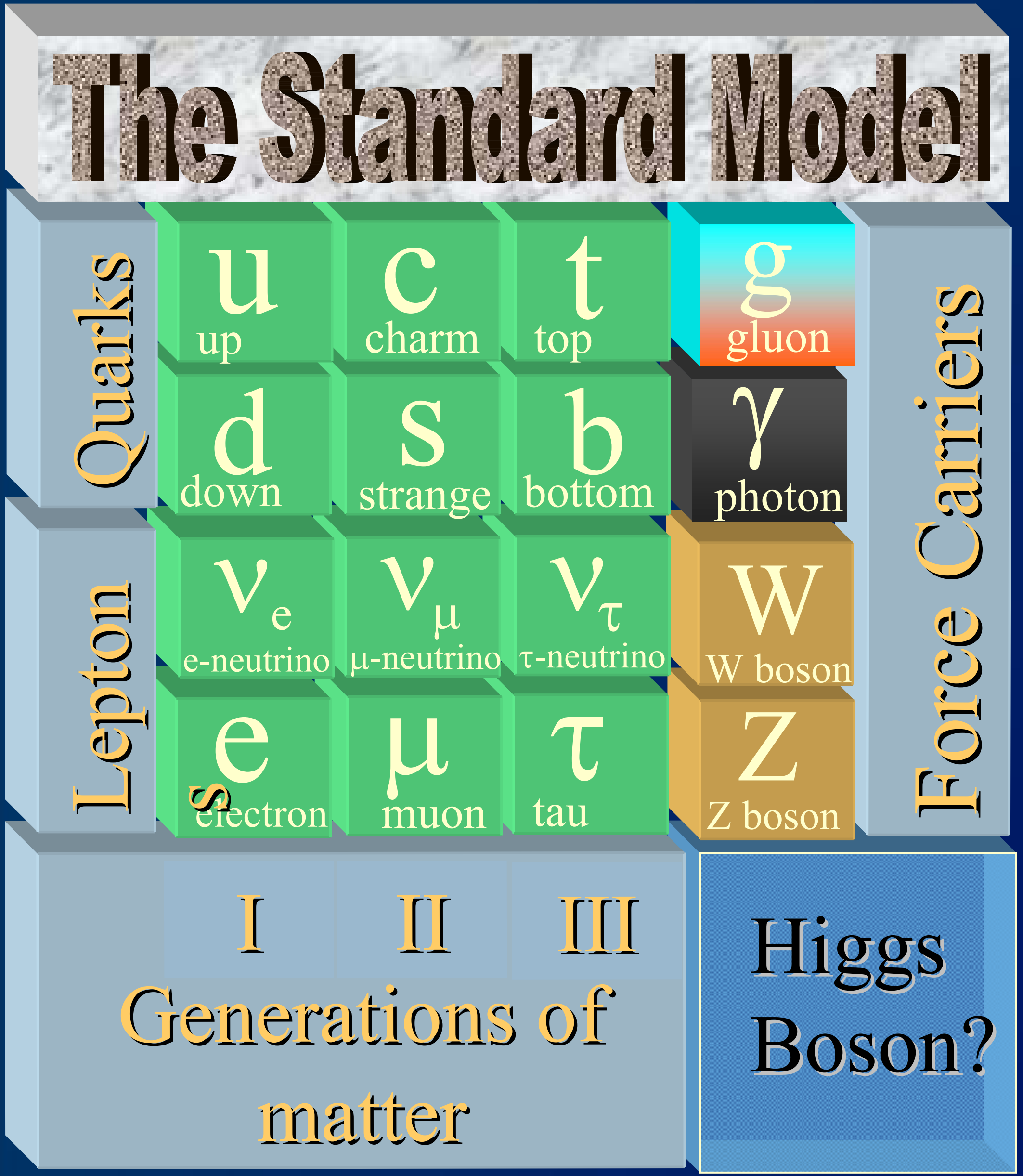
K. Long, 13 October, 2009

Imperial College London

Neutrino Factory
and
Muon Collider

The Standard Model



Quarks	u up	c charm	t top	g gluon	Force Carriers
	d down	s strange	b bottom	γ photon	
Lepton	ν_e e-neutrino	ν_μ μ-neutrino	ν_τ τ-neutrino	W W boson	
	s e electron	μ muon	τ tau	Z Z boson	
	I	II	III	Higgs Boson?	

Generations of matter

Standard Model is

Powerful and robust!

Yet known to be incomplete …

Muon accelerators for particle physics

Neutrino Factory and Muon Collider

Contents:

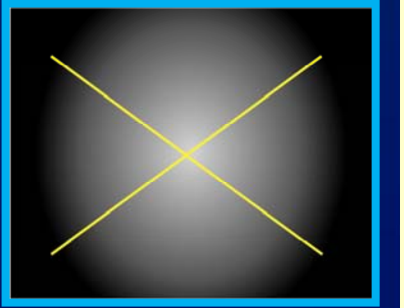
- Motivation
- The accelerator facilities
  - and highlights of the R&D programme
- Opportunities & timescales
- Conclusions

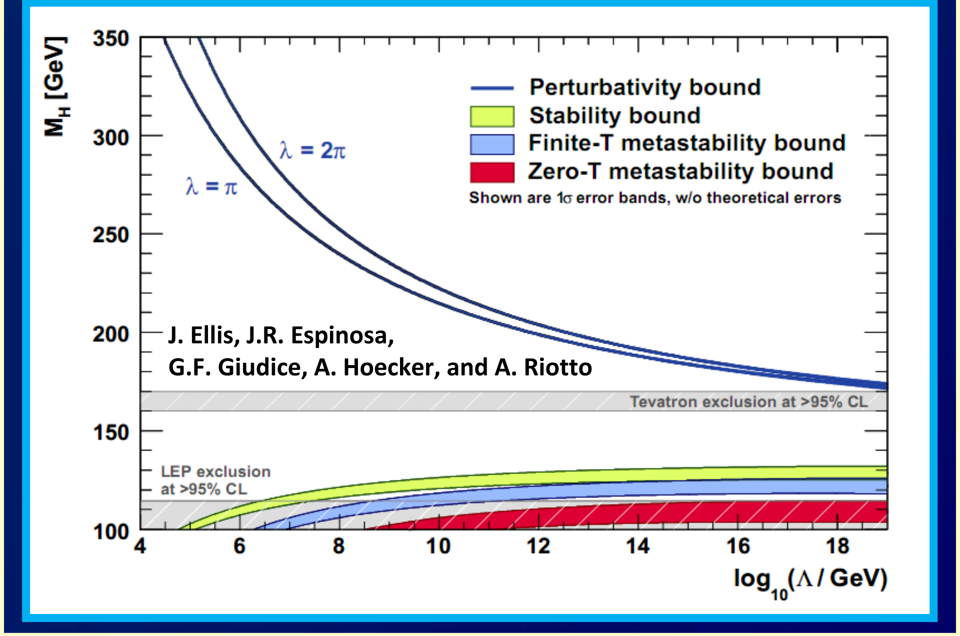
Motivation

Standard Model issues: Theoretical:

- Fits to precision measurements require the Higgs
  - But it has not been seen … *YET* …
    - … that is the exciting task of the LHC collaborations!
- Standard Model Higgs mechanism:
  - a description, not an explanation!
    - … an explanation requires a deeper theory!

- Higgs mass in SM ‘troublesome’
  - Unless $130 < M_H < 170$ GeV expect ‘new physics’ at low energy

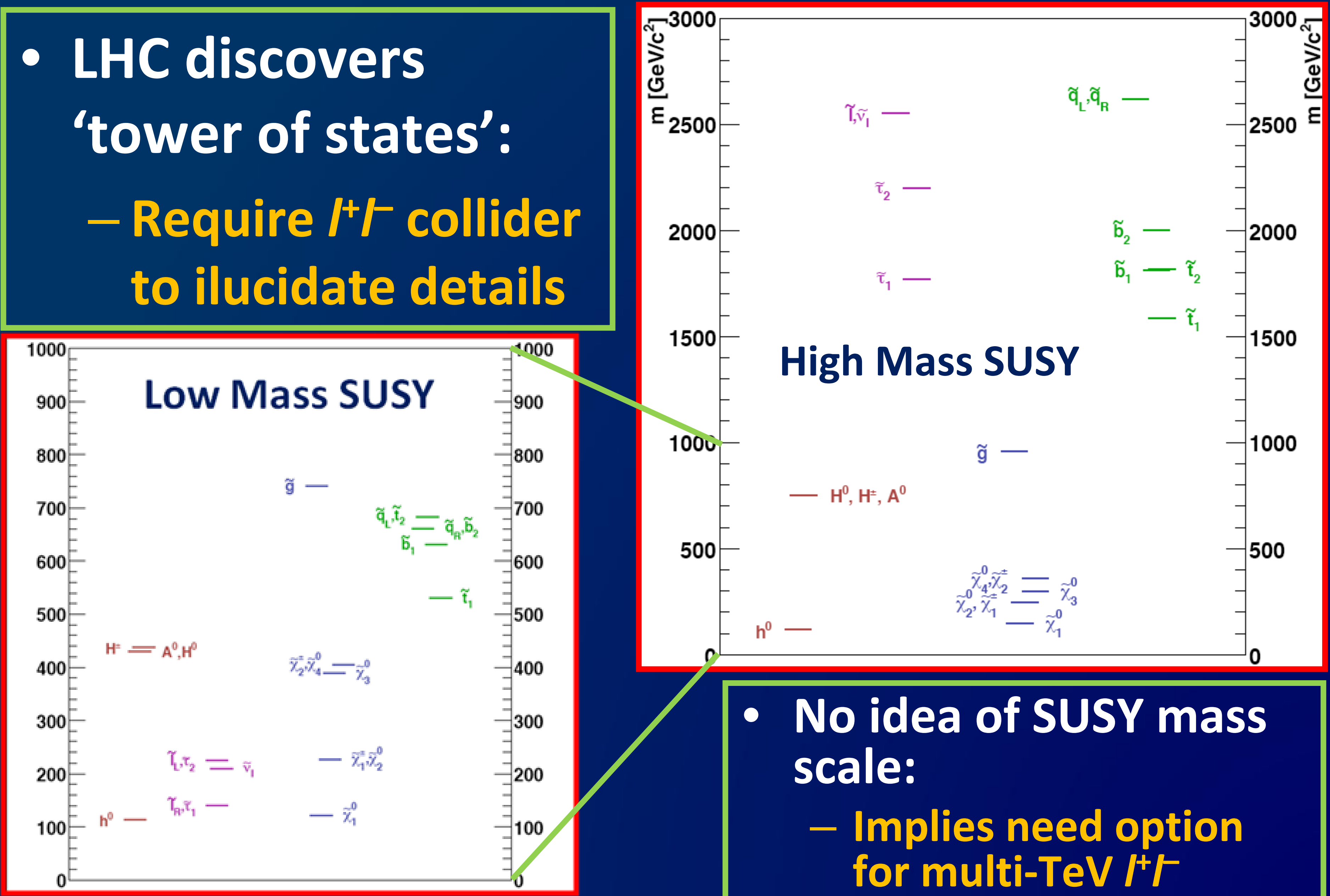




J. Ellis, J.R. Espinosa,
G.F. Giudice, A. Hoecker, and A. Riotto

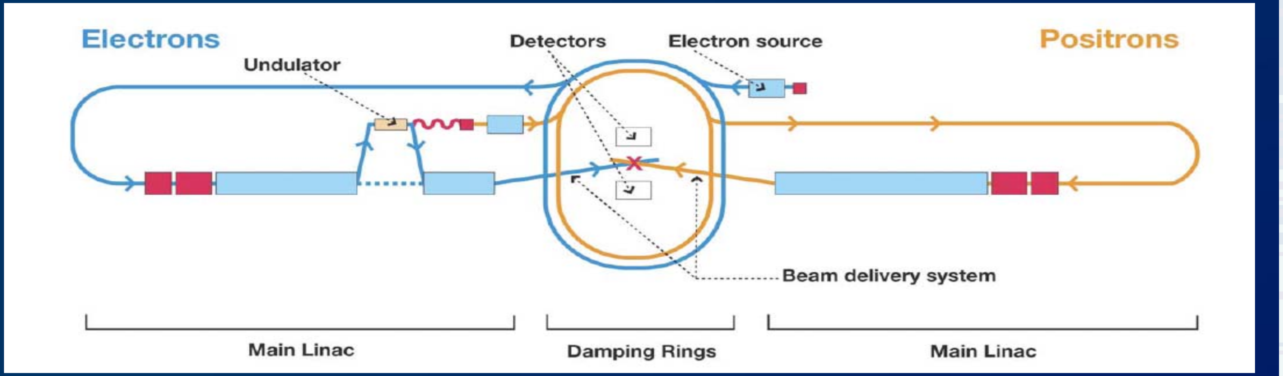
l^+l^- at high energy: the surgeon's knive!

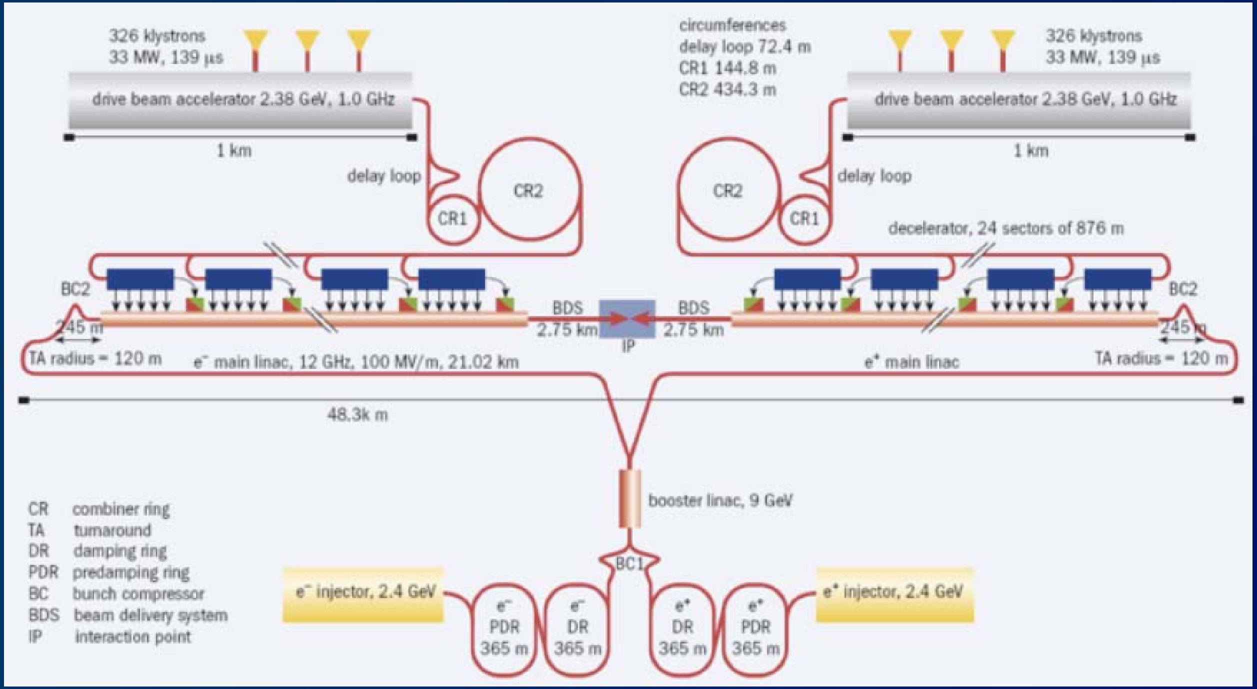
- LHC discovers ‘tower of states’:
  - Require l^+l^- collider to ilucidate details

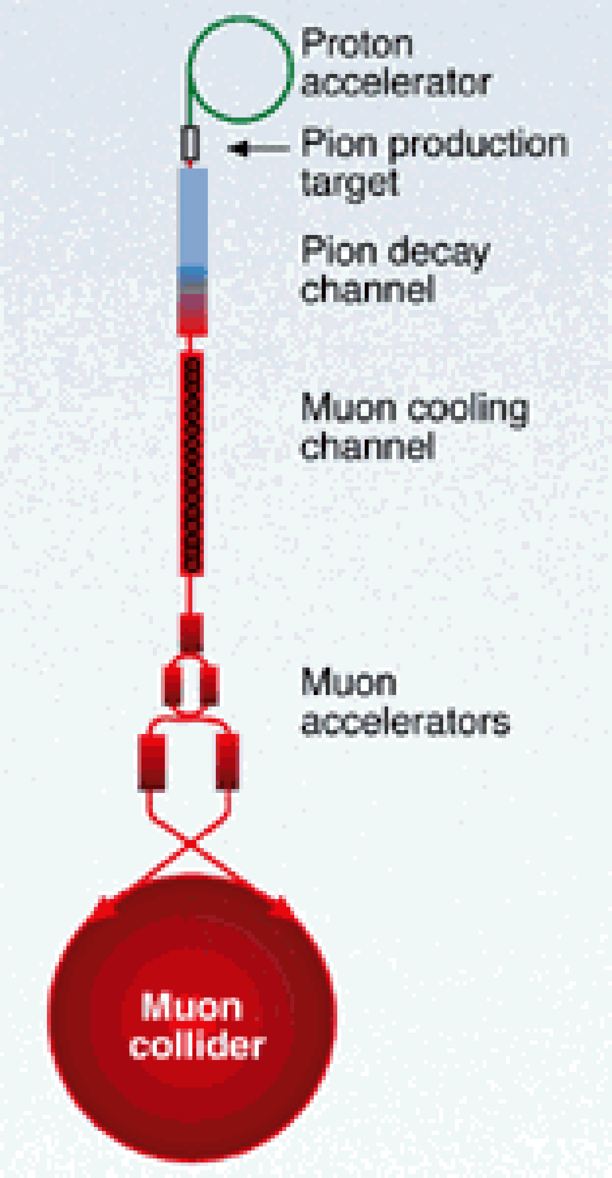


- No idea of SUSY mass scale:
  - Implies need option for multi-TeV l^+l^- collider

l^+l^- colliders: options:



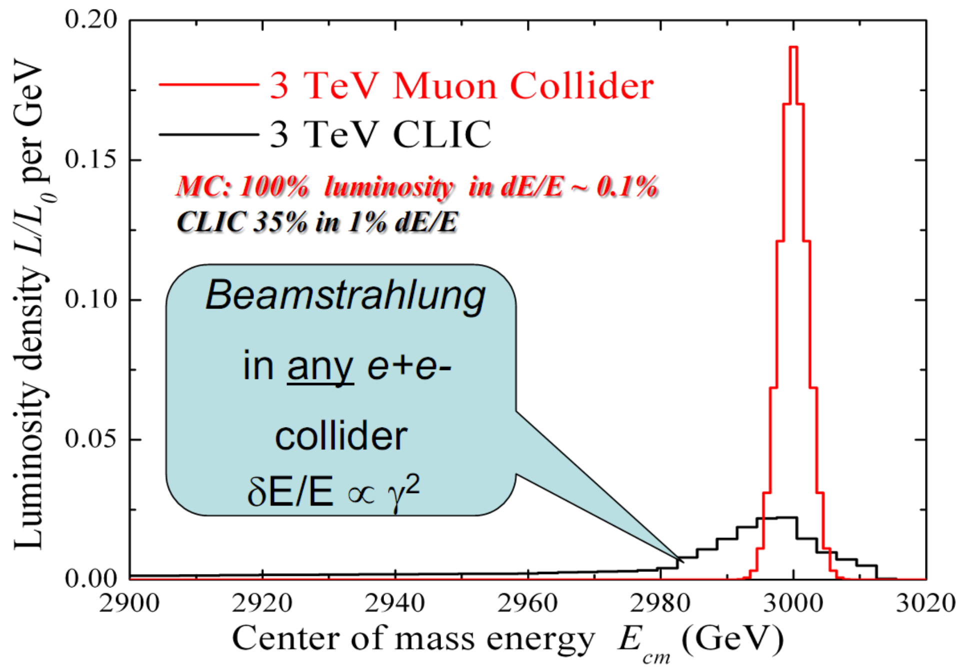


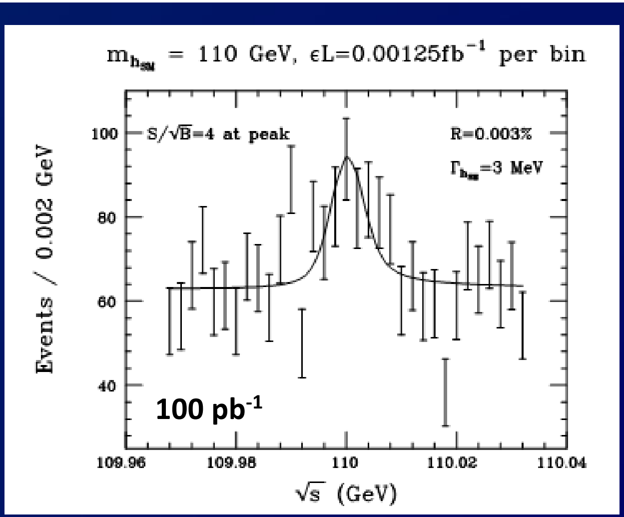


Muon Collider: basis of advantages:

- **Muon mass: 106 Mev/c^2** **Electron mass: 0.511 MeV/c^2**

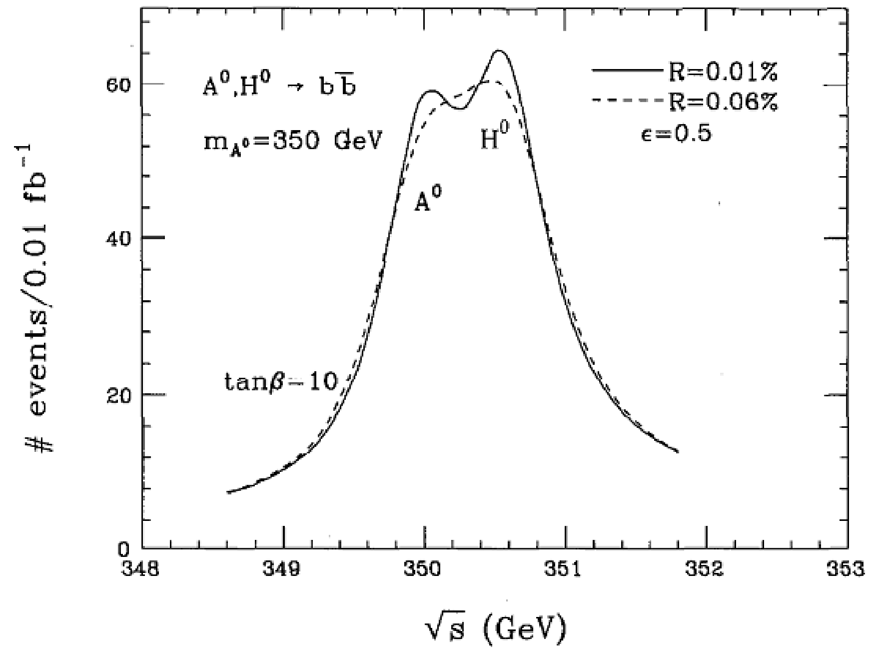
- **Consequences:**
  - **Negligible synchrotron radiation at Muon Collider:**
    - **Rate ∝ m^4:**
      ⇒ Muon Collider reduction factor: 5 × 10^{-10}
    - **Compact, *circular,* accelerator**
    - **Small energy spread**
    - **Possible to preserve polarisation at ~30% level**
      - **Yields possibility to determine beam energy precisely (0.003%) using (*g* – 2) precession**
  - **Strong coupling to Higgs:**
    - **Production rate ∝ m^2:**
      ⇒ Muon Collider enhancement factor: 5 × 10^4
    - **Large data set allows branching ratios to be measured**





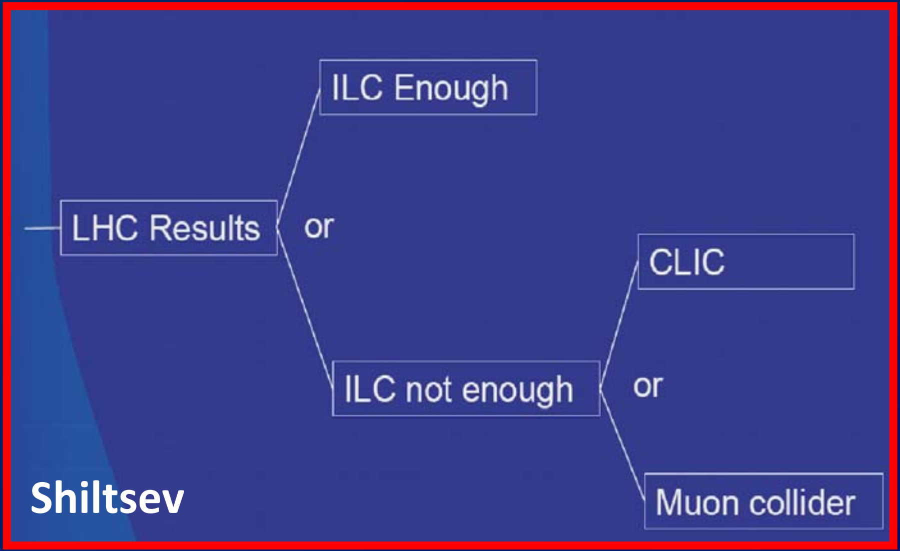
Higgs:

- **Opportunities specific to the Muon Collider:**
  - *s*-channel Higgs production:
    - Can be considered because of enhanced coupling
  - Good energy resolution could be exploited to resolve states with closely similar mass



l^+l^- annihilation at the energy frontier:

- Physics case for lepton-antilepton collider likely to be compelling;
  - Direction of l^+l^- programme will be decided based on results from LHC



Shiltsev

- If l^+l^- collider is required for full exploration of 'terascale physics', options are:
  - CLIC
  - Muon Collider

- Issues to evaluate:
  - Does the muon mass give the Muon Collider:
    - Superior physics performance;
    - Advantages in 'upgradability'?
  - What are the costs and timescales for each of the alternatives?

Standard Model issues: experimental:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \qquad \begin{pmatrix} e^+ \\ \overline{\nu}_e \end{pmatrix}$$

$$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \qquad \begin{pmatrix} \mu^+ \\ \overline{\nu}_\mu \end{pmatrix}$$

$$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \qquad \begin{pmatrix} \tau^+ \\ \overline{\nu}_\tau \end{pmatrix}$$

The Standard Model neutrino is:

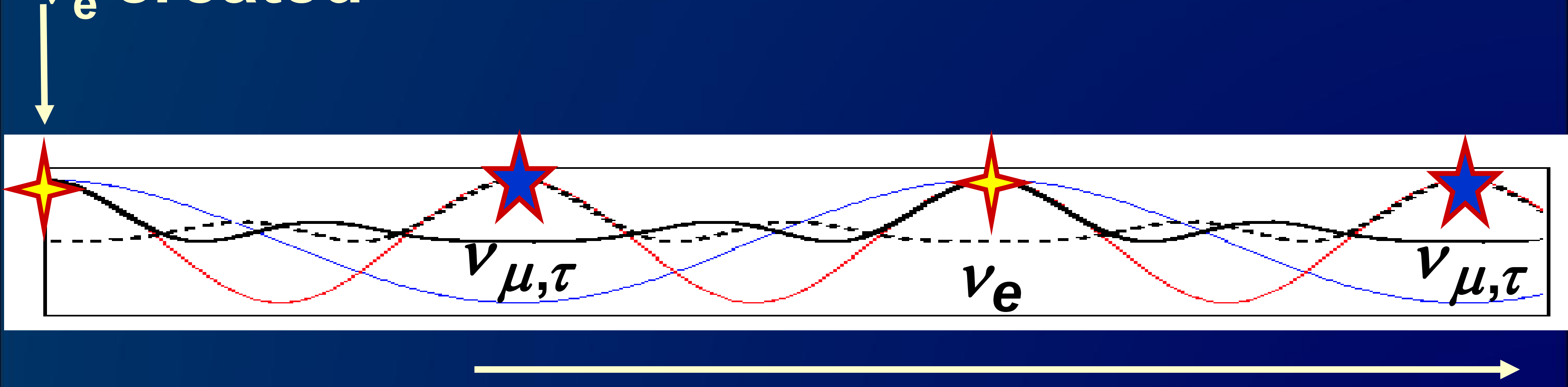
- *Massless*
- Chargeless
- Helicity eigenstate

Extend SM to include neutrino mass:

- Massive neutrino *NOT* helicity eigenstate, and …
  - – since neutrino has no conserved quantum numbers
    - (except, perhaps, a global lepton number)

quantum mechanics implies neutrinos will mix

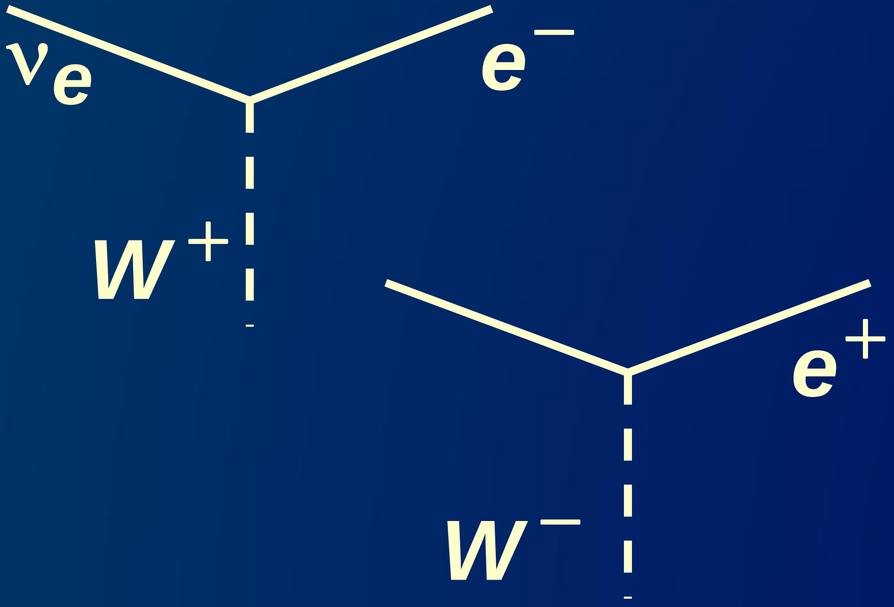
ν_e created

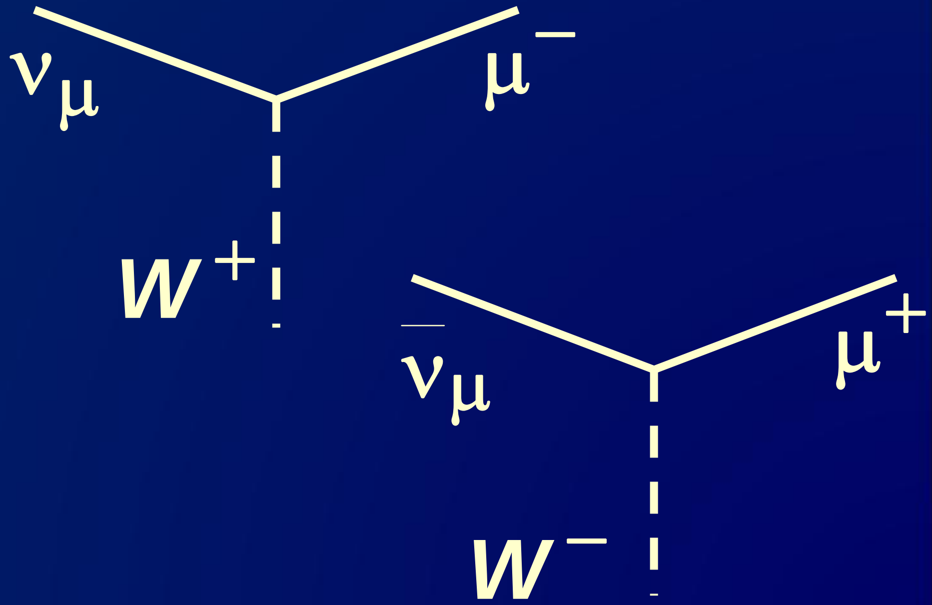


Space or time

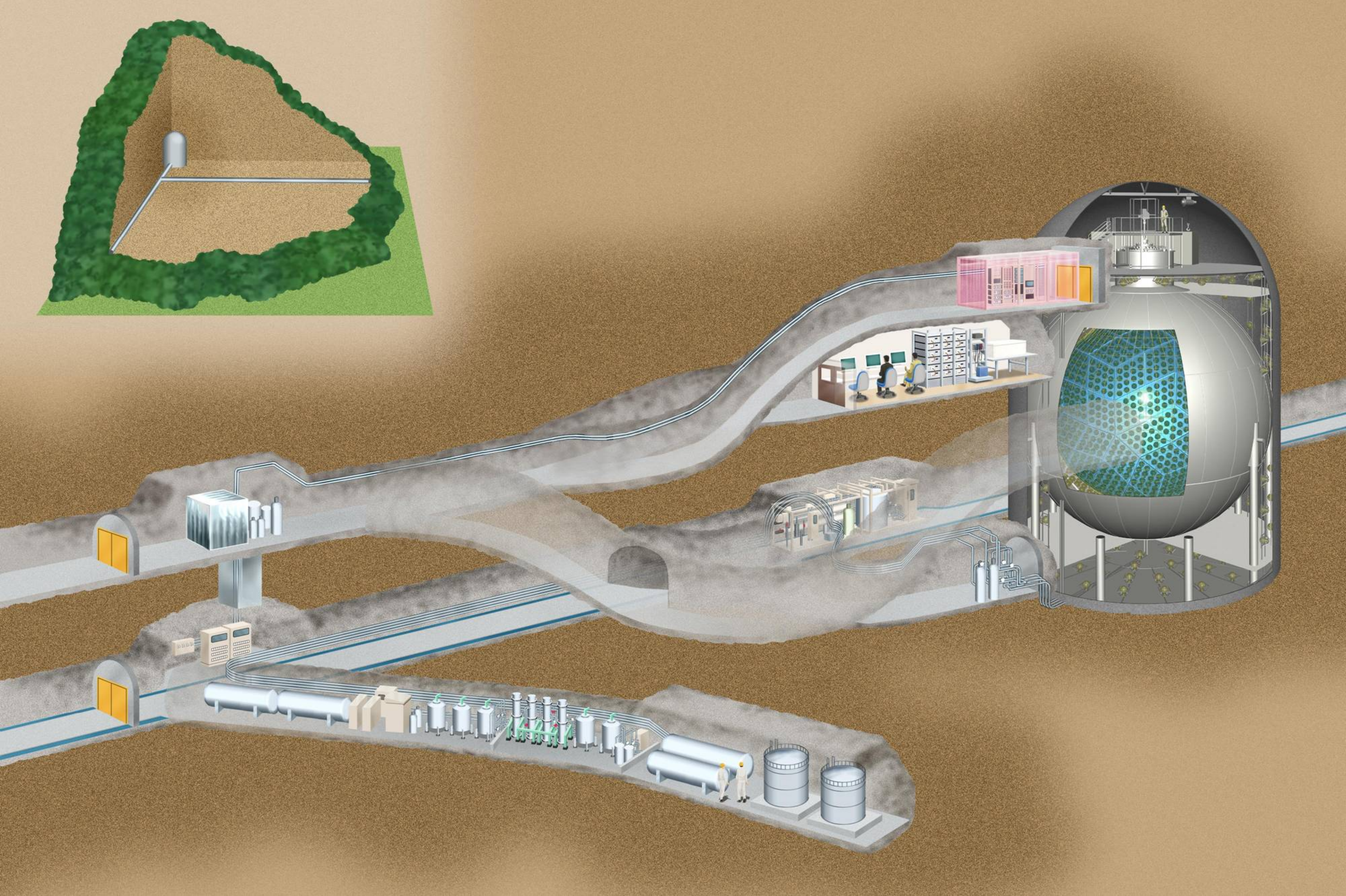
Leptons and the weak force:

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix} \qquad \begin{pmatrix}e^+\\ \bar{\nu}_e\end{pmatrix} \qquad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix} \qquad \begin{pmatrix}\mu^+\\ \bar{\nu}_\mu\end{pmatrix}$$

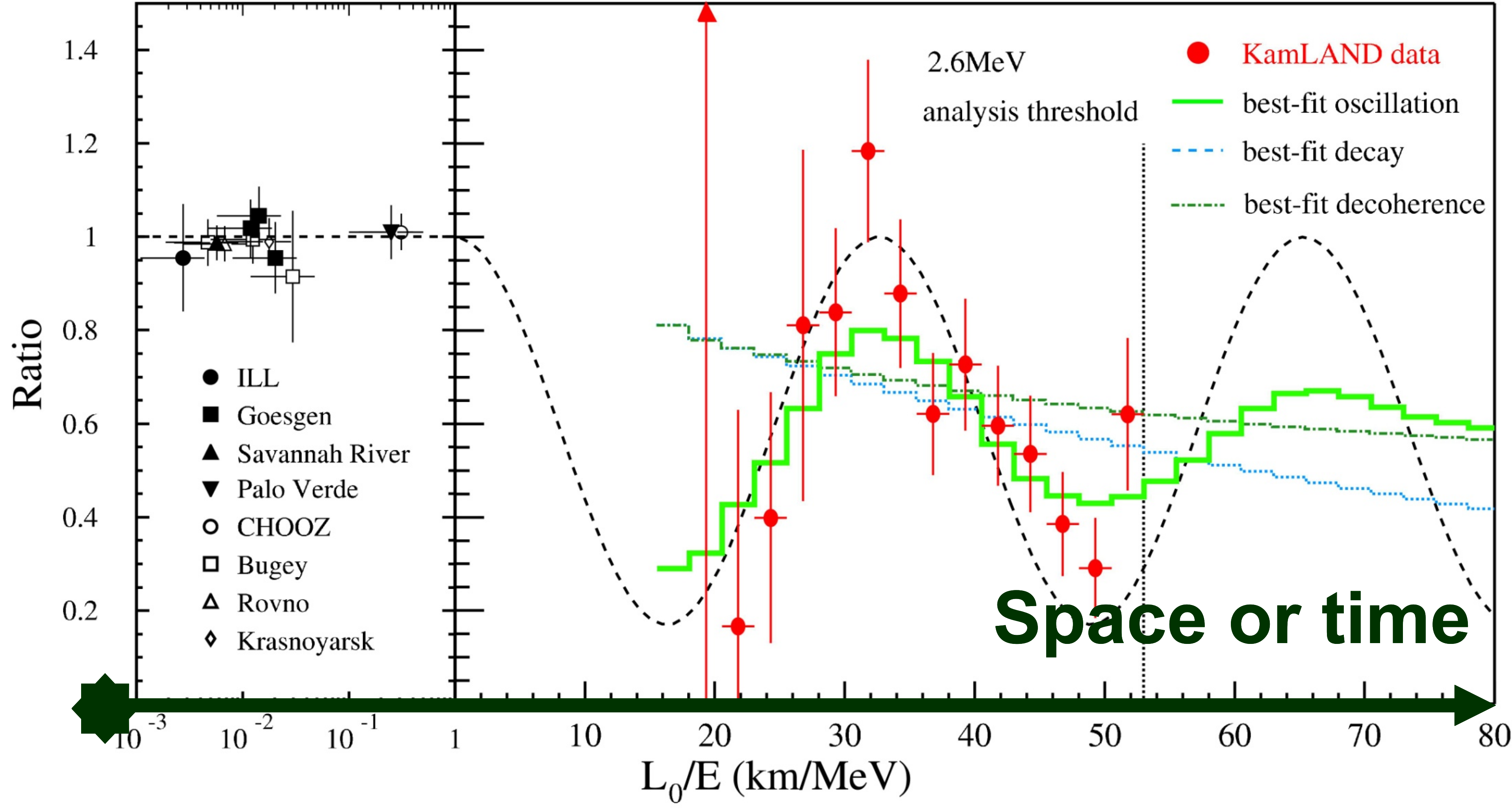




Reactor neutrinos: Kamland:



Oscillating electron (anti-)neutrinos



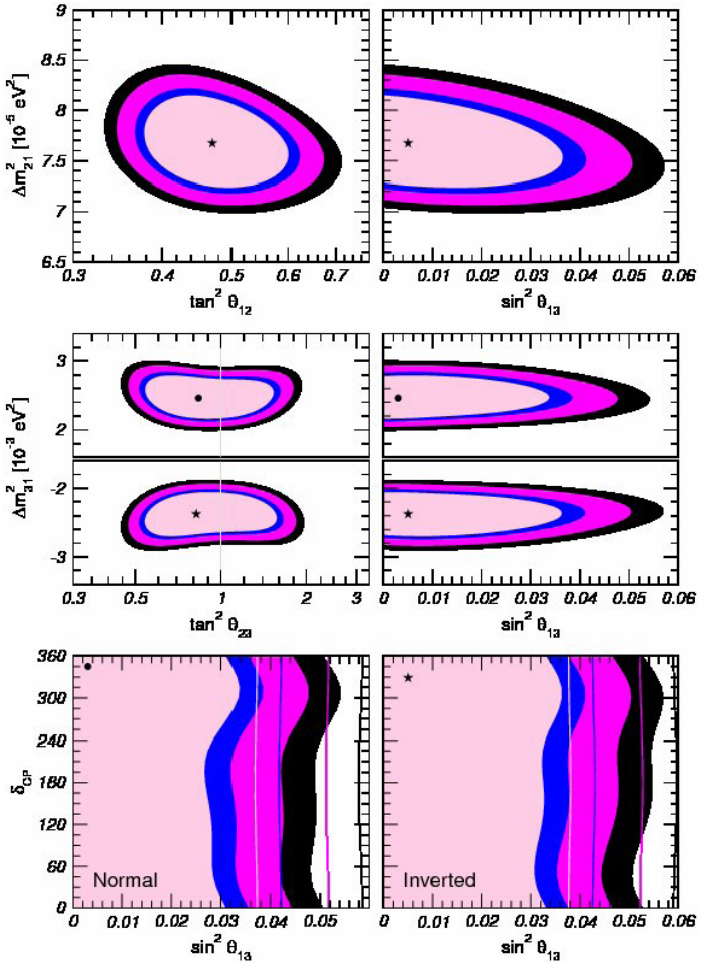
Space or time

The neutrino revolution:

- Consequences of neutrino mass:
  - If the neutrino is a ‘Dirac’ fermion:
    - Require a new physical law to distinguish neutrino from anti-neutrino
  - If the neutrino is its own anti-particle (a ‘Majorana’fermion):
    - The neutrino is a *NEW STATE of MATTER*
    - Higgs mechanism can not explain Majorana mass
  - Tiny neutrino mass appears to be related to physics at very high energy scales
- Producing the matter-dominated universe:
  - CP violation in the quark sector not sufficient
  - CP violation in the neutrino sector may make a decisive contribution; mechanism ‘Leptogensis’:
    - ‘Dirac’ phase, δ, not directly responsible;
    - Relationship of relevant (Majorana) phases to δ is model dependent
- Explanation of (absence of) large-scale structure
  - Neutrino interacts only weakly – possible means of communication across large distances?
  - In some models, super-symmetric partner to neutrino may be responsible for inflation

Standard Neutrino Model:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



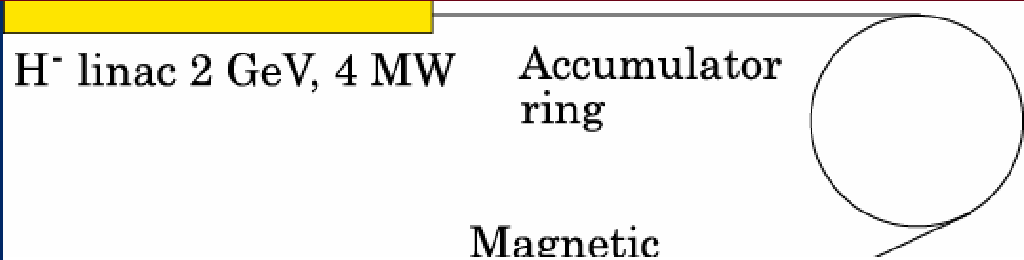
Gonzalez-Garcia and Maltoni, Phys. Rep. 460, 1 (2008)

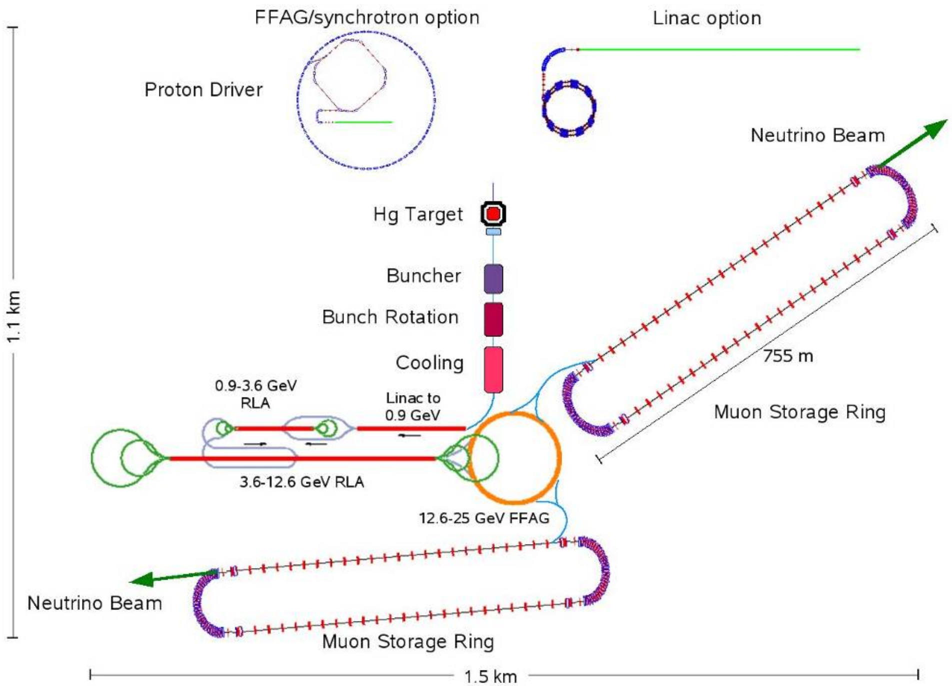
Precision-era facility must address:

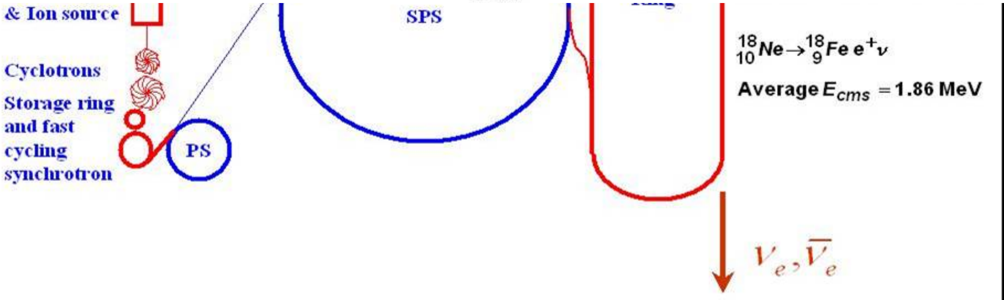
- Mass hierarchy
- CP violation
- θ_{13}
- θ_{12}, θ_{23}, Δm_{31}^2, Δm_{21}^2
- More over:
  - Is θ_{23} maximal?
  - Is θ_{13} zero?
  - Beyond the SνM:
    - NSIs
    - MVNs
    - Sterile neutrinos

Facilities for the precision era:

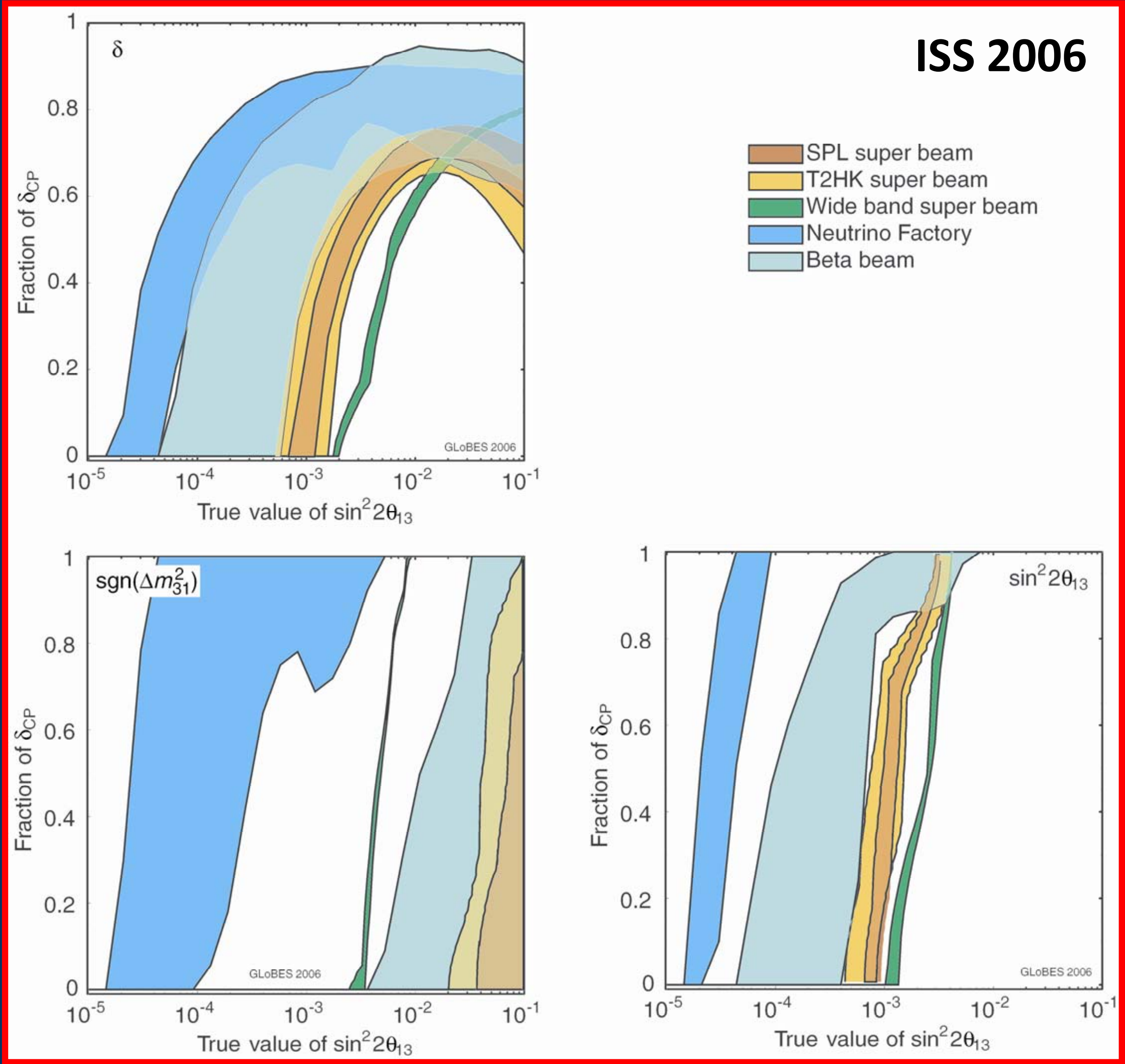
- **Second generation** (i.e. post T2K/NOνA) **super-beam**
  - CERN, FNAL, BNL, J-PARC II
    - MTon H_2O Cherenkov or LAr
- **Neutrino Factory**
    - Magnetised detector
- **Beta-beam**
    - MTon H_2O Cherenkov, liquid argon







The ISS comparison:



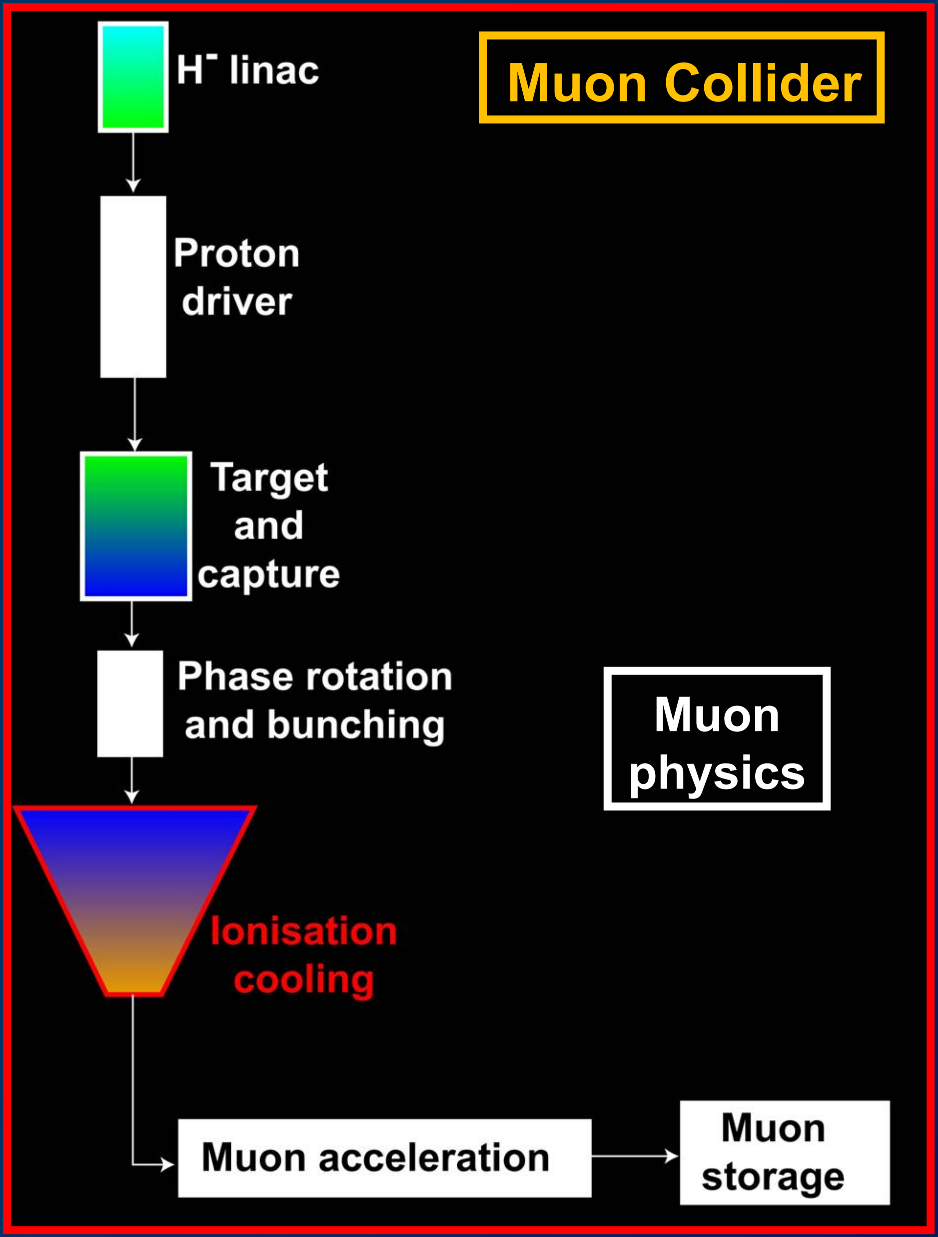
- The Neutrino Factrory offers:
  - Best discovery reach
  - Best precision
- The facility of choice!

Muon accelerators for particle physics

The accelerator facilities

Muon Collider and Neutrino Factory

Muon storage rings:



Muon Collider

H^- linac

Proton driver

Target and capture

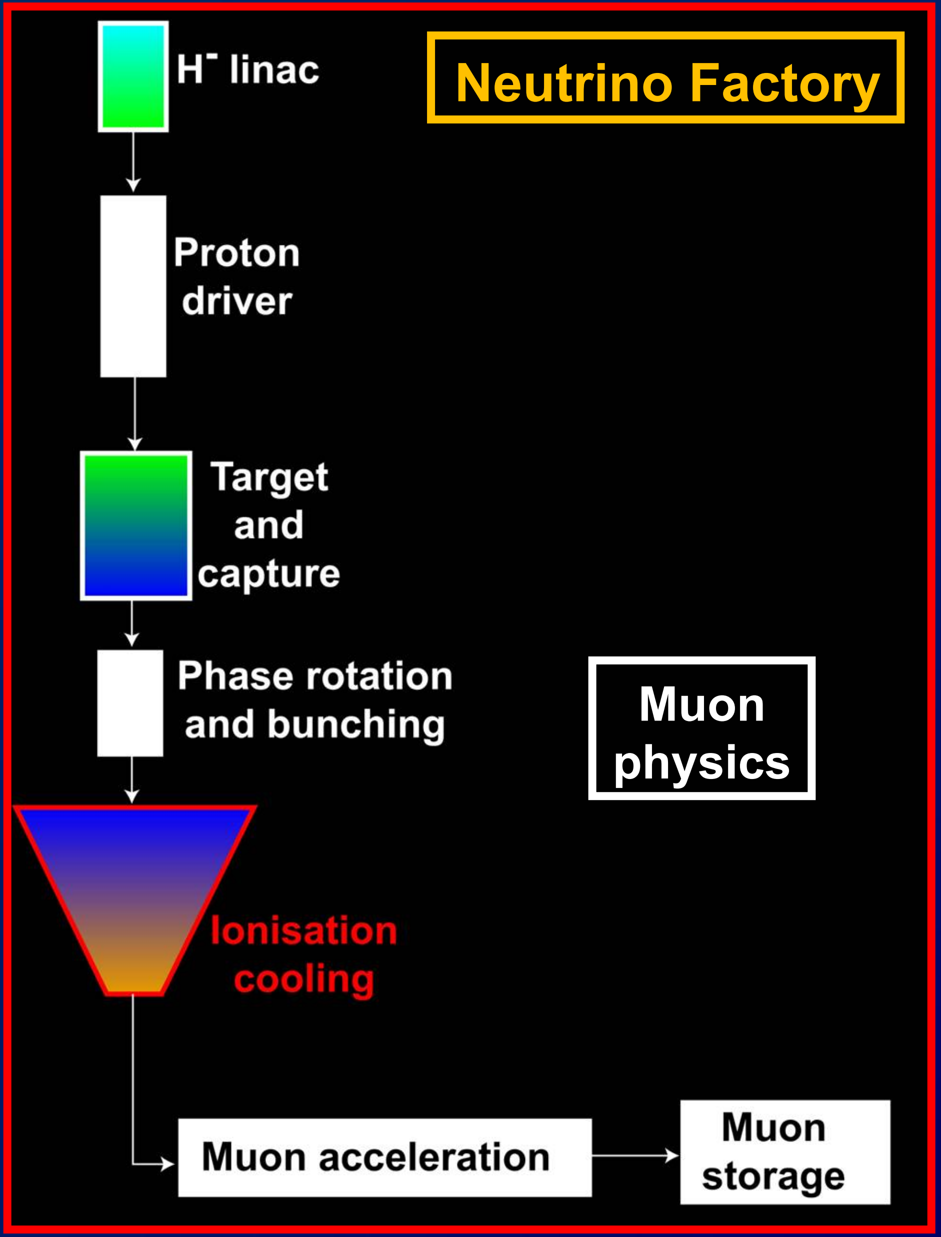
Phase rotation and bunching

Ionisation cooling

Muon acceleration

Muon storage

Muon physics



Neutrino Factory

H^- linac

Proton driver

Target and capture

Phase rotation and bunching

Ionisation cooling

Muon acceleration

Muon storage

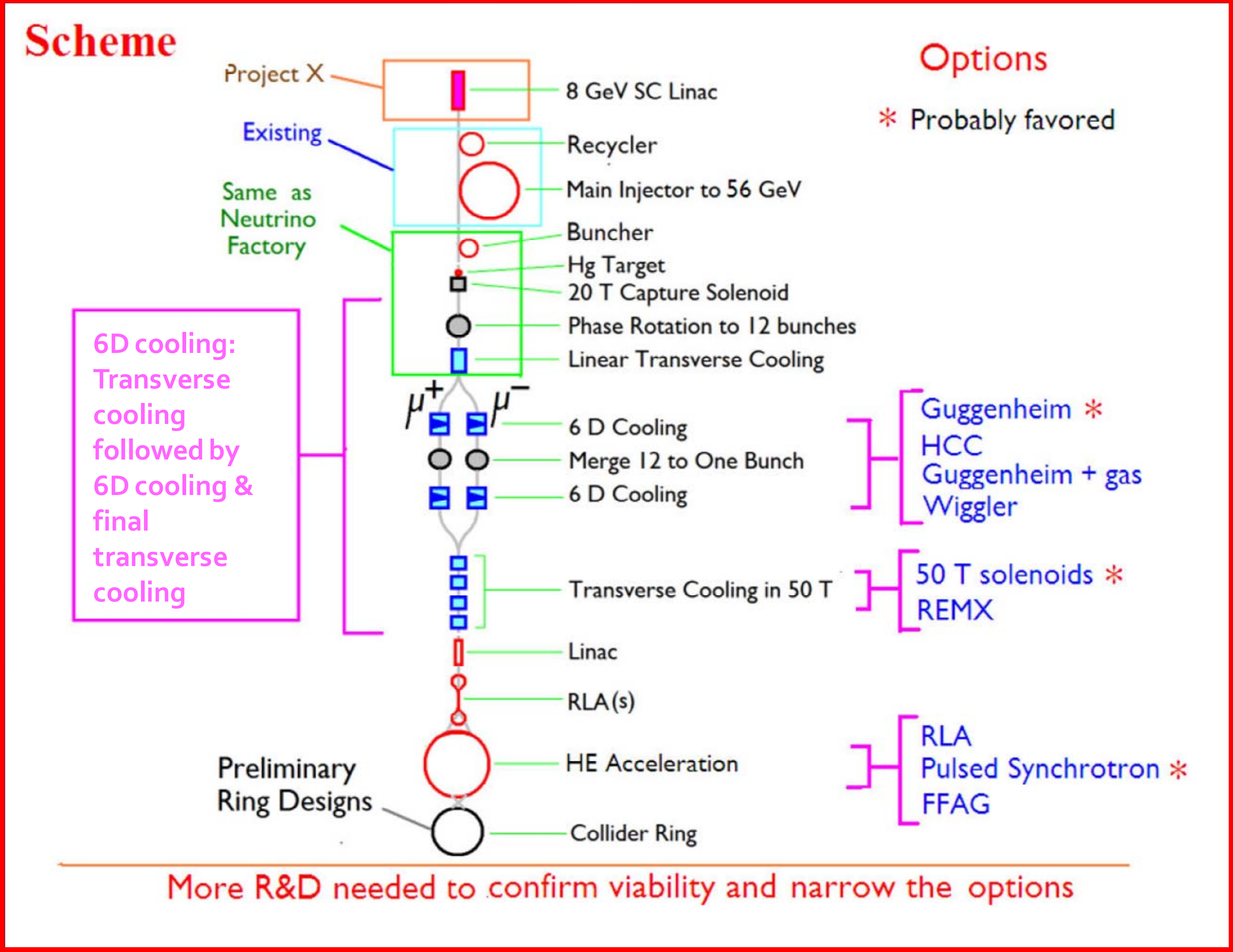
Muon physics

Muon Collider accelerator parameters:

		Muon Collider		Neutrino Factory
		1.5 TeV	4 TeV	
Luminosity	10^{34} $\mathrm{cm^{-2}s^{-1}}$	1	4	
Muons/bunch	10^{12}	2	2	10
Ring circumference	km	2	2	1.6
Beta at IP	mm	10	3	
dp/p (RMS)	%	0.1	0.12	0.17
Ring depth	m	13	135	155 and 440
Transverse emittance	mm mrad	25	25	4800
Lonitudinal emittance	mm mrad	72000	72000	
Proton driver rep. rate	Hz	12	6	50
Bunch length	ns	~1	~1	2
Bunches per pulse		(4)	4	3
Proton driver power	MW	4	2	4

- Muon Collider:
  - Depth of 4 TeV Muon Collider storage ring required to reduce neutrino-induced radiation dose off (FNAL) site to below 1 mrem/yr ?
  - Low emittance Muon Collider option actively being developed
    - Benefits include:
      - Reduced proton beam power
      - Reduced neutrino radiation
- Neutrino Factory:
  - Significant synergy in accelerator R&D requirements
    - Difference is that Muon Collider requires ‘6D cooling’ to obtain required luminosity

Muon Collider: schematic:



Scheme

Project X — 8 GeV SC Linac

Existing — Recycler; Main Injector to 56 GeV

Same as Neutrino Factory — Buncher; Hg Target; 20 T Capture Solenoid; Phase Rotation to 12 bunches; Linear Transverse Cooling

6D cooling: Transverse cooling followed by 6D cooling & final transverse cooling

μ^+ μ^-

6 D Cooling

Merge 12 to One Bunch

6 D Cooling

Transverse Cooling in 50 T

Linac

RLA (s)

HE Acceleration

Preliminary Ring Designs — Collider Ring

Options

* Probably favored

- Guggenheim *
- HCC
- Guggenheim + gas
- Wiggler

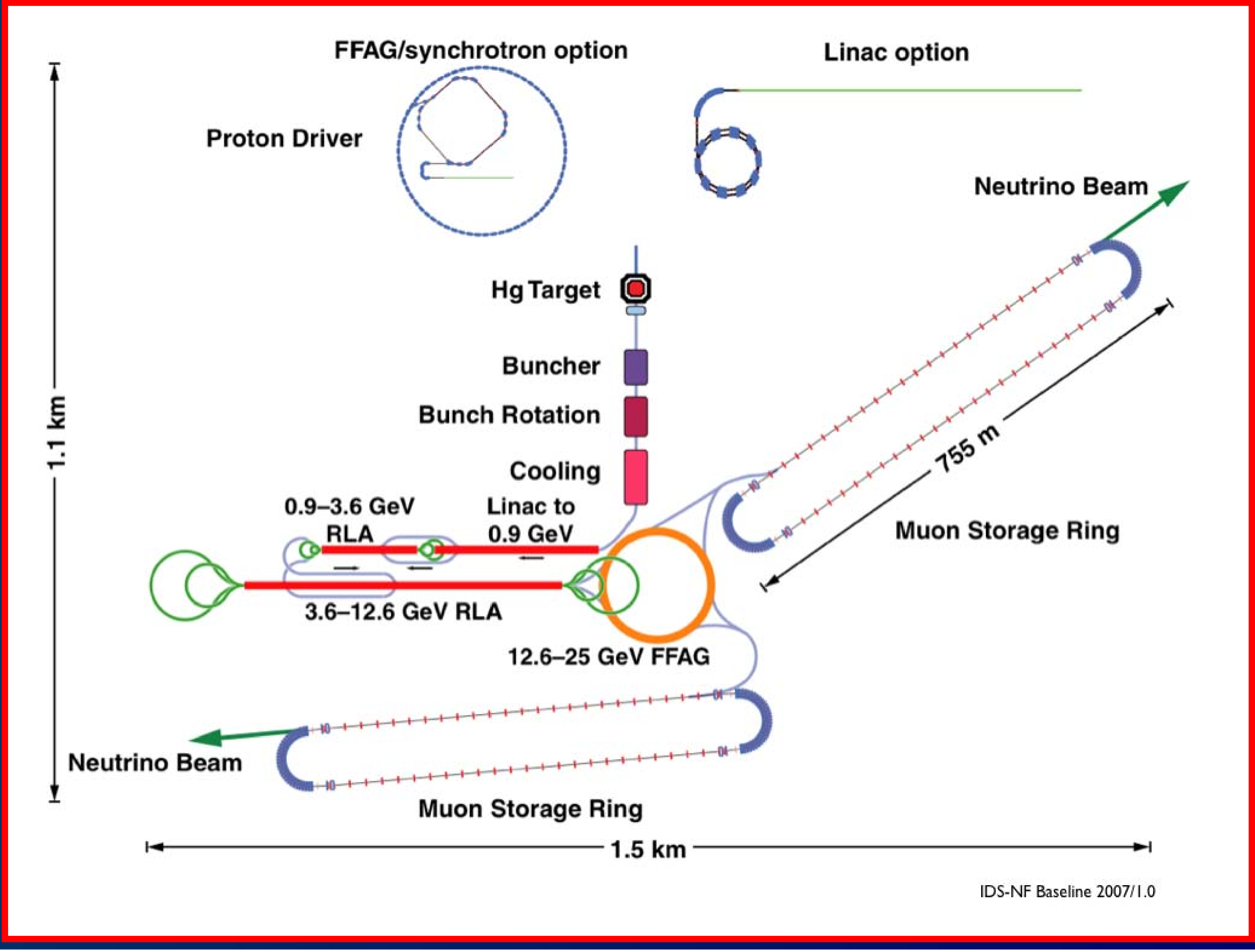
- 50 T solenoids *
- REMX

- RLA
- Pulsed Synchrotron *
- FFAG

More R&D needed to confirm viability and narrow the options

Neutrino Factory: accelerator facility:

International Design Study for the Neutrino Factory



Baseline Neutrino Fctory accelerator facility

IDS-NF-002: https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=view&target=IDS-NF-002-v1.1.pdf

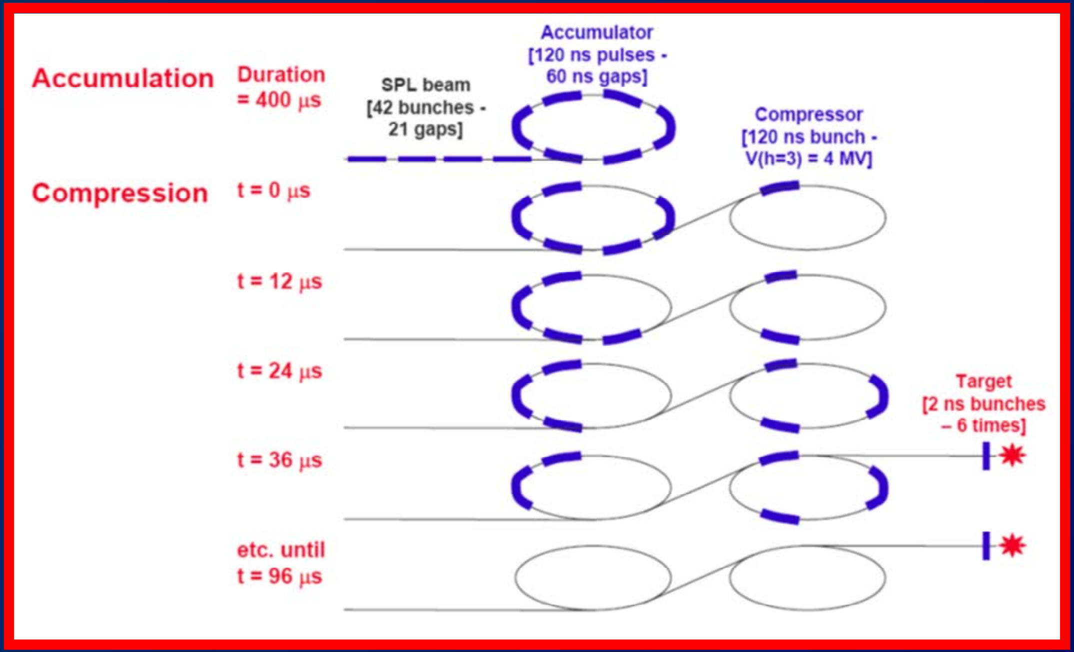
Proton driver:

Parameter	**Value**	**Comment**
Beam power	4 MW	Production rate
Beam energy	5-15 GeV	Optimum pion production
Bunch length	1-2 ns	Pion/muon capture

- Proton driver is the accelerator system most likely to be constrained by requirements of host-site
- IDS-NF approach:
  - Consider 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

CERN SPL as proton driver:

- Accumulator and compressor ring scheme:
  - Two options: 6 bunches or 3 bunches

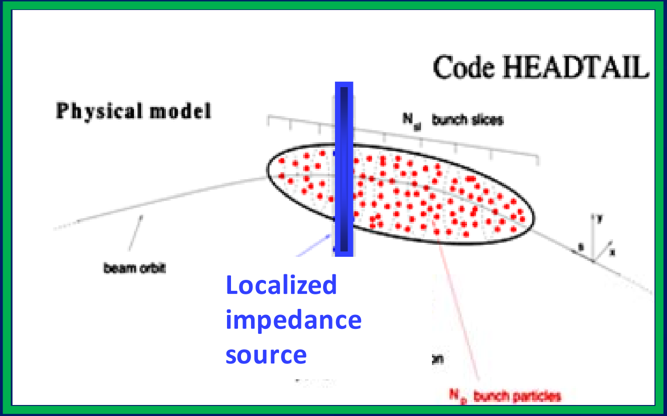


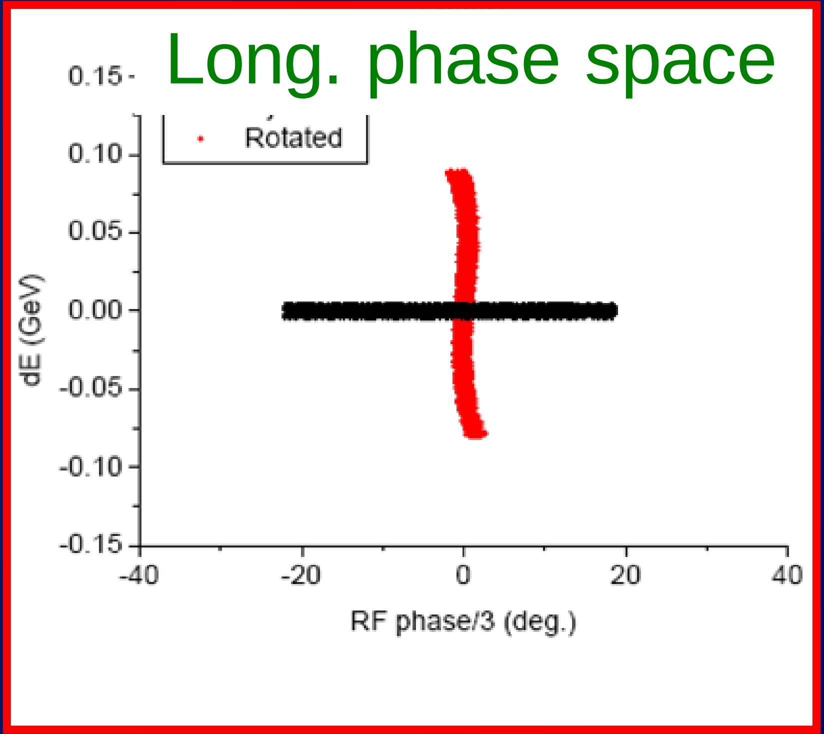
- SPL:
  - Staged scenario under consideration (Myers):
    - Low power SPL to serve LHC
    - High power SPL to serve applications such as Neutrino Factory

SPL accumulator/compressor ring design:

E.Benedetto, M.Aiba

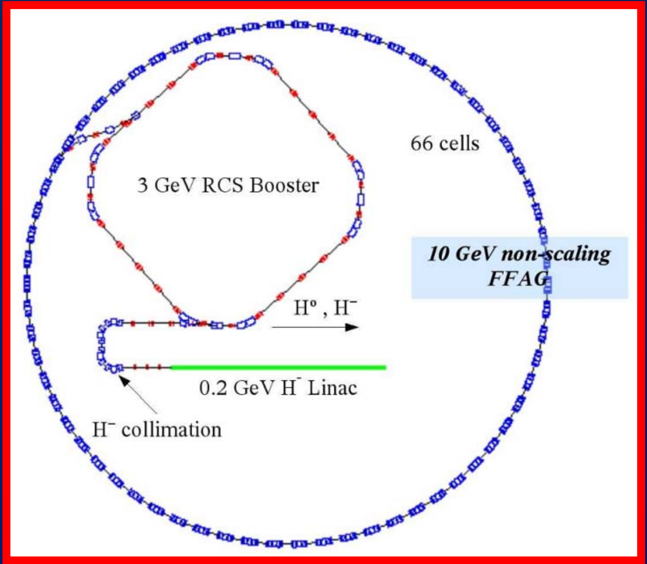
- Accumulator ring:
  - Isochronous:
    - Reduce bunch length for given $[dp/p]_{\mathrm{rms}}$
    - No RF
  - Instabilities considered
    - Instabilities are small or can be managed
- Compressor ring:
  - Two options studied:
    - Superconducting or normal
  - Phase rotation studied
    - Including space charge

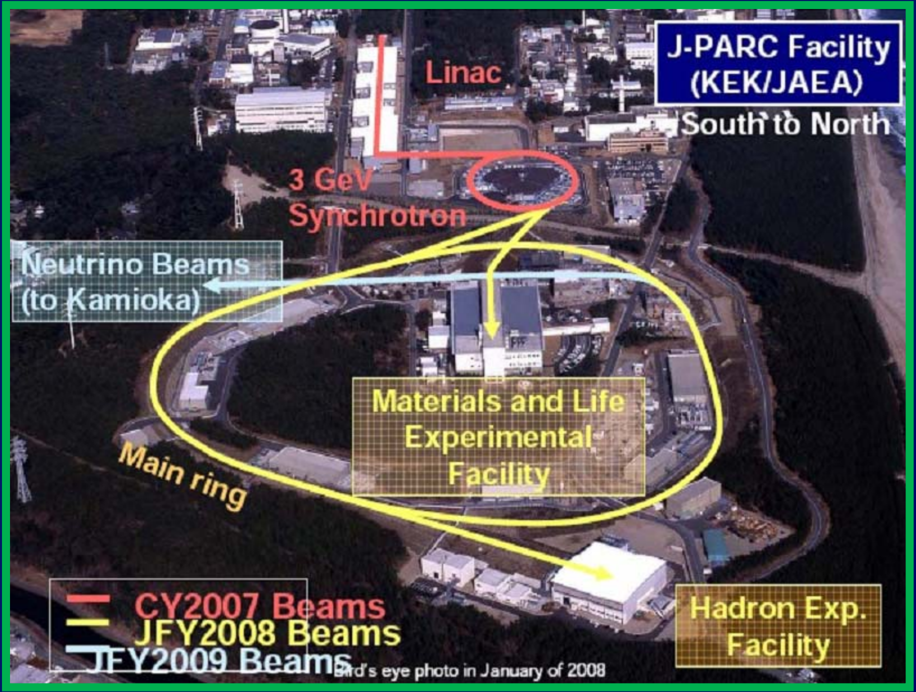




Ring-based proton driver:

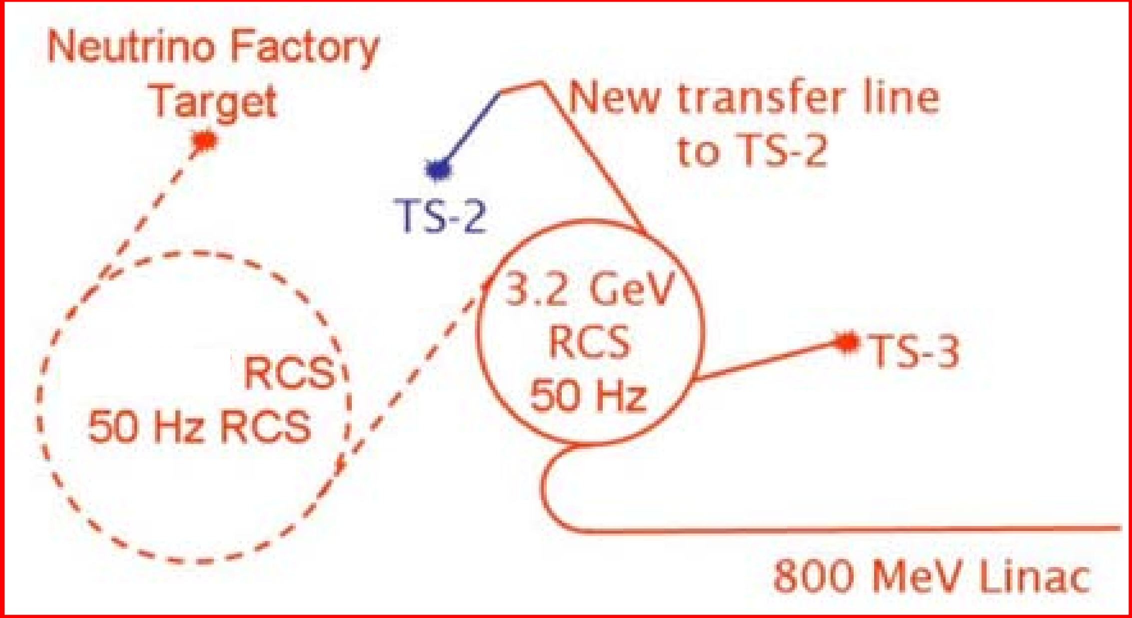
- Greenfield options:
  - H^- linac to 180 MeV;
  - Achromat for phase rotation
  - RCS and/or FFAG to reach final energy and for bunch compression
- ISIS upgrade options:
  - ISIS upgrade:
    - MW class, short pulse neutron spallation source
  - J-PARC upgrade:
    - Upgrade to 1.66 MW planned
      - Ultimate power?





Example: ISIS upgrade as proton driver:

- 3.2 GeV RCS feeds booster/compressor ring:
  - Two options considered: 6.4 & 10.3 GeV
    - 3.2 GeV RCS circulates 4 [5] bunches at 50 Hz delivering 4–5 MW
    - Extract to neutron target and Neutrino Factory target

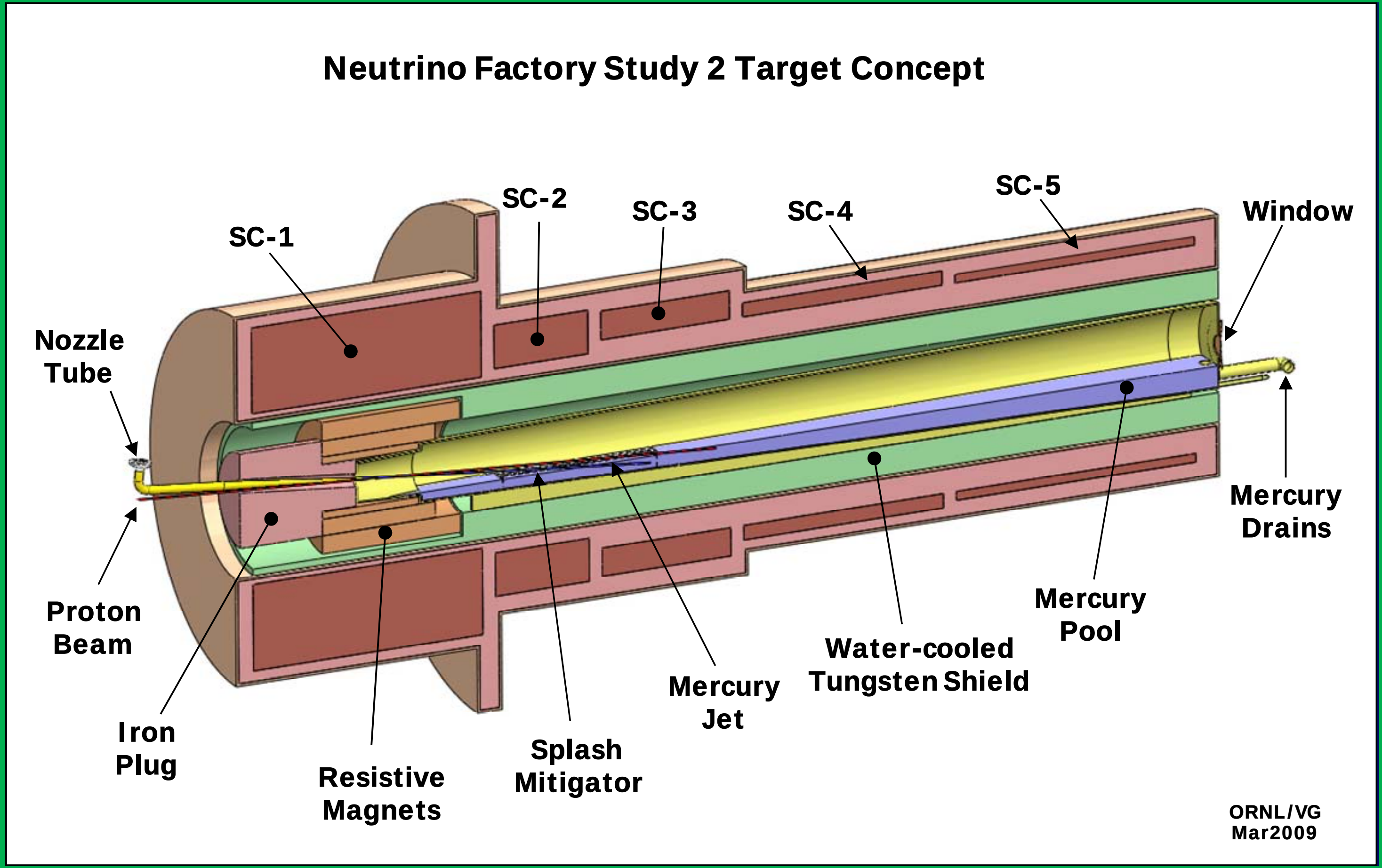


Neutrino Factory RCS parameters	
Number of superperiods	6
Circumference	708.788 m
Harmonic number	6
RF frequency	2.4717-2.5289 MHz
Betatron tunes (Q_H, Q_V)	(7.81, 7.78)
Gamma transition	7.9056
Beam power at 6.4 GeV	4 MW for 2 bunches
Bunch area	1.8 eVs
$\Delta p/p$ at 3.2 GeV	$5.3\ 10^{-3}$
Injection / extraction energy	3.2 / 6.4 [10.3] GeV
Repetition rate	50 Hz
Max B field in dipoles	1.2 T (at 10.3 GeV)
Length of long drift	14 m

J.Pasternak

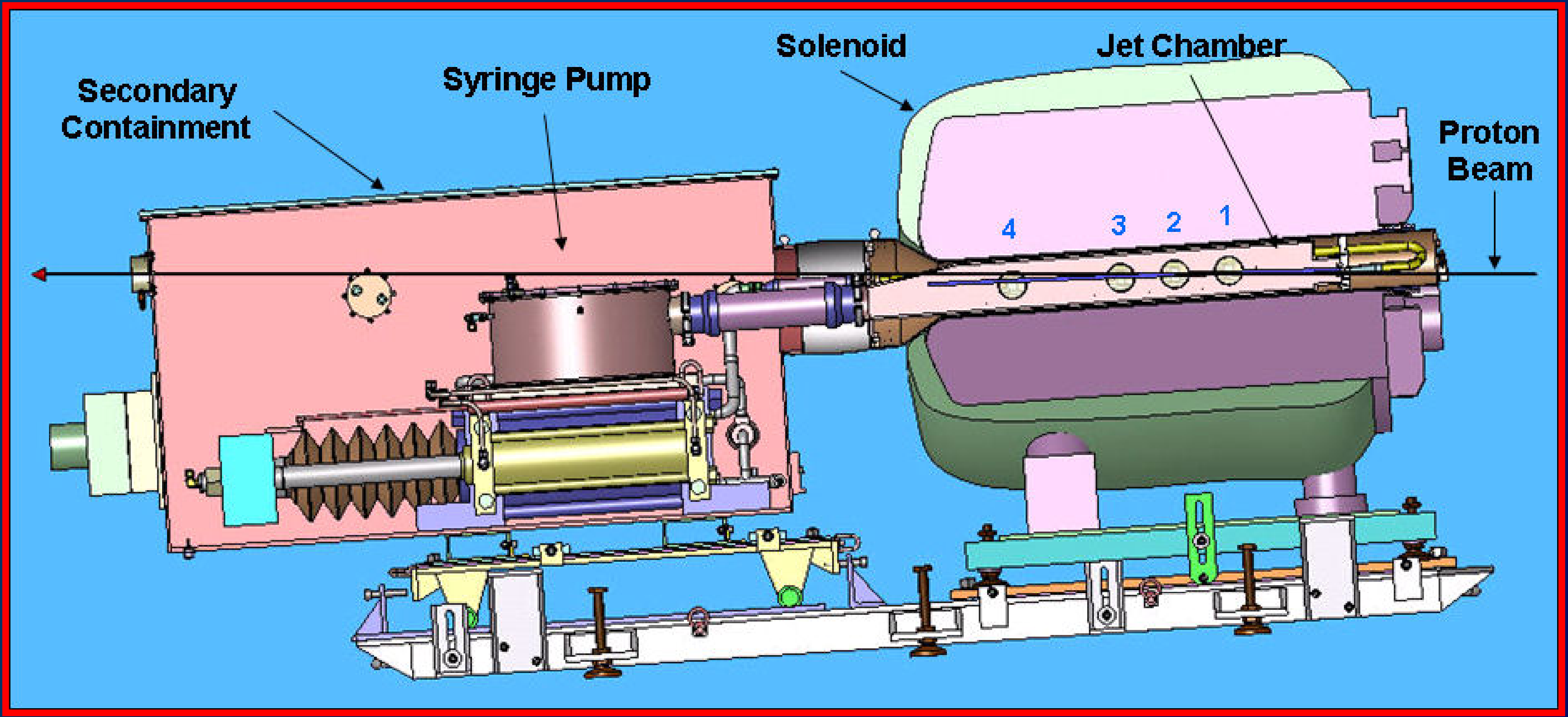
Target/capture:

Parameter	*Value*	*Comment*
Jet velocity	20 m/s	Reformation of jet
Field at i/p	20 T	Pion collection
Field at exit of capture	1.75 T	Pion focusing



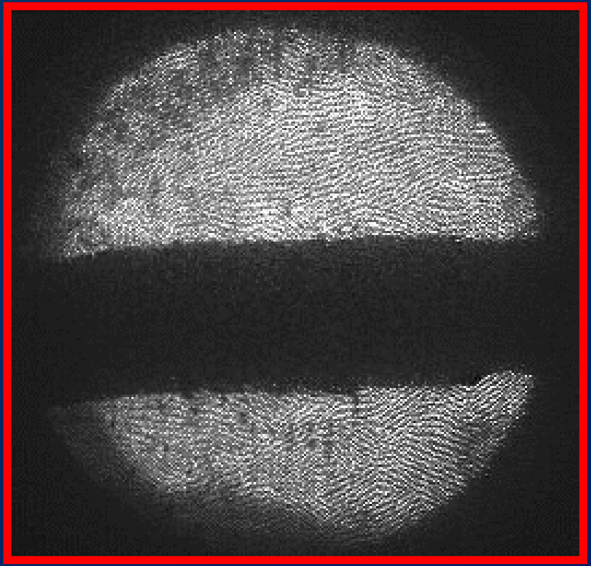
- **Baseline: mercury jet, tapered solenoid for pion capture:**
  - **20 T tapering to 1.75 T in ~13 m**

Target: proof of principal: MERIT:



- 20 m/s liquid Hg jet in 15 T B field
- Exposed to CERN PS proton beam:
  - Beam pulse energy = 115 kJ
  - Reached 30 tera protons at 24 GeV

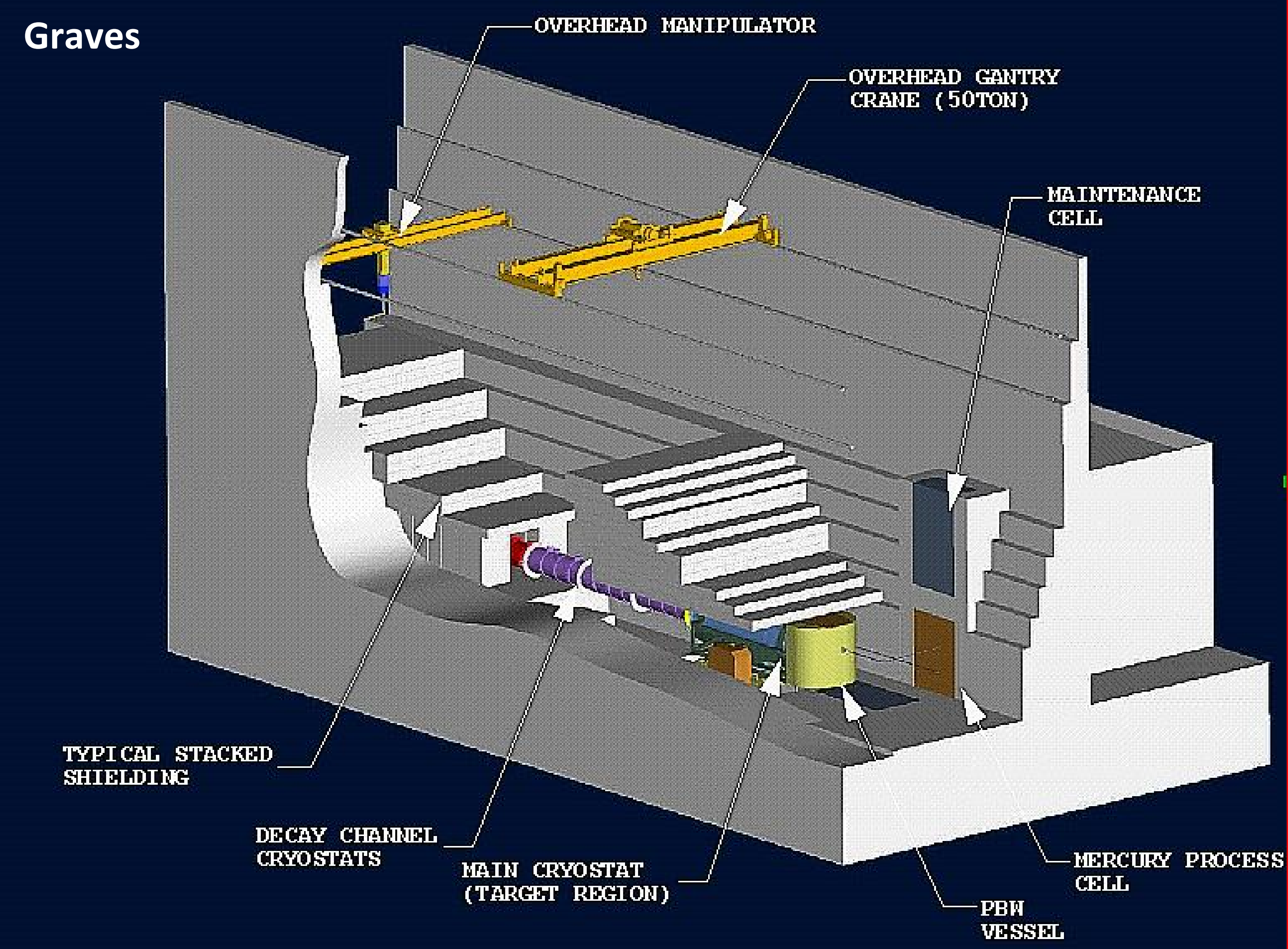
MERIT:



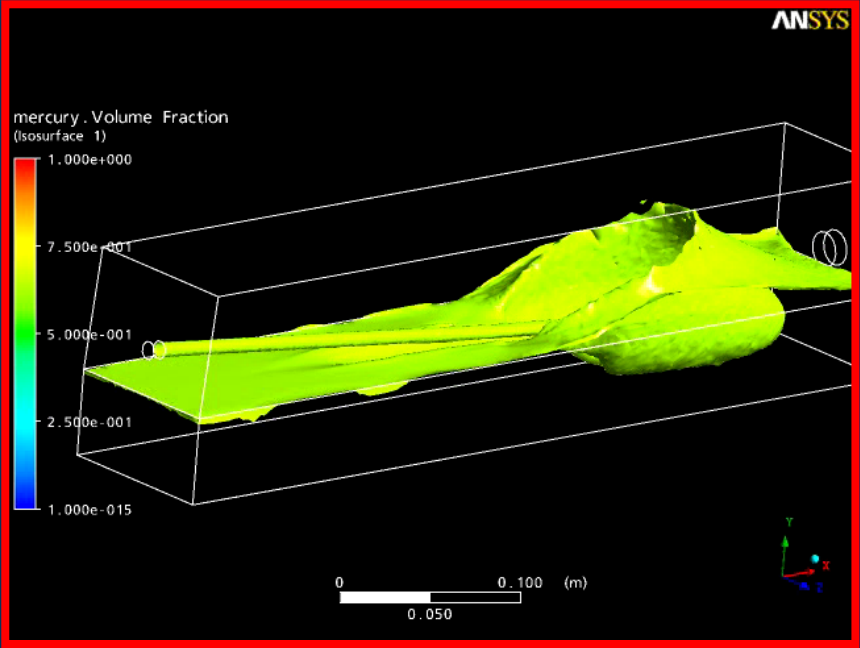
- ‘Disruption length’: 28 cm
- ‘Refill’ time: 14 ms
  - Corresponds to 70 Hz
- Hence:
  - Demonstrated operation at:
    - 115 kJ × 70 Hz = 8 MW

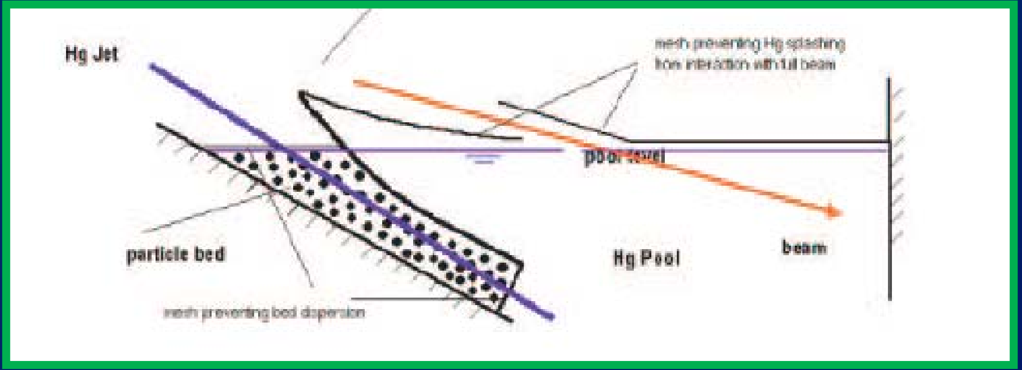
Target station engineering:

Graves

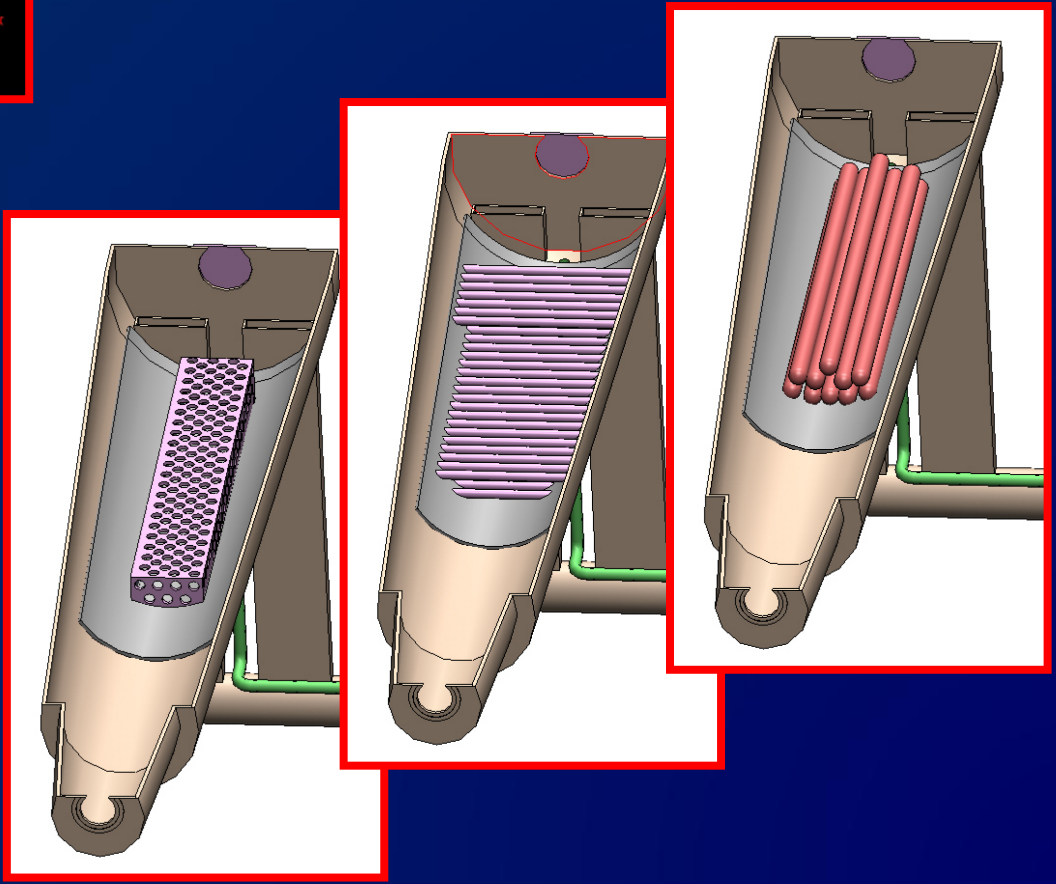


Target engineering:



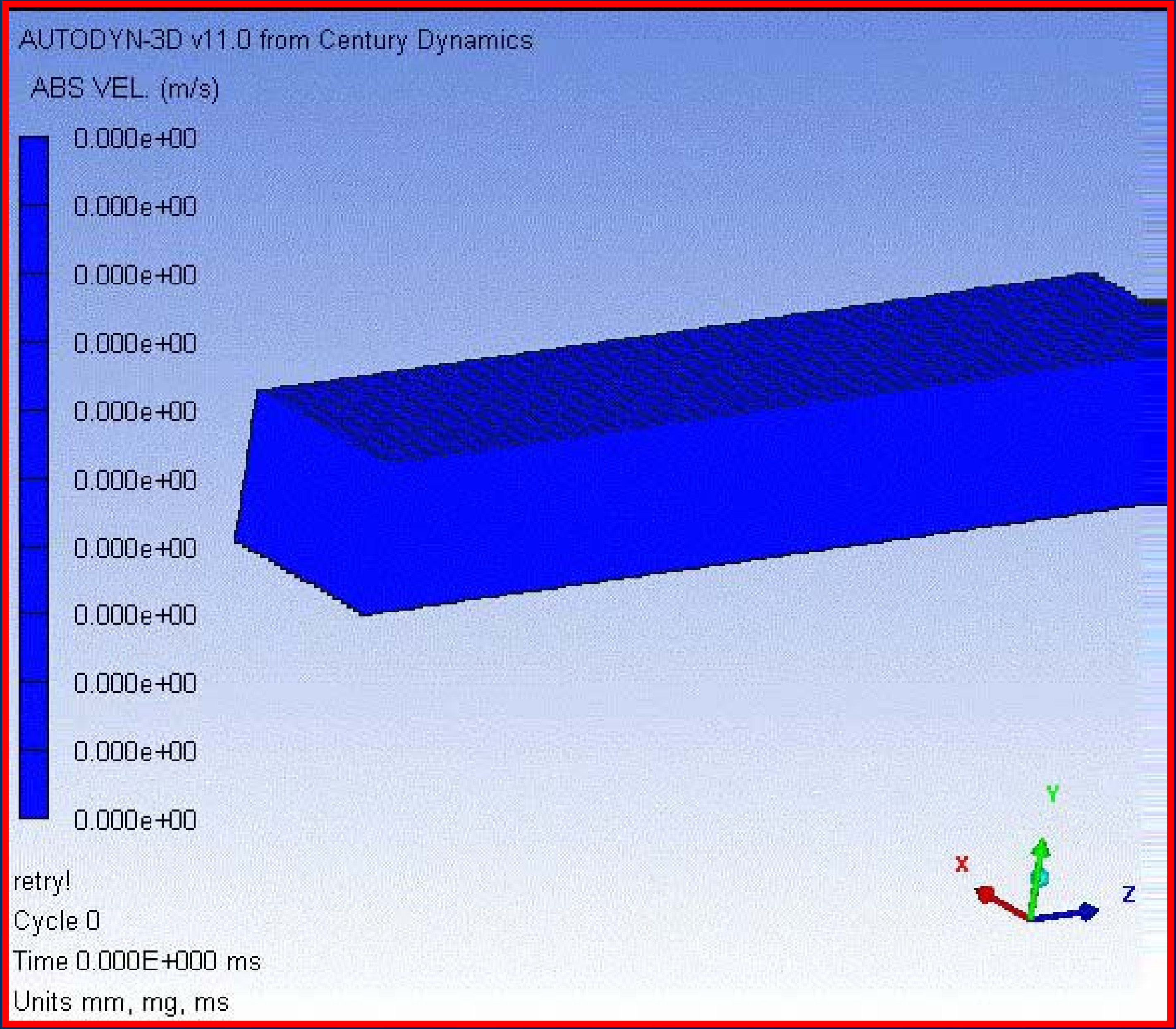


- Splash mitigation:
  - Study 2: Tn balls
- Issues:
  - Effective circulation of liquid mercury
  - Best drain topology
- Need for prototype!



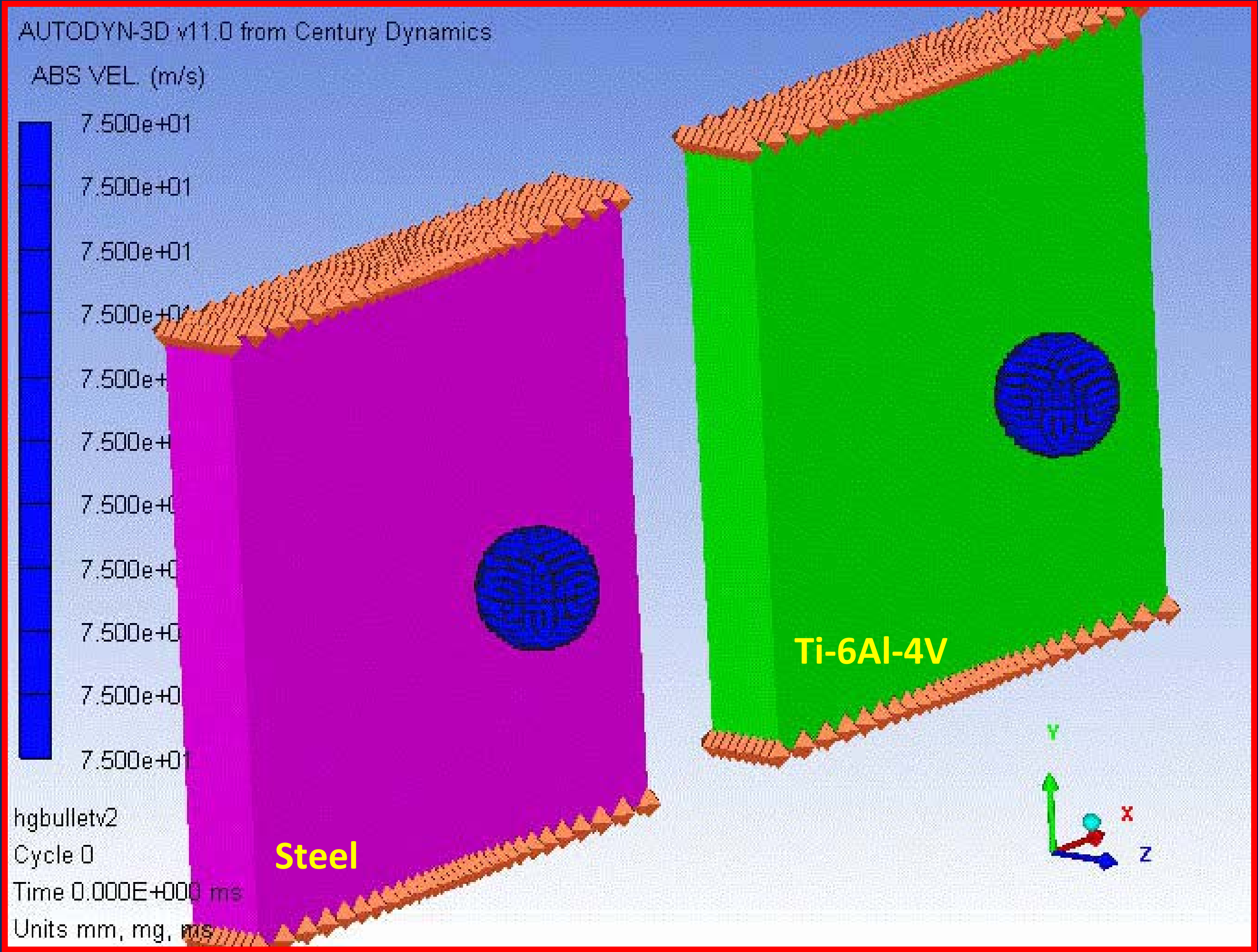
Davenne

Damage from high-velocity droplets:



Davenne

Damage from high-velocity droplets:

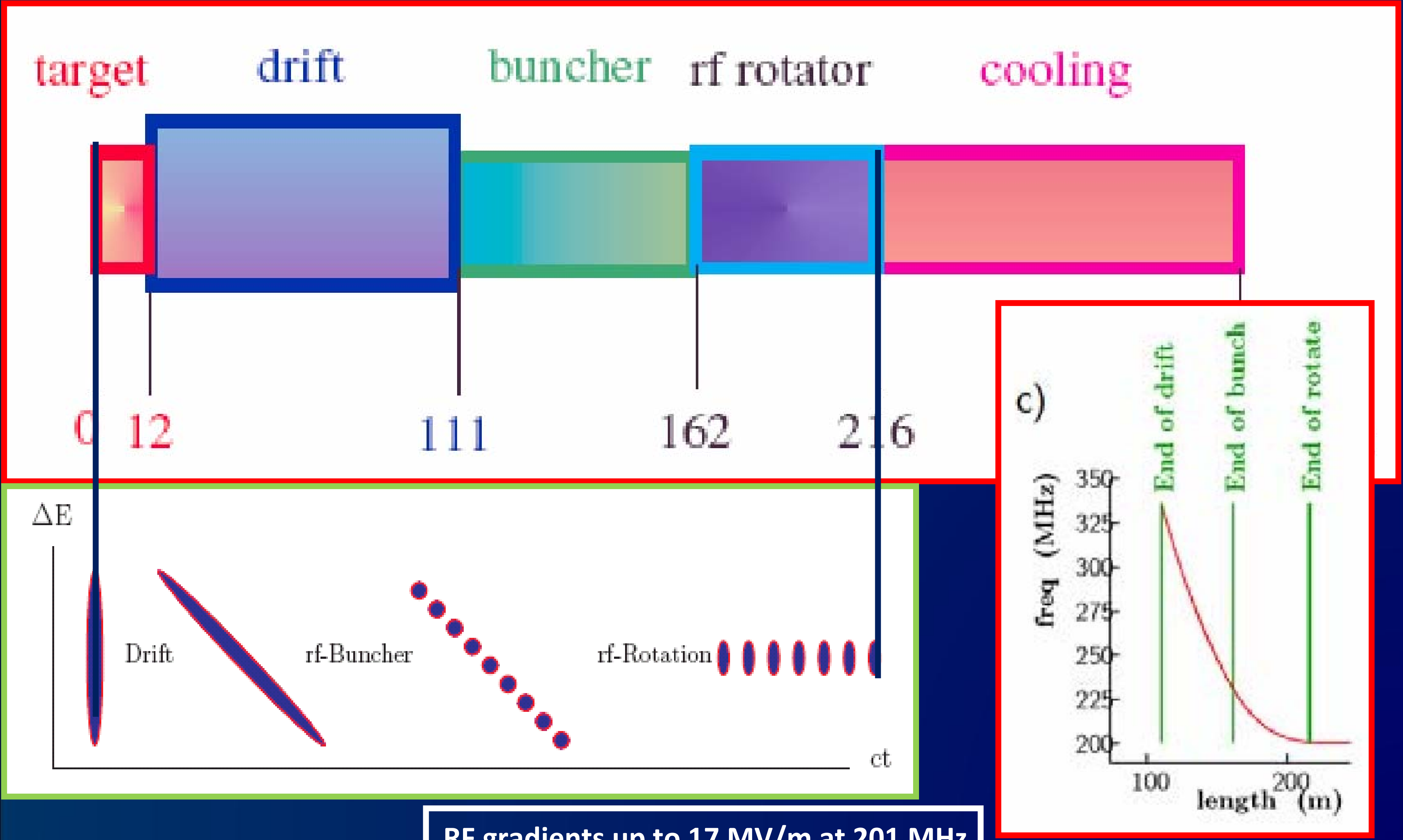


Ti-6Al-4V

Steel

Muon front-end:

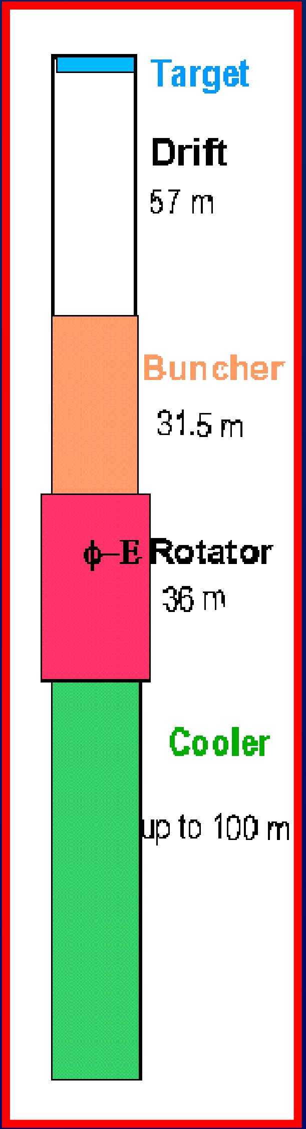
Parameter	***Value***	***Comment***
E-spread after P.R.	10%	Subsequent accel.
Freq. after P.R.	201.25 MHz	
Emittance at exit	7.4 mm rad	Subsequent accel.

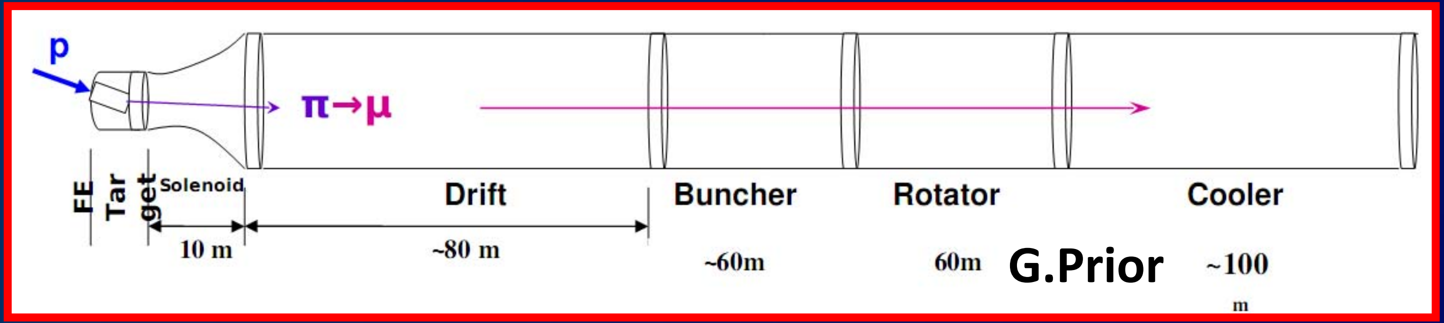


RF gradients up to 17 MV/m at 201 MHz

Alternative front-end schemes:

- Shorter phase rotation and bunching sections:
  - Improved yield, but higher gradients required
- Re-visit 44/88 MHz scheme:
  - Outline:
    - Bunching , phase rotation, intial cooling, and acceleration to 280 MeV at 44 MHz, ~ 2 MV/m
    - Cooling and acceleration to 1 GeV at 88 MHz, ~10 MV/m
  - Issues:
    - Longer channel, larger cavities
    - Gradients high for low frequency cavities
      - Effect of magnetic fields?
    - May require reconsideration of other parts of complex





G.Prior

Ionisation cooling:

- **Muon beam after phase rotation and bunching:**
  - **Wide — σ_x ~ 10(+) cm**
  - **Divergent — σ_θ ~ 150(+) mr**
  - **i.e. large normalised emittance:**

In 2D $$\varepsilon_n = \frac{1}{m_\mu c}\left(\sigma_x^2\sigma_{p_x}^2 - \sigma_{xp_x}^2\right)^{\frac{1}{2}} \rightarrow \beta\gamma\sigma_x\sigma_\vartheta$$ at a focus

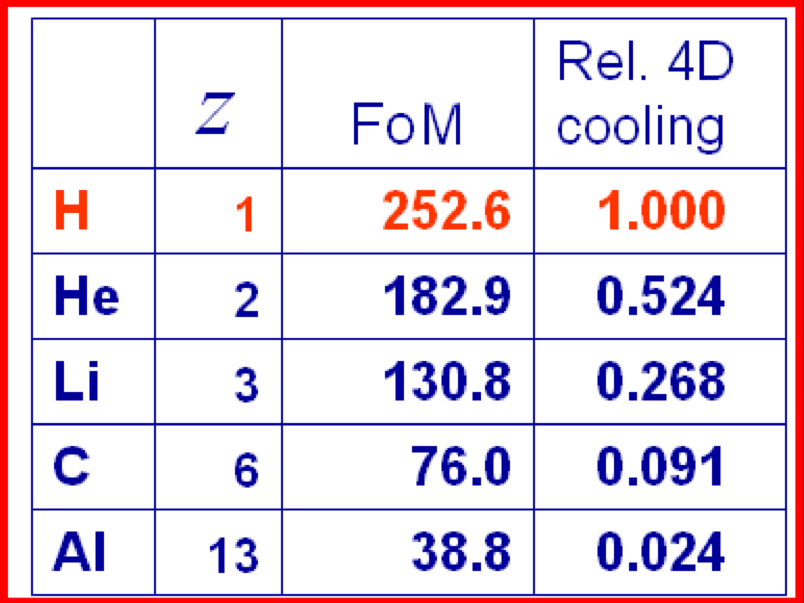
- **Cooling required:**
  - **To increase by a factor of 2—10 the number of muons in acceptance of subsequent accelerator**
- **Ionisation cooling is the only practical solution:**
  - **Muon lifetime is short (2 μs at rest)**

Ionisation cooling: principal:

- Exponential decrease in normalised emittance:

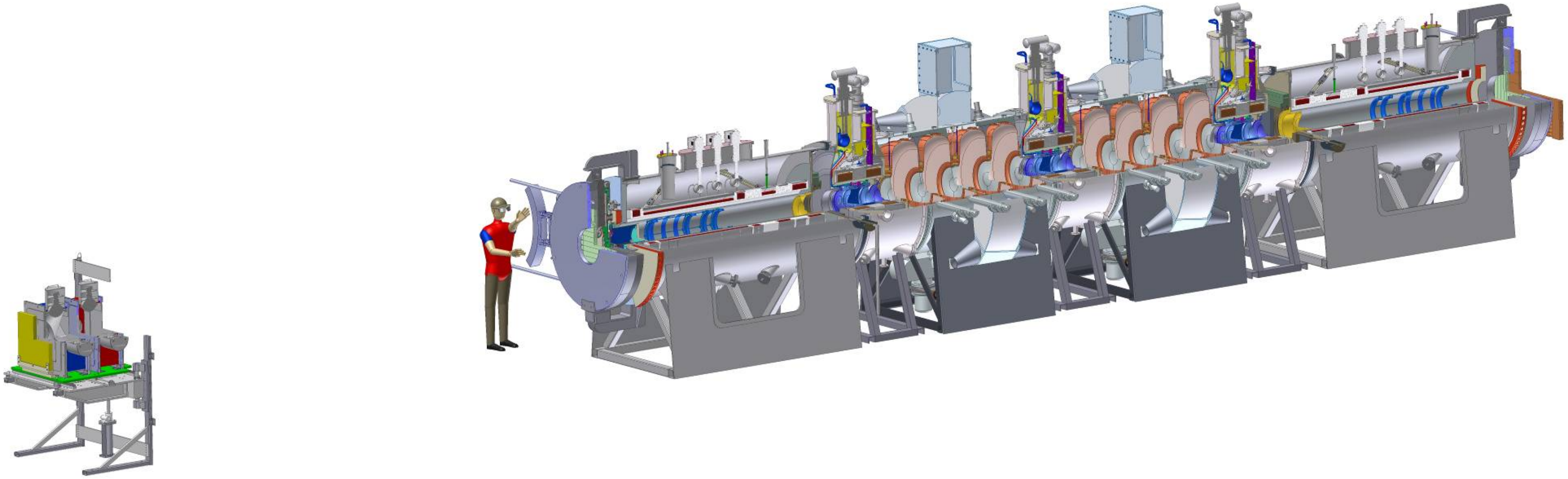
$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t \left(0.014\ \mathrm{GeV}\right)^2}{2\beta^3 E m_\mu X_0}$$

- Competition between:
  - dE/dx [cooling] and MCS [heating]
- Optimum:
  - Low Z, large X_0
  - Tight focus
  - H_2 gives best performance



	Z	FoM	Rel. 4D cooling
H	1	**252.6**	**1.000**
He	2	**182.9**	**0.524**
Li	3	**130.8**	**0.268**
C	6	**76.0**	**0.091**
Al	13	**38.8**	**0.024**

Muon ionisation cooling experiment

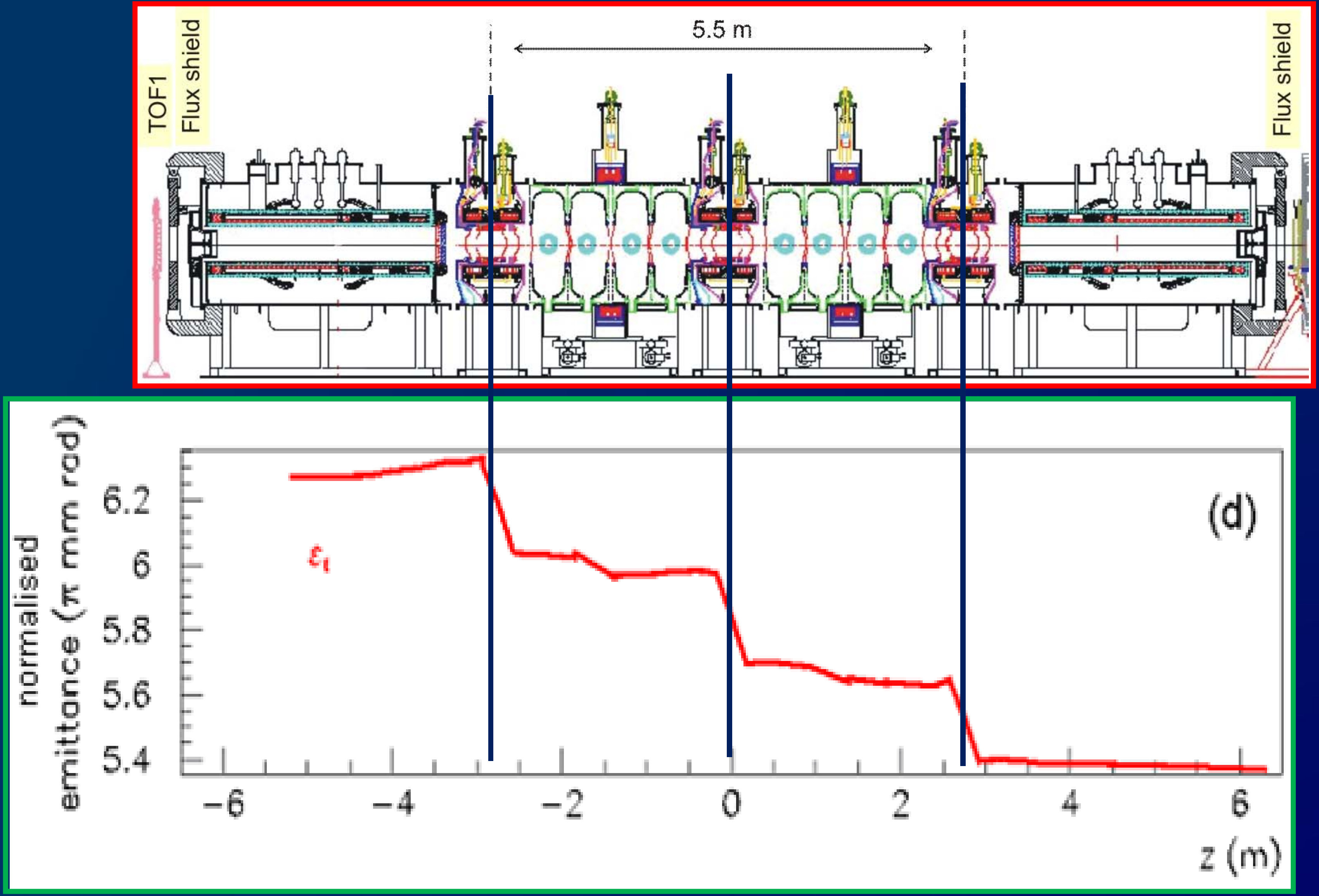


- **MICE:**
  - Design, build, commission and operate a realistic section of cooling channel
  - Measure its performance in a variety of modes of operation and beam conditions …

  … i.e. results will allow Neutrino Factory complex

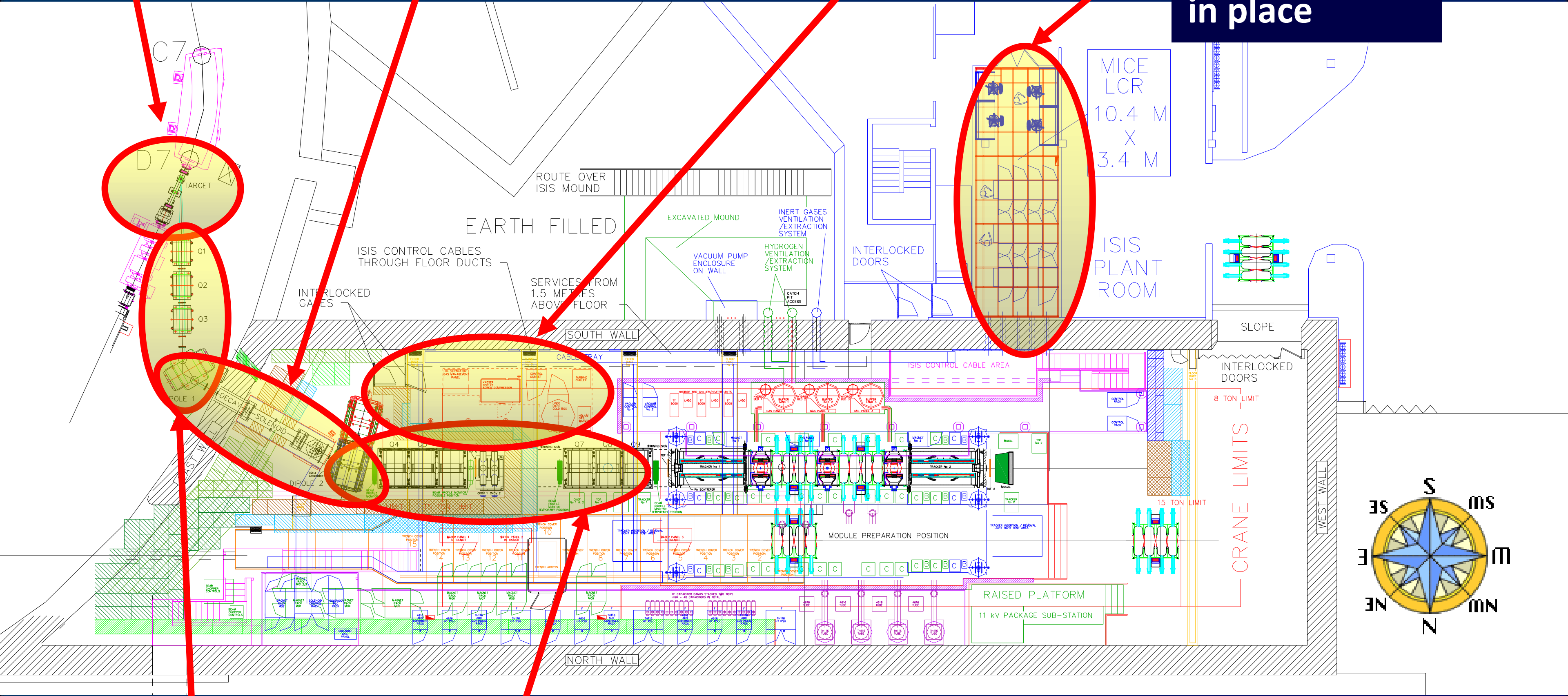
  to be optimised

Cooling performance:



- **15% cooling in MICE channel from 5% *E* loss per absorber**

Status of MICE:



Target

Decay solenoid

Linde refrigerator

MICE Local Control Room: in place

Upstream beam line

Downstream beam line

Instrumentation in place:

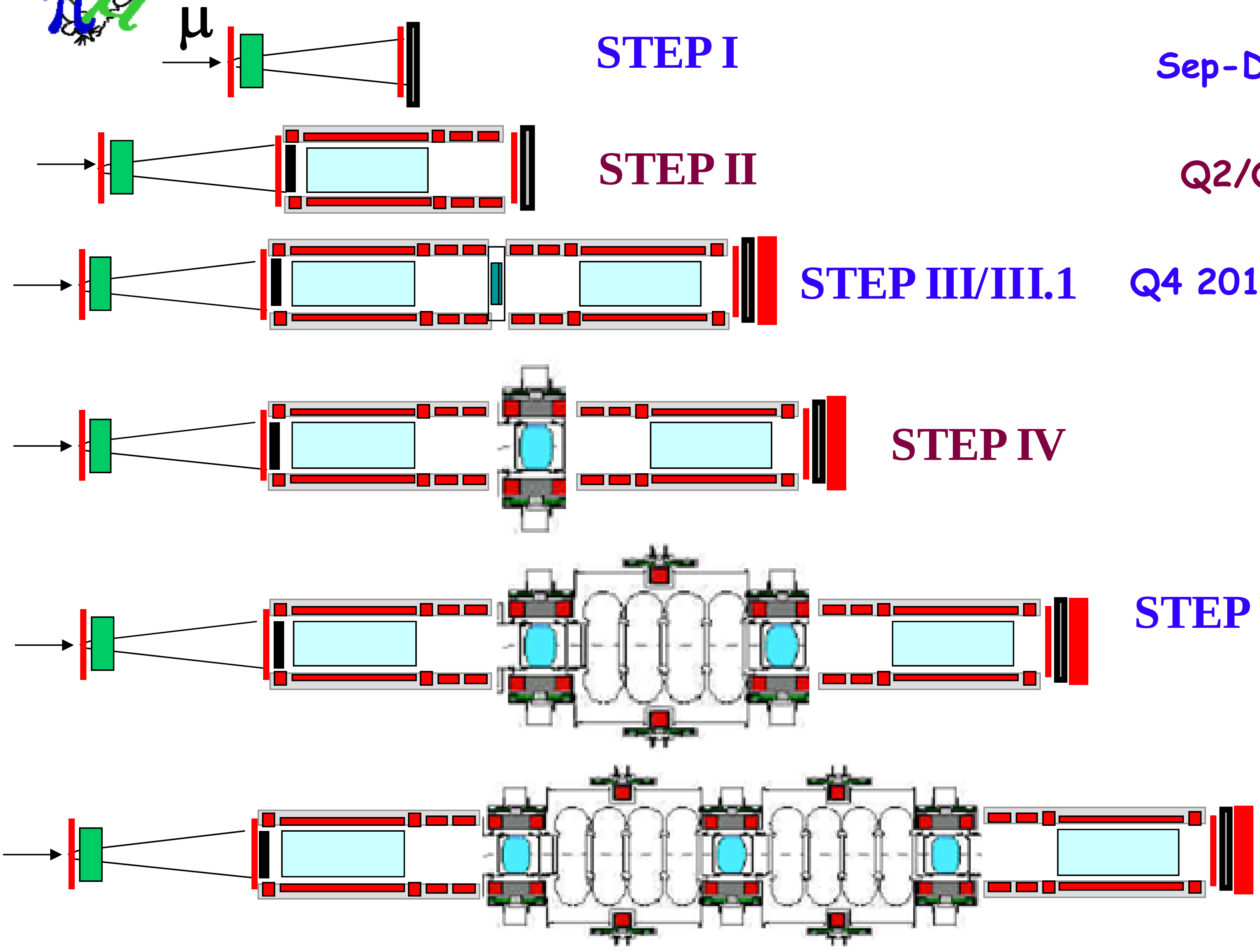
Beam profile monitors

Trigger/rate scintillators

CKovA&B, TOF0&1, KL

MICE Schedule as of Sept 2009

Run date:



STEP I Sep-Dec 2009

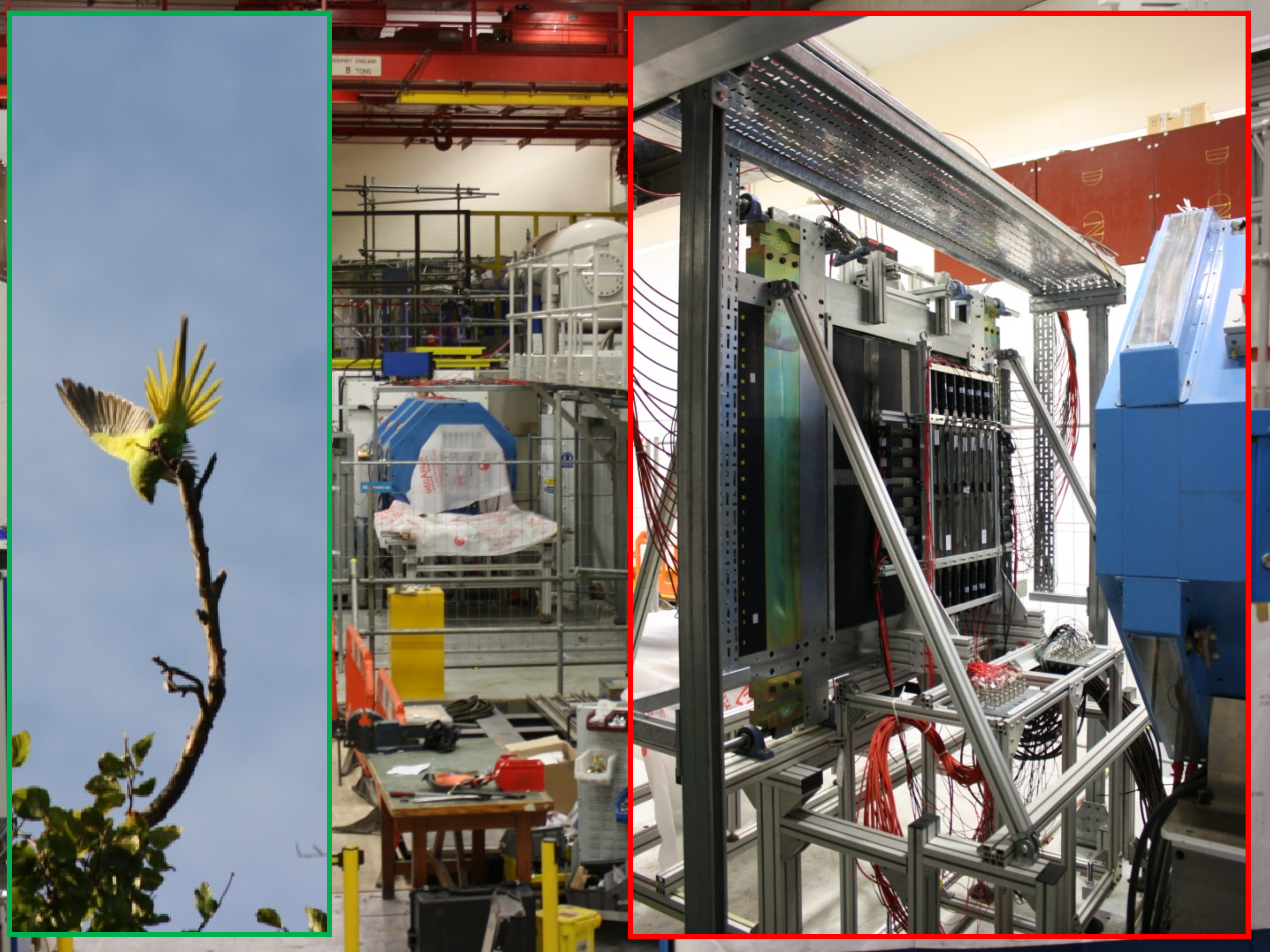
STEP II Q2/Q3 2010

STEP III/III.1 Q4 2010 -> 2011

STEP IV 2011

STEP V 2012

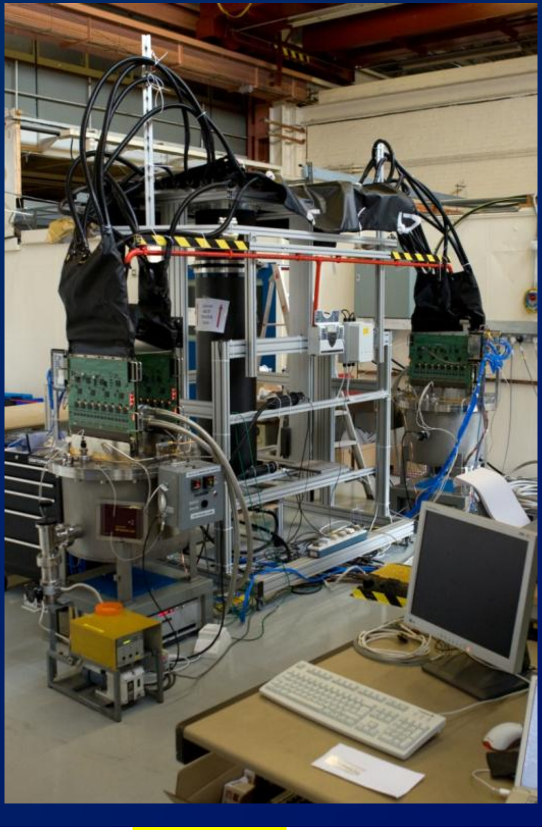
STEP VI 2013

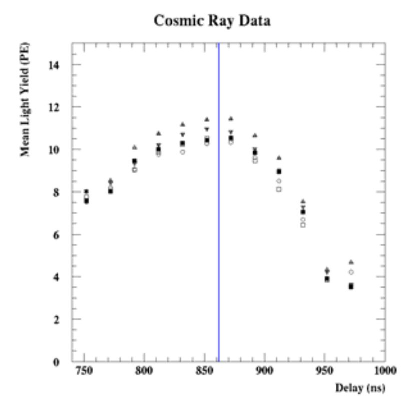

8 TONS

Brunel, FNAL, IIT, Imperial, LBNL, Riverside, UCLA, NWU

Spectrometers:

- Tracker:
  - Extended cosmic test of trackers #1 and #2
- Spectrometer solenoids:
  - Issues related to cool down of solenoid #1 imply mechanical modifications
  - Modifications are being implemented on solenoid #2
  - Plan:
    - Complete solenoid #2 at vendor (Nov/Dec09)
    - Magnetic mapping at FNAL (Dec09/Jan10)
    - Magnet sipped to RAL (Mar10)

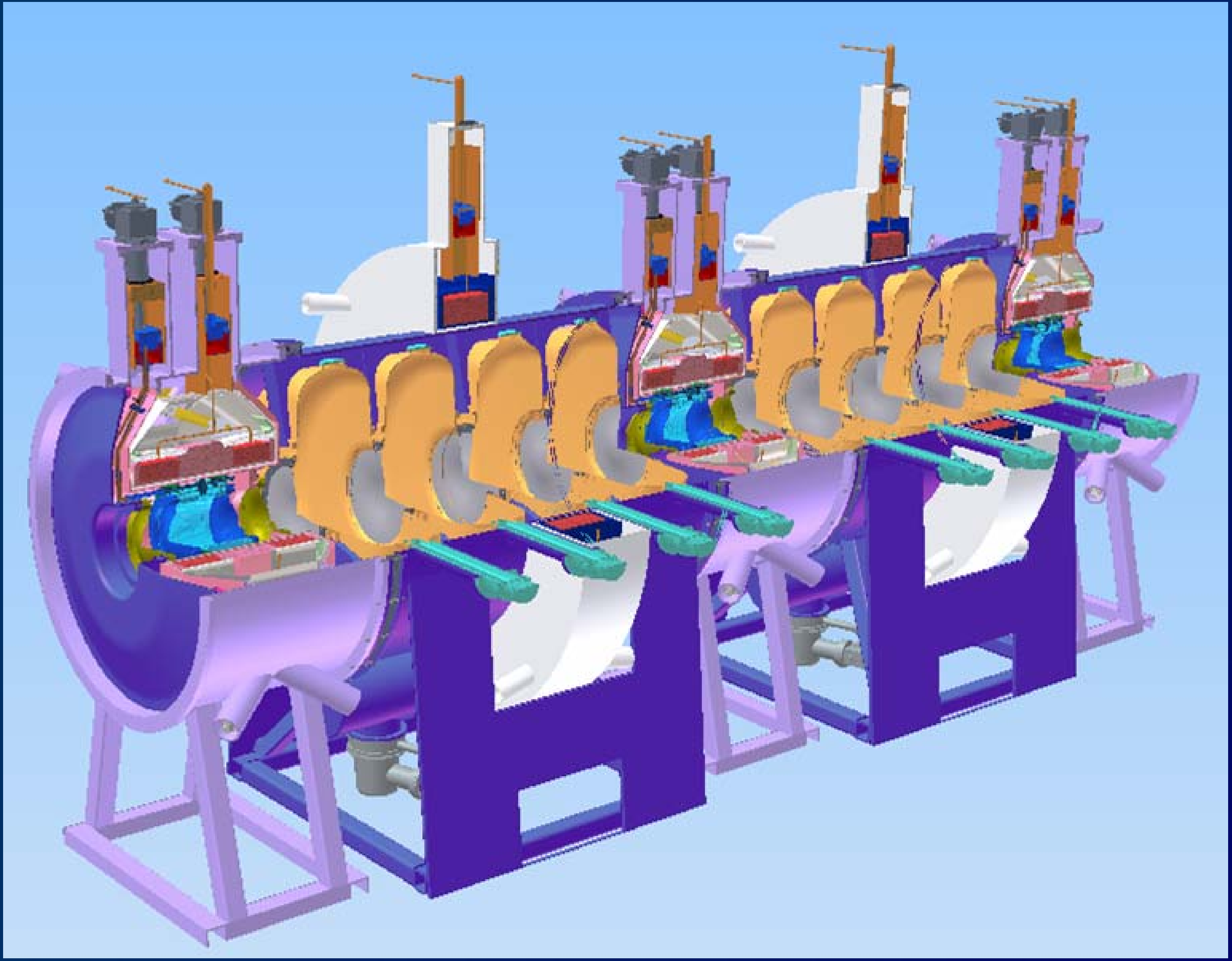




Magnet 1

Magnet 2

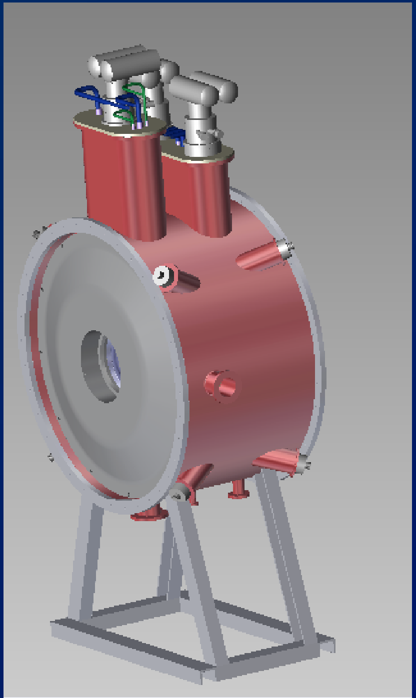
Cooling channel:

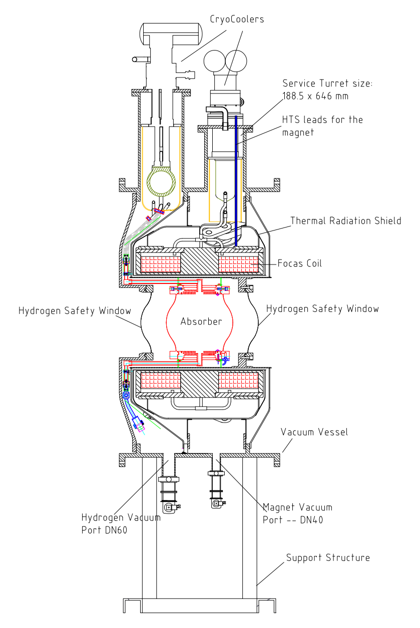


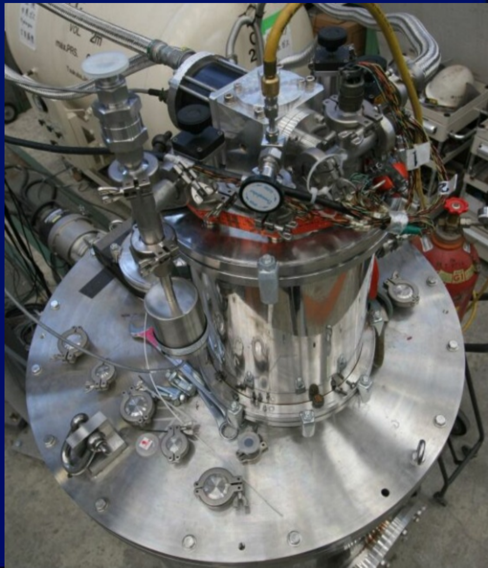
Oxford, KEK,
Mississippi

Absorber/focus-coil module:

- Focus coil module:
  - Contract awarded to TESLA
  - Presently in 'detailed design' phase:
    - Production readiness review (MICE/TESLA) last week
  - First module, summer 2010
- Absorber:
  - Prototype tested at KEK
  - Production has started:
    - Will match focus-coil schedule





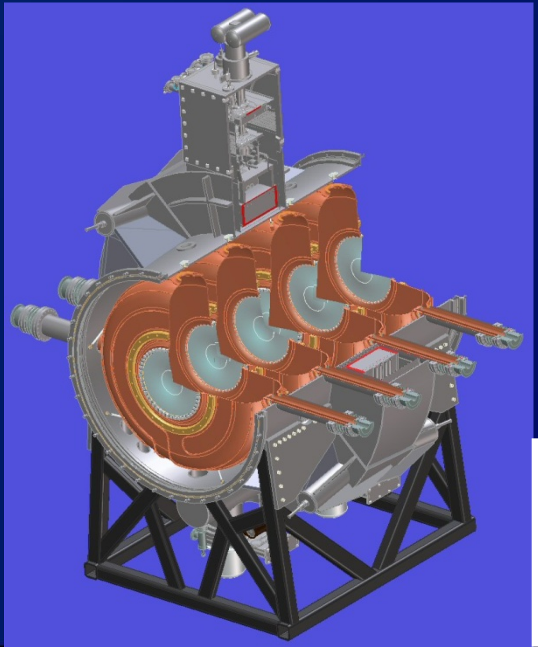


LBNL, ICST

RF/coupling-coil module:

- Coupling coil manufacturing has started at ICST, Harbin, China
  - First coil for MuCool programme
  - Second coil for MICE
- RF cavity production:
  - Design for cavities complete
    - Production readiness review Oct08
- Ship first RFCC module to RAL 2011

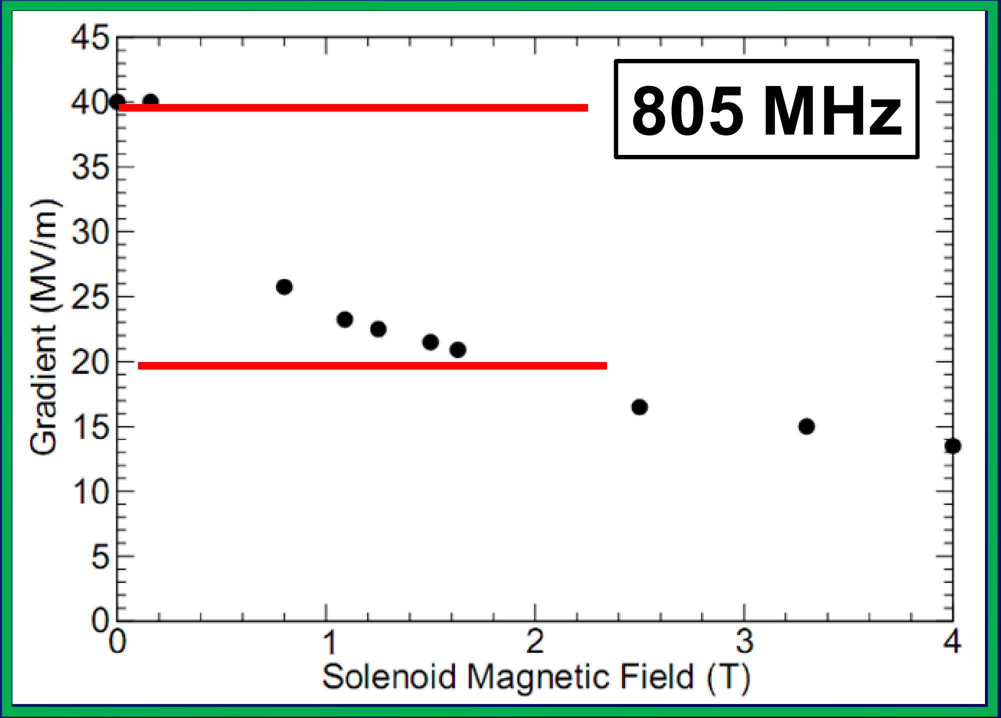
Prototype coil being prepared for cold test at Harbin



Design for RF cavity module

MuCool: RF breakdown in magnetic field:

- Principal issue for cooling channel:
  - Gradient required in baseline cooling channel:
    - 17 MV/m from 201MHz cavities
- MuCool: study breakdown in presence of magnetic field
  - 805 MHz:
    - Reduction of factor of ~2 in max. gradient
  - 201 MHz:
    - In absence of *B* have achieved 19MV/m
      - Test in magnetic field planned



Mitigation of RF gradient risk:

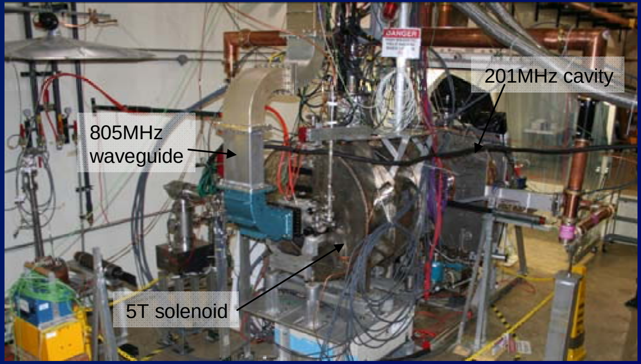
C.Rogers

- Various options being considered:
  - Modified lattices, magnetic return, bucking coils, gas filled cavities…
  - Studies emphasise:
    - Priority: expedite MICE and MuCool programmes!

- Ionisation cooling

MICE
(under construction at RAL)

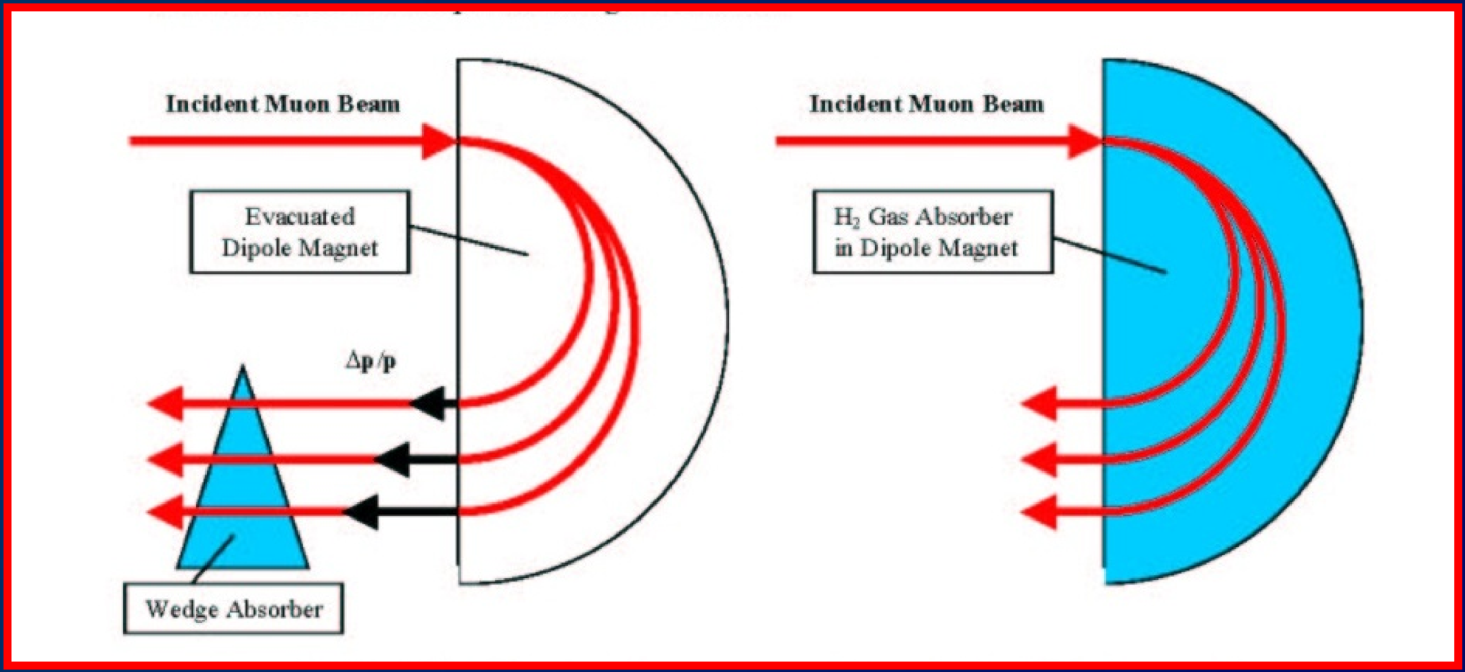
- RF cavity development



MuCool (part of US NFMCC)

Ionistion cooling and the Muon Collider:

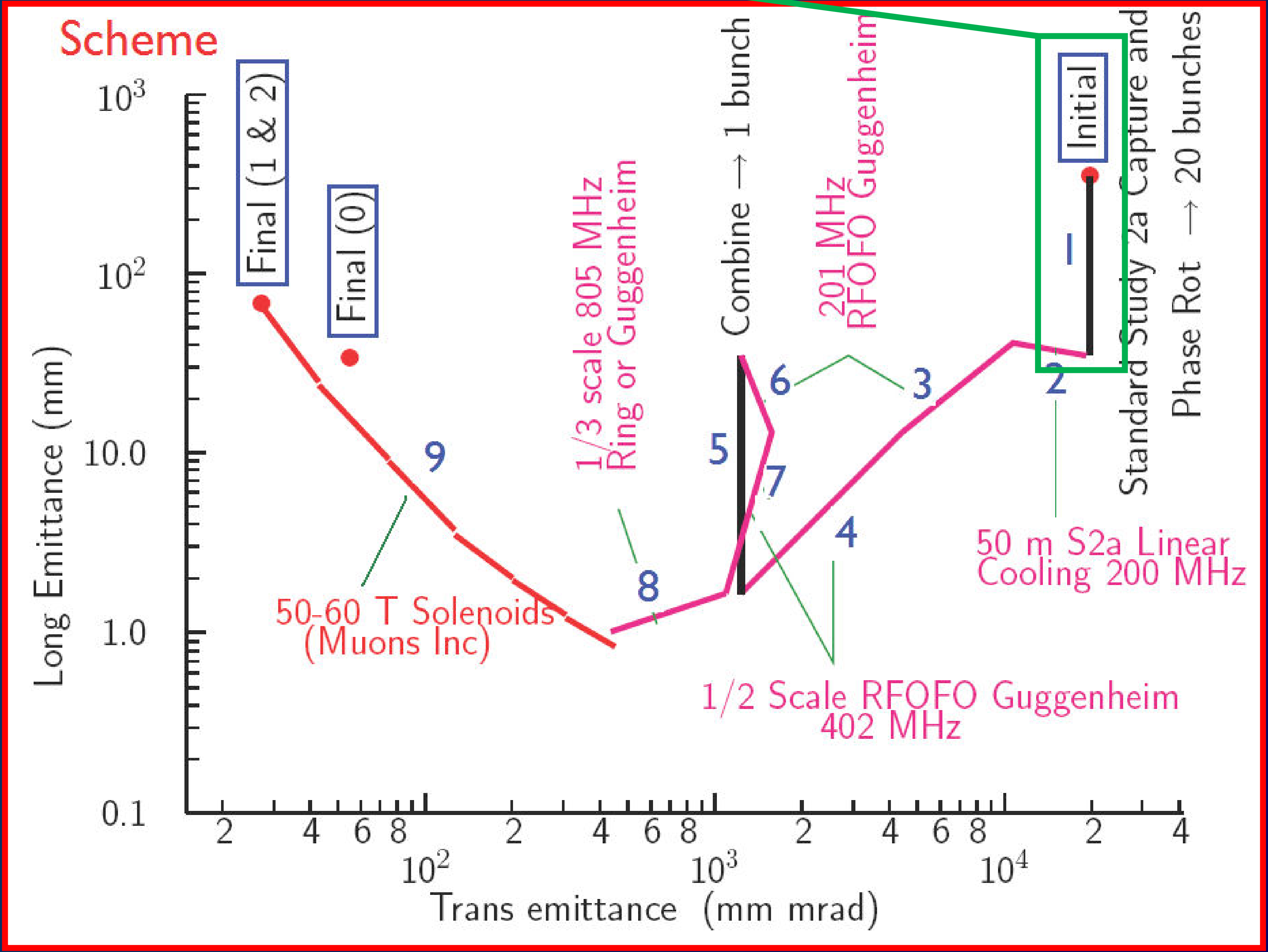
- Muon Collider requires much more aggressive cooling:
  - Must reduce emittance in all 6 phase-space dimensions
  - Requires 'emittance' exchange



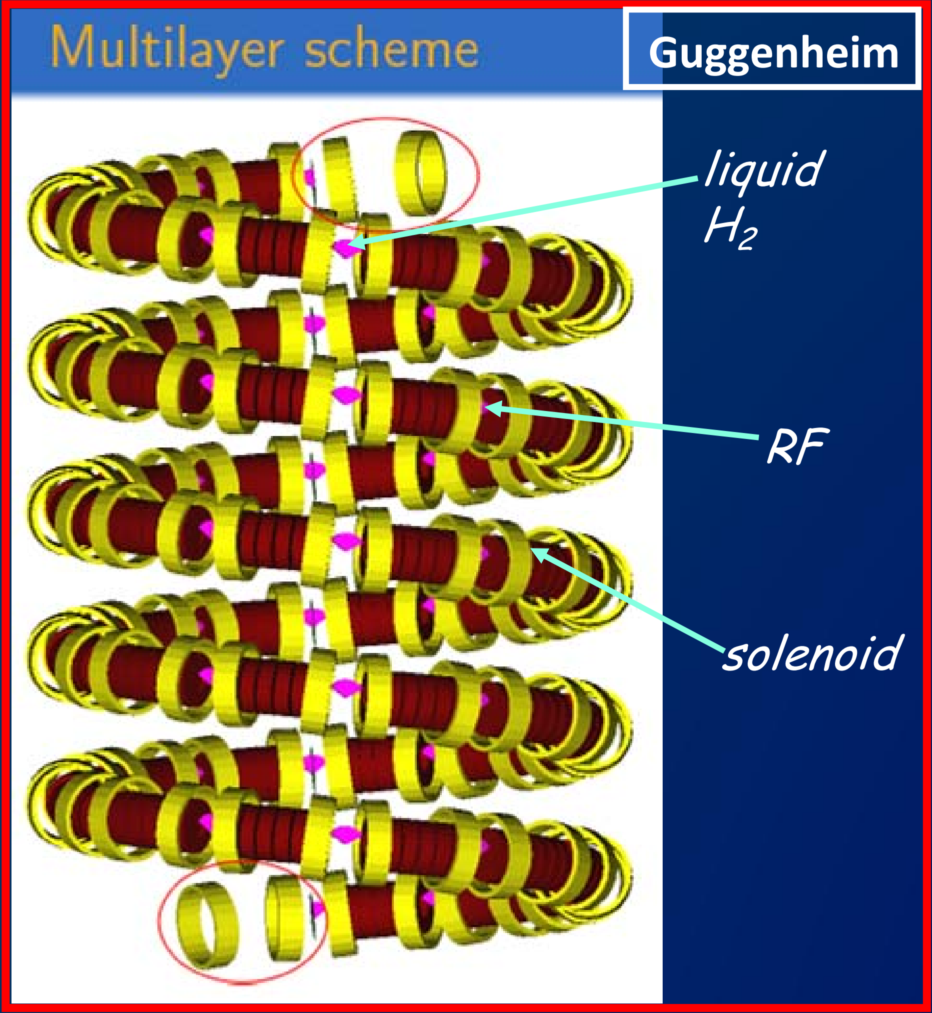
  - *The* most challenging R&D programme for the Muon Collider

6D cooling scheme:

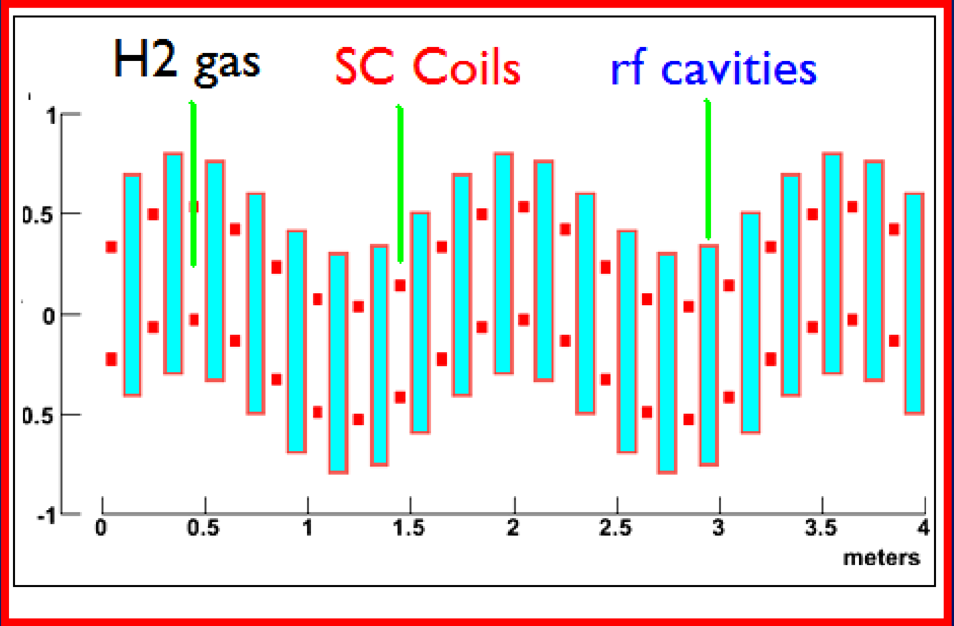
Initial cooling identical to Neutrino Factory

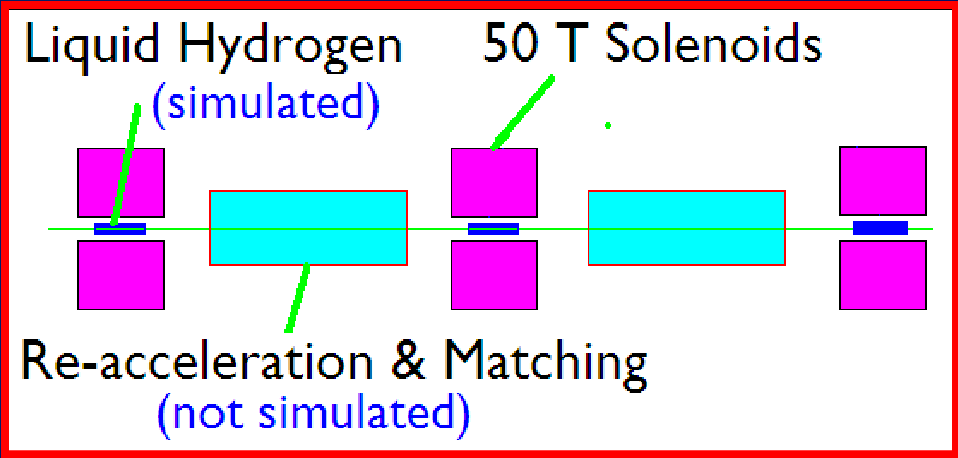


6D cooling scheme components:



Helical cooling channel





Final cooling

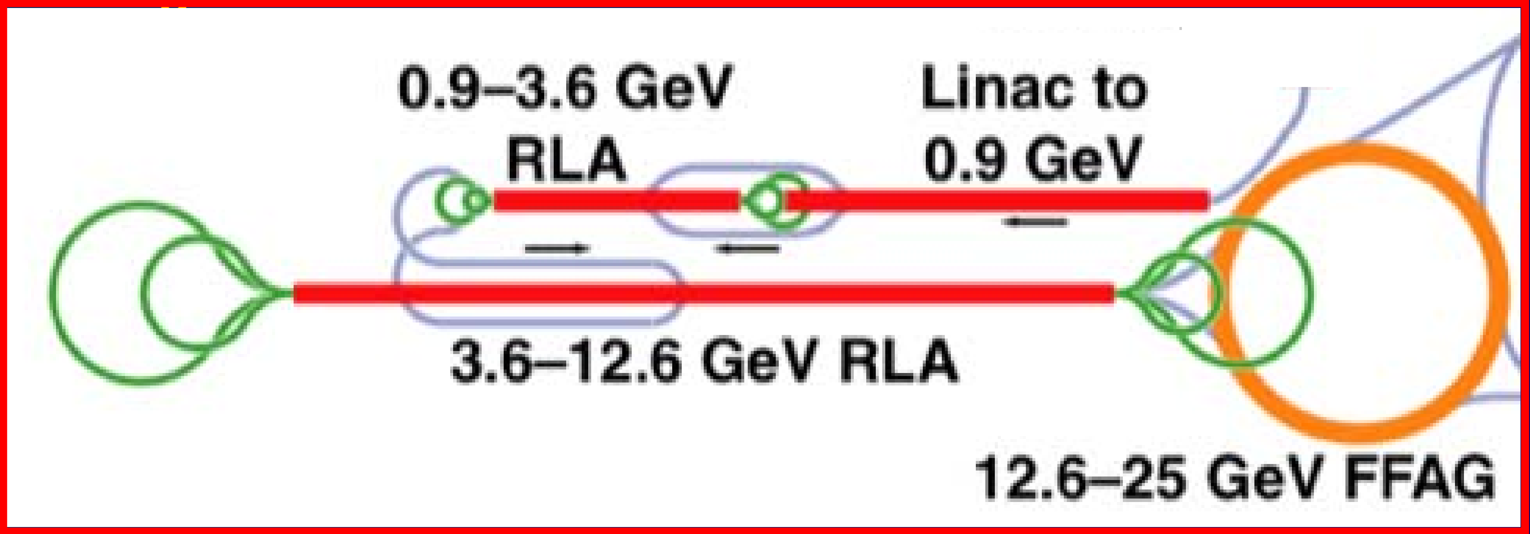
- **6D ionisation cooling experiment under discussion:**
  - **Possible use of MICE Muon Beam once MICE is complete**
  - **Critical issue: high-gradient RF in magnetic field**

Muon acceleration:

	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

- Linac/RLAs:
  - Development of optics
    - Graded focussing
  - Tracking with OPTIM and MAD-X
  - Error-tolerance analysis for droplet arcs
  - Ready for end-to-end tracking

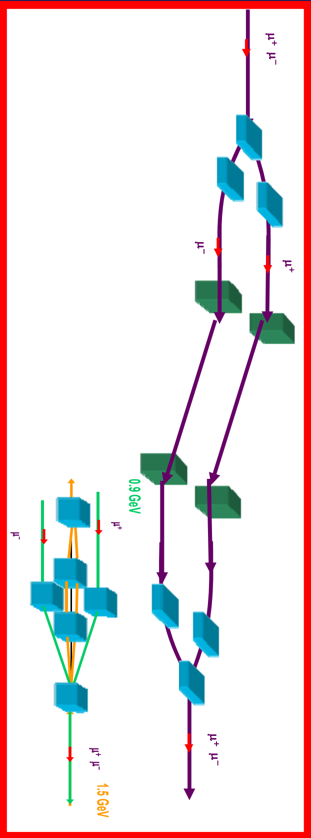
- FFAG:
  - Lattice specification update
  - Analysis of distortions & chromaticity
  - Evaluation of injection and extraction systems



A.Bogacz

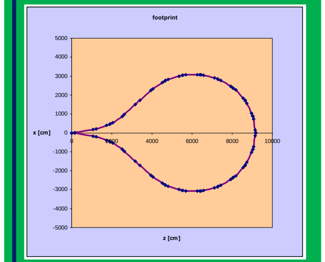
Pre-accelerator, RLA I & II:

- Solenoid focusing lattice for 0.9 GeV linac
  - Optics and first tracking complete
- Transfer section for injection into RLA I:
  - Optics and first tracking complete
- Lattice for linacs I and II complete:
  - Quadrupole focusing
- Droplet return arcs
  - Optics, first tracking, and match linacs performed



Arcs RLA I

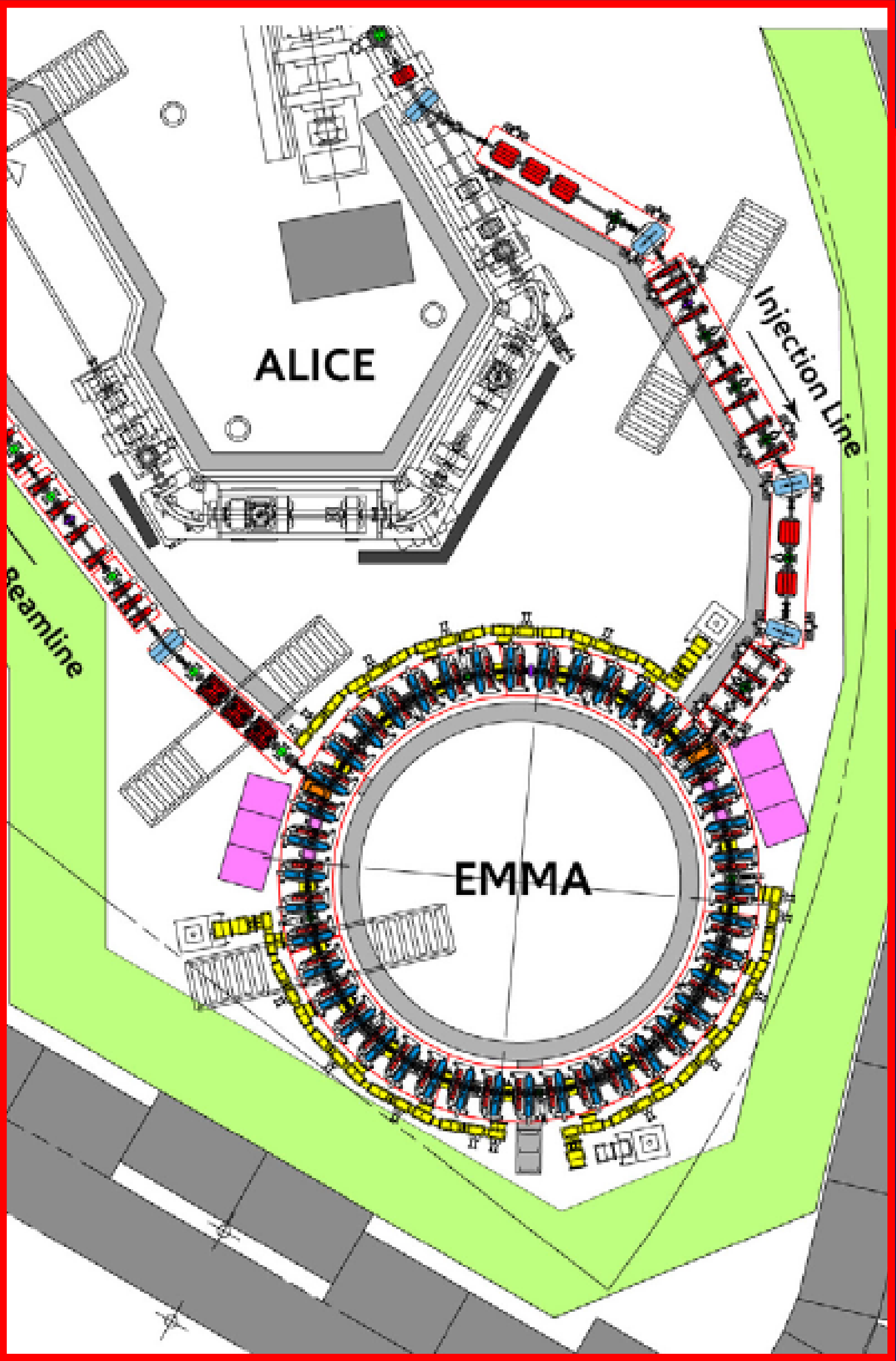
i = 1…4	E_i [GeV]	p_i/p_1	cell_out	cell_in	length [m]
Arc1	1.2	1	2 2	10	130
Arc2	1.8	3/2	2 3	15	172
Arc3	2.4	2	2 4	20	214
Arc4	3.0	5/2	2 5	25	256

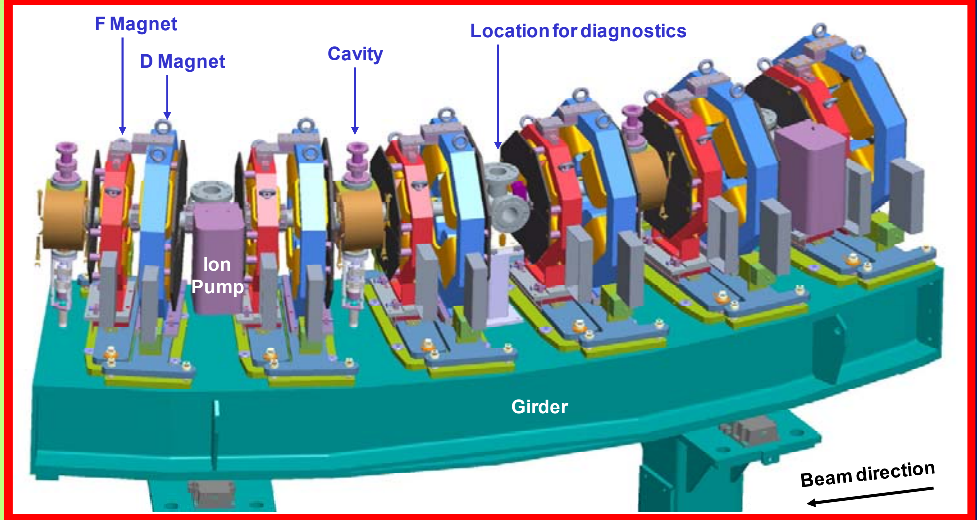


Arcs RLA II

i = 1…4	E_i [GeV]	p_i/p_1	cell_out	cell_in	length [m]
Arc1	4.6	1	2 2	10	260
Arc2	6.6	3/2	2 3	15	344
Arc3	8.6	2	2 4	20	428
Arc4	10.6	5/2	2 5	25	512

Muon nsFFAG: EMMA:

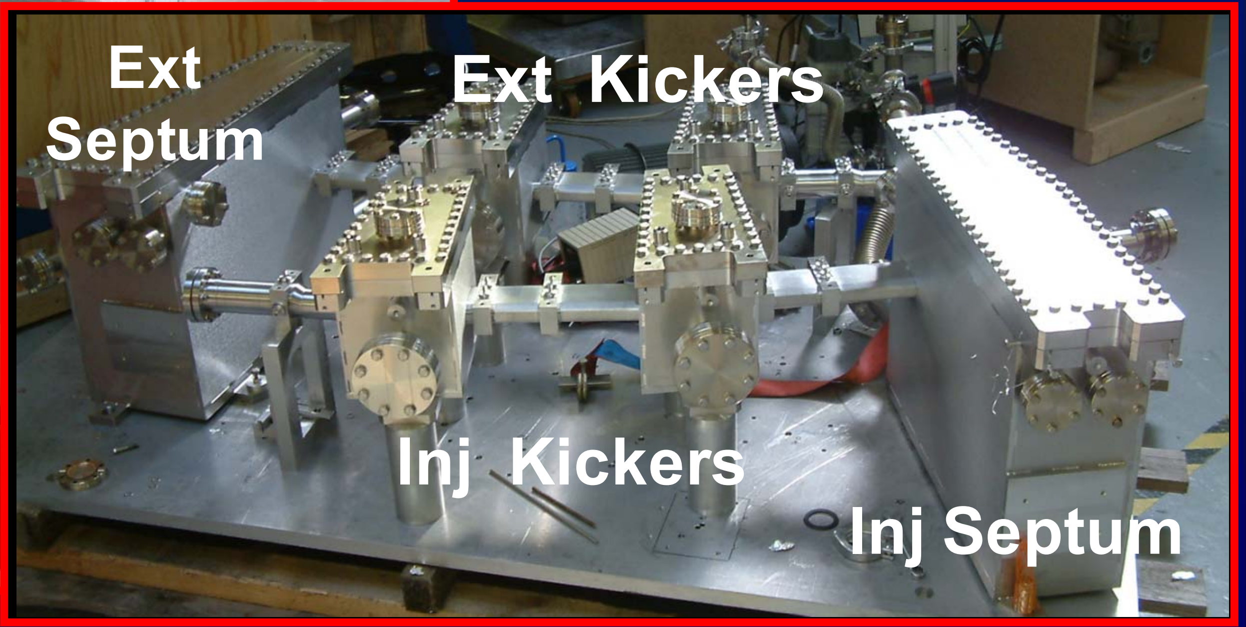




- EMMA (at DL):
  - Electron ‘model’ of muon non-scaling FFAG
    - Demonstrate feasibility of concept
- Studies:
  - Longitudinal dynamics;
  - Transmission;
  - Emittance growth
  - Influence of resonances

Status of EMMA:

- Component fabrication close to completion
- Commissioning starts early 2010

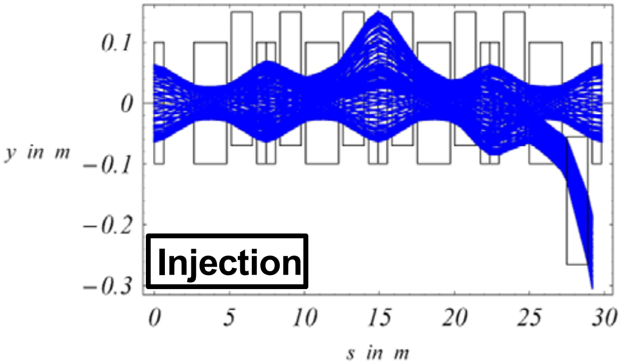


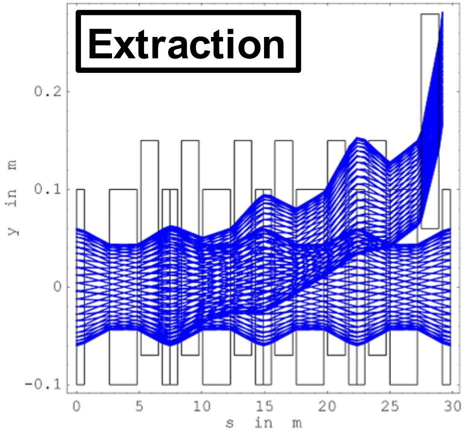
S.Berg, J.Pasternak, D.Kelliher

Muon FFAG:

- Lattice revision required to:
  - Provide drift spaces for installation of kickers
- Various options:
  - Doublet, triplet, FODO, single and 'doublet' of cavities
  - Some indicative estimate of cost
    - How to converge on a single, optimised design?
- Kicker schemes under development:

FODO case	Inject 6	Inject 10	Extract
Kickers	6	10	6
Kicker field (T)	0.12	0.08	0.10
Septum field (T)	2.5	2.5	4.0





- Orbit distortions related to magnet apertures in injection and extraction sections under study

- Chromaticity (sextupole) corrections required to mitigate time-of-flight differences

Acceleration Scheme

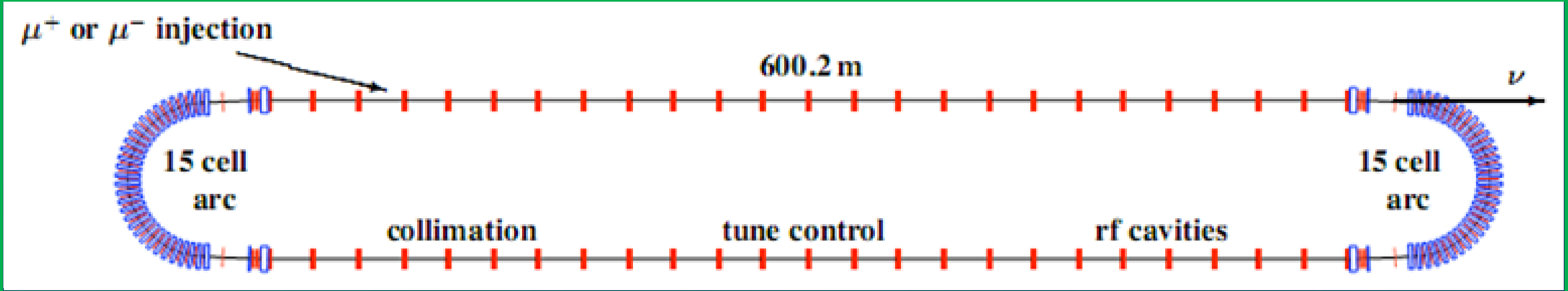
- Early Acceleration (to 25 GeV ?) could be the same as NF. Needs study.
- Main Acceleration – Attractive Candidates
  - RLAs (extension of NF accel. scheme ?)
  - Rapid cycling synchrotron – needs magnet R&D
  - Fast ramping RLA
- Options need further study → particle tracking, collective effects, cavity loading, ...

Storage rings:

C.Prior

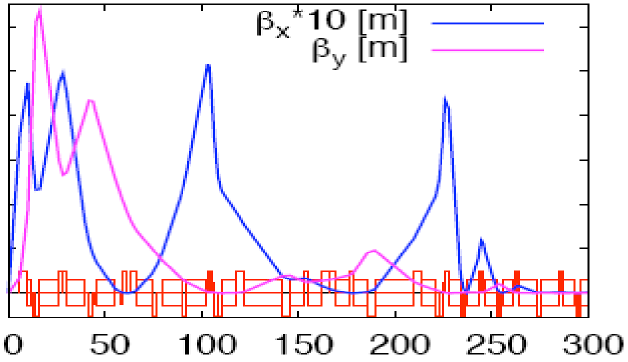
Parameter	***E_{fin} (GeV***	***Comment***
Type	Race track	Triangle as backup
N_{decays} /b.l. /yr	5×10^{20}	Baseline flux (10^{21} / yr total)
Min, bunch spacin	100 ns	Event separation

- **Three muon bunches per pulse:**
  - **Either (both?) μ^+ and μ^- in each storage ring**
  - **If counter-rotating, opposite sign bunch trains are interleaved:**
    - **80 201-MHz bunches per bunch train (total length 397.5 ns)**
    - **At injection 'gap' between μ^+ and μ^- bunch trains is 497 ns**
    - **Issues:**
      - **Require RF to maintain inter-bunch-train separation during store**
      - **Shielding against decay electrons**
      - **Chromaticity corrections and dynamic aperture**



Collider Ring

- Muons circulate for ~1000 turns in the ring
- Need high field dipoles operating in decay backgrounds → R&D
- First lattice designs exist



DESIGN PROCESS

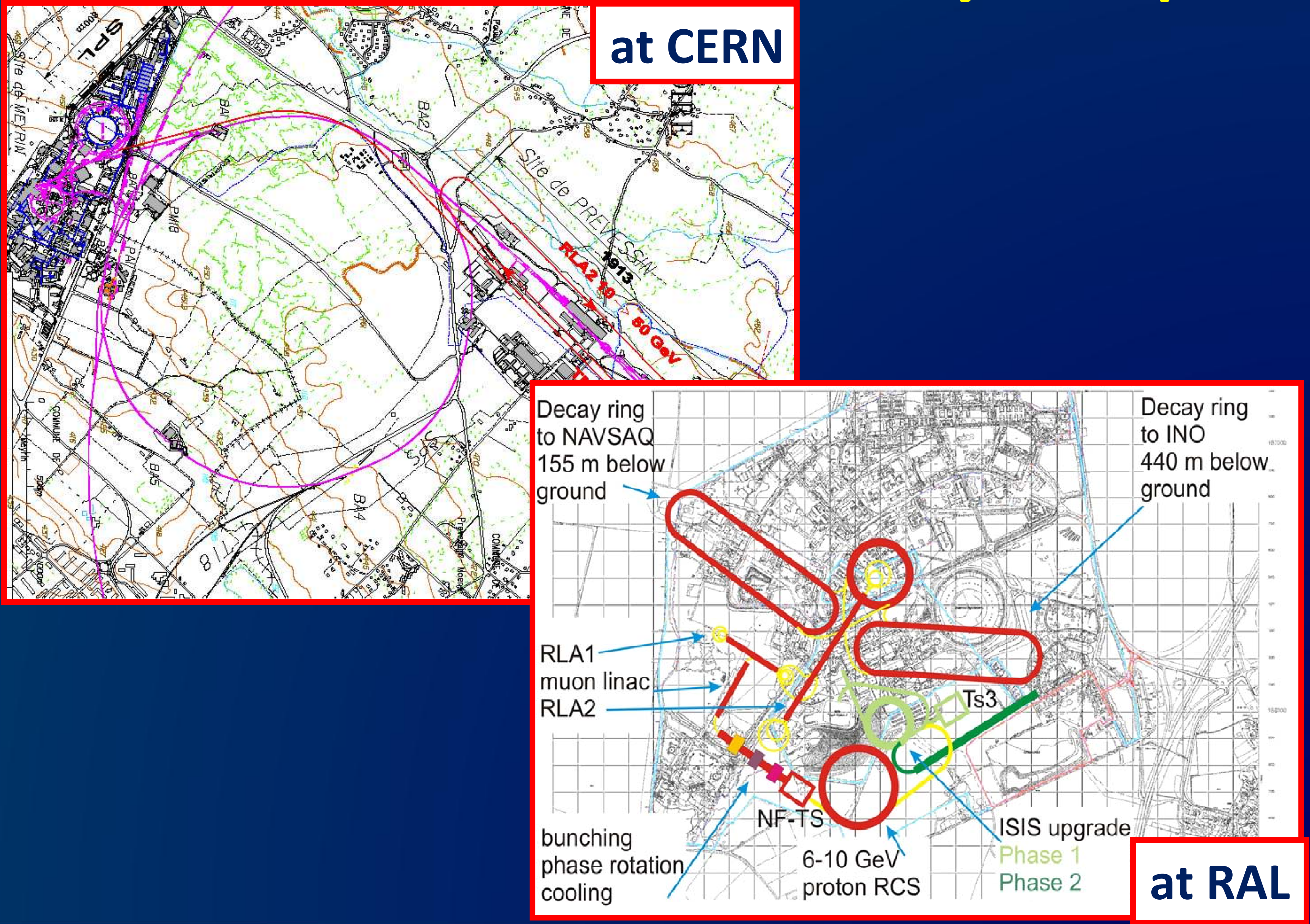
- New ideas → conceptual designs for various options
- Comparison of different schemes, choice of the baseline
- Detailed lattice design with tuning and correction “knobs”
- Dynamic aperture studies with magnet nonlinearities, misalignments and their correction
- Transient beam-beam effect compensation
- Coherent instabilities analysis

WE ARE HERE

Muon accelerators for particle physics

Opportunities and timescales

Neutrino Factory: footprint:



at CERN

at RAL

Decay ring to NAVSAQ 155 m below ground

Decay ring to INO 440 m below ground

RLA1
muon linac
RLA2

Ts3

NF-TS

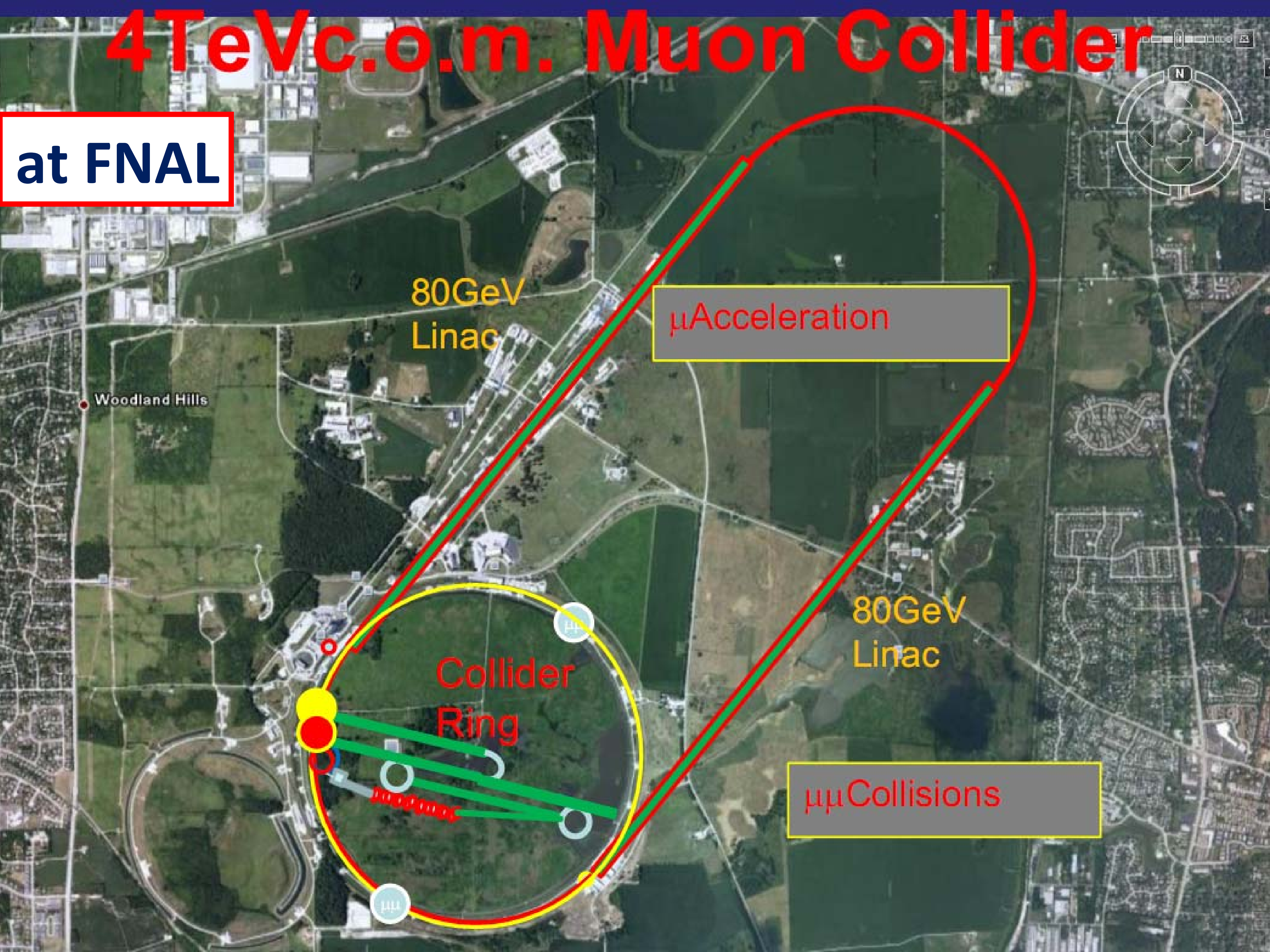
bunching
phase rotation
cooling

6-10 GeV
proton RCS

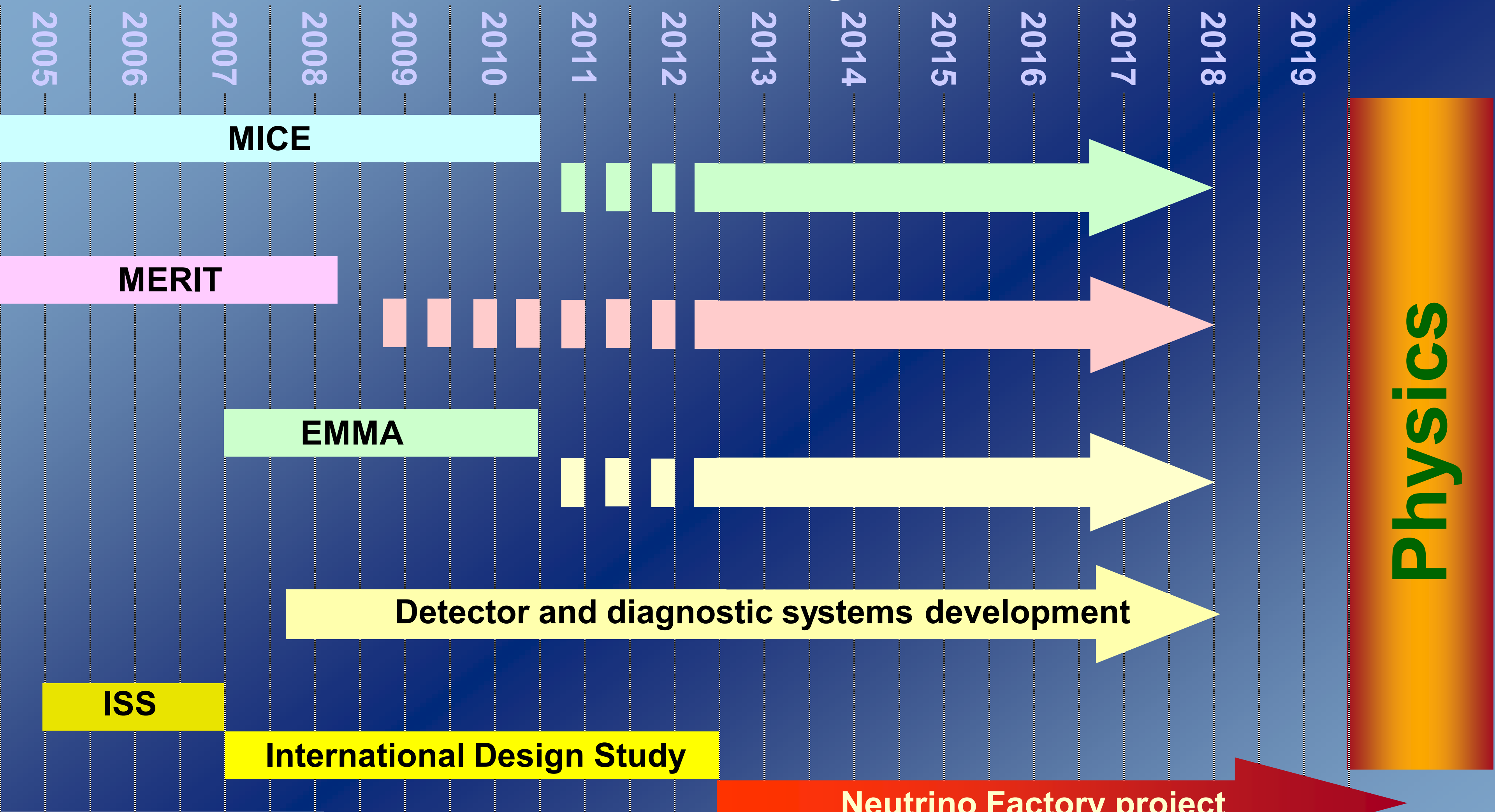
ISIS upgrade
Phase 1
Phase 2

4TeVc.o.m. Muon Collider

at FNAL



Neutrino Factory roadmap



2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019

MICE

MERIT

EMMA

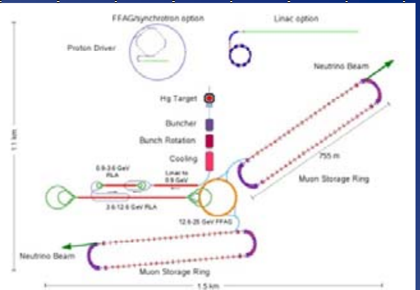
Detector and diagnostic systems development

ISS

International Design Study

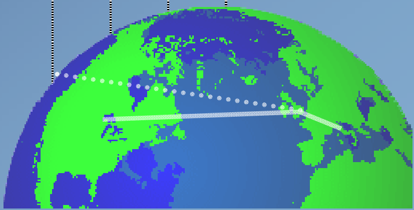
Neutrino Factory project

Physics

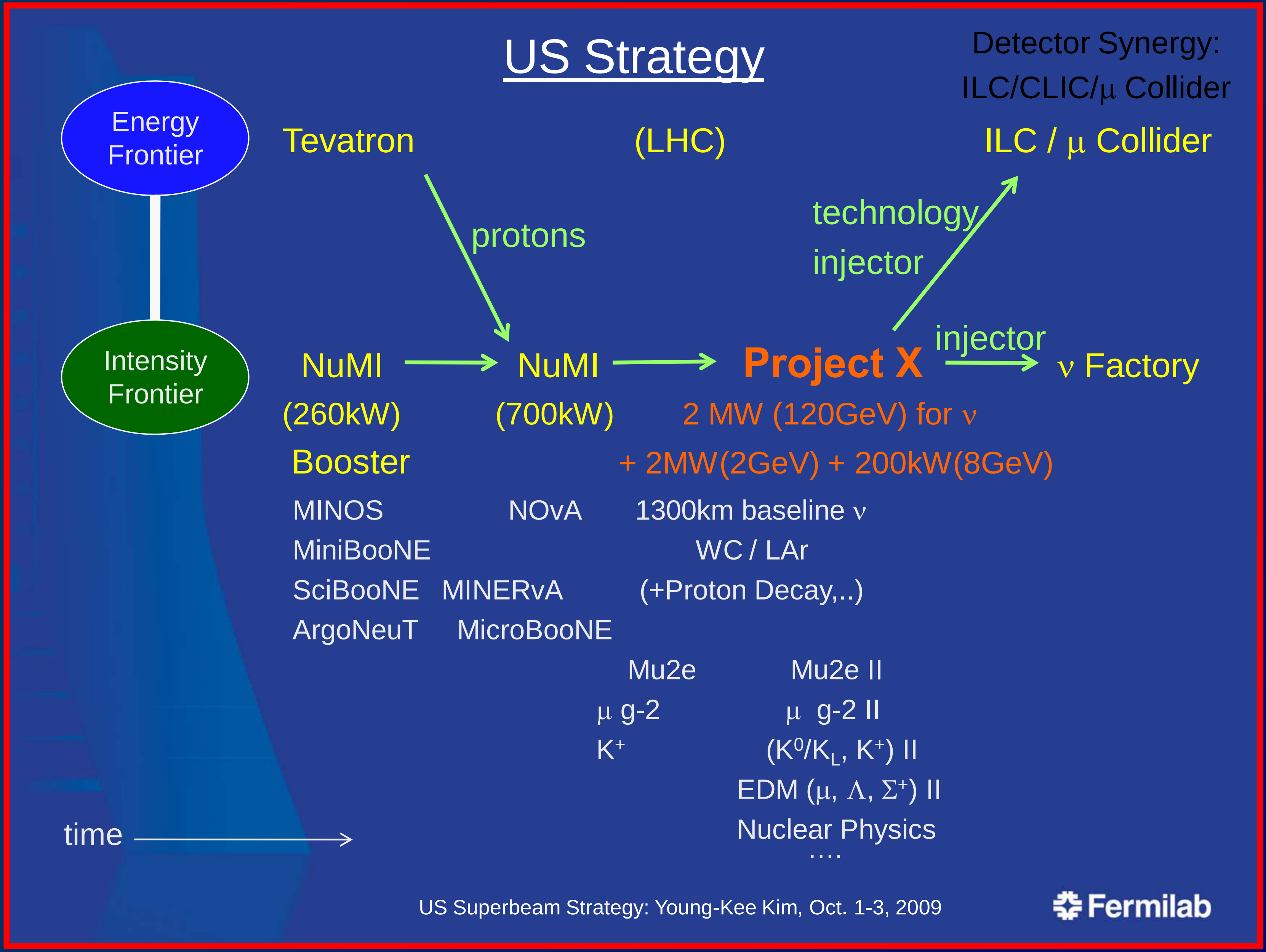


◆ **Interim Design Report**

◆ **Reference Design Report**



Muon Collider roadmap:



US Strategy

Detector Synergy:
ILC/CLIC/μ Collider

Energy Frontier

Intensity Frontier

Tevatron
(LHC)
ILC / μ Collider

protons

technology
injector

injector

NuMI
(260kW)
Booster

NuMI
(700kW)

Project X
2 MW (120GeV) for ν
+ 2MW(2GeV) + 200kW(8GeV)

ν Factory

MINOS
MiniBooNE
SciBooNE
ArgoNeuT

NOvA
MINERvA
MicroBooNE

1300km baseline ν
WC / LAr
(+Proton Decay,..)

Mu2e
μ g-2
K^+

Mu2e II
μ g-2 II
$(K^0/K_L, K^+)$ II
EDM (μ, Λ, Σ^+) II
Nuclear Physics
….

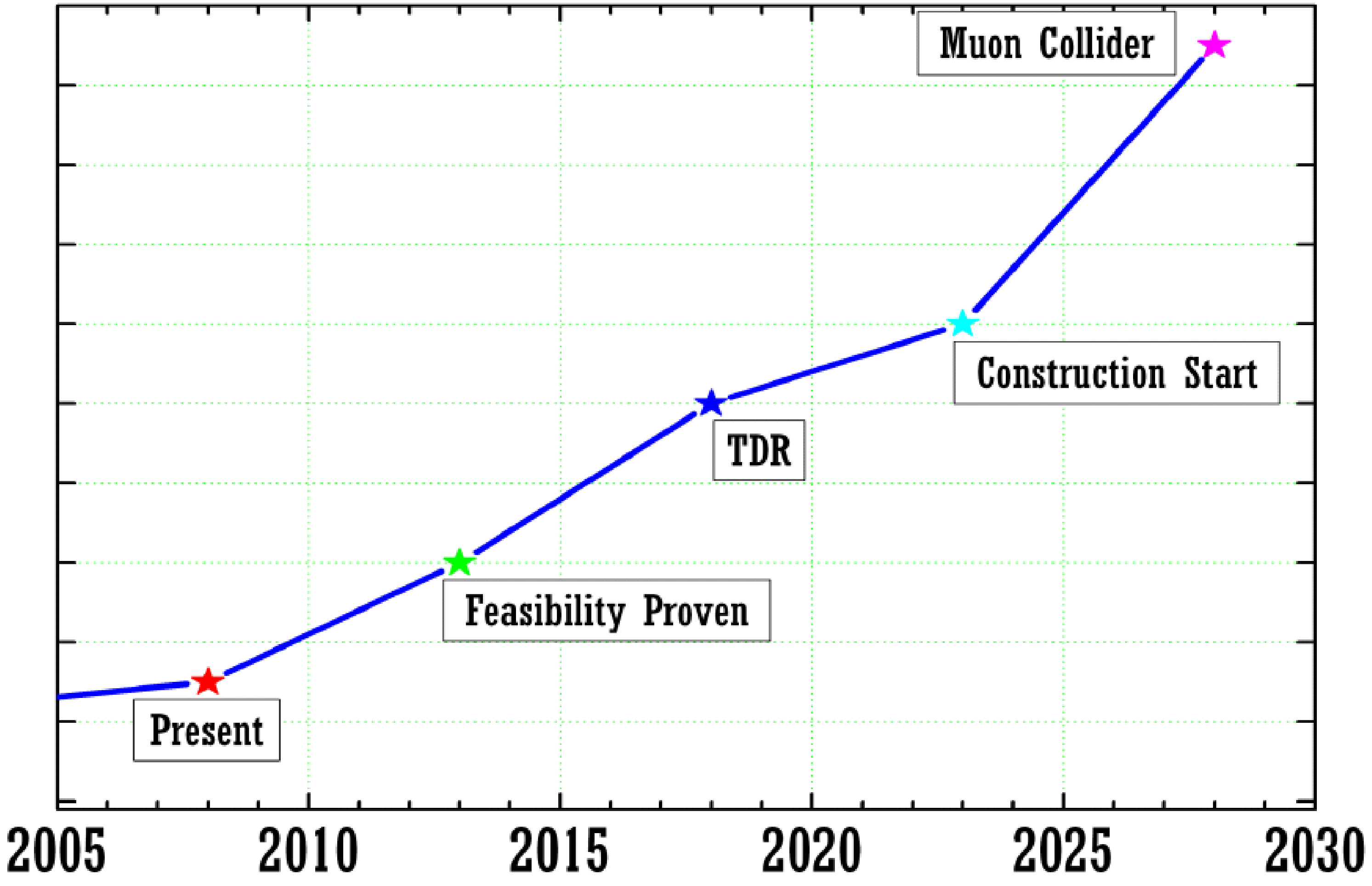
time →

US Superbeam Strategy: Young-Kee Kim, Oct. 1-3, 2009

Fermilab

MCTF

Aspirational Bigger Picture



Conclusions

Conclusions:

- Muon accelerators have the potential to serve:
  - Charged lepton flavour violation search
  - Precision measurements of neutrino oscillations
  - l^+l^- collisions at the energy frontier

  A fantastic physics potential!
- Accelerator systems and technologies highly challenging:
  - 4 MW, pulsed, proton driver with ns-scale bunches
  - High-power target
  - Ionisation cooling
  - High-gradient normal- and super-conducting RF
  - High-field, high-T_c superconducting magnets
- Scientific imperative:
  make muon accelerators an option for the field:
  - Impact potentially as significant as that of the synchrotron
  - Huge potential for knowledge exchange – medicine, energy …