Plasma Wakefield Accelerator-Based Low Emittance Muon Source

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AAC’22

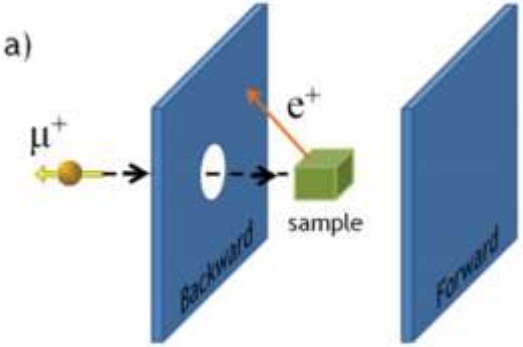
Promise of Muons

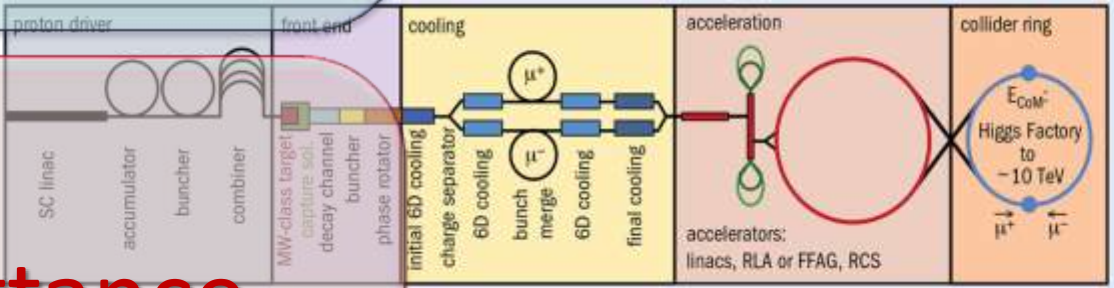
- μSR for solid state research
- Screening NNSA/DARPA applications
- g-2 and mu2e experiments

Intensity is the key

- Circular muon colliders
- Linear & crystal muon colliders

Need low emittance and high N





Challenges

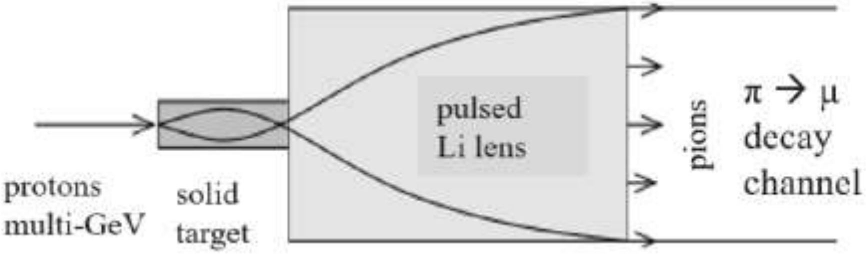
I. Muon are unstable

- 2.2 us → almost no time for collection, cooling and acceleration... all should be superfast

- Muons are secondary/tertiatry
  - Need high intensity primary (depnds on efficiency)
  - Come in large angular spread $\sim m_{muon}/E_{primary}$

Traditional Muon Sources

$$p \rightarrow \text{target} \rightarrow \pi^+(\pi^-) \rightarrow \mu^+(\mu^-)$$



pulsed short-focus Lithium lens

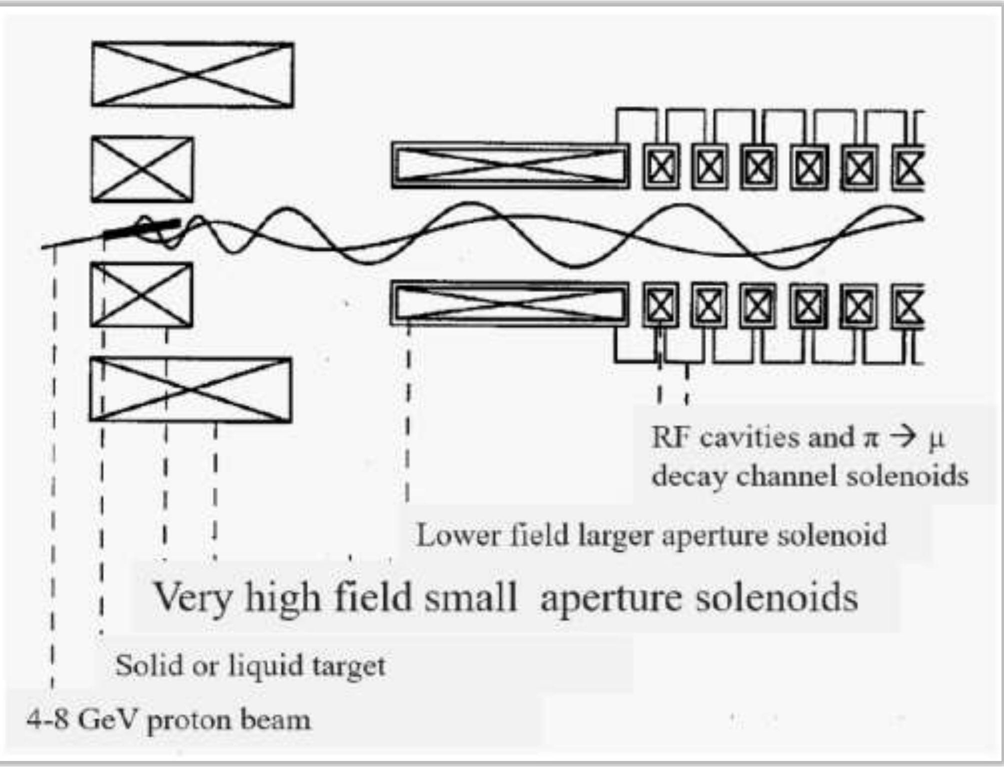
$$\theta \simeq m_\pi / P_\pi$$

FNAL g-2 experiment:

116 kA → 232 T/m

2 GeV *p+* → 3.1 GeV muons

Eff 2e-7 (dE/E ~1%)



O(30 T) target solenoid

Future 10-14 TeV muon collider/MAP:

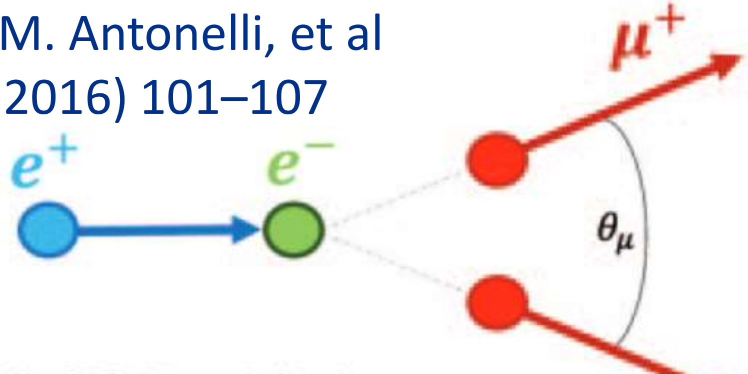
About 0.1 muon/proton

Large emit ~10(-3) rad

Ionization cooling channel ε~25μm

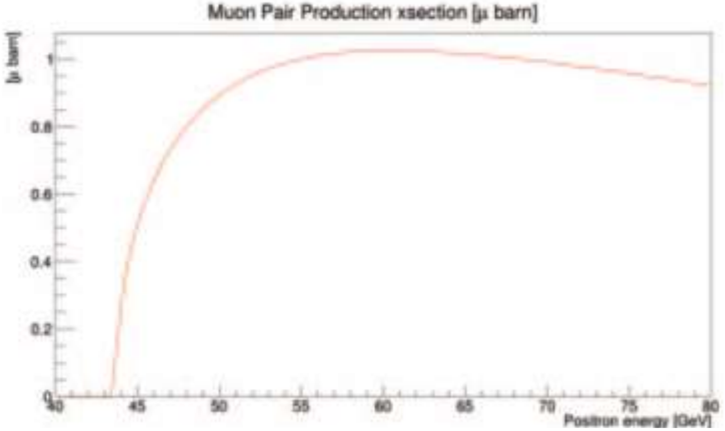
LEMMA

M.Boscolo, M. Antonelli, et al
NIM A ***807*** (2016) 101–107



Low emittance muon pair
at threshold $e^+e^- \rightarrow \mu^+\mu^-$

need 45 GeV positrons



Findings wrt MAP scheme:

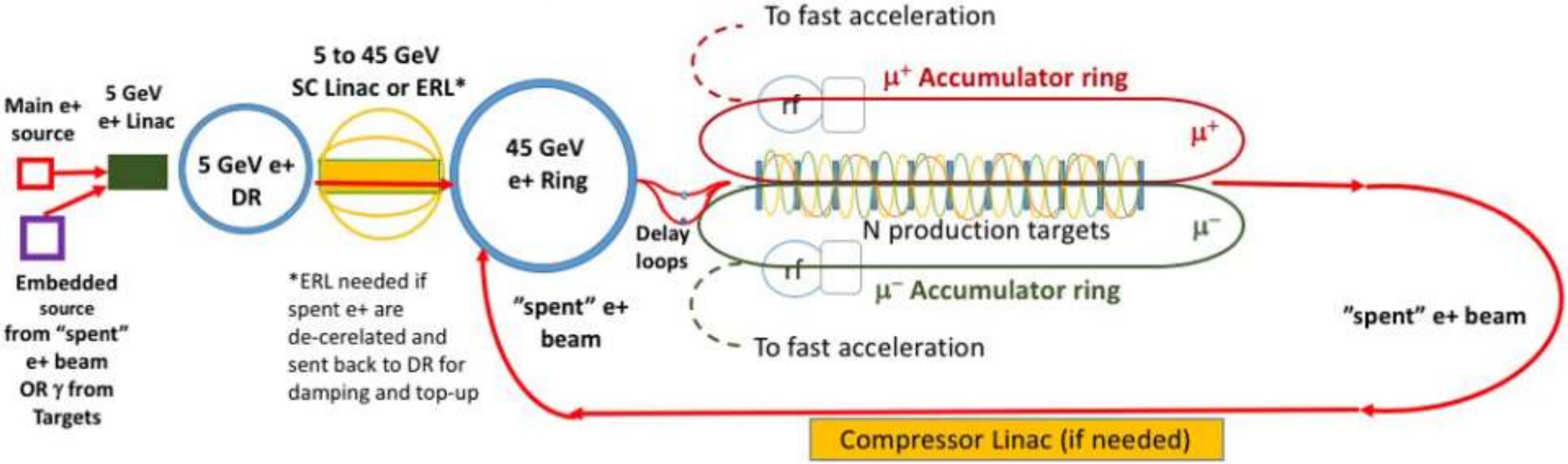
Emittance ~1/500

Intensity ~1/10,000

Luminosity ~1/1000

Cost +30%, Site power ~x2

D. Neuffer and V. Shiltsev 2018 *JINST* **13** T10003



*ERL needed if spent e+ are de-cerelated and sent back to DR for damping and top-up

Recent Idea

A muon source based on plasma accelerators

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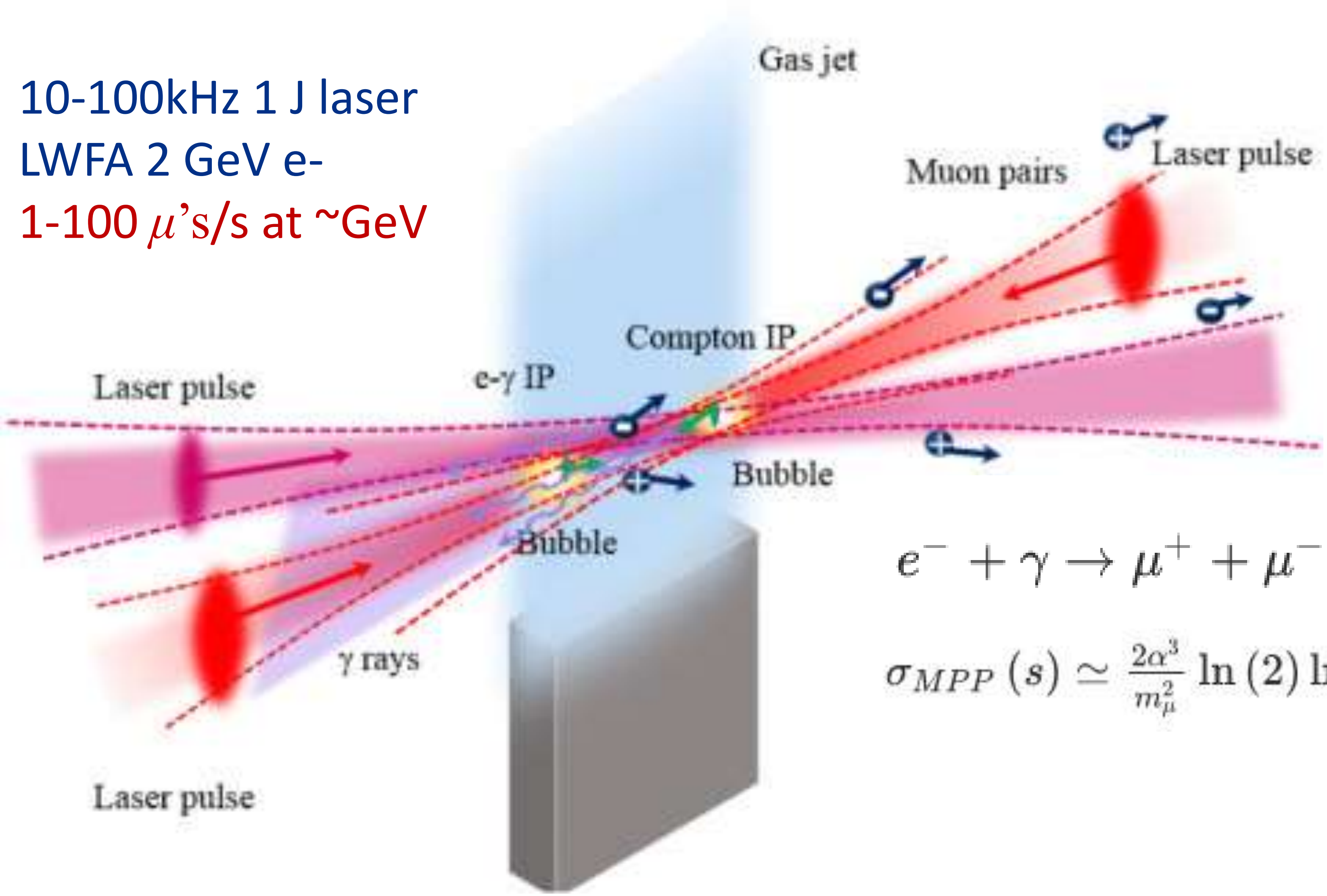
- e-gamma collider source

NIM A **909** (2018) 309–313

10-100kHz 1 J laser
LWFA 2 GeV e-
1-100 μ's/s at ~GeV



$$e^- + \gamma \to \mu^+ + \mu^- + e^-$$

$$\sigma_{MPP}(s) \simeq \frac{2\alpha^3}{m_\mu^2} \ln(2) \ln\left(\frac{s}{m_e^2}\right)$$

New (Another) Approach

I. Employ Plasma-Wakefields (PWA cells)

- They are very strong transversely – can capture lots of muons
- They are very strong longitudinally – very fast acceleration to high $\gamma = E/mc$ and long muon lifetime

II. Presumably compact

EM Fields in Plasma Waves

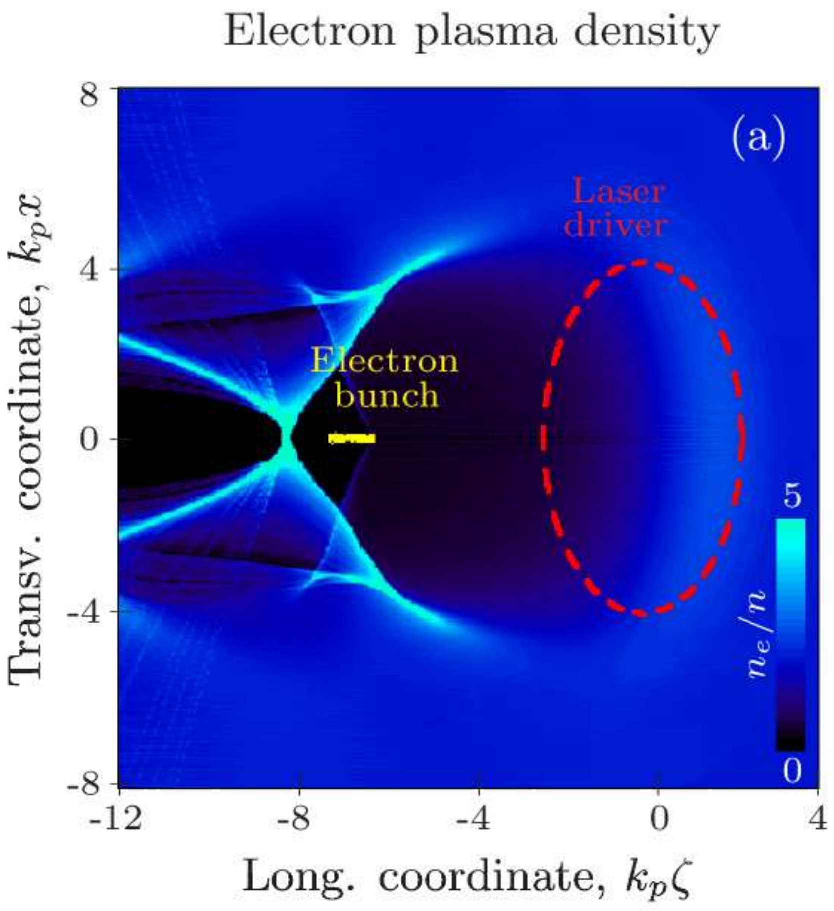
Eg in the bubble regime, forces:

$$F_z = eE_0 k_p \zeta / 2$$

$$F_r = e(E_r - B_\theta) = -eE_0 k_p r / 2$$

where

$$E_0 = mc^2 k_p / e, \text{ or } E_0[\text{V/m}] \approx 96(n[\text{cm}^{-3}])^{1/2}$$

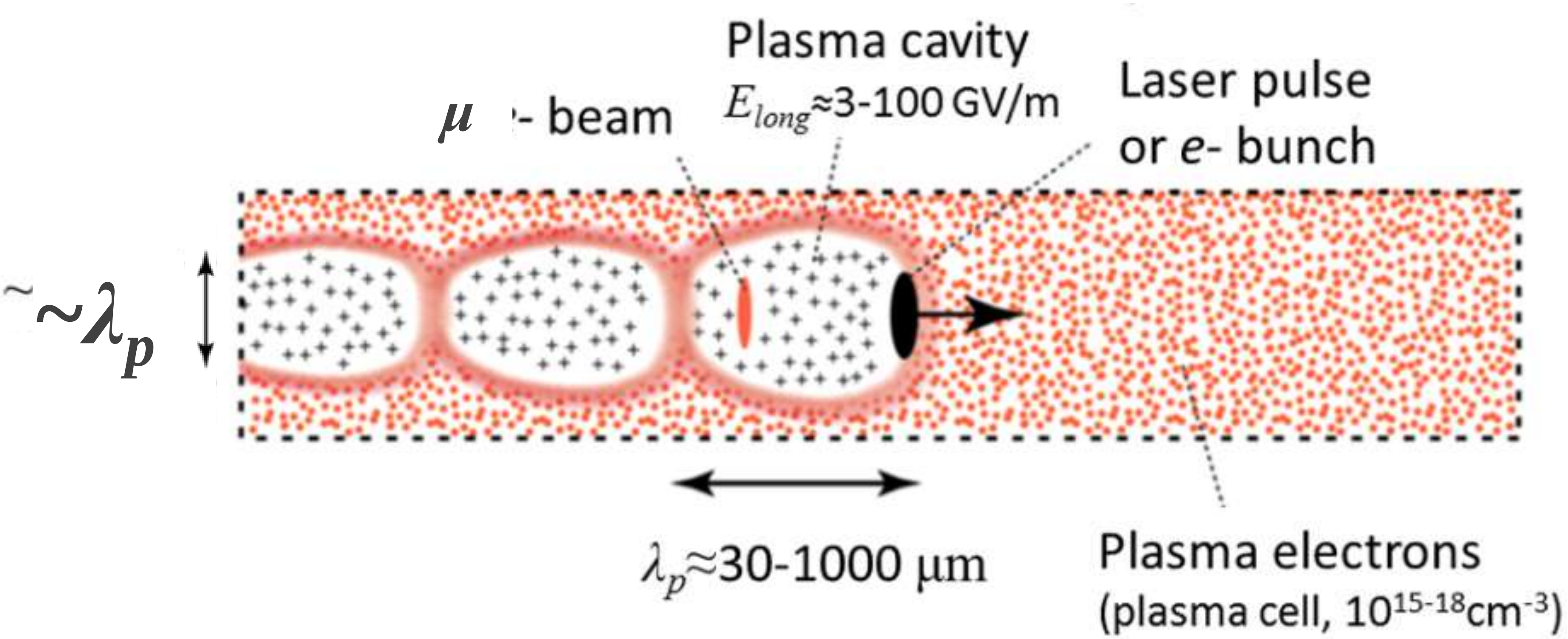


That's exactly what's needed for a muon source

Conceptual Scheme

- **Muons are born in the plasma WFA channel**
  - Either via photoproduction (need *O*(1+ GeV) *e*- beam)
  - Or via pion decay
- Muons originally have large angular spread and small transverse dimension:
  - $\theta \approx m_\mu / E_\mu$
  - r smaller than the radius of the bubble $\sim 3/k_p = \lambda_p/2$
- Muons get quickly accelerated in the plasma while being super-strongly focused by the focusing fields of the plasma:
  - Come out with small emittance
  - Come out with very high energy *O*(10 GeV)

Plasma WFA Muon Source Concept



$$\lambda_p = c/\omega_p \approx 1\ \mathrm{mm} \times \sqrt{10^{15}\ \mathrm{cm}^{-3}/n_0}$$

Generation of Muons: Two Schemes

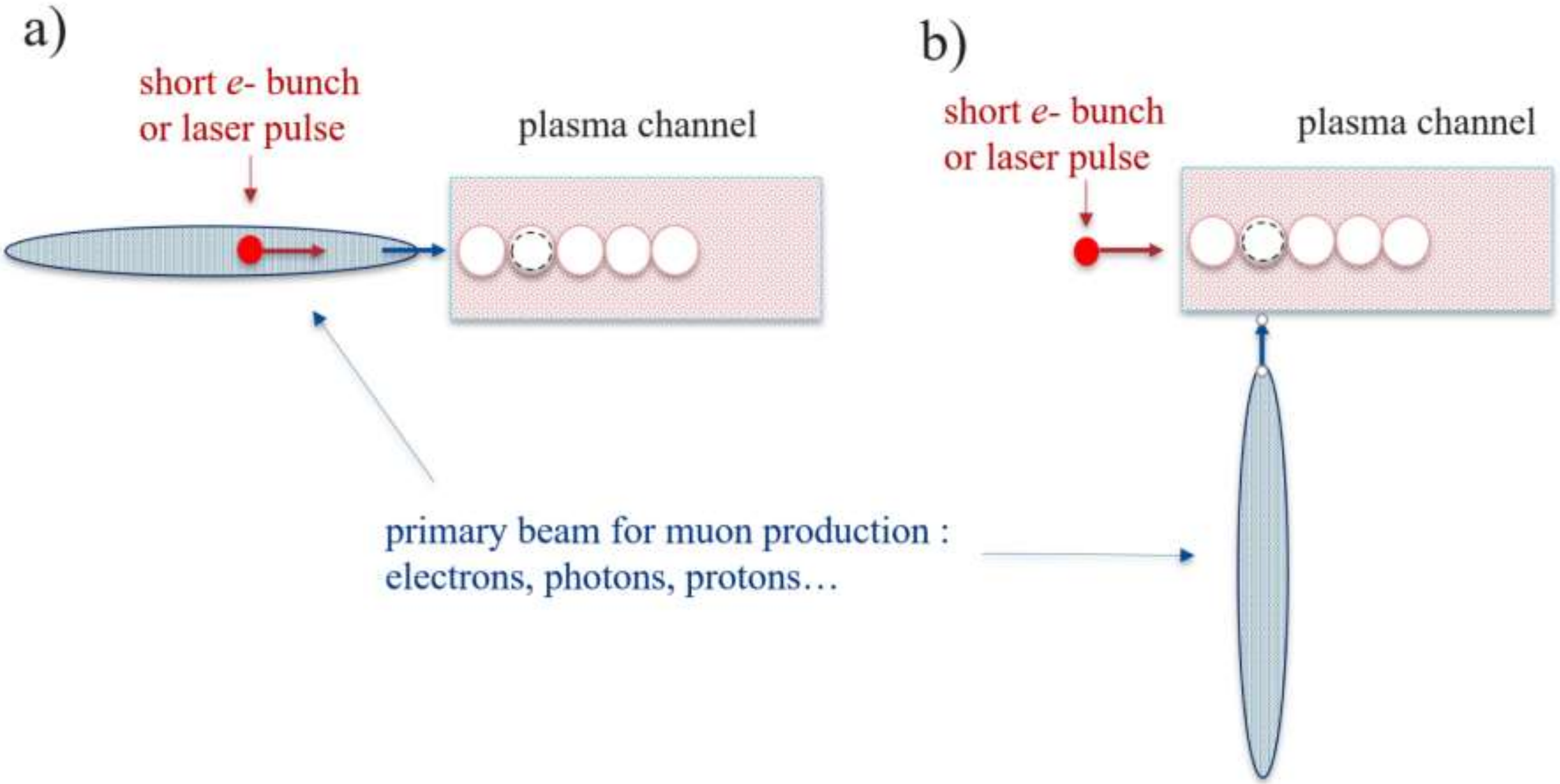


Figure 3. Muon PWA source: possible schemes for simultaneous injection of plasma wakefield drivers (laser pulses or short electron bunches) and primary beams needed for muon generation: a) collinear; b) orthogonal. Muons are produced in interaction of the primary beam with plasma, or, if suitable, with specially arranged dedicated target at the intersection of the beam with the plasma channel — see dashed circle.

Equations of Motion

$$\frac{dp_z}{dt} = F_z$$

$$\gamma_\mu = 1 + z\kappa e E_0 / m_\mu c^2 \approx z\kappa k_p (m_e / m_\mu)$$

$$\frac{dp_r}{dt} = m_\mu c^2 \frac{d}{dz}\left(\gamma_\mu(z)\frac{dr}{dz}\right) = -eE_0 \frac{k_p r}{2}$$

$$r(z) = c_1 J_0\left(2\sqrt{\frac{z\pi}{\kappa\lambda_p}}\right) + c_2 Y_0\left(2\sqrt{\frac{z\pi}{\kappa\lambda_p}}\right)$$

The betatron motion is fast

$$\beta_\mu = 1/k_\mu \approx \lambda_p \sqrt{2\gamma\mu m_\mu / m_e}$$

So the amplitude drops adiabatically

$$|r| \approx r_{\max}\sqrt{\beta_\mu/\gamma_\mu} \propto r_{\max}/\gamma_\mu^{1/4}$$

Equations on Emittance

$$r_{\max} \simeq \lambda_p/2$$

Max amplitude and angular spread define max acceptable emittance

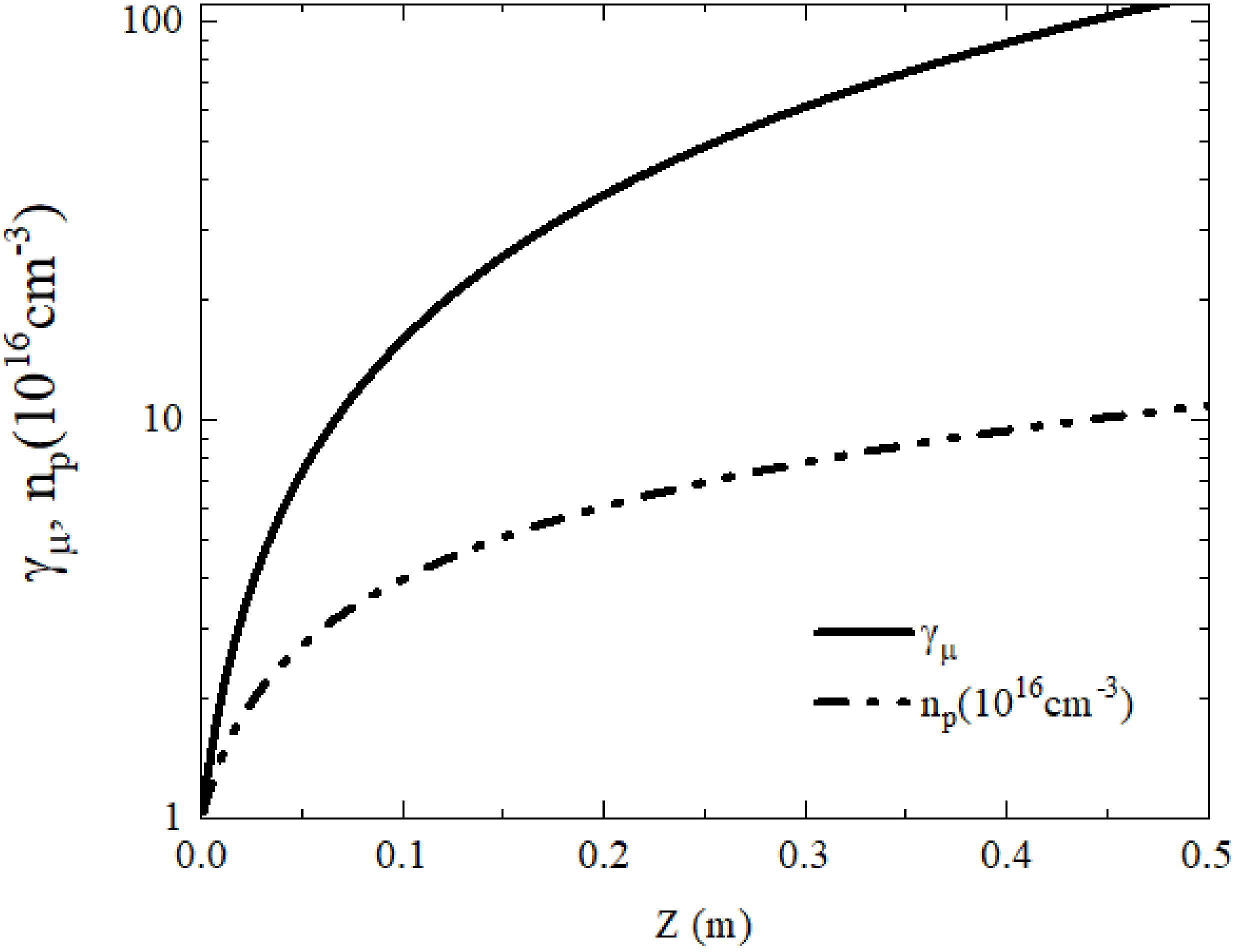
$$\theta_{\max} = r_{\max}/\beta_\mu = \pi\sqrt{\frac{m_e}{2\gamma_\mu m_\mu}} \approx \frac{0.15}{\sqrt{\gamma_\mu}}$$

$$\epsilon_\mu^{\max} = \gamma_\mu \theta_{\max} r_{\max} = \lambda_p \gamma_\mu^{1/4}\sqrt{\frac{m_e \pi^2}{8 m_\mu}} \approx 0.078\lambda_p$$

Assuming at birth γ~1, if max accepted emittance is ε~25 μm for n=10^16 cm-3 , in that case the length of a 10 GeV source is about 1 m For denser plasma n=10^18 cm-3 the max accepted emittance is ε~2.5 μm and 10 GeV source is about 10 cm.

Plasma density rampup can make the source shorter without loss of the acceptance (see next slide)

Tapered Plasma Density Rampup



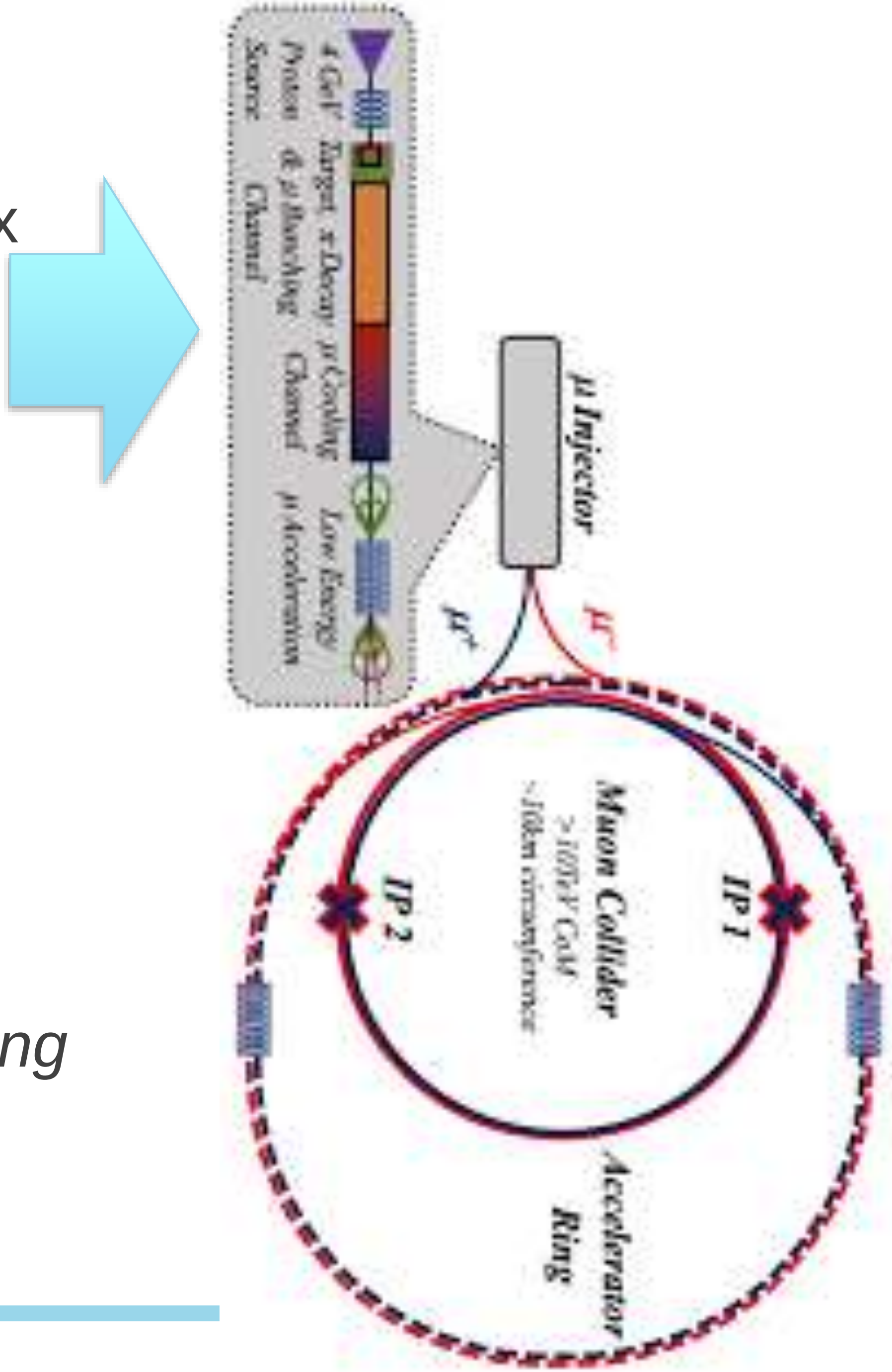
$$\gamma_p \approx (1+az)^{4/3}$$

$$n_p = n_0\,(1+az)^{2/3}$$

Plasma density and muon energy in tapered PWA-based 10 GeV muon source with normalized acceptance of 25 µm - corresponding to $\lambda_p^0 = 0.33\,\mathrm{mm}$ and $n_p^0 = 10^{16}\,\mathrm{cm}^{-3}$[b]

PWA μ Source MC

- May eliminate the most complex muon production and early acceleration part of multi-TeV muon colliders
- Very compact *O*(1 m) total
- *O*(10 GeV) beams with norm. emittance from few to tens μm
- Very large energy and angle acceptance
- *(solves so many problems of traditional muon ionization cooling scheme – from scattering and struggling to massive hardware needs, magnets and RF)*

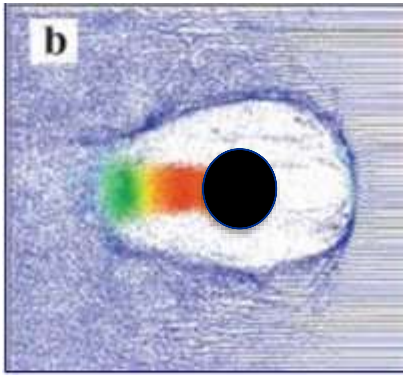


BUT : Challenges and Open Questions (1)

- Acceleration and focusing of $\mu+$ as challenging as for positrons in “traditional” LPWA and PWFA
- Collider application requires both small emittances and high intensity (ie brightness) μ beams – very hard, see next slide
- Plasma wakes are essentially low-*Q*, so only few plasma periods/bubbles can be employed → few short μ bunches
- Bubble wake will be loaded by secondaries (*e*+*e*-, pions, etc)

Muon Generation Challenges – Possible Schemes

- Photoproduction: need multi-GeV *e-* beam, BH cross-section is *1/m*$_\mu$*^2* small, *O*(1μ /pulse), wake loading by *e+e-* pairs… solid target in the bubble?



Can solid density object be inserted in the bubble?

- e+e- annihilation: even small cross-section
- Proton-nucleon: need 1-10 GeV protons, cross section is very high, but plasma density is low and pions need ~8 m to decay (in the wake)
- Prompt muons: either *D* or require *O*(100-100) GeV *p+,* cross-section is high *O*($\pi^0 \rightarrow \gamma\gamma$ t plasma density is low
- External injection: sub-mm short intense muon bunches!!!

Conclusions:

- Fast acceleration and strong focusing in plasma wakefields allow compact *O*(10 cm) 10 GeV muon source
- If muons produced inside the bubble, then captured emittance is about $\approx 0.078\lambda_p$
- Difficulties (so far) : a) probably does not work for $\mu+$ b) muon generation schemes do not promise decent intensities (other schemes?); c) bubble wake will be loaded by secondaries
- (The only practical application might be) injection of mmxmmxmm muon bunches in the plasma WFA channel

Muons are the Particles of the Future!

Thanks for your attention!

- Special thanks to
  - *Philippe Piot for inviting me to submit this work to ICFA BD Newsletter 83 (JINST)*
  - *WG5 conveners for inviting me*
- … see JINST Technical Report publication :

https://iopscience.iop.org/article/10.1088/1748-0221/17/05/T05010/meta

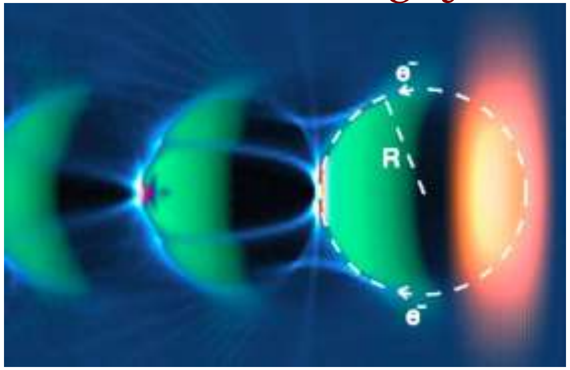
Back up slides

Linear *e+e-* Colliders

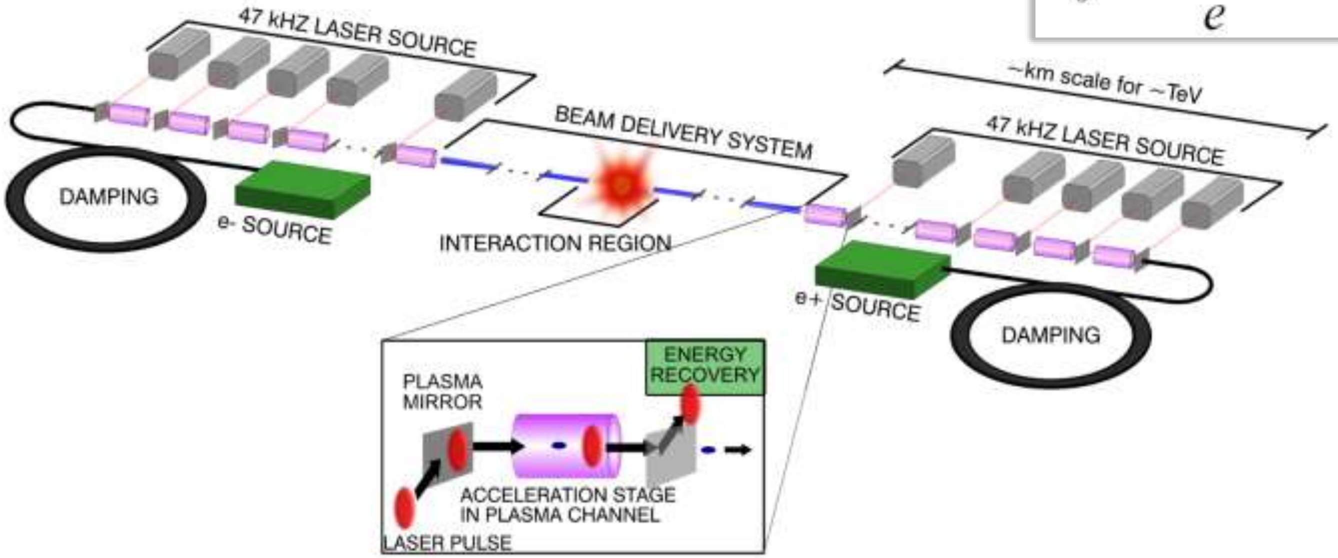
- Either RF acceleration (50-200 MeV/m) or → wake-field acceleration in plasma (2-5 GeV/m) →
- Major limitations:
  - 100% energy spread at IP (beamstrahlung)
  - One-time collisions ineffective → *Lumi ~P/(Eσ)*
  - Very long/complex *Final Focus* to get nm IP size
  - Extreme sensitivity to nm jitters of linac elements
  - In plasma – ultra-strong focusing hurts staging, impossible(?) to accelerate positrons

15 TeV *e+e-*
100+ km
10-15 km

Plasma sustains high fields



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

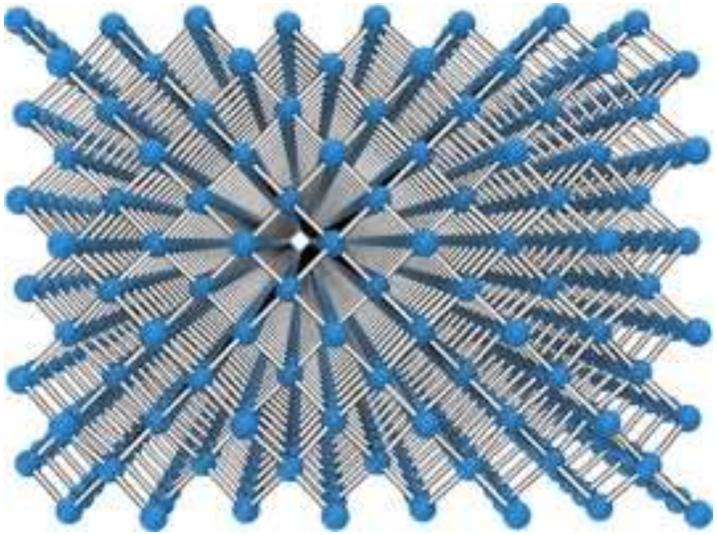


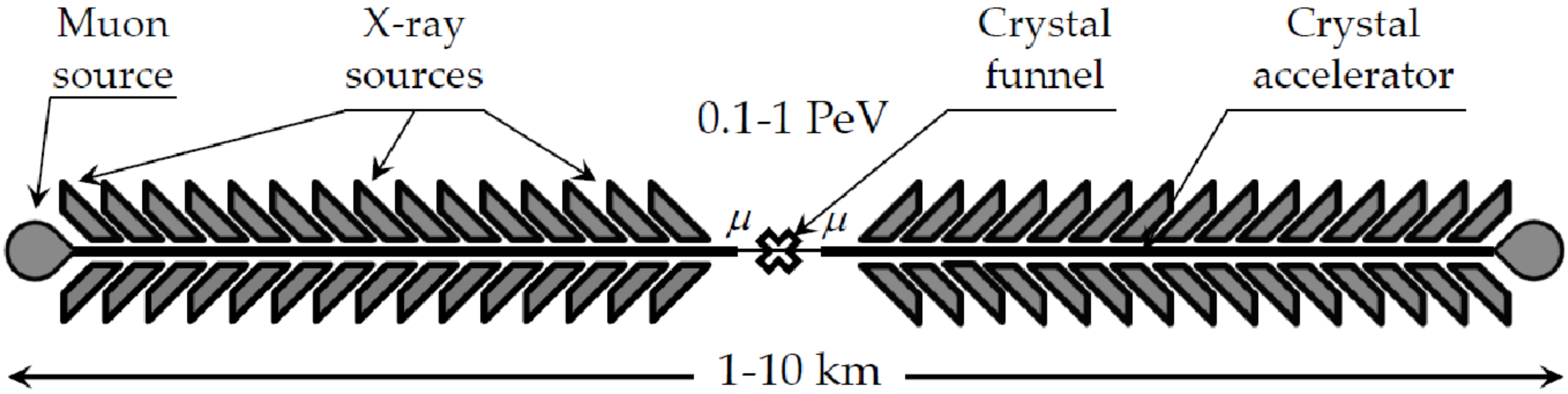
Takes about 1 GW electic power even for 15 TeV

Exotic Colliders

$$E\,[\mathrm{GV/m}] \approx 100\sqrt{n_0\,[10^{18}\,\mathrm{cm^{-3}}]}$$

- Plasma-wakefield acceleration **and** channeling in structured media, eg CNTs or crystals (***only muons!!!***)
- Major advantages:
  - solid density → 1-10 TV/m gradients
  - continuous focusing and acceleration (no cells, one long channel, particles get strongly cooled *betatron radiation*)
  - small size promises low cost
- *Lumi ~1/E*^{2} …totally unproven yet concept:
  - proof-of-principle experiment *E336* @ SLAC





Xtal Collider

$n \sim 10^{22}\ \mathrm{cm}^{-3}$, **10 TeV/m** → 1 PeV = 1000 TeV

$n_\mu \sim 1000$, $n_B \sim 100$, $f_{rep} \sim 10^6$ $L \sim 10^{30\text{-}32}$

V.Shiltsev, Phys. Uspekhy 55 965 (2012)