Accelerators-recuperators as 4th generation X-ray light sources

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Lecture 5

Status and future of light sources based on recirculating accelerators-recuperators

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CONTENTS of Lecture 5:

1. History of recirculating accelerators,

   SC-technology and accelerators-recuperators.
2. Operating FEL based on low energy accelerators-recuperators.
3. Planning ERL-FELs.
4. Planning X-ray sources based on high energy accelerators-recuperators.
5. Summary.

- Recirculating accelerators with multipass crossing accelerating sections and independent magnetic transport system for each pass – basis of the projects MARS and ERL light sources.

- Creation of microtrons, racetrack microtrons, cascaded race-track microtrons been very important steps for understanding problems of recirculating accelerators.

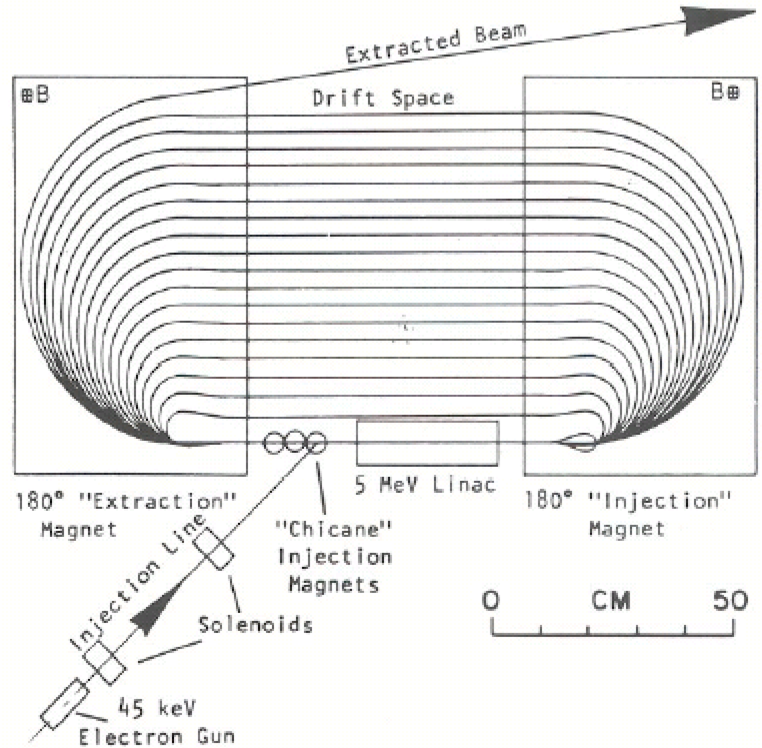
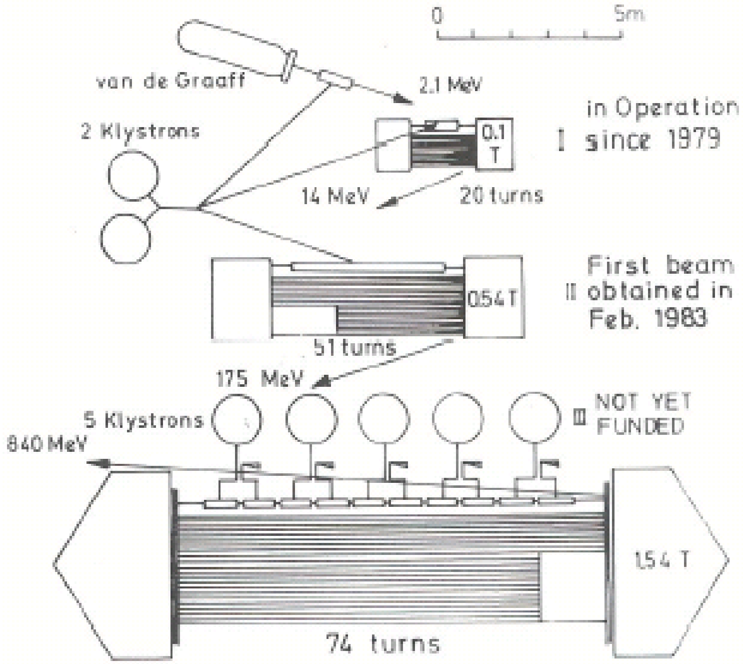


Figure 5.8 Schematic layout of the race-track microtron injector for the storage ring Aladdin at the Synchrotron Radiation Center of the University of Wisconsin (Green *et al.*, 1981; © 1981 IEEE)

UNIVERSITY OF MAINZ



Scaled scheme of MAMI

Figure 5.5 Schematic layout of the University of Mainz three-stage cascaded race-track microtron, MAMI (Herminghaus *et al.*, 1983; © 1983 IEEE)

SOME RACE-TRACK MICROTRON PROJECTS

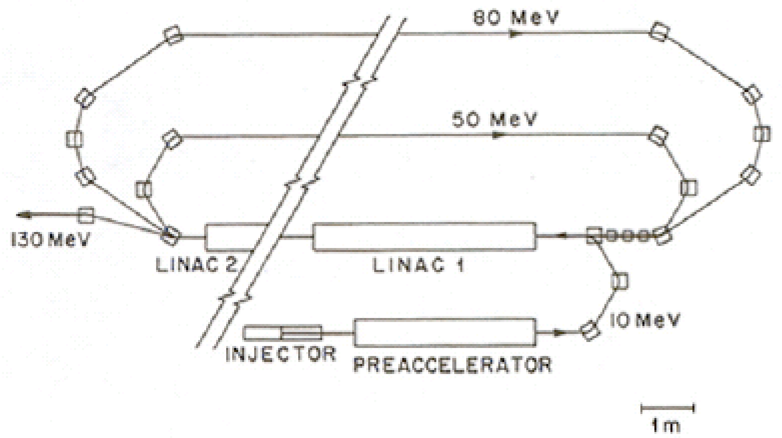
Table 5.1 Parameters of MAMI, the Mainz cascaded race-trace microtron (adapted from Herminghaus *et al.*, 1983; © 1983 IEEE)

		Stage I	Stage II	Stage III
General				
Input energy	(MeV)	2.1	14	175
Output energy	(MeV)	14	175	840
Number of passes		20	51	74
Total power consumption	(kW)	----- 280 -----		900
Magnet system				
Magnet separation	(m)	1.66	5.59	11.83
Magnetic field	(T)	0.10	0.54	1.54
Maximum orbit diameter	(m)	0.97	2.17	3.65
Magnet weight (each)	(ton)	1.3	43	305
Gap width	(cm)	6	7	12
RF system (2.449 GHz)				
Number of klystrons		----- 2 -----		5
Linac length	(m)	0.80	3.55	10.4
Total RF power	(kW)	9	64	197
Beam power	(kW)	1.2	16	67
Energy gain per pass	(MeV)	0.59	3.16	9.0
Beam performance (design, at 100 μA)				
Energy width	(keV)	± 9	± 18	± 60
Emittance: vert.	(mm mr)	0.17π	0.04π	0.01π
horiz.	(mm mr)	0.17π	0.09π	0.14π
Status		-- Operating --		Not yet funded

The Wuppertal/Darmstadt “Rezyklotron”

- The “Rezyklotron” incorporates a superconducting linac at 3 GHz.
- Beam injection energy = 11 MeV, variable extraction energy up to 130 MeV, beam current 20 μA, 100% duty factor. Energy resolution = 2 x 10^{-4} .
- Two orbits designed with 180^0 isochronous and achromatic bends and two quadrupole doublets and two triplets in the backleg.
- Isochronous beam optics

  Phase oscillations do not occur and energy resolution is determined primarily by second order effects in the linac.

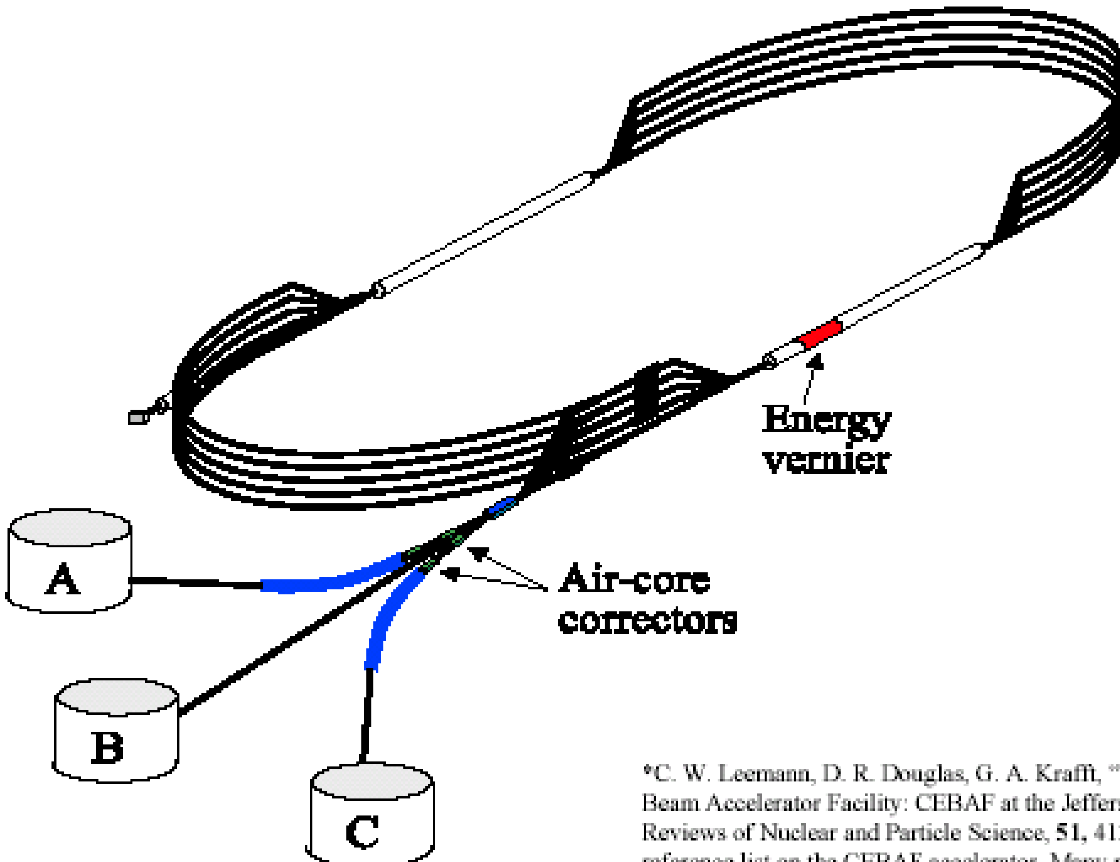


- Superconducting RF technology was developed by Cornell University, KEK, CERN, Jefferson Laboratory, DESY.

- The CEBAF at Jefferson Laboratory was first in world large scale implementation SRF technology and using multipass beam recirculation.

- The CEBAF accelerator is a 5-pass recirculating SRF linac with CW beams of up to 200 μA, full energy is nearly 6 GeV, geometric emittance $\varepsilon < 10^{-9}$ m·rad and relative energy spread of a few 10^{-5}.

CEBAF Accelerator Layout*



*C. W. Leemann, D. R. Douglas, G. A. Krafft, "The Continuous Electron Beam Accelerator Facility: CEBAF at the Jefferson Laboratory", Annual Reviews of Nuclear and Particle Science, **51,** 413-50 (2001) has a long reference list on the CEBAF accelerator. Many references on Energy Recovered Linacs may be found in a recent ICFA Beam Dynamics Newsletter, #26, Dec. 2001: http://icfa-usa/archive/newsletter/icfa_bd_nl_26.pdf

CEBAF Beam Parameters

Beam energy	6 GeV
Beam current	A 100 μ A, B 10-200 nA, C 100 μ A
Normalized rms emittance	1 mm mrad
Repetition rate	500 MHz/Hall
Charge per bunch	< 0.2 pC
Extracted energy spread	$< 10^{-4}$
Beam sizes (transverse)	< 100 microns
Beam size (longitudinal)	100 microns (330 fsec)
Beam angle spread	$< 0.1/\gamma$

History of physical proposals based on using of accelerator – recuperator:

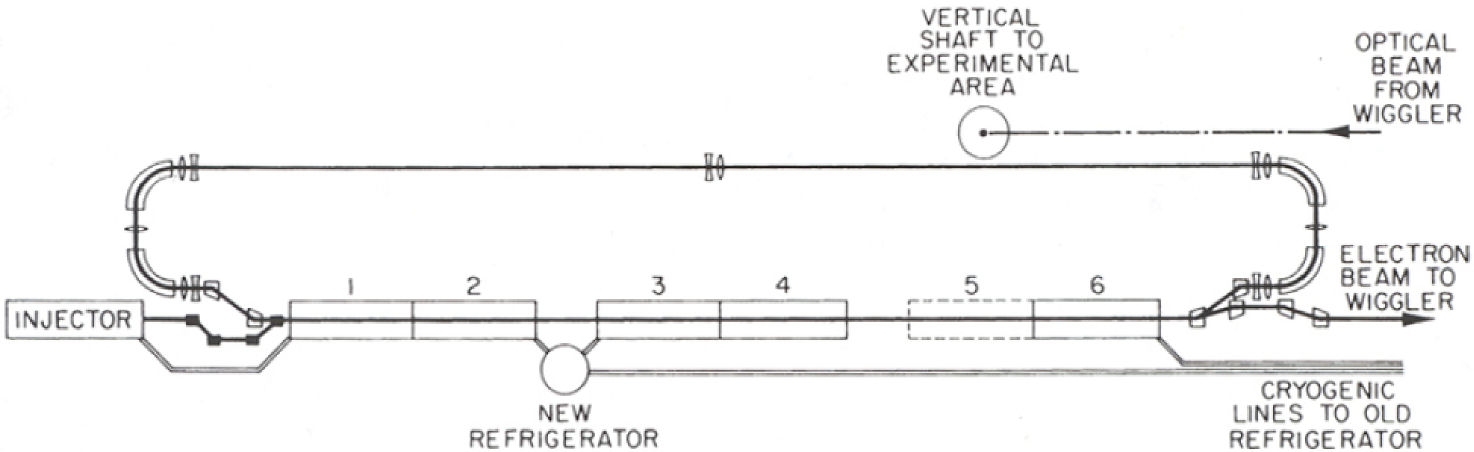
•- M. Tigner (1965) for realization of linear e^-e^- collider using SRF linacs with energy recovery; (not realized) (M. Tigner, Nuovo Cimento, **37,** (1965).)

•- G. Budker (1968) for creation electron coolers using DC electron accelerators; first demonstration of energy recovery cooler was made in Novosibirsk (1974); now all electron coolers (more 10) use energy recuperation.

•- A. Skrinsky, N. Vinokurov (1976) for increasing efficiency and power of FEL; first demonstration of energy recovery SRF linac was made at Stanford University (1986); (T. Smith e. a., NIMA, **259** (1987). Now in operation ERL-FELs in Jefferson Laboratory FEL (USA), Budker Institute of Nuclear Physics FEL (Russia), JAERI FEL (Japan).

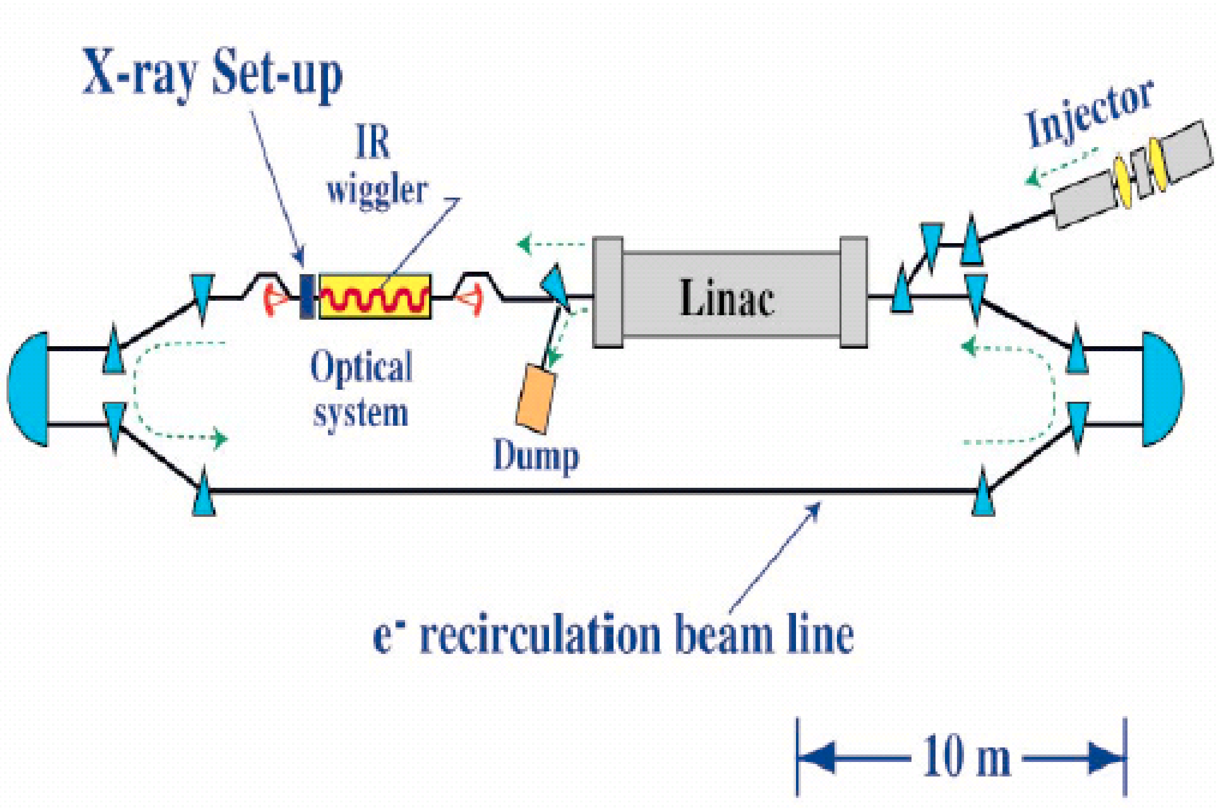
The SCA/FEL Energy Recovery Experiment

- Same-cell energy recovery was first demonstrated in the SCA/FEL in July 1986
- Beam was injected at 5 MeV into a ~50 MeV linac (up to 95 MeV in 2 passes), 150 μA average current (12.5 pC per bunch at 11.8 MHz)
- The previous recirculation system (SCR, 1982) was unsuccessful in preserving the peak current required for lasing and was replaced by a doubly achromatic single-turn recirculation line.
- All energy was recovered. FEL was not in place.



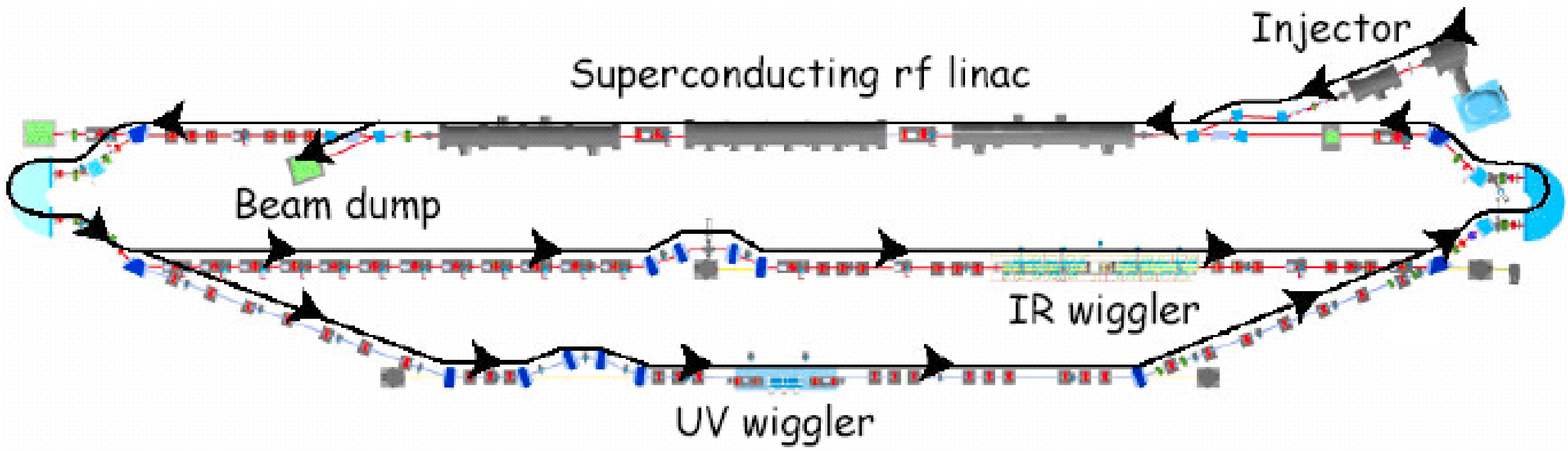
Operated FEL

Jefferson Lab FEL



Neil, G. R., *et. al, Physical Review Letters*, **84,** 622 (2000)

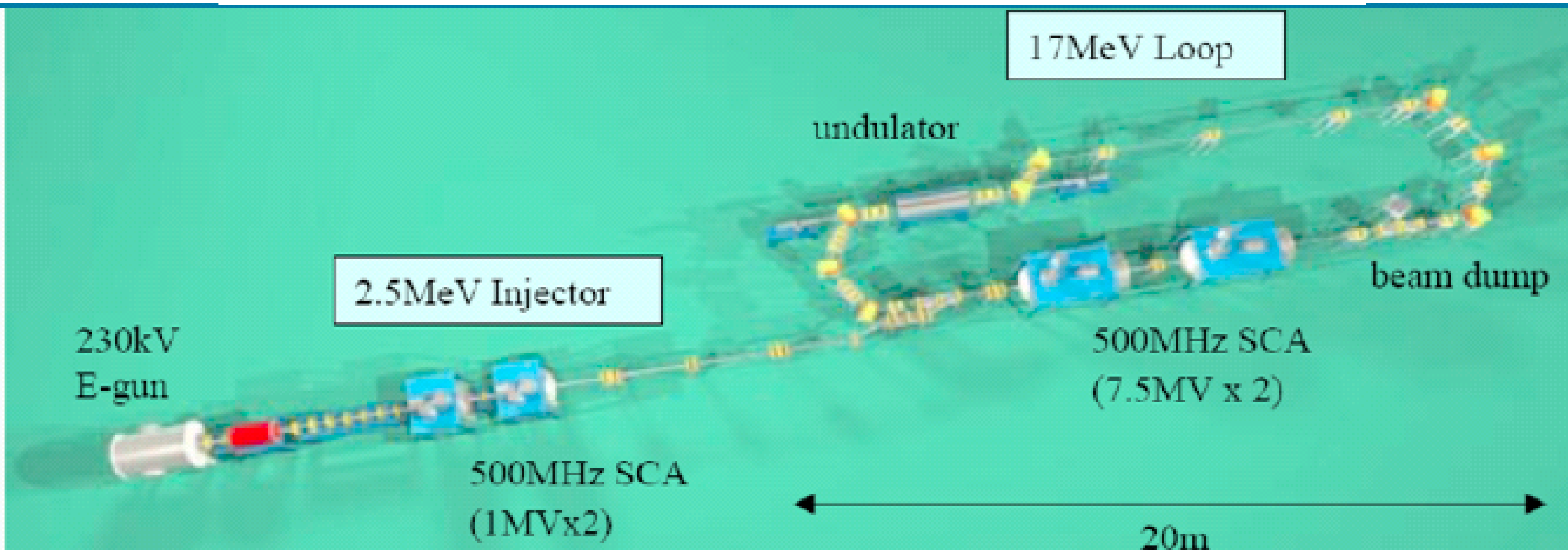
JLab 10kW IR FEL and 1 kW UV FEL



Output Light Parameters	IR	UV
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser power / pulse (microJoules)	100 - 300	25
Laser power (kW)	>10	> 1
Rep. Rate (cw operation, MHz)	4.7 – 75	4.7 – 75

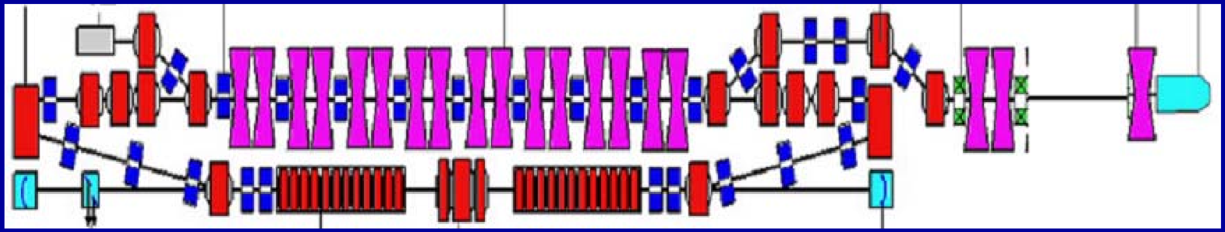
Electron Beam Parameters	IR	UV
Energy (MeV)	80-200	200
Accelerator frequency (MHz)	1500	1500
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50	0.13
Normalized emittance (mm-mrad)	<30	<11
Induced energy spread (full)	10%	5%

JAERI ERL-FEL

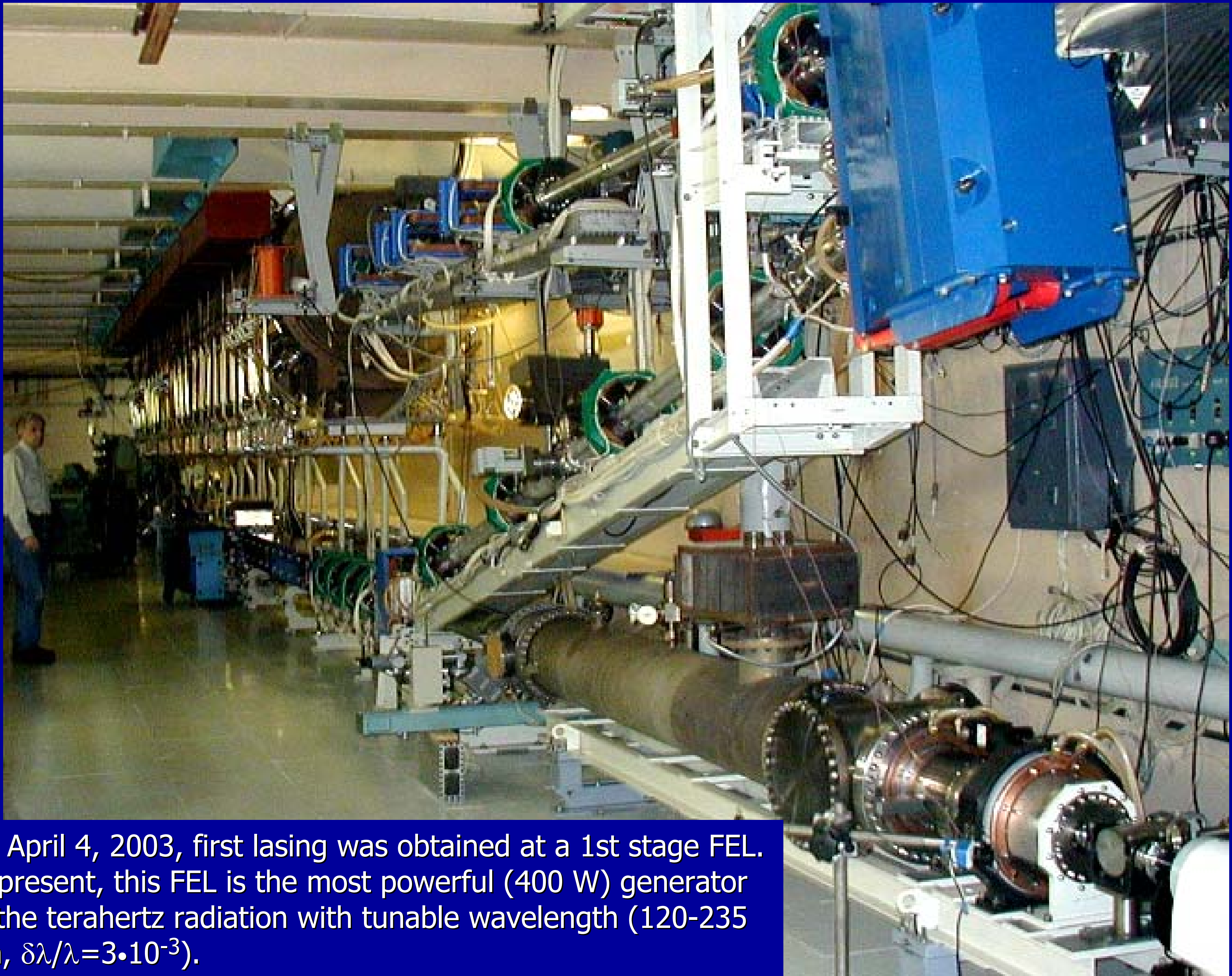


Output Light Parameters	Achieved	Goal
Wavelength range (microns)	22	22
Bunch Length (FWHM psec)	15	6
Laser power / pulse (microJoules)	10	120
Laser power (kW)	0.1	10
Rep. Rate (MHz)	10.4	83.2
Macropulse format	10ms 10Hz	CW

Electron Beam Parameters	Achieved	Goal
Energy (MeV)	17	16.4
Accelerator frequency (MHz)	500	500
Charge per bunch (pC)	500	500
Average current (mA)	5	40
Peak Current (A)	33	83
Beam Power (kW)	85	656
Energy Spread (%)	~0.5	~0.5
Normalized emittance (mm-mrad)	~40	~40
Induced energy spread (full)	~3%	~3%



The scheme and views of the 1st stage Novosibirsk accelerator-recuperator and FEL



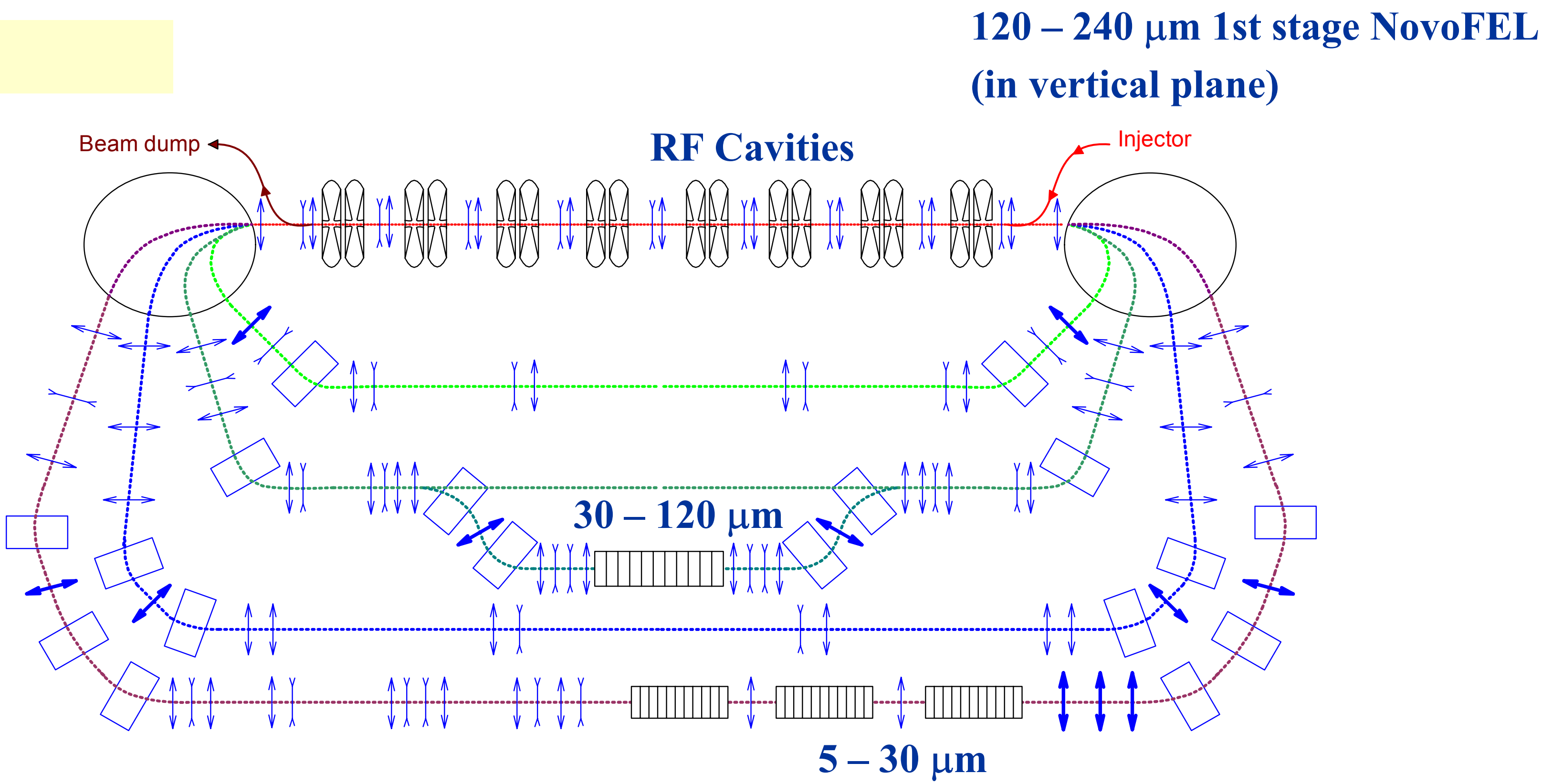
On April 4, 2003, first lasing was obtained at a 1st stage FEL. At present, this FEL is the most powerful (400 W) generator of the terahertz radiation with tunable wavelength (120-235 μm, $\delta\lambda/\lambda=3\cdot10^{-3}$).

Second stage NovoFEL

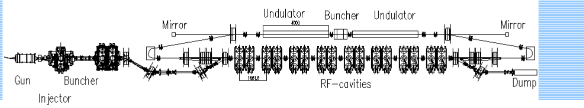
A full-scale 4-track accelerator-recuperator uses the same accelerating structure as the accelerator-recuperator of the 1st stage but in contrast to the latter, it is placed in the horizontal plane. Thus, there is no need in dismounting one for installing another.

The choice of operation regime at one of two machines and one of three FEL will be achived by simple reswitching of the bending magnets.

2-nd stage Novosibirsk FEL (in horizontal plane)



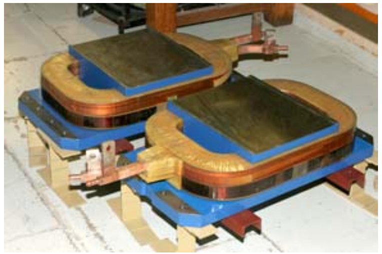
Radiation wavelength	**5 – 240 μm**
Average power	**Up to 10 kW**
E-beam energy	**up to 40 MeV**
Maximum repetition rate	**90 MHz**
Maximum mean current	**150 mA**



Status of the NovoFEL second stage

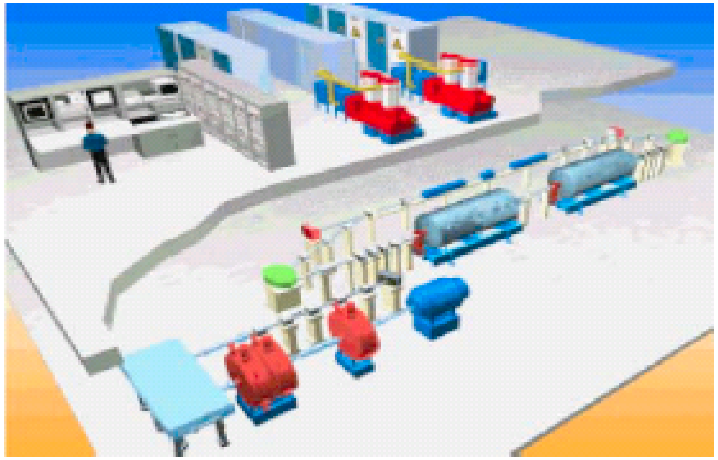
Assembly of four tracks of NovoFEL accelerator system is in progress

FEL-2007 Conference excursion,
Novosibirsk, August 29, 2007



Planned ERL-FELs

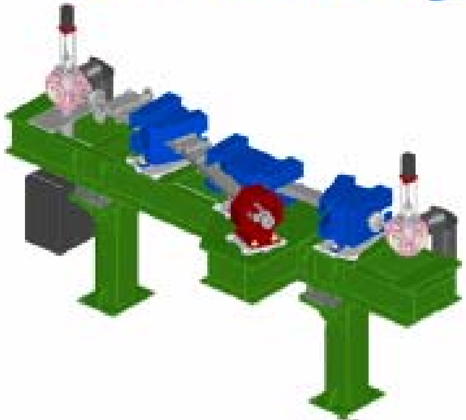
KAERI FEL

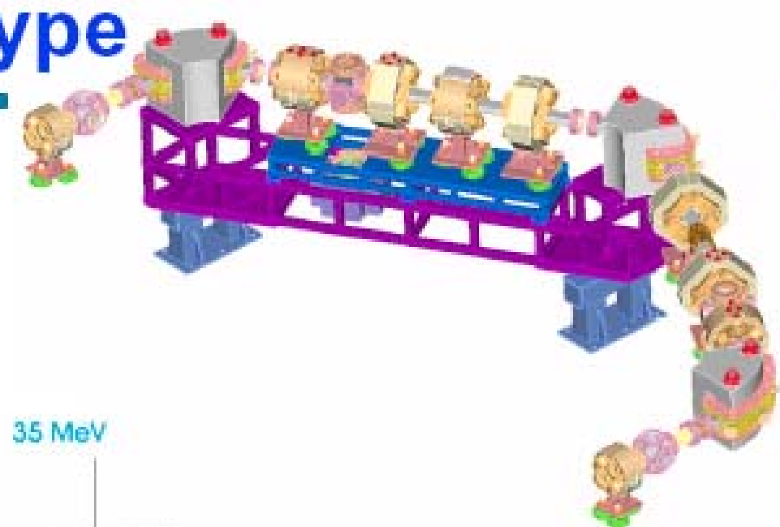


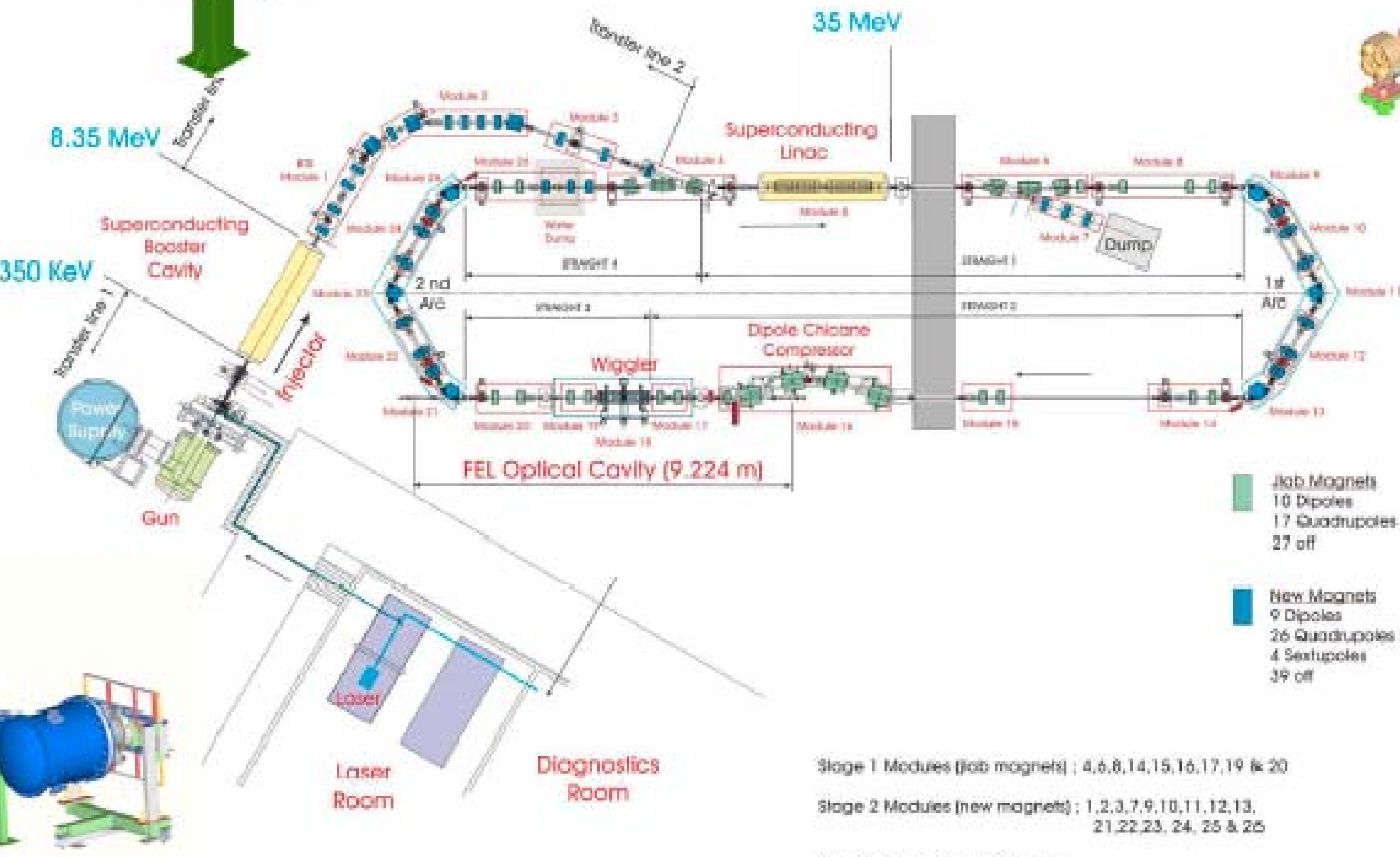
Output Light Parameters	Goal
Wavelength range (microns)	3-20
Bunch Length (FWHM psec)	20-50
Laser power / pulse (mJoules)	50-250
Laser power (kW)	1-5
Rep. Rate (MHz)	22
Macropulse format	CW

Electron Beam Parameters	Goal
Energy (MeV)	20-40
Accelerator frequency (MHz)	352
Charge per bunch (pC)	500
Average current (mA)	10
Peak Current (A)	10-25
Beam Power (kW)	200-400

Daresbury: ERL Prototype







Three phases project

- ARC-EN-CIEL phase 1 :

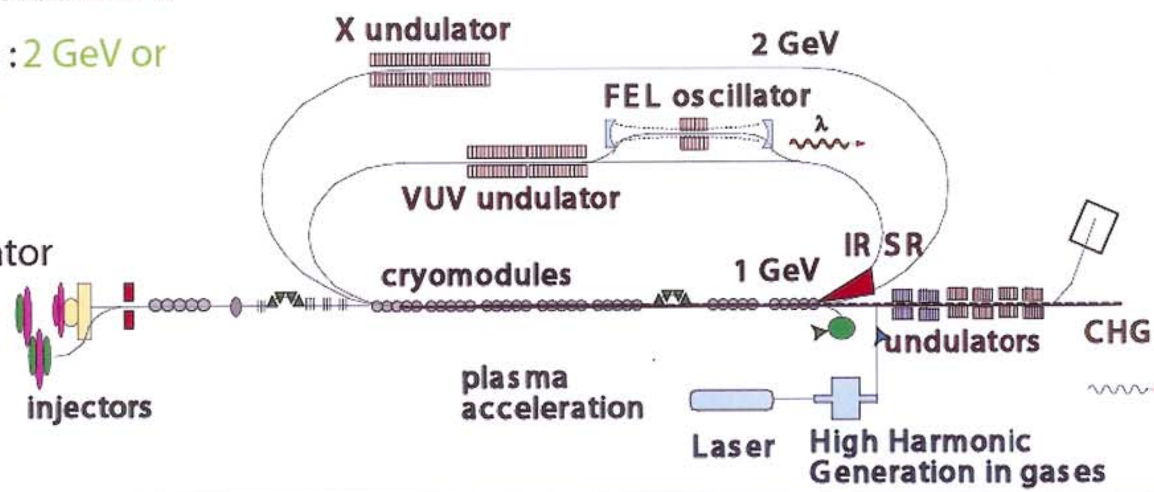
Linear accelerator : 220 MeV (or 330 MeV), low energy spread, low emittance
femtosecond HGHG sources : 100-10 nm, high brilliance and coherence

- ARC-EN-CIEL phase 2 :

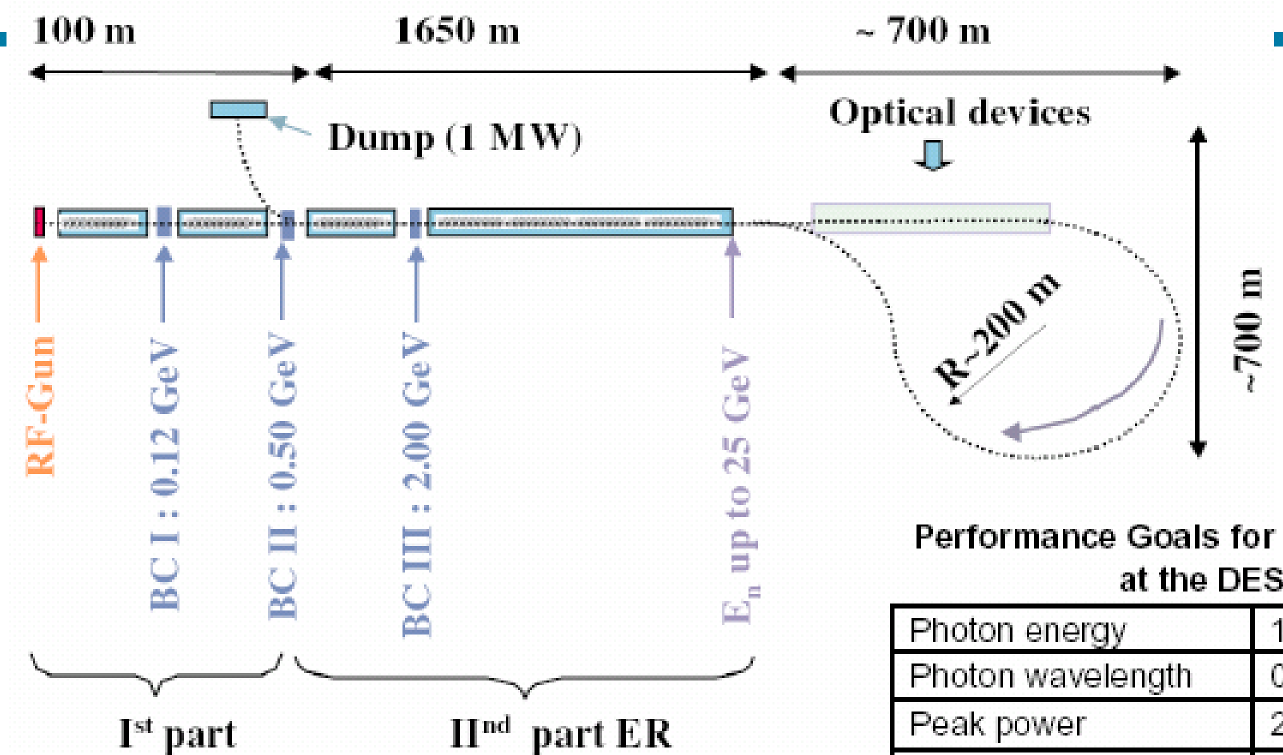
Linear accelerator : 1 GeV
HGHG sources : down to 1 nm

- ARC-EN-CIEL phase 3 :

Additionnal loops : 2 GeV or increased current
HGHG sources
UV FEL oscillator
VUV and X undulator



TESLA XFEL ERL

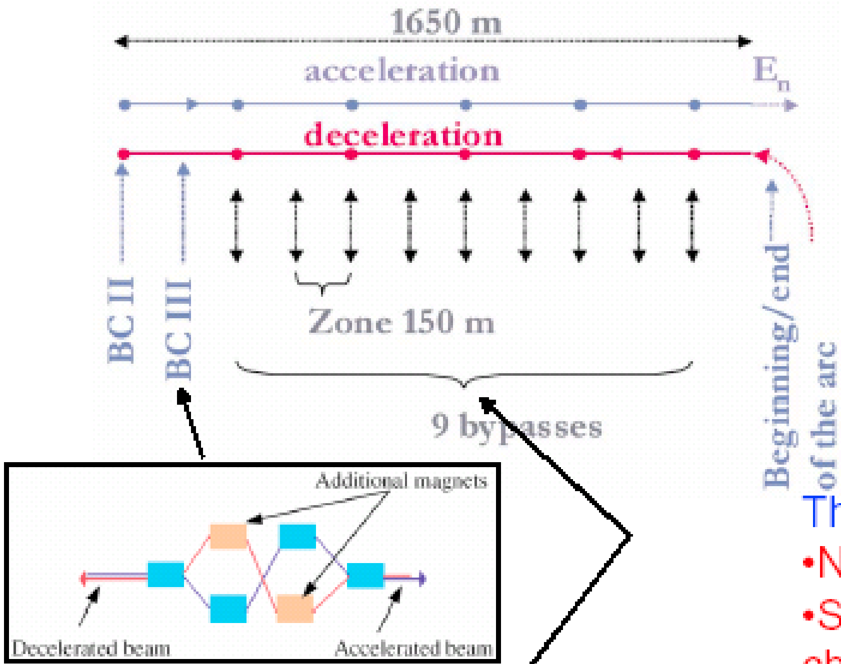


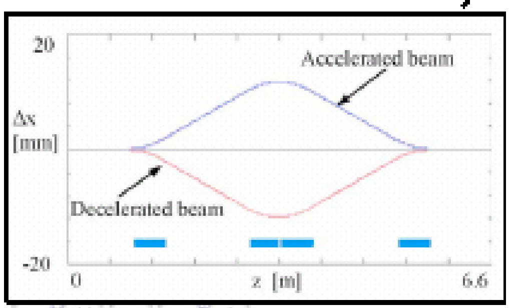
Performance Goals for SASE FEL Radiation at the DESY XFEL

Photon energy	12.4 – 0.2 keV
Photon wavelength	0.1 – 6.4 nm
Peak power	24 – 135 GW
Average power	66 – 800 W
# photons/ pulse	$1 – 430 \times 10^{12}$
Peak brilliance	$5.4 – 0.6 \times 10^{33}$ **
Average brilliance	$1.6 – 0.3 \times 10^{25}$ **
** in units of photons / (s mrad² mm² 0.1% b.w.)	

Proposed ER operation would have a rep rate of 1 MHz instead of DESY XFEL rep rate of 10 Hz, increasing the average power and brilliance by a factor of 10^5

How to avoid beam quality degradation due to beam-beam interactions of the counter-propagating beams?





At a 1 MHz rep rate there are 6 bunches in the ERL at a given time, thus 12 collision locations separated by 150 meters.

The proposed solution is to avoid collisions altogether!

Three suggested beam time structures:

- Nominal beam: 1 μpulse every μs
- Short trains of bunches: The bypass chicanes are about 4.5 m in length. Bunch trains of this length (~20 RF cycles, 15 ns) can repeat every μs without colliding.
- Long trains: The return arc plus the straight section for undulators is about 2000 m long. A 6.7 μ s train of bunches can repeat every 24 μs without colliding.

- The pioneering ERL FELs have established the fundamental principles of ERLs.
- The multitude of ERL-FEL projects and proposals worldwide promises an exciting next decade as:
  - Three currently operating ERL-FELs will reach higher performance
  - At least four more are in serious planning stages and will likely be constructed
  - New advanced concepts are being explored

- Realization of a fully spatial coherent source is possible in case of a shift from electron storage rings to accelerators with energy recuperation, which was first discussed at SRI-97 (see *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*).

- Presentation of MARS - recuperator based diffraction-limited X-ray source was made on ICFA workshop on future light sources (ANL, USA, July 1999).

- After that, the idea of using the accelerators-recuperators was actively discussed at Jefferson Lab, Cornell Uni., BNL, LBL, Erlangen Uni., Daresbury Lab., KEK.

Energy recovery demonstration at world – record energy was made at SEBAF Jefferson Laboratory at 2003:

- Demonstrated the feasibility of energy recovering a high energy (1 GeV) beam through a large (~1 km circumference), superconducting (39 cryomodules) machine.

- 80 μA of CW beam, accelerated to 1055 MeV and energy recovered at 55 MeV.

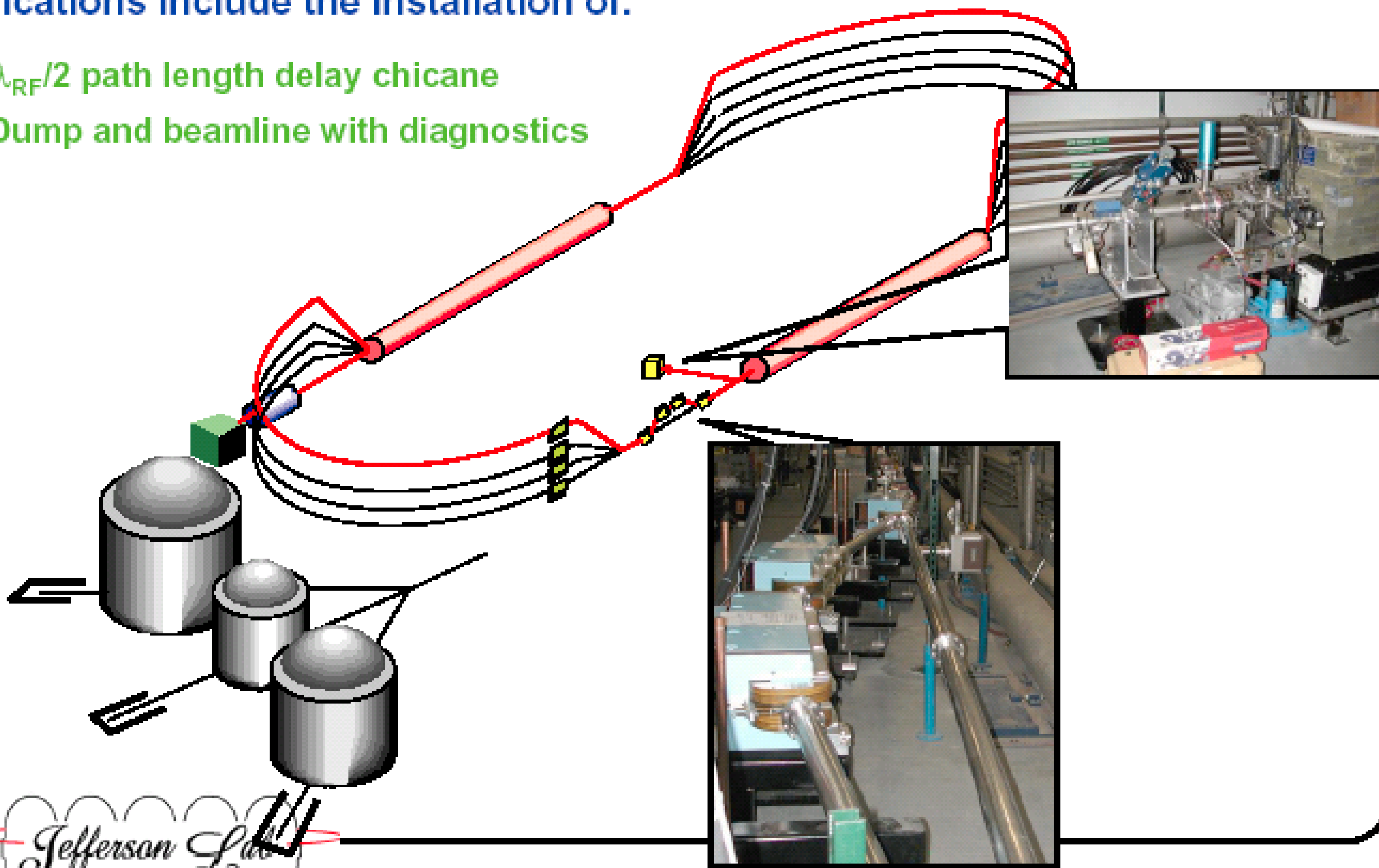
- 1 μA of CW beam, accelerated to 1020 MeV and energy recovered at 20 MeV, was steered to the ER dump.

- Tested the dynamic range on system performance by demonstrating high final-to-injectror energy ratios (E_{final}/E_{inj}) of 20:1 and 50:1.

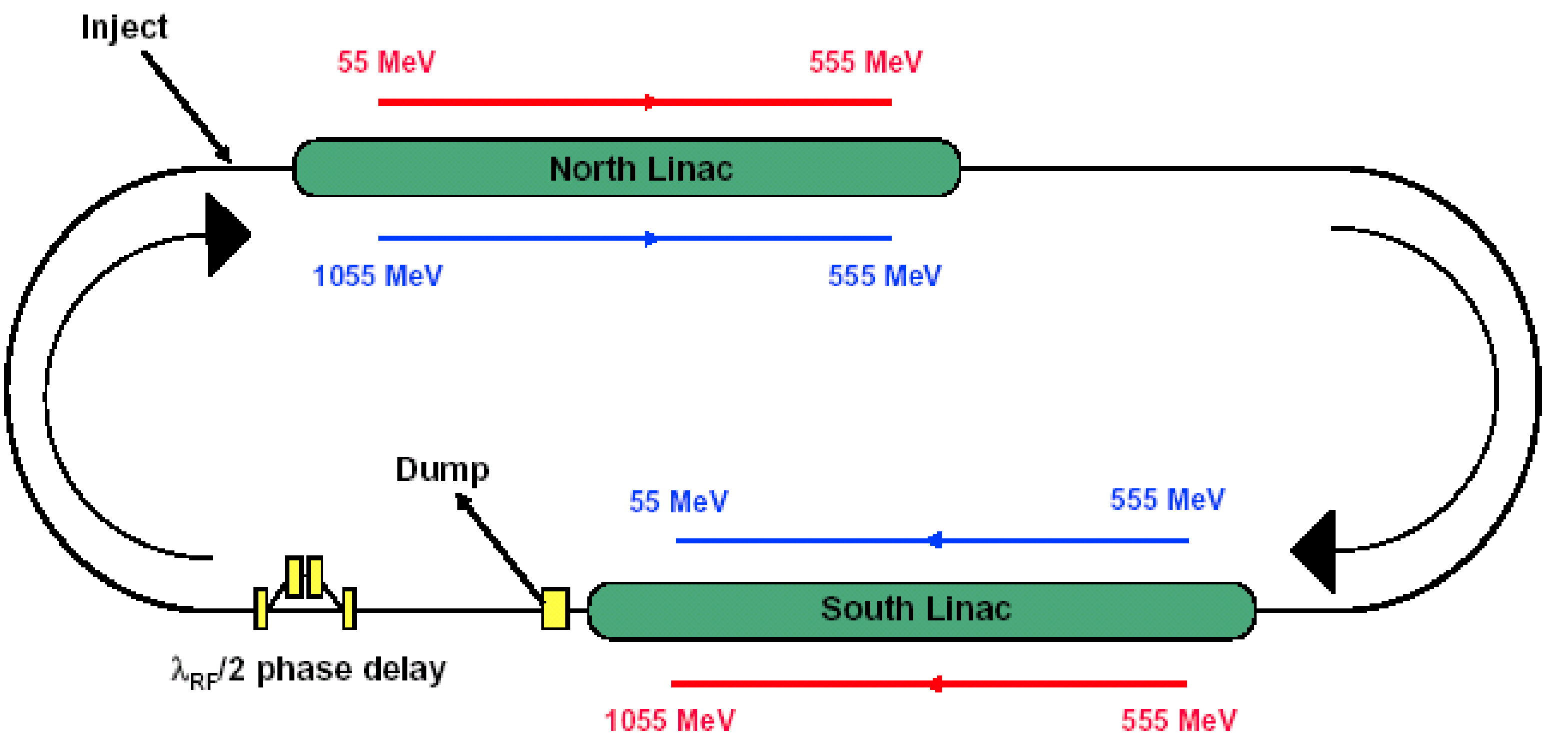
CEBAF Modifications

Modifications include the installation of:

- $\lambda_{RF}/2$ path length delay chicane
- Dump and beamline with diagnostics

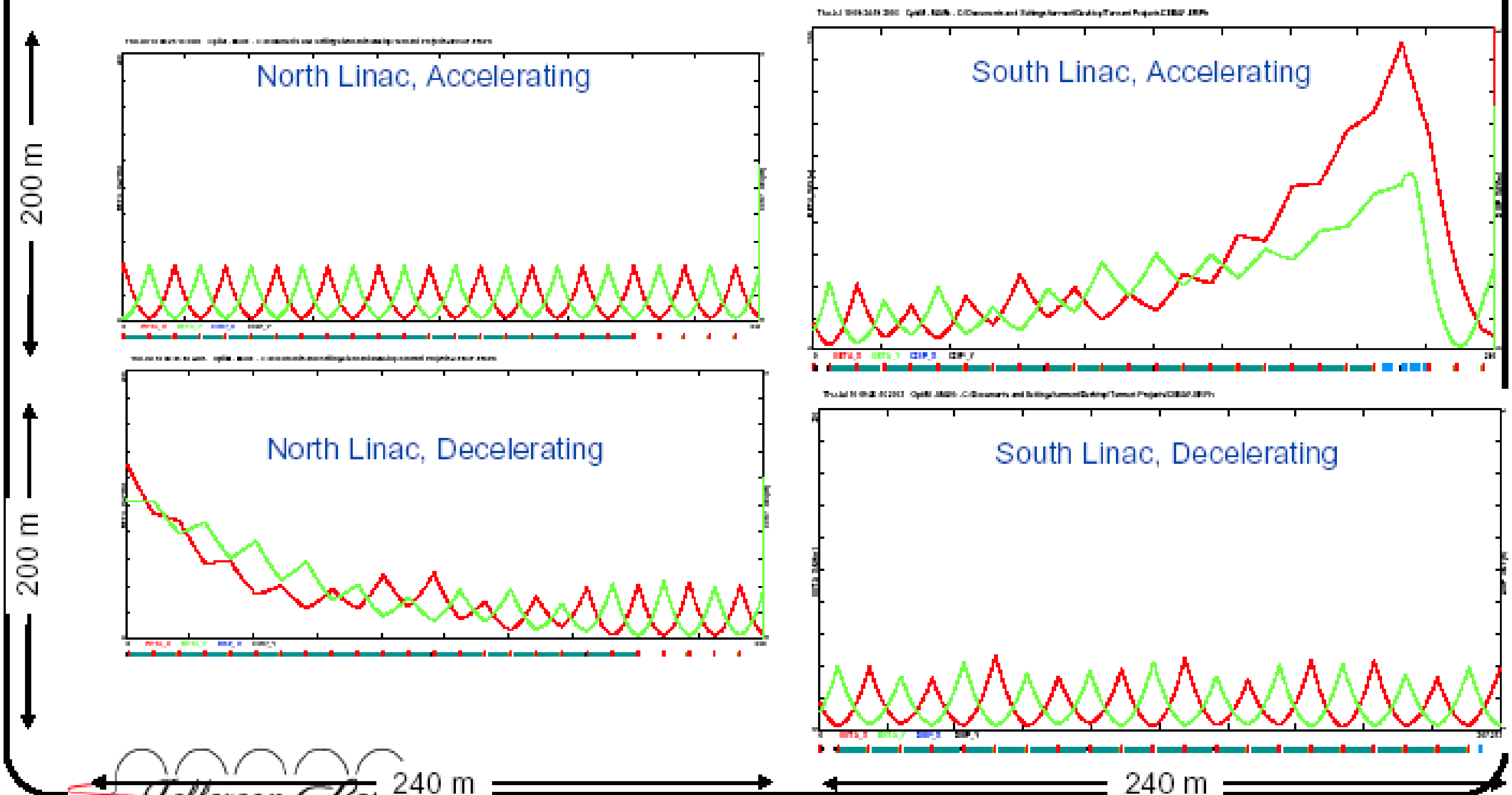


"1 Pass-Up / 1 Pass-Down" Operation



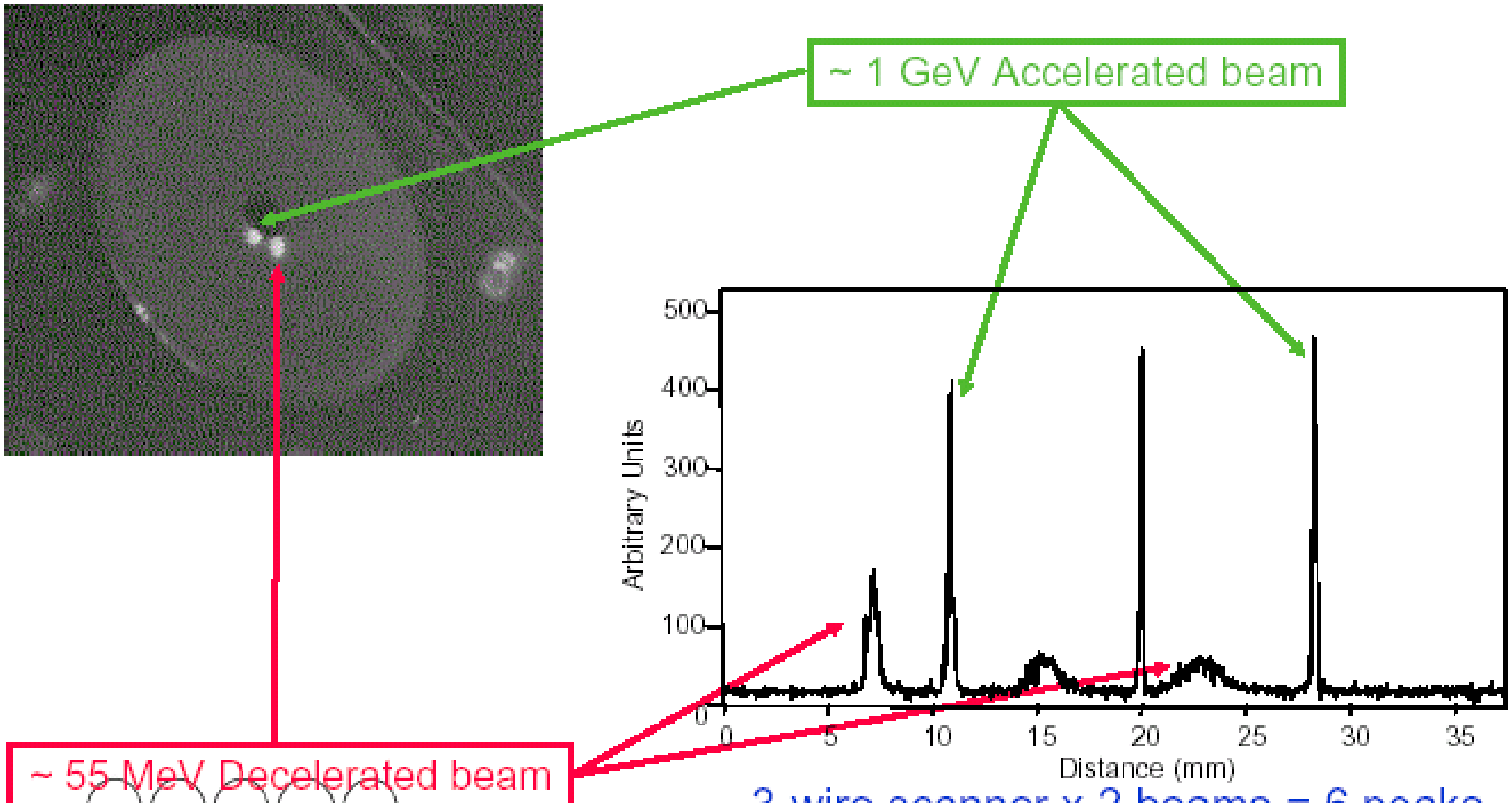
Machine Optics

Linacs - standard 120° lattice for the lowest energy beam in each linac and mismatched optics on the other pass.



CEBAF-ER Experimental Run

Beam viewer near the exit of the South Linac

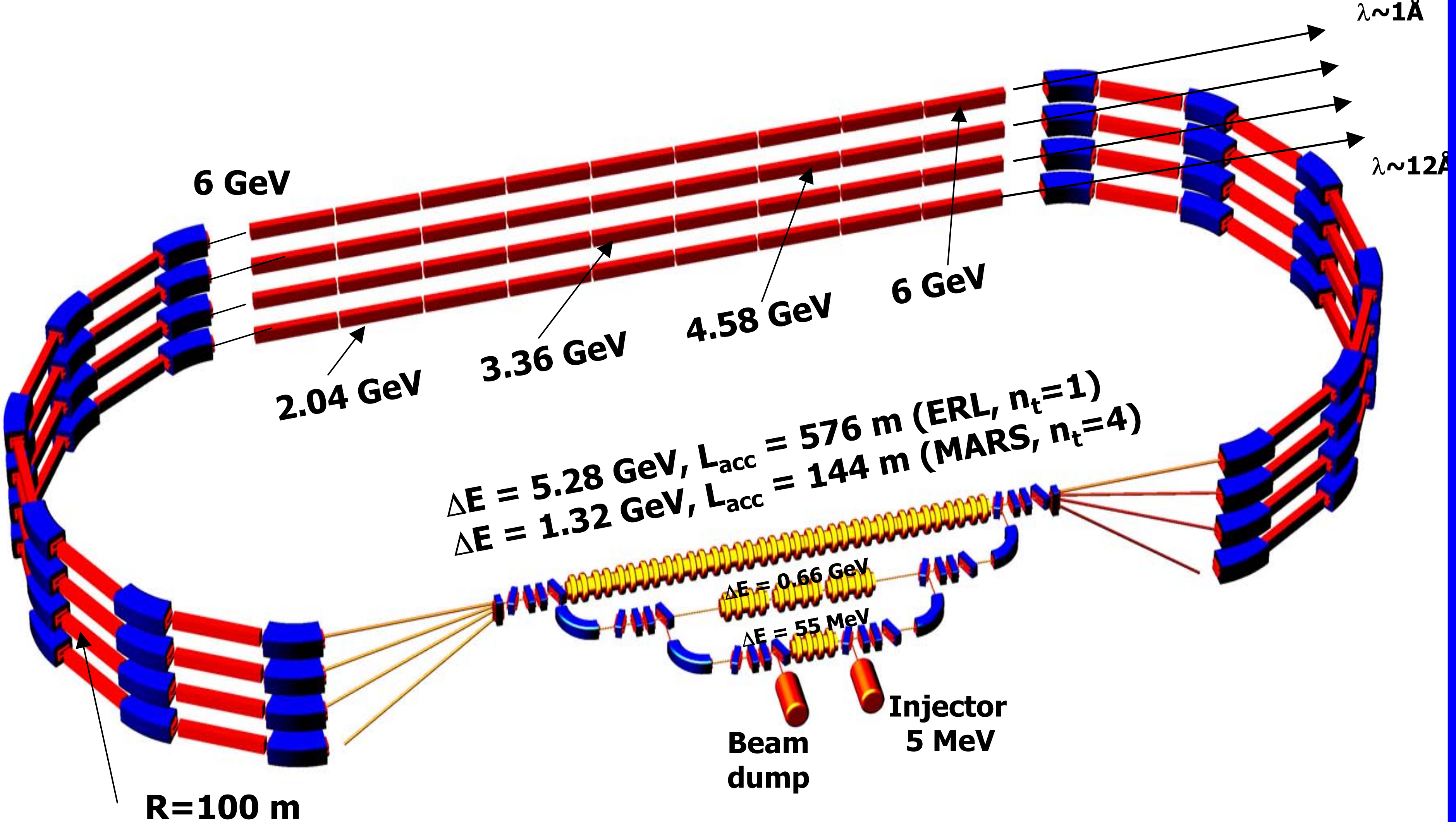


3-wire scanner x 2 beams = 6 peaks

Planned ERL- X-ray sources

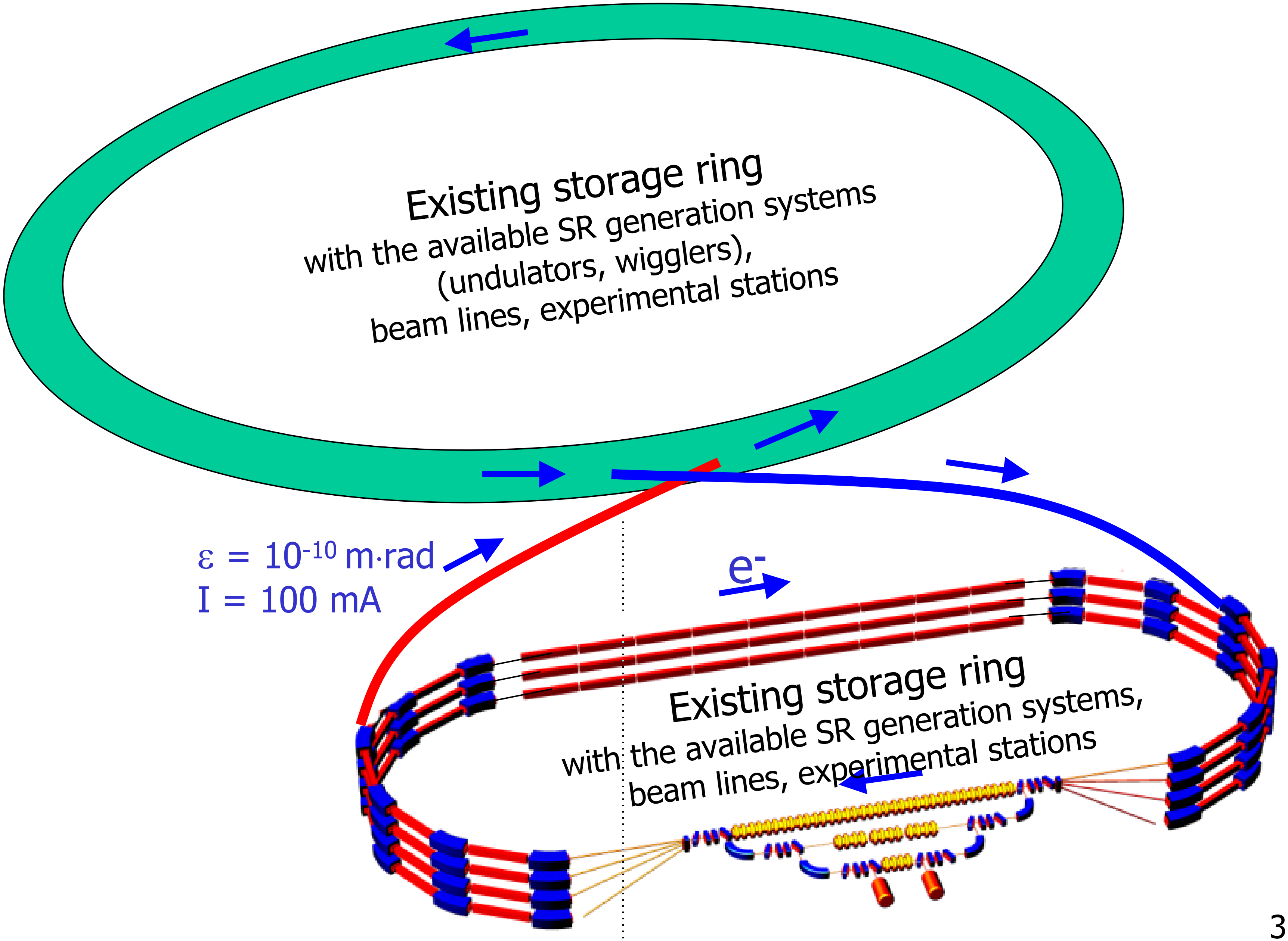
Basic overall dimensions of ERL and MARS (E_{max} = 6 GeV)

MARS: 3D view



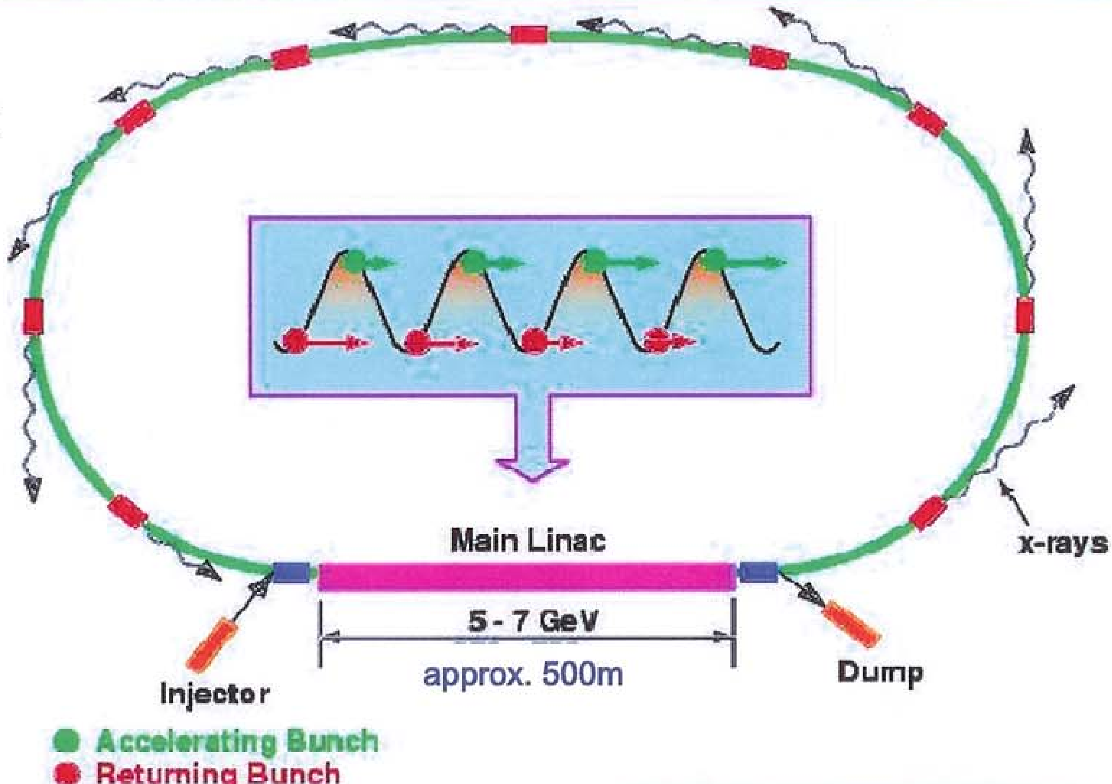
- A rough estimation has shown that in practice, the total cost of the multi-turn low electron current (<10 mA) accelerator based project is the same as the cost of the available SR source of the 3rd generation (ESRF, APS, Spring-8).

- It is quite probable that in some cases, a multi-turn accelerator-recuperator can be used for improving the brightness and for obtaining the fully spatially coherent source at the upgrade of the available SR sources of the 2nd and 3rd generations. In this case, the existing storage ring with the available generation systems, beam lines, etc can be used as the last track (I. Koop, ERL Syn-2002, Erlangen).


Existing storage ring
with the available SR generation systems
(undulators, wigglers),
beam lines, experimental stations
ε = 10-10 m·rad
I = 100 mA
e-
Existing storage ring
with the available SR generation systems,
beam lines, experimental stations

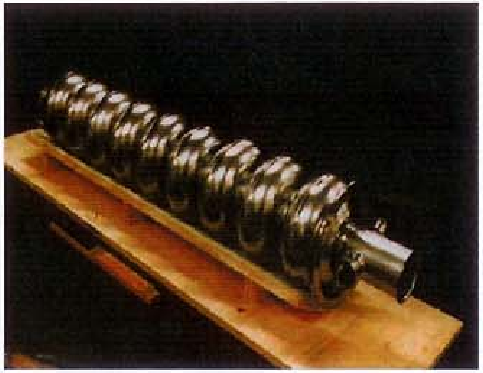
Principle of an X-ray ERL

X-ray analysis with highest resolution in space and time:

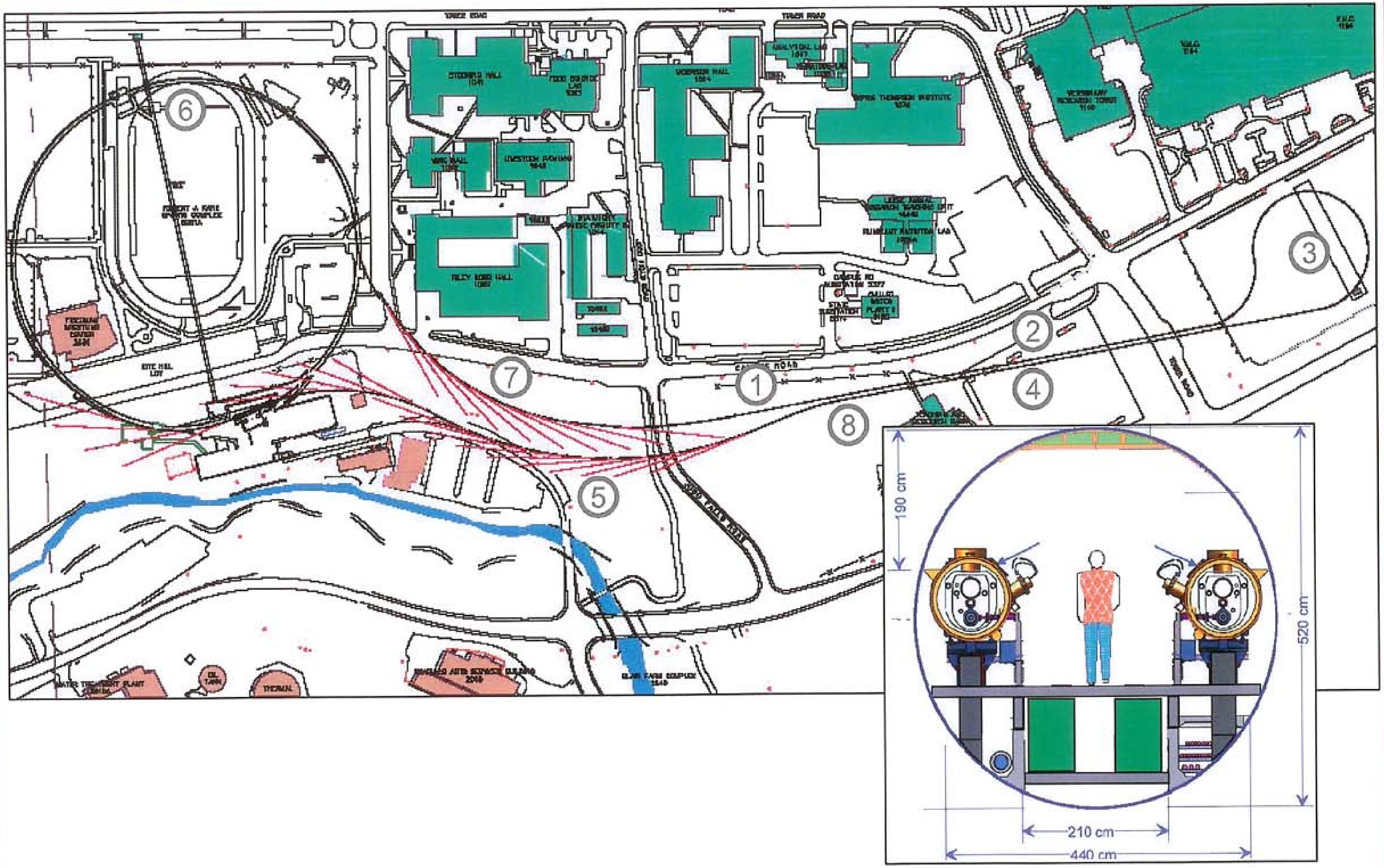


Challenges:

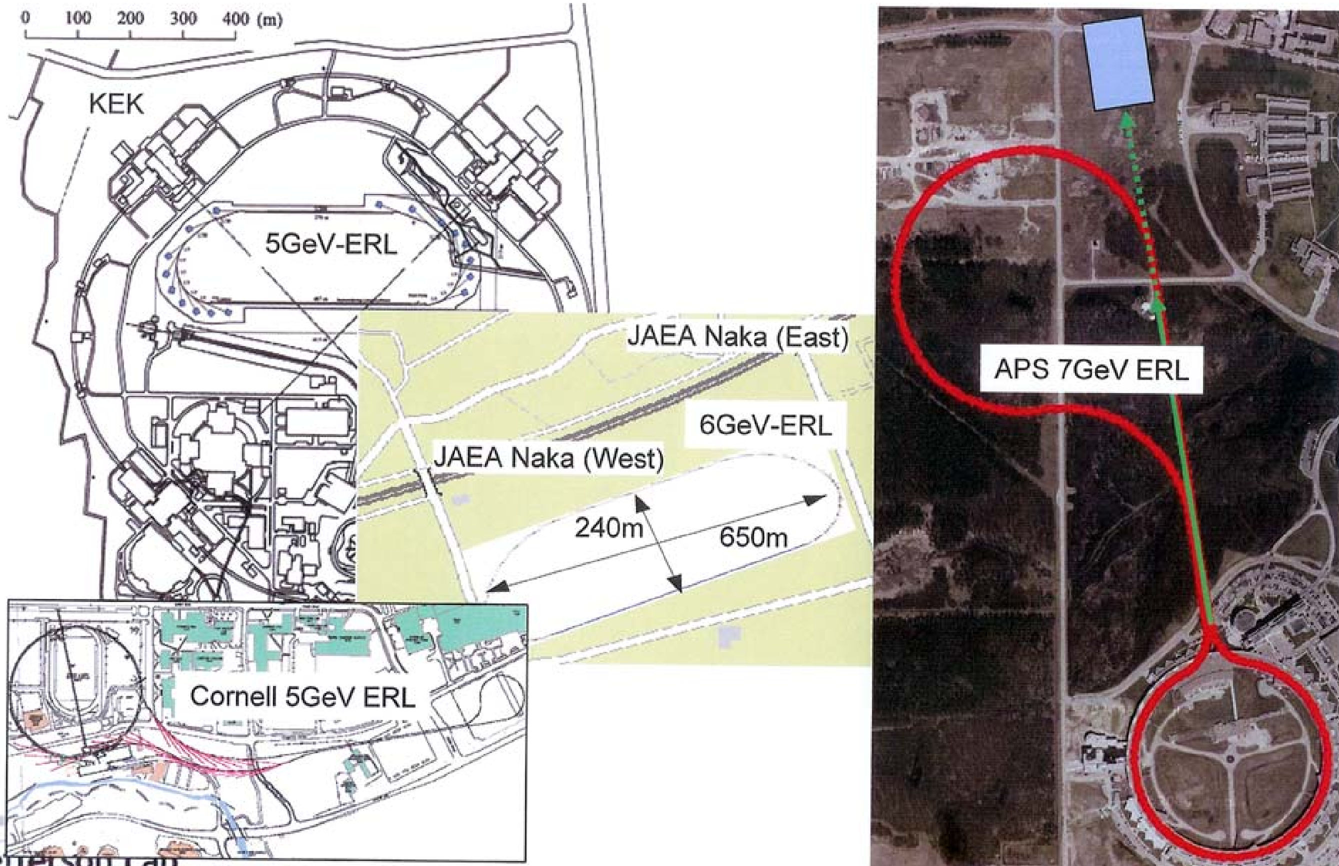
- Low emittance, high current creation
- Emittance preservation
- Beam stability at insertion devices
- Accelerator design
- Component properties, e.g. SRF



ERL@CESR design version 1.3



Cornell / KEK / JAEA / APS ERLs



Merminga, ERL2007, May 21-25 2007

APS Upgrade Review

An "Outfield" ERL Option (G. Decker[1])

- Advantages
  - Linac points away from APS[2] to give straight-ahead FEL hall[3]
  - Beam goes first into new, emittance-preserving turn-around arc[4]
  - Avoids wetlands etc. by using narrow corridor for linac and return line
- Issues
  - Big and expensive
  - Turn-around should be *bigger* than shown
  - Beam goes wrong way around the APS in this sketch (readily fixed)
  - No space for really long undulators.

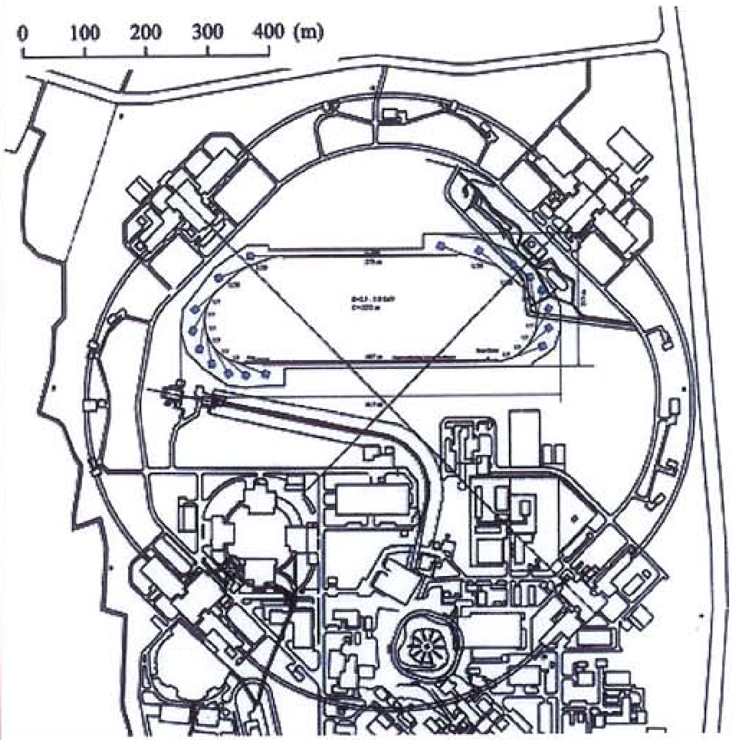
[1] G. Decker, "APS Upgrade External ERL Option," 9/27/06.
[2] M. Borland, "ERL Upgrade Options and Possible Performance," 9/18/06.
[3] M. Borland, "Can APS Compete with the Next Generation?", May 2002.
[4] M. Borland, OAG-TN-2006-031, 8/16/06.

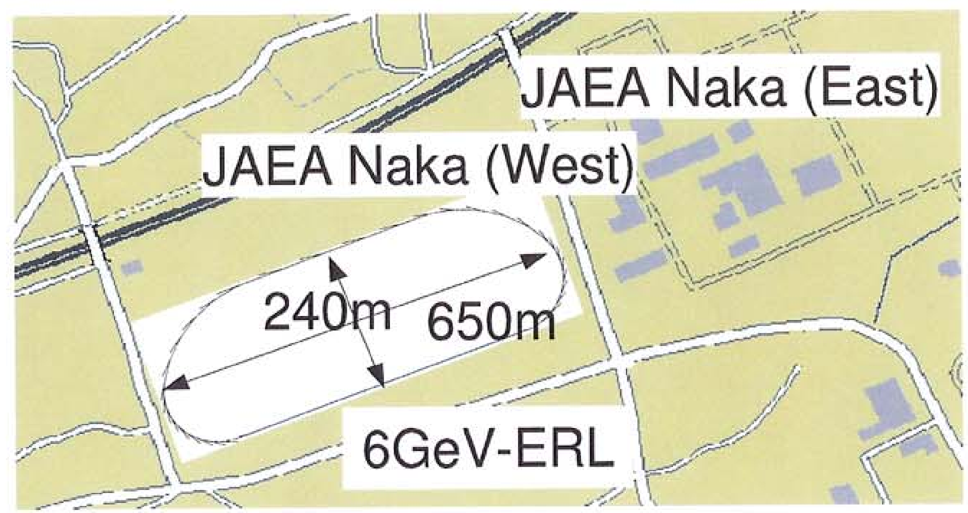
ERL Colleagues: KEK

Two Japanese institutes, KEK and JAEA, proposed each own ERL-based synchrotron light source.

KEK 5GeV ERL at Tsukuba site

JAEA 6GeV ERL at Naka site





Conclusion

- At present, the projects of the 4th generation SR sources on the basis of accelerators-recuperators are considered at Budker INP, Daresbury Laboratory, Jefferson Laboratory, Cornell University, LBL, KEK, Erlangen University, Brookhaven National Laboratory.

- 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 the project and its maintenance.

- Therefore, orientation toward the multi-turn accelerators-recuperators (MARS), which enable a substantial reduction in the power consumption and the cost of accelerating systems compared to those of single-turn ERL (for our example, 14 MW instead of 38.5 MW and 204 M$ instead of 366 M$) seems to be rather pragmatic.

Acknowledgement

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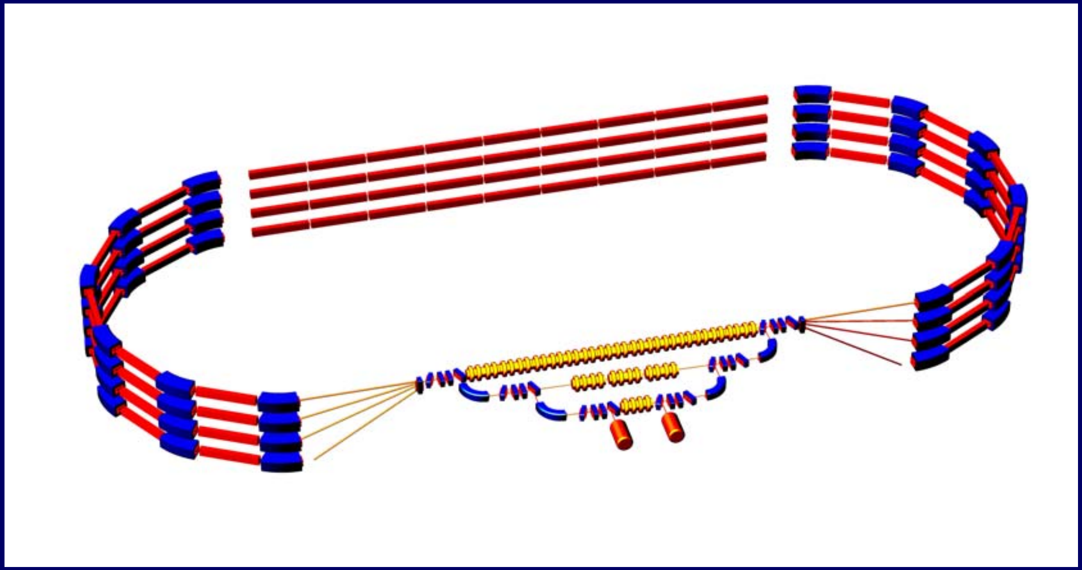

Thank you for your attention