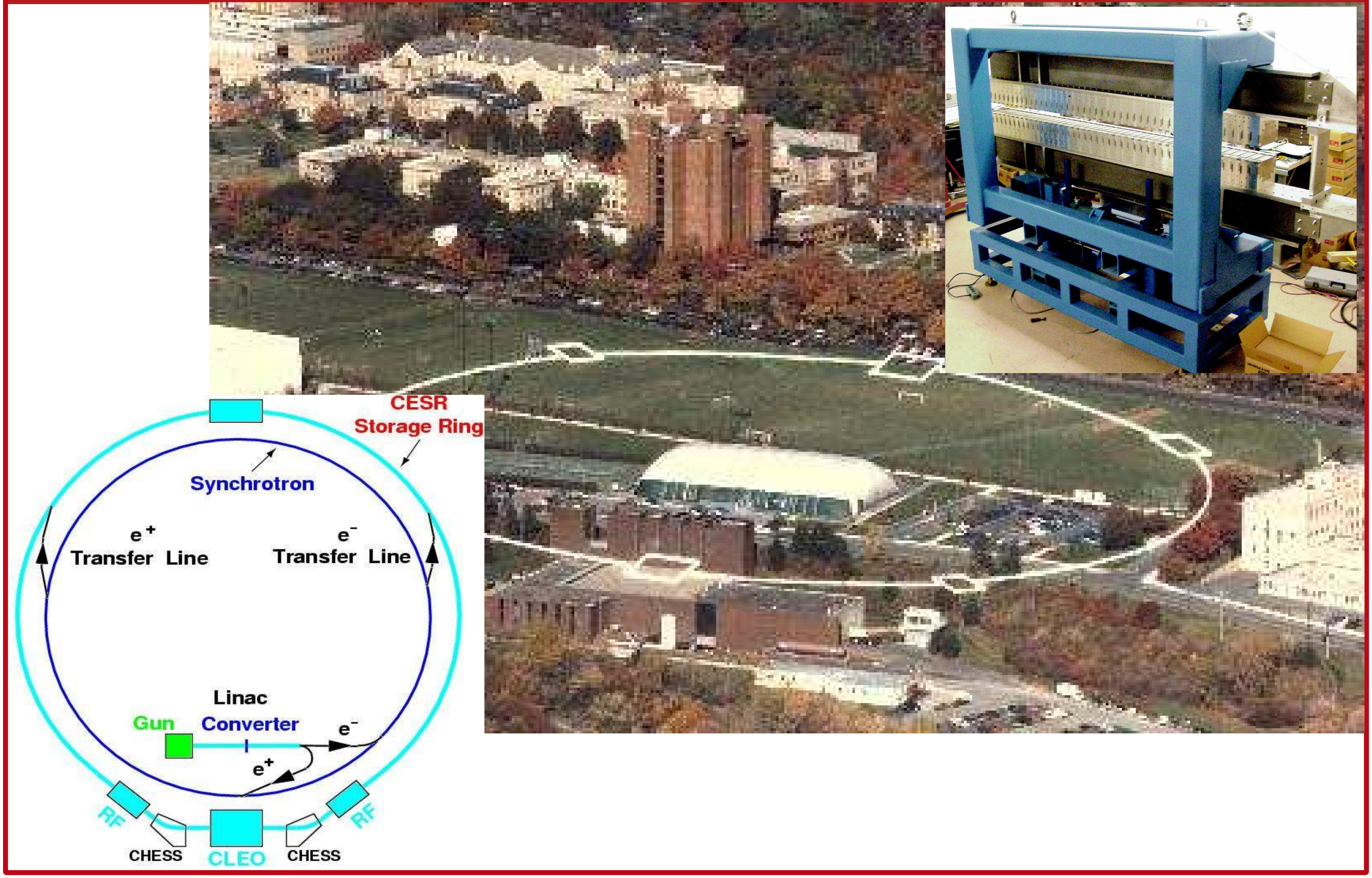
Toward an Energy Recovery Linac x-ray source at Cornell University

Georg Hoffstaetter
Cornell Physics Department
14 February 2006

- Some history
- Beams in Rings and Linacs
- The ERL principle
- What an x-ray ERL could do
- Limits of ERLs
- ERL prototyping at Cornell
- Studies for an x-ray ERL
- Other ERLs

CESR @ Cornell



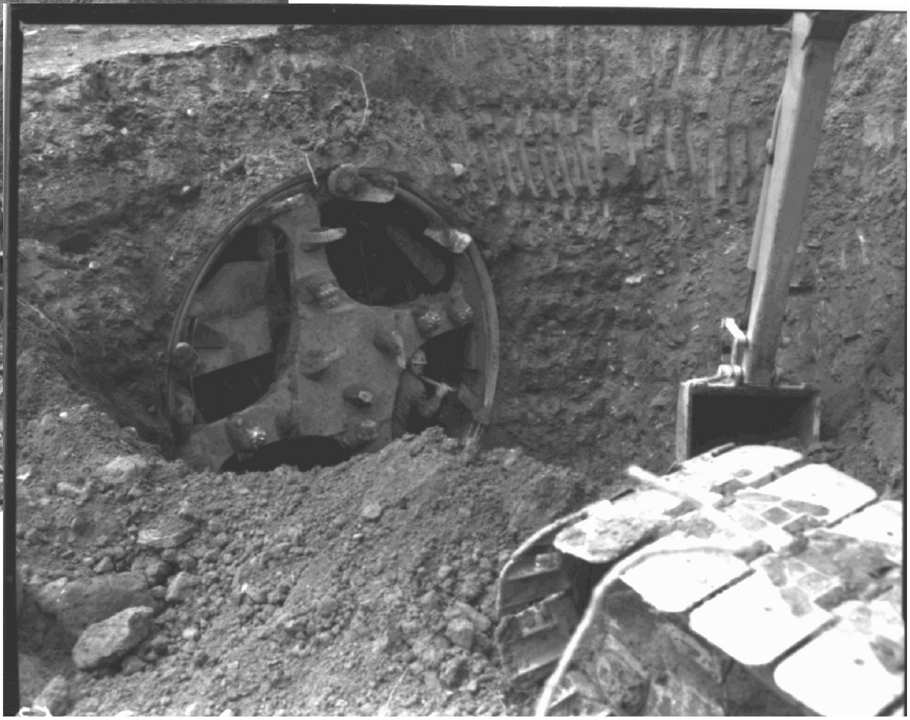
A goldmine at Cornell

CHESS & LEPP

In ...

Tunnel digging
(as of 1966)

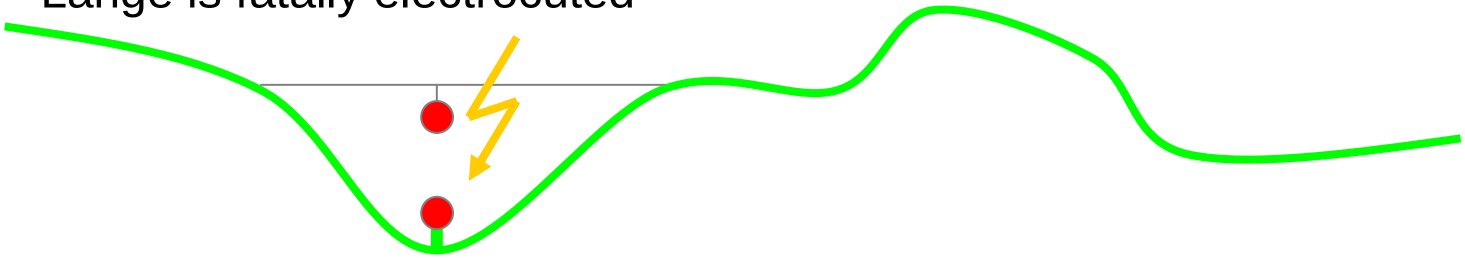
... out



Accelerator Physics @ Cornell

CHESS & LEPP

- 1932: Brasch and Lange use potential from lightening, in the Swiss Alps, Lange is fatally electrocuted



- 1934: Livingston builds the first Cyclotron away from Berkely (2MeV protons) at Cornell (in room B54)
- 1949: Wilson et al. at Cornell are first to store beam in a synchtotron (later 300MeV, magnet of 80 Tons)
- 1954: Wilson et al. build first synchrotron with strong focusing for 1.1MeV electrons at Cornell, 4cm beam pipe height, only 16 Tons of magnets.
- 1965: First paper on Linear colliders and ERLs
- 1979: 5GeV electron positron collider CESR (designed for 8GeV)
- Currently:
  - CESR operation and optimization for the CLEO experiment
  - CESR operation and optimization for CHESS
  - ERL prototyping facility (ERL e-source and injector linac)
  - ERL and CESR upgrade to an ERL
  - ILC design, simulations, damping ring studies with CESR

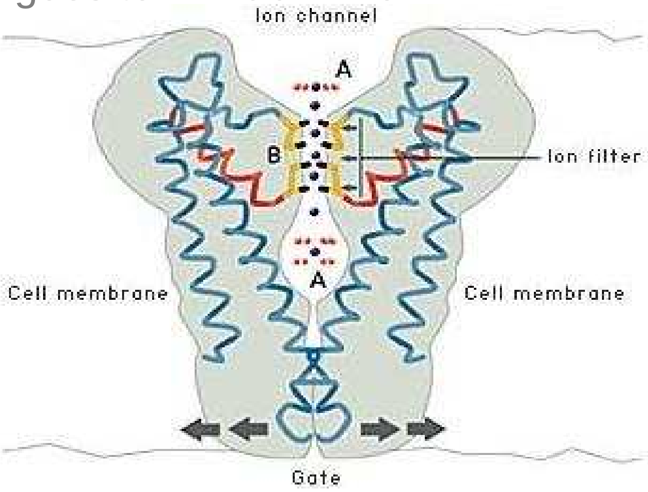
Synchrotron Radiation @ Cornell

CHESS & LEPP

- 1947: **1st** detection of synchrotron light at General Electrics. Soon advised by D.H.Tomboulian (Cornell University)
- 1952: **1st** accurate measurement of synchrotron radiation power by Dale Corson with the Cornell 300MeV synchrotron.
- 1953: **1st** measurement of the synchrotron radiation spectrum by Paul Hartman with the Cornell 300MeV synchrotron.
- Worlds **1st** synchrotron radiation beam line (Cornell 230MeV synch.)
- 1961: **1st** measurement of radiation polarization by Peter Joos with the Cornell 1.1GeV synchrotron.
- 1978: X-Ray facility CHESS is being build at CESR
- 2003: **1st** Nobel prize with CESR data goes to R.MacKinnon

Dale Corson

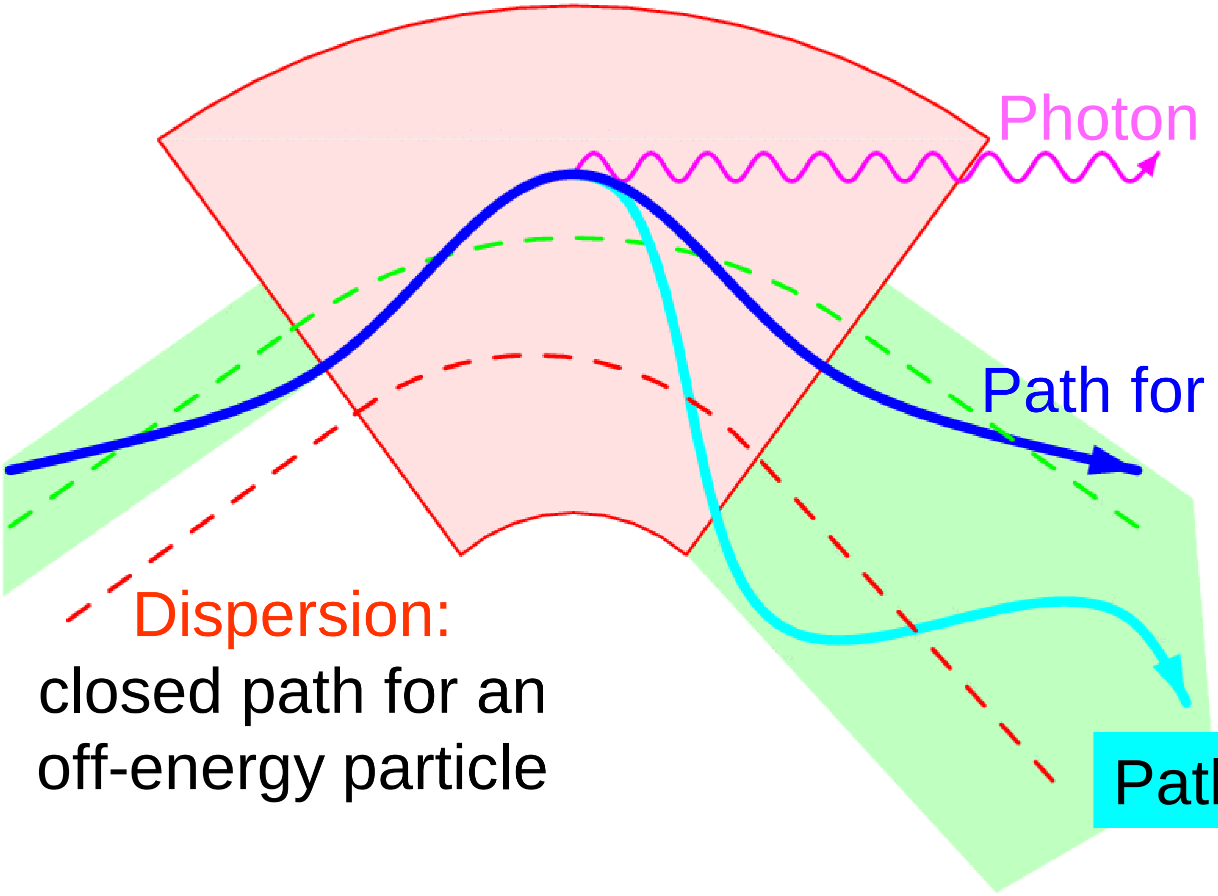
Cornell's 8th president



Roderick MacKinnon

Emittance Excitation

Smaller dispersion → Smaller emittance



Photon

Path for design energy

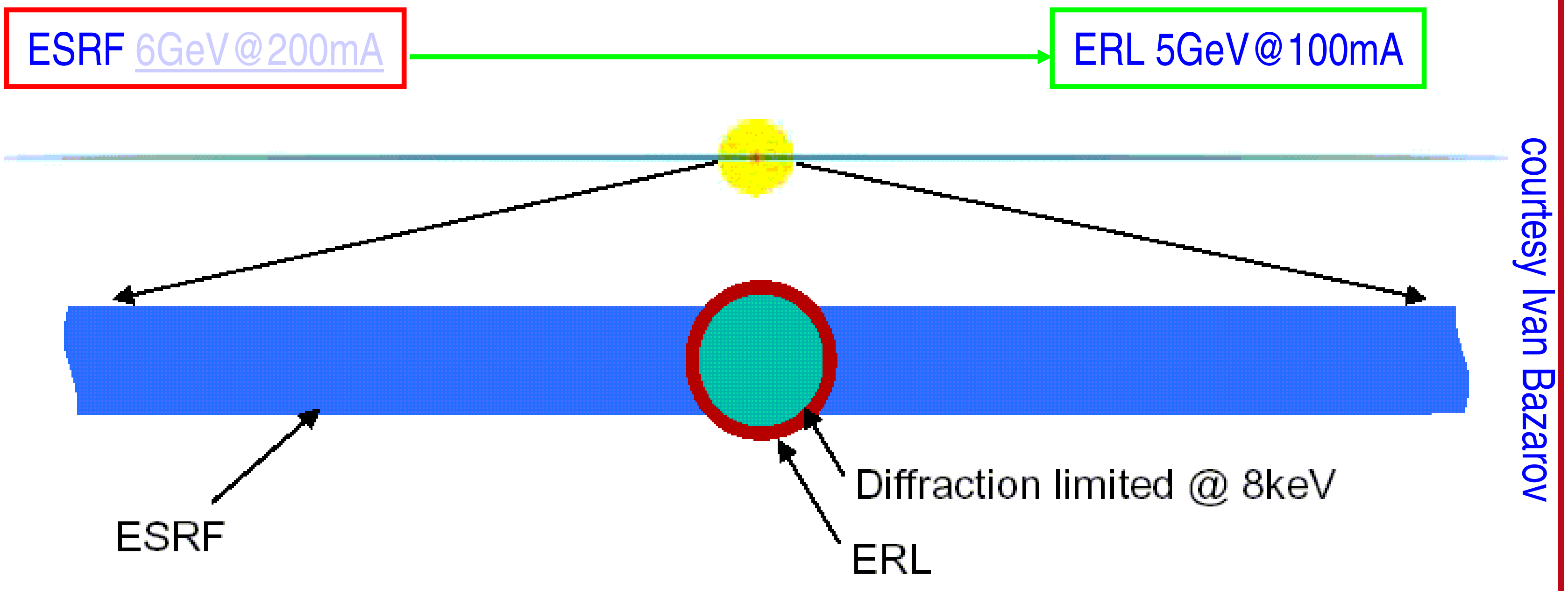
Dispersion:
closed path for an
off-energy particle

Path for smaller energy

Beam Size in a Linear Accelerator

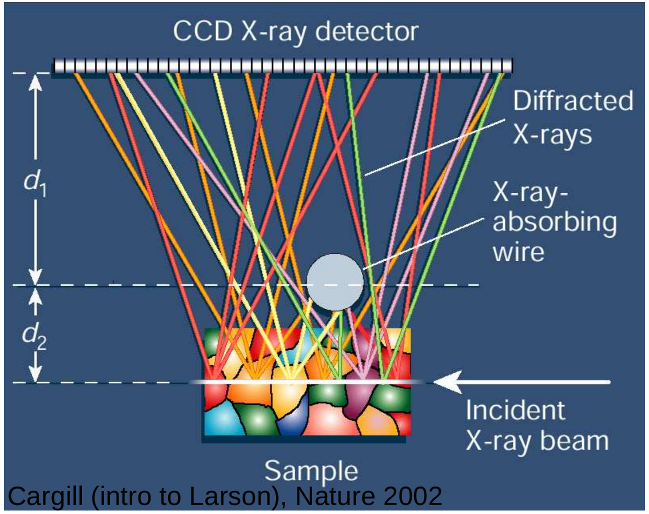
The beam properties are to a very large extend determined by the injector system:

- 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.



courtesy Ivan Bazarov

Microprobe

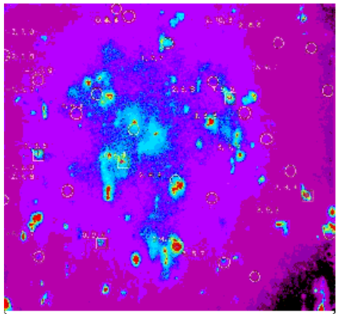


Cargill (intro to Larson), Nature 2002

Differential-Aperture
X-ray Microscopy (DAXM)

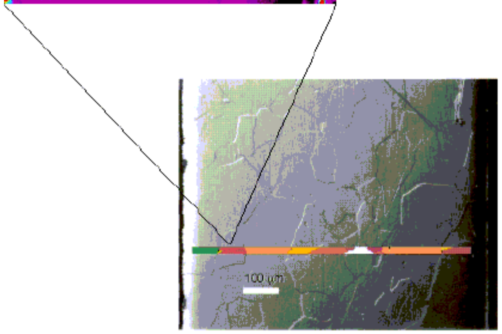
- **Smaller beams lead to better spatial resolution (currently sub μm)**

ERL: 100-1000 times smaller area



Orientation of crystals and

Stress and strain in crystals



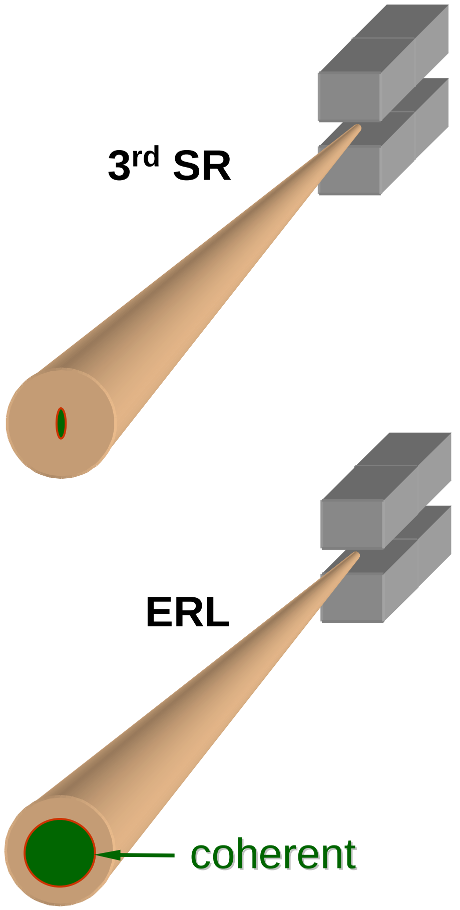
Ben Larson (2000), ERL science workshop, Cornelll

3-D Studies of Structure

Smaller Beams and more Coherence

- 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



Real-time insect breathing

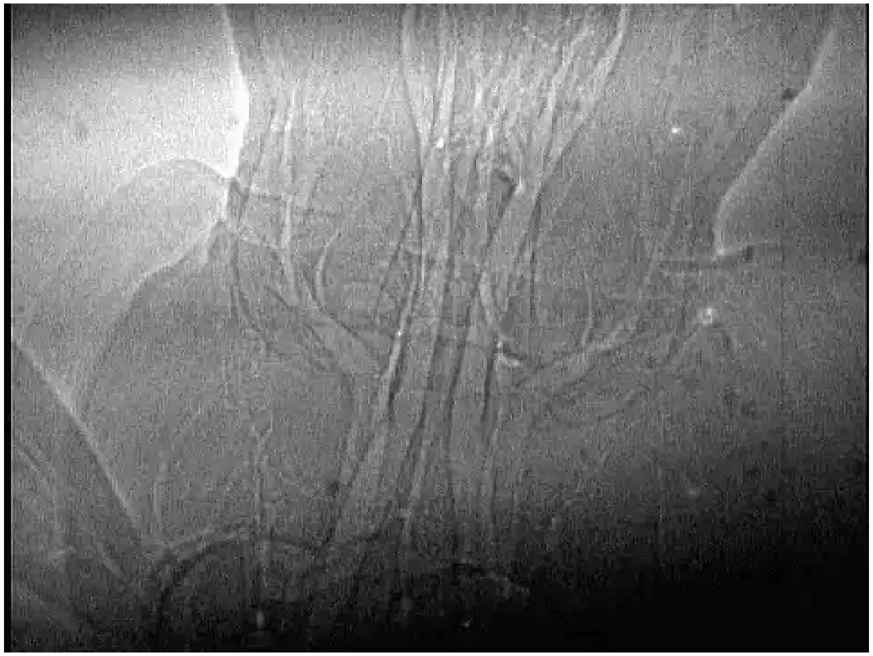
Tracheal Respiration in Insects Visualized with Synchrotron X-ray Imaging

Mark W. Westneat,*[1] Oliver Betz,[1,2] Richard W. Blob,[1,3] Kamel Fezzaa,[4] W. James Cooper,[1,5] Wah-Keat Lee[4]

Field museum of Chicago & APS, Argonne National Lab.

Science (2003) 299, 598-599.

- Animal functions
- Biomechanics
- Internal movements
- New findings



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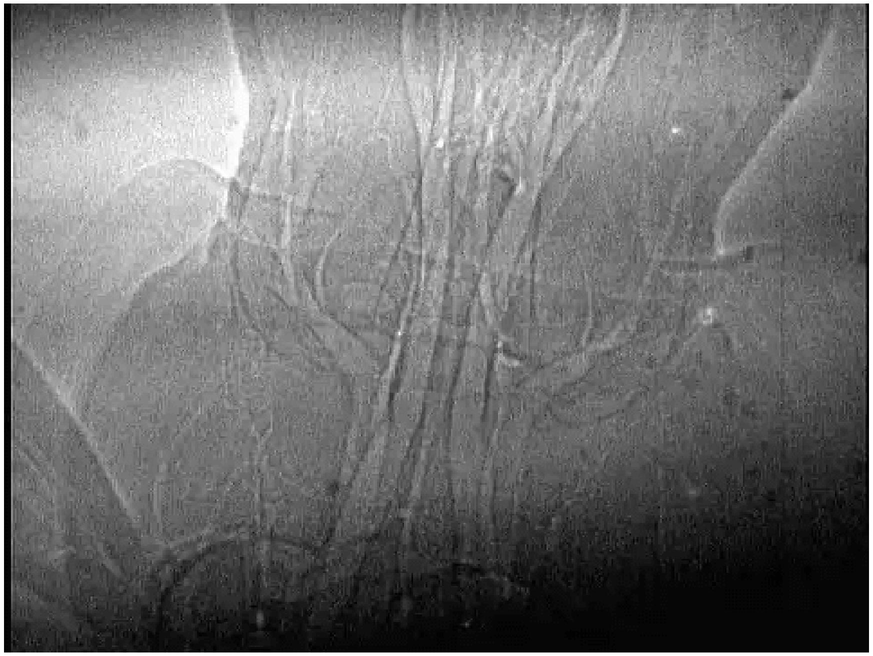
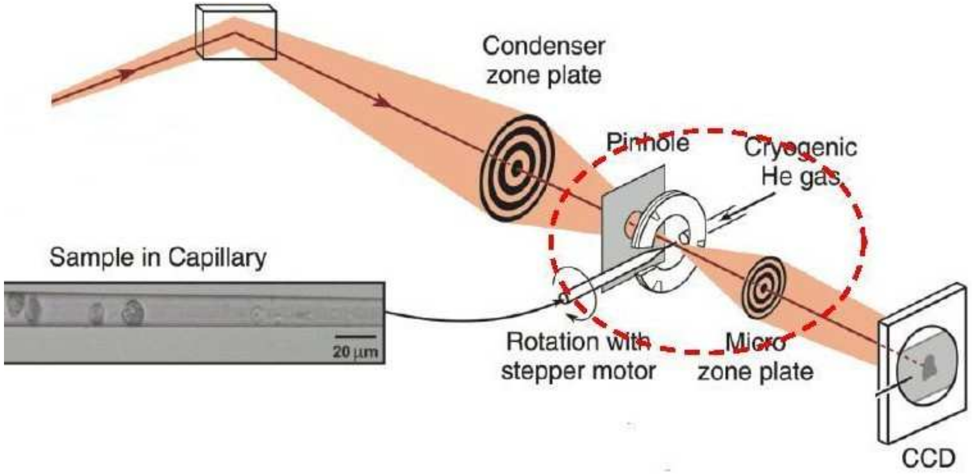
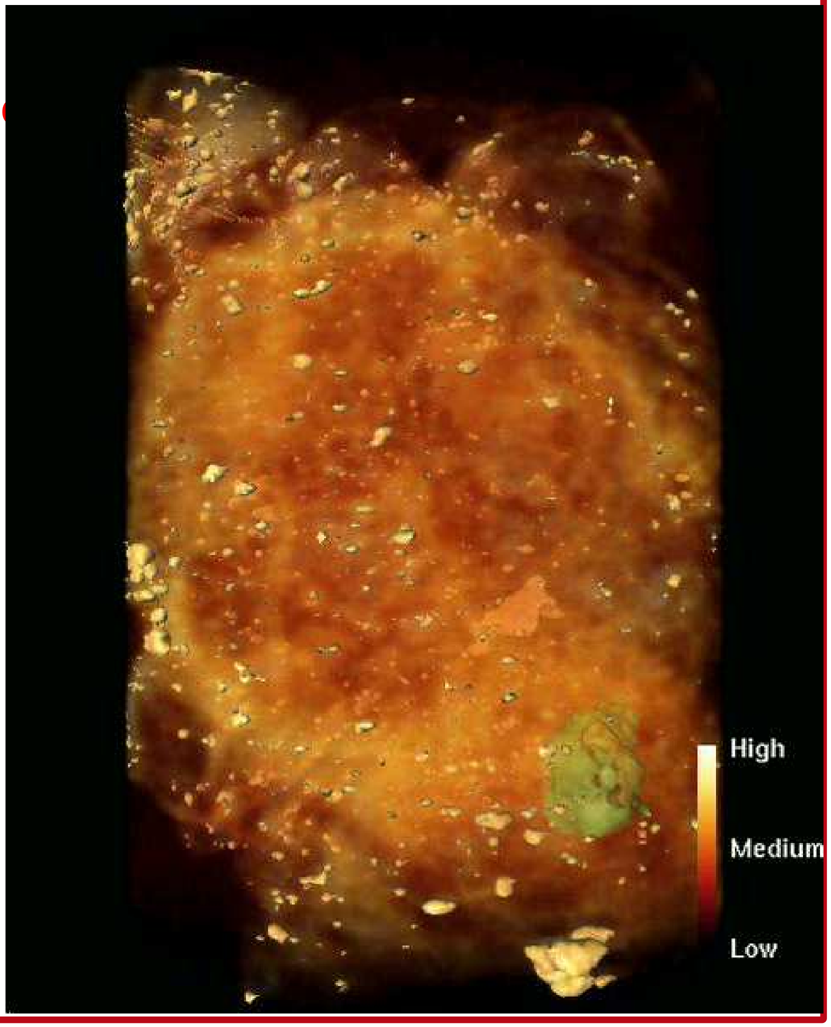


- ERL would extend these studies to much higher lateral resolution (sub µm) and faster time scales

3D Tomography of Cells



ERL: 100-1000 more brightness

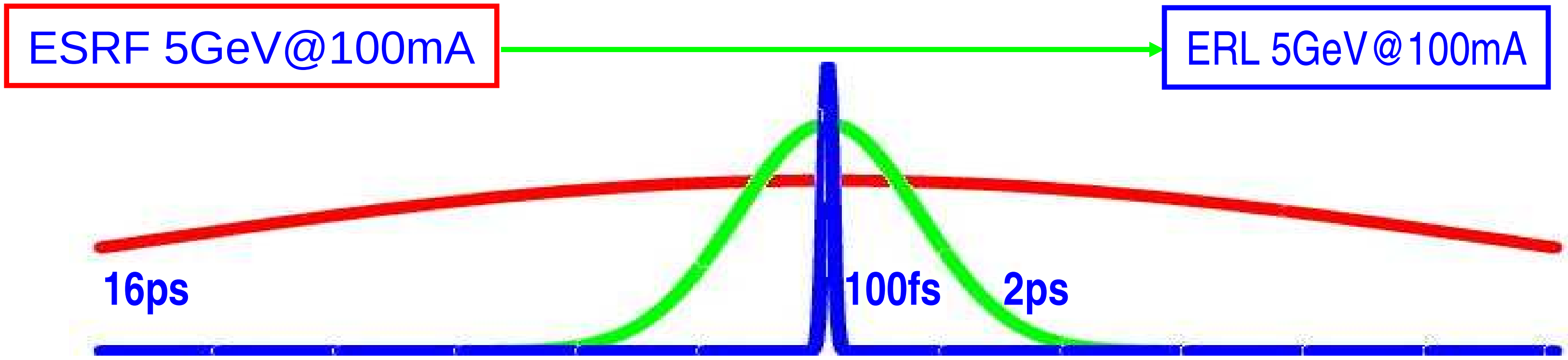


Drosophila embryonic cell
(G. Schneider, LBNL)

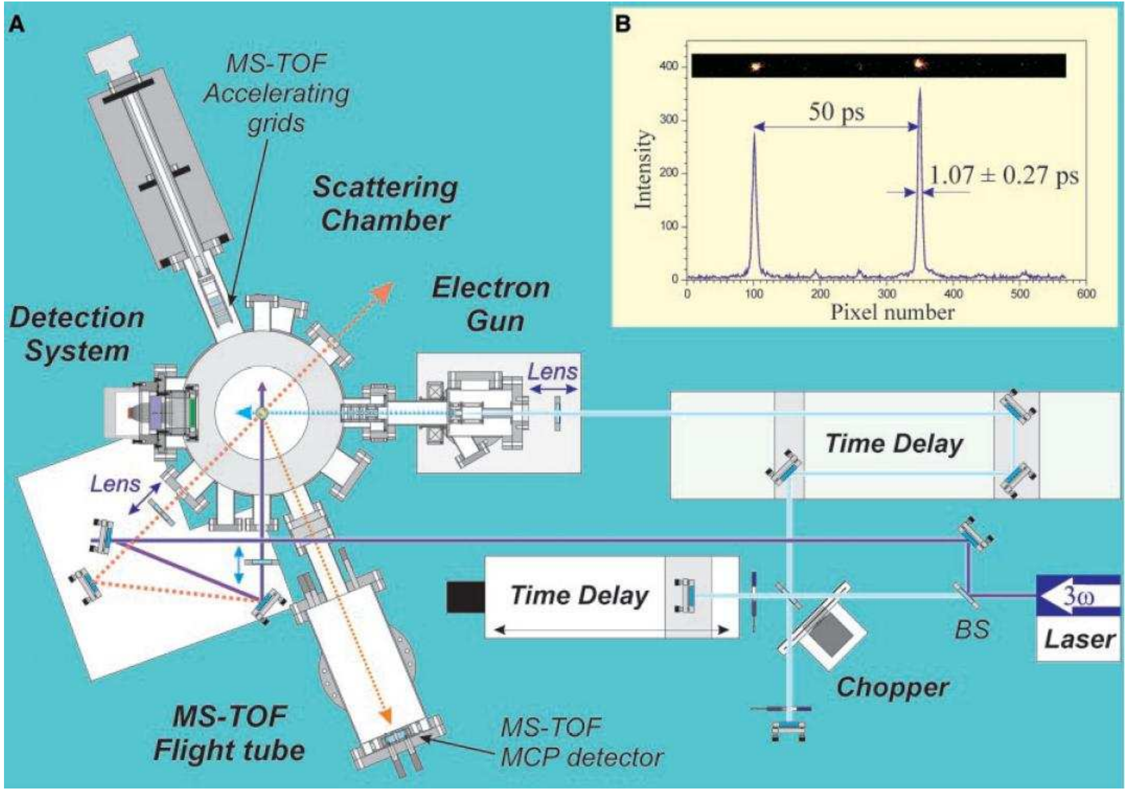
Green = nucleolus
Gold = sex-determining protein

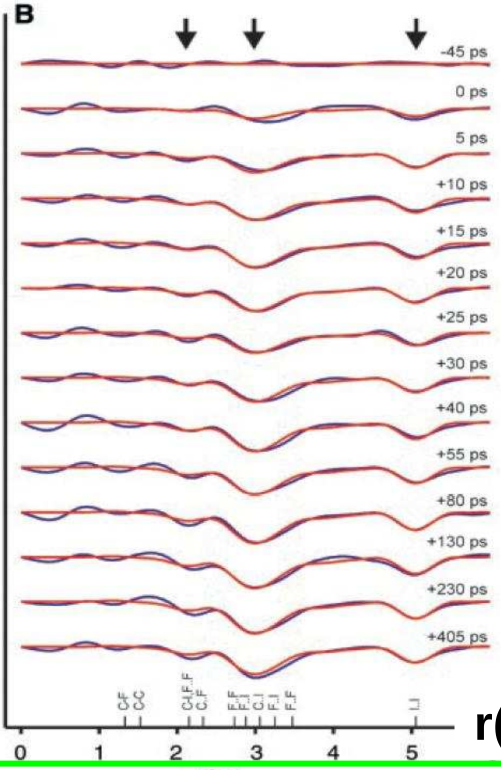
Bunch length in a Linac

- 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.

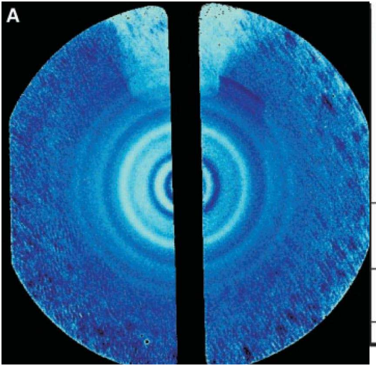


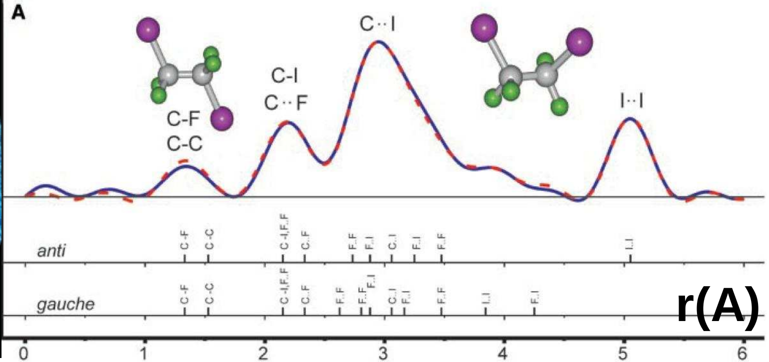
Ultra-fast Electron Diffraction

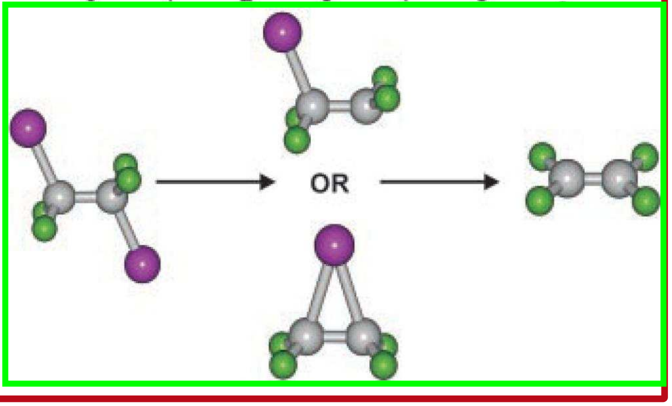




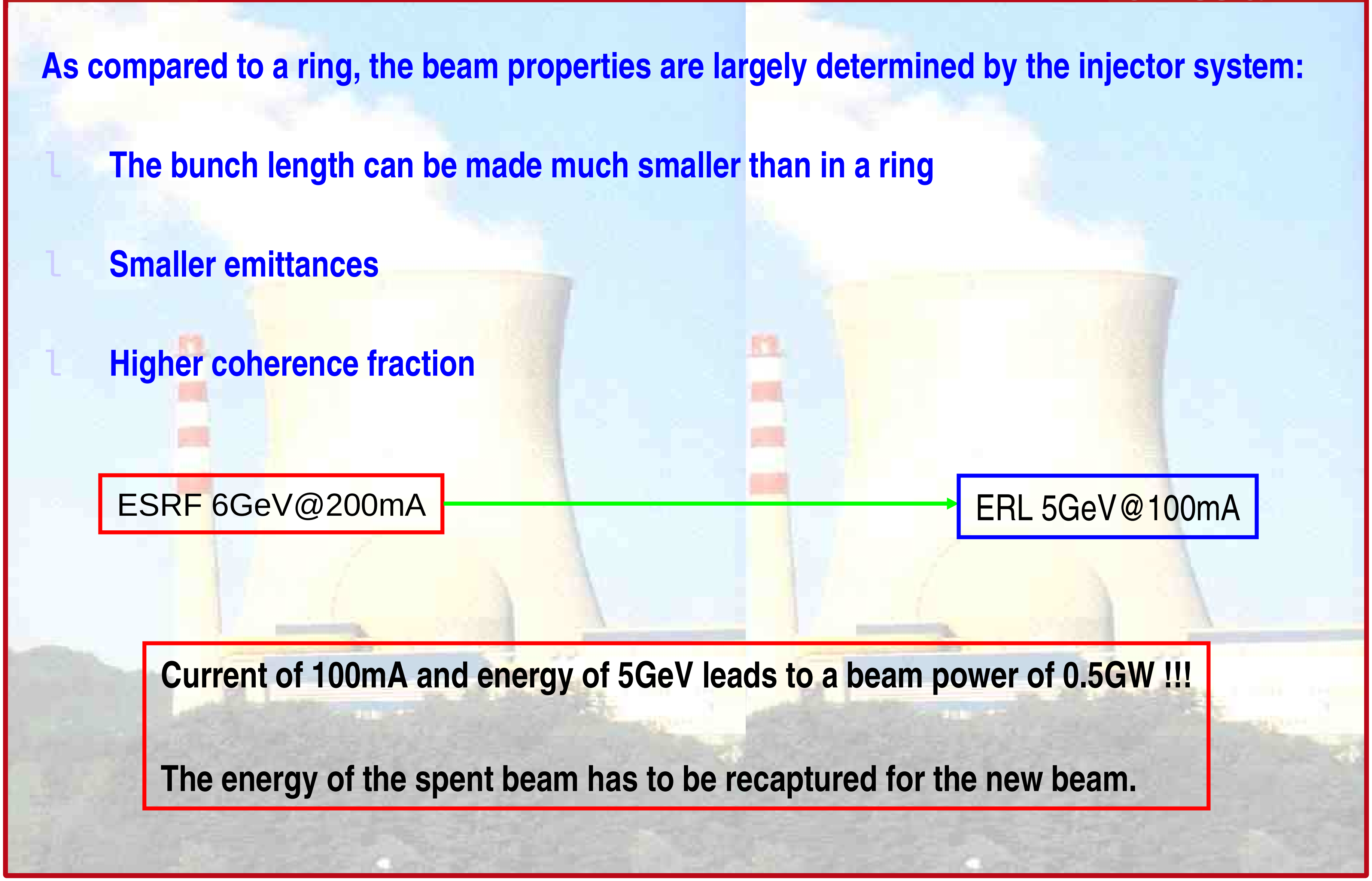
X-rays: T > 10ps, ERL T<100fs







Pro and Con for an x-ray Linac



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

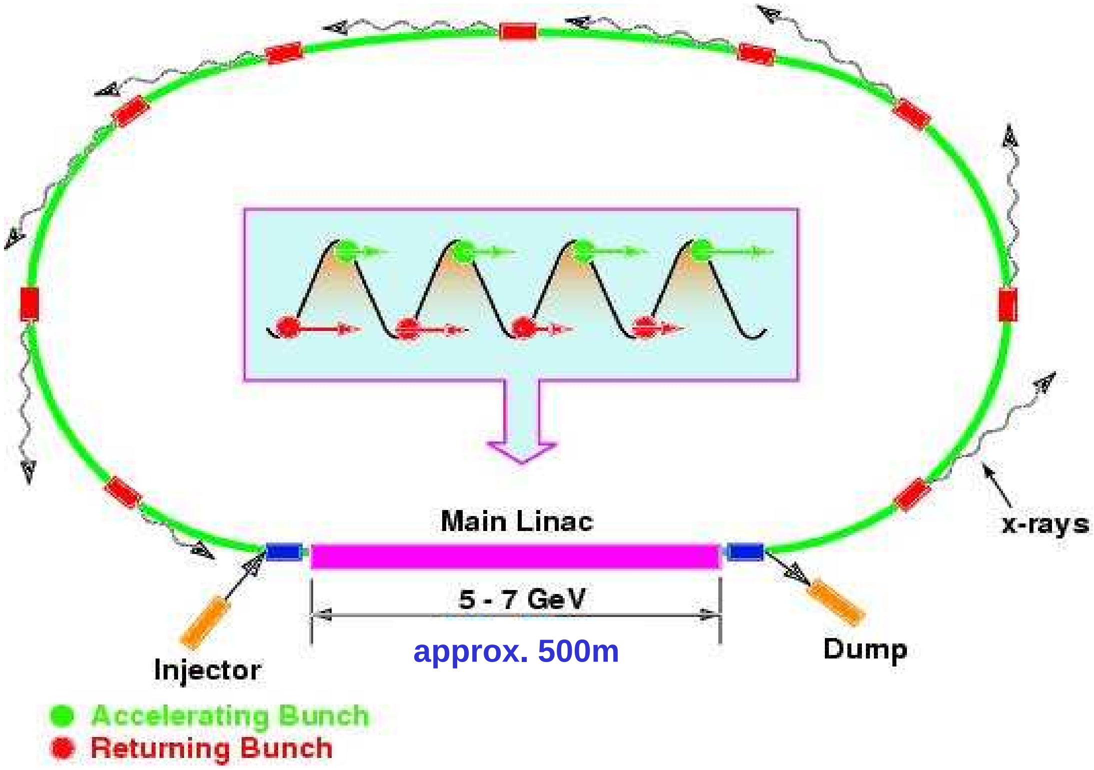
Current of 100mA and energy of 5GeV leads to a beam power of 0.5GW !!!

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

CHESS & LEPP

ERLs

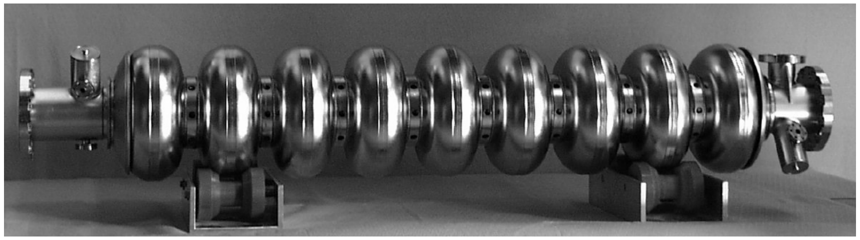
X-ray analysis with highest resolution in space and time:



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

Accelerator Physics @ CESR



$Q = 10^{10}$

$E = 20MV/m$

A bell with this Q would ring for a year.

- Very low wall losses.
- Therefore continuous operation is possible.
- Energy recovery becomes possible.

Normal conducting cavities

- Significant wall losses.
- Cannot operate continuously with appreciable fields.
- Energy recovery was therefore not possible.

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

CHESS & LEPP

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 $(\frac{\mathrm{ph}}{0.1\%\ \mathrm{s}})$	$9\ 10^{15}$	$9\ 10^{14}$	$9\ 10^{12}$
Av. brilliance $(\frac{\mathrm{ph}}{0.1\%\ \mathrm{s\ mm^2\ mrad^2}})$	$1.6\ 10^{22}$	$3.0\ 10^{22}$	$2.0\ 10^{17}$
Bunch length (ps)	2	2	0.1

Optimistic Outlook

- The ERL parameters are **dramatically** better than present 3rd generation storage rings

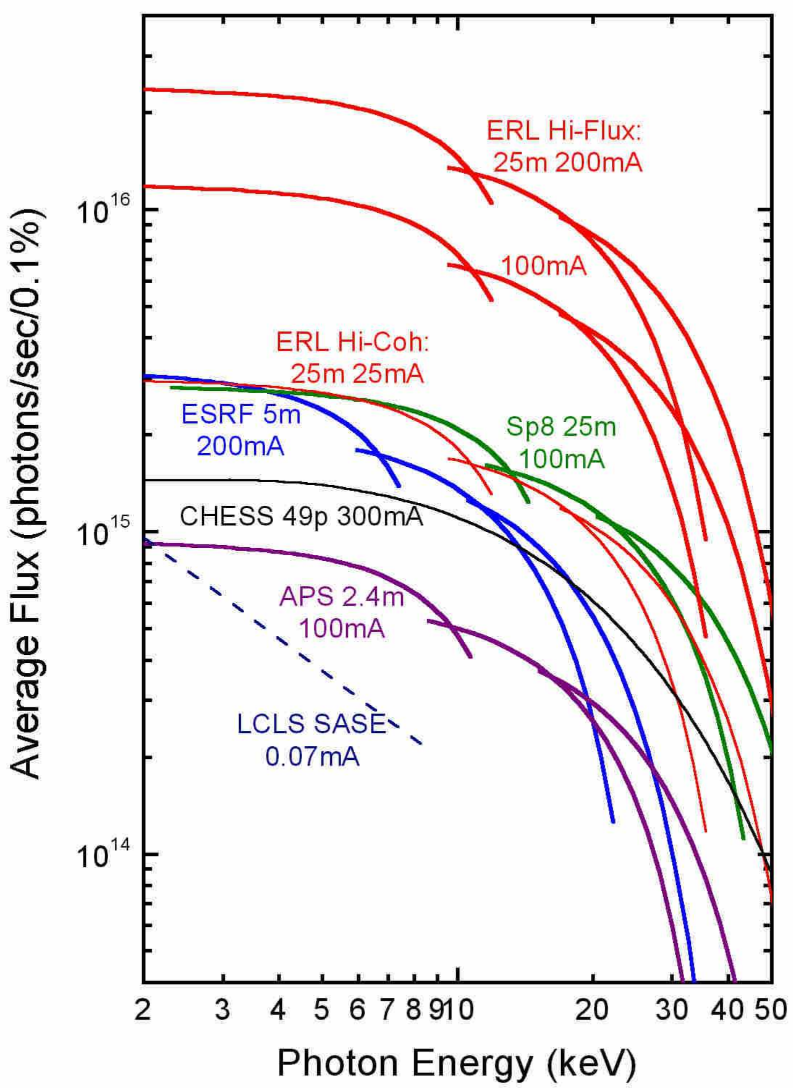
- The use of ERL microbeams, coherence, and ultra-fast timing will lead to new unique experiments that can be expected to transform the way future x-ray science experiments are conducted

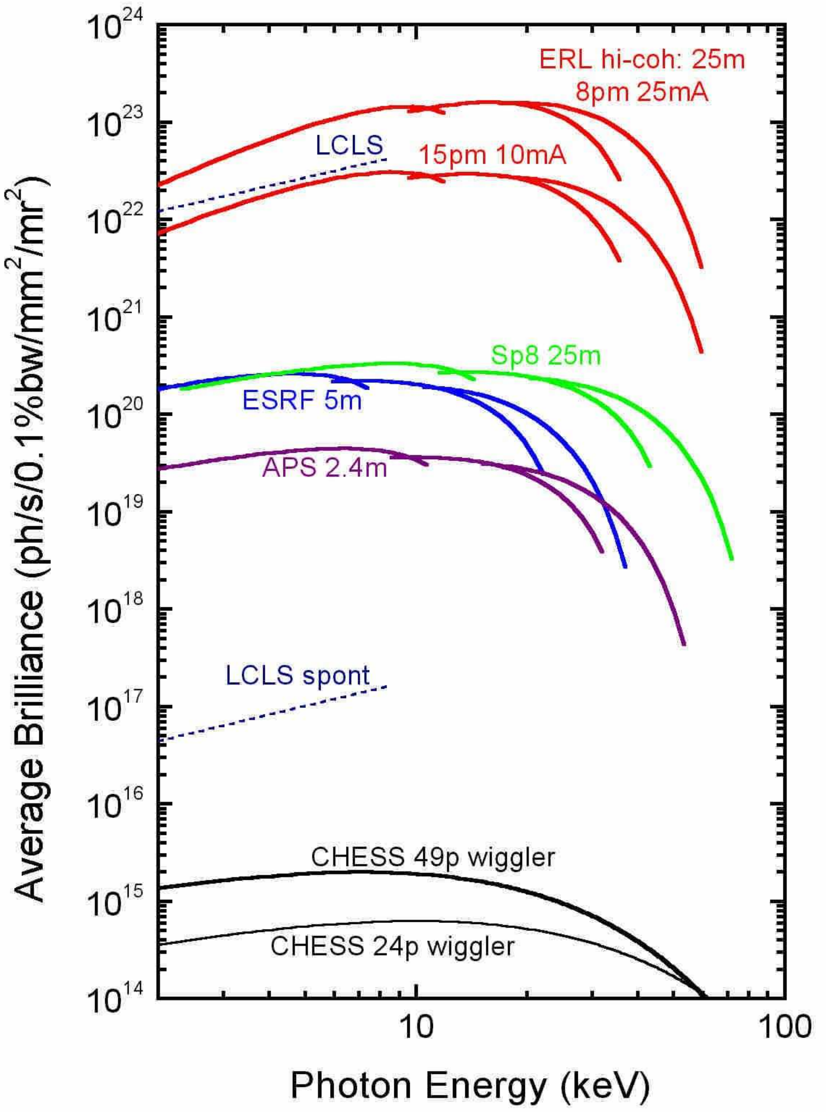
- Most critical parameters to achieve in an ERL are therefore, narrow beams, small emittances, short bunches, at large currents.

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

CHESS & LEPP

Flux and Brilliance





ERLs in the World

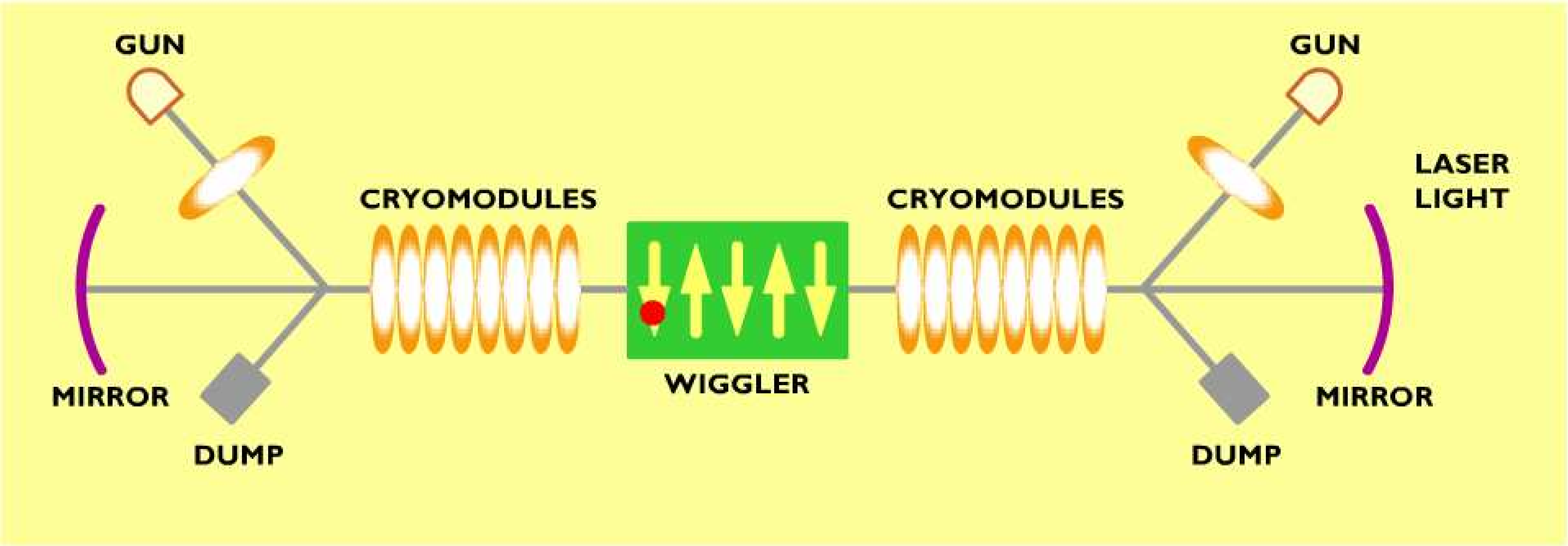
After the success of high gradient super-conducting RF, several laboratories have worked on ERLs:

Upgrades of: TJNAF, JAERI
Light production: Cornell, KEK, Daresbury, Novosibirsk
Electron Ion colliders: TJNAF
High energy electron cooling for RHIC: Brookhaven

Neither an electron source, nor an injector system, nor an ERL has ever been built for the required large beam powers and small transverse and longitudinal emittances.

Ł **A prototype at Cornell should verify the functionality**

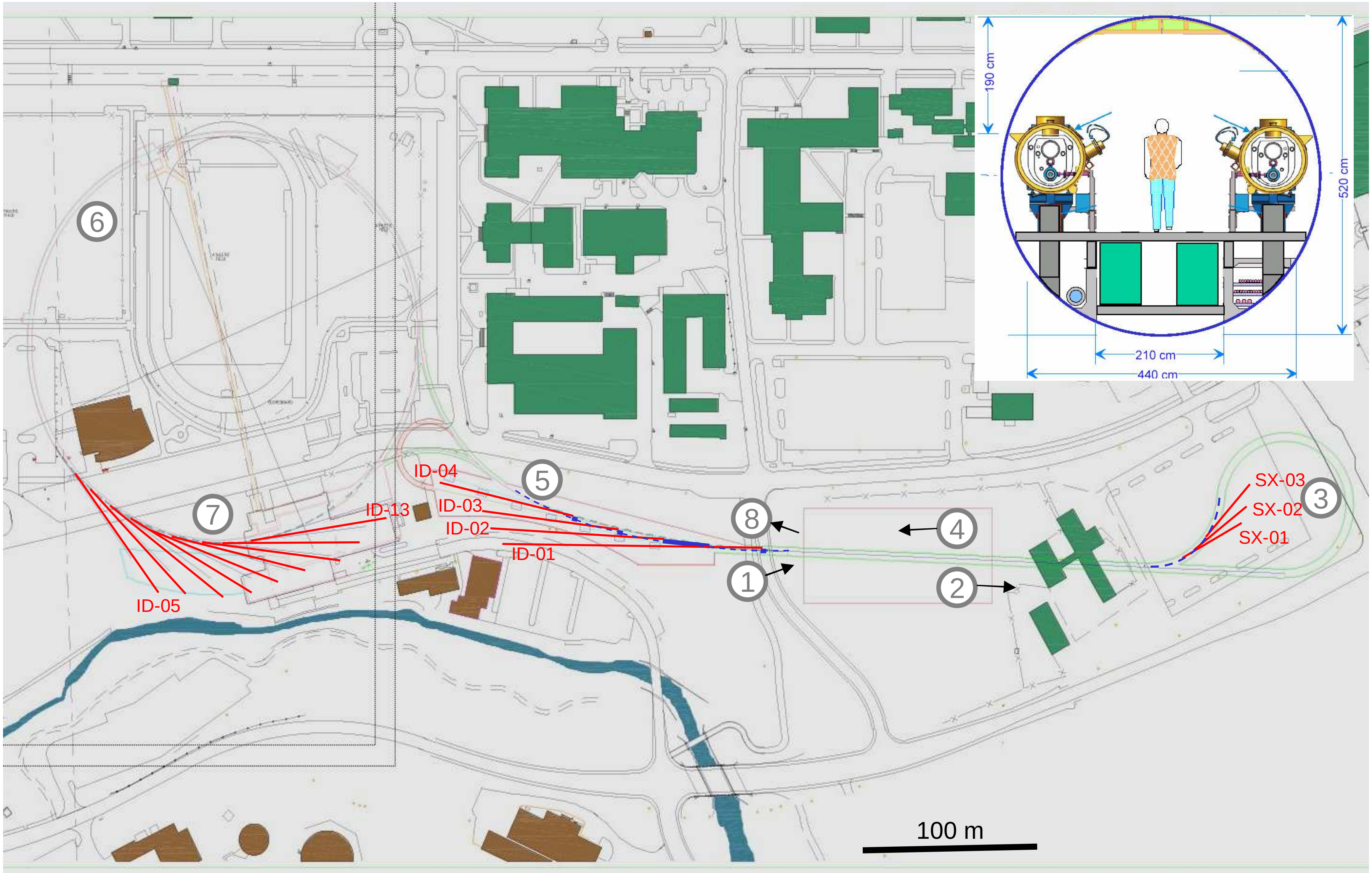
A push-pull ERL



Animation by Tom Oren

Goal: ERL @ CESR

CHESS & LEPP



Advantages of ERL@CESR

CHESS & LEPP

- 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

Limits to Energy :

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

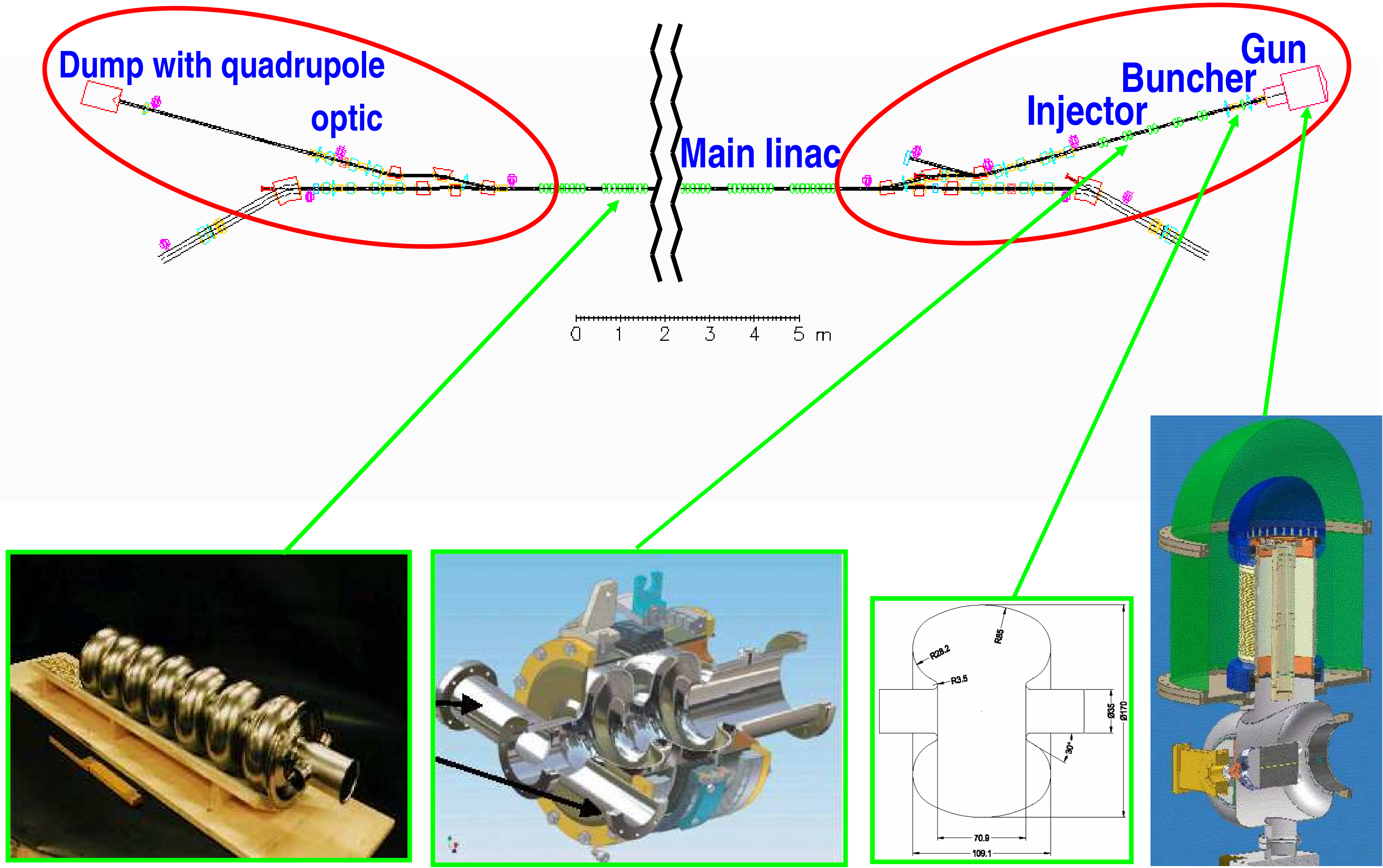
Limits to Current :

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

For small emittances in all 3 dimensions :

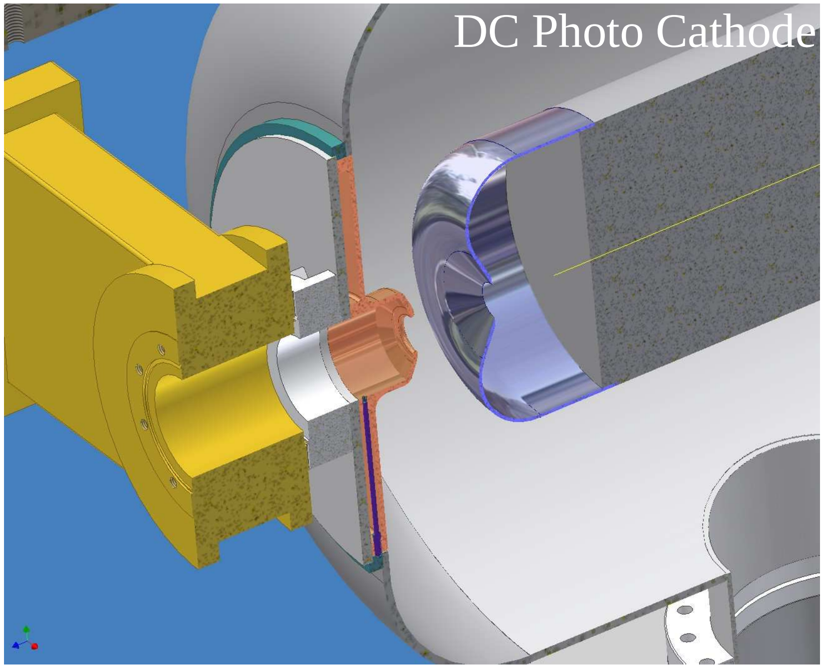
- Ø Coulomb expulsion of bunched particles (Space Charge, e-Source)
- Ø Radiation back reaction on a bunch (ISR and CSR)
- Ø Nonlinear beam dynamics
- Ø Ion accumulation in the beam potential
- Ø Stability against ground vibration (μm level)

Ongoing ERL prototyping



Ongoing Developments

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

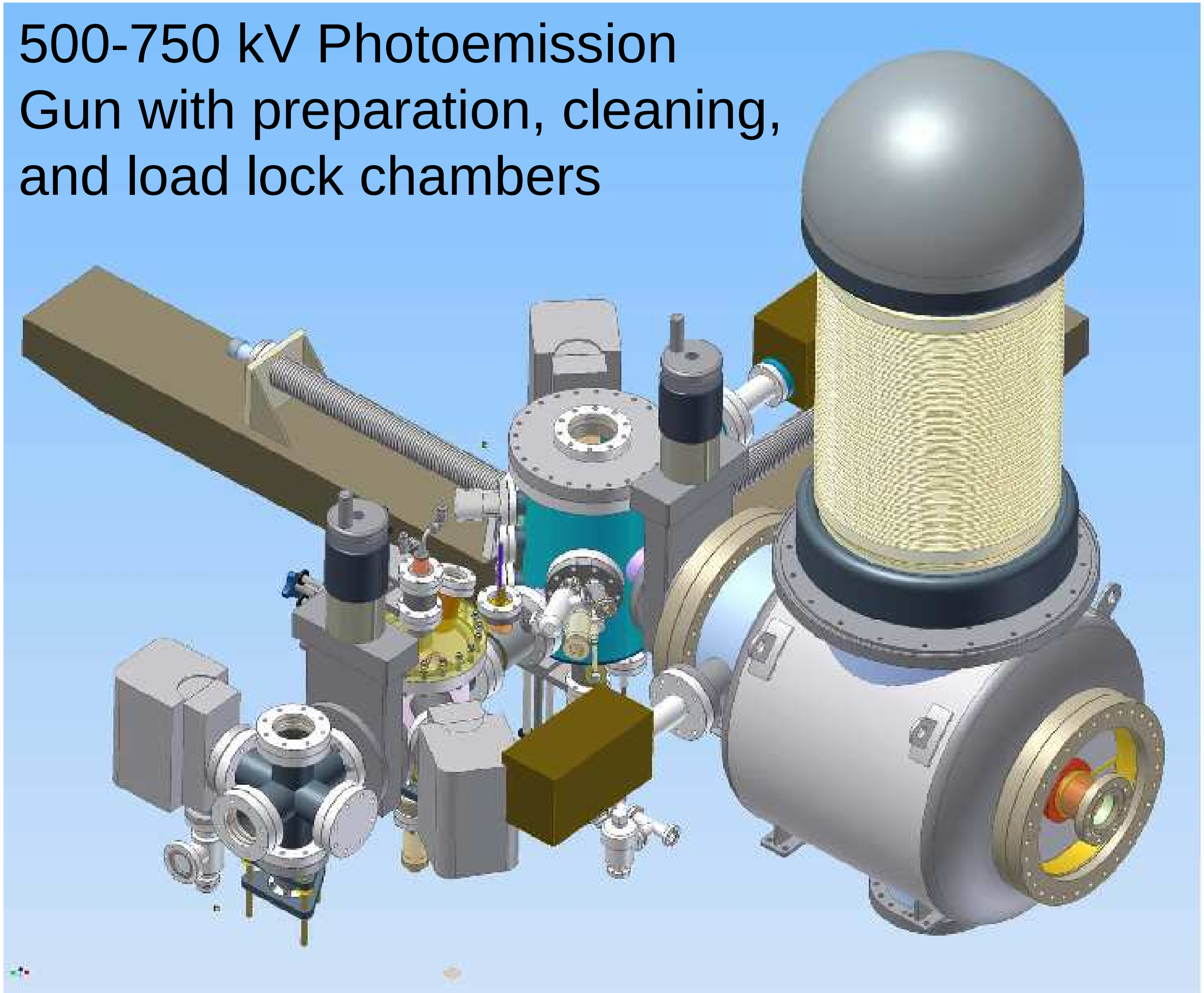


DC Photo Cathode

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

Bright Electron Source and ERL

500-750 kV Photoemission Gun with preparation, cleaning, and load lock chambers

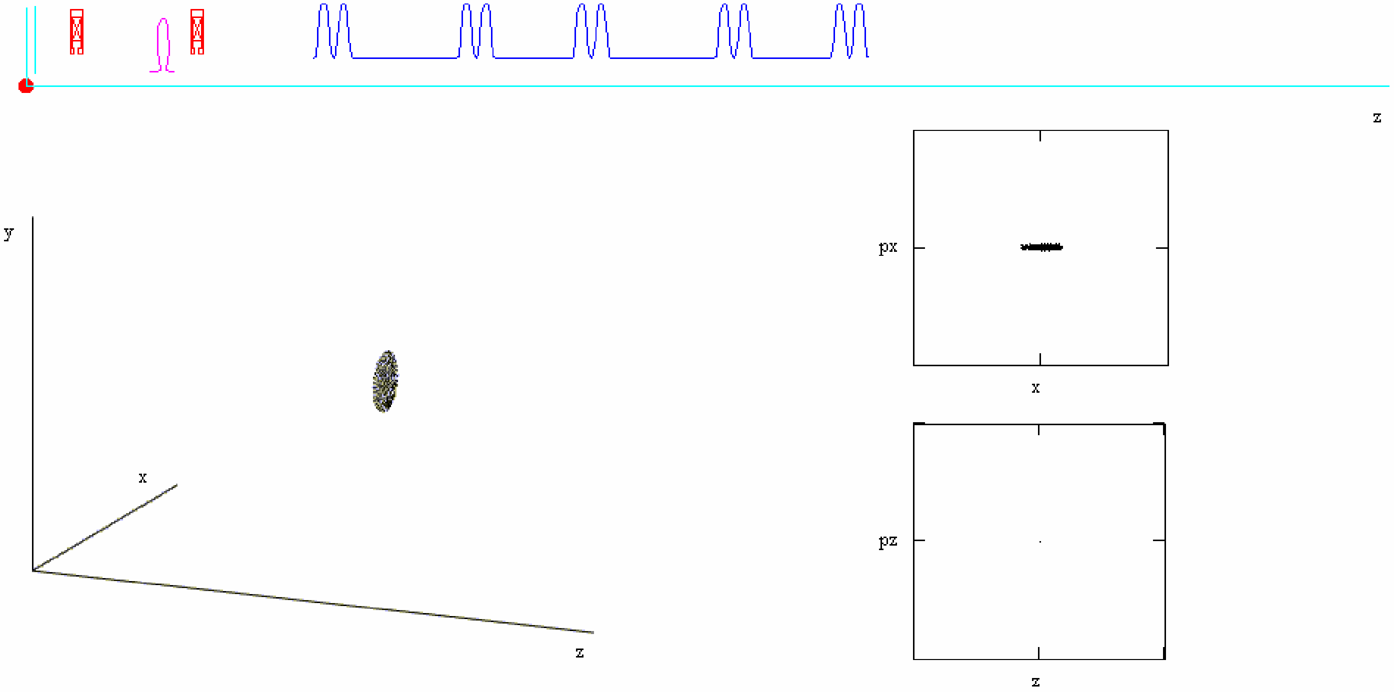


Emittances: down to 0.1mm mrad

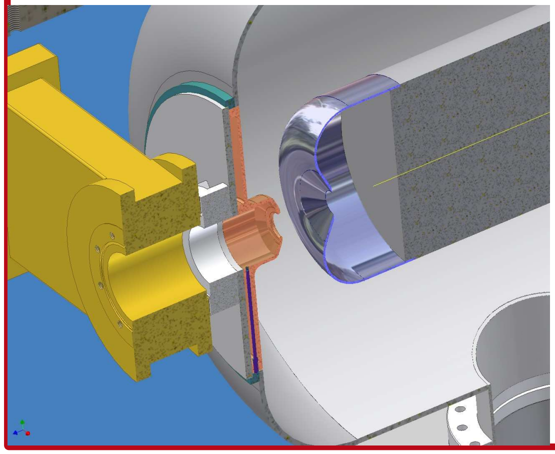
Current: up to 100mA

DC, 1.3GHz

Source development



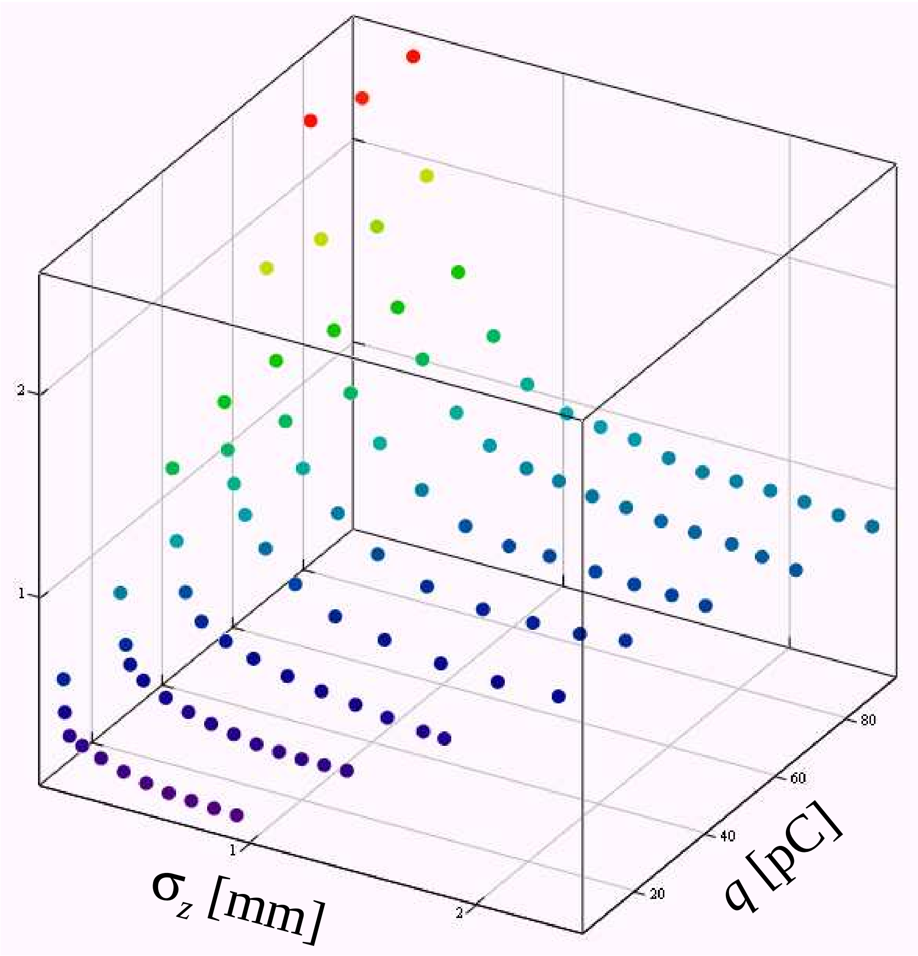
courtesy Ivan Bazarov

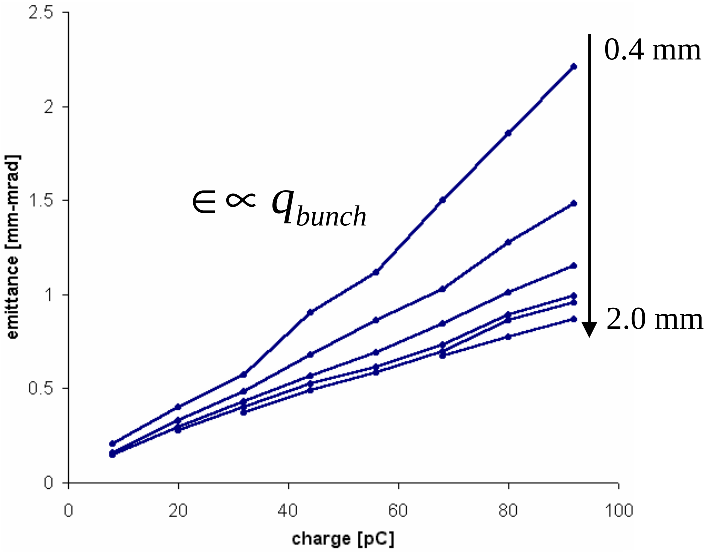


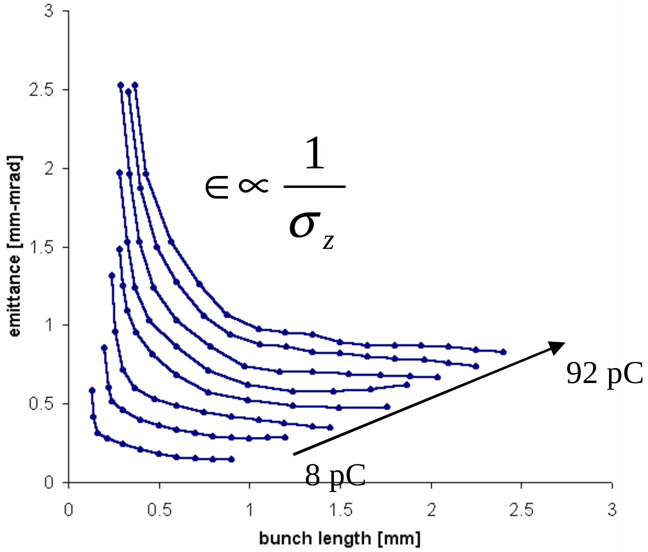
DC source for high current & low emittances

- Simulations show 10 times smaller emittances than previously thought possible, and 50 times smaller than standard.
- Gun development, coating for low field emission
- Photocathode development, neg. el. affinity GaAs, cooled
- Laser beam shaping

Injector Optimizations



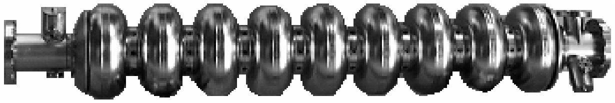




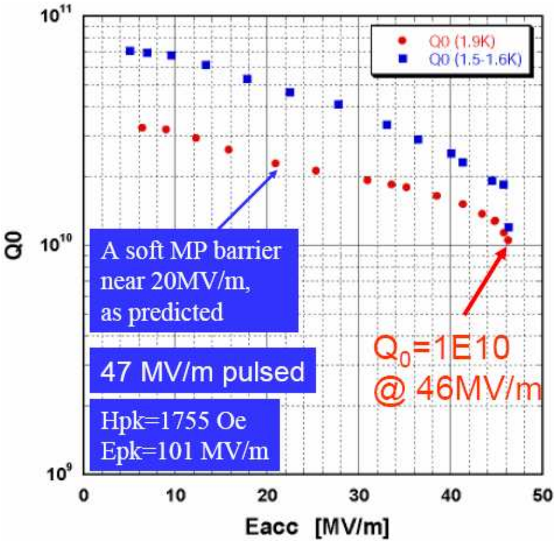
courtesy Ivan Bazarov

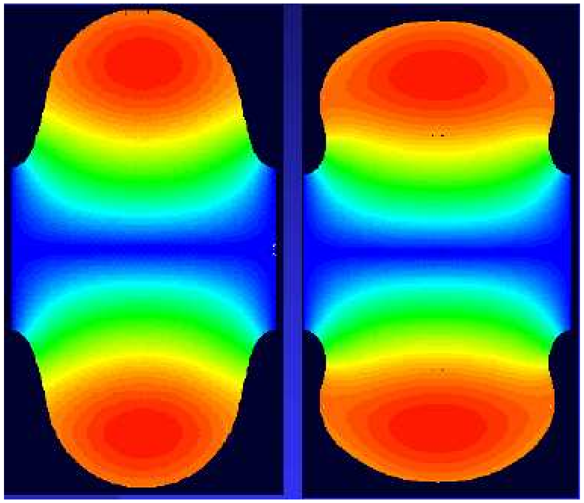
SRF & Solid State/Surface Physics

Research Subjects with Solid State Physics aspects:



- Higher gradients in solid niobium cavities (**ILC and ERL**)
- Understand the dependence on Q on field (**ILC and ERL**)
- Alternate materials for superconducting cavities, e.g. Nb3Sn, Nb bonded to Cu, Nb on Cu, single crystal cavities, epitaxial Nb surfaces,... (**ILC, ERL, Muon accelerator**)
- Improve breakdown characteristics of cavities to assure high duty factor operation (**main ERL and ILC**)





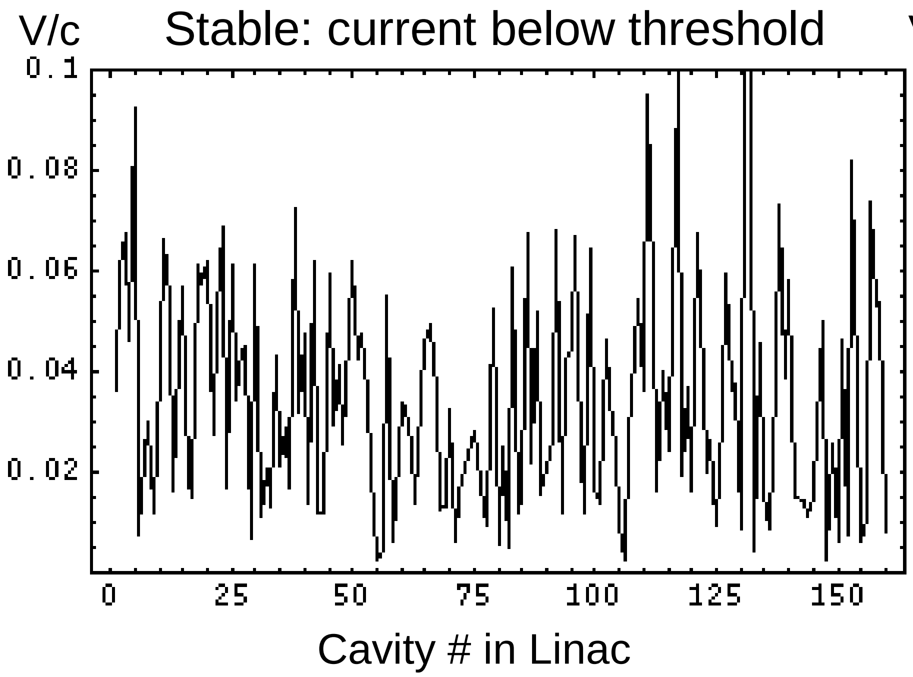
BBU: Collective Instabilities

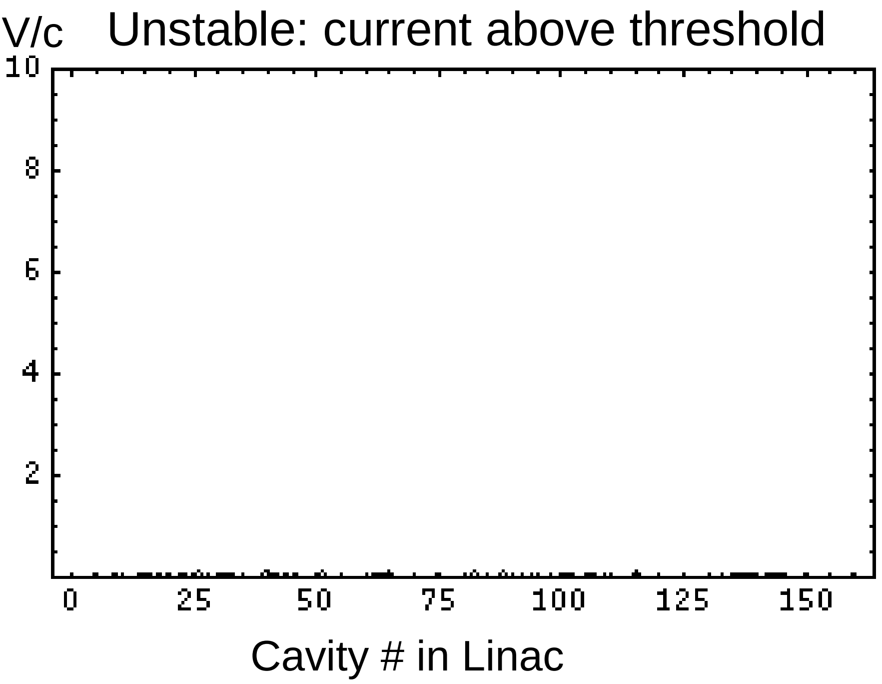
Beam break up: a potential limit to ERL currents

$$V_x(t) = T_{12}\,\tfrac{e}{c}\int_{-\infty}^{t} W_x(t-t')\,V_x(t'-t_r)\,I(t')\,dt'$$

- **Similar instabilities would occur in the Linear Collider**

HOM with BBU: Starting from Noise

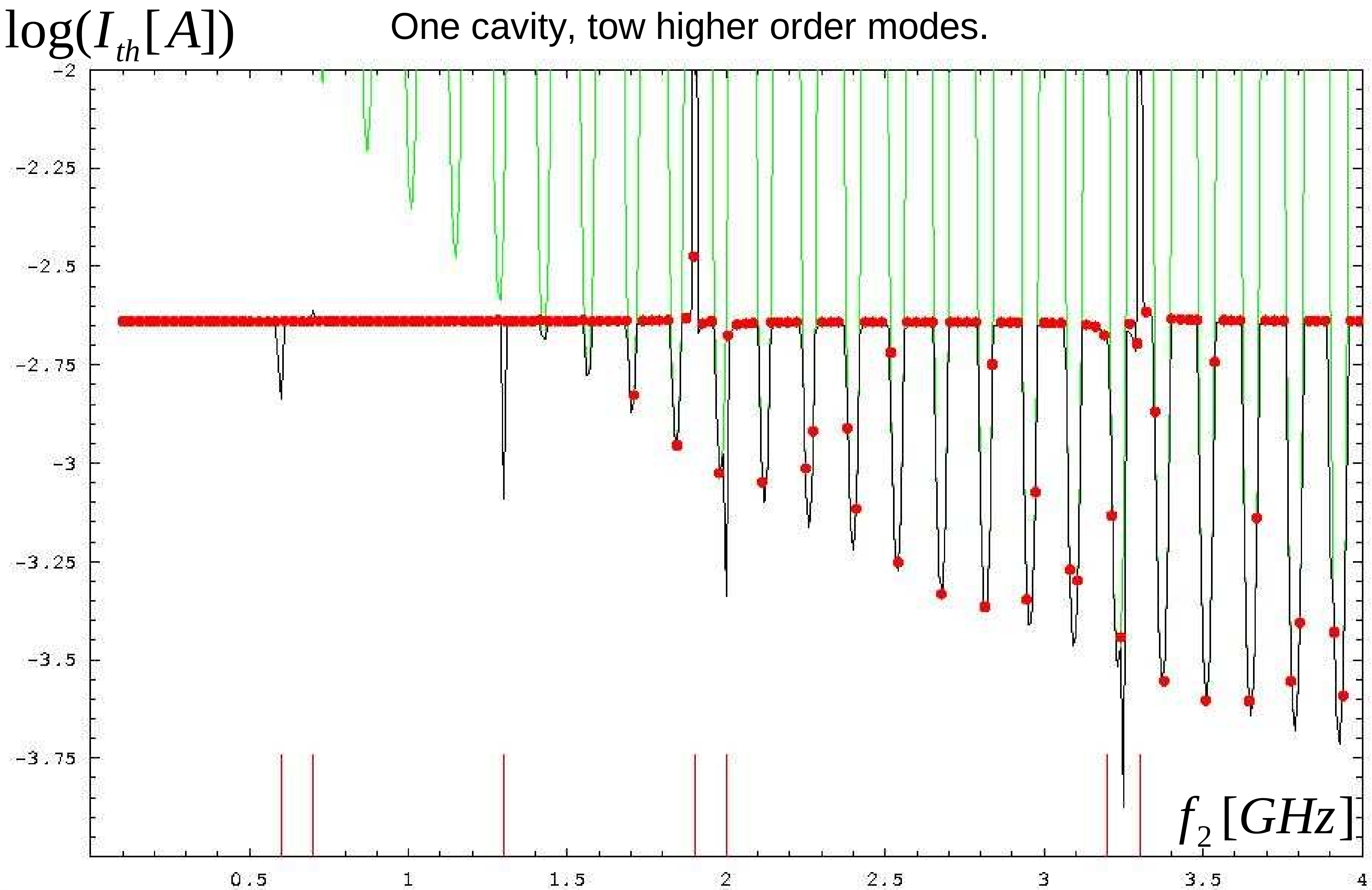




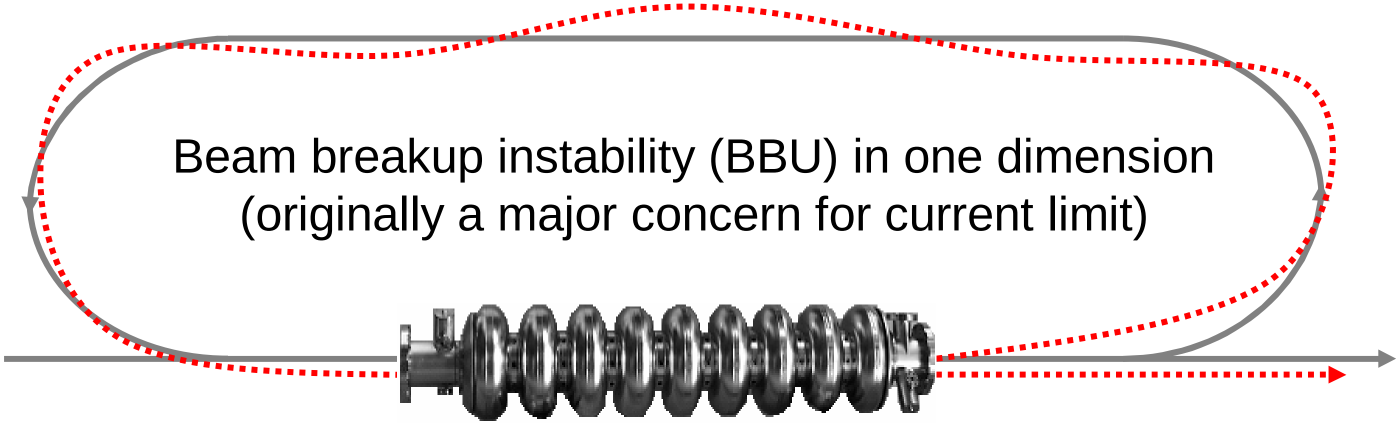
CHESS & LEPP

Isolation of modes

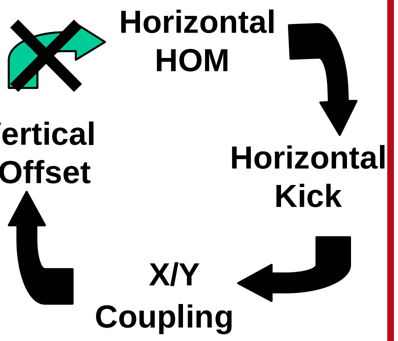
One cavity, tow higher order modes.



Current limit due to BBU



Beam breakup instability (BBU) in one dimension
(originally a major concern for current limit)

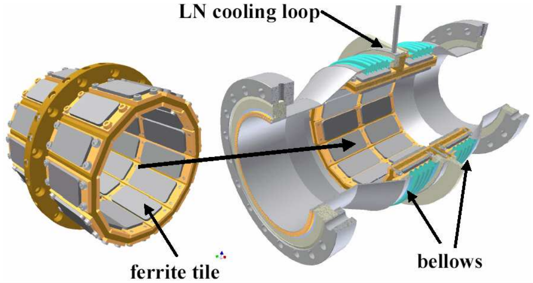


320 identical cavities → **Current limited to 25mA**

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

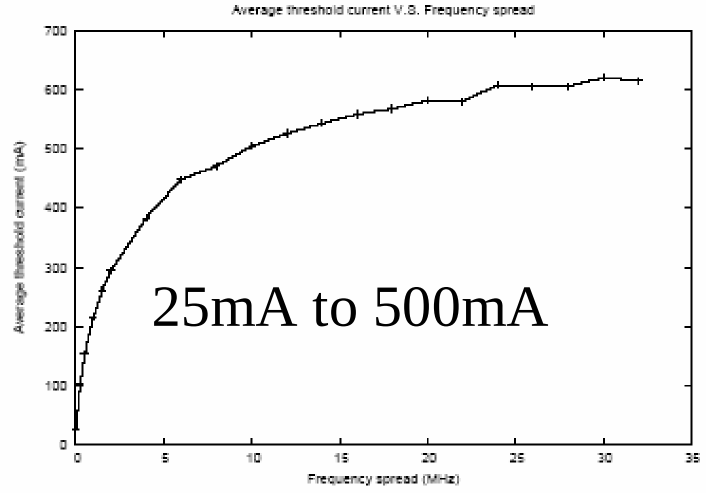
Polarized Cavities and x to y coupling → **Current limited to 2000mA >> required 100mA**

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



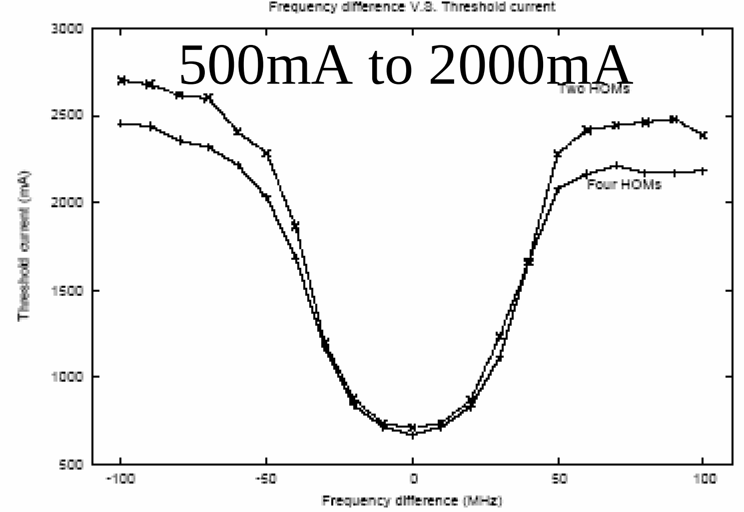
BBU for ERL@CESR

Randomization of frequencies



25mA to 500mA

x/y frequency separation

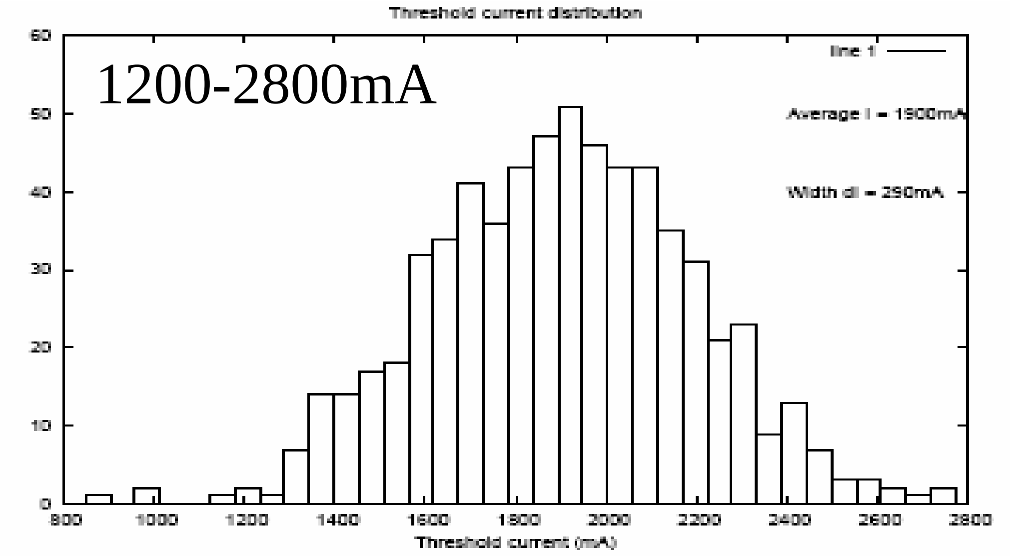


500mA to 2000mA

Model of ERL@CESR 320 polarized cavities with

fx-fy=60MHz

spread=10MHz



1200-2800mA

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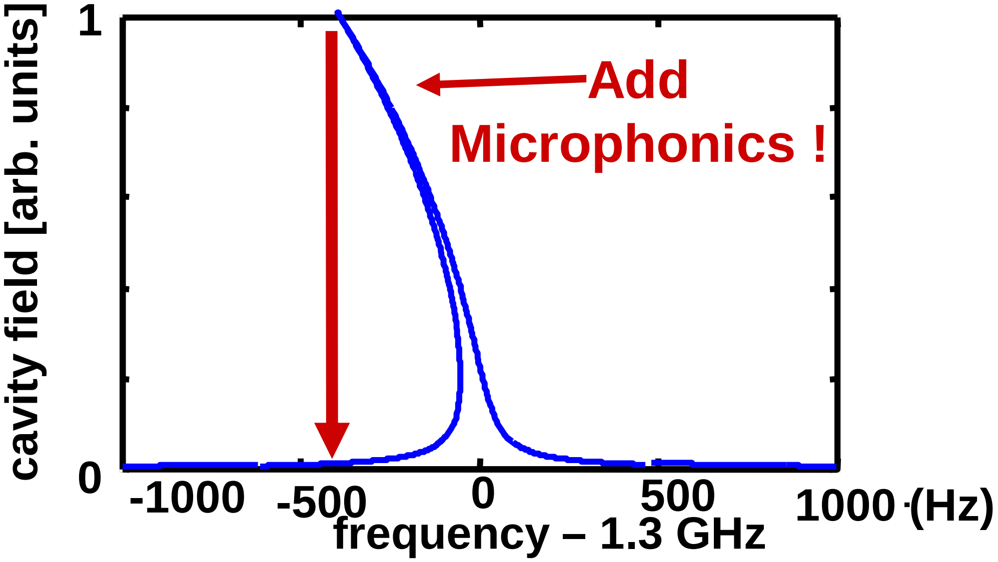
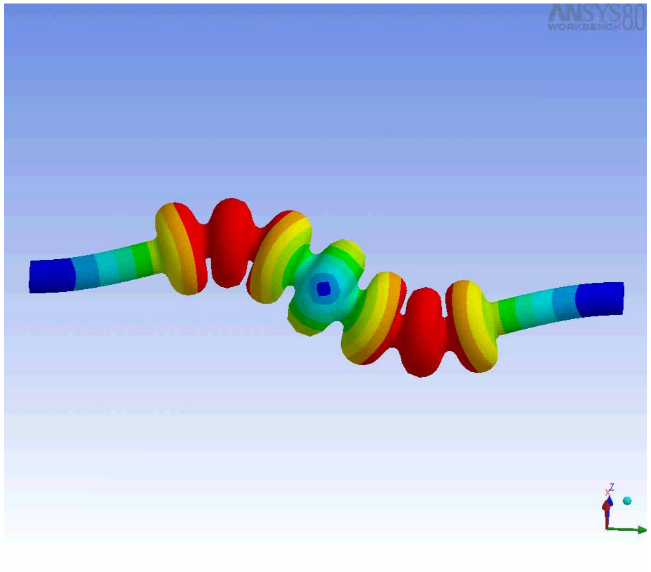
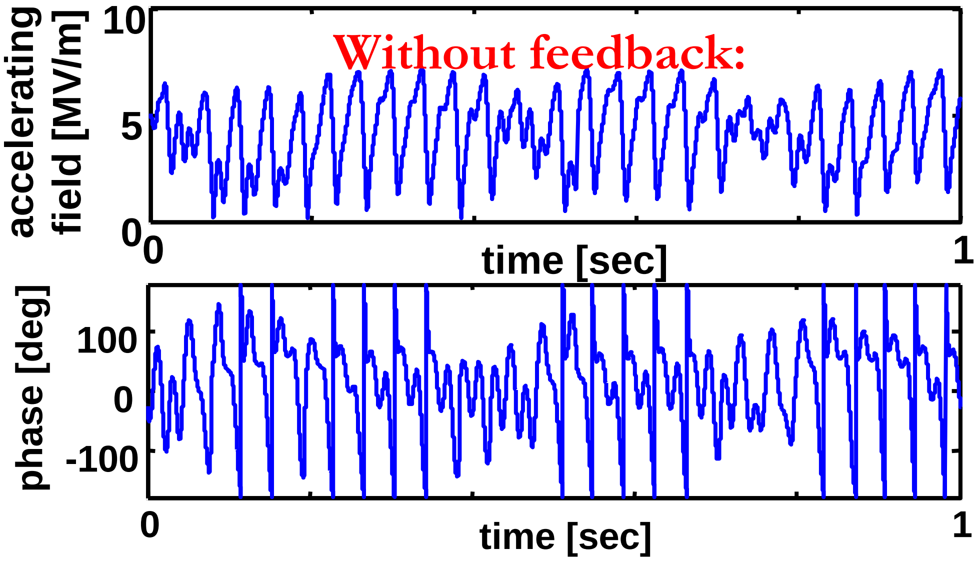
High loaded Q cavity control



Add Microphonics !



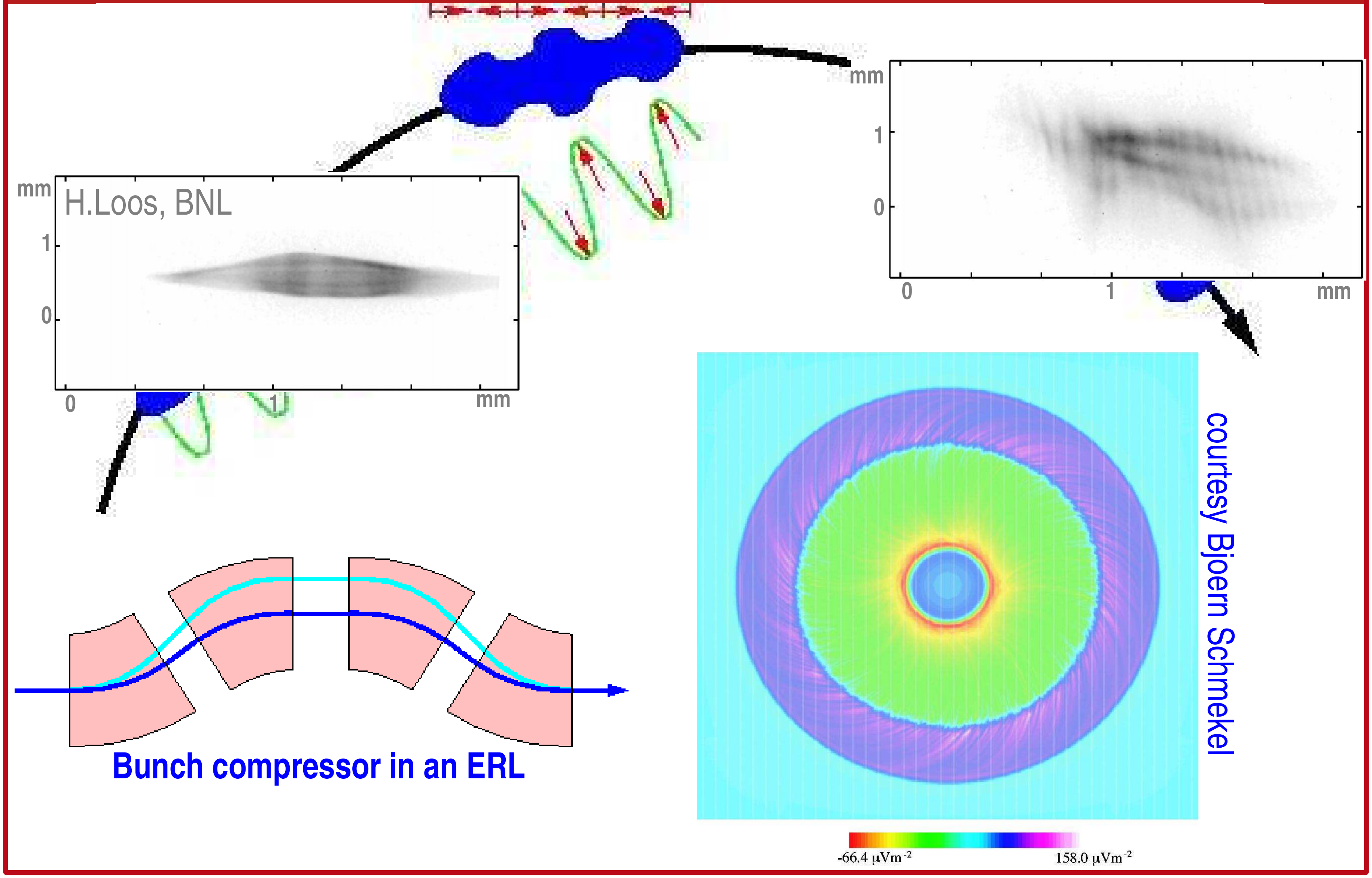
courtesy Matthias Liepe



Without feedback:

- 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!

Coherent Synchrotron Radiation



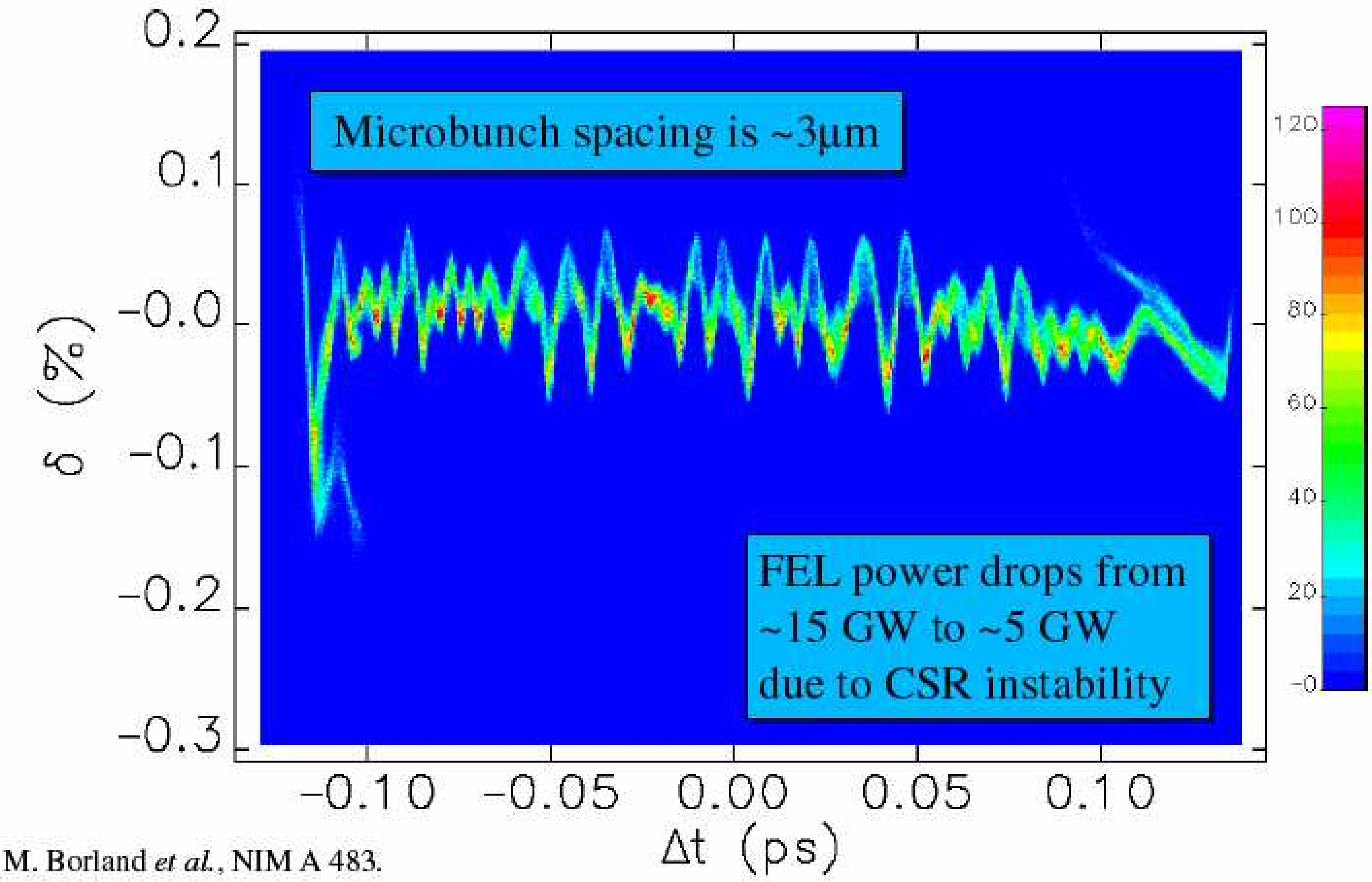
H.Loos, BNL

Bunch compressor in an ERL

courtesy Bjoern Schmekel

CSR micro-bunching: Simulations

CSR Microbunching Instability in LCLS

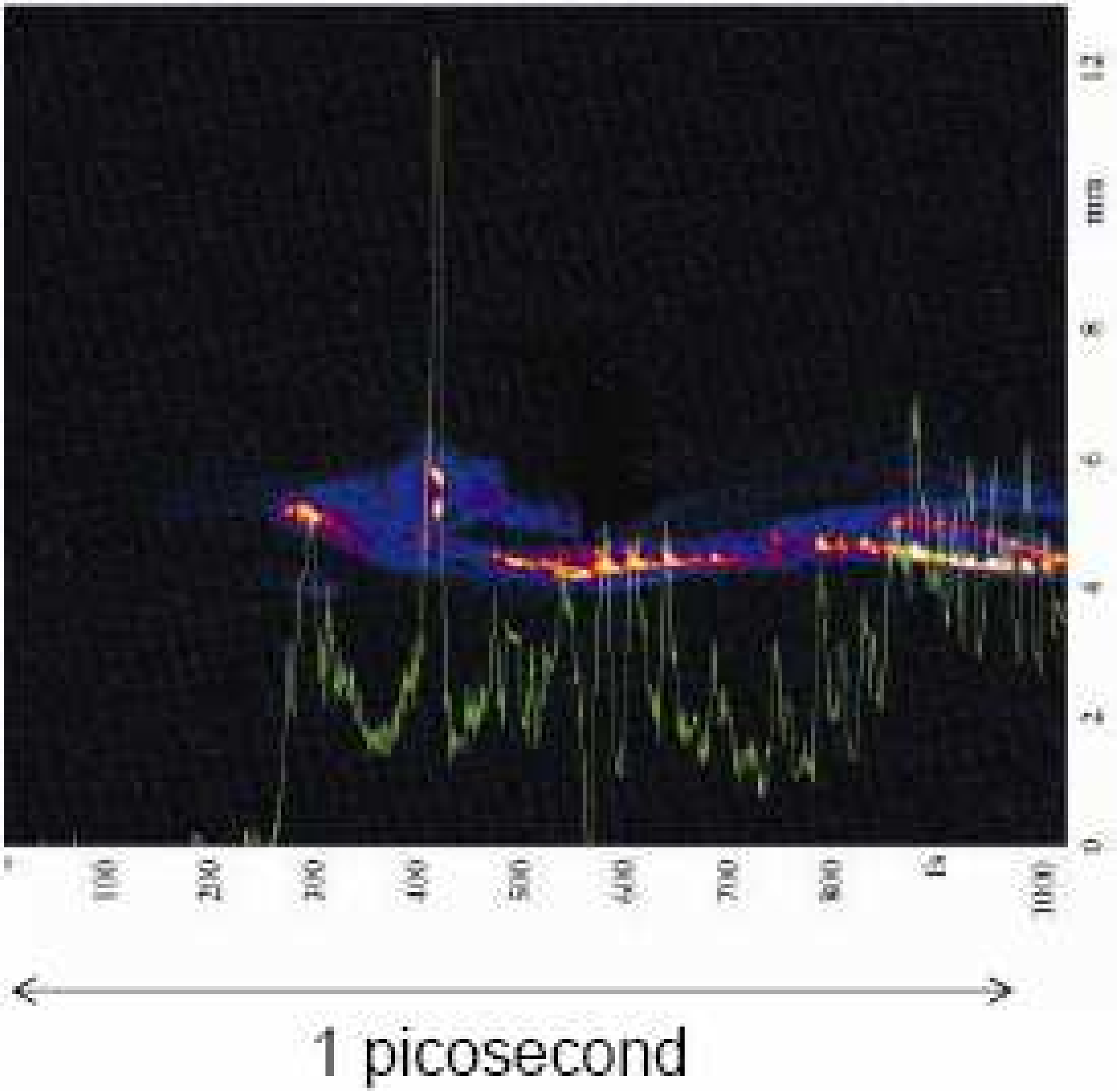


Microbunch spacing is ~3μm

FEL power drops from ~15 GW to ~5 GW due to CSR instability

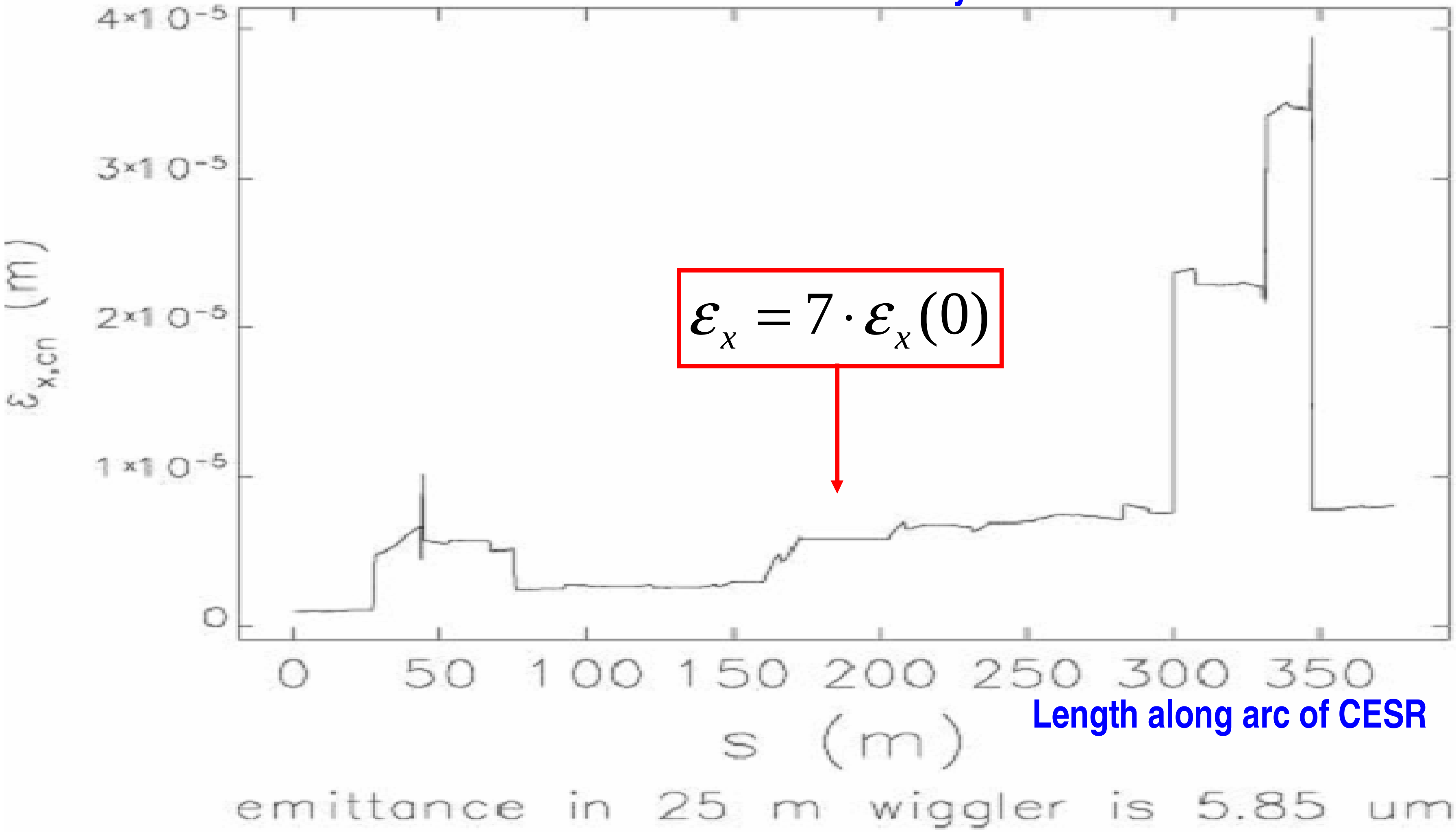
M. Borland *et al.*, NIM A 483.

Micro-bunching: Measurements at TTF



CSR for 100fs a bunch with spike

Horizontal emittance with coherent synchrotron radiation

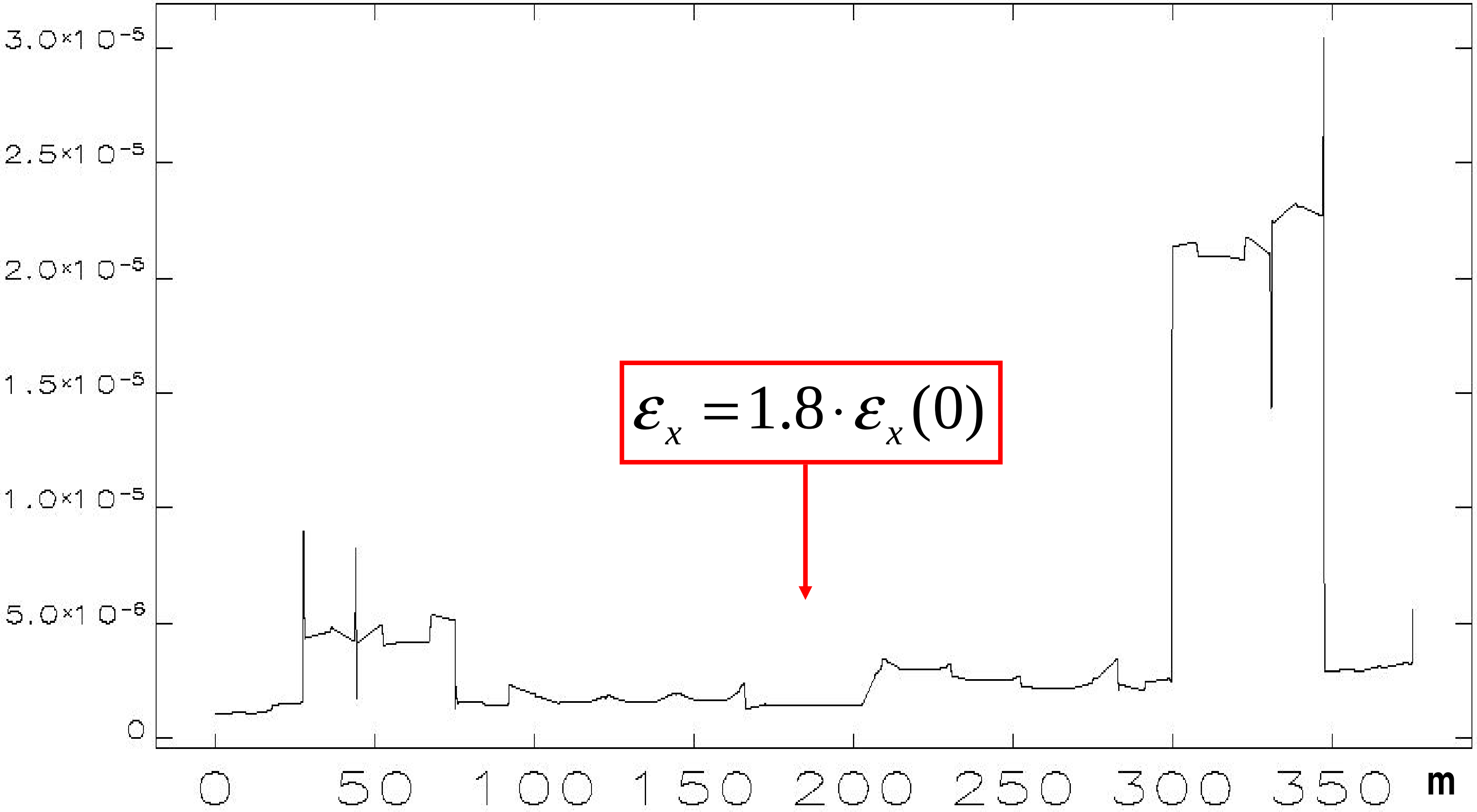


$$\varepsilon_x = 7\cdot\varepsilon_x(0)$$

Length along arc of CESR

CSR for 100fs bunch without spike

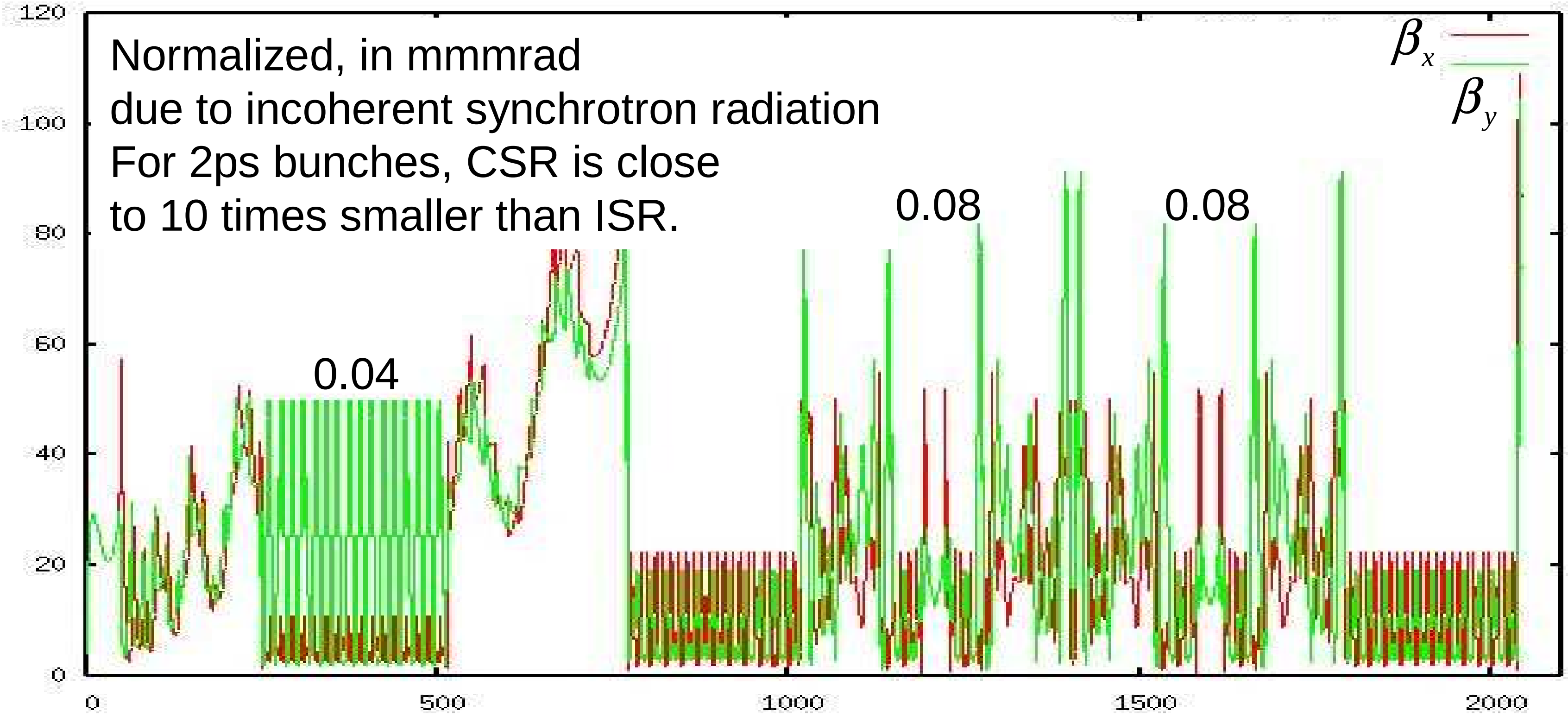
Horizontal emittance with coherent synchrotron radiation



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

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

Emittance growth along the X-ray ERL



Normalized, in mmmrad
due to incoherent synchrotron radiation
For 2ps bunches, CSR is close
to 10 times smaller than ISR.

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

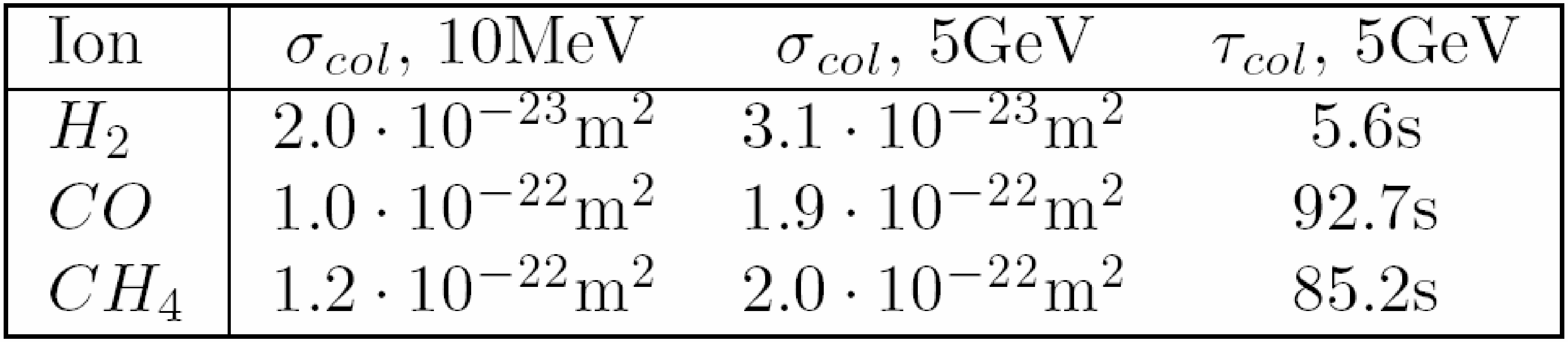
Other analyzed sources of emittance growth:

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

→ 30% of 10^{-7}m emittance

Ion accumulation in the beam potential

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.

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**)

CHESS & LEPP

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 Research

Most important things to address:

Stability issues

Beam loss and halos in ERLs

CSR and LSC suppressing designs

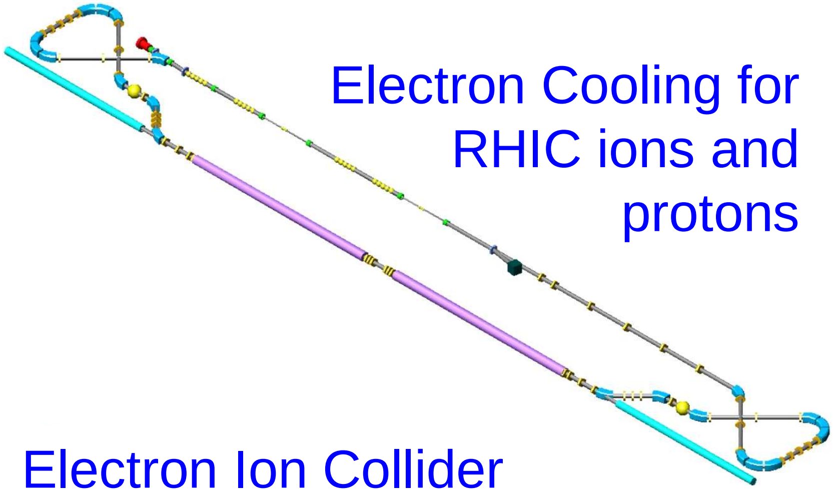
Completion of BBU test

Experimental verification of RF optics

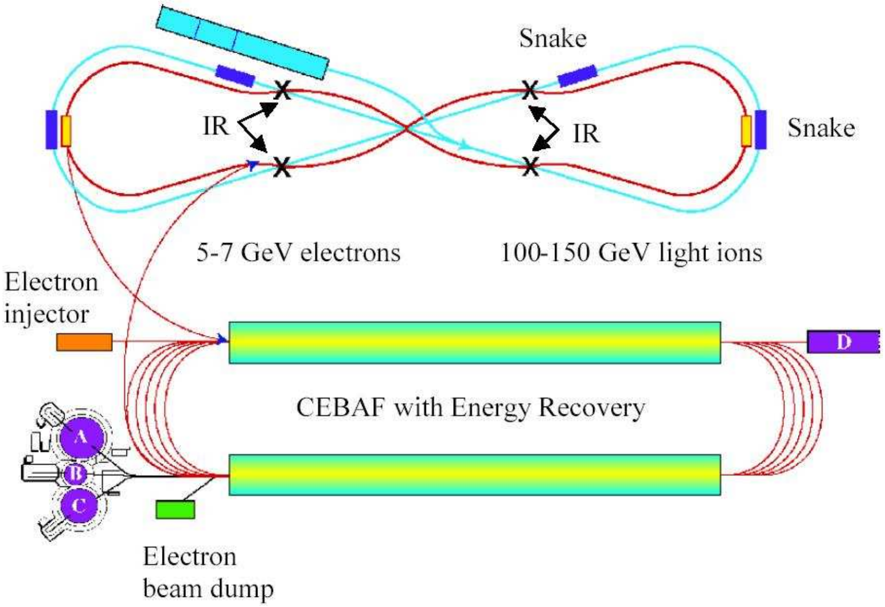
Clarification of Multi turn ERL issues

Non Light Source ERLs

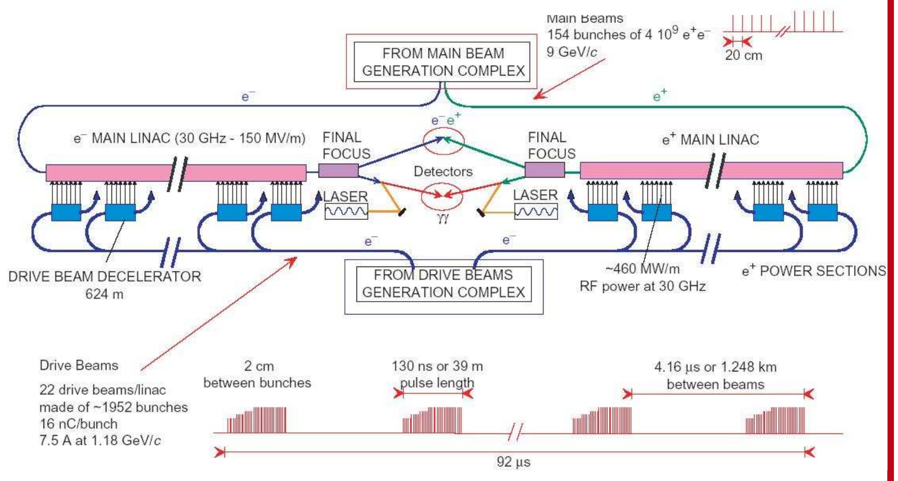
Electron Cooling for RHIC ions and protons



Electron Ion Collider



CLIC-like drive beam ERL



A low emittance RF source

Could save the electron

damping ring in a LC