Energy Recovered Linacs

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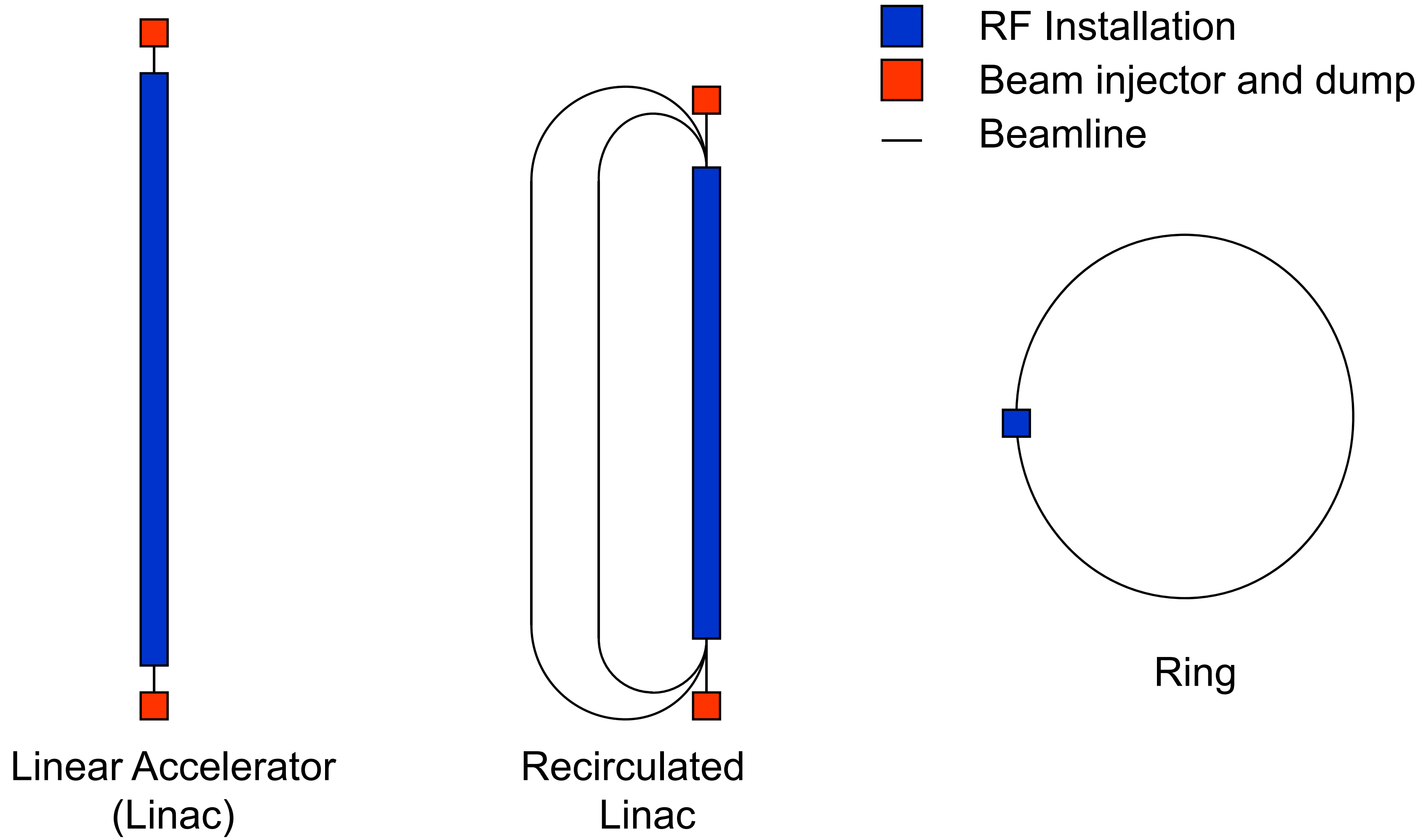
Old Dominion University

Outline

- **Recirculated linacs defined and described**
- **Energy recovered linacs**
- **Energy recovered linacs as FEL drivers**
- **Energy recovered linacs as X-ray sources**
- **Applications to HENP**
- **Conclusions**

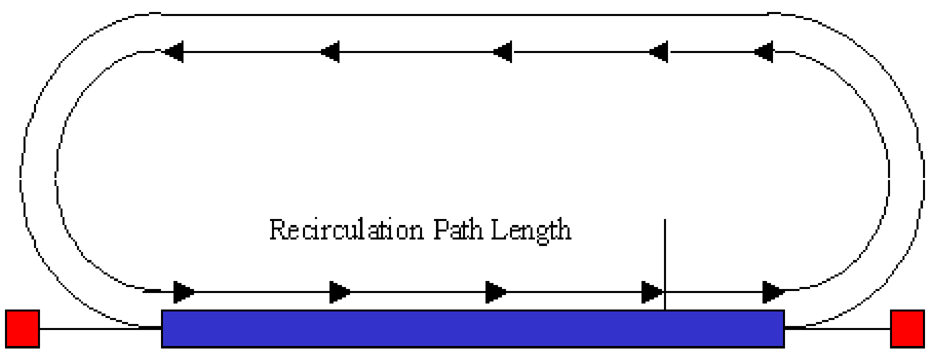
General Schematic of Accelerator Types



Why Build Recirculated Linacs?

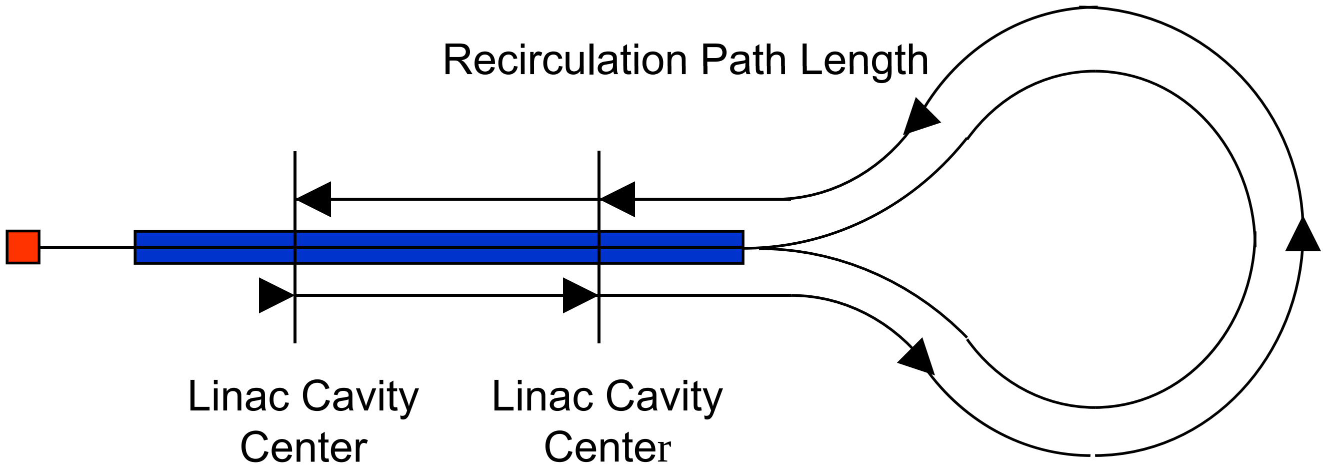
- Upgrade the energy of an existing linac
  - Stanford Superconducting Accelerator and MIT Bates Linac energies were doubled this way
- Cheaper to get a required performance
  - Microtrons re-use expensive RF systems many times to in-crease beam energy.
  - Jefferson Lab CEBAF type machines: add passes until the “decremental” gain in RF system and operating costs no longer pays for an additional beam recirculating loop
  - Jefferson Lab Free Electron Laser (FEL) and other Energy Recovered Linacs (ERLs) save the cost of higher average power RF equipment (and much higher operating costs!) at high CW operating currents by “reusing” beam energy through beam recirculation.

Beam Energy Recovery



Recirculation path length in standard configuration recirculated linac. For energy recovery choose it to be $(n + 1/2)\lambda_{RF}$. Then energy for first pass beam (accelerating) can be provided by the second pass (decelerating) beam.

Beam Energy Recovery



Recirculation path length in herring-bone configuration recirculated linac. For energy recovery choose it to be $n\lambda_{RF}$. Note additional complication: path length has to be an integer at each and every different accelerating cavity location in the linac.

Comparison: Linacs and Storage Rings

- **Advantage Linacs**
  - **The beam quality, as measured by the beam emittance, is dominated by source emittance and emittance growth down linac**
  - **Beam polarization “easily” produced at the source, switched, and preserved**
  - **Total transit time is quite short**
  - **Beam is easily extracted**
  - **Utilizing source laser control, flexible bunch patterns possible**
  - **Long undulaters are a natural addition**
  - **Bunch durations can be SMALL (10-100 fsec)**

Comparison: Linacs and Storage Rings

- **Advantage Storage Rings**
  - **Up to now, the stored average current is much larger**
  - **Very efficient use of accelerating voltage**
  - **Many user beamlines**
  - **Technology well developed and mature**

- **Disadvantage Storage Rings**
  - **Technology well developed and mature**
  - **The synchrotron radiation damping equilibrium, and the emittance, energy spread, and bunch length it generates, "must" be accepted**

Power Multiplication Factor

- **Energy recovered beam recirculation is nicely quantified by the notion of a power multiplication factor:**

$$k = P_{b,ave} / P_{rf}$$

where P_{rf} is the RF power needed to accelerate the beam

- **By the first law of thermodynamics, *k* < 1 in any linac not recirculated. Beam recirculation with beam deceleration somewhere is necessary to achieve *k* > 1**

- **If energy IS very efficiently recycled from the accelerating to the decelerating beam**

$$k >> 1$$

Comparison Accelerator Types

Parameter	High Energy Electron Linac	High k Superconducting Linac	Ring
Accelerating Gradient[MV/m]	>50	10-20	NA
Duty Factor	<1%	1	1
Average Current[mA]	<1	10 going to 100	1000
Average Beam Power[MW]	0.5	1.0 going to 500	3000
Multiplication Factor	<1	33 going to 200	1000
Normalized Emittance[mm mrad]	1	1	4
Bunch Length	100 fsec	100 fsec	20 psec

Typical results by accelerator type

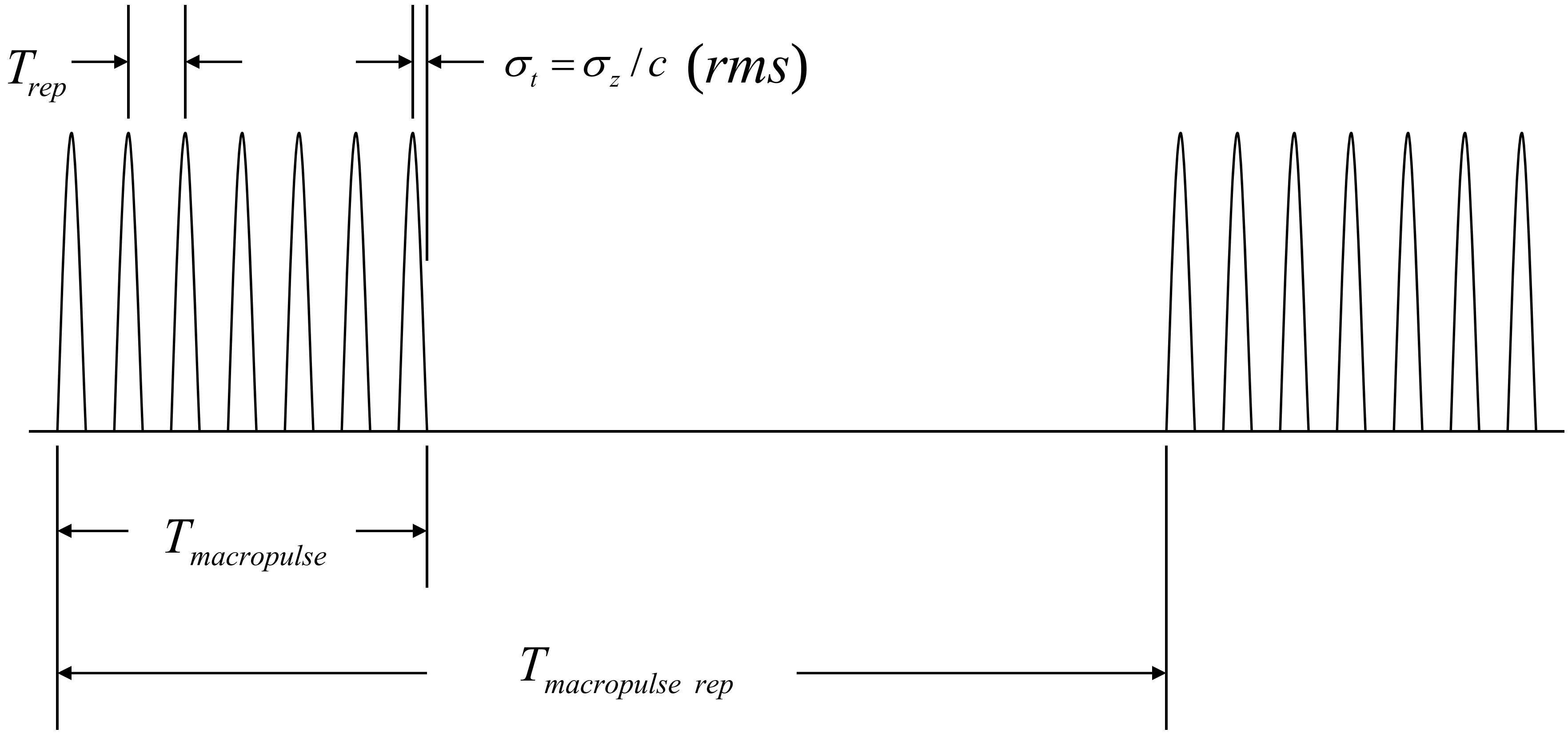
A More Modern Reason to Recirculate!

- It may be possible to achieve beam parameters “not achievable” in storage rings or in linacs without recirculation.

  ERL synchrotron source example: beam average power in a typical synchrotron source is (100 mA)(5 GV)=500 MW. This power represents roughly a third of a nuclear plant if such a power were provided continuously to run a synchrotron source without energy recovery. Idea is to use the high multiplication factor possible in energy recovered linacs to reduce the power load to acceptable levels. Full charge pulse lengths of order 100 fsec or smaller may be possible in an ERL source, which is “impossible” at a storage ring. Better emittance may be possible too.

Recirculated Linacs Have Flexible Timing

Laser photocathode control of emitted current allows new types of timing patterns and experiments. X-ray beam mirrors electron beam.

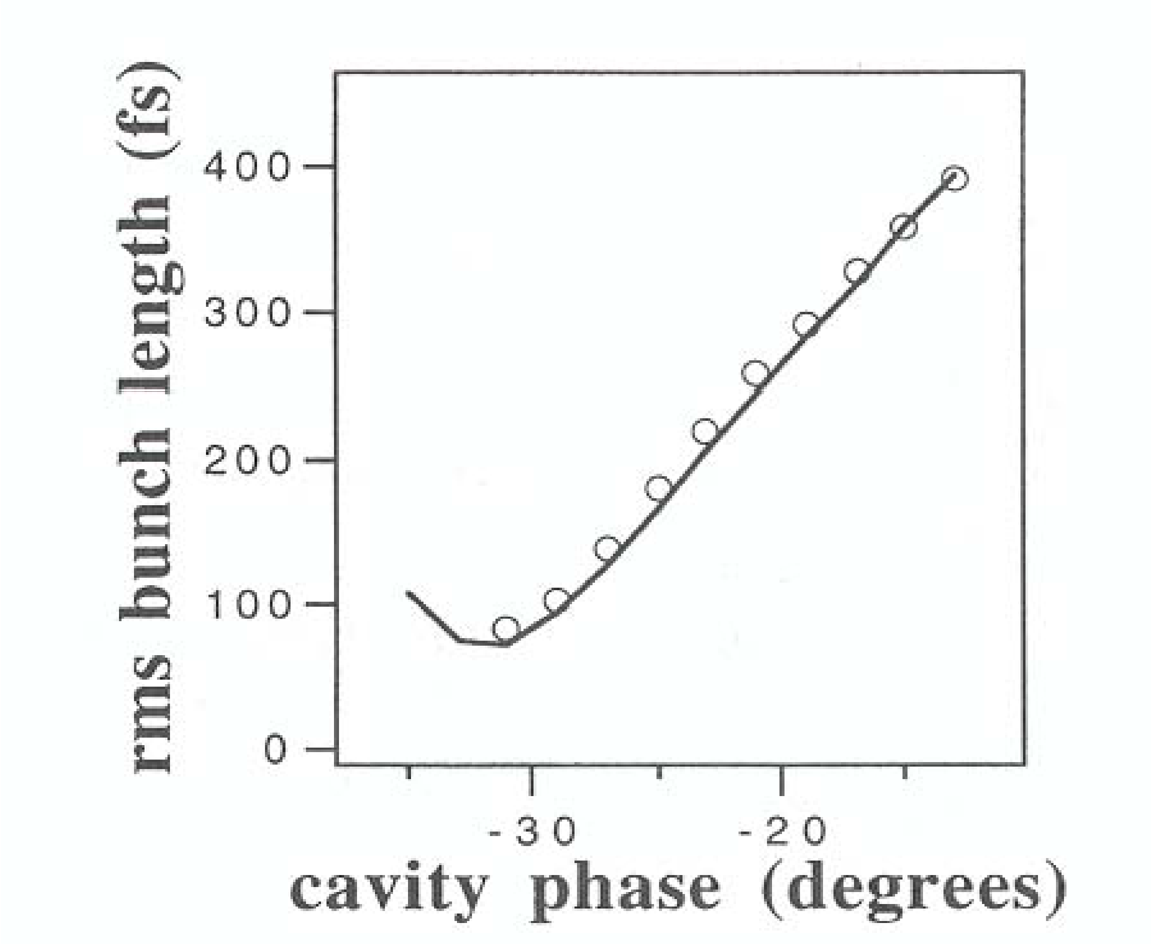


Timing Possibilities

Parameter	ERL Possibilities	Jlab FEL Demonstrated
σ_t^*	10 fsec – 10 psec	< 330 fsec
Repetition Rate	1 MHz – 1.3 GHz	2 – 75 MHz
Macropulse Duration	1 microsecond - CW	1 microsecond – CW
Macropulse Repetition Frequency	1 Hz-10 kHz	0.5 Hz – 60 Hz

* In Jlab FEL, fluctuation in pulse centroid measured less than 1 sigma

Short Bunches in CEBAF



Wang, Krafft, and Sinclair, Phys. Rev. E, 2283 (1998)

Main Challenge

- A high average current electron source is needed to provide high quality continuous beam
  - Several projects are investigating DC photocathode sources.
    - Need higher fields in the acceleration gap in the gun for high quality beam.
    - Need better vacuum performance in the beam creation region to increase the photocathode lifetimes.
    - Goal is to get the photocathode decay times, at high average current, above the present storage ring Toushek lifetimes
  - Longer term, CW RF/SRF guns are ideal solution.

Chalk River Reflexotron

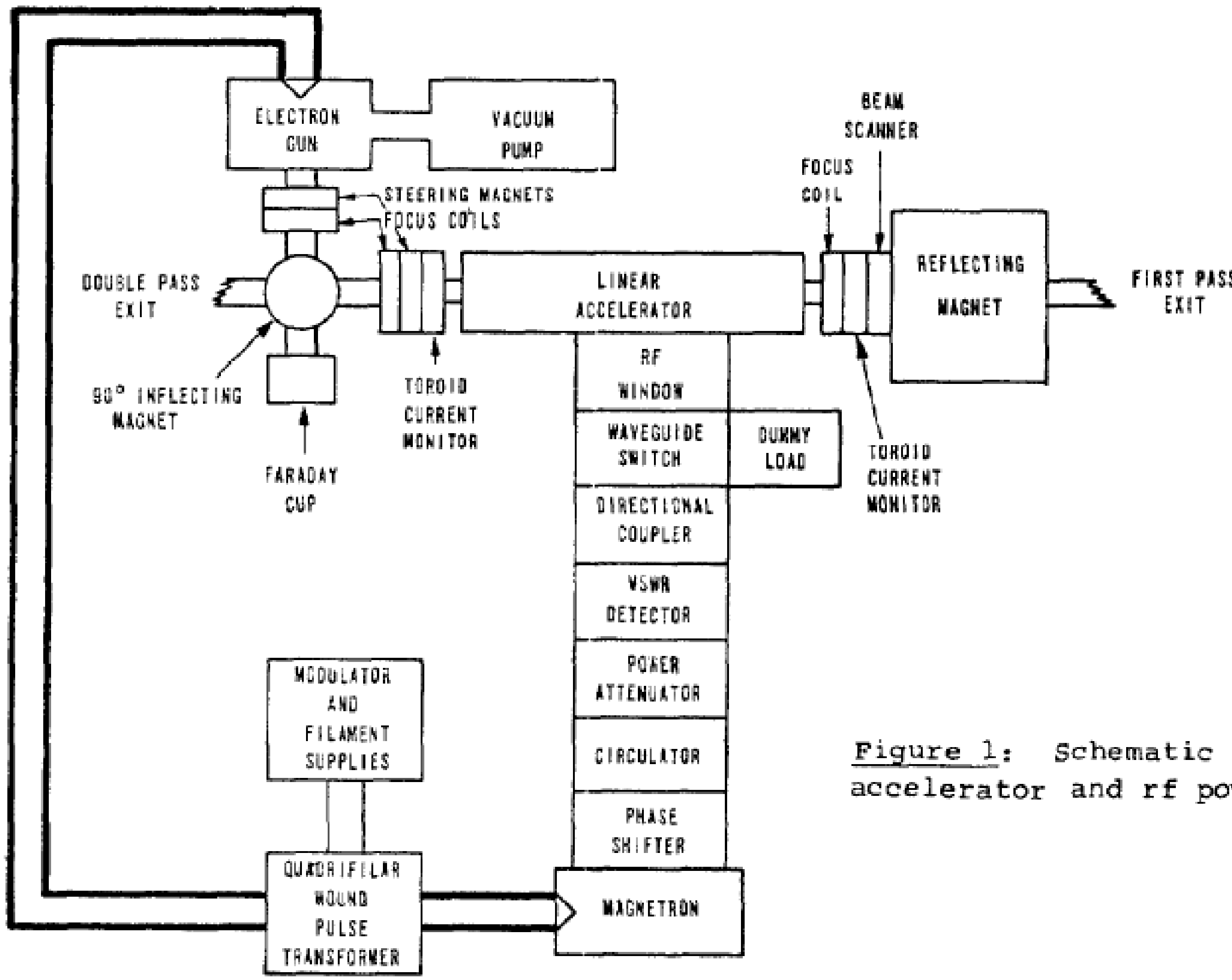


Figure 1: Schematic layout of accelerator and rf power system.

The "Chalk River Gang" and Accelerator

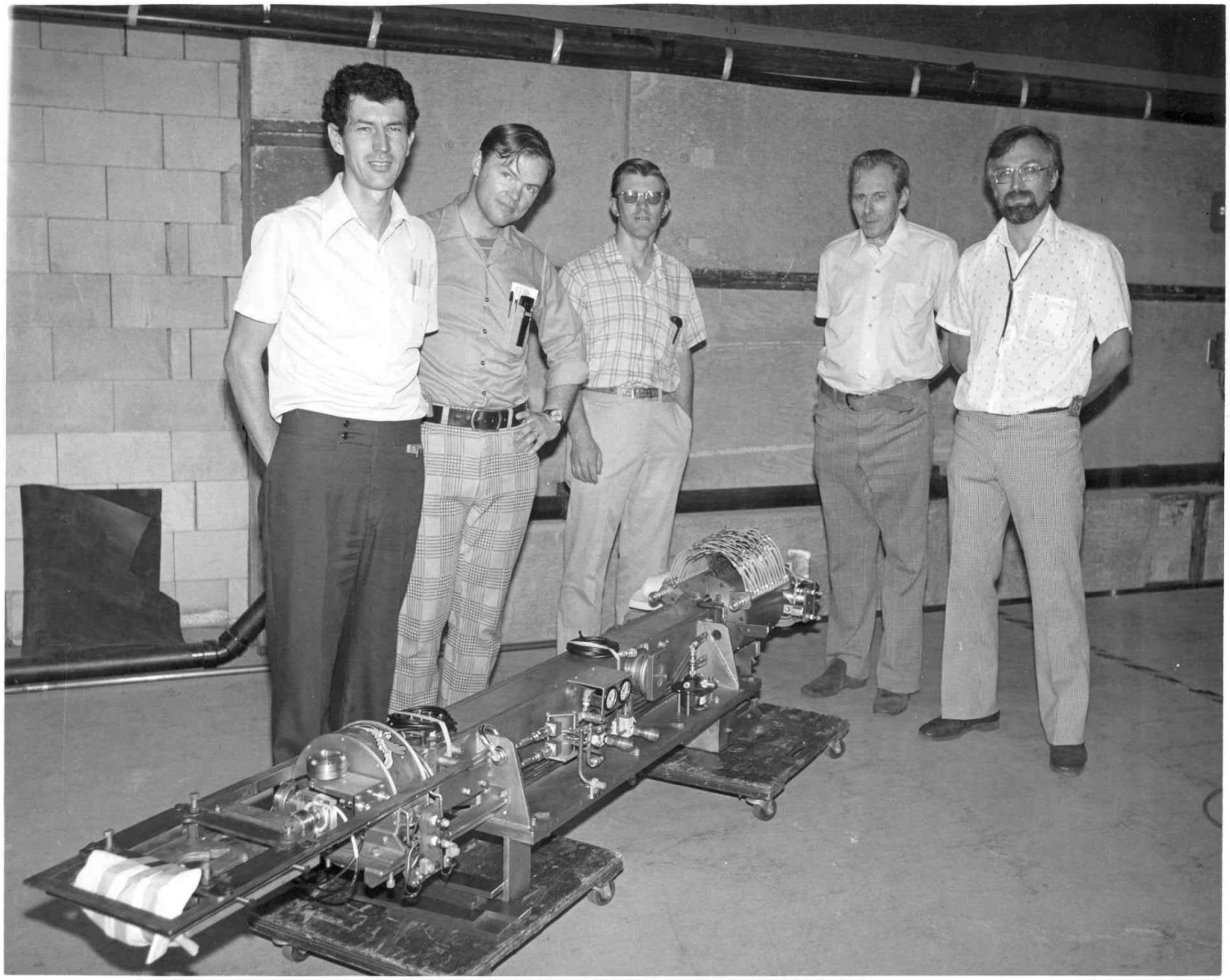


Photo Courtesy Warren Funk

Completed Reflexotron

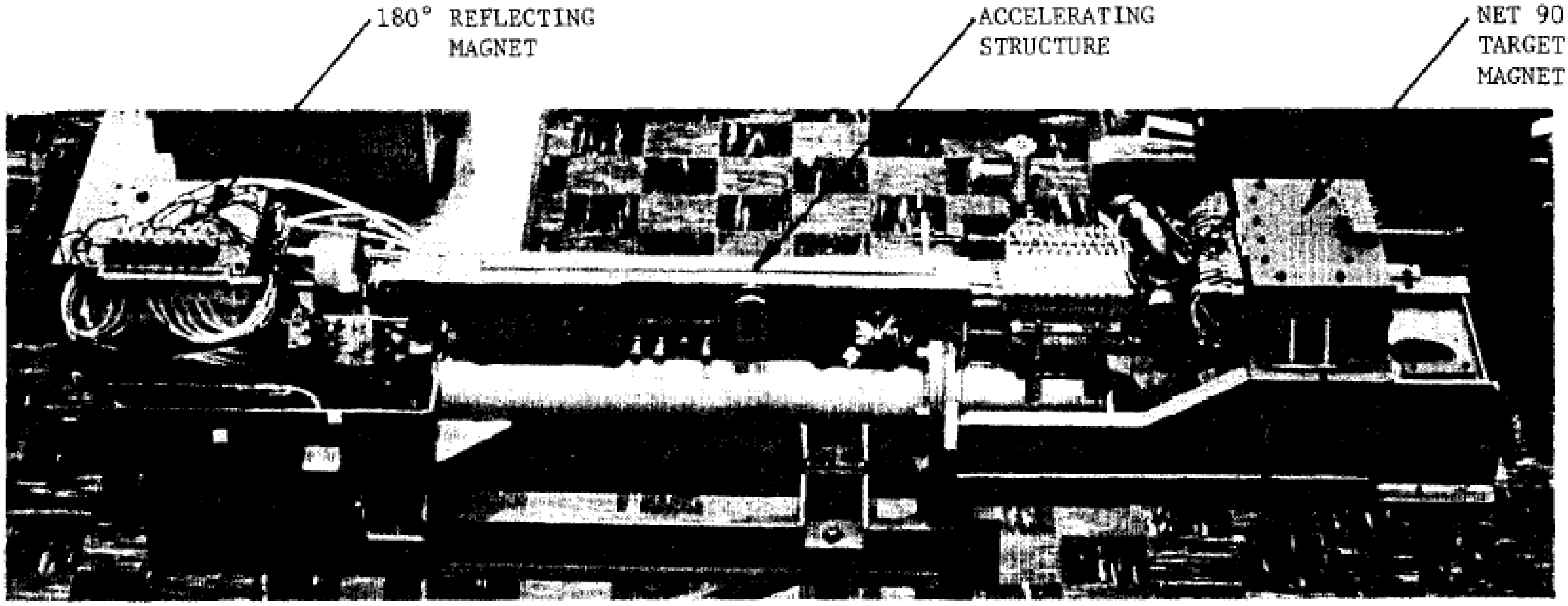
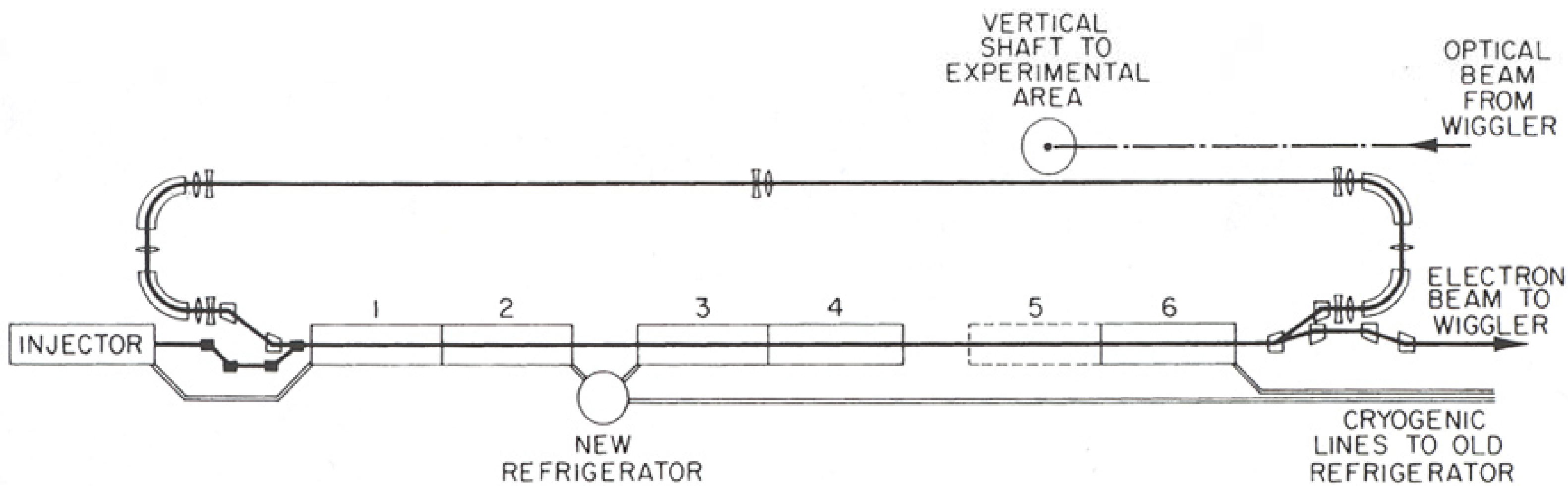


Figure 1. The 25 MeV electron accelerator attached to its strongback.

Schriber, Funk, Hodge, Hucheon, PAC1977, 1061-1063

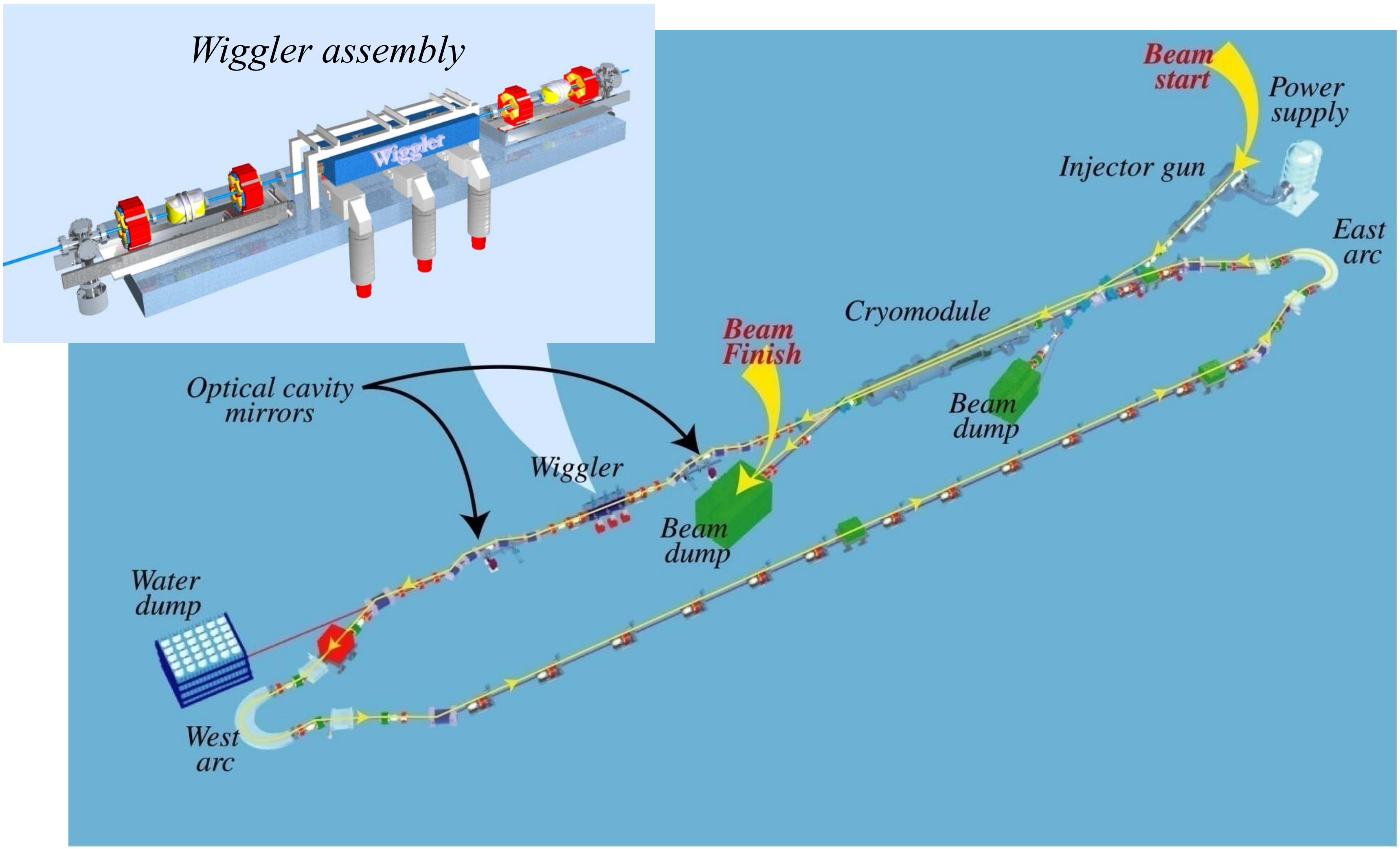
The SCA/FEL Energy Recovery Experiment

- Same-cell energy recovery was first demonstrated in an SRF linac at the SCA/FEL in July 1986
- Beam was injected at 5 MeV into a ~50 MeV linac (up to 95 MeV in 2 passes)
- Nearly all the imparted energy was recovered. No FEL inside the recirculation loop.



T. I. Smith, et al., NIM A259, 1 (1987)

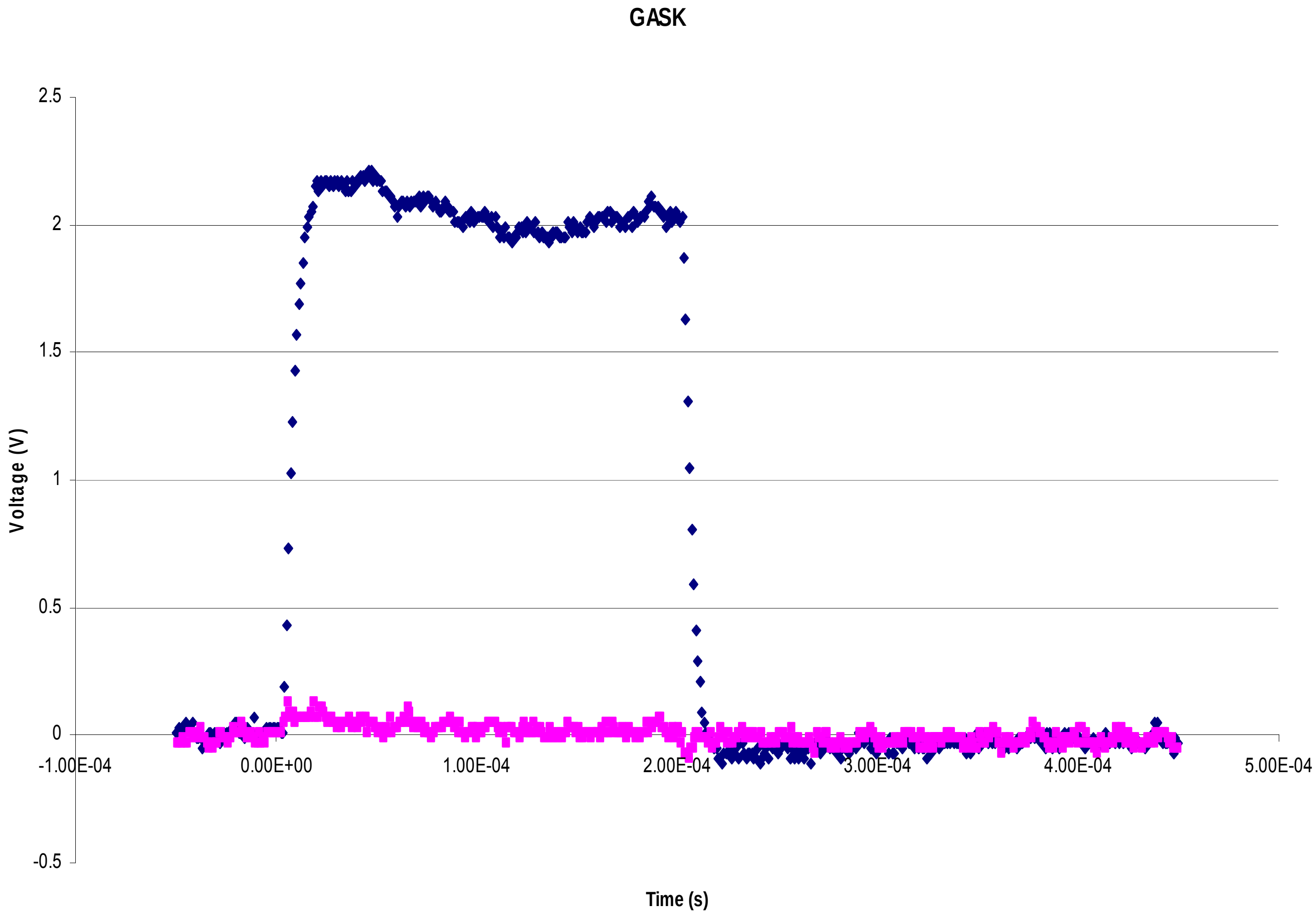
Jefferson Lab IR DEMO FEL



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

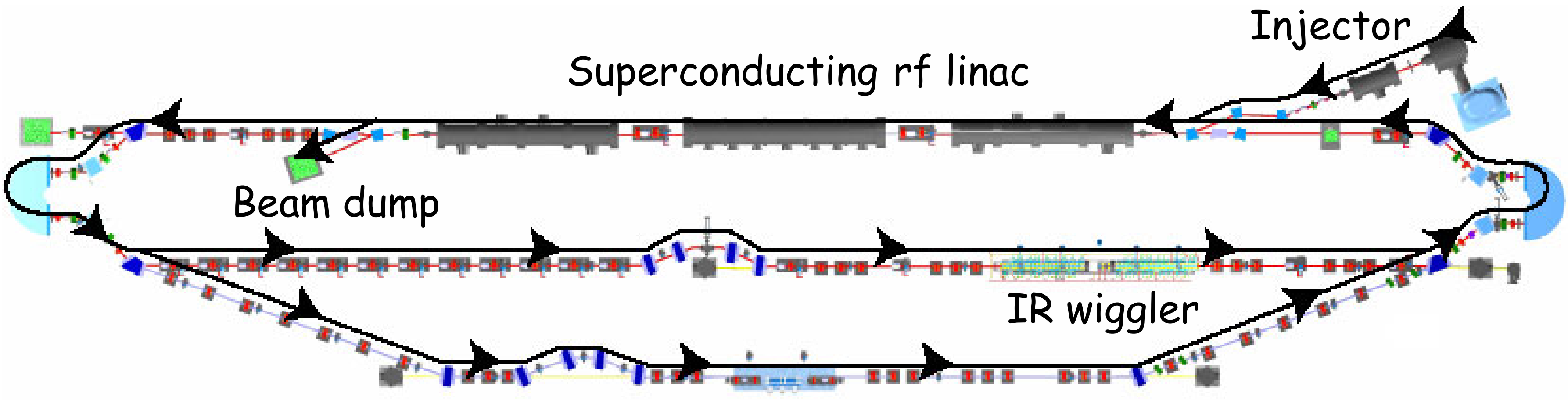
ENERGY RECOVERY WORKS

Gradient modulator drive signal in a linac cavity measured without energy recovery (signal level around 2 V) and with energy recovery (signal level around 0).



Courtesy: Lia Merminga

JLab 10 kW IR FEL and 1 kW UV FEL



Output Light Parameters	IR	UV
Wavelength range (microns)	0.9 - 10	0.25 - 1
Bunch length (FWHM psec)	0.2 - 2	0.2 - 2
Laser energy / 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)	80-150	150
Accelerator frequency (MHz)	1500	1500
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	>300	>250
Beam Power (kW)	1500	750
Energy Spread (%)	0.40	0.20
Normalized emittance (mm-mrad)	<10	<8
Induced energy spread (full)	12%	6%

14.2 kW average power from 8.3 mA, 75 MHz, CW electron beam

Courtesy: T. Smith and S. Benson

Controlling nonlinearities with sextuples and octupoles is validated by high order transport measurement

Figure 1: initial optimized setup

Figure 2: lower trim quads to -185 g from initial -215 g

Figure 3: raise trim quads to -245 g

Figure 4: quads back at -215, but sextupoles 2000 g below design, at 10726 g-cm

Figure 5: back to start: trim quads -215 g sextupoles at 12726 g-cm

Transfer Function Measurements on IR Upgrade

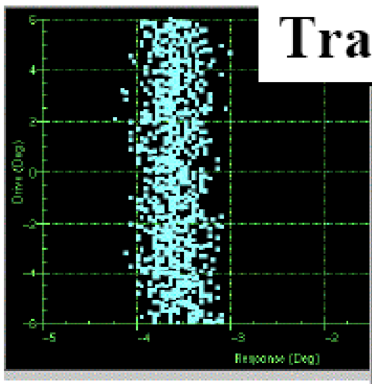


Fig. 1

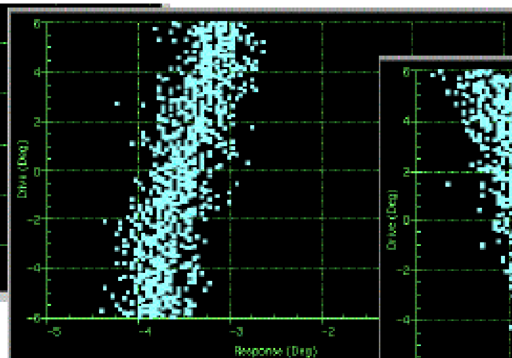


Fig. 2

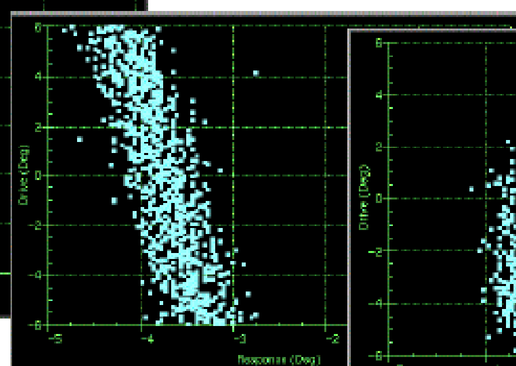


Fig. 3

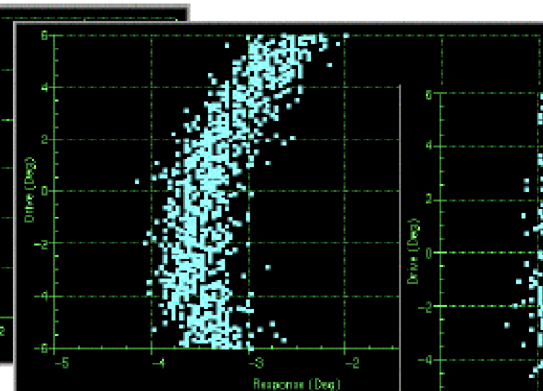


Fig. 4

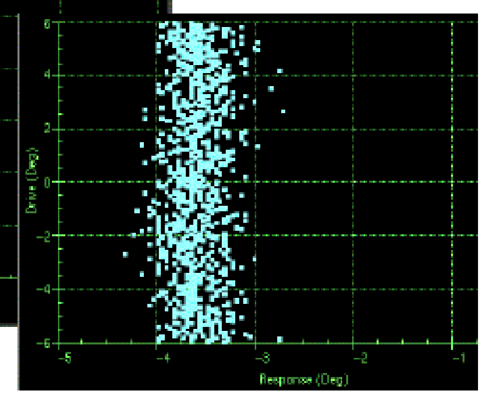
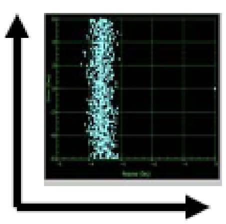


Fig. 5

Launch phase



Arrival phase

Courtesy Dave Douglas, S. Benson

Jefferson Lab User Program

- Dynamics in nanosystems, & systems driven far-from equilibrium.
  - H impurities in Si (Luepke, William & Mary)
  - Carbon nanotube production (Smith, NASA)
- Magnetism, and spin dynamics.
  - -Pulsed laser deposition of magnetic thin films (Reilly, W&M)
- Quantum coherence and control.
  - High harmonic generation (Jones, University of Virginia)
- Fundamental optical physics.
  - Bose-Einstein condensates, far-off resonance traps Sukenik (ODU)
- Laser-tissue interactions.
  - Localized heating of fatty tissue (Anderson, Harvard)
- Nuclear physics.
  - Search for light, neutral, spin-zero boson (Baker, Yale)
- Microfabrication.
  - UV int. with ceramics (Helvajian, Aerospace Corp)

Courtesy: G. Williams

Towards Higher Power ERL FELs

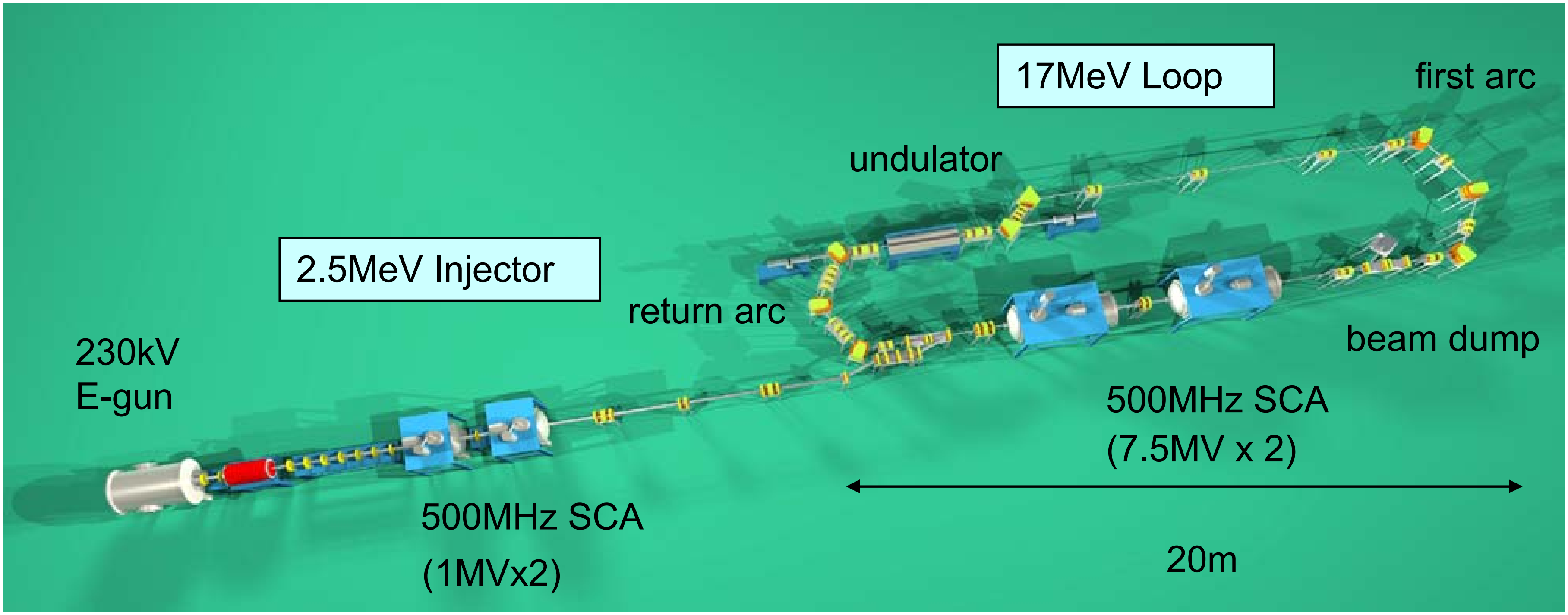
- Recent JLAB beam studies have focused on DC gun performance at high charges (up to 1 nC)

- United States Department of Defense has asked US industry to bid on the “next”, 100 kW optical power, FEL

- Jefferson Lab scientists helping with bid packages for various companies

- Contracts will be awarded soon.

17 MeV-ERL at JAEA

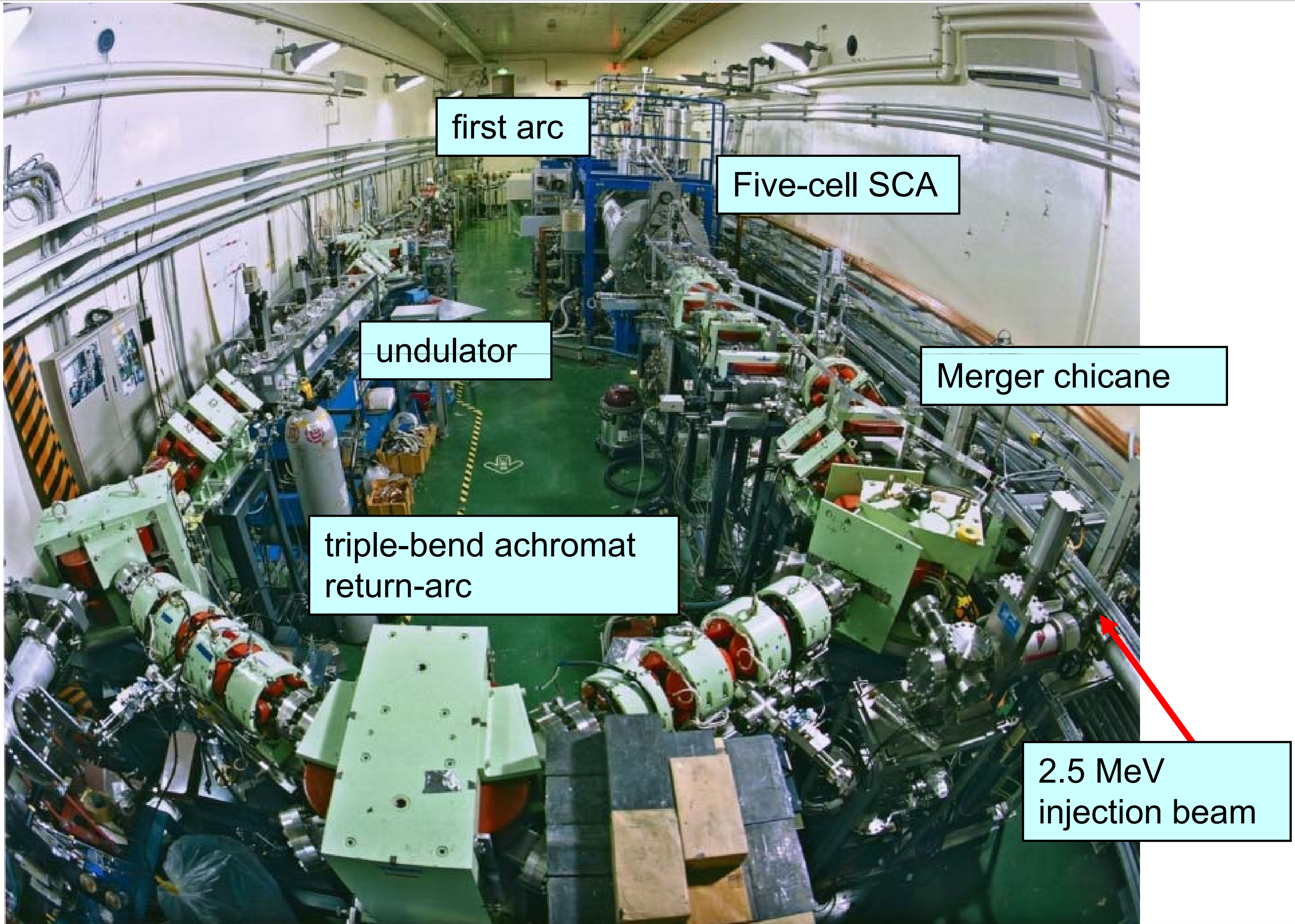


2.5 MeV injector consists of 230 keV thermionic cathode gun, 83 MHz sub harmonic buncher, and two single-cell 500 MHz SCAs.

17 MeV loop consists of a merger chicane, two five-cell 500 MHz SCAs, a triple-bend achromat arc, half-chicane, undulator, return-arc, and beam dump.

Courtesy: N. Nishimori

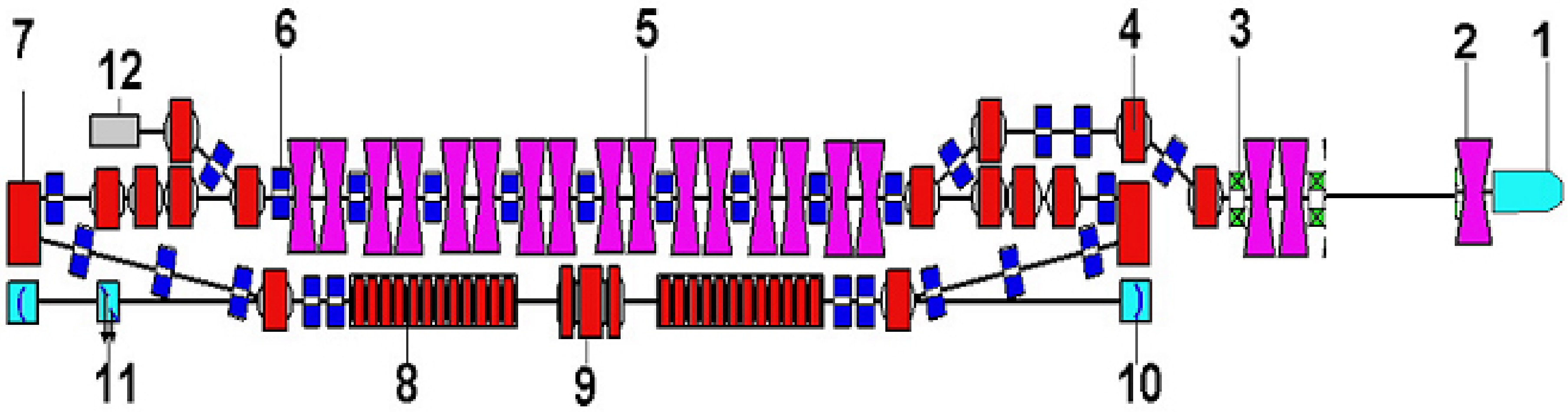
17 MeV ERL Loop



Summary

- The energy acceptance of the triple bend achromat return arc has been increased from 7% to 15% by replacing quadrupole magnets and beam ducts.
- Achieved 0.7 kW FEL oscillation in average at 22 μm wavelength using 8 mA electron beam at 230 μs macropulse.
- The FEL extraction efficiency was measured with a wire scanner and reaches 2.8%.
- Used magnetic bunch compression in the first arc with off crest acceleration in main linac modules to realize the high-efficiency FEL.
- Experimental studies on the beam dynamics in the triple bend achromat arcs during high-efficiency FEL oscillation.
- Shut down in April
- Superconducting cavities returned to KEK

Layout of the Novosibirsk FEL (1^{st} stage)



1 – an electron gun, 2 – RF bunching cavity, 3 – focusing solenoid, 4 – a small bending magnet, 5 – accelerating RF cavity, 6 – quadrupole lens, 7 – magnetic mirror (bend at 165^0) , 8 – undulator, 9 -buncher, 10 – optical cavity mirror, 11 – scrapers with calorimeters, 12 – absorber.

The electron beam from the injector after its passage through the buncher (a bunching RF cavity), drift section, 2 MeV for-accelerating cavities and the main accelerating structure is directed to the undulator, where a fraction of its energy is put into the laser radiation. After that, the beam returning to the main accelerating structure in a decelerating phase, looses its energy practically to its injection value (2 MeV) is dropped into the absorber.

Courtesy: G. Kulypanov

Parameters of the 1st stage accelerator-recuperator

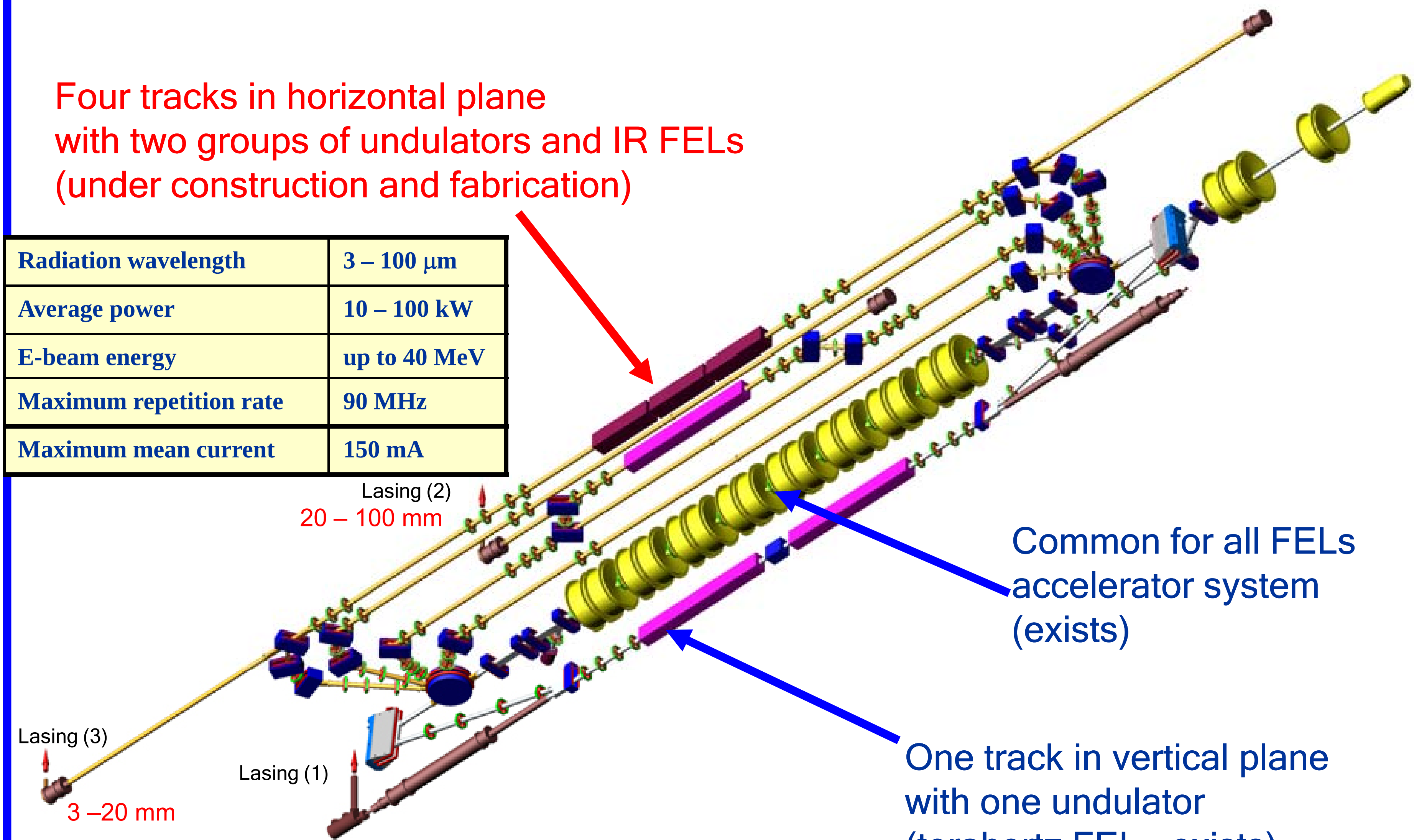
	May 2005	Plans
RF frequency, MHz	180	180
Bunch repetition rate, MHz	11.2	90
Maximum average current, mA	20	150
Maximum electron energy, MeV	12.8	14
Normalized beam emittance, mm*mrad	32	15
Electron bunch length in FEL, ns	0.07	0.1
Peak current in FEL, A	10	20

Have energy recovered the largest average current to date!

Full scale Novosibirsk FEL (bottom view)

Four tracks in horizontal plane
with two groups of undulators and IR FELs
(under construction and fabrication)

Radiation wavelength	**3 – 100 μm**
Average power	**10 – 100 kW**
E-beam energy	**up to 40 MeV**
Maximum repetition rate	**90 MHz**
Maximum mean current	**150 mA**



Common for all FELs
accelerator system
(exists)

One track in vertical plane
with one undulator
(terahertz FEL - exists)

ERLP (Energy Recovery Linac Prototype)

- conceived as a prototype of an energy recovery based 4th generation light source...

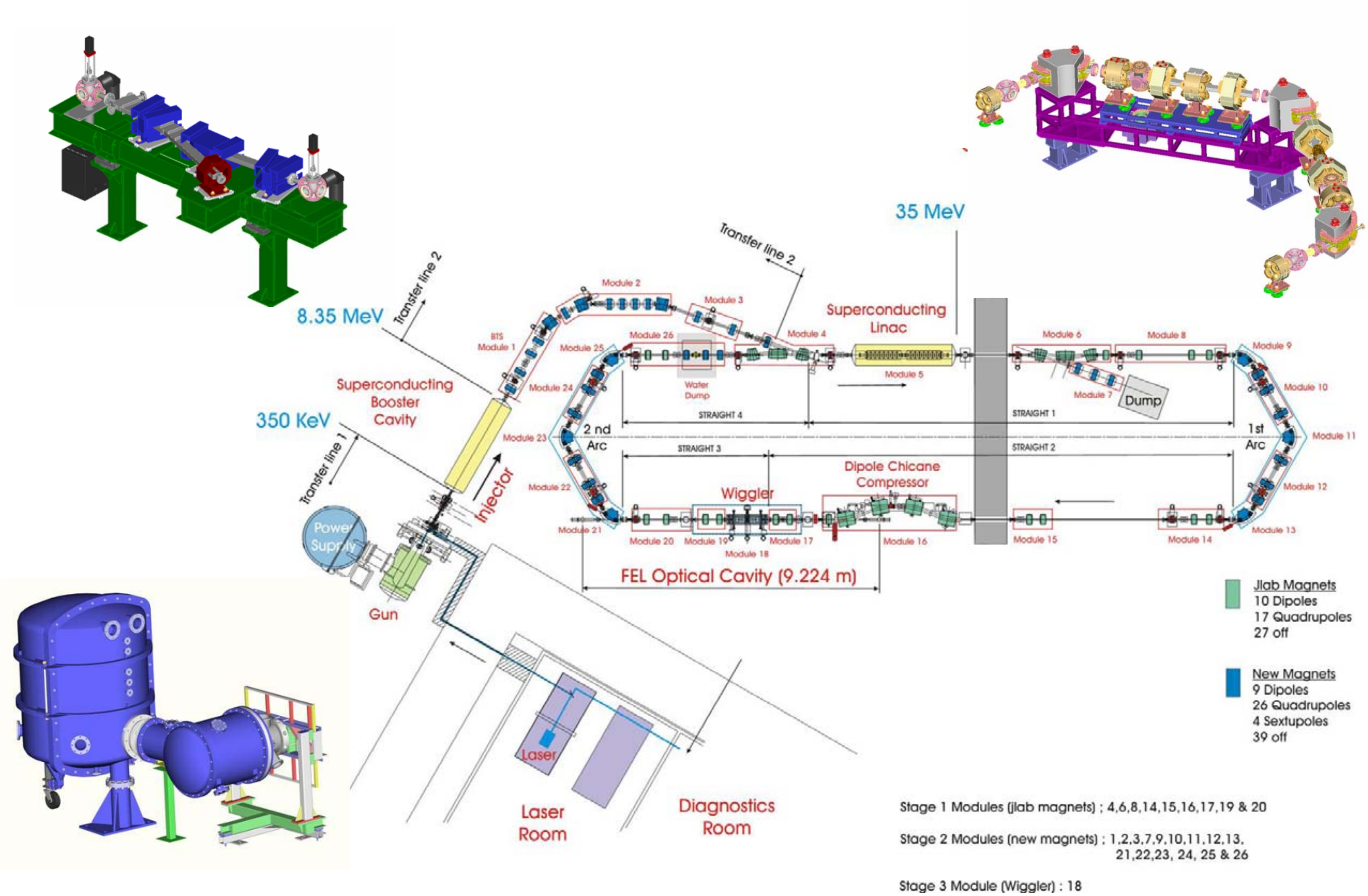
now called...

ALICE (Accelerators and Lasers In Combined Experiments)

- An R&D facility dedicated to accelerator science and technology development;
- Offering a unique combination of accelerator, laser and free-electron laser sources ;
- Enables essential studies of beam combination techniques;
- Provides a suite of photon sources for scientific exploitation.

Courtesy: D. Holder

Daresbury: ERL Prototype/ALICE



Courtesy: S. Smith

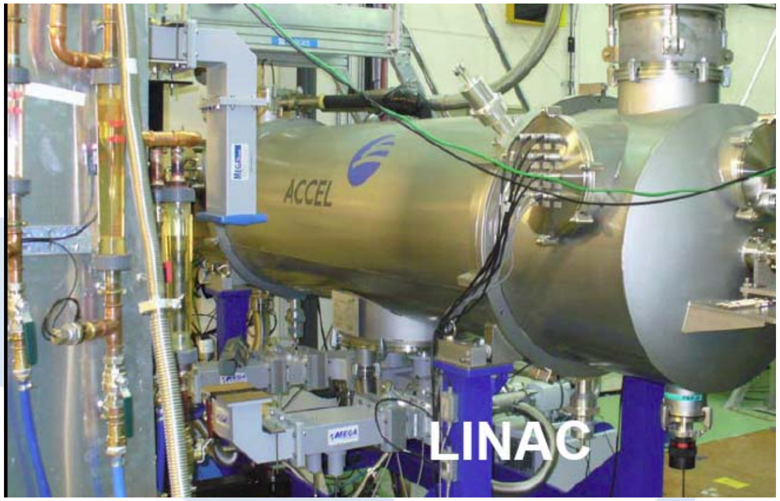
Gun Commissioning Summary

- Results
  - The gun can now be routinely **HV conditioned to 450kV**
  - **QE above ~3%** are normally achieved after cathode activations (bunch charges of well above100pC have been achieved)
  - The beam was **fully characterised** (emittance, bunch length, energy spectra) in a wide range of bunch charges from 1 to 80pC
  - A **good agreement** between the ASTRA simulations and the experimental data was found in terms of the **bunch length** and the **energy spread** but **not for the emittance**.
  - Bunch characteristics were investigated at **two different laser pulses** of 7ps and 28ps.
  - At **low Q<20pC, no significant difference** was observed. An importance of a smooth (i.e. flat-top) laser pulse for minimisation of the beam emittance was demonstrated.
- Remaining gun-related issues
  - Ensure the absence of FE spots on the cathode
  - Increase the cathode lifetime at QE level of >1.5%
  - Transverse emittance is higher than expected (FE ? QE non-uniformity?)

Courtesy: D. Holder

SC Module Commissioning Summary

		Maximum measured	Required	
Booster	Cavity 1	10.8	4.8	MV/m
	Cavity 2	13.5	2.9	MV/m
Linac	Cavity 1	16.4	13.5	MV/m
	Cavity 2	12.8	13.5	MV/m



- All 5 IOTs are successfully commissioned
- All 4 cavities show unexpected limitations due to field emission
- ALICE operation at 35 MeV is still possible
- Measurements of cryogenic losses at intermediate gradients show significant reduction compared with vertical test results.
- Measurements of high levels of FE radiation at electronic components
  - Installation of extensive lead shielding of LINAC module
  - Installation of high average current cryomodule, Summer 09.

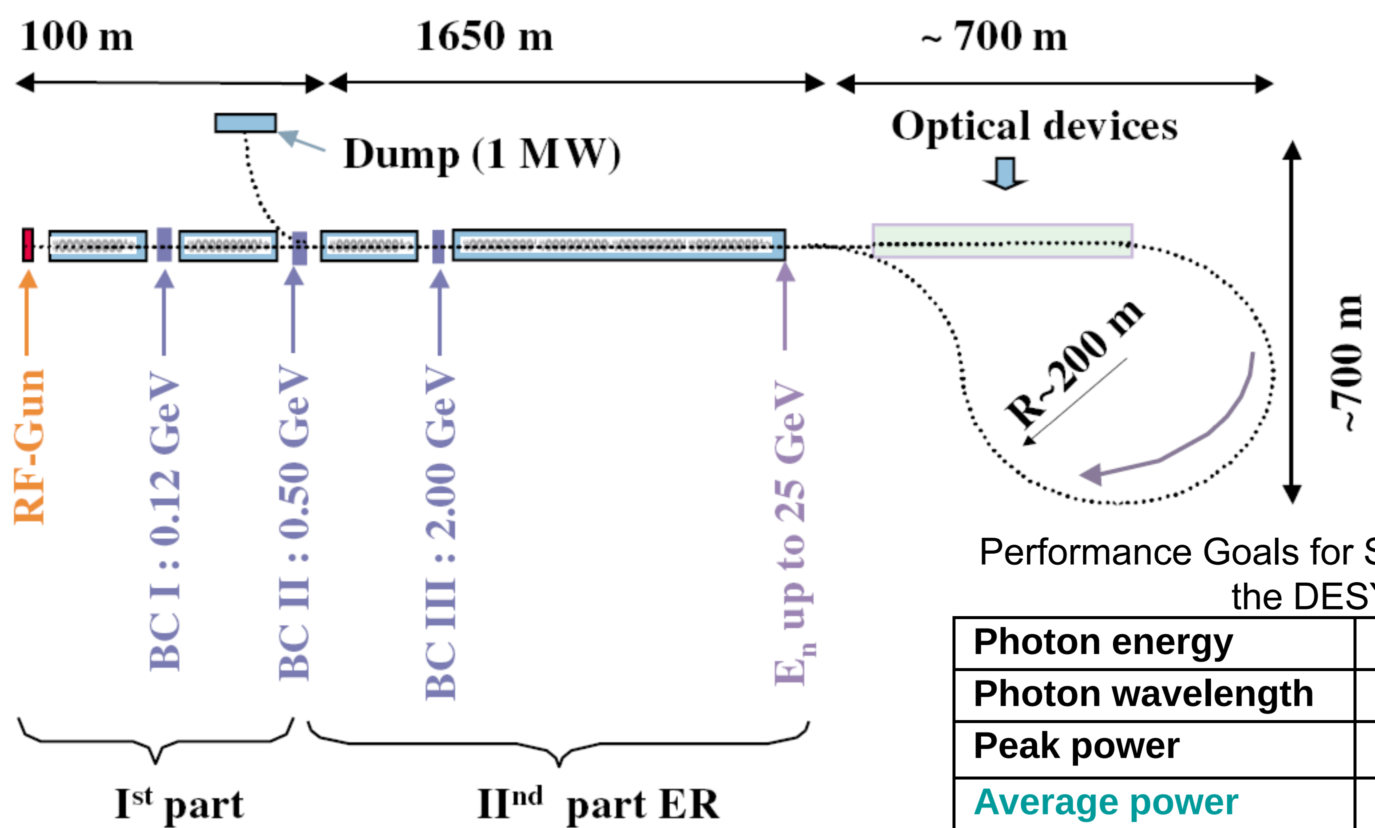
Courtesy: D. Holder

Energy Recovery

- First energy recovery (Fall 2008)
  - Without FEL, installation planned Spring 2009
- Fine tuning
  - Injector tuning for minimum emittance
  - Optimisation of energy recovery at nominal beam parameters
  - Beam diagnostics
- Short pulse commissioning stage
  - Longitudinal dynamics, electro-optical diagnostic studies
- Energy recovery with FEL (Spring 2009)
  - First light !
  - Energy recovery of a disrupted beam

Courtesy: D. Holder

XFEL ERL?



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

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 mrad^2 mm^2 0.1% b.w.)**	

ERL X-ray Source Conceptual Layout

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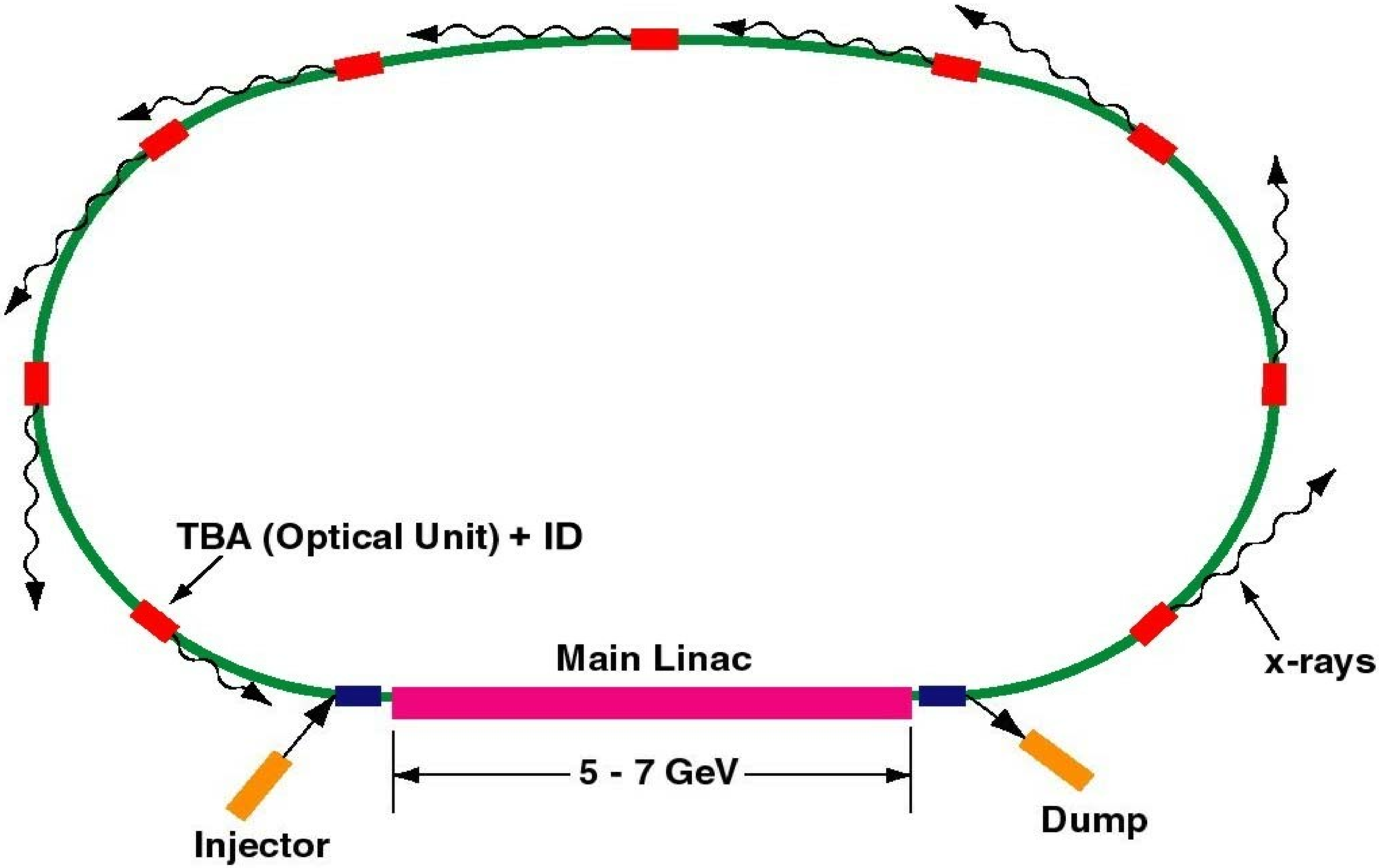

Why ERLs for X-rays?

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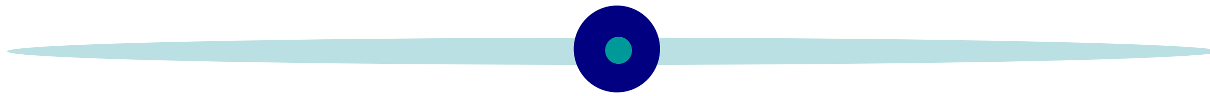
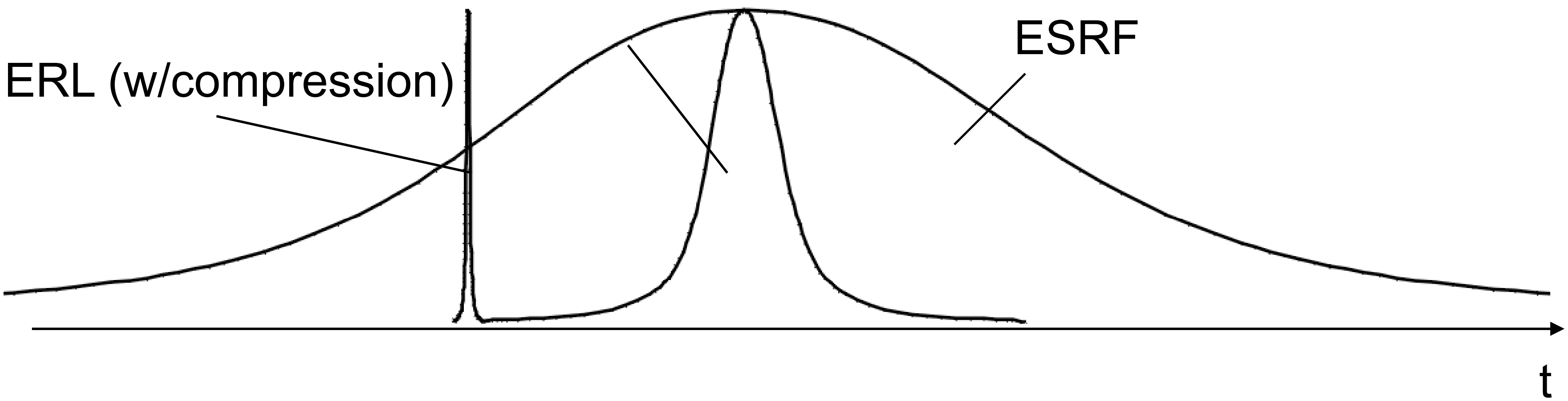


ESRF 6 GeV @ 200 mA

ε_x = 4 nm mrad
ε_y = 0.02 nm mrad
B ~ 10^{20} ph/s/mm^2/mrad^2/0.1%BW
L_{ID} = 5 m

ERL 5 GeV @ 10-100 mA

$\varepsilon_x = \varepsilon_y \rightarrow$ 0.01 nm mrad
B ~ 10^{23} ph/s/mm^2/mrad^2/0.1%BW
L_{ID} = 25 m



Brilliance Scaling and Optimization

- For 8 keV photons, 25 m undulator, and 1 micron normalized emittance, X-ray source brilliance

$$B \propto \frac{I}{\varepsilon^2} = \frac{fQ}{\varepsilon_{th}^2 + AQ^p}$$

- For any power law dependence of emittance on charge-per-bunch above 1/2, *Q*, the optimum is

$$AQ^p \approx \varepsilon_{th}^2 / (p-1)$$

- If the "space charge/wake" generated emittance significantly exceeds the thermal emittance ε_{th} from whatever source, you've already lost the game!
- BEST BRILLIANCE AT LOW CHARGES, once a given design and bunch length is chosen! Therefore, higher RF frequencies preferred
- Unfortunately, BEST FLUX AT HIGH CHARGES

ERL X-ray Source Average Brilliance and Flux

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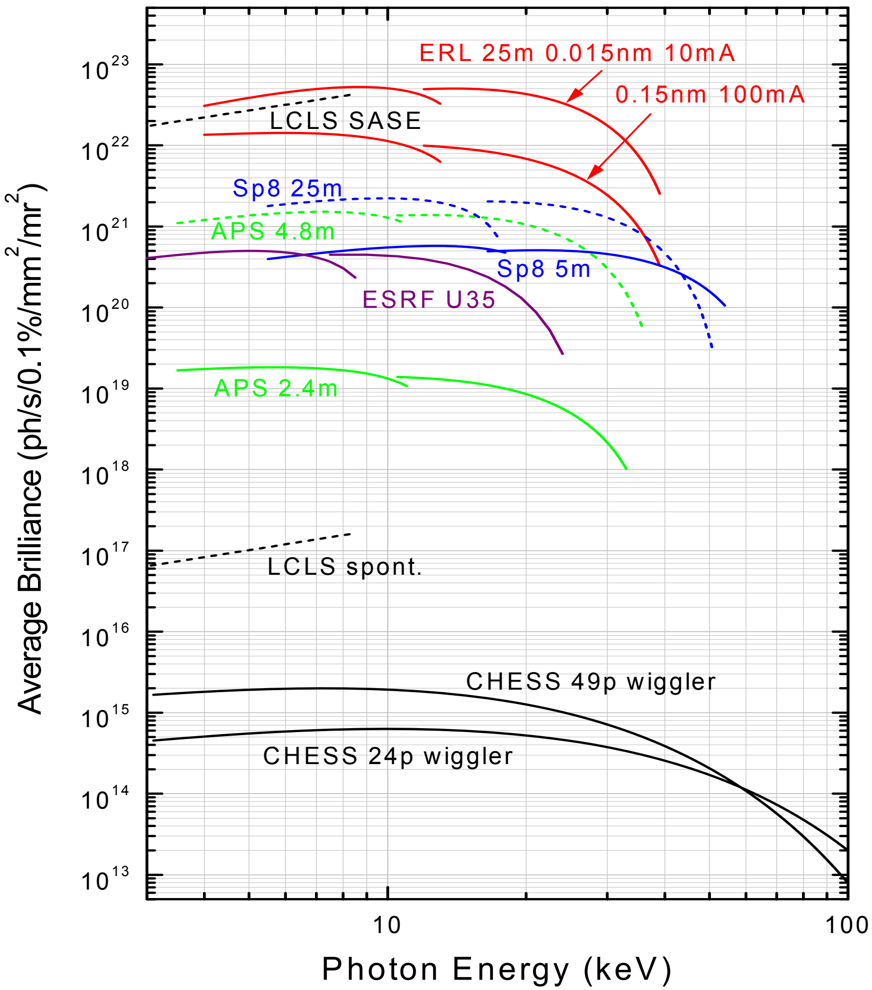
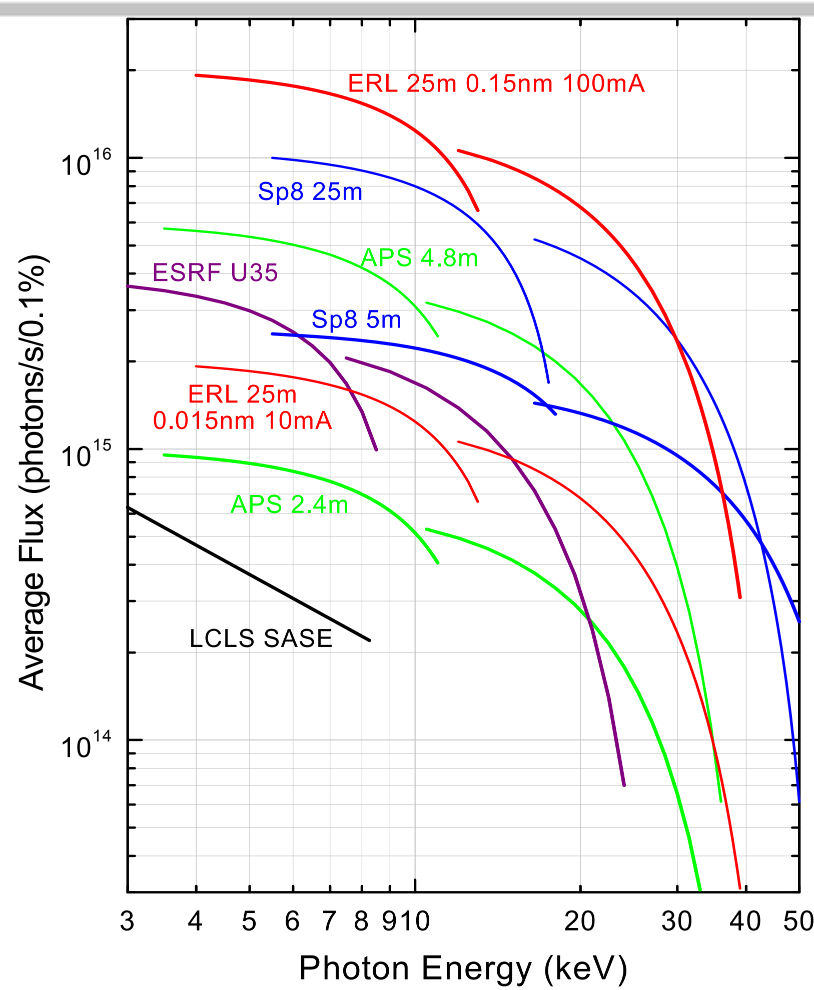
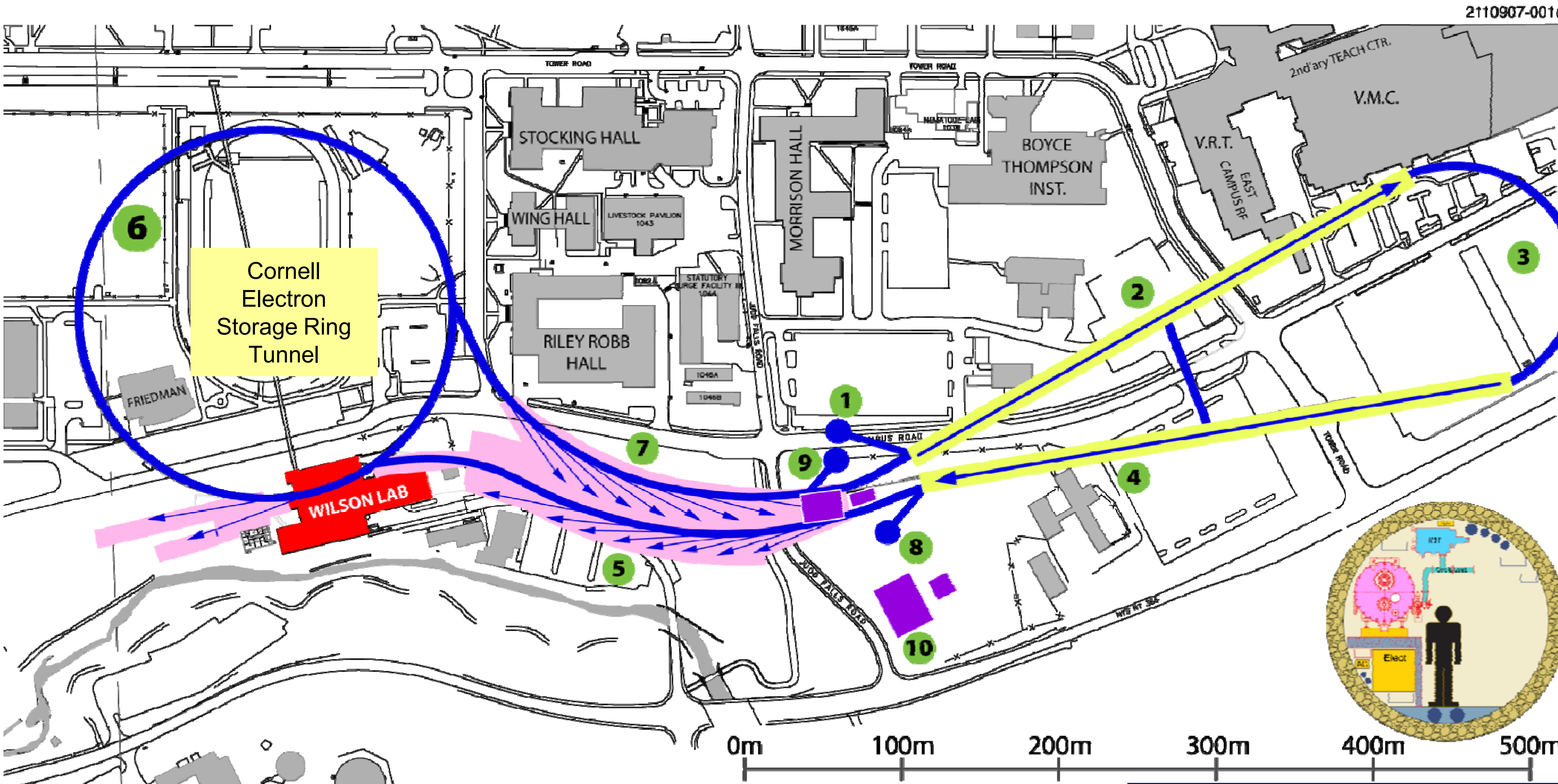




Courtesy: Qun Shen, CHESS Technical Memo 01-002, Cornell University

ERL at Cornell

Cornell University

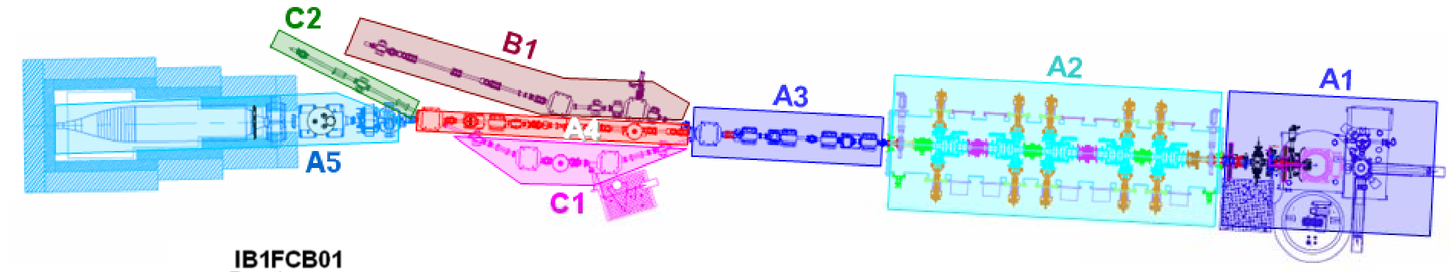


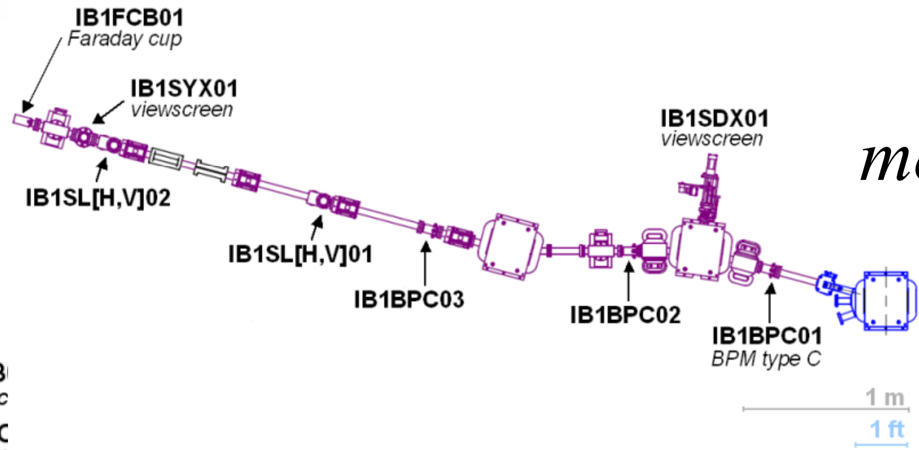
1. Injector
2. Linac 1
3. 2.5 GeV turnaround
4. Linac 2
5. X-ray beam-lines
6. 5 GeV turnaround
7. X-ray beam-lines
8. Beam dump

July 16, 2008 B. Dunham

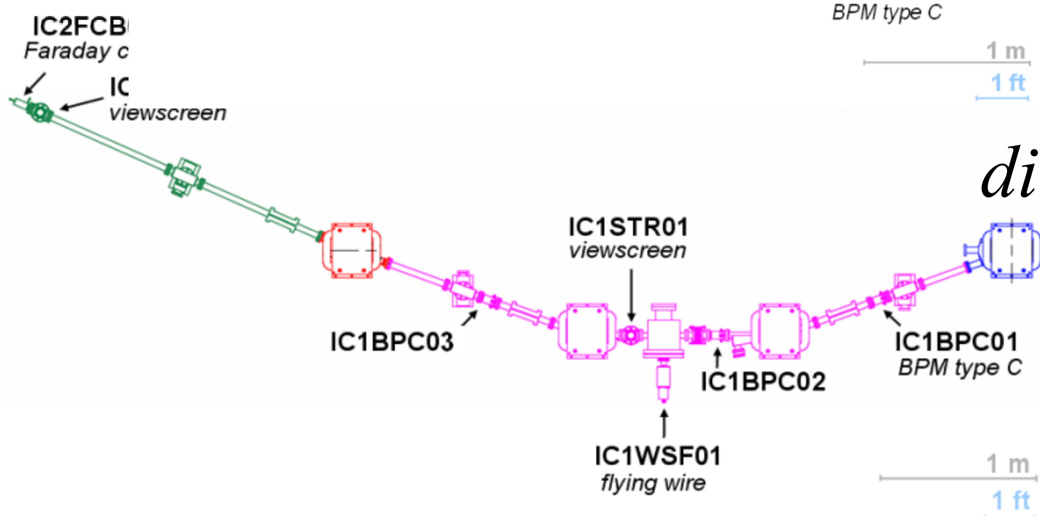
Cornell University

L0 layout: merger & chicane





merger



diagnostics chicane

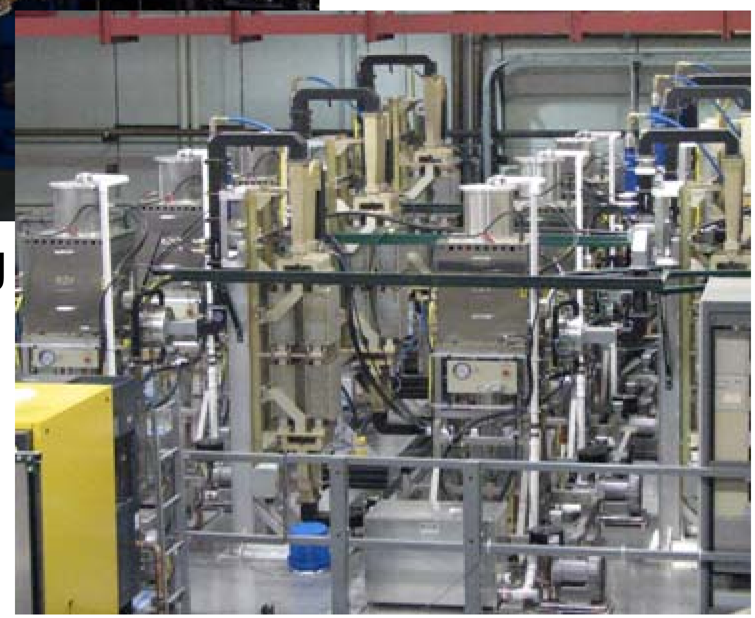
July 16, 2008 B. Dunham

SRF and RF installation

Cryomodule installed at the ERL injector

Cavity string before installation into cryomodule

Klystron gallery



Summary

- ERL Phase I injector construction is nearly complete and commissioning is beginning now! First beam obtained on July 7th. Presently, beam studies are being performed.
- Engineering studies underway for preparing a proposal for the full ERL machine

Modes:	(A) Flux	(B) High-Coherence	(C) Short-Pulse	(D) Ultra High-Coherence	(E) Ultra Short-Pulse	Unit
	Short-Term Goals			Long-Term Goals		
Energy	5	5	5	5	5	GeV
Macropulse current	100	25	1	100	1	mA
Bunch charge	77	19	1000	77	10000	pC
Repetition rate	1300	1300	1	1300	0.1	MHz
Transverse emittance (norm. rms)	0.3	0.08	5.0	0.06	5.0	mm.mrad
Transverse emittance (geometric at 5GeV)	31	8.2	511	6.1	511	pm
Bunch length (rms)	2000	2000	50	2000	20	fsec
intrabunch Energy spread (fractional;rms)	2E-4	2E-4	3E-3	2E-4	3E-3	

Short-Term goals (A-C) are commissioning goals.

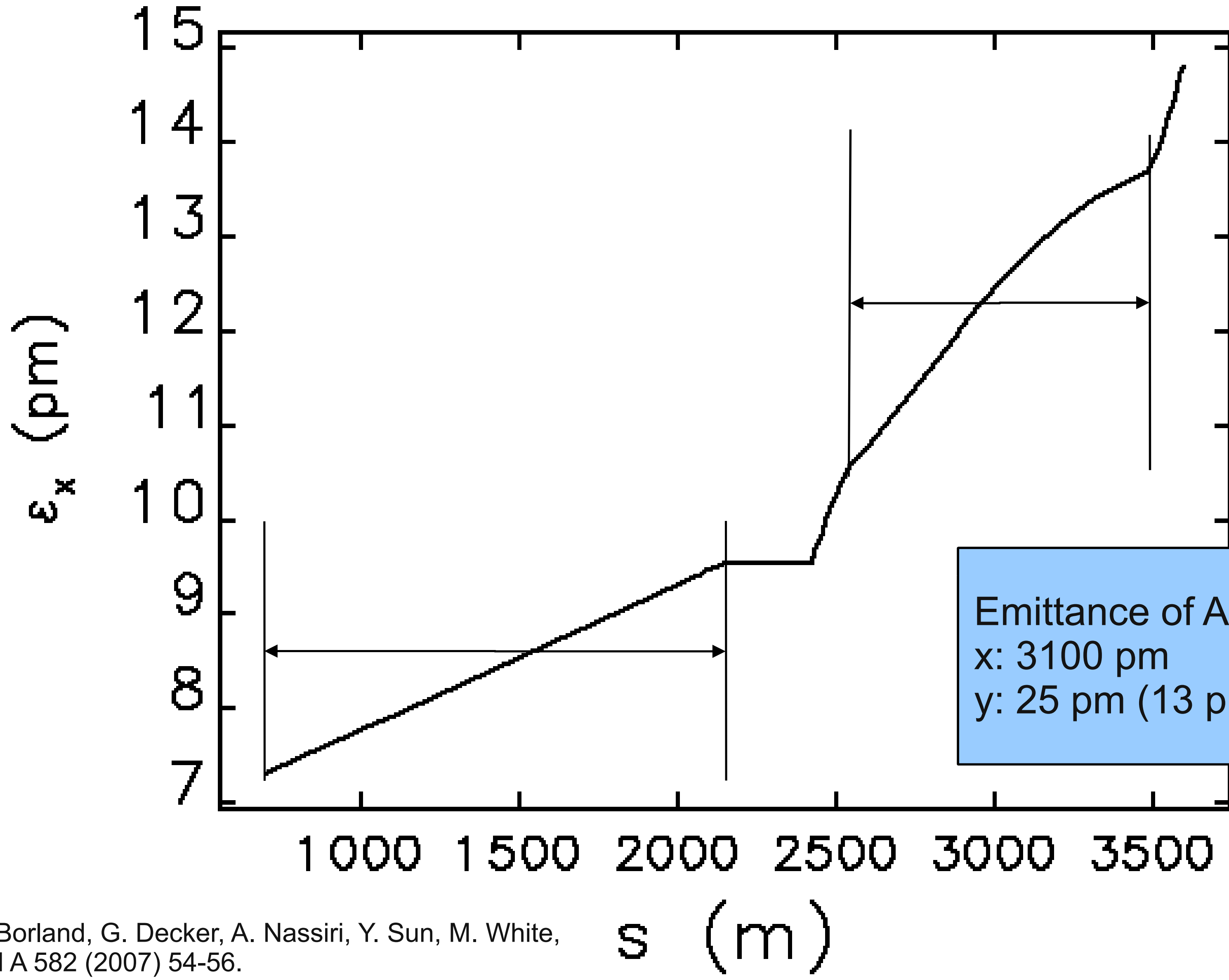
Long-Term goals (D-E) are based on simulations, and will require considerable R&D.

Ultimate APS ERL Upgrade Concept[1]

- Single-pass 7~8 GeV linac points away from APS to permit straight-ahead hard x-ray short-pulse facility
- Beam goes first into new, emittance-preserving turn-around/user arc
  – Second-stage upgrade would add many new beamlines
- ERL can benefit from very long undulators[2]
  – Higher flux and brightness
  – Could add these using somewhat different geometry
- Ability to store beam unchanged
- Existing injector complex unchanged.

[1]M. Borland, G. Decker, A. Nassiri, Y. Sun, M. White, NIM A 582 (2007) 54-56.
[2]S. Gruner *et al.*, “Synchrotron Radiation Sources for the Future,” 11/30/200.

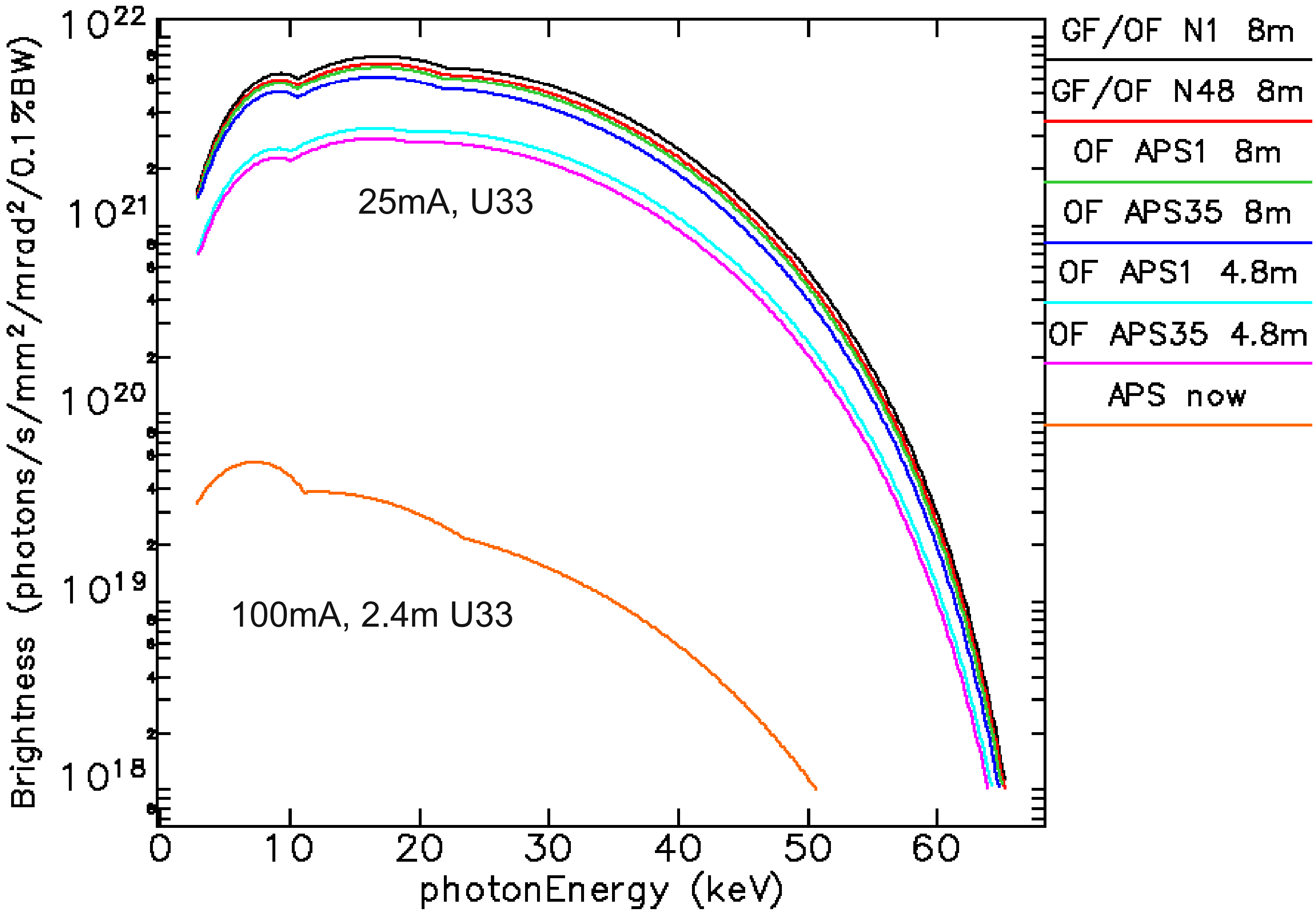
ERL@APS Modeling Results (7 GeV Portion Shown)[1]



Emittance of APS now:
x: 3100 pm
y: 25 pm (13 pm min.)

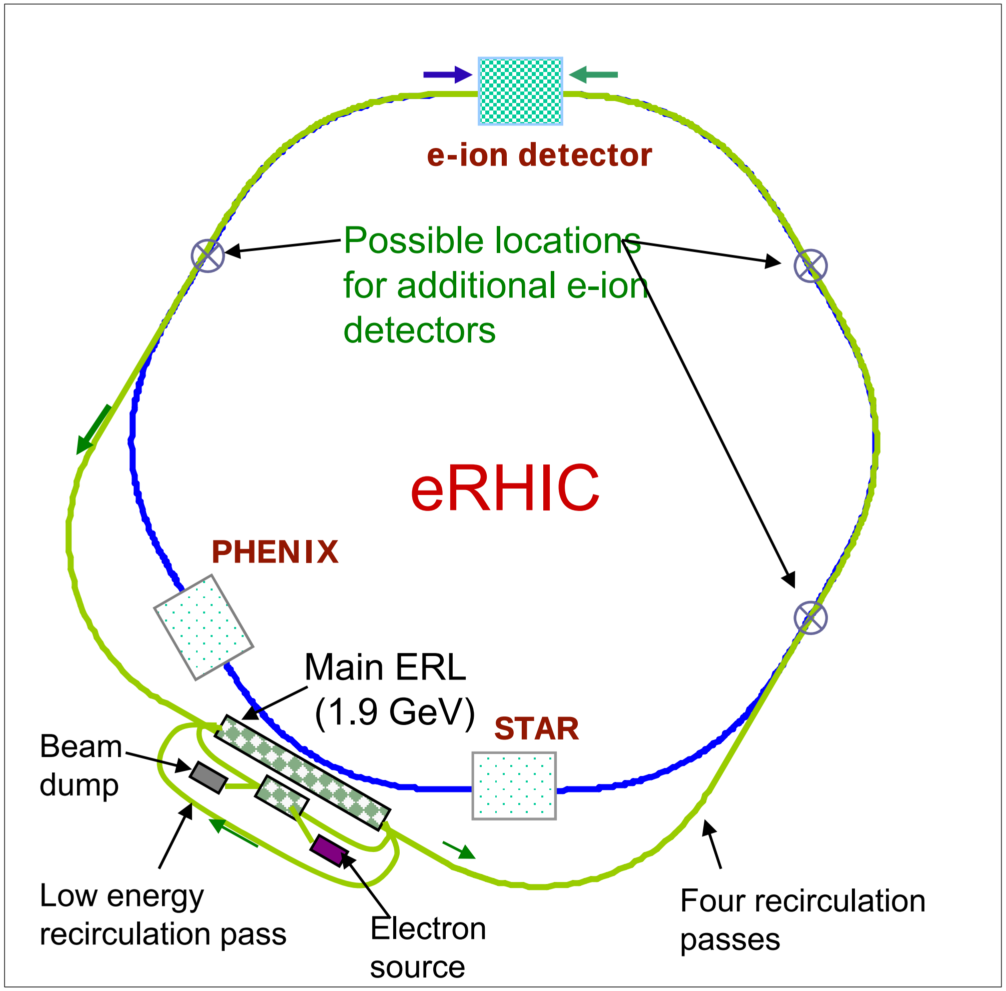
[1]M. Borland, G. Decker, A. Nassiri, Y. Sun, M. White, NIM A 582 (2007) 54-56.

Brightness Comparison for High Coherence Mode at 7 GeV



[1]M. Borland, G. Decker, A. Nassiri, Y. Sun, M. White, NIM A 582 (2007) 54-56.

ERL-based eRHIC Design



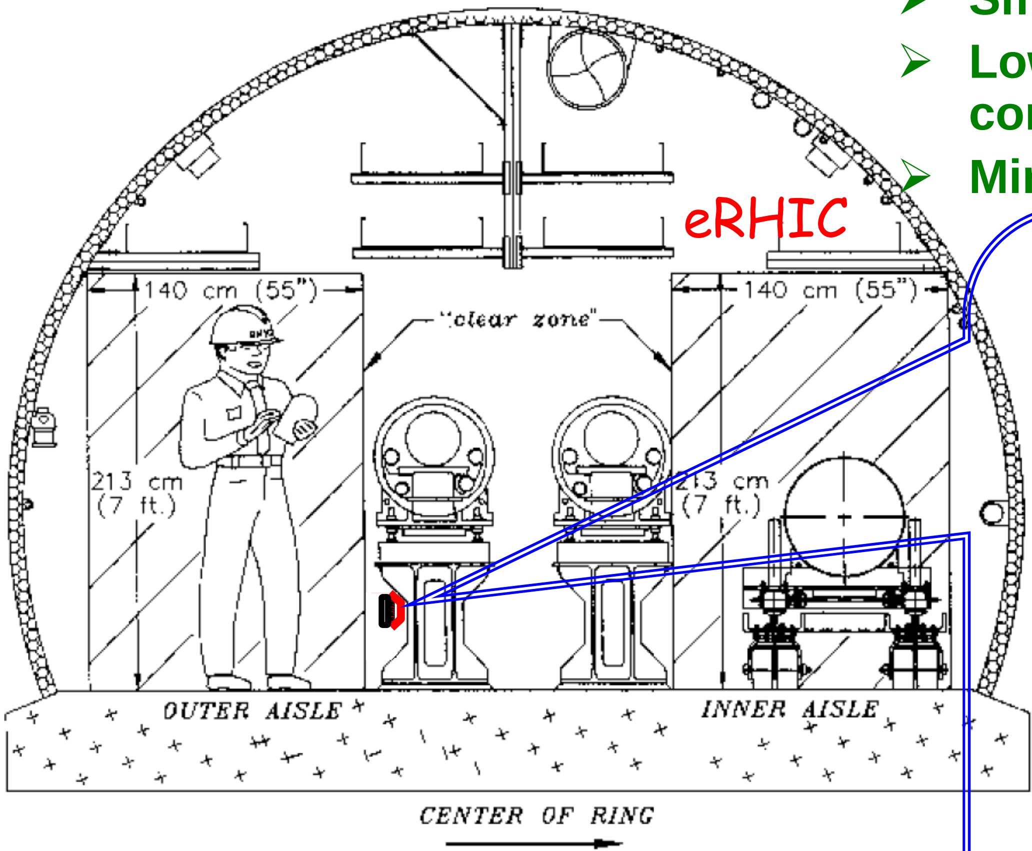
- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- Full polarization transparency at all energies for the electron beam;
- Ability to take full advantage of transverse cooling of the hadron beams;
- Possible options to include polarized positrons: compact storage ring; compton backscattered; undulator-based. Though at lower luminosity.

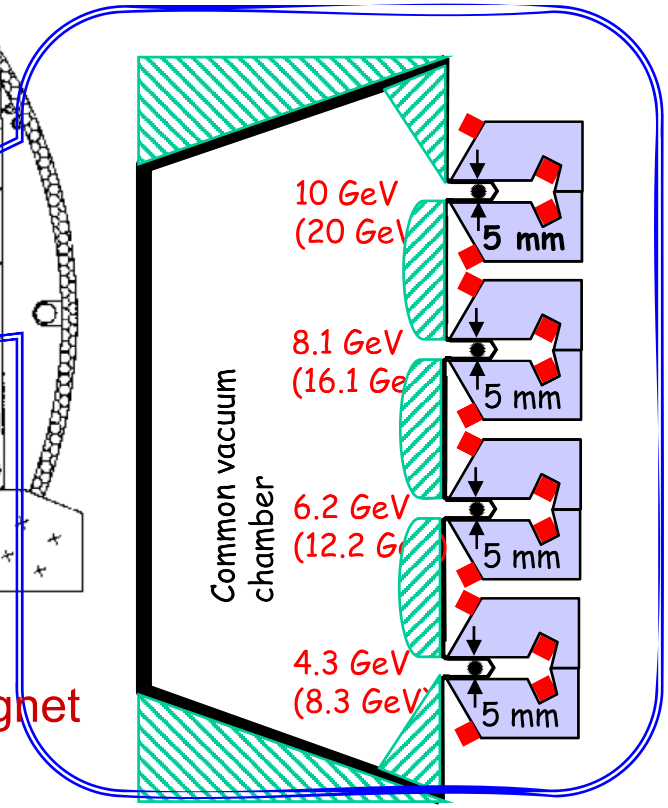
Main R&D Items

- Electron beam R&D for ERL-based design:
  - High intensity polarized electron source
    - Development of large cathode guns with existing current densities ~ 50 mA/cm^2 with good cathode lifetime.
  - Energy recovery technology for high power beams
    - multicavity cryomodule development; high power beam ERL, BNL ERL test facility; loss protection; instabilites.
  - Development of compact recirculation loop magnets
    - Design, build and test a prototype of a small gap magnet and its vacuum chamber.
  - Evaluation of electron-ion beam-beam effects, including the kink instability and e-beam disruption
- Main R&D items for ion beam:
  - Polarized ^{3}He production (EBIS) and acceleration
  - 166 bunches
- General EIC R&D item:
  - Proof of principle of the coherent electron cooling

Recirculation passes

- Separate recirculation loops
- Small aperture magnets
- Low current, low power consumption
- Minimized cost

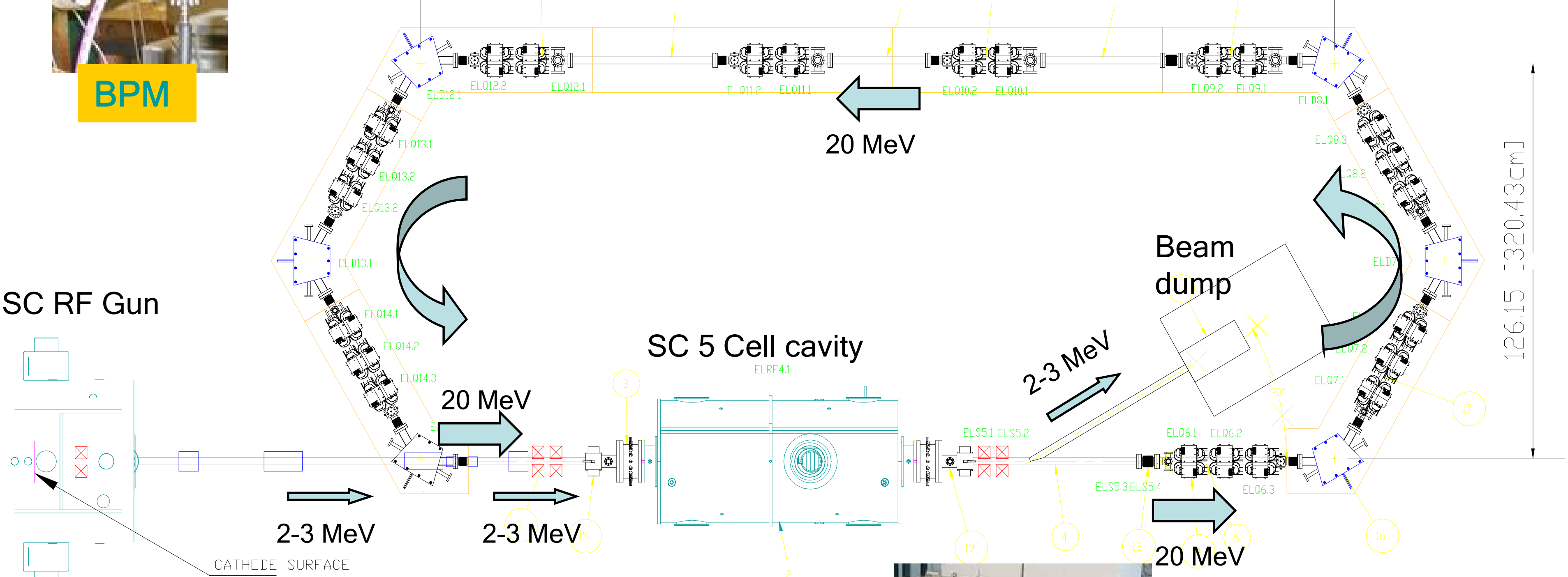




Approved LDRD for the compact magnet development

BNL R&D ERL: To be completed 2010

BPM

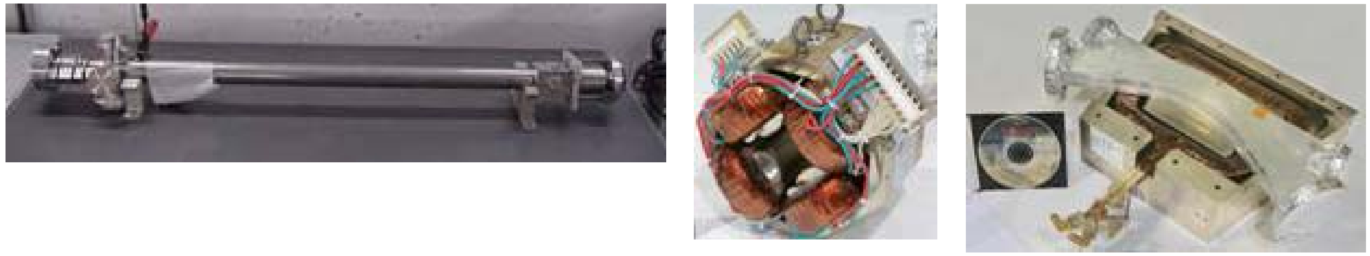


5 Cell SRF Cavity inside the cryomodule

Returning arc in place

Courtesy: D. Kayran

Loop magnets and vacuum chambers



1MW Klystron

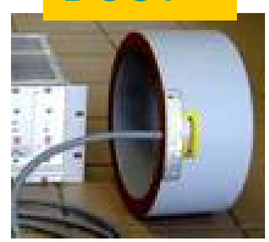
LHe Ballast Tank

50 kW Transmitter

Dummy load

Transmitter system

DCCT



Courtesy:
D. Kayran

R&D ERL Beam Parameters

Parameter Operation regime	High Current	High Current	High charge
Charge per bunch, nC	0.7	1.4	5
Numbers of passes	1	1	1
Energy maximum/injection, MeV	20/2.5	20/2.5	20/3.0
Bunch rep-rate, MHz	700	350	9.383
Average current, mA	500	500	50
Injected/ejected beam power, MW	1.0	1.0	0.15
R.m.s. Normalized emittances ex/ey, mm*mrad	1.4/1.4	2.2/2.3	4.8/5.3
R.m.s. Energy spread, $\delta E/E$	3.5×10^{-3}	5×10^{-3}	1×10^{-2}
R.m.s. Bunch length, ps	18	21	31

Courtesy: D. Kayran

BNL R&D ERL: Status

- ERL Enclosure (Vault) was constructed
- Gun is under construction at AES
- 5-cell Cavity is being processed and tested at JLAB
- Cold emission test 5-cell cavity in cryostat at BNL in November 2008
- 1 MW Gun klystron and 50 kW 5-cell cavity transmitter are installed, tested with dummy load at 0.6 MW level
- Recirculation loop magnets have been manufacture, assembled and went through complete magnetic measurements
- Recirculation loop vacuum system components are ready for installation
- Gun drive laser is been procured, will arrive in October 2008
- RF control will be based on the new digital RHIC LLRF. The LLRF system is currently under development.
- Machine protection system is being designed (BLMs, DCCTs)

BNL starts commissioning of the R&D ERL in 2009

1) the straight pass (2.5 MeV gun -> 20 MeV 5 cell cavity -> beam diagnostic) test for the beam quality studies.
2) test concept of emittance preservation in a beam merger in the same configuration as above
3) complete recirculation loop, demonstrate energy recovery with high charge per bunch and high beam current
4) study beam and stability issues relevant for high current ERLs

Courtesy: D. Kayran

Conclusions

- Energy recovered recirculated linacs are a new class of accelerators with the potential to produce unique beam properties
- The field of ERL-based FELs continues to grow and the performance of devices continues to improve
- Higher peak and average brilliance may be possible in ERLs than are possible in storage rings for the same beam current
- Many new ideas are being explored, some in conjunction with future light source applications of Energy Recovered Linacs
- The field seems to be thriving, and there is no shortage of interesting problems to work on

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