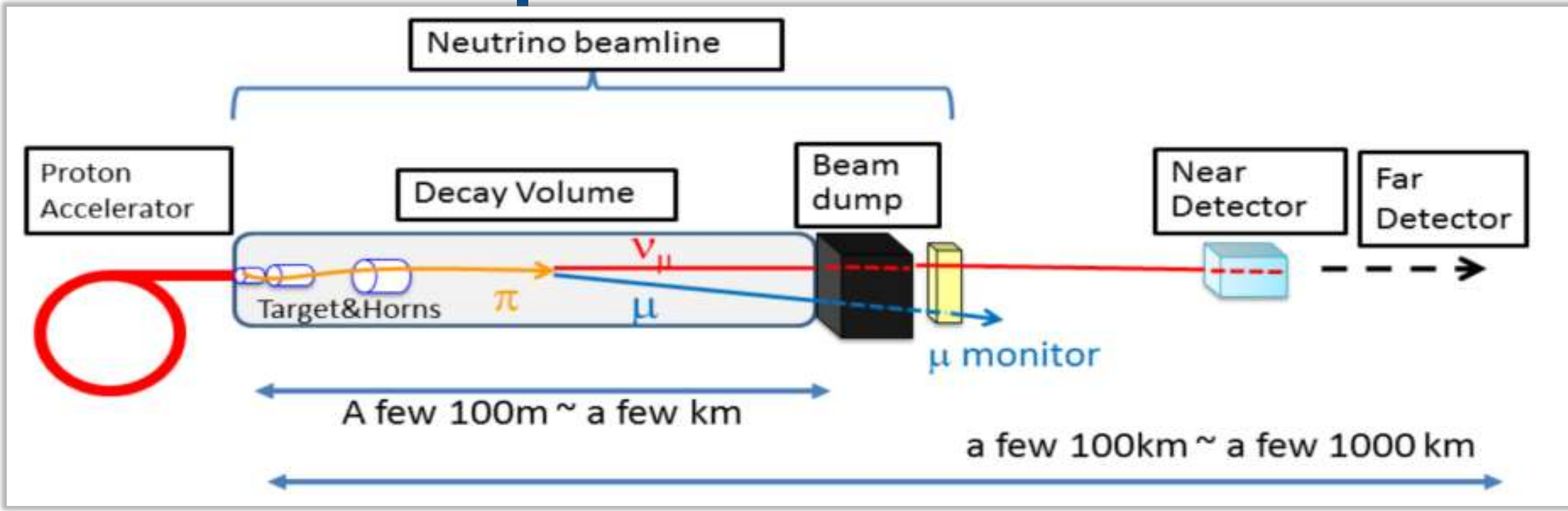
Accelerators for Dark Matter/Rare Processes Searches : Activities at Fermilab and in "Vicinity" (Snowmass)

Vladimir SHILTSEV (Fermilab)

BSW22/iFAST (Valencia, Spain)

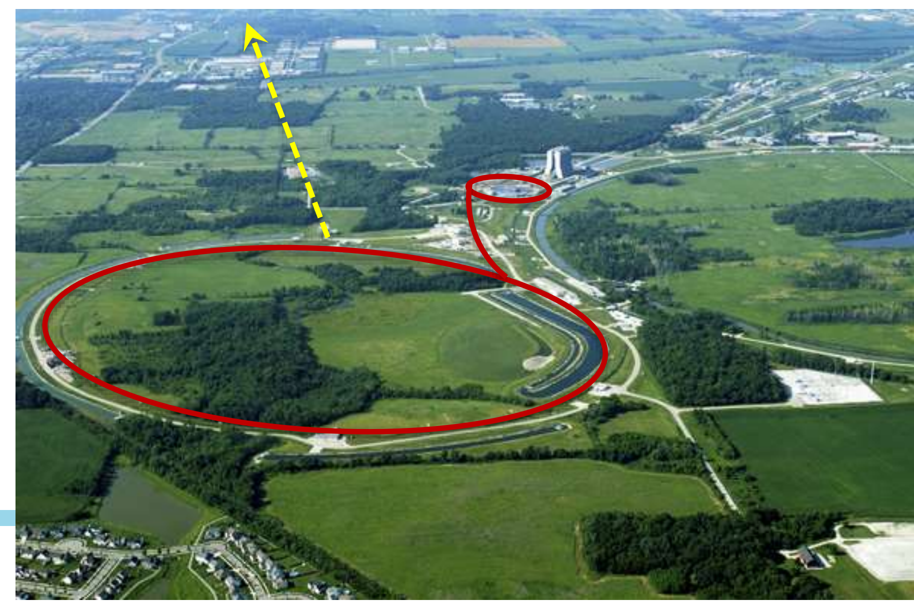
March 29 – April 1, 2022

Neutrino Superbeams – ν Oscillations

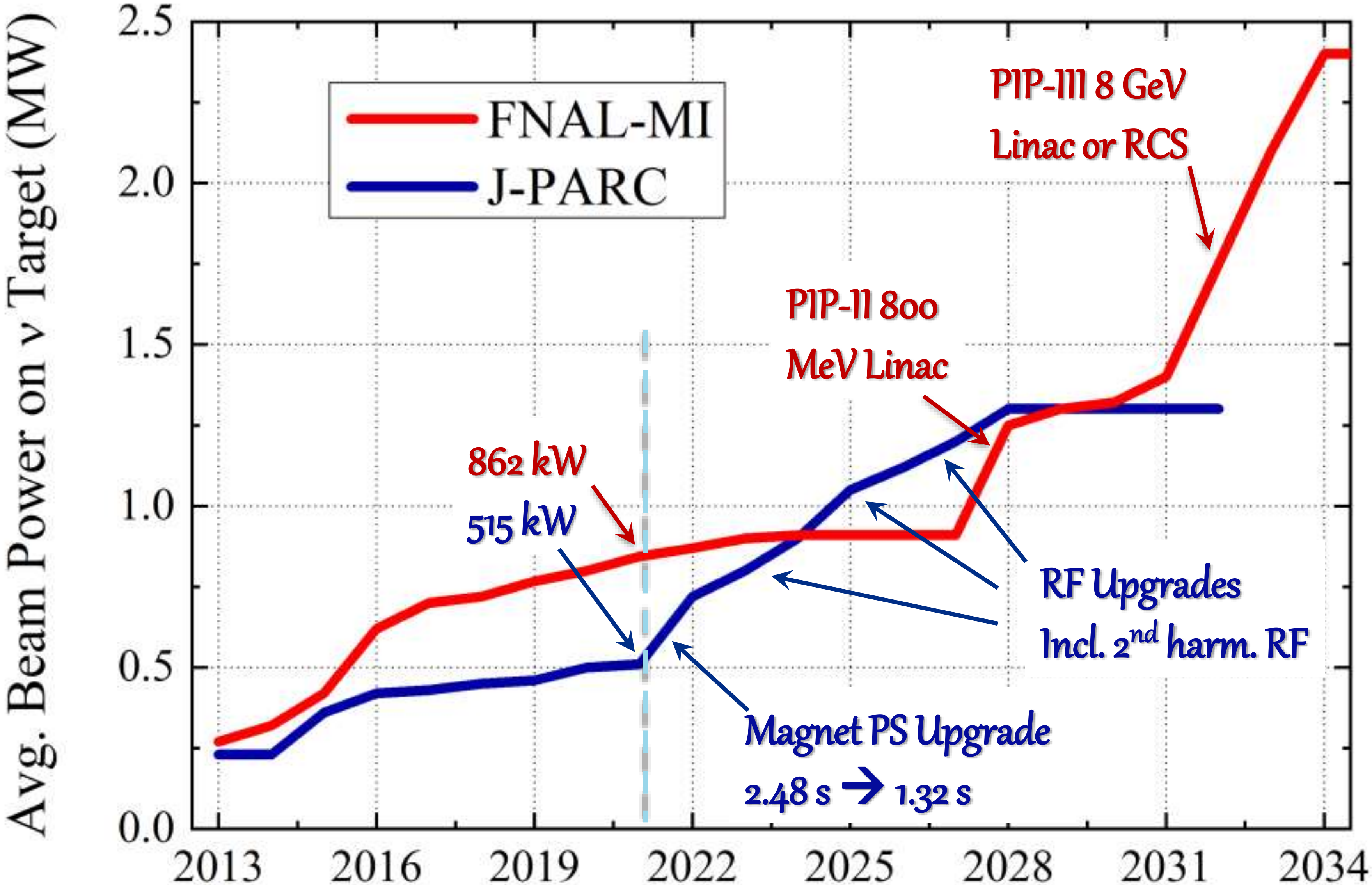


Japan Proton Accelerator Research Complex – *3/30 GeV (295 km to SuperK)*

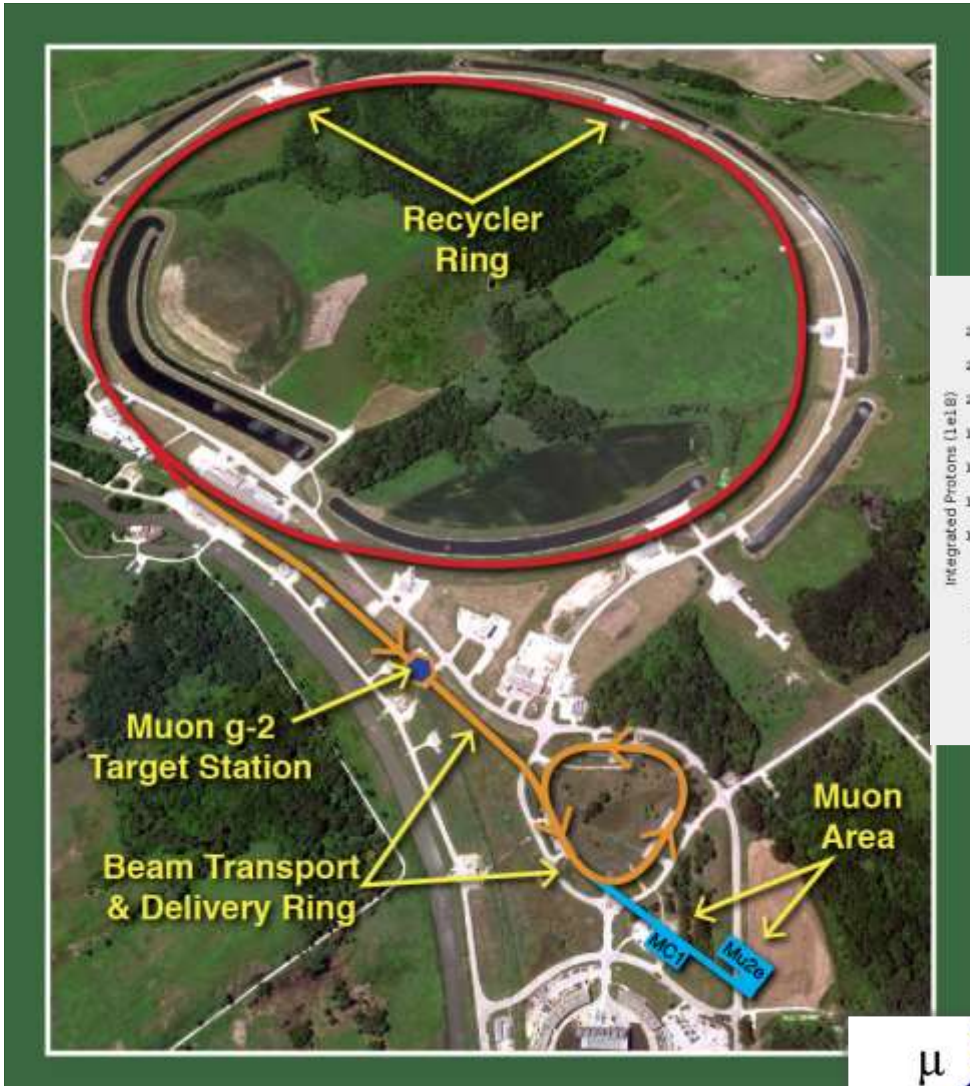
Fermilab Proton Accelerator Complex – *8/120 GeV (810 km to MINOS)*

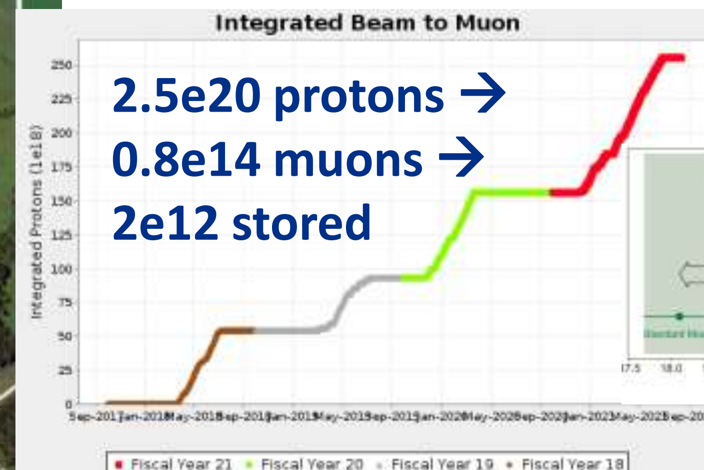


Fermilab and J-PARC Power Upgrades



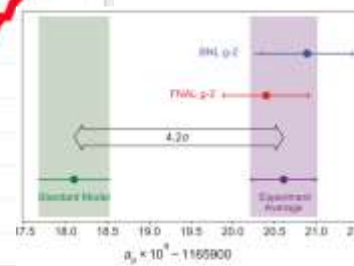
Muon *g*-2 – 2021 !



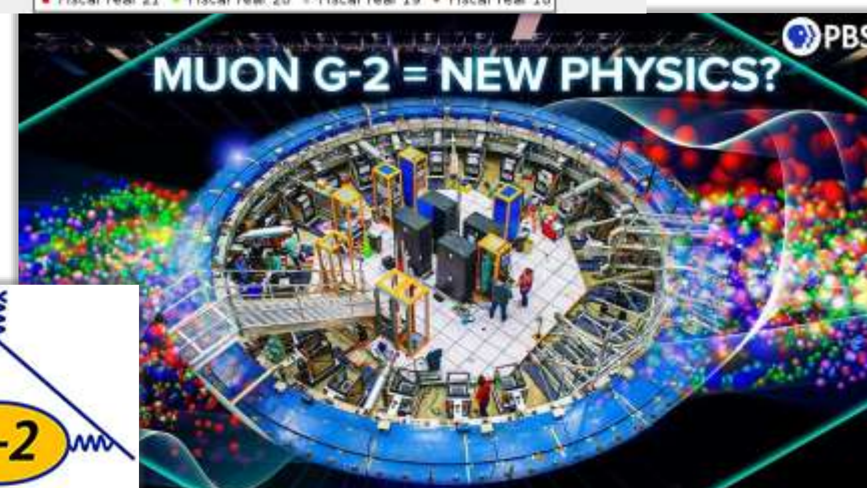


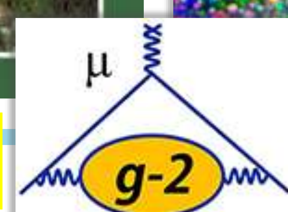
2.5e20 protons →
0.8e14 muons →
2e12 stored

Run 1:
0.46 ppm



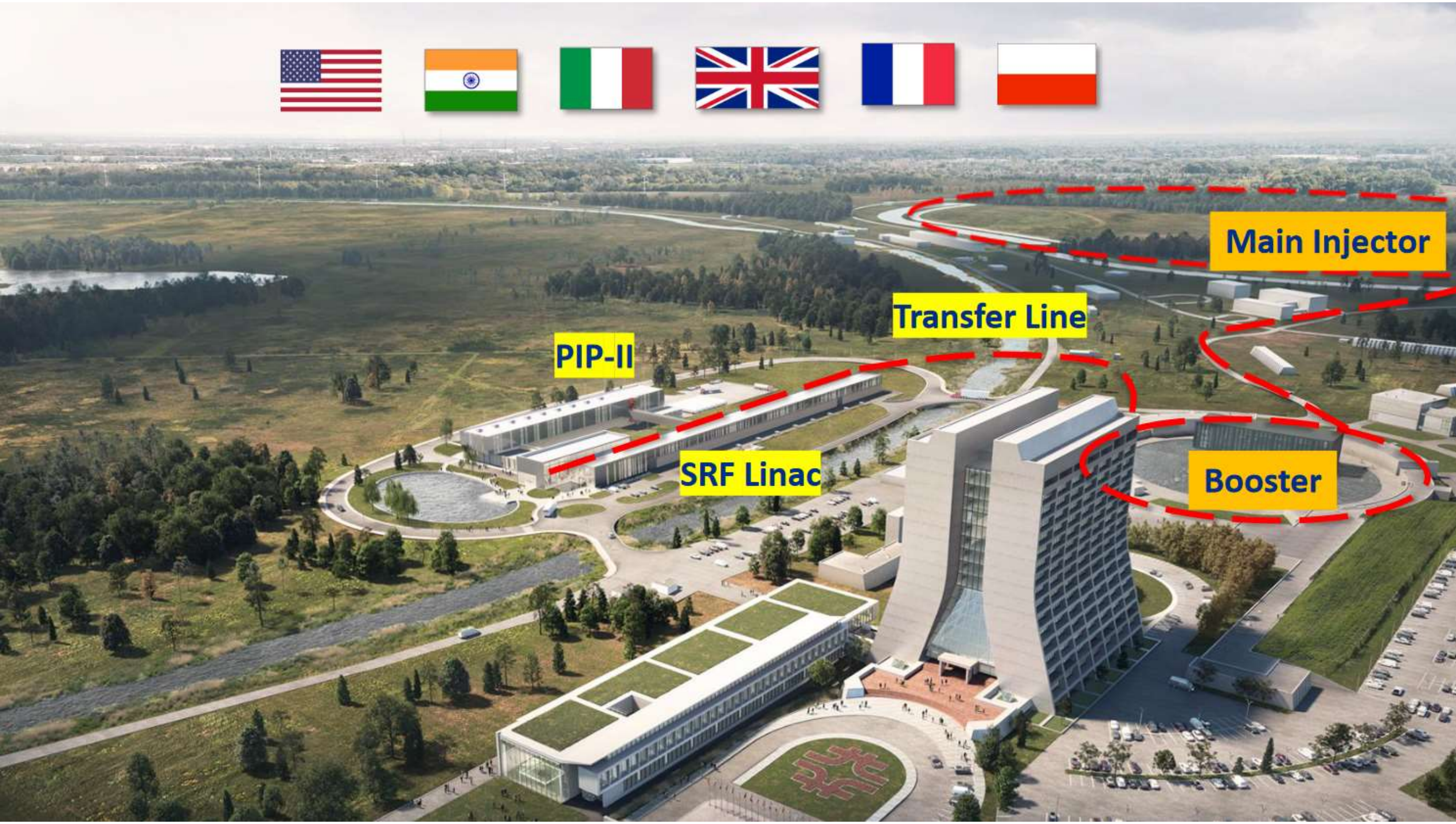
...soon x10





see Martin Ferti's talk Tuesday

800 MeV SRF *p* Linac – Proton Improvement Plan-II



Fermilab Accelerator Complex

Boundary Condition 1: PIP-II

- The PIP-II Linac was designed with the flexibility to support multiple users in mind and is also compatible with continuous wave operation.
- Thus, PIP-II is capable of simultaneously supporting a high-power long-baseline neutrino beam and supplying an additional 1.6 MW of proton beam power at 800 MeV.
- Furthermore, the PIP-II Linac tunnel includes space and infrastructure to reach 1 GeV and space to add an RF separator for beam sharing to multiple users.

Boundary Condition 2: DUNE/LBNF/PIP-II

PIP-II to be finished ca 2028

In few years – MI will be capable of 1.2 MW operations

DUNE Phase I starts 2032

Physics requires <u>Phase II:</u> three prong upgrade ca 2038

(that will surely affect everything else in the US)

arXiv > hep-ex > arXiv:2203.06100

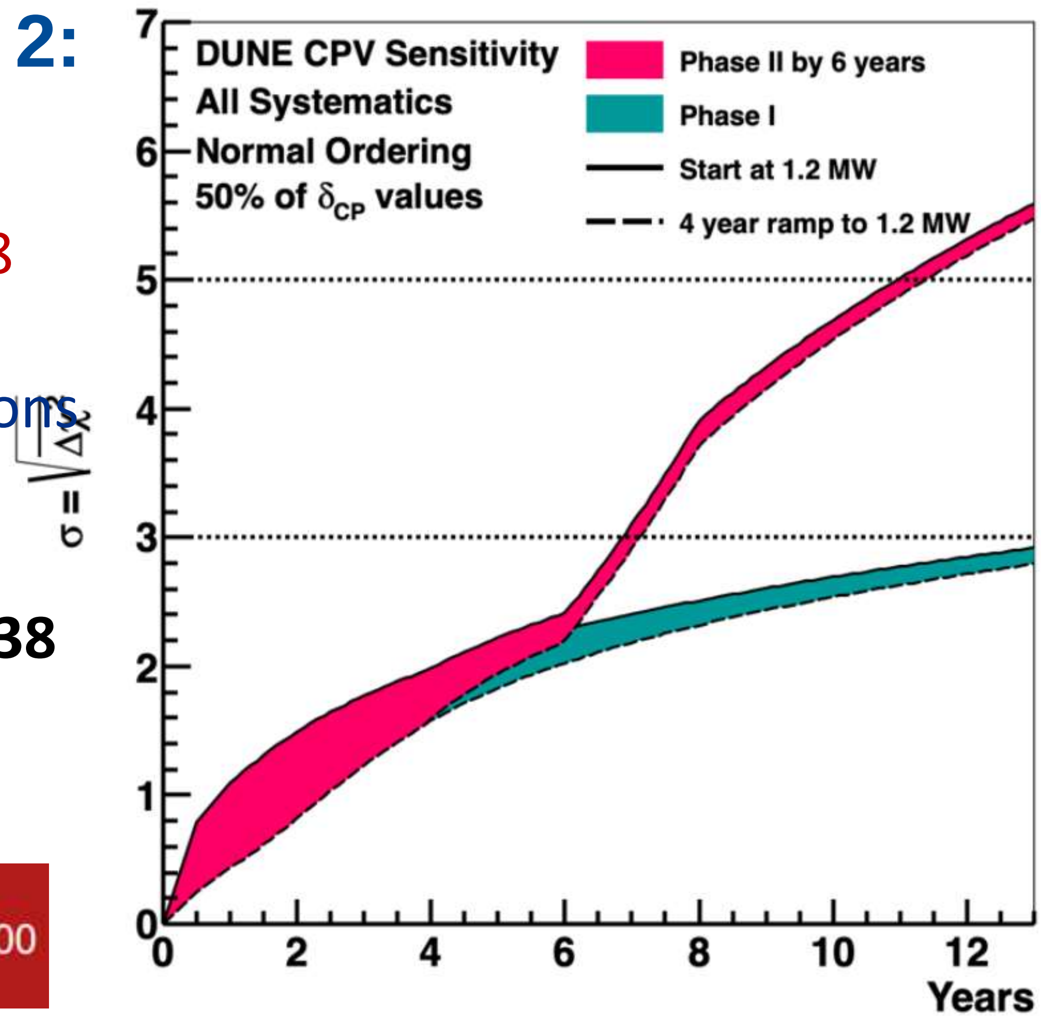


FIG. 6. Sensitivity to CP violation for 50% of δ_{CP} values in Phase I (green band) and in a scenario where Phase II is achieved after 6 years (red band). The width of the bands shows the impact of potential beam power ramp up; the solid upper curve is the sensitivity if data collection begins with 1.2 MW beam power and the lower dashed curve shows a conservative beam ramp scenario where the full power is achieved after 4 years.

https://arxiv.org/abs/2203.06100

Phase II parts: FD volume+MI power+new ND

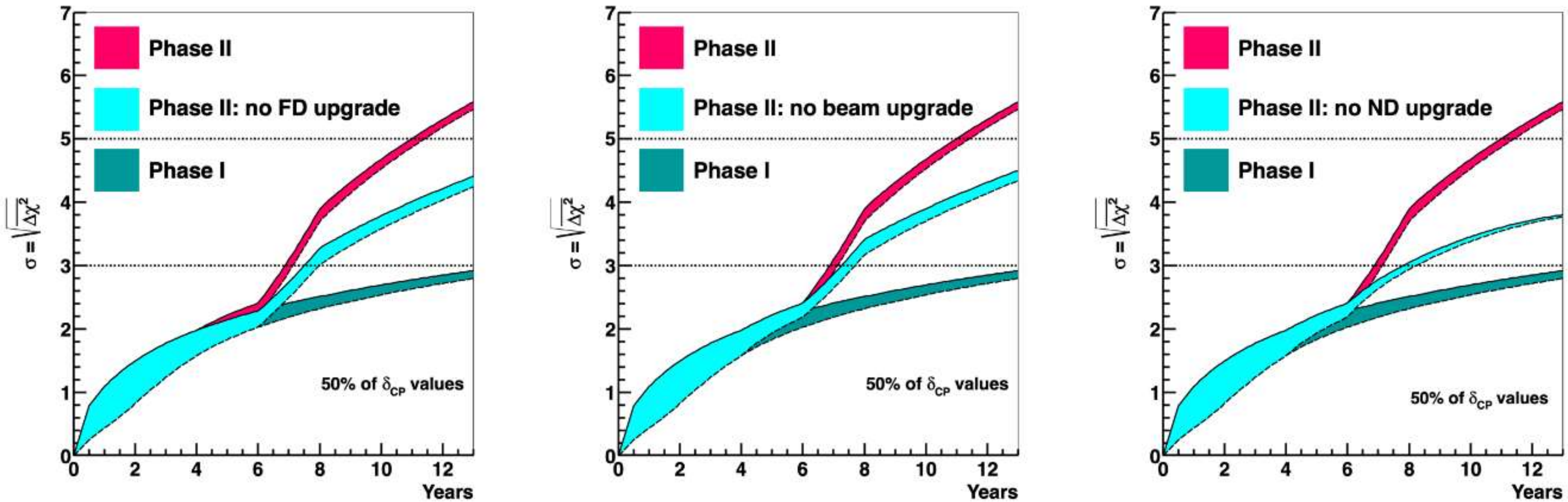


FIG. 7. Sensitivity to CP violation for 50% of δ_{CP} values, as a function of time in calendar years. The width of the bands shows the impact of potential beam power ramp up; the solid upper curve is the sensitivity if data collection begins with 1.2 MW beam power and the lower dashed curve shows a conservative beam ramp scenario where the full power is achieved after 4 years. The green bands show the Phase I sensitivity and the red bands shows the Phase II sensitivity. In each plot the cyan band shows the Phase II sensitivity if one of the three upgrades does not occur. The left plot shows the sensitivity without the FD upgrade, the middle plot shows the sensitivity without the beam upgrade, and the right plot shows the sensitivity without the ND upgrade, illustrating that each is necessary to achieve DUNE's physics goals.

Spectrum of "Post-PIPII" Accelerator Complex Upgrade Opportunities (and relevance to NP-neutrino physics, DM, MP-muon physics)

1. \$ - "Cheap" complex upgrade (Booster, RR, MI, target) to get to 1.6-1.8MW in MI at 120 GeV
   – NP, mb MP and DM
2. \$ - PIP-II upgrade to 1.0-1.2 GeV (power gain unclear)
   – NP, mb MP
3. \$ - Small ~1 GeV accumulator ring (PAR: PIPII Accum Ring)
   – DM at 1 GeV
4. \$\$ - Booster replacement 8 GeV RCS (~2.5 MW in MI)
   – NP, DM, mb MP
5. \$\$\$ - 8 GeV SRF linac+modifications MI, RR? (~2.5 MW)
   – NP, DM, mb MP

Snowmass AF/RPF Discussions– PAR White Papers

- M. Toups, R.G. Van de Water, Brian Batell, S.J. Brice, Patrick deNiverville, et al. ”PIP2-BD: GeV Proton Beam Dump at Fermilab's PIP-II Linac”, arXiv:2203.08079 [hep-ex] (pdf)
- William Pellico, Chandra Bhat, Jeffrey Eldred, Carol Johnstone, et al. ”FNAL PIP-II Accumulator Ring”, arXiv:2203.07339 [physics.acc-ph] (pdf).

PAR will enable three newly proposed 0.8-1 GeV HEP programs at Fermilab:
1. DS (dark energy sector) physics [9],
2. PRISM/PRIME type experiment [10], and
3. a charged lepton flavor violation program.[11]

[9] M. Toups et al. Fixed-Target Searches for New Physics with $\mathcal{O}$(1 GeV) Proton Beams at Fermi National Accelerator Laboratory. *Snowmass 2021 Letter of Interest*, 2020.

[10] R. Barlow. The PRISM/PRIME project. *Nucl. Phys. B Proc. Suppl., vol. 218, pp. 44-49*, 2011.

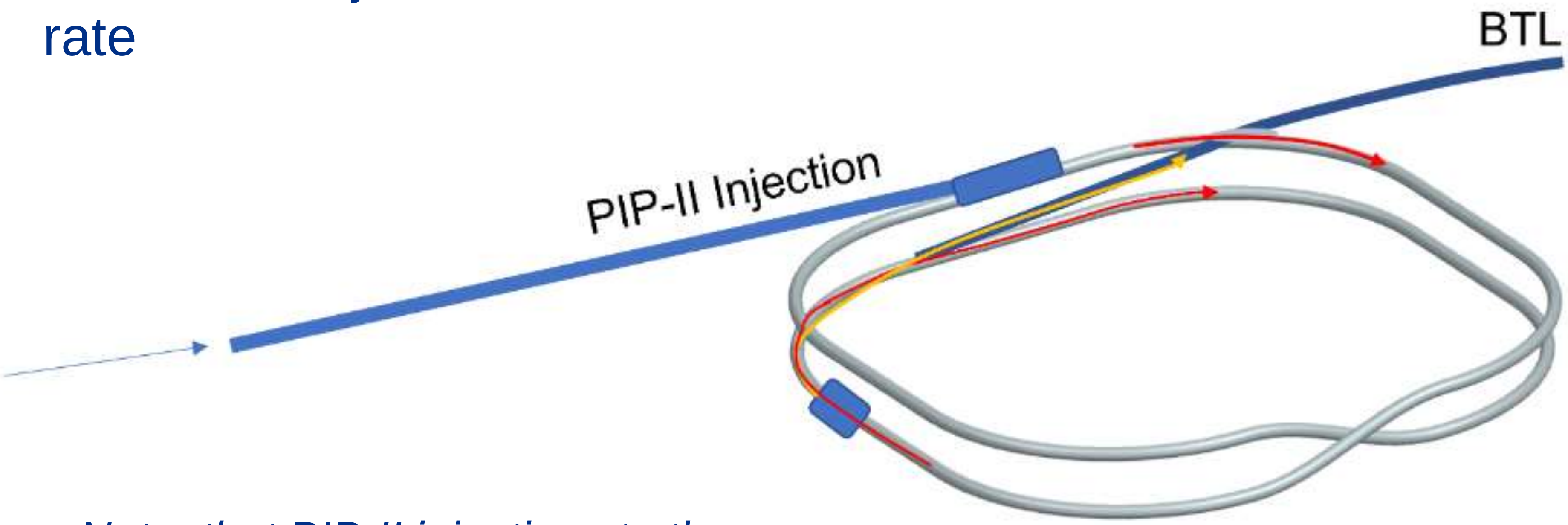
[11] R. H. Bernstein et al. A New Charged Lepton Flavor Violation Program at Fermilab. *2020, Snowmass 2021 LOI RF5-RF0-AF5-AF0-009.*

Accelerator Requirements:

- All these experiments demand 0.8 MeV intense short bunches of lengths in the range of 12 to 500 ns.
- PIP-II linac is “underemployed” by Neutrino program:
  - NP takes only 0.55 ms of 2 mA linac current every 20 Hz (duty factor of 1.1%) → 17.6kW of avg beam power
- BAR will transform long linac pulse into short bunches and will do more often:
  - rep rate from 20 Hz to 100 Hz, avg power 100 – 200 kW
- The plan is to use a 2.5 MHz (h=4) type RF system that is currently used in Recycler for 500 ns bunches and to use Booster type RF systems for short bunches.
  - Barrier bucket RF systems, that have been used in the past at Fermilab, can be used to produce compressed bunches of variable bunch lengths as needed by the experimenters.

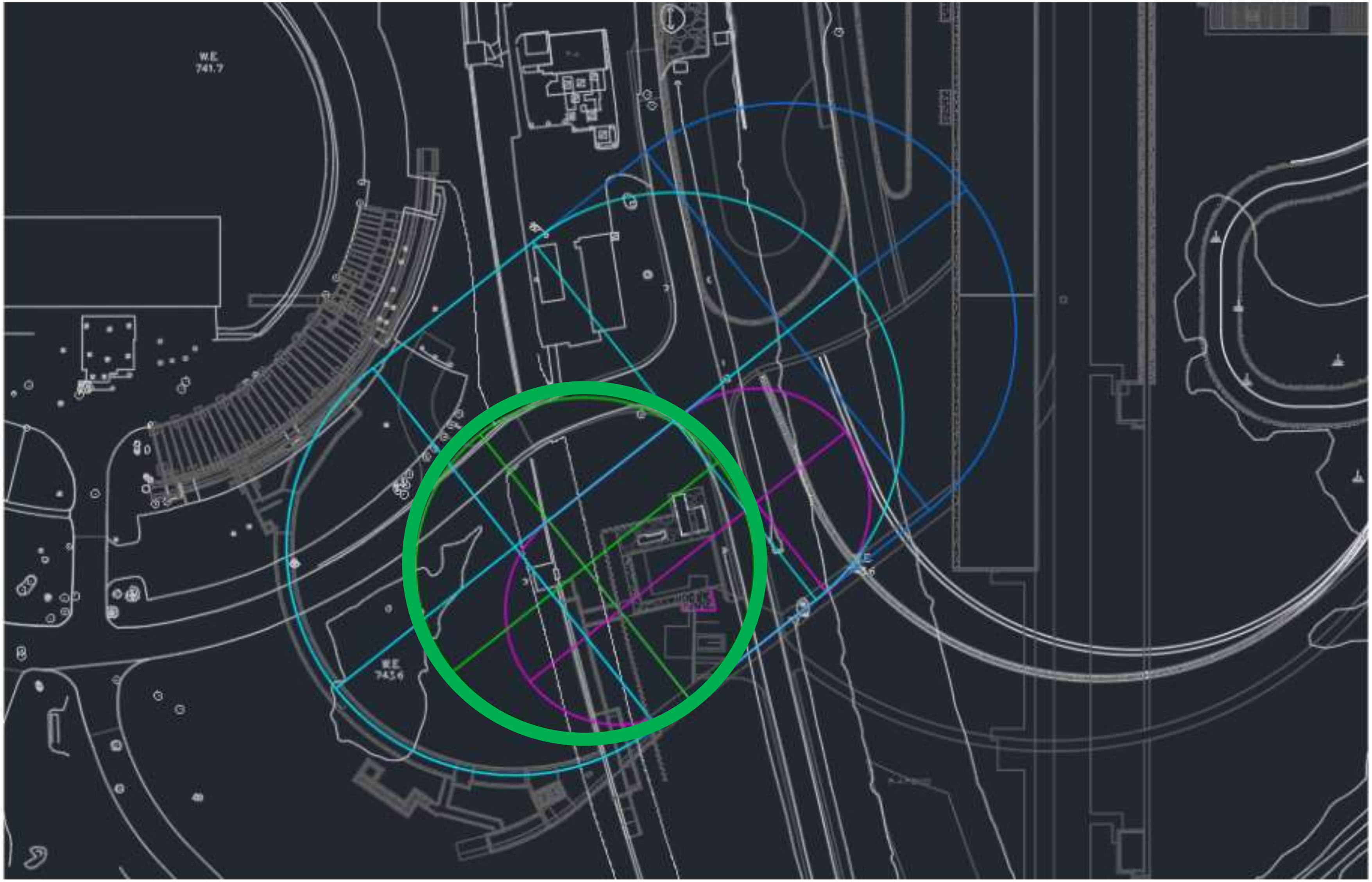
Folded ring (C~480 m in 240 m Tunnel)

Permanent magnets (energy fixed 0.8 or 1 GeV – TBD)
3” aperture
20-120 Hz injection/extraction rate

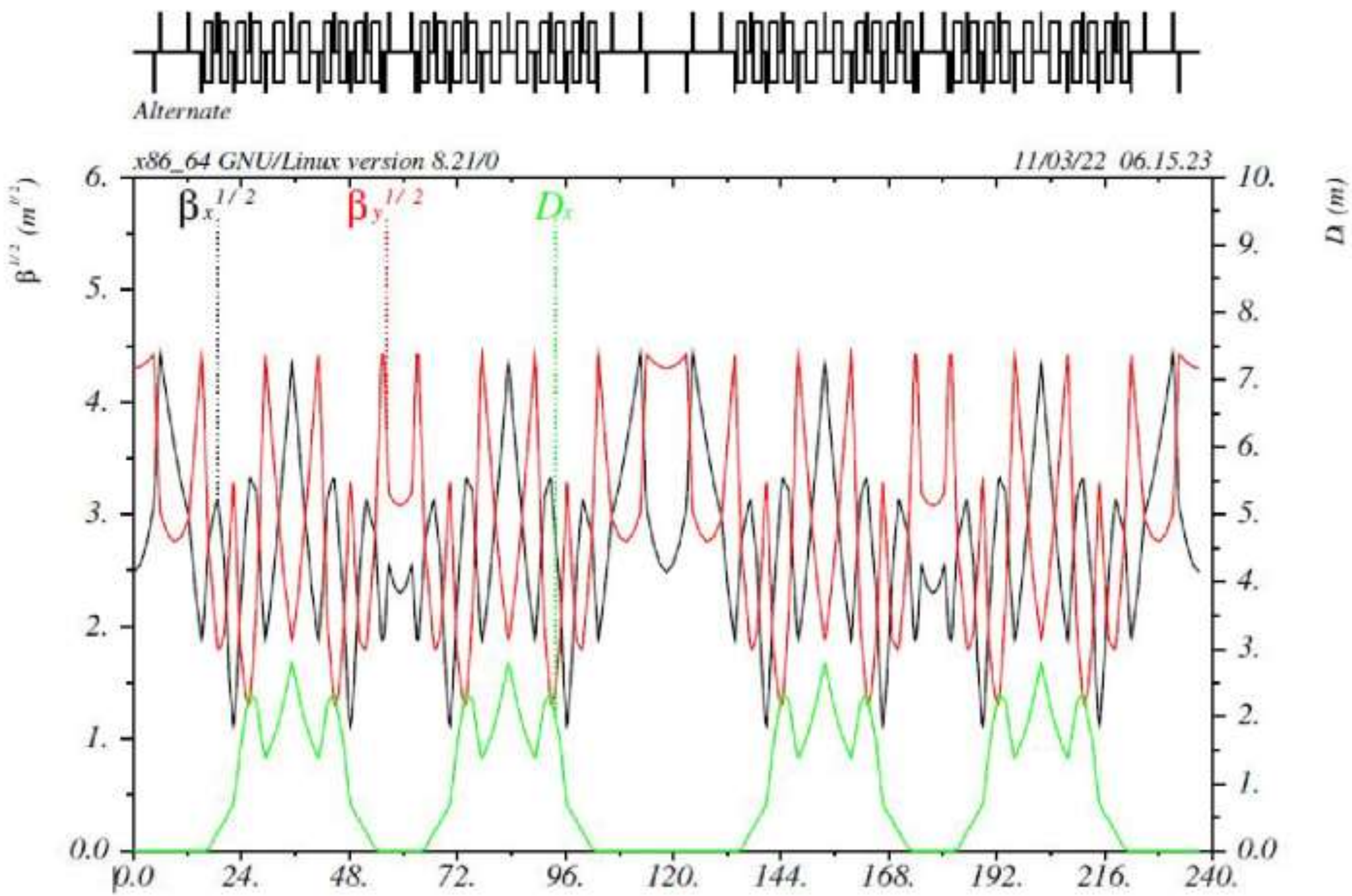


Note, that PIP-II injections to the Booster are independent, 20 Hz

BAR location and lattice



Lattice:



Challenges:

Permanent magnets vs EM
Injection foil heating
100 Hz extraction kickers
Overall cost optimization

High Demand on Protons (Short bunches)

- (Besides PAR)
- C-PAR : C=100m with 20 ns bunches, dQ_sc=0.24
- RCS-SR: in case 8 GeV RCS will be constructed, some MW of beam power might be available at its 2GeV injection energy

Facility	Beam energy (GeV)	Repetition rate (Hz)	Pulse length (s)	Beam power (MW)
PAR	0.8	100	2×10^{-6}	0.1
C-PAR	1.2	100	2×10^{-8}	0.09
RCS-SR	2	120	2×10^{-6}	1.3

Another rare process: mu→e conversion
(not mu→e and two neutrinos … e- peak at 105 MeV)

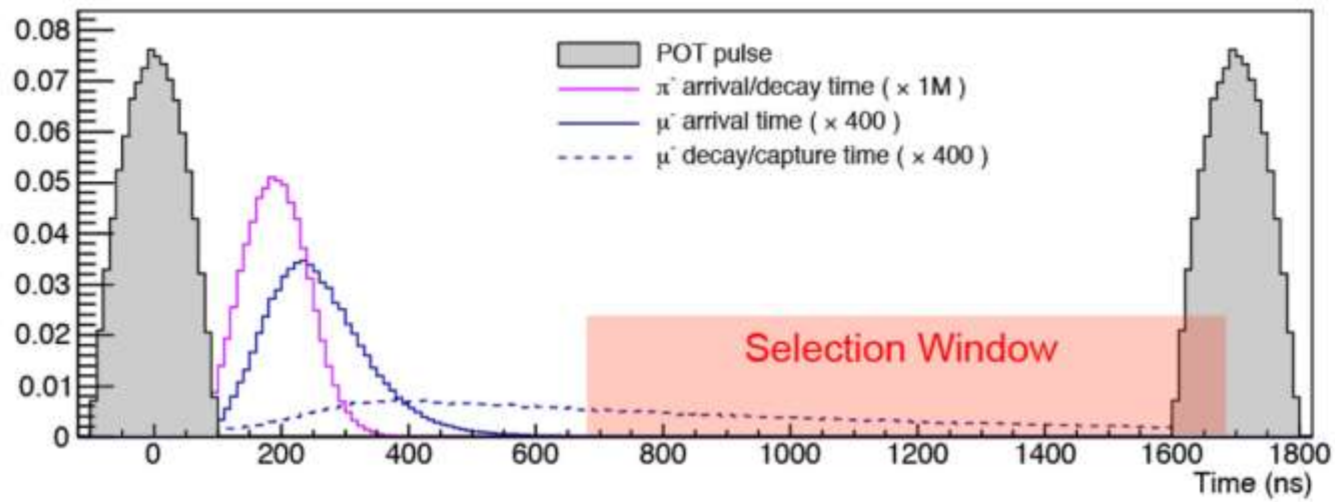
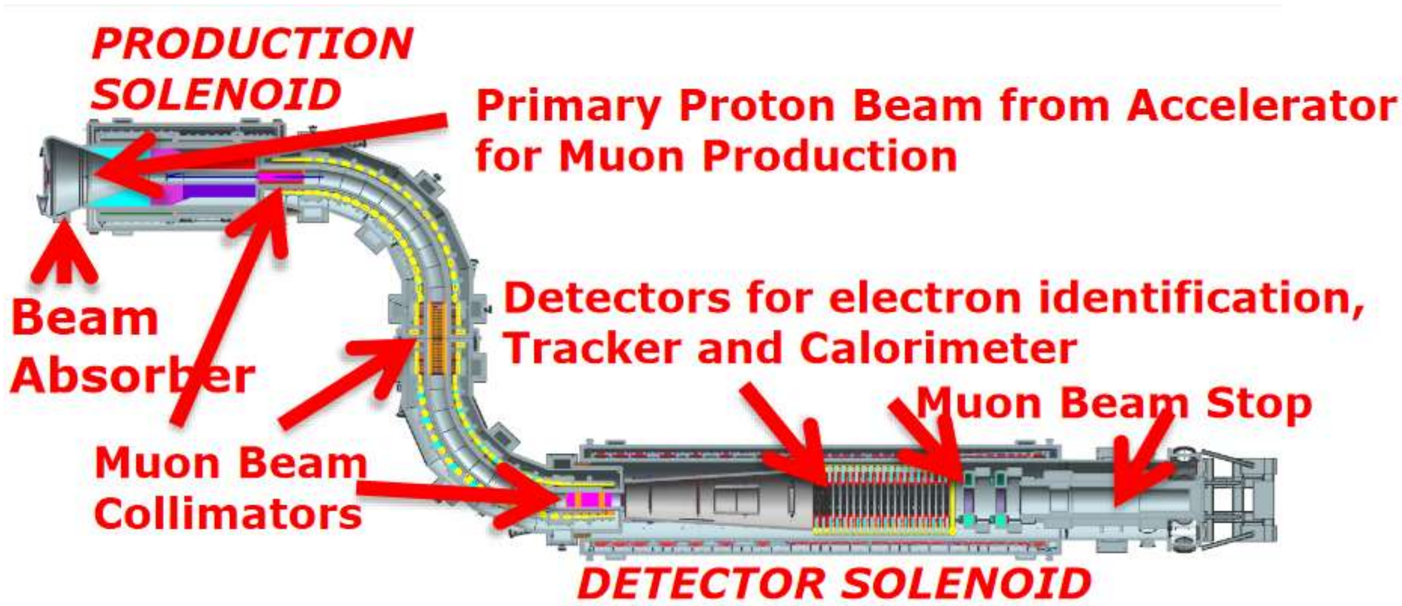


FIGURE 2 | The Mu2e beam timing. A pulse with ≈ 3.9×10^7, 8 GeV kinetic energy protons arrives every 1,695 ns. The arrival time distribution for pions that arrive at the detector solenoid (greatly reduced by the Mu2e Solenoid system) are shown, along with the arrival time for muons and the decay or capture time (both with an 864 ns lifetime). The "Selection window" is the period of time for which Mu2e will analyze data; the live gate will take data as early as about 500 ns, with the final accepted region determined through analysis. The pulse shape is more complicated than the idealized form shown here. See Bartoszek et al. [8] for more information.

- Mu2e project at Fermilab : 8 GeV proton beam, slow extracted, high extinction
- Avg beam power 8 kW

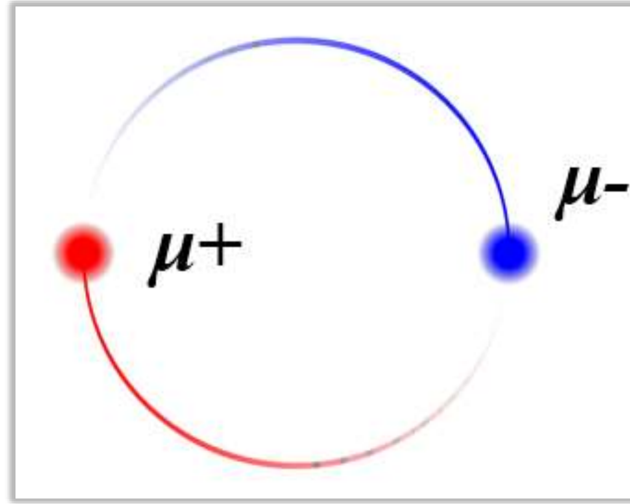
Mu2e Project in good shape = CD3… start "soon"



- Already thinking about next step – "mu2e-II"
- How this expt can benefit from having 0.1-1MW of 1 GeV protons

HEP Project Status 11

Part III : DIMUS



DIMUS at Fermilab: An Opportunity for Super Compact Di-Muon-Spectroscopy Collider

Vladimir Shiltsev, Sergo Jindariani, Patrick Fox (Fermilab)

Snowmass "White Paper"

arXiv > hep-ex > arXiv:2203.07144

Search...

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High Energy Physics - Experiment

[Submitted on 14 Mar 2022]

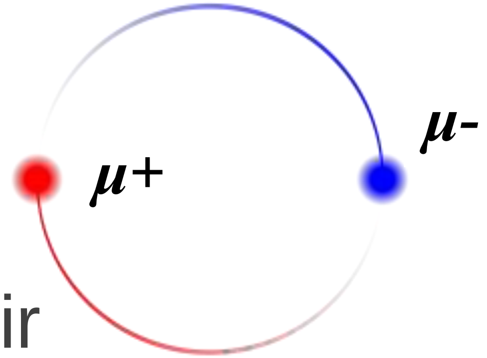
DIMUS: Super-Compact Dimuonium Spectroscopy Collider at Fermilab

Patrick J. Fox, Sergo Jindariani, Vladimir Shiltsev

While dimuonium $(\mu^+\mu^-)$ has not yet been observed, it is of utmost fundamental interest. By virtue of the larger mass, dimuonium has greater sensitivity to beyond the standard model effects than its cousins positronium or muonium, both discovered long ago, while not suffering from large QCD uncertainties. Dimuonium atoms can be created in e^+e^- collisions with large longitudinal momentum, allowing them to decay a small distance away from the beam crossing point and avoid prompt backgrounds. We envision a unique cost-effective and fast-timeline opportunity for copious production of $(\mu^+\mu^-)$ atoms at the production threshold via a modest modification of Fermilab's existing FAST/NML facility to arrange collisions of 408 MeV electrons and positrons at a 75^{o} angle. This compact 23 m circumference collider (DIMUS) will allow for precision tests of QED and open the door for searches for new physics coupled to the muon. Fermilab's FAST/NML is perfectly suited for DIMUS as there are existing SRF accelerators and infrastructure, capable of producing high energy, high current electron and positron beams, sufficient for $O(10^{32})\mathrm{cm}^2\mathrm{s}^{-1}$ luminosity and $\sim$0.5 million dimuons per year. The expansion will require installation of a second SRF cryomodule, positron production and accumulation system, fast injection/extraction kickers and two small circumference intersecting rings. An approximately meter-sized detector with several layers of modern pixelated silicon detector and crystal-based electromagnetic calorimeters will ensure observation of the decays of dimuonium to electron-positron pairs in presence of the Bhabba scattering background. An expansion of the system to would extend the physics program of DIMUS to include precision studies of rare processes with muons, pions, and η mesons produced in e^+e^- collisions.

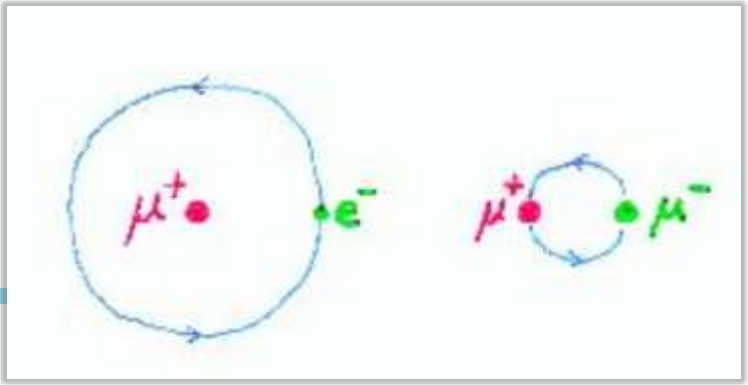
Comments: Submitted as input to Snowmass'2021

Part I: Dimuonium



- Dimuonium is a bound state of μ+ μ- pair
- Two-lepton system described by QED
- There are 6 leptonic atoms: positronium (e+e-), muonium (μ +e-), dimuonium (μ+μ -), tauonium(τ+e-), tau-muonium (τ+μ-), ditauonium (τ+τ-). Only positronium and muonium are observed.
- Dimuonium is more compact system than the positronium and muonium

$R_{\mu\,\mu} \approx (1/100)\ R_{\mu\,e} \approx (1/200)\ R_{ee}$.



Fundamental Physics

- Observation of dimuonium would be a significant discovery.
- QED tests (dimuonium ≠ positronium x m_e/m_μ)
- Muon sector anomalies:
  - About 4.2 sigma difference between the $(g\text{-}2)_\mu$ SM prediction and measurement (soon will be > 5 sigma)
  - Proton/deuteron radius puzzle
  - Hints of lepton-universality violation in rare *B* decays:

    $B+ \rightarrow K+e+e-$ and $B+ \rightarrow K+ \mu+ \mu-$ (@SuperKEKB)
- Very complex experimental task → challenge for experimentalist → development of new methods

S.J.Brodsky and R.F.Lebed Phys. Rev. Lett. 102, 213401 (2009)

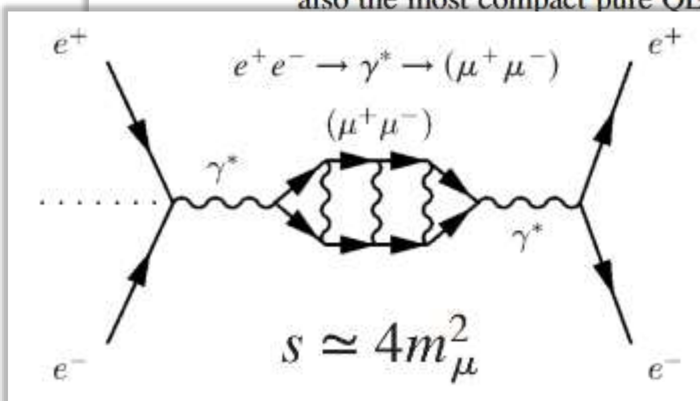
PRL **102,** 213401 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

Production of the Smallest QED Atom: True Muonium ($\mu^+\mu^-$)

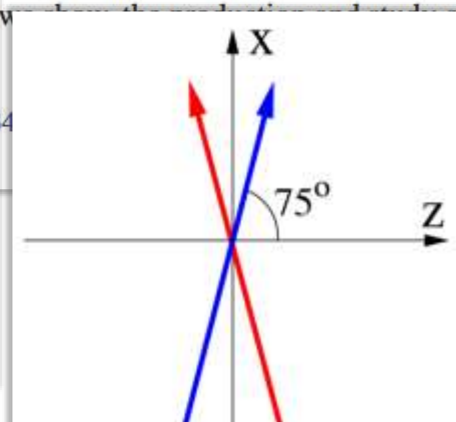
Stanley J. Brodsky*
SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94309, USA

Richard F. Lebed†
Department of Physics, Arizona State University, Tempe, Arizona 85287-1504, USA
(Received 22 April 2009; published 26 May 2009)

The "true muonium" ($\mu^+\mu^-$) and "true tauonium" ($\tau^+\tau^-$) bound states are not only the heaviest, but also the most compact pure QED systems. The rapid weak decay of



$$\vec{p} = \vec{p}_{e^+} + \vec{p}_{e^-} \neq 0$$



merge at 5º-15º

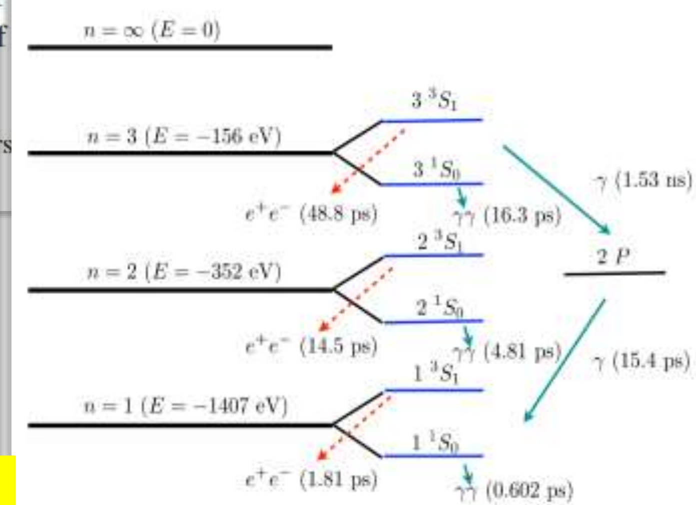


FIG. 1 (color online). True muonium level diagram (spacings not to scale).

26 J. D. Bjorken, Lect. Notes Phys. **56**, 93 (1976).

DIMUS Detector

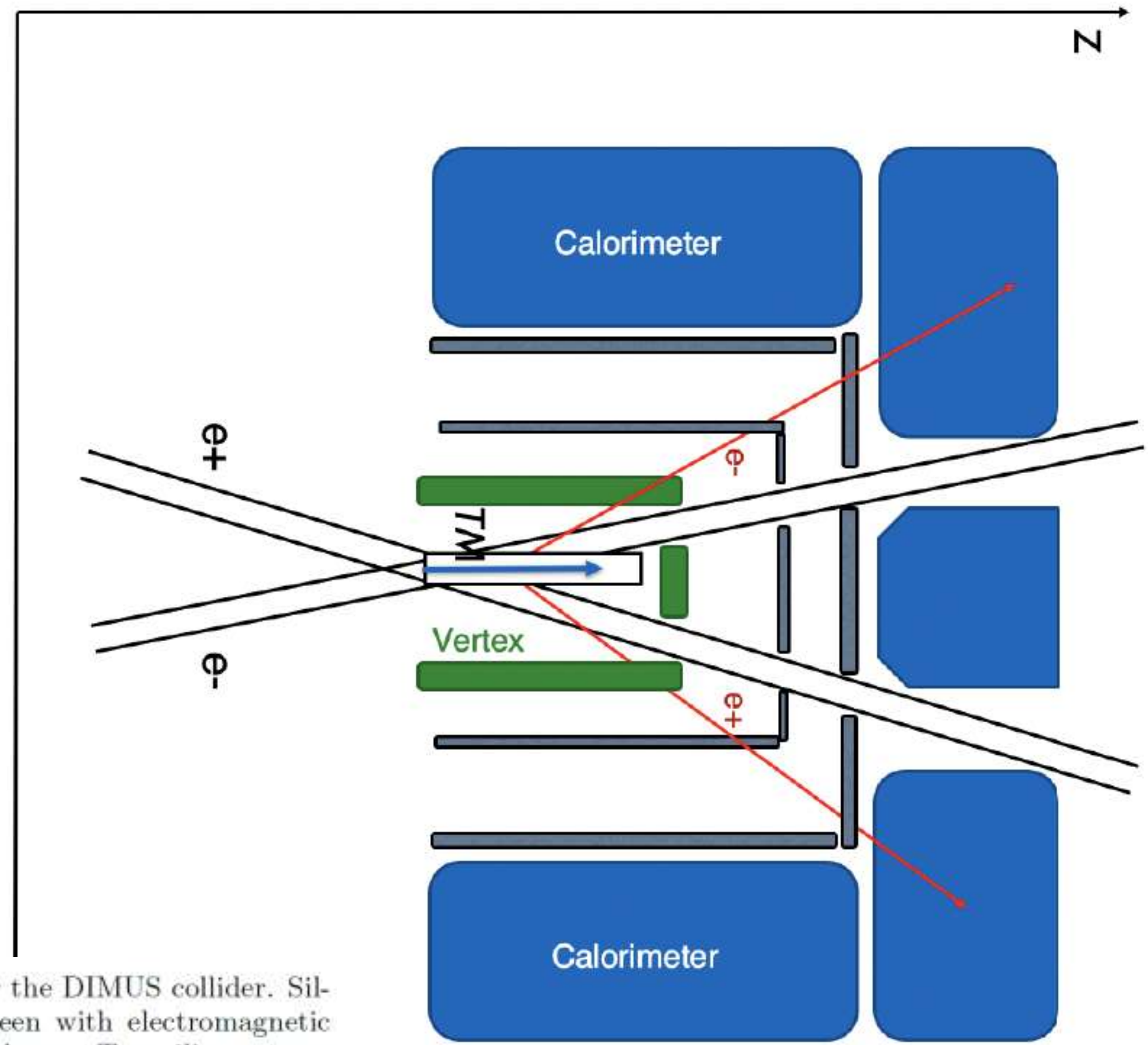


FIG. 4. Schematic of a detector for the DIMUS collider. Silicon pixel detector is shown in green with electromagnetic calorimeters illustrated by the blue boxes. Two silicon or gas detector layers shown in grey provide extra tracking capabilities for precise directionality and linking of electron/positron tracks to the EM clusters.

Physics > Accelerator Physics

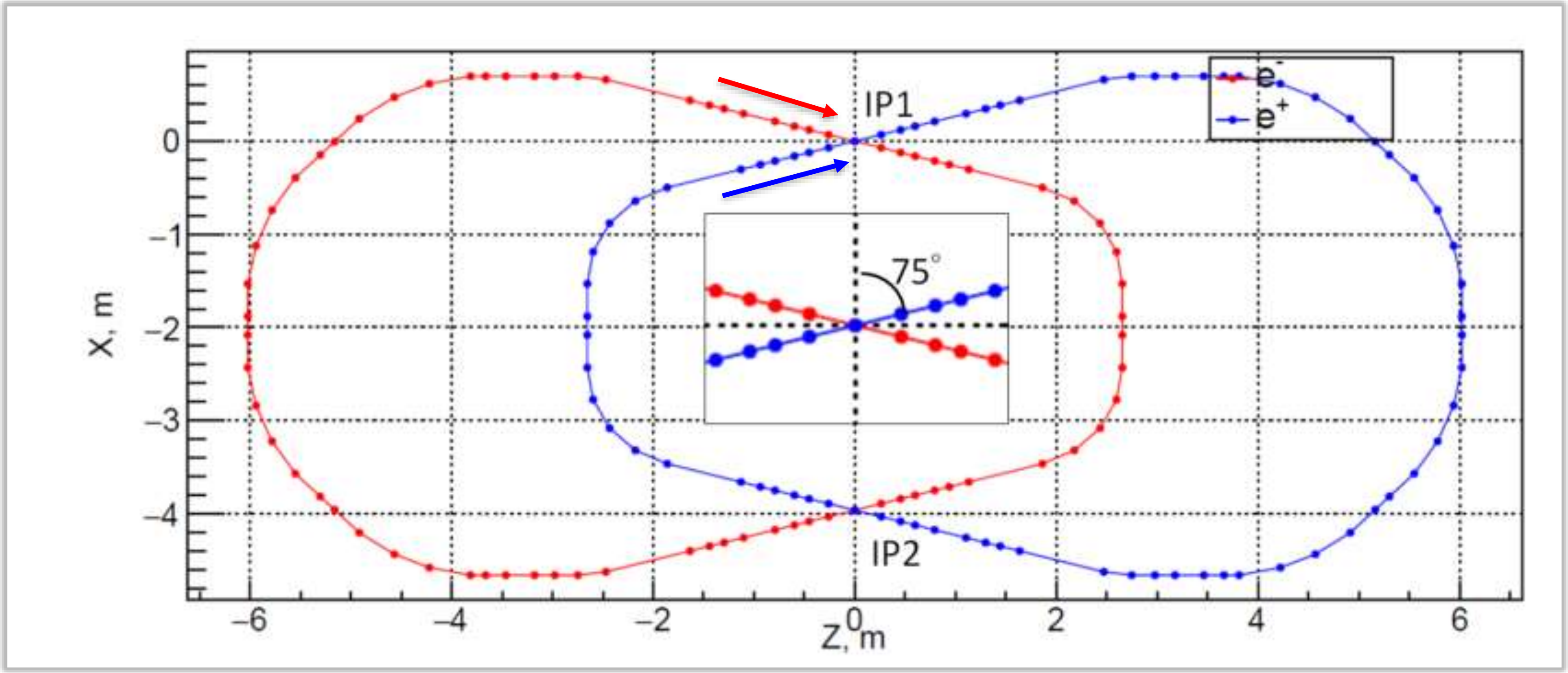
[Submitted on 19 Aug 2017]

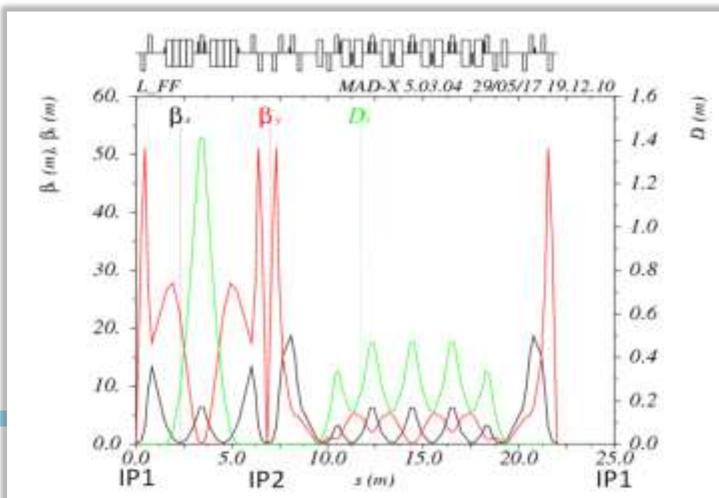
Low-energy electron-positron collider to search and study (μ^+μ^-) bound state

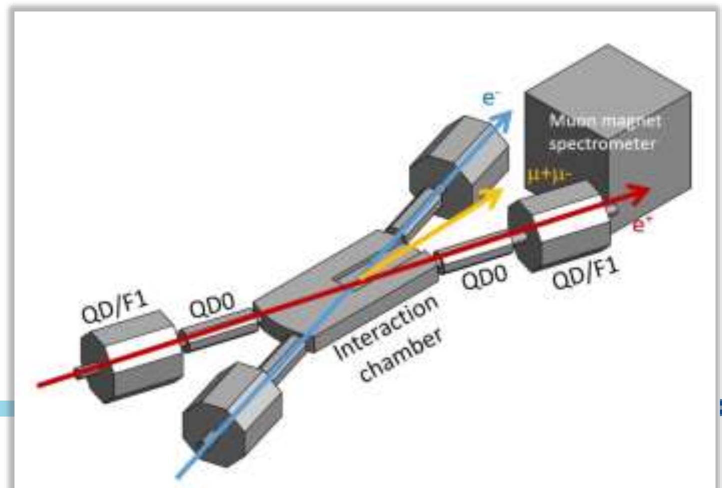
A. Bogomyagkov, V. Druzhinin, E. Levichev, A. Milstein, S. Sinyatkin

We discuss a low energy e^+e^- collider for production of the not yet observed $(\mu^+\mu^-)$ bound system (dimuonium). Collider with large crossing angle for e^+e^- beams intersection produces dimuonium with non-zero momentum, therefore, its decay point is shifted from the beam collision area providing effective suppression of the elastic e^+e^- scattering background. The experimental constraints define subsequent collider specifications. We show preliminary layout of the accelerator and obtained main parameters. High luminosity in chosen beam energy range allows to study $\pi^\pm$ and η -mesons.

Novosibirsk “Mu-Mu-Tron” Design







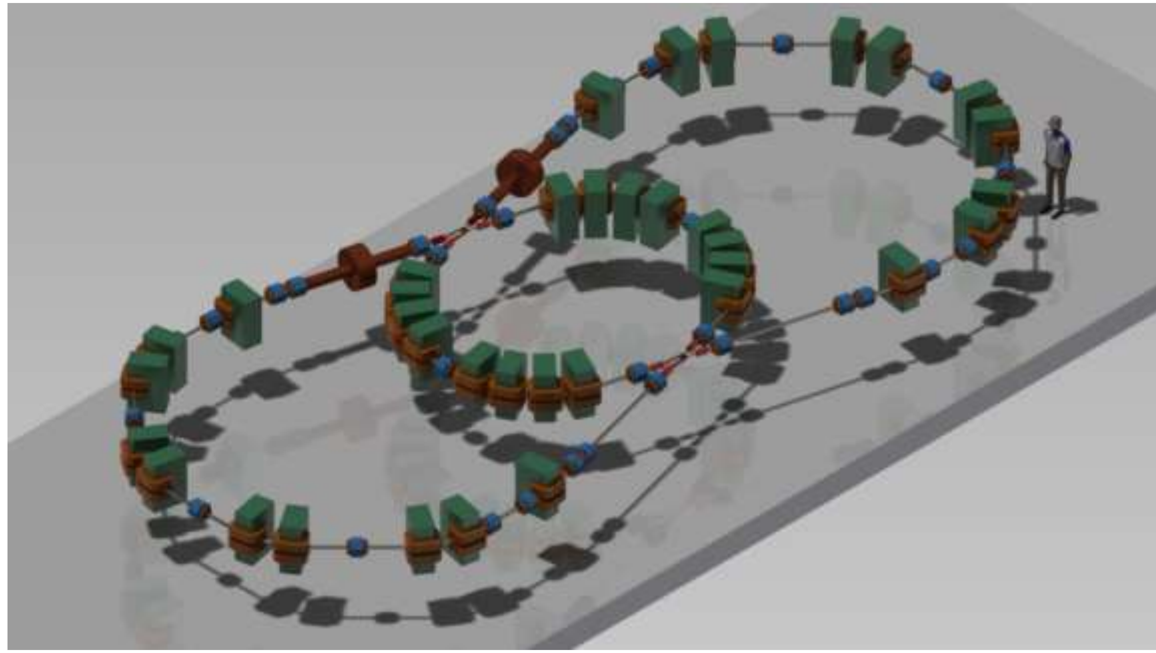
Fermilab

Novosibirsk “Mu Mu Tron” Design (2017)

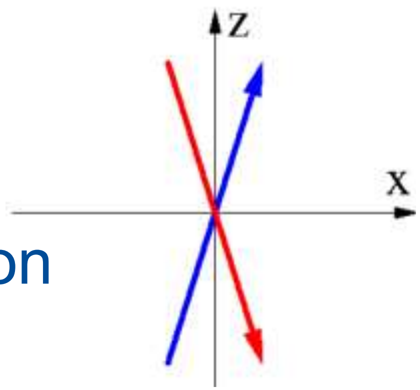
E_{beam} of	408 MeV
E_{CM}	211 MeV
Circumference	23 m
Bunch intensity	3.5×10^{10}/73 mA
Number of bunches	20
σ_x at IP	102 μm
σ_y at IP	0.84 μm
σ_z at IP	11 mm
L_{aver}	8×10^{31} cm^{-2}c^{-1}

Table 2. Estimation of dimuonium production

$(\mu^+\mu^-)$ events	For 1 h	For 4 months
Total (1S/2S/3S)	65/8/2.4	124000/16000/4600
$\Delta L > 2$, mm	19/5/1.6	55000/14000/4500



Also possible – collisions in “reverse” direction (at 15^o)



✓Covers the c.m. energy region from 500 MeV to 1000 MeV
✓This region of the ρ and ω resonances is important for the SM $(g\text{-}2)_\mu$ calculation
✓Very high luminosity O(10^{33}cm^{-2}s^{-1})

Key – e+ production

✓requires about 1 x 10^10 *e*+/s
✓BINP complex delivers about 0.2-0.5 x 10^10 *e*+/s

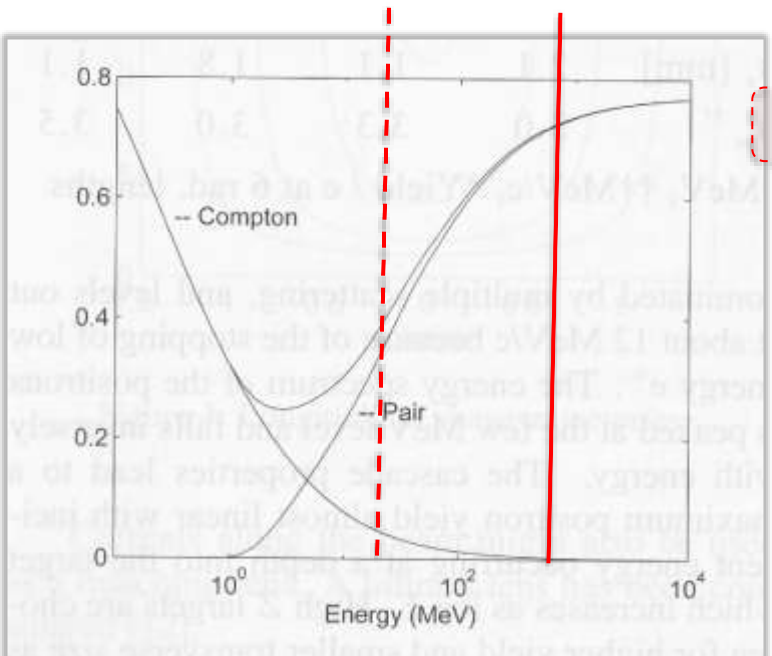


Figure 1: Probability per X_0 of e^+e^- pairs and Compton scattering vs incident photon energy.

Beam energy (MeV)	408
Circumference (m)	23
Bunch intensity/current (mA)	3.5×10^{10}/73
Revolution frequency/period (MHz)/(ns)	13.04/76.7
RF harmonic number/frequency (MHz)	26/338.98
Energy loss per turn (keV)	2.3
RF voltage (kV)	450
RF acceptance	2%
Synchrotron tune	1.71×10^{-2}
Momentum compaction α	6.4×10^{-2}
Damping time hor/ver/long (ms)	17.3/27.3/22.1
Damping partition hor/long	1.6/1.4
Horizontal emittance (without/with IBS) (nm)	26/90
Energy spread (without/with IBS), $\times10^4$	4/8.4
Bunch length (without/with IBS) (mm)	5.4/11.6
Betatron coupling	0.3%
IP horizontal angular spread $\sigma^*_{x'}\times10^4$	6.7
Invariant mass resolution (keV)	390
Hor/vert betatron function at IP (mm)	200/2
Hor/vert betatron size at IP (μm)	130/0.7
Hor/vert beam-beam parameter (ξ_x/ξ_y)	$2\times10^{-6}/1.2\times10^{-3}$
Longitudinal beam-beam parameter ξ_z	-2×10^{-3}
Peak luminosity for 1 bunch ($cm^{-2}s^{-1}$)	4×10^{30}
Peak luminosity for 20 bunches ($cm^{-2}s^{-1}$)	8×10^{31}

Positron Production: BINP and CESR ~(0.01-0.03) *e+ per e-*

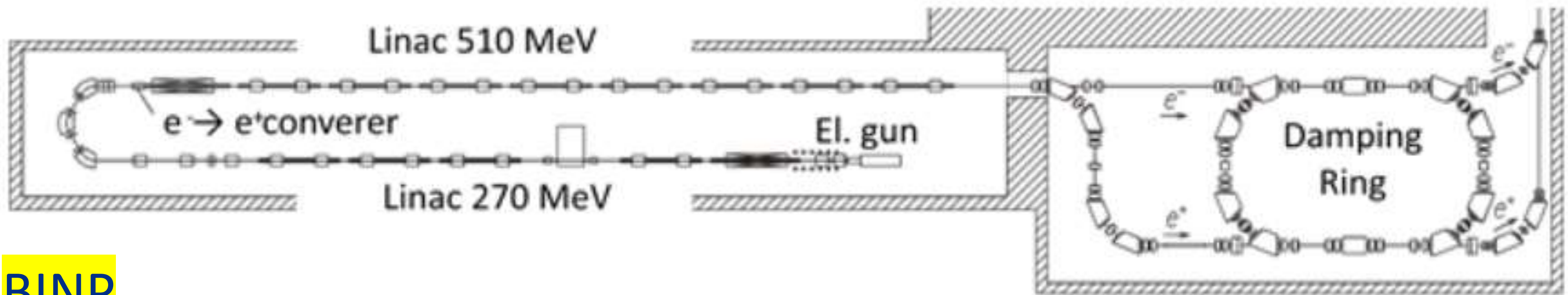
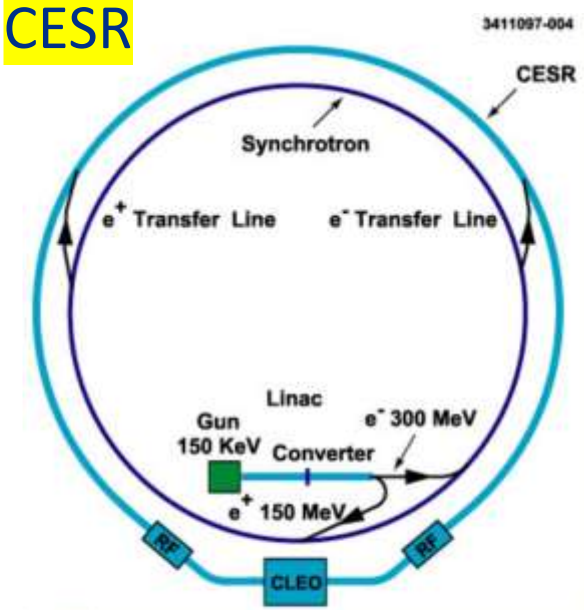
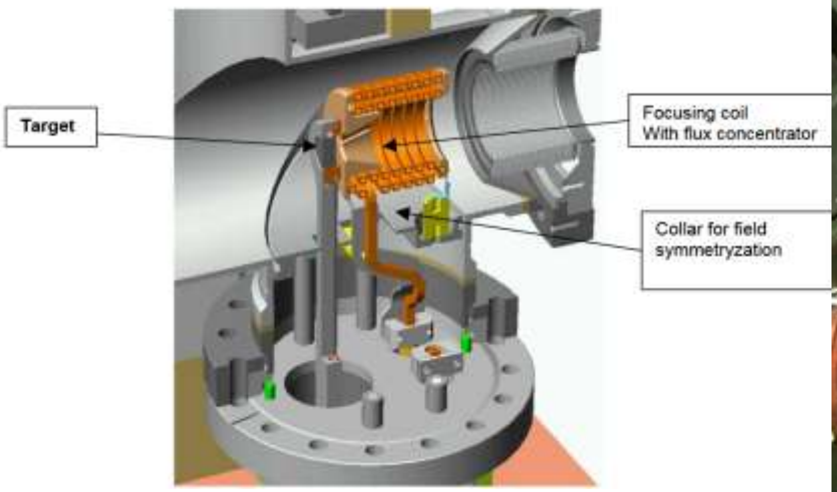
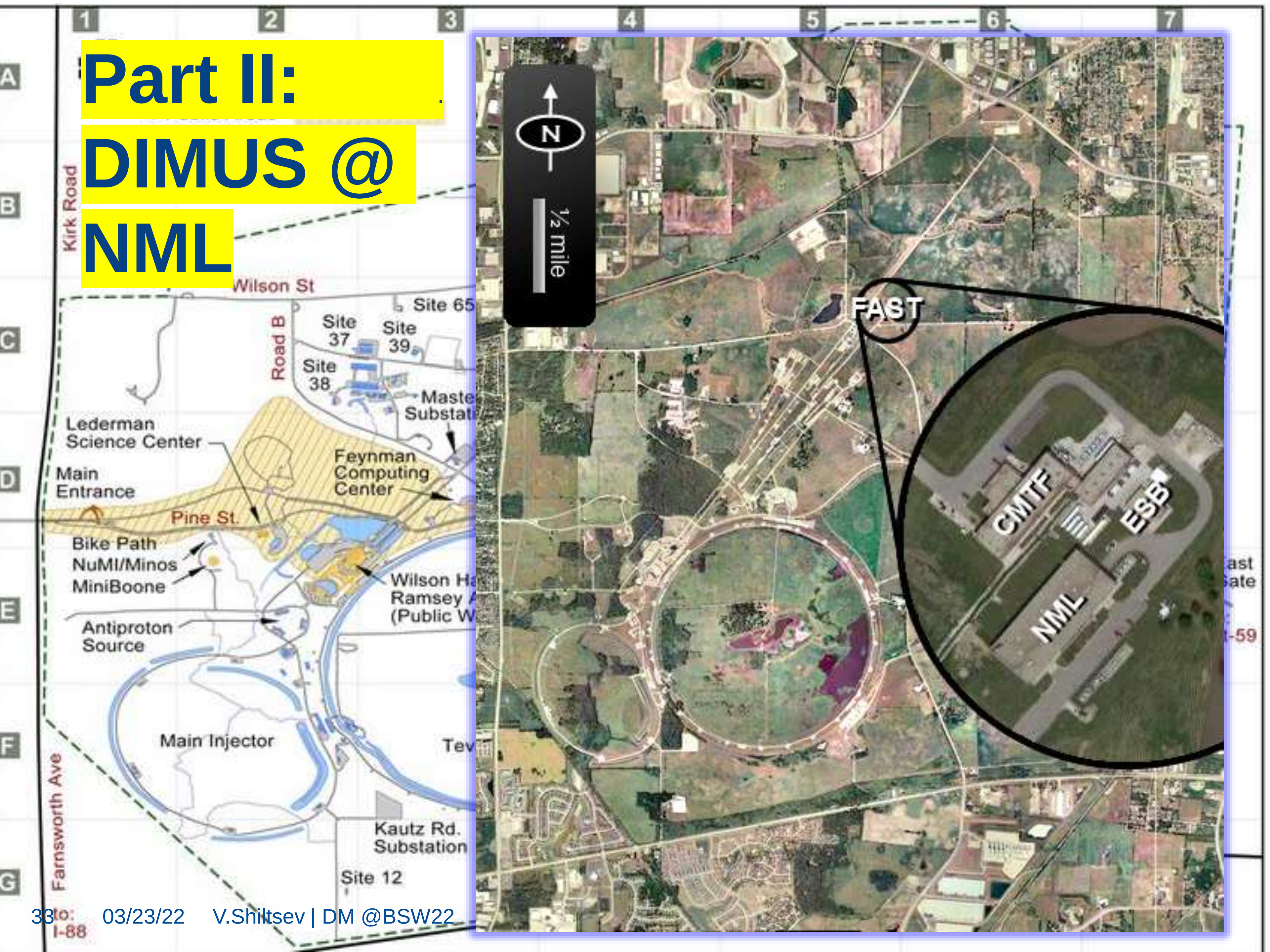


Figure 2: VEPP-5 Injection Complex layout.



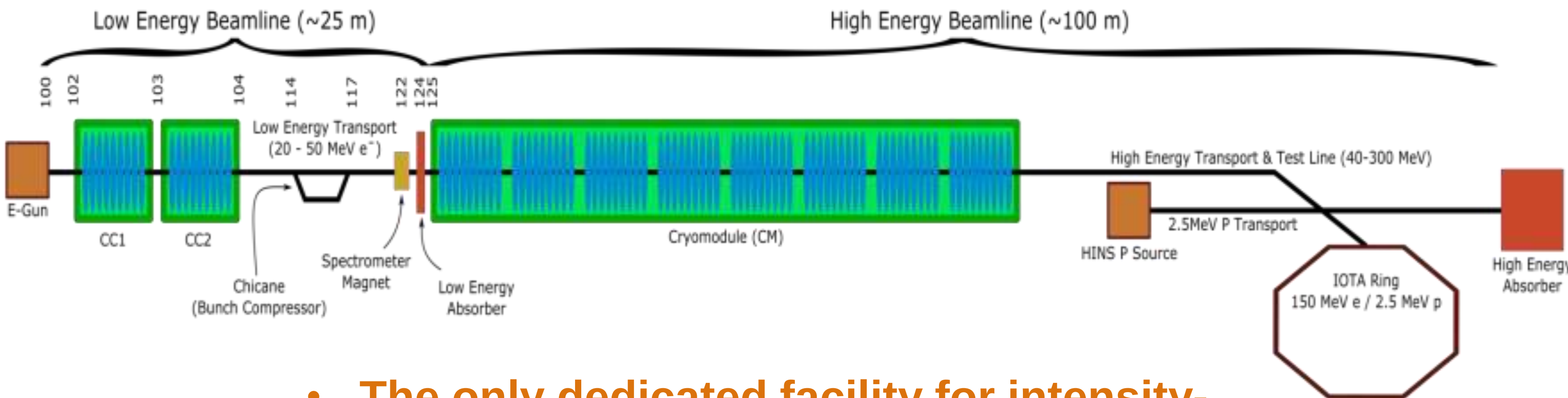


Part II: DIMUS @ NML



IOTA/FAST Facility for Accelerator and Beam Physics R&D

- **IOTA/FAST: 5 MeV e-, 50 MeV e-, 100-300 MeV e-, ring and 2.5 MeV p+**



- **The only dedicated facility for intensity-frontier accelerator R&D; ranked as top facility ("Tier 1") for acc. & beam physics thrust by recent GARD review (Jul 2018)**
- ~30 Collaborating institutions
- Nat. Lab Partnerships: ANL, BNL, LANL, LBNL, ORNL, SLAC, TJNAF
- Many opportunities for R&D with cross-office benefit in DOE/SC

DiMuonSpectroscopy (DiMuS) at NML : Opportunities

- Excellent source of high energy electrons:
  - eg 3000 bunches x 5 Hz x 2e10 = 3e14 *e*-/s
  - at 1% conversion → 3e12 *e*+/s
- DIMUS will probably need much less
  - eg 200 bunches x 1 Hz x 2e10 = 4e12 *e*-/s
  - at 1% conversion → 4e10 *e*+/s
- Efficient linac – now upto 300 MeV
  - DIMUS will need extra ~108 MeV → total of 408 MeV
- Infrastructure and expertise:
  - wide & (important) long tunnel, cryo, power, HCW, etc
  - knowledgeable people

To Covert NML into Collider Facility One Needs:

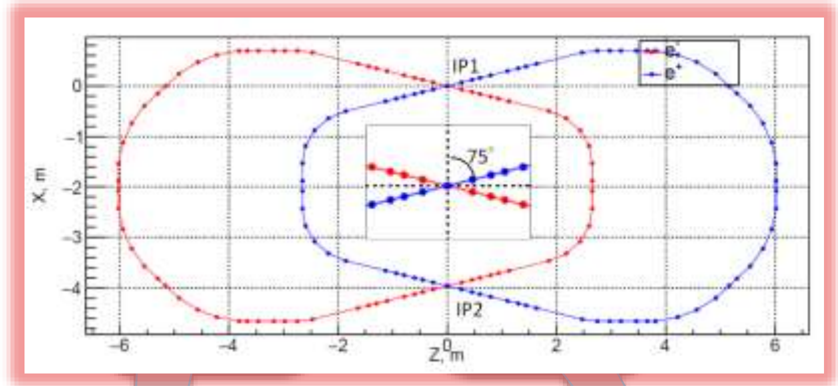
- Collider *e+e-* Rings (2 x 408 MeV)

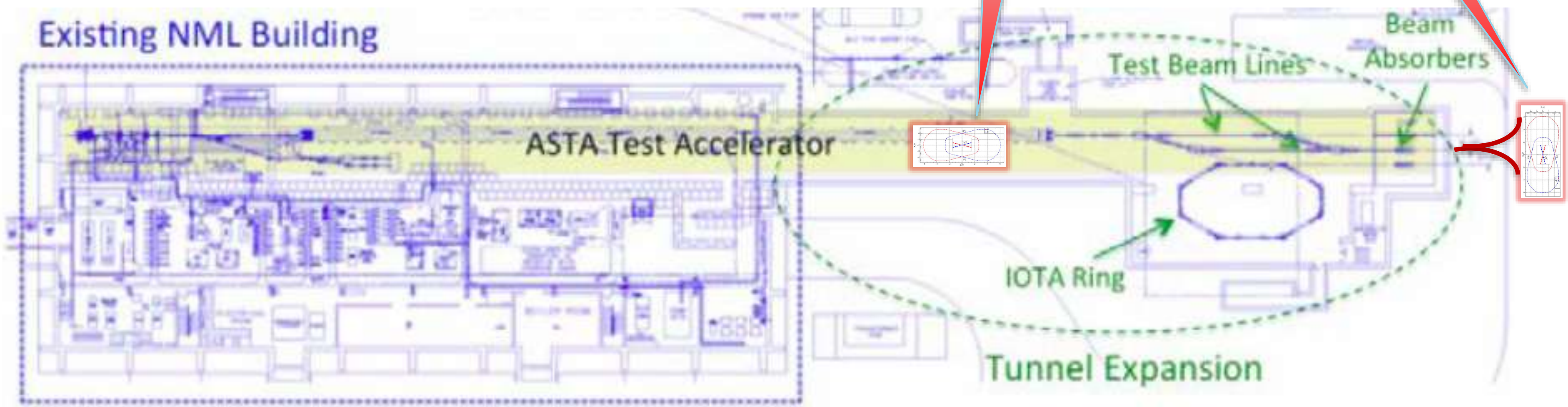
- Second CM, so the final energy 408 MeV

- Positrons:
  - Conversion/collection system
  - Acceleration
  - Storage ring accumulator

- Fast injection kickers

Placement of the DIMUS Collider





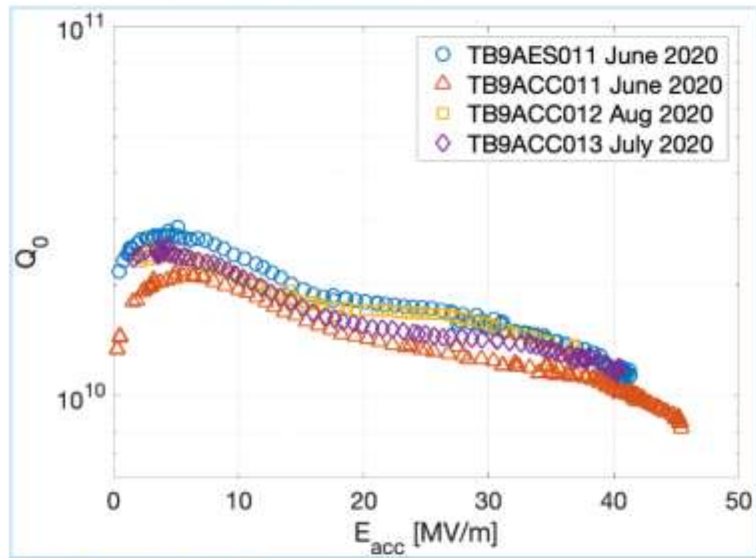
The Second CryoModule

- *will be good for 250-320 MeV*
- *DIMUS might need only 208 MeV*

High gradient cryomodule demonstration

- Fermilab is in the process of refurbishing one of the old cryomodules (CM1) to demonstrate the new SRF advances:
  - Flux expulsion
  - Two step bake (75/120)
  - Cold EP
- Supported by the ILC Cost Reduction R&D with contributions from other labs throughout the world
- Goal is to reach higher gradient than has ever been demonstrated in CM test: 38 MV/m average gradient with a stretch goal of 40 MV/m. The Q_0 goal is $1.0{\times}10^{10}$ at 38 MV/m.
- Some other CM improvements (magnetic shield, tuner, …)

Cavity candidates to date (average gradient 41 MV/m):
- TB9AES011 – 41.3 MV/m
- TB9ACC011 – 45.5 MV/m
- TB9ACC012 – 36.9 MV/m
- TB9ACC013 – 40.4 MV/m

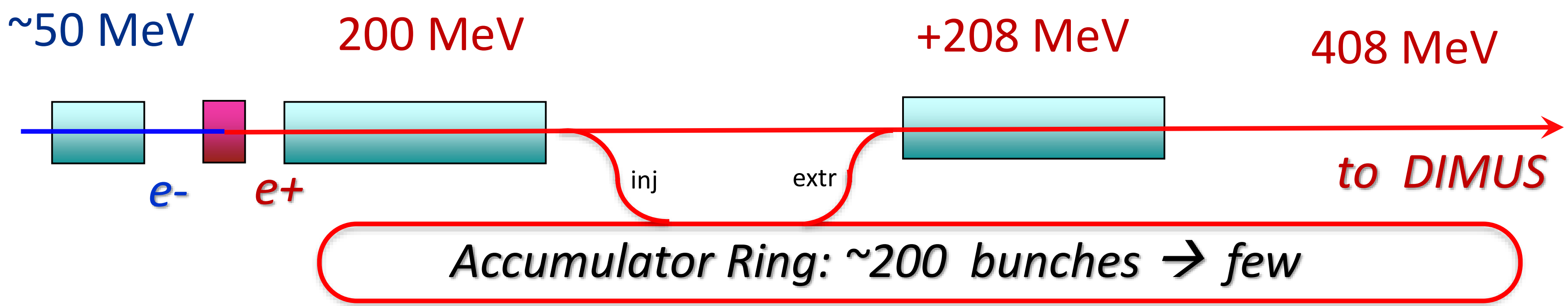


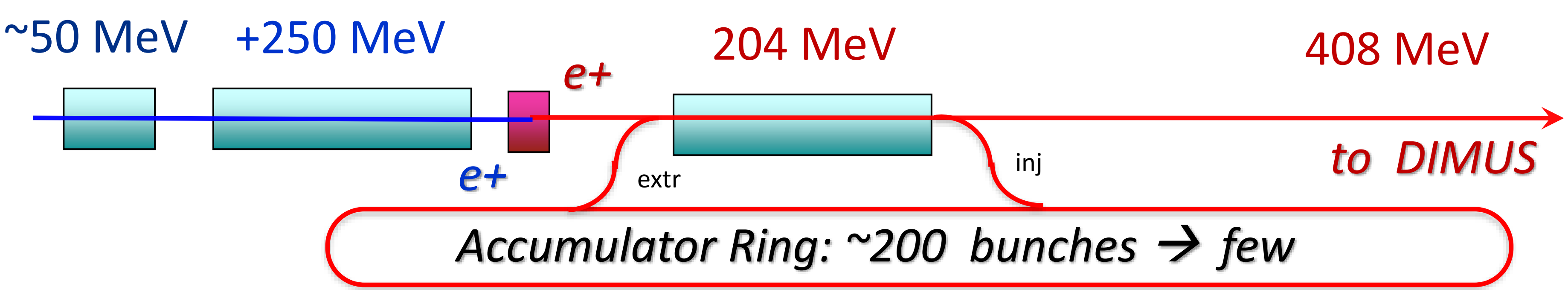
See more details in S. Posen's talk on Monday's SRF Session

Fermilab

Positron Production - Several Options

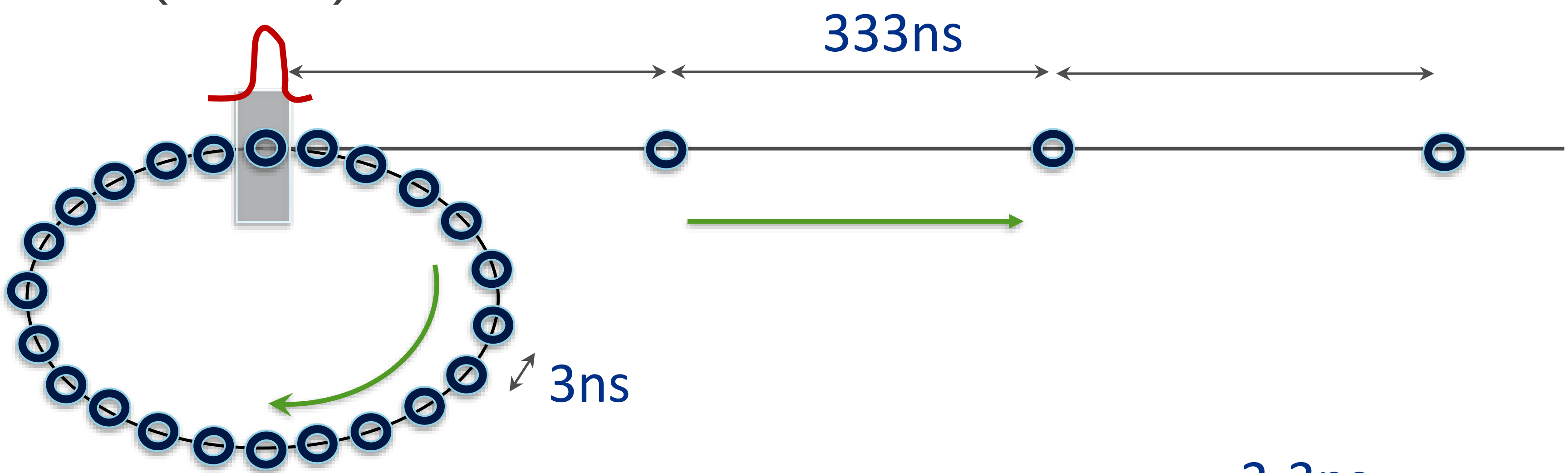
- Need (at least) two linacs:
  - Accelerate electrons (50… 300 MeV)
  - Convert them on tungsten target
  - Accelerate positrons which then go to a damping ring



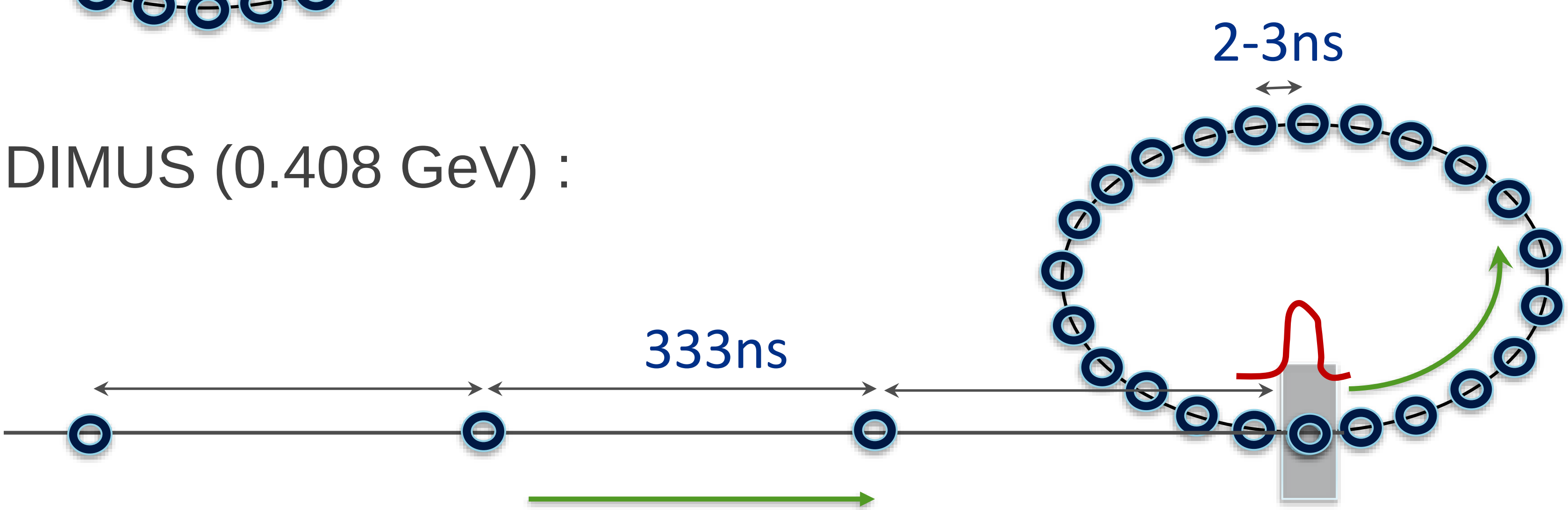


Very Fast Kickers

- ILC (5 GeV):



- DIMUS (0.408 GeV) :



Very Fast Kickers (2)

- 1997, 6ns, 300 pulses, 1.4 MHz, Grishanov, Podgorny, Rummler, Shiltsev

Nuclear Instruments and Methods in Physics Research A 396 (1997) 28–34

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER

Very fast kicker with high repetition rate for accelerator applications

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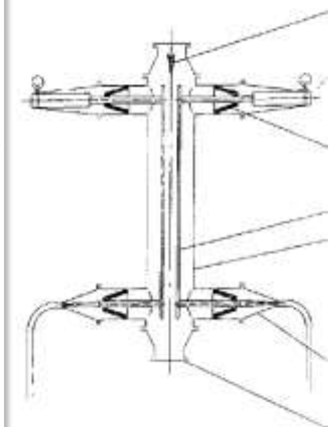
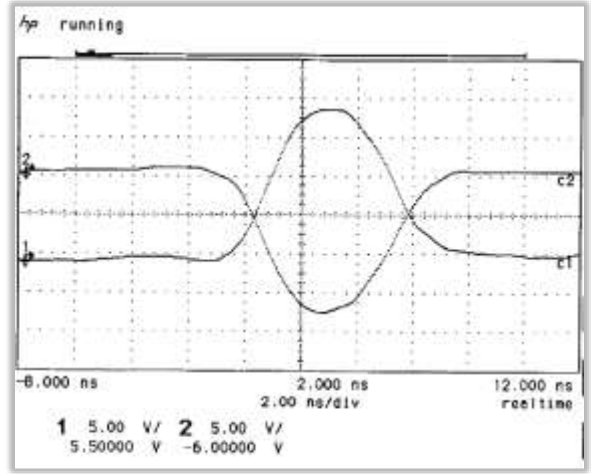
[c] Fermi National Accelerator Laboratory[1] M.S.345, P.O. Box 500, Batavia, IL 60510, USA

Received 18 February 1997; received in revised form 4 April 1997





- Now, ILC: 3ns, 3000 pulses, 1.3 MHz, KEK team

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 14, 051002 (2011)

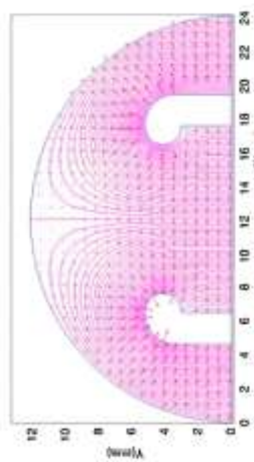
Multibunch beam extraction using the strip-line kicker at the KEK Accelerator Test Facility

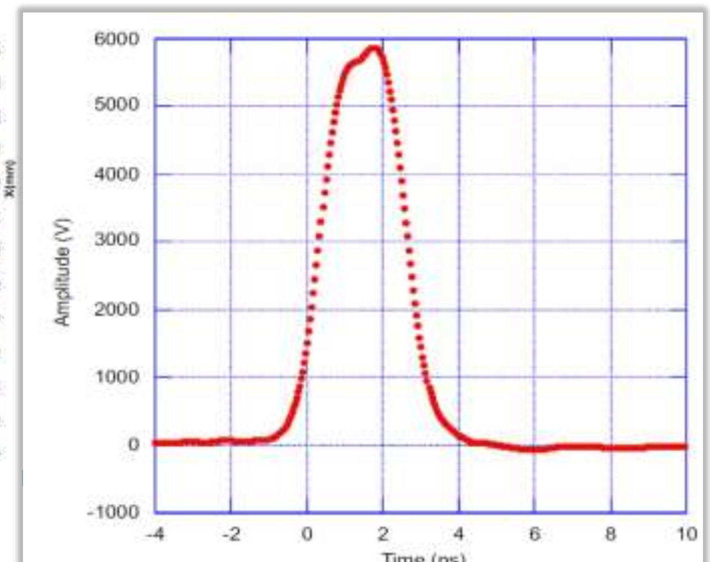
T. Naito,* S. Araki, H. Hayano, K. Kubo, S. Kuroda, N. Terunuma, T. Okugi, and J. Urakawa
KEK, Tsukuba, Japan

(Received 27 October 2010; published 18 May 2011)

The International Linear Collider (ILC) damping ring (DR) injection and extraction kickers have a very special role: the bunch spacing 189–480 ns is compressed to 3–9 ns when injected into the DR and then decompressed to 189–480 ns when leaving the DR. The kickers act as a bunch-by-bunch beam manipulator to compress and decompress the bunch spacing into/from the DR. They require a fast rise/fall time (3–9 ns) and a high repetition rate (6–2 MHz). Among the candidate technologies, the multiple strip-line kicker system is the most likely to realize the specifications for the ILC reference design. A beam extraction experiment with a prototype strip-line kicker has been carried out at the KEK Accelerator Test Facility (ATF). The kicker is composed of two units of 60-cm-long strip-line electrodes. The multibunch beam (30 bunches spaced at 5.6 ns) stored in the DR was extracted successfully with a bunch spacing of 308 ns. The measured stability of the kick angle was 3.5×10^{-4}. Some, but not all, parameters of the tested kicker meet the ILC-DR injection/extraction kicker requirements.

DOI: 10.1103/PhysRevSTAB.14.051002 PACS numbers: 29.20.−c, 29.27.Ac, 42.79.Fm





Example: 4 ns kicker = 2 ns min bunch spacing 0.6m

- Generate and accelerate ~200 *e*- bunches 2e10 each, 333ns apart
- Convert them into 200 *e*+ bunches 2e8 each, 333ns apart
- Inject them into accumulator (damping) ring 2 ns apart → 200 x 0.6 m = 120 m long (400 ns long)
- After sub-second damping time combine 200 *e*+ bunches into one with 4e10 *e*+
- Extract and accelerate that bunch to 408 MeV
- Inject into 23 m long (~80 ns) DIMUS *e*+ ring, it will be one of ~40 *e*+ bunches (others intact) → ***collide***

Fermilab

DiMuS at NML : Summary

- Dimuonium atoms are of fundamental interest
- They can be created in *e+e-* collision with large longitudinal momentum (as they quickly decay)
  – e.g. 408 MeV/beam at 75º
- FAST/NML is perfectly suitable for DIMUS:
  – SRF accelerators, plenty of *e*-, wide/long tunnels
  – potential for *O*(1e32) luminosity and ~0.5M dimuons per year
- Requires:
  – second SRF CM, positron production and accumulation system, collider rings, detector(s)

Part III: PWA Muon Source

JINST — PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

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ICFA BEAM DYNAMICS NEWSLETTER#83 —
CHALLENGES IN ADVANCED ACCELERATOR CONCEPTS

On possibility of low-emittance high-energy muon source based on Plasma Wakefield Acceleration

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E-mail: shiltsev@fnal.gov

Also FERMILAB-PUB-22-137-AD

Plasma Acceleration:

- Fast acceleration
- Very strong focusing

Eg in the bubble regime

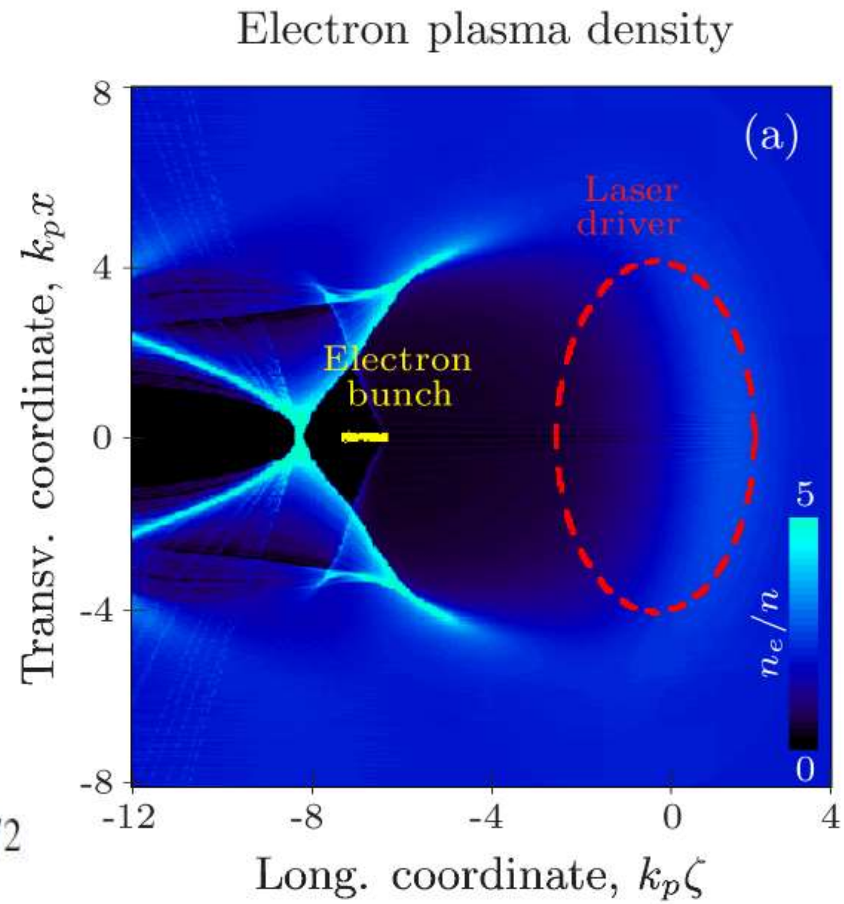
$$E_z/E_0 = k_p\zeta/2,$$

$$(E_r - B_\theta)/E_0 = k_p r/2.$$

Where

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

$10^{18}\ \mathrm{cm}^{-3}$ yields $E_0 \sim 100\ \mathrm{GV/m}$



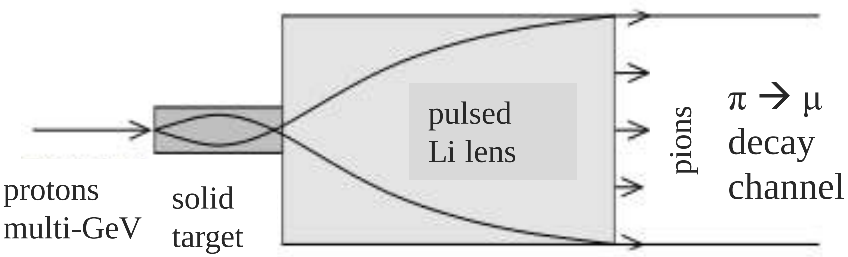
That's exactly what's needed for a muon source

Traditional Muon Sources:

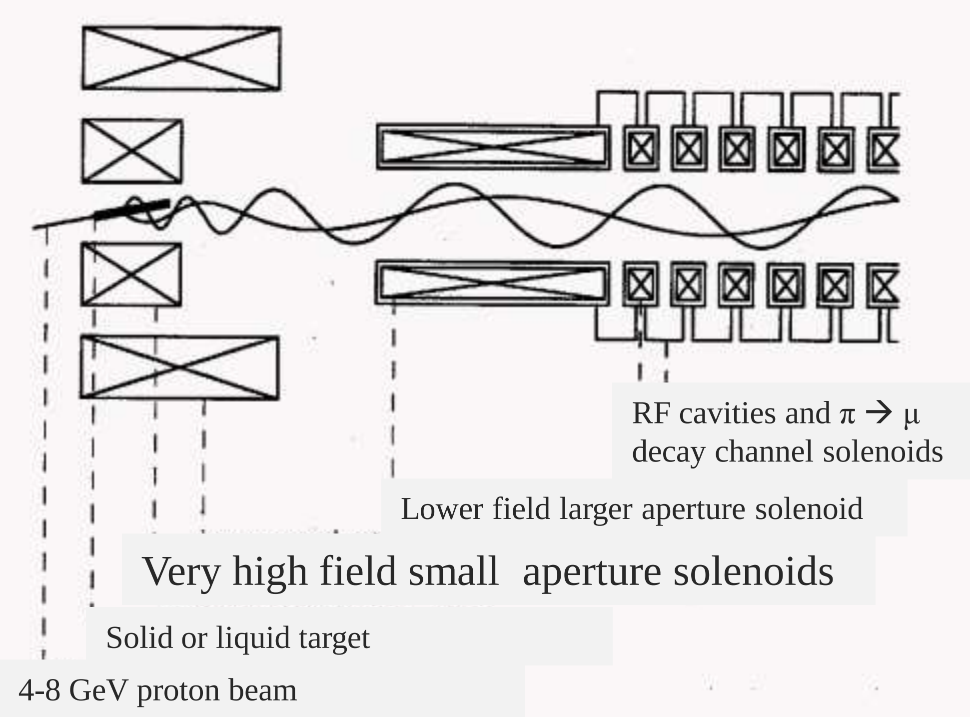
$$p \rightarrow \text{target} \rightarrow \pi^+(\pi^-) \rightarrow \mu^+(\mu^-)$$

$$\theta \simeq m_\pi / P_\pi \; O(1)$$

a) using pulsed short-focus Lithium lens O(300T/m) for collection of pions



b) using very high field SC solenoids O(20 T)



muon energy of about 200 MeV. The $p \rightarrow \mu$ conversion efficiency is very high $O(10\%)$ but resulting transverse normalized emittance of the muon beams are huge $O(0.1\ \text{m rad})$ and a sophisticated multi-stage ionization cooling section is required to reduce the transverse and longitudinal emittances by a factor of 10^6 (for 6D emittance) and to make the beams suitable for a multistage acceleration and, eventually, high luminosity $\mu^+\mu^-$ collisions.

Conceptual Scheme

- Muons can be born in a plasma channel via:

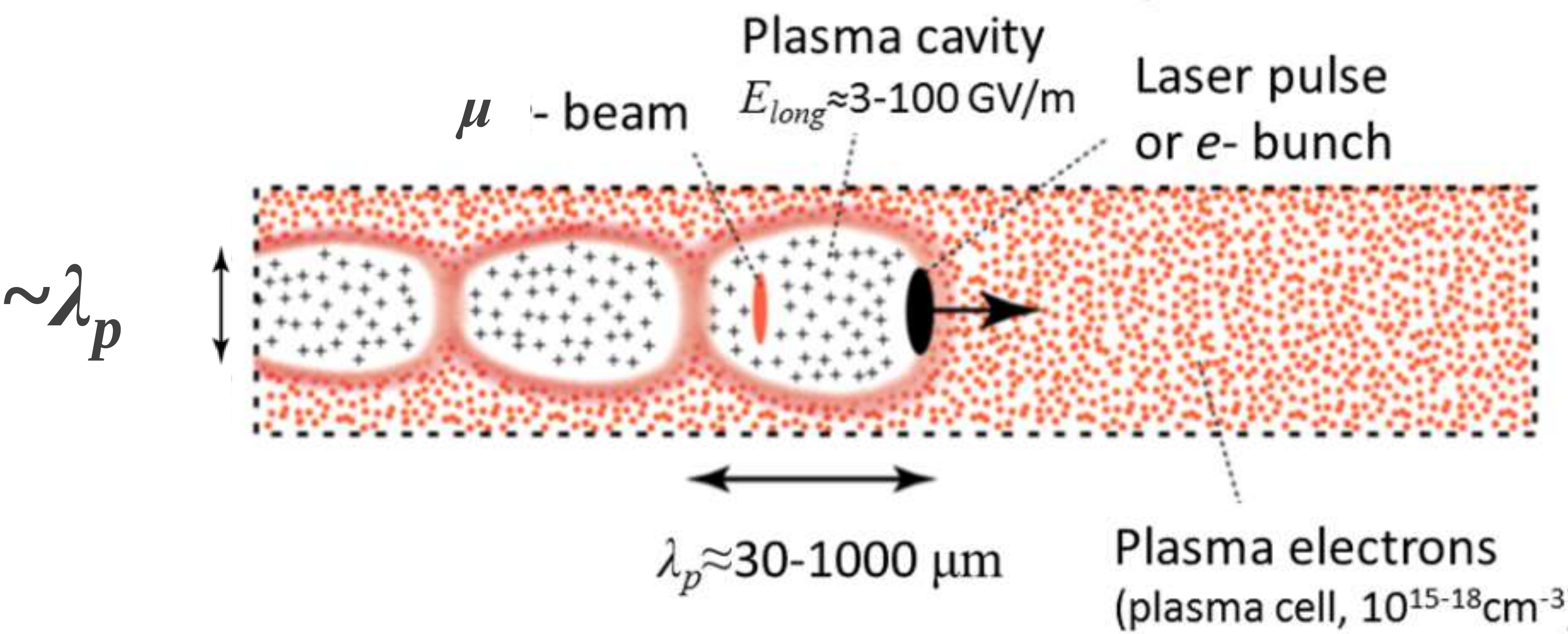
(a) photoproduction: high energy γ's or electrons on target $\rightarrow \mu^+(\mu^-)$;

(b) "standard" production scheme described above in the introduction: protons $\rightarrow$ target $\rightarrow$ pions $\rightarrow \mu^+(\mu^-)$;

(c) generation of "prompt" muons: protons $\rightarrow$ target $\rightarrow$ vector mesons $\rightarrow \mu^+(\mu^-)$.

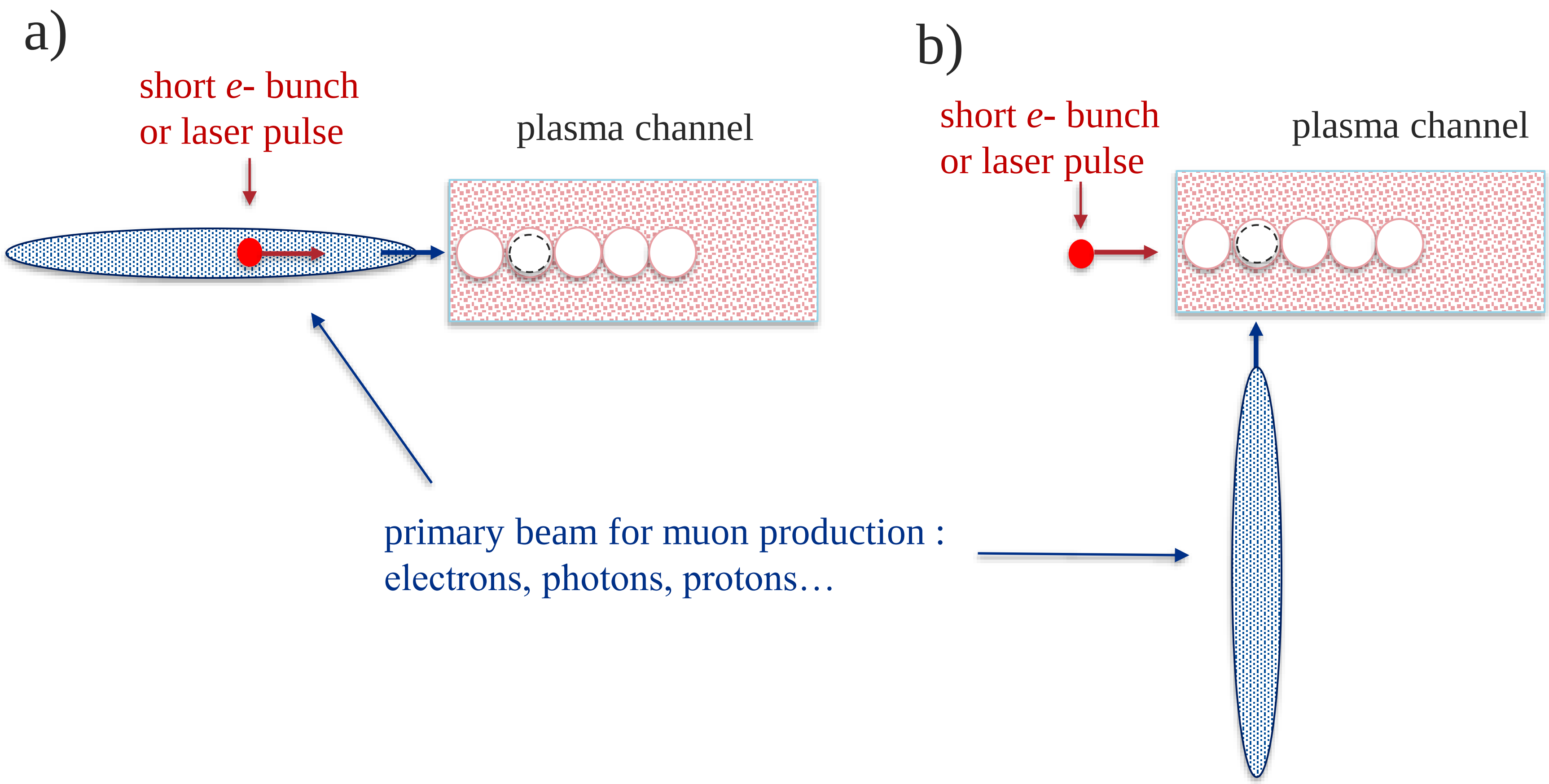
- Muons originally have large angular spread and small transverse dimension:
  - $\theta \approx m_\mu / E_\mu$
  - r smaller than the radius of the bubble $\sim\lambda_p$
- Muons get quickly accelerated in the plasma while super-strongly focused by the focusing fields of the plasma:
  - Come out with small emittance
  - Come out with very high energy O(10 GeV)

Plasma WFA Muon Source Scheme



$$\lambda_p = c/\omega_p \approx 33\,\mu\mathrm{m} \times \sqrt{10^{18}\,\mathrm{cm}^{-3}/n_0}$$

Possible arrangements:

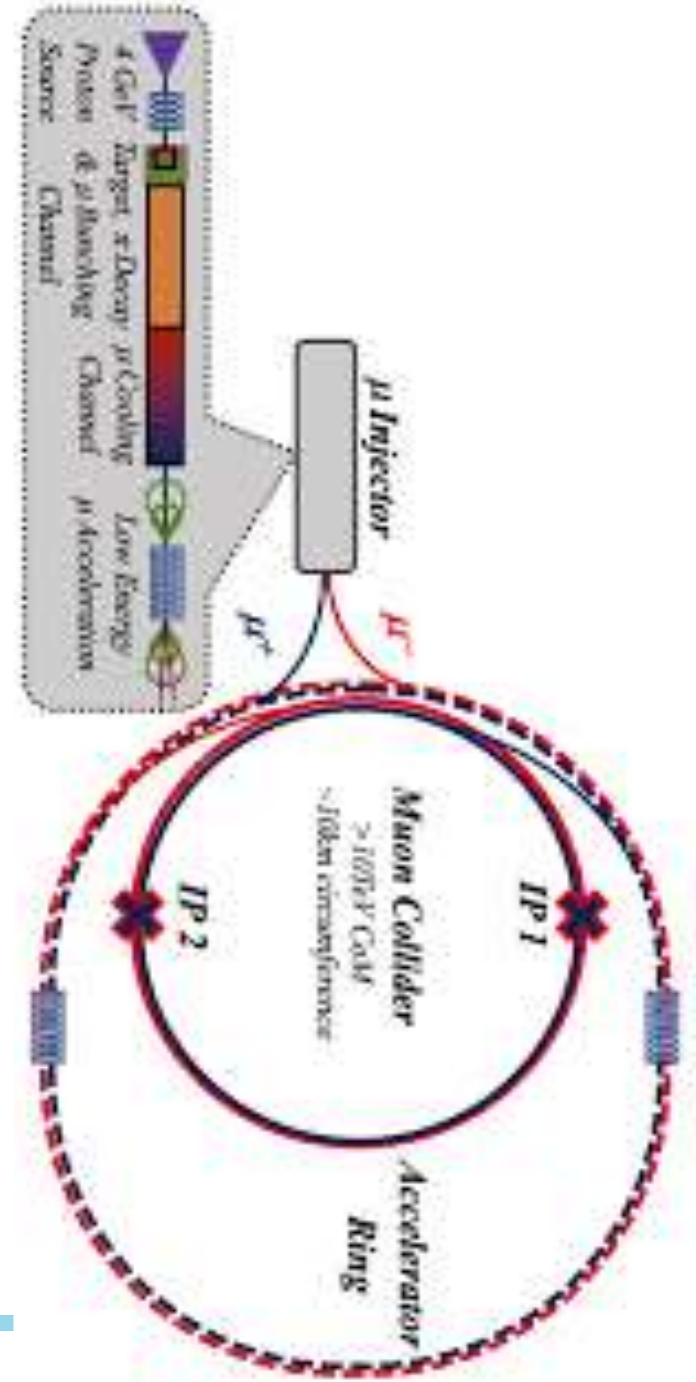


The focusing forces of the plasma bubble

$$G = E_0 k_p/2 \simeq 0.3\,\mathrm{MT/cm}(n_p/10^{18}) \sim 300\,\mathrm{kT/cm}$$

Plasma WFA μ Source Potential

- Eliminates the most complex muon production and early acceleration part of multi-TeV muon colliders
- Very compact *O*(10 m) total
- *O*(10 GeV) beams with norm. emittance from few nm to few 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)*



Muons in PWA Channel

- Longitudinal DoF:

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

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

$$\kappa \simeq 2$$

- quickly becomes relativistic

Muons in PWA Channel – Transverse Plane

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

The exact solution is:

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

- betatron oscillations are fast compared to the rate of acceleration:

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

fractional energy increase over the betatron oscillation period $\Delta\gamma_\mu/\gamma_\mu$ is small:

$$\frac{\Delta\gamma_\mu}{\gamma_\mu} = \frac{2\pi\beta_\mu\kappa k_p(m_e/m_\mu)}{\gamma_\mu} = 2\pi\kappa\sqrt{\frac{2m_e}{\gamma_\mu m_\mu}} \lesssim \frac{0.1}{\sqrt{\gamma_\mu}}.$$

Muons in PWA Channel – Transverse Plane (2)

Therefore, the transverse motion is adiabatic, the period of the muon oscillations grows as: $\sqrt{\gamma_\mu} \propto \sqrt{z}$

while the amplitude slowly diminishes as

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

The maximum angular deviation $\theta = dr/dz$ and the maximum amplitude relate to each other as $\theta_{\max} = r_{\max}/\beta_\mu \qquad r_{\max} \simeq \lambda_p/2$, thus

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

and the maximum normalized acceptance of the muons captured and accelerated in the PWA channel:

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

the estimated normalized emittance of the accelerated muon beam $\epsilon_\mu^{\max} \approx 2.6\,\mu$m for dense gaseous plasma $n_e = 10^{18}$ cm^{-3} and about 8–20 nm for solid state plasma $n_e = 10^{22-23}$ cm^{-3}. In the first

Tapering of PWA Channel to Maximize Acceptance

E.g., if one takes the desired normalized acceptance of ϵmaxμ then according to eq. (2.9), in order to keep it constant along the channel, the plasma wavelength should scale as:

$$\lambda_p(z) = \lambda_p^0 \gamma_\mu(z)^{-1/4}$$

where initial plasma density should correspond to initial wavelength of

$$\lambda_p^0 = \epsilon_\mu^{\max}/0.078.$$

Solution of is trivial,

$$n_p(z) = n_p^0 \Big(1 + \alpha z\Big)^{2/5}, \qquad \gamma_\mu(z) = \Big(1 + \alpha z\Big)^{4/5}$$

where $\alpha = (5\pi \kappa m_e)/(2\lambda_p^0 m_\mu)$

Example of "Tapered" PWA Channel

density profile for a 2.5m long 10 GeV muon source with $\epsilon max\mu$ = 25 µm (corresponding to $\lambda 0p$ = 0.33mm and $n0p$ = 10^16 cm-3.

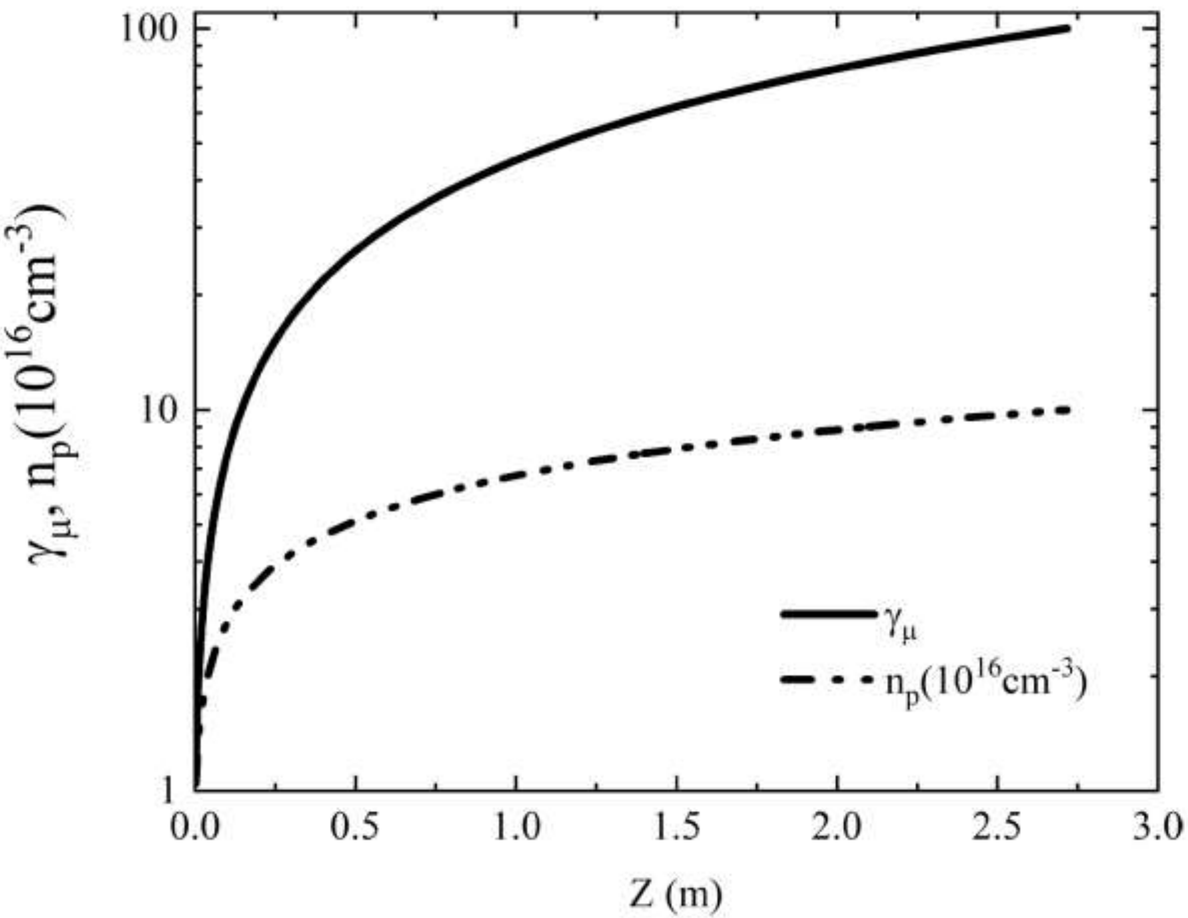


Figure 4. Plasma density and muon energy in tapered PWA-based 10 GeV muon source with normalized acceptance of 25 µm.

Photoproduction:

All these schemes have serious challenges, some of them considered in [12]. The photoproduction via Bethe-Haitler (BH) reaction $\gamma + Z \rightarrow \mu^+\mu^- + Z$ has small cross-section. Photons need to have energy far exceeding the muon production threshold of 210 MeV and can be obtained via bremstrahlung of multi-GeV electron beam in the target. Similar BH-channel efficiency for the positron production is $O(1\%)$ e^+/e^-. For the muon pair production, the BH cross-section is $(m_e/m_\mu)^2 = 1/40000$ times smaller — so, not only that muon efficiency will be $O(10^{-(5-6)})$ but also one should expect significant loading of the plasma bubble by much more numerous electrons and positrons.

Even smaller are cross-sections of the muon pair production via e^+e^- annihilation $\sigma = 87\,\mathrm{nb}/s(\mathrm{GeV}^2)$ and even with most optimistic luminosity assumptions the production rate will be in sub-Hz regime [13].

Nuclear production channels:

Muon production cross-sections via photo-meson reaction and proton-nucleon reactions can be quite high $O(100\ \mathrm{mb})$ and conversion efficiencies can indeed be high, but the problem is two fold: a) proton bunches are usually much longer $O(1-10\,\mathrm{cm})$ and only a small fraction of proton beam can interact with plasma when the short sequence of bubbles exist in the plasma after the passage of drive laser pulse or short electron bunch; b) also, the immediate products of these reactions are mesons (pions and kaons) and takes long time and distance for them to decay into muons. For charge pions it is $\tau = 26$ ns ($c\tau = 7.8$ m) and, correspondingly, these pions should stay in the plasma channel for that long to decay that creates additional difficulties.

Prompt muons:

There are fast decay options, eg $\pi^0 \rightarrow \gamma\gamma$ (τ =85 as with follow up photons possibly generation muons is of high enough energy. That would require very high energy primary proton beams $O(100\,\mathrm{GeV})$. Similarly, fast decays via vector bosons (e.g., D's) and generation of so called *prompt muons* offer another opportunity [14–16]. These reactions might have relatively high (still small) cross-section $O(1\,\mu\mathrm{b})$ and might require very high energy of primary protons $O(100\text{-}1000\,\mathrm{GeV})$. Practicality of these and other possible muon generation schemes for the PWA-based muon sources requires further, more detail examination.

Can other advanced schemes be of help?

Gamma factory?

Positron driven production?

Challenges and Open Questions

- Acceleration and focusing of $\mu+$ as challenging as for positrons in "traditional" LPWA and PWFA
- Collider application requires both small emittances <u>and high intensity </u>(ie brightness) muon beams – that needs to be studied in detail and most promising options analyzed
- Plasma wakes are essentially low-*Q*, so only one of few plasma periods/bubble can be employed → few short muon bunches
- Bubble wake loading by secondaries (e+e-, pions, etc)
- Simulation tools are widely available – detail analysis needs to be carried out

(Some) References:

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2. Bjorken FISR idea – J. D. Bjorken, *Lect. Notes Phys.* 56, 93 (1976).

3. μμTron – A.Bogomyagkov, et al, arXiv:1708.05819; *EPJ Web.Conf* 181, 01032 (2018)

4. 6 ns kicker – B. Grishanov, et al *NIM-A* 396(1-2) 28-34 (1997)

5. 4 ns kicker – T. Naito, et al, *PRAB* 14(5), 051002 (2011)

6. Positron sources – R.Chehab, 1992 *CAS CERN School, 2,* 643-678 (1994)

Table II

Beam energy, MeV	408
Number of particles/bunch current, mA	$3.5 \times 10^{10}/73$
Energy loss per turn, keV	2.3
Synchrotron frequency	1.71×10^{-2}
Damping time, hor/ver/longl, ms	17.3/27.3/22.1
Hor emittance (without/with IBS), nm	26/90
Energy spread (without/with IBS), $\times 10^4$	4/8.4
Longitudinal size (without/with IBS), mm	5.4/11.6
Invariant mass resolution, keV	390
Hor/ver IP beta function, mm	200/2
Hor/ver beam–beam parameter (ξ_x/ξ_y)	$2 \times 10^{-6}/1.2 \times 10^{-3}$
Longitudinal beam–beam parameter ξ_z	-2×10^{-3}
Luminosity (20 bunches), $cm^{-2}\ s^{-1}$	8×10^{31}