# Acceleration in Crystals & CNTs : Ideas, Challenges, Opportunities

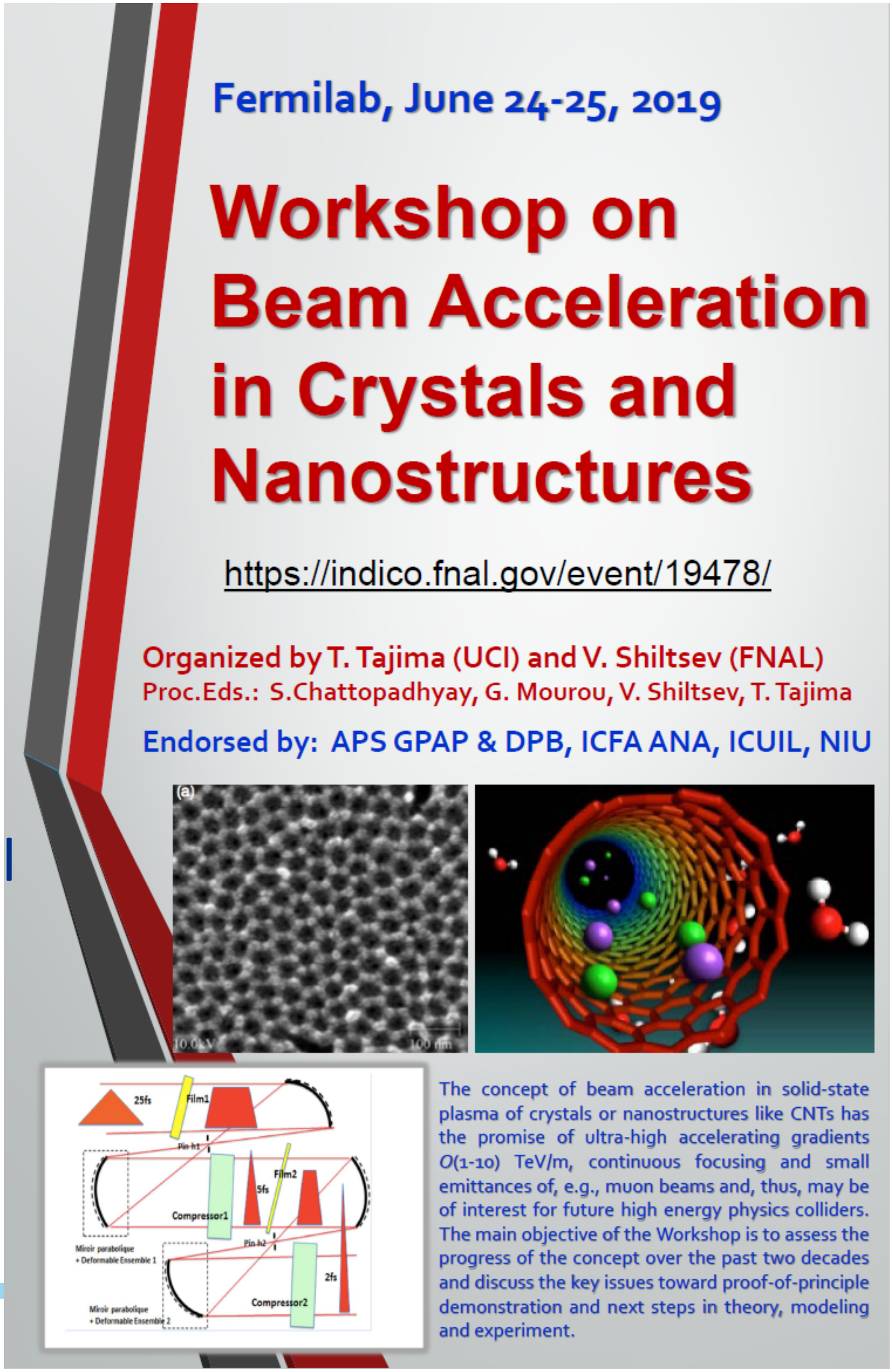
*Summary of the Workshop on Acceleration In Crystals and Nanostructures* **(June 24-25, 2019; Fermilab)**

**Vladimir SHILTSEV (Fermilab), with input from T.Tajima, A.Sahai**

FACET-II Science Workshop, Oct 31, 2019

The goal of the ***Workshop*** was to assess the progress of the concept over the past two decades and to discuss key issues toward proof-of-principle demonstrations and next steps in theory, modeling and experiment.

The Workshop was endorsed by the APS DPB and GPAP, the International Committee on Ultra-High Intensity Lasers (ICUIL) and the International Committee on Future Accelerators Panel on Advanced and Novel Accelerators (ICFA ANA).



**Fermilab, June 24-25, 2019**

# Workshop on Beam Acceleration in Crystals and Nanostructures

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

Organized by T. Tajima (UCI) and V. Shiltsev (FNAL)
Proc.Eds.: S.Chattopadhyay, G. Mourou, V. Shiltsev, T. Tajima

**Endorsed by: APS GPAP & DPB, ICFA ANA, ICUIL, NIU**

The concept of beam acceleration in solid-state plasma of crystals or nanostructures like CNTs has the promise of ultra-high accelerating gradients *O*(1-10) TeV/m, continuous focusing and small emittances of, e.g., muon beams and, thus, may be of interest for future high energy physics colliders. The main objective of the Workshop is to assess the progress of the concept over the past two decades and discuss the key issues toward proof-of-principle demonstration and next steps in theory, modeling and experiment.

# 40 participants - 2 days - 22 presentations

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

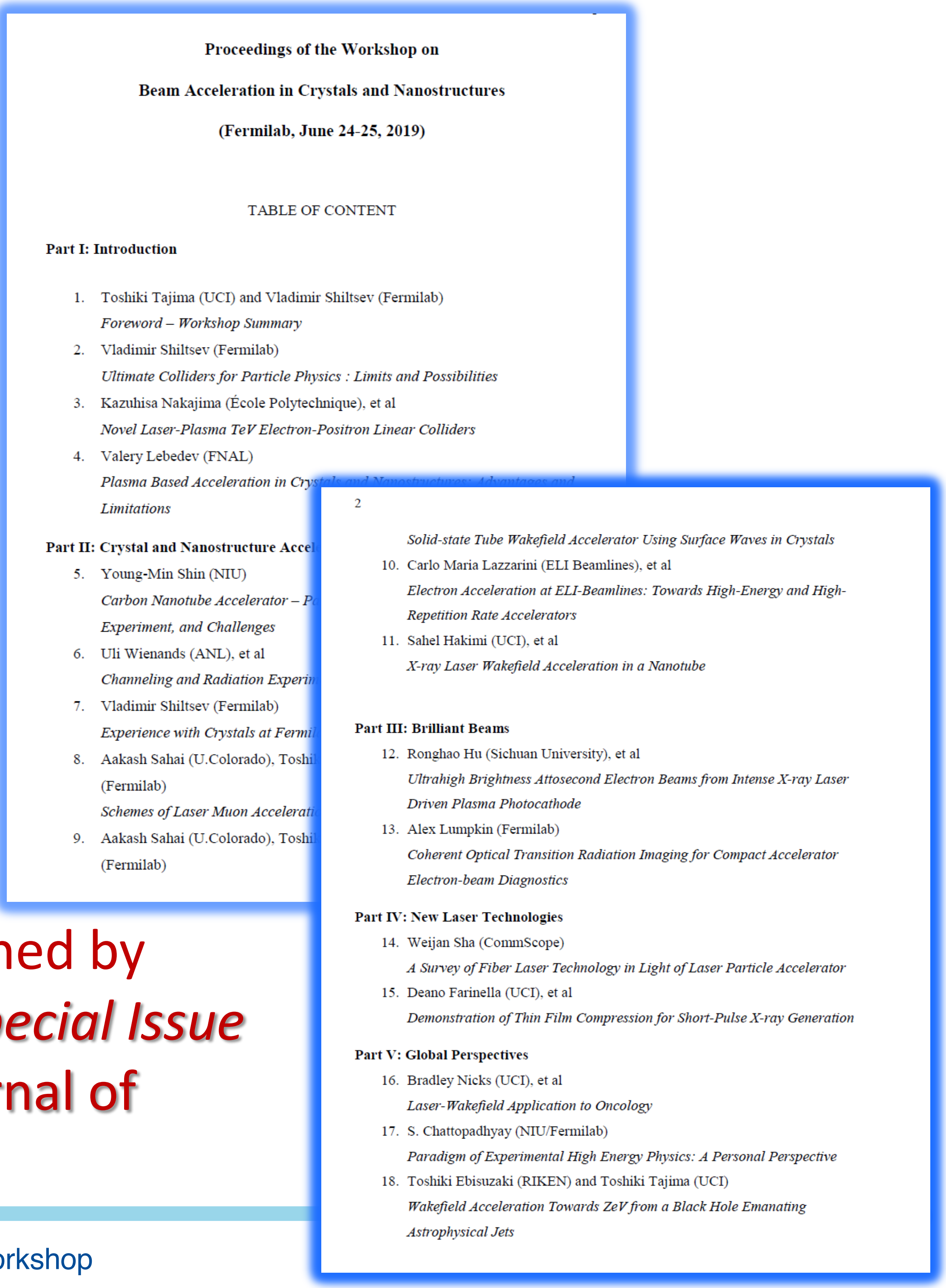
# Main Topics of Presentations and Discussions

1. overview of the past and present theoretical developments toward crystal acceleration, ultimate possibilities of the concept;
2. concepts and prospects of PeV colliders for HEP;
3. effective crystal wake drivers: beams, lasers, other;
4. beam dynamics in crystal acceleration;
5. instabilities in crystal acceleration (filamentation, etc.);
6. acceleration in nanostructures (CNTs, etc);
7. muon sources for crystal acceleration;
8. application of crystal accelerators (X-ray sources, etc.);
9. astrophysical evidence of wakefield acceleration processes;
10. steps toward "proof-of-principle": **1 GeV over 1 mm**, open theory questions, modeling and simulations;
11. possible experiments at **FACET-II, FAST, AWAKE**, AWA, RHIC, LHC, CEBAF, or elsewhere

# Workshop Proceedings

- co-edited by Profs. Gerard Mourou (Ecole Polytech, 2018 Nobel Prize in Physics), Toshiki Tajima (UCI), Swapan Chattapdhyay (NIU) and Vladimir Shiltsev (Fermilab).

- To appear as a **book**, published by World Scientific, and as a *Special Issue* of **IJMPA** (International Journal of Modern Physics A)



**Proceedings of the Workshop on**

**Beam Acceleration in Crystals and Nanostructures**

**(Fermilab, June 24-25, 2019)**

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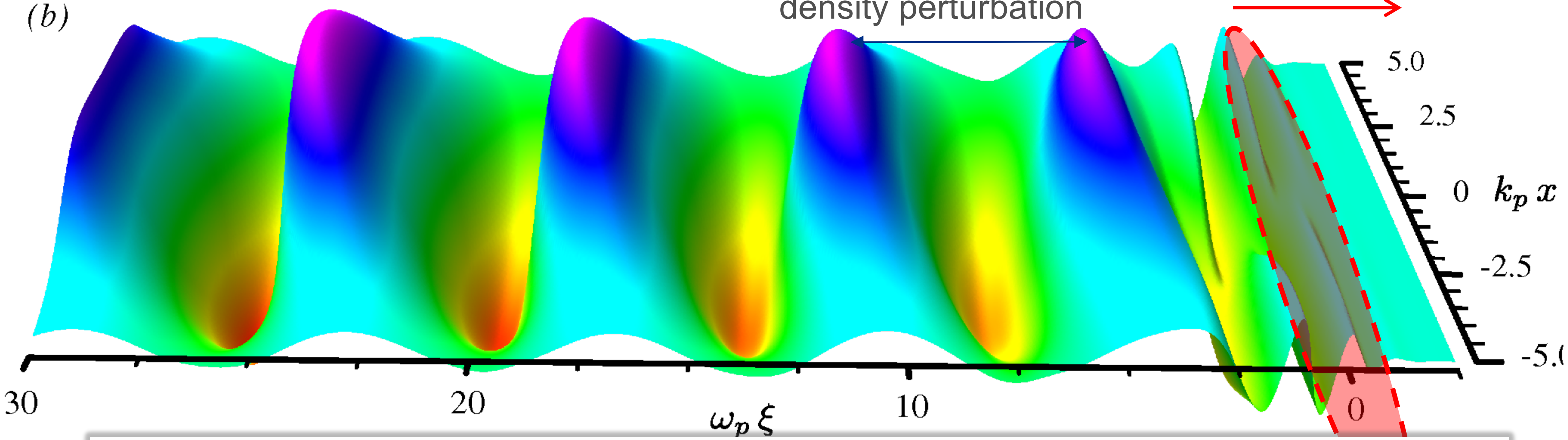
# Plasma Waves

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

Plasma wave: electron density perturbation

Laser/beam pulse ~ $\lambda_p/c$



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

**Option A:**

Short intense e-/e+/p bunch

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

**Option B:**

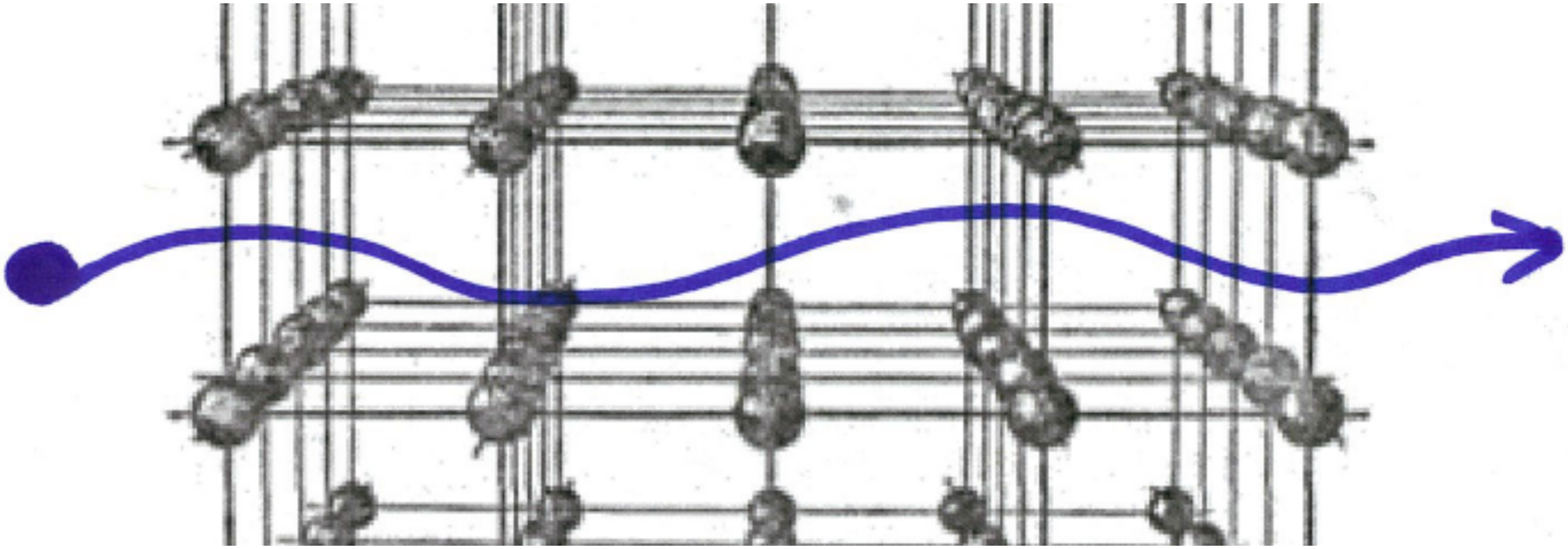
Short intense laser pulse

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

Plasma Collider Challenges: ***e+*, staging <*E*>~2 GV/m, $\varepsilon$, $\eta$,** etc

T.Tajima, M.Cavenago, Crystal X-ray Accelerator, Phys. Rev. Lett., 59(13), 1440 (1987).

# 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, $\lambda_p$~0.3µm

$10^{24}$ cm$^{-3}$ →100 TV/m, $\lambda_p$~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)

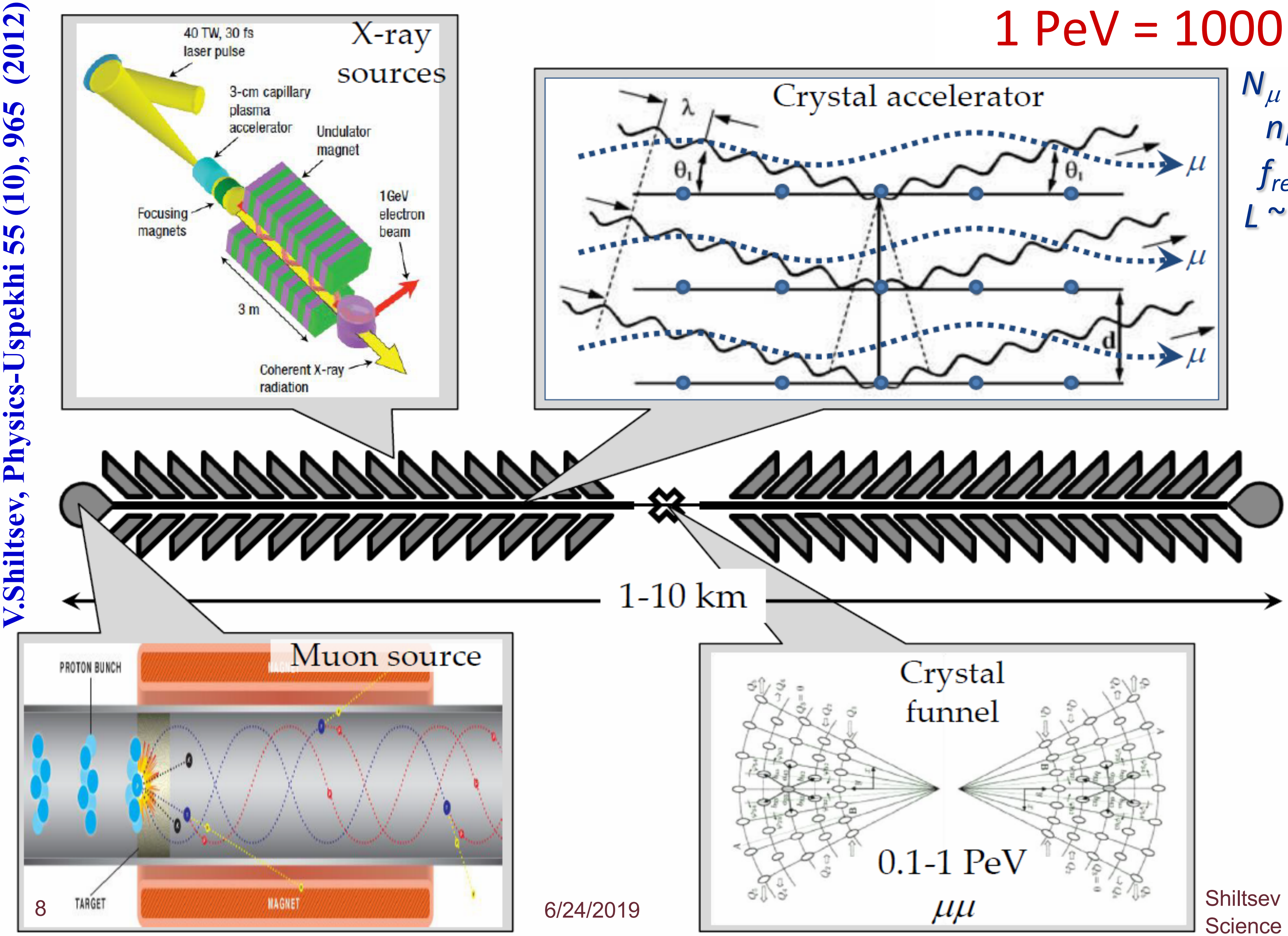
1 PeV = 1000 TeV

$N_\mu$ ~1000

$n_B$ ~100

$f_{rep}$ ~$10^6$

$L$ ~$10^{30-32}$



# Basic (“Level 0”) Questions

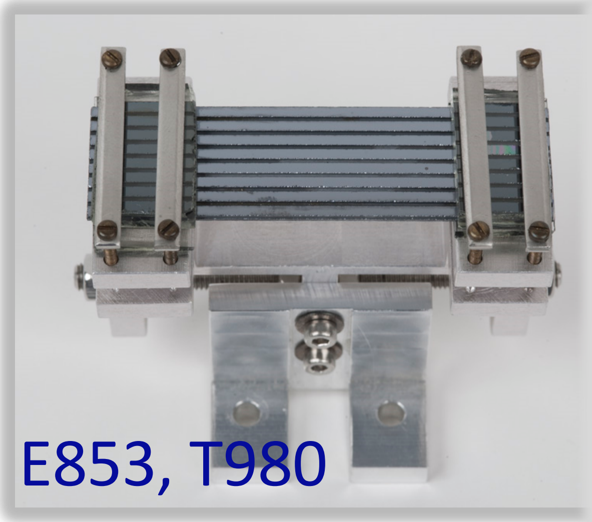
1. Structured media:
    - crystals
    - carbon nanotubes
2. Drivers of wakefields in crystals:
    - lasers
    - beams
    - else
3. Particles to accelerate:
    - muons
    - electrons
    - protons

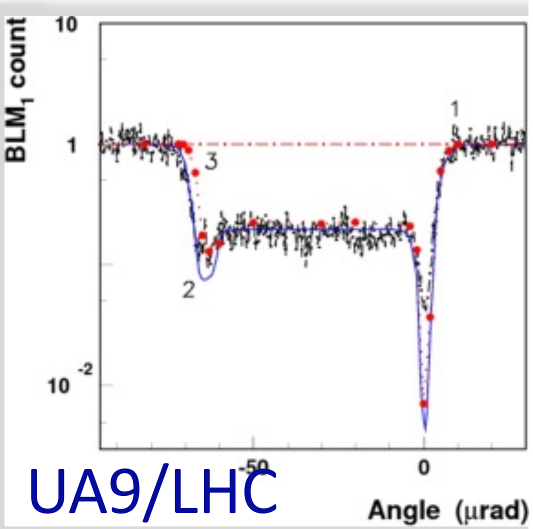
# Crystals

Used in RHIC, Tevatron, LHC for *p,i* collimation (V.Shiltsev)

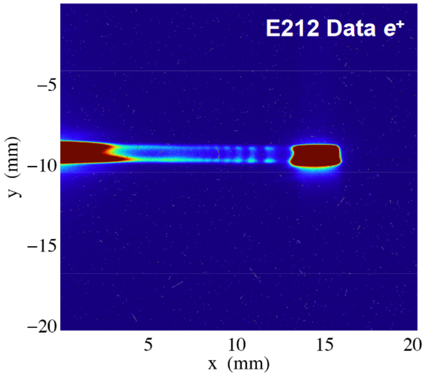
At SLAC for channeling and bending *e+/e-* (U.Wienands)

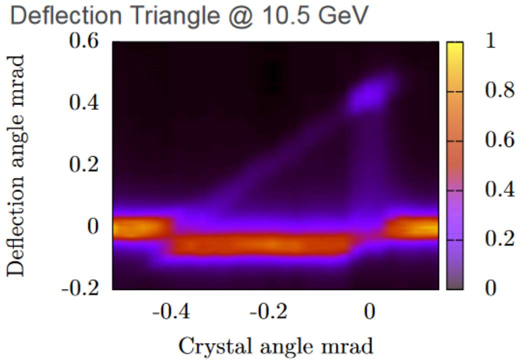
Possibility of nanomodulation (G.Stupakov)

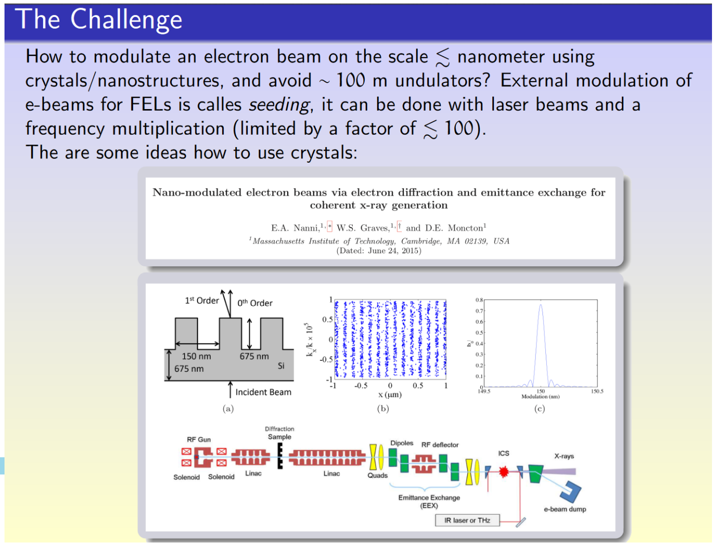




E212: First Channeling Data of 20 GeV e⁺ in Bent Crystal







The Challenge

How to modulate an electron beam on the scale $\lesssim$ nanometer using crystals/nanostructures, and avoid ~ 100 m undulators? External modulation of e-beams for FELs is calles *seeding*, it can be done with laser beams and a frequency multiplication (limited by a factor of $\lesssim 100$).
The are some ideas how to use crystals:

Nano-modulated electron beams via electron diffraction and emittance exchange for coherent x-ray generation

E.A. Nanni,[1,*] W.S. Graves,[1,†] and D.E. Moncton[1]
[1] Massachusetts Institute of Technology, Cambridge, MA 02139, USA
(Dated: June 24, 2015)

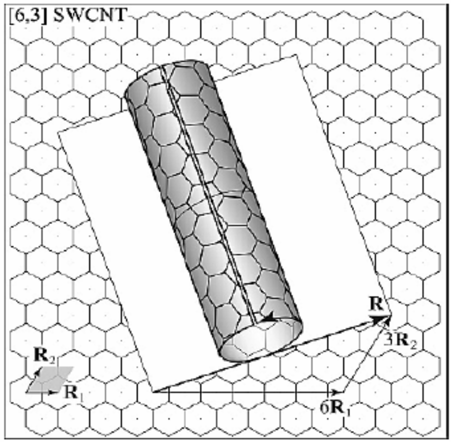
**Fermilab**

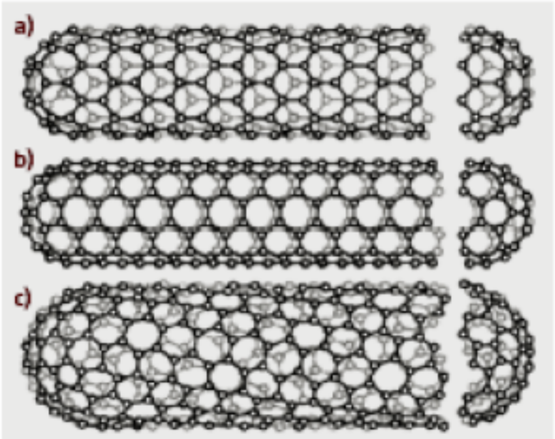
# (Carbon) Nanotubes - CNT

Y.M.Shin, et al, Nuclear Instruments and Methods in Physics Research B 355 (2015) 94–100

## - Carbon Nano Tubes (CNTs)

Rolling single graphene-sheet



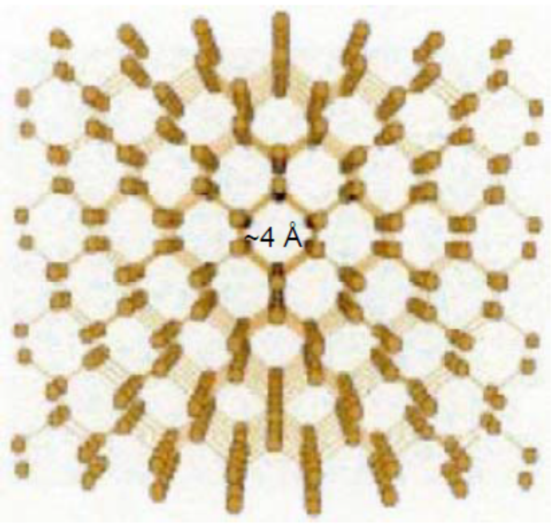


Ends usually closed

## → Possible advantages over crystals

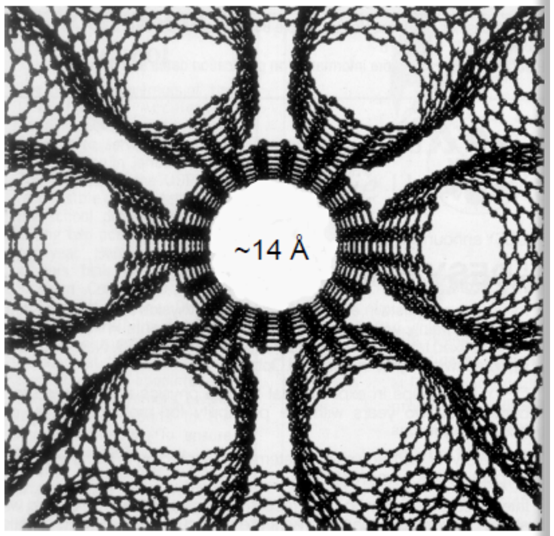
- **Wider channels: weaker de-channeling**
- **Broader beams (using nanotube ropes)**
- **Wider acceptance angles (< 0.1 rad)**
- **Lower minimum ion energies (< 100 eV)**
- **3-D control of beam bending over greater lengths**

Front view of (110) channels in Si crystal



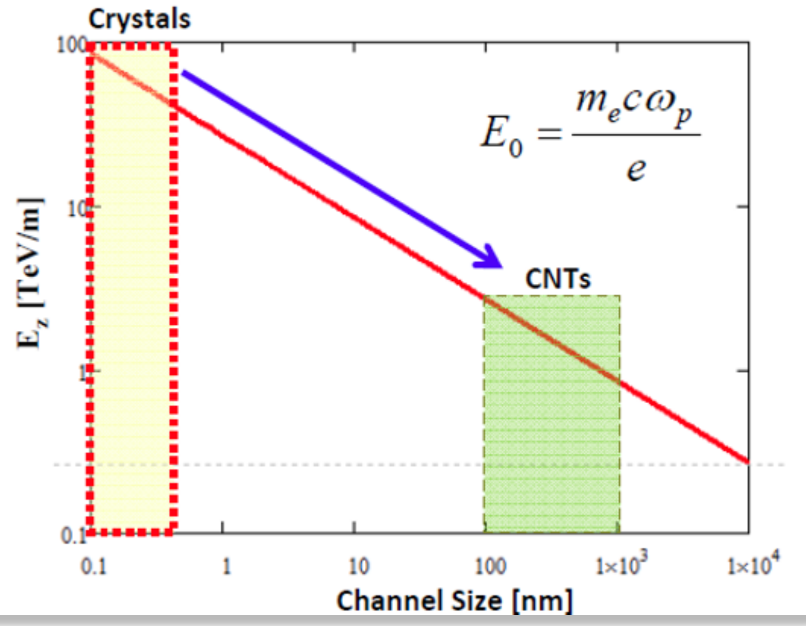
Lattice Constant of Unit Cell ~ 4 A

Entrance to a rope of (10,10) SWNTs



Lattice Constant of Unit Cell ~ 14 A

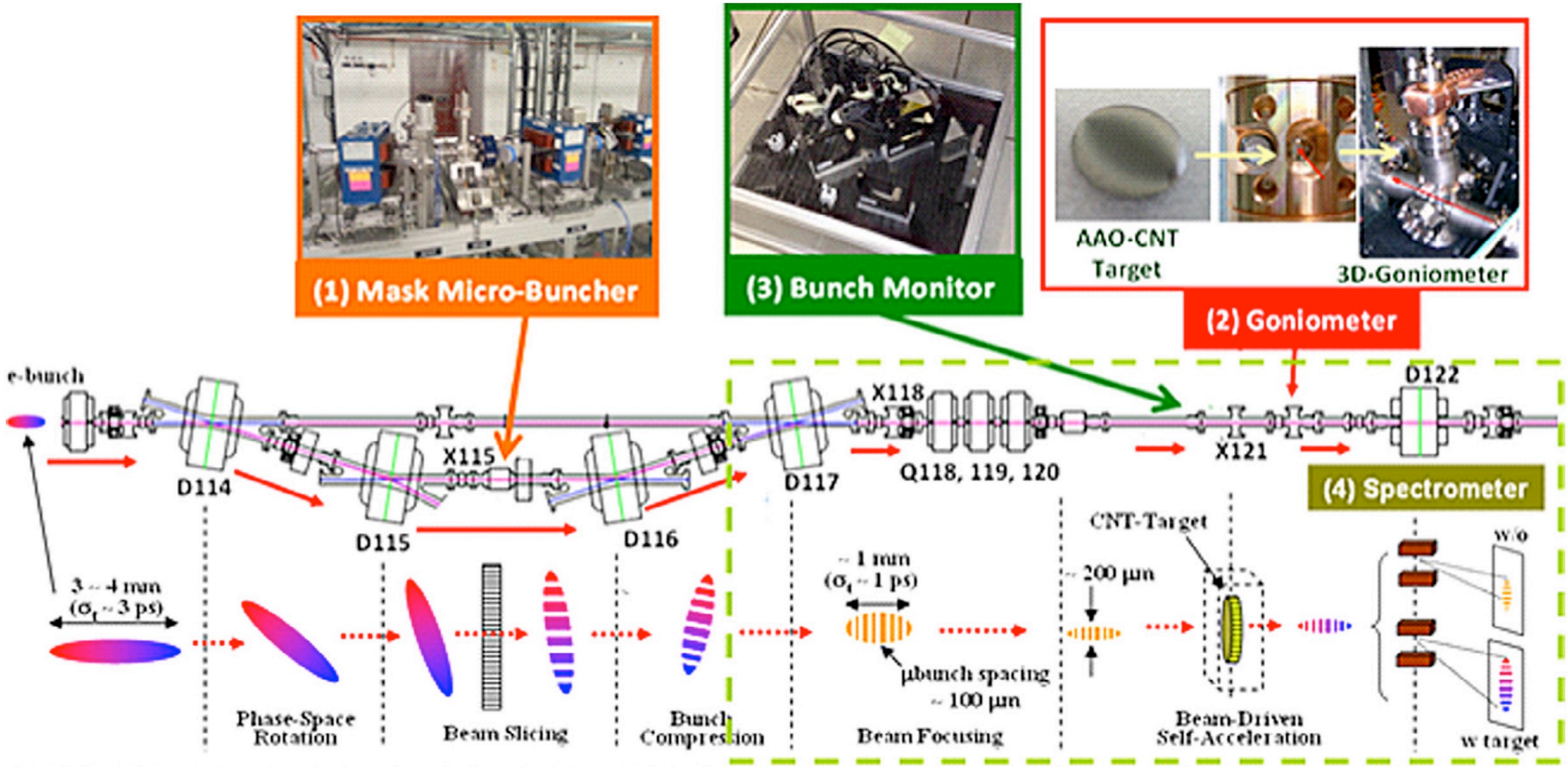
**- Acceleration Gradient**



$$E_0 = \frac{m_e c \omega_p}{e}$$

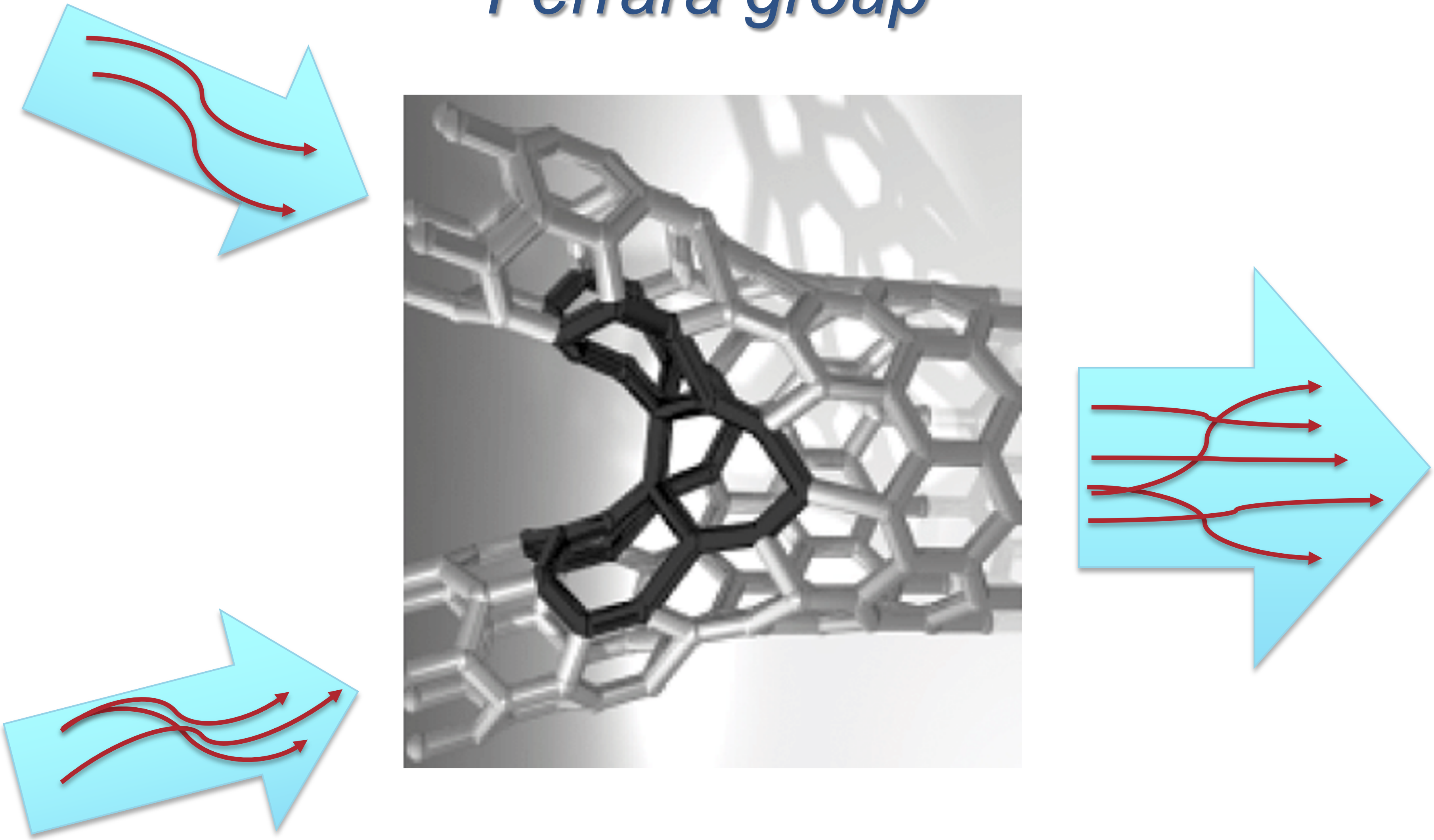
# Y.M.Shin *et al*: CNT Experiment at FAST

Slit-mask micro-bunching
1 nC; $\lambda_{mb} = 100\ \mu m$

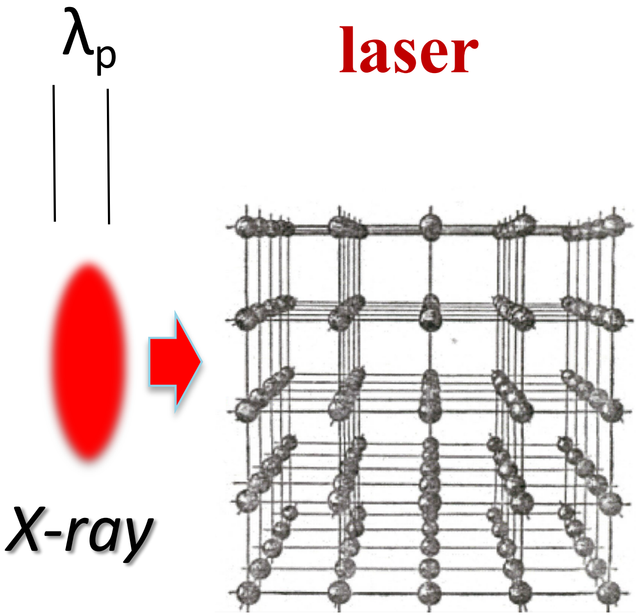


# Other Ideas: Combine Channels (funnel)

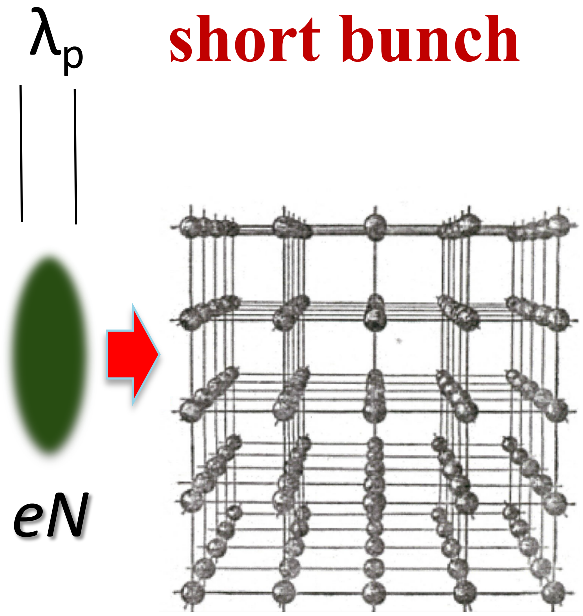
## *Ferrara group*



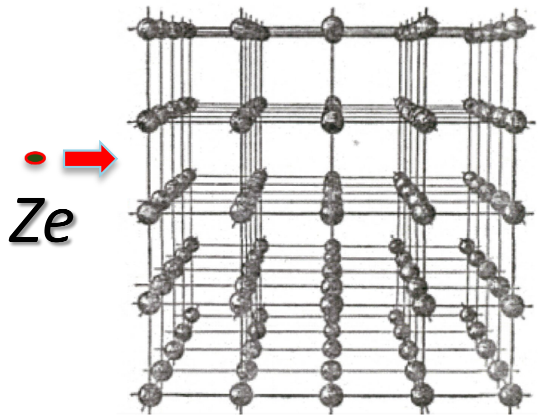
# DRIVERS



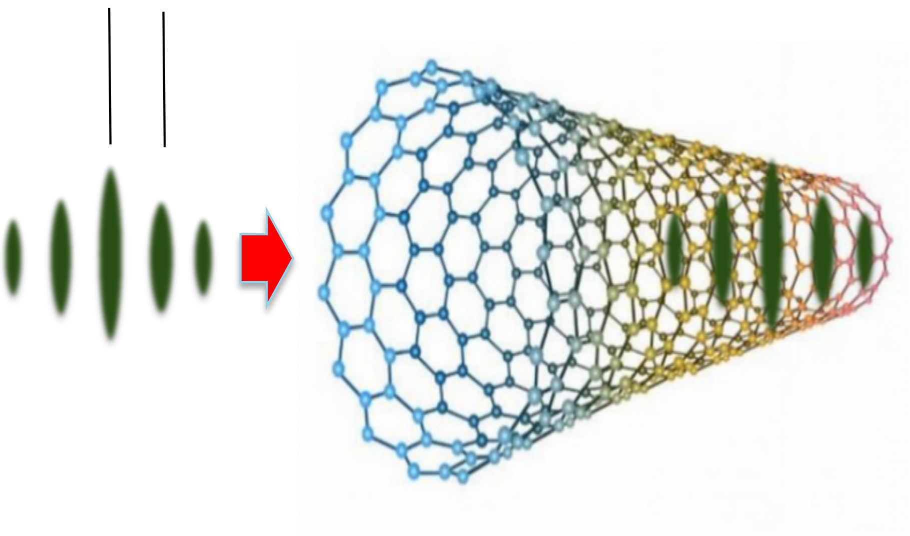
laser



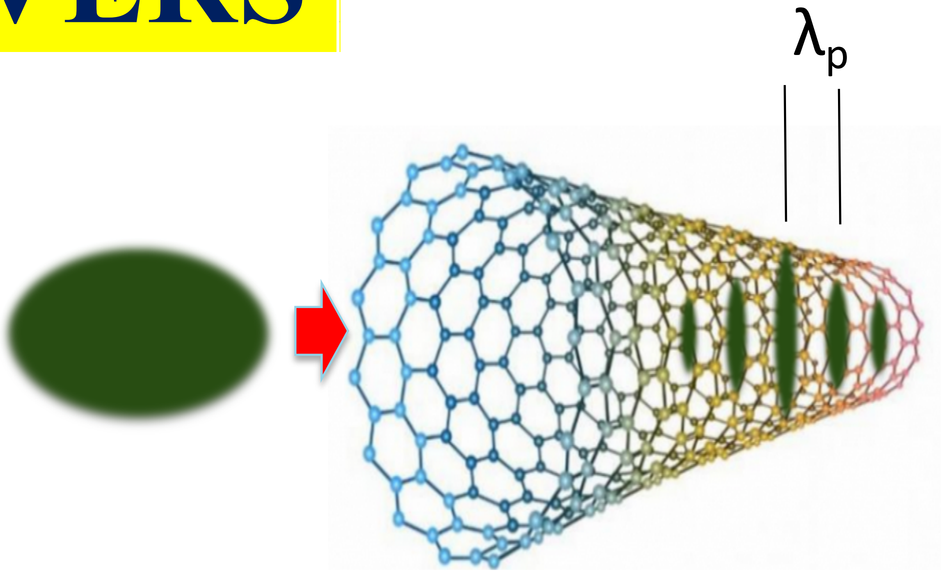
short bunch



ions



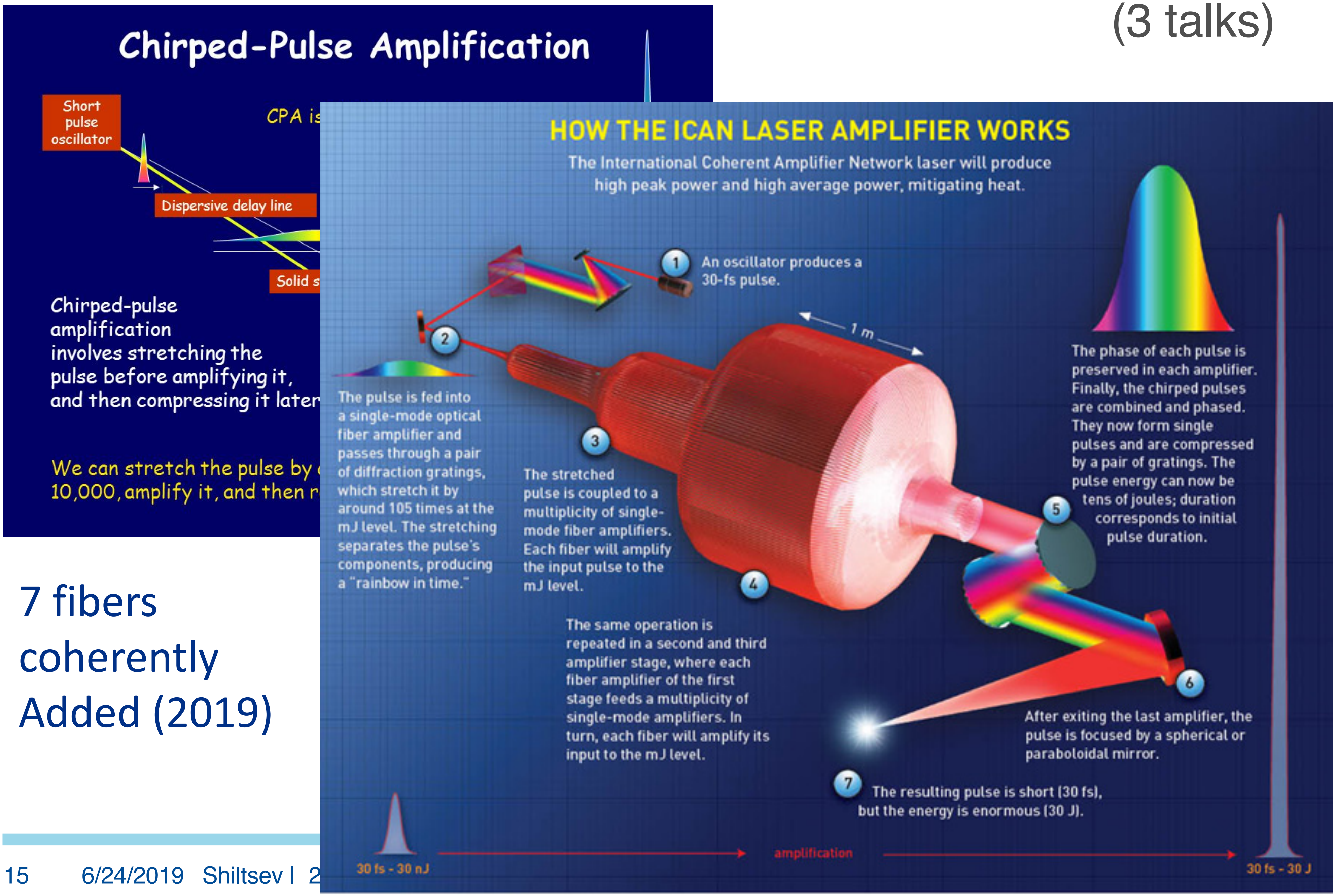
premodulated beam



self-modulating instability

# Wakes by Lasers – New Laser Concepts

(3 talks)



## Chirped-Pulse Amplification

CPA is

Chirped-pulse amplification involves stretching the pulse before amplifying it, and then compressing it later

We can stretch the pulse by
10,000, amplify it, and then r

## HOW THE ICAN LASER AMPLIFIER WORKS

The International Coherent Amplifier Network laser will produce high peak power and high average power, mitigating heat.

① An oscillator produces a 30-fs pulse.

② The pulse is fed into a single-mode optical fiber amplifier and passes through a pair of diffraction gratings, which stretch it by around 105 times at the mJ level. The stretching separates the pulse's components, producing a "rainbow in time."

③ The stretched pulse is coupled to a multiplicity of single-mode fiber amplifiers. Each fiber will amplify the input pulse to the mJ level.

④ The same operation is repeated in a second and third amplifier stage, where each fiber amplifier of the first stage feeds a multiplicity of single-mode amplifiers. In turn, each fiber will amplify its input to the mJ level.

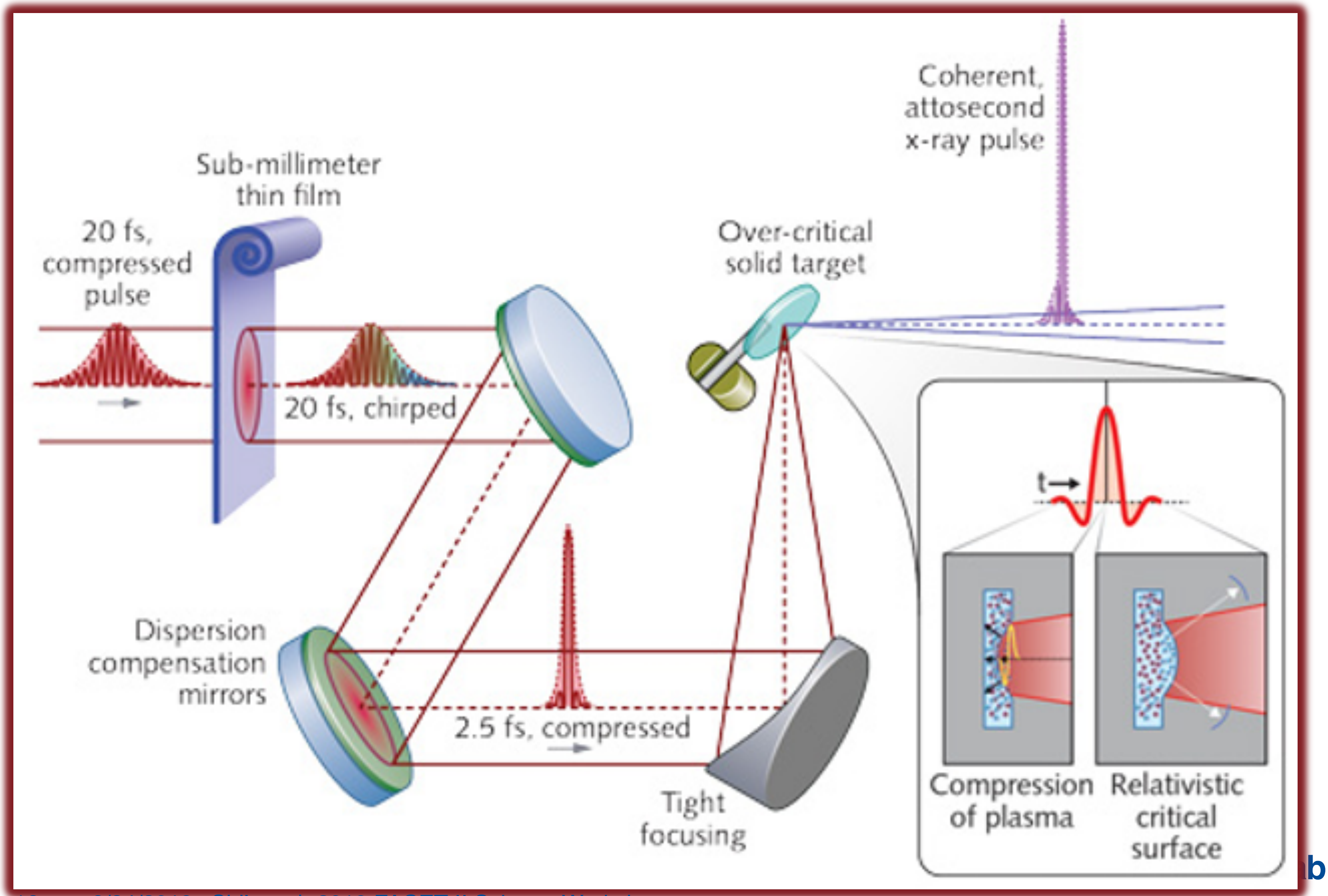
⑤ The phase of each pulse is preserved in each amplifier. Finally, the chirped pulses are combined and phased. They now form single pulses and are compressed by a pair of gratings. The pulse energy can now be tens of joules; duration corresponds to initial pulse duration.

⑥ After exiting the last amplifier, the pulse is focused by a spherical or paraboloidal mirror.

⑦ The resulting pulse is short (30 fs), but the energy is enormous (30 J).

7 fibers coherently Added (2019)

# Thin-Film Compression



# Wakes by Ions

- Bethe formula for ionization energy loss:

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left( \frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[ \ln\left( \frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

- For high Z (of ions passing thru):

$$E_i \approx 2[\mathrm{MeV}/(\mathrm{g/cm}^2)] \times Z^2$$

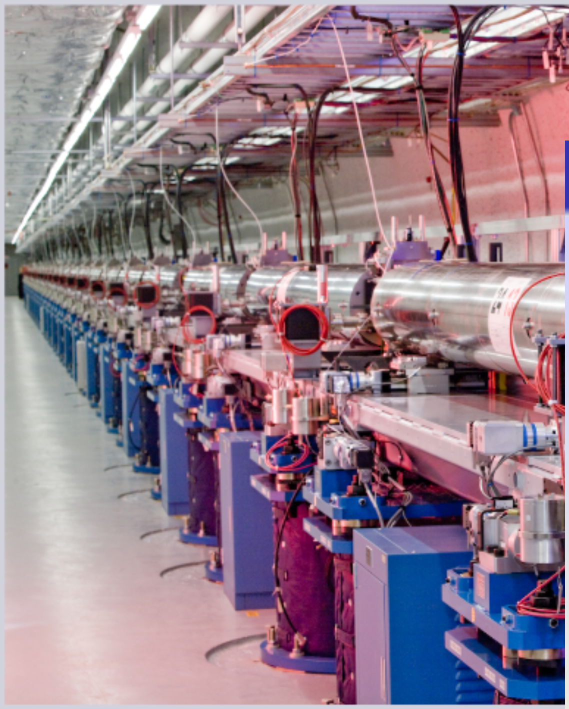
- ie **~1 TV/m** for *Z*=70-80 in silicon. Naturally, one can envision these ions either channeling in crystals ahead of the accelerating particles (e.g., muons) or being well aligned with them so the latter are always kept in sync with accelerating wake. At present, the highest energy heavy ions are available at RHIC (100 GeV/u gold, ***Z*=79**) and LHC (2.5 TeV/u lead, ***Z*=82**) and the dephasing length $2\gamma_p^2 \lambda_p$ can be as long as few cm - few meters.

# Visit to AWAKE (Oct. 2019… *ions* from SPS and *beam diagnostics* available)

# Pre-Modulated Beam Possibilities (G.Stupakov)

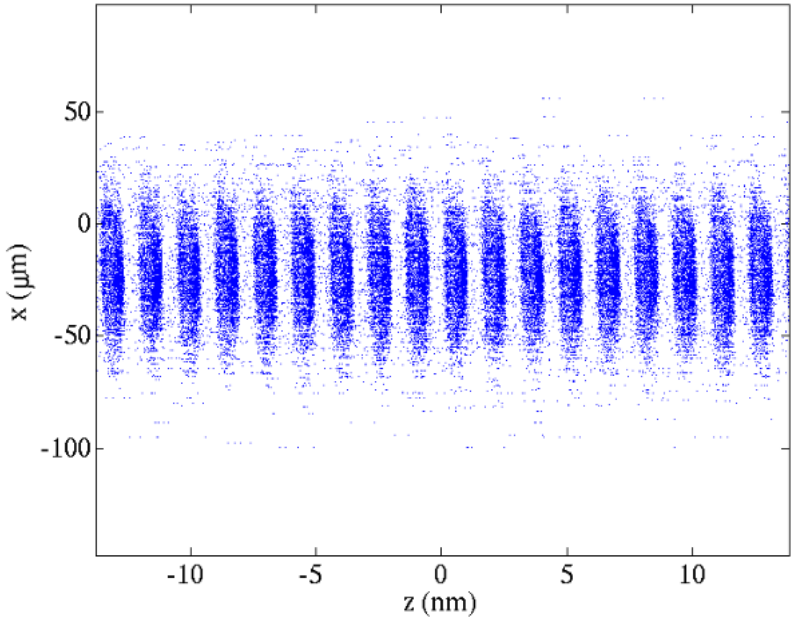
## LCLS undulator at SLAC

This is achieved in a ~ 100 m long magnetic undulator through the mechanism of an FEL instability.

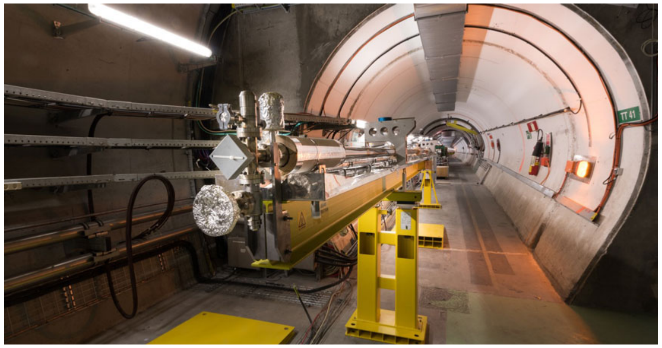


## Microbunched electron beam

FEL radiation is produced by an electron beam that is microbunched with the period $\lambda_r$.



# Self-modulated long bunches
# AWAKE



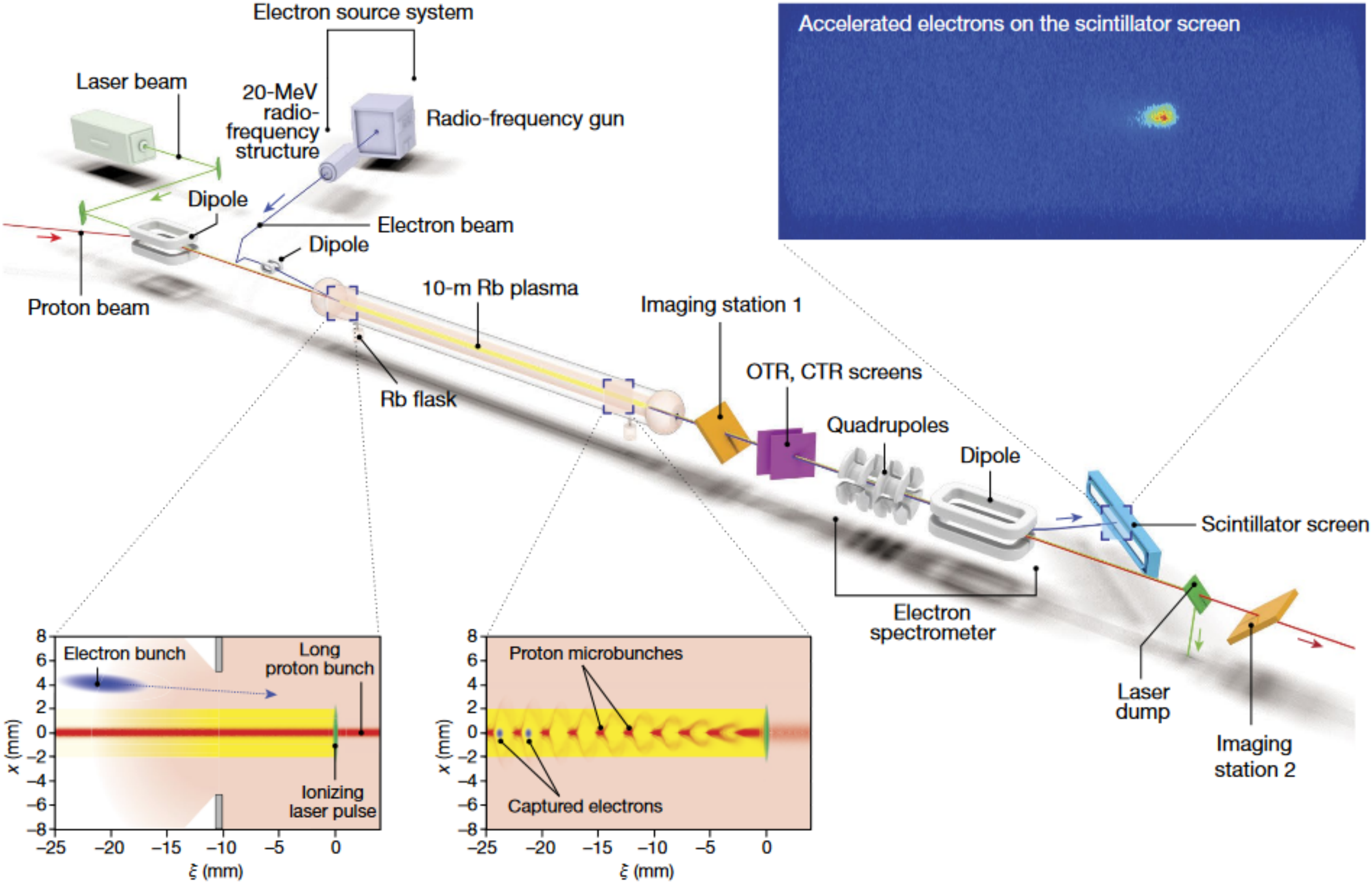
LETTER

OPEN

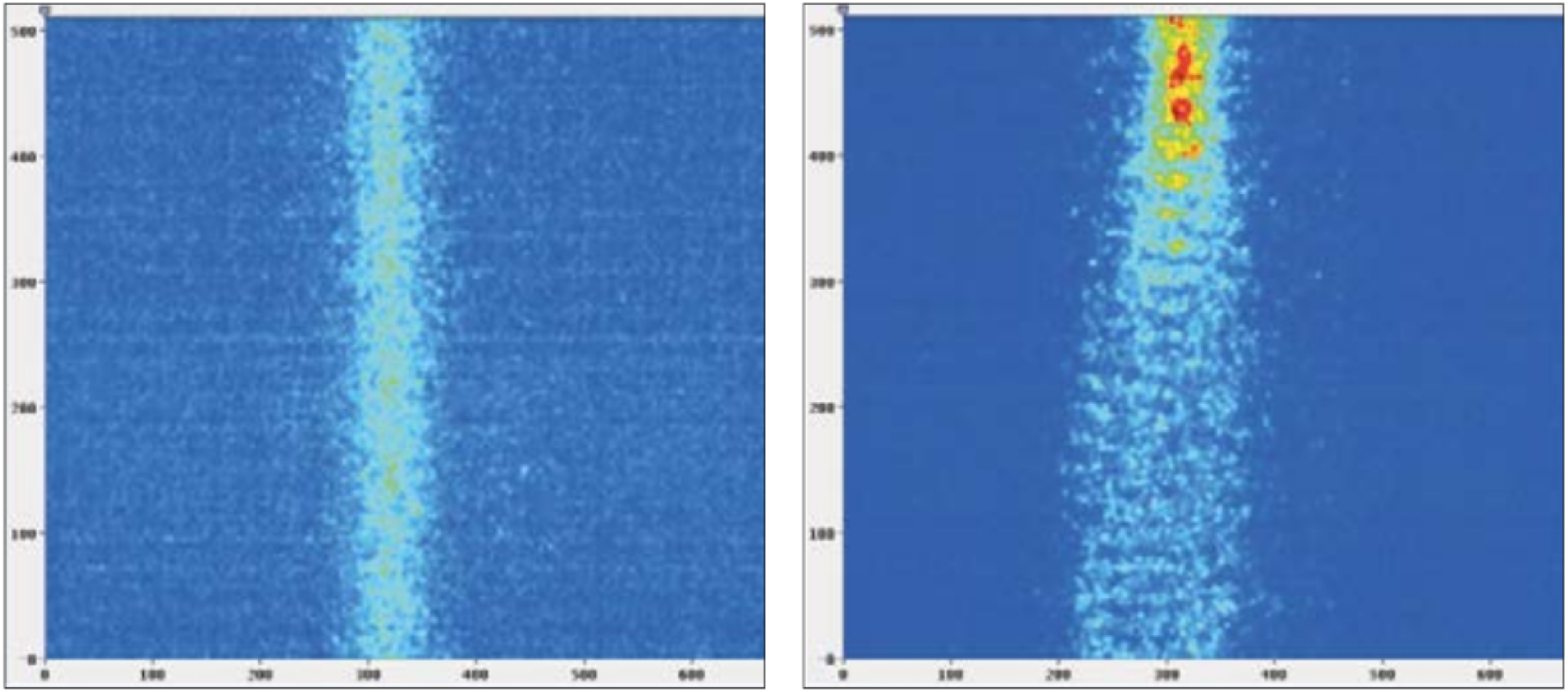
https://doi.org/10.1038/s41586-018-0485-4

**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],



# 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.*

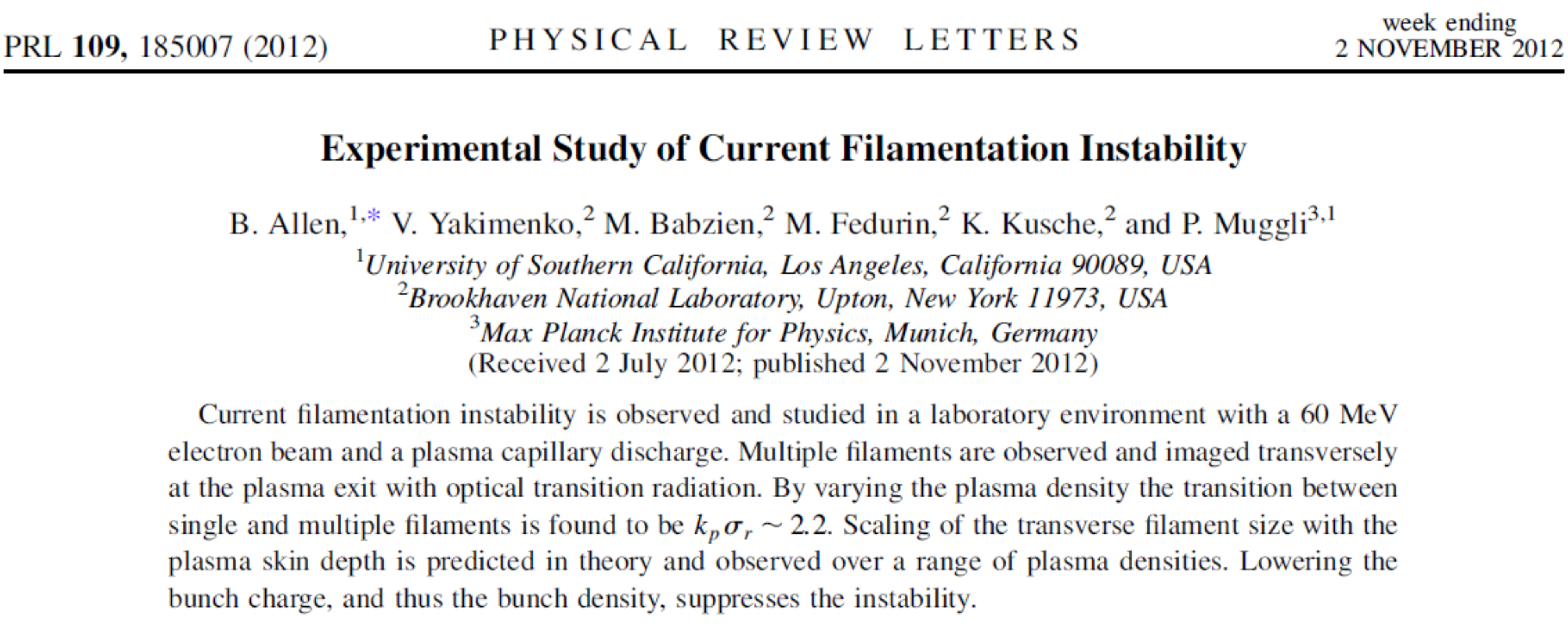
**ACCELERATOR TECHNOLOGY**

**AWAKE makes waves**

CERNCOURIER
Volume 57 Number 1 January/February 2017

# Beam at FACET-II Facility for Advanced Accelerator Experimental Tests

- 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 – effect of structured media (?)
  - Muon production and channeling
  - Acceleration



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

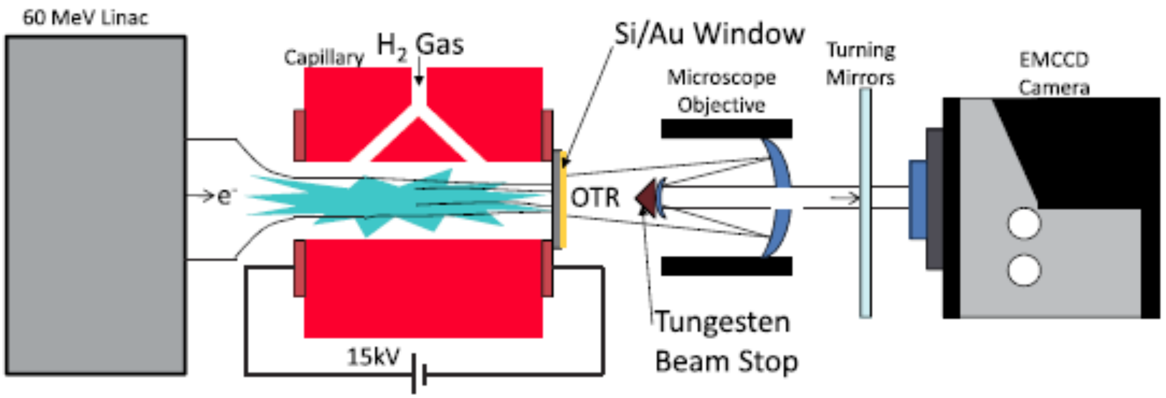
# Experimental Study of Current Filamentation Instability

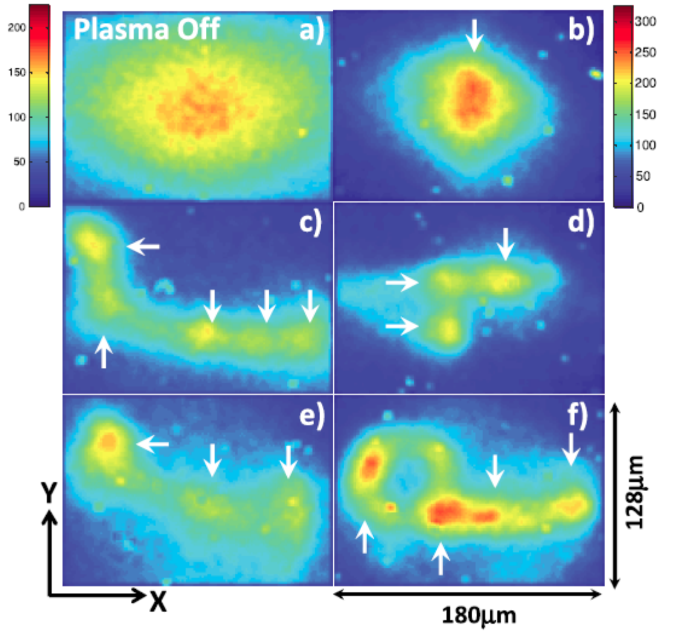
B. Allen,[1,*] V. Yakimenko,[2] M. Babzien,[2] M. Fedurin,[2] K. Kusche,[2] and P. Muggli[3,1]
[1]*University of Southern California, Los Angeles, California 90089, USA*
[2]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[3]*Max Planck Institute for Physics, Munich, Germany*

(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.

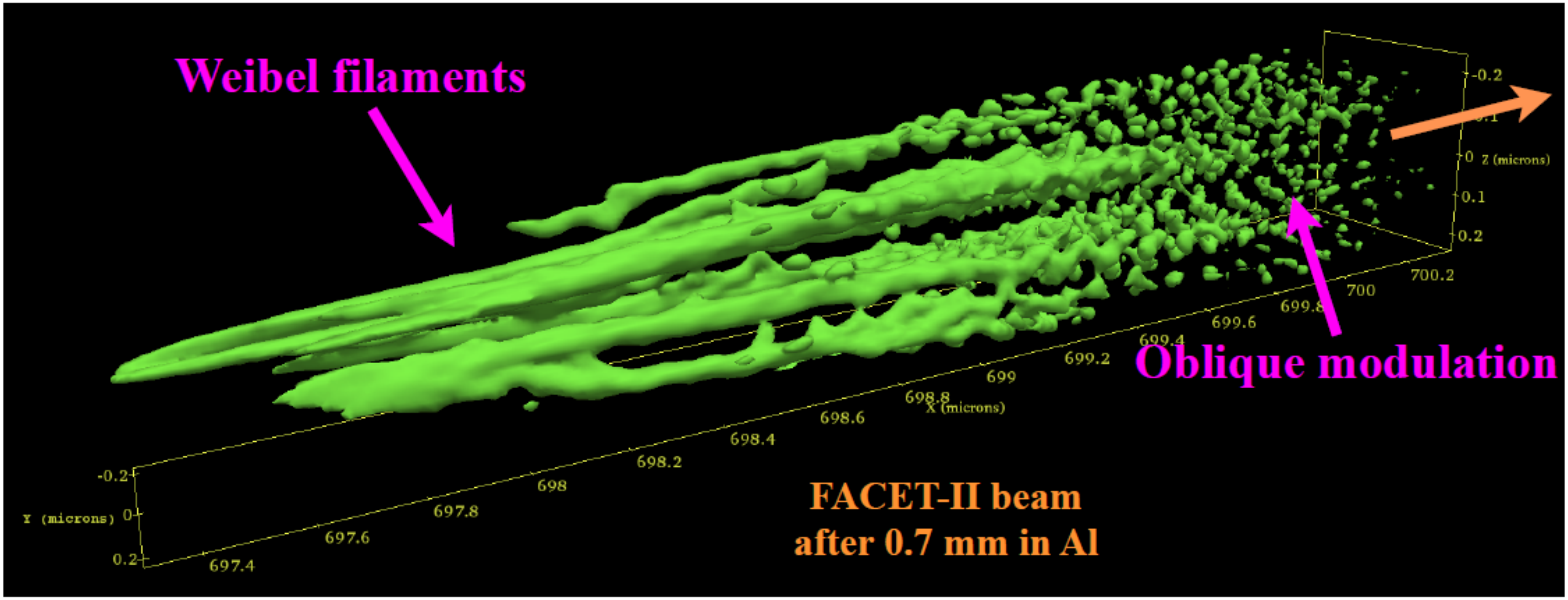
DOI: 10.1103/PhysRevLett.109.185007 PACS nu





# FACET-II

- ***Experiment E305:*** Beam filamentation and bright gamma-ray bursts
  - – Sébastien Corde(ÉcolePolytechnique/LOA)
  - – Ken Marsh (UCLA)
  - – Frederico Fiuza (SLAC)



**Weibel filaments**

**Oblique modulation**

**FACET-II beam after 0.7 mm in Al**

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

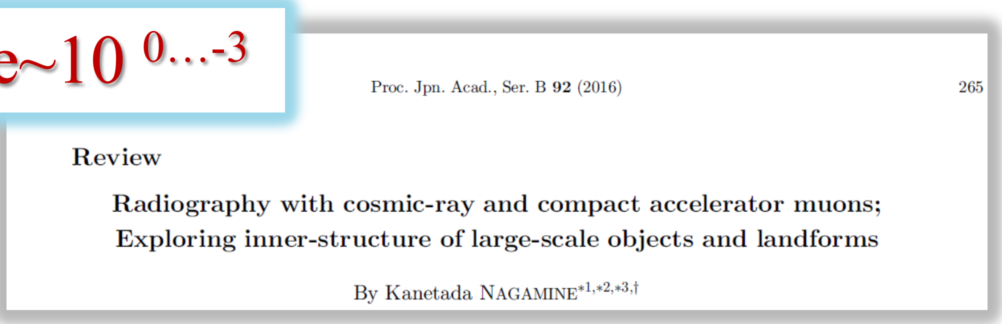
- Simulations; define optimal configuration – beams, CMTs vs crystals, etc
- Hardware assembly and tests, eg at FAST
- Beam pre-test at FAST (50-300 MeV ILC type beams)
  - E.g., *e-* channeling and SMI in the CNTs
- Consider muon production, capture and channeling, acceleration
  - Then it can be expanded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

# MUON PRODUCTION

- “Collider” schemes

* see also K.Yonehara talk

$\mu/e \sim 10^{0\ldots-3}$

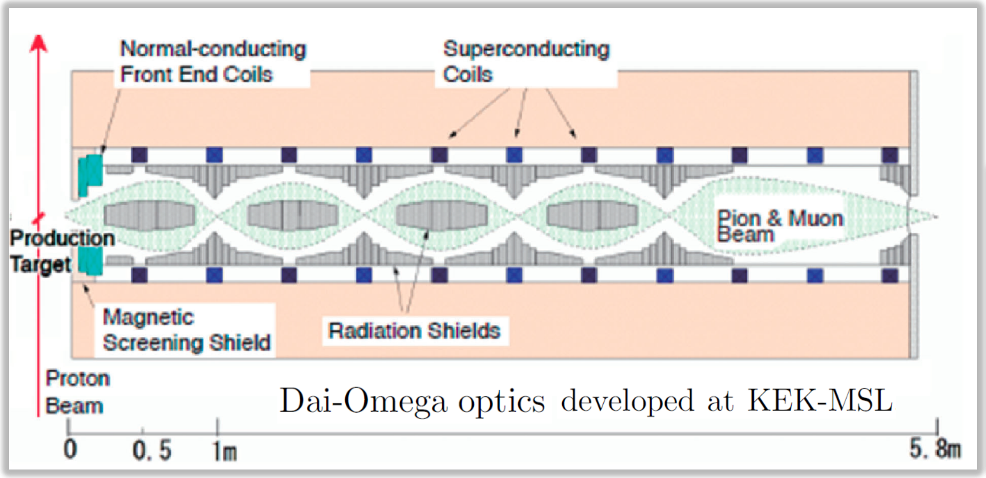


Proc. Jpn. Acad., Ser. B **92** (2016) 265

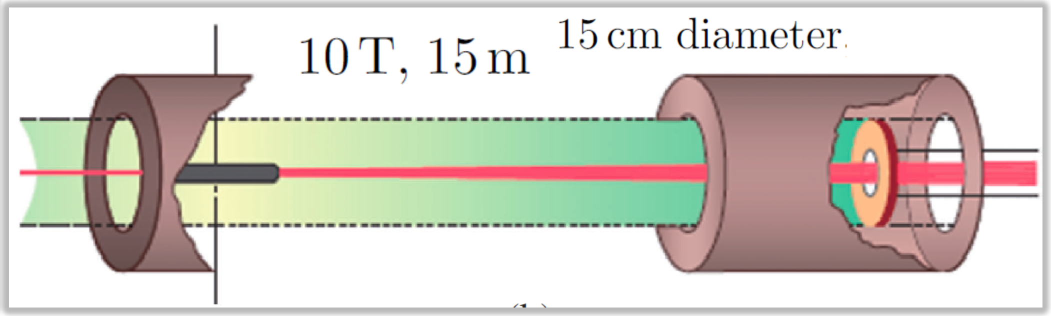
Review

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

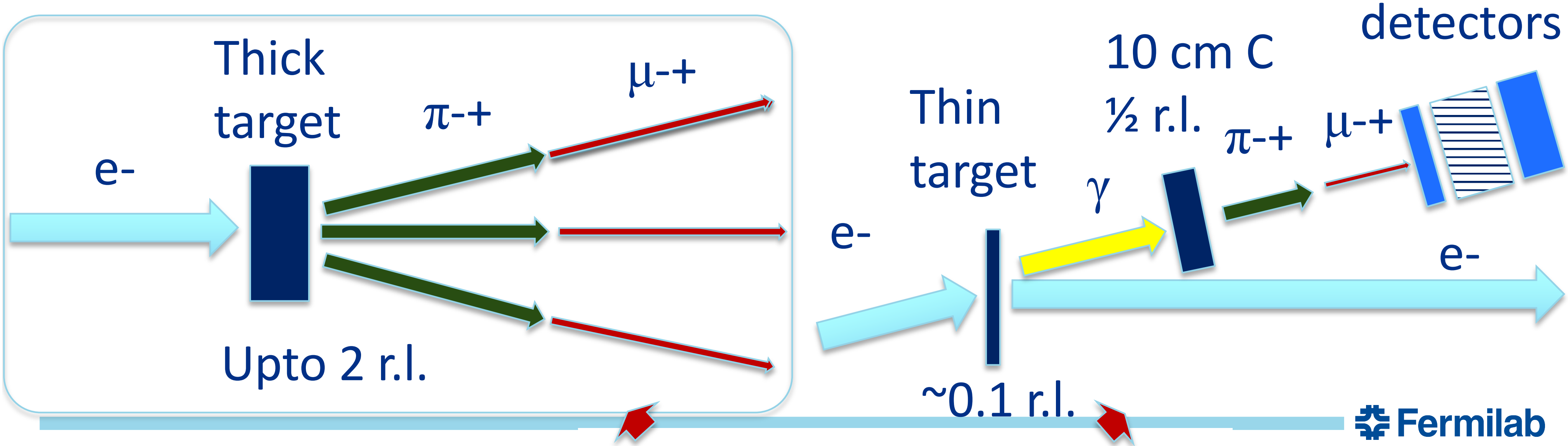
By Kanetada NAGAMINE[*1,*2,*3,†]



Dai-Omega optics developed at KEK-MSL



- Simplified schemes (for FAST/FACETII)



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

# Toward Experimental Studies of “Xtal Acc”

## Wakefield **Muon** Accelerator:
## ultrashort, micron-scale $\mu^\pm$ beams

A. Sahai (CU), V. Shiltsev (Fermi), T. Tajima (UCI)

### Proposal

1. **$\mu^\pm$ production & characterization** – ultrashort $e^-$ beam driven
   (in future, compact laser-driven $e^\pm$ -beam [when stable beams avail.])

   *We need to better understand the muon spectra from the foil as a majority of the muons are not relativistic. Nobody studied the muon spectra from an ultrashort 10um waist-size multi-GeV electron beam before*

2. **$e^\pm$ -beam driven wakefield $\mu^\pm$ acc.** – can go along with foil-$e^+$ proposal
   (extra $\mu^\pm$ detectors, foils are quite similar due to same scaling)

   *The e-beam wakefield will only trap a very small percentage (already relativistic) of the 10,00 muons produced. Secondly, the electron beam exiting the foil may be degraded and may not drive a nice wake.*

3. **laser driven wakefield $\mu^\pm$ acc.** – stage-2 is laser-driven
   (better control over wake velocity, more trapping by velocity matching)

**(A.Sahai)**

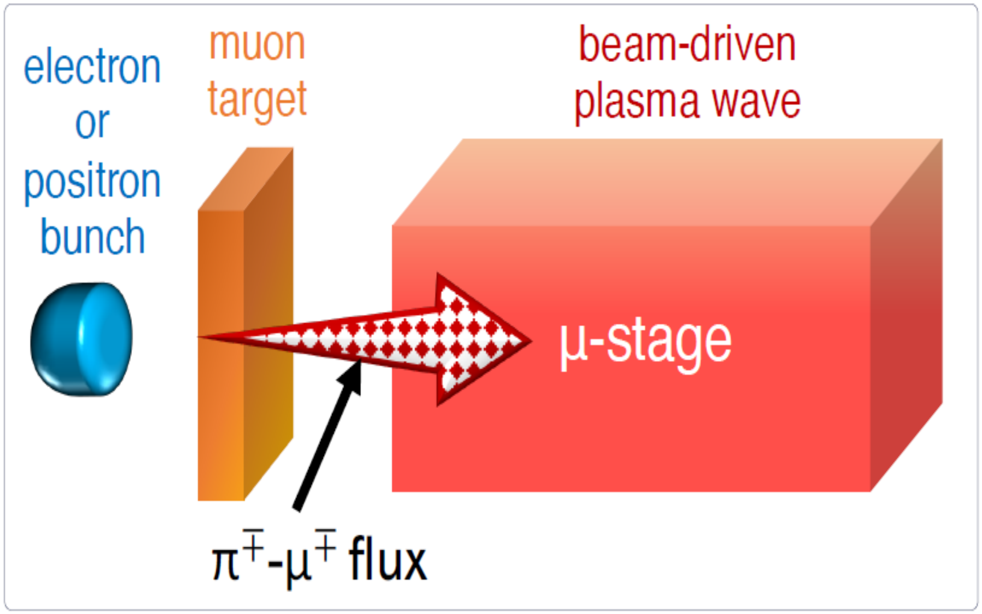
# e$^-$ beam wakefield **Muon** Accelerator

- e$^-$ beam driven wakefield phase velocity
  **very HIGH (gamma > 10000)**
  near the speed of light

- only efficiently trap the μ$^\pm$ that are
  **already relativistic**
  produced in the external foil or
  in early stages of the plasma

- e-beam wakefield will only
  **trap a small fraction** (already relativistic)
  of the 10,000 μ$^\pm$ pairs

- Moreover, e$^-$ beam exiting the foil may be degraded
  **may not** drive a high-quality wake



under further investigation !

**(A.Sahai)**

# ultrashort, micron-scale μ± production & characterization

**μ± production rate**

$\varepsilon_\gamma \gg 2m_\mu c^2$ Bremsstrahlung photon

$\varepsilon_\gamma \sim E_{e\pm} \gtrsim 3$ GeV (for validity of below BH cross-section)

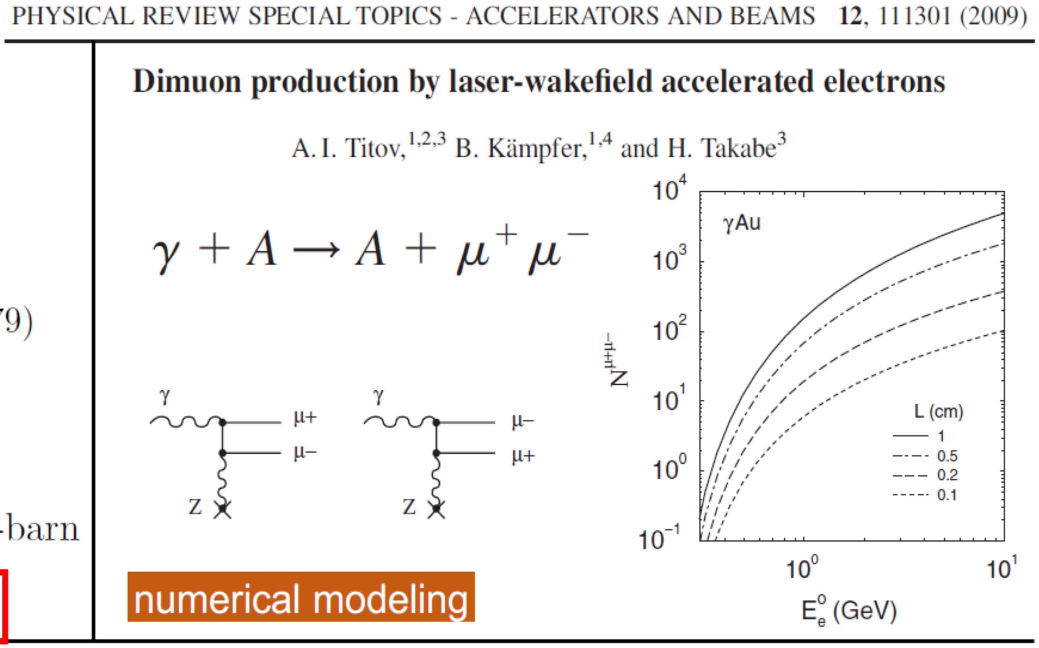
$$\sigma_{\gamma Z_1\rightarrow\mu^+\mu^- Z_2} \simeq \frac{28}{9}\, Z^2\, \alpha\, r_0^{\mu\ 2} \left(\ln\frac{2\varepsilon_\gamma}{m_\mu c^2} - \frac{109}{42}\right)$$ Bethe Heitler

$$\sigma_{\gamma Z_1\rightarrow\mu^+\mu^- Z_2} \simeq 10^{-31} m^{-2} = 0.5 \text{ milli-barn } (\varepsilon_\gamma \sim 200\text{MeV}, Z \sim 79)$$

$$\mathcal{L} = \frac{N_{\text{beam}}}{\sigma_{z-beam}/c}\, n_{\text{target}}\, T_{\text{target}}$$ (= 1cm)

$$\mathcal{R}_{\gamma Z_1\rightarrow\mu^+\mu^- Z_2} \text{ (in 50fs)} = \frac{1\text{nC}}{e}\ 5.9\times10^{28} m^{-3}\ 1cm\ 0.5 \text{ milli-barn}$$

$$\boxed{\mathcal{R}_{\gamma Z_1\rightarrow\mu^+\mu^- Z_2} \text{ (in 50fs)} \simeq 10^5 \text{ pairs } (1\text{nC}, 50\text{fs}, \sigma_r \sim 20\mu m)}$$


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 111301 (2009)

**Dimuon production by laser-wakefield accelerated electrons**

A. I. Titov,[1,2,3] B. Kämpfer,[1,4] and H. Takabe[3]

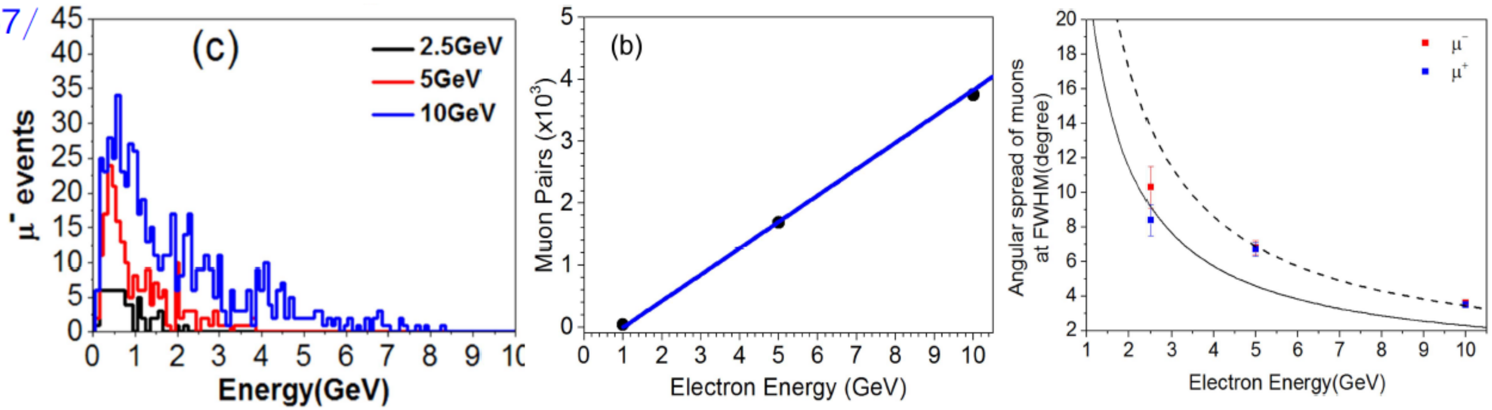
$$\gamma + A \rightarrow A + \mu^+\mu^-$$

**numerical modeling**

Bobbili Sanyasi Rao *et al* 2018 *Plasma Phys. Control. Fusion* **60** 095002
https://doi.org/10.1088/1361-6587/

Bright muon source driven by GeV electron beams

**GEANT4 data**

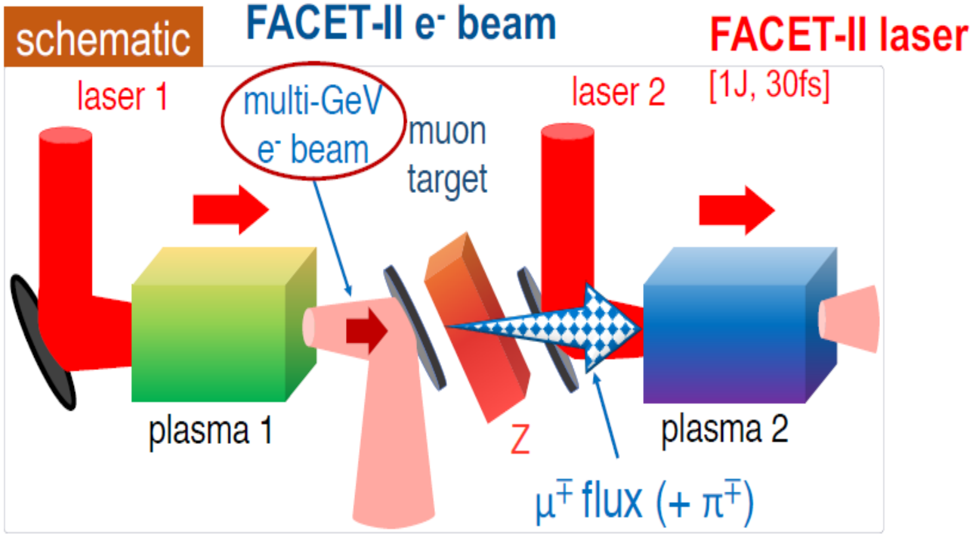


University of Colorado Denver

Fermilab

**(A.Sahai)**

# Laser **Muon** Accelerator



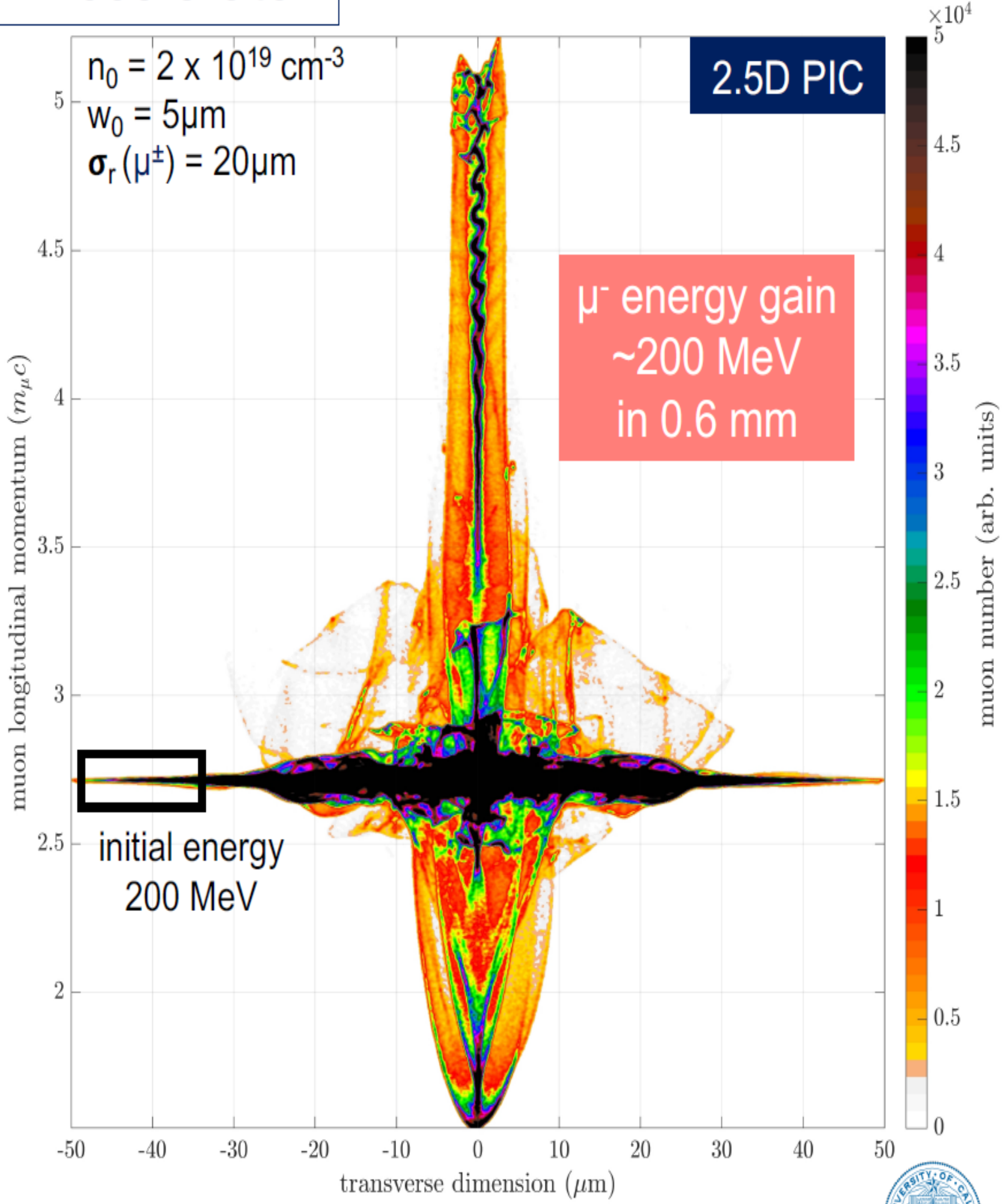
laser group velocity = wakefield phase velocity

laser group velocity ~ **controlled** using plasma density

wakefield phase velocity can be **tuned to match** $\mu^{\pm}$ spectra & optimize trapping in the wakefield

**FACET-II beam** produces $\mu^{\pm}$ in 1 cm thick target.

**FACET-II laser** driven wakefield accelerator to **trap and accelerate** $\mu^{\pm}$



μ⁻ energy gain ~200 MeV in 0.6 mm

Fermilab

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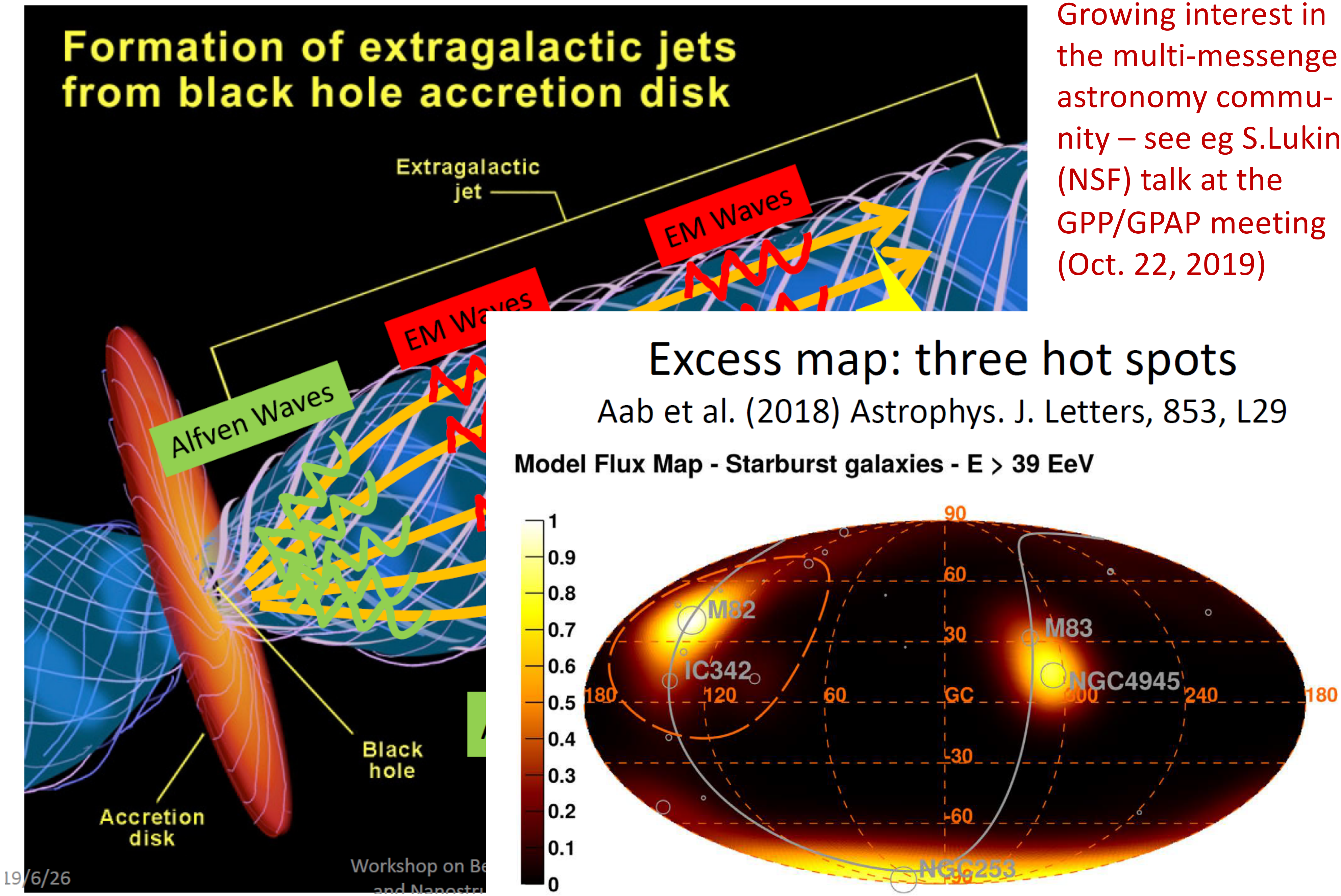
at least the spectra has got a spine

# Connection to Cosmos - Toshi Ebisuzaki(RIKEN)



Growing interest in the multi-messenger astronomy community – see eg S.Lukin (NSF) talk at the GPP/GPAP meeting (Oct. 22, 2019)

## Excess map: three hot spots

Aab et al. (2018) Astrophys. J. Letters, 853, L29

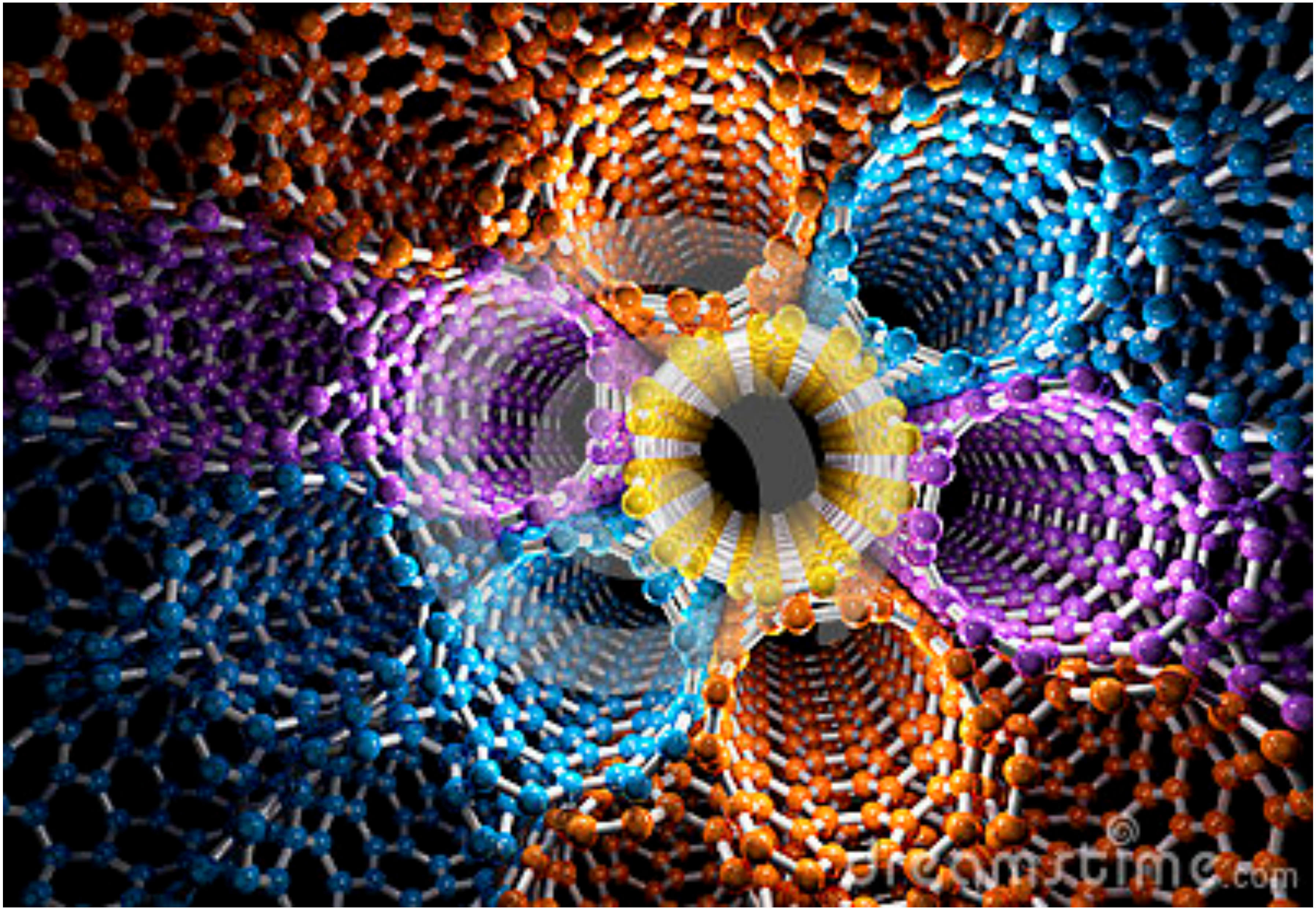
# Summary

- Acceleration of *$\mu$'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, AWAKE, etc
- 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 FACET-II : i) muon production; ii) muon detection; iii) experiment integration; iv) calibration of models
- ***A lot of serious work 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!

Several interesting proposals for further explorations or experimental tests were made by Sahel Hakimi, *et al*. (University of California, Irvine, on how to drive wakes in CNTs by ultimate or existing X-ray pulses from, e.g., the LCLS SASE FEL); by Aakash Sahai, *et al.* (University of Colorado, on production of detectable number of muons and their subsequent acceleration either at BELLA or FACET-II facilities); by Vladimir Shiltsev, *et al.* (Fermilab, on demonstration of effective micromodulation of electron beams at FAST and FACET-II and subsequent experiments with micromodulated beams sent through CNTs at FAST with kA peak current type beams and then at the FACET-II facility with upto 300 kA bunches, e.g., to demonstrate the CNT channeling or to study the electron beam filamentation phenomena in structured materials); by Gennady Stupakov (SLAC, on possibility to use 1-nm-SASE-modulated electron bunches at the end of LCLS-I undulators to excite crystals and demonstrate acceleration); by Johnathan Wheeler, *et al.,* (Ecole Polytechnique, to use the APOLLO laser facility to demonstrate Peta-Watt optical pulses/single cycle pulses via thin-film-compression technique); by Valery Lebedev (FNAL, to explore effectiveness of the wake excitation in crystals or CNTs by high-$Z$ high energy ions, e.g. by 450 GeV ion beams from the CERN SPS available at the AWAKE facility, and observation of possible acceleration of externally injected electrons).

# Nanotubes (2)



# Collider considerations

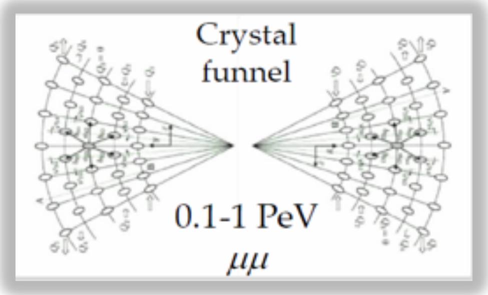
$$\mathrm{d}N/\mathrm{d}t = -N/\gamma\tau_0 \qquad \frac{N}{N_0} \approx \left(\frac{m_\mu c^2}{E}\right)^{\kappa}$$

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

i.e. irrelevant

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

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



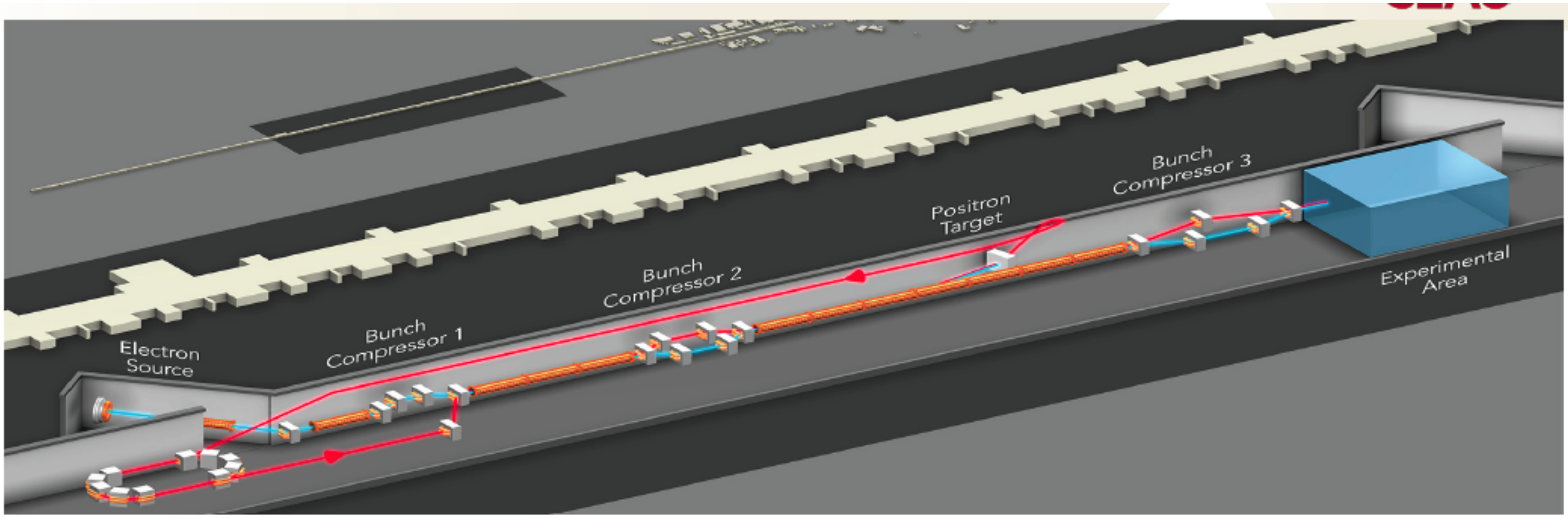
$$L\,[\mathrm{sm}^{-2}\,\mathrm{s}^{-1}] \approx 4 \times 10^{33\text{–}35}\,\frac{P^2\,[\mathrm{MW}]}{E^2\,[\mathrm{TeV}]\,f n_{\mathrm{ch}}\,[10^8\ \mathrm{Hz}]}$$

**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<br>option 2 | Optical laser<br>$e^-$ bunch | $e^-$ bunch<br>Optical laser | X-ray laser |
| Preferred particles | Any stable | $e^-$, $\mu^-$ | $\mu^+$, $p^+$ |
| Max accelerating gradient, GeV $\mathrm{m}^{-1}$ | $1-3$ | $30-100$ | $100-10^4$ |
| CM energy reach in 10 km | $3-10$ | $3-50$ | $10^3-10^5$ |
| Number of stages/10 km: option 1<br>option 2 | $10^5-10^6$<br>$10^4-10^5$ | $\sim 100$<br>$10^3-10^4$ | |

# Ultimate Testbed

**FACET-II** | Facility for Advanced Accelerator Experimental Tests

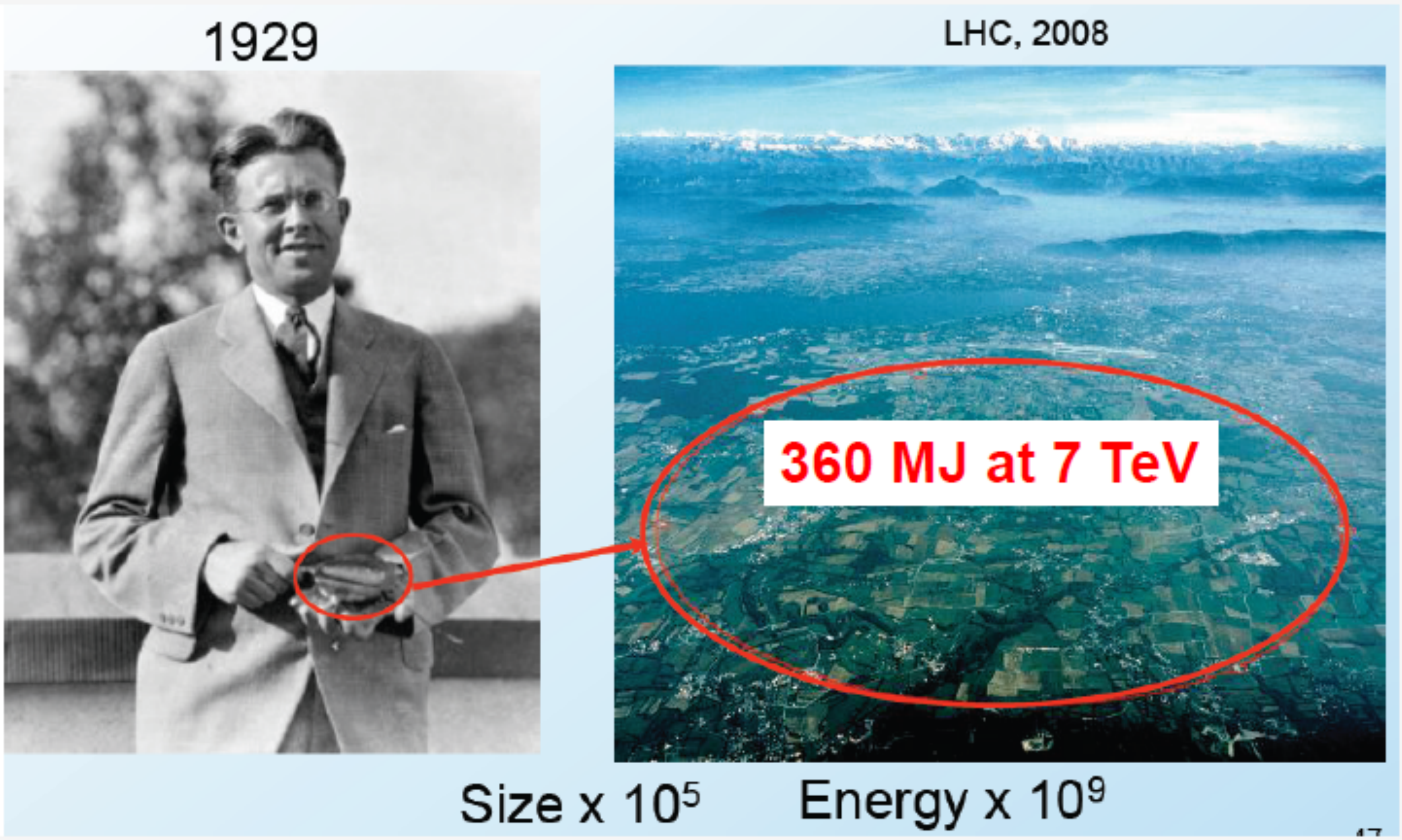


| *Electron Beam Parameter* | *Baseline Design* | *Operational Ranges* |
|---|---|---|
| *Final Energy [GeV]* | *10* | *4.0-13.5* |
| *Charge per pulse [nC]* | *2* | *0.7-5* |
| *Repetition Rate [Hz]* | *30* | *1-30* |
| *Norm. Emittance $\gamma\varepsilon_{x,y}$ at S19 [μm]* | *4.4, 3.2* | *3-6* |
| *Spot Size at IP $\sigma_{x,y}$ [μm]* | *18, 12* | *5-20* |
| *Min. Bunch Length $\sigma_z$ (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 $\sigma_z$ (rms)* | *16* | *8* |
| *Max. Peak current $I_{pk}$ [kA]* | *6* | *12* |

# High Energy Particle Physics: Progress and Challenges

- Collider physics – dominated by the LHC til 2038



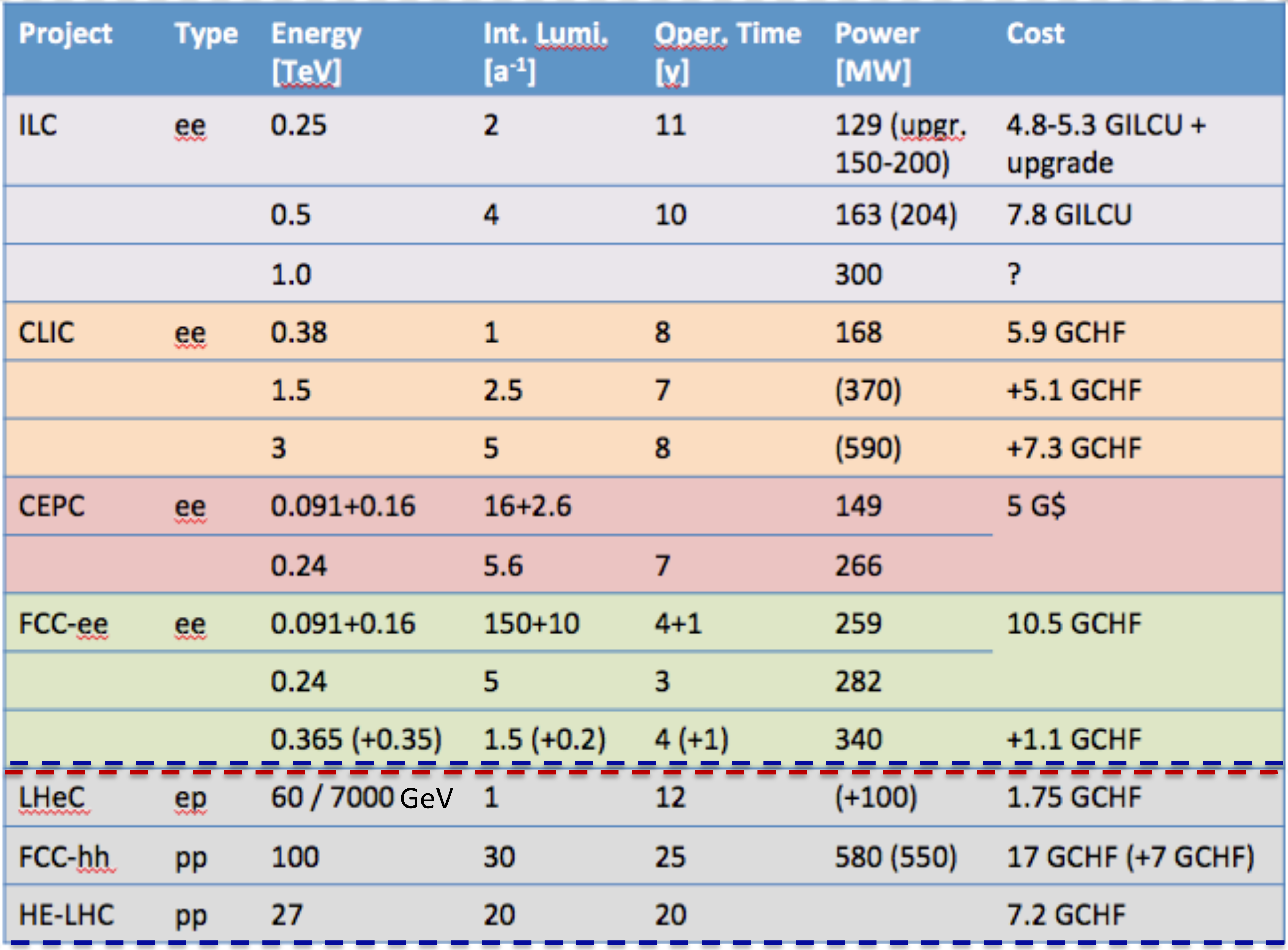
9km/13cm = 69,231 14TeV/80keV = 175,000,000

- 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:

circular collider

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**

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

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

linear collider

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

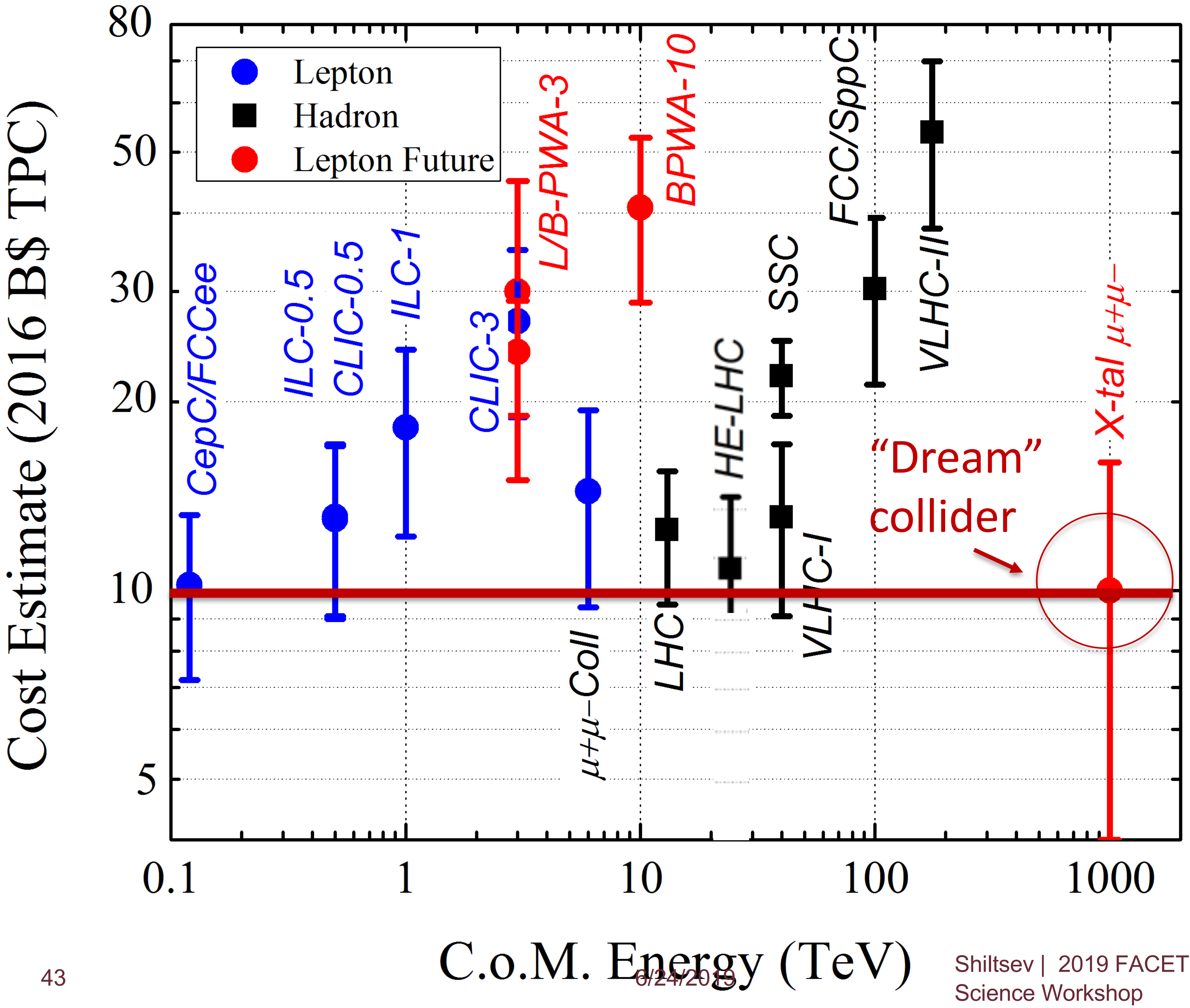
# “Phase-Space” is Further Limited

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

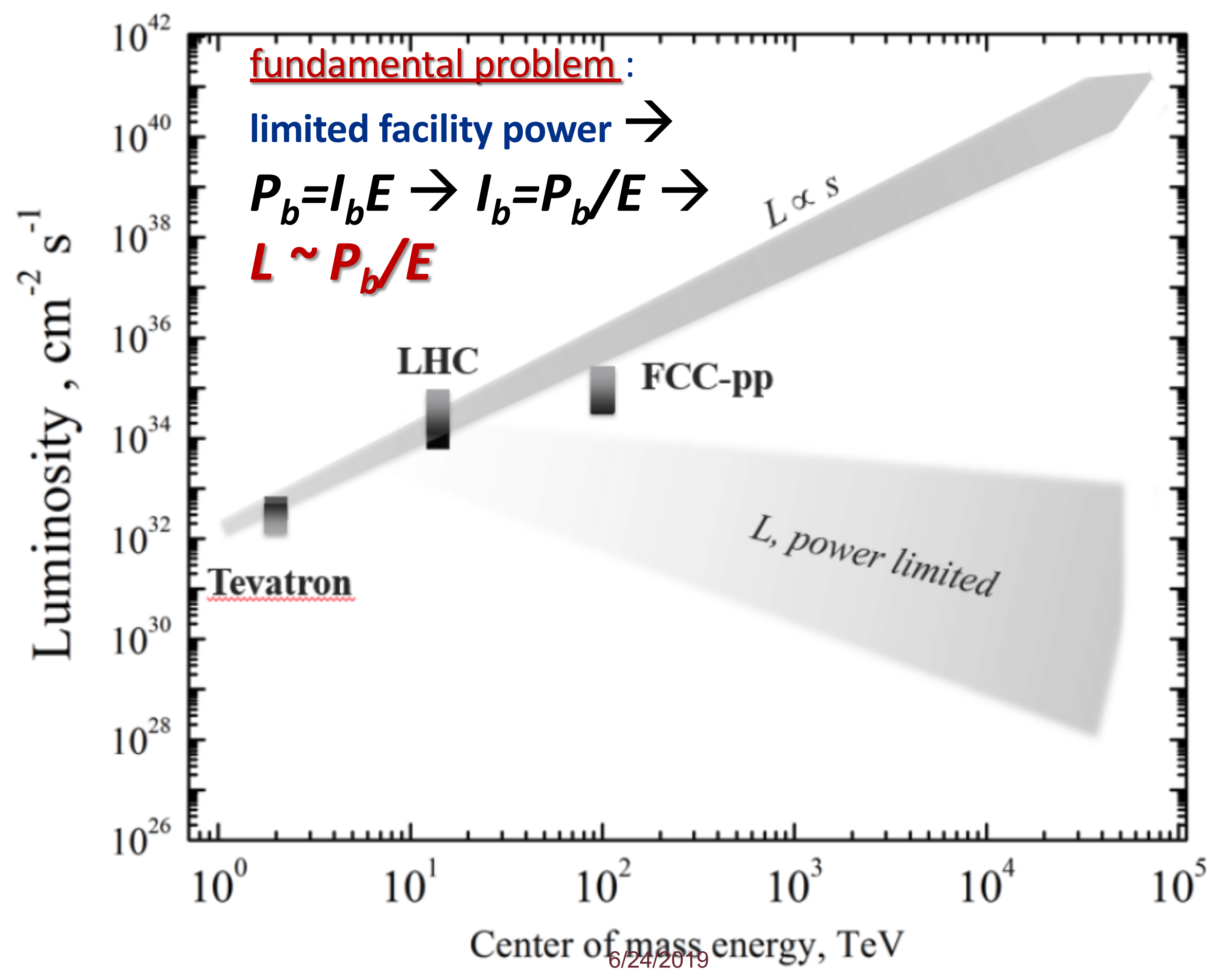
**→New technology should provide >30 GeV/m @ total component cost <1M$/m ( ~NC magnets now)**

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***

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

# Paradigm Shift : *Energy* vs *Luminosity*



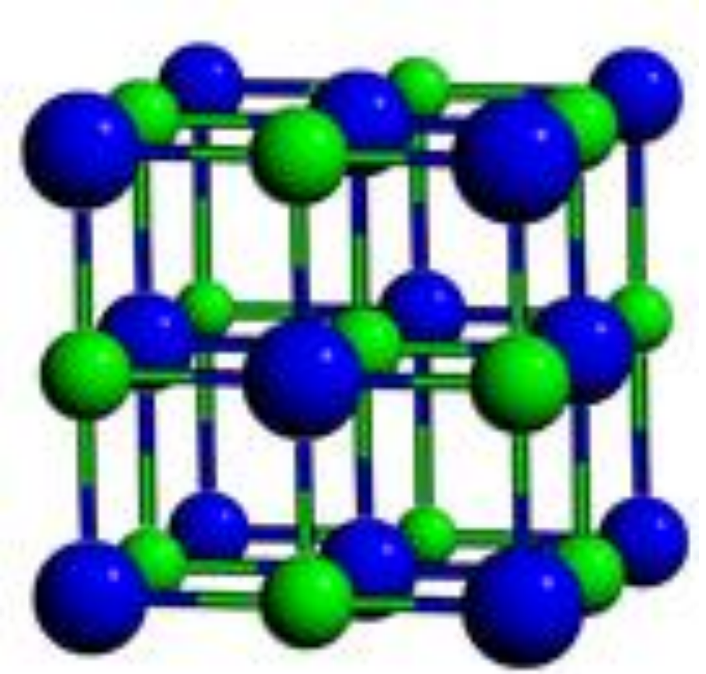
fundamental problem :

limited facility power →

$P_b=I_bE \rightarrow I_b=P_b/E \rightarrow$

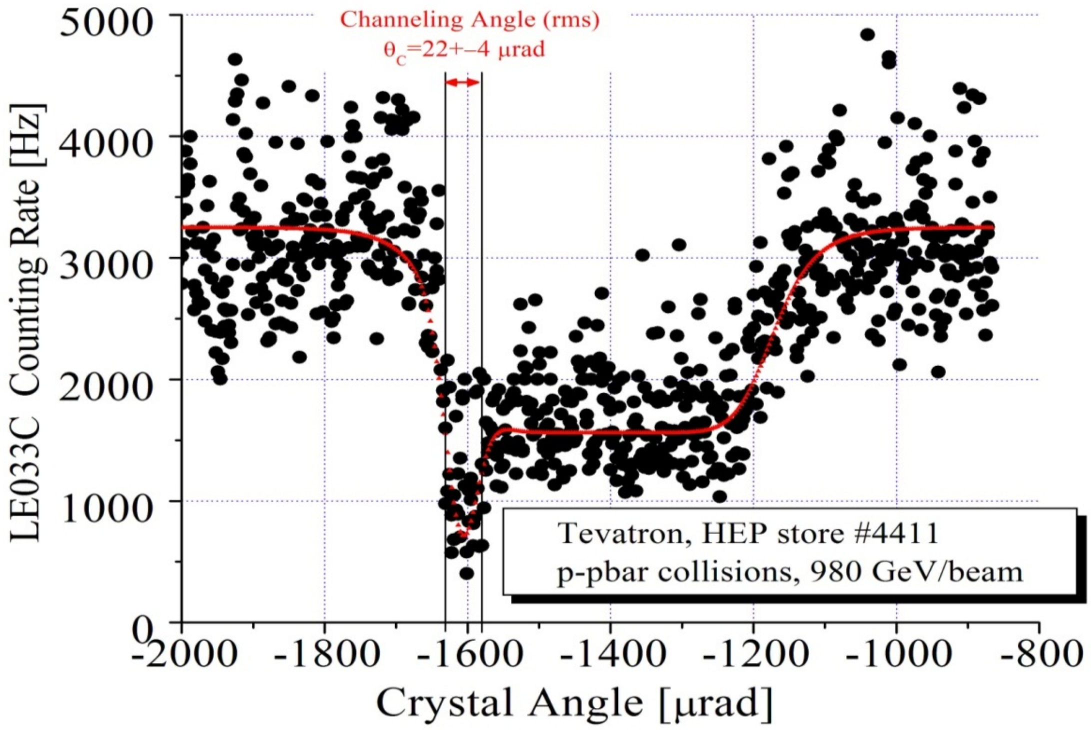
$L \sim P_b/E$

# 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)*

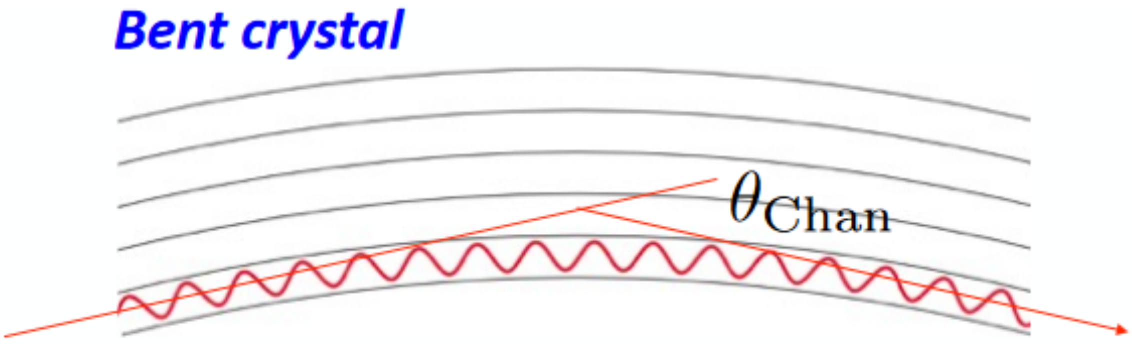


- Strong inter-planar electric fields ~10V/A=1GV/cm
- Very stable, can be used for
  - deflection/bending (*works*)
  - focusing (*works* )
  - acceleration (*if excited*)

~92.5+-5% efficiency

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

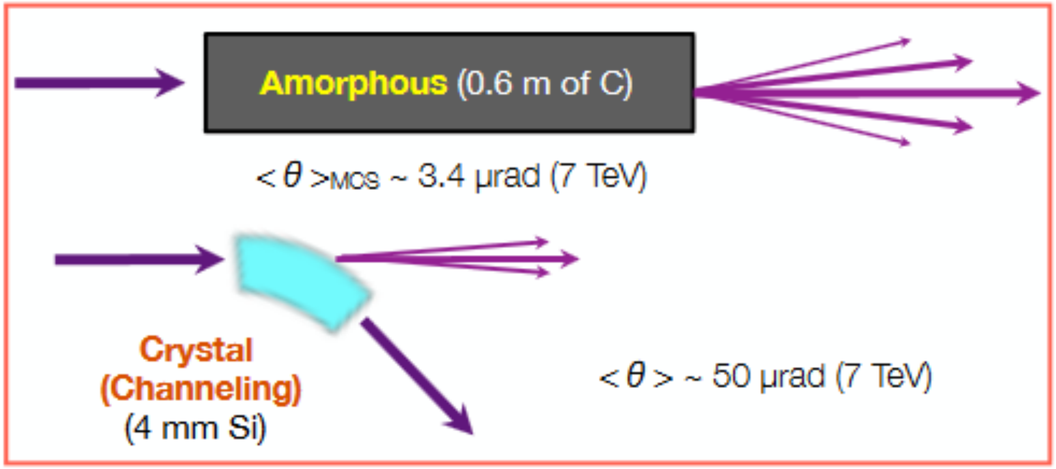
# Bent Crystals in the 7 TeV LHC Beams



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

~2 mrad at 7 TeV

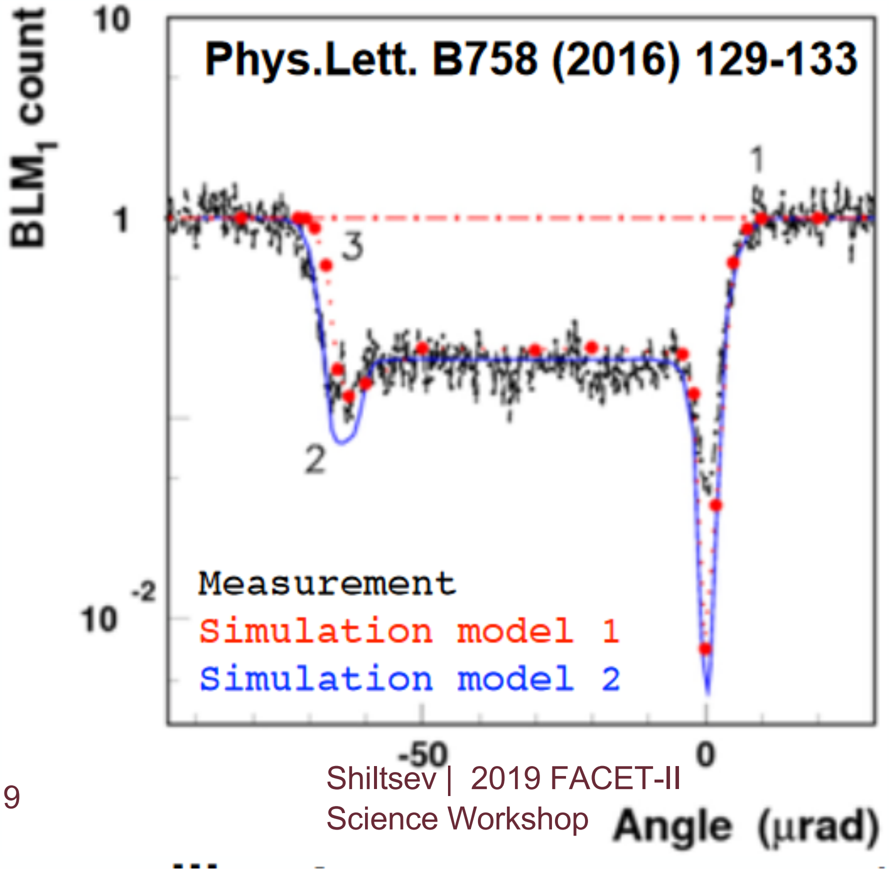
Equivalent magnetic field for **50μrad** at **7 TeV** proton beams: **310 T** (4 mm crystal)



~99.5% efficiency

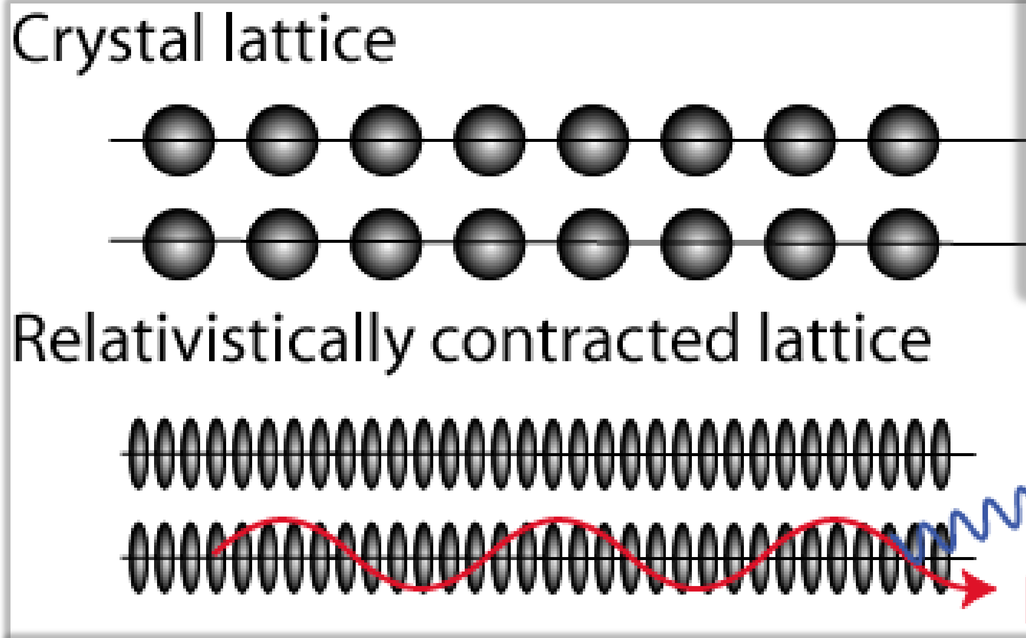
Or *l_d* ~ 4mm/0.005=0.8m

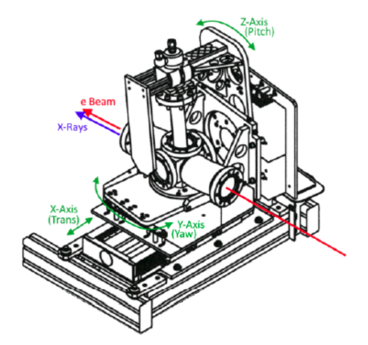
*see also U.Wienands talk on *e*- channeling at SLAC

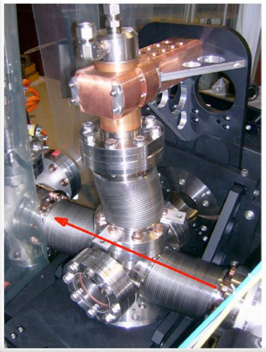


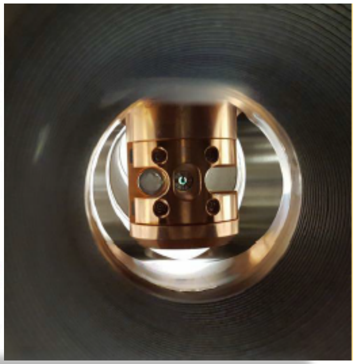
# 2015-2017 CRYSTAL CHANNELING EXPT @ FAST

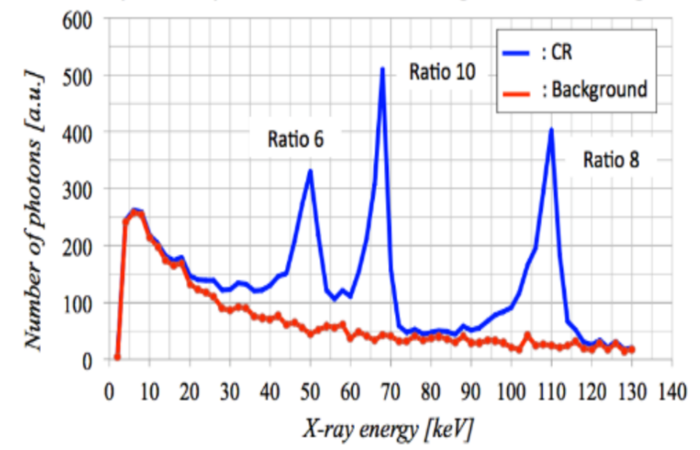
- P.Piot, T.Sen, A.Halavanau, D.Edstrom, J,Hyun, et al
- helpful experience

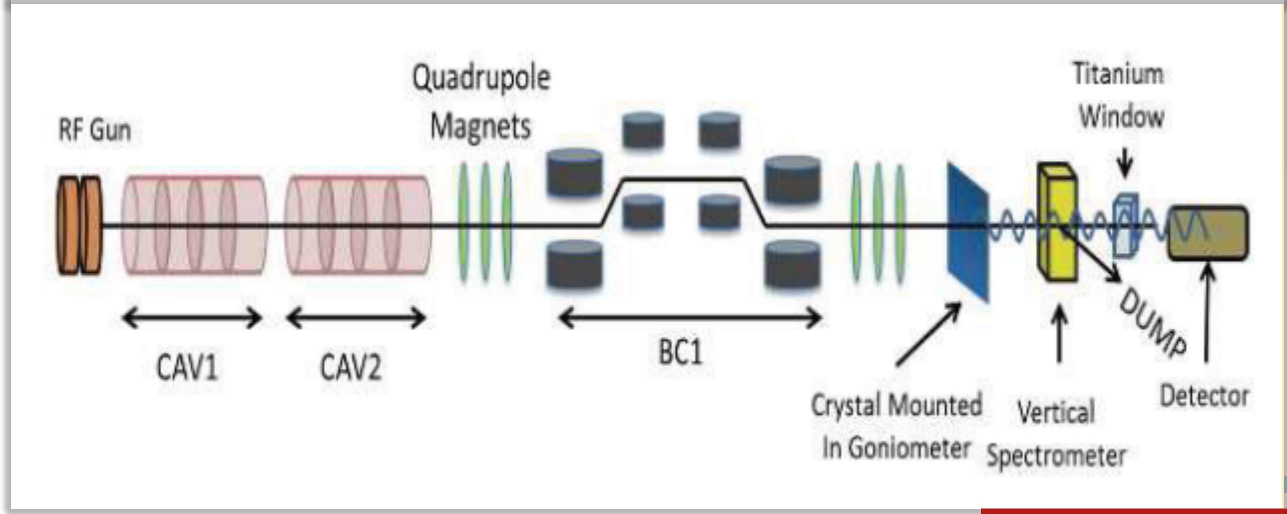


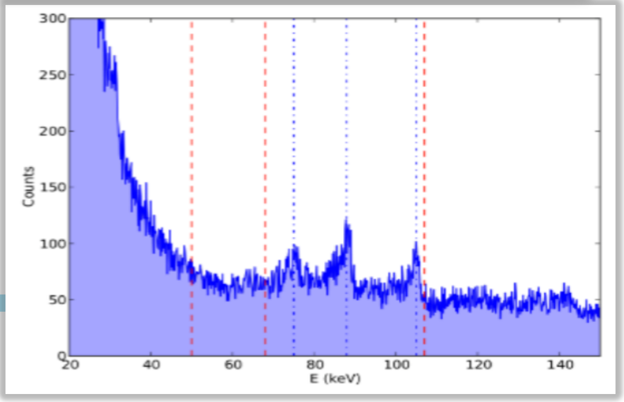










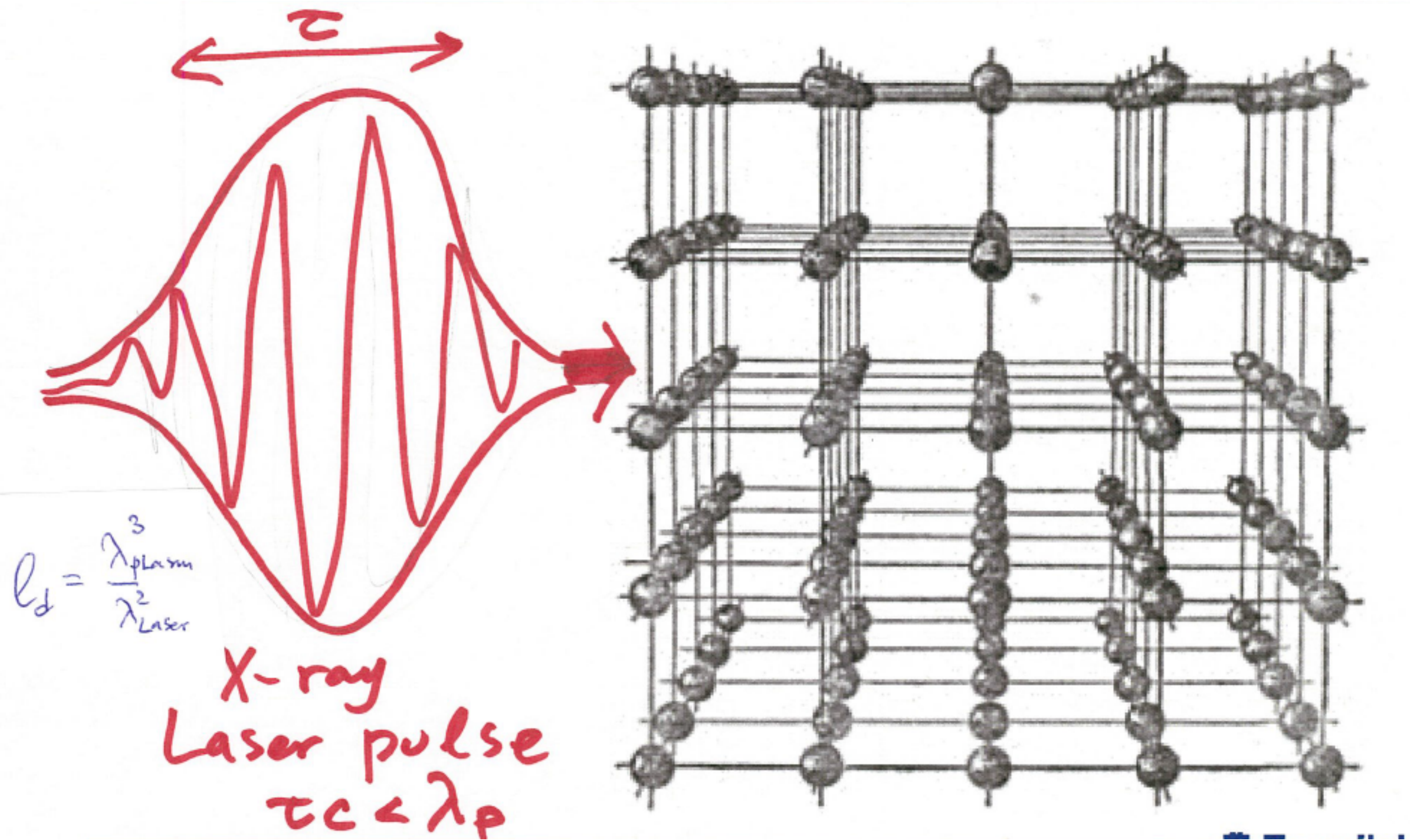


**arXiv:1612.07358**

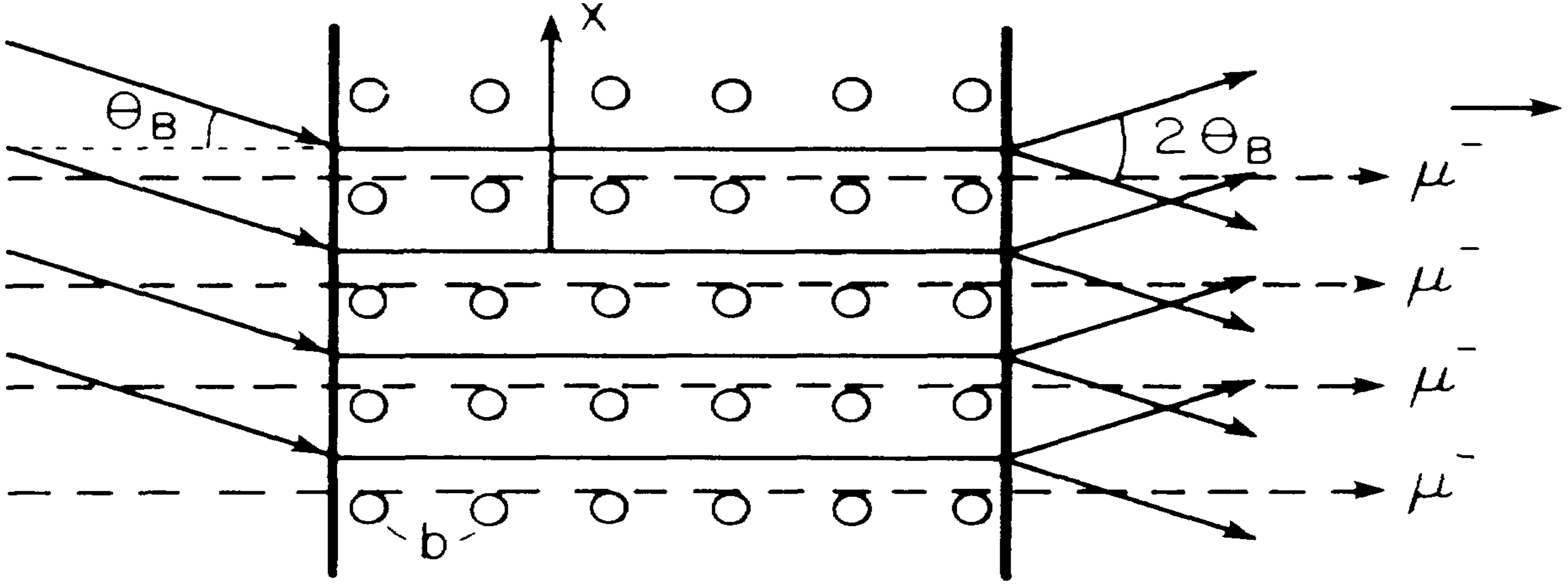
# What Do We Know About Acceleration in Xtals and Nanostructures *(besides 1…10…100 tV/m)*

- 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



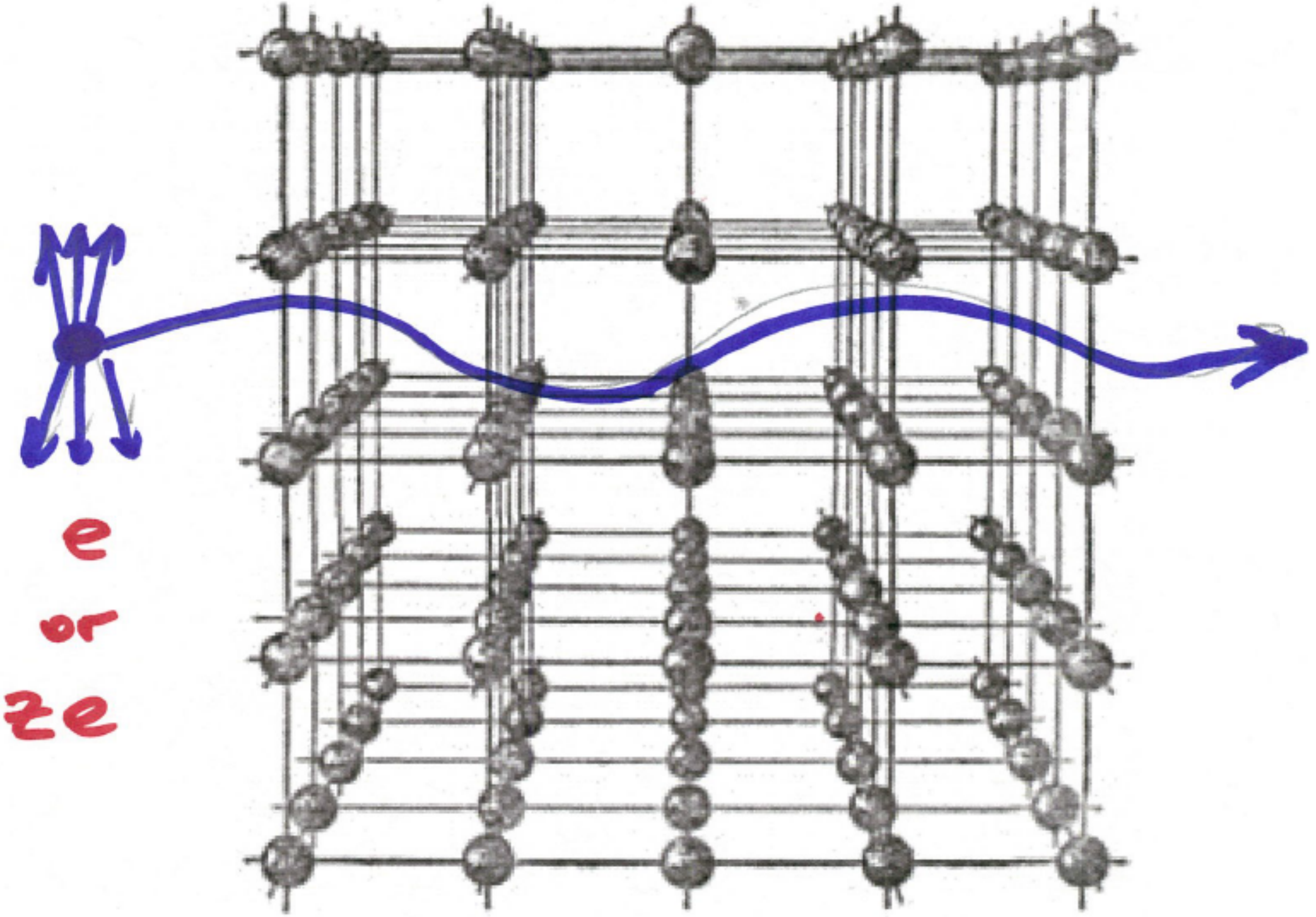
*Tajima,Cavenago, Phys. Rev. Lett. 59 (1987), 1440*

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.

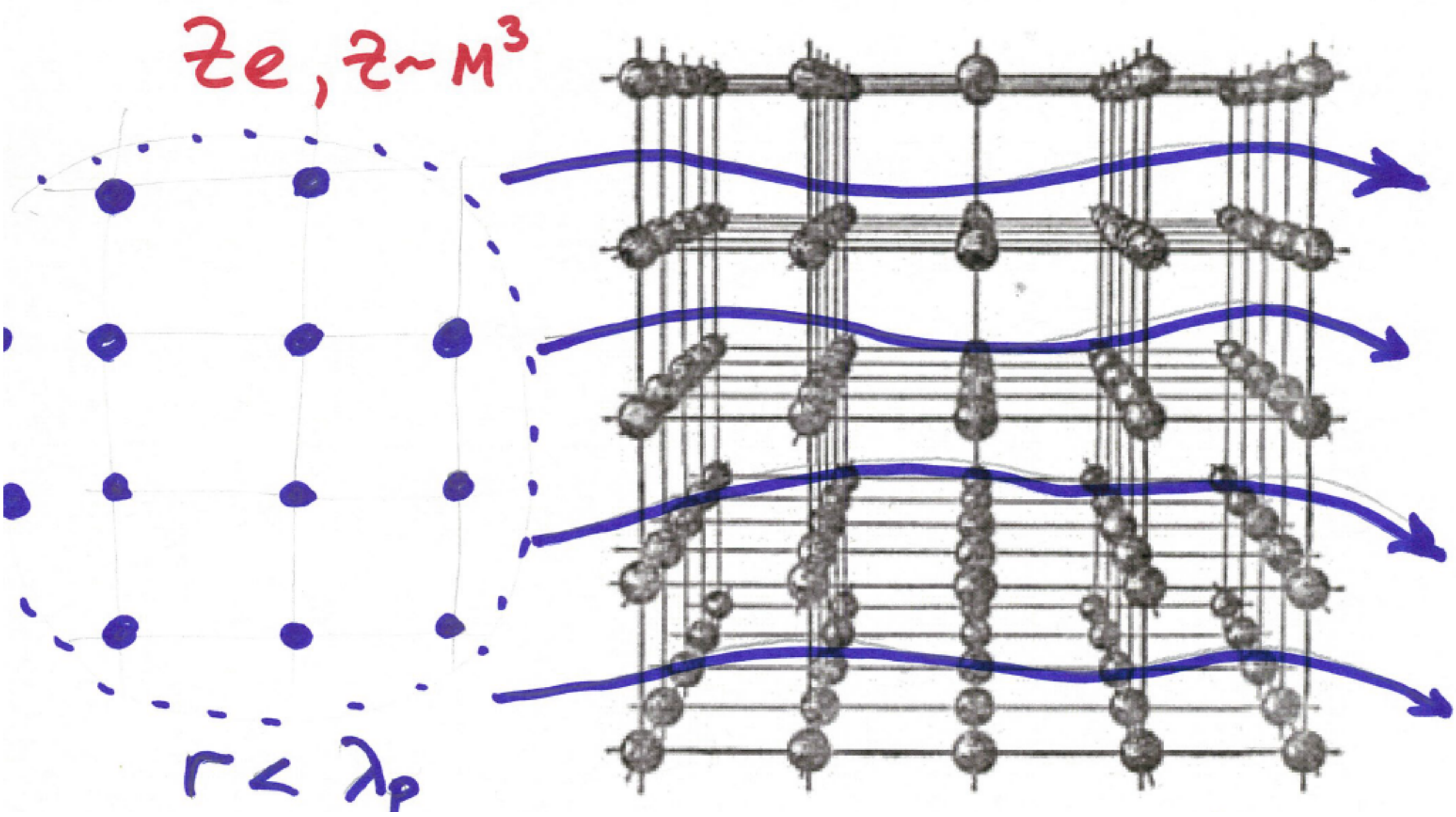
- Need 40keV high peak power x-rays
  - now available from SASE FELs like LCLS
- Gradients >1GV/cm

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

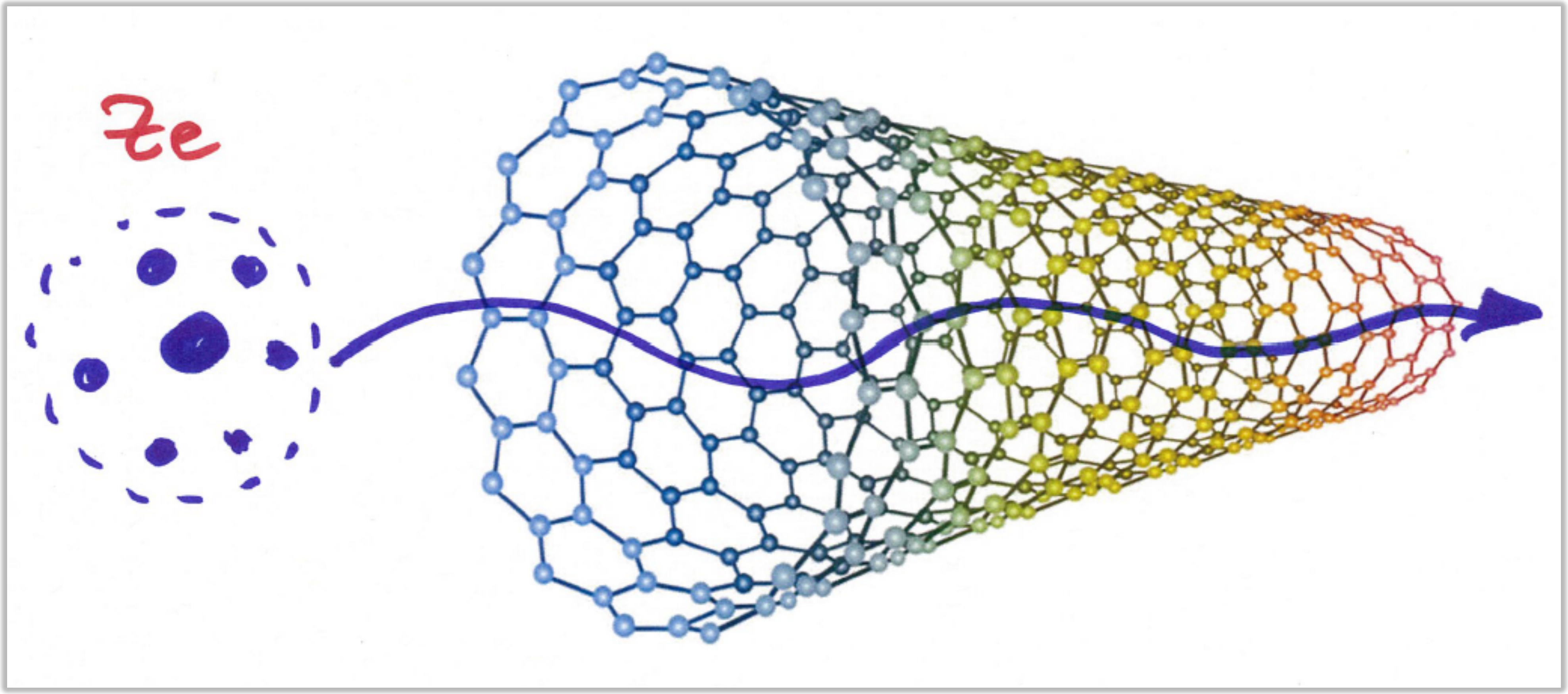
# Ways to excite the crystal (2)



# Ways to excite the crystal (3)

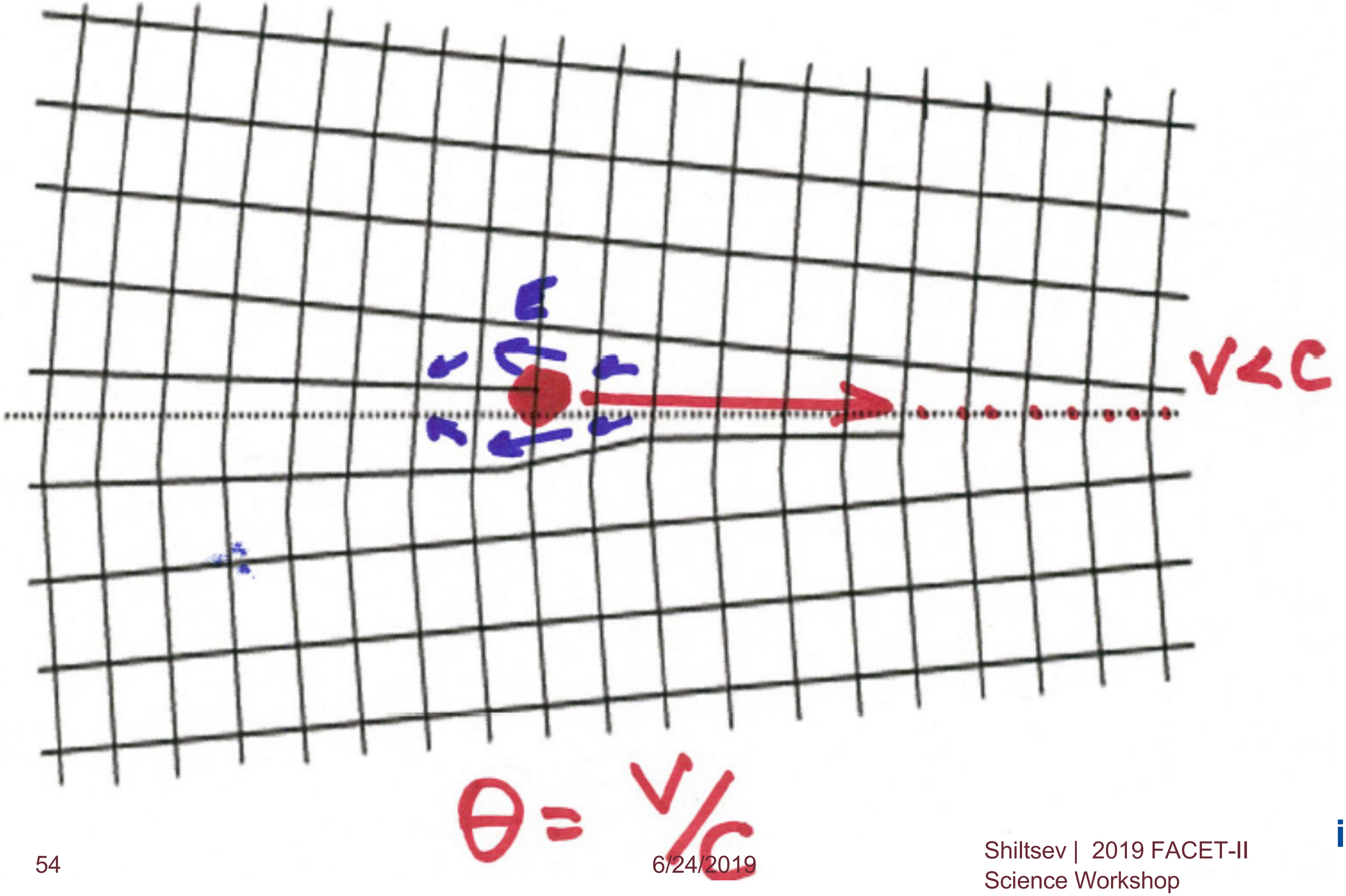


# Nanotubes



# Ways to excite the crystal (4)

Controlled generation of dislocations



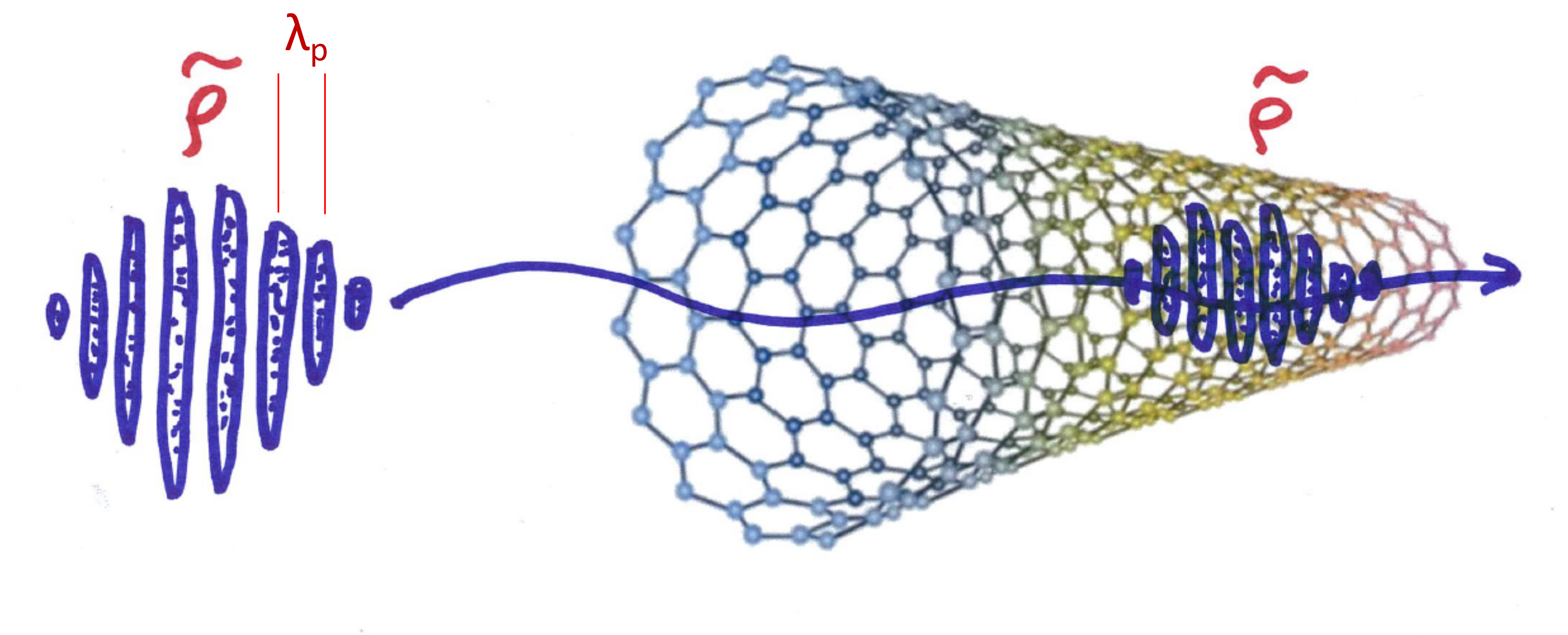
# Ways to Excite Nanotubes/Crystals (5)

## by *Optical SASE modulated electron beams*

** or slit-masking in low energy beams*

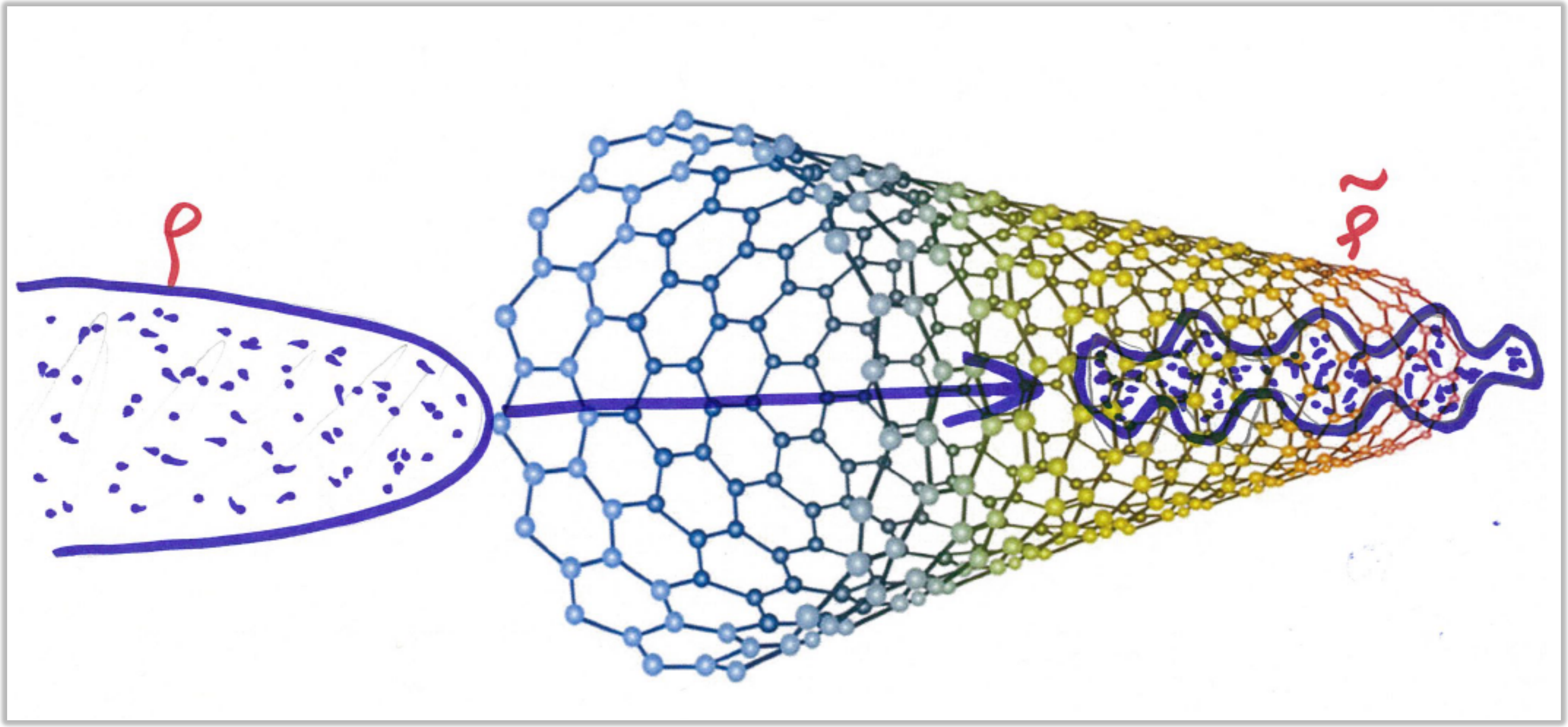
$10^{22}$ cm$^{-3}$ → $\lambda_p$~0.3µm

$10^{24}$ cm$^{-3}$ → $\lambda_p$~0.03µm

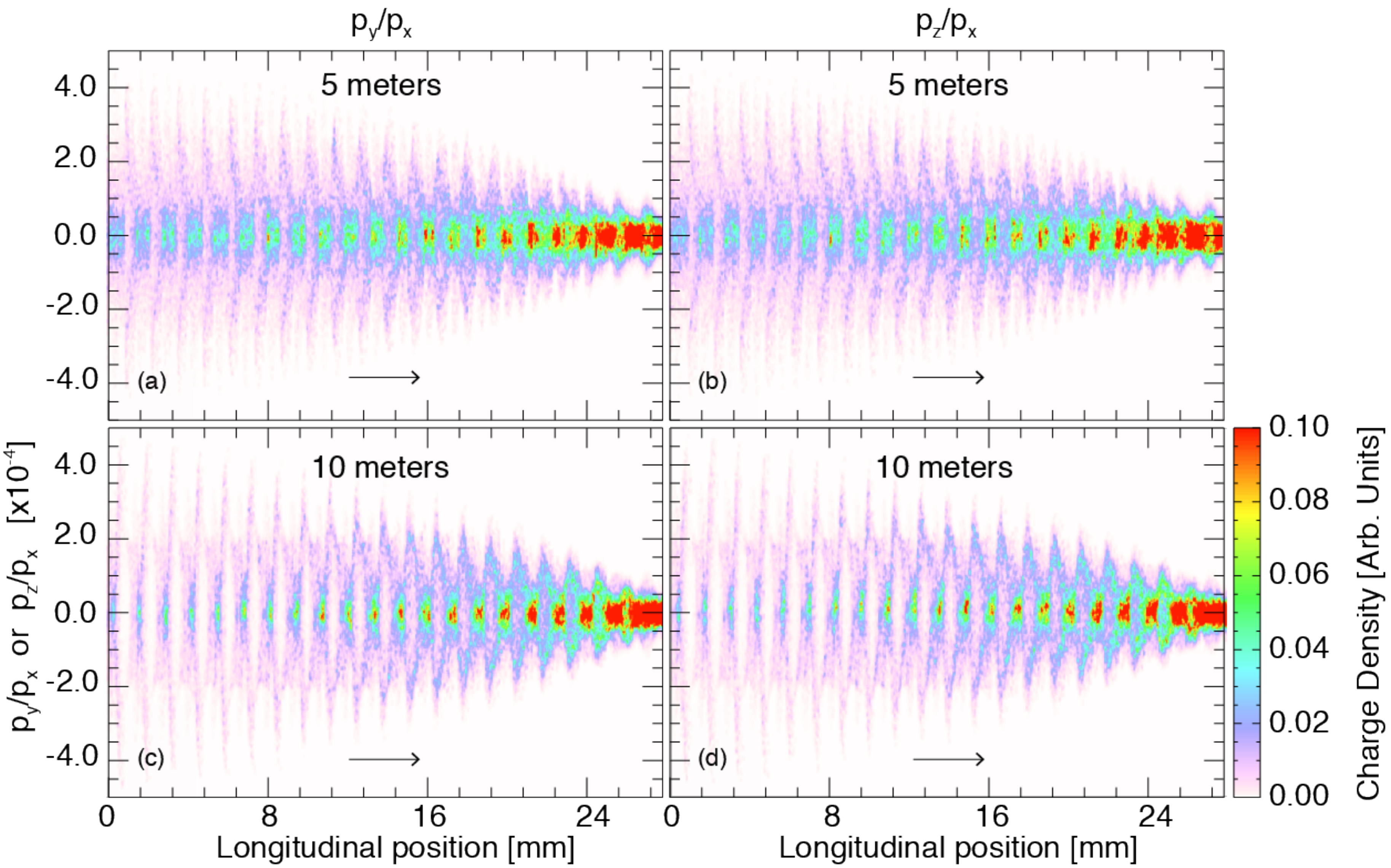


# Ways to Excite Nanotubes/Crystals (6)

## by *Self-Modulation Instability* in long(er) charge particle beams

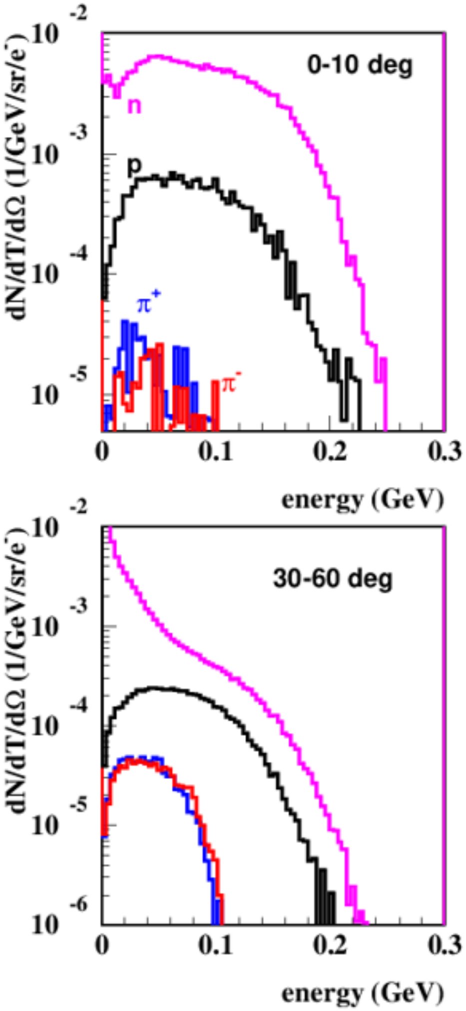


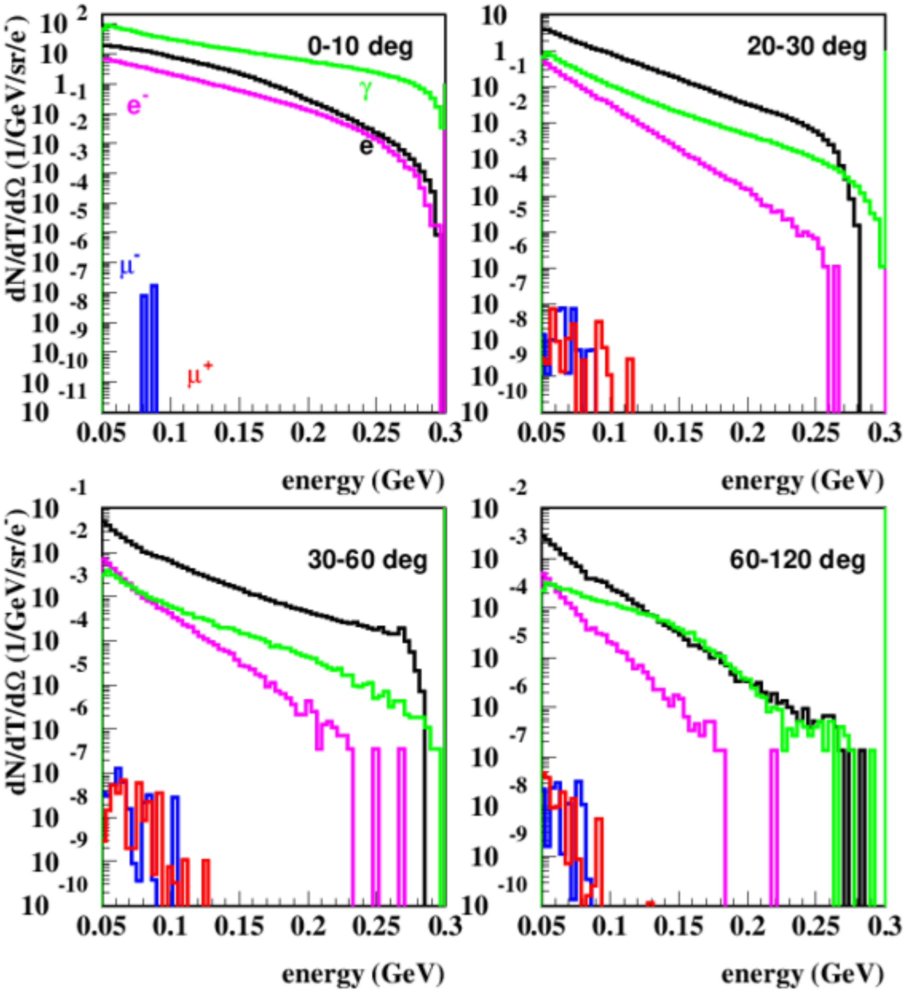
# SMI: Self-Modulation Instability (in 400 GeV protons)



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

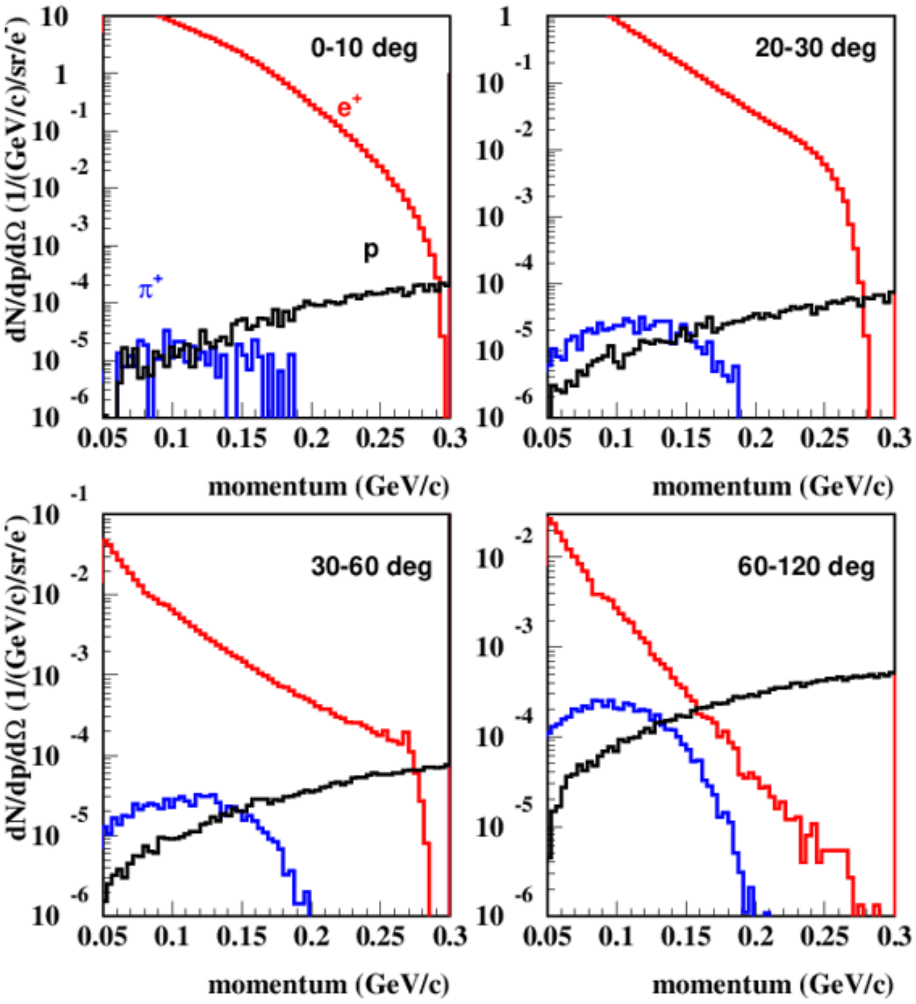
Courtesy S.Striganov

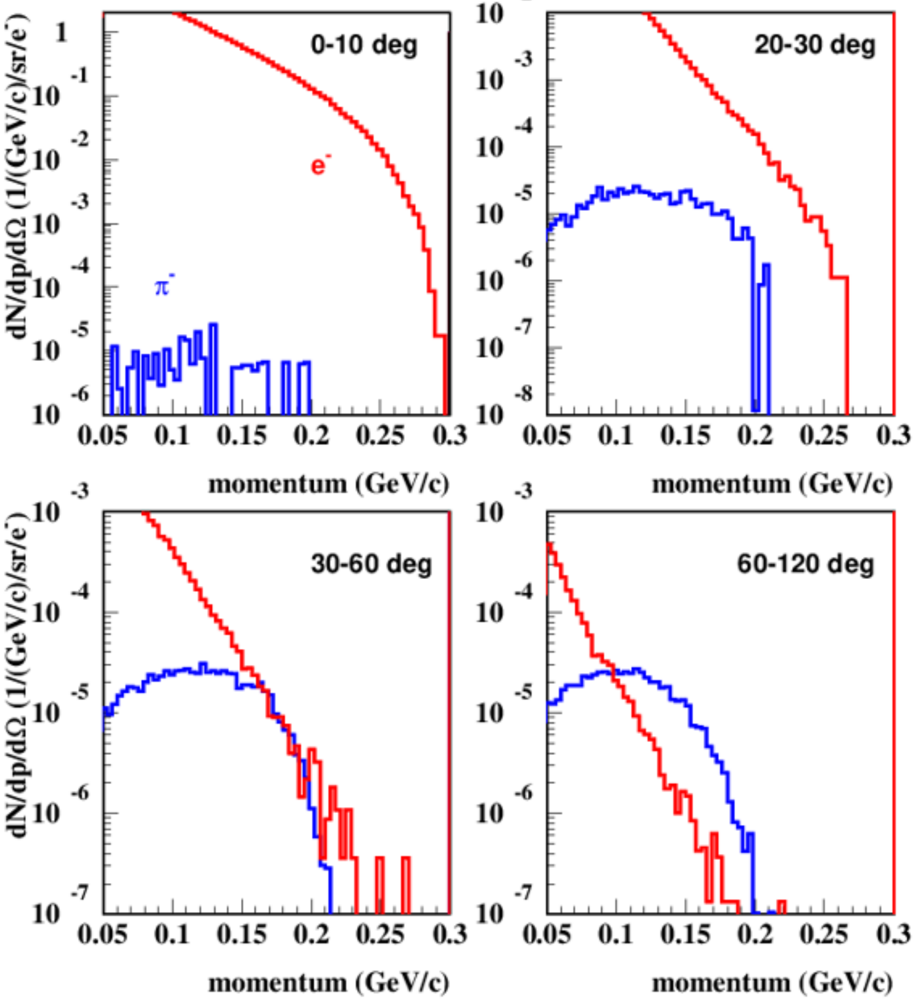




# Positive pions has very big positron/proton escort, large angle & high momentum; negative pion could be focused and extracted

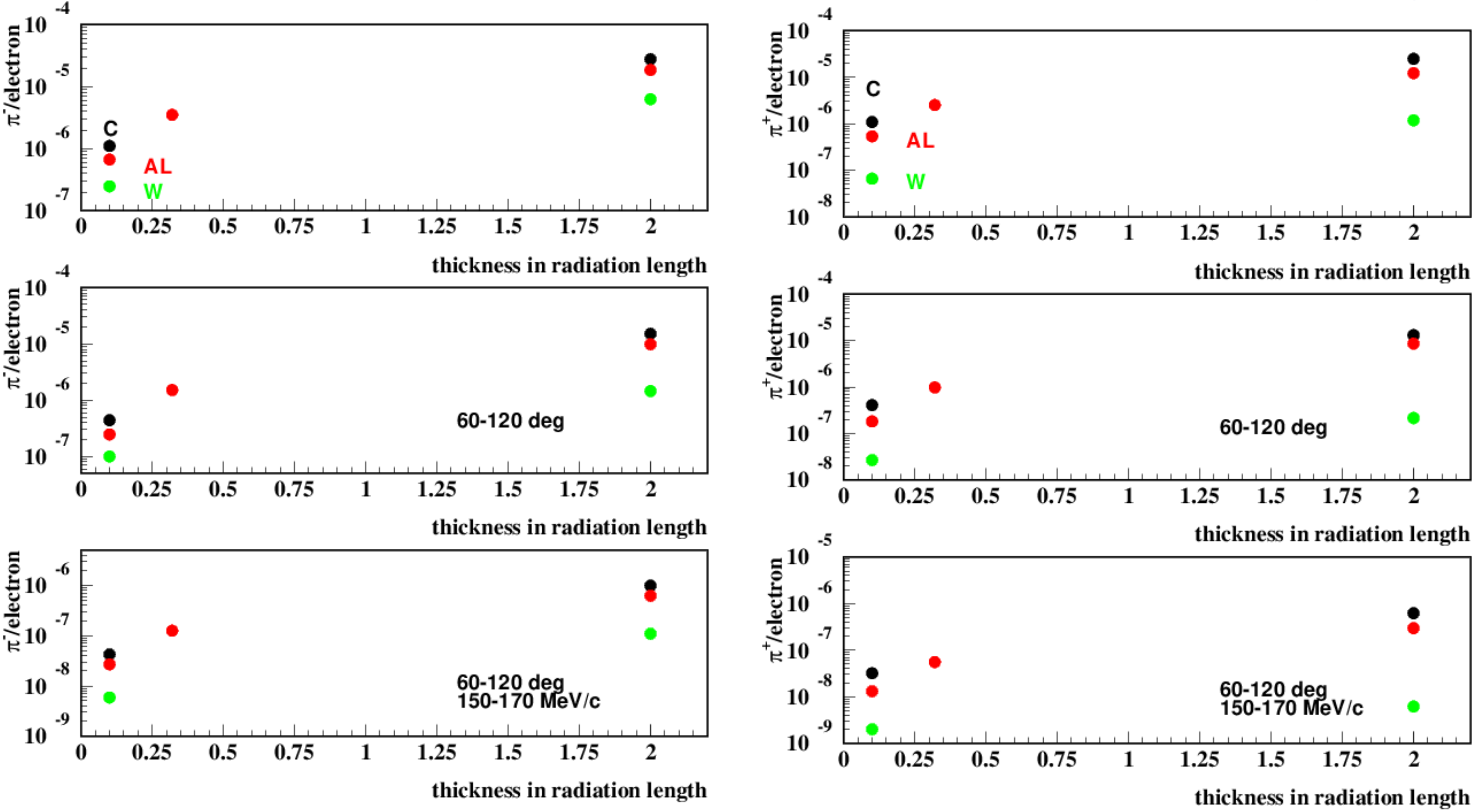
Courtesy S.Striganov





# 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



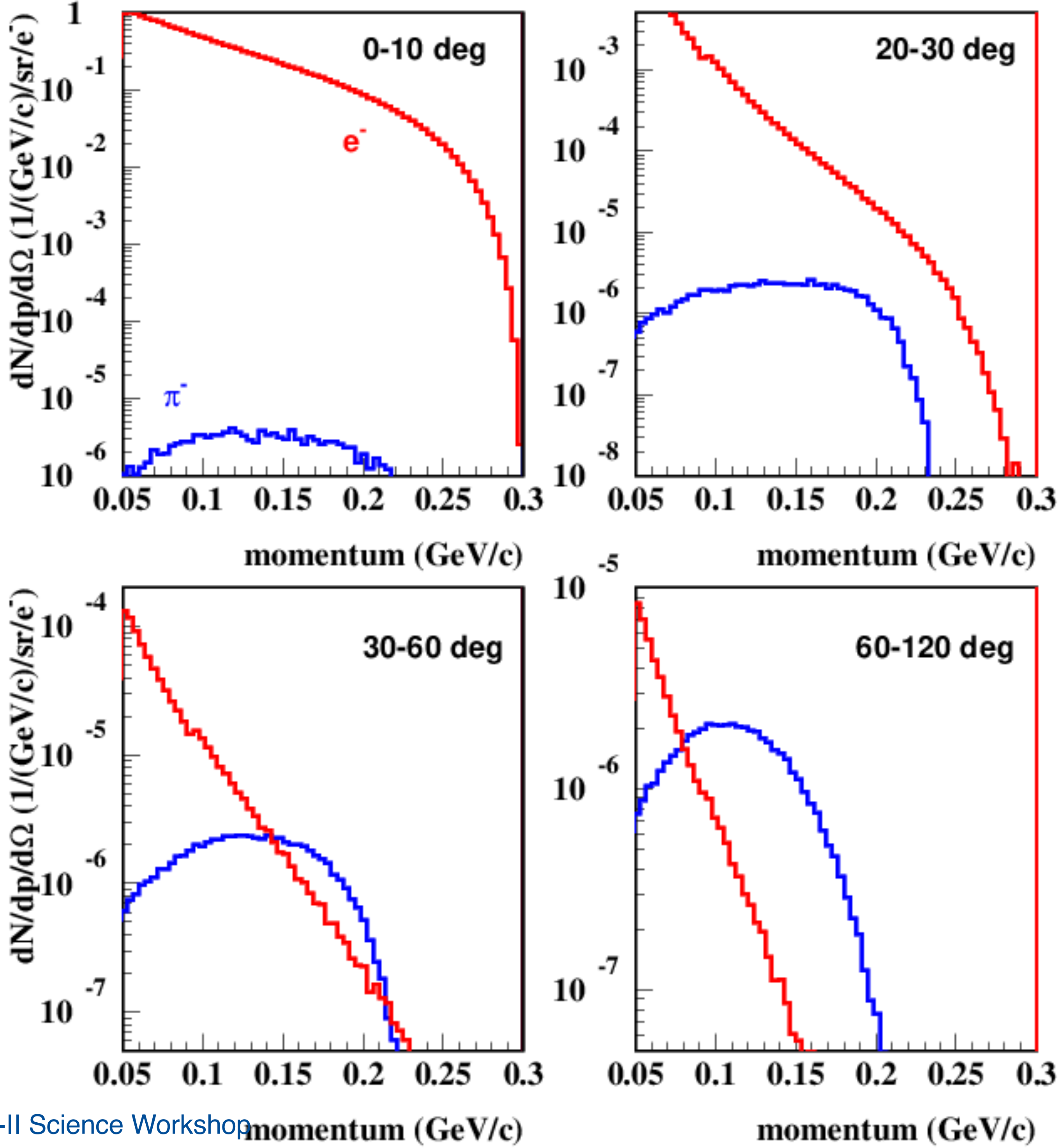
# Low radiation scenario

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

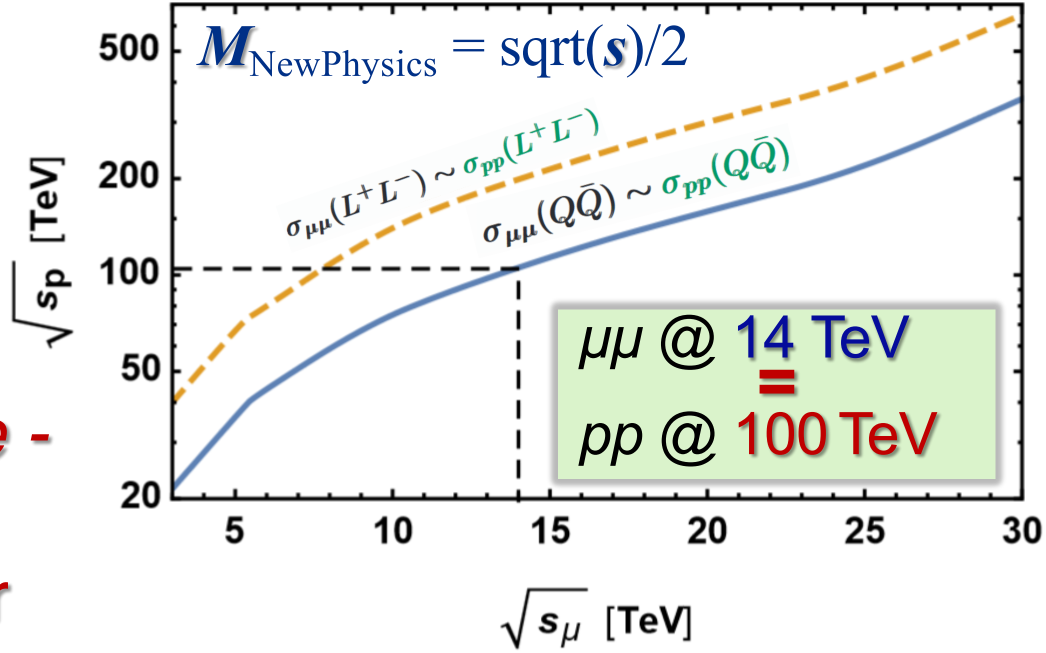
Input #120

JINST Special Issue (*MUON*)

## Advantages:

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

arXiv:1901.06150



*μμ* @ 14 TeV
=
*pp* @ 100 TeV

**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 $\rightarrow \mu^+$-$\mu^-$ , design study of acceleration, detector background and neutrino radiation

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

# Current Filamentation Instability in Laser Wakefield Accelerators

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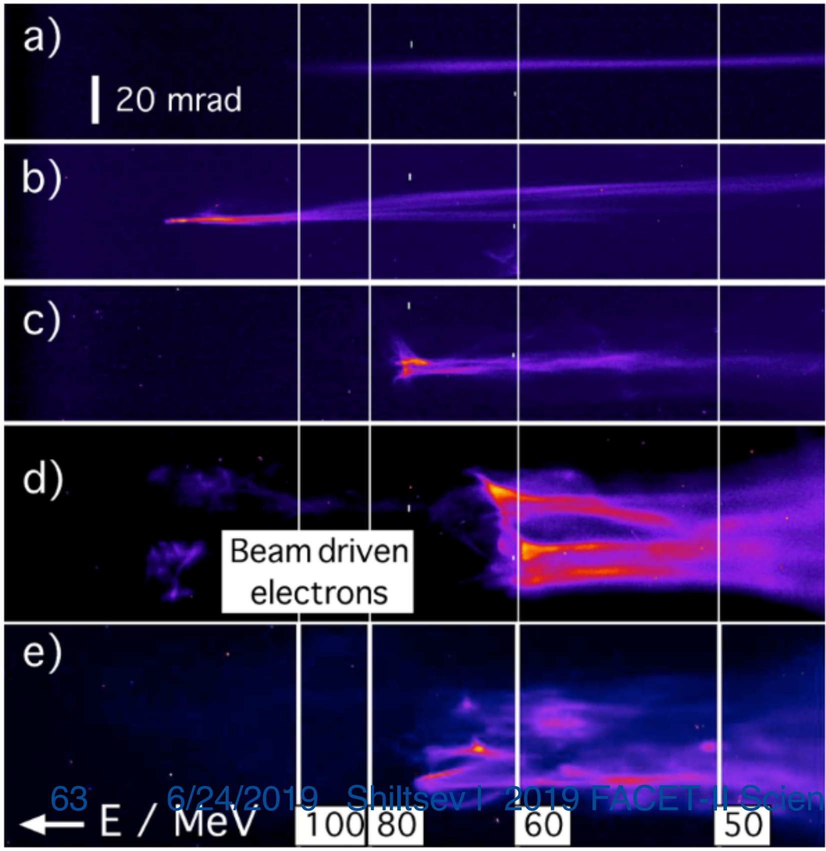
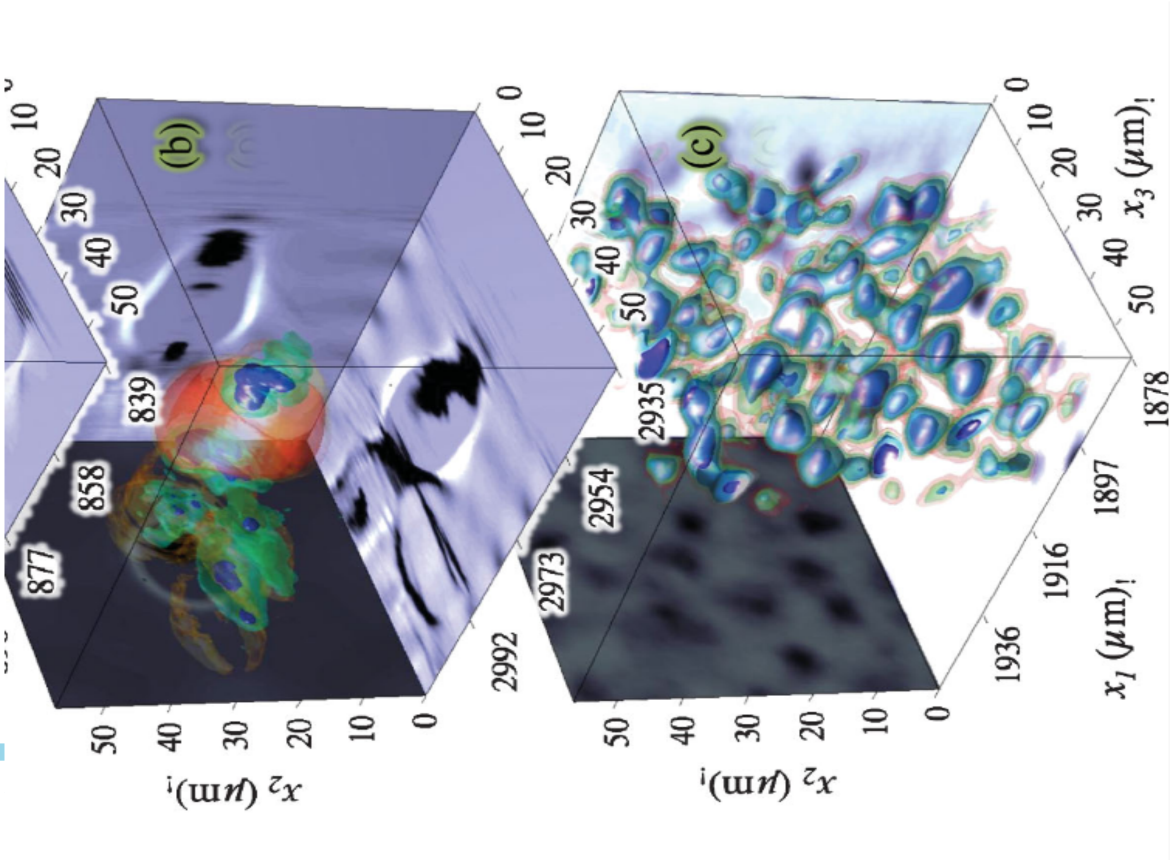
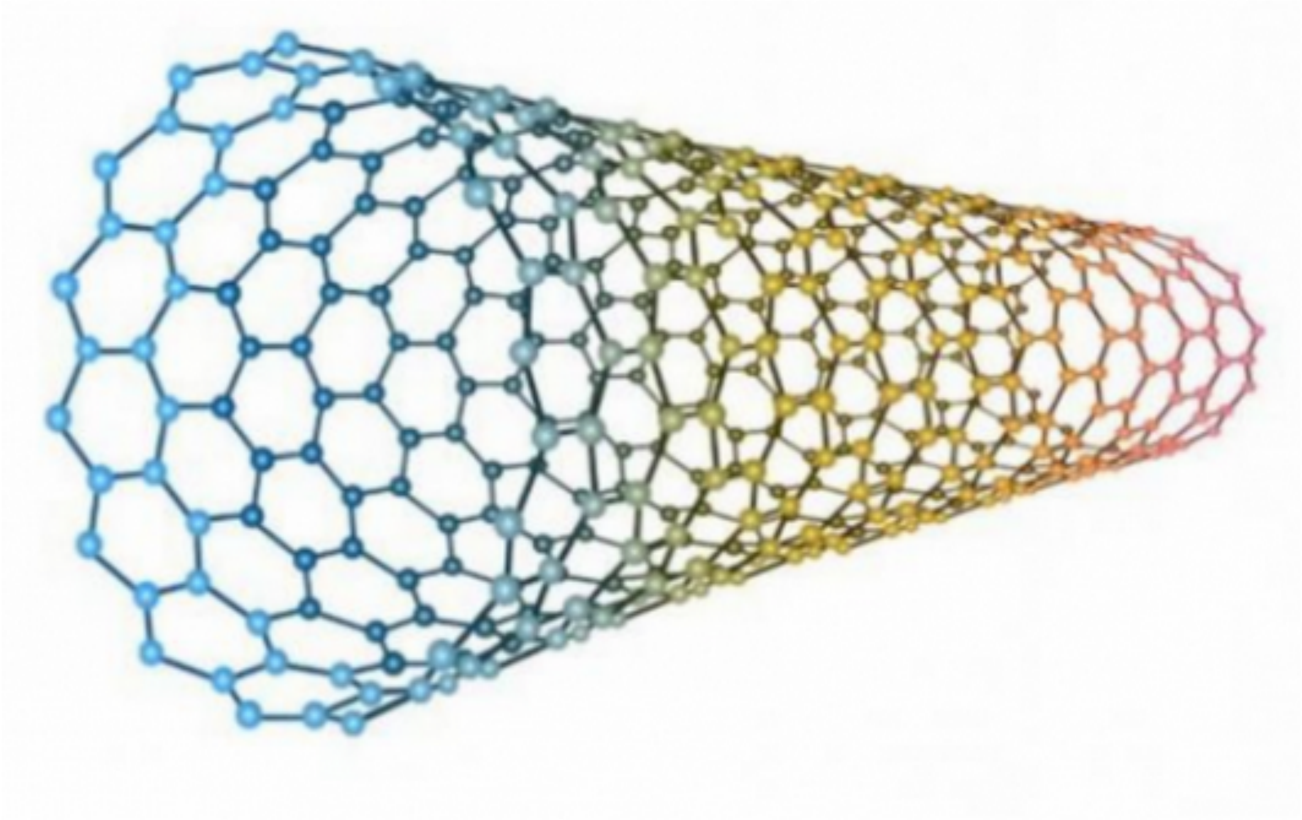
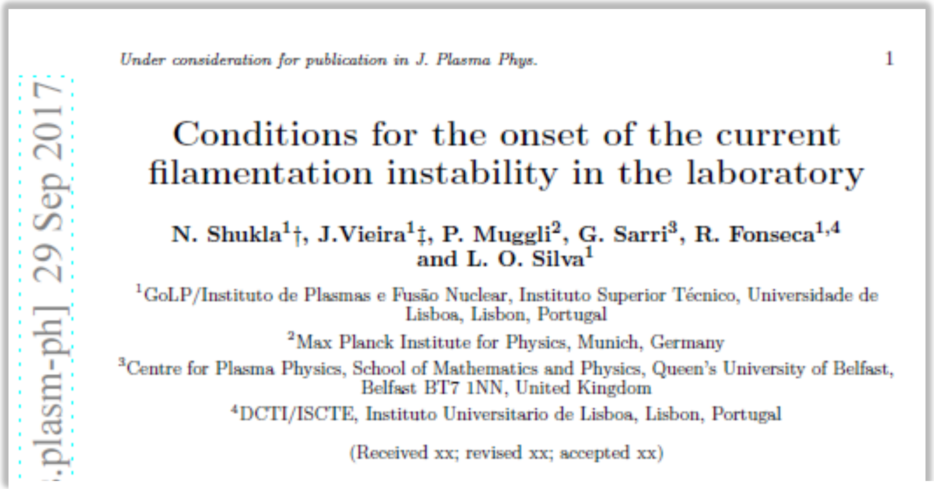






# Weibel (Filamentation) Instability



*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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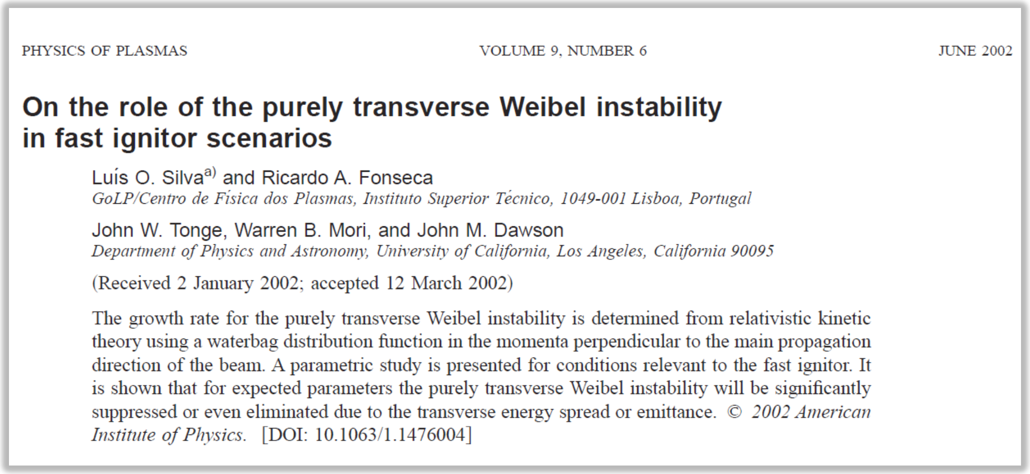

PHYSICS OF PLASMAS VOLUME 9, NUMBER 6 JUNE 2002

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

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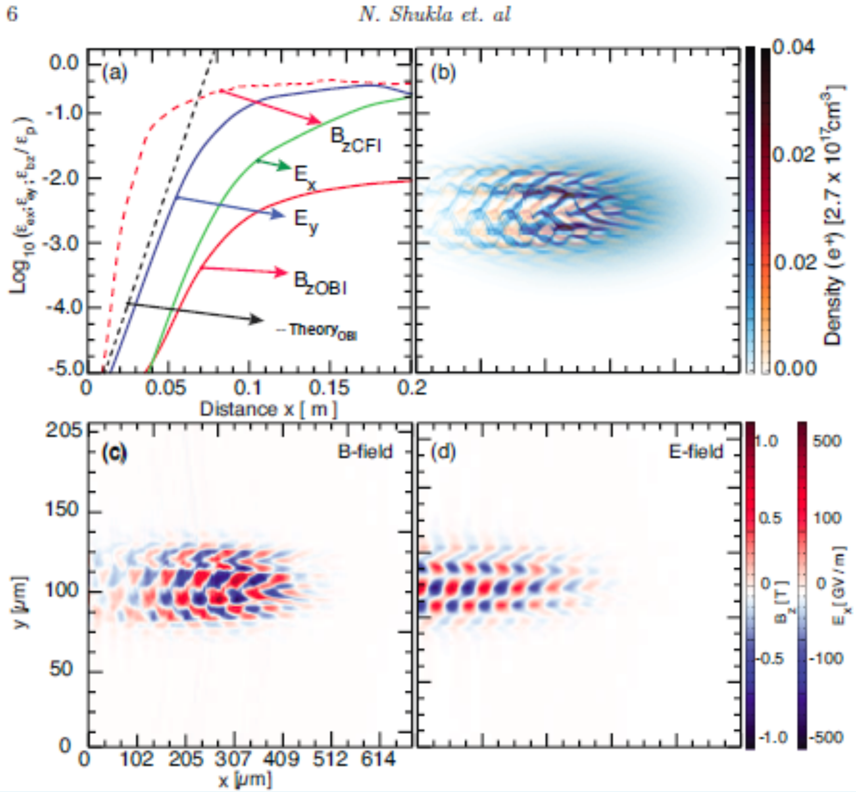
(Received 2 January 2002; accepted 12 March 2002)

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]



6 *N. Shukla et. al*

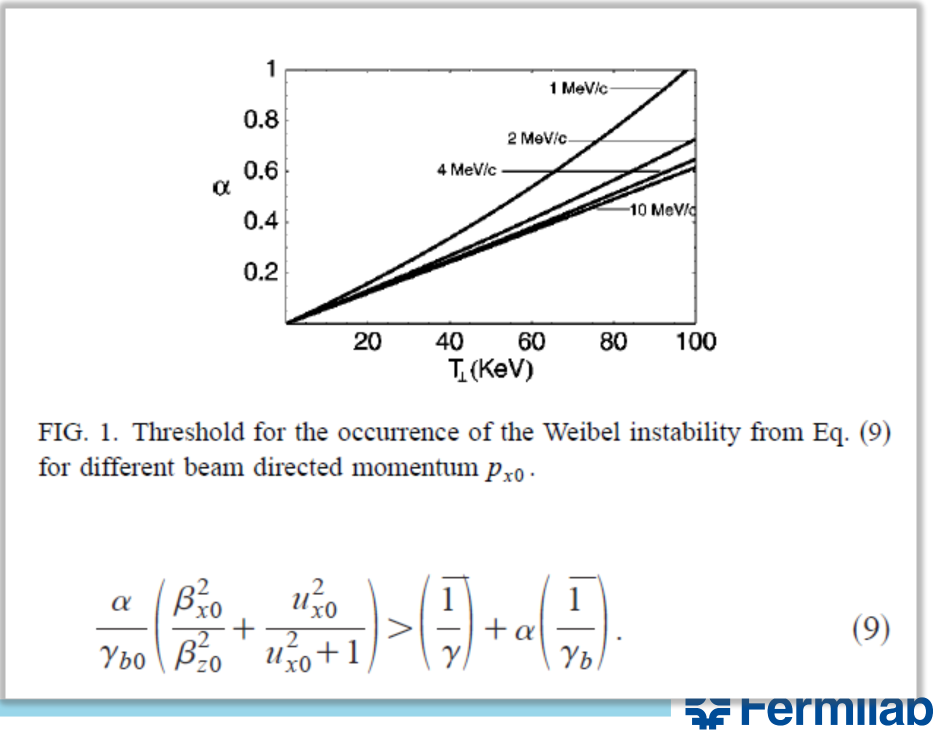


FIG. 1. Threshold for the occurrence of the Weibel instability from Eq. (9) for different beam directed momentum $p_{x0}$.

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