Current Results of SSRS4 Light Source Development at Kurchatov Institute

Sergey Polozov on behalf of SSRS4 team

Project is supported by the Ministry of Science and Education of Russian Federation, Agreement No 14.616.21.0086 from 24.12.2017, ID RFMEFI61617X0086 (Federal Targeted Program "Research and development on priority directions of scientific-technological complex of Russia in 2014 -2020 year").

Main international collaborator European Synchrotron Radiation Facility (ESRF).

SUMMARY

(from Timur Kulevoy Report on Cremlin Meeting on Jan. 2018)

- Today we are at the stage of pre **CDR development, design and preliminary numerical simulations of main components of the SSRS-4**: lattice; magnetic systems, beamlines, vacuum, etc.

- We want to take into account the **international experience** of new X-ray sources: **ESRF, European XFEL, MAX-IV, Sirius** and other **projects Russian Federation participates in.**

- The SSRS-4 should be complement to the existing European source and raised interest of the European scientific community**. We are not going to be limited to only national scientific projects**.

- **New machine shouldn’t be a replica of one of the existing sources**. SSRS-4 must enhance capabilities of new sources and effectively fits into the existing European Mega-science infrastructure.

Plans for 2018:

(from Timur Kulevoy Report on Cremlin Meeting on Jan. 2018)

General complex scheme should be fixed;

- **Beam dynamics for both schemes ("user machine" with emittance of 70-100 pm·rad and "record machine" with 20-50 pm·rad);**
- **Magnetic structure preliminary design;**
- **Linac and booster preliminary design;**
- **Injection scheme should be chosen;**
- **Vacuum system preliminary design;**
- **Diagnostic system preliminary design;**
- **Control system preliminary design;**

And foundation:

- ✓ **International Collaboration**
- ✓ **Scientific Advisory Committee**
- ✓ **Machine Advisory Committee**

SSRS4 current discussed configuration:

- *Beam energy in syncrotron - 6 GeV;*
- *Beam current up to 300 mA;*
- *Transverse emittance <100 pm·rad (two schemes are under simulation today: “user machine” with emittance of 70-100 pm·rad and “record machine” with 20-50 pm·rad);*
- *Top-up injection from linac or booster;*
- *MBA magnet structure with SR length ~1300 m and 40 superperiods;*
- *Low energy (~1.5 – 2.0 GeV SR for UV stations) as an option;*
- *Injection linac based FEL(s) as the second option (in the case of top-up linac);*
- *Four groups of RF cavities (3 or 4 cavities/group) in fully symmetries periods, solid state RF power sources, operation frequency 500 or 700 MHz;*
- *Not less than 40 stations for THz, soft, medium and hard photon energies and strongly-hard FEL on linac (as option);*

Organization

General layout and beam dynamics

- BD WG1: SR with 70-100 pm·rad + full-scale booster
- BD WG2: SR with 20-50 pm·rad + compact booster
- Injection linac
- Injection schemes

- RF
- Insertion devices and FEL’s

- Control system
- Diagnostics

- Vacuum system
- Engineering systems

Research programme

- Research Programme
- Stations and channels
- Beam requirements

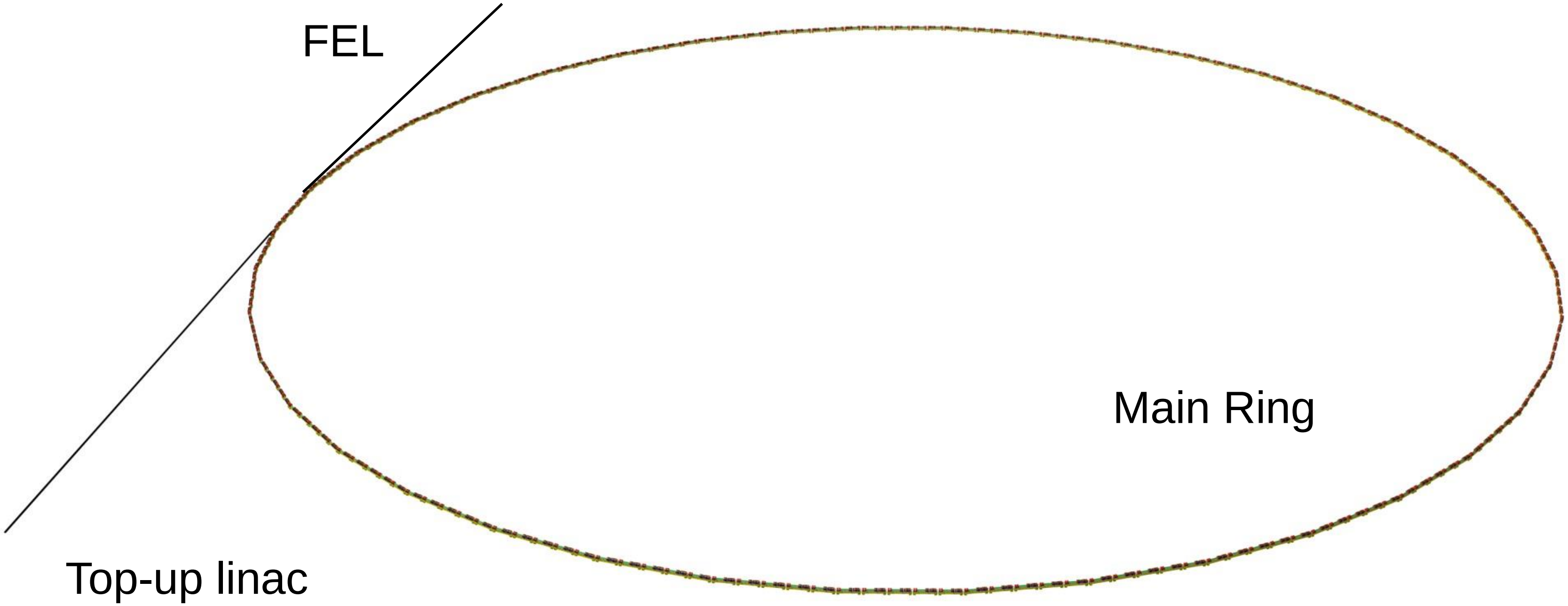
Current Status:

- **Beam dynamics for both possible ways for the main ring ("user machine" with emittance of 70-100 pm·rad and "record machine" with 20-50 pm·rad) and magnetic structure preliminary design;**
- **Linac preliminary design;**
- **Full scale booster preliminary design;**
- **Injection scheme;**
- **Vacuum system preliminary design;**
- **RF system;**
- **SSRS4 site in Protvino;**
- **Research Programme**
- **Stations and channels**
- **Diagnostic and control systems preliminary design**

6 GeV

40 periods, ~1300 m

~70 pm·rad, up to 70 ID's



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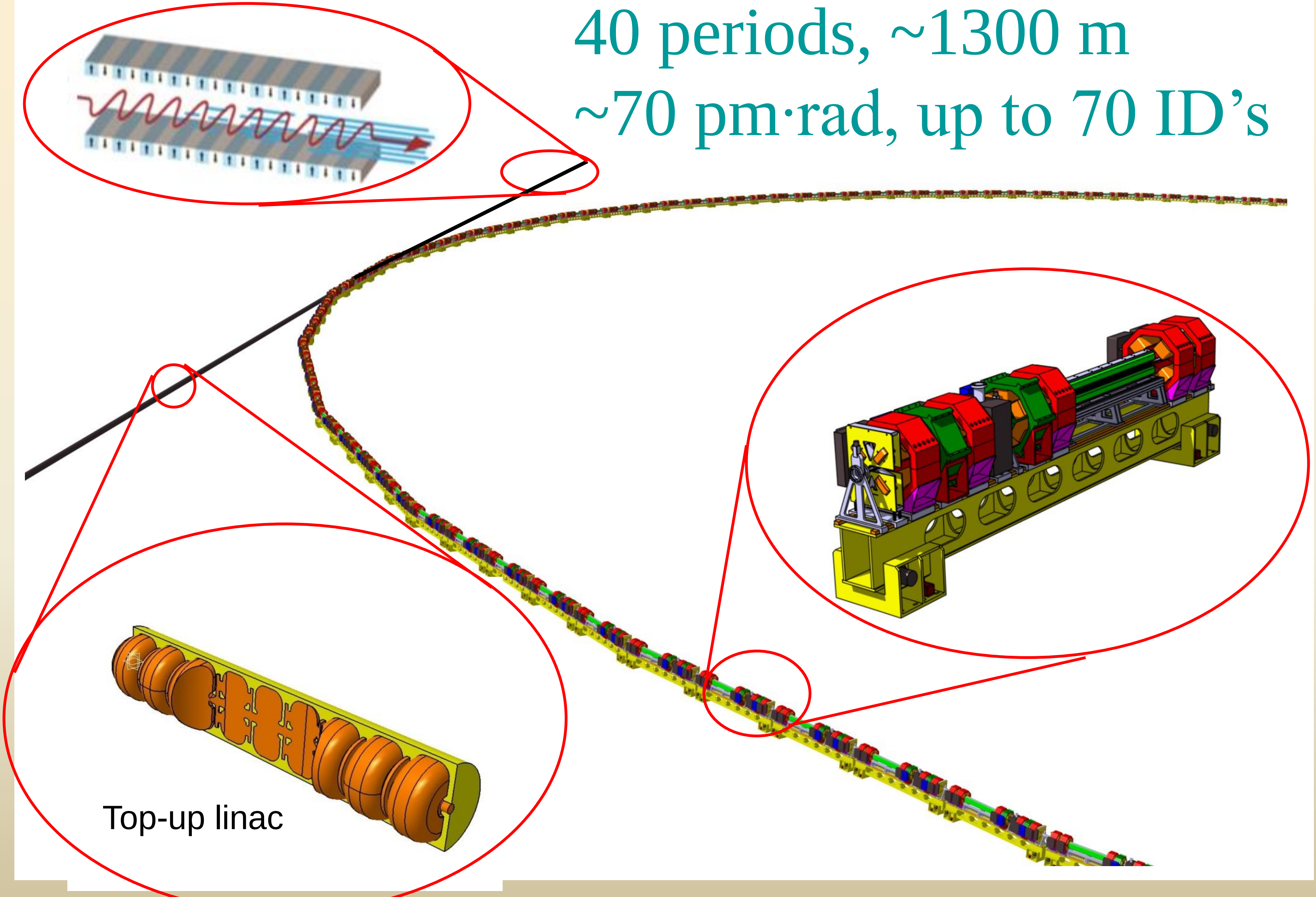
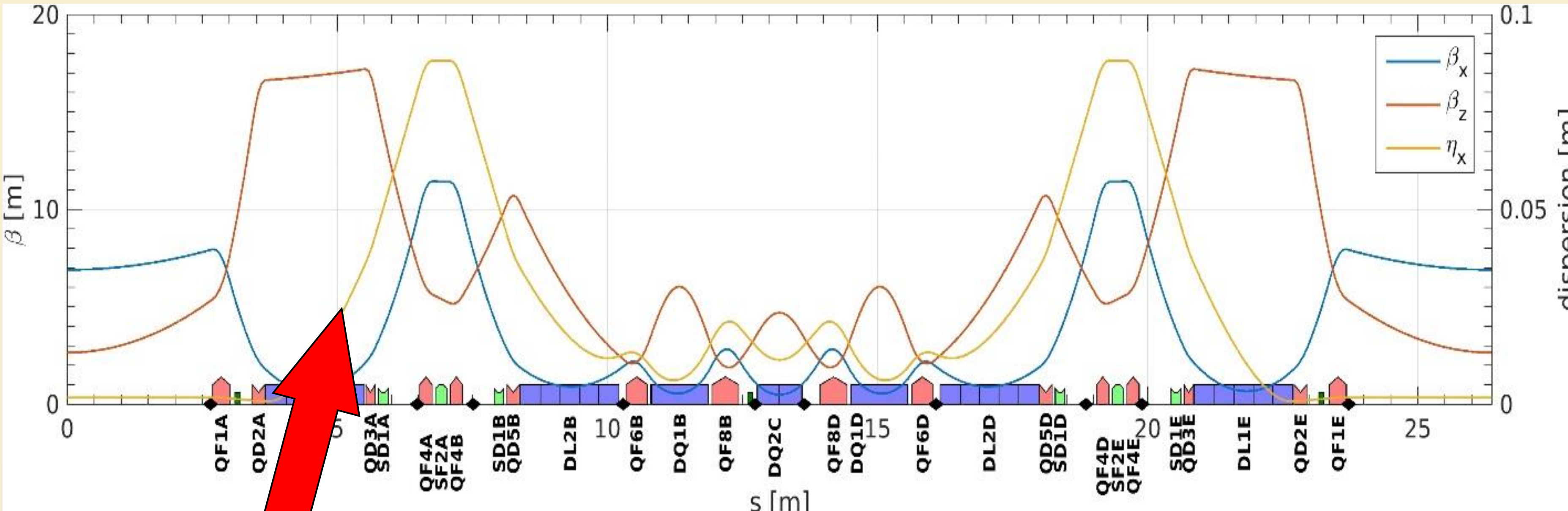


SSRS4 magnet structure:

Start configuration is based on MBA (7BA);period length 26-30 m; first structure is kindly prepared by our ESRF partners and based on scaled ESRF-ESB design

(Ministry of Education and Science of Russian Federation-ESRF collaboration contracts)



L Cell [m]	N cells	Circ. [m]	Emit. [pm]	Max. Sext. [T/m2]
26	40	1040	69	2316
30	40	1200	70	1220
30	50	1500	36	1534

Especial thanks to: Pantaleo Raimondi, Simone Liuzzo, Laurent Farvacque and Simon White

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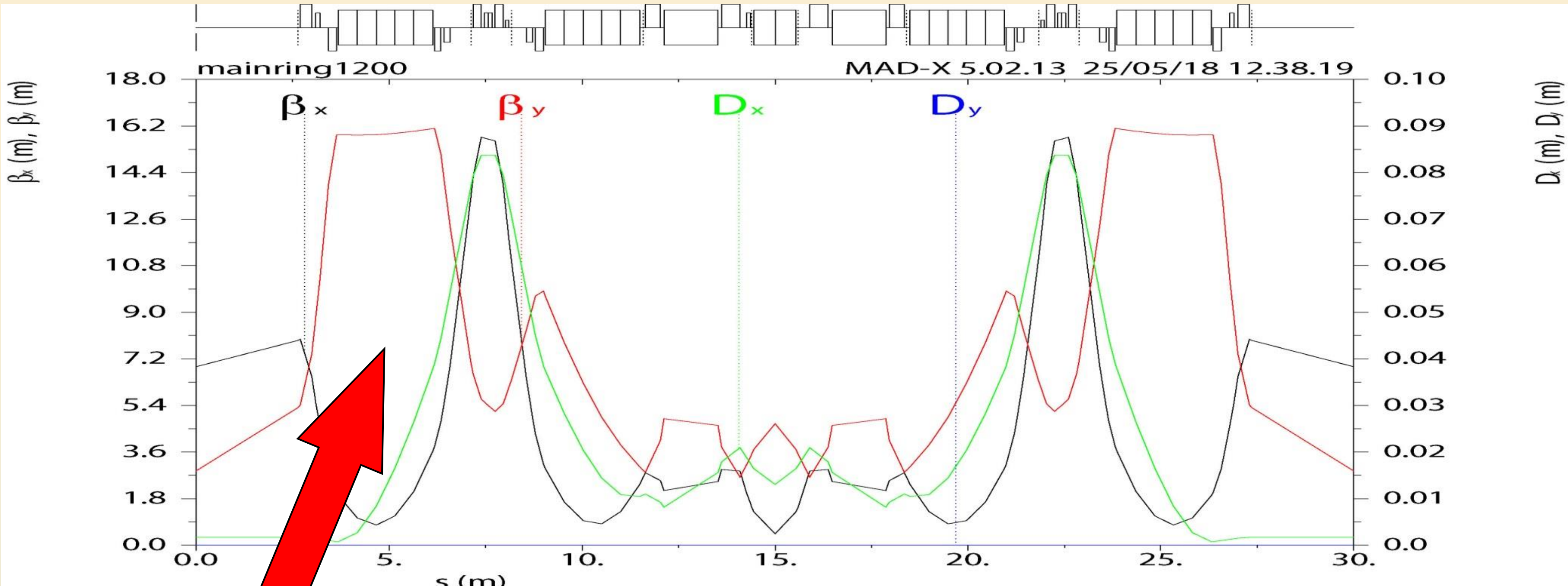

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Especial thanks to: Pantaleo Raimondi, Simone Liuzzo, Laurent Farvacque and Simon White

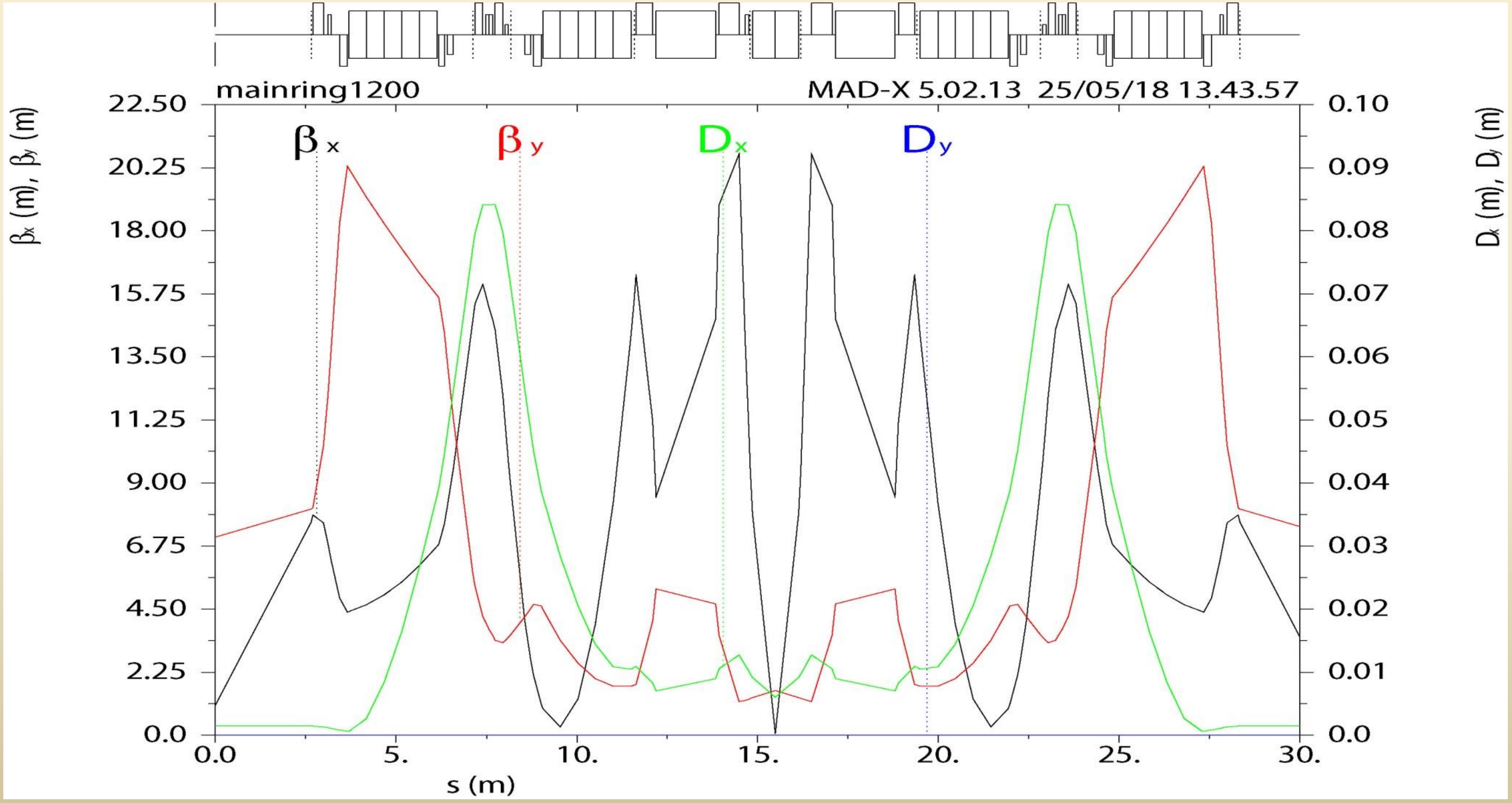
Second configuration is based on 7BA (30 m/period)

-No dipole-quadrupole combined magnet;

-Minimal aperture growth form 13 to 18 mm to decrease nonlinearities and instabilities;

-We not planned to increase fields and gradients of magnets because today we are not limited in the ring length. The length of magnets can be increased as the result.

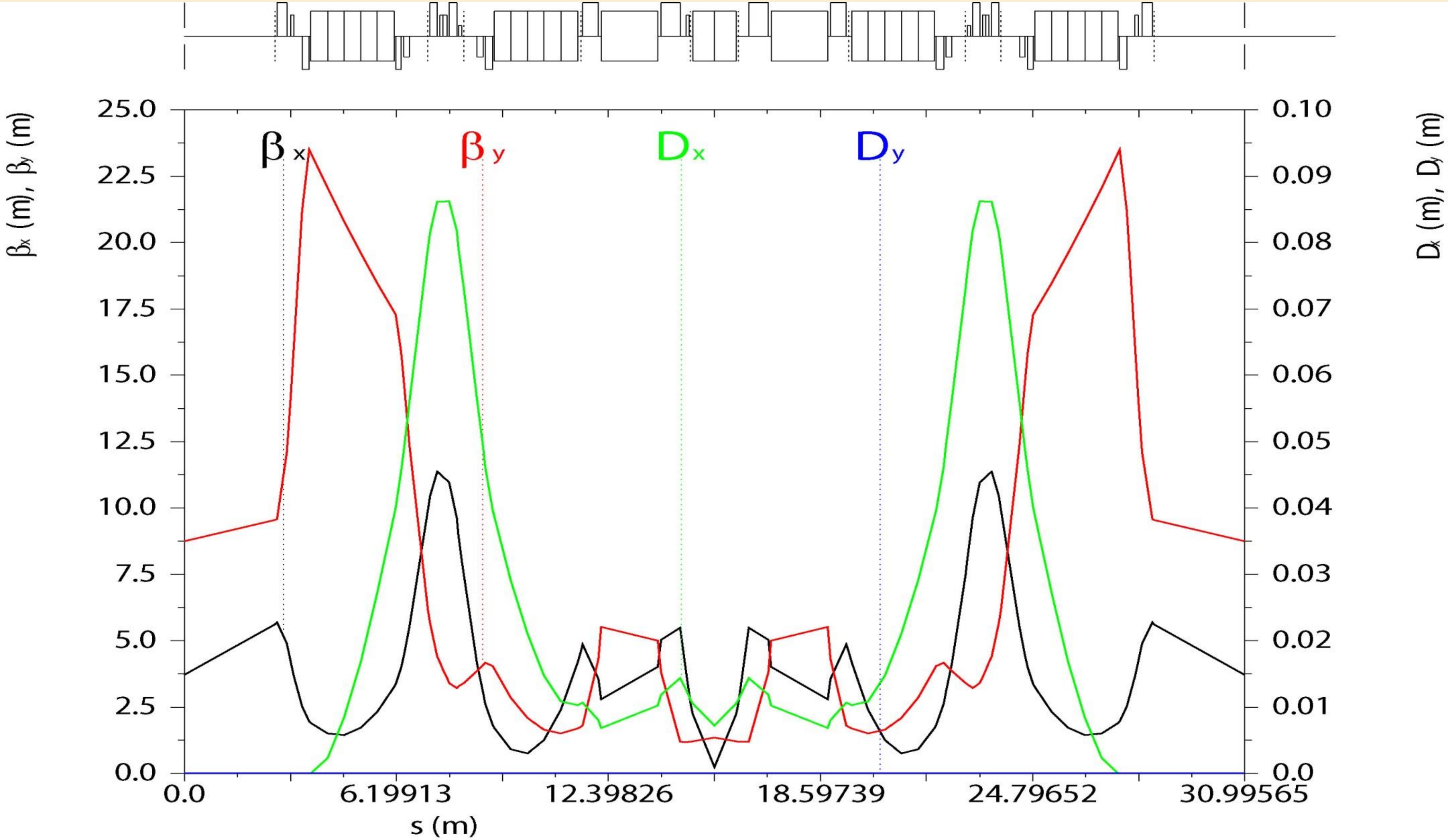
-The period length was enlarged to ~31 m to place longer "high field" magnets



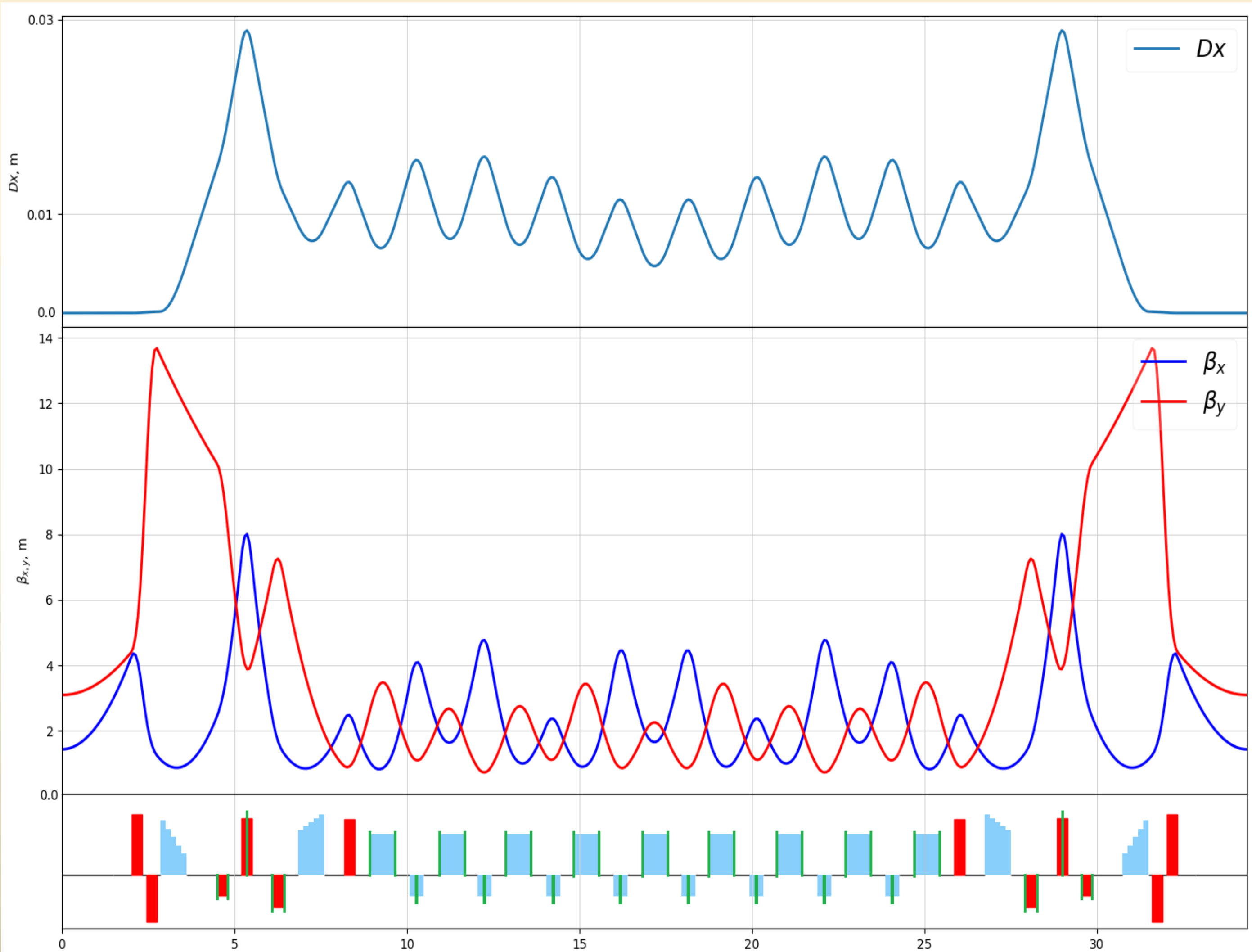
Second+ configuration is based on 7BA (31 m/period),

- Small aperture in the central part of the period was enlarged to 18 mm;

-Fields, gradients and lengths are corrected to decrease the β-function in the central region of period



Extreme SSRS4 configuration:
15 pm·rad lattice, 13BA, 48 period x 35 m

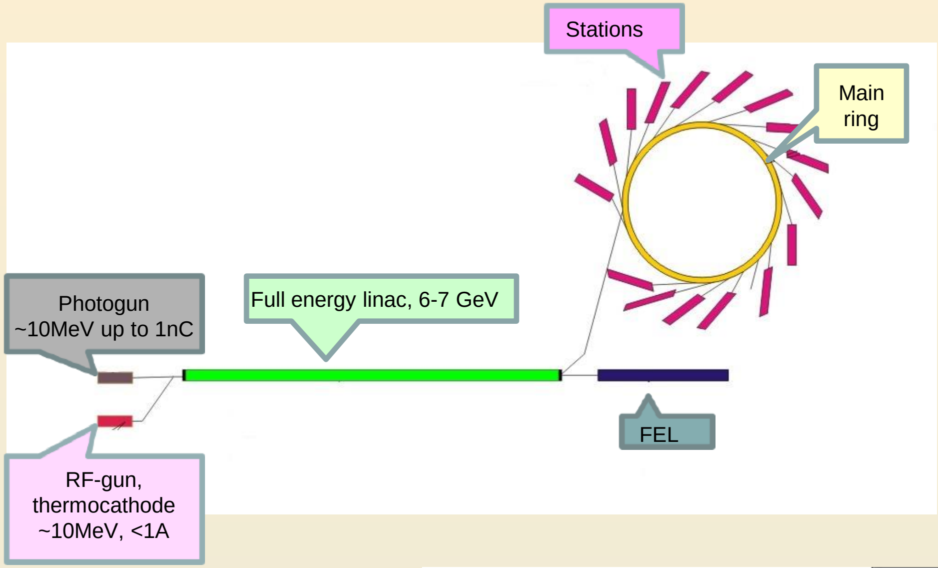


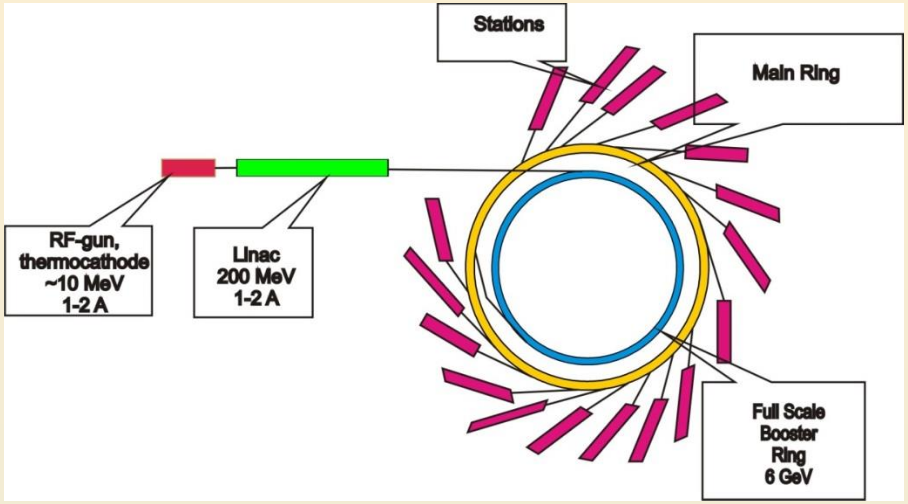
ε = 15 pm
C = 1648 m
DA: ± 1.5 mm
ξ: -203/-176

Main magnetic elements:
- bending magnets with longitudinal gradient,
- combined dipole-quadrupole magnets,
- quadrupole and sextupole magnets

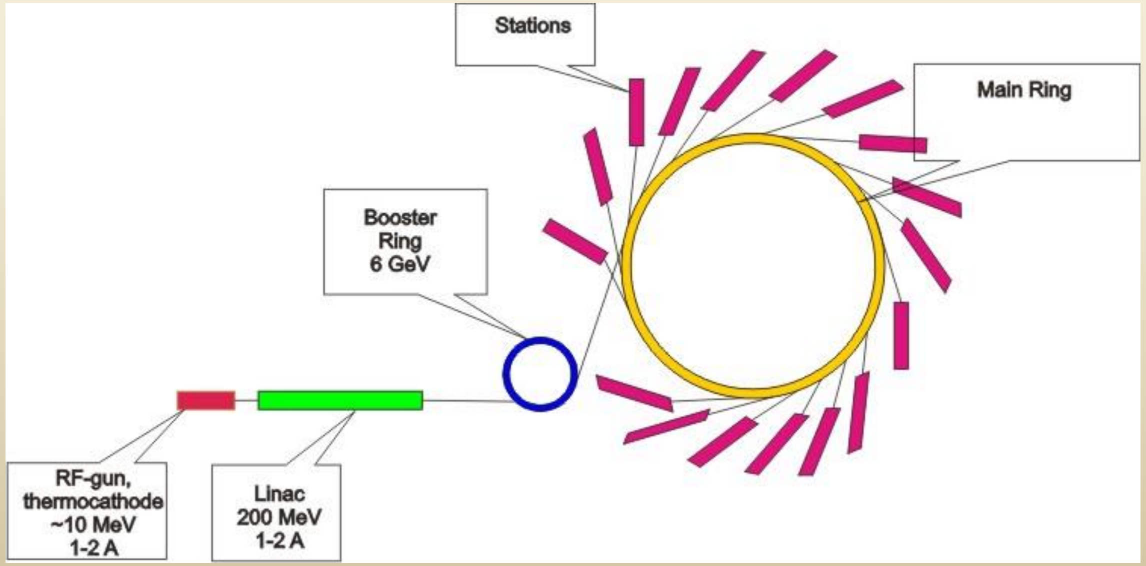
Injection: three possible ways

Top-up linac injection **OR** **full-scale booster** **???**





May be classics – compact booster ?



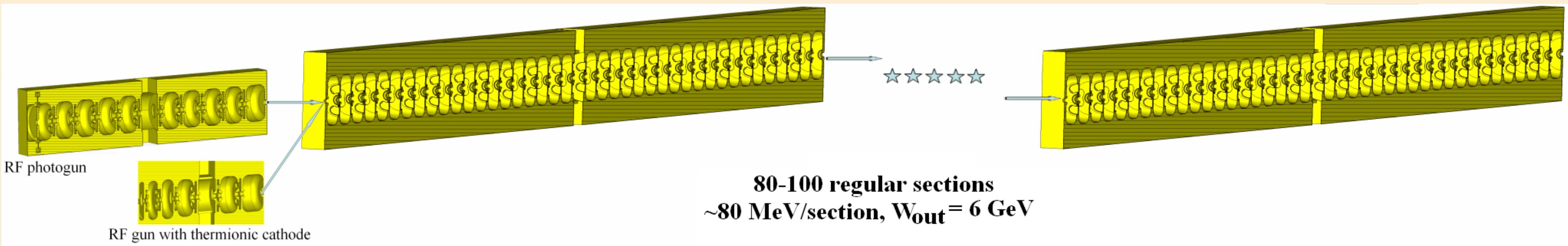
SSRS-4 Linac general concept

Injection scheme effects on linac layout and parameters

	Facility with booster ring	Facility with top-up injection
Energy	~200 MeV	6 GeV
RF gun (s)	Thermionic+ RF SW buncher 10 MeV	Photo and Thermionic+RF SW buncher 10 MeV
Linac operation mode	injector in booster ring	injector in booster ring provide beam for X-FEL
	Compact, cheaper and more safe in construction	*Promising but challenging*

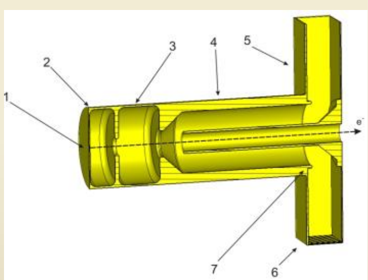
Top-up linac layout:

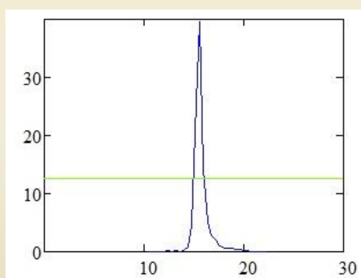
two RF-guns - photo-gun and thermionic gun (like Super-KEKB, MAX-IV, *FCC-ee*) and 80-100 regular sections



Photogun:

1.5-, 3.5- or 5.5-cell design?

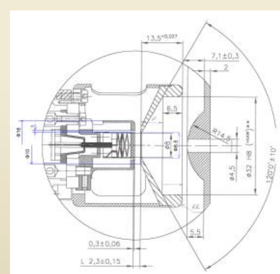


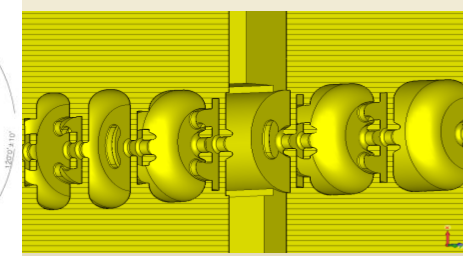


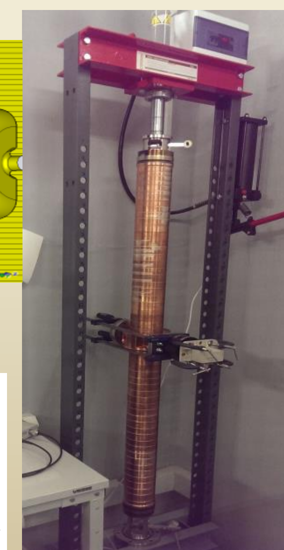
Cells	E, kV/cm	φ_{inj}	W_{max}, MeV	$\Delta W/W$, %
3.5	600	2.0	6.2	1.8
5.5	600	2.7	8.1	0.9
5.5	700	2.8	8.2	1.2

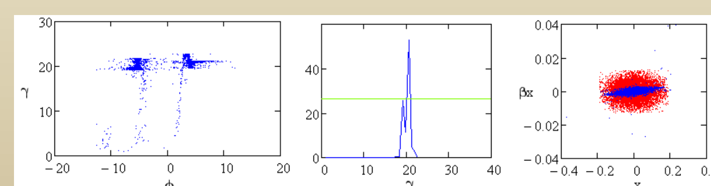
Thermogun:

We need to control the transverse emittance on low energies





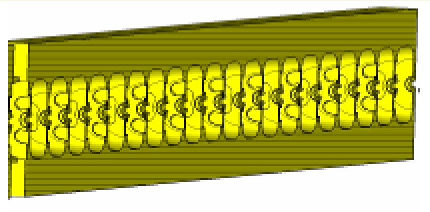




Regular section:

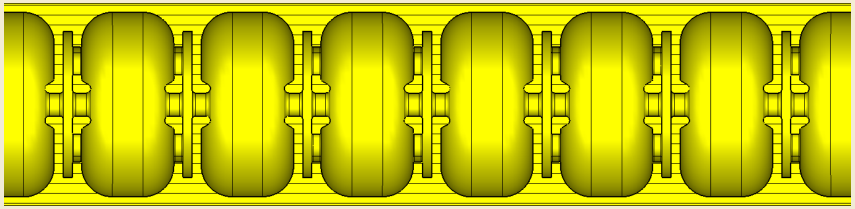
classic SLAC-type travelling wave DLW or modern standing wave structures

SLAC-type TW structure, 2π/3 mode



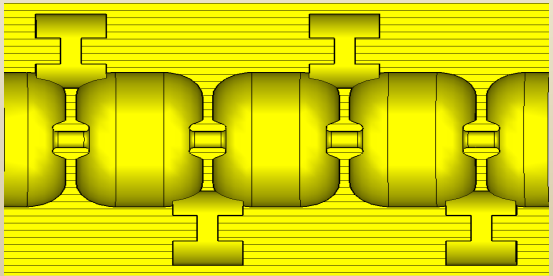
-Low coupling coefficient (2-3 % c)
-Long transient time (400-500 ns for 3m structure)
-Long RF pulse (~1 µs) is necessary
-High beam loading effect influence
- 3-5 bunches can be accelerated without of energy chirp

SW BAS



-Higher coupling coefficient (12-14 %)
-Low filling time (~200-250 ns) and shorter RF pulses
-Lower beam loading
-10-12 bunches without energy chirp

SW side-coupled

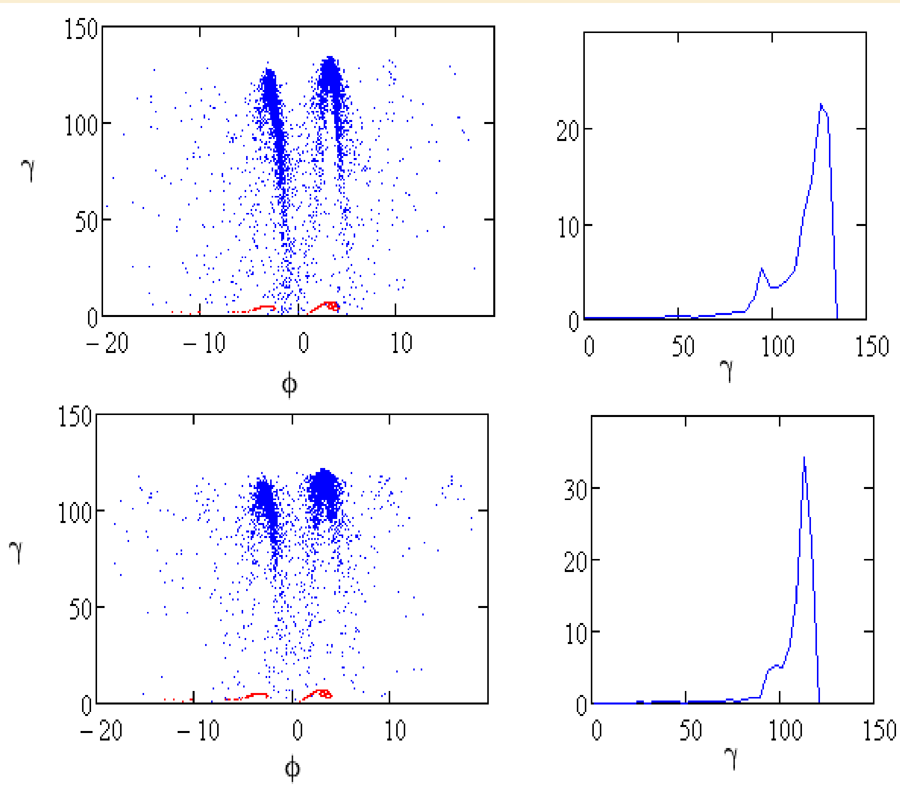


-Highest coupling as possible (30-40 %)
-Filling time ~100 ns

-Price is high but available

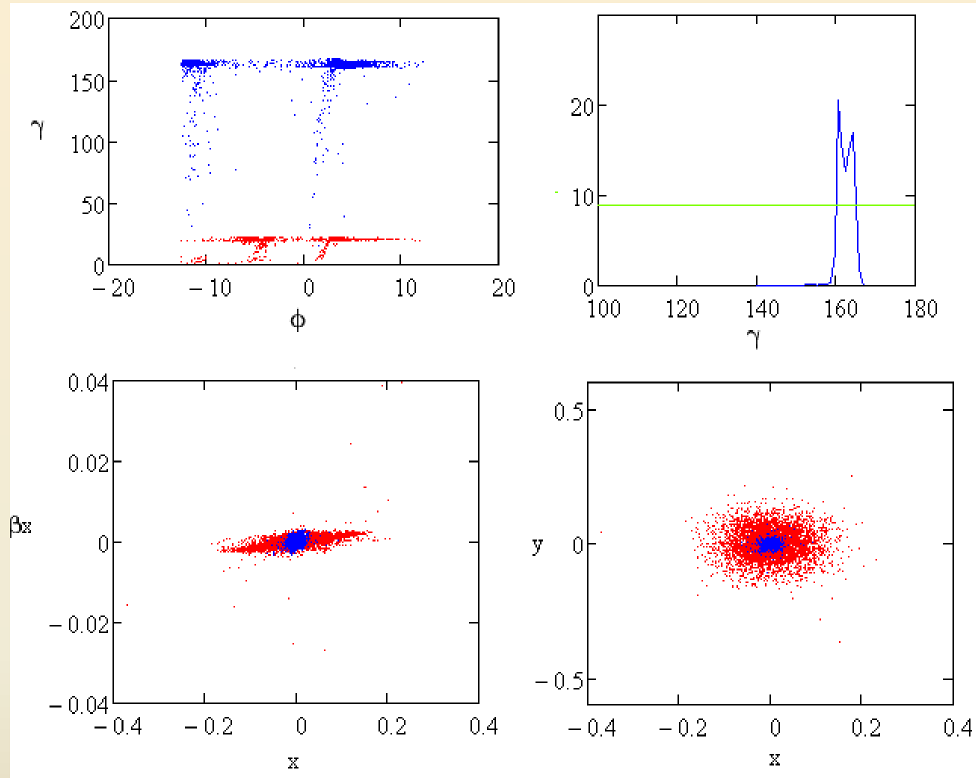
Regular section: beam dynamics

SLAC-type TW (after 1st section)



80 MeV per section (~3 m length), 6 GeV output energy
I=400 mA, Δ*W*/*W*≤3.0 % (can be optimized)
Transverse emittance ~10 μm·rad
(with non-optimised thermogun)
or ~1-5 nm·rad with photogun (250 nC per bunch)
3-5 bunches per pulse with phase chirp to compensate beam loading

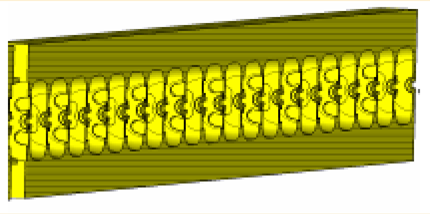
SW BAS (after 1st section)



80 MeV per section (~2 m length), 6 GeV output energy
I=400 mA, Δ*W*/*W*≤0.3 % (can be optimized)
Transverse emittance ~5 μm·rad
(with non-optimised thermogun)
or ~1-5 nm·rad with photogun (250 nC per bunch)
10-12 bunches per pulse wit compensated beam loading

Regular section: necessary RF power

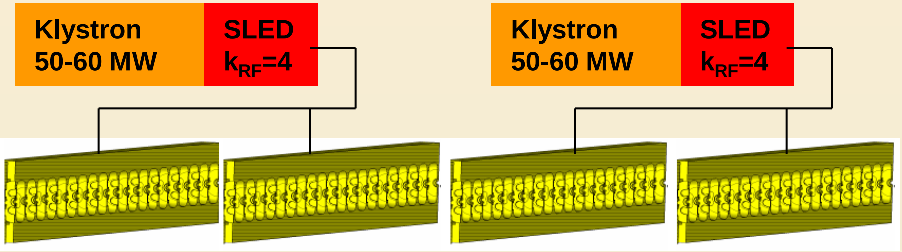
SLAC-type TW
- Low coupling coefficient
- Long RF pulse
- High beam loading effect
- Wide spectrum



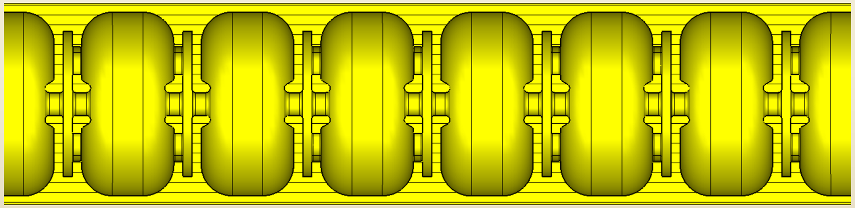
P, MW/W_{sec}, MeV/ L_{sec}, m
(compression by SLED, k_{RF}≈4)

E_z, kV/cm	SLAC	BAS	Side-coupled
400	80/60/3	40/50/2	40/55/2
500	120/75/3	70/60/2	70/70/2
600	150/90/3	100/70/2	100/80/2

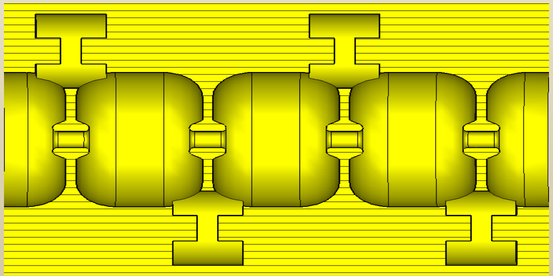
τ_{pulse}= 1-2 μs 500-600 200-400 ns
higher compression

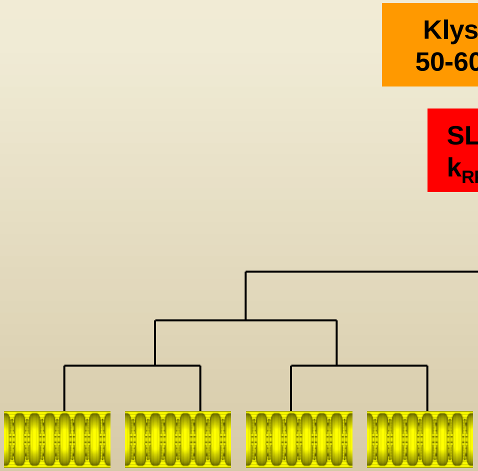


SW BAS



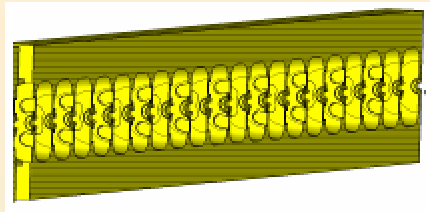
SW side-coupled

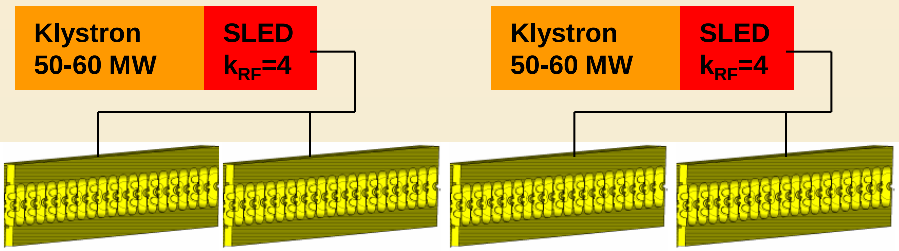




Regular section: necessary RF power

SLAC-type TW
- -Low coupling coefficient
- -Long RF pulse
- -High beam loading effect
- -Wide spectrum





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E_z, kV/cm	SLAC	BAS	Side-coupled
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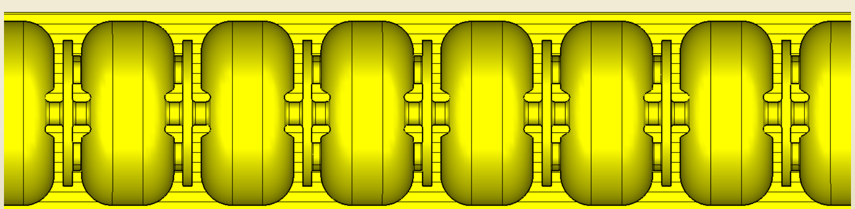
500	120/75/3	70/60/2	70/70/2
600	150/90/3	100/70/2	100/80/2

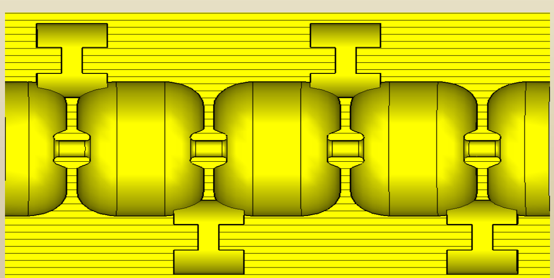
τ_{pulse}= 1-2 μs 500-600 200-400 ns

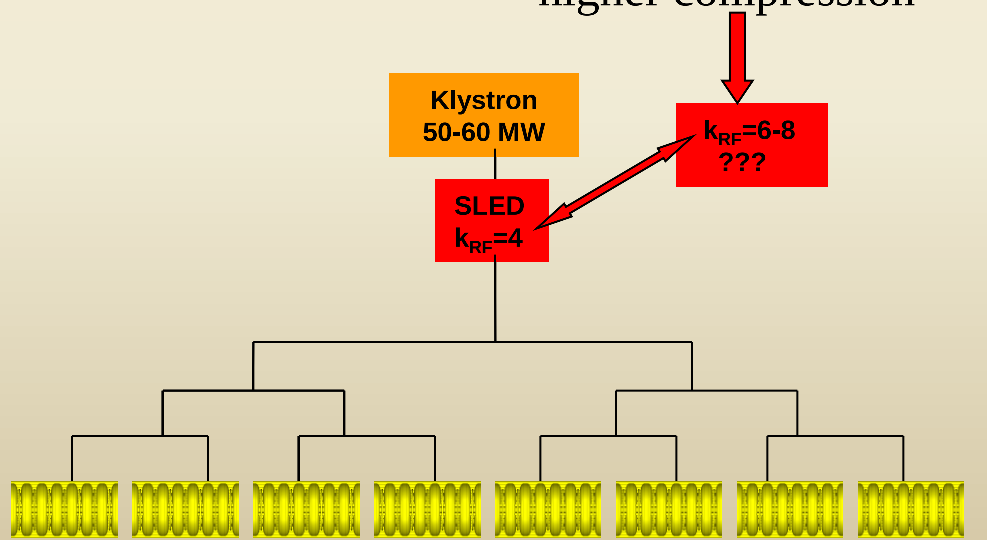
higher compression

SW BAS



SW side-coupled



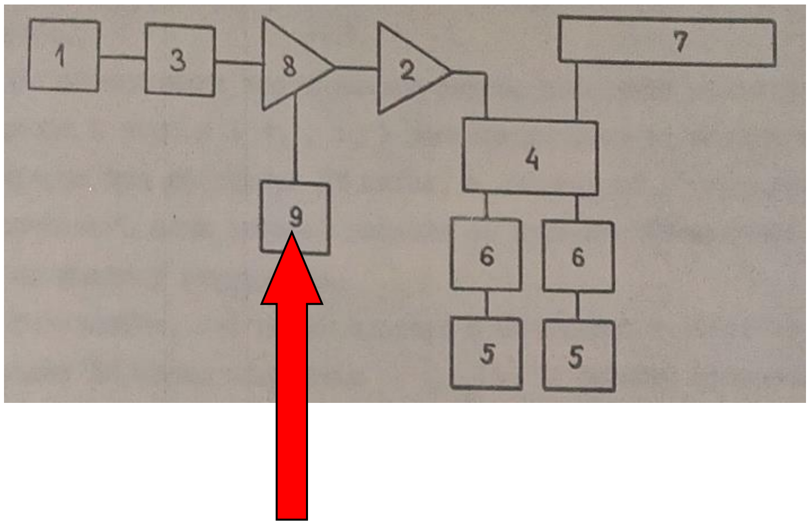


Regular section: necessary RF power

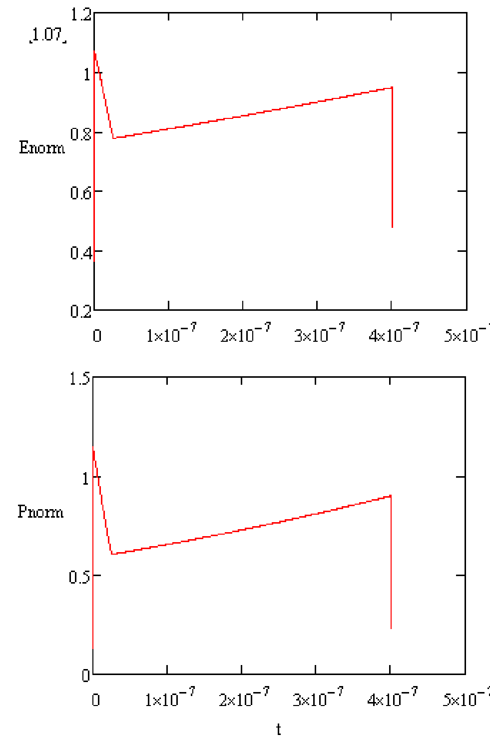
SLAC-type TW
-Low coupling coefficient
-Long RF pulse
-High beam loadi
-Wide spectrum

P, MW/W_{sec}, MeV/ L_{sec}, m
(compression by SLED, k_{RF}≈4)

SLED with controlled pulse flatness



Switch with controlled function of the pulse (with trapping-down charge) – up to 400 ns of flat beam energy distribution on U-17 at MEPhI

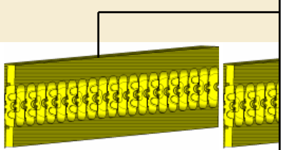


le-coupled
40/55/2
70/70/2
100/80/2

-400 ns
ression

Klystron
50-60 MW

SLE
k_{RF}=



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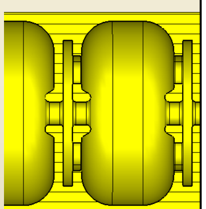
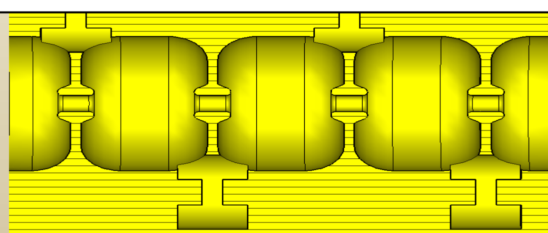
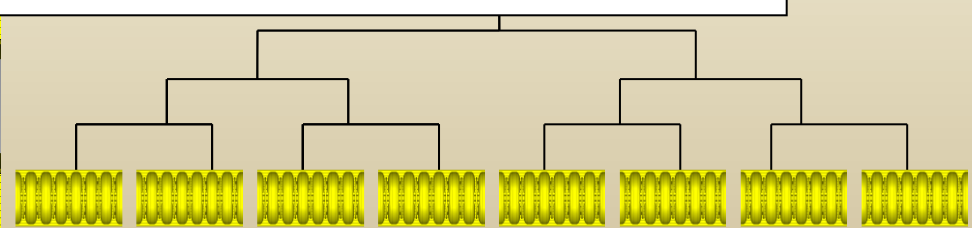
SW BAS

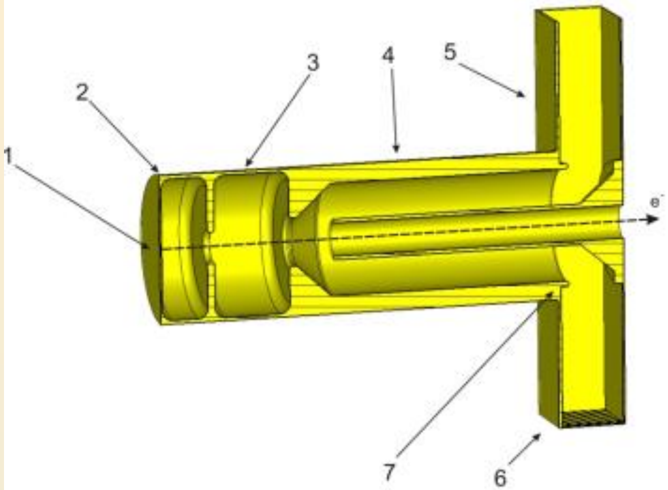


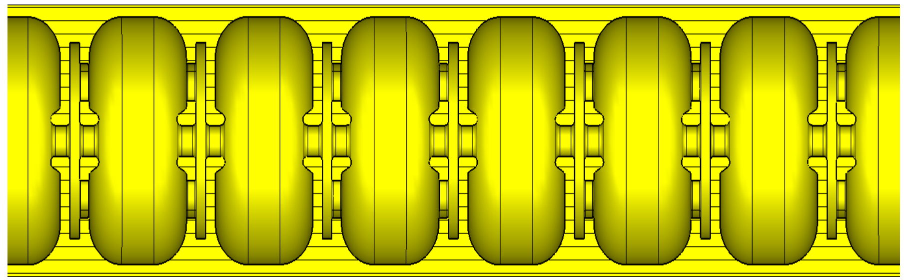
SW side-
coupled





Photogun prototype:





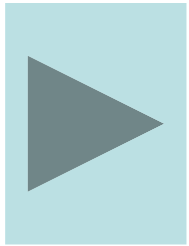


Photo-gun:
200-250 pC, ~10 MeV

One regular section:
~80 MeV/section

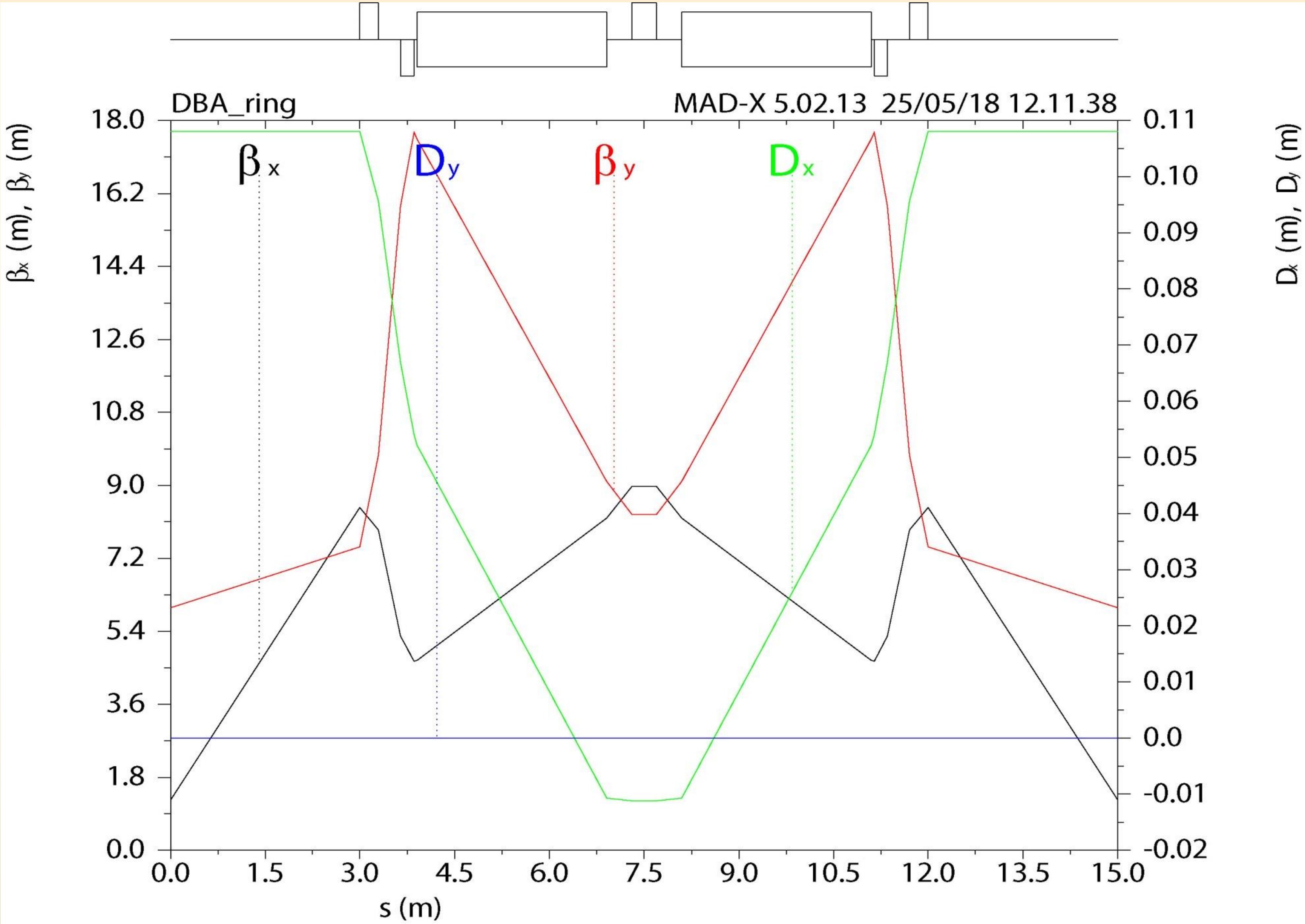
Diagnostics system

-We need a prototype of photo-gun to have the necessary experience in its commissioning and operation

- Prototype can be scaled to top-up linac
- Prototype can be used in future as an “Compact XFEL”

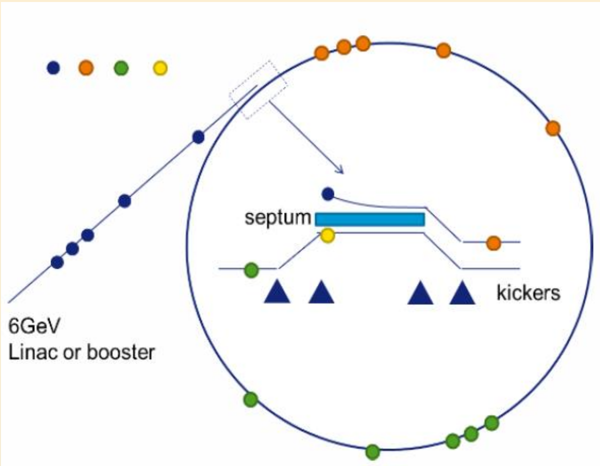
-- Studies in field of photoguns improvement (DFG-RFBR proposal with DESY-PITZ)

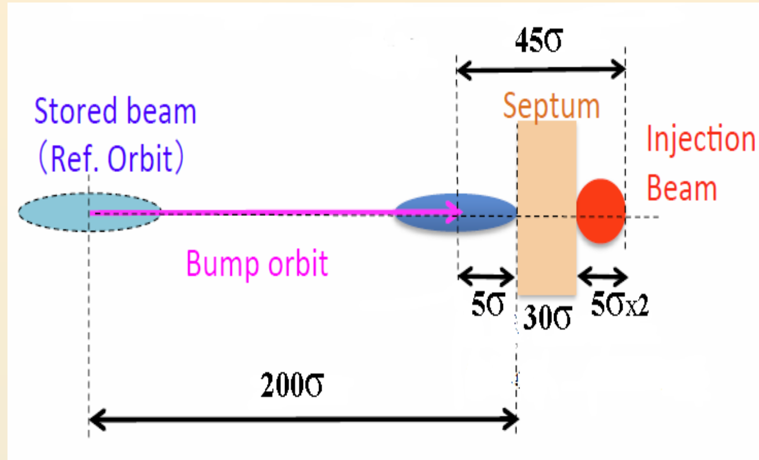
Full-scale booster design (80 periods x 15 m, 2BA)



Beam injection: off-axis

- Timeshared use of top-up linac





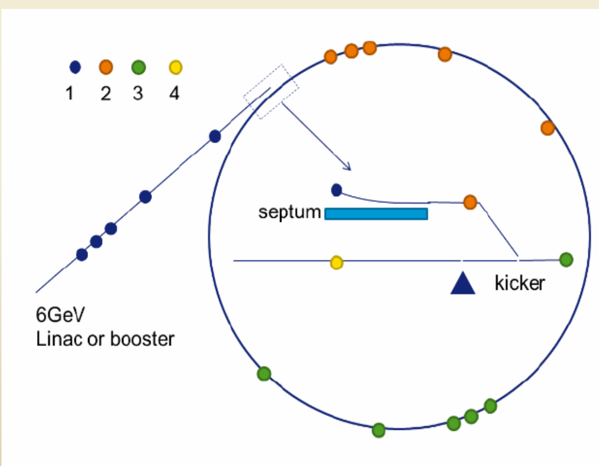
$$\sigma = \sigma_i = \sigma_s$$

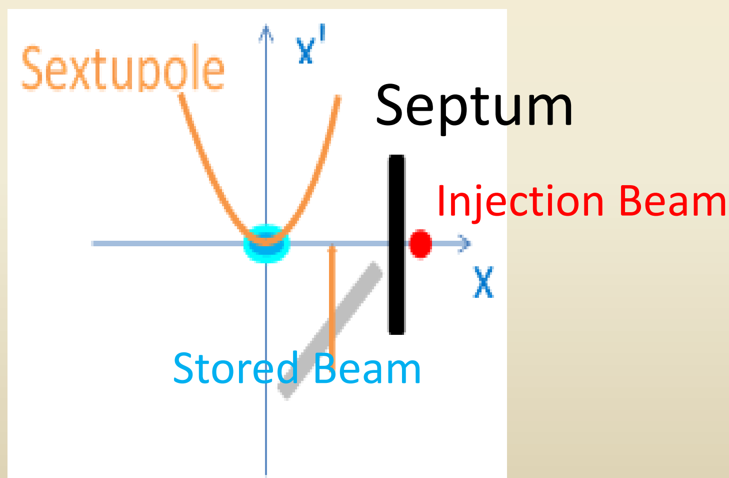
$$\varepsilon_x = 0.13nm \qquad ESRF$$

$$\beta_x = 19m$$

$$\sigma = \sqrt{\varepsilon_x \beta_x} = 0.05mm$$

Off axis + non linear kicker



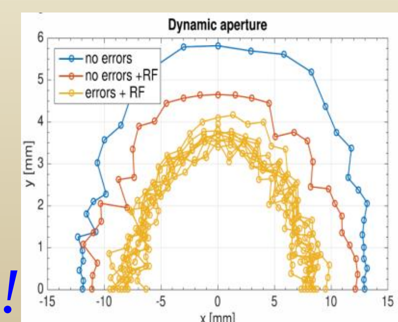


If $\varepsilon_x = 6\,nm$

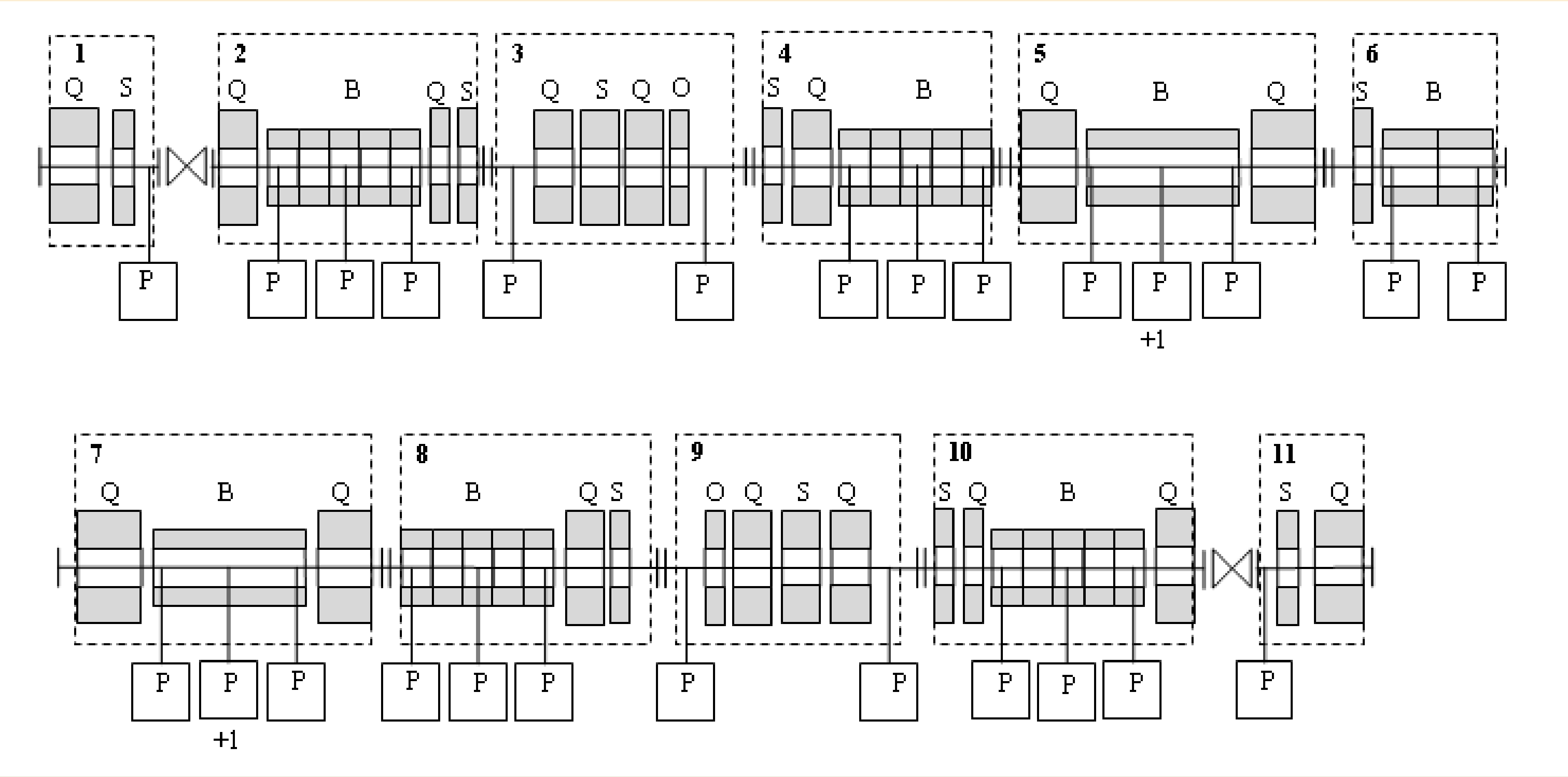
$$\beta_x = 20\,m$$

$$\sigma_i = \sqrt{\varepsilon_x \beta_x} = 0.35mm$$

ESRF DA is enough !!!

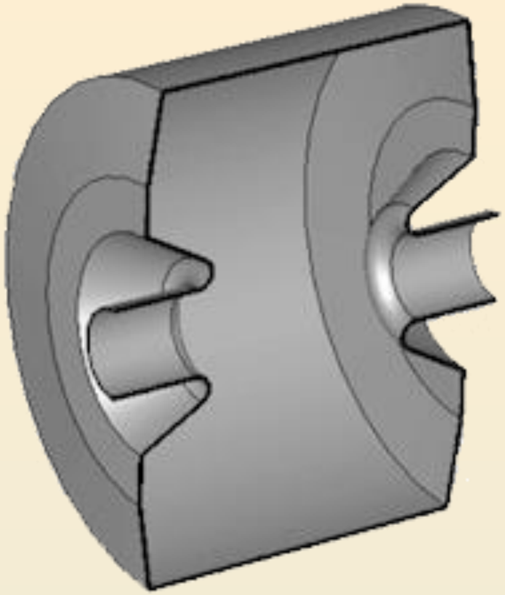


Vacuum system



Especial thanks to: Cristian Maccarrone, Hugo Pedroso Marques, Simone Liuzzo

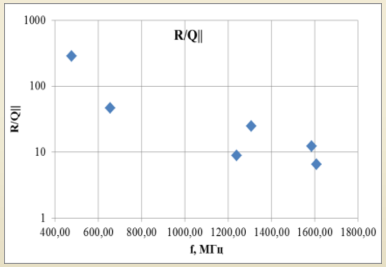
RF system: 350 MHz or higher? or lower?

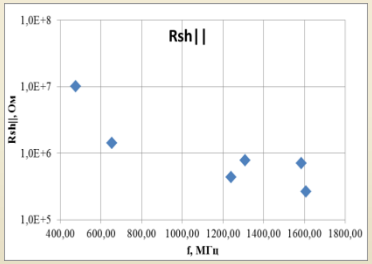


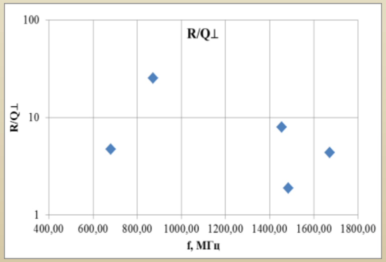
Simplest cavity model

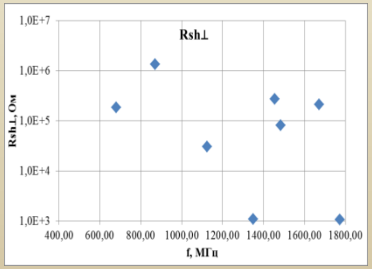
f, MHz	352	476	714
Surface field for 1 J of stored energy	11.5	14	25.5
Kilpatrick limit, MV/m	17.9	20.9	24.78
Maximal energy per cavity, J	2.4	2.22	0.94
Maximal power to beam, MW	0.57	0.53	0.23
Number of cavities for 3 MW of stored power	6	6	14

$F_{i\,,,}$ *MHz*	$R/Q_{\parallel}$	$R_{sh\ \parallel}$, MОм
F_0= 476,06	286	1,02E+07
654,57	46,7	1,43E+06
1047,21	4,82E-08	0,0035
1239,36	8,85	4,40E+05
1308,17	24,85	7,81E+05
1408,88	1,15E-07	0,008
1585,39	12,32	7,07E+05
1607,85	6,49	2,64E+05
1704,97	5,03E-07	0,056









Especial thanks to: Mikhail Zobov (LNF)

ID's: first stage

	THz	IR	Visible	UV	hν		
					VUV 50 -3000 eV	3-40 keV	50-500 keV
Undulator				>5	>5	>10	2
Wiggler					2	1	2
BM	1-2	2-3	2			>10	3

$$\mathbf{H} = -\mathbf{j}H_m \sin\frac{2\pi}{\lambda_0}z \quad (0 \le z \le L)$$

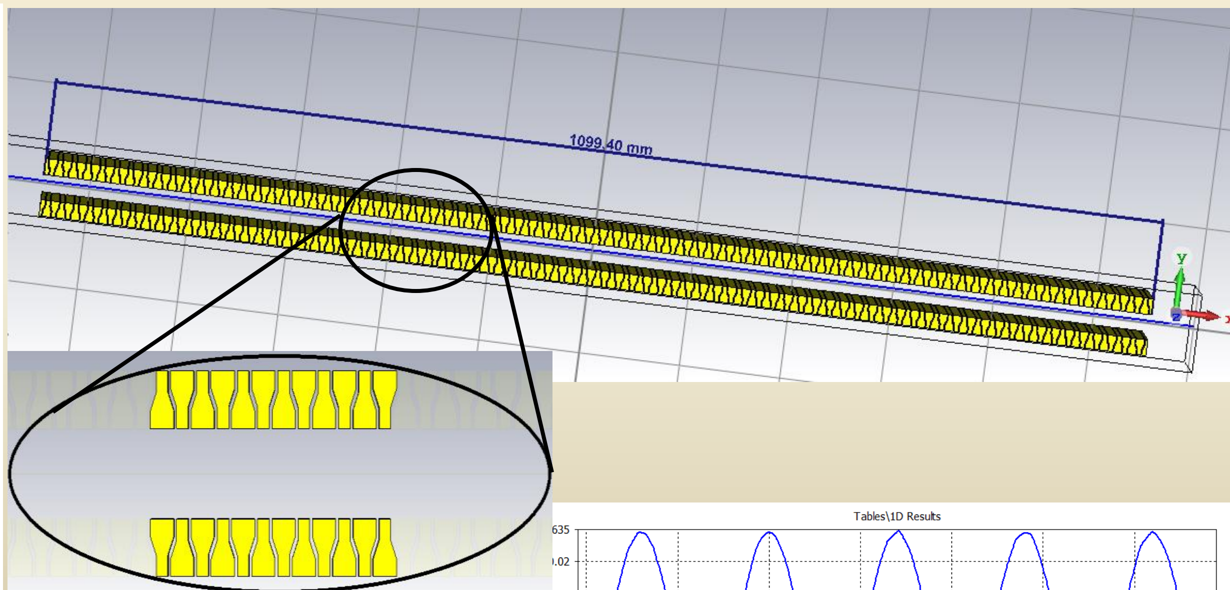
$$\alpha_m\gamma = \frac{eH_m\lambda_0}{2\pi mc^2},$$

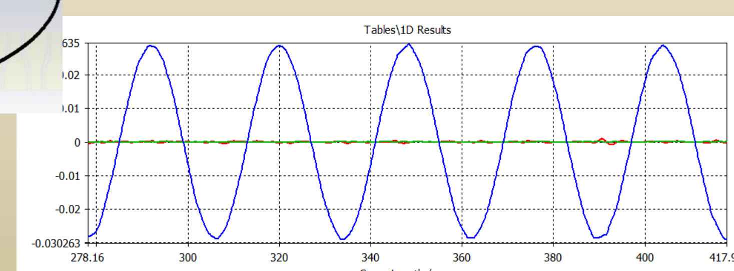
$$\omega(\theta) = \frac{\Omega}{1-\beta_{||}\cos\theta} \qquad \Omega = \frac{2\pi\beta_{||}c}{\lambda_0}$$

$$\omega_m = 2\Omega\gamma^2$$

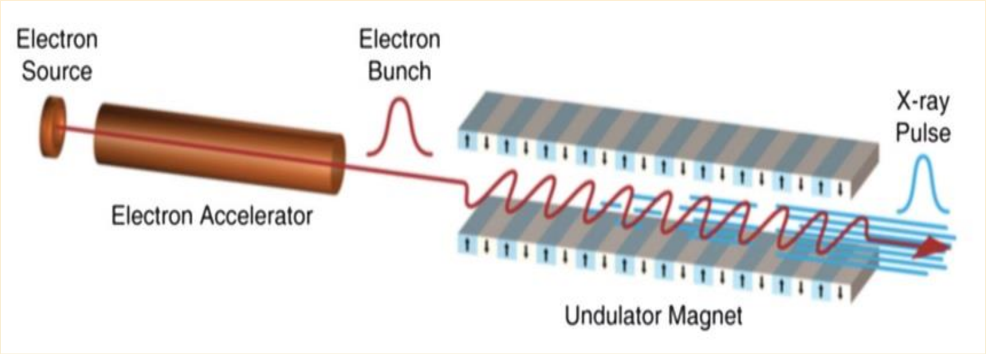
$$\frac{\Delta\omega}{\omega} = \frac{1}{2K} \qquad K = L/\lambda_0$$

$$\hbar\omega_k(\mathrm{keV}) = \frac{0,949k(E(\mathrm{GeV}))^2}{[1+p_\perp^2/2]\lambda_0(\mathrm{cm})}$$





FEL for EUV and X-rays



FELs with similar parameters:

- SwissFEL, Switzerland
- SACLA, Japan
- LCLS, USA
- SPF – MAX-IV, Sweden

Electron beam energy	5 – 7 GeV
Peak current	1 – 5 кA
Bunch charge	0.01 - 0.3 nC
Repetition rate	50 – 200 pulses per second
Normalized emittance	0.3 - 1.5 um
Photon energy	0.25 – 20 keV (1st harmonic)
Photon pulse duration	1 – 400 fs
Period of undulator, λ_U	15 – 40 mm
Undulator parameter, K	1.0 – 3.5
Peak brilliance, B_{FEL}	0.1 – 2 x 10^{33} $\mathrm{Photon/S \cdot mm^2 \cdot mrad^2 \cdot 0.1\%BW}$

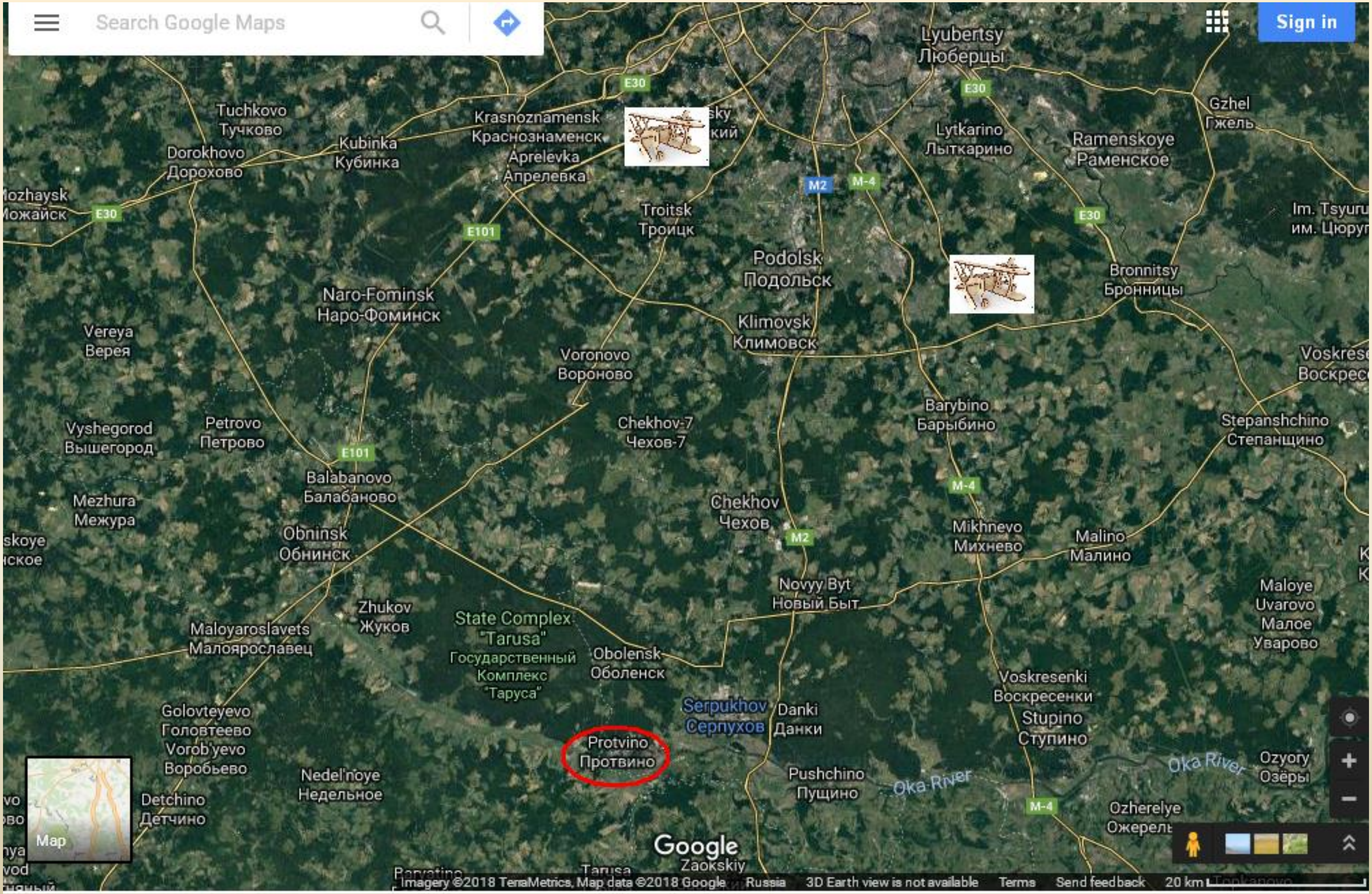
$$\lambda = \frac{\lambda_U}{2E^2}\left(1 + K^2/2\right)$$

$$K = \frac{eB_0\lambda_U}{2\pi mc^2}$$

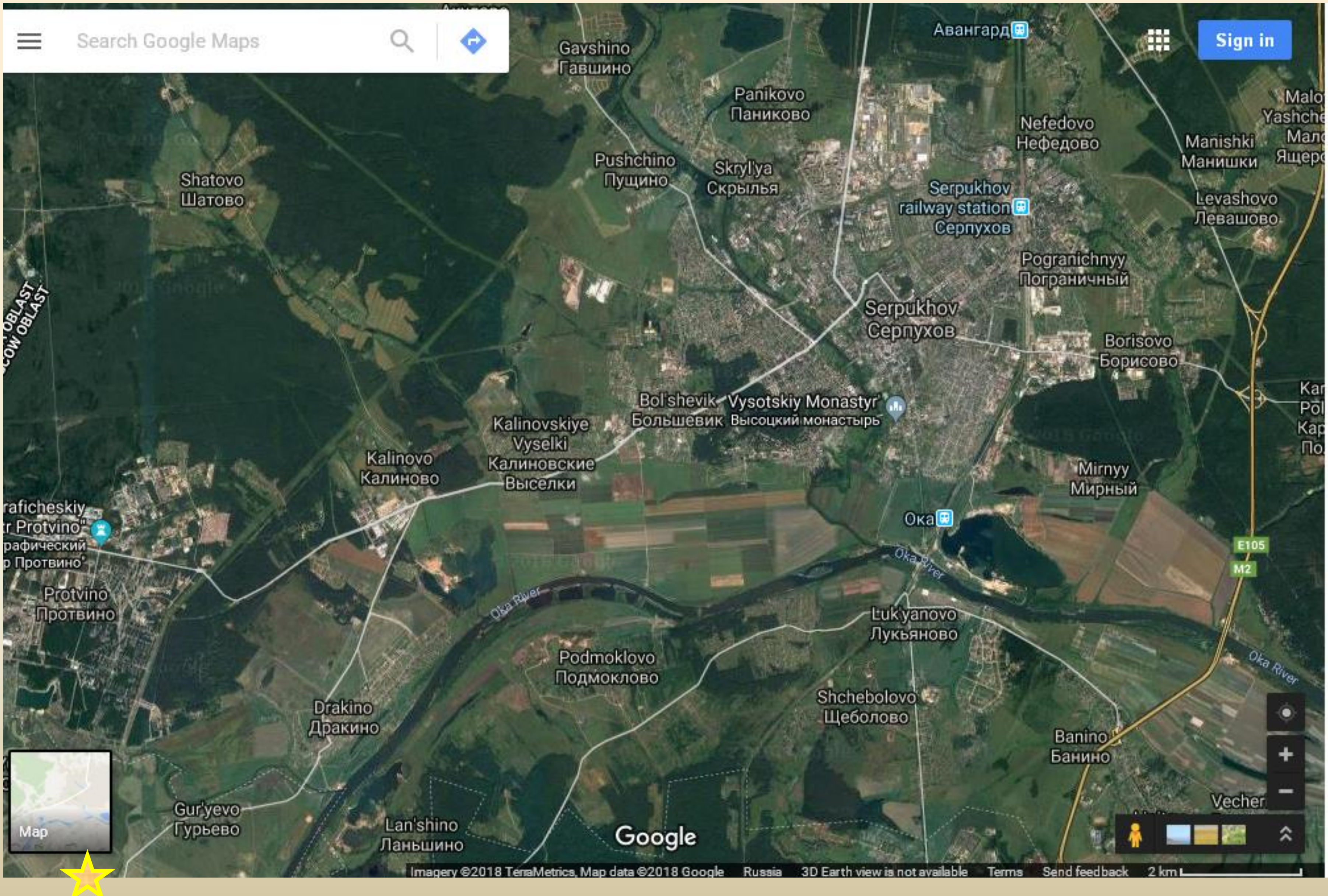
$$B_{FEL} = \frac{4N}{\lambda^2}\left(\frac{\Delta\omega}{\omega}\right)^{-1}$$

C. Pellegrini et al., The physics of X-ray FELs, Rev. of Modern Phys. 88, 1 (2016)

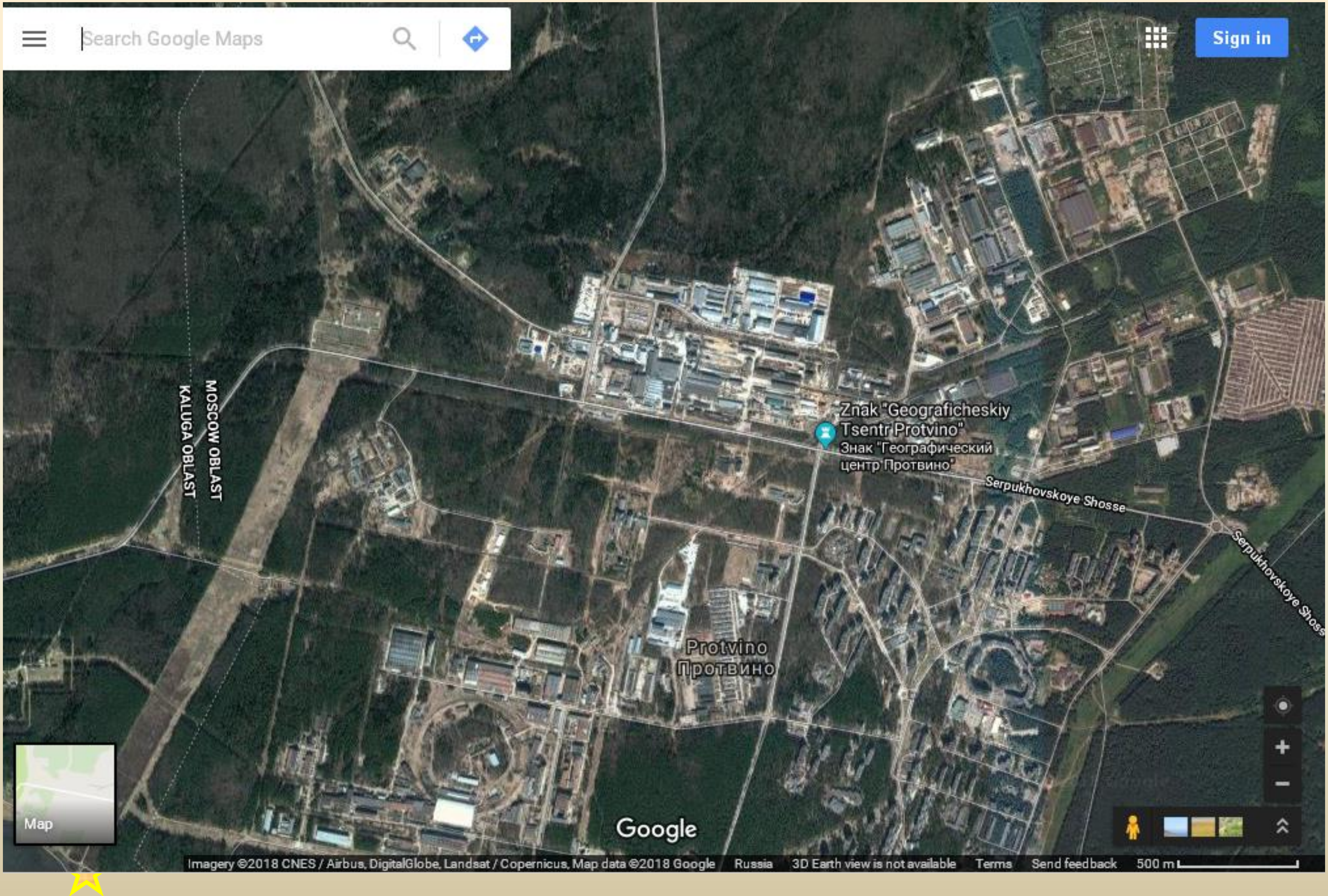
SSRS4 site in Protvino



SSRS4 site in Protvino



SSRS4 site in Protvino

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Lebedev PI

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Laboratori Nazionali di Frascati

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JINR JOINT INSTITUTE FOR NUCLEAR RESEARCH

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