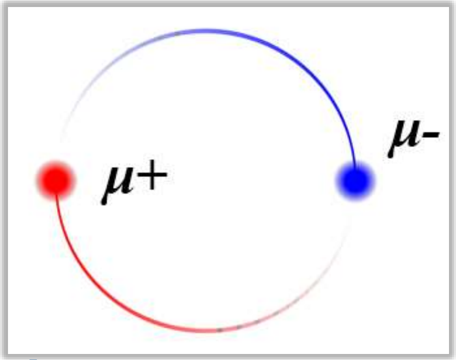
Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

DIMUS at NML: Opportunity for Di-Muon-Spectroscopy Collider



Vladimir Shiltsev

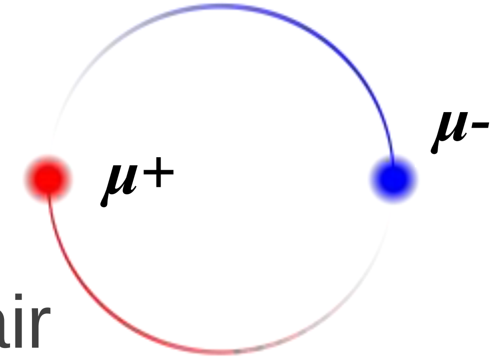
Potential Fermilab Muon Campus & Storage Ring Experiments

May 27, 2021

Content:

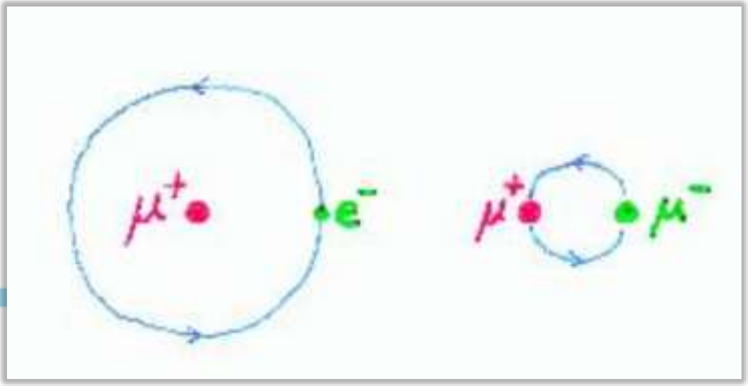
- This is the first of three talks today on DiMuonium Collider:
  - Followed by Patrick Fox (theory)
  - Followed by Sergo Jindariani (experiment)
- My talk will be mostly about accelerator systems of the DIMUS collider at the New Muon Lab (NML) facility at Fermilab
- Some details can also be fount at ***beams-doc*-9017**

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 … overy.
- QED tests (dimuonium ≠ positronium x m …
- Muon sector anomalies:
  - About 4.2 sigma differen… $(g\text{-}2)_\mu$ SM prediction and measurement… 5 sigma)
  - Proton/de… uzzle
  - Hi… iversality violation in rare B decays: … e+e- and $B+ \rightarrow K+ \mu+ \mu-$ (@SuperKEKB)
- Very complex experimental task → challenge for experimentalist → development of new methods

…see Patrick Fox's talk…

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

PRL **102,** 213401 (2009) PHYSICAL REVIEW LETTERS ...nding ...2009

Production of the Smallest QED Atom: True Muoni...

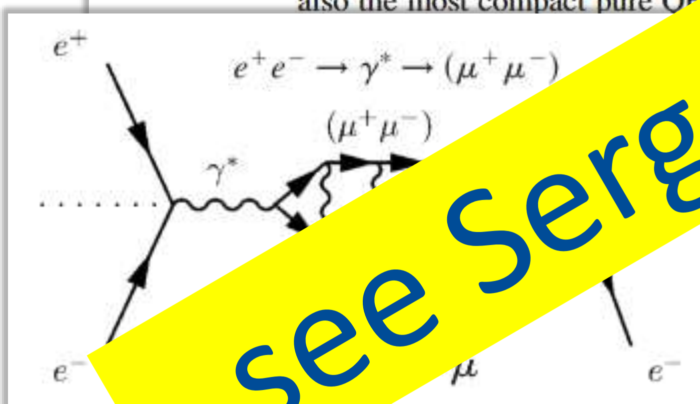
Stanley J. Brodsky*
SLAC National Accelerator Laboratory, Stanford Universi... ..., USA

Richard F. L...
Department of Physics, Arizona State ... ...5287-1504, USA

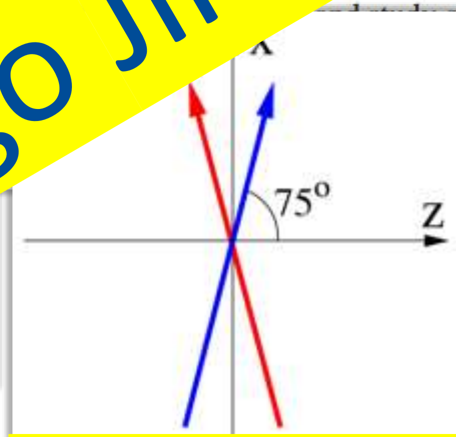
(Received 22 Apr... ...009)

The "true muonium" ($\mu^+\mu^-$) an... ...und states are not only the heaviest, but also the most compact pure QE... ...decay of the ... makes the observation of true ...

...see Sergo Jindariani's talk...



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



merge at 5°-15°

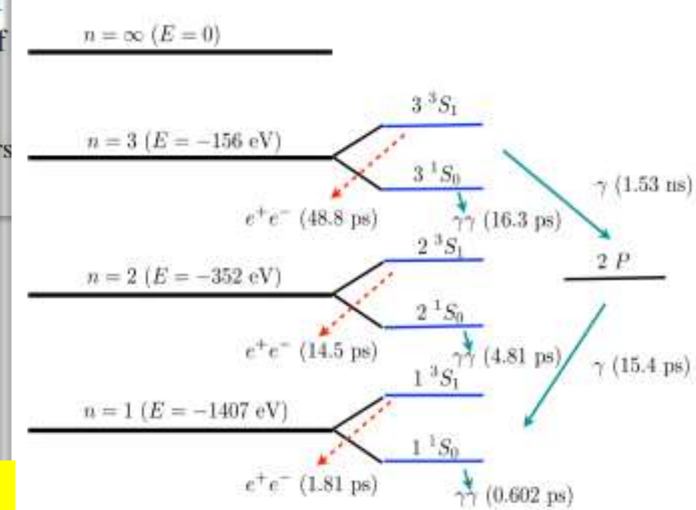


FIG. 1 (color online). True muonium level diagram (spacings not to scale).

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

Part II: e+e- Collider Design

arXiv.org > physics > arXiv:1708.05819

Search...

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Physics > Accelerator Physics

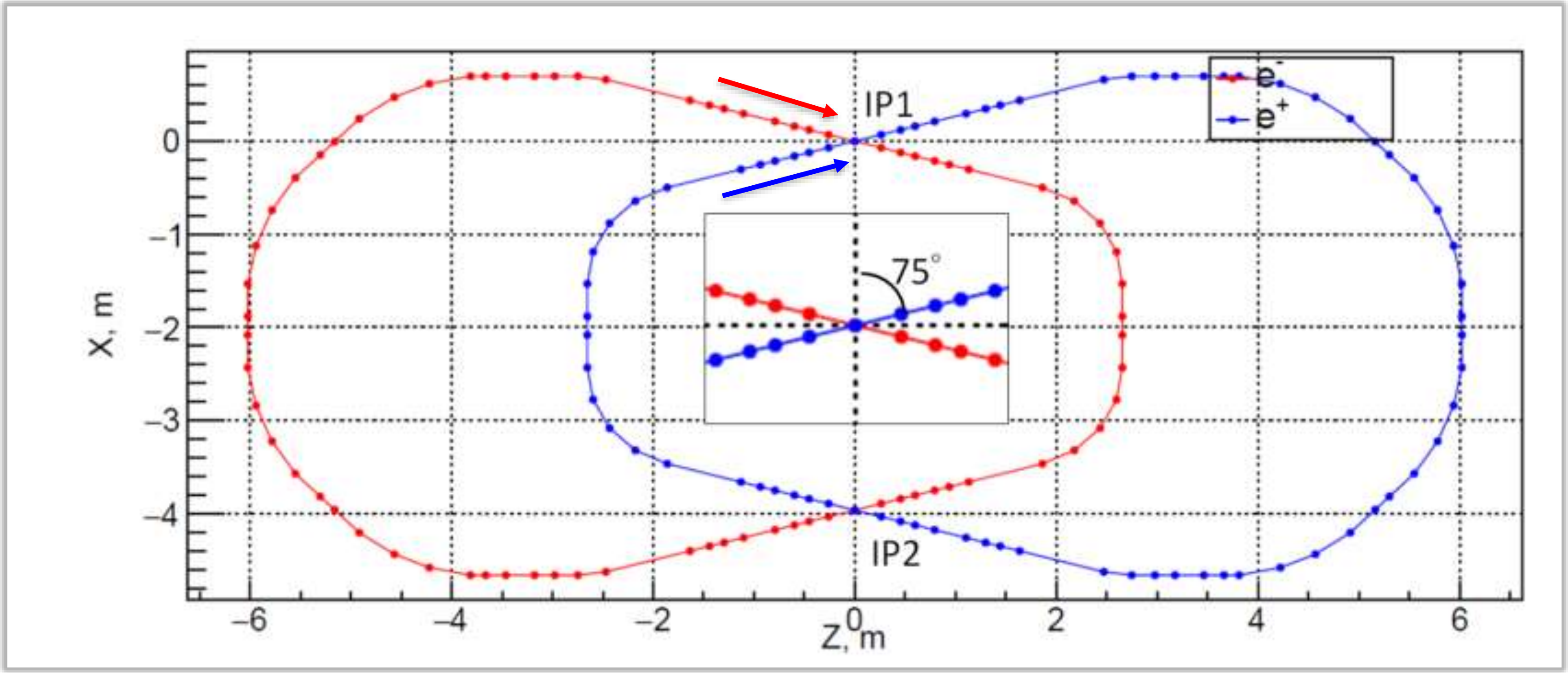
[Submitted on 19 Aug 2017]

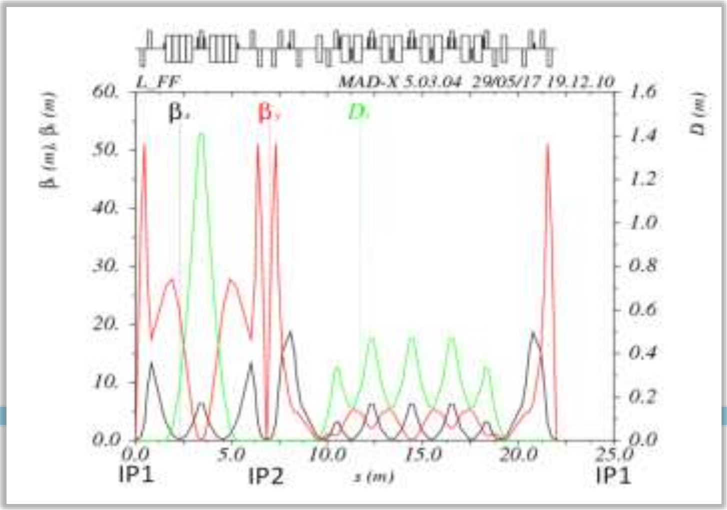
Low-energy electron-positron collider to search and study (μ^+μ^-) bound state

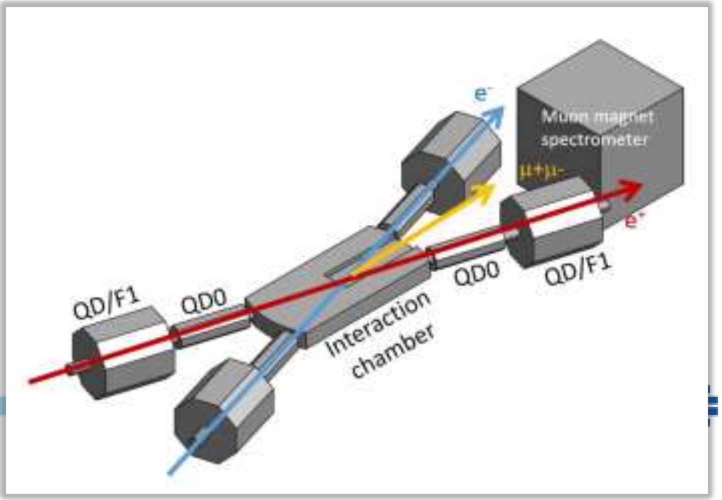
A. Bogomyagkov, V. Druzhinin, E. Levichev, A. Milstein, S. Sinyatkin

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







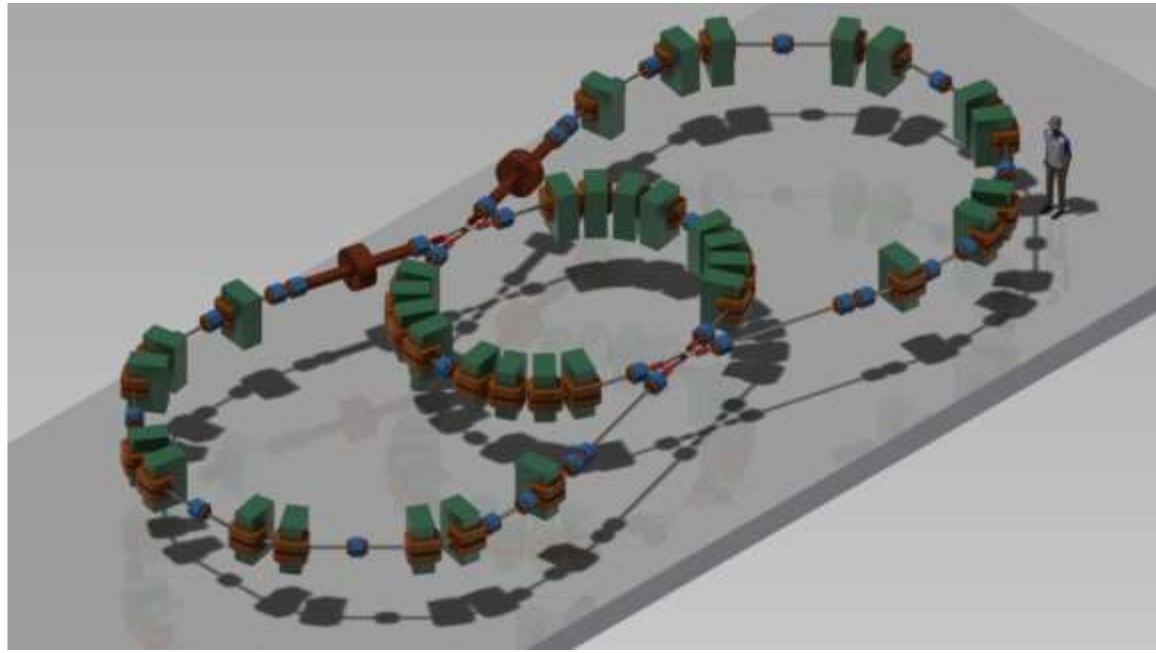
Fermilab

Novosibirsk “Mu Mu Tron” Design (2017)

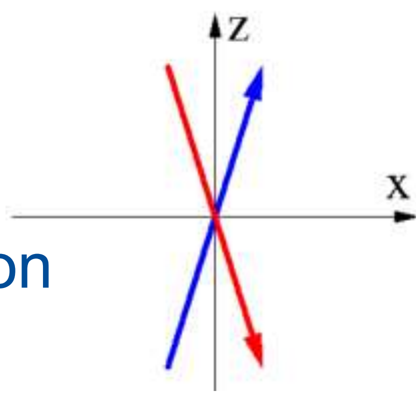
E_{beam} of	408 MeV
E_{CM}	211 MeV
Circumference	23 m
Bunch intensity	3.5×10^{10}/73 mA
Number of bunches	20
σ_x at IP	102 μm
σ_y at IP	0.84 μm
σ_z at IP	11 mm
L_{aver}	8×10^{31} $cm^{-2}c^{-1}$

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°)



- ✓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

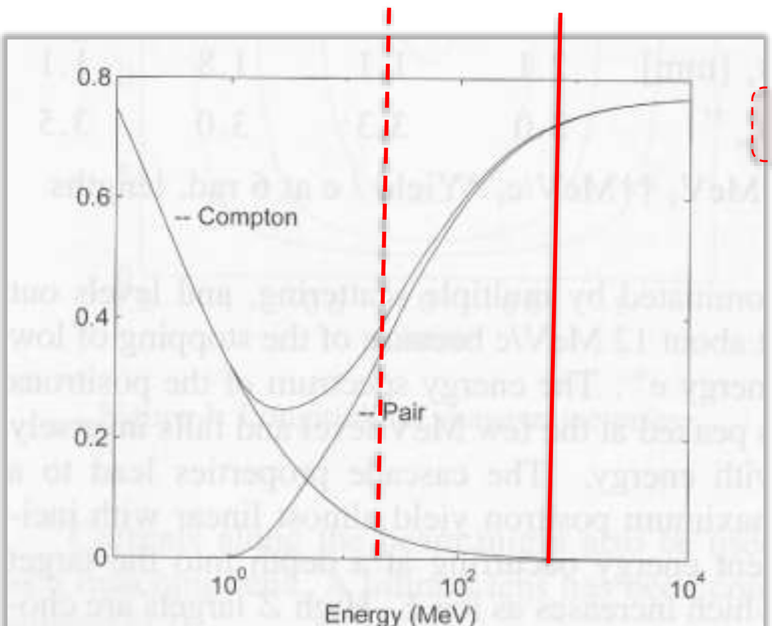
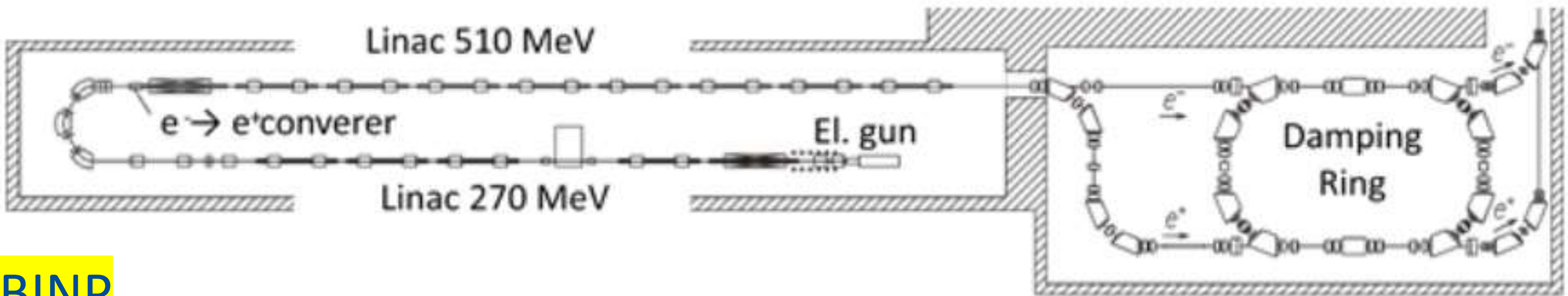


Figure 1: Probability per X_0 of e^+e^- pairs and Compton scattering vs incident photon energy.

Beam energy (MeV)	408
Circumference (m)	23
Bunch intensity/current (mA)	$3.5\times10^{10}/73$
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}

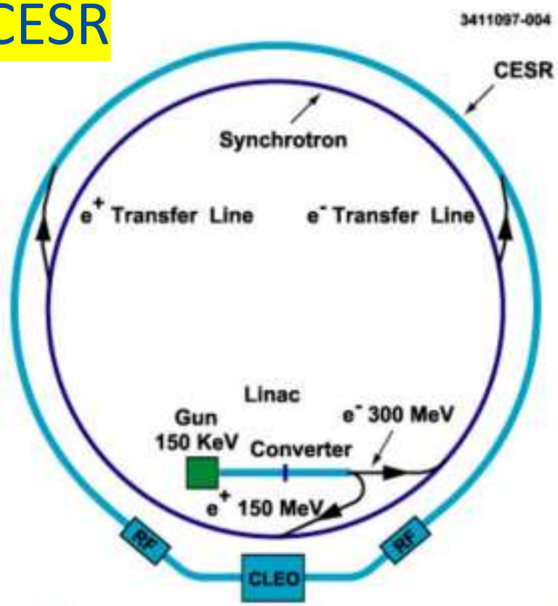
Positron Production: BINP and CESR ~(0.01-0.03) *e+ per e-*

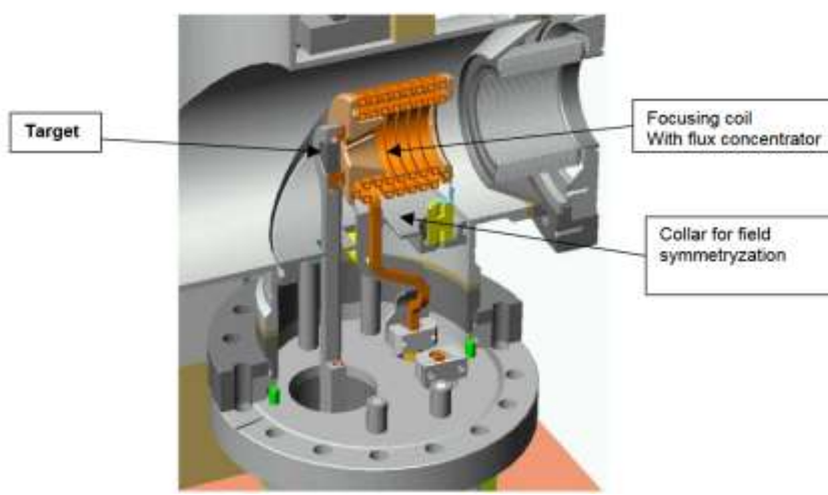


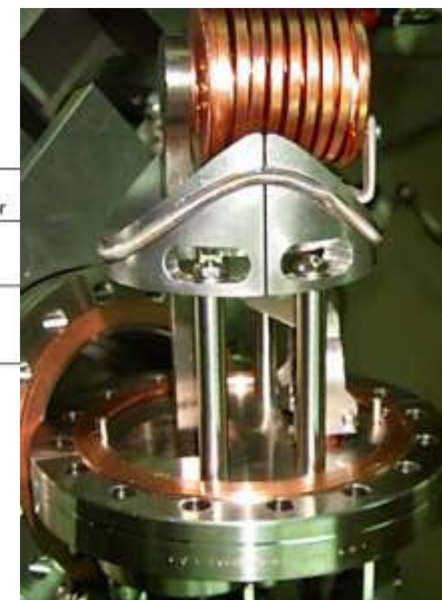
BINP

Figure 2: VEPP-5 Injection Complex layout.

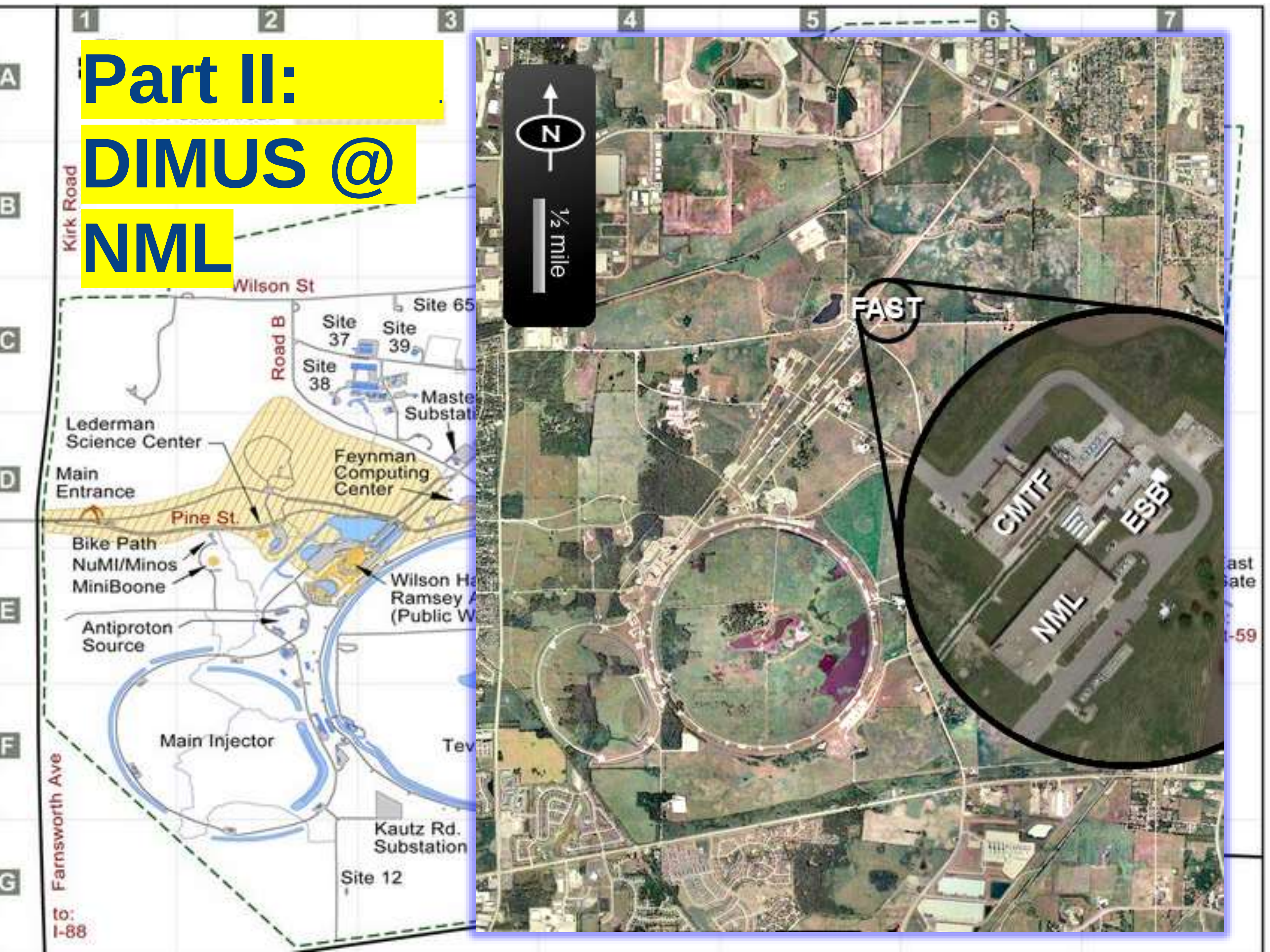
CESR





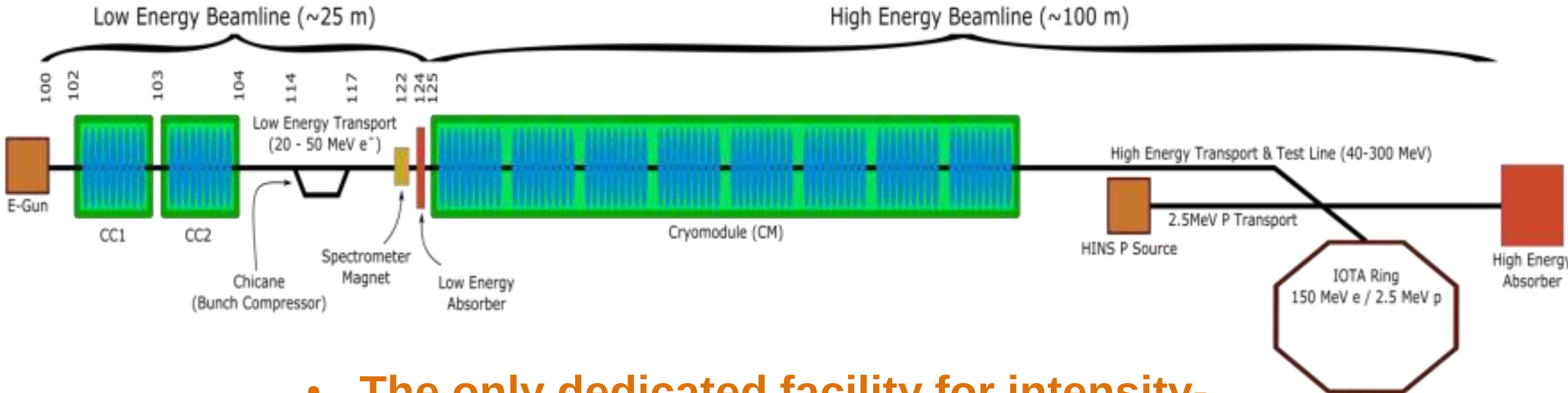


Part II: DIMUS @ NML



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


IOTA proton injector

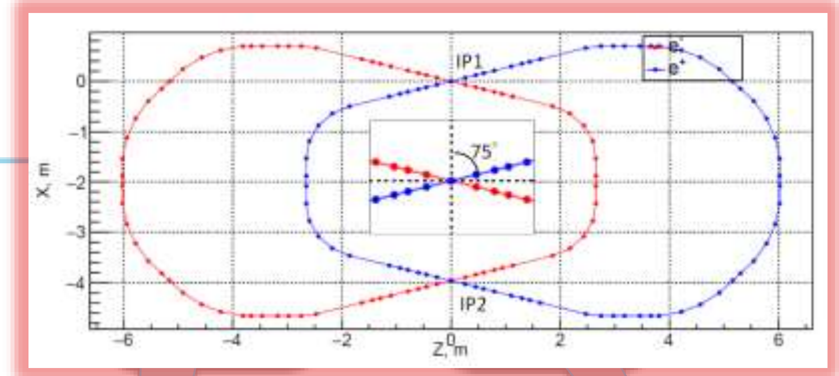
DiMuonSpectroscopy (DiMuS) at NML : Opportunities

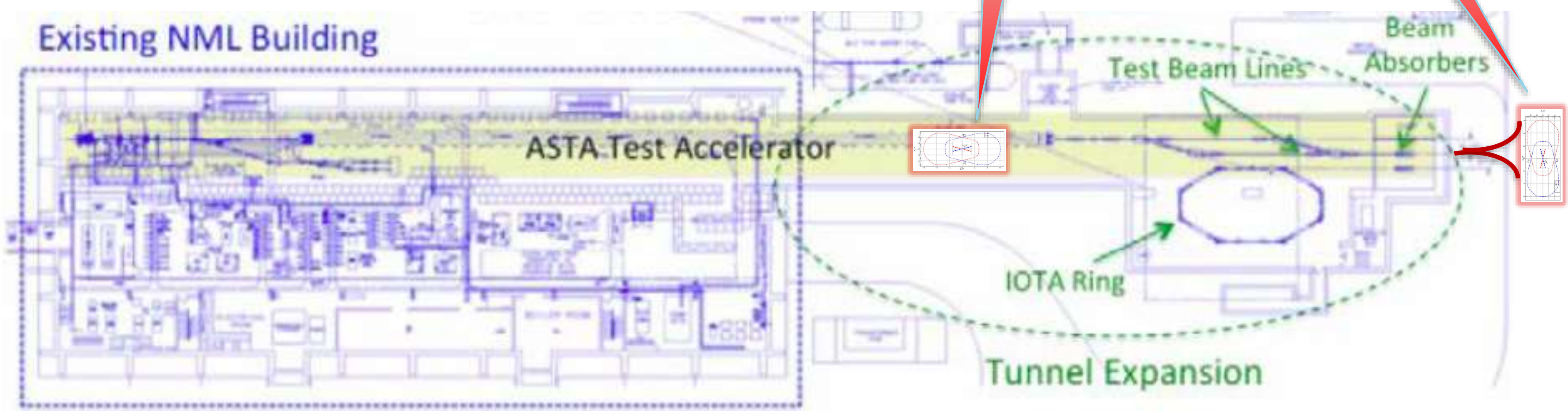
- Excellent source of high energy electrons:
  - eg 3000 bunches x 5 Hz x 2e10 = 3e14 *e*-/s
  - at 1% conversion → 3e12 *e*+/s
- DIMUS will probably need much less
  - eg 200 bunches x 1 Hz x 2e10 = 4e12 *e*-/s
  - at 1% conversion → 4e10 *e*+/s
- Efficient linac – now upto 300 MeV
  - DIMUS will need 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





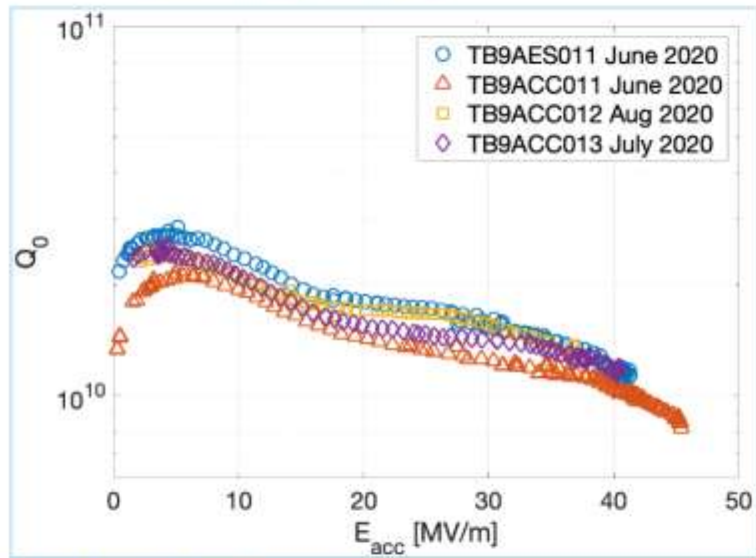
The Second CryoModule

- *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 1.0×10^{10} at 38 MV/m.
- Some other CM improvements (magnetic shield, tuner, …)

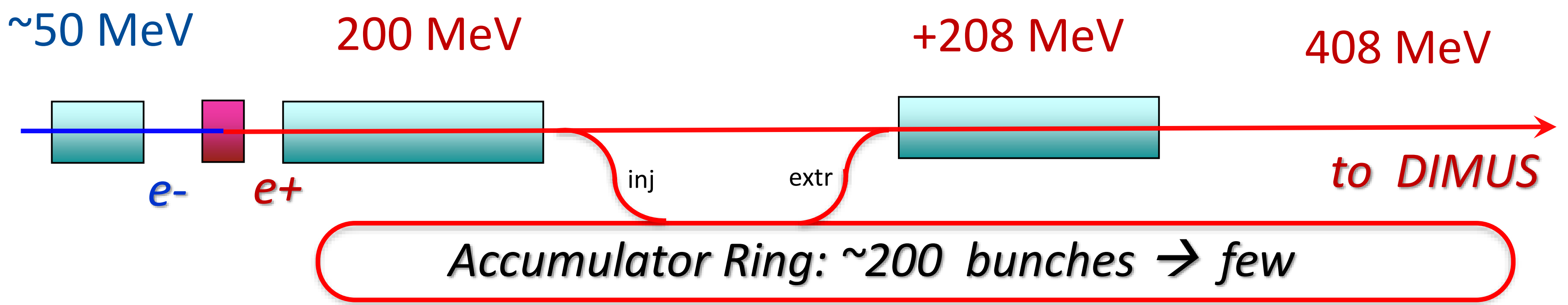
Cavity candidates to date (average gradient 41 MV/m):
- TB9AES011 – 41.3 MV/m
- TB9ACC011 – 45.5 MV/m
- TB9ACC012 – 36.9 MV/m
- TB9ACC013 – 40.4 MV/m

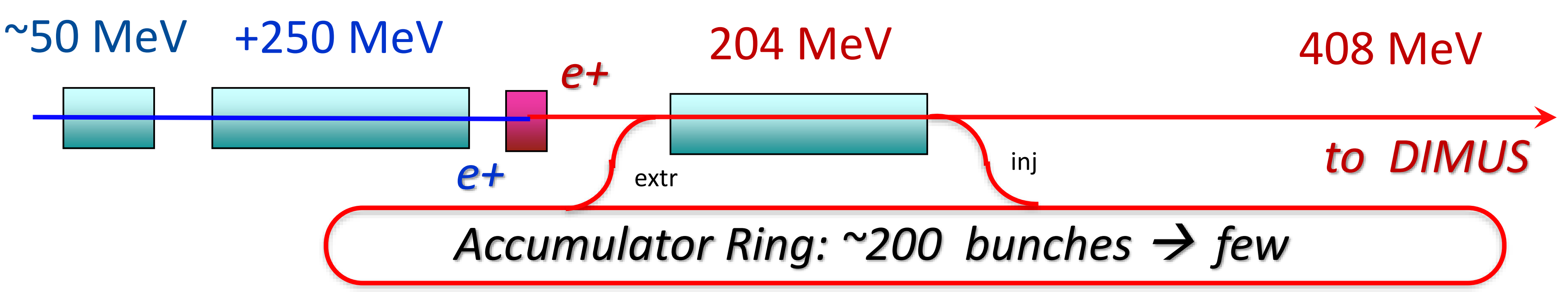


See more details in S. Posen's talk on Monday's SRF Session

Positron Production - Several Options

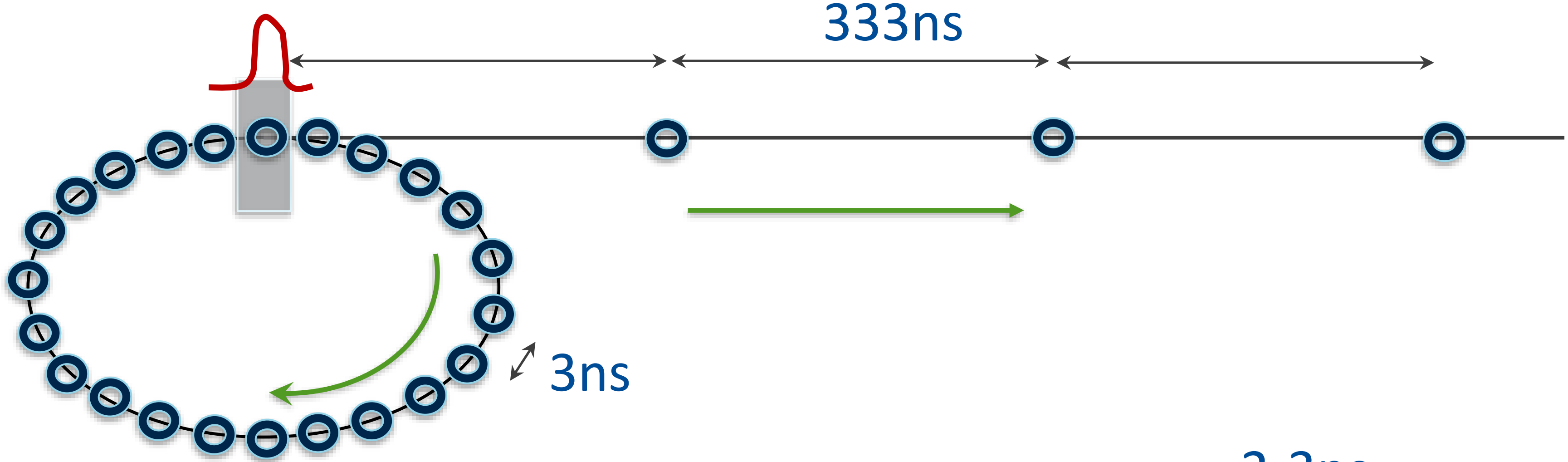
- Need (at least) two linacs:
  - Accelerate electrons (50… 300 MeV)
  - Convert them on tungsten target
  - Accelerate positrons which then go to a damping ring



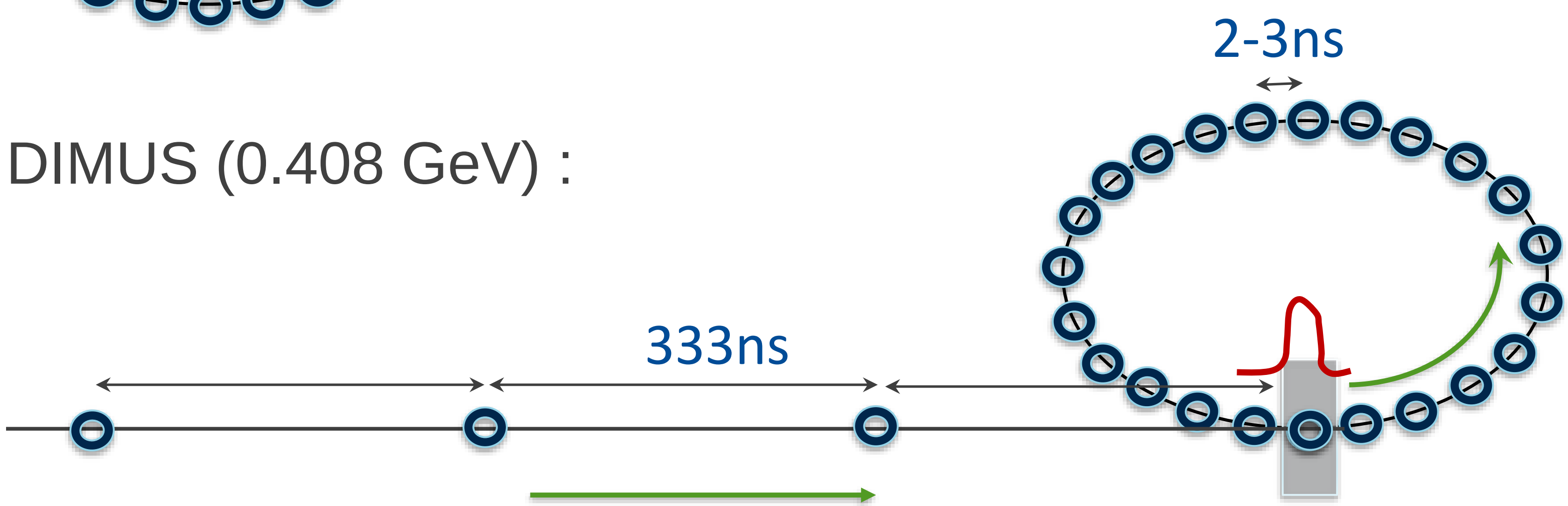


Very Fast Kickers

- 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

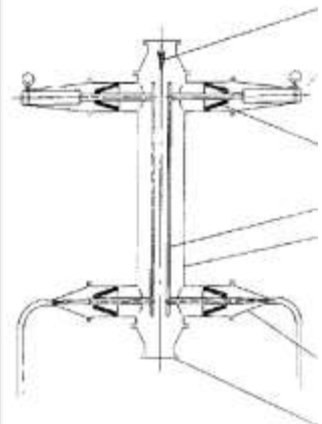
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

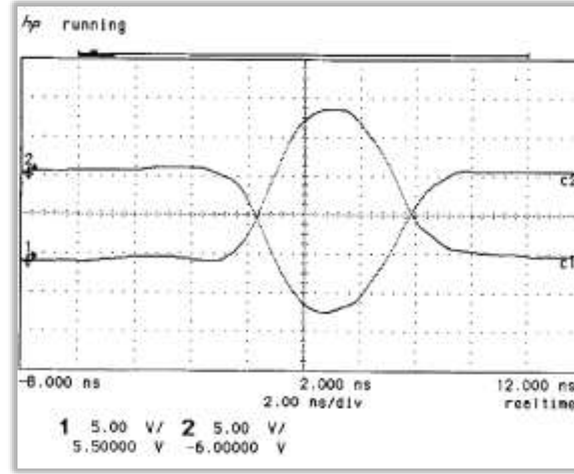
Very fast kicker with high repetition rate for accelerator applications

B.I. Grishanov[a], F.V. Podgorny[a], J. Rümmler[b], V.D. Shiltsev[c,*]

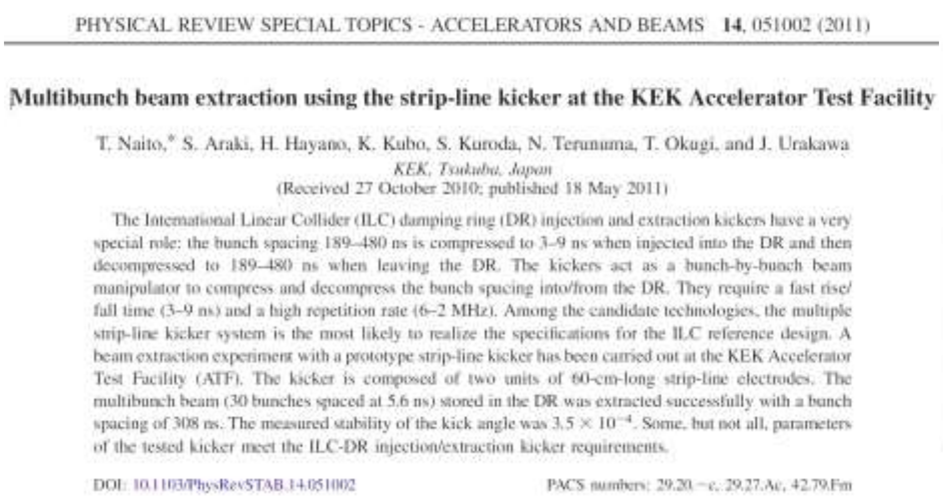
[a] Budker INP, Novosibirsk, 630090, Russian Federation
[b] DESY, Notkestrasse 85, Hamburg 22603, Germany
[c] Fermi National Accelerator Laboratory[1] M.S.345, P.O. Box 500, Batavia, IL 60510, USA

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

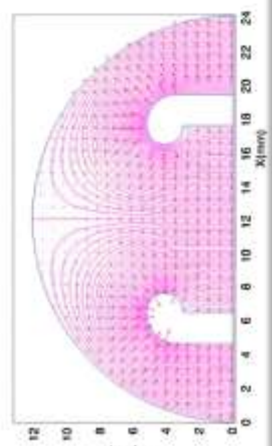
T. Naito,* S. Araki, H. Hayano, K. Kubo, S. Kuroda, N. Terunuma, T. Okugi, and J. Urakawa

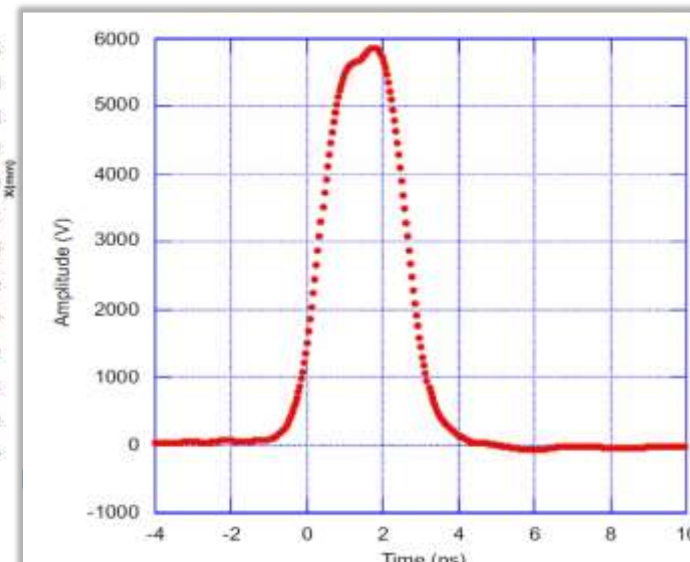
KEK, Tsukuba, Japan

(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***

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)

Thank you for your attention!

(Some) References:

1. 1st concept – S.J.Brodsky and R.F.Lebed, *Phys. Rev. Lett.* 102, 213401 (2009)

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}