International
MUON Collider
Collaboration

Collider magnets summary

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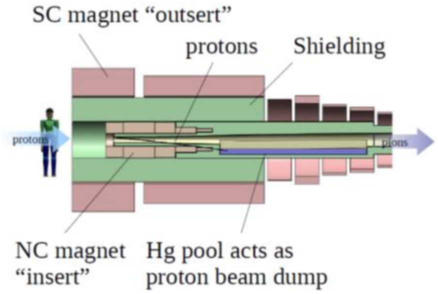
SC Magnets

- Magnets are critical in the target/front end, cooling, acceleration, and collider ring areas

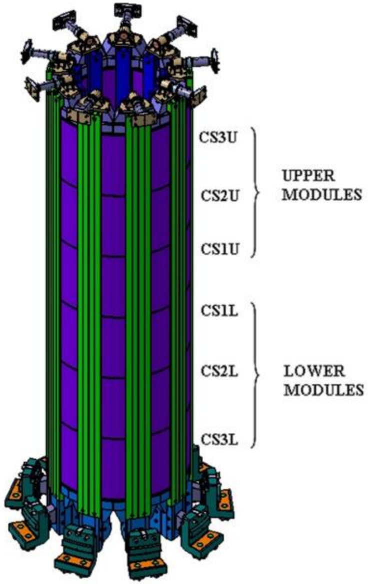
Target end



Hybrid design ?
(superconducting + resistive magnets)

- Target field from 15T to 20T, SC coil inner diameter up to 1.2m – **very challenging**
- **Limitation is coming from mechanics (Lorentz forces prop. to B^2)**

11,7T WB MRI magnets (NbTi conductor)
(68 cm bore NIH-NRI magnets from ASG, 90 cm bore for Iseult CEA)



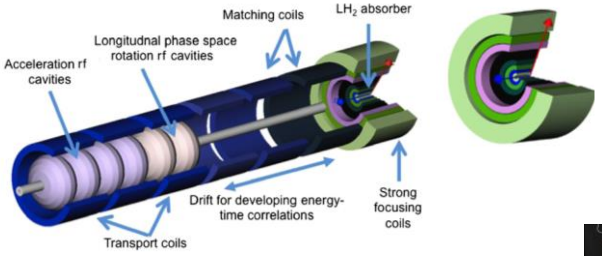
ITER central solenoid
13T - OD 4.3 m - height of 18 m

NB3Sn CICC

- Need of stabilized/reinforced NbTi/Nb3Sn conductors for large high field solenoids
- Large irradiation loads require effective cooling system as well as irradiation tolerant materials.
- Optimization of irradiation level is needed.
- NbTi is the most serious candidate for 1m ID bore / 10T

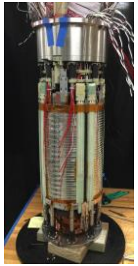
A demonstrator will be a big magnet in any case – not possible to build anything in less than 5 years
Cost will be high!

Cooling



- **Field target >30T, SC coil inner diameter of 50mm for the final cooling, as short as possible**
- **So far, achieved performances are still very far**

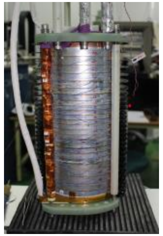
NATIONAL HIGH MAGNETIC FIELD LABORATORY



32T
17T HTS+ 15T LTS
ID 40mm

45,5T
14,5T HTS+ 31T LTS
ID 14mm

SuNAM



26,4T (HTS only)
ID 35mm

cea SACLAY LNCMI

32,5T
12,5T HTS+ 20T res.
ID 50mm

Bruker ASCEND 1.2 GHz
28.2T (LTS/HTS @ 1,9K)
54 mm bore
Strongest commercial NMR

- **For all projects, magnetic field is in the vertical direction**, **while we need horizontal magnets: mechanics is a big challenge**
- **Several demonstrators needed to address all the technical issues** (winding, joints, quench protection and detection of HTS magnets, radiation loads management, cooling management due to stagnant "Helium bubble")
- **Short term plan has to concentrate on realistic values** (**ID 50mm but only 15T to 20T or 30T but only ID 40mm to 45mm**)

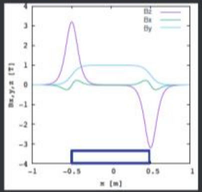
Acceleration

Vertical excursion FFA for muon acceleration is a very interesting option
Feasibility of magnets for vFFA, as well as vFFA concept itself, have to be demonstrated.

- **At STFC/RAL, feasibility study on vFFA is going on and normal conducting prototype magnet is being designed.**

- Exponentially increasing magnetic field to satisfy zero-chromatic conditions.
  Cartesian coordinates x (hor.), y (vert.), z (long.)

$$\begin{cases} B_x(x,y,z) = B_0 e^{m(y-y_0)} \sum_i b_{xi}(z)(x-x_0)^i \\ B_y(x,y,z) = B_0 e^{m(y-y_0)} \sum_i b_{yi}(z)(x-x_0)^i \\ B_z(x,y,z) = B_0 e^{m(y-y_0)} \sum_i b_{zi}(z)(x-x_0)^i \end{cases}$$



- Non-zero longitudinal field on median plane.
- Importance of fringe field modelling, (more in small machines).
- Expansion of the field in the magnet shows alternance of normal and skew components.

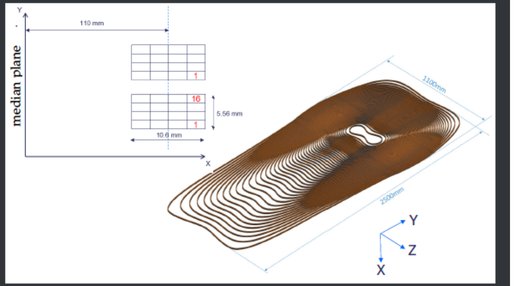
→ Strongly coupled optics

JB Lagrange 1

(Preliminary numbers)

	1st NC prototype	12 MeV proton	1.2 GeV proton	1.5 TeV muon
Aperture H [mm] x D [mm]	600 x 220	700 x 300	700 x 300	700 x 200
Length [m]	1	0.5 ~ 1	2 ~ 3	10 ~ 20
Max Field [T]	0.01	3	6	9
Normalised gradient m^* [m-1]	1.3	.3 ± 25 %	1.3 ± 25 %	6.8
Momentum ratio	2	2	2	30

$^*m = \frac{1}{B}\frac{dB}{dy}$ (y: vertical direction)



Magnet prototype at ISIS

JB Lagrange 2

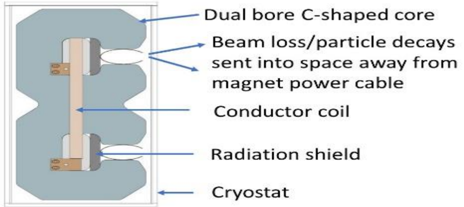
Feasibility study of vFFA magnets to be completed (mechanics, winding technics and impact of manufacturing tolerances on the field quality
Short term development plan has to be based on RAL studies

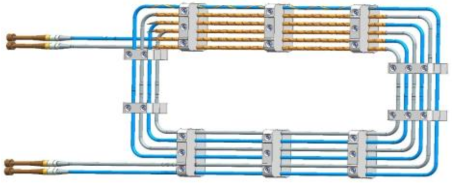
Acceleration

Need of fast ramped magnets (+/- 1.8T @ 400Hk)

- AC losses management, large stored energy -> protection?
- Power converters (link with existing R&D at CERN)

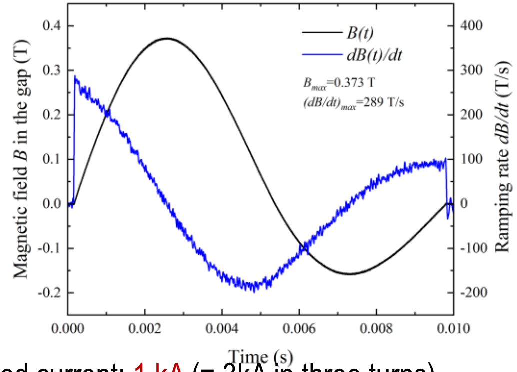
- Existing Program at Fermilab (HTS magnet, target: 0.6T @ 20Hz)





- **3 turn conductor** reduces energizing current and with 2 sub-cables/turn makes it a very narrow structure
- **4 HTS strands** (Super-Power, 2.5 mm x 0.1 mm) per sub-cable are helically wound over a 9 mm dia. cold pipe and firmly held with a single layer of Cu tape: 0.1 mm x 12.5 mm
- **Sub-cable T_C ~30 K @ 2 kA provides very safe temperature margin for currents up to 2 kA and T_{OPER} ~5 K**
- ABS printed holders keep power coil in place and insulate from magnetic core
- The coil allows to place 6 x more HTS strands to carry up to 12 kA current (36 kA for 3 turns)

H.Piekarz et al. **| 290 T/s HTS magnet**



- Applied current: 1 kA (= 3kA in three turns)
- *B* field span: **0.37 T (max) – (-0.16) T (min) = 0.52 T**
- Maximum *dB/dt*: **289 T/s**
- Avg. *dB/dt*: 170 T/s (0.37 T over 2.2 ms)
- Rep rate: 14 Hz
- Upper limit on **cryogenic power loss 0.1 W**
- Planned upgrade: current to 2 kA, B to 0.8 T

Still a lot to do!

Collider ring

- High field magnets (up to 10T) and high gradient (200T/m) with large apertures (80 mm to 160mm)
  - Combined functions
  - Geometry of combined function magnets (curved magnet such that dipolar field constant?)
  - Field quality requirements to be discussed, understood and defined
  - Open mid-plane magnets?

- **Technical issues: Stress management of large aperture high field collider magnets, magnet protection (radiation losses management)**

- On-going developments at KEK and Fermilab

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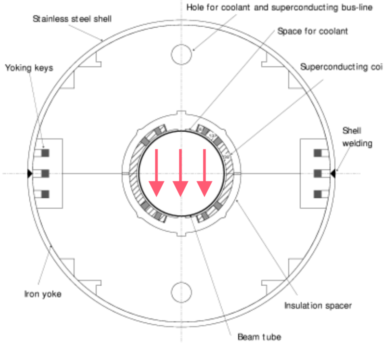
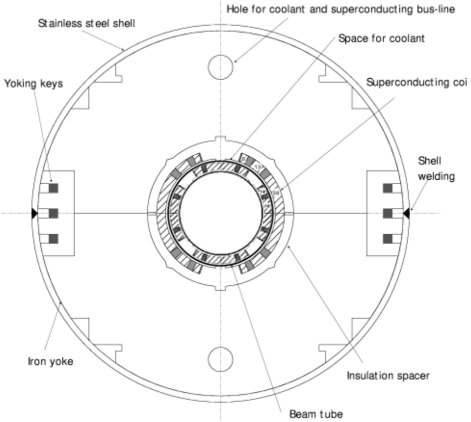
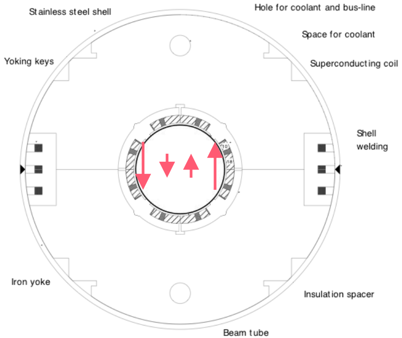
SC Combined Function Magnet Options



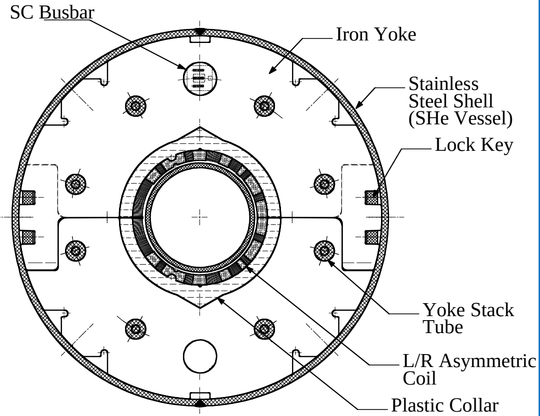
Dipole (Bending)



Nested Coils



Quadrupole (Focusing)



L/R Symmetric Coils

Nested Coils

- Full Tunability of B/Q ratio
- Simpler coils
  - Need independent dipole and quadrupole coils
- Complicated EM force
  - Large opposite current:
    - Large repulsive and sharing force
  - Stress Management

L/R Asymmetric Coils

- Limited Tunability of B/Q ratio
  - Fixed by design
  - Q/B ratio < Q:10T/m / B:1T with 150mm Coil ID.
- Simpler EM Force
  - Dipole like L/R asymmetric coil
  - Dipole like EM force
- Cheaper solution for 3TeV?

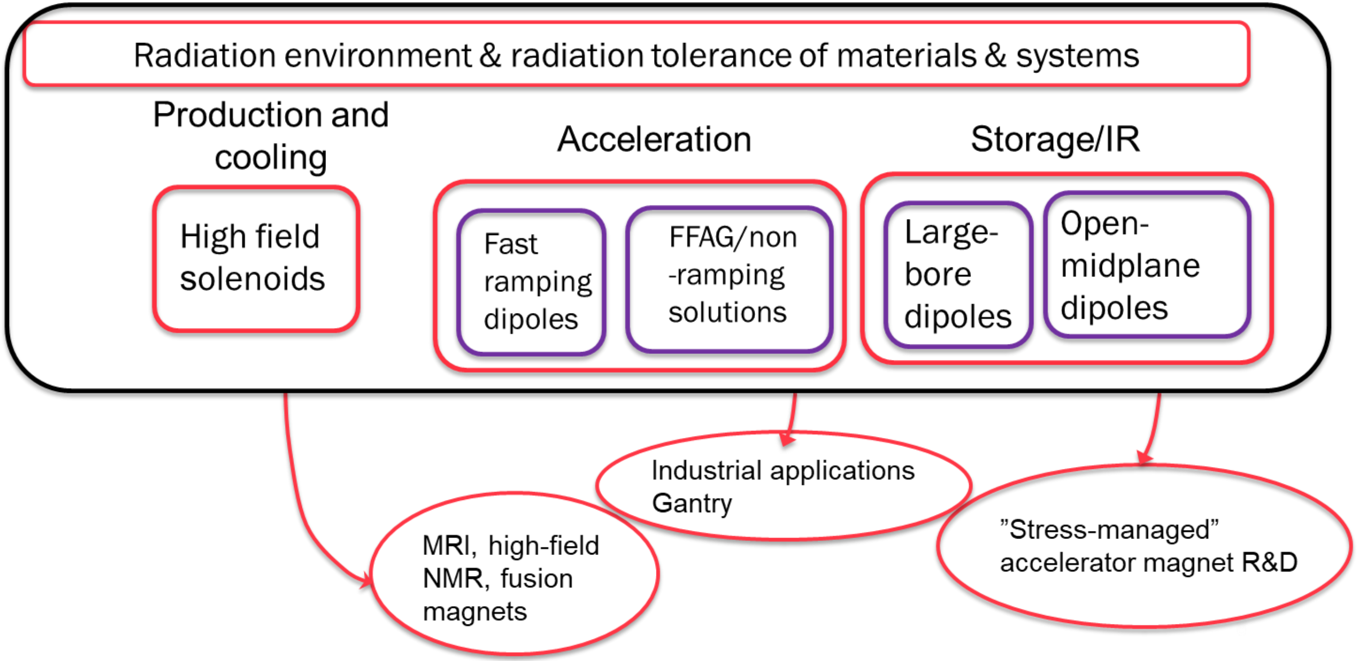
T. Ogitsu, KEK

MC SR and IR magnet summary

E. Barzi and A.V. Zlobin

- **Conceptual design studies of MC SRs and IRs with muon beam energy of 0.75 and 1.5 TeV have been performed in the U.S. in 2010-2014**
- Studies included beam optics, magnet design concepts and radiation shielding
- **It was shown that large-aperture shell-type magnet coils produce better properties than block-type coils and/or open mid-plane coils**
- **SR and IR in HE (3+ TeV) MC will need SC magnets with large aperture (~200 mm) and high operation fields (10-20 T) for highest luminosity**
  - nominal operation fields in dipoles up to 10-11 T (maximum coil field in combined Q/D magnets up to 17 T) could be achieved using present Nb_3Sn technology
  - magnets with higher operation fields will need HTS/LTS hybrid technology
- **Stress management is a critical coil design concept which needs serious theoretical and experimental studies**
  - it is an important part of the U.S. Magnet Development Program
  - there is possible synergy also with Europe, for instance PSI is also working on this concept

Main R&D areas and synergies with other programs



Courtesy Soren Prestemon

Possible Collaboration & Synergies in World Wide

Synergy with US Superconductors and Magnets Programs (to be confirmed)

- **US-MDP** (BNL, FNAL, LBNL, ASC-NHMFL-FSU): LTS (Nb_3Sn) and HTS(Bi2212, ReBCO) wire and cable; HF magnets; magnet structural materials, technologies, diagnostic, protection
- **FNAL:** fast cycling HTS magnets
- **OSU:** LTS/HTS wires and cables, magnetization and AC losses
- **TAMU:** fast cycling magnets, magnet structural materials, technologies

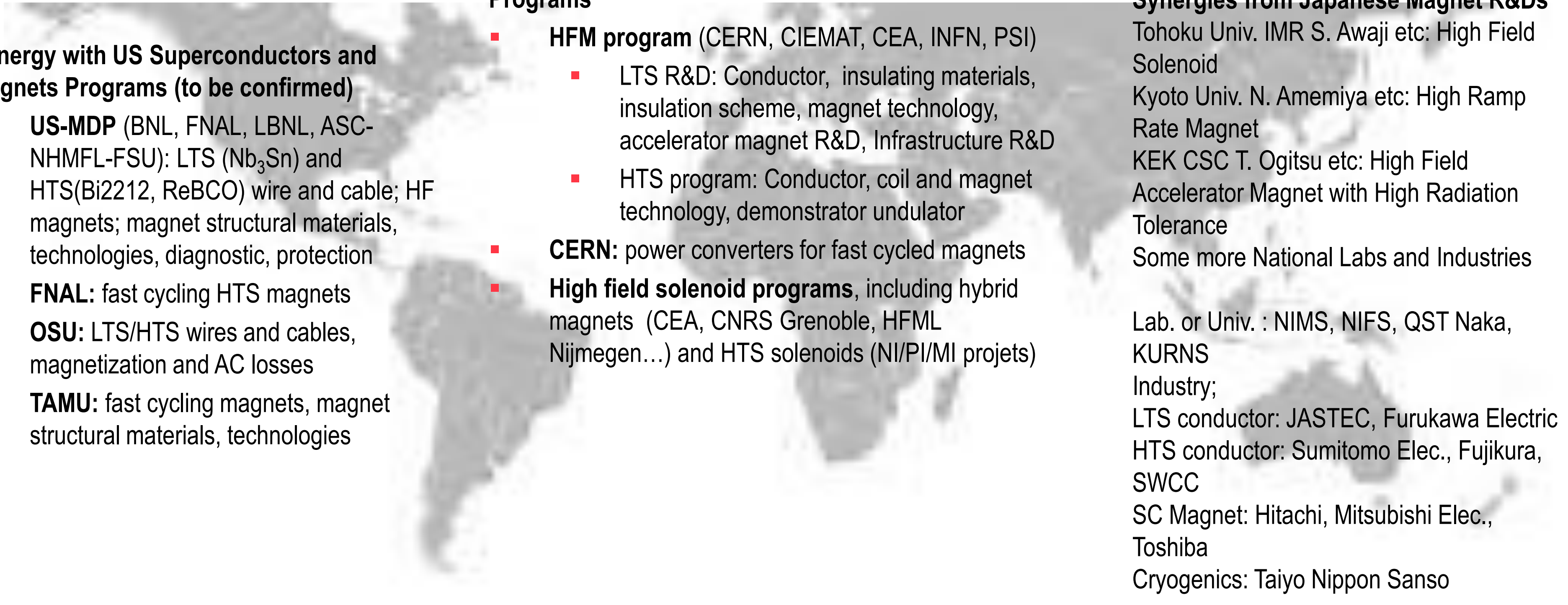
Synergy with European Superconductors and Magnets Programs

- **HFM program** (CERN, CIEMAT, CEA, INFN, PSI)
  - LTS R&D: Conductor, insulating materials, insulation scheme, magnet technology, accelerator magnet R&D, Infrastructure R&D
  - HTS program: Conductor, coil and magnet technology, demonstrator undulator
- **CERN:** power converters for fast cycled magnets
- **High field solenoid programs**, including hybrid magnets (CEA, CNRS Grenoble, HFML Nijmegen…) and HTS solenoids (NI/PI/MI projets)

Synergies from Japanese Magnet R&Ds

Tohoku Univ. IMR S. Awaji etc: High Field Solenoid
Kyoto Univ. N. Amemiya etc: High Ramp Rate Magnet
KEK CSC T. Ogitsu etc: High Field Accelerator Magnet with High Radiation Tolerance
Some more National Labs and Industries

Lab. or Univ. : NIMS, NIFS, QST Naka, KURNS
Industry;
LTS conductor: JASTEC, Furukawa Electric
HTS conductor: Sumitomo Elec., Fujikura, SWCC
SC Magnet: Hitachi, Mitsubishi Elec., Toshiba
Cryogenics: Taiyo Nippon Sanso



PRELIMINARY R&D LIST AND SHORT TERM PLAN

- Strong design activity of SC magnets based on realistic performances and specifications
- Push the development of HTS material performances
- R&D needed to address the key technical challenges:
  - Reinforced NbTi/Nb3Sn conductors for large high field magnets,
  - Magnet protection against radiation heat loads, specially for HTS magnets, and accelerator magnets
  - Investigate HTS solenoids insulation options (NI/PI/MI)
  - Material aging against radiation
  - Material aging, power converter performances, AC losses for fast cycled magnets
  - Mechanics for the VFFA option
  - Stress management of collider magnets

Thank you for your attention