Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Ultimate Colliders for Particle Physics : Limits and Possibilities

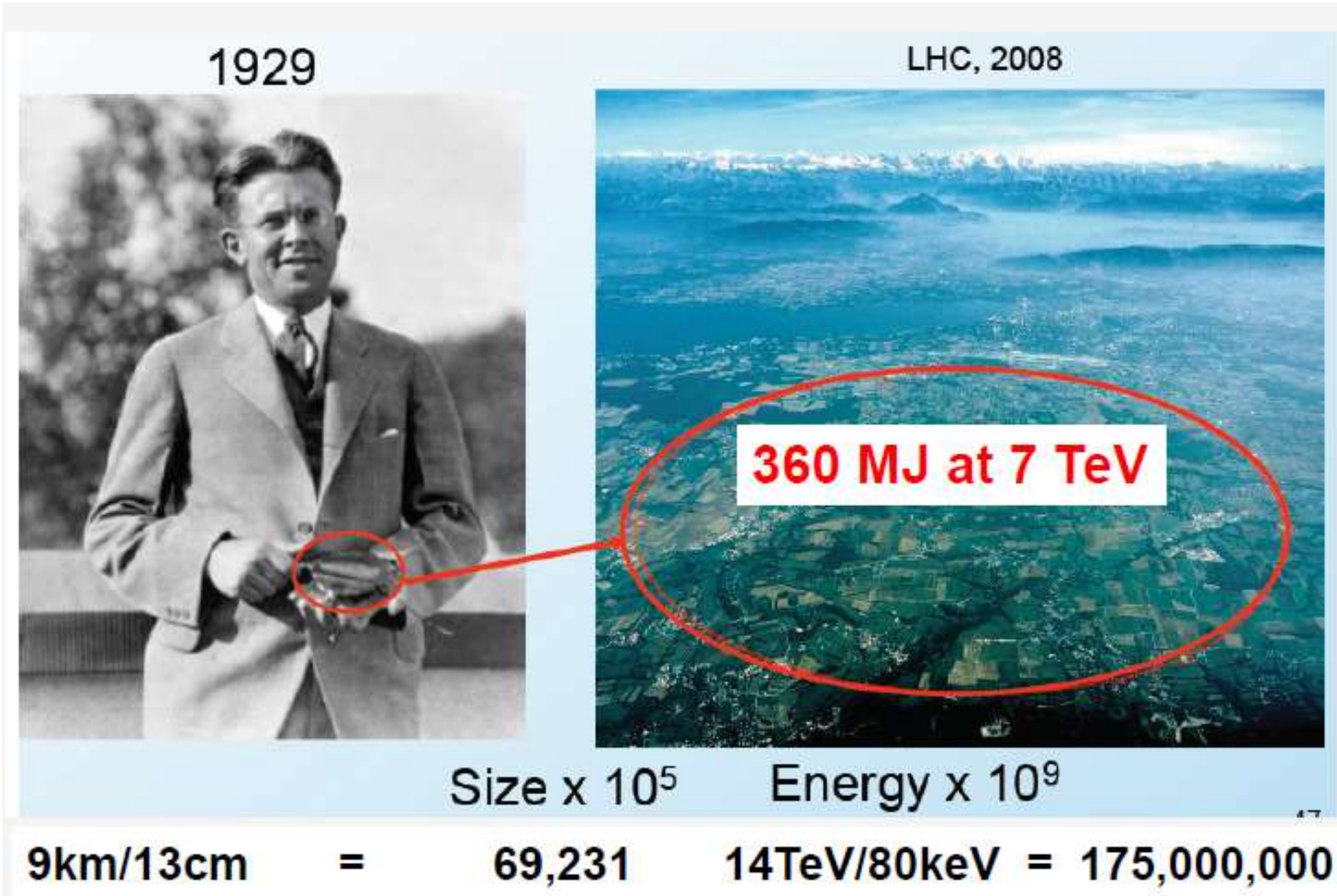
Vladimir SHILTSEV (Fermilab)

Workshop on Acceleration In Crystals and Nanostructures

June 24-25, 2019 - Fermilab

High Energy Particle Physics: Progress and Challenges

- Collider physics – dominated by the LHC til 2038



- Neutrino physics – multi-mW beams at Fermilab ~ till ~2040

What's Next?

- **HEP Int'l Community planning:**
  - European Strategy 2012-2013
  - US "Snowmass", P5, HEPAP 2013-2014
  - European Strategy Update 2019-2020
  - ILC250 in Japan? Decision by Feb. 2020
  - Potential of CepC in China?
  - US "Snowmass", P5, HEPAP 2019-2022
- **Planning for longer term HEP future in general (20-50 yrs) and "Post-2026" Era in particular (next cycle)**
  - Collider Physics Step 1: Higgs Factory(ies)
  - Collider Physics Step 2: Energy Frontier (50-100 TeV pp or 6-15 TeV lepton)
- **Challenges:**
  - a) Cost and Feasibility; b) What's in the "Far Future"?

Glimplse onto "*Cost and Feasibility*"

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000 GeV	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

From D.Schulte, EPPSU Symposium, Granada, Spain,. May 2019

A Vision for "Ultimate" Colliders

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

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**

circular collider

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

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

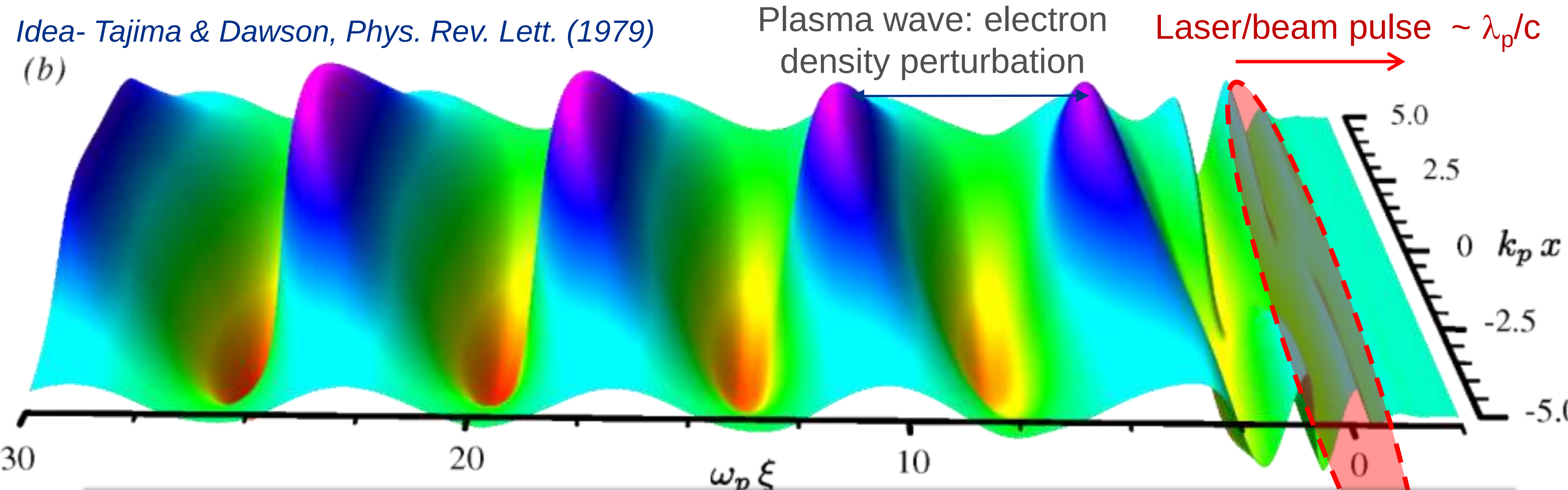
- "Live within our means": for 20-100×LHC
  - < 10 B$
  - < 10 km
  - < 10 MW (beam power, ~100MW total)

→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



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

Option A:

Short intense e-/e+/p bunch

Few 10^{17}cm^{-3}, **9 GV** over 1.3m

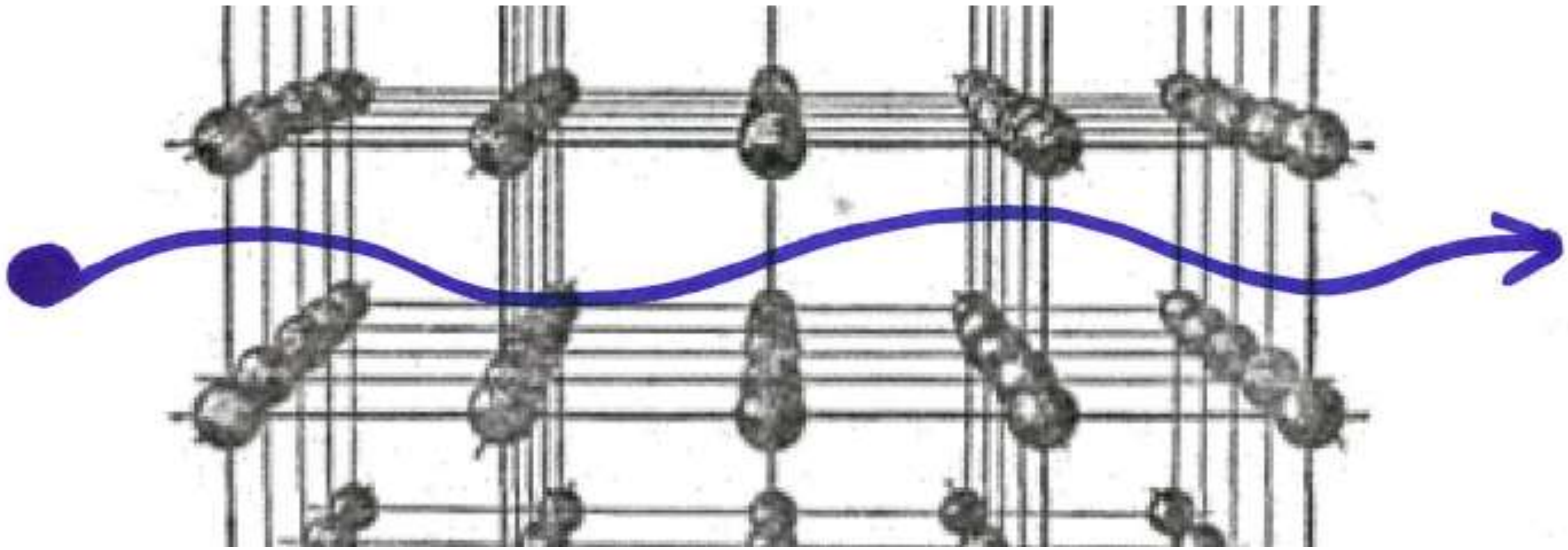
Option B:

Short intense laser pulse

~10^{18}cm^{-3}, **8 GV** over ~0.2m

First looks into "Plasma-Collider": **staging kills ! <*E*>~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

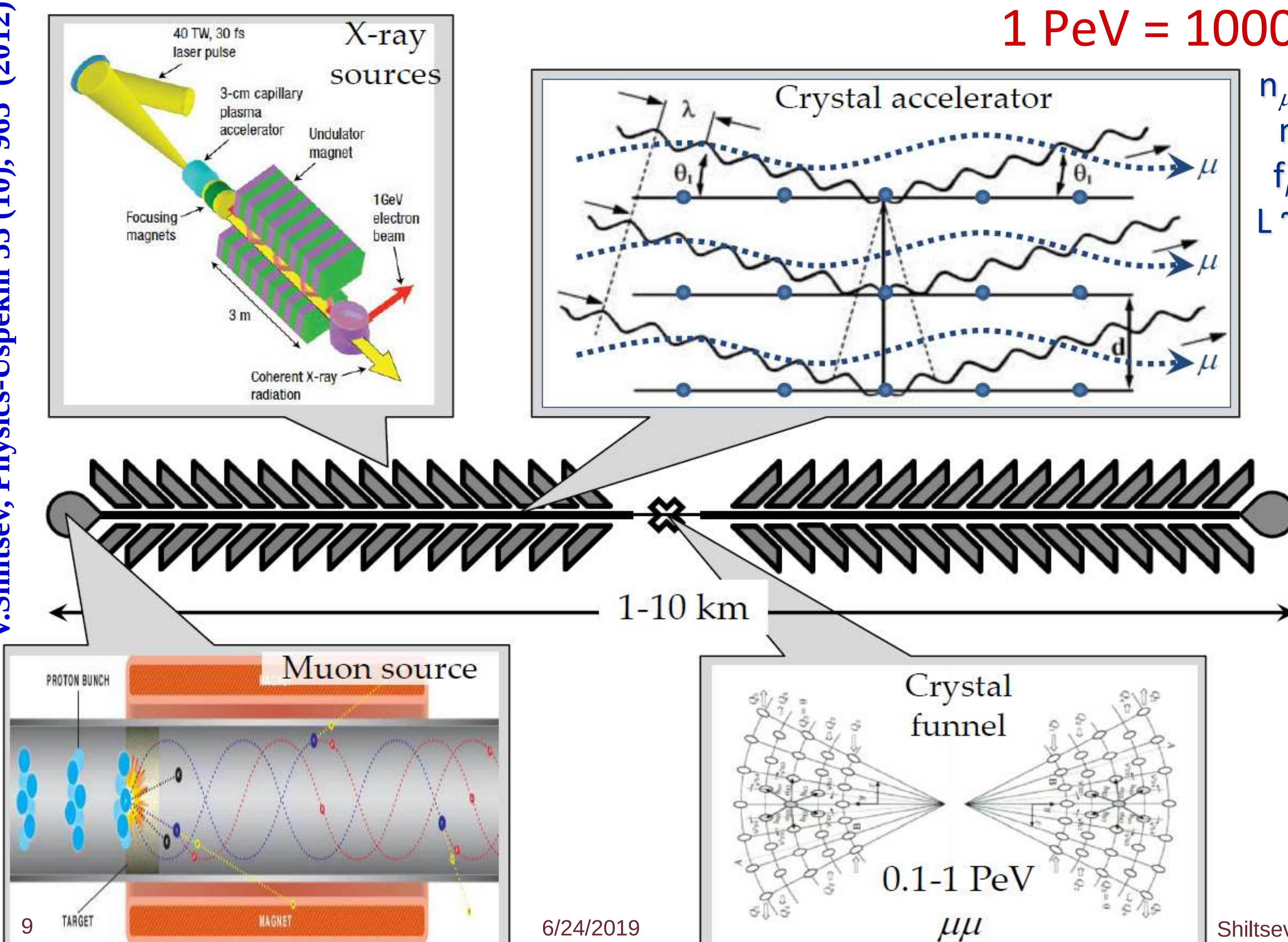
Chen P, Noble R J *AIP Conf. Proc.* **398** 273 (1997)

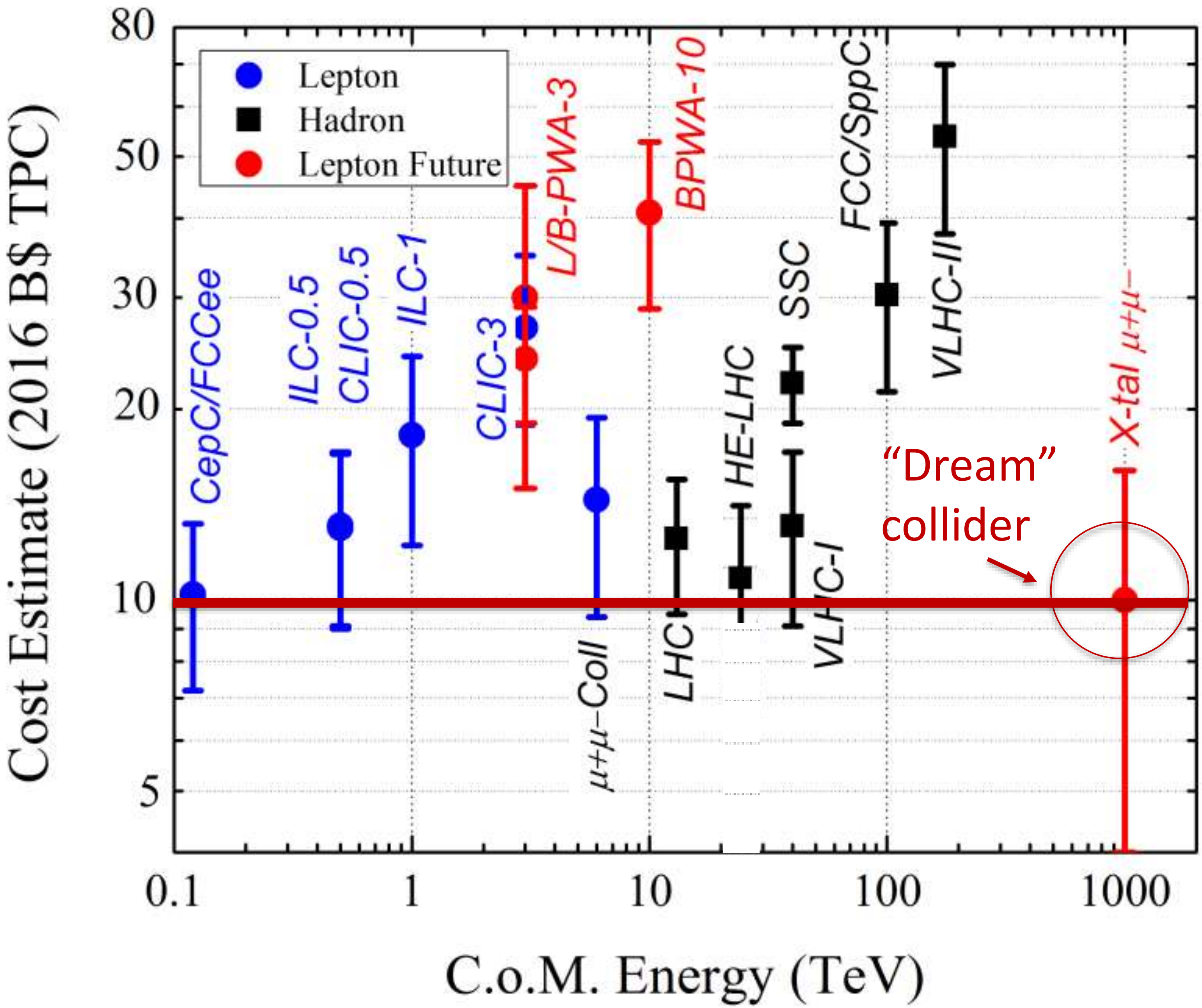
Linear μ+μ- Crystal X-ray Collider

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

1 PeV = 1000 TeV

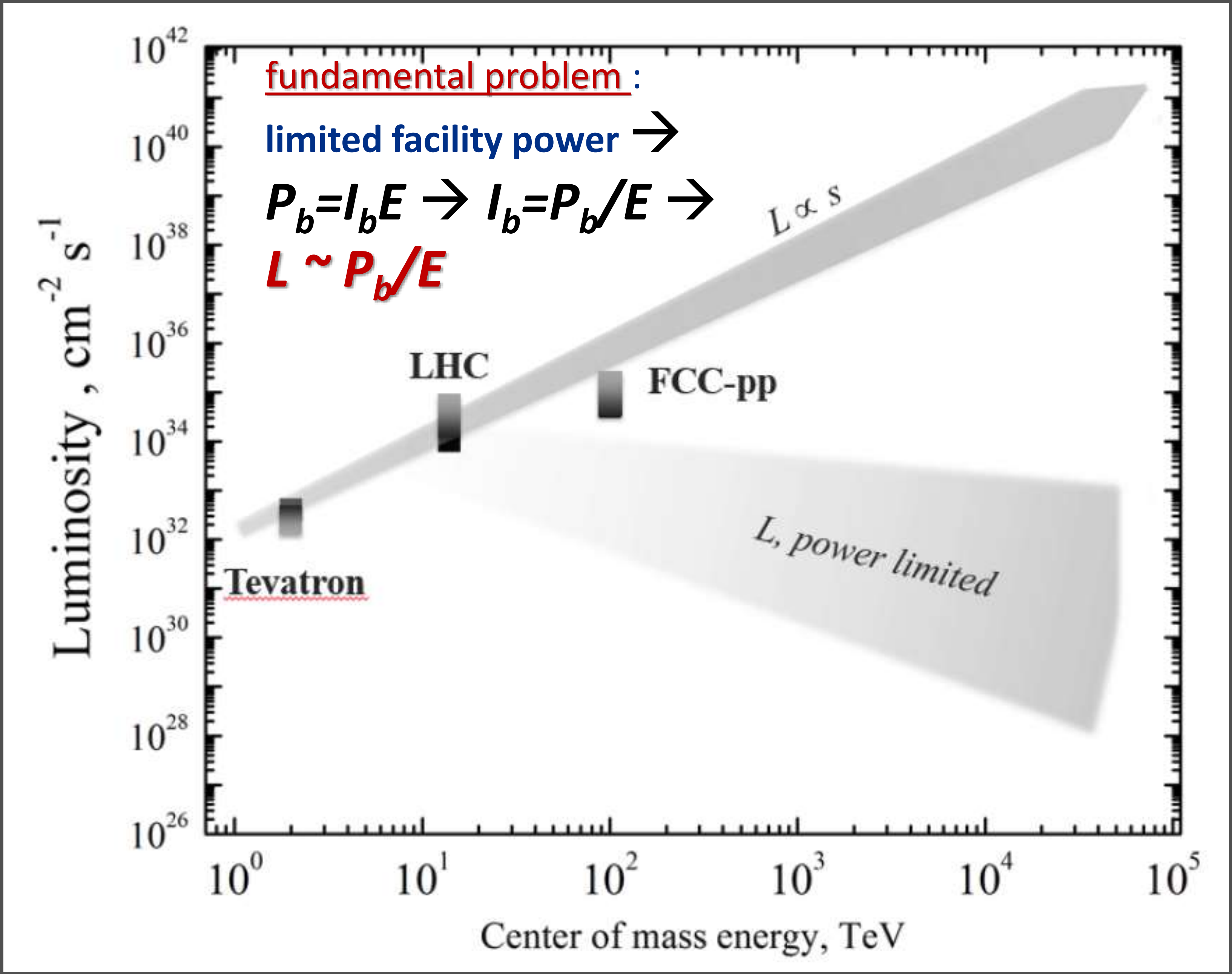
n_μ ~1000
n_B ~100
f_{rep} ~10^6
L ~$10^{30\text{-}32}$



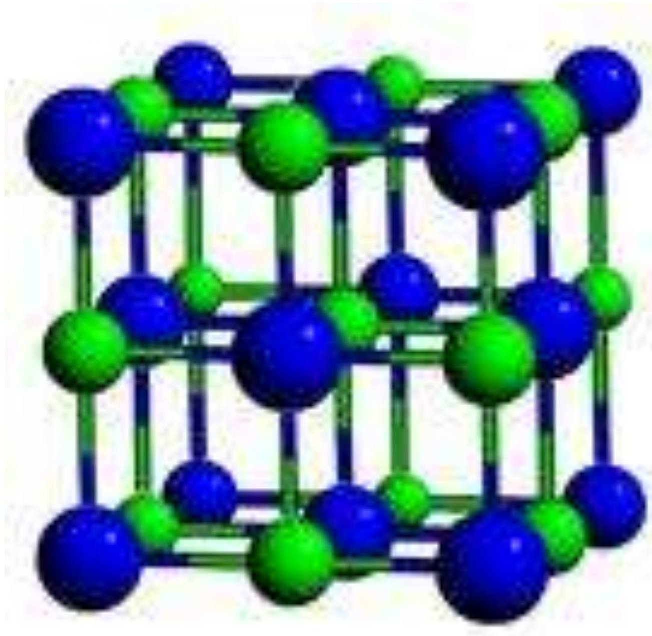


Lepton
Hadron
Lepton Future
CepC/FCCee
ILC-0.5
CLIC-0.5
ILC-1
CLIC-3
L/B-PWA-3
μ+μ−Coll
BPWA-10
LHC
HE-LHC
SSC
VLHC-I
FCC/SppC
VLHC-II
X-tal μ+μ−
"Dream" collider
80
50
30
20
10
5
0.1
1
10
100
1000
Cost Estimate (2016 B$ TPC)
C.o.M. Energy (TeV)

Paradigm Shift : *Energy* vs *Luminosity*

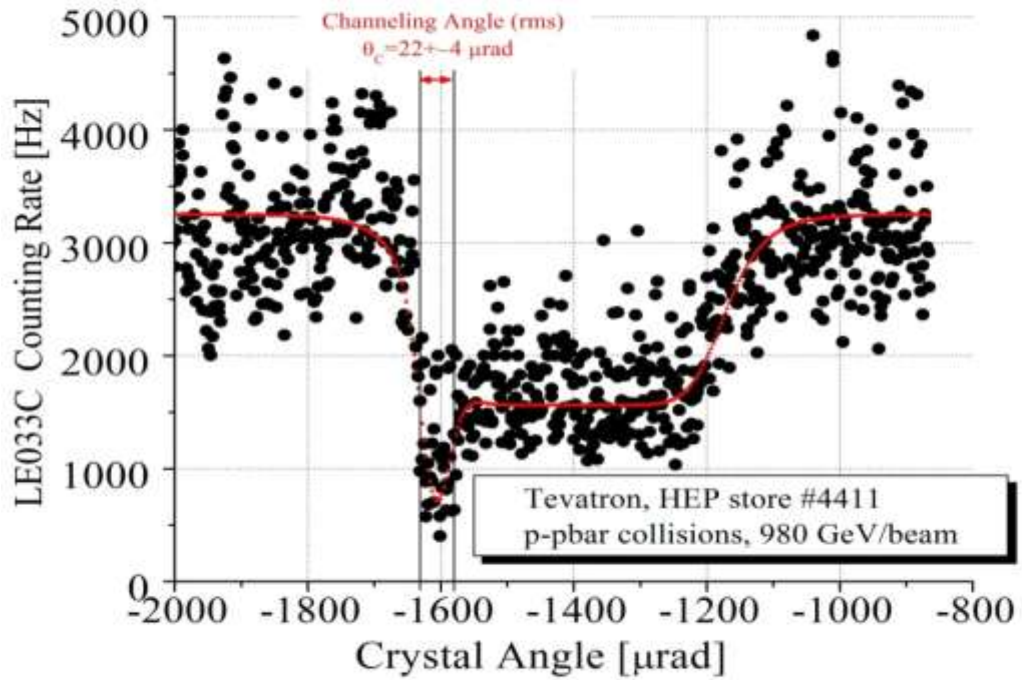


What Do We Know about Crystals?



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

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

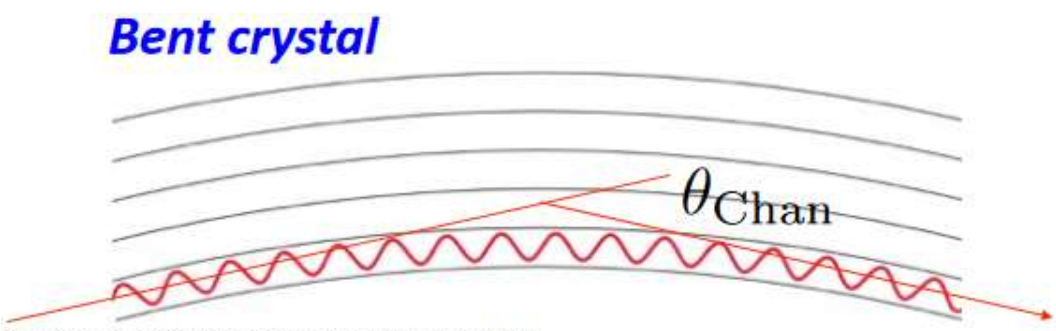


- Strong inter-planar electric fields ~10V/A=1GV/cm
- Very stable, can be used for
  - deflection/bending (*works*)
  - focusing (*works*)
  - acceleration (*if excited*)

~92.5+-5% efficiency

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

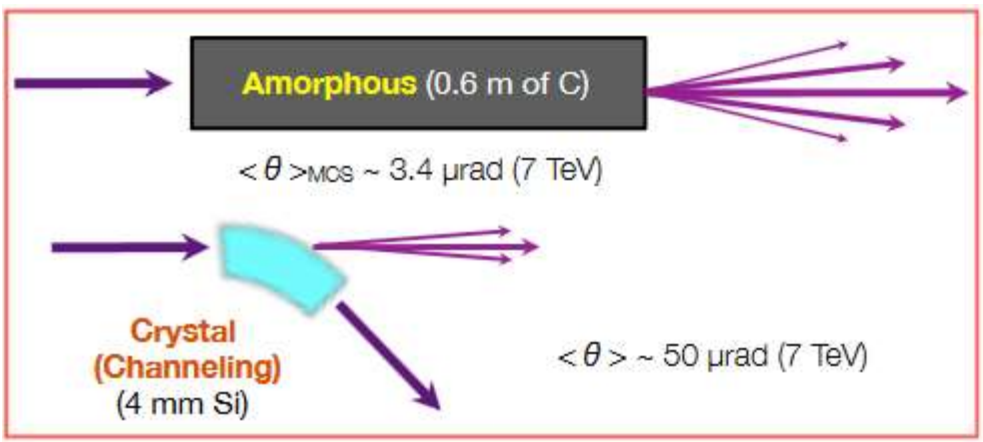
Bent Crystals in the 7 TeV LHC Beams

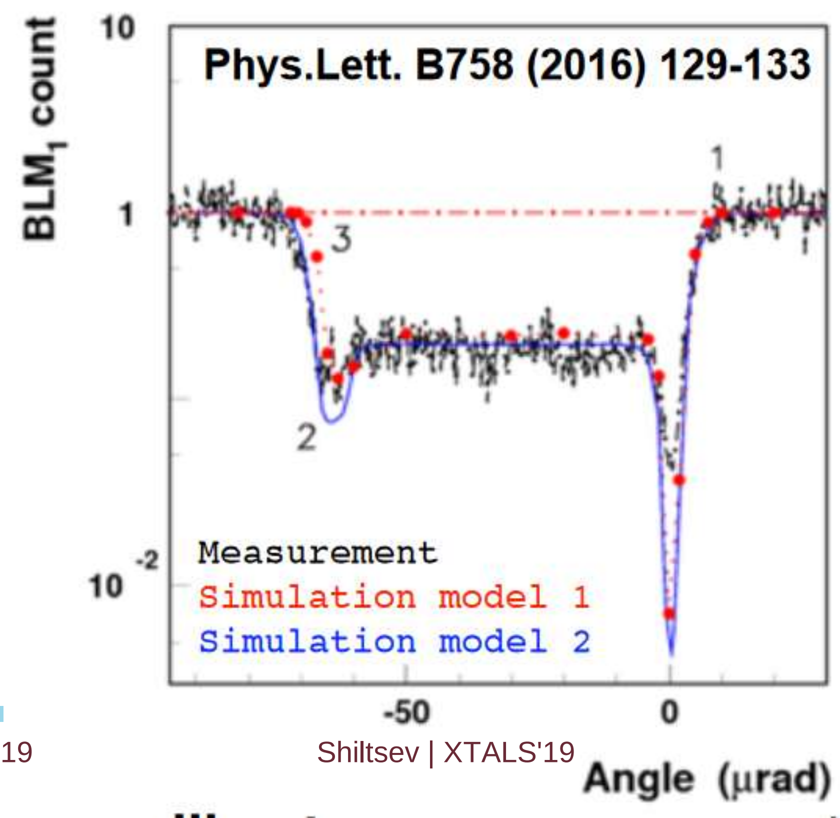


S. Redaelli, Physics Beyond Colliders, 06/09/2016

~2 mrad at 7 TeV

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





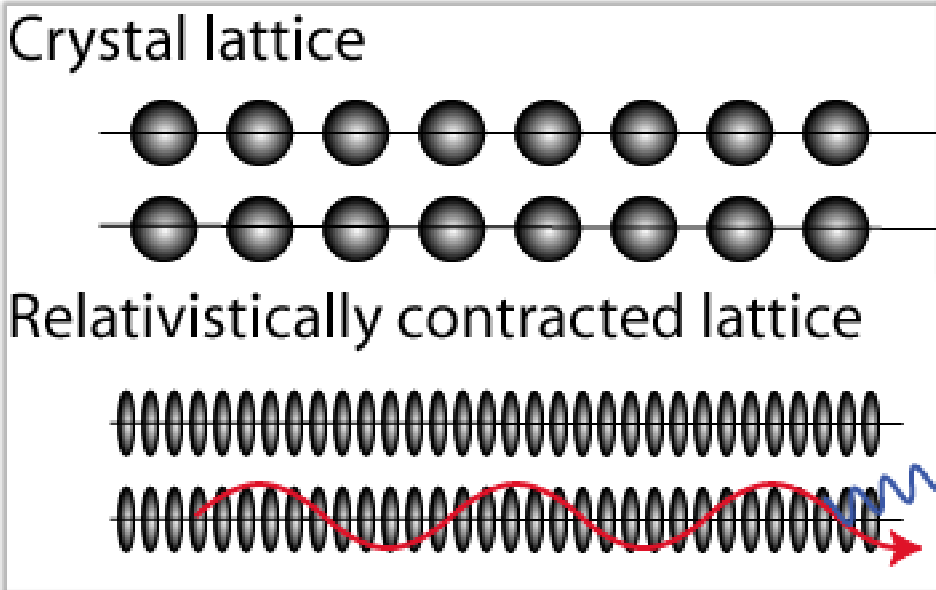
~99.5% efficiency

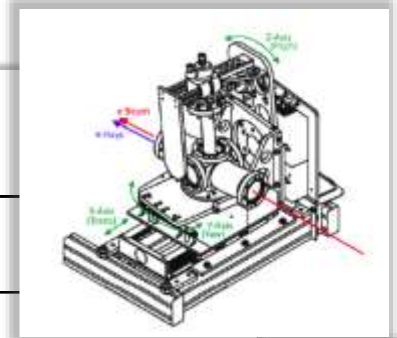
Or *l_d* ~ 4mm/0.005=0.8m

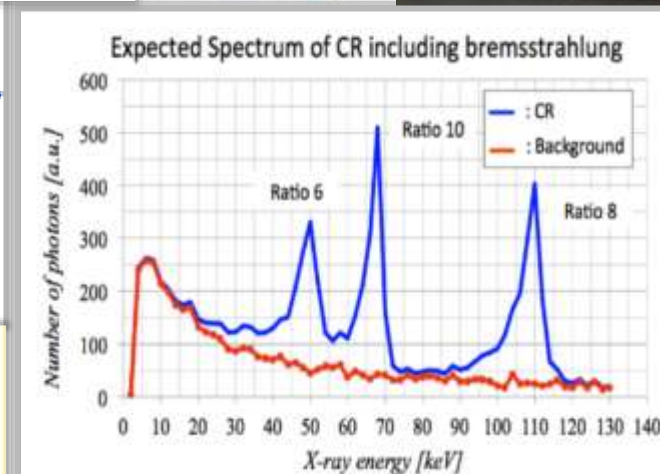
*see also U.Wienands talk on *e*- channeling at SLAC

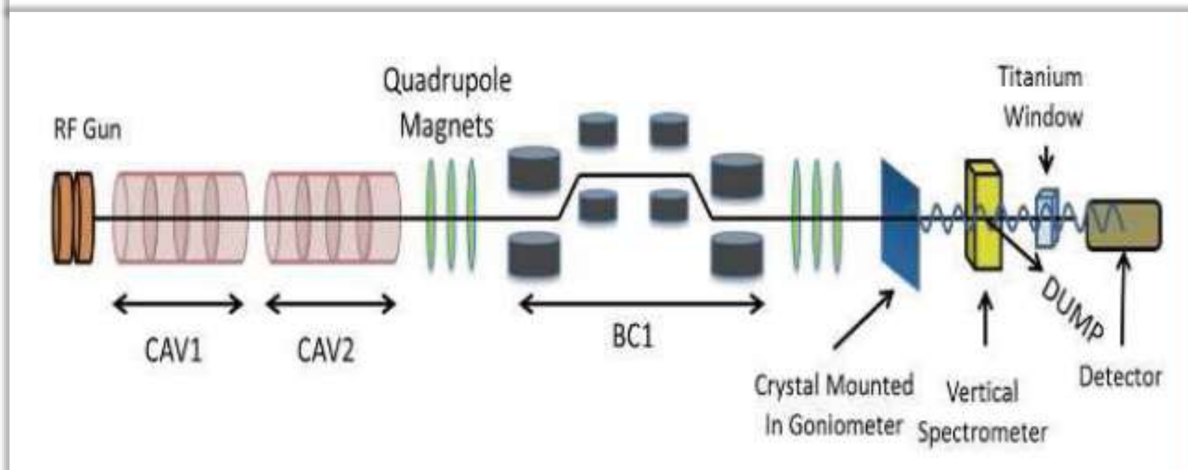
2015-2017 CRYSTAL CHANNELING EXPT @ FAST

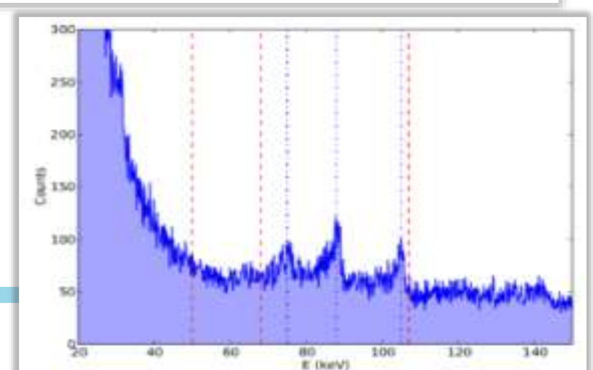
- P.Piot, T.Sen, A.Halavanau, D.Edstrom, J,Hyun, et al
- helpful experience









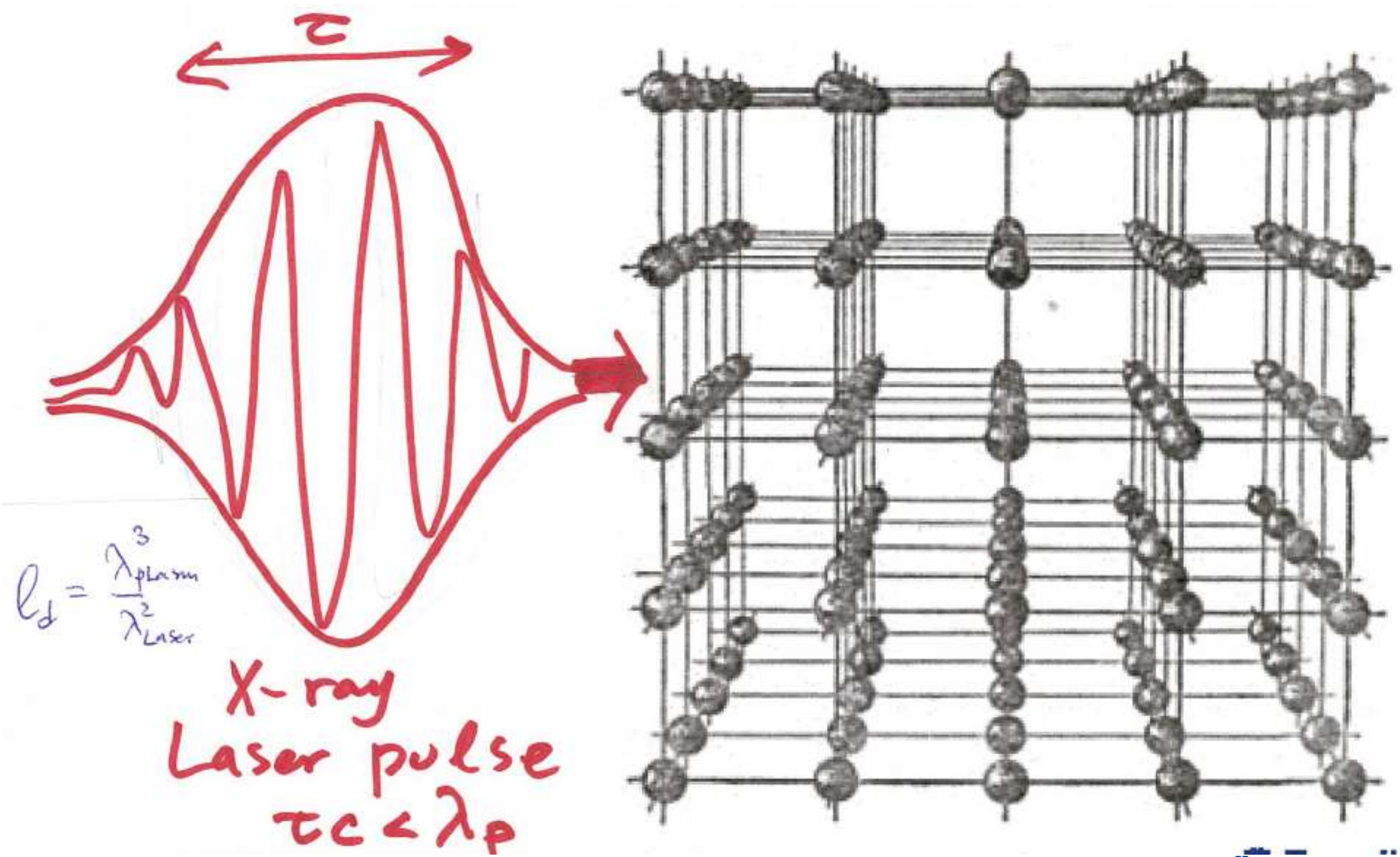


arXiv:1612.07358

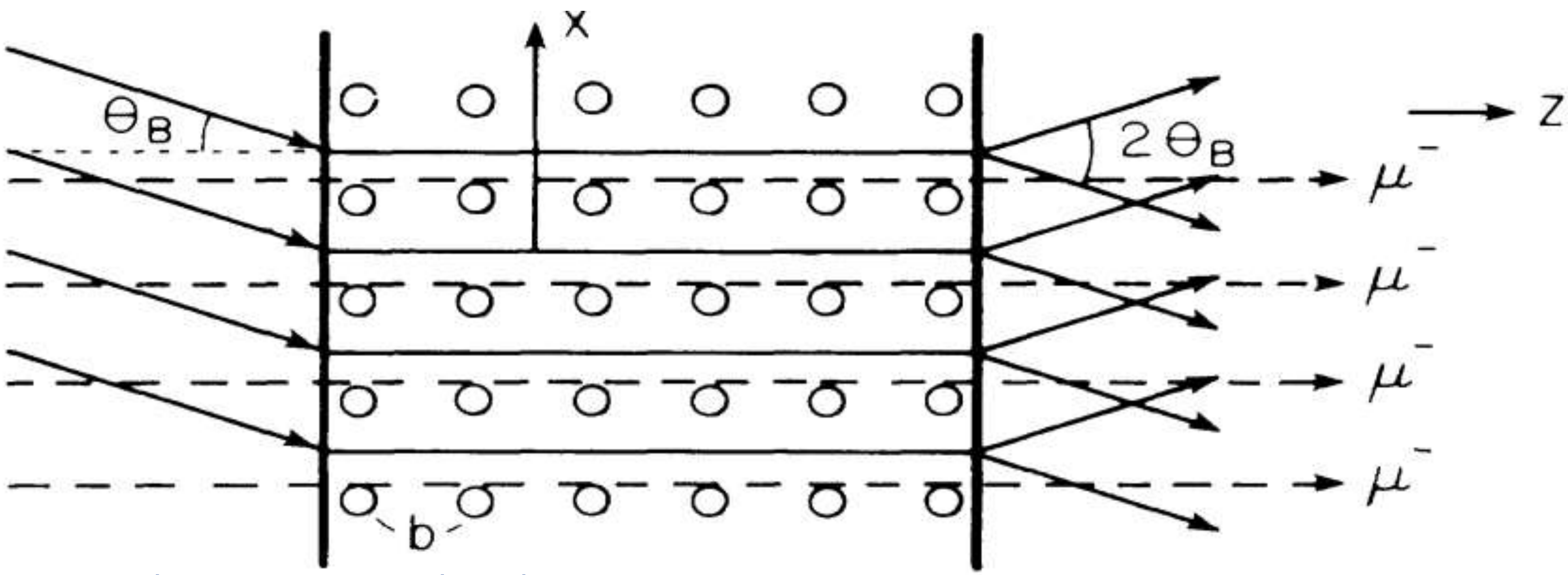
What Do We Know About Acceleration in Xtals and Nanostructures *(besides 1…10…100 tV/m)*

- 1987 - the idea: T.Tajima and M.Cavenago,
  - Bormann angle X-ray injection
  - Phys. Rev. Lett. 59 (1987), 1440
- 1990's – P.Chen and R.Noble, scattering and cooling considerations, crystal damage, etc
  - SR losses balance *E* gain: 0.3TeV for *e*+, 10 PeV for *mu*+, 1000 PeV for *p*+
  - AIP Conf. Proc. 398 (1997), 273
- 2008 – I.Dodin and N.Fisch, theory of acceleration in plasma channels, scattering, friction, damping
  - Phys. Plasmas 15 (2008), 103105
- 2012 – V.Shiltsev, prospects of linear crystal muon colliders
  - Phys. Uspekhy 55 (2012), 965
- 2010's – Prospects of superlasers, superbeams (FACET-II), CNTs
  - Shin, *APL*105(2014),114106; NIMA355(2015),94 ; Zhang,et al PRAB 19 (2016),101004

Ways to excite the crystal (1)



Crystal Excitation by X-Rays



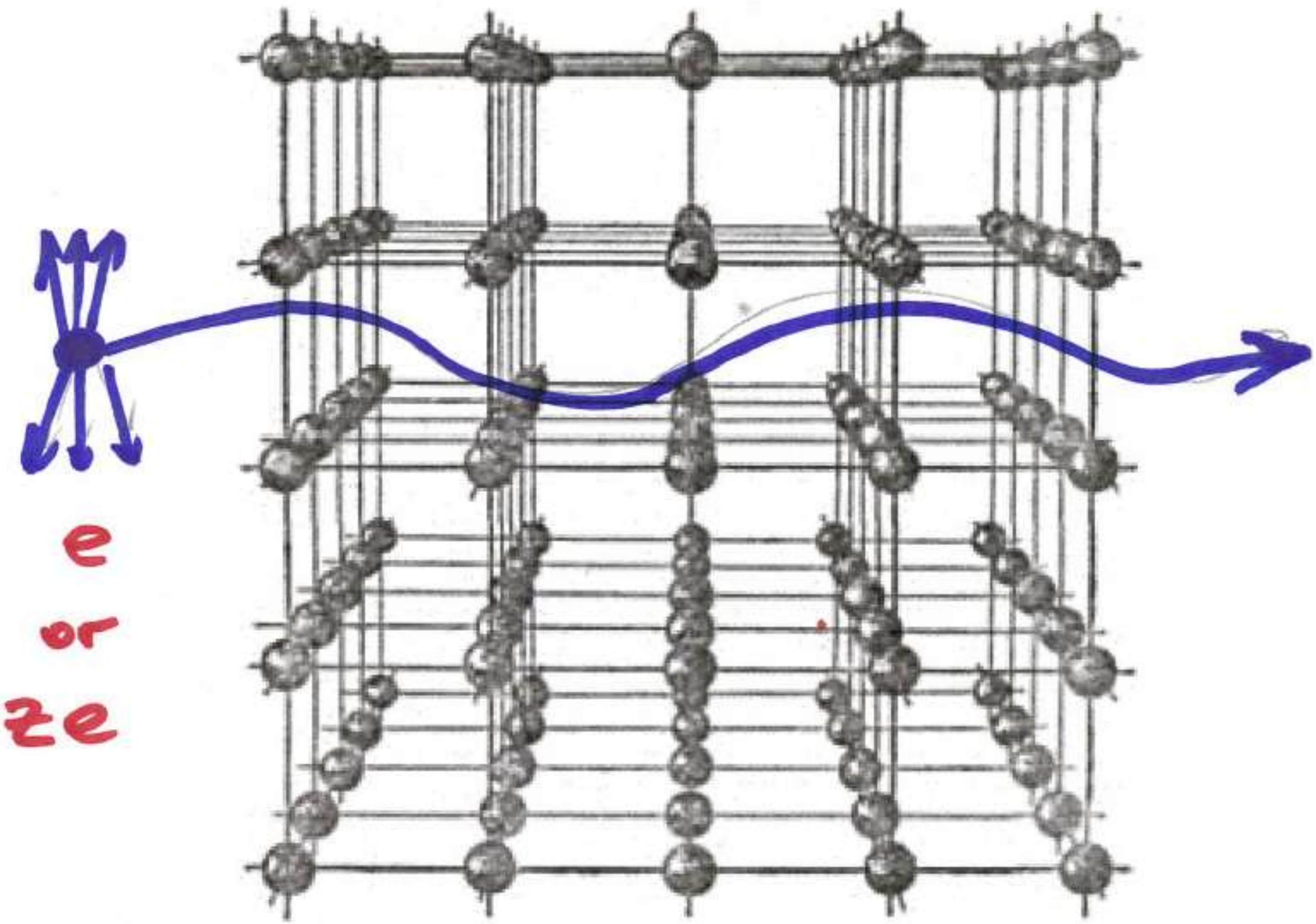
Tajima,Cavenago, Phys. Rev. Lett. 59 (1987), 1440

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.

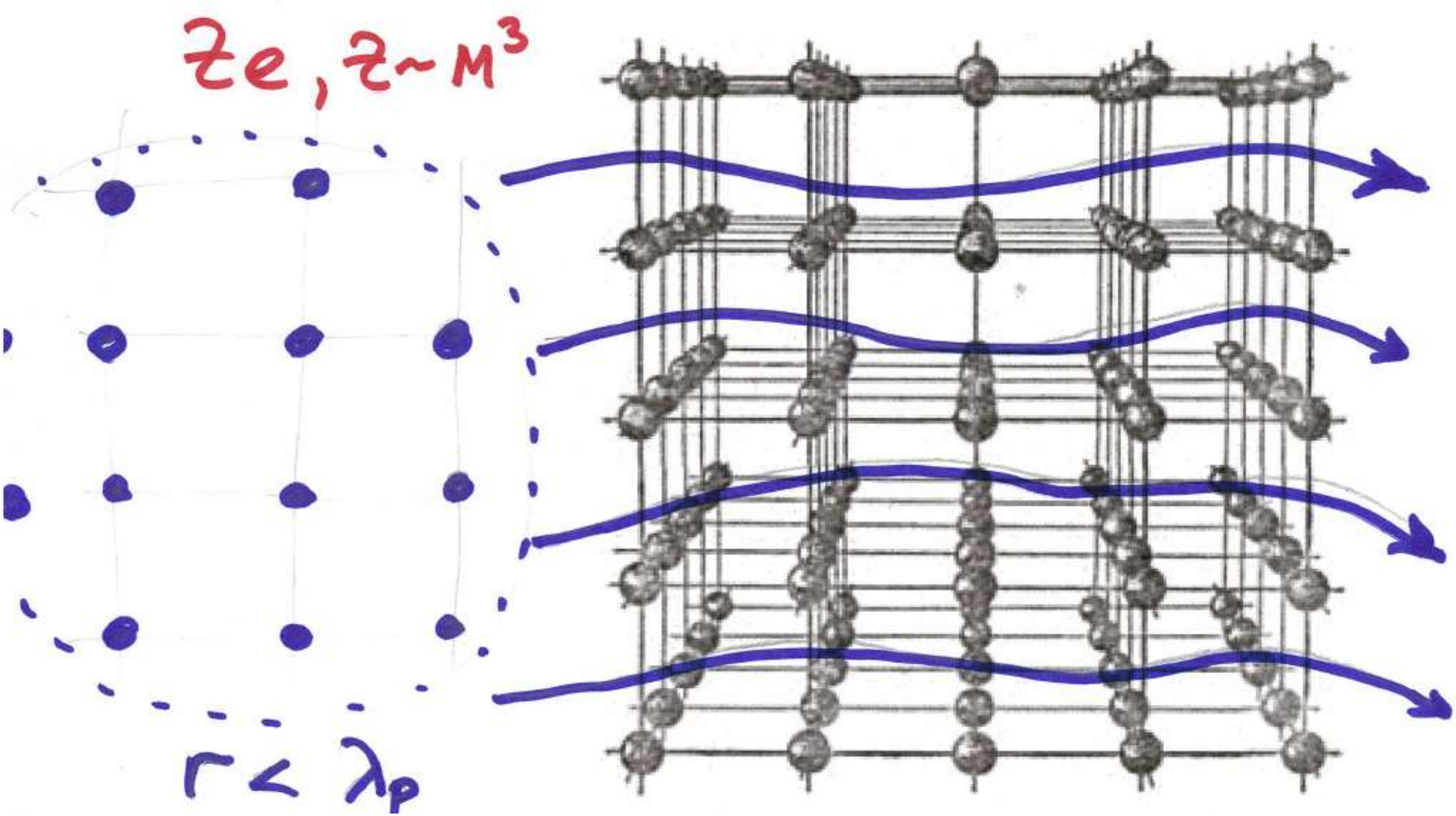
- Need 40keV high peak power x-rays
  - now available from SASE FELs like LCLS
- Gradients >1GV/cm

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

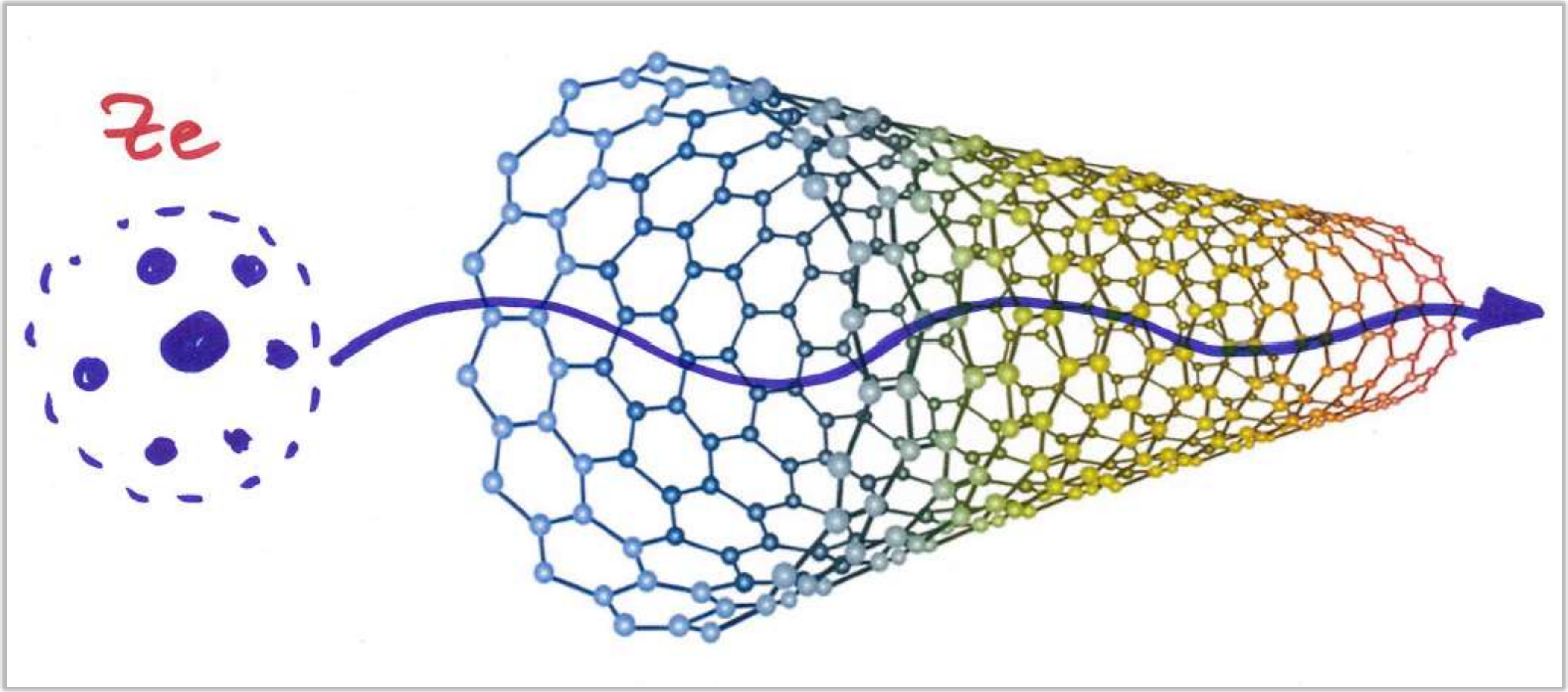
Ways to excite the crystal (2)



Ways to excite the crystal (3)

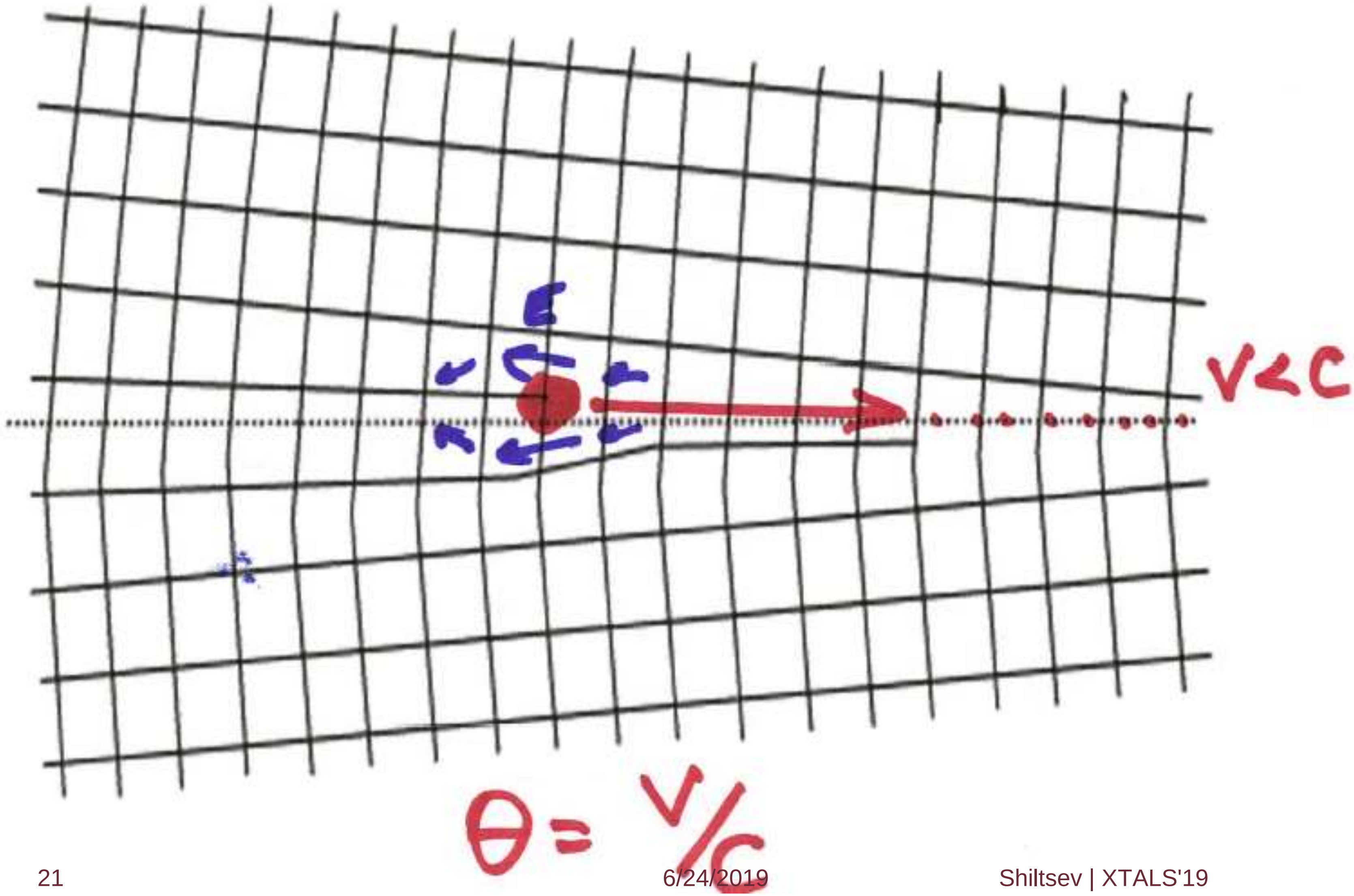


Nanotubes



Ways to excite the crystal (4)

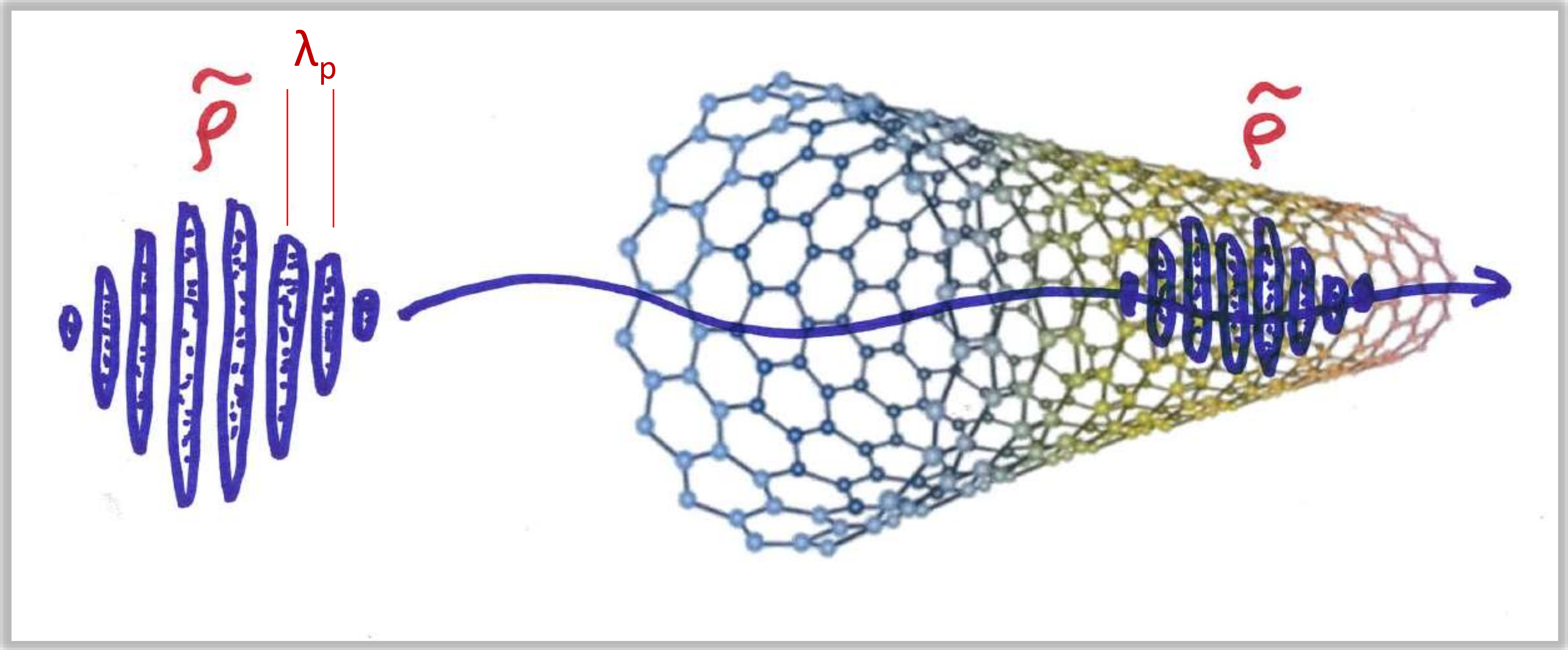
Controlled generation of dislocations



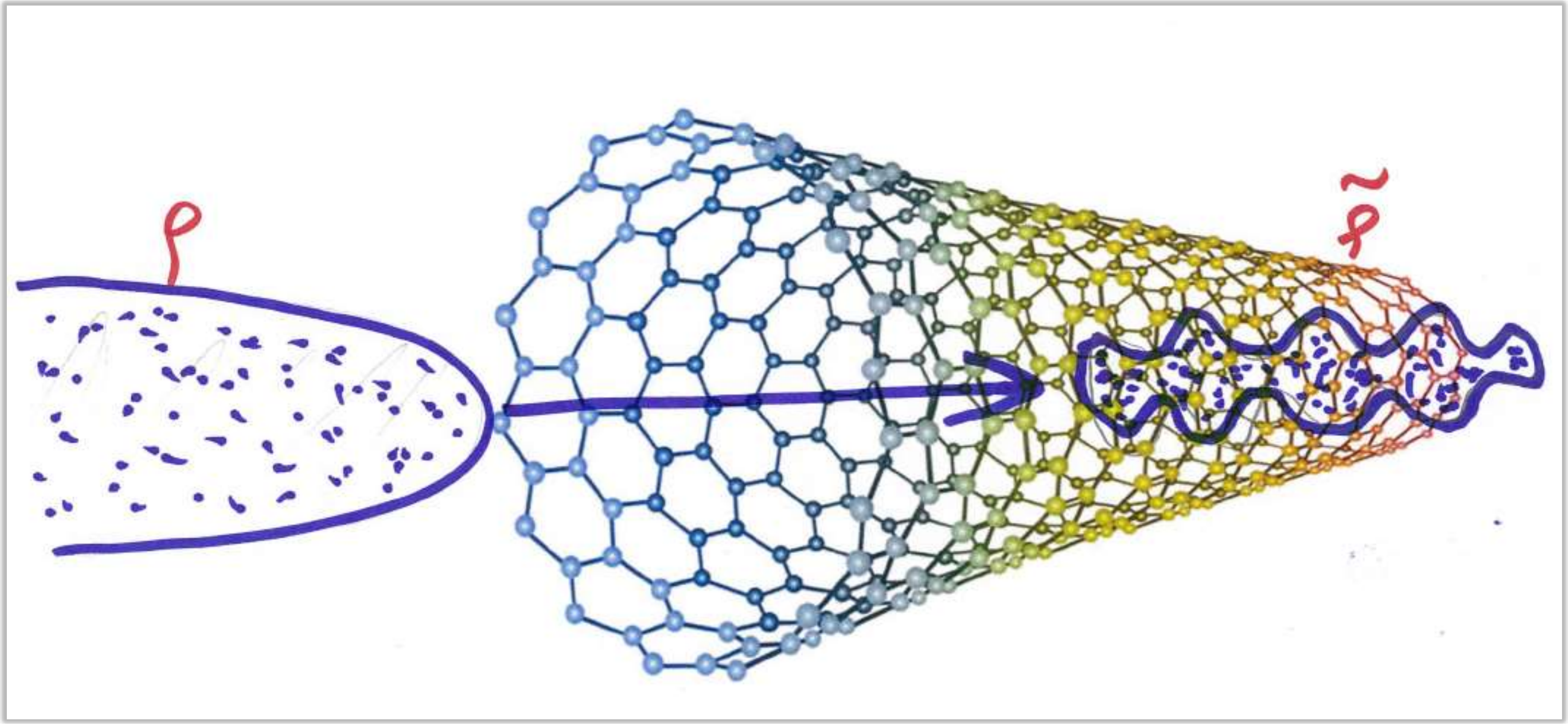
Ways to Excite Nanotubes/Crystals (5)
by *Optical SASE modulated electron beams*

** or slit-masking in low energy beams*

10^{22} cm^{-3} → λ_p~0.3μm
10^{24} cm^{-3} → λ_p~0.03μm

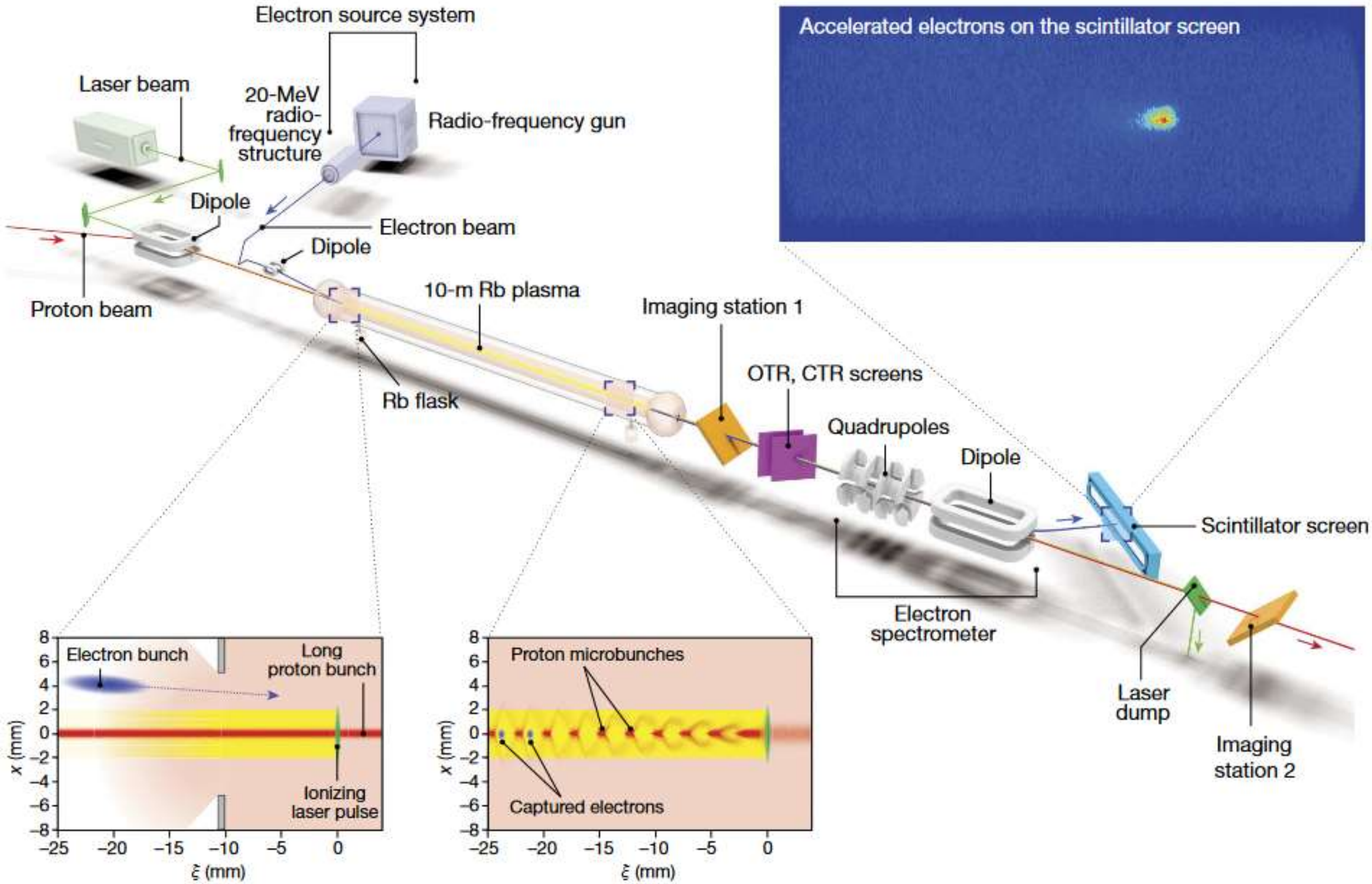


Ways to Excite Nanotubes/Crystals (6)
by *Self-Modulation Instability* in long(er) charge particle beams

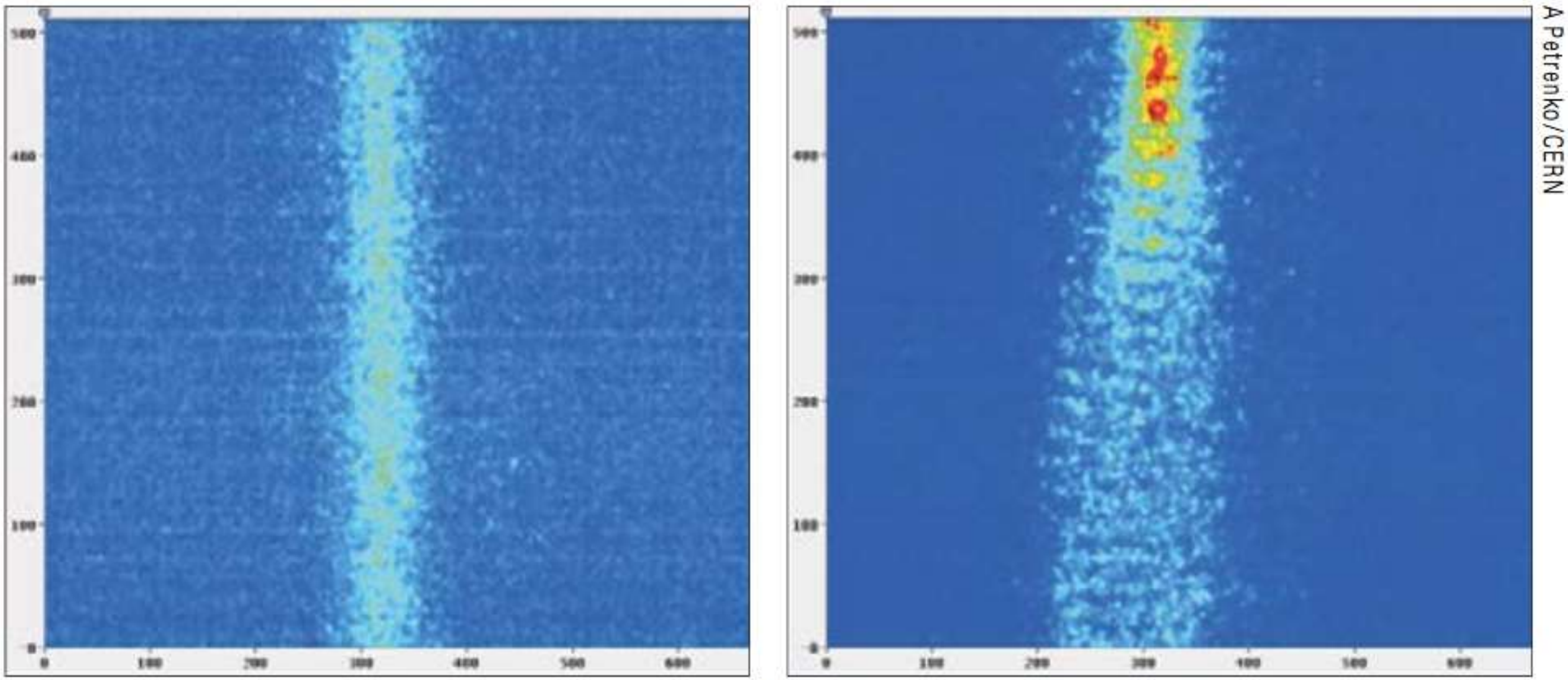


AWAKE


OPEN
LETTER
Acceleration of electrons in the plasma wakefield of a proton bunch



Self-Modulation Instability in AWAKE p+ Bunch



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

CERN COURIER

Volume 57 Number 1 January/February 2017

What Are the Questions for Us Today?

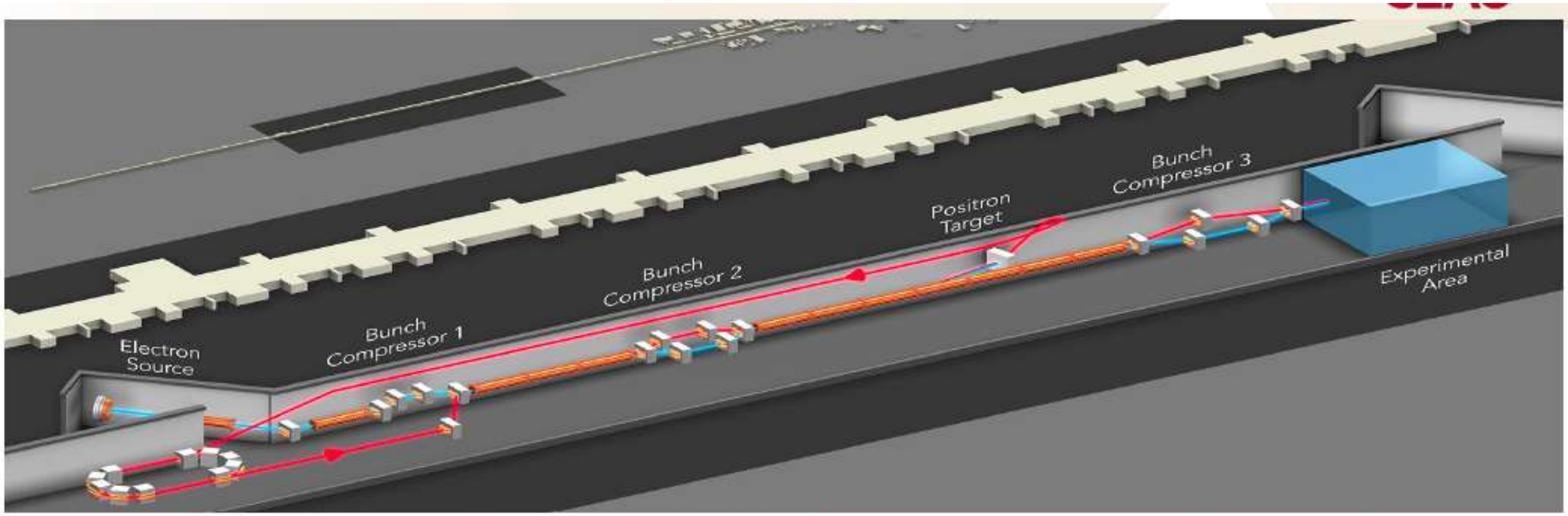
TOPICS FOR STUDIES (WORKSHOP'19)

- 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-II, FAST, AWAKE, AWA, or elsewhere

* can be studied experimentally

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 !
- What can be studied there:
  - Weibel(filamentation) and SMI instabilities
  - Muon production and channeling
  - Acceleration

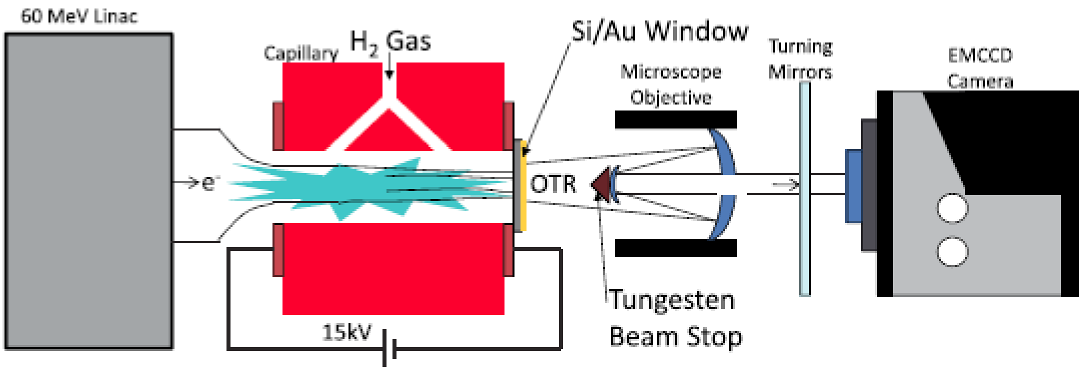
PRL 109, 185007 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

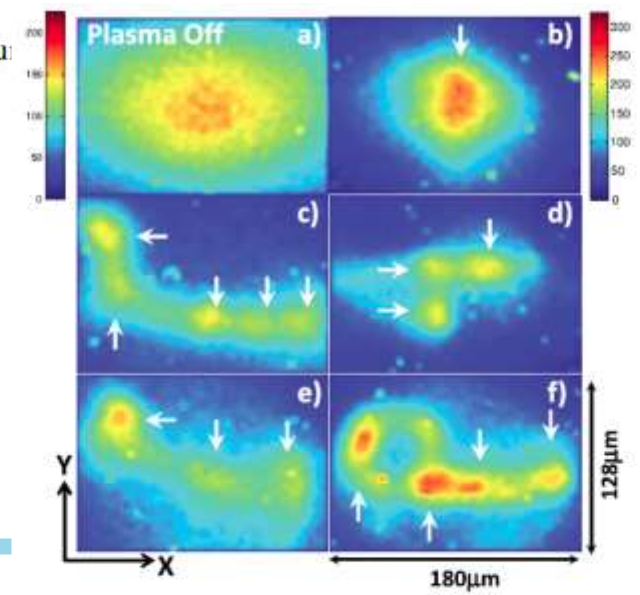
Experimental Study of Current Filamentation Instability

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.

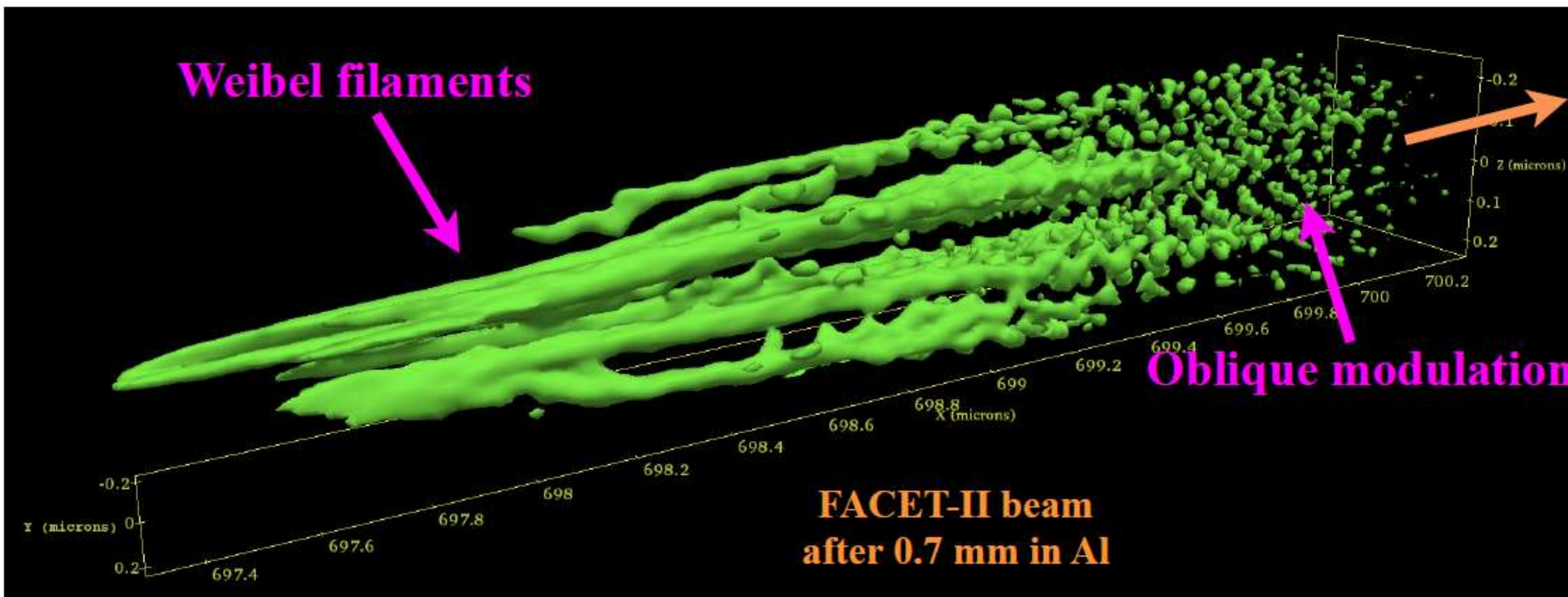
DOI: 10.1103/PhysRevLett.109.185007 PACS nu





FACET-II

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



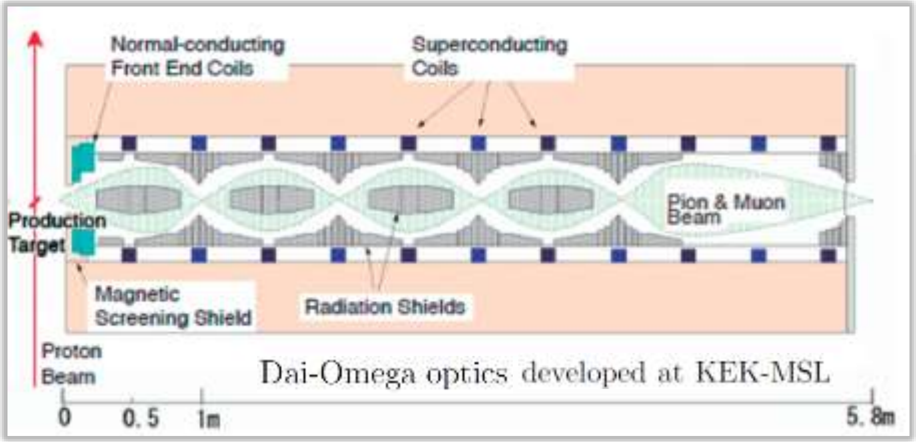
“Prepare for FACET-II” : what can be done

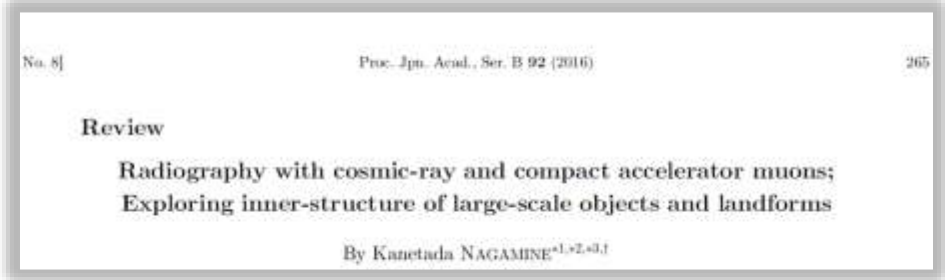
- Simulations; define optimal configuration – beams, CMTs vs crystals, etc
- Hardware assembly and tests, eg at FAST
- Beam pre-test at FAST (50-300 MeV ILC type beams)
  - E.g., *e*- channeling and SMI in the CNTs
- Consider muon production, capture and channeling, acceleration
  - Then it can be expanded to FACT-II (10 GeV *e*- to mu) or else where (BELLA has GeV *e*- beams)

MUON PRODUCTION AND CHANNELING

- Advanced schemes

* see also K.Yonehara talk

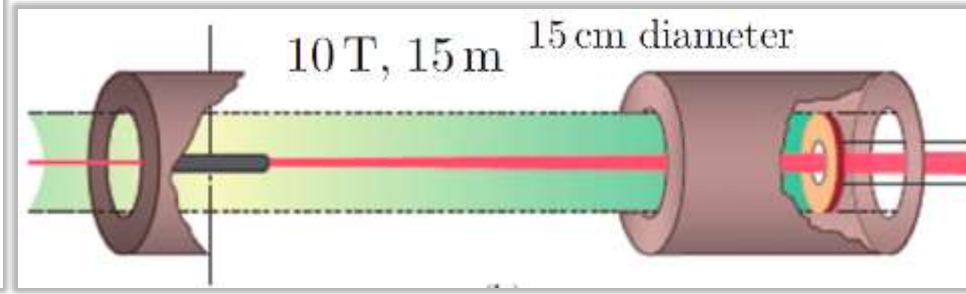



No. 8] Proc. Jpn. Acad., Ser. B 92 (2016) 265

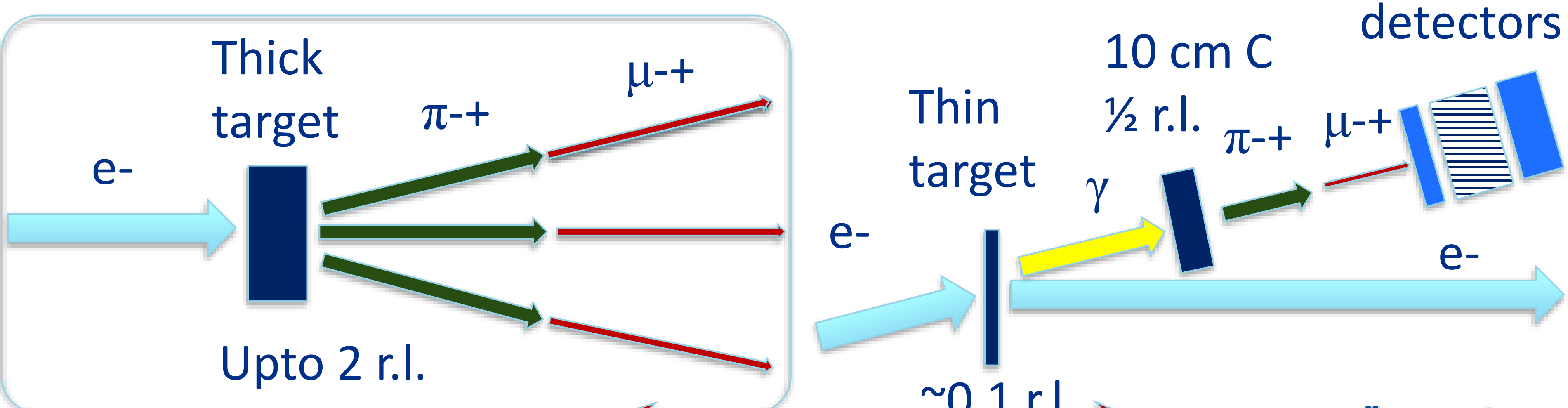
Review

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)



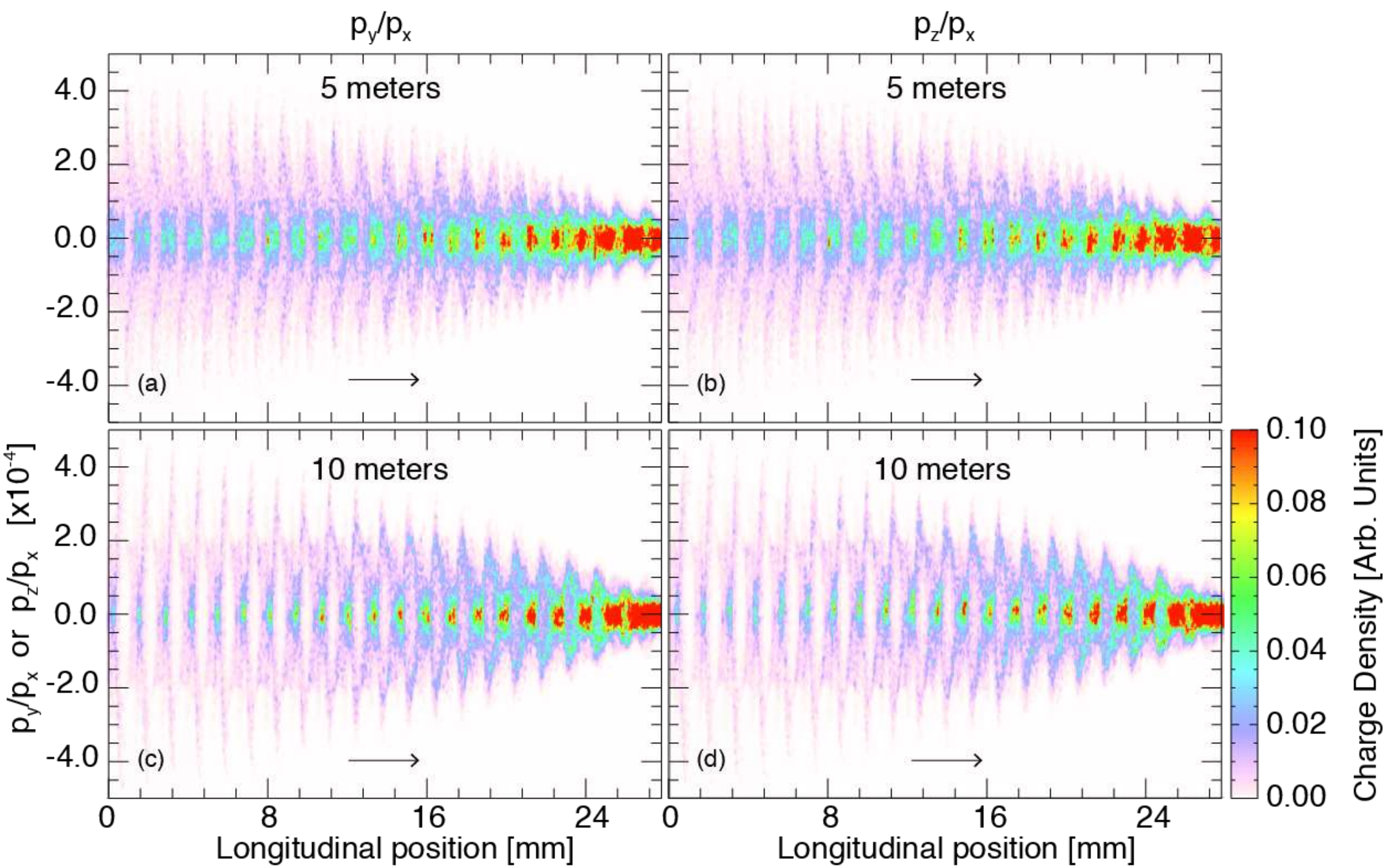
$\mu/e \sim 10^{-5}$ S.Striganov $\mu/e \sim 3\ 10^{-8}$

Summary

- Acceleration of *μ's in crystals or 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 beam facilities such FACET-II, FAST, BELLA, etc – *eg by SMI*
- Beam filamentation is of serious concern and can be studied first at, e.g., FAST, then elsewhere (FACET-II, etc)
  - 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
- ***Serious work is ahead to understand the most optimal ways to excite Xtals/CNTs, explore beam acceleration and dynamics via theory, modeling, and experiment***

Thank You for Your Attention!

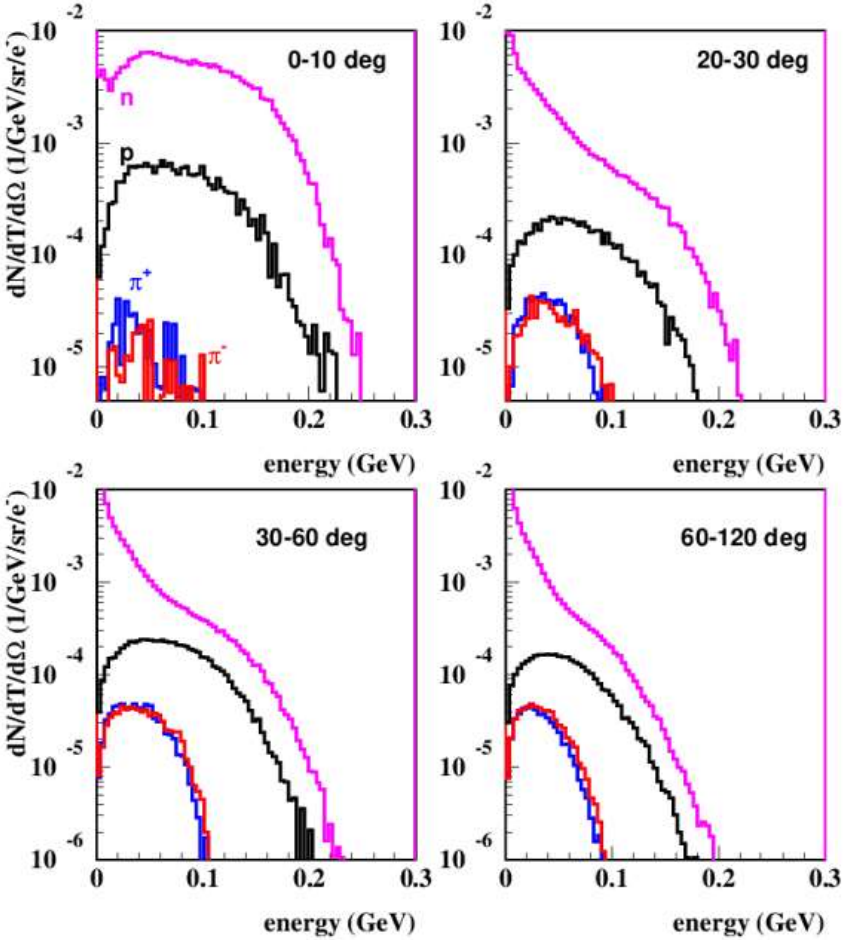
SMI: Self-Modulation Instability (in 400 GeV protons)

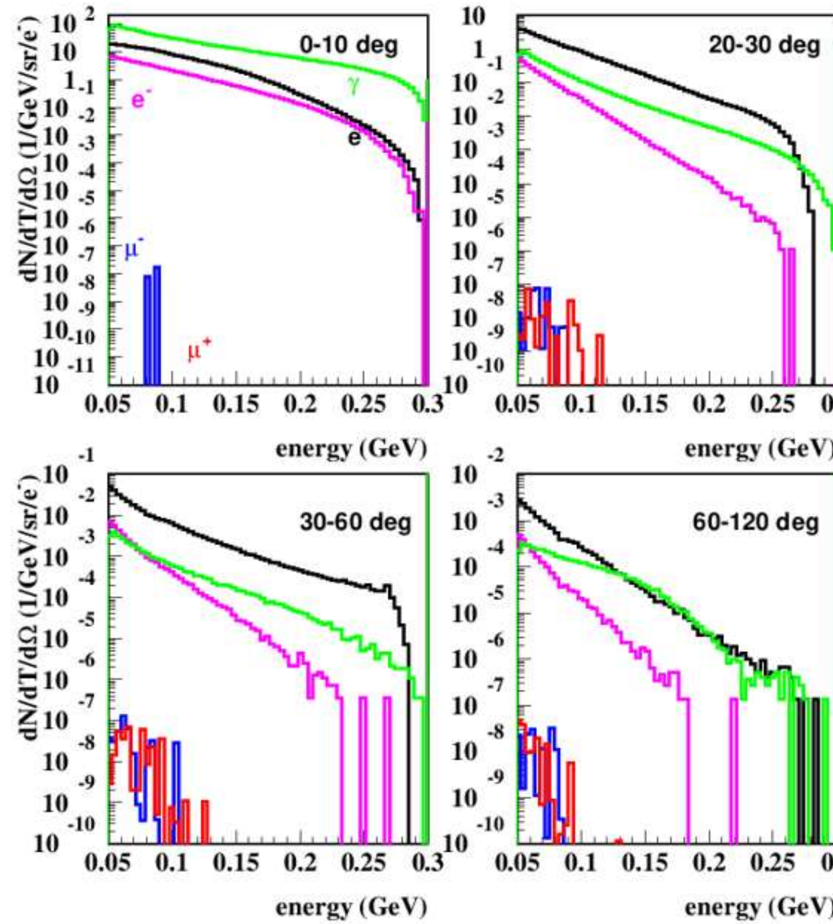


Fermilab

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

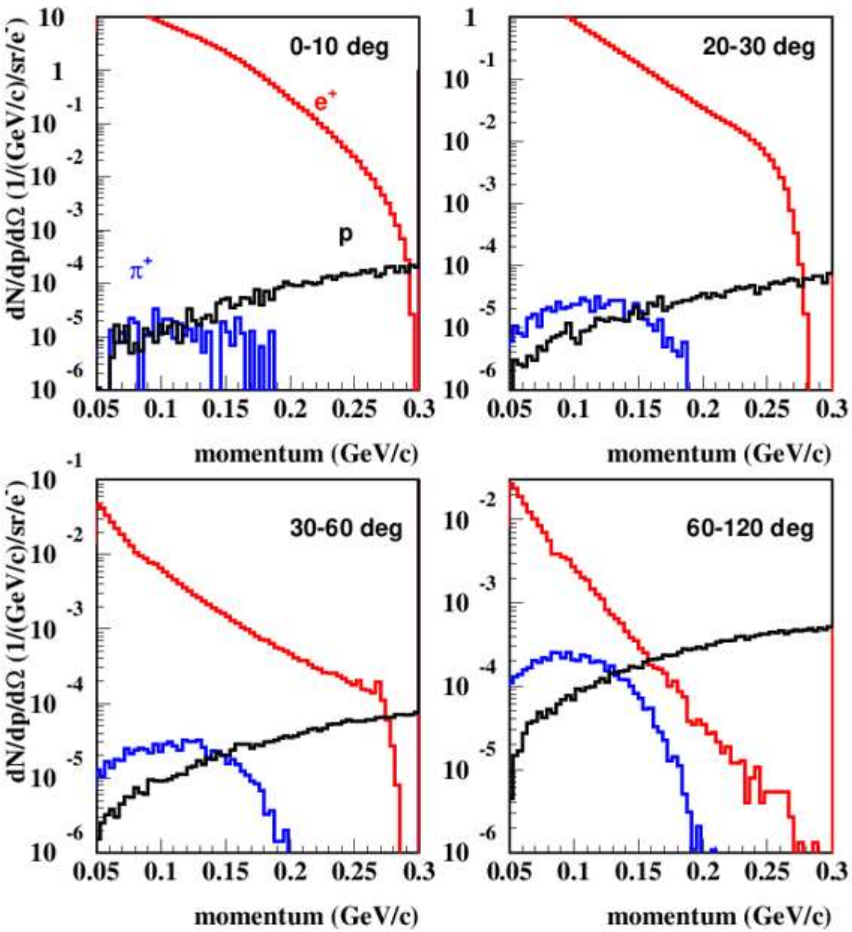
Courtesy S.Striganov

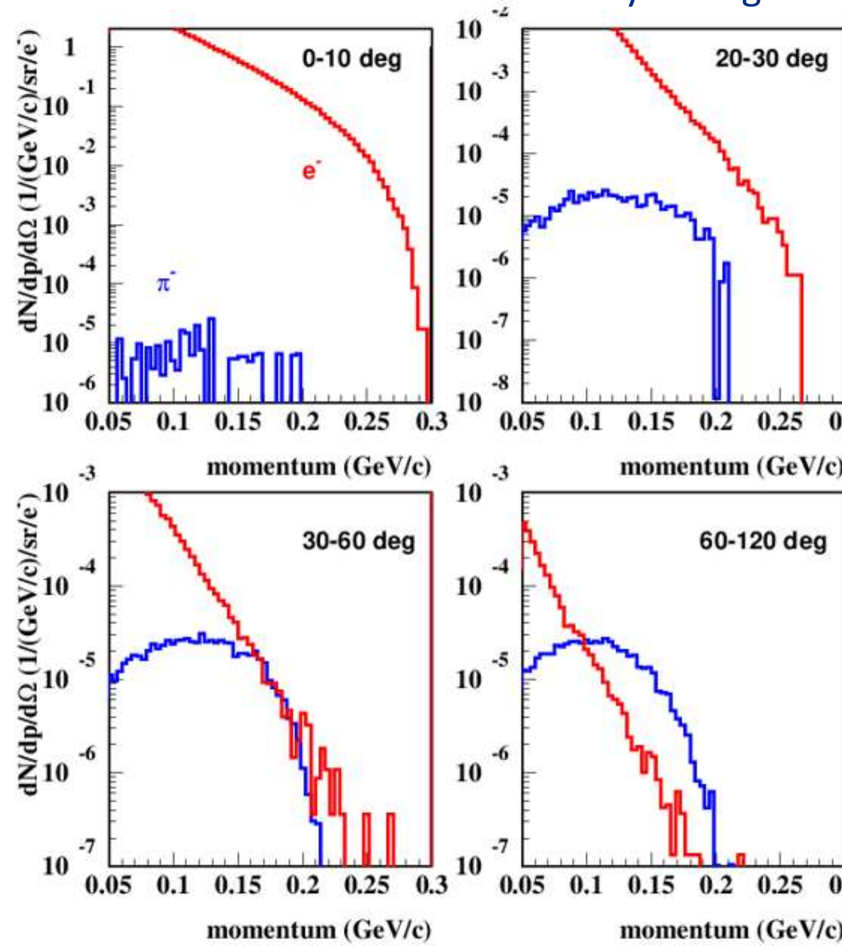




Positive pions has very big positron/proton escort, large angle & high momentum; negative pion could be focused and extracted

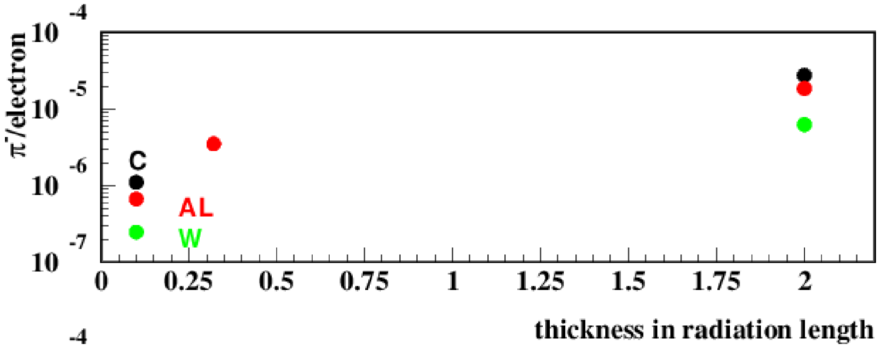
Courtesy S.Striganov

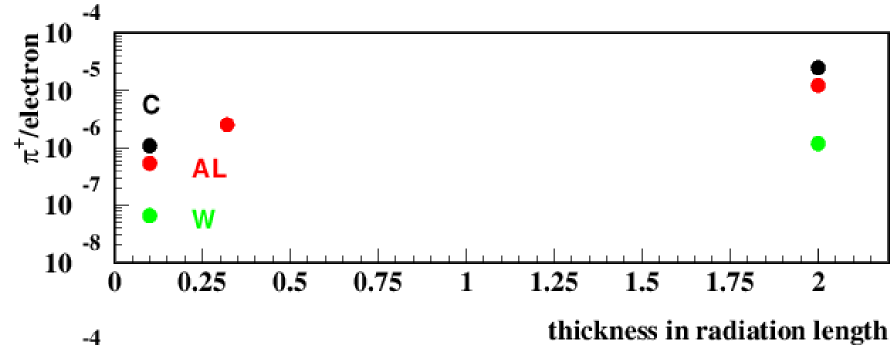


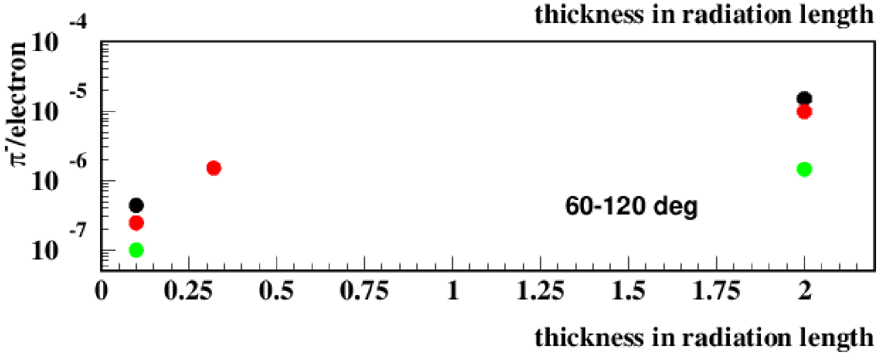


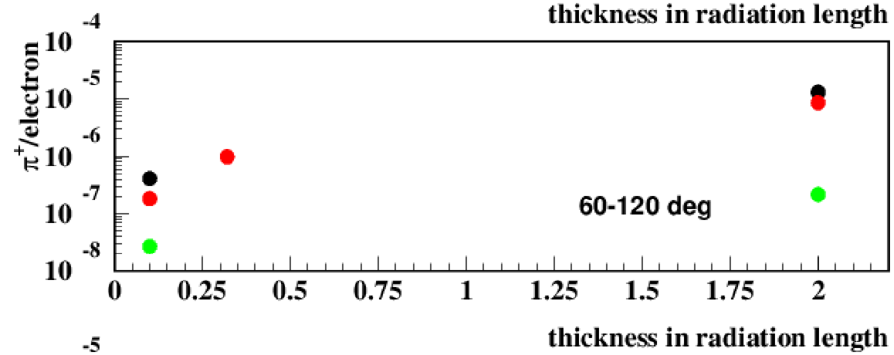
More pion could be obtained for larger thickness & low Z. target material. Larger thickness – large radiation problem, low Z - longer target (more difficult to collect)

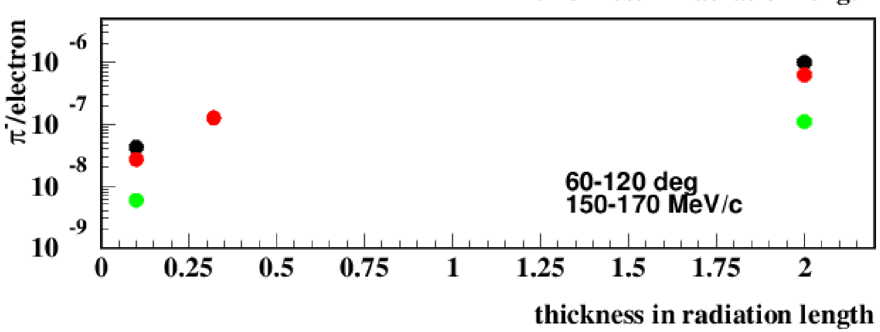
Courtesy S.Striganov

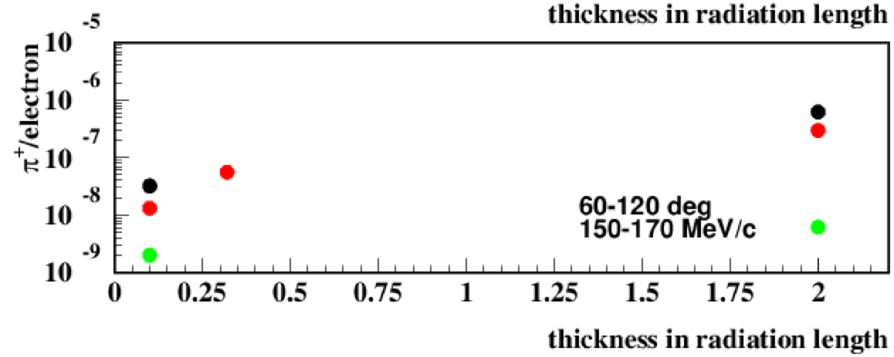












Low radiation scenario

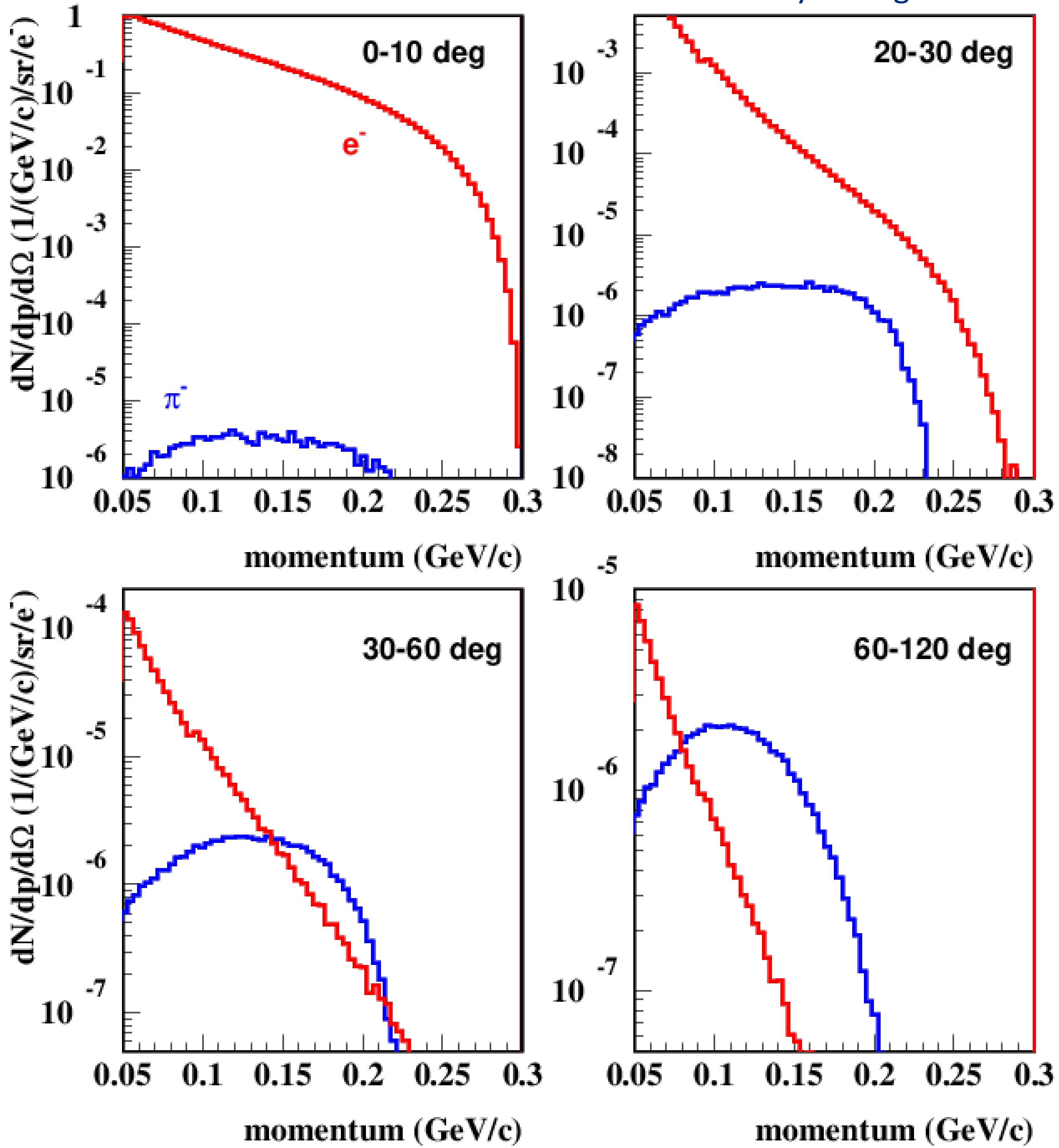
Two production targets – photon production and pion/muon production.

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



High Energy $\mu+\mu-$ Colliders

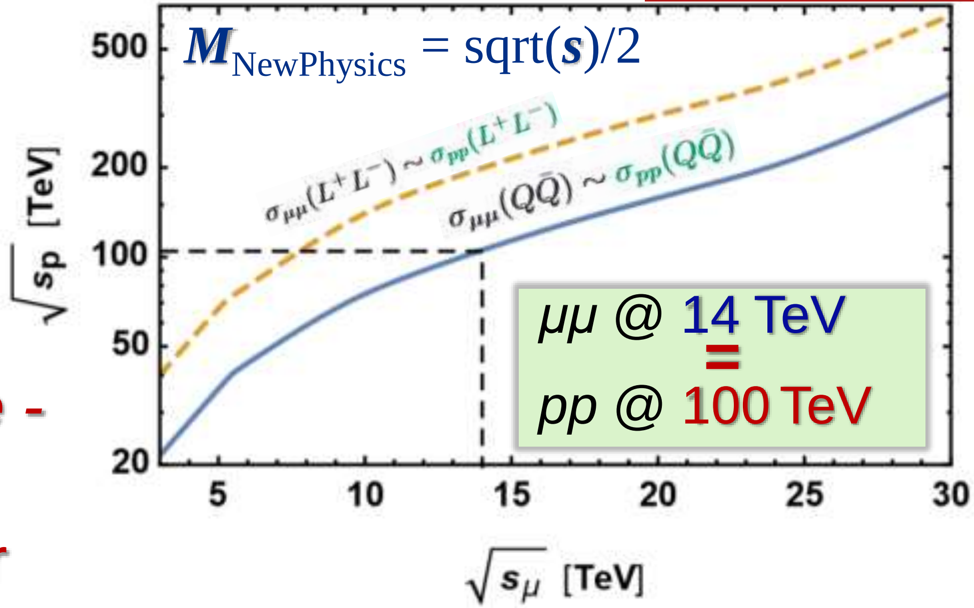
Input #120

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:

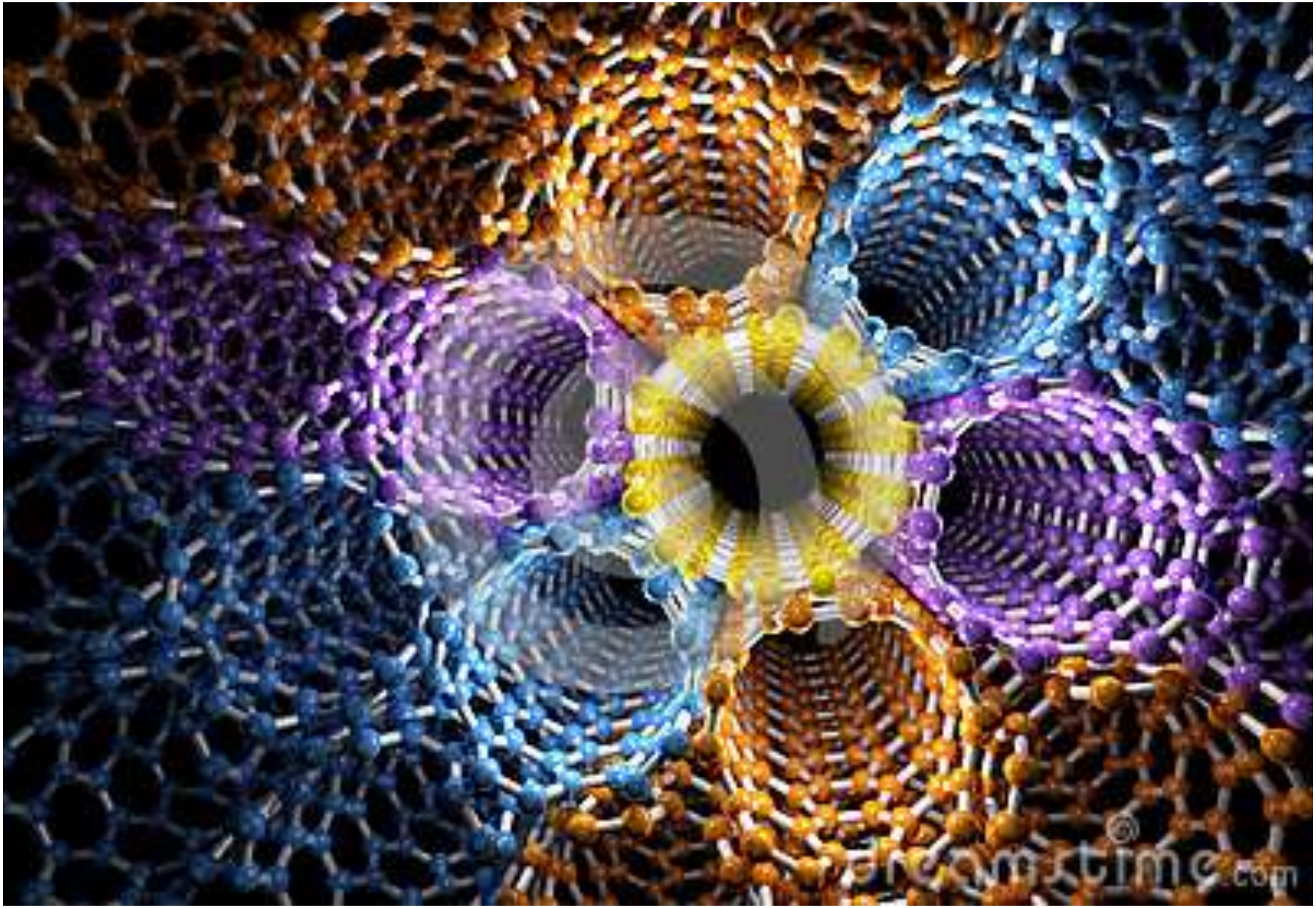
- US MAP feasibility studies were very successful → MCs can be built with present day SC magnets and RF; there is a well-defined path forward
- ZDRs exist for 1.5 TeV, 3 TeV, 6 TeV and 14 TeV * in the LHC tunnel

** more like "strawman" parameter table*

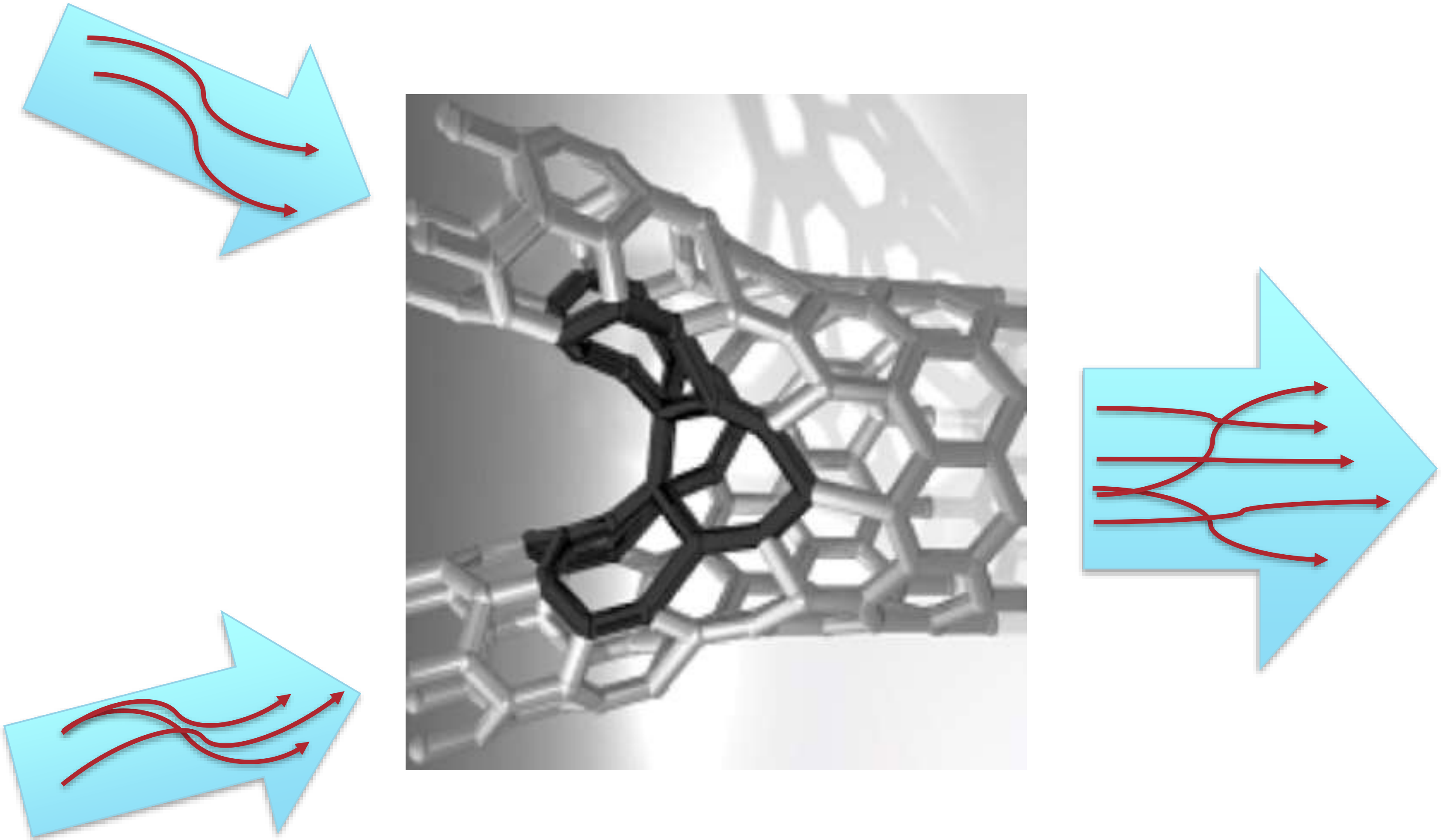
Key to success:

- 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

Nanotubes (2)



Combine (funnel) Channels



Collider considerations

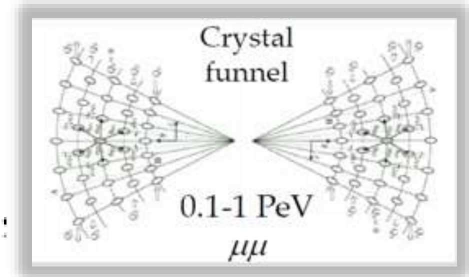
$$dN/dt = -N/\gamma\tau_0 \qquad \frac{N}{N_0} \approx \left(\frac{m_\mu c^2}{E}\right)^{\kappa}$$

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

i.e. irrelevant

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

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



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

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 [illegible]-10^4	~ 1

PRL **106,** 105001 (2011) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2011

Current Filamentation Instability in Laser Wakefield Accelerators

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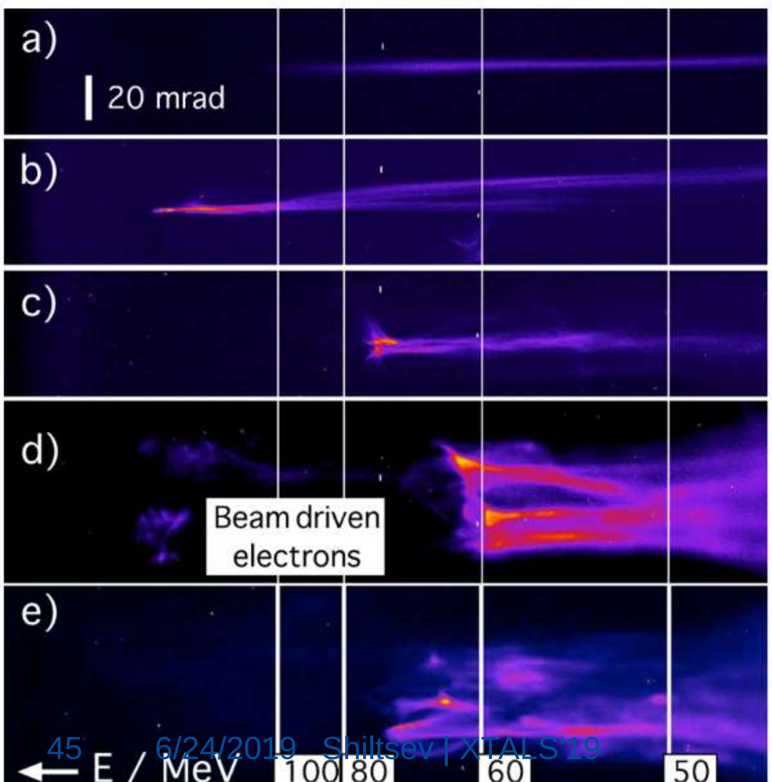
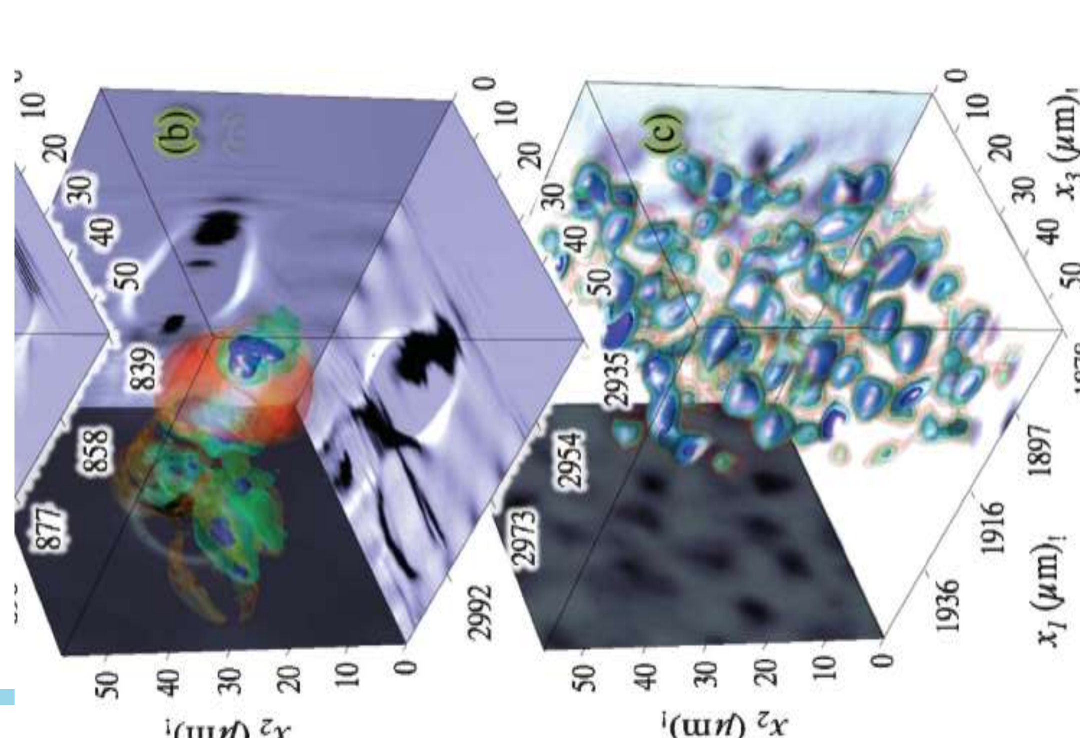
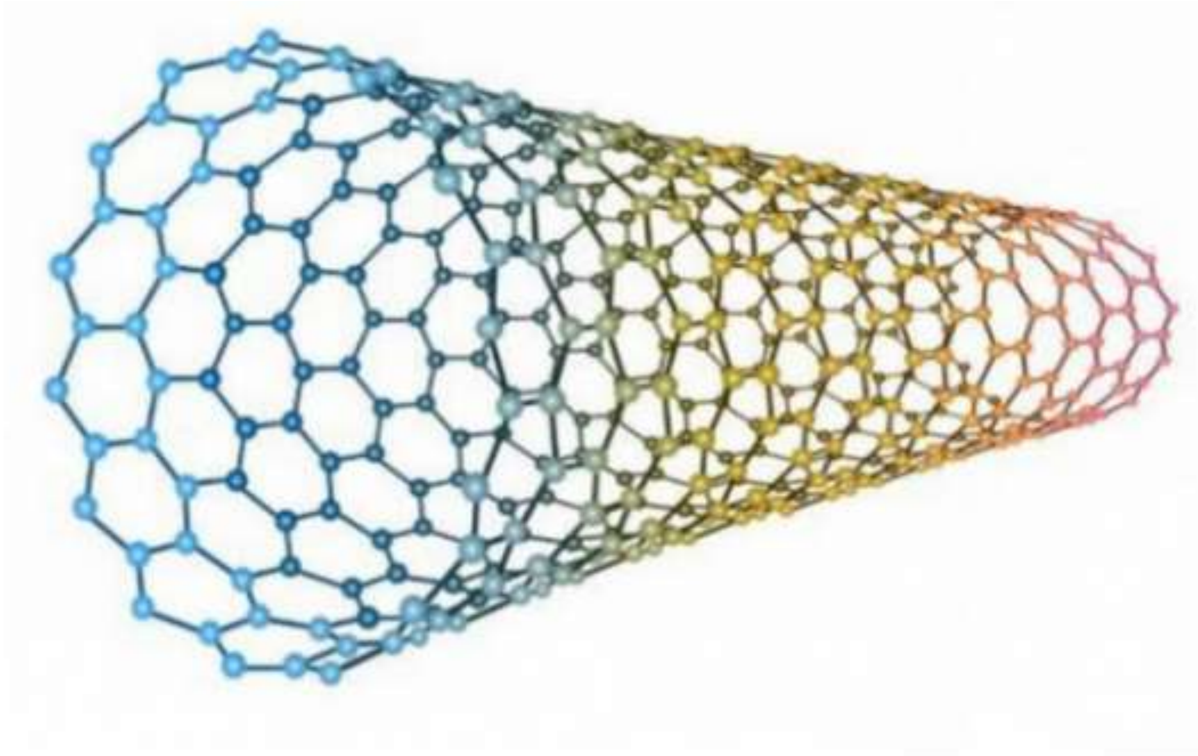
(Received 16 November 2010; published 8 March 2011)







Weibel (Filamentation) Instability

Under consideration for publication in J. Plasma Phys. 1

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

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PHYSICS OF PLASMAS VOLUME 9, NUMBER 6 JUNE 2002

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

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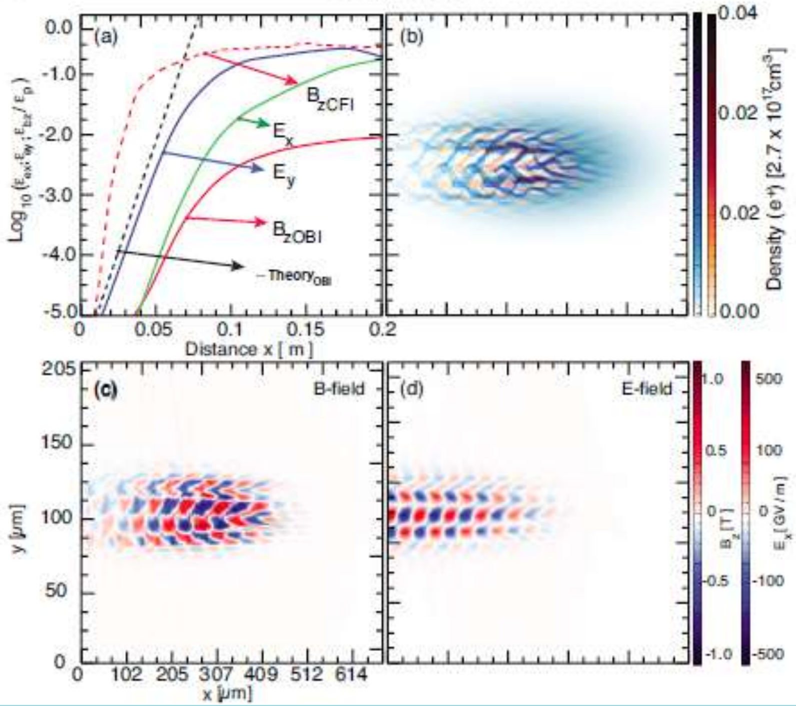
(Received 2 January 2002; accepted 12 March 2002)

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]



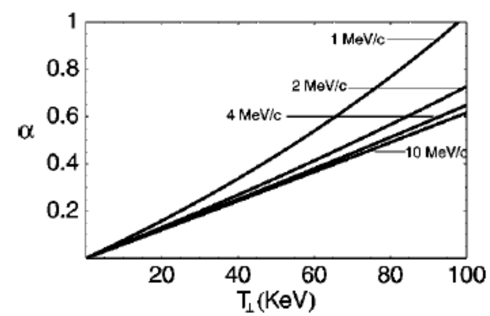


FIG. 1. Threshold for the occurrence of the Weibel instability from Eq. (9) for different beam directed momentum p_{x0}.

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