Physics and Applications of High Brightness Beams: Towards a Fifth Generation Light Source

March 25-28, 2013 in San Juan, Puerto Rico

High Brightness Electron Beam workshop HBEB-2013

M.Krasilnikov, PPS, 16.04.2013

HBEB-2013 program

Mo, 25.03.2013

- General aspects (5th generation light sources)
- Advanced acceleration techniques (LPA, PWFA, DWA)

Tue, 26.03.2013

- General aspects (HBEB)
- FEL radiation manipulations

Wed, 27.03.2013

- HBEB, technologic challenges

|| Session A

- Magnets
- Thomson/Compton sources

|| Session B

- E-sources, injectors

- Panel Discussion: 5th Generation Light Sources: Critical Issues in the Next Five Years

Thursday, 28.03.2013

- E-sources, technological challenges

HBEB-2013 program

Mo, 25.03.2013

- →Elements of the 5th Generation Light Source, *James Rosenzweig (UCLA)*
- →High-harmonic generation off a spooling tape as seed for the laser-plasma-accelerator-driven free electron laser, *Jeroen Van Tilborg (Lawrence Berkeley National Laboratory)*
- →GALAXIE : A Compact X-ray FEL, *Brian Naranjo (UCLA)*
- Water-Window X-Ray Pulses from a Laser-Plasma Driven Undulator, *Andreas Maier (CFEL/UHH)*
- Tuning Electron Injection in Laser Plasma Accelerators Using Multiple Pulses, *Nicolas Matlis (Lawrence Berkeley National Laboratory)*
- →Dream beams based on implanting ultracold electrons into beam-driven plasma waves, *Bernard Hidding (UCLA/Uni Hamburg/DESY)*
- Optical transverse injection in laser-wakefield acceleration, *Remi Lehe (LOA, France)*
- →The LCLS-II and FEL R&D, *Tor Raubenheimer (Stanford University)*
- →Current Status of the Matter and Radiation In Extremes (MaRIE) Materials Science Facility at Los Alamos National Laboratory, *Steve Russell (Los Alamos National Laboratory)*
- Recent Advancements at FACET and Plans for FACET-II, *Mark Hogan (SLAC)*
- →Dielectric Laser Accelerators, *Joel England (SLAC)*
- Direct laser acceleration of 28 keV electrons at a single dielectric grating, *John Breuer (MPI)*
- →High Repetition-Rate, Soft X-ray FEL User Facility based on a Collinear Dielectric Wakefield Accelerator, *John Power (Argonne National Laboratory)*

Wed, 27.03.2013

- Laser Systems for Particle Accelerators, *Igor Jovanovic (Penn State University)*
- →Coherent diffraction imaging of microbunched relativistic electron beams: imaging the microstructure of high-brightness beams, *Agostino Marinelli (SLAC)*
- →Issues with phase space characterization of laser-plasma generated electron beams, *Alessandro Cianchi (University of Rome "Tor Vergata" & INFN)*

|| session B:

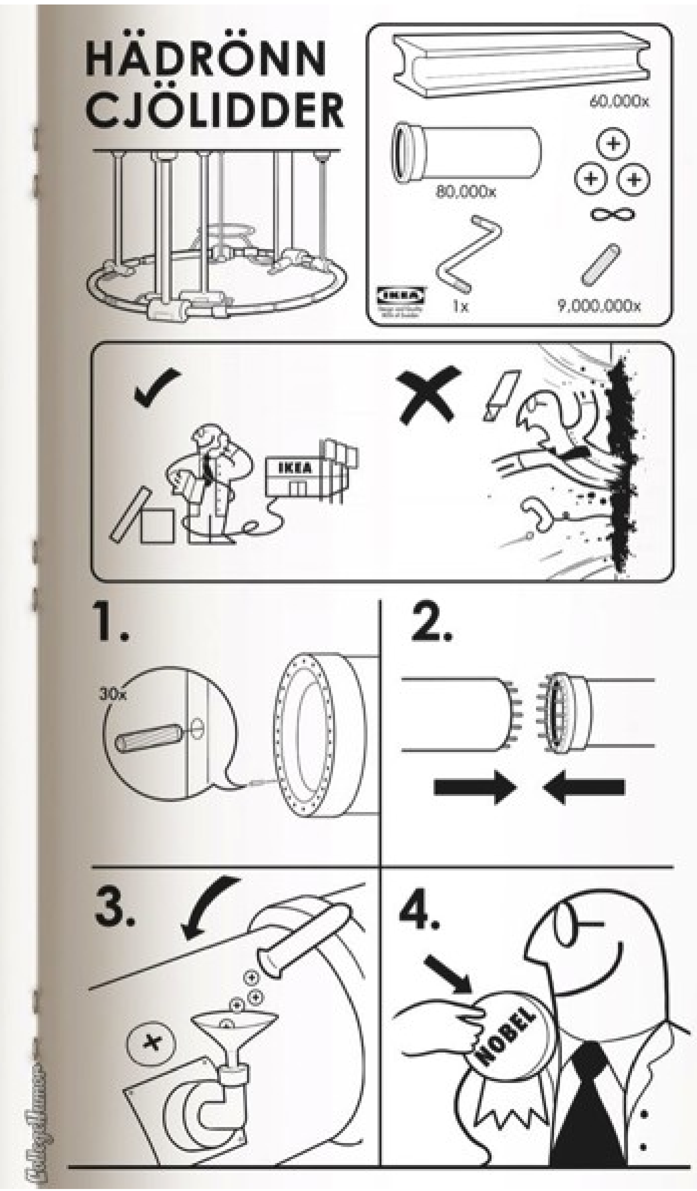
- Field emission technology for light source applications, Jonathan Jarvis (AES)
- →The Cornell University photinjector, *Luca Cultrera (CLASSE - Cornell University)*
- →High repetition rate photo-injectors, *Daniele Filippetto (LBNL, Berkeley)*
- →External-Injection experiment at SPARC_LAB, *Andrea Rossi (INFN – MI)*
- Progress on the Hybrid Gun Project at UCLA, *Atsushi Fukasawa (UCLA)*
- →Ultra Short electron bunches by Laminar Velocity Bunching, *Alberto Bacci (INFN – MI)*
- →Recent Advancements in RF Guns, *Luigi Faillace (RadiaBeam Technologies)*
- →Initial X-Band Photoinjector Performance at SLAC, *Cecile Limborg (SLAC)*

Thursday, 28.03.2013

- →Optimizing Design of SRF Electron Guns, *Joseph Bisognano (SRC/UWisconsin-Madison)*
- Laser Systems and cavities for Compton Sources, *Fabian Zomer (LAL/Universite P11)*
- →High Brilliance X-rays from Compact Sources, *William Graves (MIT)*
- →Ultracold and ultrafast electron source, *Jom Luiten (Eindhoven University of Technology)*
- →Generation of high-brightness electron beams from a needle cathode and their application to make channeling x-rays, *William Gabella (Vanderbilt University)*
- Direct laser acceleration of 28 keV electrons at a single dielectric grating, *John Breuer (Max Planck Institute of Quantum Optics)*

Elements of the 5th Generation Light Source, *James Rosenzweig (UCLA)*

Miniaturizing the collider and FEL: some popular views…



- Shrinking the accelerator: ultra-high fields and high energy density → compact FEL, single spike lasing
- High brightness electrons beget high brightness photons
- Coherence: the importance of the phase information

5th generation injector schemes

- To $\varepsilon < 10^{-8}$ m; new approaches needed
- Ultra-cold sources (Luiten)
- Controlled plasma injection
  - Trojan Horse injection (Hidding, Xi)

Thus… a compact FEL:

High brightness beam

pC beam, *attosecond* pulse, few 10^{-8} emittance

High field, short λ_u undulator

With *high brightness beam*, $>\rho$, $<L_g$: *short undulator*

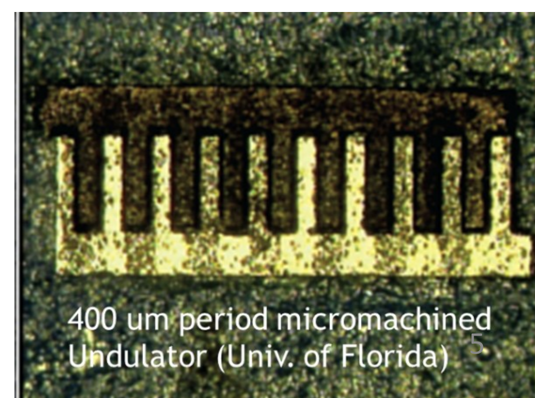
Dramatically lowers e- energy needed

~2 GeV (or less) X-ray FEL

Compact accelerator

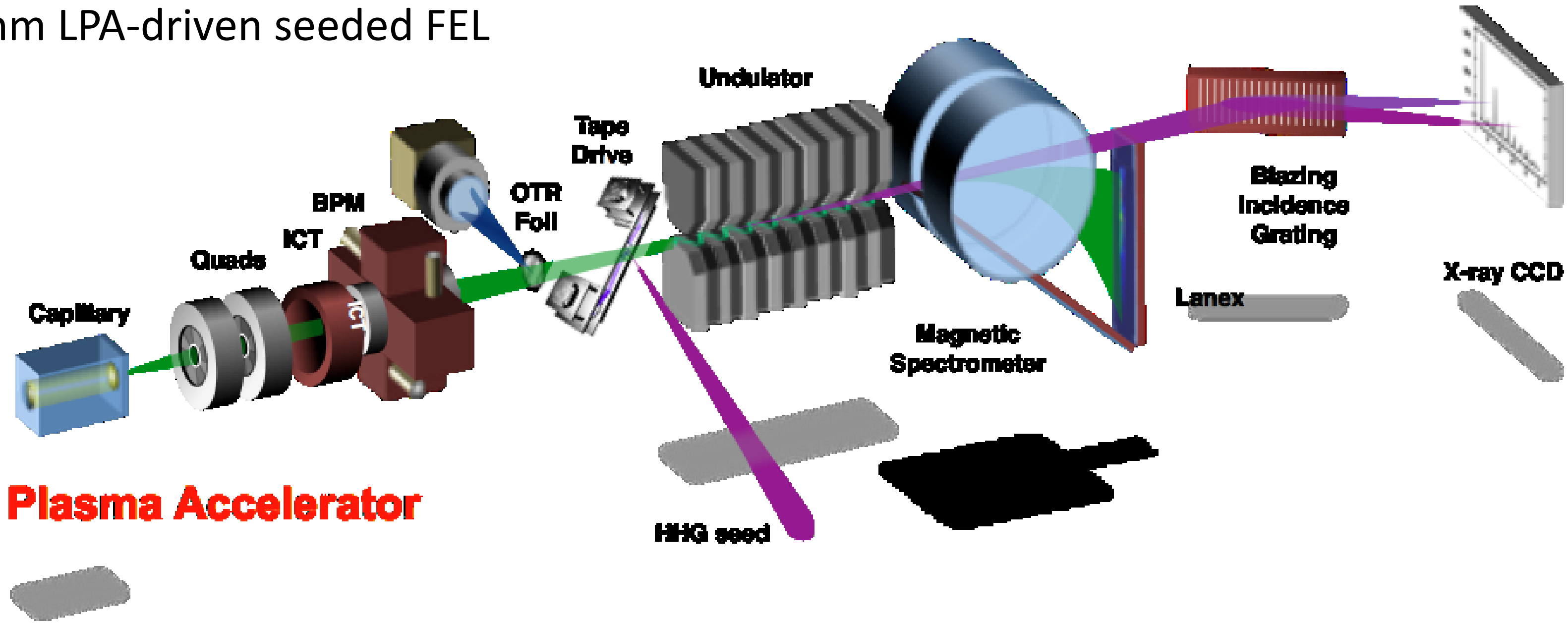
Push further? Why not?

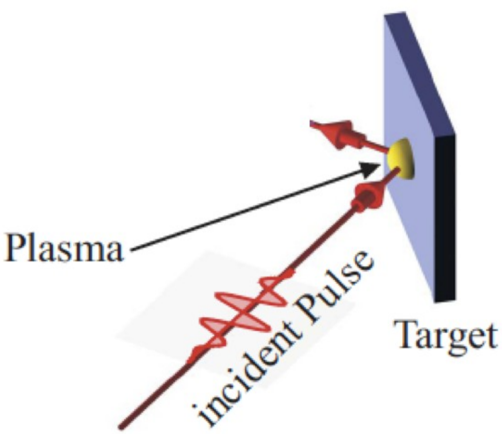
GALAXIE: An Illustrative Example of *Integrated* Table-top X-ray SASE FEL


400 um period micromachined Undulator (Univ. of Florida)

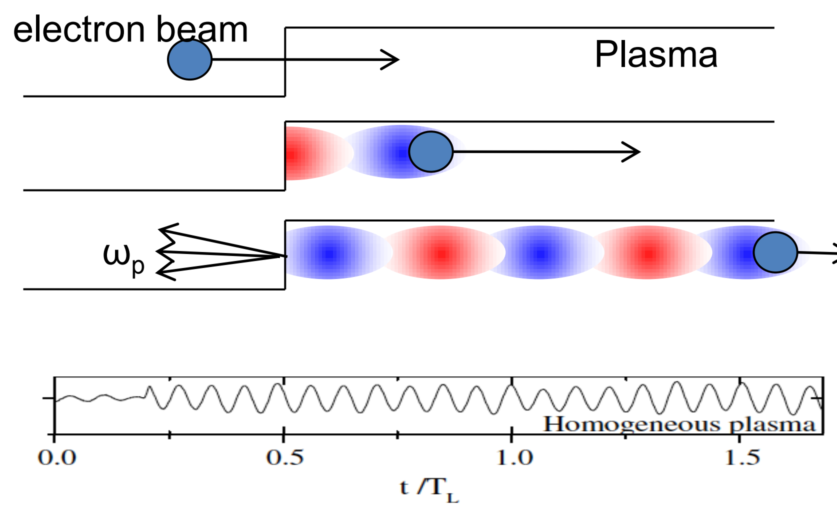
High-harmonic generation off a spooling tape as seed for the laser-plasma-accelerator-driven free electron laser, *Jeroen Van Tilborg (Lawrence Berkeley National Laboratory)*

Goal: 53-nm LPA-driven seeded FEL





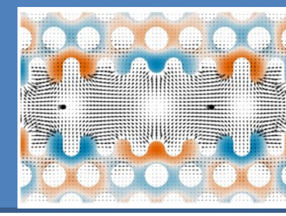
- Step 1 & 2: Electrons are pulled out of plasma into vacuum, and back into target
- Step 3: Electron beamlets drive wake and emit radiation at (plasma) density step



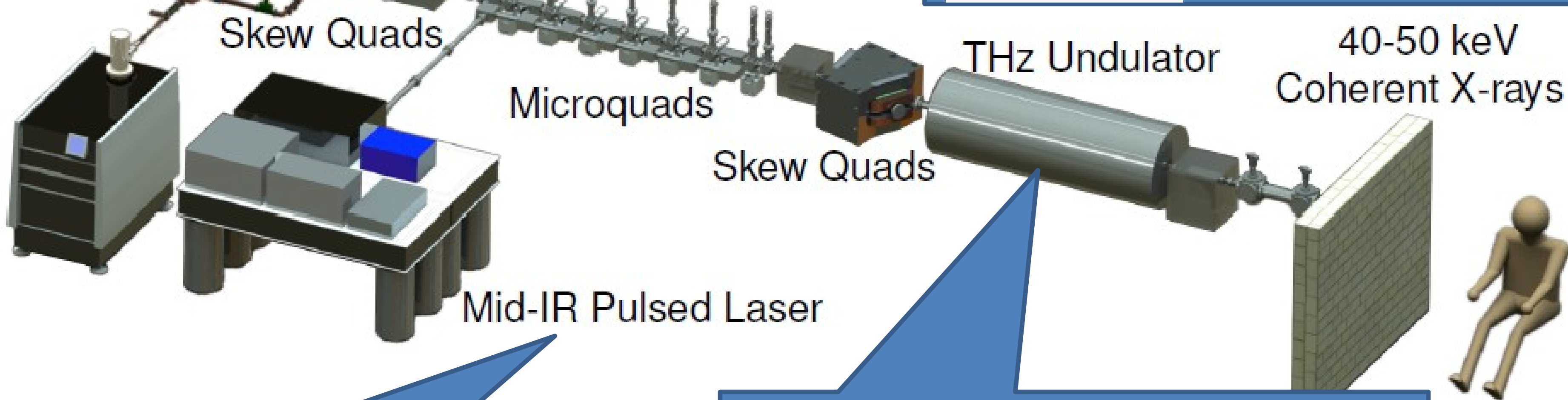
GALAXIE : A Compact X-ray FEL, *Brian Naranjo (UCLA)*

- Pulse duration = 1 ps
- Pulse current = 1 A
- Beam energy = 3-8 MeV
- Normalized emittance = $\epsilon_x^* = \epsilon_y^* = 2 \times 10^{-8}$ m · rad
- Spot size < 100 μm

- Final beam energy = 1 GeV
- Peak acceleration gradient > 1 GeV/m
- Beam opening dimensions = 2 μm $\times$ 500 mm
- Final longitudinal bunching factor > 300
- Final longitudinal momentum spread = $\sigma_{\delta p/p_0}$;<; 10^{-4}

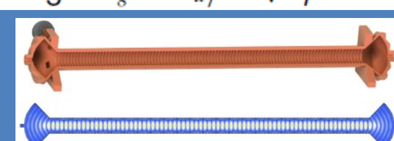


- Resonant spatial harmonic provides acceleration.
- Nonresonant spatial harmonics provide focusing.
- Hole diameters approximately 800 nm.



- Wavelength = 5 μm
- Pulse duration = 1 ps
- Pulse energy = 500 μJ
- Repetition rate = 10 Hz (later, up to 10 kHz)

- Undulator wavelength $\lambda_u \approx 100\ \mu$m
- Undulator strength parameter $K = eB\lambda_u/2\pi mc \approx 0.1$
- Required deflecting force $\approx ec(10$ T$)$ = 3 GeV/m
- 1D Pierce parameter $\rho = 10^{-4}$
- Gain length $L_g = \lambda_u/4\pi\sqrt{3}\rho \approx 50$ mm

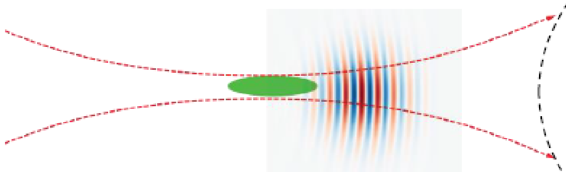


L~1-2m

Dream beams based on implanting ultracold electrons into beam-driven plasma waves, *Bernard Hidding (UCLA/Uni Hamburg/DESY)*

Rethink LWFA and PWFA: laser pulses are great for ionization, while electron bunches are better drivers

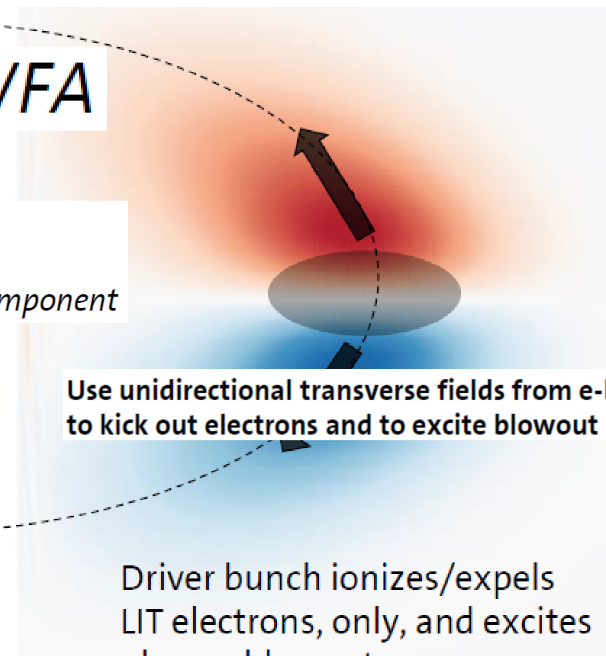
Hybrid LWFA & PWFA



Use oscillating fields from laser pulse to ionize and to generate low-transverse momentum electrons

Combine both in media w/
Low-ionization-threshold (LIT) and
High-ionization-threshold (HIT) component

"Trojan Horse PWFA"



Use unidirectional transverse fields from e-bunch to kick out electrons and to excite blowout

Synchronized laser pulse is strongly focused to HIT, releases HIT electrons in focus

Driver bunch ionizes/expels LIT electrons, only, and excites plasma blowout

What's needed:

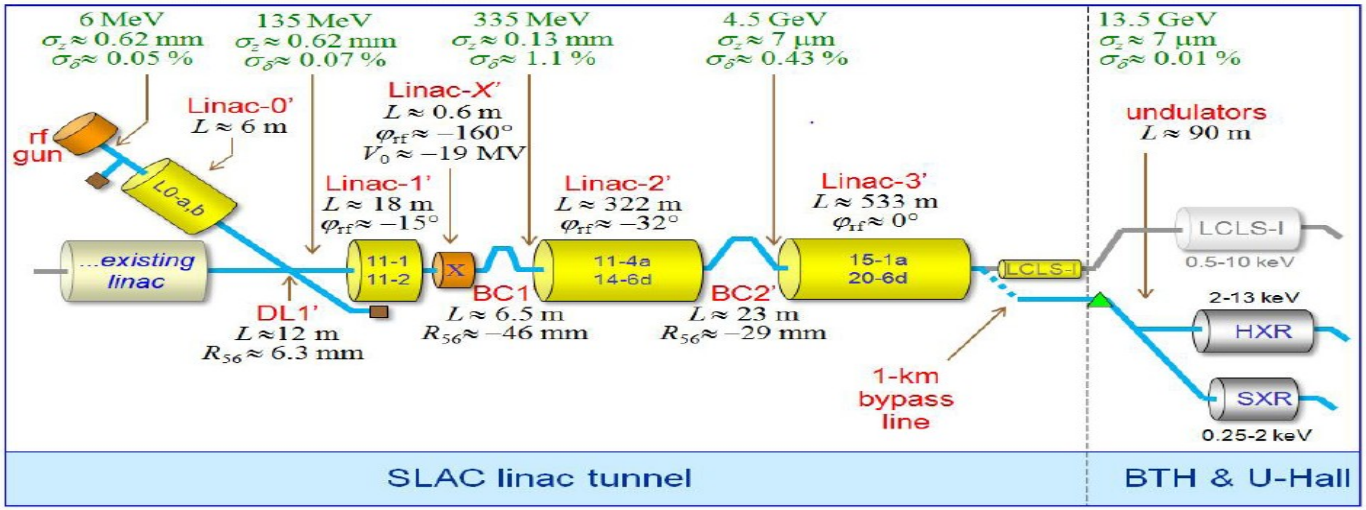
- LIT/HIT medium
- reliable electron bunch driver to set up LIT blowout
- synchronized, low-intensity laser pulse to release HIT electrons within blowout

Photocathode + Space Charge Screening: Space charge screening during low-γ transit due to simultaneously born LIT+ ions on axis

The LCLS-II and FEL R&D, *Tor Raubenheimer (Stanford University)*

LCLS-II Accelerator for 250 pC, 120 Hz

SLAC

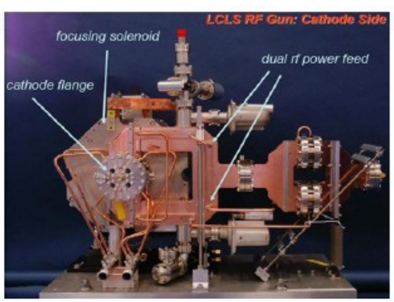


Injector, linac, and compression parameters are all very similar to *LCLS-I*, but not exact

Dedicated new injector at Sector 10

<u>Cathode Test Facility</u>

- Study cathodes and lasers including materials, cleaning, and coatings

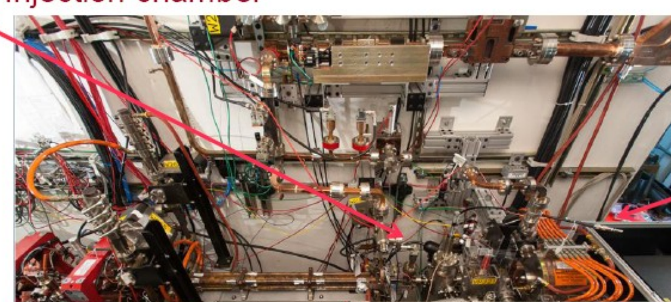


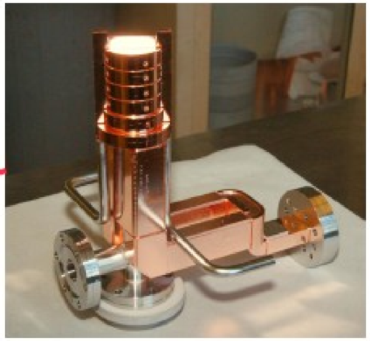
Spare LCLS rf gun with dedicated laser in ASTA bunker

XTA beamline in NLCTA

8x higher brightness vs LCLS

Laser Injection chamber

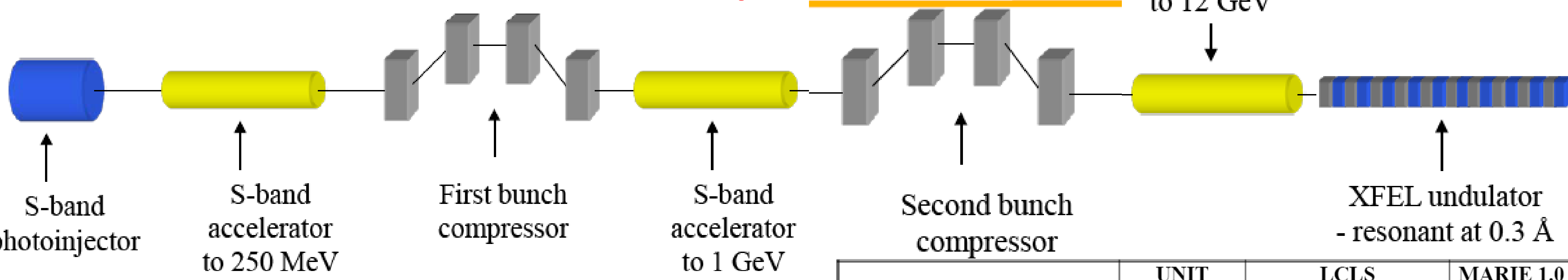




Current Status of the Matter and Radiation In Extremes (MaRIE) Materials Science Facility at Los Alamos National Laboratory, *Steve Russell (Los Alamos National Laboratory)*

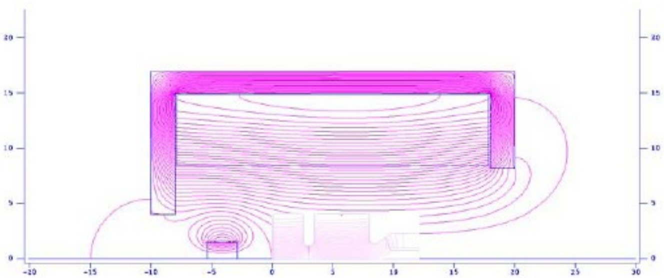
~$2B

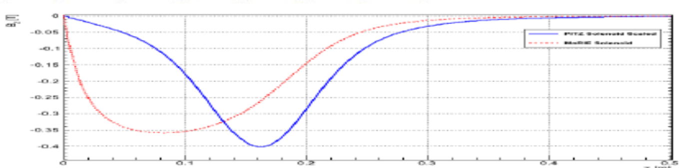
The baseline MaRIE X-FEL is LCLS inspired



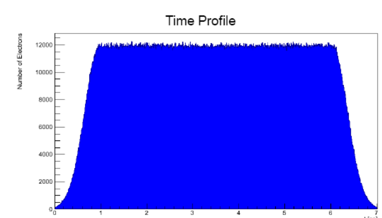
	UNIT	LCLS	MARIE 1.0 baseline
Wavelength	Å	1.5	0.293
Beam energy	GeV	14.35	12.0
Bunch charge	pC	250*	100
Pulse length (FWHM)	fs	80*	30
Peak current	kA	3.0*	3.4
Normalized rms emittance	mm-mrad	0.3-0.4	0.2
Energy spread	%	0.01	0.01
Undulator period	cm	3	1.86
Peak magnetic field	T	1.25	0.70
Undulator parameter, a_w		2.48	0.86
Gain length, 1D (3D)	m	(3.3)*	(6.0)
Saturation length	m	65	80
Peak power at fundamental	GW	30*	8
Pulse energy	mJ	2.5*	0.24
# of photons at fundamental		2 x 10^{12}*	2x10^{10}

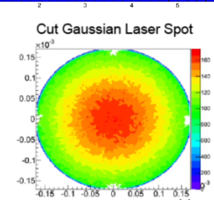
Emittance requirements demonstrated at PITZ, DESY.→*Phys. Rev. STAB*, **15**,, p. 100701 (2012).





By using a permanent magnet as our bucking solenoid, we can ramp up the magnetic field more rapidly. In turn, the beam envelope stays smaller through the injector.





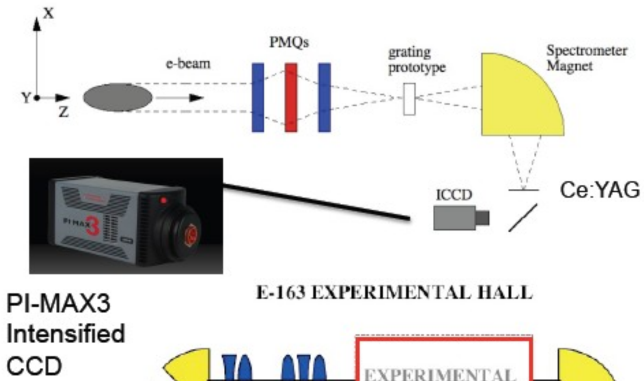
F. Zhou et. al., ***Impact of the spatial laser distribution on photocathode gun operation***, *Phys. Rev. STAB*, **15**, p. 090701 (2012)

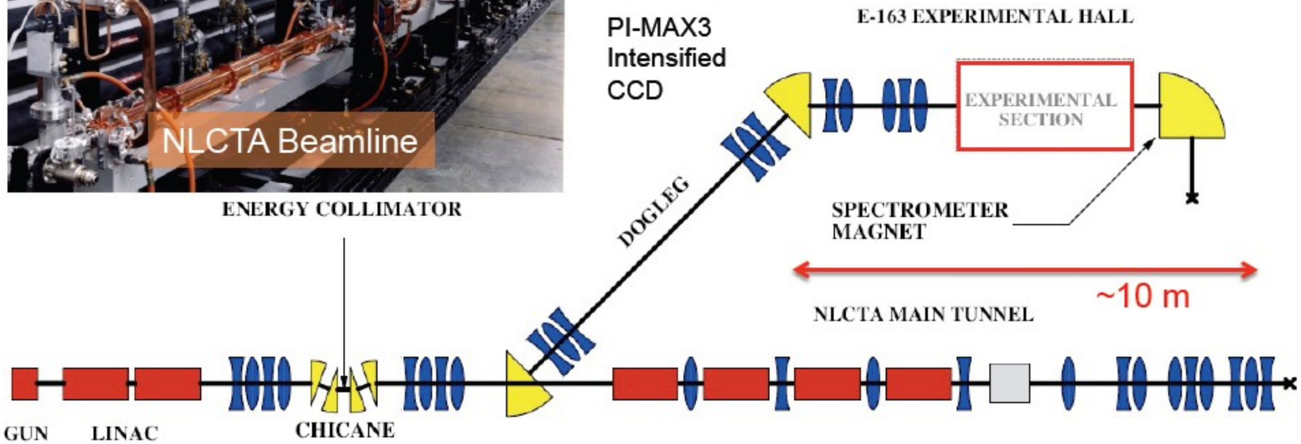
Final Electron Beam Properties at ~250 MeV

Property	Value
Transverse ε_n	65 nm
Thermal ε_n (atomically clean copper*)	44 nm
Residual ε_n	48 nm
RMS Length	2.1 ps
RMS Energy Spread	0.08%

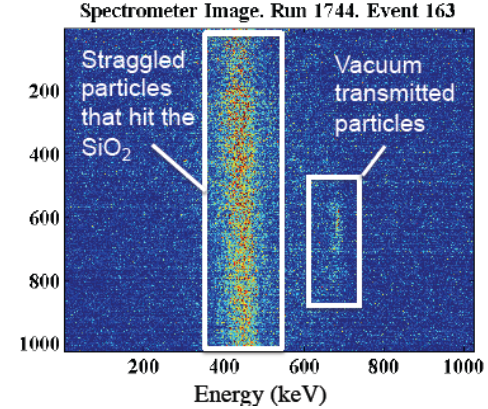
DLA Test Facility at SLAC

E163 @ NLCTA: A facility for testing laser-driven accelerator structures.
Beam energy = 60MeV; σ_t = 1ps; σ_E = 0.1%; 800nm Ti:Sapph laser





Raw camera image



[Note: there is an arbitrary offset on the energy axis in these plots relative to the 60 MeV center energy.]

Fitted spectra

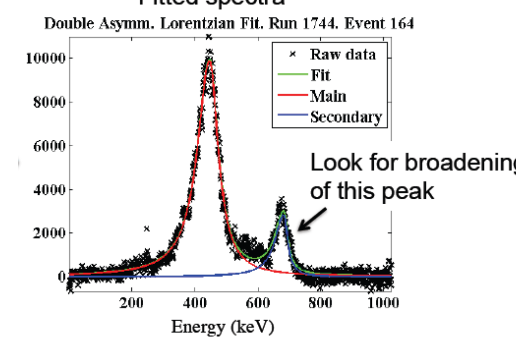
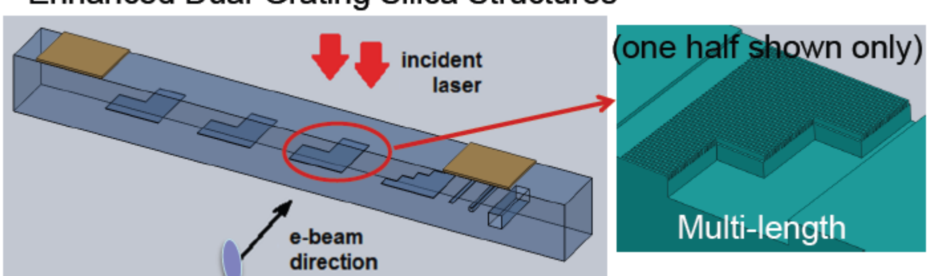


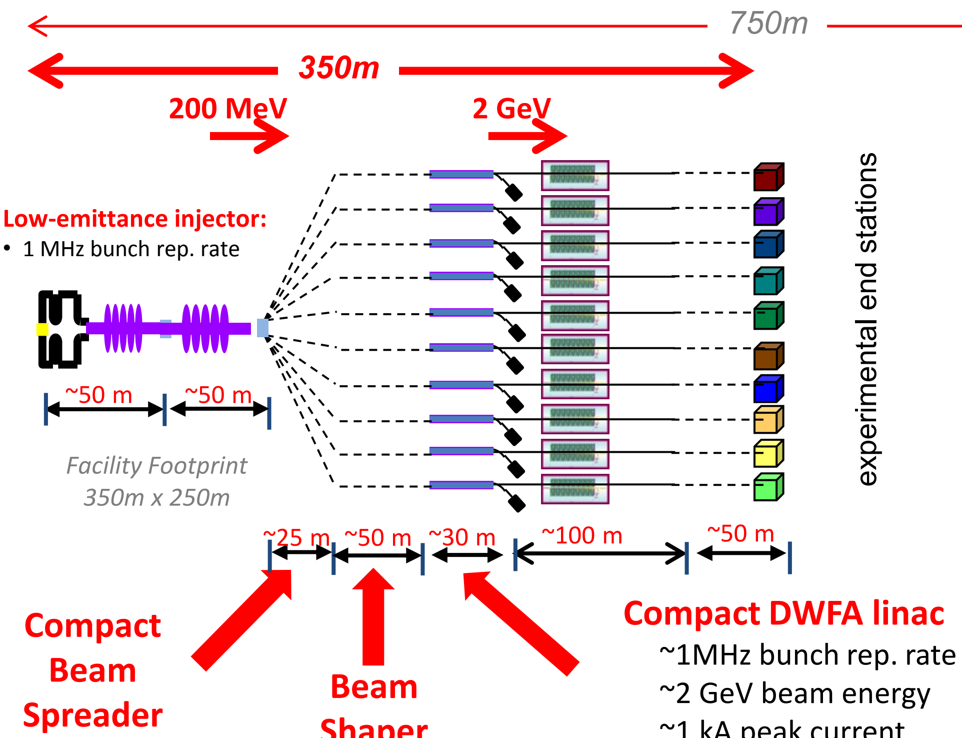
Figure of merit for acceleration is energy modulation (or broadening) of the higher energy peak.

Enhanced Dual-Grating Silica Structures

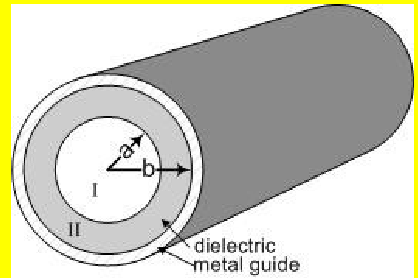


SLAC/Stanford E163:
- Multi-length gratings
- 1x 400nm gap
- 1x 800nm gap
- 1x1200nm gap
- 1x test structure
- Symmetric process
- Alignment channels
- IR reflectors
  (for laser alignment)

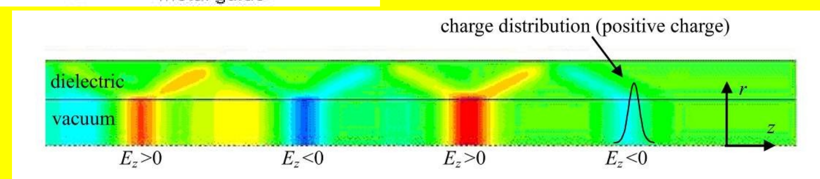
High Repetition-Rate, Soft X-ray FEL User Facility based on a Collinear Dielectric Wakefield Accelerator, *John Power (Argonne National Laboratory)*



Cylindrical Dielectric Wakefield Accelerator



- *Simple geometry*
- *Capable of high gradients*
- *Easy dipole mode damping*
- *Tunable*
- *Inexpensive*

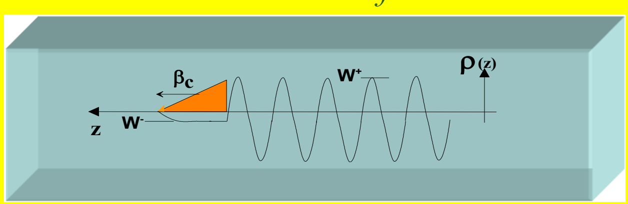


Recent results (obtained for Linear Collider development):

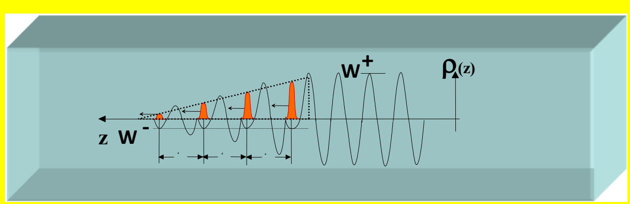
- 1000MV/m level in the THz domain (UCLA/SLAC group)
- 100 MV/m level in the MHz domain (AWA/ANL group)

Methods to increase R>2 in a collinear wakefield accelerator

Ramped Bunch



Ramped Bunch Train
(demonstrated at ANL)

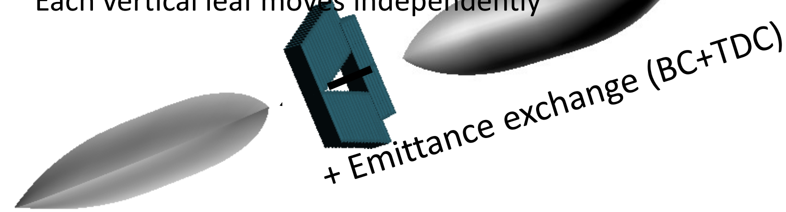


Reference: Schutt et. al., Nor Ambred, Armenia, (1989)

General (nonlinear) shapes are possible

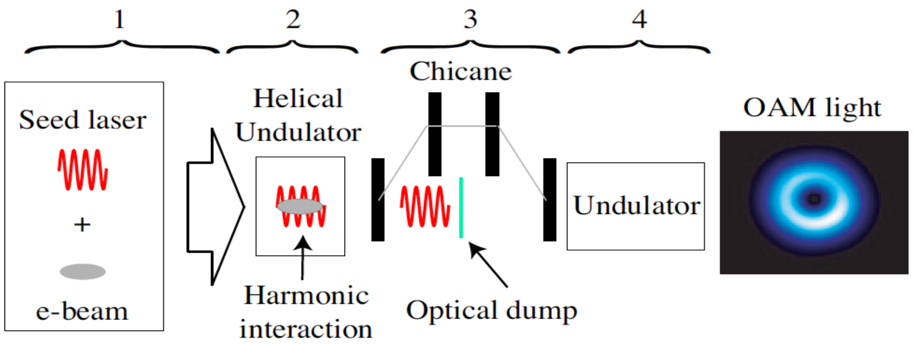
Multi-leaf collimator :

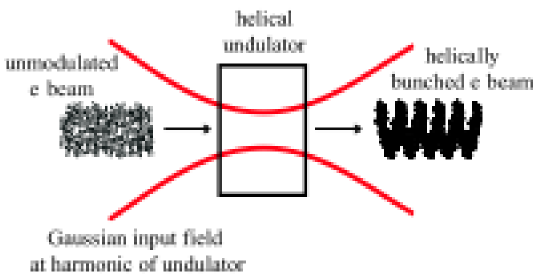
- Used in medical linacs to shape the x-rays
- Each vertical leaf moves independently



AWA: L-band gun(Cs2Te) 100nC!

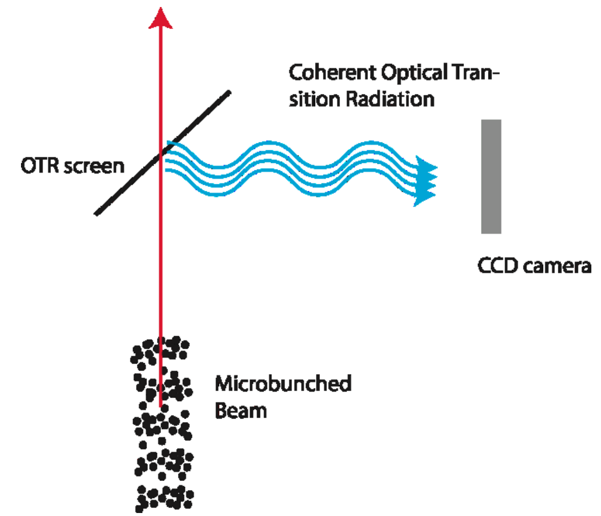
Coherent diffraction imaging of microbunched relativistic electron beams: imaging the microstructure of high-brightness beams, *Agostino Marinelli (SLAC)*





Helical charge perturbation from harmonic interaction in a helical undulator:

COTR is a well established diagnostic for microbunched beams ➔ Experimental Demonstration at NLCTA



Spatially
Oversampled
Far-field
Image
Analysis

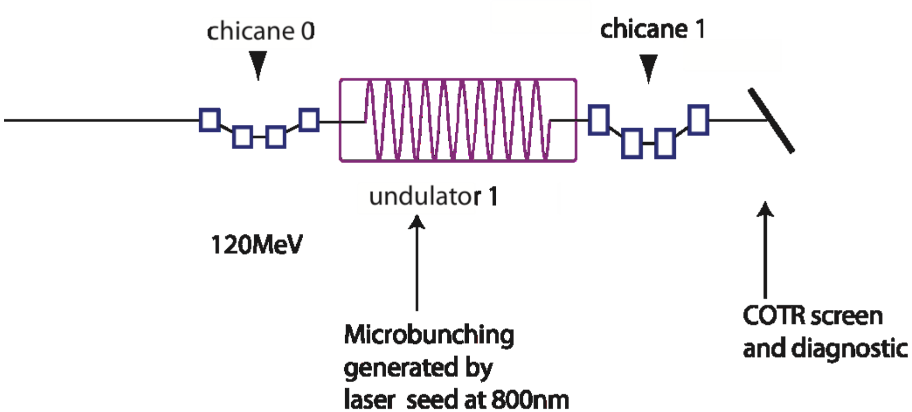
800 nm seeded microbunching

-Acquire far-field coherent image

-Divided far-field intensity distribution by single-particle diff. spectrum

-Apply **phase-retrieval** algorithm to reconstruct bunching

-Turn off laser and compare reconstruction to near-field OTR

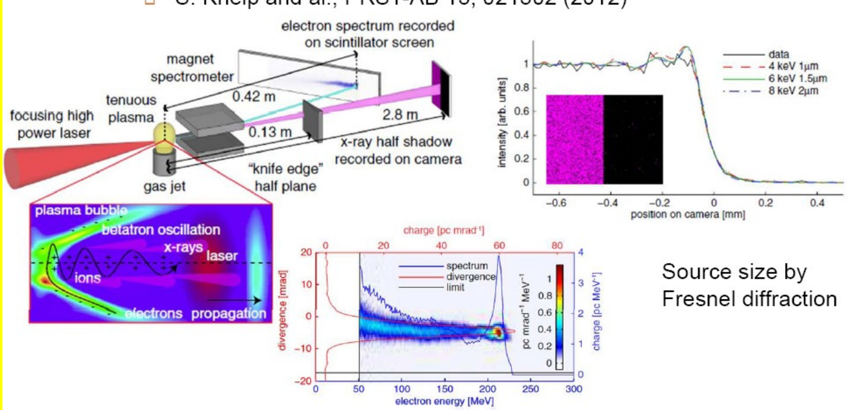


Issues with phase space characterization of laser-plasma generated electron beams, *Alessandro Cianchi (University of Rome "Tor Vergata" & INFN)*

- Conventional diagnostic are sometimes not adequate, mainly due to the energy spread and the large angular divergence.
- The same meaning of normalized emittance must be revised.
- Pepper pot is not adequate for strongly correlated beams
- Interesting techniques has been tested to measure the beam emittance and the longitudinal properties:

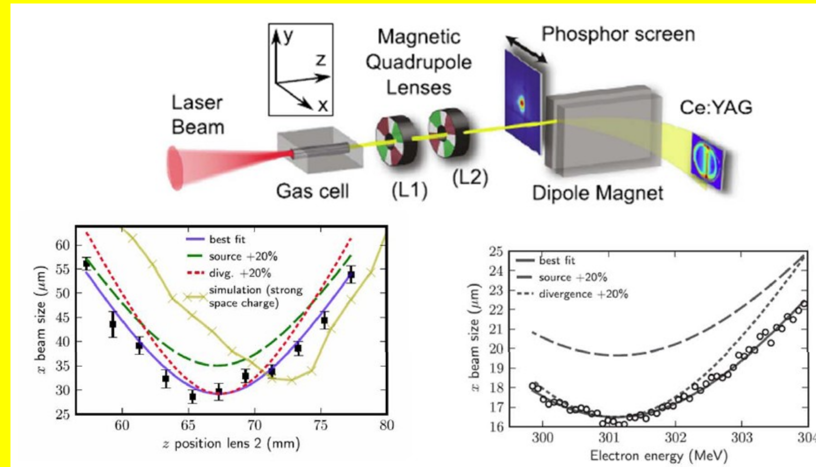
σ σ' γ $\Delta\gamma$ at the same time

- S. Kneip and al., PRST-AB 15, 021302 (2012)



Energy, energy spread and divergence behind the dipole

A new kind of Quadscan



- R. Weingartner and al., PRST-AB 15, 111302 (2012),

- Anyway large energy spread (>few%) seems to be an ‘hic sunt leones’ for reliable beam measurements. $\varepsilon_n^2 = <\gamma>^2 \left(s^2\sigma_\varepsilon^2\sigma_{x'}^4 + \varepsilon^2\right)$

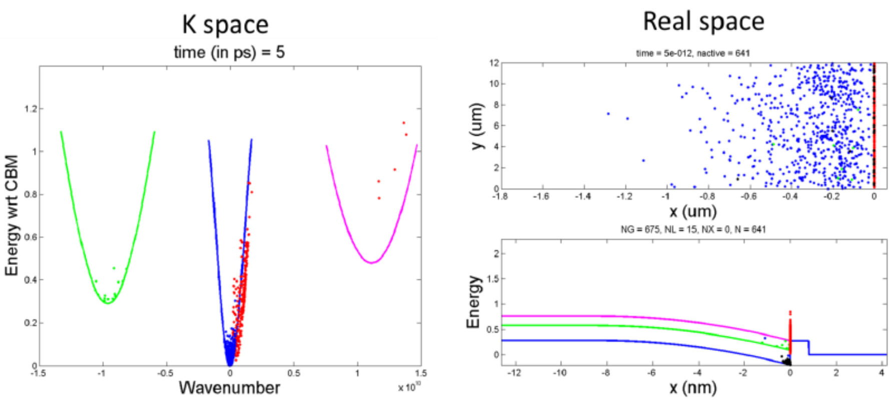
The Cornell University photinjector, *Luca Cultrera (CLASSE - Cornell University)*

Photoemission modeling

Monte-Carlo simulation tool for III-V family photocathodes

–Fully developed for non-layered reflective cathodes, now working on layered & transmission mode structures

Simulation snapshot



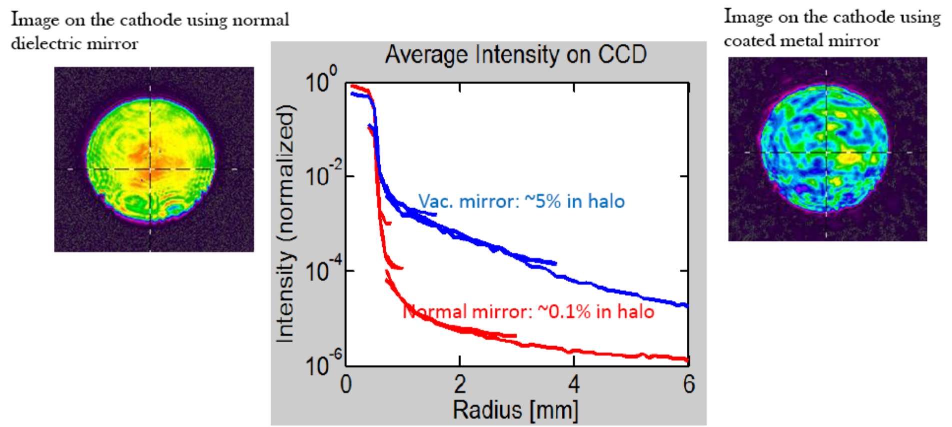
BLUE – Electrons in Gamma Valley

GREEN – Electrons in L Valley

PURPLE – Electrons in X Valley

RED– Emitted electrons

Halo & Vacuum Laser Mirror

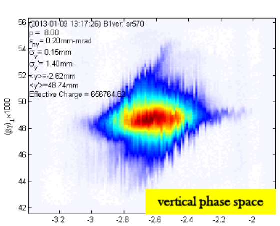


Our final laser mirror scattered ~50x more light compared to dielectric mirrors (which we cannot use). A new mirror with 2 nm-rmssurface roughness was installed to fix the problemImage on the cathode using coated metal mirror

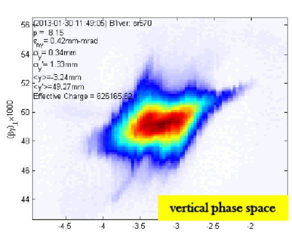
Following work by a group at DESY

Beam emittance at the merger

20 pC/bunch



80 pC/bunch



Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps rms

20 pC/bunch	80 pC/bunch
0.22/0.15 mm-mrad	0.49/0.29 mm-mrad

Normalized rms core emittance (horizontal/vertical) @ core fraction (%)

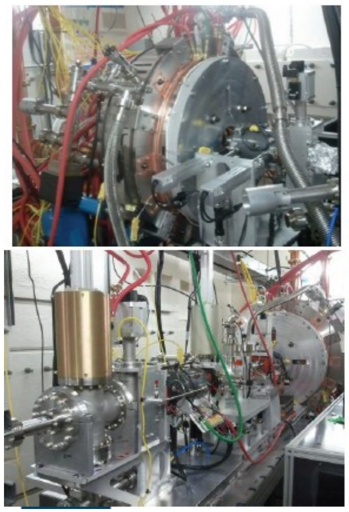
20 pC/bunch	80 pC/bunch
0.14/0.09 mm-mrad @ 68%	0.24/0.18 mm-mrad @ 61%

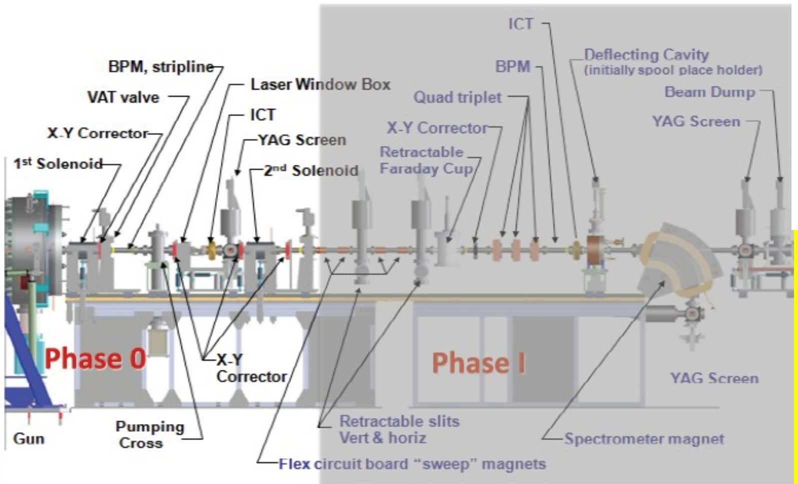
<u>100x the brightness at 5 GeV</u> of the best storage ring (1nm-rad hor. emittance 100 mA)!

<u>Similar to the best NCRF guns emittance</u> but with > 10^6 repetition rate (duty factor = 1)

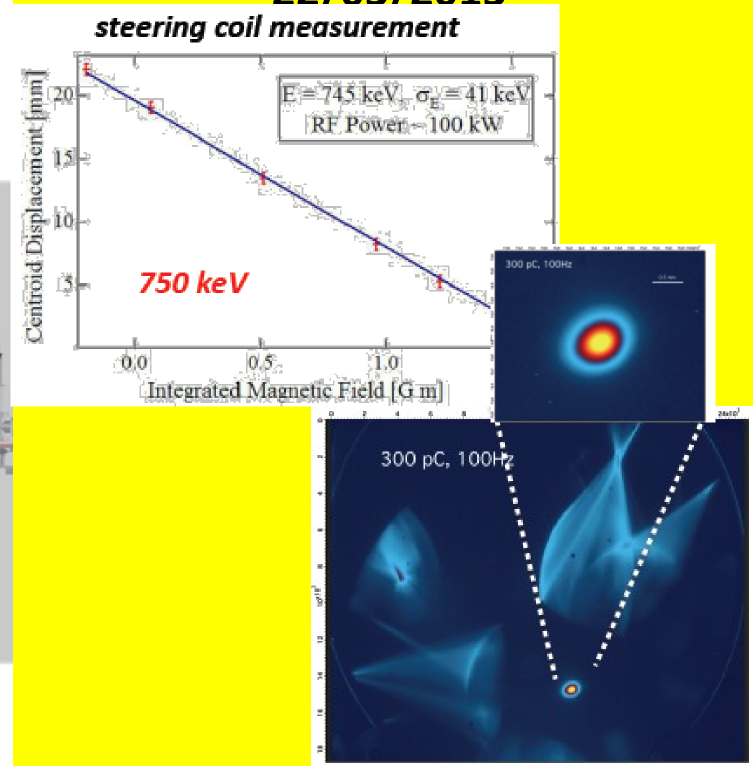
High repetition rate photo-injectors, *Daniele Filippetto (LBNL, Berkeley)*

- High rep.rate photo injectors overview
- APEX gun @ LBNL has achieved the nominal field and vacuum levels and is now testing the first Cs2Te cathode.

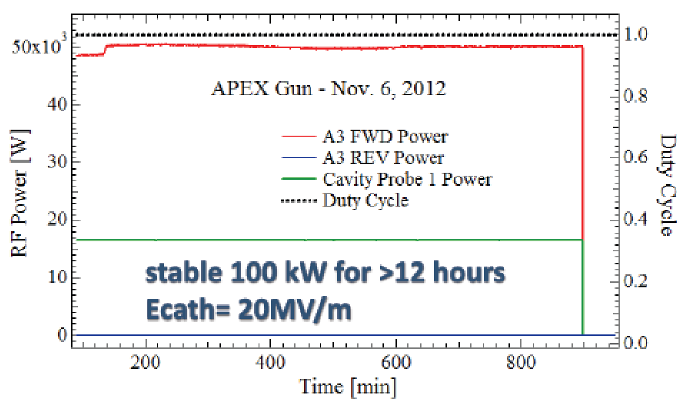


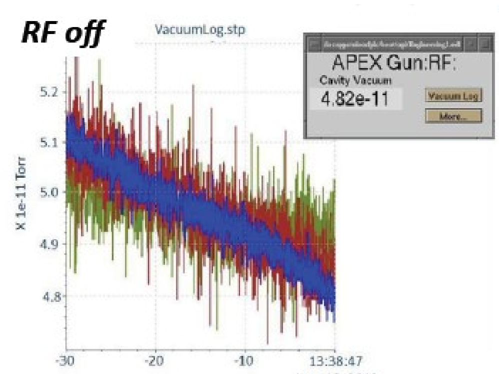


First measurements with Cs2Te 15-22/03/2013

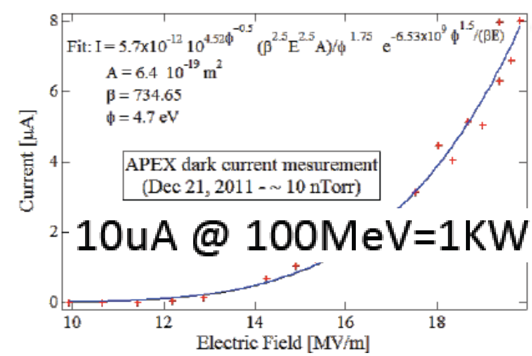


RF and vacuum gun performances:





Dark Current



External-Injection experiment at SPARC_LAB, *Andrea Rossi (INFN – MI)*

- Simulations for the external injection experiment at SPARC_LAB are ongoing
- Interaction chamber and diagnostics station design is ongoing
- First experimental results are scheduled for beginning of 2015

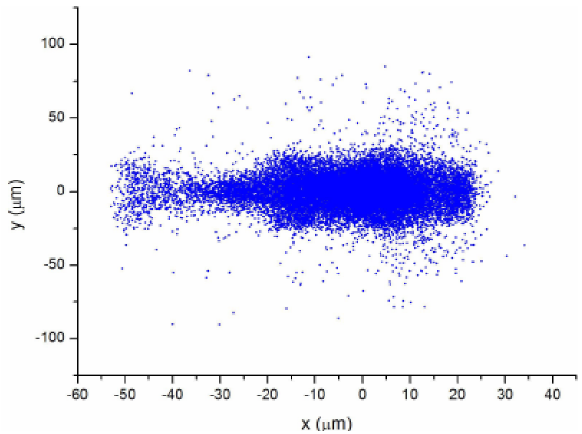
EXIN goals

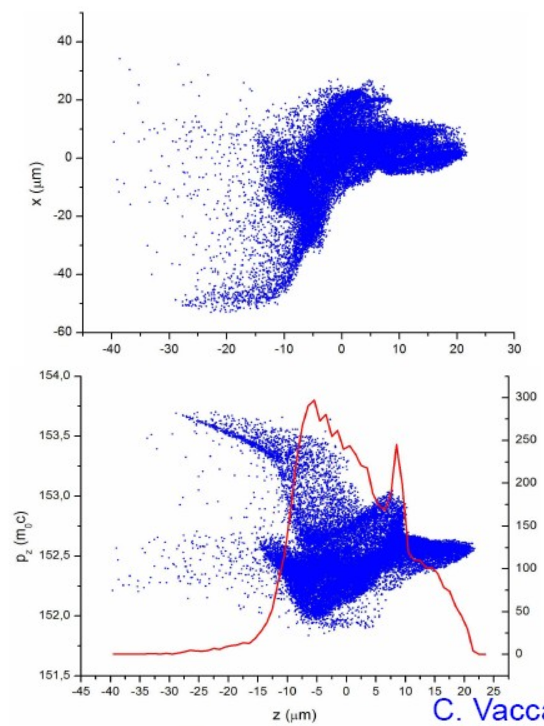
- Demonstrate an energy increase preserving as much as possible beam 6D volume.
- Stability.
- Reproducibility.
- Everything above in the easiest way (leading philosophy).

Highest energy record in LWFA is NOT a goal!

S2E simulation: beam transport

Transport has been performed using ELEGANT with space charge effects turned OFF, from the end of the second accelerating structure at 8.66 m from cathod.





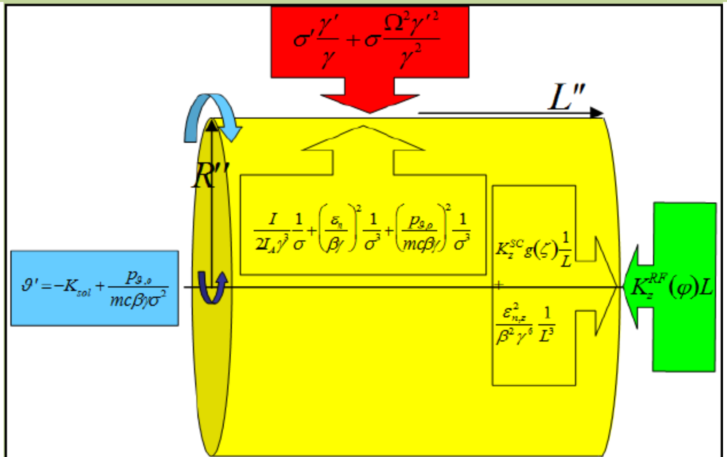
Final beam parameters: $\sigma_x \approx \sigma_y = 12.7$ μm, $\sigma_z = 9.8$ μm, $\varepsilon_x = 2.7$ μm, $\varepsilon_y = 0.4$ μm, E= 71 MeV, $\delta\gamma/\gamma = 0.2\%$.
Very mild compression: cf= 2.
Non particular optimization.
X emittance overestimated!

C. Vaccarezza

Ultra Short electron bunches by Laminar Velocity Bunching, *Alberto Bacci (INFN – MI)*

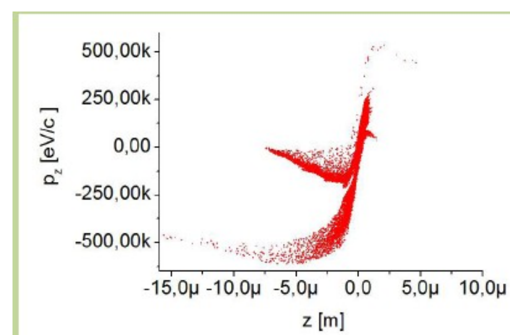
Velocity Bunching (VB) and Laminar VB: a compressing regime of peculiar equilibrium between external RF longitudinal focusing and internal space-charge defocusing forces. Forces damped at final compression

The idea is to maintain the longitudinal space charge regime (laminarity) along the whole compression; preventing over-compression, permitting an energy spread damping and at the same keeping valid the emittance compensation



compression performed with a proper control of the envelope, acceleration gradient (ponderomotive ext. fources) and injection phase

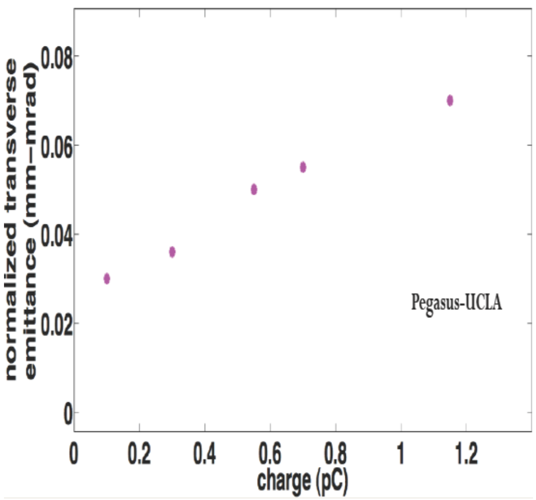
I_s [A]	$\sigma_{z,s}$[sec]
135	< 0.5fs
812	< 1.0fs

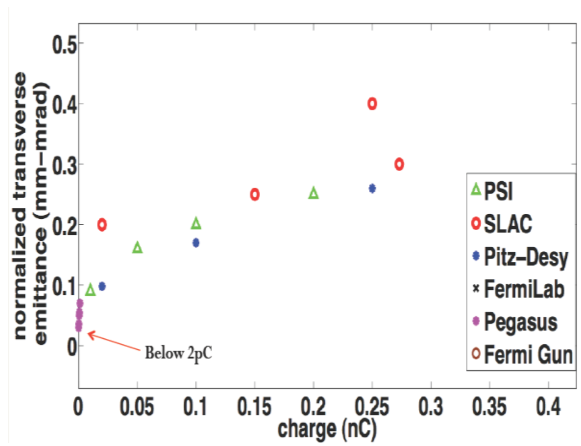


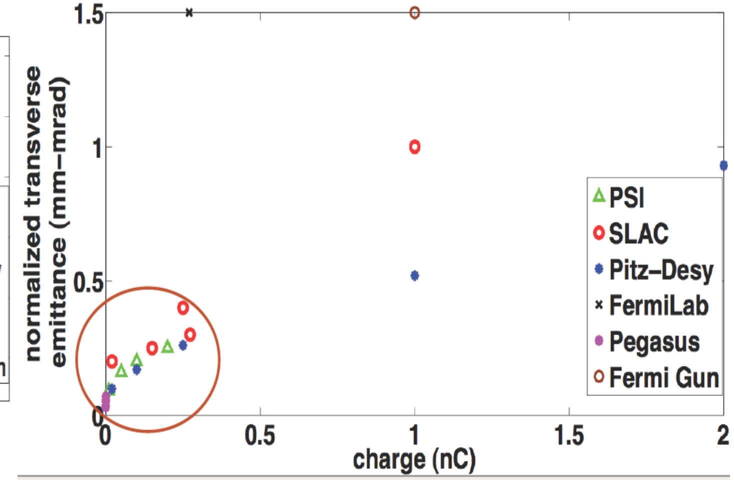
GIOTTO ***G****enetic* ***I****nterface for* ***O****p****T****imising* ***T****racking with* ***O****ptics*

Recent Advancements in RF Guns, *Luigi Faillace (RadiaBeam Technologies)*

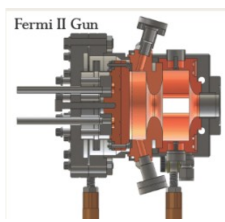
Plot of Emittances from different RF Guns







- The new RF gun for the Fermi FEL at Sincrotrone Trieste was successfully installed and conditioned at high-power (11MW, 1.5µs and 50Hz)



Frequency	2.998 GHz
Mode separation	14.2 MHz
Shunt Impedance	54 MΩ/m
Quality factor Q_0	13800
Coupling Beta	1.8
Input Power (E=120MV/m at cathode)	9.5 MW

- Fermi II RF Gun is an improved and more compact version of the current gun (Fermi Gun 1.5 mm mrad) and it will hopefully allow to achieve much lower emittance values. First beam at the end of April 2013.
- The design of the “Super Gun” for the GALAXIE project represents a break-through in the field of RF multi-cell Guns → new materials, material technology (e.g. Free Form Fabrication?), surface handling, laser shaping…

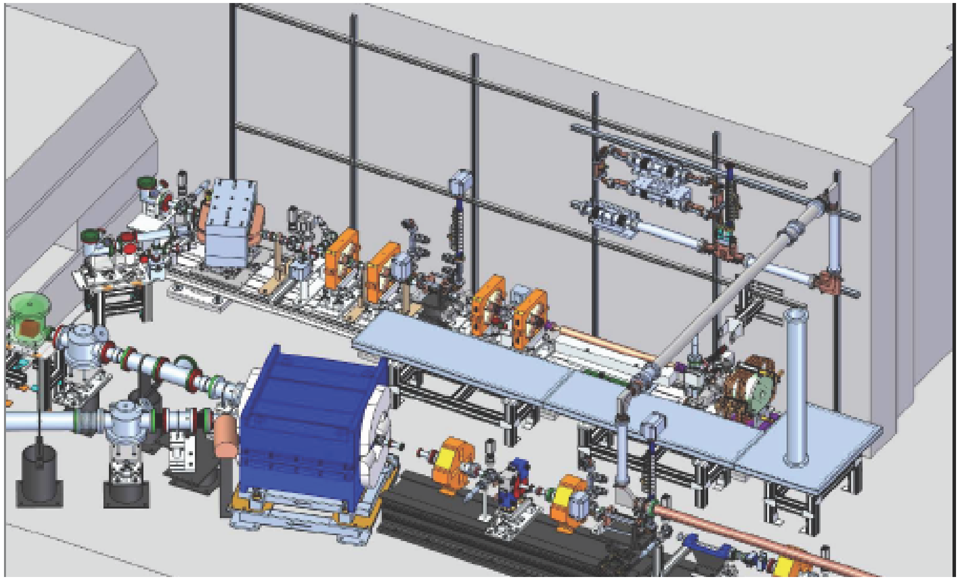
❖ Injector: high field gun with a magnetized cathode (1pC, 1ps beam with angular momentum content)

- Point of interest for many Labs at the moment a⍰ beam charge from 40pC to 300pC

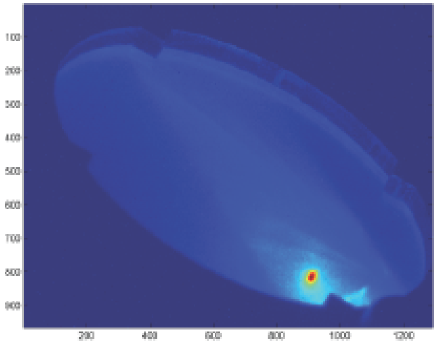
Initial X-Band Photoinjector Performance at SLAC, *Cecile Limborg (SLAC)*

X-Band Photoinjector at SLAC

5.5 cell X-Band gun



XTA located in NLCTA at SLAC



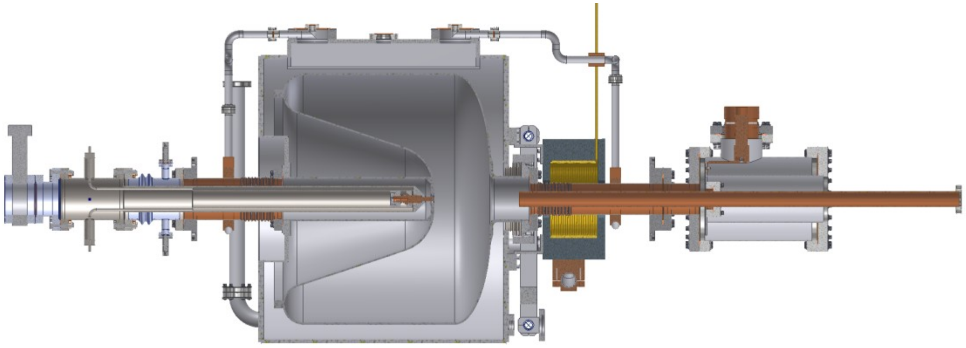
1st e-beam July30th 2012

- e-beam out of gun E~ 7.5MeV ($V_{RF,peak}$~ 200MV/m)
- dark current acceptable
- e-beam at 70 MeV after 1.05 m linac
- charge up to 40pC , QE just in 1e-5 range
- bunch length measured ~ 250 fs rms for 20pC
- energy spread rms 15 keV at 70 MeV (15 pC)
- emittances < 3 mm-mrad (but very preliminary optimization)

Optimizing Design of SRF Electron Guns, Joseph Bisognano (SRC/UWisconsin-Madison)

Electron Gun for CW WiFEL

Gun repetition frequency	5 MHz or higher
I peak at a soft X-ray undulator	1000 Amps
$\Delta E / E$ at a soft X-ray undulator	< few 10^{-4}
Normalized $\varepsilon_{Transverse}$	<1 mm-mrad
Bunch length at undulator, rms	70 fsec (seed jitter concerns)
Charge/bunch	200 pC
I average	1 mA



	UW Gun	BNL QWR	FZD Gun
E_{Peak} / E_{Cath}	1.31	2.63	2.7
B_{peak} / E_{Cath}, T/MV/m	1.57	1.92	5.76

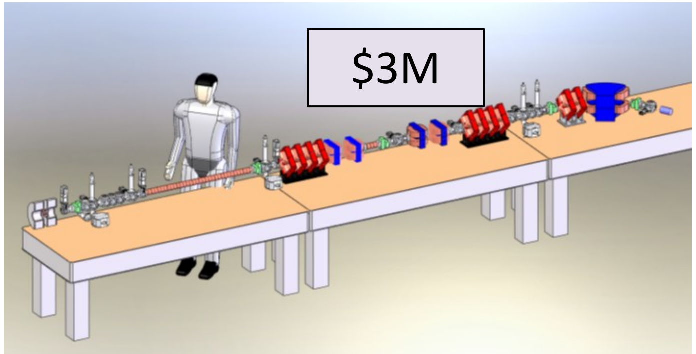
Key Bunch Parameters

- RMS bunch length at gun exit – 0.18 mm
- Cathode spot ~1 mm for 0.85 mm-mrad thermal emittance
- At gun exit, $\delta p/p$ ~ 2.5%, divergence – 7 mrad
- Q – 200 pC
- Kinetic energy – 4.0 MeV
- With smaller spot, can be operated in lower charge modes with lowered emittance; also more exotic cathode materials

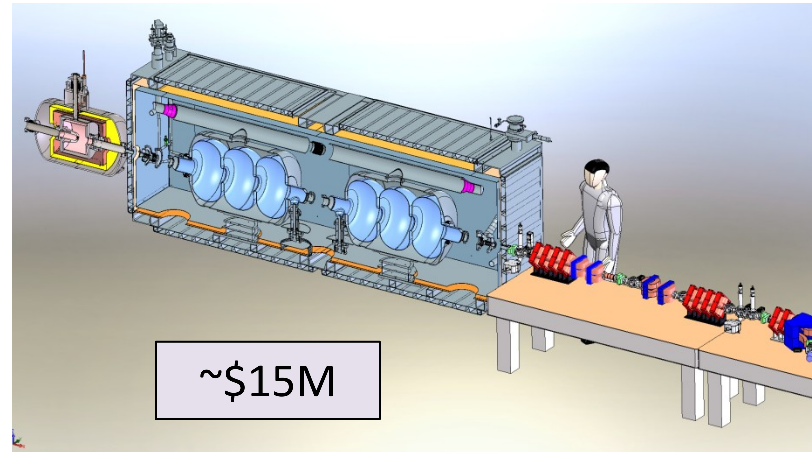
Key Gun Parameters

- Electric field at cathode – up to 45 MV/m
- Peak surface magnetic field – 93 mT
- Dynamic power loss into He – 39 W at 4K
- Q – 2.5E9
- Frequency – 199.6 MHz

High Brilliance X-rays from Compact Sources, *William Graves (MIT)*



- kHz rep rate x-band gun & linac using only 6 MW total RF power

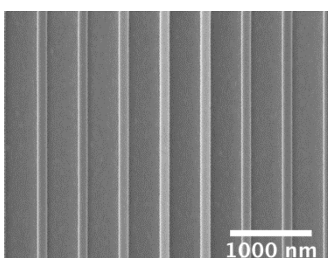


- SRF at 4K with low heat load and modular construction

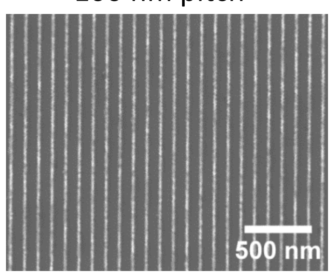
Nanostructured Cathodes

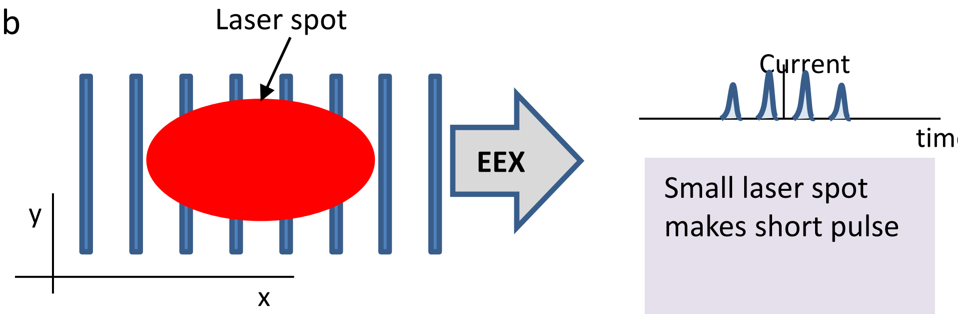
SEMs of tips fabricated by R. Hobbs, MIT Nano Structures Lab

110 nm wide Au lines at 500 nm pitch

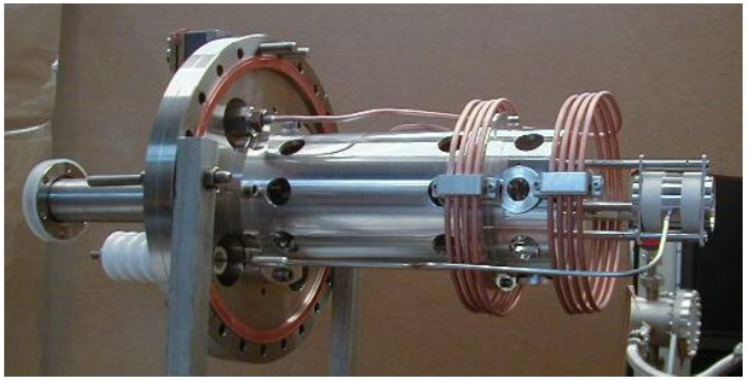


18 nm wide Au lines at 100 nm pitch

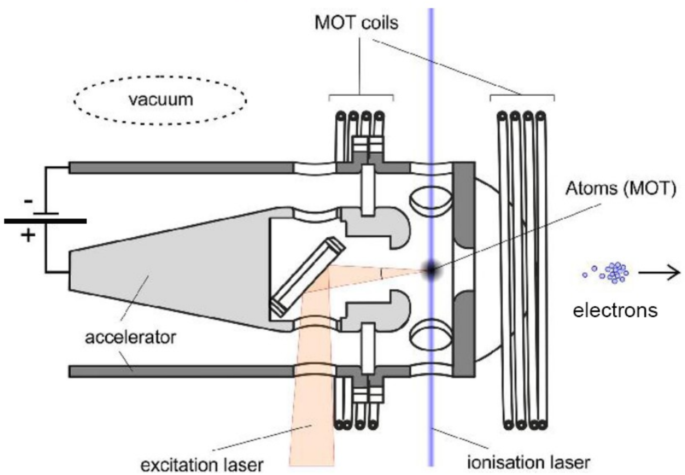


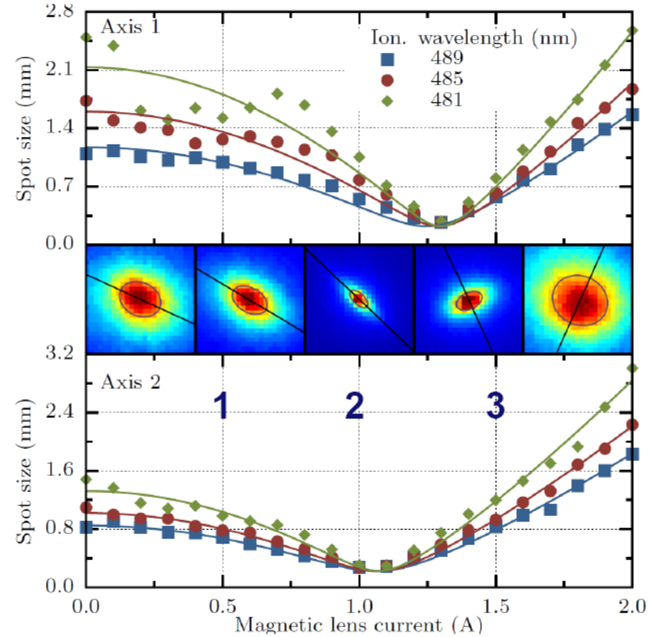


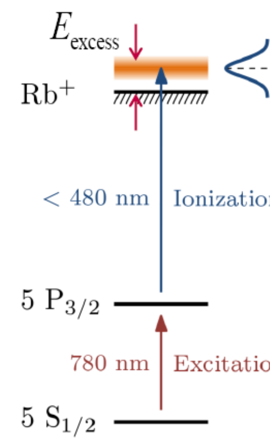
Ultracold and ultrafast electron source, *Jom Luiten (Eindhoven University of Technology)*

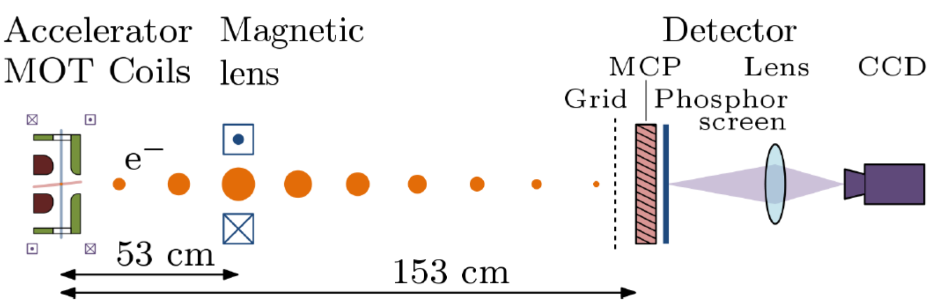


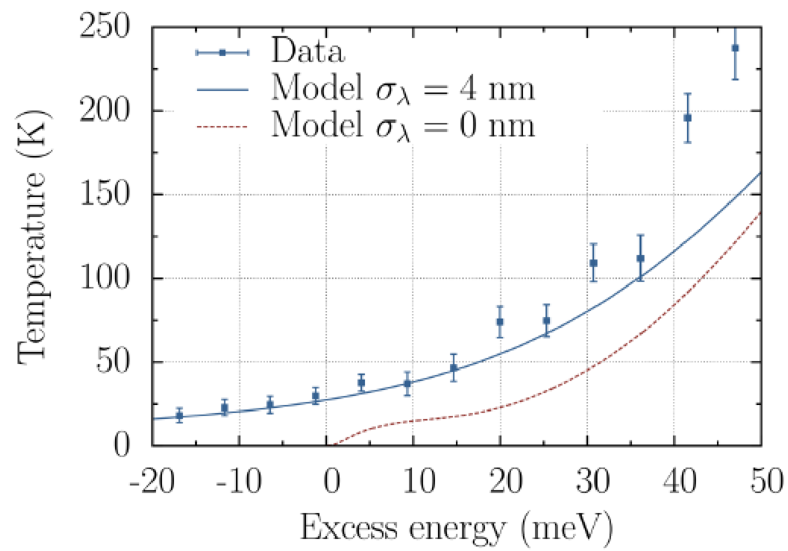
Atom trap inside coaxial accelerator







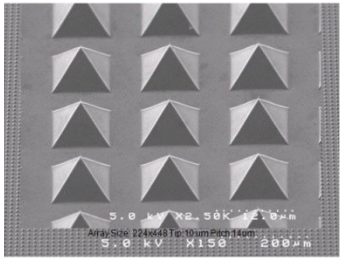


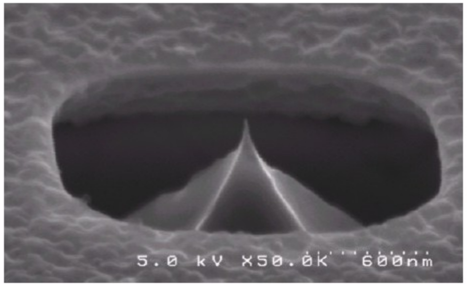


Generation of high-brightness electron beams from a needle cathode and their application to make channeling x-rays, *William Gabella (Vanderbilt University)*

- Field emission from single, diamond, needle cathodes gives an electron source with small emittance.
- Emittance can be preserved through acceleration to 30-40 MeV, in the sense, that "enough" electrons in the beam have small emittance.
- A small emittance electron beam can be used as a source of channeling radiation making x-rays of small source size.

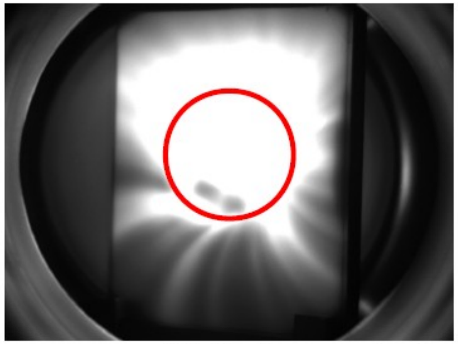
diamond tips and **gated diamond tips**





Silicon-On-Insulator (SOI)

HBESL (A0) has seen electrons from a Vanderbilt diamond field emitter array



23.6 MV/m

Ugly beam, but a beam

Channeling means the electron is confined by the charges in a plane or along an axis.

diamond 110 plane, ebeam view