OVERVIEW OF ACCELERATOR ACTIVITIES AT ARGONNE

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MSU ASET Lecture
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WHO AM I?

- Ph.D. from Cornell University in 1991 working on the Cornell Electron Storage Ring
- Scientist at Berkeley Lab from 1991-2017 working on a variety of machines including the PEP-II B-Factory, the Advanced Light Source and the LCLS.
- Worked on a broad range of topics including RF design and measurement, beam instabilities and feedback systems, coherent synchrotron radiation, and femtosecond timing and synchronization.
- Long time instructor at USPAS for the Microwave Measurement course.
- Currently working at Argonne National Laboratory. Accelerator Systems Division Director and head of the Argonne Accelerator Institute.

Accelerator Science, Engineering and Technology is a rich field that can keep you interested (and hopefully employed!) your entire career.

ACCELERATORS ARE A SMALL WORLD

Many people stay in this field their entire careers…..

Steve at Berkeley in 2005. I was his supervisor.

Peter visiting Berkeley in 2004

Jie when he was at Brookhaven working on SNS

WE ARE NOW IN A GOLDEN AGE OF ACCELERATORS

- We are building more new machines around the world than ever before with performance that was only dreamt of a decade ago.
- We can design machines with micron beam sizes of microns over kms
- We can measure and control timing jitters down to femtoseconds.

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WELCOME TO ARGONNE!

The definition of a “green field site.”

2nd APS

Full energy Linac for APS-U injection AND FEL (MaRIE Test Facility)

Linear Collider Test Facility or Isotope Production

Hadron Therapy Center

OVERVIEW

Selected “tasting” of accelerator activities at Argonne

- Advanced Photon Source and the $0.815B Upgrade
- RF Conversion from Klystrons to Solid-State
- Linac Extension Area
- Development of Superconducting Undulators
- Cavity-Based XFELs
- A new concept for a high repetition rate Free Electron Laser based on Wakefield Acceleration

I’ll try to supply some of the basics of Unfortunately I will not cover any of the Nuclear or High Energy Physics accelerator activities at Argonne.

APS ACCELERATOR COMPLEX

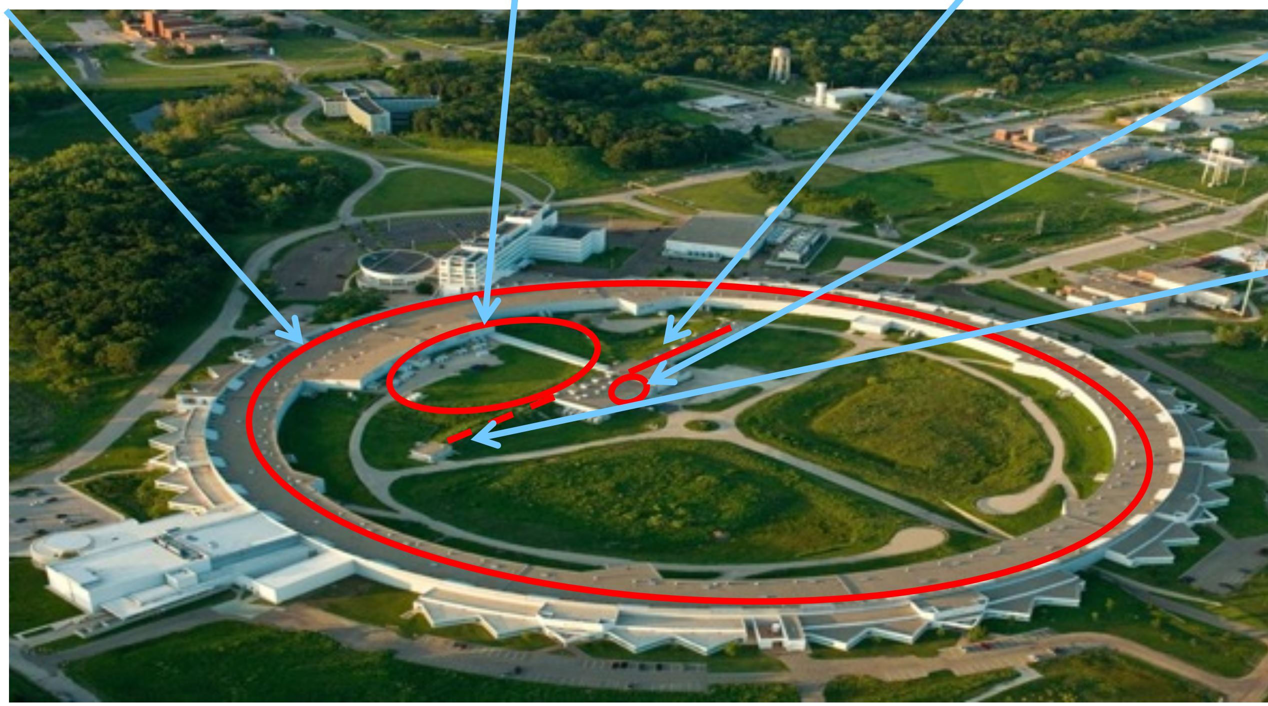
7 GeV, 100 mA, 46 ID,
21 bend magnet BL,
3 fill patterns

Booster: 0.38-7 GeV, 2 Hz

Linac: S-band, 0.38 GeV, 30 Hz

PAR: 0.38 GeV,
2 Hz, 1-4 nC

Linac Extension
Area



The APS Upgrade (APS-U) will replace the main storage ring but keep the radio-frequency (rf) system. Injector systems will be reused and require increased performance.

APS UPGRADE

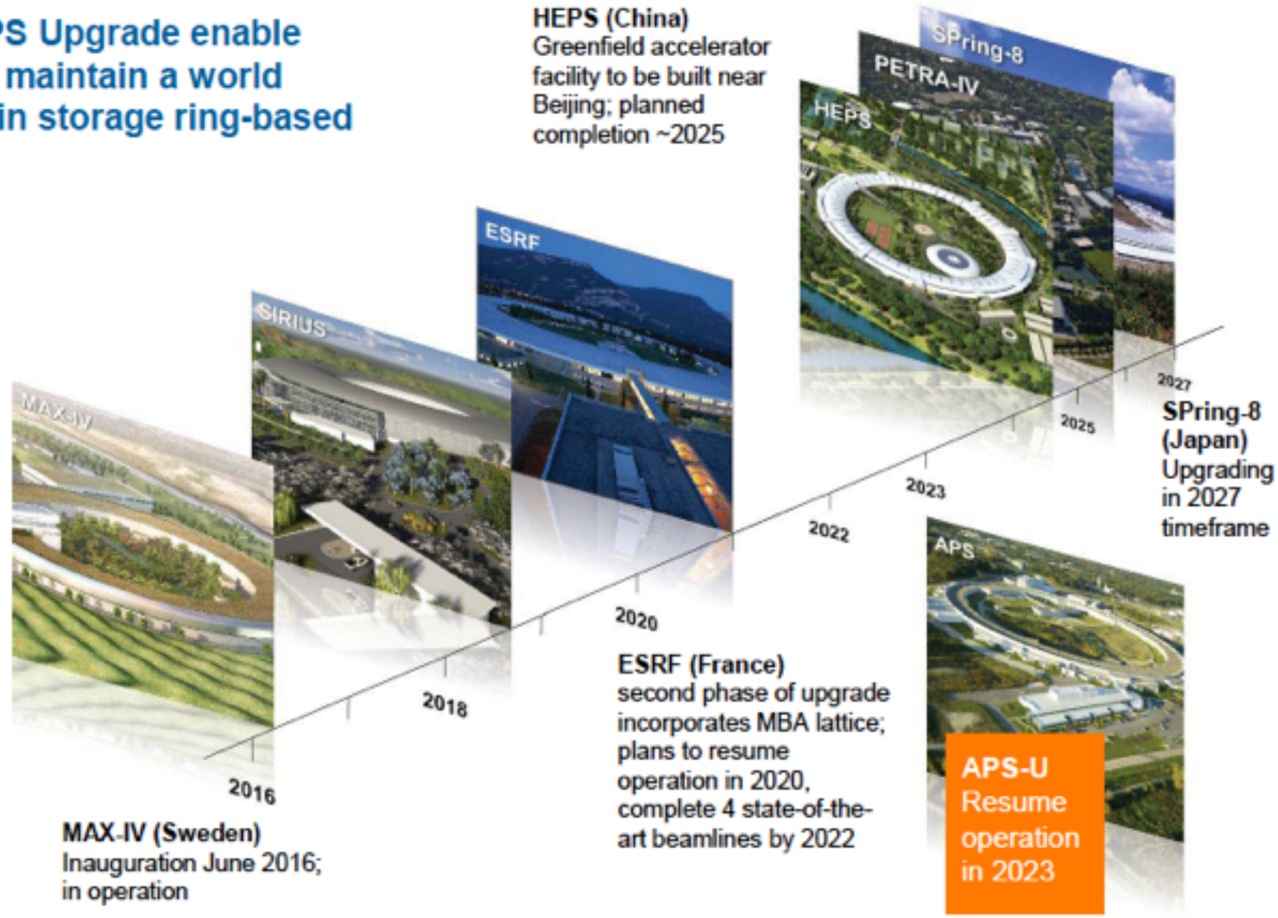
Diffraction-limited Storage Rings

$$\frac{\lambda}{4\pi}$$

$\lambda = 1\text{Å} \Rightarrow \varepsilon_{diff} = 8$ pm-rad

To stand still is to lose ground

Our plans for the APS Upgrade enable the United States to maintain a world leadership position in storage ring-based x-ray sources



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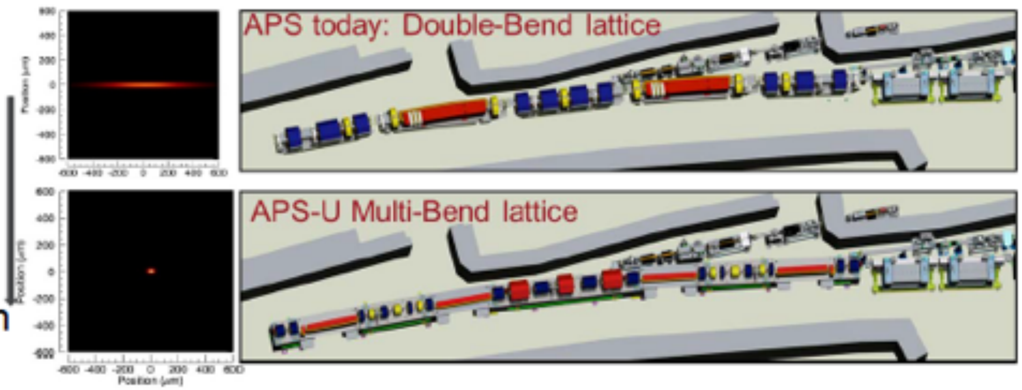
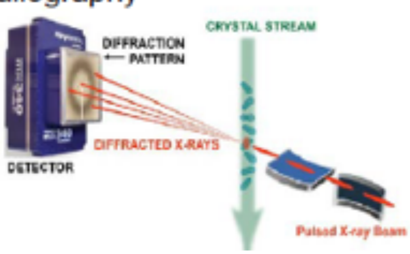
THE APS Upgrade:
Building a world leading hard x-ray facility

- Design optimized to provide orders of magnitude improvements in brightness, coherent flux, and nano-focused flux
- MBA lattice optimized with reverse bends, reduces emittance from 67 pm to 42 pm
- Beamline proposal selection and roadmap complete
- Technical prototypes well along; Preliminary Design Report complete; procurements starting



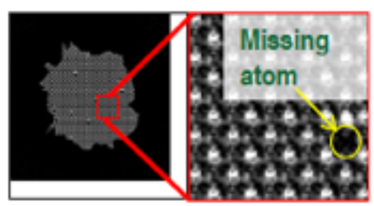
Small-Beam Scattering & Spectroscopy

Nanometer imaging with chemical and structural contrast; few-atom sensitivity
Room-temperature, serial, single-pulse pink beam macromolecular crystallography



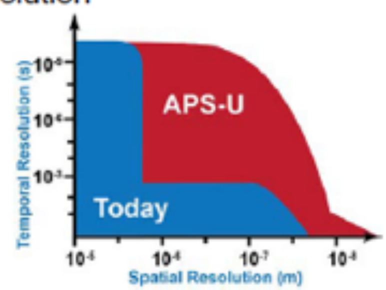
Coherent Scattering & Imaging

Highest possible spatial resolution: 3D visualization; imaging of defects, disordered heterogeneous materials
XPCS to probe continuous processes from nsec onward, opening up 5 orders of magnitude in time inaccessible today,

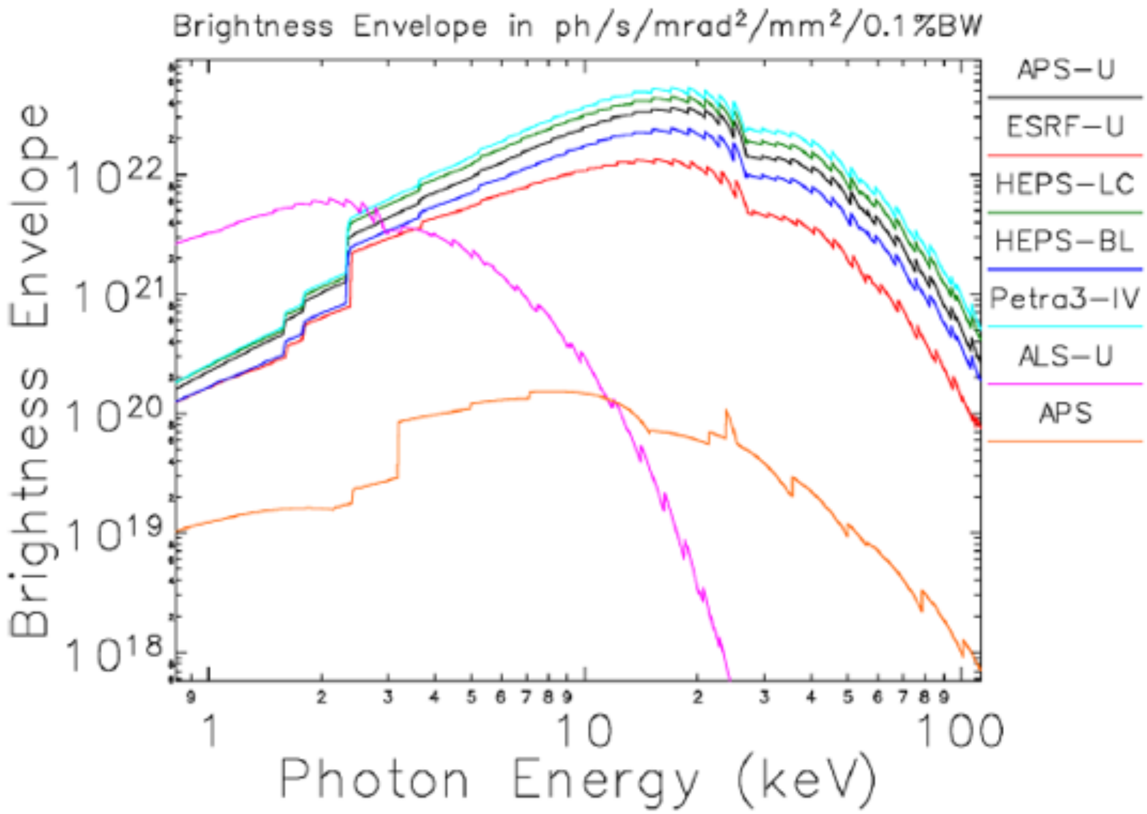


Resolution @ Speed

Mapping all of the critical atoms in a cubic millimeter
Detecting and following rare events
Multiscale imaging: enormous fields of view with high resolution



APS-U WILL KEEP THE US AT THE FOREFRONT OF LIGHT SOURCES



Curves for APS, ESRF-EBS, PETRA-IV and HEPS based on present designs, assuming identical undulators

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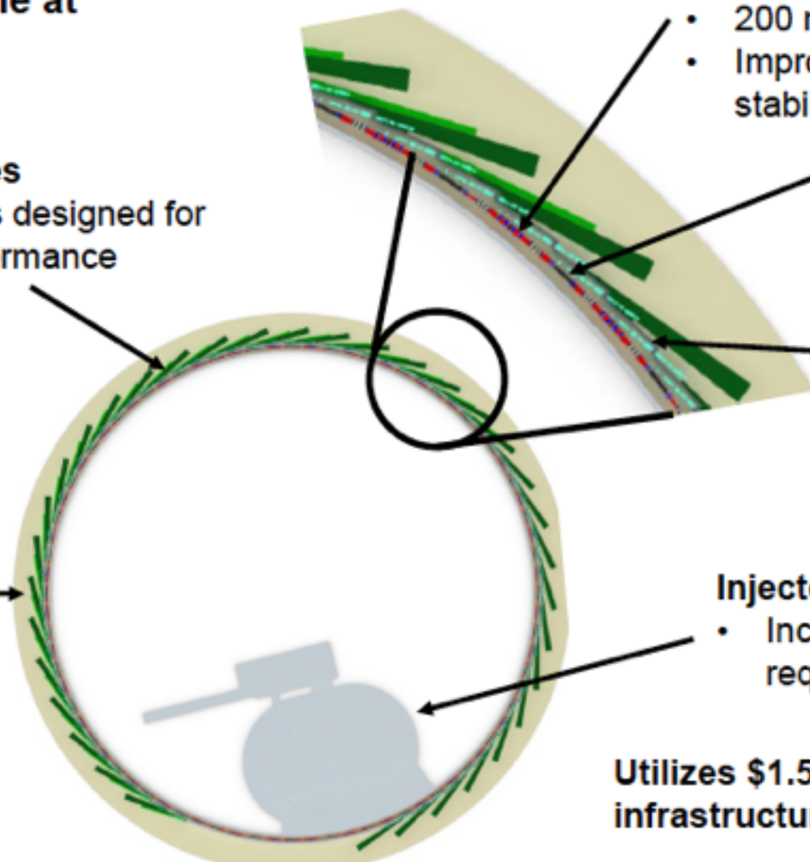
APS-U Project Scope

All existing beamlines incorporated in plans to come back online at conclusion of APS-U

Feature beamlines
Suite of beamlines designed for best-in-class performance

Beamline Enhancements: improvements to make beamlines "Upgrade Ready"



New Storage Ring
- 6 GeV MBA lattice
- 200 mA current
- Improved electron/photon stability

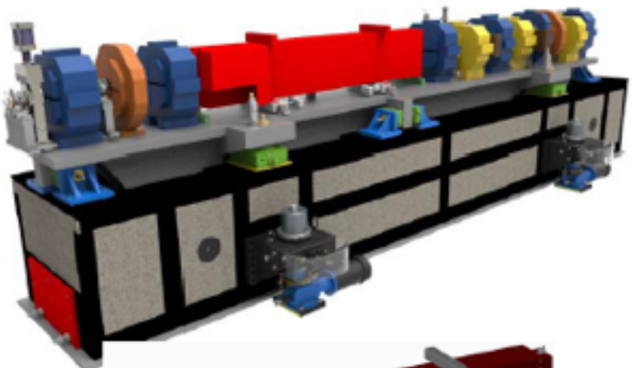
New Insertion Devices
- Incorporate SCUs on selected beamlines

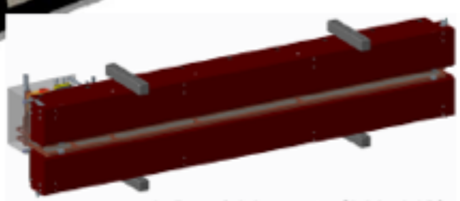
New/upgraded Front-ends
- Common design for maximum flexibility

Injector improvements
- Increase performance as required to meet APS-U needs

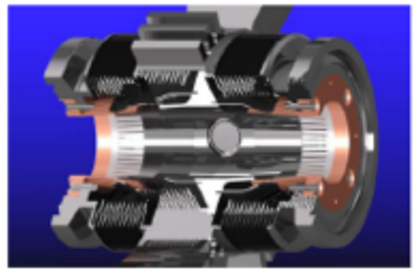
Utilizes $1.5B in existing infrastructure

APS-U Technology

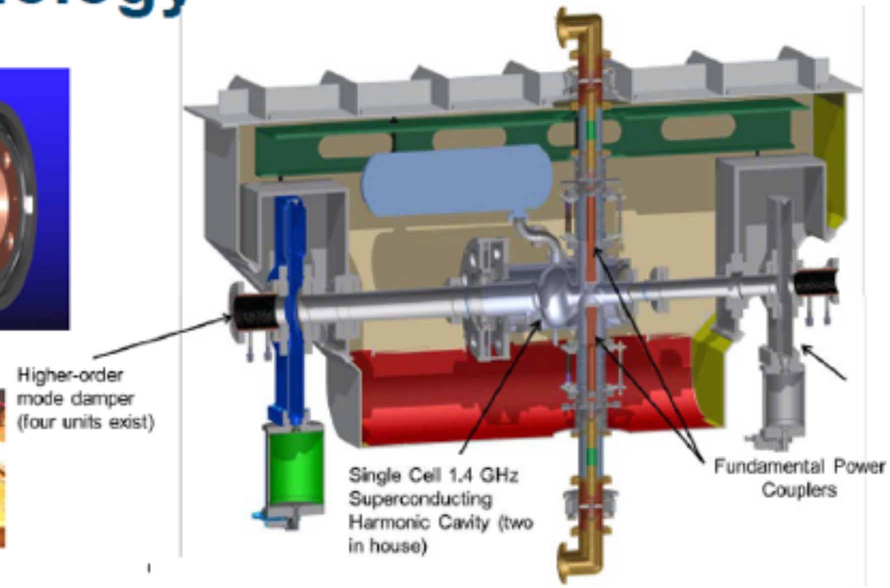


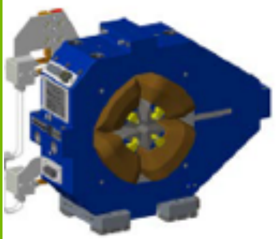


L-Bend Magnets (M1, M2)

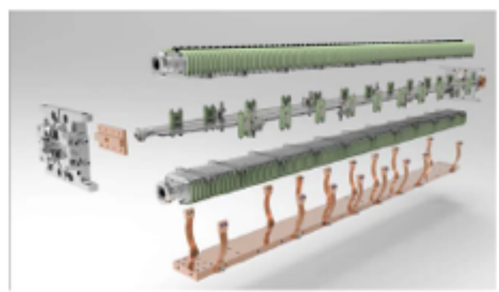


In-House Design
Fast Bipolar Power Supply*

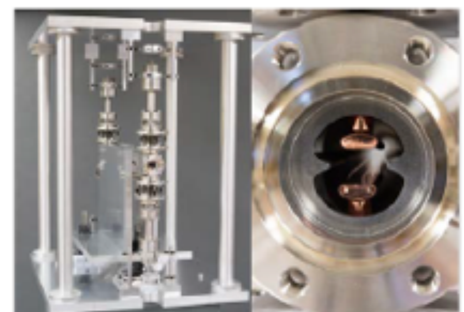




Q-Bend Magnets M3,M4

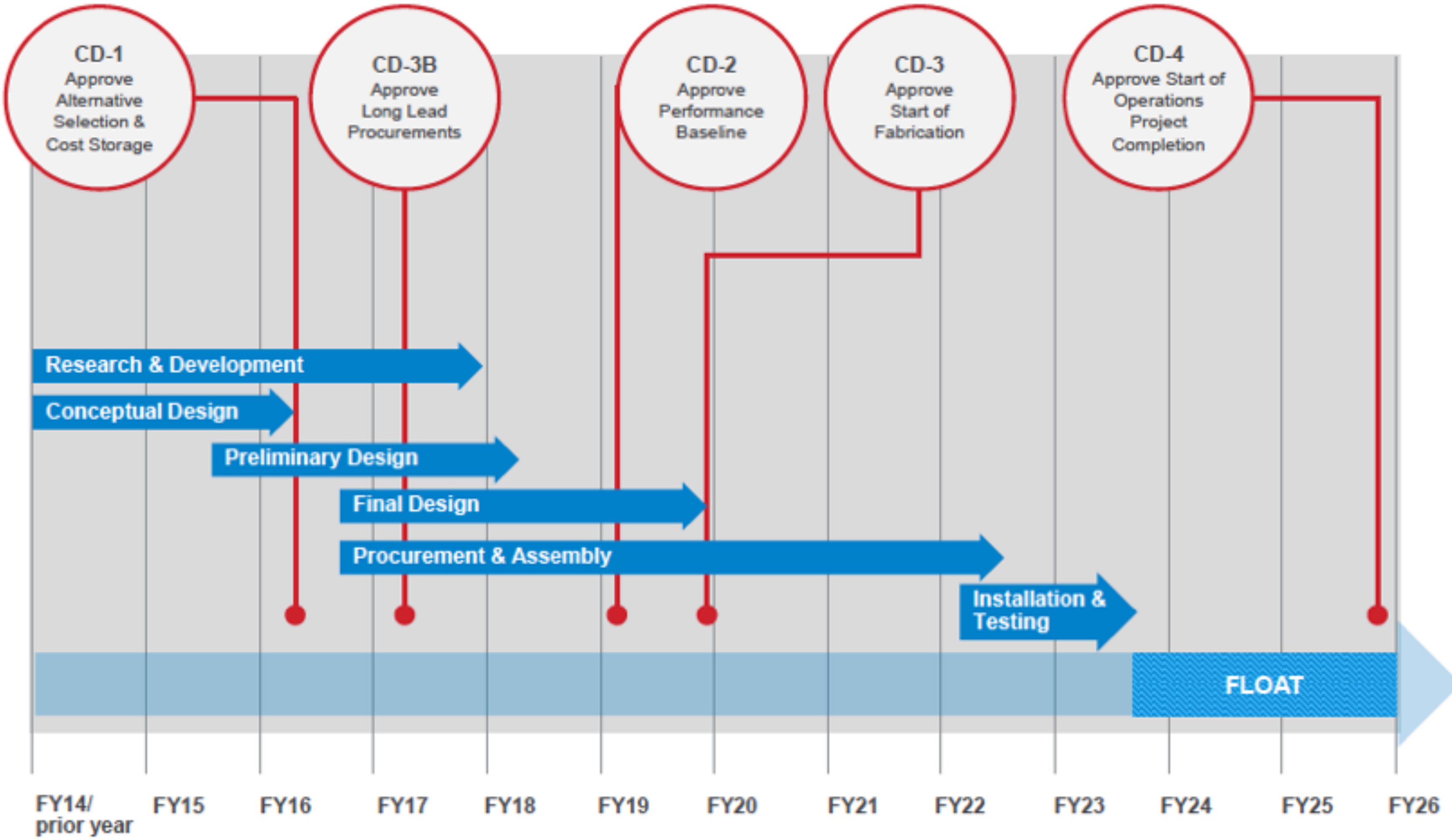


Exploded view of planar SCU design model with vacuum chamber

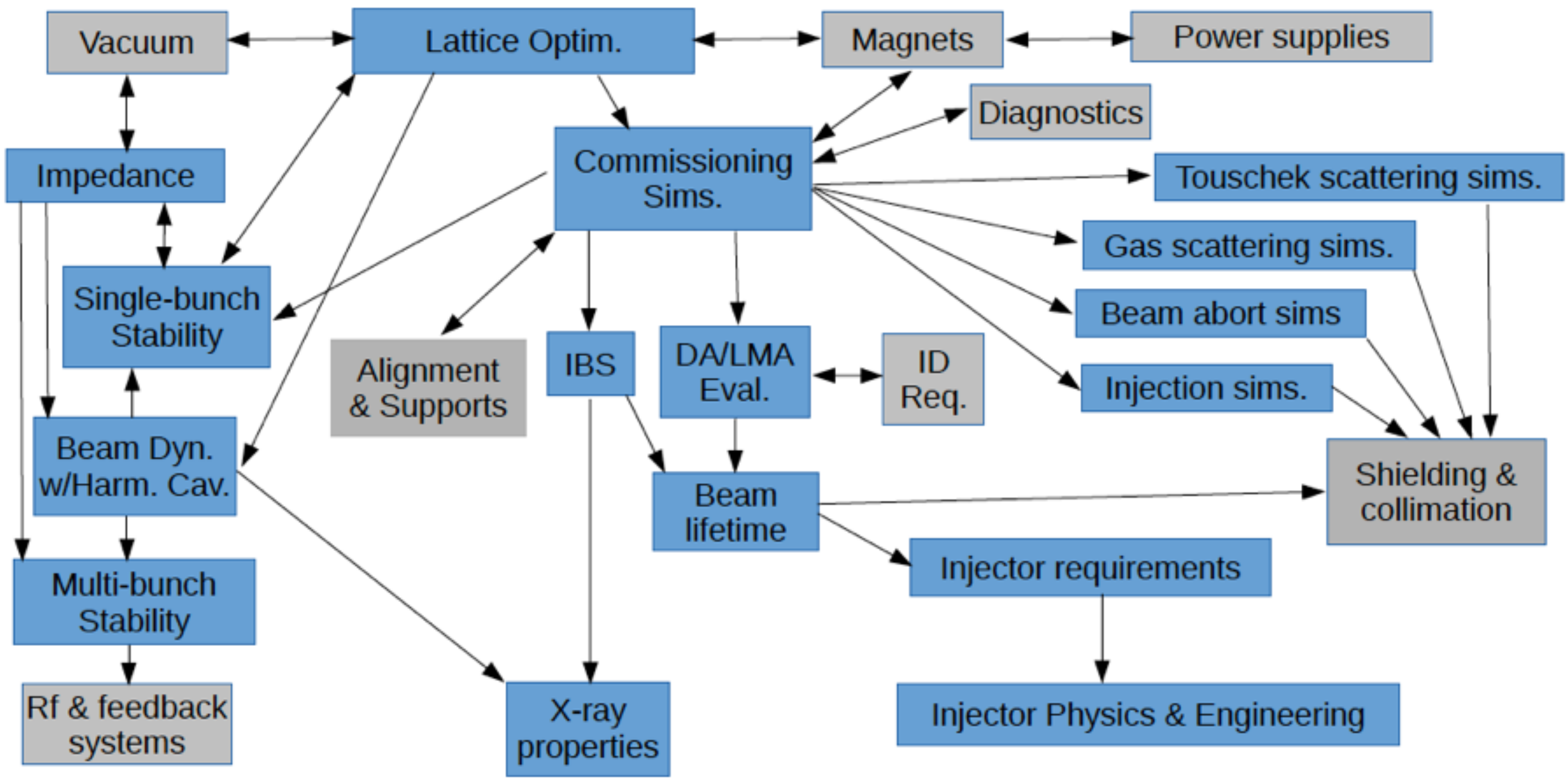


Prototype Stripline Kicker used for successful BTX Beam Tests

APS Upgrade Project Schedule



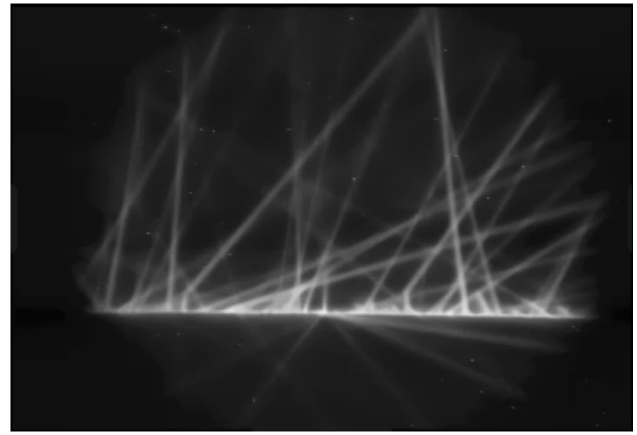
APS-U beam physics workflow (simplified)



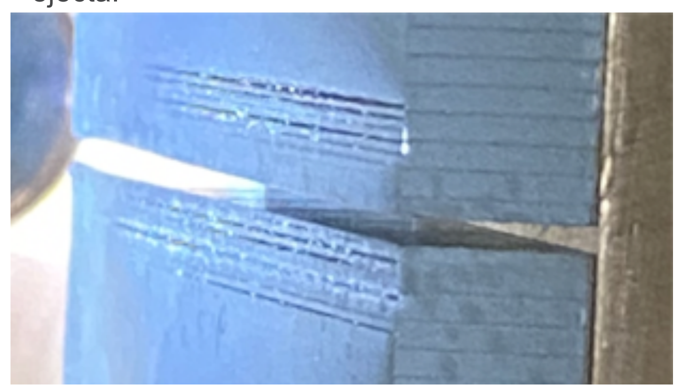
APS-U PREP: COLLIMATOR STUDIES

APS-U beams are very good electron beam welders (and unwelders!)

- Low-beta optics and operation at 200 mA approximates APS-U beam energy density.
- The scraper is moved close the beam. We then move the beam onto the scraper using correctors and observe scraper image. Beam position can be moved to strike scraper at different positions.
- We were able to hit the scraper in multiple locations and multiple times in the same location. A number of interesting images.
- Scraper assembly has now been removed and collimator is under metallurgical study. More results to come in the near future.
- We are much more confident that we can find a solution for APS-U collimators.



Frame grab of video image during a strike showing ejecta.

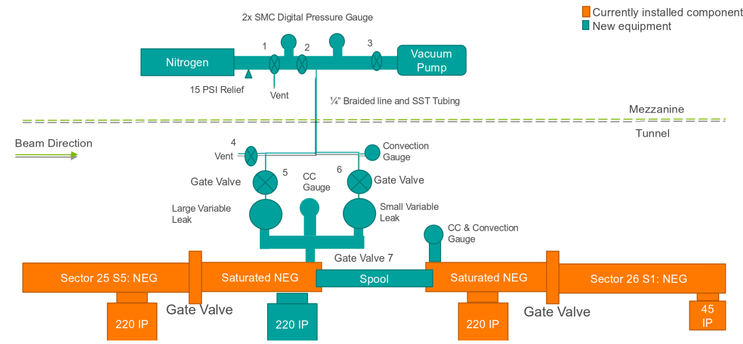


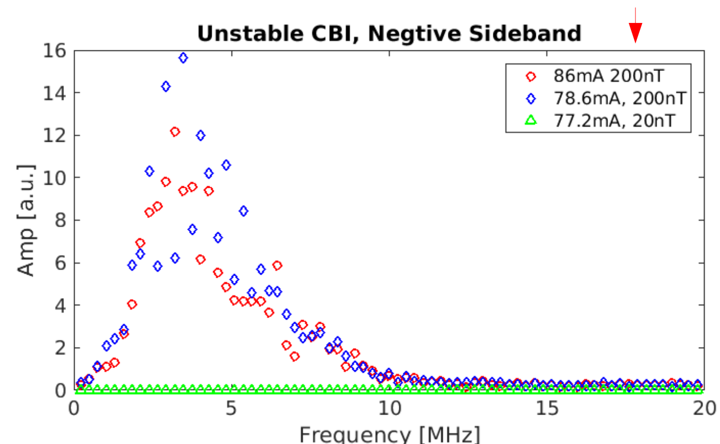
Collimator assembly after multiple full0beam strikes. Under metallurgy tests now.

APS-U PREP: GAS INJECTION EXPERIMENT TO FULLY UNDERSTAND APS-U ION INSTABILITIES

Nominal APS-U beam filling pattern (324 bunch) shows ion instability problems. Remediation techniques have been tested in APS.

- Controlled gas leak installed in Sector 25 to create a pressure “bump” with a known beta function. Fully tested with no impact on storage ring pressure outside of the sector.
- Use existing suite of tools to characterize instability behavior as a function of pressure, current, filling patterns, etc.
- Latest machine studies on July show excellent results. Demonstrates ion instability goes away with APS-U fill pattern. Studies will continue over next year. Led by Joe Calvey.
- We plan for this to be the “definitive” study of ion effects for 4th gen storage rings.

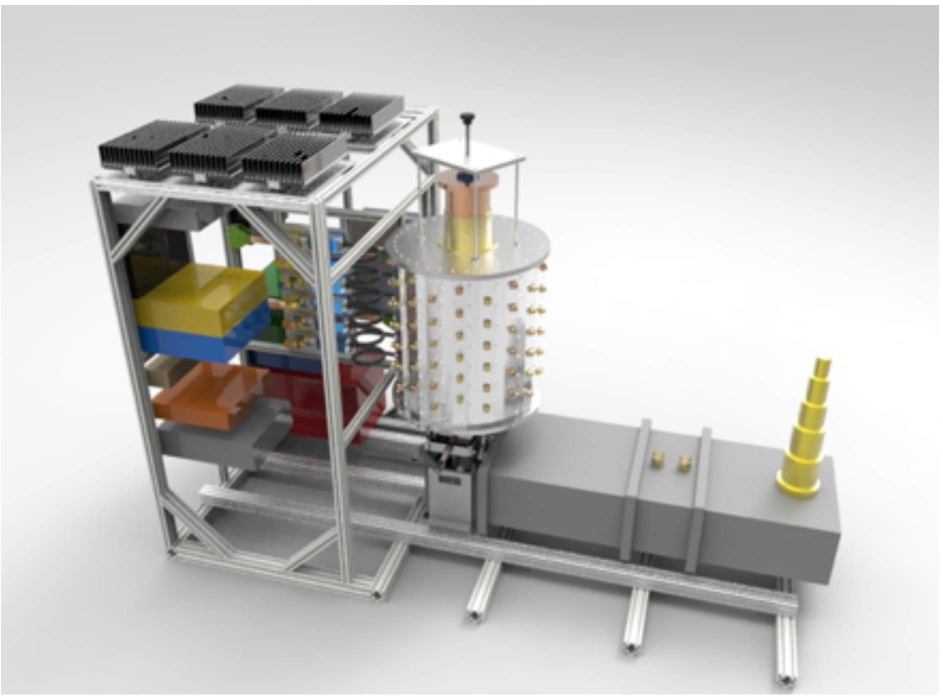




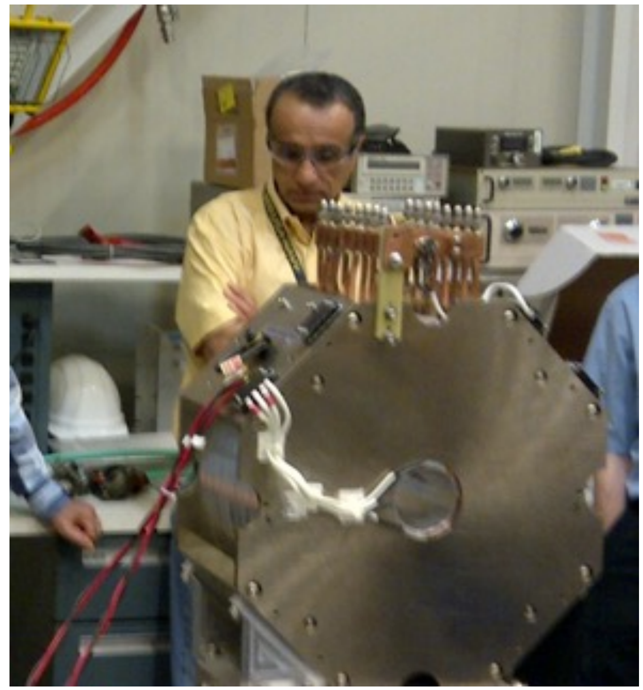
ACCELERATOR R&D INITIATIVES

POTENTIAL CONVERSION OF APS RF SOURCE FROM KLYSTRON TO SOLID-STATE

- With the vanishing number of vendors of MW-class tubes, the ageing APS HV infrastructure, we are pursuing a path towards modular solid-state rf sources combined to reach ~200 kW units.



ASD RF Group SSPA concept using combiner cavity



Led by Ali Nassiri

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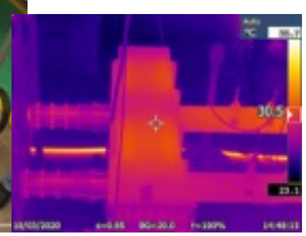
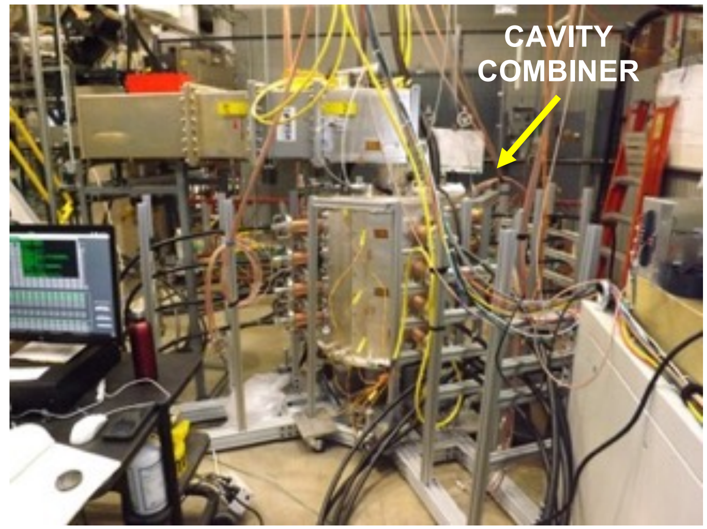
R&D TO DEMONSTRATE CAVITY COMBINER SUCCESSFULLY COMPLETED

Tests of 32 kW prototype unit, combining cavity, and monitoring controls complete

- Test of resonant cavity combiner driven by sixteen 2kW solid-state amplifier modules
- 28.5kW cw combined output achieved with expected losses in connecting cables
- The combining cavity was successfully tested to 200kW cw in a back-feed configuration



Waveguide backfeed test with IR inset.

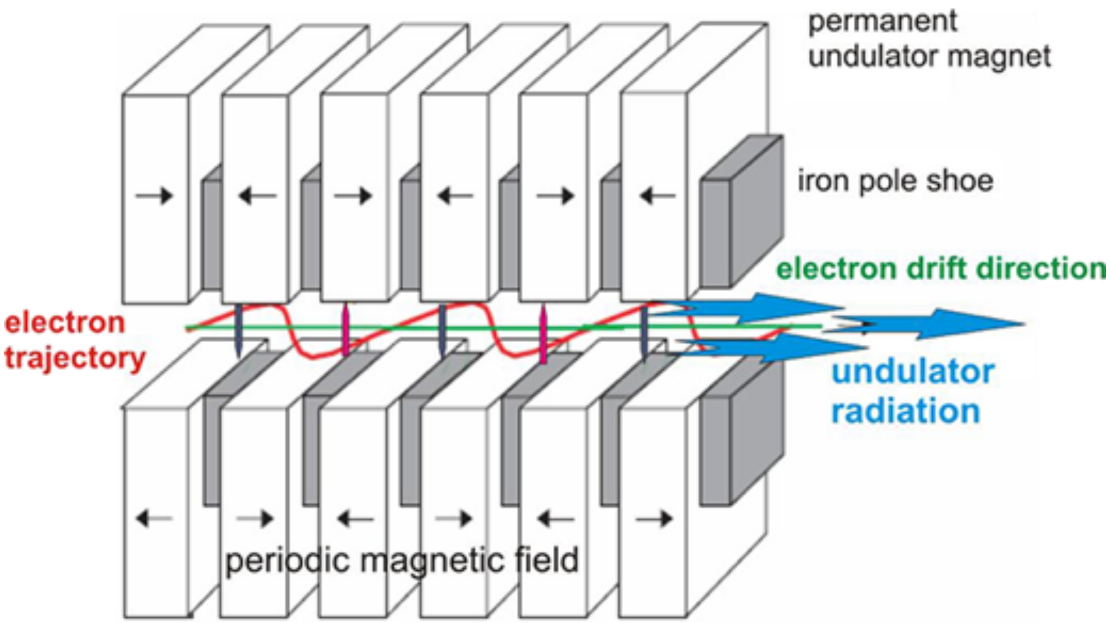


CAVITY COMBINER DRIVEN BY SIXTEEN 2kW SSA MODULES

BASICS OF UNDULATOR RADIATION

Periodic radiators allow narrowband radiation.

- The wavelength is given by the Lorentz-transformed undulator period
- The wavelength can be adjusted over a range by varying the magnetic field
- 3rd Gen storage ring sources were optimized for undulators



$$\lambda_n = \frac{\lambda_1}{n} = \frac{\lambda_u}{n}\left(\frac{1-u/c}{u/c}\right) \cong \frac{\lambda_u}{2n\gamma^2}\left(1+\tilde{k}^2\right),$$

$$k = eH_0\lambda_u \Big/ 2\pi mc^2,$$

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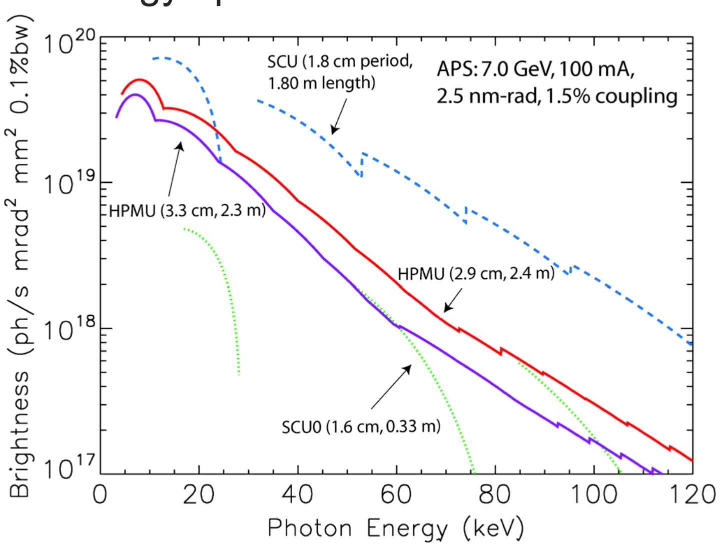
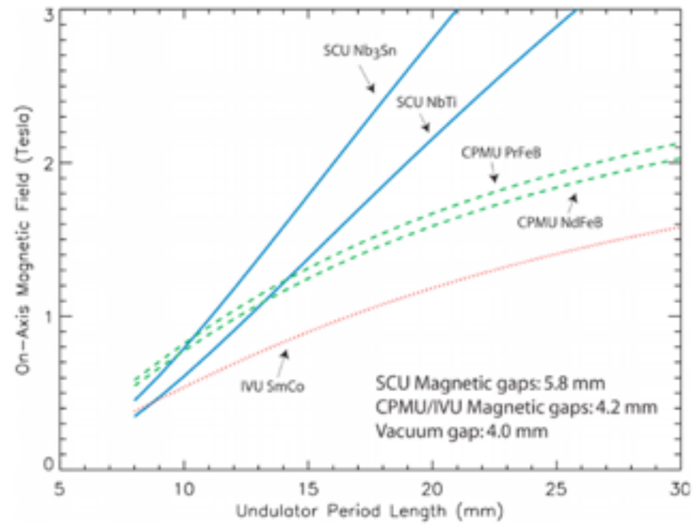
MAGNETIC FIELD OF VARIOUS INSERTION DEVICE TECHNOLOGIES

Motivation for Superconducting Undulators

- A superconducting undulator (SCU) is an electromagnetic undulator that utilizes superconducting coils for generating magnetic field.
- Superconducting technology-based undulators outperform all other technologies in terms of peak magnetic field and, hence, **energy tunability** of the radiation
- Superconducting technology opens a new avenue for insertion devices

Calculated tuning curves for SCUs and for hybrid undulators.



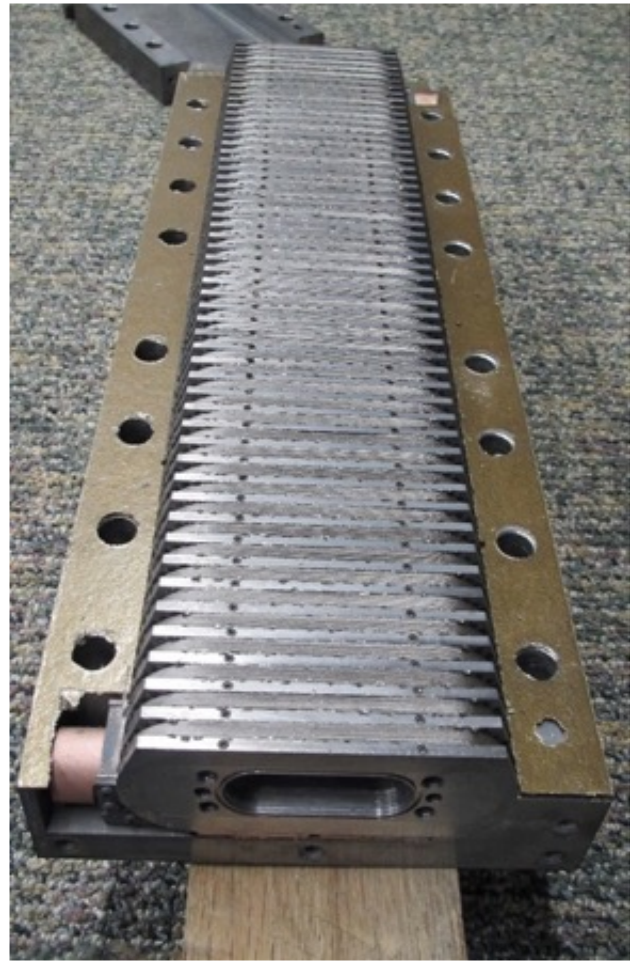


Calculated on-axis magnetic fields of two cryogenic permanent magnet undulators (CPMUs), two superconducting undulators (SCUs) and on in-vacuum undulator (IVU) for a vacuum gap of 4.0 mm for period length from 8 mm to 30 mm.

E. Moog, R. Dejus, and S. Sasaki, “Comparison of Achievable Magnetic Fields with Superconducting and Cryogenic Permanent Magnet Undulators – A Comprehensive Study of Computed and Measured Values”, ANL/APS/LS-348, 2017.

R&D ON NB_3SN UNDULATOR

- DOE has funded 3-year project, Efim Gluskin is the PI
- Goal: Develop, build and install on the APS ring a two-magnet Nb_3Sn undulator (in a long cryostat) a year before the APS-U 'dark time' starts.
- Collaboration with FNAL, LBNL and SLAC.
- Plan:
  – R&D phase – build and test short magnet models
  – 0.5-m long prototype
  – Full scale magnet and cryostat
  – Undulator assembly, test, installation on the APS ring.

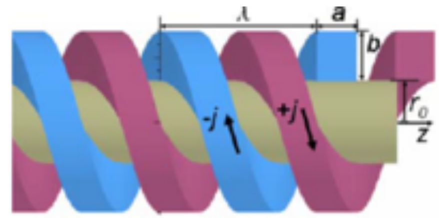


First half of Nb3Sn 0.5 m prototype after winding and reaction processes (left) and after epoxy impregnation and assembling the test set-up (right).

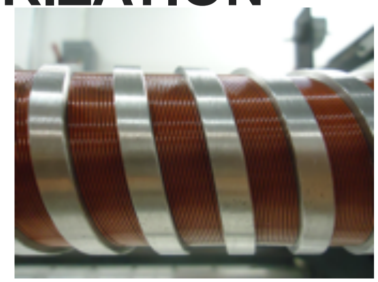
HELICAL UNDULATORS ALLOW ELLIPTICAL POLARIZATION

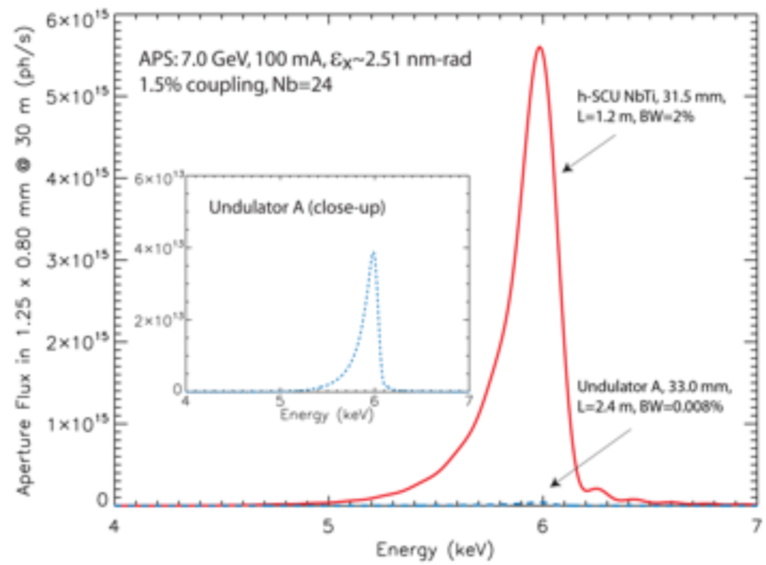
- SCU technology offers the possibility of building circular polarizing helical undulators
- We have recently completed a helical SCU (HSCU) for the APS
- X-ray photon correlation spectroscopy program at the APS will benefit from the increased brilliance provided by an HSCU

Parameter	HSCU
Cryostat length (m)	1.85
Magnetic length (m)	1.2
Undulator period (mm)	31.5
Magnetic bore diameter (mm)	31.0
Beam vacuum chamber vertical aperture (mm)	8
Beam vacuum chamber horizontal aperture (mm)	26
Undulator peak field Bx=By (T)	0.4
Undulator parameter Kx=Ky	1.2



Magnetic model of HSCU.

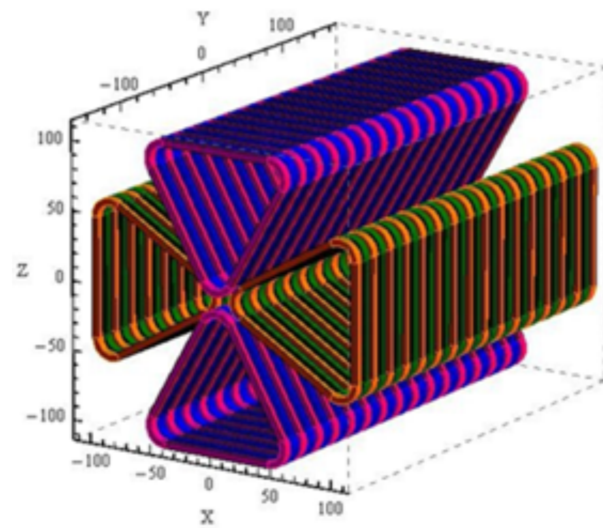

HSCU prototype coil winding.



Calculated photon spectrum of helical SCU.

VARIABLE POLARIZING SCU— SCAPE

- Users of APS POLAR beamline would like to have an undulator that can generate both circular and planar polarized photons
- To answer this challenging request, we have developed the concept of a Super Conducting Arbitrarily Polarizing Emitter, or SCAPE
- This electromagnetic superconducting undulator employs four planar magnetic cores assembled around a cylindrical beam vacuum chamber
- The APS Upgrade multi-bend achromat lattice enables round beam chambers (6 mm ID) for insertion devices
- The SCAPE concept has been tested in a prototype

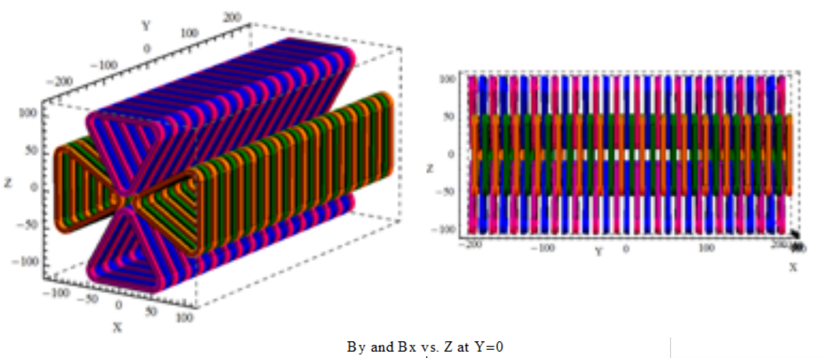


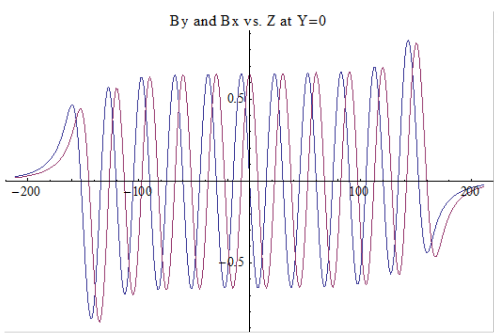
Concept of SCAPE: a universal SCU with four planar superconducting coil structures. A beam chamber is not shown.

SCAPE DESIGN

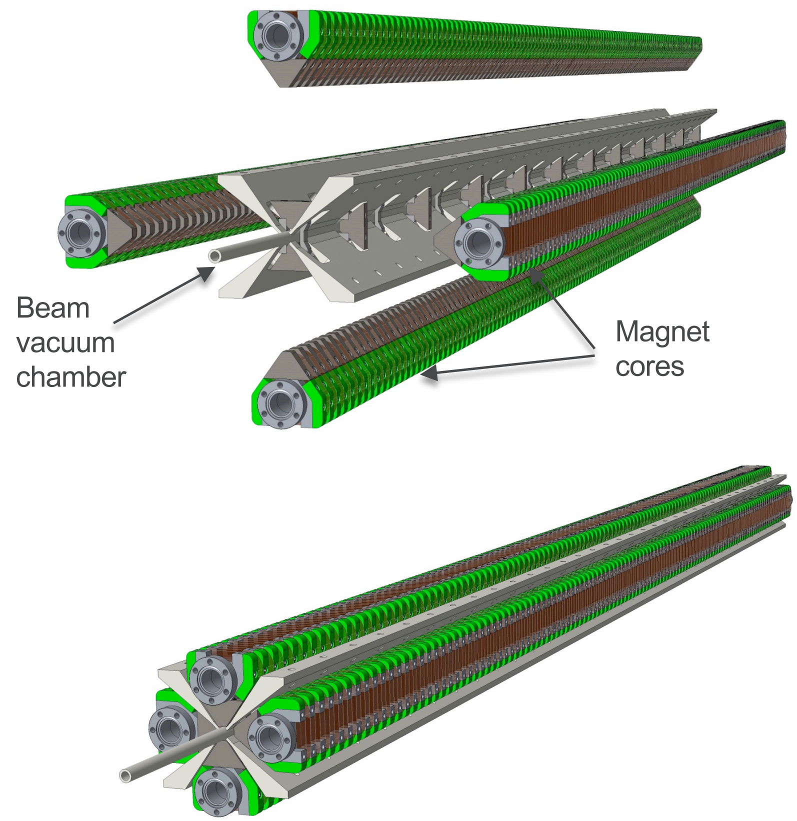
- Magnetic simulation of SCAPE was performed in Radia
- Mechanical design was then developed

Radia model of SCAPE



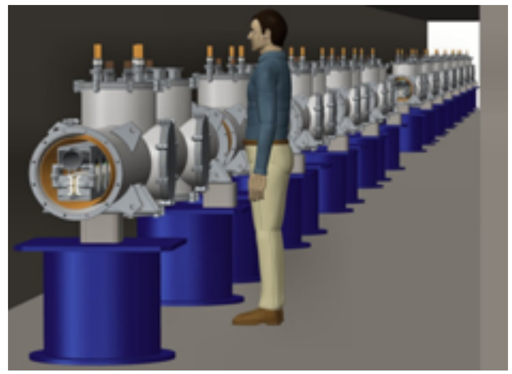


Typical SCAPE field profile.

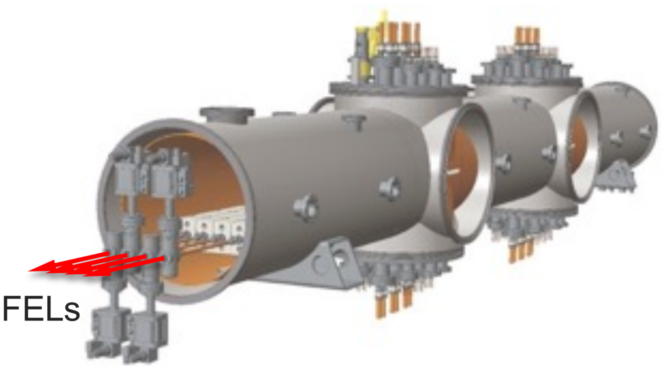


SCUs FOR FELs

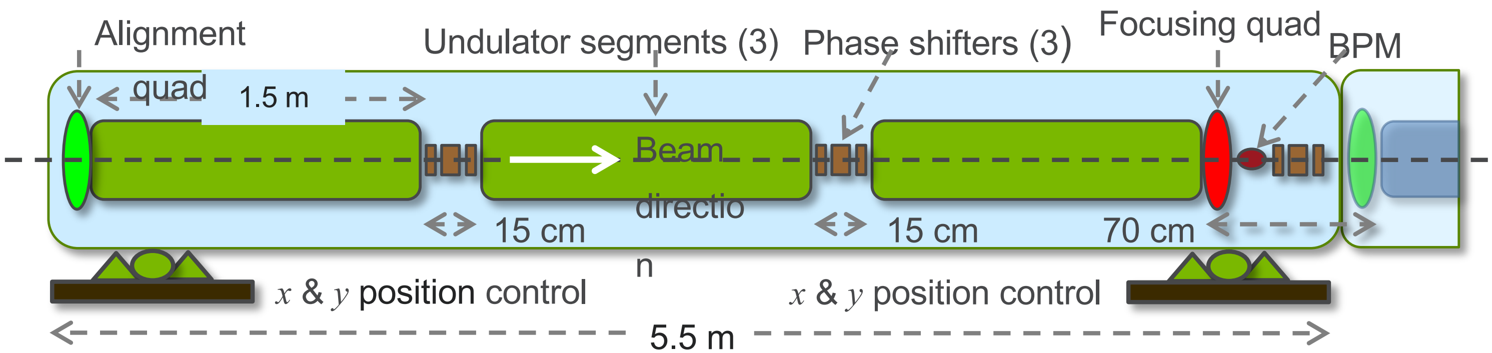
- Superconducting undulators should become a baseline for future FELs.
- Several FEL undulators in one cryostat is a possibility.



Possible LCLS SCU line



A cryomodule with four FELs



FEL SCU cryomodule concept

Courtesy of J. Fuerst, APS

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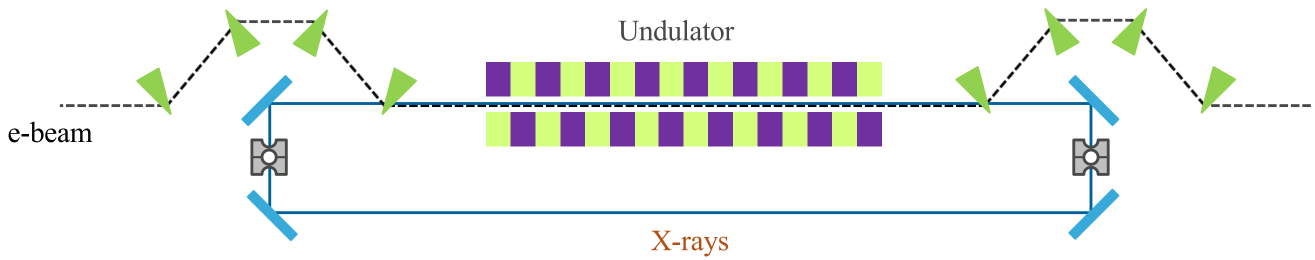
CAVITY BASED X-RAY FEL (CBXFEL)

Achieve longitudinal coherence via an optical resonator at x-ray energies



- Two proposed schemes:
  - Regenerative Amplifier FEL (SLAC)
    - Requires only a few passes in optical cavity. Results in higher peak power ultrashort pulses.
  - X-ray FEL Oscillator (Argonne)
    - Requires long buildup of x-rays in cavity. Results in 2-3 order magnitude brightness increase over LCLS-II.

PROPOSAL TO BUILD CAVITY AND INSTALL IN LCLS AND TEST CONCEPT ON LCLS-I

Use two-bunch beam pulse in CuRF linac to test effect on 2nd bunch

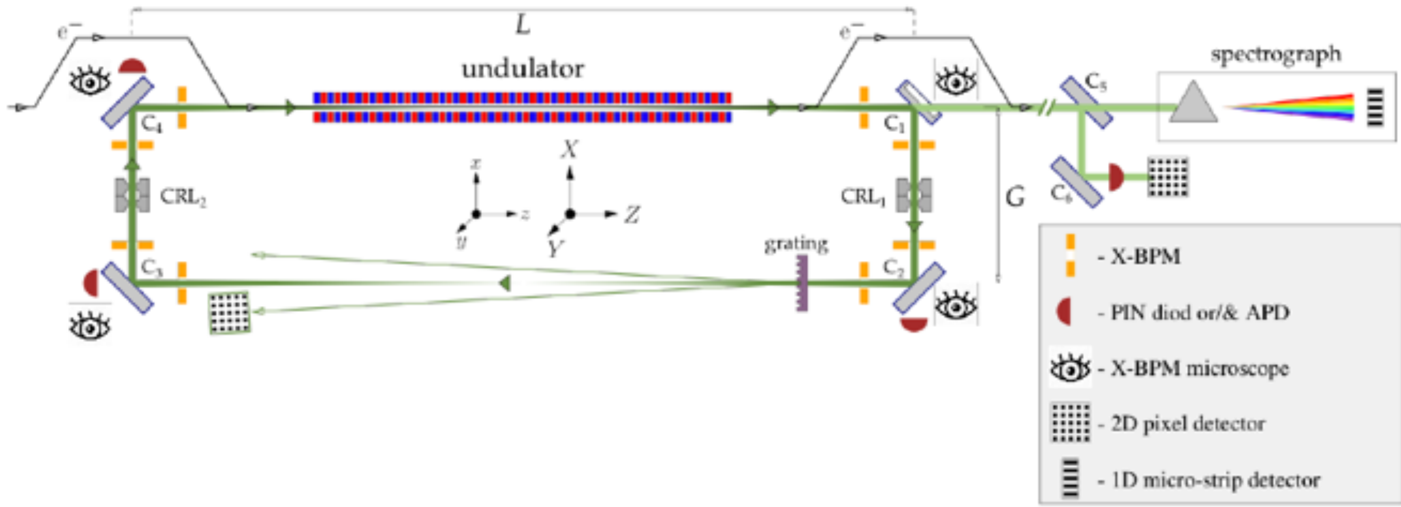
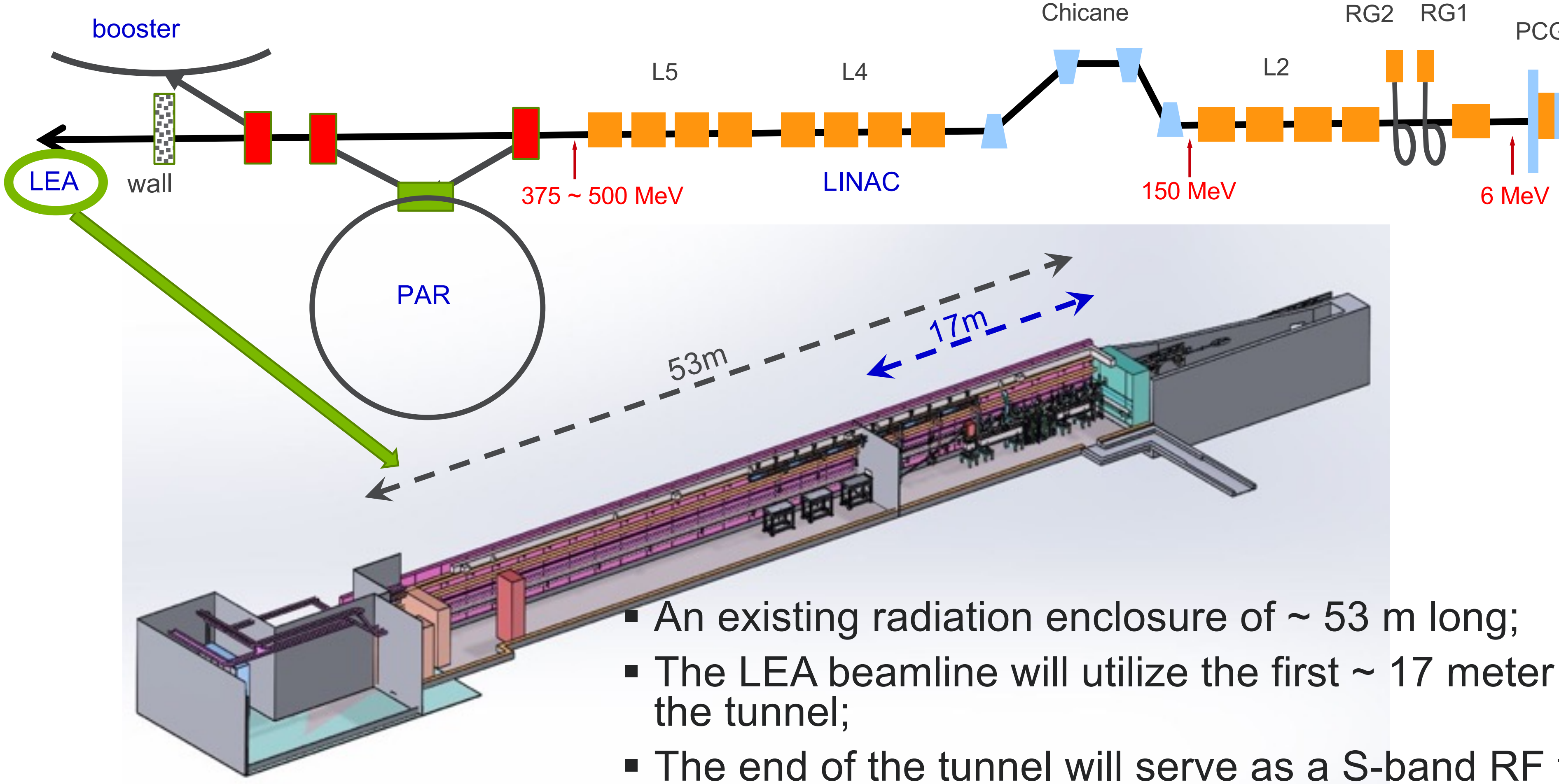


Figure 6.1: Figure 5.1.1: A schematic of the XFELO test experiment. The undulator consisting of seven LCLS II hard X-ray undulator modules fits in the space between two chicanes in the LCLS-II undulator hall. The X-ray forms a rectangular path (green) deflected by crystals C1, C2, C3, C4. The distance L between C4 and C1 is 32 m. The transverse dimension is greatly exaggerated for ease of illustration, the distance G being 1m. Various diagnostic elements are indicated.

Total budget: $12.6M
ANL: $7.0M

Key Argonne Personnel: Kwang-Je Kim (PI), Yuri Shvyd'ko (co-PI), Deming Shu (co-PI), Marion White (PM), Ryan Lindberg, Lahsen Assoufid, Xianbo Shi

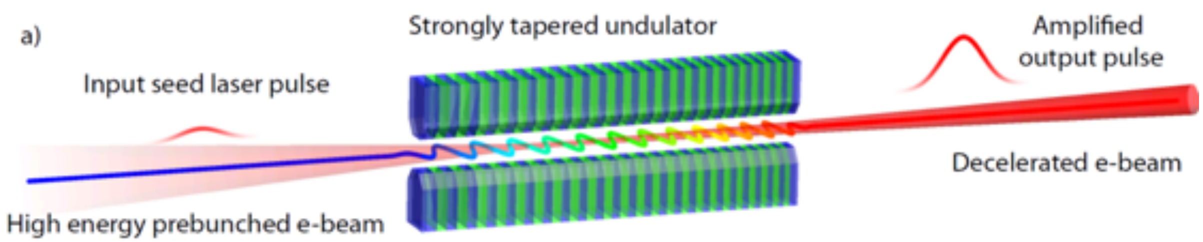
LEA: LINAC EXTENSION AREA

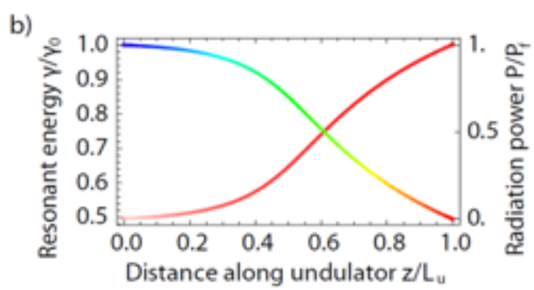


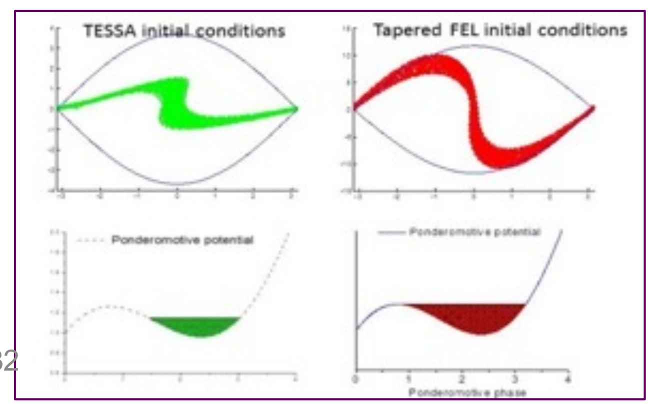
- An existing radiation enclosure of ~ 53 m long;
- The LEA beamline will utilize the first ~ 17 meter of the tunnel;
- The end of the tunnel will serve as a S-band RF test stand.

PROPOSED LEA EXPERIMENT: TAPERING ENHANCED STIMULATED SUPERRADIANT AMPLIFICATION (P. MUSUMECI, UCLA)

- Modern SASE FELs only extract a small fraction (0.1%) of the electron beam energy.
- How can we get higher x-ray pulse energy from FELs?
- We can extract a large fraction of the energy from an electron beam provided:
  - A high current, microbunched input e-beam
  - An **intense input seed**
  - Gradient matching to exploit the growing radiation field.





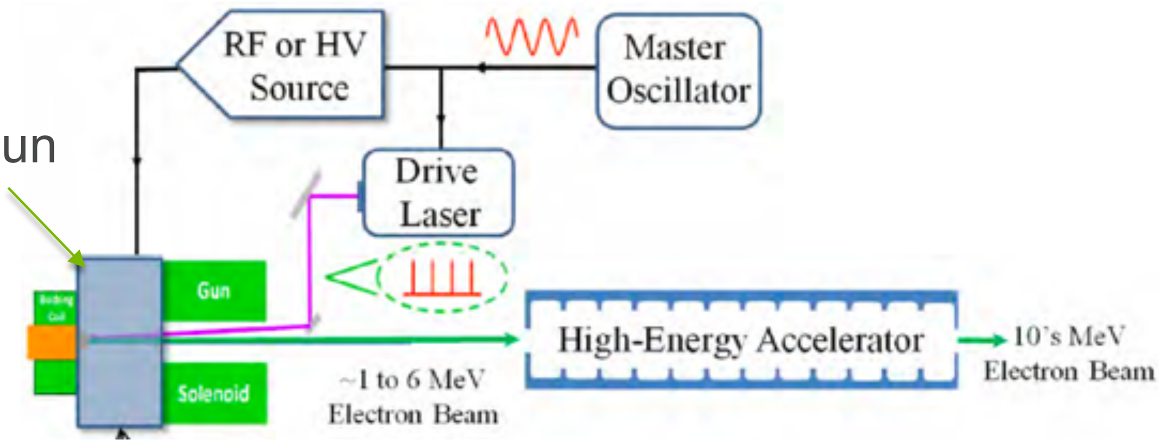


Duris et al. NJP (2015)

HIGH BRIGHTNESS PHOTOINJECTORS ARE A ENABLING ACCELERATOR TECHNOLOGY

Basis for all Free Electron Lasers; several new applications

Gun



Beam brightness is current/unit phase space area

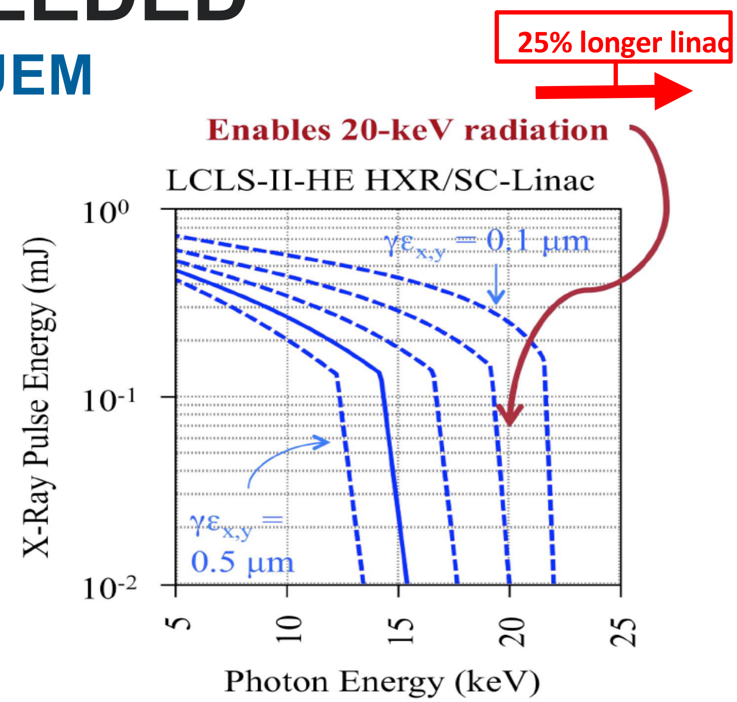
$$B_n = \frac{2I}{\pi^2 \varepsilon_{n,x} \varepsilon_{n,y}}$$

- Beam brightness proportional to electric field at cathode (E^n, n>1)
- Pulsed RF guns can achieve high fields but are limited to low duty factor (0.1%) and low rep rate (0.1-1 kHz)
- Future science needs are driving high repetition rates (LCLS-II) and RF guns with 100% duty factor (aka CW operation.) The most promising option is an SRF gun that has **not yet been demonstrated**.

HIGH BRIGHTNESS, HIGH REPETITION RATE ELECTRON SOURCES ARE NEEDED

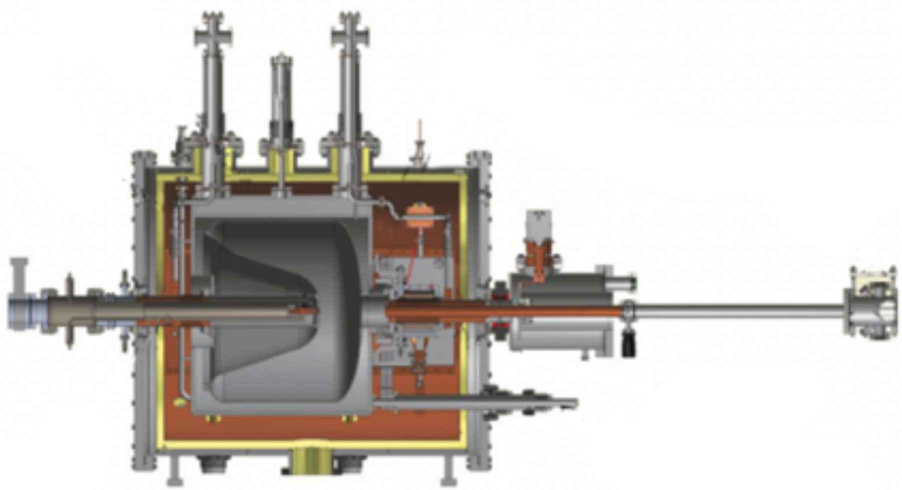
Applications for XFEL injectors and UED/UEM

- The next phase for XFELs is to increase rep rate and energy reach.
- Lower emittance (i.e. higher brightness) is needed to allow lasing at higher energies.
- This is achieved with higher electric field gradients at the photocathode **AND 100% DF.**
- This is a strong case for SRF guns.
- Another emerging application is time-resolved electron diffraction and microscopy using very similar technology.
- Argonne is an ideal place to contribute to this effort.

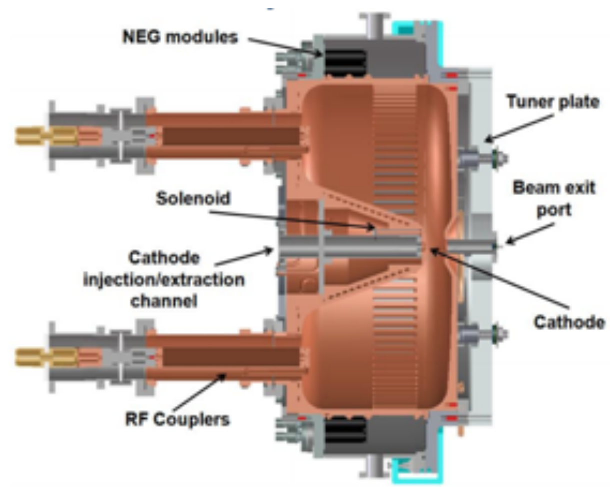


THE NEXT STEP IS HIGH REPETITION RATE

High brightness, high rep-rate (~MHz) e-guns have been under development for the past decade for LCLS-II



Superconducting gun

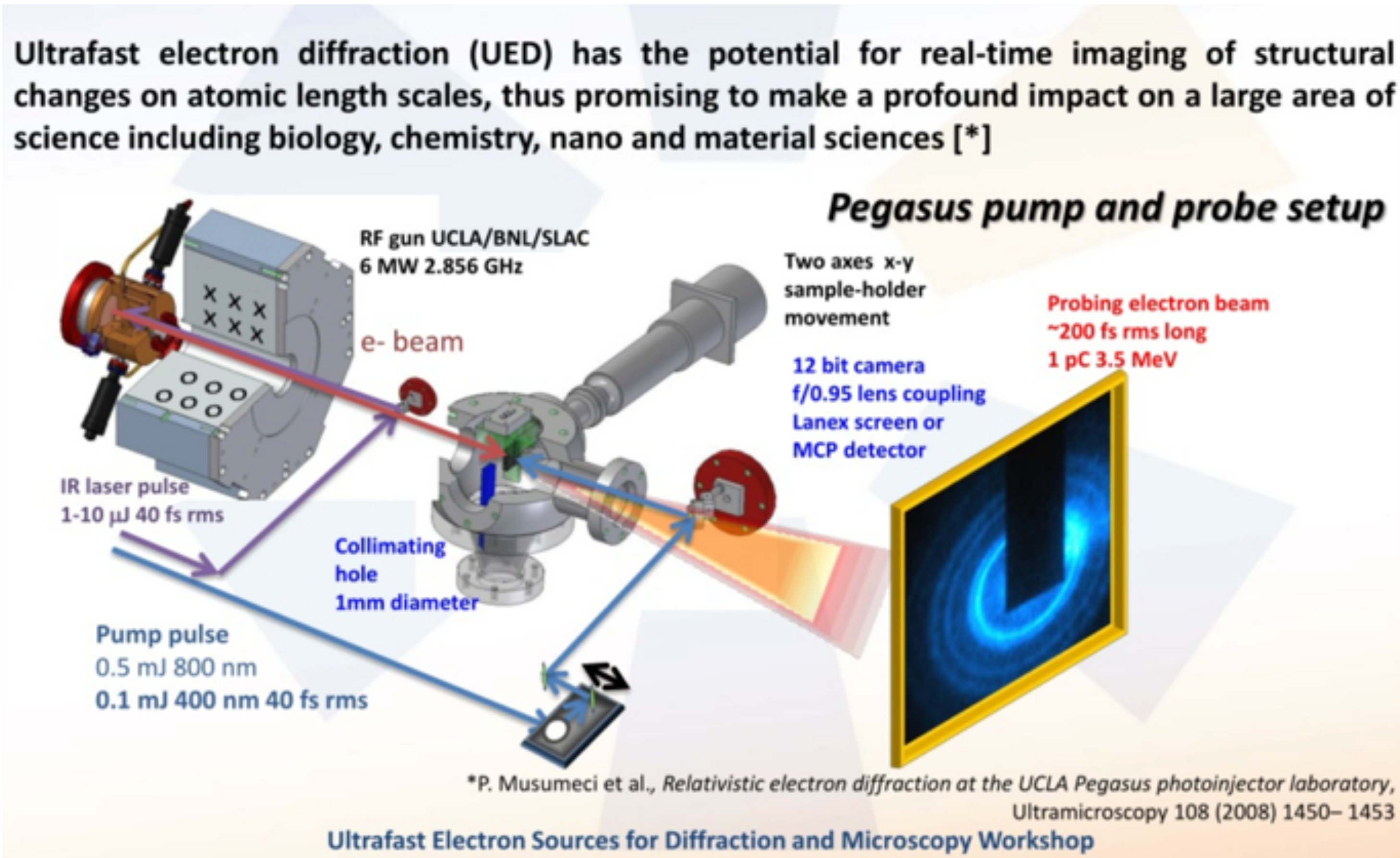


Normal conducting gun (LBNL)

SLAC is not able to divert attention from LCLS-II for a new SRF gun project. DOE/BES has contacted ANL and other labs with SRF capability for expressions of interest to adopt this gun. We are making a strong proposal to bring it to Argonne.

ULTRAFAST ELECTRON SCATTERING

Leverages development of high brightness e-guns over past 3 decades



A NEW PROGRAM IN UED HAS JUST BEGUN AT SLAC USING A PULSED ELECTRON GUN

Machine Status | Schedules | User Resources | User Portal Login | LCLS Internal Site

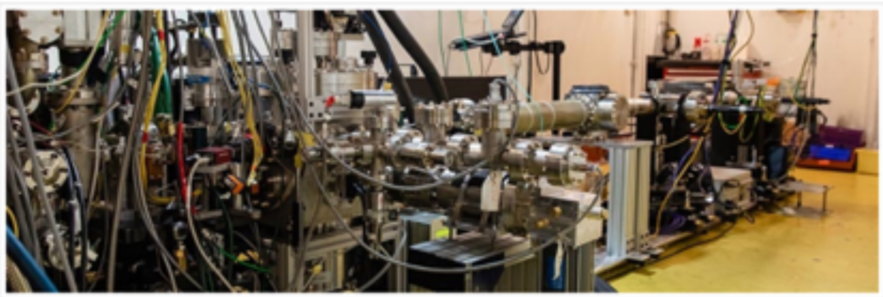
LCLS Linac Coherent Light Source

Home | News | About | User Resources | Publications | Instruments | Machine | Departments | LCLS-II | Useful Links

SLAC MeV-UED

INSTRUMENTS

- AMO - Atomic, Molecular & Optical Science
- CXI - Coherent X-ray Imaging
- MEC - Matter in Extreme Conditions
- MFX - Macromolecular Femtosecond Crystallography
- SXR - Soft X-ray Materials Science
- XCS - X-ray Correlation



SLAC Megaelectronvolt Ultrasfast Electron Diffraction Instrument: MeV-UED

Short Description

MeV-UED Contact Info

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GUN TO BE SITED IN EXISTING SRF TEST BUNKER

- Cryostat modified for operation with refrigerator versus dewar operation.
- Normal conducting cathode under repair.
- Covid-19 has delayed testing. First cooldown this month.

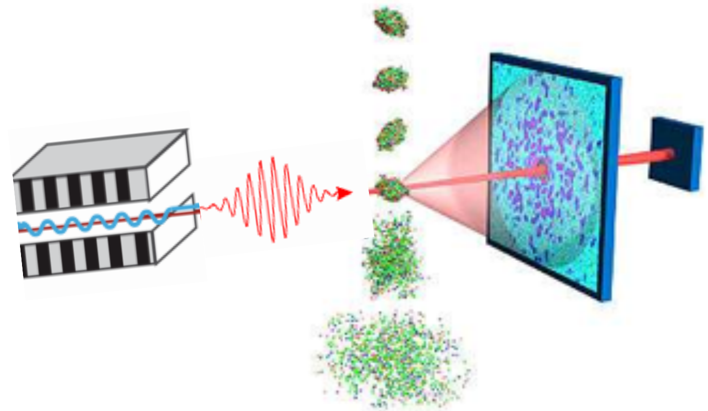
- Liquid helium refrigerator & shielded test cave – At least 6 months/year access for next two years
- RF/LLRF systems at 200 MHz
- Cryomodule assembly area & access to SRF chemistry, clean facilities

THE FREE ELECTRON LASER: EXTREME BRIGHTNESS, NANOMETER AND FS RESOLUTIONS

Enables diffraction imaging of aperiodic biological molecules

Optimal x-rays*)

- Photon energy 8–13 keV
- Pulse duration: a few fs or less
- Pulse rep. rate 50 kHz



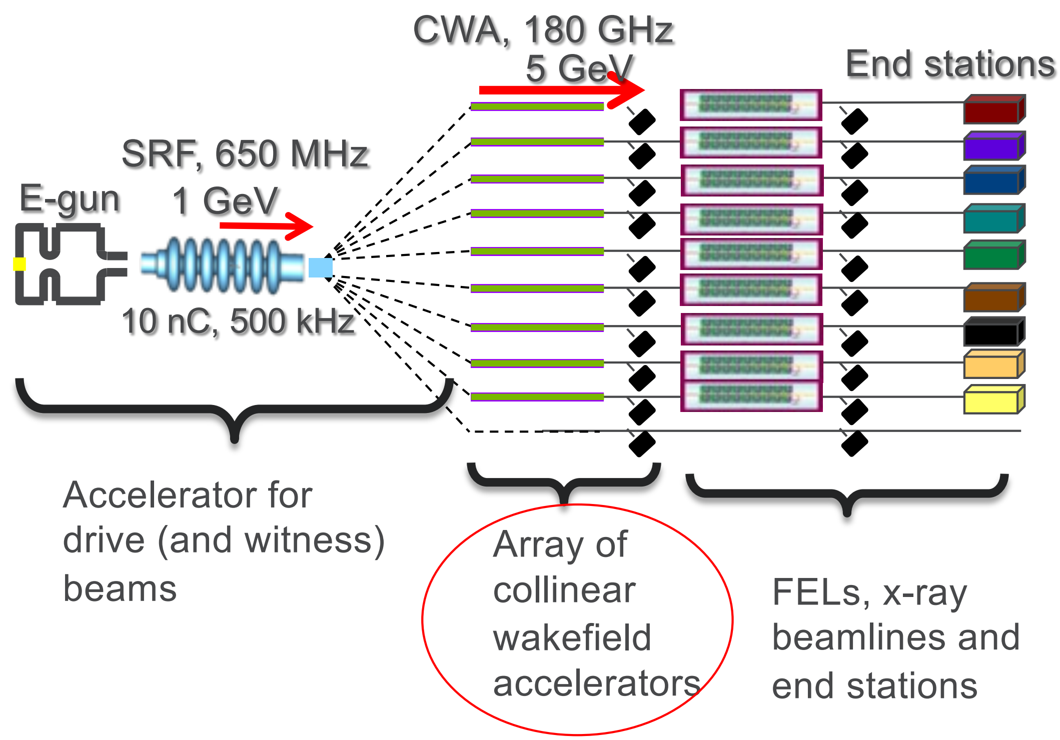
A protein exposed to an ultra-short X-ray pulse. Images show the molecule before, at and after interaction (see also Neutze, R. Wouts, D. van der Spoel, E. Weckert, and J. Hajdu, “Potential for biomolecular imaging with femtosecond X-ray pulses,” Nature 406 (2000) 752).

*) H. Chapman *et al*., Physical Review E 71, 061919 2005

A CONCEPT OF A MULTI USER FEL FACILITY BASED ON THE ARRAY OF COLLINEAR WAKEFIELD ACCELERATORS

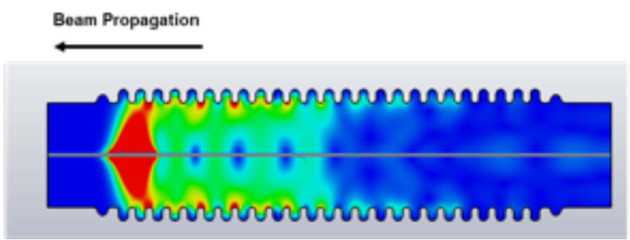
High repetition rate operation is essential goal

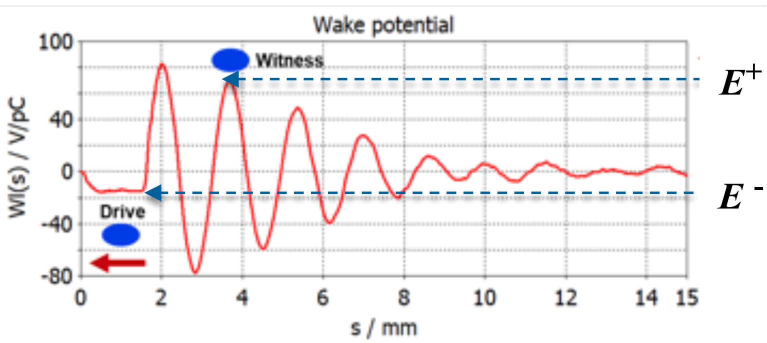
- Multiple FELs maximize facility productivity.
- Each FEL uses its own accelerator.
- Single SRF gun and single SRF linac drive 10 collinear wakefield accelerators.
- Collinear wakefield accelerators increase witness beam energy from 1 GeV up to 5 GeV.
- Repetition rate up to 50 kHz per FEL minimizes data collection time.



WAKEFIELD ACCELERATION*)

Focus is less on developing record breaking accelerating gradients and more on energy-transfer efficiency, simplicity and cost





The Lorentz force is integrated over the beam trajectory to find the change in energy, given by the wake potential W:

$$\vec{W}(r_1,s) = \frac{1}{q_1}\int_{-\infty}^{\infty} dz \left[\vec{E}(r_1,z,t) + c\vec{e_z} \times \vec{B}(r_1,z,t)\right]_{t=(s+z)/c}$$

Transformer ratio

$$R = \frac{\max|E_+|}{\max|E_-|}$$

Accelerating field

$$\max|E_+| \leq \frac{4\kappa_{\parallel}|Q|}{R}$$

loss factor

total charge

41

"The more energy efficient is the accelerator, the less is the accelerating field for the witness bunch"

*) S. Baturin and A. Zholents, PRAB, 061302 (2017)

Goals and compromises:

- Extract 80% of drive bunch energy.
- Obtain highest energy witness bunch. E^+
- Obtain on the order of 100 MV/m.

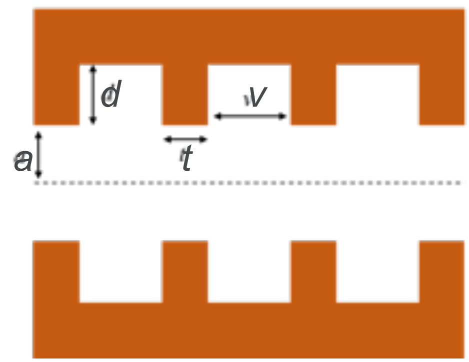
$R = 5$

*) G. A. Voss and T. Weiland, DESY M-82-10, 1982

WAVEGUIDE WITH CORRUGATIONS

Inner radius largely defines loss and kick factors due to wakefield

a: inner radius of cylinder.
d: depth of corrugations.
t: corrugation “tooth” width.
v: gap width between teeth.



Theoretical models*) predict the wakefield’s dependence on inner radius *a:*

Longitudinal wake loss factor: $\kappa_0 = \frac{Z_0 c}{2\pi a^2}$

Transverse wake kick factor: $W_x \approx \frac{2 Z_0 c}{\pi a^4}$

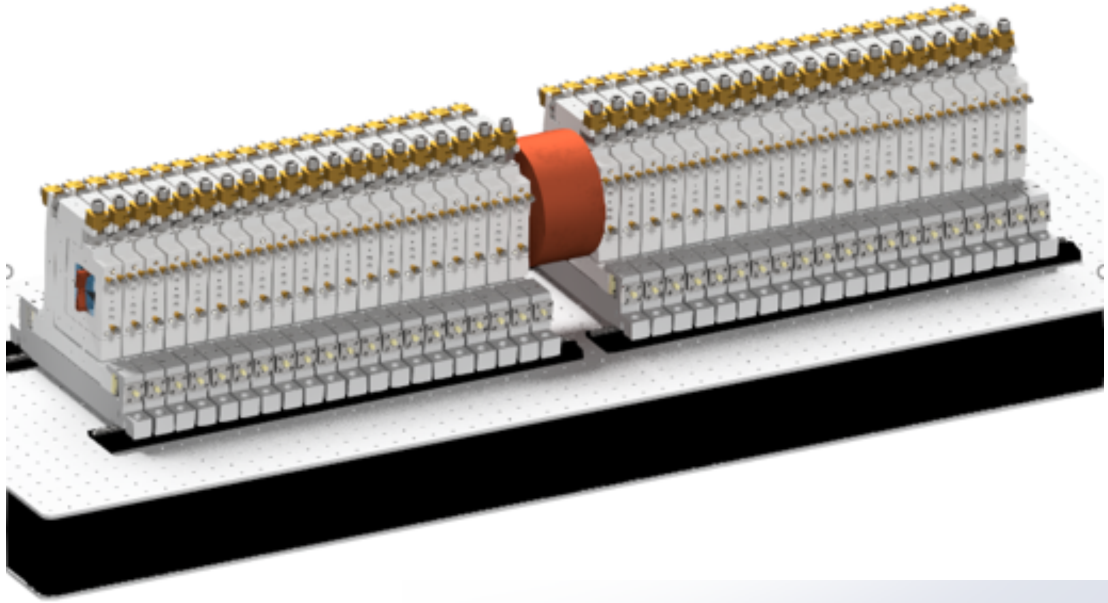
Goals and compromises:
Choose small **a** to maximize κ_0
or
Choose large **a** to minimize W_x

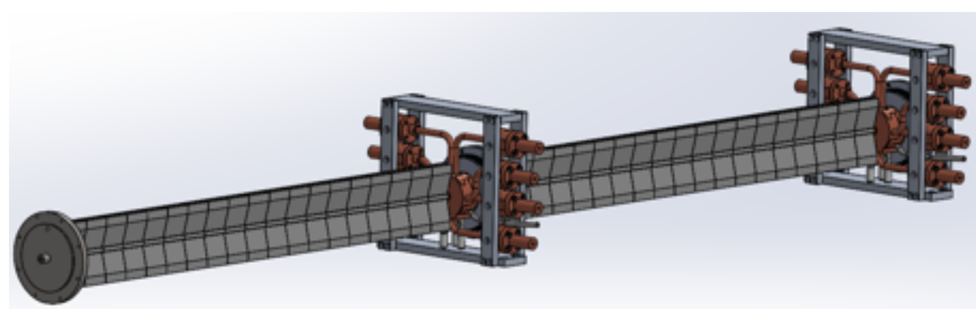
Value chosen: *a* =1mm

*) K. Bane and G. Stupakov, Nucl. Instrum. Meth. Phys. Res., Sect. A 677, 67 (2012).

NEAR TERM GOAL IS CONSTRUCTION OF CWA MODULE

Two accelerator sections shown with and without quadrupoles

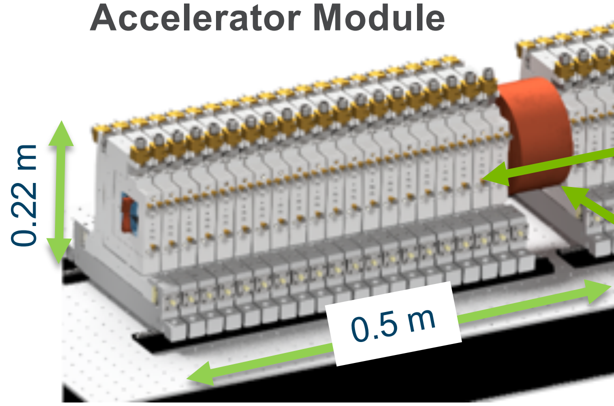




Argonne NATIONAL LABORATORY

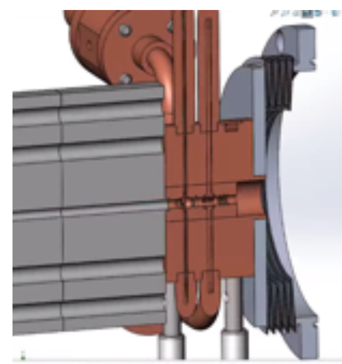
COMPONENTS IN ACCELERATOR MODULE

Accelerator Module



Vacuum chamber surrounded by focusing quadrupole magnets.

Transition Section



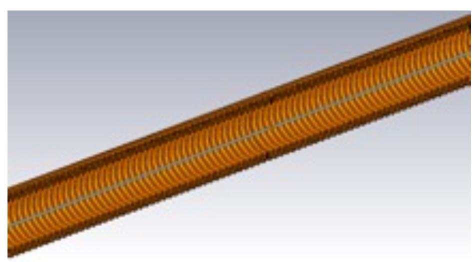
Extracts excess beam radiation and measures beam position.

Vacuum chamber

Corrugated waveguide embedded in water cooled copper block.

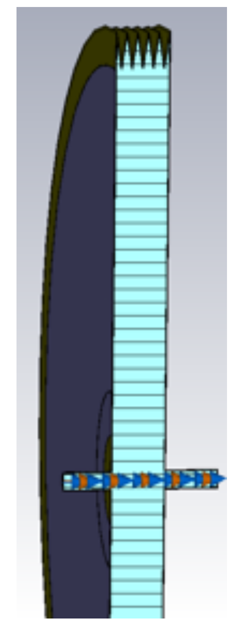
Water in and out channels.

Corrugated Waveguide



Assists with the increases of beam energy by ~ 50 MeV.

Bellows



Bellows attaches to next accelerator module.

SUMMARY

- The most sophisticated electron storage ring in the world (APS-U) is being built and will be installed and commissioned in 2022-3.
  - Numerous leading-edge developments in accelerator technology and beam physics.
- Funding for several high priority BES accelerator R&D projects is now funded
  - Nb3Sn SCUs
  - CBXFEL
  - SRF photogun
- We are working to leverage the 500 MeV APS linac and available tunnel space for a unique accelerator R&D tool that would be highly complementary to the AWA facilities.
- Work is ongoing looking to future light sources.
- Argonne is fully engaged in the present golden age of accelerator development. Please come join us!