Future Neutrino Beams and Muon Collider

Magnets Challenges

Credits:
Neutrino Factory and Muon Collider collaboration members (Bross, Palmer, Jansson, Johnson, Zlobin, Tollestrup, Green, Zisman…)
MICE collaboration (Bradshaw, Lau, Yang, Li…)
MERIT Collaboration (Kirk, McDonald, Efthymiopoulos…)
International Scoping Stdy and Design Study
Beta-beam collaboration (Lindroos, Windner)
Connection: BENE workpackage of CARE

Motivations

1 The neutrino revolution:

Discovery that neutrinos have mass implies Physics Beyond the Standard Model

New particle: right handed neutrinos ν_R must exist, never seen/produced

Dirac solution ν_R is light … but requires new conservation law which distinguishes particle from anti-particle (apart from charge)

Majorana solution (favored) ν_R is extremely heavy (GUT scale 10^{15} GeV)

Majorana neutrino mass is ***not*** generated by Higgs mechanism

Fundamental issues

- lepton number violation, family ordering
- Leptonic matter-antimatter asymmetry (Leptonic CP violation)
- physics at HE scales, origin of neutrino masses and mixing , see-saw
- Leptogenesis and baryon asymmetry of the universe.

Many of these issues will not be addressed by the High Energy Frontier (LHC, ILC, VLHC, MC…)

Motivate high intensity, clean, neutrino beams

Towards a high-intensity neutrino programme

EP2010:

« pursue an internationally coordinated, staged program in neutrino physics »

CERN-SG:

Studies of the scientific case for future neutrino facilities
and the R&D into associated technologies are required to
be in a position to define the optimal neutrino programme
based on the information available in around **2012;**
Council will play an active role in promoting a coordinated European participation in a global neutrino programme.

Motivations

2 The compact & precision lepton collider

Present technique(s) for high energy lepton collider appear (too) costly

-- **muon collider:** high mass electron

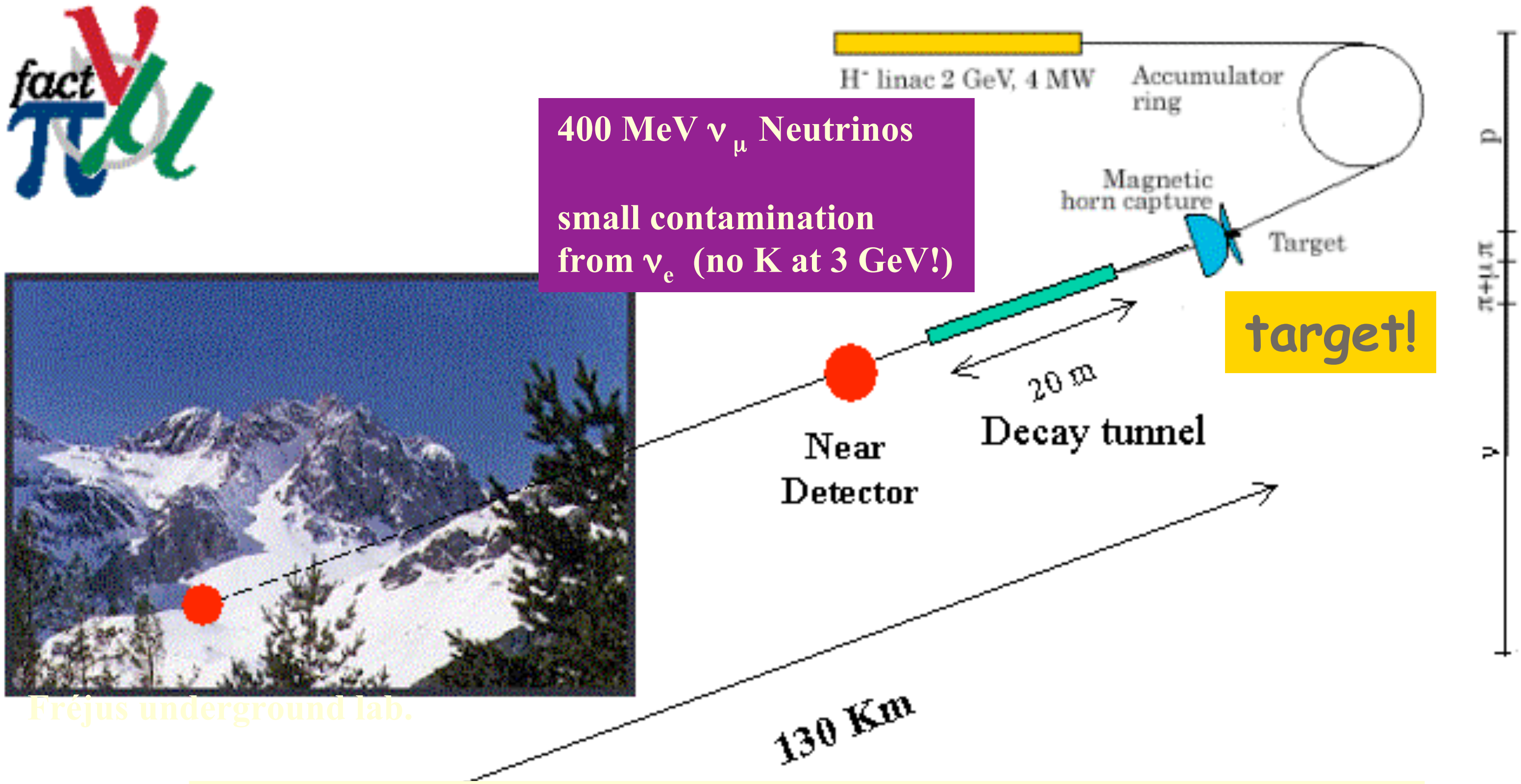
Beamsstrahlung and synchrotron radiation suppressed as $1/m^4$
Direct Higgs coupling as m^2
Economy of accelerating structures

Accelerator challenges:

Muon prooduction in high radiation environment
Muon ionization cooling
Muon acceleration and storage

Many of these challenges are similar to neutrino factory,
some far more challenging
invoke high to very high field magnets (5-50T)

CERN-SPL-based Neutrino **SUPERBEAM**

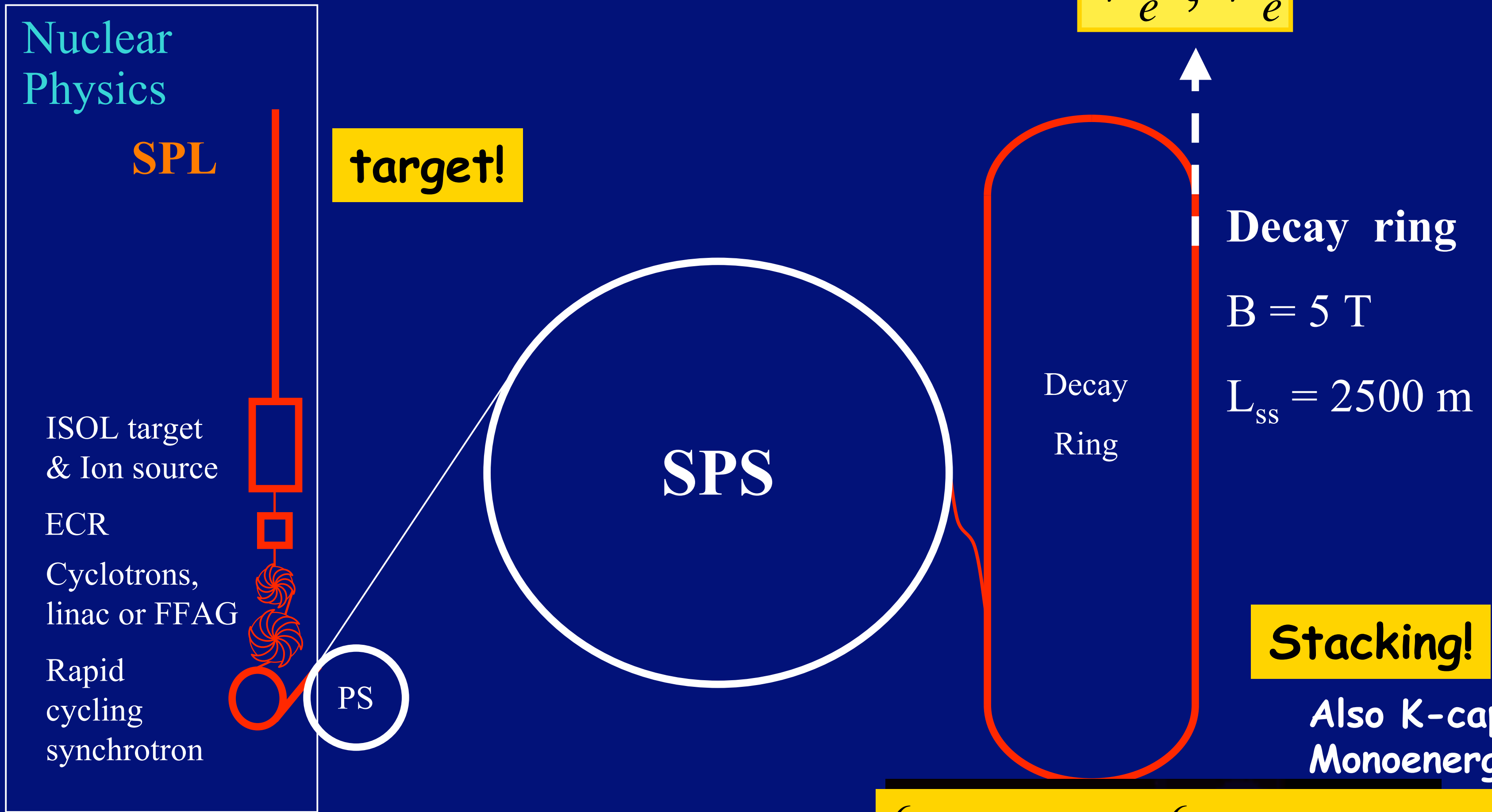


Challenges: High power proton acceeterator and accumulator, Horn focusing

A possible layout of a Low Energy Neutrino Super Beam

CERN: β-beam baseline scenario

$\nu_e , \bar{\nu}_e$



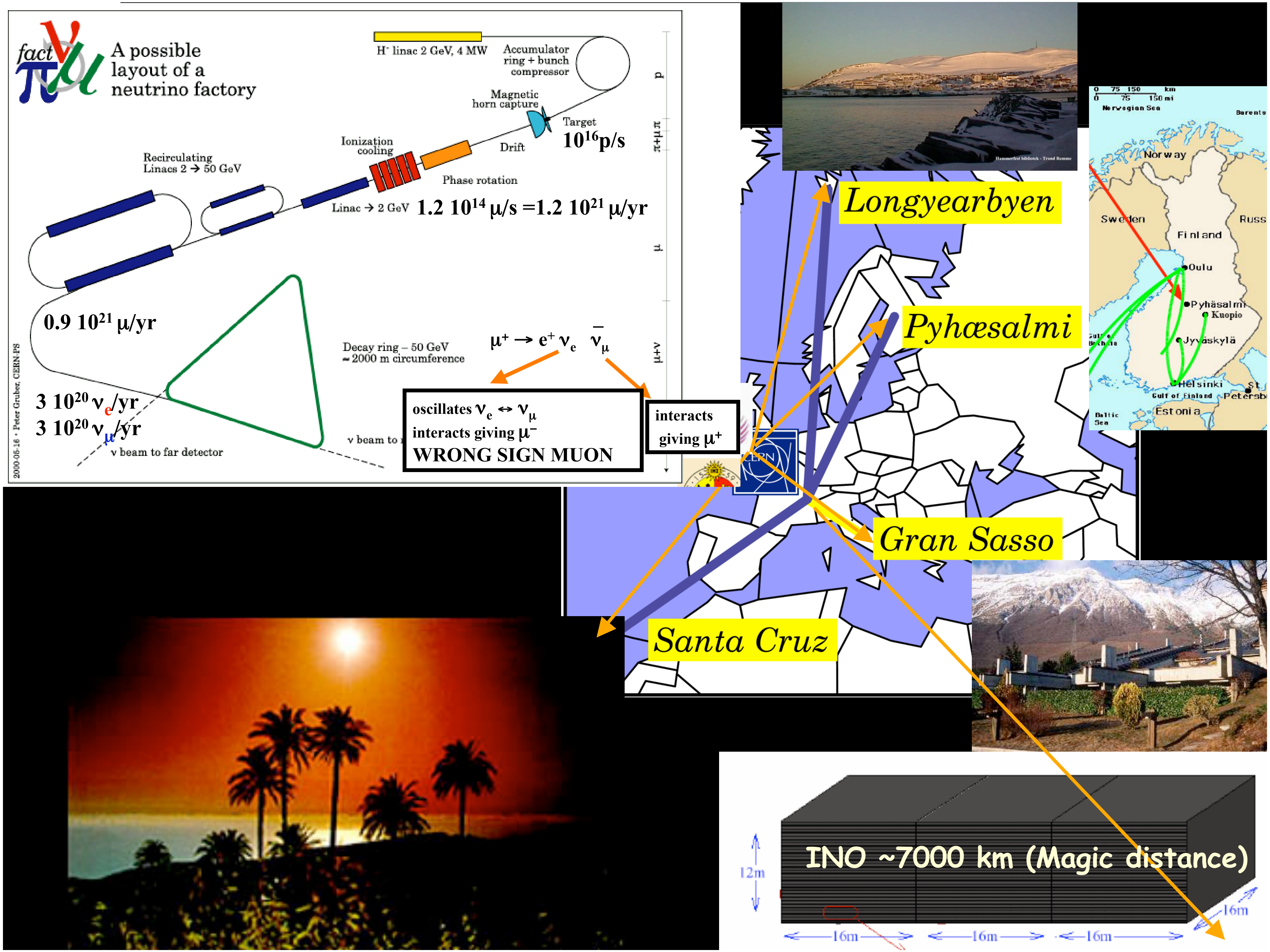
Also K-capture
Monoenergetic

$$^{6}_{2}He^{++} \rightarrow {}^{6}_{3}Li^{+++} \, \bar{\nu}_e \, e^{-}$$

$$^{18}_{10}Ne \rightarrow {}^{18}_{9}F \, \nu_e \, e^{+}$$

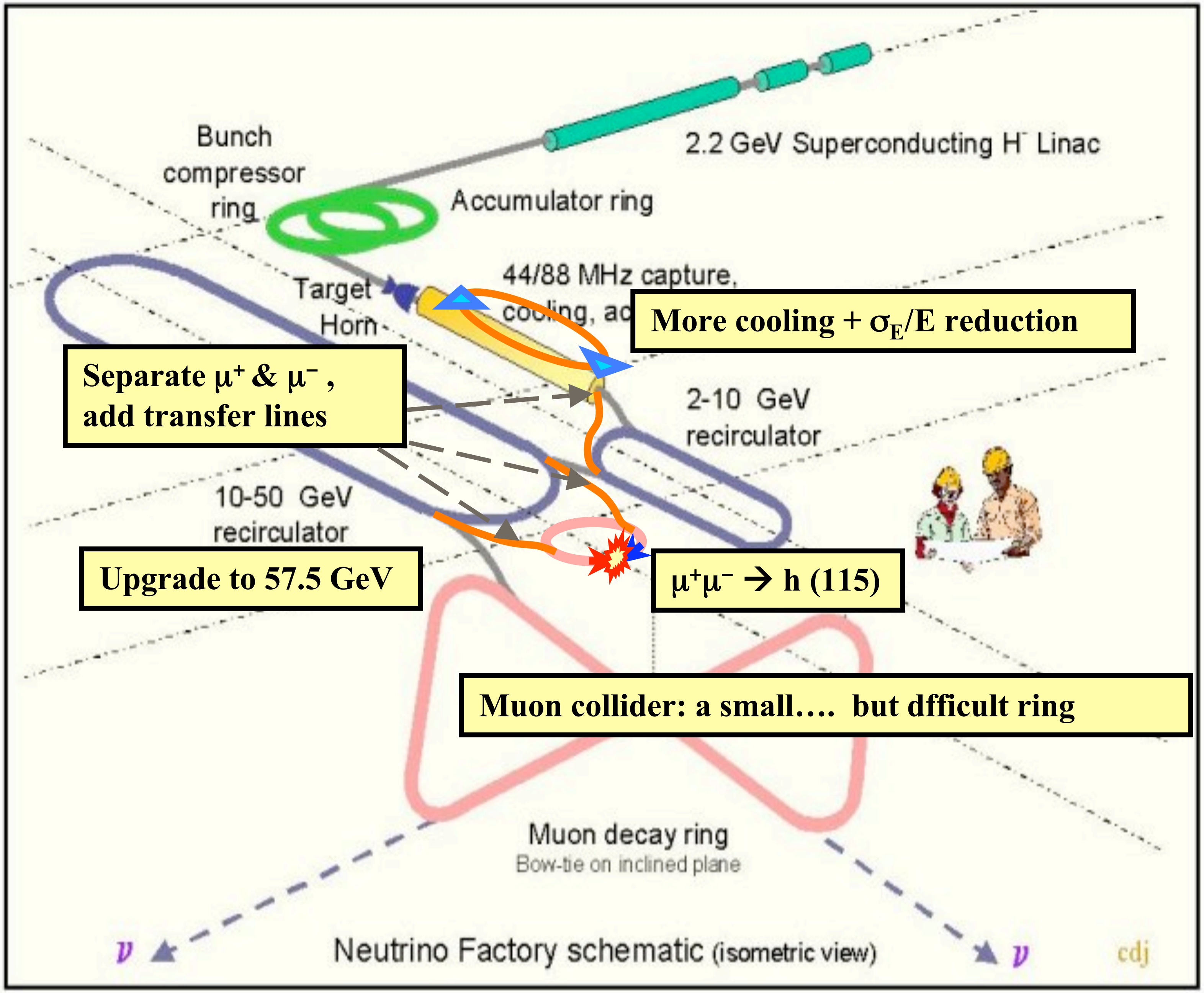
neutrinos of E_{max}=~600MeV

Same detectors as Superbeam !

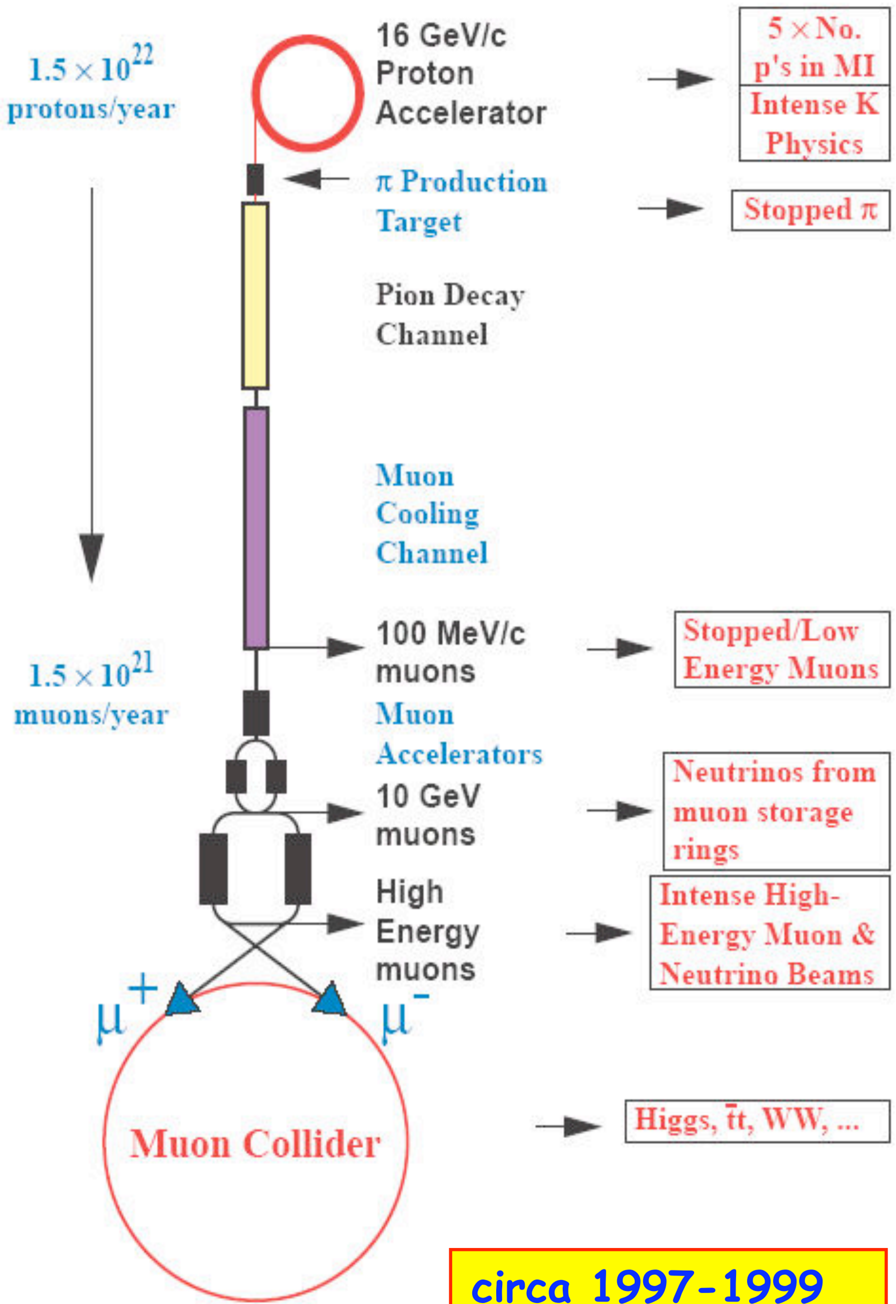


fact
A possible layout of a neutrino factory
H⁻ linac 2 GeV, 4 MW
Accumulator ring + bunch compressor
Magnetic horn capture
Target
10^16 p/s
Drift
Ionization cooling
Phase rotation
Recirculating Linacs 2 → 50 GeV
Linac → 2 GeV
1.2 10^14 μ/s =1.2 10^21 μ/yr
0.9 10^21 μ/yr
Decay ring – 50 GeV
≈ 2000 m circumference
μ+ → e+ νe ν̄μ
3 10^20 νe/yr
3 10^20 νμ/yr
ν beam to far detector
ν beam to
oscillates νe ↔ νμ
interacts giving μ−
WRONG SIGN MUON
interacts
giving μ+
2000-05-16 • Peter Gruber, CERN-PS
p
π+μ+π
μ
μ+ν
Longyearbyen
Pyhæsalmi
Gran Sasso
Santa Cruz
CERN
Norwegian Sea
Barents
Norway
Sweden
Finland
Russ
Oulu
Pyhäsalmi
Kuopio
Jyväskylä
Helsinki
Gulf of Finland
St Petersb
Estonia
Baltic Sea
INO ~7000 km (Magic distance)
12m
16m
16m
16m
16m

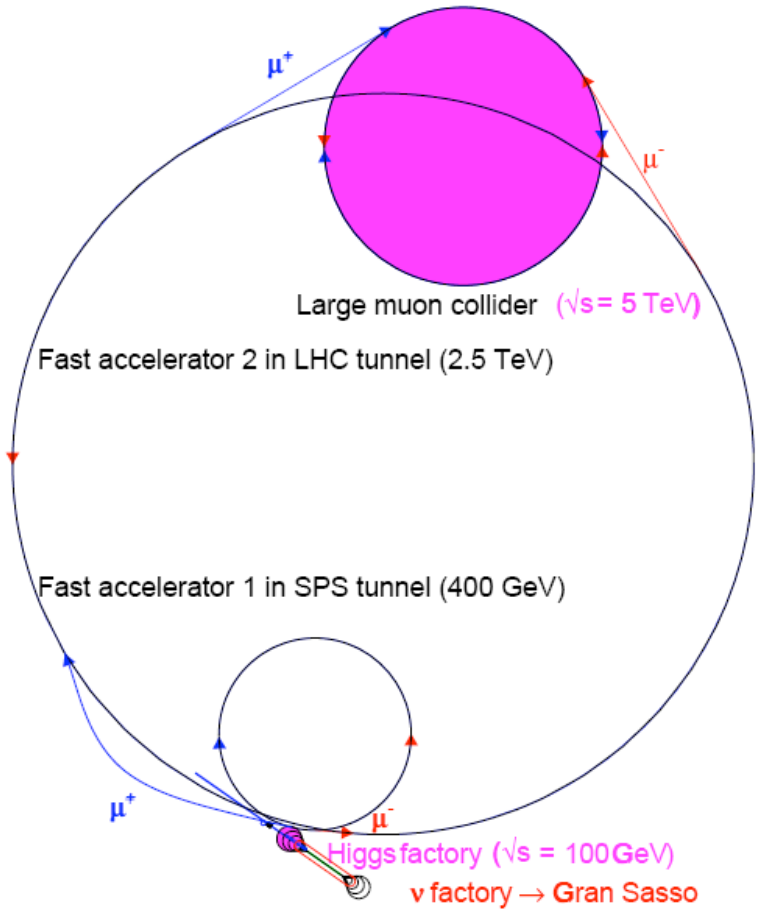
From neutrino factory to Higgs collider



Intense K physics
Intense Low-E muons
Neutrino Factory
Higgs(es) Factory(ies)
Energy Frontier -> 5 TeV

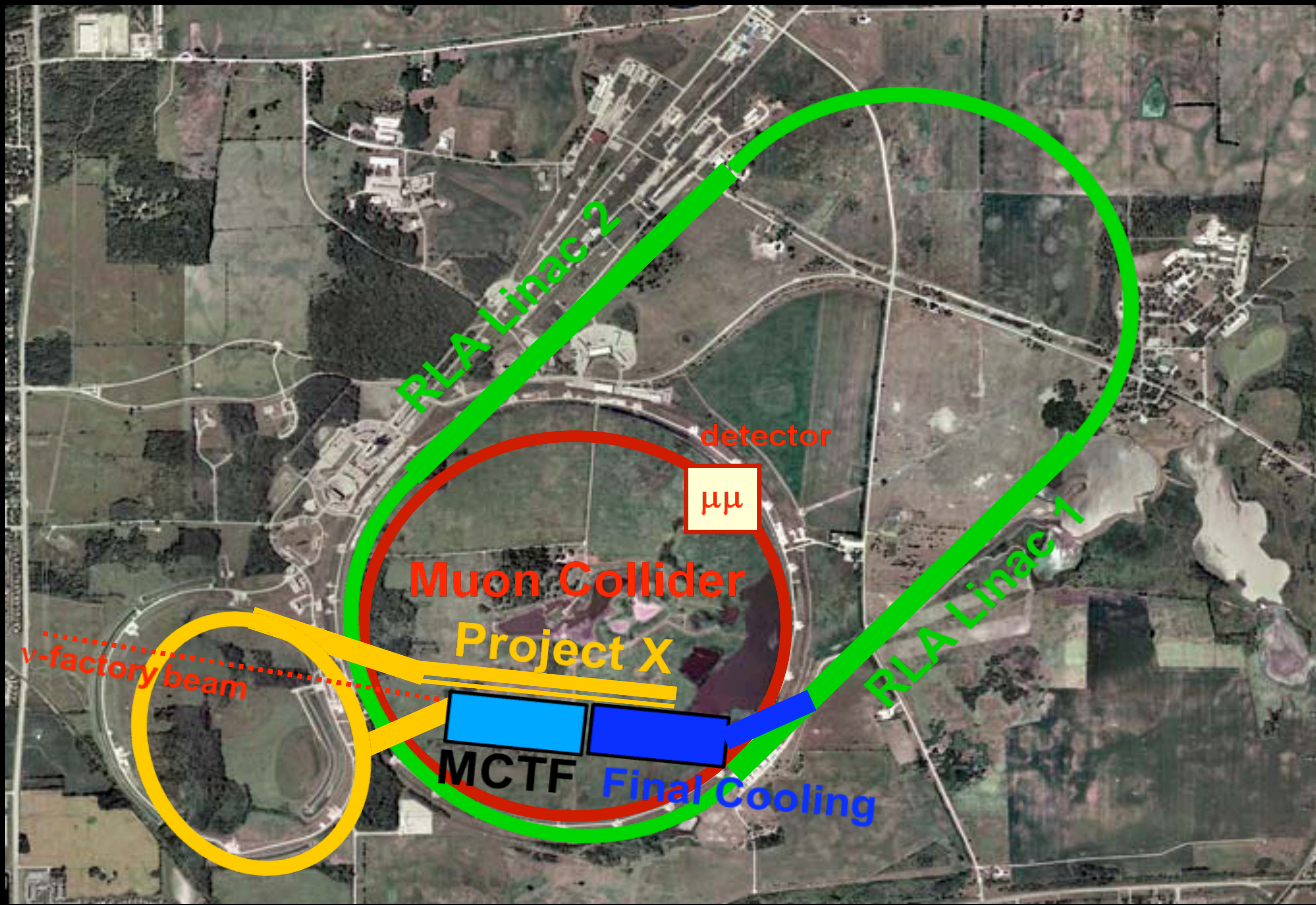


circa 1997-1999
US, Europe, Japan

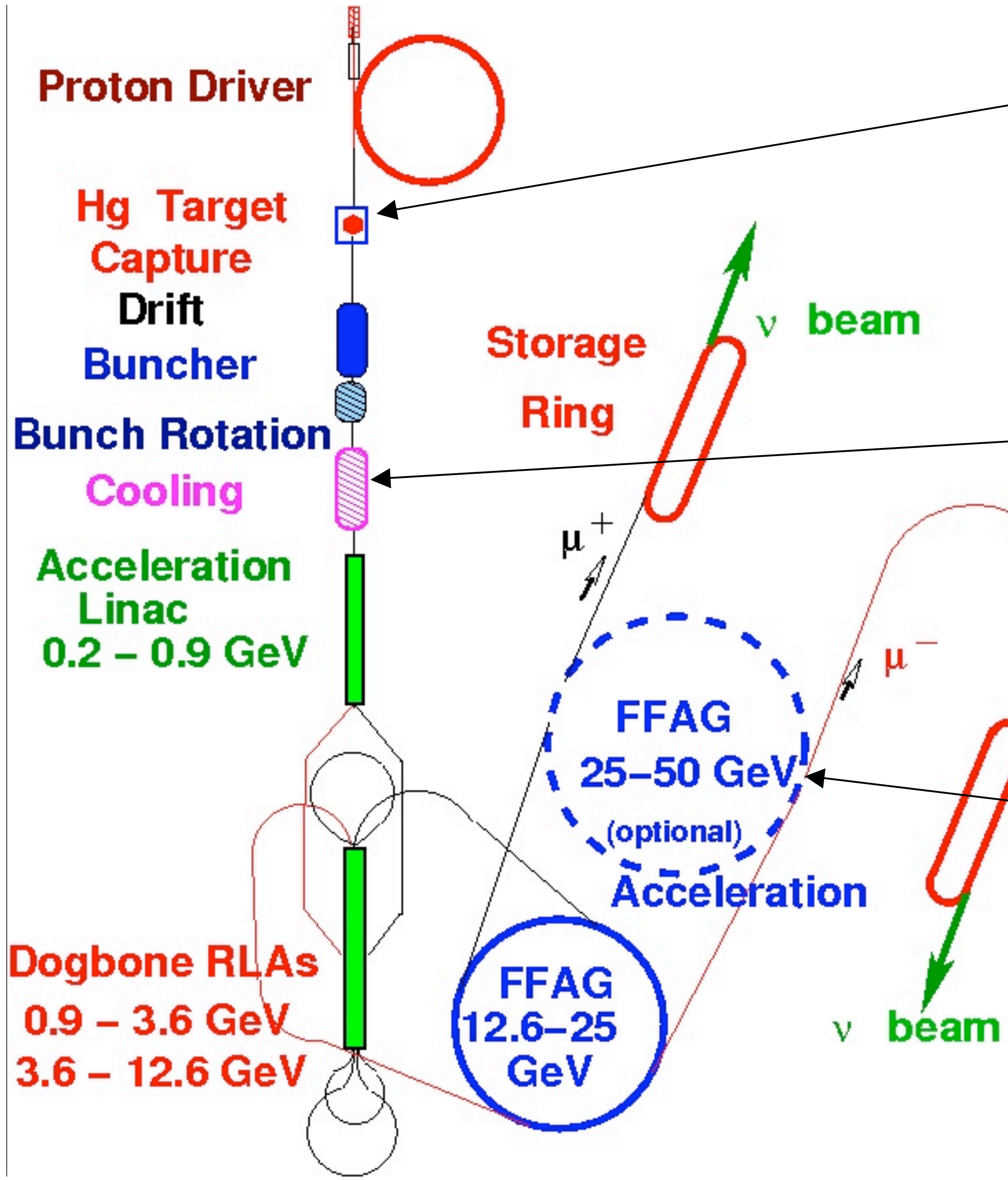


Possible layout of a muon complex on the CERN site.

Fermilab Muon Complex - *Vision*



Major challenges tackled by R&D expts



High-power target
. 4MW
. good transmission
MERIT& HARP experiments @CERN

Fast muon cooling
MICE experiment (RAL)
MUCOOL (FNAL)

Fast, large aperture accelerator (FFAG)
EMMA (Daresbury)

ISS baseline

Key R&D issues

- High Power Targetry – NF & MC *(MERIT Experiment)*
- Initial Cooling – NF & MC *(MICE (4D Cooling))*
- 200 MHz RF - NF & MC *(MuCool and Muon's Inc)*
  - Investigate Gas-Filled RF cavities
  - Investigate RF cavities in presence of high magnetic fields
  - Obtain high accelerating gradients (~15MV/m)
- Intense 6D Cooling – MC
  - RFOFO "Guggenheim"
  - Helical Channel Cooling *(MANX Proposal)*
  - Parametric Resonance Ionization Cooling
- Bunch Recombination
- Acceleration– cost driver for NF & MC but in very different ways
  - FFAG's – *(EMMA Demonstration)*
  - Multi-turn RLA's – a BIG cost reducer
  - RCS for MC
- Storage Ring(s) – NF & MC
- Theoretical Studies NF & MC
  - Analytic Calculations
  - Lattice Designs
  - Numeric Simulations

Magnetic field

20T

5 T

3T

5 to 50 T

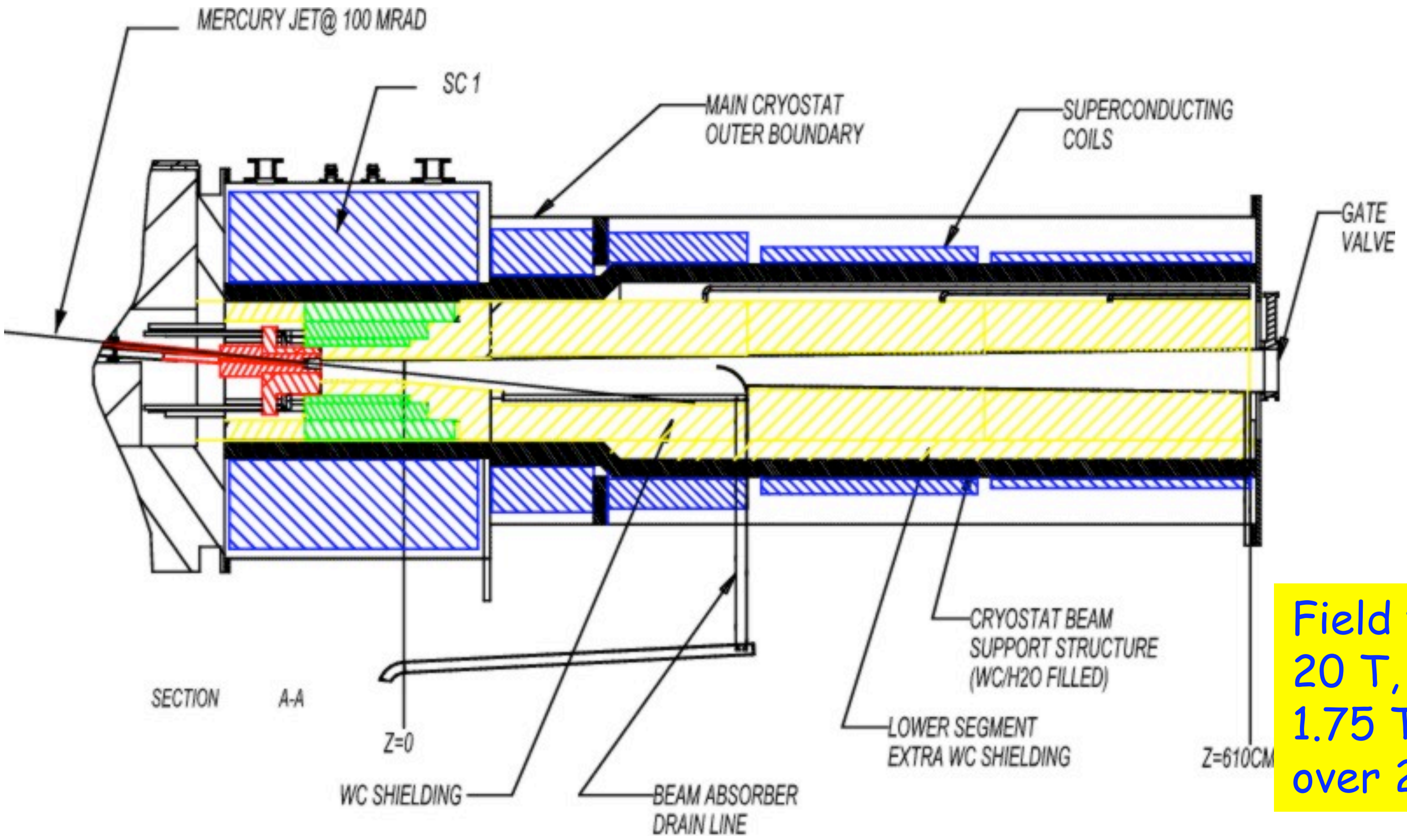
FFAG magnets

Open 5T

Target (1)

Favored target concept based on Hg jet in 20-T solenoid

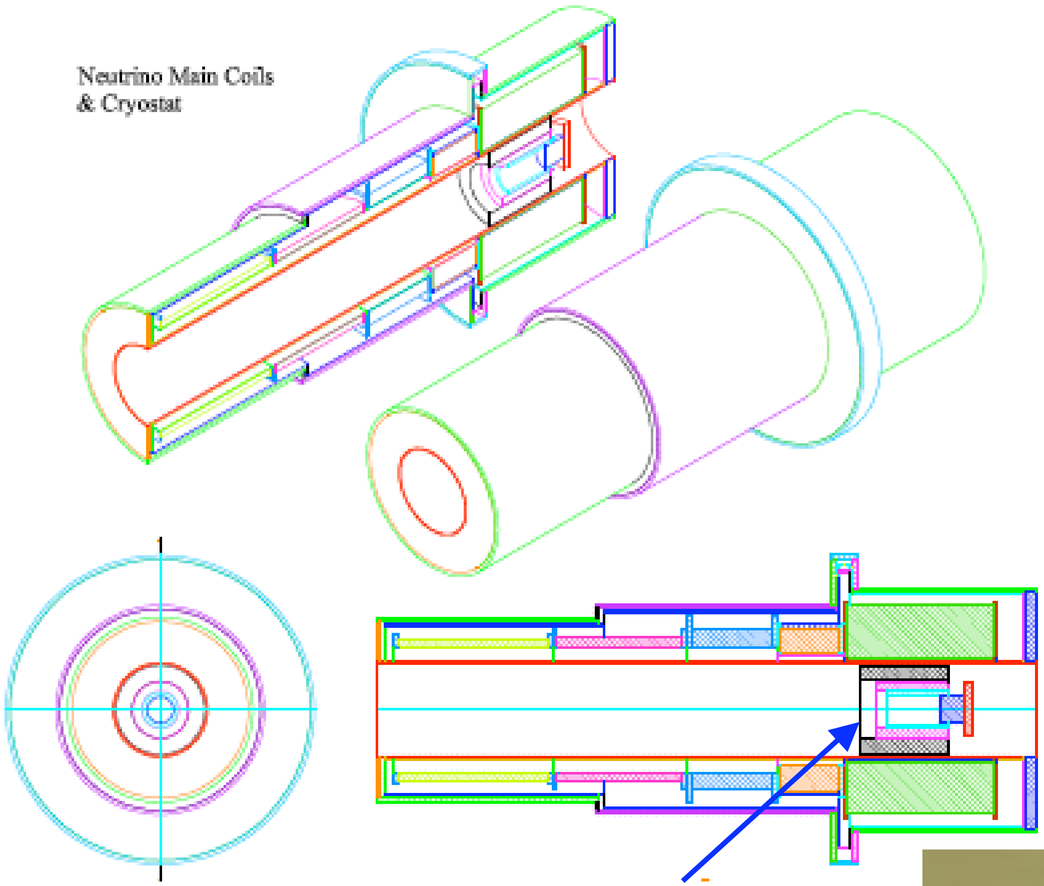
jet velocity of 20 m/s establishes "new" target each beam pulse

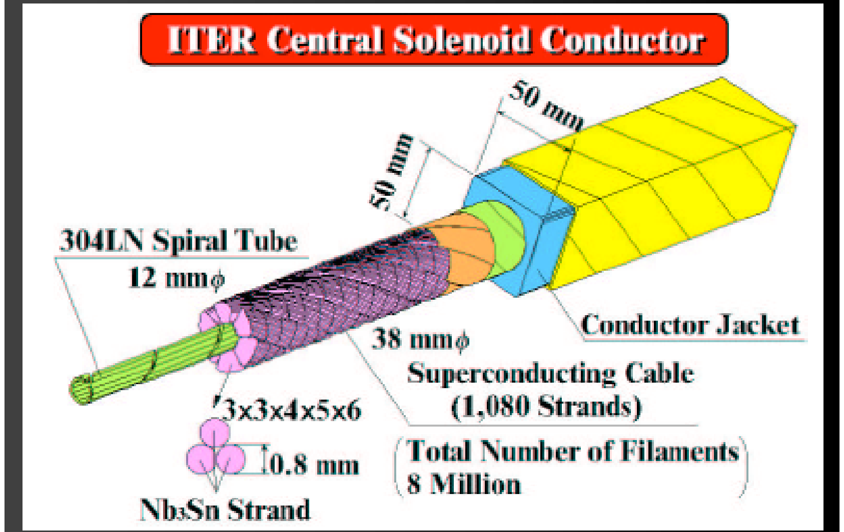


Field tapers from 20 T, 15 cm to 1.75 T, 60 cm over 20 m

NC inner coil: hollow copper conductor
SC outer coil; magnet life over 40 years

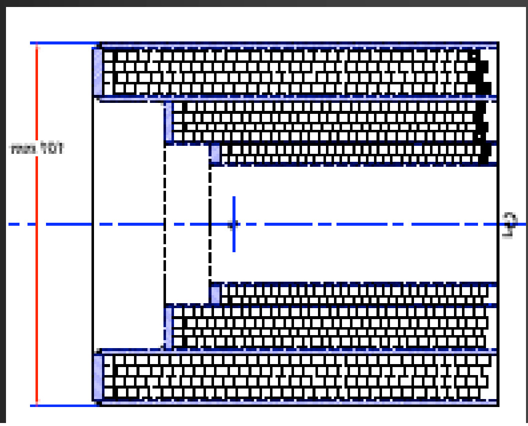
20 T Target magnet concept -- Study II (2002) --





Outer part: SC solenoid -- à la ITER

Inner part: hollow copper resistive magnet



Target (2)

Looked at energy deposition in the target magnet coils

- 20 T target magnet is hybrid with SC outer coil, NC inner coil, and iron plug for field uniformity
  - lifetimes acceptable at 4 MW but regular replacement of inner shielding and possibly NC magnet coil will be needed (calculated lifetime several years)

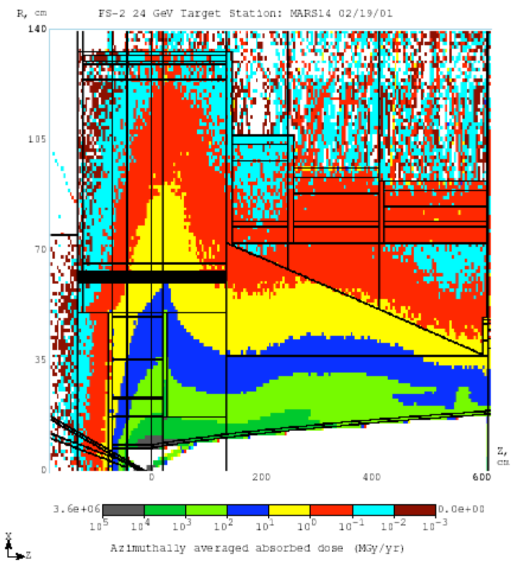


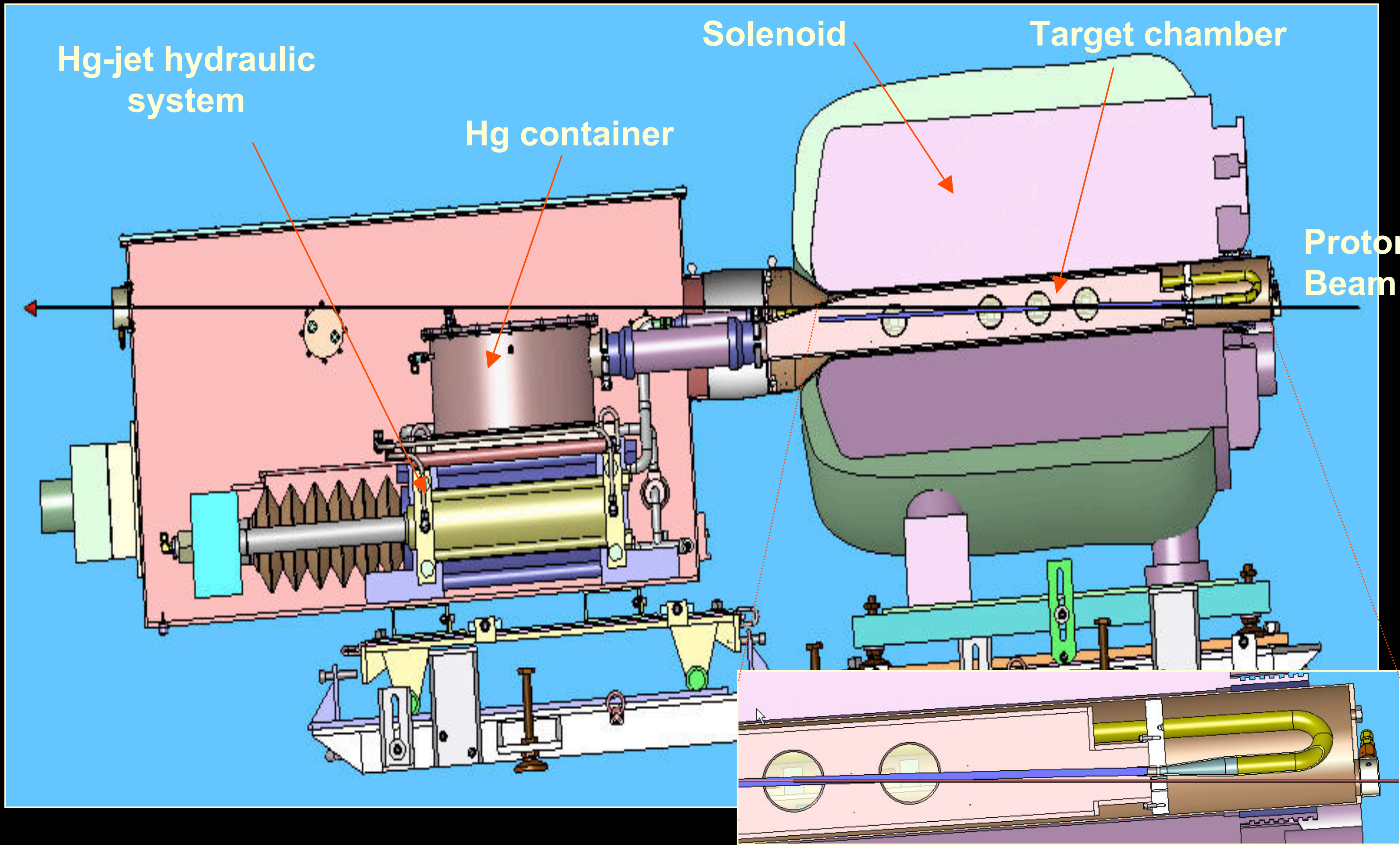
Table 3.4: Radiation doses and lifetimes of some components of the target system.

Component	Radius (cm)	Dose/yr (Grays/2×10^7 s)	Max allowed Dose (Grays)	1 MW Life (years)	4 MW life (years)
Inner shielding	7.5	2×10^{11}	10^{12}	5	1.25
Hg containment	18	2×10^{9}	10^{11}	50	12
Hollow conductor	18	1×10^{9}	10^{11}	100	25
Superconducting coil	65	6×10^{6}	10^{8}	16	4

A challenging set of solenoids, but not beyond the state-of-the-art

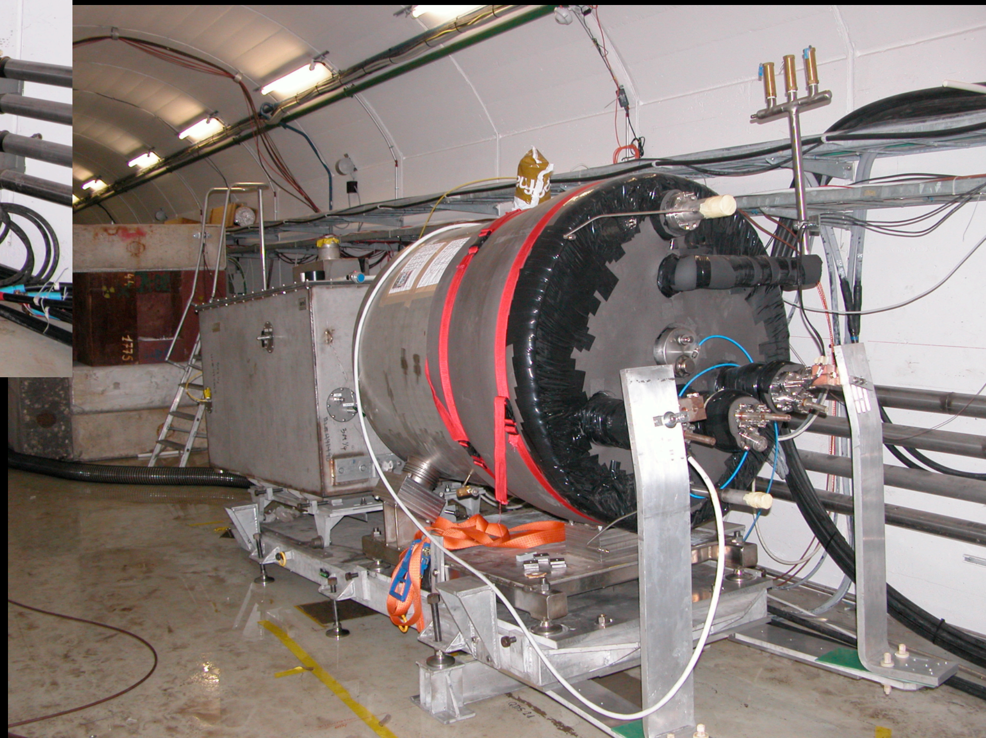
MERIT Experiment – The apparatus

Pulsed N2 cooled copper magnet in three concentric layers. 1 pulse / 20 min.



Installed in the CERN TT2a Line

Before Mating



After Mating and Tilting

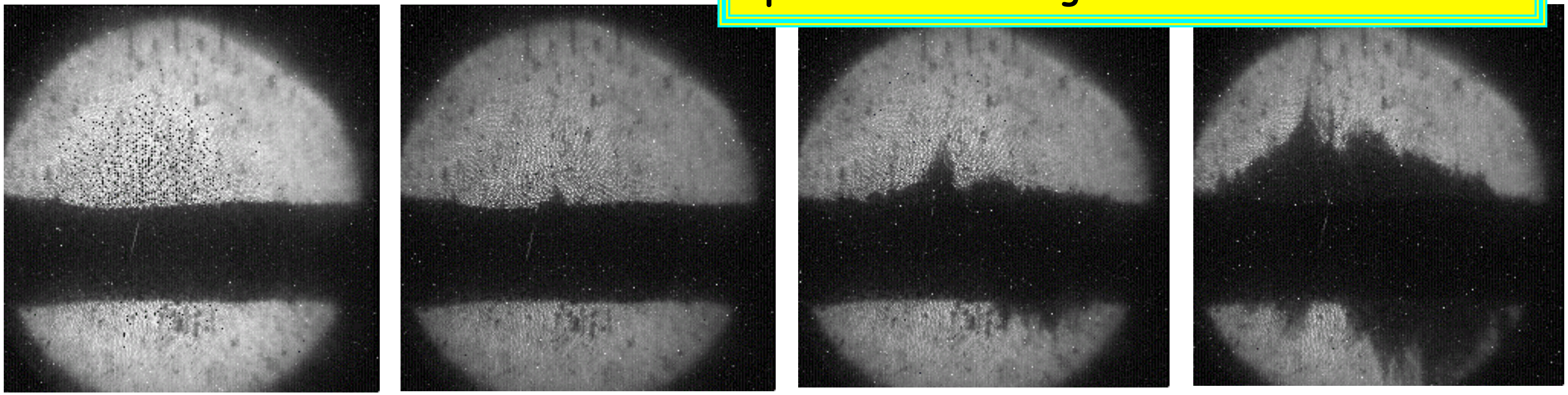
MERIT EXPERIMENT at CERN

BNL, MIT, ORNL, Princeton University CERN, RAL

Splash velocity – 24 GeV beam

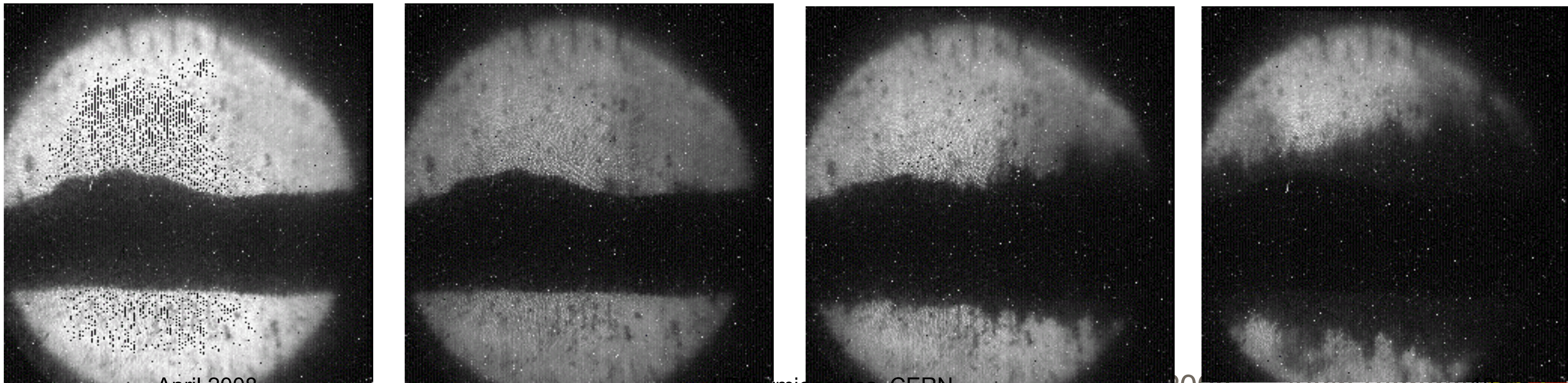
Demonstrated liquid mercury jet technology for neutrino factory and muon collider up to 8MW on target *Oct22-Nov12 2007*

10TP, 10T *V = 54 m/s*



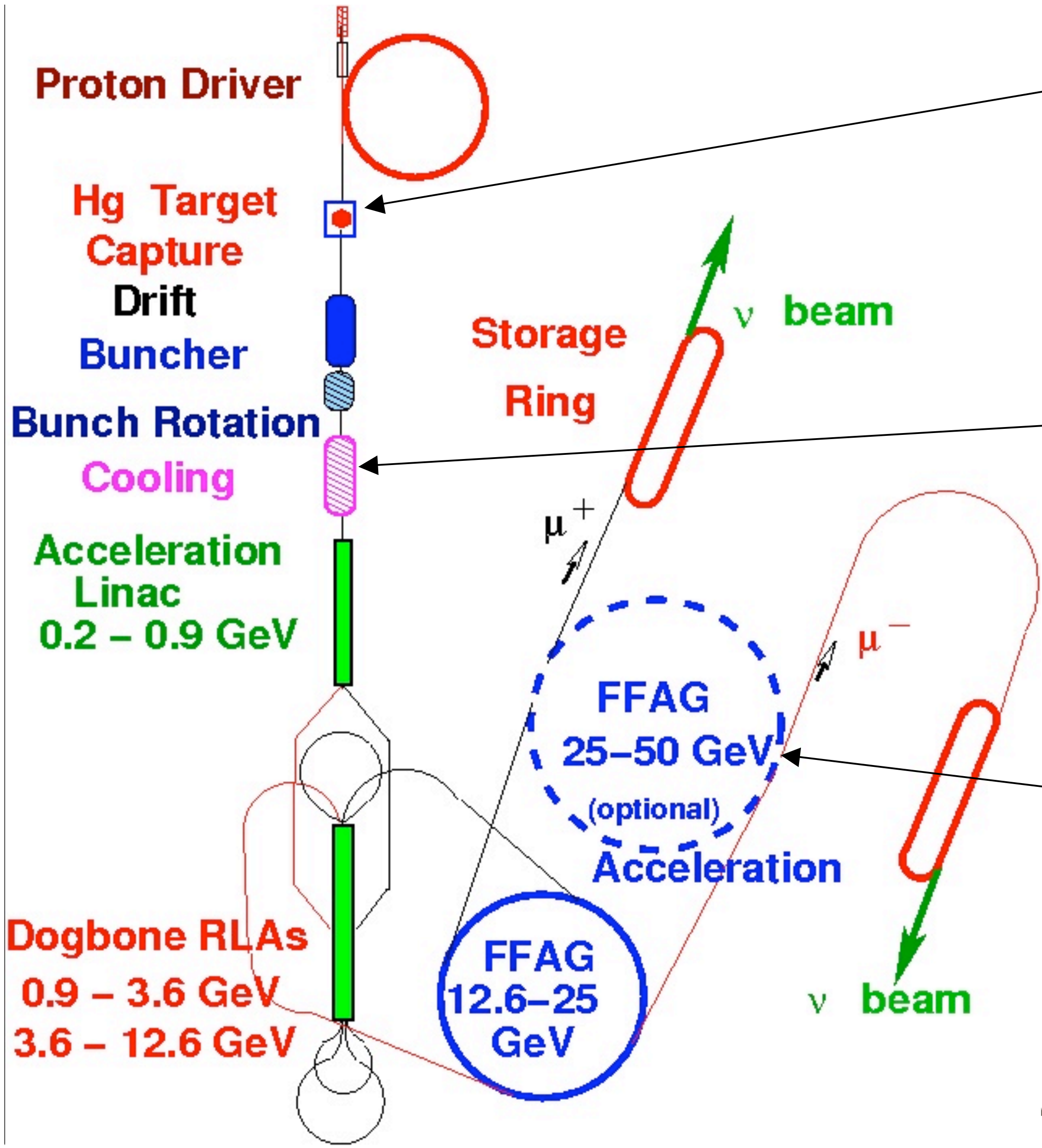
t=0 *t=0.075 ms* *t=0.175 ms* *t=0.375 ms*

20TP, 15T *V = 65 m/s*



t=0 *t=0.050 ms* *t=0.175 ms* *t=0.375 ms*

Major challenges tackled by R&D expts



High-power target
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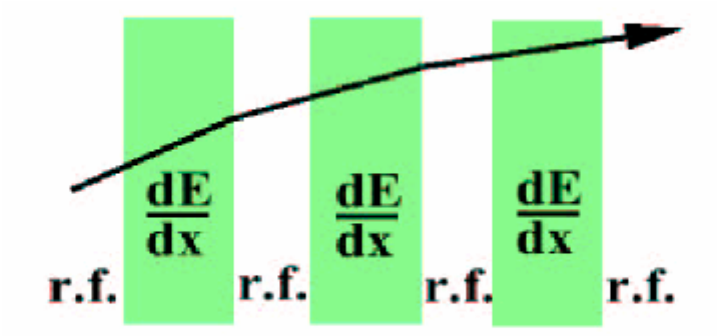
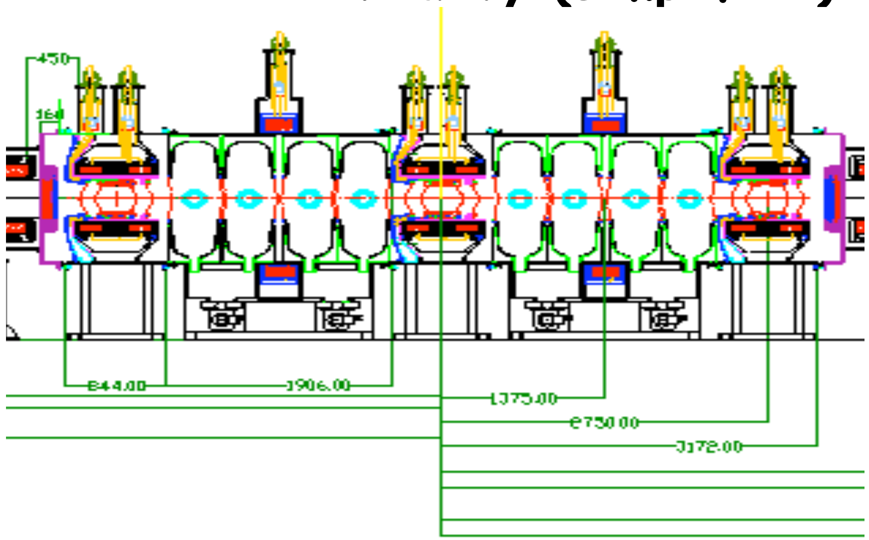
IONIZATION COOLING

principle:



this will surely work..!

reality (simplified)



Front elevation of the Cooling Channel

….maybe…

Cooling is necessary for Neutrino Factory and crucial for Muon Collider.
Delicate technology and integration problem
Need to build a realistic prototype and verify that it works (i.e. cools a beam)

Can it be built? Operate reliably? What performance can one get?
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

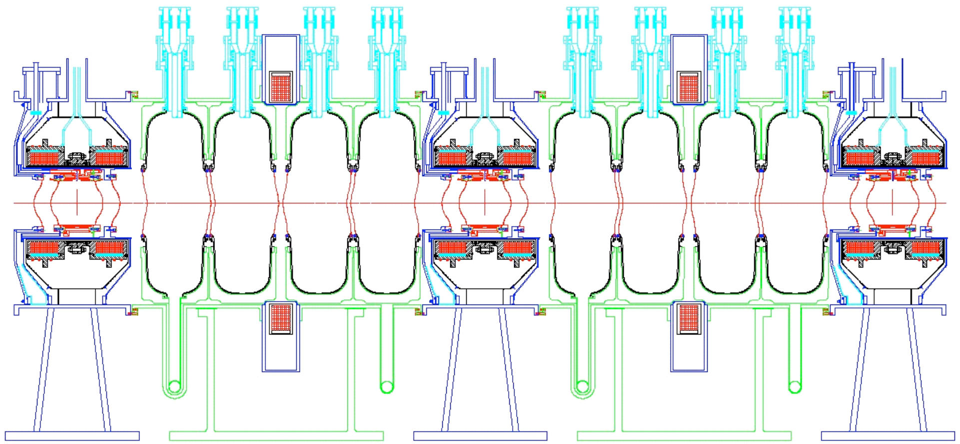
state-of-the-art particle physics instrumentation will test state-of-the-art accelerator technology.

Cooling Channel Design

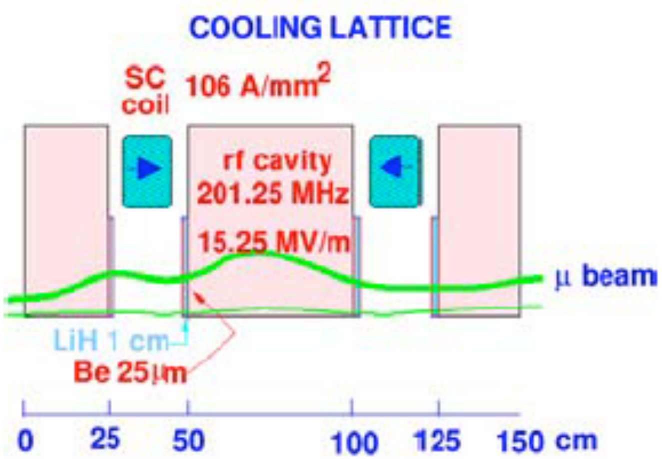
Several styles of cooling channel have been investigated

- Study 2 channel is being tested in MICE
- Study 2a channel is more cost effective version with fewer magnets and cavities and simpler absorbers

All use the same basic ingredients: large bore solenoids, 201 MHz RF cavities, low-*Z* absorbers



Study 2 channel ≡ MICE channel



Study 2a channel

Cooling Channel Magnets

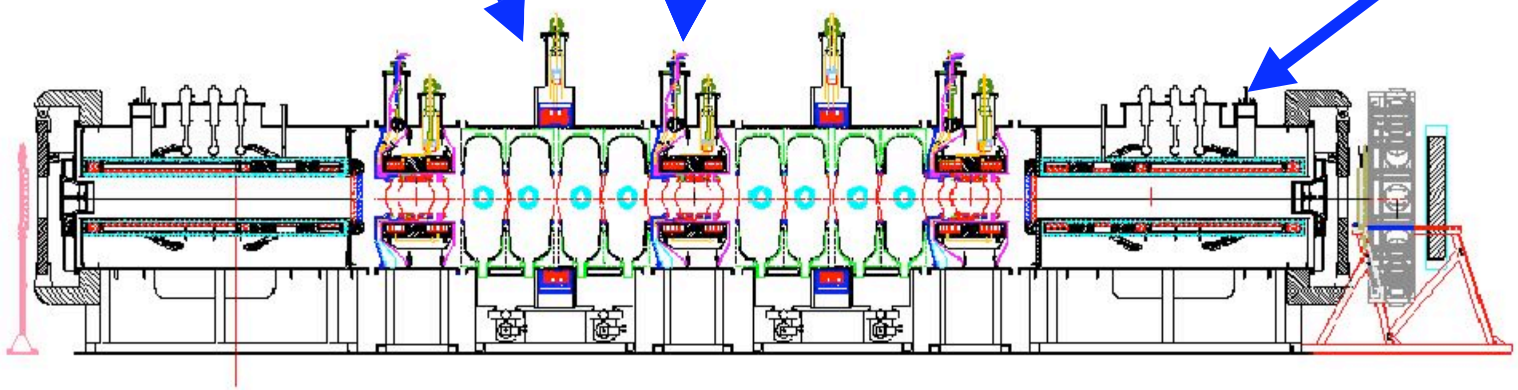
Magnets are challenging, but practical

- design issue is mainly cost optimization, not feasibility
  - all magnets cooled with cryocoolers (for MICE)

Two magnet types needed for Study 2 cooling channel

- focusing coils (FC)
- coupling coils (CC)

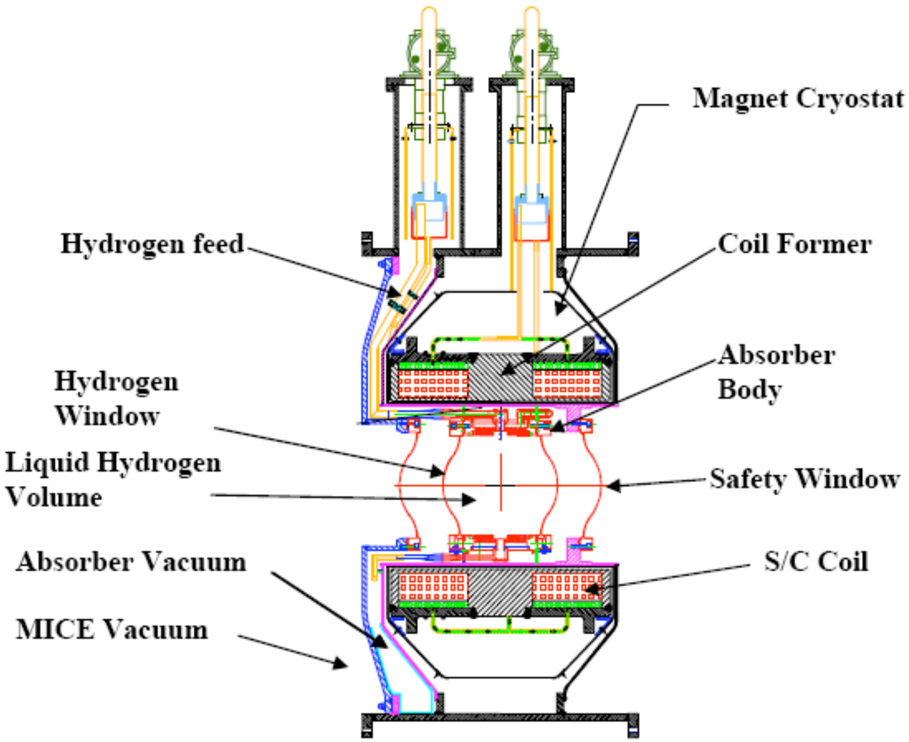
MICE requires third type, spectrometer solenoids (SS)

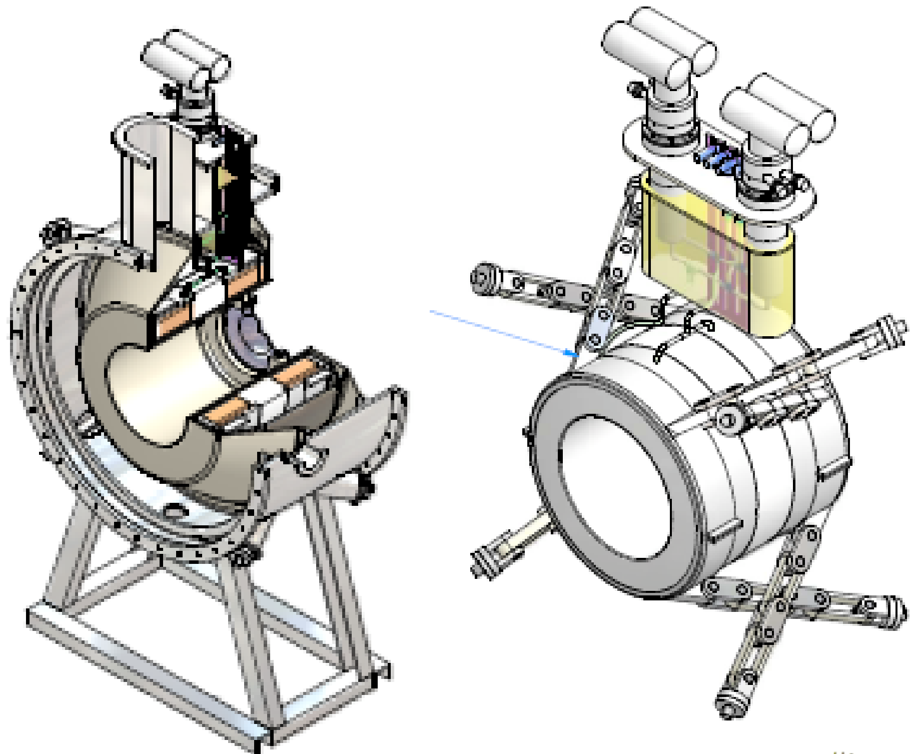


Focus Coils (1)

Design led by UK (Baynham, Bradshaw, Green, Lau, Yang)

- magnet comprises two coils that can be run with same polarity (solenoid mode) or opposite (bucking) polarity (flip mode)
  - cold mass supports must handle forces for both configurations
  - Now ordered at Tesla Inc.





Focus Coils (2)

Focus coil parameters:

Parameter		Value
Inner vacuum vessel radius (mm)		687
Outer vacuum vessel radius (mm)		707
AFC module overall length (mm)		842
Focusing magnet cryostat warm bore radius (mm)		235
Focusing magnet cryostat outer radius (mm)		707
Focusing coil magnet length (mm)		720
Cold-mass inner radius (mm)		247
Solenoid coil inner radius (mm)		263
Solenoid coil thickness (mm)		84
Length of individual solenoid coil (mm)		210
Longitudinal spacing between coils (mm)		200
No. of layers per coil		76
No. of turns per layer (each coil)		127
Design current, flip mode [a] (A)		208.3
Av. Coil current density at design current [a] (Amm^{-2})		113.9
Magnet self-inductance, flip mode (H)		~69
Stored energy at design current [a], flip mode (MJ)		~1.5
Peak field in winding at design current [a], flip mode (T)		6.39
Design temperature margin at design current [a] (K)		~1.1
Inter-coil force at design current [a] (MN)		1.82
Peak cold-to warm force at design current [a] (MN)		~0.30

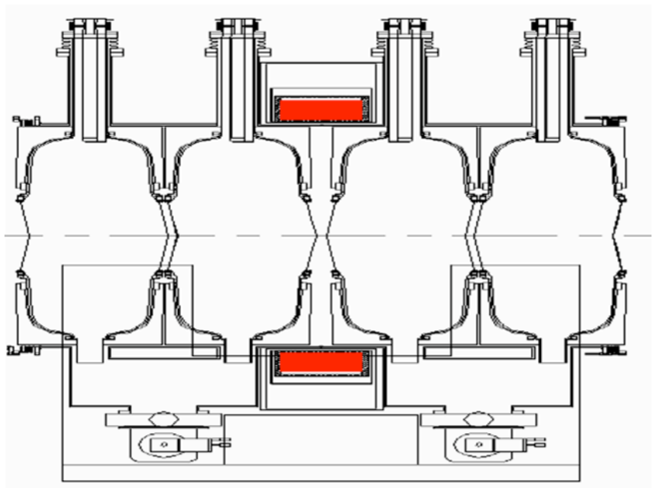
[a] Design current corresponds to a central momentum of 200 MeV/c and $\beta_{\perp}$ = 420 mm.

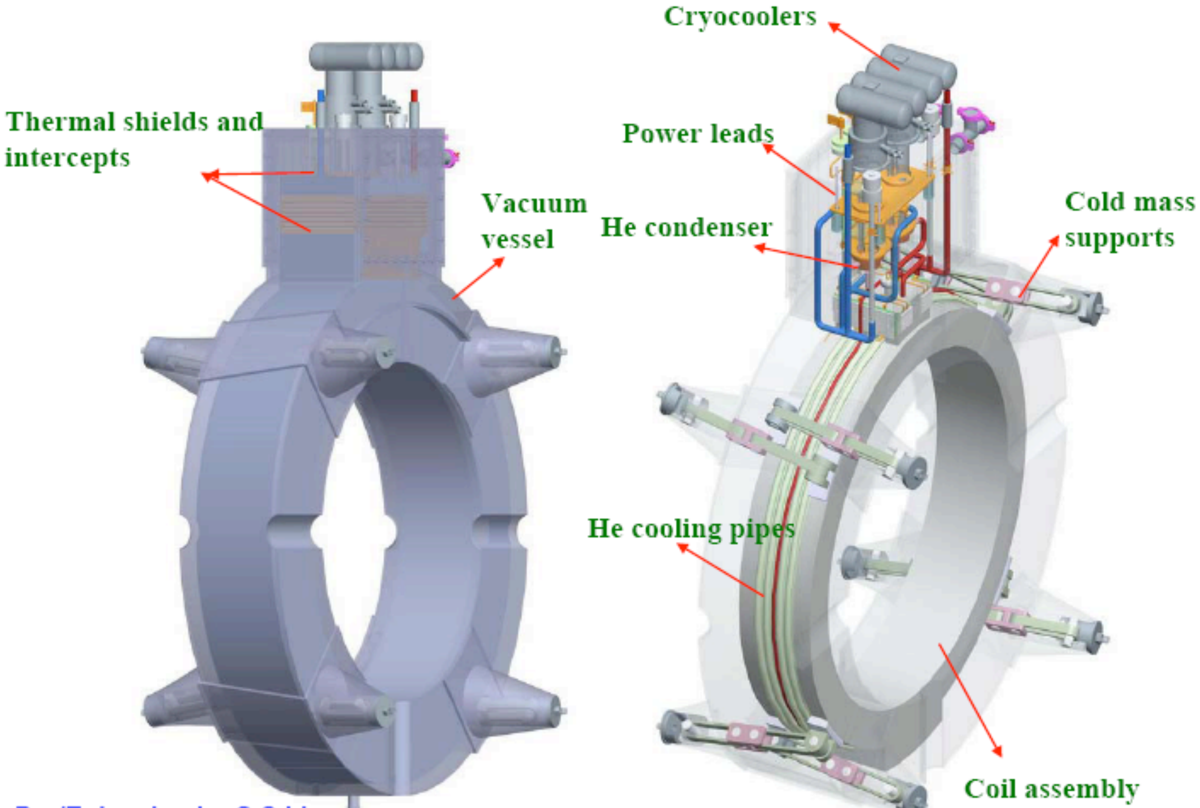
Coupling Coil (1)

construction by LBNL(USA) ICST/HarbinIT(China) (Green, Jia, Virostek, Li Wang)

magnet is a single 1.5 m diameter coil that fits outside of RF cavities

哈尔滨工业大学
低温与超导技术研究所





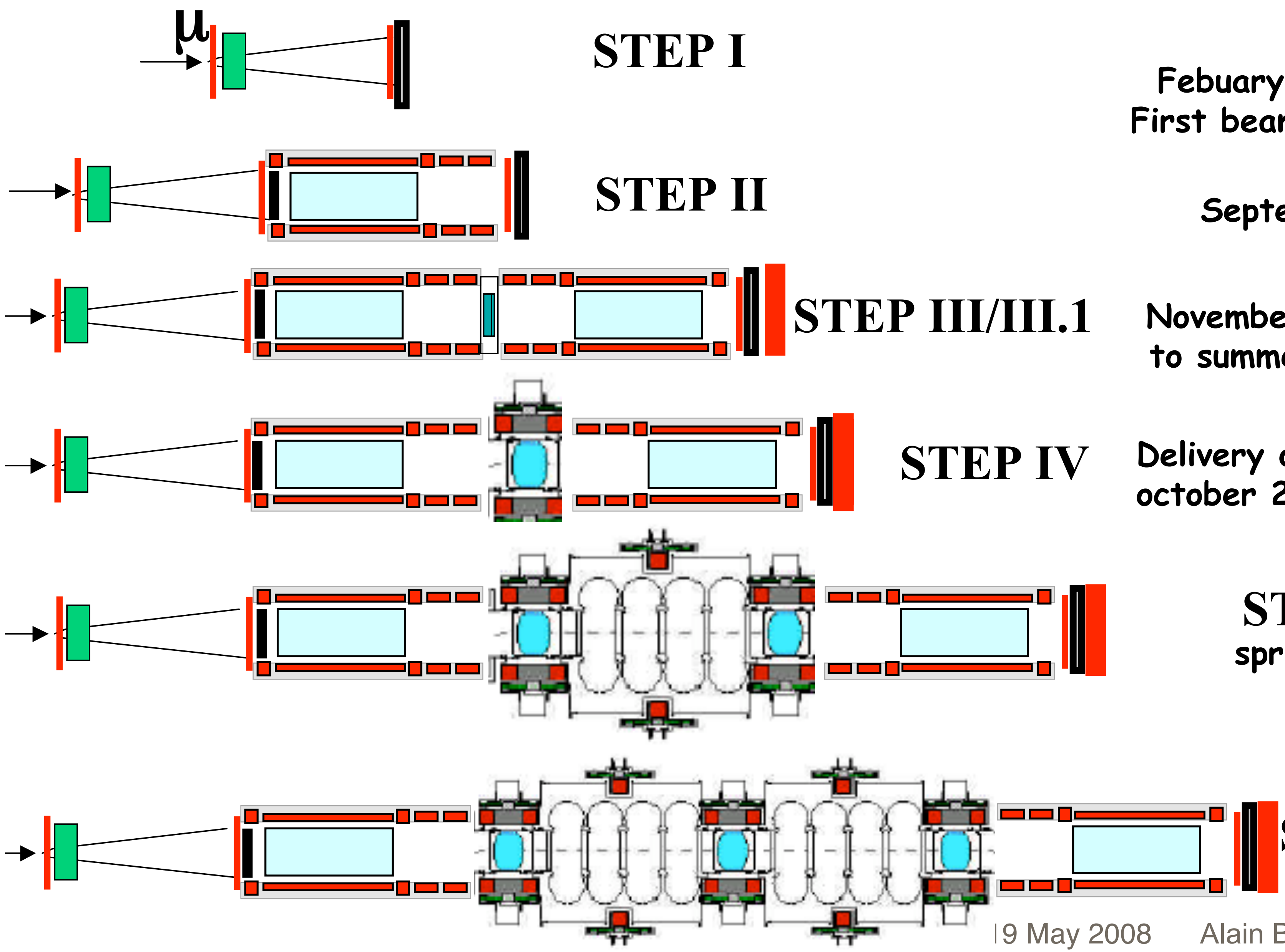
Pro/E drawing by C.S.Liu

Coupling Magnet (2)

Coupling coil parameters:

	Tracker solenoid conductor	
Parameter	Non-flip	Flip
Coil Length (mm)	285	285
Coil Inner Radius (mm)	744	744
Coil Thickness (mm)	102.5	102.5
Number of Layers	96	96
No. Turns per Layer	166	166
Magnet J (A mm-2)*	90.11	95.53
Magnet Current (A)*	165.2	175.1
Magnet Self Inductance (H)	~564	~564
Peak Induction in Coil (T)*	5.85	6.20
Magnet Stored Energy (MJ)**	~7.7	~8.6
4.2 K Temp. Margin (K)*	~1.8	~1.6

Aspirational MICE Schedule as of April 2008



STEP I — Febuary-July 2008
First beam observed!

STEP II — September 2008

STEP III/III.1 — November 2008
to summer 2009

STEP IV — Delivery of 1st FC
october 2009!

STEP V — spring 2010

STEP VI — Q4 2010
-20

MUON ACCELERATION

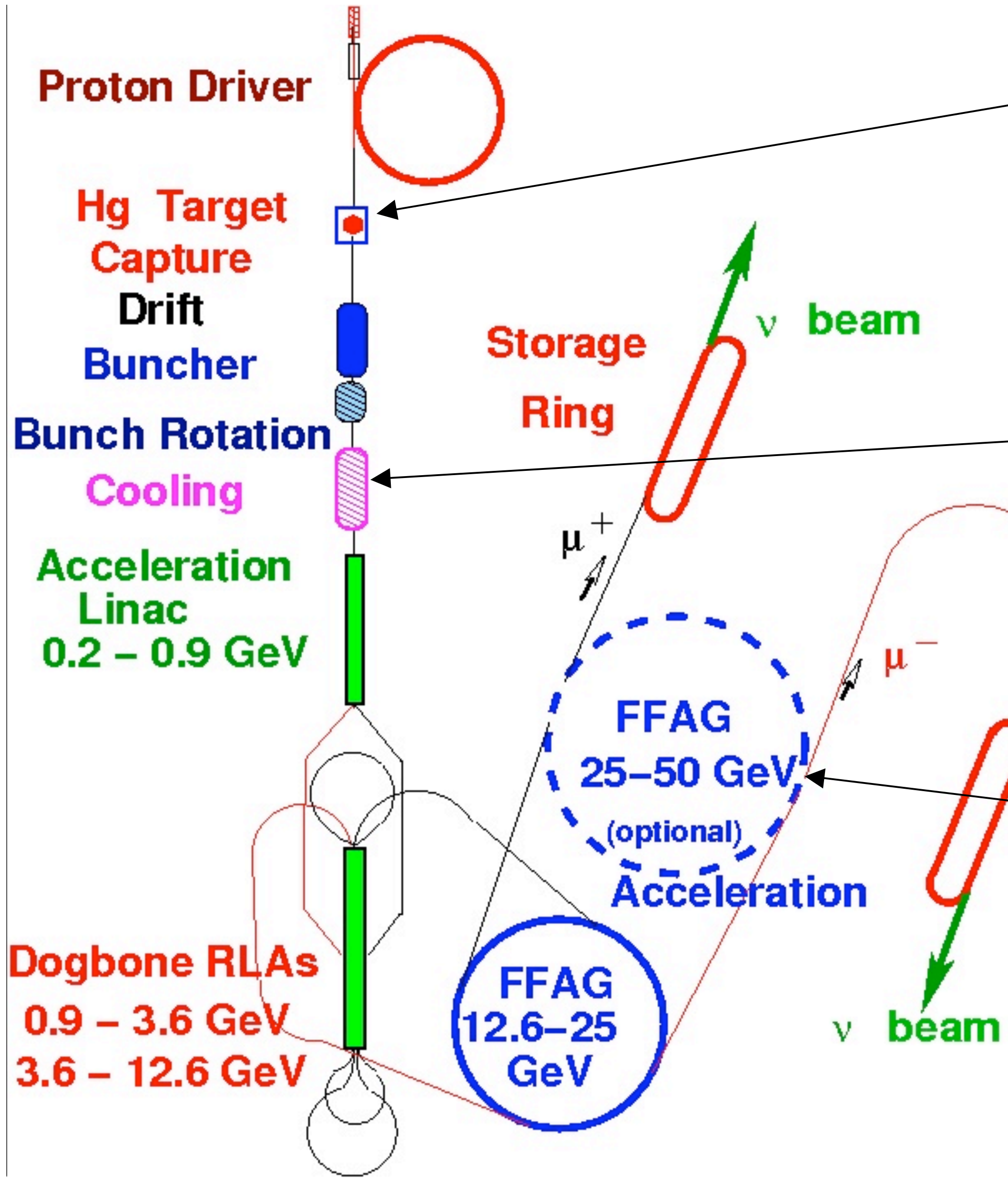
Muon life time 2.2 microseconds (no time for a meeting!)

Fixed field magnets

Recirculating linacs (race track or Dog-Bone) : 1 turn per arc

FFAG: several turns per arc.

Major challenges tackled by R&D expts



High-power target
. 4MW
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MERIT& HARP
experiments @CERN

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EMMA (Daresbury)

ISS baseline

PRISM-FFAG Magnet

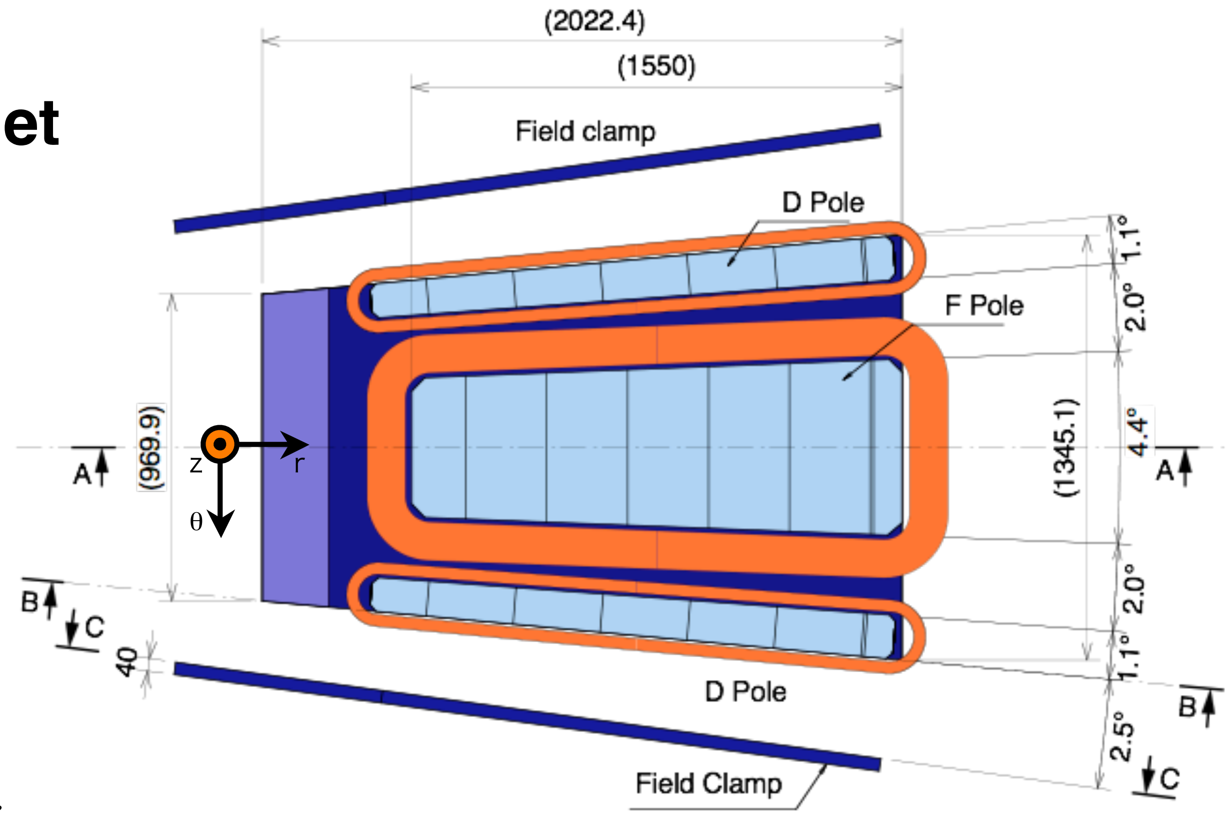
C-shape yoke
Effective Aperture

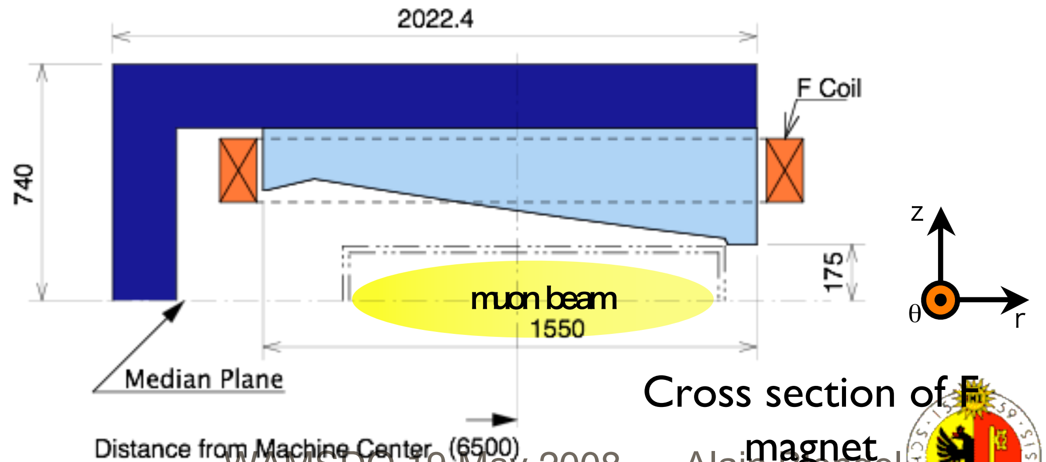
- 100 cm (horizontal)
- 30 cm (vertical)

Narrow shape
- to make room for RF cavities in the straight section
- Length along beam axis : ~1.2 m

Slant pole shape

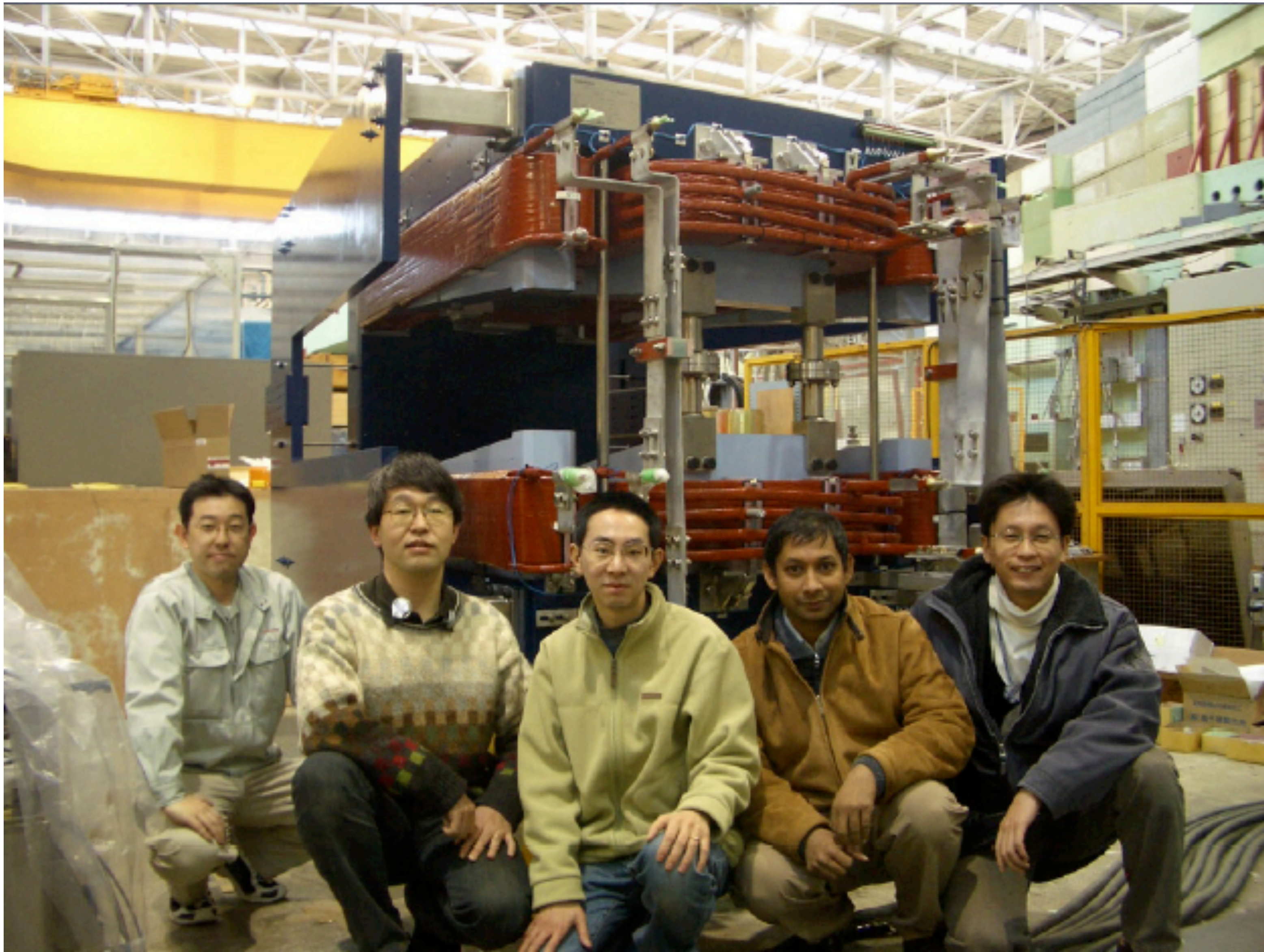
- Field index = 4.6





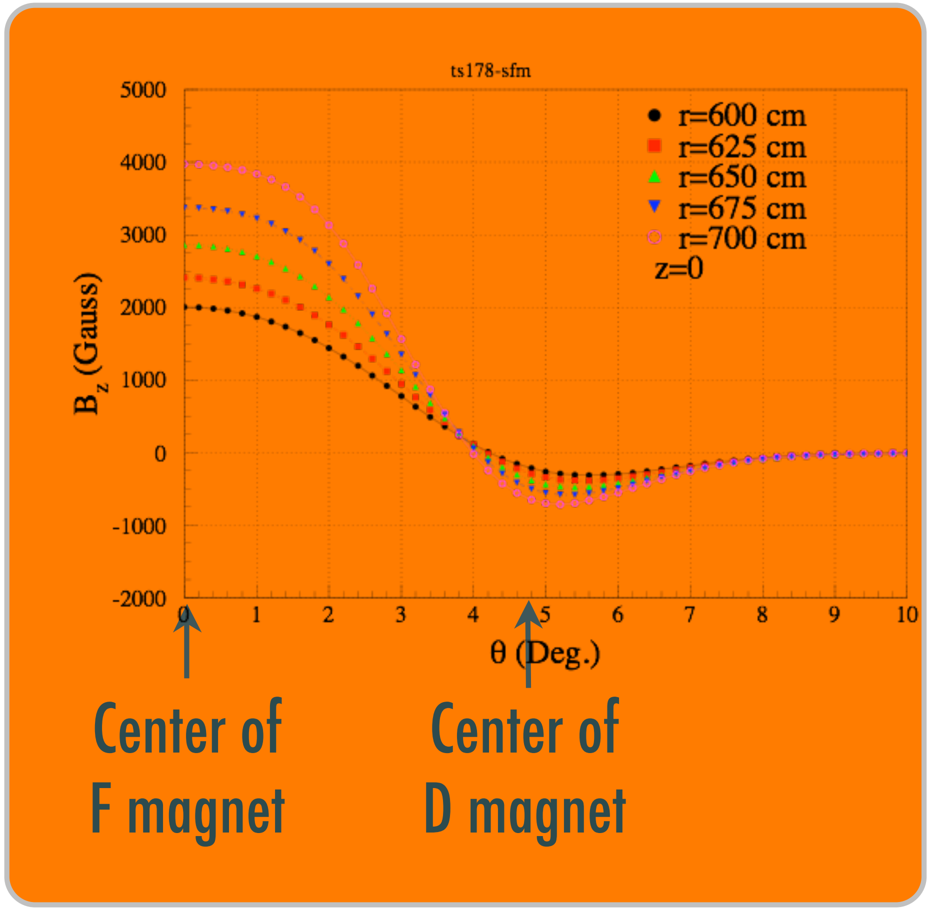
Cross section of F magnet

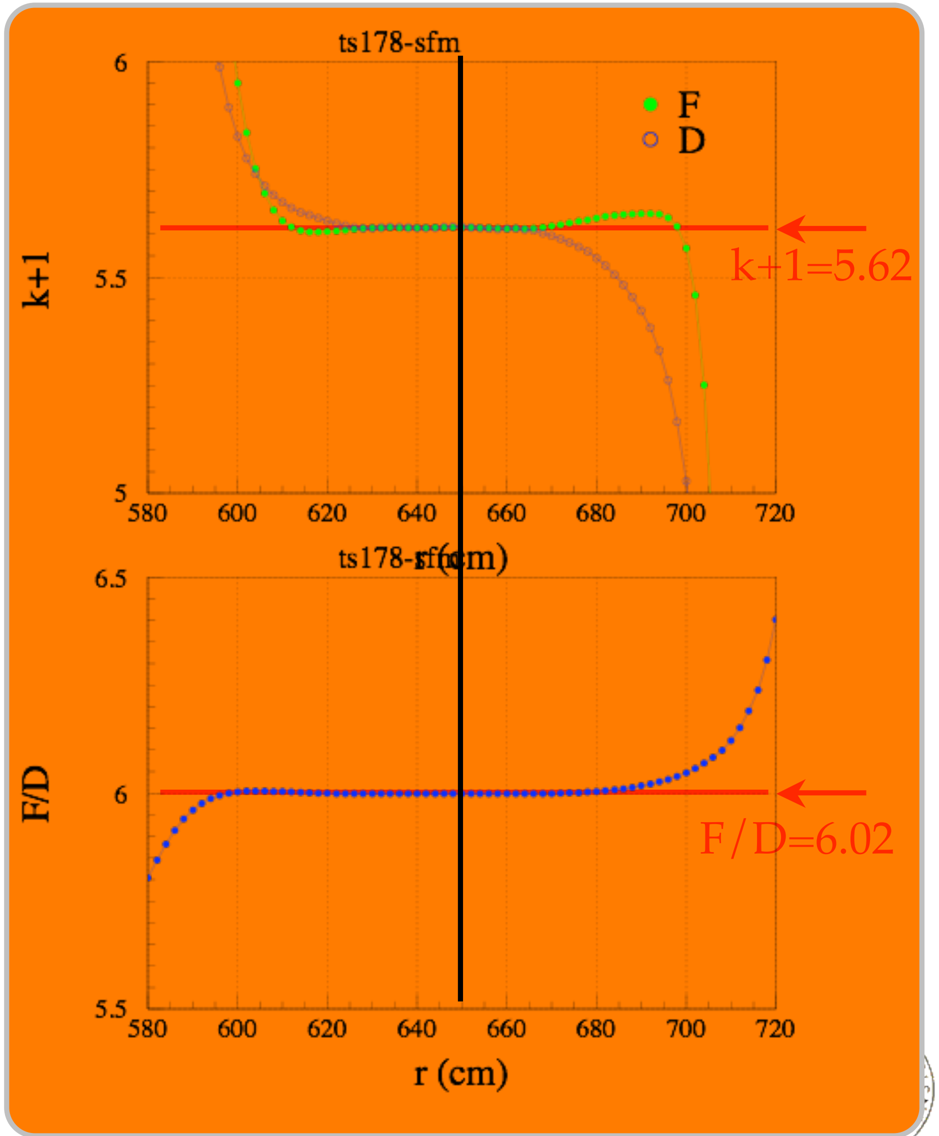
PRISM-FFAG Magnet



Design Field

TOSCA calculation





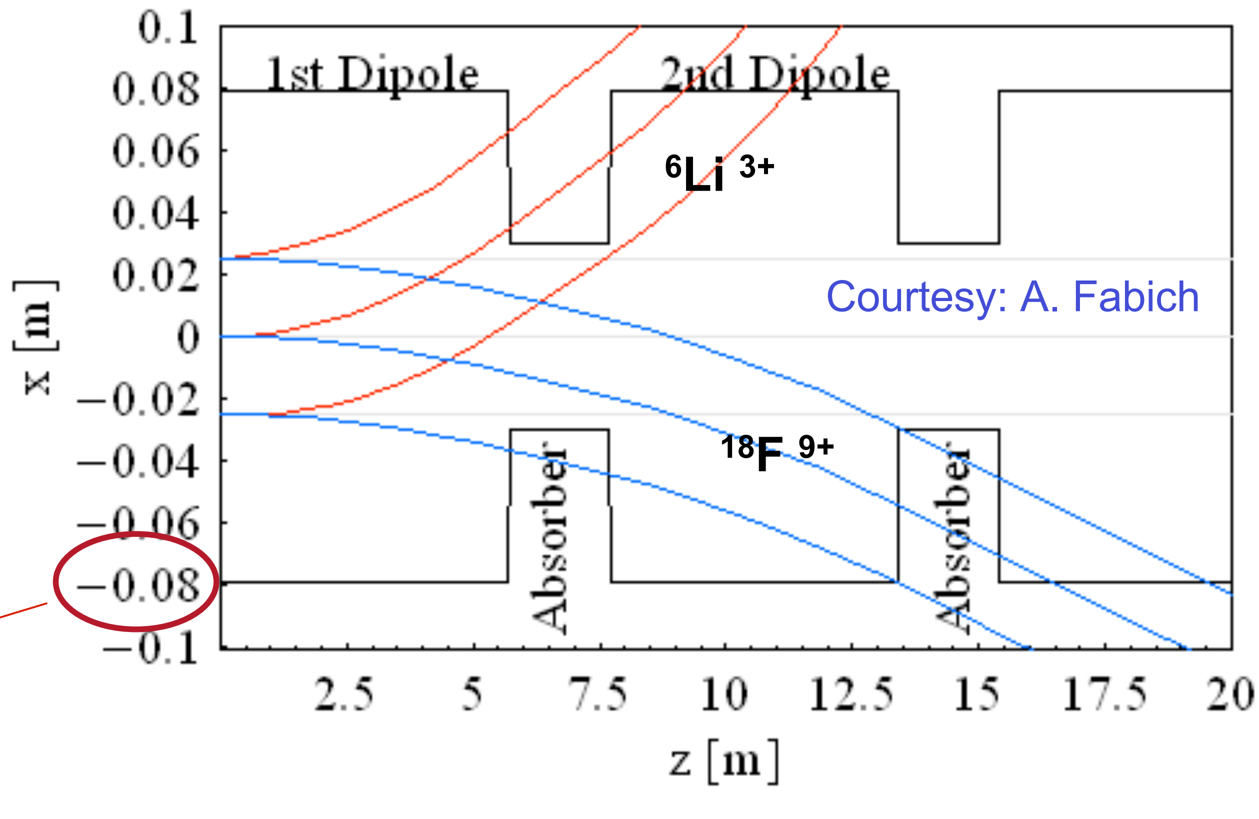
Decay ring

Similar problem for muon or beta-beam decays.

Muon decay ring is relatively benign for neutrino factory
muons decay into electrons which cn be easily shielded
Issue with polarimeter magnet

Much more serious for the beta beam decay ring
> 99% of the energy goes into decay ion.
Study made at CERN in the framework of EURISOL design study

The Dipole Coil Size



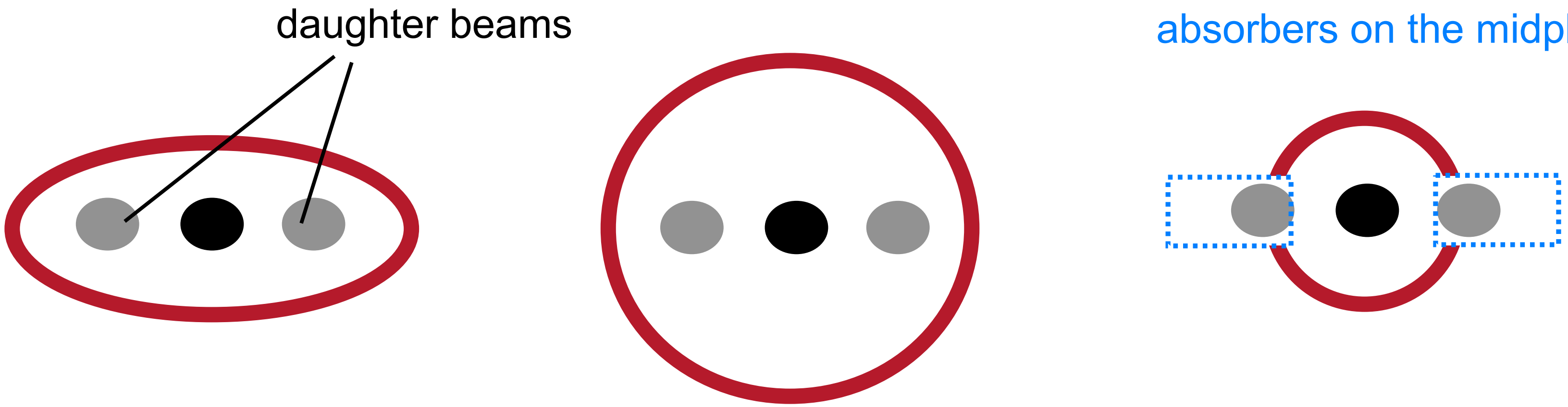
8 cm radius needed for the **horizontal plane** where the decay products cause daughter beams

4 cm for the vertical plane

The Alternatives

Depending on the severity of the heat-deposition and on construction constraints, several options are possible:

Eventually, we can put absorbers on the midplane



Elliptic coil cross section more adapted to the total beam size but may have mechanical constraints

Circular coil cross section is a "safe" solution for first estimate

"Open Mid Plane" if the coil cannot stand the heat deposition from the decay products in the mid plane

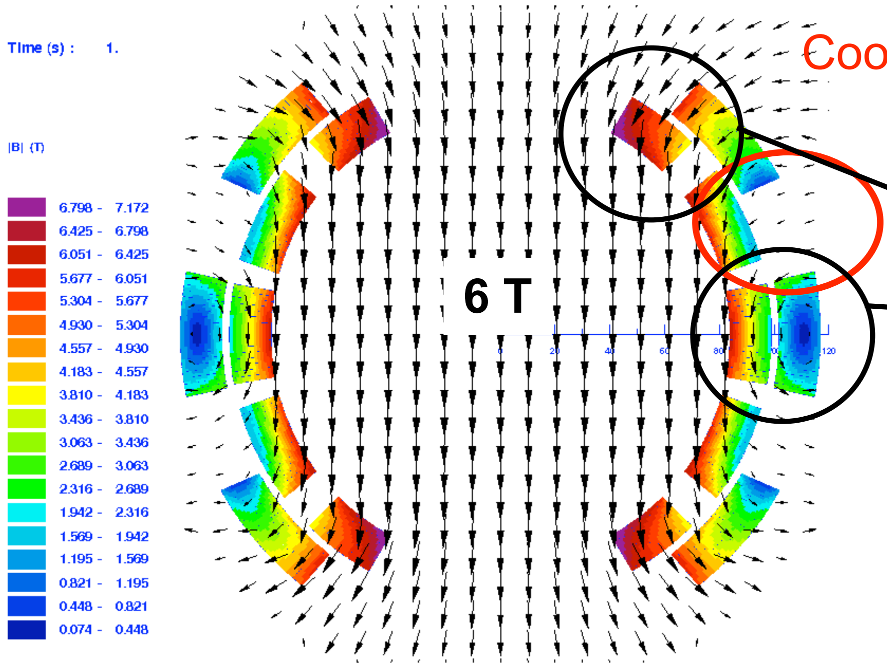
The Dipole

Classical LHC technology (wellknown):

NiTi cable Cable Size: 15.1 mm x 1.73 mm Double Layer

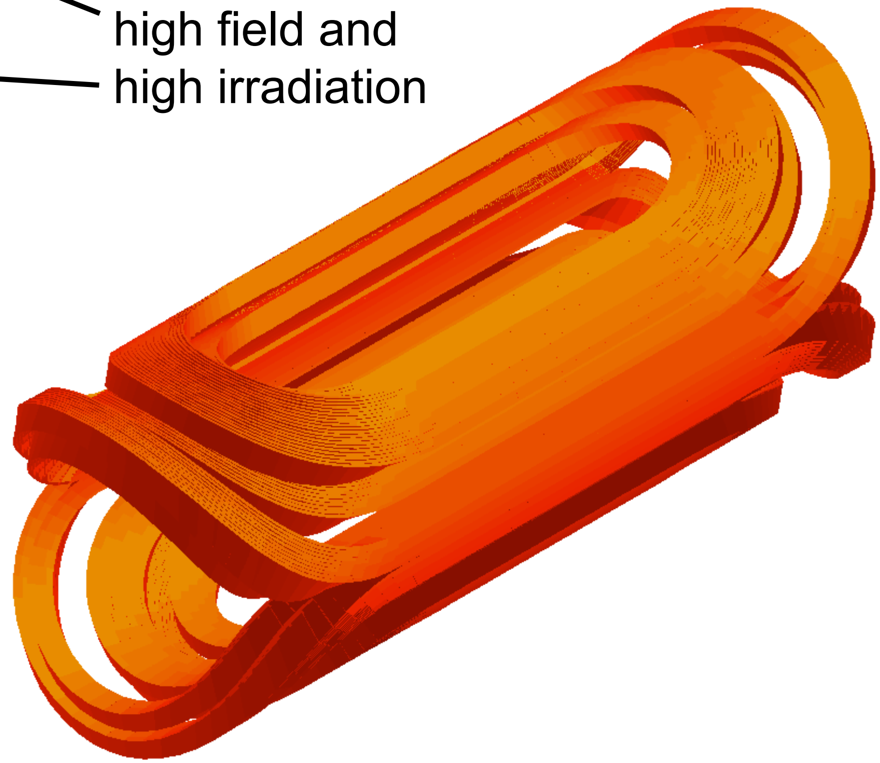
1.9 K, Superfluid Helium

beam pipe size: 16 cm diameter Length 6 m Compact coil end



Cooling channel for inner layer can be added if needed.

2 critical regions in coil cross-section: high field and high irradiation



Aim is a compact coil end to reduce impinging particles

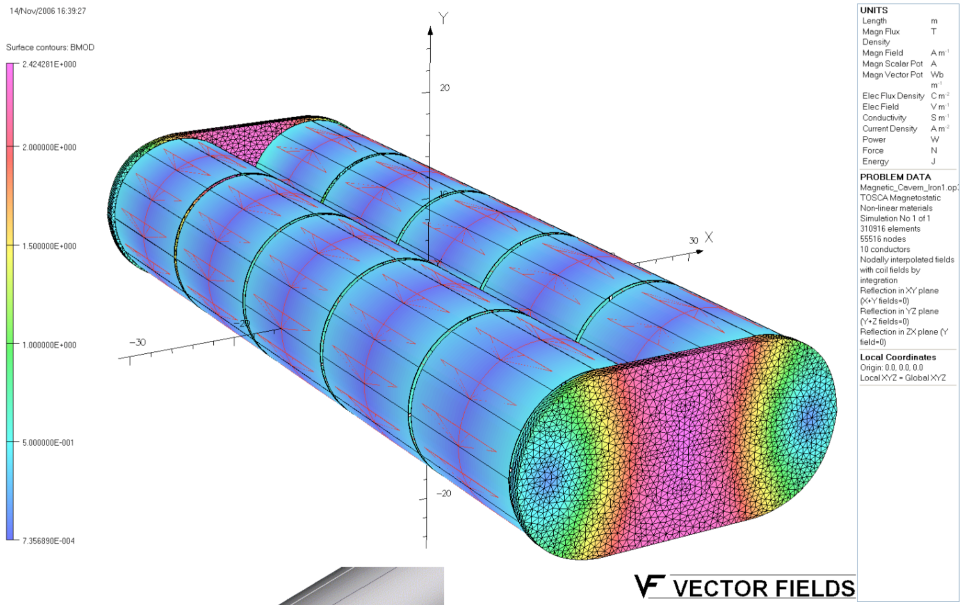
Neutrino Factory detector magnets

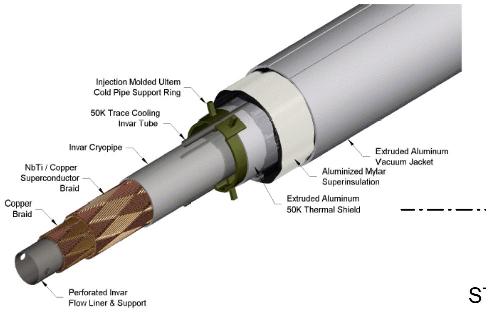
Magnetic field required to separate signal from background.

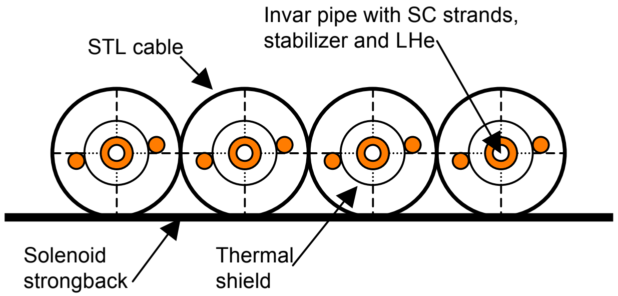
Easy (baseline)solution: magnetized iron detector --but not trivial for 100 kton!

Challenge for more fine grained technologies
(electron or tau detection in scintillator, Liquid Argon or emulsion detector)

NF Detector R&D: Magnetic Cavern







Cable based design (Fermilab)

Features

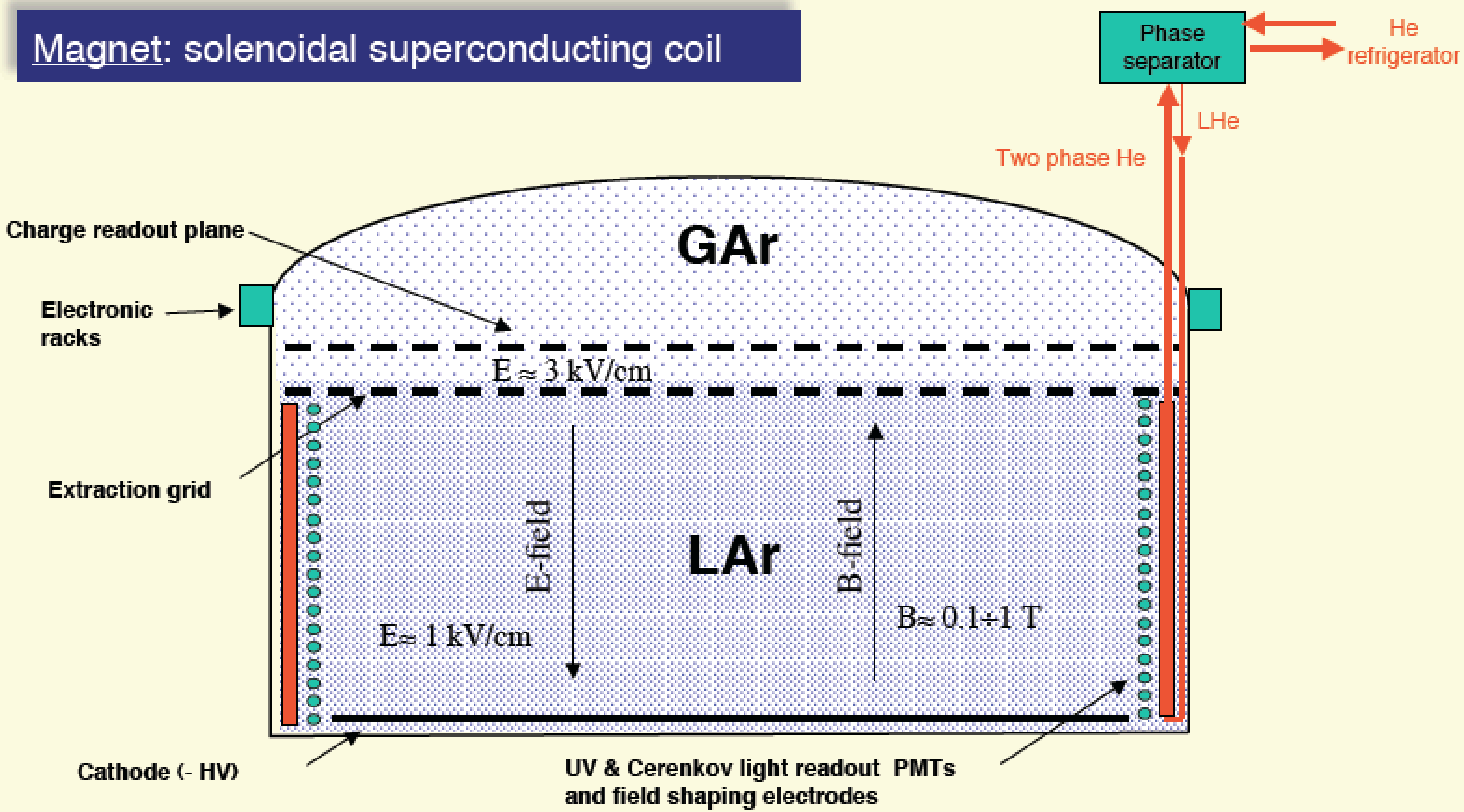
- 10 solenoids
- 15-m long 15 m ID each
- Bnom~0.5 T (50% margin)
- 1 m iron wall, B~2.4 T
- Good field uniformity

Solve technical problems

Reduce detector cost

Tentative layout of a large magnetized GLACIER

Magnet: solenoidal superconducting coil



LHe Cooling: Thermosiphon principle + thermal shield=LAr

CONCLUSIONS

High performance Neutrino facilities are key to neutrino mass hierarchy and CP violation

1. Study and R&D recommended by European Strategy for Particle Physics
2. Difficult but well established. Considerable challenges for magnet builders
3. Main difficulties lie in
   -- inclusion of target inside horn or 20T solenoid with high level radiation
      MERIT success
   -- cost reduction for the solenoidal cooling system
      MICE will demonstrate first cooling channel operation by 2010-11
   -- acccelerator magnets (FFAG) and storage ring SC magnets
      with large emittance and high power beam (beam losses)
   -- magnets for fully active detectors (Scintillator, LArgon)

Muon colliders offer alternative and attractive route to high precision/energy colliders

1. depend on ability to produce sophisticated or extreme magnets
2. Helicoidal channel for 6D cooling
3. 50 T HTS or hybrid solenoid for final cooling stages

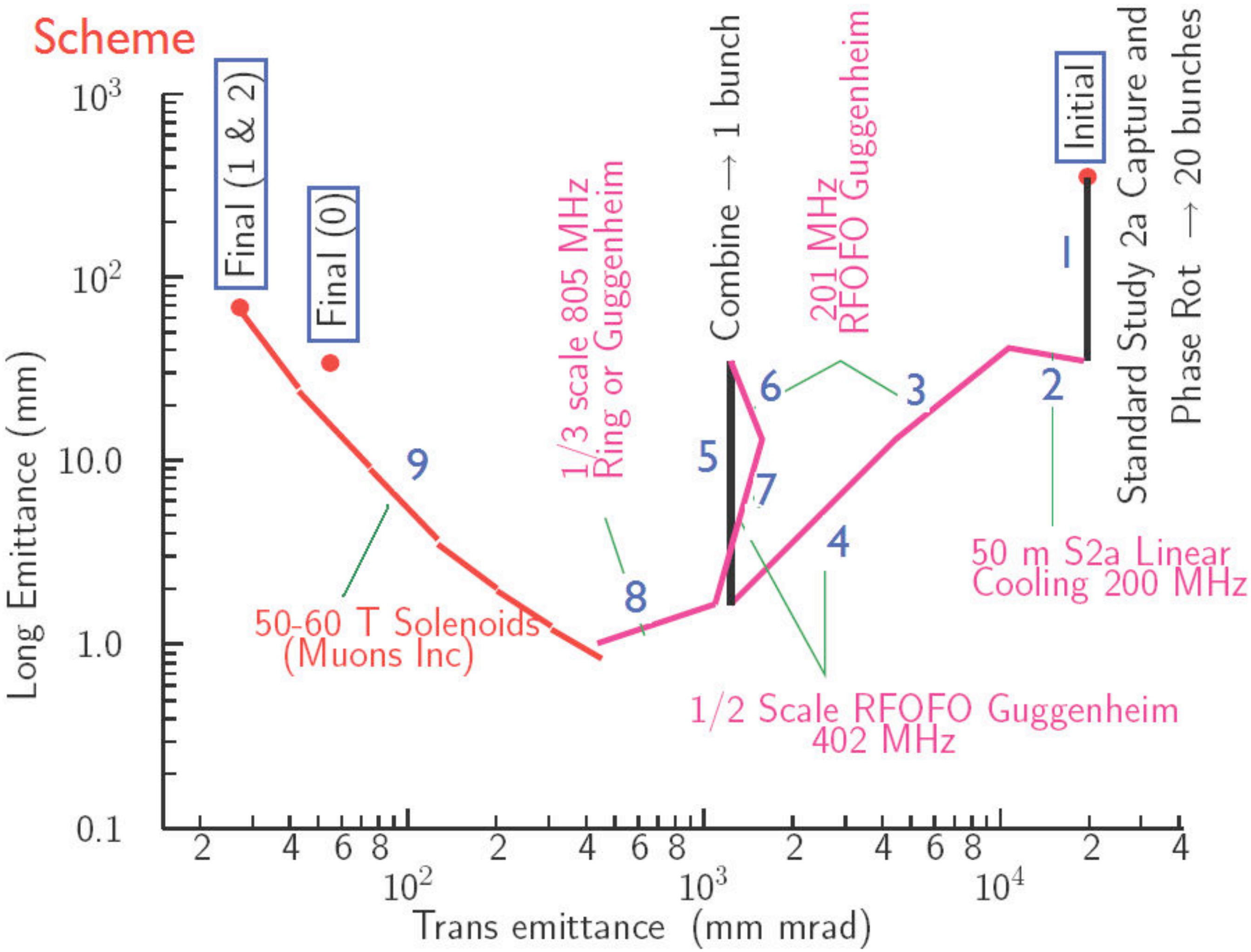
More Challenges: Cooling for the Muon Collider

Collider Parameters

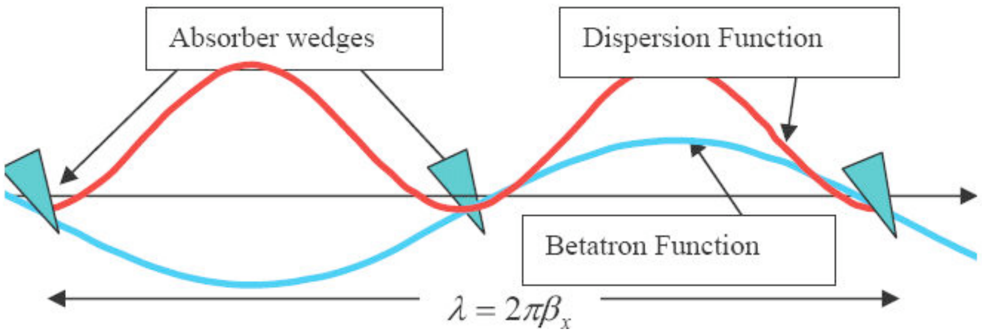
	Low emit	Base	Base	
C of m Energy	1.5	1.5	4	TeV
Luminosity	2.7	1	4	10^{34} cm^{2}sec^{-1}
Muons/bunch	0.1	2	2	10^{12}
Ring circumference	2.3	3	8.1	km
Beta at IP $= \sigma_z$	5	10	3	mm
rms momentum spread	1.0	0.1	0.12	%
Required depth for ν rad	35	13	135	m
Muon survival	0.3	0.07	0.07	
Repetition Rate	65	12	6	Hz
Proton Driver power	3.6	$\approx$4	$\approx$ 1.8	MW
Muon Trans Emittance	2.1	25	25	pi mm mrad
Muon Long Emittance	370,000	72,000	72,000	pi mm mrad

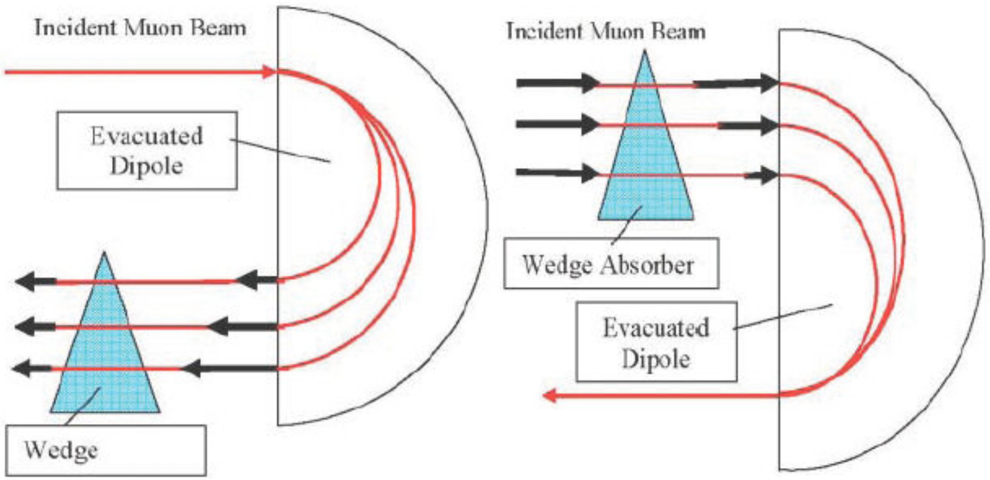
- Luminosities are comparable to CLIC's
- Baselines use real Collider Ring designs, though both have problems
- Baseline emittance and intensity requirement same for two energies
- Lower emittance desirable because allows (but more) smaller bunches
  but required 'Parametric Ionization Cooling' not yet simulated

A muon collider cooling scenario



Extreme μ Cooling -PIC & REMEX





Parametric-Resonance Ionization Cooling

Drive a ½-integer parametric resonance

Hyperbolic Motion

Emittance Exchange

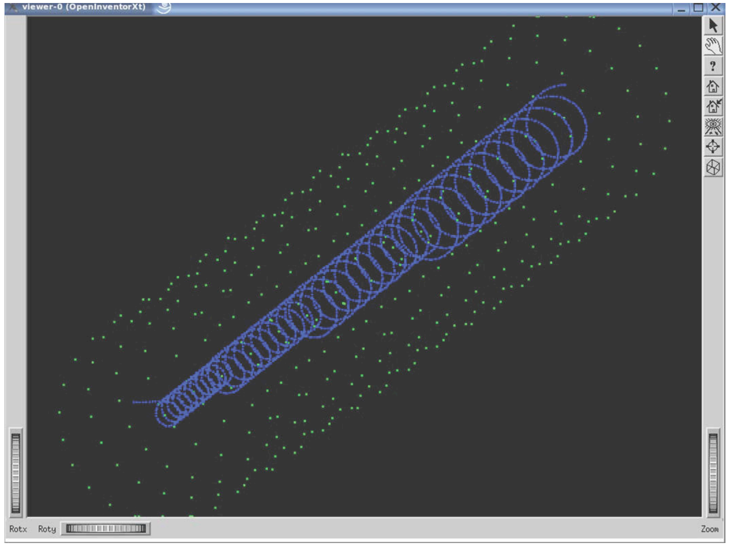
Increase or decrease longitudinal ε

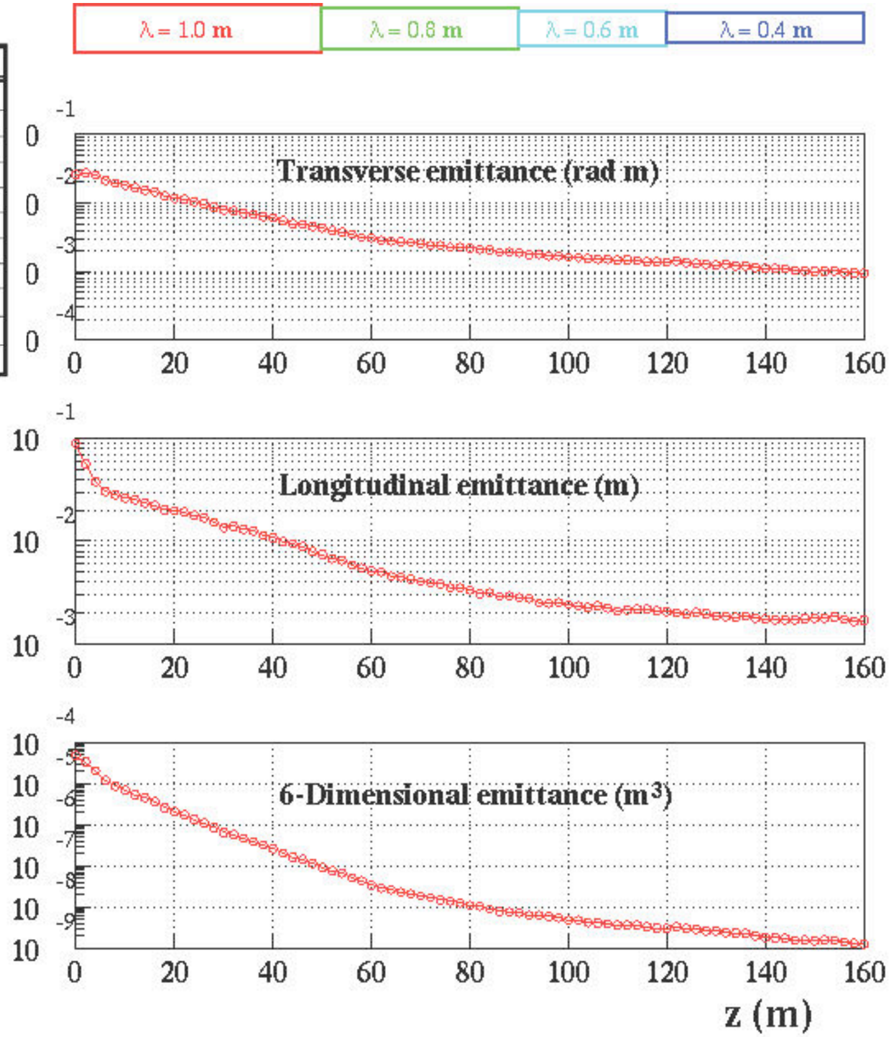
decrease or increase transverse ε

Space-Charge Effects Could be Critical

Helical Cooling Channel

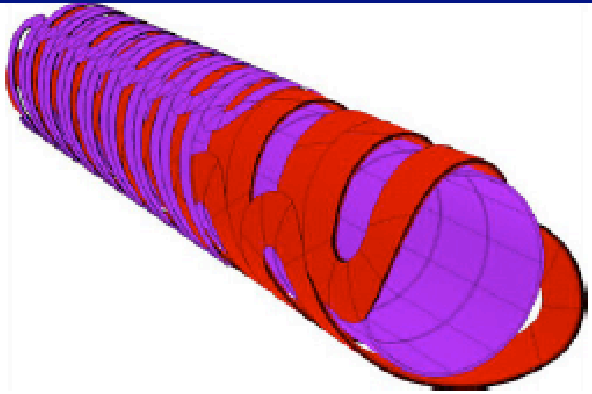
Series HCCs						
			Segment			
			1st	2nd	3rd	4th
L	*Length*	m	50	40	30	40
λ	*Helix period*	m	1.0	0.80	0.60	0.40
a	*Reference orbit radius*	m	0.16	0.13	0.095	0.064
κ	*Helix pitch*		1.0	1.0	1.0	1.0
B	*Solenodial component*	T	-6.95	-8.68	-11.6	-17.4
b_d	*Helix dipole coefficient*	T	1.81	2.27	3.02	4.53
b_q	*Helix quadrupole coefficient*	T/m	-0.35	-0.44	-0.59	-0.88
b_1	*Helix sextupole coefficient*	T/m2	0.031	0.039	0.051	0.077

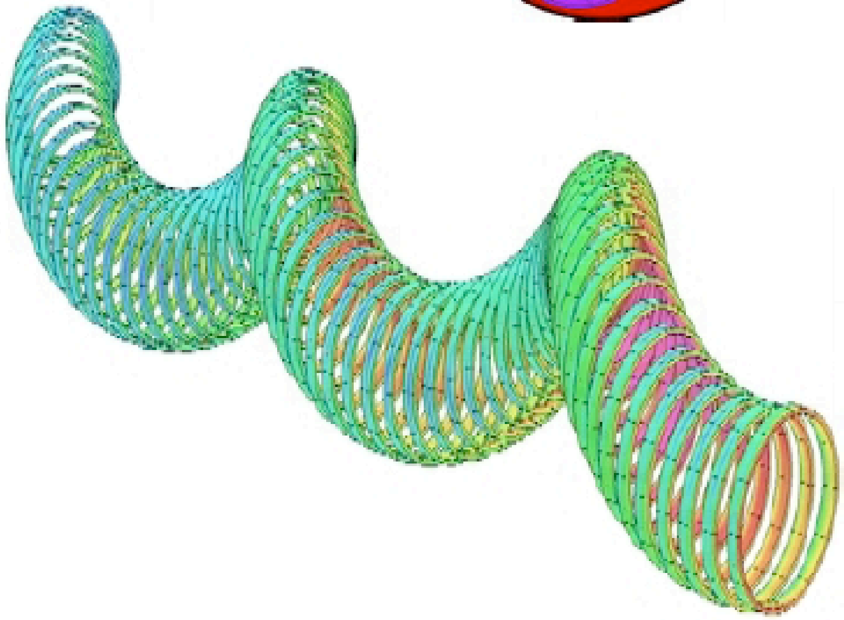




HCC magnet design considerations

- HCC requires superimposed solenoid, helical dipole and helical quadrupole fields
- Helical solenoid (HS) use smaller coils than a "traditional" design
  - Lower peak field
  - Less stored energy
  - Lower cost
- Field components in HS determined by geometry
  - Over constrained
  - Coil radius is not free parameter





V.Kashikin

4-coil Helical Demonstration Model

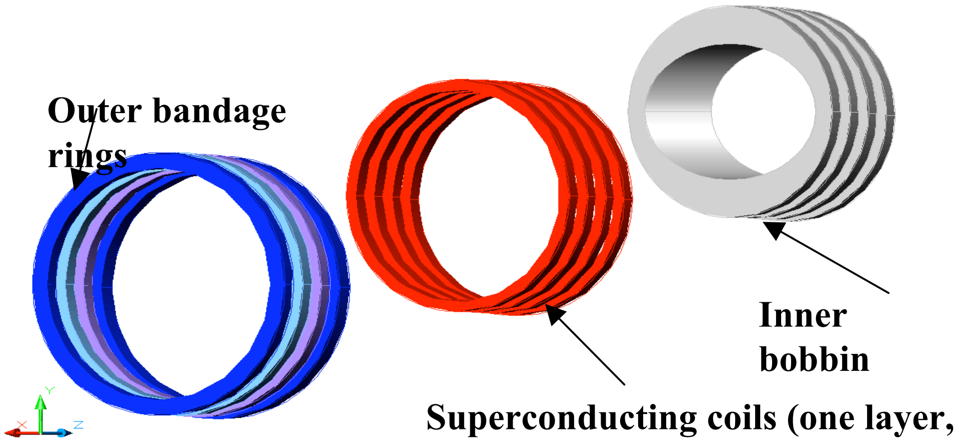
Goals:

- validate mechanical structure and fabrication methods
- study quench performance and margins, field quality, quench protection

Features:

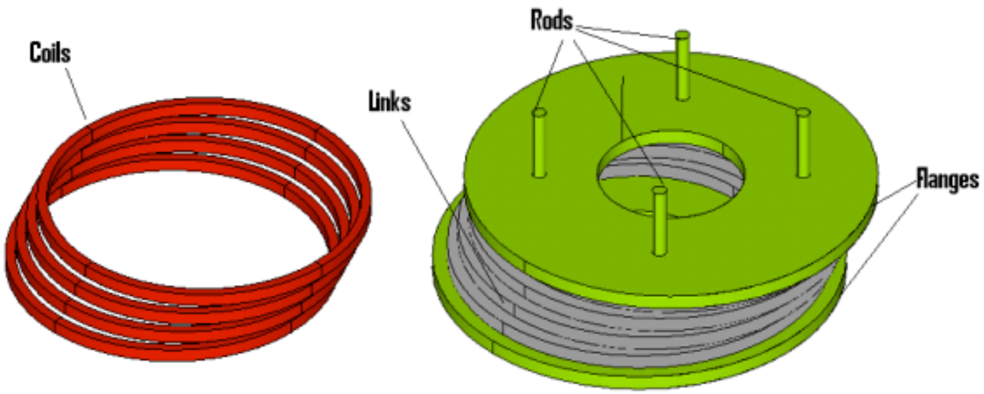
- use existing SSC cable
- fields and forces as in the HS for CDE

Funded by MCTF and Muons Inc.



Parameter	Model Nominal	Model Max	MANX
Peak superconductor field	3.3 T	4.84 T	5.7 T
Current	9.6 kA	14 kA	9.6 kA
Number of turns/section	10	10	10
Coil inner diameter	420 mm	420 mm	510 mm
Lorentz force/section, Fx	70 kN	149 kN	160 kN
Lorentz force/section, Fy	12 kN	25 kN	60 kN
Lorentz force/section, Fxy	71 kN	151 kN	171 kN
Lorentz force/section, Fz	157 kN	337 kN	299 kN

4-coil model Analysis

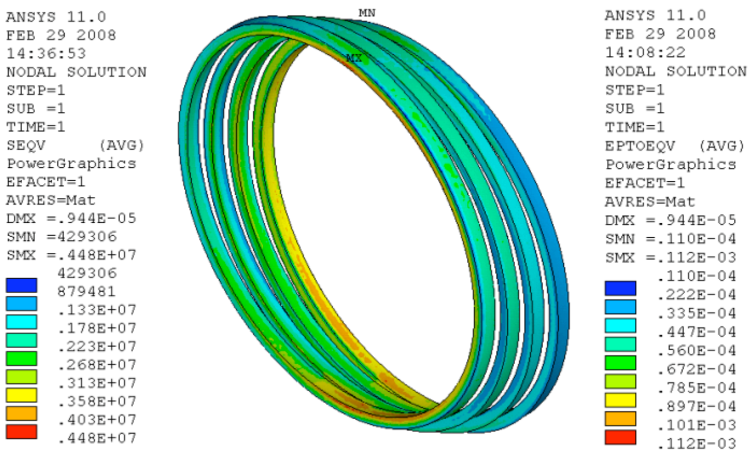


Magnetic and mechanical engineering design complete:

- 3D field distribution
- 3D stress/strain analysis in coils and mechanical structure

Von Mises Stress

Von Mises Stress

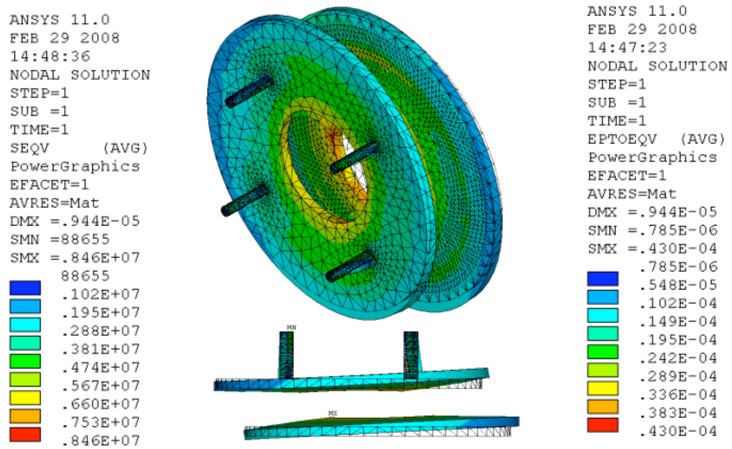


Max. Stress: 4.48*MPa*

Max. Strain: 0.0112%

Von Mises Stress

Von Mises Strain



Max. Stress: 8.46*MPa*

Max. Strain: 0.0043%

4-coil fabrication status

Parts:

design complete

procurement in progress

Cable:

Extracted strand samples were tested

Practice winding complete:

cable stability and support during hard bend winding

coil size control

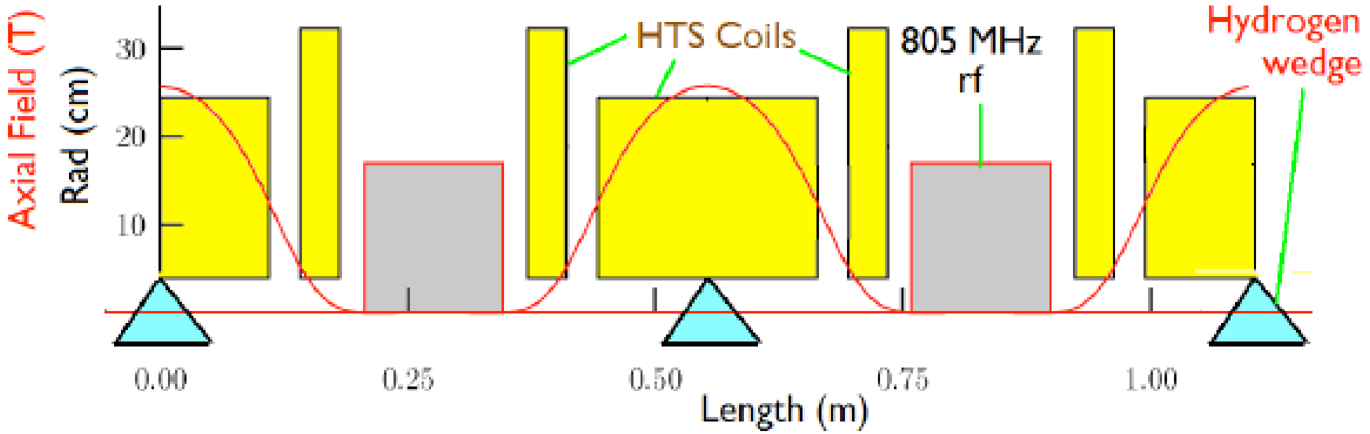
Instrumentation:

development started

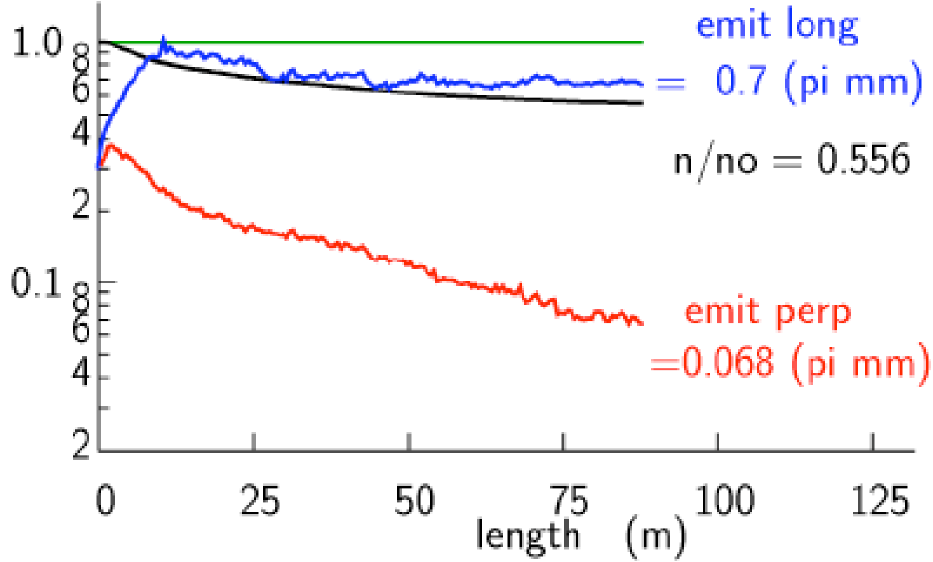
Model test:

September 2008

d) "Bucked Field" non flip lattice (Fernow, Alexahin)



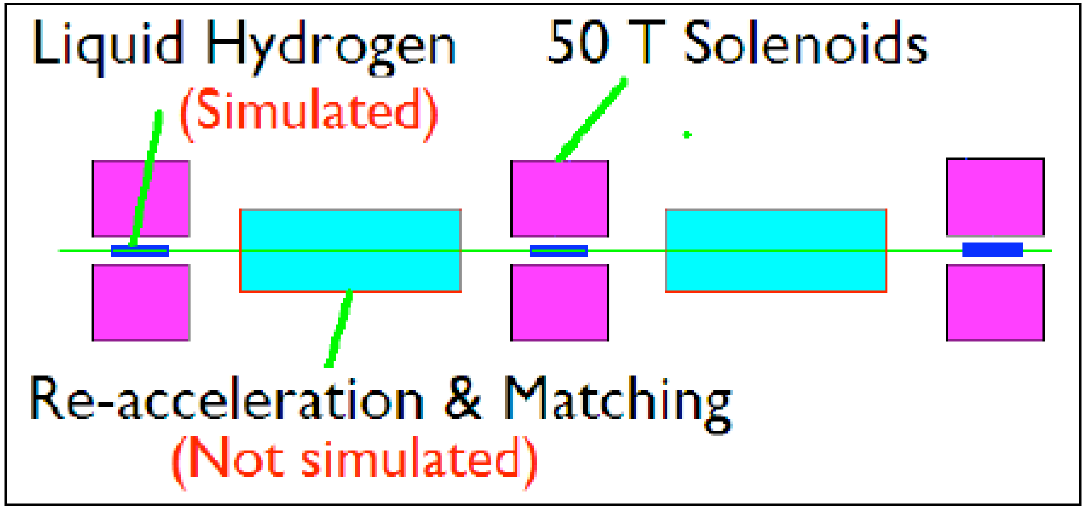
- $\Delta p/p$= 9.6 % ok for final cooling
- Bucking coils remove the field on RF
- 0.125 T By: 33 m circumference
- Transverse → 68 (mm-mrad)
  cf final = 25 (mm mrad)
- $\epsilon_{\|} = 0.7\ \pi$ mm (dp/p=2.5%)



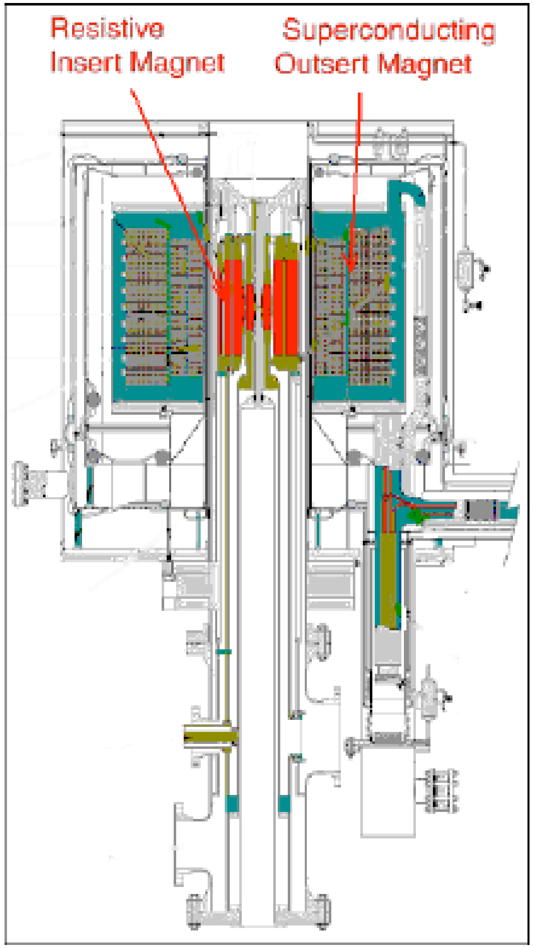
Loss rate greater than other systems - not fully understood

Final Transverse Cooling in High Field Solenoids

- Lower momenta allow transverse cooling to required low transverse emittance, but long emittance rises: Effectively reverse emittance exchange

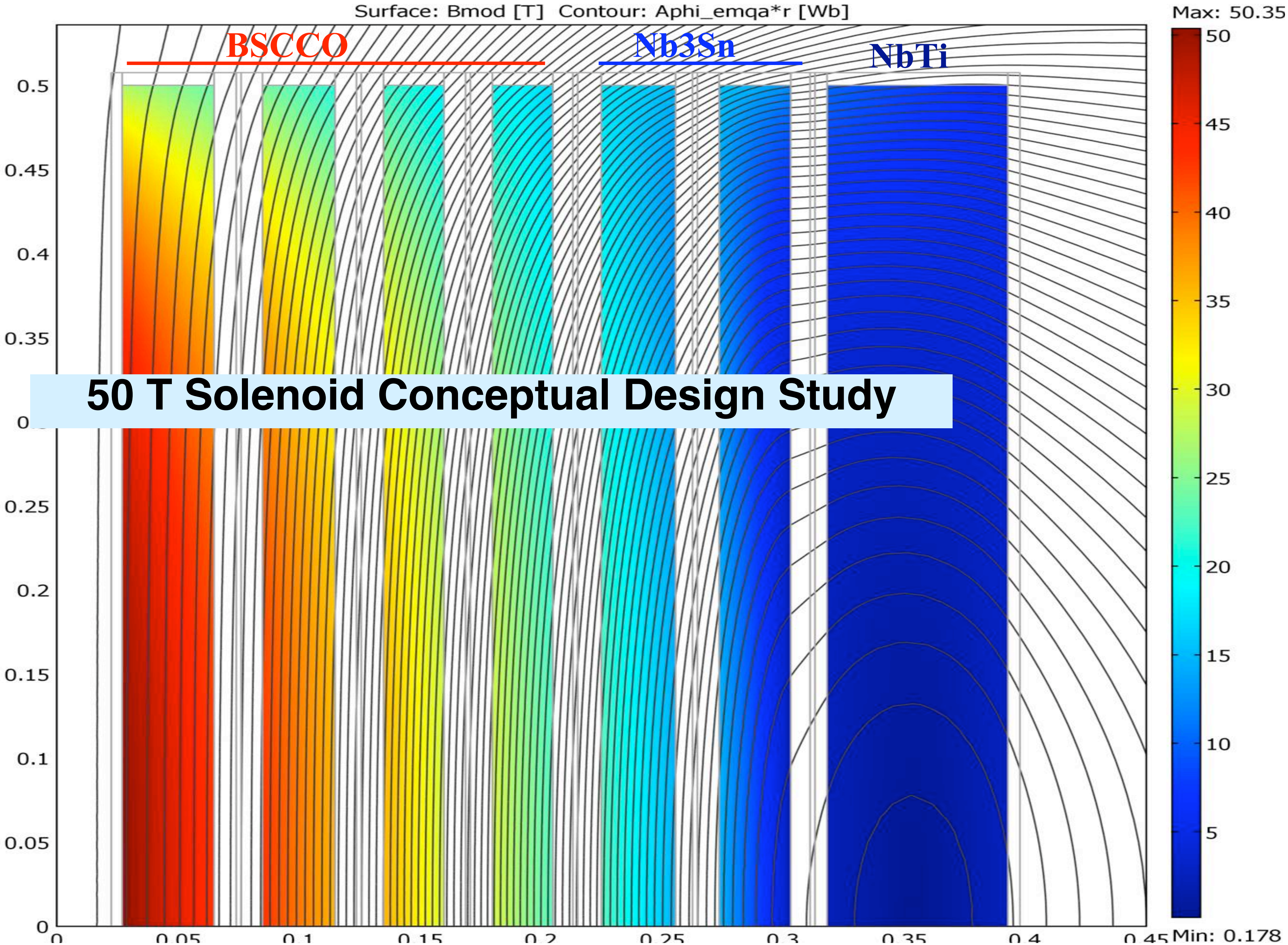


- ICOOL Simulation of cooling
  but with ideal matching & re-acceleration
- 45/50 T Solenoids
  - 45 T hybrid at NHMFL, but uses 30 MW
  - 30 T all HTS under construction
  - 50 T Design with HTS tape has rad=57 cm
- Parameters at each stage in appendix 3

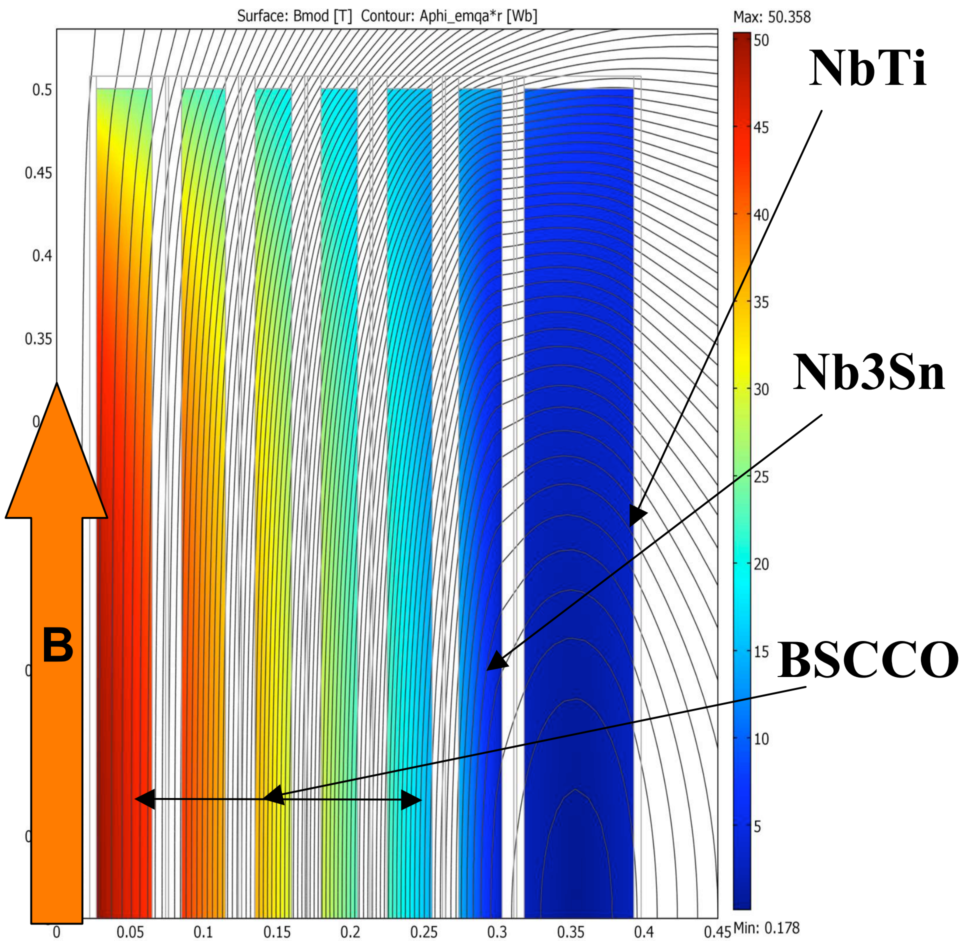


NHMFL 45 T Hybrid Magnet

50 T Solenoid Conceptual Design Study



50 T Solenoid Conceptual Design Study



Coil radius, m

Key design issues:

superconductor Jc

effect of field direction on Ic in case of HTS tapes

stress management

quench protection

cost

Solutions:

hybrid coil design

coil sections

CONCLUSIONS

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2. Helicoidal channel for 6D cooling
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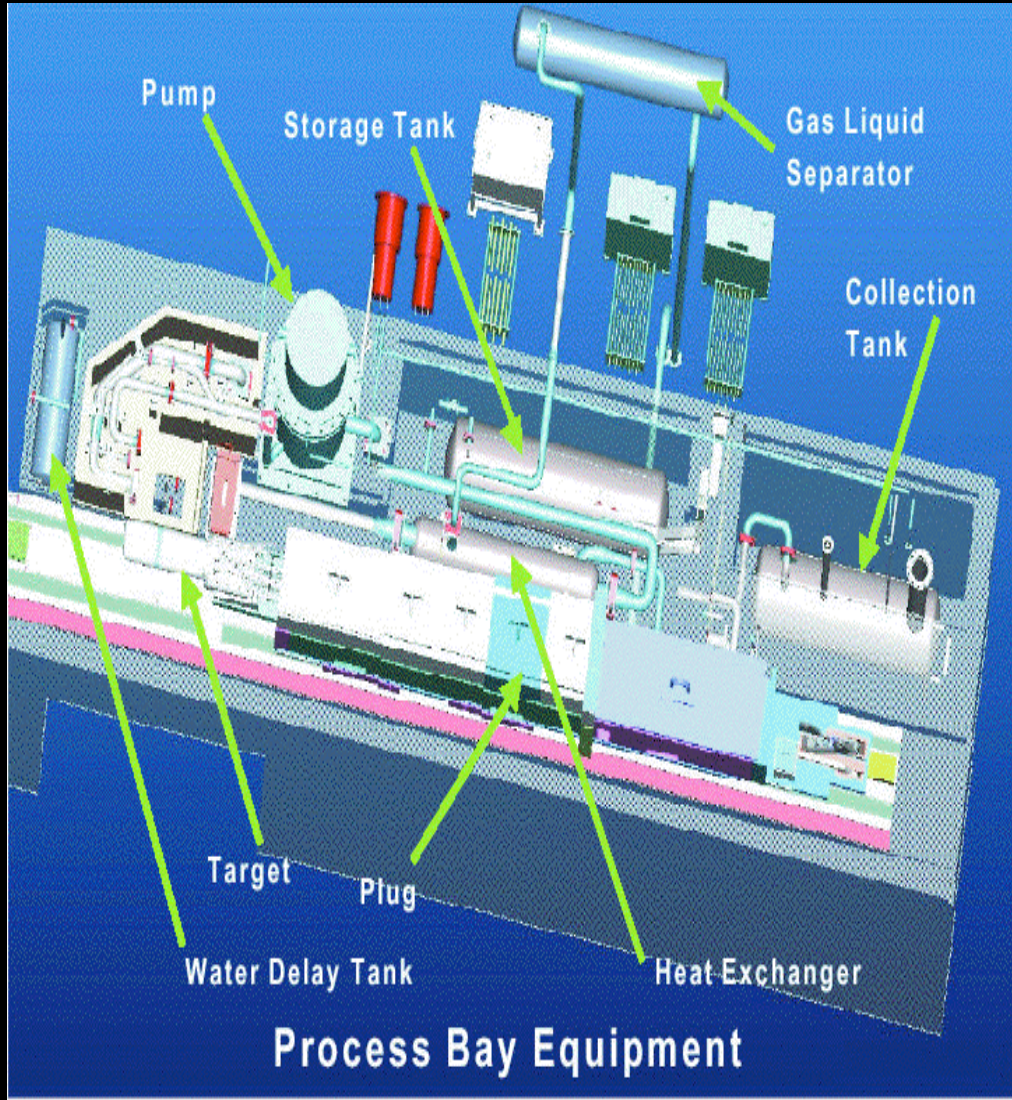
extra slides

Hg-jet system

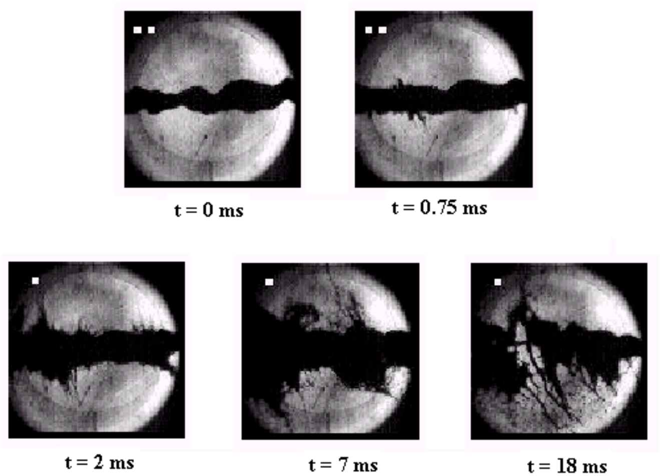
Power absorbed in Hg-jet	1 MW
Operating pressure	100 Bar
Flow rate	2 t/m
Jet speed	30 m/s
Jet diameter	10 mm
Temperature	
- Inlet to target 30° C	
- Exit from target	100° C
Total Hg inventory	10 t
Pump power	50 kW



Target: Hg jet tests

E951

- 1 cm
- v=2.5 cm/s
- 24 GeV 4 TP p beam
- No B field

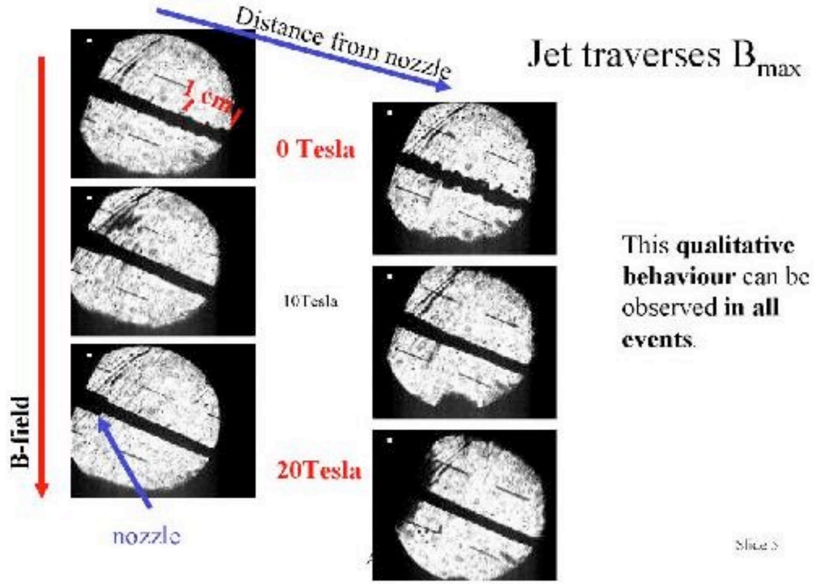


Hg jet dispersal properties :

- proportional to beam intensity
- velocities ~½ times that of "confined thimble" target
- largely transverse to the jet axis
- delayed 40 ms

CERN/Grenoble

- 4 mm
- v=12 m/s
- No p beam
- 0,10,20T B field



- The Hg jet is stabilized by the 20 T B field
- Minimal jet deflection for 100 mrad angle of entry
- Jet velocity reduced upon entry to B field

Target & collection

Proposal to test a 10m/s Hg Jet in a 15T Solenoid with an Intense Proton Beam

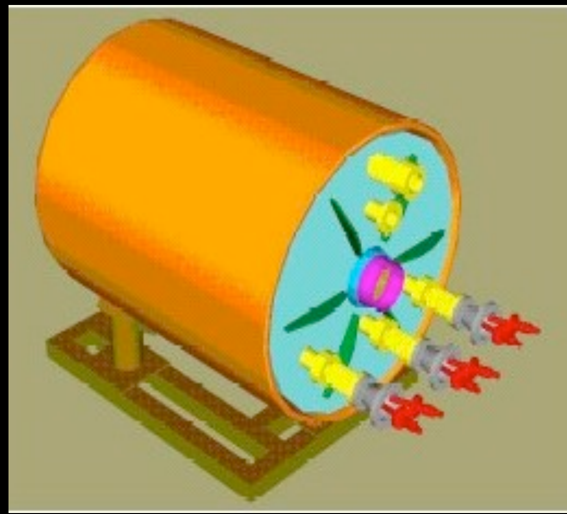
CERN-INTC-2003-033
INTC-I-049
26 April 2004

A Proposal to
the ISOLDE and Neutron Time-of-Flight Experiments Committee

Studies of a Target System for a 4-MW, 24-GeV Proton Beam

J. Roger J. Bennett[1], Luca Bruno[2], Chris J. Densham[1], Paul V. Drumm[1], T. Robert Edgecock[1], Tony A. Gabriel[3], John R. Haines[3], Helmut Haseroth[2], Yoshinari Hayato[4], Steven J. Kahn[5], Jacques Lettry[2], Changguo Lu[6], Hans Ludewig[5], Harold G. Kirk[5], Kirk T. McDonald[6], Robert B. Palmer[5], Yarema Prykarpatskyy[5], Nicholas Simos[5], Roman V. Samulyak[5], Peter H. Thieberger[5], Koji Yoshimura[4]

Spokespersons: H.G. Kirk, K.T. McDonald
Local Contact: H. Haseroth

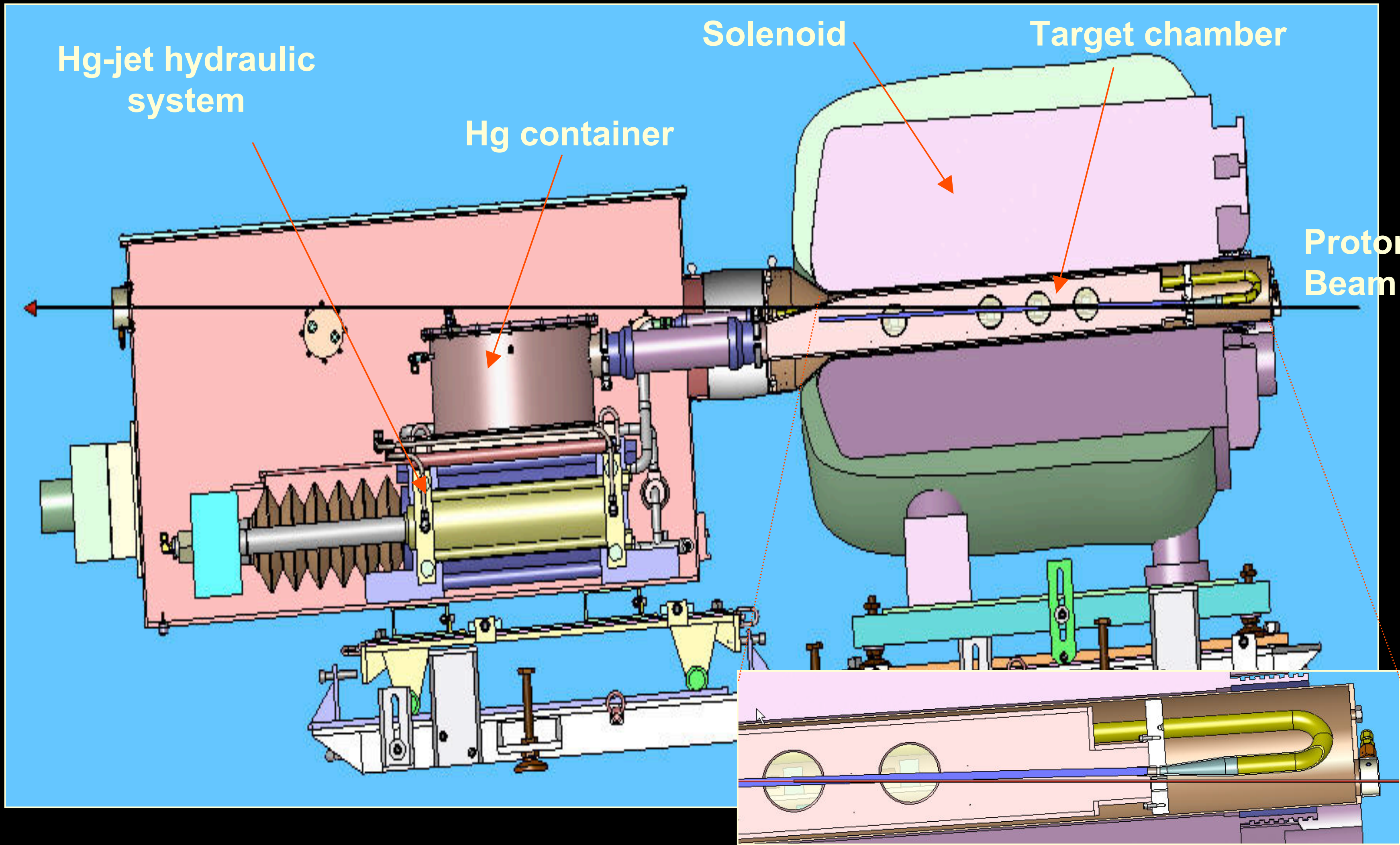


Participating Institutions
1) RAL
2) CERN
3) KEK
4) BNL
5) ORNL
6) Princeton University

aim:
Installation and commissioning at CERN by April 2006

MERIT Experiment – The apparatus

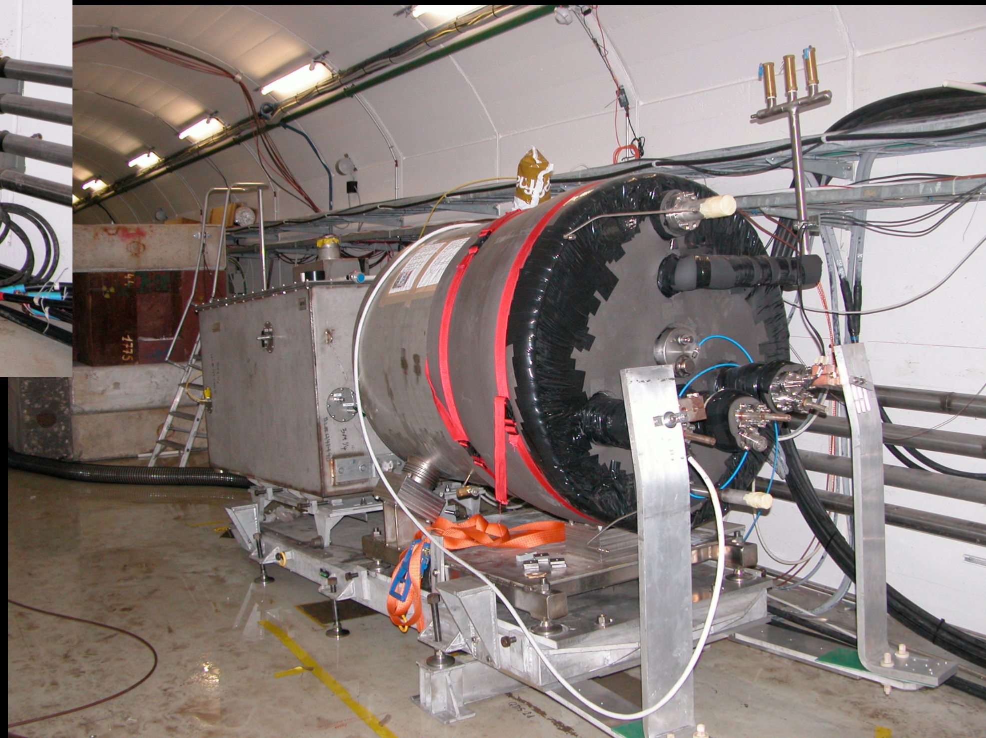
Pulsed N2 cooled copper magnet in three concentric layers. 1 pulse / 20 min.



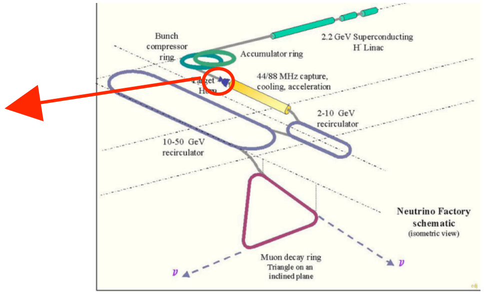
Installed in the CERN TT2a Line

Before Mating

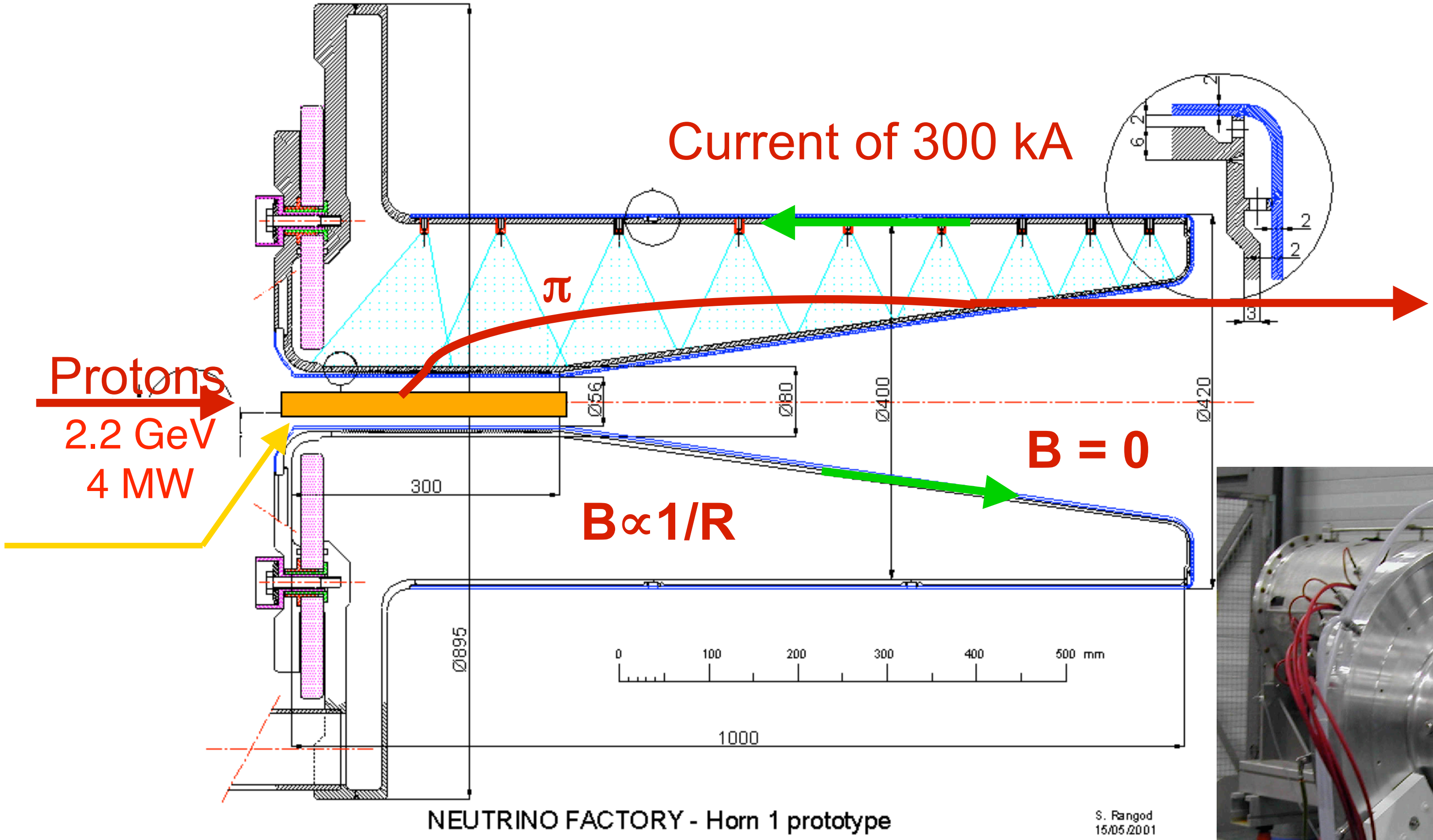
After Mating and Tilting



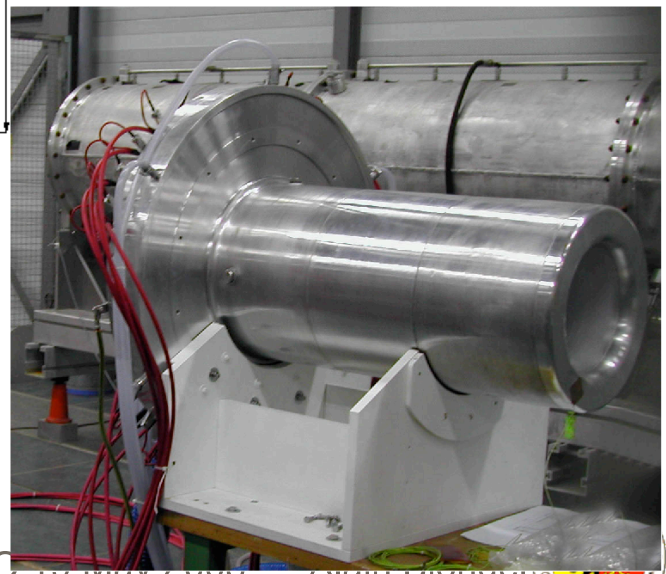
Target & collection



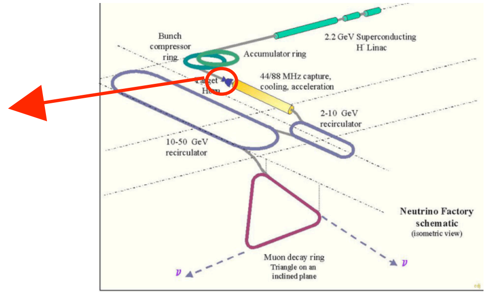
The CERN magnetic horn for pion collection



Prototype built at CERN



Target & collection



Achieve intense muon beams by

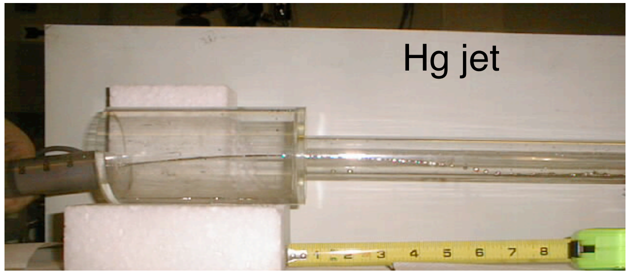
maximizing production of π+ <u>and</u> π-

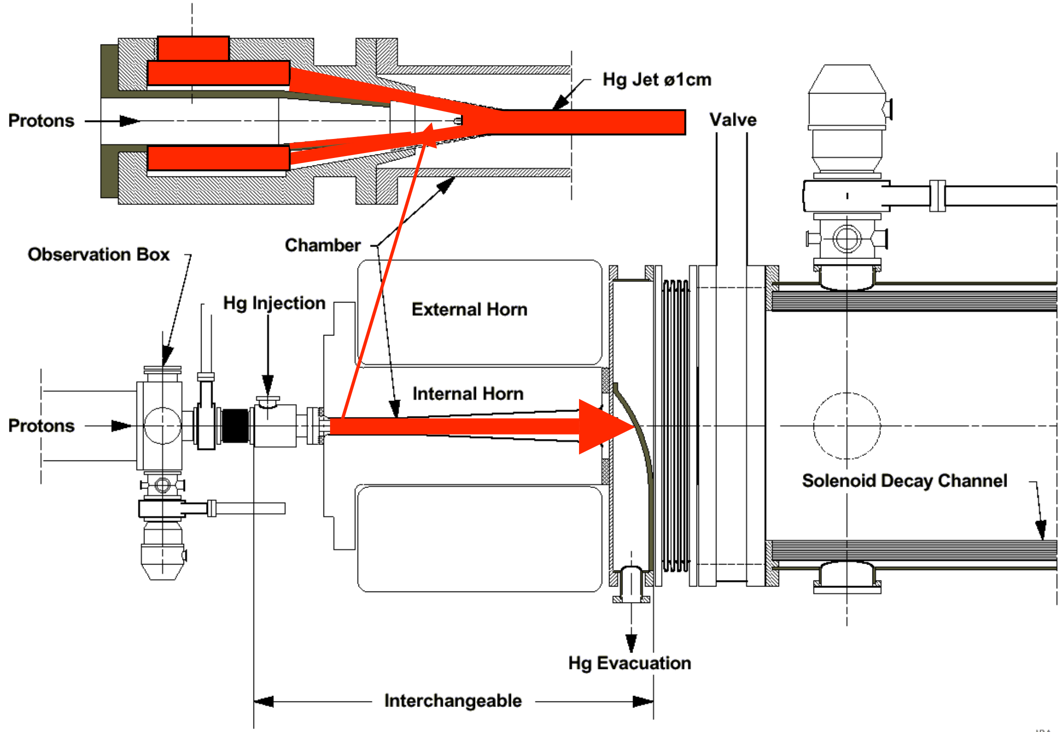
Soft pion production

- HARP cross-section results
- High Z material

High magnetic field

Sustain high power

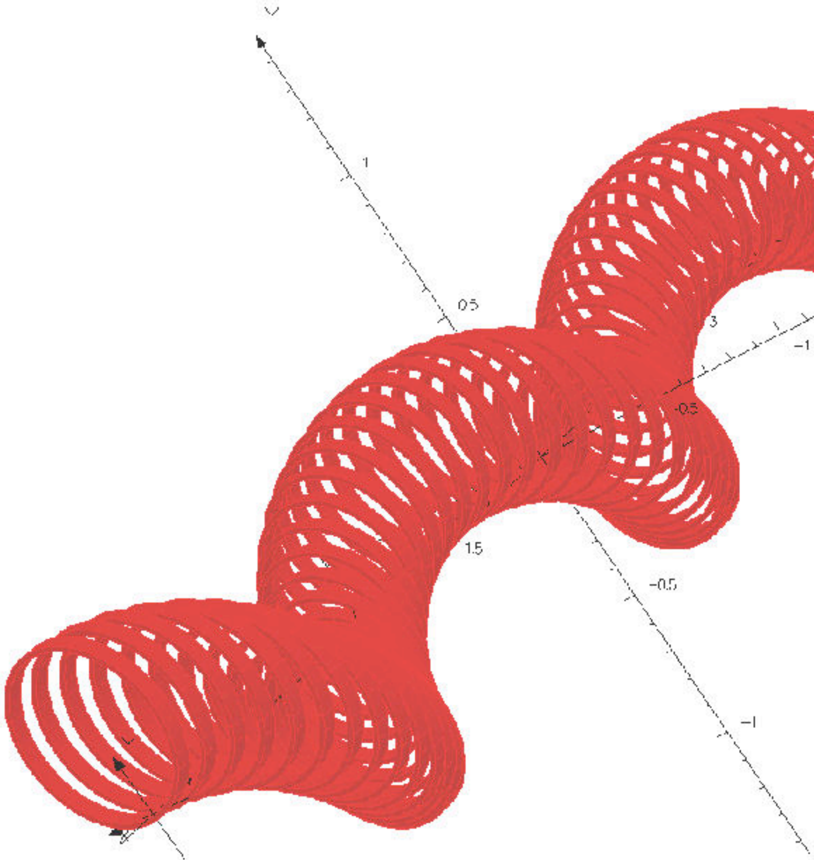




Helical Cooling Channel

HCC

- Solenoid + rotating dipole (Siberian Snake)
- Can also be implemented only using solenoids whose center follows reference trajectory

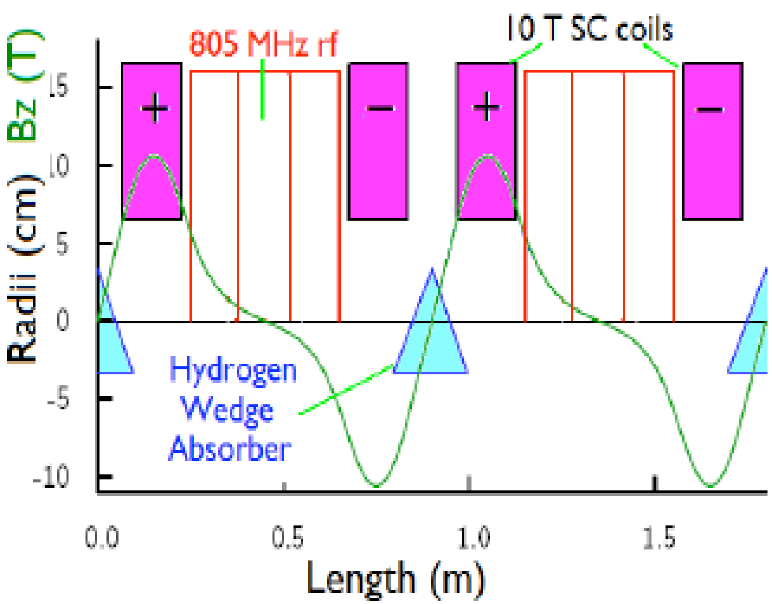


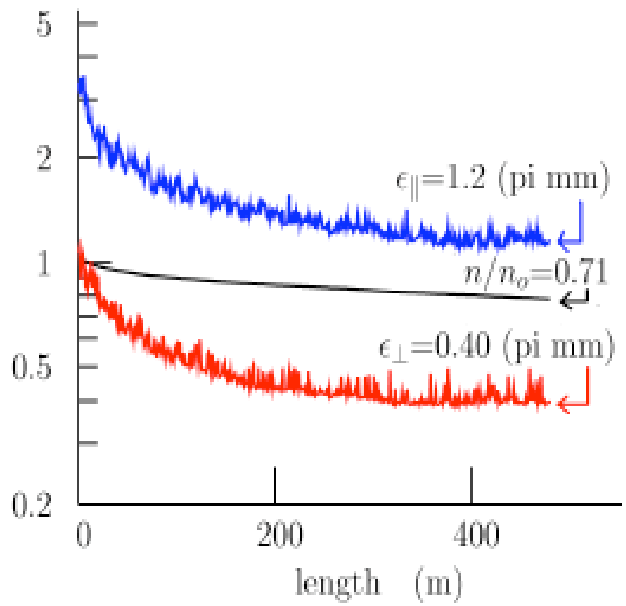
6D Cooling   Several schemes under study

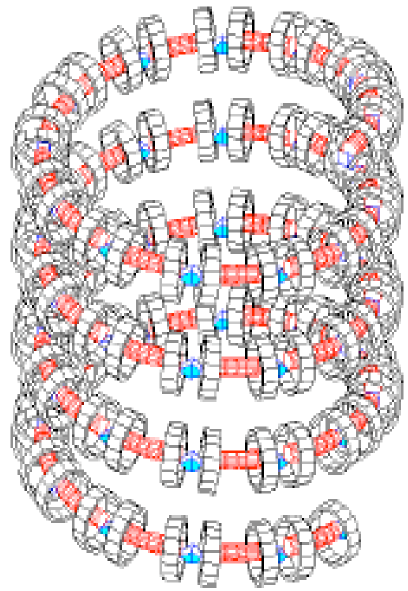
a) "Guggenheim" RFOFO Lattice   (Palmer et al)

- Lattice arranged as 'Guggenheim' upward or downward helix
- Bending gives dispersion Higher momenta pass through longer paths in wedge absorbers giving momentum cooling (emittance exchange)
- Starting at 201 MHz and 3 T, ending at 805 MHz and 10 T
- Many simulations for ring Work in progress for true Guggenheim   Snopok

e.g. 805 MHz 10 T cooling to 400 mm mrad

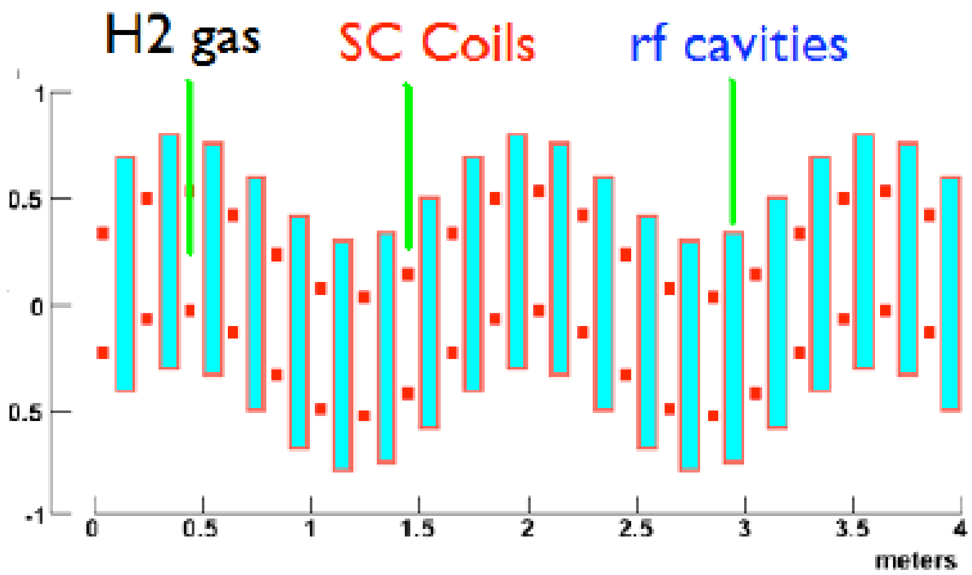


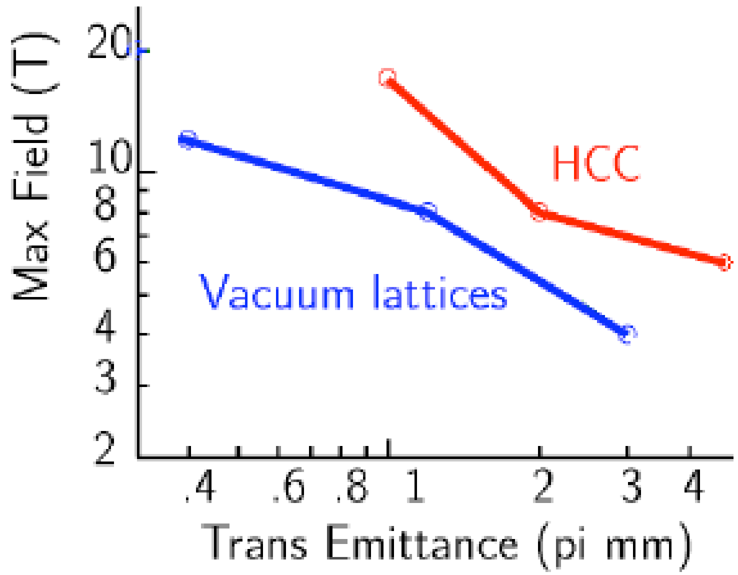




b) Helical Cooling Channel (HCC) (Derbenev et al)

- Muons move in helical paths in high pressure hydrogen gas
- Higher momentum tracks have longer trajectories giving momentum cooling





- Simulations (Balbekov) favor $\frac{\lambda_{rf}}{\text{pitch}} \approx 1.5 \quad \rightarrow \quad \frac{r_{cav}}{r_{coil}} \approx 1.8$
- But studies (Kahn) indicate fewer coils per period may be ok
- Magnetic fields are higher than in vacuum lattices that can have low β foci

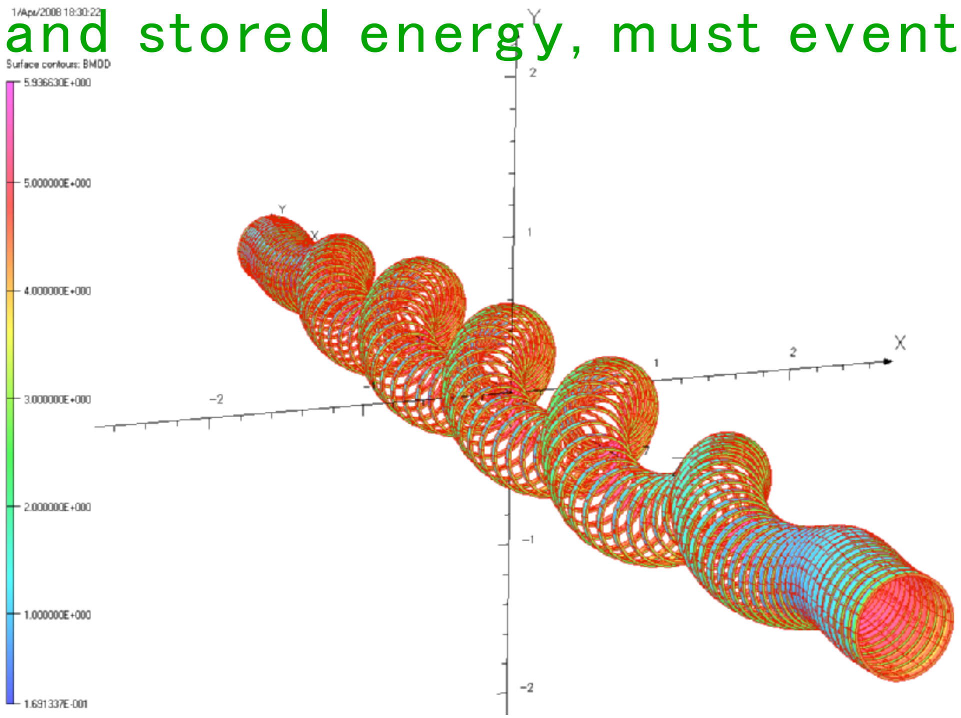
---

Engineering integration of rf not well defined

HS for Cooling Demonstration Experiment

Goals: cooling demonstration, HS technology development

Features: SSC NbTi cable, B_{max} ~ 6 T, coil ID ~ 0.5 m, length ~ 10 m => Complex magnet, significant magnetic forces and stored energy, must eventually incorporate RF.



Status: conceptual design complete

- solenoid
- matching sections

Next: engineering design

- mechanical structure
- field quality, tolerances
- cryostat
- quench protection

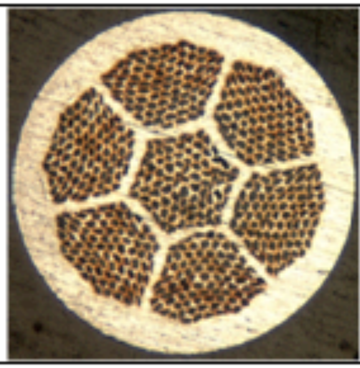
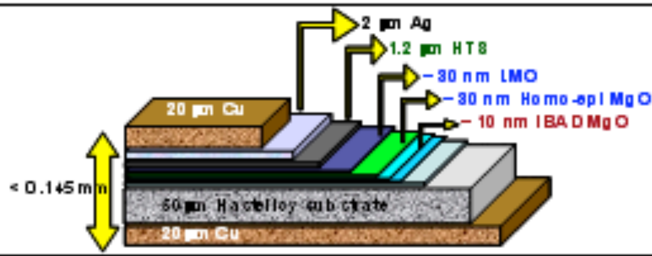
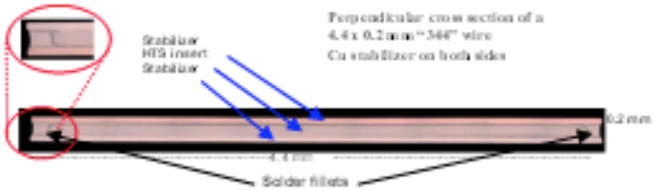
50 T Solenoid: next steps

- Build and test smaller HTS and HTS/Nb3Sn hybrid solenoid models
  - Field range: up to 20-25 T
  - HTS material: BSCCO (G1) or YBCO (G2)
  - Conductor type: round strands, cables or tapes
  - Technologies: React-&-wind or wind-&-react
- Motivate progress in HTS conductor technology
  - National US Conductor Program

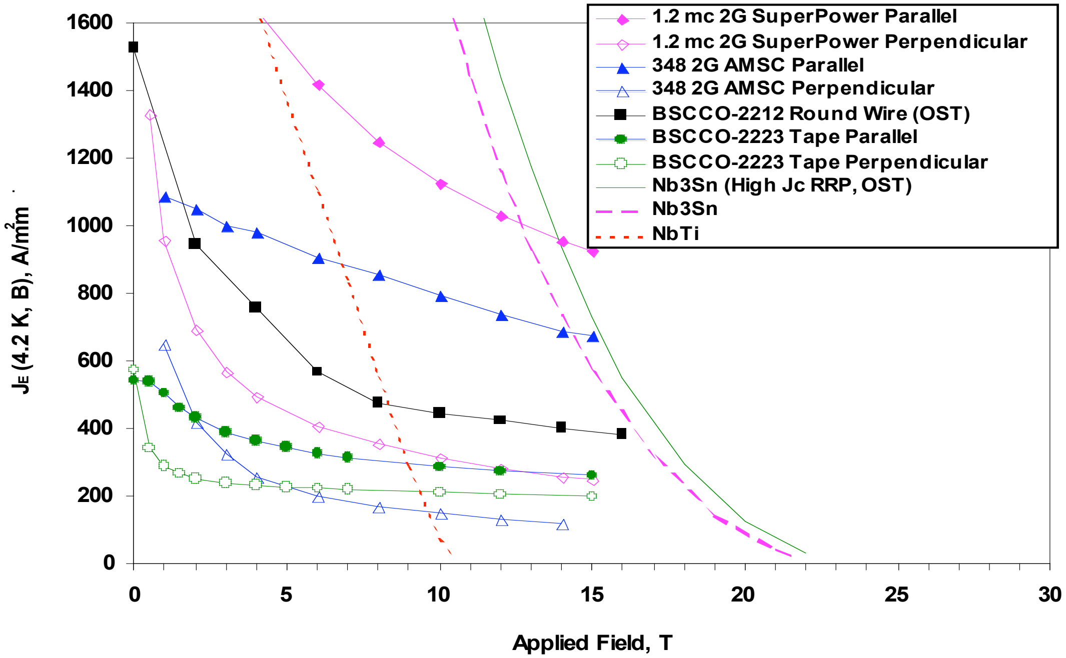
MCTF Conductor Program

- Emphasis on HTS strands, tapes and cables
  - Nb3Sn and Nb3Al strand and cable R&D is supported by other programs (DOE, LARP, NIMS/FNAL/KEK, CARE, etc.)
- Collaborator as part of National HTS Program
- R&D infrastructure
  - Two Oxford Instrument Teslatron stations with 16T and 17T solenoids, and test temperatures from 1.9K to 70K
  - 42-strand cabling machine
  - Probes to measure
    - Ic of HTS strands and tapes as a function of field, temperature, and field orientation
    - transverse pressure sensitivity of strand Ic in a cable
  - 28 kA SC transformer to test cables at self-field in LHe

Strand and Tape Samples

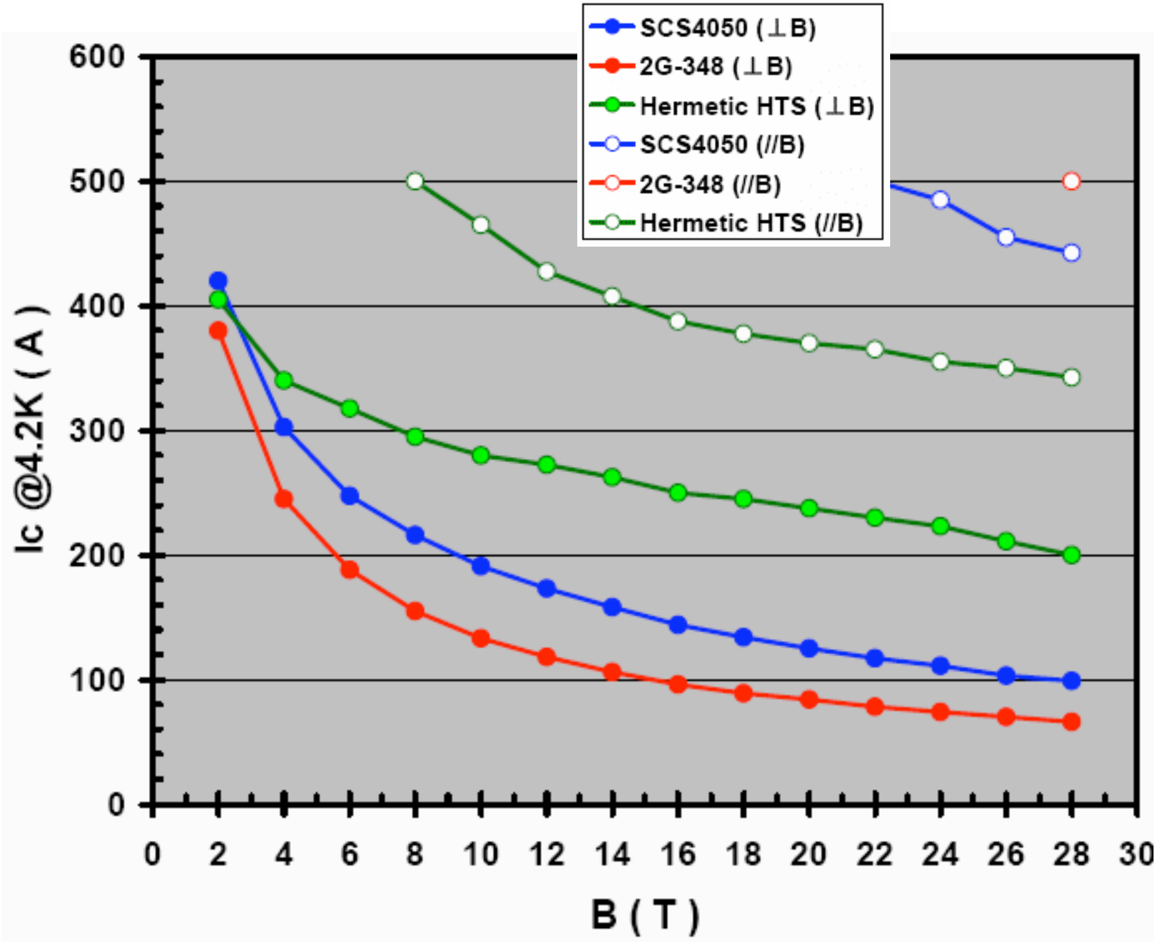
Superconductor	Conductor Type	Company	
BSCCO-2212	Round strand	Oxford SC Technologies	
BSCCO-2223	Hermetic tape	American Superconductor	
YBCO-123	SCS4050 tape	Super Power	
YBCO-123	2G-348 tape	American Superconductor	

HTS and LTS Performance at 4.2 K



- Measurement on round strands and tapes in magnetic fields up to 17T
  - Ic for tapes depends on field orientation
  - Detailed measurement of Ic angular dependence for HTS tapes at fields up to 15-16 T
  - LTS samples show better performance than HTS at low fields
- Input data for High Field HTS Solenoid design studies

High field HTS tests



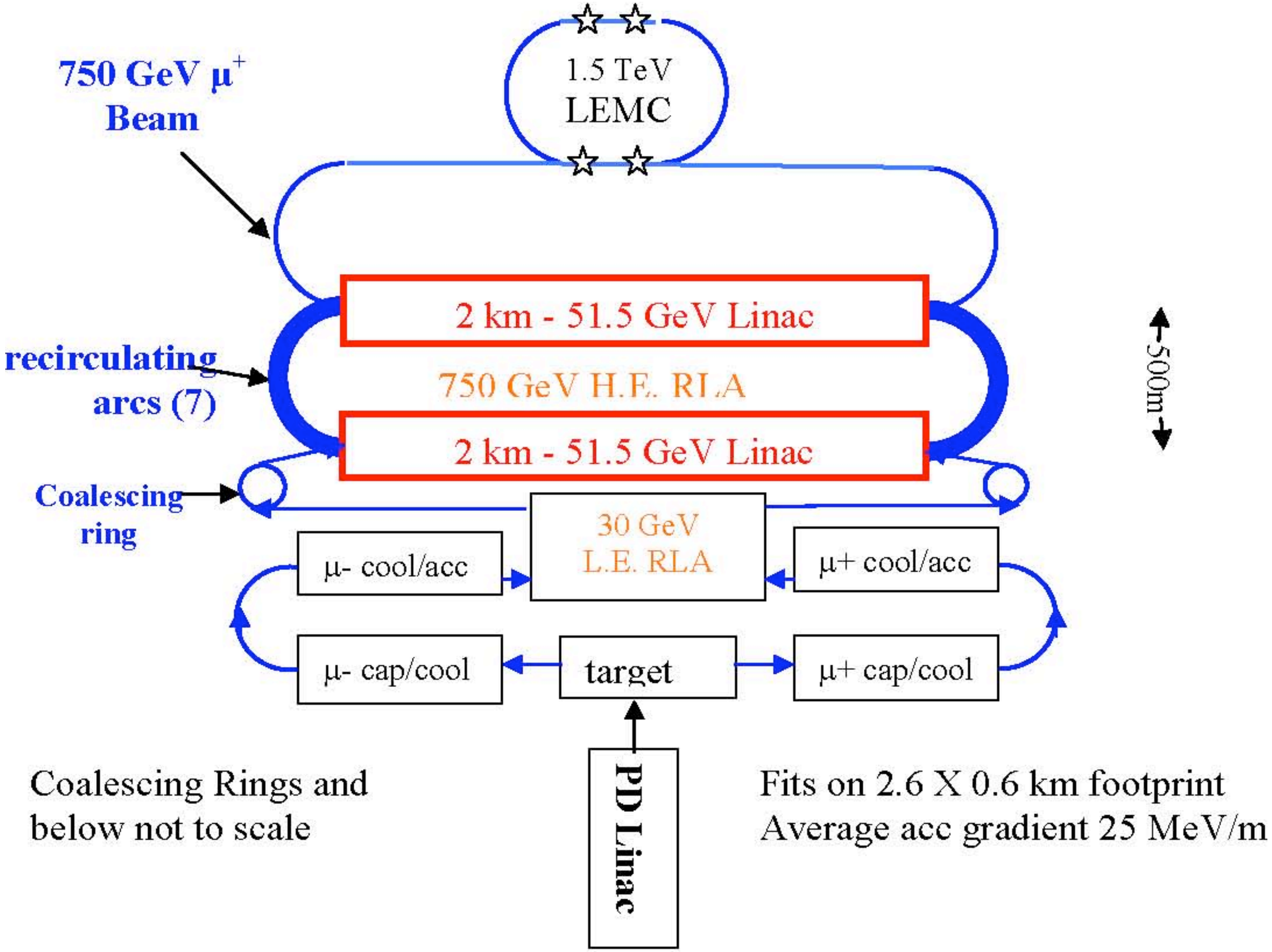
- HTS tape Ic measurements at 4.2 K (with NIMS, Japan)
  - transverse fields up to 28T
  - two field orientations
- Input data for High Field HTS Solenoid design studies
  - reduce uncertainty in conductor performance at high fields

Low-Emittance Muon Collider (LEMC)

Parameter List:

E_{cm} = 1.5 TeV
Peak L = $7X10^{34}$
#μ's/bunch = 10^{11}
Av Dipole B = 10T
δp/p = 1%
β^*(cm) = 0.5 (!)

Proton driver:
E = 8 GeV
Power ≈ 1 MW

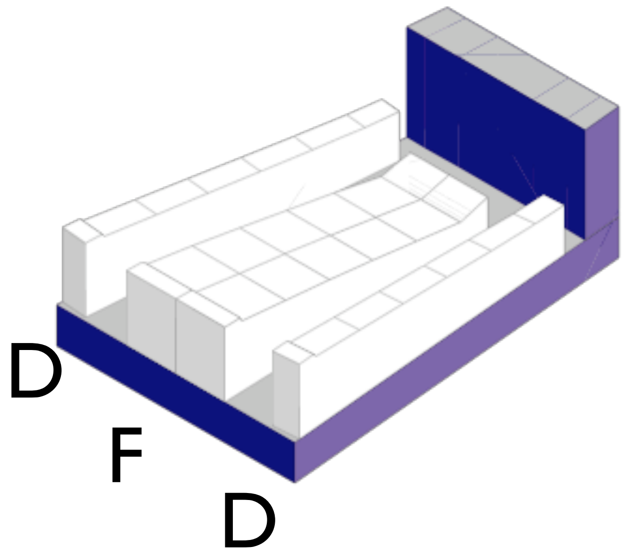


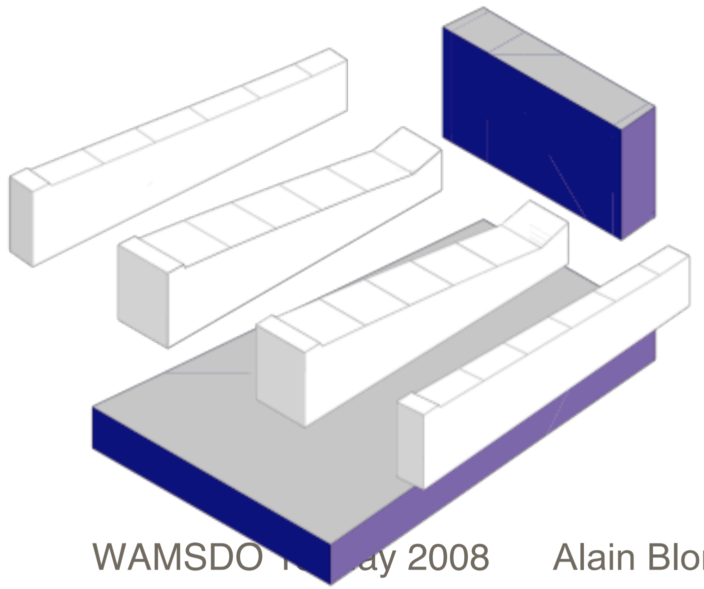
Production of Magnet

The magnet consists of 6 constructional members.

Each piece is made from commercially-available thick iron plates

This configuration provides good cost performance, comparing to forged magnet.





Magnet parameters

Weight of magnet		17 t/1 cell
Current (per 1 coil)	F magnet	1750 A/ 84000 A*T
	D magnet	1034 A/ 30000 A*T
Power		100 kW/ 1 cell
Flow rate of cooling water	F magnet	61.7 ℓ/min
	D magnet	38.3 ℓ/min
Pressure drop (per 1path)	F magnet	4.8 kg/cm^2
	D magnet	1.9 kg/cm^2