# Highlights of the ERL07 Workshop

**Lia Merminga, Matt Poelker, Bob Rimmer, Kevin Jordan**

**Jefferson Laboratory**

**2nd Workshop on Energy Recovery Linacs**

**May 21-25, 2007**
**Daresbury Laboratory, UK**

# Plenary Program

- Welcome and Goals of Workshop - M. Poole (ASTeC)/S. Chattopadhyay (Cockcroft)
- Operating ERL-Based FELs and Future Upgrades - L. Merminga (JLAB)
- Future ERL-Based FELs - J. Clarke (ASTeC)
- ERLs as Hard X-ray Sources - G. Hoffstaetter (Cornell University)
- ERLs in HENP - V. Litvinenko (BNL)
- High Current  Research and Development ERLs - I. Ben-Zvi (BNL)
- ERL Prototype at Daresbury - S. Smith (ASTeC) Daresbury
- New Developments In Injectors - J. Lewellen (ANL)
- High Current Superconducting RF and RF Control - T. Grimm (Niowave/MSU)
- Synchronization - G. Hirst (STFC)
- Diagnostics - K. Jordan (JLAB)
- Drive Lasers for Photoinjectors - I.Will (MBI)

# Working Groups

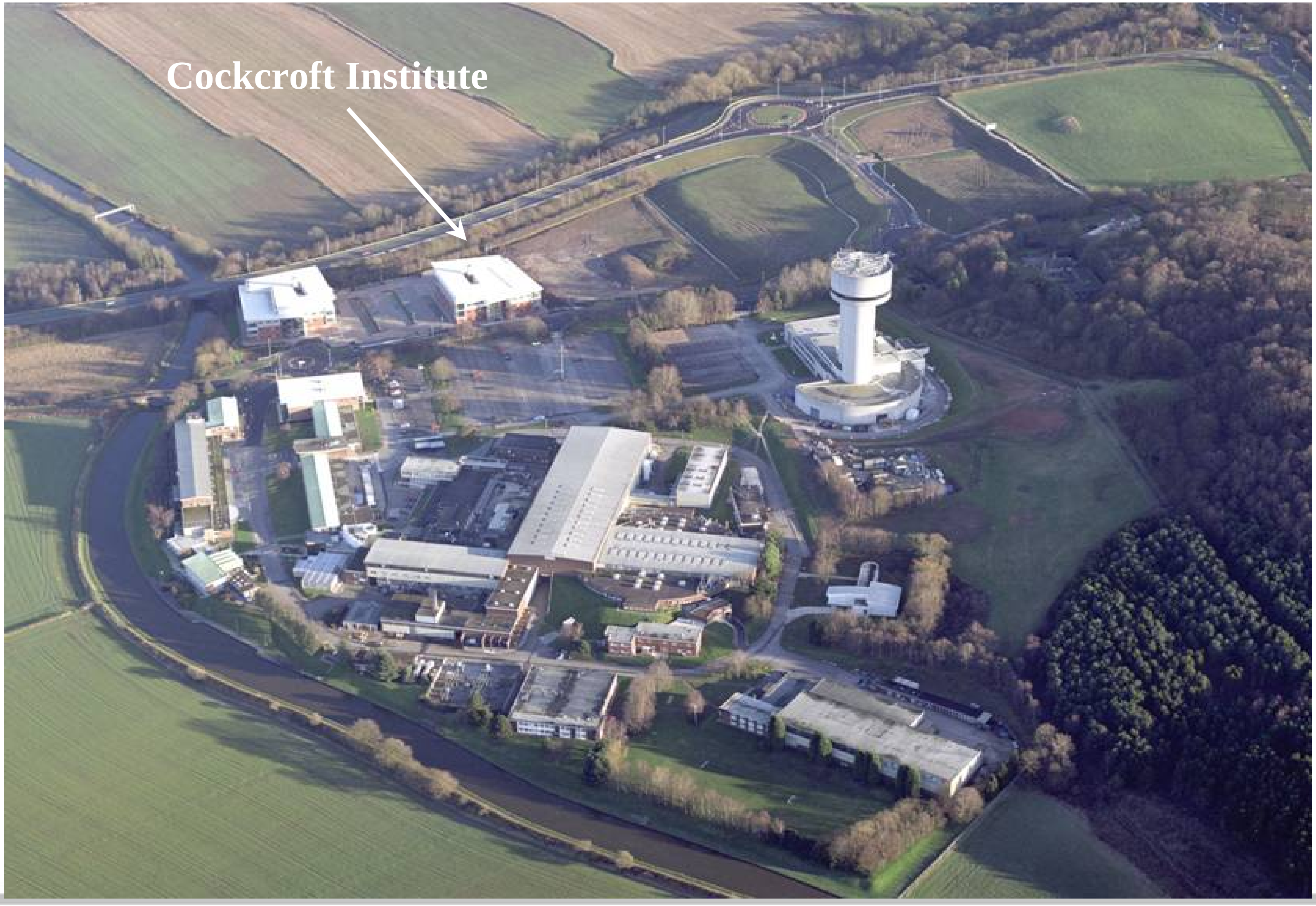
**Working Group 1:**
**Electron Guns and Injector Designs**
**A. Burrill (BNL), Matt Poelker (JLab)**

**Working Group 2:**
**Optics and Beam Transport**
**R. Hajima (JAEA), Hywel Owen (DL)**

**Working Group 3:**
**Superconducting RF and RF Control**
**T. Smith (Stanford University), Bob Rimmer (JLab)**

**Working Group 4:**
**Synchronization and Diagnostics/Instrumentation**
**K. Jordan (JLAB)**

# Daresbury Campus



# Cockcroft Institute Building

THE UNIVERSITY of LIVERPOOL

LANCASTER UNIVERSITY

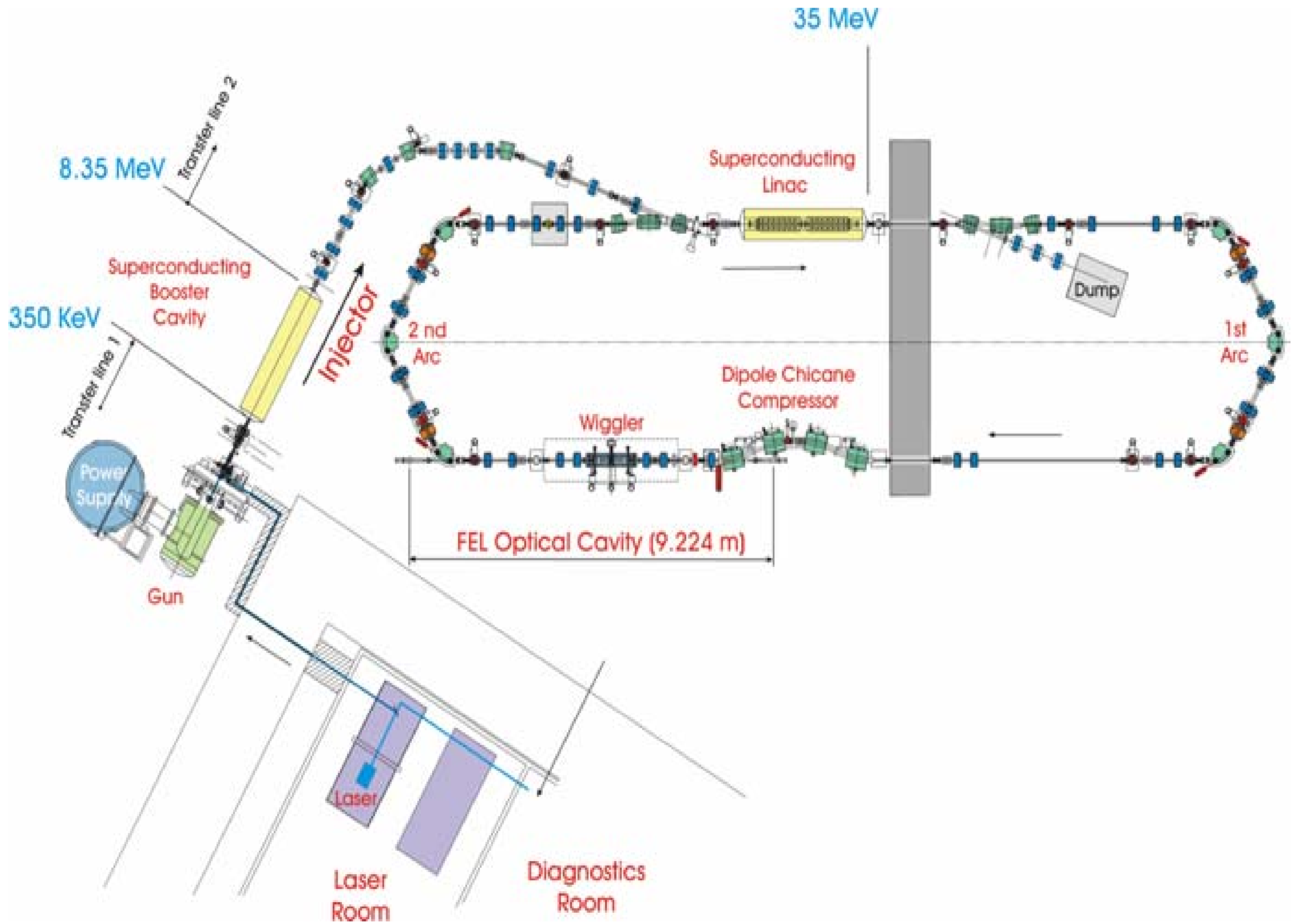

MANCHESTER 1824 The University of Manchester

PPARC

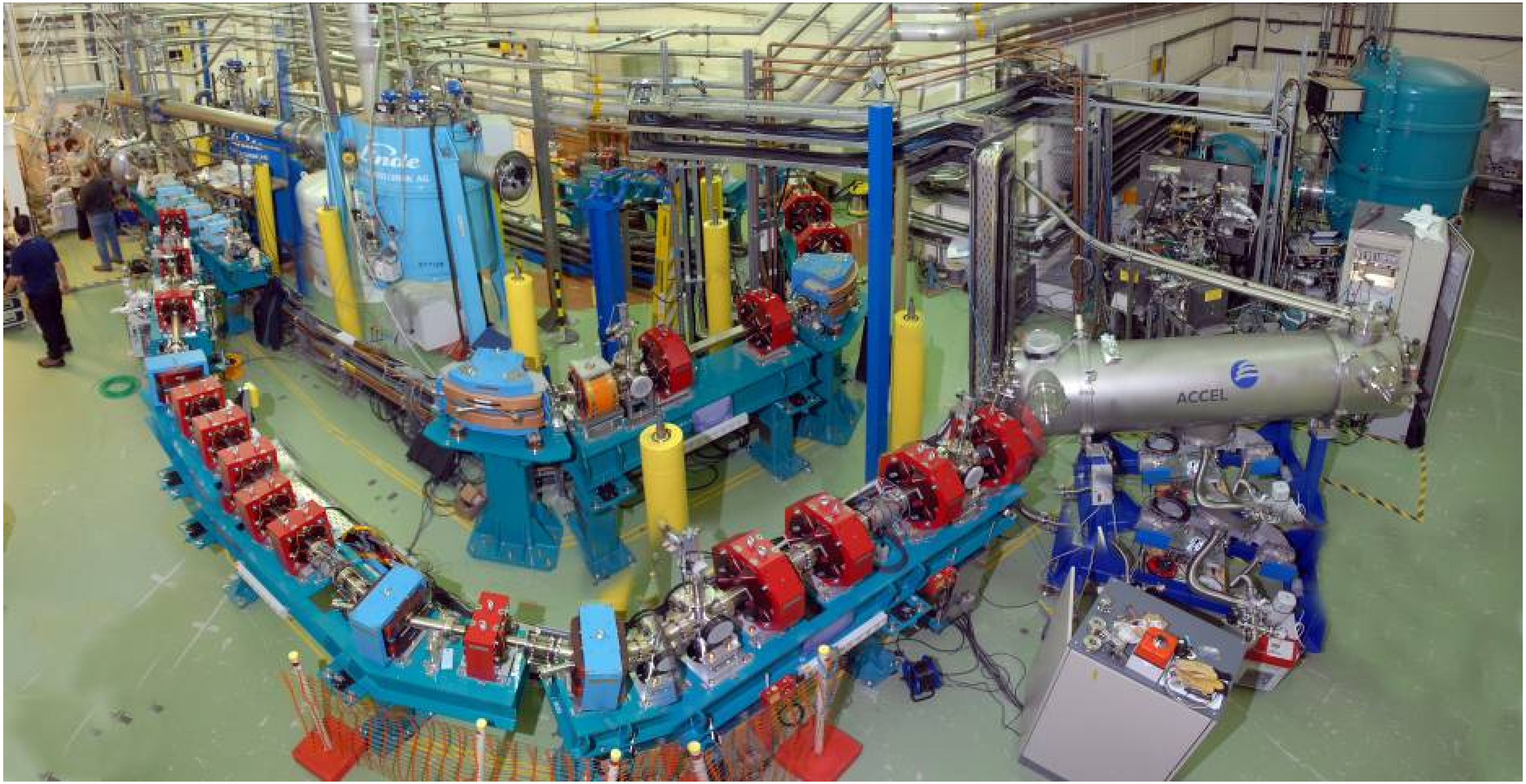
CCLRC

ASTeC

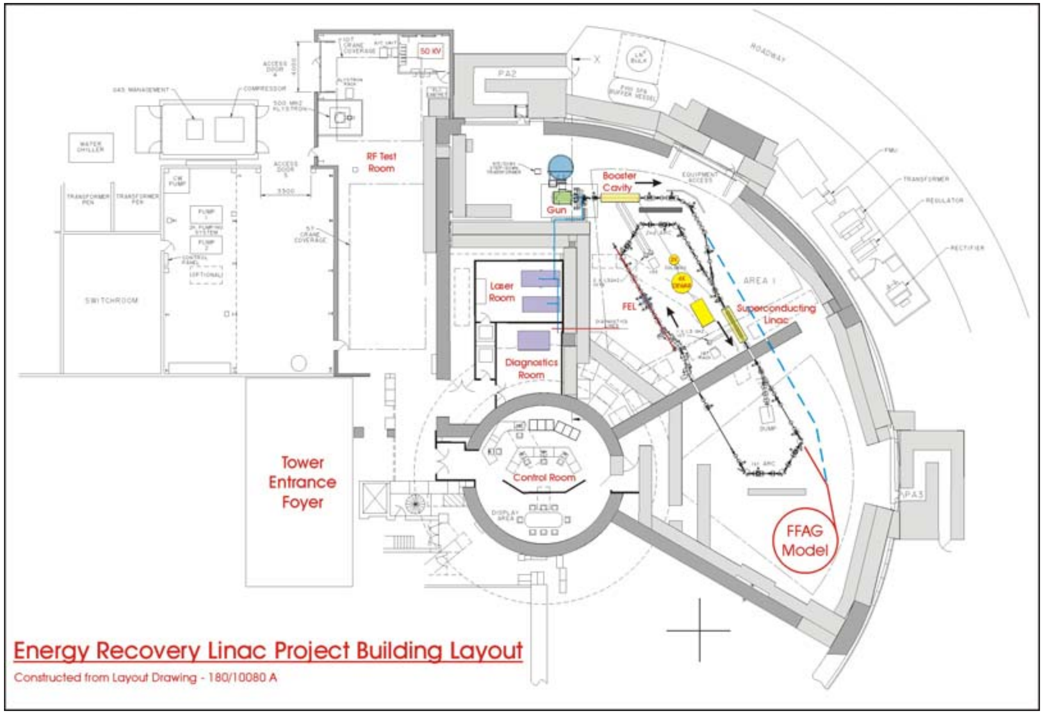
# Demonstrator Project - ERLP Layout

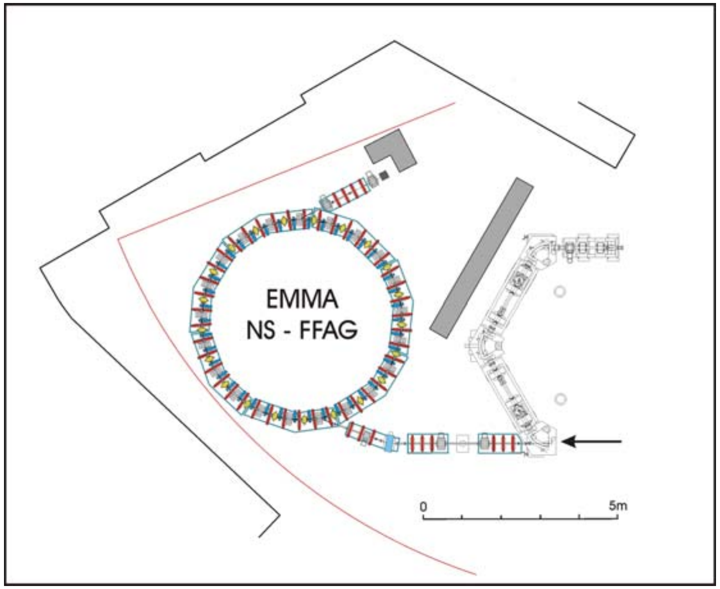


# ERLP Status



# ERLP as an Accelerator Test Facility




**Novel form of FFAG – CONFORM project funded from April 2007**

**EMMA = 20 MeV demonstrator**

**£5.6M (£3.8M capital £1.8M staff)**

**Duration 3.5 years (2.5 to beam)**

# Workshop Planning

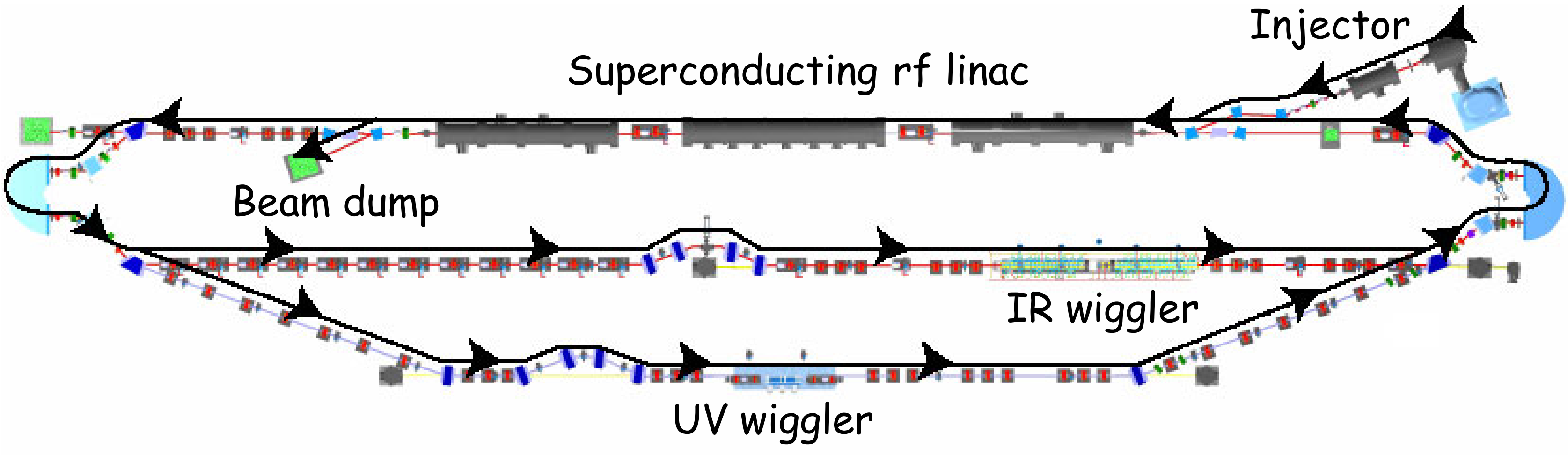
- Build on success of 1st International Workshop at JLab (March 2005)
- Dates agreed at EPAC06 (DIPAC not known)
- ICFA umbrella includes JACOW decision - Open Access publishing
- Thanks to Sponsors: STFC CI e2v JLab APS
- Valuable advice - especially
  - **Ilan Ben-Zvi, Georg Hoffstaetter, Lia Merminga**
- Please help your Convenors in the Working Group sessions
- 105 registered (host + 61) (JLab was 159 - host + 51)

# Workshop Goals

- Review state of art ERL developments
- Understand proposed project demands
- Examine R&D challenges - ERLs and associated features
- Summarise future development priorities
- Recommend necessary steps - physics and technology
- Strengthen international collaborations

# The Jefferson Lab IR FEL Upgrade

## Energy recovered up to 9.1 mA at 150 MeV




| JLab IR FEL Electron Beam Parameters | Design | Achieved |
|---|---|---|
| Energy (MeV) | 145 | 160 |
| Bunch charge (pC) | 135 | 270 |
| Average current (mA) | 10 | 9.1 |
| Bunch length* (fs) | 500 | 150 |
| Norm. emittance* (mm-mrad) | 30 | 7 |
| Max. Bunch rep. rate (MHz) | 74.85 | 74.85 |

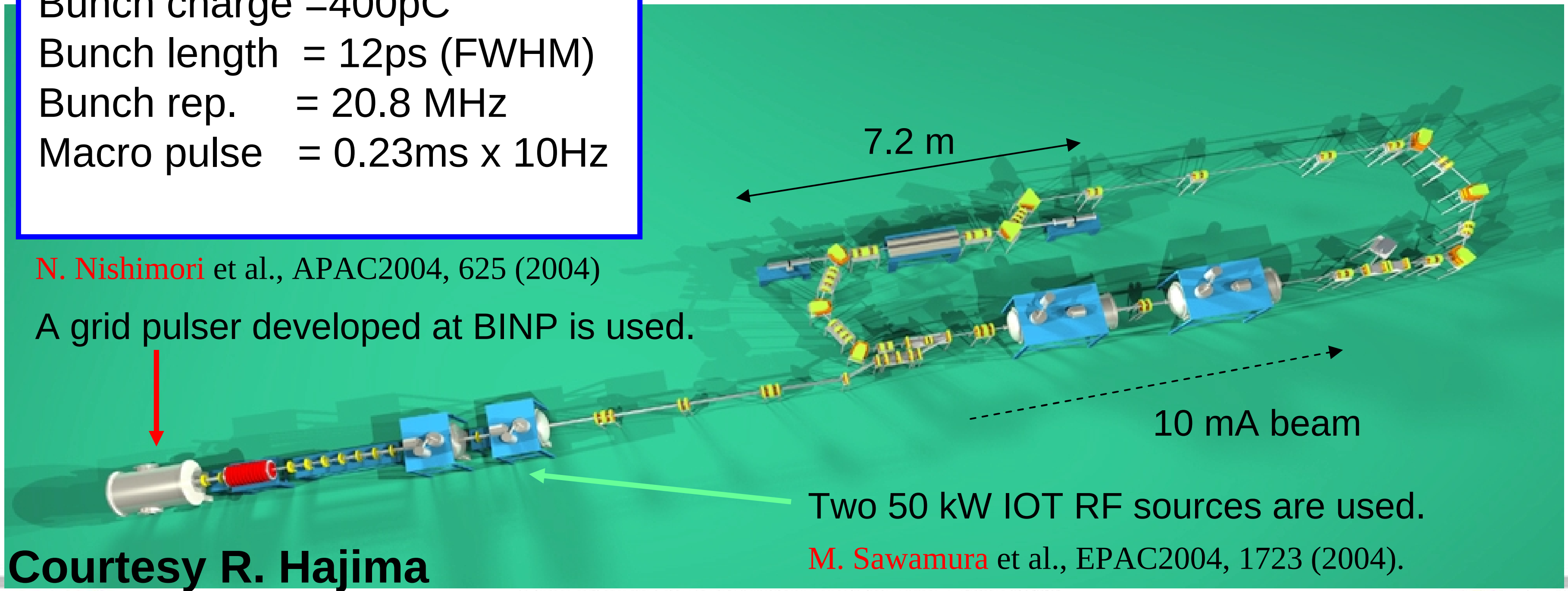
*Quantities are rms

# JAEA ERL Upgrade since 2004

1. Doubled bunch repetition rate of the gun grid pulser to 20.8 MHz (10mA)
2. Increase of RF sources for the injector SCAs from 8 kW to 50kW
   Improvement of low-level RF controller
3. Doubled energy acceptance of the return arc from 7% to 15%

Energy = 17MeV
FEL : $\lambda$ = 22$\mu$m
Bunch charge =400pC
Bunch length = 12ps (FWHM)
Bunch rep. = 20.8 MHz
Macro pulse = 0.23ms x 10Hz

R. Nagai et al., FEL2006, 312 (2006).




N. Nishimori et al., APAC2004, 625 (2004)

A grid pulser developed at BINP is used.

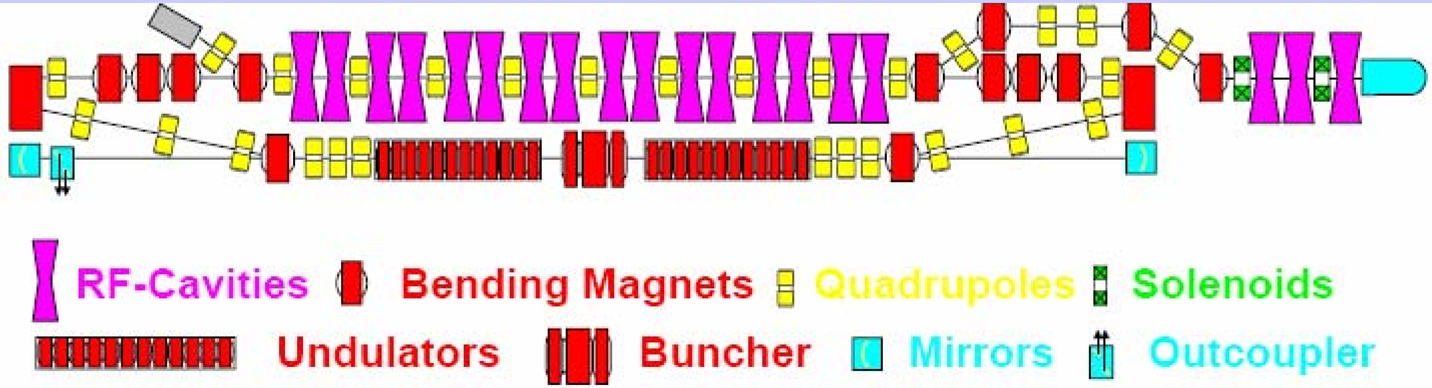
Two 50 kW IOT RF sources are used.

M. Sawamura et al., EPAC2004, 1723 (2004).

**Courtesy R. Hajima**

# The Novosibirsk High Power THz FEL

**Energy recovered highest average current to date: 20 mA at 1.7 nC per bunch**




| | May 2005 | Plans |
|---|---|---|
| RF frequency, MHz | 180 | 180 |
| Bunch repetition rate, MHz | 11.2 | 90 |
| Maximum average current, mA | 20 | 150 |
| Maximum electron energy, MeV | 12 | 14 |
| Normalized beam emittance, mm*mrad | 30 | 15 |
| Electron bunch length in FEL, ns | 0.07 | 0.1 |
| Peak current in FEL, A | 10 | 20 |

# On-going R&D in Operating ERL-FELs

…includes:

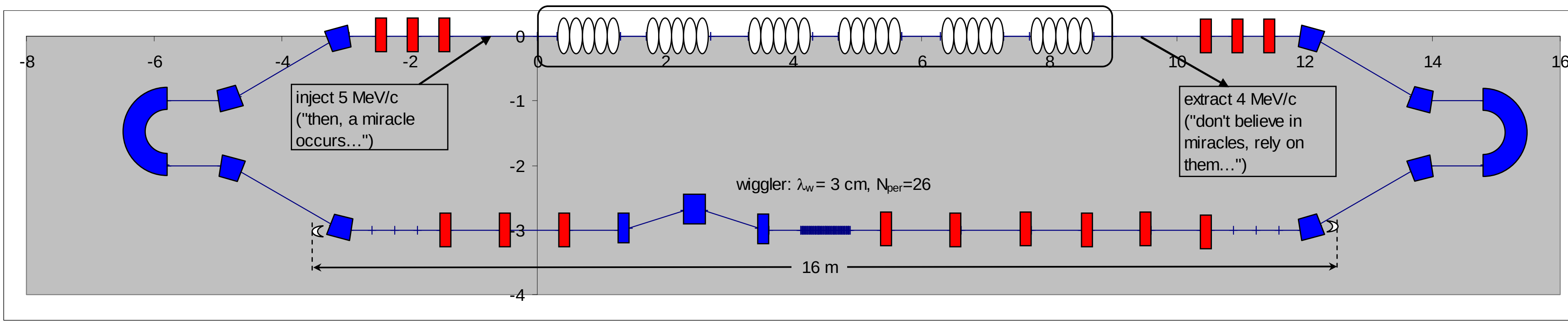
- High order transport measurements
- BBU observation, characterization, and suppression
- RF control tests at high $Q_L$
- Beam loss measurements and control
- Resistive wall wakefield effects
- LSC and CSR effects
- Transverse and longitudinal acceptance of an ERL
- High FEL extraction efficiency studies
- ERL Diagnostics development

# BrightLight: Palletizable 100 kW FEL Driver

- ERL driven 1-1.6 mm 100 kW FEL
- Considerable operational flexibility, but relatively compact
- Based on JLab 750 MHz “1 Amp Cryomodule” (in prototype)
- Supports either cavity oscillator (illustrated) or amplifier FEL

| | |
|---|---|
| I | 100 mA<br>(75 MHz X 1.4 nC or<br>750 MHz X 135 pC) |
| $E_{inj/full/dump}$ | 5, 100, 4 MeV |
| $f_{RF}$ | 748.5 MHz |
| $h_{FEL}$ | 1% |
| $P_{e^-\ beam/FEL}$ | 10 MW/100 kW |

**Courtesy: D. Douglas**

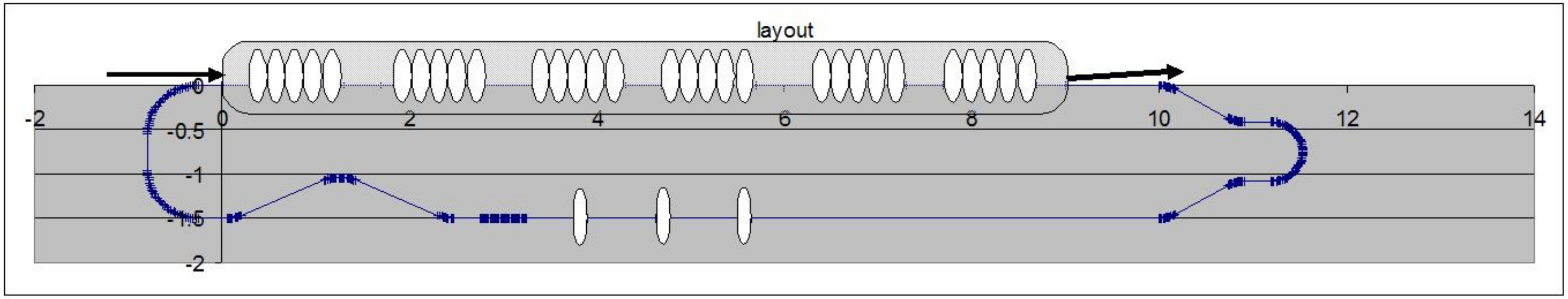


# "MADMAN" – compact transportable system

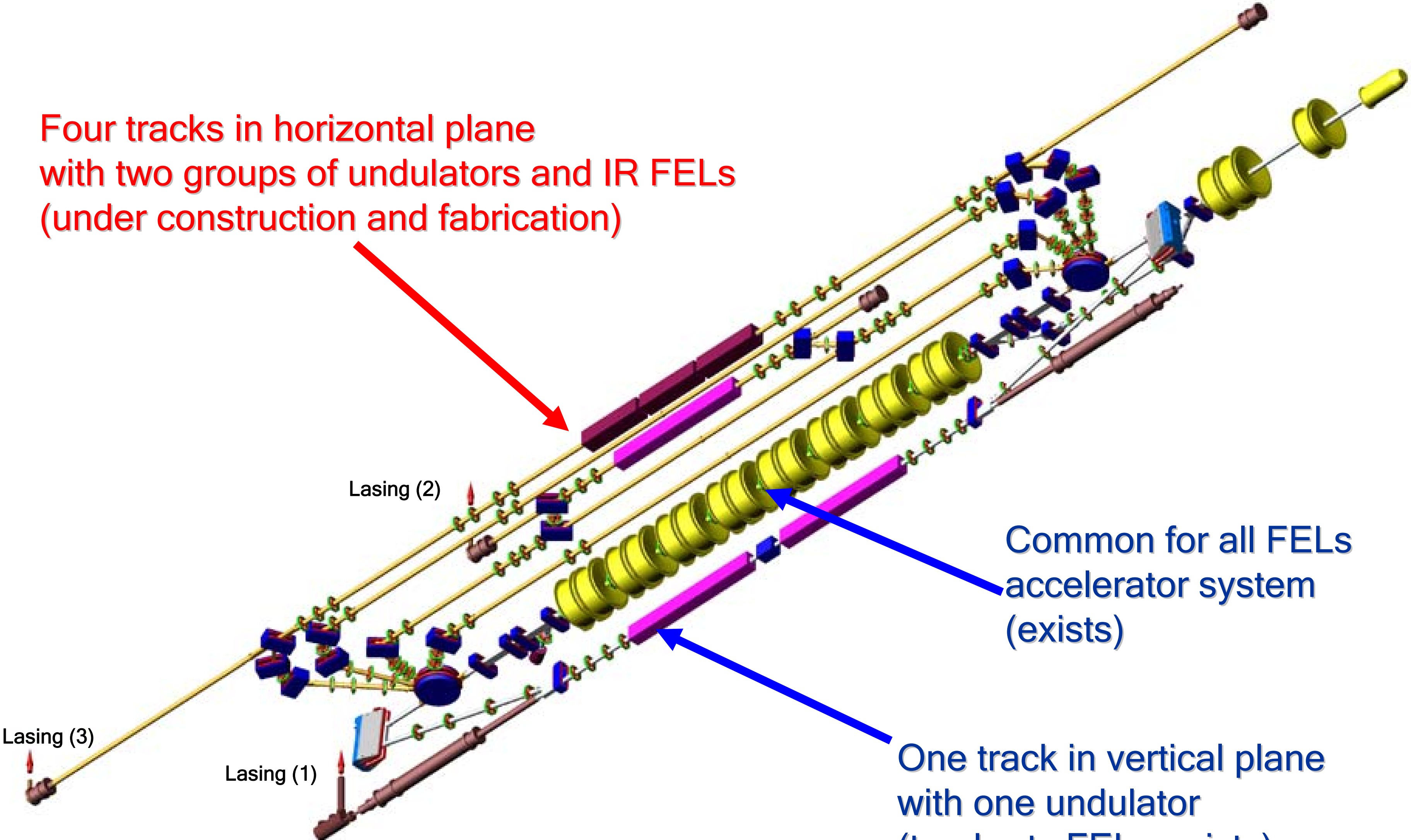
**Courtesy: D. Douglas**

- ERL driver for high power THz & FEL sources
- Extremely compact with low parts count; "turn-key" operation
- Based on JLab 750 MHz "1 A Cryomodule" (in prototype)
- Supports either cavity oscillator (illustrated) or amplifier FEL
- Uses "direct" injection/extraction (no merger)

| | |
|---|---|
| I | 100 mA+ |
| $E_{inj/full/dump}$ | 2, 100, 2 MeV |
| $f_{RF}$ | 748.5 MHz |
| $h_{FEL}$ | >1% |
| $P_{e^-\ beam/FEL}$ | 10 MW+/100 kW+ |



# Full scale Novosibirsk FEL (bottom view)

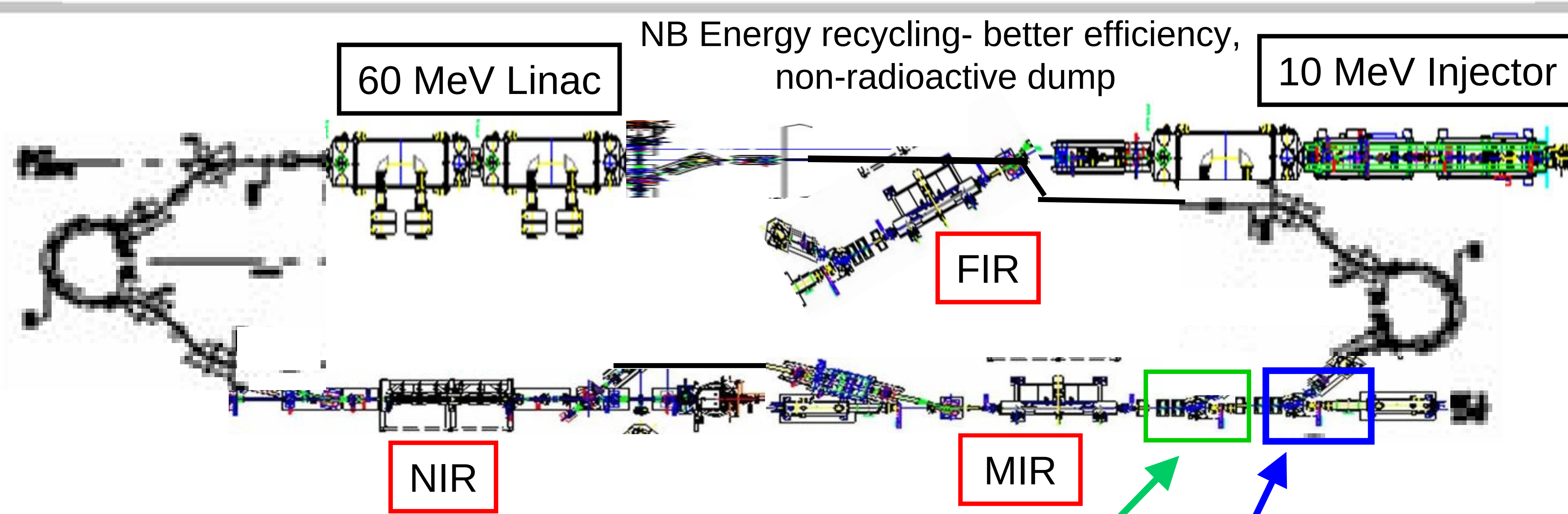


# Future ERL-based FEL Projects

- NHMFL
- KAERI
- PKU-ERL-FEL
- ERLP
- Arc-en-Ciel
- 4GLS

Apologies to any project that has not been mentioned !

# NHMFL's "Big Light" Source - Conceptual View




Three FEL Undulators for NIR-MIR-FIR. FIR driven by injector.

'CUFT' = Coherent Undulator for Terahertz Spectroscopy; gives frequencies up to 10 THz.

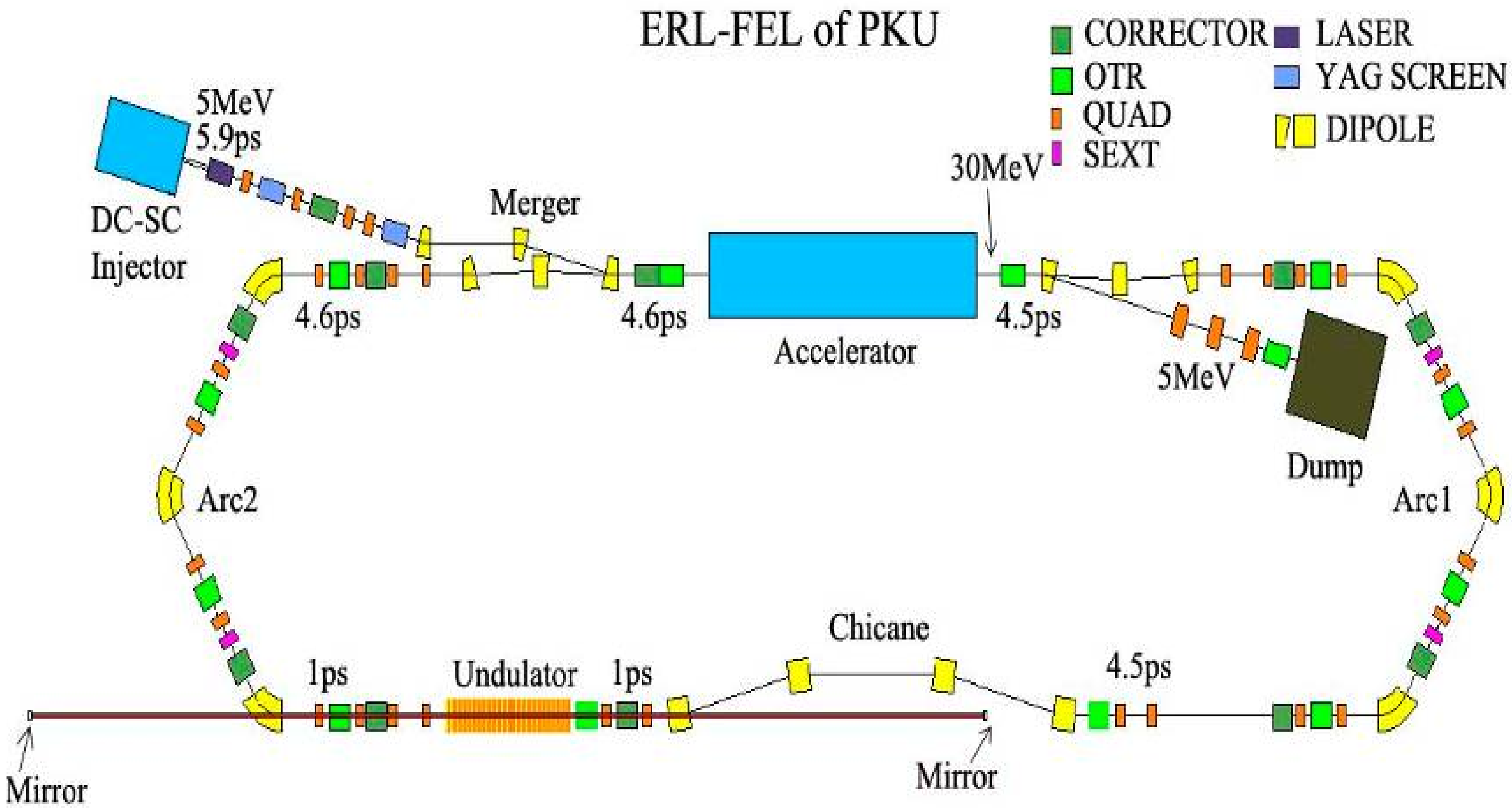
Broad-Band Terahertz Source; to 3 THz approx.

**10 m**

Thanks to George Neil (Jlab); apologies to Dresden for (mis)use of their images.

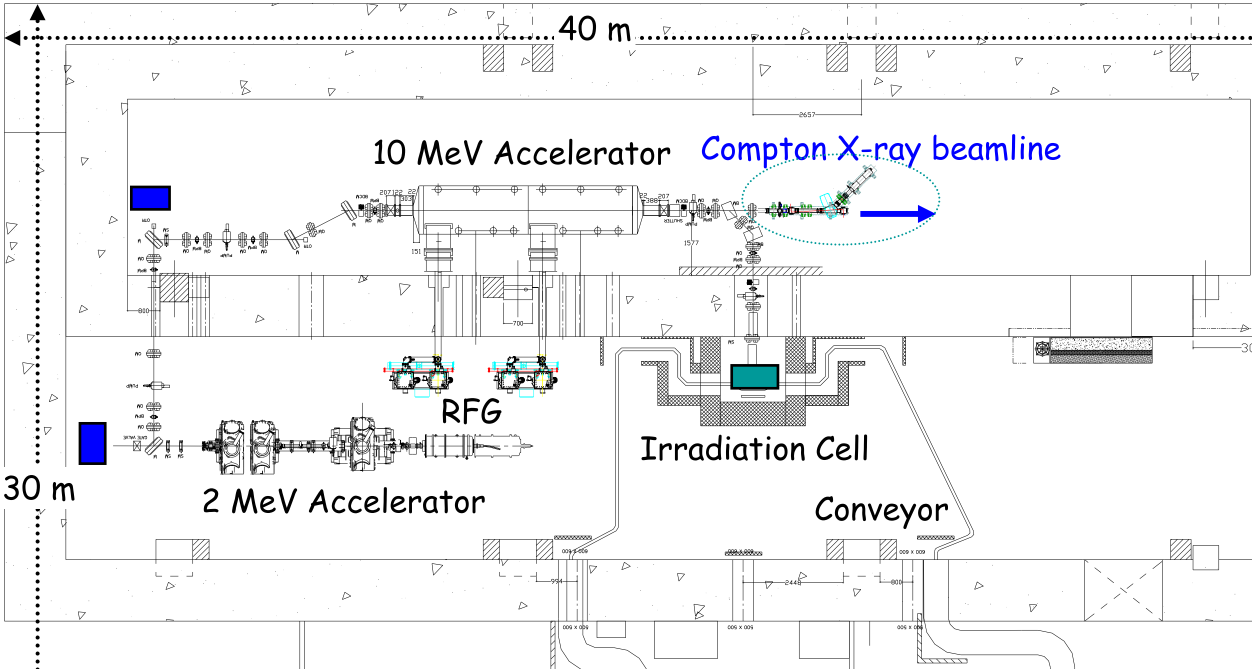
# PKU-ERL-FEL

## Draft design of PKU-ERL-FEL facility




Liu Xiangyang, PKU (from Beijing ILCWS 07)

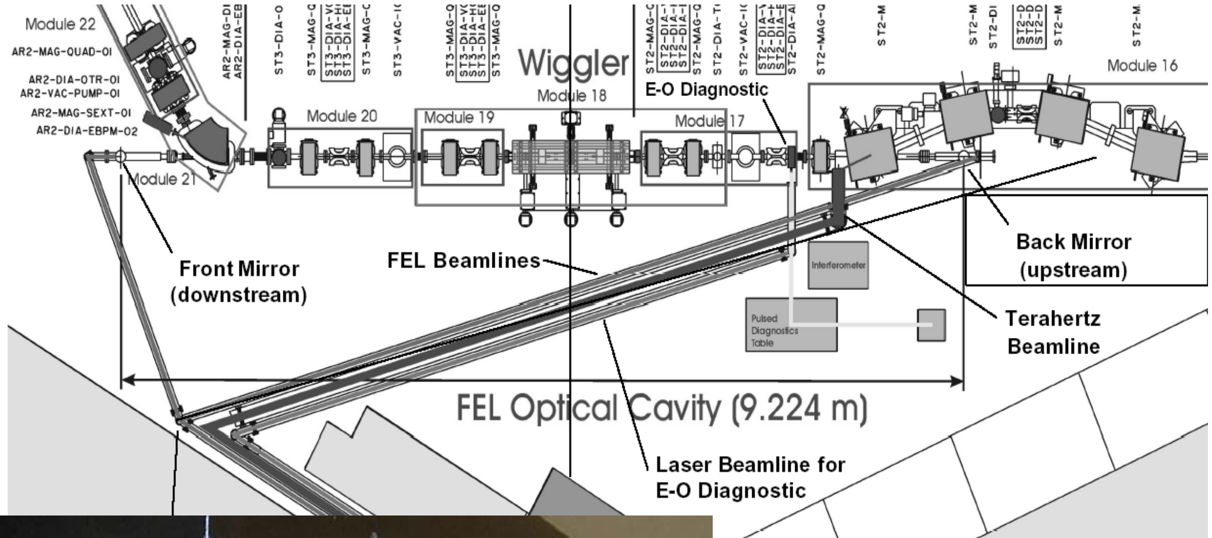
# Status of KAERI Electron Accelerator Facility

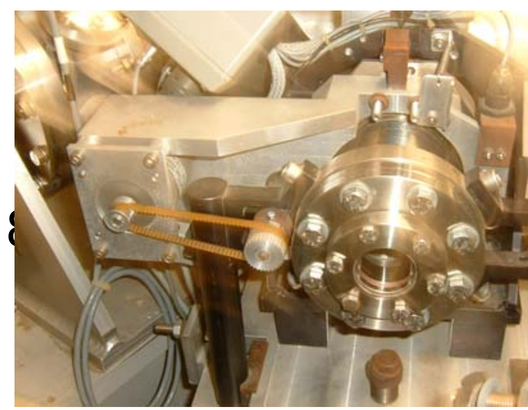







# The ERLP IR-FEL



0.6 ps

# Three phases project

- ARC-EN-CIEL phase 1 :

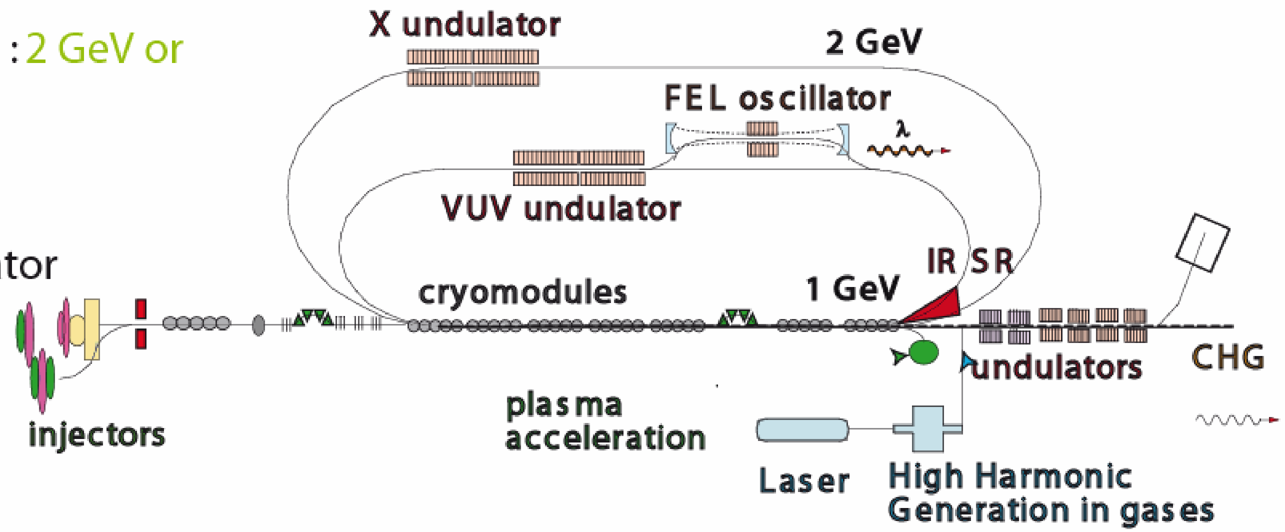
  Linear accelerator : 220 MeV (or 330 MeV), low energy spread, low emittance
  femtosecond HGHG sources : 100-10 nm, high brilliance and coherence

- ARC-EN-CIEL phase 2 :

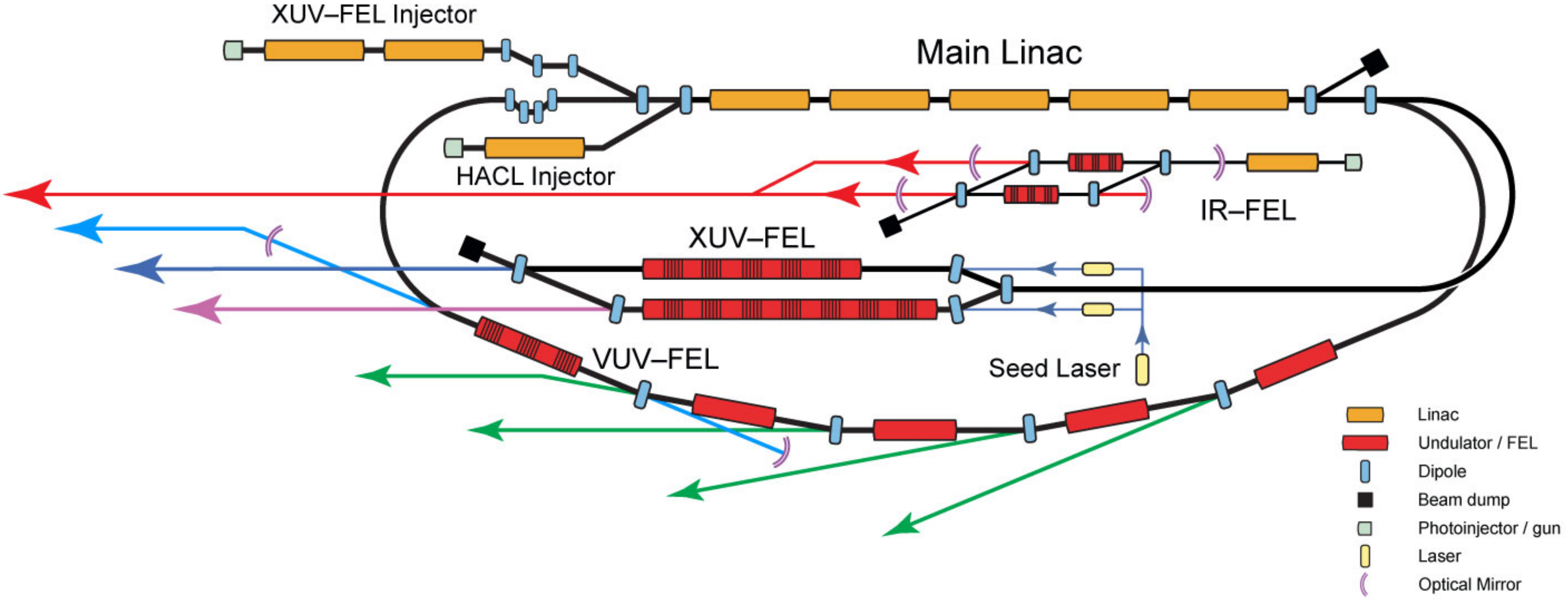
  Linear accelerator : 1 GeV
  HGHG sources : down to 1 nm

- ARC-EN-CIEL phase 3 :

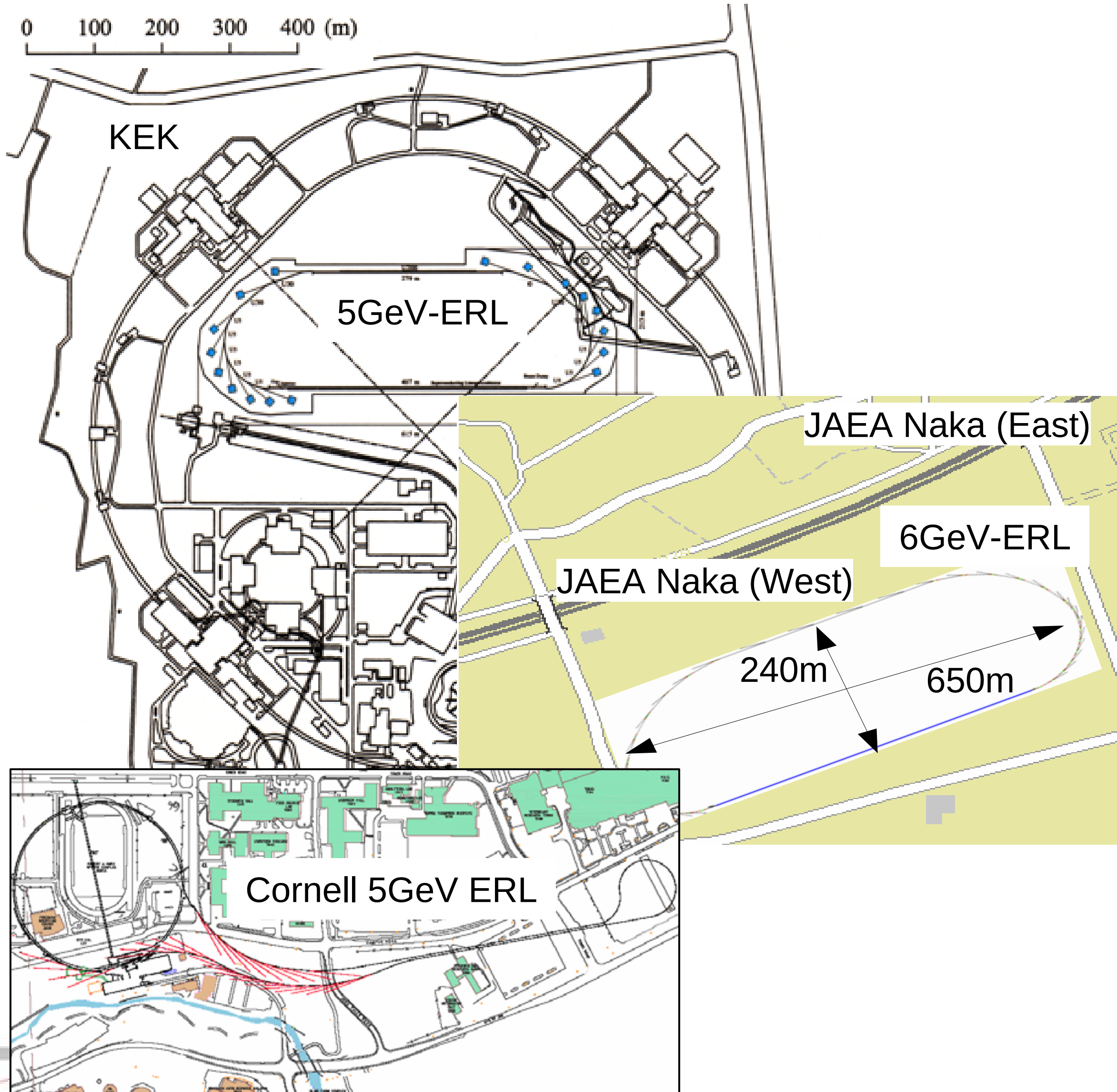
  Additionnal loops : 2 GeV or increased current
  HGHG sources
  UV FEL oscillator
  VUV and X undulator

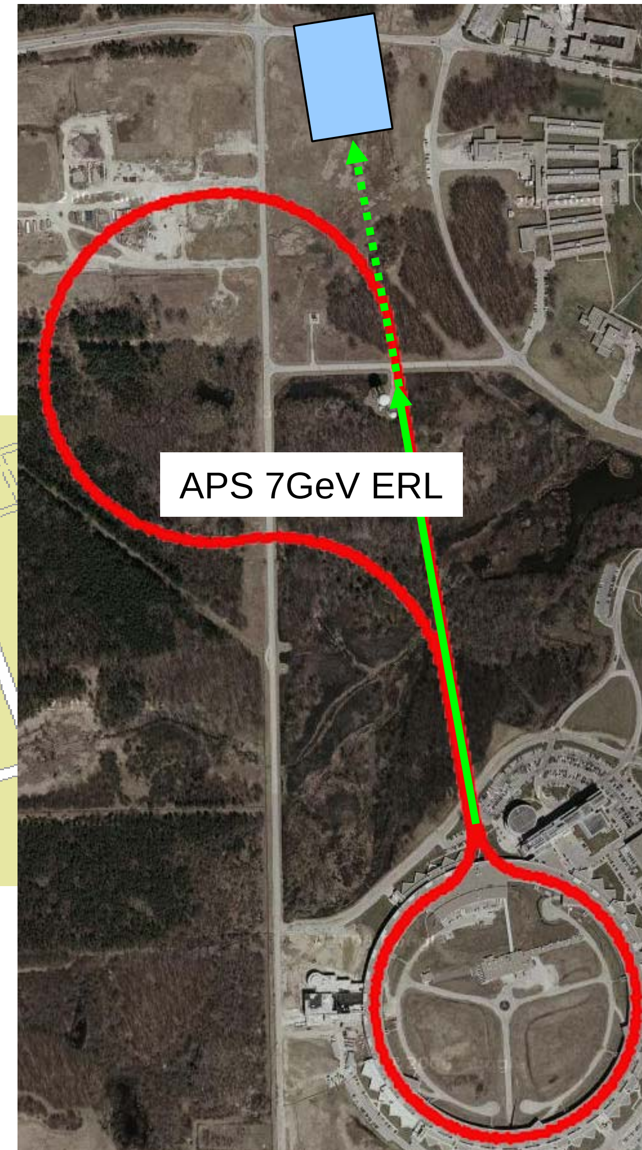


# The 4GLS Concept



# Cornell / KEK / JAEA / APS ERLs



# Challenges for x-ray ERLs

- Production of low emittances + limiting emittance growth (WG1 / WG2)
  - Limit coupler kicks / cavity misalignments
  - Limit optics errors and adjust fields to radiated energy
  - Low emittance growth optics similar to light sources
- Limit energy spread after deceleration, e.g. 5GeV to 10MeV (WG2)
  - Accurate time of flight correction, including sextupoles
  - Limit energy spread from wake fields
  - Limit energy spread from intra beam scattering (IBS) and rest gas scattering
  - Limit energy spread from incoherent / coherent synchrotron radiation (ISR / CSR)
- Manage user community
  - Running with different modes, bunch patterns, currents
- Beam stabilization – as stable as rings (WG4)
  - Limit beam breakup instability (BBU)
  - Limit beam jitter by feedback
  - Tolerances
- Beam loss concerns
  - Beam loss from IBS / Tourschek
  - Rest gas scattering
  - Disturbance from ions / ion removal
  - Halo development
- Superconducting RF challenges (WG 3)
  - Phase and amplitude control for very narrow frequency window ($10^{-8}$)

ERL07 41st Advanced ICFA Beam Dynamics Workshop on Energy Recovery Linacs
Daresbury Laboratory, UK, May 21-25, 2007

# ERLs in High Energy and Nuclear Physics

Vladimir N. Litvinenko,

Ilan Ben-Zvi, Yue Hao, Dmitry Kayran, Vadim Ptitsyn, Thomas Roser

*Collider-Accelerator Department*

*Brookhaven National Laboratory*

Acknowledgements:

BNL teams working on electron cooling and eRHIC

V. Yakimenko, BNL

R. Hajima, JAERI

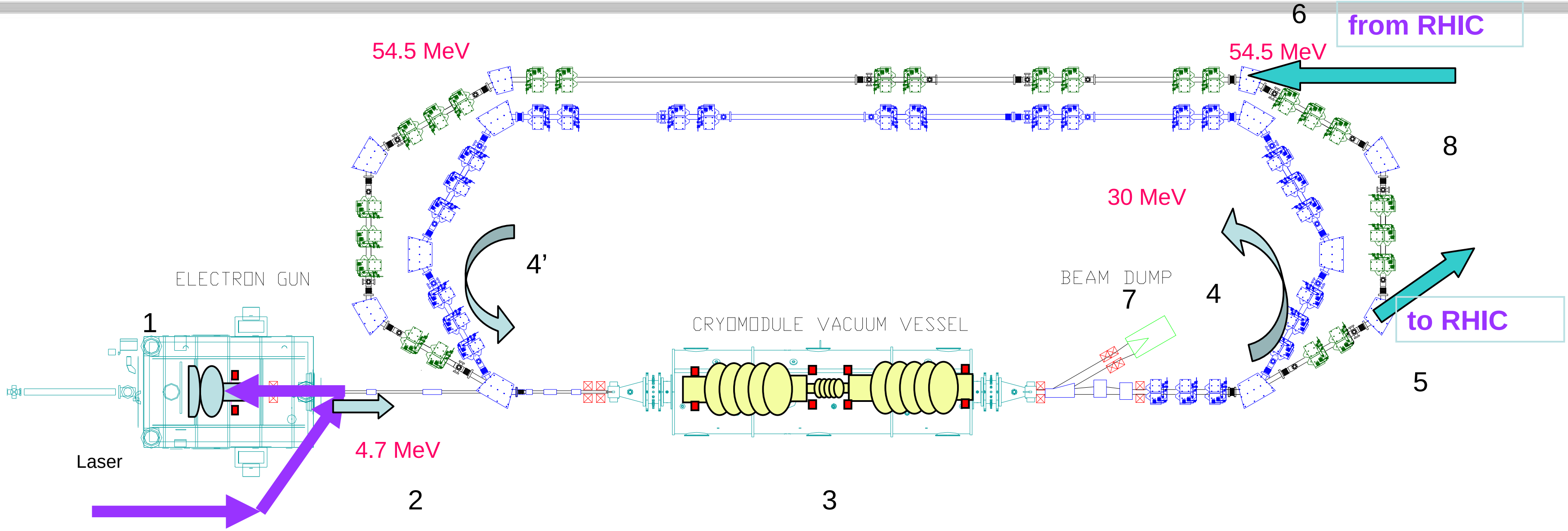
T. Omori, M. Kuriki (KEK)

BROOKHAVEN NATIONAL LABORATORY

*Vladimir N. Litvinenko, ERL 2007 workshop, Daresbury Lab, May 21, 2007*

RHIC

# E-cooler: 2 passes ERL layout




1. SRF Gun,
2. Injection merger line
3. SRF Linac two 5-cell cavities and 3rd harmonic cavity

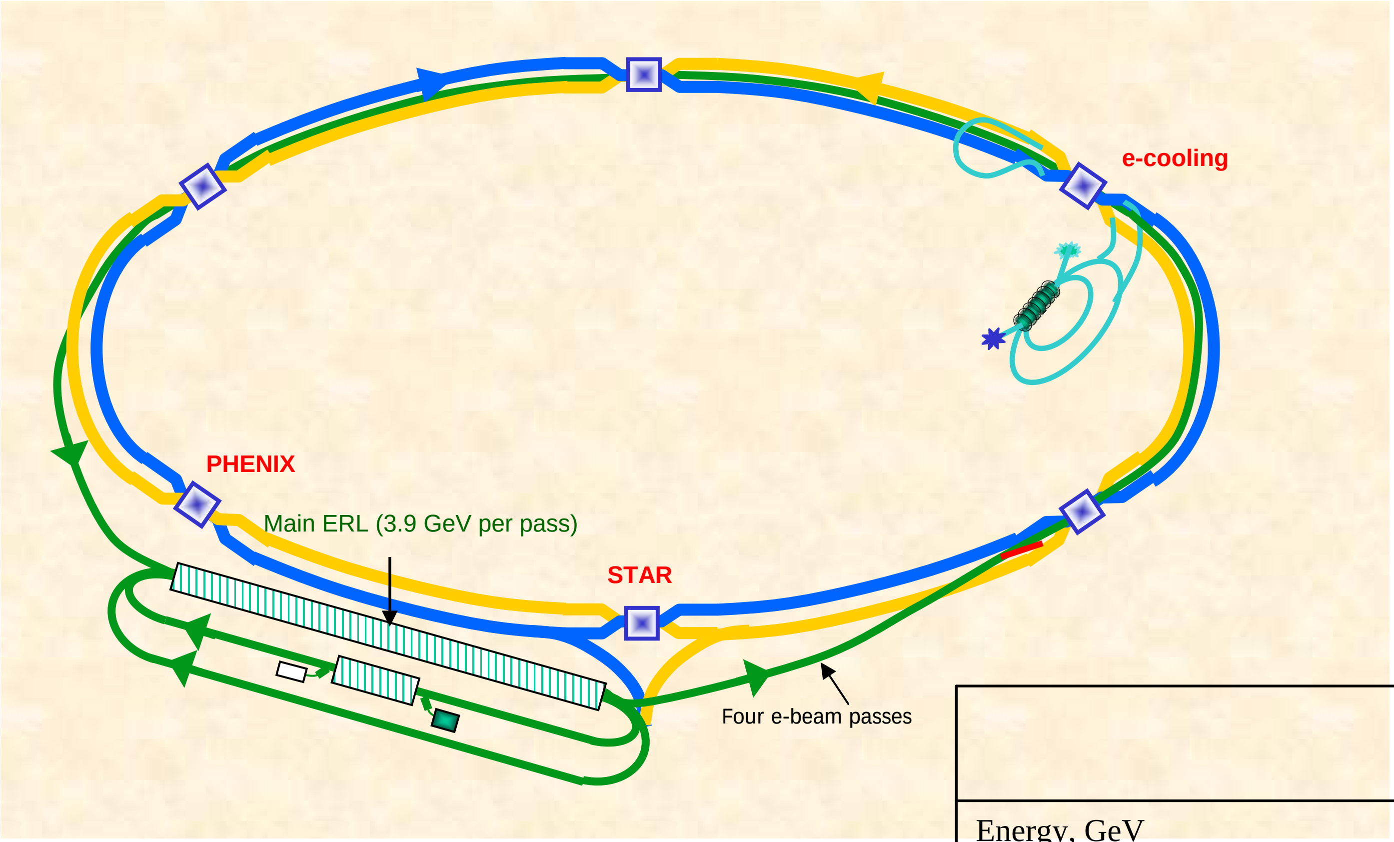
4, 4'. 180° achromatic turns

5, 6. Transport lines to and from RHIC,

7. Ejection line and beam dump
8. Short-cut for independent run of the ERL.

54 MeV, 5 nC at 9.4 MHz. RF 703.75 MHz. Gun 5 MeV

# Second objective: ERL based eRHIC




High current
AND
High charge

| | High energy setup | |
|---|---|---|
| | p | e |
| Energy, GeV | 250 | 20 |
| Bunch intensity, $10^{11}$ | 2 | 1.2 |
| Beam current, mA | 420 | 260 |
| Peak Luminosity, 1.e33 $cm^{-2}s^{-1}$ | 2.6 | |

Presented by Vladimir

# Conclusions

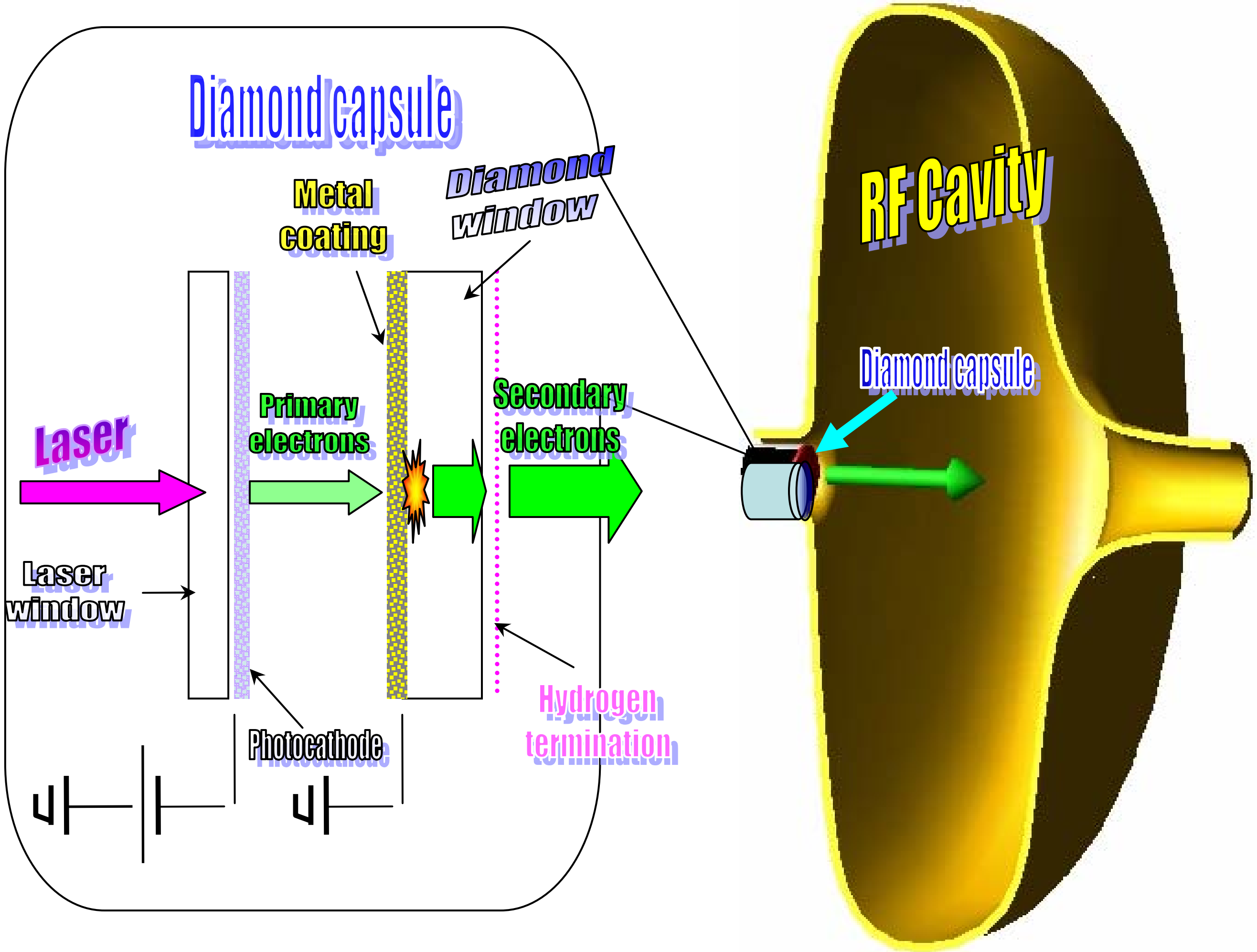
- Bright future for ERL in High Energy and Nuclear Physics: from supporting roles to head-on collisions
- High energy electron cooling of hadrons (both traditional and stochastic) is one of the most promising applications for ERLs: example *ERL-based e-Cooler for RHIC @ BNL*
- High energy, high luminosity ERL-based electron-ion and polarized electron-proton collider is the most promising approach : example *ERL-based electron-ion collider eRHIC @ BNL*
- ERLs can play important role in generating very intense beams of $\gamma$-rays for many applications in HENP: producing beams of rare isotopes, polarized positrons or transmutation of nuclear waste.
- R&D on high current, high brightness ERL address many issues required for such applications: *R&D ERL at BNL - talk this afternoon by Ilan Ben Zvi*

# The BNL High-Current R&D ERL

- Aimed at pushing the limits for beam current: 0.5 amperes
- Testing of novel components and techniques:
  - Superconducting electron gun
  - Diamond amplified photocathode
  - Z-bend ERL beam merging
  - High-current SRF cavity at 703.75 MHz
  - Diagnostics and more.
- Working with industry (AES) on many aspects

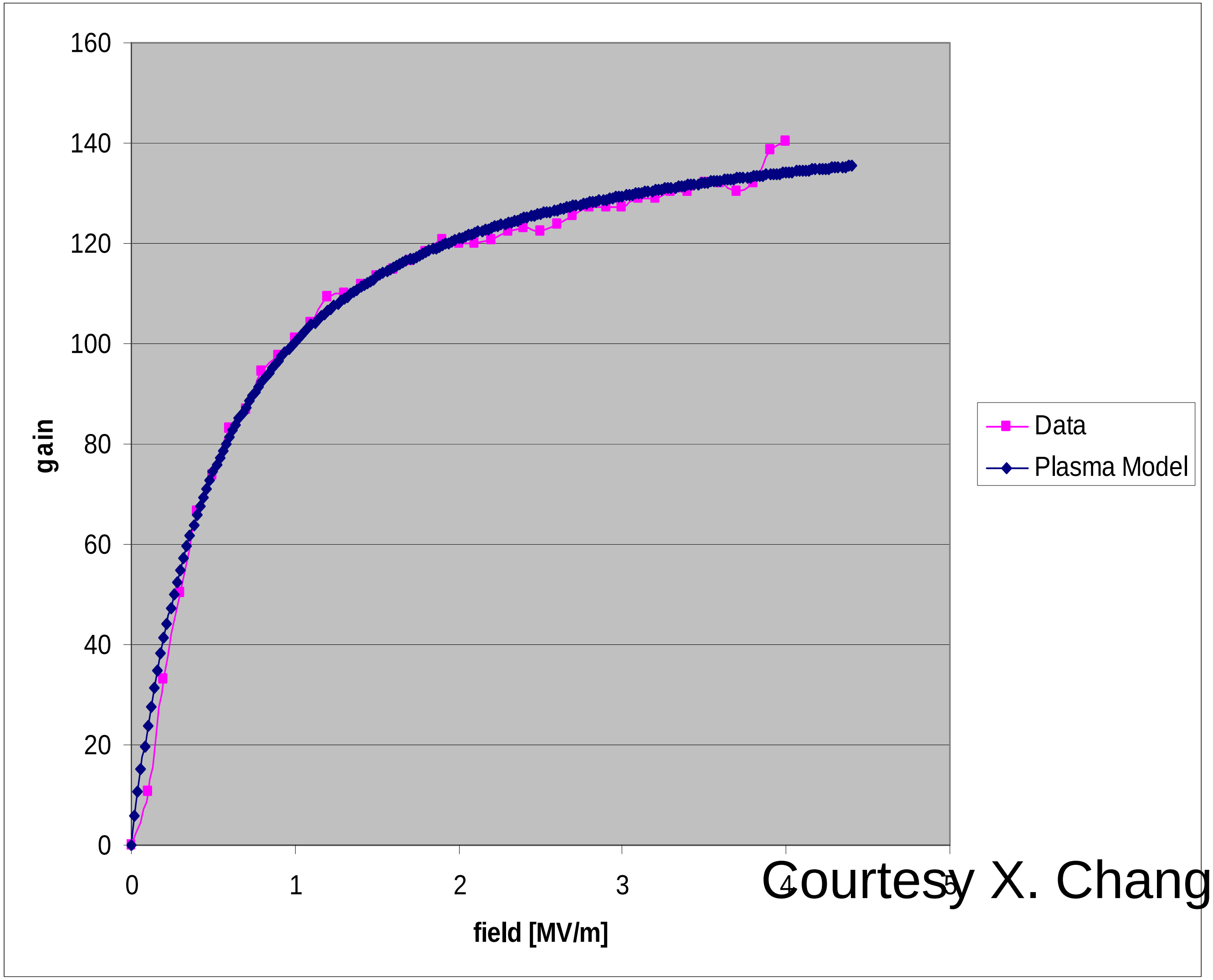
# Some of the installed equipment

# Diamond amplified photocathode



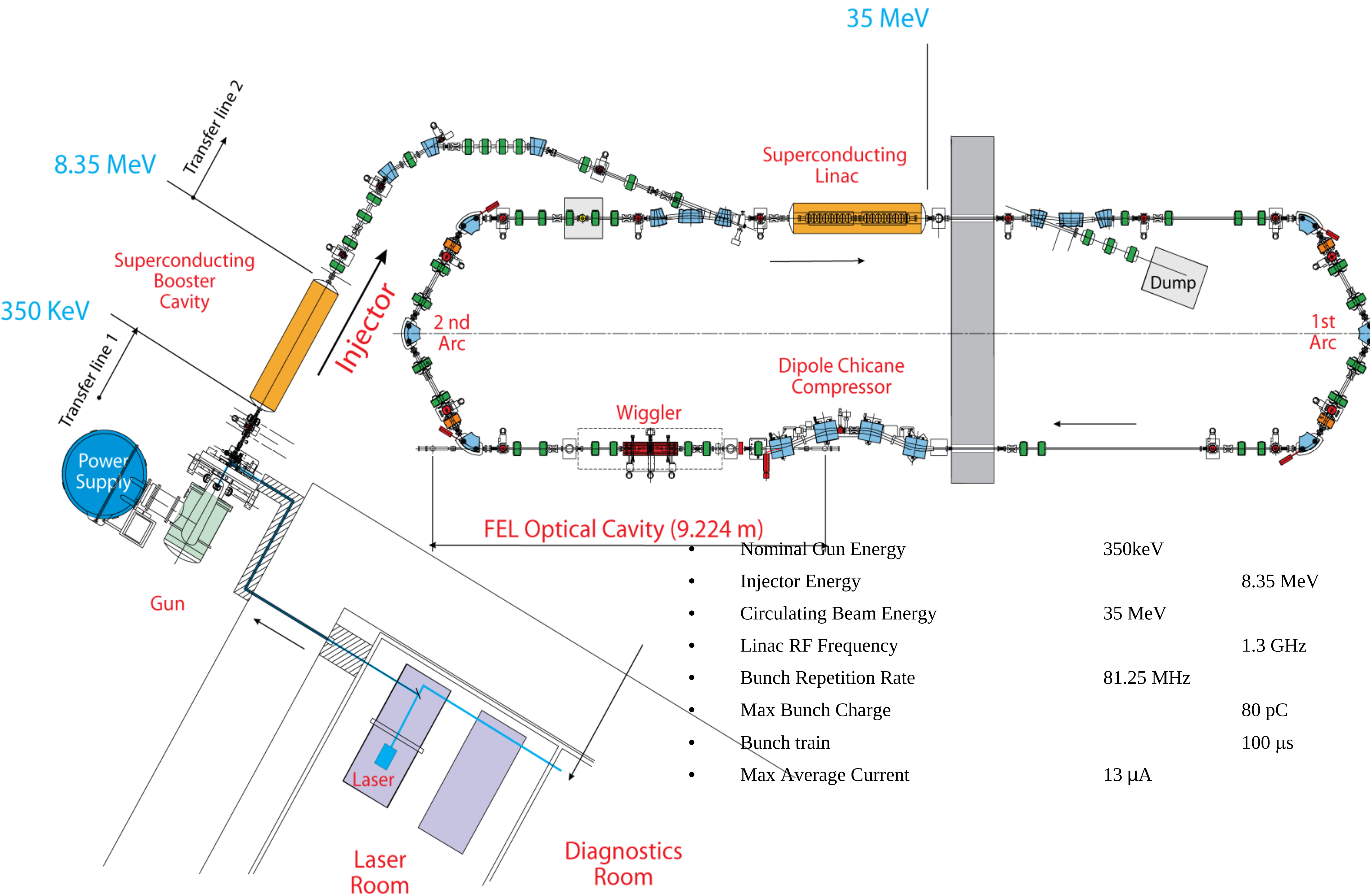

Courtesy Xiangyun Chang. See talk by Triveni Rao.

# Gain measured in emission into vacuum



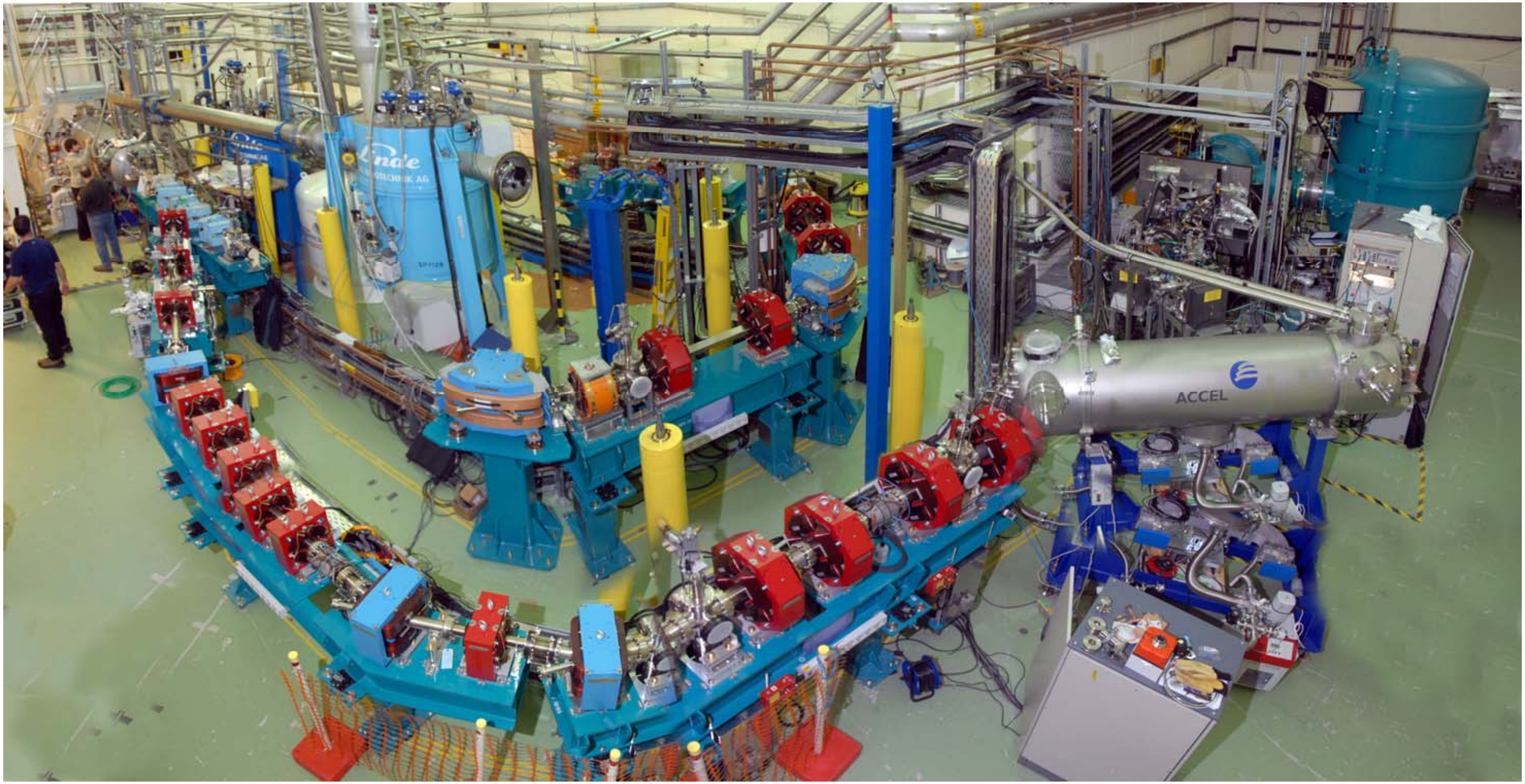

Courtesy X. Chang

# ERLP Accelerator Layout




- Nominal Gun Energy 350keV
- Injector Energy 8.35 MeV
- Circulating Beam Energy 35 MeV
- Linac RF Frequency 1.3 GHz
- Bunch Repetition Rate 81.25 MHz
- Max Bunch Charge 80 pC
- Bunch train 100 µs
- Max Average Current 13 µA

# ERLP Accelerator installation



# ERLP Ongoing work

- Baking of injector
- High gradient tests of linac module
- Commissioning of booster RF system for acceptance tests
- Cryo system optimisation with RF
- Commissioning of beam transport system systems
    - Controls
    - Diagnostics
    - Machine protection system

# ERLP Future Plans

- Confirmation linac gradient this week
- Confirmation booster gradient end August
- Gun & diag line studies finished mid August
- Booster repositioned early Sept
- Beam through booster Oct
- Beam through the linac end Nov
- **Energy recovery demonstrated** Christmas!

2008

- Compton backscatter phase 1
- Install wiggler
- Energy recovery from FEL-disrupted beam
- Produce output from the FEL

# Summary of Working Group 2

ERL07 41st Advanced ICFA Beam Dynamics Workshop on Energy Recovery Linacs
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## Summary of Working Group 2 Optics and Beam Transport

Ryoichi Hajima (JAEA)
Hywel Owen (DL)

ICFA WS ERL07 | Summary of WG2 | 1

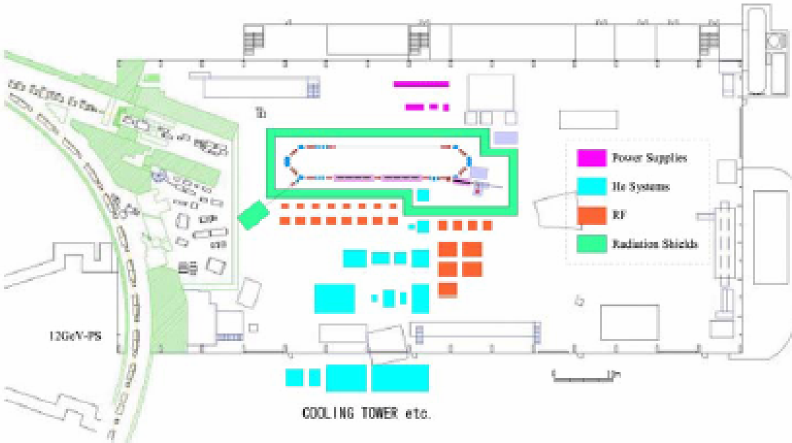
# WG2 issues

- classical but important
  - linear and nonlinear optics
  - emittance preservation
  - bunch compression
  - effects of CSR
  - BBU
- unresolved or ERL-specific
  - trapped ions
  - long-range resistive wall
  - energy spread after deceleration
  - path length correction
  - beam loss: sources and management
- issues raised from recent progress of components
  - cavities for high-average current →multi-turn operation
  - ultra-high-brightness electron sources → precise simulation technique

# Lattice and optics designs of the planned test ERL in Japan

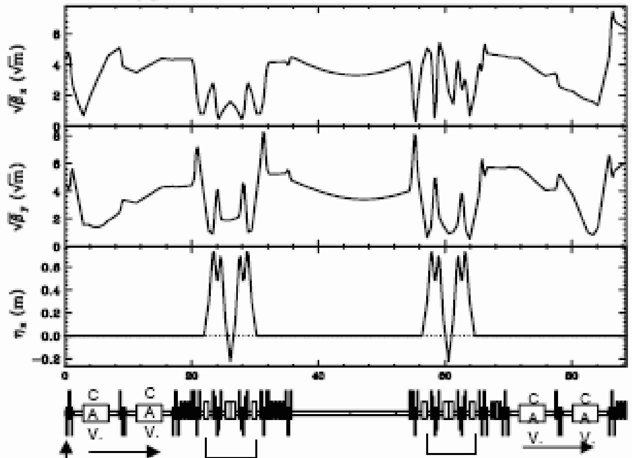
Shogo Sakanaka

Planned test ERL at KEK Counter Hall.

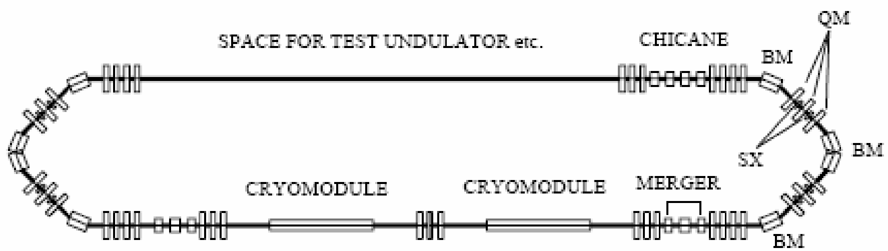



Principal parameters.

| | |
|---|---|
| Beam energy | ~ 60 MeV (160-200 MeV) |
| Injection energy | 5 MeV (10-15 MeV) |
| Beam current | 10 mA (100 mA) |
| Normalized emittance | 1 mm·mrad (0.1 mm·mrad) |
| Rms bunch length | Usual mode : $\sigma_\tau$ = 1-2 ps<br>Short bunch mode : $\sigma_\tau$ ~ 100 fs? |



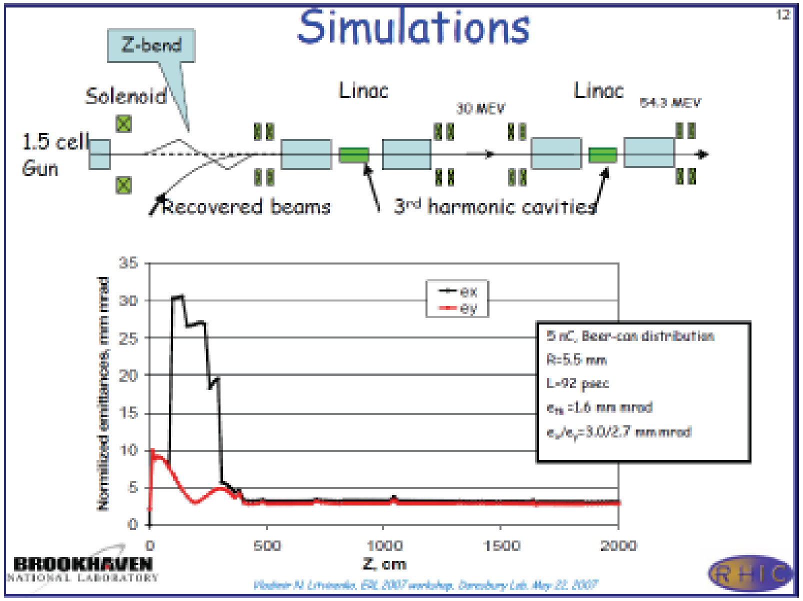

Lattice of the test ERL



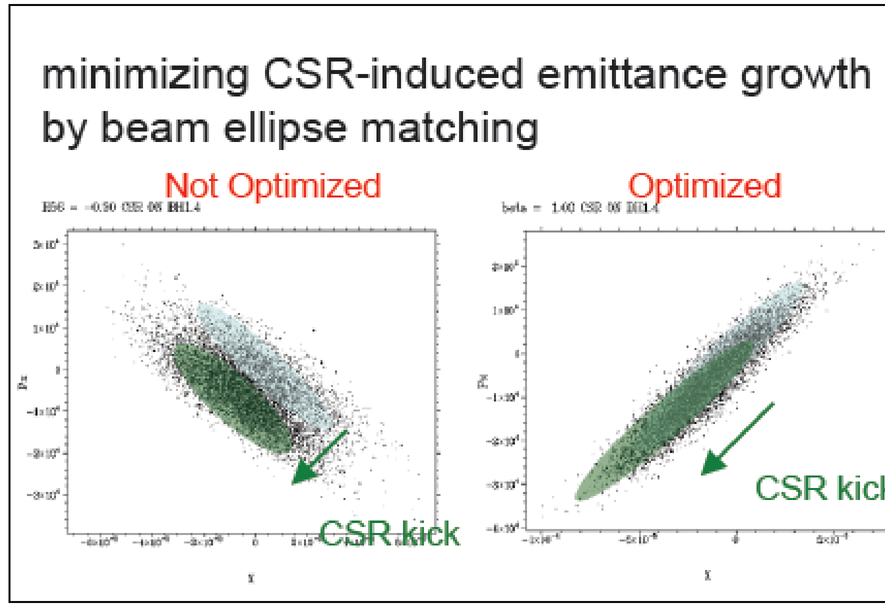
# emittance preservation

always critical, many talks involve this subject.

V. Litvinenko




Miho Shimada

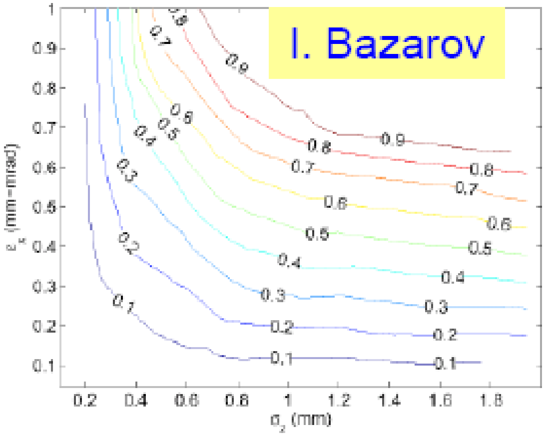



we are eagerly awaiting experimental proof.

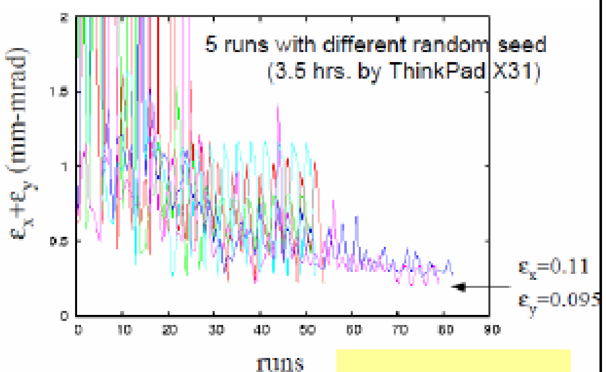
# multi-variants optimization

ERL 2005

I. Bazarov




5 runs with different random seed
(3.5 hrs. by ThinkPad X31)

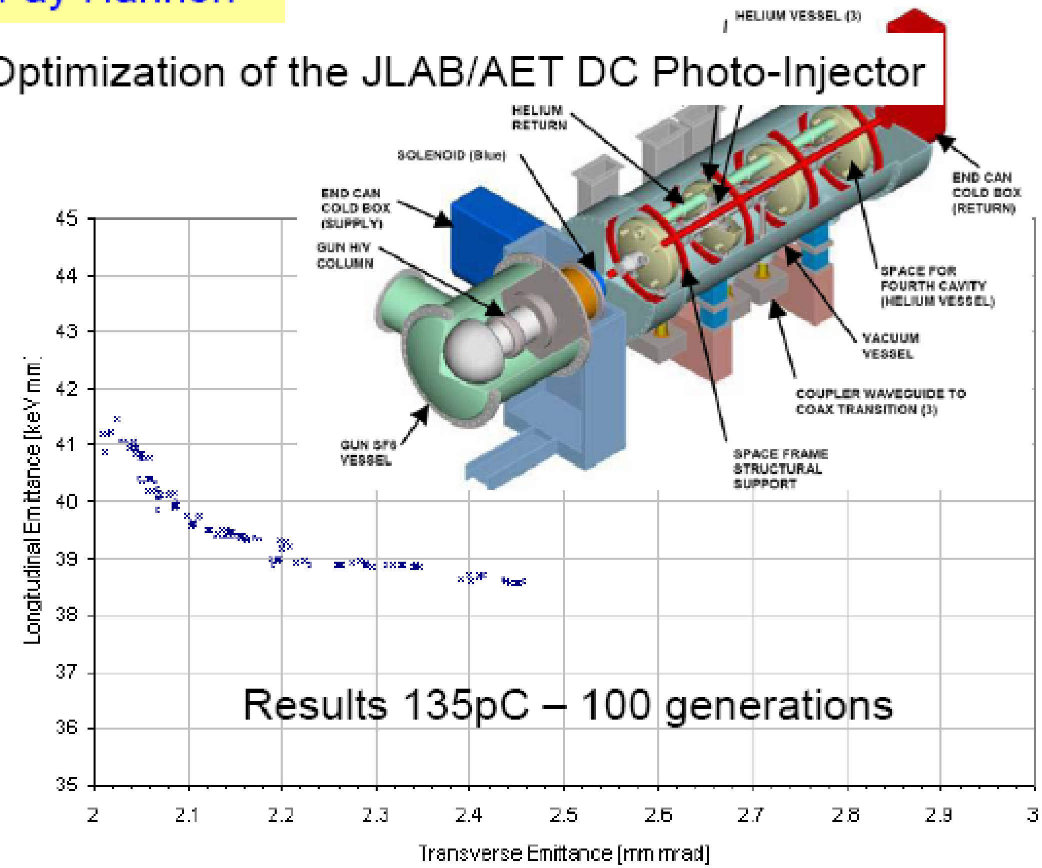



R. Hajima

New at this workshop

Fay Hannon

Optimization of the JLAB/AET DC Photo-Injector




Results 135pC – 100 generations

# multi-variant optimization

- Powerful tool to design ERL injectors
  - minimizing transverse & longitudinal emittance during capture, compression, acceleration of an electron bunch from zero-energy to several MeV.
- Quite efficient with evolutionary algorithm (GA).
- Don't be ignorant about physics behind.

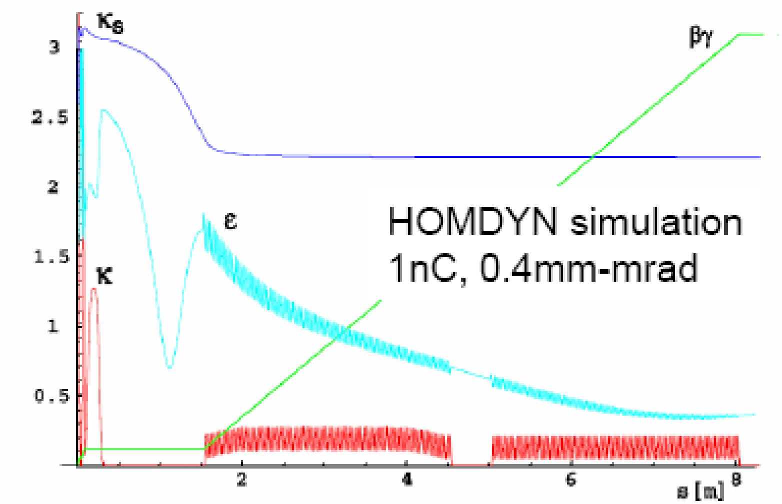
# extended envelope analysis in an injector

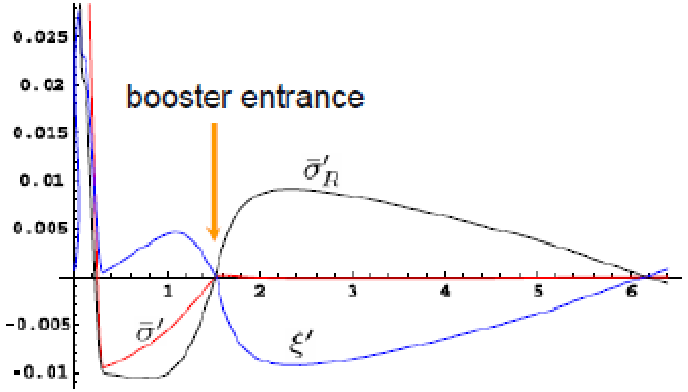
Chun-xi Wang

- Introduce an optics framework for analyzing emittance evolution close to an arbitrary reference envelope, which can be far from the invariant envelope, especially during the emittance compensation process

new condition for superior emittance compensation → $\bar{\sigma}'(s_b) = \bar{\sigma}'_R(s_b) = \xi'(s_b) = 0$

*Example: optimized SPARC injector for SASE FEL*




The SPARC design fulfils the above criteria, though they didn't know them.

Question; Do the results of multi-variant optimization follow the condition?

# Touschek scattering

M. Borland

- Touschek scattering (single Coulomb scattering) is expected to be a significant source of beam loss in ERLs due to low emittance and short bunches
- In APS ring, we want loss current below 170 pA, due to thickness of existing shielding
- Using Piwinski's formalism, we can estimate the required energy aperture needed to keep the loss rate below a specified level
  - For ERL beam, need energy acceptance of +/- 1% in APS ring
  - +/- 2% acceptance would give about 11 pA loss current
- We optimized the energy acceptance by tracking with parallel version of **elegant**
  - Insert single-scattering elements after each magnet with +/- 2% energy deviation
  - Adjust sextupoles until transmission through system is optimized
  - Resulting energy acceptance of APS portion is +/- 5%
  - Losses in external turn-around arc reduced 23-fold
- We also modeled the use of perfect collimators at a few locations and found them effective in reducing losses in sensitive areas
- Plan to add a physically correct model of Touschek scattering to **elegant** to give more quantitative results.

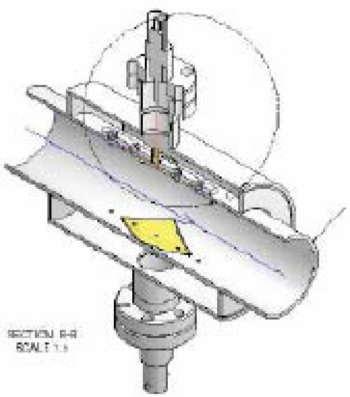
# Ions in ERLs

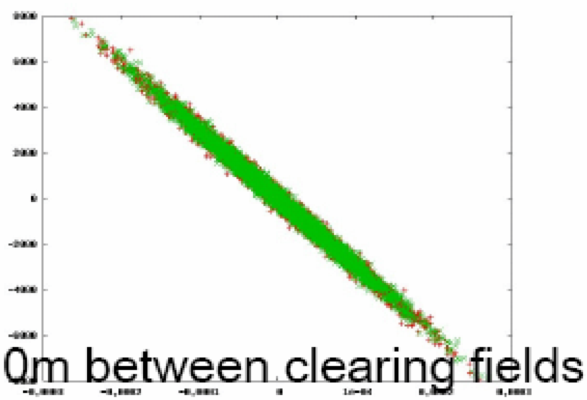
Ion trapping may cause large betatron tune-shifts or fast ion instabilities in ERLs.

G. Hoffstaetter

Ion clearing electrodes:

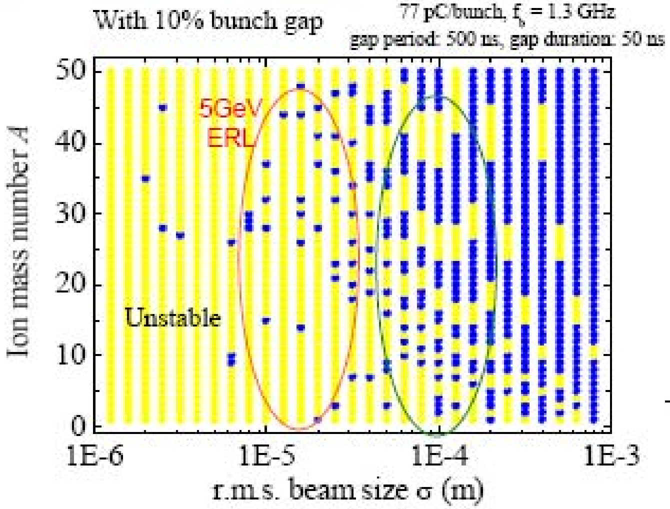
- A set of electrodes that draw ions out of the beam potential.
- They have to be located at the minimums of the electron beam, where the ions would otherwise accumulate.
- The damage from this density can be made acceptably small by spacing clearing electrodes close enough together (about 10m).





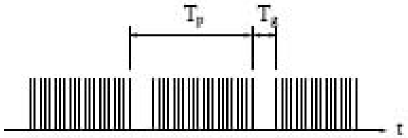
# Effect of bunch-gaps on ion trapping

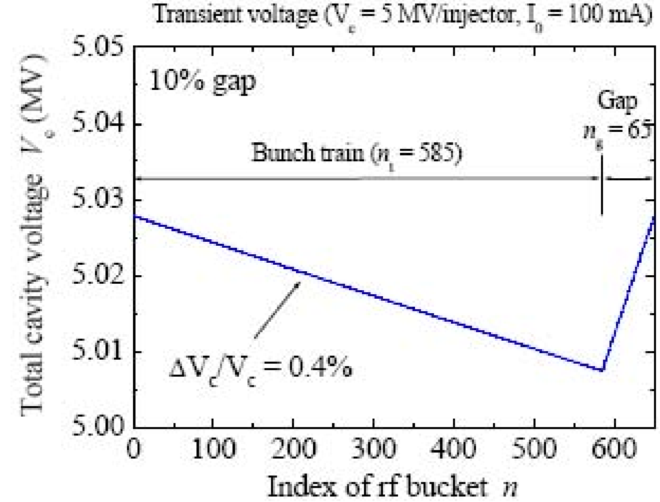
S. Sakanaka



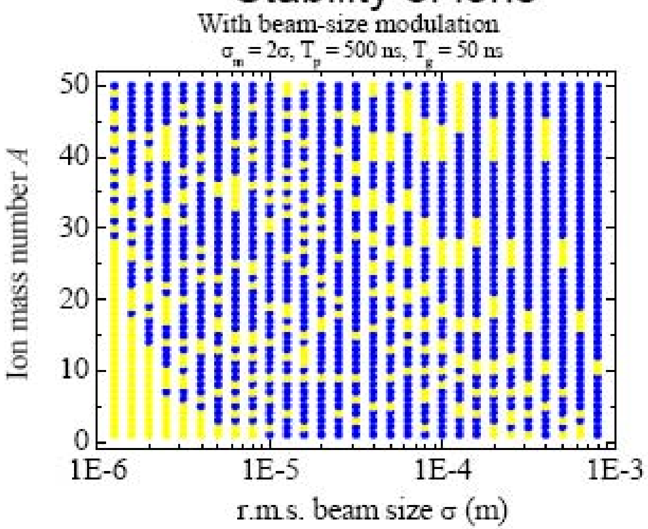

Stability of ions

2 MHz
10% gap

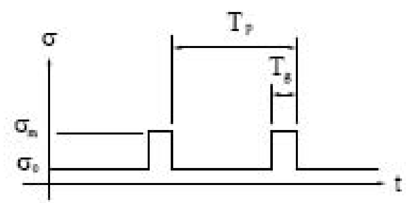



Bunch-gap transient in injector




Beam-size modulation
× 2, 2 MHz




Short bunch-gaps (~50 ns)
+
ultra-high vacuum
can be a strong candidate for the cures for ion trapping

# shield relaxes CSR

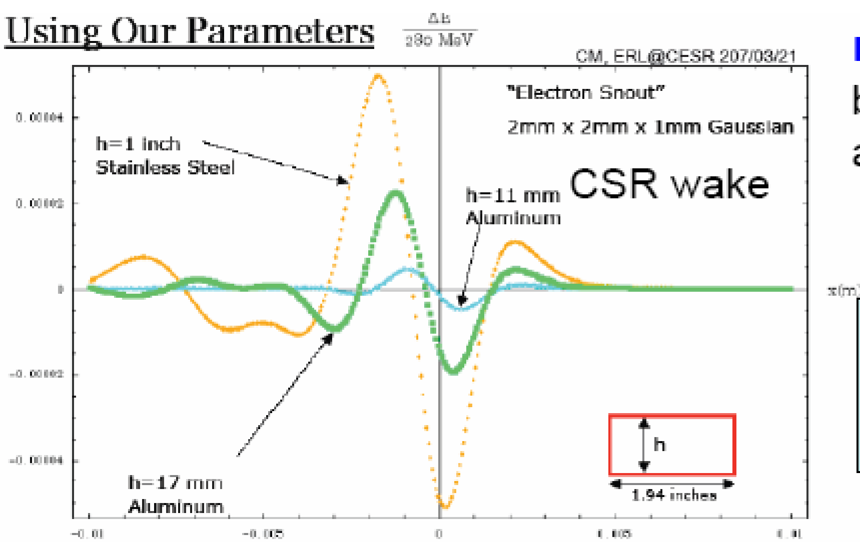
G. Hoffstaetter

CSR in Cornell turn around loop for 2ps bunch

Coherent radiation:

| | mode A | mode B | mode C 1nC |
|---|---|---|---|
| Emittance grwoth | 1% | 0.2% | 1% |
| Energy spread growth | 4 $10^{-5}$ | $10^{-6}$ | 1% |

difficult to decelerate




- a 10-20mm vertical gap reduces both CSR-induced energy loss and energy spread

We need to find an optimum gap taking into account CSR, resistive wall, beam loss ...

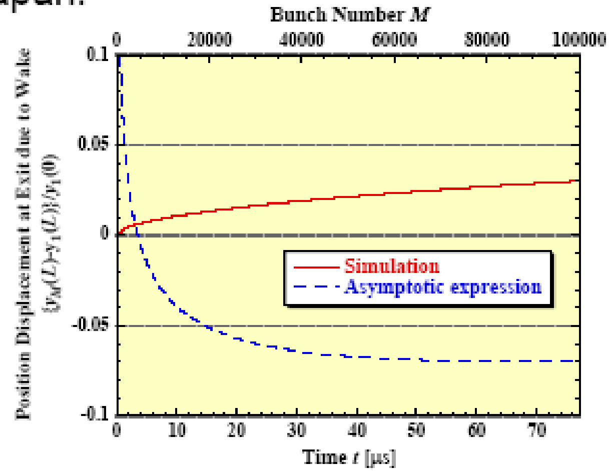
ERL07

# Resistive-Wall Beam Breakup

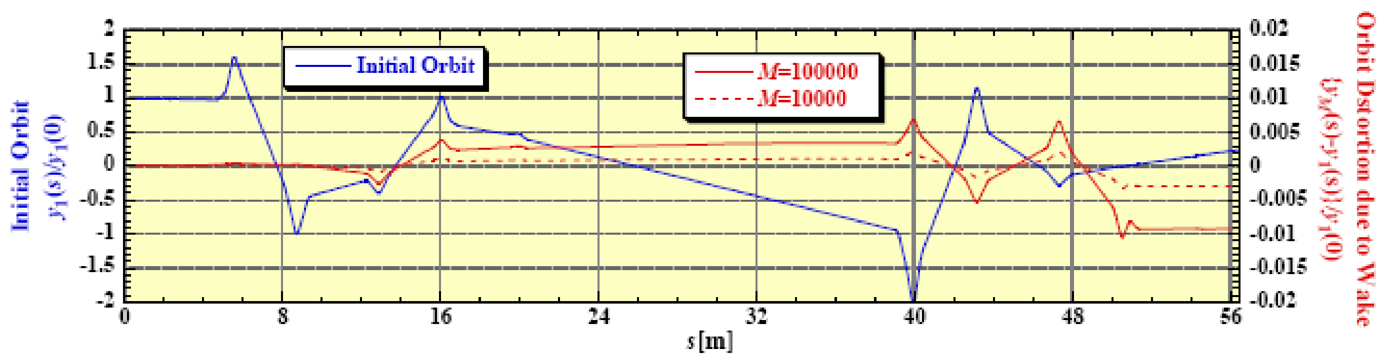
Norio Nakamura

- RWBBU can be a serious problem in ERLs and should be fully understood.
- Development of simulation program ← limitations of asymptotic expression
- Application of simulation program to the test ERL in Japan.
  - RWBBU grows with $t^{1/2}$ in its early stage.
  - Orbit distortion due to RW wake is ~ 1% (max.) of injection error at $t$=77 μs.
  - A small-gap ID duct significantly increases orbit distortion.
  - ID focusing suppresses orbit distortion, but it is changeable.
  - Orbit correction and copper-coating of ID duct will help reducing the RW wake.

- Discussion & Homework
  - Effect of resistive pipe thickness on wake-function
  - Consistency with real machine (e.g. J-Lab) operation



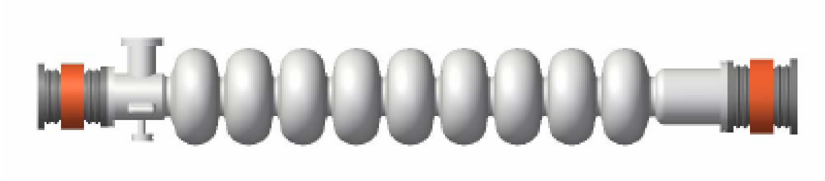

Position displacement due to RW wake as a function of time (Q-magnets off)

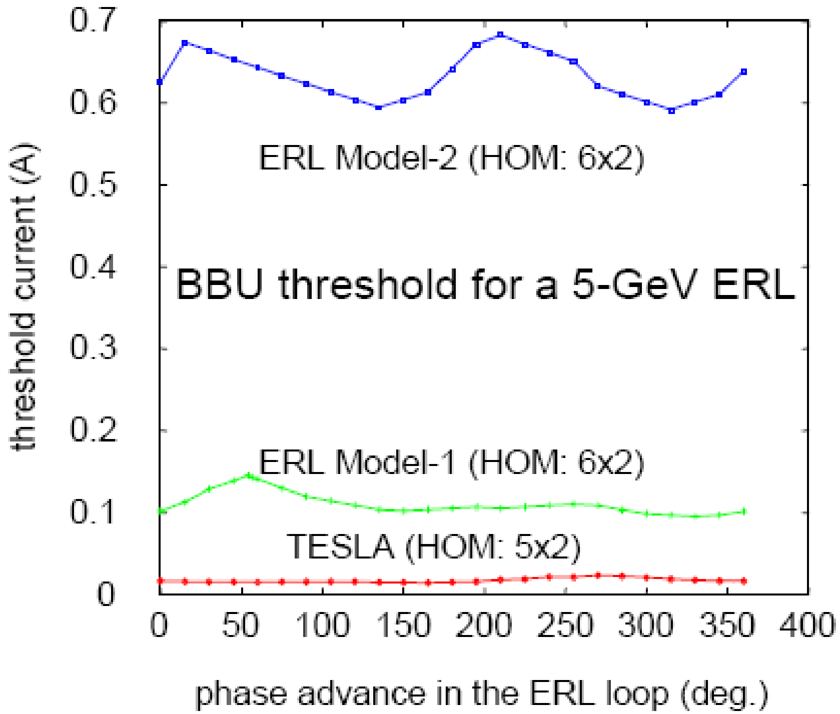



Initial orbit and Orbit distortion due to RW wake (Q-magnets on)

# HOM-BBU

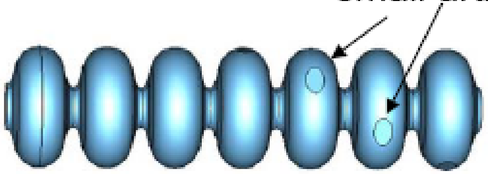
R. Hajima






Emma Wooldridge

small artificial defect



Early results suggest that alternating the perturbation in x then y produces significantly higher thresholds

Dipole-HOM seems not a critical issue from a point view of BBU.

Multi-turn layout possible?

Extraction of large HOM power is still a challenging task.

# Computer Codes

We all rely on computer codes – ASTRA, PARMELA, TRANSPORT, MAFIA ....
*elegant* is one of the most utility one for ERL design studies.

M. Borland

### *Parallelization and Other New Features in elegant*

- Review of elegant
  - Tool-based approach using self-describing files and a generic toolkit of programs ("SDDS") for pre- and post-processing
  - Basic element types include single particle dynamics, time-dependent elements, and collective effects
- Parallelization strategy allows gradual parallelization
  - Necessitated by on-going development of serial version
  - Allows use of parallel features during development effort
  - Program automatically switches between parallel and serial mode
- Other new features (last three years) include deflecting cavities, fast chromatic matrix tracking, coupled lattice functions,
- Accelerator physics toolkit cooperates with elegant for lifetime, undulator, and related computations
- Development plan includes parallelization of longitudinal space charge, Touschek scattering, true multibunch simulation for BBU, electron cloud, and ion effects.

ERL07

## FEL oscillator revisited

ERLs are fully compatible with FEL oscillators

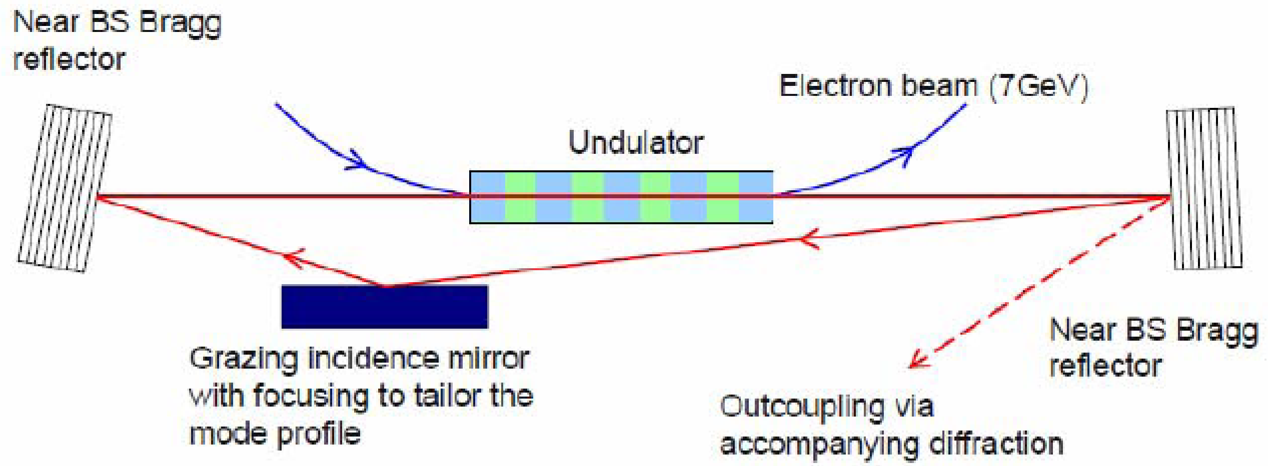
# XFEL Oscillator

ERL07

K-J. Kim

***A Novel Concept for X-Ray Optical Cavity Using Near Backscattering & Accompanying Diffraction***

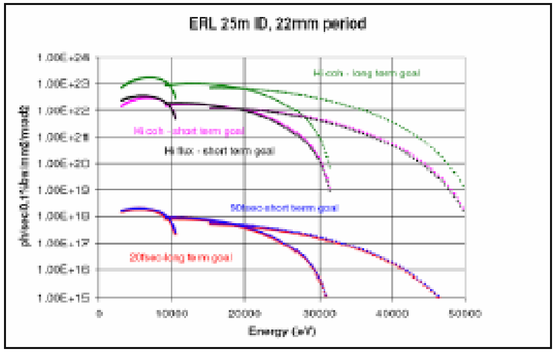
*(KJK & Shvyd'ko)*




- Cornell-ERL parameters scaled to 7-GeV (19-60pC, 2ps, ε=6pm, ΔE/E=0.02%) ⟶ $\varepsilon < \lambda / 4\pi$ for 1Å
- FEL single-pass gain ~ 50% for 60pC, Lu=23m case.
- Energy spread of 0.05% (after FEL lasing) is acceptable for ERL operation.

# ERL07 Photon Performance of X-FEL-O

- **Wavelength around 1-Å, or 10 keV**
- **Per pulse**
  - Pulse length: 2ps (rms)
  - Pulse energy: 0.1 μJ, or $10^9$ photons

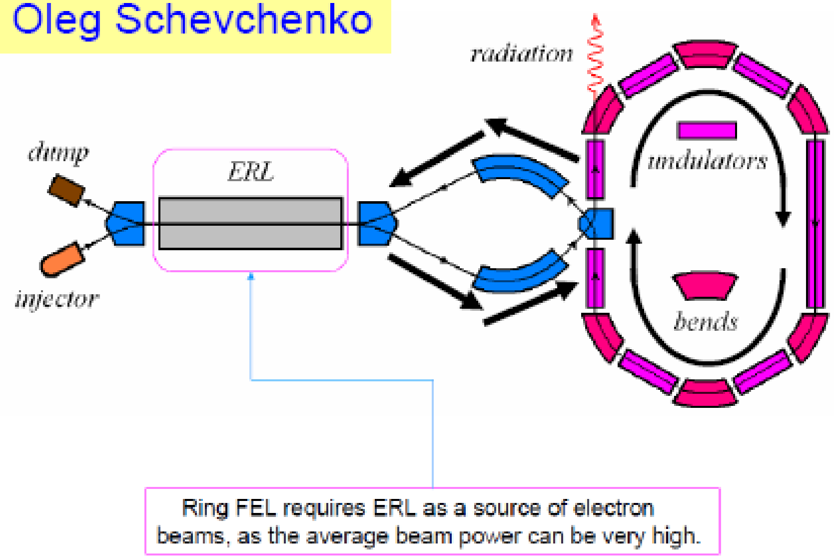


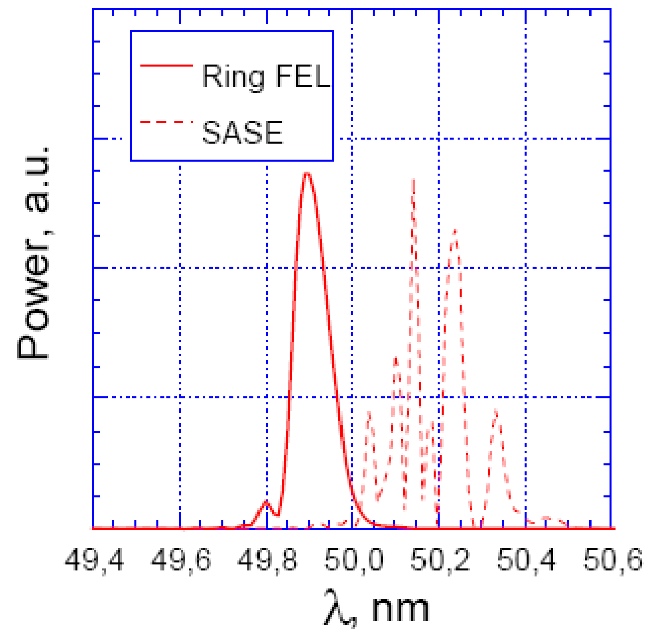

- **Full transverse coherence**
- **Full temporal coherence**
  - $\Delta\nu/\nu$=1-2 $10^{-6}$ ; $h\Delta\nu$=10 meV
- **Rep rate 1 MHz ( one optical pulse stored in cavity) or higher limited by crystal, 100MHz?**
  - Average brightness $10^{28}$ ($\rightarrow 10^{30}$) #photons/(mm-mr)$^2$(0.1%BW)

- **Photon performance complementary to SASE---higher coherence but less raw power**

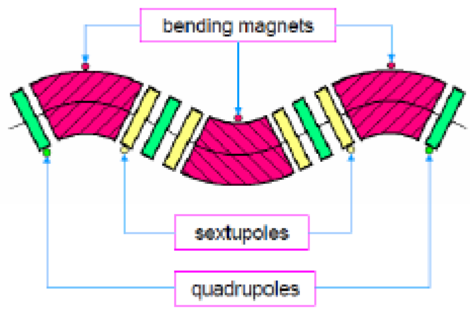
# ~~Ring~~ Loop FEL

Oleg Schevchenko




- isochronous bendings to keep FEL micro-bunching
- feedback FEL signal every turn
- two examples were presented.
  - 485MeV, 50nm – $50M
  - 50MeV, 6μm – $22M




- no mirrors → wide tunability of FEL wavelength
  free from mirror heating problems

# ERL R&D Roadmap

**Very much work in progress – just starting.**

**Purpose of the exercise:**

- **Identify opportunities for international collaboration – avoid unnecessa duplication of limited resources.**
- **Identify existing test facilities and maximize/optimize their use for ERL studies.**
- **Identify topics that are not addressed in existing or planned R&D facili**
- **Identify new facilities needed to address these topics.**

# ERL R&D Roadmap

1. Top level users requirements
   (e.g. X-ray energy, X-ray flux, X-ray spectral brightness, pulse repetition, ion cooling rate,..)
2. Top-Level Accelerator/Beam Parameters
   (e.g. Energy, current, bunch length, bunch repetition, emittances, energy spread, …)
3. Design choices
   - 3.1 RF frequency choice
   - 3.2 Bunch structure/patterns
   - 3.3 Layout
     - 3.3.1 Single pass
       [JLab FEL, BNL R&D ERL Feb 2009, ERLP 2008, BINP, JAEA]
     - 3.3.2 Multi-pass
       [BINP 2008, CEBAF-Multipass ER, induce BBU?]
     - 3.3.3 Reverse-direction ERL
4. Beam Dynamics: Theory, Design, Simulations, Experimental validation of codes – Review of cc
   - 4.1 RF focusing model development/validation
     [JLab FEL]
   - 4.2 SC dynamics / validation incl. sensitivity studies
   - 4.3 SC/CSR model development / validation [merger]
     [JLab FEL, BNL ERL, APS, SLAC-LCLS, Cornell ERL, PITZ]
   - 4.4 BBU code validation incl. multipass
     - 4.4.1 Suppression
   - 4.5 Halo: Model development/validation
     [JLAB FEL, CEBAF, BNL ERL, Cornell, PITZ – APS Model development]
   - 4.6 Ions: Model development/Validation/Cure
     [JLab FEL, APS, Cornell ERL (2008), BNL, CESR: Fast ion instabilities]
   - 4.7 CSR: Model extension/validation
   - 4.8 QBBU: Model development/validation/Suppression
   - 4.9 Impedance budget
   - 4.10 Wakefield effects (incl. RWBBU: Validation) [very short bunches]
   - 4.11 Lattice optics corrections – tuning, non-linear corrections, sensitivity
   - 4.12 S2E Self-consistent simulations

# ERL R&D Roadmap

1. Technology
   1.1 Injector – One-pass systems?
      1.1.1 Energy choice – energy ratio
      1.1.2 Polarization [JLab, MIT]
      1.1.3 Guns
         1.1.3.1 DC [Cornell, 4GLS, Jlab, JAEA]
         1.1.3.2 SRF [BNL, FZD]
         1.1.3.3 RF [Los Alamos]
            Cathode quantum efficiency and lifetime
            Cathode material
            Laser
            - Pulse shaping
            - Rep rate
      1.1.4 Injector SRF
         1.1.4.1 Cavity shape /CM
         1.1.4.2 Tuners
         1.1.4.3 High power couplers [for 1.3 GHz]
            Cornell, BNL,
         1.1.4.4 HOM couplers/absorbers
            Cornell, BNL, Daresbury, JLab
         1.1.4.5 RF Power sources
         1.1.4.6 Cryostat [New system development]
      1.1.5 Dump design

# ERL R&D Roadmap

- 1.1 Linac and return loop Technology
  - 1.1.1 SRF cavities/CMs
    - 5.2.2. $Q_0$ at field
      - Cornell, ANL
    - 5.2.3. Cavity shape
    - 5.2.4 HOM couplers/absorbers
      - Cornell, BNL, Daresbury
    - 5.2.5. RF control
      - [Single vs. multiple cavities per klystron, Ferro-electric shifters]
      - [JLab, BNL, APS]
  - 1.1.2 Cryo
    - 1.1.2.1 Optimum T
      - JLab, ANL
    - 1.1.2.2 System optimization
  - 1.1.3 SRF Integration
- 1.2 Global systems
  - 1.2.1 Diagnostics –
    - Cornell, APS, BNL, JLab, ERLP
  - 1.2.2 Synchronization
    - Cornell, ERLP
  - 1.2.3 Stability/Feedback
    - Transverse
    - Energy
    - Energy spread
  - 1.2.4 Collimation
  - 1.2.5 Reliability
    - [ERLP/Cornell/LBNL, JLab FEL, ILC]
  - 1.2.6 Radiation protection
  - 1.2.7 Machine protection

2. Users/Light
   - 2.1 Undulators
   - 2.2 Photon diagnostics
   - 2.3 Optical cavity/mirrors
3. Global optimization [risk/cost/performance]