bending and focusing with plasmas and crystals - potential and challenges

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EuCARD2013, 11 June 2013

photo SLAC

outline

- plasmas
  - plasma lenses
  - plasma wiggler
  - plasma dipole
- crystals
  - crystal channeling & reflection
  - leptons in crystals
  - crystal accelerators
  - crystalline beams

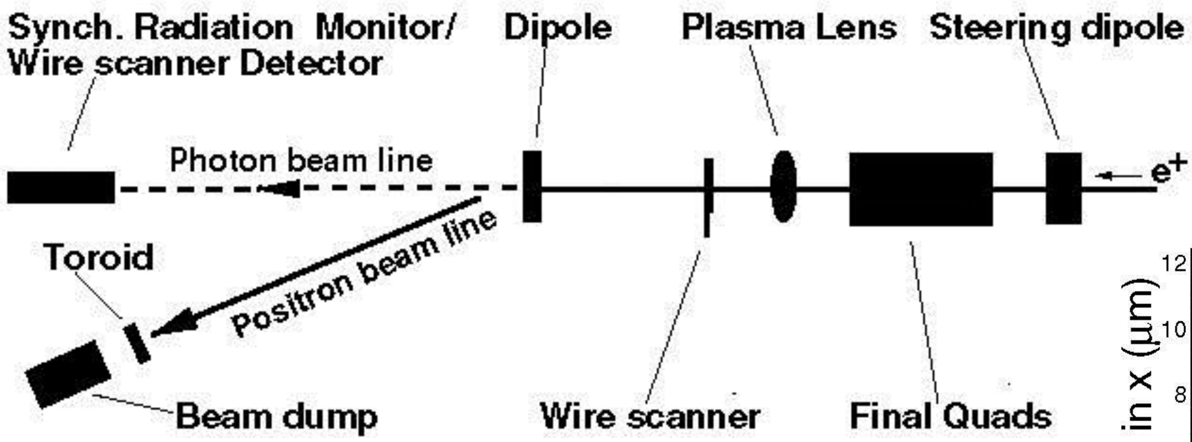
plasma focusing: plasma lens

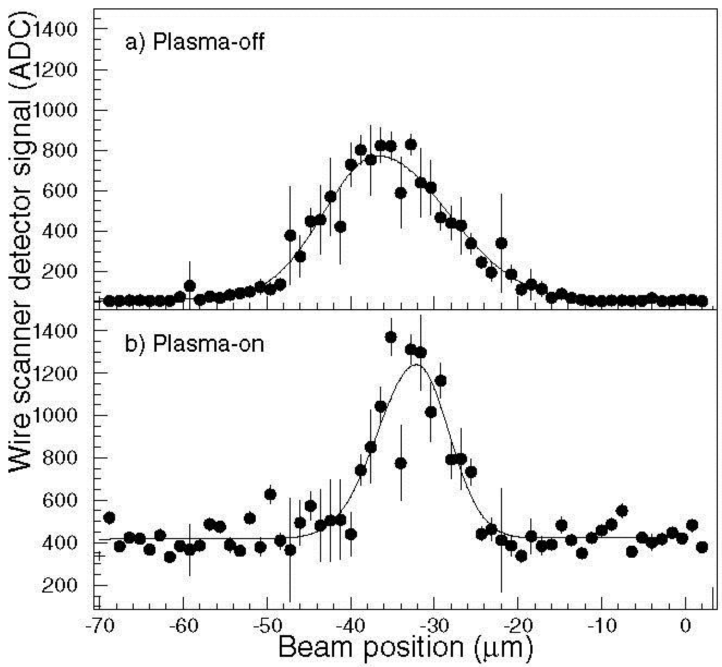
- proposed as **final focusing element for future high energy electron-positron colliders**
  - P. Chen, 1987
- early experiments with e^- at low energy (50 MeV)
  - J. Rosenzweig, H, Nakanishi etc, 1990, 1991
- **SLAC FFTB experiment** (2001): focusing of **28.5 GeV e^+ beam** using plasma formed by ionizing a 3-mm N_2 gas jet; **simultaneous focusing in both transverse dimensions**
- effective focusing strength: **10^6 T/m**

plasma density
$n \approx 5 \times 10^{17}$ cm^{-3}

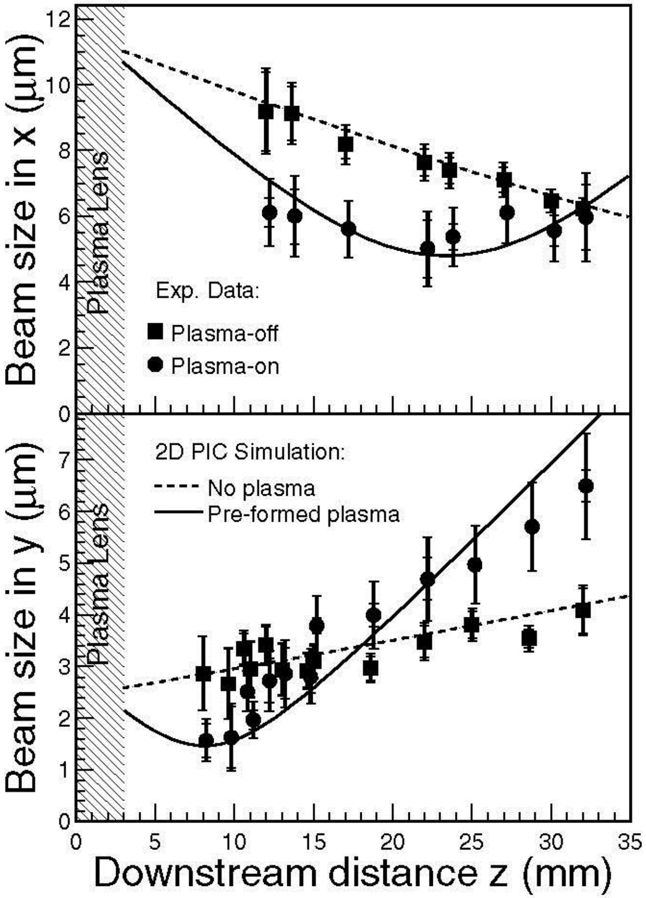
plasma lens @ FFTB (2001)

J. S. T. Ng et al,
Phys. Rev. Letters
87, 24 (2001)



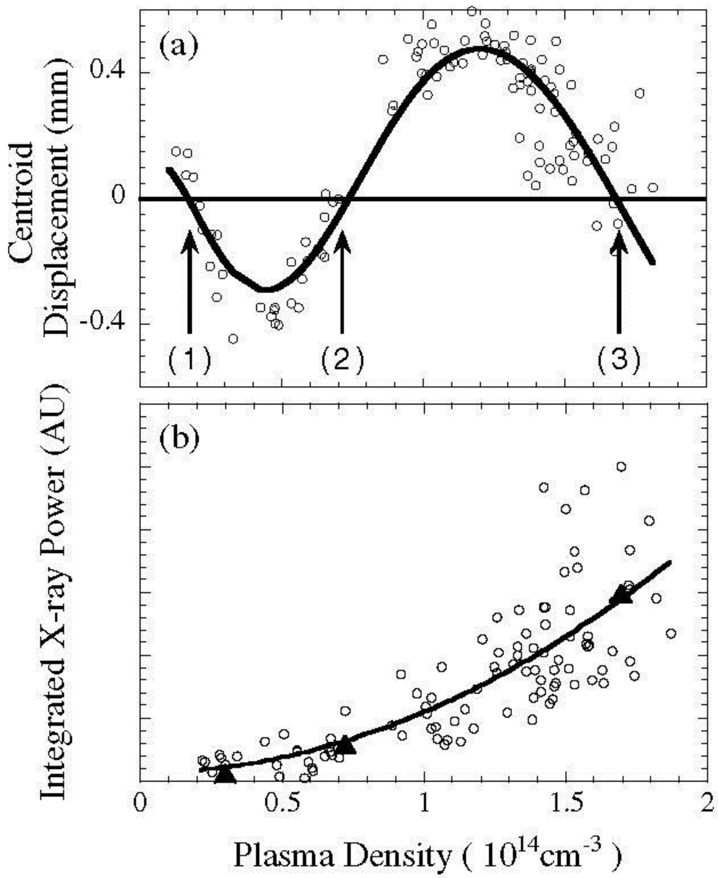


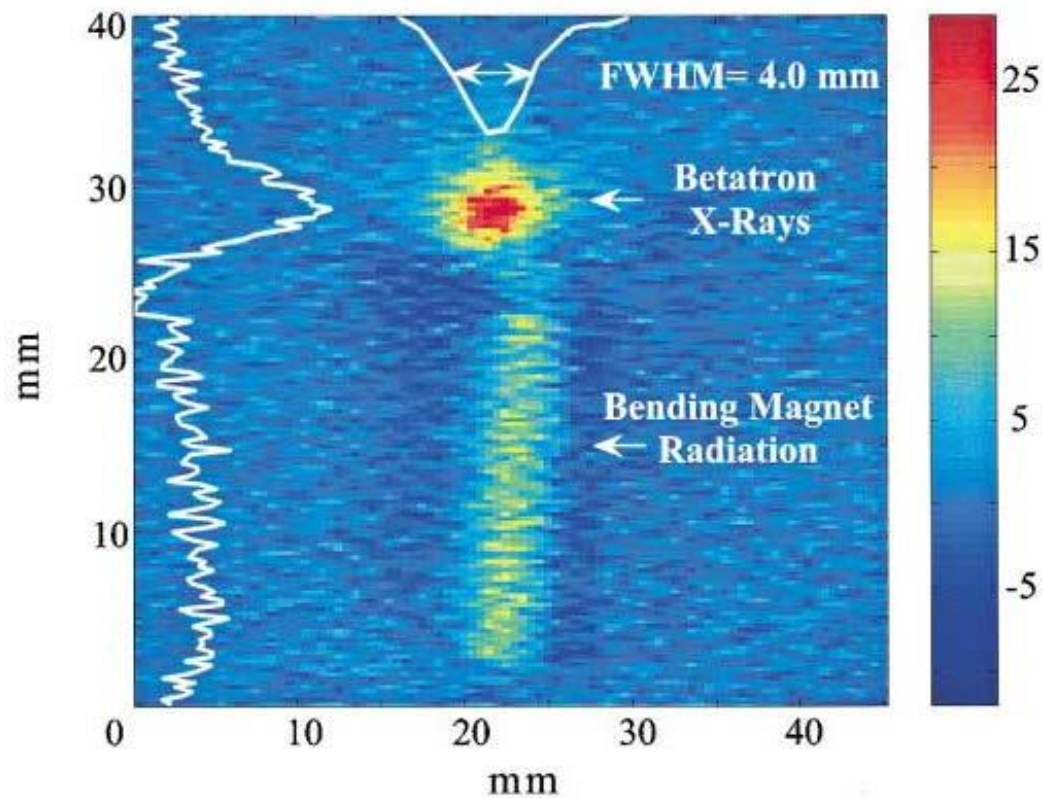
minimum area of beam spot reduced by factor ~2



plasma betatron wiggler: FFTB (2001)

n=1.7x10^{14}cm^{-3}: focusing force ~5x10^6 T/m, shrinking beam size from 40 μm to <5 μm



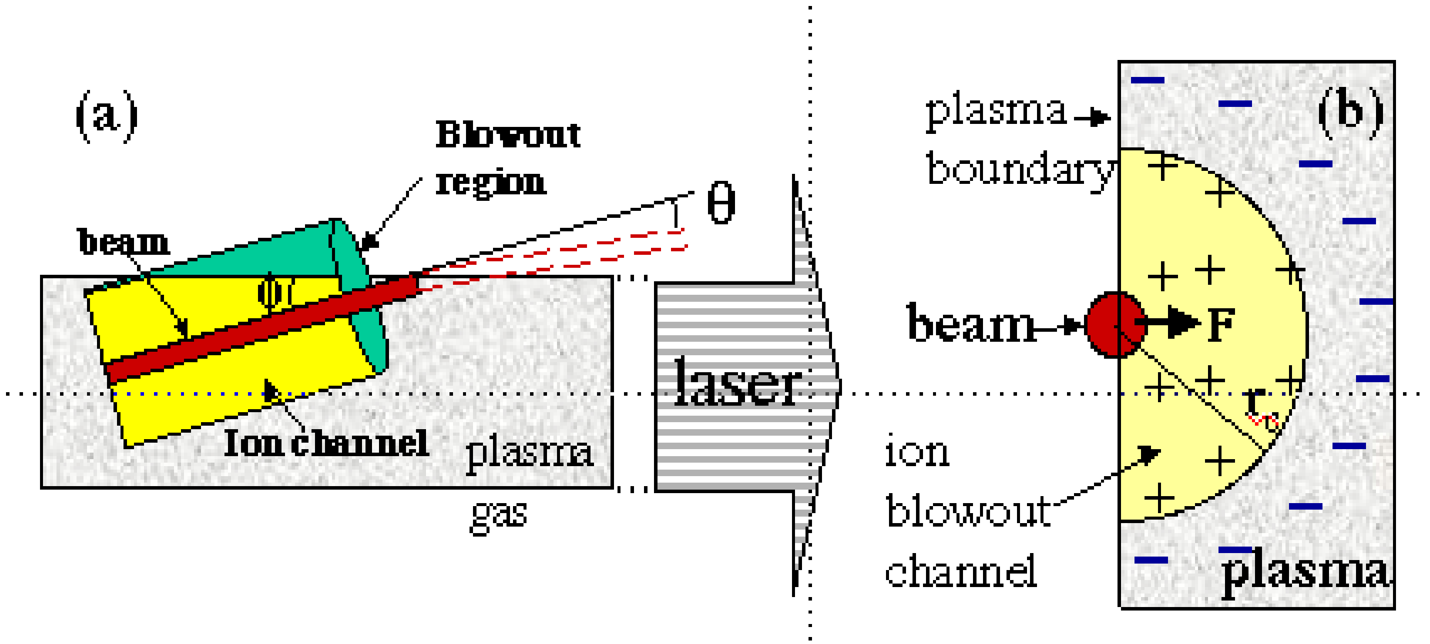


S. Wang et al, Phys. Rev. Letters, 88, 13 (2002);
also see M. Litos, S. Corde, SLAC-PUB-15215 (2012)

plasma bending: FFTB (2000)

Collective Refraction of a Beam of Electrons at a Plasma-Gas Interface *Nature* **411**, 43 (3 May 2001)

collective response of the plasma produces a deflection of the electron beam of the order of one millirad

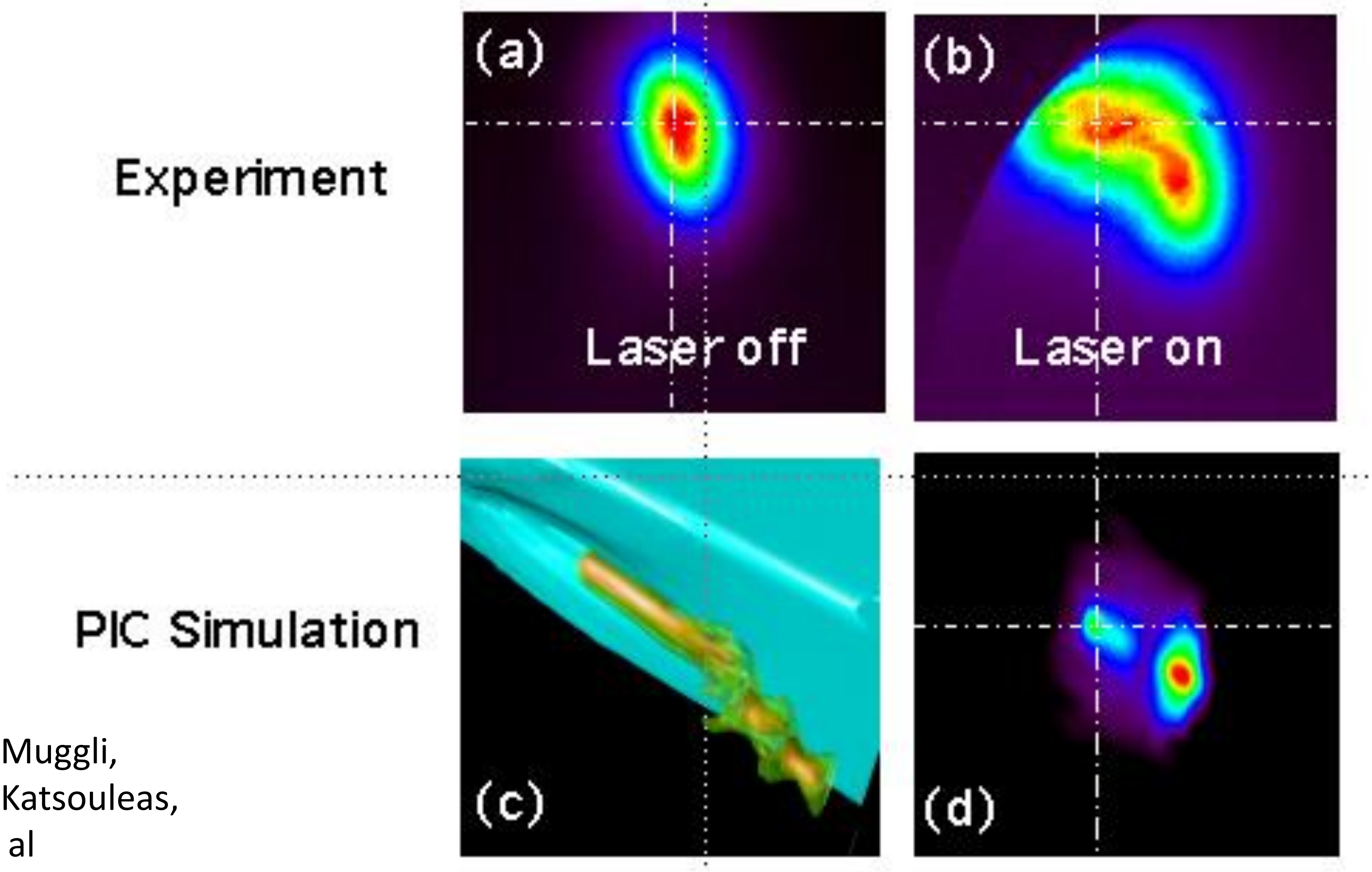


P. Muggli, T. Katsouleas, et al

1.9×10^{10} electrons at 28.5 GeV in a Gaussian bunch of length σ_z=0.7mm and spot size $\sigma_x \sim \sigma_y \sim 40$ μm

plasma bending at FFTB

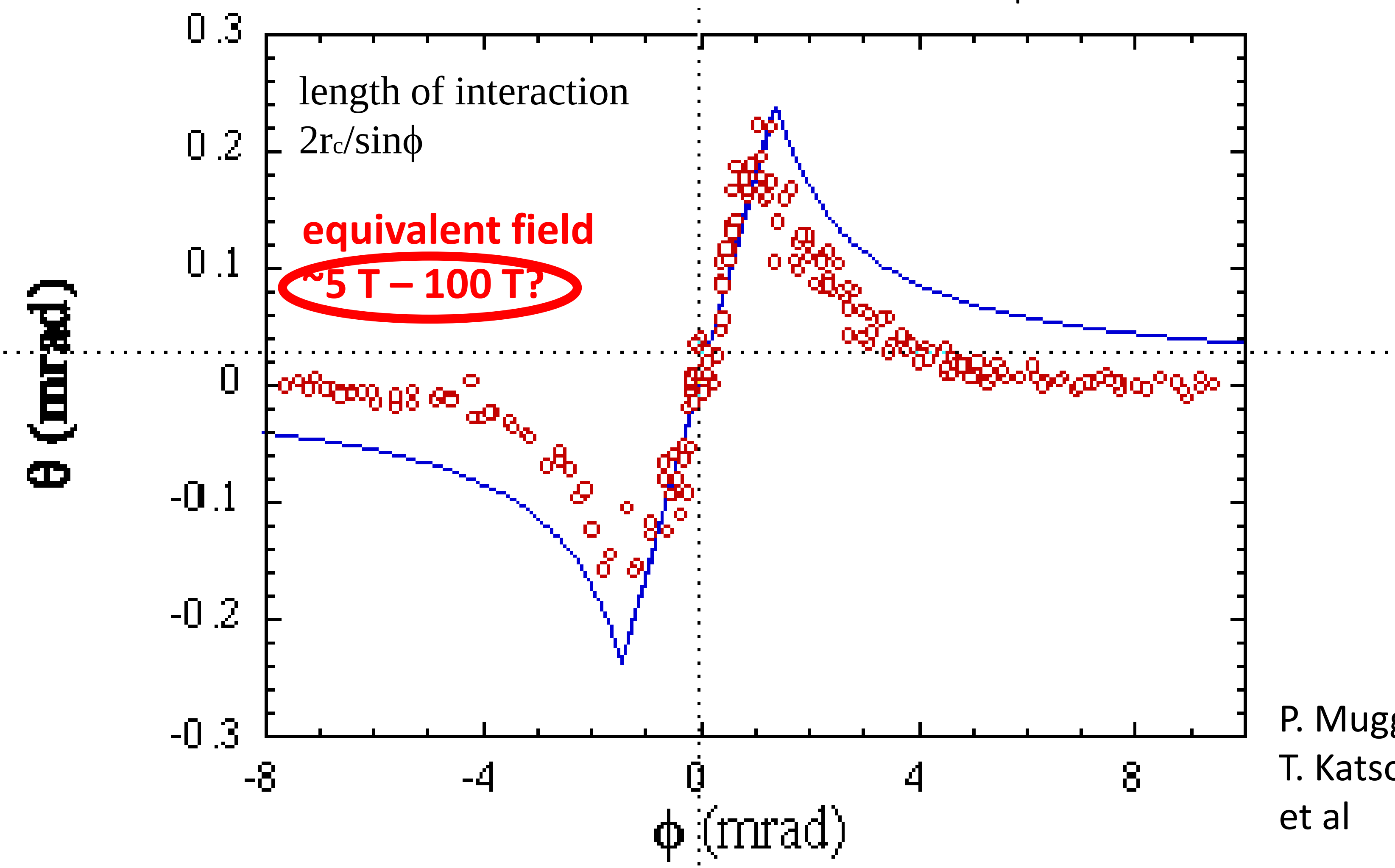
Cerenkov images of e^- beam showing refraction of a portion of the beam with the plasma (i.e., laser on) & PIC simulation



P. Muggli,
T. Katsouleas,
et al

plasma bending at FFTB

Measured e- beam deflection θ versus angle ϕ between laser and e-beam/ Solid curve is an analytical model prediction. The bunch length & plasma density were 0.7 mm and $1\text{x}10^{14}$ cm^{-3} (λ_p~3 mm, r_c~0.2 mm?)



P. Muggli, T. Katsouleas, et al

from plasmas to crystals !?

maximum field in a plasma

$G \approx 100$ GV/m $(n_0\ [10^{18}\ \mathrm{cm}^{-3}])^{1/2}$;

$n_0 \approx 10^{17}\text{-}10^{18}\ \mathrm{cm}^{-3}$

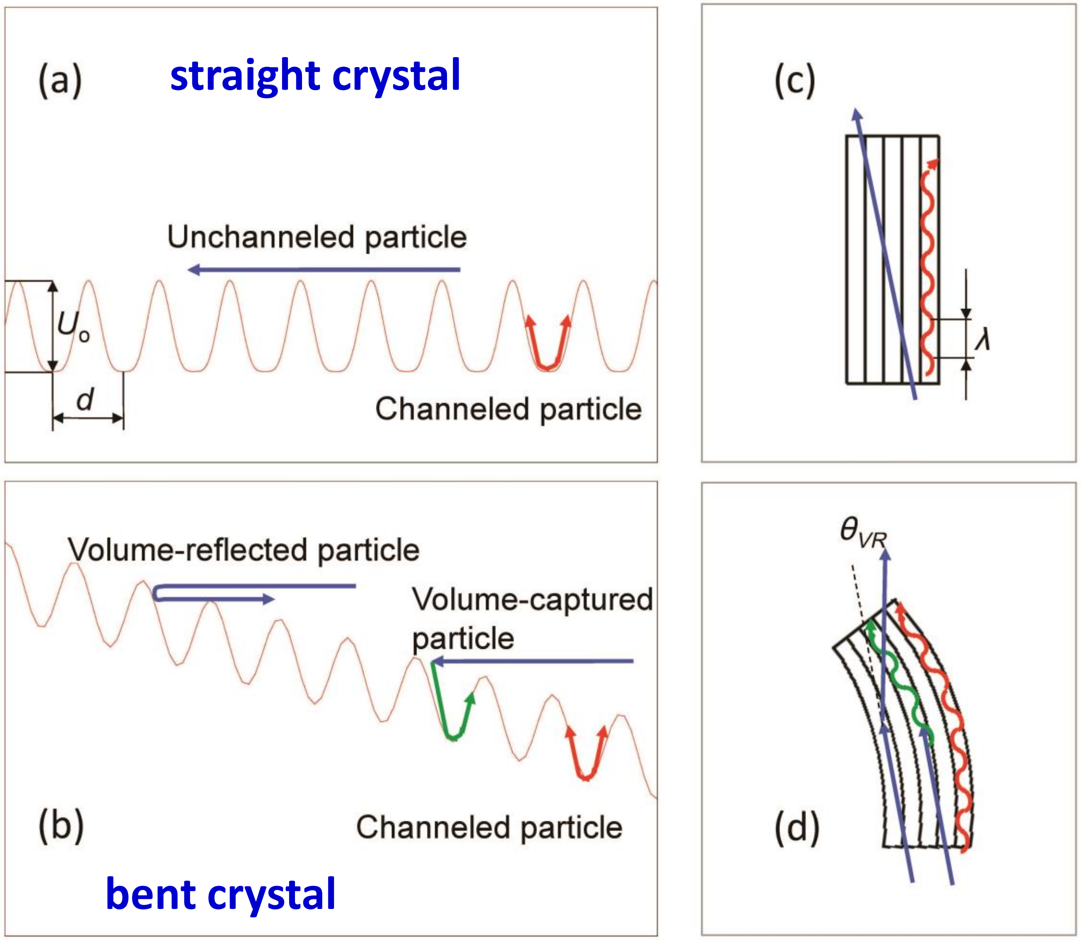
maximum field in a crystal

$G \approx 10$ TV/m $(n_0\ [10^{22}\ \mathrm{cm}^{-3}])^{1/2}$;

$n_0 \approx 10^{22}\text{-}10^{23}\ \mathrm{cm}^{-3}$

crystals are also more regular and could be cooled → less beam interaction with nuclei, etc.

crystals - world's strongest "magnets



crystal focusing strength

ϕ~20-60 eV/Å^2

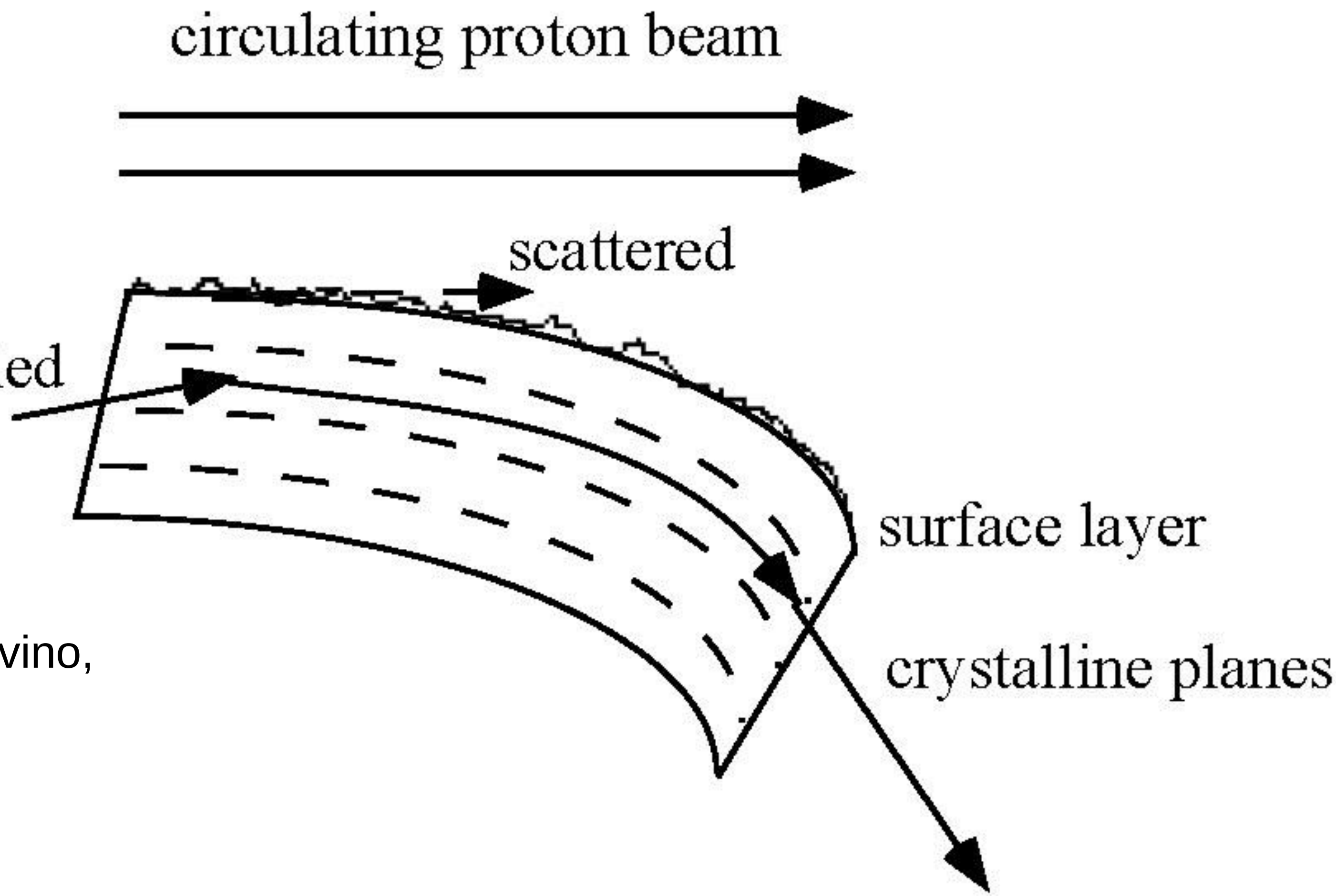
B_{max}≈2000 T !

$\lambda=2\pi\beta=2\pi\ (E/\phi)^{1/2}$

W. Scandale, MPL A (2012)

S.A. Bogacz, D. Cline, 1997

crystal extraction from stored proton/ion beam



Dubna, Protvino,
CERN SPS,
Tevatron

since 1978 crystals are used for extracting high-energy protons or ions from storage rings; can they also be used for a circular collider?!

channeling condition: angle of incidence < Lindhard **critical angle ~5 μrad (Z/p [TeV/c])$^{1/2}$**

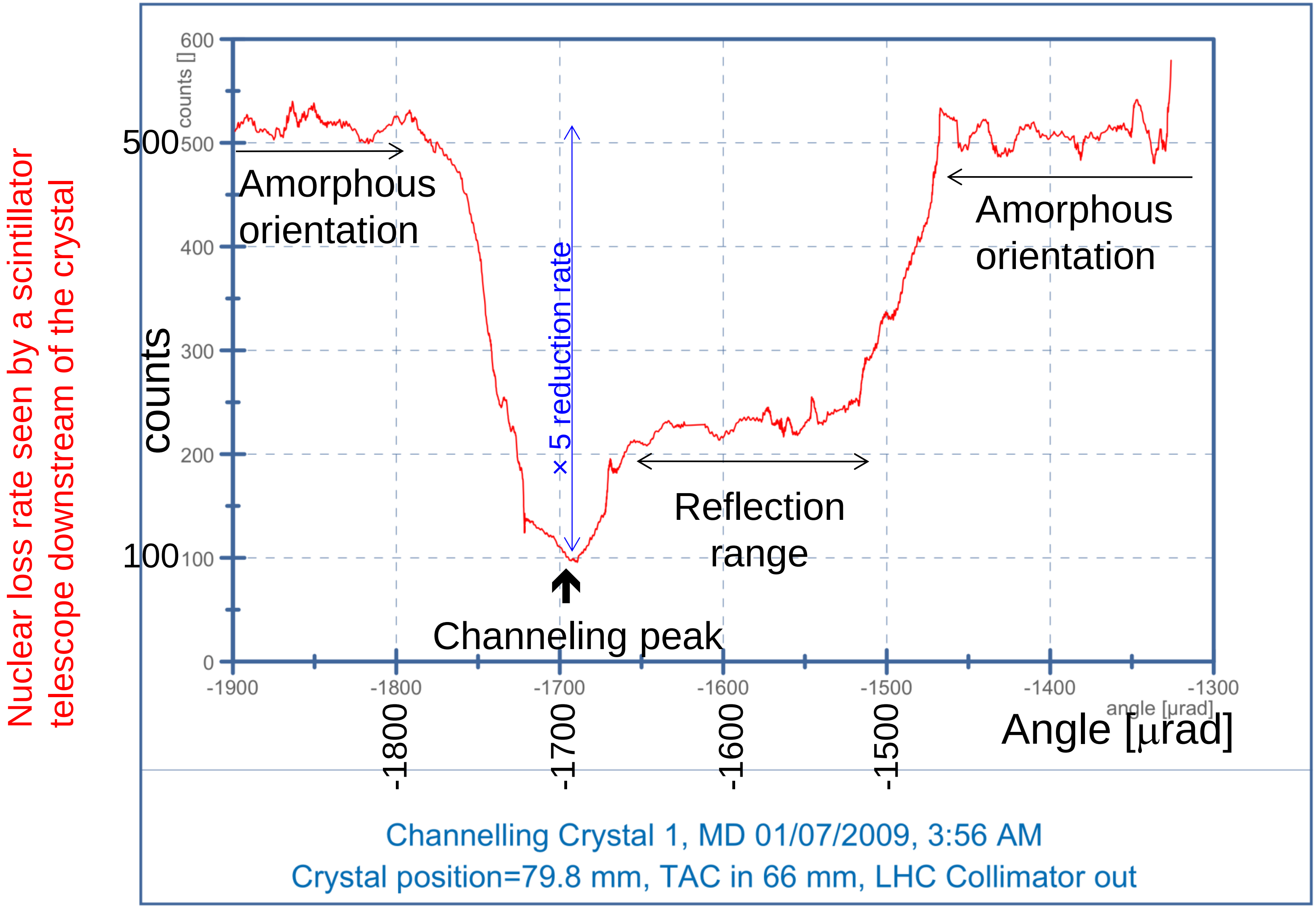
thermal vibrations, discreteness of lattice, electrons → **dechanneling** (exponential decrease of channeled protons)

dechanneling length L_0~0.9 m p[TeV/c]

cooling of crystal increases L_0

minimum bending radius for channeling **R_c~0.4 p [TeV/c] meter**

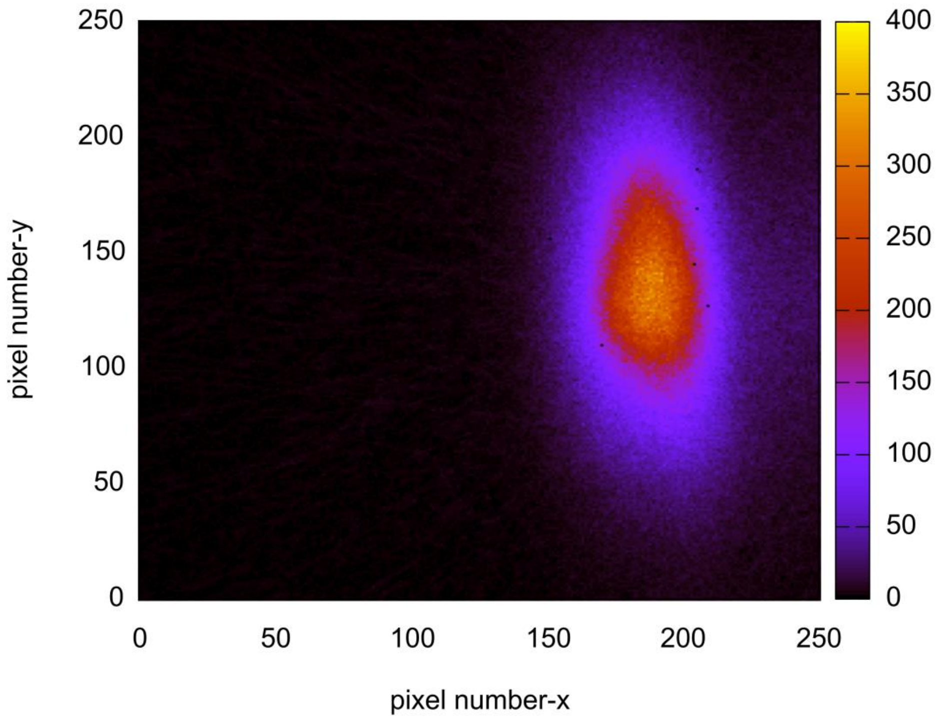
crystal extraction experiment UA9 at SPS (2009)

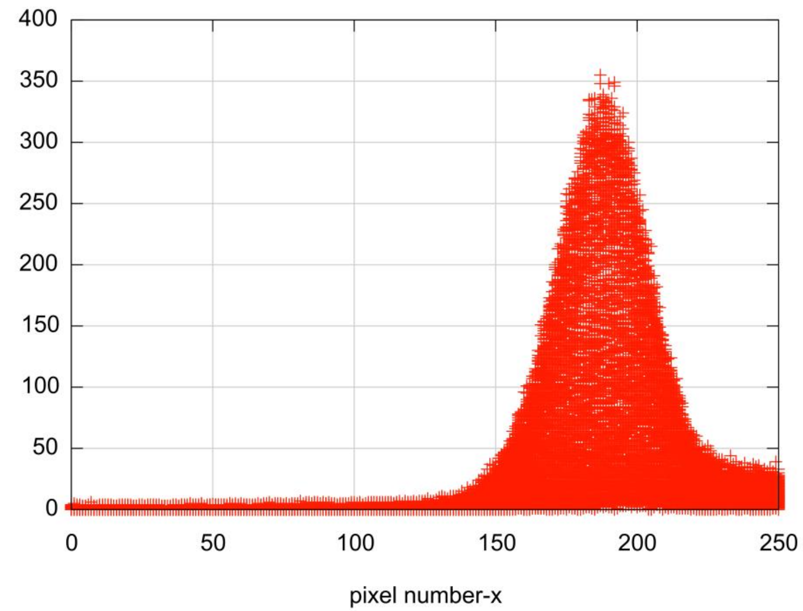


- *Nuclear loss rate* (including diffractive) strongly depressed

W. Scandale

profile of "beam" deflected by crystal

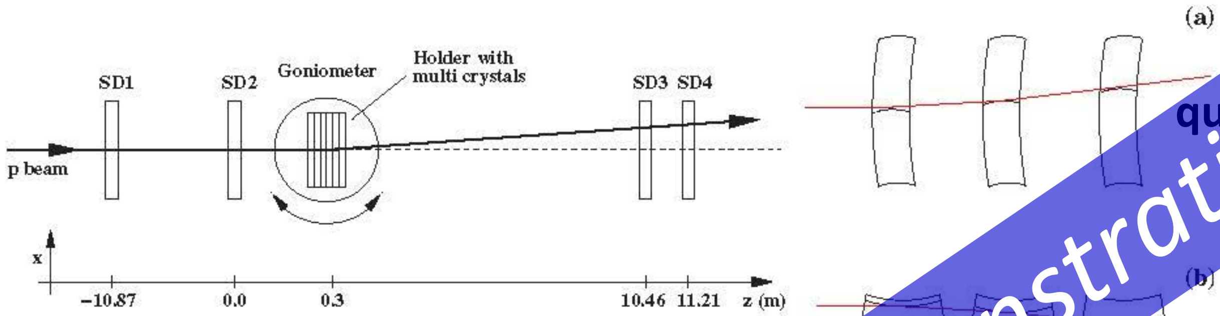




- 256×256 square pixels
- 1 pixel size = 55 μm
- 1 frame integration time 1 s

W. Scandale

staging of crystal deflectors

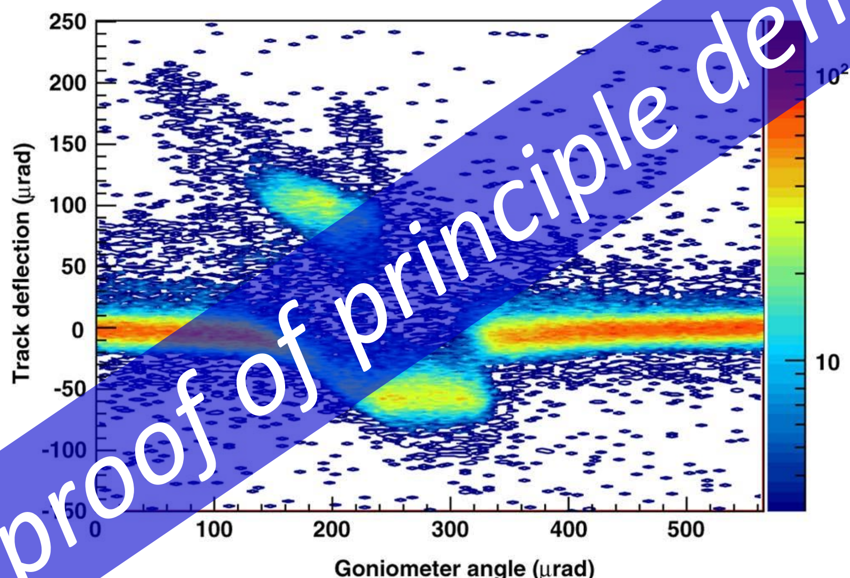


quasimosaic

strip crystals

schematic layout of the experimental setup used to study multiple volume reflection at the H8 beam line of the CERN SPS

proof of principle demonstration!



6 strip crystals in series (each 2 mm long): **400 GeV/*c* protons reflected by 40±2 μrad** [effective field **16 T**] with **efficiency 0.93±0.04**

W. Scandale et al, Observation of Multiple Volume Reflection of Ultrarelativistic Protons by a Sequence of Several Bent Silicon Crystals, Phys.Rev.Lett. 102 (2009) 084801

crystal channeling efficiency

for single crystal traversal: **present deflection efficiency >0.8-0.9 t.b.c.w. 1990’s : 0.1-0.2**

gain in deflection probability over last decades:

- now short crystals bent with constant curvature (anticlastic bending); crystal length in the 1990’s was 5 cm or more and now it is 5 mm or less

multi-reflection / multi-strip crystal - drawbacks:

1. difficult to produce a multi-crystal with coherent reflections (alignment imperfections)
2. for high energy the multi-crystal length should be large
   – large production of diffractive protons !
3. larger radiation damage of the crystal (larger ionization energy deposition again because of longer paths)

W. Scandale

radiation damping in ideal crystal

transverse radiation damping

- independent of particle energy!

no quantum excitation

decay to transverse ground state

minimum beam emittance: $\gamma\varepsilon_{min} = \hbar/2mc$

limited only by the uncertainty principle

particle can be accelerated along focusing channel in its ground state without any energy loss

Z.Huang, P.Chen, R.D.Ruth, Radiation reaction in a continuous focusing channel, Phys.Rev.Lett. 74 (1995) 1759-1762

crystal accelerators

acceleration in crystal channels

G≈ 10 TV/m (n_0 [10^{22} cm^{-3}])$^{1/2}$; n_0 ≈10^{22}-10^{23} cm^{-3}

driven by x-ray laser

now/soon available!
LCLS, Spring-8, XFEL, SwissFEL …

<u>max. energy</u> set by radiation emission due to betatron oscillations between crystal planes, excited by multiple scattering off channel e^-

E_{max} ≈300 GeV for e^+, 10^4 TeV μ, 10^6 TeV for p ?!

Chen & Noble 1997; Dodin & Fisch 2008; Shiltsev '12

10 TV/m – disposable crystal accelerator

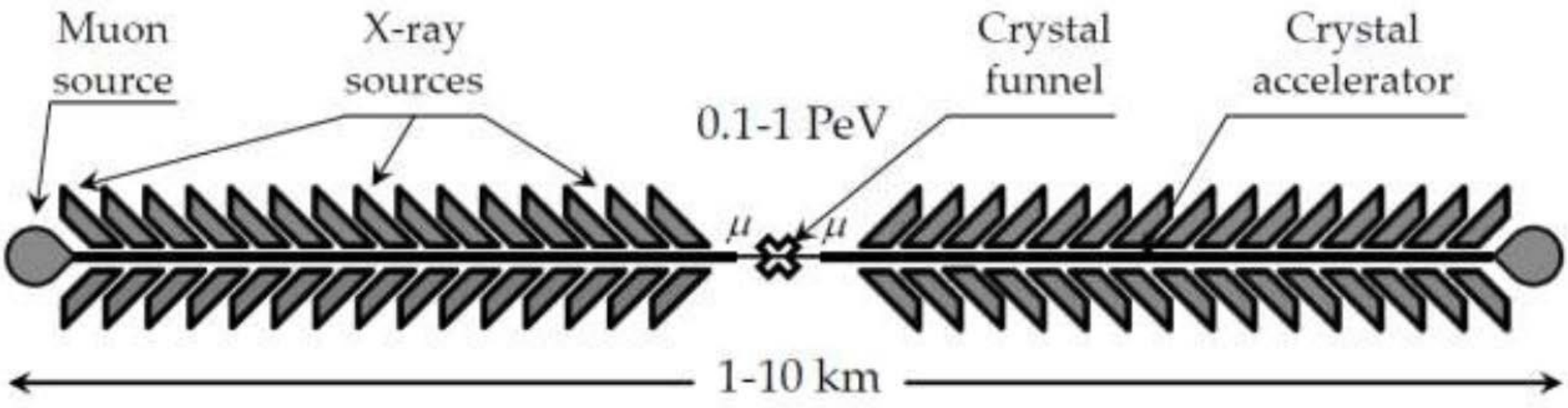
or 0.1 TV/m – reusable crystal accelerator

side injection of x-ray pulses using long fibers

$e^{\pm}$ may soon run out of steam in the high-gradient world!

→ need to change particle type

linear X-ray crystal μ collider

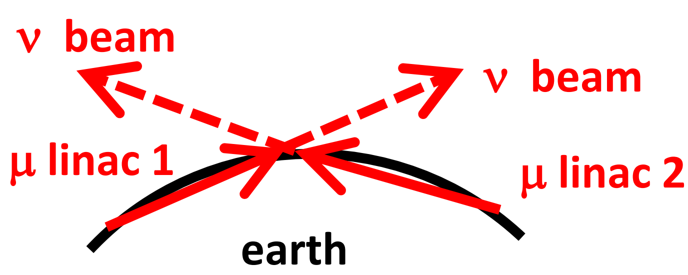


Vladimir Shiltsev, 2012

issues:

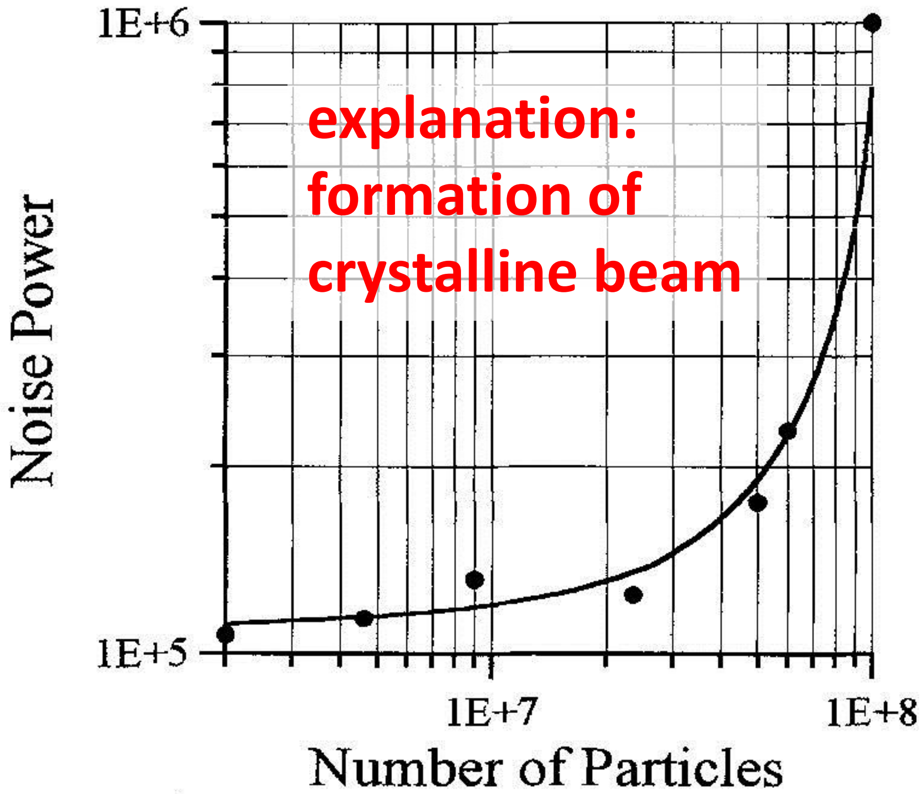
μ production rate

neutrino radiation



crystalline beams

e-cooled *p* beam at BINP NAP-M, 1980



$$\sigma^2 = \frac{{\sigma_0}^2}{1 - N/N_{th}}$$

$$\sigma_0 = 1.4x10^{-6}$$
$$N_{th} = 1.2x10^8$$

Schottky noise power vs number of particles in the beam (*N*)

E.N. Dementiev et al., Sov. J. Tech. Phys. 50 (1980) 1717.
V.V. Parkhomchuk and D.V. Pestrikov, Sov. J. Tech. Phys. 50 (1980) 1411.
D. Pestrikov, NIM A 379, 1996

theoretical studies:

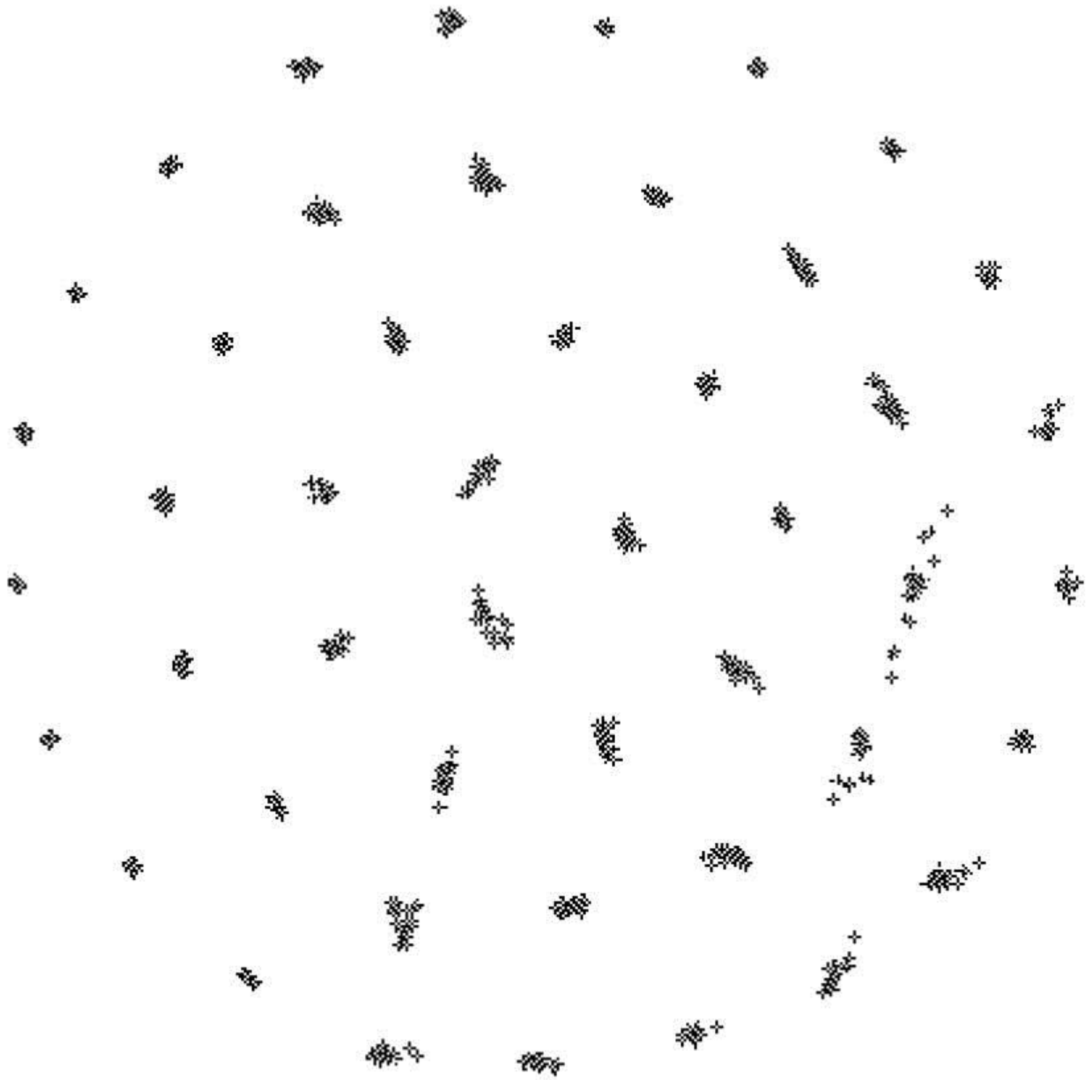
constant gradient rings, alternating focusing, effect of bending-magnets shear… :

A. Rahman and J.P. Schiffer, Phys. Rev. Letts. 57, 1133 (1986);
R.W. Hasse and J.P. Schiffer Annals, of Physics 203, 419 (1990).
J. Wei, T.P. Li, and A. Sessler, Phys. Rev. Letts. 73, 3089 (1994).

increasing beam density:

1-D crystal → 2-D crystal → 3-D crystal

molecular dynamics simulations



J.P. Schiffer
IEEE 1996

projection onto *x*-*y* plane with strong continuous cooling

experiments on crystalline beams

J. S. Hangst et al., Phys. Rev. Letts. 67, 1238 (1991).

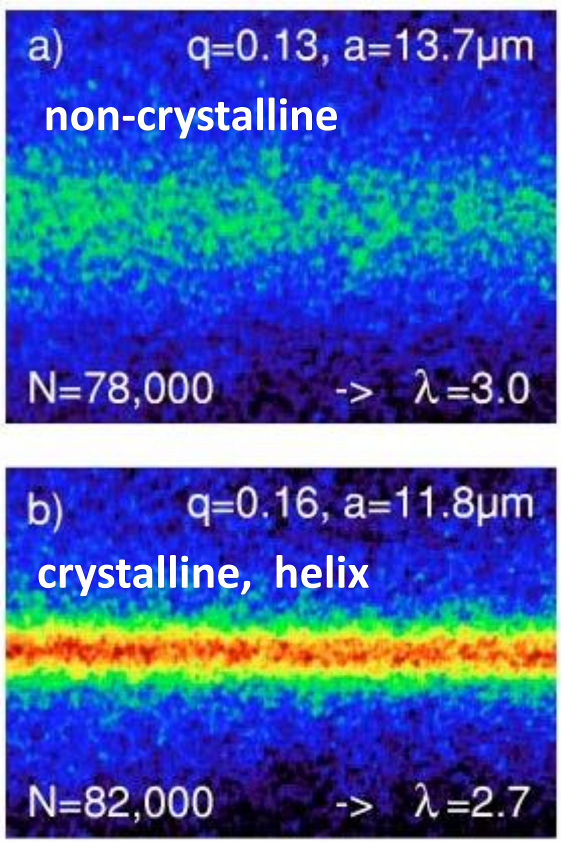
BINP NAP-M, e-cooling

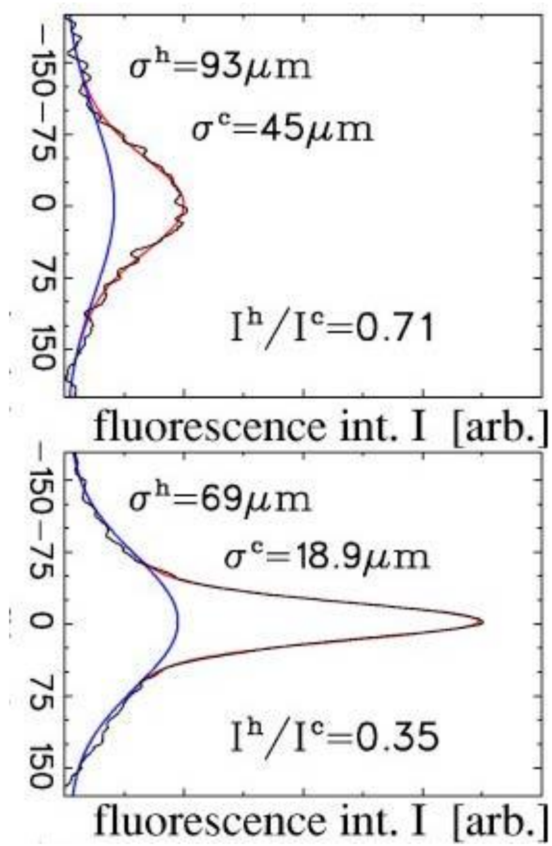
TSR Heidelberg, laser cooling, < 1 K

ASTRID Arhus, laser cooling Laser , ~mK

PALLAS, LMU Munich

U. Schramm et al, PRE 66 (2002)





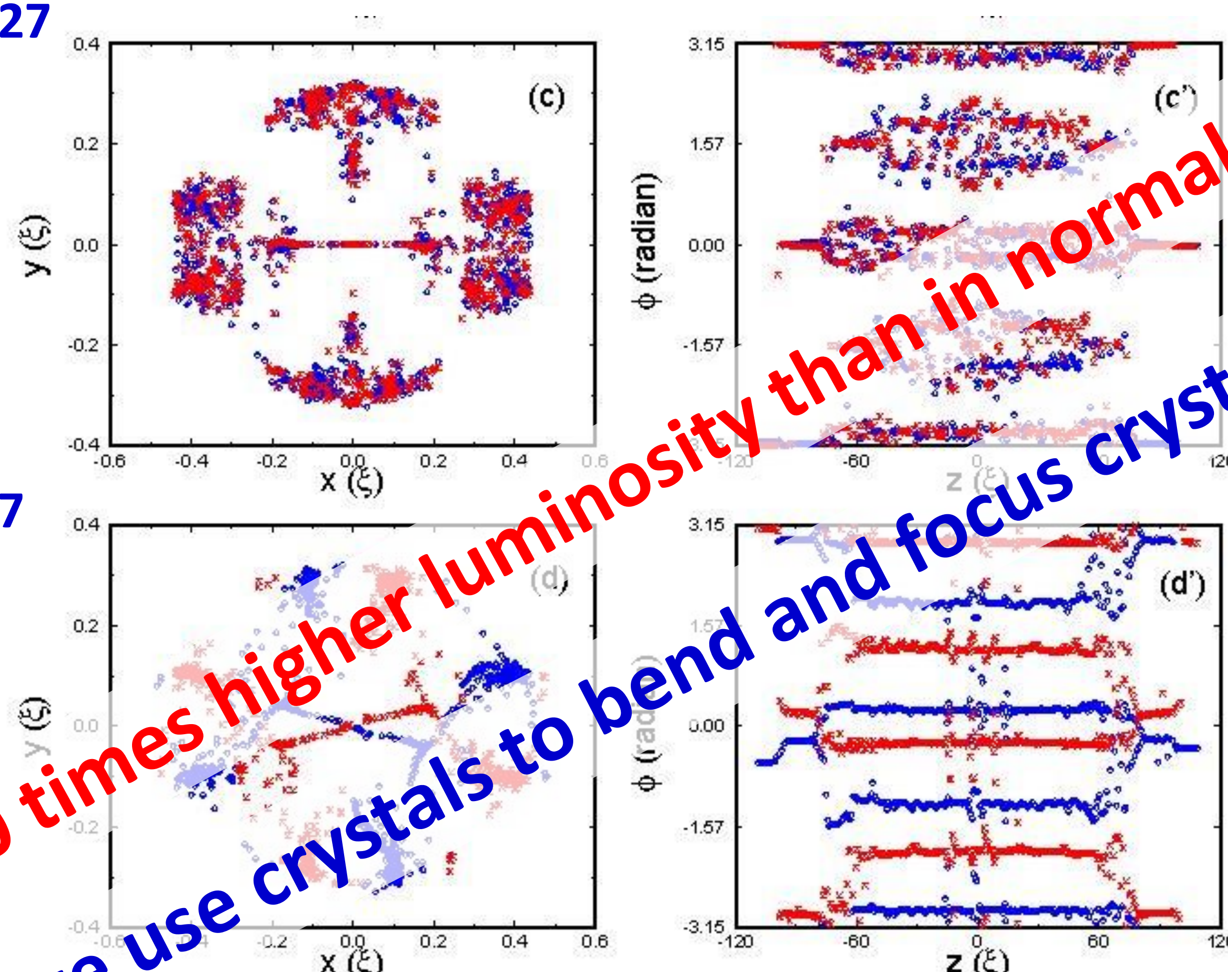
higher line density

lower line density

colliding crystalline beams

ΔQ_{bb}=0.27

ΔQ_{bb}=2.7



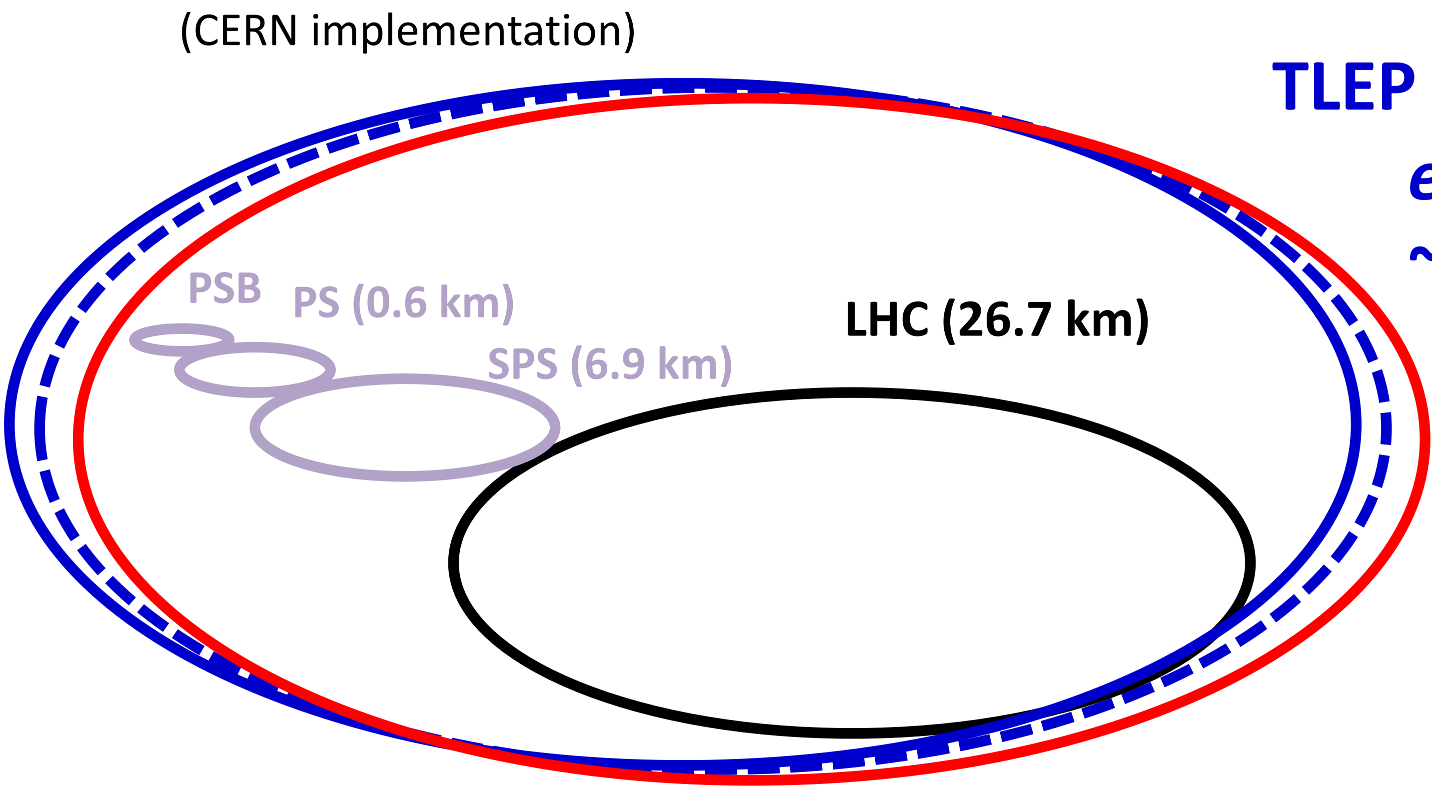
100 times higher luminosity than in normal colliders!

can we use crystals to bend and focus crystalline beams?

MD simulations showing formation of crystalline ground states with 1000 macro-particles / beam

J. Wei, A. Sessler, Colliding Crystalline Beams, BNL-65137, 1998

possible long-term strategy



TLEP (80-100 km, *e*⁺*e*⁻, up to ~350 GeV c.m.)

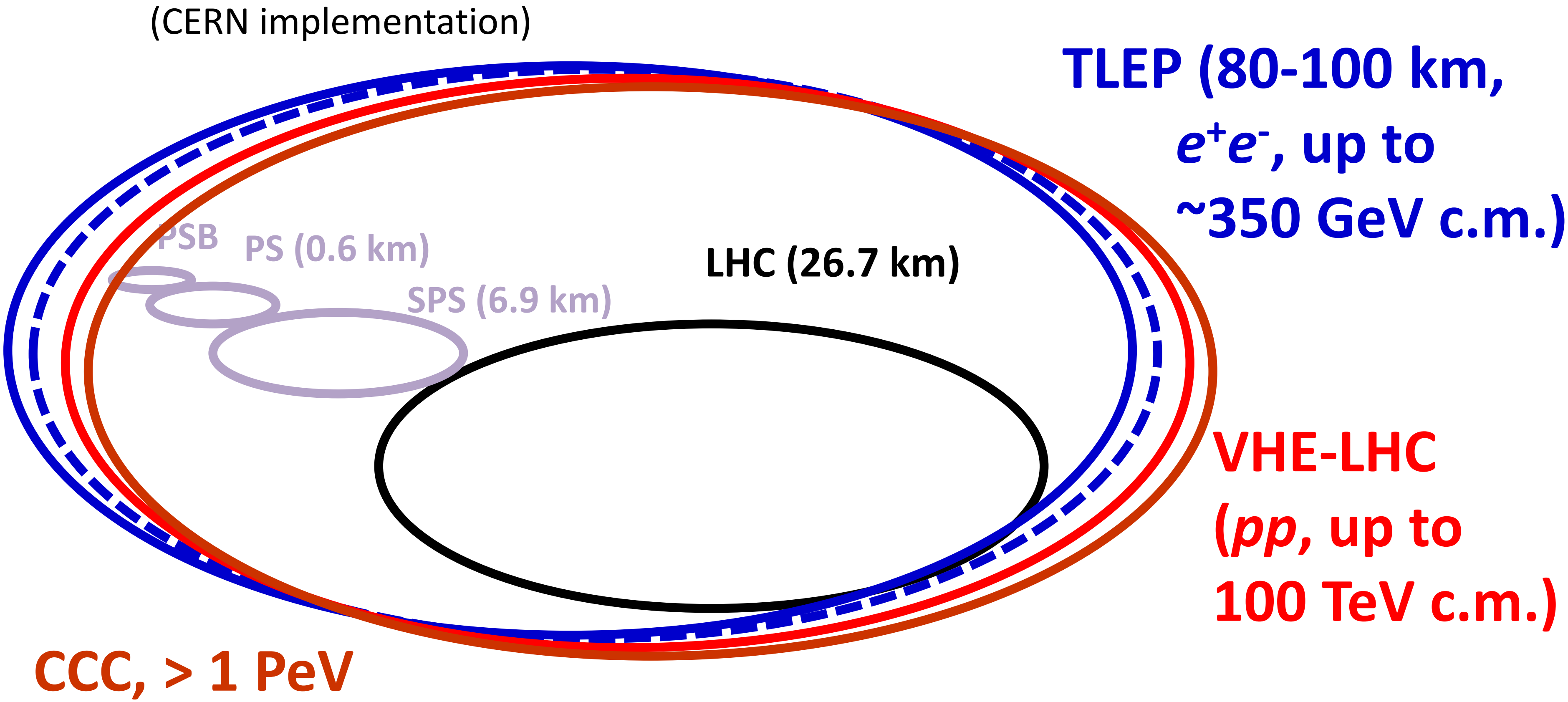
VHE-LHC (*pp*, up to 100 TeV c.m.)

& ***e***$^{\pm}$ **(120 GeV) – *p* (7, 16 & 50 TeV)** collisions (**[(V)HE-]TLHeC**)

≥50 years of *e*⁺*e*⁻, *pp*, *ep/A* physics at highest energies

100 TeV *pp* collider may not be enough ?!? (D. Schulte)

possible longer-term strategy

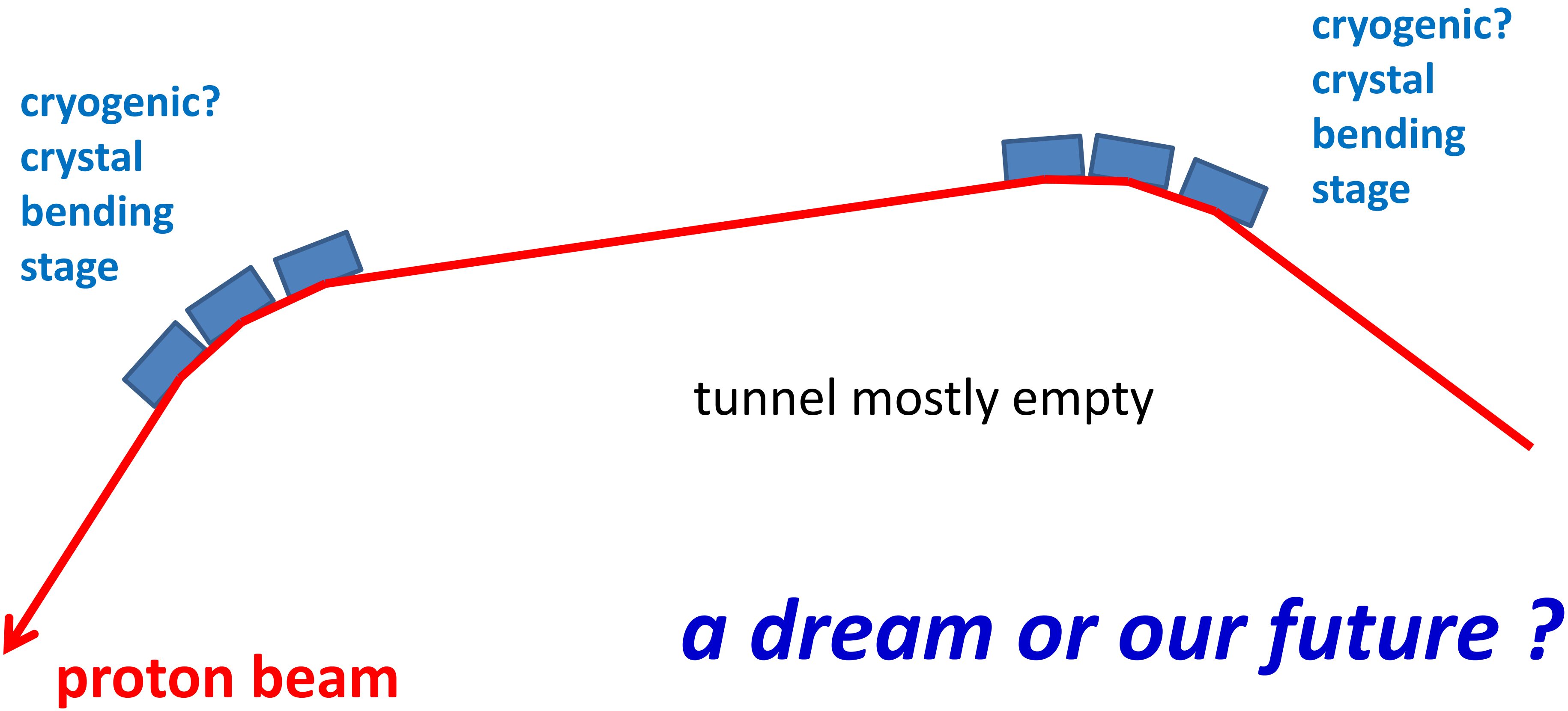


& $e^{\pm}$ **(120 GeV) – *p* (7, 16 & 50 TeV)** collisions **([(V)HE-]TLHeC)**

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

followed by >1 PeV circular crystal collider (CCC)?!?

circular crystal collider?

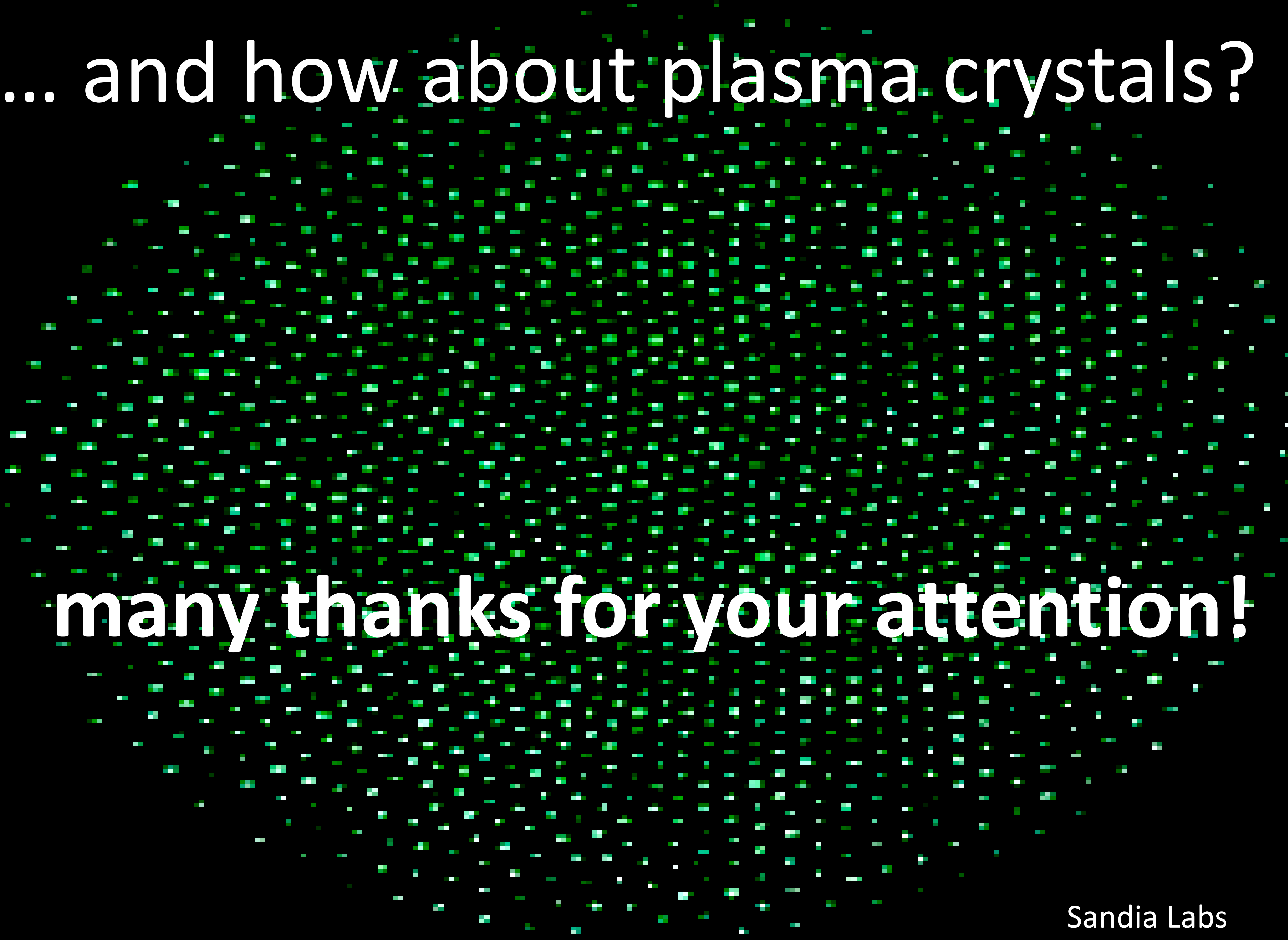


energy ramp using induction acceleration?

conclusions

- **plasmas & crystals demonstrate large focusing forces, 10^3-10^4x stronger than SC quadrupoles**
- they could also provide large **dipole field**; so far bending fields of **5-100 T** demonstrated
- **beam-matter interaction & efficiency** are the critical issues for circular ring applications
- straightforward **use in single-pass systems**
- **incentive to strengthen crystal R&D!**

… and how about plasma crystals?



many thanks for your attention!

Sandia Labs