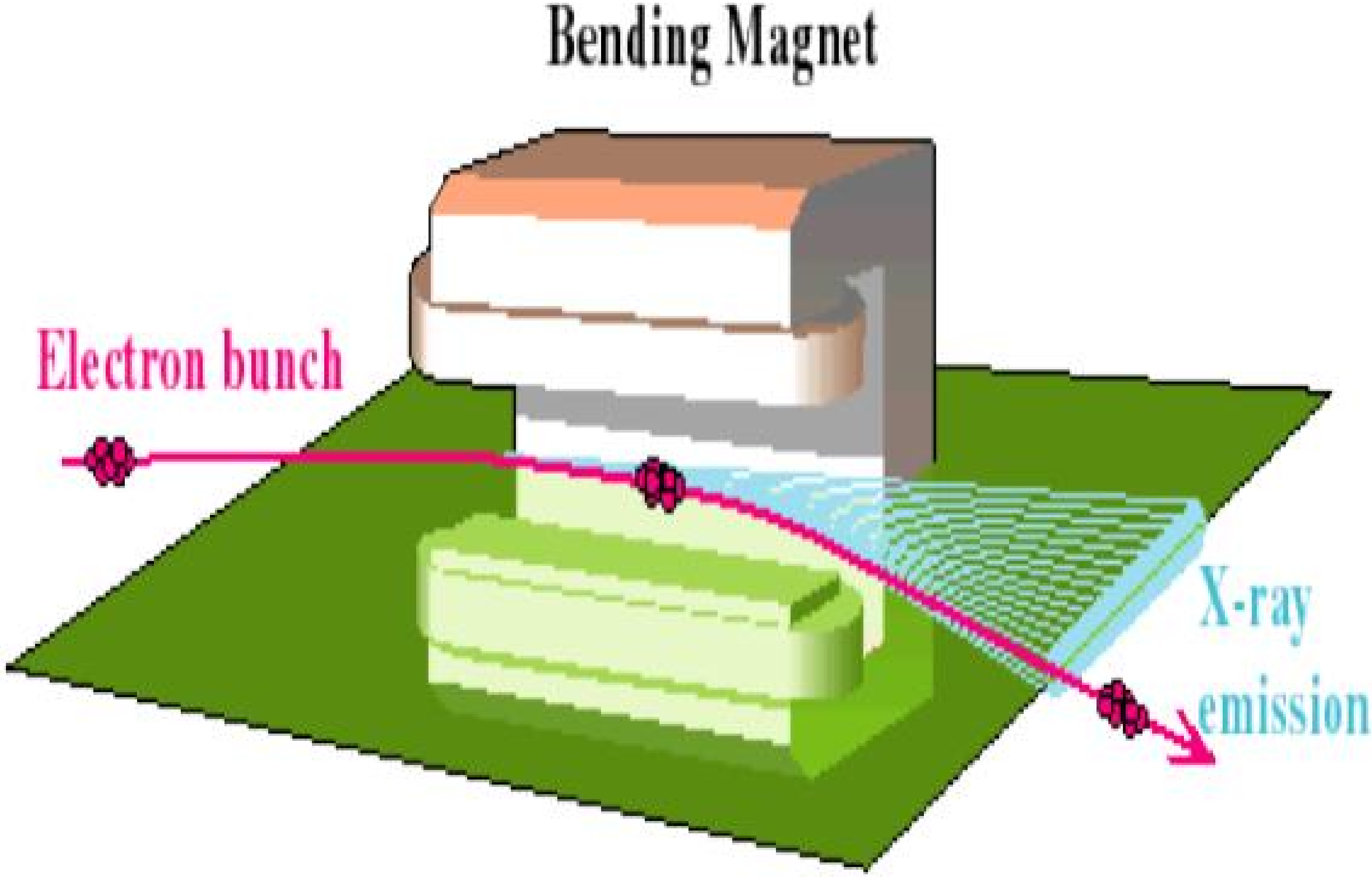
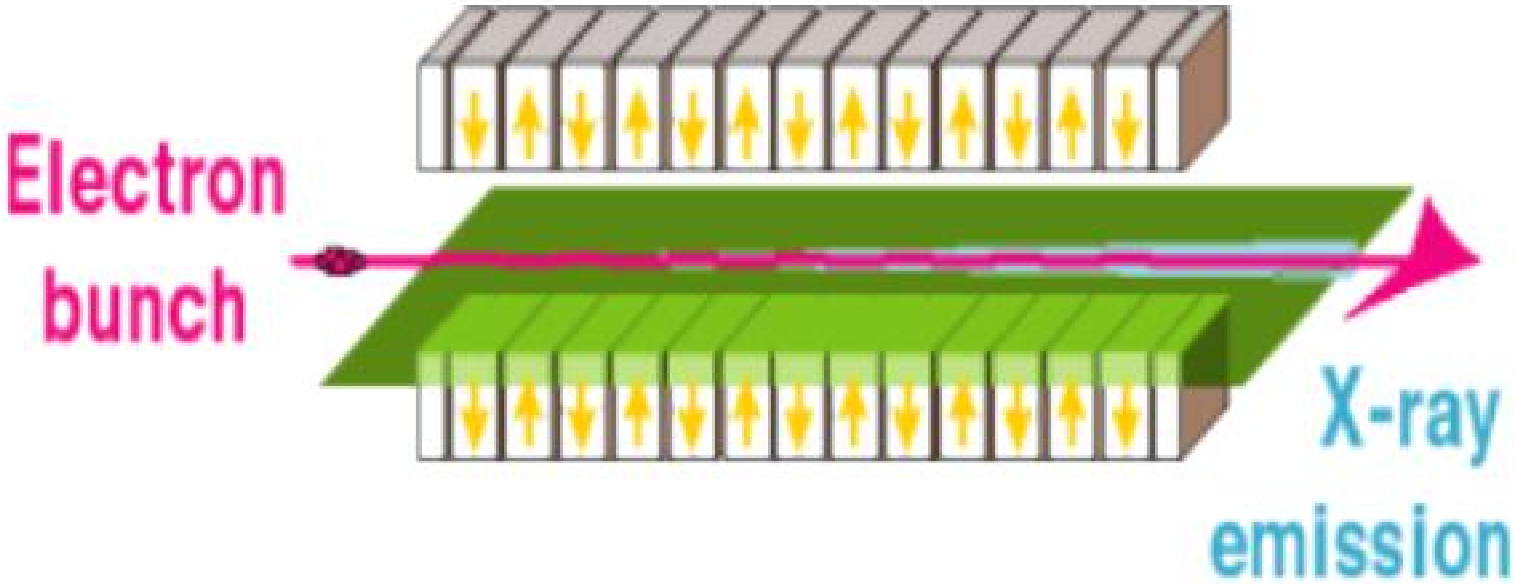
Electromagnetic radiation sources based on relativistic electron and ion beams

E.G.Bessonov



Bending Magnet
Electron bunch
X-ray
emission

Undulator radiation



Radiation by moving charges

Lienard-Wiechert Fields for a Point Charge in arbitrary motion

$$\vec{E}(t) = \frac{e}{c}\left[\frac{\vec{n}\cdot(\vec{n}-\vec{\beta})\,\dot{\vec{\beta}}}{(1-\vec{n}\beta)^{3}R}\right]_{t'},$$

$$\vec{B}(t) = \vec{n}(t)\times\vec{E}(t), \qquad t' = t - R(t')/c.$$

The radiation is emitted in the forward direction, tangentially to the orbit and confined within a narrow cone, having an opening angle given by

$$\psi \approx \frac{1}{\gamma}, \qquad \gamma = \frac{\varepsilon}{mc^{2}}.$$

Properties of radiation emitted in external fields are determined by a Fourier transform

$$\vec{E}_{\omega} = \frac{1}{2\pi}\int \vec{E}(t)\exp(i\omega t)dt, \qquad \vec{E}(t) = \int \vec{E}_{\omega}\, d\omega \;,$$

$$E_{\omega,j} = |E_{\omega j}|\exp[i\varphi_j(\omega)],$$

In particular, the energy radiated per unit solid angle per unit solid angle

$$\frac{\partial^2 \varepsilon}{\partial\omega\partial O} = cR_0^2\,|\vec{E}_{\omega}|^2,$$

Useful substitution

$$\frac{[\vec{n}[(\vec{n}-\vec{\beta})\dot{\vec{\beta}}]]}{(1-\vec{n}\vec{\beta})^2}=\frac{d}{dt'}\frac{[\vec{n}[\vec{n}\vec{\beta}]]}{(1-\vec{n}\vec{\beta})},$$

permits to simplify calculations of the Fourier transform and to present them in the form:

$$\vec{E}_{\omega}=\frac{e}{2\pi cR_0}[\vec{n}[\vec{n}\vec{B}_{\omega}]],\qquad \vec{B}_{\omega}=\vec{B}'_{\omega}+\vec{B}''_{\omega},$$

$$\vec{B}'_{\omega}=\frac{\vec{\beta}_f}{1-\vec{n}\vec{\beta}_f}exp[i(\omega t'_f-\vec{k}\vec{r}_f)]-\frac{\vec{\beta}_i}{1-\vec{n}\vec{\beta}_i}exp[i(\omega t'_i-\vec{k}\vec{r}_i)],$$

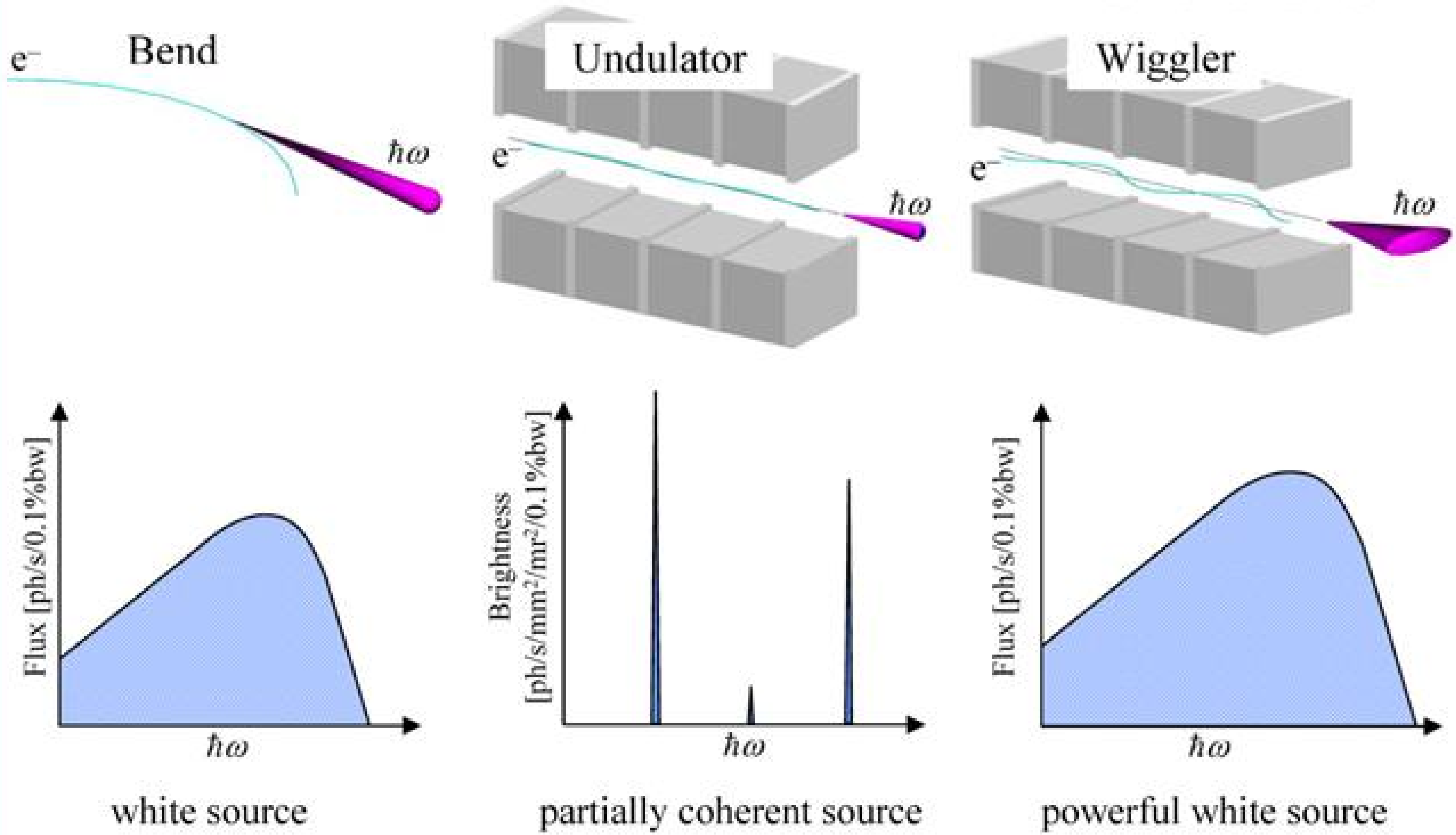
$$\vec{B}''_{\omega}=-\omega\int_{t'_i}^{t'_f}\vec{\beta}(t')exp[i(\omega t'-\vec{k}\vec{r})])]dt'.$$

Generations of Synchrotron radiation sources

- First generation SR sources were parasitic upon HEP colliders.
- Second generation SR sources are dedicated for high-flux production of X-rays using many magnetic dipols and a few wiggler/undulator sources.
- Third generation SR sources are additionally optimized for brilliance by reducing the machine emittance and incorporating many more ID's.
- Forth generation SR sources will be FEL's, which would deliver ultra-bright, ultra-short X-ray punses.
- ---------------------------------------
- Flux referes to the number of photons/s/0.1percentBW
- Brightness referes to: photons/s/unit solid angle/0.1percentBW
- Brilliance referes to: photons/s/unit solid angle/0.1percentBW/unit area

Flux, brightness and brilliance of a photon source refer to main characteristics of the photon beams produced by the source.

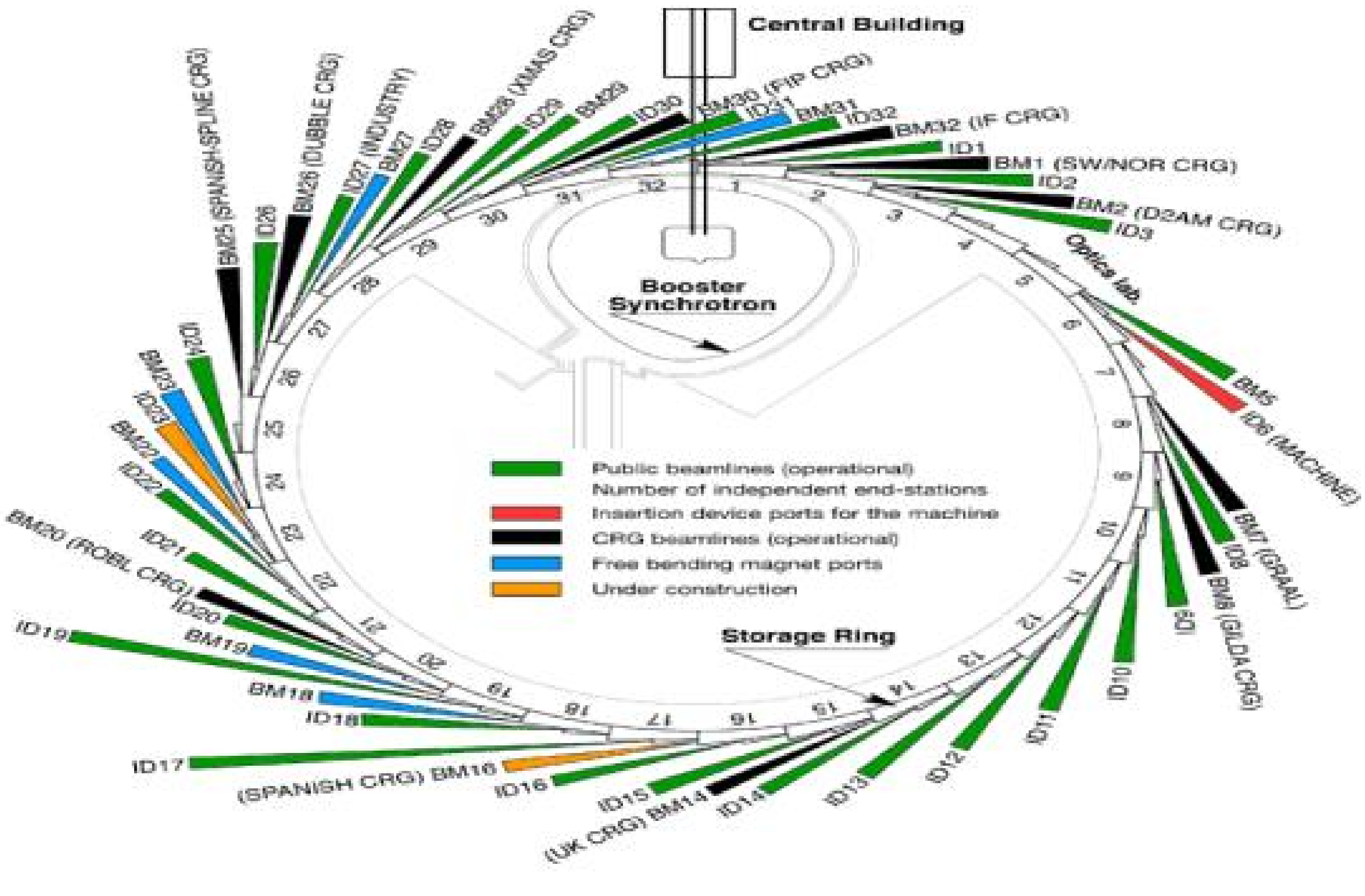
- The higher the generation of the *SR* sourses, the higher the brilliance. This is not an absolute criterion and, in fact, obscures essential distinctions between particular machines which determine if the machine is suited for a given application. A full characterization of a *SR* source involves specification of the flux, brightness, brilliance, polarization, spectrum, coherence (both temporal and space), and time structure of the emitted radiation.
- FEL's and *S*torage rings (*SR*, UR, backward Compton/Rayleigh scattering sources et al.) will each be best suited for different uses. FEL's will not replace *S*torage Ring-like sources. FEL's will open new science areas. The development of FEL's does not lessen the need to improve ring-source technology.



Bend
e⁻
ħω
Undulator
e⁻
ħω
Wiggler
e⁻
ħω
Flux [ph/s/0.1%bw]
ħω
white source
Brightness [ph/s/mm²/mr²/0.1%bw]
ħω
partially coherent source
Flux [ph/s/0.1%bw]
ħω
powerful white source

The **6 GeV ESRF** is an outstanding example of European cooperation in science. **18** nations work together to use the extremely bright beams of light produced by the ESRF's high-performance storage ring to study a remarkably wide range of materials.

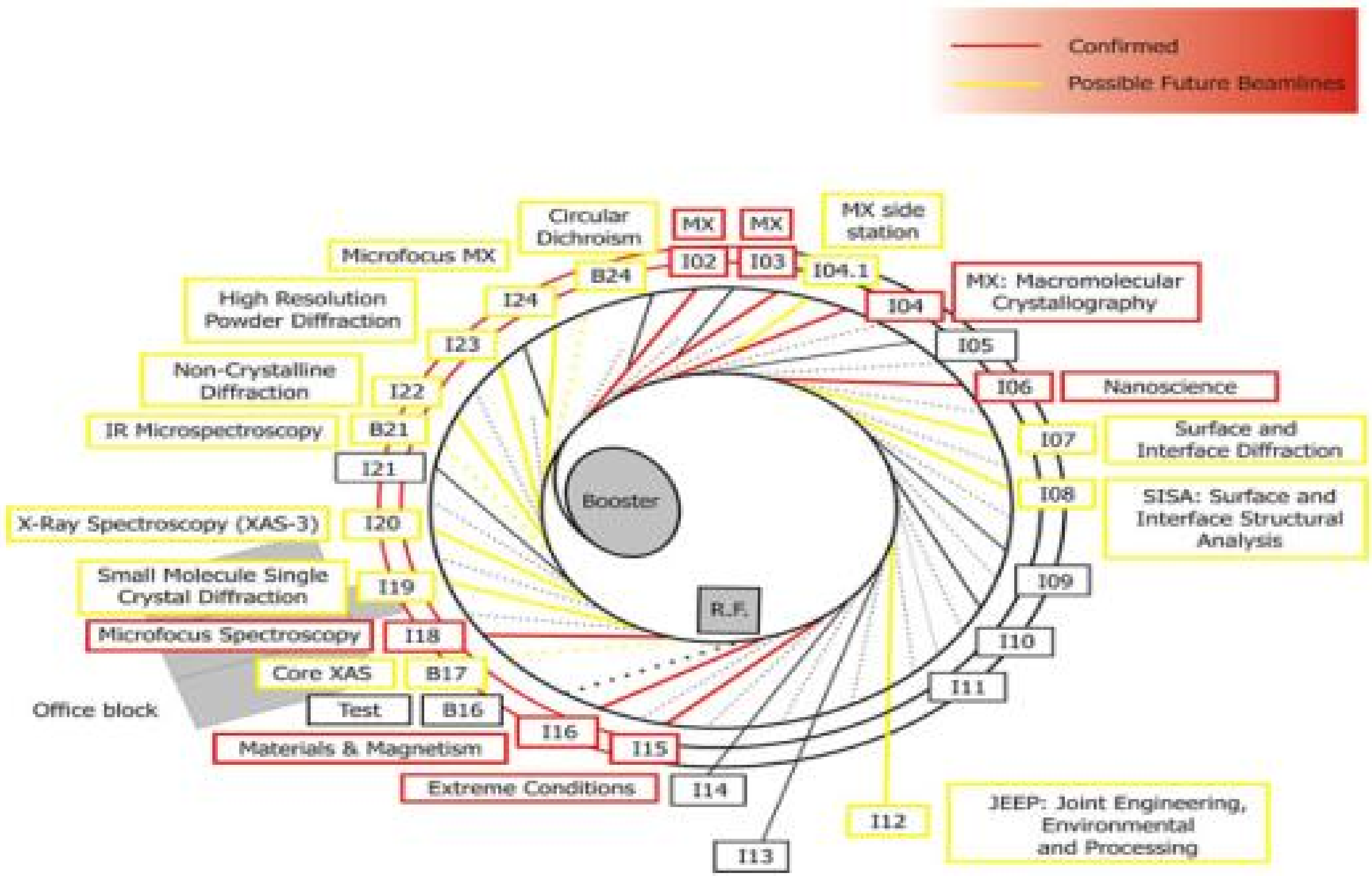
Plan of the Experimental Hall and Links to All Beamlines



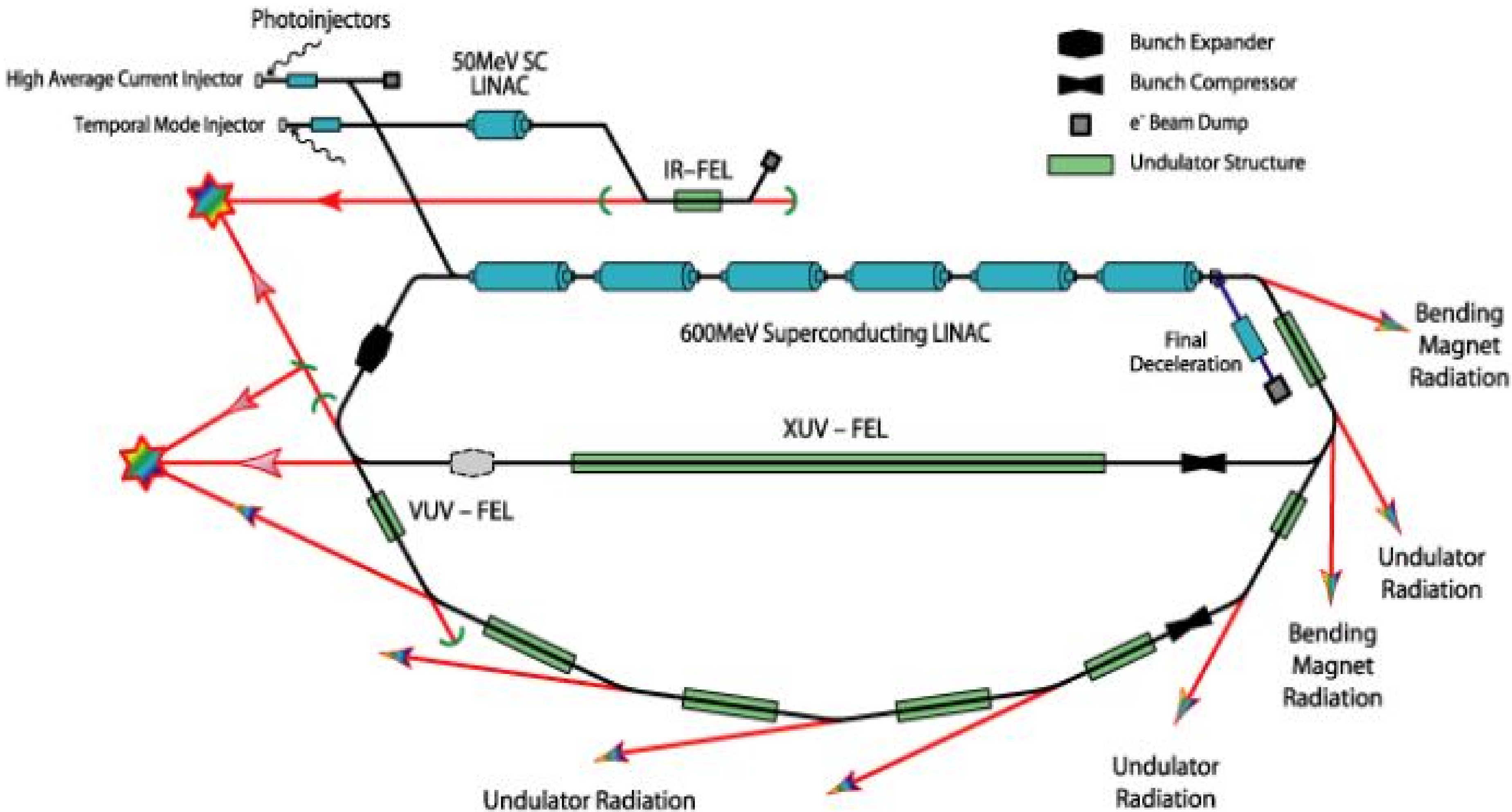
3.0 GeV *Electron Storage ring* **Diamond**

Harwell/Chilton Science Campus, UK.

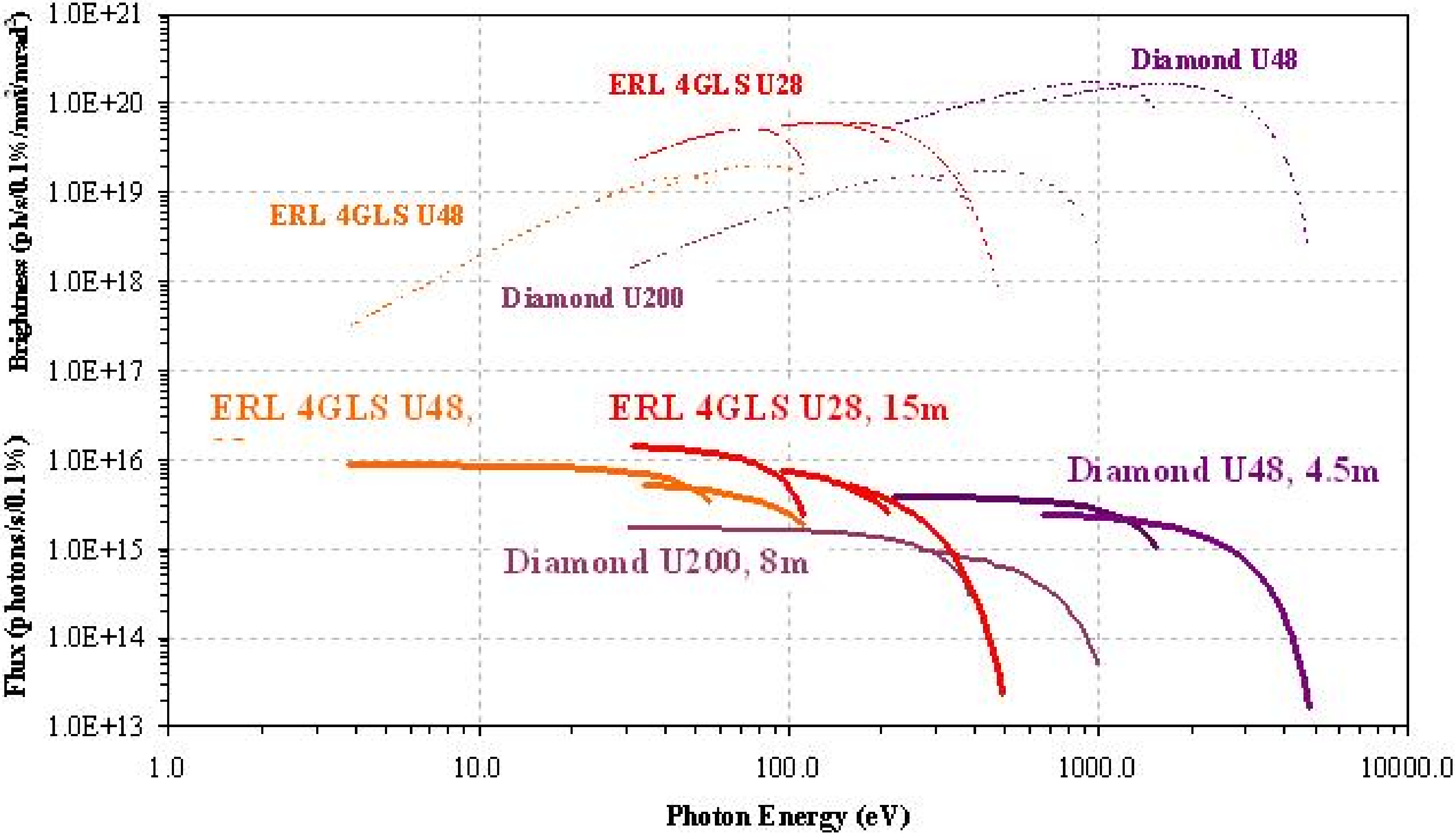
Circumference 561.6 m; *No. of cells* 24 (6 fold symmetry)
Electron beam current 300 mA; *Minimum beam lifetime* 10 hours;
Emittance – horizontal 2.7 nm-rad; *Emittance - vertical* 0.03 nm-rad;
No. of Insertion Devices (IDs) Up to 22; *Free straight lengths for IDs:* 18x5 m, 6x8; *gap* 10 mm; *Building diameter* 235 m



4-th Generation Light Source, Daresbury, UK.

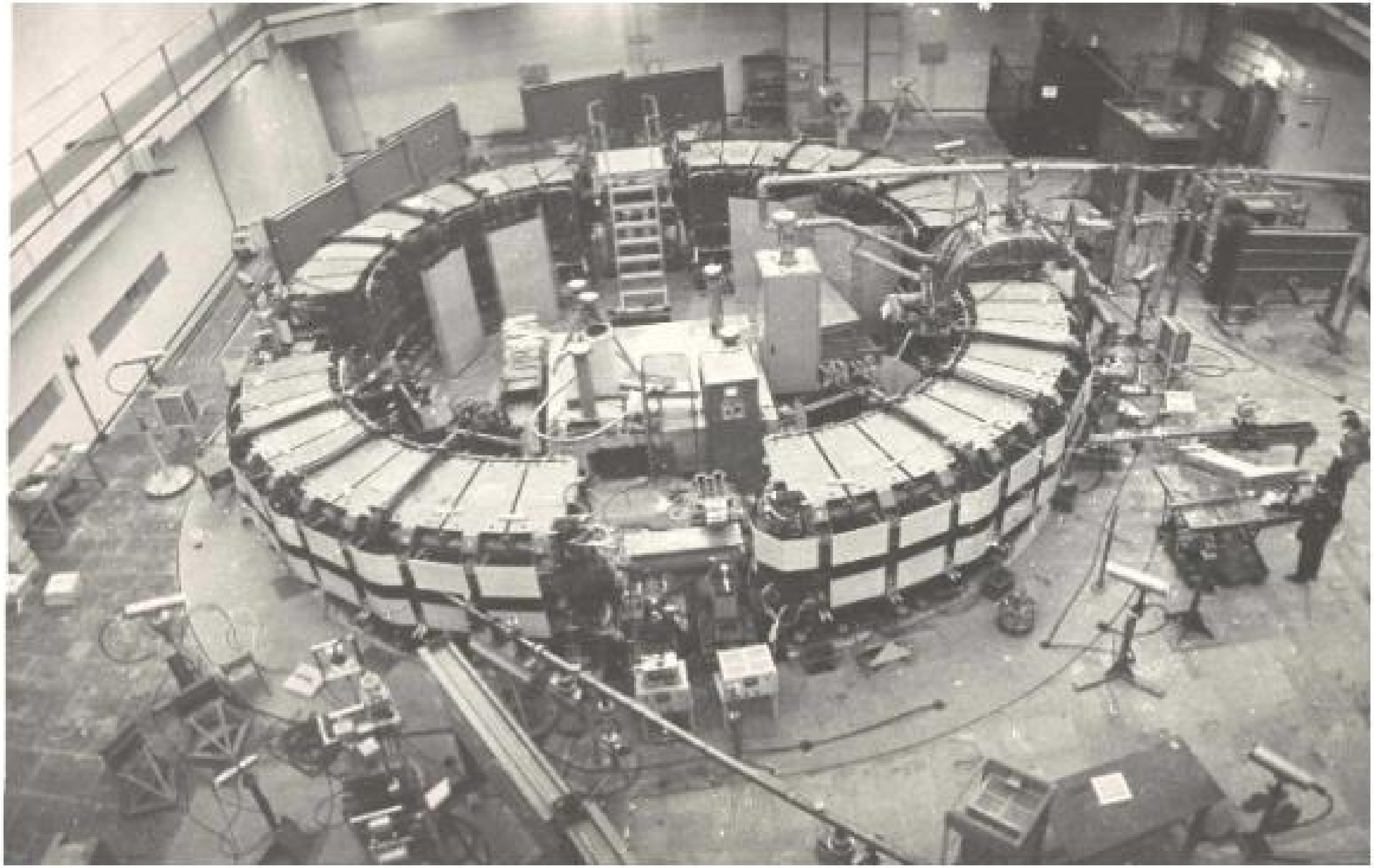


ERL & DIAMOND (UK)

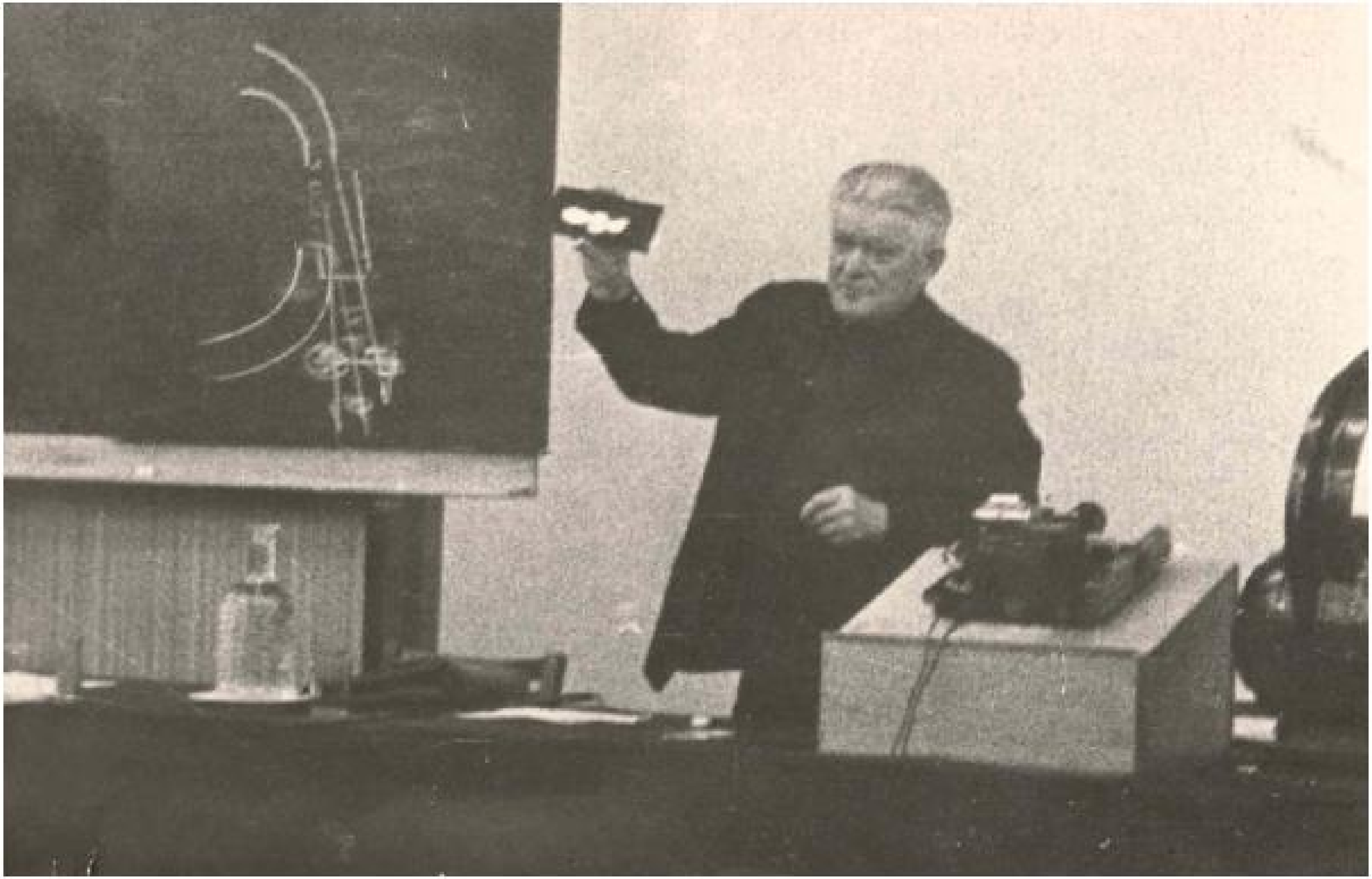


An international team using the superconducting linac at the TESLA Test Facility (TTF) at DESY, Hamburg, has set a new record for the shortest wavelength of radiation ever achieved with a Free Electron Laser (FEL) - Photo DESY.

Synchrotron Pakhra (1973-2004)



P.A.Cherenkov show picture of UR Pakhra, 1977



Scheme of the Pakhra prebunched FEL (1987)

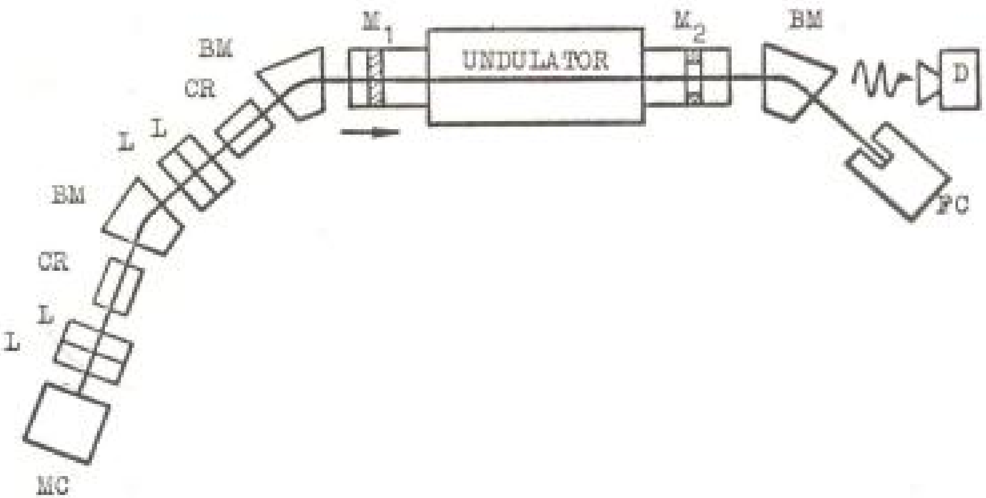
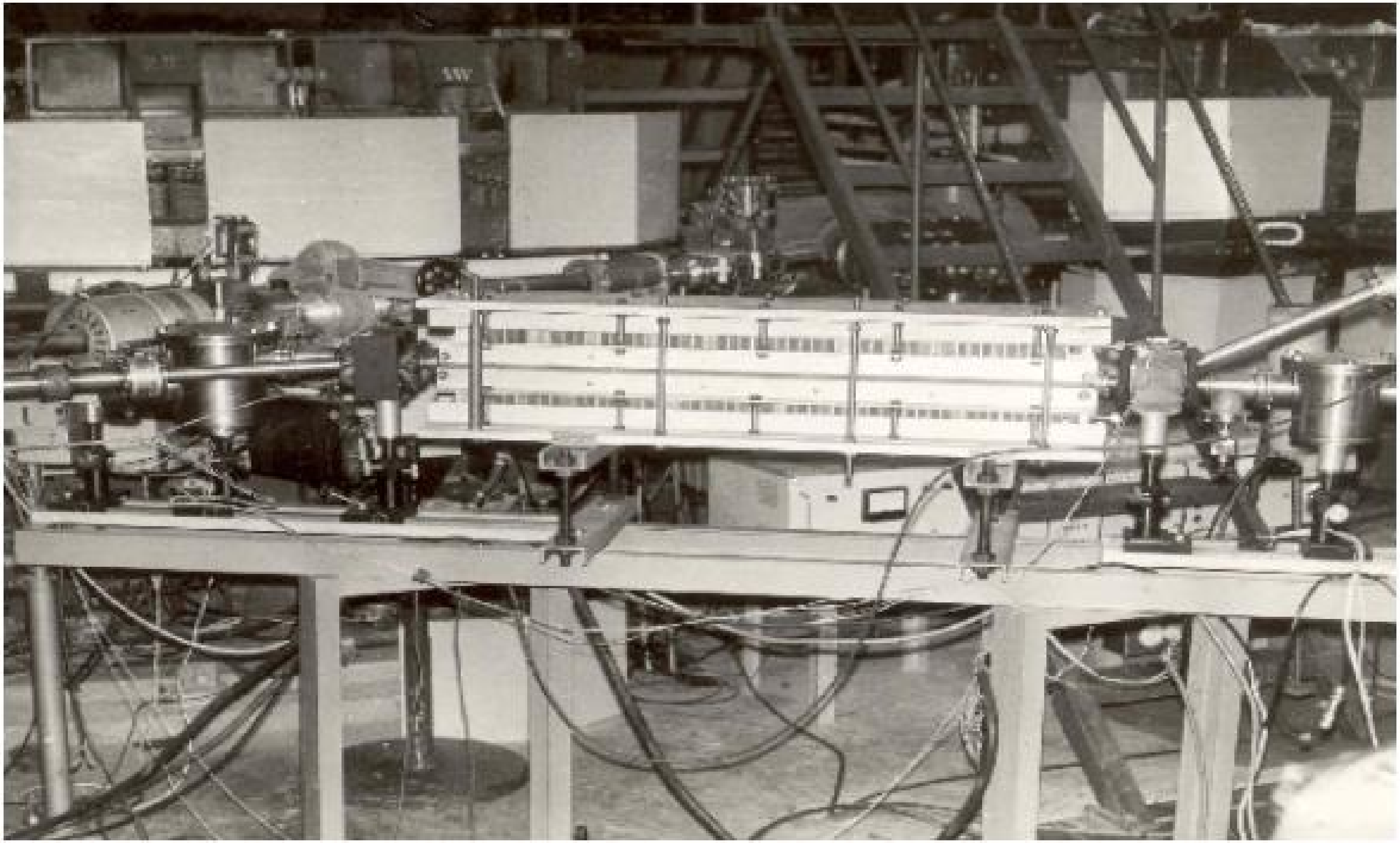


Fig. 1. Schematic of the FEL. MC: microtron, L: quadrupoles, CR: correcting coils, BM: bending magnets, M_1, M_2: mirrors, FC: Faraday cup, D: detector.

Prebunched FEL (Pakhra, 1987)



Dependence of intensity of prebunched FEL on a distance between mirrors (Microtron based FEL, Pakhra, 1987)

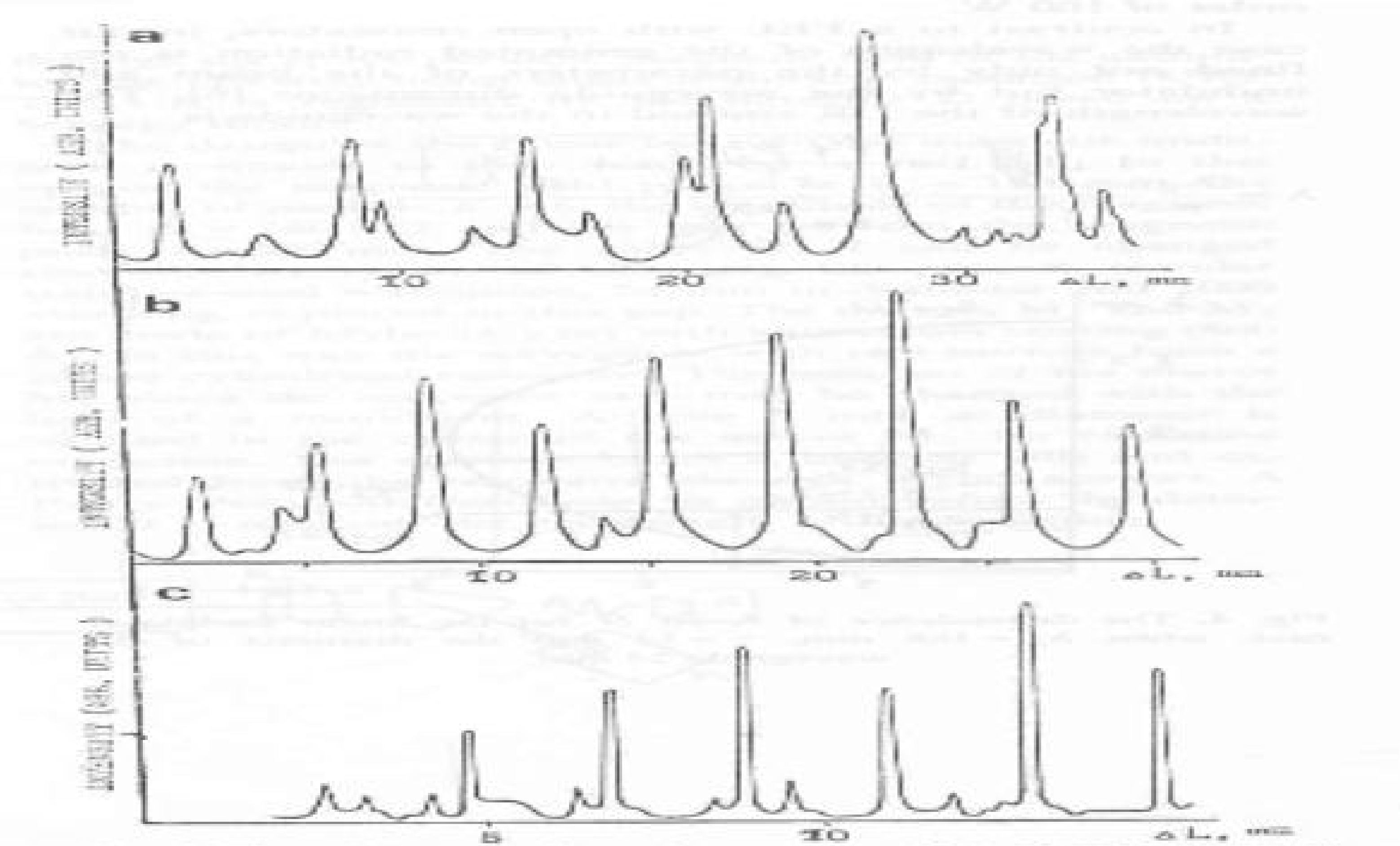
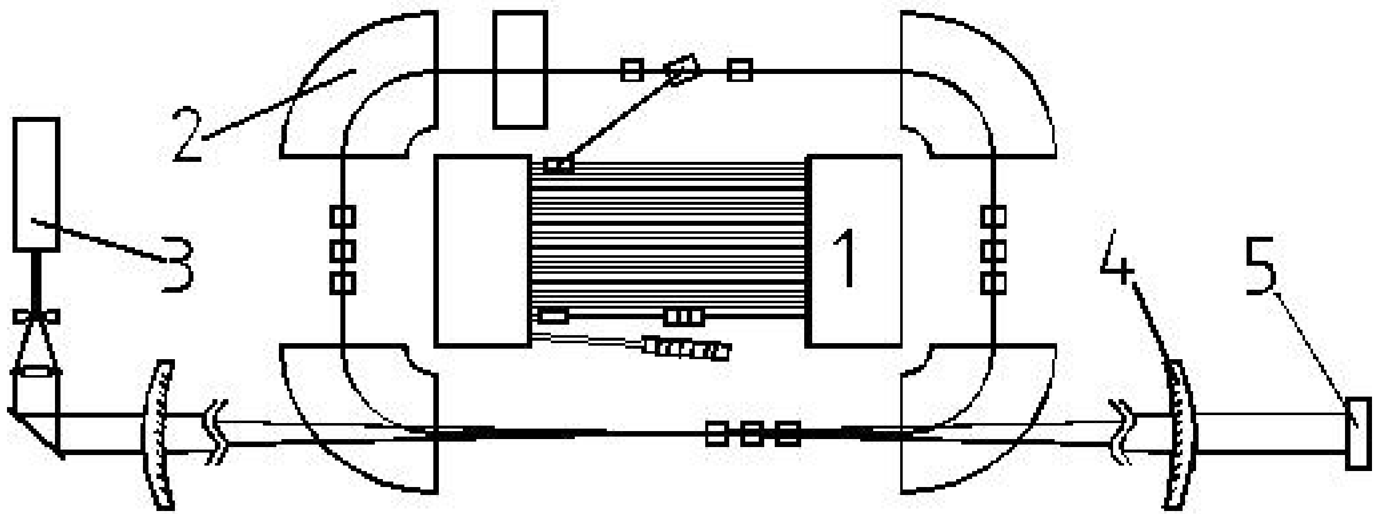


Fig. 3. The microwave intensity as a function of optical cavity length for (a, b) $H = 2600$ G and (c) $H - 1500$ G.

The scheme of laser-electron X-ray generator: 1 - injector, 2 – storage ring, 3 - laser, 4 – optical cavity, 5 – a damp for laser beam

Lebedev Physical Institute, Moscow state University (project)



Conclusion

- FEL's and Storage rings (SR, UR, backward Compton/Rayleigh scattering sources et al.) will each be best suited for different uses. FEL's will not replace Storage Ring-like sources. FEL's will open new science areas. The development of FEL's does not lessen the need to improve ring-source technology.