration of radiation pulses can be attained at the linac based X-ray SASE FEL with a high pulse current (I_p >1 kA).

- All the remaining requirements are easier and cheaper realized with the use of radiation from the long undulators installed at the accelerator-recirculator with energy recovery.

- The accelerating schemes and most of the systems , which make the basis of the projects, have already been tested in many laboratories (Jefferson Laboratory, DESY, MAMI, LEP, Budker INP, KEK, MAX).
- There is no any essential physical problems in the development of the 4th generation SR sources on the base of accelerators-recuperators with average current < 10 mA.
- The main problem is the cost of such SR source and its further maintenance.

Multiturn ERL X-ray Source (MARS) Feasibility Study



Requirements for ERL light source	Realization
Full spatial coherence ($\lambda \sim 0.1 nm$)	$\varepsilon_n \sim 10^{-7} m \cdot rad$ $I_{\max} \sim 5mA(n_u = 2)$ $Q \sim 10\, pC$ $E_{\max} = 5.6GeV$
Full photon flux at the level of the 3-rd generation SR sources	Light sources only from undulators $N_u \sim 10^2$ $N_u \sim 10^3$ $N_u \sim 10^4$
Highest temporal coherence ($\Delta\lambda / \lambda < 10^{-4}$) without additional monochromatization	$N_{u\max} \sim 10^4$ $\Delta E / E < 10^{-4}$
Servicing the multi-user community	7 und for *5.6 GeV,* 4 undulators for *3.8, 3, 1.2 GeV*

Thank you for your attention