Opportunities for Crystal Acceleration Research at FAST

Vladimir SHILTSEV , with input from Sergey Striganov

IOTA/FAST Collaboration Meeting and Workshop on High Intensity Beams in rings

June 12, 2019 - Fermilab

Motivation: "Ultimate" Colliders

- Post-100 TeV "Energy Frontier" assumes
  - ❖ 300-1000 TeV (*20-100 × LHC*)
  - ❖ "decent luminosity" (TBD)
- Surely we know:

circular collider

$$L \propto \frac{\eta P_{wall}}{E^3}\frac{\xi_y}{\beta_y}$$

1. For the same reason there is no circular ***e+e-*** collider above Higgs-F there will be no circular ***pp*** colliders beyond 100 TeV → **LINEAR**

2. Electrons radiate 100% *beam-strahlung* (<3 TeV) and in focusing channel (<10 TeV) → ***μ+μ-*** or ***pp***

linear collider

$$L \propto \frac{\eta_{\text{linac}} P_{wall}}{E}\frac{N_\gamma}{\sigma_y}$$

"Phase-Space" is Further Limited

- "Live within our means": for 20-100×LHC
  - < 10 B$
  - < 10 km
  - < 10 MW (beam power, ~100MW total)

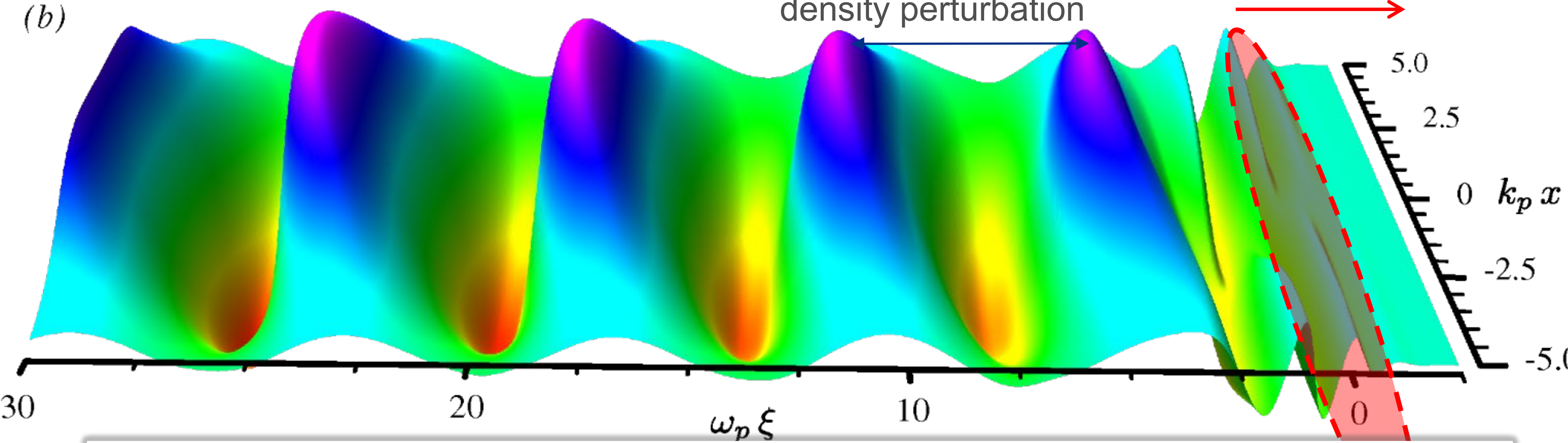
→New technology should provide >30 GeV/m @ total component cost <1M$/m (~NC magnets now)

SC magnets equiv. ~ 0.5 GeV per meter (LHC)

3. Only one option for >30 GeV/m known now:
dense plasma→ that excludes *protons*→ only *muons*

Plasma Waves

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)



Plasma wave: electron density perturbation

Laser/beam pulse ~ λ_p/c

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

Option A:

Short intense e-/e+/p bunch

Few 10^{16}cm^{-3}, **6 GV/m** over 0.3m

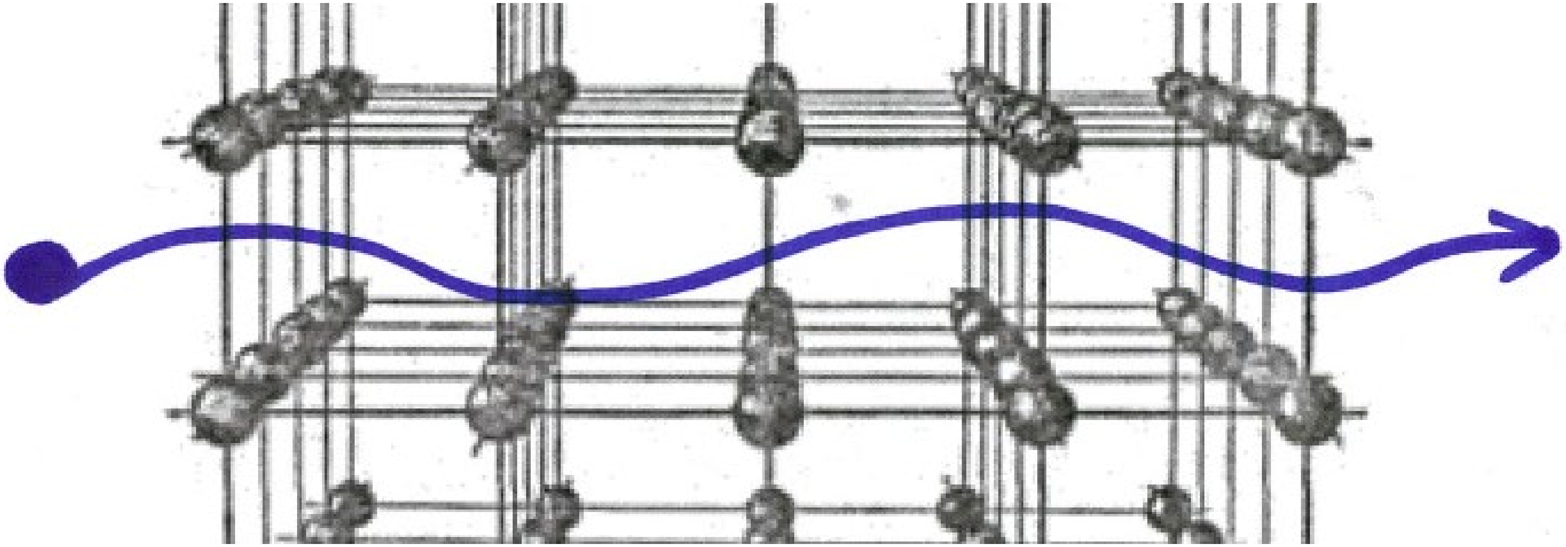
Option B:

Short intense laser pulse

~10^{18}cm^{-3}, **50 GV/m** over 0.1m

First looks into “Plasma-Collider”: **staging kills ! $\langle E \rangle$~2 GV/m,ε**

Novelty of the Approach:
Acceleration in Continuous Focusing Channel



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

10^{22} cm^{-3} → 10 TV/m, λ_p~0.3μm

10^{24} cm^{-3} → 100 TV/m, λ_p~0.03μm

Synchtrotron radiation losses balance energy gain:
0.3TeV for positrons
10 000 TeV for muons (+)
1000 000 TeV for protons

Chen P, Noble R J *AIP Conf. Proc.* **398** 273 (1997)

Linear $\mu+\mu-$ Crystal X-ray Collider

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

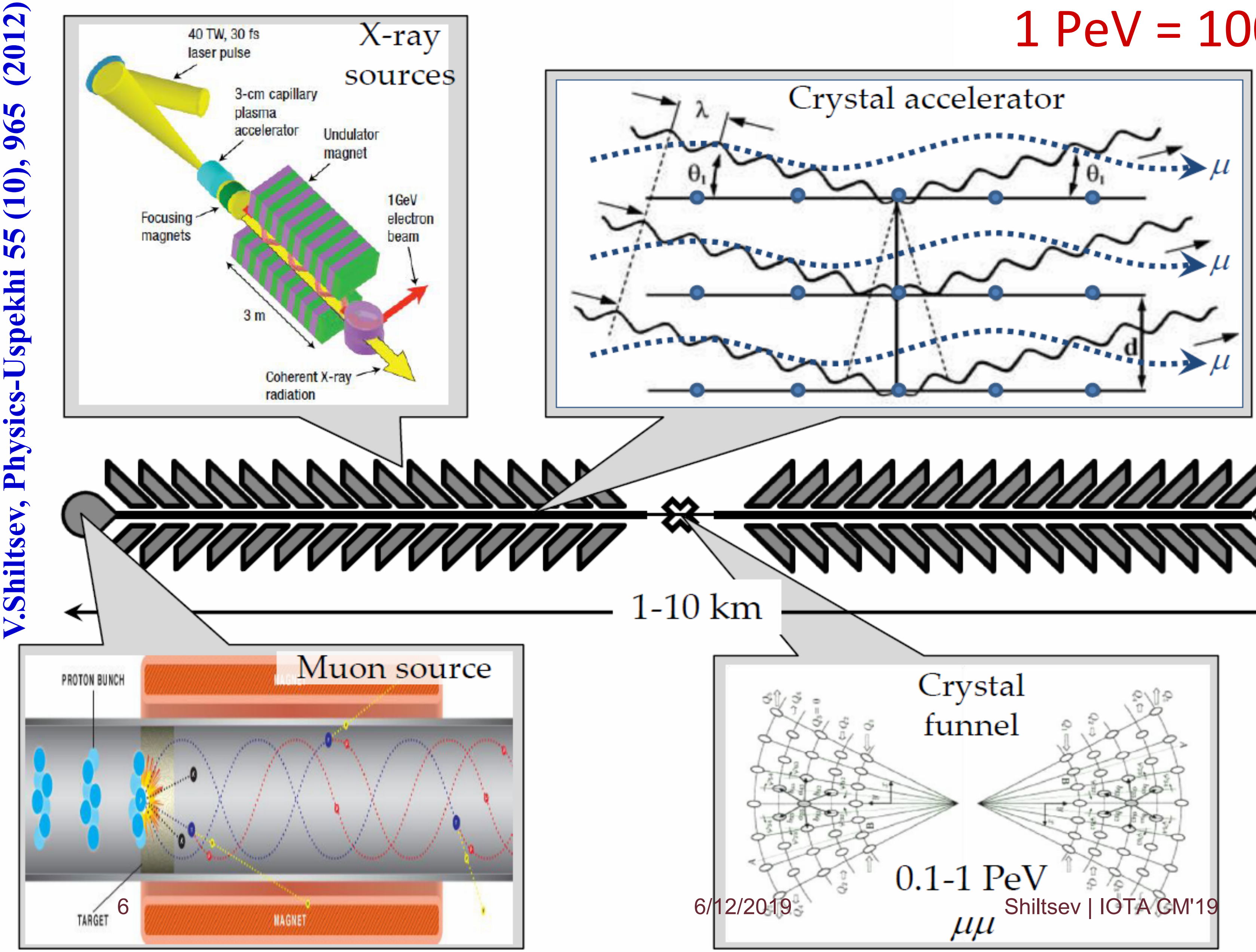
1 PeV = 1000 TeV

n_μ ~1000

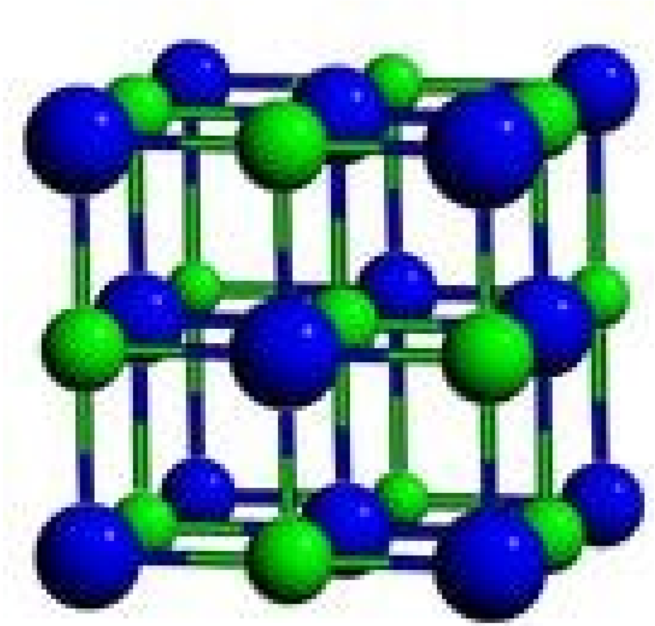
n_B ~100

f_{rep} ~10^6

L ~10^{30-32}

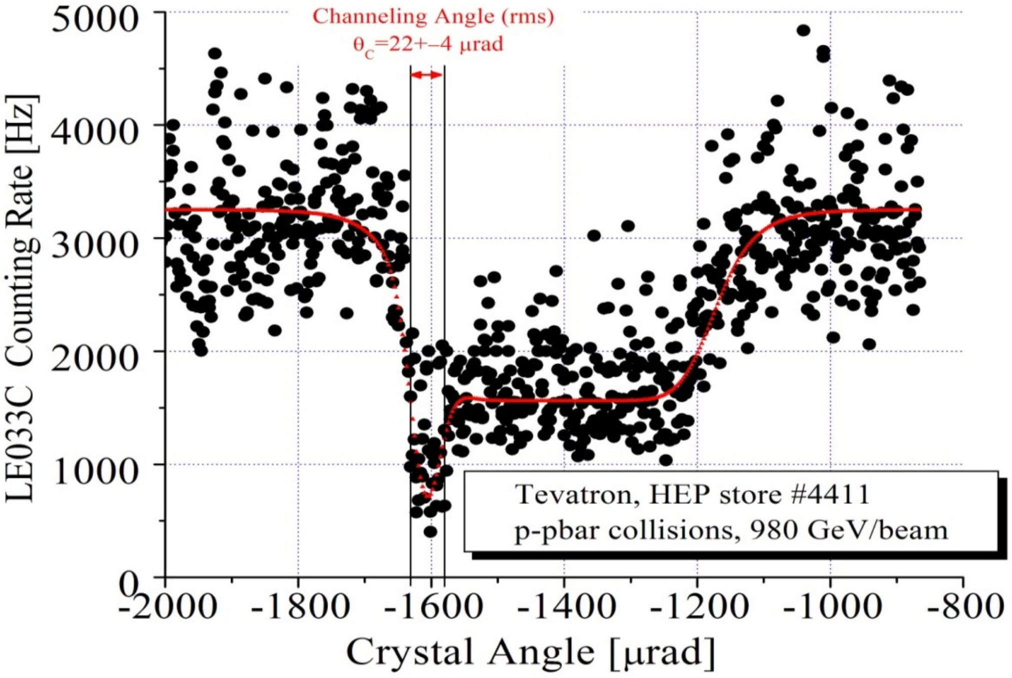


What Do We Know about Crystals?



$$l_{\mathrm{d}}\,[\mathrm{m}] \sim E\,[\mathrm{TeV}]$$

T980 experiment at Tevatron, *N.Mokhov et al JINST 6 T08005 (2011)*

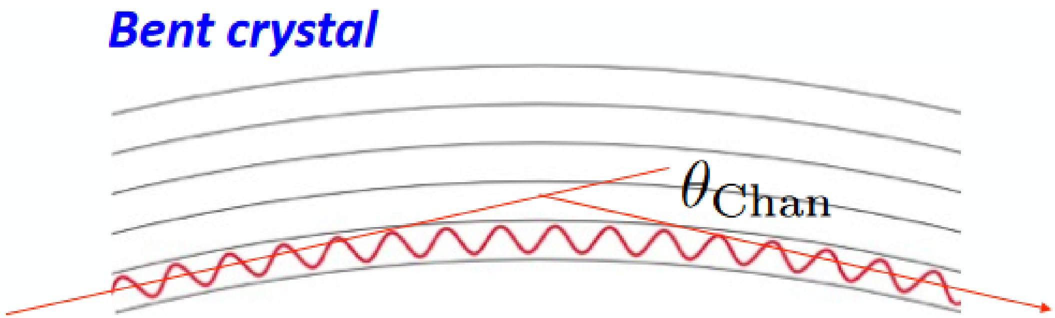


- Strong inter-planar electric fields ~10V/A=1GV/cm
- Very stable, can be used for
  - deflection/bending (*works*)
  - focusing (*works*)
  - acceleration (*if excited*)

~92.5+-5% efficiency

Or *l_d* ~ 5mm/0.025 < 0.2m

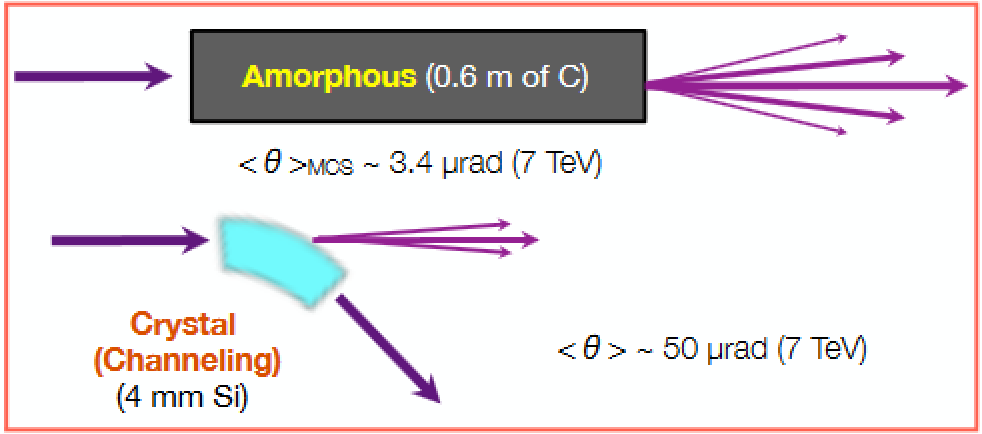
Bent Crystals in the 7 TeV LHC Beams



S. Redaelli, Physics Beyond Colliders, 06/09/2016

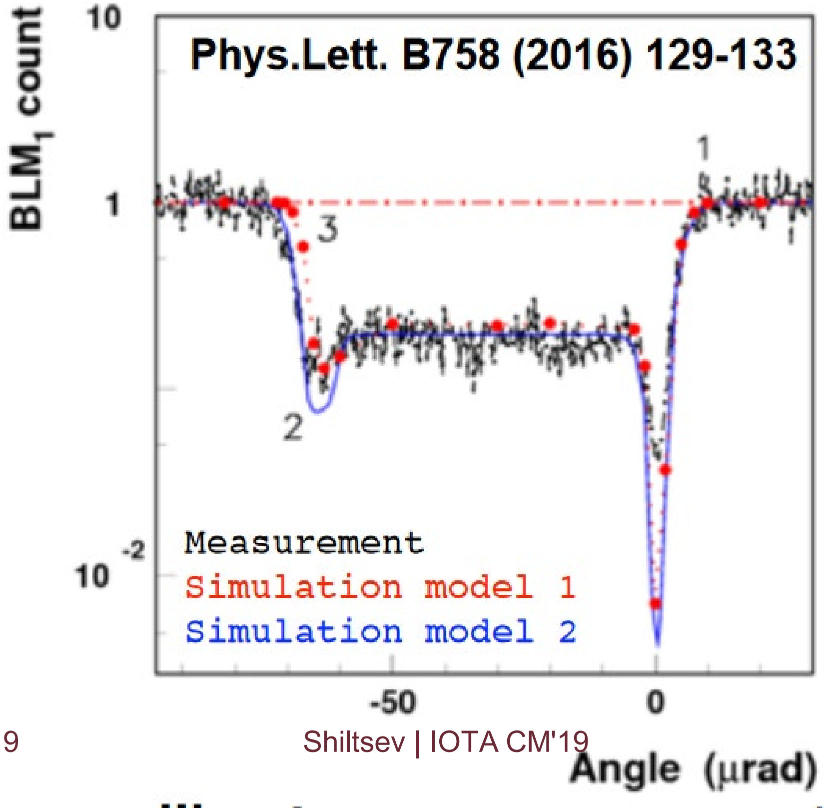
~2 mrad at 7 TeV

Equivalent magnetic field for **50µrad** at **7 TeV** proton beams: **310 T** (4 mm crystal)

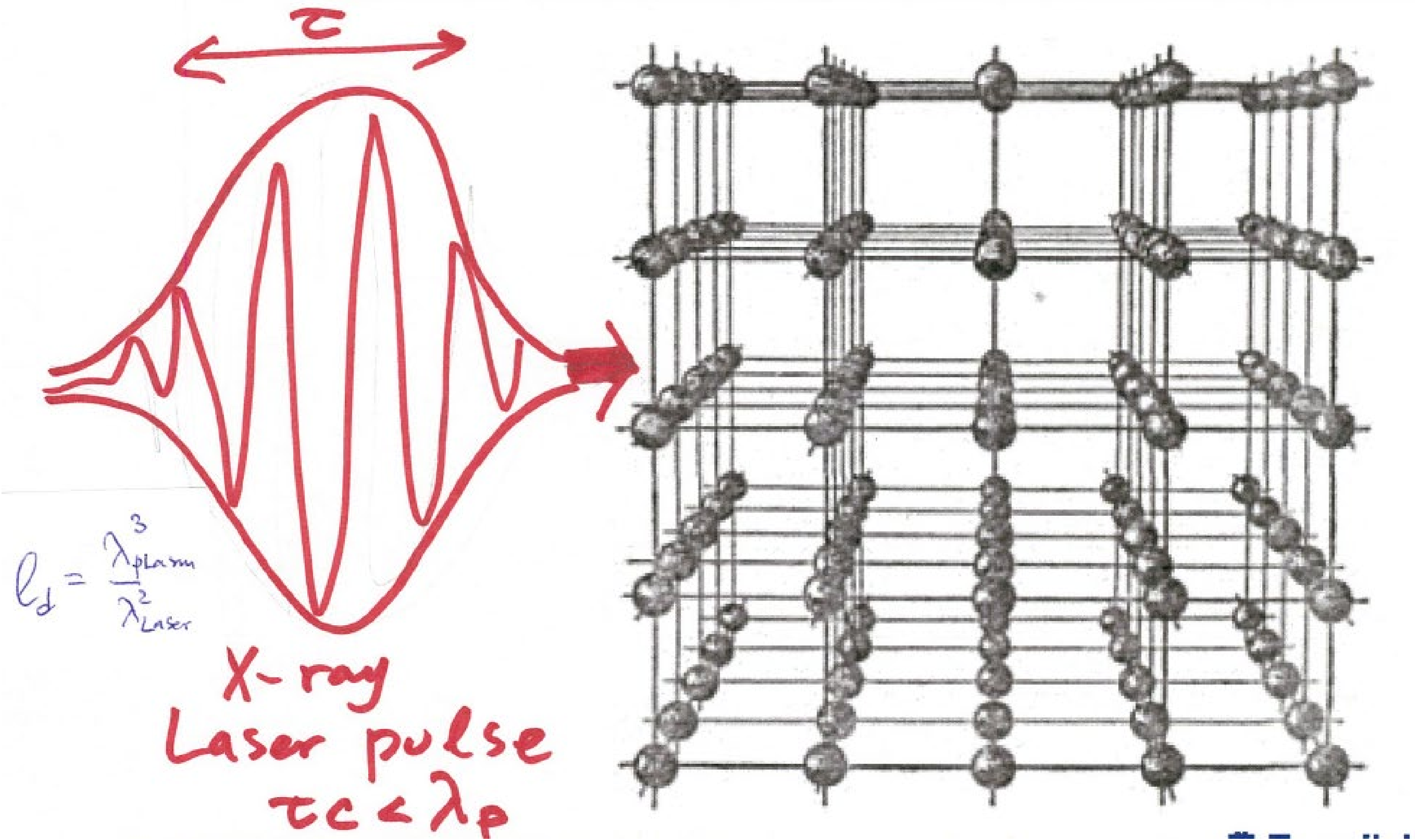


~99.5% efficiency

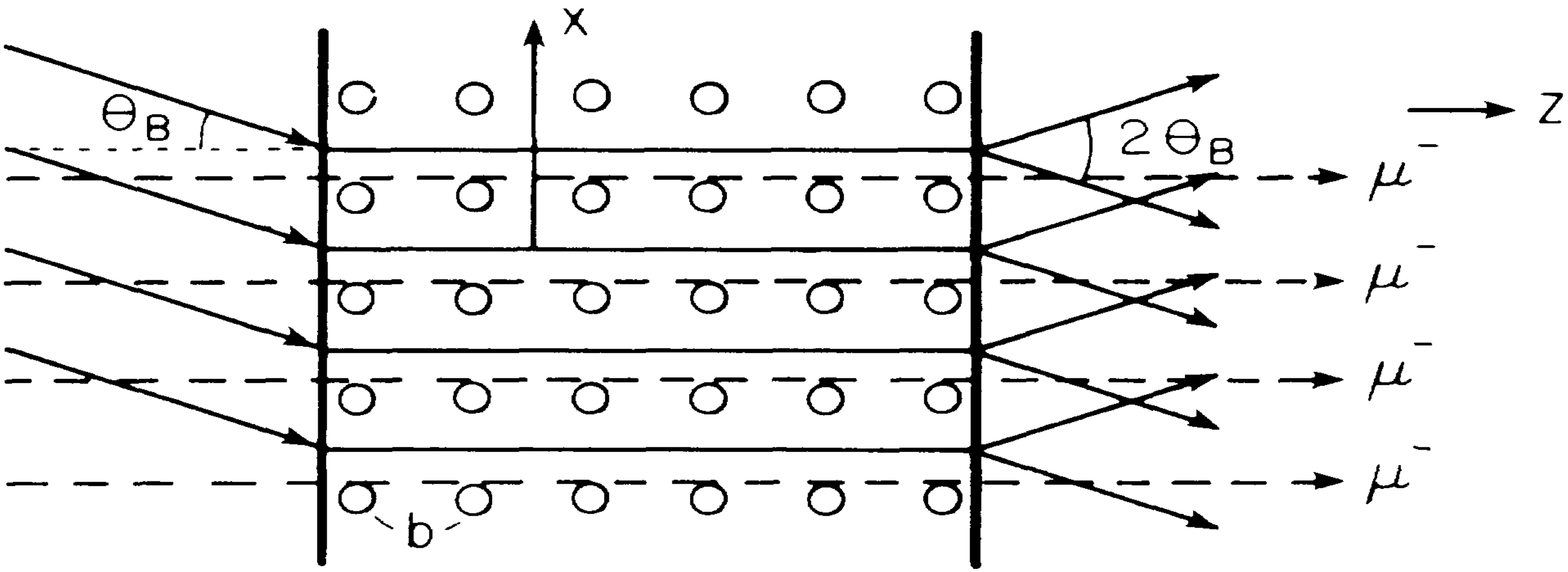
Or *l_d* ~ 4mm/0.005=0.8m



Ways to excite the crystal (1)



Crystal Excitation by X-Rays



Tajima,Cavenago, Phys. Rev. Lett. 59 (1987), 1440

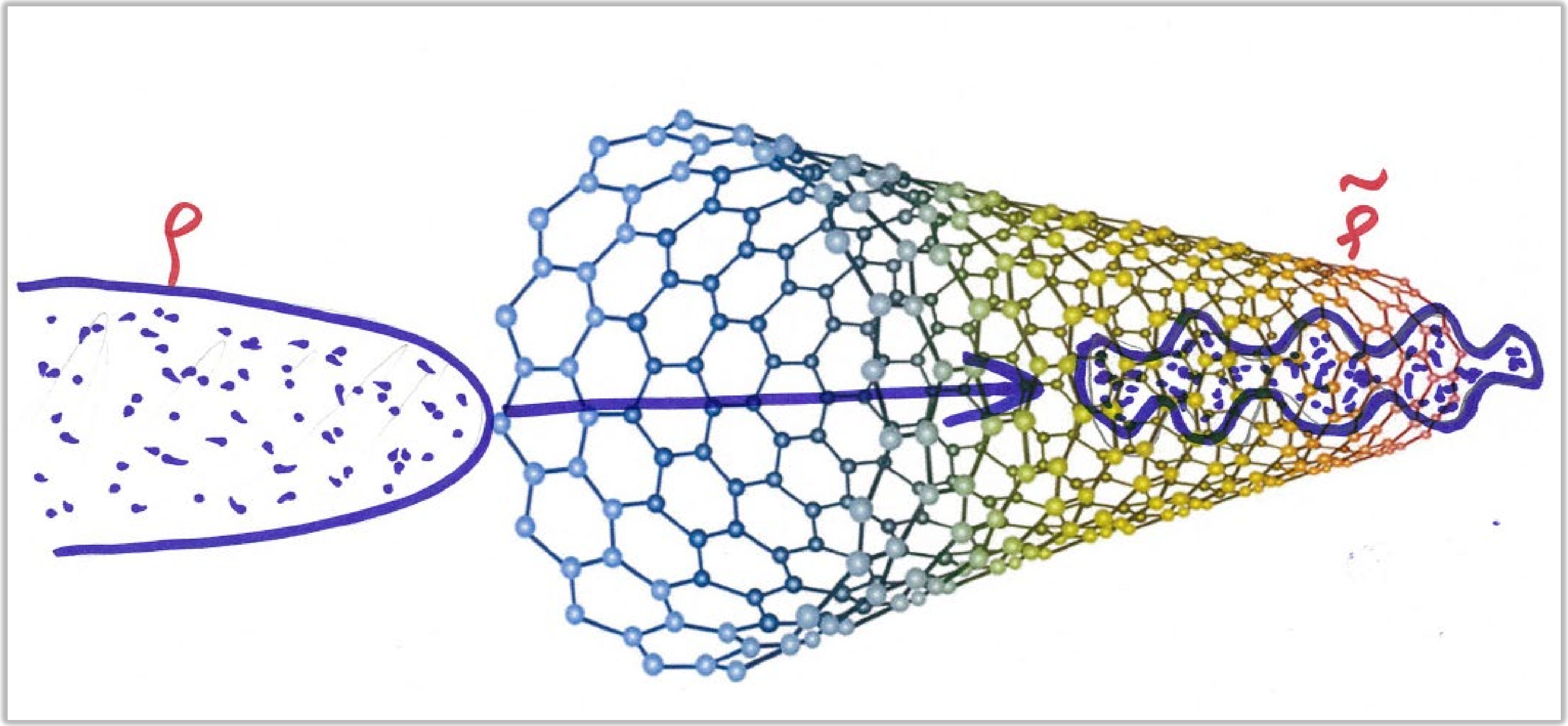
FIG. 1. Bormann anomalous transmission. When the x rays are injected at the Bragg angle, the Bormann effect takes place. Particle beams are injected along the crystal axis.

- Need 40keV high peak power x-rays
  - ➢ now available from SASE FELs like LCLS
- Gradients >1GV/cm

- Muons preferred
  - ➢ No bremstrahlung, no nucl.
- μ+ rad length 10^9 cm
  - ➢ total energy~10^9 GeV

…several other ways were proposed (short bunches, ion clusters, dislocations, etc)…

Excite Nanotubes/Crystals (5) by Self-Mod'n Instability in long(er) charge particle beams



AWAKE

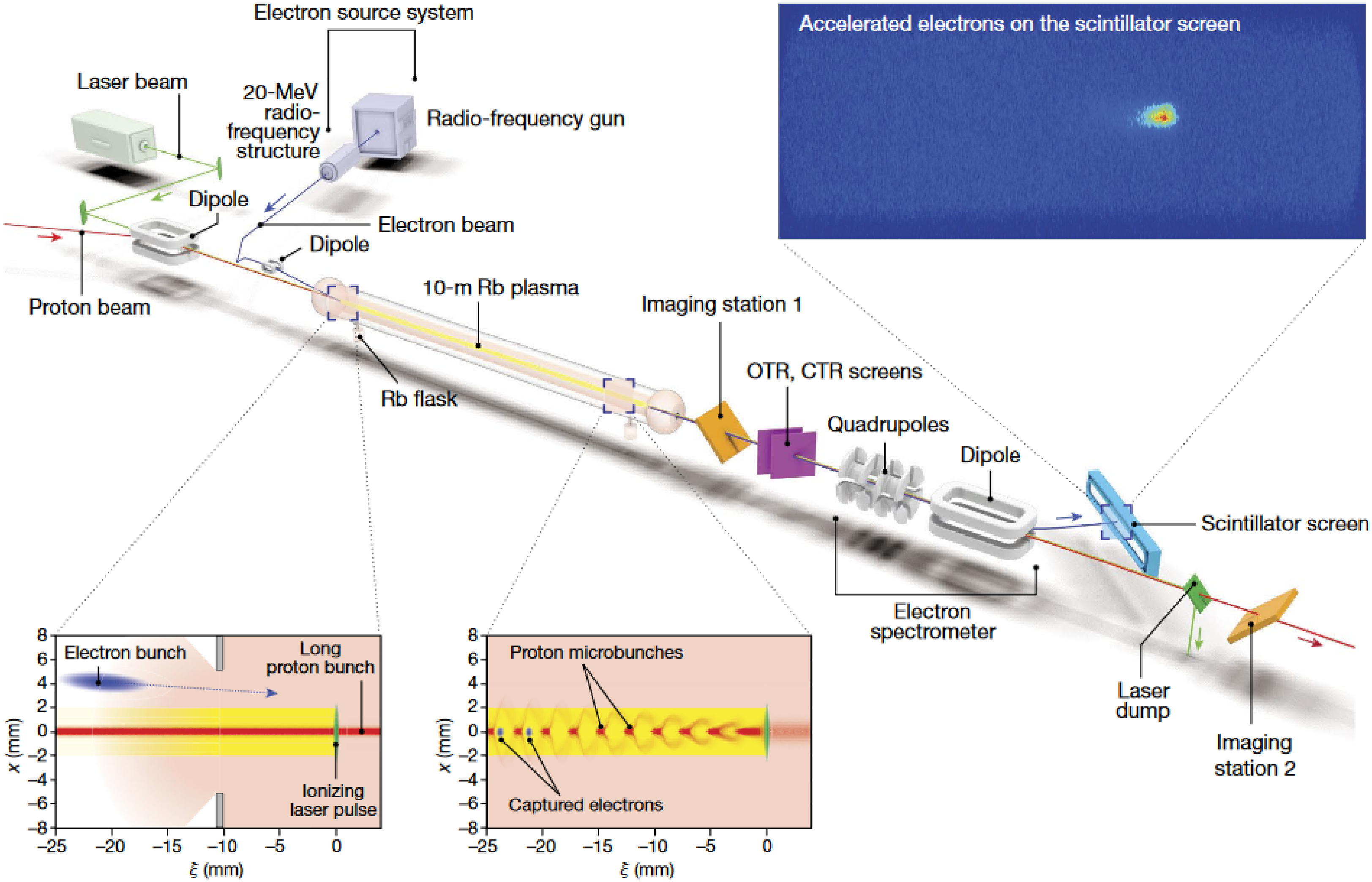
LETTER

OPEN

https://doi.org/10.1038/s41586-018-0485-4

Acceleration of electrons in the plasma wakefield of a proton bunch

E. Adli[1], A. Ahuja[2], O. Apsimon[3,4], R. Apsimon[4,5], A.-M. Bachmann[2,6,7], D. Barrientos[2], F. Batsch[2,6,7], J. Bauche[2],



Fermilab, June 24-26, 2019

Workshop on Beam Acceleration in Crystals and Nanostructures

https://indico.fnal.gov/event/19478/

Organized by T. Tajima (UCI) and V. Shiltsev (FNAL)
Proceedings Editors: G. Mourou, V. Shiltsev, T. Tajima

Endorsed by: APS GPAP, APS DPB, ICFA ANA, ICUIL

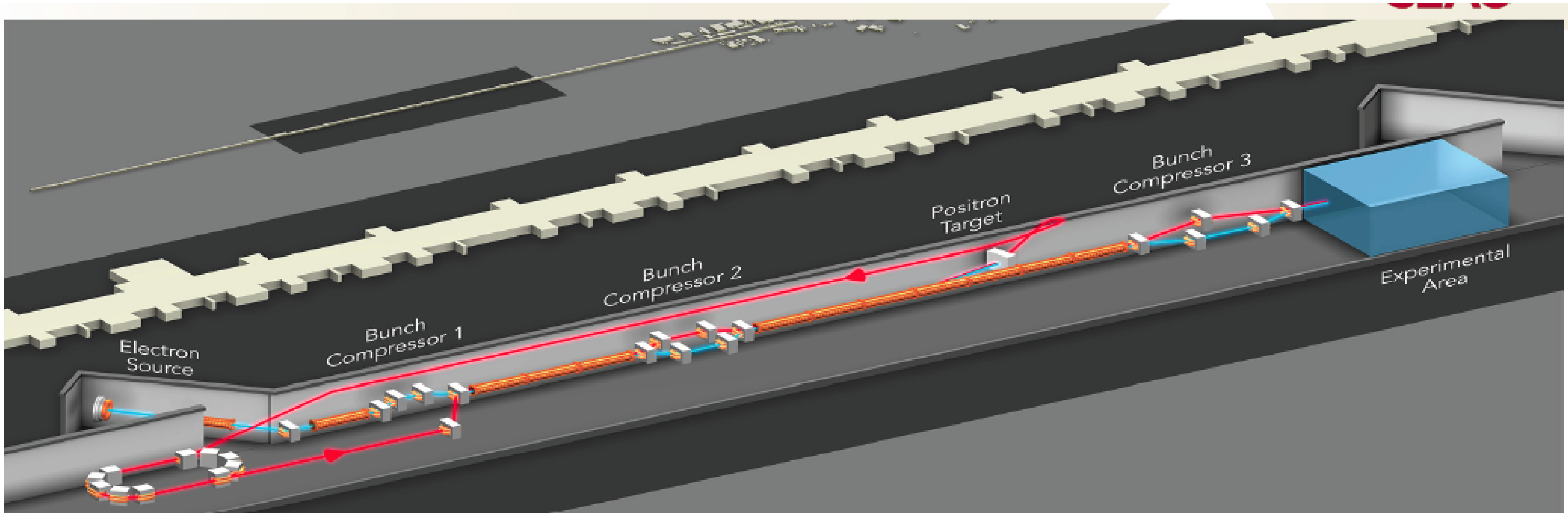
TOPICS FOR STUDIES (WORKSHOP'19)

- overview of the past and present theoretical developments toward crystal acceleration, ultimate possibilities of the concept
- concepts and prospects of PeV colliders for HEP
- effective crystal wave drivers : beams/SMI*, lasers , other
- beam dynamics* in crystal acceleration
- instabilities in crystal acceleration (filamentation*, etc)
- acceleration in nanostructures (CNTs*, etc)
- muon sources* for crystal acceleration
- application of crystal accelerators (Xray sources, etc)
- steps toward "proof-of-principle" : 1 GeV gain over 1 mm, open theory questions, modeling and simulations
- possible experiments at FACET, FAST, AWAKE, AWA, or elsewhere

* can be studied at FAST

Ultimate Testbed

FACET-II | Facility for Advanced Accelerator Experimental Tests



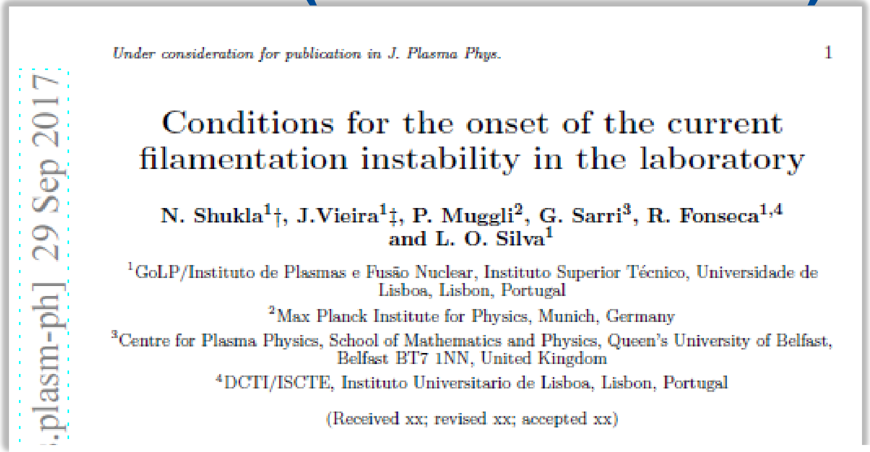
Electron Beam Parameter	*Baseline Design*	*Operational Ranges*
Final Energy [GeV]	*10*	*4.0-13.5*
Charge per pulse [nC]	*2*	*0.7-5*
Repetition Rate [Hz]	*30*	*1-30*
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19 [μm]	*4.4, 3.2*	*3-6*
Spot Size at IP $\sigma_{x,y}$ [μm]	*18, 12*	*5-20*
Min. Bunch Length σ_z (rms) [μm]	*1.8*	*0.7-20*
Max. Peak current I_{pk} [kA]	*72*	*10-200*

Positron Beam Parameter	*Baseline Design*	*Operational Ranges*
Final Energy [GeV]	*10*	*4.0-13.5*
Charge per pulse [nC]	*1*	*0.7-2*
Repetition Rate [Hz]	*5*	*1-5*
Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19	*10, 10*	*6-20*
Spot Size at IP $\sigma_{x,y}$ [μm]	*16, 16*	*5-20*
Min. Bunch Length σ_z (rms)	*16*	*8*
Max. Peak current I_{pk} [kA]	*6*	*12*

FACET-II Beams

- Compression X Y Z 8x7x2 um , 2 nC →
  - n_e~0.6e19 cm-3
- Compression X Y Z 2x2x0.4 um , 2 nC →
  - n_e~2e20 cm-3
- Peak currents:
  - 70…100…300 kA !

Weibel (Filamentation) Instability



Conditions for the onset of the current filamentation instability in the laboratory

N. Shukla[1]†, J.Vieira[1]‡, P. Muggli[2], G. Sarri[3], R. Fonseca[1,4] and L. O. Silva[1]

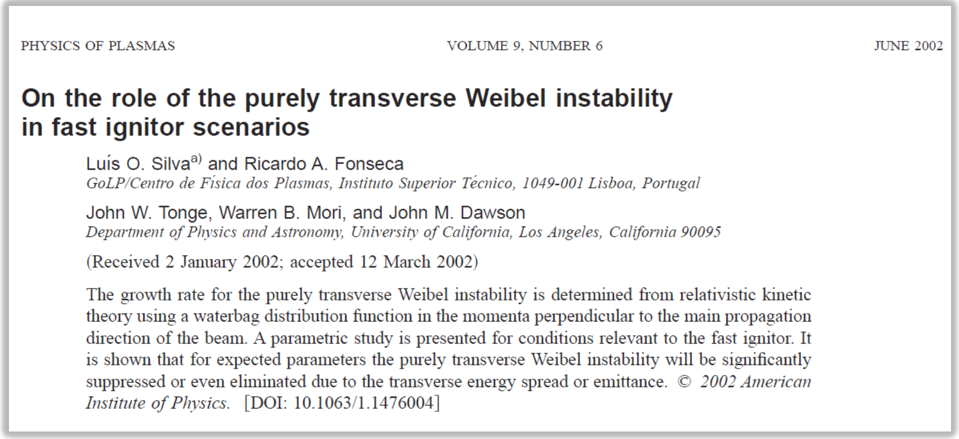
[1]GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

[2]Max Planck Institute for Physics, Munich, Germany

[3]Centre for Plasma Physics, School of Mathematics and Physics, Queen's University of Belfast, Belfast BT7 1NN, United Kingdom

[4]DCTI/ISCTE, Instituto Universitario de Lisboa, Lisbon, Portugal

(Received xx; revised xx; accepted xx)



PHYSICS OF PLASMAS VOLUME 9, NUMBER 6 JUNE 2002

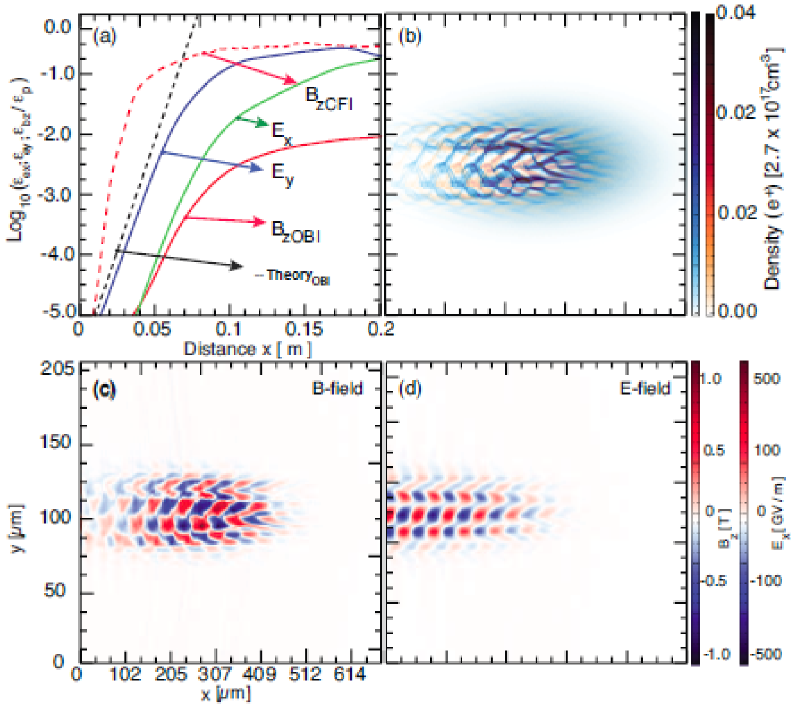
On the role of the purely transverse Weibel instability in fast ignitor scenarios

Luís O. Silva[a] and Ricardo A. Fonseca
GoLP/Centro de Física dos Plasmas, Instituto Superior Técnico, 1049-001 Lisboa, Portugal

John W. Tonge, Warren B. Mori, and John M. Dawson
Department of Physics and Astronomy, University of California, Los Angeles, California 90095

(Received 2 January 2002; accepted 12 March 2002)

The growth rate for the purely transverse Weibel instability is determined from relativistic kinetic theory using a waterbag distribution function in the momenta perpendicular to the main propagation direction of the beam. A parametric study is presented for conditions relevant to the fast ignitor. It is shown that for expected parameters the purely transverse Weibel instability will be significantly suppressed or even eliminated due to the transverse energy spread or emittance. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1476004]



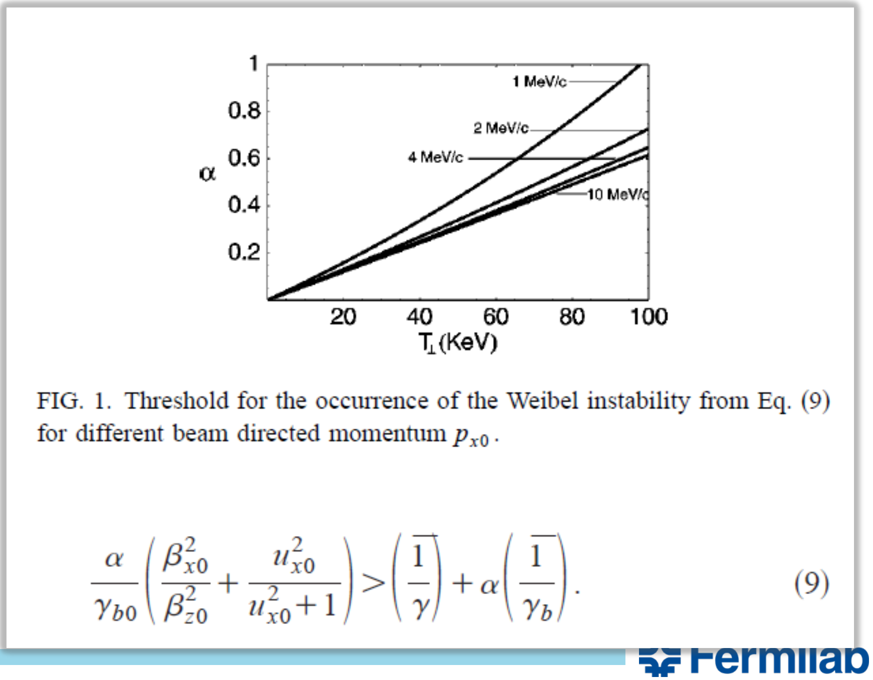
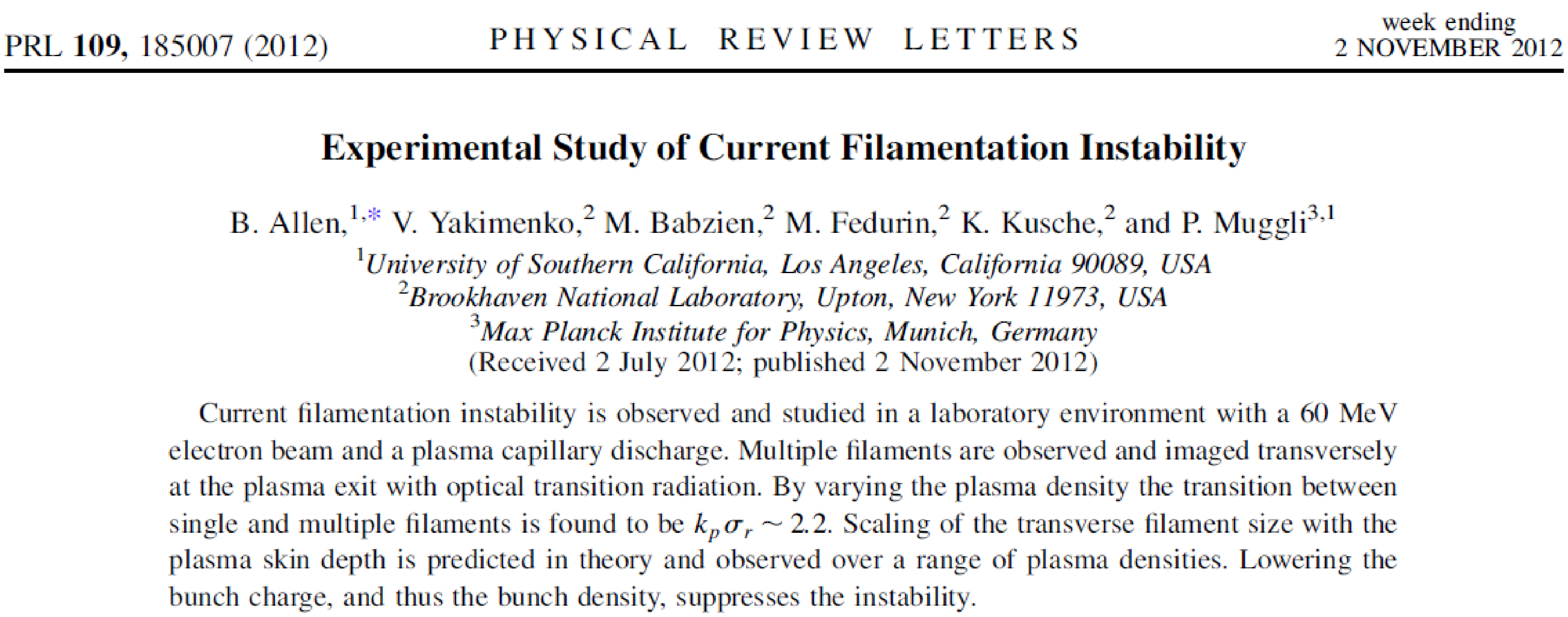


FIG. 1. Threshold for the occurrence of the Weibel instability from Eq. (9) for different beam directed momentum p_{x0}.

$$\frac{\alpha}{\gamma_{b0}}\left(\frac{\beta_{x0}^2}{\beta_{z0}^2}+\frac{u_{x0}^2}{u_{x0}^2+1}\right)>\left(\overline{\frac{1}{\gamma}}\right)+\alpha\left(\overline{\frac{1}{\gamma_b}}\right). \tag{9}$$



PRL **109,** 185007 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

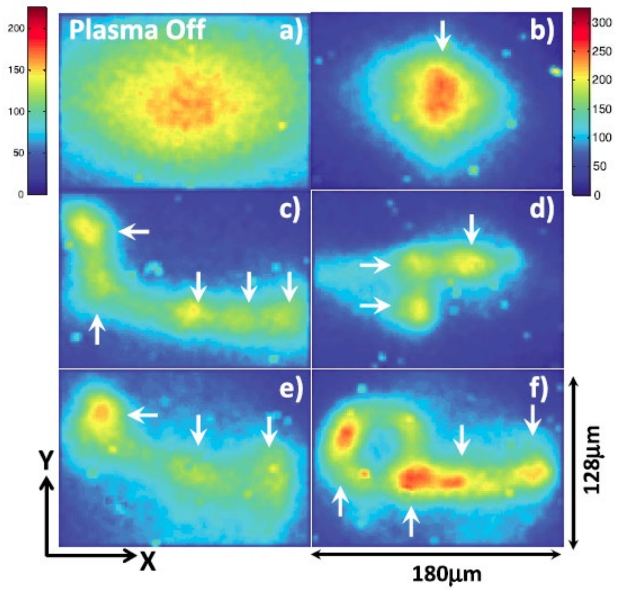
Experimental Study of Current Filamentation Instability

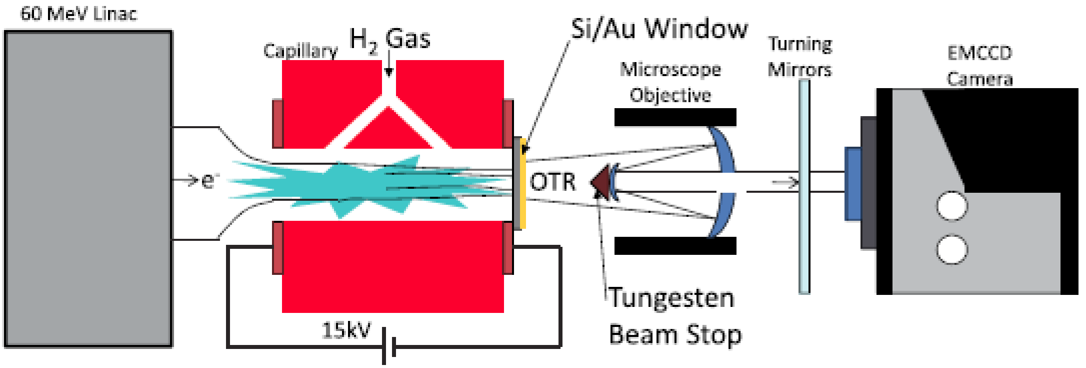
B. Allen,[1,*] V. Yakimenko,[2] M. Babzien,[2] M. Fedurin,[2] K. Kusche,[2] and P. Muggli[3,1]
[1]*University of Southern California, Los Angeles, California 90089, USA*
[2]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[3]*Max Planck Institute for Physics, Munich, Germany*

(Received 2 July 2012; published 2 November 2012)

Current filamentation instability is observed and studied in a laboratory environment with a 60 MeV electron beam and a plasma capillary discharge. Multiple filaments are observed and imaged transversely at the plasma exit with optical transition radiation. By varying the plasma density the transition between single and multiple filaments is found to be $k_p\sigma_r \sim 2.2$. Scaling of the transverse filament size with the plasma skin depth is predicted in theory and observed over a range of plasma densities. Lowering the bunch charge, and thus the bunch density, suppresses the instability.

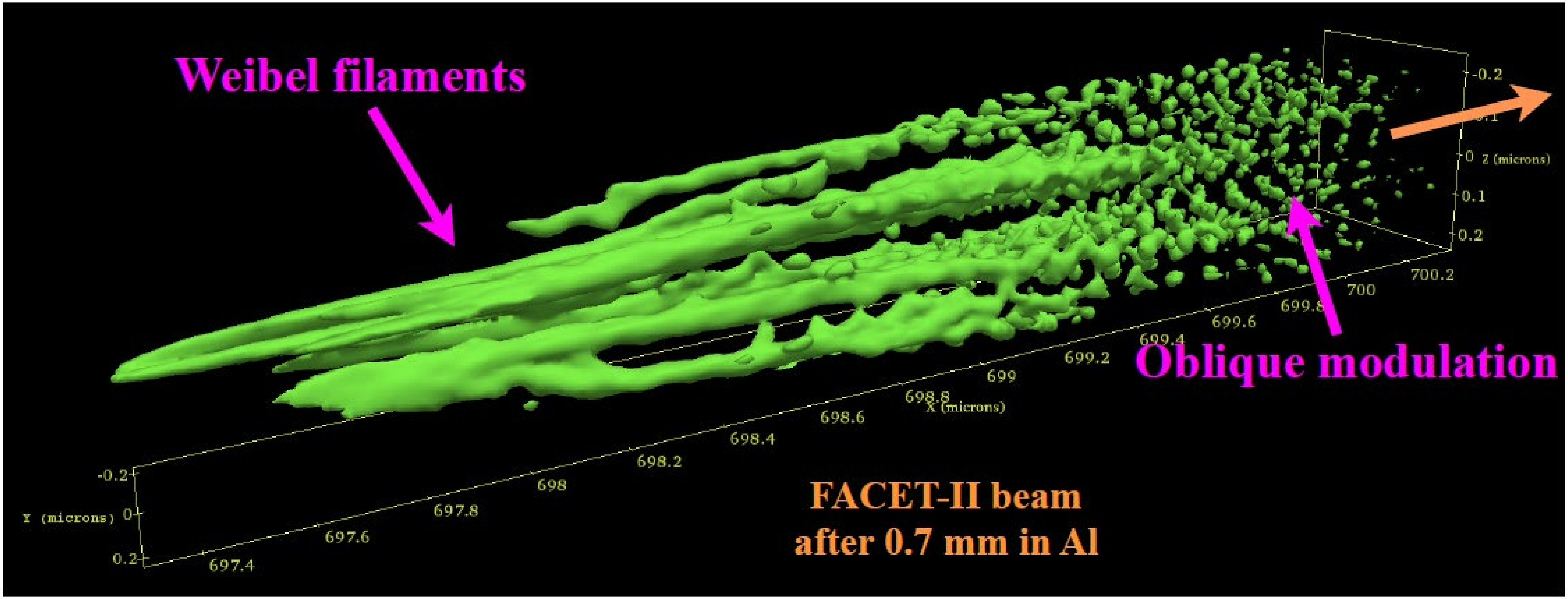
DOI: 10.1103/PhysRevLett.109.185007 PACS nu





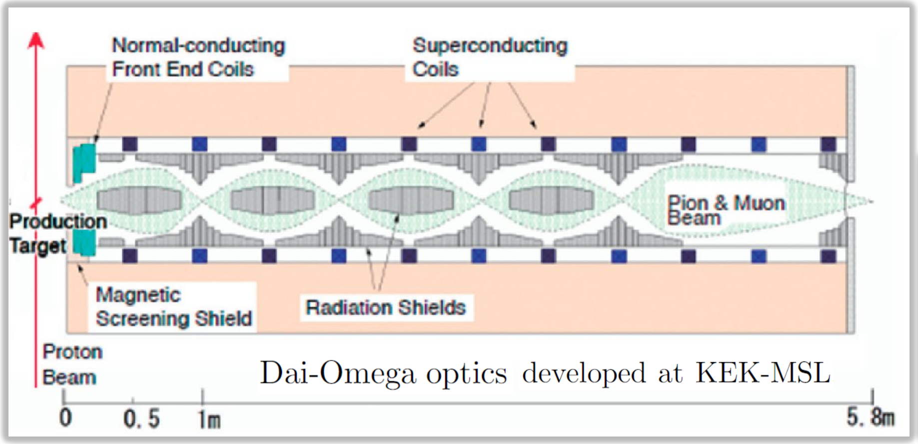
FACET-II

- *Proposal #43:* Beam filamentation and bright gamma-ray bursts
  - Sébastien Corde(ÉcolePolytechnique/LOA)
  - Ken Marsh (UCLA)
  - Frederico Fiuza (SLAC)

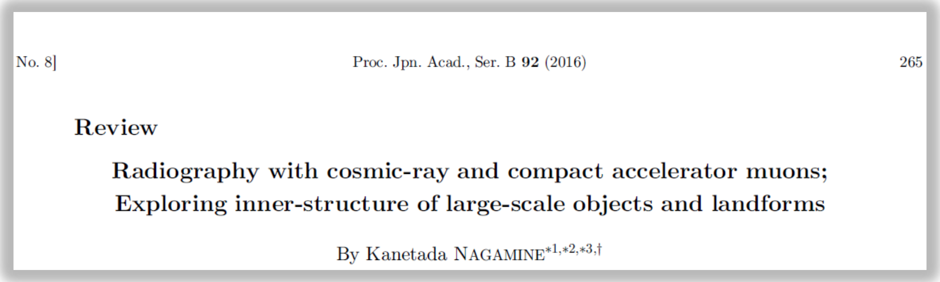


MUON PRODUCTION AND CHANNELING

- Advanced schemes



Dai-Omega optics developed at KEK-MSL

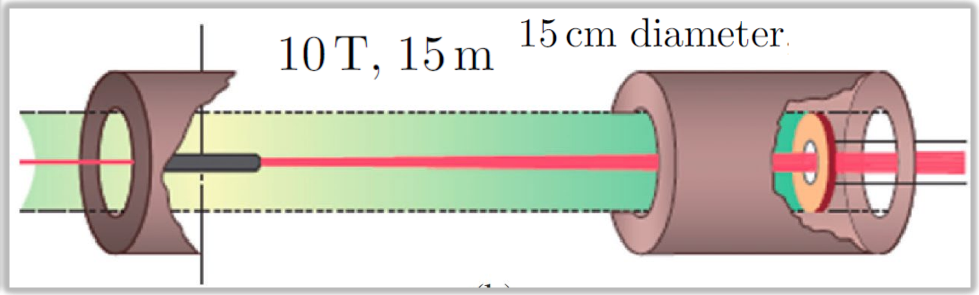


No. 8] Proc. Jpn. Acad., Ser. B **92** (2016) 265

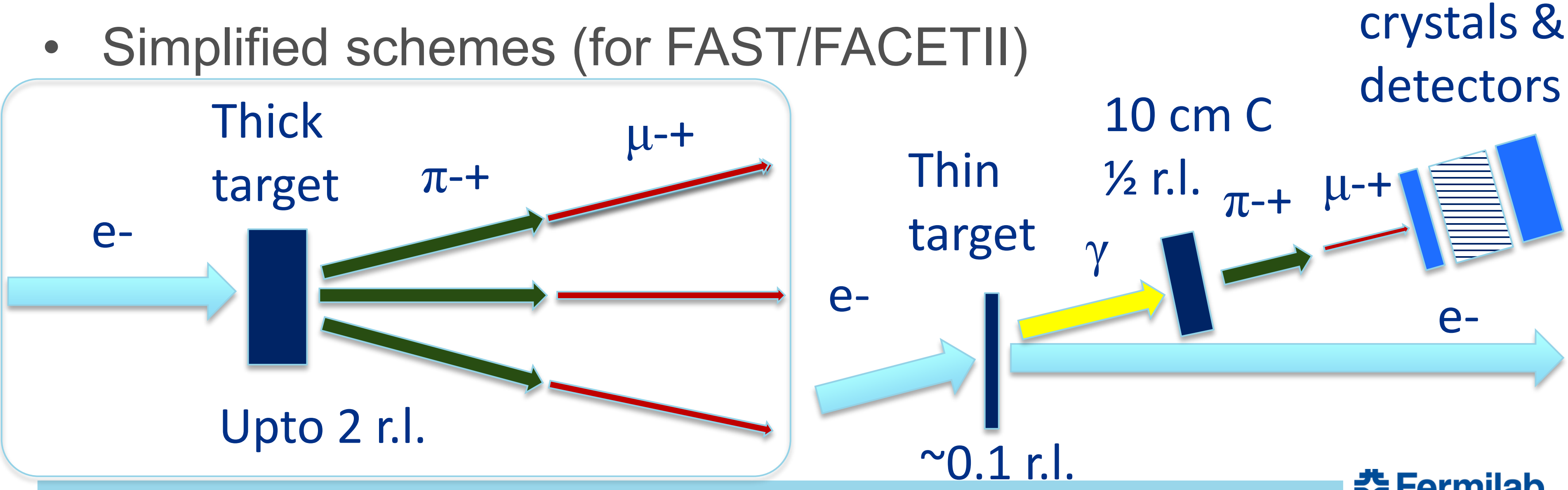
Review

Radiography with cosmic-ray and compact accelerator muons; Exploring inner-structure of large-scale objects and landforms

By Kanetada NAGAMINE[*1,*2,*3,†]



- Simplified schemes (for FAST/FACETII)



e-

Thick target

π-+

μ-+

Upto 2 r.l.

e-

Thin target

~0.1 r.l.

γ

10 cm C

½ r.l.

π-+

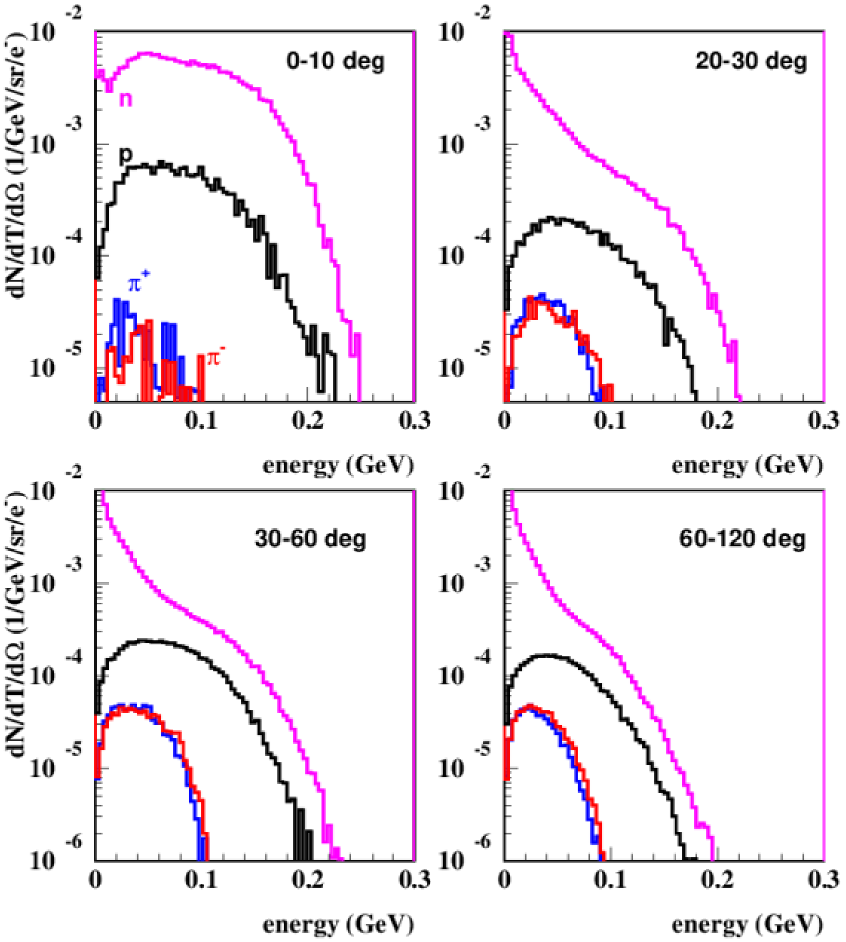
μ-+

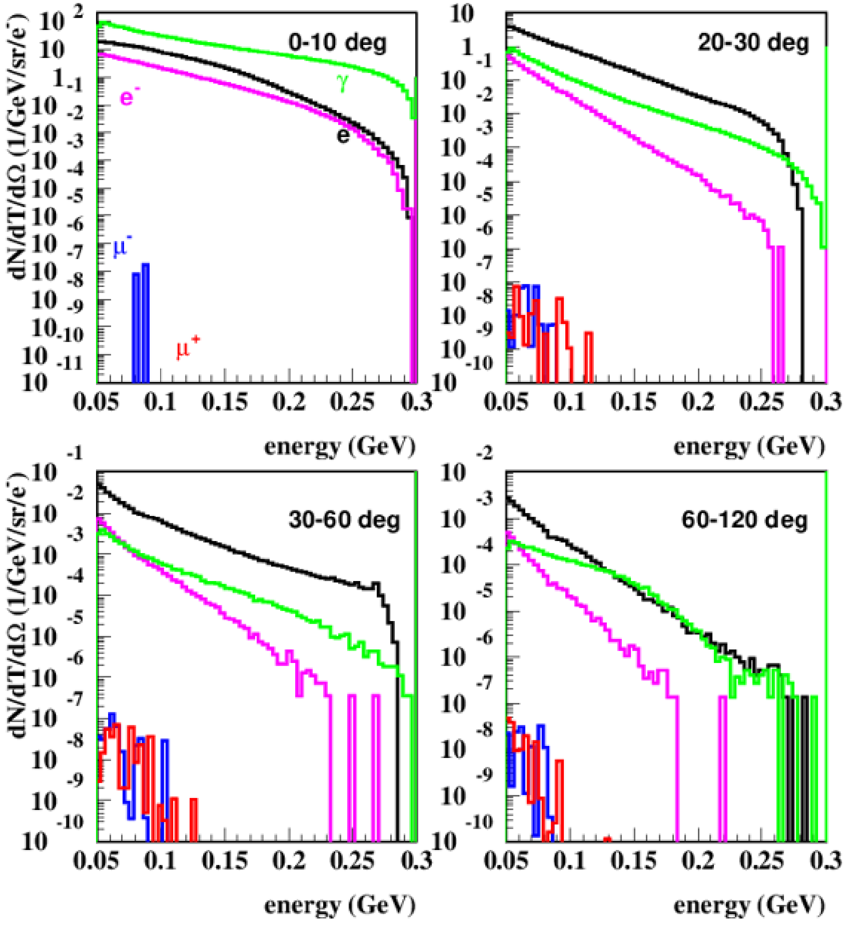
crystals & detectors

e-

Secondary particle production
300 MeV electron on 2 radiation length of carbon target

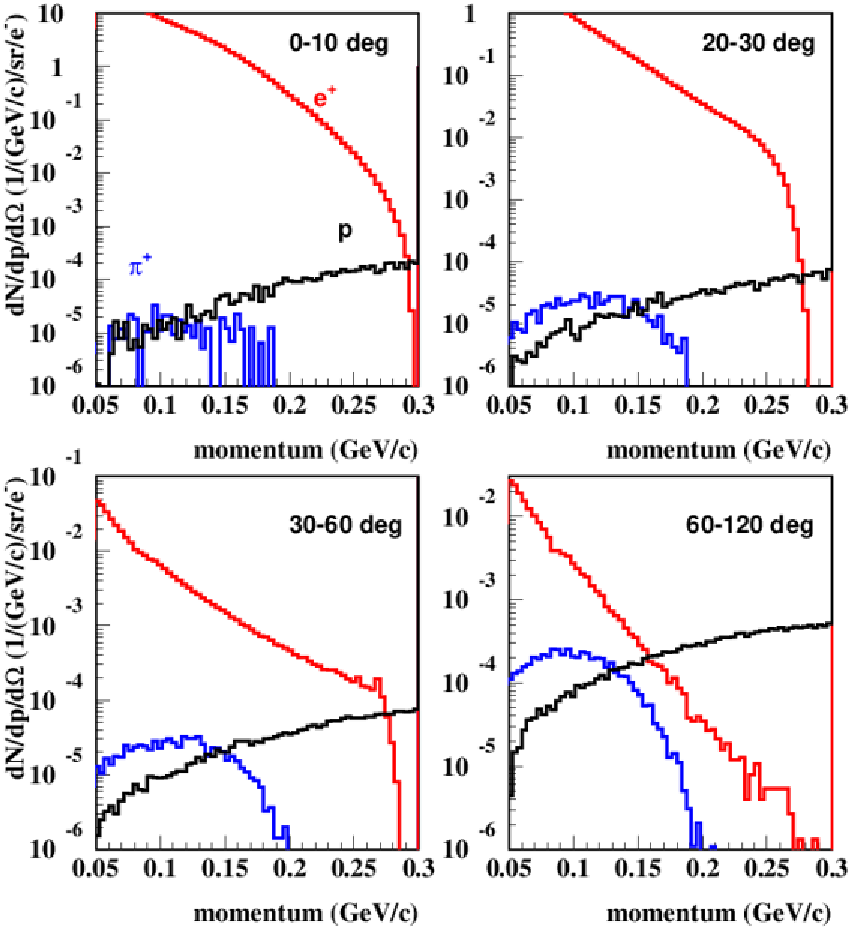
Courtesy S.Striganov

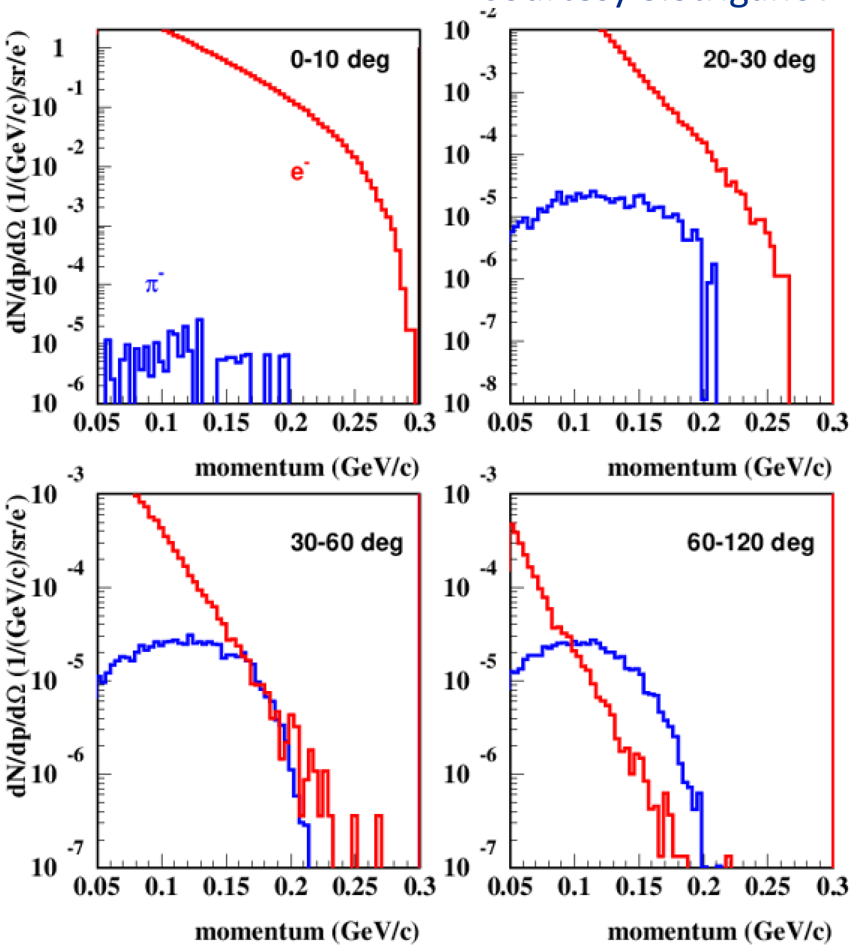




Positive pions has very big positron/proton escort, large angle & high momentum; negative pion could be focused and extracted

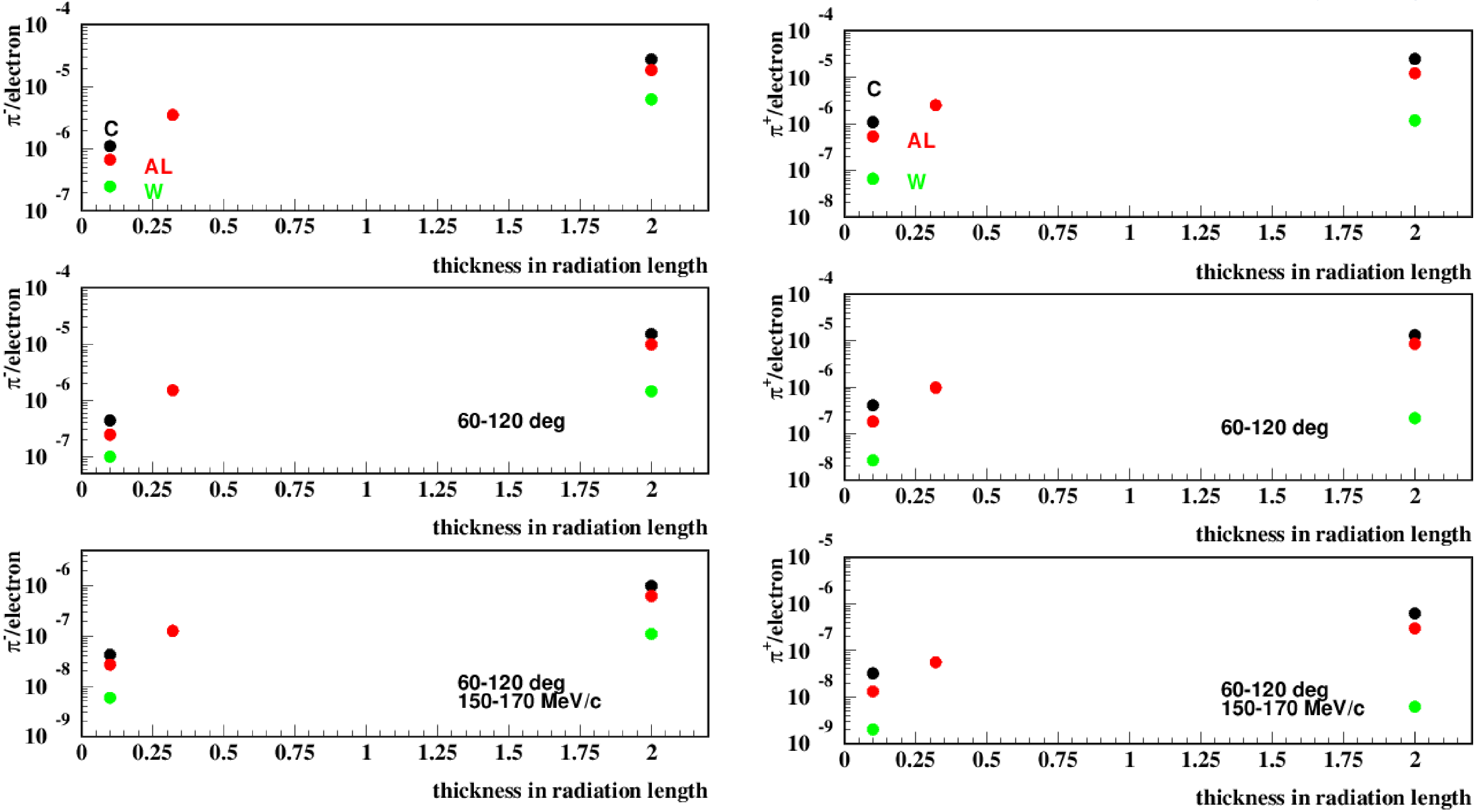
Courtesy S.Striganov





More pion could be obtained for larger thickness & low Z. target material. Larger thickness – large radiation problem, low Z - longer target (more difficult to collect)

Courtesy S.Striganov



Low radiation scenario

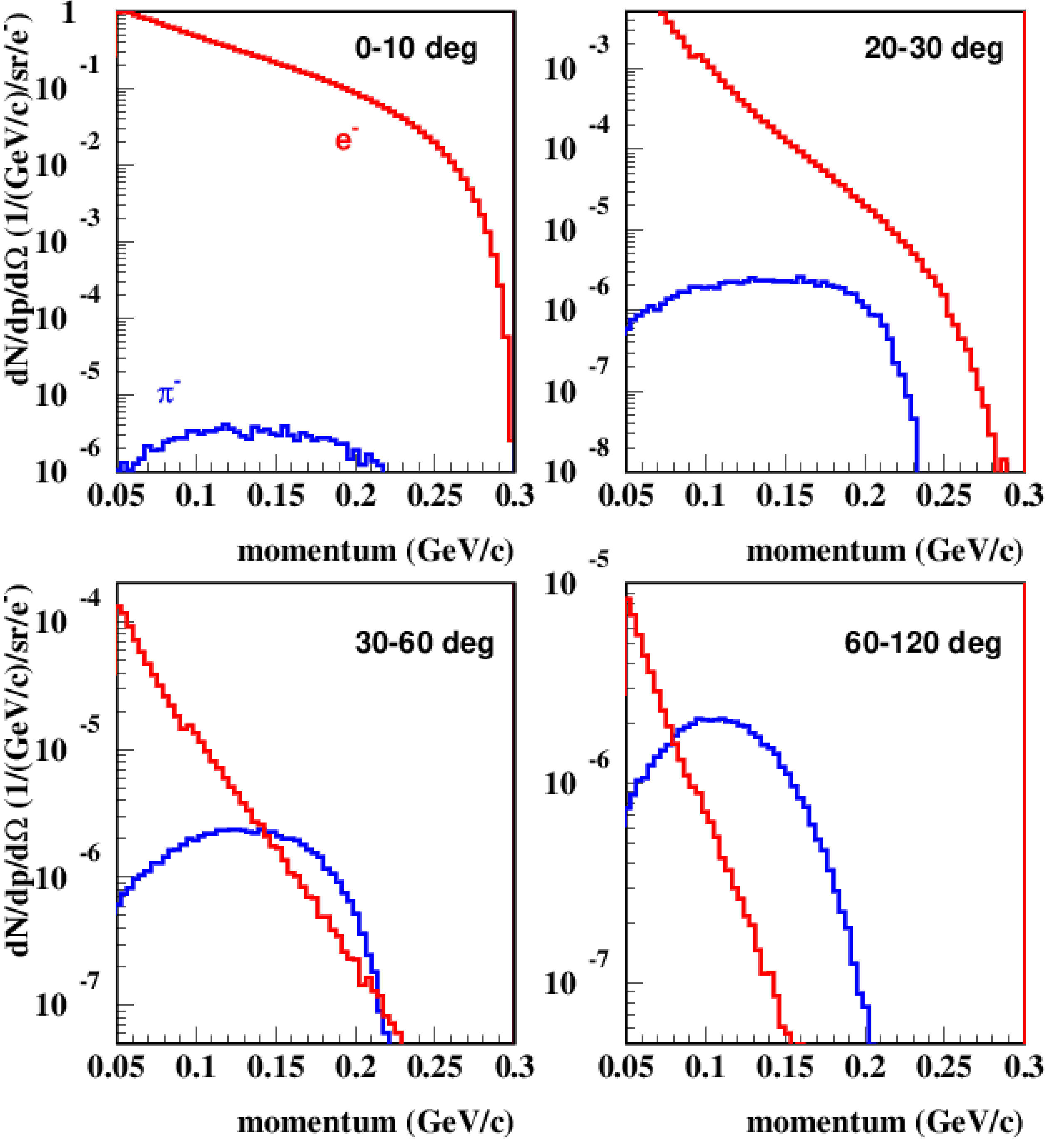
Two production targets – photon production and pion/muon production.

Photon production target should be thin (~10% radiation length). Primary electrons can be swept and miss pion/muon target – compact muon source design (Nagamine at al 2001).

They made analytical estimate for 10% tungsten photon and 10 cm carbon pion/muon production target. For pion produced at 45 degree with acceptance 1 steradian and momentum from 150 to 163 MeV/c they got $3.5\ 10^{-9}$ π/electron in 2001 ($4.7\ 10^{-8}$ π/electron in 2016). Our simulation shows that at 45 degree pions have heavy electron/positron escort, but at 90 degree we could get **$3.7\ 10^{-8}$** negative pion/electron in above angular & momentum range. With such two target design we could get about 3 times more pion then with one 10% radiation length carbon target.

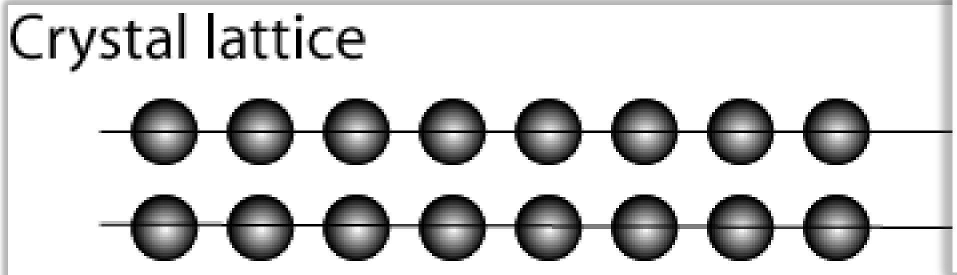
Large Omega muon optics channel could capture pion beam with dE=10 MeV and dΩ=1 steradian and produce 0.4 muon/pion.

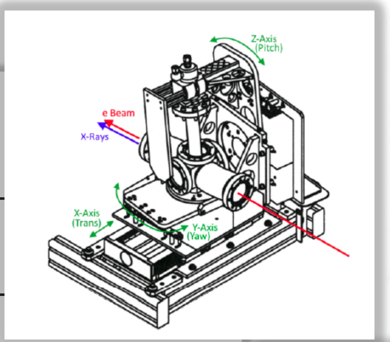
Courtesy S.Striganov

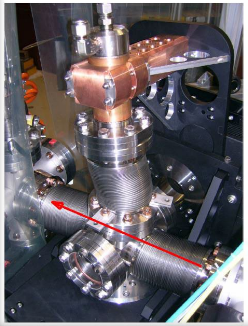


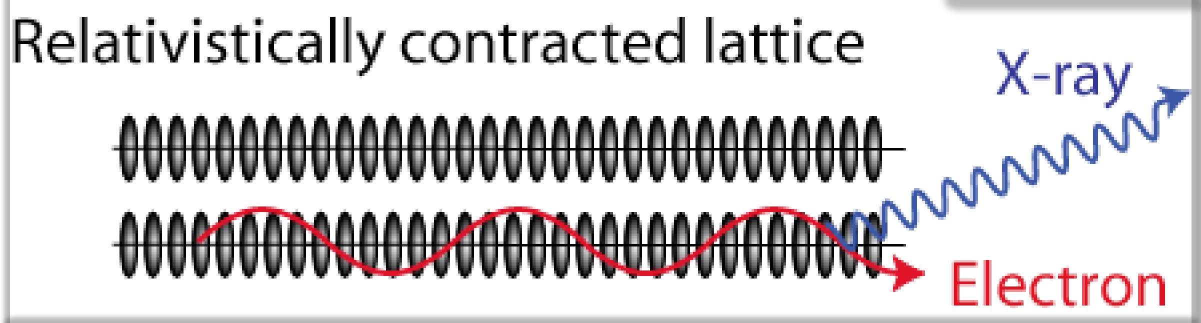
2015-2017 CRYSTAL CHANNELING EXPT @ FAST

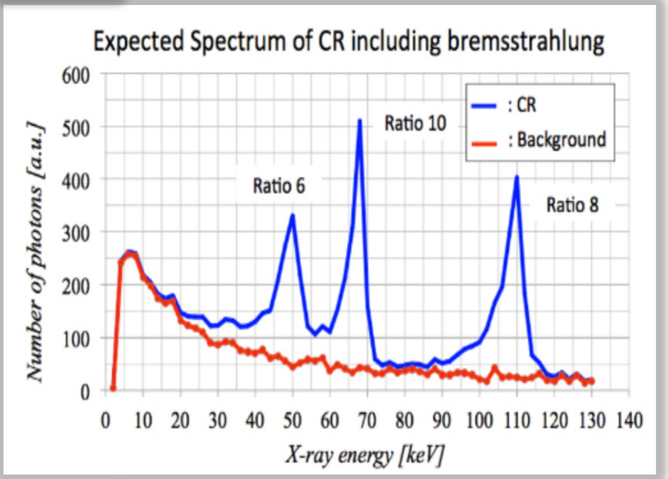
- P.Piot, T.Sen, A.Halavanau, D.Edstrom, J,Hyun, et al
- helpful experience

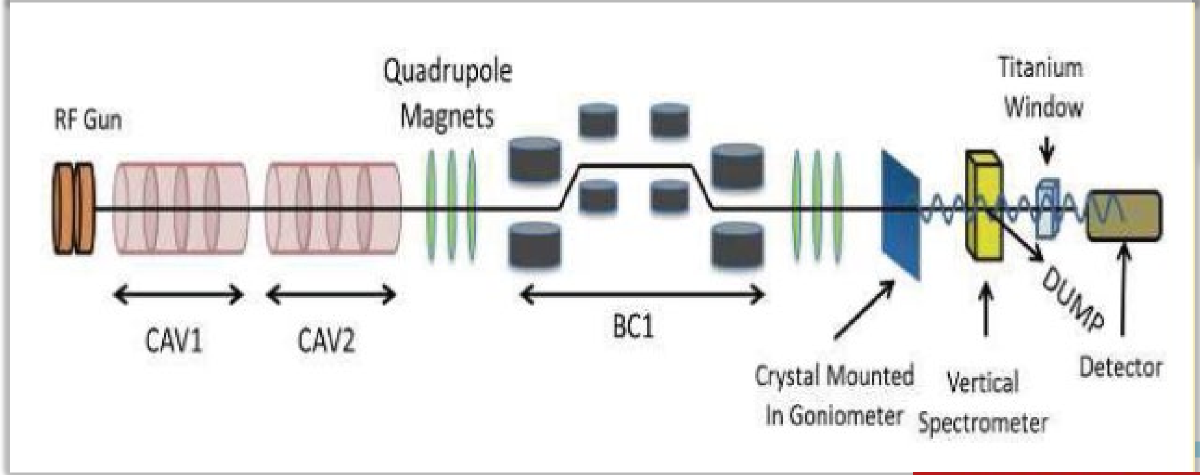


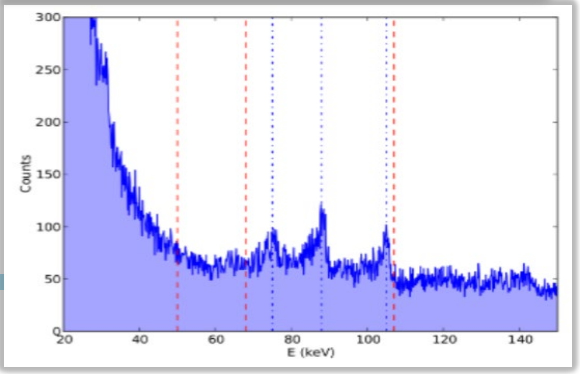












arXiv:1612.07358

Summary

- Acceleration of muons in crystals/CNTs has great promise
- There are many issues related to muon production, channeling and acceleration
- Some modes of the crystal/CNT excitations can be tested at FACET-II – eg by SMI
- Beam filamentation is of serious concern and can be studied at, e.g., FAST
  - Past experience and hardware very helpful
- Also can be tried at FAST : i) muon production; ii) muon detection; iii) experiment integration; iv) calibration of models
- ***“Workshop on Acceleration in Crystals & Nanostructures”*** *will take place at Fermilab, June 24-25 – please, join!*

Thank You for Your Attention!

High Energy $\mu^+\mu^-$ Colliders

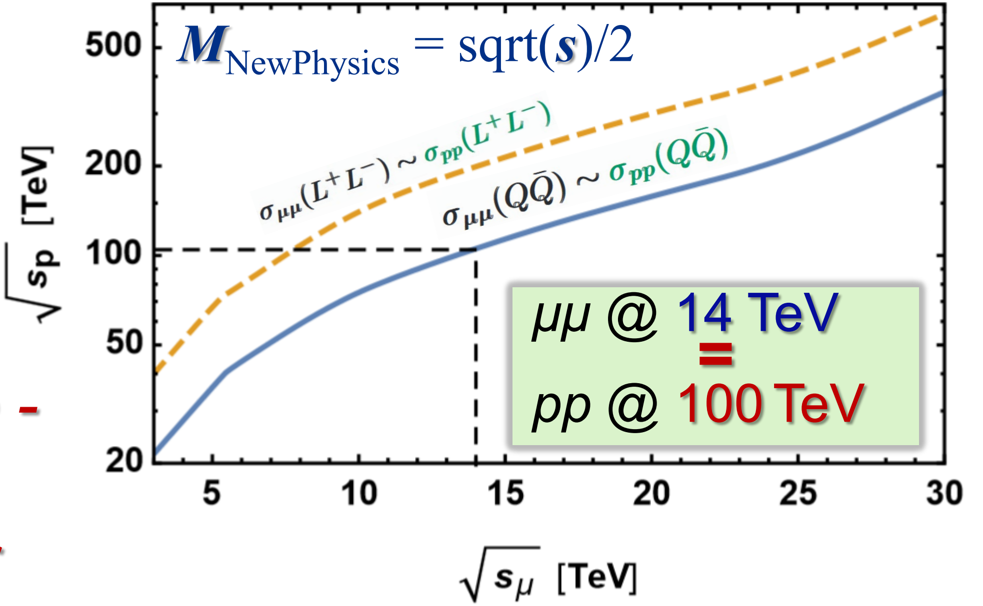
Input #120

JINST Special Issue (*MUON*)

arXiv:1901.06150

Advantages:

- ***μ***’s do not radiate / no beamstrahlung → acceleration in rings → *low cost & great power efficiency*
- ~ x7 energy reach vs *pp*



Offer *“moderately conservative - moderately innovative”* path **to cost affordable** energy frontier colliders:

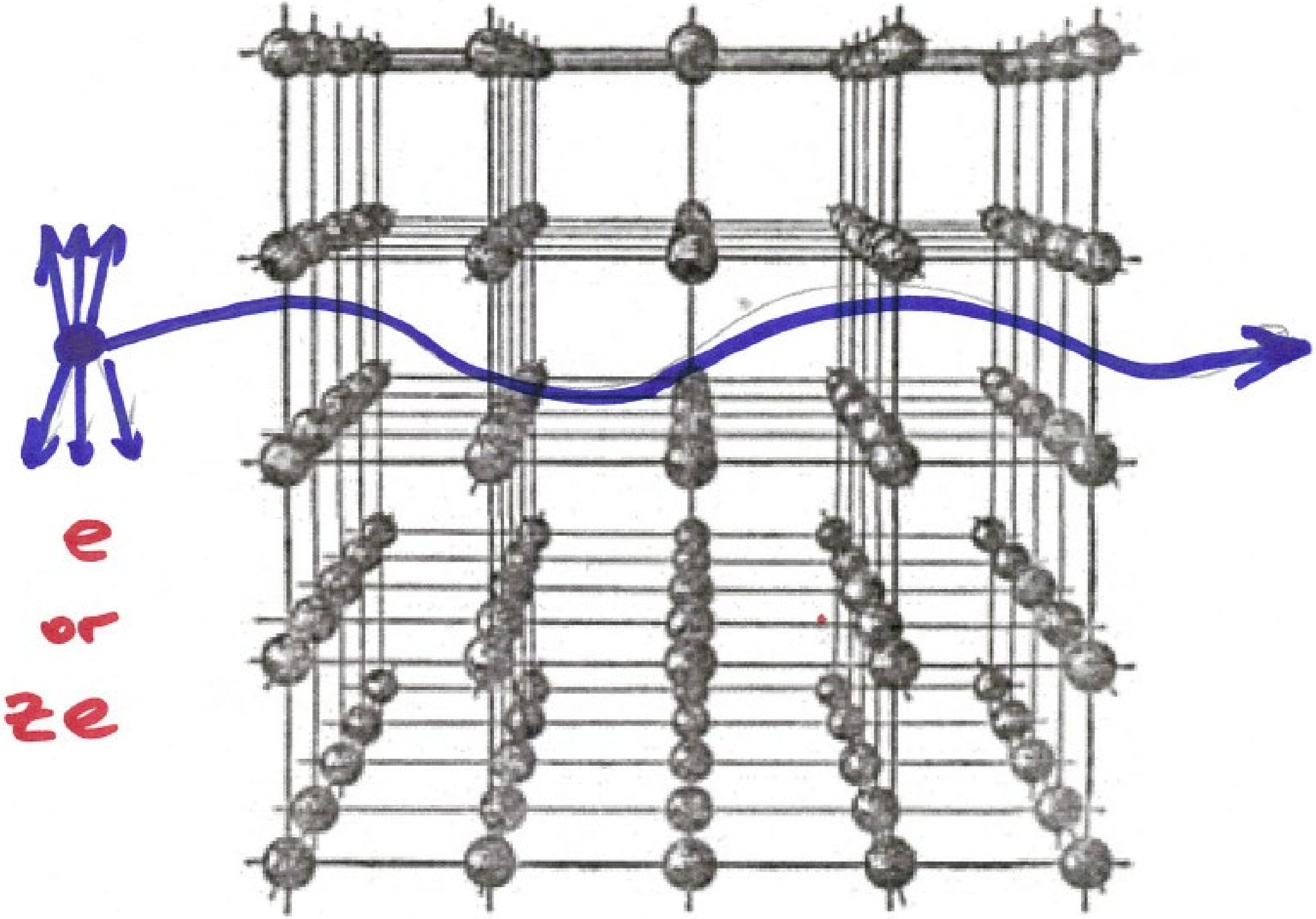
- US MAP feasibility studies were very successful → MCs can be built with present day SC magnets and RF; there is a well-defined path forward
- ZDRs exist for 1.5 TeV, 3 TeV, 6 TeV and 14 TeV * in the LHC tunnel

** more like “strawman” parameter table*

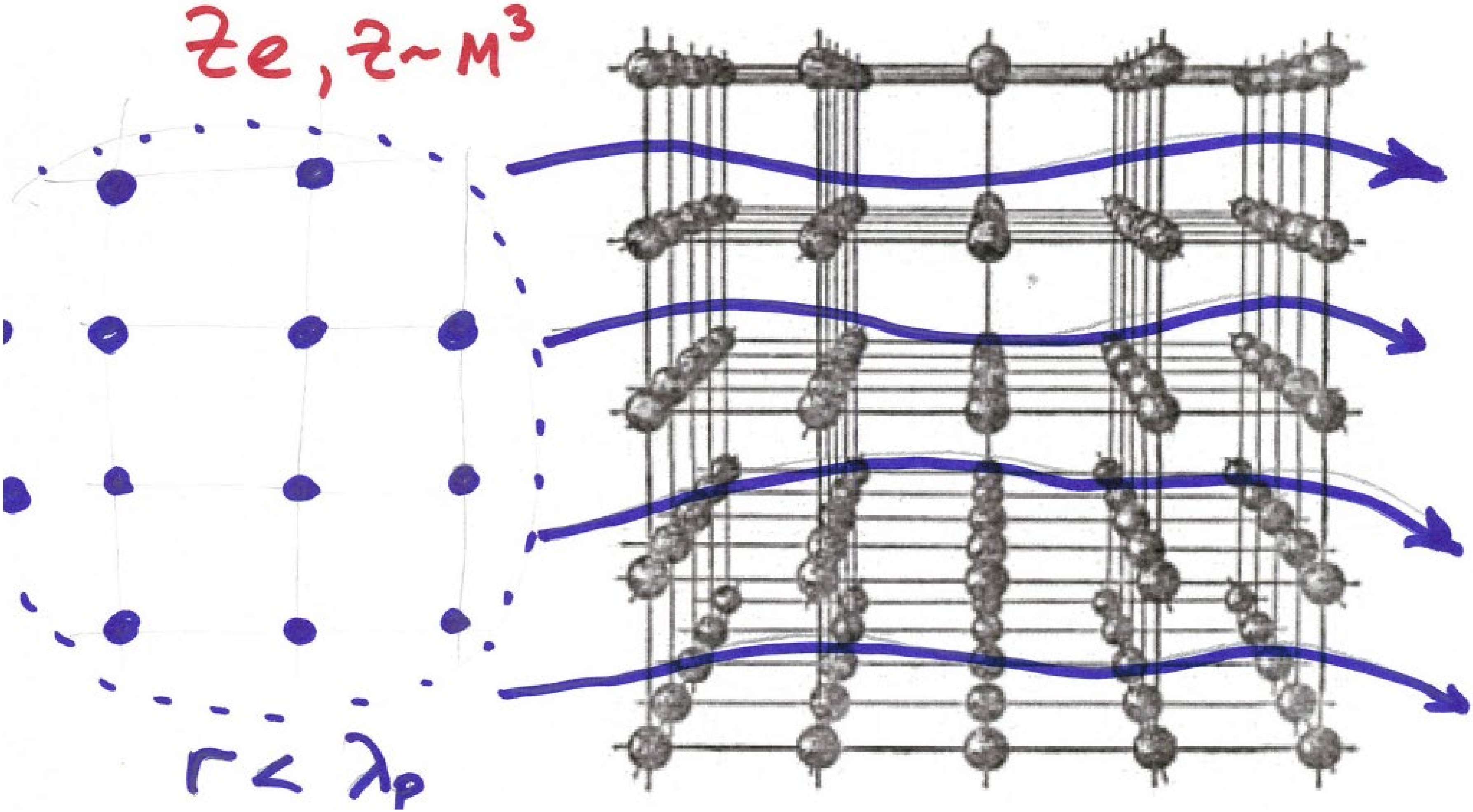
Key to success:

- Test facility to demonstrate performance implications - muon production and 6D cooling, study LEMMA e^+-45 GeV + e^- at rest → μ^+-μ^- , design study of acceleration, detector background and neutrino radiation

Ways to excite the crystal (2)

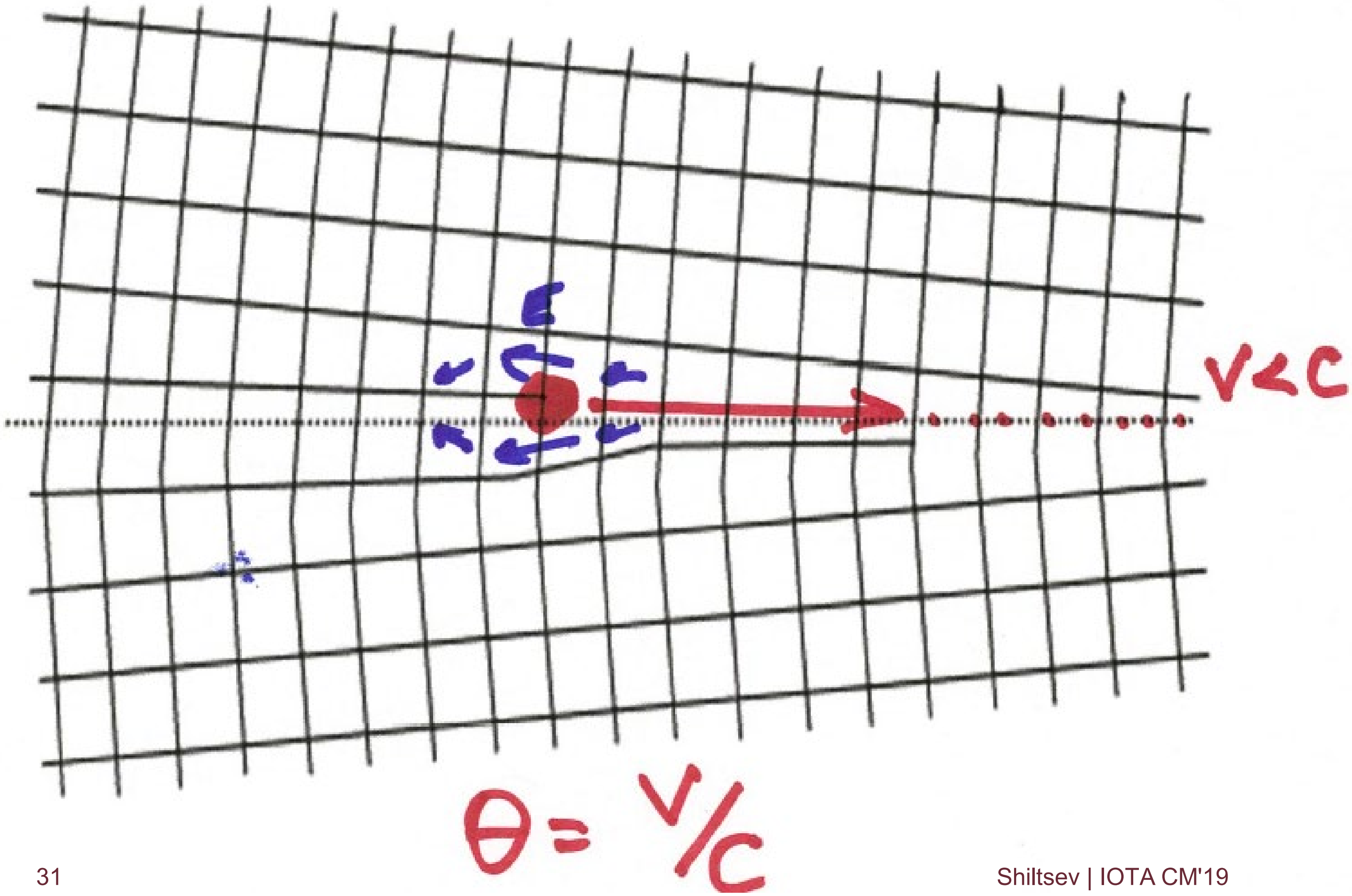


Ways to excite the crystal (3)

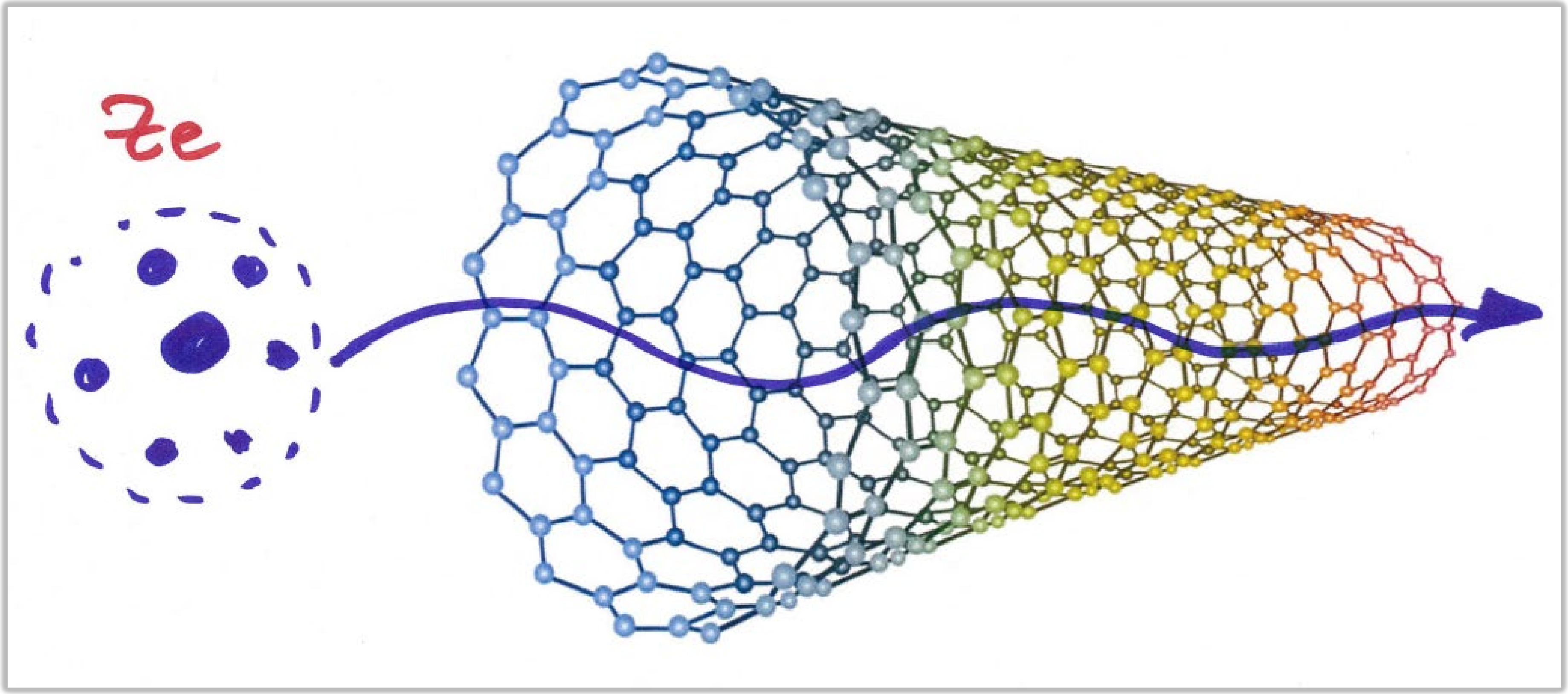


Ways to excite the crystal (4)

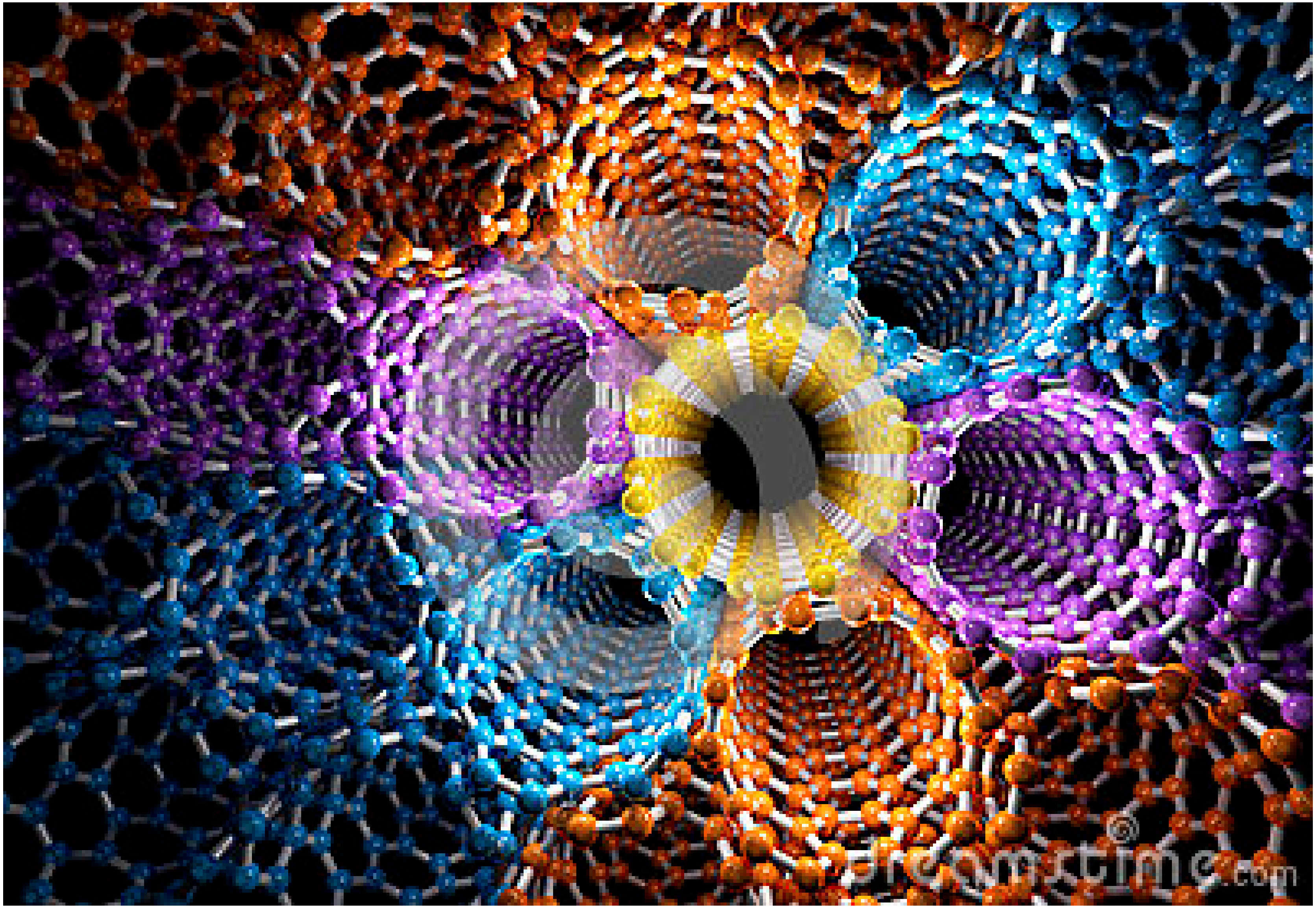
Controlled generation of dislocations



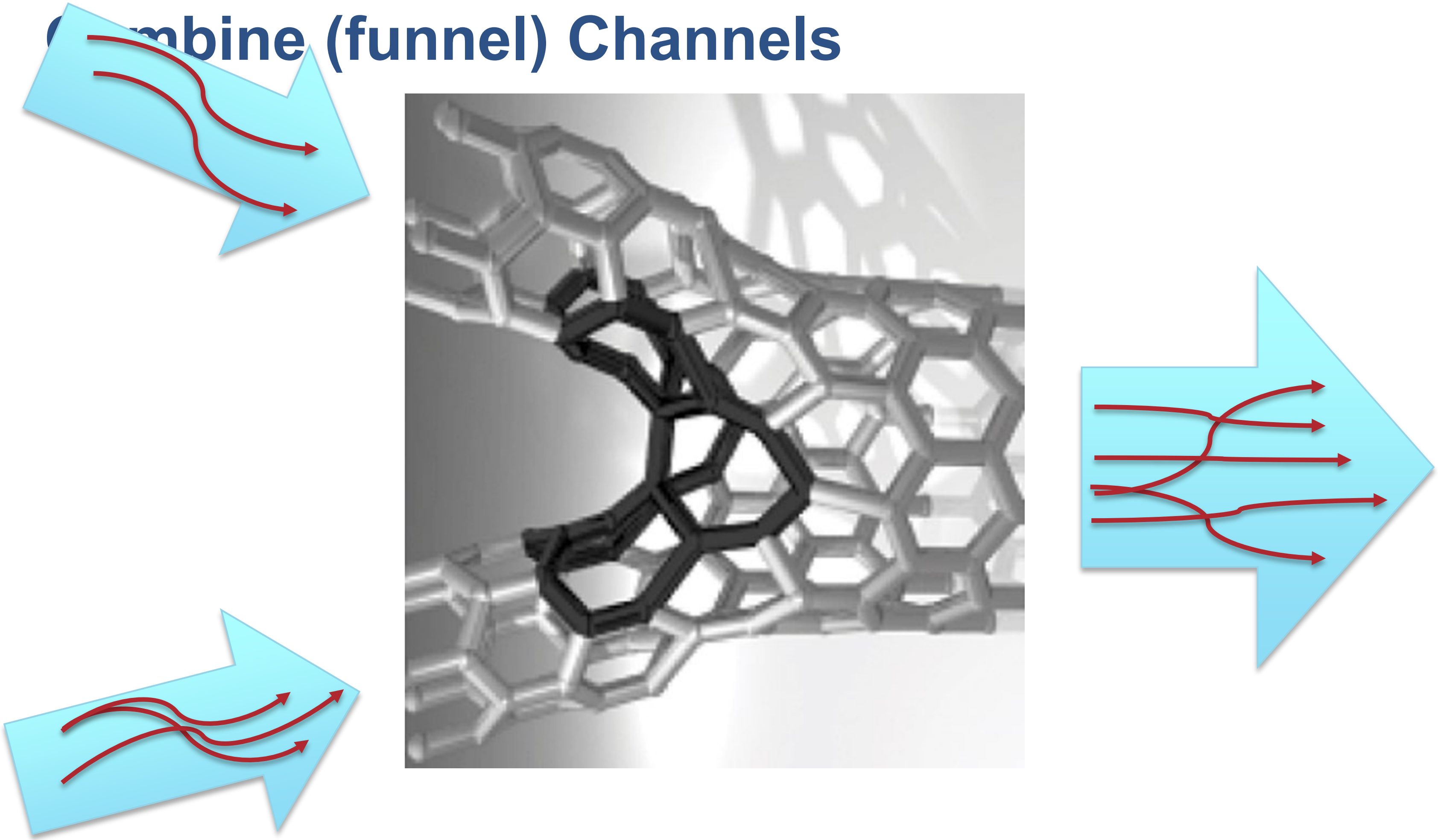
Nanotubes(1)



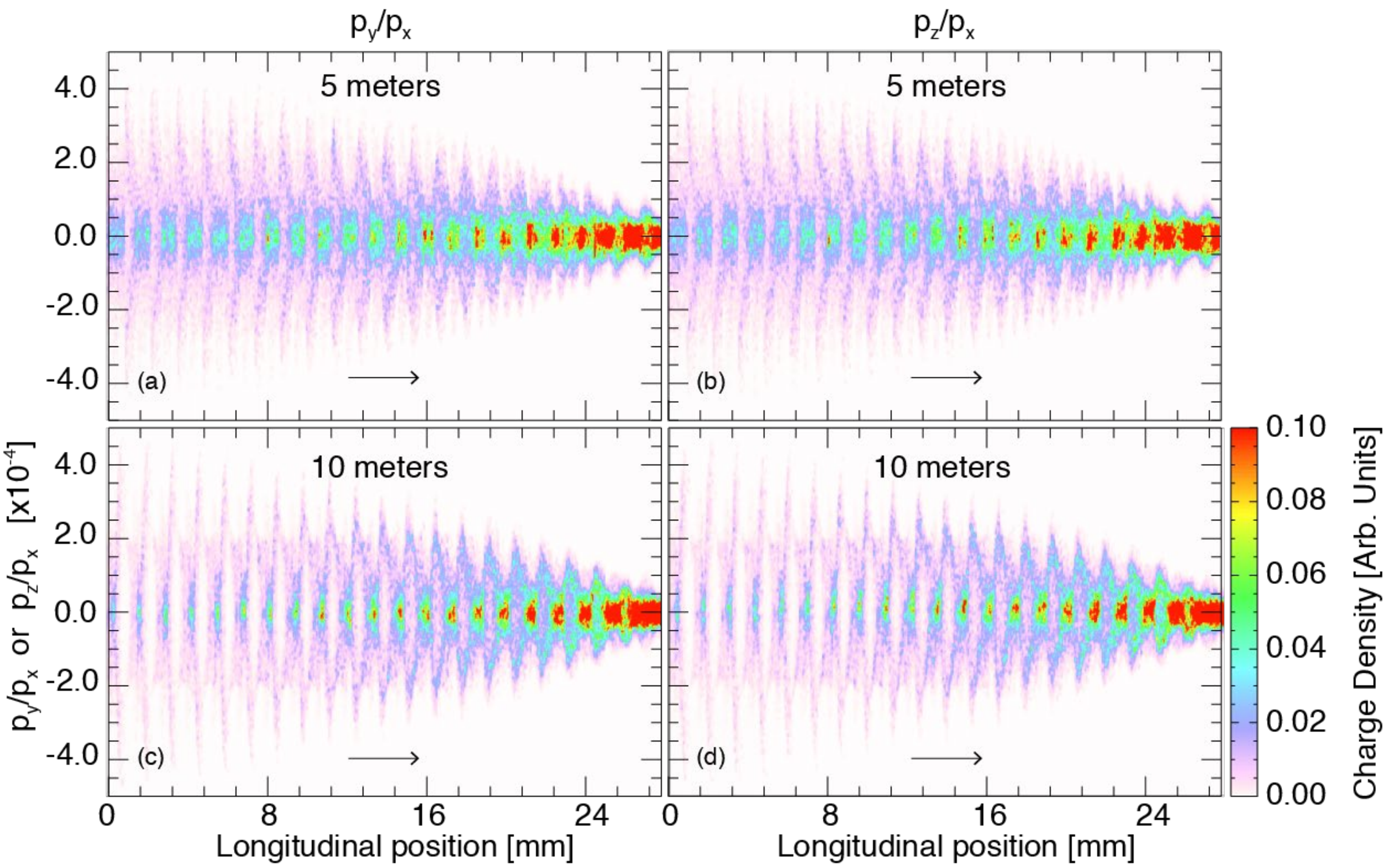
Nanotubes (2)



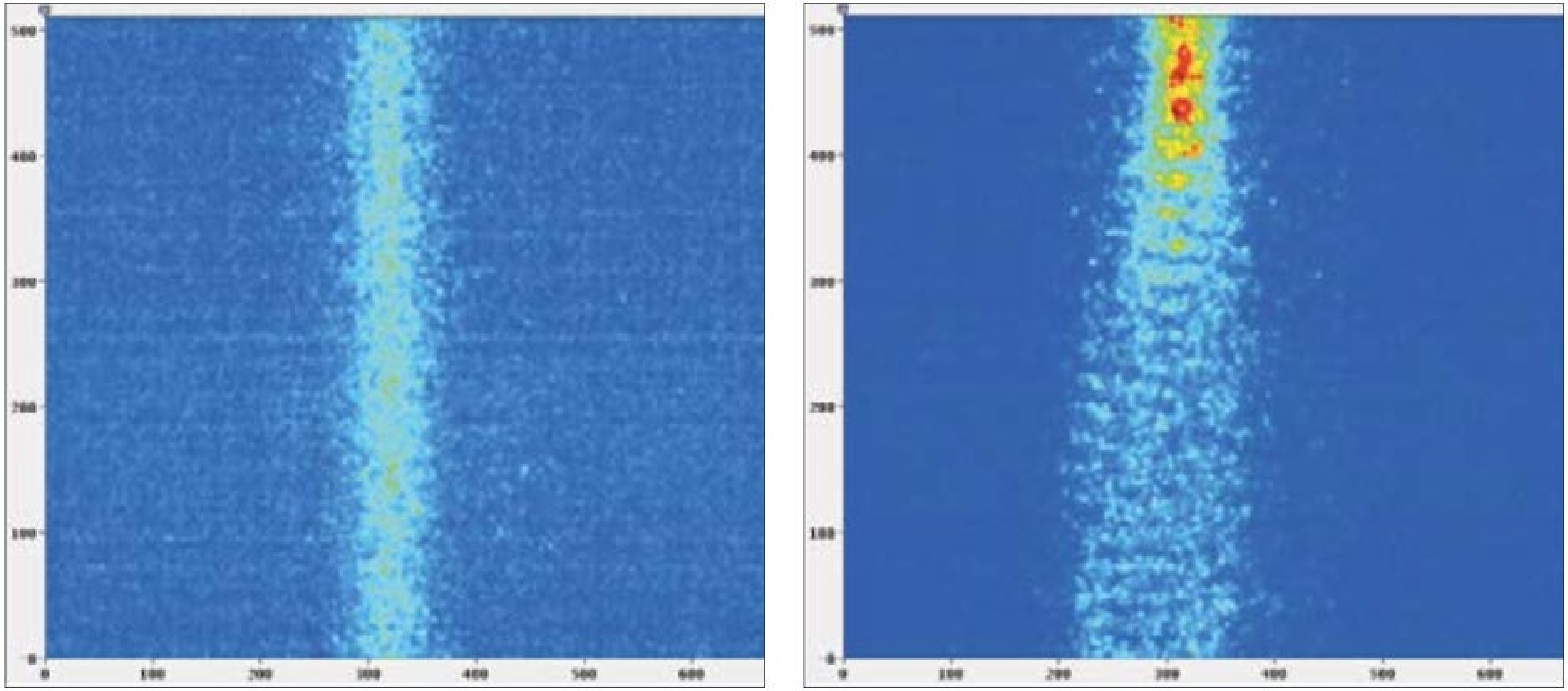
Combine (funnel) Channels



SMI: Self-Modulation Instability (in 400 GeV protons)



Self-Modulation Instability in AWAKE p+ Bunch



A Petrenko/CERN

Comparison of the proton-bunch longitudinal profile (left, no plasma) with the profile for a bunch passing through plasma (right), showing the strong modulation of the bunch.

ACCELERATOR TECHNOLOGY

AWAKE makes waves

CERNCOURIER

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Collider considerations

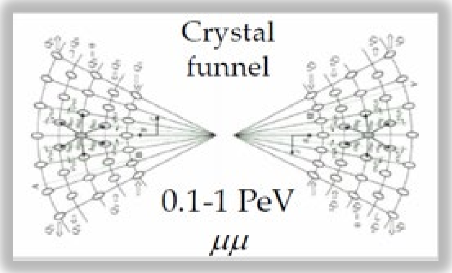
$$\mathrm{d}N/\mathrm{d}t = -N/\gamma\tau_0 \qquad \frac{N}{N_0} \approx \left(\frac{m_\mu c^2}{E}\right)^{\kappa}$$

$$\kappa = (m_\mu c/\tau_0 G) \ll 1/\ln(E/m_\mu c^2)$$

i.e. irrelevant

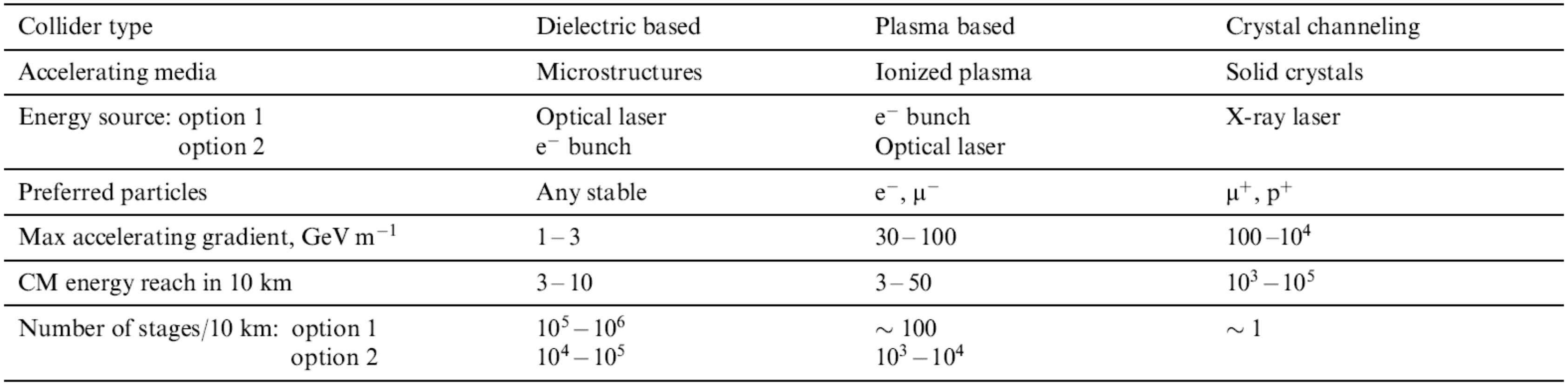
$$A \sim 1\ \text{Å}^2 = 10^{-16}\ \mathrm{cm}^2 \qquad N_0 \sim 10^3\ \text{particles}$$

$$L = fN^2/A = f \times 10^{16} \times 10^6\, n_{\mathrm{ch}}\ [\mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$$



$$L\,[\mathrm{sm}^{-2}\,\mathrm{s}^{-1}] \approx 4 \times 10^{33\text{–}35}\,\frac{P^2\,[\mathrm{MW}]}{E^2\,[\mathrm{TeV}]\, f n_{\mathrm{ch}}\,[10^8\ \mathrm{Hz}]}$$

Table 4. Options for future particle colliders.



Collider type	Dielectric based	Plasma based	Crystal channeling
Accelerating media	Microstructures	Ionized plasma	Solid crystals
Energy source: option 1 option 2	Optical laser e^- bunch	e^- bunch Optical laser	X-ray laser
Preferred particles	Any stable	e^-, μ^-	μ^+, p^+
Max accelerating gradient, GeV m^{-1}	1 – 3	30 – 100	$100 – 10^4$
CM energy reach in 10 km	3 – 10	3 – 50	$10^3 – 10^5$
Number of stages/10 km: option 1 option 2	$10^5 – 10^6$ $10^4 – 10^5$	~ 100 $10^3 – 10^4$	~ 1

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Current Filamentation Instability in Laser Wakefield Accelerators

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