NOCE 2017 @ Arcidosso Castle

Thanks to:

Simone Di Mitri

and

Max Cornacchia

and

The Organizing and Program Committee

for

the kind invitation!!!

"Particle Beam Physics in Arcidosso – 20 years later!"

Talk Title Created by Simone DiMitri and Max Cornacchia and kindly offered to:

Swapan Chattopadhyay

My Interpretation:

"Developments in Beam Physics since the first workshop in Arcidosso, 1994 > 20 years ago!"

OR,

"What have we learnt since then?"

Swapan Chattopadhyay

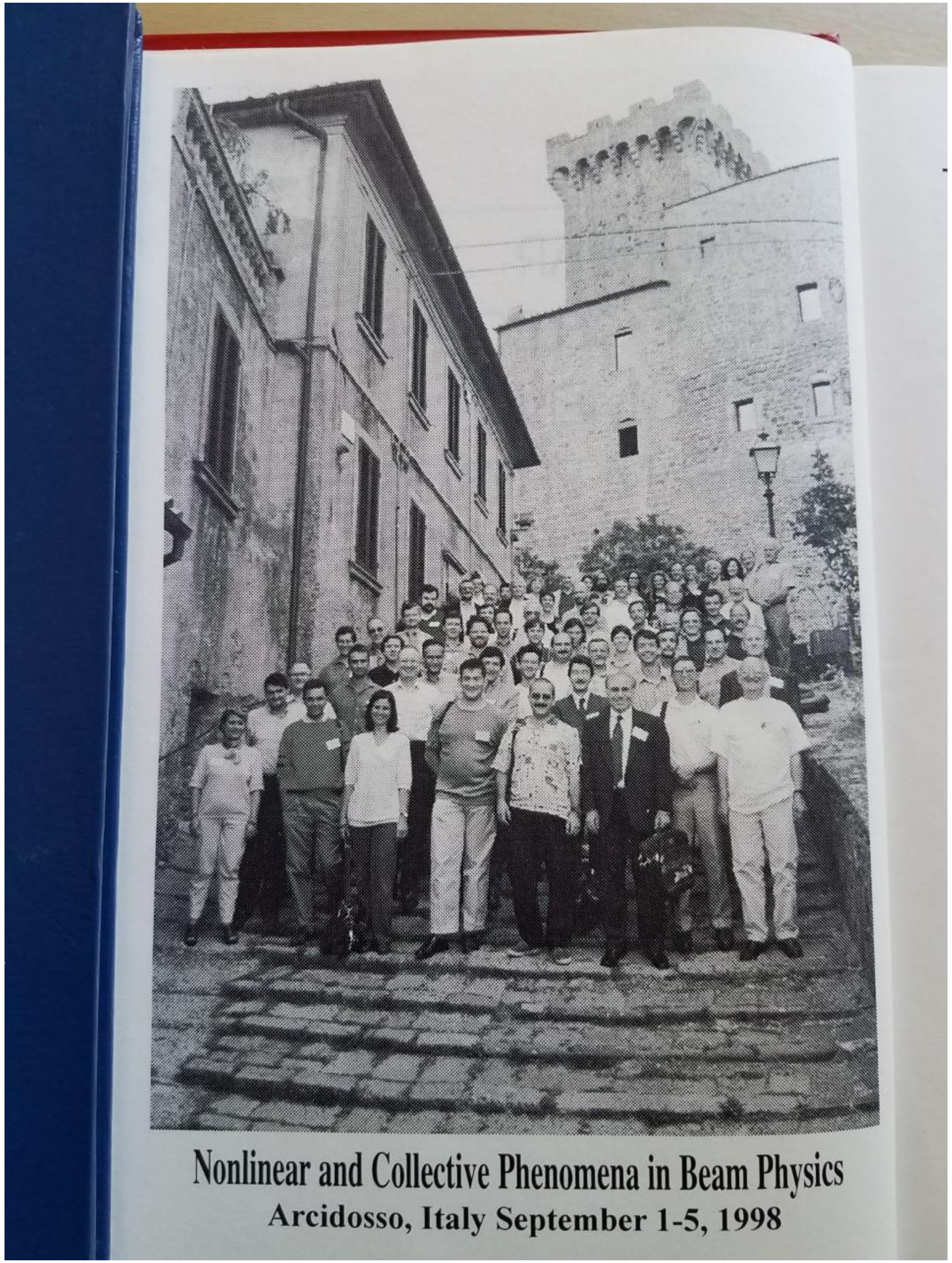
Acknowledgment

Aside from my own thoughts, I have had some direct feedback from a few colleagues about latest developments:

Simone Di Mitri (Elettra, Trieste)
Paul Emma (LCLS-II/SLAC)
Nikolay Solyak (XFEL/DESY and LCLS-II/SLAC)
Joe Bisognano (Wisconsin)
Kwang-Je Kim (APS/ANL)
Alexander Zholents (APS/ANL)
Richard Walker (DIAMOND)
Riccardo Bartolini (DIAMOND/Oxford)
Tanaji Sen (FNAL)
Alexander Valishev (FNAL)
Philippe Piot (NIU/FNAL)

Arcidosso 1994

Arcidosso 1998



The “Arcidosso Series”

1994: “Nonlinear Dynamics in Particle Accelerators: Theory and Experiments”

1996: “Nonlinear and Collective Phenomena in Beam Physics”

1998: “Nonlinear and Collective Phenomena in Beam Physics”

2000: “Physics of, and Science with, the X-ray Free-Electron Laser”

2017: “NOnlinear dynamics and Collective Effects in particle beam physics”

⋮

CONTENTS:

Linear and Nonlinear Dynamics, Collective Effects, and Innovative Designs of Storage Rings and Linear Accelerators and Advanced Laser-Plasma Concepts

Particle/Nuclear Physics facilities: Hadron and Lepton Circular and Linear Colliders and Fixed Target Facilities

CC/LC/FT

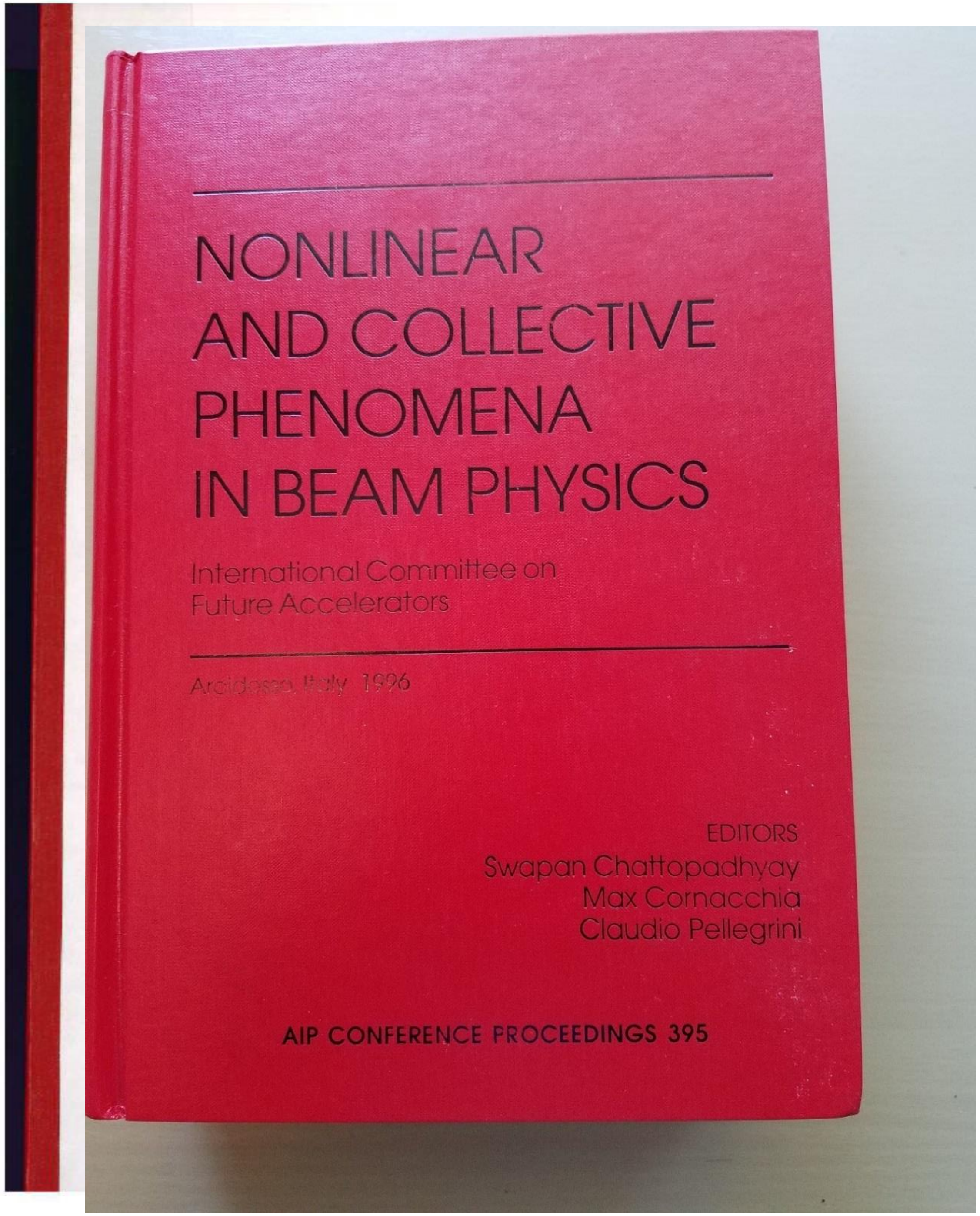
Synchrotron Radiation and other Light Sources and Free Electron Lasers

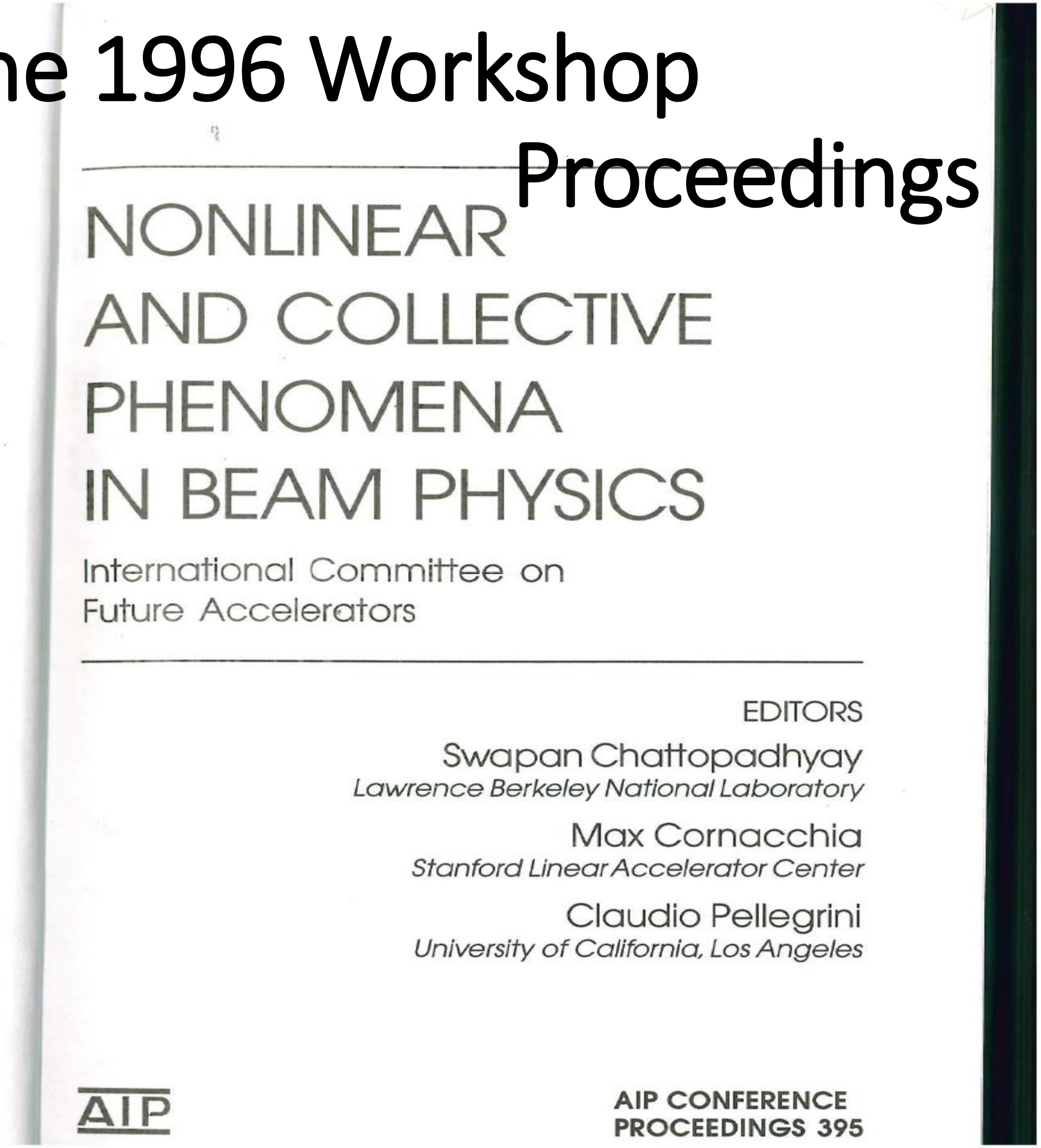
SR/FEL

Advanced Laser-Plasma Concepts

LP

The 1996 Workshop Proceedings




NONLINEAR
AND COLLECTIVE
PHENOMENA
IN BEAM PHYSICS

International Committee on
Future Accelerators

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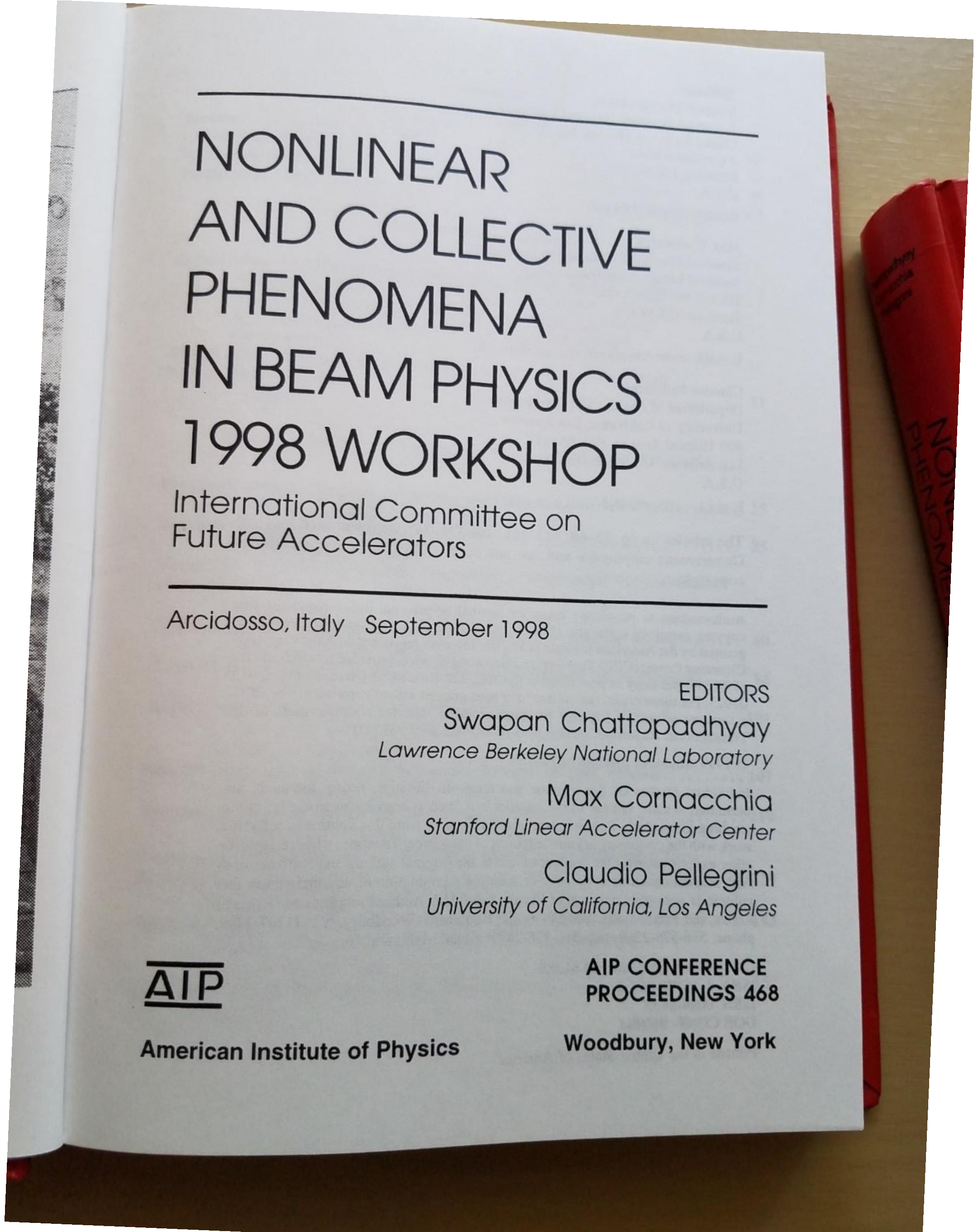
The 1998 Workshop Proceedings



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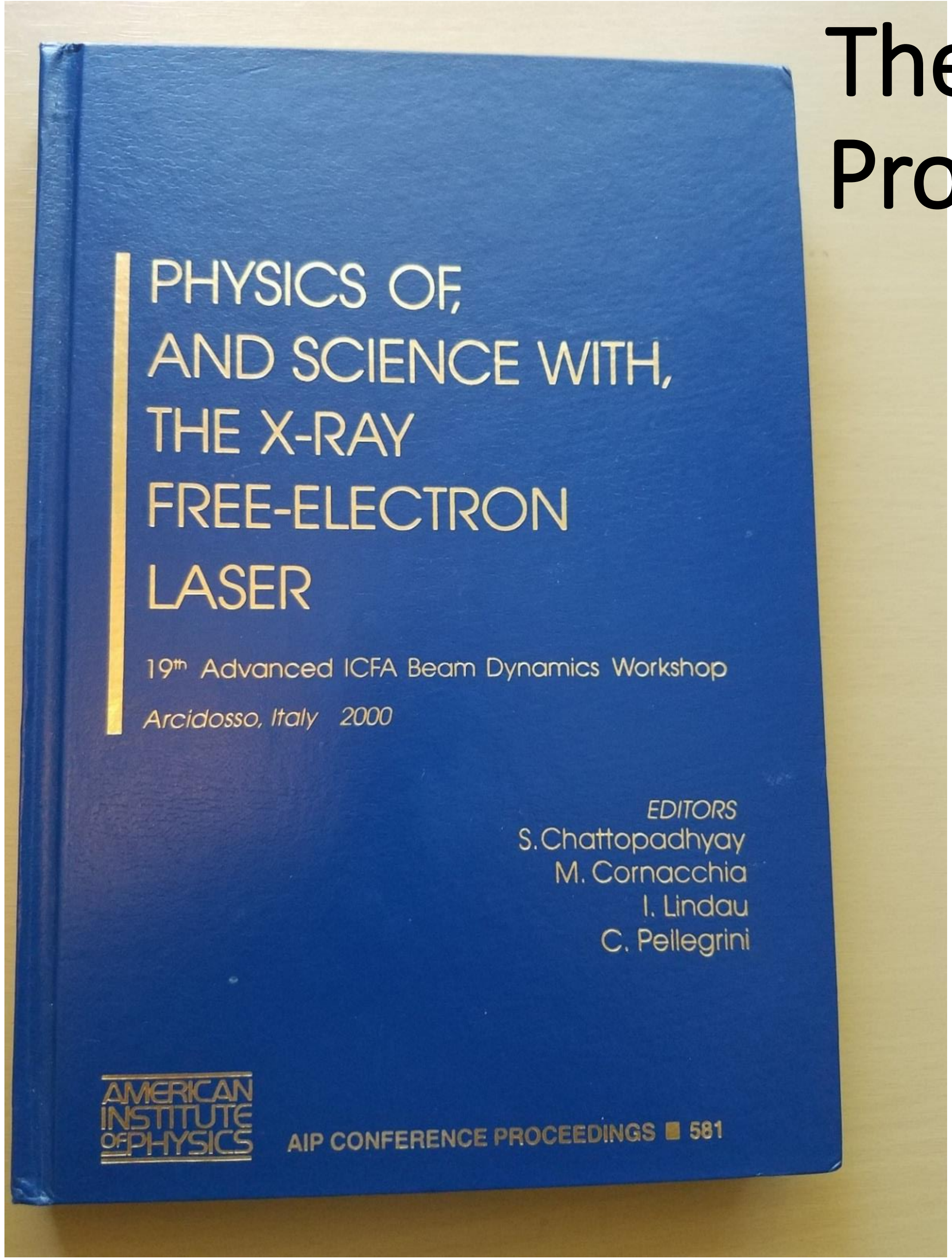
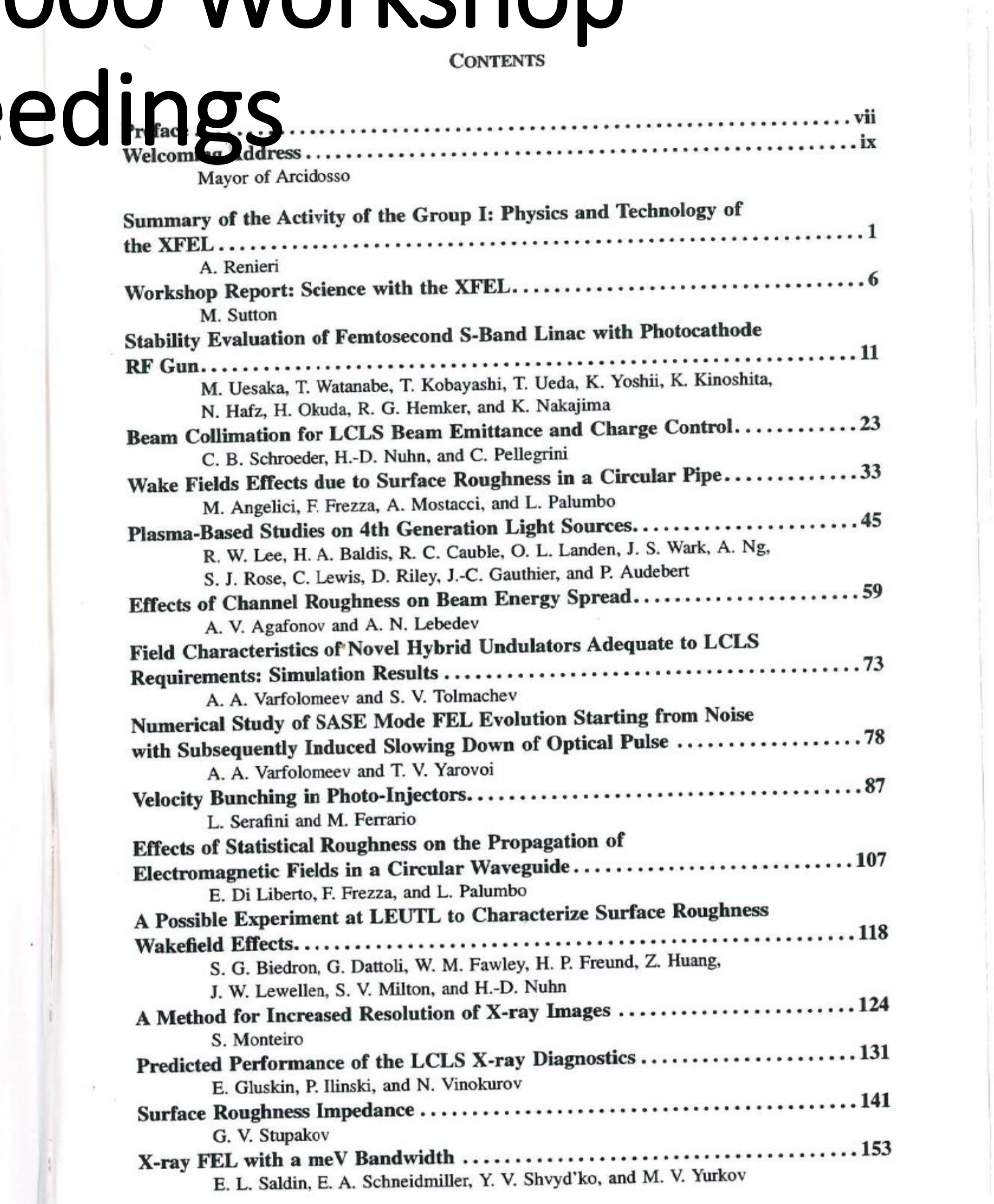
WORKING GROUP ON CREATION AND MANIPULATION OF HIGH PHASE DENSITY BEAMS

WORKING GROUP ON PHYSICS OF, AND PHYSICS WITH, HIGH ENERGY DENSITY BEAMS

The 2000 Workshop Proceedings





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PREFACE

The 19th Advanced ICFA Beam Dynamics Workshop on "The Physics of, and Science with, X-ray Free-Electron Lasers" took place in Arcidosso, Italy, from the 10th to the 15th of September, 2000. The workshop was sponsored by the International Committee for future Accelerators, the U.S. Department of Energy, the University of California at Los Angeles, the Stanford Linear Accelerator Center, the Deutsches Electronen-Synchrotron, and the Lawrence Berkeley National Laboratory, together with local authorities of Tuscany, Grosseto, and Arcidosso. The Workshop was chaired by M. Cornacchia (SLAC), I. Lindau (SLAC/Lund University), and C. Pellegrini (UCLA). Seventy-five scientists attended the Workshop: 50 are involved in the physics and technology of accelerators, free-electron lasers and x-ray optics, and 25 pursue the scientific applications. There were plenary and parallel sessions and many lively discussions during and after the regular Workshop schedule.

Arcidosso is a medieval town in southern Tuscany, close to the city of Sienna. The meeting took place in the historically evocative setting of an 11th-century castle atop a hill dominating the nearby valley. The castle was restored in 1989, and preserves the atmosphere and ruggedness of medieval Europe.

There were two invited lectures on Monday, September 11, to open the subjects and two summary talks in the afternoon on Friday, September 15. All the other presentations were either informal or in the form of posters.

The group on "Physics and Technology of the XFEL," with introductory talks by Kwang-Je Kim (ANL) and Jamie Rosenzweig (UCLA), was coordinated by Alberto Renieri (ENEA-Frascati).

The group on "Science with the XFEL" was coordinated by Mark Sutton (McGill University) with introductory talks by Andreas Freund (ESRF) and Ingolf Lindau (SLAC/Lund University).

On behalf of the Organizing Committee, we would like to thank the sponsoring institutions for supporting the Workshop. We would also like to thank the Mayor, Ing. Attilio Marino, and the Administration of Arcidosso for hosting the meeting. We are grateful to the regional and provincial administrations, to the "Comunità Montana del Monte Amiata," to the representatives of local authorities and to the Cassa di Risparmio di Firenze for providing valuable support. Special thanks are due to the Workshop Coordinator, Ms. Melinda Laraneta, and the coordinator of the local organization, Sig. Gianfranco Nanni. The people of Arcidosso, as always, have contributed to creating a pleasant atmosphere with their welcome, warmth, and friendship. We thank the Program Committee, and the working group coordinators and speakers, who contributed to an exciting scientific program of presentations and discussions, and worked hard and with enthusiasm to implement it.

M. Cornacchia, I. Lindau, C. Pellegrini

The “Arcidosso Series”
Visible Trend of Rapid Developments in Photon Sources

1994: “Nonlinear Dynamics in Particle Accelerators: Theory and Experiments”

1996: “Nonlinear and Collective Phenomena in Beam Physics”

CC/LC/FT: 70%   SR/FEL: 13%   LP: 17%

1998: “Nonlinear and Collective Phenomena in Beam Physics”

CC/LC/FT: 44%   SR/FEL: 49%   LP: 7%

2000: “Physics of, and Science with, the X-ray Free-Electron Laser”

CC/LC/FT: 5%   SR/FEL: 90%   LP: 5%

⋮

2017: “NOnlinear dynamics and Collective Effects in particle beam physics”

CC/LC/FT: 18%   SR/FEL: 80%   LP: 2%

MAJOR ISSUES: WHAT HAVE WE LEARNED in LAST 20 YEARS?

Brightness, Brightness, Brightness,….

→ *FELs, SR and other light sources (intensity vs. spectral purity, gain length, Dynamic Aperture, Stability, "Conditioned" bunches,….)*

Nonlinear Dynamics, Space Charge, Beam Diffusion, Halo, Instabilities

→ *Hadron Linacs, Rapid-Cycling Boosters and Colliders*

And everything else that degrades performance, e.g.

→ *Magnetic Lattice, Insertion Devices, CSR, Beam Handling/"Conditioning", Scattering, RF and Laser Manipulations, Injection of ultra-low-emittance diffraction-limited beams, Beam Cycling and Echoes, …*

THERE IS DEEP THEORY BEHIND THIS ALL, BUT I WILL BE CONCEPTUAL RATHER THAN THEORETICAL IN THIS TALK

Source Emittance, Temperature and Brightness:

Novel sources will be characterized by significantly lower transverse Emittance (hence transverse Temperature) and higher Brightness:

Emittance ←→ Temperature

Brightness:

$$B_{\perp} = \frac{I}{4\pi\,\varepsilon_x \varepsilon_y} = \frac{mc^2 J}{\pi k T}$$

Ultimate "Brightness" gets progressively Coulomb- and Quantum-limited:
Cold, Super-cold, Ultra-cold and Quantum-degenerate

For FELs, it is the beam "6-D handling" along the FEL chain which is as important as the source brightness(Chicanes, Bunch Compressors, CSR,….) .

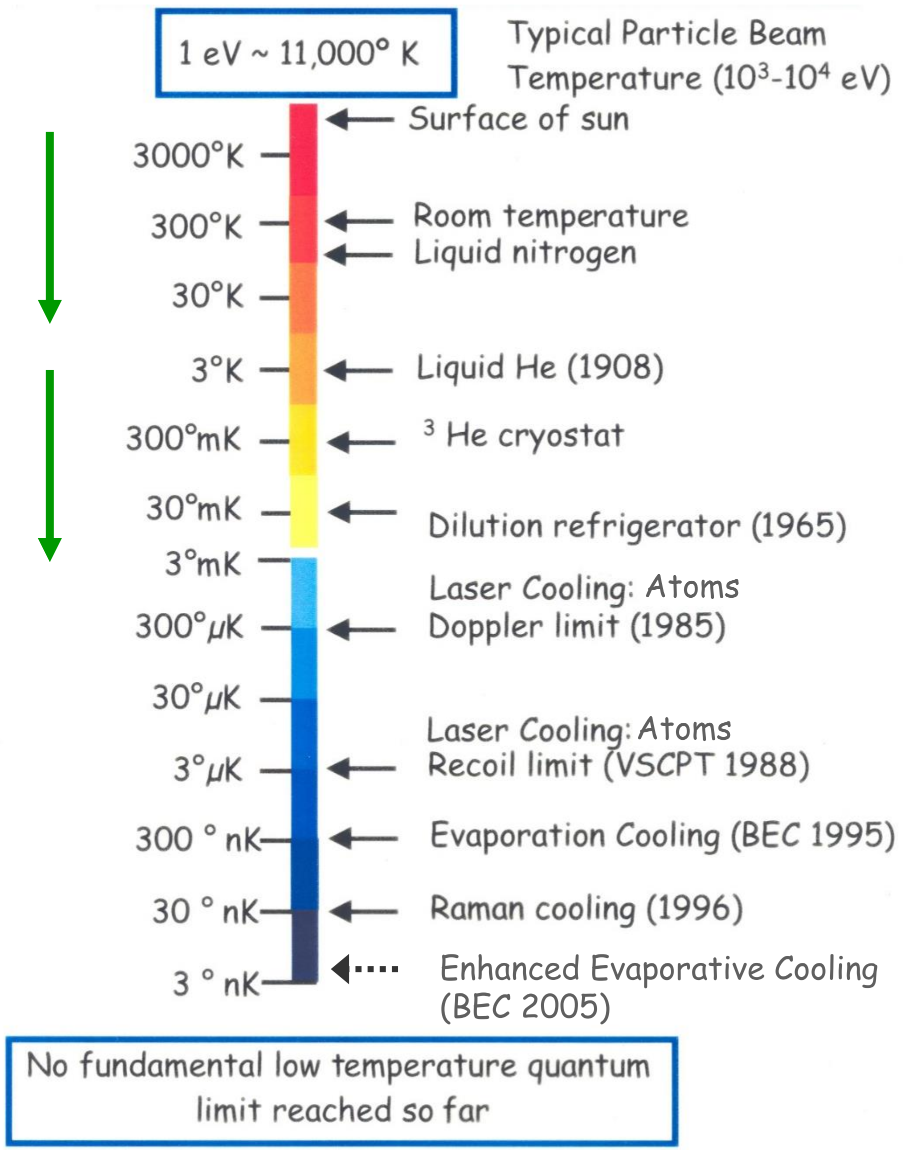
For, SR sources, it is the integrity and long-term stability of ultra-low emittance "diffraction-limited" , high-brightness beams that matters.

Lowest Temperature Achieved in the Laboratory

Temperature Scales

Electrons/charged Particle Beams need to get "colder" and "brighter" for higher intensity and spectrally purer coherent light

Typical electron beam temperatures are many 1000 degrees K. What if we could get colder electron beams at 1 degree K?
From 1 micro-meter → 1 nanometer



Report of the DOE Basic Energy Sciences on the Future of Electron Sources
September 8-9, 2016, SLAC
Relevant to all FELs, FEL Sources, and other "Designer" Beams and Sources

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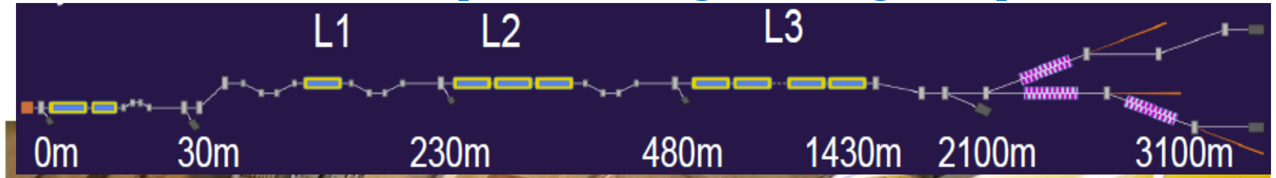
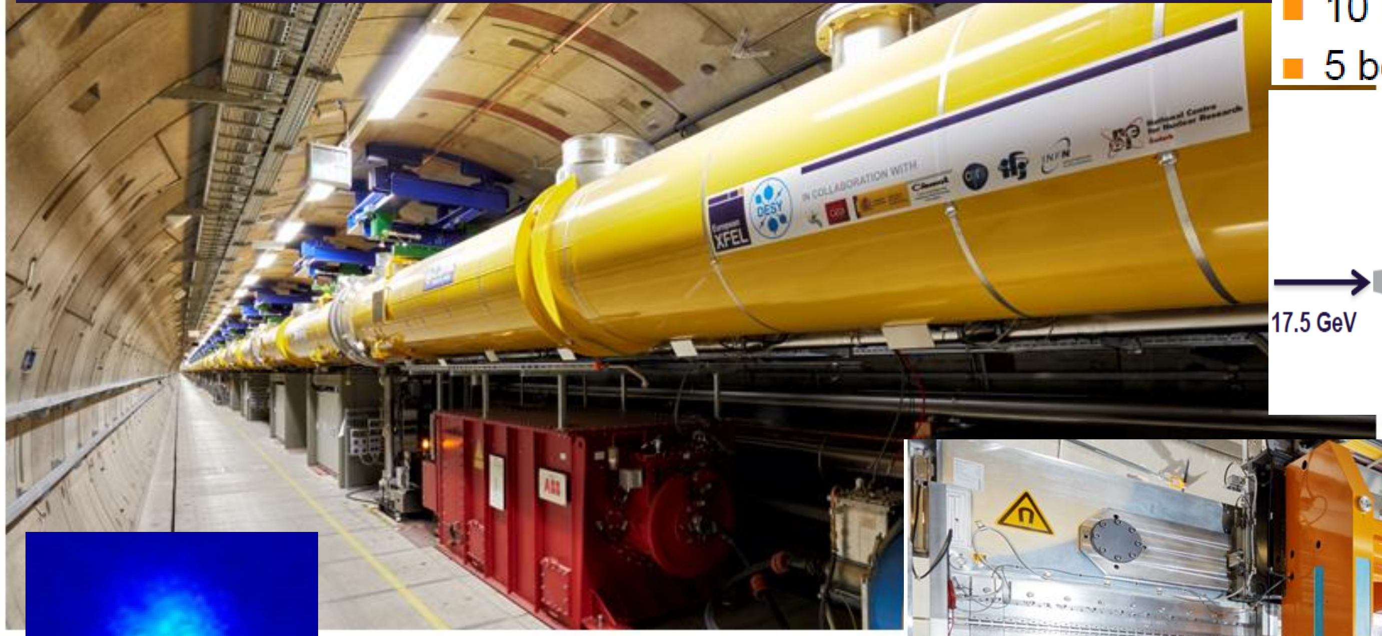
XFEL (DESY), LCLS-II (SLAC), MARIE (LANL), XFELO,…

Paul Emma, Nikolay Solyak, Joe Bisognano, Kwang-je Kim, Bruce Carsten,…

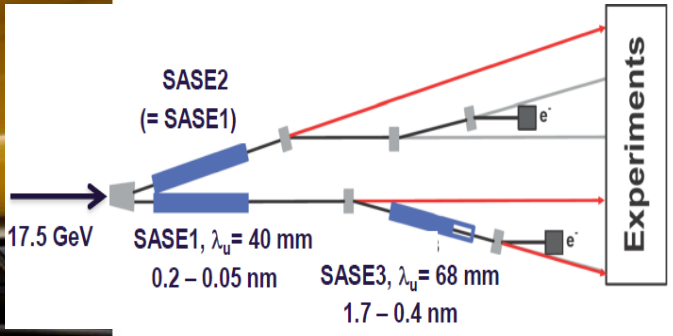
XFEL (DESY) - FEL based on SCRF linac *(Nicolay Solyak)*

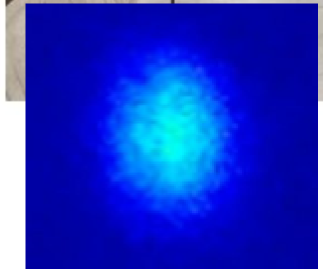




Some specifications

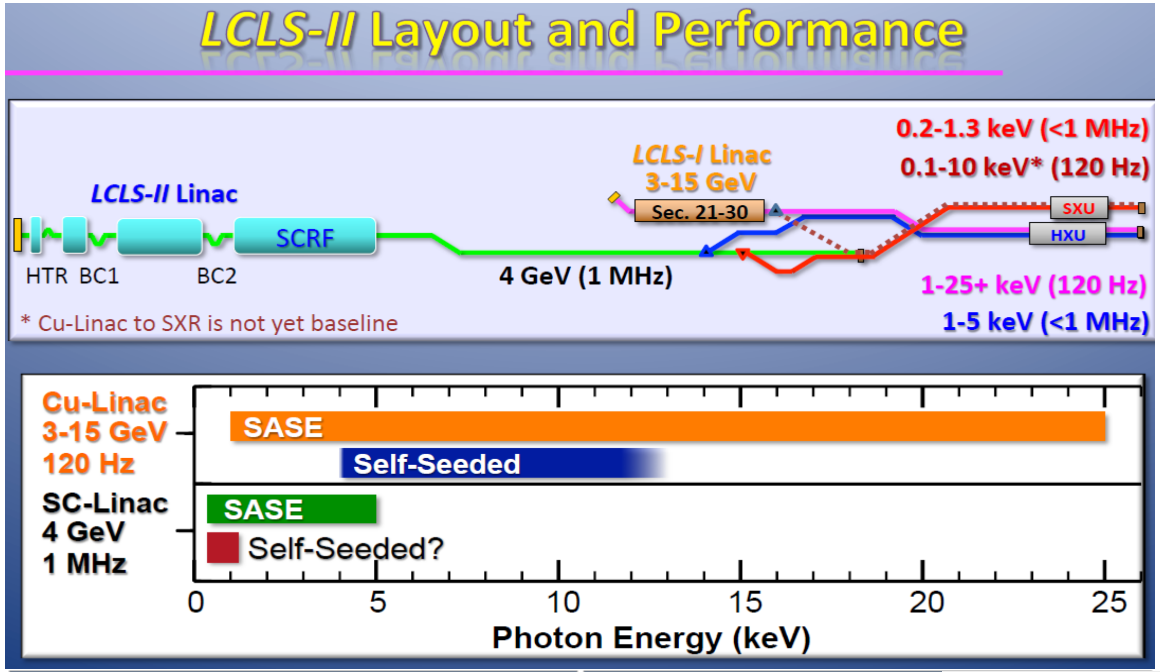
- Photon energy 0.3 - 24 keV
- Pulse duration ~ 10 - 100 fs
- Pulse energy few mJ
- Superconducting linac 17.5 GeV
- 10 Hz (27 000 b/s)
- 5 beam lines / 10 instruments



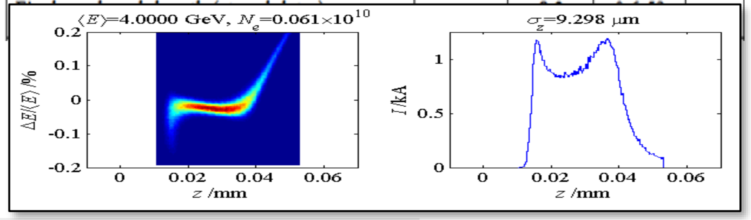


May 04, 2017 - First lasing detected
Sept.1, 2017 – Start operation
Possible future upgrade to cw operation

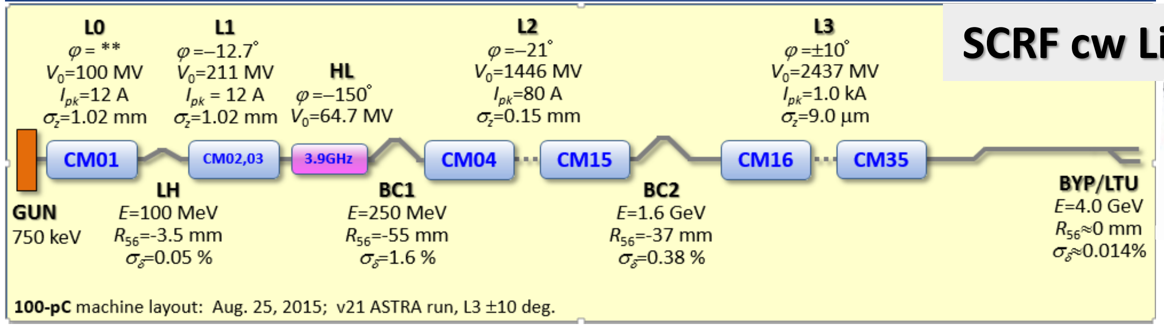
LCLS-II/SLAC – XFEL machine based on SCRF cw linac *(Nicolay Solyak)*



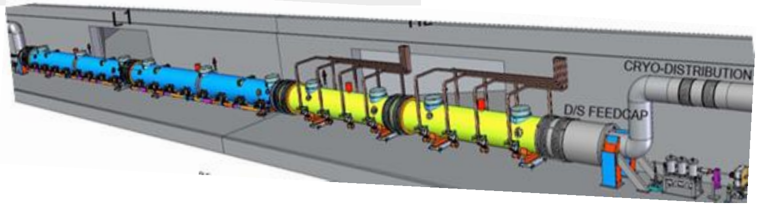
Electron Beam Parameters	symbol	nominal	range	units
Final electron energy (operational)	E_f	4.0	2.0-4.5 [a]	GeV
Max. upgrade energy (or if reduced duty factor) [b]	E_{max}	7.5	-	GeV
Electron bunch charge (limited by beam power)	Q_b	0.10	0.01-0.3	nC
Max. bunch repetition rate in linac (CW) [c]	f_b	0.62	0-0.93	MHz
Average electron current in linac	I_{av}	0.062	0-0.3 [d]	mA
Average electron beam power at linac end (limit)	P_{av}	0.25	0-1.2 [e]	MW
Norm. rms transverse slice emittance at undulator	$\gamma\varepsilon_{\perp\text{-}s}$	0.45	0.2-0.7 [f]	μm
Final peak current (at undulator)	I_{pk}	1000	500-1500	A



P.Emma talk

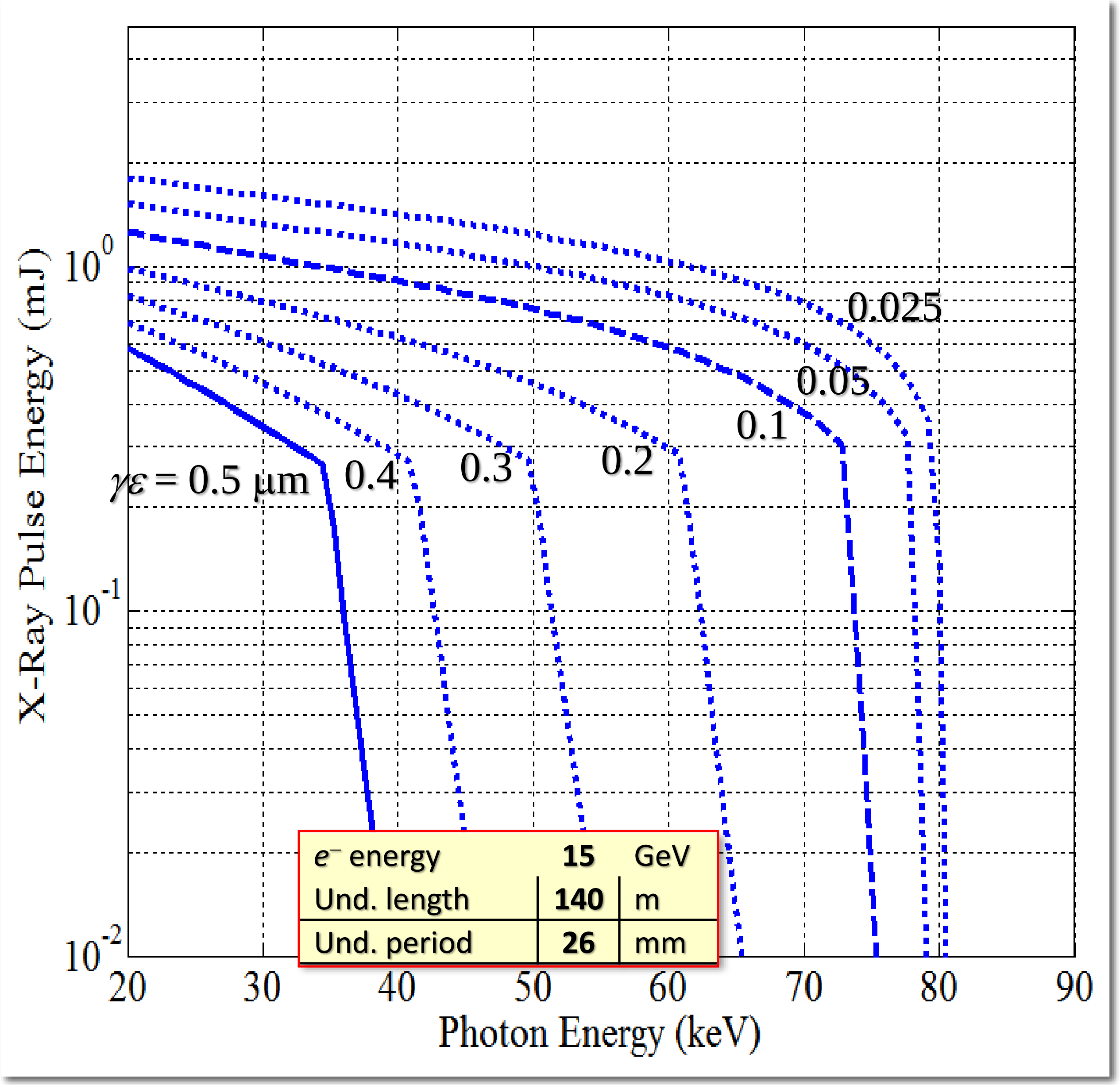


SCRF cw Linac configuration



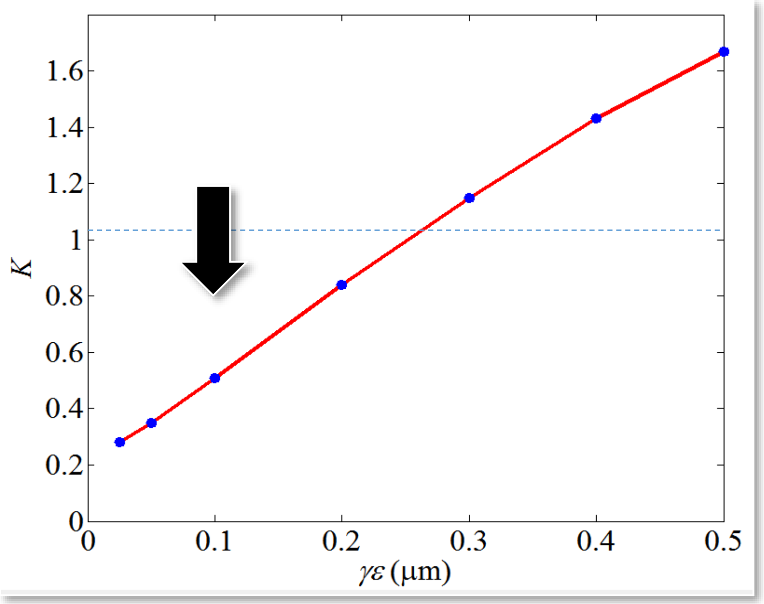
As the world's most powerful X-ray laser, the LCLS creates unique light that can see details down to the size of atoms and processes that occur in less than 10^{-12} sec.

Emittance Leverage at LCLS-II/HXR (100 pC) *(Paul Emma)*



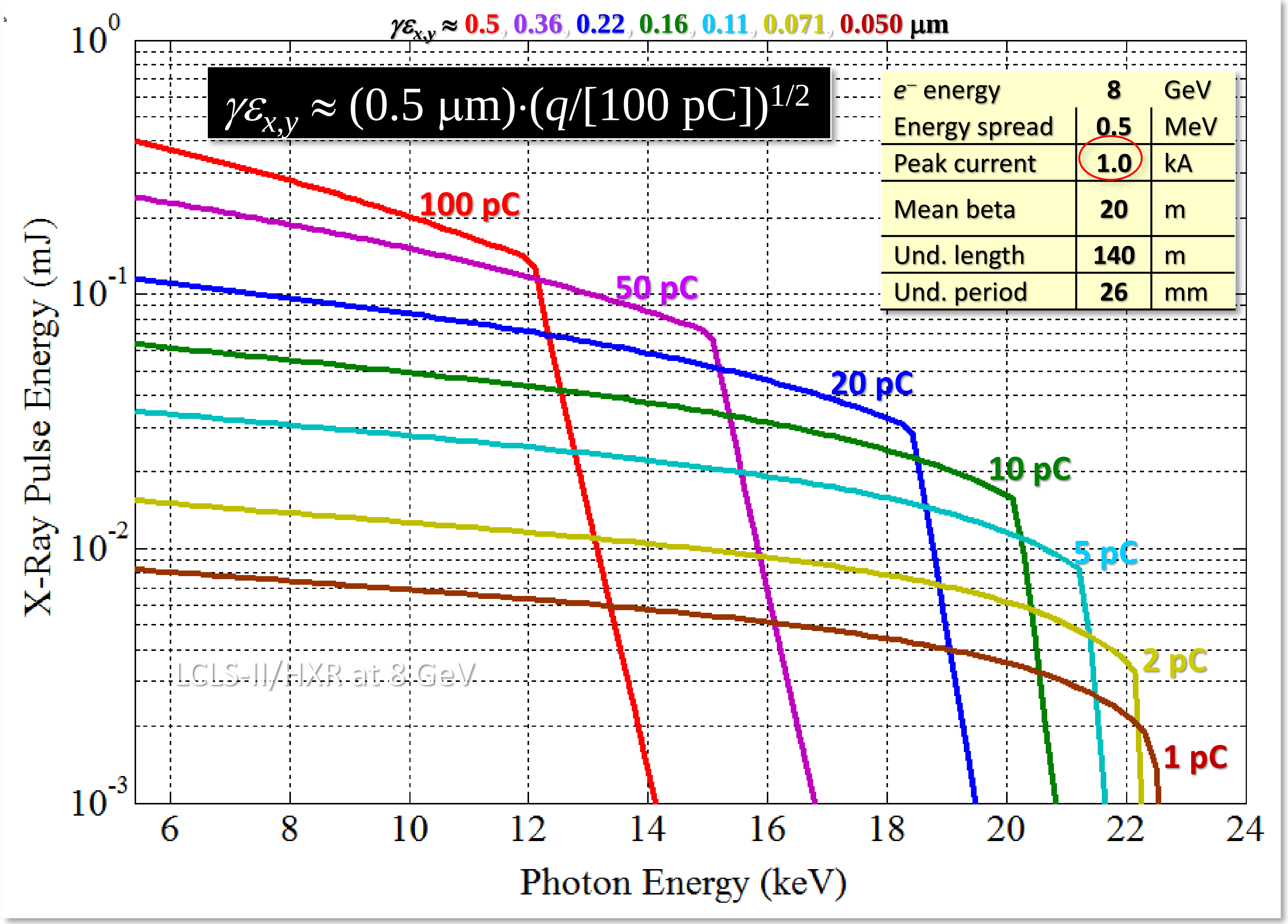
e^- energy	15	GeV
Und. length	140	m
Und. period	26	mm

- Smaller emittance enables higher photon energies (const. *E*, λ_u)
- But resonance condition forces lower *K* (< 1)
- At some point, higher e^- energy or shorter periods are needed

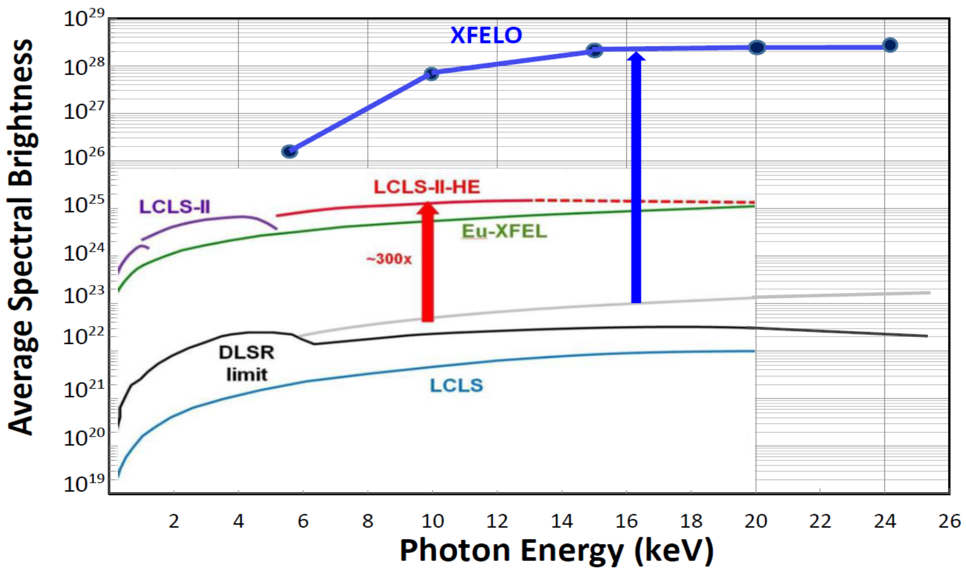


Can exceed 100 keV if we use 2 km of *SLAC* linac (25 GeV)

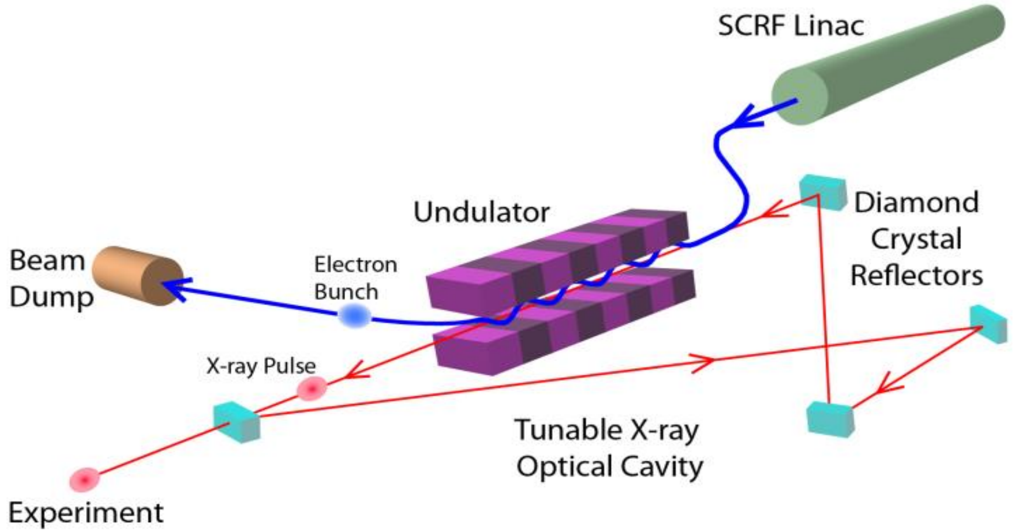
Reduced Charge → smaller emittance, shorter pulse, but slippage (< 1 fs) may limit power



X-Ray FEL Oscillator



XFELO Opportunities Retreat, June 29 – July 1, 2016



- 10^{10} γ's ~ 10^{-2} × SASE , $\Delta\omega/\omega$ ~ 10^{-7} ~ 10^{-4} × SASE
- $\mathcal{B}$~#/$\Delta\omega/\omega$ → $\mathcal{B}$ (XFELO/SASE) ~100 !!
- Works best where Bragg reflection has high R and not too small BW--- 5-25 keV
- Diamond crystal intact after 4 hrs with 10-20 kW/mm^2 (expected intra cavity power level)
- 8 GeV SCRF linac: LCLS-II-HE, Shanghai, Euro-XFEL with CW conversion
- neV spectral lines → science with "ultrafine" spectral resolution vs. science with "ultra-short" time resolution!!

But it all starts at the source!!!
Source Brightness Landscape

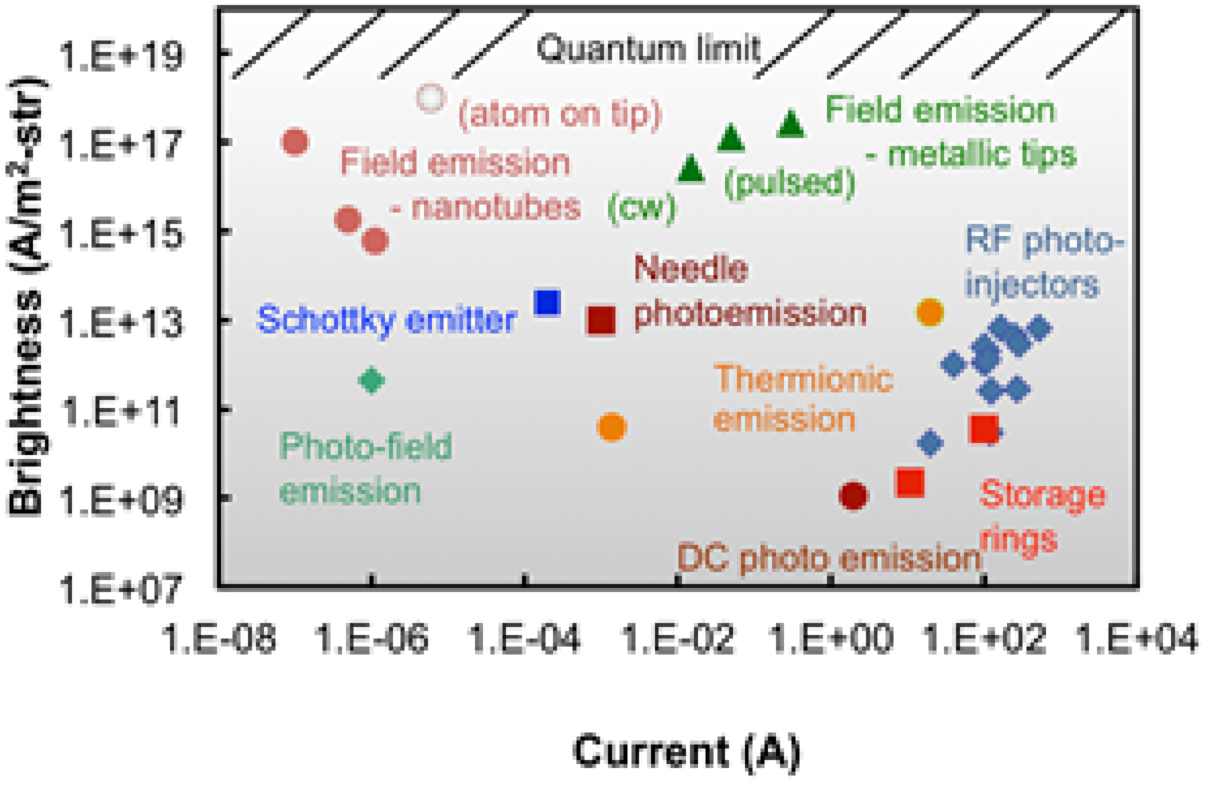


Figure 1. Brightness of various electron sources (Courtesy of C. A. Brau, Vanderbilt University).

Novel Source Types

(Current experimental and theoretical studies of sources)

ELECTRONS 'BORN' COLD:

→ *Cold Atom Sources*

→ *Engineered Structures as Better Cathodes*

- → *Field Emission from Nano- Tips*
- → *Diffraction Gratings as Secondary Cathodes*

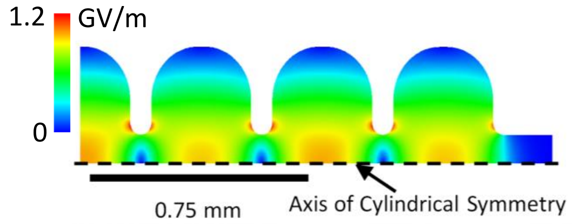
→ *Plasma-based Laser- and Beam-driven Sources*

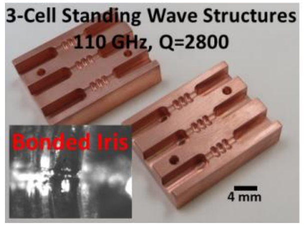
ELECTRONS MANIPULATED in PHASE-SPACE:

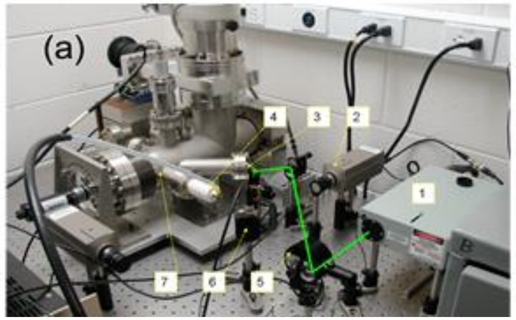
→ *Conventional Photo-cathode Sources in a THz gun*

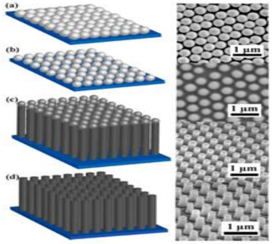
→ *All-optical bunching/compression*

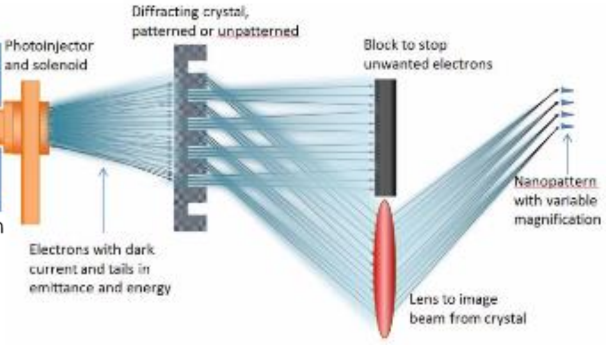
Present R&D on Various Low-emittance, High-brightness Source Techniques

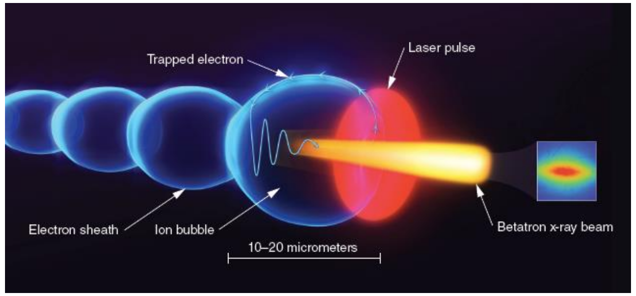


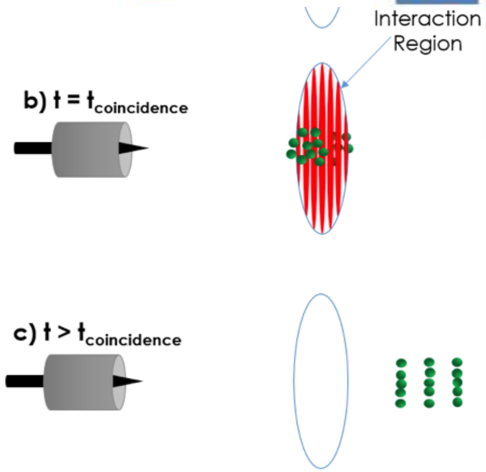


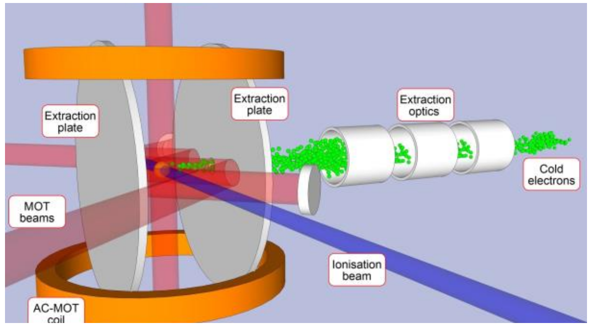


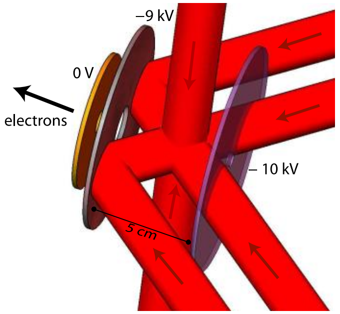












Different applications will demand different techniques:

- *For FELs, beam "phase-space density" and its preservation is at the core of FEL physics*

  → beam "brightness" with higher density and cooler beams important

  → structures, tips and ponderomotive force of light itself maybe more appropriate.

- *For Ultrafast Coherent Electron Diffraction studies of materials, larger electron cross-section relative to photons and coherent scattering adds a (137 N)X(137 N) enhancement to signal:*

  → Being "super-cold" is more crucial than being merely "bright"

  → Cold Atom Sources may be more appropriate

“Designer Beams”

• *Alexander Zholents*

“Designer Beams by conditioning”

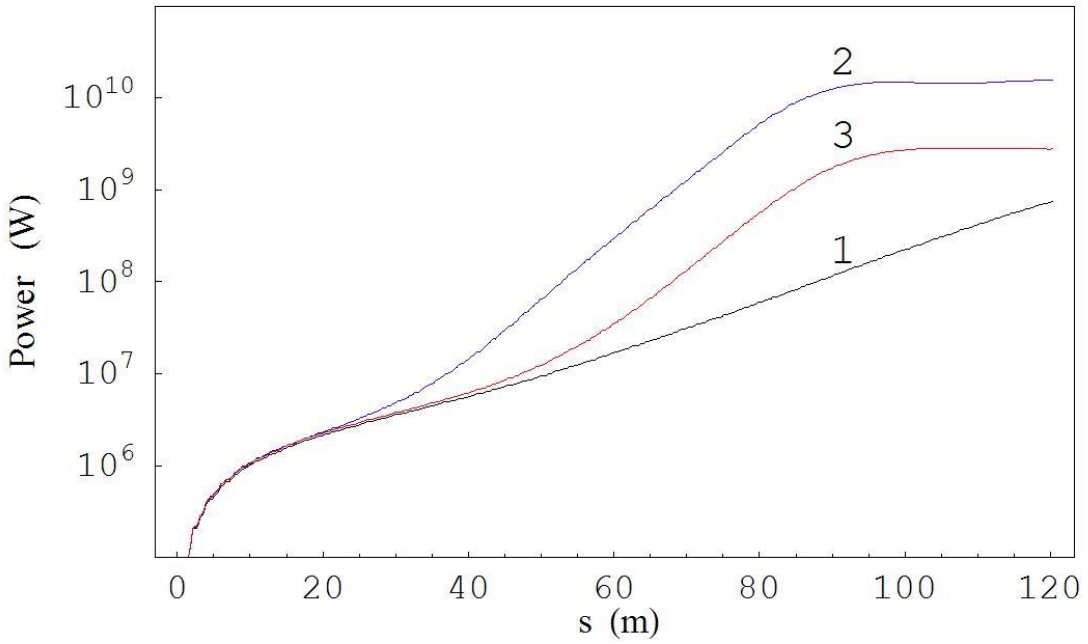
Provide correlation between the amplitude of electron transverse oscillation and electron energy

Laser-assisted electron beam conditioning*

Beam conditioning relaxes requirements on the beam emittance in FELs

Example: LCLS-like FEL with 5 times of LCLS emittance

GENESIS simulations
Beam parameters:
energy = 14 GeV
peak current = 3.4 kA,
energy spread = 1.2 MeV,
emittance = 2.4 mm-mrad,
beta-function = 20 m.

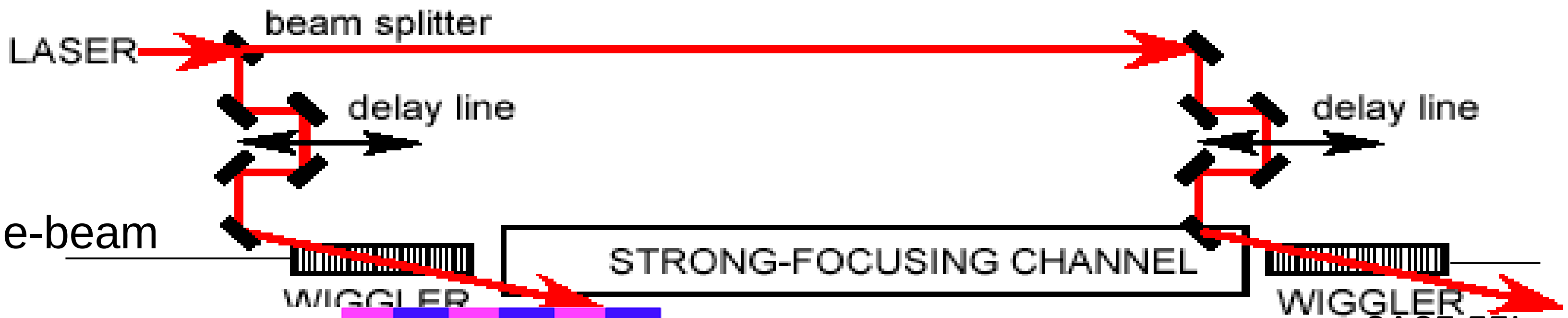


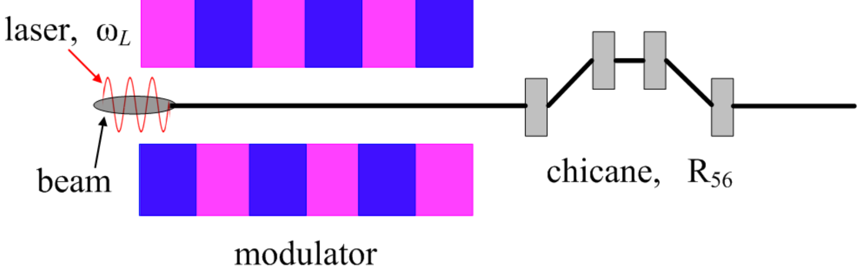
1 - no conditioning,
2 - ideal conditioning (all electrons),
3 - proposed conditioner.

*) Zholents, Phys. Rev. ST–Acc. and Beams, **8**, 050701, (2005)

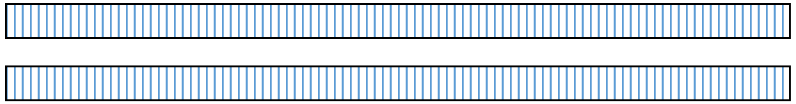
Various Beam Conditioning Tricks using magnetic modulators (undulators) and Chicanes to produce "atto-second" pulses, echo-enabled "harmonic generation", etc.

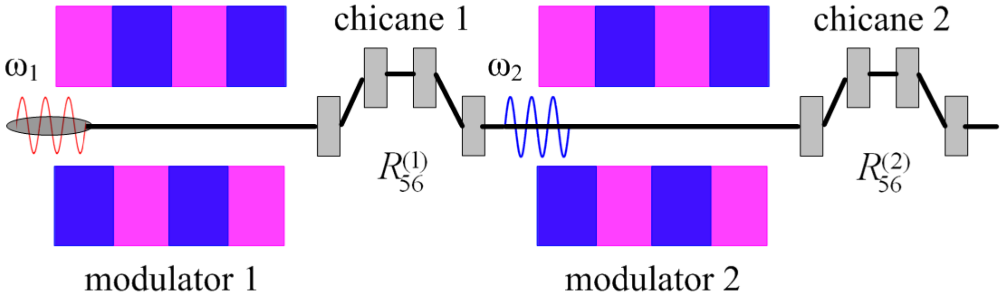
→ Preserving "Brightness" and total "Flux" is still a big issue!!!!

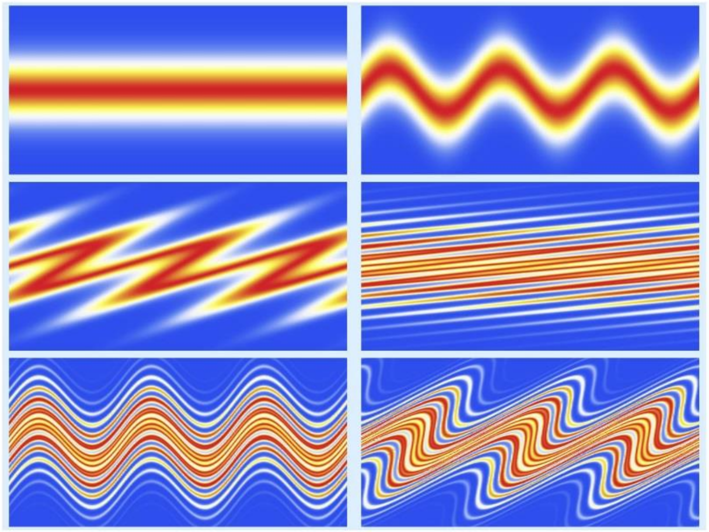




SASE FEL



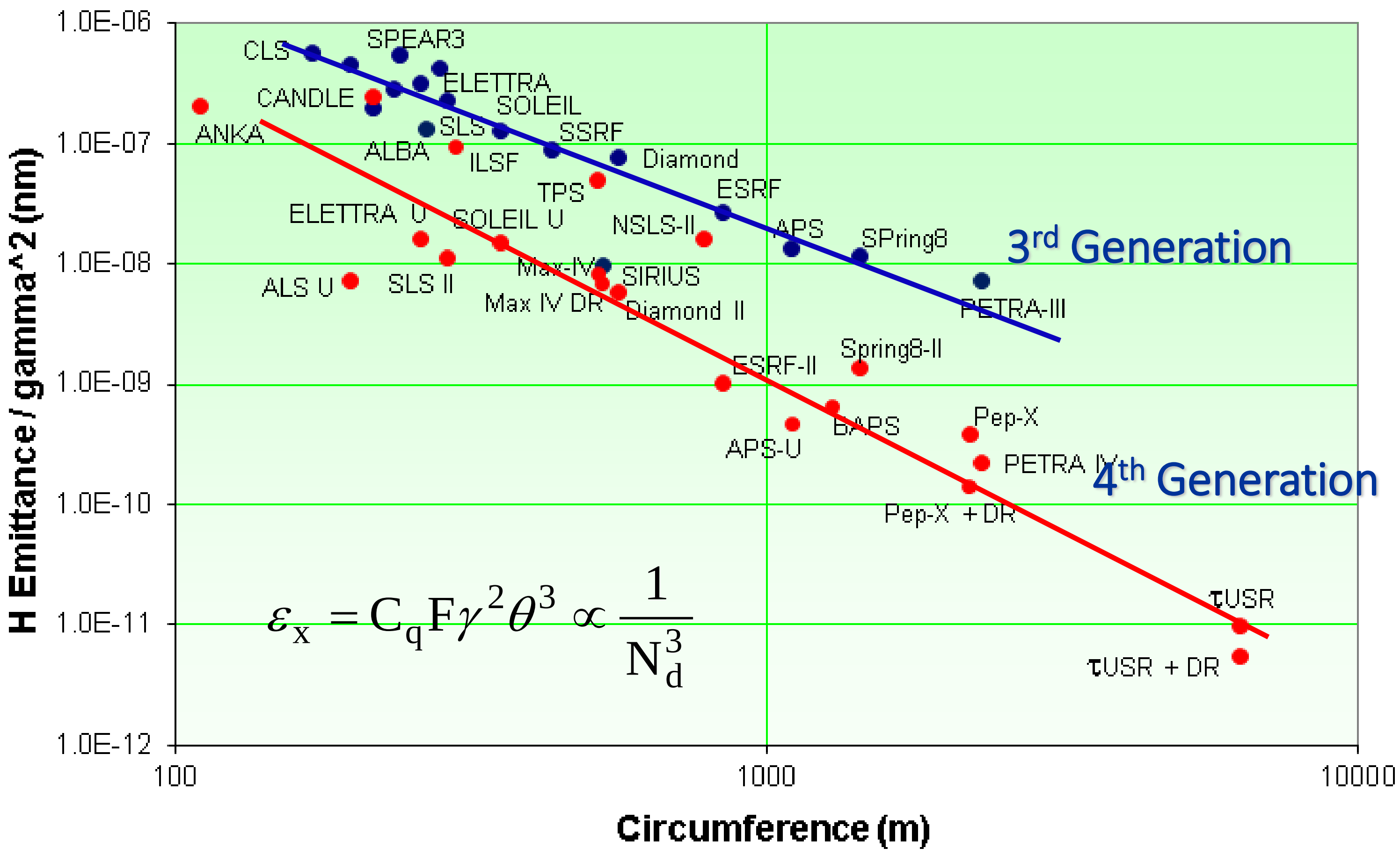




SR Sources:

Richard Walker, Riccardo Bartolini, Simone Di Mitri, David Robin, Pantaleo Raimondi, Peter Kuske,….

Survey of low emittance lattices for light sources



Blu = operating machines

Red = new projects

Key drivers of Beam Dynamics in SR Sources

- **Improving performance and expanding operational modes of 3 - GeV e-beam:**

  Emittance vs. number of IDs, short vs. long bunch operation, high-flux coherent emission via long IDs, storage ring how- and high-gain FELs, coupling control and stability, beam lifetime, etc.

- **Stronger science case based on:**

  Higher brightness/transverse coherence, small photon beam size/divergence, cleaner spectral flux

- **Growing confidence (and first experience!) with MBA lattices:**

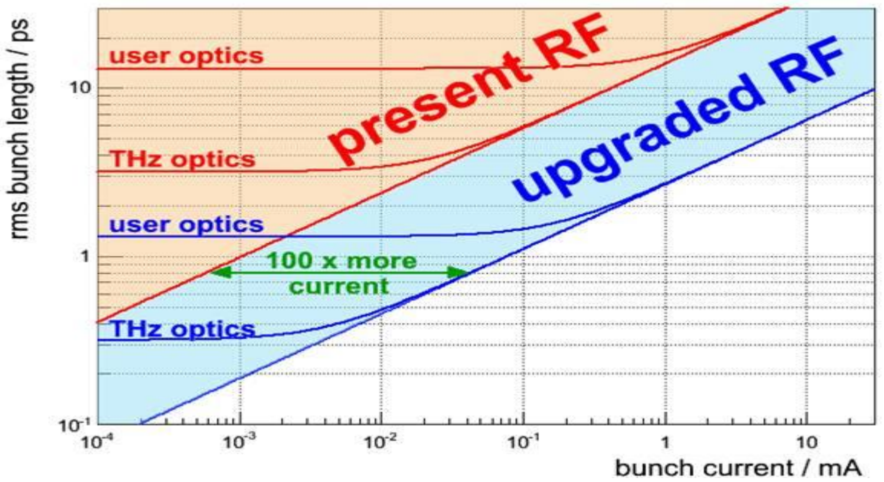
  Linear optics, nonlinear optics, instabilities

- **Growing confidence (and first experience!) with technolgical subsystems:**

  Magnets, vacuum, diagnostics, feedback, fast pulsed kickers (e.g. striplines) allow novel ON- AXIS INJECTION reducing the requirements on the Dynamic Aperture

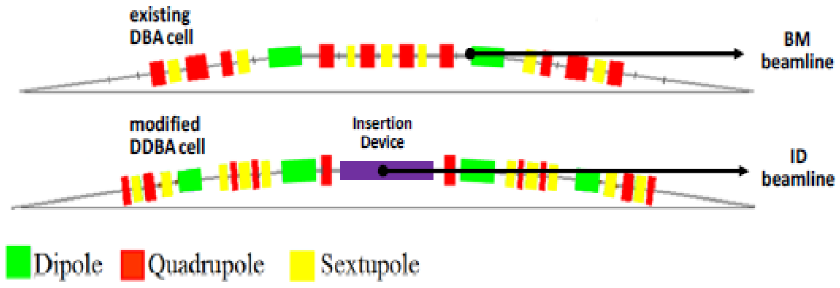
BESSY-II

Wustefeld et al., ***Simultaneous Long and Short Electron Bunches in the BESSY II Storage Ring*****, IPAC'11**



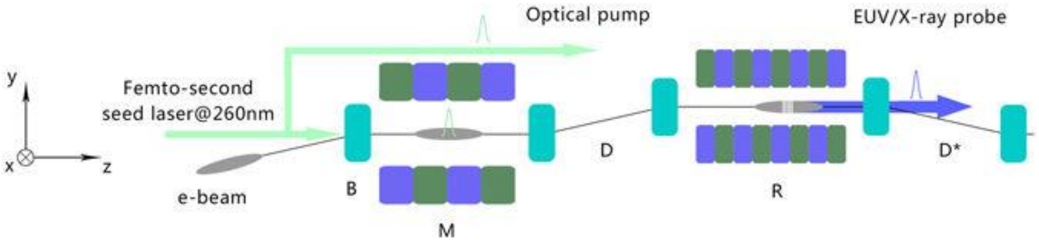
DIAMOND

Walker, ***Preparation for the DDBA installation in DLS*****, IPAC'16**



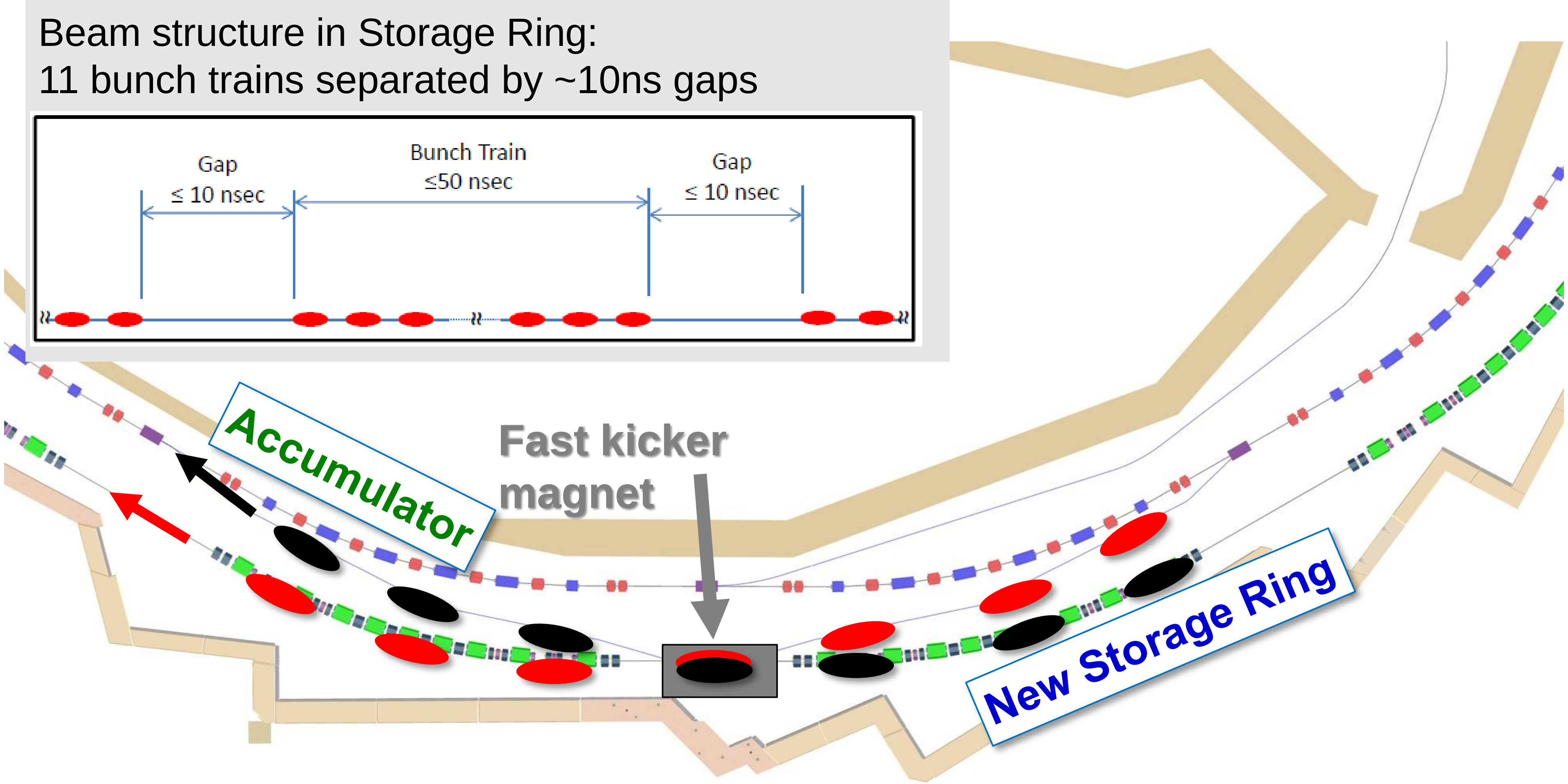
Storage Ring-FEL

Feng & Zhao, ***A Storage Ring Based Free-Electron Laser for Generating Ultrashort Coherent EUV and X-ray Radiation*****, Scientific Rep. 2017**



ALS-U: swap out injection

Very aggressive design, but small DA (few mm) not allowing off-axis injection
Accumulator will enable on-axis injection with bunch-train swap-out



- Pulser prototype being developed at LBNL has demonstrated ~5ns rise/fall time
- Preliminary Accumulator design achieves $\varepsilon_x < 2nm$ with 5BA lattice.

General Nonlinear Dynamics and Collective Effects:

Significant Progress in last 20 years!

- **Nonlinear Integrability :** A real test-bed "IOTA" (Fermilab)
- **Birkhoff Normal Forms:** Dynamics in all Storage Rings
- **"Square Matrices":** Applications to Storage Rings and SR Sources
- **Hamiltonian Diffusion and Chaos:** A real test-bed "IOTA" (Fermilab)
- **Stochasticity in Hamiltonian Systems:** Hadron Rings/Colliders
- **Various Fokker-Planck Methods:** Hadron Rings/SR sources with "damping"
- **Beam Echoes:** Linacs and Storage Rings
- **Multi-bunch Instability:** SR Sources
- **RF-cavity manipulations:** e.g. "Crab"-cavity etc.

→**Alexander Valishev, Armando Bazzani, Giorgio Turchetti, Li-Hua Yu, Tanaji Sen, Wolfram Fischer, Gennady Stupakov, Alex Chao,….**

Echoes and Beam Halos:

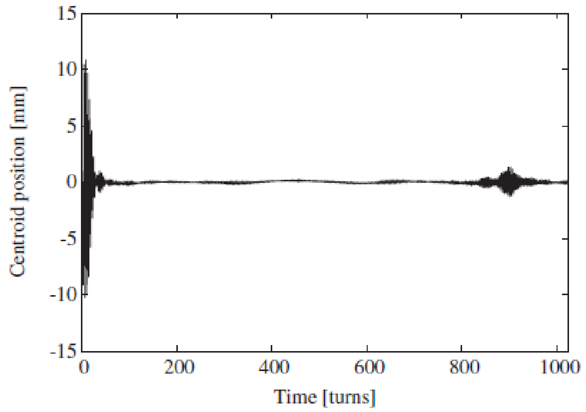
- **Beam echoes can be excited with a single dipole kick, followed by a single quadrupole kick and variations. Echoes are exquisitely sensitive to diffusion – presents opportunities and challenges e.g. allows measurements of diffusion in fast cycling rings;**

- **Echoes observed at RHIC (ca. 2004 – 2005) and SLAC linac (ca. 2011)**

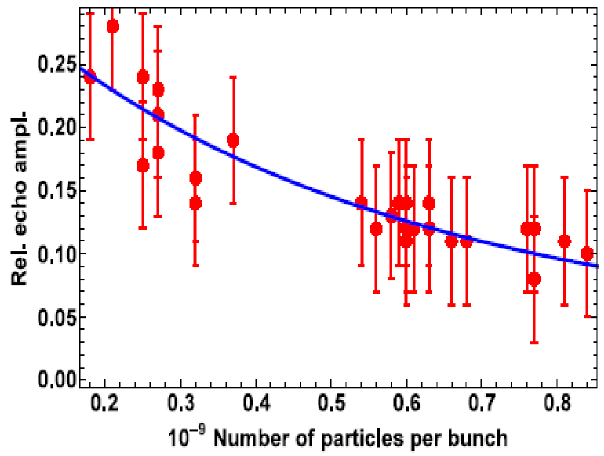
- **Low emittance increases echo amplitude**

- **Nonlinear Integrability in IOTA and emittance growth, halo development in other "fast-cycling" hadron rings.**

Echo observation at RHIC



Echo vs bunch intensity: theory & observations



Please enjoy this very special place for the rest of the week!
For me, Arcidosso has a very deep emotional resonance since Janet and my two lovely girls, Tatiana and Katia, first came here in 1994.

Max Cornacchia

Tatiana and Katia say 'Hello' to the Arcidosso Community and wish they were here!!

Gianfri Nanni

Janet, Tatiana and Katia

Thank You!