
WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Stephane Sanfilippo on behalf the magnet section : Paul Scherrer Institut

Challenges for the magnet projects at the Paul Scherrer Institut

International Magnetic Measurement Workshop 20 @Diamond Light Source

Outline

- On-going projects
- Magnetic measurement system development
- Infrastructure development

Projects and R&D activities-Status June 2017

- **Free electron laser at PSI (SwissFEL)**
  - **104** Magnets, **16** undulators for the soft X ray line-*Production & prototype Phase*
  - Short period, high K undulator development for beam line “Porthos”: 7 GeV energy and expanded range of wave length (1/3 Å)-*R&D phase (2018-2019)*
- **Upgrade of the Swiss Light Source (SLS 2)** : Conception phase
  - 6T superbend dipole prototype: *Concept design completed*
  - Conventional magnets (dipoles, quadrupoles, sextupoles-option 2T superbend with permanent magnets)

    (Concept design started in March 2017→to be completed Fall 2017)
- **COSAMI (Compact & stable & brilliant storage ring source for micro electronic purpose) →not discussed here**
  - **117** Magnets and 1 undulator : *Concept design completed, February 2017*
- **Canted Cosine Theta option for the 16-T FCC-hh main dipole**

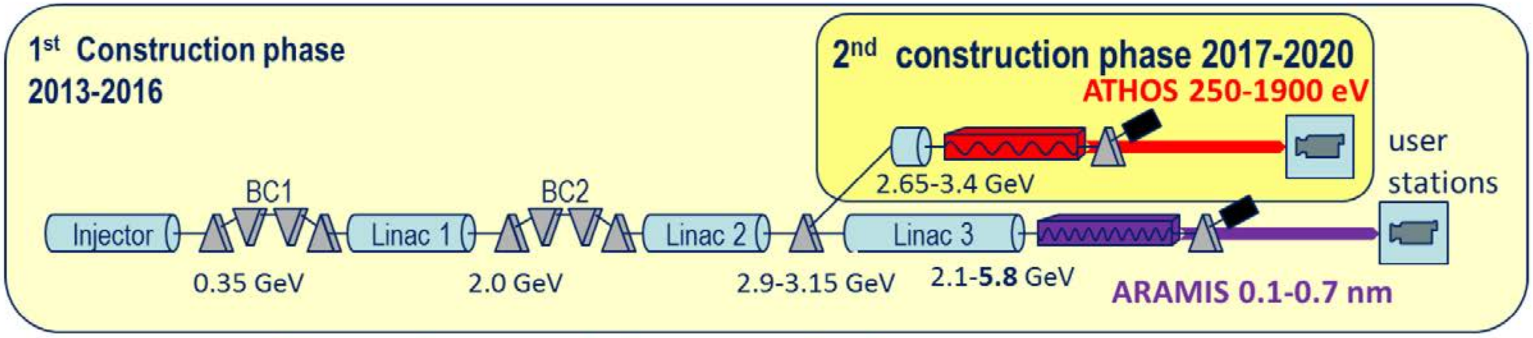
  R&D Phase on model magnets till 2020
- **Superconducting magnets for compact proton therapy gantries**

  Concept design for the combined function dipole and quadrupole completed

Swiss Free electron laser (Project SwissFEL)

1 injector, 2 bunch compressor chicanes, 3 linacs for a beam energy up to 3.4 GeV

- **Hard X-ray Beamline Aramis: SASE FEL (1 – 7 Å) installed, fully operational in 2017**
- ***Soft X-ray Beamline Athos: SASE FEL (7 – 70 Å) in preparation***



Soft X-ray Beamline (2017-2019) :

- ***13 Dipoles,*** 76 quadrupoles, 7 sextupoles, 8 correctors
- ***2-m long, apple X undulators, 16 units***

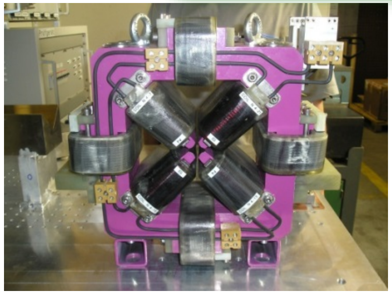
Bundespräsident J. N. Schneider-Ammann &

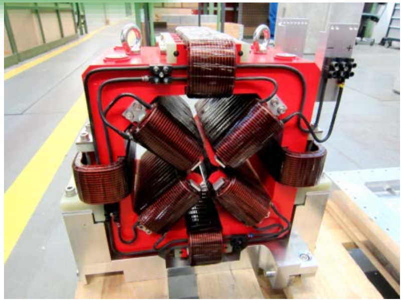
PSI-Director J.Mesot: PSI, 5 December 2016

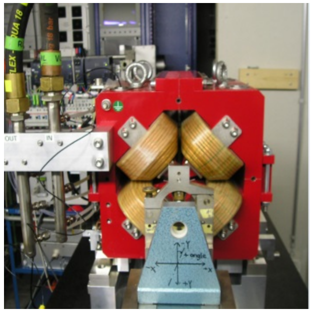
Main magnets for the soft X-ray beam line

- **Strengths ranging up to 1.8 T**
- **Lengths ranging up to 2 m !**
- ***Small apertures (12 mm, 22 mm)***
- **Combined function Quads (correctors included)**
- **Air cooled quadrupoles working at I_{max}~10 A**

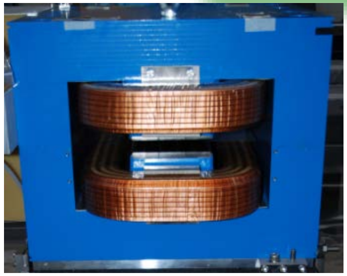
Quadrupoles

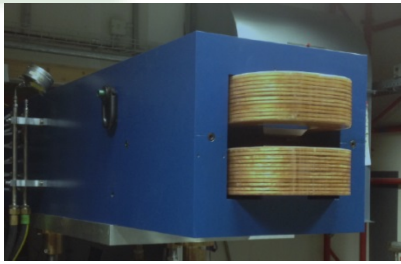

(50T/m Φ=12 mm, L=80 mm)-34 p.

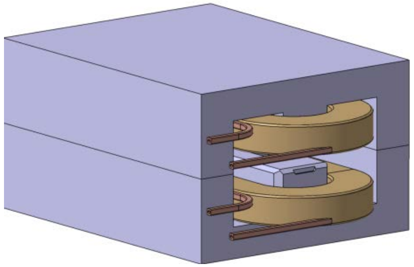

(20T/m Φ=22 mm, L=150 mm)-32 p.


(50T/m Φ=22 mm, L=300 mm)-8 p.

Dipoles

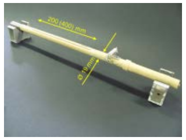

(0.96 T, Gap=22 mm, L=0.5 m)-4 p.

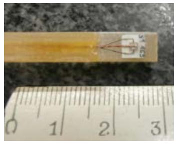

(1.77 T, Gap=20 mm,L=2 m)

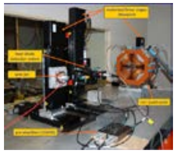

(0.8 T, Gap=8 mm, L=0.3 m)-4p.

- **Delivery: November 2017- Mid 2018**
- ***Magnetic tests (100%) : January-December 2018***

✓ **Field integral**
✓ **Multipoles**
✓ **Magnetic axis**
✓ **Field maps**



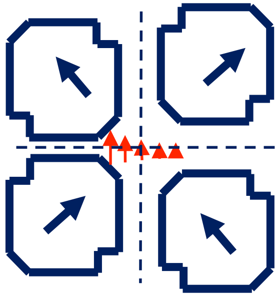


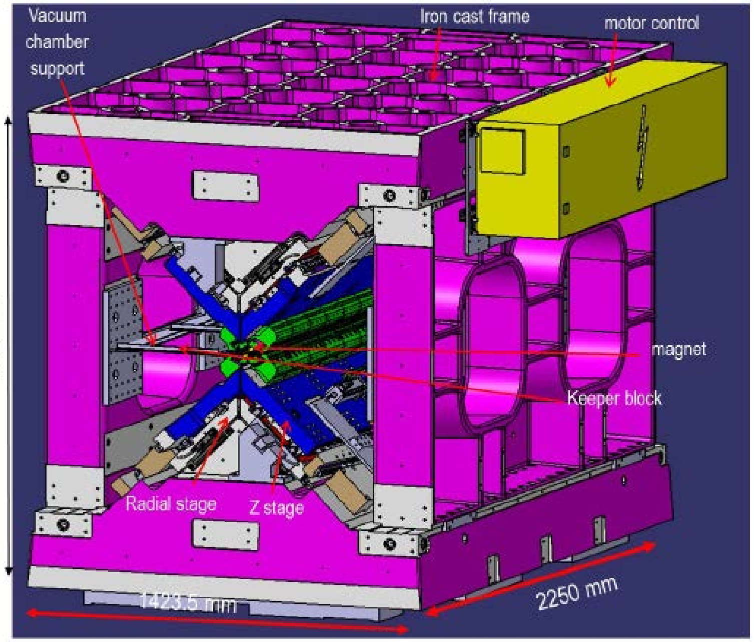


Apple X-Undulator for the athos beam line

Delta cross-section with each array can be moved radially in a symmetric way radial “gap“ variation

each magnet row is ***individually adjustable*** in gap and shift



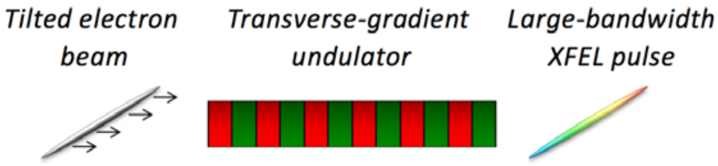


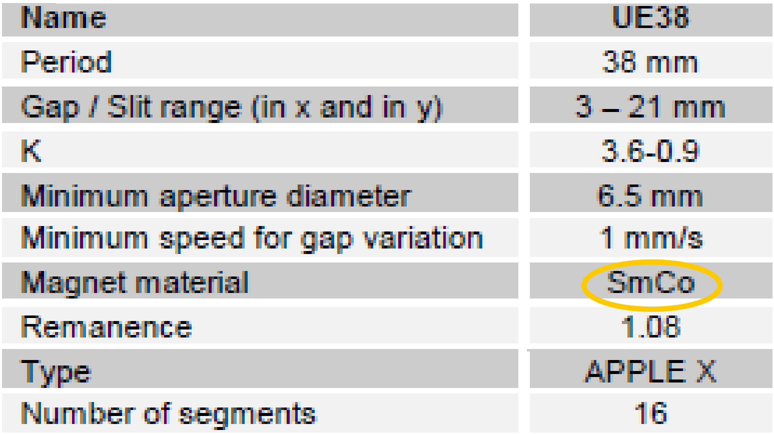
UE38 undulator (courtesy-PSI insertion Device Group)

1st use of ***transverse gradients in undulators*** opens advanced operation modes for SwissFEL

*Field gradients will reduce the dispersion (energy vs transverse offset) and keep **the resonance condition for all the electron trajectories**: generate an ultra large badd with of variation*

M. Calvi et al, Transverse gradient in Apple-type undulators, J. Synchrotron Rad. (2017). 24, 600-608





Name	UE38
Period	38 mm
Gap / Slit range (in x and in y)	3 – 21 mm
K	3.6-0.9
Minimum aperture diameter	6.5 mm
Minimum speed for gap variation	1 mm/s
Magnet material	SmCo
Remanence	1.08
Type	APPLE X
Number of segments	16

First prototype - end of 2017

Magnetic characterisation - 2018

Short period, high K undulator development

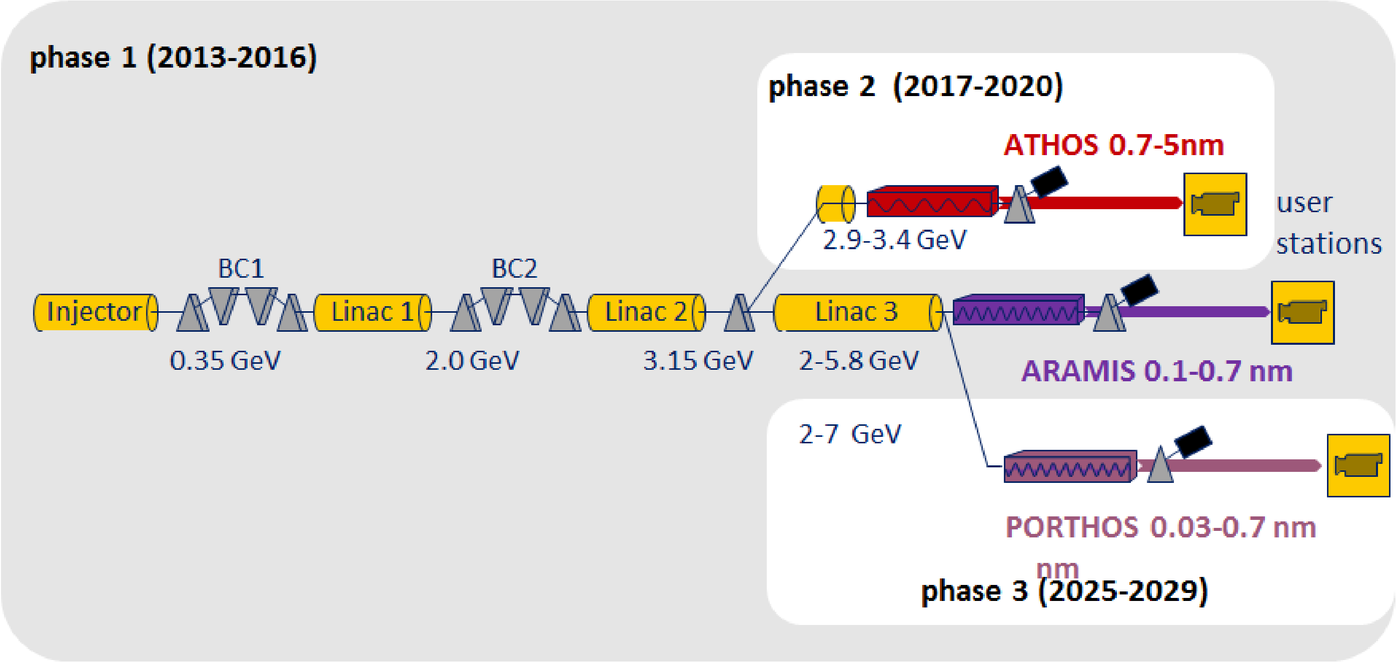
(courtesy of Th. Schmidt & M. Calvi)

Context : SwissFEL Project for another line “Porthos”

Porthos beamline (7 GeV):

expand wavelength range -> 1/3 Å (36 keV)

better performance at 1 Å



$$K = 0.93 \cdot B[T]\lambda_U[cm]$$

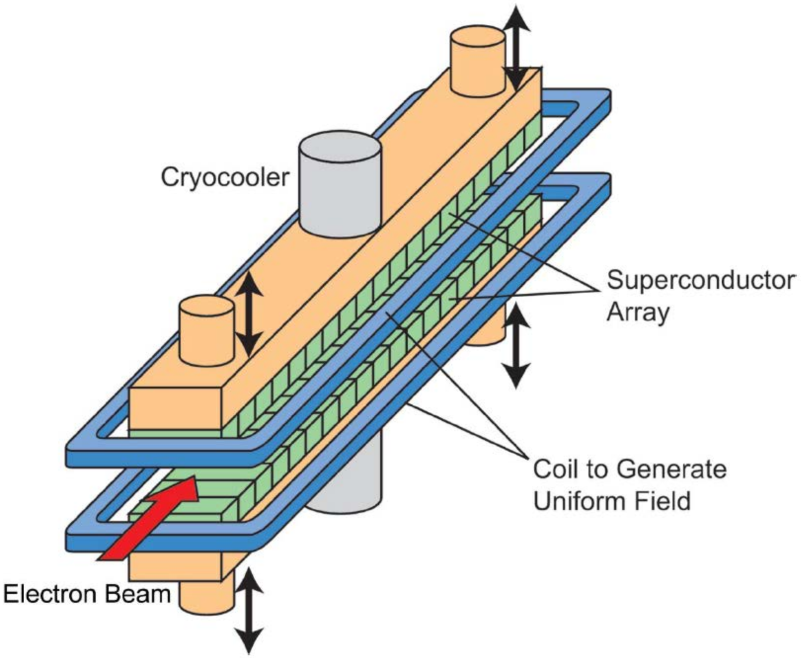
$$\lambda = \frac{\lambda_U}{2\gamma^2}\left(1+\tfrac{1}{2}K^2\right)$$

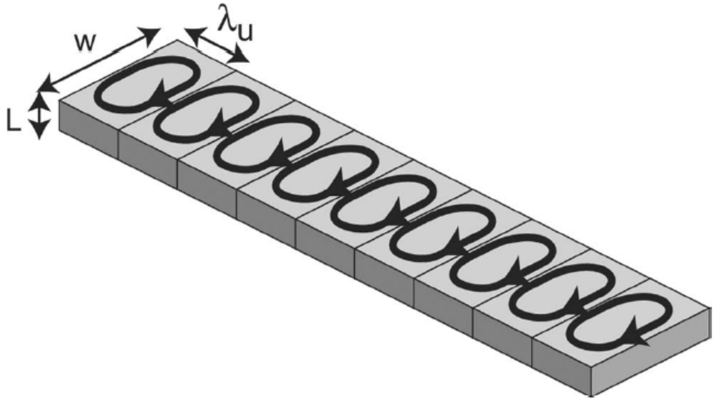
e^- 5.8 -> 7 GeV

Constraints on the IDs in the Porthos line:

Gap=4 mm, λ_u=10 mm, K=2.4→ B~2.6 T, SC ID !

Bulk HTC undulator- one direction of investigation





blocks of Gd-Ba-Cu-O

(T_C = 92K)

Coils need also to be superconducting (Cryogen free elements):

Idea : Block of Gd-Ba-Cu-O magnetized by

a 0.5 m long - 10T racetrack coil out of Nb_3Sn

proof of principle at 59K with a 2T field produced by the blocks [1]

[1] Tanaka T, Tsuru R, Kitamura H, Pure-type superconducting permanent-magnet undulator, Journal of Synchrotron Radiation 12, 442-447, (2005)

Roadmap

Phase I *Modelling overview* end of 2017

(Postdoc starting in 11’17 - 2 years)

Phase II *Test of a short length model* 2018/19

1 row few periods, but

with 10T racetrack coil, T = 4.2K

(Horizon 2020: compact light source)

Phase III *CDR SC undulator for Porthos U10 / SLS 2.0 U10* 2019

Phase IV *full size prototype 0.5m* >2020
SC- coil

integration of phase matcher, bpm, quad

Magnets for the SLS upgrade (low emittance ring)

Goal : Design and build a small emittance circular light source (emittance improved by 30) keeping the existing SLS ring size

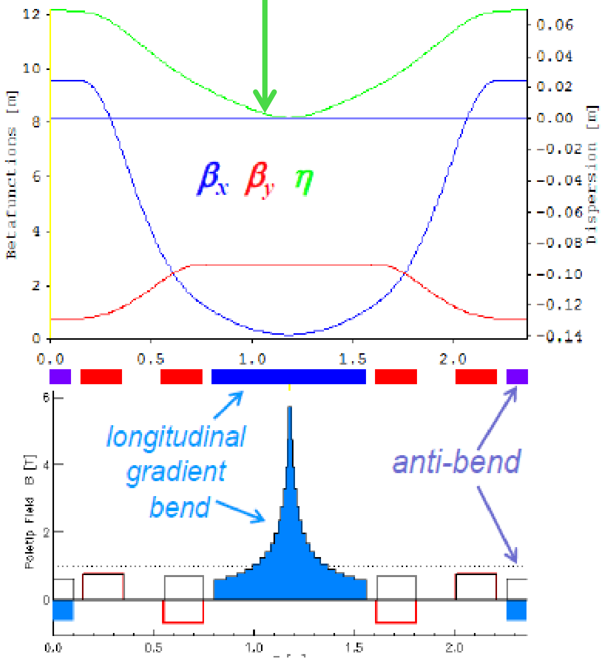
Compact low emittance cell → Multi-bend achromatic design
(breaking up dipoles and putting focusing (quadrupoles) between)

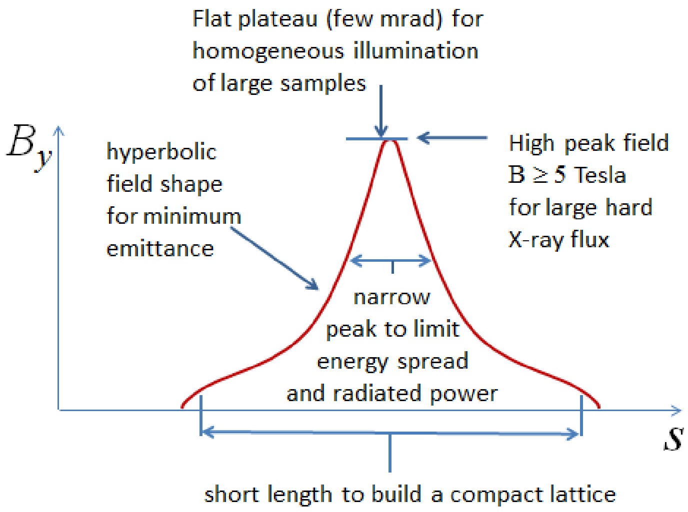
$E = 2.4$ GeV, $C = 288$ m, $\varepsilon_x \propto (\text{Energy})^2 / (\text{Circumference})^3$

Various concept lattice designs for ~150 pm emittance

- based on a **7-bend achromatic** arc (5 full bends+2 anti bends)
- **Longitudinal gradient bends**+ **super-bends of 5-6 T peak field** with (hyperbolic field variation)→L~80 cm+**2** **anti-bends**

Dispersion →zero on peak field





Magnet inventory SLS 2.0

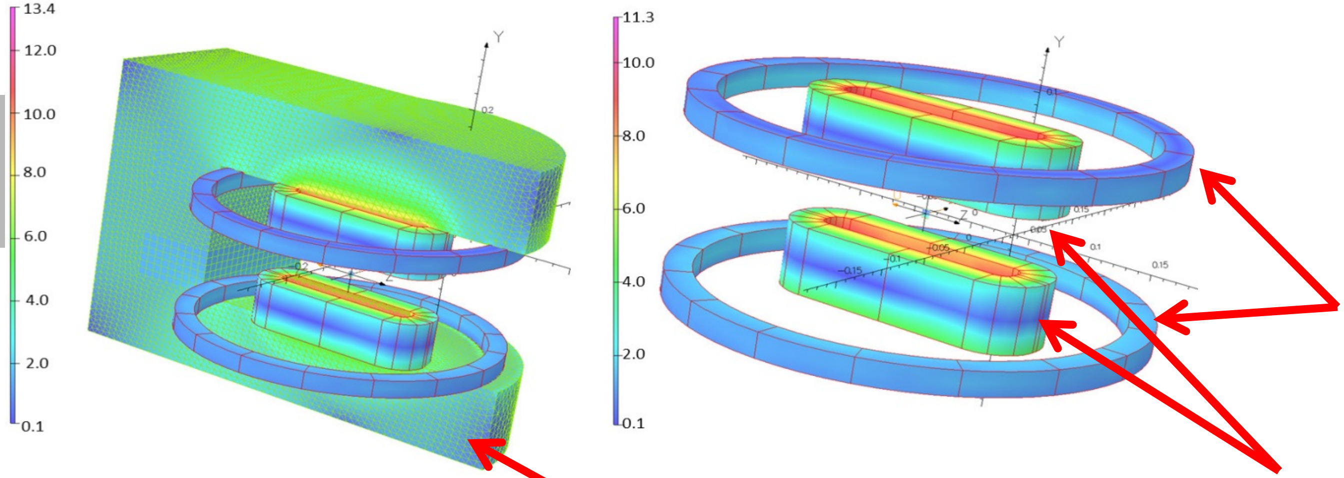
	Magnets SLS-2	(circuits)	[May 2017]
dipoles	372	(?)	[372]
...from which	363 in 147 blocks		
	0...369 as permanent?		
	3 superbends 6 T		
quadrupoles	72	(72)	[96]
sextupoles	288	(288?)	[288]
octupoles	144	(5 or 144?)	[288?]
HV correctors	144	[in sextupoles]	[120]
aux. sextupoles	---		
skew quadrupoles	144? [in sext. or oct.]		
BPMs	144		[120]

An amount of 1100 magnets !

114 longitudinal gradient bend dipoles + 3 high field superbends

SLS 2 superbend prototype :Magnetic design

Magnet geometry : split racetracks + solenoids



Outer coils
to guarantee
the required
field integral

ARMCO^R (better V-permendur) to enhance
the field and reduce the stray field

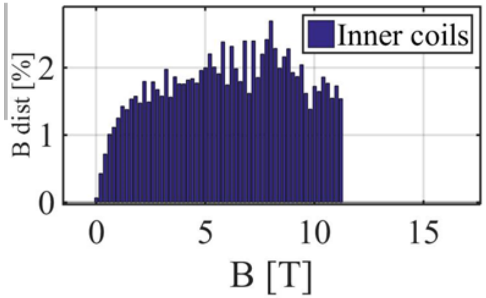
Inner coils
to produce the B-field peak

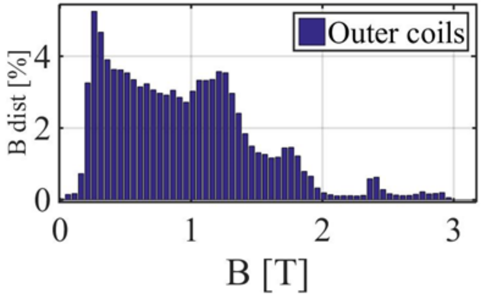
Inner coils

50% of the winding pack experiences a field above 6 T

10% of the winding pack experiences a field above 10 T.

Peak field: 11.3 T → Nb$_3$Sn





Outer coils

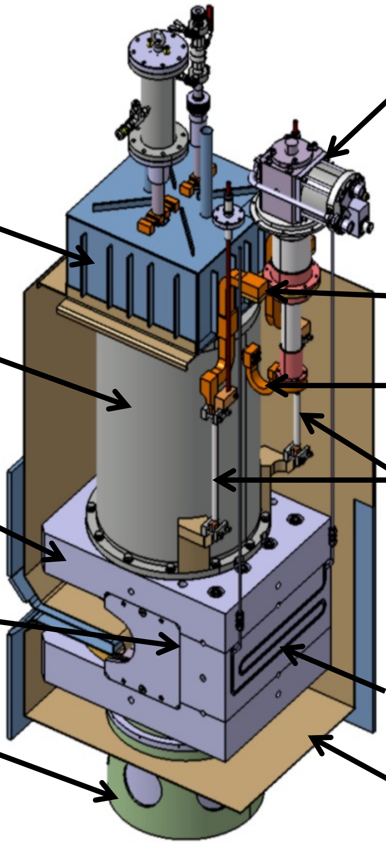
50% of the winding pack experiences a field above 0.8 T.

10% of the winding pack experiences a field above 1.7 T.

Peak field: 2.9 T → Nb-Ti

Superbend main components and parameters

To guarantee 8-10 hours autonomy in case of cryocooler failure.



LN_2 vessel

LHe vessel

ARMCO^R

(or V-permendur)yoke

316 L yoke reinforcement

G10/Steel Support

Gifford-McMahon

(or pulse tube) cryocooler

50 K

thermal connection

4 K

thermal connection

HTS current leads

Pre-cooling pipe

Cryostat

inner wall

	Outer coils	Inner coils
Conductor type:	Nb-Ti	Nb_3Sn (RRP)
Insulation:	Formvar	S-glass
I_c @ 4.2 K (A)	752 @ 5T	810 @ 12T
Magnetic energy (kJ) (1 coil)	3.8	16.6
Inductance (mH) (1 coil)	50	210
Current per turn (A)	400	400
N. turns (1 coil)	200	1485
Extraction Voltage (V) (τ_{damp}=0.4s)	340	140
Horizontal aperture (mm)		53
Peak field at conductor (T)	2.8	11.3
Peak temperature (K)	4.2	4.3

Challenges & next steps

Challenges

- Inner coil ***manufacturing***: Nb_3Sn single filaments
    - Heat treatment
    - Impregnation

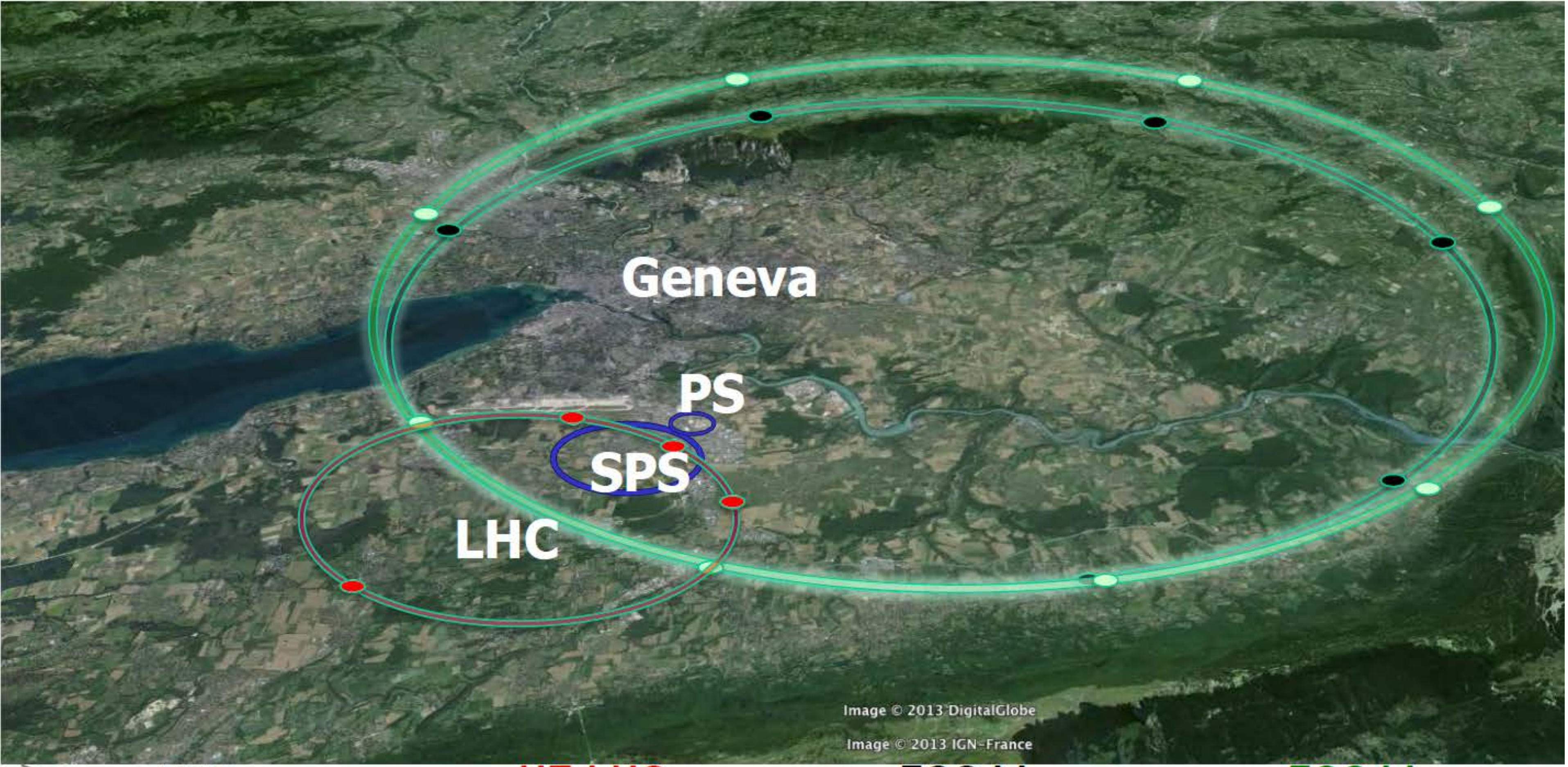
- ***Temp. margin*** : B-field with a narrow peak: high current density in the inner coil + narrow bore + Cryogen free cooling system

- ***Field quality measurements !***

Further steps: Construction and test at 4.5 K of a prototype

1. Technical design: 2017-2018
2. Coil manufacturing &magnet assembly : 2018-2019 (PSI/external partner)
3. Qualification tests at 4.5 K: at PSI in 2020?
    1. Quench;
    2. Magnetic measurements

R&D on the Canted Cosine Theta option for the 16-T FCC-hh main dipole



T and bey

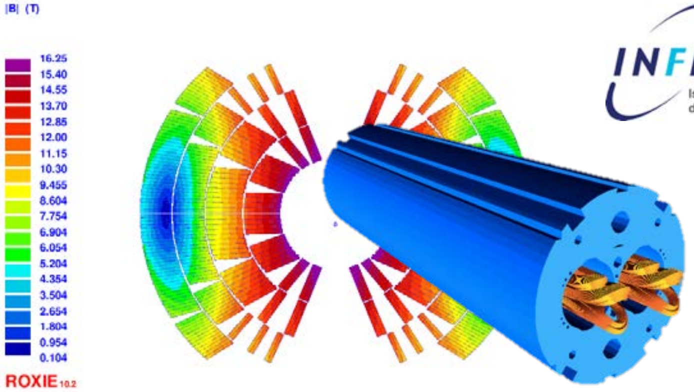
LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, 20 T	80 km, 20 T	100 km, 16 T
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

Magnet Types for a 16 T dipole

Cosine Theta Coil

Highest efficiency. Difficult stress management and coil end design.

INFN Istituto Nazionale di Fisica Nucleare

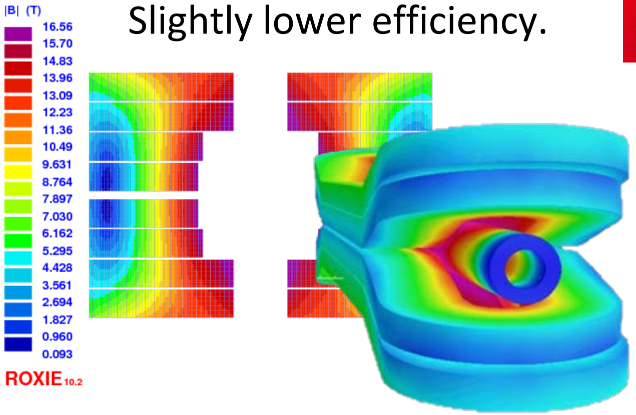


Block Coil

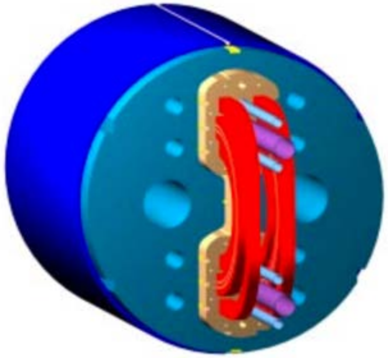
On paper simpler mechanics.

Difficult transition in ends. Slightly lower efficiency.

cea



Common Coil



Simple coil ends.

Difficult horizontal force containment

More energy, less efficiency.

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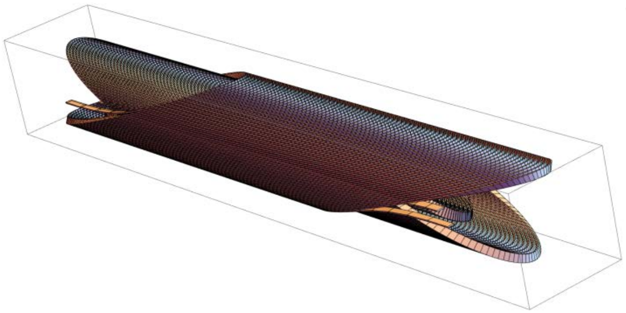
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Canted Cosine Theta (Tilted Helices)

Simple manufacturing, low coil stress, field quality
Reduced efficiency

Swiss contribution via PSI



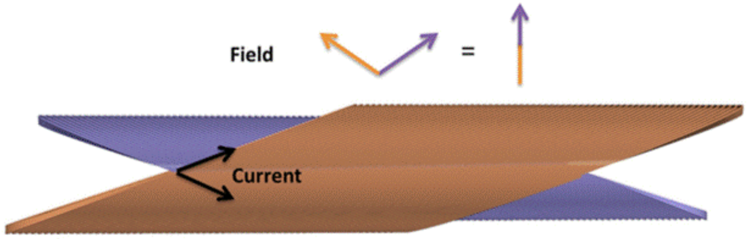
Bore diameter: 50 mm

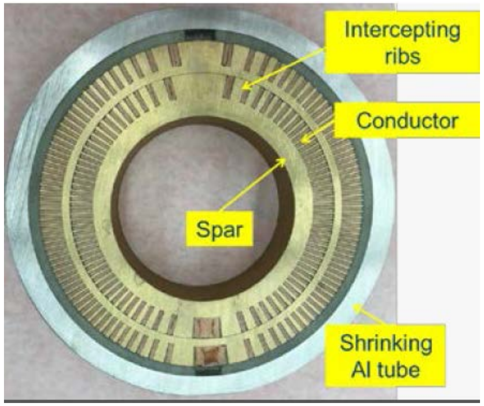
Dipoles: $4578\ units, 14.3\ m\ long, 16\ T \Leftrightarrow \int Bdl \sim 1\ MTm$

CHART CCT Magnet R&D @ PSI

CCT= Canted Cosine Teta (tilted helice)

The current distribution of any canted layer generates a pure harmonic field as well as a solenoid field that can be cancelled with a similar but oppositely canted layer





canted cosine theta (CCT) design

(2 layers cross-section)

The CCT geometry is studied as an option for the 16-T FCC-hh main dipole

First Goal for the next three years : As a proof-of-principle, design, manufacture and test model magnets:

to qualify the components, the tools, the manufacturing process for the CCT geometry

PSI/CERN/LBNL collaboration

CCT type dipole - questions & challenges

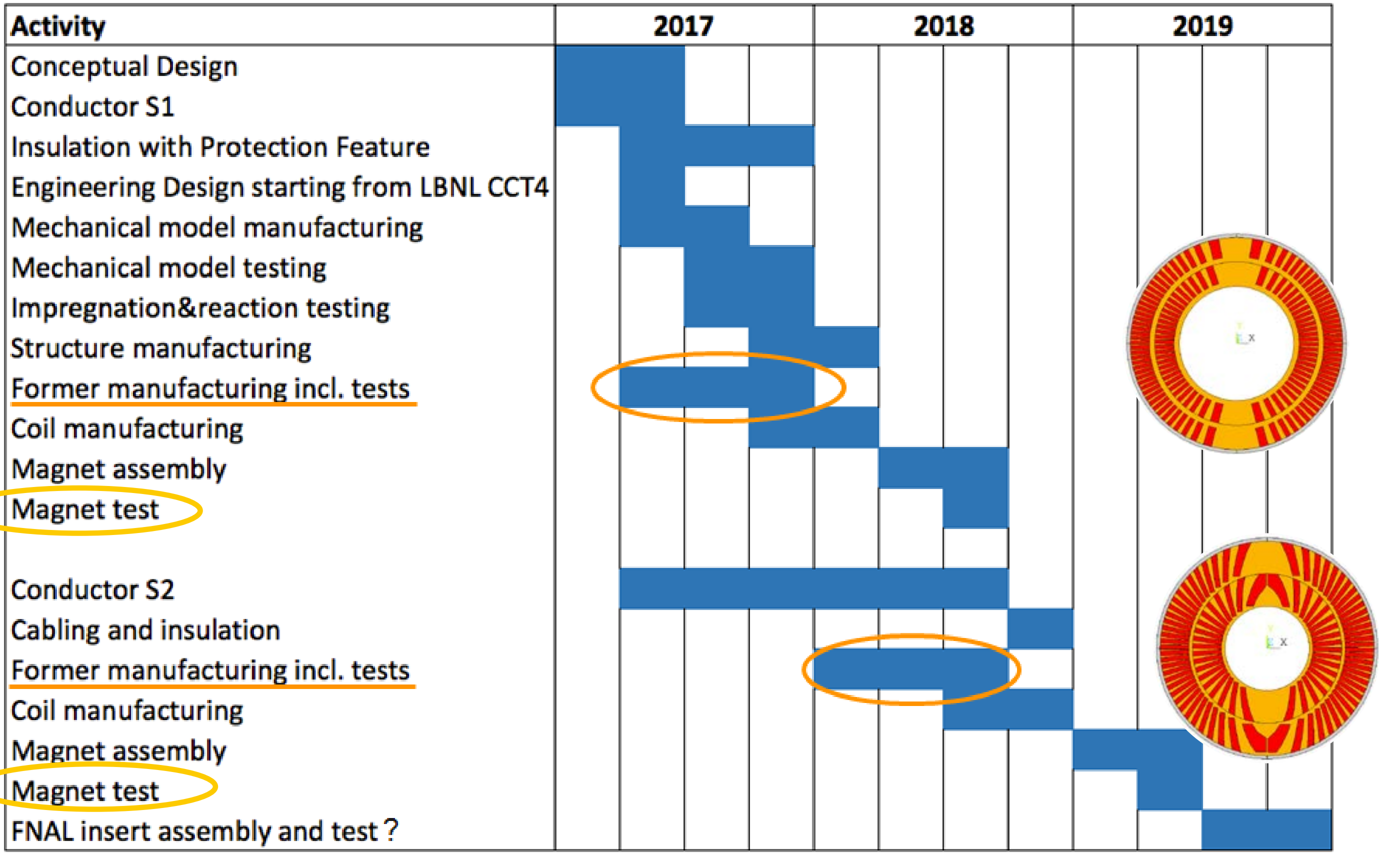
- ***Windability***: can a CCT be wound with large cable on 50-mm ap.?

answer : Winding tests completed successfully

- ***Former manufacture, which technique***? thin laminations; 3-D printing; 5-axis machining;
- ***Winding automation***: optimization of winding procedure; robot
- ***Long-coil assembly ?***
- ***Quench protection***: Which system (no turn to turn propagation)→development of simulation tools
- ***Performance/training***: combined or individual impregnation of layers; porous formers
- ***Magnetic measurement at 300 K (PSI) and 4.2 K (CERN/LBNL) for the models***

16 T CCT Program: Status and PSI Plans

- Magnetic design with four layer coils is completed
- Mechanic design and former manufacturing trials on going;
- Staged approach: Canted Dipole 1 with radial 10-mm-deep channels; Canted Dipole 2 with inclined, 16-mm-deep channels
- Test of CD1 **fall 2018**, test of CD2 in the FNAL insert **end of 2019**



Activity	2017				2018				2019			
Conceptual Design	■	■										
Conductor S1	■	■										
Insulation with Protection Feature		■	■	■								
Engineering Design starting from LBNL CCT4		■										
Mechanical model manufacturing		■	■									
Mechanical model testing			■	■								
Impregnation&reaction testing			■	■								
Structure manufacturing				■	■							
Former manufacturing incl. tests		■	■	■								
Coil manufacturing				■	■							
Magnet assembly						■	■					
Magnet test							■					
Conductor S2		■	■	■	■	■	■					
Cabling and insulation								■				
Former manufacturing incl. tests					■	■	■					
Coil manufacturing							■	■				
Magnet assembly									■	■		
Magnet test										■		
FNAL insert assembly and test ?											■	■

Superconducting magnets for future Gantries: Motivations

Why a superconducting magnet?

- Work at higher B-field → reduce the gantry size
  bending radius : $\rho = B\rho / B_{Mag}$
- Work at higher Gradient-field (+ large aperture) → high momentum acceptance i.e. energy scanning without changing magnetic fields;
- Reduce the magnet weight;
- Reduce power consumption

Proton therapy Gantry 2 (PSI)
8m x12m , 200 tons

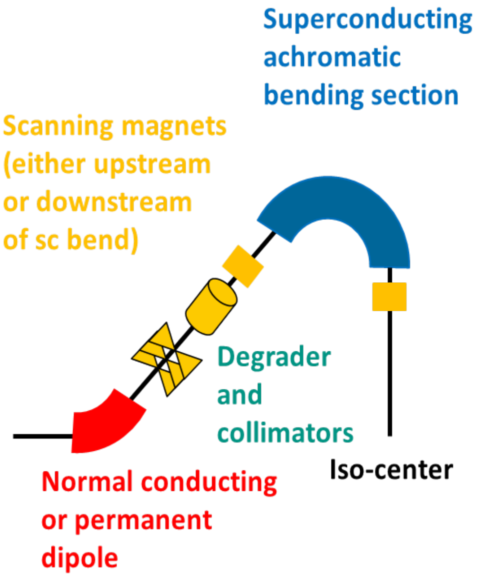
Heidelberg Ion Therapy, Carbon Ion Gantry
22m x 13 m , 600 tons
(1/10 of the Eiffel Tower)

Issues:

- Reliability (risks of quenches);
- Mechanical stability (huge Lorentz Forces);
- Cooling system complexity (magnet rotation);
- AC Losses;
- Challenges dealing with stray fields
  (0.5 mT at patient);

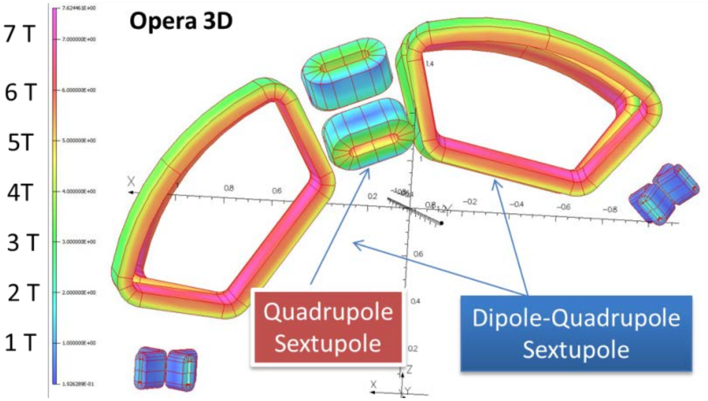
Light and compact gantries with superconducting magnets-PSI proposal

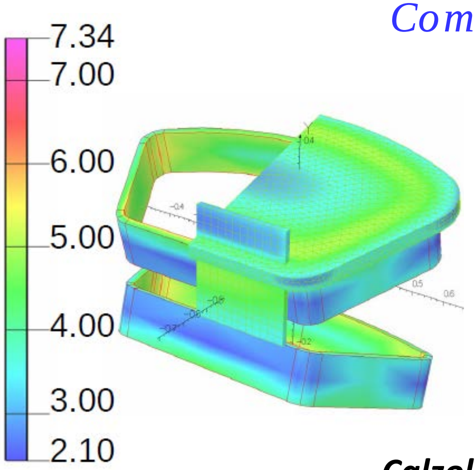
- Locally achromatic design (bending section);
- ***Superconducting combined function magnets*** to reduce the number of quadrupoles (compactness)
- Large aperture (H-220 mm, V-80 mm)
- Cryogen free magnets (cryo-coolers)-rotating structure



Achromatic bending section : ***Series of combined function magnets with a racetrack geometry (Nb3Sn)***

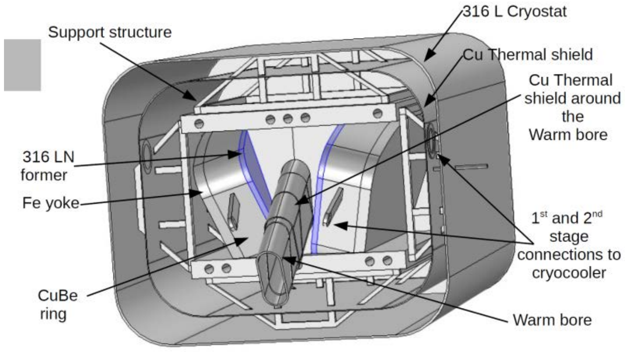
Magnetic design-bending section





Calzolaio- PSI 2017

Combined function dipole

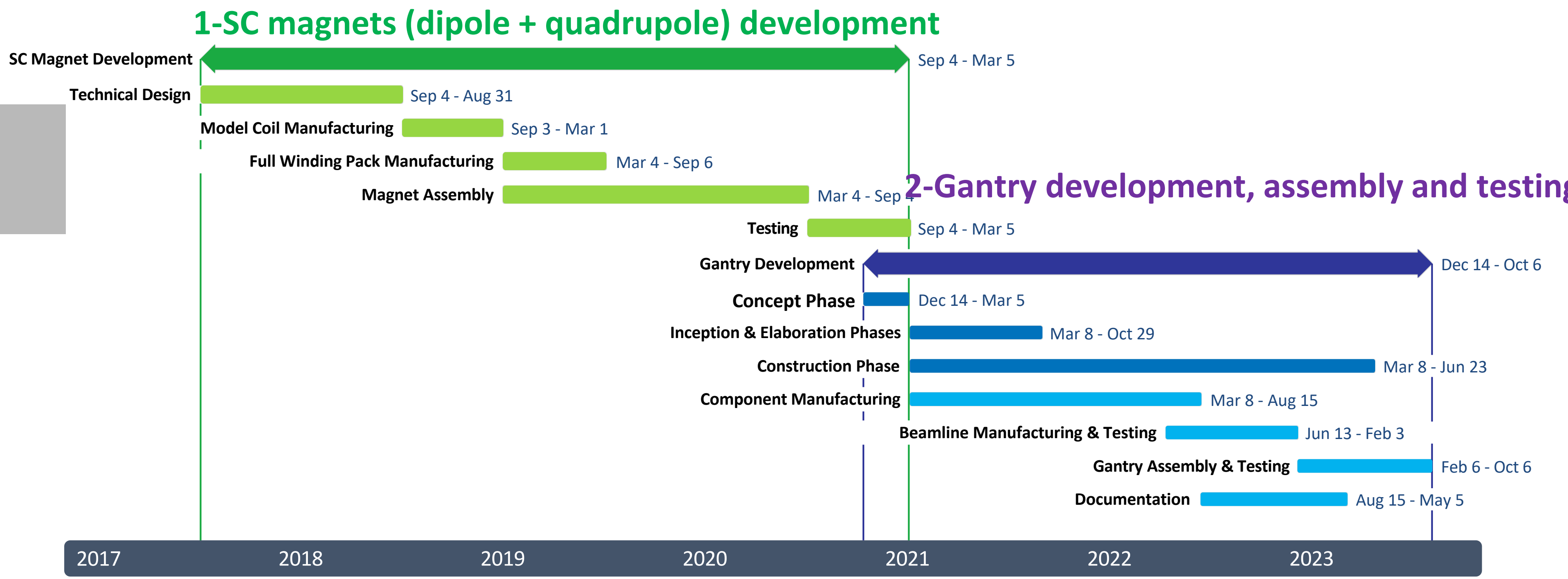


Calzolaio-Sidorov- PSI 2017

Magnetic field measurements (field maps, multipoles) ?

Traveling three axis sensor + traveling rotating coil

Superconducting gantry prototype at PSI
Roadmap (2017-2023)-2 phases



- SC magnets (dipoles + quadrupoles) produced and tested: mid 2021
- Gantry construction phase: Completed End of 2023

Recent developments in measurement systems

- Miniature High Precision Three Axis Hall Sensor : Improvements and integration in the existing measurement system (see presentation of Ch. Wouters) *2016-2017*

- Assembly and commissioning of a field mapper based on PCB coils to determine magnetically the Center Current Line of the ITER Torroidal Field Coil -2016 (PSI/CERN/ITER-presentation of M. Buzio)

- Rotating coil: Consolidation of the existing systems (PSI-CERN collaboration)
  - DAQ with post processed integration –no integrators (September-December 2016)
  - Commissioning of a ***Ø8 mm ,150 mm long, PCB rotating coil*** (January-March 2017)
  - Design an construction of a ***Ø9 mm, 0.5 m long PCB rotating coil*** (from April 2017)

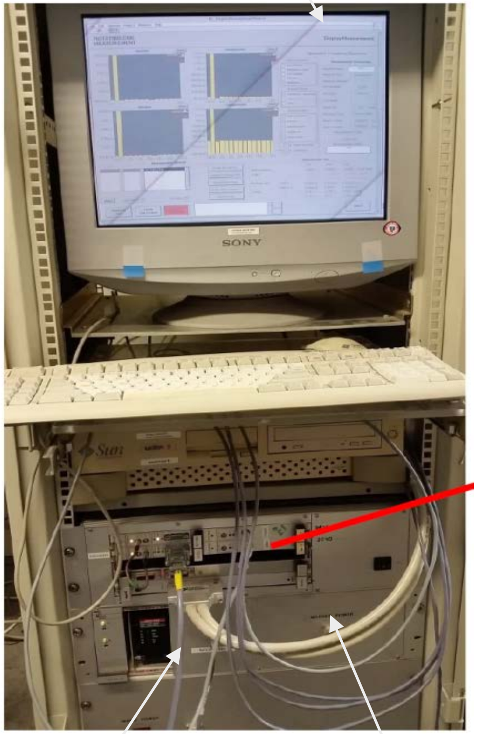
    designed to measure series of quads with 10-12 mm aperture (SwissFEL, COSAMI, SLS 2.0.....)

- New system for bent and strongly non-homogenous superconducting magnets
  - Design and construction of traveling 3 D Hall probe system and rotating coil system- **PhD grant from Idea-League Program** (PSI/ETH/CERN/Poli Milano-**2017-2020**)

« Integratorless integrators» for rotating coils

Previous DAQ system

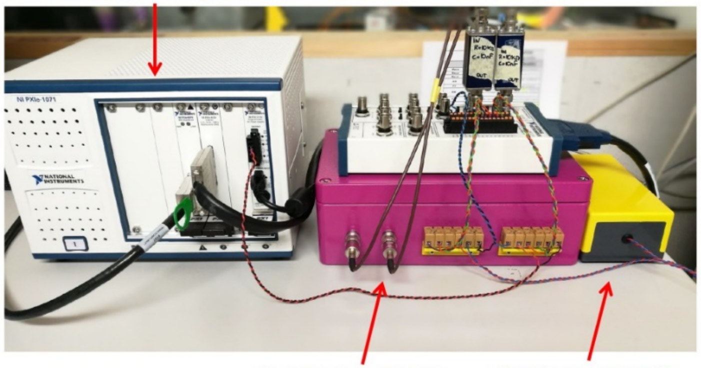
Magn. Meas.Program ()
on Sun workstation
(Labview)`



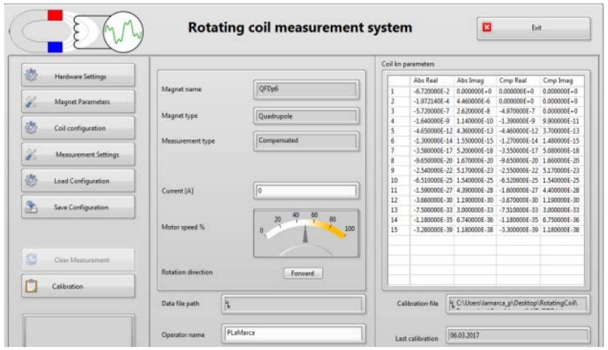
VME Integrators

Motor control and drive unit

New Hardware configuration



New interface with integrated post-processing



Magnet name: QFDp6
Magnet type: Quadrupole
Measurement type: Compensated
Current [A]: 0
Motor speed %: 0, 20, 40, 60, 80, 100
Rotation direction: Forward
Data file path:
Operator name: PLaMarca
Calibration file: C:\Users\lamarca_p\Desktop\RotatingCoil\
Last calibration: 06.03.2017

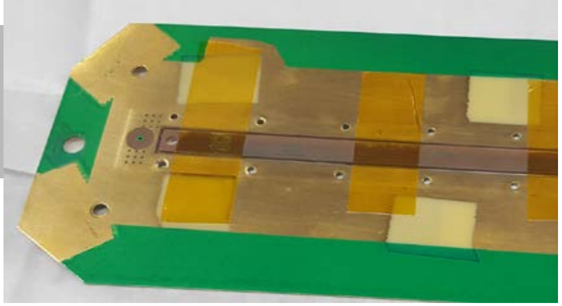
Coil kn parameters

	Abs Real	Abs Imag	Cmp Real	Cmp Imag
1	-6.720000E-2	0.000000E+0	0.000000E+0	0.000000E+0
2	-1.972140E-4	4.460000E-6	0.000000E+0	0.000000E+0
3	-5.720000E-7	2.620000E-8	-4.970000E-7	0.000000E+0
4	-1.640000E-9	1.140000E-10	-1.390000E-9	9.900000E-11
5	-4.650000E-12	4.360000E-13	-4.460000E-12	3.700000E-13
6	-1.300000E-14	1.550000E-15	-1.270000E-14	1.480000E-15
7	-3.580000E-17	5.200000E-18	-3.550000E-17	5.080000E-18
8	-9.650000E-20	1.670000E-20	-9.650000E-20	1.660000E-20
9	-2.540000E-22	5.170000E-23	-2.550000E-22	5.170000E-23
10	-6.510000E-25	1.540000E-25	-6.520000E-25	1.540000E-25
11	-1.590000E-27	4.390000E-28	-1.600000E-27	4.400000E-28
12	-3.660000E-30	1.190000E-30	-3.670000E-30	1.190000E-30
13	-7.500000E-33	3.000000E-33	-7.510000E-33	3.000000E-33
14	-1.180000E-35	6.740000E-36	-1.180000E-35	6.750000E-36
15	-3.280000E-39	1.180000E-38	-3.300000E-39	1.180000E-38

- Rotating coil DAQ based on off-the-shelf National Instrument electronics, developed in collaboration with CERN
- Fast, multi-channel, synchronous acquisition of analog (absolute and compensated coils) and digital (angular encoder) channels
- Streamlined baseline functionality easy to implement and maintain (raw data saved to file + post-processing to express as a function of the angle, integrate and correction flux)
- PSI version includes motor control and harmonic analysis integrated in LabView
- Flexible, simplified architecture.

Rotating coils: developments CERN-PSI

Commissioning at PSI of an innovative miniaturized PCB coil for high-precision magnetic measurements designed and built at CERN PCB service : *150 mm long*



PCB inside the frame

(copper tracks-10 μm)

- **Coils : Extreme thin PCB**: 1.38mm for 13 double layers where 4 radial coils are printed using laser direct imaging technique;
- **High mechanical quality support**: synthetic sapphire probe of 7.5mm diameter made of two halves in which a PCB is sandwiched;

✓ straightness 8μm max ,
✓ the flatness of surface where the PCB is glued is below 20μm
✓ support concentricity is limited to 1μm

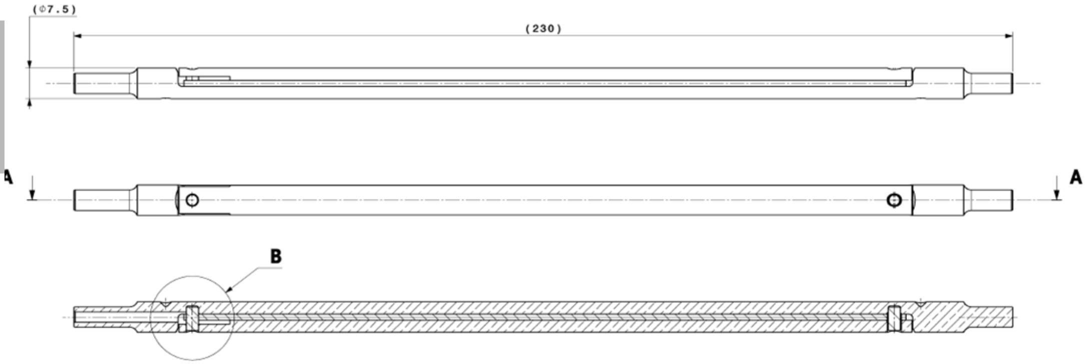
- **On-board bucking**: the signal compensation is performed directly on the PCB in order to have **three output signals**

✓ unbucked,
✓ dipole bucked,
✓ dipole and quadrupole bucked

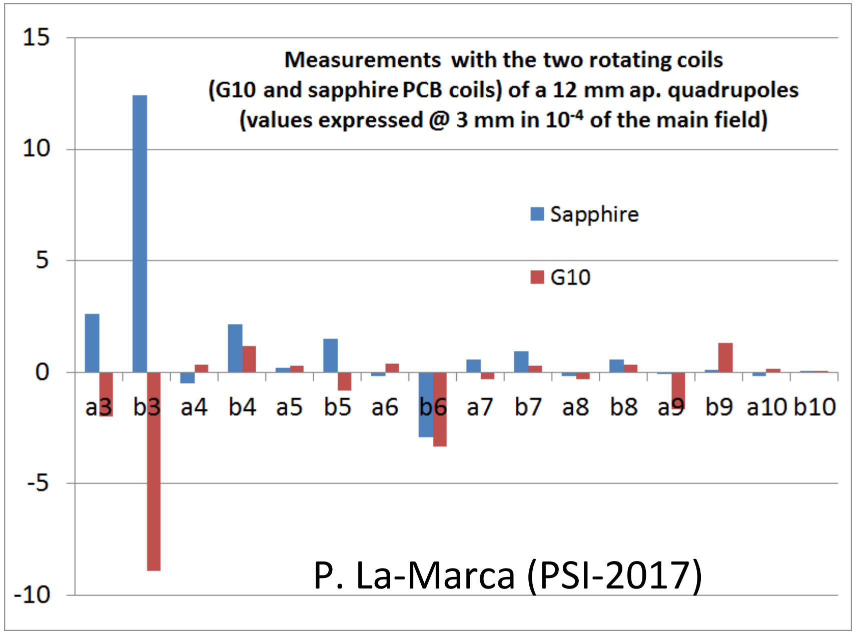
150 mm long rotating coil

Rotating coils: developments CERN-PSI(2)

Commissioning at PSI of an innovative miniaturized PCB coil for high-precision magnetic measurements designed and built at CERN PCB service : *150 mm long*



- The shaft has designed in two halves (cover, base) between which the PCB will be sandwiched. The cover is fixed to the second half by means of sapphire pins.
- The shaft has been adapted at PSI to an existent bench (2011) developed for the Ø 8mm coil
- The Kn coefficients were first determined by G. Severino at FERMILAB and checked at PSI



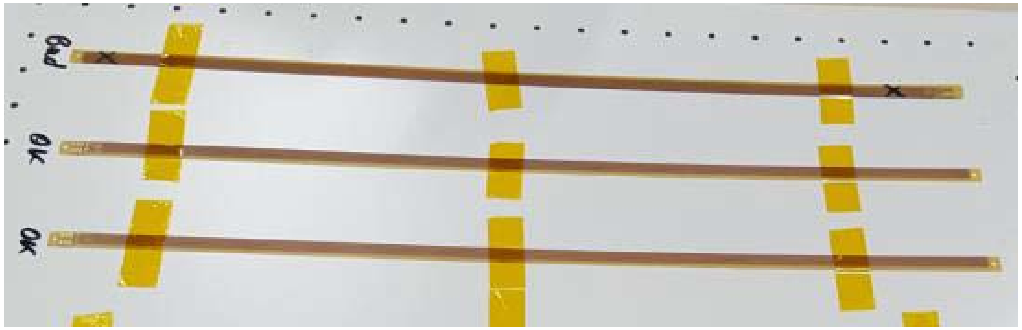
P. La-Marca (PSI-2017)

- Dipole bucking ratio ~ 10 times better than the previous one
- Excellent repeatability (<2 units)
- Differences w.r.t to previous rotating coil with G10 body within +/5 units except for b_3

PCB Rotating coil- step 2: 500 mm long

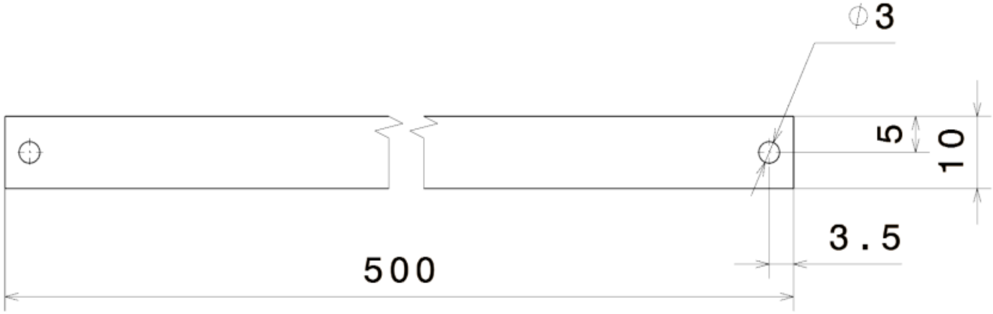
design and manufacturing of a PCB coil

with 9 mm diameter and *500 mm length*



PCB produced at CERN with a maximum total thickness of 1mm

- **12 single layers** with **four radial coils** with the **on-board bucking** implemented to suppress dipole and dipole+quadrupole

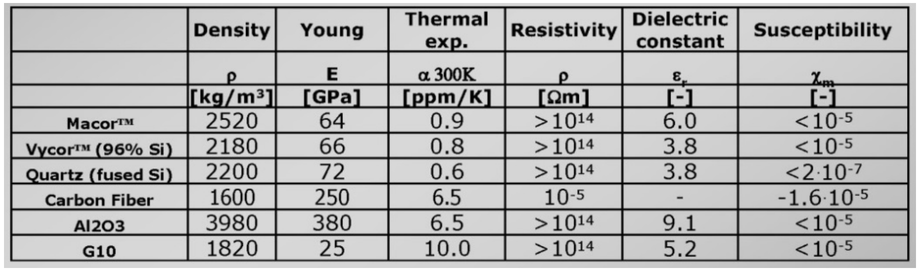


Design and manufacturing and calibration of the shaft will be carried out at PSI for the end of 2017

500 mm long PCB Rotating coil status and next steps

- **Mechanical design of the shaft - *OK April 2017***
- **Material choice for the body** (on-going)
  - Low magnetic susceptibility;
  - Non-conductive material to avoid eddy currents;
  - Mechanical stability in terms of rigidity and hardness;
  - Machinability and **cost**

“Standard materials”



	Density	Young	Thermal exp.	Resistivity	Dielectric constant	Susceptibility
	ρ	E	α 300K	ρ	ε_r	χ_m
	[kg/m³]	[GPa]	[ppm/K]	[Ωm]	[-]	[-]
Macor™	2520	64	0.9	$>10^{14}$	6.0	$<10^{-5}$
Vycor™ (96% Si)	2180	66	0.8	$>10^{14}$	3.8	$<10^{-5}$
Quartz (fused Si)	2200	72	0.6	$>10^{14}$	3.8	$<2 \cdot 10^{-7}$
Carbon Fiber	1600	250	6.5	10^{-5}	-	$-1.6 \cdot 10^{-5}$
Al2O3	3980	380	6.5	$>10^{14}$	9.1	$<10^{-5}$
G10	1820	25	10.0	$>10^{14}$	5.2	$<10^{-5}$

“New materials”

- Synthetic sapphire;
- *Blue stone or equivalent (PerFORM);*
- 3D printed Titanium sponge
- ….

- **Assembly** (support manufacturing trials on going): one main constraint is the significant length of the probe compared to the diameter.

Body of the 0.5 mm long shaft made of PerFORM® (3 D printing) Digitale Produktion Basel

Coils connections

- **Installation/Commissioning (End of 2017)** : the sensor will tested using SwissFEL spare magnets at PSI

Infrastructure (1): The Magnet-ID laboratory

Concept:

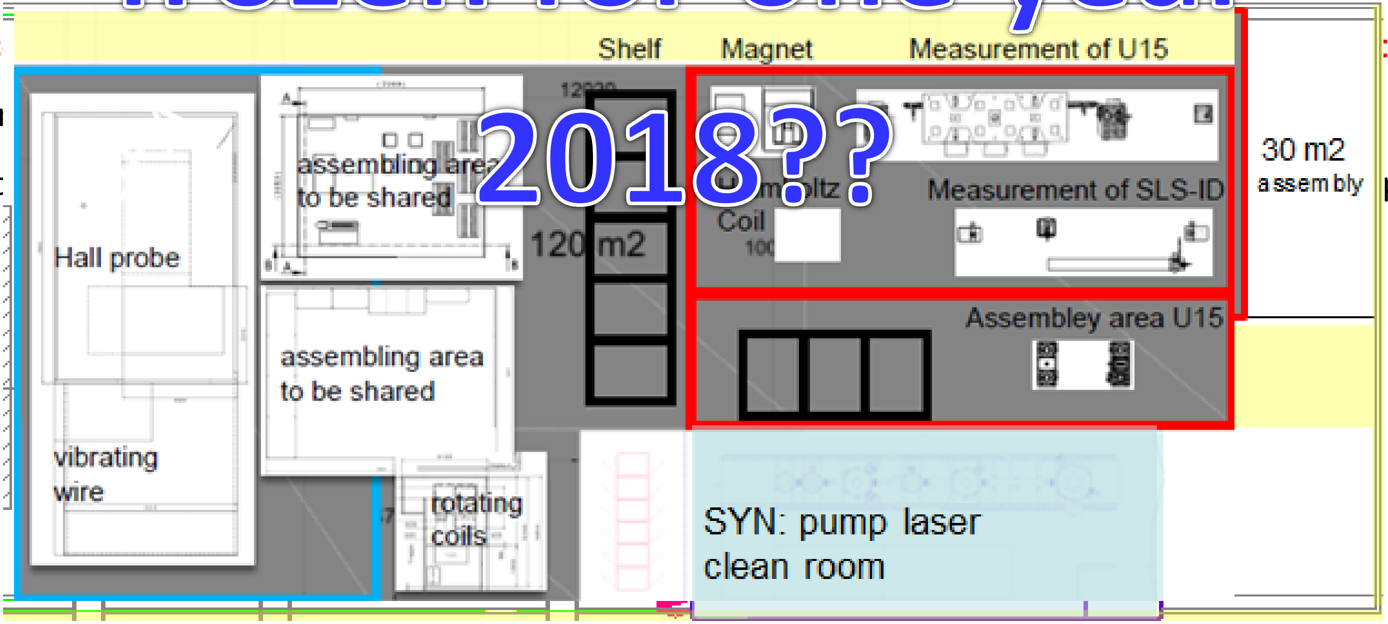
- Merging the Insertion Device and the Magnet laboratories presently sitting in two different places
- Surface : **410 m²** (150 m² ID, 150 m² Magnets and 110 m² shared)
- Floor plan divided into three functional areas: assembling area & workshops, measurement area magnets and measurement area undulators

Final approval

Advantages

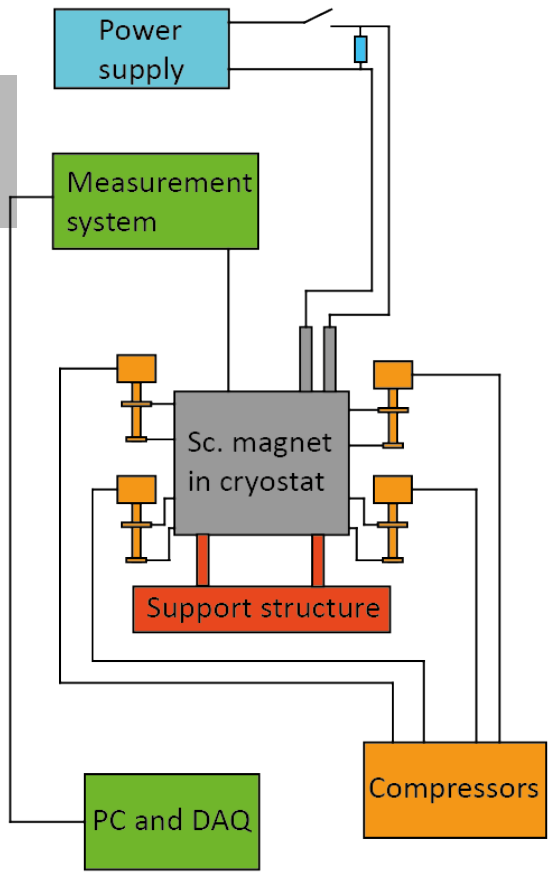
- Rationalize the space : sharing test stations and Instrumentation for magnetic measurements
- Common mechanic w k ho f r ma ne n und l to a sem ly / ep a
- **Synergies of c** ... **ic tests**
- Gain in efficie
- Reduction of t ... place and the test statio

frozen for one year



2018??

Infrastructure (2): Test stand at PSI for superconducting cryogen-free magnets



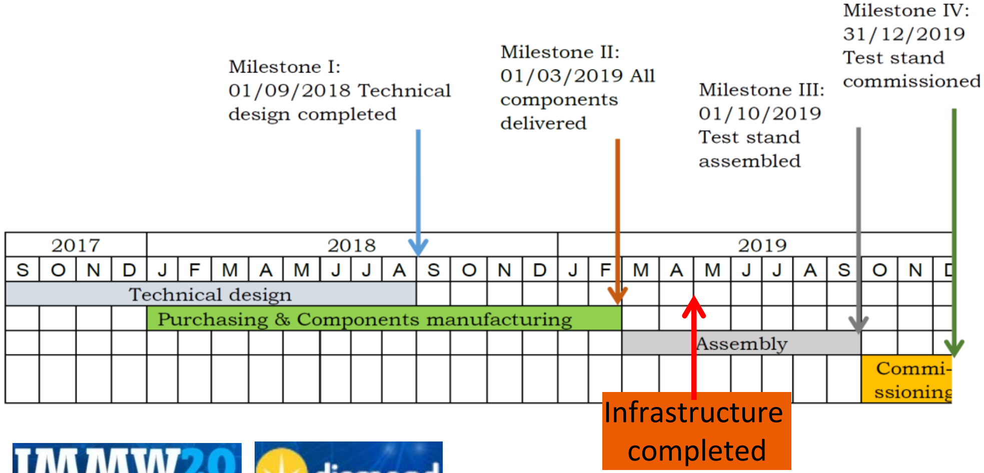
Footprint : 110 m2

GOAL

To build an infrastructure at PSI for the qualification of sc. magnets under operating conditions @4.5 K

KEY FEATURES

- Adjustable for testing different sc. magnets e.g. sc. Gantry, SLS 2.0 super-bend, SLS 2.0 sc. undulator
- **Cryogen-free** cooling power provided by four Cryocoolers
- ***Dedicated magnetic measurement system (traveling 3 axis sensors, rotating mole)- PhD, 2017-2020***



Milestone I: 01/09/2018 Technical design completed

Milestone II: 01/03/2019 All components delivered

Milestone III: 01/10/2019 Test stand assembled

Milestone IV: 31/12/2019 Test stand commissioned

Infrastructure completed

Summary

- The Swiss-Free Electron laser facility:
  - Main project at PSI with the construction of a second beam line (soft X-ray) and R&D developments on high K superconducting undulators for a possible third beam line after 2020
  - The soft X-ray- line will imply the measurement of about 100 magnets and 16 apple X, 2-m long undulators.

- A concept design for the upgrade of the Swiss Light Source will be prepared for Fall 2017 (review –end of september). This implies the production of longitudinal gradient bend conventional magnets and the development of a 6T superbend.

- A three-axis Hall sensor prototype with high spatial resolution and significant compensation of the planar Hall effect has been designed, assembled and tested. The sensor is implemented in the Hall probe measuring machine

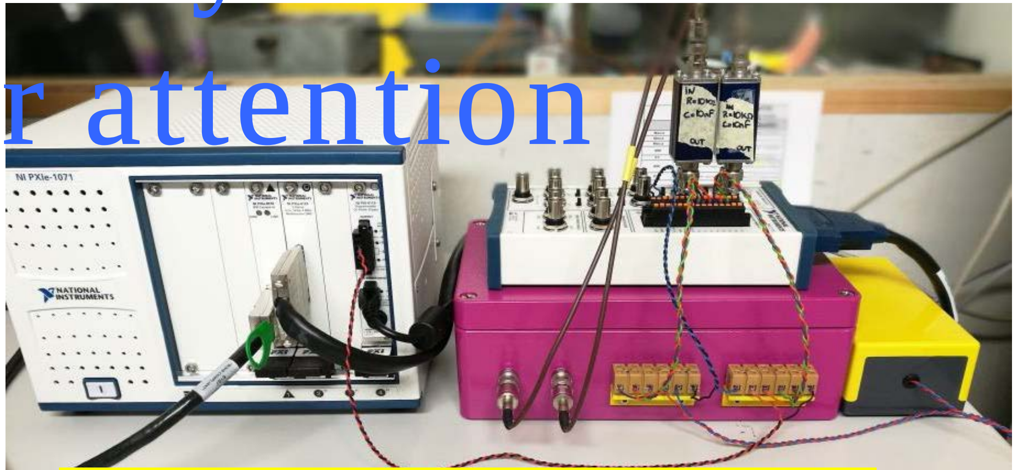
- Two other challenging projects including the design and procurement of superconducting dipoles are on-going
  - A combined function magnet based on a $NbSn_3$ racetrack coil geometry for a compact and light gantry
  - A 16 T dipole with the Canted Cosine Theta geometry as an option the main dipoles of the FCC

- Several developments on rotating coils and probes to consolidate the park of magnetic measurement systems were performed or planed for the measurements of the conventional or superconducting cryogen-free magnets related to the several future PSI projects (FEL lines, gantry, SLS 2.0…)

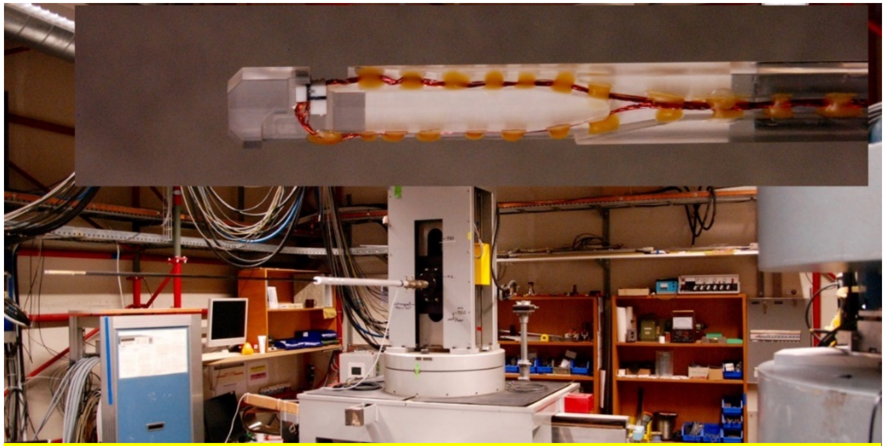
- Infrastructure : The construction of a test stand for the qualification of the cryogen free magnets at 4.5 K is proposed.

Thank you for your attention

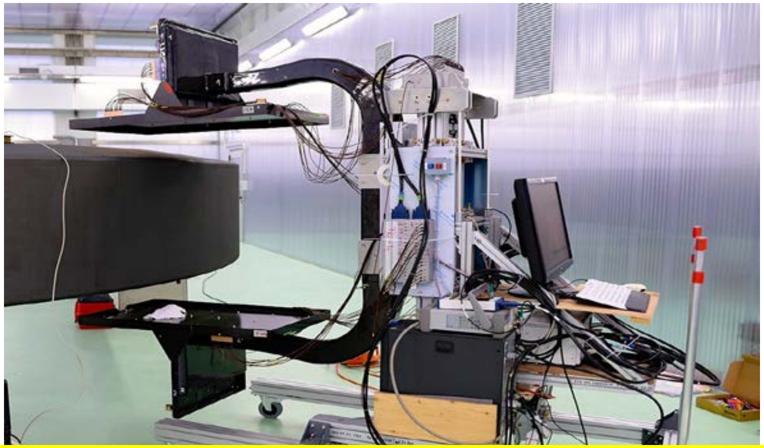
CCT model coil (few turns) wound at PSI



Rot. coil DAQ system without using integrators



Three axis Hall sensor in the PSI meas. machine

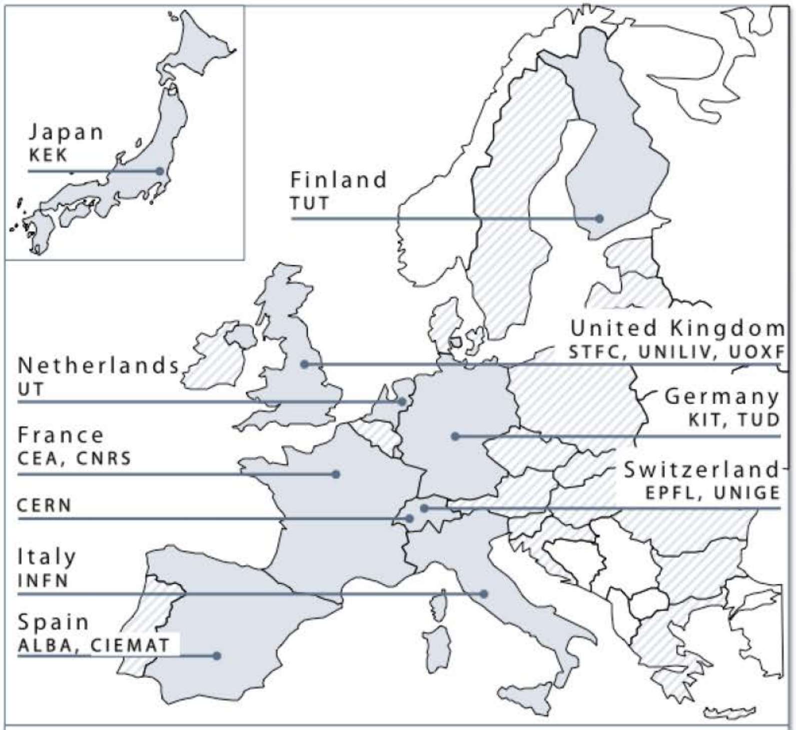


Field mapper to measure the first TF ITER coil

Additionnal Slides

CERN-EU program ‘EuroCirCol’ on 16 T dipole design

UNIVERSITY OF TWENTE.
INFN
TAMPERE UNIVERSITY OF TECHNOLOGY
cea
cnrs dépasser les frontières
CERN
UNIVERSITY OF OXFORD
TECHNISCHE UNIVERSITÄT DARMSTADT
KIT Karlsruher Institut für Technologie
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
UNIVERSITY OF LIVERPOOL
UNIVERSITÉ DE GENÈVE
ALBA
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
MANCHESTER 1824



EuroCirCol consortium, federating 16 partners, 1 from Japan and 1 IEIO

European Union Horizon 2020 program

- Support for FCC study
- Grant agreement 654305
- 3 MEURO co-funding

Scope:

FCC hadron collider

- Optics Design
- Cryo vacuum design
- 16 T dipole design, construction folder for demonstrator magnets

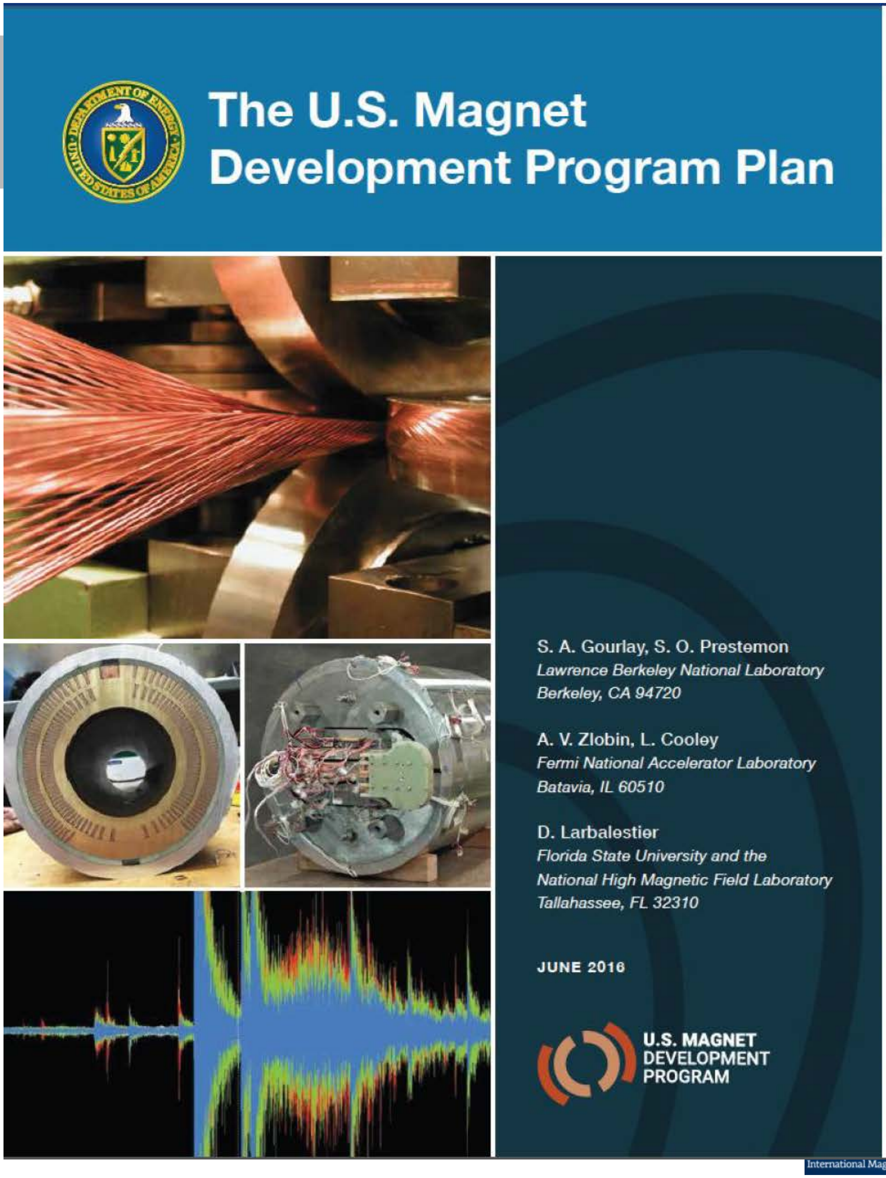
Collaboration with the US magnet development program

Challenges-Superbend prototype

1. Nb_3Sn coils → Wind and react technique:
    1. Cabling of Rutherford cables (12 strands) → cabling machine needed
    2. Heat treatment and vacuum impregnation of a full size coil → VPI chamber + oven needed (size: ≈1m×1m×1m)
    3. Mechanical tooling: mold, support structure
2. Cooling system → cryogen-free
    1. Localized heat sink: → thermal gradients
    2. Low cooling power
    3. Thermo-mechanical structure design: reduce the heat input from the external environment and guarantee sufficient mechanical support
    4. Careful materials choice: low electrical conductivity to reduce the eddy currents but good thermal conductivity to connect the heat inputs to the heat sink.
3. Magnetic field shielding → yoke laminations
    1. Cryocooler: drive motor: 50-80 mT
    2. Patient: < 0.5 mT
4. Magnetic field measurements → traveling three axis sensor + traveling mole

U.S. Magnet Development Program

The main goal is a large improvement in cost-performance



The U.S. Magnet Development Program Plan

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Berkeley, CA 94720

A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory
Batavia, IL 60510

D. Larbalestier
Florida State University and the
National High Magnetic Field Laboratory
Tallahassee, FL 32310

JUNE 2016

U.S. MAGNET DEVELOPMENT PROGRAM

Program (MDP) Goals:

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

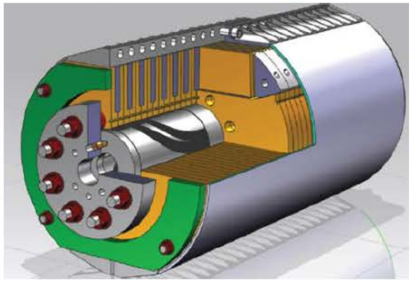
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:

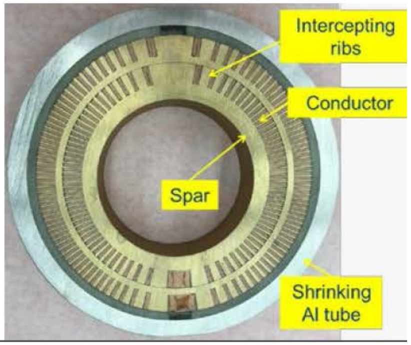
Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

Under Goal 1:

16 T cos theta dipole design

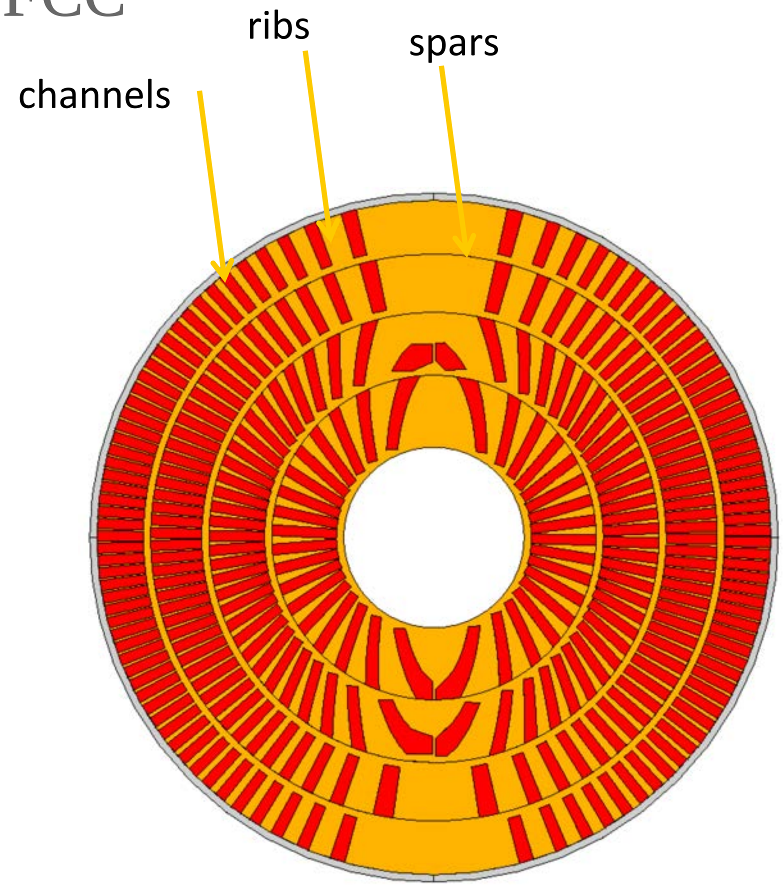


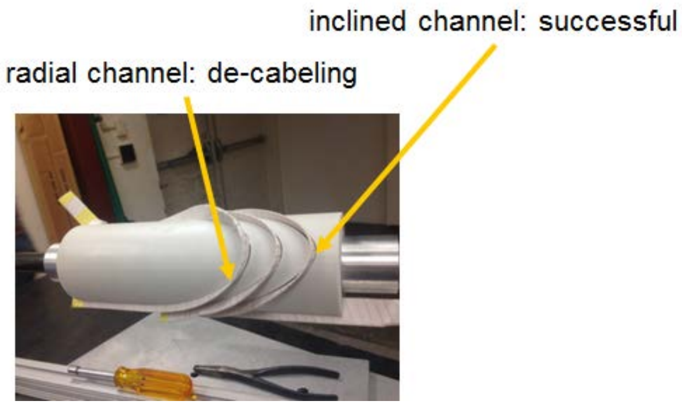
16 T canted cos theta (CCT) design



PSI’s CCT Design for FCC

- Keys to an efficient CCT design:
  - Thin spars, wide cable, large strands.
  - Reduces amount of ribs and increases J_e
- 4 layer coils using Nb_3Sn cables
  - ~30% more SC than Cosine Teta geometry.
- Mechanical structure:
  - Laminations in welded steel shell
  - Low coil stresses
  - Bladder and Key technology
- Windability:
  - Need to incline channels

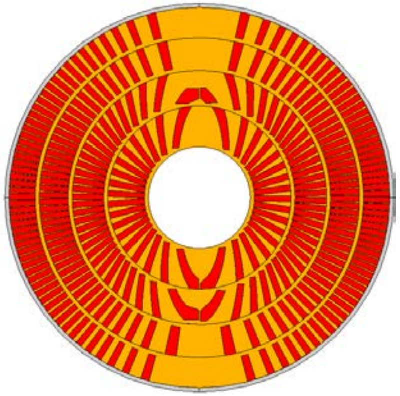


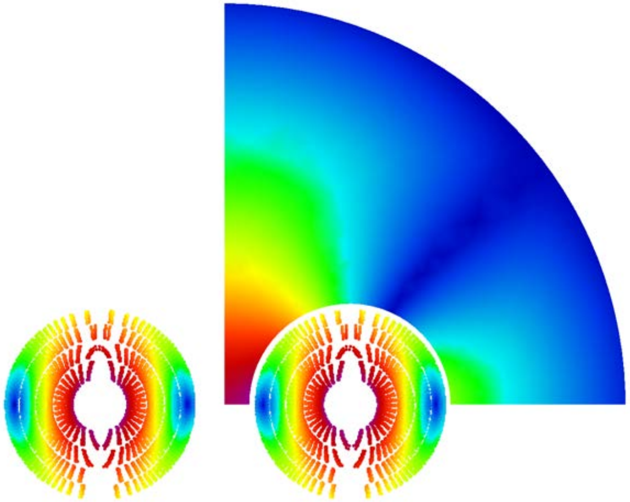


Why a high field magnet with CCT geometry

CCT= Canted Cosine Teta (tilted helice)

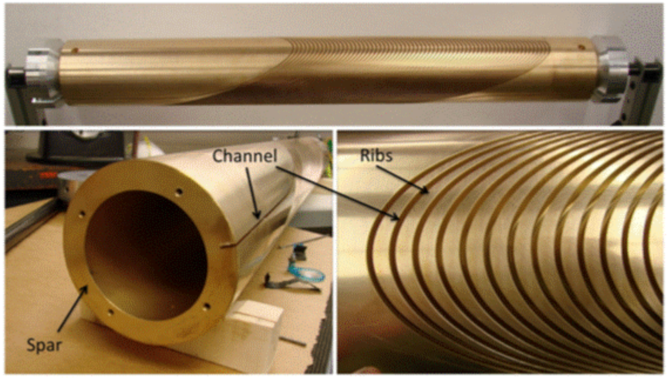
- Accelerator-grade field quality
- No need for coil pre-stress during assembly
- Reduced coil stresses should improve magnet training and avoid performance degradation
- Fast prototyping, short turnaround times
- Fewer components than traditional designs – this might translate to reduced costs (although this currently has not been fully demonstrated)

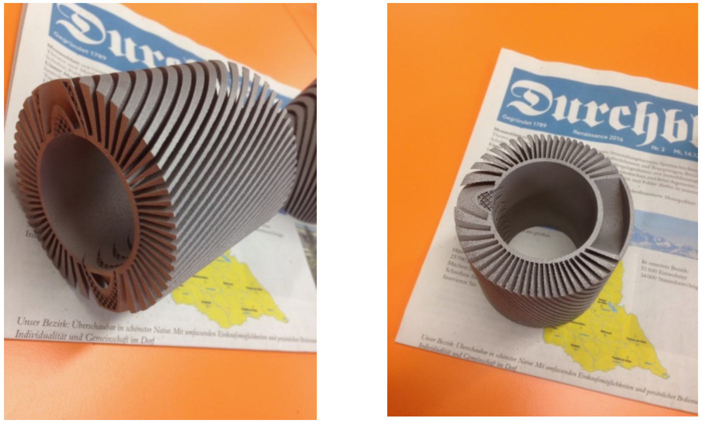




One particular issue: former manufacturing

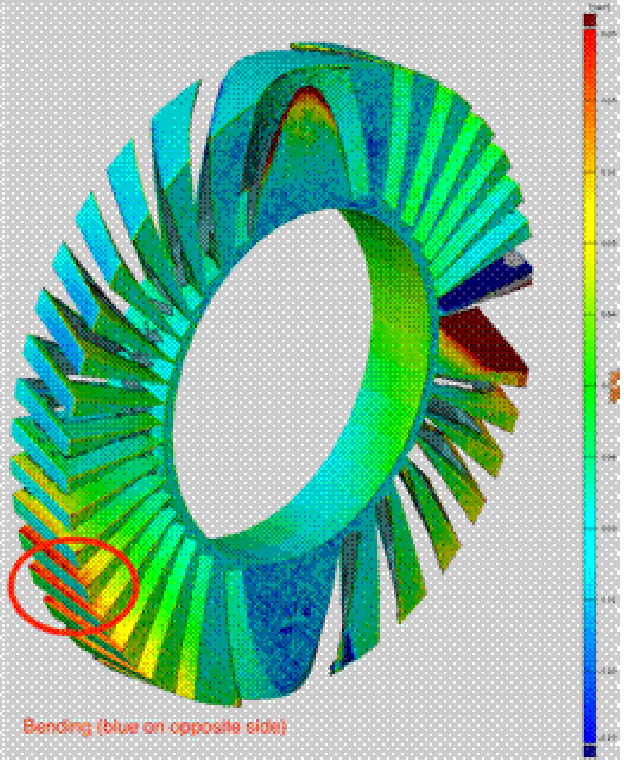
- Conventional: 3-axis machining into Al-Bronze cylinder (CD1)
  - Windability of wide cable + inclined channel requires a 5-axis machining
  - Price quickly exceeds that of conductor → not credible for the CCT option for FCC.
- Other manufacturing process:
  1. 3-D printing (steel)
  2. Laminated former





Former Manufacturing Trials

- Numerous problems have been encountered with selective laser melting.
- No matter the orientation, many surfaces hang at angles < 45º.



PSI Goals : Proof of principle of the CCT technology for the FCC magnets

- Thin spars
- Exterior Bladder and Key structure
- Impregnation system (NHMFL resin, etc.).
- Fast quench detection and CLIQ protection.
- Wide Rutherford cable.
- Inclined channels manufacturing.
- Former manufacturability and cost reduction

CD1

CD2

PSI program to be complementary to US MDP program.

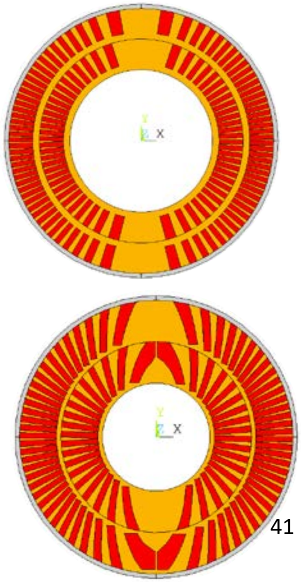
Staged approach: Mechanical construction of two models with two layers

CD1 with radial 10-mm-deep channels;
CD2 with inclined, 16-mm-deep channels

CD1:
- **LBNL CCT cable** (0.85 mm diam, RRP 108/127, 21 strand),
- **10.6 mm channel depth**, 3 mm spar, 0.5 mm assembly gap
- Layer-2 OD = 122 mm, ID = 65.6 mm (clear bore).

CD2:
- **15-T High Lumi cable**, (1 mm diam, RRP 150/169, 28 strand)
- **16 mm inclined channel**,

Layer-2 OD = 122 mm, ID = 48 mm (clear bore).

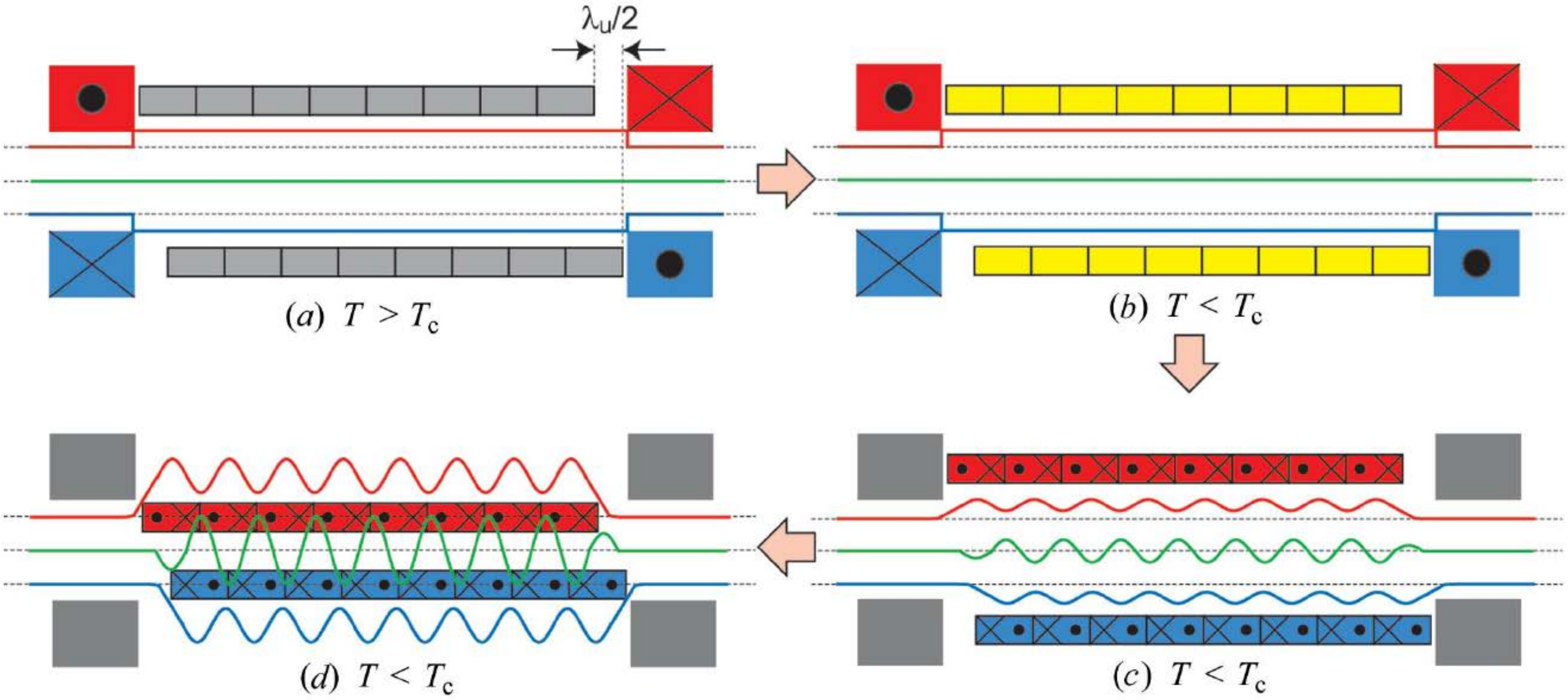


CD2 inserted and tested at cold in a cos-teta Fermi Lab magnet

Magnet technical choices

Choices	Impact
Racetrack geometry	Easier to manufacture (+)
Large aperture magnets	Magnet geometry: $B_{conductor}/B_{GFR}$ large (-)
Reduce ramp rate (0.1 T/s max)	Reduce the impact of the AC losses (+)
Cooling : 4 Cryocoolers directly coupled to the cold no cryogenic fluid in the magnet because of the gantry rotation, **T_{op}~4.5 K**	Heat removal is limited (~1.5 W at 4.2 K)
Superconductor: Bronze routed Nb_3Sn cables	Comfortable temperature margin (+) Brittle : React and wind process (-)
Use of an iron yoke	Reduce the winding pack size (+) (cost of the conductor) Weight increase (-)

Bulk HTC undulator: principle



HTC as permanent magnets 1 block per period

[1] Tanaka T, Tsuru R, Kitamura H, Pure-type superconducting permanent-magnet undulator, Journal of Synchrotron Radiation 12, 442-447, (2005)

• Magnets for COSAMI (2)

Compact & stable & brilliant storage ring source

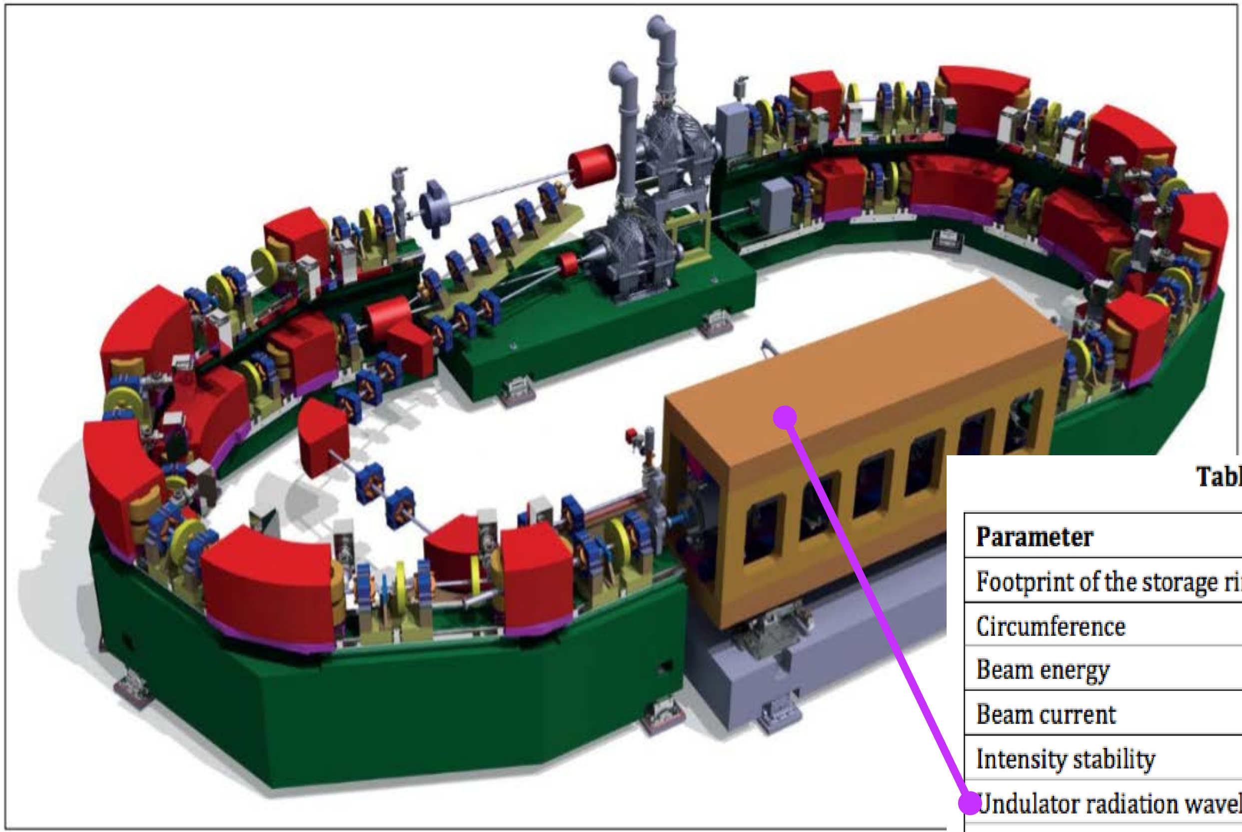


Table 1: Basic COSAMI parameters

Parameter	**Unit**	**Value**
Footprint of the storage ring	m^2	12×5
Circumference	m	25.8
Beam energy	MeV	430
Beam current	mA	150
Intensity stability	%	0.1
Undulator radiation wavelength	nm	13.5
Flux	ph/s/0.1% BW	$1.35 \cdot 10^{15}$
Brilliance	ph/s/mm^2/$mrad^2$/0.1% BW	$1.8 \cdot 10^{18}$
Coherent fraction	%	6.2

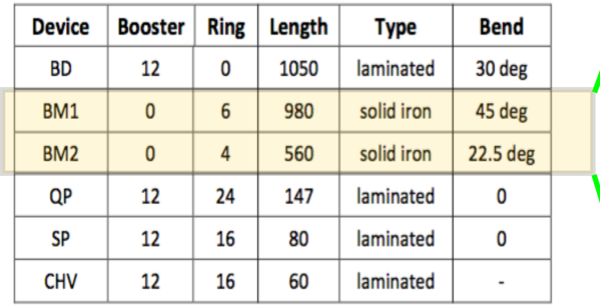
12 m @ 430 meV

Magnets for COSAMI (3)

compact and cost effective:

lattice optimized to minimize the number of magnet types

Table 10: Number of magnet units in Booster and Ring. Length expressed in mm. Bend indicates the beam deflection angle in degrees.



Device	Booster	Ring	Length	Type	Bend
BD	12	0	1050	laminated	30 deg
BM1	0	6	980	solid iron	45 deg
BM2	0	4	560	solid iron	22.5 deg
QP	12	24	147	laminated	0
SP	12	16	80	laminated	0
CHV	12	16	60	laminated	-

gradient bend model: straight

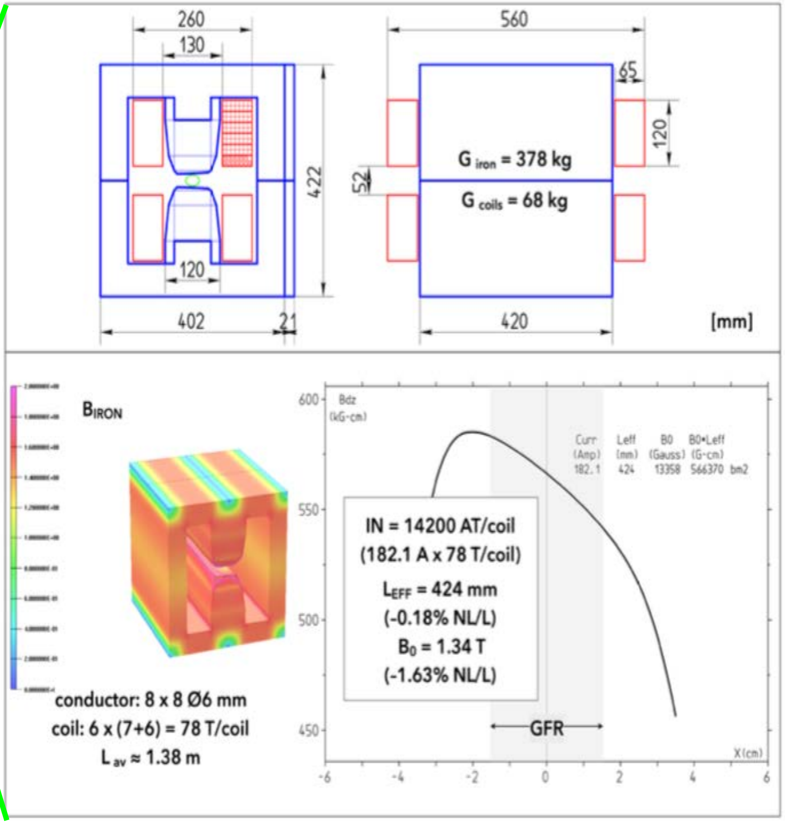
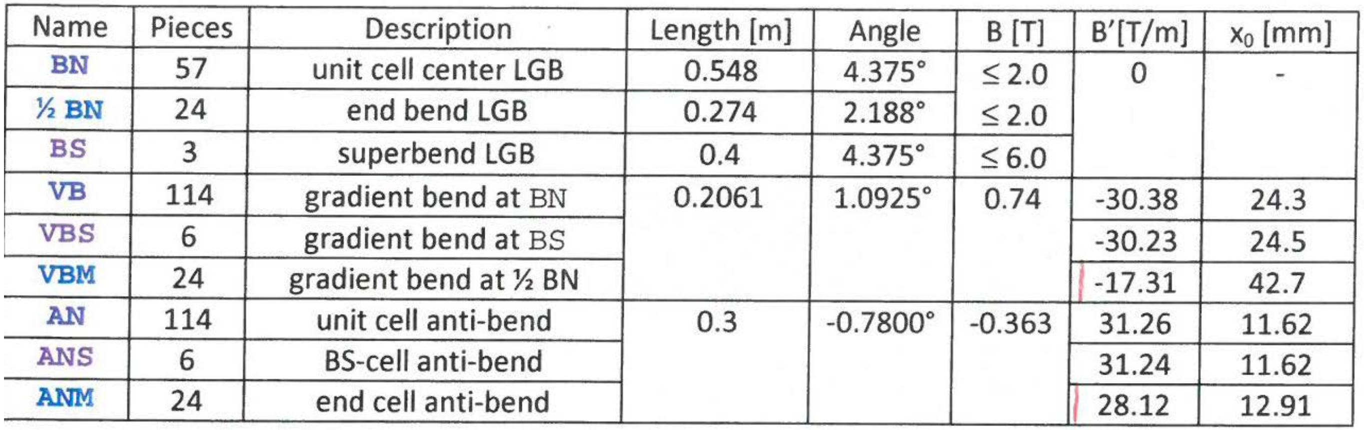


Figure 22: 22.5° SR dipole BM2, straight model with simple pole-end chamfer geometry (not optimized).

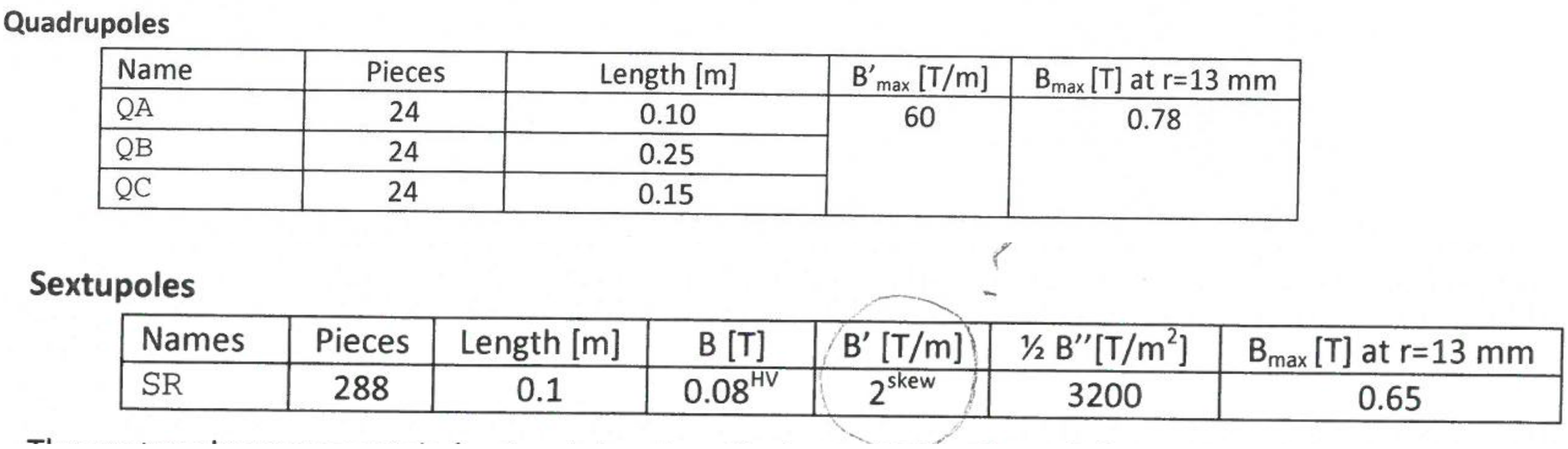
gradient bend magnet are foreseen as sector units

SLS 2.0 : Conventional magnets

Bending magnets (mostly gradient bend)



Name	Pieces	Description	Length [m]	Angle	B [T]	B'[T/m]	x_0 [mm]
BN	57	unit cell center LGB	0.548	4.375°	≤ 2.0	0	-
½ BN	24	end bend LGB	0.274	2.188°	≤ 2.0		
BS	3	superbend LGB	0.4	4.375°	≤ 6.0		
VB	114	gradient bend at BN	0.2061	1.0925°	0.74	-30.38	24.3
VBS	6	gradient bend at BS				-30.23	24.5
VBM	24	gradient bend at ½ BN				-17.31	42.7
AN	114	unit cell anti-bend	0.3	-0.7800°	-0.363	31.26	11.62
ANS	6	BS-cell anti-bend				31.24	11.62
ANM	24	end cell anti-bend				28.12	12.91



Quadrupoles

Name	Pieces	Length [m]	B'_{max} [T/m]	B_{max} [T] at r=13 mm
QA	24	0.10	60	0.78
QB	24	0.25		
QC	24	0.15		

Sextupoles

Names	Pieces	Length [m]	B [T]	B' [T/m]	½ B''[T/m²]	B_{max} [T] at r=13 mm
SR	288	0.1	0.08^{HV}	2^{skew}	3200	0.65

Design on going