Physics 417/517
Introduction to Particle Accelerator Physics

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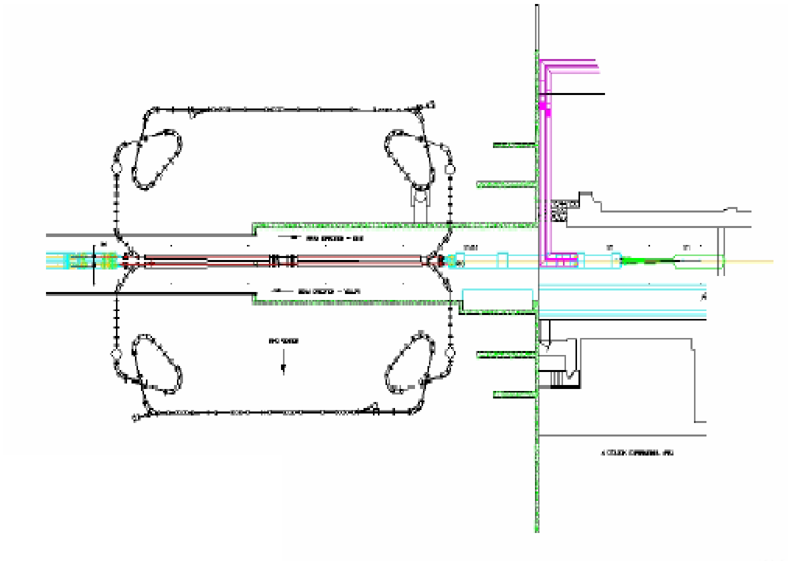
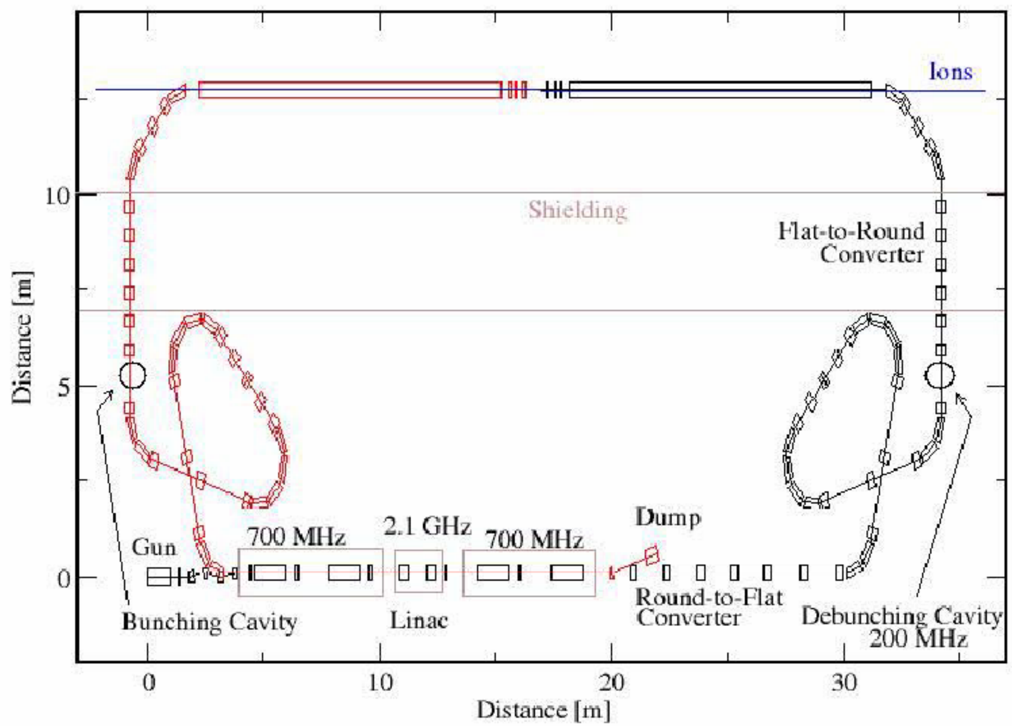
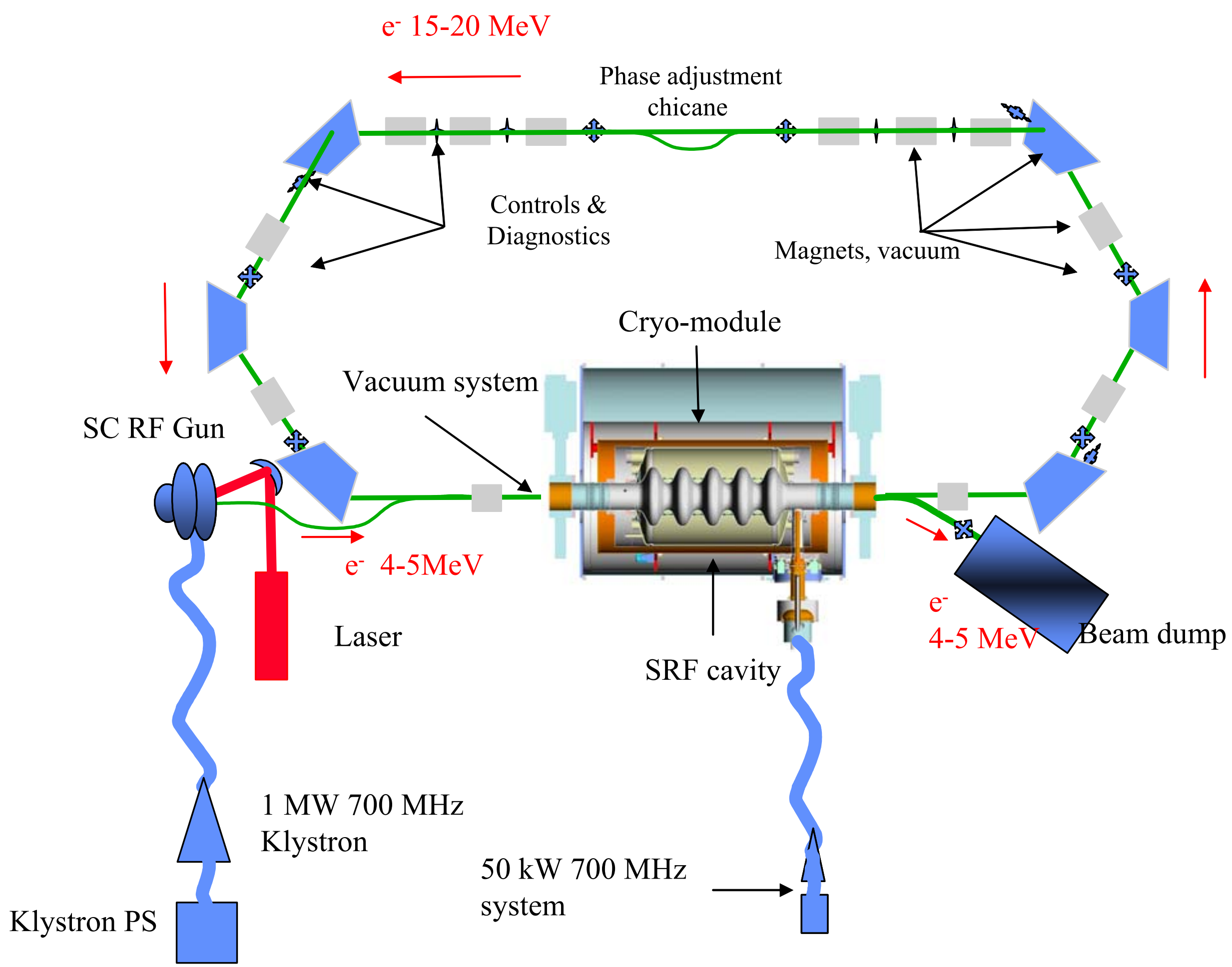
ERL-Based Electron Cooler



RHIC electron cooler is based on a 200 mA, 55 MeV ERL
20 nC per bunch, 9.4 MHz

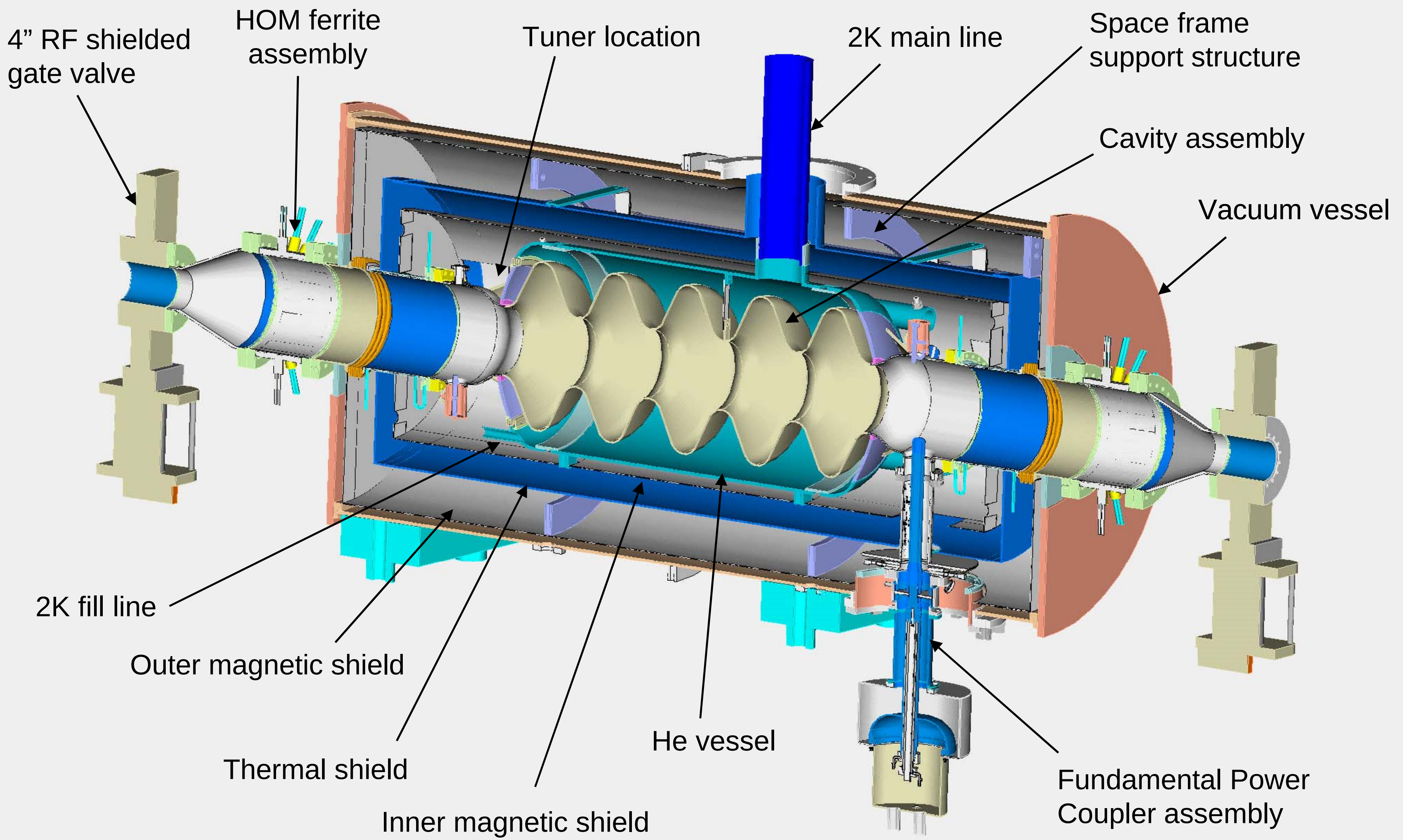


BNL ERL R&D Facility



ERL
Under construction

Cryomodule Design



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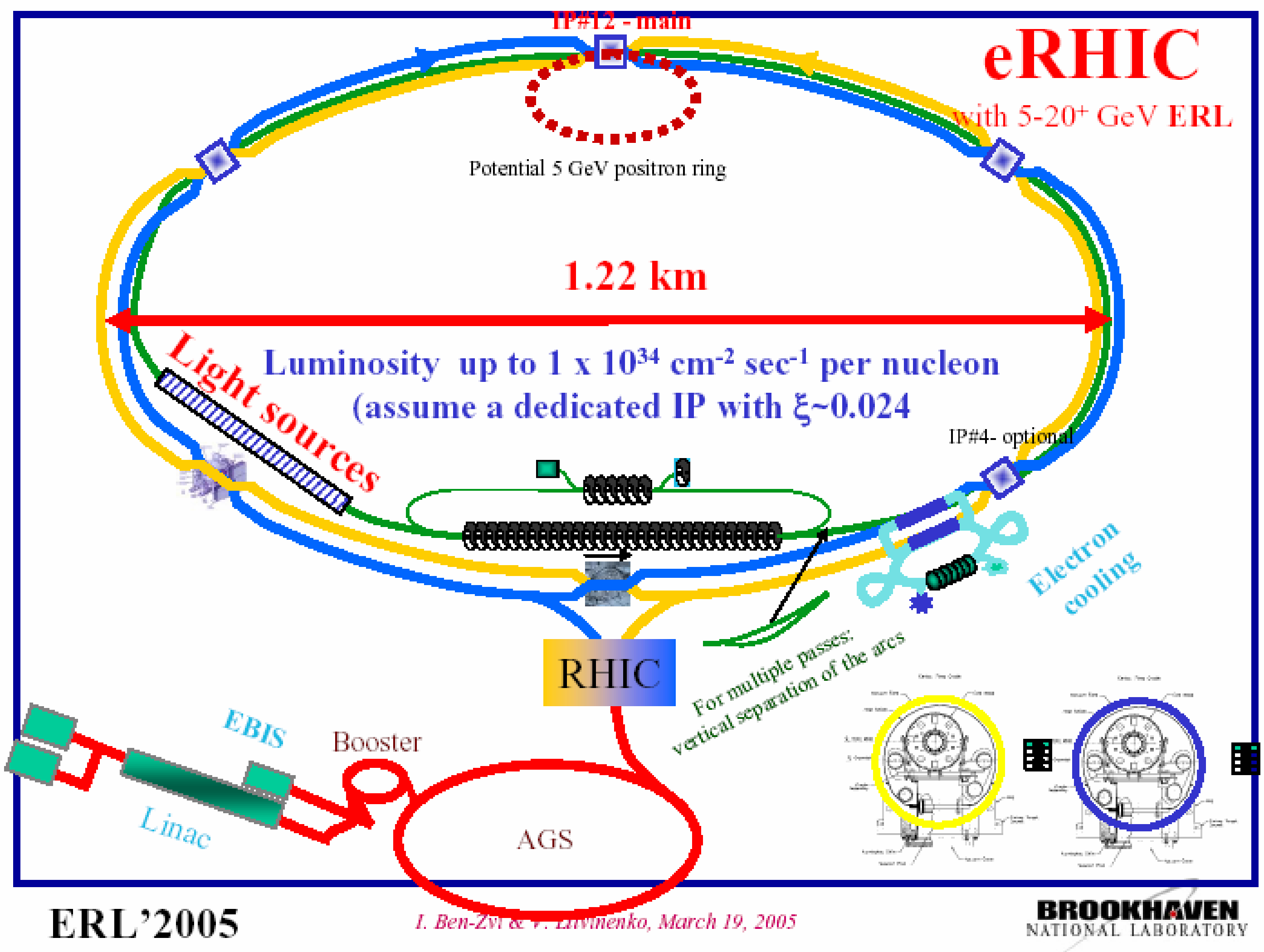
Advanced Energy Systems, Inc.

eRHIC

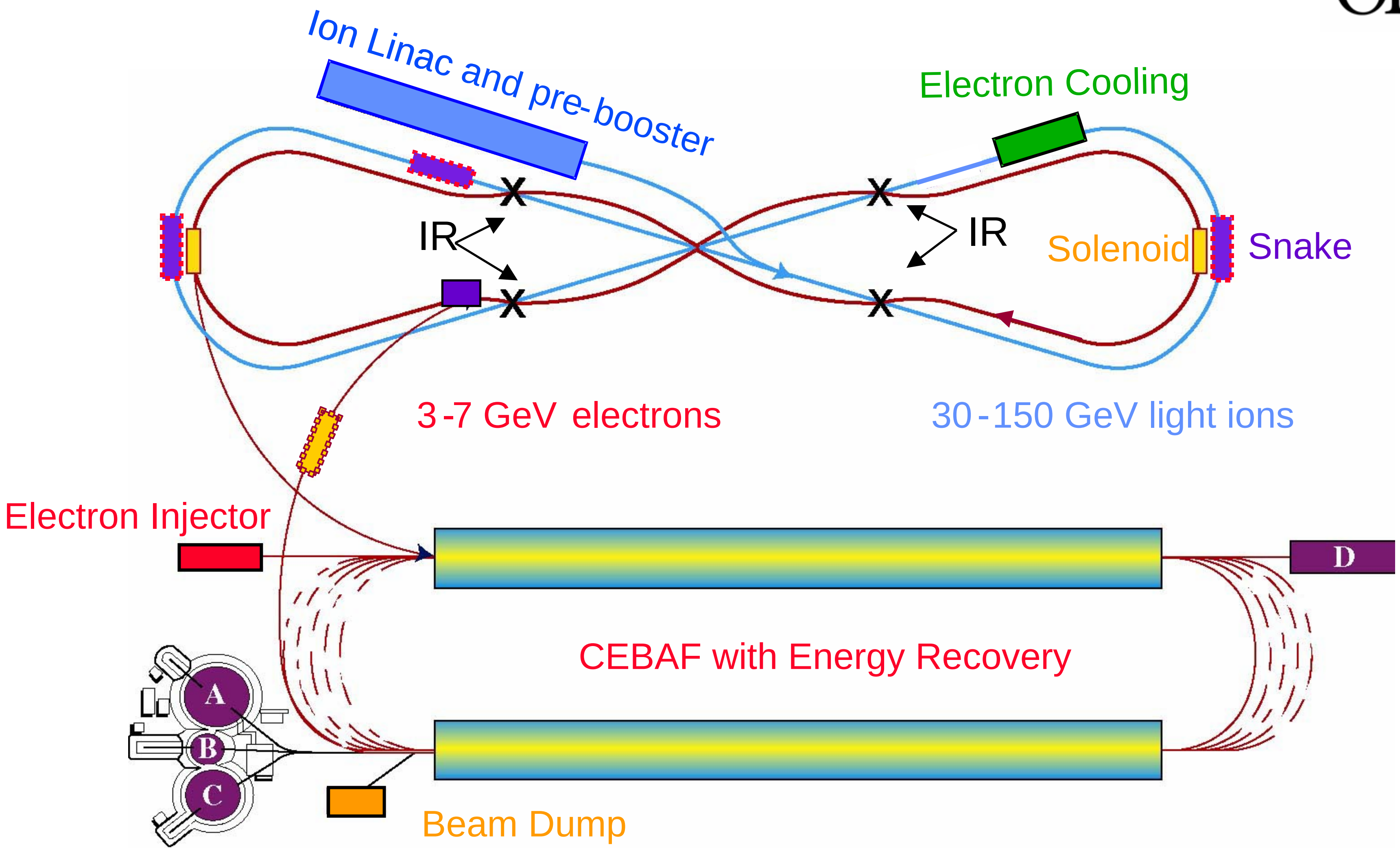

IP#12 - main
eRHIC
with 5-20+ GeV ERL
Potential 5 GeV positron ring
1.22 km
Light sources
Luminosity up to 1 x 10^34 cm^-2 sec^-1 per nucleon
(assume a dedicated IP with ξ~0.024
IP#4- optional
Electron cooling
RHIC
For multiple passes: vertical separation of the arcs
EBIS
Booster
Linac
AGS
ERL'2005
I. Ben-Zvi & V. Litvinenko, March 19, 2005
BROOKHAVEN NATIONAL LABORATORY

eRHIC Beam Parameters

RHIC	main case	*option*
Ring circumference [m]	3834	
Number of bunches	360	
Beam rep-rate [MHz]	28.15	
Protons: number of bunches	360	*120*
Beam energy [GeV]	26 - 250	
Protons per bunch (max)	$2.0 \cdot 10^{11}$	$6 \cdot 10^{11}$
Normalized 96% emittance [μm]	14.5	
β^* [m]	0.26	
RMS Bunch length [m]	0.2	
Beam-beam tune shift in eRHIC	0.005	
Synchrotron tune, Qs	0.0028 (see [2.4])	
Gold ions: number of bunches	360	*120*
Beam energy [GeV/u]	50 - 100	
Ions per bunch (max)	$2.0 \cdot 10^{9}$	$6 \cdot 10^{9}$
Normalized 96% emittance [μm]	6	
β^* [m]	0.25	
RMS Bunch length [m]	0.2	
Beam-beam tune shift	0.005	
Synchrotron tune, Qs	0.0026	
Electrons:		
Beam rep-rate [MHz]	28.15	*9.38*
Beam energy [GeV]	2 - 10	
RMS normalized emittance [μm]	5- 50 *for $N_e = 10^{10} / 10^{11}$ e⁻ per bunch*	
β^*	~ 1m, *to fit beam-size of hadron beam*	
RMS Bunch length [m]	0.01	
Electrons per bunch	$0.1 - 1.0 \cdot 10^{11}$	
Charge per bunch [nC]	1.6 – 16	
Average e-beam current [A]	0.045 – 0.45	*0.015 – 0.15*

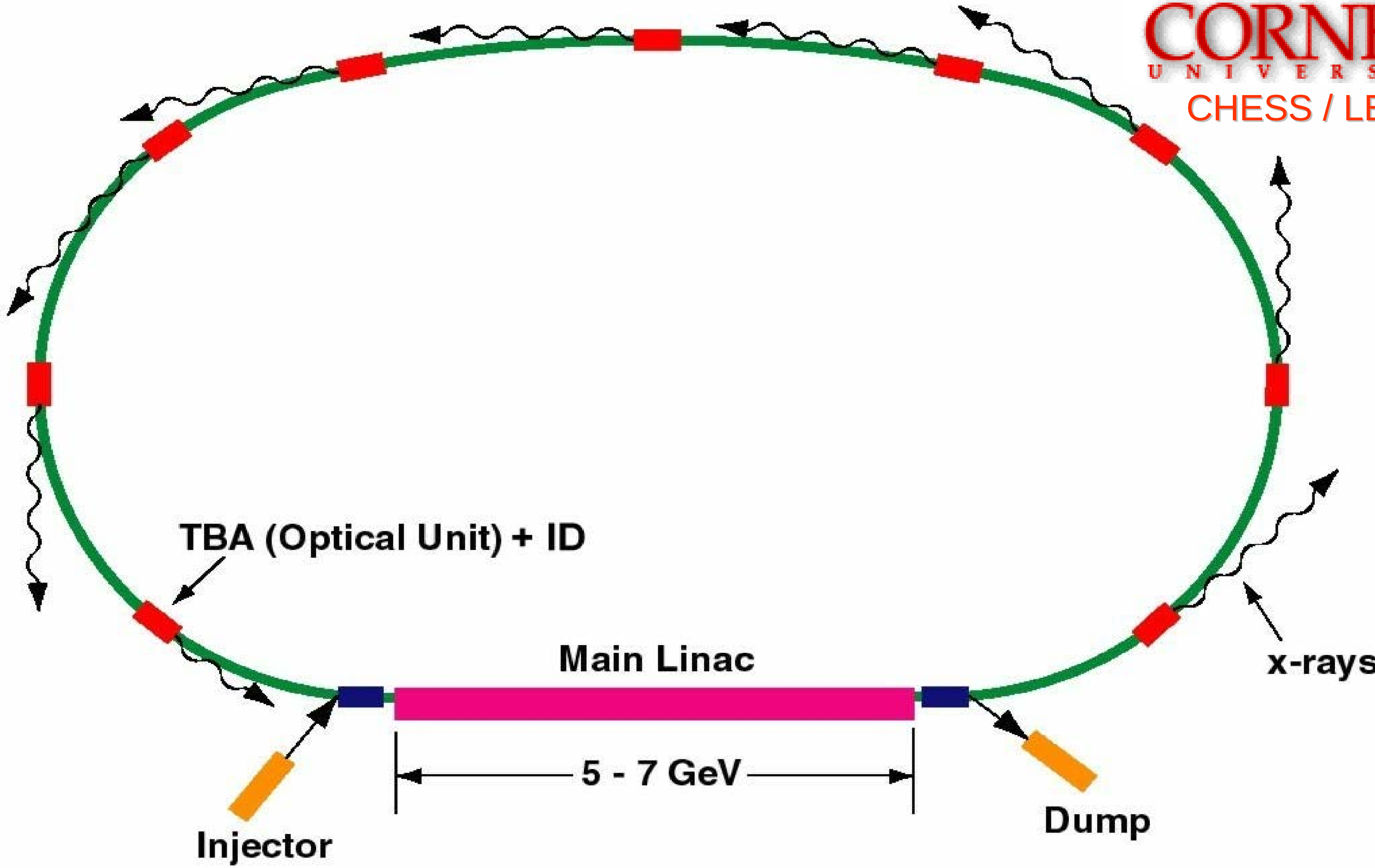
Beam parameters

ELIC Design



Ion Linac and pre-booster
Electron Cooling
IR
IR
Solenoid
Snake
3-7 GeV electrons
30-150 GeV light ions
Electron Injector
D
CEBAF with Energy Recovery
A
B
C
Beam Dump

ERL X-ray Source Conceptual Layout



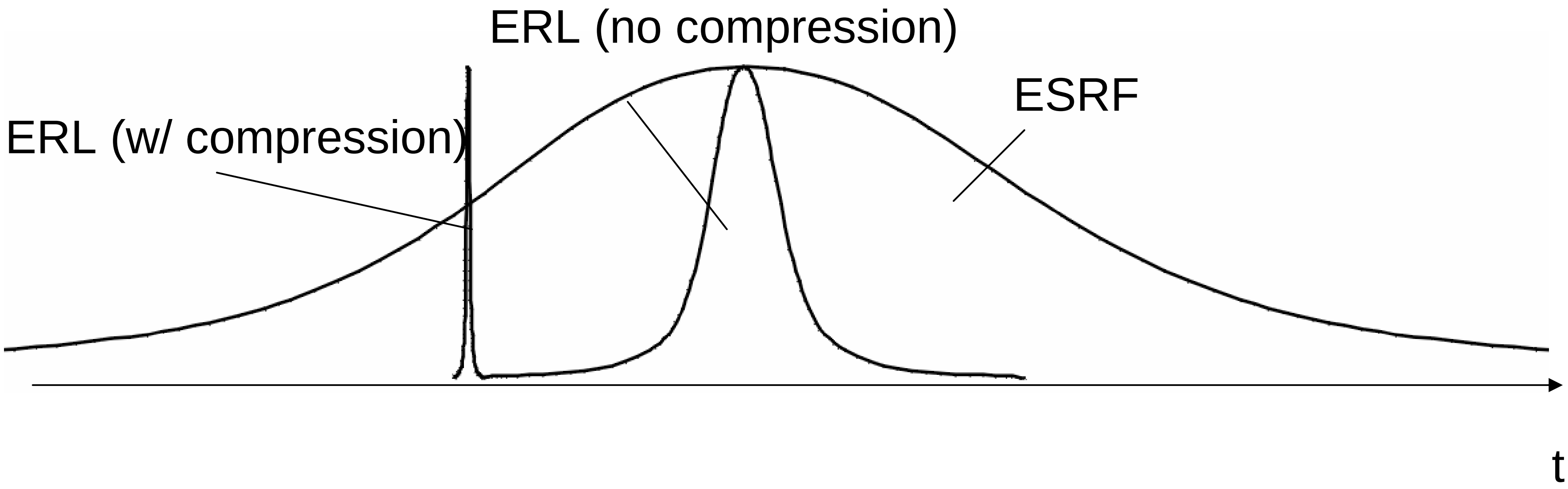
Why ERLs for X-rays?

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 on charge-per-bunch, Q, the optimum is

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

- If the "space charge/wake" generated emittance 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!
- Unfortunately, best flux at high charge

ERL Source Sample Parameters

Parameter	Value	Unit
Beam Energy	5-7	GeV
Average Current	100 / 10	mA
Fundamental frequency	1.3	GHz
Charge per bunch	77 / 8	pC
Injection Energy	10	MeV
Normalized emittance	2 / 0.2*	µm
Energy spread	0.02-0.3*	%
Bunch length in IDs	0.1-2*	ps
Total radiated power	400	kW

* rms values

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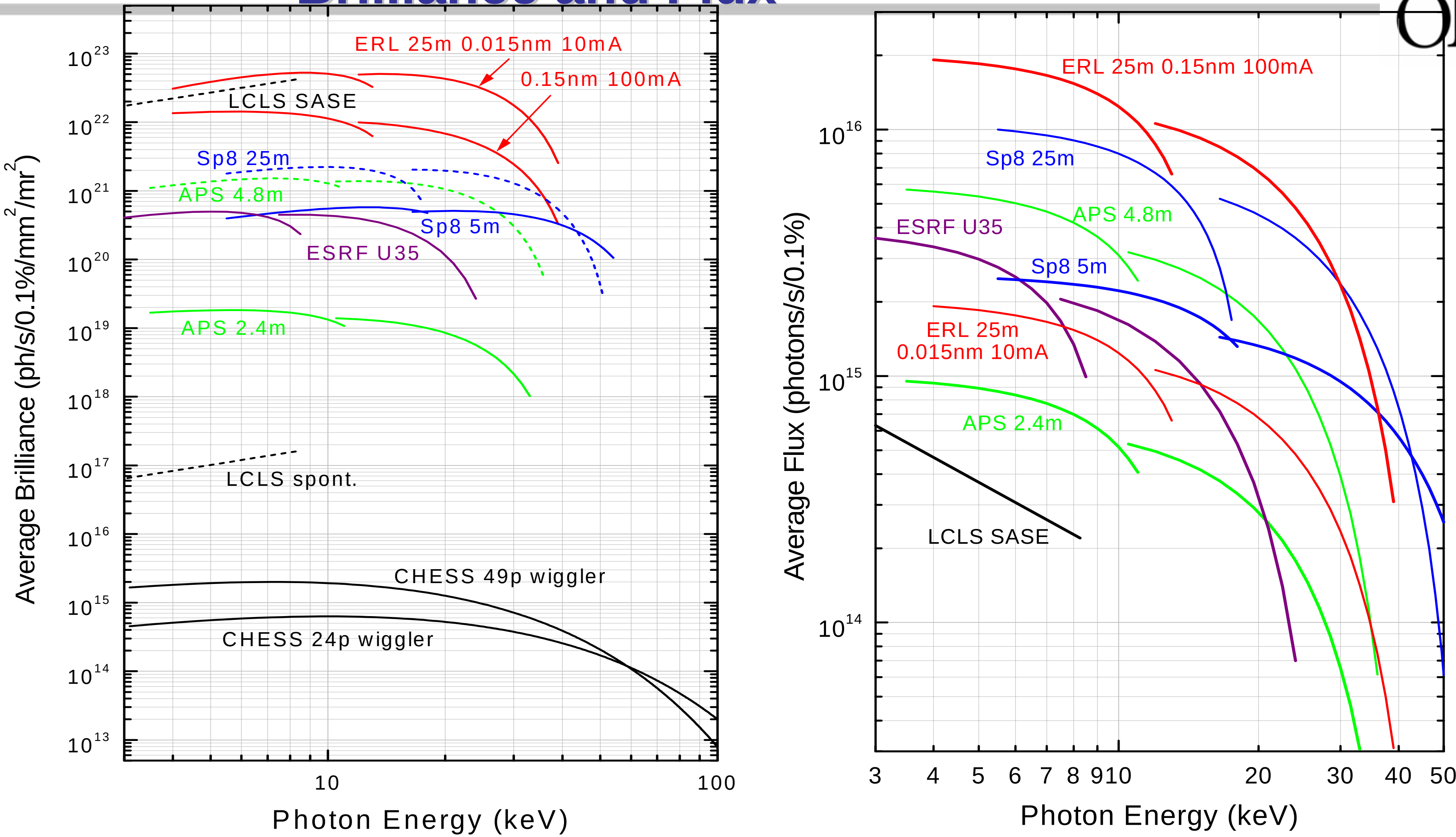
ERL X-ray Source Average Brilliance and Flux



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

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ERL Peak Brilliance and Ultra-Short Pulses

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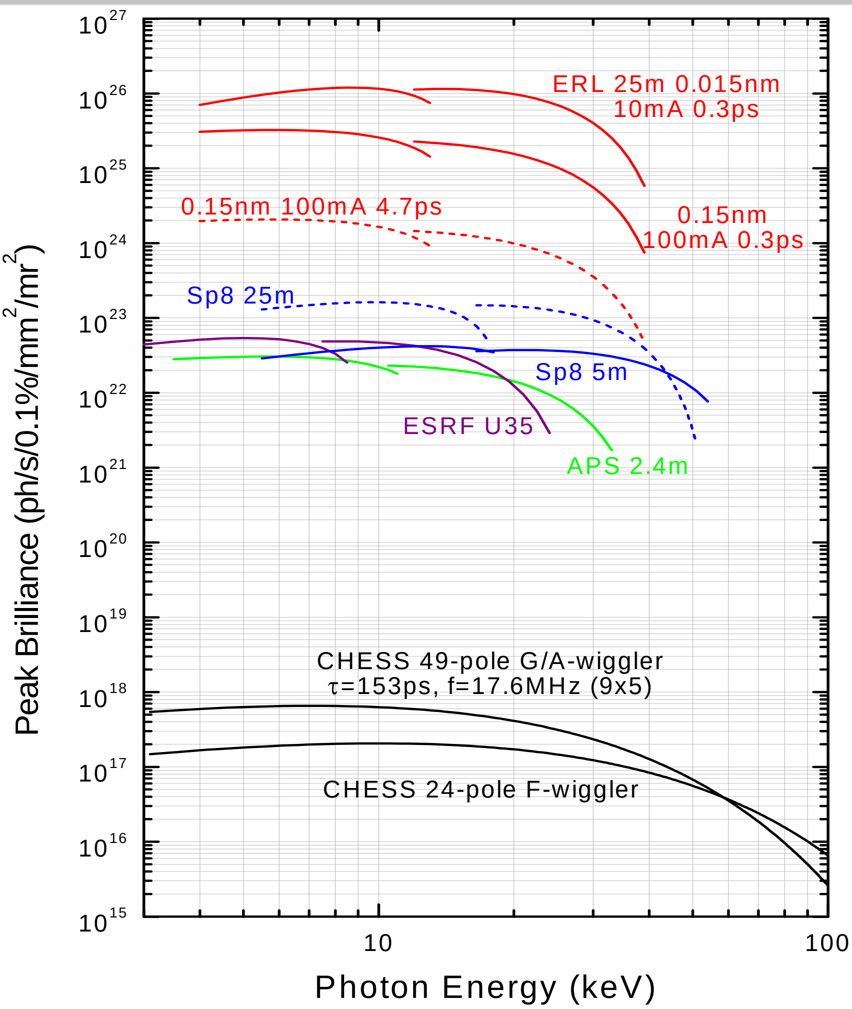
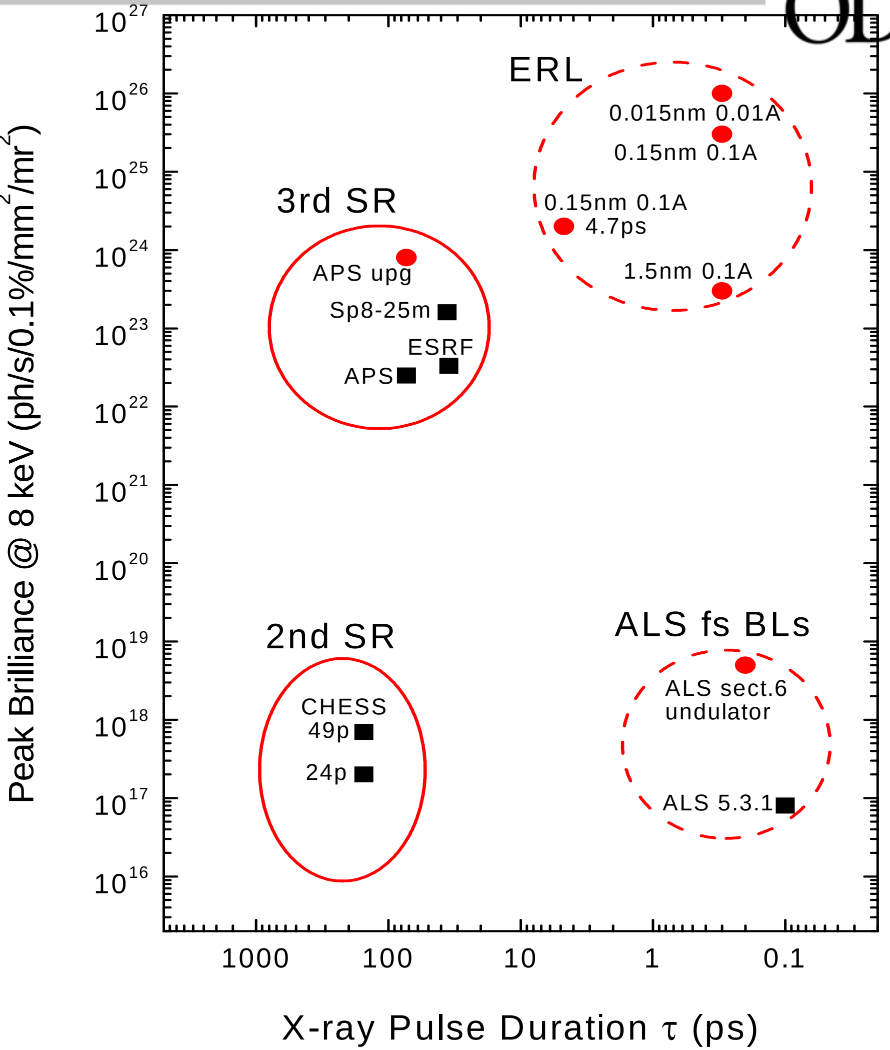
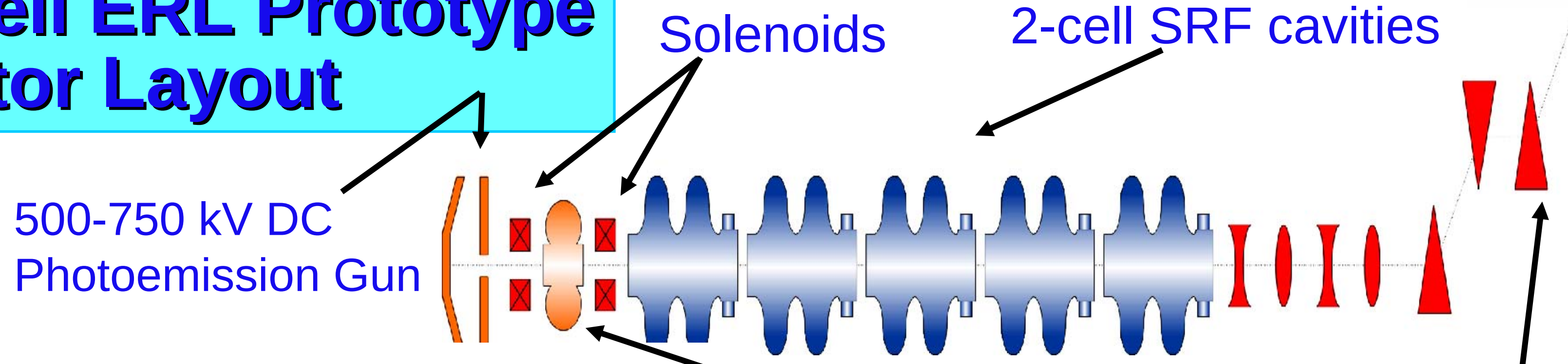




Courtesy: Q. Shen, I. Bazarov

Beyond the space charge limit

Cornell ERL Prototype Injector Layout



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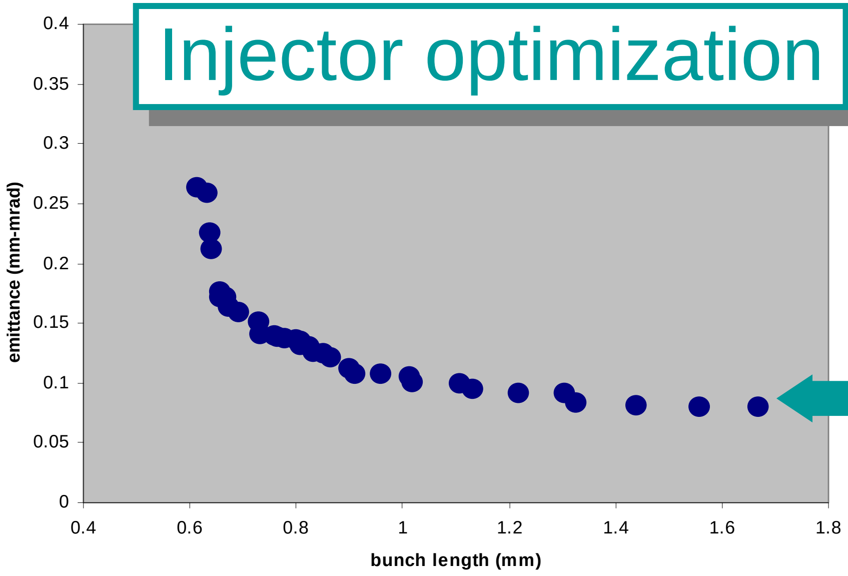
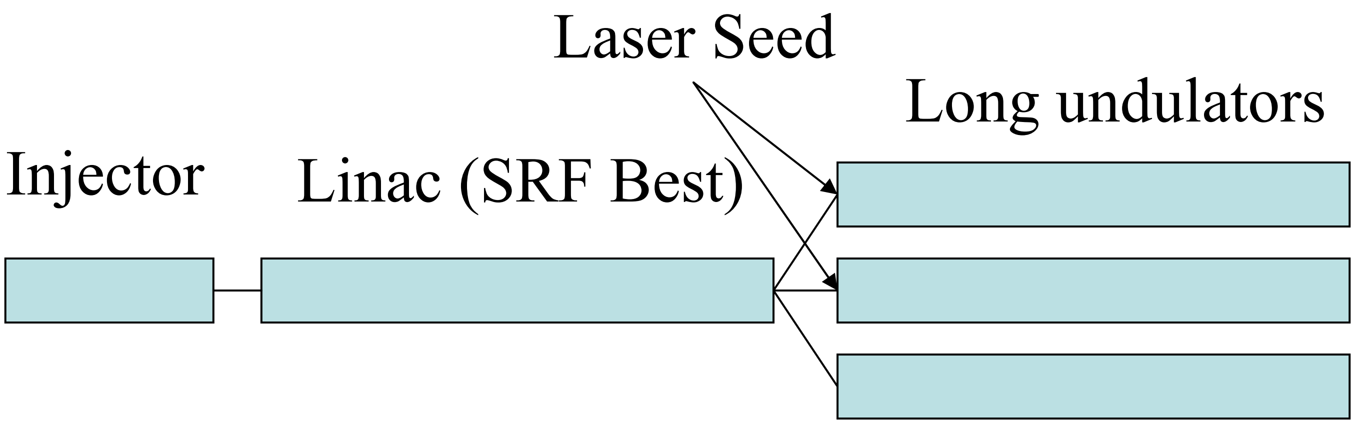
Injector optimization



0.1 mm-mrad, 80 pC, 3ps

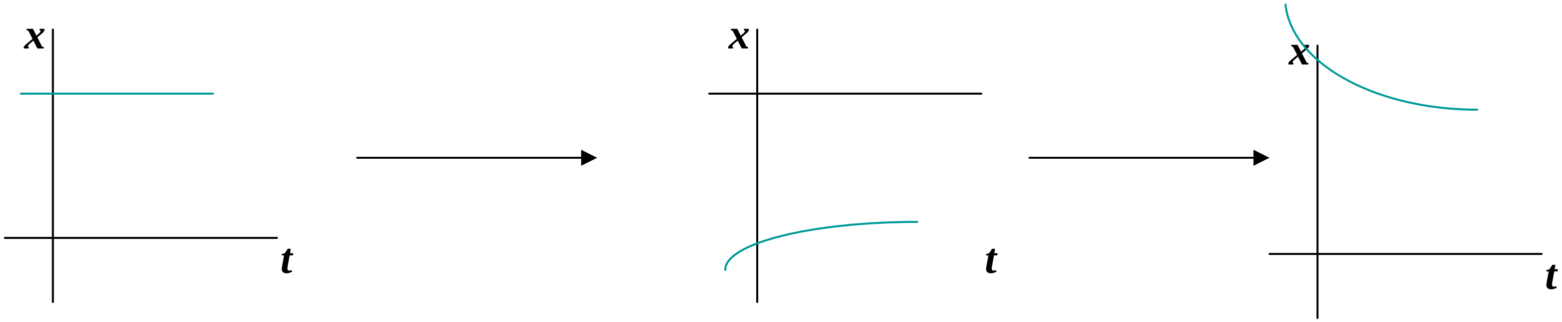
Courtesy of I. Bazarov

SASE or Seeded FEL



Single Bunch Transverse Instability*

- Analyzed by Chao, Richter, and Yao
- Displaced beam, through interactions with transverse wake in cavities, causes a transverse displacement that grows along the bunch and increases as one traverses the accelerator



- Mitigated by BNS damping and its variants (Balakin, Novakhatsky, Smirnov)

***See Krafft and Bisognano, PAC89, 1256 (1989)**

Simulation Parameters

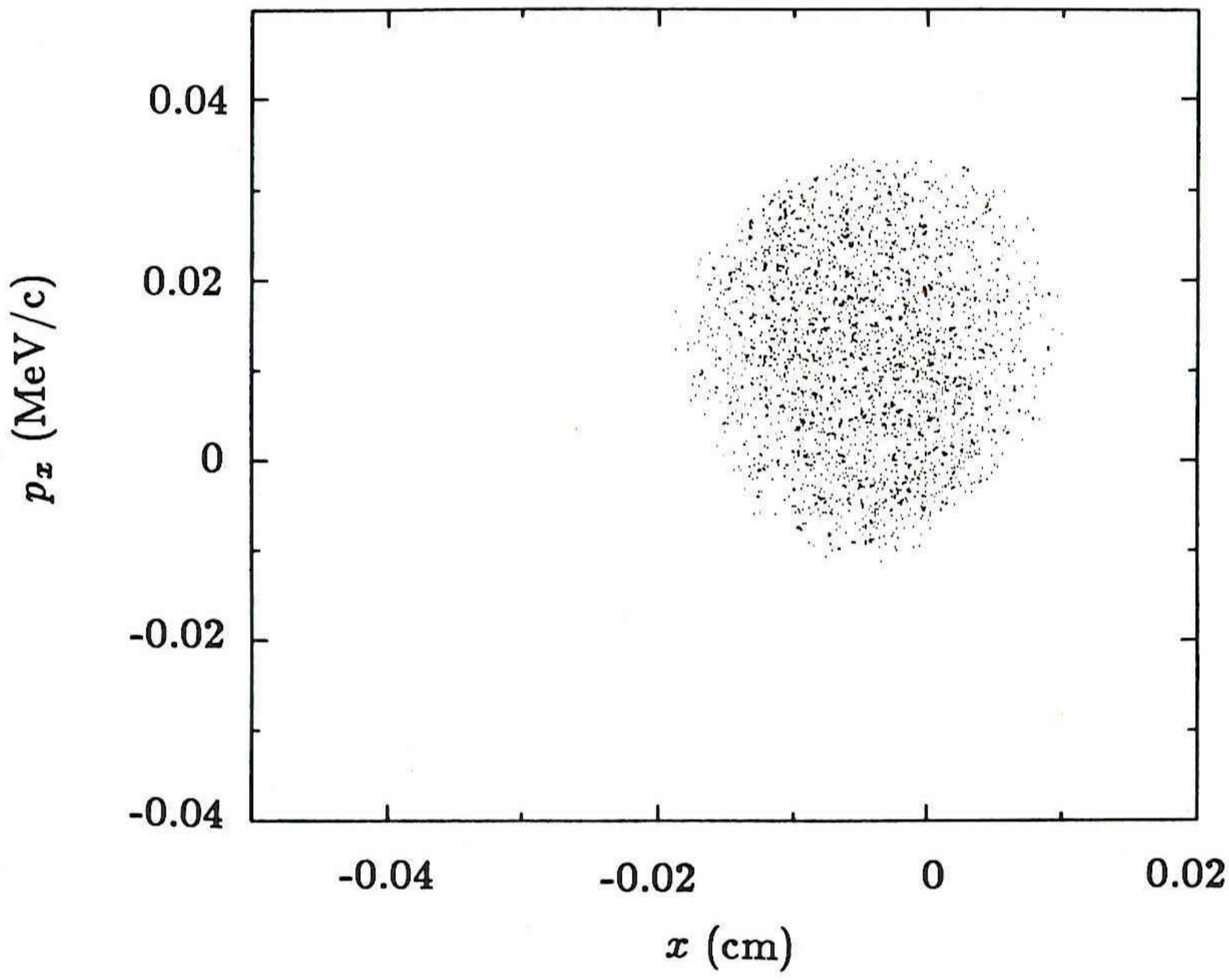
CEBAF Accelerator

Frequency	1500	MHz
Inj. Energy	45	MeV
Final Energy	4	GeV
Inj. Emittance	1	μm rad
Transverse Wake	30	V/pCcm^2
Longitudinal Wake	41	V/pC
Bunch Length	2.2	psec

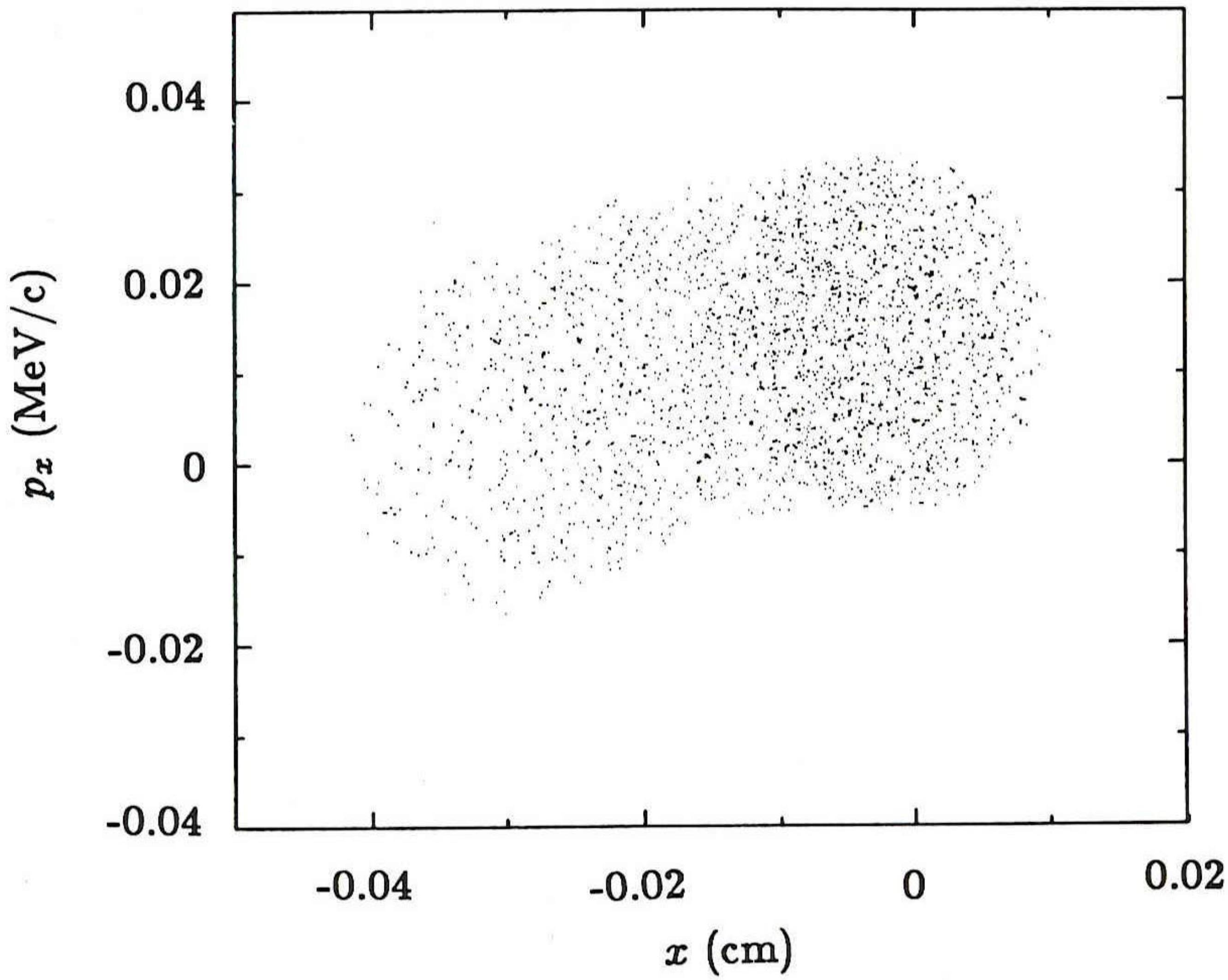
500 MHz Driver Accelerator

Frequency	500	MHz
Inj. Energy	10	MeV
Final Energy	1	GeV
Inj. Emittance	1	μm rad
Transverse Wake	0.8	V/pCcm^2
Longitudinal Wake	7	V/pC
Bunch Length	22	psec

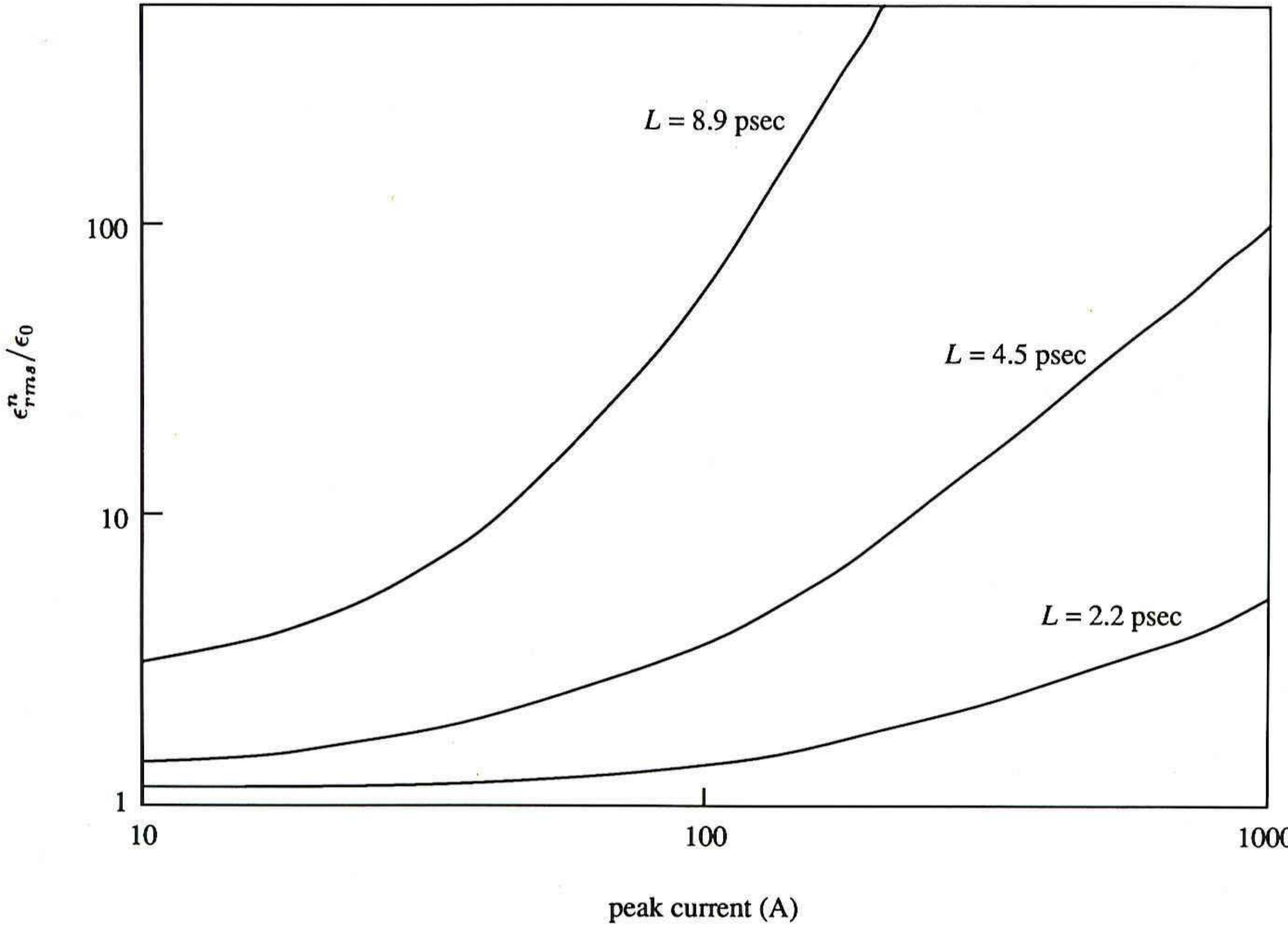
Projected Emittance: No Charge



Projected Emittance: Full Charge

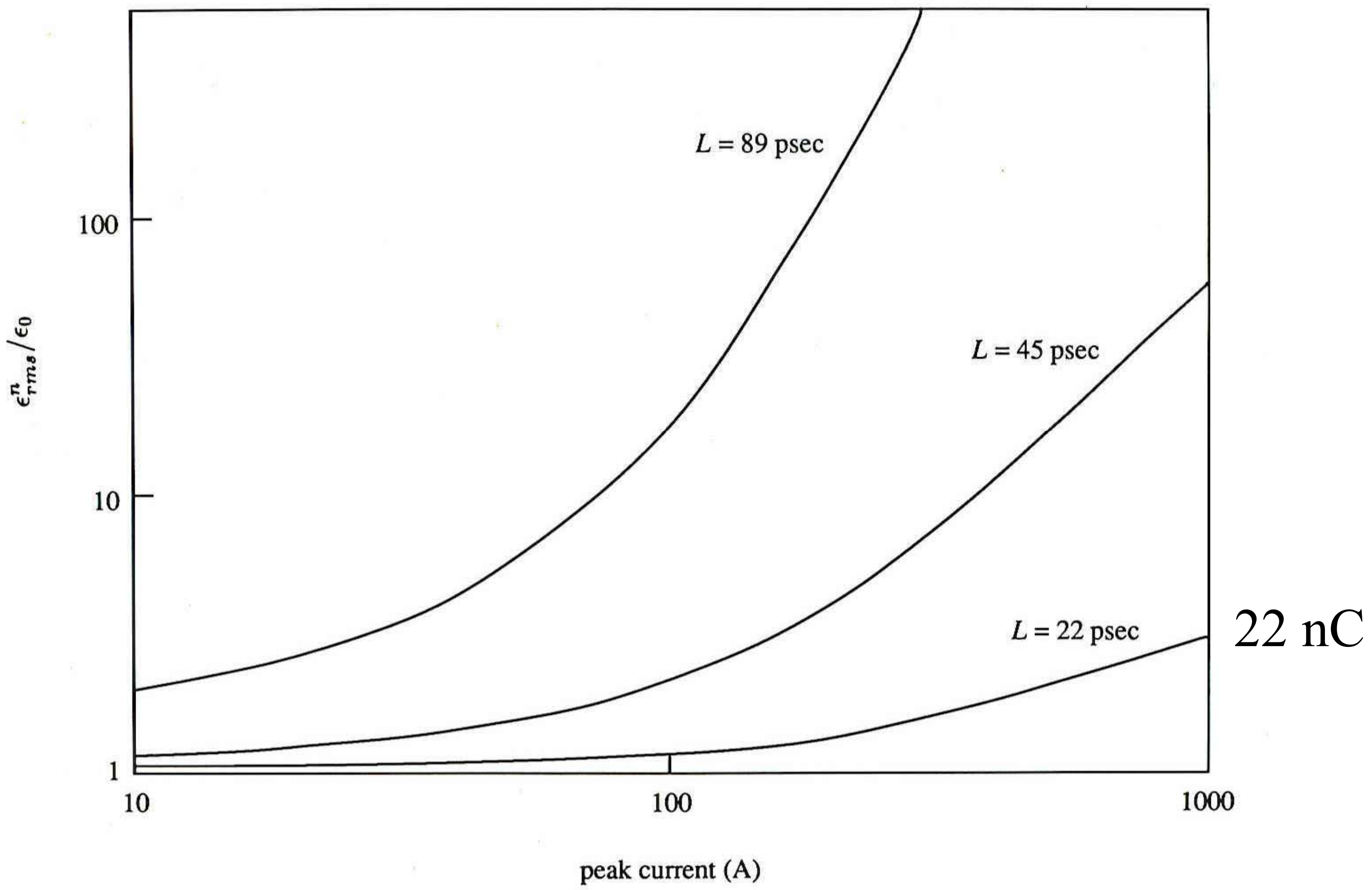


Emittance Growth for CEBAF Simulations

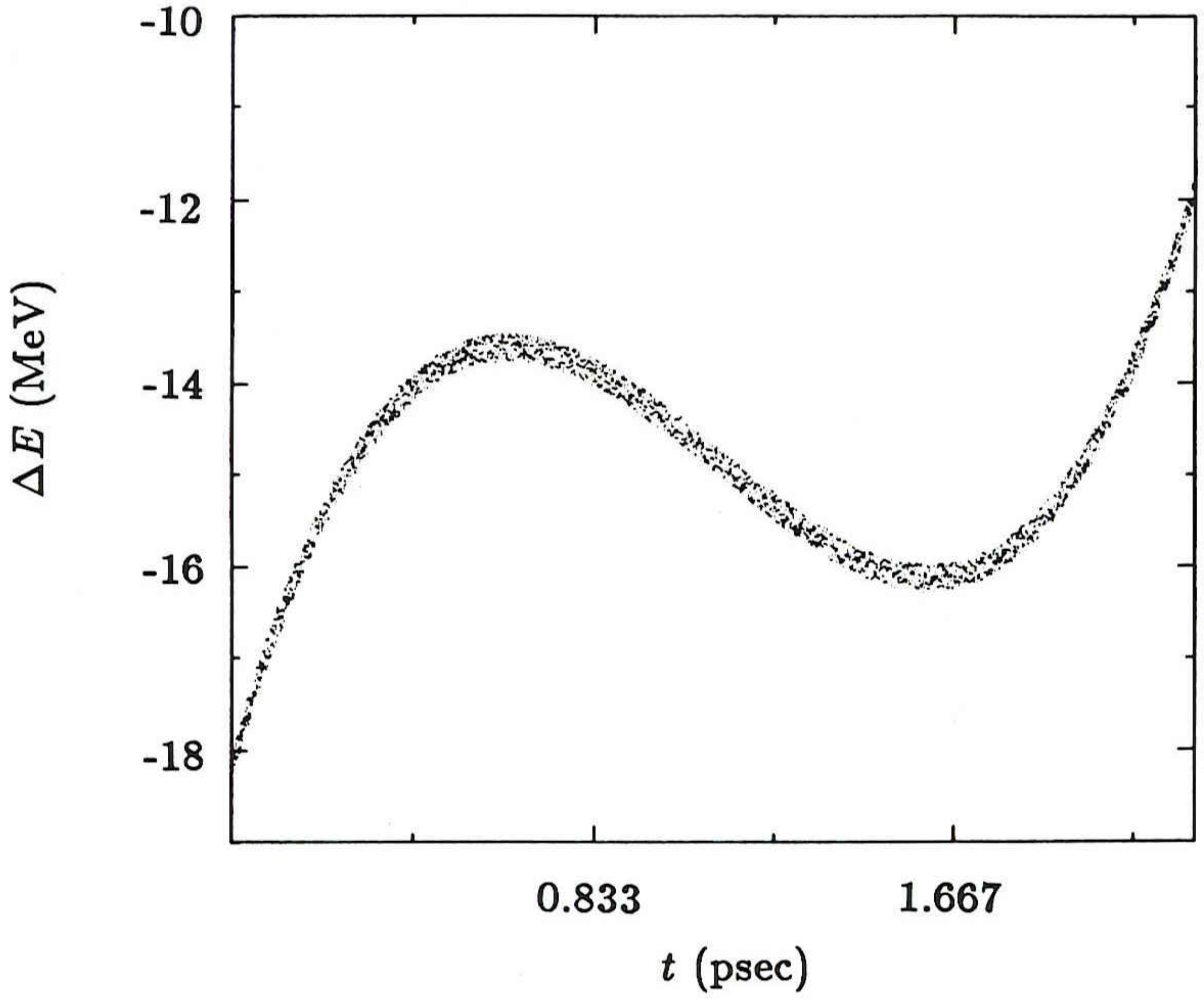


2.2 nC

Emittance Growth in 500 MHz Driver



Longitudinal Phase Space for CEBAF Simulations



Large Gain in Wake Behavior

- CEBAF could support 1 nC bunches without excessive emittance growth
- A properly designed 500 MHz system could support >10 nC without excessive emittance growth
- Other Potential Advantages of Lower Frequency
  - Because CW, will be running the accelerator at lower average gradient (15-20 MV/m) anyway. The “main” advantage of the 1300 MHz cavities becomes less important
  - Less RF parts
  - Naturally stiffer cavities and purposely extra stiff for SNS design: maybe allows higher Q_L
  - IOTs for the lower frequency?

Cooling needed for 2 GeV

cavity frequency (MHz)	1300	1300	805	805
	15 MV/m	20 MV/m	15 MV/m	20 MV/m
V_c (MV)	15.6	20.8	16.8	22.4
number of cavities	128	96	119	89
heat/cavity@Q0 10^{10} (W)	23	41	43	77
dynamic heat (kW)	3.0	4.0	5.1	6.6

This may be unduly pessimistic: If could claim better Q_0 at low frequency no reason not to prefer the lower for any SASE driver

Typical Gun Requirements

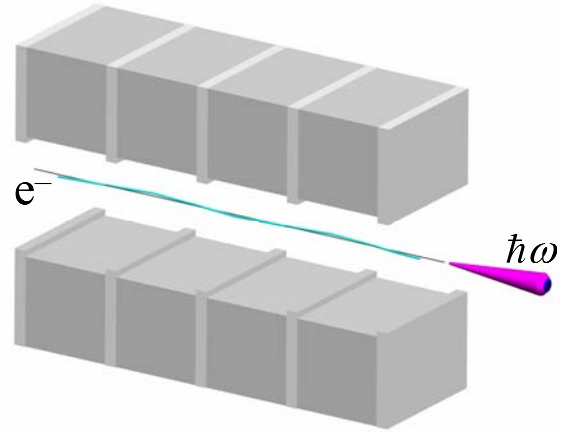
- Charge-per-bunch: order 1 nC
- Repetition rate 1 kHz $\longrightarrow$ 1 MHz recently (multiple users)
- Normalized *rms* Emittance: 2π mm mrad
- >100 kHz probably requires Energy Recovery

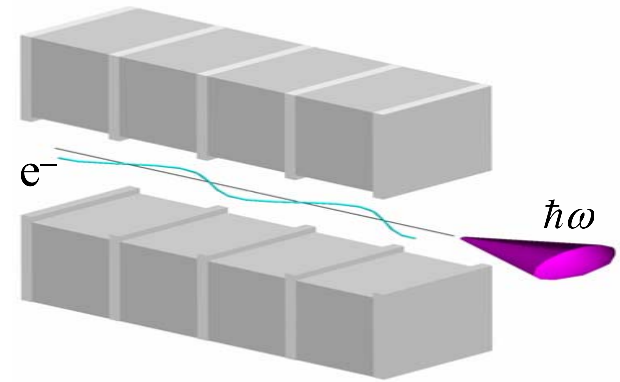
- For seeded designs: seed laser a major headache at high repetition rate. Seeding ideas limited by high rep rate high average power seeding laser needed. Usually talk about gangs, separately controlled by each user.

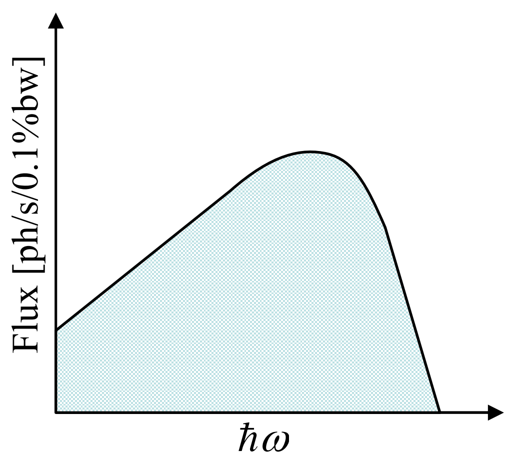
Compact Source Drivers

- Various applications of compact drivers
  - Positrons
  - THz
  - Compton X-rays
  - High average current injectors
  - Etc.
- Key R&D activity: small self-contained cooling systems
- University Scale?
  - Best tended in universities?
  - ODU Center for Accelerator Physics

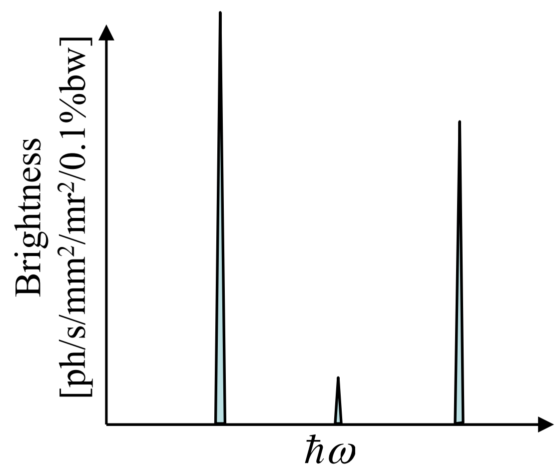
Bend | Undulater | Wiggler



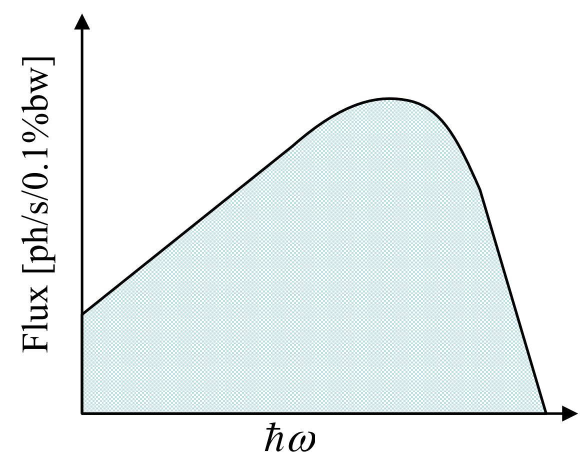




white source

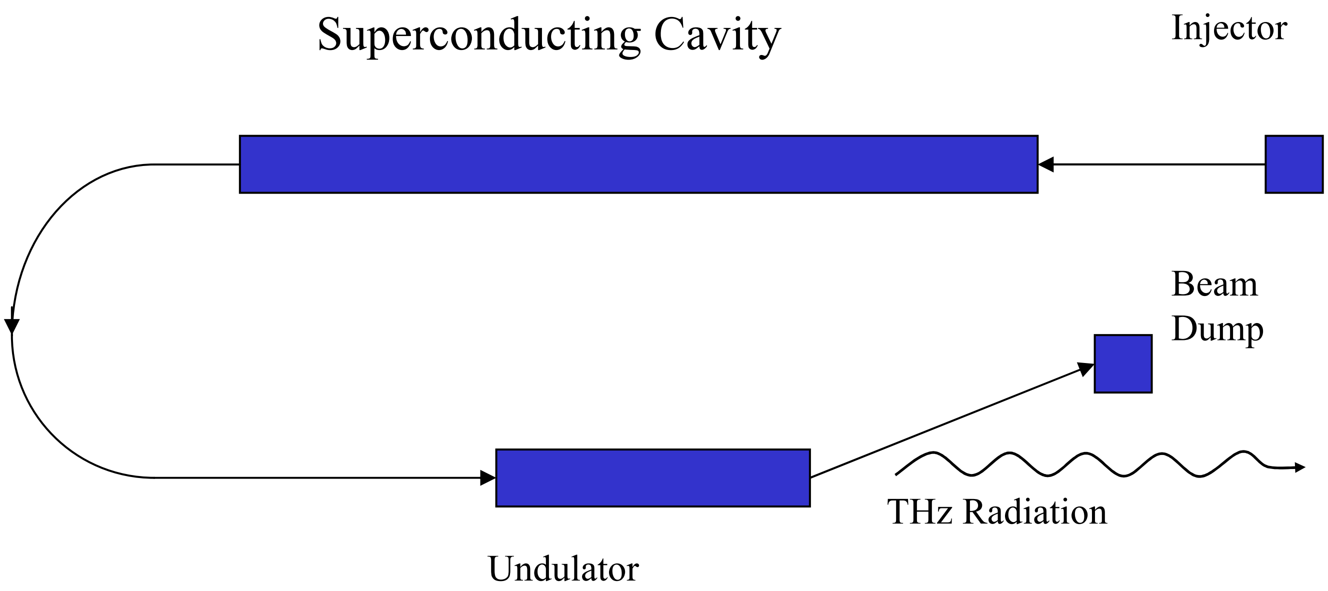


partially coherent source



powerful white source

Compact THz Source



U. S. Patent 6,753,662 assigned to Jefferson Lab

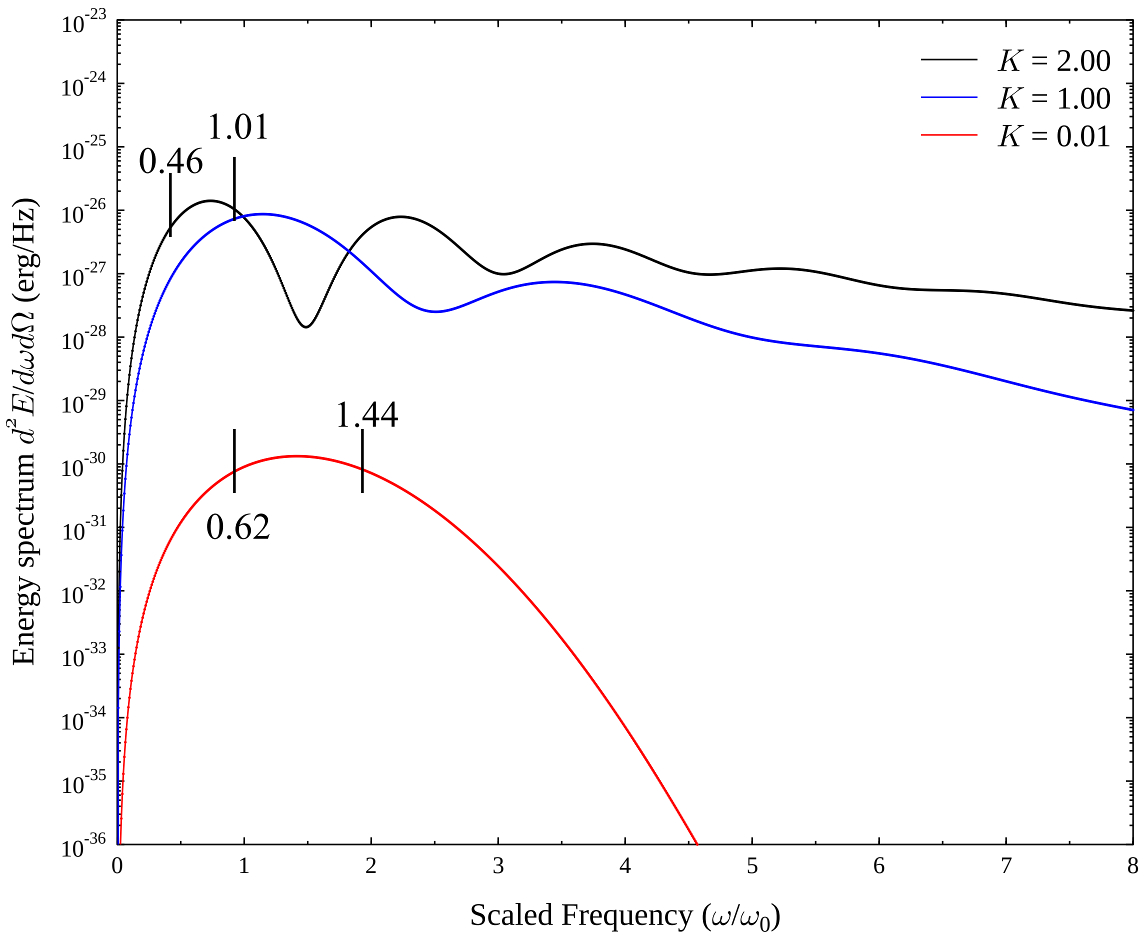
THz Source Accelerator Parameters

Quantity	Value	Unit
Beam Energy	8.8	MeV
Average Beam Current	225	μA
Charge per Beam Bunch	100	pC
Bunch Repetition Rate	2.25	MHz
Normalized *rms* Beam Emittance	5	mm-mrad
Longitudinal *rms* Emittance	10	keV-degrees
rms Bunch Length at undulater	300 (90)	fsec (μm)

Undulator and Optical Parameters

Quantity	Value	Unit
Undulator		
Length Parameter σ	4	cm
Wavelength of Maximum Power	0.3	mm
Maximum Field B_{max}	1160	G
Field Strength, $K = eB_{max}\sigma / mc^2$	2.7	
Fundamental Optical Power	10	W
Fundamental Flux at Max	1×10^{19}	photons/sec in 0.1% BW
Optical Pulse Length	80	μm

Forward Emission Energy Spectrum



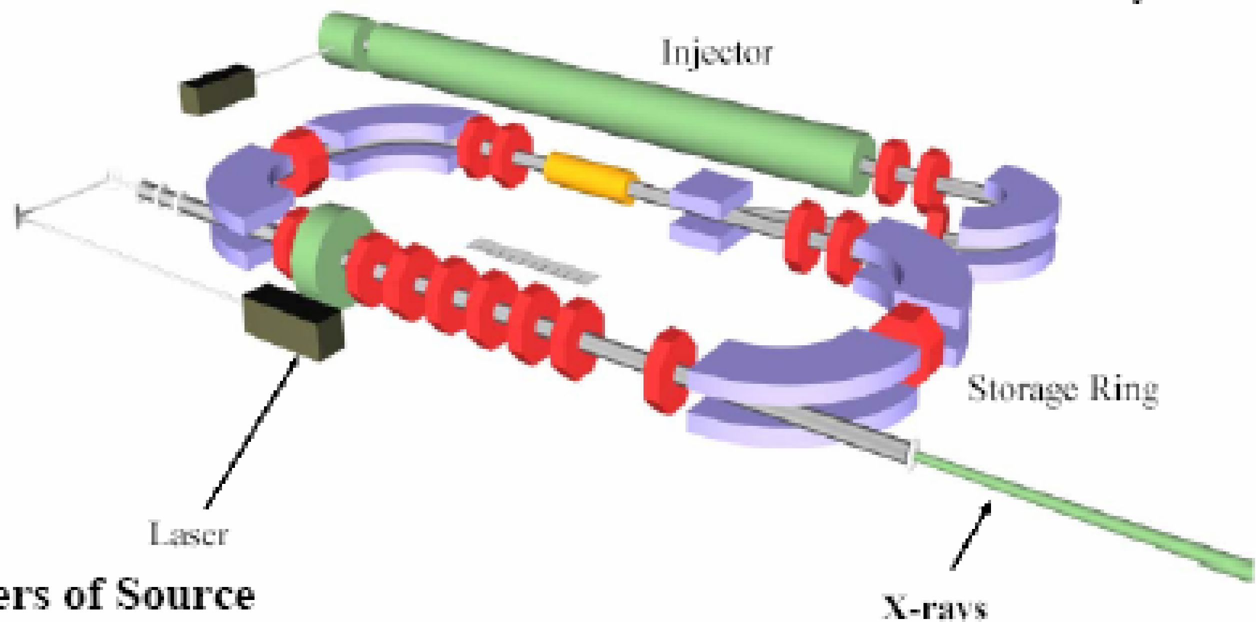
$$\omega_0 \approx 2\gamma_0^2 c / \sigma$$

Lyncean Technologies Compact Source Concept

A Conceptual Picture of the CLS

(The 30 cm ruler in the middle is shown for scale.)

Courtesy of Ron Ruth



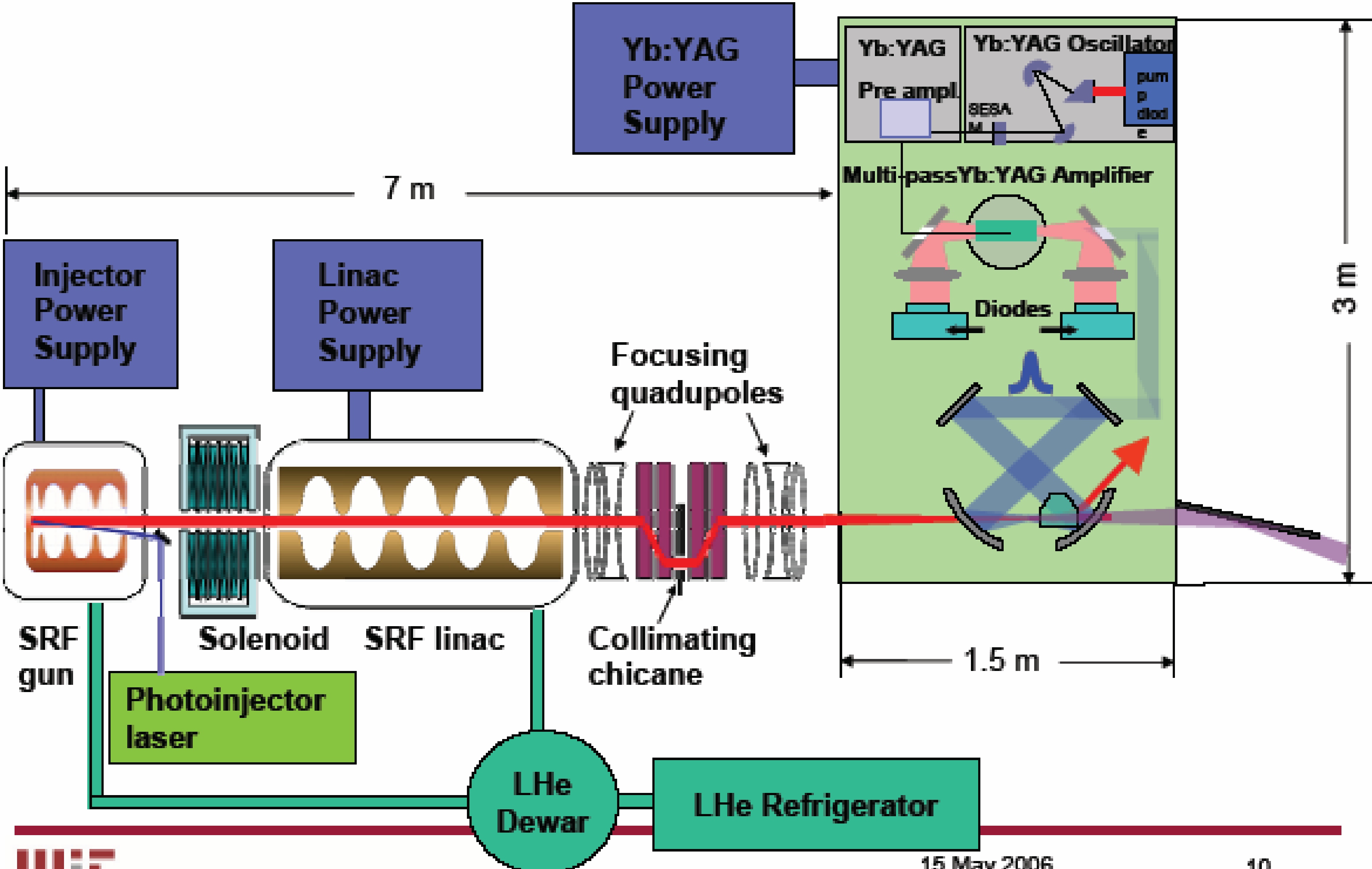
Parameters of Source

Average flux 10^{12} photons/sec

Source size 100 microns

"This is not a good time now for us to present results because we are in the middle of tune up"—5/11

MIT Inverse Compton Source Concept



Advantages of an SC Linac: Low Emittance, Short Pulses, High Rep Rate

- Like conventional synchrotron beams, the figures of merit for Inverse Compton Sources will be flux and brilliance (brightness).
- High performance will depend on achieving low electron emittance, short pulses, and high time-average currents (and excellent laser properties as well).
  - **Low Emittance:** Normalized electron emittance may approach 0.3 μm. With electron energies of 25 MeV ($\gamma = 50$) the electron beam emittance would be 6 nm—comparable to APS (3 nm)!
  - **Short Pulses:** Pulse durations below 1 ps will enable full advantage to be taken from the low emittance beams
  - **High Current:** Superconducting linac-driven Inverse Compton Sources will employ photo-cathode guns operating at 10 MHz with 0.1 nano-coulomb charge. Currents of 1 milli-amp are generated.
- SC linacs outperform storage rings, and are more reliable.
- They are the next generation ICS after the Lyncean machine

Parameters of Various "Compact" Devices

Specifications	NPA Injector	CTHz	Diffraction Source	PC Gun	ILC Gun	Compton	Positrons	Light Source	NP App.	ERL	Parameter Ranges
Current (mA)	1-2	0.1	Source	<100	0.1	1	10	Max. Possible	1-2	Max Possible	0.1-100
Beam Energy (MeV)	10	<10	2	0.5	0.12-0.30	10	10	10	50	50	10--50
Bunch Charge (pC)	NA	10	100	1000	6400	100	100	0-1000	NA	100	1-1000
Trans. emittance (mm mrad)	20	10	1	5		2	20	0.1-1	20	10	0.1-20
Bunch Length (ps)	NA	1	NA	50	2000	0.5	NA	0.1	NA	1	0.1-10
Rep. Rate (MHz)	>7.5 kHz	10	MHz OK	1500	3 MHz, 1ms@5 Hz	10	1000	1500	>7.5 kHz	1500	0.01-1500
Long. emittance (keV psec)	30	5	5			5	30	2	30	5	1-30
Polarization	No	No	No	Yes	Yes	No	Yes	No	No	No	

Conclusions

- For SASE FELs, it may be quite beneficial to consider operating at lower frequencies (<750 MHz). The penalty, with the present performance of SNS cavities as a guide, is increased cooling by perhaps 50%, but the advantages are reduced cavity and other parts count, better wake-field performance, and easier RF sources at lower frequencies. With Q_0 higher than 2×10^{10}, has a cooling advantage.
- ERL light sources prefer higher SRF frequencies. Coherence enhanced by lower charge-per-bunch more frequently.
- Interesting compact source drivers could be assembled without much R&D now, given a customer willing to actually pay.