

**The Accelerator Complex from the
International Design Study
of the Neutrino Factory**

**ICHEP12 Conference, Melbourne
on behalf of IDS-NF Collaboration**




Paul Soler, 7 July 2012



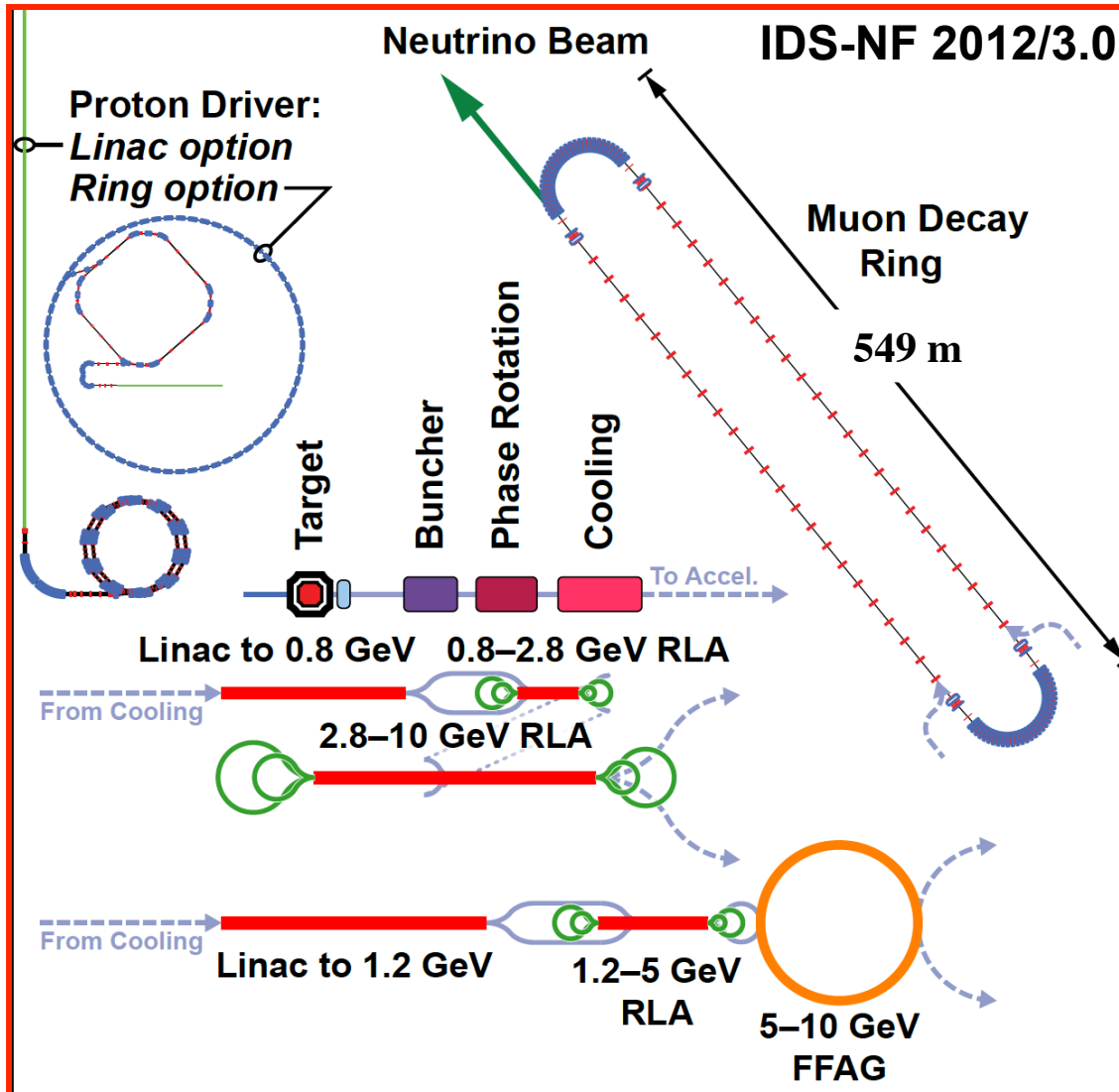
**University
of Glasgow**

International Design Study

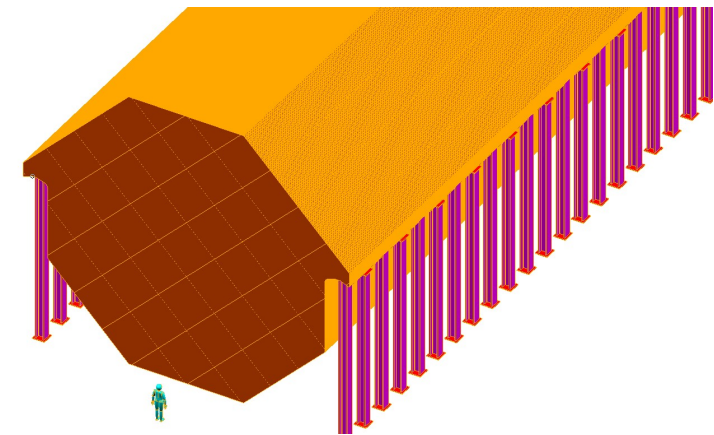
- ❑ **International Design Study for a Neutrino Factory (IDS-NF)**
 - Principal objective: deliver Reference Design Report by 2013
 - Physics performance of the Neutrino Factory
 - Specification of each of the accelerator, diagnostic, and detector systems that make up the facility
 - Schedule and cost of the Neutrino Factory accelerator, diagnostics, and detector systems.
 - Co-sponsored by EU through EUROnu 
 - Web site: <https://www.ids-nf.org/wiki/FrontPage>
- ❑ **Interim Design Report: IDS-NF-020** arXiv:1112.2853 delivered 2011
 - IDR was used to measure progress in planning for these facilities and detailed performance parameters at half way point of study
 - Reviewed by International Panel organised by ECFA, chaired by Prof Francis Halzen (Wisconsin)

Reported back to community at EPS-HEP in Grenoble 2011

Neutrino Factory Baseline



- Magnetised Iron Neutrino Detector (MIND):
 - 100 kton at ~2000 km



**Baseline recently reviewed:
from 25 GeV to 10 GeV muons
in light of large θ_{13} results**

Neutrino Oscillations in Matter

- Matter oscillation results for three neutrinos:
(MSW effect)

$$P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)}(x) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\mp} \right)^2 \sin^2 \left[\frac{B_\mp}{2} x \right]$$

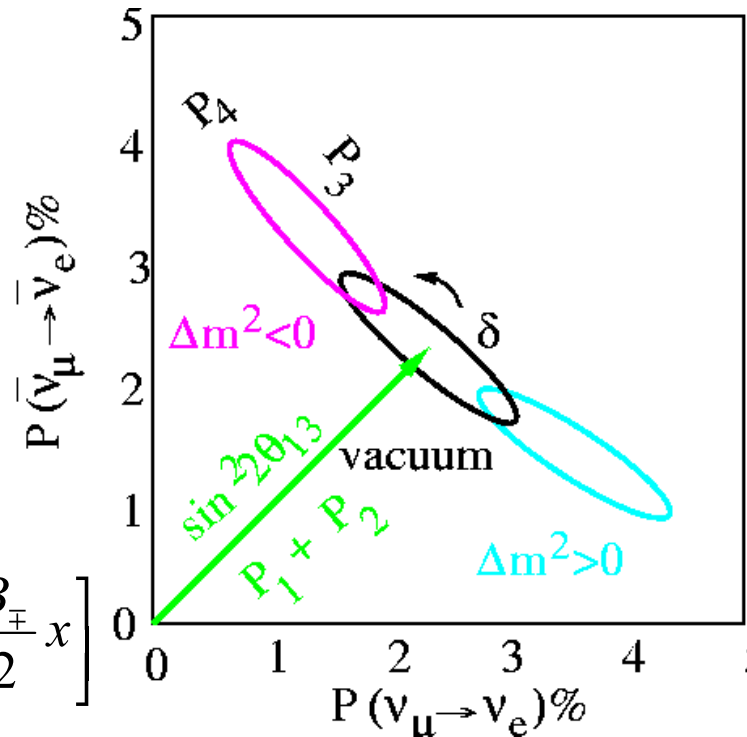
$$P_2 = c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A} \right)^2 \sin^2 \left[\frac{A}{2} x \right]$$

$$P_3 = \tilde{J} \cos \delta \cos \left[\frac{\Delta_{13}}{2} x \right] \left(\frac{\Delta_{12}}{A} \frac{\Delta_{13}}{B_\mp} \right) \sin \left[\frac{A}{2} x \right] \sin \left[\frac{B_\mp}{2} x \right]$$

$$P_4 = \pm \tilde{J} \sin \delta \sin \left[\frac{\Delta_{13}}{2} x \right] \left(\frac{\Delta_{12}}{A} \frac{\Delta_{13}}{B_\mp} \right) \sin \left[\frac{A}{2} x \right] \sin \left[\frac{B_\mp}{2} x \right]$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E} \quad A \equiv \sqrt{2} G_F n_e \quad \text{where } \pm \text{ is for } \nu, \bar{\nu} \quad \tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

$$\text{with } B_\mp \equiv \sqrt{(\Delta_{13} \cos 2\theta_{13} \mp A)^2 + \Delta_{13}^2 \sin^2 2\theta_{13}} \approx |\Delta_{13} \mp A|$$

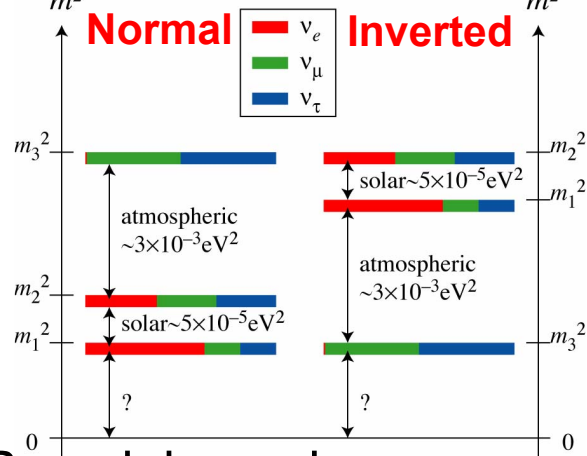


Minakata & Nunokawa JHEP 2001

Neutrino Oscillation fits

Impact of large θ_{13} from fits:

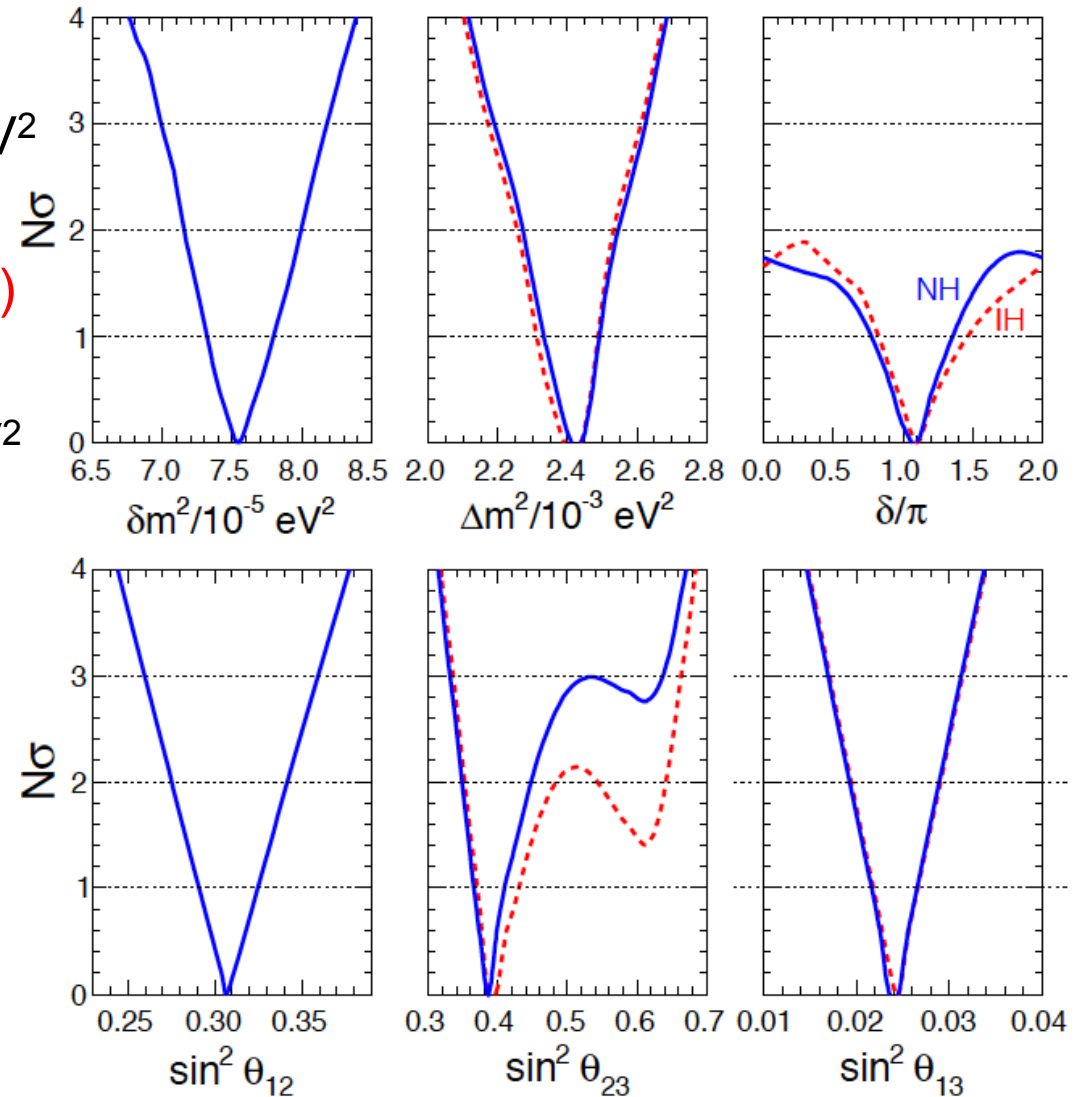
- $\sin^2\theta_{12}=0.307^{+0.018}_{-0.016}$
- $\Delta m_{21}^2 = 7.54^{+0.26}_{-0.22} \times 10^{-5} \text{ eV}^2$
- $\sin^2\theta_{13}=0.241^{+0.015}_{-0.025}$
- $\sin^2\theta_{23}=0.386^{+0.024}_{-0.021}$ (NH)
- $\sin^2\theta_{23}=0.392^{+0.039}_{-0.022}$ (IH)
- $\Delta m_{31}^2=2.43^{+0.06}_{-0.10} \times 10^{-3} \text{ eV}^2$



Remaining unknowns:

- Is $\theta_{23} = \pi/4, < \pi/4$ or $> \pi/4$?
- Mass hierarchy: sign Δm_{31}^2
- CP violation phase δ

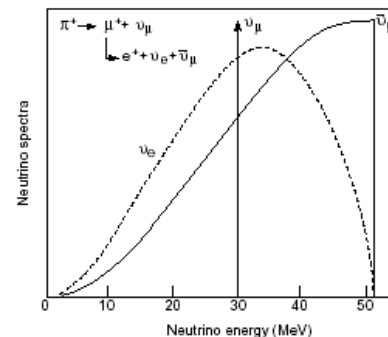
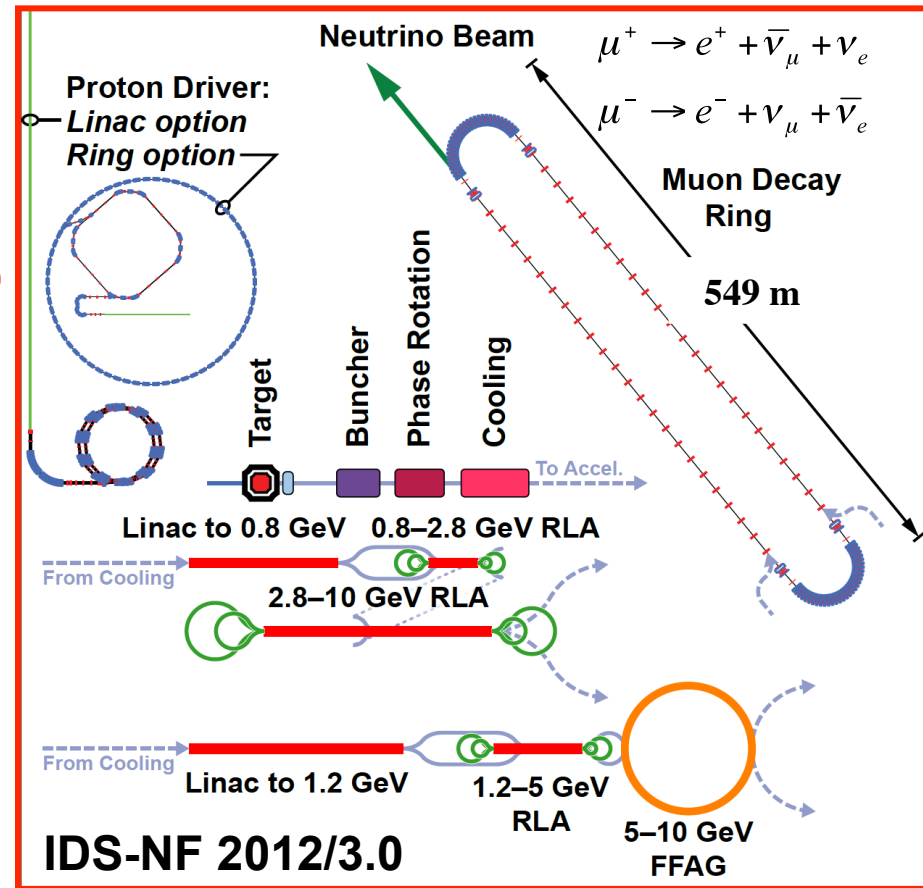
Synopsis of global 3ν oscillation analysis



Neutrino Factory Baseline

- ❑ Proton driver
 - Proton beam ~8 GeV on target
- ❑ Target, capture and decay
 - Create π , decay into μ (MERIT)
- ❑ Bunching and phase rotation
 - Reduce ΔE of bunch
- ❑ Cooling
 - Reduce transverse emittance (MICE)
- ❑ Acceleration
 - 120 MeV \rightarrow 10 GeV with RLAs or additional FFAG
- ❑ Decay ring
 - Store for ~100 turns
 - Long straight sections

See talk Ken Long at Neutrino session



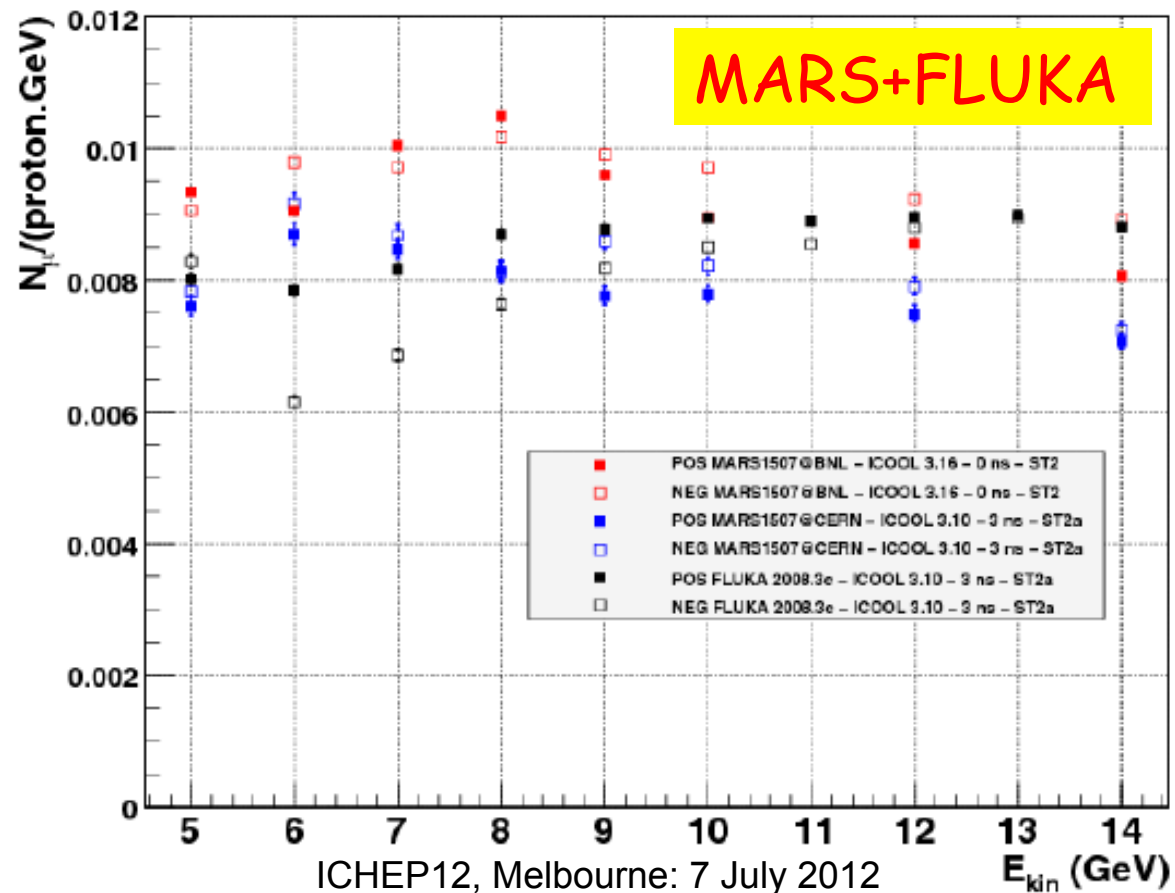
Neutrino spectra calculable to high accuracy

Optimum energy proton driver

Optimum beam energy

Adopted 10 ± 5 GeV

- Depends on choice of target
- Optimum energy for high-Z targets around 8 GeV
- Results validated by HARP hadron production experiment



Proton Driver

□ Requirements:

Parameter	Value
Kinetic energy	5–15 GeV
Average beam power	4 MW
	$(3.125 \times 10^{15}$ protons/s)
Repetition rate	50 Hz
Bunches per train	3
Total time for bunches	240 μ s
Bunch length (rms)	1–3 ns
Beam radius	1.2 mm (rms)
Rms geometric emittance	< 5 μ m
β^* at target	\geq 30 cm

□ Choice is regional decision

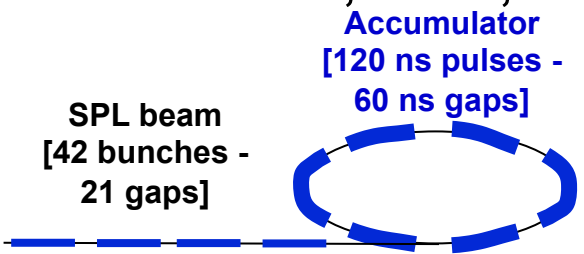
- LINAC based (SPL) proton driver at CERN: most advanced
- Synchrotron(s)/FFAG based proton driver (green field solution) – under study at RAL.
- Project X LINAC based solution at Fermilab.

Proton Driver (SPL)

❑ Superconducting Proton LINAC, SPL, at CERN: 5 GeV

Accumulation

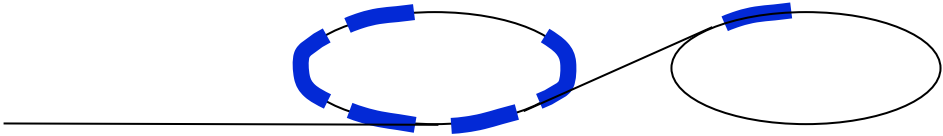
Duration = 400 μ s



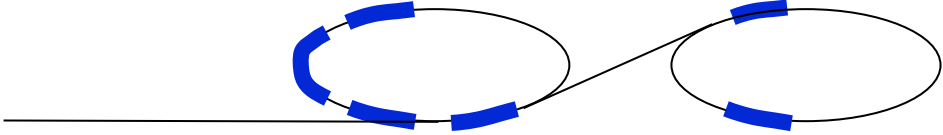
Compressor
[120 ns bunch - $V(h=3) = 4$ MV]

Compression

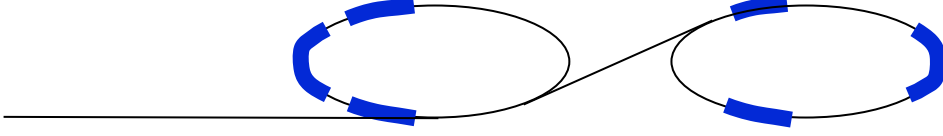
t = 0 μ s



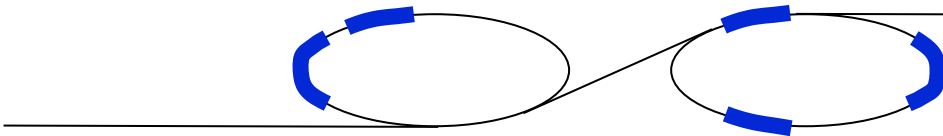
t = 12 μ s



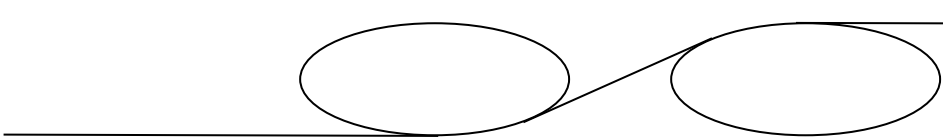
t = 24 μ s



t = 36 μ s



etc. until t = 96 μ s



Target
[2 ns bunches - 6 times]

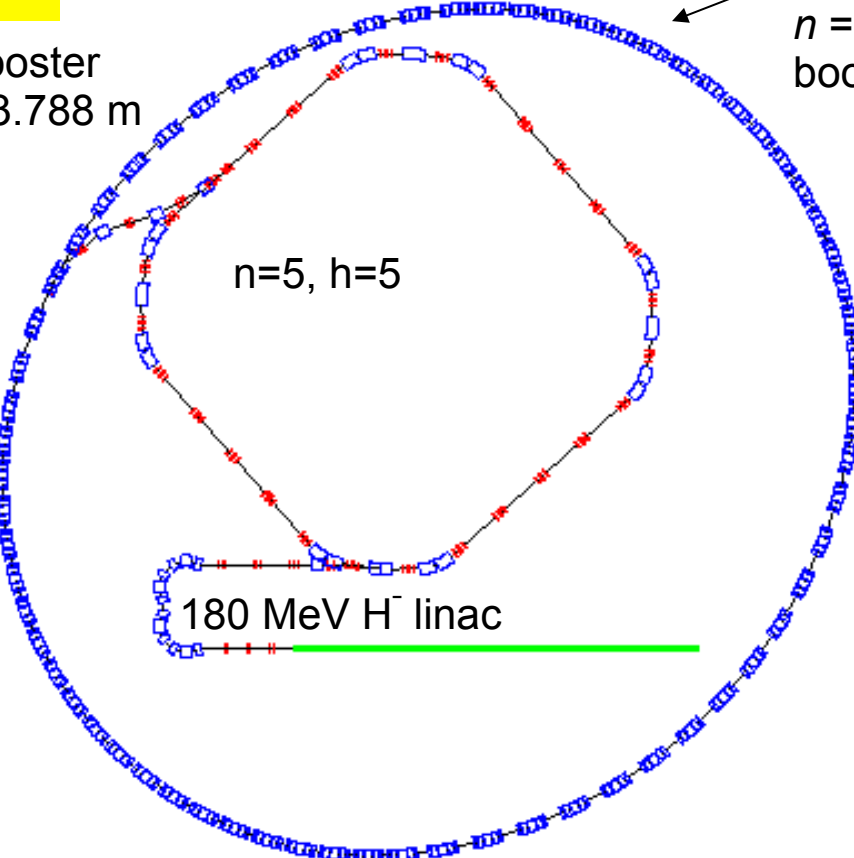
Proton Driver (FFAG)

- Hardware options: 4 MW operation
 - Fixed Field Alternating Gradient Synchrotron (FFAG)

Rees, Prior
(RAL)

3 GeV RCS booster
mean radius = 63.788 m

10 GeV non-scaling FFAG
 $n = 5, h = 40$, radius = twice
booster radius = 127.576 m



Bunch compression for 5 bunches:

Longitudinal bunch area = 0.66 eV-s

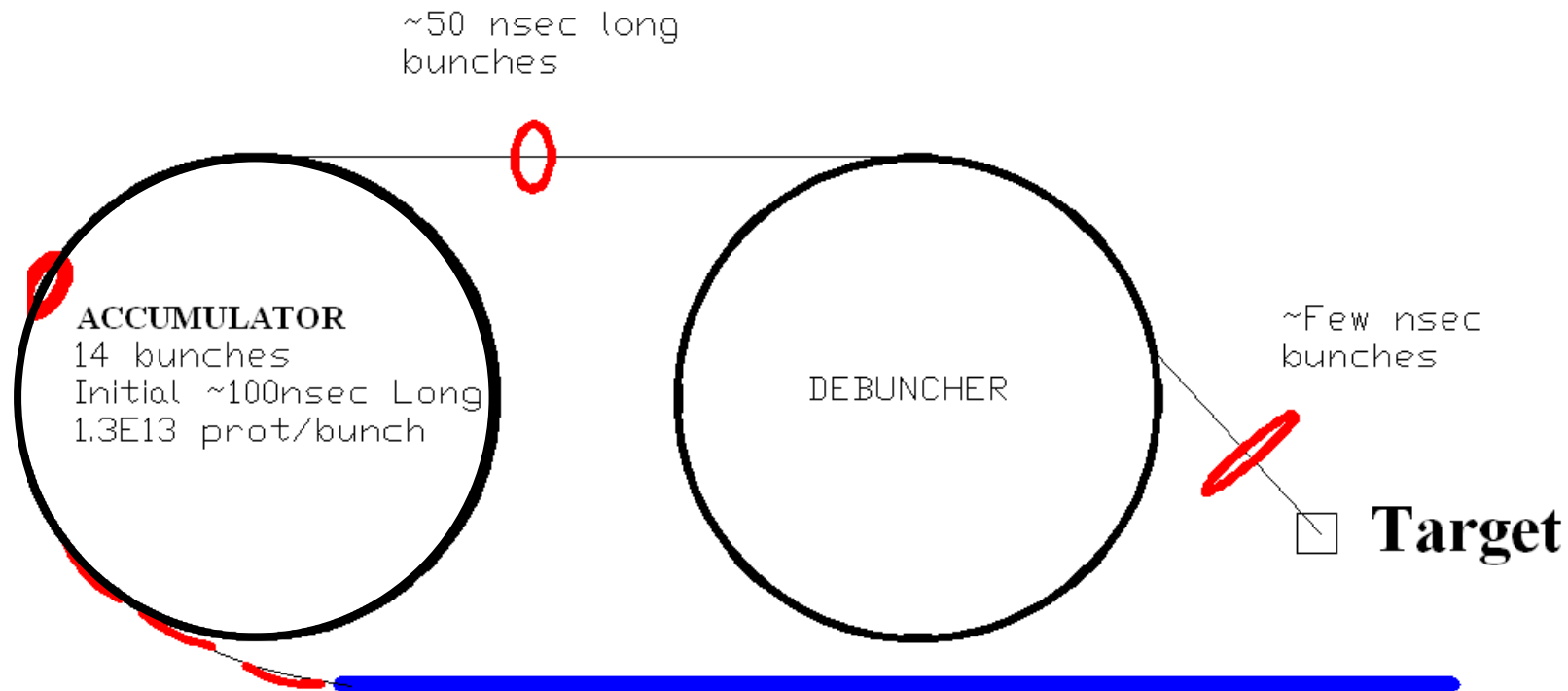
1.18 MV/turn compresses to 2.1 ns rms

Add $h = 200$, 3.77 MV/turn for 1.1 ns rms

Achromatic H^- collimation line

Proton Driver (Project X)

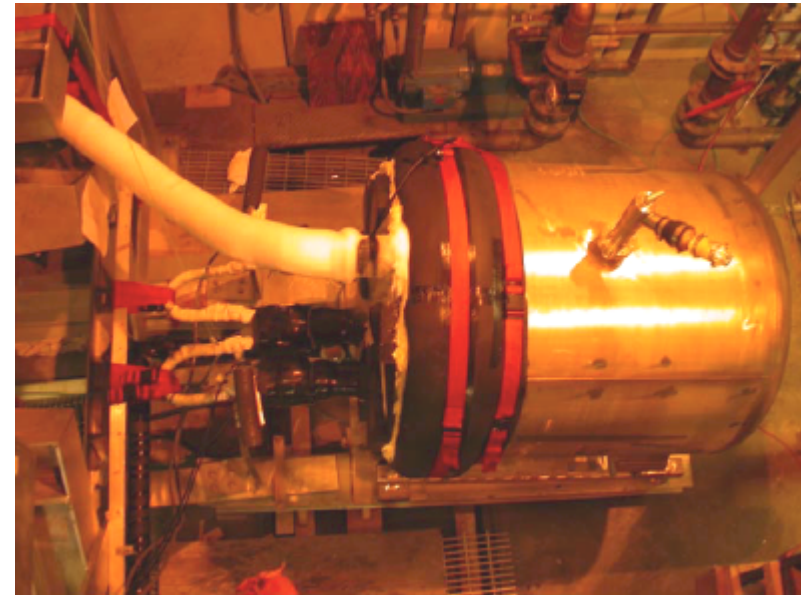
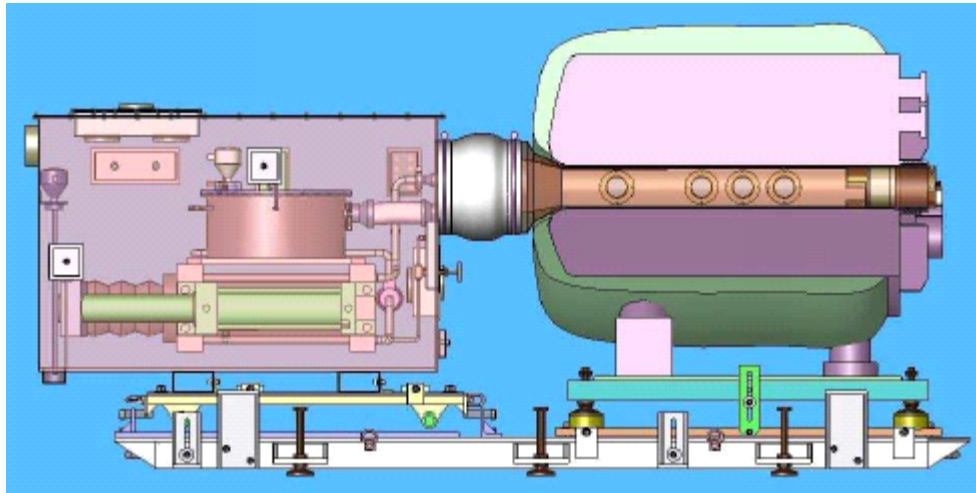
- Hardware options: 4 MW operation
 - Project X at Fermilab



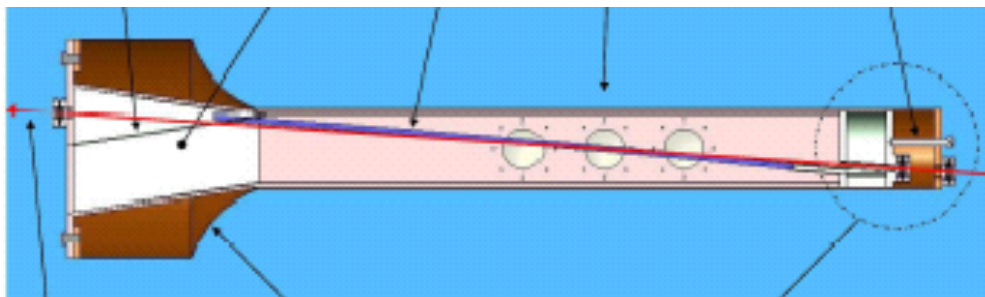
8 GeV LINAC

Target R&D: MERIT

- ❑ MERIT experiment tested Hg jet in 15-T solenoid
 - 24 GeV proton beam from CERN PS
 - Ran Autumn 2007



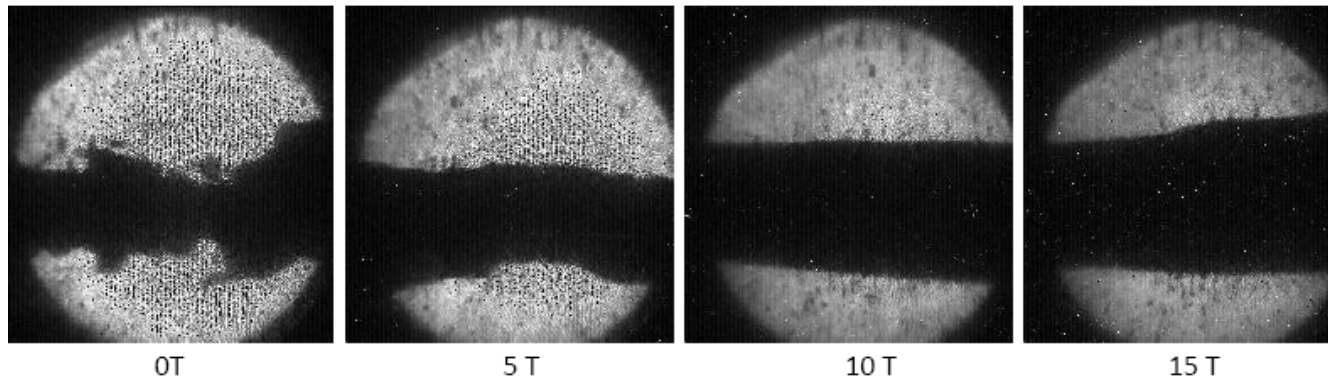
15-T solenoid during tests at MIT



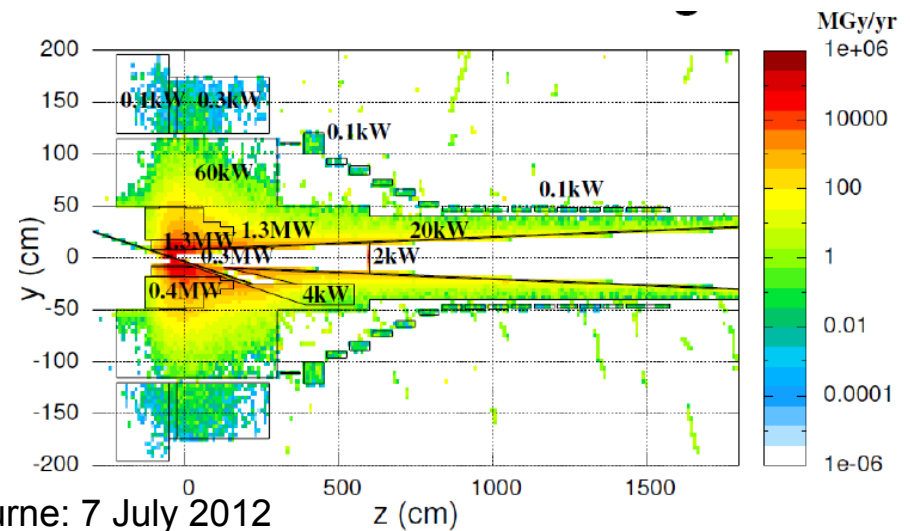
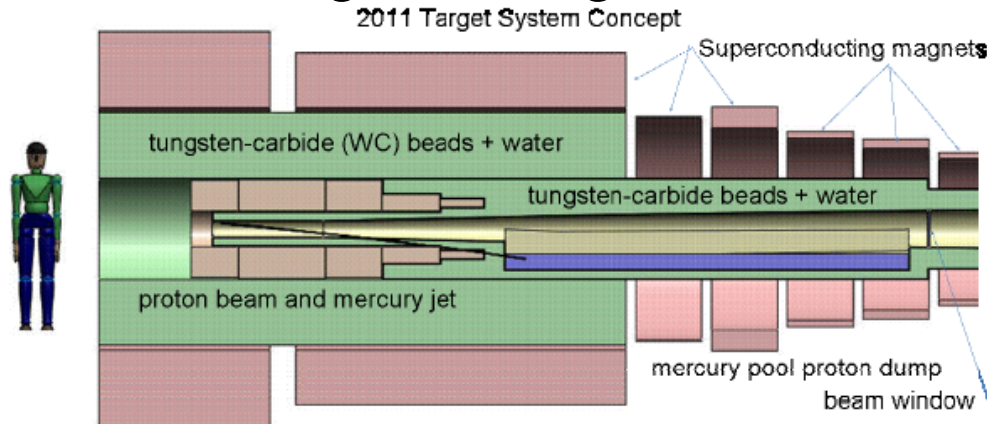
MERIT experiment showed proof-of-principle of Hg jet system in magnetic field - rated up to 8 MW

MERIT and Target

- Results MERIT:
 - Hg jet target operated at 8 MW in 15 T magnetic field with $v=15$ m/s



- Had to increase radiation shielding in solenoid surrounding new design for target station

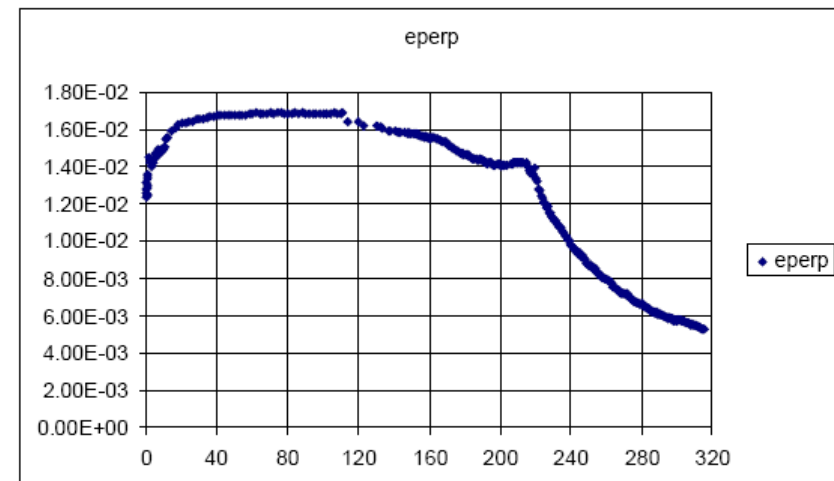
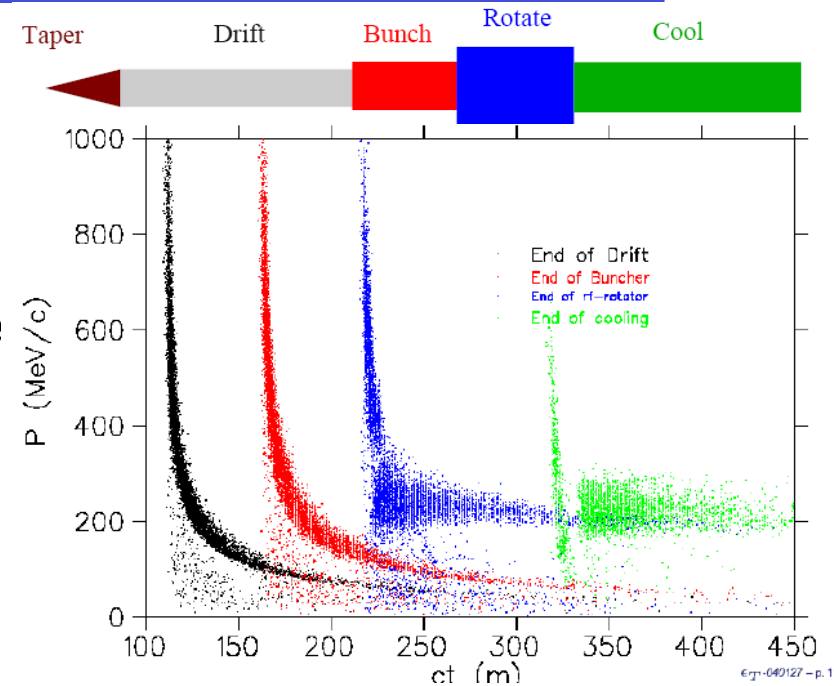


ICHEP12, Melbourne: 7 July 2012

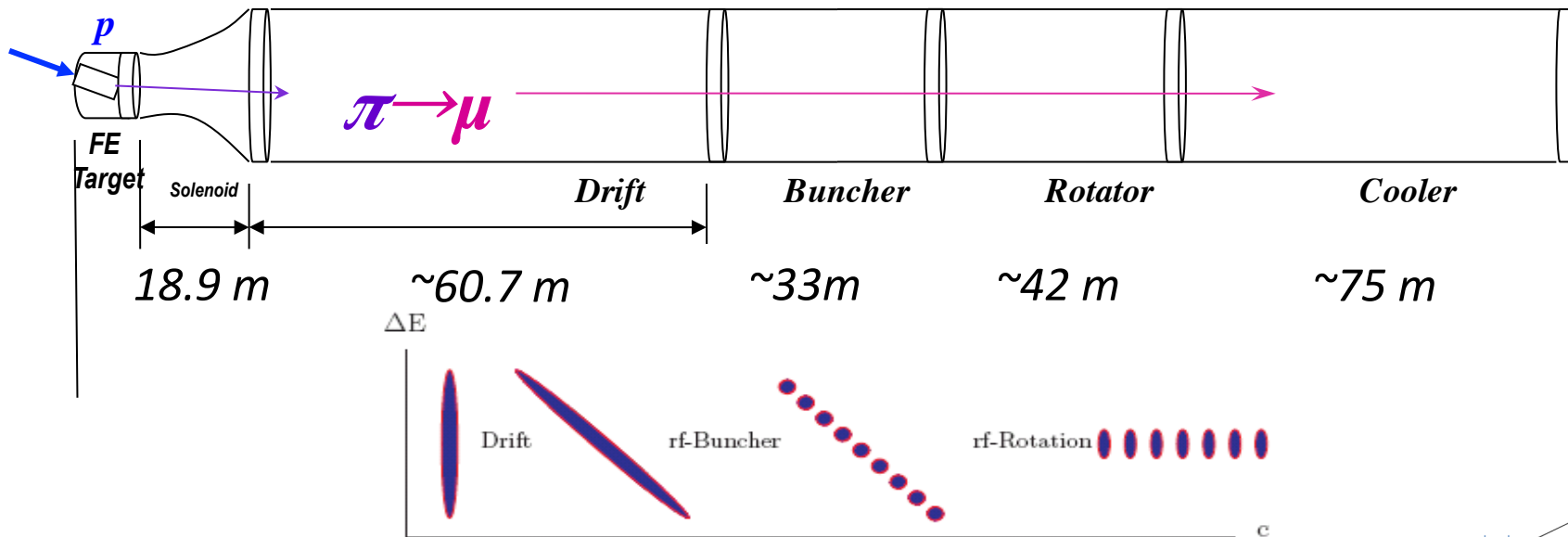
Muon Front End

- ❑ Adiabatic B-field taper from Hg target to longitudinal drift
- ❑ Drift in ~ 1.5 T, ~ 100 m solenoid
- ❑ Adiabatically bring on RF voltage to bunch beam
- ❑ Phase rotation using variable frequencies
 - High energy front sees -ve E-field
 - Low energy tail sees +ve E-field
 - End up with smaller energy spread
- ❑ Ionisation Cooling
 - Try to reduce transverse beam size
 - Prototyped by MICE

See MICE talk – Ken Long

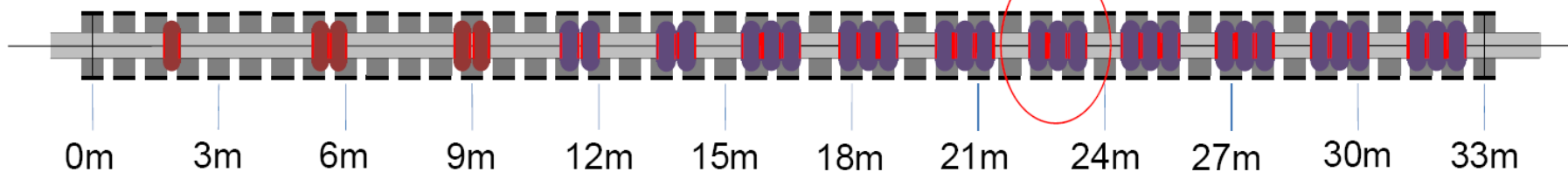
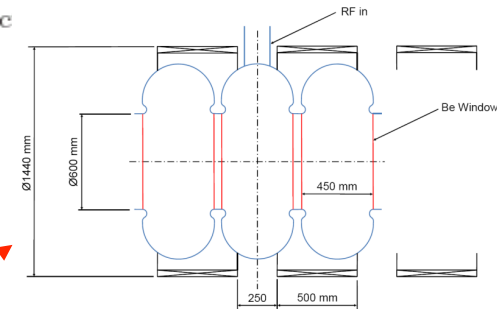


Muon Front End

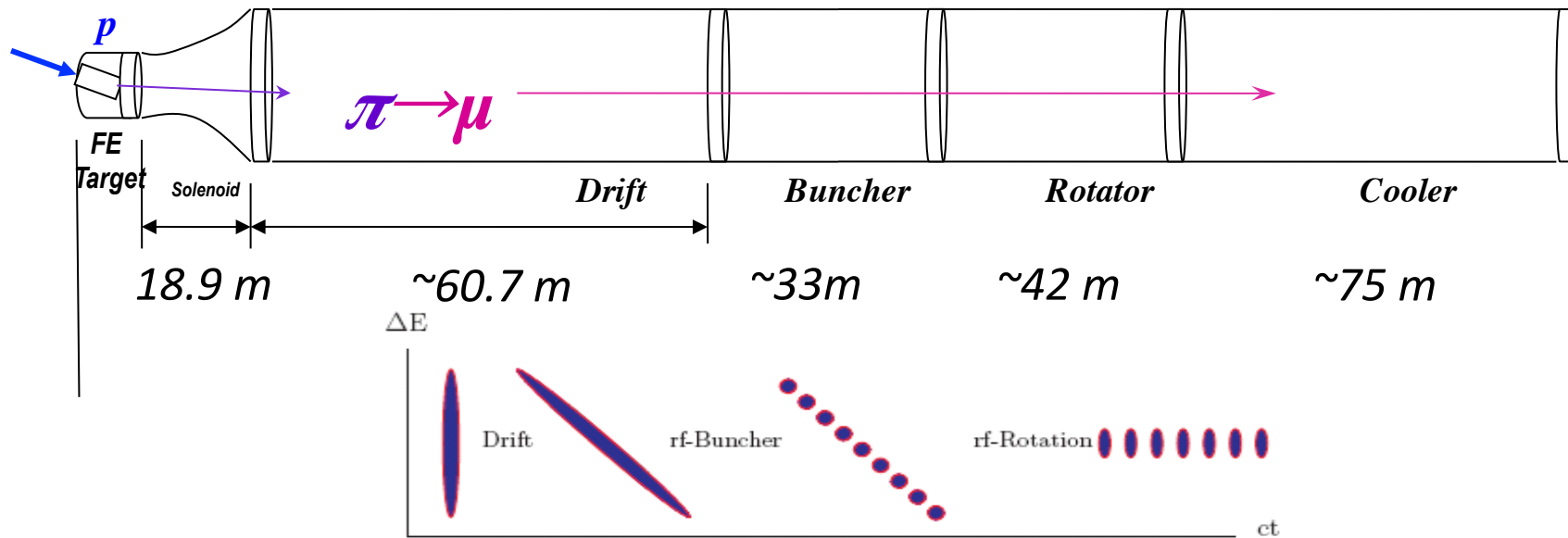


□ Buncher:

- 33 normal conducting RF cavities
- RF frequency: 320-234 MHz
- Gradient: 3.4-9.7 MV/m

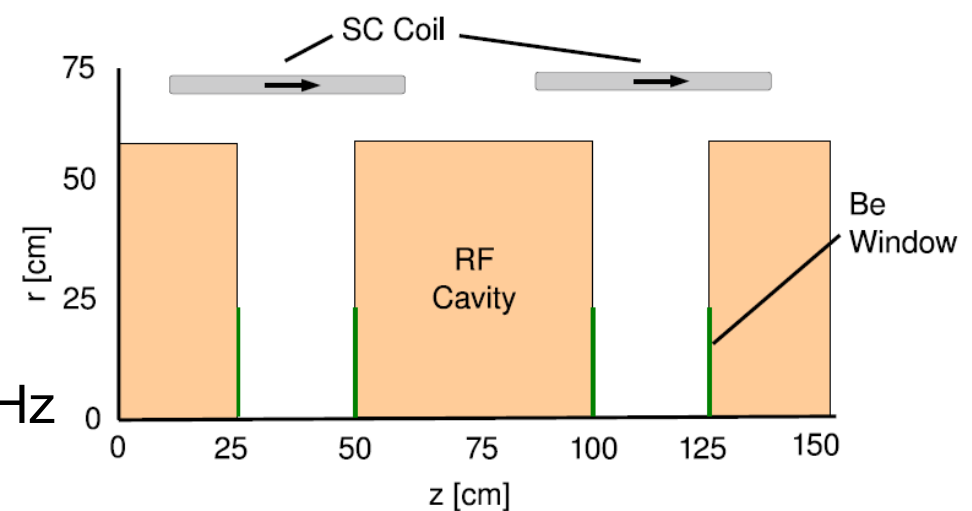


Muon Front End

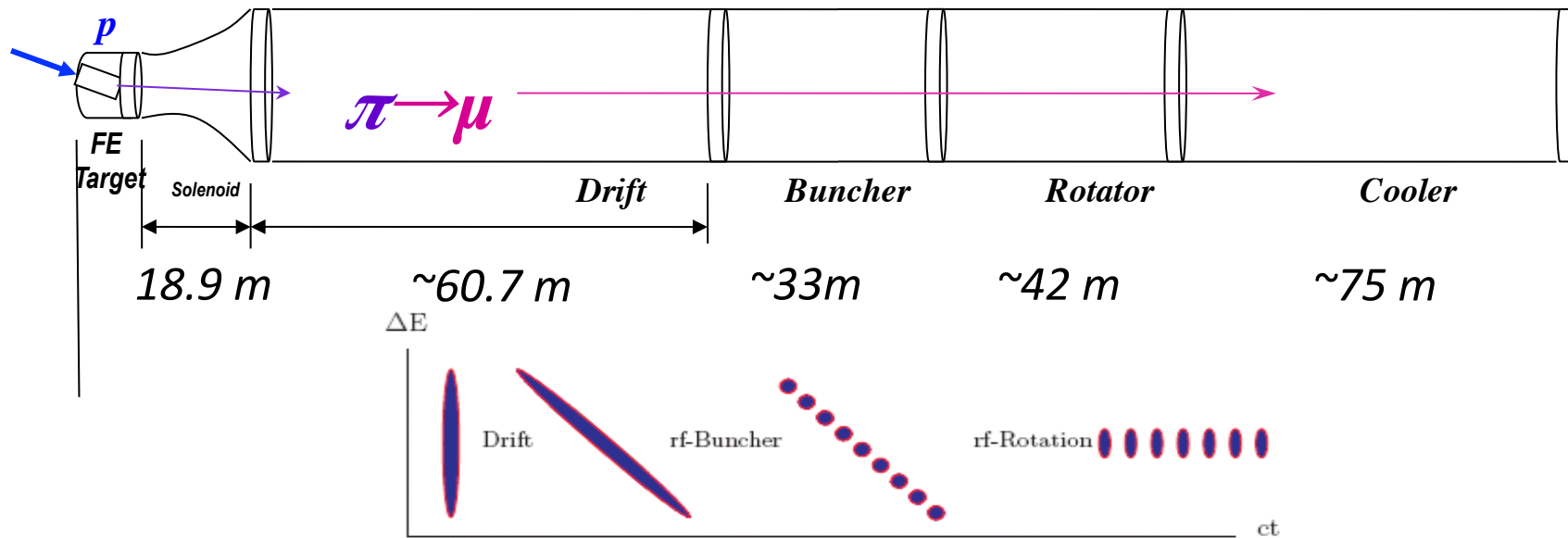


Phase rotation:

- 56 cells of 0.75 m length
- Total length: 42 m
- 56 normal conducting RF cavities with SC coils
- RF frequency 230.2- 202.3 MHz
- Gradient 12 MV/m

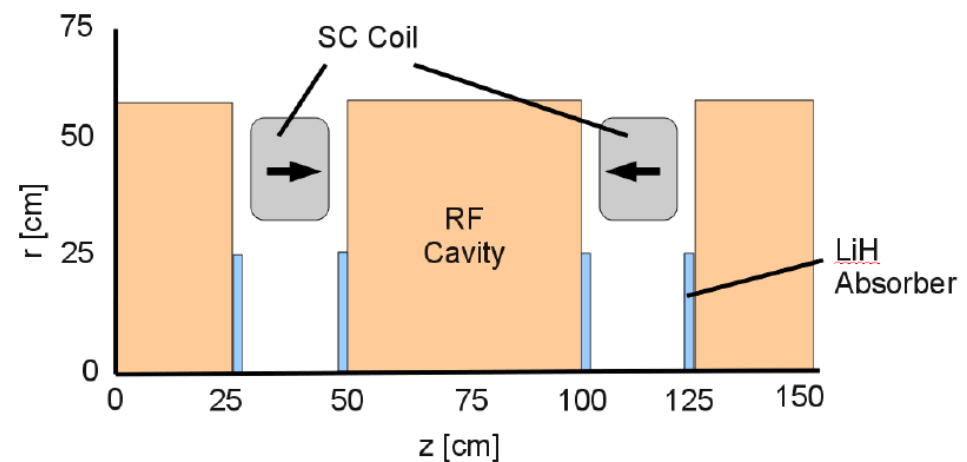


Muon Front End



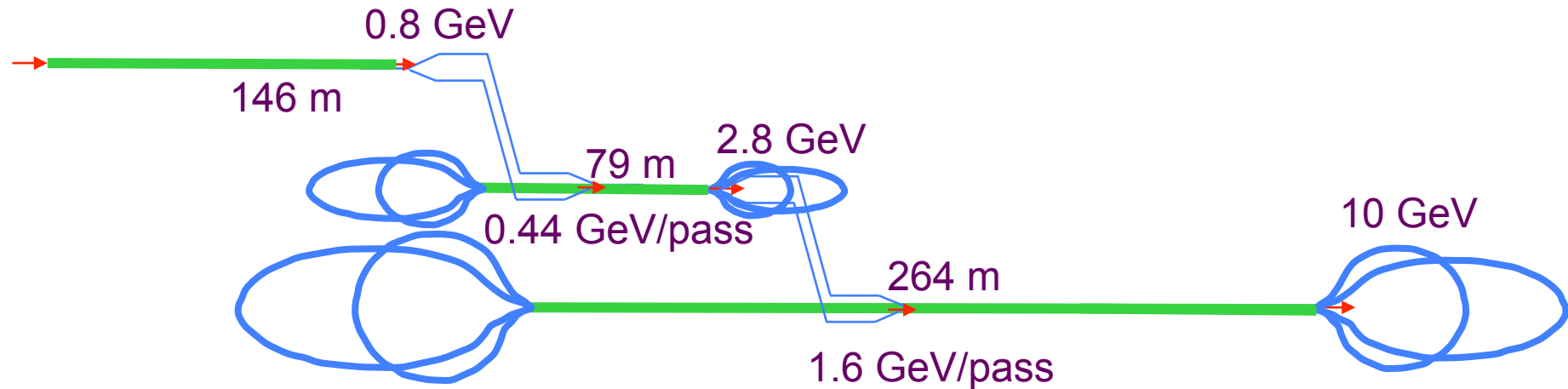
❑ Cooling channel:

- 100 cells of 0.75 m length
- Total length: 75 m
- 100 normal conducting RF cavities with SC coils
- RF frequency 201.25 MHz
- Gradient 15 MV/m
- LiH absorbers (11 cm)

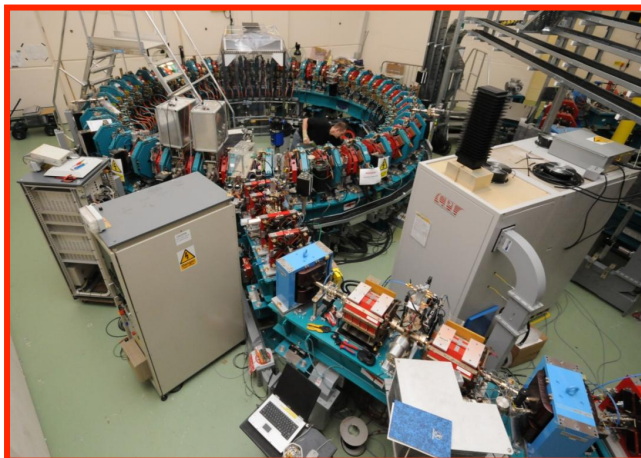


Acceleration

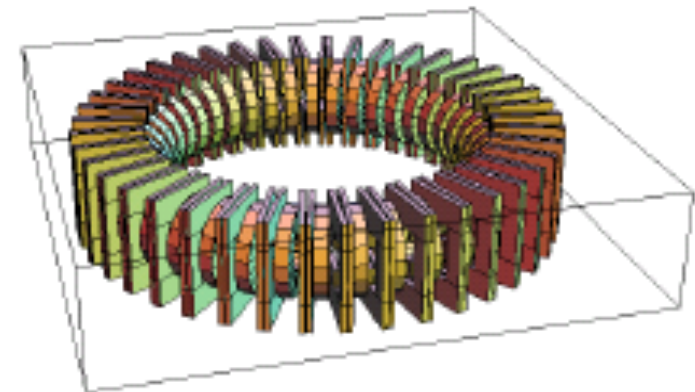
- ❑ Redefined baseline after moving to 10 GeV (IDR: 25 GeV)
 - One possibility: Recirculating Linear Accelerators (RLA) up to 10 GeV



- Another possibility, Fixed Field Alternating Gradient (FFAG): LINAC up to 1.2 GeV, RLA up to 5.0 GeV and FFAG from 5.0 –10.0 GeV

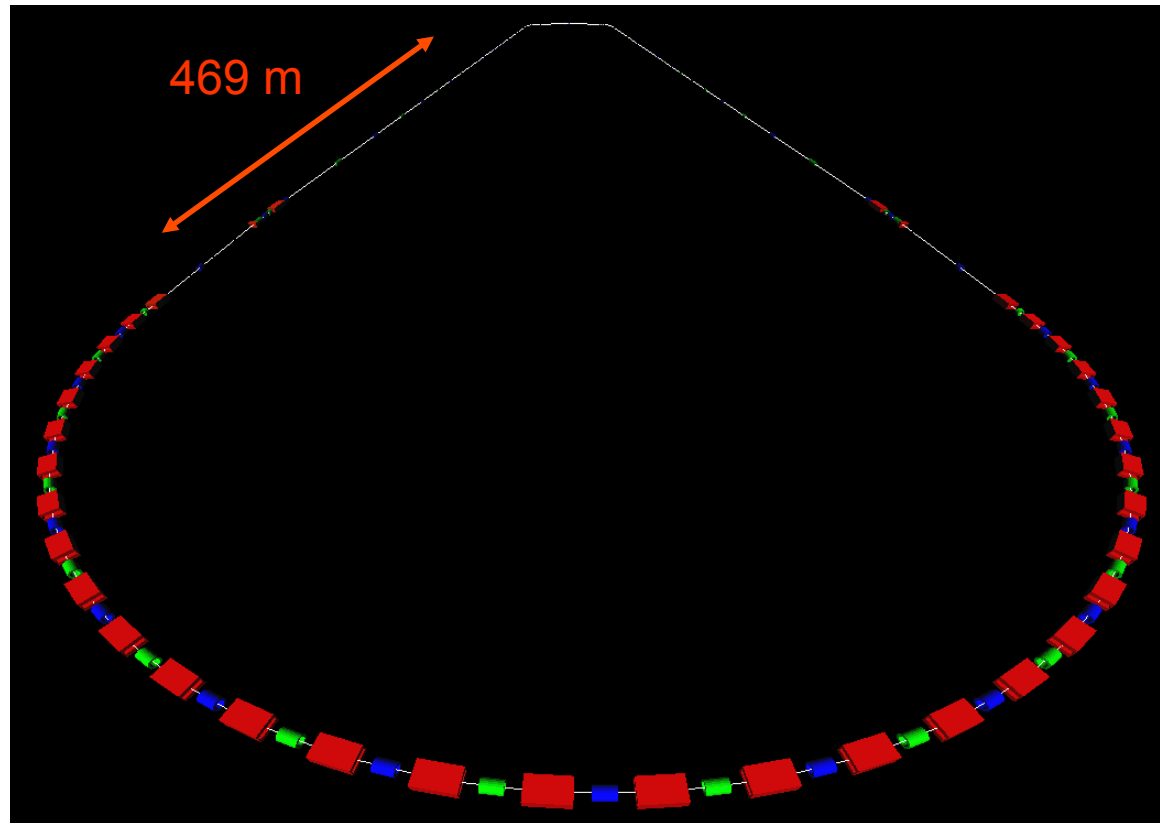
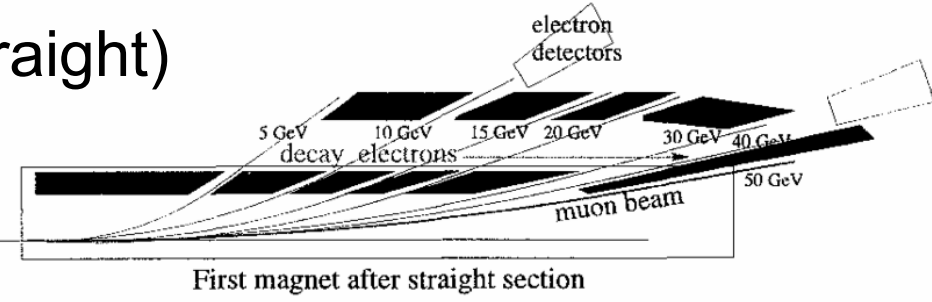


EMMA: first demonstration of non-scaling FFAG with electrons



Decay Ring Geometry

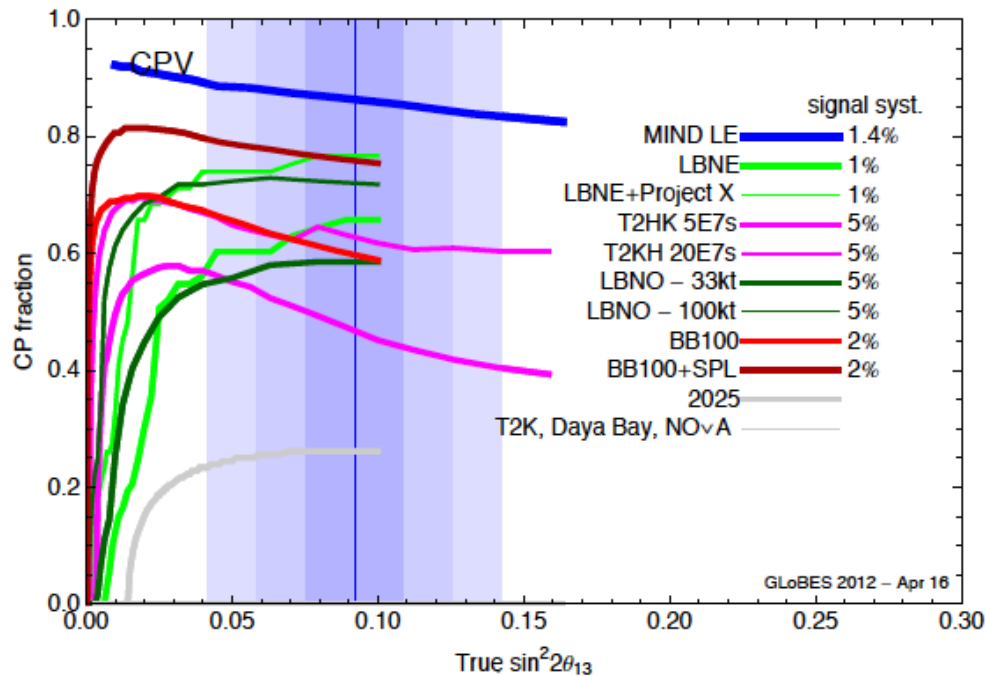
- ❑ Racetrack geometry (469 m straight)
- ❑ Decay electron energy used to measure muon polarization



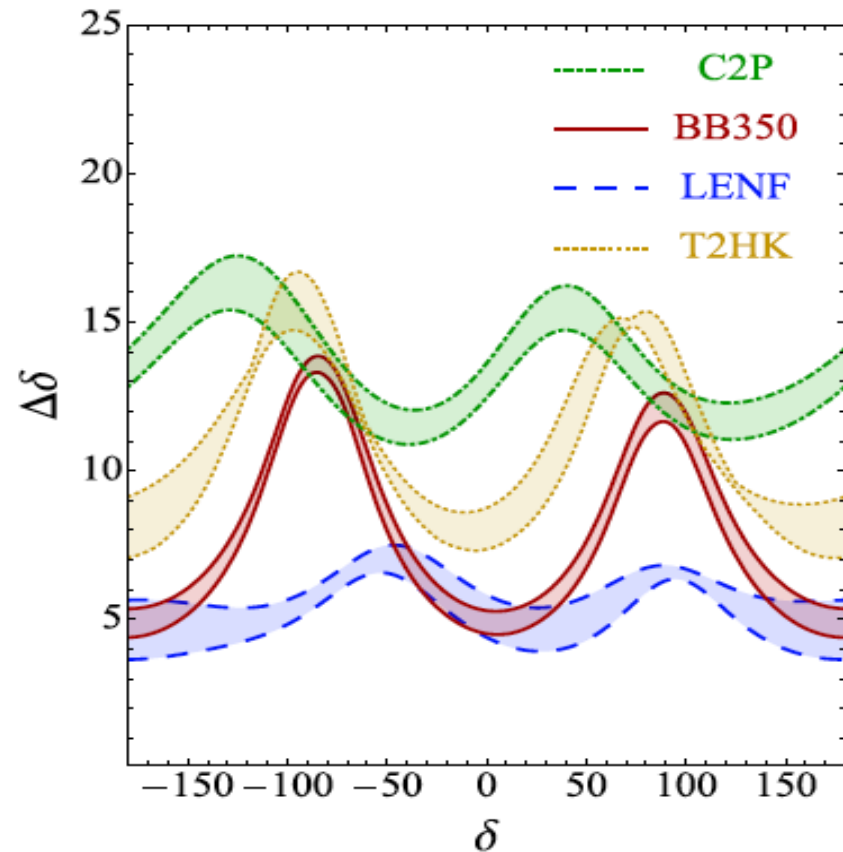
Performance 10 GeV Neutrino Factory

- Optimisation for 10 GeV Neutrino Factory with 100 kton MIND at 2000 km gives best sensitivity to CP violation, even at latest value of $\sin^2 2\theta_{13} \sim 0.09$

arXiv:1203.5651



NF yields $\Delta\delta \sim 5^\circ$, regardless of value of δ



Conclusions

- ❑ International Design Study is progressing on course
 - Interim Design Report delivered March 2011
 - Successful ECFA review May 2011
 - EUROnu preliminary report by October 2012
 - On target to produce Reference Design Report, including performance and costs by 2013
- ❑ Main concepts for accelerator systems have been defined
 - Main areas of work are at interfaces between components
- ❑ 100 kton Magnetised Iron Neutrino Detectors (MIND) at standard Neutrino Factory (10 GeV) for $\sin^2 2\theta_{13} \sim 10^{-1}$
 - Best sensitivity for CP violation of all possible future neutrino facilities
- ❑ Outlook: options for staging a Neutrino Factory are currently being considered in order to deliver physics with increased level of sensitivity at reduced cost
 - NuStorm (see K Long talk) → NF without cooling → full NF?