WG5: ERL Applications Summary

Peter McIntosh (CI/STFC Daresbury Laboratory)
Ivan Konoplev (JAI/Oxford University)

WG5: ERL Applications Programme

Tue 20th June	Session 1		Application
08:30 – 08:55	LERF - New Life for the Jefferson Lab FEL	Chris Tennant (Jlab)	**FEL**
08:55 – 09:20	Novosibirsk ERL based FEL as User Facility	Vitaly Kubarev (BINP)	**FEL, THz, Compton**
09:20 – 09:45	Asymmetric, Dual Axis Cavity for ERL: recent R&D and possible applications	Ivan Konoplev (JAI)	**EUV, THz**
	Session 2		
10:00 – 10:25	Photon Science Exploitation of ALICE in Biomedical Science	Mark Surman (STFC)	**FEL**
10:25 – 10:50	EUV ERLs for Semiconductor Integrated Circuit Lithography	Norio Nakamura (KEK)	**EUV**
10:50 – 11:15	Applications for CBETA at Cornell	Georg Hoffstaetter (Cornell)	**THz, Compton**
11:15 – 11:40	Applications by means of the accelerator technologies based on cERL	Hiroshi Kawata (KEK)	**Compton, Isotopes**
Thur 22nd June	Session 3		
13:15 – 13:40	ERL Upgrade Plans for the ARIEL e-Linac	Bob Laxdal (TRIUMF)	**FEL, THz, Compton**
Fri 23rd June	**Session 3**		
08:30 – 08:55	Generation of High-flux High-energy Ultra-short Vortex Photon Beams from JLab ERL Facility	Shukui Zhang (Jlab)	**Compton**
08:55 – 09:20	Nuclear Physics Experiments at Mesa	Kurt Aulenbacher (Mainz U)	**Polarised beams**
09:20 – 09:45	ERL developments for eRHIC	Vladimir Litvinenko (Stony Brook U)	**Cooling**

FEL, THz & Photon Applications

Field	Application	Group	Energy (MeV)	Current/Charge	Key Parameters	Size	Critical Performance Needs?	Challenges
THz	TD Spectrometry & Photochemistry	BINP			2.12THz			
	Optical Discharge	BINP			2.3THz, 66ps pulses			
	Material optical properties (ellipsometry)	BINP						
	Biological irradiation	BINP						
	Detonation dynamics	BINP						
	Pump-probe	BINP						
	Surface Plasmon Polaritons	BINP						
	Bessel Beams	BINP						
	CBETA	Cornell	135	500pC @ 10ps, 320mA, 4-pass	4THz	35m x 15m	Low ERL loss rate	
IR-FEL	Spintronics (magnetoactive materials)	BINP			λ=9.3um			
	ARIEL ERL Upgrade	TRIUMF	50	10mA	λ=1 - 20um		High brightness PI	RLA & ERL switching
	LERF – Dark matter search	JLab		60pC @ 3.3ps		60m x 5m	Reduce backg'd rad'n & beam loss	
	IR Microscopy – Cancer Diagnostics	Daresbury	30	80pC @ 0.1ps	λ=9.3um	40m x 25m	FEL λ and power	FEL Stability
Compton	CBETA	Cornell			412keV, 0.4% BW	35m x 15m	Low ERL loss rate	
	Compact LCS (X-ray imaging)	KEK	20	58uA	6.9keV	90m circ.	Laser power	
	LCS γ-ray (nuclear detection)	KEK	350					
EUV	Compact ERL	JAI	30	1A		5m x 2m	Small footprint	High current injector
	Industry ERL	KEK	800	10mA, 60pC,	λ=13.5nm, >10kW	200m x 20m	FEL stability, Availability (>98%)	
Isotopes	^{99}Mo/^{99m}Tc	KEK	20-50	<10mA				

Will work with speakers to populate

Particle & Nuclear Physics Applications

Field	Application	Group	Energy (MeV)	Current/Charge	Key Parameters	Size	Critical Performance Needs?	Challenges
Compton	X-ray vortex photon beams (LERF)	JLab	100	1mA	0.1 – 10keV		LG Laser power	OAM characterisation
	γ-ray vortex beams (CEBAF)	JLab	12000	0.07	3.6GeV			
Polarised Beams	Low momenta characterisation	Mainz U	155	150uA			Polarised electron injector	
Cooling	Spin physics, imaging, strong colour physics	BNL	30	3.7nC			Polarised electron injector	SRF linac & HOMs

ERL Needs & Challenges

For THz, Compton, IR, EUV and X-Ray, NP and PP applications:

- Key performance requirements:
  - Stability areas, availability …..
- Challenges generating ERL output.
- Delivery mitigation strategies.
- Future application field priorities (demand):
  - THz
  - Compton
  - FEL
  - EUV
  - X-Ray
  - Nuclear Physics
  - Particle Physics

THz Applications

Performance Requirements:

- High power & high spectral range is key requirement – ideally upto 3THz.
- Broadband, short-pulse & high repetition-rate plus highly-monochromatic coherent THz are conflicting needs.
- Ideal would be to have the same ERL deliver both!
- High charge, high repetition rate, with good pulse-pulse stability is key ERL requirement.
- ELBE@HZDR delivers high-field pulses with 1nC bunches, providing 0.2THz to 5THz.

Challenges:

- Jlab FEL generates ~1kW THz which presents beam-dynamics problems.
  - Electron beam performance impacts significantly on THz generated (bunch length, RF phase).
  - Difficult to generate consistent THz characteristics.
- THz transport over long distances, ideally should be close to ERL.

Mitigation:

- The use of a THz cavity would generate a more consistent THz beam for users.
- For optimum THz transport, precise alignment and source-point tracking essential – Jlab use a HeNe laser alignment system.

Demand:

- ELBE provides 6wk operation, every 6 months, factor of 3 over-subscribed!
- As storage rings move towards diffraction-limited performance, the availability of THz is expected to increase.

FEL Applications

Performance Requirements:

- Machine stability cited as a primary requirement – wavelength, power, beam pulse-pulse stability.
- High stability needed throughout the entire accelerator chain.

Challenges:

- Achieving required FEL stability.

Mitigation:

- Fast feedback systems: Laser, RF, FEL, temperature etc.

Demand:

- ERLs can potentially achieve much higher repetition rates than a single-pass linear machine, and this is something which should be pursued at national lab level – particularly delivering hard x-rays, combined with a gamma ray Compton source.

EUV Applications

Performance Requirements:

- High EUV power >10kW typically needed, with >98% availability.
- High stability needed throughout the entire accelerator chain.

Challenges:

- Achieving required FEL stability and availability.

Mitigation:

- High levels of sub-system redundancy needed: Photo-injector, linac, cryoplant, FEL – even complete machine redundancy!
- Reduce sub-system trips, relaxing operational levels, simplifying system integration, reduce accelerator size.

Demand:

- Industry EUV FEL accelerators driven by IC customer demands for higher transistor density.
- Next generation technology will require <13.5nm capability.
- Industry not yet fully committed to accelerator technology delivery, but this could switch very quickly if IC customer demand intensifies.

Compton (X-ray & γ-ray) Applications

Performance Requirements:

- For LCS medical imaging, require 50MeV, 10mA and >100kW laser power to get ~40keV X-ray energy.
- Need high energy for short exposure times.
- High energy ERL needed for γ-ray LCS with high power LG laser.

Challenges:

- Achieving required laser power in small footprint for both X-ray and γ-ray generation.

Mitigation:

- Laser enhancement cavity, store 2-beams simultaneously with fast polarisation switch – double laser power of LCS (KEK/CBETA) – not yet demonstrated.

Demand:

- Compact ERL footprint to fit in hospital environment (10m x 6m) for X-ray LCS.

NP/PP Applications

Performance Requirements:

- High performance polarised electron injector is key technology requirement for cooling and spin polarised experiments.

Challenges:

- Achieving required peak current and operational QE.
- Precise control of beam current needed for spin polarisation measurement of exotic particles.

Mitigation:

- Optimised diagnostics needed to effectively characterise emittance, energy spread and PC performance.

Demand:

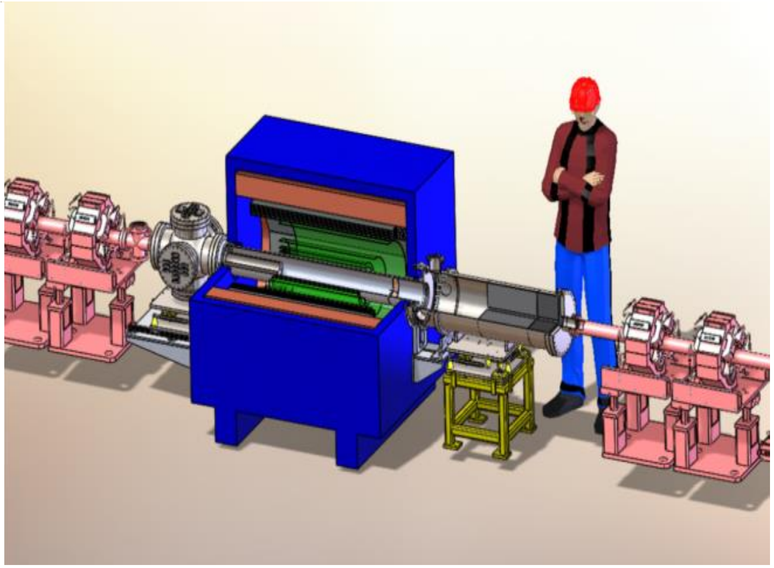
- Spin physics and imaging

LERF - New Life for the Jefferson Lab FEL

Chris Tennant (Jlab)

- The Dark-Light Experiment – overview and the future work
- Goal of the recent experiments: run power with internal gas target.
- MIT took data with and without gas at various magnet strengths.
- Development of the machine and possible applications.

- Design of single pass ERL cooler
- Design of multi-turn CCR cooler
- Demonstration of CCR using LERF infrastructure
- Medical isotope production
- Low energy target irradiation
- Intense positron source



Novosibirsk ERL based FEL as User Facility

Vitaly V. Kubarev (BINP)

Laser	Terahertz	Far-Infrared	Infrared
Status	In operation since 2003	In operation since 2009	In operation since 2015
Wavelength, µm	90 – 240	37 – 80	8 – 11 (7–30)
Relative line width (FWHM), %	0.2 – 1	0.2 – 1	0.1 – 1
Maximum average power, kW	0.5	0.5	0.1
Maximum peak power, MW	0.9	2.0	10
Pulse duration, ps	30 – 120	20 – 40	10 – 20
Pulse repetition rate, MHz	3.7 – 22.4		
Polarization	Linear, > 99.6 %		
Beams	Gaussian beams with diffraction divergence		

1. 14 different applications are developed and conducted at Novosibirsk FEL.

2. 26 working stations.

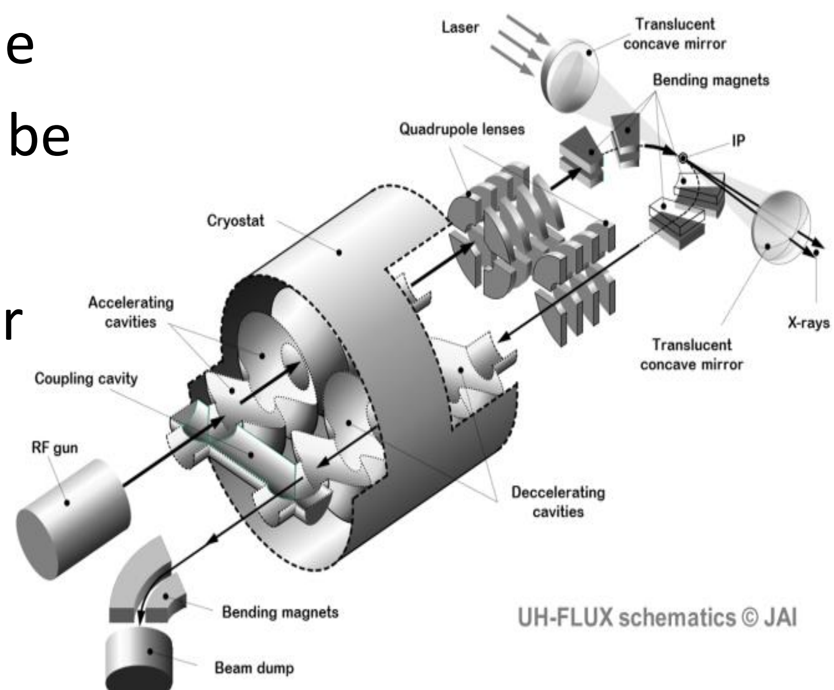
3. Users have access to the facilities 4-5 days a week with the stops of machine operation during the summer period.

Typical radiation of THz NovoFEL - continuous train of 100 ps pulses:

Asymmetric, Dual Axis Cavity for ERL: Recent R&D and applications

Ivan Konoplev (Oxford university)

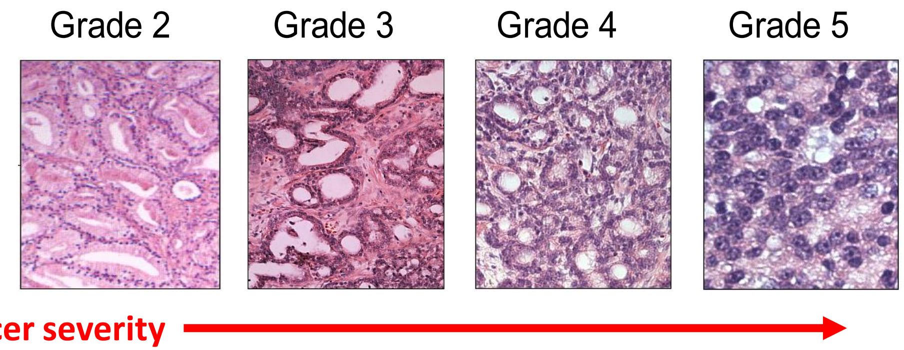
- Overview of possible applications outside research community with market values for each application.
- Presented the most recent development of the asymmetric dual axis cavity for ERL.
- 7-cell and 11-cell cavities are in the laboratory and the RF studies will be carried out during this summer.
- Goal to get 1A class ERL system for THz and EUV applications.



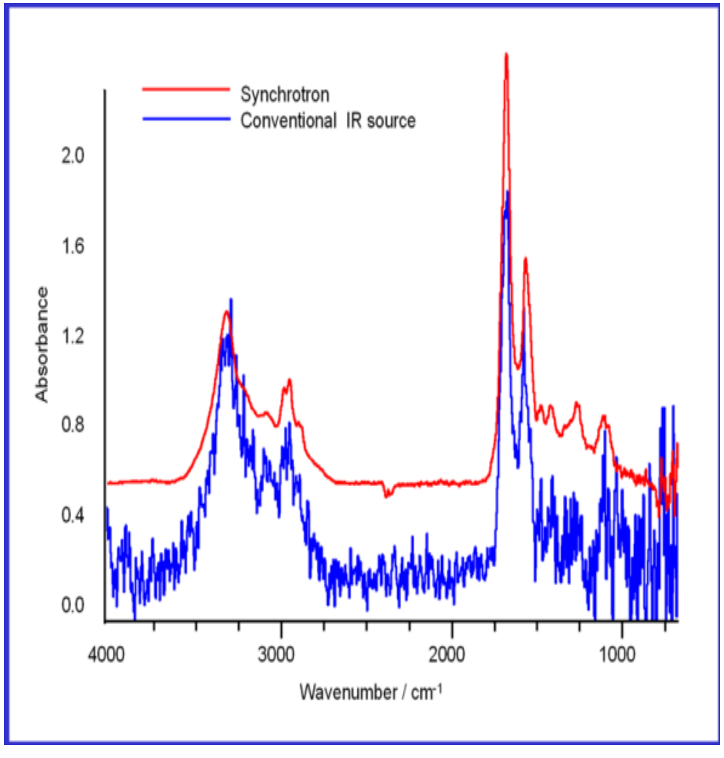
Photon Science Exploitation of ALICE in Biomedical Science

Mark Surman (STFC)

1. Development of a more effective cancer diagnostic scale.

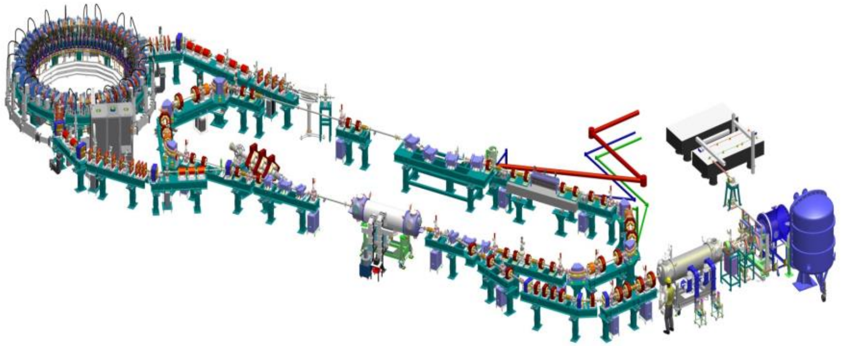


2. Advantage of electron beam driven source of radiation over conventional IR source shown.



3. Improving Spatial Resolution Breaking through Diffraction Limit: sub-micron imaging.

4. ALICE: "Accelerators and Lasers in Combined Experiments" progress was discussed.



EUV ERLs for Semiconductor Integrated Circuit Lithography

Norio Nakamura (KEK)

Industry Study Group

The University of Tokyo
S. Ishihara (Leader)

The University of Tokyo
I. Matsuda

宇都宮大学
Utsunomiya Univ.
T. Higashiguchi

Univ. of Hyogo
H. Kinoshita

Waseda Univ.
M. Washio

Osaka Univ.
T. Kozawa

Industries

TOSHIBA Leading Innovation
MITSUBISHI HEAVY INDUSTRIES MECHATRONICS SYSTEMS, LTD.
Hitachi Metals, Ltd.
GIGAPHOTON
EIDEC
TAIYO NIPPON SANSO The Gas Professionals
HITACHI
TOYAMA
TOSHIBA Leading Innovation TOSHIBA ELECTRON TUBES & DEVICES CO.,LTD.
MITSUBISHI ELECTRIC Changes for the Better
NTT AT

Industrialization of High Power EUV light source based on ERL@KEK and FEL@QST

QST R. Hajima

KEK H. Kawata et al.

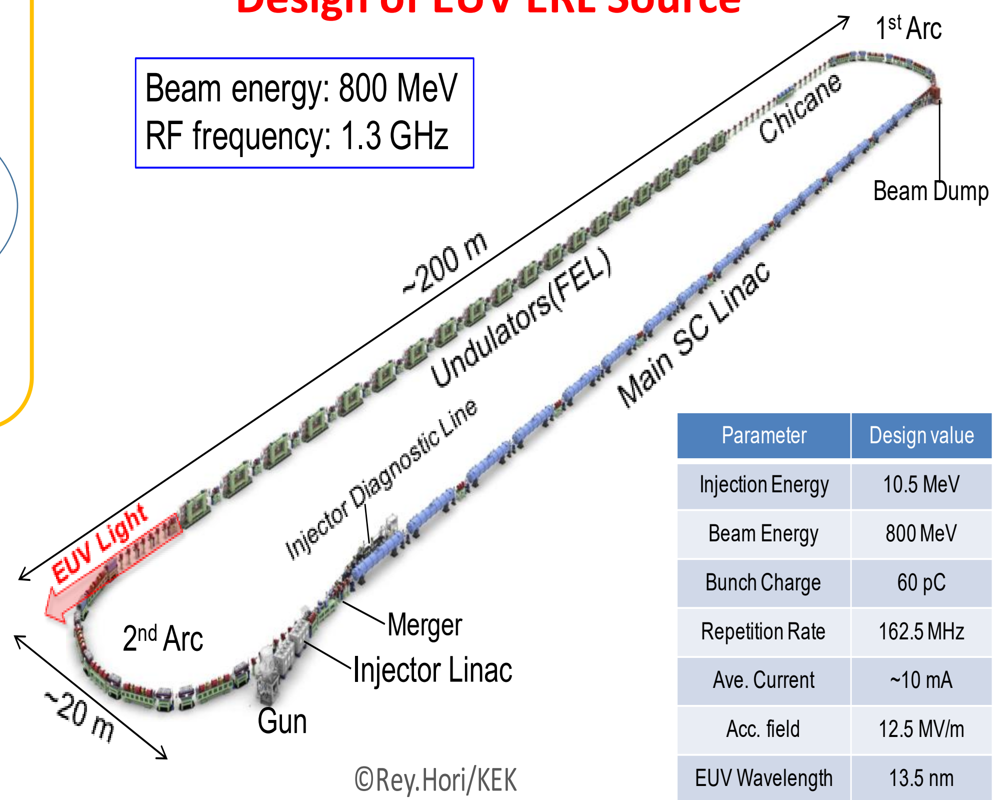
AIST N. Sei

Key challenge to achieve >98% availability:

- Electron gun – PC lifetime & exchange
- SRF linac – processing & trip rate
- Undulator – demagnetisation issues
- Cryoplant – high pressure operation and maintenance

Design of EUV ERL Source

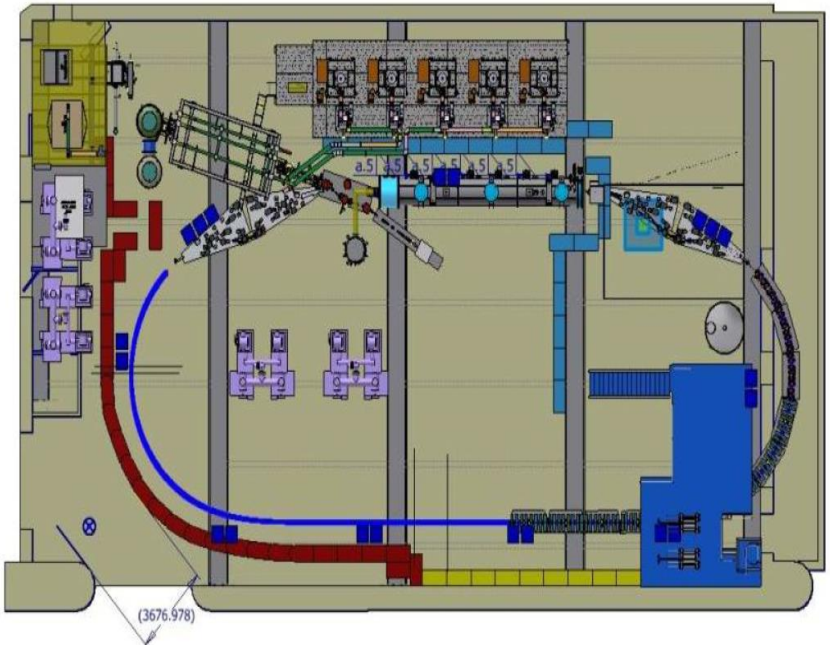
Beam energy: 800 MeV
RF frequency: 1.3 GHz



Parameter	Design value
Injection Energy	10.5 MeV
Beam Energy	800 MeV
Bunch Charge	60 pC
Repetition Rate	162.5 MHz
Ave. Current	~10 mA
Acc. field	12.5 MV/m
EUV Wavelength	13.5 nm
EUV power	> 10 kW

Applications for CBETA at Cornell

Georg Hoffstaetter (Cornell University)



- DarkLight – an experiment to find dark matter particles
- Compact Compton source for hard x-rays – complementing CHESS' range
- THz laser – complementing CHESS' range
- Beam for time-resolved electron diffraction from 1-6MeV
- Beam for **Plasma Wakefield Acceleration with High Transformer Ratio**
- eRHIC accelerator testing – more detailed eRHIC R&D
- eRHIC cavity testing with beam
- ASML medical isotope cavity testing with beam
- Generic ERL accelerator physics
- Electron cooler tests – ERL tests for JLEIC
- Preparations for Perle
- Preparations for LHeC
- High-Power beam dynamics testing
- Permanent magnet and FFAG test bed for future accelerators

- ERLs-new beam operating regime: Linear acceleration and deceleration to capture the energy of spent beam, like a linac but without the power limit on beam current, as spent beam provides the power.
- Loss rates have to be limited.

Applications of the Accelerator Technologies based on cERL

Hiroshi KAWATA (KEK)

Medical imaging – LCS

Result of March/2014

X-ray Energy 7keV
Exposure time 600sec

2. High resolution X-ray imaging device for medical use
From the view point of neurosurgery

Main issues for medical application
Intravascular surgery of the neurosurgery
1) Cooling exposure time
2) Too low energy

coil: Stuffed aneurysm and stop bleeding
Stent: Support stabilizing coil

(50MeV, 10mA)
>100kW laser cavity)

X-ray Energy 40keV
Exposure time 0.1sec

Starting point of medical application

Using a large synchrotron radiation facility

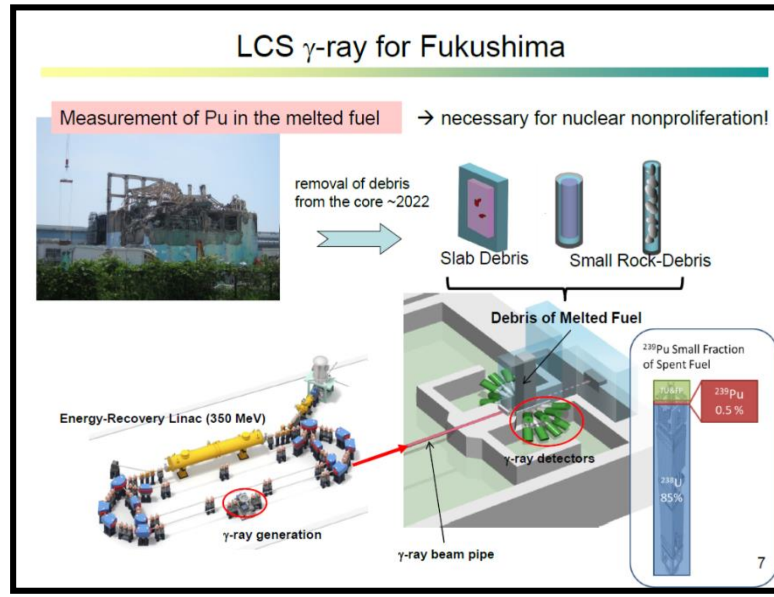
High resolution

Image under surgery
The stent can not be seen

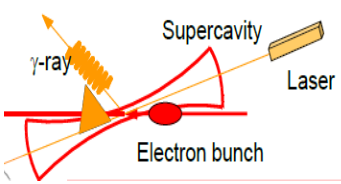
Stents can be clearly visualized

Provided by the Department of Neurosurgery, University of Tsukuba

Nuclear security – LCS γ-Ray

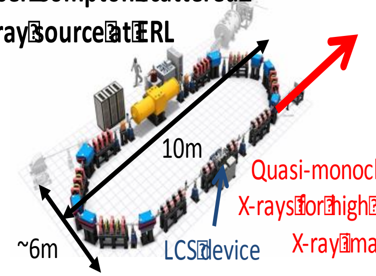


If we can make a compact high-resolution X-ray source in a hospital!



Potential of quasi-monochromatic X-rays for high resolution X-ray imaging by laser Compton scattering (LCS)

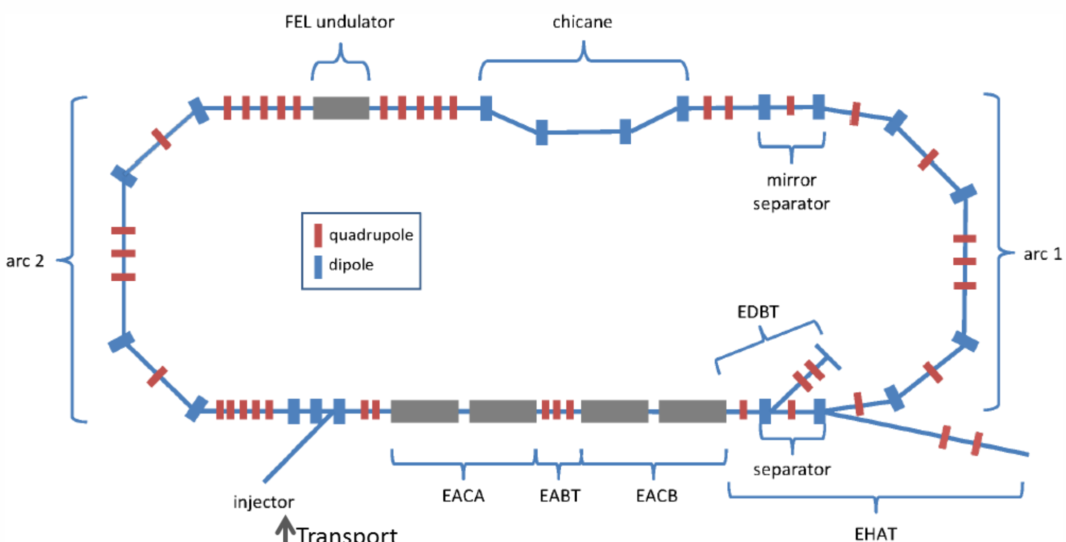
Laser Compton scattered X-ray source at cERL



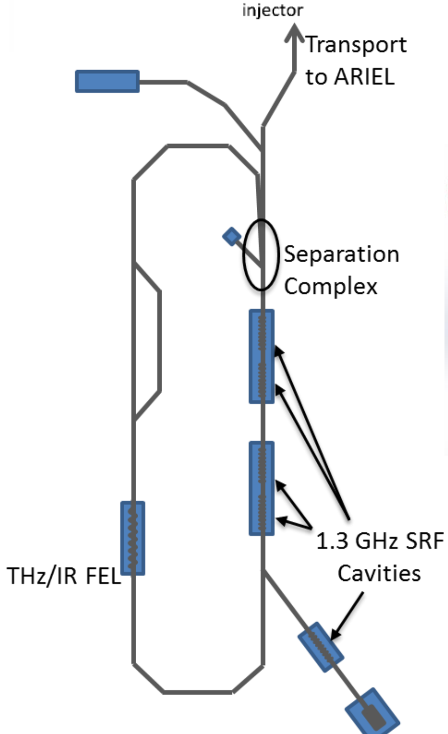
Quasi-monochromatic X-rays for high resolution X-ray imaging

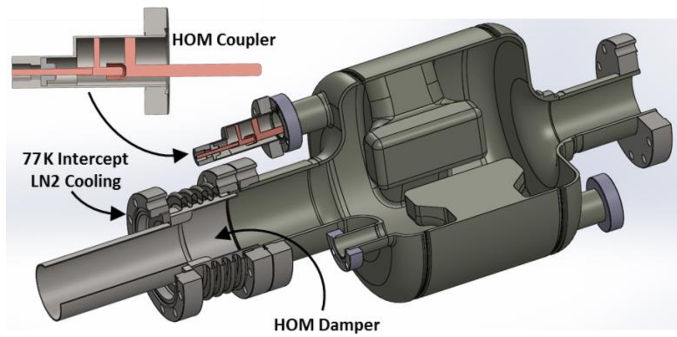
ERL Upgrade Plans for the ARIEL e-Linac

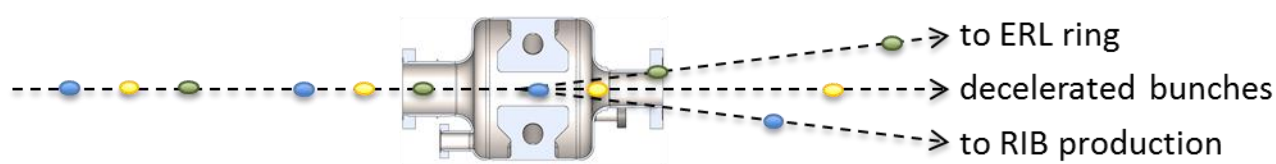
Bob Laxdal (TRIUMF)



Electron Beam Parameters		
Energy	MeV	30-50
RF frequency	GHz	1.3
Average current	mA	10
Charge per bunch	pC	77
Bunch rep freq.	MHz	130
Bunch length (rms)	ps	1
Energy spread (rms)	%	0.1
Output Light Parameters		
Wavelength range	µm	1-20
Micropulse energy	µJ	30
Laser power	kW	3-5

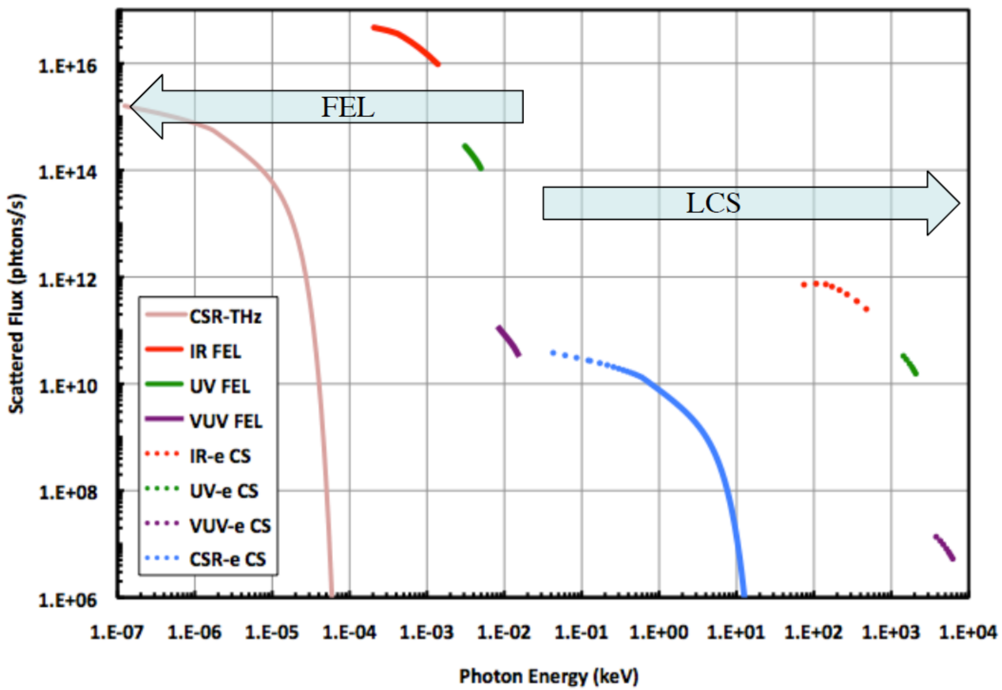




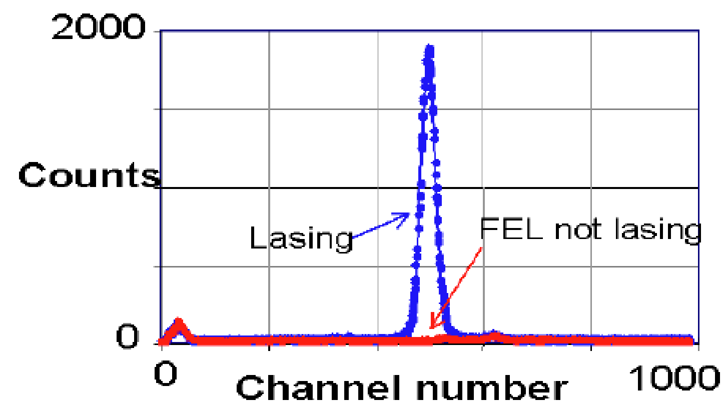


Generation of High-flux High-energy Ultra-short Vortex Photon Beams from JLab ERL Facility

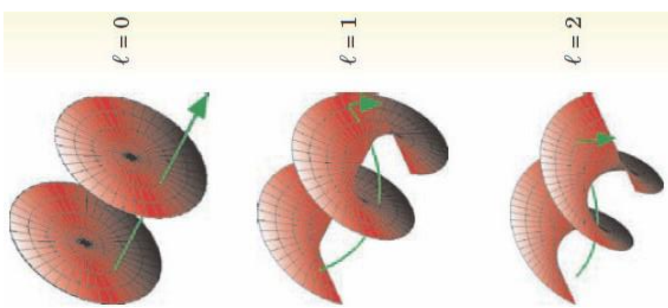
LERF FEL

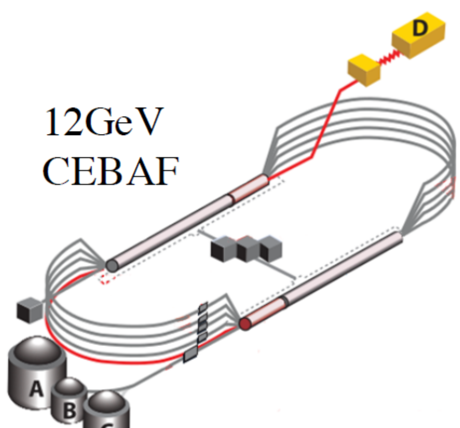


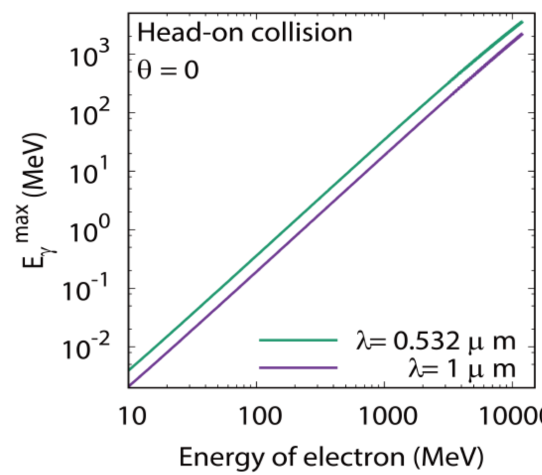
Shukui Zhang (Jlab)



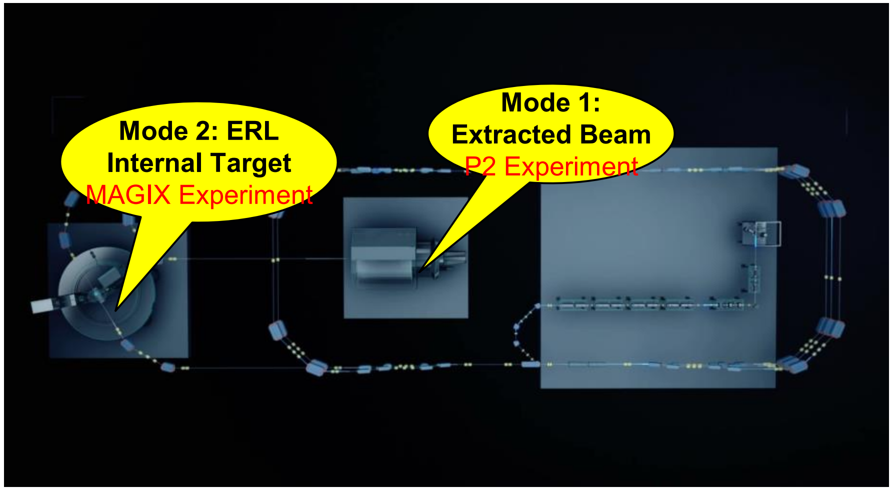
Measured 5.12 keV X-ray Spectrum
(Tunable from 3.5 to 18keV)





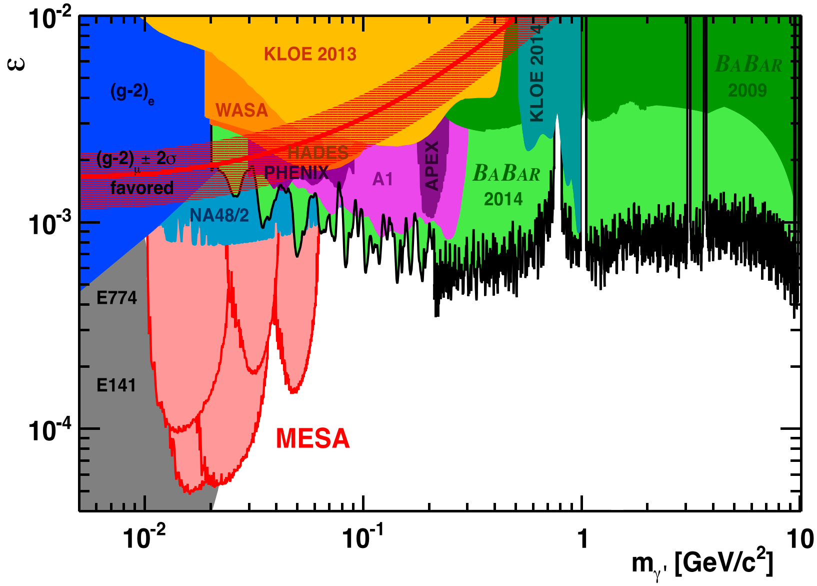


Nuclear Physics Experiments at Mesa



Kurt Aulenbacher (Mainz U)

MESA Dark photon research



MAGIX

Operation of a high-intensity (polarized) ERL beam in conjunction with light internal target

- → **a novel technique in nuclear and particle physics**
- → **measurement of low momenta tracks with high accuracy**
- → **competitive luminosities**
- → **Small device if compared to GeV scale spectrometer set ups!**

ERL developments for eRHIC

Vladimir Litvenenko (Stony Brook U)

Speaker input still needed!

- Please provide additional input to parameter table, send to:
  - Peter.mcintosh@stfc.ac.uk
  - Ivan.Konoplev@physics.ox.ac.uk