Cornell University

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Toward an Energy Recovery Linac x-ray source at Cornell University

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- The ERL principle
- Limits of ERLs
- Studies for an x-ray ERL

- Ultra low emittance creation
- Gun prototyping
- Gun diagnostics
- Laser optimization

CESR @ Cornell

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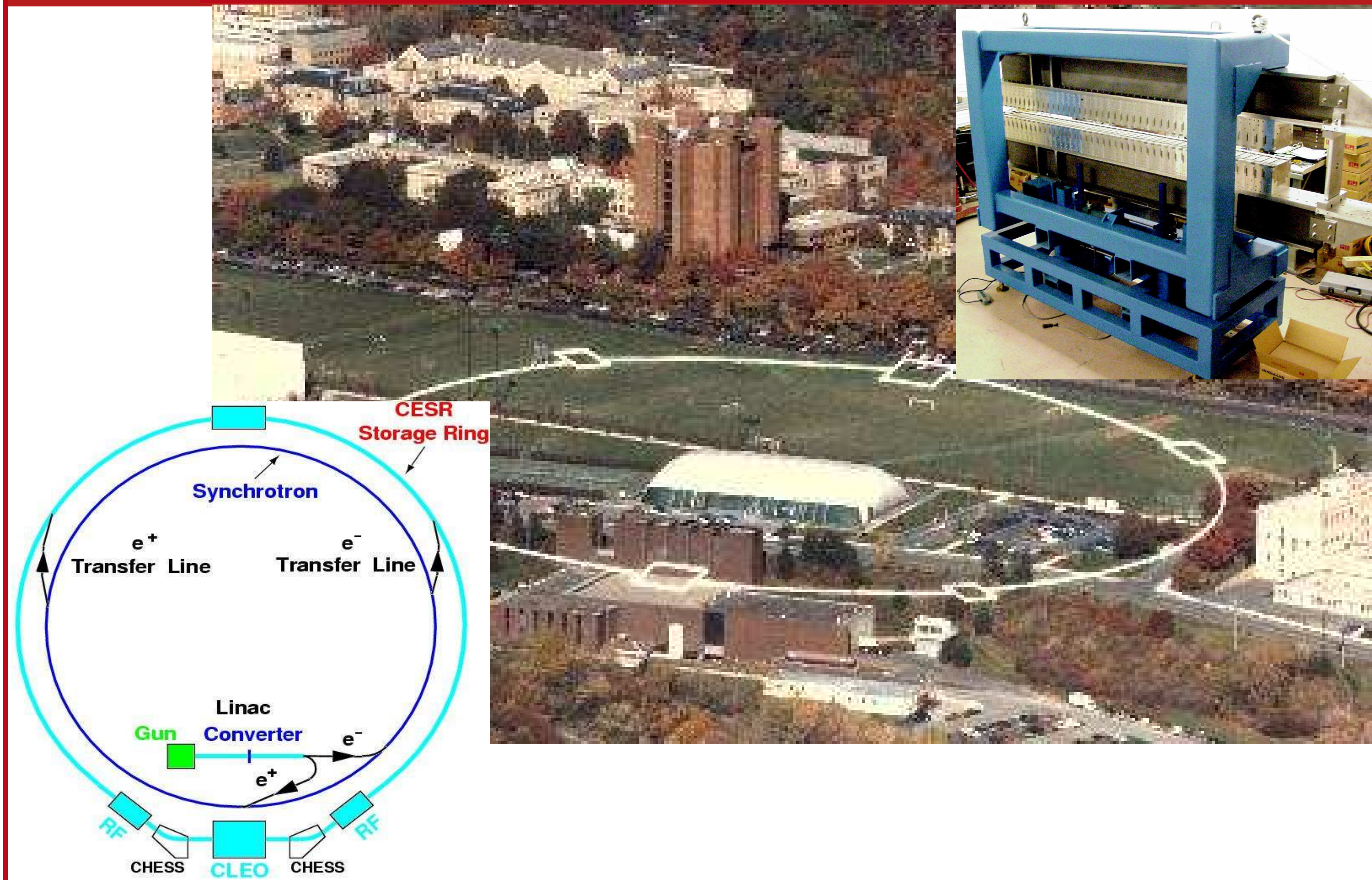

Emittance Excitation

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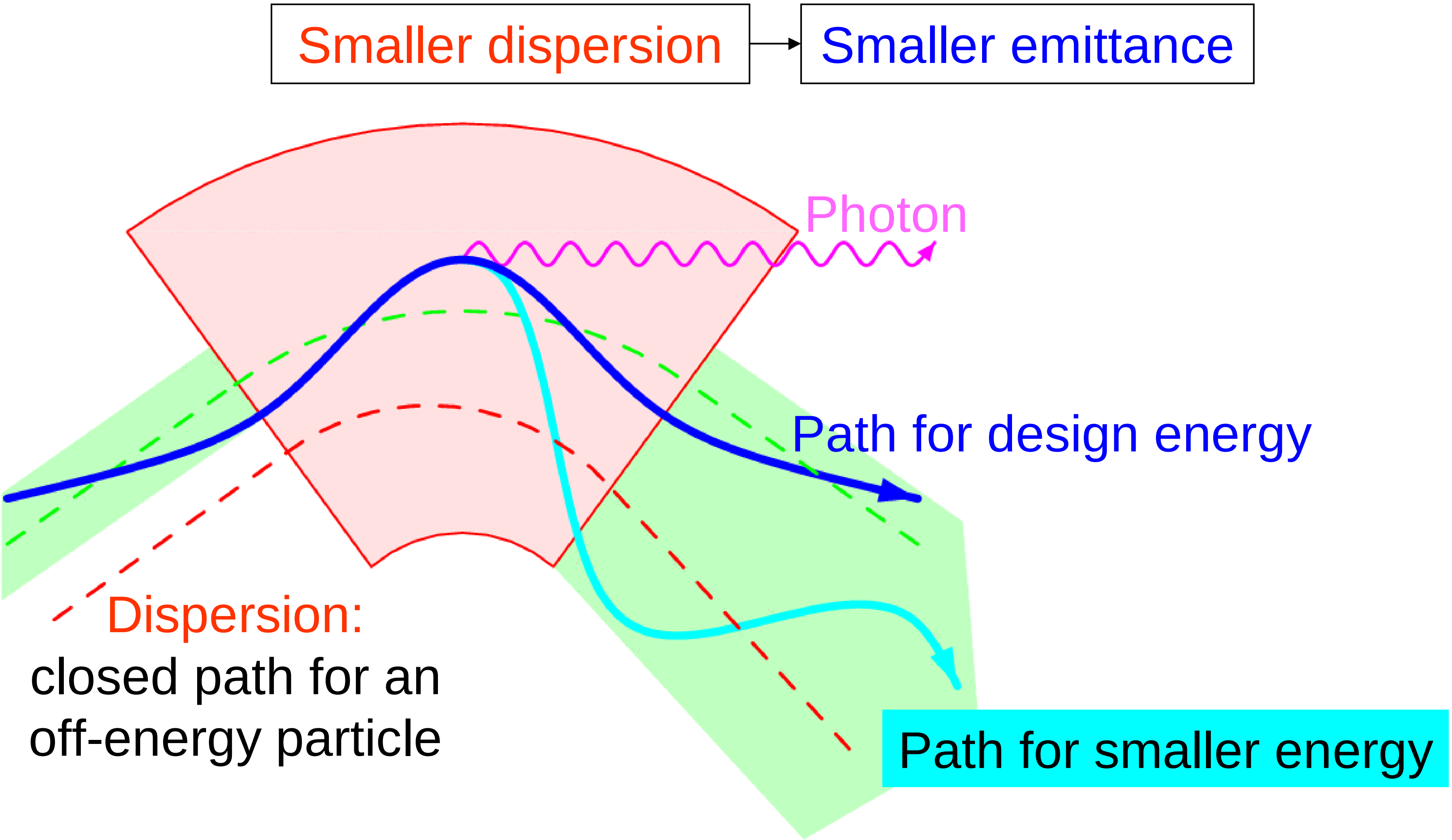

Beam Size in a Linear Accelerator

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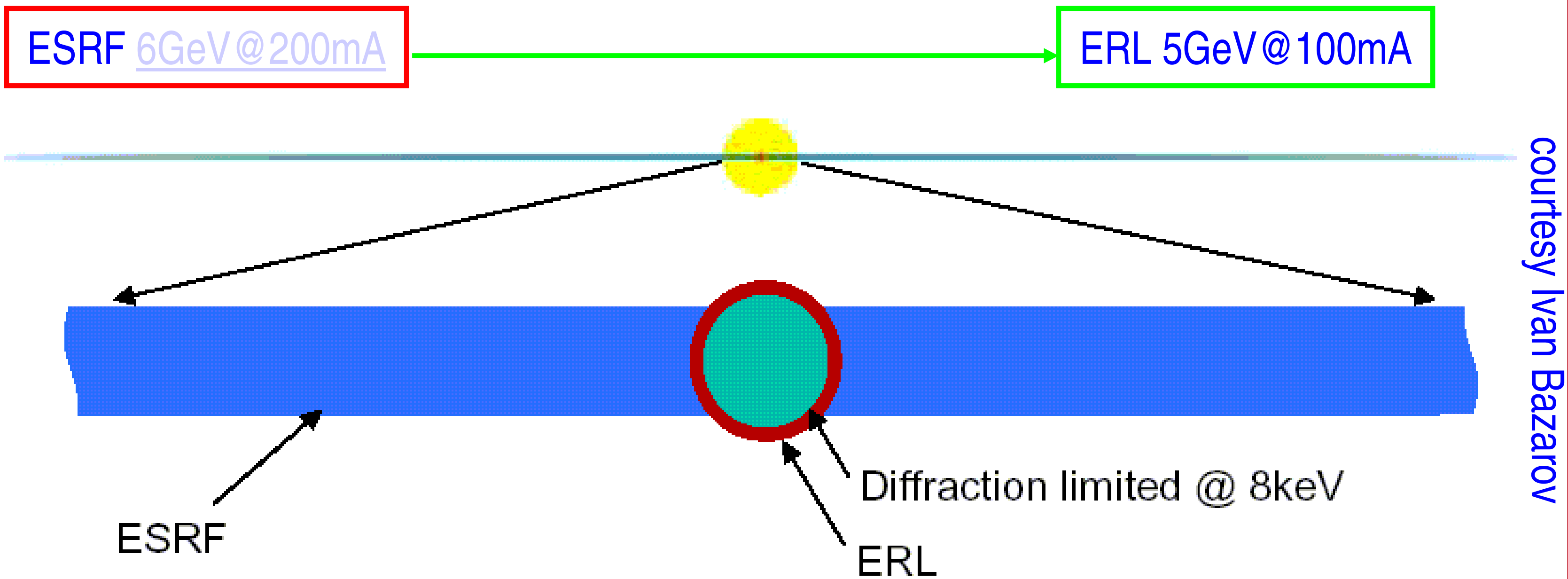
The beam properties are to a very large extend determined by the injector system:

- **The horizontal beam size can be made much smaller than in a ring**
- **While the smallest beams that are possible in rings have almost been reached, a linear accelerator can take advantage of any future improvement in the electron source or injector system.**



Smaller Beams and more Coherence

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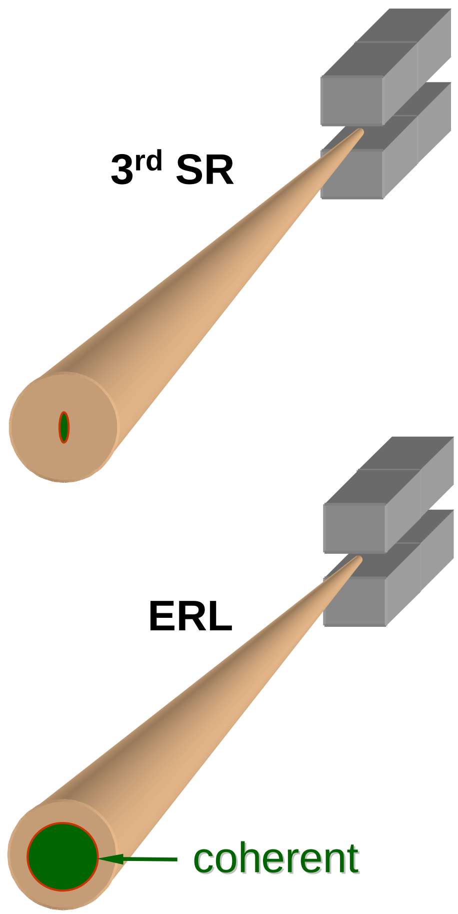
- Coherent x-ray diffraction imaging
- It would, in principle, allow atomic resolution imaging on non-crystalline materials.
- This type of experiments is completely limited by coherent flux.



Factor 100 more coherent flux for ERL for same x-rays, or provide coherence for harder x-rays

Bunch length in a Linac

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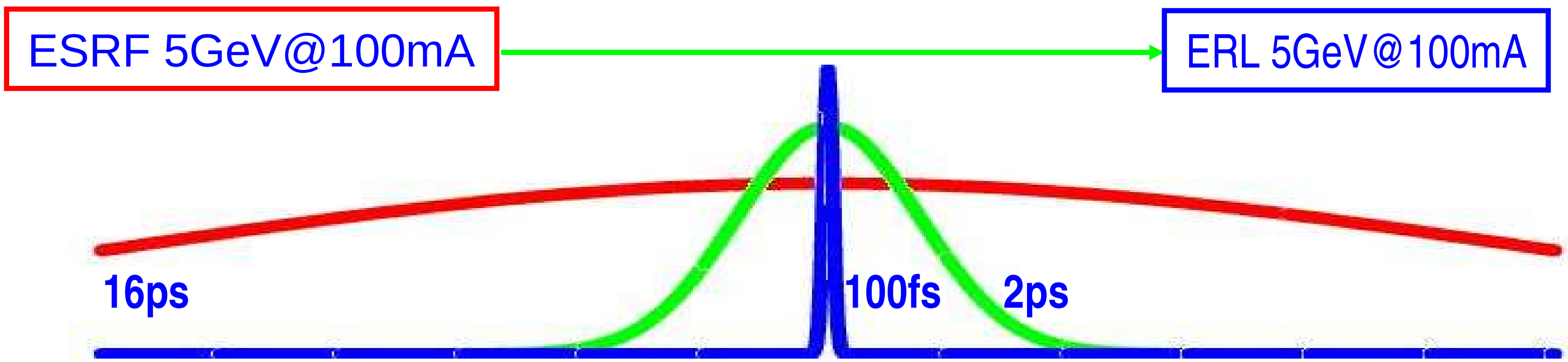
- The bunch length can be made much smaller than in a ring
- While the shortest bunches possible in rings have almost bean reached, a linear accelerator can take advantage of any future improvement in the source source or injector system.



Pro and Con for an x-ray Linac

CHESS & LEPP

As compared to a ring, the beam properties are largely determined by the injector system:

- The bunch length can be made much smaller than in a ring
- Smaller emittances
- Higher coherence fraction

ESRF 6GeV@200mA → ERL 5GeV@100mA

Current of 100mA and energy of 5GeV leads to a beam power of 0.5GW !!!

The energy of the spent beam has to be recaptured for the new beam.

Pro and Con for an x-ray Linac

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ERLs

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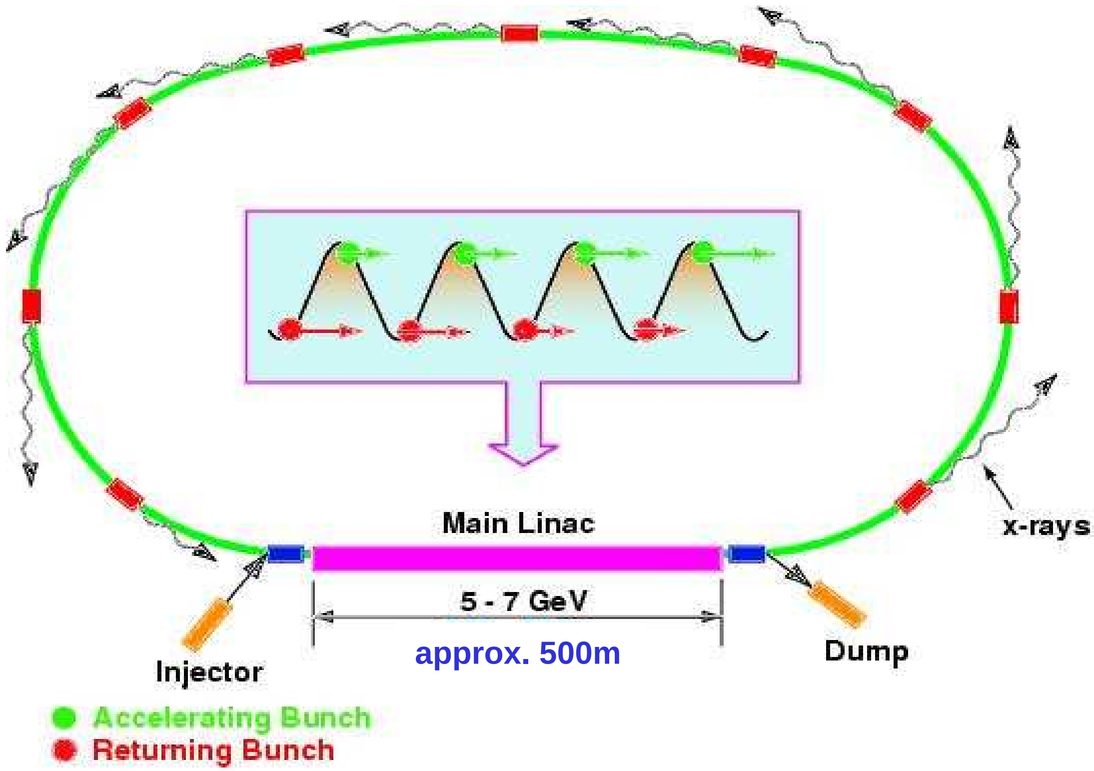
X-ray analysis with highest resolution in space and time:



Challenges:

- Invented in 1965
- Needs superconducting RF, otherwise high Voltage CW cavities melt
- High Voltage SRF only had a boost end of ’90s due to the linear collider

Nominal Parameters for 5GeV electron beam (Contain safety factors)

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Operation mode	High Flux	Coherence	Short pulse
Current (mA)	100	10	1
Charge/b (nC)	0.08	0.008	1.0
$\epsilon_{x/y}$(nm)	0.1	0.015	1
Energy (GeV)	5.3	5.3	5.3
Rep. rate (GHz)	1.3	1.3	0.001
Av. flux $\left(\frac{\text{ph}}{0.1\%\ \text{s}}\right)$	$9\ 10^{15}$	$9\ 10^{14}$	$9\ 10^{12}$
Av. brilliance $\left(\frac{\text{ph}}{0.1\%\ \text{s mm}^2\ \text{mrad}^2}\right)$	$1.6\ 10^{22}$	$3.0\ 10^{22}$	$2.0\ 10^{17}$
Bunch length (ps)	2	2	0.1

Optimistic Outlook

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- The ERL parameters are **dramatically** better than present 3rd generation storage rings
- The use of ERL microbeams, coherence, and ultra-fast timing will lead to new unique experiments that can be expected to transform the way future x-ray science experiments are conducted
- Most critical parameters to achieve in an ERL are therefore, narrow beams, small emittances, short bunches, at large currents.

Parameter	APS ring	ERL*	Gain factor
Rms source size(μm)	239(h) x 15(v)	2(h) x 2(v)	1/900 in area
x-ray beamsize	100nm - 1μm	1 nm	100 to 1000
Coherent flux x-rays/s/0.1% bw	3×10^{11}	9×10^{14}	3,000
Rms duration	32 ps	0.1 ps	over 300

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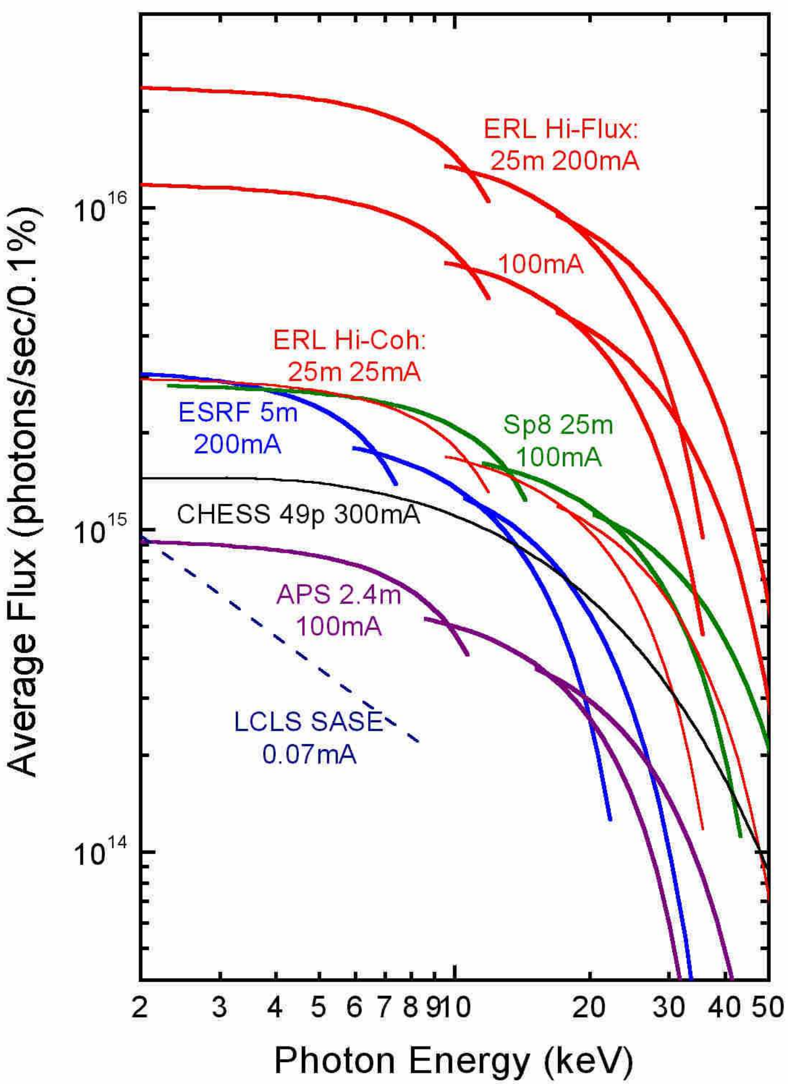
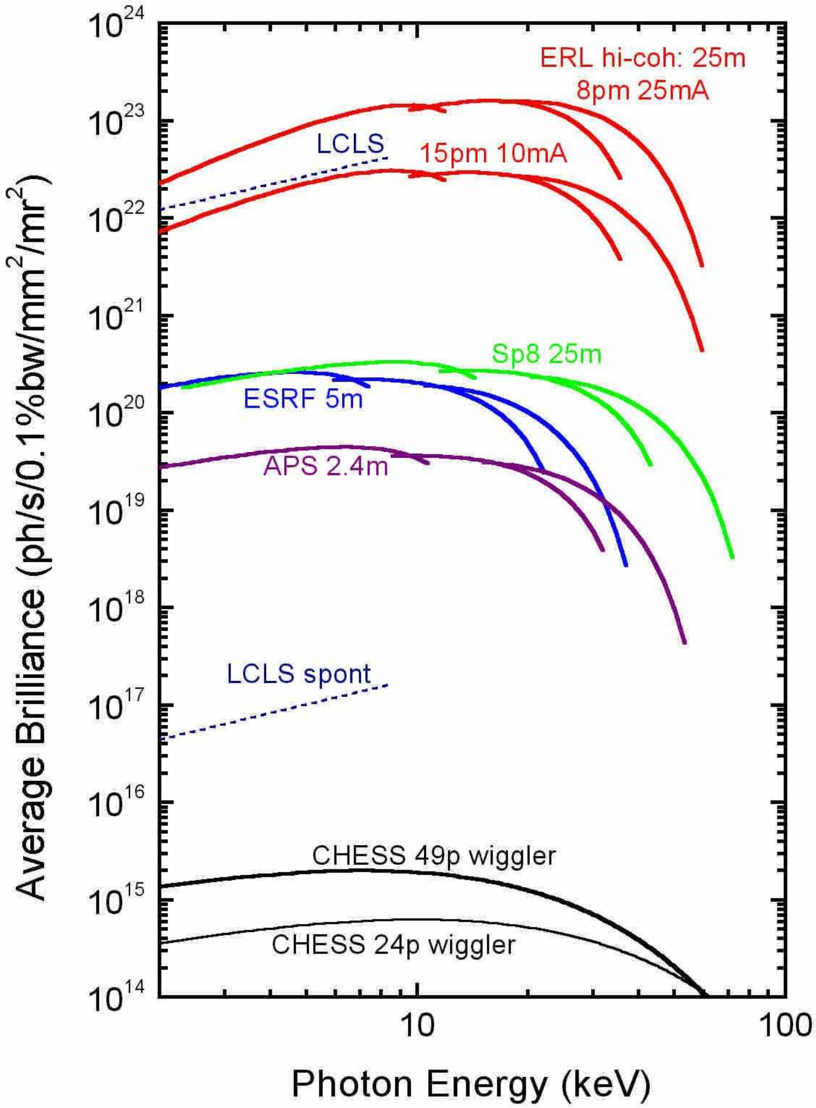
Flux and Brilliance





Accelerator Physics @ CESR

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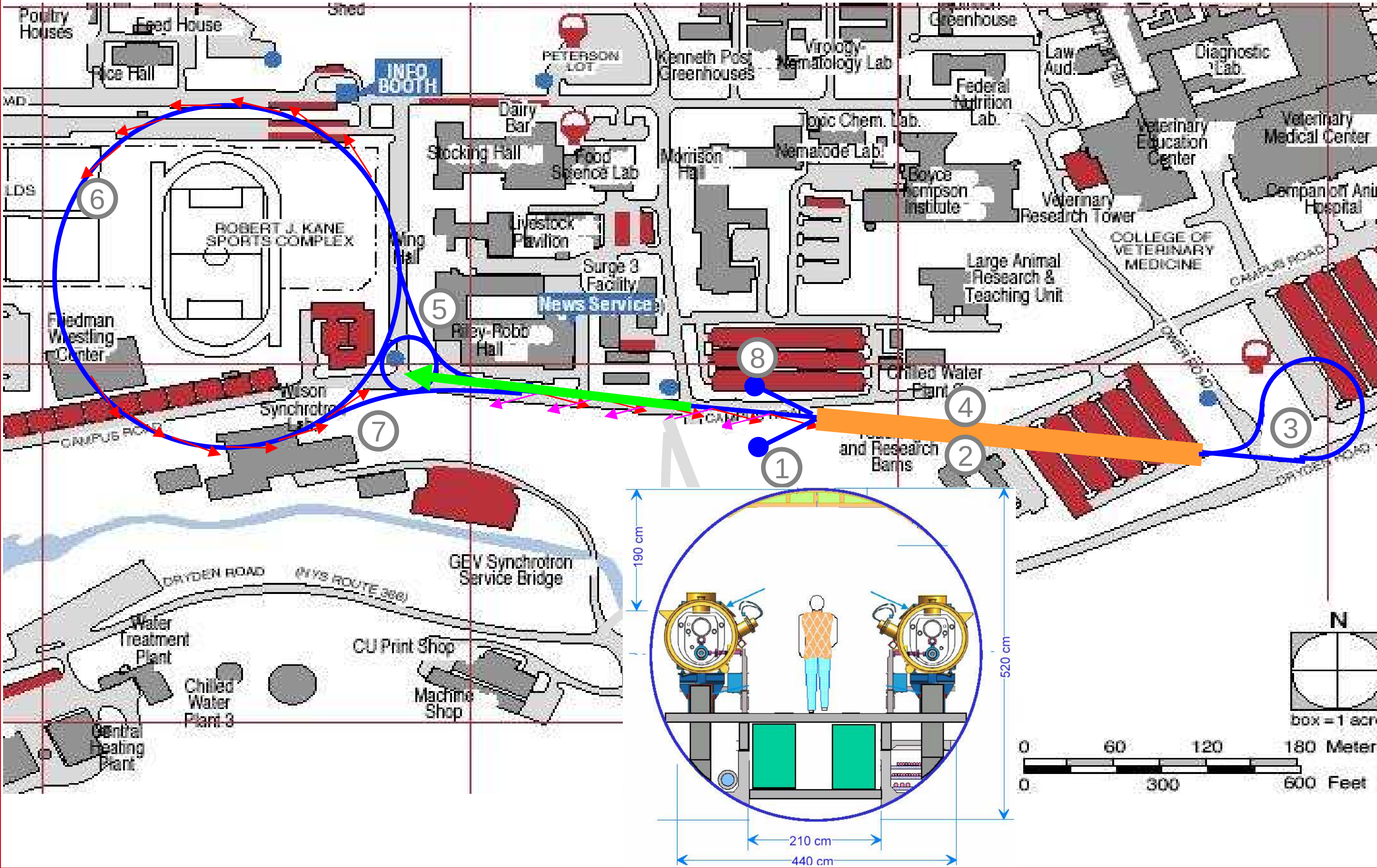

Advantages of ERL@CESR

- Operation of CESR and ERL test simultaneously.
- Use all of the CESR tunnel.
- Lots of space for undulators.
- Space for future upgrades, like an FEL.
- No basements of existing buildings to worry about.
- Only one tunnel for two linacs.
- Less competition, since other sights cannot offer upgrades.
- Example character for other existing light sources.

Limits to an ERL

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Limits to Energy :

- Length of Linac and power for its cooling to 2K (supercond. RF)

Limits to Current :

- Beam Break Up (BBU) instability (collective effects)
- HOM heating (supercond. RF)

For small emittances in all 3 dimensions :

- Coulomb expulsion of bunched particles (Space Charge, e-Source)
- Radiation back reaction on a bunch (ISR and CSR)
- Nonlinear beam dynamics
- Ion accumulation in the beam potential
- Stability against ground vibration (μm level)

Superconducting RF infrastructure

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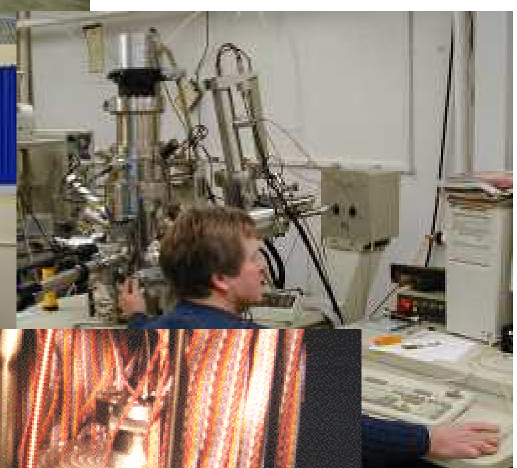
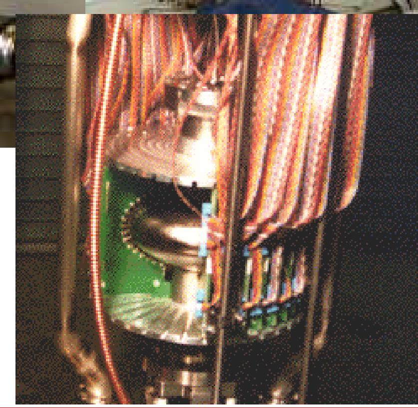
- RF measurement lab
- Shielded test pits, cryogenics
- Clean room
- Chemical handling
- Precision coordinate measurement
- Scanning electron microscope, Auger analysis
- Advanced μ-Kelvin thermometry





Ongoing ERL prototyping

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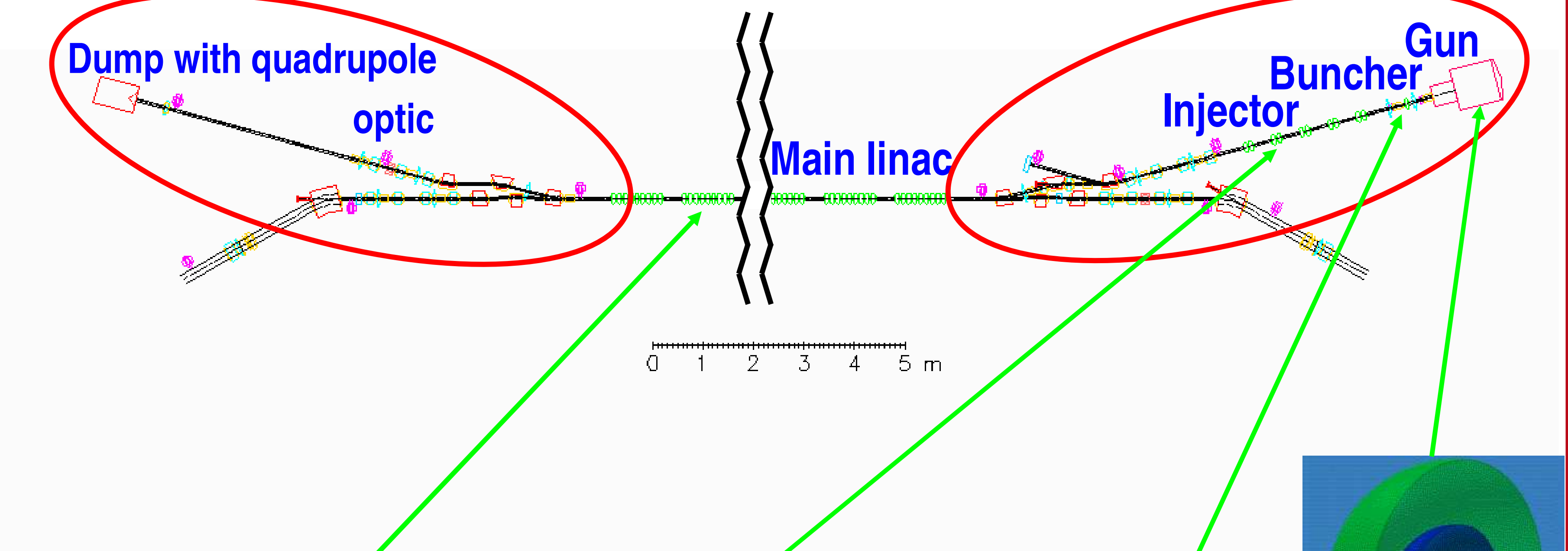

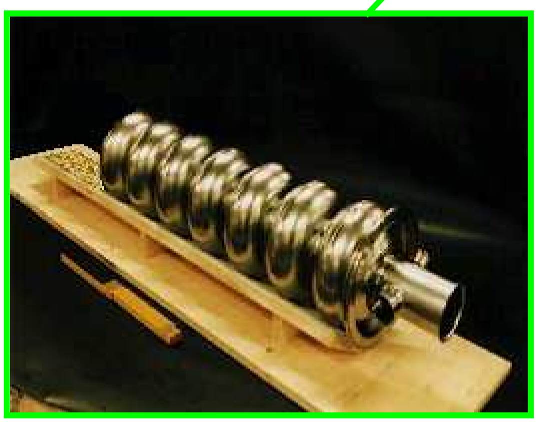

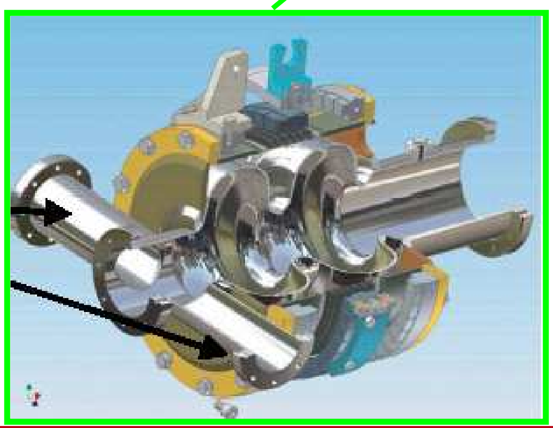

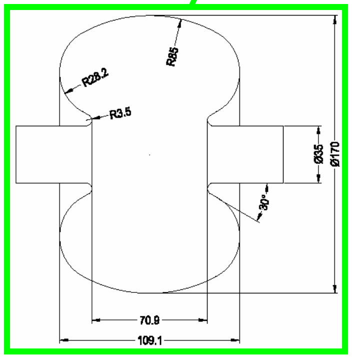

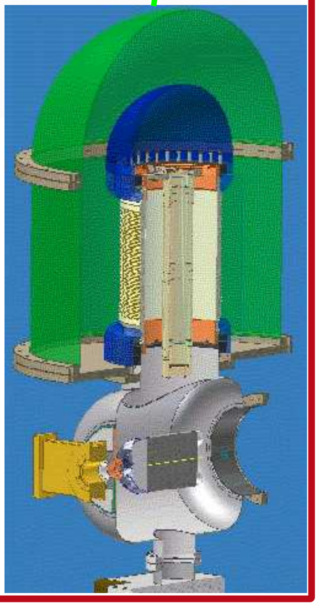

Ongoing Developments

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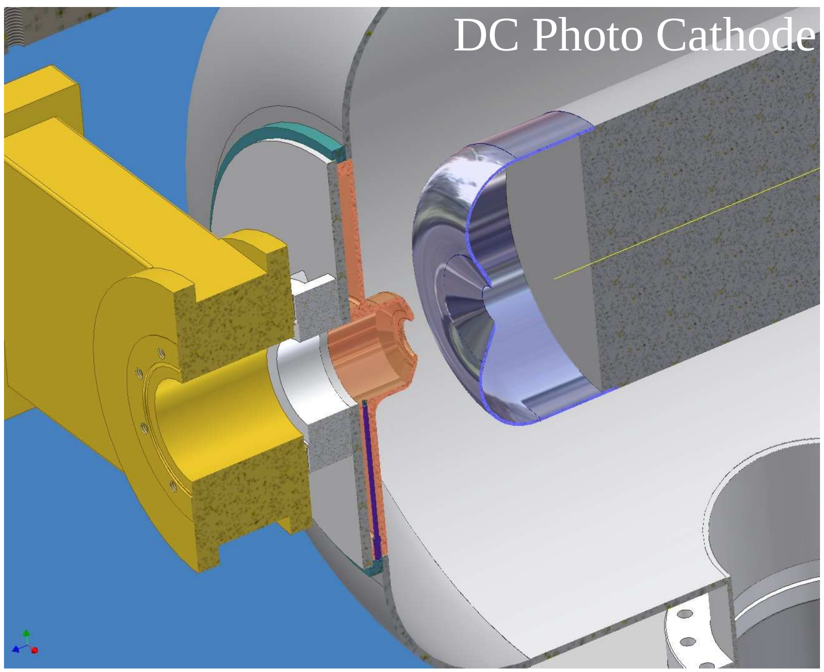
1) DC electron source
   - Gun development
   - HV power supply
   - Photocathode development
   - ERL injector lab
   - Laser system development



2) Superconducting RF
   - RF control (tests at CESR/JLAB)
   - HOM absorbers
   - Injector klystron
   - Input coupler (with MEPI)
   - Injector cavity / Cryomodule
3) Beam dynamics
   - Injector optimization with space charge
   - Beam break up instability (BBU)
   - Optics design / ion clearing
4) Accelerator design
   - Optics
   - Beam dynamics
   - Beam stability
5) X-ray beamline design
   - X-ray optics
   - Undulator design

Ongoing ERL prototyping

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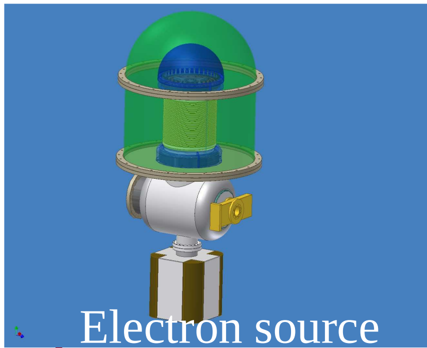

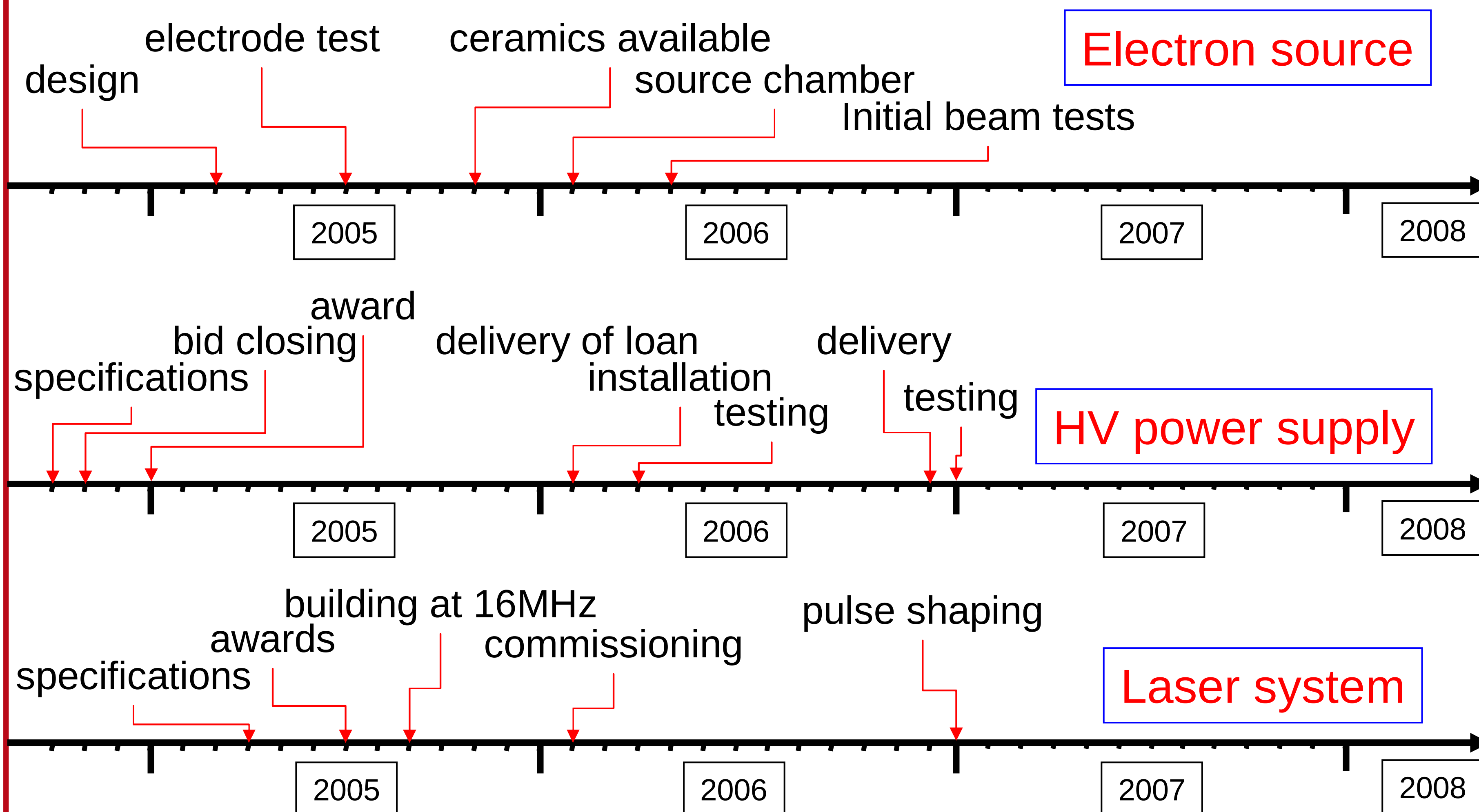

Ongoing ERL prototyping

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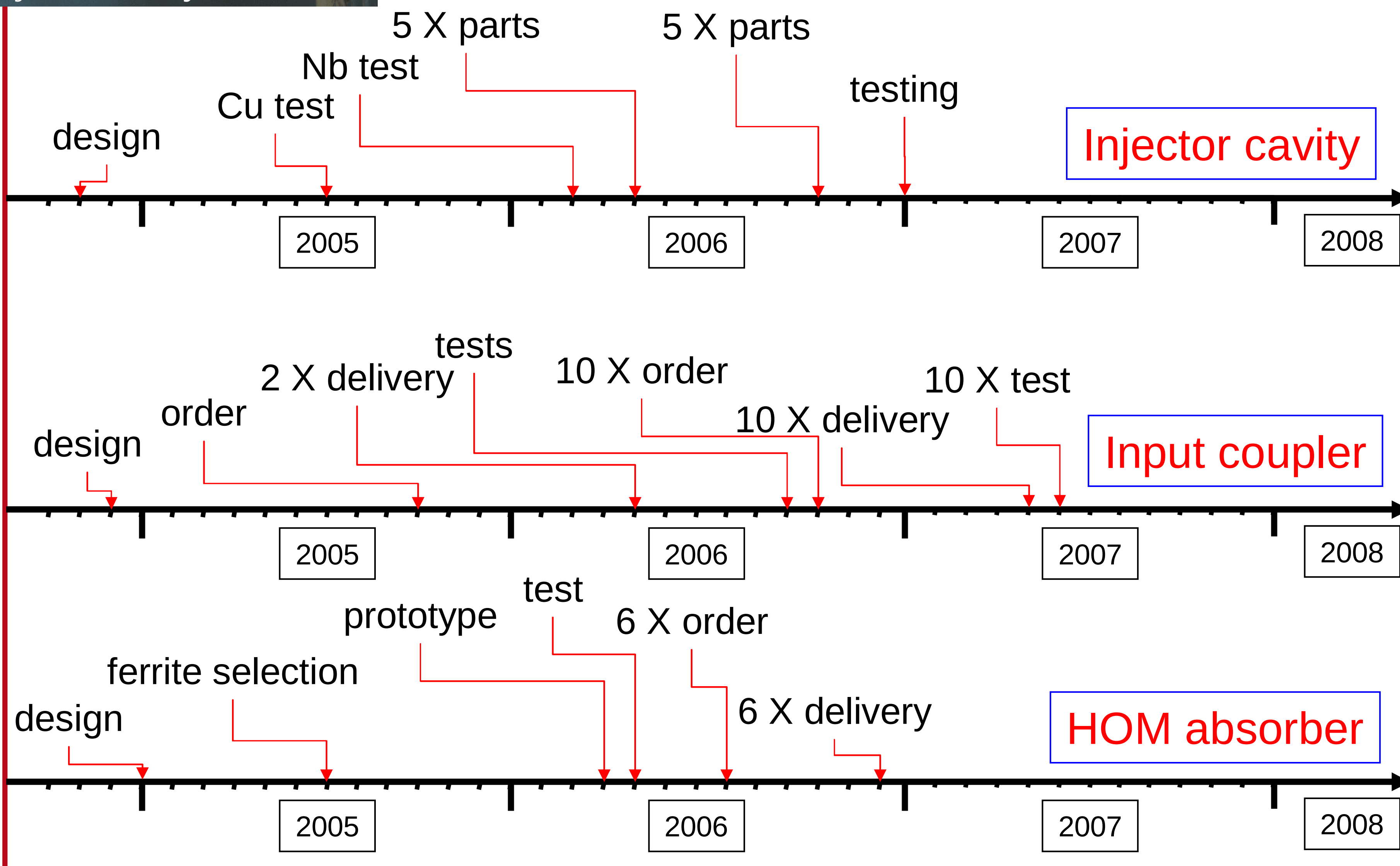

Injector cryomodule Plans and Timeline

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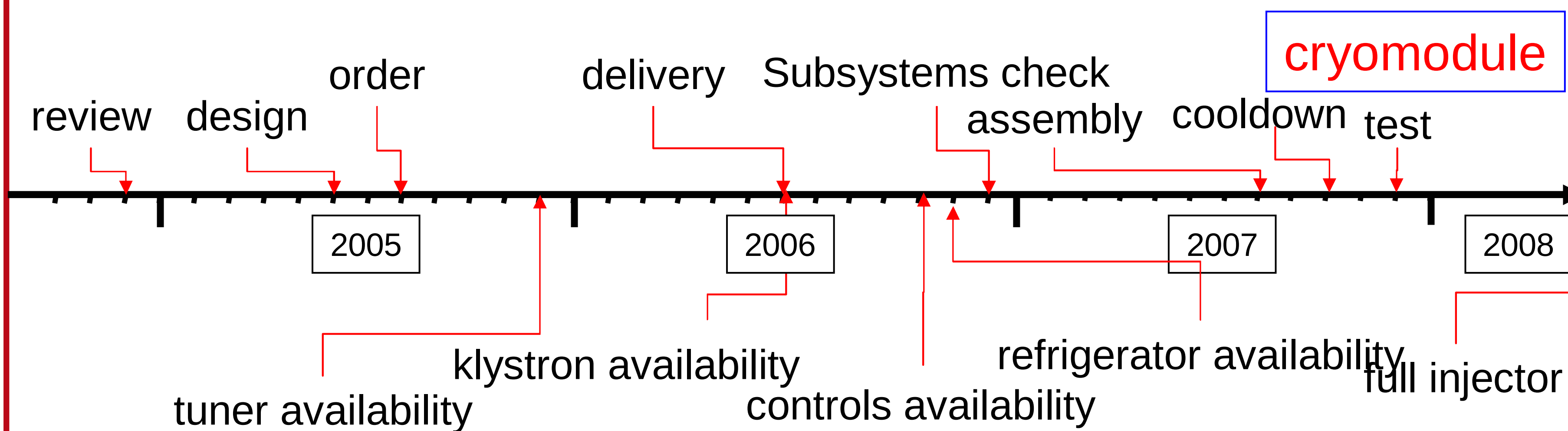
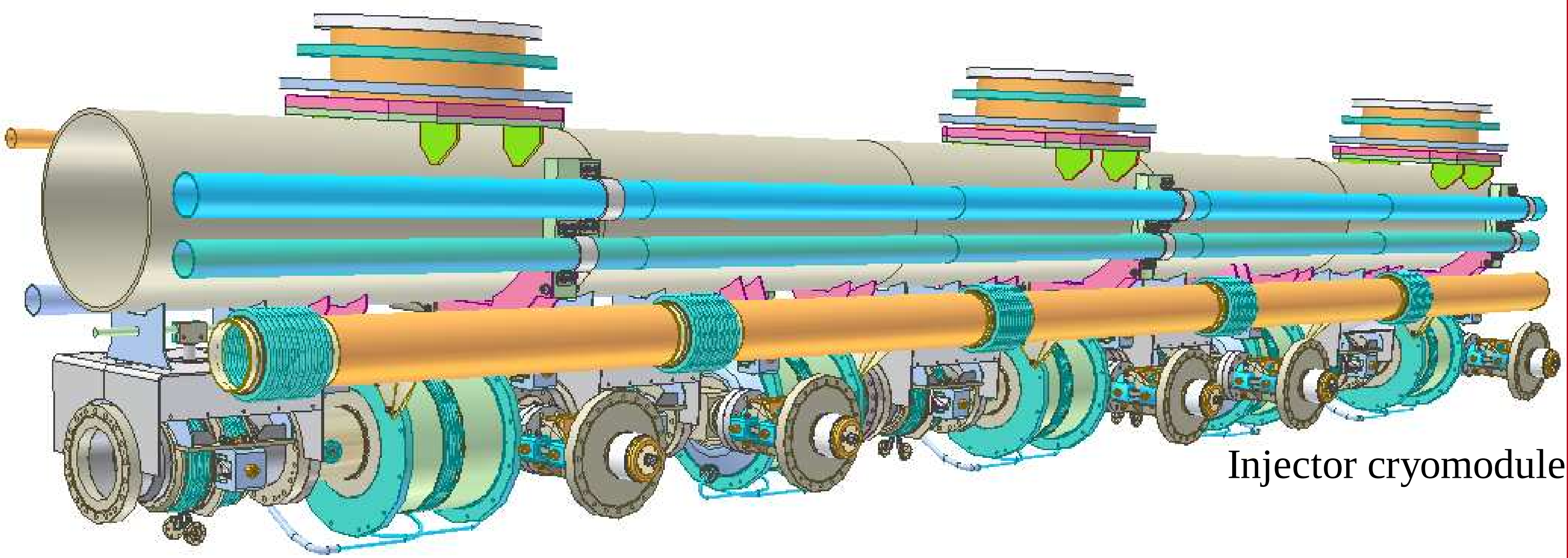
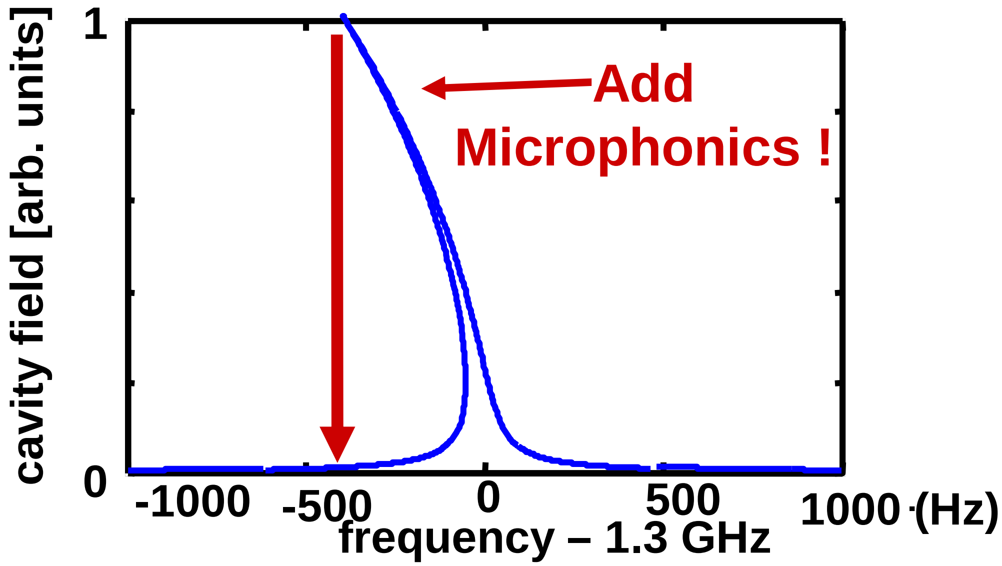
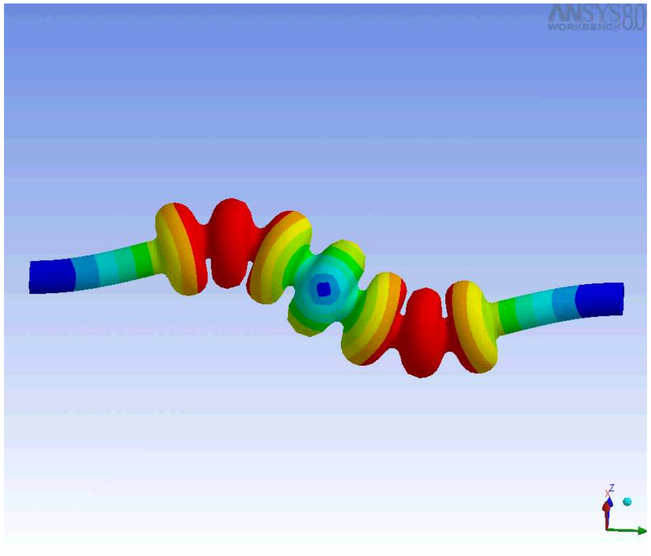


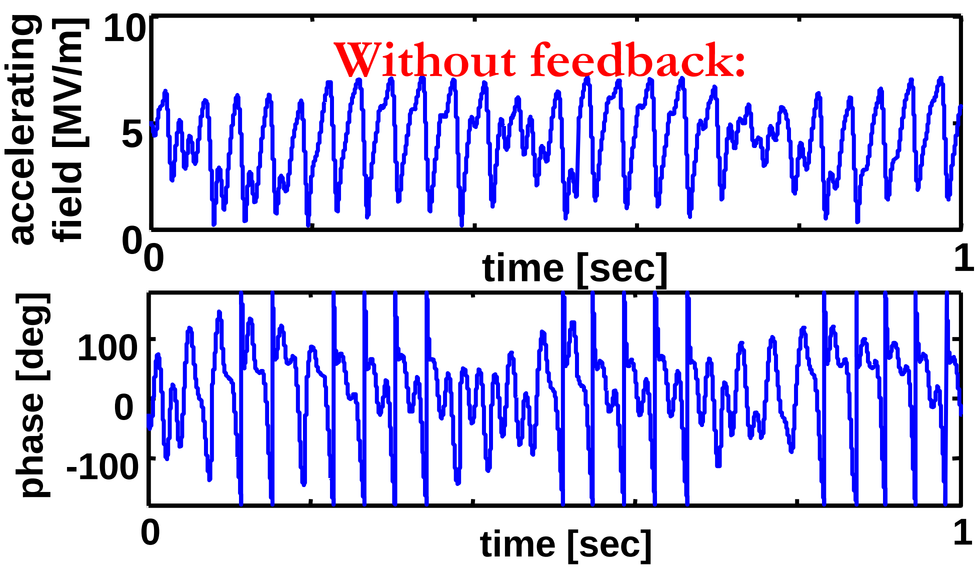


Injector cryomodule

High loaded Q cavity control

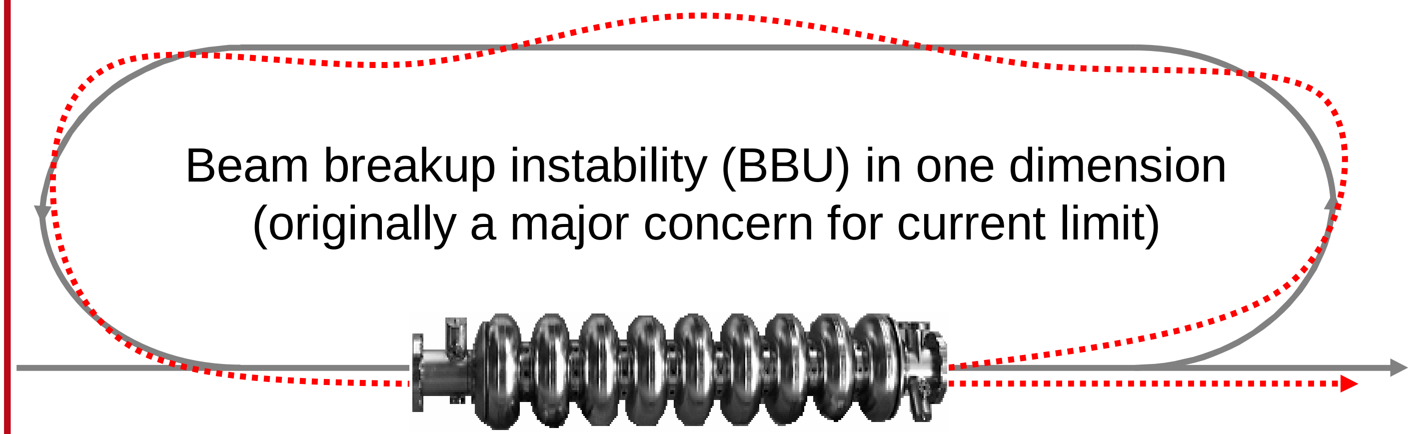


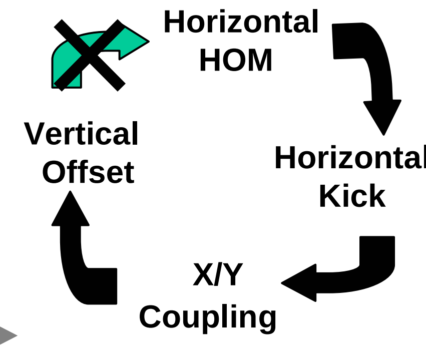




- Run cavity at highest possible loaded Q for Energy recovery linac mode, i.e. without beam loading
- But: The higher the loaded Q, the maller the cavity bandwidth!

Current limit due to BBU



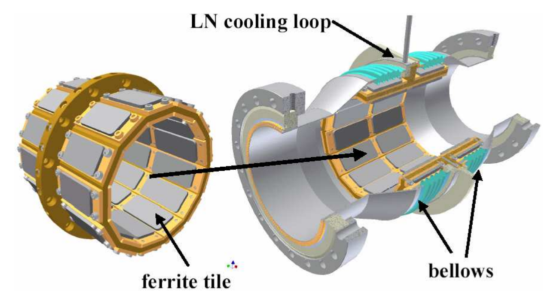


320 identical cavities ➡ **Current limited to 25mA**

Randomized frequencies with rms of 10MHz ➡ **Current limited to 500mA**

Polarized Cavities and x to y coupling ➡ **Current limited to 2000mA >> required 100mA**

Now the current limited by a technical choice:
Cooling capacity of the HOM Dampers



HOM with BBU: Starting from Noise

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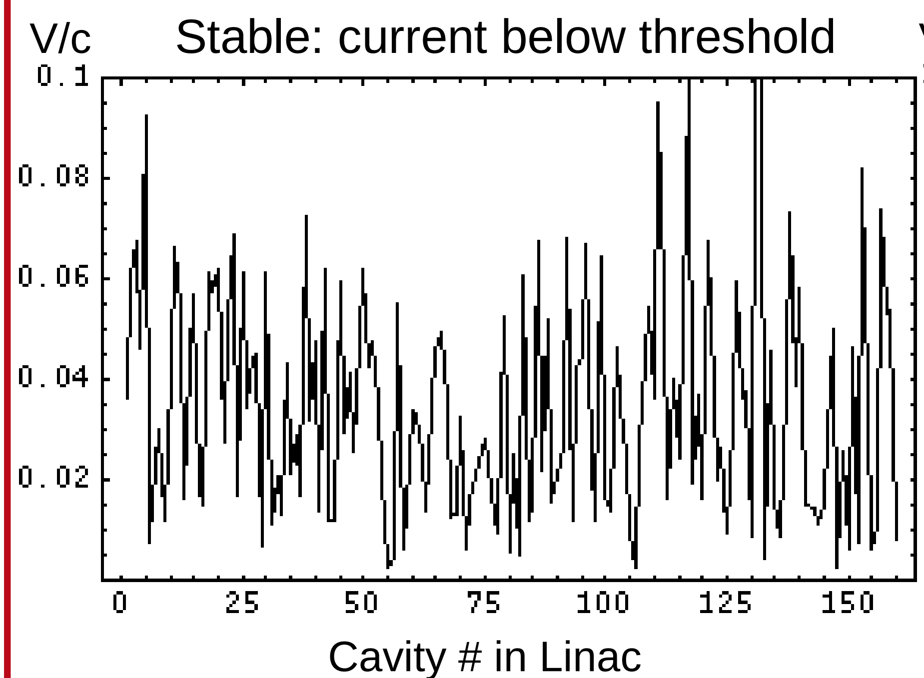
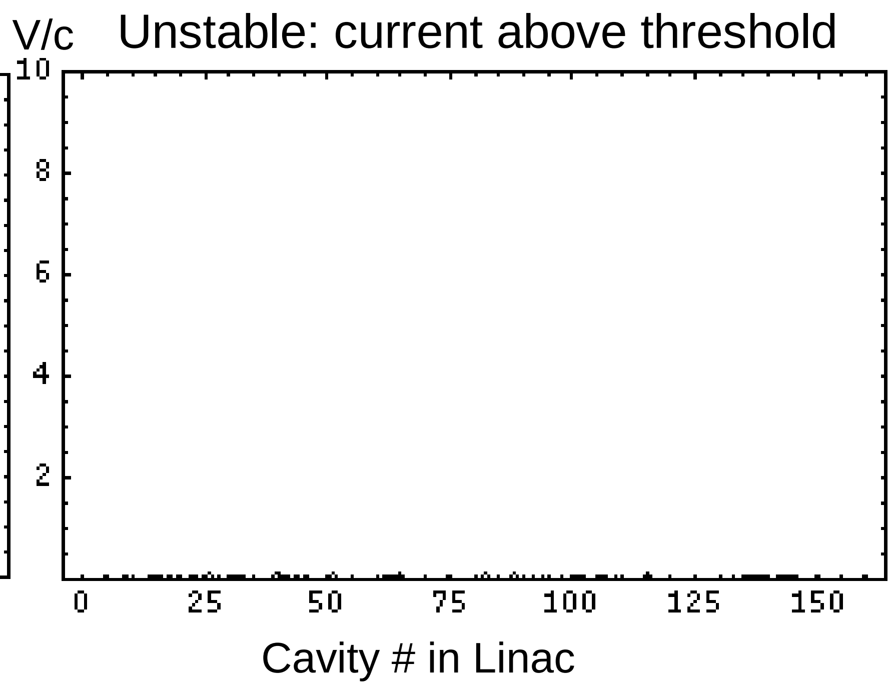
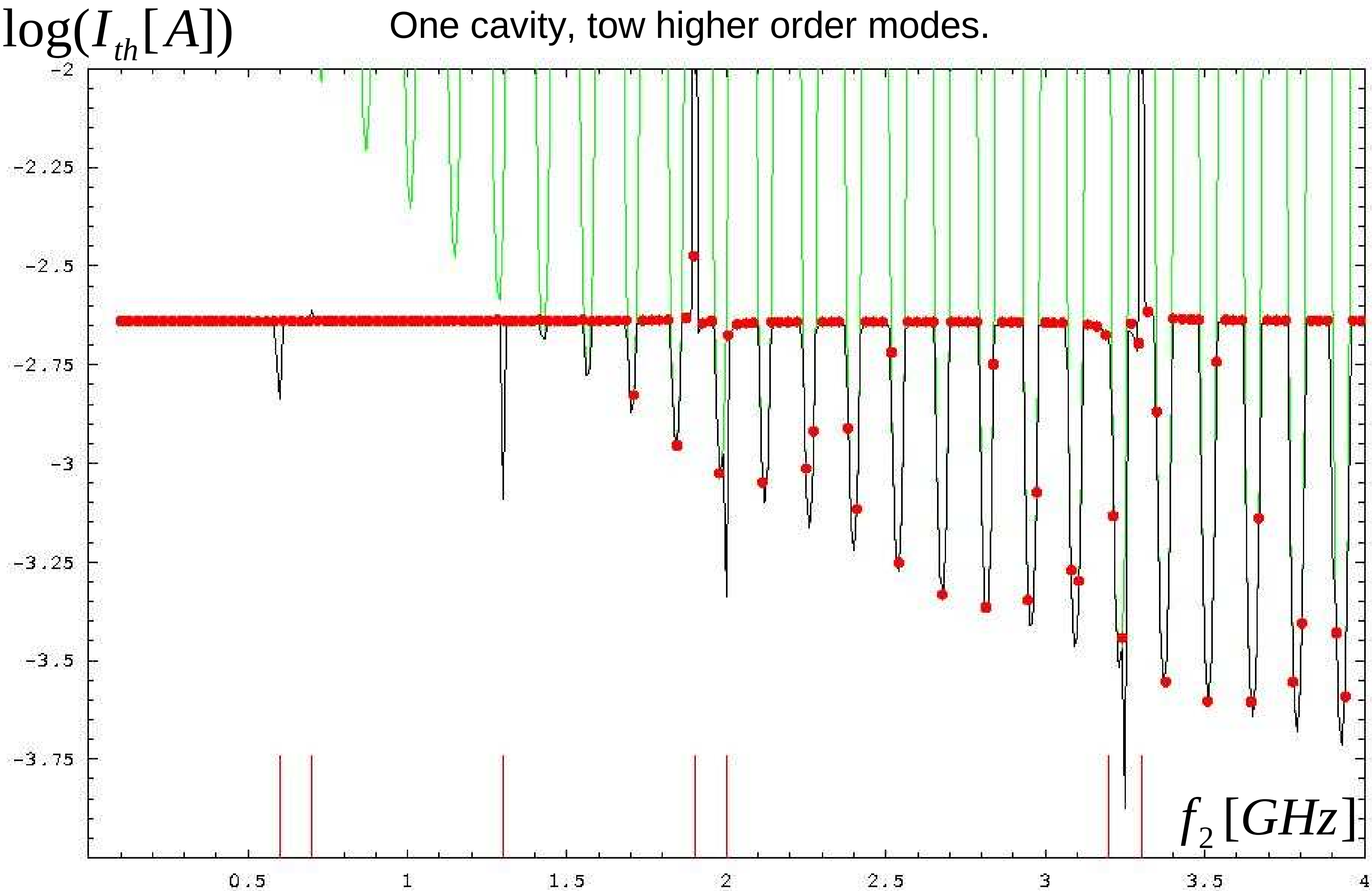




Isolation of modes

One cavity, tow higher order modes.



BBU for ERL@CESR

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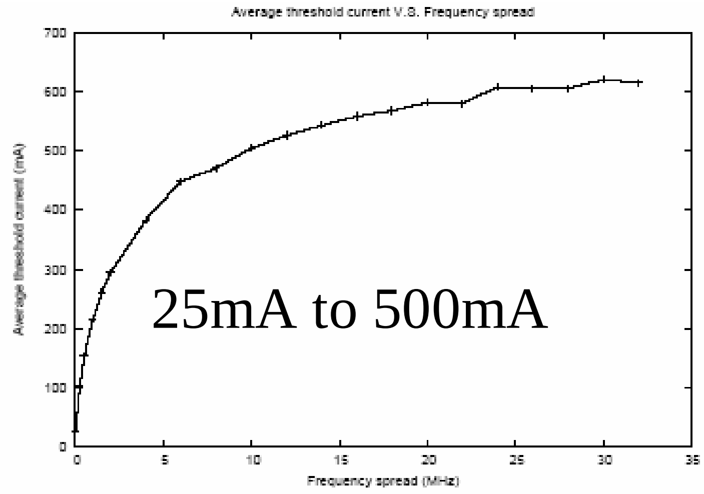
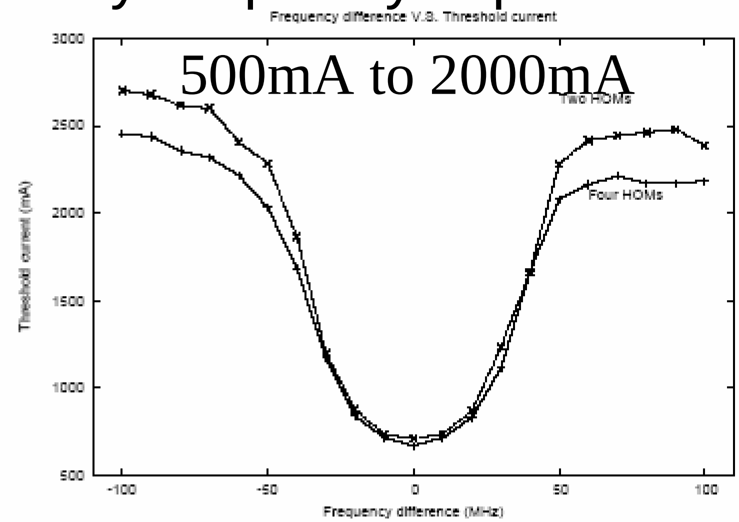
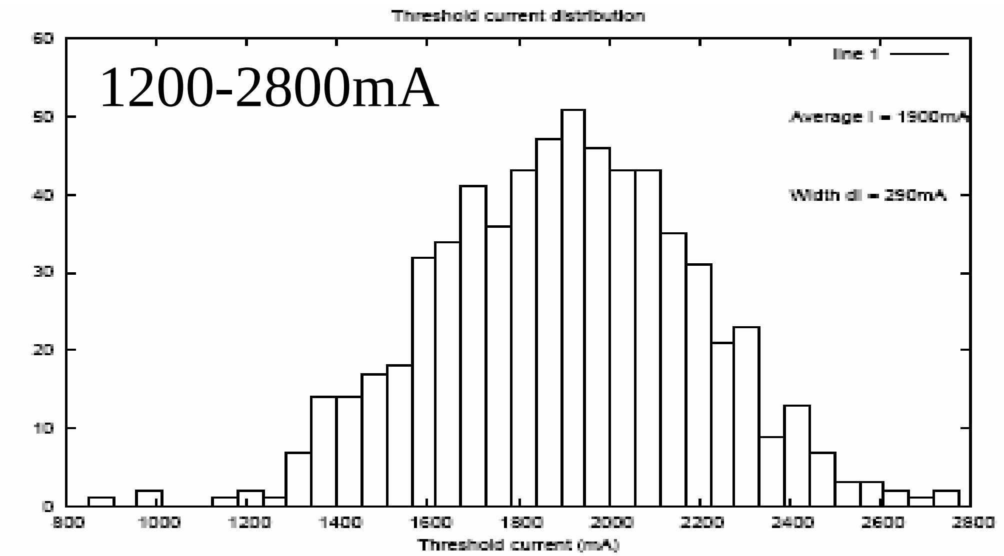
Randomization of frequencies



x/y frequency separation



Model of ERL@CESR
320 polarized cavities with
fx-fy=60MHz
spread=10MHz



Ion accumulation in the beam potential

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Ion are quickly produced due to high beam density

Ion	σ_{col}, 10MeV	σ_{col}, 5GeV	τ_{col}, 5GeV
H_2	$2.0 \cdot 10^{-23}\mathrm{m}^2$	$3.1 \cdot 10^{-23}\mathrm{m}^2$	5.6s
CO	$1.0 \cdot 10^{-22}\mathrm{m}^2$	$1.9 \cdot 10^{-22}\mathrm{m}^2$	92.7s
CH_4	$1.2 \cdot 10^{-22}\mathrm{m}^2$	$2.0 \cdot 10^{-22}\mathrm{m}^2$	85.2s

- Ion accumulate in the beam potential. Since the beam is very narrow, ions produce an extremely steep potential – they have to be eliminated.
- Conventional ion clearing techniques can most likely not be used:
  1) Long clearing gaps have transient RF effects in the ERL.
  2) Short clearing gaps have transient effects in injector and gun.
- DC fields of about 150kV/m have to be applied to appropriate places of the along the accelerator, without disturbing the electron beam.

CSR for 100fs bunch without spike

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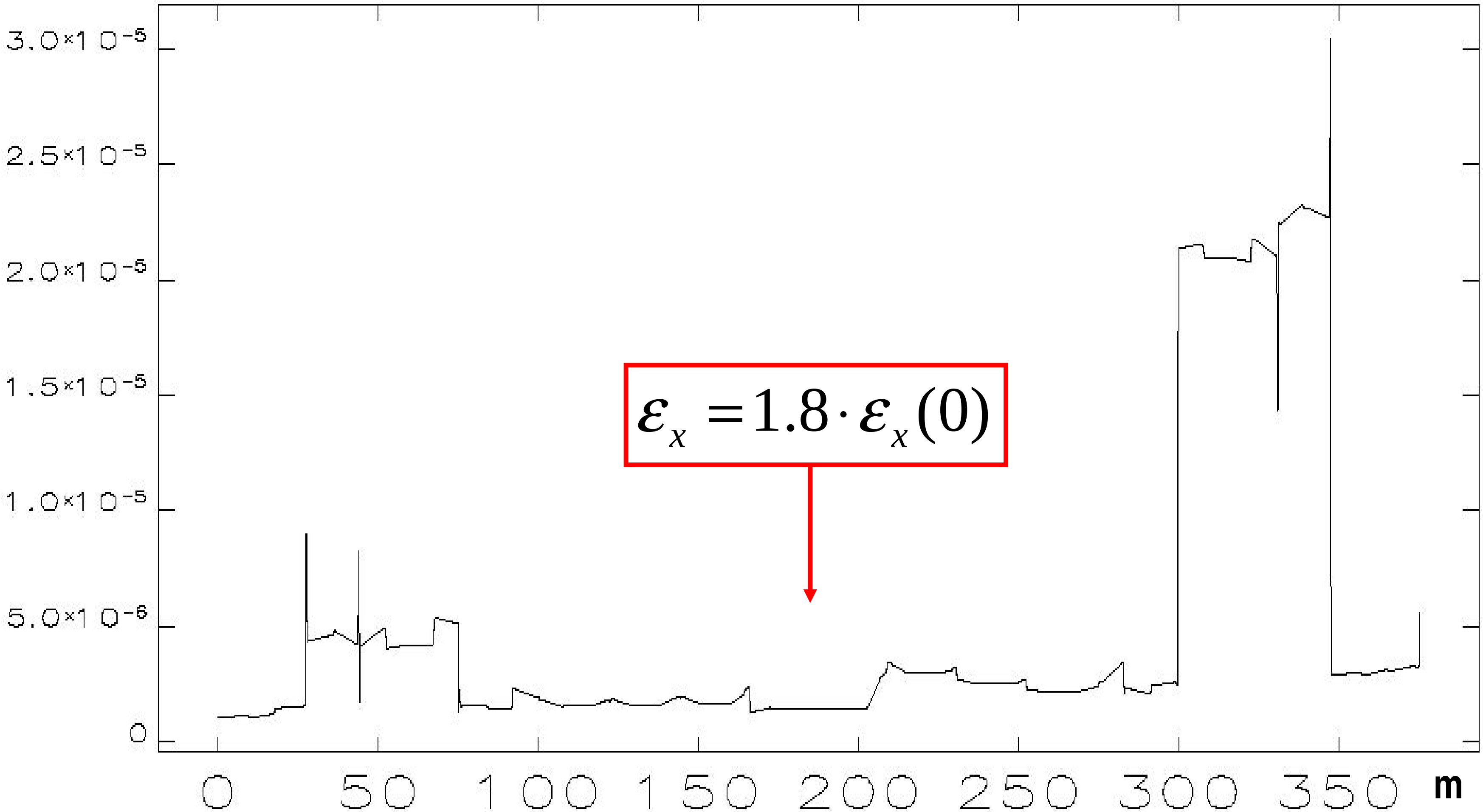
Horizontal emittance with coherent synchrotron radiation



$$\varepsilon_x = 1.8 \cdot \varepsilon_x(0)$$

Result: **After suitable nonlinear bunch length manipulation, the emittance growth can be controlled in all undulators.**

Emittance growth along the X-ray ERL

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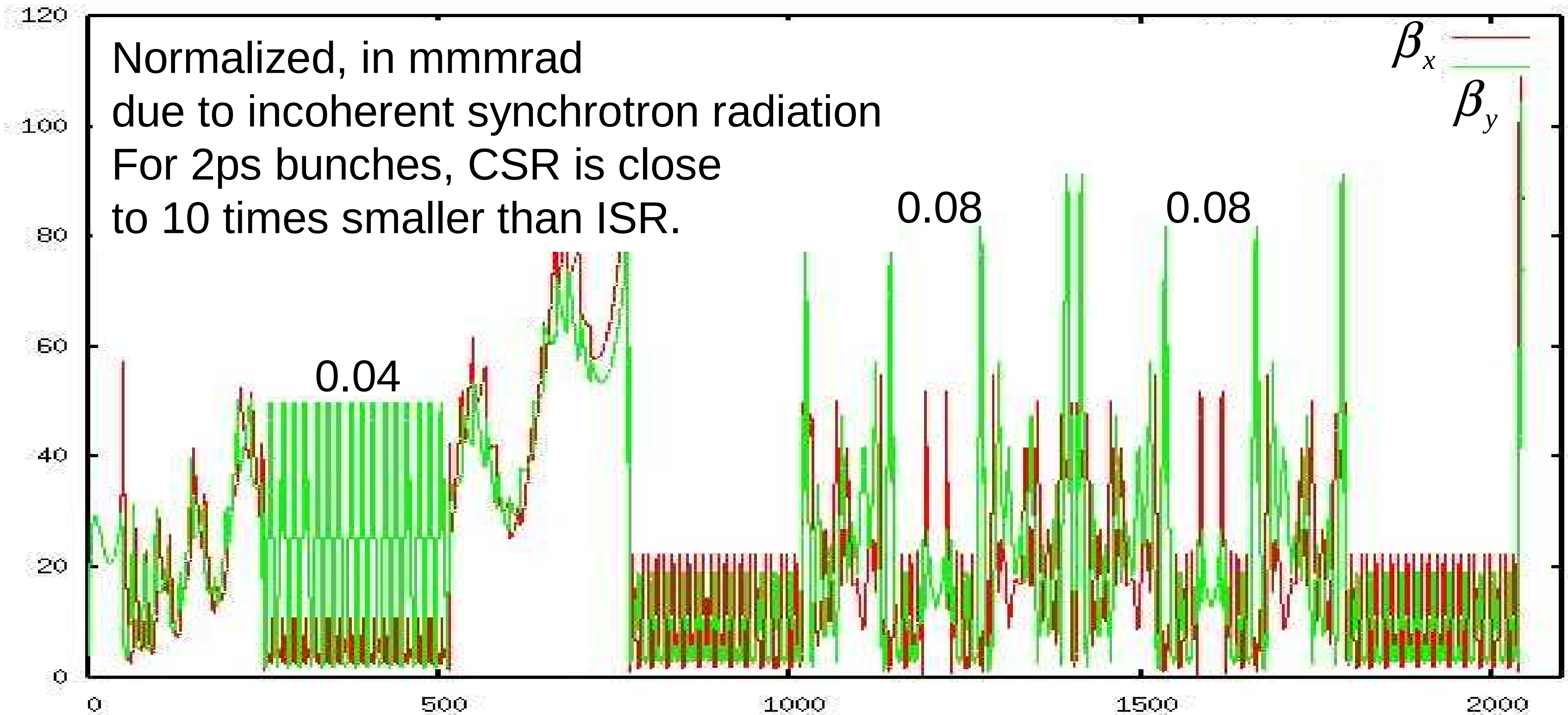

A mini-workshop on ultra low emittance light-sources in July addressed this issue.

Other analyzed sources of emittance growth:

Coupler kick → 7% of 10^{-6}m emittance

→ 30% of 10^{-7}m emittance

Bright Electron Source and ERL

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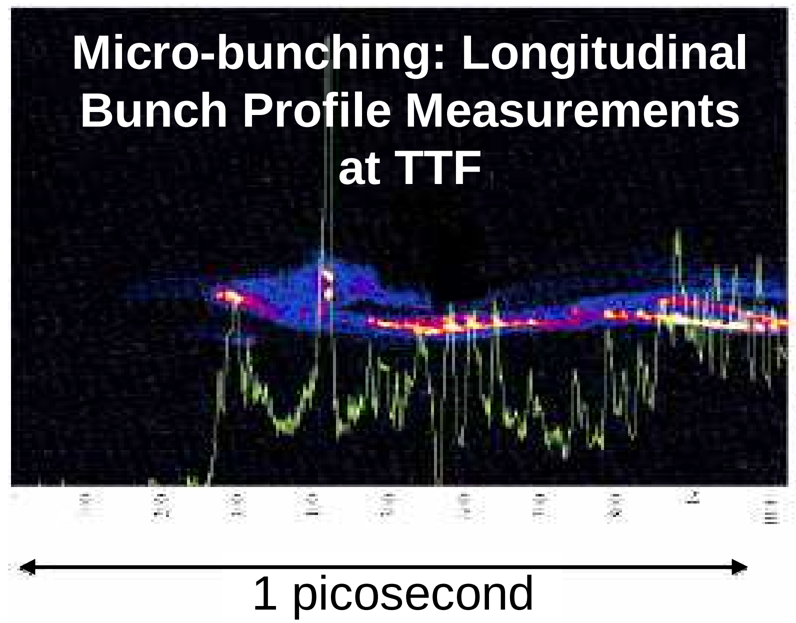
Aspects of x-ray ERL that are of general relevance for future accelerators

- Bright electron beams, gun developments for ILC and beyond.
- Component and technology development
- Space charge dominated beams
- Coherent Synchrotron Radiation
- Bunch compression



First quantitative CSR/bunch length measurements (A.Sievers et al. at Cornell)

- **Ongoing measurement developments**

R&D toward an X-ray ERL

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- Full average current injector with the specified emittance and bunch length
- Emittance preservation during acceleration and beam transport:
  - Nonlinear optics (**code validation at CEBAF**), coherent synchrotron radiation (**JLAB,TTF**), space charge
- Delivery of short duration (ca. 100 fs, and less in simulations), high charge bunches (**TTF**)
- Dependence of emittance on bunch charge
- Stable RF control of injector cryomodule at high beam power
- Stable RF control of main linac cavities at high external Q, high current, and no net beam loading (**JLAB to 10mA**)
- Understanding of how high the main linac external Q can be pushed (**JLAB**)
- Study of microphonic control using piezo tuners (**JLAB, SNS, NSCL, TTF**)
- Recirculating beam stability as a function of beam current with real HOMs, and benchmarking the Cornell BBU code (**JLAB**)
- Feedback stabilization of beam orbit at the level necessary to utilize a high brightness ERL
- Photocathode operational lifetime supporting effective ERL operation
- Performance of high power RF couplers for injector cryomodule
- Demonstration of non-intercepting beam size and bunch length diagnostics with high average current at injector energy and at high energy (**TTF**)
- HOM extraction and damping per design in injector and main linac (**code validation from Prototype**)
- Performance of HOM load materials to very high frequency
- Performance of full power beam dump
- Detailed comparison of modeled and measured injector performance
- Study of halo generation and control in a high average current accelerator at low energy and with energy recovery (**JLAB**)
- Study of beam losses and their reduction in recirculation of high average current with energy recovery (**JLAB**, **NAA**)
- Precision path length measurement and stabilization (**Prototype**, **JLAB**)

R&D toward an X-ray ERL

1. Emittance preservation during acceleration and beam transport
2. Recirculating beam stability (**JLAB**)
3. Diagnostics with high average current at injector energy and at high energy (**TTF**)

   Delivery of short duration (ca. 100 fs, and less in simulations), high charge bunches (**TTF**)
4. Stable RF control of main linac cavities at high external Q, high current, and no net beam loading (**JLAB to 10mA**)

   Understanding of how high the main linac external Q can be pushed (**JLAB**)

   Study of microphonic control using piezo tuners (**JLAB, SNS, NSCL, TTF**)

- HOM extraction and damping per design in injector and main linac (**code validation from Prototype**)
- Study of halo generation and control in a high average current accelerator at low energy and with energy recovery (**JLAB**)
- Study of beam losses and their reduction in recirculation of high average current with energy recovery (**JLAB**, **NAA**)
- Precision path length measurement and stabilization (**Prototype**, **JLAB**)

ERL injector needs

- An *ultimate* ERL X-ray source → diffraction limited emittance, high average current similar to that of storage rings
- 5 GeV machine producing hard X-rays → 0.1 mm-mrad normalized rms emittance from the source at moderate charge per bunch (e.g. 80 pC)
- ERL becomes compelling (spectral brightness) if 0.1 mm-mrad can be achieved from the source starting from ~ 8 pC / bunch (10 mA average current); *ultimately* one would like to have such emittance at ×10 current
- We have 3 more years to demonstrate a source capable of up to 100 mA average current with 0.1-1 mm-mrad transverse emittance

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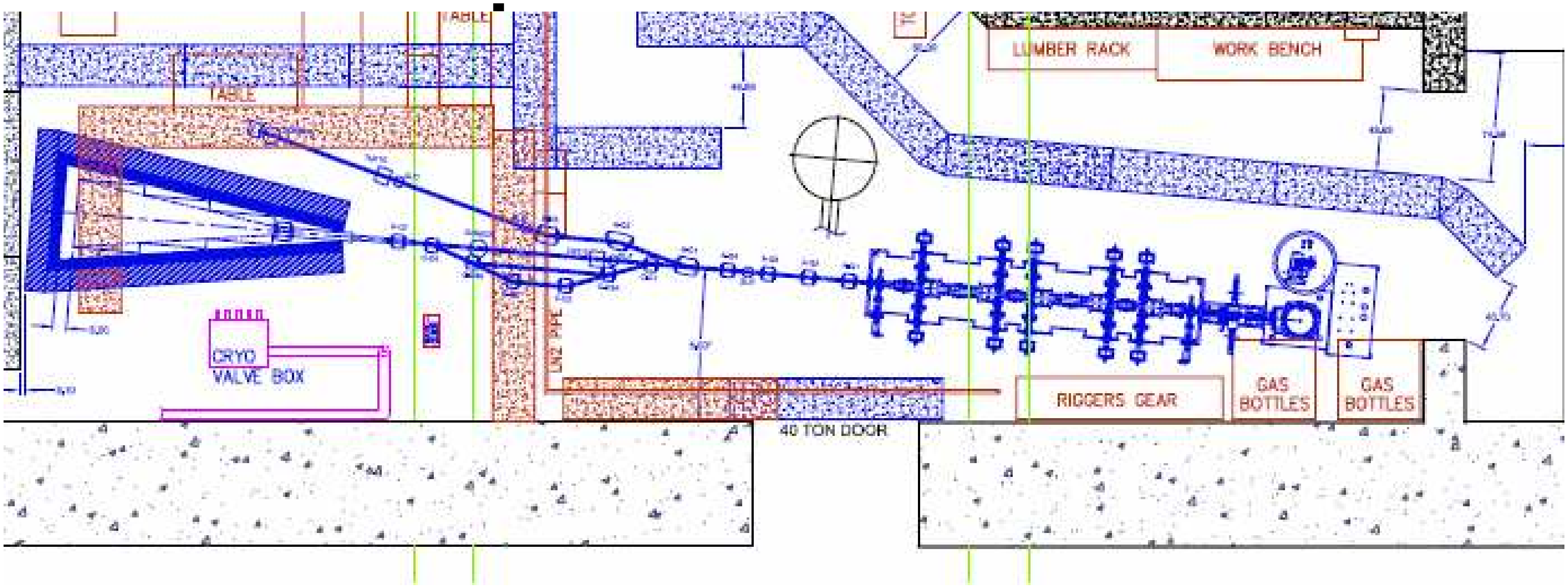
ERL injector



Max current	100 mA
Energy range	5 – 15 MeV
Installed RF power	0.5 MW + 75 kW HV PS
Emittance goal	0.1 – 1 mm-mrad
Typical bunch length	2-3 ps rms (shortest 0.2 ps)

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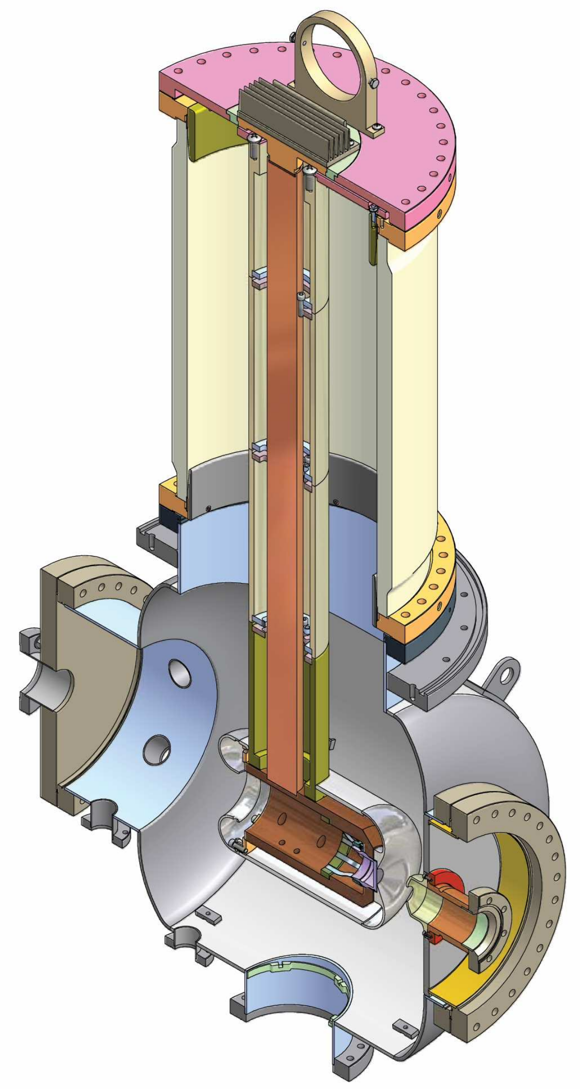
Photocathode gun technology choice

DC gun

- Designed for 750 kV max voltage
- Excellent vacuum is essential for good lifetime of NEA cathodes
- 400 C air-bake to reduce (H) outgassing
- Load-lock system for cathode transport 20,000 l/s NEG pumping capacity + 400 l/s ion pump combination should bring the vacuum down to lower 10^{-12} Torr range
- The gun is already built



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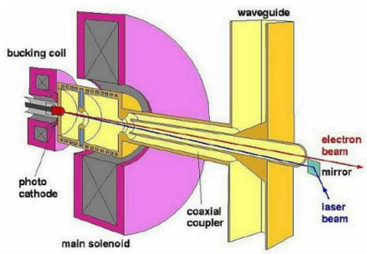
DC/SFR/NCRF: emit. compensation works

NCRF

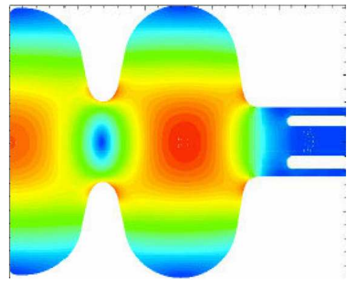


pulsed!

E_{cath} = 120 MV/m
τ_{laser} = 2.7 ps rms
σ_{laser} = 0.5 mm rms

$\tau_{laser} \rightarrow z$ = 0.08 mm

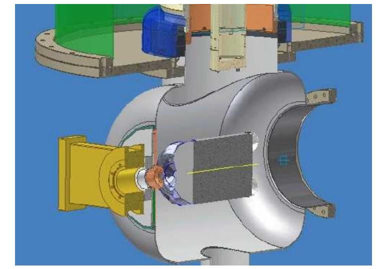
SRF



E_{cath} = 43 MV/m
τ_{laser} = 5.8 ps rms
σ_{laser} = 0.85 mm rms

$\tau_{laser} \rightarrow z$ = 0.12 mm

DC



E_{cath} = 8 MV/m
τ_{laser} = 13 ps rms
σ_{laser} = 2 mm rms

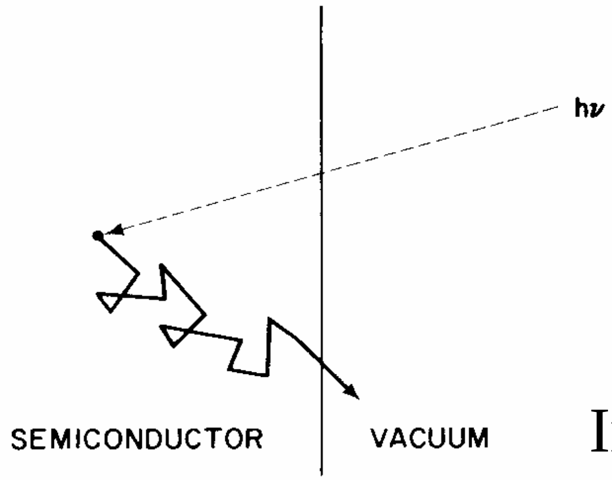
$\tau_{laser} \rightarrow z$ = 0.12 mm

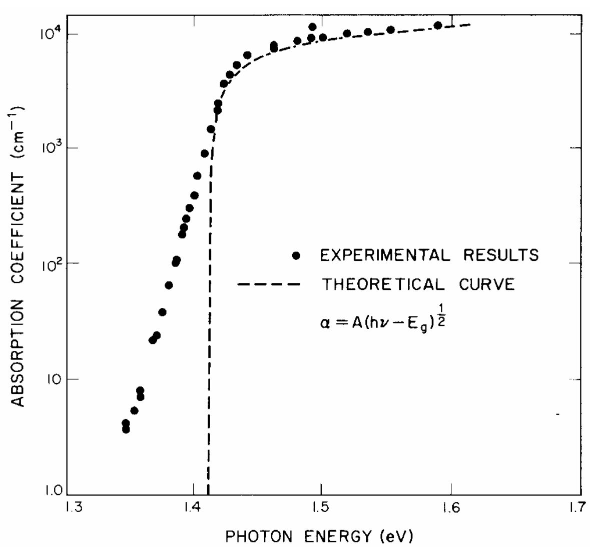
2×18 MV/m   2×6 MV/m   2×1 MV/m

$E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$ = $E_{cath} / E_{s.charge}$

same simulated emittance

Low thermal emittance photocahode





ıperature.

(1) photon excites electron to a higher-energy state;

(2) electron-phonon scattering (~0.05 eV lost per collision);

(3) escape with kinetic energy in excess to E_{vac}

In GaAs the escape depth is sufficiently long so that photo-excited electrons are *thermalized* to the bottom of the conduction band before they escape – *low thermal emittance allows larger illuminated laser spot (reduces space charge forces)*

Response time ~ (10^{-4} cm)/(10^{7} cm/s) = 10 ps (wavelength dependant)

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Simulated performance for the injector

Final emittance is dominated by the photocathode

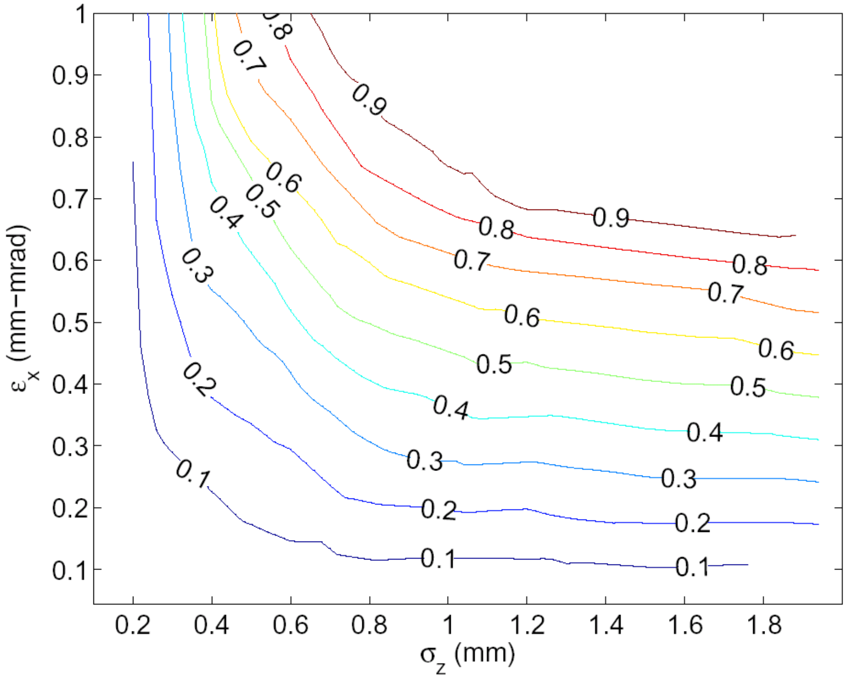

FIG. 10: Transverse emittance vs. bunch length for various charges in the injector (nC).

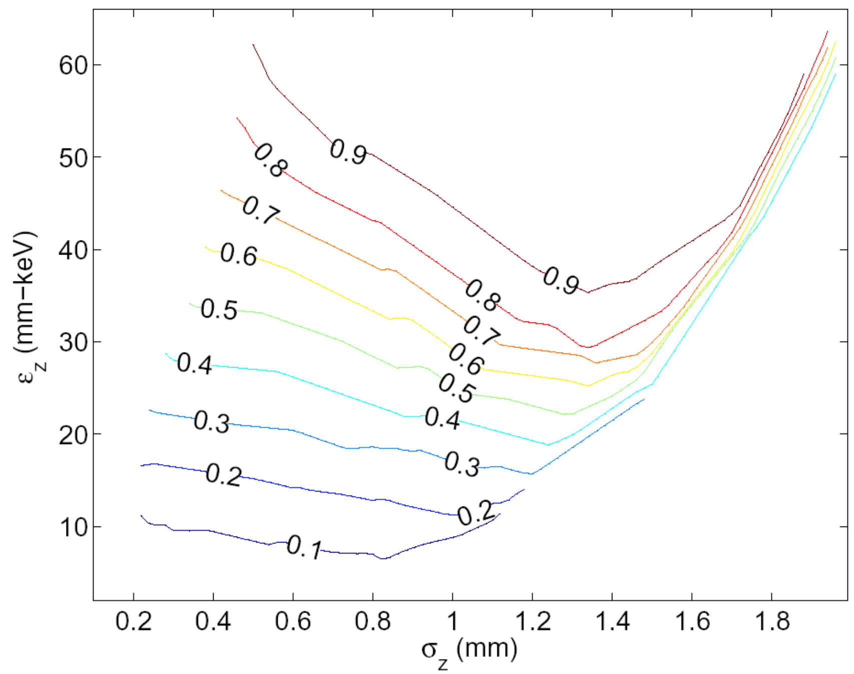

FIG. 11: Longitudinal emittance vs. bunch length for various charges in the injector (nC).

ε_n[mm-mrad] $\approx (0.73+0.15/\sigma_z[\text{mm}]^{2.3}) \times$ q[nC]

good approx. in 0.1-1 nC / bunch range

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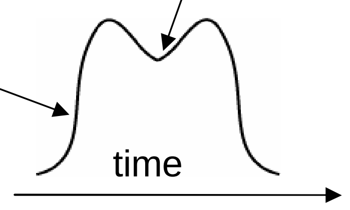
Laser requirements

Optional depression in the middle

Steep fronts



Time shaping
Transverse shaping

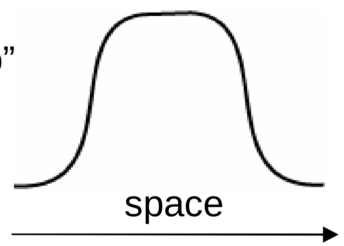
> 20 W average "green" power

f_R = 1.3 GHz

E_{pulse} ~ 15 nJ

Gun entrance window

"Flat-top"



Pulse width: 10 ps – 40 ps

+/- 1% rms energy

< 0.2 ps time jitter

seed → amplifier → Rep-rate control → SHG → Time and space shaping

λ = 1060 nm
~ 100 mW

~ 100 W
Linear polarization

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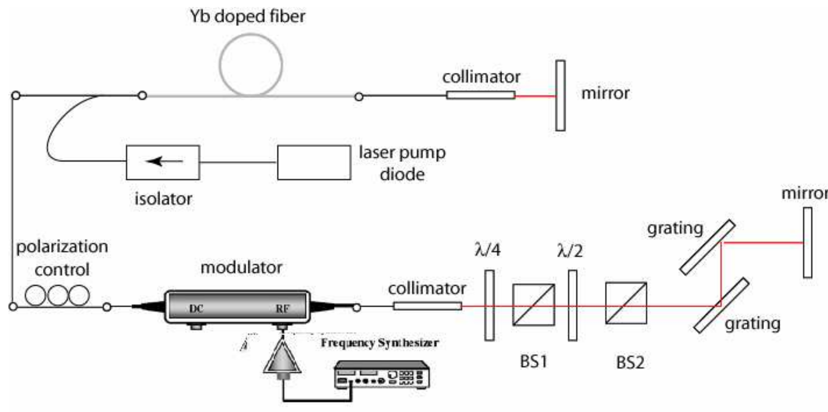
Laser work



• close collaboration with the Department of Applied Physics at Cornell University

• (Mostly) all fiber solution

• Seed R&D harmonically mode-locked fiber laser – passive HML seed operational at 1.3 GHz, work underway on actively harmonically mode-locked Yb-doped fiber version

• Longitudinal shaping: two options are being evaluated experimentally – self-phase modulation + dispersion in fiber and "stacking" of pulses with birefringent plates

• First pulse laser system meeting single pulse requirements (downsized rep. rate) will be ready in 2-3 months

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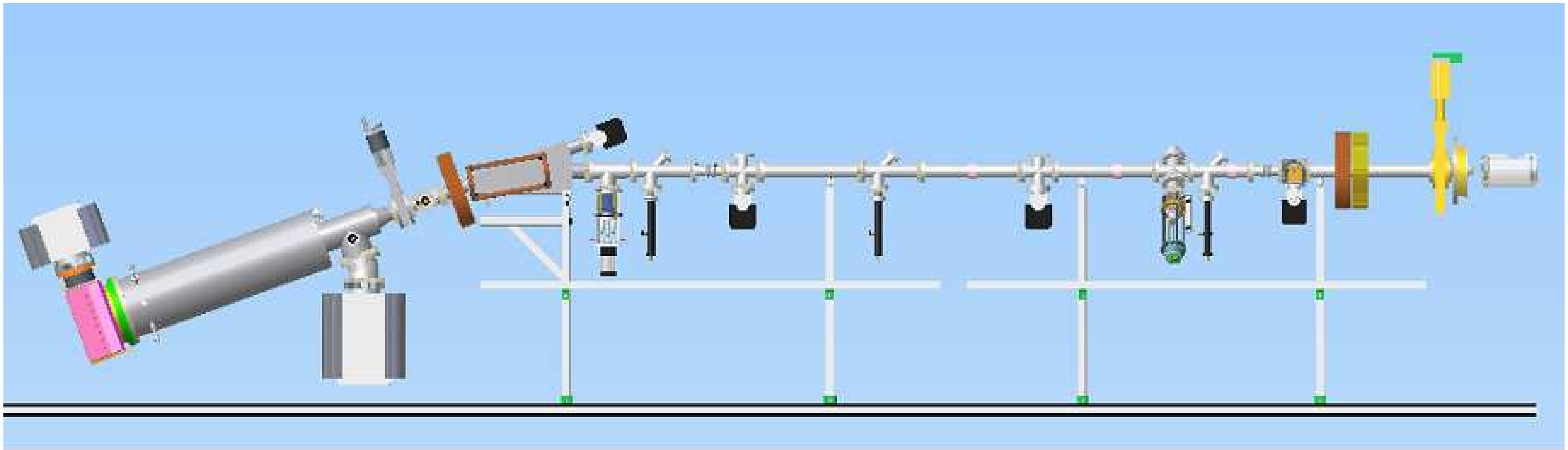
Stages of commissioning of the injector

- photogun lab setup for initial beam test



- Initial power supply from the vendor for 300 kV
- 100 mA DC beam tests: a) cathode (GaAs, GaAsP, K_2CsSb) lifetime / ion backbombardment; b) thermal emittance characterization vs. wavelength

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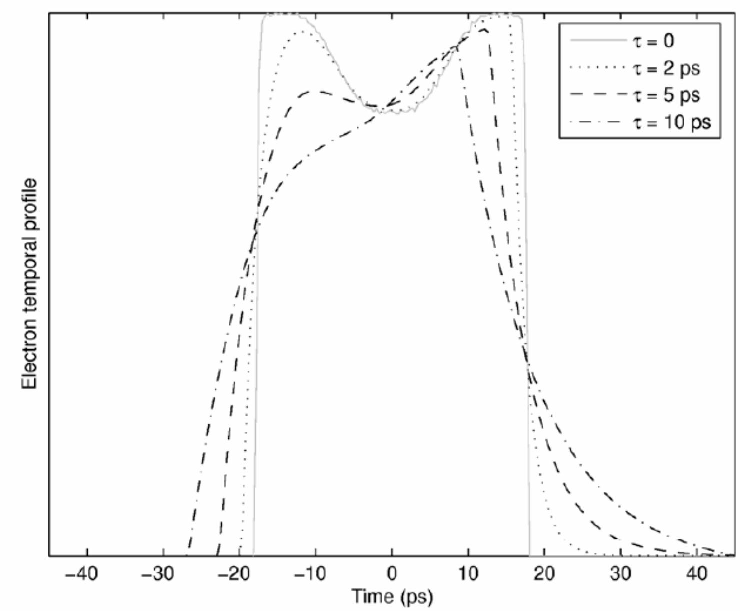
Planned sequence of activities

Photogun lab

- Pulsed laser ready in 3 month → measurements on space charge dominated beam (gun + solenoid)
- TM110 cavity & ps laser / RF synchronization → temporal response of photoemission for different cathodes

Trade-off between low thermal emittance / photoemission response time is not obvious, literature data for GaAs are not precise enough



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Planned sequence of activities

Photogun lab

- 750 kV power supply to arrive late this year; repeat measurements with s.c. dominated bunches
- Gun transported to its final location by 2008

L0 area

- Piece-wise installation of components & beam characterization: gun, straight ahead dump section, solenoids, buncher, cryomodule, merger

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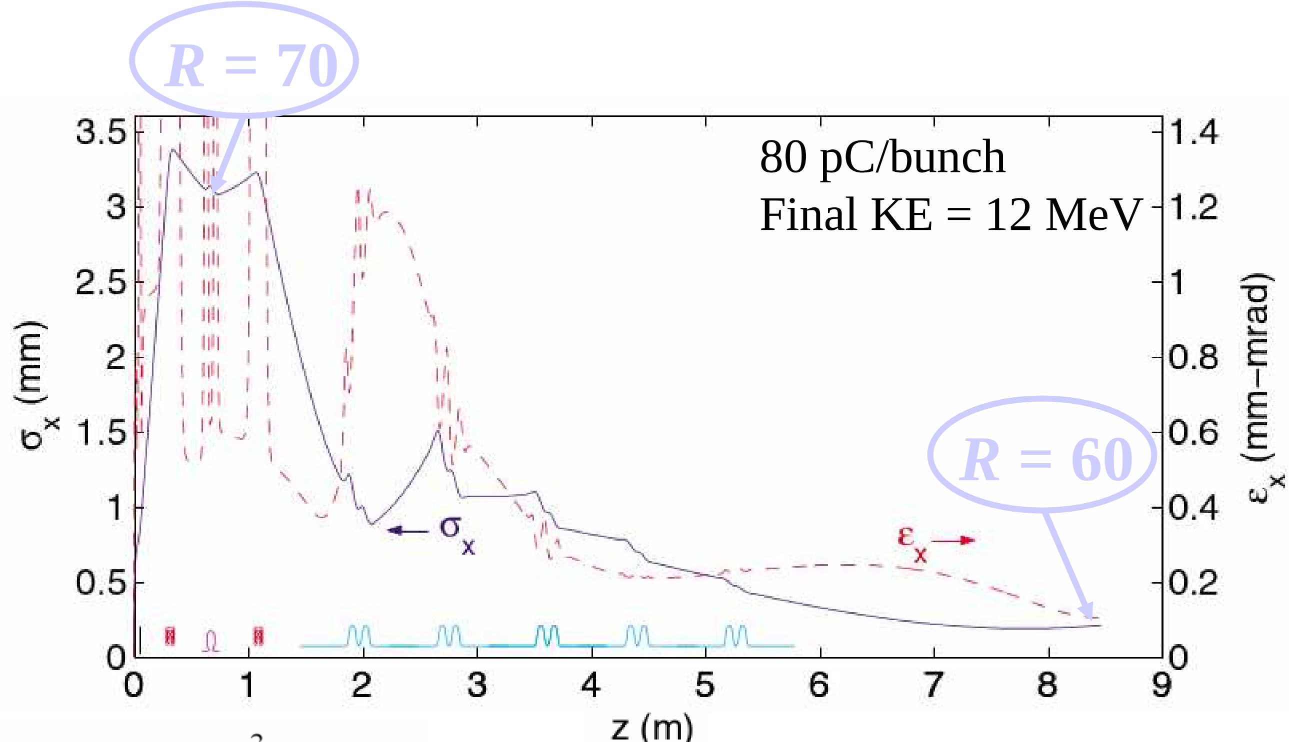
Space charge dominated beam all the way



$$R \equiv \frac{I}{I_0 \beta\gamma} \frac{\sigma_x^3}{(\sigma_x + \sigma_y)\varepsilon_{n,x}^2}$$

space charge dominated if $R >> 1$

Beam in optimized injector is space charge dominated even at > 10 MeV; interceptive diagnostics essential

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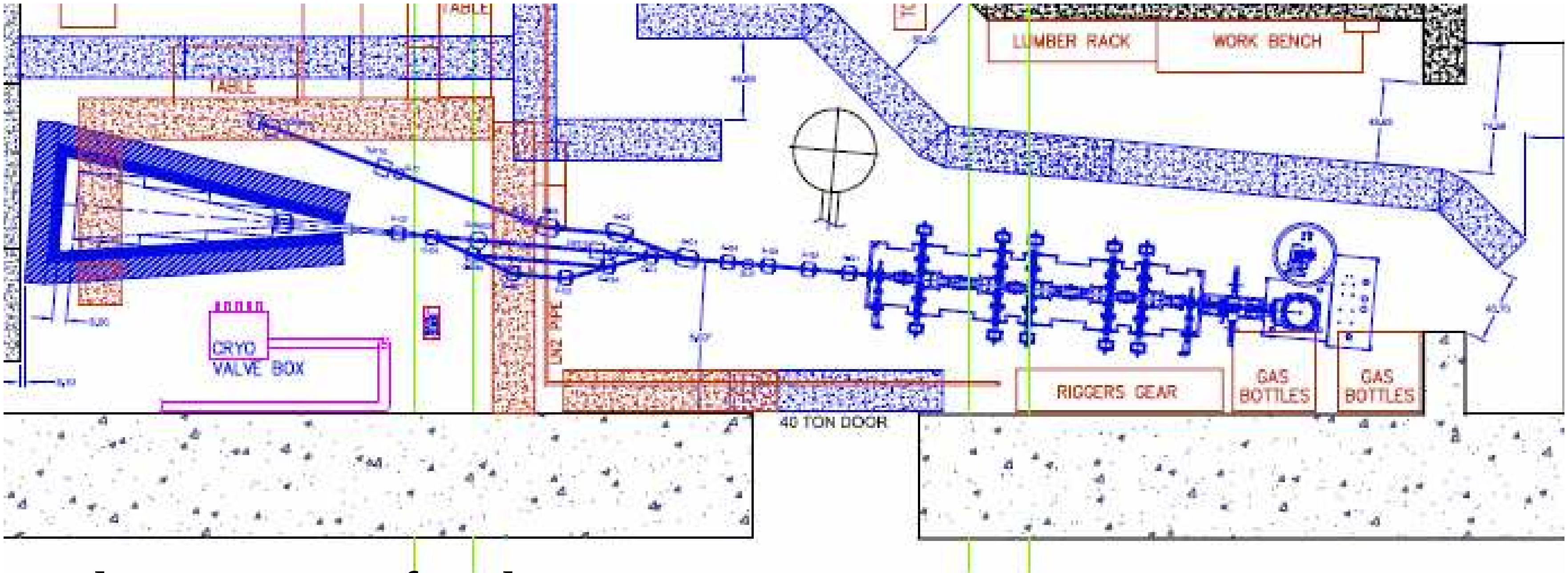
Diagnostics being developed



- slit & TM110 for slice emittance measurements
- flying wire
- CSR spectrum measurements for bunch profile autocorrelation

Under consideration:

- small period high harmonic PPM undulator; μs RF kicker line; …

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Summary

- Cornell has a long an successful history of accelerator physics, has the facilities and scientific groups to build a large scale accelerator based on SRF technology.
- The planned x-ray ERL is an extension to the existing CESR ring
- Significant ERL R&D is done with a prototyping facility, other issues have to be studied in collaboration with other facilities.
- Numerous activities are underway both short range (injector) and long range (x-ray source ERL)
- Wrap up for the injector phase is in 2008, proposal for the full scale machine is planned for 2007
- Sufficient overlap exists with BNL activities – e.g. source development, low energy high brightness beam diagnostics, ID design, simulation tools, etc. – plenty of room for collaboration