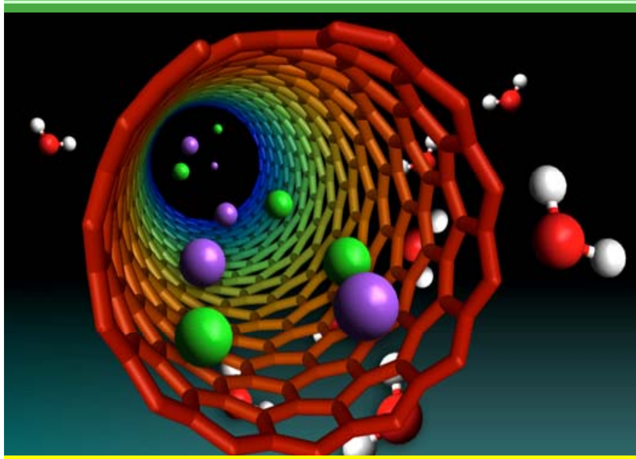
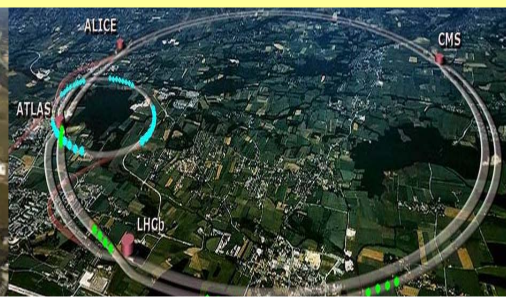
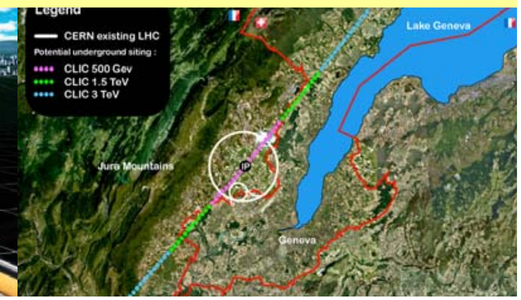
6th International Conference - Channeling 2014



TeV/m Nano-Accelerator

Current Status of CNT-Channeling Acceleration Experiment





Y. M. Shin[1,2], A. Green[1], R. Kreml[2], A. H. Lumpkin[2], J. C. Thangaraj[2], R. M. Thurman-Keup[2], and V. Shiltsev[2]

Thanks to X. Zhu, D. Broemmelsiek, D. Crawford, D. Mihalcea, D. Still, K. Carlson, J. Santucci, J. Ruan, E. Harms, P. R. G. Piot

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Department of Physics, Northern Illinois University

[2]Fermi National Accelerator Laboratory (FNAL)

Northern Illinois University

Fermilab

11:30 am – 12:00 pm, S.4.2: Charged Beam Shaping, Wednesday, October 08, 2014

Content

- HEP Colliders and HG Accelerators for Energy Frontier
- Wakefield Acceleration in a Ultra-Dense Plasma
- Channeling Acceleration → HG Acceleration and Continuous Focusing
- CNTs for Channeling Acceleration
- Proof of Principle Experiment @ Fermilab - ASTA
  - Test Beamline Configuration with Diagnostic Apparatuses
  - Micro-Bucher: Pre-Modulated Beam with Micro-Bunches
  - Beam-Driven Wakefield Excitation → Self-Acceleration
  - Full Scale Assessment with Beam Parameters
  - Prospective Schedule for POP Experiment
- Conclusion and Future Plan
- Multi-Institutional Collaboration: Positron Crystal Channeling Acceleration Expt.

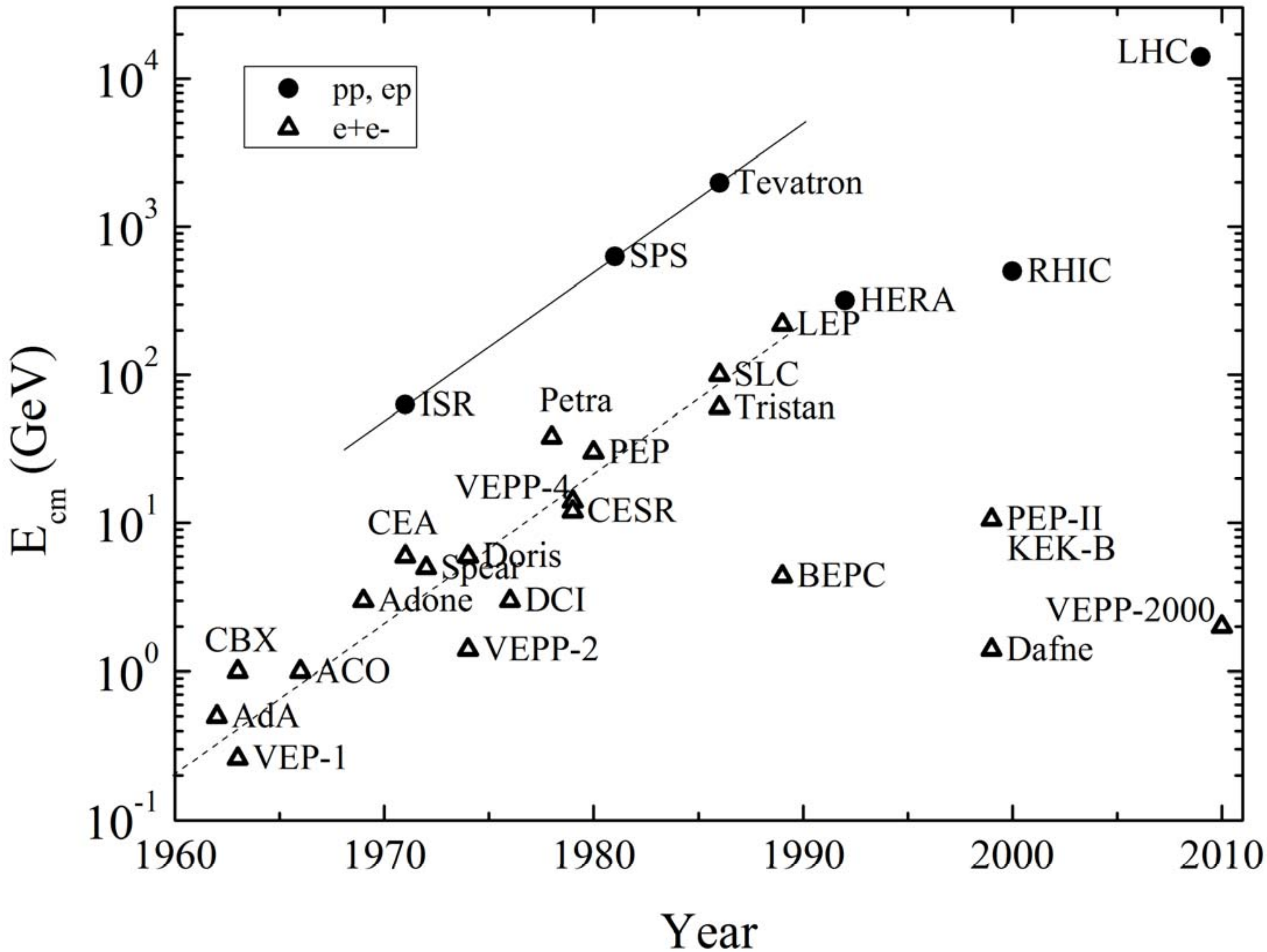
Advance of Accelerator Technology in a Century

1^{st} cyclotron, ~1930
Ernest O. Lawrence
11-cm diameter
1.1 MeV protons

Large Hadron Collider (LHC), 2008,
9-km diameter
7 TeV protons

after ~80 years
~10^7 x more energy
~10^5 x larger

Particle Colliders Over The Decades



V. Shiltsev, Physics-Uspekhi, 2012

Foreseeing Prospective Budget and Accelerator R&D of HEP Colliders

Category	Cost, billions of dollars	Facility
I	$\leqslant 0.3$	NICA, ENC
II	$0.3-1$	Super-B factories, $c-\tau$ factory, eRHIC, ELIC
III	$1-3$	Higg factory, HL-LHC
IV	$3-10$	HE-LHC, LHeC, MC, Higgs factory–ILC
V	$10-30$	ILC, CLIC

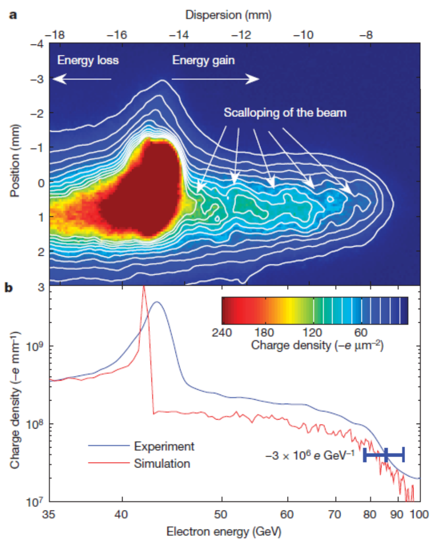
V. D. Shiltsev, Physics - Uspekhi 55 (10) 965 - 976 (2012)

“ There are profound questions to answer in particle physics, and recent discoveries reconfirm the value of continued investments. Going much further, however, requires changing the capability-cost curve of accelerators, which can only happen with an aggressive, sustained, and imaginative R&D program. A primary goal, therefore, is the ability the future-generation accelerators at dramatically low cost.”

- P5 Report (Scenario-C)

→ ***Novel High Gradient Accelerator Technology***

Gas-State Plasma

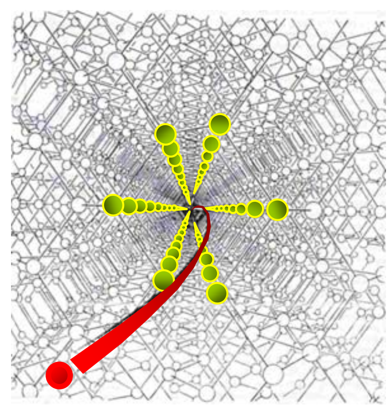


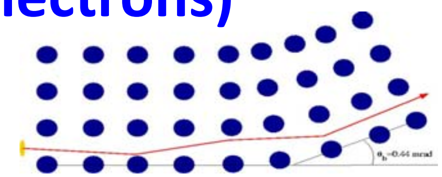
$10^{16} - 10^{18}cm^{-3} \rightarrow 10 \sim 100$ GeV/m

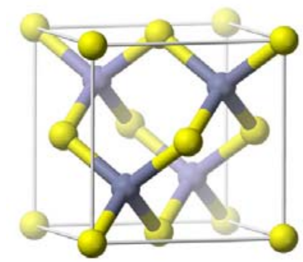
Nature 445, 741-744 (2007)

Energy Doubling: ~ 52 GV/m (@ 42 GeV)

Solid-State Plasma (Conduction Electrons)







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

$10^{20} - 10^{23}$ cm$^{-3} \rightarrow 1 \sim 30$ TeV/m

[1] P. Chen and R. J. Noble, AIP Conf. Proc. **156**, 222 1987; also SLACPUB-4042 1986.
[2] R. A. Carrigan and J. Ellison Plenum, New York, 1987, p. 517; also NATO ASI Ser., Ser. B **165**, 517 1987; SLAC-PUB-4187 1987.
[3] P. Chen, Z. Huang, and R. D. Ruth, AIP Conf. Proc. **356**, 331 1996; also SLAC-PUB-95-6814 1995.
[4] P. Chen and R. J. Noble, AIP Conf. Proc. **396**, 95 1997; also FERMILAB-CONF-97-097 1997; SLAC-PUB-7673 1997.
[5] P. Chen and R. J. Noble, AIP Conf. Proc. **398**, 273 1997; also SLACPUB-7402 1997; FERMILAB-CONF-96-441 1997.
[6] D. S. Gemmell, Rev. Mod. Phys. **46**, 129 1974.
[7] T. Tajima and M. Cavenago, Phys. Rev. Lett. **59**, 1440 1987.

Crystal Accelerators

$$\Delta E_{\max} = \left(\frac{M_b}{M_p}\right)^2 (\Lambda G)^{1/2} \left(\sqrt{\frac{G}{z^3 \times 100[GV/cm]}}\right) \cdot 10^5 [TeV]^*$$

(M_b *and* M_p are the mass of the beam particle and mass of the proton respectively, Λ is the de-channeling length per unit of energy, *G* is the accelerating gradient, and *z* is the charge of the beam particle)

- 0.3 TeV for electrons/positrons,

- 10^4 TeV for muons,

- 10^6 TeV for protons

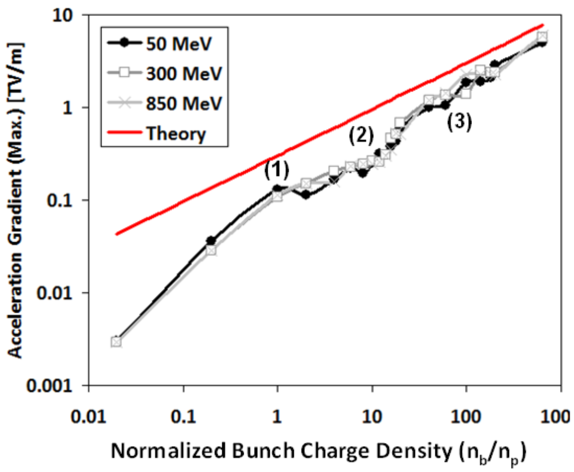
*P. Chen and R.J. Noble, in: Relativistic Channeling, eds. R.A. Carrigan, Jr and J.A. Ellison (Plenum, New York, 1987) p. 517.

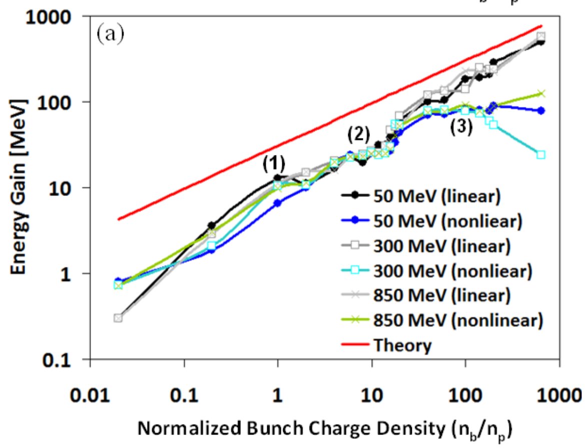
	Dielectric based	Plasma based	Crystal channeling
Accelerating media	micro-structures	ionized plasma	solid crystals
Energy source: option 1 option 2	optical laser e^- bunch	e^- bunch optical laser	x-ray laser particle beam
Preferred particles	any stable	e^-, μ	μ^+, p^+ (e+, e-)
Max acc gradient	1-3 GV/m	30-100 GV/m	0.1-10 TV/m
c.m. energy in 10 km	3-10 TeV	3-50 TeV	10^3-10^5 TeV
# stages/10 km: option 1 option 2	10^5 - 10^6 10^4 – 10^5	~100 10^3 - 10^4	~ 1

- V. Shiltsev, Physics-Uspekhi (2012)
- F. Zimmermann, "The future of highest energy accelerators", CERN, Geneva, Switzerland

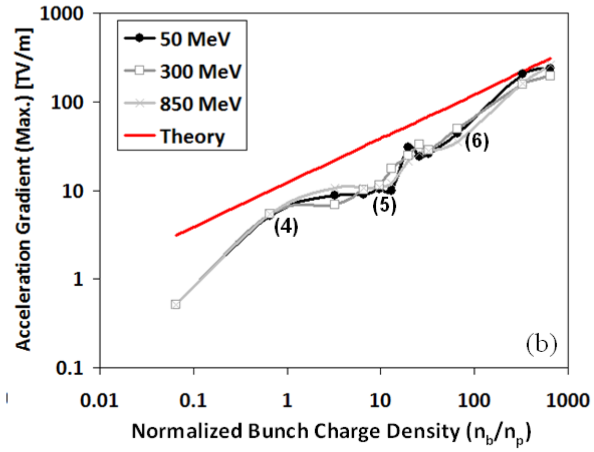
Beam-Driven Acceleration in Dense Plasma (Solid-State Level)

$n_p = 10^{25}\ m^{-3}$

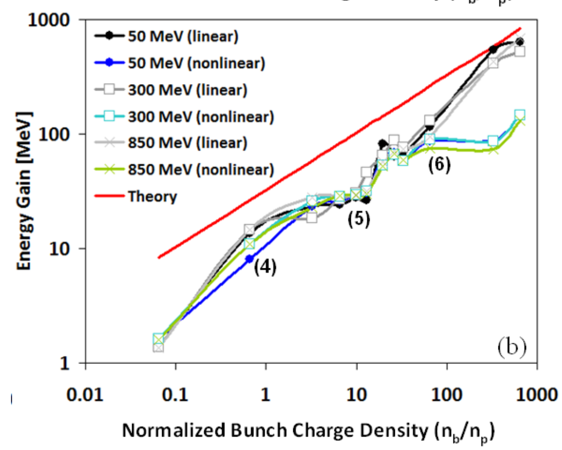


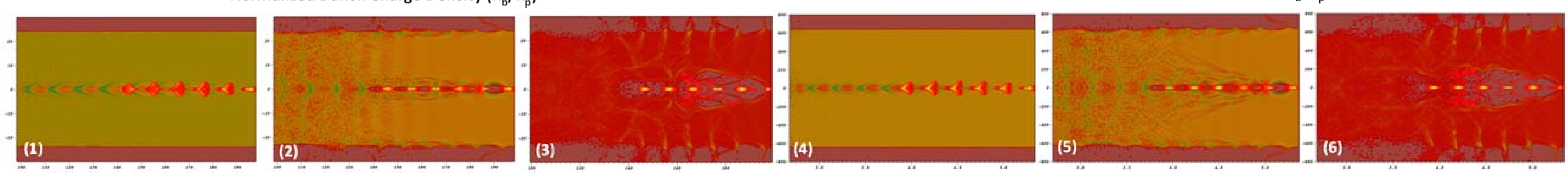


$n_p = 10^{28}\ m^{-3}$



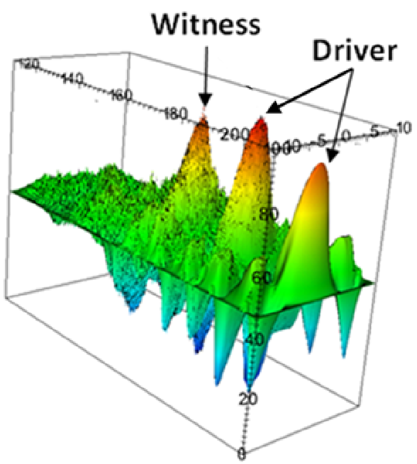
Length of Plasma = 10 λ_p

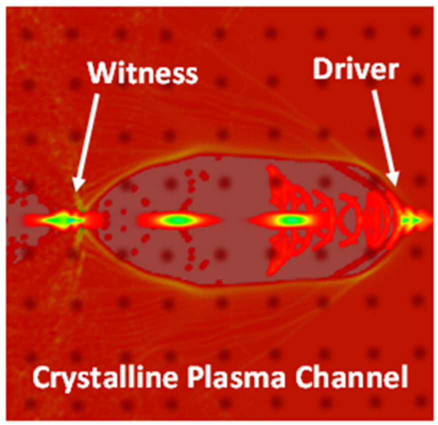




Crystal Channeling Acceleration: Wakefield and Diffraction

Wakefield Acceleration



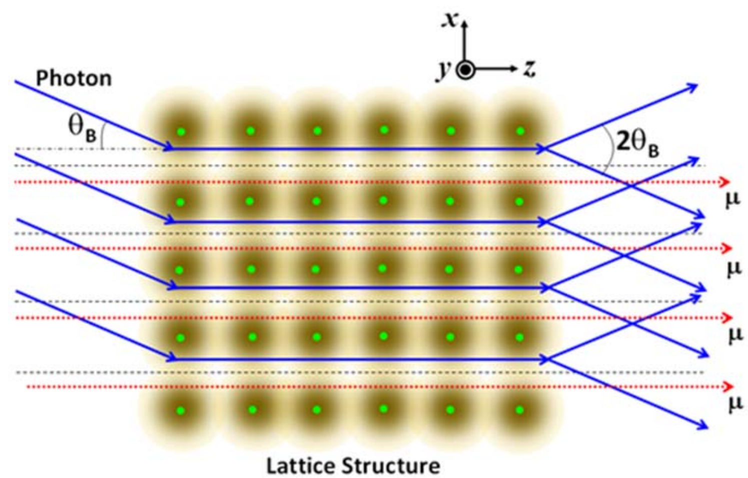


→ P. Chen and R. J. Noble, AIP Conf. Proc. 156, 222 1987

Driving Source: Beam, Laser

Particle Species: e+, e-, μ+, μ-, p+

Diffraction Acceleration

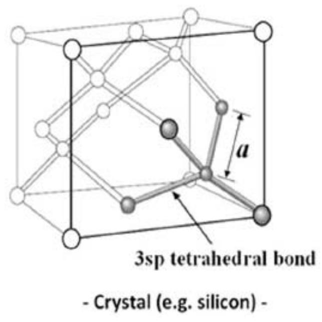


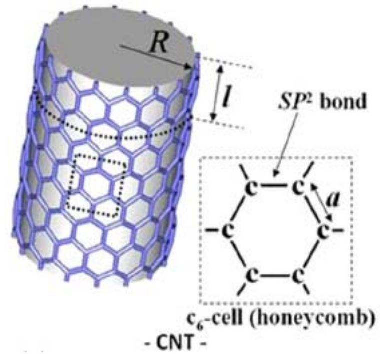
→ T. Tajima and M. Cavenago, Phys. Rev. Lett. 59, 1440 1987

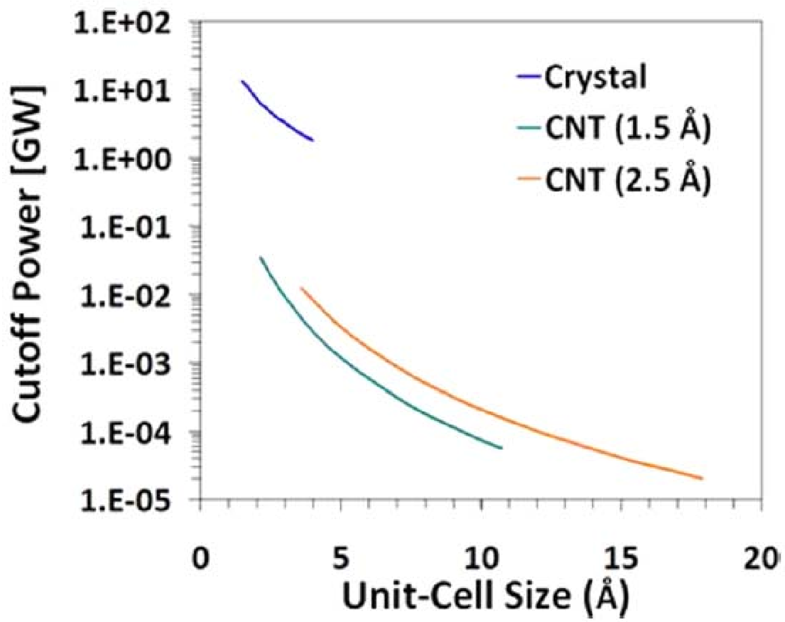
Driving Source: X-Ray Laser

Particle Species: μ+, μ-, p+

Channeling Acceleration in Carbon Nanotubes (CNTs)







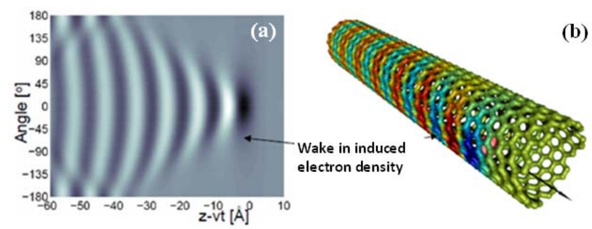
Y. M. Shin, D. A. Still, V. Shiltsev, Phys. Plasmas 20, 123106 (2013)

- **CNT vs Crystal**

(1) Readily controllable channel size (up to micron). The larger channel can
→ decrease de-channeling rates
→ increase acceptance
→ mitigate power requirement of driving sources

(2) Thermally and mechanically stronger than crystals, steels, and even diamonds (*sp_2* bond > *sp_3* bond)
→ Higher durability in extremely intense channeling radiation/ acceleration

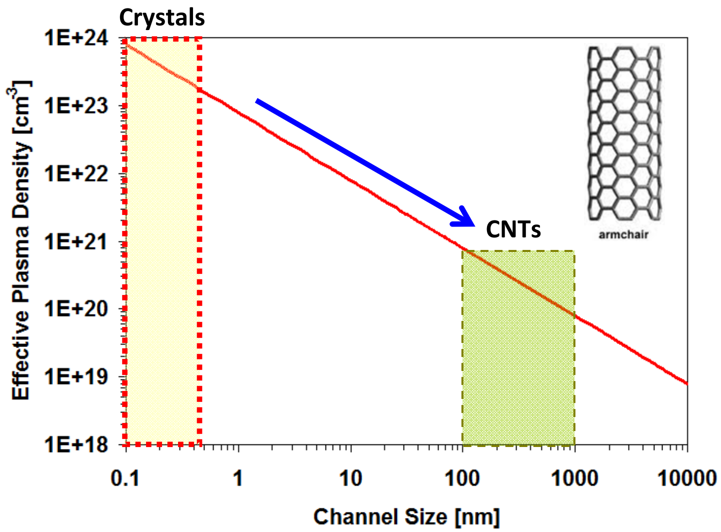
(3) Single-mode interaction (Stable Acceleration)



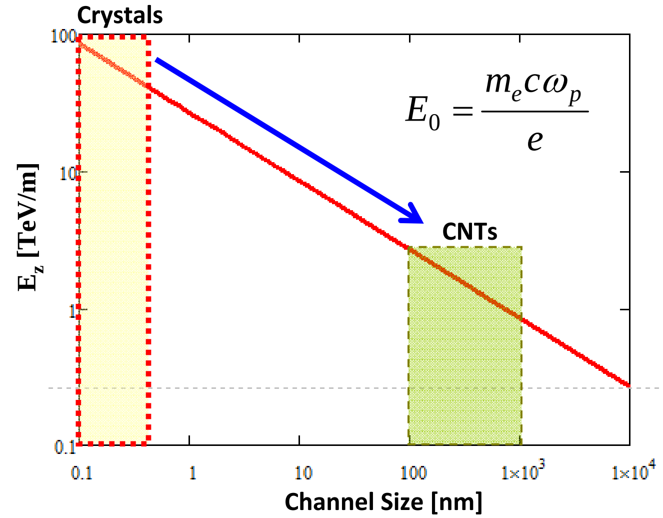
→ Zoran Miskovic, "Prospects of on channeling through carbon nanotubes", REM talk

Effective Plasma Parameters of CNT-Channel

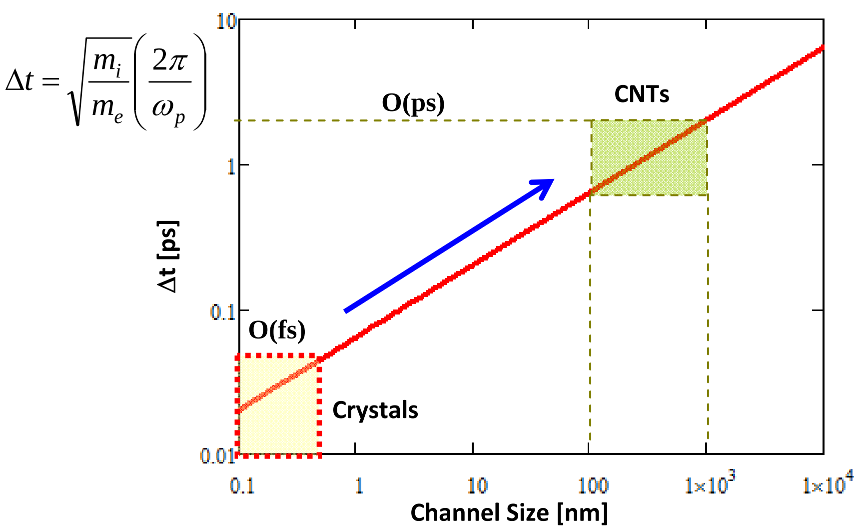
- Effective Plasma Density



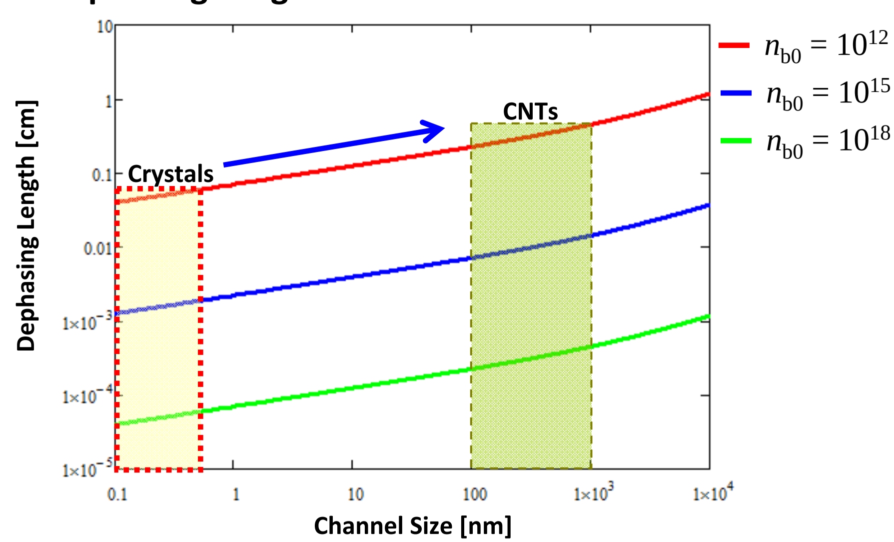
- Acceleration Gradient



- Time Scale for Lattice Disassociation*



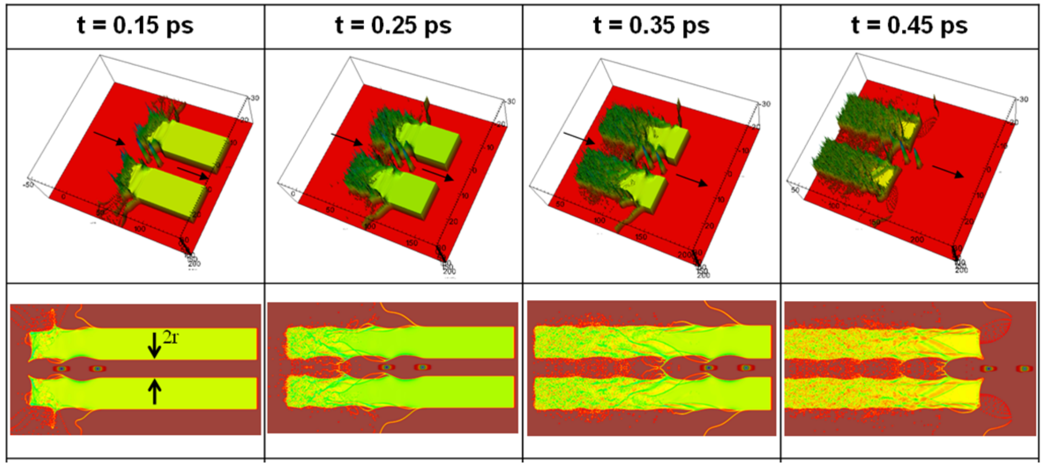
- Dephasing Length**

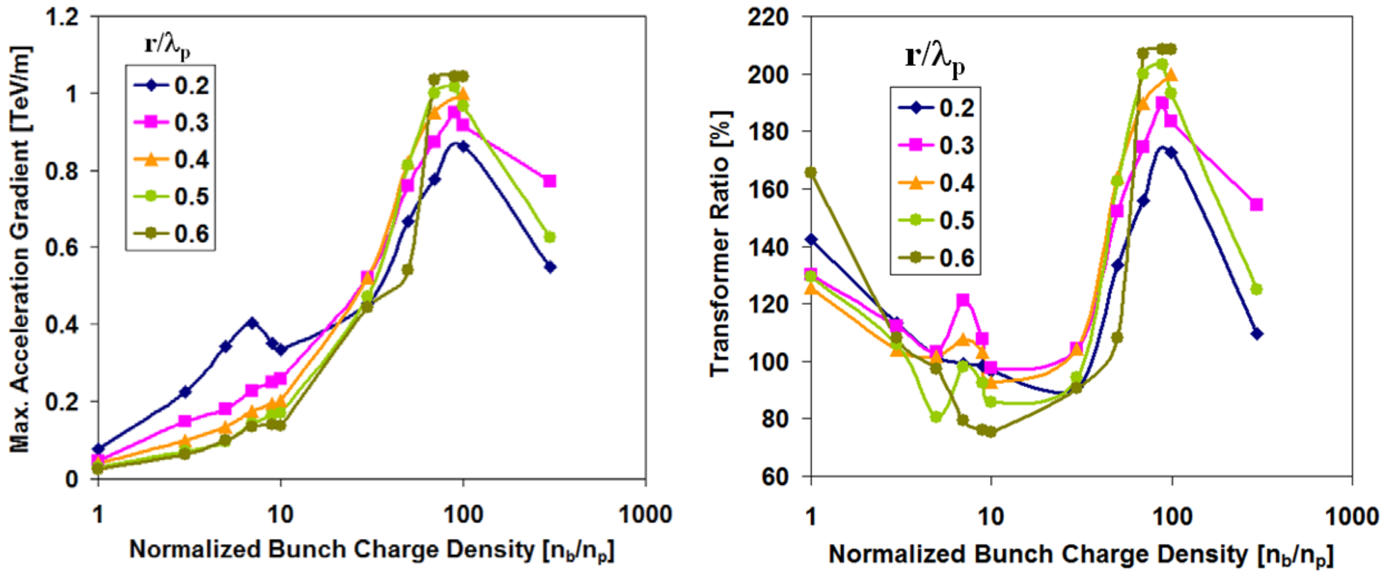


*P. Chen, R. J. Noble, "Crystal Channel Collider: Ultra-High Energy and Luminosity in the Next Century", SLAC-PUB-7402 (1996)

**C. B. Schroeder, C. Benedetti, E. Esarey, F. J. Gr¨uner, and W. P. Leemans, "Growth and phase velocity of self-modulated beam-driven plasma waves", arXiv:1108.1564 (2011)

Beam-Driven Acceleration in a Hollow Nano-Channel (CNT)

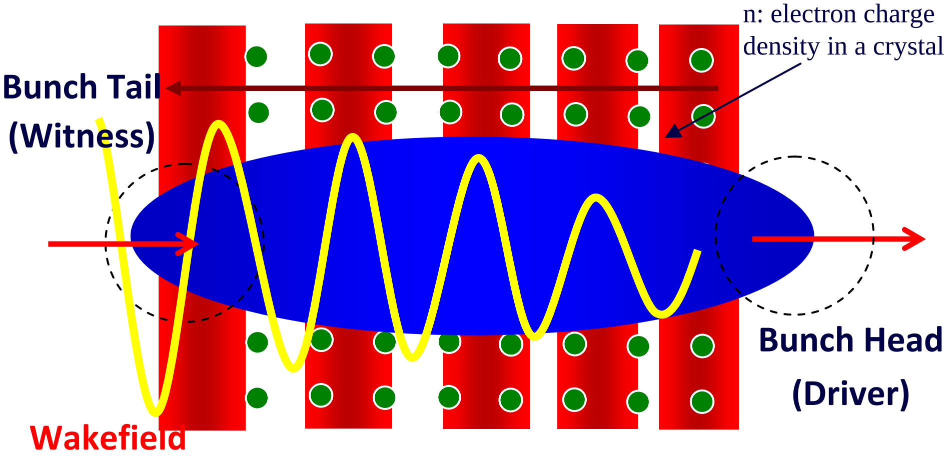




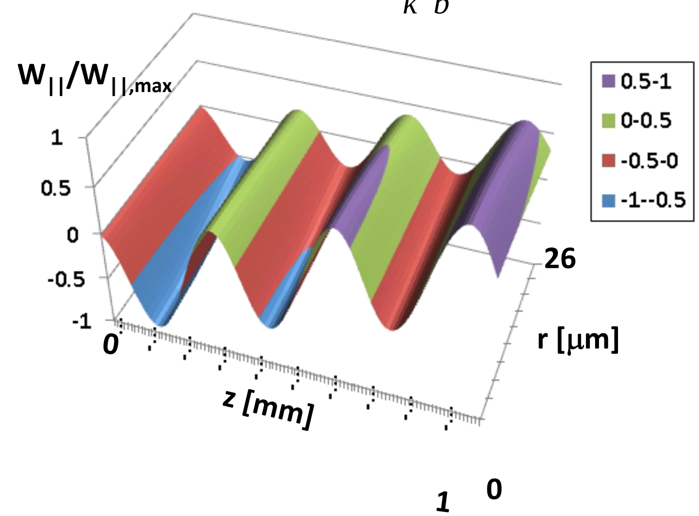
(a) maximum acceleration gradient and (b) transformer ratio versus bunch charge distribution normalized by bunch charge density with various tunnel radii ($r = 0.2 - 0.6\lambda_p$)

Y. M. Shin, "Beam-driven acceleration in ultra-dense plasma media", Appl. Phys. Lett. 105, 114106 (2014)

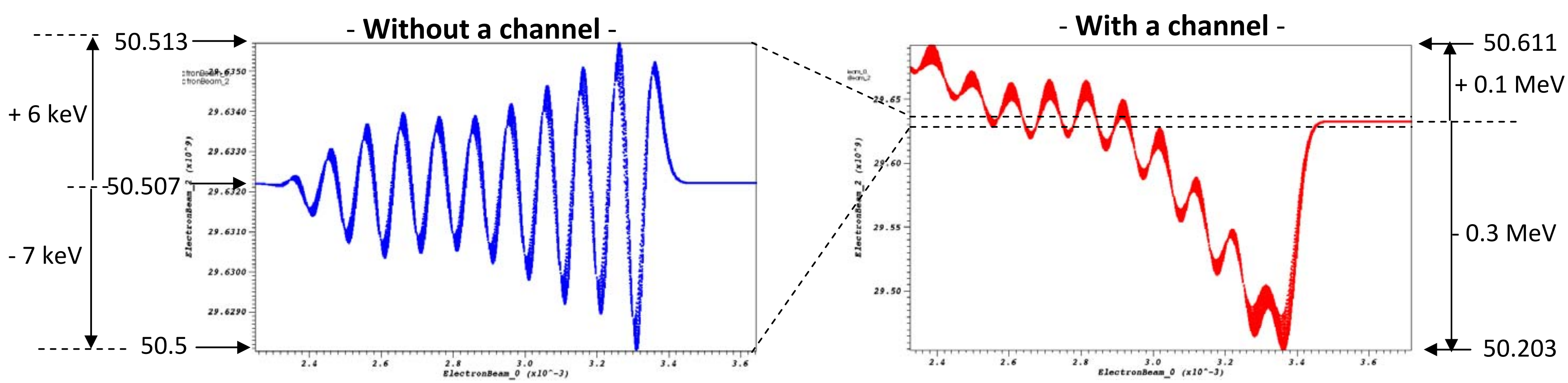
*Proof-Of-Concept Experiment: Self-Acceleration**



$$eW_{\|} = \frac{16\pi e^2 \rho_b}{k^2 b} F_{\|}(r) G_{\|}(\zeta)$$



- 50 MeV (1 nC)



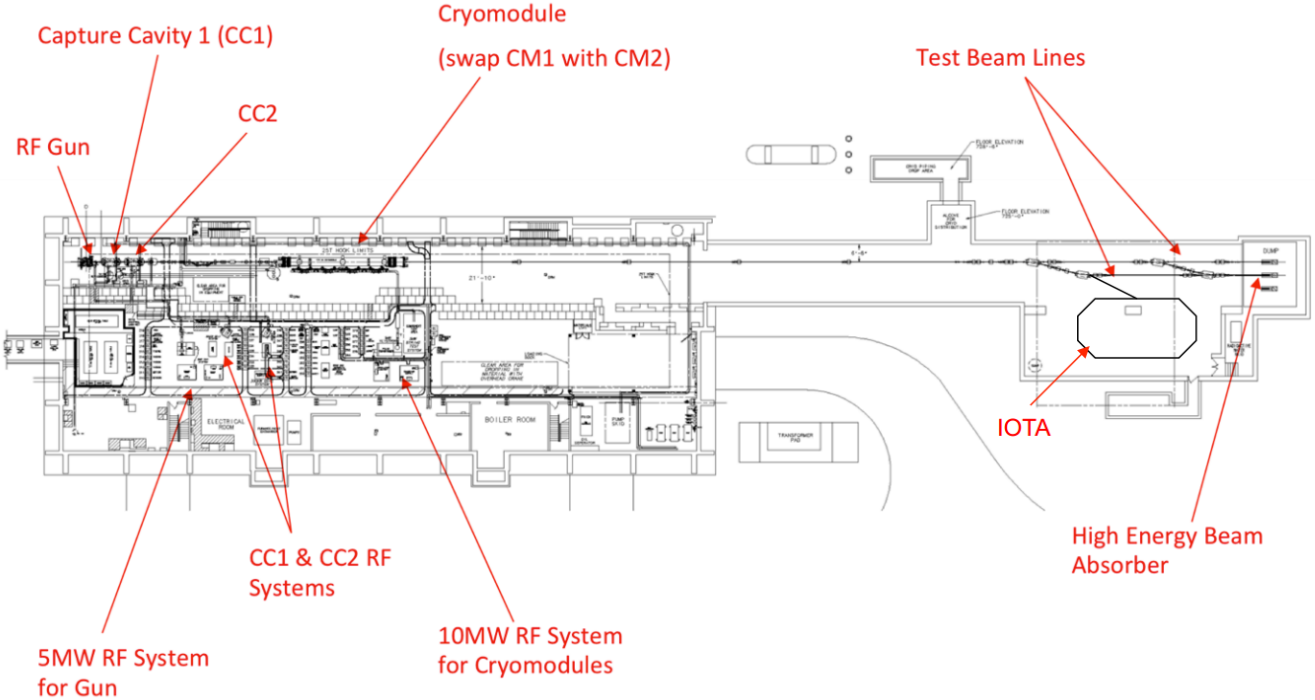
*[1] P. Chen. D. B. Cline, and W. E. Gabella, SLAC-PUB-6020

[2] G. Xia, C. Welsch, et. al., "A plasma wakefield acceleration experiment using CLARA beam", Nuclear Instruments and Methods in Physics Research A 740 (2014)

Test Facility: ASTA @ Fermilab

Advanced Superconducting Test Accelerator (ASTA) Facility @ Fermilab

- Construction of ASTA began in 2006 as part of ILC/SRF R&D and later American Recovery and Reinvestment Act (ARRA)



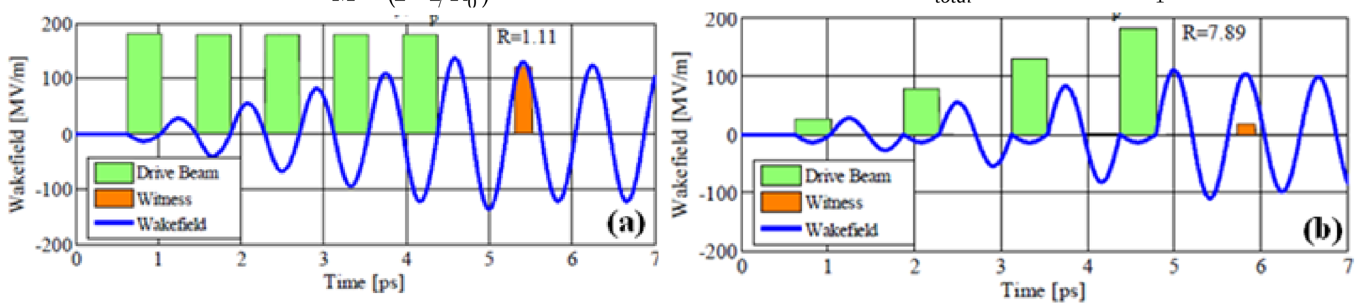
parameter	ILC RF unit test	range
bunch charge	3.2 nC	10's of pC to >20 nC
bunch spacing	333 nsec	<10 nsec to 10 sec
bunch train length	1 msec	1 bunch to 1 msec
bunch train repetition rate	5 Hz	0.1 Hz to 5 Hz
norm. transverse emittance	~25 mm-mrad	<1 mm-mrad to >100 mm-mrad
RMS bunch length	1 ps	~10's of fs to ~10's of ps
peak bunch current	3 kA	> 9 kA
injection energy	50 MeV	5 MeV to 50 MeV
high energy	820 MeV	50 MeV to 1500 MeV

Channeling Acceleration with Micro-Bunch (or Modulated) Driver

• Micro-Bunching/Density Modulation on Plasma Acceleration Performance

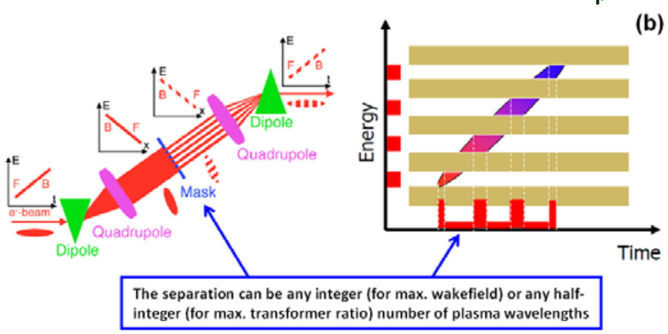
- When using micro-bunches (or modulated driver), by controlling their position and charge the accelerator can be tuned to either maximize the wakefield, the transformer ratio, or the efficiency of the system.

$$R_{total} = \frac{M}{M - (1 - 1/R_0)} \qquad\qquad R_{total} = 2M = M \cdot R_1$$



Plasma-beam phase matching conditions for (a) max. wakefield (bunch separation ~ λ_p) (b) max. transformer ratio (bunch separation ~ 1.5 λ_p) - Kallos, E. et al., 12th AACW, 520 (2006).

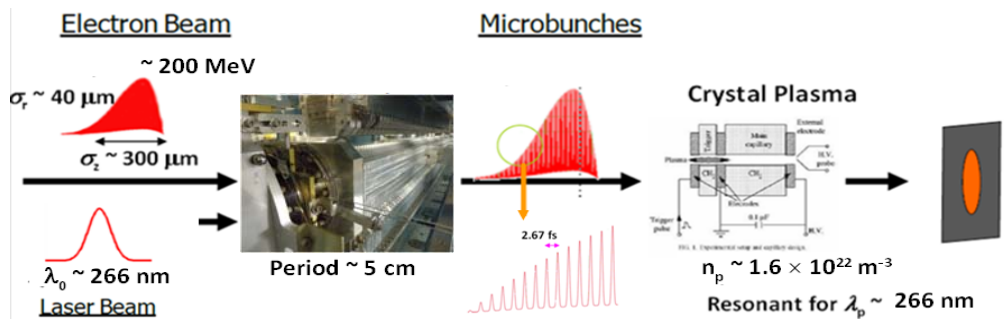
• Slit-Mask Micro-buncher (Sub-mm λ_p)



(L) The beam with a correlated energy spread enters the dog-leg on the left, is dispersed in space, goes through the mask, and then is brought back to energy-time correlation.

- D.C.Nguyen, B.E.Carlsten, NIM-A 375, 597-601 (1996)
- P. Muggli, et. al., PRL PRL 101, 054801 (2008)
- J.C.T.Thangaraj, et al. PRST 15, 110702 (2012)

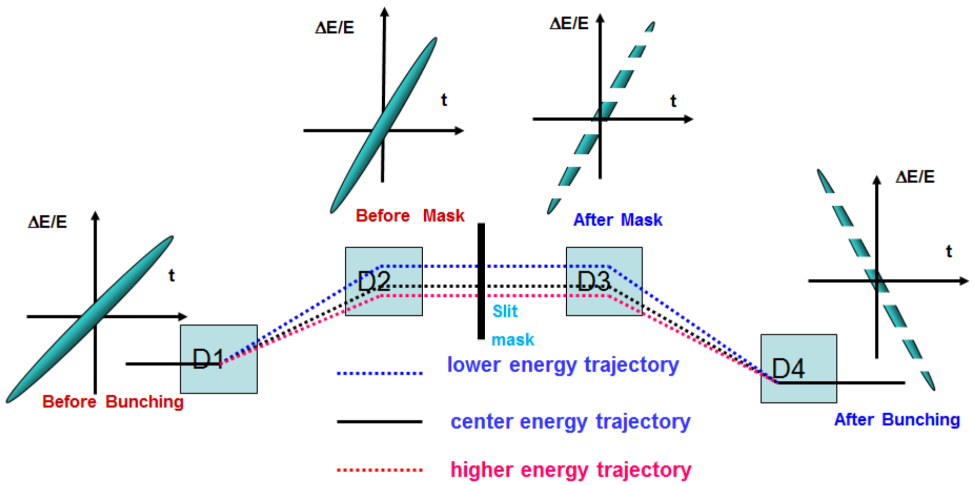
•Laser-Induced Micro-Buncher (Sub-μm λ_p)



The unmodulated electron beam is inserted co-propagating with a laser in the undulator. The output modulated beam is then fed into a crystal channel, and the energy change imparted onto the beam is imaged with a spectrometer on a phosphor screen.

- Kallos, E. et al., 12th AACW, 520 (2006).
- A.H. Lumpkin, J. Ruan, J.M. Byrd and R.B. Wilcox, FERMILAB-CONF-12-579-AD

Masked Chicane Technique for Density Modulation (Micro-Bunching)



D.C.Nguyen, B.E.Carlsten, NIM-A 375, pp. 587 – 601 (1996)
J.C.T.Thangaraj, R,Thurman-Keup, et al., PRST-AB 15, 110702-1~10

$$R_{56} = \gamma \frac{dz}{d\gamma} = -4L\sec\theta + 4R\theta - 2D\sec\theta\tan^2\theta$$

$$\eta_x = \gamma \frac{dx}{d\gamma} = -2L\tan\theta + 2R\left(1-\cos\theta\right) - D\tan\theta\left(1+\tan^2\theta\right)$$

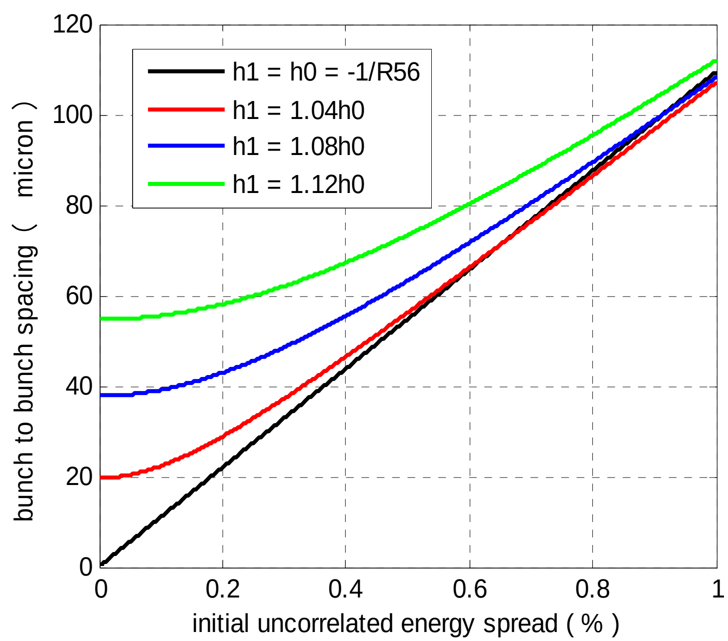
$$N_b = \frac{\sigma_{\eta,mask}}{w}$$

$$\sigma_{\eta,mask} = \sqrt{\epsilon_x\,\beta_{x,mask} + \left(\eta_{x,mask}\sigma_\delta\right)^2} \cong \eta_{x,mask}\sigma_\delta$$

$$\sigma_\delta^2 = \tau^2\sigma_{\delta i}^2 + h_1^2.\sigma_{z,i}^2$$

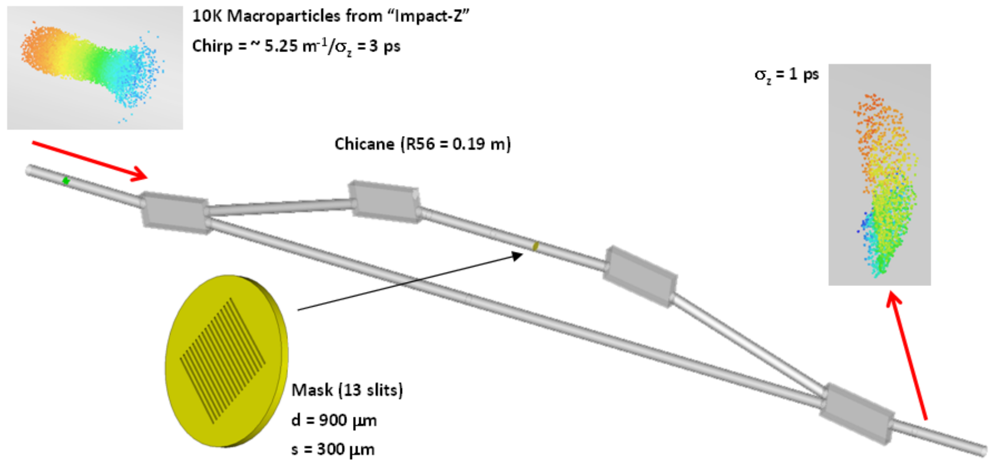
$$N_b = \frac{\eta_{x,mask} h_1.\sigma_{z,i}}{W}$$

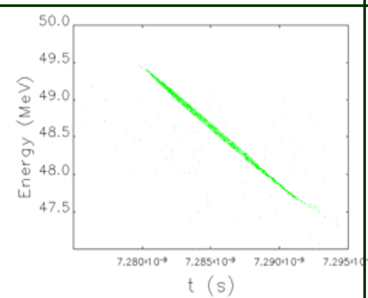
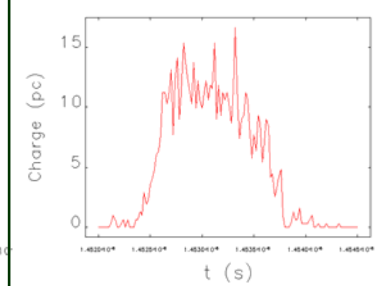
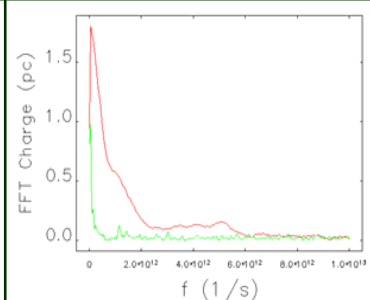
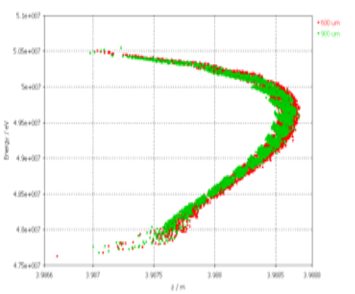
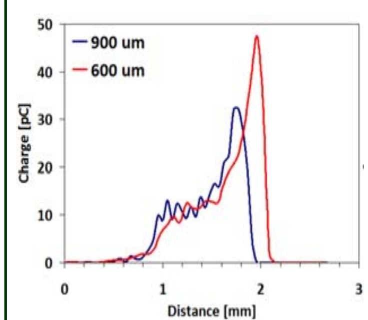
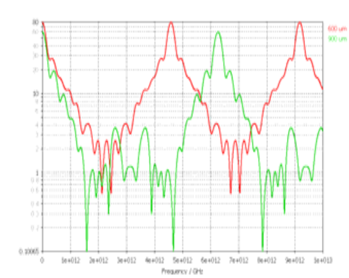
$$\Delta z = W\,\frac{\sqrt{\left(1+h_1R_{56}\right)^2\sigma_{z,i}^2 + \tau^2R_{56}^2\sigma_{\delta i}^2}}{\eta_{x,mask}h_1.\sigma_{z,i}}$$



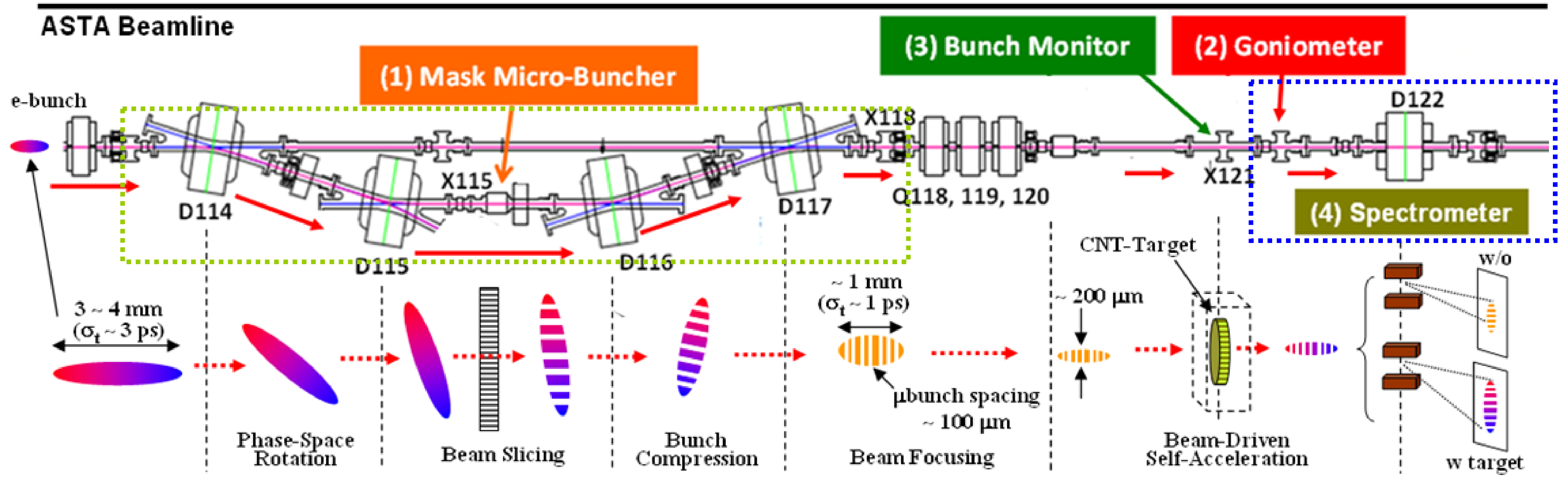
Bunch-to-bunch spacing vs initial energy spread.

Simulation Analysis

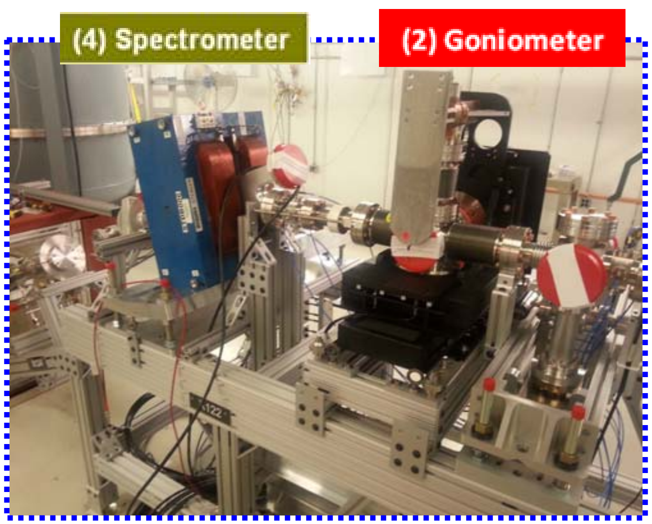


	Energy Distribution	Charge Distribution	FFTed Charge Signal
Elegant + Shower in Time (t)			
CST-PS + Impact-Z in Longitudinal Distance (z)			

Outlined Beamline Configuration for POC Experiment



Martin-Puplett Interferometer (MPI)



Equipment for Beam Energy and Radiation Measurement

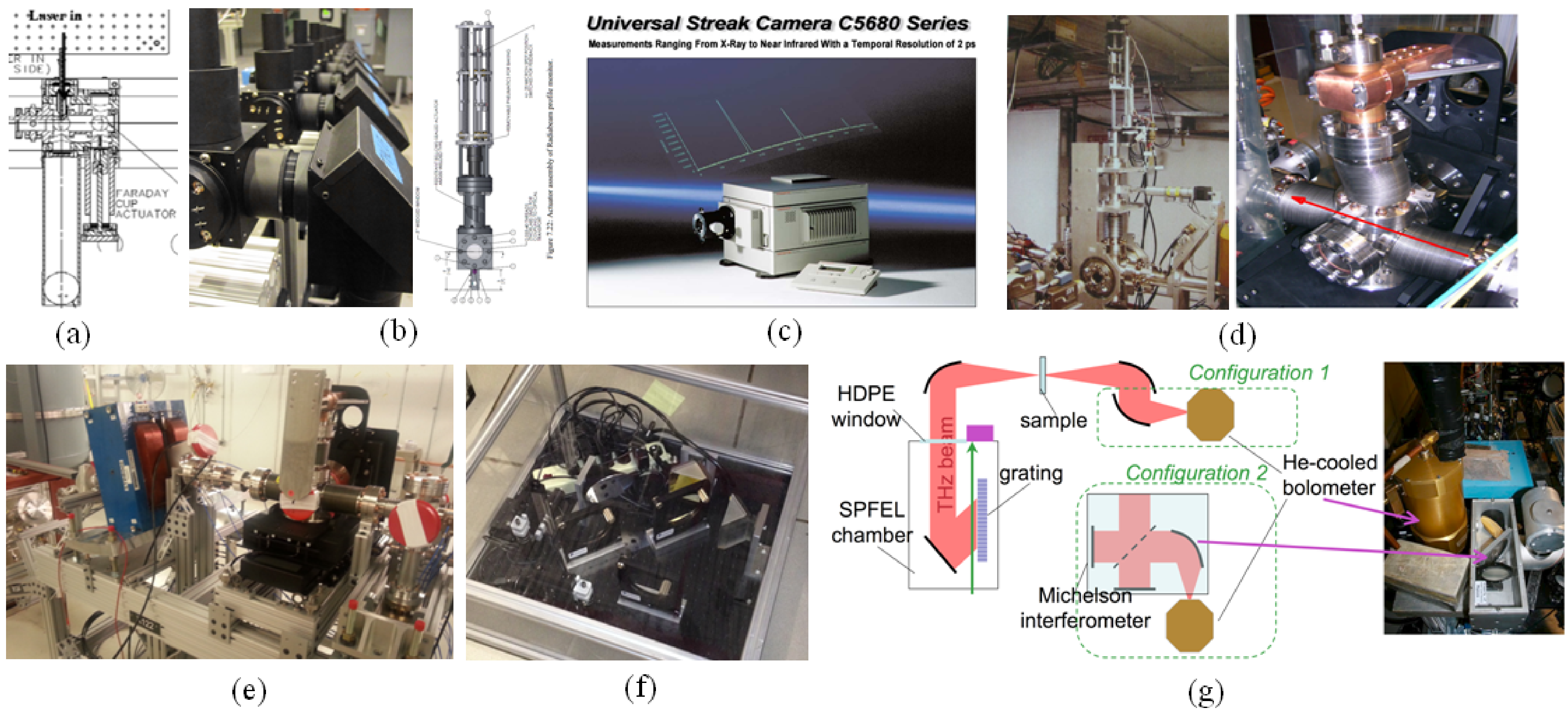
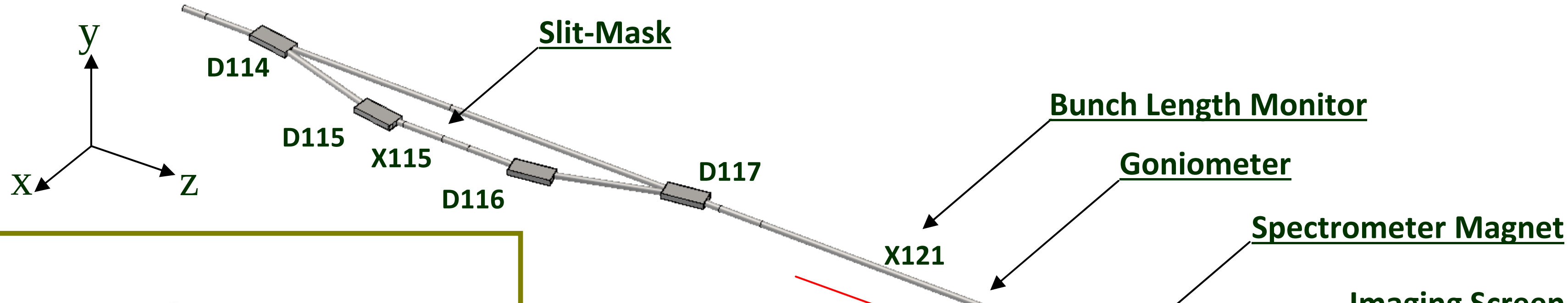
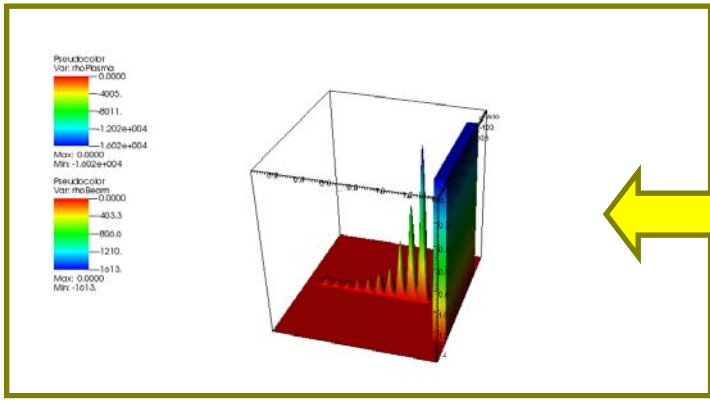
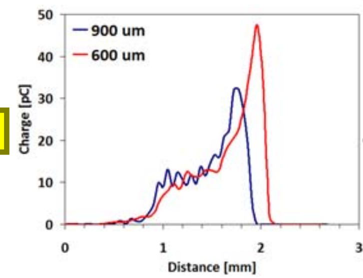


Photo images of instruments available for the project tasks at Fermilab (A0-HBESL and ASTA) (a) Faraday cup (b) beam profile monitors (c) c5680 streak camera (d) goniometers (L: A0-HBESL, R – ASTA), (e) beam spectrometer with the ASTA-goniometer, (f) MPI, and (g) THz Michelson interferometer with He-cooled bolometer.

Simulation Assessment of POC Experiment







- Charge Distribution in z-axis (time unit)

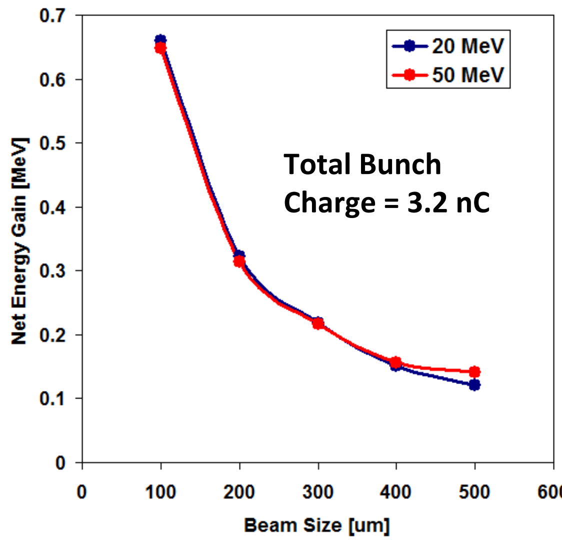
- Beam Parameters

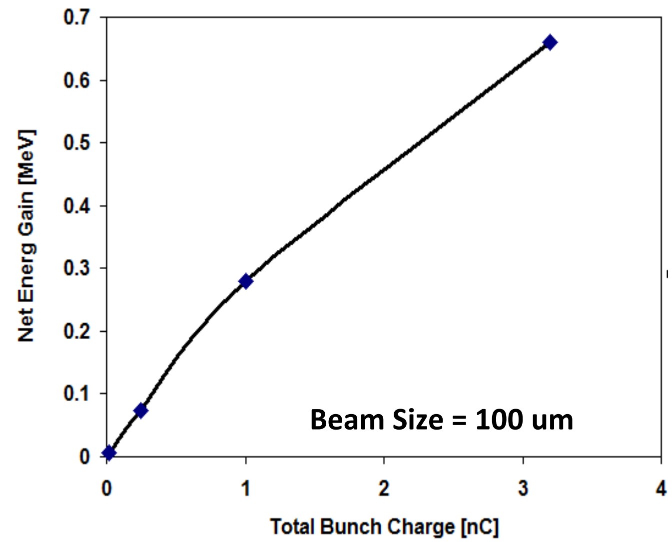
50 MeV

3.2 nC (Max.)

100 – 200 μm wide

~ 100 μm spacing





What's Next?

- ASTA Schedule

		FY2014*				FY2015				FY2016				FY2017				FY2018				FY2019			
Stage	**Description - following Figures 2, 3, 4 and 5**	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
0	as is: photoinjection to low-energy dump																								
I.2	add CM #1 (~ 300 MeV), experimental area, and diagnostics area																								
I.3	add IOTA Storage Ring (50-150 MeV)																								
III	add HINS 2.5 MeV H-/proton injector																								

9 Months Ops./3 months shutdown per year

fabrication & construction	(not interfering with beam operations)
installation & commissioning	
experimental operations	(9 months per year)
Planned maintenance/Installation	(3 months per year)

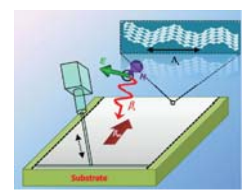
- **Start commissioning 50 MeV injector into beam dump in this Fall**

- Possible Accelerations beyond the Feasibility Test

Electron CNT-Channeling Acceleration Experiment

→ ***Proton Beam-Driven Acceleration***

→ ***Laser-Driven Acceleration (UV)***



M. Farhat, S. Guenneau, and H. Bagc, PRL 111, 237404 (2013)

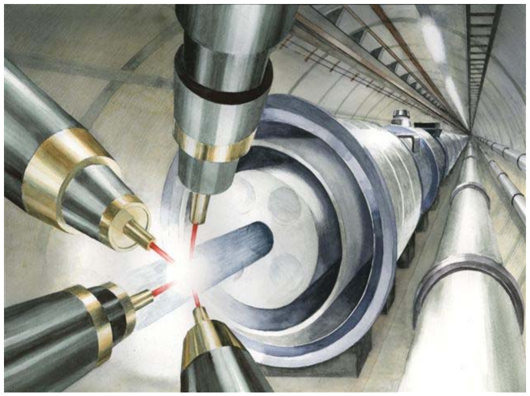
→ ***X-Ray Driven Acceleration***

http://cerncourier.com/cws/article/cern/55000

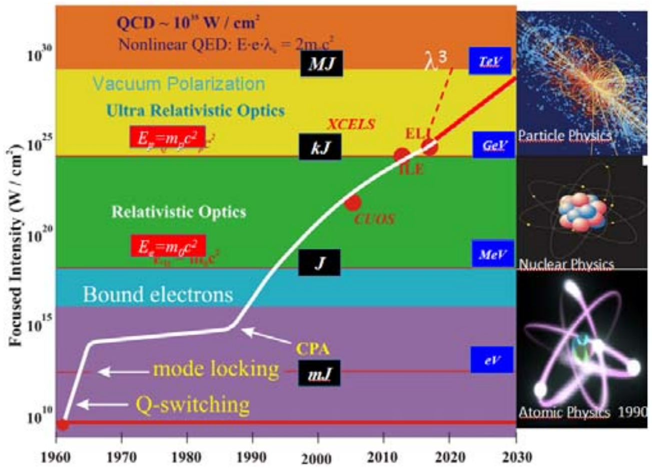
Collaboration on Channeling Acceleration Research

THEXAC

Transformative High Energy X-ray Acceleration in Crystals



"SAREC14"



"Extreme Light Roadmap", **Courtesy of T. Tajima**

Activities :

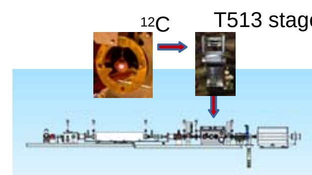
X-ray Acceleration in Crystal (THEXAC) (integrated overall team)

← (1) Conceptual development, theoretical support, and overall direction (UCI subteam)*

(2) Proof-of-Principle demonstration of single-oscillation X-ray laser pulse in extreme power (EW) (ELI-NP/Romania – Ecole Polytechnique subteam)*

(3) Wakefield Generation with a short charged electron and proton bunches in structured crystals carbon nanotubes (Fermilab – NIU subteam)*

(4) Positron channeling in crystals and wakefield generation in crystals with short, intense bunches at GeV energy; Linear X-ray Optics in crystal (SLAC/FACET/LCLS subteam)



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University of California Irvine

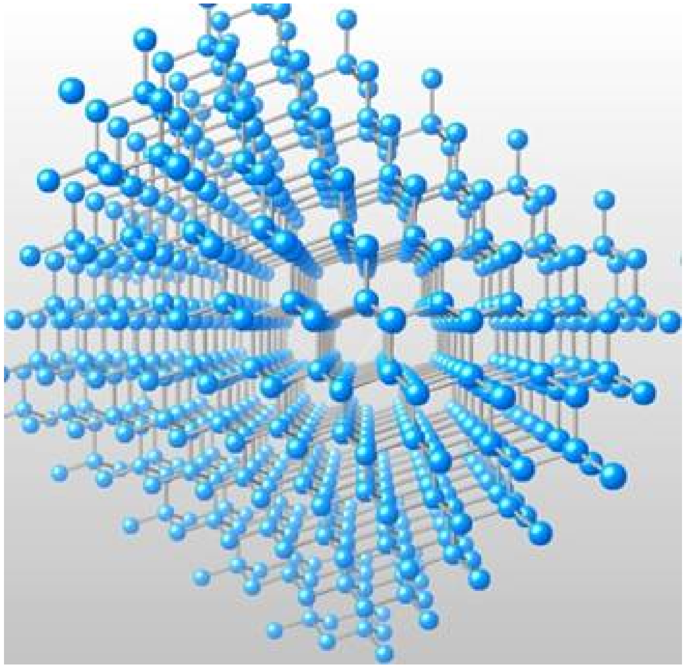
Northern Illinois University

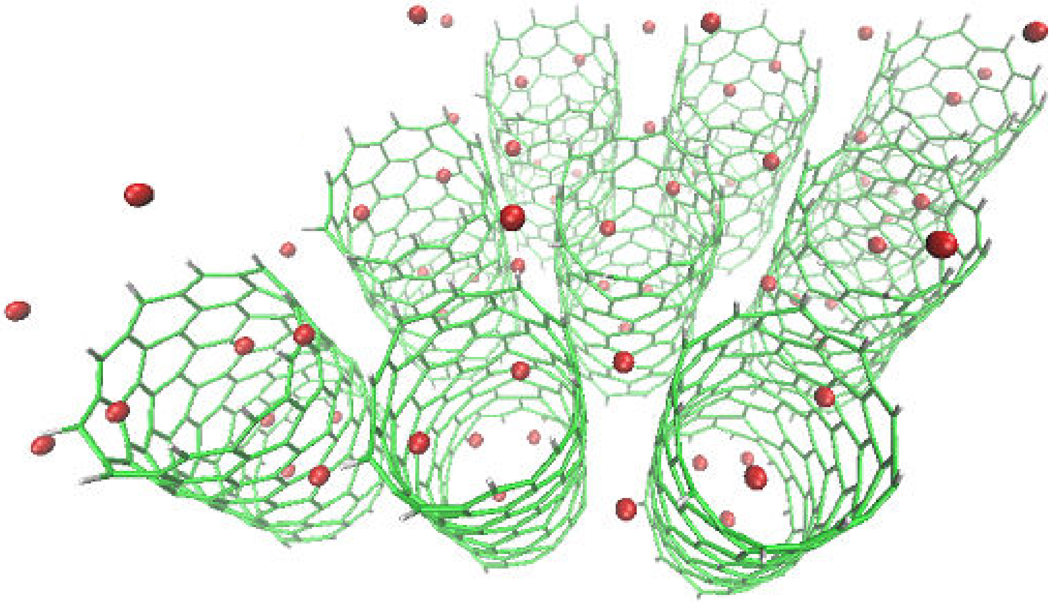
École Polytechnique Montréal

SLAC

Fermilab

eli extreme light infrastructure





Thank You!