Status of the magnet and of the undulator activities for the X ray Free Electron Laser SwissFEL at the Paul Scherrer Institute

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Paul Scherrer Institute

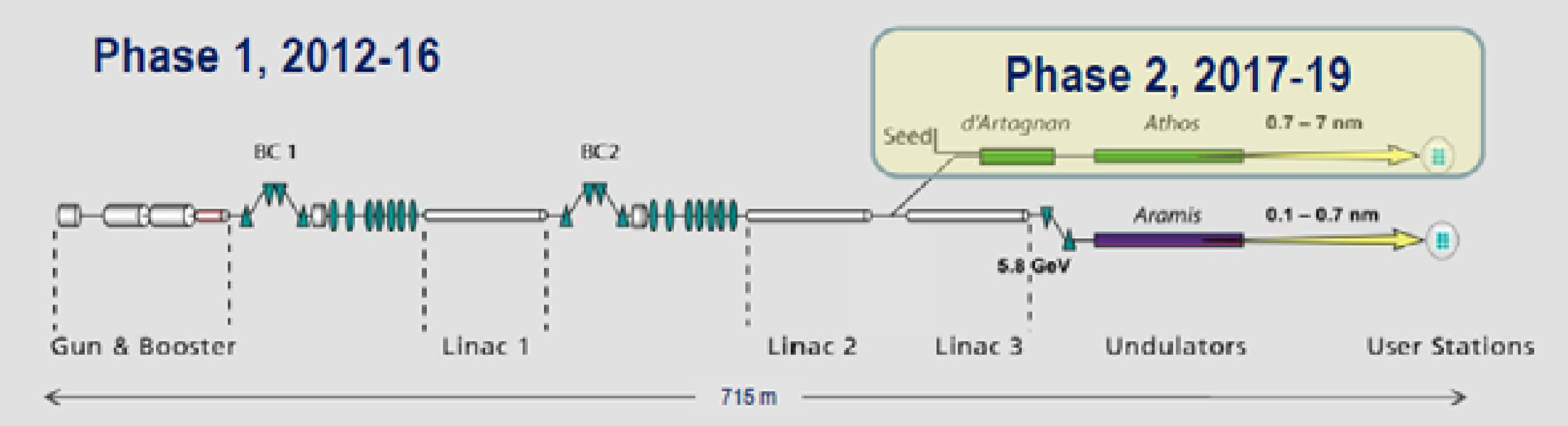
Outline

- ❑Swiss FEL Project (Status August 2011)
- ❑Magnets and Measurements for the SwissFEL Facility
  - ▪Magnet characteristics
  - ▪Measurement Plan (Serie Phase)
  - ▪Measurement systems
- ❑ SwissFEL Undulators
  - ▪Hard X ray undulator design
  - ▪Integrated Hall probe measurement system
- ❑Summary and perspectives

The SwissFEL Project
(Status August 2011)

The SwissFEL facility

SwissFEL: source of high brilliance :peak of 1.3 10^{33} photons/(s. 0.1 % bandwith. $mm^2.mrad^2$)

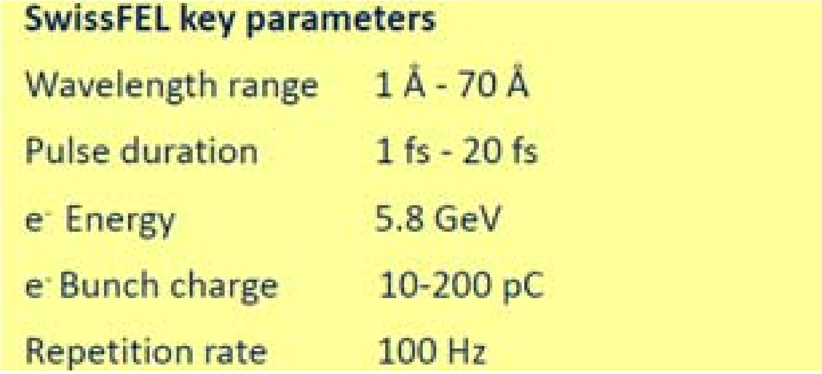


Aramis: 1-7 Å hard X-ray SASE FEL,
In-vacuum , planar undulators with variable gap.
User operation from mid 2017

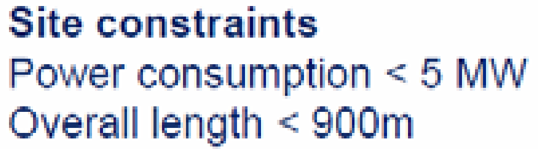
Athos : (2nd phase) 7-70 Å soft X-ray FEL for SASE & Seeded operation .
APPLE II undulators with variable gap and full polarization control.
User operation end 2019?

D'artagnan: FEL for wavelengths above Athos, seeded with a High Harmonic Generation and Athos as radiator.

SwissFEL Conceptual Design Report, http://www.psi.ch/swissfel/



SwissFEL key parameters	
Wavelength range	1 Å - 70 Å
Pulse duration	1 fs - 20 fs
e^- Energy	5.8 GeV
e^- Bunch charge	10-200 pC
Repetition rate	100 Hz



Site constraints
Power consumption < 5 MW
Overall length < 900m

The SwissFEL Parameters

Overview of the components in the Concept Design Report,
http://www.psi.ch/swissfel/

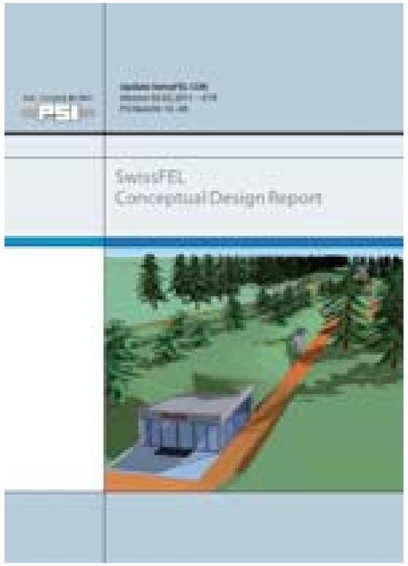
- Developments
- Prototype
- Test
- Installation
- Commissioning

For example :

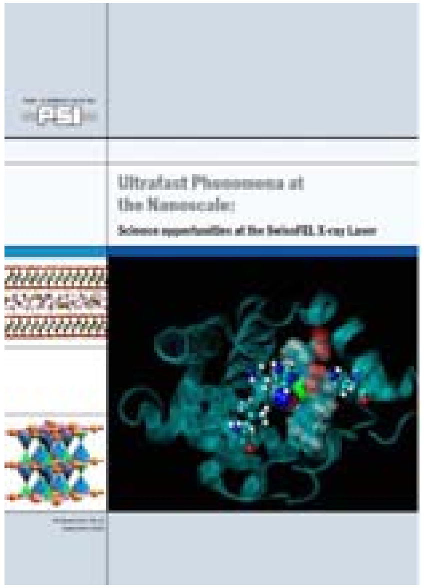
- Injector;
- Linac modules;
- Undulator;
- Magnets;

SwissFEL science case,

http://www.psi.ch/swissfel/



SwissFEL
Conceptual Design Report

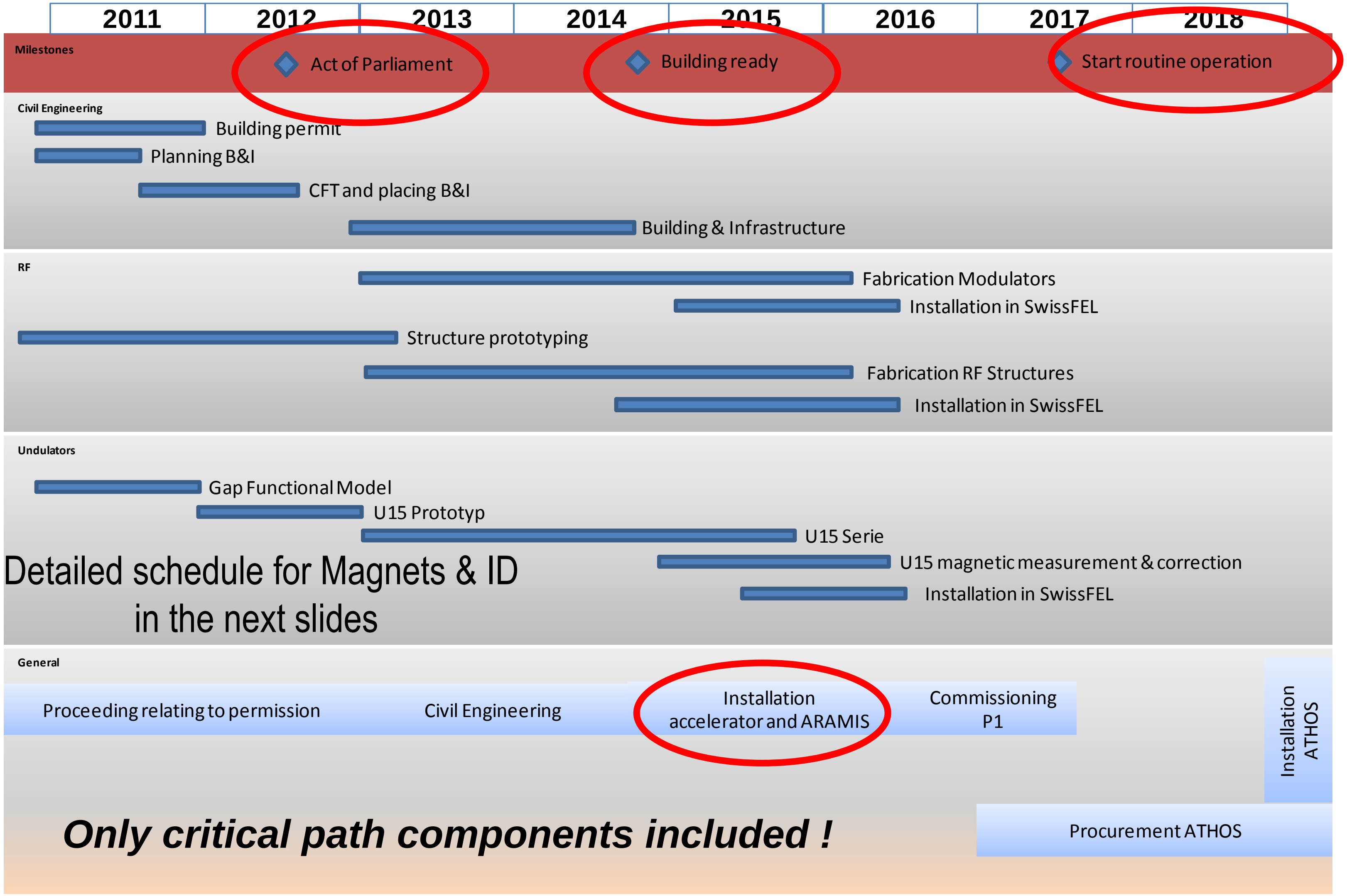


Ultrafast Phenomena at
the Nanoscale:
Science opportunities at the SwissFEL X-ray Laser

SwissFEL Schedule (March 2011)

M. Lüthy, H.H. Braun

SwissFEL Schedule March 2011



Milestones

- Act of Parliament
- Building ready
- Start routine operation

Civil Engineering

- Building permit
- Planning B&I
- CFT and placing B&I
- Building & Infrastructure

RF

- Fabrication Modulators
- Installation in SwissFEL
- Structure prototyping
- Fabrication RF Structures
- Installation in SwissFEL

Undulators

- Gap Functional Model
- U15 Prototyp
- U15 Serie
- U15 magnetic measurement & correction
- Installation in SwissFEL

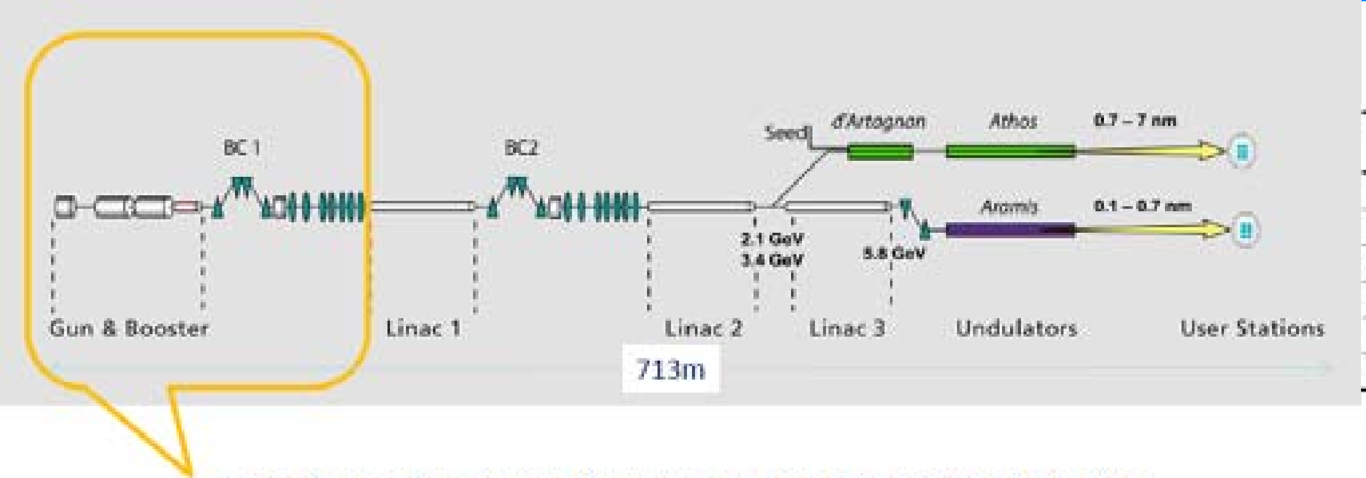
Detailed schedule for Magnets & ID
in the next slides

General

- Proceeding relating to permission
- Civil Engineering
- Installation accelerator and ARAMIS
- Commissioning P1
- Installation ATHOS
- Procurement ATHOS

Only critical path components included !

The SwissFEL injector test facility



Test of overall system performance in SwissFEL 250 MeV Injector

- **Phase 1: Electron source and diagnostics**

  - March 2010 to May 2010
  - Characterization of the electron source
  - Installation of remaining machine behind shielding wall
- **Phase 2: Phase 1 + (some) S-band acceleration**

  - August 2010 to December 2010 (official injector inauguration 24 August)
  - Emittance damping in S-band booster (invariant envelope)
  - Jaguar (Nd:YLF) laser
- **Phase 3: The full machine**

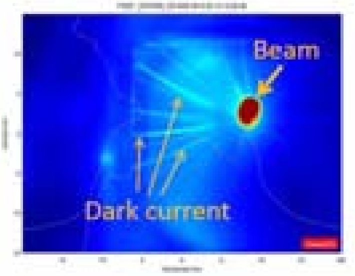
  - End of 2010 / early 2011 (installation bunch compressor and X-band cavity)
  - Pulsar (Ti:Sapph) laser

The whole injector beamline will in 2015 be moved to the SwissFEL

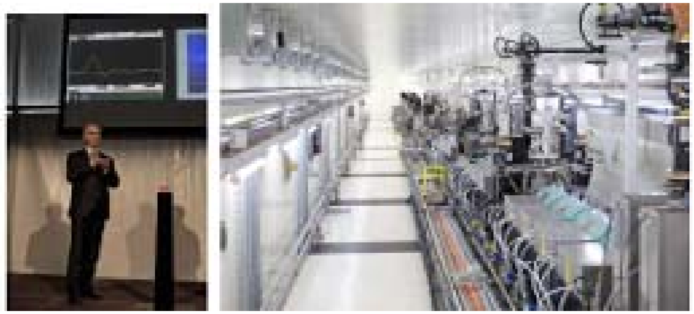
Goal beam parameters

Parameter	Goal Test facility	
Charge – operation mode (pC)	10	200
Projected norm. Emittance (mm.mrad)	0.15	0.5
Slice norm. emittance (mm.mrad)	0.11	<0.43
Uncorrelated energy spread (keV)	<50	<50
Peak current (A)	100	300
Energy (MeV)	250	250

YAG screen image



24 March 2010: First beam



24 August 2010: Inauguration

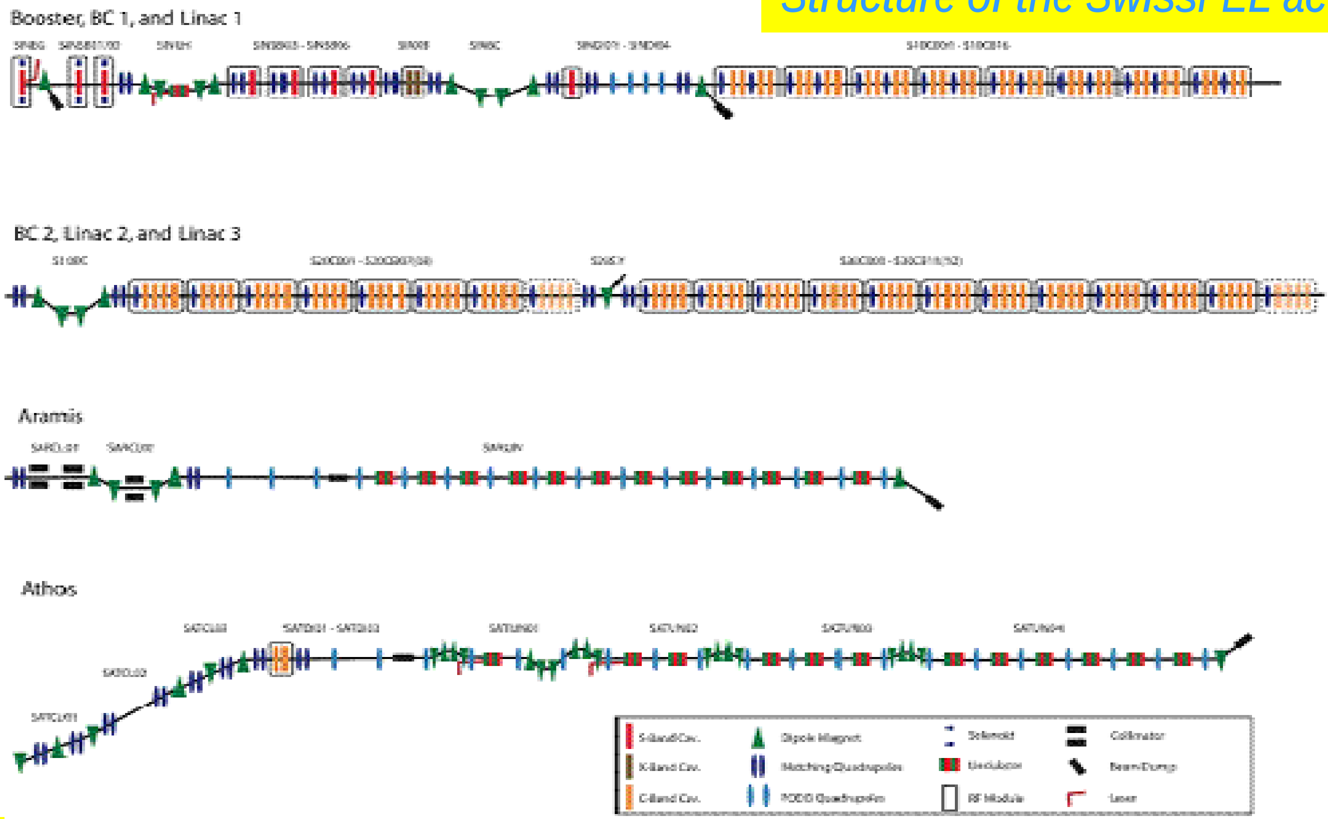
Magnets for the 250 MeV Injector

Magnet type	Characteristics	Quantities to measure	Accuracy (if specified)
BC Dipole V2 (4) Measured mid 2010	B_{Nom}=0.4T,GFR~60 mm angle= 5 deg max @350 MeV **Gap**=30mm, L_{mag}=0.25m	Magn. Length, Field integral ∫Bdl ∫ Bdl=f(I), field maps (5 planes)	10^{-4}
Quadrupoles (28)	G_{Nom}=25T/m, Φ=45mm, L_{mag}=0.175 m	Magn. Length, integrated gradient ∫Gdl ∫ Gdl=f(I), field maps Multipoles	10^{-4} 10^{-3}
Gun solenoid ([illegible])	B_{Nom}=0.35 T, Φ=80mm, L_{mag}=0.26m	Magn. Length, Field integral ∫Bdl ∫ Bdl=f(I), field maps Magnetic axis position	10^{-4} 0.1 mm
S band solenoid (17) Measured end 2009	B_{Nom}=0.1T, Φ=220mm, L_{mag}=0.75m	Magn. Length, Field integral ∫Bdl ∫ Bdl=f(I), field maps Magnetic axis position	10^{-4} 0.1 mm
Correctors (28)	B_{Nom}=20 mT, Φ=80mm, L_{mag}=0.05m	Magn. Length, Field integral	10^{-3}

84 magnets built, measured and delivered (last ones in Sommer 2010)

Magnets and Measurements
for the SwissFEL Facility

Structure of the SwissFEL accelerator



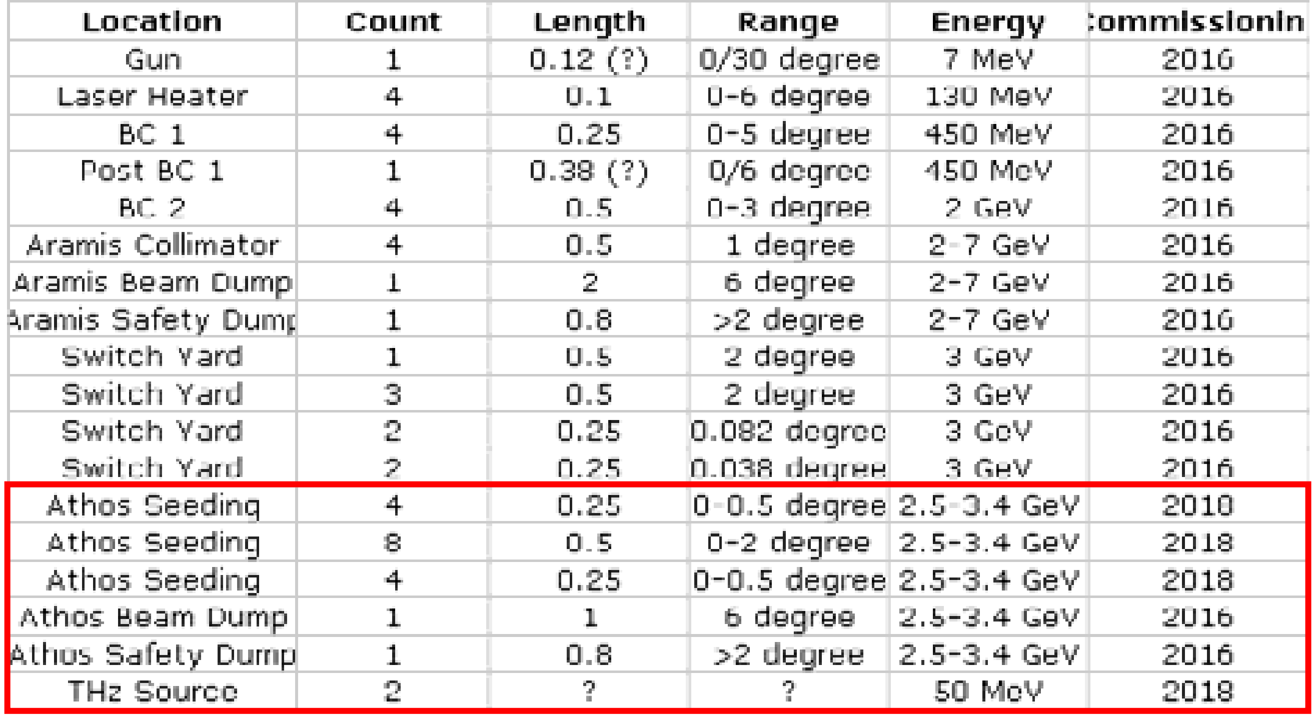
Magnets : 48 dipoles, 238 quads,17 solenoids (injector), correctors, special magnets

SwissFEL magnets (1)

48 dipoles of 6 types:

- Working at energy from 7 MeV to 7 GeV
- field ranges from 0.5 mT up to 1T (dump dipoles)
- Magnetic length ranges from 0.1 m to 1 m

Bunch compressor dipole



Location	Count	Length	Range	Energy	ommissionin
Gun	1	0.12 (?)	0/30 degree	7 MeV	2016
Laser Heater	4	0.1	0-6 degree	130 MeV	2016
BC 1	4	0.25	0-5 degree	450 MeV	2016
Post BC 1	1	0.38 (?)	0/6 degree	450 MeV	2016
BC 2	4	0.5	0-3 degree	2 GeV	2016
Aramis Collimator	4	0.5	1 degree	2-7 GeV	2016
Aramis Beam Dump	1	2	6 degree	2-7 GeV	2016
Aramis Safety Dump	1	0.8	>2 degree	2-7 GeV	2016
Switch Yard	1	0.5	2 degree	3 GeV	2016
Switch Yard	3	0.5	2 degree	3 GeV	2016
Switch Yard	2	0.25	0.082 degree	3 GeV	2016
Switch Yard	2	0.25	0.038 degree	3 GeV	2016
Athos Seeding	4	0.25	0-0.5 degree	2.5-3.4 GeV	2010
Athos Seeding	8	0.5	0-2 degree	2.5-3.4 GeV	2018
Athos Seeding	4	0.25	0-0.5 degree	2.5-3.4 GeV	2018
Athos Beam Dump	1	1	6 degree	2.5-3.4 GeV	2016
Athos Safety Dump	1	0.8	>2 degree	2.5-3.4 GeV	2016
THz Source	2	?	?	50 MeV	2018

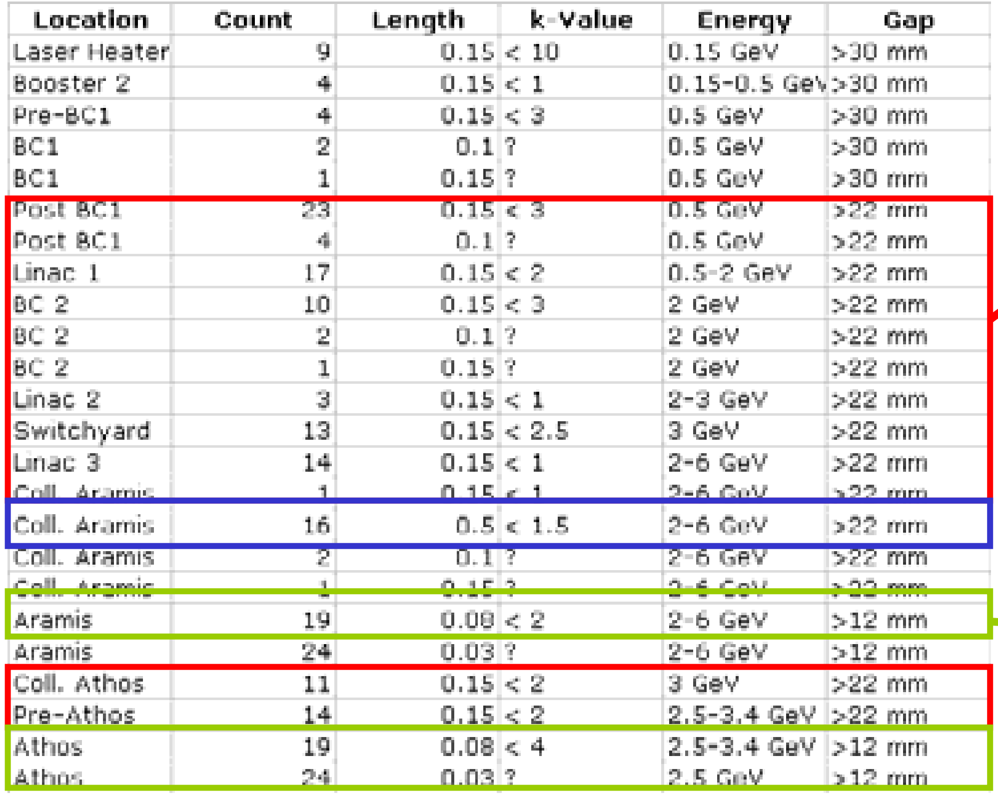
Phase 2
2018

(source: S. Reiche, 14.04.11)

SwissFEL magnets (2)

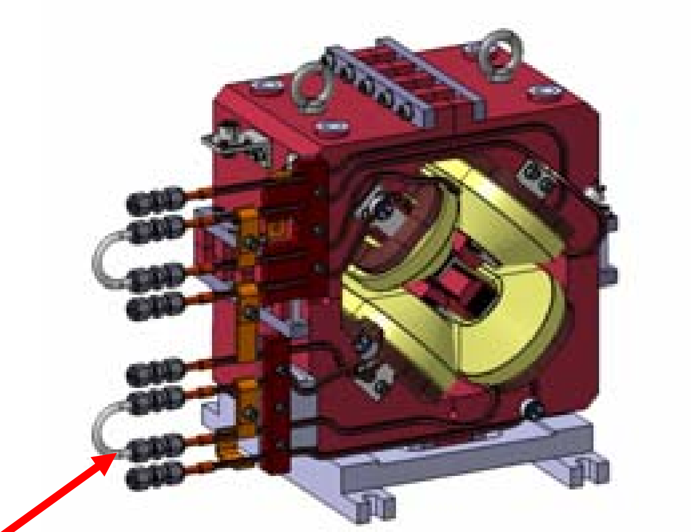
238 quadrupoles of 4 types:

- Working at energy from 0.15 GeV to 6 GeV
- Field gradient ranges from 0.5 mT up to 50 T/m
- Magnetic length ranges from 0.03 m to 0.15 m
- Aperture diameters: 10 mm, 22 mm, 45 mm

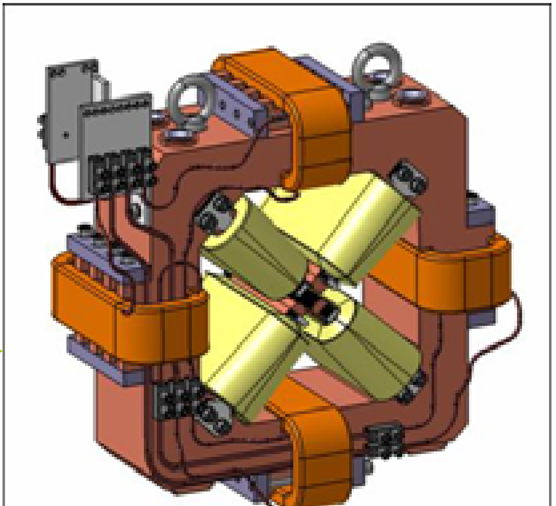


Location	Count	Length	k-Value	Energy	Gap
Laser Heater	9	0.15	< 10	0.15 GeV	>30 mm
Booster 2	4	0.15	< 1	0.15-0.5 GeV	>30 mm
Pre-BC1	4	0.15	< 3	0.5 GeV	>30 mm
BC1	2	0.1	?	0.5 GeV	>30 mm
BC1	1	0.15	?	0.5 GeV	>30 mm
Post BC1	23	0.15	< 3	0.5 GeV	>22 mm
Post BC1	4	0.1	?	0.5 GeV	>22 mm
Linac 1	17	0.15	< 2	0.5-2 GeV	>22 mm
BC 2	10	0.15	< 3	2 GeV	>22 mm
BC 2	2	0.1	?	2 GeV	>22 mm
BC 2	1	0.15	?	2 GeV	>22 mm
Linac 2	3	0.15	< 1	2-3 GeV	>22 mm
Switchyard	13	0.15	< 2.5	3 GeV	>22 mm
Linac 3	14	0.15	< 1	2-6 GeV	>22 mm
Coll. Aramis	1	0.15	< 1	2-6 GeV	>22 mm
Coll. Aramis	16	0.5	< 1.5	2-6 GeV	>22 mm
Coll. Aramis	2	0.1	?	2-6 GeV	>22 mm
Coll. Aramis	1	0.15	?	2-6 GeV	>22 mm
Aramis	19	0.08	< 2	2-6 GeV	>12 mm
Aramis	24	0.03	?	2-6 GeV	>12 mm
Coll. Athos	11	0.15	< 2	3 GeV	>22 mm
Pre-Athos	14	0.15	< 2	2.5-3.4 GeV	>22 mm
Athos	19	0.08	< 4	2.5-3.4 GeV	>12 mm
Athos	24	0.03	?	2.5 GeV	>12 mm

(source: S. Reiche, 14.04.11)



Linac quadrupoles



Aramis line quadrupoles

SwissFEL magnets (3)

Magnet type	Quantities to measure	Accuracy (if specified)	Remark
Dipole (48)	Magn. Length, Field integral ∫Bdl ∫ Bdl=f(I), field maps (5 planes)	10^{-4}	
Quadrupoles (238)	Magn. Length, integrated gradient ∫Gdl ∫ Gdl=f(I), field maps Multipoles Magnetic axis Roll	10^{-3} 10^{-3} 0.05 mm 0.1 mrad	
Correctors ,special magnets	Magn. Length, Field integral		Feed back system Bandwidth 100 Hz

Magnet design, assembly and test

Specification and design at the Paul Scherrer Institute

- Design based on beam dynamics calculations, on cost/space constraints
- Design with POISSON 2D (pole profiles) and Opera 3D /TOSCA programs

Magnet design (in House) and construction (selected companies)

- Coil/magnet constructions performed in external companies
- Corrector construction and final assembly in house

Same strategy as for the injector magnets

Reception tests and magnetic measurements : in house

- Visual inspection (coil, current supply, thermocouple), check of test certificates
- Electrical integrity : insulation tests coil vs ground at 500 V
- Coil resistance measurements (1% variation accepted coil by coil)
- Leak and flow test at 30 bars during 12 hours (max 2 bars drop)
- Magnetic tests (hall probe, rotating coils, vibrating wire) →

Rigorous and flexible Magnetic Measurement Plan is needed

To master all the critical steps from design to delivery

Why a magnetic measurement plan?

Motivations-aims

- Context : Large scale of magnet production to be tested.

(field ranges from 0.5 mT up to 0.5 T, issues on field strength, harmonics, mag. axis)

- Guarantee the conformity of the magnet to the (tight) specifications:
  - ❖ Field integral value (at the level of 01-0.01%)
  - ❖ Harmonics value (at the level of the 0.1%)
  - ❖ Quadrupole roll angles
  - ❖ Magnetic axis position of quadrupoles (50 μm RMS error) /fiducials

- Provide information for the installation (alignment) and the operation (hysteresis curve, …).
- Increase the quality of measurements and the reliability of the results.
- Increase the efficiency (schedule is tight, measurements completed end of 2015 for the 0.1-0.7 nm line).

The working plan will include:

- Characterization of the measurement systems (systematic and random errors).
- Selection of the measurement equipment.

  (w.r.t. specifications, allocated time and resource)
- Cross-checks measurements (some %) with different measuring techniques or systems.

Measurement equipments

Equipment	Units	Aim	Status	Comments
Hall probe system	1	integral and local field in dipoles Cross calibration of the Gdl	System operational	
∅ 45 mm rotating mole test bench	1	integral field gradient, harmonics and axis in 45 mm apertures quadrupoles	System operational	CERN / PSI collaboration
∅ 19 mm rotating mole test bench	1	integral field gradient, harmonics and axis in 19 mm apertur quadrupoles (linac)	Unit being tested at CERN; Procurement for the end of 2011;	CERN / PSI collaboration
∅ 10 mm rotating mole test bench	1	integral field gradient, harmonics and axis in undulator lines quadrupoles	Prototype in test at CERN; Procurement foreseen for 2012;	CERN / PSI collaboration
Moving Vibrating Wire system	1	Magnetic axis of quadrupoles (injector, linac, undulator lines)	System fully operational In October 2011	
FARO Arm	1	3-D survey of fiducials on quadrupoles and on measurement systems	Commercial product; At PSI since December 2010;	

Hall probe measurement bench

Transverse Hall Probe	Siemens SVB 601S1
Semicond. material	InAs
Active area	2.6 mm^2
I max	400 mA DC
Sensitivity	60 mV/T
Hall Probe absolute accuracy	***0.1 to 0.3 G***
Hall probe resolution	***1 μT***
Longitudinal range	2100 mm
Horizontal range	650 mm
Vertical range	360 mm
Maximum calibrated Field	3.1 T
Non linearity (0-1T)	<0.2 %
Temperature sensibility	70 ppm/°C

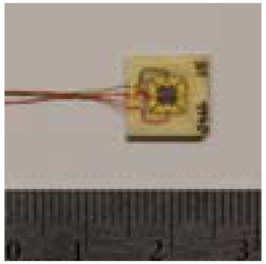
Measurement procedure:

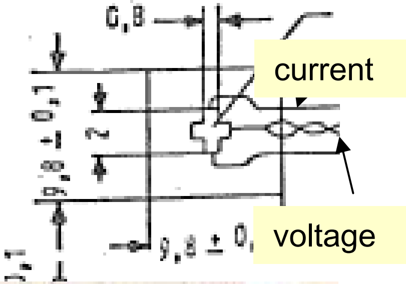
❖Leveling of the magnet

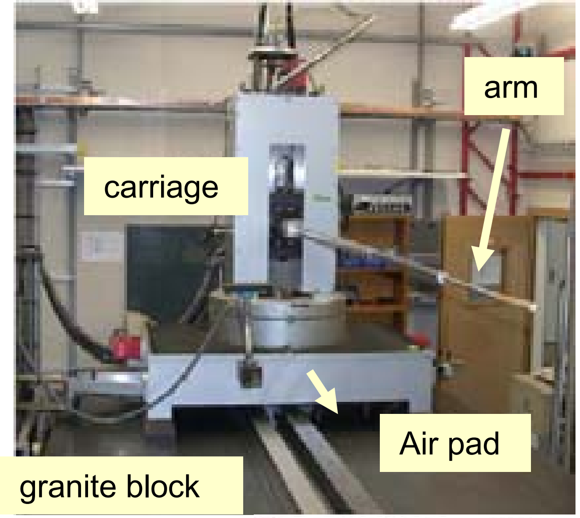
❖Longitudinal variation on the probe (step of 2 mm, 20 ms time) (line integral in one axis)

❖DAQ of voltage (HP/Agilent 3458A digital multimeter)

❖Post processing of the data
- ✓**Local field, field integral, magnetic length**
- ✓**Field quality**
- ✓**2D/3D field maps (volume in scanning five vertical planes)**



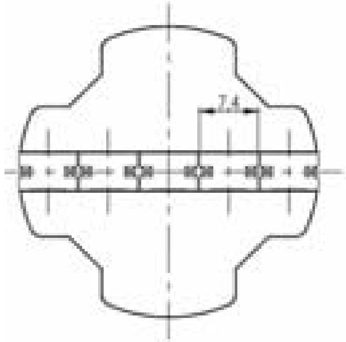




Digital multimeters (2)

Program interface

Rotating coil (1) ∅ 39 mm CERN mole



5 coils
(E2,M2,C,M1,E1)

Mult. Filament Wire	20, ϕ=60μm
Coil length	750 mm
Coil surface	1.97 m^2
Coil width	7.4 mm
Number of turns	400
Coil core	G10

mole

Electronic rack

Gdl: **50 10^{-4} abs**. accuracy
Multipoles : 10^{-5} (@17 mm)
reproducibility

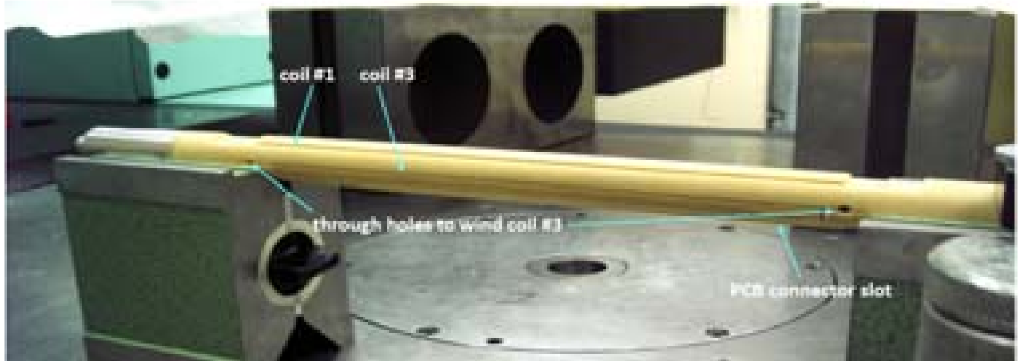
Abs : **E1** (E2=spare) for gradient
Cmp :**E1-M2-C+M2** for harmonics
(reject Dipole and Quadrupole)

(PSI-CERN- collaboration, at the PSI since January 2009)

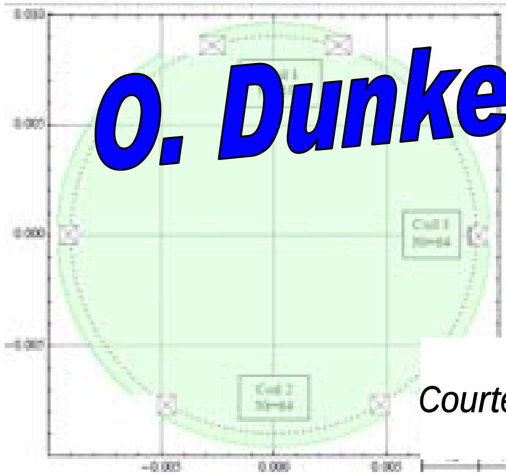
System used to measure the harmonics and the field gradient of the 45 mm aperture quadrupoles for the 250 MeV injector

Rotating coils (2) : CERN ⌀ 19 mm diameter mole

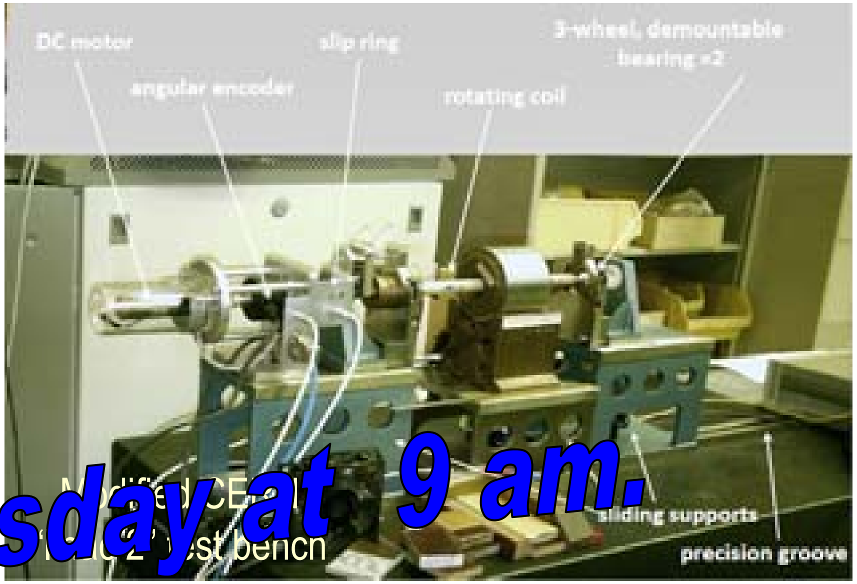
CERN“linac 4” coil (second generation)



3 coils to reject dipole and quadrupole components



O. Dunkel, Talk Tuesday at 9 am.



Courtesy M. Buzio, L. Dunkel CERN

- ø19 mm x 400 mm coil head
- 3 tangential coils with B1+B2 bucking
- Monolithic design
- Higher sensitivity (multiwire flat cable)

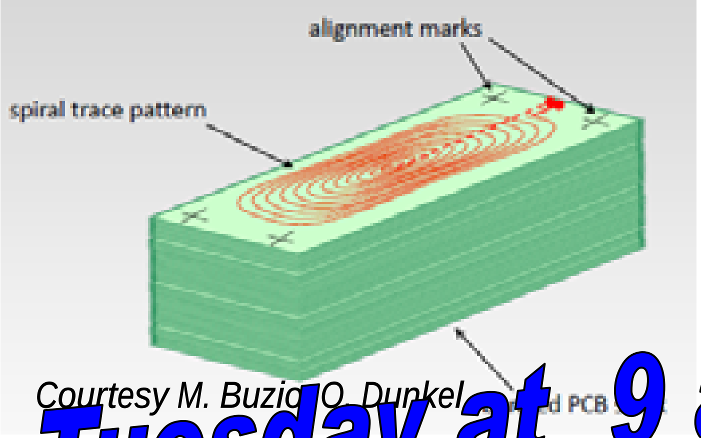
(PSI-CERN- collaboration, at the PSI end of 2011)

Goals: Measure the harmonics and the field gradient of the 22 mm aperture quadrupoles for SwissFEL linac and matching sections

Rotating coils (3) : CERN ∅ 10 mm diameter mole

Prototype in test at CERN: PCB coils, monobloc,

Courtesy O. Dunkel



Courtesy M. Buzio, O. Dunkel

O. Dunkel, Talk Tuesday at 9 am.

- Ø7.8 mm x 100 mm coil head
- 3 coils, 200 turns each
- Bloc=30 stacks + separators
- Shaft inserted in “a linac 4 bench” type

(O. Dunkel, IMMW16 (2009))

(in development at CERN, at PSI end of 2012?)

Goals: Measure the harmonics and the field gradient of the 12 mm aperture quadrupoles in the SwissFEL undulator lines

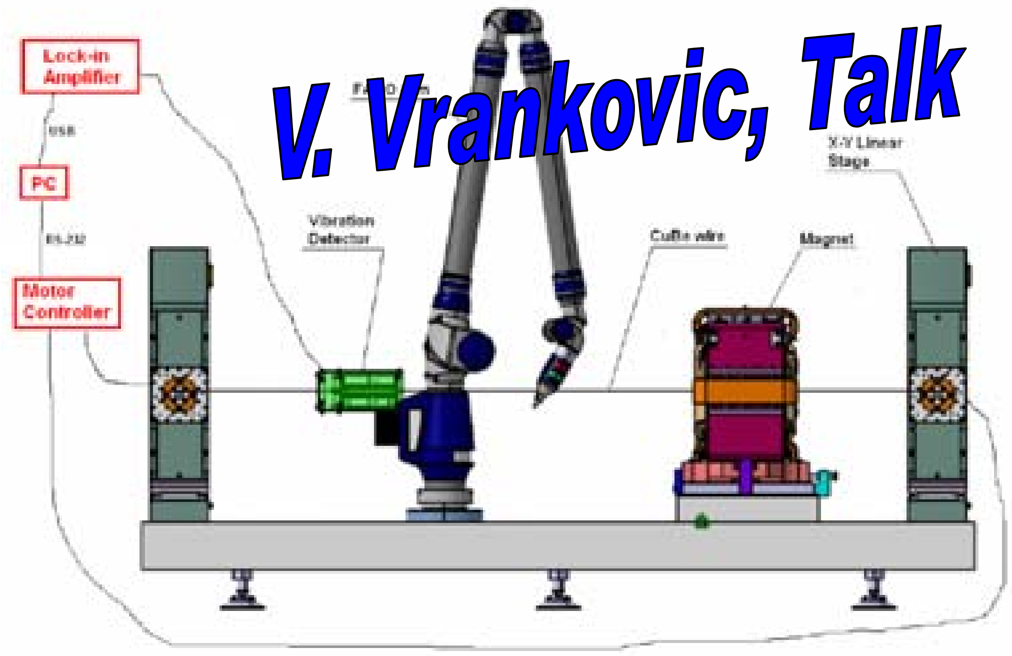
Moving vibrating wire system at PSI

Vibrating wire characteristics

Moving Wire	CuBe, 1-1.5 m,Φ=120 mm
Newport X-Y linear stages	accuracy 2.5 μm, resolution 0.5 μm
Support table	aluminum, 2 m
A vibration detector	4 pick-up coils or photo diode, μm wire motion
DC/AC current source	100 ppm stability
Lock-in amplifier HF2LI	2 channels, 2 signal generators, 50 MHz range+ Phase Lock loop
Quantum arm FARO, 2.4 m, 6 axis	resolution of the survey equipment is +/- 28 μm on 2.4 m

Vibrating wire system (August 2011)

V. Vrankovic, Talk Thursday at 9.30 am.



Goal: Measure magnetic axis of the quadrupoles (linac, matching, undulators

Estimation of the errors

Error sources : Measuring system & method; environment; ~~operator~~

Well defined procedure

An <u>estimation</u> of the all possible and known sources of systematic error is

Estimated contribution		
Environment	<5	[µm]
Resolution of vibration detection:	<1	[µm]
Locate wire relative to pin holes	<10	[µm]
Alignment of stages:	<1	[µm]
Faro arm:	<28	[µm]
Total (rms)	**<30**	**[µm]**

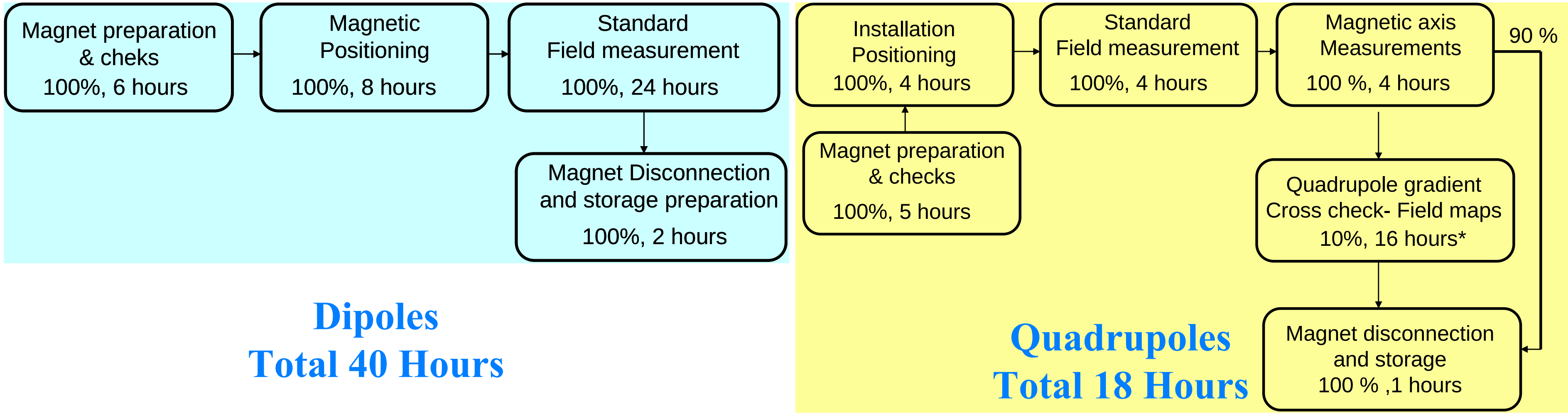
To be added in the budget: 30 µm error for the fiducialisation procedure with a laser tracker in the tunnel (Source K. Dreyer)

Total fiducialisation budget : <50 µm

Magnetic Measurement Plan

Test of 100 % of magnets

- Magnetic tests should be performed systematically on all magnets of the machine;
- Magnetic axis measurements of quadrupoles with respect to external fiducials have to be systematically performed;
- Cross-check measurements for the integrated field gradient and the magnetic center position will be performed on a statistical basis;



Magnet preparation & cheks 100%, 6 hours → Magnetic Positioning 100%, 8 hours → Standard Field measurement 100%, 24 hours → Magnet Disconnection and storage preparation 100%, 2 hours

Dipoles Total 40 Hours

Magnet preparation & checks 100%, 5 hours → Installation Positioning 100%, 4 hours → Standard Field measurement 100%, 4 hours → Magnetic axis Measurements 100 %, 4 hours → Quadrupole gradient Cross check- Field maps 10%, 16 hours* → Magnet disconnection and storage 100 % ,1 hours

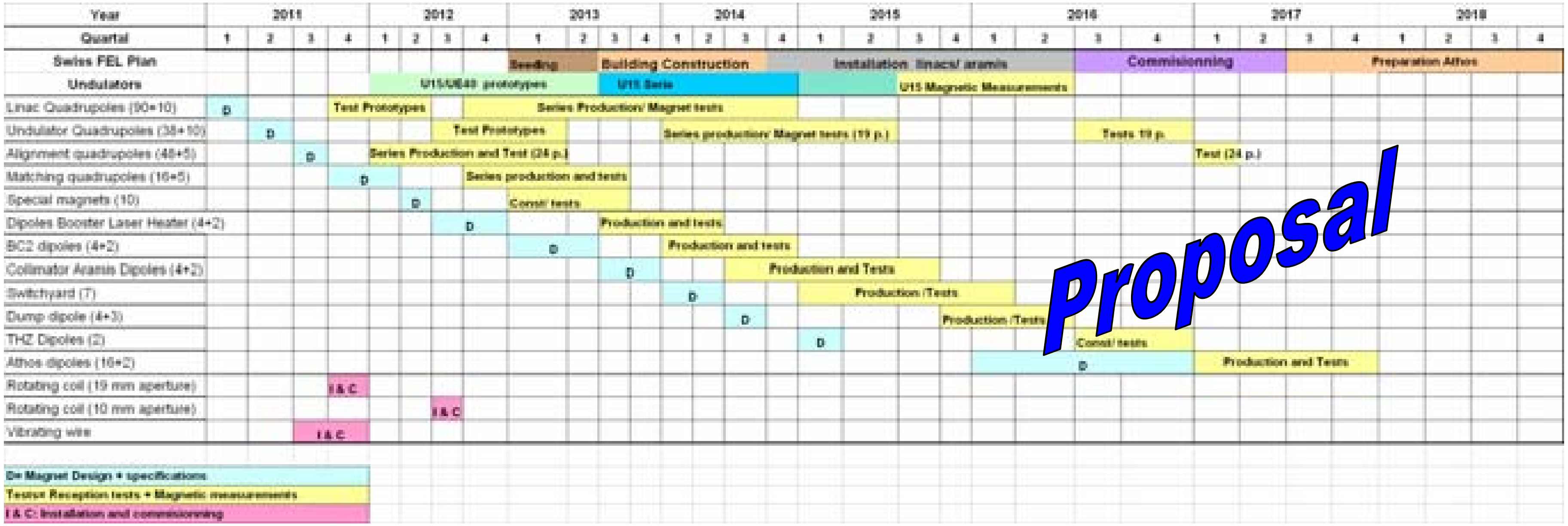
90 %

Quadrupoles Total 18 Hours

Flow-chart of the test-plan for the series production of SwissFEL magnets

Construction and testing - Milestones

Test of 100 % of magnets



Year	2011				2012				2013				2014				2015				2016				2017				2018			
Quartal	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Swiss FEL Plan									Seeding		Building Construction					Installation linacs/ aramis							Commisionning				Preparation Athos					
Undulators					U15/UE40 prototypes						U15 Serie								U15 Magnetic Measurements													
Linac Quadrupoles (90+10)	D			Test Prototypes				Series Production/ Magnet tests																								
Undulator Quadrupoles (38+10)		D					Test Prototypes						Series production/ Magnet tests (19 p.)										Tests 19 p.									
Alignment quadrupoles (48+5)			D		Series Production and Test (24 p.)																				Test (24 p.)							
Matching quadrupoles (16+5)				D				Series production and tests																								
Special magnets (10)						D			Const/ tests																							
Dipoles Booster Laser Heater (4+2)							D				Production and tests																					
BC2 dipoles (4+2)									D				Production and tests																			
Collimator Aramis Dipoles (4+2)											D				Production and Tests																	
Switchyard (7)													D				Production /Tests															
Dump dipole (4+3)															D					Production /Tests												
THZ Dipoles (2)																	D						Const/ tests									
Athos dipoles (16+2)																					D				Production and Tests							
Rotating coil (19 mm aperture)				I & C																												
Rotating coil (10 mm aperture)							I & C																									
Vibrating wire			I & C																													

D= Magnet Design + specifications

Tests= Reception tests + Magnetic measurements

I & C: Installation and commissioning

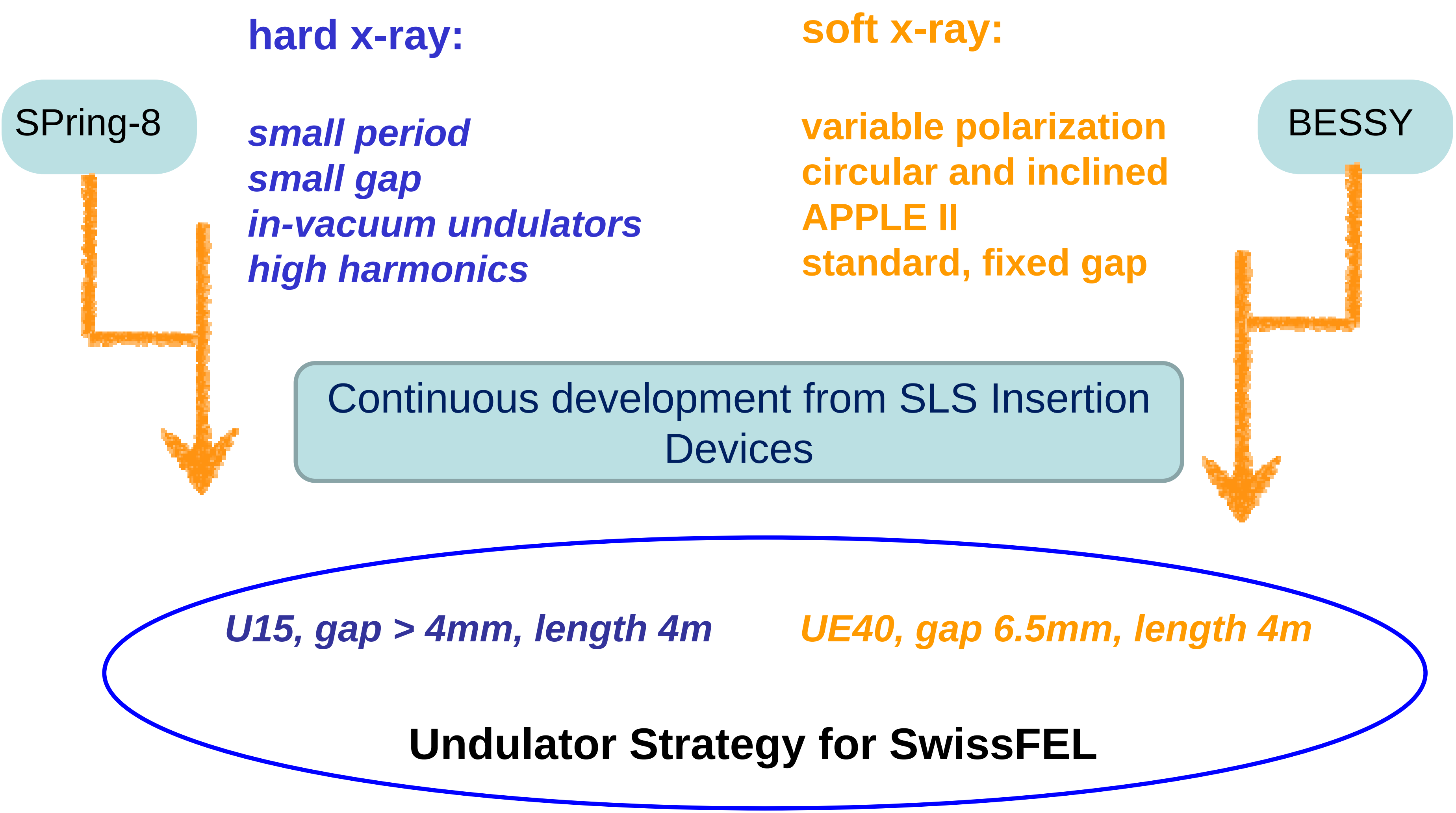
Cascaded work with 1 designer, 2 teams for assembly and measurements

Important dates for production and tests:

- Linac/undulator series quadrupoles 2012-2015
- Matching quadrupoles: 2013
- Dipoles for the hard x-ray line: 2013-2015
- Magnets for soft x-ray line: Not before 2016

Undulators for the SwissFEL
Beam lines

Undulator strategy



hard x-ray:

soft x-ray:

SPring-8

small period
small gap
in-vacuum undulators
high harmonics

variable polarization
circular and inclined
APPLE II
standard, fixed gap

BESSY

Continuous development from SLS Insertion Devices

U15, gap > 4mm, length 4m

UE40, gap 6.5mm, length 4m

Undulator Strategy for SwissFEL

Time schedule for SwissfEL undulators

For SwissFEL planned:

ARAMIS hard x-ray	U15, 12 modules	2016
ATHOS soft x-ray	U40/UE40, 12 modules	~ 2018

Milestones (U15)

- U15 full prototype (265 periods) : autumn 2012
  - mechanics
  - magnetics
  - vacuum

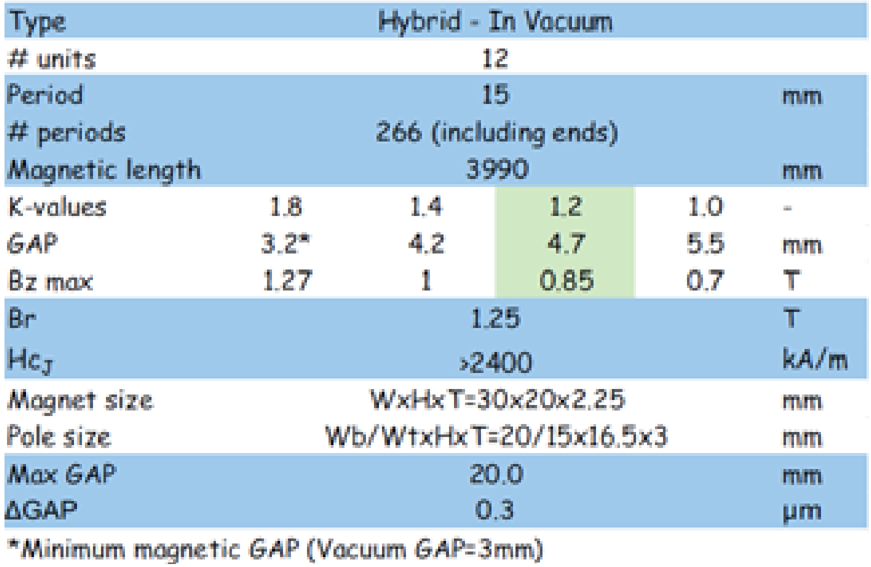
- Qualify the prototype for the series:
- Tests in 250 MeV linac -2013

- U15 production : 2013 – 2015
- Field optimization : Mid 2015 – Beginning 2016

- Installation finished : Mid 2016

U15 Prototype Undulator design

Hard X-ray Undulator U15 parameters



Type	Hybrid - In Vacuum				
# units	12				
Period	15				mm
# periods	266 (including ends)				
Magnetic length	3990				mm
K-values	1.8	1.4	1.2	1.0	-
GAP	3.2*	4.2	4.7	5.5	mm
Bz max	1.27	1	0.85	0.7	T
Br	1.25				T
Hc_J	›2400				kA/m
Magnet size	WxHxT=30x20x2.25				mm
Pole size	Wb/WtxHxT=20/15x16.5x3				mm
Max GAP	20.0				mm
ΔGAP	0.3				µm

*Minimum magnetic GAP (Vacuum GAP=3mm)

Permanent Magnets

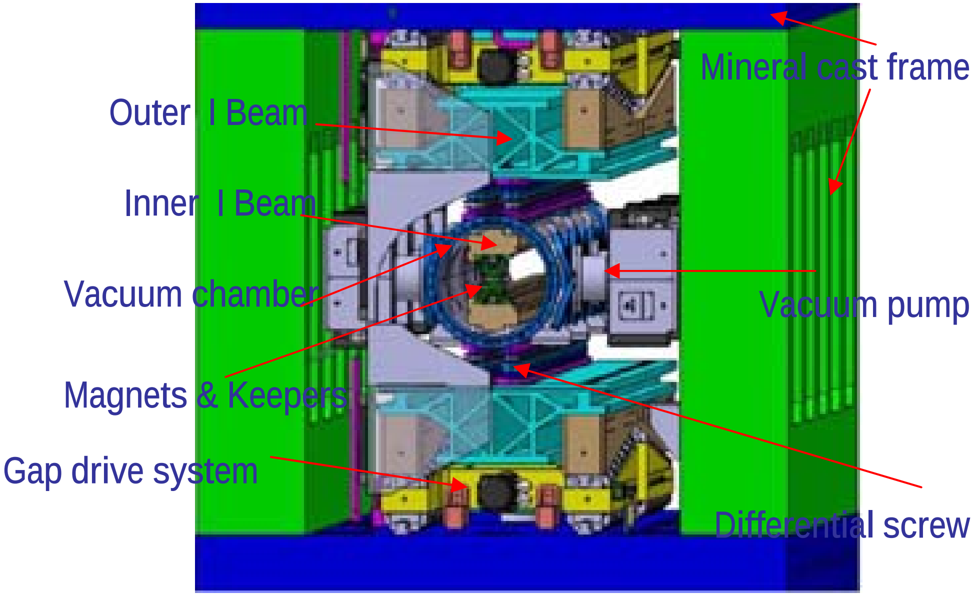
- •Vapor diffusion of Dy into the machined magnet (Hitachi Metals Ldt.) $Nd3_{1-x}\ Dy_x\ Fe_{14}B$
- •Increase stability without reduction of remanence (Hc_j~2300 kA/m).

T.Schmidt, S. Reiche, Undulators for the SwissFEL (FEL,2009)

New design for all types

- ▪ High stiffness : close support structure;
- ▪Frame : Cast mineral bases and sides (cheap, good damping, light, non-magnetic)
- ▪Cost effective extruded and wire eroded aluminum keepers

In Vacuum Permanent Magnet Undulator U15



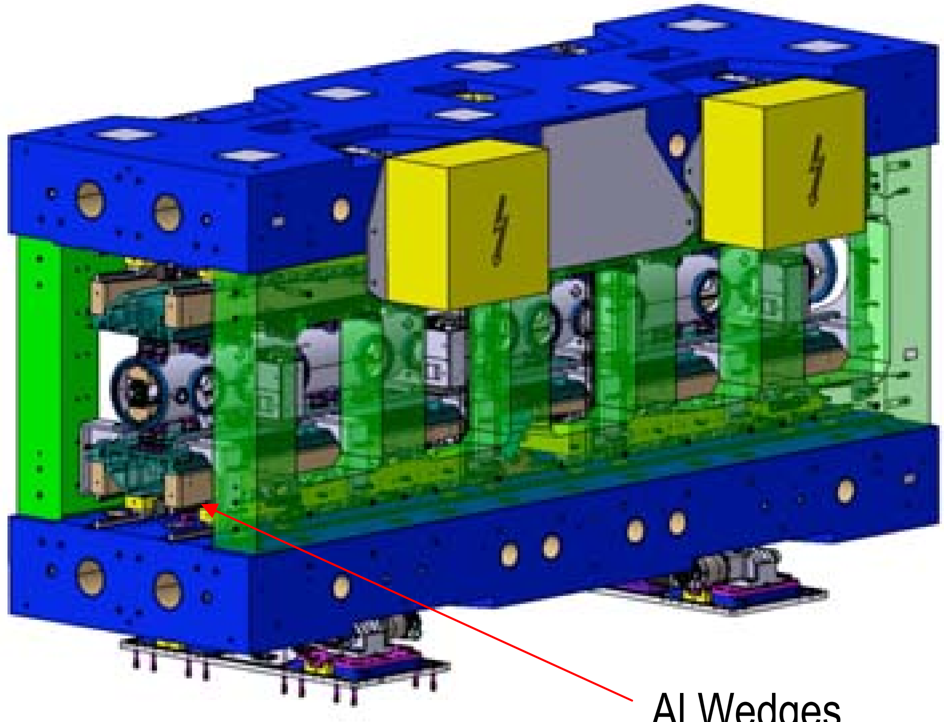
Dim: 4m x 1.4m x 2.2m, ~ 20to
ARAMIS: U15 12 modules

Prototype U15 undulator - Optimisation

- gap adjustment with system of 4 wedges :3 mm-30 mm range (required precision 0.3 μm)
- Advantage: Support the structure everywhere.
- servo motor driven, roller spindel with 1mm/turn
- no gear -> backslash minimized
- Alignment with 4 cam-shaft movers:

SLS system with 5 degrees of freedom :vertical and horizontal direction and all angles, tilt, roll and yaw

Status (September 2011)
- System in development
- Test, end of 2011



Three dimensionnal view of the U15 (hard X-ray line)

U15 Tolerances

Gap setting	0.3 μm
Position y	± 30 μm
Position x	± 200 μm
Trajectory straightness	1 μm
Phase error	1°
Temperature ΔT	0.1°

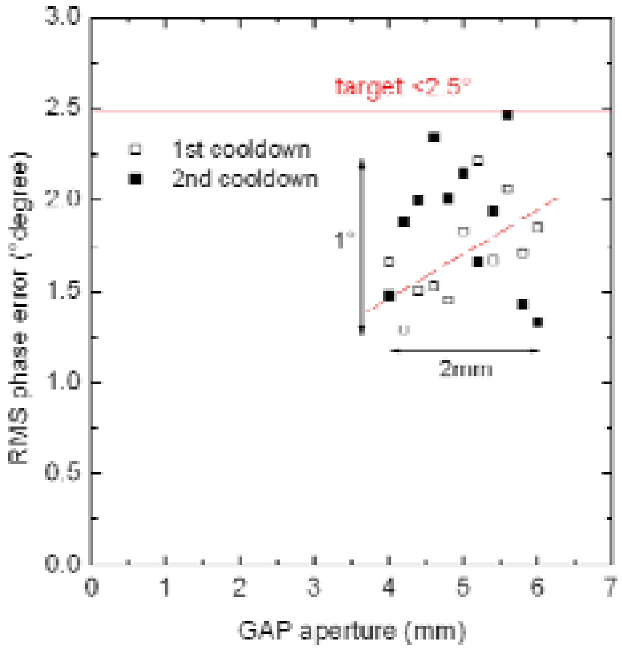
T.Schmidt, S. Reiche, Undulators for the SwissFEL (FEL,2009)

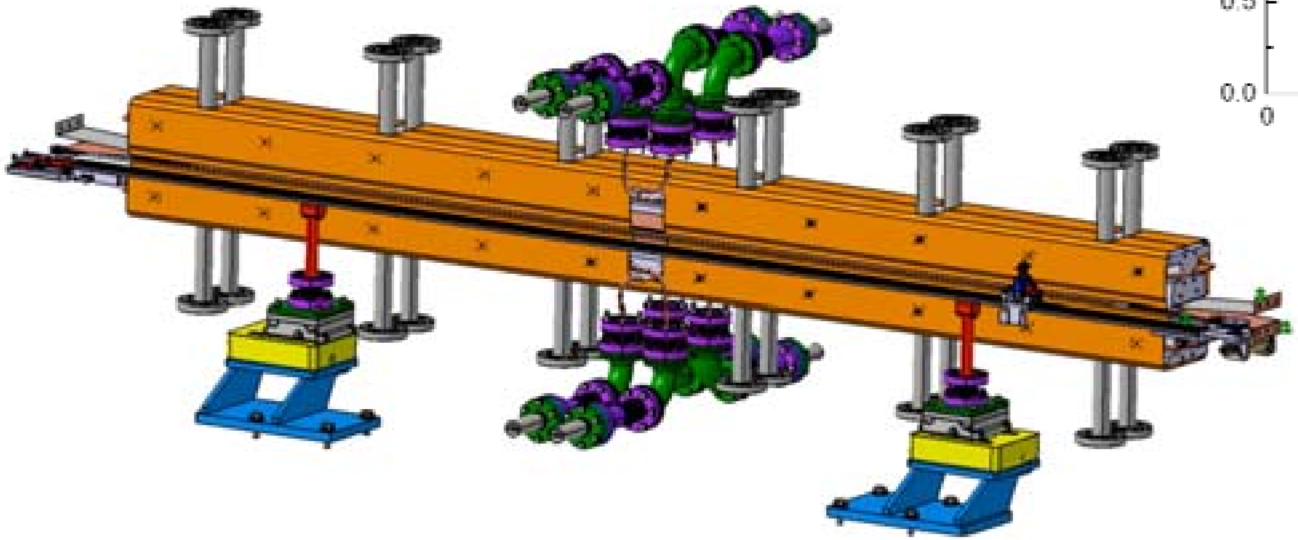
Tests of the U14 CPMU at the SLS (10-12/2010)

U14 joined project SPring-8 / Hitachi Metal Ltd / PSI

- Design and room temperature optimization: Hitachi Metal Ltd/ SPring-8
- LN2 measurements:SPring-8 , vacuum measurement system developed by Takashi Tanaka, proof of principle at gap = 7mm
- LN2 Test (135 K) at PSI with full control of cooling system and for the entire gap range (4 mm-6 mm)
- Installed in the SLS beam line beginning 2011

phase error





Experienced gained for SwissFEL In Vacuum Permanent Undulator (IVPMU) :
“In situ magnetic measurement” system *(T. Tanaka et al.,Phy. Review.B 12 (2009))*

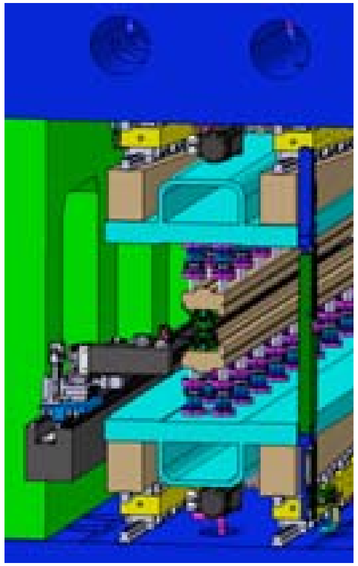
Integrated measurement system for U15

1) Magnetic optimization of IVPMU :

- Measurement w/o the vacuum chamber
- Automatized adjustment of pole heights (avoid swapping PM) based on Hall probe trajectory and phase error measurements.

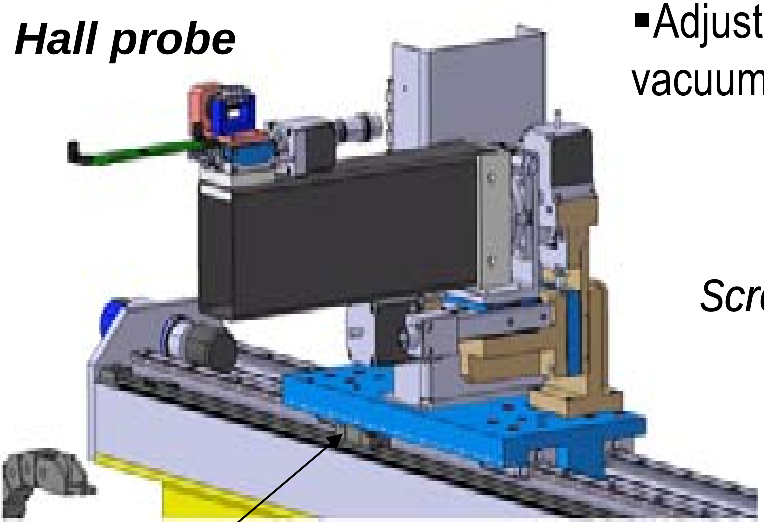
2) Field mapping with the vacuum chamber

- Dismounting of the Out-vacuum beam /out vacuum shafts/PM array;
- Insert the vacuum chamber/ PM array;
- Hall Probe measurements;
- Adjustment of the gap value using the out vacuum shafts.

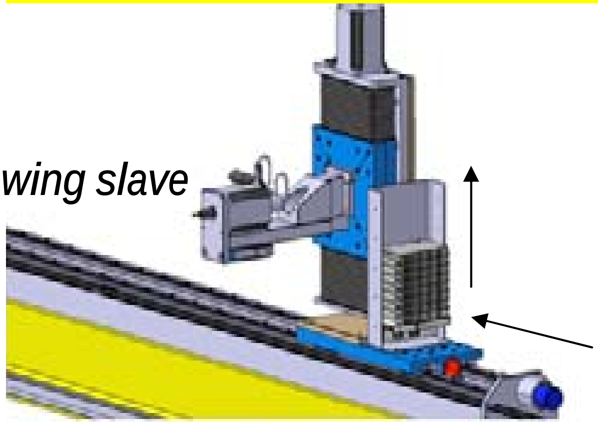


Integrated system

3D Hall probe



Screwing slave



- Hall probe and tooling on a common linear motor attached inside to the mineral frame for measurements
- Similar system with piezo walk motors for measurements after installation of the vacuum chamber

Status (September 2011)
- Hardware procured
- Software in development

Summary : Challenges and Issues

Technical challenges

- Small aperture quadrupoles (∅22 mm, ∅12 mm) and length (150 mm, 80 mm):
- Field quality requirements (gradient, multipoles at 0.01-0.1 %)
- Magnetic axis (below 30 μm)

- Closed in vacuum undulators (difficult access for measurements)
- Undulators short period and with variable gap
- Long length (4 m)

Resource Issues

- Procurement of main equipment is running. One critical item: field measurements on ∅12 mm quads;
- About personnel : ~180 magnets and 12 undulators to be designed, produced and tested till 2016;
  Allocated manpower for 100% of the tests (other PSI running facilities at PSI: SLS, HIPA,PROSCAN)

Response

Well defined design concept;
Precise measurement strategy & measurement plan;
Well defined test procedures;
Realistic production/measurement schedule ;
Collaboration with Institutes and companies;
PSI synergy potential .....

Perspectives 2012-2014

SwissFEL magnets/undulators (phase 1-Hard X-ray line)

- Quadrupole :Design (on-going), ends in 2011- Prototype and series measurements 2012-2014
- Dipoles :Design in 2012-2013 - Series measurements :2013-2015

- In vacuum U15 undulators;
  - Prototype : Autumn 2012
  - Series production 2013-2015
  - Magnetic tests: 2014-2016

Magnetic measurement systems

- Commissioning of the ∅19 mm rotating coil system *beginning of 2012* ;
- ∅10 mm rotating coil system expected *end of 2012*;
- Evolution of the vibrating wire towards a “rotating vibrating wire” to measure the also multipoles (*expected for the end of 2012*);
- Integrated Hall probe measurement system ready for the prototype U15 , *end 2011*;
- Hall probe measurement system inside the vacuum chamber, *end 2011-beginning 2012*.
- Adaptation of the already built systems: moving wire and pulse wire systems (on-going).

Thank you for your attention

Any questions?

Some related contributions at IMMW17 , MT22, FEL2011

S. Reiche (PSI) – Status of the SwissFEL facility at the Paul Scherrer Institute (FEL2011);

M. Negrazus et al. PSI) - Magnet Design and Measurement Results of the Solenoids and Bunch Compressor Bending Magnets of the SwissFEL Test Facility (MT22);

C. Wouters et al. (PSI) - Vibrating Wire Technique and Phase Lock Loop for Finding the Magnetic Axis of the Quadrupoles in the Swiss Free Electron Laser (MT22);

IMMW17

O. Dunkel (CERN) – A rotating coil array in Mono-bloc Printed circuit Technology for Small Scale Harmonic Measurements at CERN

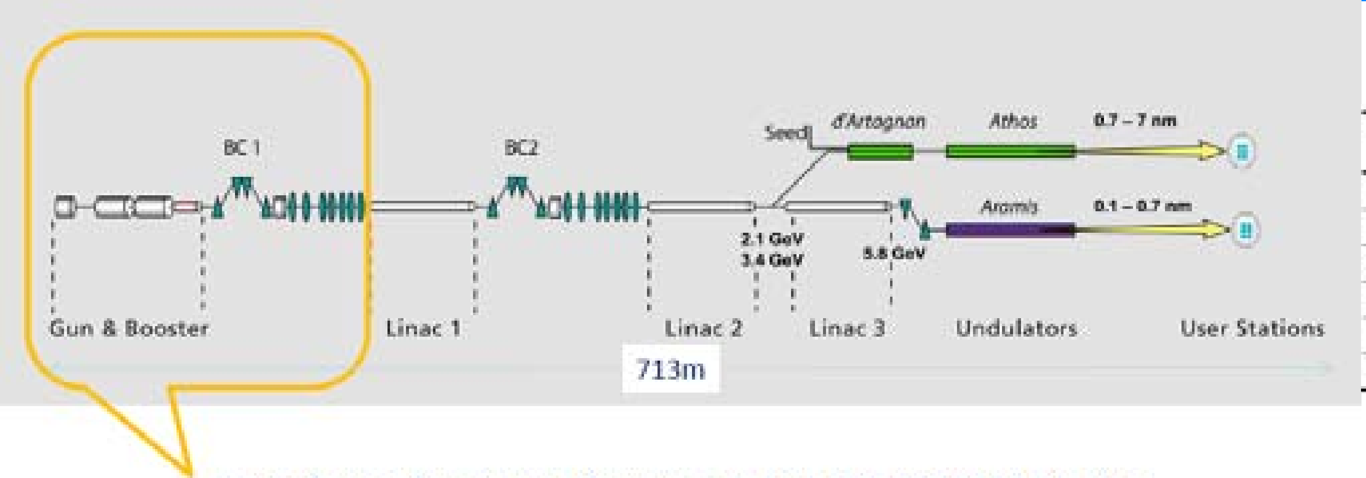
J. G. Perez (CERN) - Measurements of small aperture Quadrupoles for Linac4 and Clic Projects

V. Vrankovic (PSI) - Experiences with the single streched vibrating wire test stand at PSI

C. Petrone (CERN) – Measuring field strength and multipoles of small apertures quadrupoles with vibrating wire

Magnets for the 250 MeV Injector test

The SwissFEL injector test facility

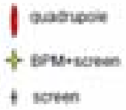


Test of overall system performance in SwissFEL 250 MeV Injector

Goal beam parameters

Parameter	Goal Test facility	
Charge – operation mode (pC)	10	200
Projected norm. Emittance (mm.mrad)	0.15	0.5
Slice norm. emittance (mm.mrad)	0.11	<0.43
Uncorrelated energy spread (keV)	<50	<50
Peak current (A)	100	300
Energy (MeV)	250	250

- **Phase 1: Electron source and diagnostics**



  - March 2010 to May 2010
  - Characterization of the electron source
  - Installation of remaining machine behind shielding wall

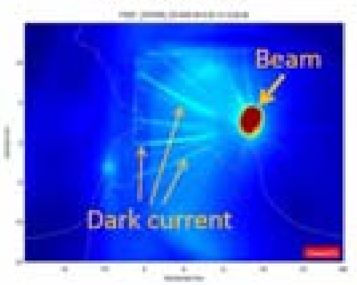
- **Phase 2: Phase 1 + (some) S-band acceleration**

  - August 2010 to December 2010 (official injector inauguration 24 August)
  - Emittance damping in S-band booster (invariant envelope)
  - Jaguar (Nd:YLF) laser

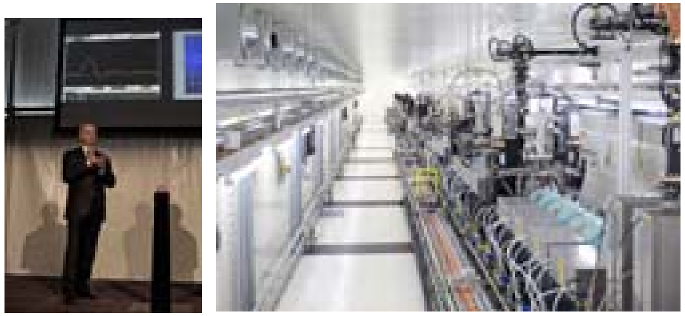
- **Phase 3: The full machine**

  - End of 2010 / early 2011 (installation bunch compressor and X-band cavity)
  - Pulsar (Ti:Sapph) laser

YAG screen image



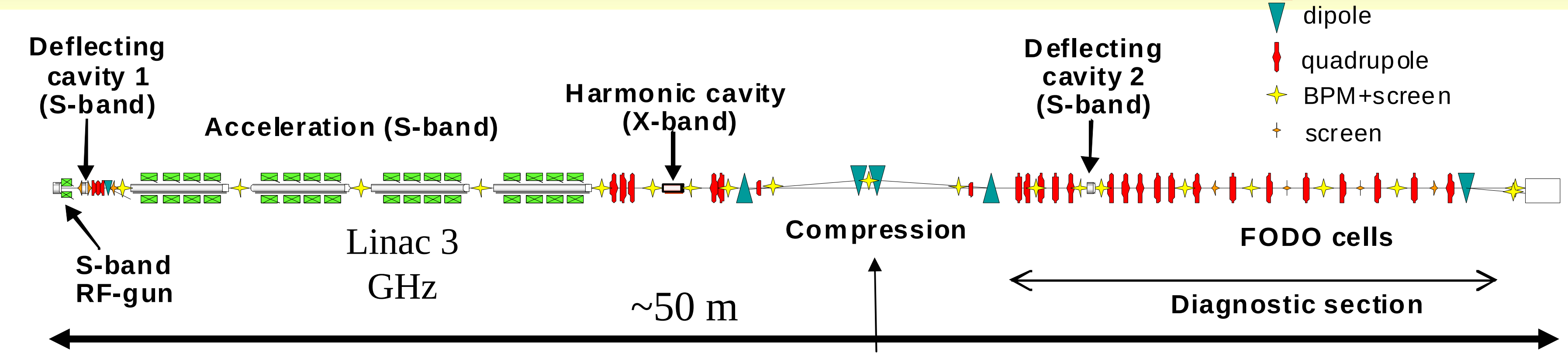
24 March 2010: First beam



24 August 2010: Inauguration

Magnets for the 250 MeV Injector

Aims: Source of electron with low emittance, accelerate the beam and shape the e- bunch



▼ dipole
quadrupole
✦ BPM+screen
✦ screen

Deflecting cavity 1 (S-band)

Acceleration (S-band)

Harmonic cavity (X-band)

Deflecting cavity 2 (S-band)

S-band RF-gun

Linac 3 GHz

Compression

FODO cells

Diagnostic section

~50 m

e- source+ compression
I=5.5 A to 30 A

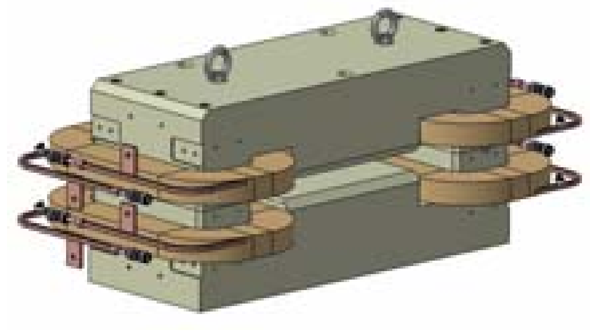
Magnetic compression
I=30 A to 350 A

Solenoids:
Gun solenoid+16 in acceleration

Gun solenoid (0.35T, A=80 mm, L=0.260 m)

S-Band Solenoid
0.1 T, Φ=220mm,
L=0.75 m

6 dipoles:
chicane (4), dump, diagnostics



BC dipole
0.4T, G=30 mm, L=0.25 m

28 Quads:
FODO, Diag, compression

QFA Quad (25T/m, 45 mm)

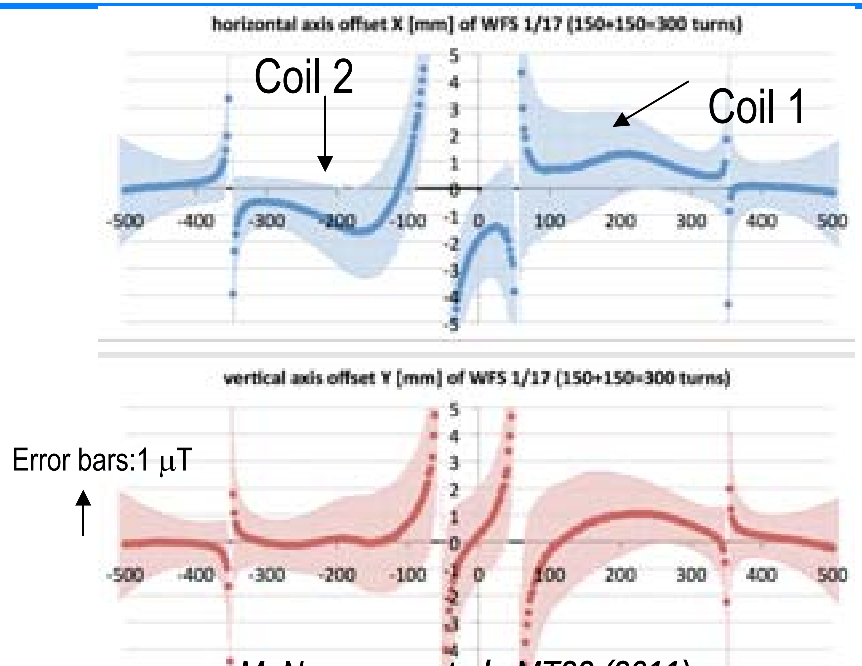
Magnets for the 250 MeV Injector (2)

Magnet type	Characteristics	Quantities to measure	Accuracy (if specified)
BC Dipole V2 (4) Measured mid 2010	B_{Nom}=0.4T,GFR~60 mm angle= 5 deg max @350 MeV **Gap**=30mm, L_{mag}=0.25m	Magn. Length, Field integral ∫Bdl ∫ Bdl=f(I), field maps (5 planes)	10^{-4}
Quadrupoles (28)	G_{Nom}=25T/m, Φ=45mm, L_{mag}=0.175 m	Magn. Length, integrated gradient ∫Gdl ∫ Gdl=f(I), field maps Multipoles	10^{-4} 10^{-3}
Gun Solenoid ([illegible])	B_{Nom}=0.35[illegible], Φ=80mm, L_{mag}=0.26m	Magn. Length, Field integral ∫Bdl ∫ Bdl=f(I), field maps Magnetic axis position	10^{-4} 0.1 mm
S band solenoid (17) Measured end 2009	B_{Nom}=0.1T, Φ=220mm, L_{mag}=0.75m	Magn. Length, Field integral ∫Bdl ∫ Bdl=f(I), field maps Magnetic axis position	10^{-4} 0.1 mm
Correctors (28)	B_{Nom}=20 mT, Φ=80mm, L_{mag}=0.05m	Magn. Length, Field integral	10^{-3}

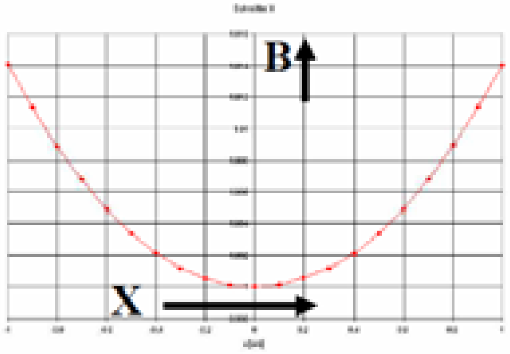
84 magnets built, measured and delivered (last ones in Sommer 2010)

S Band solenoids: Axis measurements

Not a real magnetic axis measurements
Looking for an extremun of the main field component



M. Negrazus et al., MT22 (2011)



Transverse position

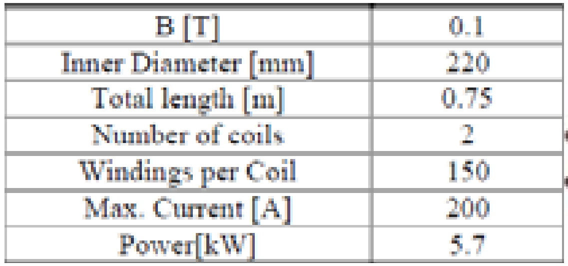
Quadratic fit of the magnetic field as a function of X for one Z position

V. Vrankovic et al., IMMW16 (2009)

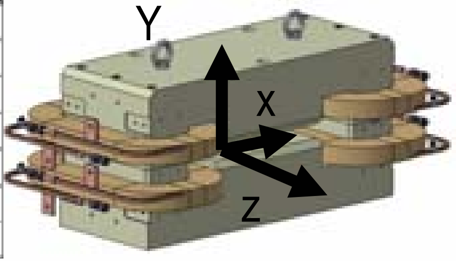
17 solenoids measured with a single axis Hall probe :

- **XY field maps every z =20 mm.**
- **The offsets ΔX_c, ΔY_c are defined as the difference from minimum (maximum) of a quadratic fit of the measured magnetic field (X_c,Y_c) at each z with respect to the geometrical center.**
- **Inside the coils ΔX_c, $\Delta Y_c \leq 1$ mm (ΔB equiv. to 1 µT)**
- **Between the coils the error becomes big: results are not relevant (magnet too homogeneous).**

Bunch compressor dipoles



B [T]	0.1
Inner Diameter [mm]	220
Total length [m]	0.75
Number of coils	2
Windings per Coil	150
Max. Current [A]	200
Power[kW]	5.7

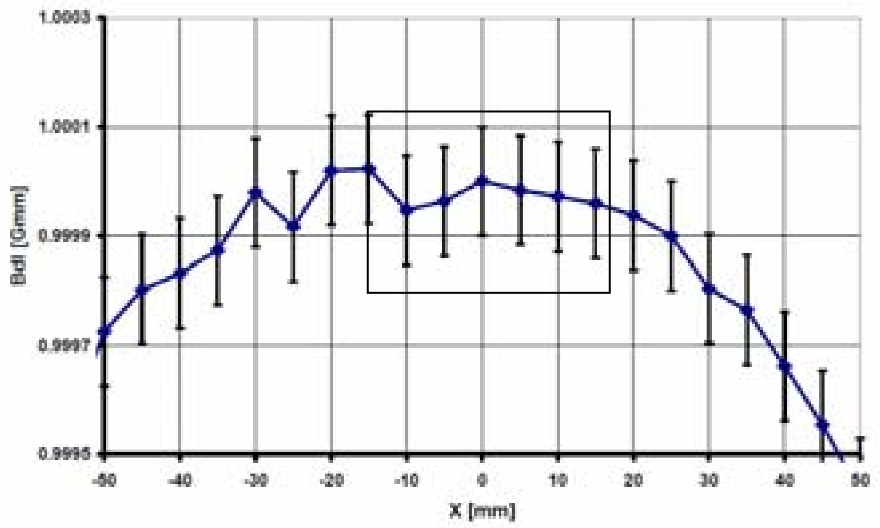


Magnet	Field in the center [T]	Field integral [Tm]	Average effective length [mm]
#1	**0.46005**	**0.13935**	**302.9**
#2	**0.46005**	**0.139219**	**302.6**
#3	**0.46011**	**0.139197**	**302.5**
#4	**0.46005**	**0.139219**	**302.6**
Average	**0.46007**	**0.13925**	**302.65**
Sigma (units)	**0.7**	**5.0**	**5.8**

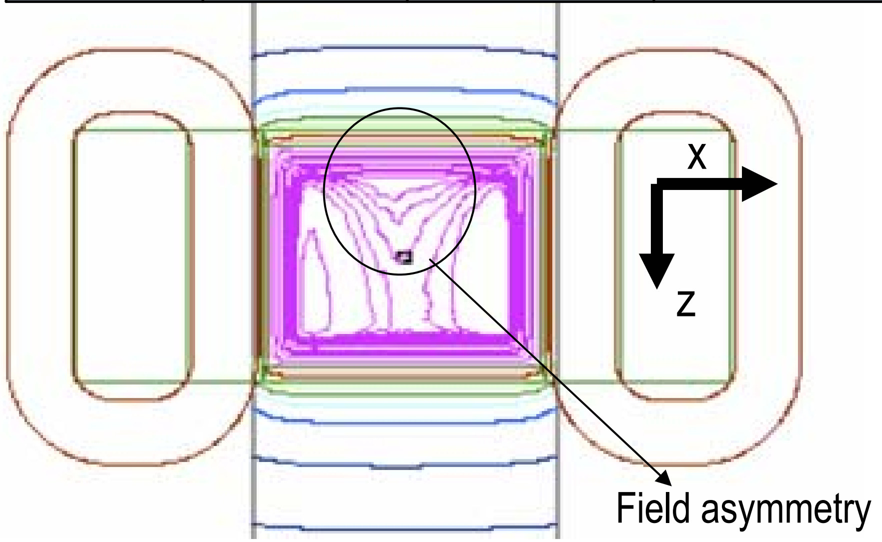
Field map in the magnet horizontal mid-plane,I = 200 A,

- ±700 mm (along the beam direction)
- ±150 mm (across the beam direction)

Δ Bdl $<\pm10^{-4}$ *In the specs!*



Longitudinal integrated and normalized magnetic field integral Bydz at 200 A



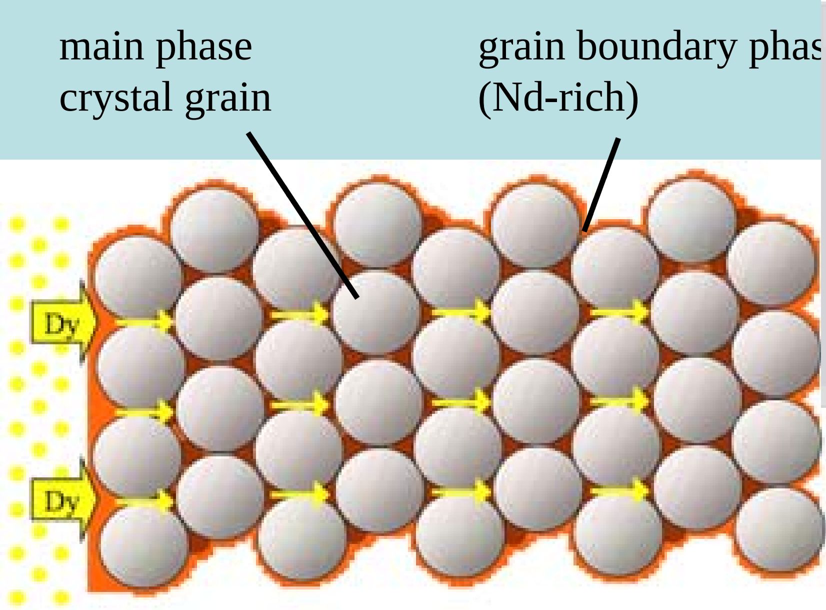
Contour plot of the magnetic field in the horizontal XZ plane

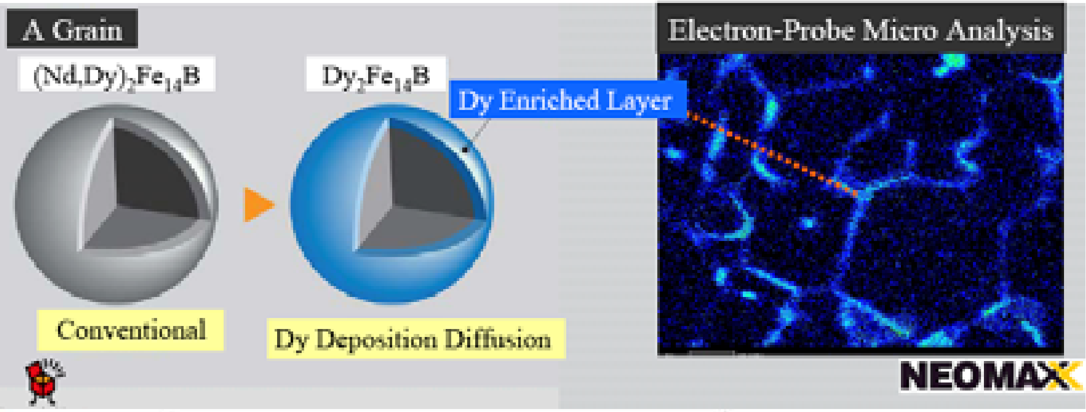
M. Negrazus et al., MT22 (2011)

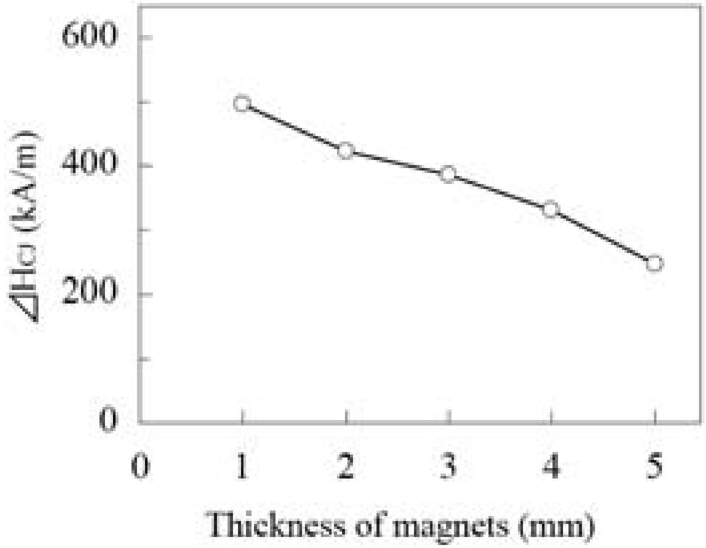
New fabrication technique

vapor diffusion of Dy into the machined magnet (Hitachi Metals Ldt.)

increase of stabilization without reduction of remanence







for thin magnets only
(U15 magnets: ~2mm)

(all figures courtesy:Hitachi Ltd)