Overview of Accelerator Facilities Considered by the FNAL Steering Group

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with contributions from SG3,4,5 members and speakers

The list

#1: 6 GeV ILC Linac
#2: High Intensity Proton Source
#3: ILC DR Test Facility
#4: Super B factory
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#6: LHC Luminosity Upgrade
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#10: 1 TeV fixed target protons from Tevatron
#11: Antiproton Sources
#12: Tevaron B-physics
#13: Beta-beams
#14: Muon Cooling Facility
#15: Muon Collider
#16: VLHC

For each facility :

1. Brief description/basics of operation
2. Anticipated performance parameters
3. Anticipated cost range (<$100M, $100M – $0.5B, >$0.5B)
4. Critical R&D issues need to be resolved before construction
5. Estimated construction duration
6. Potential synergies with other programs
7. References (when available)

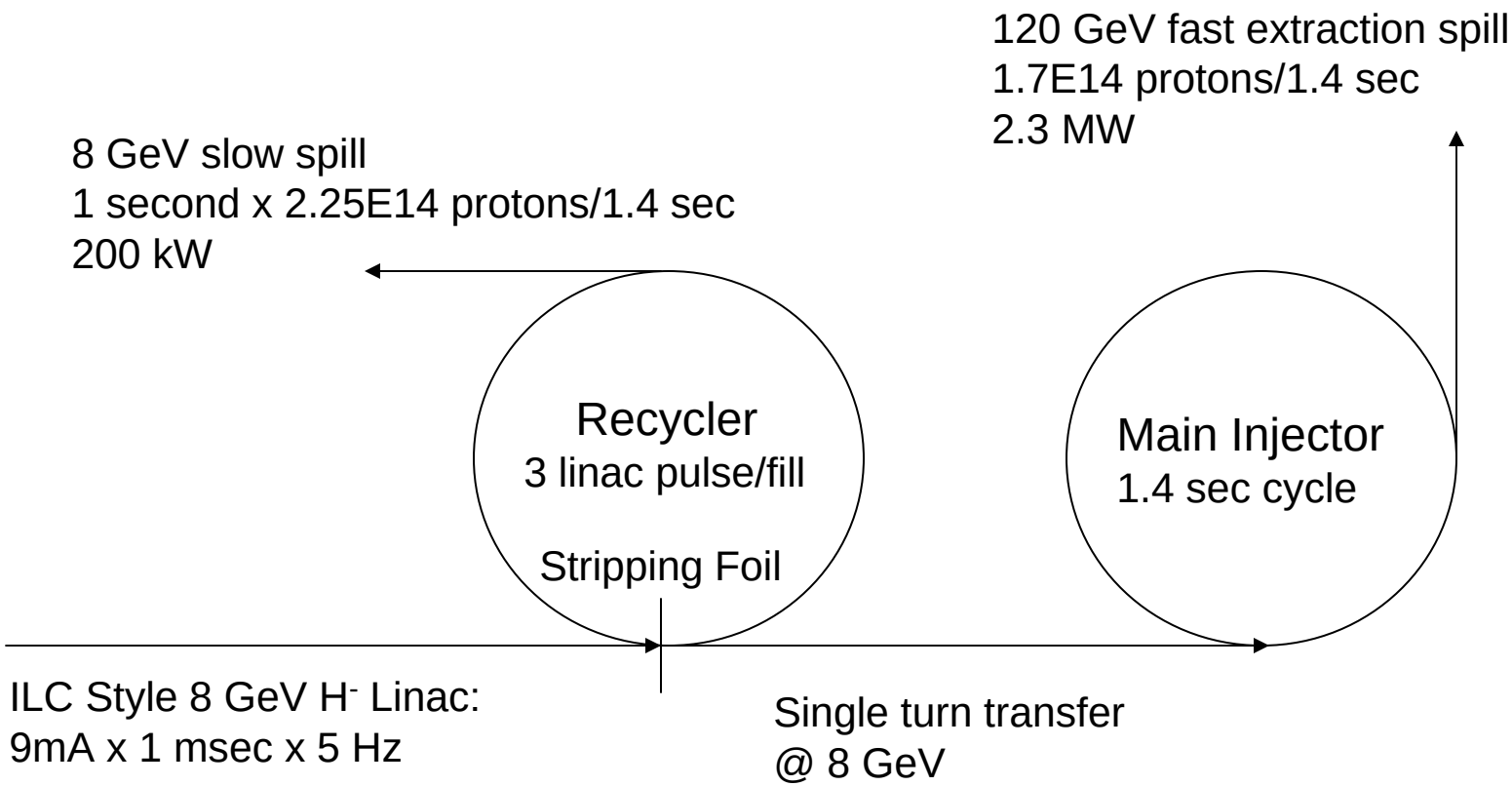
#1: 6 GeV ILC-Type Linac

1	1% ILC demonstration facility. Consists of : ILC-type electron source (RF photo gun, 50 MeV photoinjector), main linac in ILC-type dual-tunnel with ILC type cryomodules and RF systems, beam diagnostics and beam dump.
2	Total energy gain 5-7 GeV (depends on purpose – ILC demonstration or use as H- linac). 15-28 ILC cryomodules with average gradient >31.5MeV/m (design), 250-350 MeV/12 m cryomodule, ILC type klystrons and RF distribution/control, RF pulse width 1ms, average pulse current 9mA, total length is ~300 m, accelerates 3000 e- bunches with 2e10 bunch, emittance 1-4 pi um and rep rate of 5Hz
3	Cost range: medium M$100-M$500
4	Critical R&D needed: reliable demonstration of the ILC design gradient and 90% cavity production output
5	Estimated construction duration : 3-5 years
6	Potential synergies : a) with ILC DR R&D facility if DR built in TeV tunnel; b) with neutrino research program if used as 7 GeV beta=1 H- linac ; c) with muon collider – if used for muon generation on target;
7	References : ILC RDR; D.McGinnis talk at SG 4; S.Geer talk at SG5

#2: High Intensity Proton Source

1	Convert from 6 GeV ILC test linac to 8 GeV H- linac. 2 GeV H- SC RF linac and 60 MeV HINS are used as a front end. Couple with an upgraded Main Injector and Recycler.
2	6GeV e- ILC type 1.3GHz SC RF linac will operate at 5 Hz rep rate and 1ms pulse duration of 9 mA of H- current. That is not enough for 2 MW MI 120 GeV operation (by factor of 3). Possibilities to provide 2 MW are: a) increase pulse duration to 3 ms (different RF system); b) increase pulse current to 27 mA (different RF); c) 270-turn injection into a stripping ring 1/3 of RR circumference, uploading into RR and injection into MI after 3 linac cycles; d) 90-turn injection of 3 linac pulses into Recycler, followed up by a single turn injection into MI. For the latter scenario, MI 120 GeV fast extraction spill of 1.7E14 protons every 1.4 sec is equivalent to 2.3 MW of average power on target; simultaneously - 1-s slow spill of 2.25E14 protons from Recycler with 1.4 sec period provides 200 kW power for 8GeV experiments. The front end is : a) 60 MeV 9(upto 40)mA H- linac as the one which is being constructed and assembled in the Meson Detector Building. Has significant R&D component : for the first time will be tested a new technique to distribute power from one 325MHz klystron to RT and SC RF cavities with use of fast ferrite phase shifters, very low transition from RT to SC RF at 10 MeV, acceleration in RT spoke resonators immersed in strong magnetic field of SC solenoids; b) SC RF linac with varying beta (beam velocity) upto beta=0.81 at 1.3 GeV; c) 1.3 GHz ILC type linac with beta=1 from 1.3 to 2 GeV.
3	Cost range: large >M$500
4	Critical R&D needed: a) front end linac R&D in MDB; b) space charge, electron cloud, instabilities and transition loss limitations in MI; c) stripping methods and injection; d) loss control and collimation
5	Estimated construction duration : 3-5 years
6	Potential synergies : a) ILC 1.5% demonstration; b) ILC DR test facility; c) muon collider R&D; d) neutrino factory front end
7	References : G.Apollinary, S.Holmes talks at SG; 8 GeV Proton driver study

#2: High Intensity Proton Source



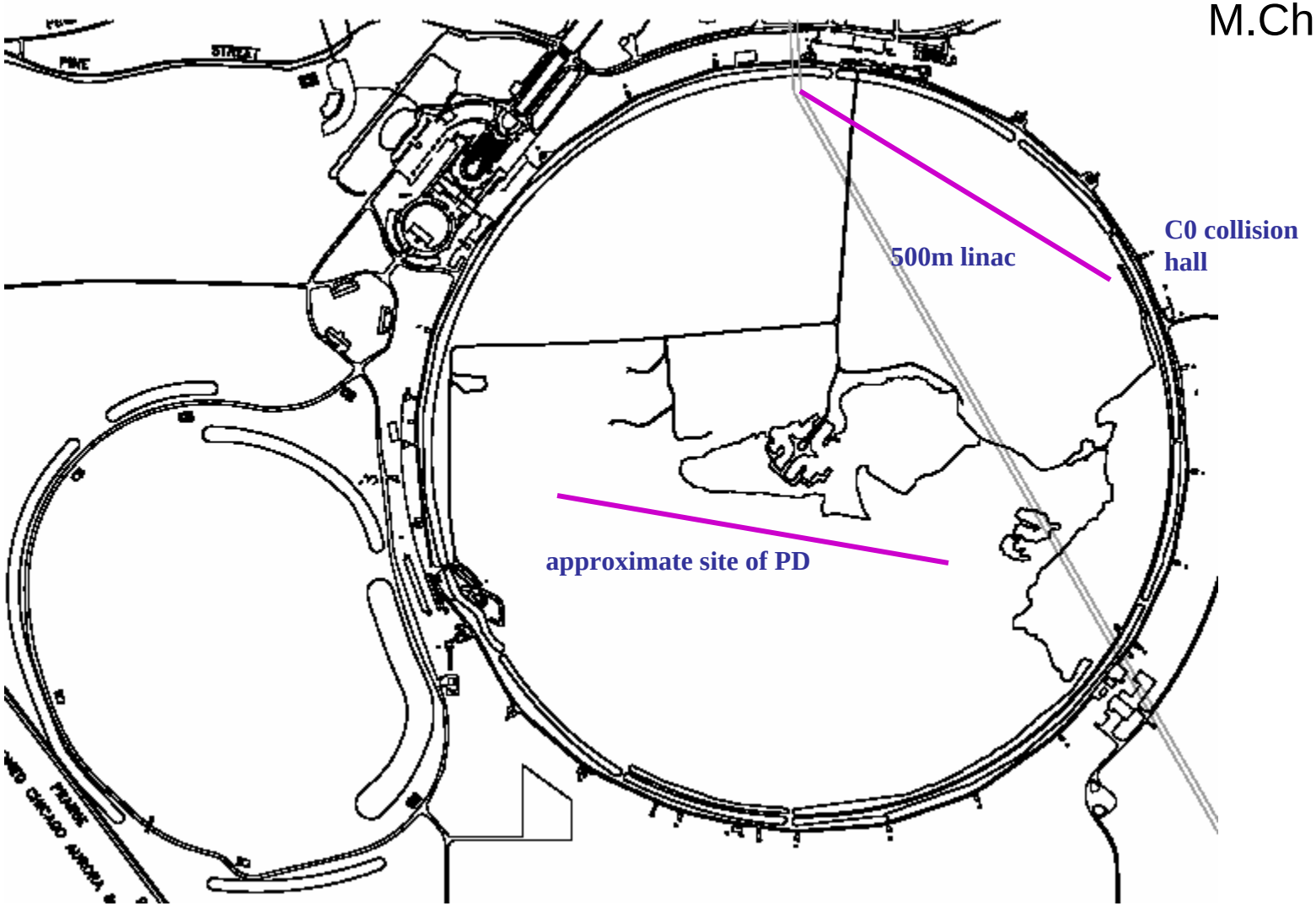
D.McGinnis
S.Holmes

#3: ILC DR Test Facility

1	Full scale ILC DR R&D facility. Requires 5GeV e- linac. Consists of :5 GeV DC low-emittance DR in Tevatron tunnel, fast injection and extraction kickers (6 ns zero-to-zero) , low-energy beam transport (LEBT) from DR to 5 GeV linac, beam diagnostics and beam dump, positron production target possible.
2	5GeV e- ILC type beam will be injected into 6.3km DR by using 6ns 0-to-0 kickers to study attainment of 0.02 pi um vertical emittance in 0.2 sec. Low emittance beam can be extracted thru LEBT to the same 5 GeV linac to study emittance preservation algorithms and low-emittance diagnostics. Operation with positrons very desired (5 GeV e- from linac on target, thru collection system into the DR, high intensity will help to study electron cloud effects in the ILC DR .
3	Cost range: small <M$100 (depending on configuration, assumes use of existing Tevatron tunnel)
4	Critical R&D needed: a) e-cloud suppression methods (to decide on beam pipe in case of e+ operation)
5	Estimated construction duration : 3-5 years
6	Potential synergies : a) Super-B factory
7	References : L.Emery talk at SG ; M.Church ILC-docDB-252, 254

Possible Location of 500m Linac Inside Tevatron Ring

M.Church



ILC Beam Test Facilities (doc-2222)

M.Church

	e^- source	+ 3 cryomod linac	+ 17 additional cryomod linac	+ e^- damping ring	+ e^+ source and beamlines
training for staff and students	limited	limited	yes	yes	yes
RF gun R&D	yes	yes	yes	yes	yes
system test of 1 RF unit		yes	yes	yes	yes
BPM, bunch phase/length detector tests		yes	yes	yes	yes
HOM diagnostics		yes	yes	yes	yes
assembly line beam tests of cryomodules		yes	yes	yes	yes
cavity dark current measurements		yes	yes	yes	yes
laser wire tests; global instrumentation tests			yes	yes	yes
system test of multiple RF units, including failure modes and 2-tunnel issues			yes	yes	yes
emittance preservation in linac			yes	yes	yes
Synchronization between DR and linac				yes	yes
collective beam effects				yes	yes
kicker, wiggler, and vacuum tests				yes	yes
RF feedback				yes	yes
equilibrium emittance				yes	yes
dynamic aperture				yes	yes
electron cloud					yes

#4: Super B-factory in Tevatron Tunnel

1	Asymmetric collider at ϒ(4S) resonance
2	A low energy asymmetric 4x7 GeV circular e+e- collider with L=1e36, based on ILC DR design. Goal is to deliver 50-100 ab-1 of data for studies of rare decays of b,c, and tau. Significant luminosity increase wrt B-factories is going to be due significantly smaller emittances (factor of 50, by extensive use of wiggler magnets to enhance SR damping) and use of novel (untested yet) "crabbed waist" design of IR (another factor of 2). Beam polarization desired. Current design (see Ref.) assumes reuse of 2.2 km PEP-II magnets in a new ring in Italy, though placing it in the Tevatron tunnel seems to be possible.
3	Cost range: medium M$100-M$500
4	Critical R&D needed: a) "crabbed waist" requires strong sextupoles in the IR design and more research is needed to understand its effect on dynamic aperture
5	Estimated construction duration : 4-6 years
6	Potential synergies : a) with ILC damping ring test facility ; b) with PEP-II and KEK-B factories
7	References : D.Hitlin SG talk at http://www.fnal.gov/directorate/Longrange/Steering_Public/files/070507_Super B_at_Fermilab_Hitlin.pdf

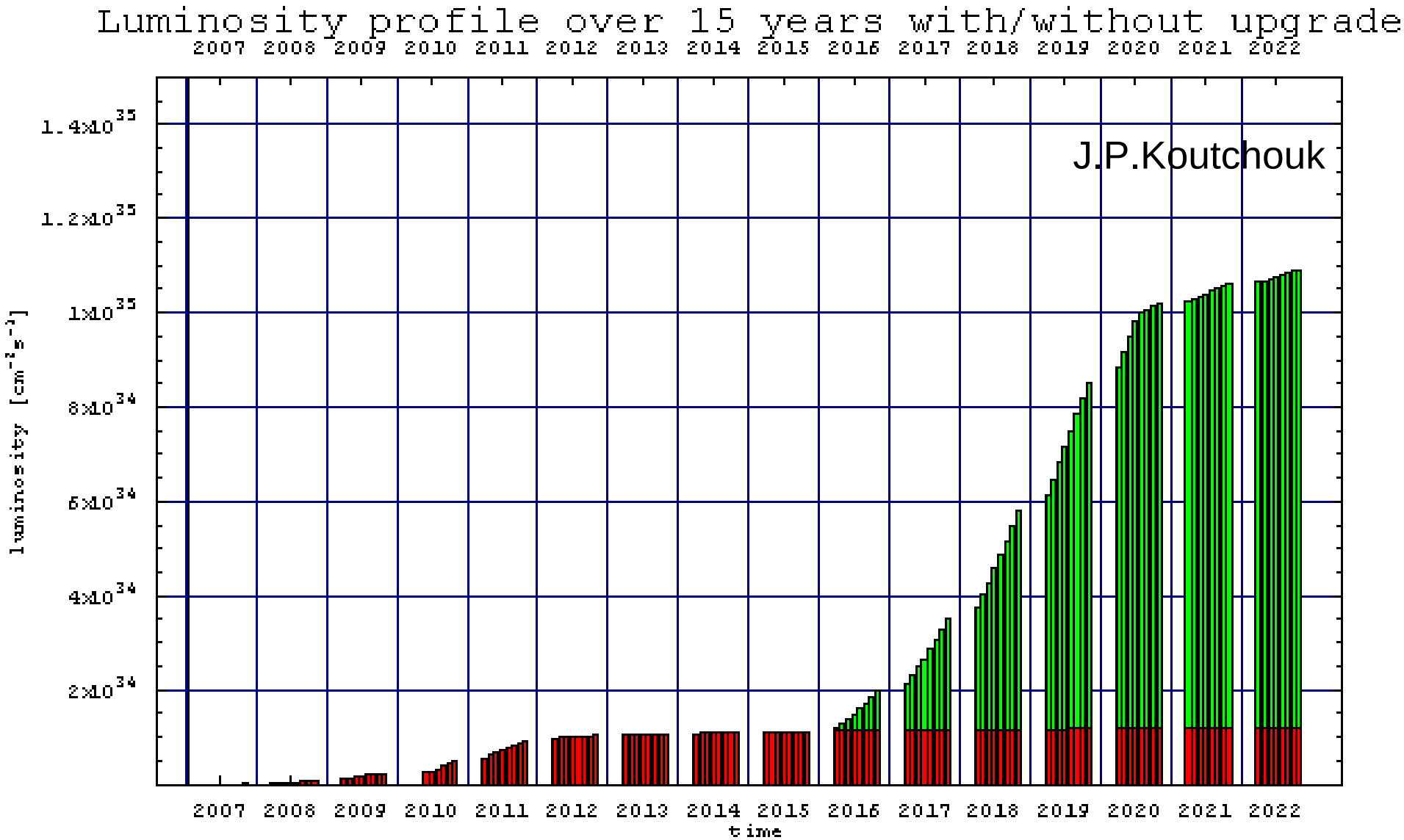
#5: Giga-Z factory

1	High luminosity Z-factory to deliver 10^9 Z-events/year.
2	45GeV+45 GeV e+e- linear collider based on ILC technology (1/5th of the ILC) with luminosity of (3-5)e33 cm-2 s-1 that delivers 10^9 Z's /yr (35nbarn cross- section). Consists of full scale ILC-type injection complex and 20% of the ILC linac operation with design ILC beam parameters (5Hz rep rate, 3000 3.2 nC bunches with small emittances. C.m. energy spread ~0.1% will be dominated by beamstrahlung which scales as E^2. May require a dedicated detector.
3	Cost range: large >M$500
4	Critical R&D needed: IP design to reduce c.m. energy spread - though beam-strahlung at 45GeV is ~30 times less then in ILC, another factor of 5-10 is needed (below 0.01%)
5	Estimated construction duration : 5-7 years
6	Potential synergies : a) ILC: Giga-Z as 1st stage of the ILC
7	References : Snowmass 2001 "orange book" of facilities, chapter on Giga-Z

#6: LHC Luminosity Upgrade

1	~10-fold upgrade of the LHC luminosity to upto 1e35 cm-2 s-1
2	Complex of measures to improve luminosity: a) install new IR optics to reduce beta* from 55 cm to 25cm or even 12 cm; b) upgrade injectors (most notably – new Linac, PS and SPS) to produce higher than nominal bunch charge of 1.1e11 protons in the same emittance (upto 2e11); c) modify collimation system accordingly to protect the machine with simultaneous reduction of collimator impedance; d) compensate geometrical luminosity loss (now close to 50%) either by crab-cavities or by early separation dipoles; e) compensate beam-beam effects. Feermilab and LARP could be interested in building 20-30 Nb3Sn large aperture magnets for the IR upgrade.
3	Cost range: medium M$100 – M$500
4	Critical R&D needed: a) demonstration of accelerator quality large aperture Nb3Sn quadrupole magnet swith >200T/m gradient; b) find acceptable solutions for collimation and protection systems; c) understanding crtical beam dynamics effects (coherent instabilities, electron cloud, beam-beam interactions and compensation).
5	Estimated construction duration : 2-3 years
6	Potential synergies : a) VLHC and muon collider – both will benefit from development of Nb3Sn magnets
7	References : S.Peggs talk at SG; W.Scandale and F.Zimmermann, in Proc. CERA-HHH Workshop (Valencia, Oct 2006).

#6: LHC Luminosity Upgrade



#6: LHC Luminosity Upgrade

S.Peggs

Item	Total Cost $M	Technical Risk	Lumi Gain	LARP R&D
MAGNETS	**100**			
IR triplet Nb3Sn quads	90	Low	High	Ongoing
Slim magnets in detectors	10	Low	Moderate	FY08+
Magnetized TAS absorbers	-	Moderate	Moderate	
BEAM-BEAM COMPENSATORS	**4**			
Electron lenses for head-on	3	High	High	FY08+
Wires for long range	1	Low	Moderate	Ongoing
Small angle crab cavities	-	High	Moderate	Prelim.

Notes:

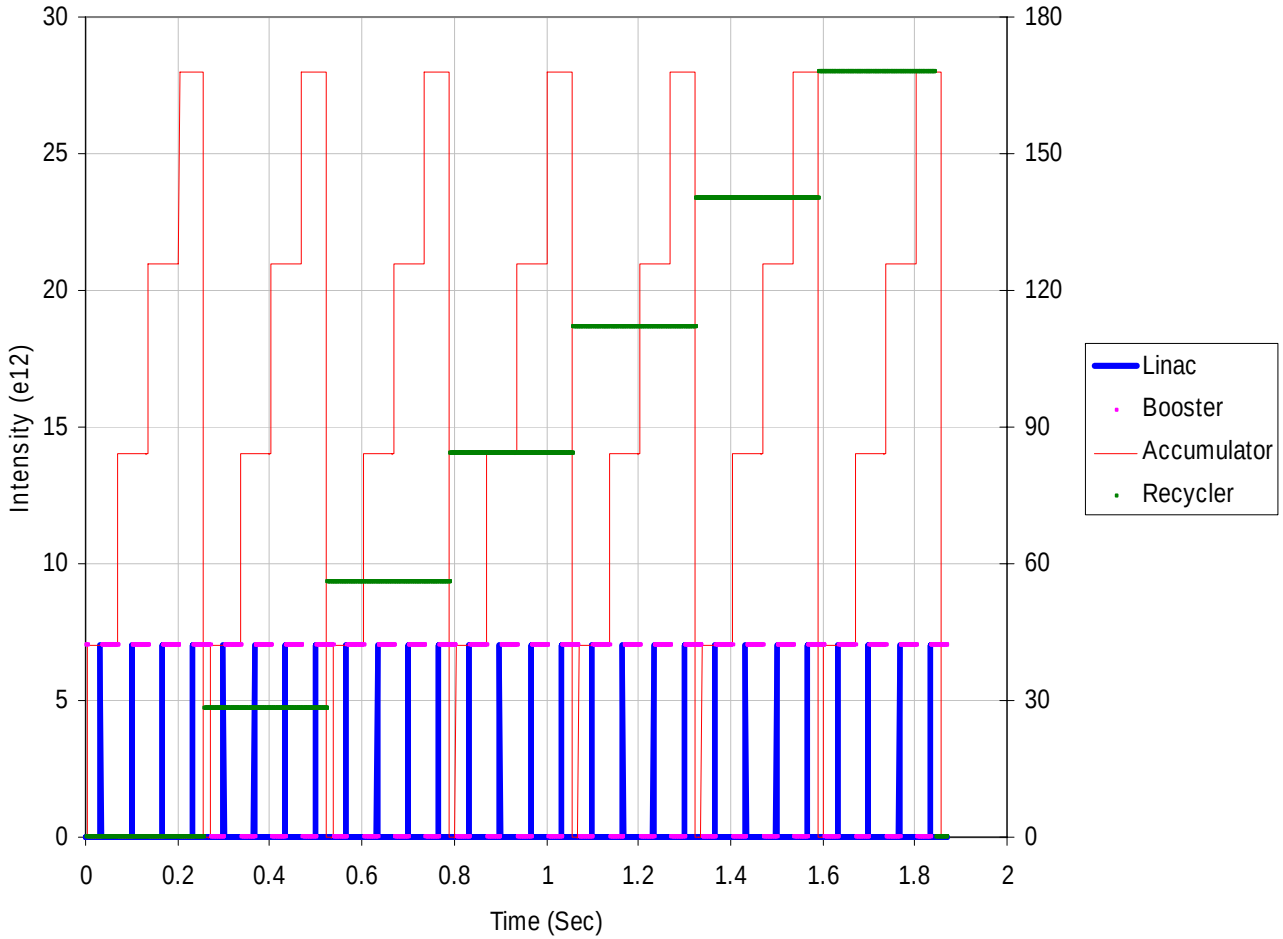
- Triplet quads: "low risk" assumes LARP R&D success in 2009.
- Slim magnets: ongoing discussion of scenarios at CERN.
- Electron lenses: R&D with beam at Tev & RHIC to lower risk.
- Crab cavities: back up plan for worst case beam-beam scenario.

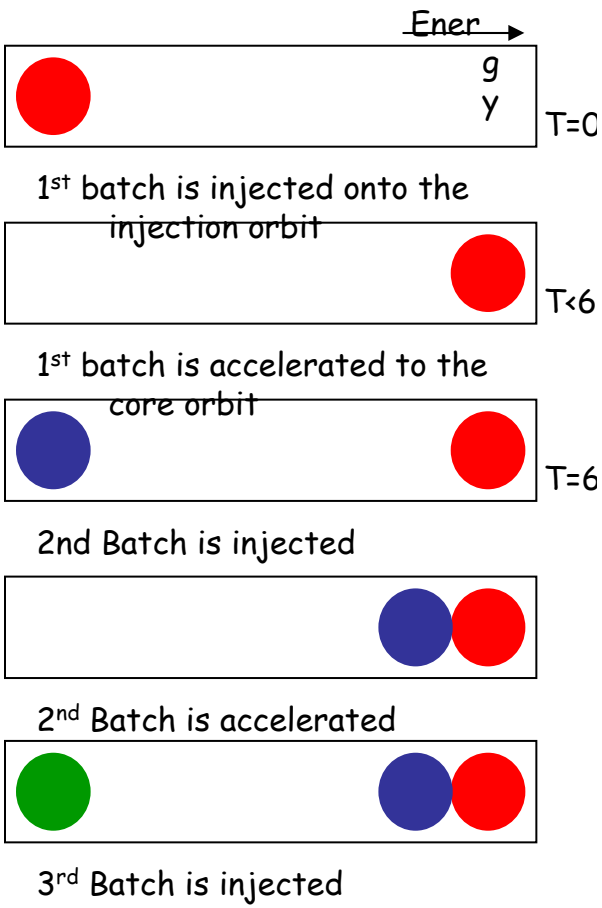
#7: Proton Sources by Reconfiguration of Collider Complex

1	Accumulator as a momentum stacker, Recycler as a box car stacker Debuncher as an 8 GeV slow spiller, Tevatron as a 120 GeV slow spill stretcher ring.
2	Momentum stack in the Accumulator(AA): a) inject in a newly accelerated Booster batch every 67 mS onto the high momentum orbit of the AA; b) Decelerate new batch towards core orbit and merge with existing beam; c) Momentum stack 3-4 Booster batches; d) Extract a single AA batch every 200 – 270 ms, at an intensity of 3-4x a single Booster batch. Box Car Stack in the Recycler (RR): a) load in a new Accumulator batch every 200-270ms' b) Place six AA batches sequentially around the RR; c) then the Main Injector in a single turn. The plan simultaneously supports three experimental programs: a) upto 1.2 MW 120 GeV MI beam for Neutrino production; b) a 8 GeV experimental facility with fast and slow spill capability and a flux of 2.5e20 protons/year (4 Booster batches out of every 22 will produce 4.6e16 prot/hr); c) a 120 GeV slow spill beam from Tevatron with a flux of (0.3-1.0)e20 protons/year (5e13 protons per spill twice a minute, separated kaon flux 10 MHz).
3	Cost range: small <M$100
4	Critical R&D needed: a) resonance generation in and extraction from Debuncher; b) space charge, electron cloud, instabilities and transition loss limitations in AA, RR, MI; c) loss control and collimation in all machines
5	Estimated construction duration : 2-3 years
6	Potential synergies : a) 480 GeV double SF proton accelerator in Tev tunnel
7	References : D.McGinnis talk at SG; M.Syphers beams-doc-2222

#7: Proton Sources by Reconfiguration of Collider Complex

D.McGinnis



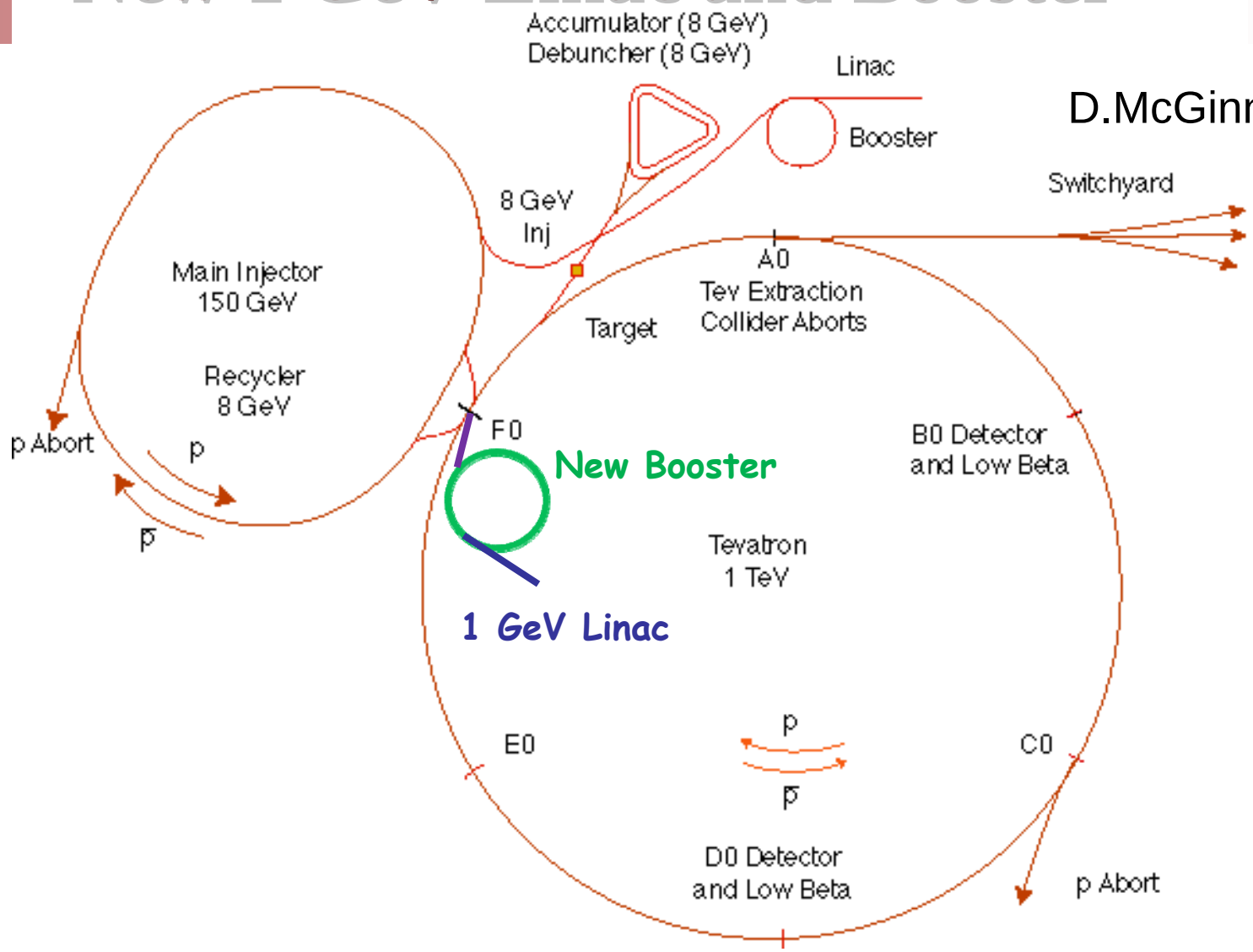


#8: Proton Sources with 1 GeV H- linac & new Booster

1	1 GeV H- linac injecting into a new large aperture Booster (B-2) to increase proton power at 120 GeV in MI upto 2.1 MW
2	A 1 GeV Linac based on the HINS front-end technology coupled with new Booster will operate at 5 Hz : a) fill the Recycler with six new Booster batches; b) Fill the Main Injector in a single turn; c) support 43e16 protons/hour at 120 GeV. B-2 will have ~0.5 km circumference, 24e12 batch intensity, and support ~150kW of beam power at 8 GeV. In the 1 GeV Linac era, B-2 strips at 1 GeV and ramps to 8 GeV. In the 8 GeV H- Linac era, B-2 strips at 8 GeV and coasts at 8 GeV can support 100e16 protons/hour. Same 1 GeV H- linac injecting into an existing Booster (B-1) can increase B-1 batch population by factor 2.5 and – if followed along NoVA beam scenario with slip stacking in RR - can increase proton power at 120 GeV in MI upto 1.7 MW.
3	Cost range: medium M$100 - $M500
4	Critical R&D needed: a) HINS R&D in MDB; b) space charge, electron cloud, instabilities and transition loss limitations in B2, RR and MI; c) stripping methods and injection in B2; d) loss control and collimation
5	Estimated construction duration : 3-5 years
6	Potential synergies : a)
7	References : D.McGinnis talk at SG4

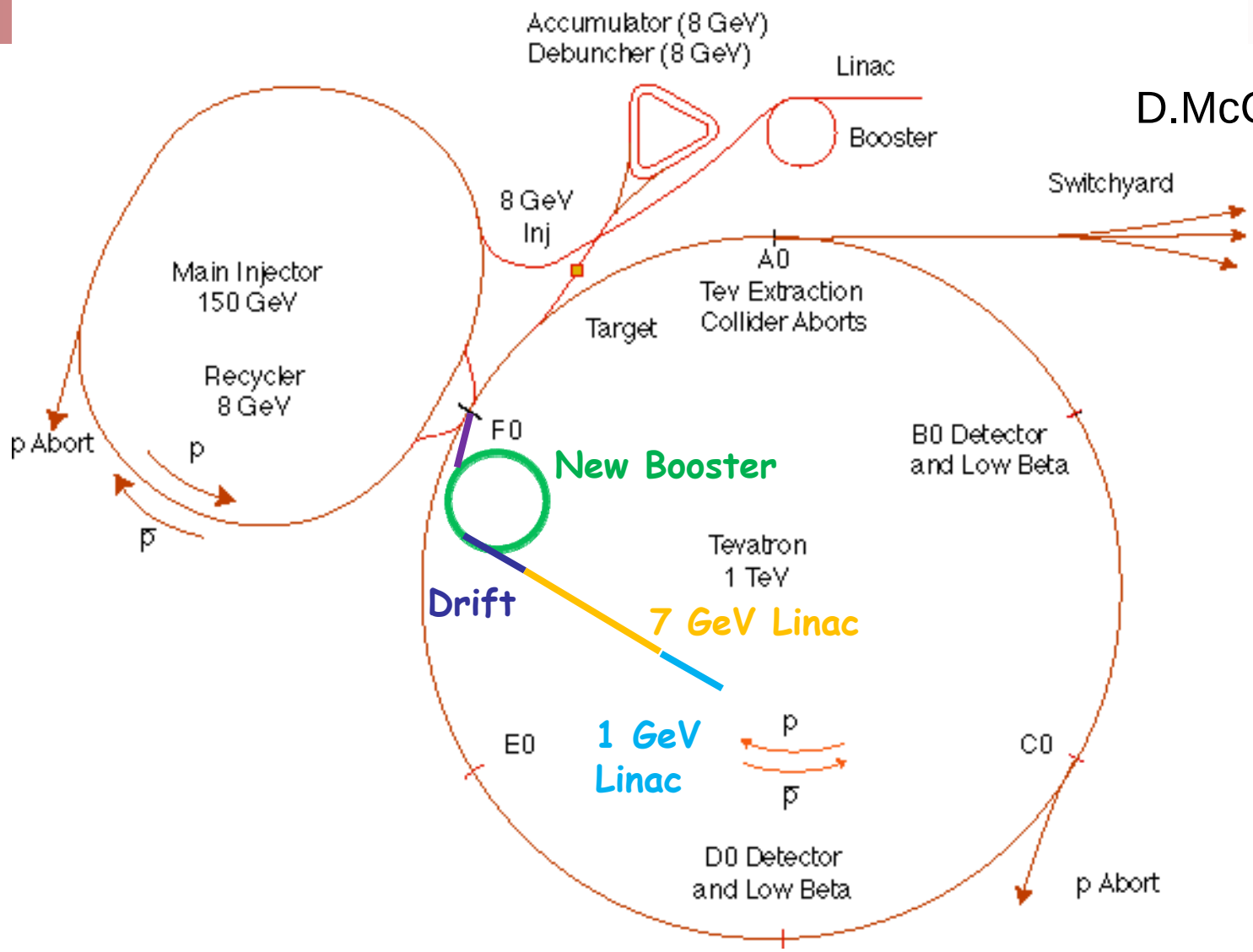
New 1 GeV Linac and Booster

D.McGinnis

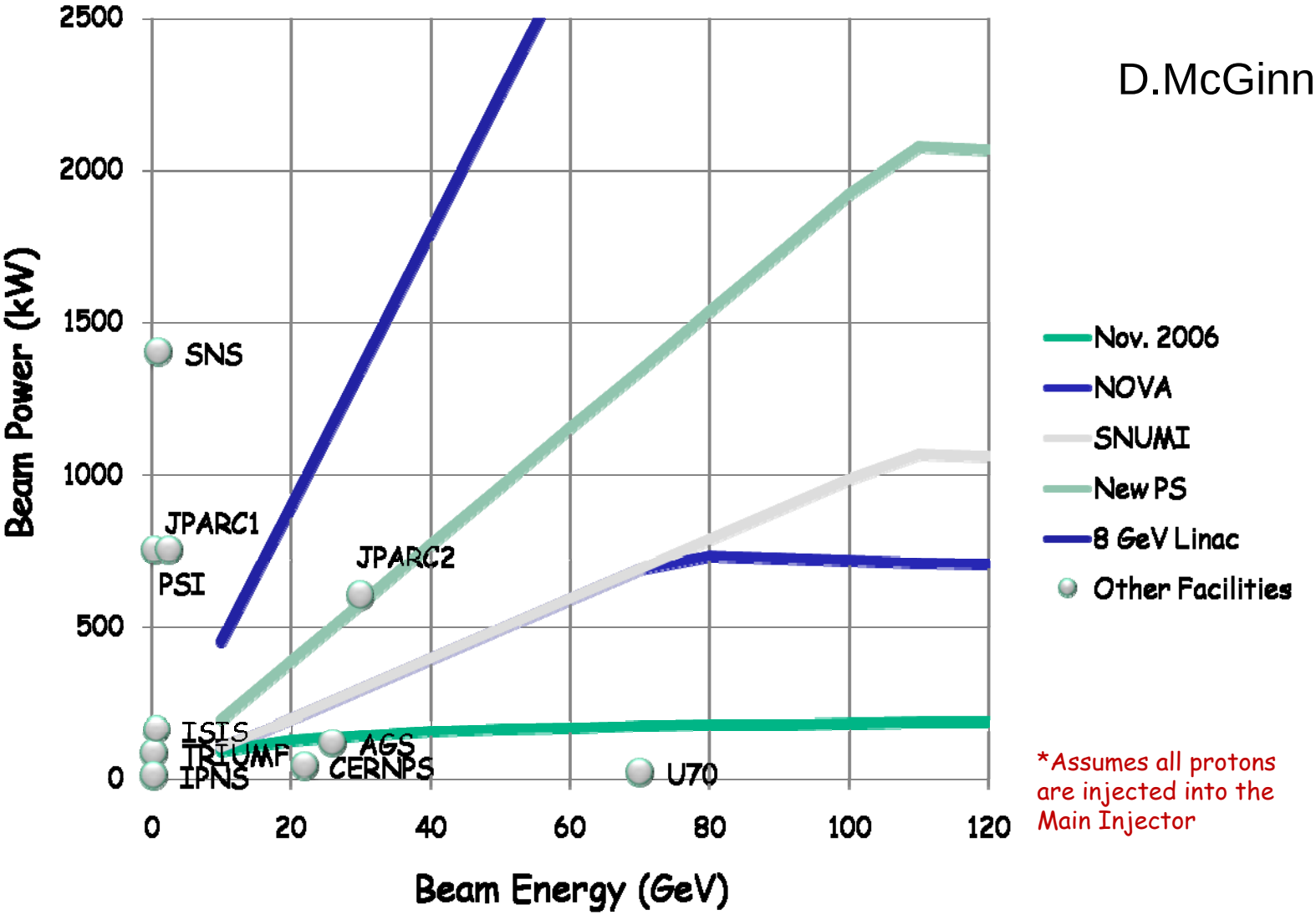


Superconducting 8 GeV Linac and Stripping Ring

D.McGinnis



Proton Beam Power* Scenarios



D.McGinnis

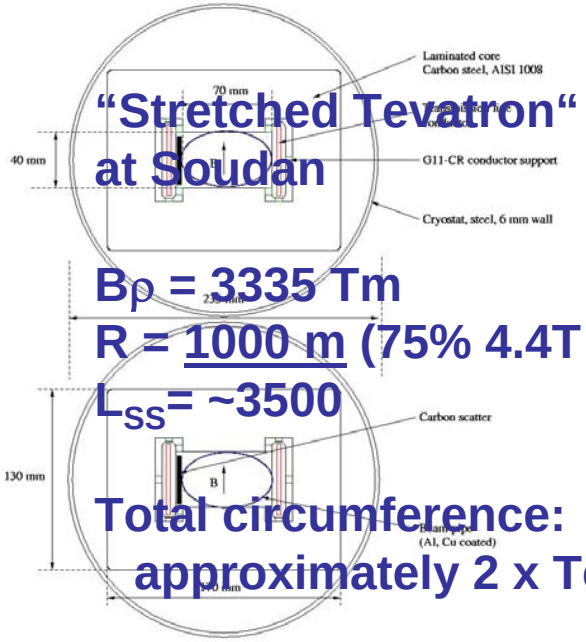
*Assumes all protons are injected into the Main Injector

#9:Double 480 GeV fast cycling proton accelerator

1	10 MW proton synchrotron accelerator for fix target experiments with upto 480 GeV proton beams. Design is based on feasibility of fast ramping superferric magnets energized by 100kA NbTi transmission line. Two rings to be placed in Tevatron tunnel, accelerated beam extracted onto upto 3 targets (old targets for NUMI and Nova can also be used, if desired).
2	Two rings of 40 mm aperture, 2T max field window-type transmission line combined function magnets accept 1.6e14 protons/cycle at 40 GeV from MI and accelerate to 480 GeV in 1 sec. 2 seconds full cycle time calls for 2T/s magnetic field ramp rate, that is feasible with either NbTi or 344S-HTS conductor and thin laminated iron (Fe 3% Si). Three 1-km long decay tunnels considered: a) 8 deg to Mt.Harrison (1500km); b) 15 deg – to Mt. Whitney (2700km) and 42 deg to Gran Sasso (7500km)
3	Cost range: large >M$500
4	Critical R&D needed: a) demonstration of required cycling time (2 s) and accelerator field quality in window-type transmission line magnet
5	Estimated construction duration : 6 years
6	Potential synergies : a) VLHC booster – fast cycling magnets can reduce injection time Potential conflict: a) with other neutrino experiments/programs as the accelerator consumes all the protons produced by the Booster
7	References : H.Piekarz talk at SG; FNAL-TM-06-192 (2006)

#9:Double 480 GeV fast cycling proton accelerator

H.Piekarz



"Stretched Tevatron" aimed at Soudan

$B\rho$ = 3335 Tm

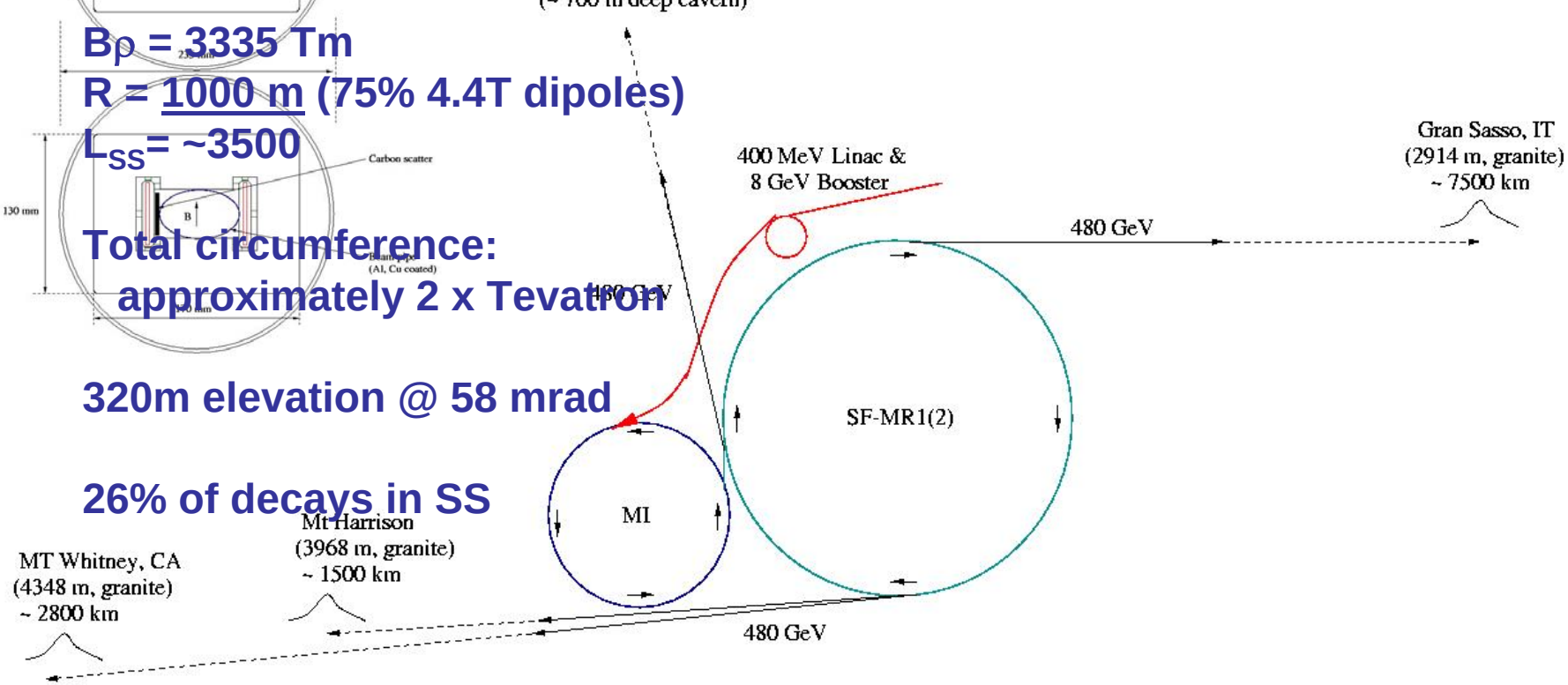
R = <u>1000 m</u> (75% 4.4T dipoles)

L_{SS}= ~3500

Total circumference: approximately 2 x Tevatron

320m elevation @ 58 mrad

26% of decays in SS



#10: ~1 TeV Tevatron Fixed Target

1	Continued fixed target operations of the Tevatron as a slow-cycling 800GeV synchrotron; ~5 x 10^{19} protons per year
2	Tevatron can accelerate ~(8-12)e13 protons to 800 GeV in a 40 sec cycle (~250-350 kW).
3	Cost range: small <M$100
4	Critical R&D needed: a) none(?)
5	Estimated construction duration : 0 years for accelerator
6	Potential synergies : none(?) Potential conflict: a) will reduce proton flux to all other neutrino experiments/programs by ~10%
7	References : J.Conrad proposal presentation at SG3

#11:Antiproton Sources

1	Exploitation of existing antiproton production complex (Debuncher, AA and m.b. Recycler) for dedicated HEP experiments / physics of c-cbar or b-bbar. Continued operations of the Pbar source for antiproton production and storage. May require 1-2 additional rings for internal target experiments and deceleration/extraction to traps.
2	Fermilab's antiroton complex holds world records of pbar production (23e10 pbars/hr) at 8GeV. For the most of the experiments considered, antiprotons should be decelerated to lower energy, or even ~stopped before being trapped.
3	Cost range: small <M$100
4	Critical R&D needed: a) decide on what kind of experiment can be done
5	Estimated construction duration : 1- 3 years
6	Potential synergies : a) ? Potential conflicts : a) NoVA, SNuMI and other neutrino experiments
7	References : D.Kaplan talk at the SG

#12: Tevatron B-physics

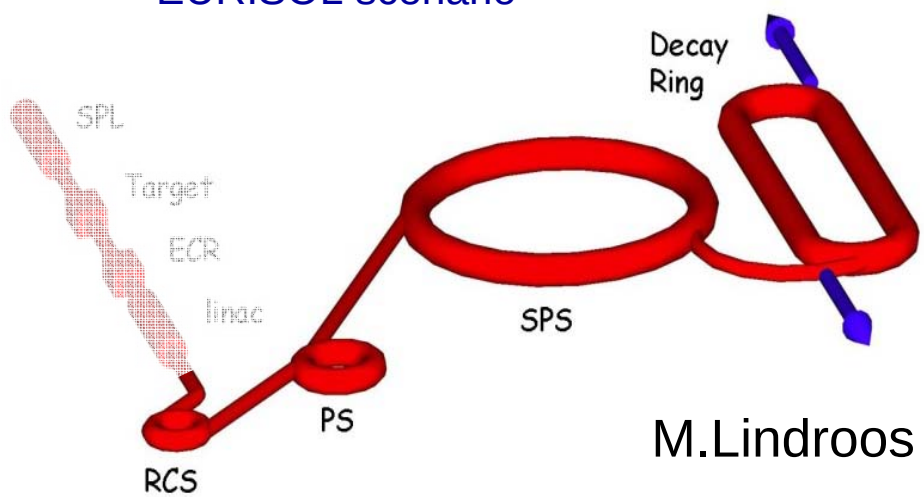
1	Runing Tevatron Collider in the LHC era to continue exploration of the physics of B-mesons
2	Luminosity of the Collider will be determined by availability of the MI and RR for antiproton production. Ideally can be as high as (200-300)e30 cm-2 s-1, or ~1-1.5 fb-1/yr.
3	Cost range: medium (?) M$100-M$500
4	Critical R&D needed: understand detector upgrades
5	Estimated construction duration : 1(?) years
6	Potential synergies : a) ILC: Giga-Z as 1st stage of the ILC Potential conflicts: a) pbar complex operation in high proton intensity era
7	References : BTeV design report

#13: Beta-beams

1	Neutrino source based on beta-dacaying ions
2	Two scenarios: either a) accelerate 6He or 18Ne using existing accelerators (Booster, MI and Tevatron) and put them in a new decay racetrack ring approximately the size of the Tevatron. The rest energy of the neutrino is a ~2MeV, which gives an average neutrino beam energy of ~1.5-2 GeV at Tevatron top energy (gamma=350-500). Expected intensity is ~1e18 nu/yr. b) accelerate 8Li or 8B to Main Injector top energy (gamma=60-100) and put them in new MI-size decay ring. The resulting neutrino beam energy is about the same, since the neutrino rest energy is higher. However, beam will be less focused due to the lower gamma. This may be compensated by a higher flux, perhaps ~1e19 nu/yr, since the slow ramping Tevatron is not used. Both cases requires a new ion production facility.
3	Cost range: large >M$500 for Tev size facility, medium for MI-size facility
4	Critical R&D needed: a) high intensity ion source R&D – mostly for Ne18 and for B8; b) beam power handling, especially, in the 4-5T magnet decay ring; c) RF manipulations in Booster, MI and Decay Ring. Some design R&D is presently being done at CERN.
5	Estimated construction duration : 5 years for case a), 3-4 for case b)
6	Potential synergies : a) muon collider open mid-plane magnets; b) proton driver will separate beta-beam facility from the present Booster; c) RIA (Argonne). Potential interference : will compete for MI accelerator time with other projects.
7	References : Eurisol Design Study http://beta-beam.web.cern.ch/beta-beam/task/index.asp

#13: Beta-beams

EURISOL scenario



M.Lindroos

"Stretched Tevatron" aimed at Soudan Bρ = 3335 Tm
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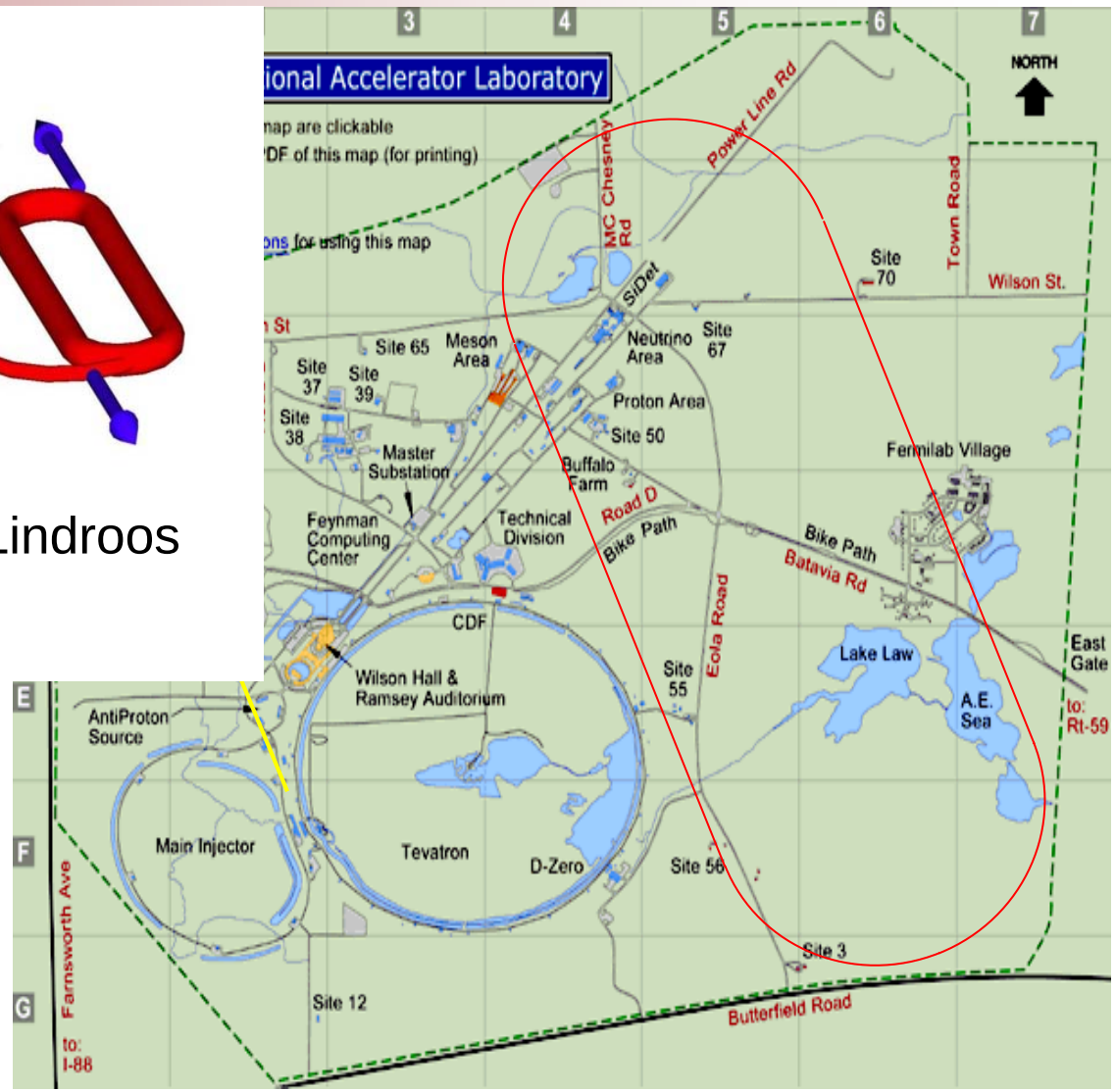
L_{SS}= ~3500

Total circumference 12km

320m elevation @ 58 mrad

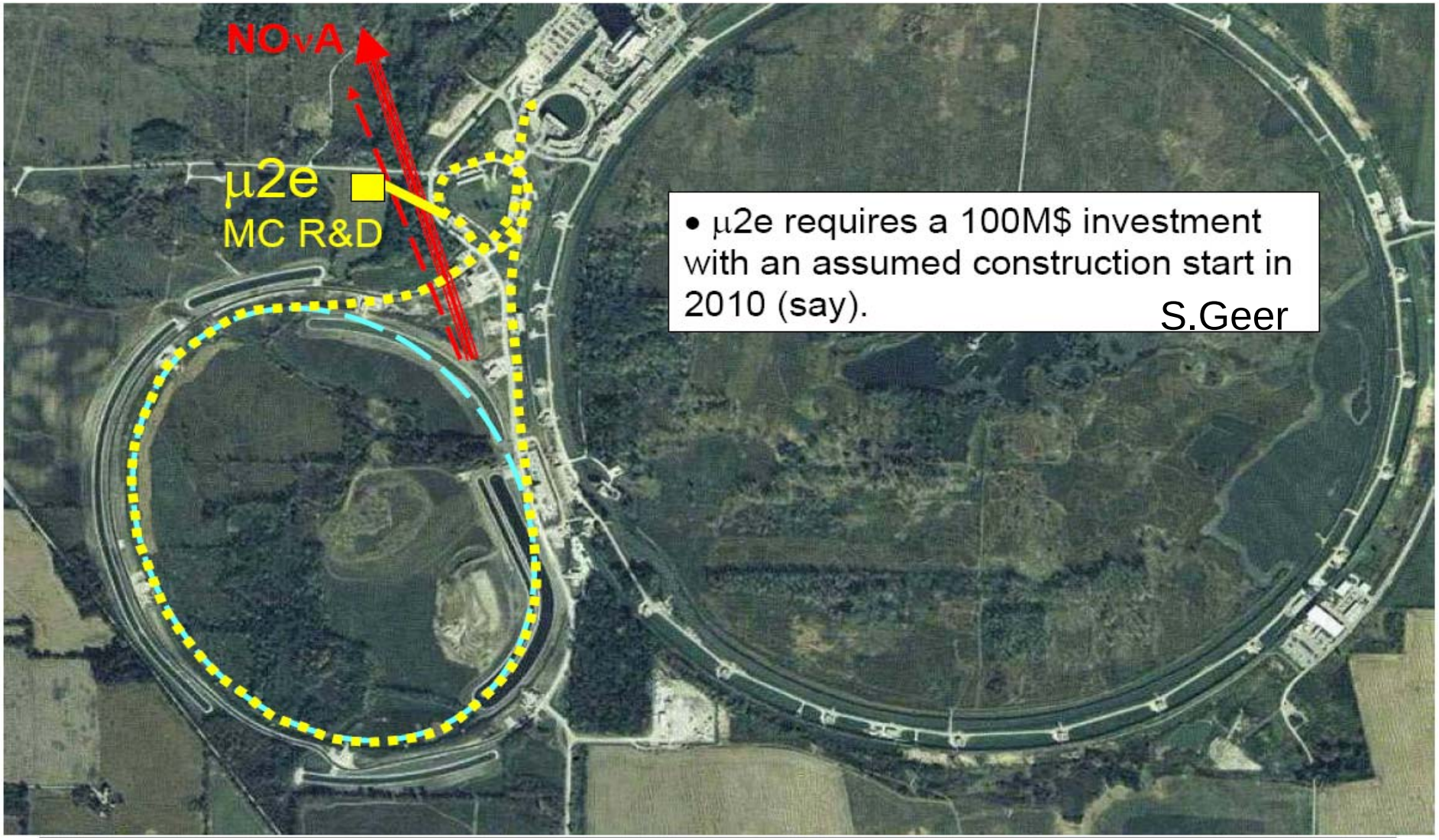
26% of decays in SS



#14: Muon Cooling Facility

1	6D muon ionization cooling test facility
2	~10% test of the final muon cooling channel to demonstrate significant ~x5 reduction of 6D emittance. Uses flux of muons produced for the m2e experiment, going thru sequence of gas filled 5-10 T solenoids and high gradient 10-50 MeV/m 200MHz or 800MHz cavities (alternating : solenoids, Li absorbers, RF cavities). Advanced muon diagnostics in complex fields will be tested.
3	Cost range: small <M$100
4	Critical R&D needed: a) cooling channel design choice will be based on the 6D cooling experiment at MTA results – without RF; b) choice of RF (gas-filled or vacuum, strong or weak magnetic field) can be done after corresponding beam tests in MTA
5	Estimated construction duration : 3 years
6	Potential synergies : mu2e experiment
7	References : S.Geer presentation at the SG

#14: Muon Cooling Facility



- μ2e requires a 100M$ investment with an assumed construction start in 2010 (say).

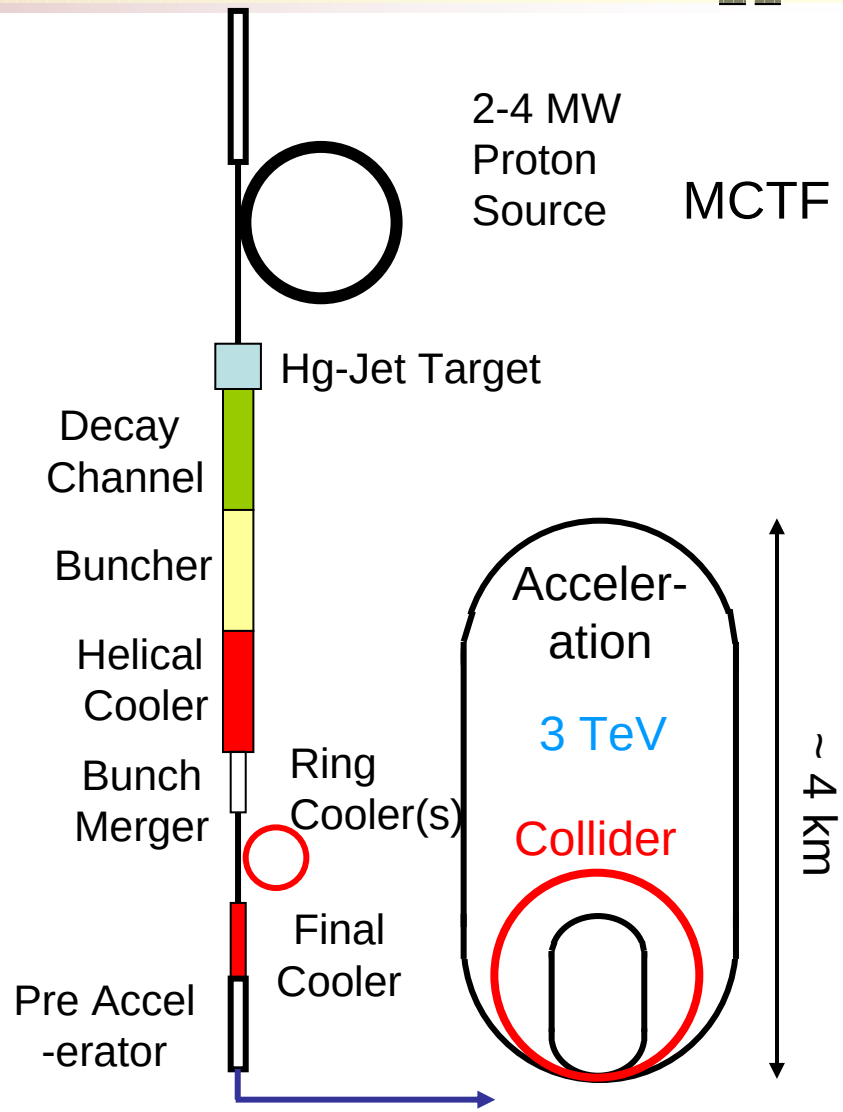
S.Geer

#15: Muon Collider

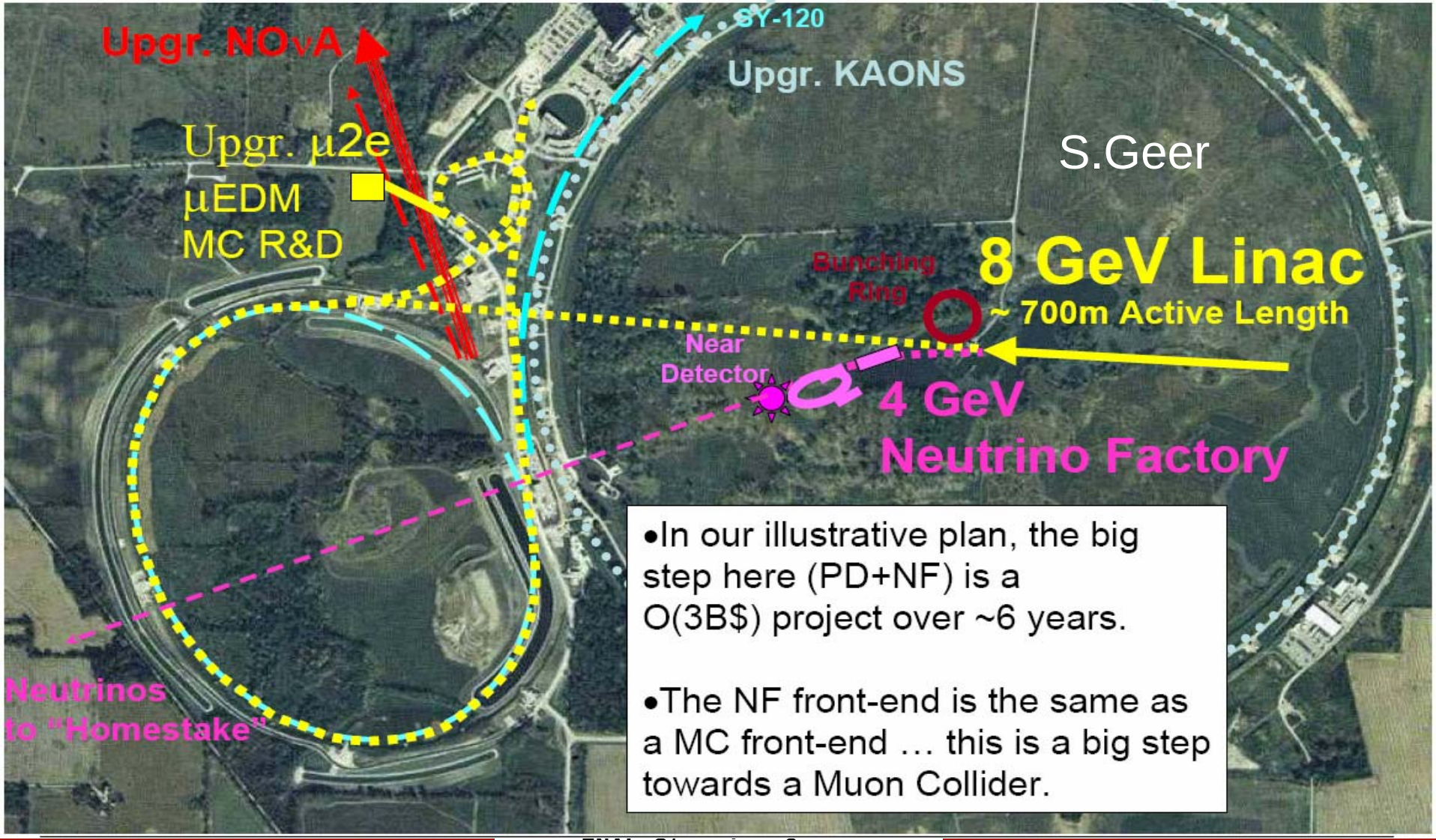
1	1.5 – 4 TeV c.m.e. mu+ mu- collider to explore physics beyond LHC and ILC. Major components include 2-4 MW 5-15 GeV proton driver, target and pion collection system, 6D cooling channel, series of RLAs, collider ring. The Muon Collider is potentially stageable – e.g. a 4GeV Neutrino factory can be the first stage (delivers upto 1e20 muon decays/yr). Low energy muon collider (Higgs factory) can be another intermediate stage (120 +120 GeV with luminosity of about 1e30-1e31).
2	Energy frontier collider with luminosity >1e34 cm-2 s-1. Fits FNAL site at enrgies upto 4TeV cm. Requires ~1e11 muons per beam with emittances ~2-20 pi (rms norm) in the collider ring wirth beta*=0.55-5 cm , colliding over ~1000 turns, rep. rate 10-50 Hz (50 for Low Emittance MC). Possibilities for fast acceleration are ILC-type linac (10 Hz, ~25-30MeV/m, 0.5 ms RF pulse, much smaller than ILC ave current) or series of FFAG accelerators. Cooling channel ~1km long should reduce the emittance of muon by factor 1e6 in 6D. Existing 8 GeV 2MW Proton Driver design fits the MC requirements, but will need an additional debunching ring before target station.
3	Cost range: large >M$500
4	Critical R&D needed: a) demonstration of feasibility of 6D muon cooling scheme(s); b) demonstration of technologies enabling final cooling (last factor of 50 in 6D emittance) – possibly with 30-50T HTS solenoids; c) design studies of the fast acceleration techniques (RLAs, FFAGs, etc); d) large momentum acceptance collider optics design; c) large aperture high field (>10T) open mid-plane magnets for the collider ring and IR. Other issues are being addressed by ongoing R&D programs (targetry – MERIT, 2D cooling – MICE, absorber and other components – MUCOOL)
5	Estimated construction duration : 5-7 years
6	Potential synergies : a) Neutrino factory – MC and NF can use same muon production complex; b) ILC – 1.3 GHz SC RF linac can be used for fast muon acceleration to top energy; c) LHC L- and E- Upgrades and VLHC – high gradient Nb3Sn and/or HTS magnets needed for the IR design.
7	References : S.Geer presentation at the SG; Phys. Rev. ST Accel. Beams 2, 081001 (1999); MCTF proposal (2006)

Muon Collider Ingredients

- Proton Driver
  - primary beam on production target
- Target, Capture, and Decay
  - create π; decay into μ
- Bunching & Phase Rotation
  - reduce ΔE of bunch
- **Cooling**
  - **reduce 6D emittance**
- Acceleration
  - 130 MeV $\rightarrow$ up to 1.5 TeV
- Storage Ring
  - store for ~1000 turs
  - One IP



#15: 4 GeV neutrino factory and 8 GeV Linac

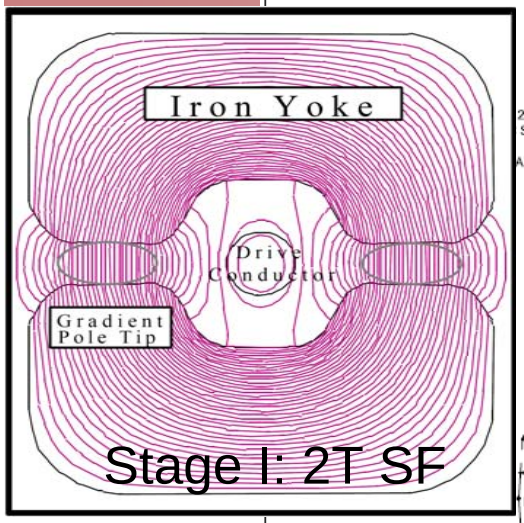


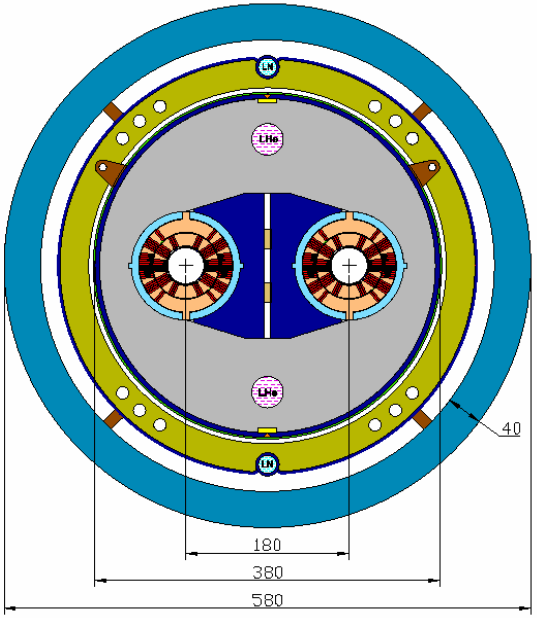
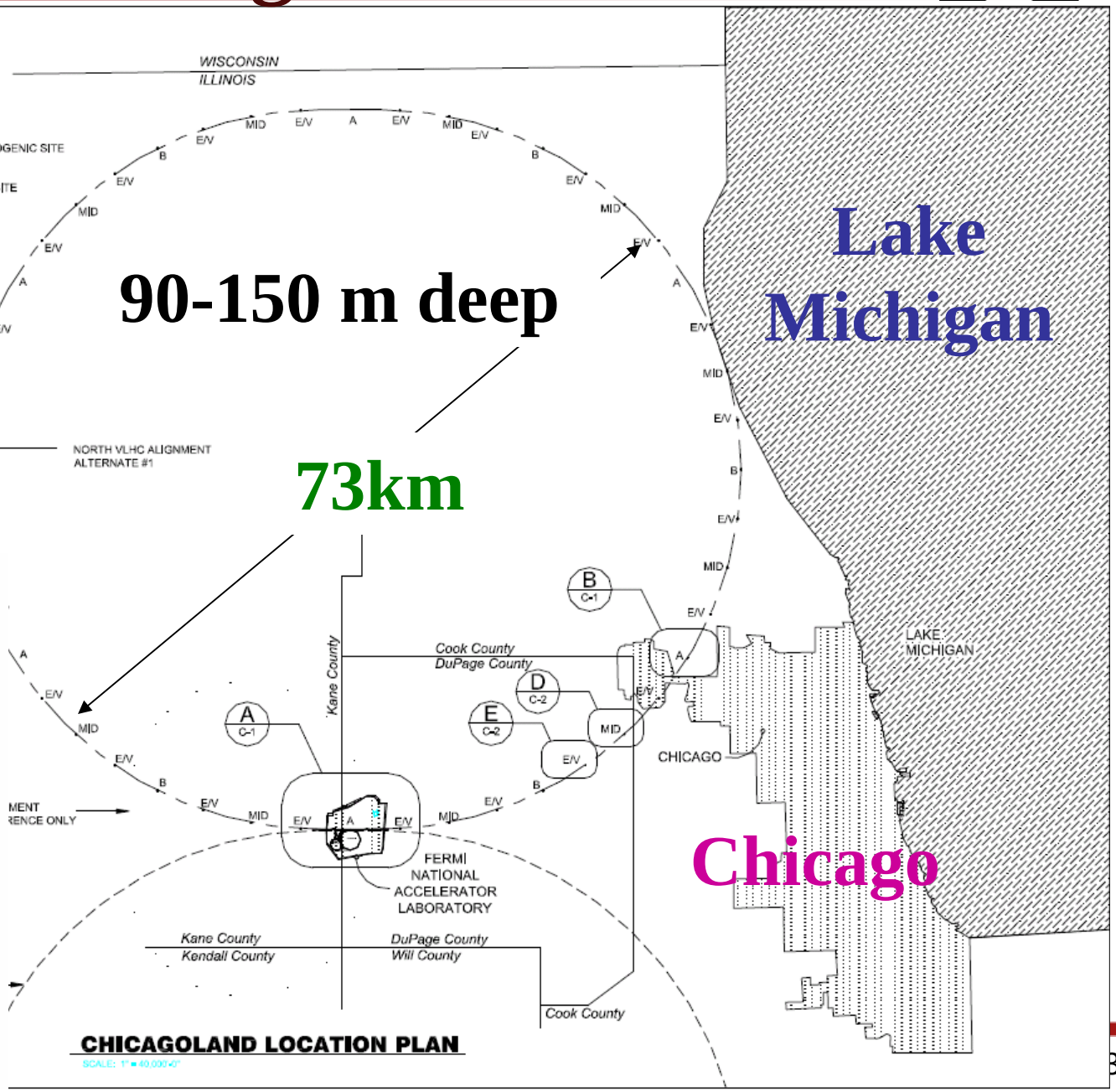
- In our illustrative plan, the big step here (PD+NF) is a O(3B$) project over ~6 years.
- The NF front-end is the same as a MC front-end … this is a big step towards a Muon Collider.

#15: VLHC

1	Very Large Hadron Collider with c.m.e. 3x to x14 times the LHC. In the FNAL-TM-2149 configuration consists of Tevatron injection complex, Tevatron as 1TeV injector into 233km circumference TeV collider. After years of operation, Stage-I ring will be used as injector into higher field synchrotron-ollider with 200TeV cme in the same tunnel.
2	Staged energy frontier machine: stage I is 20+20 TeV p-p collider in 233km-circumference tunnel using Tevatron as 1TeV injector and double aperture 2T transmission line superferric magnets in main tunnel. Beta*=0.3m, 35000 bunches in the machine, bunch intensity ~2e10 – allow to reach L~1e34. 11.2T Phase II magnets are NbTi or Nb3Sn. Synchtroron radiation of protons will help to achieve ~x2 larger luminosity integral (peak ~2e34 cm-2s-1 at 100+100 TeV cme). SR absorbers to integral part of the vacuum system. Alternative magnet designs may allow to reduce the circumference of the tunnel or/and top energy of VLHC-I
3	Cost range: large >M$500
4	Critical R&D needed: a) energy scale of the VLHC needs to be determined; b) development of 5-transmission lines 5T SC magnets - can allow to reduce circumference of the 40 TeV cm Phase I VLHC to 90km; c) >12 T magnet R&D for Phase II VLHC; d) development of fast cycling superferric magnets for faster injector in the Tevatron tunnel; e) beam instabilities in VLHC-I; f) handling synchrotron radiation in the VLHC-II.
5	Estimated construction duration : 7-9 years
6	Potential synergies : a) LHC lumi upgrade Nb3Sn magnets; b) muon collider HTS high field magnets; c) 480 GeV fast cycling proton accelerator; d) proton driver
7	References: FNAL-TM-2149 (2001)

VLHC: Long Tunnel



Stage I: 2T SF

Stage II: 11T NbTi