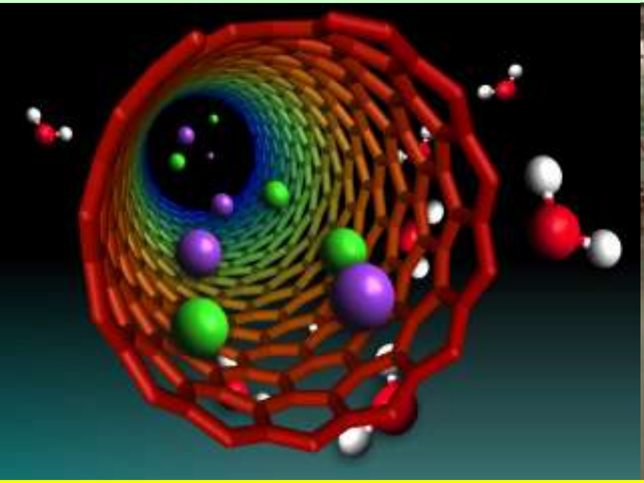
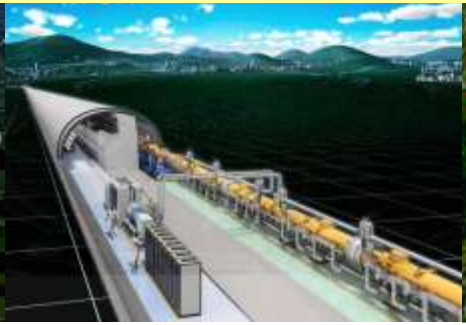


TeV/m Nano-Accelerator

- Feasibility Test of CNT-Channeling Acceleration -



Y. M. Shin, A. H. Lumpkin, J. C. Thangaraj, R. M. Thurman-Keup, P. Piot, and V. Shiltsev

Thanks to X. Zhu, D. Broemmelsiek, D. Crawford, D. Mihalcea, D. Still, K. Carlson, J. Santucci, J. Ruan, and E. Harms

Foreseeing Prospective Budget and Accelerator R&D on HEP Colliders

Category	Cost, billions of dollars	Facility
I	$\leqslant 0.3$	NICA, ENC
II	0.3 – 1	Super-B factories, c – τ 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)

“ ***The U.S. could move boldly toward development of transformational accelerator R&D.*** 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***.

- For example, the primary enabling technology for pp colliders is high-field accelerator magnets. For e+e- colliders, primary goals are improving the ***accelerating gradient and lowering the power consumption***. Although these are R&D priorities in the constrained budge scenarios, larger investments could make these ***far-future accelerators technically and financially feasible on much shorter timescales***.
- Would also have large, positive impacts beyond particle physics.
- As work proceeds worldwide on long-term future-generation accelerator concepts, the U.S. should be counted among the potential host nations.” – P5 Report

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

HG-Accelerator: Towards Shorter Wavelengths

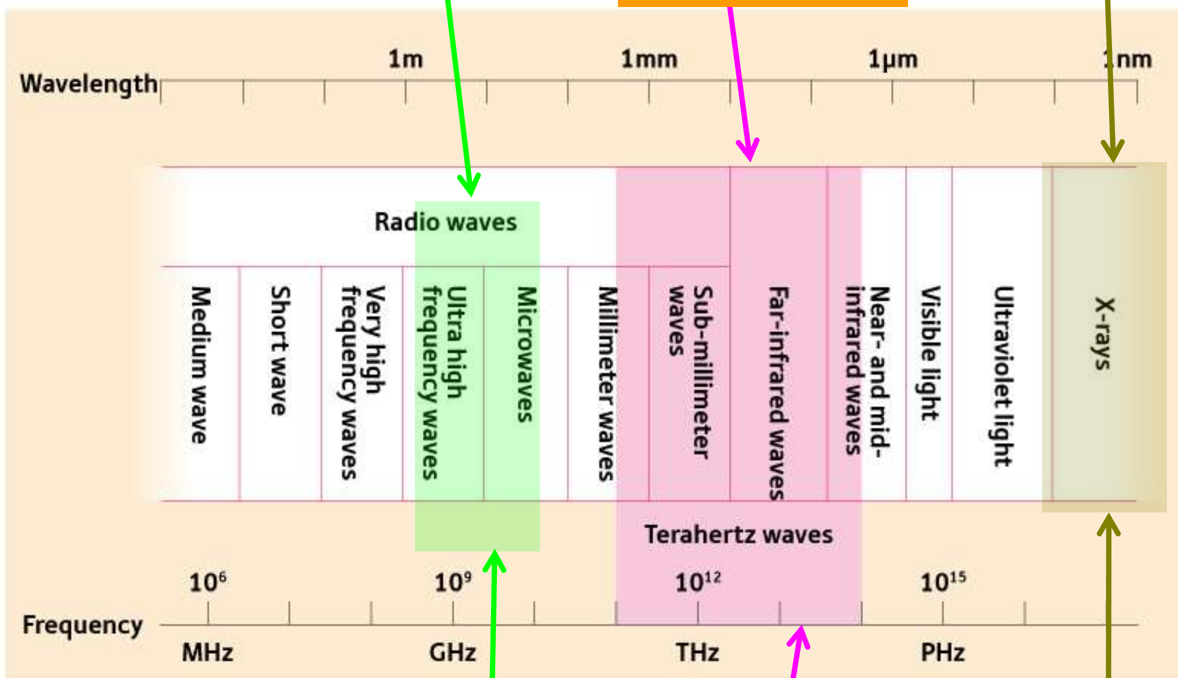
Accelerator type

Conventional RF Accelerators

Dielectric & Plasma Based Accelerators

Crystal Accelerators

Spectral Band



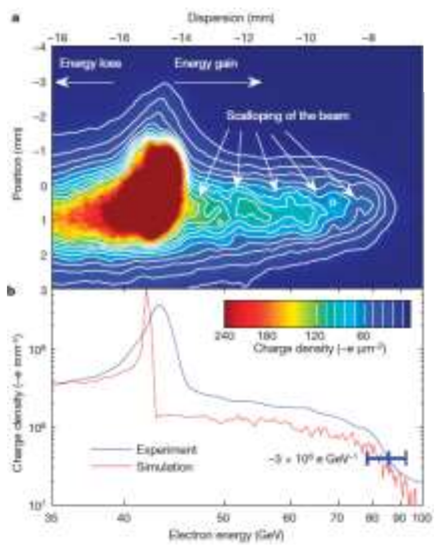
Driving Source

tetrodes, IOTs, klystrons, solid-state amplifiers,…

***e-* (*p*) beam or laser**

Intense X-ray laser Ultra-short pulse e- (p) beam

Gas-State Plasma



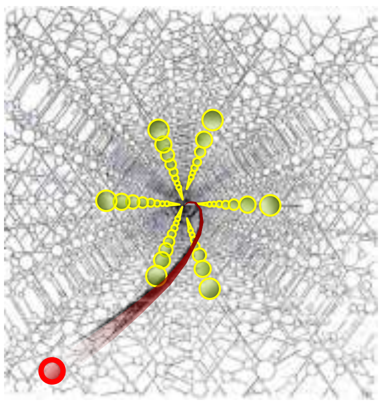
$10^{17} - 10^{18} cm^{-3} \rightarrow 30 \sim 100$ GeV/m

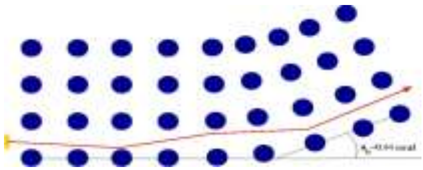
Nature 445, 741-744 (2007)

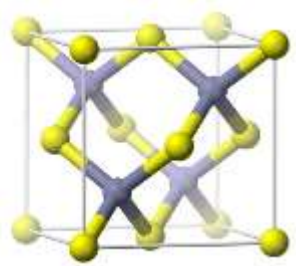
Energy Doubling: ~ 52 GV/m (@ 42 GeV)

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

Solid-State Plasma (Conduction Electrons)







$10^{19} - 10^{23} cm^{-3} \rightarrow 0.3 \sim 30$ TeV/m

Advanced HG-Accelerator Concepts

	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

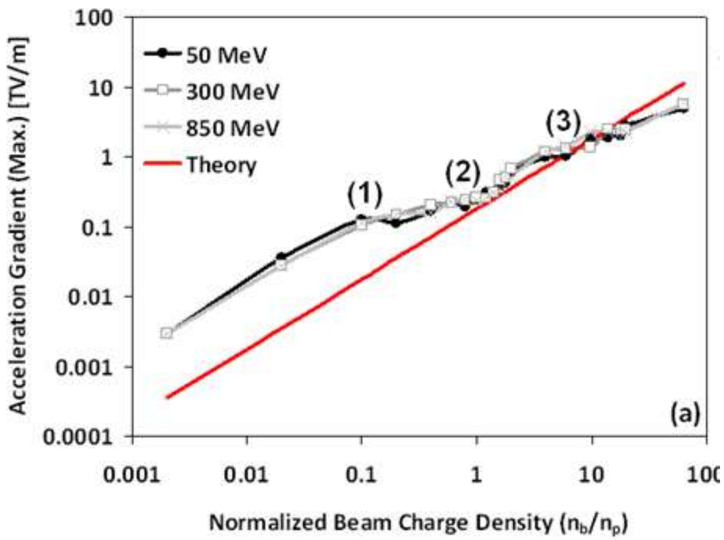
E_{max} (maximum energy) ≈ $(M_b/M_p)^2(\Lambda G)^{1/2}\{G/(z^3\times 100\ \mathrm{GV/cm})\}^{1/2}10^5$ TeV

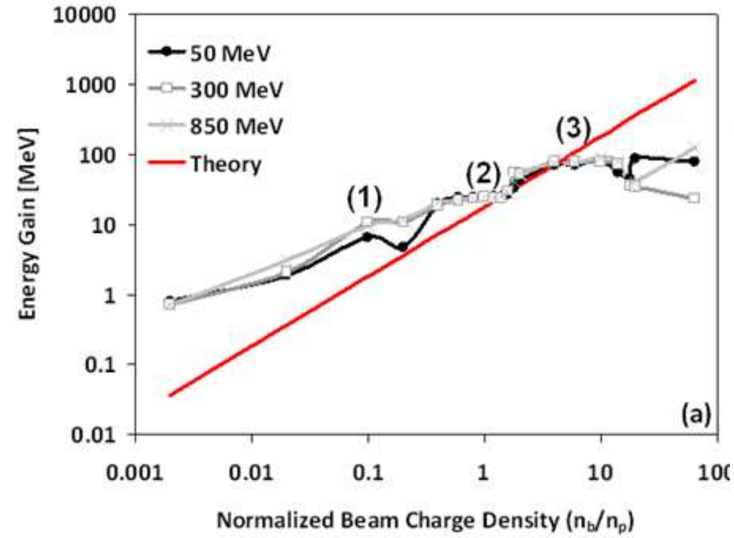
(M_b and M_p are the mass of the beam particle and mass of the proton respectively, Λ is the de-channeling length per unit of energy, G is the accelerating gradient, and z is the charge of the beam particle)

0.3 TeV for electrons/positrons, 10^4 TeV for muons, and 10^6 TeV for protons

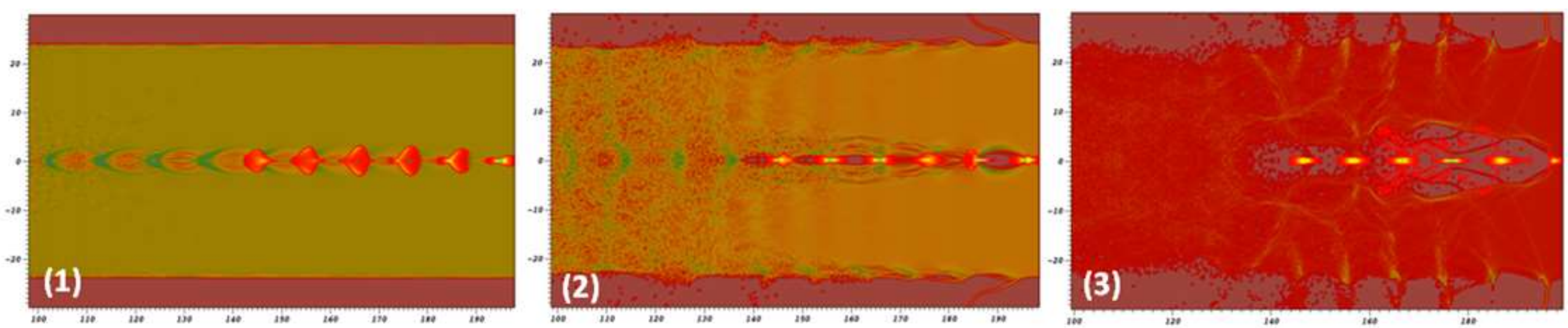
Dodin I Y, Fisch N J Phys. Plasmas 15 103105 (2008)

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





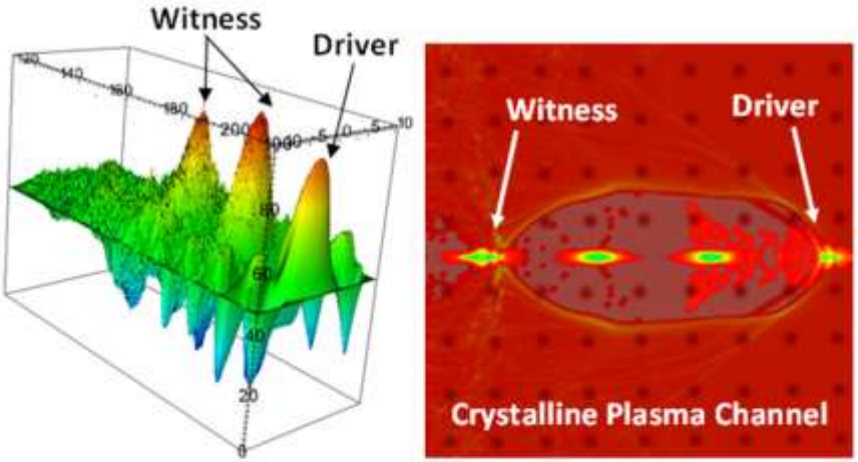
→ (a) Acceleration gradient and (b) energy gain versus bunch charge graphs (a) $n_p = 10^{25}$ m^{-3}, $\Delta z = 10$ μm, $\sigma_{zm} = 1$ μm



→ Spatial charge distributions of plasma channel and beam of (1) – (3) with $n_p = 10^{25}$ m^{-3}

Crystal Channeling Acceleration: Wakefield and Diffraction

Wakefield Acceleration

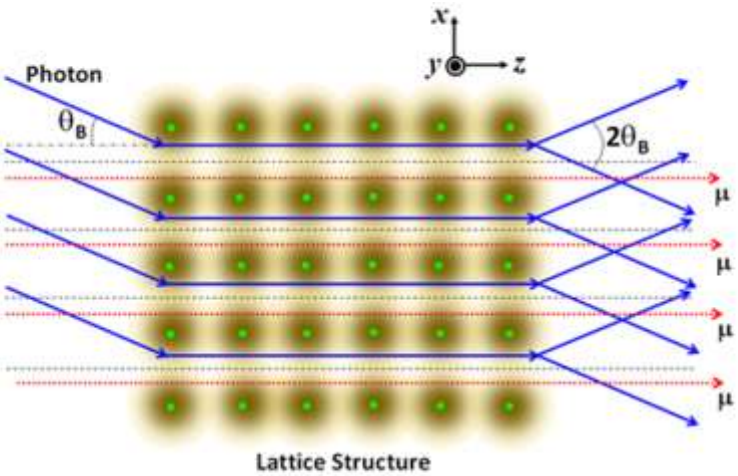


→ P. Chen and R. J. Noble, AIP Conf. Proc. 156, 222 1987

Driving Source: Beam, Laser

Particle Species: e+, e-, μ+, μ-, p+

Diffraction Acceleration

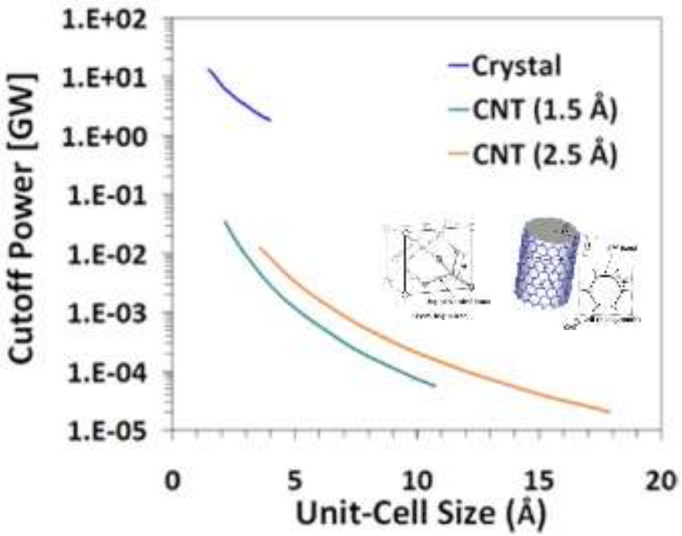


→ T. Tajima and M. Cavenago, Phys. Rev. Lett. 59, 1440 1987

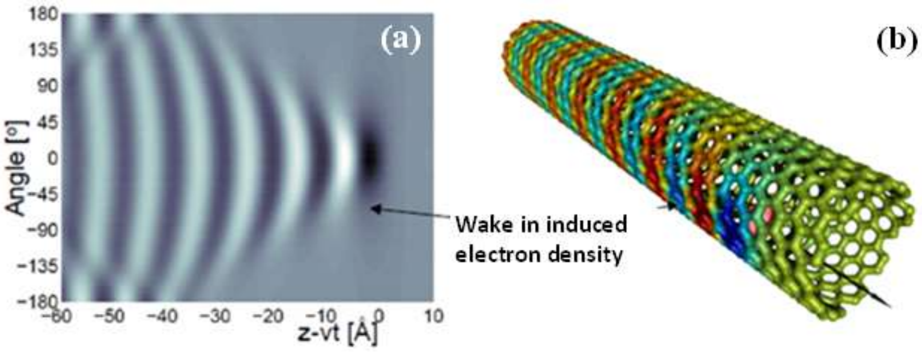
Driving Source: X-Ray Laser

Particle Species: μ+, μ-, p+

Channeling Acceleration in Carbon Nanotubes (CNTs)



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



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

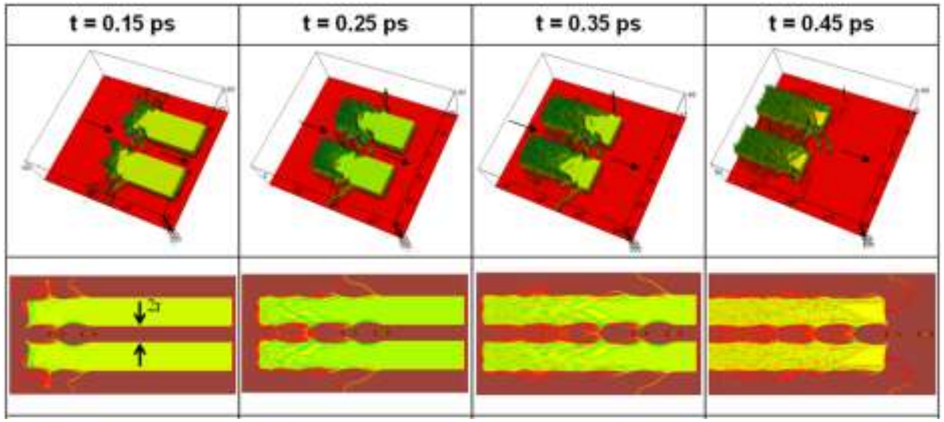
- **CNT vs Crystal**

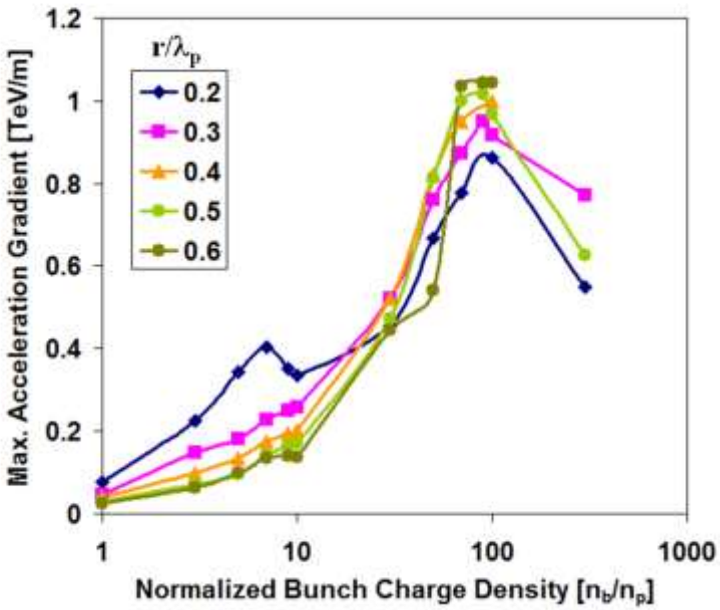
(1) Readily controllable channel size (up to micron). The larger channel can
→ decrease de-channeling rates
→ increase acceptance
→ mitigate power requirement of driving sources

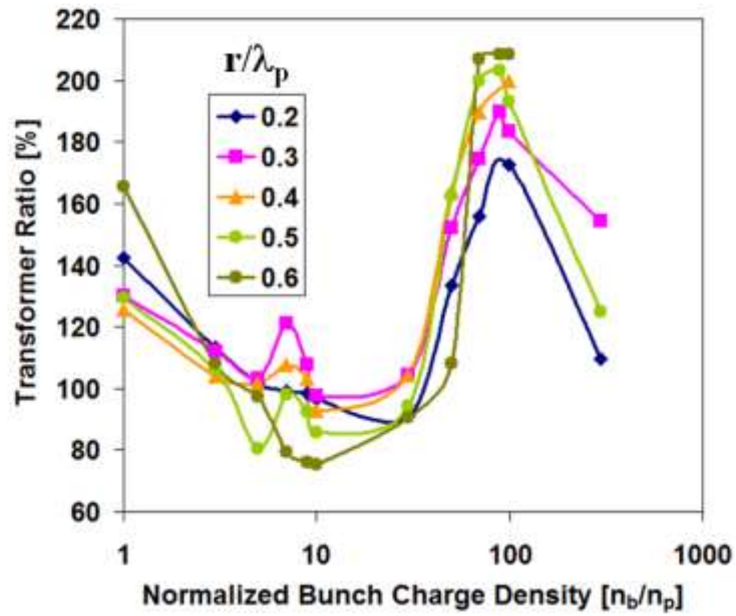
(2) Thermally and mechanically stronger than crystals, steels, and even diamonds (sp_2 bond > sp_3 bond)
→ Higher durability in extremely intense channeling radiation/acceleration

(3) Single-mode interaction (Stable Acceleration)

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



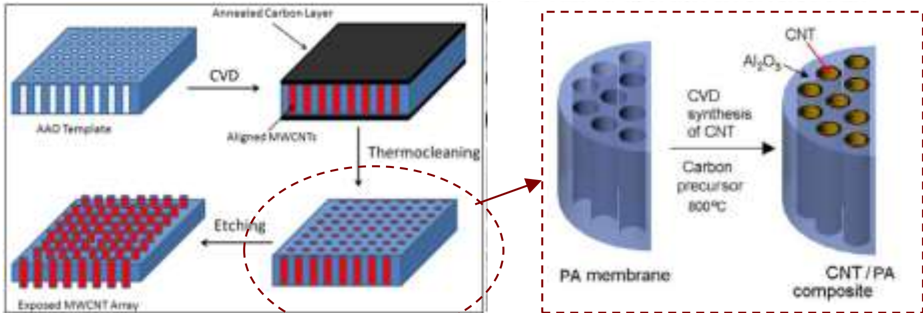




(a) maximum acceleration gradient and (b) transformer ratio versus bunch charge distribution normalized by bunch charge density with various tunnel radii (r = 0.2 − 0.6λ_p)

CNT-Channel: AAO-CNT

AAO (Anodic Aluminum Oxide) CNT Fabrication Technique



Membranes **2011**, *1*, 37-47; doi:10.3390/membranes1010037

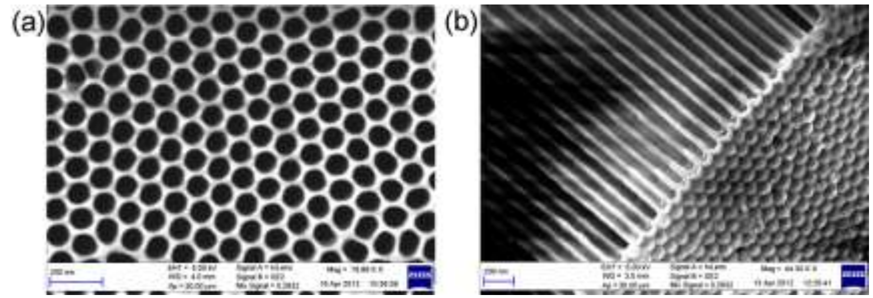
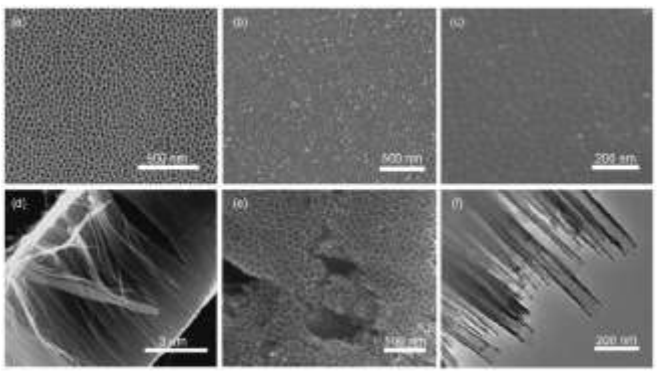


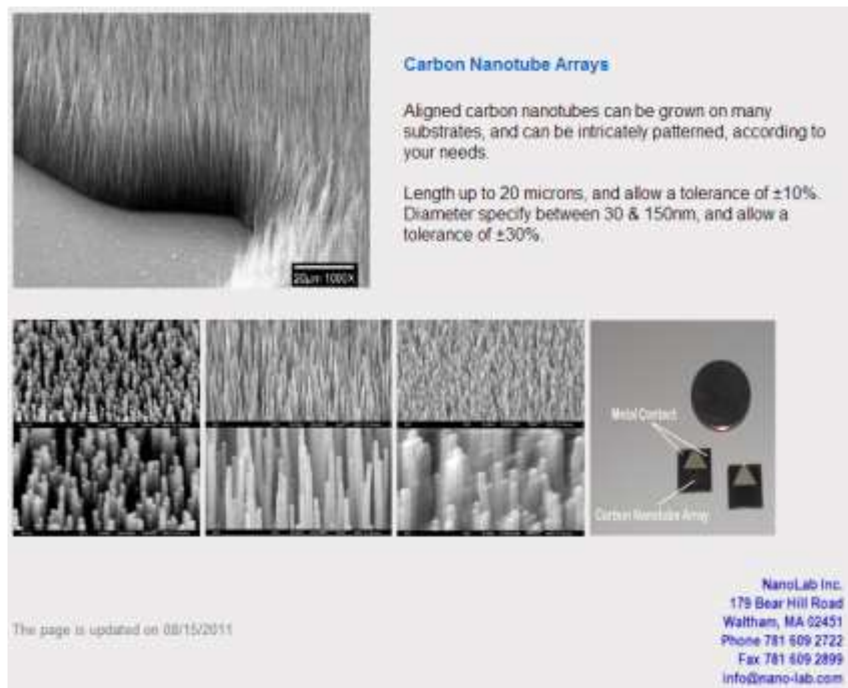
Figure 2. (a) Topview of a AAO template (b) side and bottom of a AAO template. (ref. 1)



- H. PengXiang, L. Chang, S. Chao, and C. HuiMing, Chinese Science Bulletin 57, 187 (2012)

AAO-CNT samples are fabricated by the NanoLab Inc., Waltham, MA

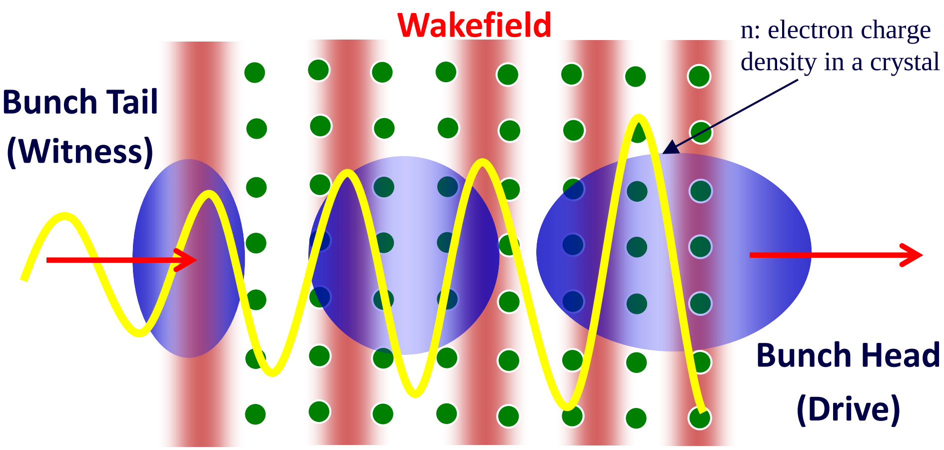
T. Xu of NIU Chemistry Dept. is currently in the collaboration with technical discussion and nanostructure fabrication



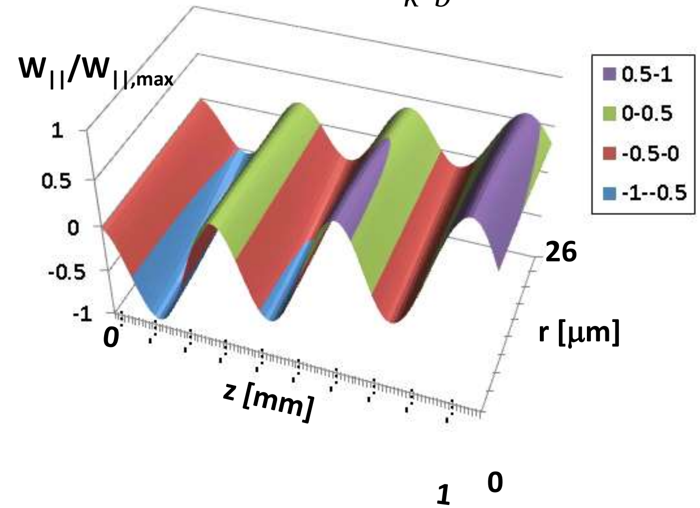
AAO-CNT (Synkera AAO Template)

[1] Nanotechnology and Nanomaterials » "Syntheses and Applications of Carbon Nanotubes and Their Composites", book edited by Satoru Suzuki , ISBN 978-953-51-1125-2, Published: May 9, 2013 Chapter 2 “Large Arrays and Networks of Carbon Nanotubes: Morphology Control by Process Parameters” By I. Levchenko, Z.-J. Han, S. Kumar, S. Yick, J. Fang and K. Ostrikov

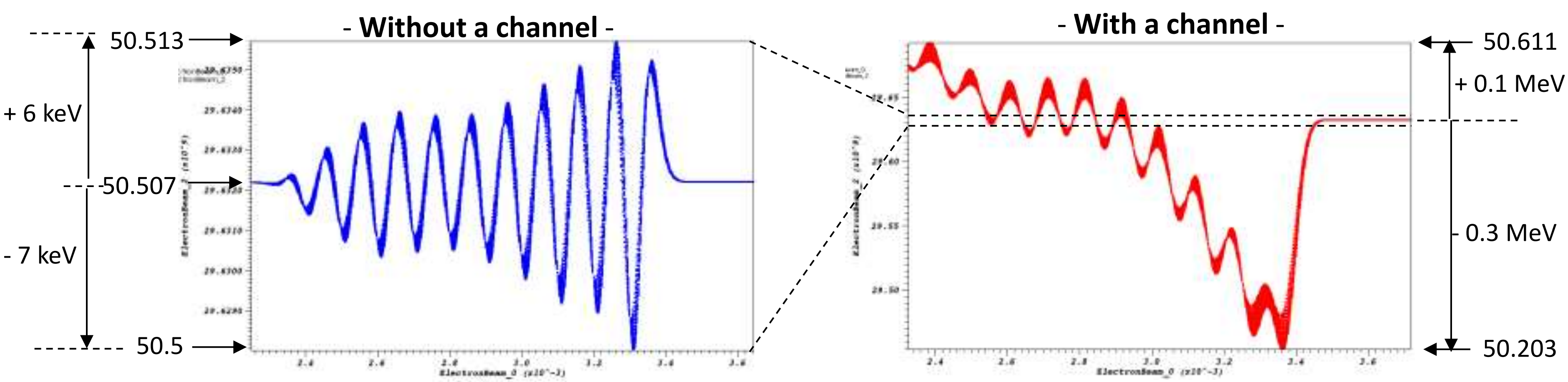
*Proof-Of-Concept Experiment: Self-Acceleration**



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



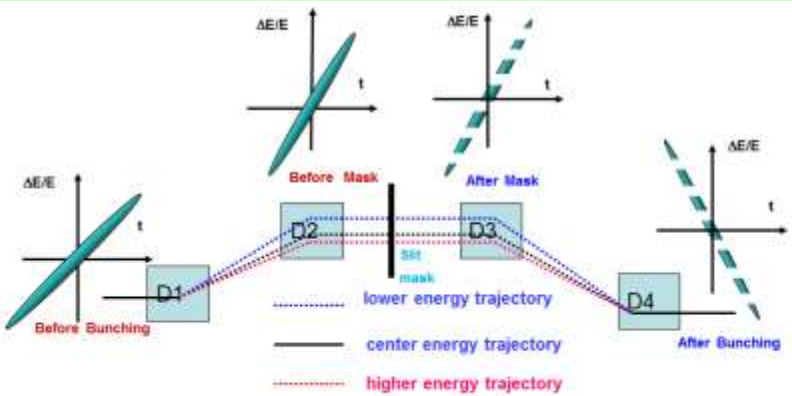
- 50 MeV (1 nC)

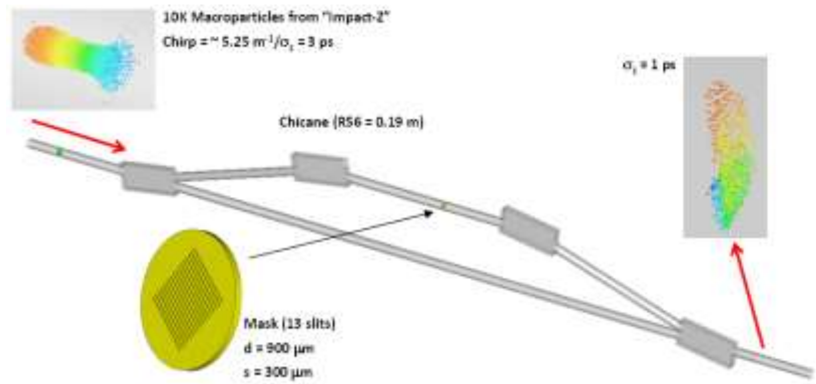


*[1] P. Chen. D. B. Cline, and W. E. Gabella, SLAC-PUB-6020

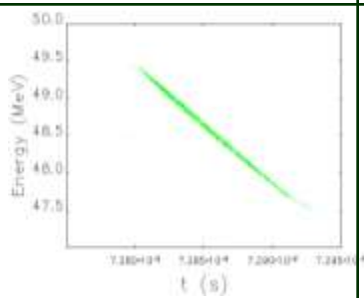
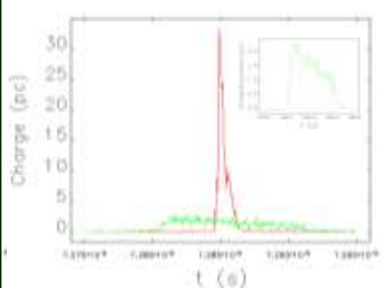
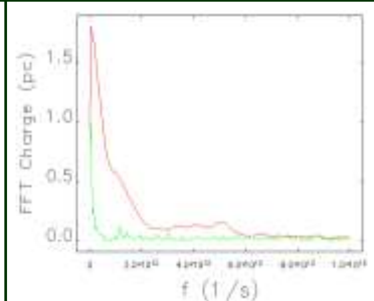
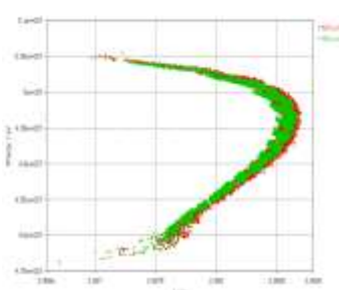
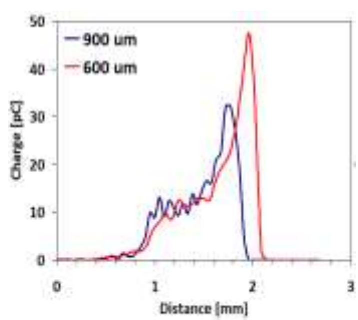
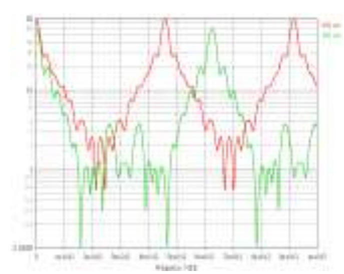
[2] G. Xia, C. Welsch, et. al., "A plasma wakefield acceleration experiment using CLARA beam", Nuclear Instruments and Methods in Physics Research A 740 (2014)

Slit-Mask Chicane Technique for Density Modulation (Micro-Bunching)

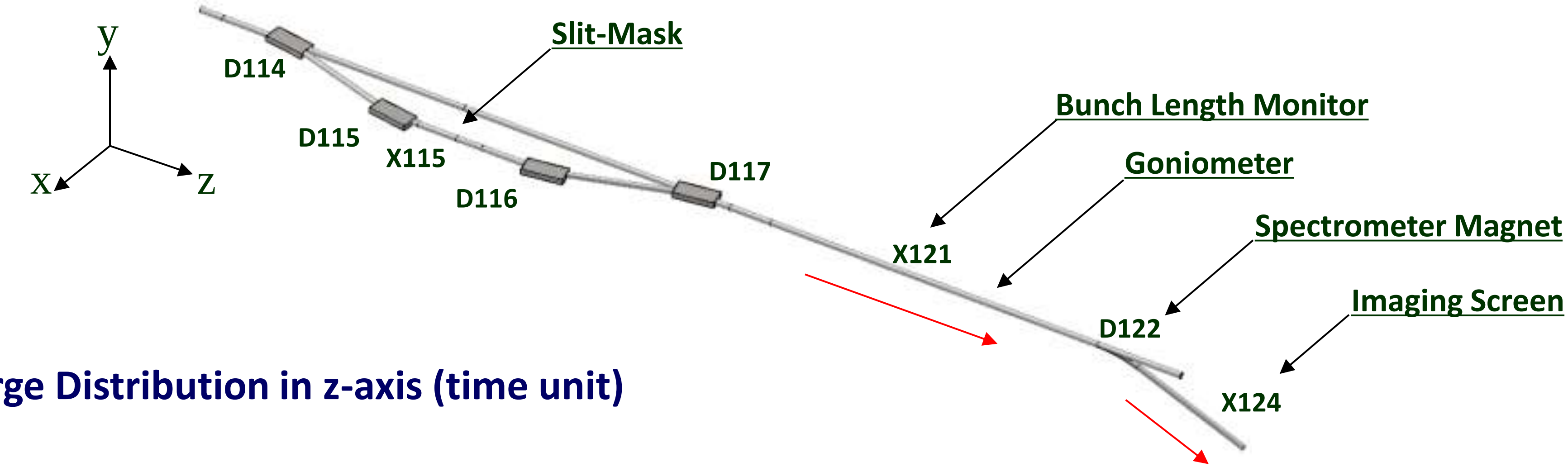




D.C.Nguyen, B.E.Carlsten, NIM-A 375, pp. 587 – 601 (1996)
J.C.T.Thangaraj, R,Thurman-Keup, et al., PRST-AB 15, 110702-1~10

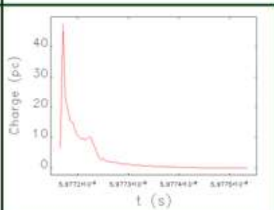
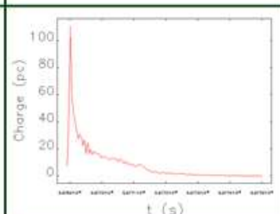
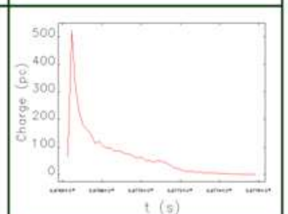
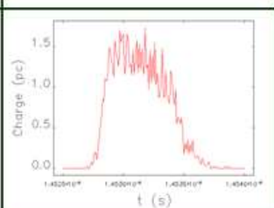
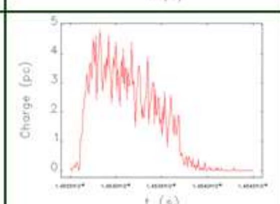
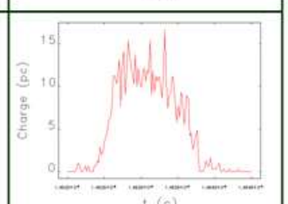
	Energy Distribution	Charge Distribution	FFTed Charge Signal
Elegant + Shower in Time (t)			
CST-PS + Impact-Z in Longitudinal Distance (z)			

Beamline Simulation with a Slit-Mask (Elegant + Shower)

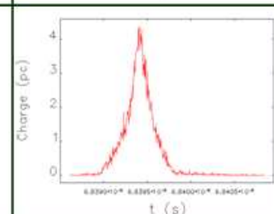
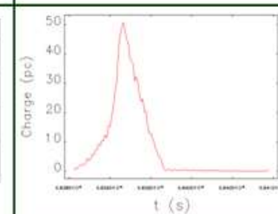
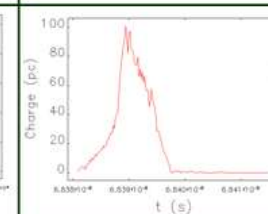
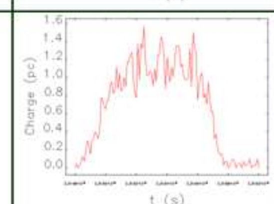
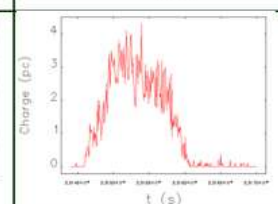
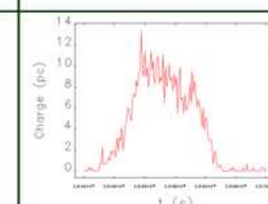


- Charge Distribution in z-axis (time unit)

@ X121

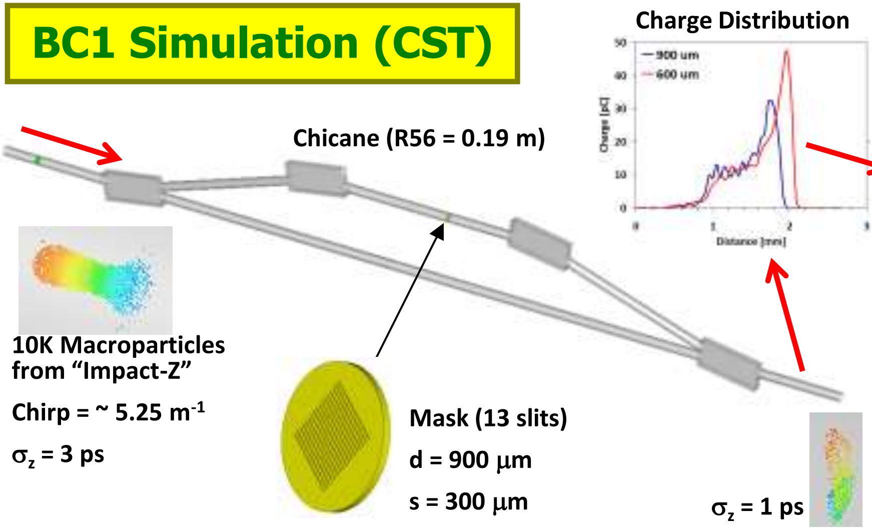
	250 pC	1 nC	3.2 nC
w/o Mask			
w Mask			

@ X124

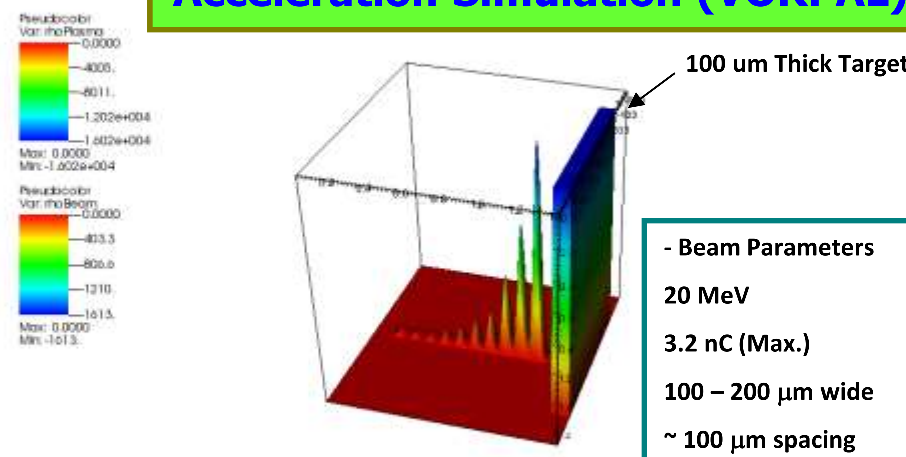
	250 pC	1 nC	3.2 nC
w/o Mask			
w Mask			

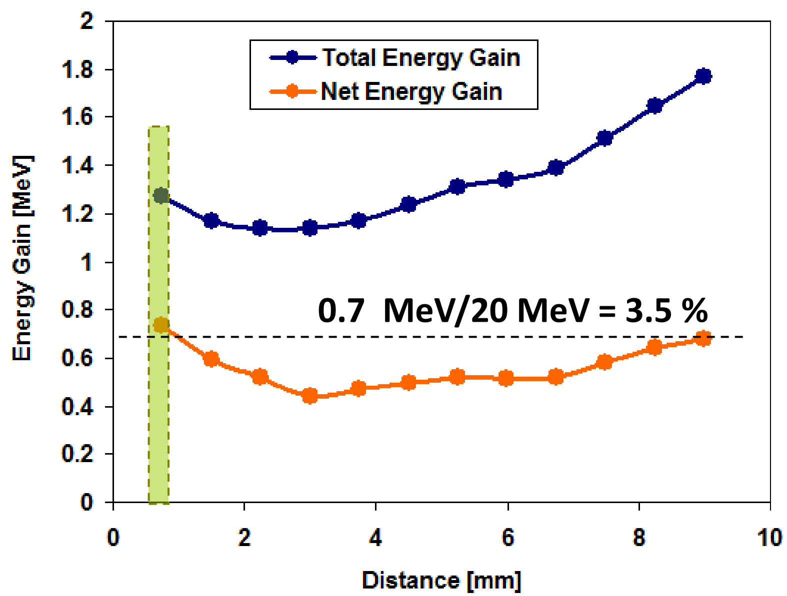
Simulation Assessment of POC Experiment

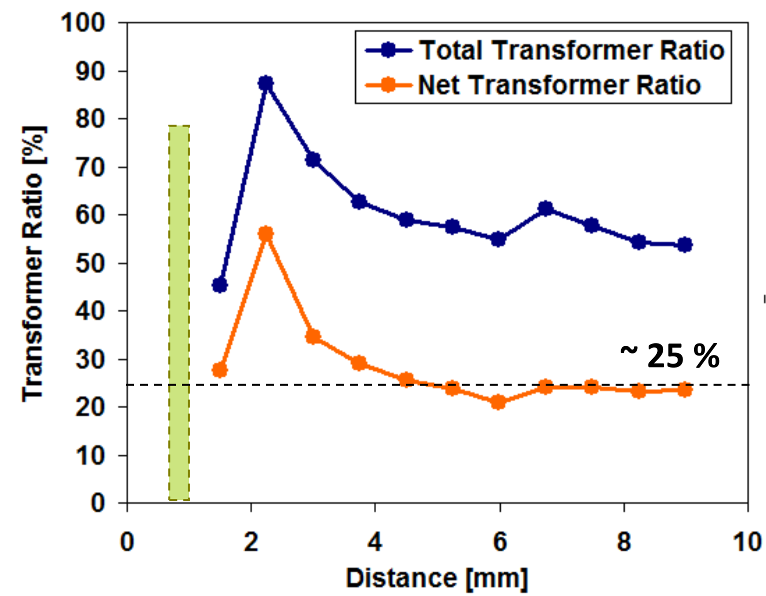
BC1 Simulation (CST)



Acceleration Simulation (VORPAL)

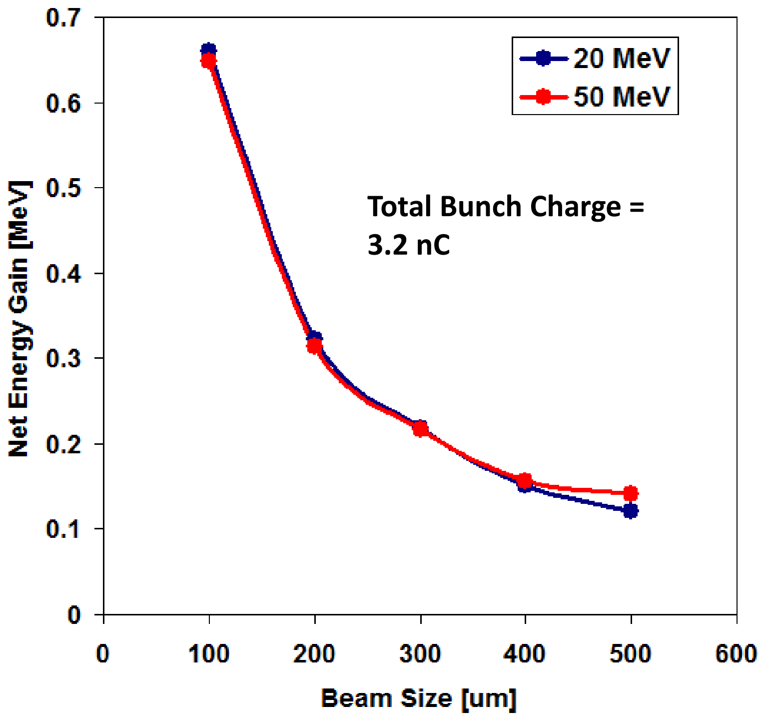




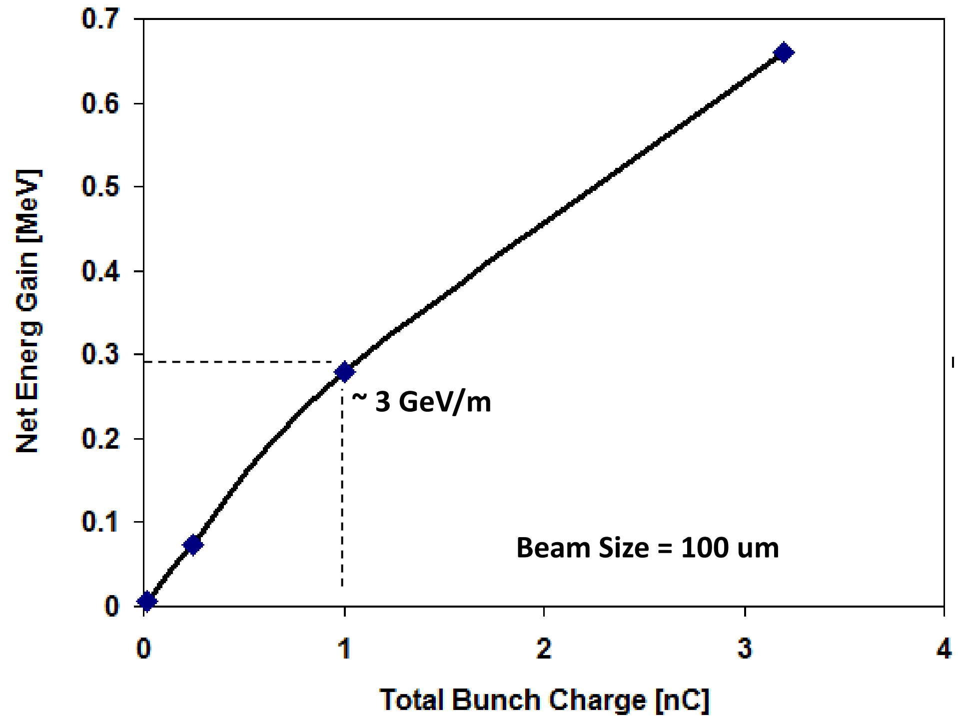


Energy Gain vs Beam Size and Bunch Charge

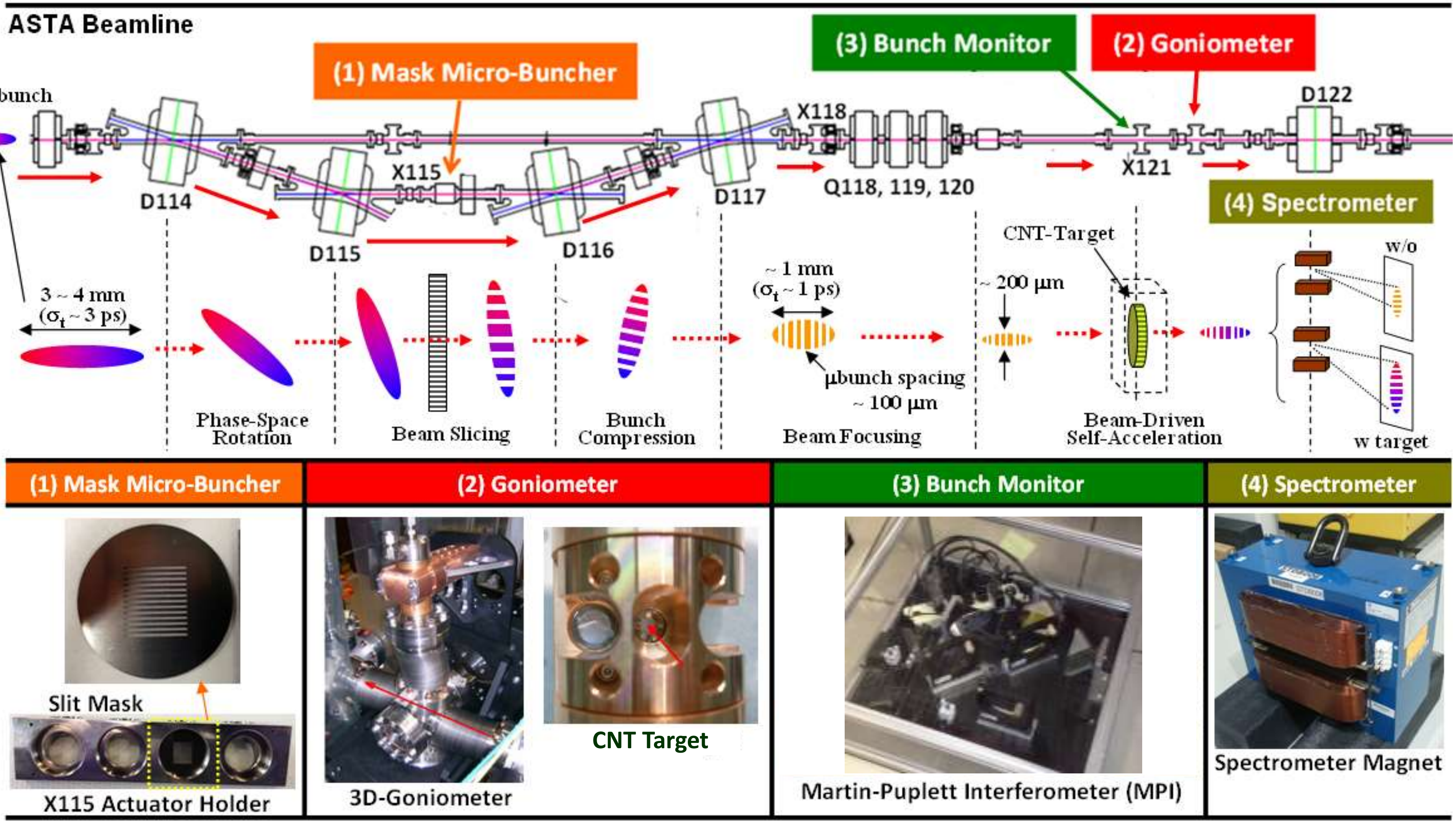
Energy Gain vs Beam Size



Energy Gain vs Bunch Charge



Outlined Beamline Configuration for POC Experiment



Prospective Timeline of Planned Activities

	FY14	FY15	FY16
Simulation Assessment of Beam-Driven Channeling Acceleration			
Extensive Simulation Design Analysis of Nano-Crystal Channeling Models			
Comprehensive Modeling of CNT Channeling Acceleration			
Preparation and Inspection of CNT Test Samples			
Preliminary Commissioning Test of the Slit-Mask Microbuncher			
Beam-Modulation Demonstration and Parametric Assessment of a Slit-Mask Micro-Buncher			
Proof-Of-Concept Acceleration Test			
Experimental Specification of Beam-Driven Channeling Acceleration			

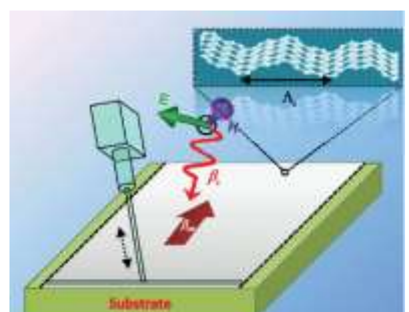
TeV/m Nano-Accelerator

- CNTs/Graphenes and Nanostructures -

Electron Beam-Driven Acceleration (POP Test)

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

*“**Crystal based linear collider:***

Challenges:

There several new effects at higher densities are due to intense energy radiation and scattering while particles are accelerated in along major crystallographic directions stronger for electrons, weaker for muons and protons. Acceleration inside CNTs (carbon nanotubes) can offer some advantages in that regard. Feasibility of the wave excitation by X-ray lasers or modulated drive beams needs careful exploration. Any methods to combine multiple micro-beams into one bunch can provide significant increase in the luminosity reach.

Facilities:

The first proof-of-principle experiments with CNTs and/or crystals can be performed with high brightness electron beams available at ASTA (FNAL) and FACET (SLAC).” **Snowmass2013 Report – Accelerator Technology Test-Beds and Test Beams**

Thank You!!

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Can Natural Crystals Survive in Channeling Acceleration?

***Rough Estimate** of Thermal Tolerance (Damage Threshold) of Crystal Acceleration*

Crystal Damage Threshold (Acceleration)

G (gradient) proportional to $(n_p)^{1/2}$, P (power) prop to n_b

For G = 1 GeV/cm, P = 10^5 J/cm^3 → 10^{18} - 10^{19} W/cm^3 for O(10 fs) @ 1 GeV/cm

"R. Carrigan Jr., NATO Workshop, August 29, 2004"/R. Carrigan Jr. and J. A. Ellison, "Relativistic Channeling"

O(1 ps) ⇒ { 10^{15} W/cm^3 (Theory); 10^{16} W/cm^3 (Experiment) } —r ~ 100 μm→ { Power (peak) Threshold of a Crystal in Acceleration: 10 GW (Theory); 100 GW (Experiment) }

Thermal Conductivity

Crystal (Si) ~ 150 W/m/K

←20 Times→ CNT ~ 3,000 W/m/K

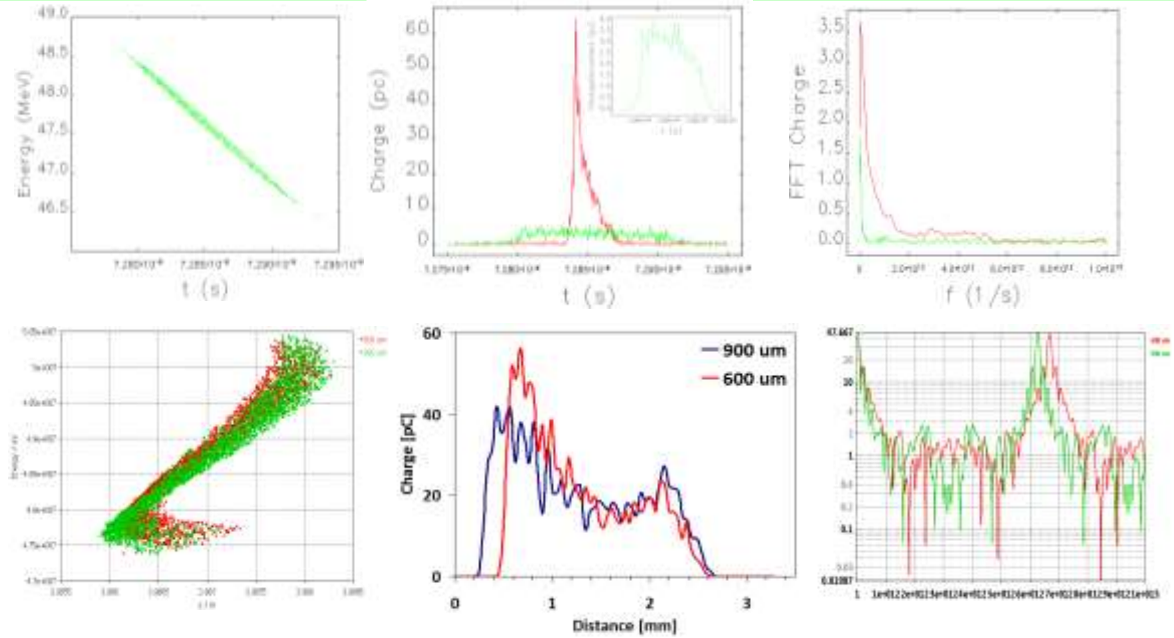
ASTA Beam Power (Peak):
20 – 150 GW
(= [20 MeV × 1 kA] ~ [50 MeV × 3 kA])

O(1 ps) ⇒ **Power (peak) Threshold of a CNT in Acceleration: 200 GW – 2 TW**

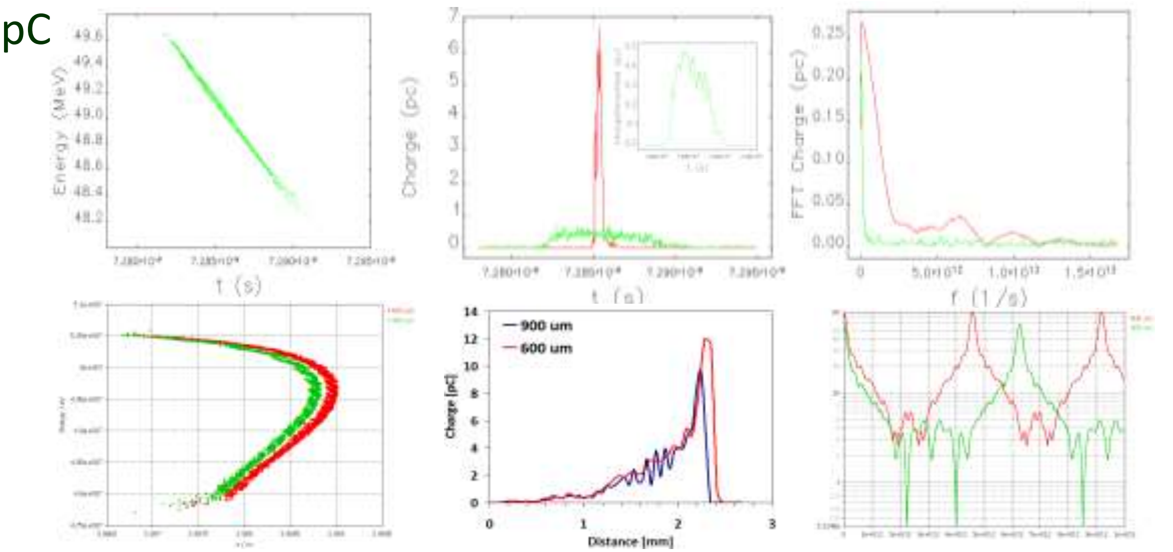
Relaxation Time (τ_s) ~ O (10ps) << 333 ns: No transient thermal heating

Bunch Charge

3 nC



250 pC



Crystal survivability?

Process

excite electronic plasma

tunnel ionization

partial or total lattice ionization

electronic plasma decay

via interband transitions

lifetime: (plasma frequency)-O(fs) $$\omega_p = \left(4\pi n_0 e^2 / m_e\right)^{1/2}$$

excitation of phonons in lattice

crystal disorder, fracture, or vaporization

lattice dissociation via

plasmon absorption

lifetime: (ion plasma frequency)$^{-1}$ $$\omega_{pi} = (m_e / m_i)^{1/2} \omega_p$$

vaporization O(10-100 fs)

hydrodynamic heating O(1-10 ps) [Livermore]

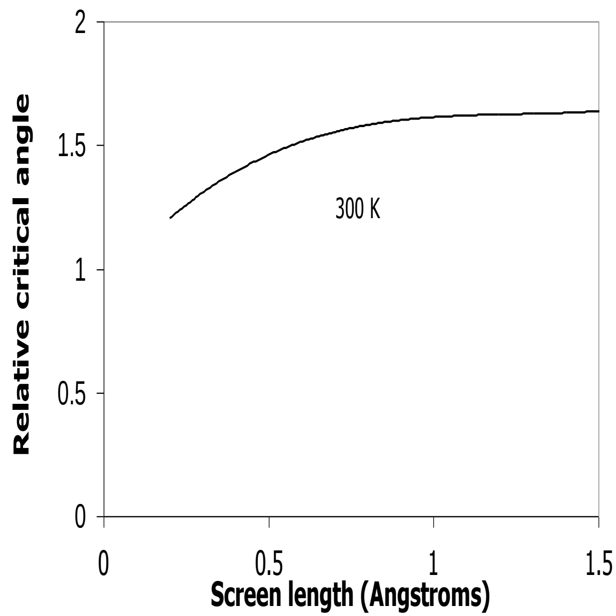
Dynamic channeling

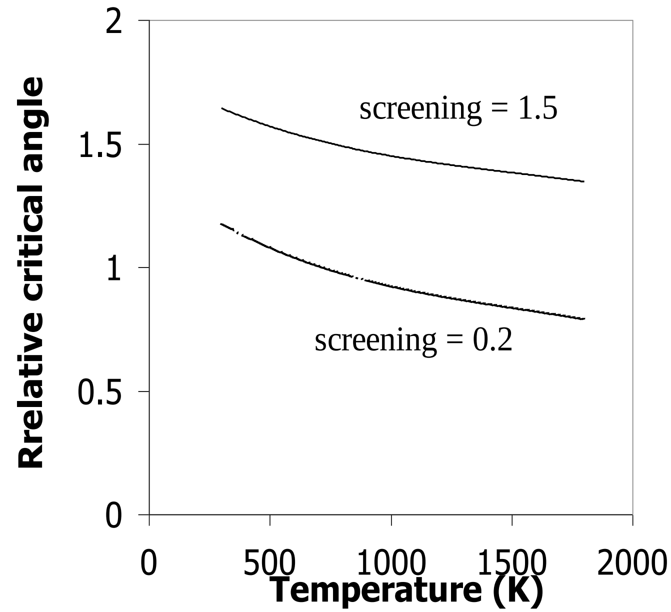
Intense beam through crystal could blow away electrons in much less than a picosecond

Acts like a larger screening length

$$\Psi_{1/2} = \frac{\Psi_L}{\sqrt{2}} \sqrt{\ln\left(\frac{r_0^2}{u_2^2 \ln 2}\right) + \ln\left(\frac{(Ca_{TF})^2 + u_2^2 \ln 2}{(Ca_{TF})^2 + r_0^2}\right)}$$

Andersen 96





Crystal destruction

ACCELERATION

G (gradient) proportional to $(n_0)^{1/2}$, P (power) prop to n_0

for G = 1 GeV/cm   P = 10^5 J/cm^3

10^{19} W/cm^3

for O(10 fs) @ 1 GeV/cm

LASER

10^{11} W/gm

Belotshitkii & Kumakhov (1979)

or 10^6 a/cm^2 for particle beam

10^{12} W/cm^3 ns long pulses

10^{13} W/cm^3 Chen-Noble (1987)

fracture threshold

O(0.1 ns) ref 16

Skin depth < 0.1 mm

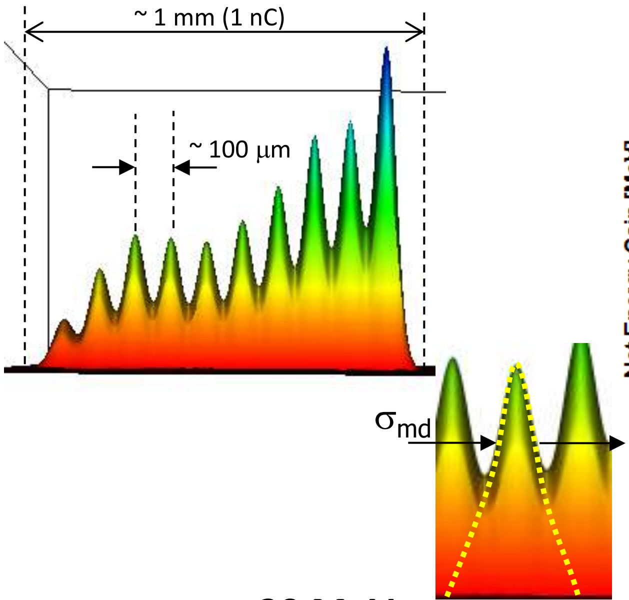
LATTICE IONIZED

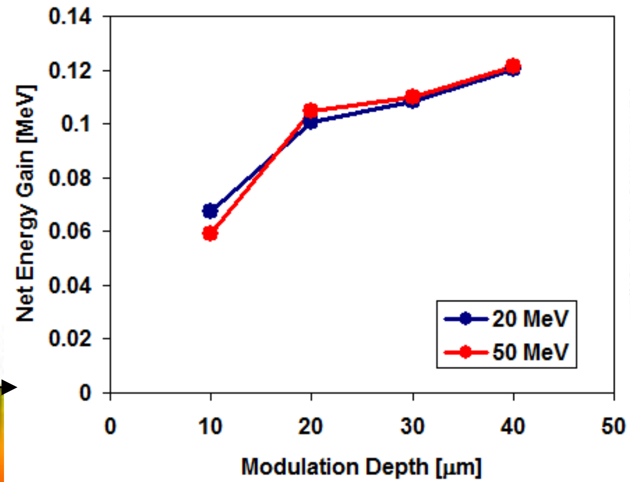
10^{15}-10^{16} W/cm^2 Chen & Noble (1996)/laser

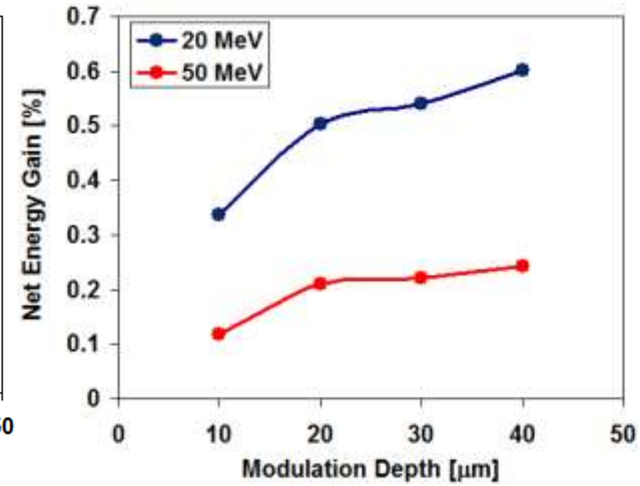
PARTICLE BEAM

10^{11} A/cm^2 Chen & Noble (1987) (crystal OK for 10 fs)

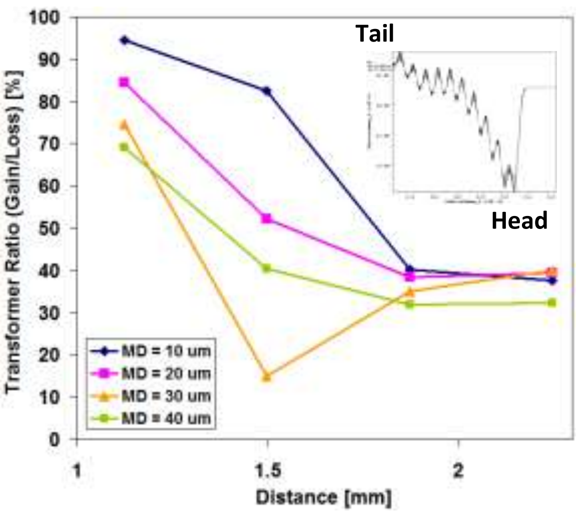
Energy Gain vs. Modulation Depth



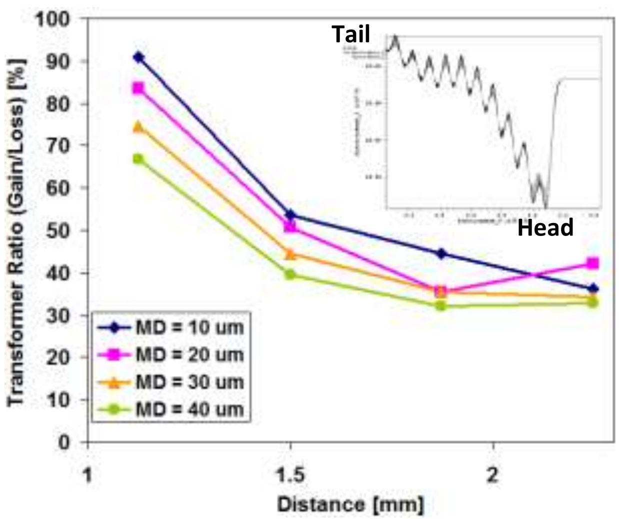


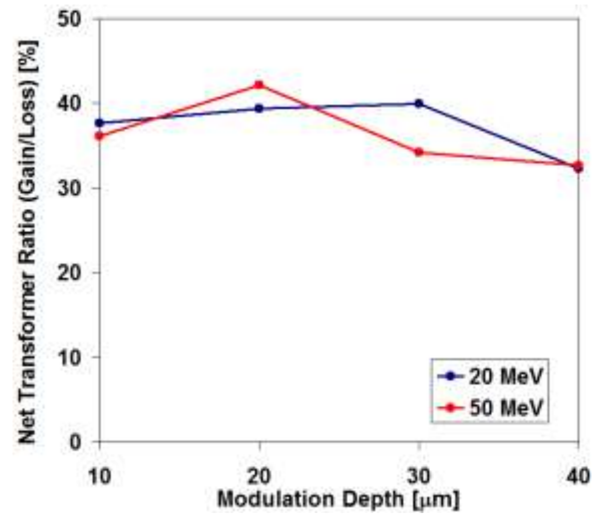


- 20 MeV -

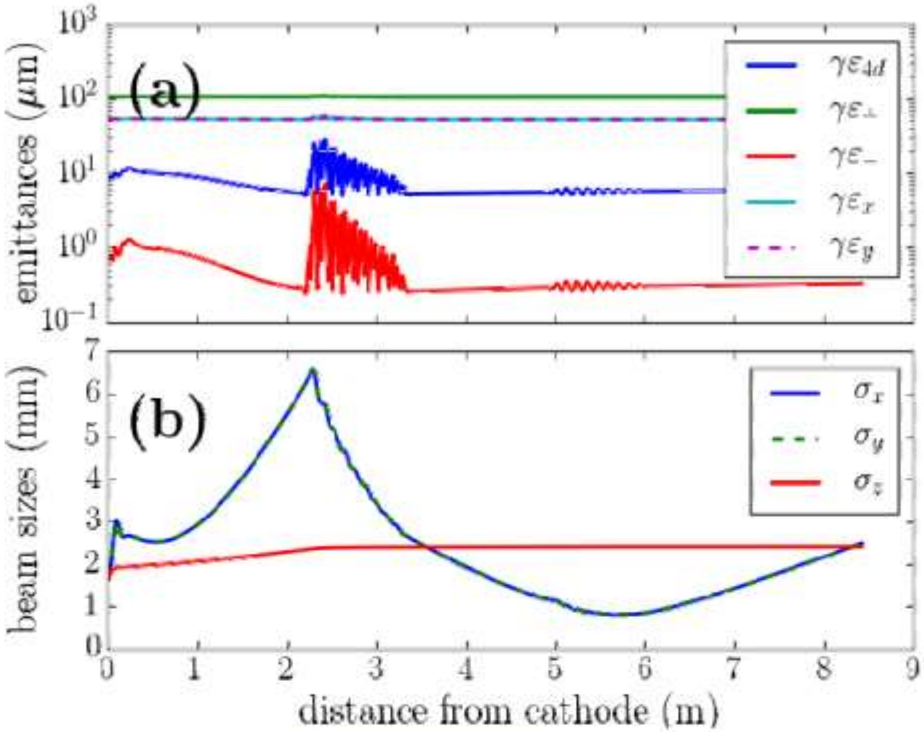


- 50 MeV -





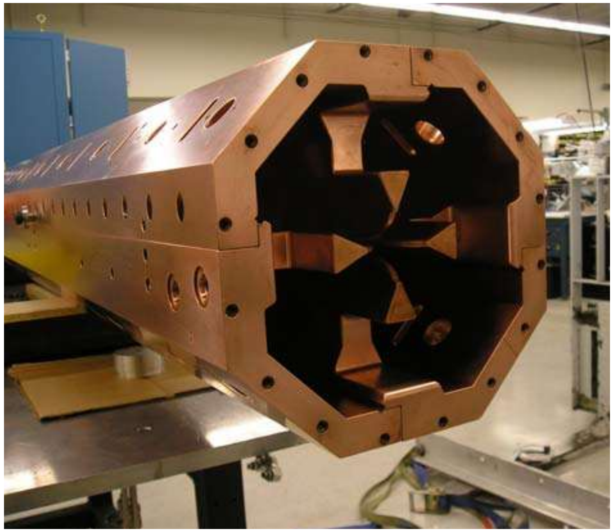
Minimum Spot Size



parameter	flat-beam configuration	round-beam configuration	units
Q	3.2	3.2	nC
E	47.18	48.77	MeV
ε_x	105.04	5.43	μm
ε_y	0.31	5.44	μm
ε_{4D}	5.53	5.44	μm
ρ	$\simeq 334$	$\simeq 1$	–

ice

RFQ Design and Specifications



Pulsed 4-vane RFQ:

Table 1. Initial Specifications for the RFQ Design

Input energy	50 keV
Output energy	2.5 MeV
Frequency, MHz	325
Accelerating beam current, mA	40
Peak surface field, kV/cm	<330
Acceleration efficiency,%	>95
Pulsed power losses in copper, kW	<450
Duty factor, %	1
Total length of vanes	302.428 cm
Average bore radius	3.4 mm
Input rms transverse emittance, normalized π mm mrad	0.25
Transverse emittance growth factor	<1.1
Longitudinal rms emittance, π keV deg	<150
Separation between operating and nearest dipole modes	>4 MHz

Longitudinal Diagnostics

Technique	Resolution	Charge needed
Streak camera	~0.6 ps sigma at 800 nm, range 0.5-25ps, phase stable*	8-10 nC
MPI	0.15 ps, range 0.3 to 1ps. CTR,CSR,CDR	10-50 nC, depends on σ_t
Ceramic gap	0.5 – 5 ps range	

*Temporal Jitter demonstrated at 0.5 ps rms shot to shot on laser.