International
Muon Ionization Cooling Experiment

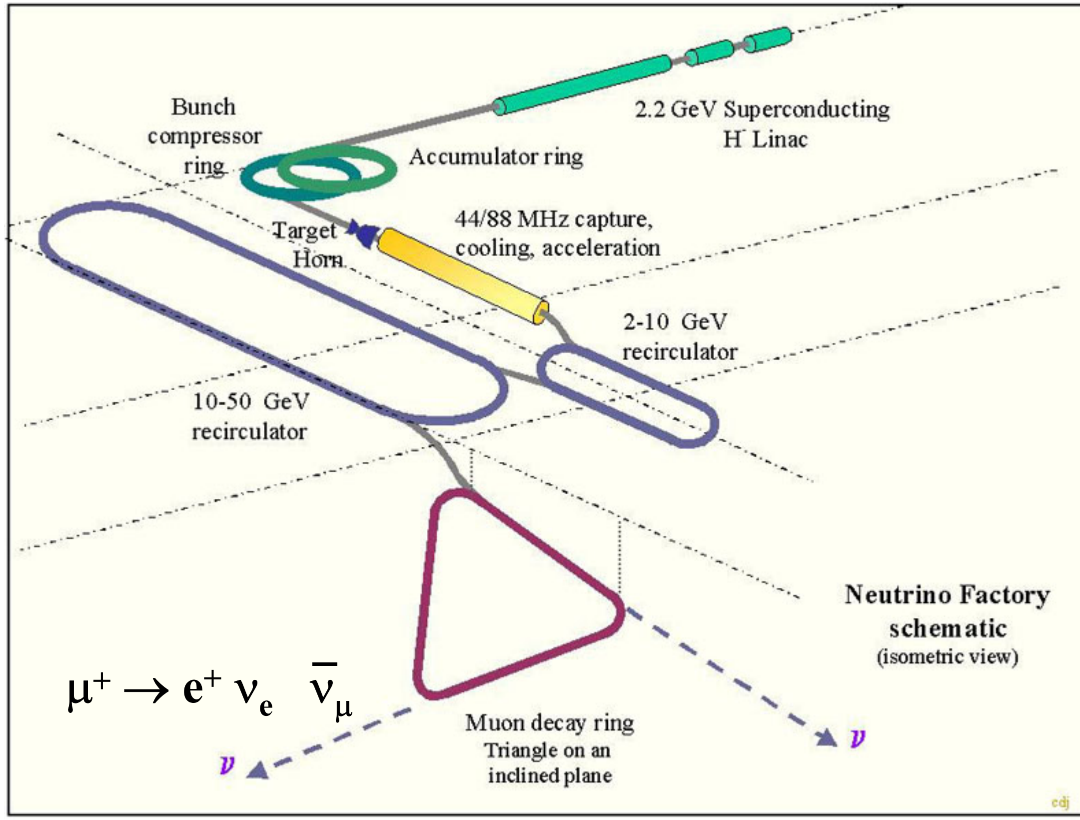
1. Why MICE?
2. Measurement
3. Status and schedule

http://www.mice.iit.edu
MICE proposal, WBS, MICE TRD (technical ref. document)

Why MICE?

Based on Muon collider ideas and development (Palmer et al, 92->),
the Neutrino Factory concept (Geer, 1998) resonated in 1998 with the
final demonstration of Atmospheric Neutrino Oscillations by the SuperK Collaboration.

International workshops:
NUFACT 99 (Lyon, France)
NUFACT 00 (Montery, California)
NUFACT 01 (Tsukuba, Japan)
NUFACT 02 (London, UK)
NUFACT 03 (Columbia,NY,USA)
NUFACT 04 (Osaka, Japan)
NUFACT 05 (Frascati,Italy)

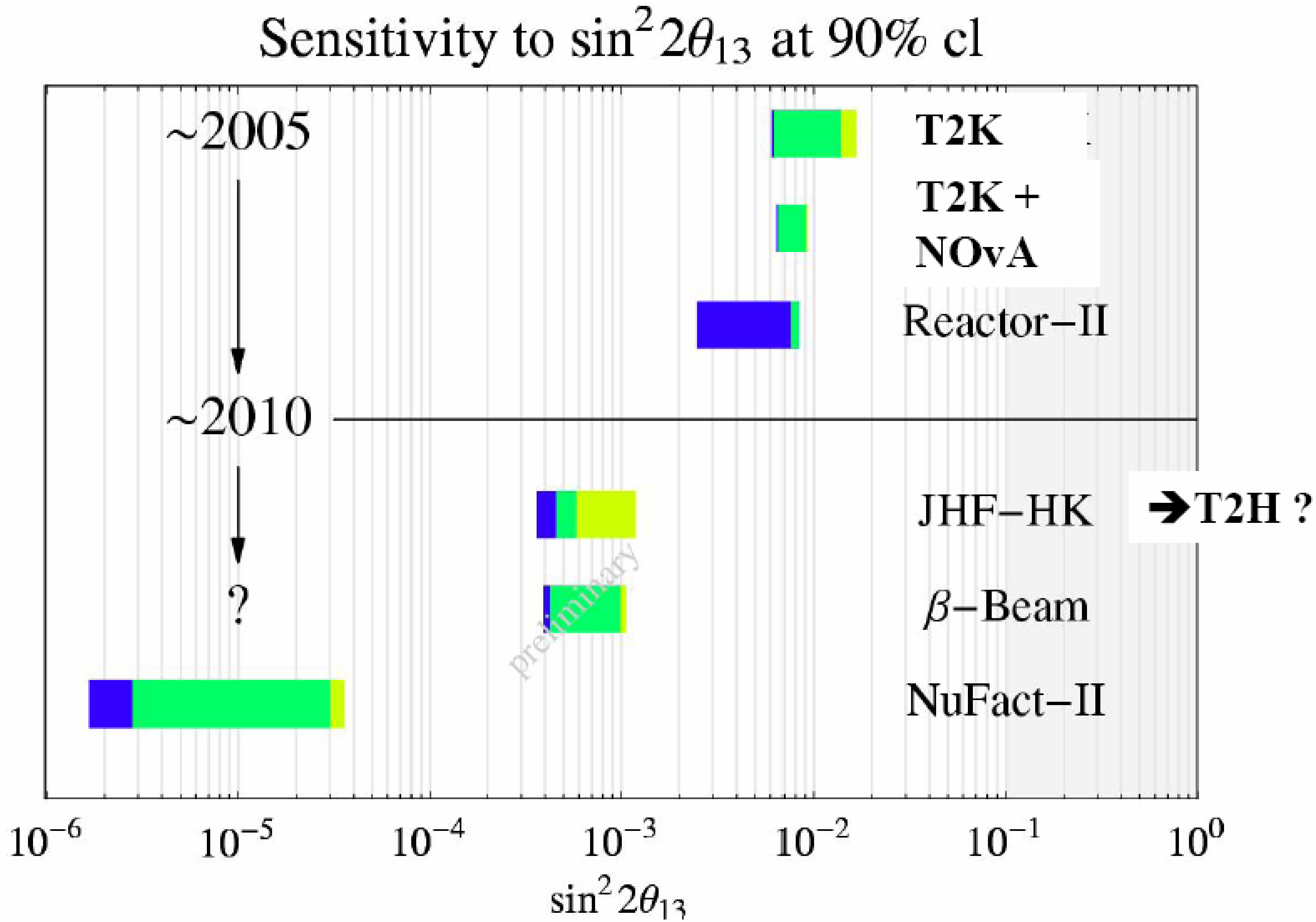


⇒ Neutrino Factory
is the ultimate tool for study
of Neutrino Oscillations

-- unique source of high energy ν_e
-- reach/sensitivity better by
order(s) of magnitude wrt other
techniques (e.g. super-beams) for

* θ_{13} *
** matter effects **
*** leptonic CP violation ***
**** $\nu_e \rightarrow \nu_\mu$ and ν_τ ****

NB : leptonic CP violation is a key ingredient
in the leading explanations for the mystery of
the baryon-antibaryon asymmetry in our universe



M. Lindner et al.

Neutrino factory physics conclusions

1. The Neutrino Factory remains the most powerful tool imagined so far to study neutrino oscillations

Unique: High energy $\nu_e \rightarrow \nu_\mu$ *and* $\nu_e \rightarrow \nu_\tau$ transitions
at large θ_{13} has the precision
at small θ_{13} has the sensitivity

2. The complex offers many other possibilities

3. It is a step towards muon colliders

US Study IIa!

4. There are good hopes to reduce the cost significantly thus making it an excellent option for CERN in the years 2011-2020

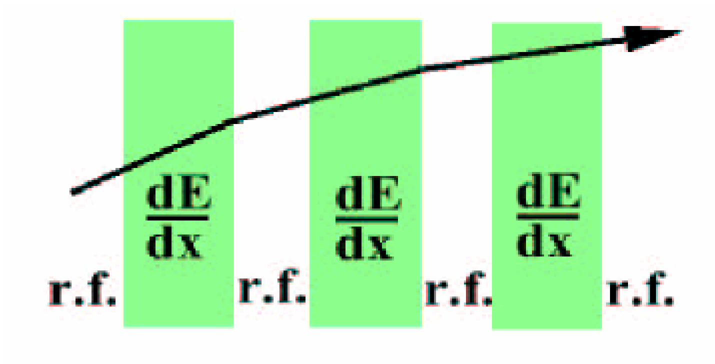
5. Regional and International R&D on components and R&D experiments are being performed by an enthusiastic and motivated community
(rate of progress is seriously funding limited, however)

Pioneered by US MC
ex. MUCOOL

Opportunities in Europe:
HI proton driver, (SPL@CERN, RCS@RAL)
Target experiment @ CERN
Collector development @CERN
MICE @ RAL
FFAG project

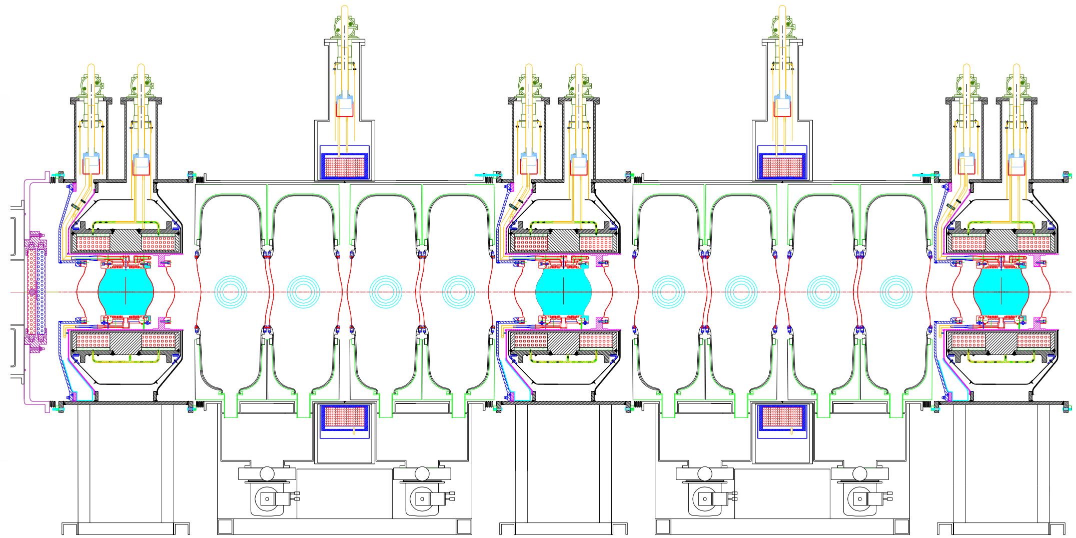
IONIZATION COOLING

principle:



this will surely work..!

Reality (simplified)



A delicate technology and integration problem

⇒ Need to build a realistic prototype and verify that it works as expected (i.e. cools a beam by the predicted amount)

Difficulty: affordable prototype of cooling section only cools beam by 10%, while standard emittance measurements barely achieve this precision.

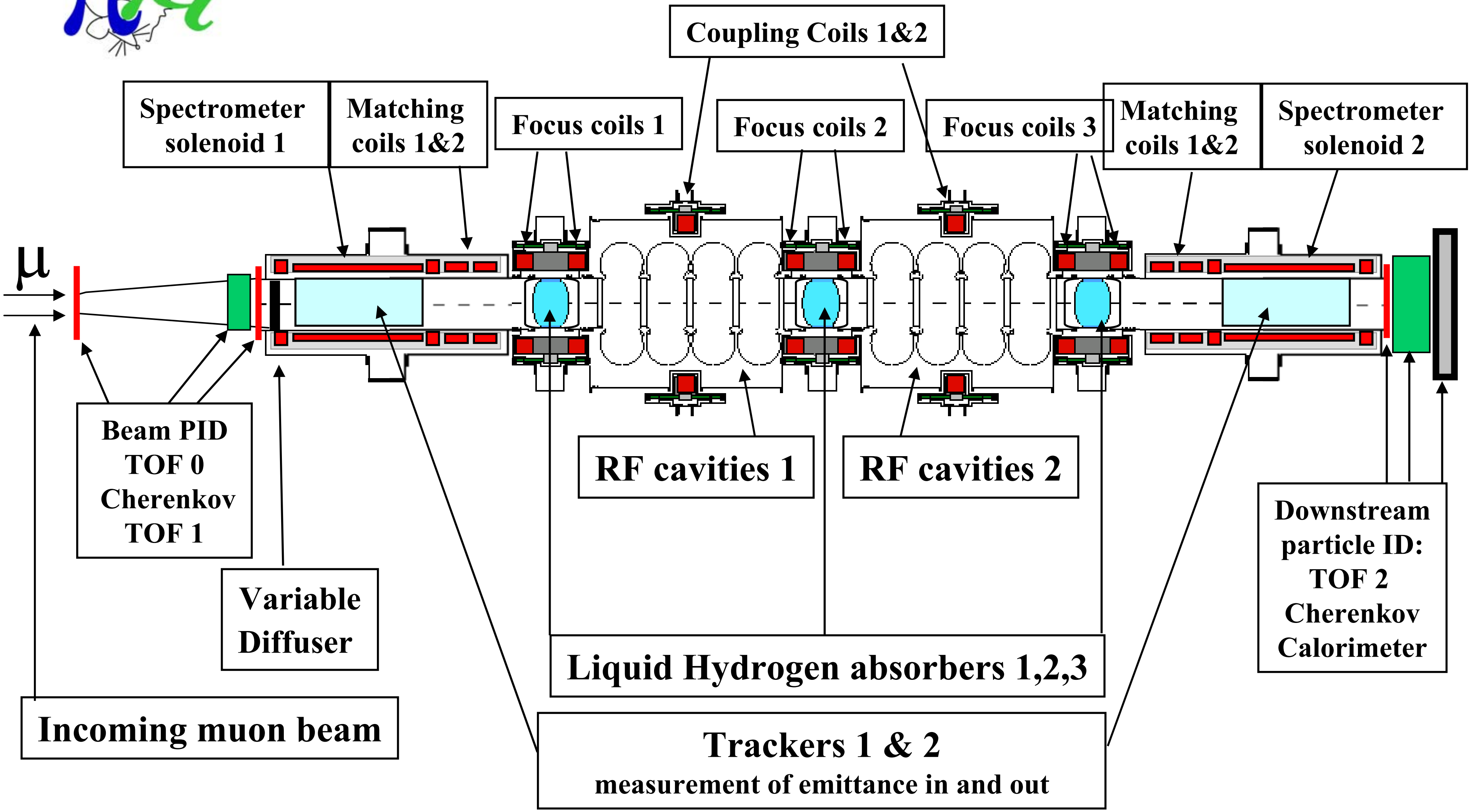
Solution: measure the beam particle-by-particle

10% cooling of 200 MeV/c muons requires ~ 20 MV of RF

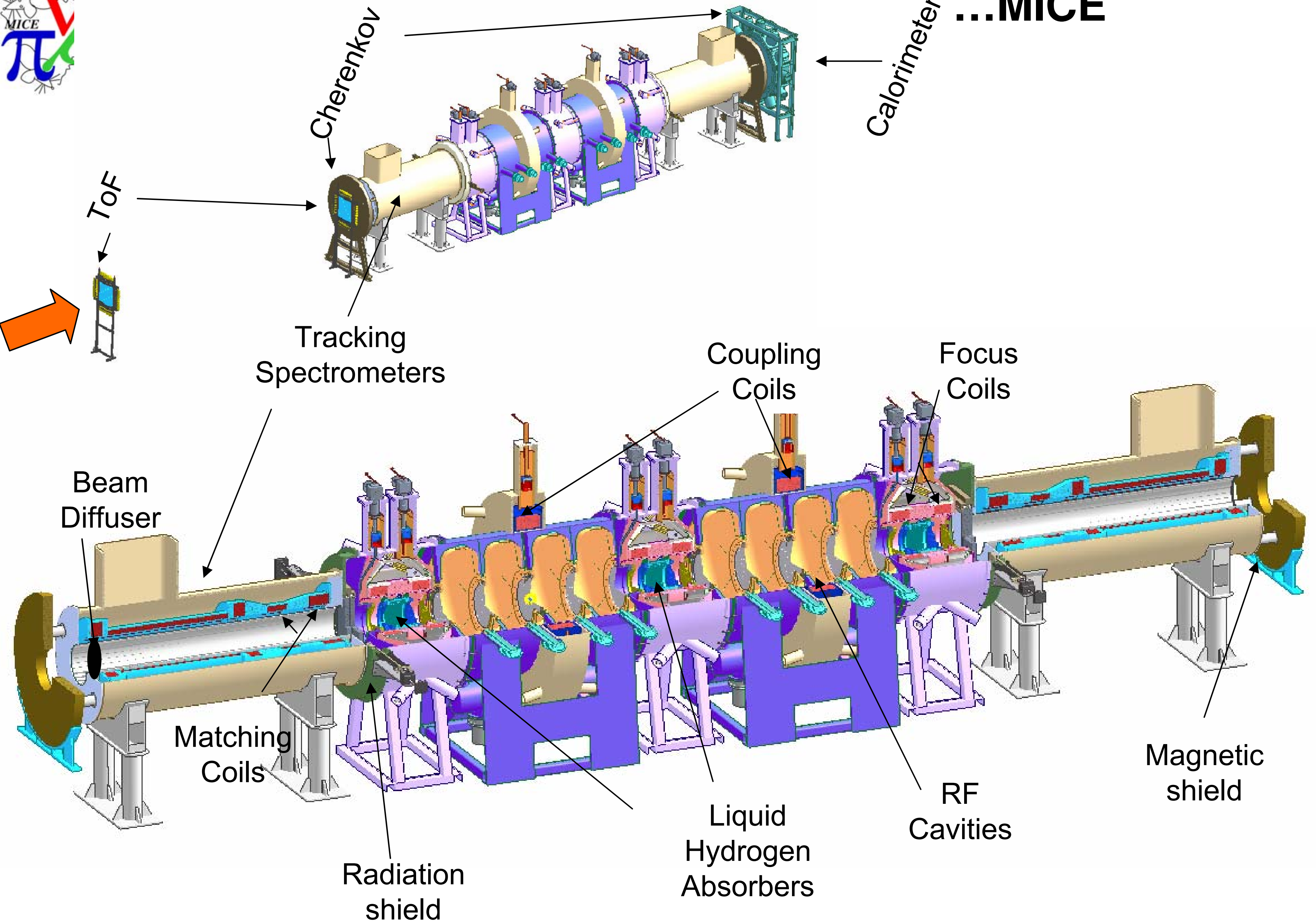
single particle measurements =>

measurement precision can be as good as $\Delta(\varepsilon_{out}/\varepsilon_{in}) = 10^{-3}$

never done before either…



…MICE


Cherenkov
Calorimeter
ToF
Tracking Spectrometers
Coupling Coils
Focus Coils
Beam Diffuser
Matching Coils
Radiation shield
Liquid Hydrogen Absorbers
RF Cavities
Magnetic shield

Some challenges of MICE:

1. Operate RF cavities of relatively low frequency (200 MHz) at high gradient (16 MV/m) in highly inhomogeneous magnetic fields (1-3 T)
   dark currents (can heat up LH_2), breakdowns

2. Hydrogen safety (substantial amounts of LH_2 in vicinity of RF cavities)

3. Emittance measurement to relative precision of 10^{-3} in environment of RF bkg
   requires low mass and precise tracker
   low multiple scattering
   redundancy to fight dark current induced background
   excellent immunity to RF noise

And…

4. Obtaining funding for R&D towards a facility that is not (yet) in the plans of a major lab
   Positive signs from CERN
   (recommendation from committees to support NUFACT design studies)
   Very positive signs from RAL (MICE approval, call for scoping design study)

John Dainton
Villars 2004
October 7th 2004
CERN seminar

SPSC

- Future neutrino facilities offer great promise for fundamental
2010 discoveries (such as CP violation) in neutrino physics, and a post-LHC construction window may exist for a facility to be sited at CERN.
- CERN should arrange a budget and personnel to enhance its participation in further developing the physics case and the technologies necessary for the realization of such facilities. This would allow CERN to play a significant role in such projects wherever they are sited.
- A high-power proton driver is a main building block of future projects, and is therefore required.
- A direct superbeam from a 2.2 GeV SPL does not appear to be the most attractive option for a future CERN neutrino experiment as it does not produce a significant advance on T2K.
- We welcome the effort, partly funded by the EU, concerned with the conceptual design of a β-beam. At the same time CERN should support the European neutrino factory initiative in its conceptual design.

Scoping study: request for proposal by John Wood, RAL CEO

For CCLRC to consider acting as 'host' for the scoping study, I would like to ask the UK Neutrino Factory (UKNF) collaboration to consider how best to establish an international effort that will:

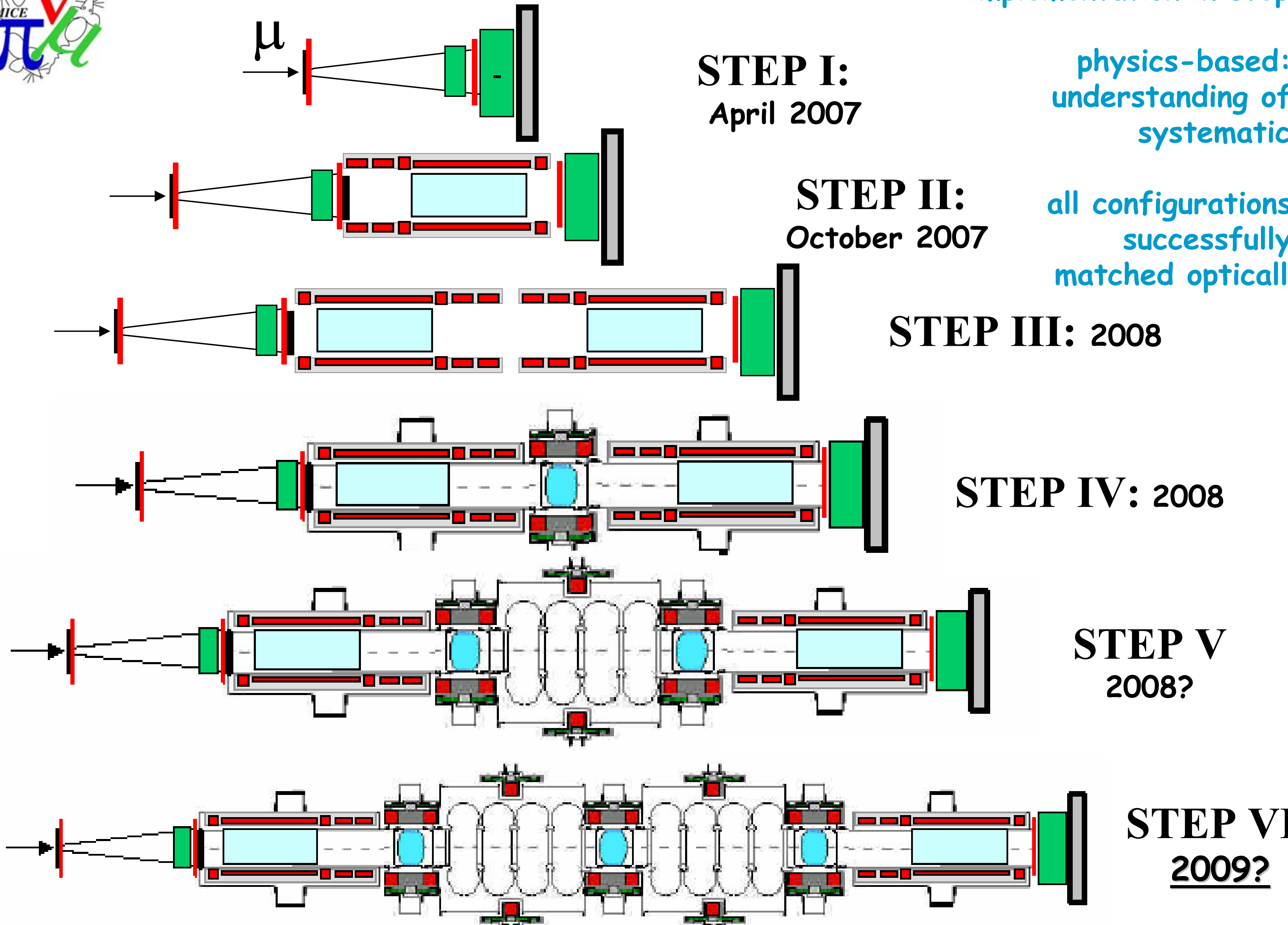
- Review the physics case for the Neutrino Factory with a view to defining the baseline specification for the facility;
- Review the options for the accelerator complex with a view to defining a baseline, agreed among the various interested parties, that can form the basis of the full design study;
- Review the options for the neutrino-detection systems that such a facility would require with a view to defining a baseline set of options that can form the basis for further study;
- Define the simulation, design and hardware development programmes that will be required to produce a robust conceptual design by the end of the decade.

A short document defining how such a 'scoping study' could be carried out should be submitted to me by the 27th May 2005. The document should describe the proposed organisation of the study, indicate how the international community will be integrated into the work and identify the resources required for the scoping study to be successfully concluded in one year.

implementation in steps

physics-based:
understanding of
systematics

all configurations
successfully
matched optically



Further Explorations

We have defined a baseline MICE, which will measure the basic cooling properties of the StudyII cooling channel with high precision, for a moderate gradient of ~8 MV/m, with Liquid Hydrogen absorbers.

Many variants of the experiment can be tested.

1. Other absorbers: the design of absorbers allows other materials to be tested solids (LiH, Be, C) and LHe

2. Other optics and momentum: nominal is 200 MeV/c and $\beta = 42$ cm.
   Exploration of low β (down to a few cm at 140 MeV/c)
   Exploration of momentum up to 240 MeV/c
   will be possible by varying the currents.

3. The focus pairs provide a field reversal in the baseline configuration, but they have been designed to operate also in no-flip mode which could have larger acceptance both transversally and in momentum (Fanchetti et al)

4. Higher gradients can be expored on the cavities, either by running them at liquid nitrogen temperature (the vessel is adequate for this) (gain 1.5-1.7) or by connecting to the 8 MW RF only one of the two 4-cavity units (gain 1.4)

5. Possible extensions

Manx helicoidal dipole cooling (Johnson), Lithium lens (Skrinsky)

Universite Catholique de Louvain **Belgium**

INFN: Bari, Frascati, Genova, Legnaro, Milano, Napoli, Padova, Trieste
ROMA TRE university, **Italy**

KEK, Osaka University **Japan**

NIKHEF **The Netherlands**

CERN

Geneva, PSI **Switzerland**

Brunel, Edinburgh, Glasgow, Liverpool, Imperial, Oxford, RAL,
Sheffield **UK**

ANL, BNL, FNAL, JLab, LBNL,
Universities of Fairfield, Chicago, UCLA Physics, Northern Illinois,
Iowa, Mississippi, UC Riverside, Illinois-UC
Enrico Fermi Institute, Illinois Institute of Technology **USA**

☺ *anybody?*

THE MICE COLLABORATION

3 continents
7 countries
40 institute members
140 individual members
- Engineers & physicists (part. & accel.)

MICE is an international effort from the start.

NUFACT00	Re-activated the recognized need for muon cooling expt
2000-2001	Workshops on Muon Cooling Experiment (CERN, Chicago, London)
NUFACT01 7:30 am	Steering group formed
Sept. 2001	Workshop at CERN where final experiment took shape.
November 2001	Letter of Intent (LOI) submitted to PSI and RAL
January 2002	PSI cannot host experiment, will collaborate (beam solenoid)
June 2002	RAL IPRP Review Panel encouraged submission of a proposal
January 2003	Proposal submitted
July 2003	Recommendation by International Peer Review Panel
October 2003	'Scientific approval' by RAL CEO John Wood
	Project Manager appointed (P. Drumm, RAL)
	RAL CM: collaboration charter approved
December 2003	Gateway 1 review
June 2004	Gateway 1 passed on 'amber'
20 December 2004	Gateway 2/3 passed: 10 green + 4 amber (MICE PHASE I)
March 2005	UK funding released by PPARC and CCLRC 9.7 M£ (beam line, part of tracker, R&D for phase II)

At this point MICE (PhaseI) is an approved and funded project in 5 countries

-- UK: 9.7M£ (beam+infr. + tracker + R&D for phase II)

-- USA: MUCOOL programme (R&D on components)
1.2 M$ approved for next three years (NSF+DOE) +MRI proposal + MC support
(RF source + Spectrometer solenoids+ RFCC module)

-- Japan: US-Japan ~$100k/yr, UK-Japan (travel funds)
(+ 500k$ requested)

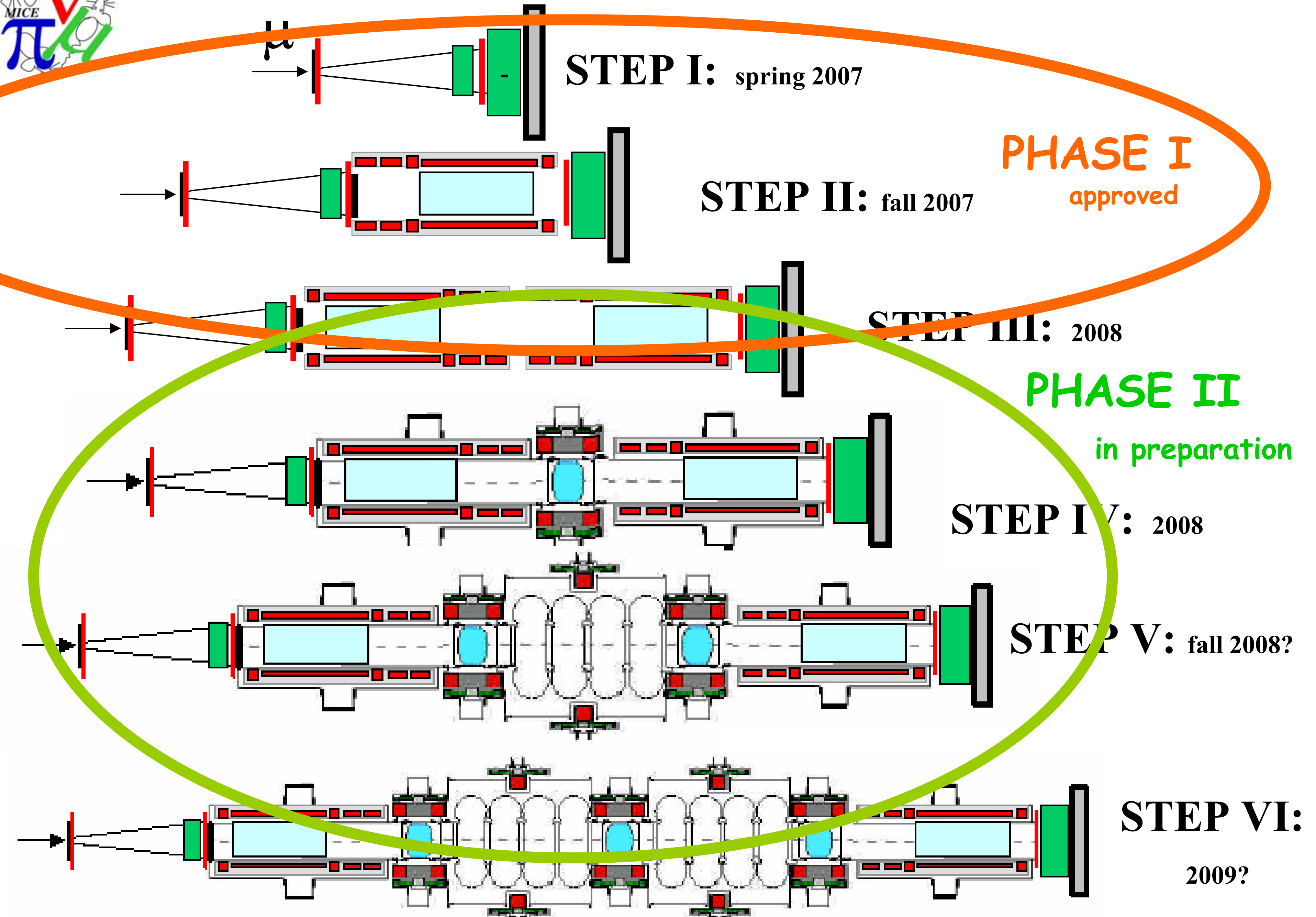
-- Switzerland: PSI solenoid + Uni-Geneva-NSwissF (80KCHF/yr+ 1 PDA+1PhDS)

-- Netherlands: Mag probes + 1 PhDS

-- CERN: Spare hardware for two RF power sources has been earmarked for MICE

+ Proposal prepared in Italy (PID) and submitted in Belgium (Cherenkov)
further requests investigated in CH…(coupling coil?)
EU funding not before 2008

MICE is a recognized experiment at CERN


μ
STEP I: spring 2007
STEP II: fall 2007
PHASE I
approved
STEP III: 2008
PHASE II
in preparation
STEP IV: 2008
STEP V: fall 2008?
STEP VI:
2009?

Meanwhile….

MICE is being
designed
simulated
reviewed
MOU'ed
dug
and prototyped!

OPTICS *Bravar, Palmer*

ICOOL *(Fernow)*

Solutions for flip/non-flip/semi-flip operating modes:

a) p = 140, 170, 200, 240 *MeV/c;*

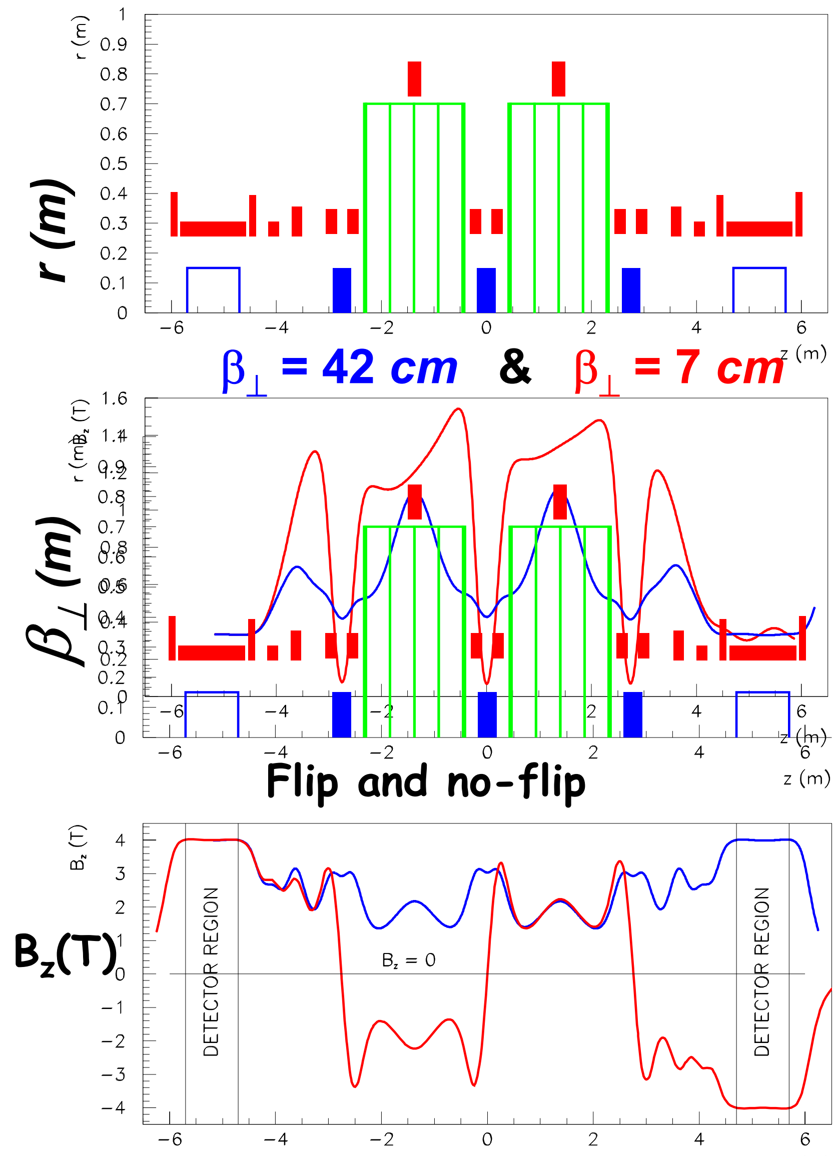
b) $\beta_\perp$ = 7, 15, 25, 42 *cm* in LH_2.

+(many) solutions for all steps of MICE

- not all viable but most are.

- issues: chromaticity, scraping

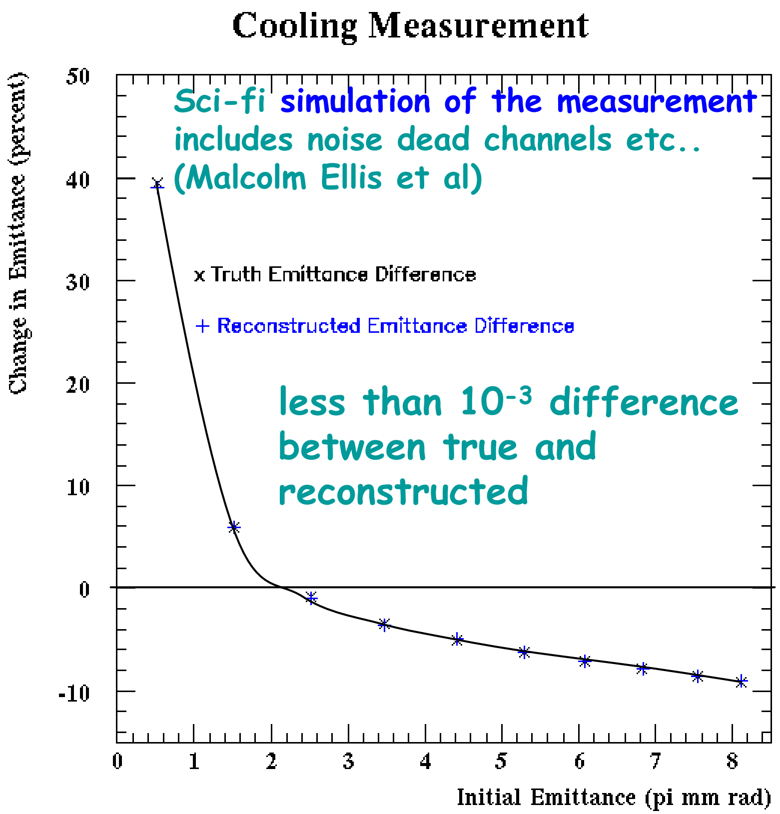
full analysis to be done.



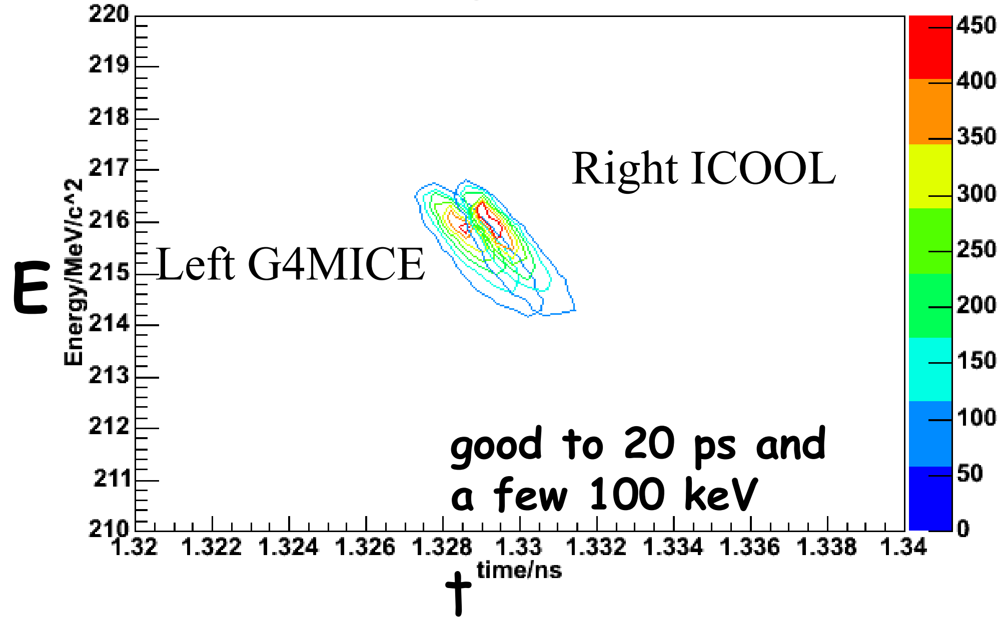
SIMULATION and software.

'Simple things should be easy and complicated things should be possible'

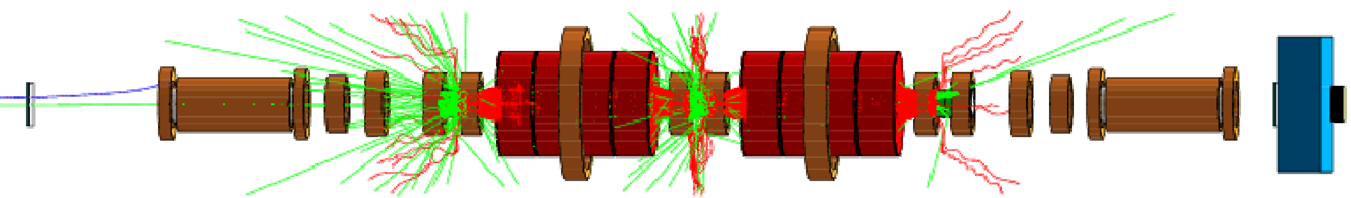
'Students are taking over the project'
Torun



G4MICE-ICOOL comparisons
Chris Rogers



RF emission of X-rays (Rikard Sandstrom)→ energy and time distributions are predicted



will be validated against MTA meas.

requirements on spectrometer system:

1a reject incoming e, p, π (TOF 0, TOF1)
1.b reject outgoing e => TOF2, Cerenkov + Calorimeter

2. measure x,y,Px, Py E (tracker) and t (TOF counters)
to build 6D emittance particle by particle

3. resolution better than 10% of width at equilibrium emittance
$\sigma^2_{meas} = \sigma^2_{true} + \sigma^2_{res} = \sigma^2_{true}\ [\,1 + (\sigma_{res}/\sigma_{true})^2\,]$ (→correction less than 1%)

4. robust against noise from RF cavities

➔ Sci-Fi tracker was validated with calculations based on G4MICE
-- experimental input from prototype (dead channels, efficiency, resolution)
-- calculated spectrum and time structure of RF field emission based on LabG 800MHz
-- still will need to be scrupulous about multiple scattering in tracker → stepIII

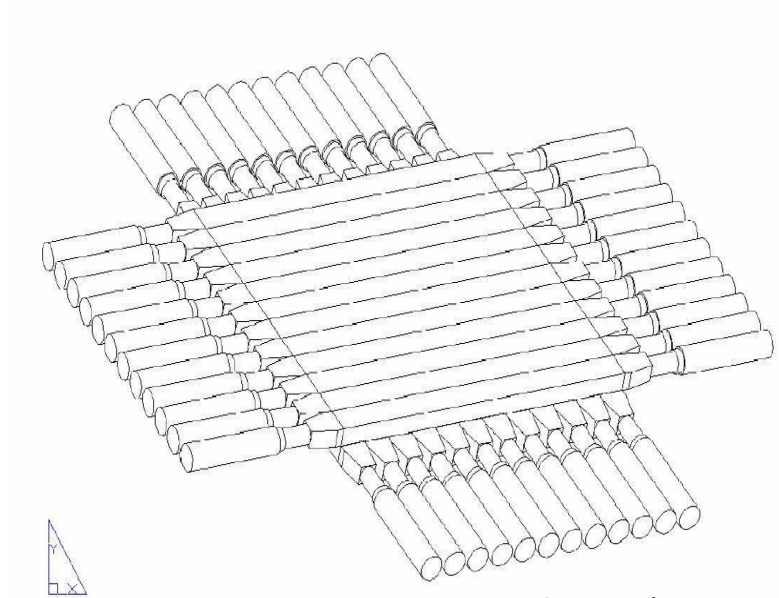
Sci-fi prototype II presently assembled
test ongoing at KEK in magnetic field!!
(see Dan Kaplan's talk)

Now same exercize needs to be done for TOF

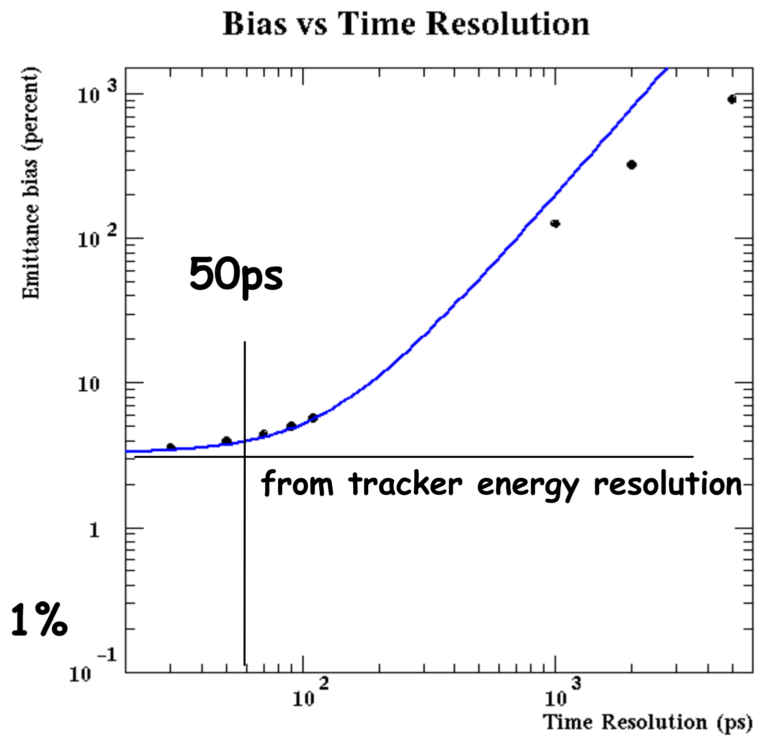
requires measured 50ps resolution

→ double layer scintillator

construction of TOF0 prototype this year
(Milano,Pavia, Padova, Geneva)
funding available (GVA) or request prepared (It

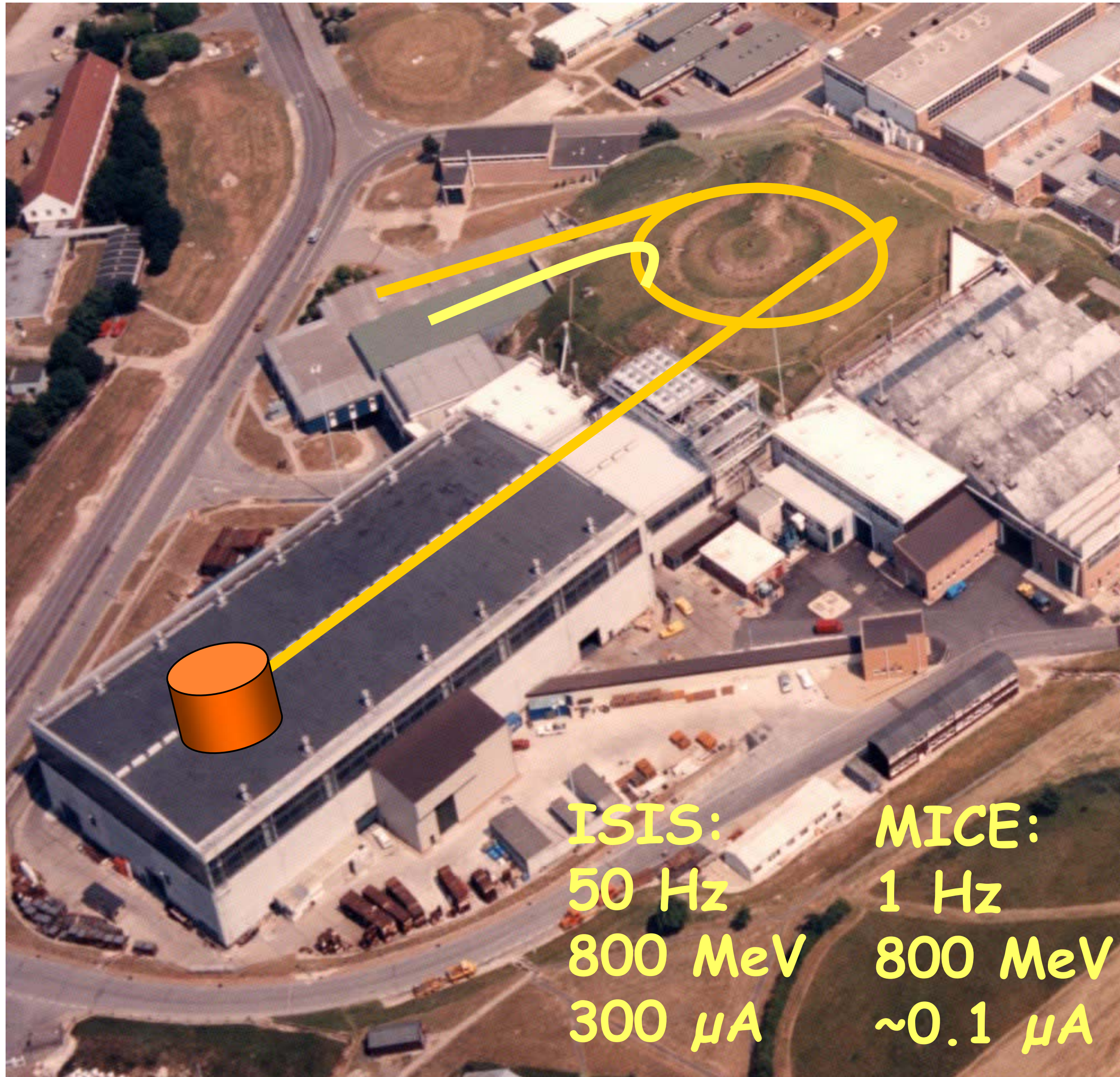


bias on longitudinal emittance ratio

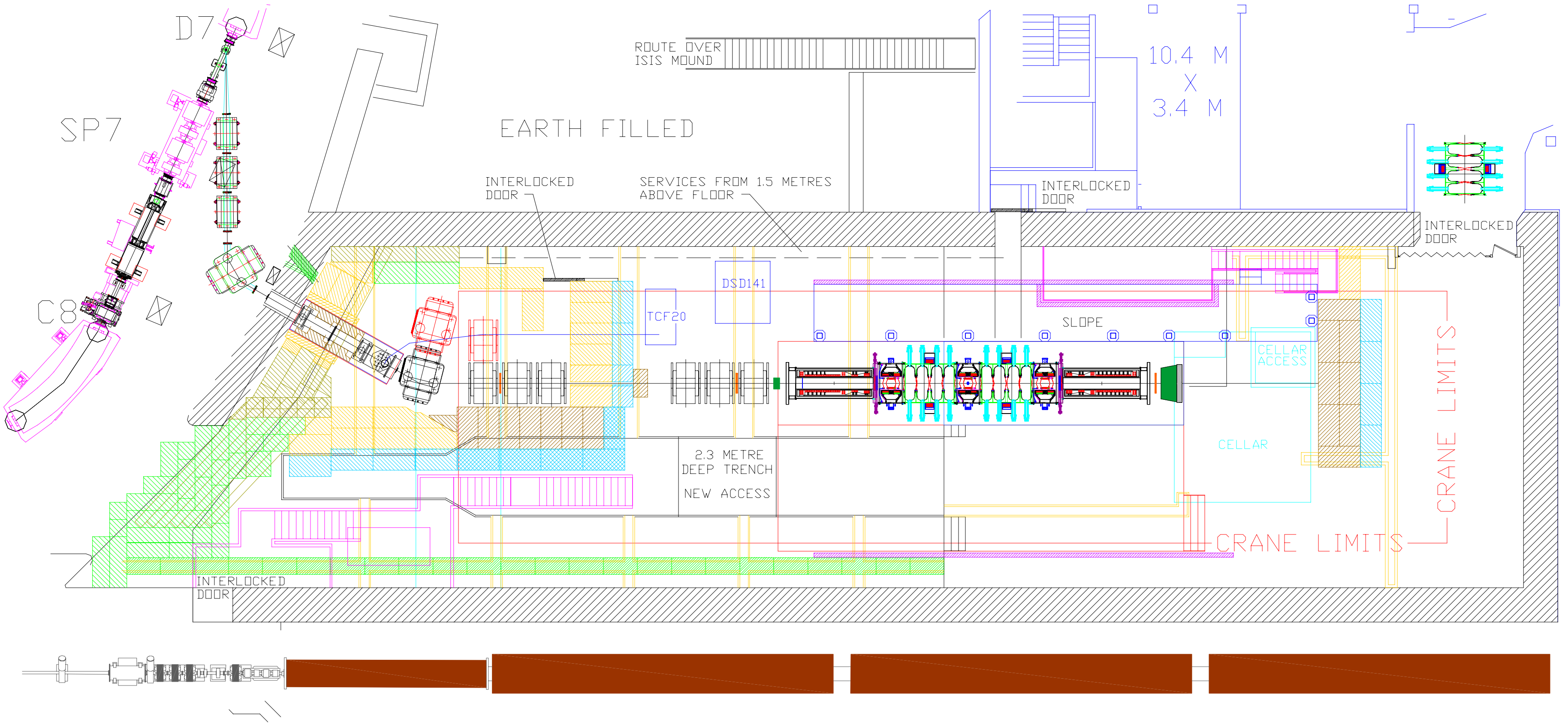


TOF0 (R4998 Hamamatsu with Bicron scintillator)

Implementing MICE on ISIS

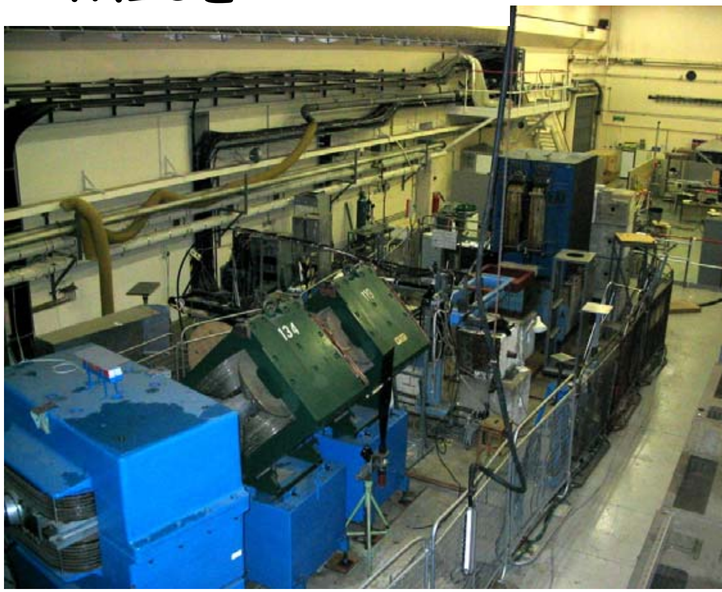


Implementing MICE in ISIS

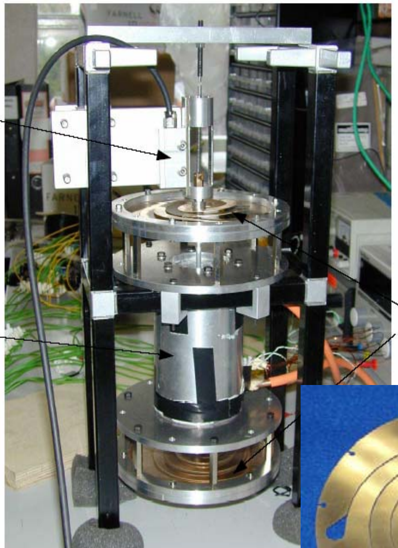


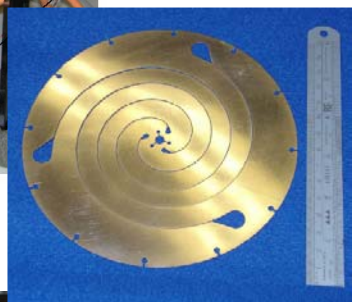
Nimrod linac hall
HEP test beam
⇨ MICE

MICE Hall



Beam Line Elements

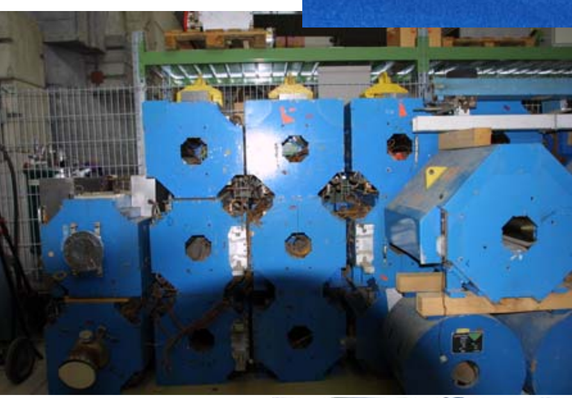




Pion decay channel :

5T, 12cm bore 5m long solenoid.
supercritical helium cooled

20yrs old, gift from PSI(CH) requires
(modest) liquid helium plant



quads and dipoles from old beam line

quads from DESY

Prof. Dr. Ralph Eichler, Director, PSI

MOU for PSI solenoid counter-signed

Paul Drumm
MICE Project Manager

Prof. John Wood RAL CEO

RF Power System

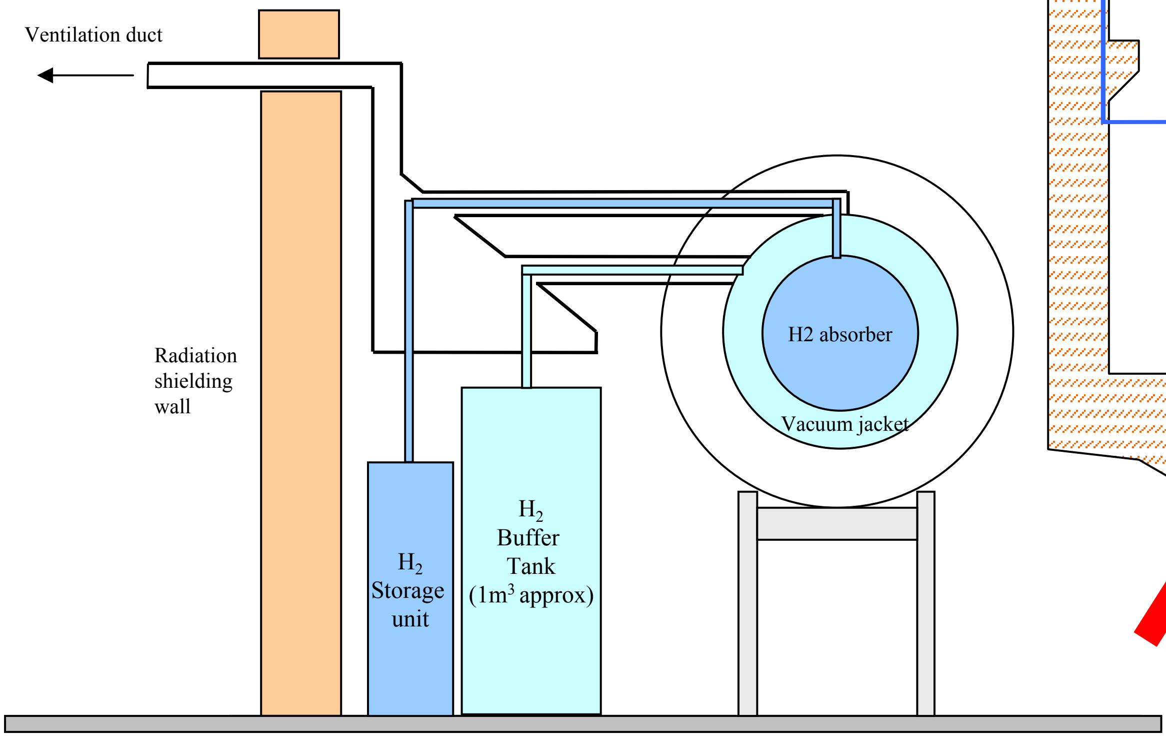
Berkeley's power arrived at Daresbury

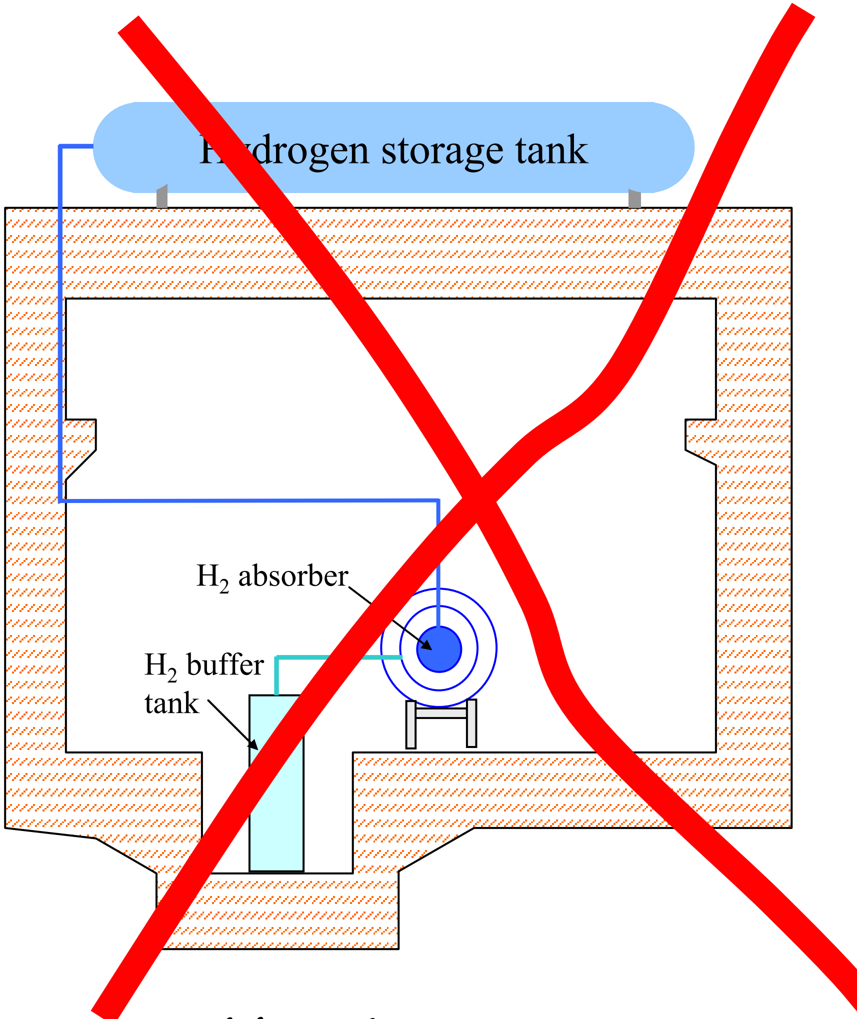
TH 116 / TH170

Large devices!
Baseline 8 MW
- identified 4 × >2.5MW
- subject to R&D (Daresbury)

RF power source from CERN earmarked…
to be refurbished.

Hydrogen system layout:
we have chosen metal hydride storage!





Venting turns out to be the most likely time for accidents

MICE Design and safety working group

nominated (Wing Lau et al)

to ensure that

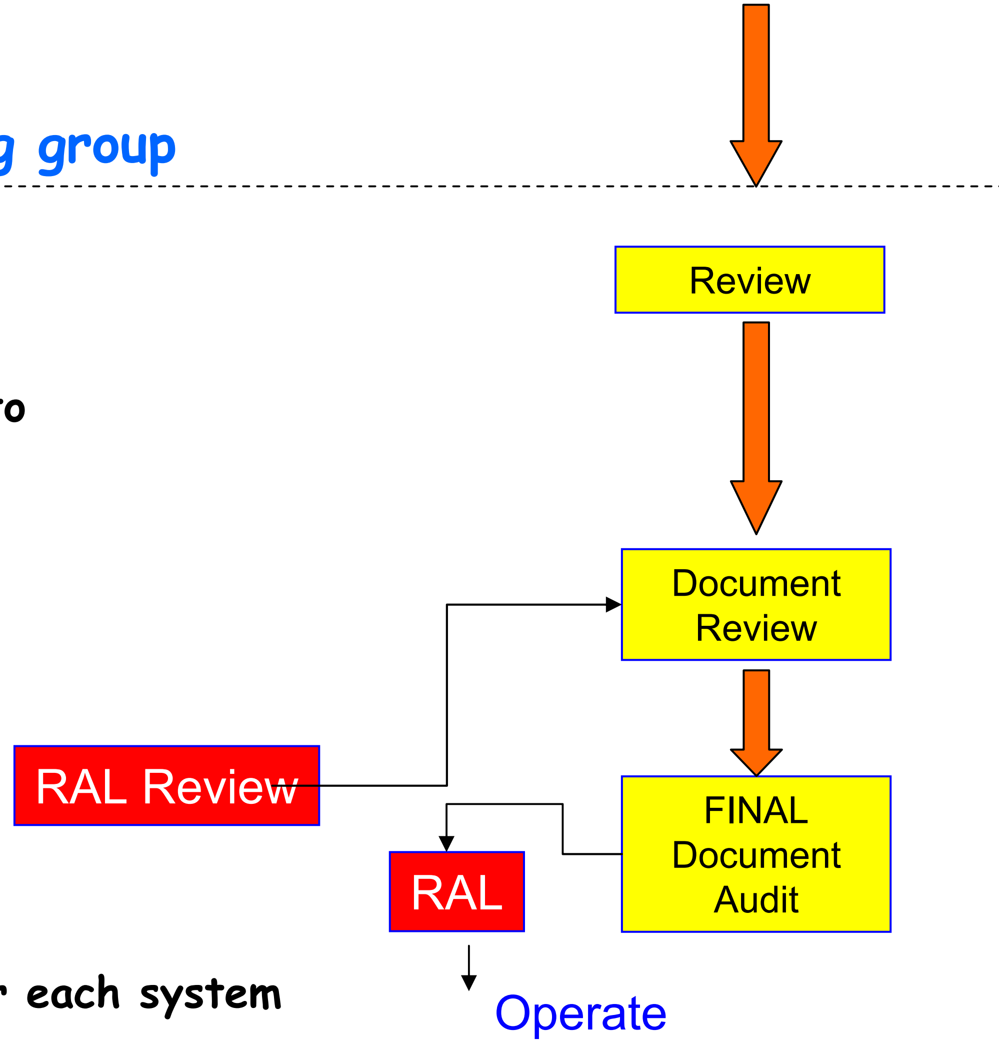
MICE is designed and built according to
appropriate and safe engineering
and according to RAL safety rules.
(and in time!)

3 successive milestones

internal audit

external review (production readiness)

external review (OK to operate)



production reviews being organized for each system
all those pertinent to PHASE I
will have to be passed before end 2005

An important credit:

The US developed the first credible concepts for both the muon collider and the neutrino factory through the pioneering work, in particular, of David Neuffer, Robert Palmer and Steve Geer, as well as through two detailed feasibility studies.

The concept of the MICE cooling cells is based upon the US Study II, and the actual magnetic layout of the experiment is the result of Robert Palmer's ideas.

US groups have provided the lion's share of the R&D work for the cooling channel modules so far, and have also been actively involved in developing the beam line optics, the overall simulation of the experiment, and the tracker prototype. In particular, the construction of the first MICE-compatible 201-MHz RF cavity prototype is now complete.

In addition, our US colleagues have already shipped to RAL parts for two 201-MHz RF power sources that should, after refurbishment, provide half of the RF needs of the experiment.

The planning prepared by M. Zisman provides MICE with a US contribution to the MICE magnet system that will allow the US collaborators to play the role they rightly deserve. This contribution is vital for the success of the experiment!

Time Line

If all goes well Muon Ionization cooling will have been demonstrated and measured precisely by 2009.

This target date is allowed by committment of US collaborators who propose to build the spectrometer solenoids.
This assumes that additional funding will come from international collaborators (CH, Japan, It) so as to pick up at least part of the coupling coils (see MZ's talk). MICE will work very hard in this direction. Fault of this MICE will get delayed.

At that time:
MINOS and CNGS will have started and measured Δm_{13}^2 more precisely
J-Parc-SK (and reactor expt) will be about to start (θ_{13} measurement)
LHC will be started

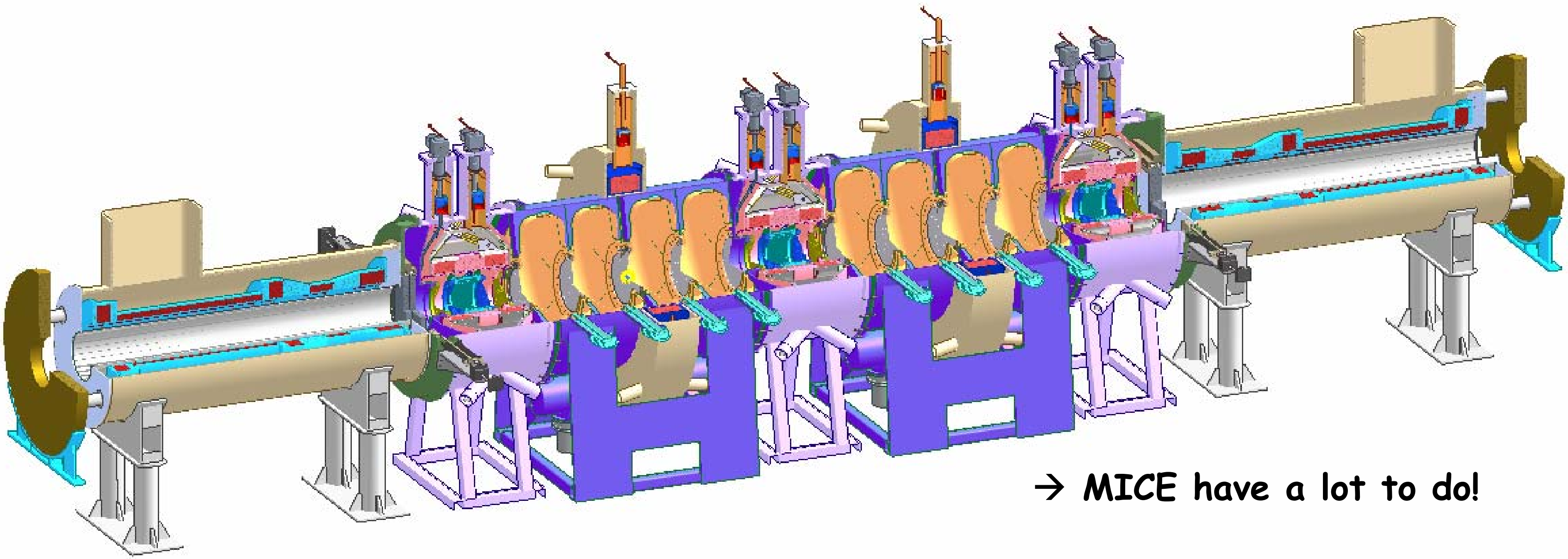
It will be timely (...and not too soon!) to have by then a full design for a cost-optimized neutrino factory, with no questions about

practical feasibility of ionization cooling

MICE is getting REAL!

First beam 1st April 2007

******   365*2-25= 705 days to data taking !!!**



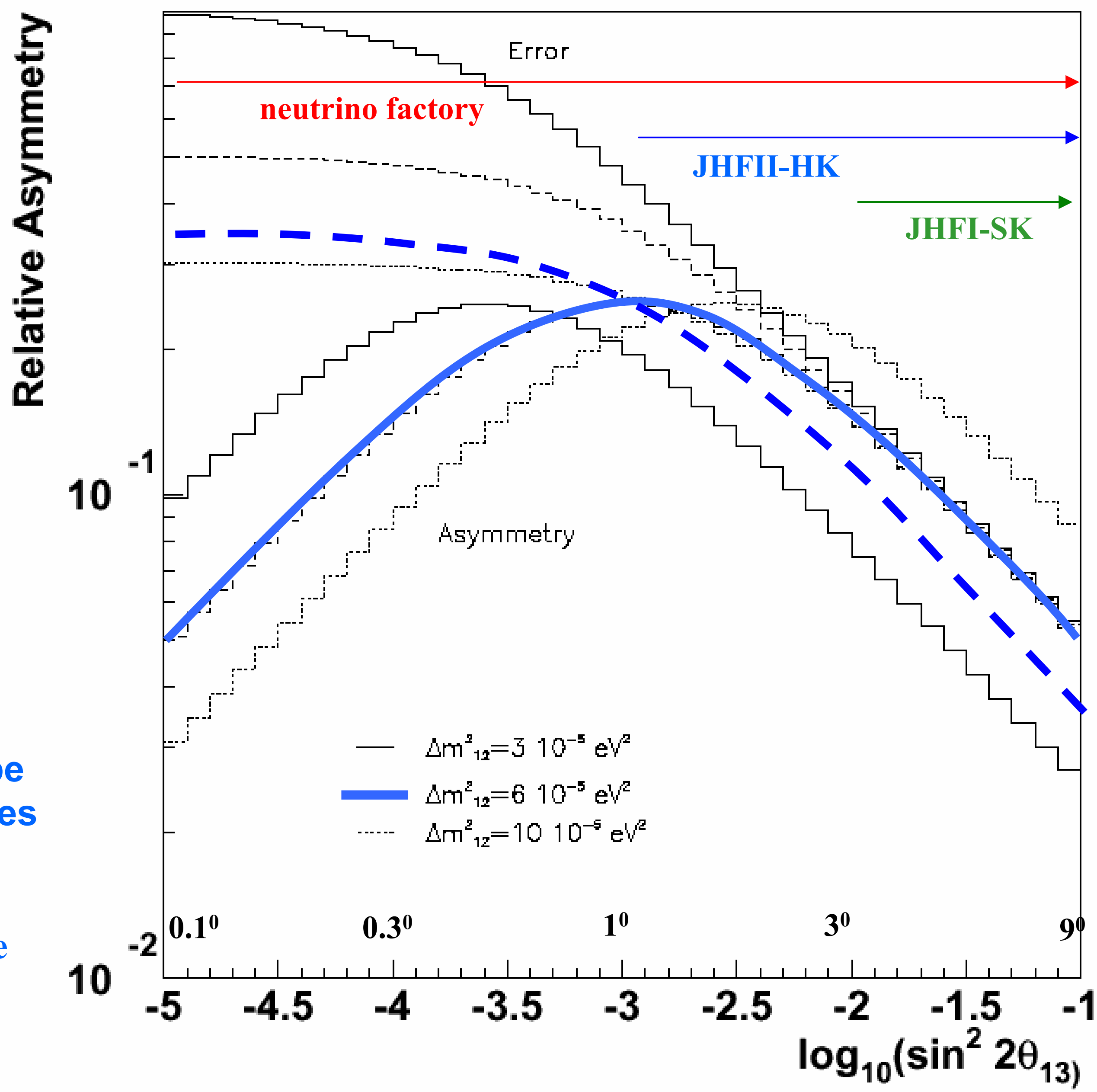
→ **MICE have a lot to do!**

Further info…

T asymmetry for $\sin\delta = 1$

!

asymmetry is a few % and requires excellent flux normalization (neutrino fact., beta beam or off axis beam with not-too-near near detector)



NOTE:
This is at first maximum!
Sensitivity at low values of θ_{13} is better for short baselines, sensitivity at large values of θ_{13} may be better for longer baselines (2d max or 3d max.)

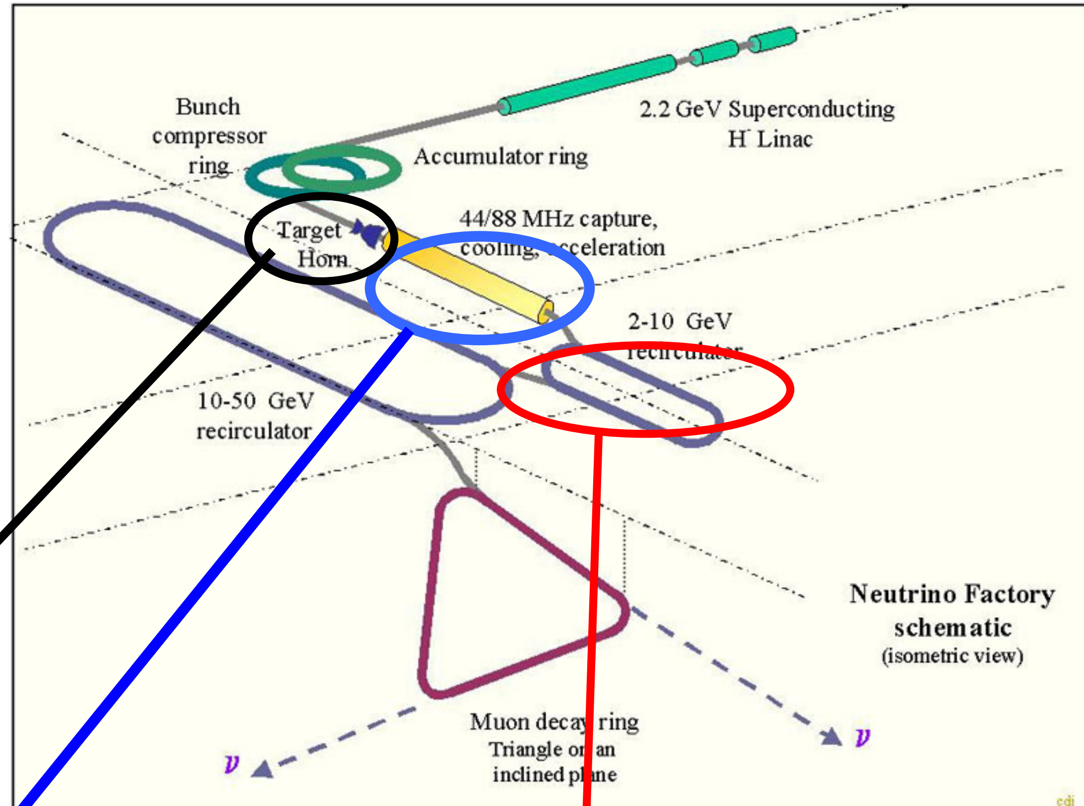
asymmetry is small at large θ_{13} and large at small θ_{13}

Particle physicist:
Q: Can a Neutrino Factory be built?

Accelerator physisicst:
A: YES! *(US Study II, CERN)*

but… it is expensive,
and many ingredients
have never been demonstrated!

⇒ R&D is needed. (est. 5yrs)
to
1. ascertain performance
2. reduce costs



among critical items:

*** Target ***

*** Cooling ***

*** Acceleration ***

Cooling component development programme + 'blast test':
MUCOOL collaboration (US-Japan-UK)

ECFA recommendations (September 2001:)

4) an improved educational programme in the field of accelerator physics and increased support for accelerator R&D activity in European universities, national facilities and CERN.

For the long-term:

5) a co-ordinated collaborative R&D effort to determine the feasibility and practical design of a neutrino factory based on a high-intensity muon storage ring;

MUTAC (14-15 jan 2003)(US)
The committee remains convinced that <u>this experiment</u>, which is absolutely required to validate the concept of ionization cooling, and the R&D leading to it <u>should be the highest priority of the muon collaboration</u>. Planning and design for the experiment have advanced dramatically(…)

EMCOG: (6 feb 2003) (Europe)
(…)EMCOG was impressed by the quality of the experiment, which has been well studied, is well organized and well structured. <u>The issue of ionization cooling is critical and this justifies the important effort that the experiment represents.</u>
EMCOG recommends very strongly a timely realization of MICE.

MUTAC: Muon Technical Advisory Committee (Helen Edwards, et al) (US)
EMCOG: European Muon Coordination and Oversight Group (C. Wyss et al)

SPSC

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2010 discoveries (such as CP violation) in neutrino physics, and a post-LHC construction window may exist for a facility to be sited at CERN.

..CERN should arrange a budget and personnel to enhance its participation in further developing the physics case and the technologies necessary for the realization of such facilities. This would allow CERN to play a significant role in such projects wherever they are sited.

..A high-power proton driver is a main building block of future projects, and is therefore required.

..A direct superbeam from a 2.2 GeV SPL does not appear to be the most attractive option for a future CERN neutrino experiment as it does not produce a significant advance on T2K.

..We welcome the effort, partly funded by the EU, concerned with the conceptual design of a β-beam. At the same time CERN should support the European neutrino factory initiative in its conceptual design.

encouraging signs from CERN…
report from Scientific Policy Committee to council

Recommendations

- CERN should make every reasonable effort to deliver the approved p.o.t. to CNGS.
- Future neutrino facilities offer great promise for fundamental discoveries. CERN should join the world effort in developing technologies for new facilities : Beta beams, Neutrino Factory…wherever they are sited.
- Focus now on enabling CERN to do the best choice by 2010 on future physics programme.
- Explore further synergies with EURISOL

17 December 2004 Council Meeting, J.Feltesse 13

Emittance measurement

Each spectrometer measures 6 parameters per particle
x y t Px Py E

Determines, for an ensemble (sample) of N particles, the moments:
Averages <x> <y> etc…
Second moments: variance(x) $\sigma_x^2 = \langle\, x^2 - \langle x\rangle^2 \,\rangle$ etc…
covariance(x) $\sigma_{xy} = \langle\, x.y - \langle x\rangle\langle y\rangle \,\rangle$

Covariance matrix

$$M = \begin{pmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xt} & \sigma_{xx'} & \sigma_{xy'} & \sigma_{xt'} \\ \cdots & \sigma_y^2 & \cdots & \cdots & \cdots & \sigma_{yt'} \\ \cdots & \cdots & \sigma_t^2 & \cdots & \cdots & \sigma_{tt'} \\ \cdots & \cdots & \cdots & \sigma_{x'}^2 & \cdots & \sigma_{x't'} \\ \cdots & \cdots & \cdots & \cdots & \sigma_{y'}^2 & \sigma_{y't'} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \sigma_{t'}^2 \end{pmatrix}$$

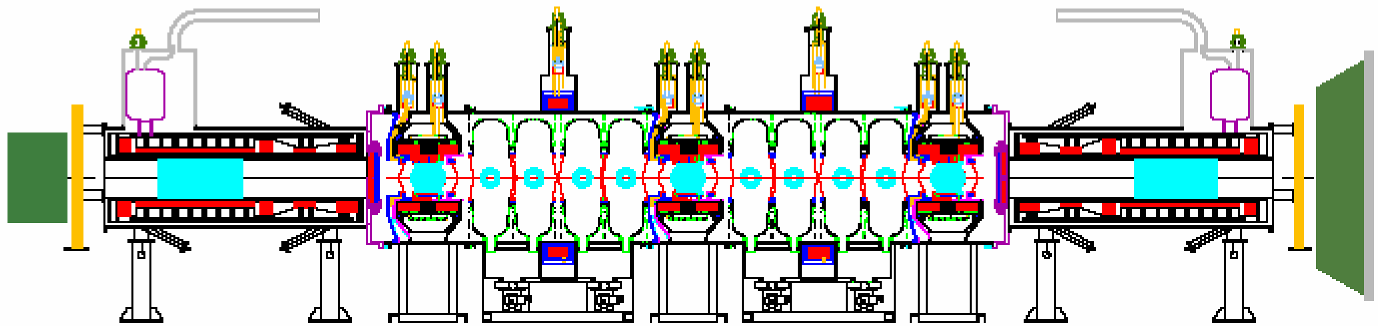
Getting at e.g. $\sigma_{x't'}$ is essentially impossible with multiparticle bunch measurements
→ single particle experiment

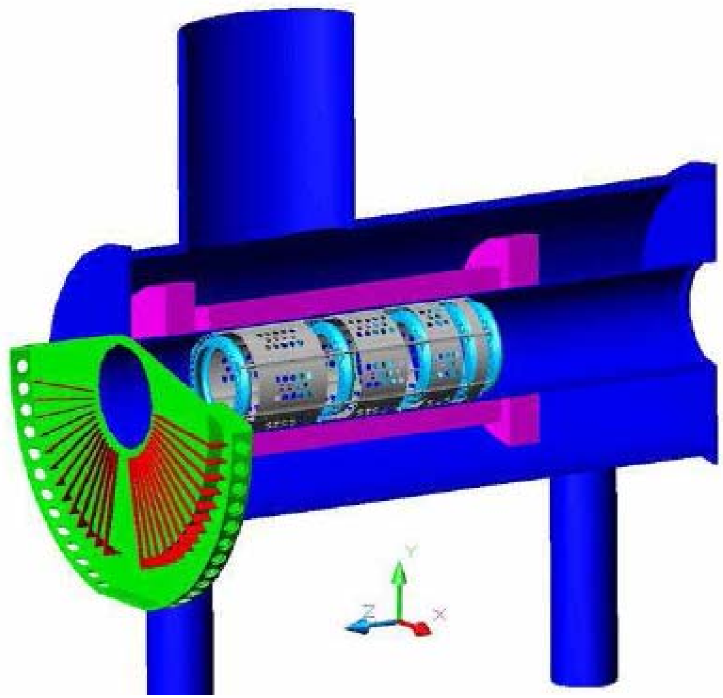
Evaluate emittance with:

$$\varepsilon^{6D} = \frac{1}{mc}\sqrt[6]{\det(M_{xytPxPyE})}$$

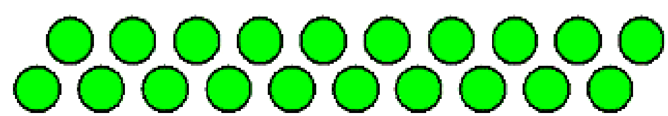
$$\varepsilon^{4D} = \frac{1}{mc}\sqrt[4]{\det(M_{xyPxPy})}$$

Compare ε^{in} with ε^{out}

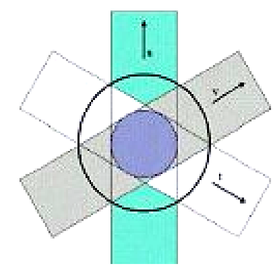




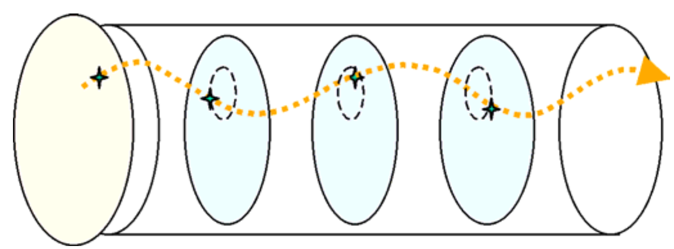
5 stations of scintillating fibers
3 coordinates each
two layers each 350 microns diameter
VLPC readout (' à la D0 ')



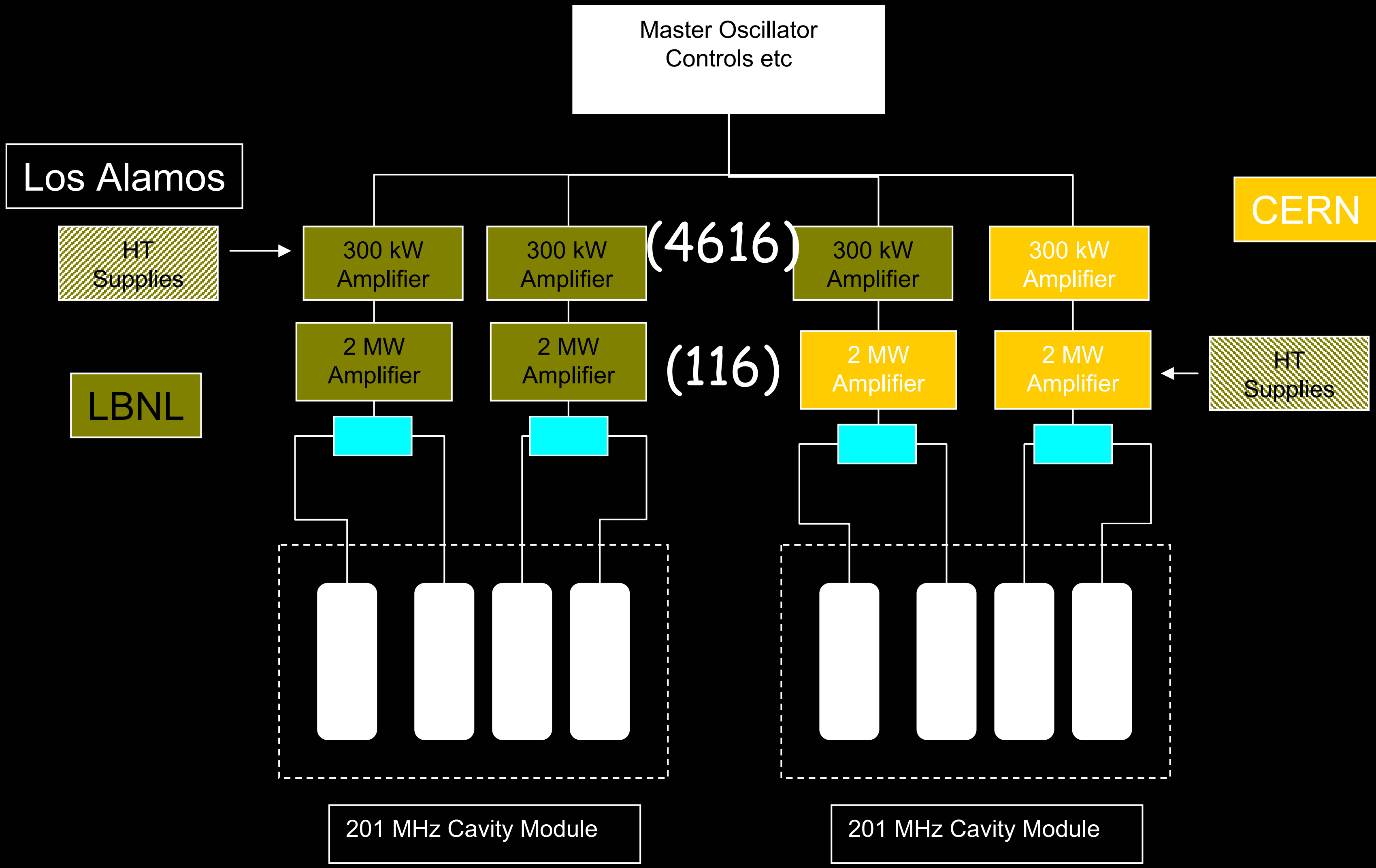
a)



b)



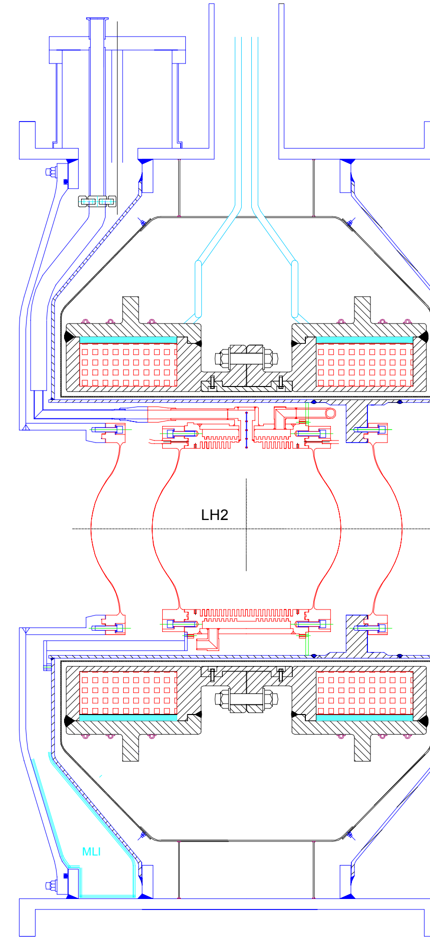
simulation shows that
DPt= 1.5 MeV/c DPz = 3 MeV/c
for individual muons at 200 MeV/c
at equilibrium emittance. TRACKER CHOICE WAS VALIDATED feb. 2005


Master Oscillator
Controls etc
Los Alamos
HT Supplies
300 kW Amplifier
300 kW Amplifier
(4616)
300 kW Amplifier
300 kW Amplifier
CERN
2 MW Amplifier
2 MW Amplifier
(116)
2 MW Amplifier
2 MW Amplifier
HT Supplies
LBNL
201 MHz Cavity Module
201 MHz Cavity Module

Hydrogen Safety

Safety Review process under way

***Internal* review organized in Berkeley in Dec. 2003**
Reviewers:
D. Allspach (FNAL), G. Benincasa (CERN), M. Seely (Jlab), L. Starritt (NASA), J. Weisend (SLAC), J. Wells (RAL)



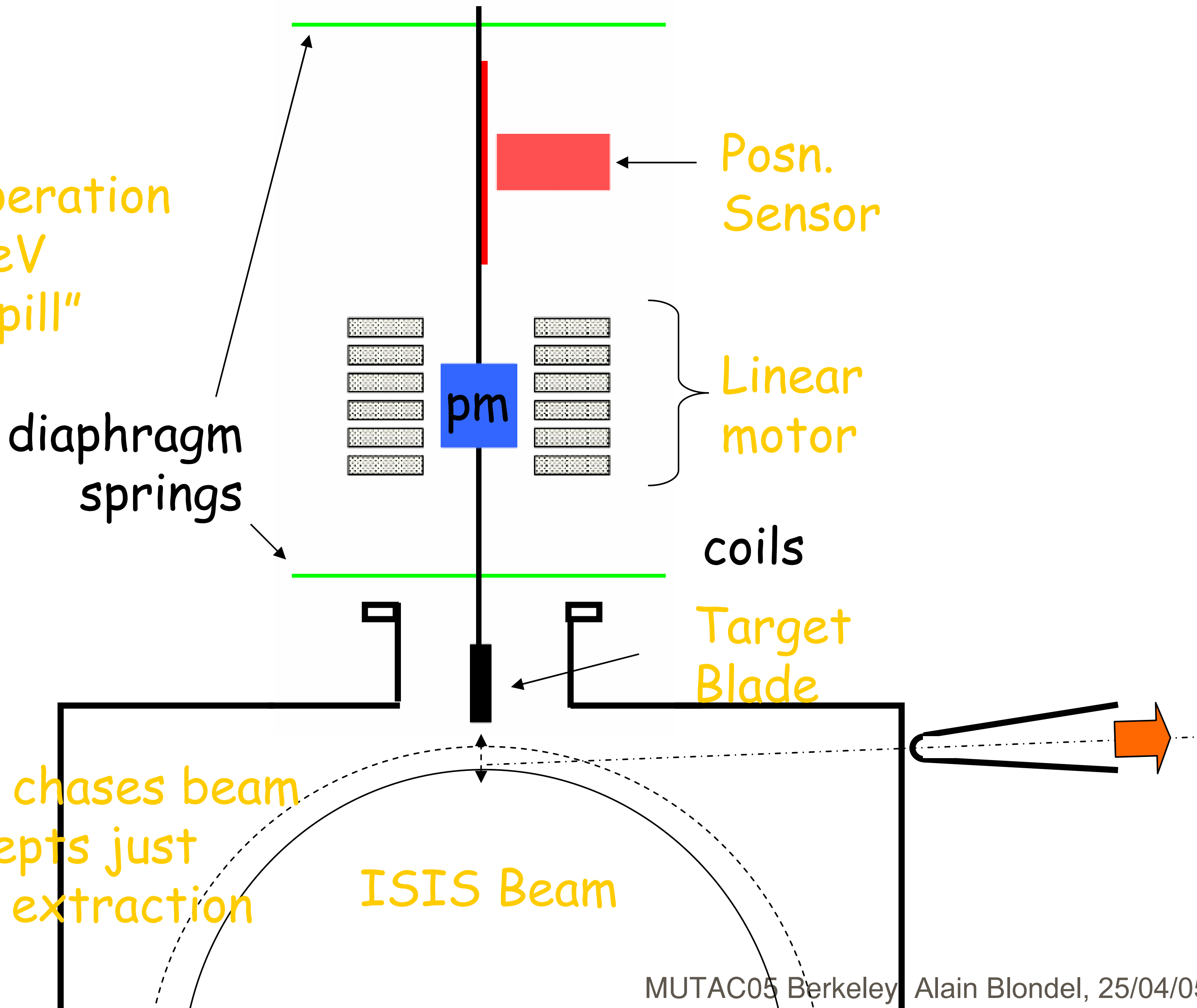
The committee was impressed by the amount of thought and effort expended on the safety aspects of this project. The MICE collaboration clearly understands the seriousness of the hazards involved and has done a laudable job of designing safety into the system from the start. The early consideration of quality control issues and formal failure mode analysis is particularly valuable. We believe that the MICE collaboration is ready to proceed to detailed engineering design and eventual review by the RAL External Safety Committee. We did not see any significant safety issues that were omitted nor do we find any technical show stoppers. There are 3 issues that we believe need additional development.

Evacuated buffer tank needed?	**NO**
Burst valves and relief valves?	**YES**
Separate vents for vacuum and hydrogen?	**YES**

Detailed answers issued. Proceeding now to *full* safety revue (toward end of 2005)

Target Concept

1 Hz operation
800 MeV
1 ms "spill"

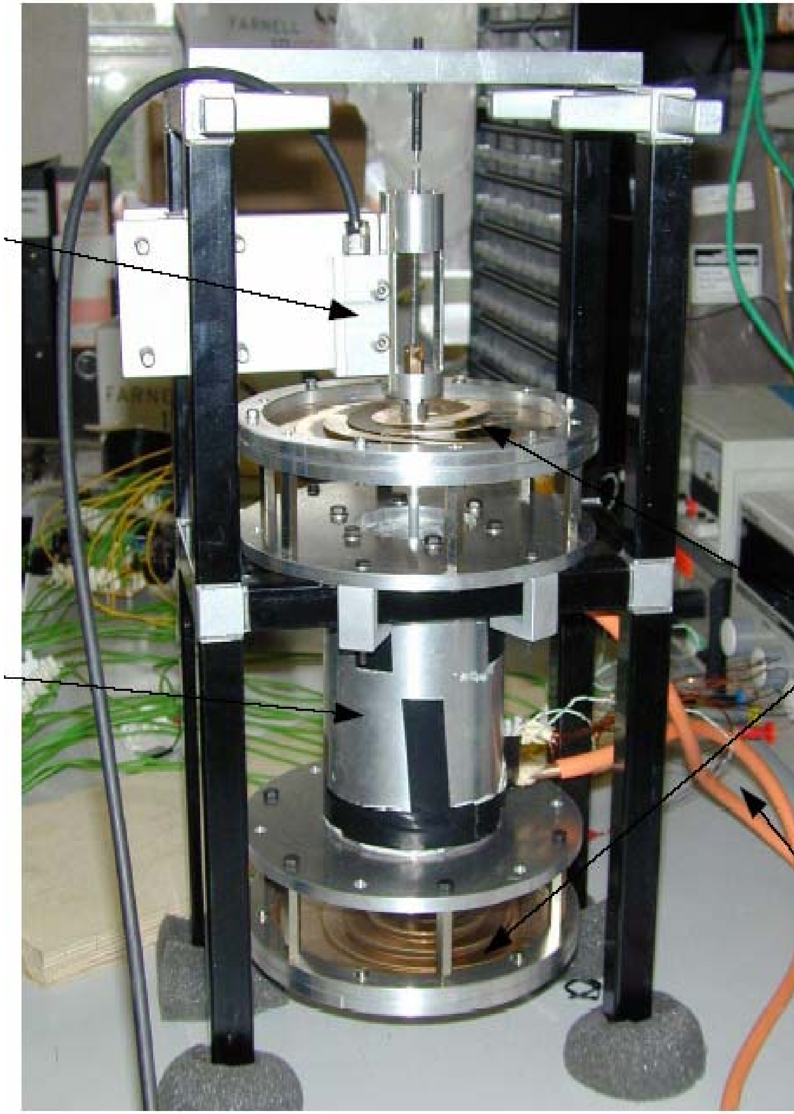


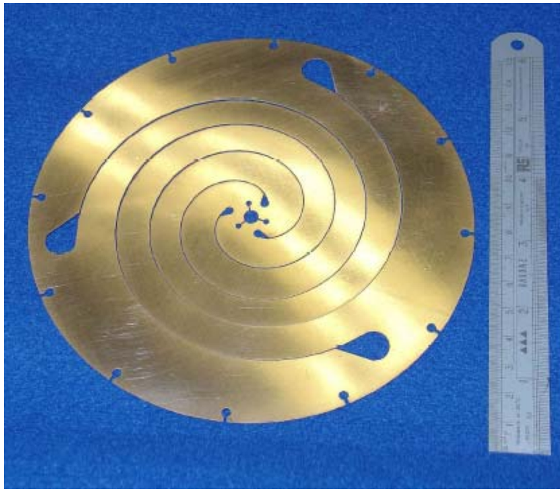
Target chases beam
Intercepts just
before extraction

Pre-proto-type model

Readout

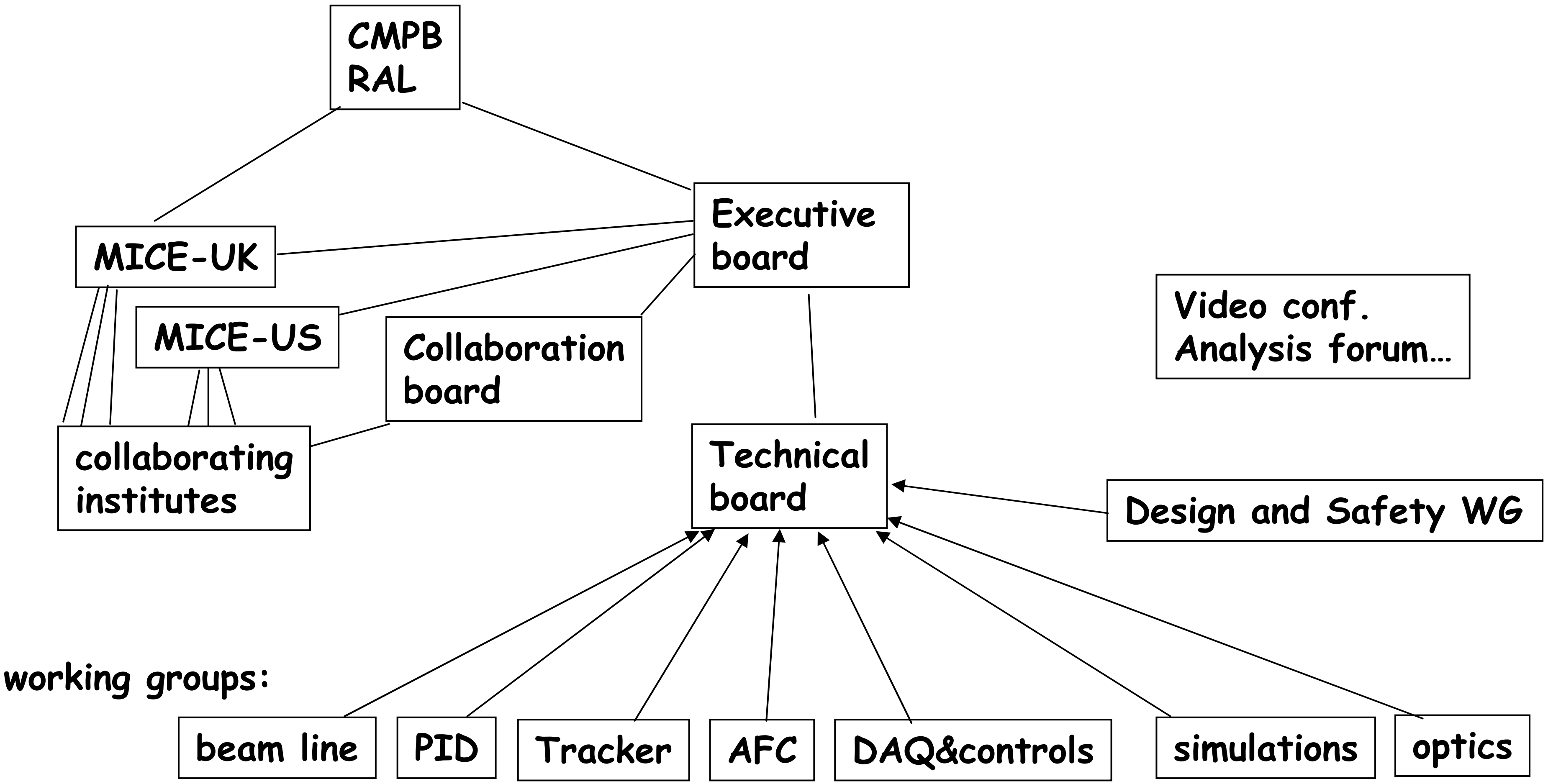
Coil
Assembly





diaphragm springs

Cooling


CMPB
RAL
Executive board
MICE-UK
MICE-US
Collaboration board
collaborating institutes
Technical board
Video conf.
Analysis forum…
Design and Safety WG
working groups:
beam line
PID
Tracker
AFC
DAQ&controls
simulations
optics

Cryo-coolers

we have decided to go for cryocoolers for all systems
Small local cooling devices (solid state + closed loop helium)
low power but no transfer lines.

→ Careful thermal design of magnets and absorber

→ Cool down times made practical by using initial charge of LN_2 & LHe – Cryo-cooler then maintains against heat leaks & keeps temperature

- 8 hours with pre-cool
  - Days without!

:) Decay solenoid – supercritical He - requires its own refrigerator (TCF20)