Imperial College London

K. Long, 8 November, 2010

Synergy with Neutrino Factory R&D

Apologies and thanks:

I would very much have liked to come to this workshop both to engage in the discussions and to make this contribution. Unfortunately, I have not been able to do this.

I would like to apologise to Yoshi Kuno and the organisers for not being at the meeting and I would like to thank Ajit Kurup for presenting these slides on my behalf.

Contents:

- The physics of flavour
- Accelerator facilities
- Conclusion and opportunity

Synergy with Neutrino Factory R&D:

The Physics of Flavour

- Neutrino oscillations, an established phenomenon
  - → Neutrino mass is not zero and neutrinos mix
    - i.e. Standard Model is incomplete
  - → Either:
    - Majorana neutrino: a new state of matter; or
    - New physics:
      - To distinguish Dirac neutrino from Dirac anti-neutrino

- Observations:
  - Neutrino mixing pattern substantially different to that of the quarks
  - Neutrino masses are tiny

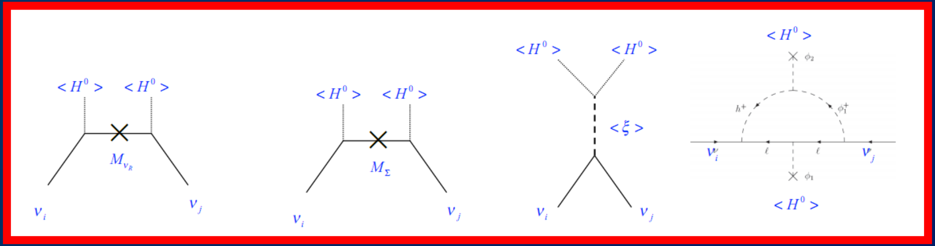
- Phenomenological description:
  - Mixing of mass states → flavour states
    - Potentially yields additional source of CP violation

- Theory presently unable to offer *explanations*
  - Many ideas, many predictive, none established

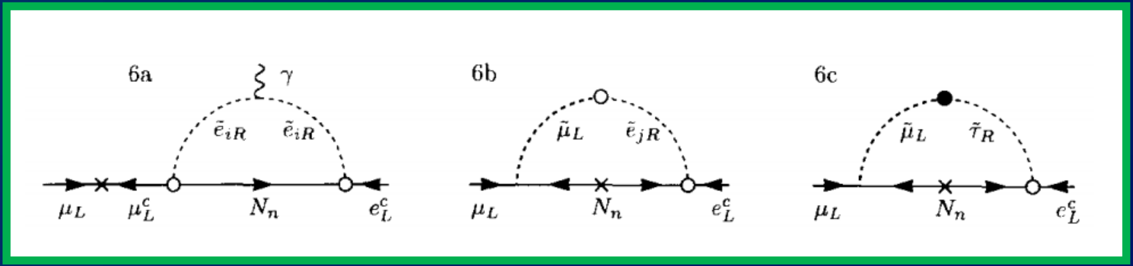
- Lepton-flavour physics is led by *experiment!*
  - Imperative: devise best experimental programme:
    - Best sensitivity for discovery, best precision on parameters

Synergy:

- Neutrino oscillations:



- Charged lepton flavour violation:

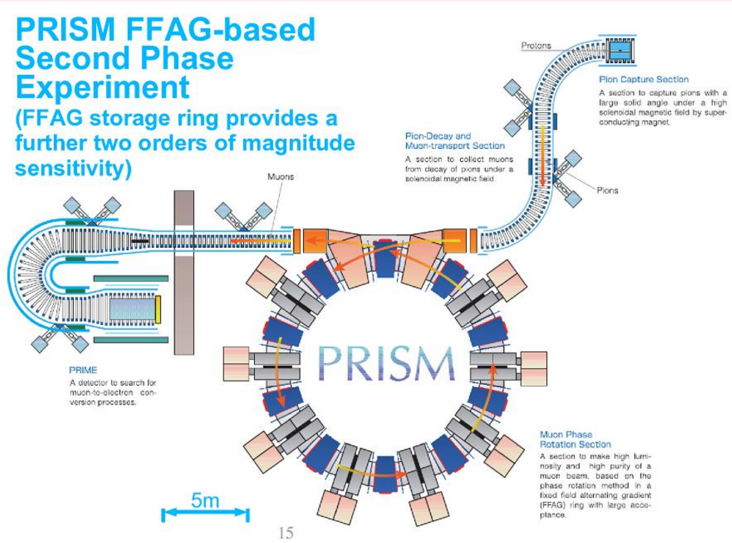


- Related processes?
  - Again, many theories, in some there is strong relation between explanation of neutrino oscillations and CLFV, in others there is not
  - Experimentally led, therefore greatest benefit from combining:
    - Neutrino oscillations, CLFV searches, LFV at colliders
- Can we articulate a 'muon programme'?
  - Definitive CLFV programme
  - Definitive neutrino oscillations programme
  - The route to the energy frontier in lepton-antilepton collisions

Synergy with Neutrino Factory R&D:

Accelerator facilities

Overview:



PRISM FFAG-based Second Phase Experiment

(FFAG storage ring provides a further two orders of magnitude sensitivity)

Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by super-conducting magnet.

Pion-Decay and Muon-transport Section

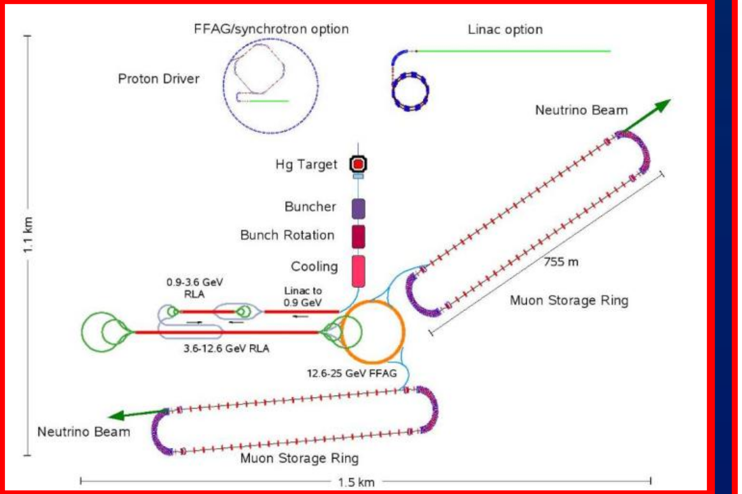
A section to collect muons from decay of pions under a solenoidal magnetic field.

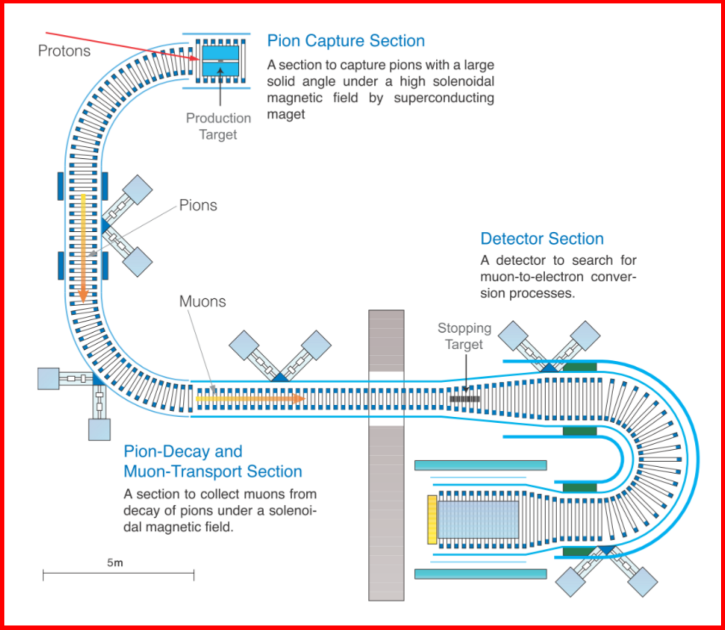
PRIME

A detector to search for muon-to-electron conversion processes.

Muon Phase Rotation Section

A section to make high luminosity and high purity of a muon beam, based on the phase rotation method in a fixed field alternating gradient (FFAG) ring with large acceptance.





Pion Capture Section

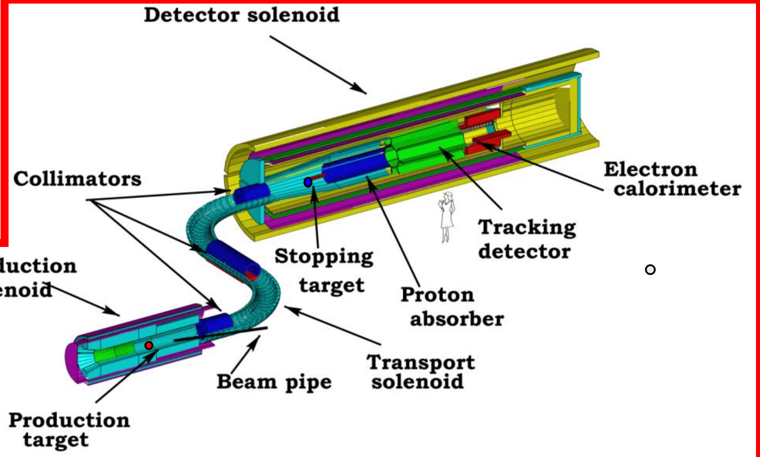
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget

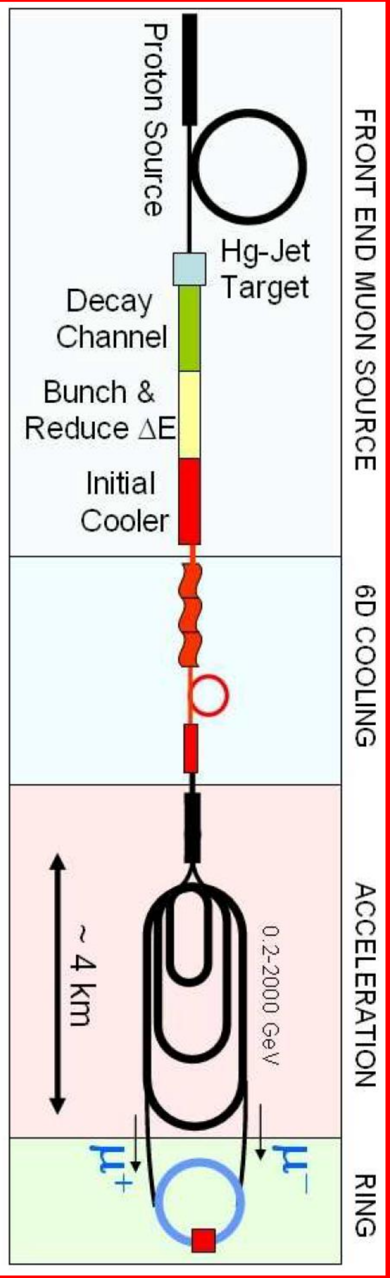
Detector Section

A detector to search for muon-to-electron conversion processes.

Pion-Decay and Muon-Transport Section

A section to collect muons from decay of pions under a solenoidal magnetic field.





Proton driver:

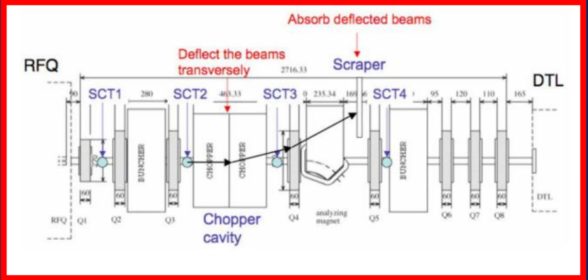
- Requirements:

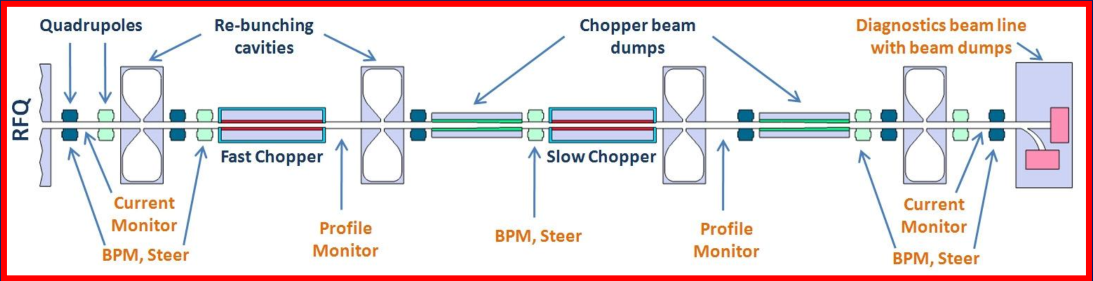
	COMET/Mu2e	PRISM	Neutrino Factory
Power (kW)	56	750--2000	4000
Energy (GeV)	8	2--8	5--15 (8)
Extinction	10^{-9}		
Bunch length (ns)	100	10	2

- Short proton bunch length common requirement:
  - COMET/Mu2e: 100 ns ‘achievable’:
  - PRISM: 10 ns at high power, low energy requires development
  - Neutrino Factory: 2 ns at high power and low energy requires development
- Chopping:
  - Also common requirement

Chopping/extinction:

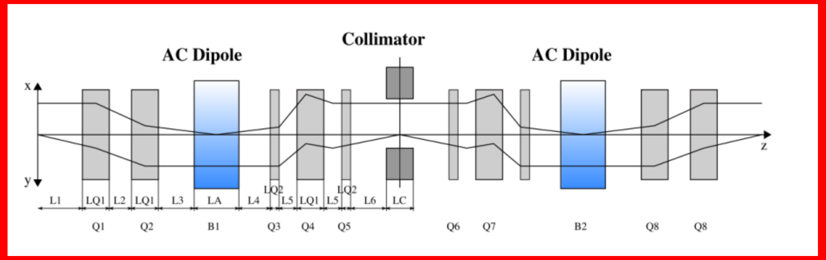
- Chopping: for preparation of linac beam for injection into synchrotron:



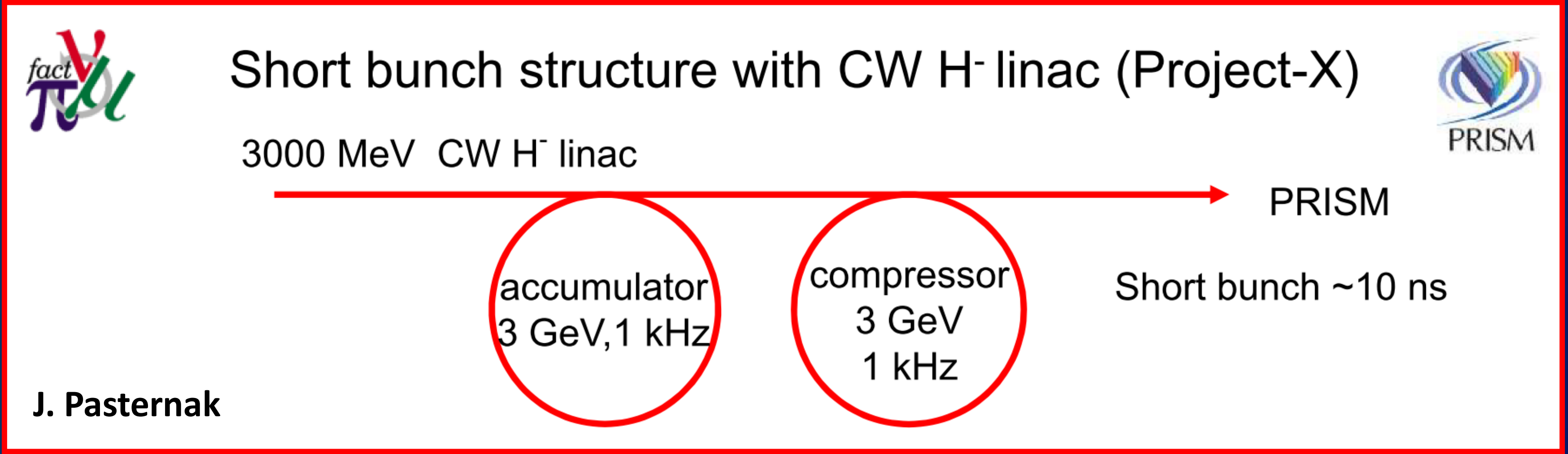


  - Development required (and in hand) for high-power beams (PRISM, Neutrino Factory, Muon Collider)

- Extinction:
  - CLVF: background handling



Bunch compression:



Short bunch structure with CW H^- linac (Project-X)

3000 MeV CW H^- linac

accumulator 3 GeV,1 kHz

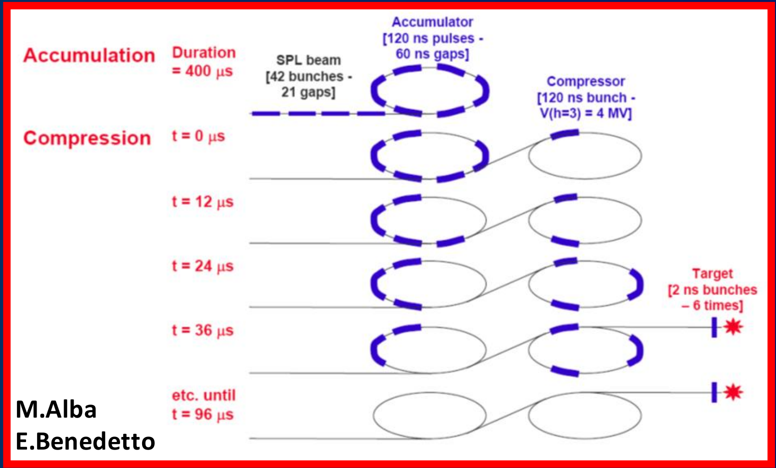
compressor 3 GeV 1 kHz

PRISM

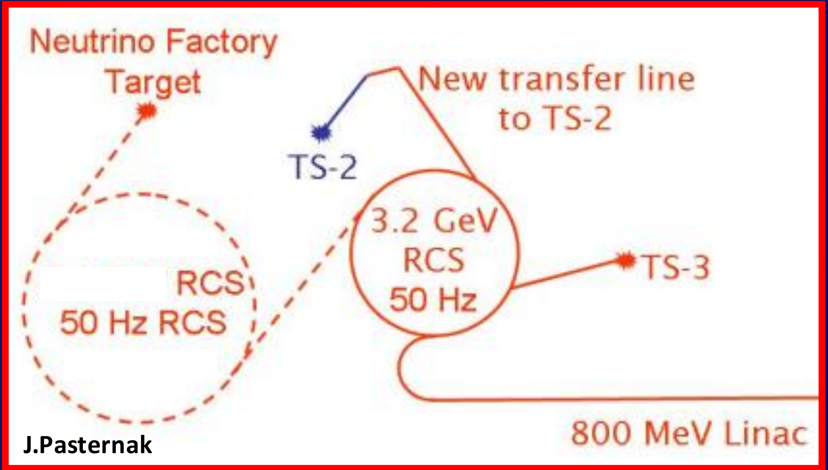
Short bunch ~10 ns

J. Pasternak

- **IDS-NF considering two generic options:**
  - **LINAC:**
    - **Possible development option for SPL (CERN) or Project-X (FNAL)**
    - **Requires accumulator/compressor rings**
  - **Rings:**
    - **Development option for J-PARC or RAL or possible 'green-field' option**
    - **Requires bunch compression**



M.Alba
E.Benedetto



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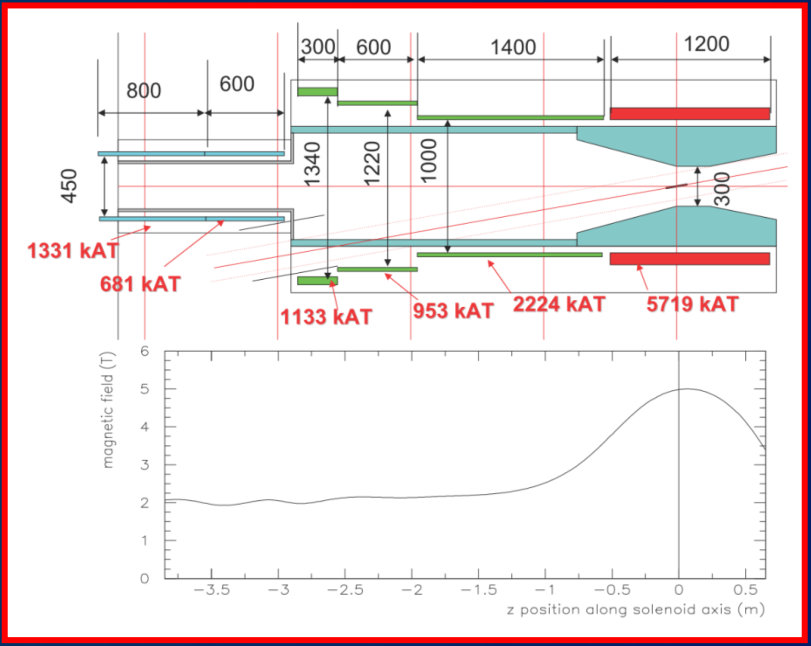
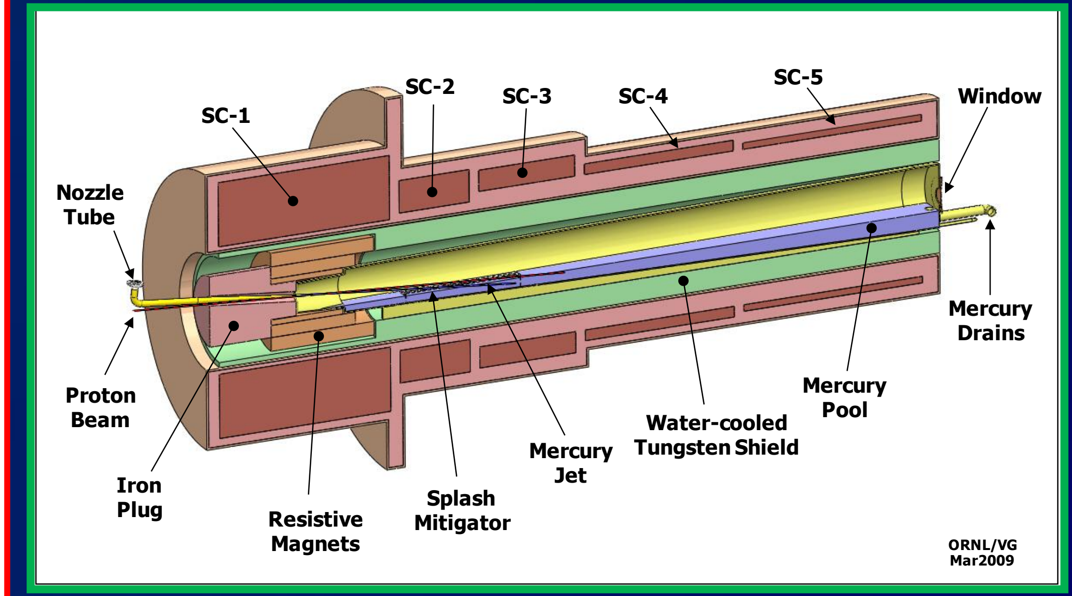
Pion-production and capture:

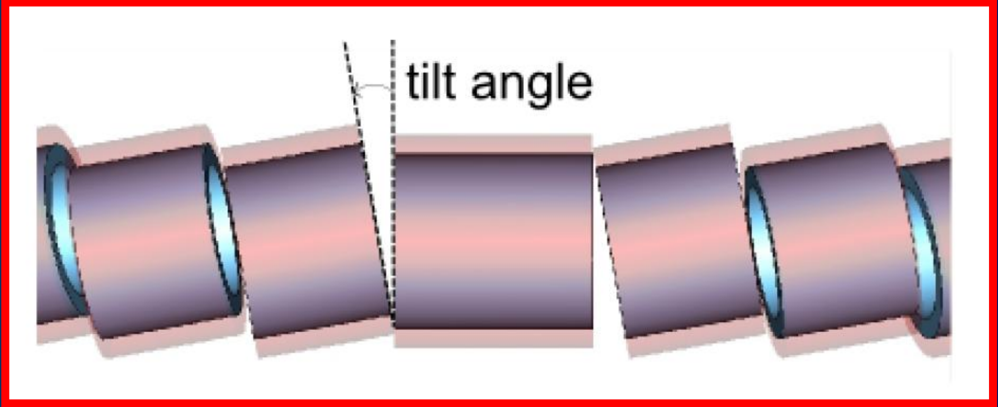
- Differences:
  - CLFV: capture backward-going pions
  - Neutrino Factory: capture in forward direction
- Nevertheless, capture systems all based on high-field solenoids:

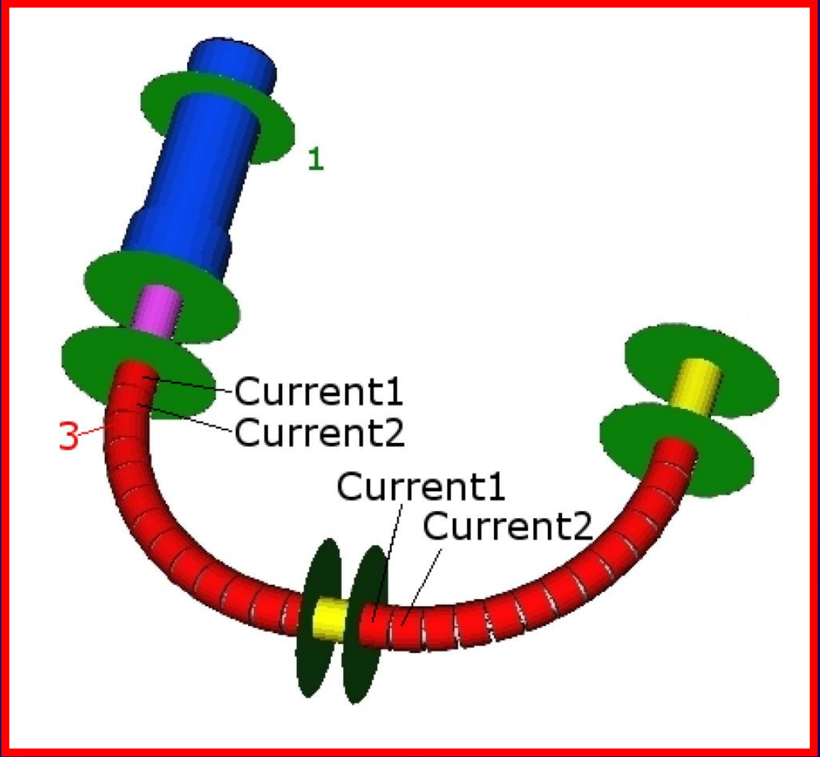




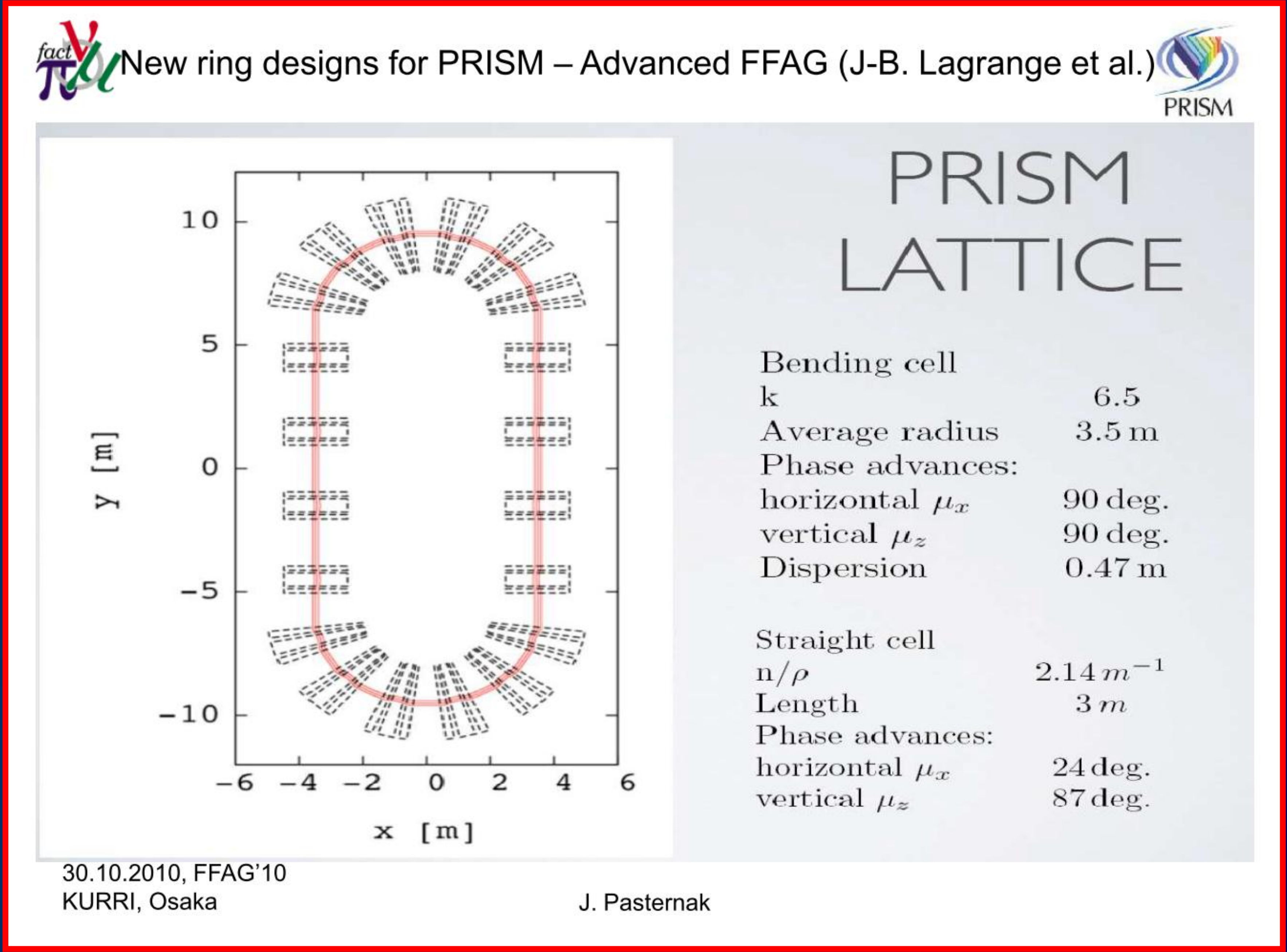
Muon-beam transport:

- Muon beam is a tertiary beam:
  - Typically large emittance
- Solenoidal transport common to CLFV, Neutrino Factory, and Muon Collider
  - COMET requirment:
    - 'Twisted solenoids' to introduce vertical dipole component
  - Possible application in Neutrino Factory front-end





Muon FFAG:



New ring designs for PRISM – Advanced FFAG (J-B. Lagrange et al.)

PRISM LATTICE

Bending cell	
k	6.5
Average radius	3.5 m
Phase advances:	
horizontal μ_x	90 deg.
vertical μ_z	90 deg.
Dispersion	0.47 m

Straight cell	
n/ρ	$2.14\,m^{-1}$
Length	$3\,m$
Phase advances:	
horizontal μ_x	24 deg.
vertical μ_z	87 deg.

30.10.2010, FFAG'10
KURRI, Osaka

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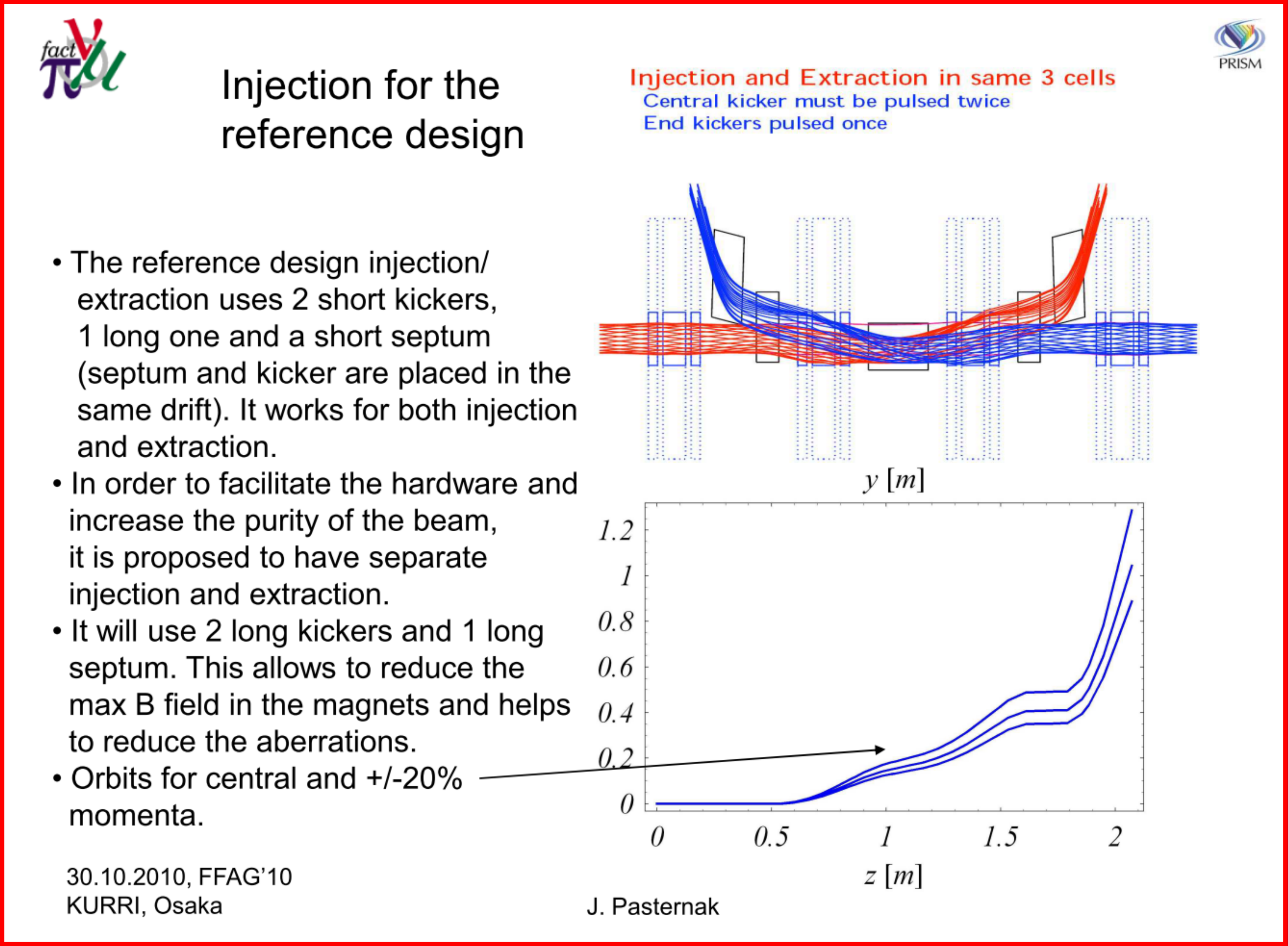
Injection/extraction:



Injection for the reference design

- The reference design injection/ extraction uses 2 short kickers, 1 long one and a short septum (septum and kicker are placed in the same drift). It works for both injection and extraction.
- In order to facilitate the hardware and increase the purity of the beam, it is proposed to have separate injection and extraction.
- It will use 2 long kickers and 1 long septum. This allows to reduce the max B field in the magnets and helps to reduce the aberrations.
- Orbits for central and +/-20% momenta.

Injection and Extraction in same 3 cells

Central kicker must be pulsed twice

End kickers pulsed once

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KURRI, Osaka

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	E_{fin} (GeV)	Comment
Pre-accel. Linac	0.9	Change in γ
RLA I	3.6	Switch-yard congestion
RLA II	12.6	Switch-yard congestion
FFAG	25.0	Large acceptance, use of RF

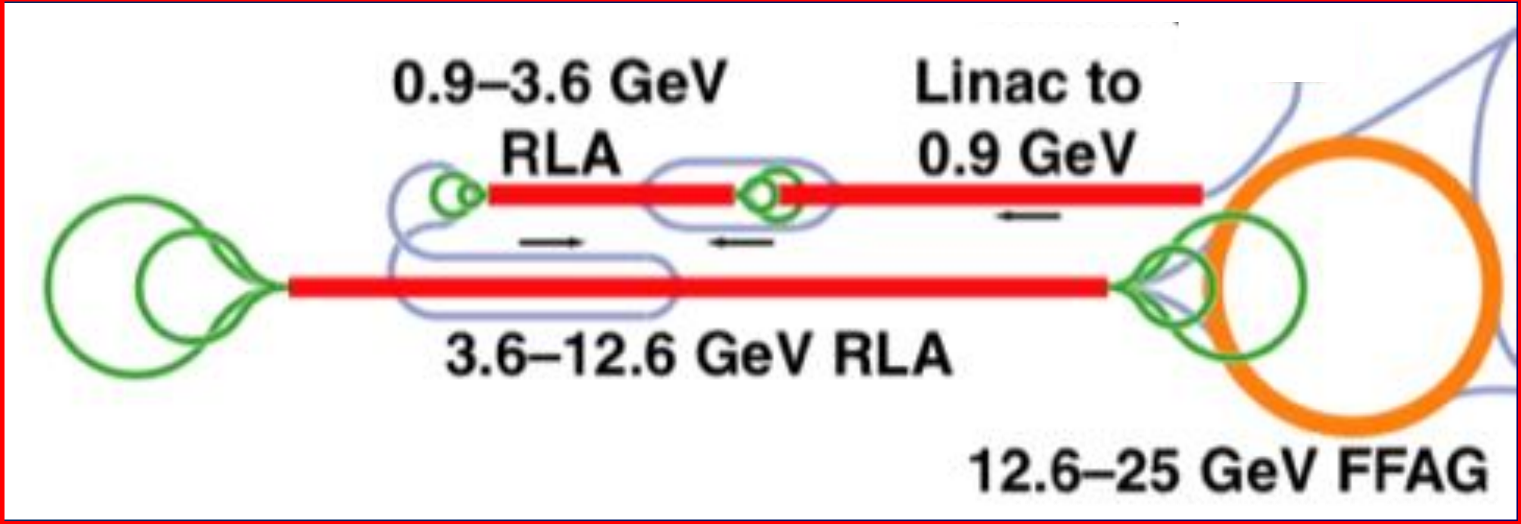
Muon acceleration:

Rapid acceleration!

- **Linac/RLAs:**
  - Superconducting linac:
    - Large acceptance;
    - Rapidly increase γ to increase effective lifetime
  - Recirculating linacs (RLAs):
    - Continue rapid acceleration
    - More cost-effective use of RF

- **Fixed Field Alternating Gradient (FFAG) accelerator:**
  - Large aperture magnets with fixed field:
    - Continued rapid acceleration
    - Improved cost-efficiency in use of RF
  - Injection/extraction challenging:
    - Development of appropriate schemes in progress

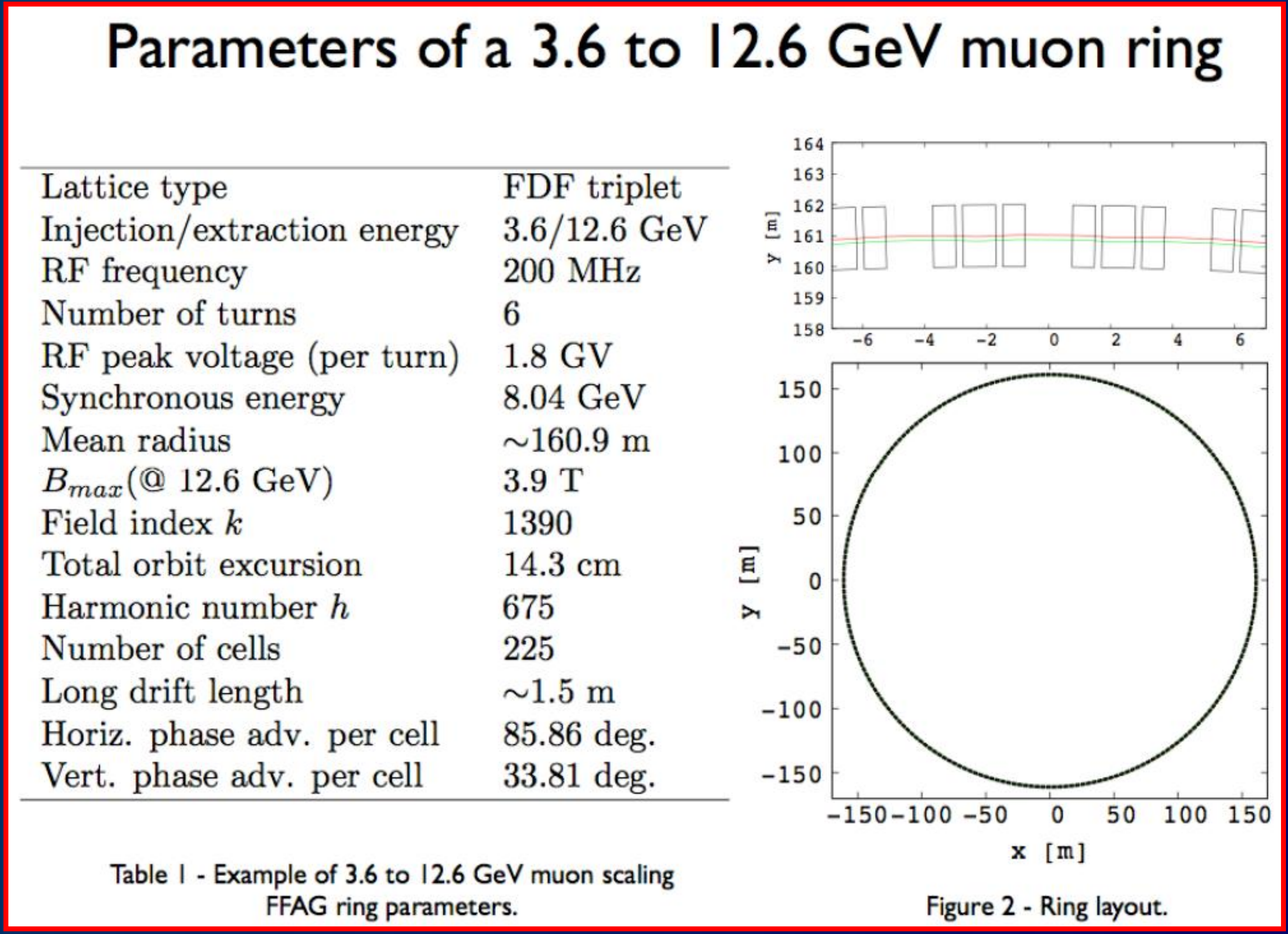
IPAC10: WEPE060, THPEB035,THPE033, THPD093



T.Planche

3.6—12.5 GeV alternative:

- Possibility of cost saving through use of an FFAG alternative to Linac/RLAs under study



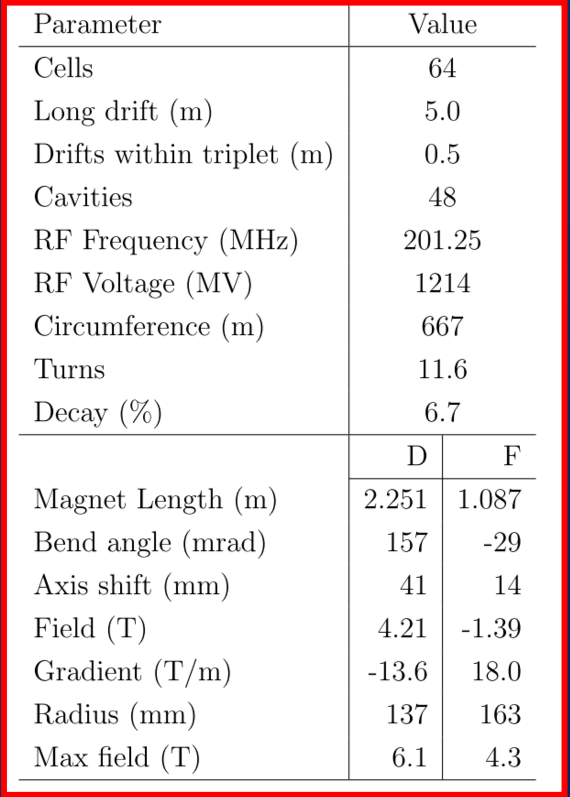
Parameters of a 3.6 to 12.6 GeV muon ring

Lattice type	FDF triplet
Injection/extraction energy	3.6/12.6 GeV
RF frequency	200 MHz
Number of turns	6
RF peak voltage (per turn)	1.8 GV
Synchronous energy	8.04 GeV
Mean radius	~160.9 m
B_{max}(@ 12.6 GeV)	3.9 T
Field index k	1390
Total orbit excursion	14.3 cm
Harmonic number h	675
Number of cells	225
Long drift length	~1.5 m
Horiz. phase adv. per cell	85.86 deg.
Vert. phase adv. per cell	33.81 deg.

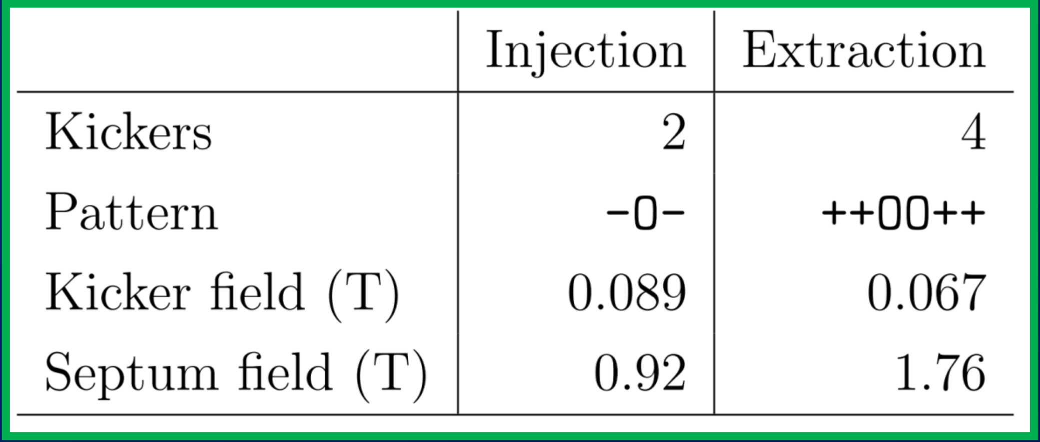
Table 1 - Example of 3.6 to 12.6 GeV muon scaling FFAG ring parameters.

Figure 2 - Ring layout.

Muon acceleration; 12.6—25 GeV FFAG:

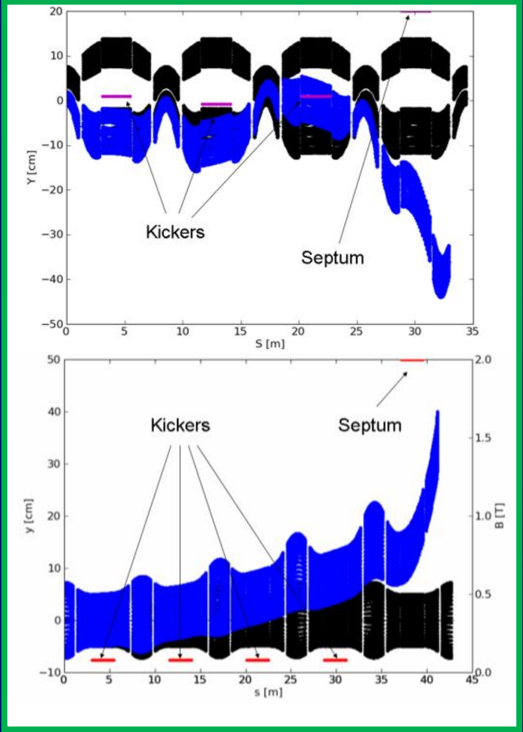


Parameter	Value	
Cells	64	
Long drift (m)	5.0	
Drifts within triplet (m)	0.5	
Cavities	48	
RF Frequency (MHz)	201.25	
RF Voltage (MV)	1214	
Circumference (m)	667	
Turns	11.6	
Decay (%)	6.7	
	D	F
Magnet Length (m)	2.251	1.087
Bend angle (mrad)	157	-29
Axis shift (mm)	41	14
Field (T)	4.21	-1.39
Gradient (T/m)	-13.6	18.0
Radius (mm)	137	163
Max field (T)	6.1	4.3

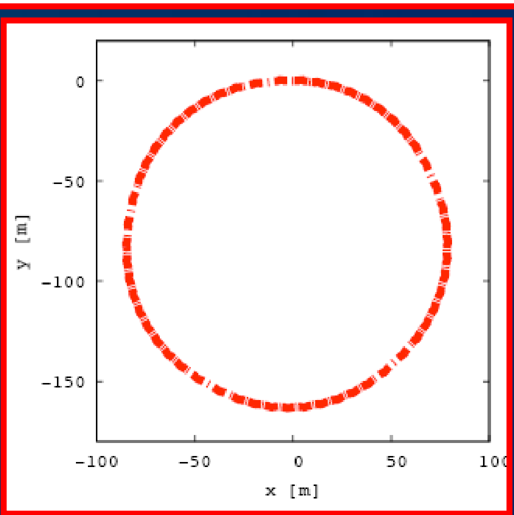


	Injection	Extraction
Kickers	2	4
Pattern	-0-	++00++
Kicker field (T)	0.089	0.067
Septum field (T)	0.92	1.76

IPAC10: MOPEC043, MOPE085,WEPE057



- **Lattice, including insertions, close to 'freeze';**
  - **Septum magnets, especially extraction septum, challenging**



FFAG R&D:

- FFAG machine R&D:
  - Osaka, Kurri:
    - Scaling FFAG machines for various applications
  - Daresbury Laboratory:
    - EMMA: non-scaling FFAG
- Common interest:
  - Magnets:
    - Combined function, large aperture, etc.
  - Kickers:
    - Magnets, septa, power supplies and pulse-forming networks;
      - Opportunity to develop hardware demonstrators

Synergy with Neutrino Factory R&D:

Conclusions and opportunity

Conclusions:

- Scientific case for searches for charged-lepton flavour violation, which was always strong, now compelling in the light of emerging understanding of neutrino oscillations

- Field of study of (lepton) flavour physics is *experimentally* led:
  - Implies the need to define the experimental programme most likely to:
    - Discover leptonic CP violation and CLFV
    - Determine the lepton mixing parameters with the requisite precision

- Muon beams offer a rich, staged, particle physics programme that includes:
  - Increasingly sensitive searches for CLFV
  - Definitive measurements of neutrino oscillations
  - The route to the energy frontier in lepton-antilepton collisions

Opportunity:

- **Develop an internationally coordinated R&D activity that can deliver the benefits of this muon-physics programme**

		Technology or capability												
			Components and systems											
		Concept development	*Proton driver*	*Target and collimator*	*Ionisation cooling*	*Linac/RLA*	*FFAG*	*Kicker/septum*	*HiTc magnets*	*High-field magnets*	*RF power sources*	*Warm resonator*	*S/c resonator*	*Failure mode analysis*
Facility or application	Science and innovation													
	Neutron													
	Proton (LHC)													
	Neutrino SB													
	COMET/Mu2e													
	PRISM/PRIME													
	Neutrino Factory													
	Muon Collider													
	Impact and society													
	PBT													
	ADSR													
	Secturity													