Broad Update on the Progress towards Future Light Sources, Including R&D Progress

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The objectives of this presentation

- As the title says: "Broad Update" – (of a broad topic!)
  - This leaves no room for details
  - This meeting and presentation aims to inform
    - Participants
    - Funding agencies
- The presentation is also intended to stimulate the discussion that follows.

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Vitaly Yakimenko

Material arranged by subject, not by person / laboratory

Outline

The objectives of this presentation:

- What are the future light sources (FLS)?
- Recent milestones towards future light sources
- Recent progress in R&D
- Where do we go from here? Discussion.

The LCLS is the present! What is the future?

A. Borrowing from Herman Winick: Any light source that improves on current light sources by two orders of magnitude in some parameter.

B. Quoting Tsumoru Shintake:

(1) Near future: Multi-bunch in a pulse train, splitting into multi FEL lines.

(2) More compact machines. He believes 100 m total length is possible.

(3) Far future --> Ring FEL

What is a possible FLS?

C. Quoting Claudio Pellegrini:
   1. Short pulse; Terawatt X-ray; Compact FEL; Specialized FELS
   2. LCLS is just the beginning of coherent X-ray sources. Using tapered undulators the peak brightness can be increased by another factor of a thousand. Results on beam emittance and compression at low bunch charge, few to tens pC, demonstrate the feasibility of compact, fs-to-as FELs, including fully coherent single SASE spikes. FELs designed for short pulses or small line-width can be optimized to reduce cost and improve capabilities.

D. Quoting Evgeny Saldin:
   1. Full transverse coherence and Fourier limited
   2. Terawatt level peak power
   3. Tunable bunch length from sub fs to 100 fs
   4. Claim: All possible with present performance

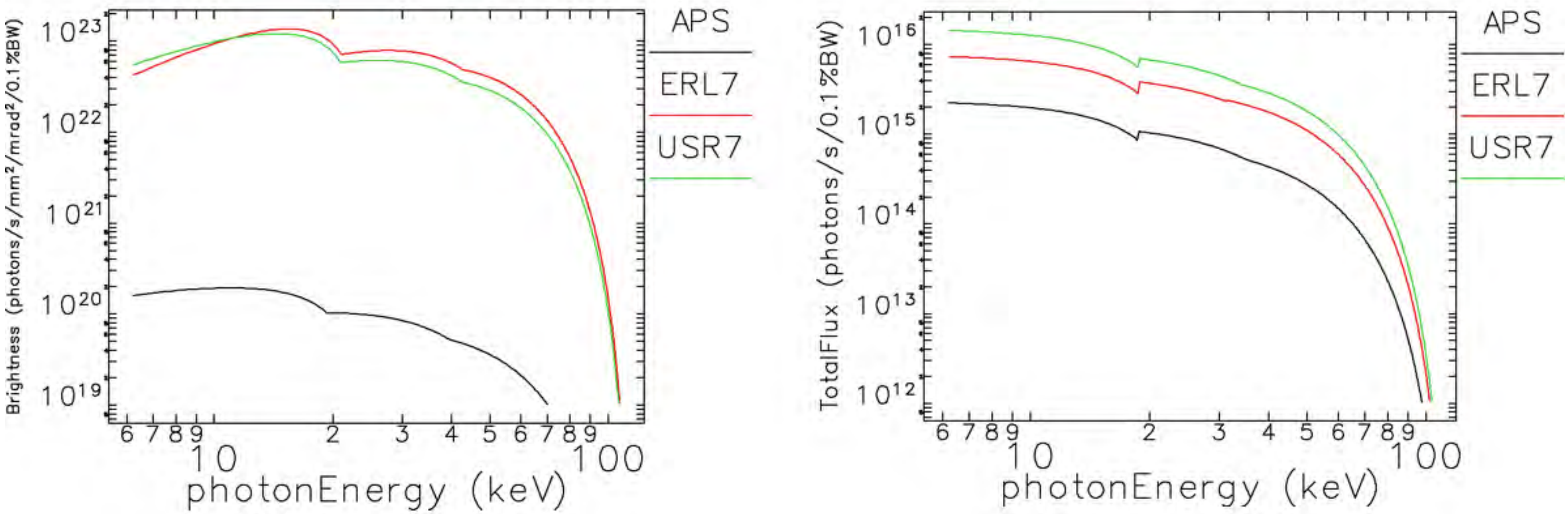
X-ray FEL Performance: †Present and Future

Parameter	Now	Future
Photon energy (keV)	Up to 10	**Up to 100**
Pulse repetition rate (Hz)	≤ 120	10^2- **$\geq 10^6$**
Pulse duration (fs)	~2-300	**<1-1000**
Coherence, transverse	diffraction limited	diffraction limited
Coherence, longitudinal	not transform limited	**transform limited**
Coherent photons/pulse	$2x10^{12}$-$3x10^{13}$	10^9-**10^{14}**
Peak brightnes	10^{33}	10^{30}-**10^{34}**
Peak/average power (W)	$7x10^{10}$/~1	**> 10^{12}/$\geq 10^3$**
Average brightness	$4x10^{22}$	10^{18}-**10^{27}**
Polarization	linear	**variable, linear to circular**
Stability – intensity/energy RMS	3-15%	**< 3%**
Stability – time (fs) RMS	50	**< 5**
Stability – % mode size	10%	**< 10%**

† @ Bob Hettel

Present day technology carried to the future:

Ultimate Storage Rings Promise Dramatic Brightness Increase



- Storage ring technology continues to advance (PETRA-II, NSLS-II, MAX-IV)
- USRs promise diffraction-limited performance at ~8 keV
  - Round beams with 10~20 pm emittance in both planes and 100~300mA average current
- Ideal for experiments that cannot use/tolerate high peak brightness
- Comparable to projected ERLs, but with many more high-brightness end-stations

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@ Michael Borland

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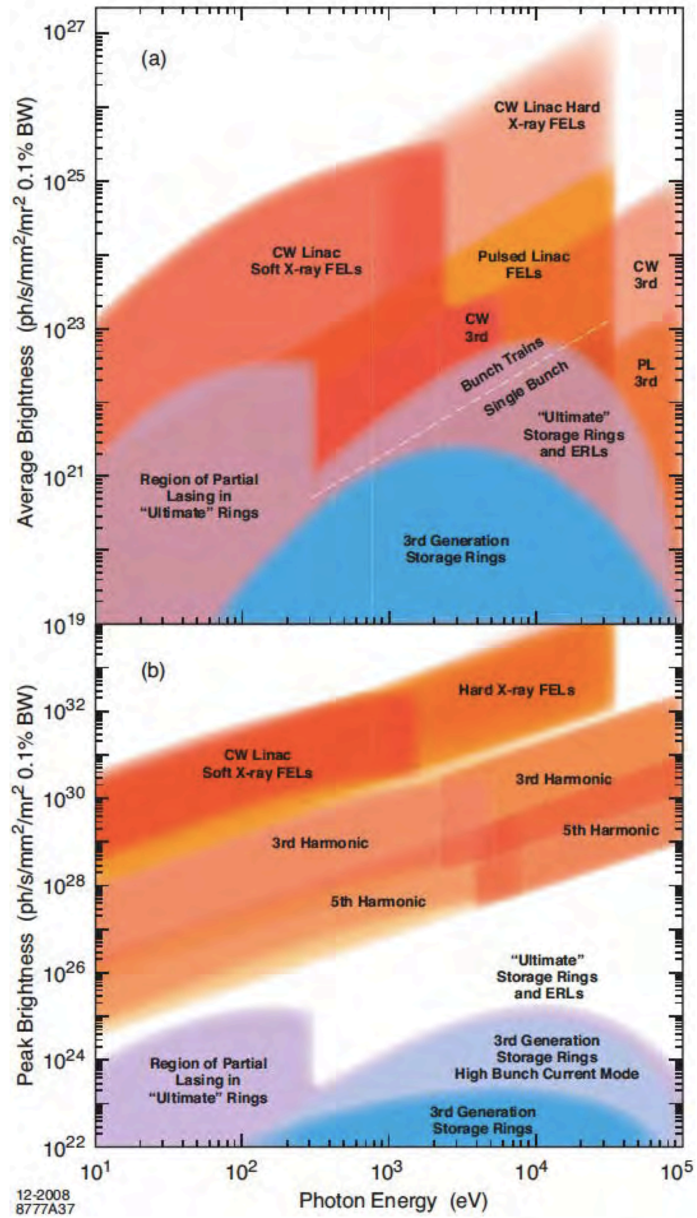
What performance is required?

- An outstanding guide to what we should ask from a FLS, starting with the science questions, can be found in Ref. [1], (Science and Technology of Future, Light Sources, A White Paper, December 2008, ANL; BNL; LBNL; SLAC.)
- The reports states "We have concluded that the nation's scientific needs will not be met entirely by current facilities and those under construction"
- Essential New X-Ray Capabilities:
  1. X-Ray Time Structure—Complete Control of Longitudinal Phase Space – (reach attosecond; Fourier transform limited)
  2. Full Transverse Coherence
  3. High Average Flux and Brightness
  4. Tunability, Polarization Control, and Extended Photon Energies

Realistic outlook in the 10-20 years time –frame [1]

- Ultimate performance is predicted for CW FELs, for both peak brightness and average brightness.
- Saldin, based on LCLS achievements and his calculations, says: "With very high repetition rate at XFEL and nominal charge mode of operation (0.25 nC) fully coherent output leads to 10^{37} peak brilliance and (very important) 10^{28} average brilliance. … for baseline parameters…"



[1] Science and Technology of Future Light Sources, A White Paper, December 2008, ANL-08/39; BNL-81895-2008; LBNL-1090E-2009; SLAC-R-917, Arthur L. Robinson and Brad Plummer, editors.

Observation by White Paper [1]:

- One may be led to conclude that all future sources should be FELs. The situation is however considerably more complex... Many experiments will be unable to exploit the high average brightness of an FEL, because they will be overwhelmed by the huge peak brightness.
- **This sounds to me like R&D Challenge.**

Claudio's wish list for 5th generation

Photon energy, keV	0.1-100
Pulse repetition rate, HX	10^2-10^6
Pulse duration, fs	<1-1000
Coherence, transverse	Diffraction limited
Coherence, longitudinal	Transform limited, L_{bunch} to $L_{cooperation}$
Coherent photons/pulse	10^9-10^{14}
Peak brightness, ph/mm^2 mrad^2 0.1% bandwidth	10^{30}-10^{34}
Average Brightness	10^{18}-10^{27}
Polarization	Variable, linear to circular

@ Claudio Pellegrini

Progress towards FLS

- Based on the introduced requirements, consider:
  - Multi-bunch into multiple FEL lines.
  - High average brightness.
  - Compact machines.
  - FEL oscillators.
  - Full transverse coherence.
  - Transform limited.
  - Short, tunable length pulses.
  - Terawatt peak power.
  - Extended photon energy range.
  - Polarization control.

What is the required accelerator and FEL physics and technology?

- High-brightness electron sources.
- High repetition rate, including ERL.
- Multiple beam lines.
- Seeding techniques (including self-seeding).
- Bunch compression to attosecond.
- Temporal diagnostics and timing.
- Short period undulators.
- Synchronized laser / high power THz radiation
- Compact – low cost (dedicated?) schemes
- Beam line / detector (not covered here).

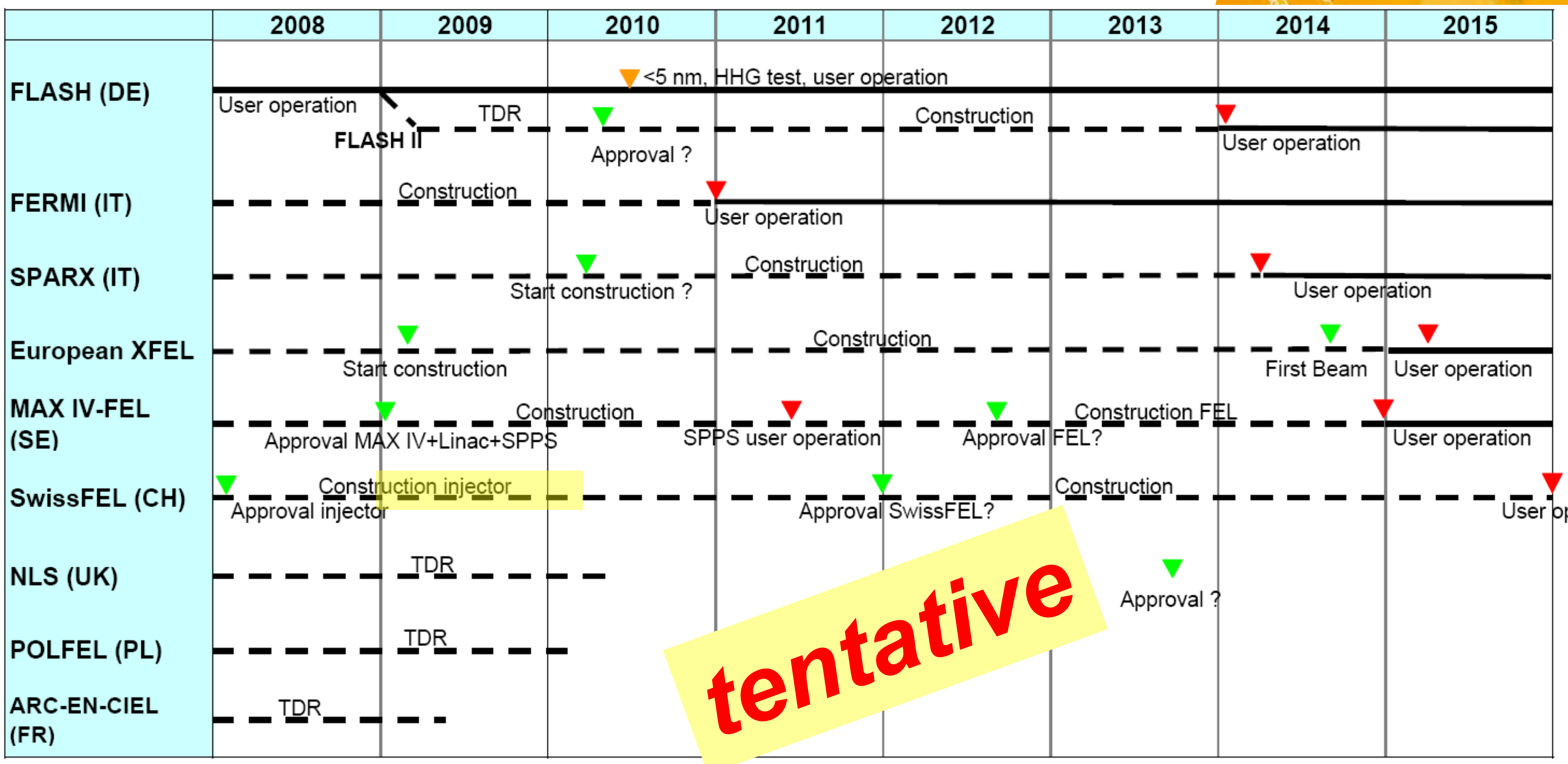
International program

- A lot of facility and R&D activities overseas.
- FLASH continues to be very productive.
- SACLA lased.

FEL projects in Europe

Two European FEL projects are on the ESFRI roadmap

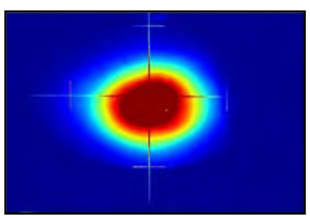
- **European XFEL: GmbH, international shareholders**
- **EuroFEL: consortium of national FEL facilities**

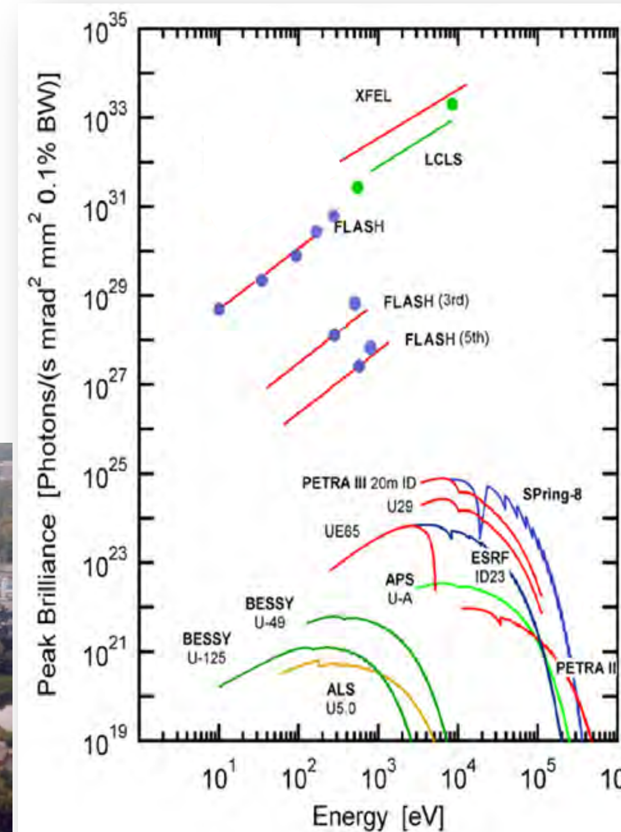


@ Josef Feldhaus

FLASH at DESY in Hamburg

- High-gain SASE FEL
- Photon from VUV to soft X-rays
- Femtosecond pulses with high brilliance
- User facility since Summer 2005
  - 1st period: Jun 2005 – Mar 2007
  - 2nd period: Nov 2007 – Aug 2009
  - 3rd period: Sep 2010 – Sep 2011
  - 4th period: scheduled for 2012
- 2nd undulator in preparation
  - construction start Autumn 2011





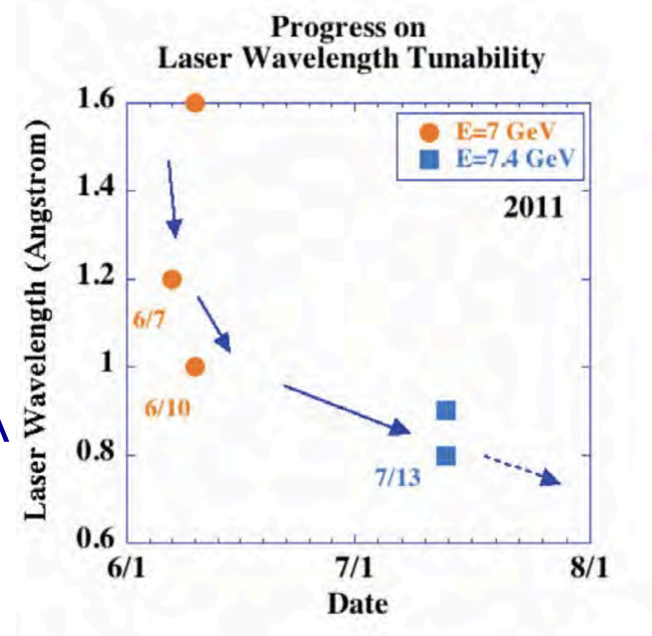
@ Siegfried Schreiber

SwissFEL - wide range of capabilities in a single facility, economic

	LCLS	Eu-XFEL	SACLA	FLASH I & II	FERMI	SwissFEL
Shortest wavelength reach (fundamental)	0.15nm	0.05 nm	0.1 nm	4 nm	4 nm	0.1 nm
Soft X-ray circ. Polarization	no	no	no	no	yes	yes
Variable gap	no	yes	yes	yes (FLASH II)	yes	yes
Soft X-ray seeding	no	no	no	yes (FLASH II)	yes	yes
RF Rep. rate	120	10	60	10	10 (50)	100
FEL pulses/RF pulse	1	2700	1	2700	1	2
independent THz source in Exp. hall	no	no	no	no	no	yes
peak current	3 kA	5kA	3 kA	2.5 kA	0.75 kA	2.7 kA
max. bunch charge	0.25 nC	1 nC	0.2 nC	1 nC	0.25nC	0.2 nC
max. electron energy	13.6 GeV	17.5 GeV	8 GeV	1.2 GeV	1.5 GeV	5.8 GeV
No. RF stations	81	29	69	5	15	31
Facility length	1.7km	3.4 km	0.8km	0.32 km	0.5 km	0.7km
Start operation	2009	2014	2011	2005 / 2013	2010	2016

SACLA – recent lasing

2004~2006 SCSS Test Accelerator construction
2006 June: First lasing at 49 nm in SCSS
2006~2011: XFEL/SPring-8 Construction
2011 March completed, New name SACLA
2011 June: First lasing at 1.2 Angstrom in SACLA
Currently at 4 GW, 18% intensity fluctuations



- Near future plans:
- combined use of XFEL with SPring-8 SR
- seeding technology in X-ray wavelength region
- high beam repetition rate at around 1 kHz
- flexible operation
- fast switching of multiple Beam Lines

700 meters total length (mid level compact)

@ Tsumoru Shintake and Hitoshi Tanaka

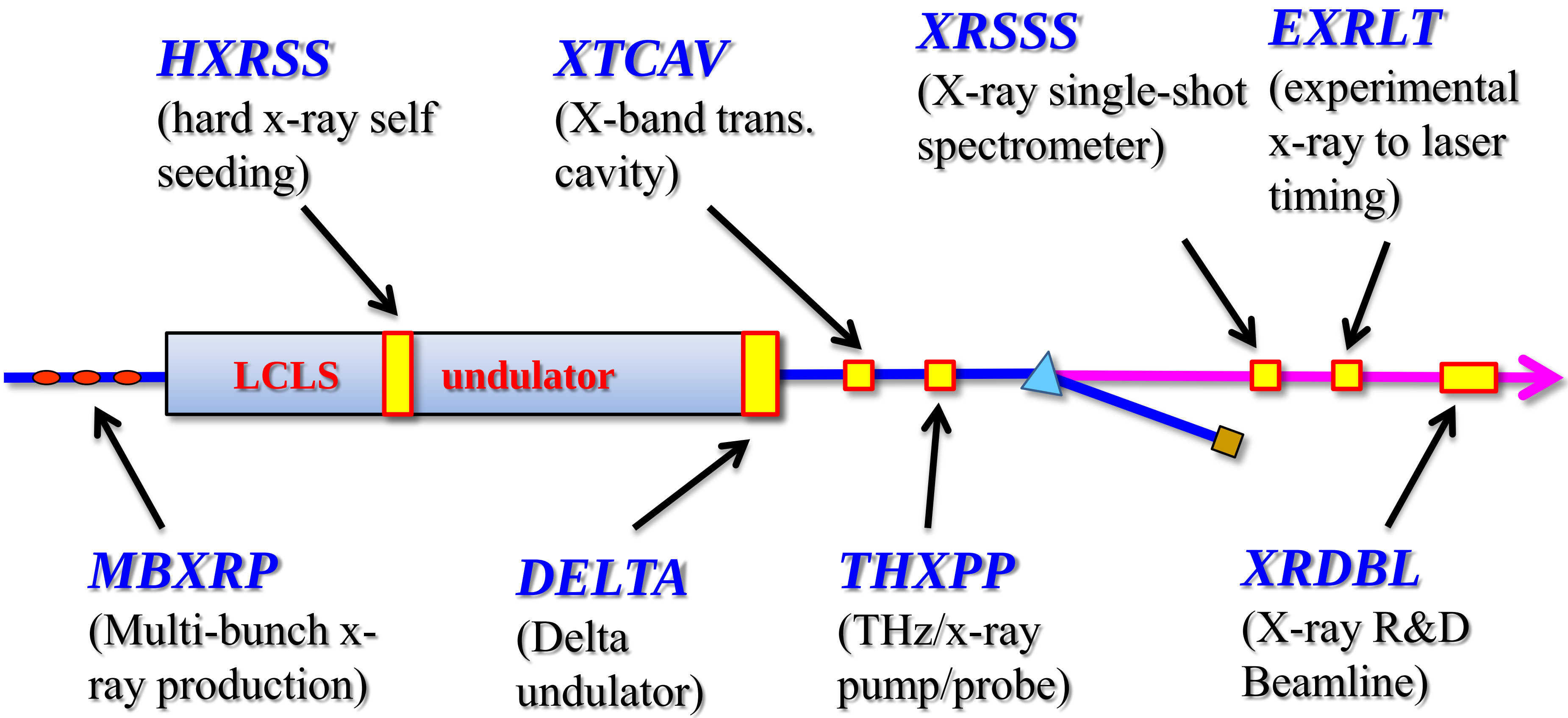
R&D progress

- USR
- Seeding
- Photocathodes
- Electron guns
- Accelerators / ERLs
- Short pulses – slicing
- Short pulse – compression
- Short period undulators
- Extended energy range
- X-FEL Oscillators
- Compact FELs
- Laser and timing
- Computational R&D
- Test facilities
- Further research

R&D for USRs Extends Well-Known Physics

- No apparent show-stoppers for USRs
- Lattice design well advanced
- MAX-IV with 7BA lattice will provide critical test
- Latest PEPX design quite robust in simulation
- Collective effects
- Microwave instability, ion trapping need study
- Kicker development
- Require fast rise/fall times, longish flat top for “swap-out” injection
- Superconducting undulators allow lowering the beam energy while maintaining hard x-ray reach
- On-going R&D at ANL, elsewhere
- Cost reduction
- Innovative magnet developments needed to reduce cost

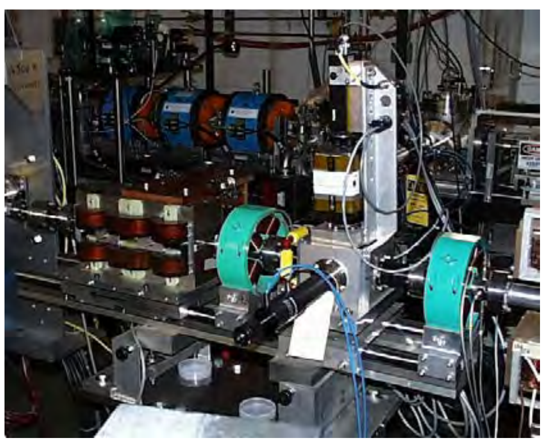
LCLS R&D Projects under development

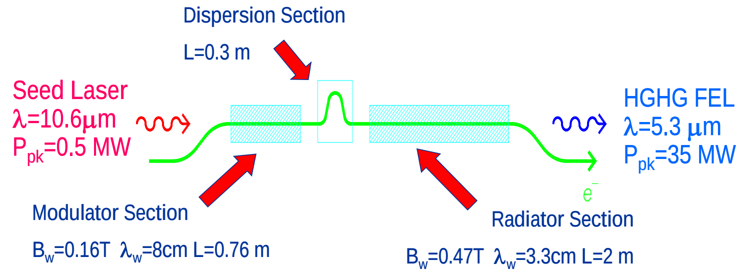


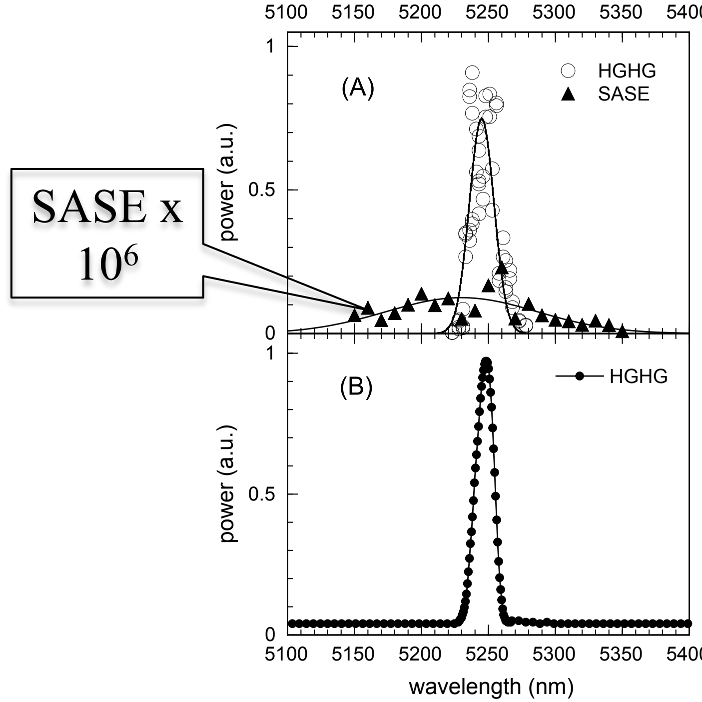
Seeding

- Seeding or self-seeding schemes allow a higher brightness and shorter pulse to be achieved as compared to Self Amplified Spontaneous Emission (SASE).
- Self seeding is achieved by filtering a SASE seed. Allows very short pulse, ~10 fs or less.
- Seeding can be done by a High Harmonic Generation (HHG) of a conventional laser or by harmonic generation of a laser seed or more complex scheme (ECHO).

The dispersive section of the ATF HGHG experiment

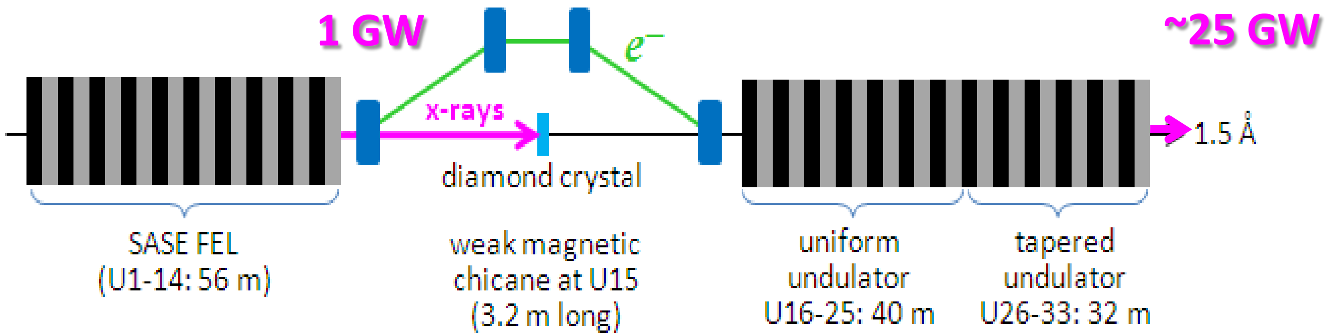


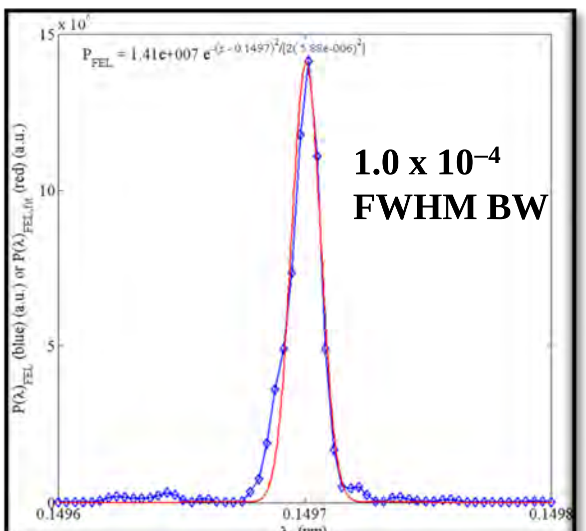


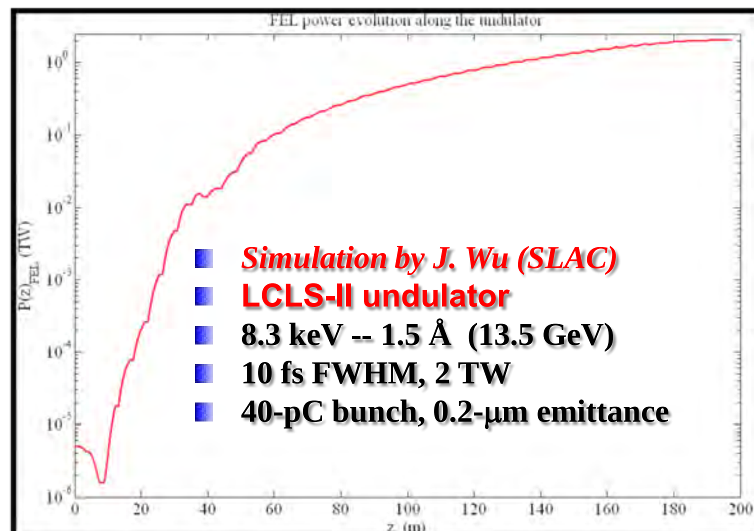


Hard X-ray Self-Seeding (*HXRSS*)

Self-seeding of 1-μm e^- pulse at 1.5 Å yields **10⁻⁴ BW** with 20-pC mode. Undulator taper provides 30×brightness & 25 GW. P. Emma (SLAC), A. Zholents (ANL) Geloni, Kocharyan, Saldin (DESY)





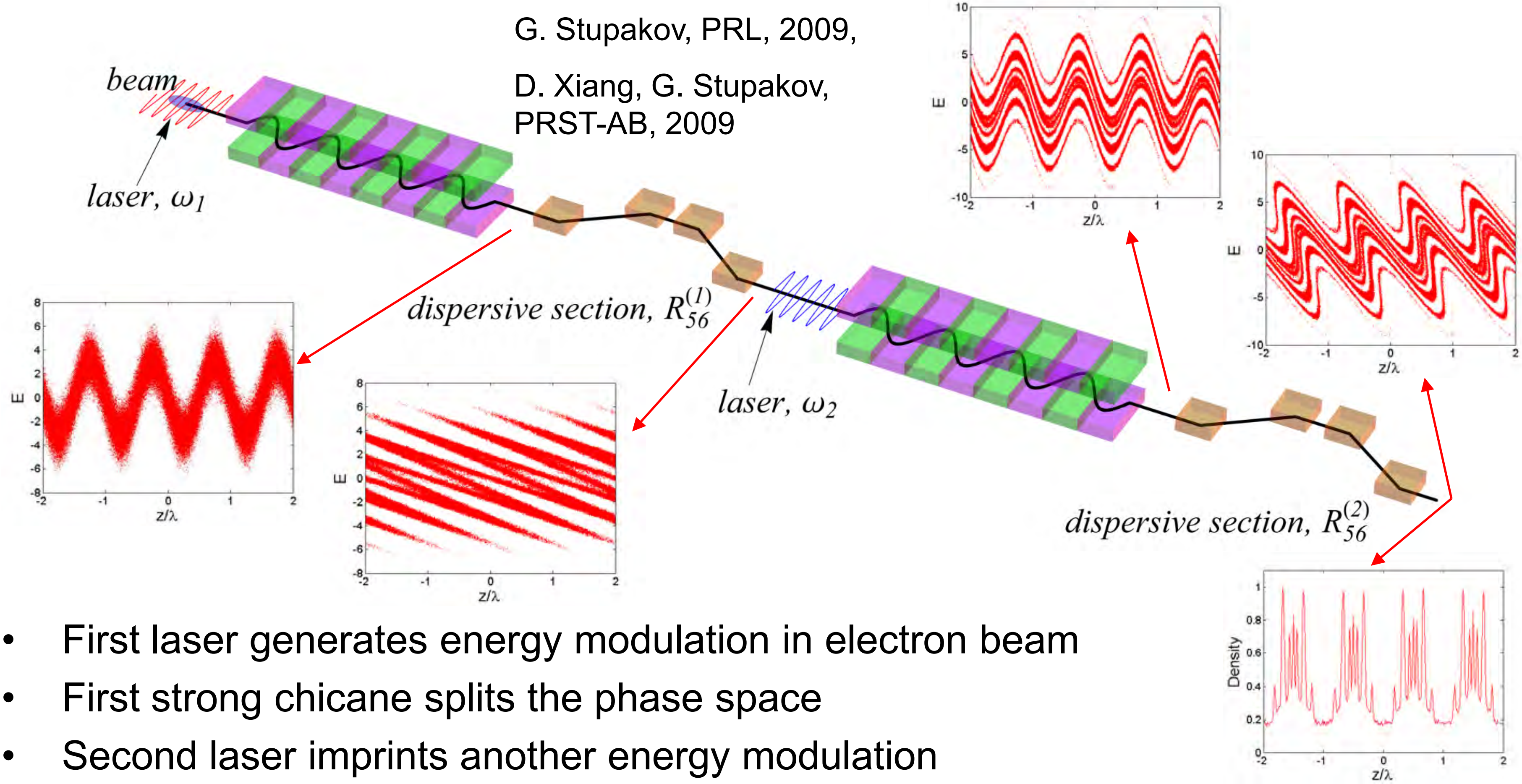


@ Zhirong Huang

ECHO-seeding technique

G. Stupakov, PRL, 2009,

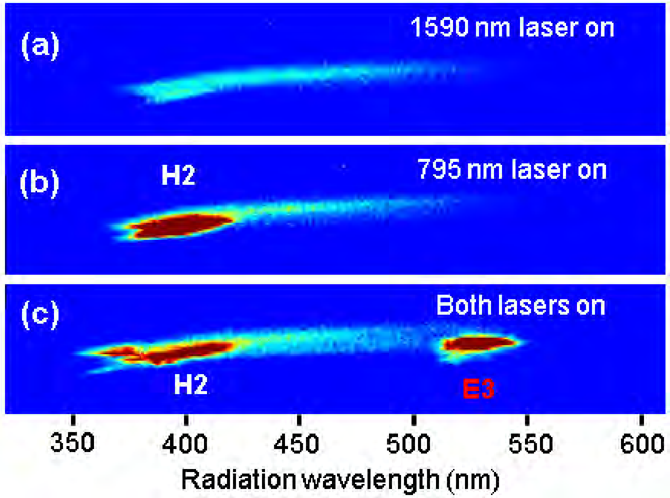
D. Xiang, G. Stupakov, PRST-AB, 2009



- First laser generates energy modulation in electron beam
- First strong chicane splits the phase space
- Second laser imprints another energy modulation
- Second chicane converts energy modulation into density modulation

ECHO-7 @ NLCTA

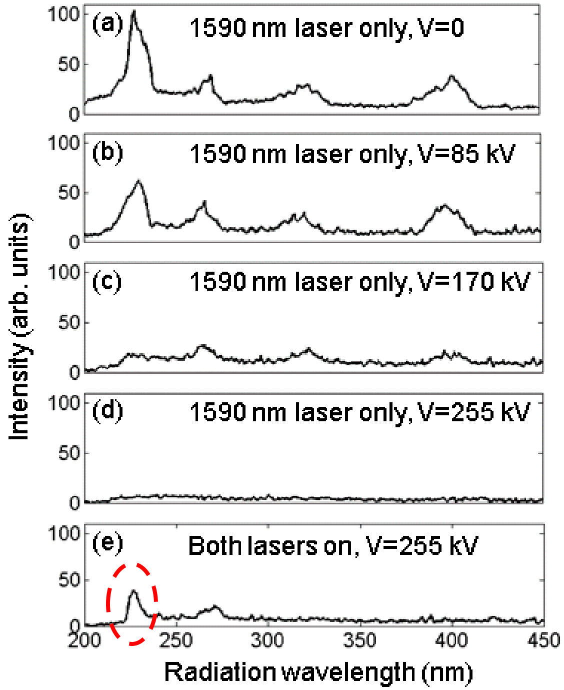
First echo signal on 07/02/2010



D. Xiang *et al.*, PRL, 2010

- 3^{rd} and 4^{th} harmonic from interplay of the two lasers observed
- The experiment verified the basic physics of EEHG and demonstrated that phase space correlation could be preserved

Evidence of high harmonics 07/14/2011



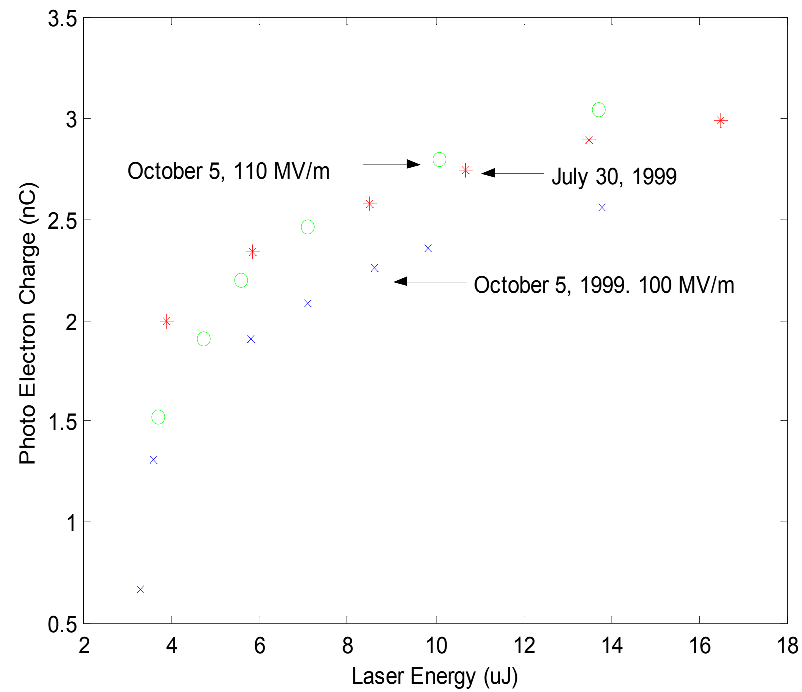
- Beam slice energy spread increased by a transverse cavity
- 7^{th} harmonic generated when energy modulation is twice the slice energy spread

Photocathodes

- Where it all begins…
- The photocathode is the first frontier where emittance can be won or lost, by thermal emittance, non- uniformity of emission or temporal tails.
- The FLS will require high repetition rate, placing premium on the photocathode quantum efficiency and lifetime.
- The photocathode is considered a “long pole” in the tent of FELs.

Personal note: Metal photocathodes R&D at the ATF

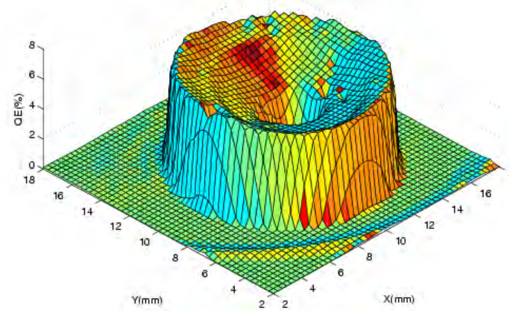
- We developed copper and magnesium cathodes from 1988 onwards.
- We developed a procedure for cathode laser cleaning.
- QE is about 0.3%, it decays to about 0.1% in one day, then steady for a month.
- Cathode uniformity achieved < 10% peak-to-peak.
- Copper cathode basis for LCLS



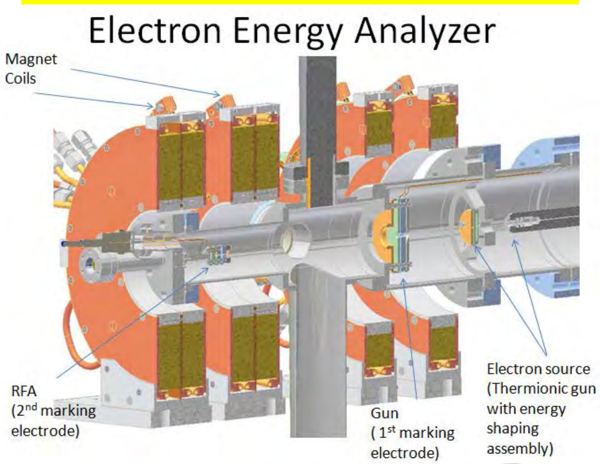
Photocathode R&D @ Cornell
(high quantum efficiency)

- Mission: to **understand photocathode physics**
  - **Better materials (lower thermal emittance, longevity, photocathode "engineering")**
  - **High impact on injector performance;**
  - **Exciting physics;**
- **Three-pronged approach**
  - **Grow/procure new materials (both NEA** and **PEA);**
  - **Evaluate performance in the actual accelerator;**
  - **Theoretical modeling and properties characterization;**
- **Considerable progress in all three areas:**
  - **8 photocathode peer-reviewed publications including 3 Physical Review Letters or Applied Physics Letters over 2008-2011.**

QE scan after delivering ~1000C showing some damage from ion-backbombardment



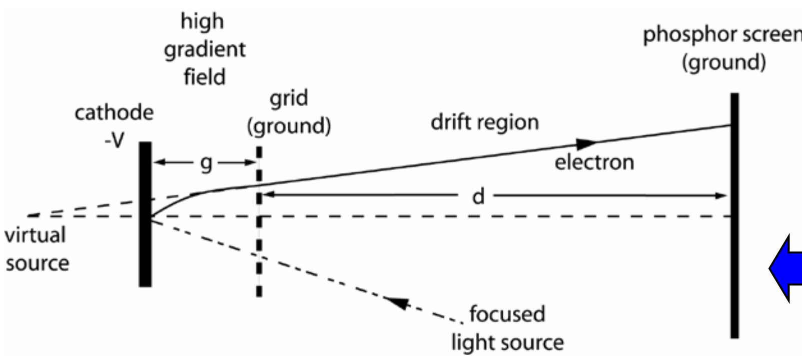
Photoelectron energy analyzer

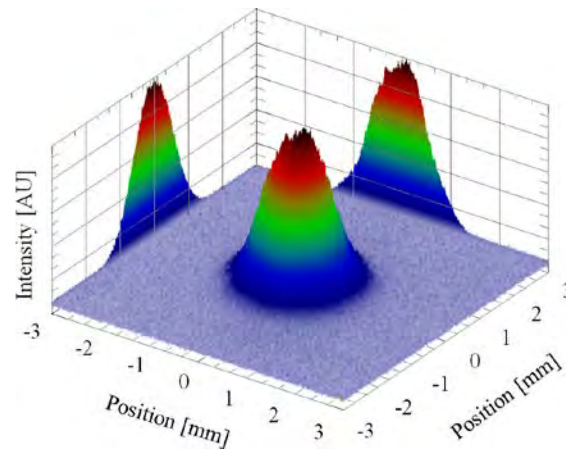


PhD student project (DOE career)

K2CsSb: An excellent photocathode (BNL, LBNL, Stony Brook collaboration)

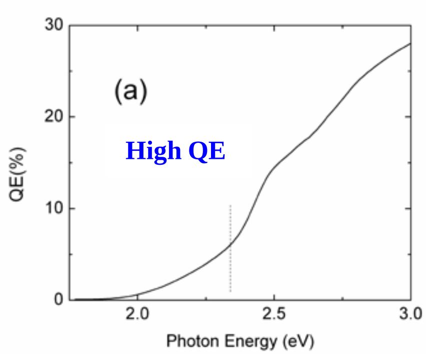
Applied Phys. Letters **99** 034103 (2011)

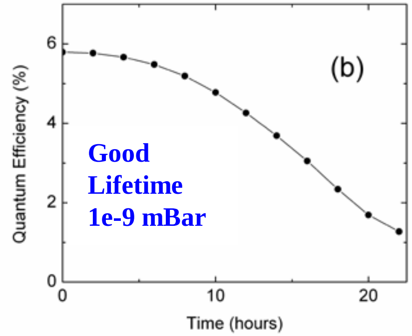


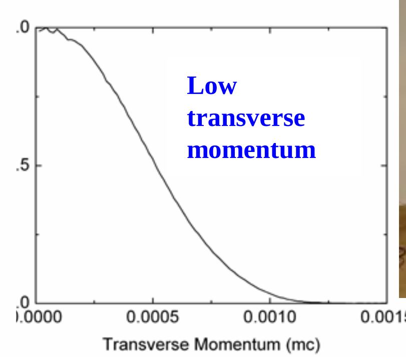


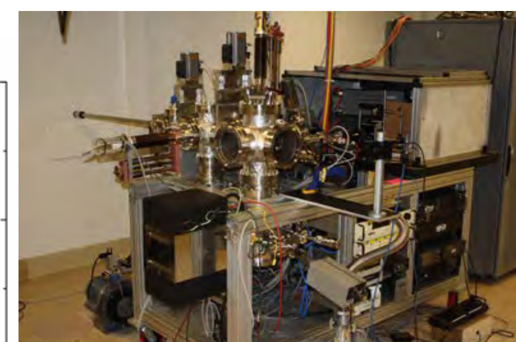
Transverse momentum image measurement at 543 nm
- rms = 0.36 mm / micron rms beam size

Fast (msec), high field (4 MV/m; can be > 10 MV/m) measurement of transverse momentum







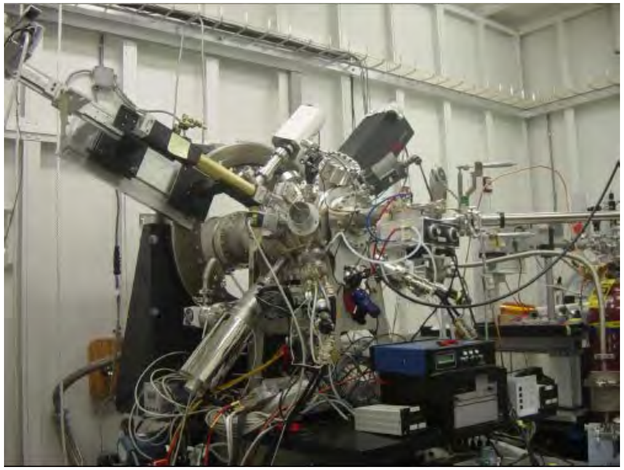


@ Howard Padmore

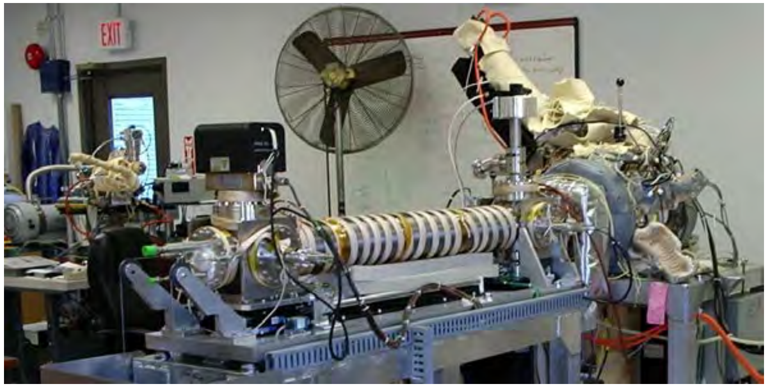
Alkali Antimonide Growth

Materials science based approach to cathode growth

- Cathode chemistry with XPS and XRF/EDX
- Cathode structure with XRD and SEM
- Performance with QE mapping,
- ARPES and momentum measurement
- Diagnostics integrated into growth chambers



User facilities expands capabilities



Gun, lifetime and exposure tests

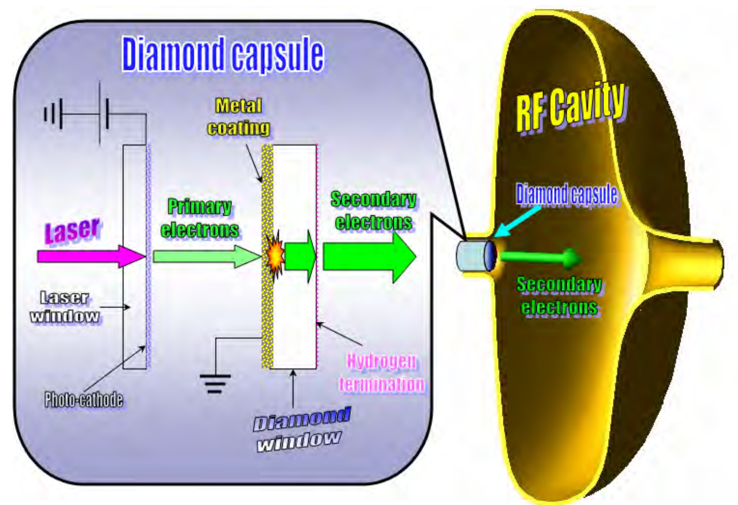
- Test cathodes in “real-world” environments
- Follow-up analysis

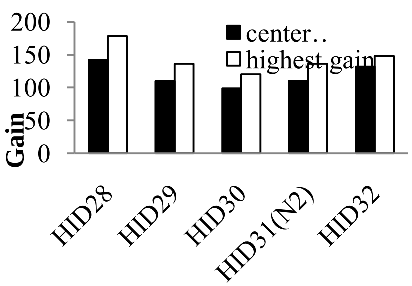
Take the cooking out of making cathodes

@ John Smedley

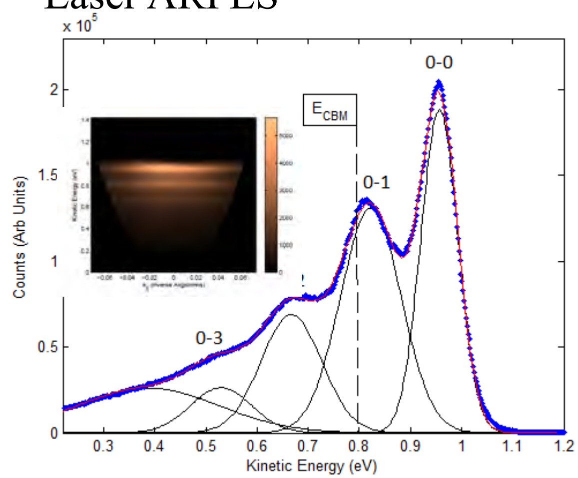
Diamond amplifier –
(BNL, LBNL, Stony Brook collaboration)

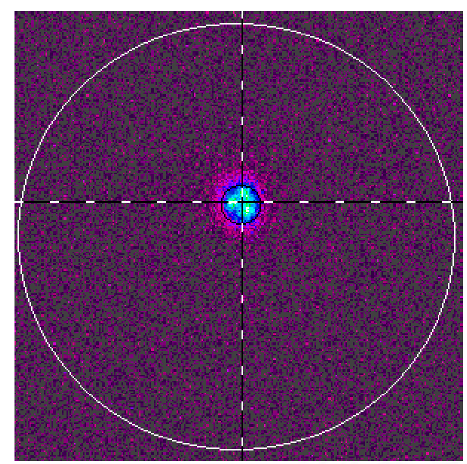
- Increase QE by orders of magnitude
- Robust – can be exposed to air
- NEA material – good thermal emittance
- Measured 0.12±0.01eV rms energy spread
- Capable of high current – A/cm^2
- Various PRL – PRST-ABs





Laser ARPES



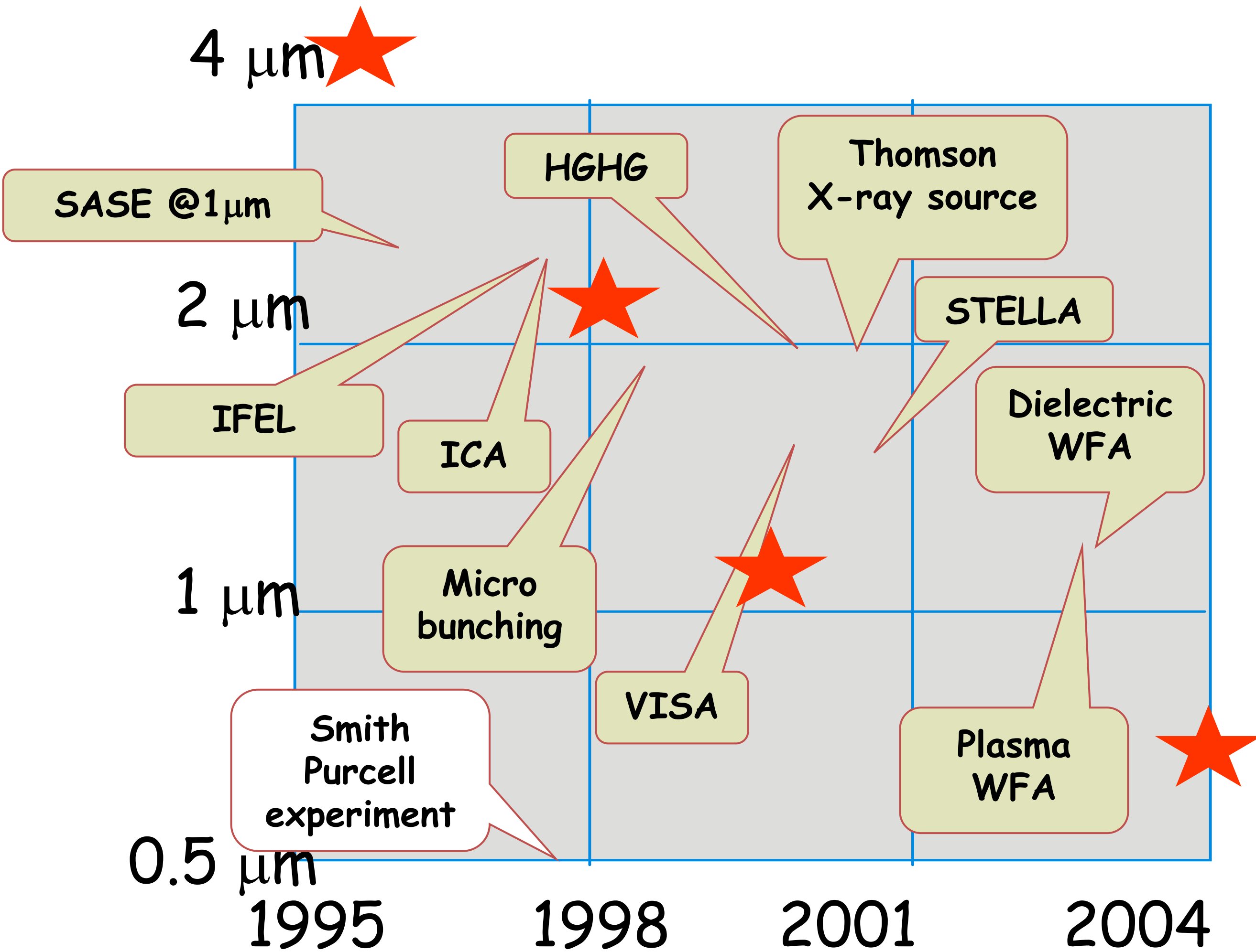


@ Ilan Ben-Zvi

Electron gun

- Where the photocathode lives (and dies…)
- The next critical element in generating the premium electron beams we require.
- We still do not have the electron gun for FLS.
- We need:
  – High accelerating field at the cathode
  – High voltage (get the electrons relativistic ASAP)
  – Reasonable power consumption

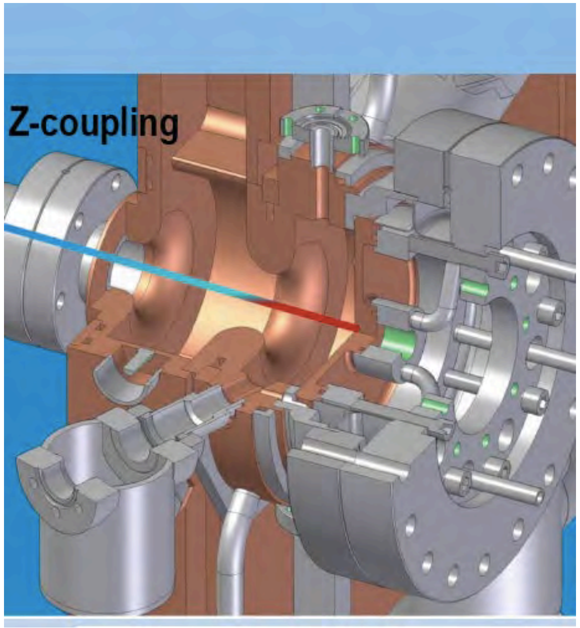
Personal note:
The BNL S-band RF guns series

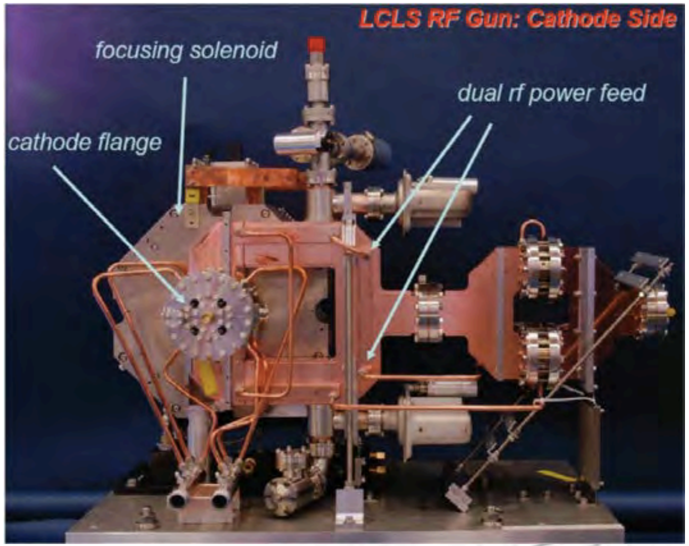


BNL III gun
AKA the
BNL/UCLA/SLAC gun
precursor of LCLS gun

@ Vitaly Yakimenko

LCLS gun





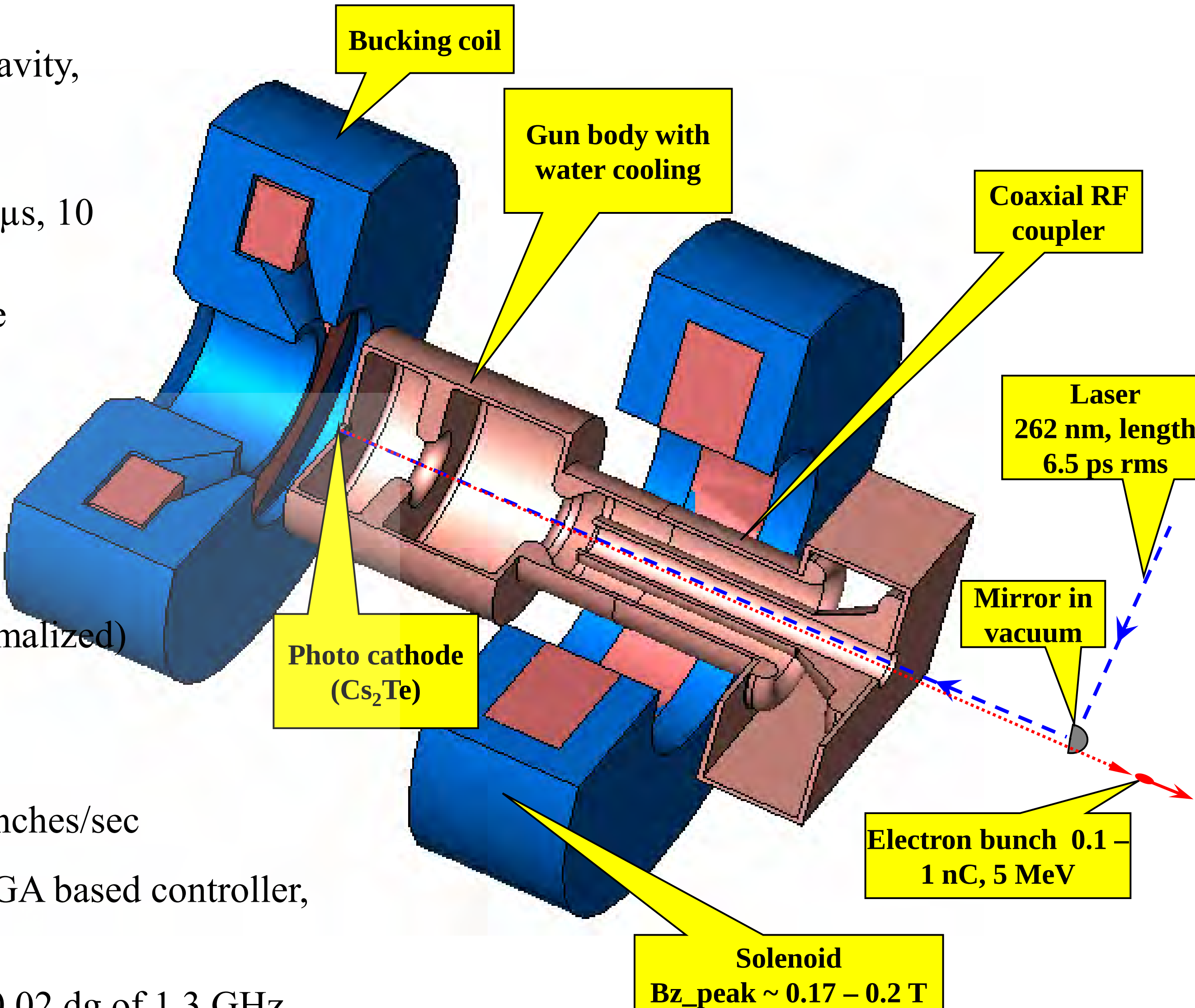
- Pulsed heating mitigated with longitudinal coupling and increasing radius of RF aperture
- Increased RF mode separation
- Symmetric RF fields in gun
- Improved cooling for 120 Hz at up to 140 MV/m
- Emittance compensation solenoid field with quadrupole correctors
- Cathode surface roughness <40 nm ptp

FLASH RF Gun

- RF gun: 1.3 GHz copper cavity, 1 ½ cell
- RF power 3.8 MW, RF pulse length up to 850 μs, 10 Hz
- Driven with laser on Cs_2Te photocathode

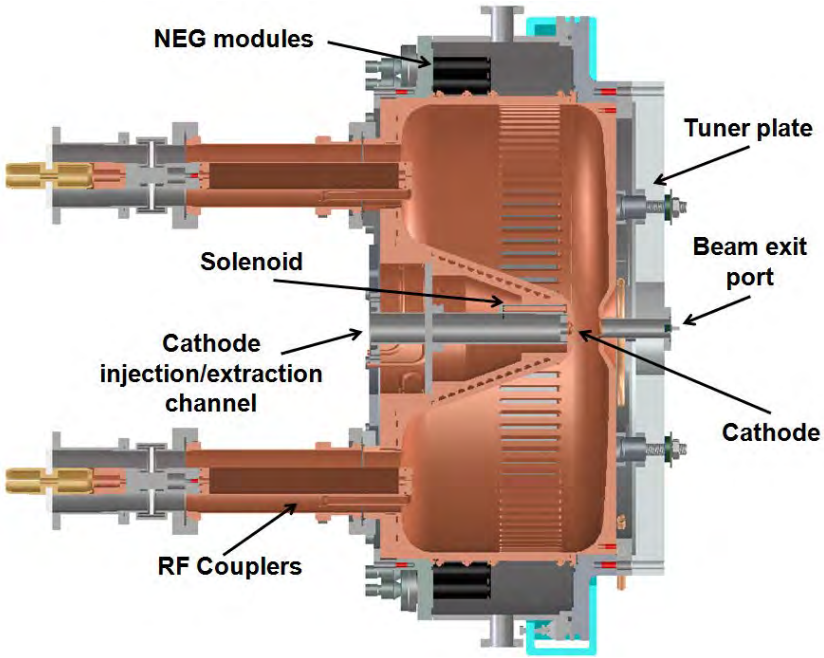
> Electron beam:

- Charge 0…3 nC
- Bunch length 2 mm rms
- Emittance (projected, normalized) < 1.5 mm mrad
- Peak current 40 to 100 A
- Trains of thousands of bunches/sec
- Low level RF system: FPGA based controller, latency 150 ns
- Excellent phase stability 0.02 dg of 1.3 GHz



@ Siegfried Schreiber

The LBNL CW VHF Gun



J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

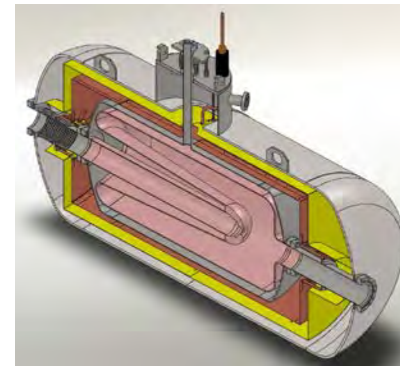
K. Baptiste, et al, NIM A 599, 9 (2009)

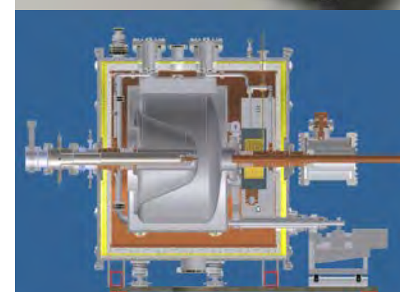
Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.47 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	87.5 kW
Stored energy	2.3 J
Peak surface field	24.1 MV/m
Peak wall power density	25.0 W/cm^2
Accelerating gap	4 cm
Diameter	69.4 cm
Total length	35.0 cm

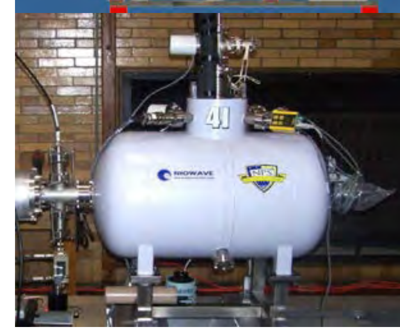
- At the 187 MHz, power density is sufficiently low to allow water cooling and CW mode
- Also, the long λ_{RF} allows for large apertures and thus for high vacuum conductivity.
- Based on mature and reliable normal-conducting RF and mechanical technologies.
- **187 MHz compatible with both 1.3 and 1.5 GHz super-conducting linac technologies.**

New breed – QWR SRF guns for high-brightness AND high repetition-rate

Parameter	Units	BNL	U. Wi.	NPS
Frequency	MHz	112	200	500
Aperture (beam tube)	cm	10	10	6.35
Cavity Diameter	cm	42	60	24
Cavity Length	cm	110	50.3	20.3
Planned beam energy	MeV	2	4	1.2
Peak electric field	MV/m	38	53	51
Peak magnetic field	mT	73	80.4	78
Peak / cathode field-		2.63	1.31	1.8
QRs (geometry factor)	Ω	38	85	125
R/Q (linac definition)	Ω	126	147	195
Q0 (no cathode, 4.5K)	$x10^9$	3.7	3.3	1.2

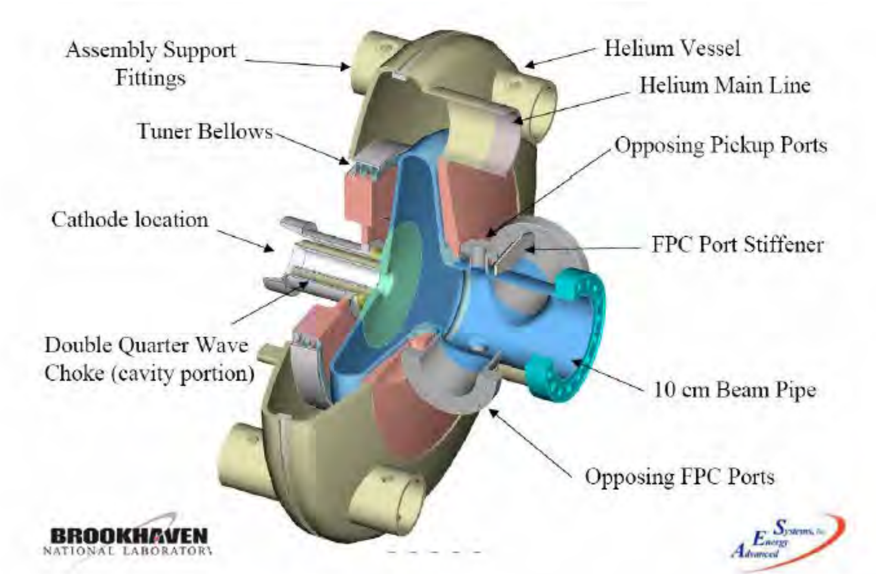






BNL's 500 mA 704 MHz SRF gun

2 MeV at 500 mA – 1 MW RF power
Load-lock for high QE photocathode
Tested vertically,
in assembly for horizontal test
Will drive 500 mA ERL

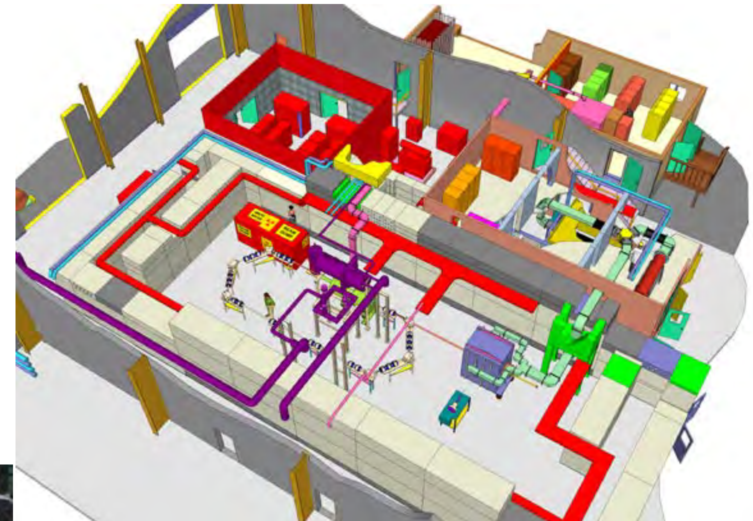


Accelerator

- The accelerator for the FLS will be superconducting.
- What is still an open question is the frequency of the accelerating cavities, ERL or linac, HOM damping etc.
- The TESLA (or ILC) cavities are in common use, but were not designed for CW operation OR ERL service.

Personal note: Lower frequency for ERL

- Improved RF / cryogenic losses
- Larger aperture – reduced wake fields
- Improved Beam Breakup threshold
- Improved damping of HOMs

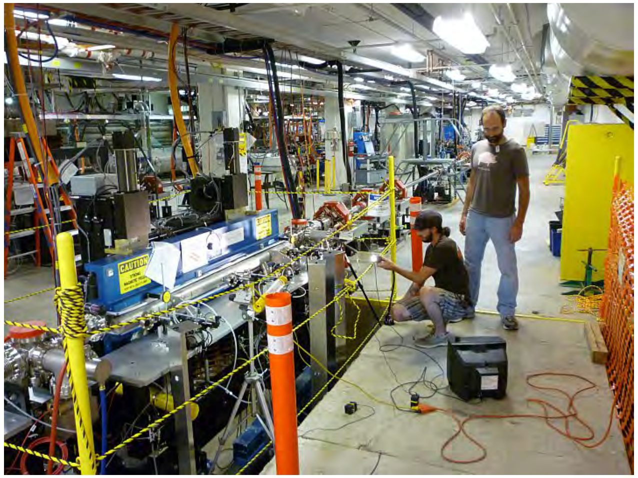


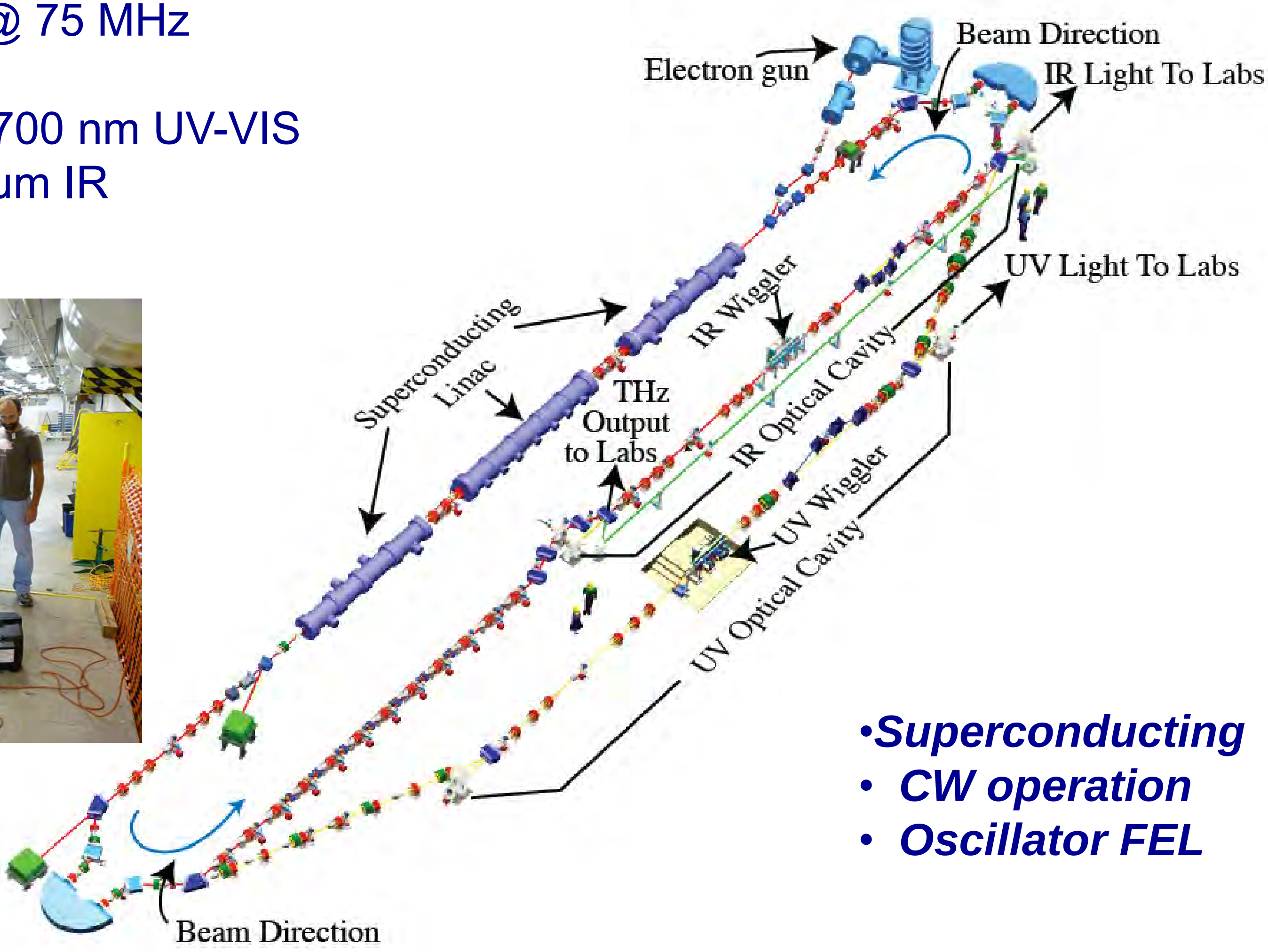
Above: 500 mA 20 MeV ERL under construction
Left: 704 MHz 5-cell cavity
Brookhaven National Lab

JLab Energy Recovered Linac THz/IR/UV/VUV Light Source

E = 135 MeV
Up to135 pC pulses @ 75 MHz

20 µJ/pulse in (250)–700 nm UV-VIS
120 µJ/pulse in 1-10 µm IR
1 µJ/pulse in THz

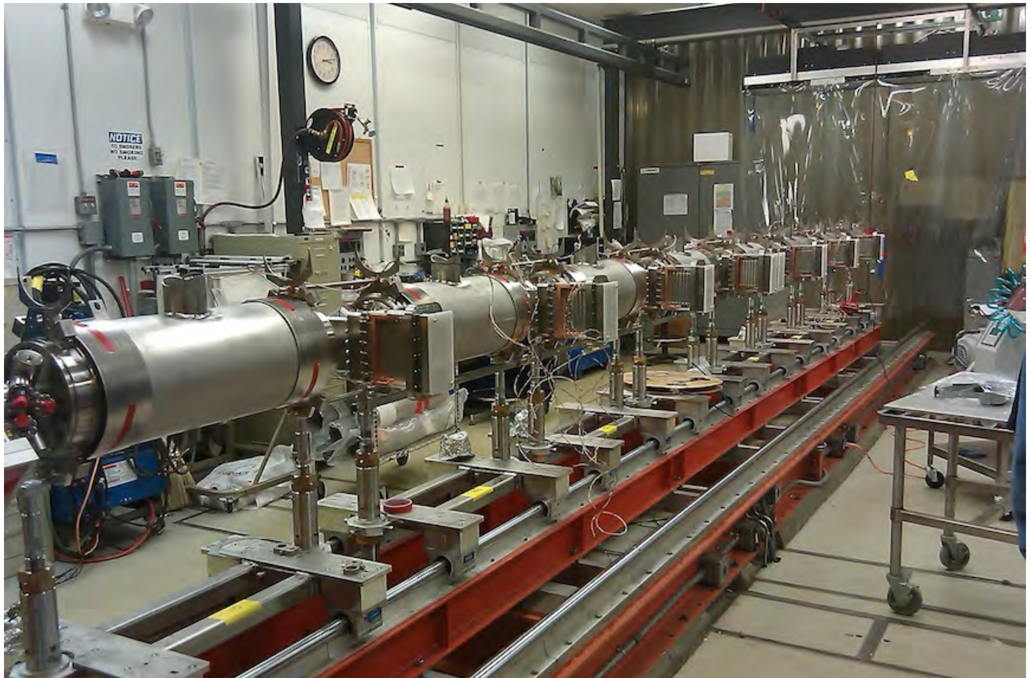


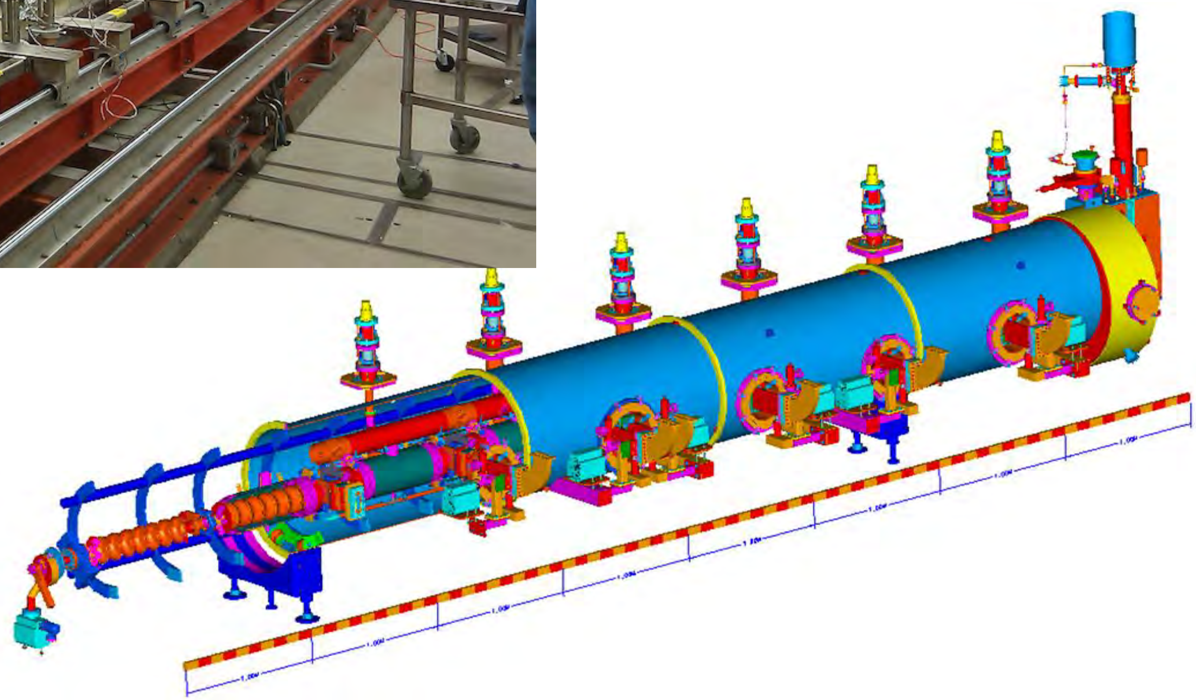


- *Superconducting*
- *CW operation*
- *Oscillator FEL*

@ George Neil

Jefferson Laboratory 100 MeV High Gradient Module

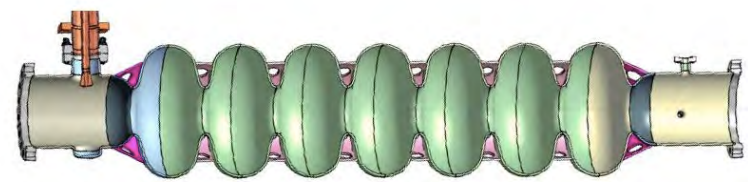


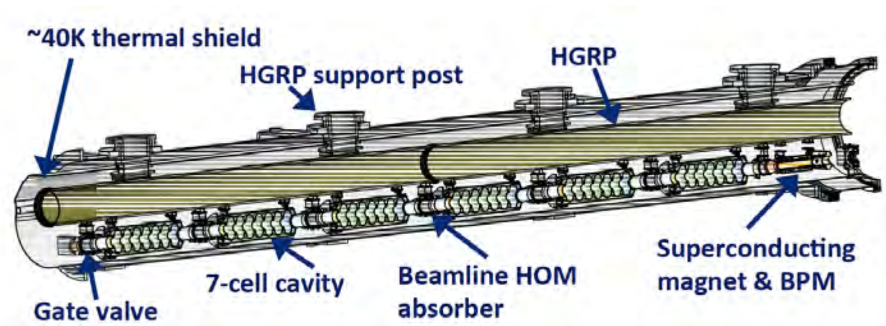


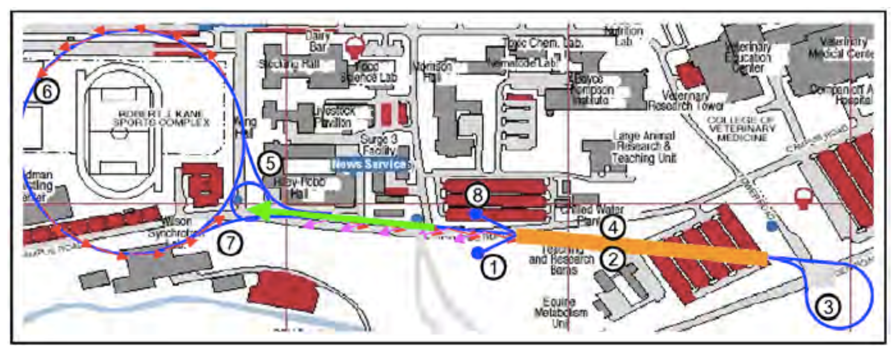
@ George Neil

Cornell ERL R&D

- R&D issues being pursued
  - Cryomodule, cavity and RF control
  - Optics optimization
  - Orbit and optics correction
  - BPMs for 2 beams
  - Feedback analysis
  - Beam-breakup instability
  - Ion removal, ion-gap
  - Ion instabilities
  - Energy spread budget
  - CSR shielding
  - Coupler kicks
  - Distribution of pumps / pressure
  - Gas and IBS scattering
  - Halo creation
  - Loss rates, radiation background, and collimator design



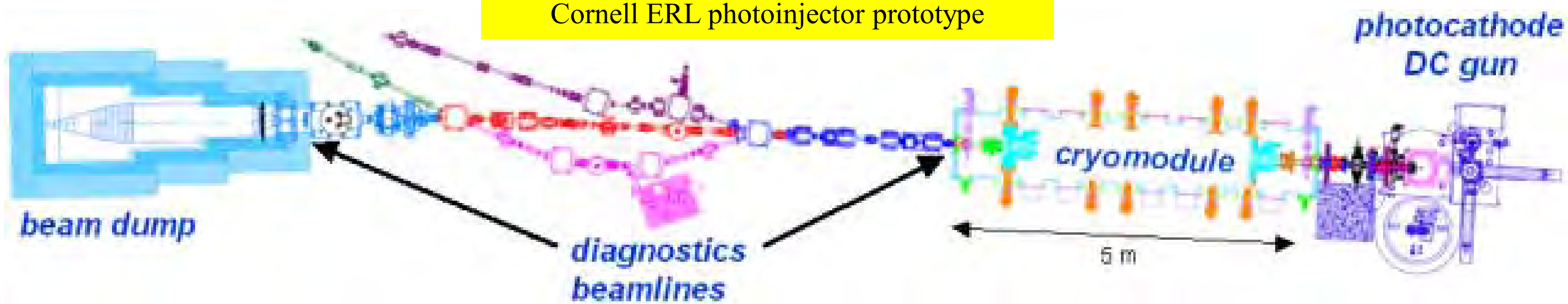




Cornell ERL Photoinjector Accelerator

The world's highest operating average current photoinjector

Cornell ERL photoinjector prototype



Energy 5-15 MeV (achieved to-date 13.5 MeV)
CW current 100 mA (25 mA)
Bunch duration 1-3 ps
Norm. rms emittance (80pC) 2 µm, core 0.4 µm (2.8 µm, core 0.5 µm)

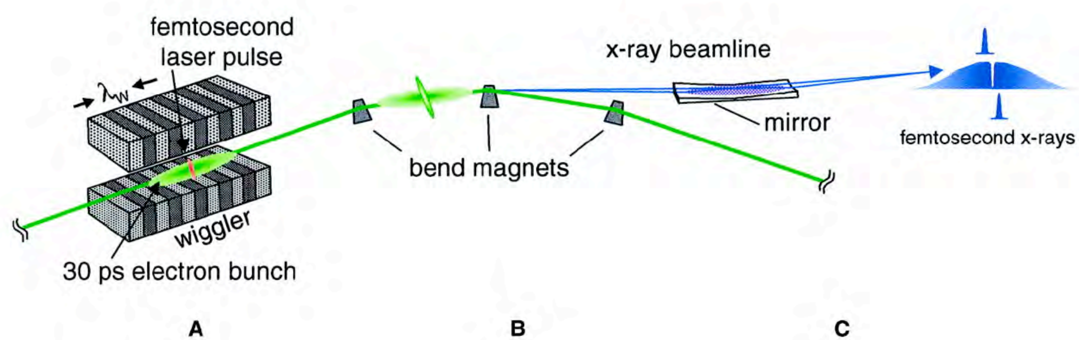
- Well-instrumented beamline to measure 6D phase space of the beam
- Integrated photogun, laser, and photocathode research
- University environment provides unique hands-on training environment to graduate students and post-docs

@ Ivan Bazarov

Short pulse - slicing

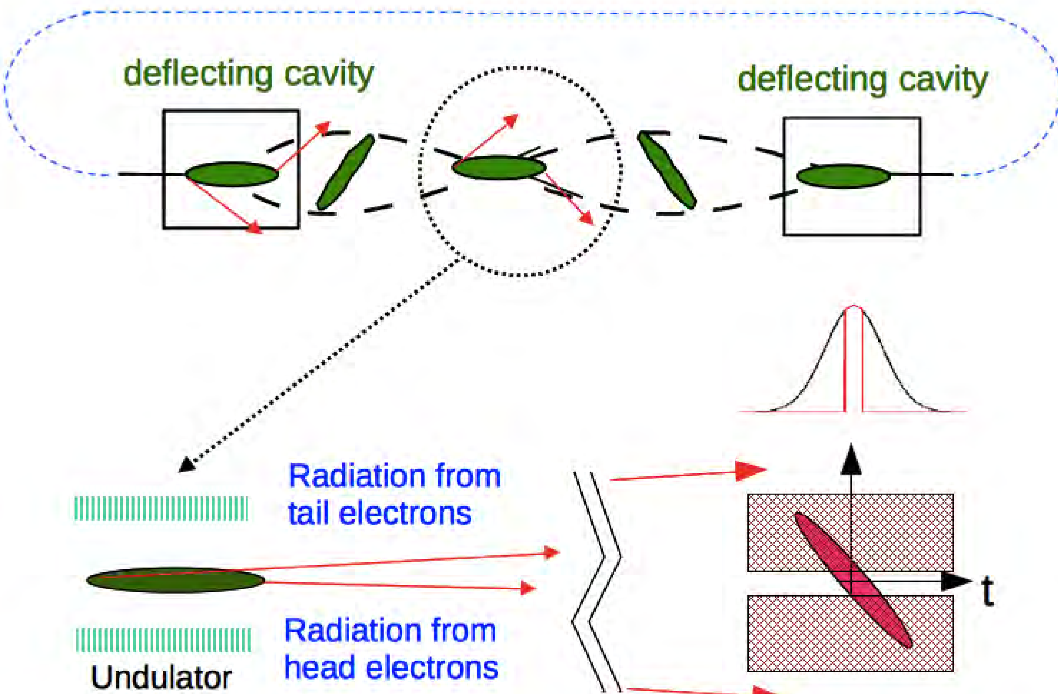
- Slicing a short pulse out of a storage ring is a future technique, achieving what a storage ring does not like to do – short pulses.
- This is a field for a lot of innovation, from laser acceleration schemes to crabbed bunches to electron beam kickers.

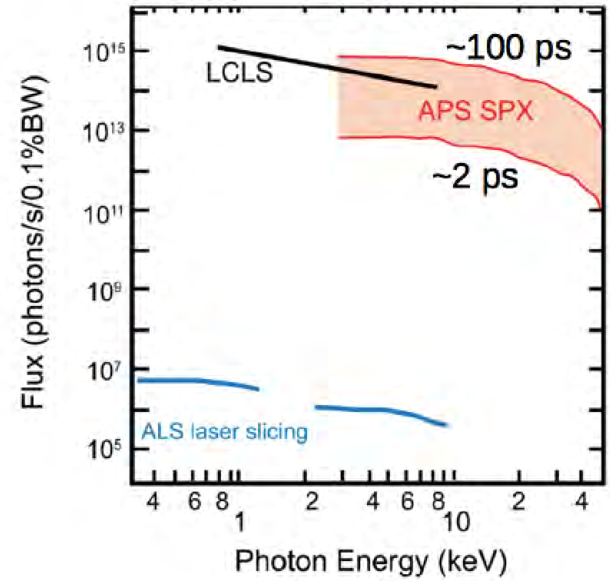
Schoenlein et al.,
Science **287** (5461): 2237-2240
March 2000



APS Short-Pulse X-ray (SPX) Project

- Goal: Create a unique, world-class facility for picosecond time-resolved x-ray studies
  - Tunable source of high-energy x-rays
  - High average brilliance and flux
- Use Zholents' deflecting cavity scheme[1]

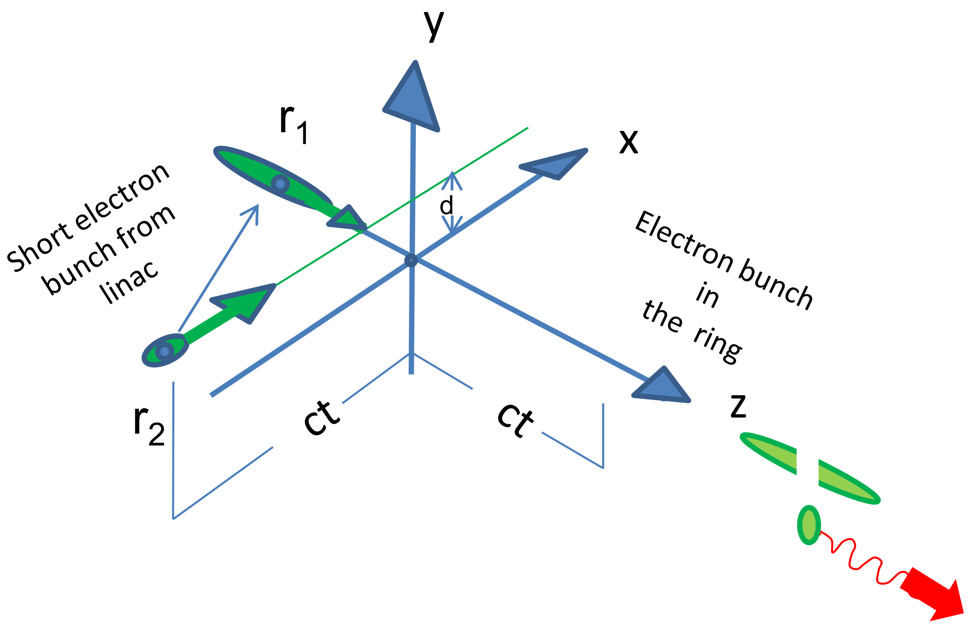




Much higher flux/brightness than femto-slicing sources, but gentler x-ray probe than LCLS (R. Dejus, APS).

[1] A. Zholents et al., NIM A 425, 385 (1999).

Femto-second X-ray Pulse Generation by Electron Beam Slicing



Basic Idea:

When short electron bunch from linac (5MeV, 100pC,100fs) passes above a storage ring bunch (30 ps), it kicks a slice (150fs) vertically.
(Ferdinand Willeke)

The radiation from short slice is separated from the core bunch.

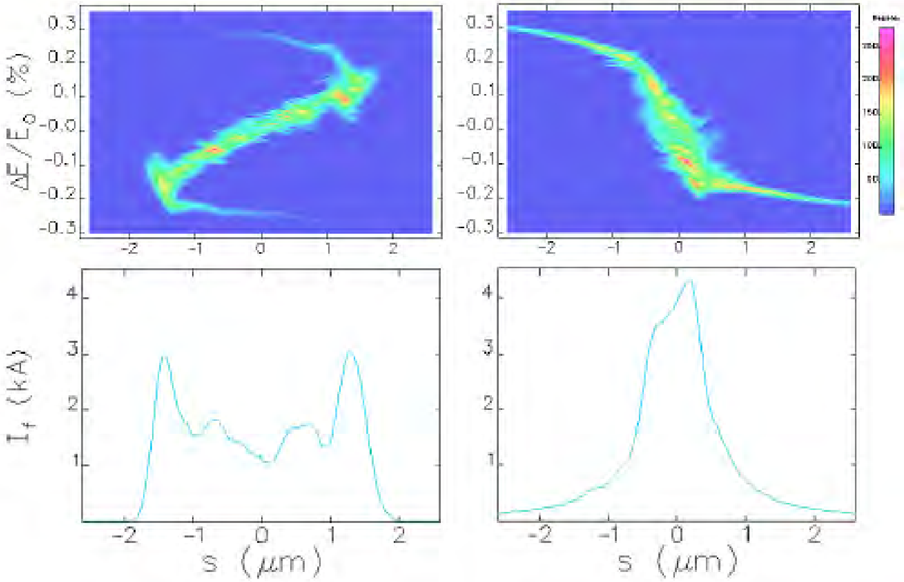
Advantage when compared to other schemes:

- Need much smaller space in storage ring for interaction point, compared with crab cavity
- Pulse length (150fs) much shorter than crab cavity method (1-2ps)
- The flux per pulse may be increased significantly compared with laser slicing (> x 6-10)
- Rep rate can be many orders of magnitude higher than laser slicing (>10 MHz compared with 1-10kHz)
- 10^4~10^5 of magnitude higher rep. rate, more stable than LCLS for short x-ray pulse

Short pulse - compression

- As mentioned above, a single "spike" of SASE can be selected by self-seeding to produce fs or sub-fs X-ray pulses.
- Another route for short pulses is compression of the electron beam. Femtosecond pulses can be achieved.

Longitudinal emittance and fs bunches

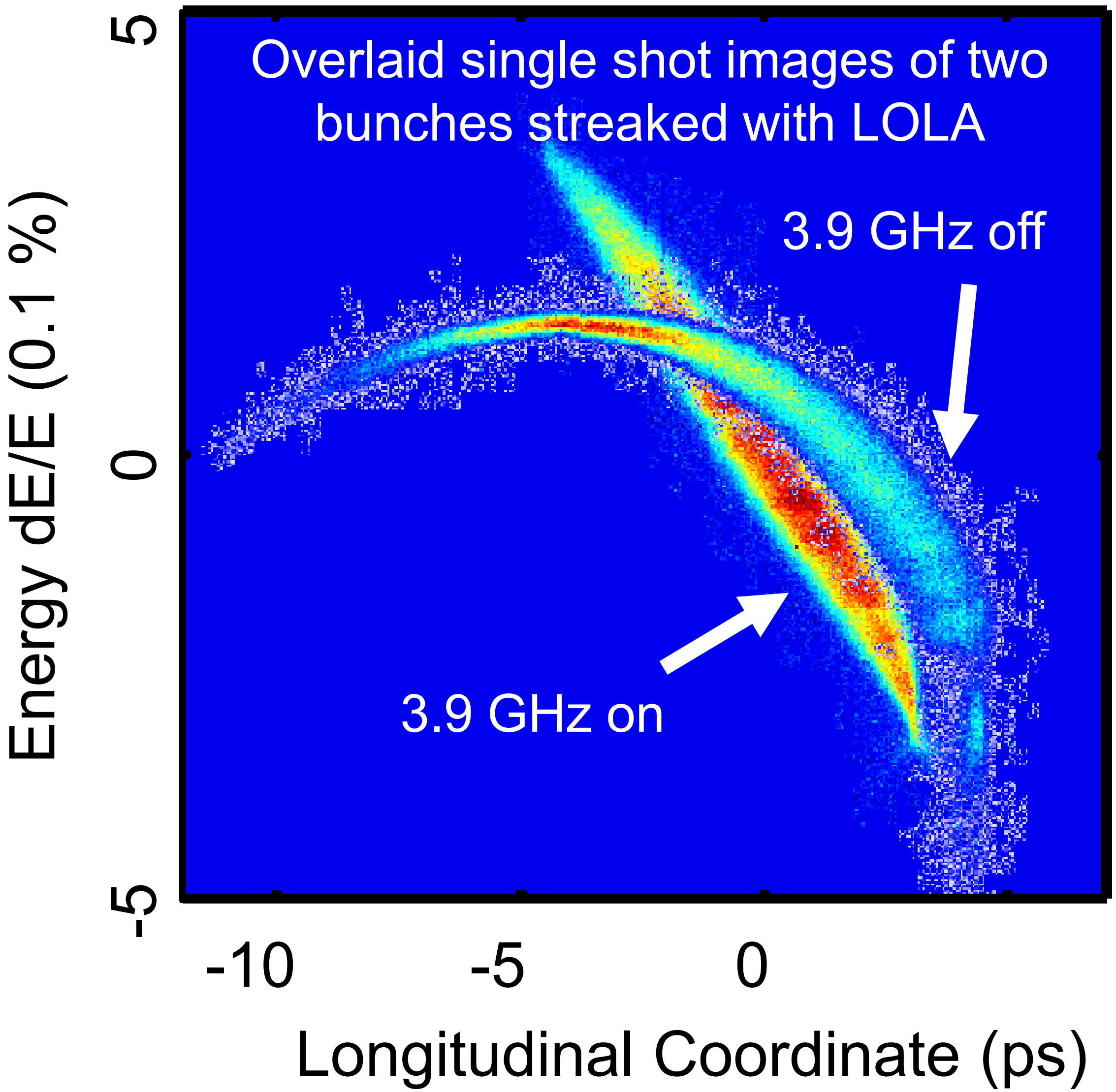


Longitudinal phase space measurements after the second bunch compressor, and before the final acceleration. Under-compression and over-compression phase space and current profile. Beam energy ~4 GeV. The bunch head to the left.

Y. Ding et al. Phys. Rev. Lett., 102, 254801 (2009).

Longitudinal emittance ~6keVps

Linearization of phase space @FLASH



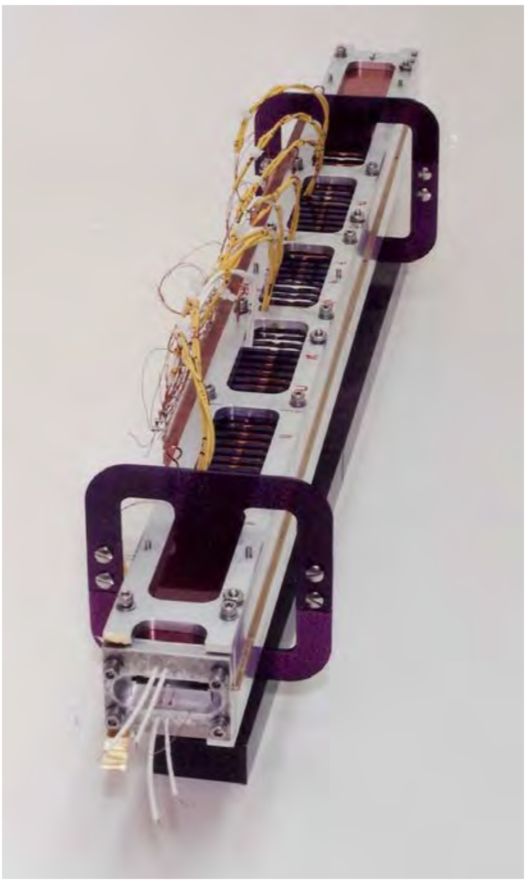
- Measured with LOLA,
- dispersive section
- beam energy 700 MeV
- Slight compression with 1st module (ACC1)
- 3.9 GHz cavities on/off

Short period undulators

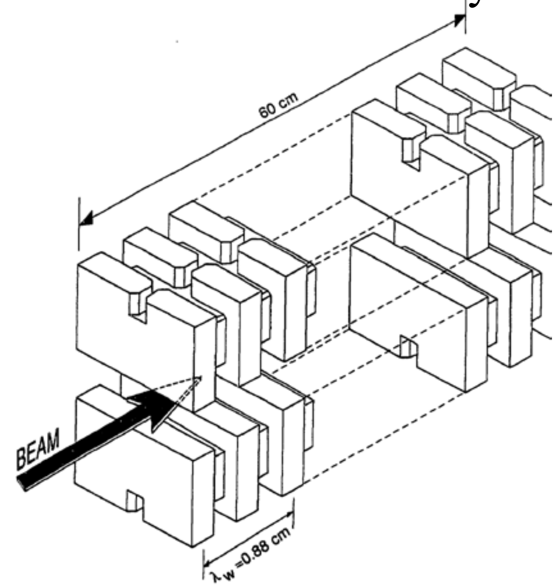
- As the emittance of electron sources becomes smaller, a lower energy (shorter) accelerator can be used but a short period (and altogether quite short) undulator is required.
- Making short period undulators is another R&D frontier for FLS.

Personal note:
1996 micro-undulator work

G. Ingold, I. Ben-Zvi, L. Solomon, M. Woodle, Nuclear Instruments and Methods in Physics Research A 375 (1996) 451-455

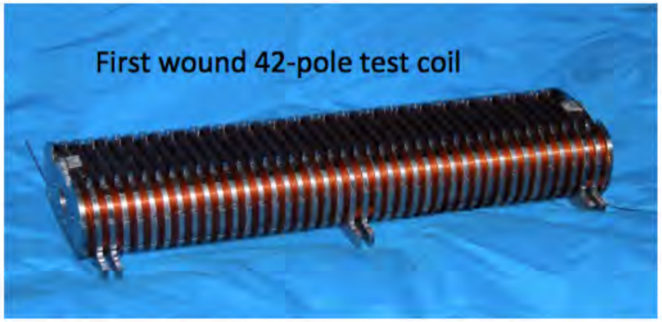


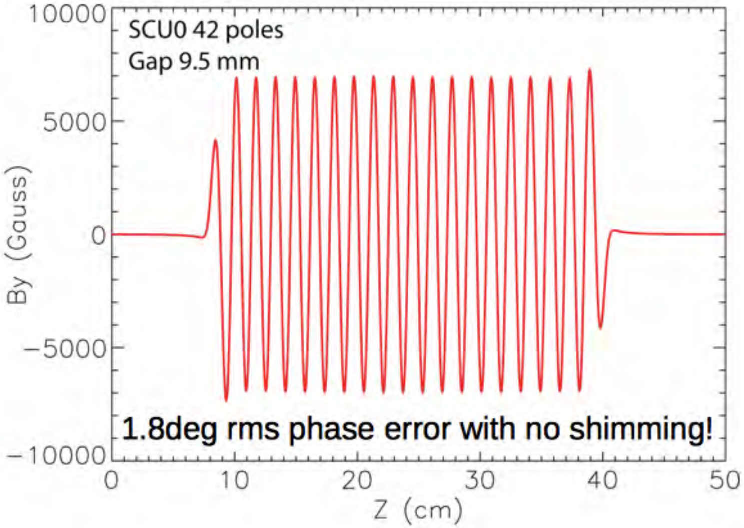
- Super-ferric undulator
- 8.8 mm period
- 4 mm gap
- 0.5 Tesla on axis
- Built and successfully tested



APS Superconducting Undulator Program

- Achieving high energy and high brightness requires short period and sufficiently strong magnetic field
- Conventional approach: in-vacuum undulators (IVU)
  - Beam impedance of IVUs is large
  - Incompatible with dominant APS fill patterns (timing mode)
- APS developing 16-mm period superconducting undulator
  - 0.65 T provides 20-25 keV first harmonic from our 7 GeV beam
- Several prototype cores characterized in vertical dewer





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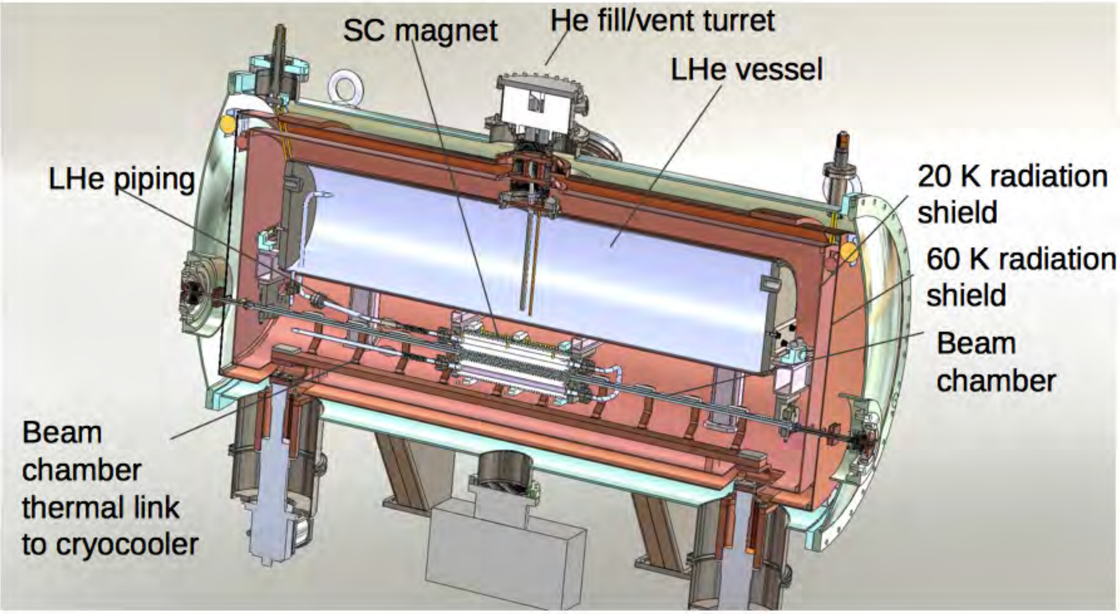
APS SCU Cryostat Structure

- Cryostat design is based on concept used by BINP for SC wigglers
- Major concern is heating of undulator by beam via chamber
  - Beam chamber and undulator are thermally isolated
  - Separate cryocoolers used for chamber and undulator
- Cryostat will be tested with a short device in 2012, followed by longer prototype in same cryostat



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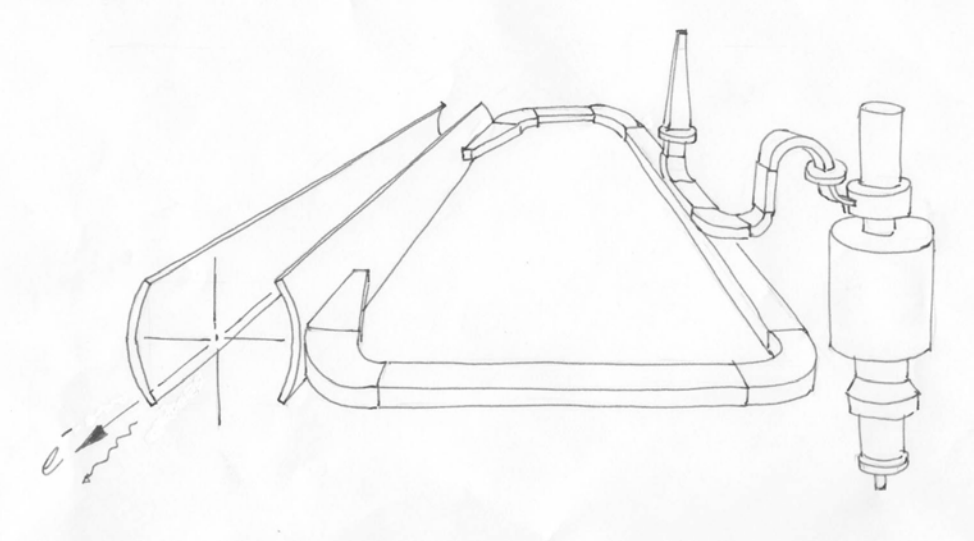
Microwave waveguide undulator

- Fast dynamic control of
  - Polarization
  - Wavelength
  - K
- Large aperture (cm vs mm for static undulator)
- No issue with permanent magnet damage by radiation
- Economic considerations

SRF undulator test layout

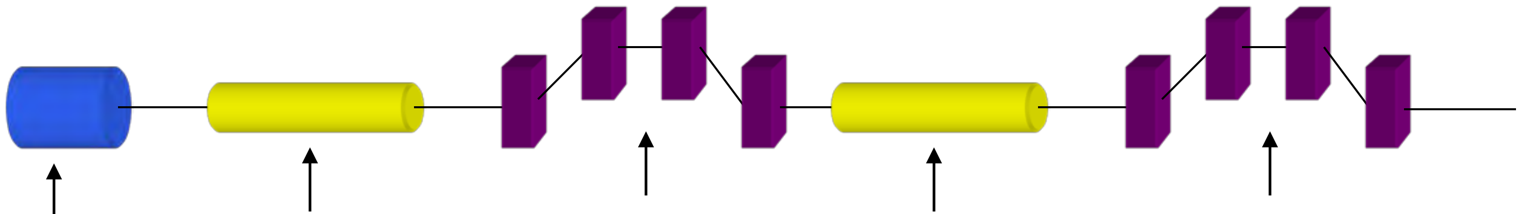
Ring resonator: Because of the integration of RF pulses in a resonant ring the rf pulse in the undulator can be smoothed. Further, the ring can have a multiplication factor of more than 10, resulting in 5 GW of RF power through the undulator waveguide.

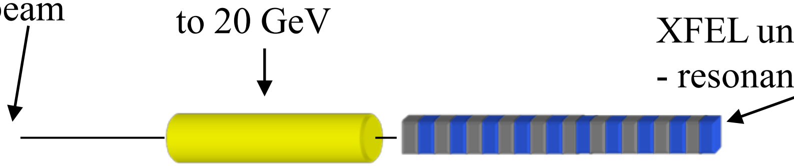


Extended energy

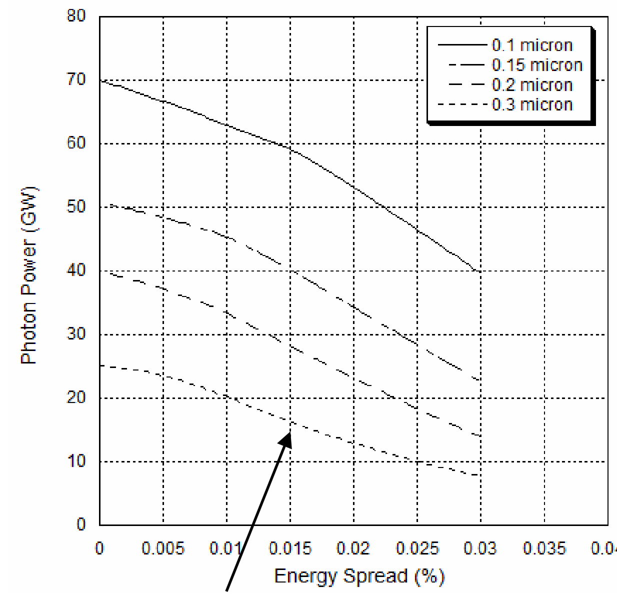
- An extended energy range has been suggested by the 2008 White Paper “Science and Technology of Future, Light Sources”.

MaRIE: From "observing" to "controlling" materials





17 GW, ~ 4 10^{10} X-rays
~ 10^{-3} spectral bandwidth



First x-ray scattering capability at high energy and high repetition frequency with simultaneous charged particle dynamic imaging

100 pC, 30 fsec, 3.4 kA,
0.015% energy spread
0.30 μm emittance

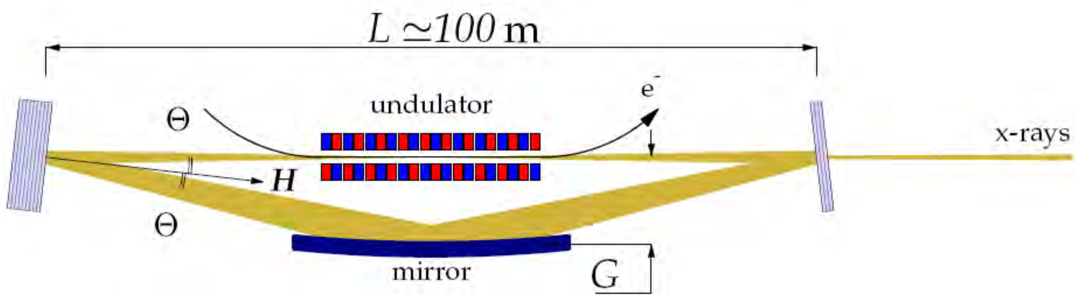
X-FEL Oscillators

- For the ultimate average brightness one could use an X-ray FEL oscillator. Is this just a dream?
- Two schemes have been suggested.

XFELO may revolutionize the hard x-ray techniques developed at third generation light sources and find new applications in areas complementary to SASE FELs

- Inelastic x-ray scattering
- Mössbauer spectroscopy
  - 10^3/pulse, 10^9/sec Mössbauer photons (14.4 keV, 5 neV BW)
- Bulk-sensitive Fermi surface study with HAXPES
- Time-resolved methods (0.1 -1 ps)
- X-ray imaging with near atomic resolution (~1nm)
  - Smaller focal spot with the absence of chromatic aberration
- X-ray photon correlation spectroscopy
  - 10^{15} photons/sec is a game changer, temporal coherence is a huge advantage

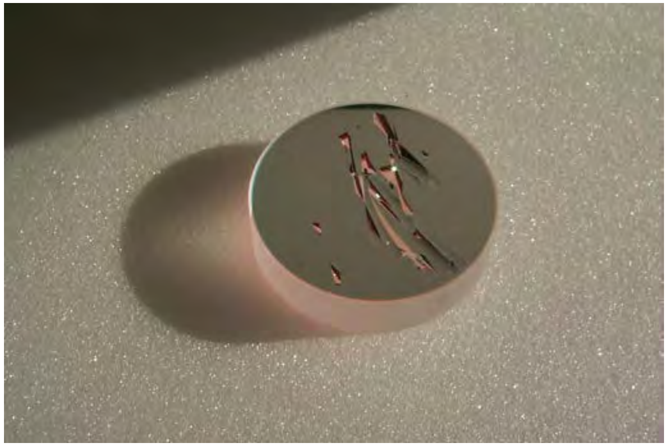
An X-ray FEL Oscillator (XFELO)

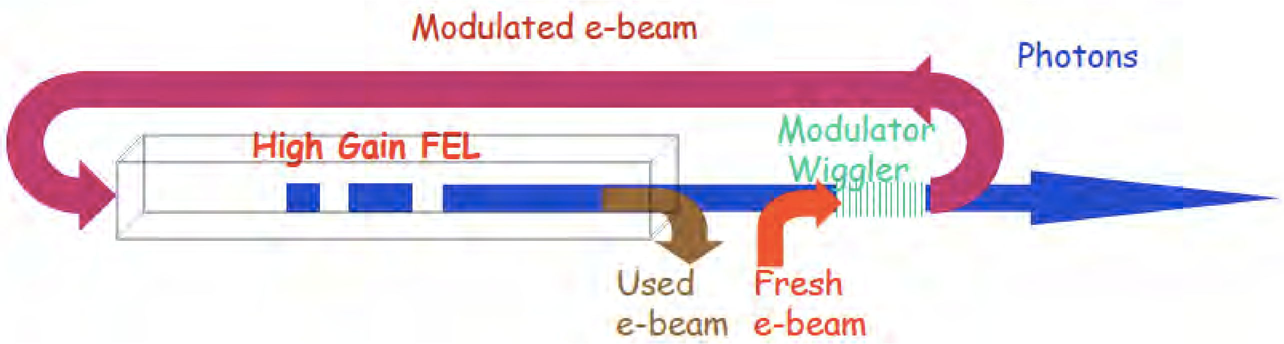


- Full coherence with narrow BW: $\Delta\omega/\omega \sim 10^{-7}$, $\delta\omega$ ~ meV
- High pulse rep rate ~ 1 MHz, high average brightness
- Low pulse intensity ~ 10^9 photons/sec, but peak brightness comparable to LCLS
- Pulse length: 0.1 – 1 ps
- Proposed by Collela and Luccio at a 1983 BNL WS where the SASE concept was proposed
- The feasibility of with an ERL type electron beam was shown in 2008 (KJK, S. Reiche, Y. Shvyd'ko, PRL 100, 244802)

Can we get rid of the mirrors?

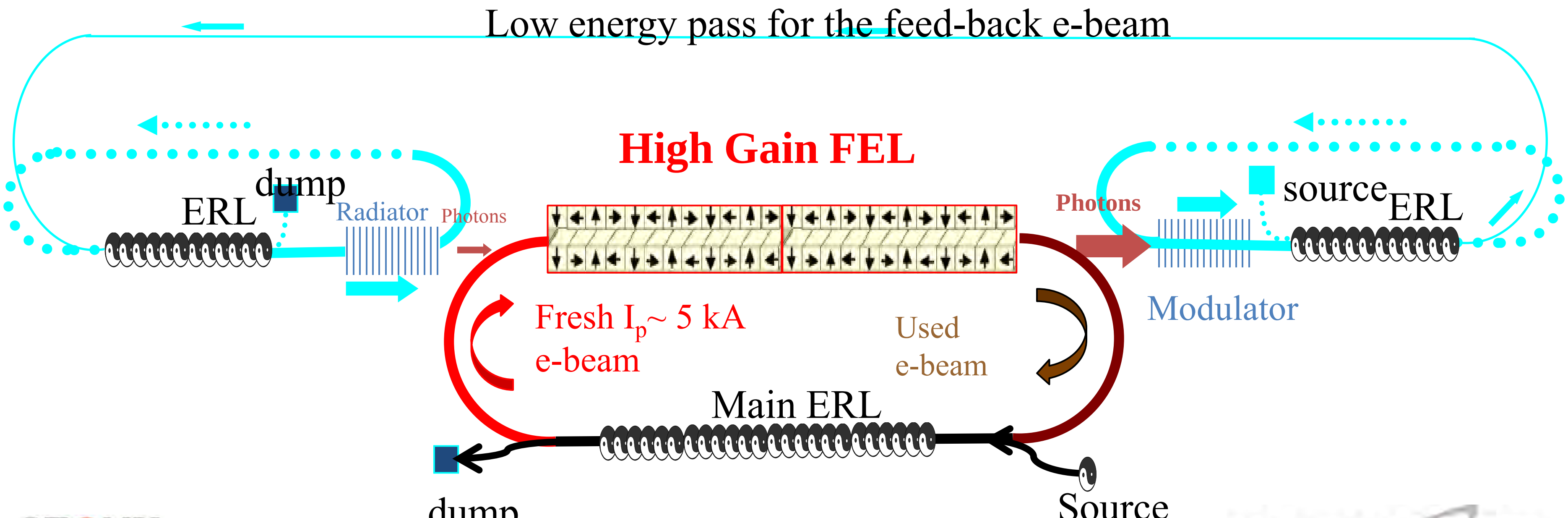
- Key words: narrow Fourier-limited linewidth, single transverse mode, higher spectral brightness, higher stability, full wavelength tunability…





Most advanced OFFELO scheme

- Use beam with necessary energy for effective energy modulation (i.e. use of a typical wiggler)
- Decelerate the feed-back beam to much lower energy (*let's say ~100 MeV)* where synchrotron radiation is mitigated
- Turn the beam around, accelerate it to radiate in the radiator, decelerate it and dump it. Use optics developed by A. Zholents for the isochronous transport.

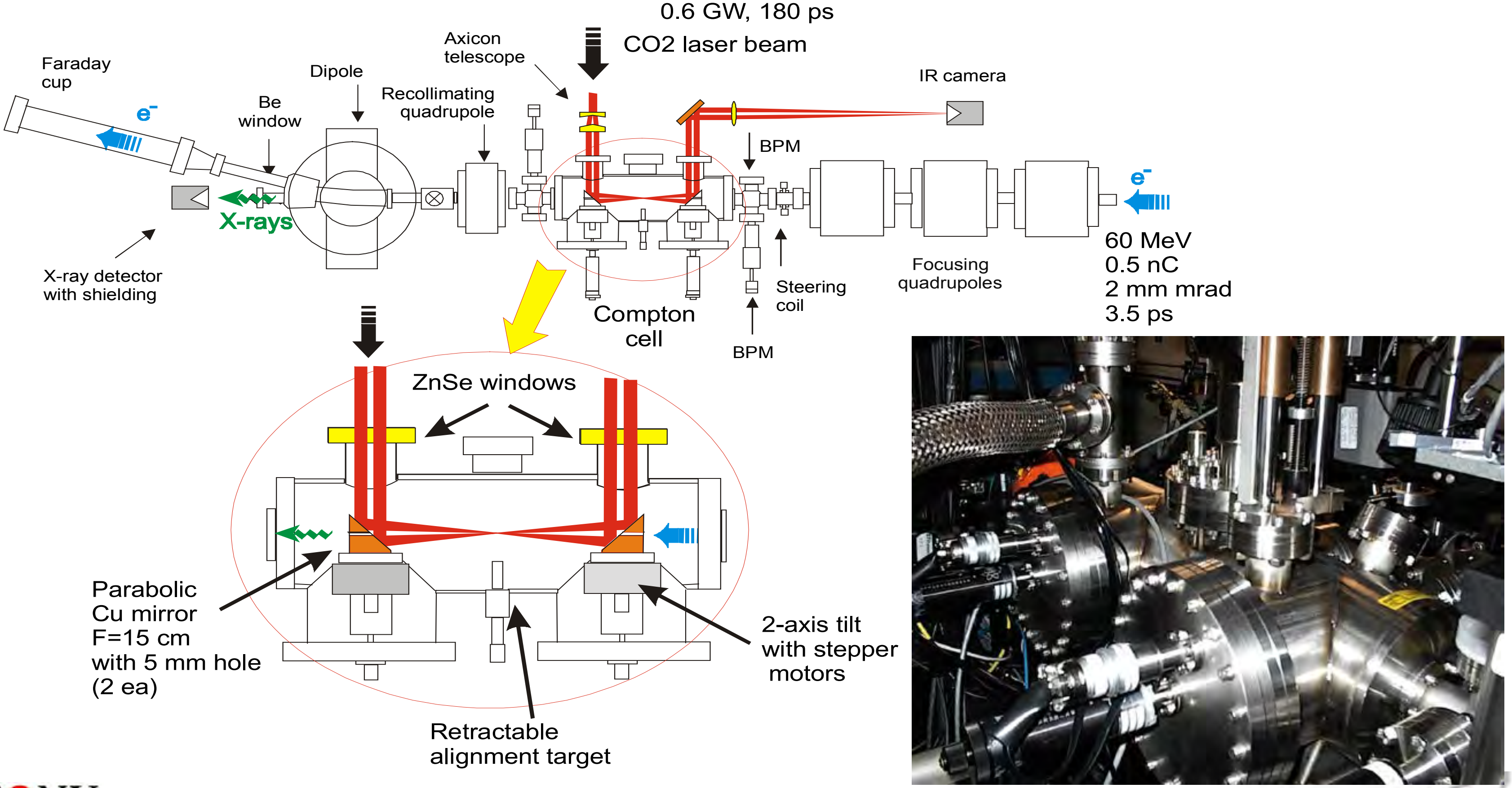


Compact

- Inverse Compton Scattering leads to an ultra-compact X-ray source at a cost of some performance parameters.
- 100 total facility length is an objective for compact X-ray FELs.
- Ultra-compact hard X-ray facilities may become possible with plasma acceleration.

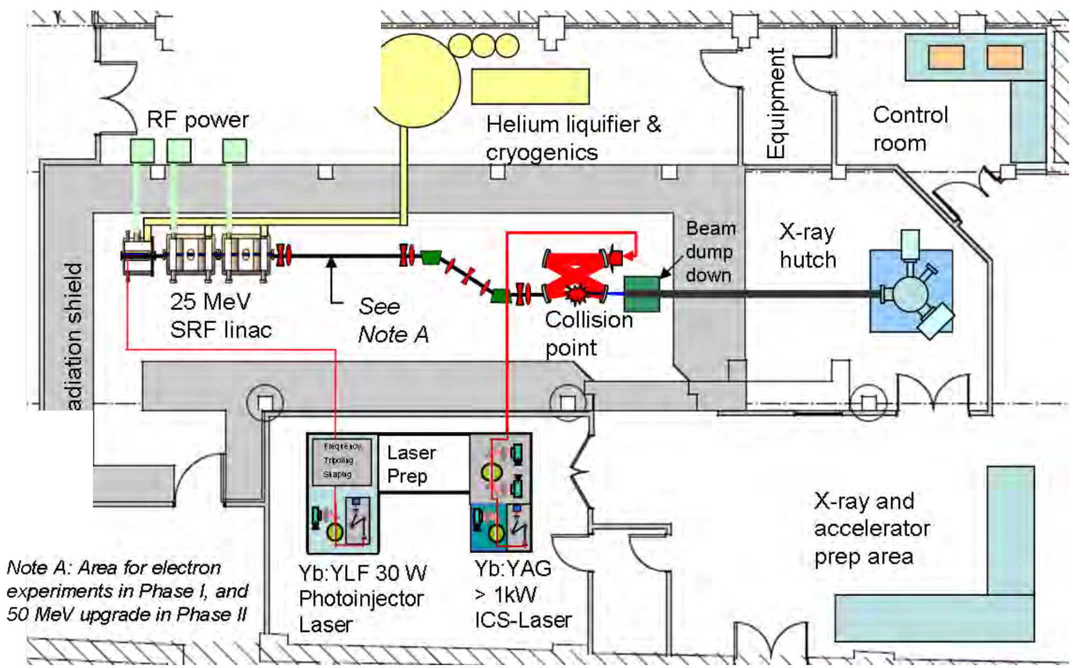
Personal note: Inverse Compton Scattering at the BNL ATF

- 1998 world record in photons/pulse



ICS R&D Objectives / layout

- Development of **state-of-the-art electron guns** and **innovative SRF linacs** that benefit both large and small facilities.
- Advances in lasers including **fs optical timing** systems and **high power solid-state lasers**. Optical timing and synchronization benefits all future sources, and high power lasers benefit seeded FELs and HHG sources.
- R&D on **nanoengineered cathodes** in pursuit of structured electron beams that may emit coherent x-rays.



@ Bill Graves

Short pulse compact X-ray FELs

- One attractive feature of X-rays FELs - the generation of femtosecond to attosecond X-ray pulses.
- X-rays FEL can be optimized for this purpose, reducing the electron beam energy, thus making the system more compact, using a very short electron bunch, 1 μm or less, to generate a short FEL pulse. The bunch charge is few pC leading to a small emittance. Large peak current, ~1 kA, can be obtained with velocity and magnetic compression. The result is a single SASE spike, fully coherent.

- [J. Rosenzweig et al., Nucl. Instr. And Meth.A593, 39 (2008); S. Reiche et al., Nucl. Instr. And Meth.A593, 45 (2008)]

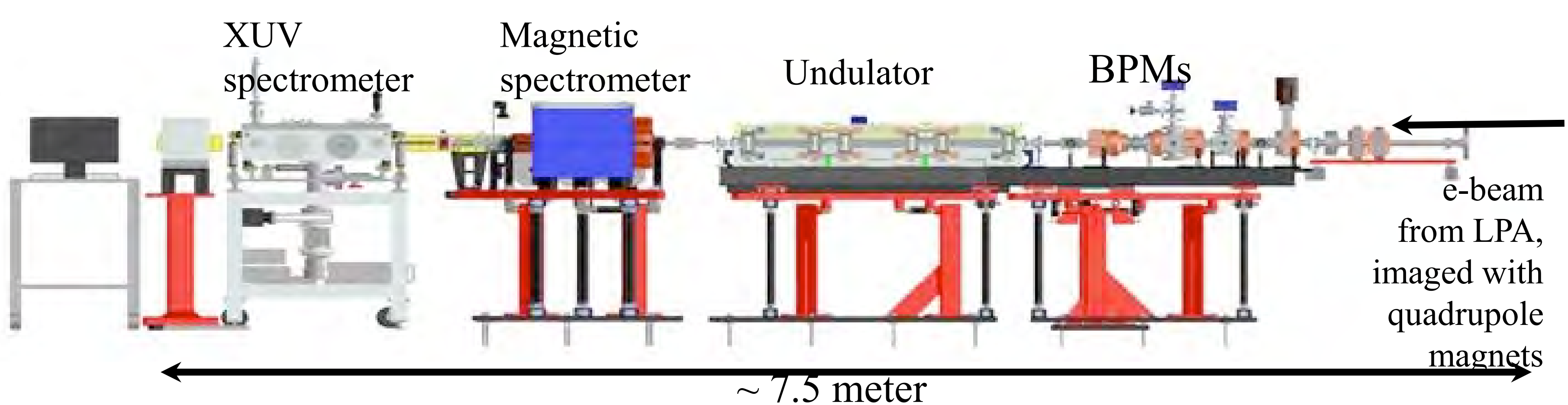
Examples: a 1nm, short pulse FEL

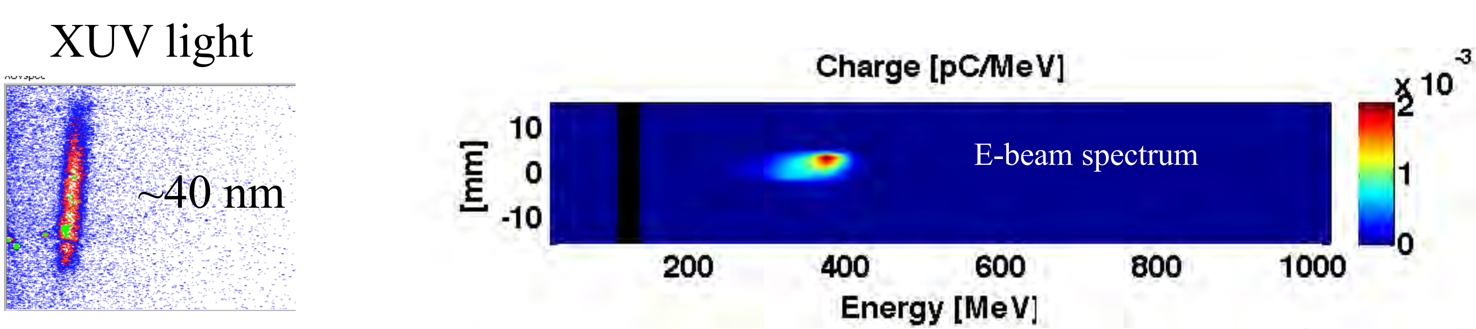
Energy Gev	Charge pC	λ_U, cm /K	L, nm	σ_L, fs	L_G, m/ρx10^3	P, GW	N_{pho}/ pulse 10^9	N_{spikes}
1.17	1	0.7/1	1	1	0.26/1.7	0.7	3.4	1.3
1.17	10	0.7/1	1	4	0.21/1.9	2.2	44	6.3
1.7	1	1.5/1	1	1	0.5/2	1	4.5	1.4
1.7	10	1.5/1	1	4	0.4/2	3.2	63	7.2

A 1 nm, 1 fs FEL can be built with a beam energy of about 1.2 GeV.

First light for laser-plasma acceleration: undulator diagnostic of beams at LBNL

- **Uses combined gas jet + capillary discharge based LPA**
  - **Beam imaging with permanent quadrupoles onto undulator entrance ~4.5 meter away: observed first light!**

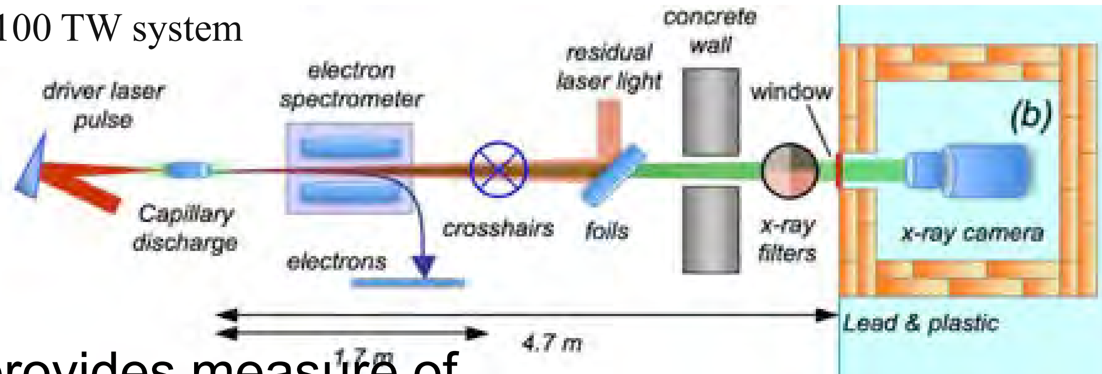




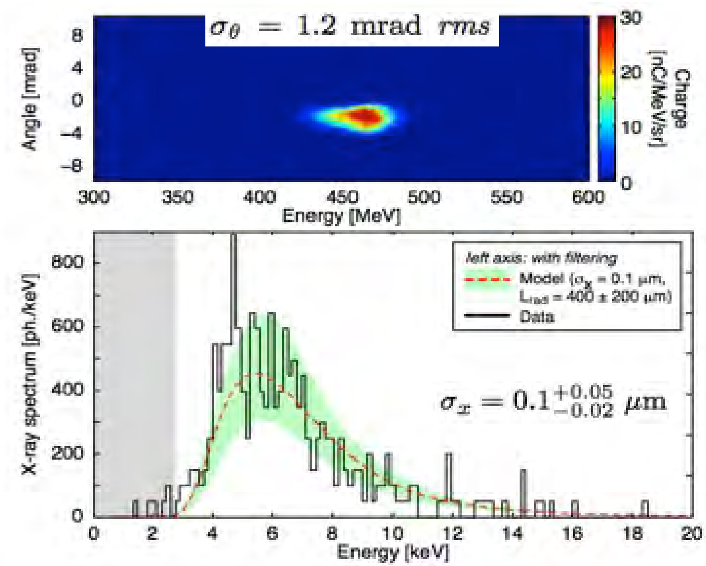
@ Wim Leemans

Ultra-low emittance measured using x-ray spectroscopy of betatron radiation of laser plasma accelerator beams

100 TW system



- X-ray spectrum provides measure of beam size *inside* accelerator:
- 0.1-0.15 micron
- Simultaneous divergence and beam energy measurement provides normalized emittance
- $\varepsilon_x \sim \gamma \sigma_x \sigma_\Theta \sim$ 0.1-0.2 mm-mrad-normalized
- Value consistent with simulations

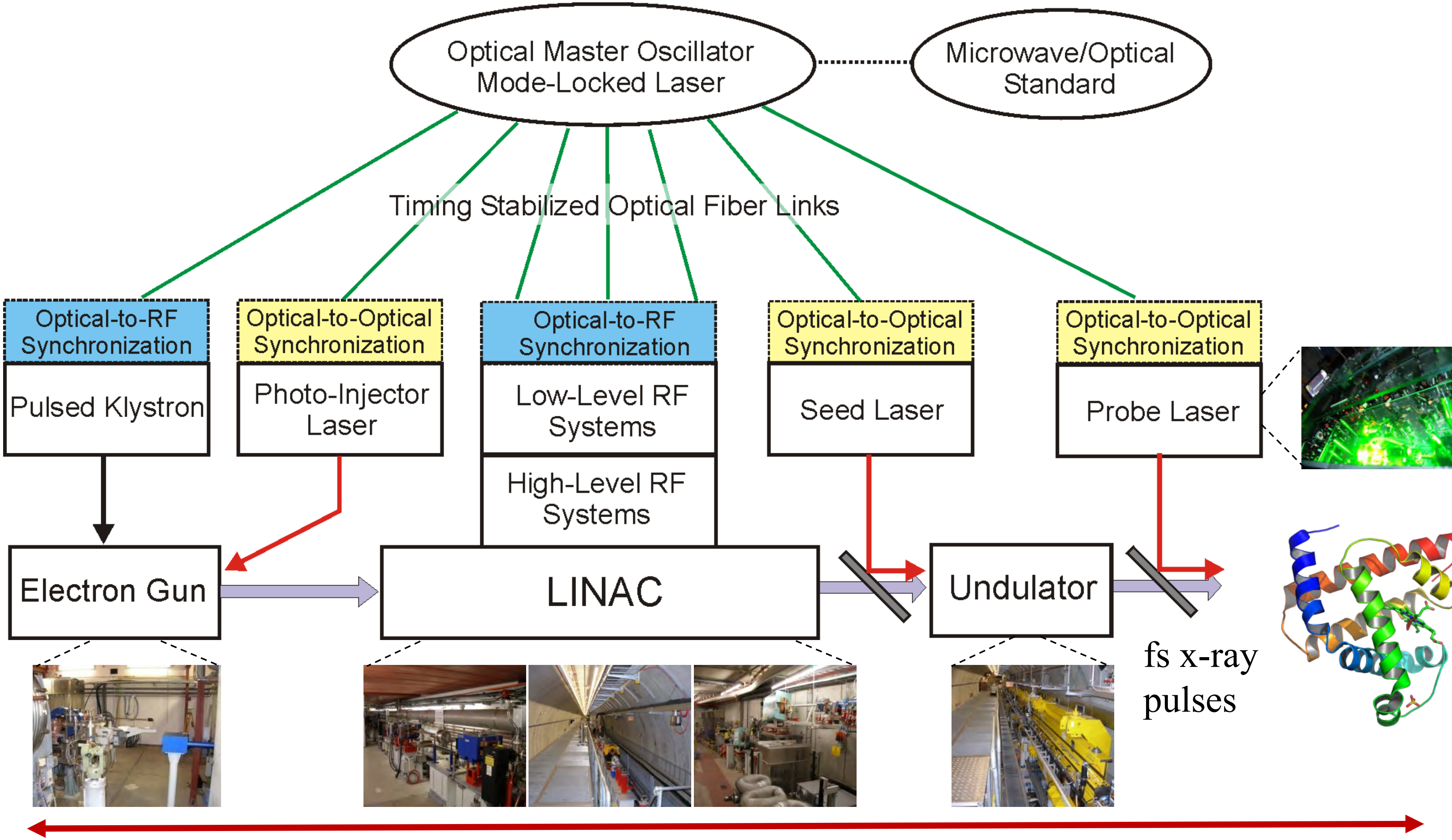


X-ray spectrum

[1] G. R. Plateau et al., submitted (2011)

Laser and timing

Timing of X-ray Free Electron Lasers

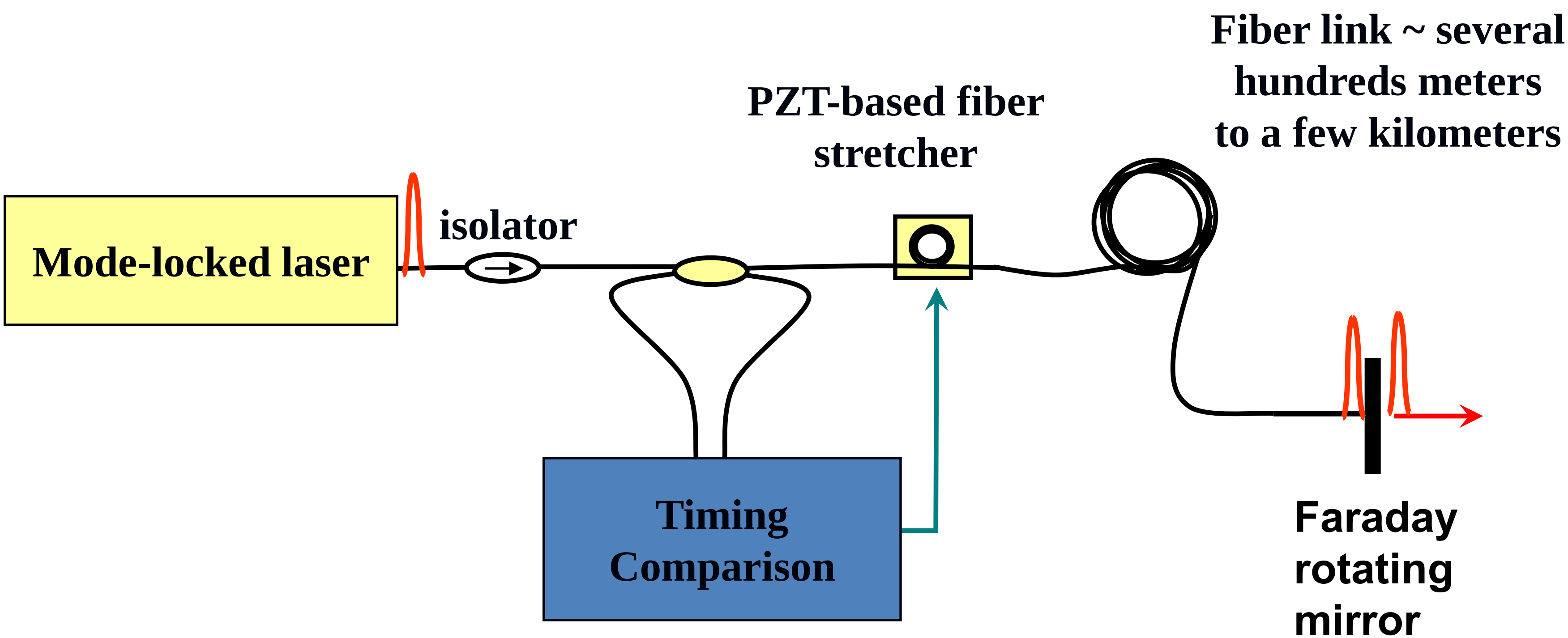


J. Kim et al., FEL 2004, Nat. Photonics 2, 733 (2008)

@ Franz Kaertner

Timing-Stabilized Fiber Links

5 fs (rms) drifts over one week of operation demonstrated



Cancel fiber length fluctuations that are slower than the pulse travel time (2nL/c).

1 km fiber: travel time = 10 μs ~100 kHz BW

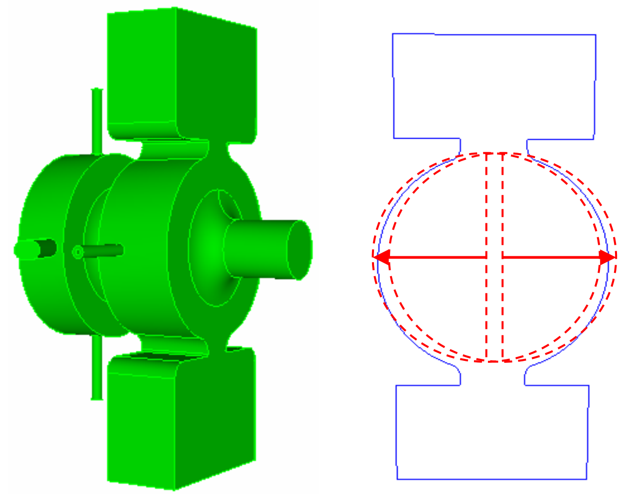
Computational physics

- It is unimaginable that we could design the future facilities without powerful computational tools.
- Some such tools have been developed by individuals and made widely available to become an essential asset to the community (e.g. ELEGANT by Michael Borland, GENESIS by Sven Reiche and more) .
- Massively parallel computer require dedicated teams for software development.
- The tools developed must be easily shared.

Omega3P – LCLS RF Gun Cavity Design

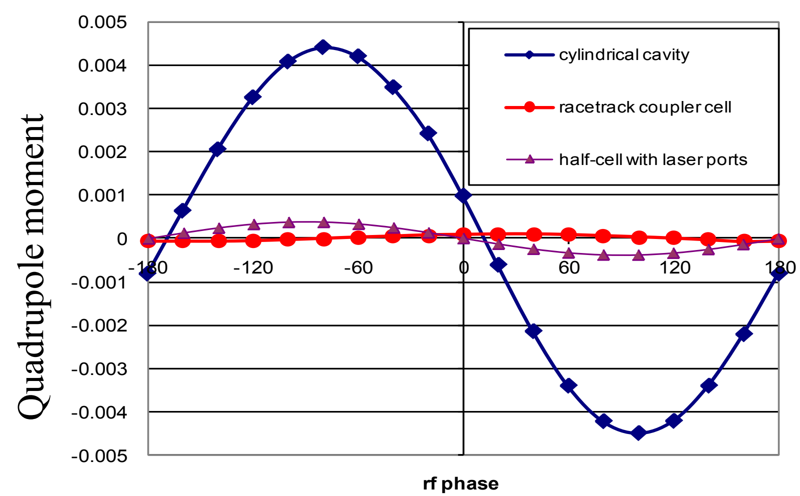
Provided dimensions for LCLS RF gun cavity to meet design requirements:

- *Reduce pulse heating by rounding of the z-coupling iris*
- *Minimize dipole and quadrupole fields via a racetrack dual-feed coupler design*

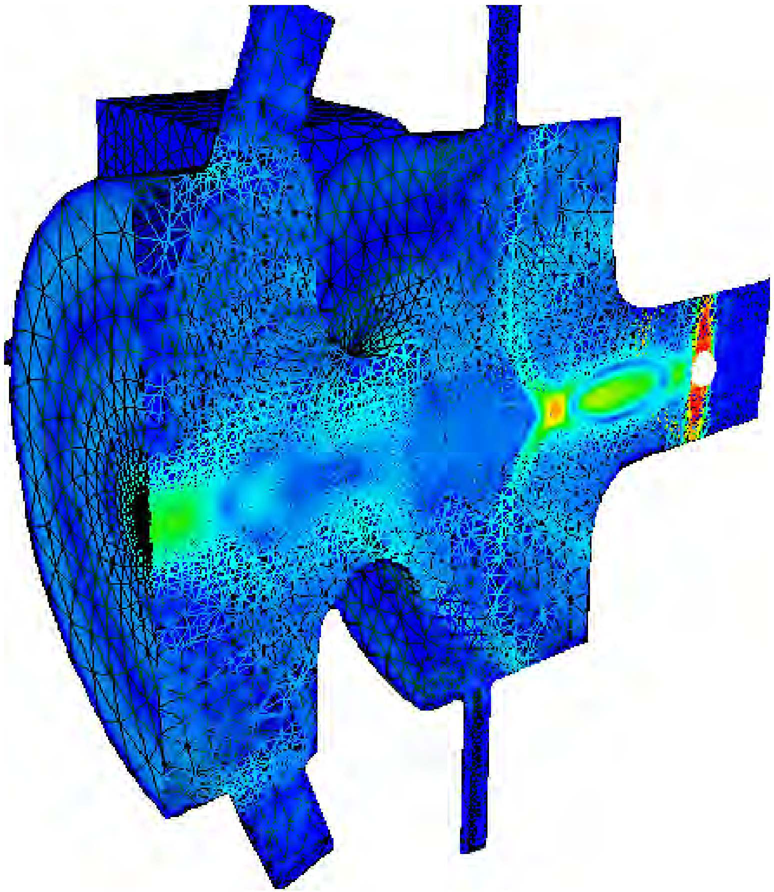


Code validated by Measurement

RF parameter	Design	Measured
f_π (GHz)	2.855987	2.855999
Qo	13960	14062
β	2.1	2.03
Mode Sep. Δf (MHz)	15	15.17
Field balance	1	1

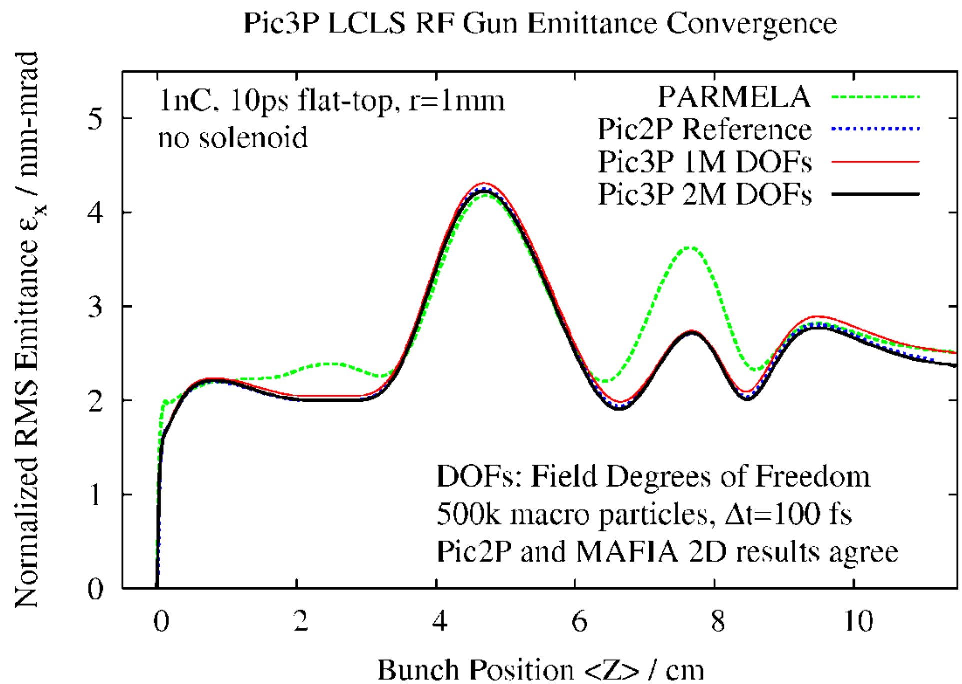


Pic3P – LCLS RF Gun Emittance



Snapshot of electron bunch and scattered self-fields

Racetrack cavity design: Almost 2D drive mode. Cylindrical bunch allows benchmarking of 3D code Pic3P against 2D codes Pic2P and PARMELA



Unprecedented Accuracy due to Higher-Order Particle-Field Coupling and Conformal Boundaries

Test facilities

- Test facilities have been repeatedly recommended by committees and workshops
- Test facilities are an essential step towards a successful users' facility as the LCLS proved
- They are hotbeds of innovation and save money in the long run
- We have a few valuable test facilities already in existence

Personal note:
The BNL Accelerator Test Facility

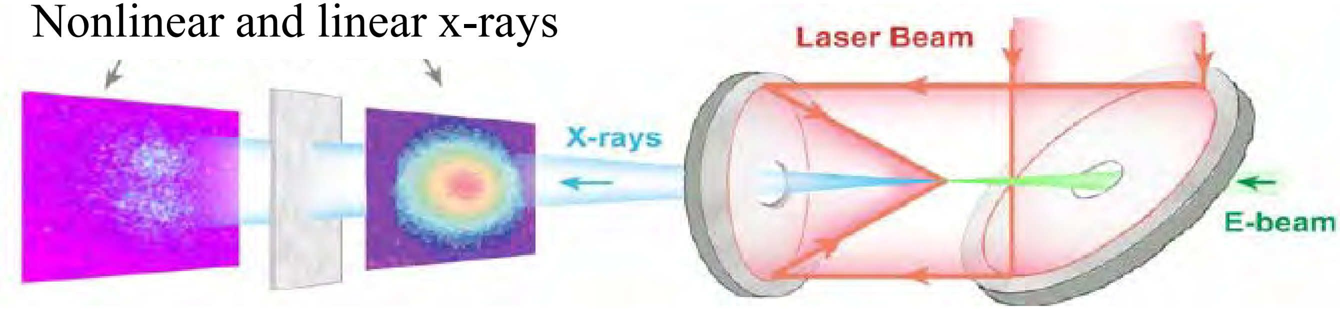
- The ATF is a Users' Facility serving the community with high-brightness electron beams, high-power synchronized lasers, FELs and advanced beam instrumentation.
- The ATF program is governed by a blue-ribbon Program Advisory Committee.
- Landmark developments towards the LCLS were made at the ATF, including the electron gun development and the VISA SASE experiment, as well as the historic first seeding / HGHG experiment.
- ATF current experimental program
  - CO2 laser (5TW near term, 10-20TW later)
  - Laser Generated Ion beams
  - Compton back scattering X ray beams
  - High Gradient / X band option at ATF
  - Plasma WFA
  - Dielectric WFA

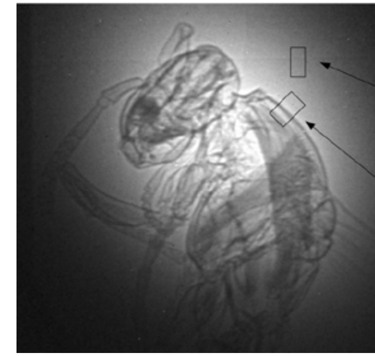
The VISA undulator: POP experiment for the LCLS, done at the ATF

@ Vitaly Yakimenko

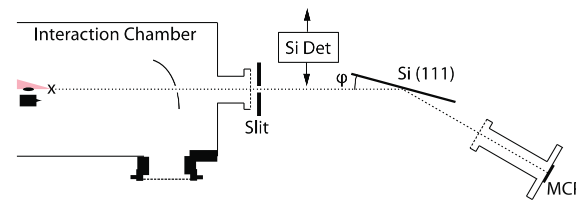
Compton X ray Source

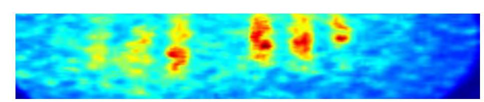
Measured CCD images
Nonlinear and linear x-rays





- Compton based 6KeV x ray source with a record number of photons (PRE 1998)
- Observation of the second harmonic (PRL 2001)
- Single shot phase contrast imaging (APL 2010)
- Single shot Diffraction (in preparation)



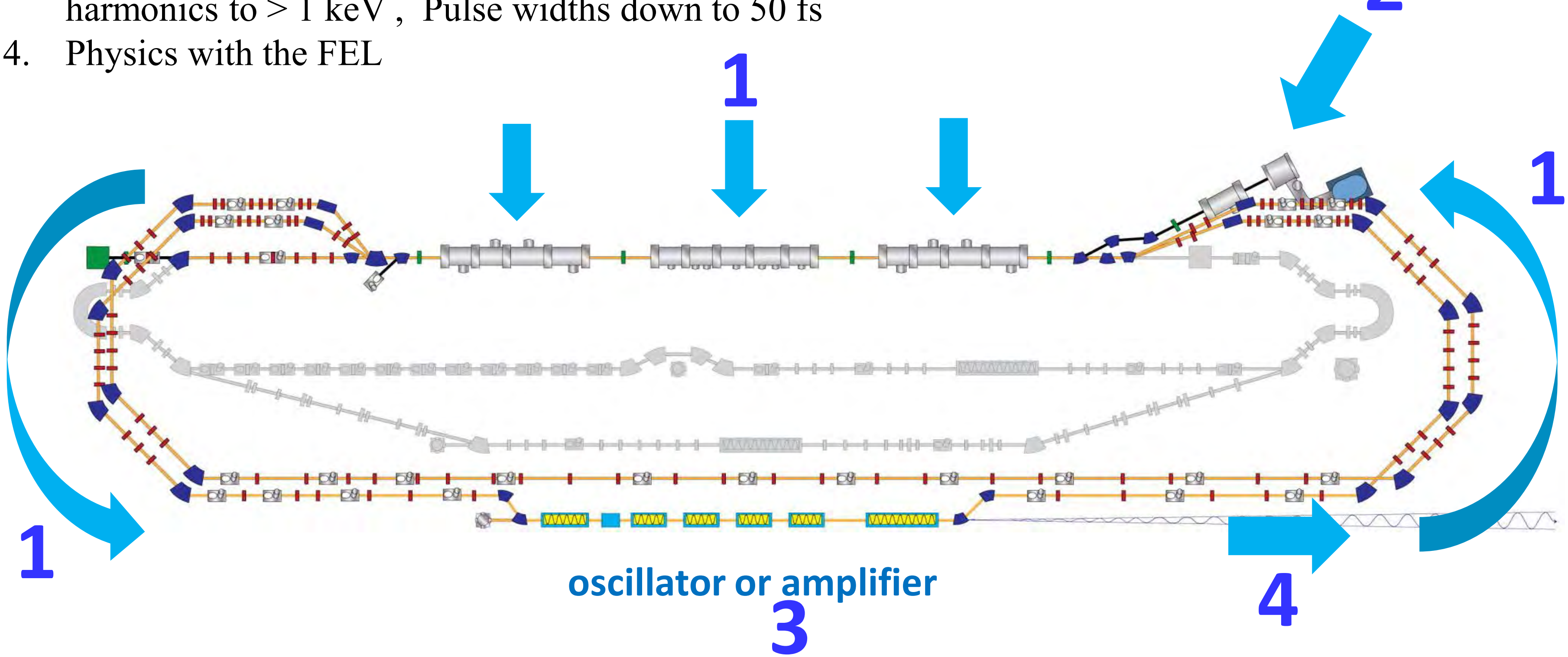


- 100fs X ray camera
- Recirculation cavity to increase average flux
- Gamma source for polarized positron source

Jlab ERL FEL: R&D possibilities on injectors, SRF linacs of high gradient and low loss, low emittance beam transport.

Possible R&D topics using existing facility:

1. Recirculation with energy recovery: 600 MeV, 2 pass acceleration, 900 MeV 3 pass
2. CW Injector: 200 pC, 1 mm mrad injector -up to 75 MHz CW rep. rate
3. Oscillator and amplifier physics. 10 eV – 100+ eV fundamental output, GW peak power, harmonics to > 1 keV , Pulse widths down to 50 fs
4. Physics with the FEL



@ George Neil

BNL Source Development Laboratory (SDL) FEL & Bright Beams Test Bed

$$\lambda_{Output} = \lambda_{Laser} / n$$

$$\lambda_{Input} = \lambda_{Laser}$$

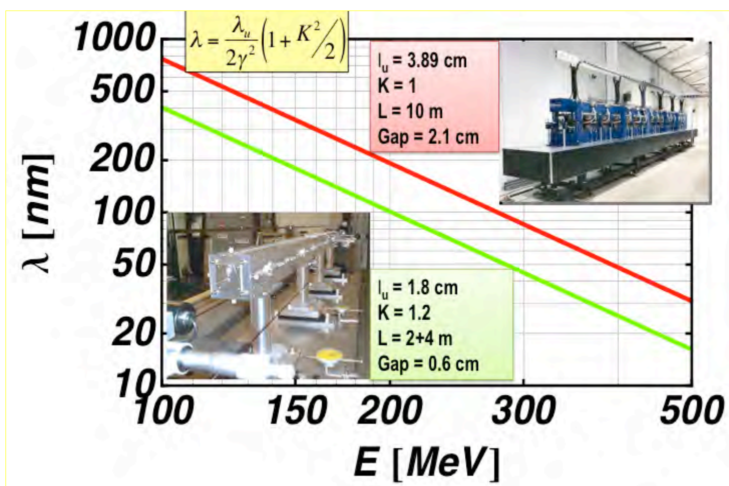
Laser seeded FEL Amplifier

300 MeV Linac

SDL is an *operational* facility, and it is ideally suited for testing laser seeded FEL schemes, such as :

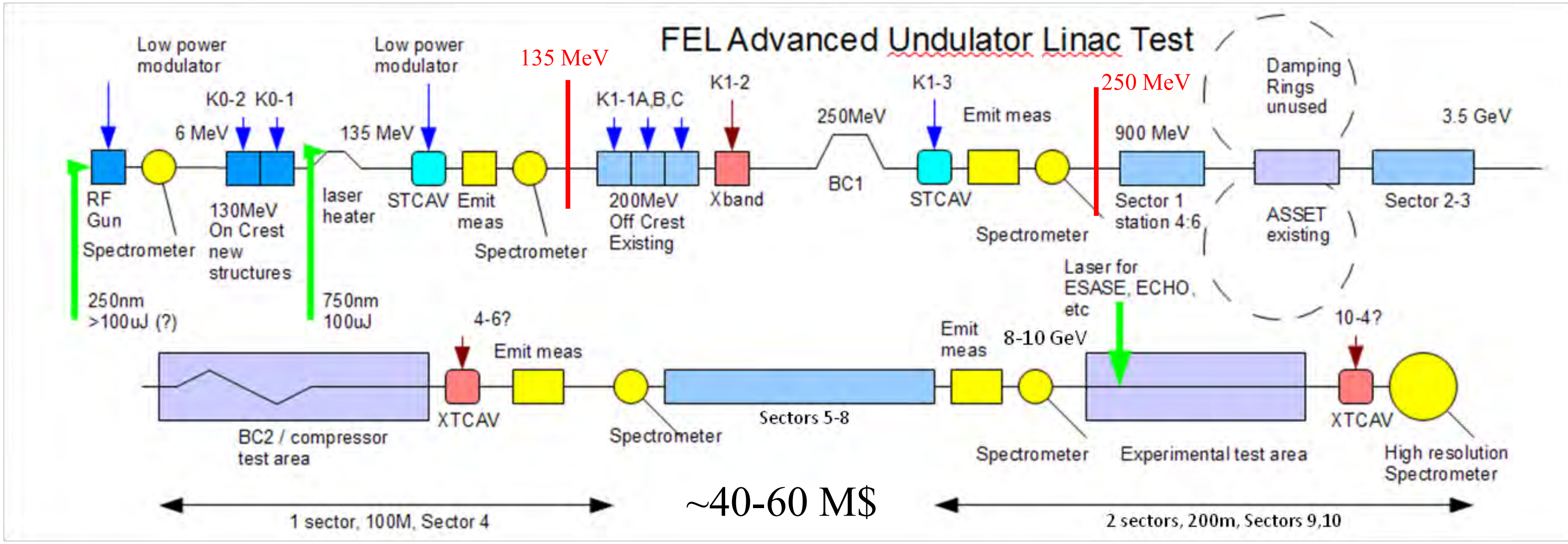
- EEHG FELs
- HHG Seeded FELS

- Laser seeded FEL: superradiance, tapering &detuning; 3rd & 4th HGHG.
- Single-spike SASE.
- Intense THz & appl.
- Ultrafast Electron Diffraction (UED).
- Electron Beam Microbunching.
- Surface photoemission.



@ Xijie Wang

SLAC FEL Integrated Test Facility – Future?



135 MeV:
- Gun brightness optimization
- Test new guns
- Multi-bunch tests.
- Low charge diagnostics
- Emittance exchange (with added equipment)

250 MeV:
- Compression Studies
  - Velocity bunching
  - Nonlinear optics
  - Micro-bunch, COTR, CSR
- Laser heater studies
- Other Applications
  - Compact /efficient THz source
  - ….

2-10 GeV:
- High-E bunch compression
- short wavelength seeding, ESASE
- Beam property preservation
- Ultrafast diagnostics (e-/X-ray)
- Multi-bunch fast kickers
- Short (~1GL) undulator tests

@ Bob Hettel

Direction for future R&D

- Objective: Jumps start the discussion.
- Some future R&D is obvious.
- Much hopefully can be revealed by the following discussion.
- More will spring on us unexpectedly and the funding agencies must be ready for unplanned R&D.

Photocathodes and guns

- Clearly all future light sources (other than USR) depend on the performance of photocathodes and better electron guns.
- Superconducting RF guns are particularly important for high repetition rate and high-brightness beams.
- We need a high QE, robust and long-life photocathode compatible with SRF guns which has a low thermal emittance.

X-ray FEL R&D identified by SLAC

FEL seeding schemes

- X-ray self-seeding (hard and soft)
- high harmonic seeding
- laser seeding at nm wavelength (Echo, HHG, …)
- laser R&D

Beam brightness and manipulation

- low-rep rate cathode/gun
- high-rep rate cathode/gun
- low-E compression/manipulation, CSR, etc
- preserving beam properties at high E
- high-E bunch compression/manipulation

Ultrafast techniques

- temporal diagnostics and timing/synchronization
- fs/as x-ray pulses

Terahertz and polarization

- THz/X-ray pump probe
- polarization control

Technology development

- multi-bunch linac R&D (NC)
- high-rep rate linac (SC)
- short-period + novel undulators
- spreader R&D
- X-ray diagnostics
- detector R&D

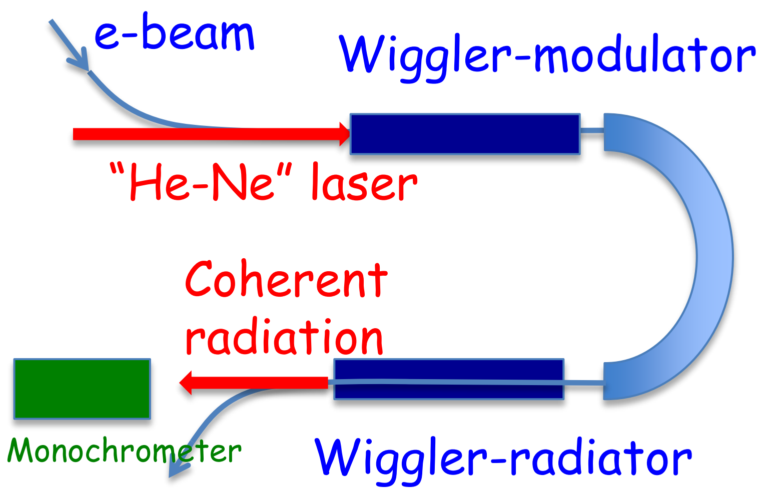
R&D issues for X-ray oscillators

Diamond reflector

- High-reflectivity > 98% was demonstrated (TISNCM, Russia).
- Ultra small expansion coefficient measured at cryogenic temperature
- The crystal damage issues should be understood and mitigated

The tight angular stability tolerance (< 10 nrad)

Specs for grazing incidence focusing mirrors are at the limit of the current state-of-the-art



Optics-free:
e-beam
Mirror at
the ATF

Finally some questions:

- Can we control the peak intensity of FELs so that we can obtain high average brightness and safe peak brightness?
- Can we operate a large number of FELs off a single bunch stream (linac or ERL)?
- What is the role of small dedicated test facilities as compared with using machine studies time at a users' facility?

Discussion:

- The following discussion is aimed at a prioritization of R&D topics, identifying essential R&D during various time frames: next 3 years; next 6 years, etc.

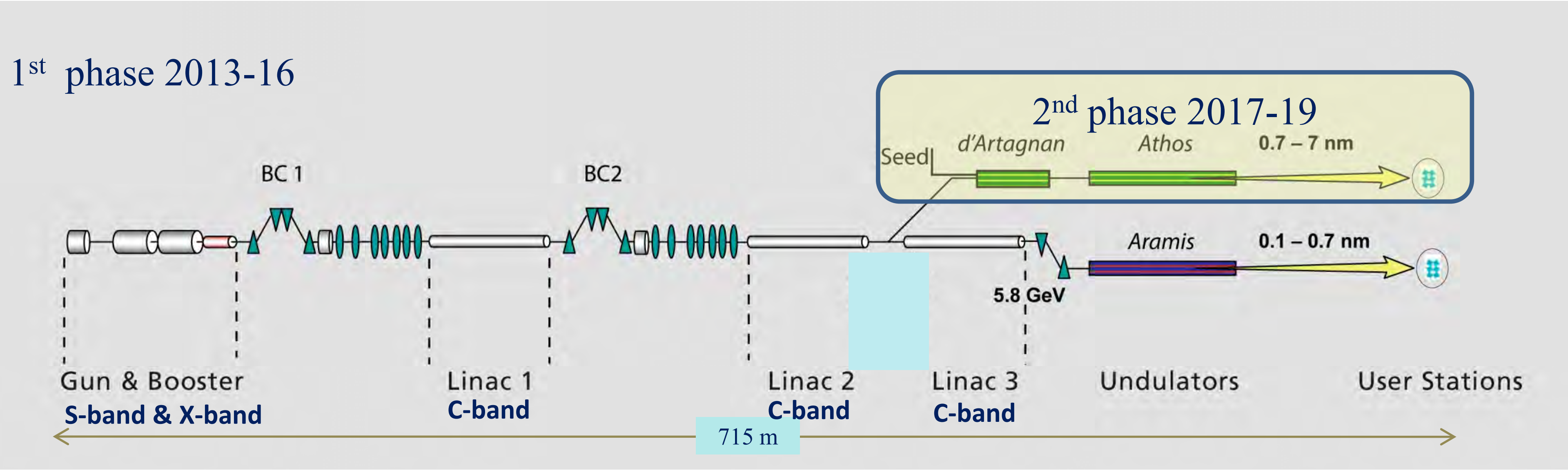
Acknowledgement

Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy and at Stony Brook University under grant DE-SC0005713.

Additional material

- This material actually belongs to the presentation but could not be covered in the limited time available.

SwissFEL



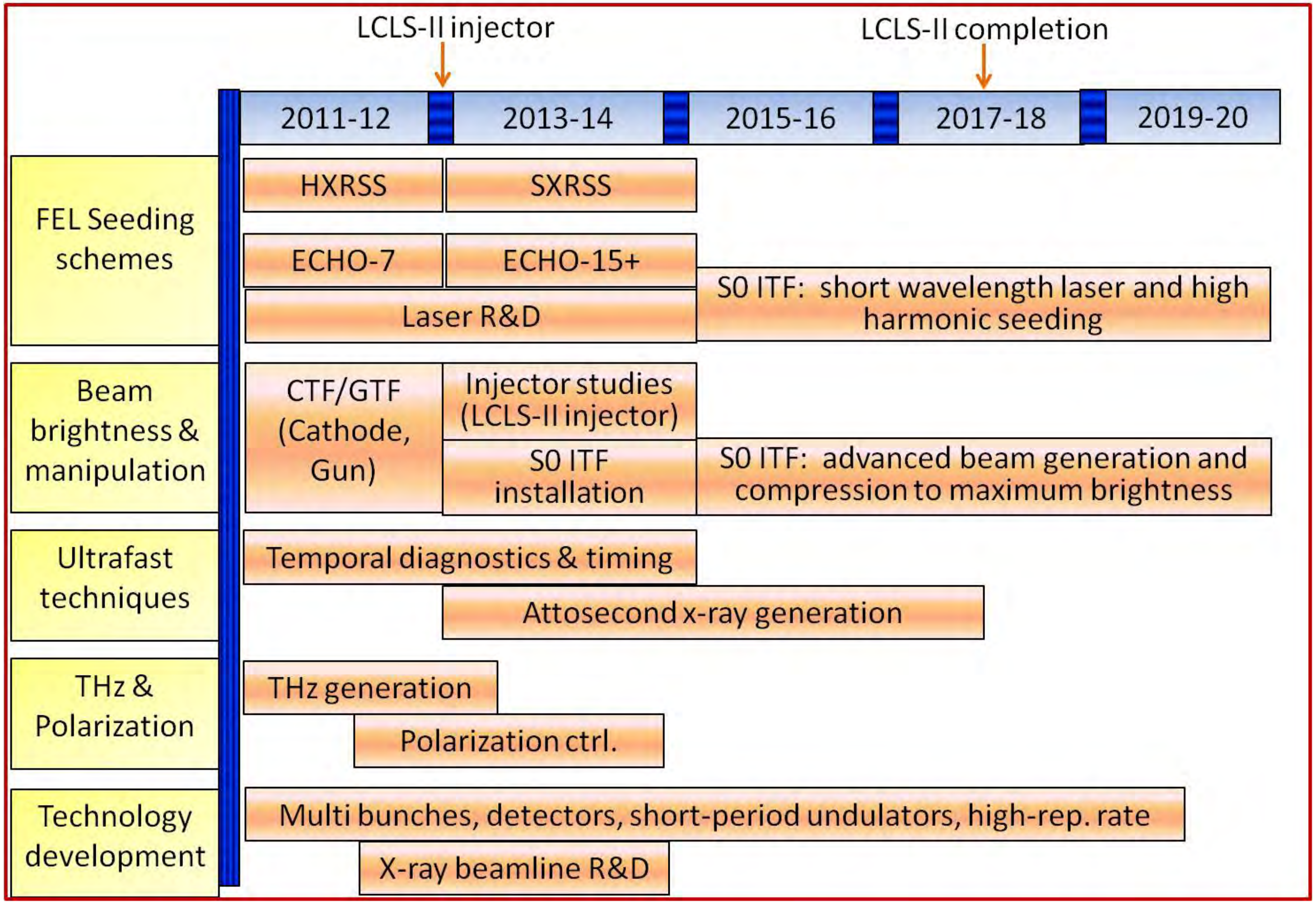
Aramis: 1-7 Å hard X-ray SASE FEL,
In-vacuum , planar undulators with variable gap.
User operation from mid 2017

Athos : (2nd phase) 7-70 Å soft X-ray FEL for SASE & Seeded operation .
APPLE II undulators with variable gap and full polarization control.
User operation end 2019?

Core Activities of EuroFEL

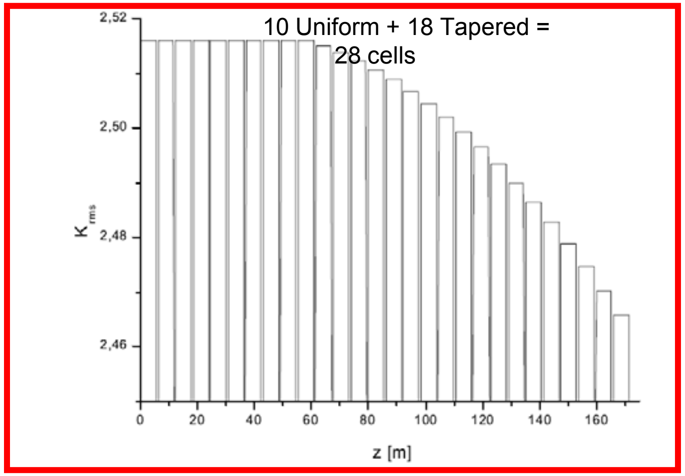
1. Promote the development, construction and operation of complementary, world-class FEL or short-pulse facilities for multidisciplinary research with open access
2. Ensure transparent and efficient access and optimum support of users
3. Coordinate technical developments
4. Coordinate training and education
5. Ensure efficient communication, external and internal
6. Represent European FEL science and technology

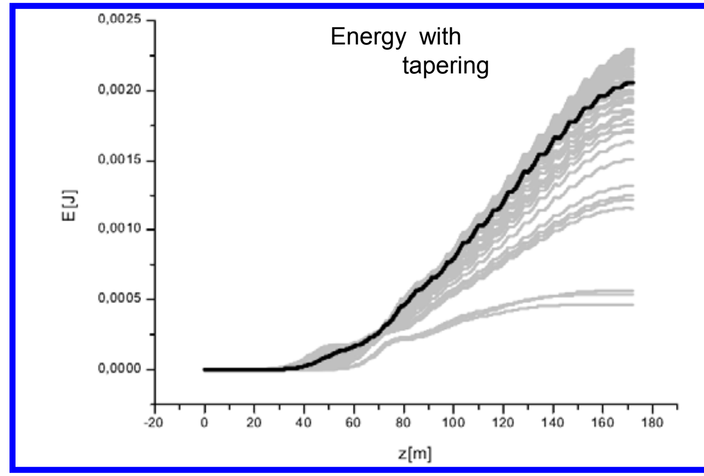
FEL R&D Program with essential components for LCLS II, NGLS and other FELs

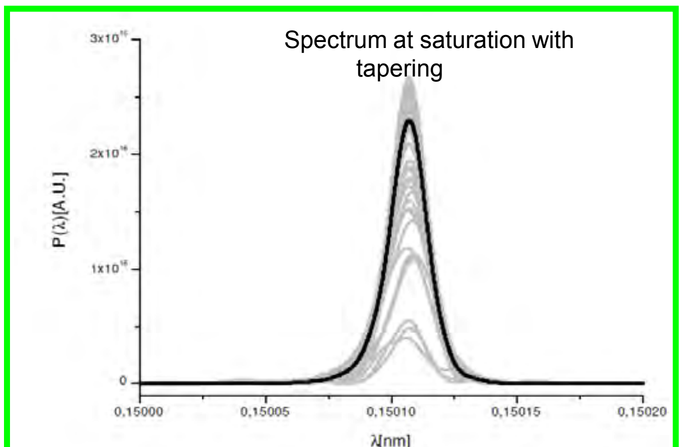


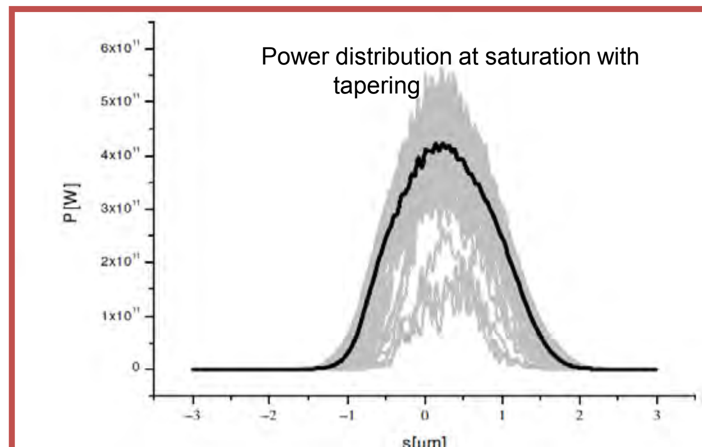
HXRSS: hard x-ray self-seeding
SXRSS: soft x-ray self-seeding

Feasibility study for the European XFEL





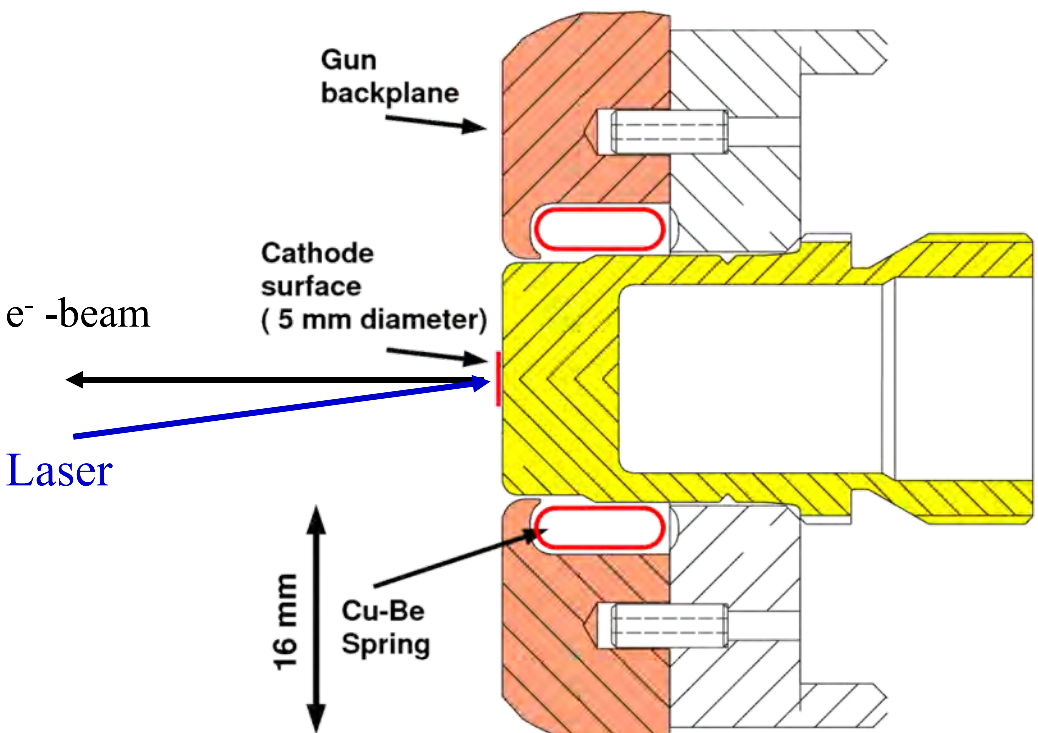


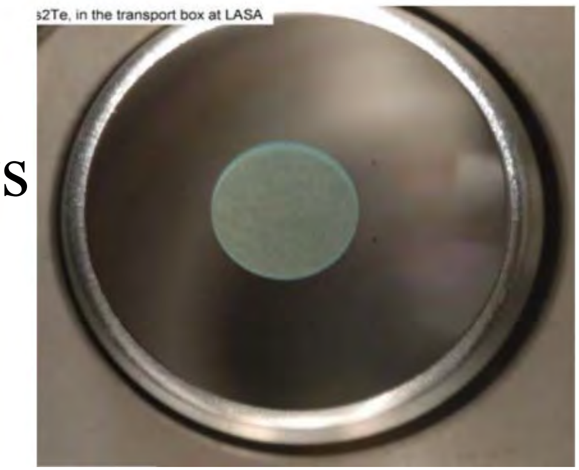


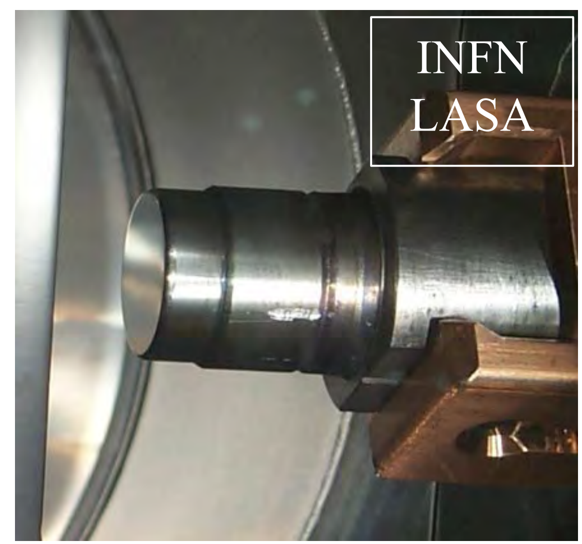
400 GW peak power, 5 fs FWHM i.e 2 mJ energy at 0.15 nm. Bandwidth is about 0.01 %. In other words fully coherent output pulse (Fourier limited bandwidth and full transverse coherence)

FLASH Cs_2Te Cathodes

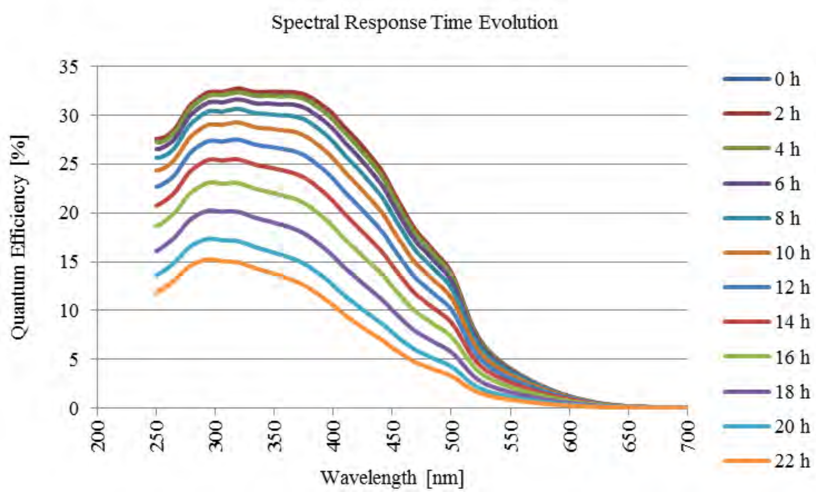
- Cs_2Te: high quantum efficiency at high beam currents
- Thin film on Mo, quantum efficiency ~ 10 %
- Lifetime depends on vacuum condition
  - FLASH gun: ~10^{-10} mbar → lifetime > 100 days



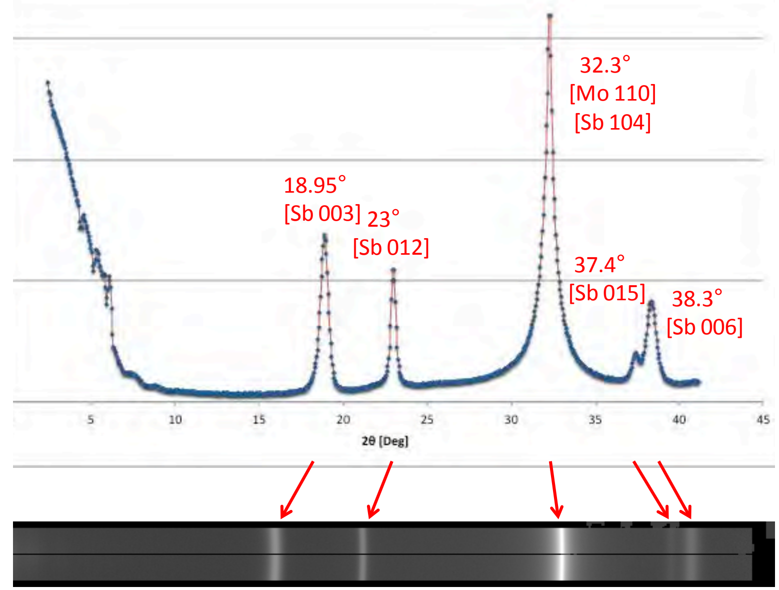




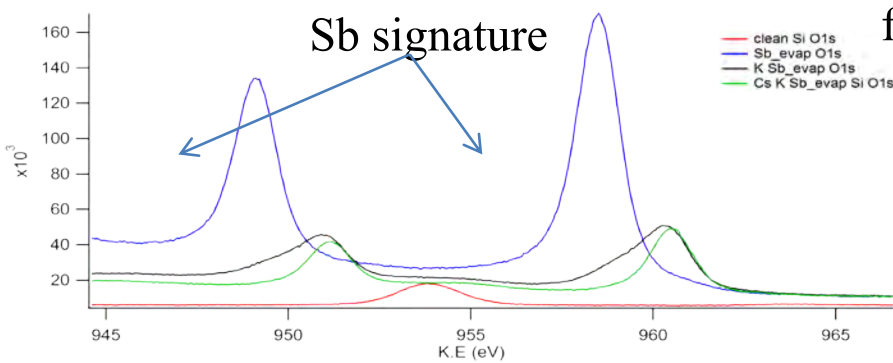
@ Siegfried Schreiber



Time evolution of K_2CsSb spectral response during exposure to 2pBar of O_2



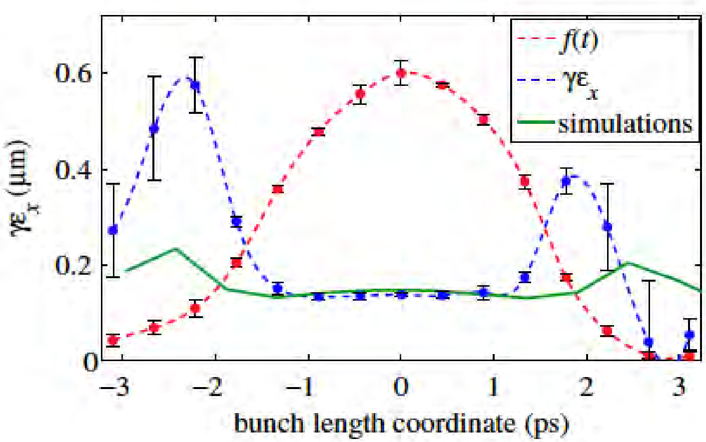
XRD of in-situ grown Sb layers, showing film texture and grain size



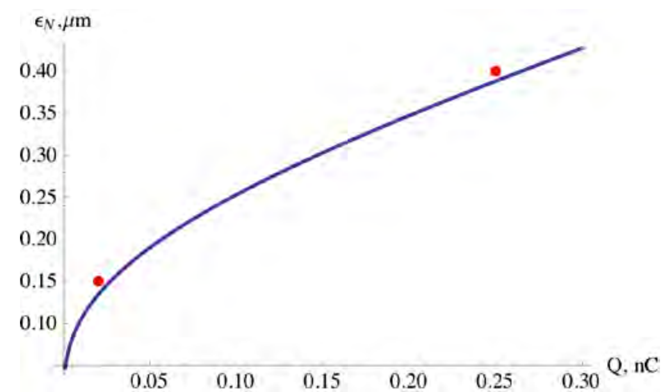
XPS Spectrum of K_2CsSb at various stages of growth, showing the disappearance of the substrate Si peak, and the chemical shift of the Sb peak during growth

Kiessig fringes from provide precise measurement of film thickness

Scaling of transverse emittance with charge



LCLS results at 20 pC: slice emittance <0.2μm. Y. Ding et al., Phys. Rev. Lett. 102, 254801 (2009)



Emittance scaling. ε_N in μm, Q nC. For Q <0.3 nC the RF term is negligible. Ferrario et al., Nucl. Instr. And Meth. A57, 98 (2006).

Thermal Space charge RF

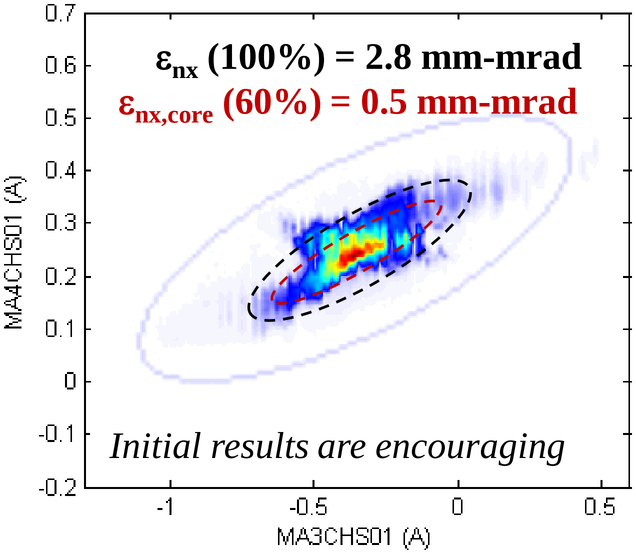
$$\varepsilon_N = 1.4\sqrt{0.111Q^{2/3} + 0.18Q^{4/3} + 0.18Q^{8/3}}$$

The red dots are LCLS experimental results. The empirical factor 1.4 indicates a thermal emittance larger than theoretical value

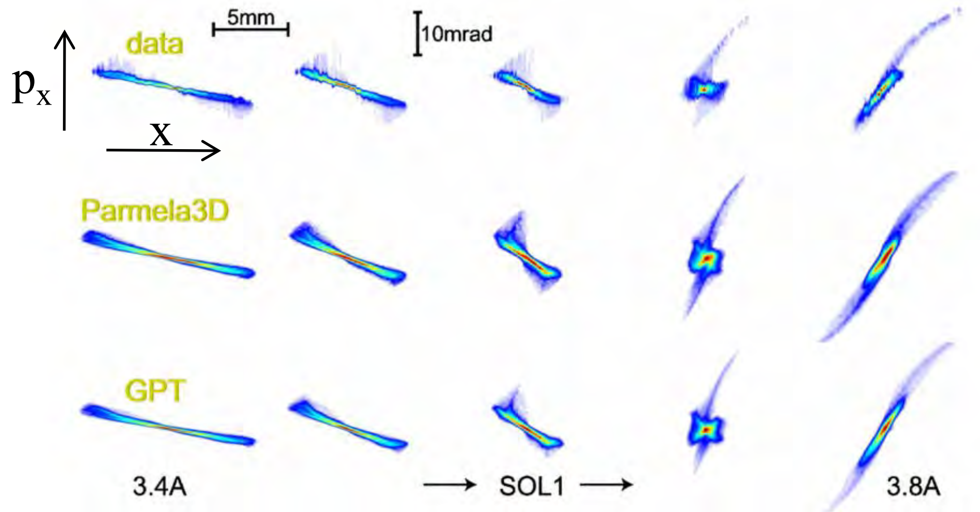
Snapshots of photo-injector investigations at Cornell

p_z = 5.2 MeV/c, 80pC/bunch

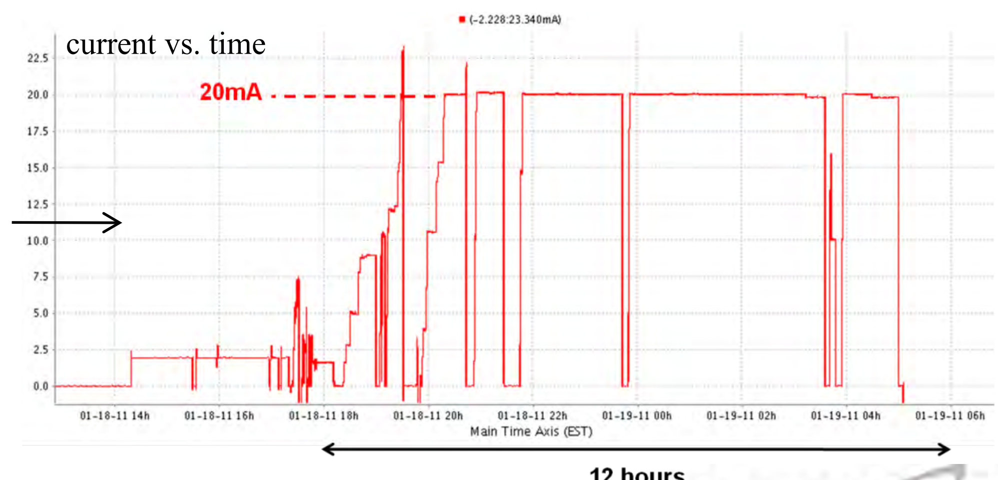
example of emittance measurements from the photoinjector



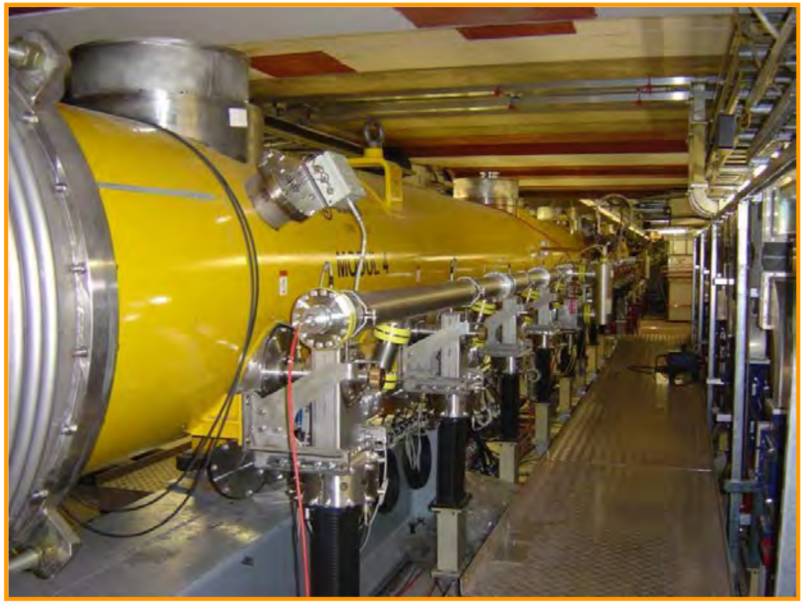
direct phase space benchmarking of 3D space charge codes



Demonstration of > 1000C 1/e lifetime from K2CsSb photocathode and the highest average current from a DC photoinjector gun

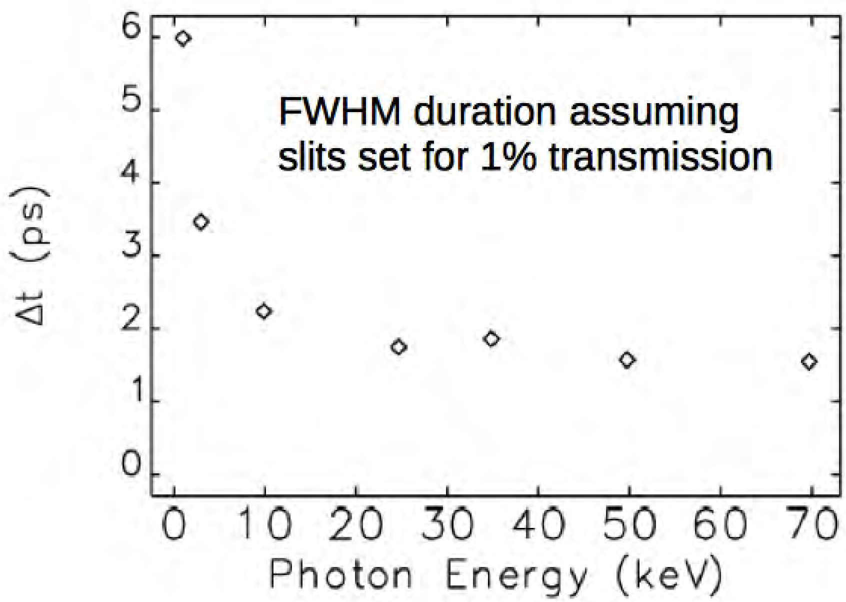


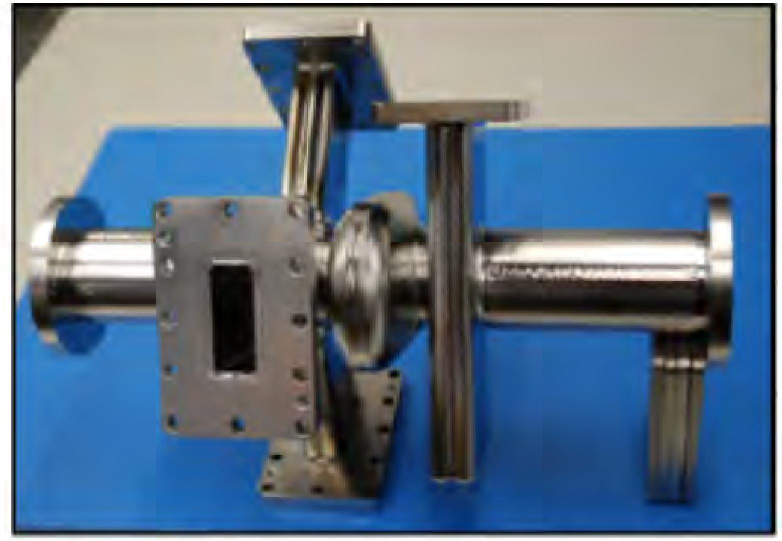
FLASH uses TESLA technology
An ERL variant is planned at Cornell



@ Siegfried Schreiber

APS Short-Pulse X-ray (SPX) Project





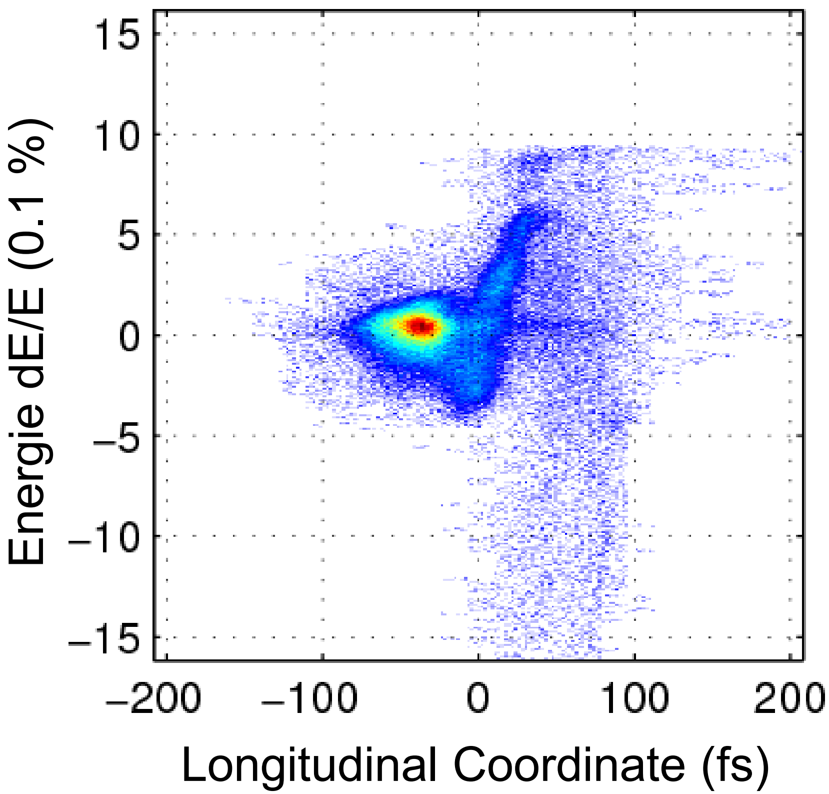
"Mark I" SPX cavity designed by APS and built by JLab.

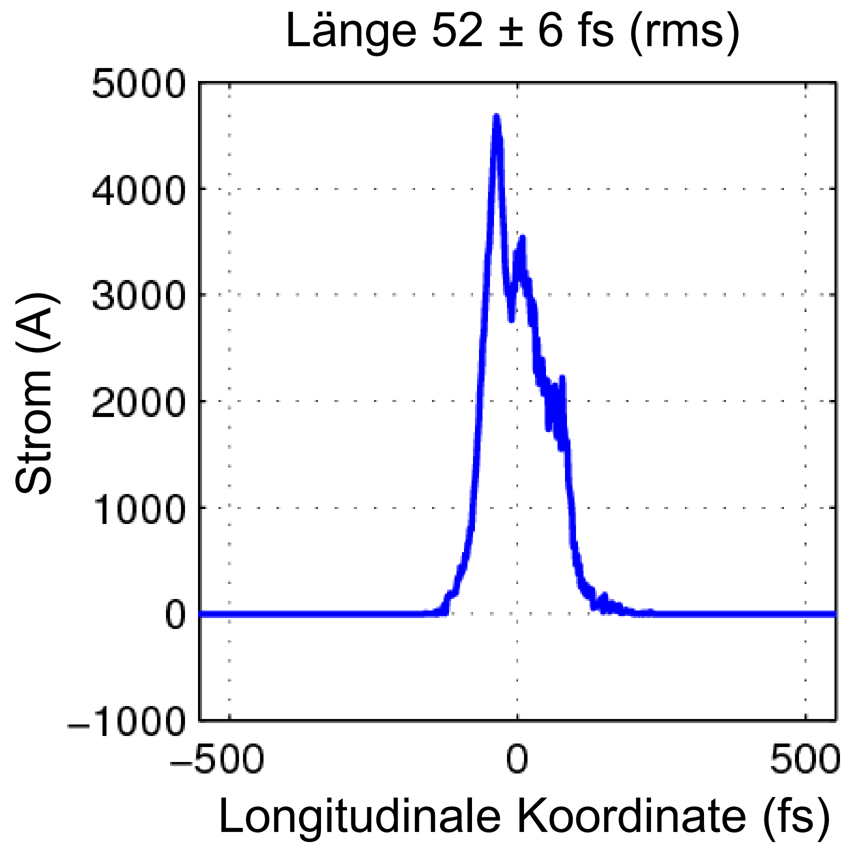
- Detailed simulations have been performed using ELEGANT
  - Allows prediction of pulse duration and other properties
  - Sensitivities and tolerances also explored
- Mark I cavity tests completed at JLAB
  - Provides 10% margin on required deflecting voltage.
  - Mark II prototype fabricated, under test

@ Michael Borland

Short Bunches < 50 fs

- Reduction of charge to mitigate space charge effects allow compression to very short bunches

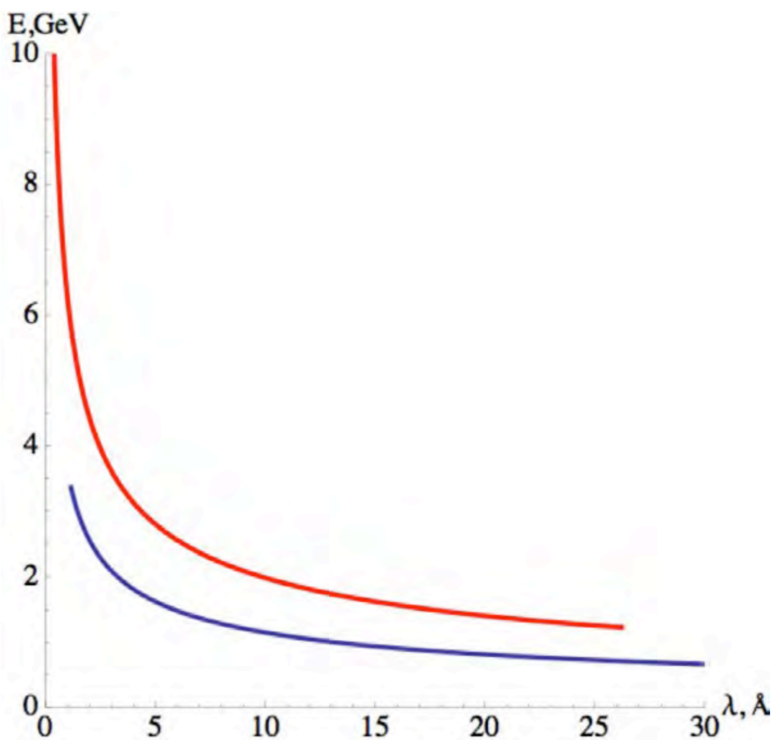




@ Siegfried Schreiber

Wavelength and energy scaling with charge: reducing the beam energy at low charge

Satisfying the transverse phase space matching, Σ_N/©H⎣/4□ requires a smaller beam energy at low charge.

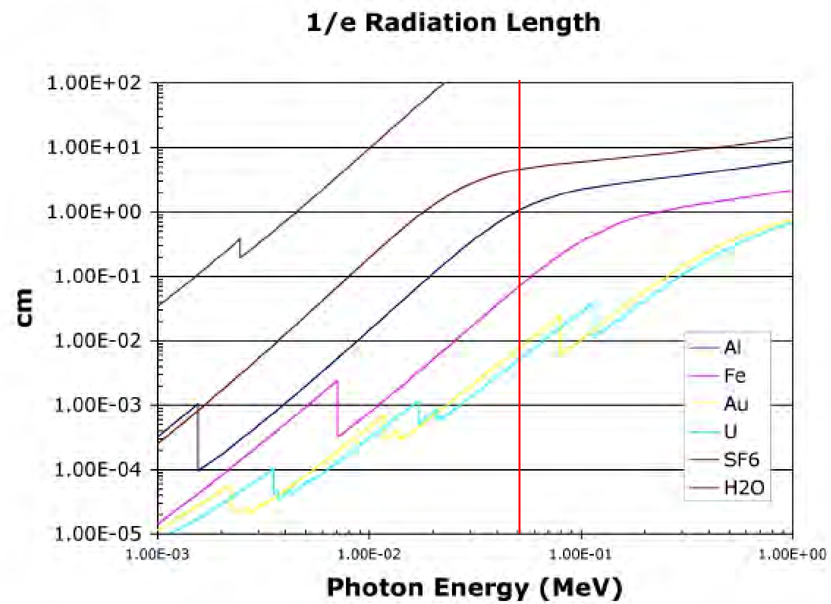


Using a shorter undulator period reduces the beam energy needed for a given wavelength.

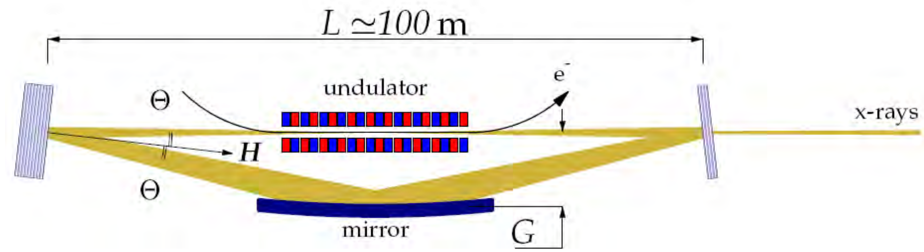
Electron energy vs λ: 1.5 cm period, K=1 undulator (red line); 0.5 cm period, K=1 undulator (black line). As λ changes the charge is adjusted in the range 1 to 250 pC, to satisfy the phase space matching condition

Why 50 keV XFEL?

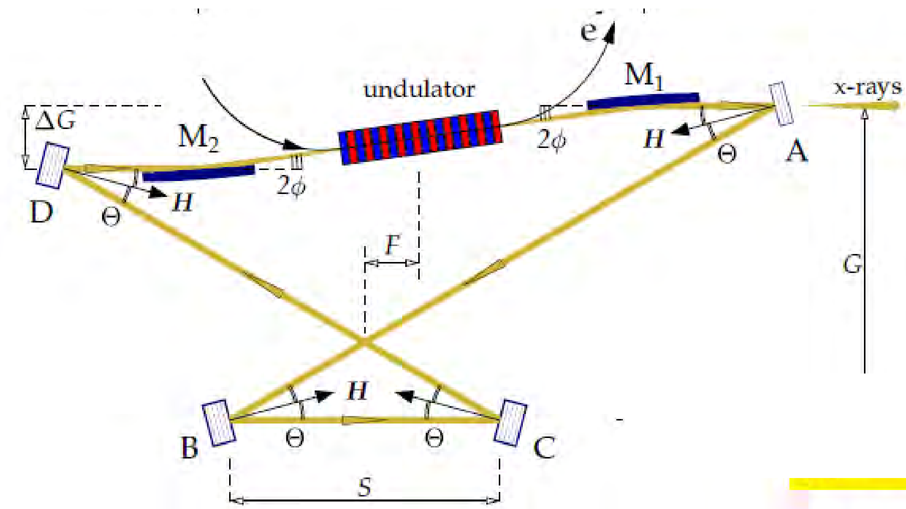
MaRIE seeks to probe *inside* multigranular samples of condensed matter that represent bulk performance properties with sub-granular resolution. With grain sizes of tens of microns, "multigranular" means 10 or more grains, and hence samples of few hundred microns to a millimeter in thickness. For medium-Z elements, this requires photon energy of 50 keV or above, which also allows multiple measurements on the same sample (reduces the absorbed energy per atom)



Tunable X-ray Cavity



- Two crystal scheme
  - a *very* limited tuning since θ must be kept small
- A tunable four crystal scheme with four crystals
  - Any spectral regions of interest can be covered by one crystal material
  - Choose diamond as highest reflectivity & best mechanical and thermal properties



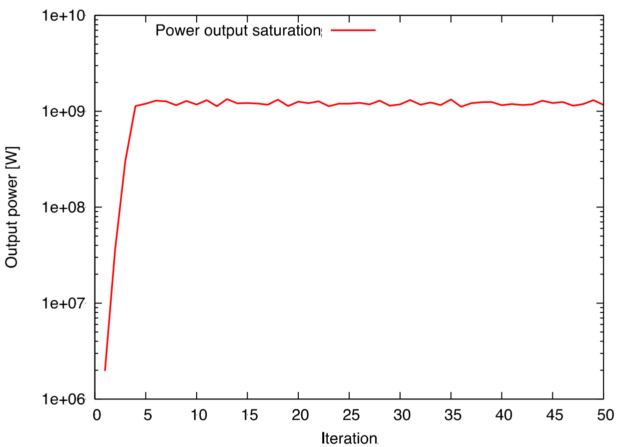
R. M.J.Cotterill, APL, 403,133 (1968)
KJK & Y. Shvyd'ko, PRSTAB (2009)

Test simulations results

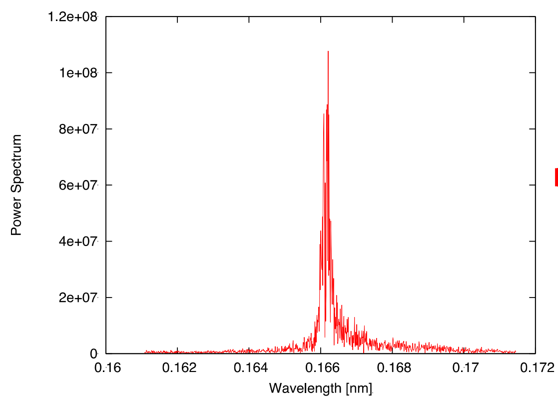
Parameters of high energy beam	Values
Electron Energy (GeV)	13.6
Energy Deviation dE/E	1e-4
Peak Current (A)	3000
Normalized Emittance (mm-mrad)	1.5
Undulator Period [m]	0.03
Undulator Length [m]	60
Undulator Parameter K	2.616
Radiation Wavelength [10^{-10} m]	1.66
Average beta function [m]	18

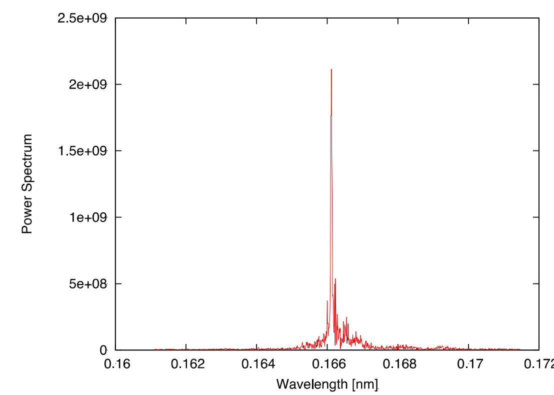
Parameters of the feed-back beam	Values
Electron energy (GeV)	1
Energy deviation dE/E	1e-5
Peak current (A)	15
Normalized emittance (mm-mrad)	0.015
Undulator period [mm]	0.636
Number of undulator period (Modulator/Radiator)	120/800
Undulator parameter K	0.1
Radiation wavelength [nm]	0.166
R56 of the transport arc	0

Time Independent Simulation

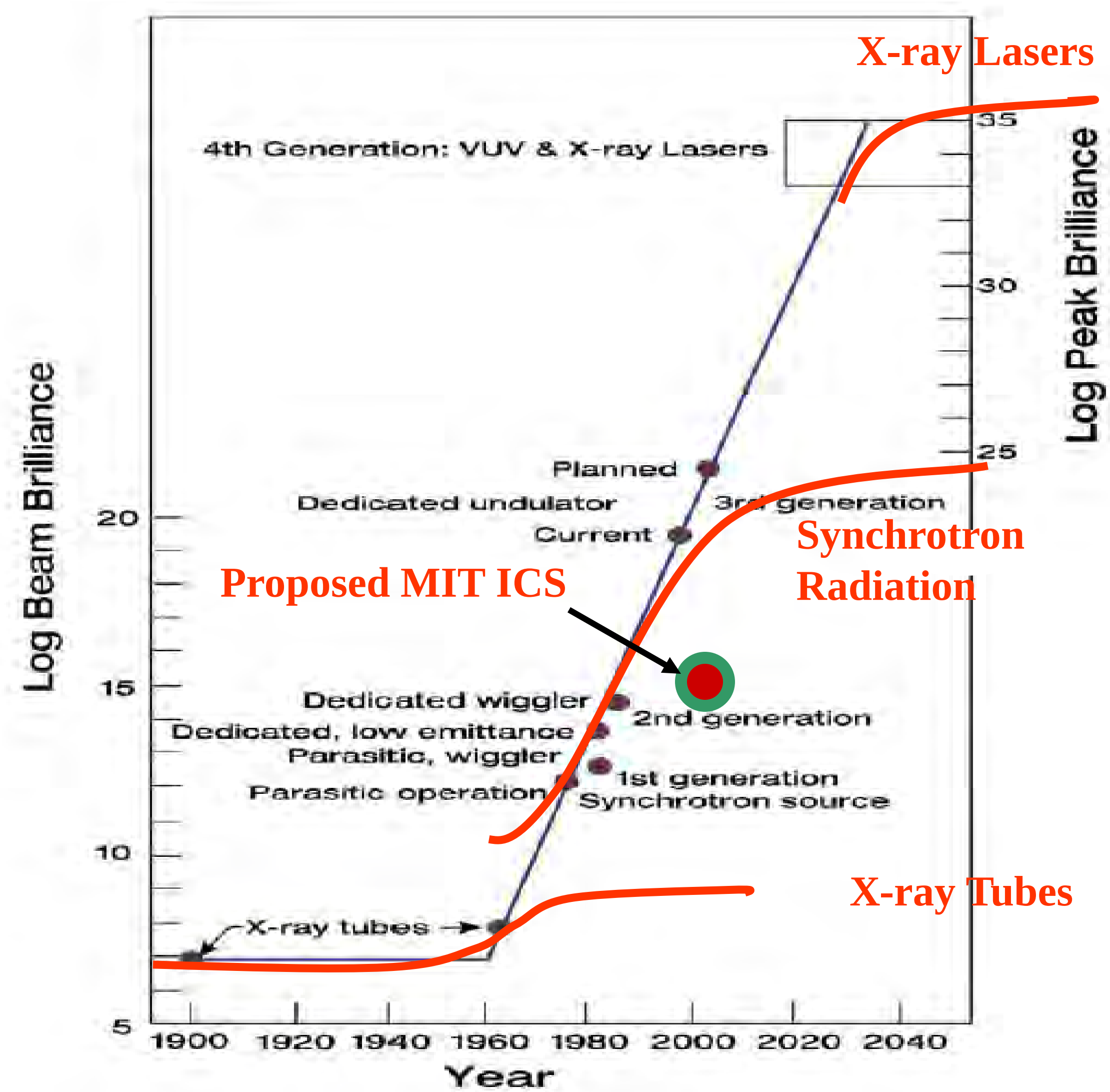


Time Dependent Simulation – 10 turns



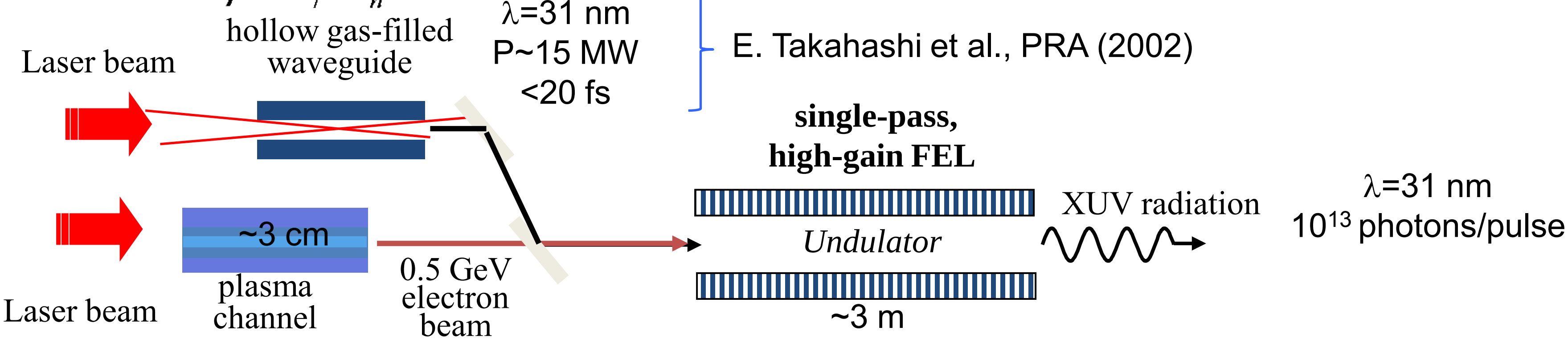


MIT ICS Design Performance

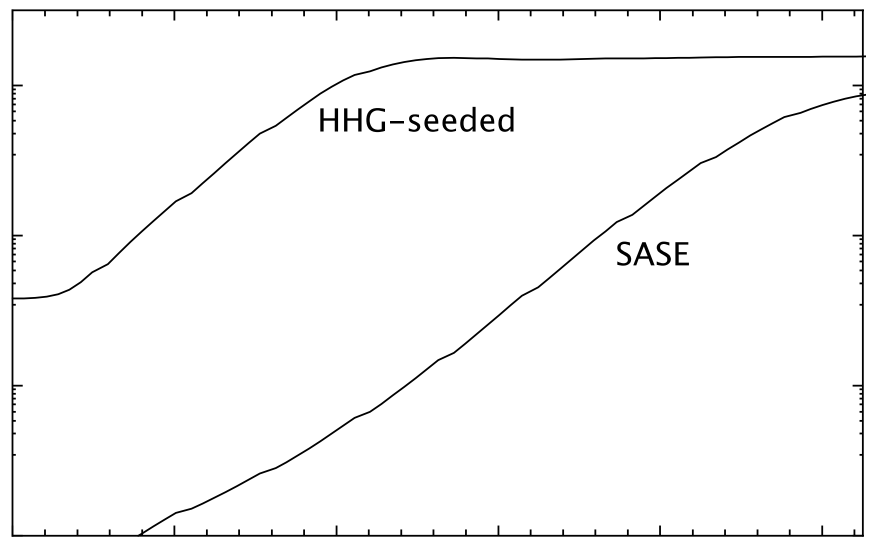


HHG Seeding experiment under way

HHG seed: $\rho < 1/N_h$



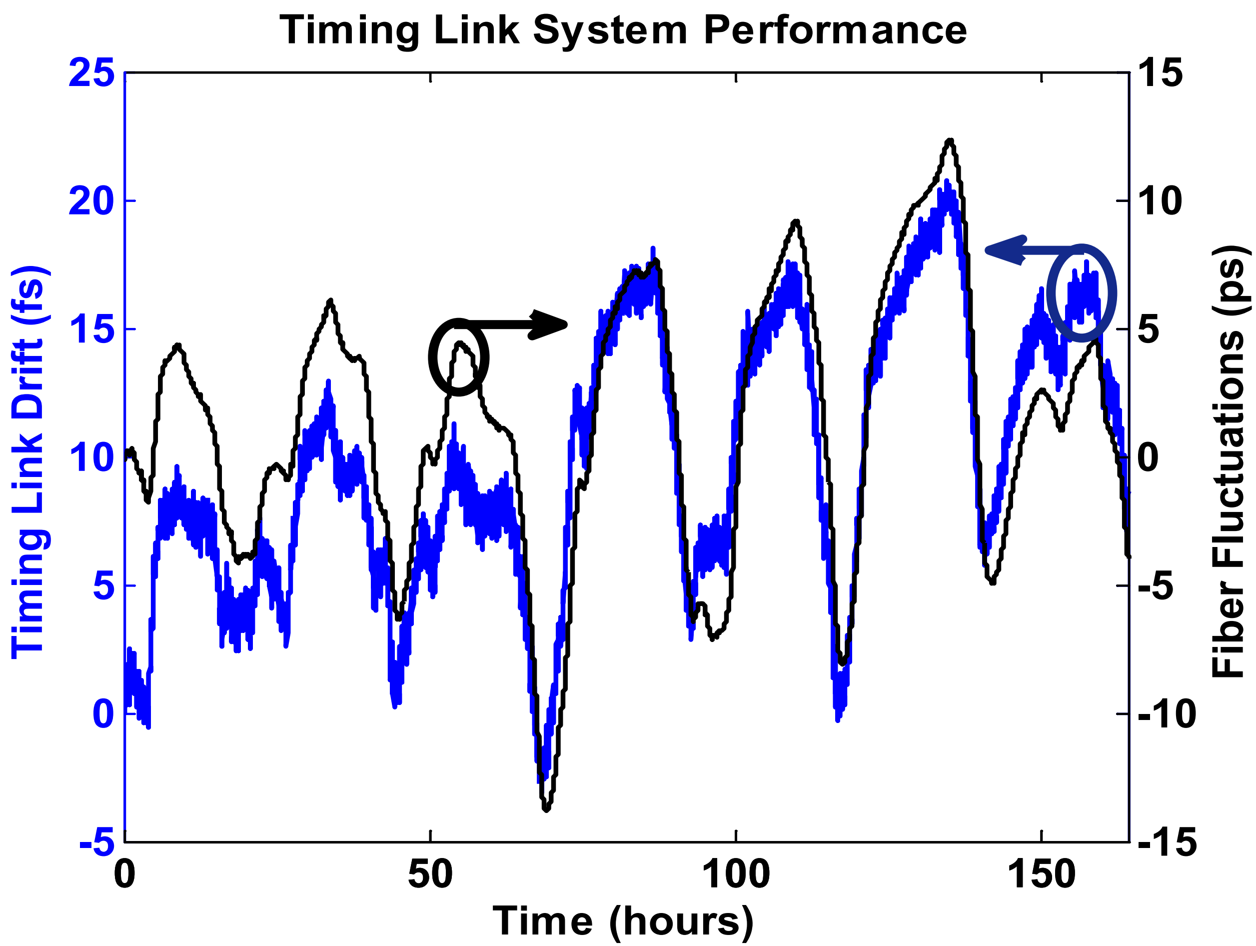
Laser-plasma accelerator



- Reduced saturation length
- Reduced power fluctuations
- Improved coherence
- Intrinsic synchronization (laser, harmonics, electron beam)

GINGER simulation

1-week operation w/ Pol. Control



Similar Links deployed at FLASH.

5-link system installed at FERMI @ Trieste, 10 days < 10 fs

5 fs (rms) drifts over one week of operation

Parallel EM Code Suite ACE3P and User Community

ACE3P (Advanced Computational Electromagnetics 3P) Code Suite

https://slacportal.slac.stanford.edu/sites/ard_public/bpd/acd/Pages/Default.aspx

- conformal, higher-order, C++/MPI parallel finite-element based electromagnetic codes
- supported by SLAC and DOE HPC Grand Challenge (1998-2001), SciDAC1 (2001-06), SciDAC2 (2007-12)

Modules include

Frequency Domain:	**Omega3P**	**– Eigensolver (damping)**
	S3P	**– S-Parameter**
Time Domain:	**T3P**	**– Wakefields,Transients**
Particle Tracking:	**Track3P**	**– Multipacting, Dark Current**
EM Particle-in-cell:	**Pic3P**	**– RF Gun, Klystrons**
Multi-Physics:	**TEM3P**	**– EM, Thermal & Structural Analysis**

ACE3P Code Workshop

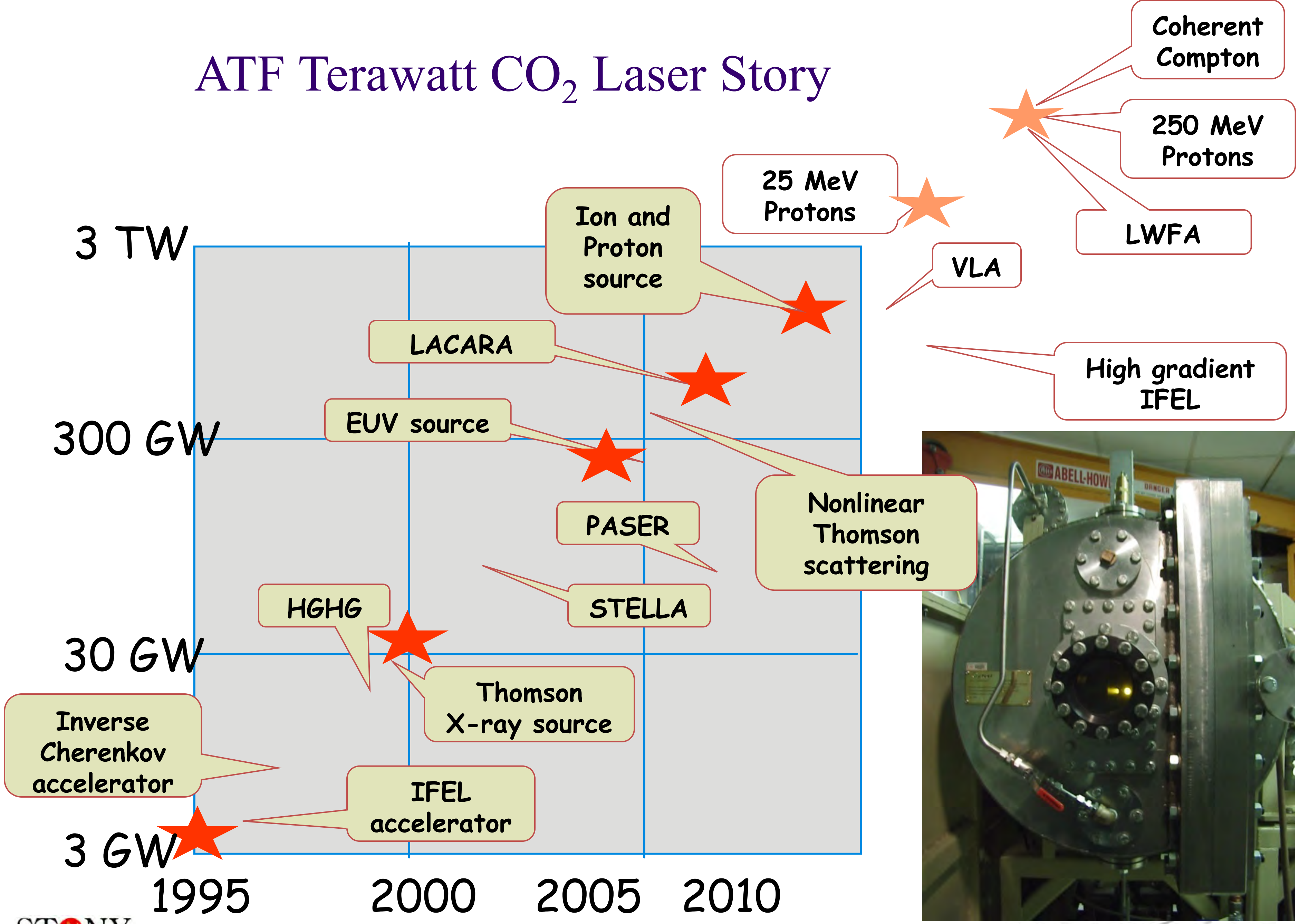
CW09 (15 attendees from 13 institutions) – 1 day

CW10 (36 attendees from 16 institutions) – 2.5 days

CW11 planned for 5 days

@ Ng Cho-Kuen

ATF Terawatt CO_2 Laser Story

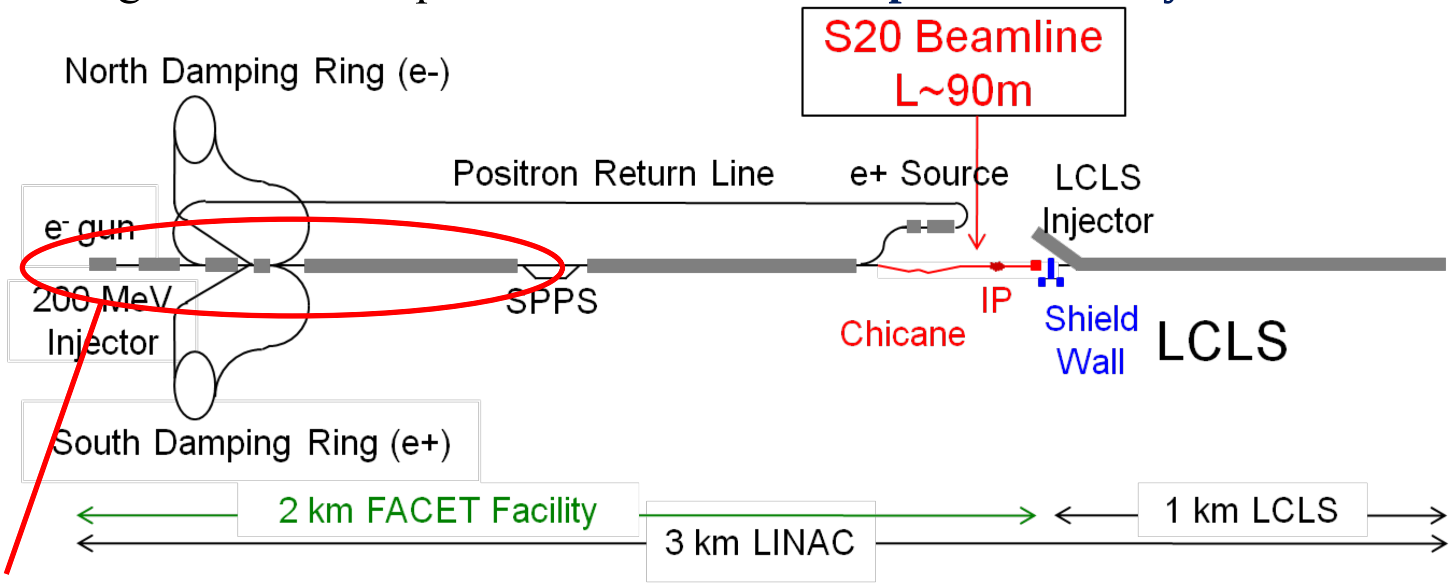


@ Vitaly Yakimenko

SLAC Test Facilities – FACET and Future FEL ITF

Facility for Advanced Accelerator Experiment Tests (FACET, user facility)

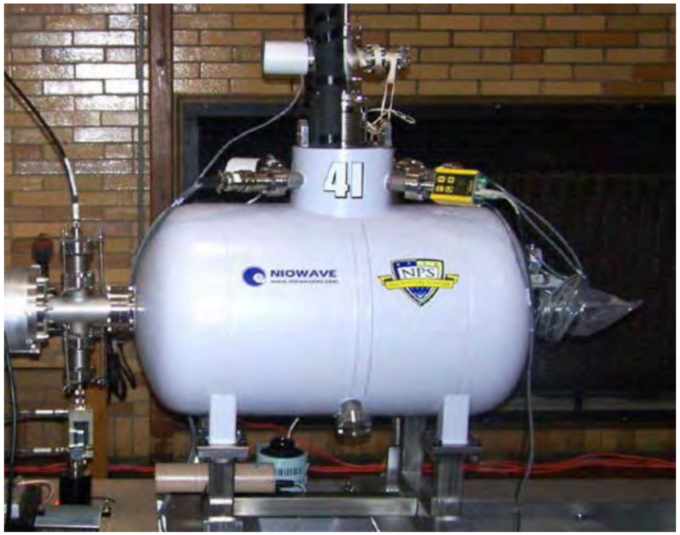
- plasma wakefield acceleration is primary goal
- THz source development
- beam diagnostics development
- **Operates 4 mo/yr for HEP**

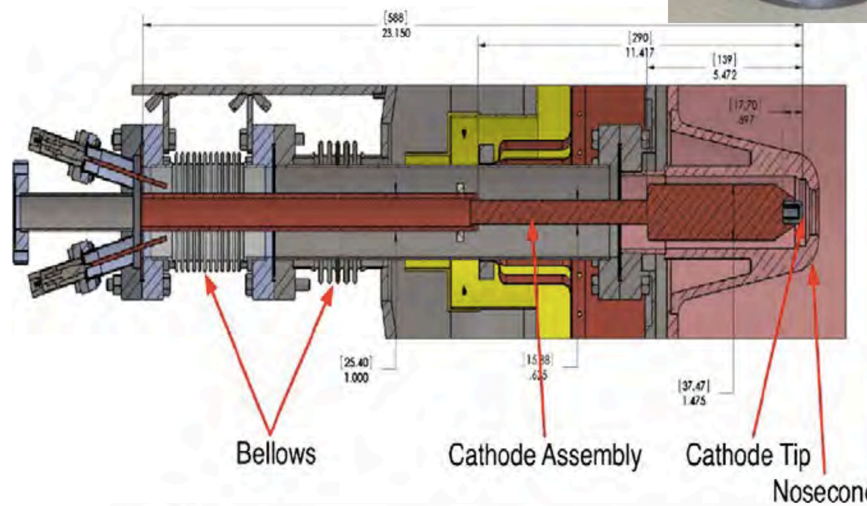


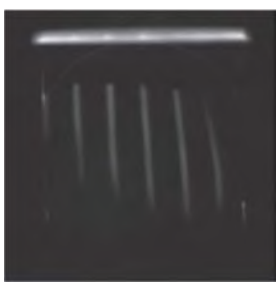
S0 Injector (FEL) Test Facility **– future >GeV FEL test facility (?)**

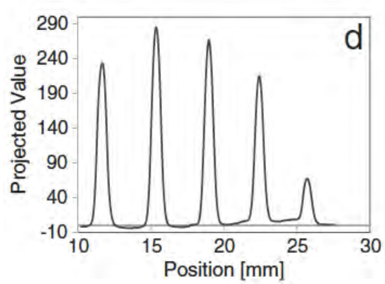
- high energy laser seeding and beam manipulation (e.g. Echo-100, ESASE)
- high energy bunch compression
- advanced undulator testing

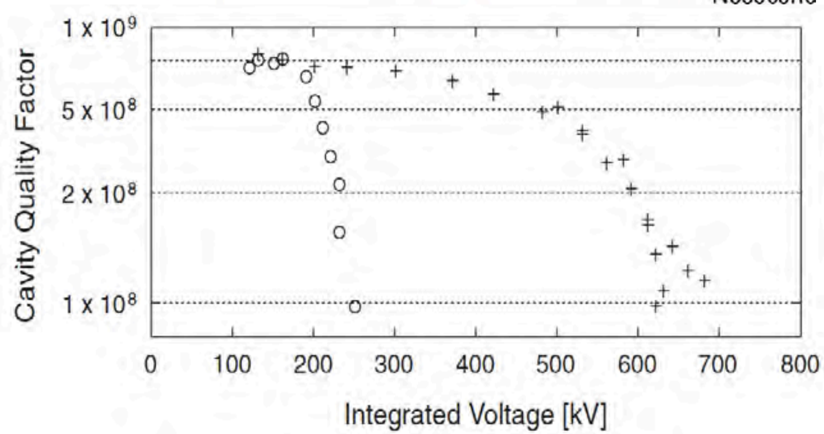
NPS 500 MHz gun





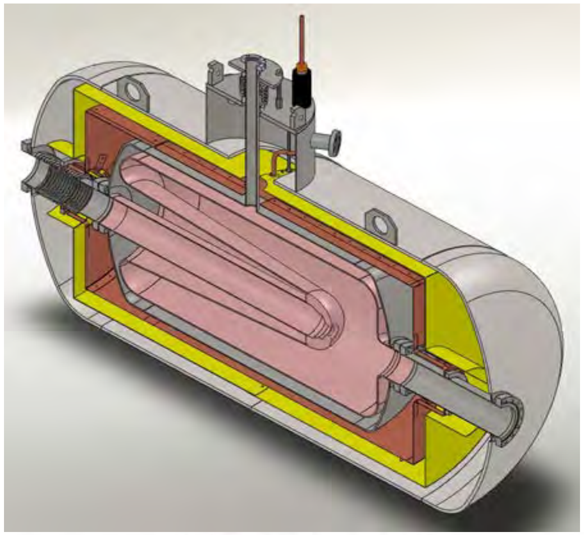


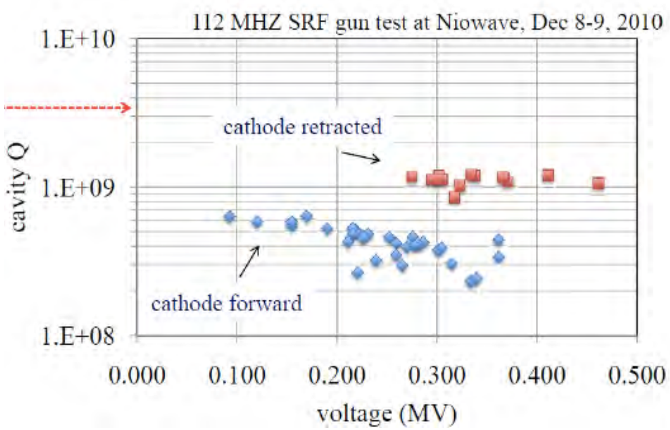




PRST-AB **14**, 053501 (2011)

BNL 112 MHz gun





S. Belomestnykh et al, proc. PAC11

Wisconsin Free Electron Laser (WiFEL)

- WiFEL R&D
  - electron gun, including a high repetition rate (several megahertz) photocathode drive laser
  - R&D on photocathode materials, including novel approaches, by Angle Resolved Photo Emission Spectroscopy (ARPES) studies on the Aladdin storage ring at SRC
  - Studies of the laser high harmonic generation (HHG) process to establish the necessary noise performance as a seed laser source
  - Evaluation of FEL facility architectures with the specific goal of cost containment
  - Studies of laser-beam interactions

WiFEL

WiFEL 200 MHz SRF gun