

CNT Accelerator - Path Toward TeV/m Acceleration: Dynamics of Plasmon- Assisted Acceleration in CNTs

ACN (Application of Crystals and Nanotubes for acceleration or bending) 2020

Young-Min Shin

10:20 AM, March 10 2020

Content

1. Introduction

- Background/Crystal Acceleration – TeV/m Gradient

2. CNTs – How Does it Benefit Accelerations in a Dense Plasma Medium

3. Conceptual Rationales

- Beam-Driven Acceleration
- Laser-Driven Acceleration

4. Prior Efforts to Prove the Concept (POC-Test)

- Test Facilities
- Experimental Layouts
- Sample Preparation
- Outcomes and Challenges

5. Takeaway and Outlook

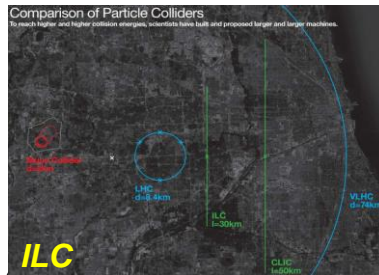
Size Does Matter! – Too Expensive and Too Big!



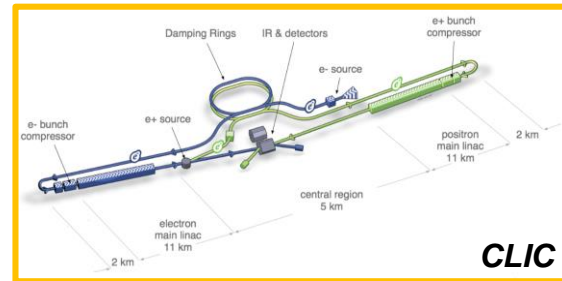
Tevatron/Fermilab
6.86 km up to 1 TeV:
\$ 120 – 150 M



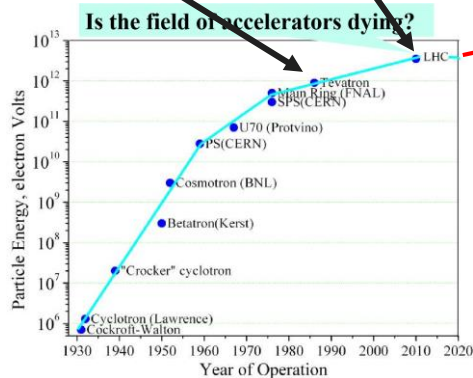
LHC/CERN
27 km, 6.5 TeV (13
TeV total, 2015), \$4.4B



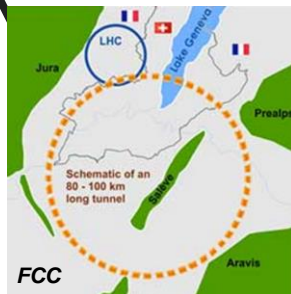
ILC
ILC (0.5 TeV, \$15 B)



CLIC
CLIC (3 TeV, \$ 15 – 20 B)



Livingstone Plot



FCC
100 TeV (80 – 100 km, \$?? B)

- **Practical Limit of Accelerator Technology at the Energy Frontier:**
→ Significant increase of construction and operation costs (Cost increase per GeV CM by an order of magnitude for last 40 Years): Strong Demand for **New Technology**

Prospective Colliders for Future HEP Research

Project	Type	Energy TeV, c.m.e.	Int. Lumi./Oper. Time.	Power years	Cost B (unit)
ILC	e+e-	0.25	2 ab ⁻¹ /11 yrs	129	5.3ILCU
		0.5	4 ab ⁻¹ /10 yrs	163 (204)	7.8ILCU
		1		300	?
CLIC	e+e-	0.38	1 ab ⁻¹ /8 yrs	168	5.9CHF
		1.5	2.5 ab ⁻¹ /7 yrs	370	+5.1CHF
		3	5 ab ⁻¹ /8 yrs	590	+7.3CHF
CEPC	e+e-	0.091	16 ab ⁻¹ / 4 yrs	149	5 \$
		0.24	5.6 ab ⁻¹ /7 yrs	266	+ ?
FCC-ee	e+e-	0.091	150 ab ⁻¹ /4 yrs	259	10.5CHF
		0.24	5 ab ⁻¹ /3 yrs	282	
		0.365	1.5 ab ⁻¹ /4 yrs	340	+1.1 CHF
LHeC	ep	0.06/7	1 ab ⁻¹ /12 yrs	(+ 100)	1.75 CHF
HE-LHC	pp	27	20 ab ⁻¹ /20 yrs	220	7.2 CHF
FCC-hh	pp	100	30 ab ⁻¹ /25 yrs	580	24 CHF
μμColl.	μμ	14	50 ab ⁻¹ /15 yrs	230	10.7* CHF

Ref.: V. Shiltsev, arXiv:1907.01545

Linear Colliders (Due to beam-strahlung)
e+e-: < 3 TeV (IP) and 10 TeV (focusing channel)

Circular Colliders (Due to Synchrotron Radiation)
e+e-: < 0.25 TeV (Higgs Factor)
proton-proton: < 100 TeV

Only Option: Dense Plasma Acceleration

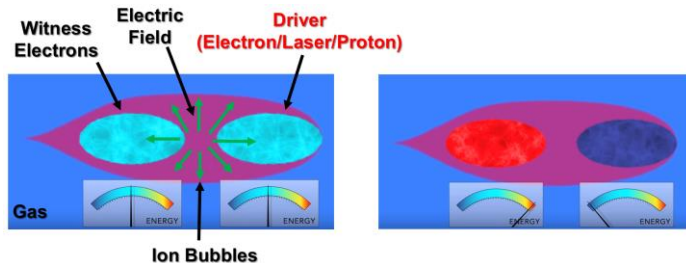
> 30 GeV/m

μ+μ- or pp Colliders within 10 km foot print

Plasma Acceleration in Solids?

Plasma Wakefield Acceleration

(T. Tajima, J. Dawson 1979) → Gas-Phase Plasma



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left[\frac{\text{GeV}}{m} \right] \cdot \sqrt{n_0 [10^{18} \text{cm}^{-3}]}$$

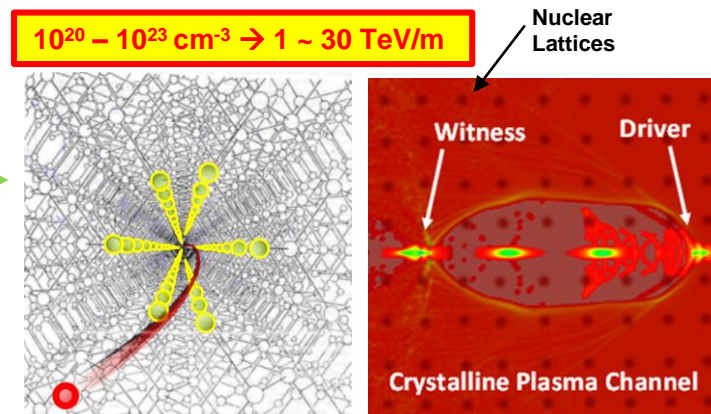
BELLA (LBNL): 8 GeV over 20 cm
 FACET (SLAC): 9 GeV over 1.3 m
 AWAKE (CERN): 2 GeV over 10 m

**Opportunity
for Multi-TeV
Colliders**

Drawbacks

- Low Photon-Beam Power-Conversion Efficiency
- Positron Accelerations
- Staging Efficiency
- Beam Emittance Control
- Energy Spread (30 % for 10 TeV, 80% for 30 TeV)

Plasma Acceleration in Solids??

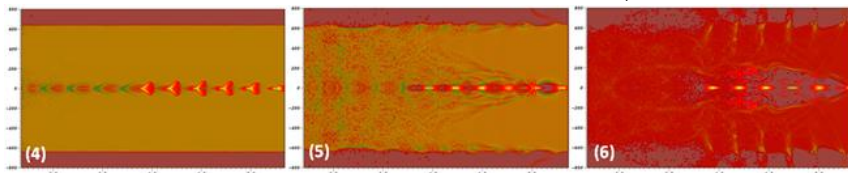
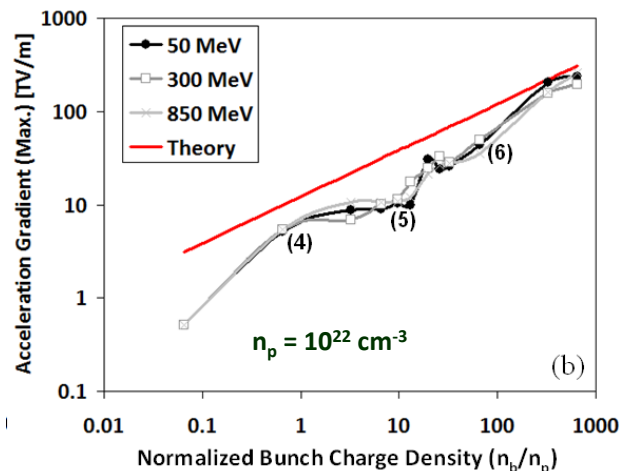


Channeling Accelerating in “Crystals”??

- Ultra-High Gradient (TeV/m scale?) (Final Energy = Gradient X Distance)
- Strong Focusing
- Beam Control (Bending, Collimation)
- “Inexpensive” Method: → Cost Effective, → Less # of Stages for Re-focusing/Re-Phasing → Single Stage

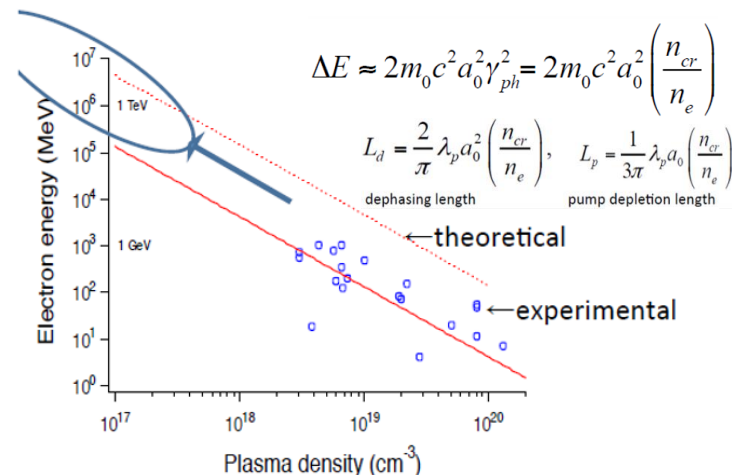
Acceleration in Dense Plasma (Solid-Level)

Beam-Driven Acceleration



- Y. M. Shin, et. al., NIU, Fermilab

Laser-Driven (X-Ray) Acceleration



$$n_{cr} \propto \lambda_{ph}^{-2} \propto E_{ph}^2$$

$$n_{cr} = 10^{21} \text{ (1eV photon)}$$

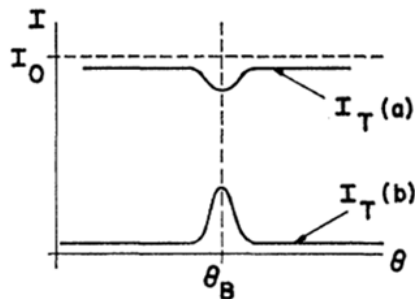
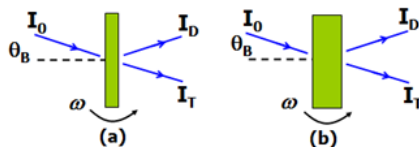
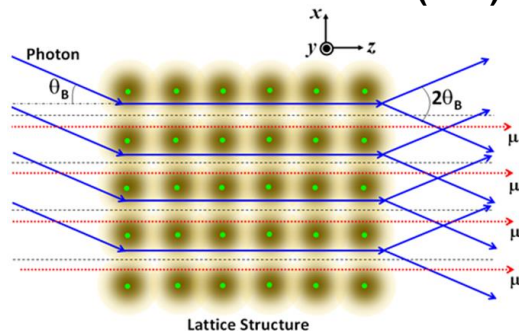
$$\rightarrow 10^{29} \text{ (10keV photon)}$$

$$n_e = 10^{16} \text{ (gas)} \rightarrow 10^{23} \text{ (solid)}$$

- T. Tajima, et. al., UCI

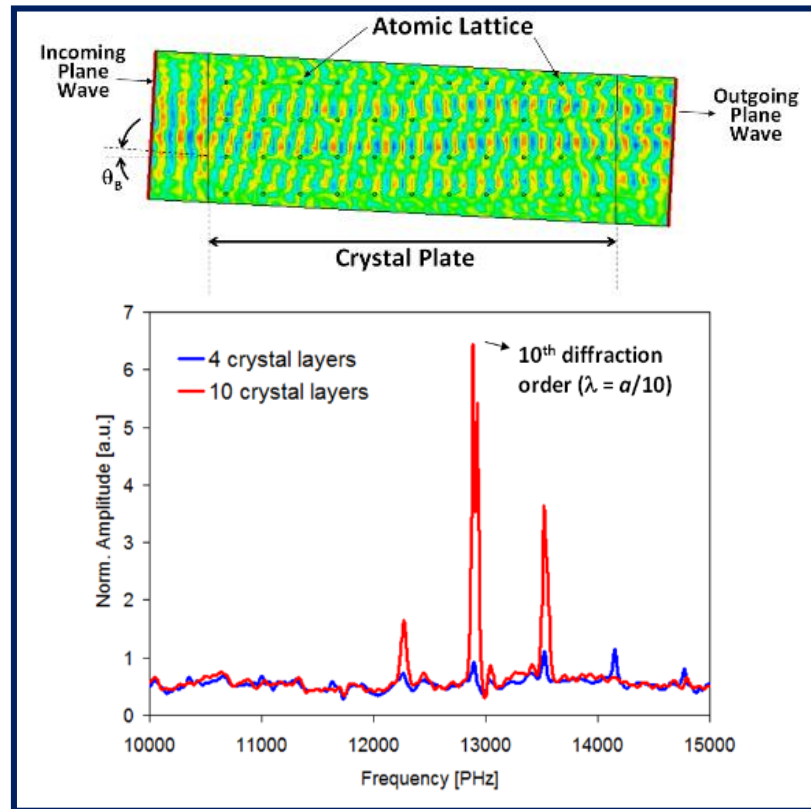
Acceleration in Solids (XRD Acceleration)

- XRD Acceleration Using Bormann Anomalous Transmission (BAT)



- T. Tajima, M. Cavenago,
PRL 59, 1440

- Simulation Validation (BAT)



Challenges on Acceleration in Solids

Challenges (V. Lebedev @ Fermilab)

• For Positive Particles Crystal Channels

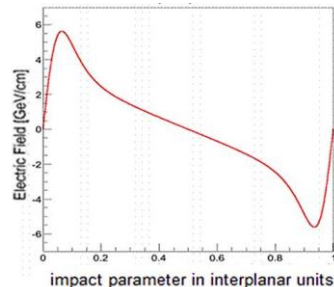
Reduce Multiple-Scattering
→ Focusing (Channel) $\sim 2 \times$ defocusing
(Plasma Wave)

However,

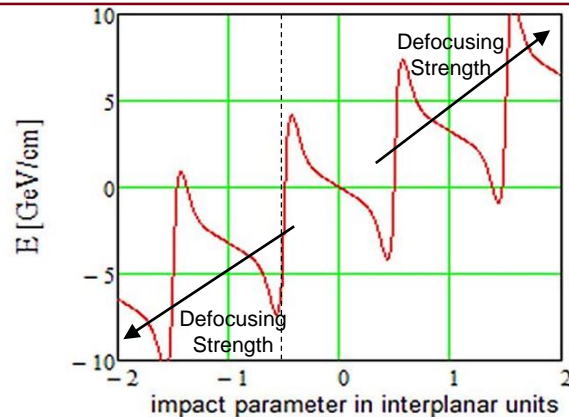
Limited Focusing Area (Bubble Regime)
→ Only Central Channels for Focusing
(Wakefield Defocusing > Channel-Focusing)
Too Low Acceptance of the Channel: 4 orders of magnitude smaller than gas-plasma with the same electron density
(e.g. Single Channel: ~ 5 pm for 10 GeV Muons)

• For Negative Particles

- Focusing around Crystal Plane/Axis → Greatly Increases Multiple Scattering
- Acceleration to high energy requires focusing in both “Transverse planes” → Axial Channeling must be used



Electric field on distance between two crystal planes



Electric field with a Plasma Wave in a Bubble Regime (Over 4 Planes)

- Channeling may avoid nuclei-scattering, but still electron-scattering is present in the channel.
- Acceleration Condition in Crystal-Channel,

Channel Acceptance \geq Emittance Growth

$$\left(\varepsilon_n \approx k_p a_0^2 \sqrt{\frac{m\gamma}{2M}} \right) \quad \left(\delta \varepsilon_n \approx \frac{r_e L_c}{(E_{acc}/E_0)} \sqrt{\frac{\gamma M}{2m}} \right)$$

$E_{acc}/E_0 \geq 10$ (for μ^+)
→ Acceleration at the maximum possible rate is desirable

Bigger Size of Channel Structure

Acceleration Condition vs. Channel Size

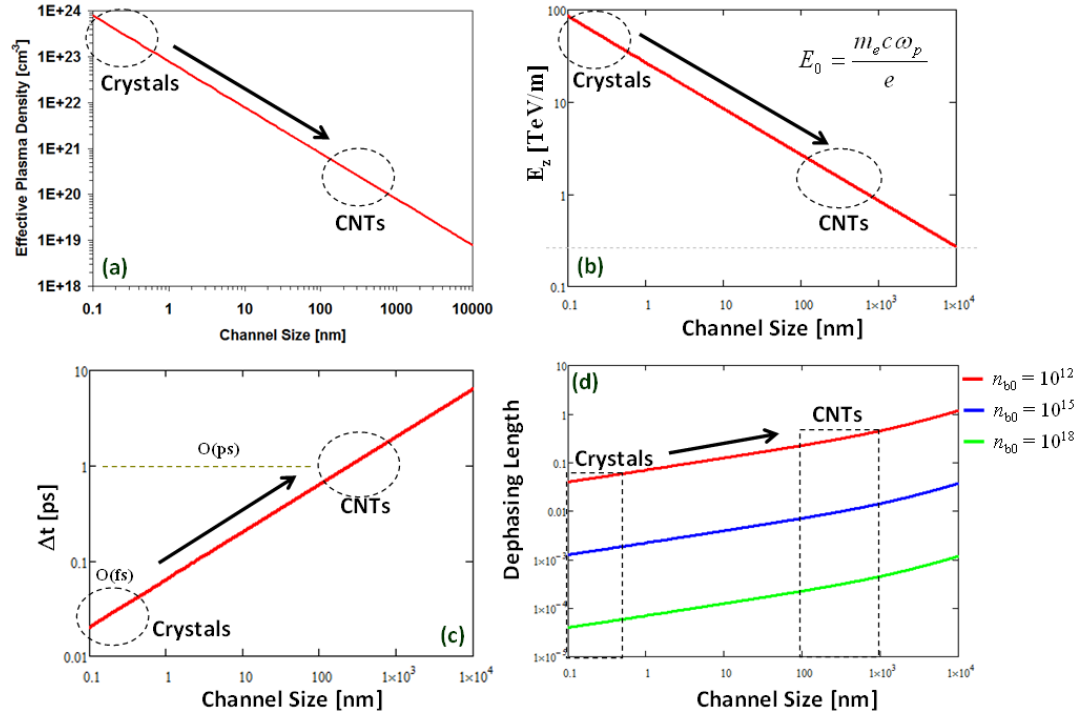
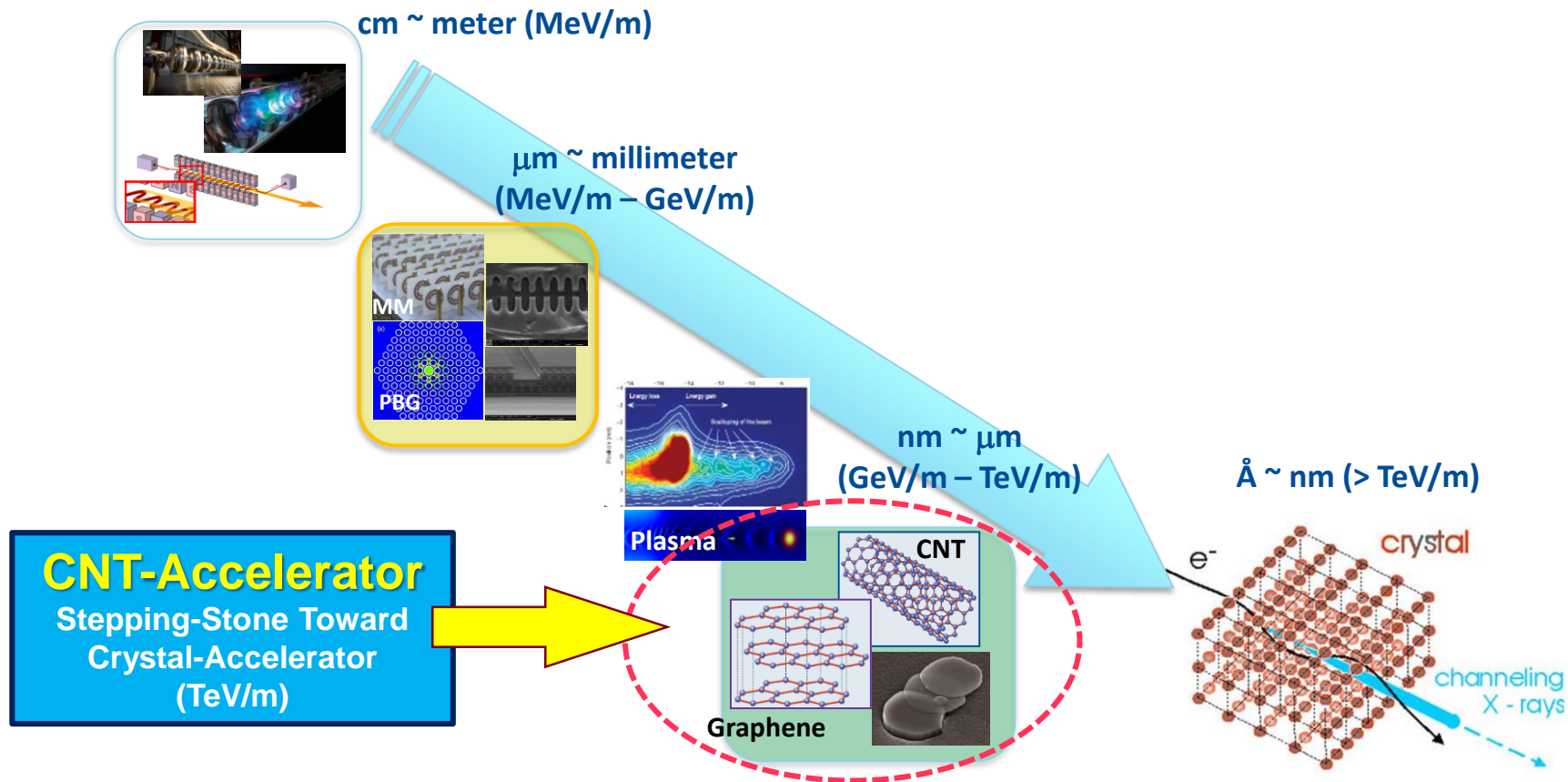


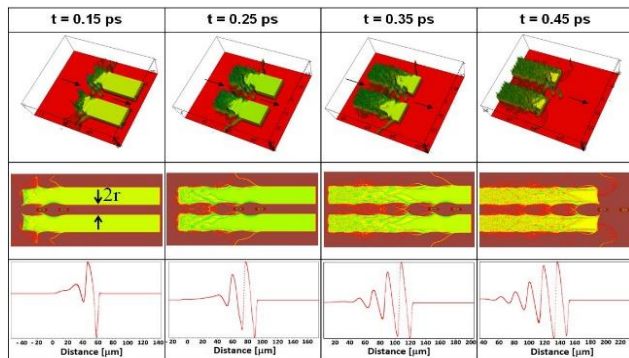
Fig. 2. (a) Effective plasma density, (b) acceleration gradient, (c) dissociation time scale, and (d) dephasing length versus channel size (carbon-based).

Nanostructures: Path Toward TeV/m Acceleration

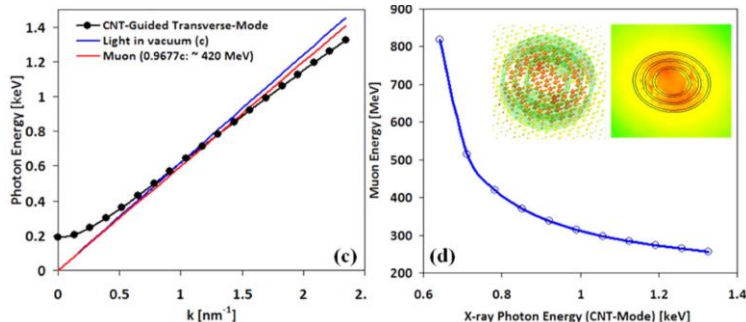


Acceleration in Nanotubes

Beam-Driven (Self-Driven) Acceleration



Y. M. Shin, APL (2014)

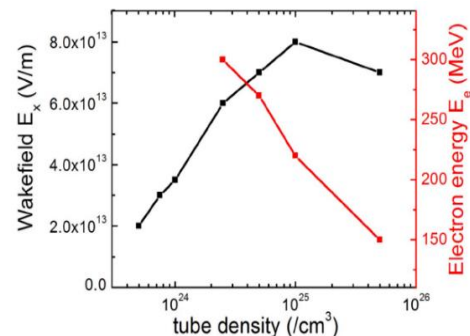
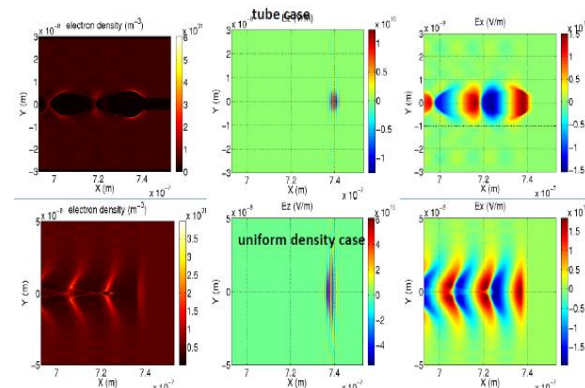


Y. M. Shin, D. A. Still, V. Shiltsev, Phys. Plasmas 20, 123106 (2013)

Laser-Driven Acceleration

w. Arrayed Holes

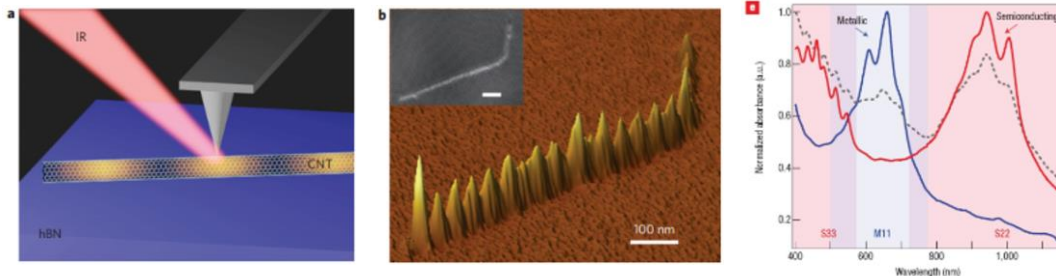
w/o Arrayed Holes (Uniform)



X. Zhang, D. Farinella, Y. M. Shin, P. Taborek, and T. Tajima, PRST-AB (2015)

Plasmon (Plasma-Osc.) Accelerations in CNTs

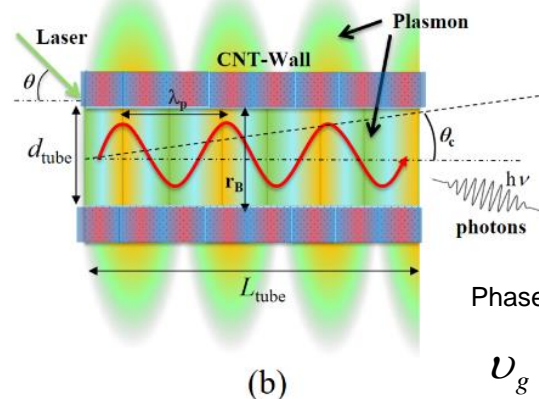
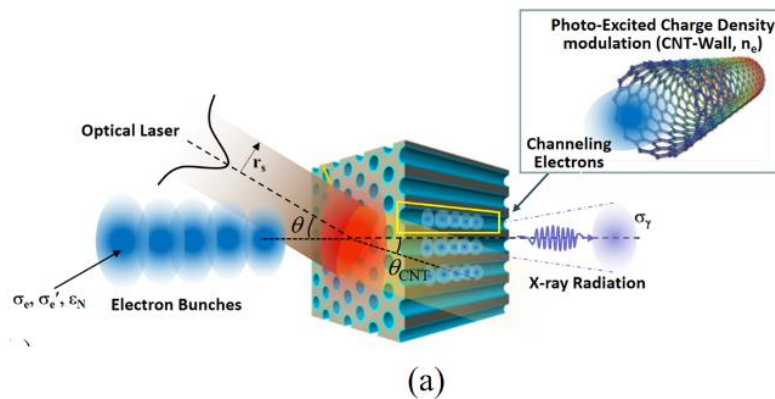
(Photo-Excited) Plasmons in a CNT (Luttinger-liquid: 1D Fermi-Liquid)



Ref.

Nature Photonics, 2015
 Appl. Phys. Lett. 106, 182905 (2015)
 RSC Advances Issue 42, 2016, Issue in Progress
 Synthetic Metals Volume 103, Issues 1–3, June 1999, 2555 – 2558
 Optics Express 21, 022053
 PRL 115, 173601 (2015)
 Physics Letters 87, 173102 (2005)
 Nature Photonics 7, 550–554 (2013)

Phase-Matched Plasmon Acceleration (~ Plasma Acceleration in Linear Regime) in CNTs



Phase-Velocity Matching Condition

$$v_g = c \sqrt{1 - \omega_p^2 / \omega^2}$$

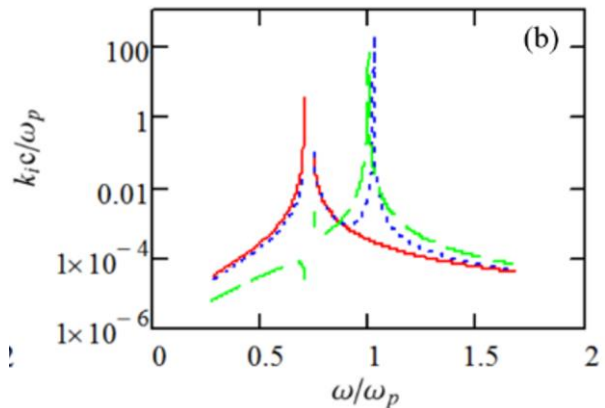
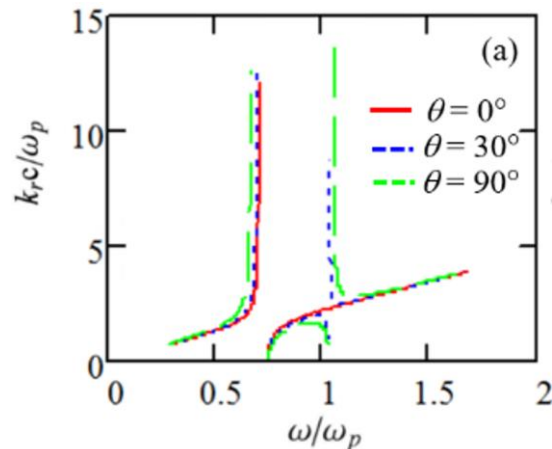
Plasmon-Phasing Condition in CNTs

Dispersion/Absorption Relations (CNT-Bundle)

$$\kappa = k_r + ik_i$$

$$k_r(\omega) = \frac{\omega}{c} \sqrt{\frac{\left(\varepsilon_L - \frac{\omega_p'^2}{\omega^2 - \omega_p^2/2}\right) \left(\varepsilon_L - \frac{\omega_p'^2}{\omega^2 - \omega_p^2}\right)}{\varepsilon_L - \left(\omega_p'^2/\omega^2 - \omega_p^2\right) \left(\cos^2 \theta + \frac{\omega^2}{\omega^2 - \omega_p^2/2} \sin^2 \theta\right)}}$$

$$k_i(\omega) = \frac{\omega^3 \nu \omega_p'^2}{2c^2 (\omega^2 - \omega_p^2)^2 k_r} \left(\frac{\varepsilon_L - \frac{\omega_p'^2}{\omega^2 - \omega_p^2/2} + \left(\varepsilon_L - \frac{\omega_p'^2}{\omega^2 - \omega_p^2}\right) \left(\frac{(\omega^2 - \omega_p^2)^2}{(\omega^2 - \omega_p^2/2)^2}\right)}{\varepsilon_L - \frac{\omega_p'^2}{\omega^2 - \omega_p^2} \left(\cos^2 \theta + \frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_p^2/2} \sin^2 \theta\right)} - \frac{\left(\varepsilon_L - \frac{\omega_p'^2}{\omega^2 - \omega_p^2/2}\right) \left(\varepsilon_L - \frac{\omega_p'^2}{\omega^2 - \omega_p^2}\right) + \left(\cos^2 \theta + \frac{(\omega^2 - \omega_p^2)^2}{(\omega^2 - \omega_p^2/2)^2} \sin^2 \theta\right)}{\left(\varepsilon_L - \frac{\omega_p'^2}{\omega^2 - \omega_p^2} \left(\cos^2 \theta + \frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_p^2/2} \sin^2 \theta\right)\right)^2} \right)$$



CNT-Acceleration Parameters (e.g. Laser-Driven)

a) Laser-Driver (Gaussian)

$$E_L = A_0 e^{-r^2/4r_s^2} e^{-i(\omega t - kz)}$$

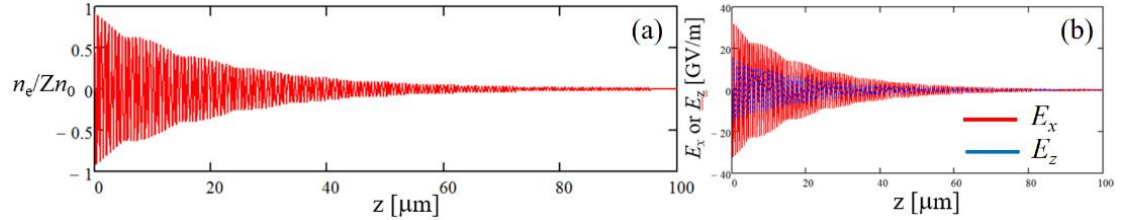
b) Laser-Excited Electron Density in CNT-Walls

$$n_e = Zn_0 \left(1 + a_0 e^{-\frac{r^2}{2r_s^2}}\right)^{-2} e^{i(kz - \omega_{laser} t)}$$

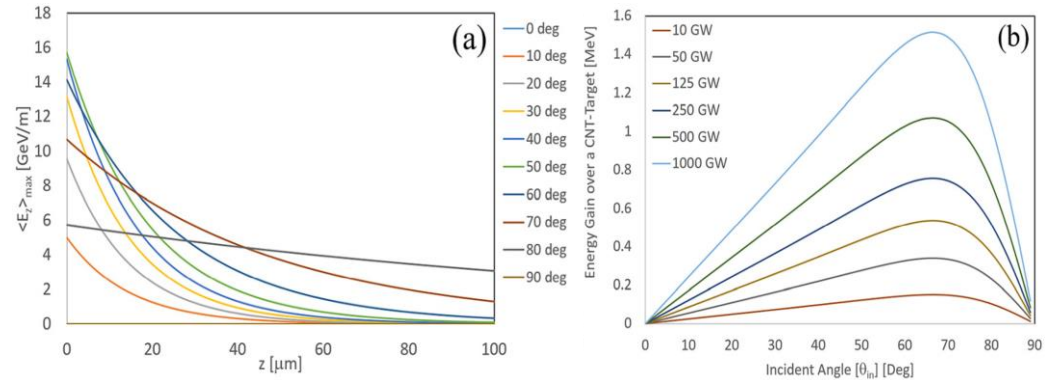
$$\text{where } a_0 = \frac{eA_0 \cos \theta \cdot \sqrt{s}}{m(\omega_{laser}^2 - \omega_p^2/2)r_c}$$

c) Energy gain of Accelerated Ions

$$W_z = \left(\frac{Zn_0 e}{2\varepsilon_0}\right) \left(a_0 r_c e^{-\frac{r^2}{2r_s^2}}\right) \left(\frac{1 - e^{-k_i z}}{k_i}\right) \sin \theta_{CNT}$$



(a) Normalized electron plasma density and (b) electric field amplitudes (E_x : red, E_z : blue) versus distance (z) graphs.



Acceleration field ($\langle E_z \rangle_{\max}$) versus distance (z) graphs with respect to (a) incident angle (θ_{in}) and energy gain (W_z) versus incident angle (θ_{in}) over CNT-implanted target ($z = 100 \mu\text{m}$) with respect to laser power (P_{laser})

Prior Efforts on POC Experiment (Case-1)

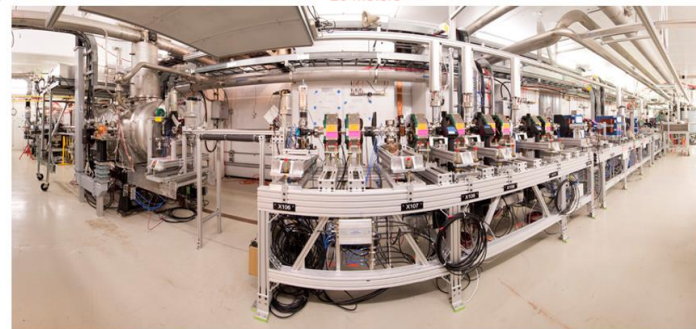
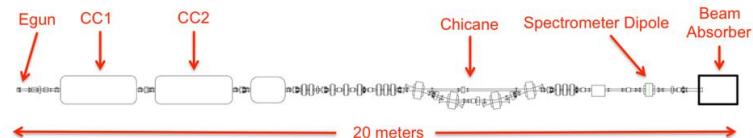
: Test Facility

Fermilab FAST Injector Beamline



Beamline Parameters

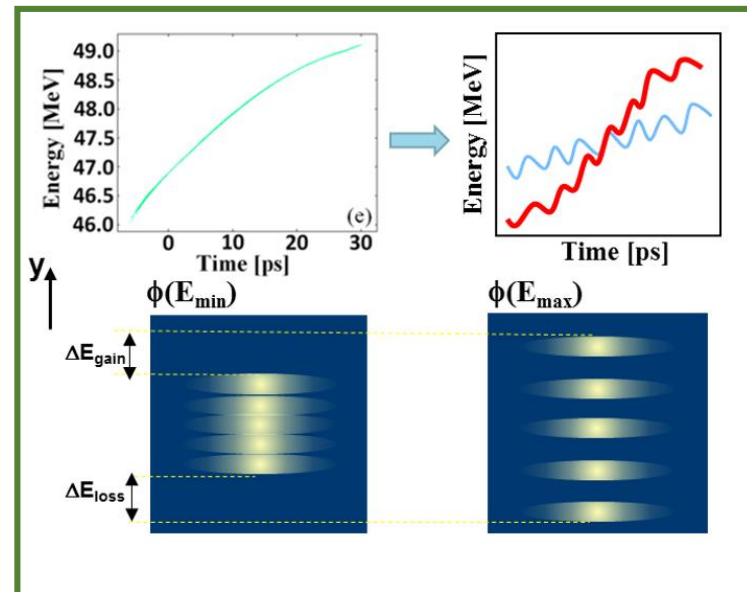
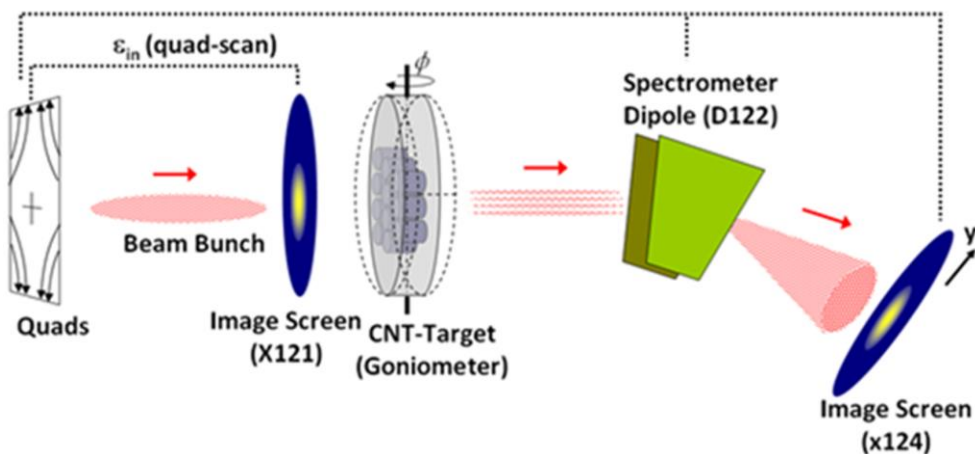
Parameter	Nom. Value	Unit
Energy	50	MeV
Bunch Charge (Q)	≤ 3.2	nC
Bunch Length	≤ 300	μm
Trans. Emittance	$2.11Q^{0.69}$	mm-mrad
Long. Emittance	$30.05Q^{0.84}$	mm-mrad
Peak Current	3	kA



Prior Efforts on POC Experiment (Case-1)

: Test Scheme

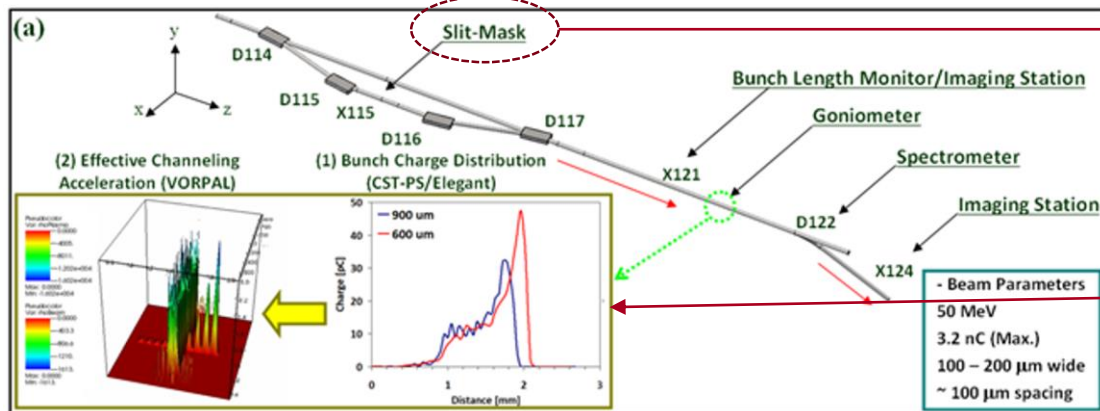
- Direct Energy-Shift Measurement



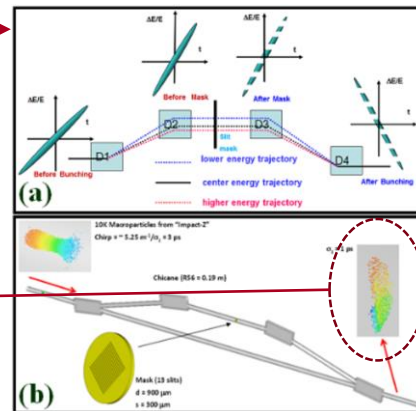
Ref: Y. M. Shin, A. H. Lumpkin, and R. M. Thurman-Keup, NIMB (2015)

Prior Efforts on POC Experiment (Case-1) : Modeling Analysis of Energy Gain

a) Beam Simulation of Fast Injector Beamline (50 MeV)

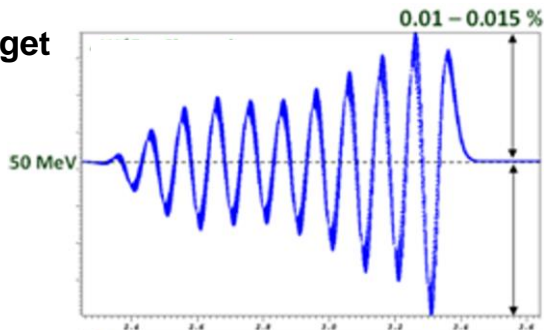


b) Chicane-Model with a Slit-Mask

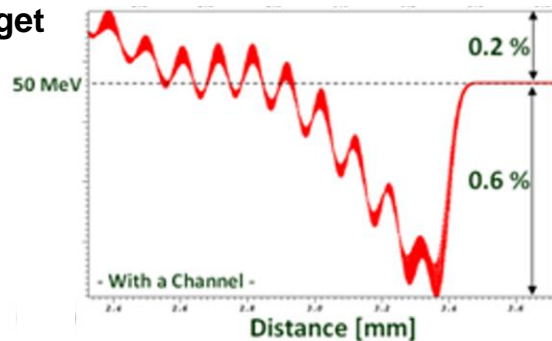


c) Gain Analysis (Effective Plasma Models with Imported Bunch Profile)

A. w/o a Target

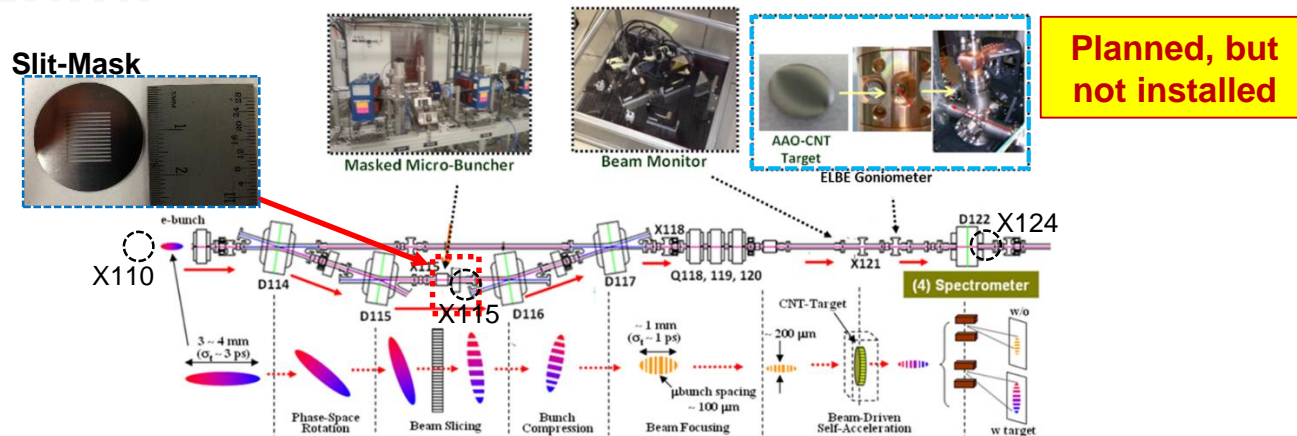


B. with a Target

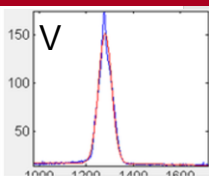
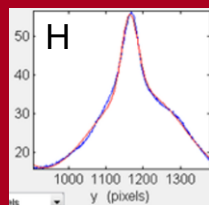
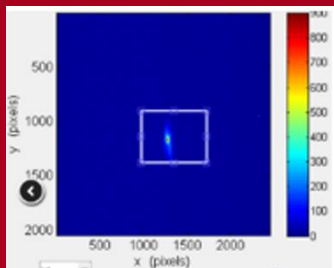


Prior Efforts on POC Experiment (Case-1)

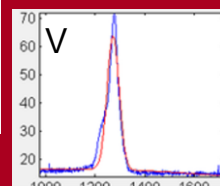
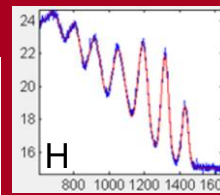
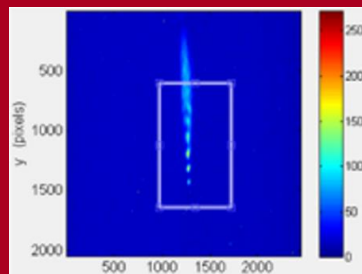
: Test-Setup (Incomplete)



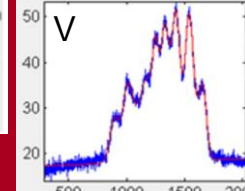
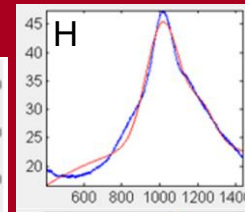
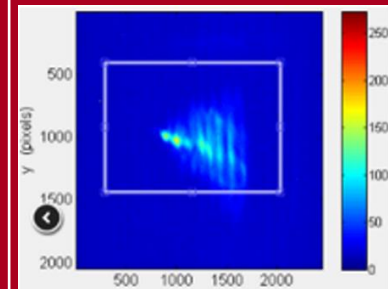
X110



X115



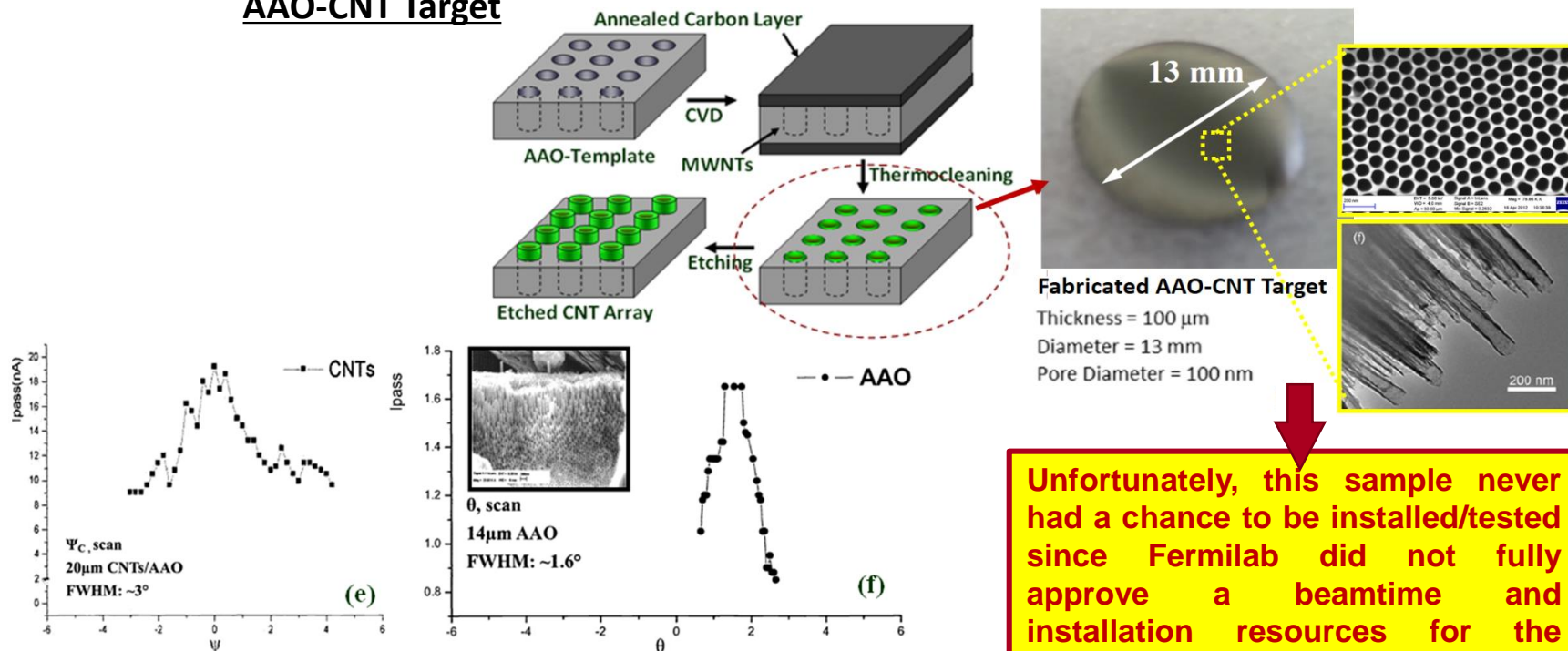
X124



Prior Efforts on POC Experiment (Case-1)

: Sample Preparation

AAO-CNT Target



Current intensity distributions as a function of incident angle of 2 MeV $^4\text{He}^+$ beam for (L) CNT and (R) AAO (inset: CNTs grown by CVD in AAO) (Courtesy of Zhiyuan Zhu [1])

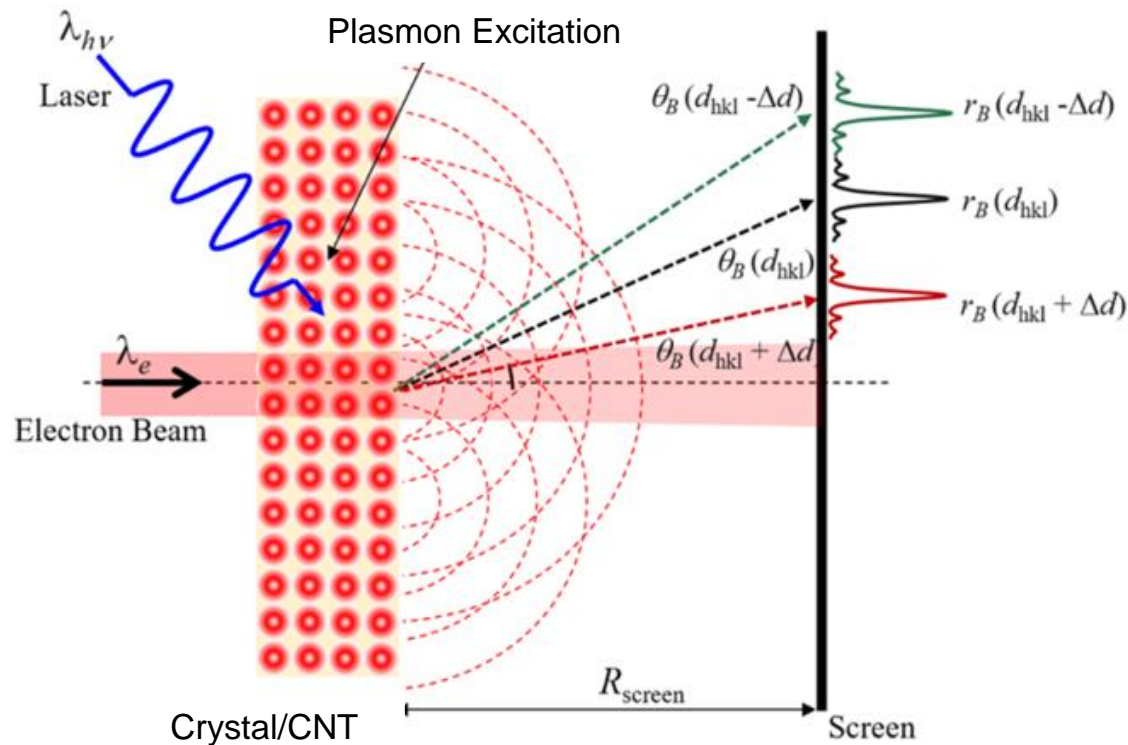
Unfortunately, this sample never had a chance to be installed/tested since Fermilab did not fully approve a beamtime and installation resources for the experiment.

Prior Efforts on POC Experiment (Case-2)

: Test Scheme

Time-Resolved Electron Diffraction

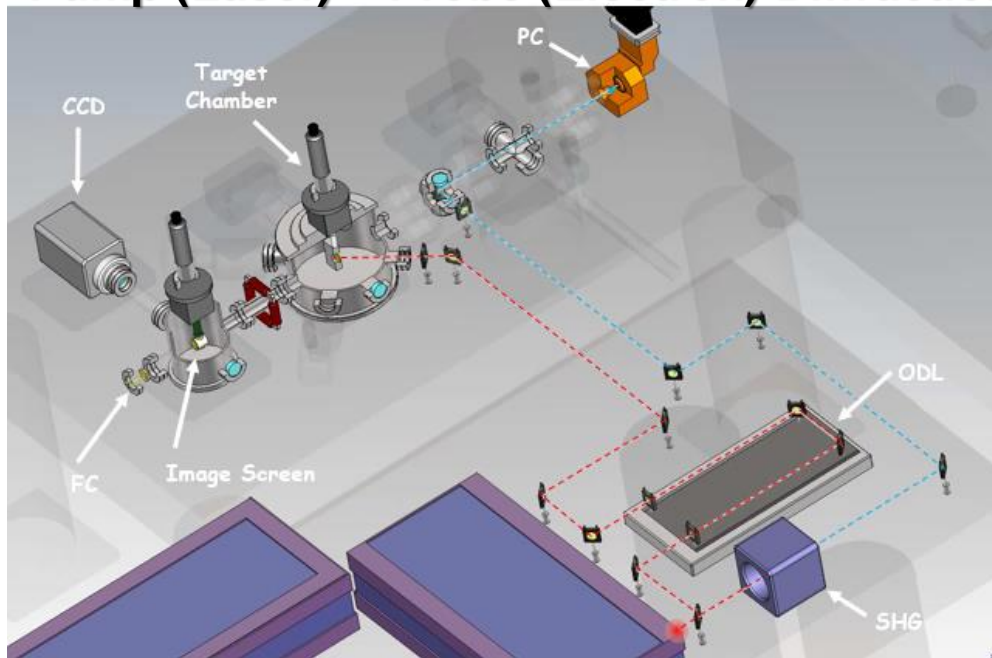
Conceptual drawing of laser-pumped crystal on the diffraction imaging process ($E_{\text{laser}} < \text{Photoionization Threshold}$)



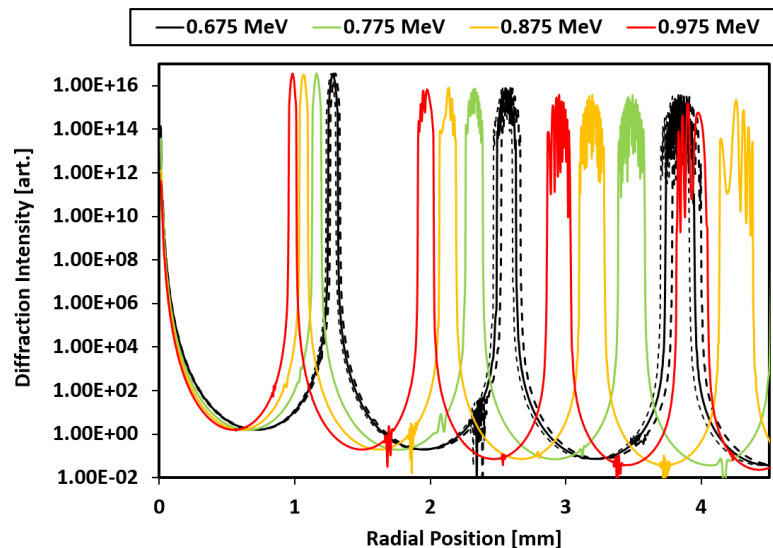
Prior Efforts on POC Experiment (Case-2)

: Test Scheme

Pump (Laser) – Probe (Electron) Diffraction Imaging



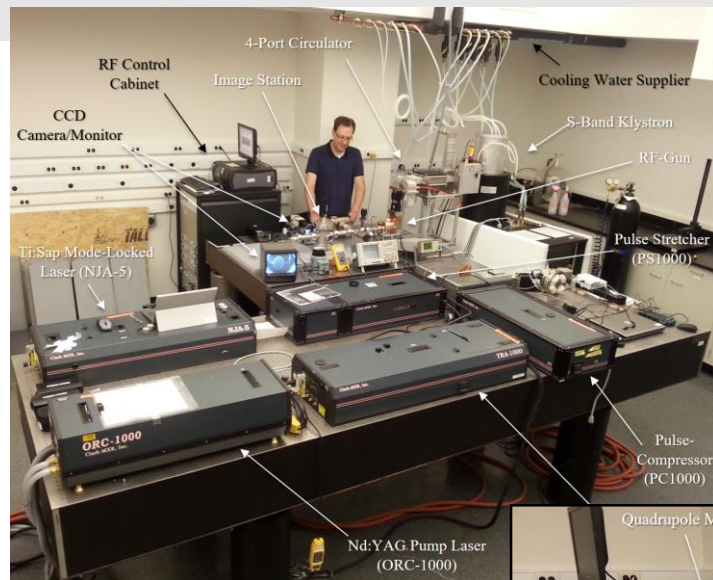
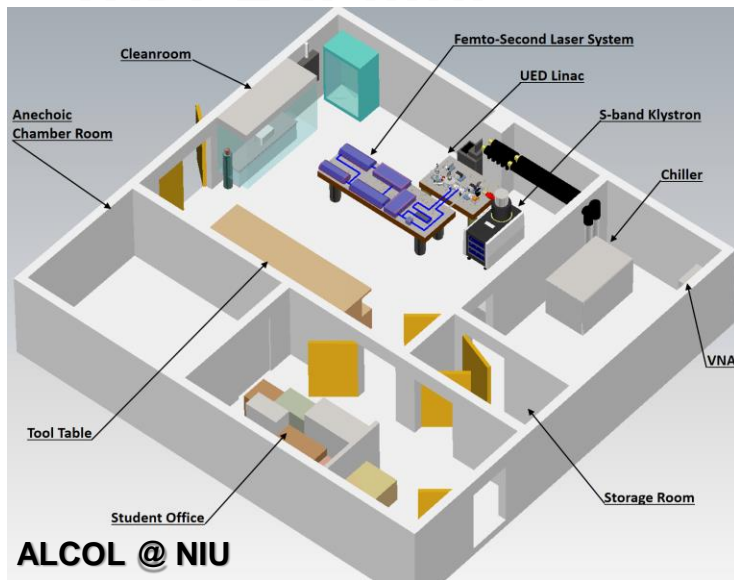
Energy-Dependent Diffraction Plots
(Analytic Solution)



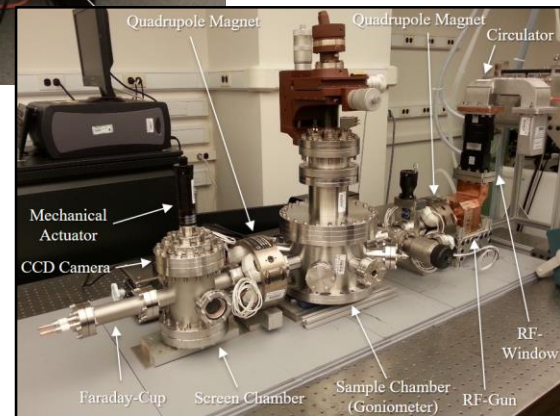
$$I_{diff} / I_0 = |A|^2 = |F|^2 \left(\frac{\sin^2(N_x \vec{K} \cdot \vec{a} / 2)}{\sin^2(\vec{K} \cdot \vec{a} / 2)} \right) \left(\frac{\sin^2(N_y \vec{K} \cdot \vec{b} / 2)}{\sin^2(\vec{K} \cdot \vec{b} / 2)} \right) \left(\frac{\sin^2(N_z \vec{K} \cdot \vec{c} / 2)}{\sin^2(\vec{K} \cdot \vec{c} / 2)} \right)$$

Prior Efforts on POC Experiment (Case-2)

: Test Facility



The RF-gun was set up and running, but the laser system was not fully installed and engaged in the experiment. NIU decided to recommission the lab for other purposes before starting the experiment.



System	Parameters	Value/Range	Unit
fs-Laser	Wavelength	775 (pump)	nm
	Wavelength	258 (probe)	nm
	Energy	≤ 0.8	mJ
	Power (Peak)	≤ 5	GW

System	Parameters	Value/Range	Unit
Electron Beam (Probe)	Energy	0.5 - 1	MeV
	Charge	0.16 – 1.6	pC
	Length (σ_L)	0.16 (@ gun exit)	mm
	Emittance	0.07	μm

Any Better Places for POC Experiment?

Parameter	FAST	CLEAR	CLARA	LCLS	FACET	ASTA	FLASH	ELI-NP
Energy [MeV]	50 - 300	60 - 220	250	3500 – 16500	20000	3.68	0.35 - 1250	80 – 720
Bunch Charge (Q) [nC]	≤ 3.2	0.01 - 05	0.25	0.125	1.6 – 3.2	60fC	-	0.025 – 0.4
Bunch Length [μm]	≤ 300	100 - 1200	-	550	30 -500	102 [fs]	-	-
Emittance [mm-mrad]	1.6 – 3.4	3 - 20	< 1	0.37 – 0.45	-	0.018	1.4	-
Peak Current [kA]	3		0.125 – 1.5	1 - 3	-	-	1 – 2.5	-
(uncorr.) Energy Spread	$\leq 1 \%$	$< 0.2 \%$	0.01 – 0.06	0.1	-	0.066	0.04 – 143	0.04 – 0.1

Takeaway and Outlook

1. Future Energy Frontier HEP Needs a Ground-Breaking Idea

CNT Accelerator: Stepping Stone Toward Crystal Acceleration (\geq TeV/m)

- Conceptually Sound and Feasible, but
- Not Experimentally Demonstrated Yet
- 1st Effort to Implement the POC-Test in Fermilab Ended Up Being Unsuccessful
- HEP Community Still Conservative, Not Ready for Paradigm Change
- OTOH, Continuously Explore Practical Ways To Overcome Technical Challenges

2. Where Do We Go from Here?

- Search for a Facility and Supports to Continuously Voyage on the POC-Test
- Vision: Detect a Clue of Acceleration (Energy-Gain) in a Solid Target (CNT)
- Coherent, Multilateral, and Multidisciplinary Collaboration?

Acknowledgement

1. This work was supported in part by the DOE contract No. DEAC02-07CH11359 to the Fermi Research Alliance LLC and Northern Illinois University (NIU).
2. Thanks to Accelerator Division (AD) and FAST/IOTA Team for the Technical Supports in the Plan to Install Test Setups
3. Many Thanks to [Toshiki Tajima](#) of the University of California – Irvine (UCI) and [Vladimir Shiltsev](#) of Fermilab for the Helpful Discussions and Supportive Collaboration.
4. Many Thanks to [Frank Zimmerman](#) of CERN for his Continuous Endorsement for the Idea and for giving me the chance to Overview the Activities in this Workshop.

References on CNT-Acceleration

- (1) Young-Min Shin, “**Carbon nanotube accelerator – Path toward TeV/m acceleration: Theory, experiment, and challenges**”, IJMPA 34 (34), 1943005 (2019)
- (2) Y. M. Shin, and M. Figora, “**Quasi-relativistic ultrashort electron beam source for electron diffractions and spectroscopies**”, RSI 88, 103302 (2017)
- (3) Young-Min Shin, “**Optically Controlled Coherent X-Ray Radiations from Photo-Excited Nanotubes**”, NIM-B 407, 276 (2017)
- (4) Young-Min Shin, “**Plasmon-Driven Acceleration in a Photo-Excited Nanotube**”, POP 24, 023115 (2017)
- (5) Xiaomei Zhang, Toshiki Tajima, Deano Farinella, Youngmin Shin, Gerard. Mourou, Jonathan Wheeler, Peter Taborek, Pisin Chen, Baifei Shen (2016). “**X-ray Wakefield Acceleration and Betatron Radiation in Nanotubes**”, PRST-AB 19(10), 101004-1 ~ 101004 (2016).
- (6) X. Zhu, D. R. Broemmelsie, Young-Min Shin, “**Theoretical and numerical analyses of a slit-masked chicane for modulated bunch generation**”, JINST 10, P10042 (2015).
- (7) Young-Min Shin, Lumpkin, A. H., Thurman-Keup, R., “**TeV/m Nano-Accelerator: Channeling Acceleration Research at Fermilab - Advanced Superconducting Test Accelerator (ASTA) Facility**”, NIM-B 355, 94 (2015).
- (8) Young-Min Shin, “**Beam-driven acceleration in ultra-dense media**”, APL 105 (11), 114106 (2014)
- (9) Young-Min Shin, Dean A. Still, and Vladimir Shiltsev, “**X-ray driven channeling acceleration in crystals and carbon nanotubes**”, POP 20 (12), 123106 (2013)

Backup Slides

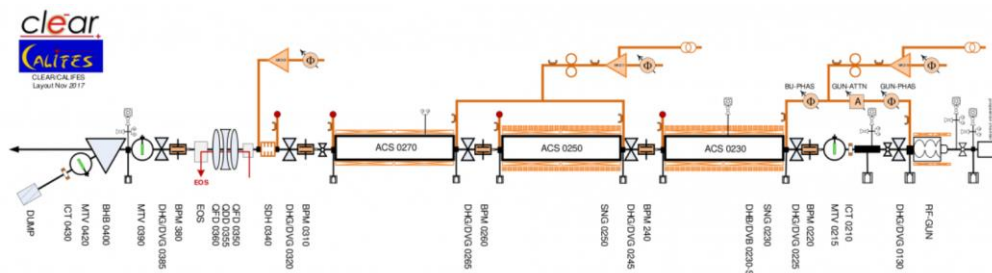
Any Better Places for POC Experiment?

The Beam Line (CLEAR @ CERN)

The CLEAR facility is hosted by the CLEX experimental area at CERN - [building 2010](#). The CLEAR Beam Line is built on the basis of [CALIFES](#), previously used at [CTF3](#) as Probe Beam injector for testing the [CLIC](#) Two Beam Acceleration concept.

On the spectrometer at the end of the CALIFES injector is placed the VESPER (see its official [web page](#)): a test stand for irradiation studies.

The layout of the linear accelerator and VESPER is as follows:



Beam Parameters

The beam parameters at the end of the linac are summarised in the following table:

Beam parameter (end of linac)	Value range
Energy	60 - 220 MeV
Bunch charge	0.01 - 0.5 nC
Normalized emittances	3 μm for 0.05 nC per bunch 20 μm for 0.4 nC per bunch (in both planes)
Bunch length	$\sim 100 \mu\text{m}$ - 1.2 mm
Relative energy spread	$< 0.2 \%$ rms ($< 1 \text{ MeV}$ FWHM)
Repetition rate	1 - 5 Hz (25 Hz with upgrade)
Number of micro-bunches in train	1 and more than 100
Micro-bunch spacing	1.5 GHz

Any Better Places for POC Experiment?

CLARA @ Daresbury

Table 1: Main Parameters for the Five CLARA Operating Modes

Parameter	Seeding	SASE	Ultra-short	Multibunch	Industrial
Max Energy (MeV)	250	250	250	250	100
Macropulse Rep Rate (Hz)	100	100	100	100	400
Bunches/macropulse	1	1	1	20	TBC
Bunch Charge (pC)	250	250	20 – 100	25	250
Peak Current (A)	125 – 400	400	1500	400	TBC
Bunch Length (fs)	250 – 850 (flat)	250 (rms)	<30	250	TBC
Norm. Emittance (mm-mrad)	<1	<1	<1	<1	<1
RMS Energy Spread (keV)	25	100	150	100	TBC
Radiator Period (mm)	27	27	27	27	-

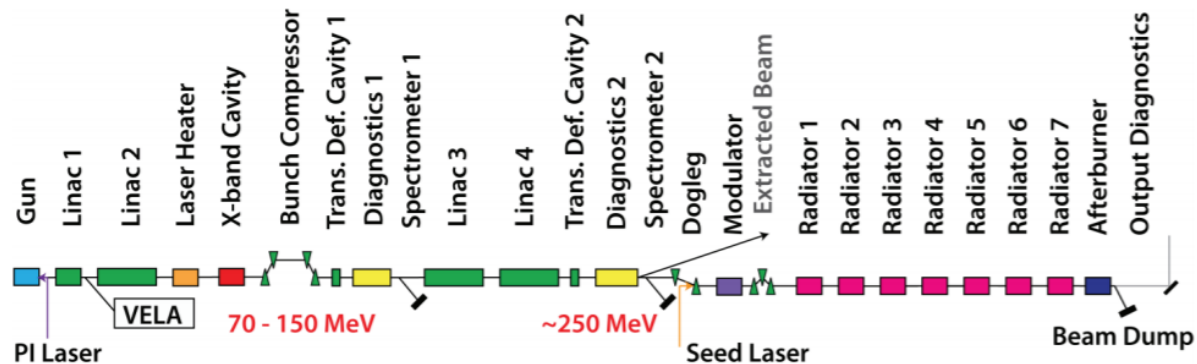


Figure 1: CLARA layout overview.

Any Better Places for POC Experiment?

LCLS @ SLAC

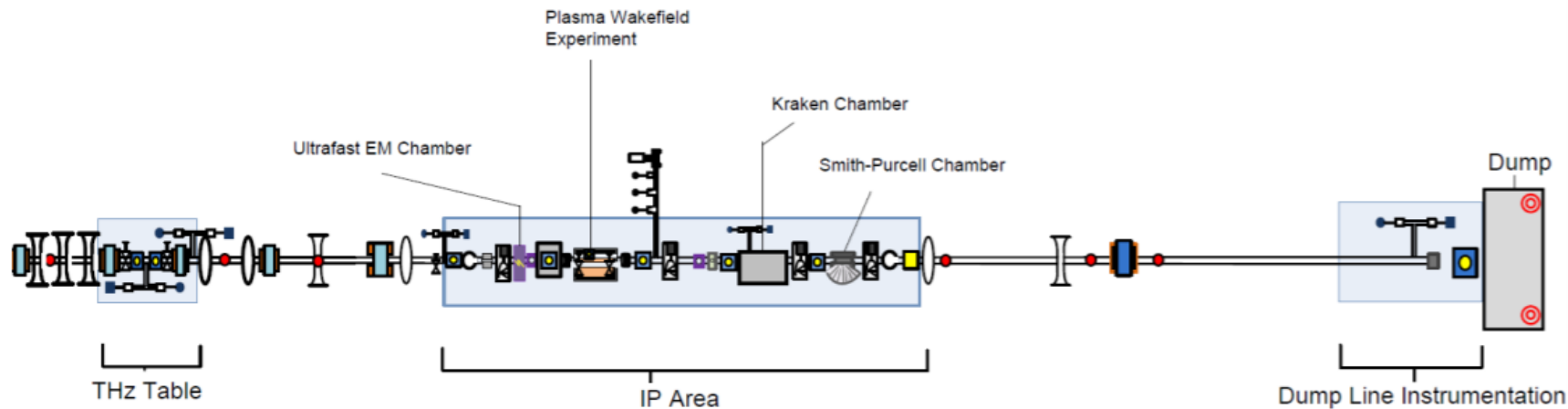


Photon Beam Parameters	Symbol	Cu - HXU x-rays	Cu - SXU x-rays	Unit
Fundamental wavelength	λ_e	0.5 – 12.4	2.5 – 62.0	Å
Photon Energy Range	$\hbar\omega$	25000 – 1000	5000 – 200	eV
Final linac e- energy	γmc^2	16.5 – 3.3	10.0 – 3.5	GeV
FEL 3-D gain length	L_G	4.0 – 1.0	2.5 – 1.0	m
Peak power	P	20 – 50	40	GW
Pulse duration range (FWHM)		10 – 50	10 – 250	fs
Nominal pulse duration (FWHM)	Δt_f	30	50	fs
Pulse Energy*	U	0.6 – 1.5	2.0	mJ
Photons per pulse*	N_γ	0.15 – 9	2.5 – 62	10^{12}
Peak brightness*	$B_{ph, SASE}$	7800 – 266	1800 – 25	10^{30}
Average brightness (120Hz)*	$\langle B \rangle$	280 – 10	110 – 2	10^{20}
SASE bandwidth (FWHM)	$\Delta\omega/\omega$	30 – 2	10 – 2	eV
Photon source size (rms)	σ_s	8 – 20	16 – 46	μm
Photon far field divergence (FWHM)	$\Theta_{FWHM, x}$	1 – 12	3 – 25	μrad
Max. Beam Rate	Φ_{FEL}	120	120	Hz
Avg. x-ray beam power	P_x	0.08 – 0.18	0.24	W
Linear Polarization (100%)	$\langle P \rangle$	Vertical	Horizontal	
Electron Beam Parameters				
Nominal Bunch Charge	Q	125	125	pC
Total Energy Spread	$\sigma E/E$	10^{-3}	10^{-3}	1
Inject. bunch length (rms)	σ_{z0}	550	550	μm
Undul. bunch length (rms)	σ_z	16 – 3	16 – 5	μm
Final peak current	I_{pk}	1.0 – 5.0	1.0 – 3.0	kA
Proj. Emittance (injector)	$\gamma \epsilon_{x,0}$	0.45	0.45	μm
Slice Emittance (injector)	$\gamma \epsilon'_{x,0}$	0.37	0.37	μm
Proj. Emittance (Undulator)	$\gamma \epsilon'_{x,u}$	0.5-1.6	0.5-1.6	μm
Max. Single Bunch Rep. Rate	F	120	120	Hz
UV laser energy on cath.	u_l	15	15	μJ
UV laser beam diam. on cath.	$2R$	1.2	1.2	mm
e- energy stability (rms)	$\Delta E/E$	0.02	0.07	%
e- x,y stability (rms)	x/σ_x	15,10	25,20	%
e- timing stability (rms)	Δt	50-100	50-100	fs
Peak current stability (rms)	$\Delta I/I$	10	6	%
Charge Stability (rms)	$\Delta Q/Q$	2.5	2.5	%
FEL pulse energy stability	$\Delta N/N$	<10	<10	%

Any Better Places for POC Experiment?

FACET @ SLAC

Parameter	Uncompressed	Compressed	Two-bunch ¹
Particle ²	Electrons	Electrons	Electrons
Energy	20 GeV	20 GeV	20 GeV
Charge/pulse ³	1.6 nC	1.6-3.2 nC	
IP Spot Size ⁴	30 μm x 30 μm	30 μm x 30 μm	
Bunch Length ⁵	500 μm	30 μm	
Rep. Rate	1-30 Hz	1-30 Hz	1 Hz



Any Better Places for POC Experiment?

ASTA @ SLAC

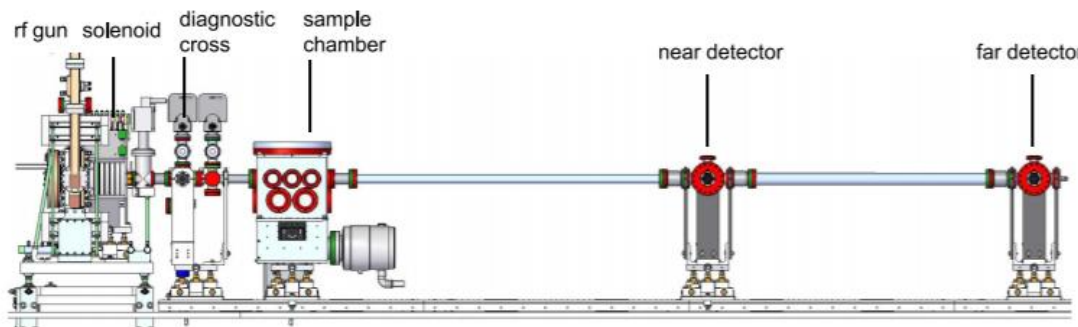


FIG. 1. Schematic of the MeV UED beam line at SLAC's ASTA facility.

TABLE I. Typical machine and beam parameters of the MeV UED system.

Parameters	Values
Repetition rate	120 Hz
Gun gradient	79.5 MV/m
Launching phase	10°
Solenoid strength	0.314 kG-m
UV spot size, rms	$40\ \mu\text{m}$
UV pulse duration, FWHM	60 fs
UV energy stability, rms	2.5%
Initial beam charge	75 fC
Intrinsic emittance	0.5 mrad
Collimator diameter ($z = 55.8\ \text{cm}$)	$500\ \mu\text{m}$
At the sample ($z = 1.16\ \text{m}$)	
Beam charge	60 fC
Beam size (diameter)	$400\ \mu\text{m}$
Normalized emittance	18 nm-rad
Bunch length, rms	102 fs
Kinetic beam energy	3.68 MeV
Relative energy spread, rms	6.6×10^{-4}
IR pump spot size (diameter)	1.5 mm
IR pump pulse duration, FWHM	60 fs

Any Better Places for POC Experiment?

FLASH @ DESY

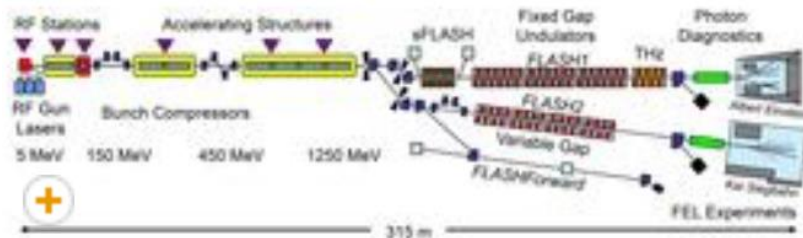


Figure 1: Schematic layout of FLASH (not to scale). Beam direction is from left to right, the total length is 315 m.

Electron beam

Energy	MeV	0.35 - 1250	0.4 - 1250
Peak current	kA	1 - 2.5	1 - 2.5
Emittance, norm. (x,y)	$\mu\text{m rad}$	1.4	1.4
Nb. of bunches per second		10 - 5000	10 - 5000
bunch train duration	ms	<0.8	<0.8
Rep. rate	Hz	10	10
Energy spread	keV	200	500

Any Better Places for POC Experiment?

ELI-NP @ Romania

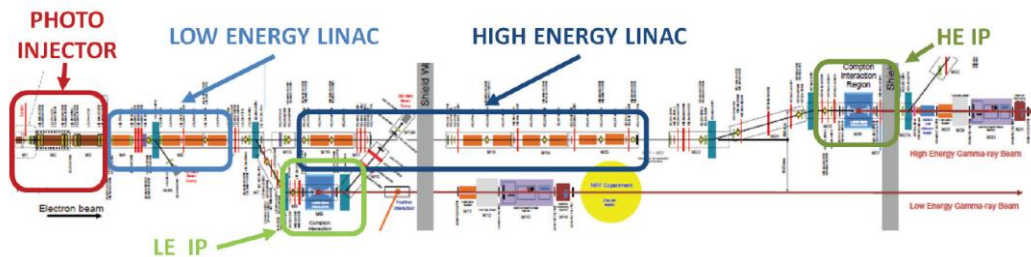
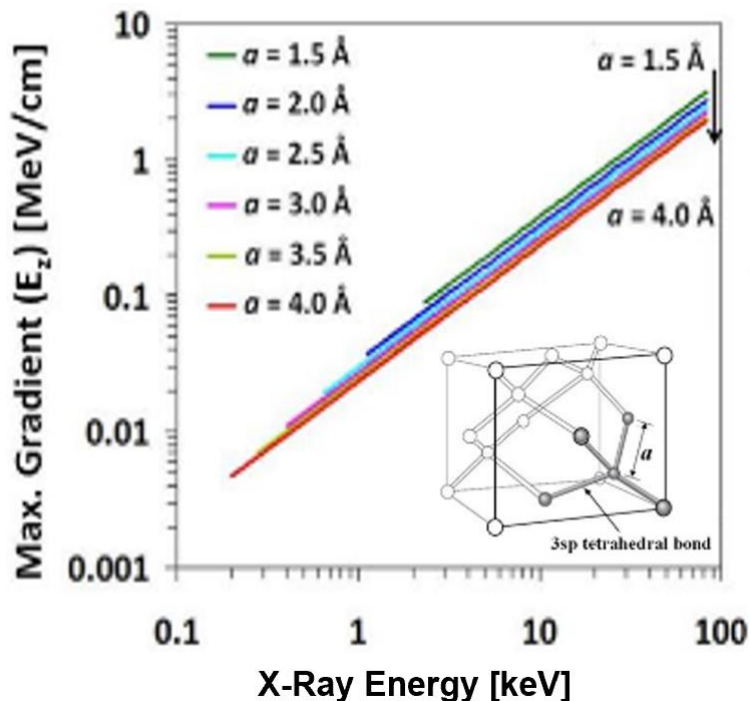


Figure 1: ELI-NP Gamma Beam System (GBS) layout: a SPARC-like S-band high brightness injector [2] followed by two C-band RF linacs (low and high energy) that through the relative transfer lines provide the electron beam to the Low and High Energy Interaction Points (LE IP and HE IP) respectively [1].

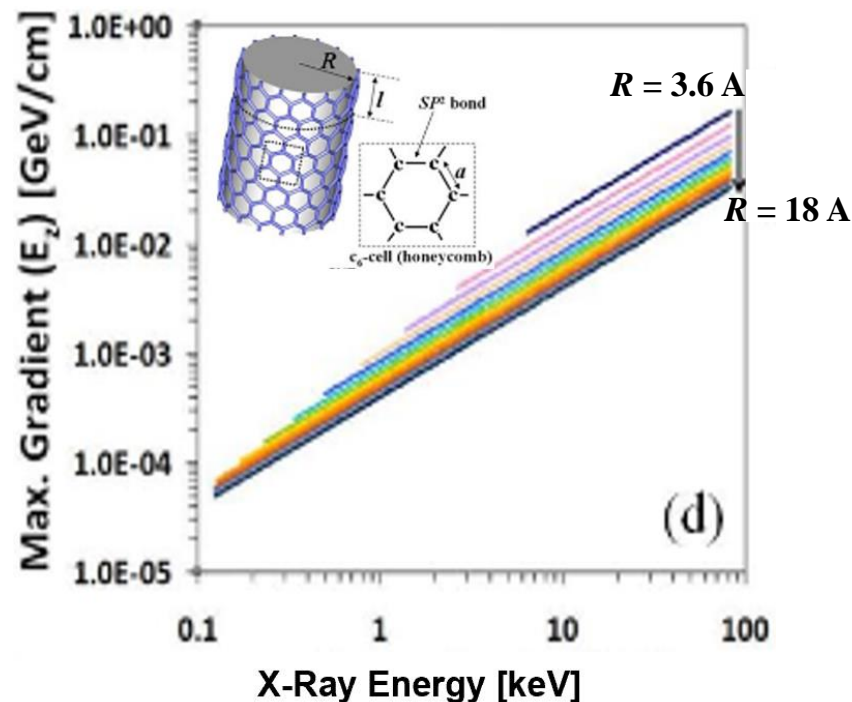
Parameter	Value	Unit
Beam Energy	80-720	MeV
Bunch charge	25-400	pC
Bunch separation	16.1	ns
Bunches per pulse	≤ 32	units
Bunch energy spread	0.04-0.1	%
Focal spot size	> 10	μm
Pulse repetition rate	100	Hz

CNT-Acceleration (e.g. X-Ray Diffraction)

Crystal (Silicon)

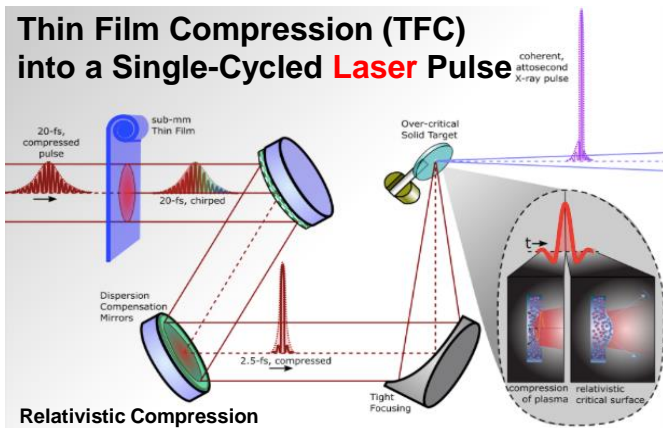


CNT



CNT-Acceleration (e.g. X-Ray Diffraction)

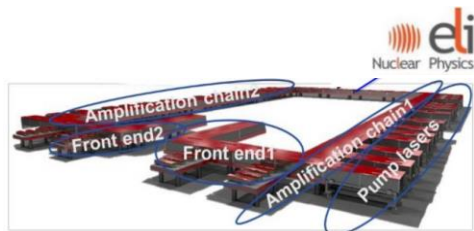
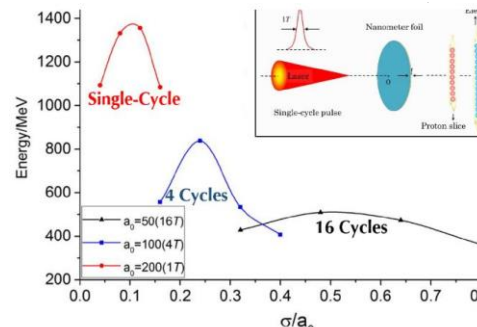
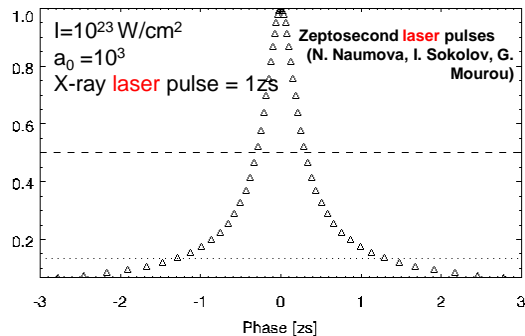
Thin Film Compression (TFC) into a Single-Cycled Laser Pulse



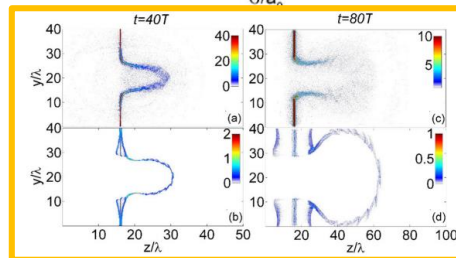
Relativistic Compression

Naumova, et al.
(2004)

→ Proton energies with varying σ/a_0 (the normalized thickness σ divided by the normalized vector potential a_0)



ELI-NP (Laser-Driven Acceleration)



Prior Efforts on POC Experiment (Case-2)

: Test Scheme

Time-Resolved Electron Diffraction

Temporal energy profile of prospective diffraction patterns of photo-excited crystal phases (t_1 : condensed matter, t_2 : hollow atom solid, t_3 : warm dense matter, t_4 : plasma)

