MARS: Fourth Generation X-Ray Light Source Based on Multiturn Energy-Recovery Linac

G. N. Kulipanov, Ya. V. Getmanov, O. A. Shevchenko, A. N. Skrinsky, (Budker INP SB RAS), N. A. Vinokurov (Budker INP SB RAS and KAERI), M. V. Kovalchuk, V. N. Korchuganov (NRC Kurchatov Institute)

Outline

- *Requirements for 4-th generation light source*
- *NovoFEL - the first multipass ERL*
- *MARS scheme*
- *MARS main features*
- *Prototype of MARS at energy 1 GeV*
- *Conclusion*

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.

The radiation brightness

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

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

$$(\Delta S \cdot \Delta\Omega)_{\min} = \frac{\lambda^2}{4}$$ (for Gaussian radiation beam).

In storage ring based radiation sources

$$\varepsilon_x = \sigma_x \cdot \sigma_{x'} >> \frac{\lambda}{4\pi} \qquad \varepsilon_y = \sigma_y \cdot \sigma_{y'} >> \frac{\lambda}{4\pi}$$

and

$$\Delta S \cdot \Delta\Omega = (2\pi)^2 \varepsilon_x \varepsilon_y >> \frac{\lambda^2}{4}$$

The diffraction-limited undulator radiation spectral brightness

$$B = \frac{2\pi\alpha N}{\lambda^2}\frac{K^2}{1+K^2/2}\left[J_0\left(\frac{K^2}{4+2K^2}\right)-J_1\left(\frac{K^2}{4+2K^2}\right)\right]^2\frac{I}{e}$$

- if emittances of electron beam are small enough:

$$\varepsilon_x = \sigma_x \cdot \sigma_{x'} \le \frac{\lambda}{4\pi}\,, \quad \varepsilon_z = \sigma_y \cdot \sigma_{y'} \le \frac{\lambda}{4\pi}\,,$$

the source provide full spatial coherence of radiation.

As the linewidth of the undulator radiation is 1/N, the spectral brightness is not reduced for low energy spread only. Namely,

$$\frac{\sigma_E}{E} < \frac{1}{4N}\,.$$

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

- It is impossible to satisfy all requirements for future light source using only one type of sources. The high peak brightness and femtosecond duration of radiation pulses can be attained at the X-ray SASE FEL based on the linac with high pulse current (I_p >1 kA).
- All other requirements are easier and cheaper realized by using the radiation from the long undulators installed at the accelerator-recirculator with energy recovery

Main requirements to ERL for 4th generation X-ray sources:

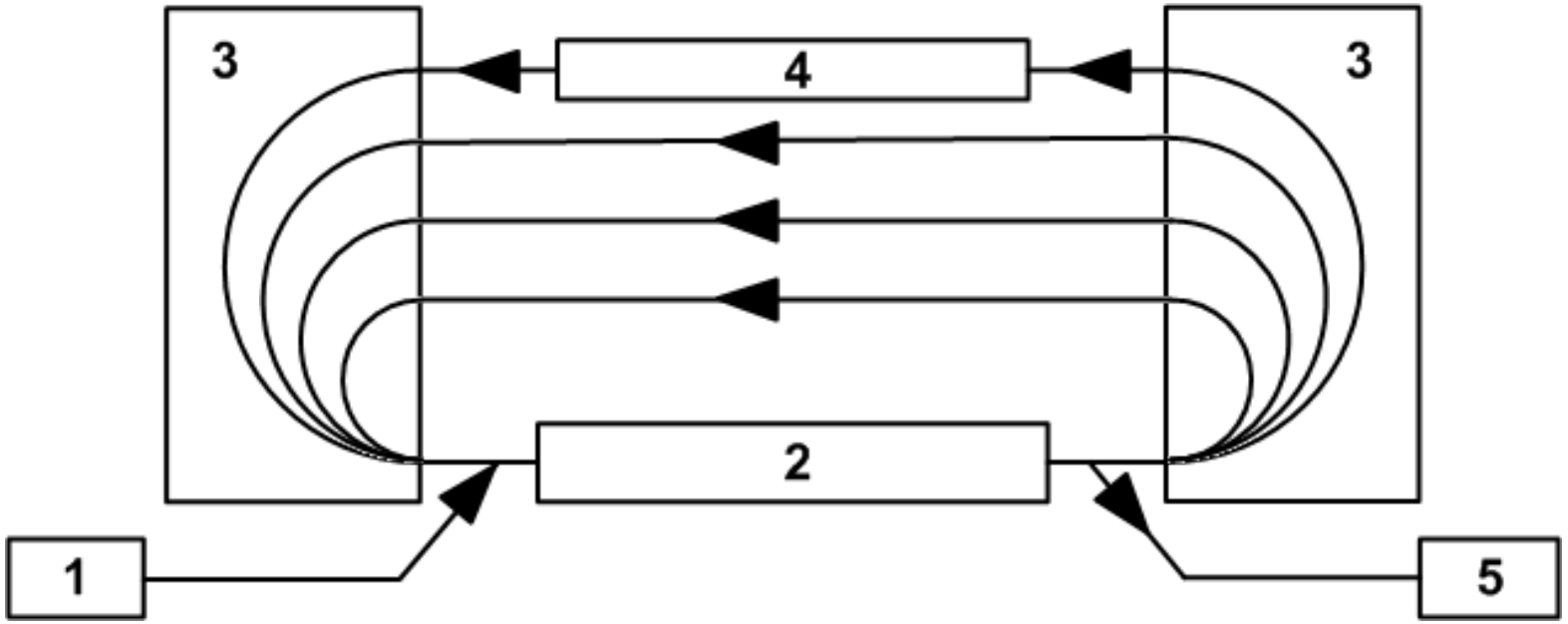
- Decreasing the electron beam emittance down to the diffraction limit

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

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

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

Energy Recovery Linac



1 – injector, 2 – linac, 3 – bending magnets, 4 – undulator, 5 – dump

❑ Main motivation for accelerator-recuperator:

combination of the advantages of the 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);

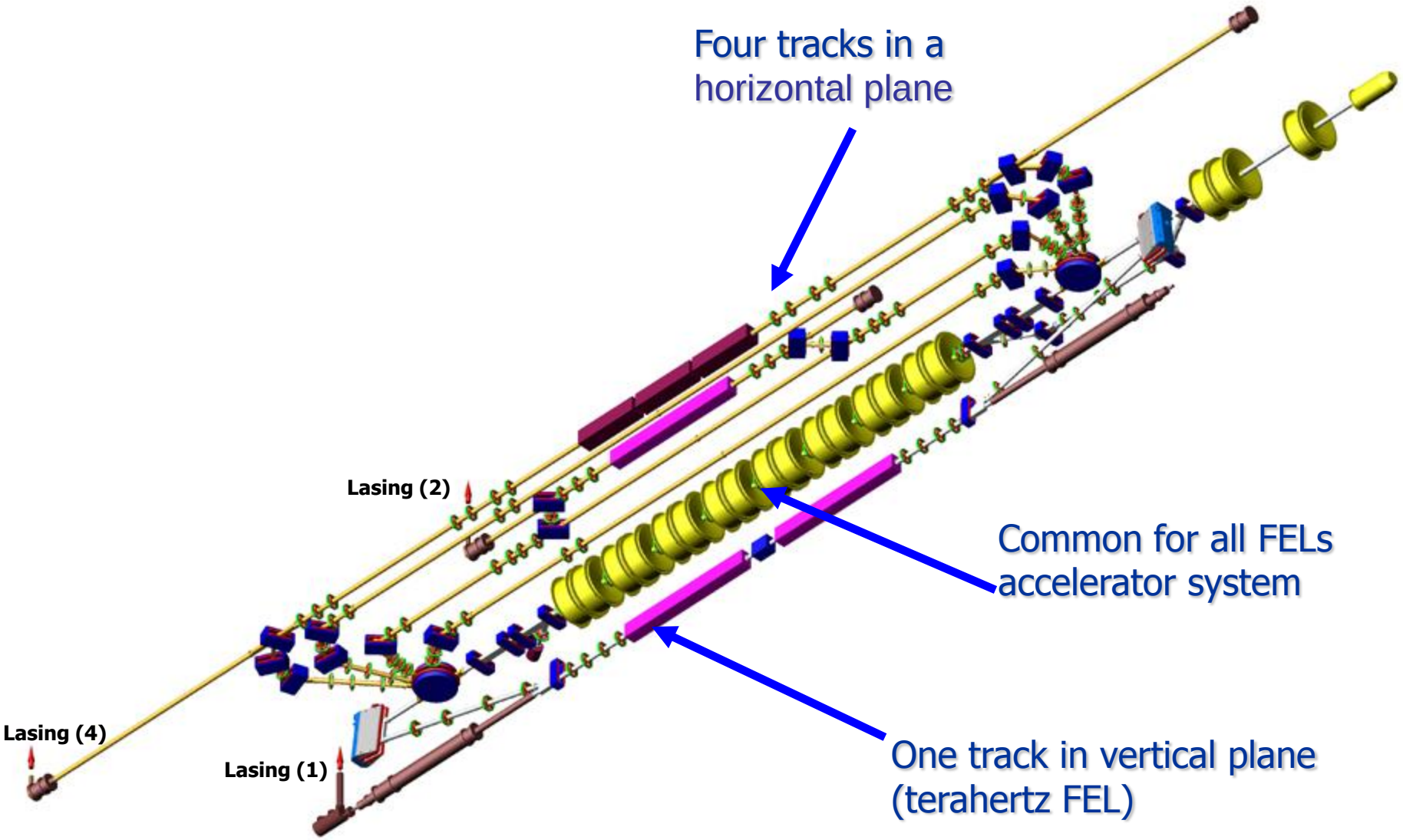
radiation hazard can be eliminated due to energy recovery and the cost of construction will be reduced.

❑ Main motivation for multi-pass accelerator-recuperator:

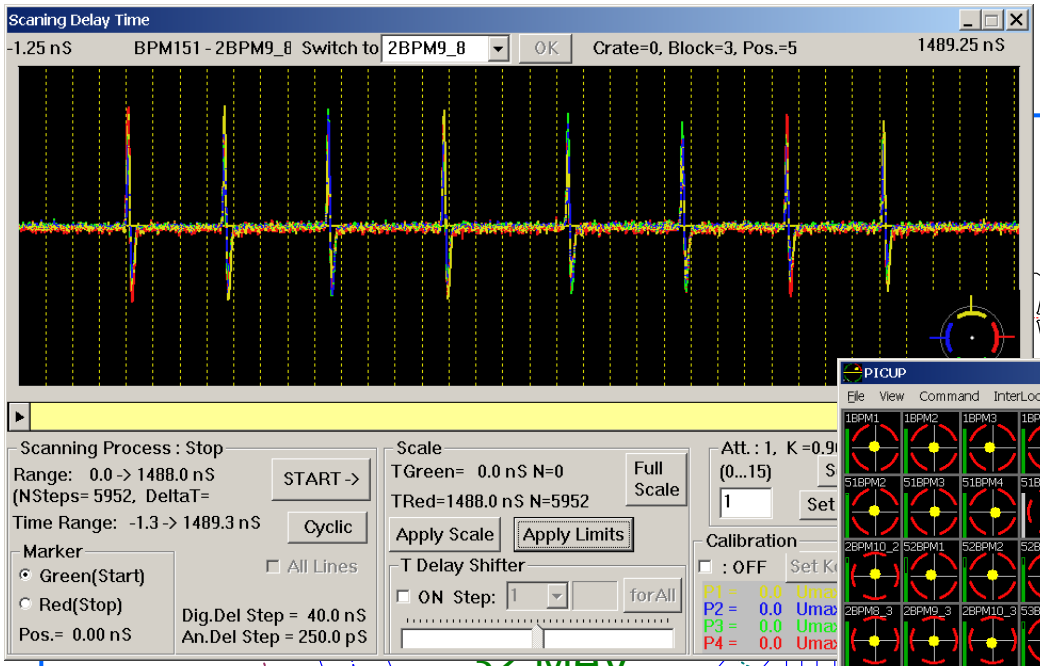
reducing the cost of the accelerating RF system due to multipass acceleration.

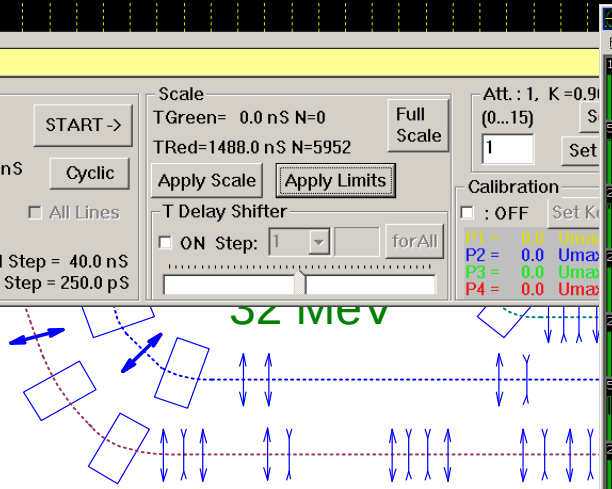
NovoFEL – the first multipass energy recovery linac (the talk by O. A. Shevchenko today)

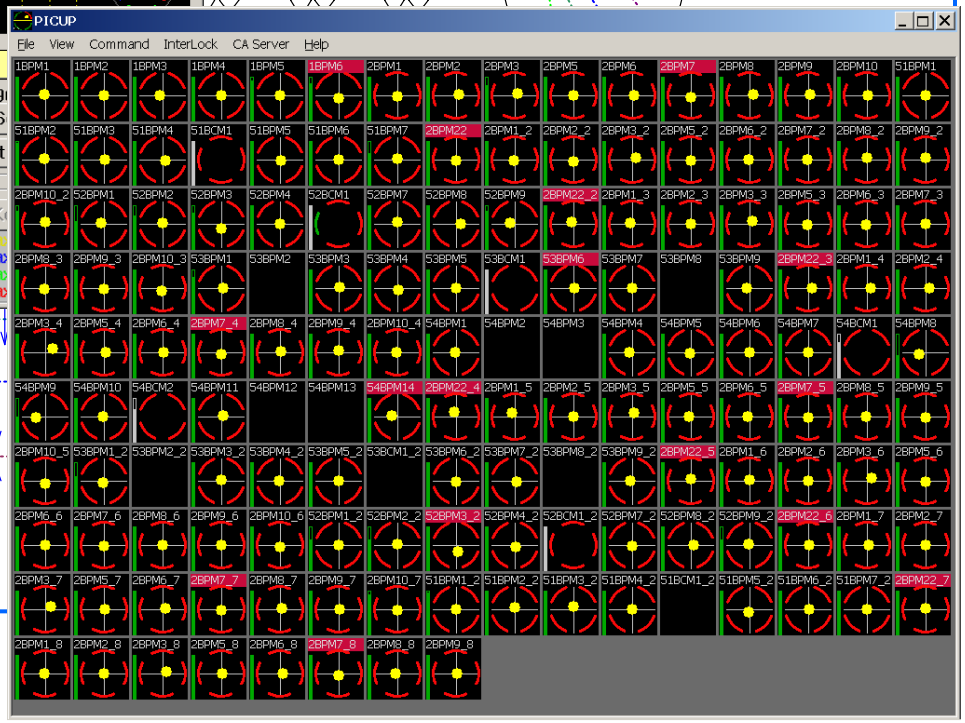
Novosibirsk ERL (bottom view)

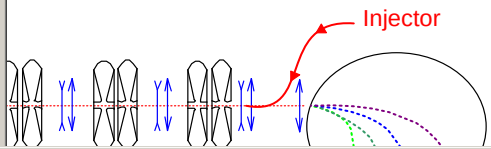


Third Stage NovoFEL: four pass ERL



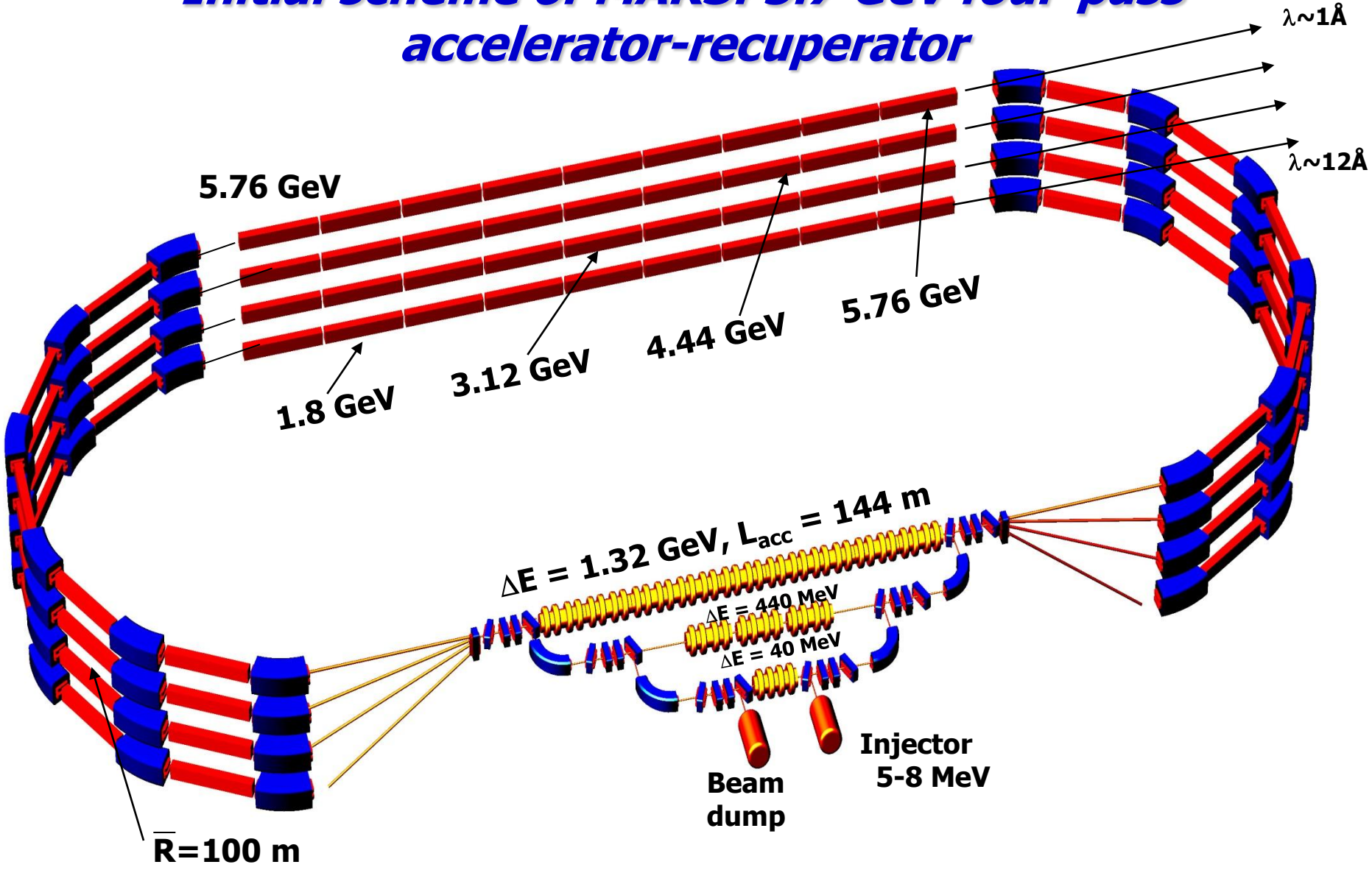






42 MeV

Initial scheme of MARS: 5.7 GeV four-pass accelerator-recuperator

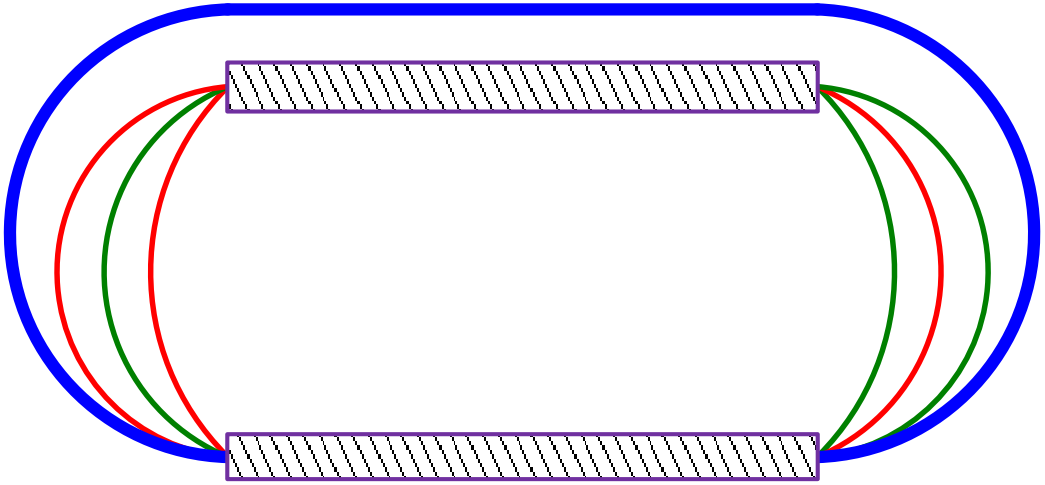


ERL with separated tracks for accelerated and decelerated beams

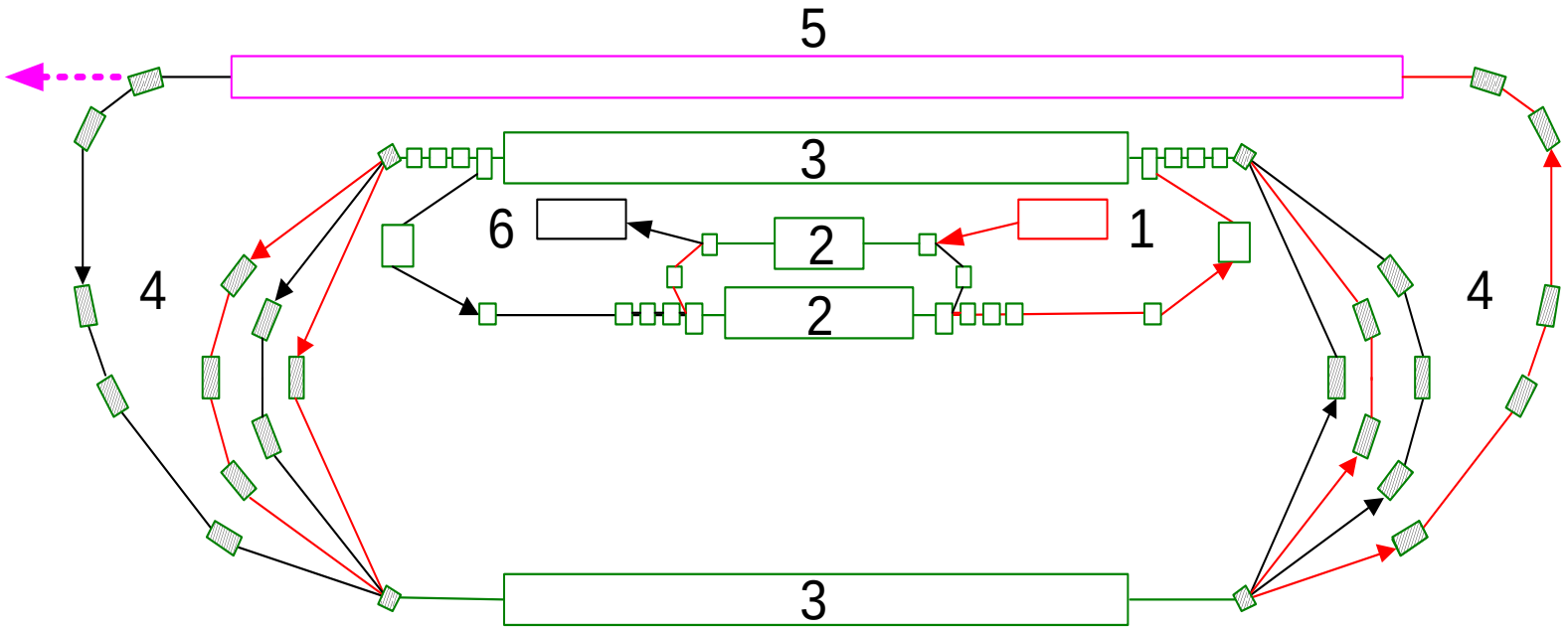
The initial scheme of the accelerator-recuperator MARS has serious intrinsic problems. The main one is that two beams – under acceleration and deceleration – are circulating simultaneously on all the tracks, which creates two sources of radiation from undulators on those tracks.

For this reason it was suggested 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.

Energy-Recovery Linac with two accelerating structures (D. Douglas, 2001)



Scheme of ERL with two linacs



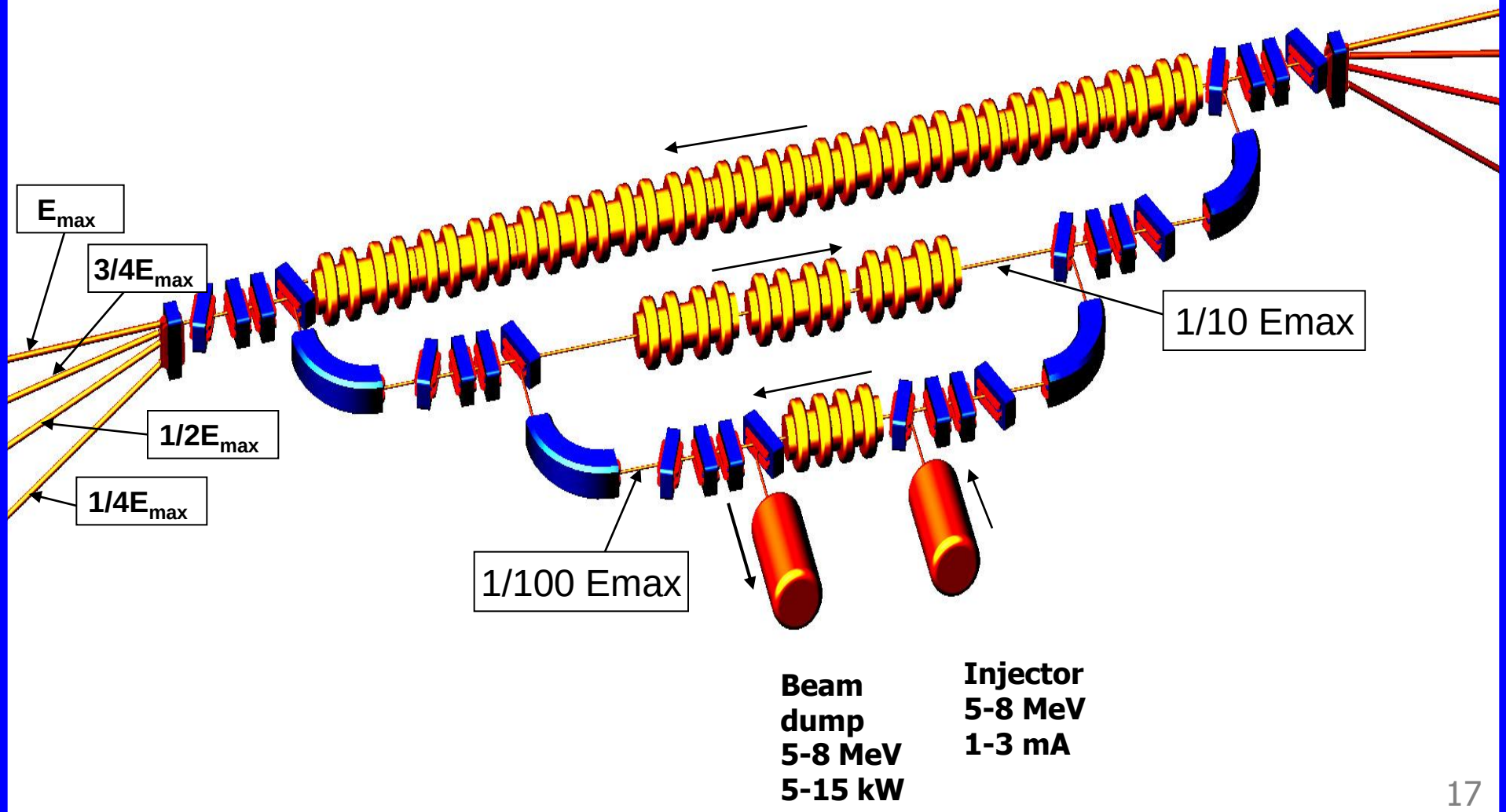
1 – injector, 2 – preliminary accelerating system, 3 – main accelerating RF structure, 4 – magnets, 5 – undulator, 6 – dump.

red arrows – accelerating beam

black arrows – used decelerating beam

Cascade injection – effective solution of the 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 higher injection energy.

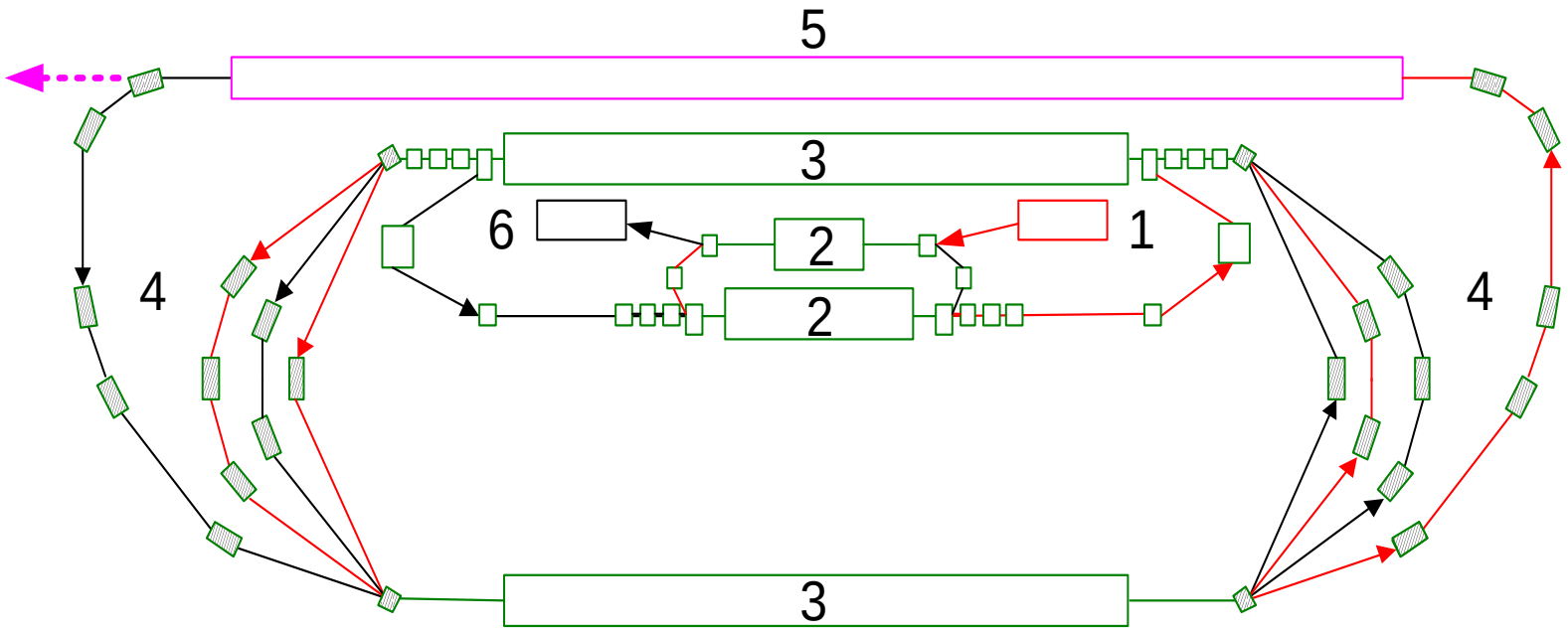
The maximum value of electron current

- In order to achieve full spatial coherence of the source we suggest that the charge in one bunch should not exceed Q= 7.7 • 10^{-12} C. For F_{RF}=1.3 GHz that corresponds to an average current value of 10 mA. The low charge per bunch allows to obtain required low emittance from the gun and decreases its degradation due to coherent synchrotron radiation.

- 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 3rd generation SR sources, we shall use radiation of very long (N=10 000) undulators. 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 one.

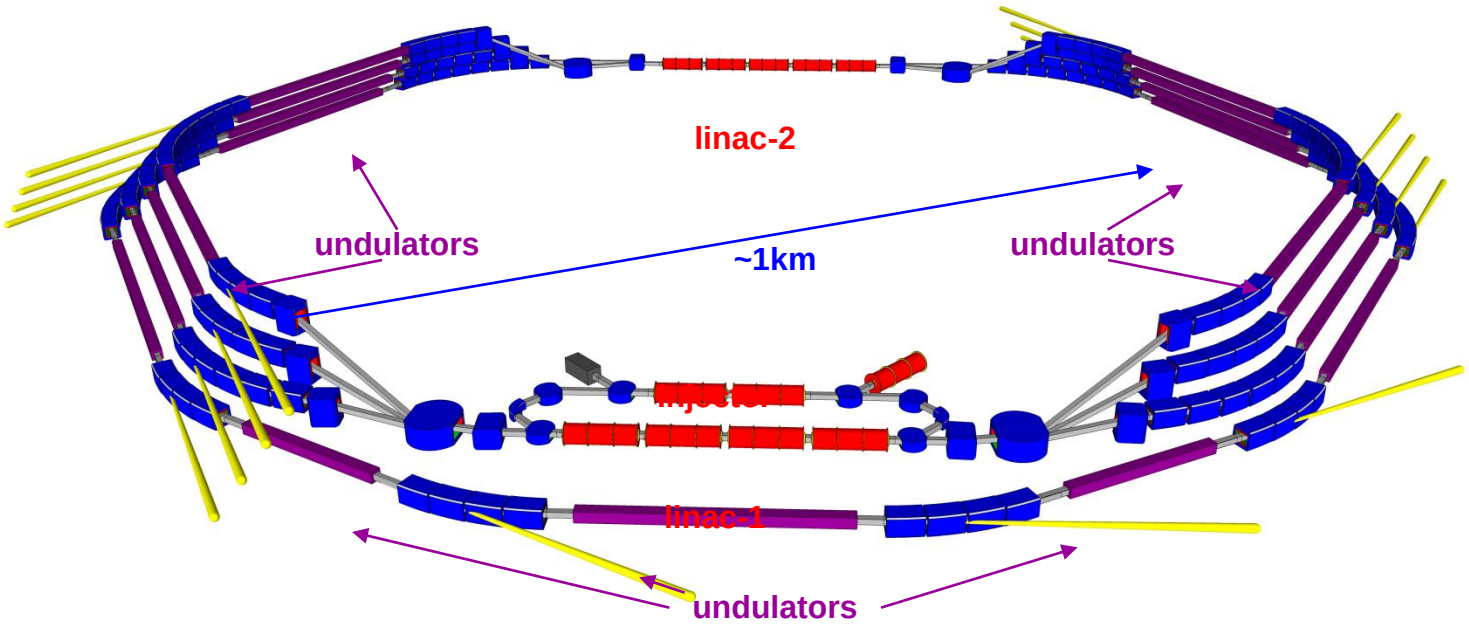
Minimal ERL-based radiation source



Another advantage of split accelerating structure is a possibility of servicing the multi-user community.

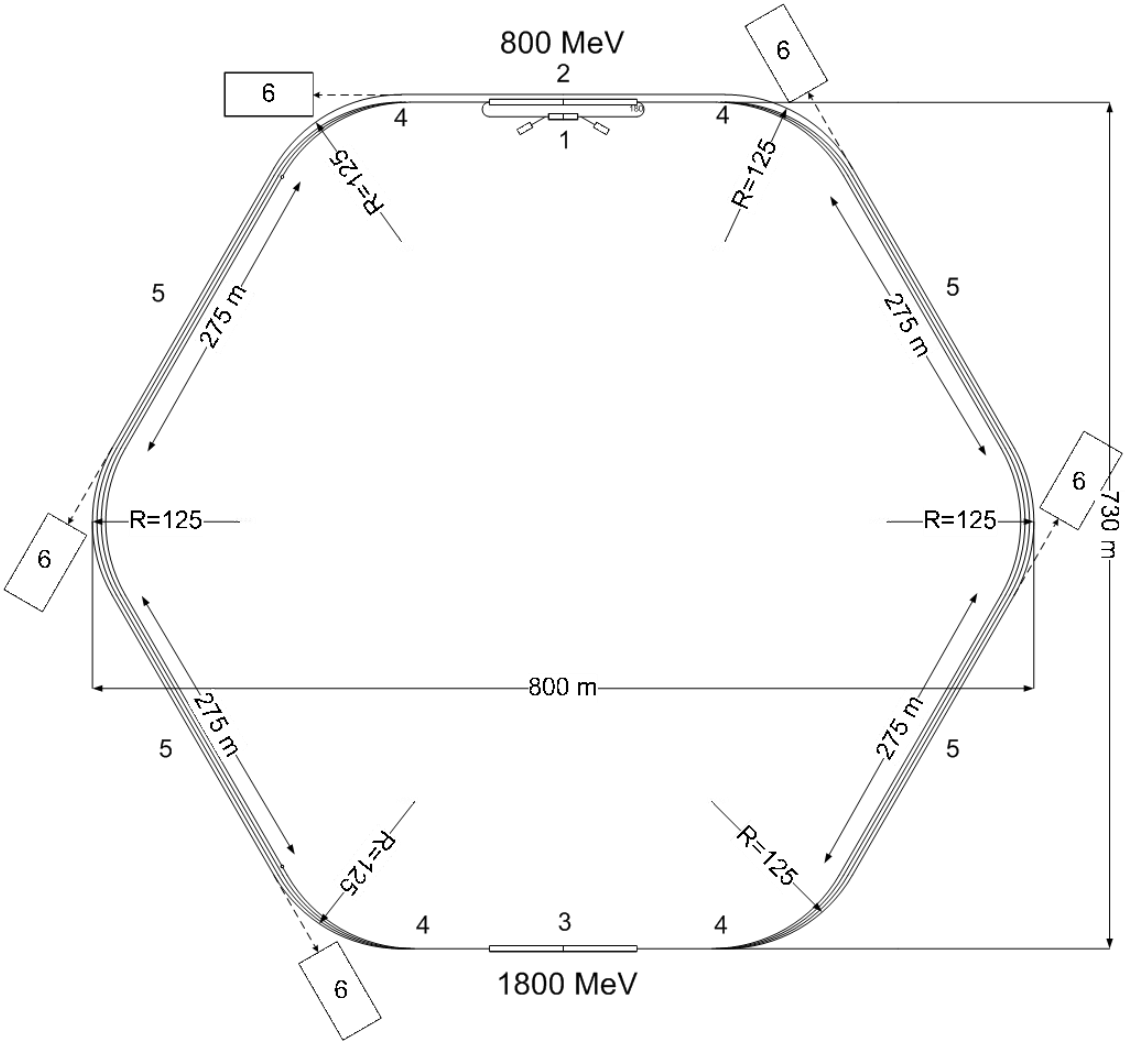
A scheme with one undulator can be extended by installations of the long undulators into bending arcs 4.

Full Spatial Coherent multiturn ERL X-Ray Source MARS

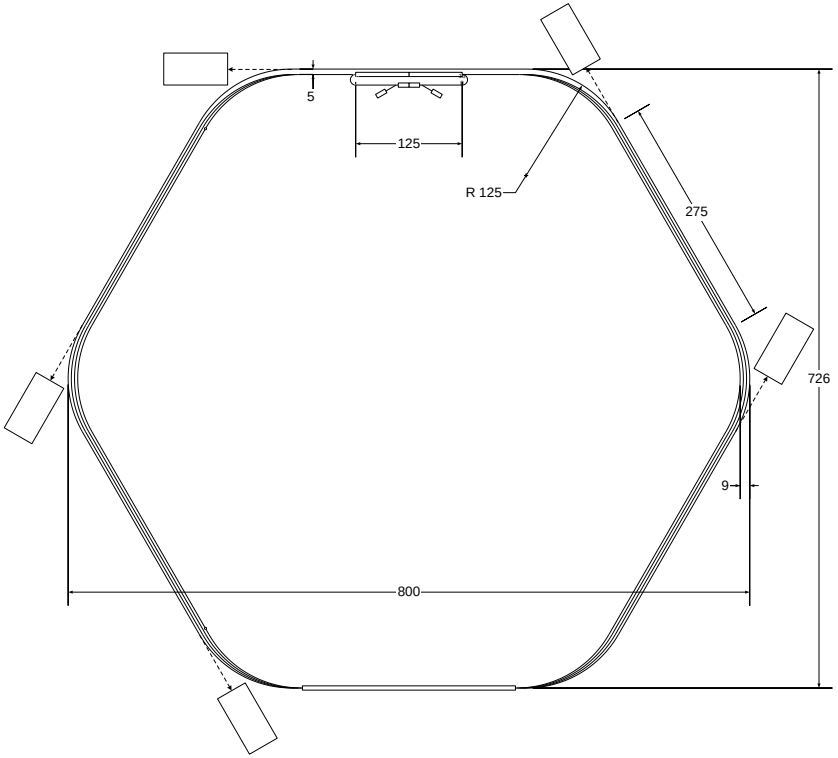


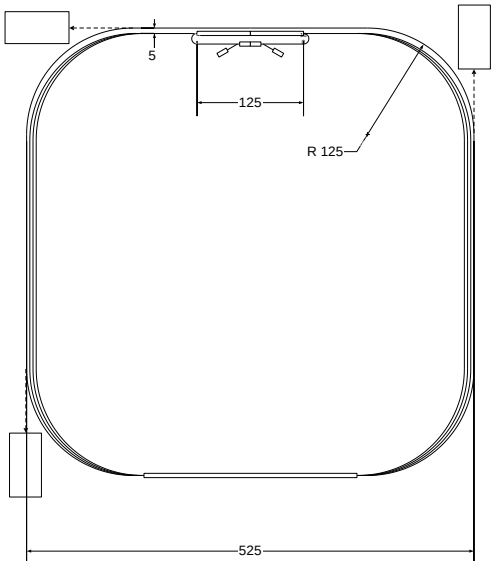
♦Energy range	5.6, 3.8, 3, 1.2 GeV	♦Bunch length	0.1 – 1 ps
♦Average current	10 mA	♦7 undulators for	5.6 GeV
♦Peak current	10 A	♦4 undulators for	3.8 GeV
♦Normalized Emittance	10^{-7} m·rad	♦4 undulators for	3 GeV
♦Bunch charge	10^{-11} Cl	♦4 undulators for	1.2 GeV

Multy-pass Accelerator-Recuperator with two linacs



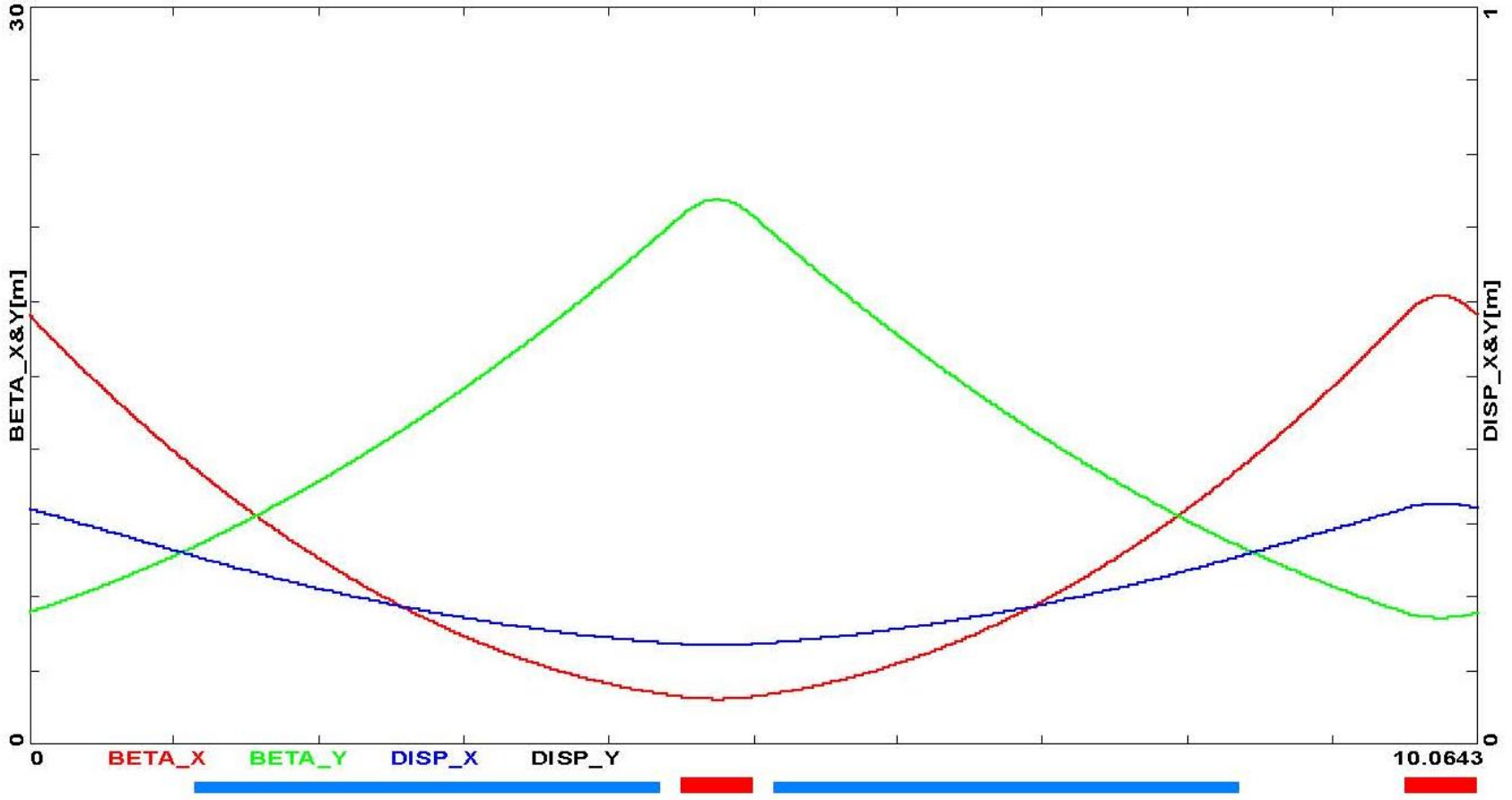
1 – injector, 2 – 1st linac, 3 – 2nd linac, 4 – spreders & recombiners, 5 – undulators, 6 – user stations





Other polygon shapes are possible, but the size is defined by the length of undulators (200 m)

The bends have to provide low energy spread and emittance growths. Therefore the bending radius was chosen to be 80 m. The parameters of FODO-type lattice were optimized for minimum emittance growth (code OPTIM by V. Lebedev, FNAL).



MARS main features

- Using multiturn energy-recovery scheme

- Emittance of the electron bunch with energy 5÷6 GeV is less than 10^{-11}m·rad, which corresponds to the normalized emittance 10^{-7}m·rad

- Charge per bunch should not exceed 10 pC. That corresponds to a 10 mA beam current.

- Photon flux from source proportional to the average current of the accelerator. To compensate the current decrease, it is necessary to use the radiation from undulators and wigglers with large number of periods.

- To provide a low level of radiation hazard and eliminate induced radioactivity, electron energy in the beam dump should not exceed 10 MeV.

MARS main features (cont.)

- To provide easily achievable conditions for simultaneous movement of the electron bunches with different energies in accelerating (decelerating) RF structures, it is necessary to use cascade scheme of injection.

- For simultaneous multi-users servicing a scheme with two separated accelerating structures can be used. This eliminates the main disadvantage of the scheme with single linac, where accelerating and decelerating bunches create two radiation sources in each undulator, and simplifies the control of the beam.

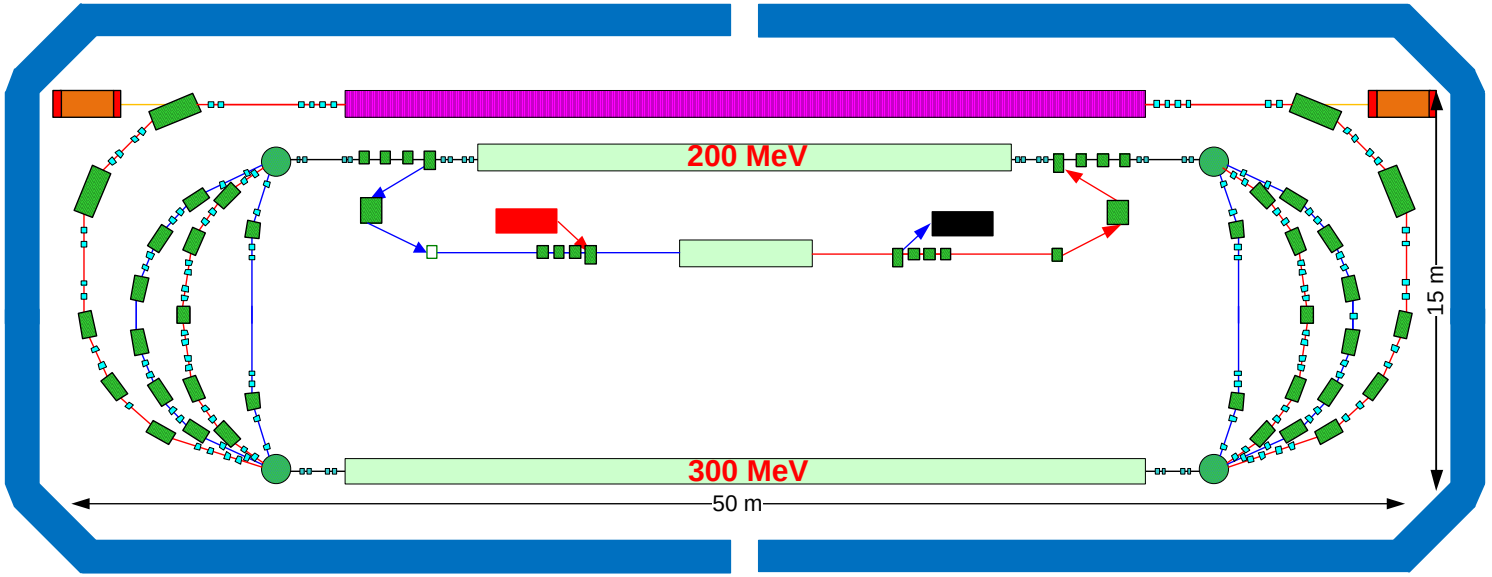
- Magnetic structure should contain long interspaces (L>200 m) for mounting a large number of undulators with number of periods 10^3-10^4.

- Relative energy spread of electron bunch at low energy should not exceed 10^{-4} .

- A bending radius of magnetic arcs should exceed 60 m to suppress quantum fluctuation of the synchrotron radiation.

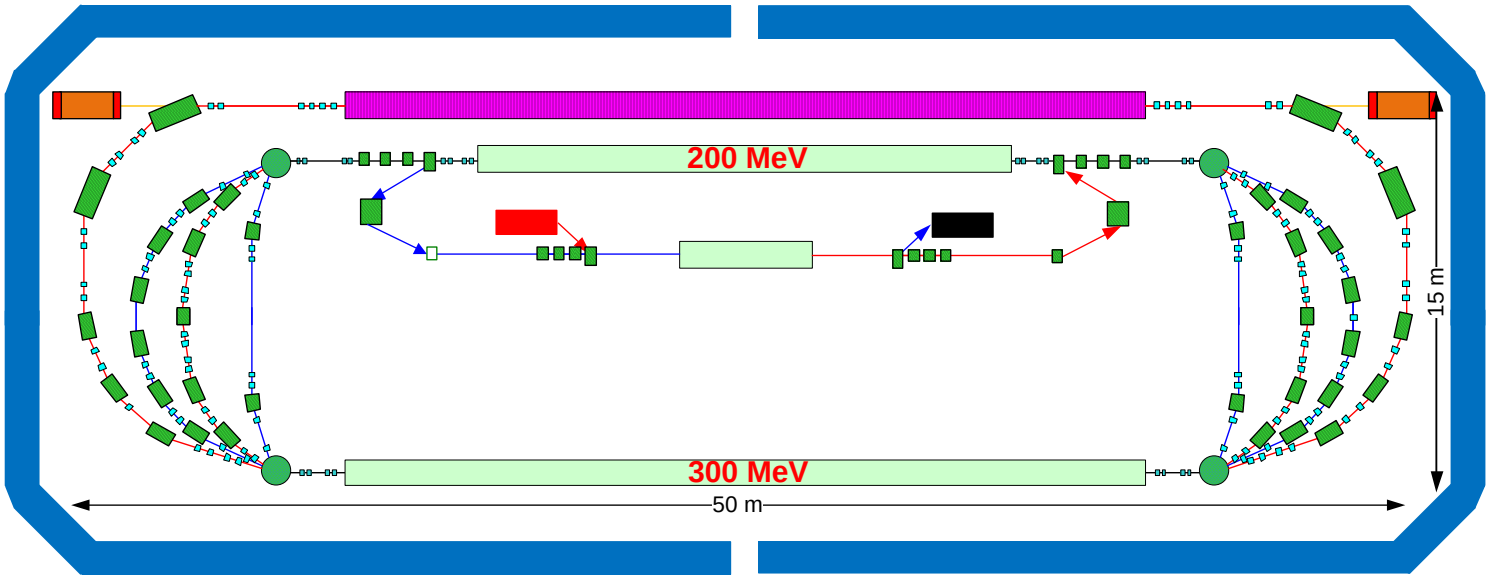
The smaller-scale prototype

(Compact 13.5-nm free-electron laser for extreme ultraviolet lithography,
Y. Socol, G. N. Kulipanov, A. N. Matveenko, O. A. Shevchenko and N. A. Vinokurov,
PRST AB, Vol. 14, No 4. – 040702-1 – 040702-7, 2011)



Wavelength	13.5 nm
Electron energy	1 GeV
Average EUV power	5 kW
Beam average current	5-10 mA
Geometry	20×50 m^2
SR source	Undulator with 2-3 cm period

Short x-ray pulse generation



With 10-T superconducting magnet the 1-GeV ERL may be used to generate 20-fs periodic x-ray pulses, which are necessary for time-resolved experiments. Such experiments use femtoslicing technique at storage rings now. But, the number of useful photons at ERL will be thousands times more.

Conclusion

- 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 4^{th} 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.
- The commissioning of the four-passes NovoFEL ERL proved the feasibility of the multipass ERL.
- The next step of MARS development should be a building of its prototype – ERL with two separated linacs and one 13.5 nm free-electron laser for extreme ultraviolet lithography.

Thank you for your attention