DIAGNOSTICS OF ULTRASHORT ELECTRON BUNCHES DEVELOPED AT JINR

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FLASH diagnostics:

MCP-based photon detectors

Bunch length diagnostic on basis of FAR infrared undulator

Proposed XFEL diagnostics

MCP-based detectors for SASE XFEL

Optical Replica synthesizer

Laser heater

Hybrid Pixel Array Detector.

ILC diagnostics:

Magnetic spectrometer for electron energy measurements

Synchrotron radiation detector for electron energy measurements

PARAMETERS OF ULTRASHORT ELECTRON BUNCHES

Parameters	FLASH	XFEL	ILC
Electron energy, GeV	1	17.5	250
Bunch charge, nC	1	1	3.2
Normalized emittance, π·mm·mrad	2	1.4	10/0.04
Bunch length, μm	50	25	300
Bunch repetition rate, MHz	2	5	2.7

MCP based photon detector

FLASH operation strongly depends on the quality of the radiation detector:

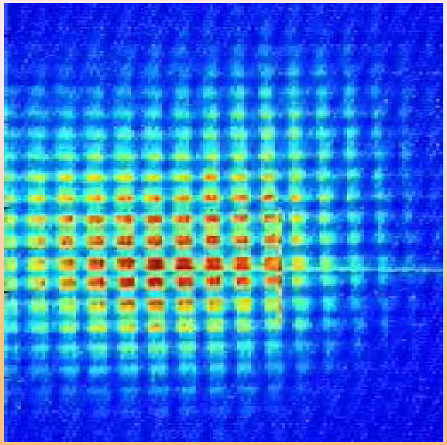
wide wavelength range (from 6 to 100 nm),
wide dynamic range (from the spontaneous emission level to the saturation level)

high relative accuracy of measurements which is crucial for detection of radiation amplification and characterization of statistical properties of the radiation.

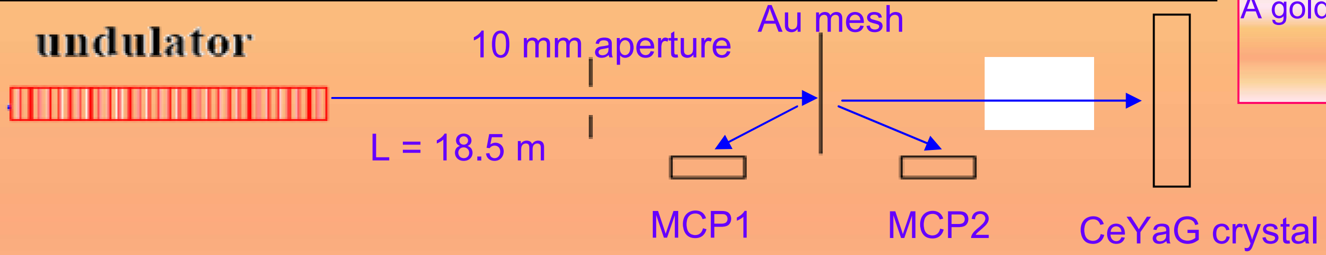
Key element of the detector is wide dynamic range MCP which detects scattered radiation from a target.

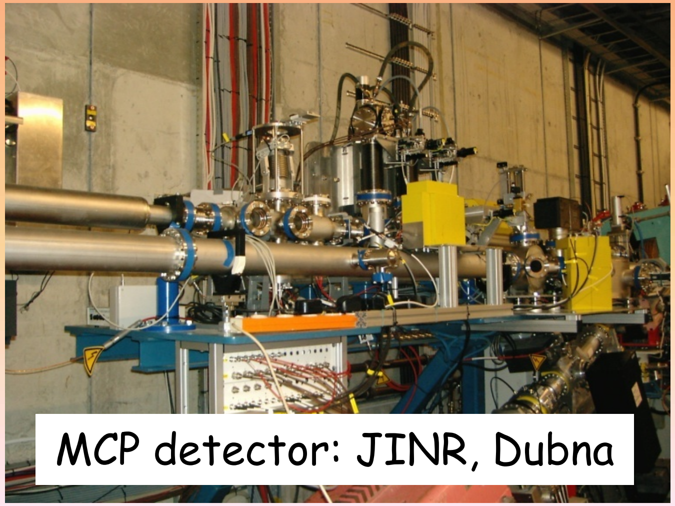
Parameters of FEL radiation, FLASH MCP detector in 2004-2007

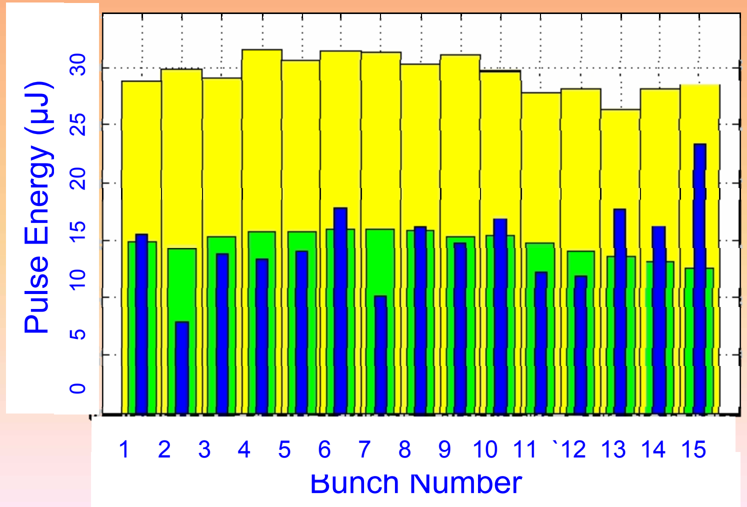
Wavelength	13-100 nm
Average energy per pulse	up to 50 μJ
Maximum energy per pulse	up to 130 μJ
Radiation pulse duration	25-30 fs
Peak power (from average)	up to 1 GW
Spectral width (FWHM)	0.8%
Angular divergence (FWHM)	160 μrad
Peak Brilliance	~ 10^{28} ph/s/mrad^2/mm^2/(0.1%bw)



A gold mesh of MCP detector (0.31 mm pitch) in front of the Ce:YAG screen is used as intensity monitor.

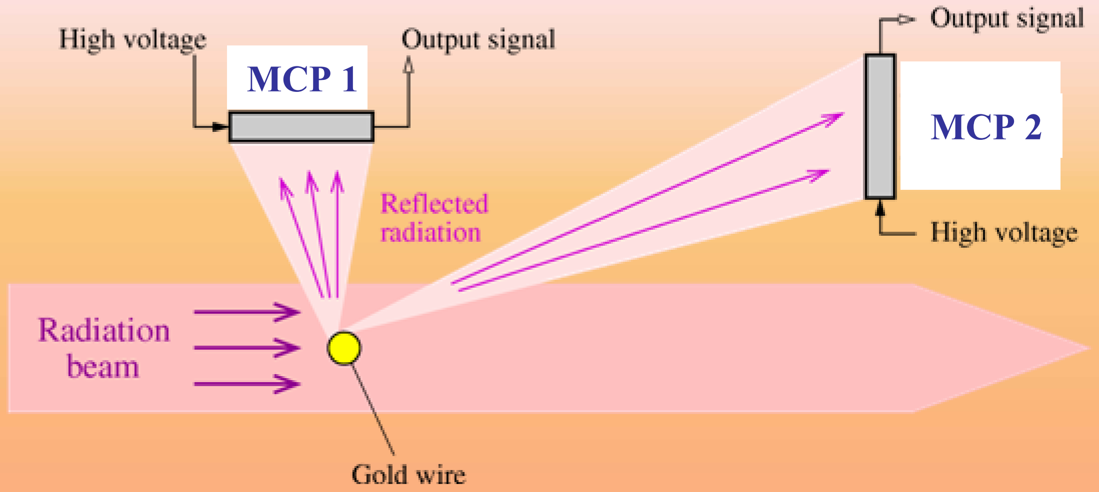


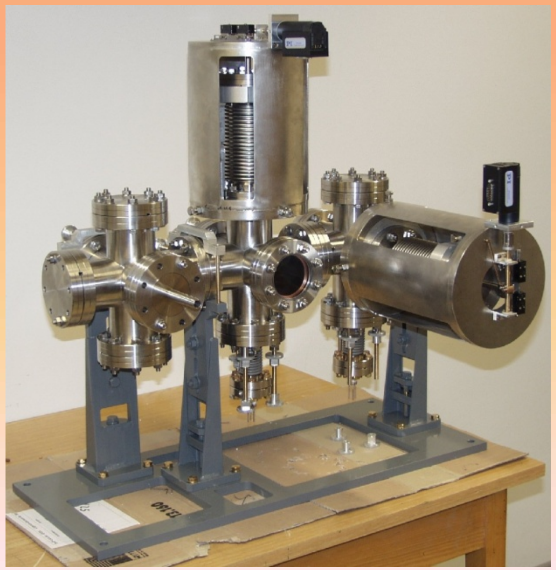


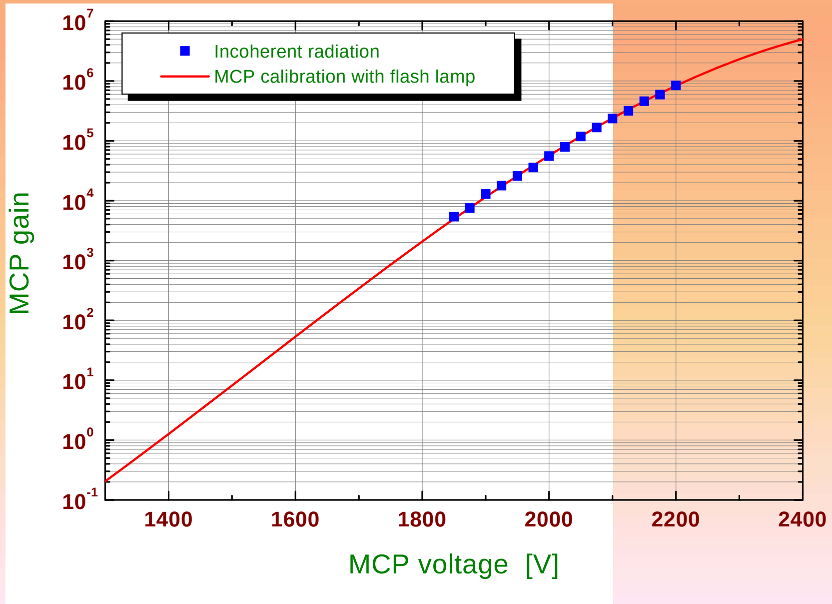


MCP detector

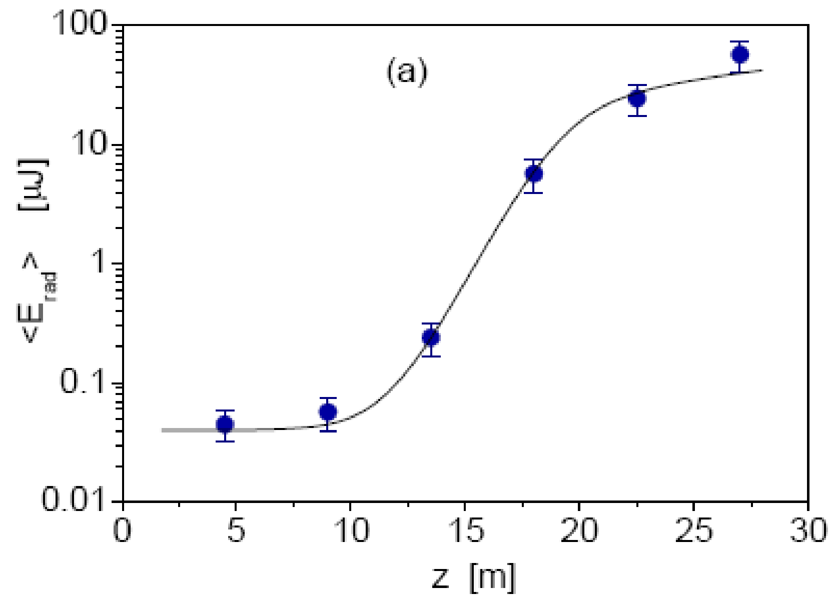
JINR provides construction and electronic developments

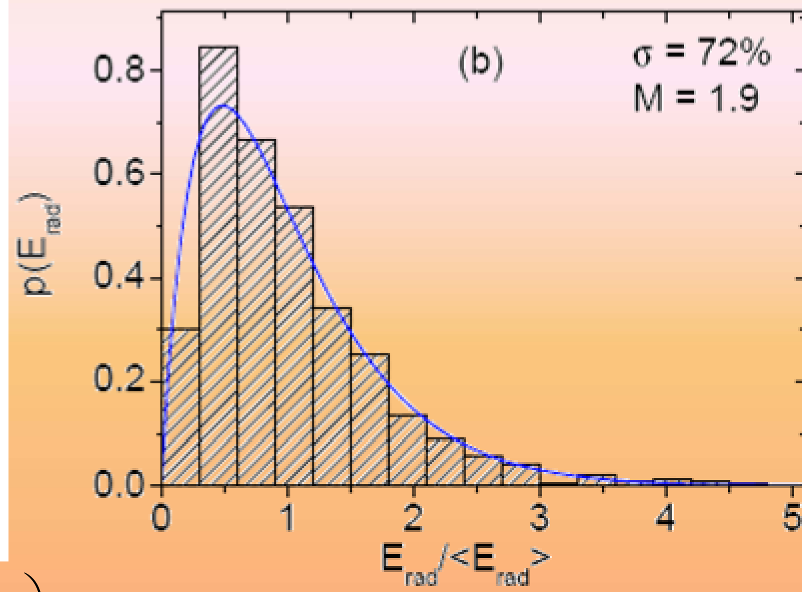






FLASH MCP MEASHUREMENTS



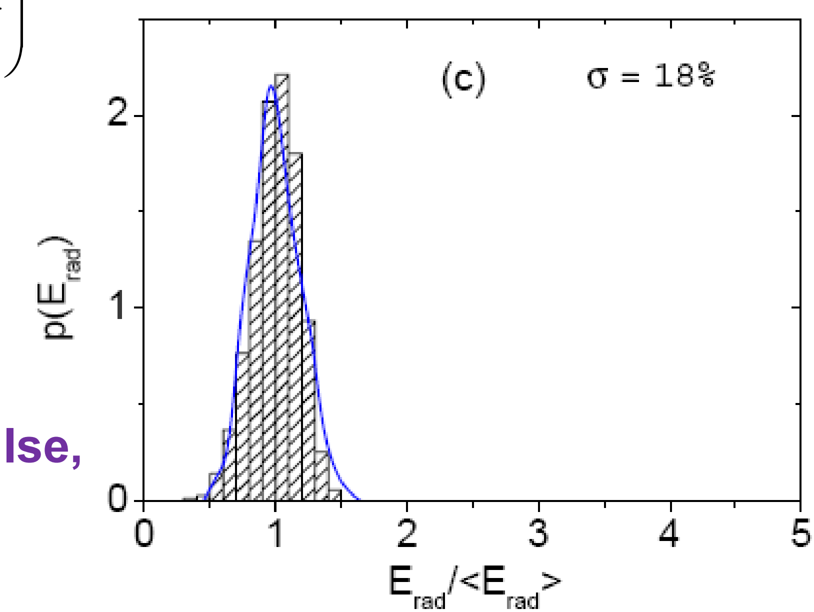


$$P(W) = \frac{M^M}{G(M)} \cdot \left(\frac{W}{\langle W \rangle} \right)^{M-1} \cdot \frac{1}{\langle W \rangle} \cdot \exp\left(-M \frac{W}{\langle W \rangle} \right)$$

$$\sigma_w = \left(\left\langle (W - \langle W \rangle)^2 \right\rangle \right)^{1/2}$$

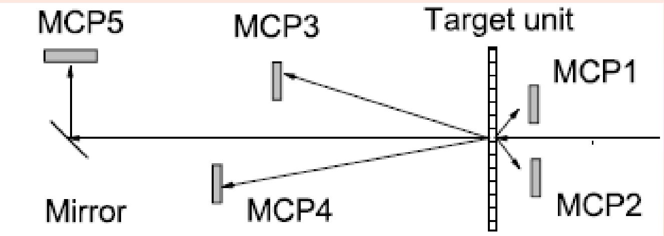
Energy in radiation pulse and integrated spectral density should fluctuate with the gamma distribution

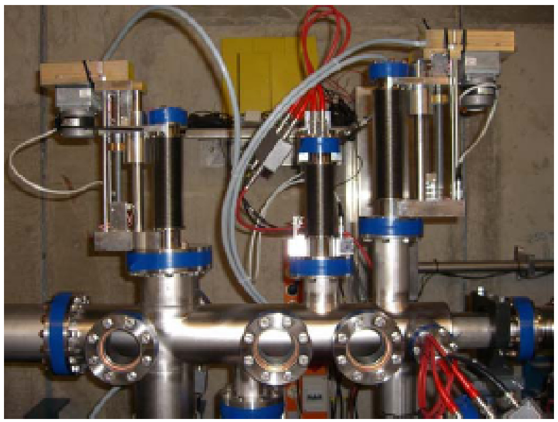
$M=1/\sigma_w^2$- number of modes in radiation pulse,
$M=\sigma_z/c\tau_c$, σ_z – bunch length,
τ_c-coherence time at saturation

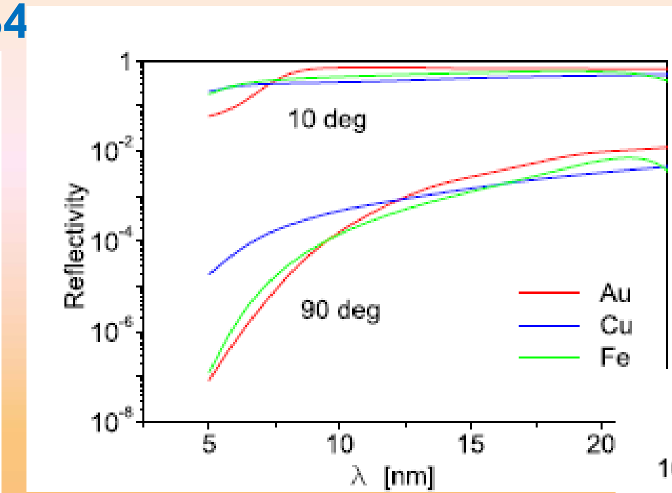


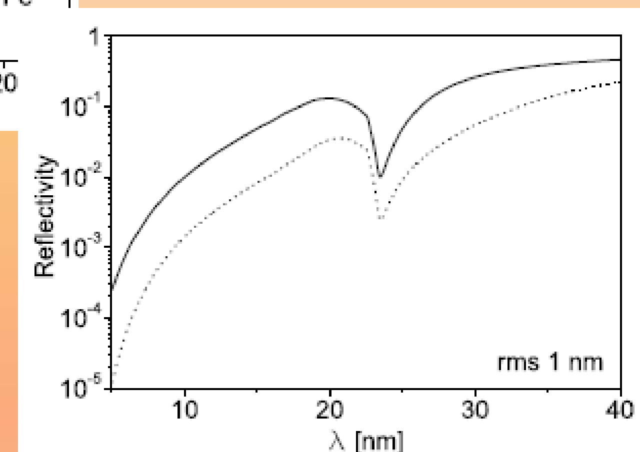
MCP detector with extended wavelength

M. Yurkov et al., FEL07, p.334









Layout of MCP detector (version MCP07) with extended wave length installed at FLASH in 2007.

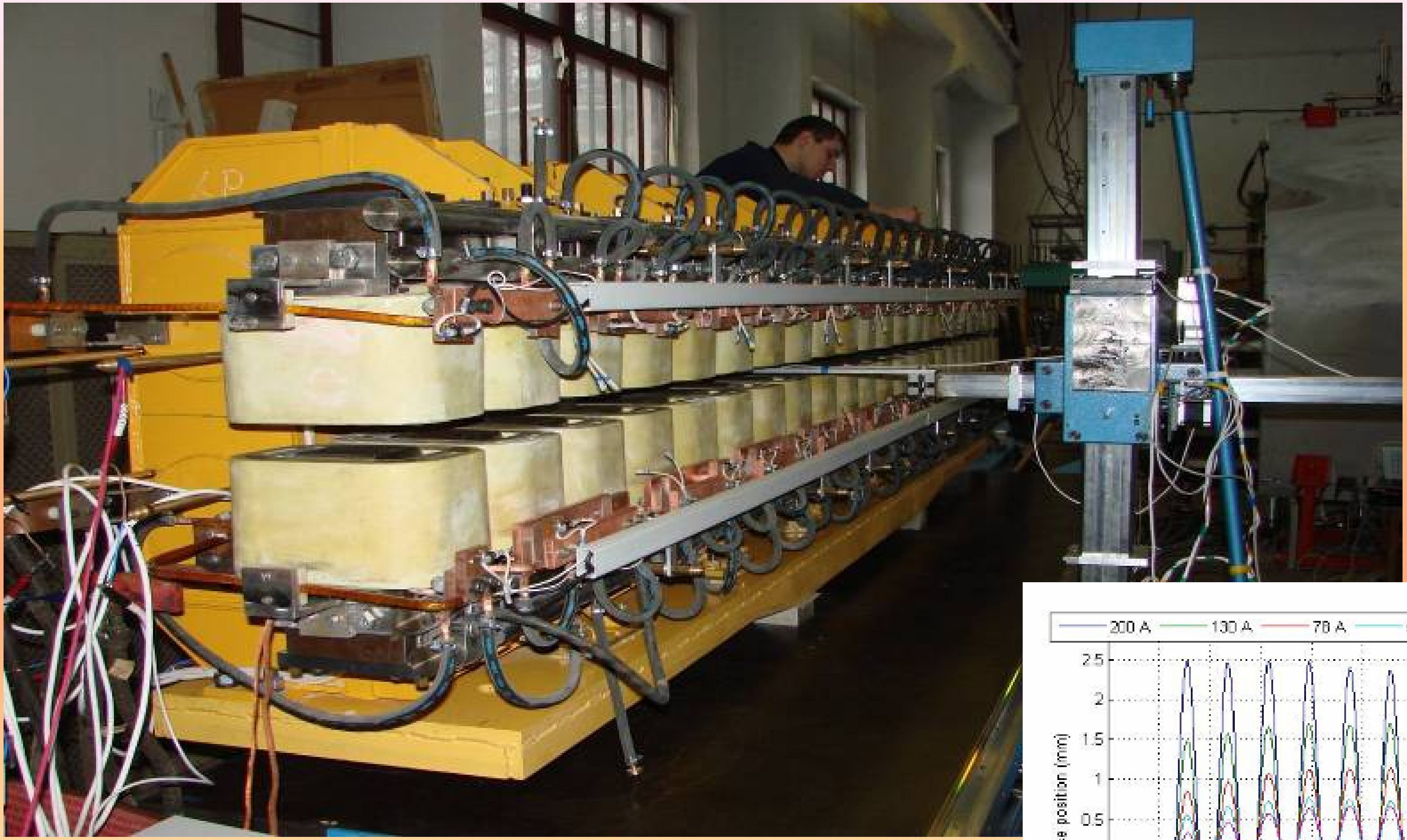
Present FLASH detector covers wavelength range from 6 to 100 nm, and dynamic range of the radiation intensities, from the level of spontaneous emission up to the saturation level of SASE FEL.

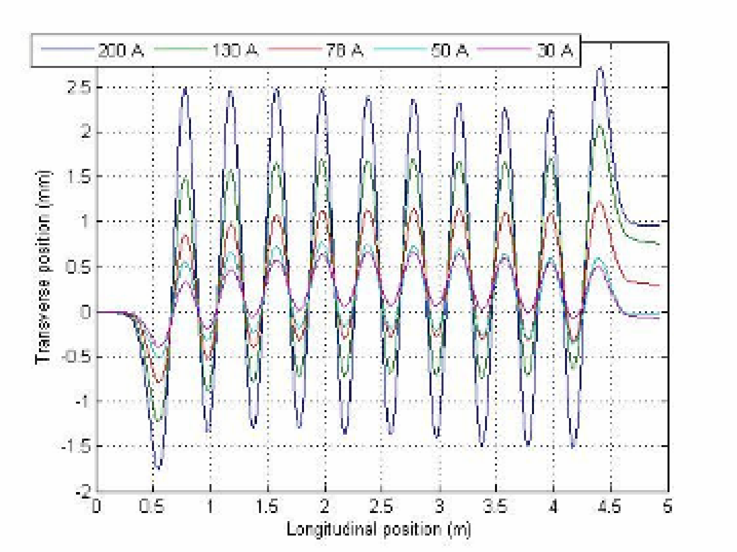
The gold target is perfect for use in the wavelength range above 10 nm, however its reflectivity falls dramatically for shorter wavelengths. Additionally to gold mesh, we added three more targets: two iron meshes (88% and 79% open area), and one copper mesh (60% open area).

Construction of FLASH FIR undulator in JINR

2006, JINR Workshop

Magnetic measurements of infrared undulator at DLNP test bench





January 2007, JINR

JINR infrared undulator applied for short bunch measurements and pump probe experiments in FLASH-DESY tunnel

June 2007, DESY

SHORT XFEL BUNCH MEASHUREMENTS

Parameters of FLASH FIR undulator constructed in JINR

Electron beam parameters

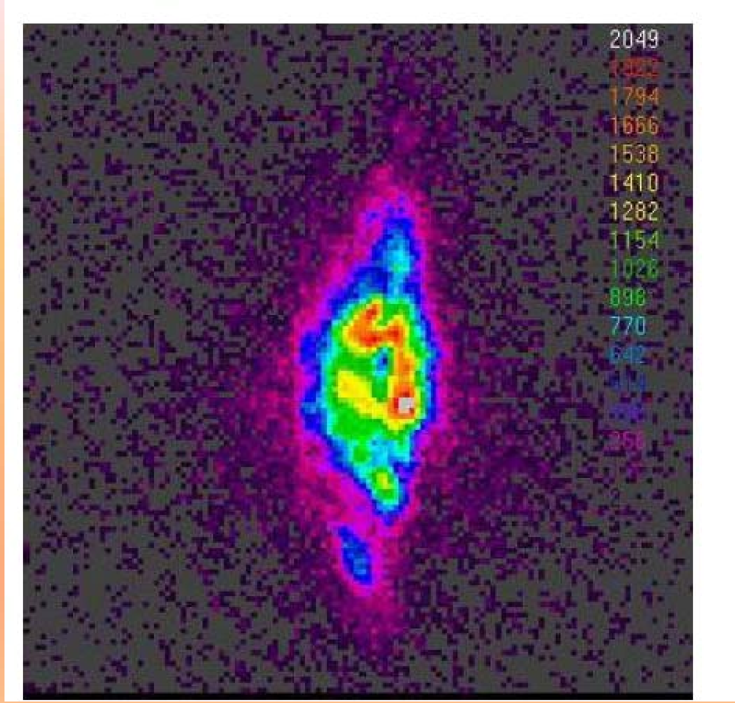
Electron energy, GeV	0.5-1
Bunch charge, nC	1
Rms bunch length, μm	50
Normalized emittance, π ·mm·mrad	2
Rms energy spread, MeV	2.5

Undulator

Period, cm	40
Number of periods	9
Magnetic field, T	0.1-1.1

Output radiation

Wavelength, μ m	5-200
Peak power, MW	100
Micropulse energy, mJ	1
Micropulse duration, ps	1-10



Coherent radiation of FLASH infrared undulator constructed at JINR measured by SPIRICON camera

Parameters of electromagnetic infrared undulator

$$K = 93{,}4 B_{z\,[T]} \cdot \lambda_{u\,[m]}$$

K=44,8 - undulator parameter

λ_u=40 cm - undulator period

B_z=1,2 T - magnetic field.

The wavelength of undulator radiation for first harmonic

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

λ=107 μm at electron energy of 700 MeV

λ=204 μm at electron energy of 500 MeV.

Energy radiated by electron bunch in infrared undulator

$$\varepsilon_{coh} = \pi e^2 A_{jj}^2 \omega K^2 / \left[c\left(1 + K^2/2\right)\right] \times \left[N + N(N-1)\left|\overline{F}(\omega)\right|^2\right]$$

$A_{jj}=J_0(q)-J_1(q)$, J_0, J_1-Bessel functions, $q=K^2/(4(1+K^2/2)$

Energy radiated by electron bunch

$$E \propto p(\omega)\cdot\left(N + N(N-1)|F(\omega)|^2\right)$$

p(ω)-energy spectrum radiated by single electron

F(**ω**)**- Fourier transform of the bunch profile function**

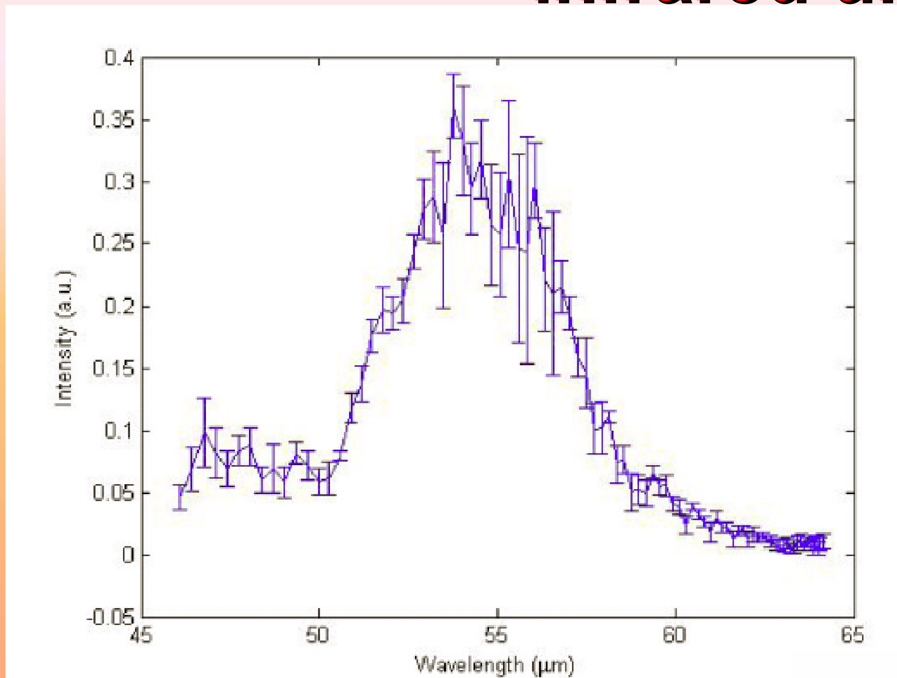
$$F(\omega) = 1 \qquad l_{bunch}/\lambda << 1;$$

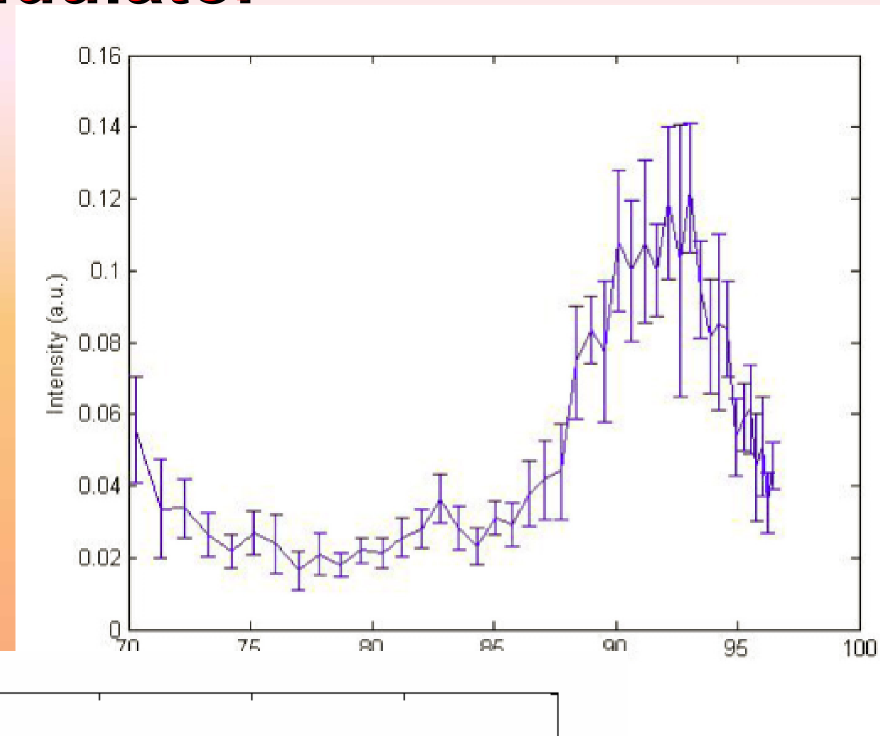
$$F(\omega) \approx 1 \qquad l_{bunch}/\lambda \approx 1;$$

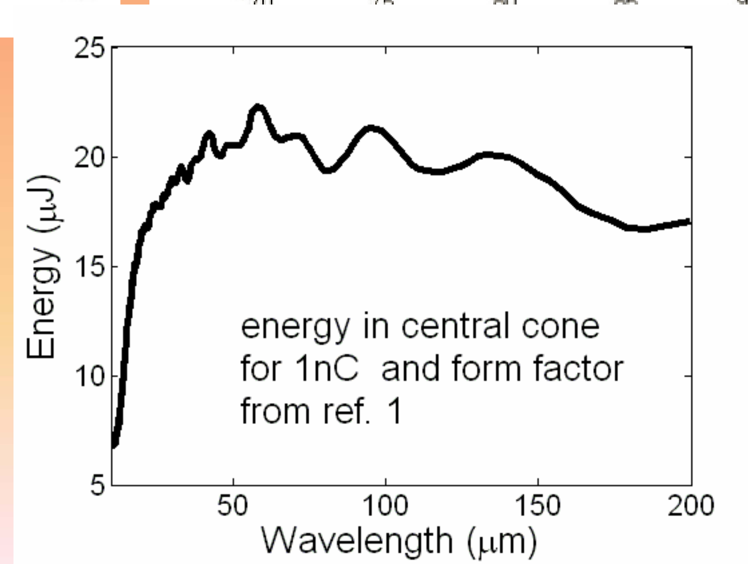
$$F(\omega) = 0 \qquad l_{bunch}/\lambda >> 1.$$

Measurement of energy radiated by bunch versus radiation frequency brings information about Fourier transform of the bunch profile function F(**ω**)**, which gives information about longitudinal bunch shape**

FLASH spectral measurements with JINR infrared undulator

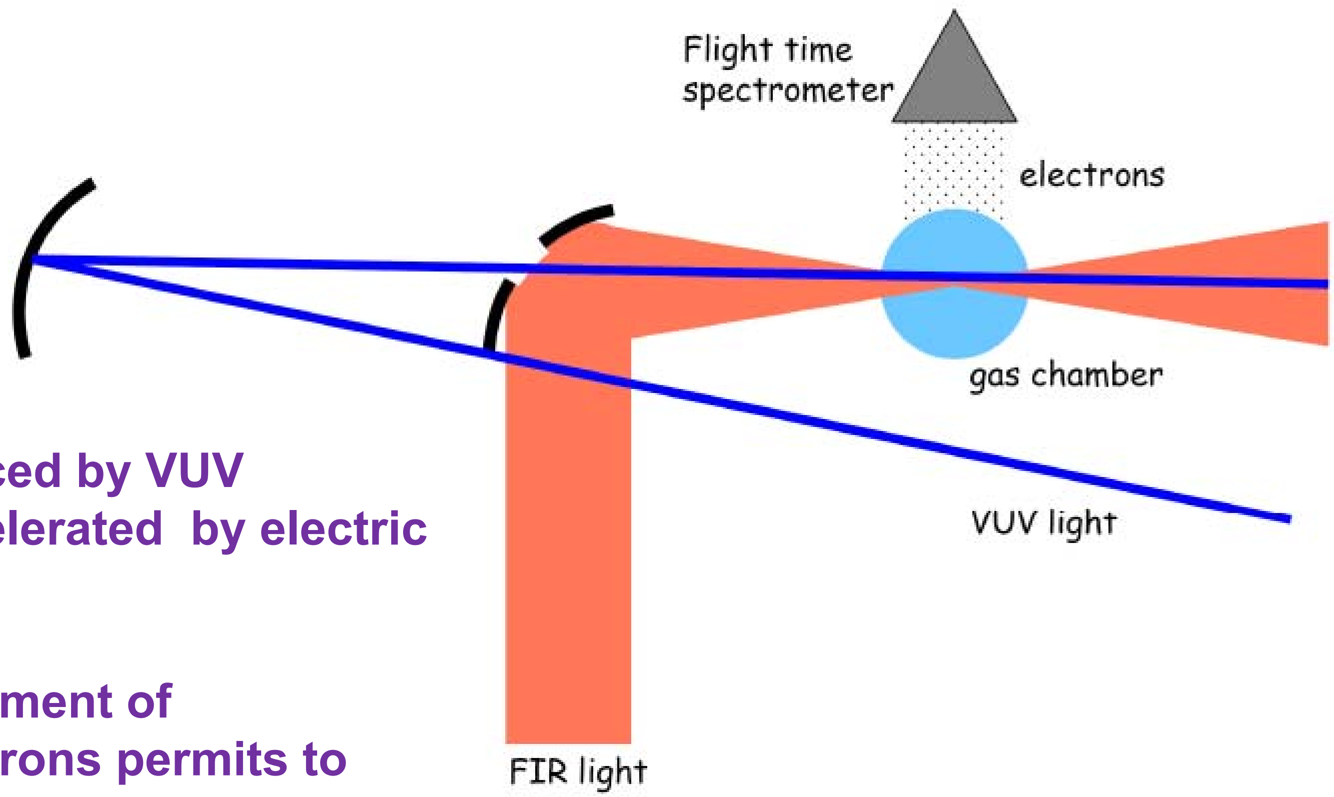






FLASH First Pump –Probe experiments with VUV and FIR undulators

Reconstruction of the FLASH VUV pulses



Electrons produced by VUV photons are accelerated by electric field of IR light.

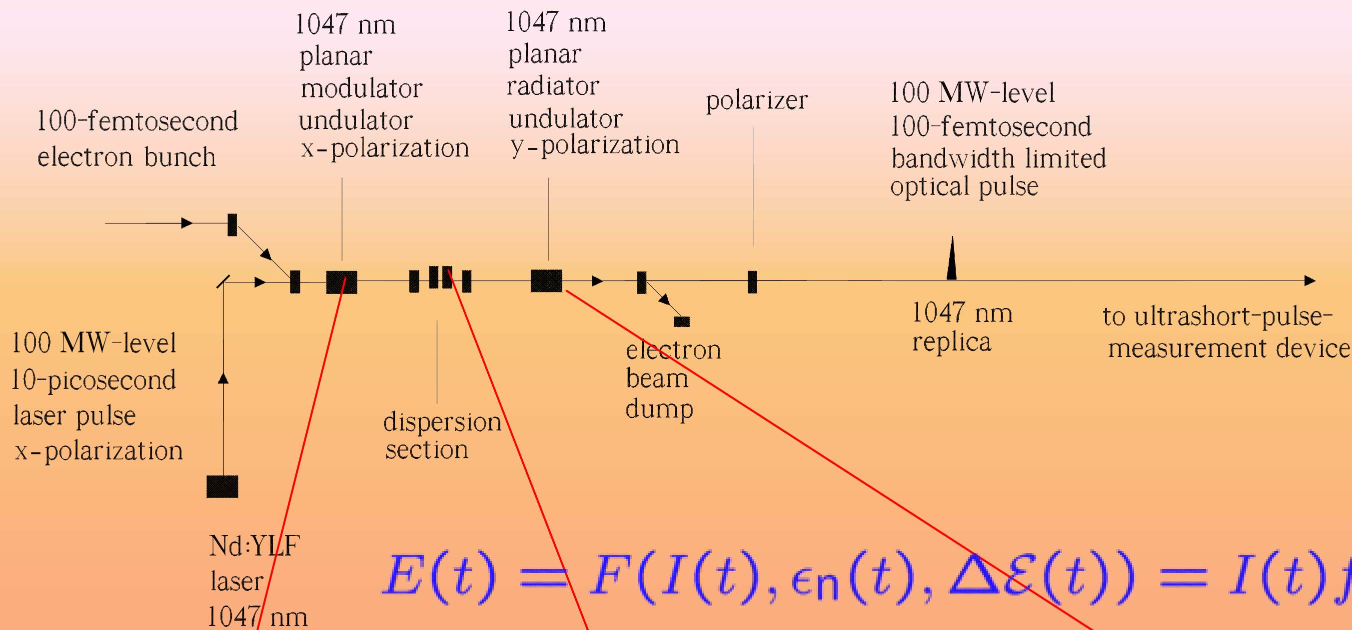
Spectra measurement of accelerated electrons permits to reconstruct the FLASH VUV pulses

JINR Proposal of XFEL Equipment construction

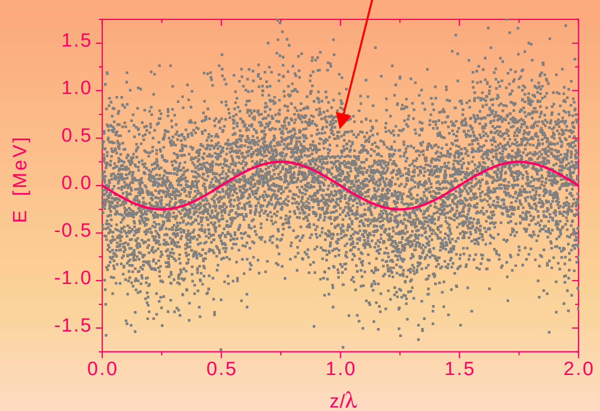
WP 18 OPTICAL REPLICA

JINR propose to design and to construct the Optical Replica synthesizer (ORS). Optical replica synthesizer is a novel type of electron beam diagnostics. The principle of operation is based on a production of optical replica of the electron bunch with subsequent use of modern optical techniques for deriving properties of the electron bunch (current profile, emittance, energy spread) with a femtosecond resolution. ORS consists of a seed optical laser, two undulators , dispersion section, and optical diagnostic station. Two ORS setups can be installed in the XFEL.

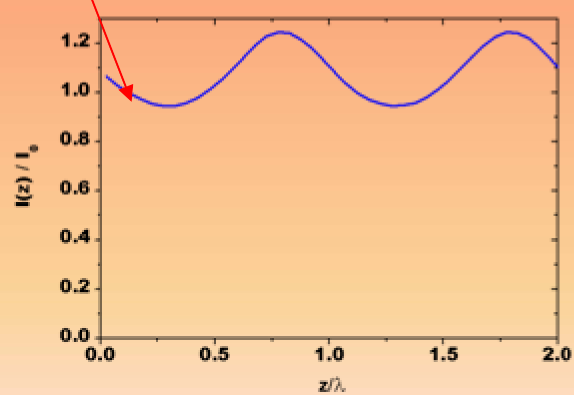
The optical replica synthesis through optical modulation of electron bunch and coherent radiation in the output undulator



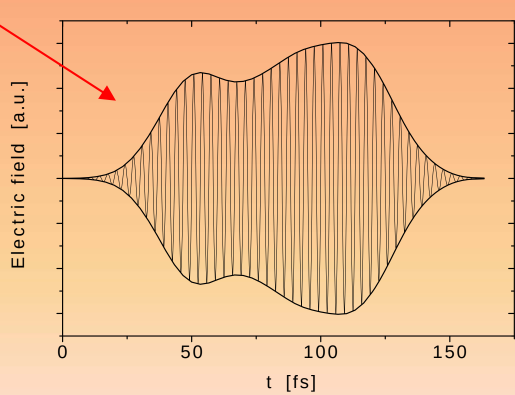
$$E(t) = F(I(t), \epsilon_n(t), \Delta\mathcal{E}(t)) = I(t) f(\epsilon_n(t), \Delta\mathcal{E}(t))$$



Energy modulation



Density modulation



Optical replica

XFEL INJECTOR ORS

The injector replica is placed in region between 39-44 m. The total injector replica length is about 5m. The electron energy corresponds to 130 MeV

Chicane	
Number of dipole magnets	4
Magnet length, cm	10
Magnetic field, kG	1.15
Bending angle, mrad	26.6
Parameter R_{56}, μm	460
Total chicane length, cm	75
Microbanch spread	0.35

Modulator	
Undulator period, cm	10
Magnetic field, T	0.09
Undulator parameter K	0.84
Laser wave length, μm	1.047
Number of periods	5
Total undulator length with edge poles, m	0.75
Beta function in undulator, m	4
Transverse size, μm	250
Diffraction parameter, N	0.26
Electron energy modulation by laser, keV	15

Radiator	
Undulator period, cm	10
Magnetic field, T	0.09
Undulator parameter K	0.84
Laser wave length, μm	1.047
Number of periods	5
Total undulator length with edge poles, m	0.75
Beta function in undulator, m	4
Transverse size, μm	250
Diffraction parameter, N	0.25
Ratio to electron trajectory radius to beam transverse size	10

JINR Proposal of XFEL Equipment construction

WP 24 CALORIMETRIC SYSTEMS FOR FEL RADIATION MEASHUREMENTS

JINR propose to design, to construct and to delivery MCP-based detectors. MCP stands for microchannel plate are effectively used at FLASH for measurements of FEL radiation in wide dynamic range and they can be applied for SASE XFEL.

WP14 LASER heater

'Laser heater' is a magnet chicane of two meters long with an undulator magnet which the electron beam traverses together with a laser beam. It adjusts the uncorrelated energy spread up to 40 keV. It permits to avoid electron beam instabilities driven by space charge and coherent synchrotron radiation.

Undulator parameters

Number of periods - 10
Period length, cm- 3
Peak field, T- 0.5
Nd:YLF laser (second harmonic), μm -052
Laser power, W- 300
Electron energy modulation -20 keV

JINR Proposal of XFEL Equipment construction

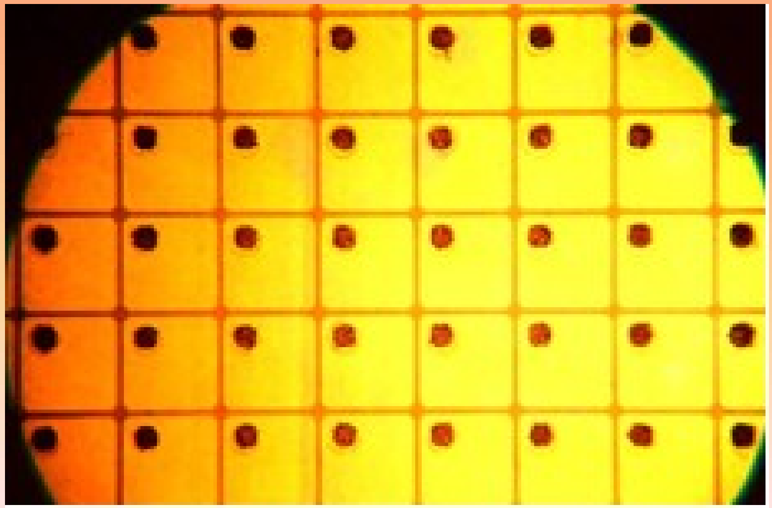
GaAs HYBRID PIXEL ARRAY DETECTOR

JINR and Tomsk University Collaboration

WP 26 HYBRID PIXEL ARRAY DETECTOR

The main task of XFEL complex – new research of nanostructures with femtoseconds time resolution – requires a new generation of instrumentation and analysis tools - Large area Hybrid Pixel Array Detector.

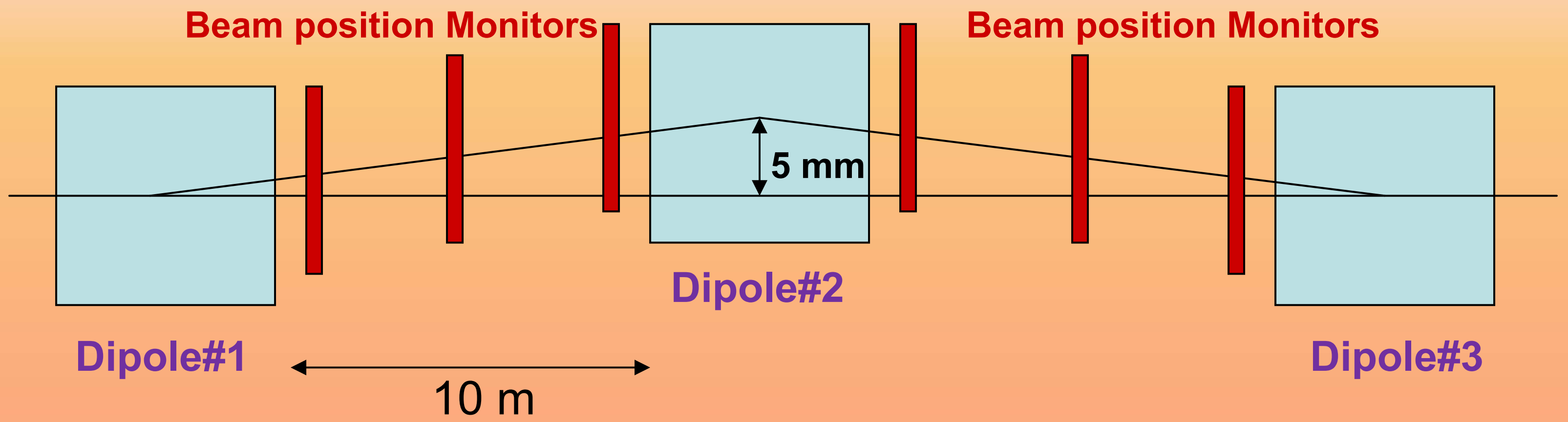
Pixel detector



Strip detector

Method to measure the beam energy in ILC

Magnetic Spectrometer (e.g. proposed in LC-DET-2004-031)
JINR-DESY (Zeuthen) collaboration



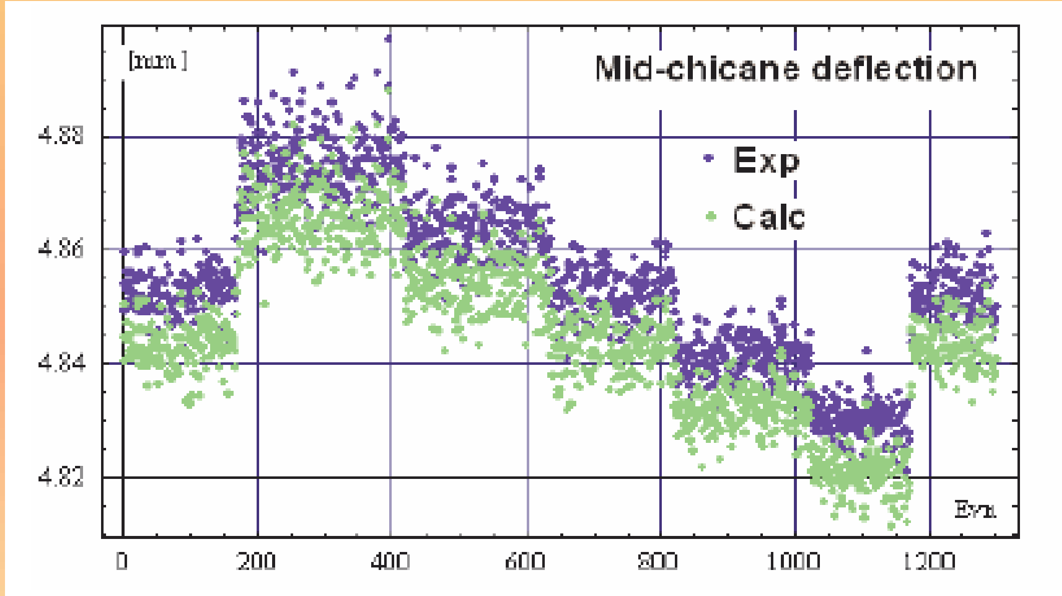
E= 250 GeV, Bl = 0.4 Tm, σ_{BPM} = 100 nm → $dE_b/E_b \sim 5 \times 10^{-5}$

Beam energy measurement is based on precise angular measurement and on precise B-field integral ($\Delta B/B = 2\ 10^{-5}$) of the spectrometer mag

Electron energy measurements at prototype SLAC spectrometer

R. Arnold et al., PAC07, 3085.

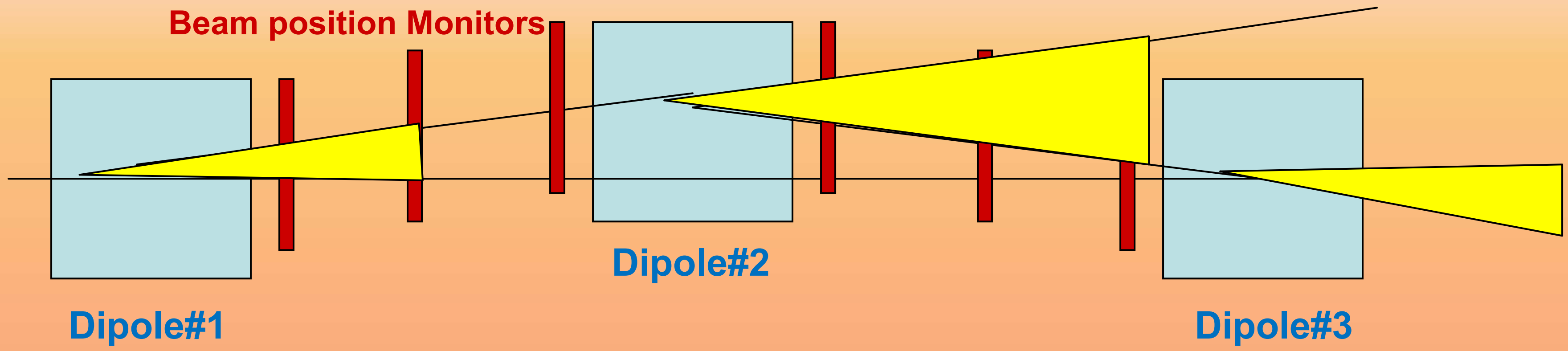
SLAC T-474 project realized
in framework of JINR-SLAC-DESY(Zeuthen) collaboration
Electron energy - 28.5 GeV beam
BPM resolution ≈ 1 μm
Accuracy of the magnetic field integral is 100 ppm.
Relative electron energy resolution is $2.5 \cdot 10^{-4}$.



Experimentally measured and calculated mid-chicane beam deflection during 5 steps of energy scan in range ±0.2 GeV

Synchrotron Radiation Fan

K. Hiller, H.J.Schreiber, E. Syresin et al., NIM A 585 (2007) 1191.



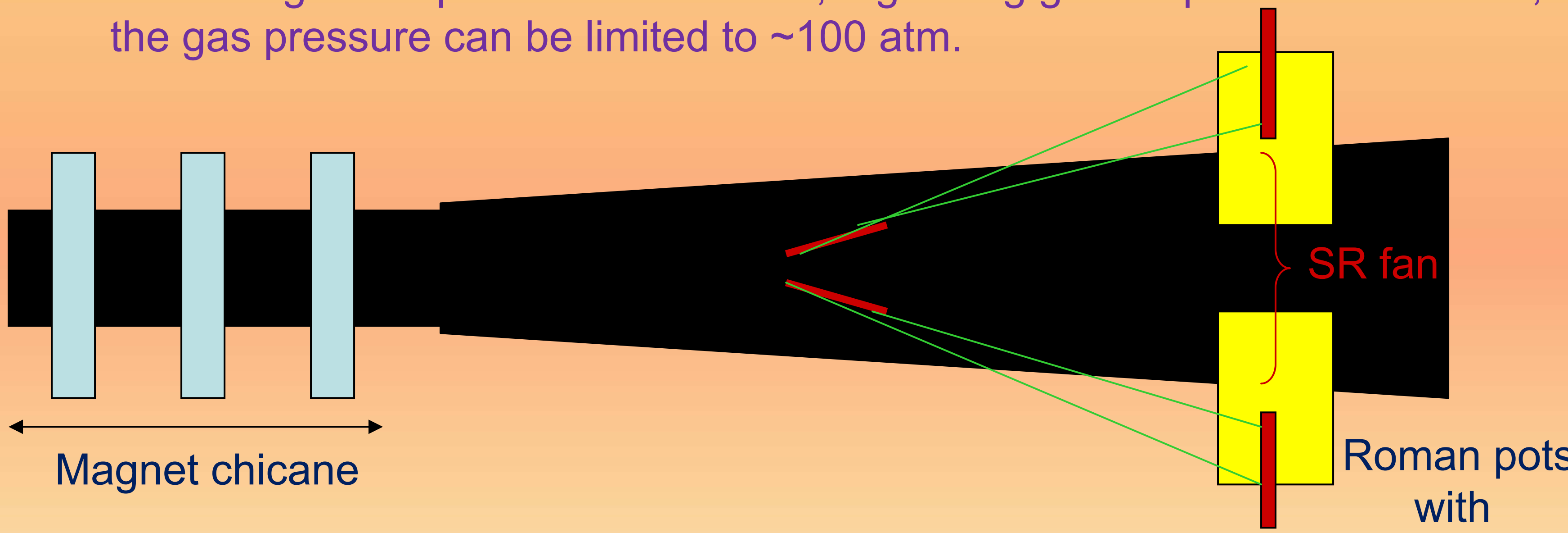
3 radiation fans cover exactly the electron bending angle

→Measurement the width of the fan resp. the position of both edges allows to determine E_b

Due to the ***large radiation dose*** expected in the detector

→ set-up is supplemented by Rh **mirrors**

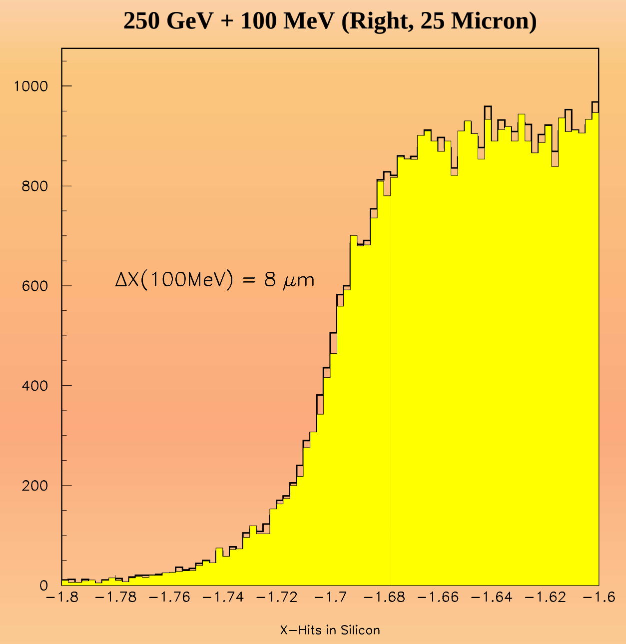
- reflection of only photons < 20 keV,
  (with total reflection only below critical angle φ_{max} ~ [0.08/E_γ(keV)] = 0.4 mrad)
- improve of position resolution of incident gammas (to 1-3 μm)
- sensitive area of the detector reduced to few millimeter (3-5 mm)
- if some signal amplification is needed, e.g. using gas-amplification detector, the gas pressure can be limited to ~100 atm.

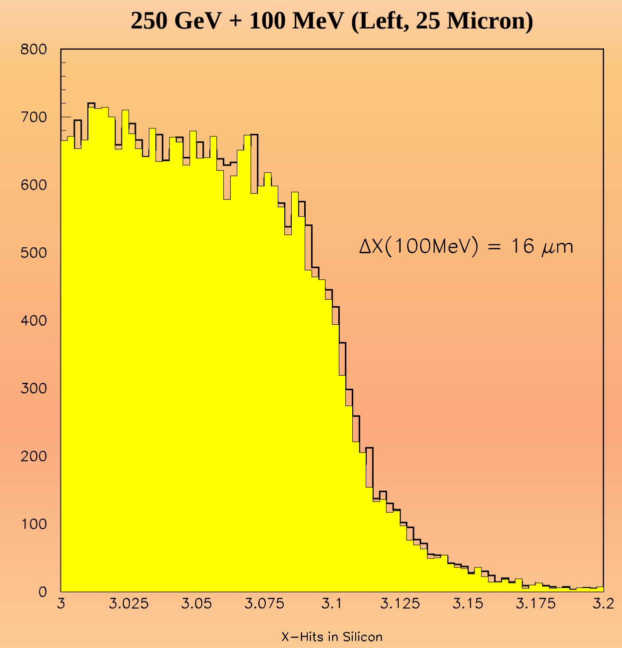


Now, SR reaching the detector is strongly reduced and limited to photons with energies < 20 keV

GEANT simulation (including bunch sizes, energy spread, fringe fields)
→ tracking of SR photons to the detector (Si)

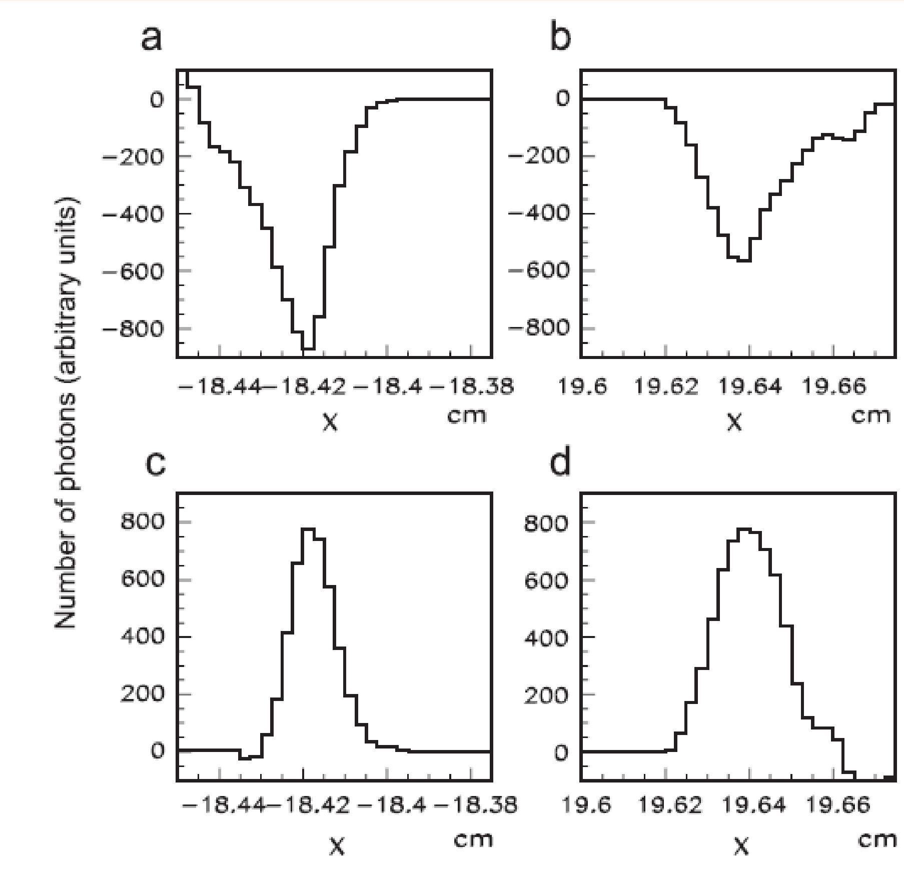
In each plot, two histogram are superimposed
- one for nominal E_b = 250 GeV, the other (in yellow) for 250 GeV + 100 MeV





→ shift of right edge position in x = 8 μm; shift of left edge position = 16 μm
so that the total width shrinks by 24 μm

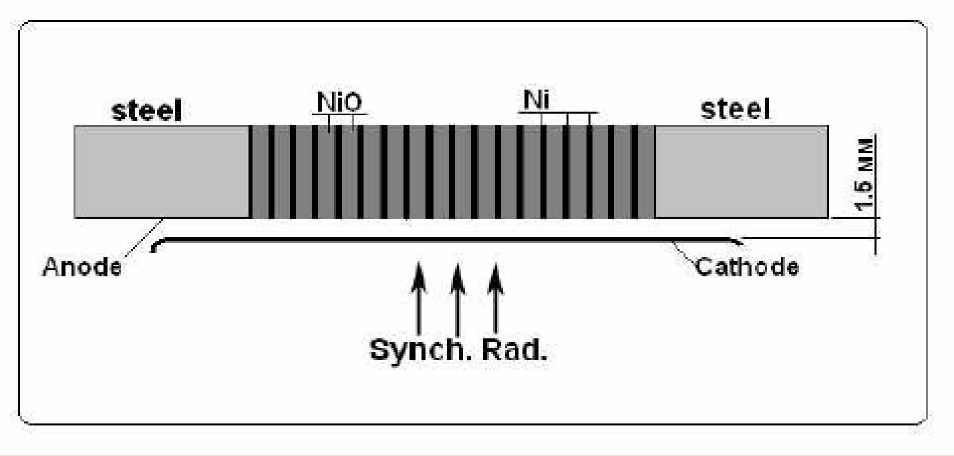
Energy resolution at GIANT simulations



Simulated differences of SR spectra versus x coordinate close to the right (a) and (c) and left (b) and (d) fan edges at electron energies of 250 GeV and 250 ±0.25 GeV.

Method of beam energy measurement based on synchrotron radiation (SR) at photon energy 1-20 keV emitted in the dipole magnets of the energy spectrometer is proposed to realization at an uncertainty of $\Delta E/E \cong 5\cdot10^{-5}$

GAS AMPLIFICATION DETECTOR



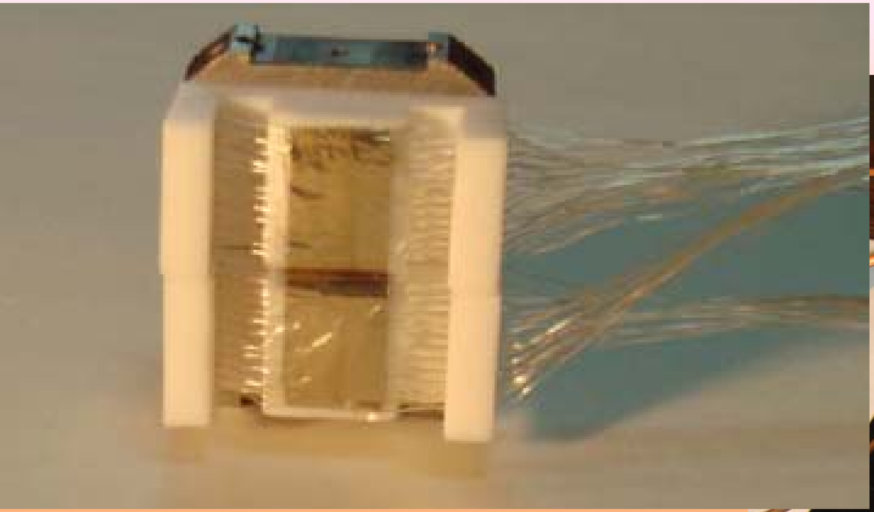
$$N=N_0 \exp(\alpha d_{c-a})$$

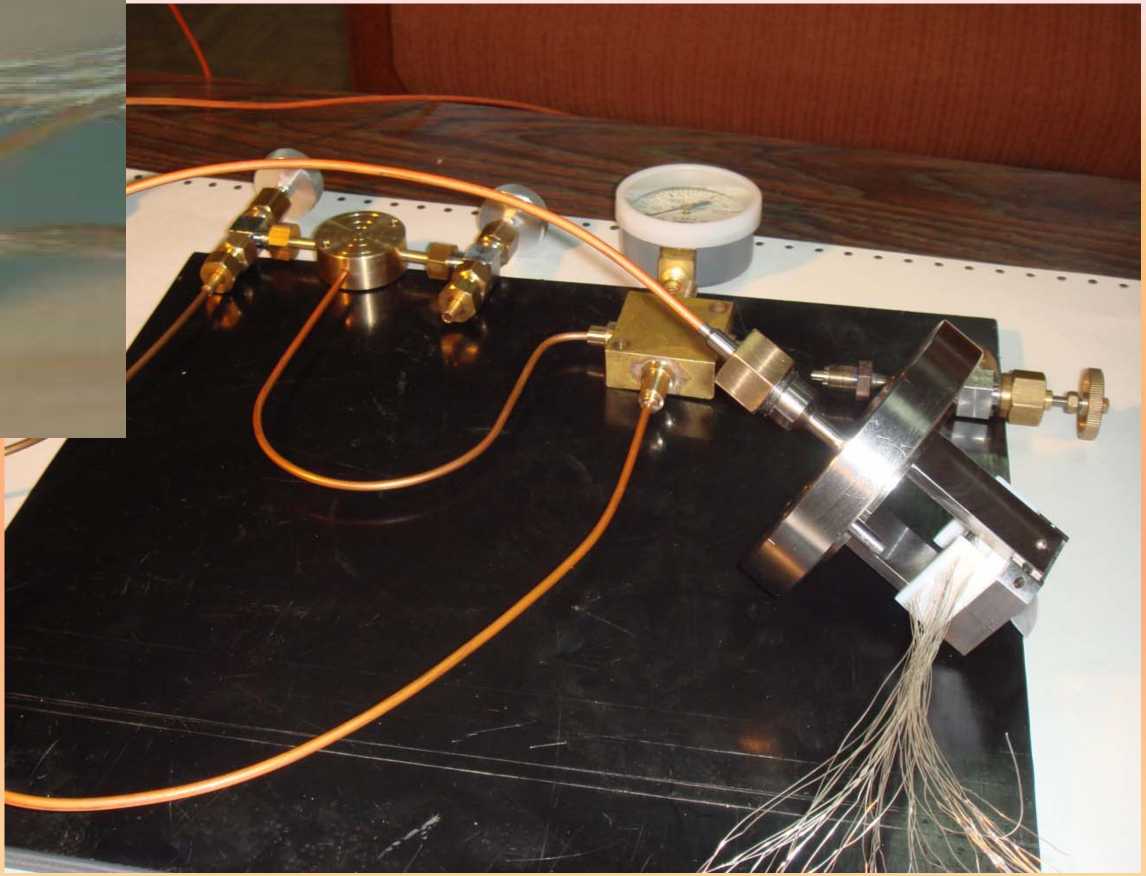
P=60 Atm at t=16 C- critical pressure for liquid Xe
liquid Xe density is of 3.05 g/cm^3

720 Al layers at a thickness of 1 mkm
strip pitch is 3 mkm

Number of soft photons at E≈10 keV per strip	$N_\gamma \approx 10^6$
Number of secondary electrons per strip	$N_e \approx 10^8$
After amplification at K=10	$N_e \approx 10^9$
The signal at amplifier conversion of 5 V/1 nC	V≈1.5 V

High pressure system for SR Gas amplification detector





48 channels
Strips from Al foil of 0.75 μm

A prototype of a gas amplification strip detector with 48 channels and resolution of 3 μm was constructed. The construction of high pressure (150 atm) chamber for a gas amplification strip detector was performed. The assembling of SR is planed in near future.

Thank you for you attention !