Development of a MARS superconducting cold mass for future generations of ECRIS

P. Ferracin

Lawrence Berkeley National Laboratory

2023 NP Accelerator R&D PI Exchange Meeting

December 7th, 2023

Acknowledgements

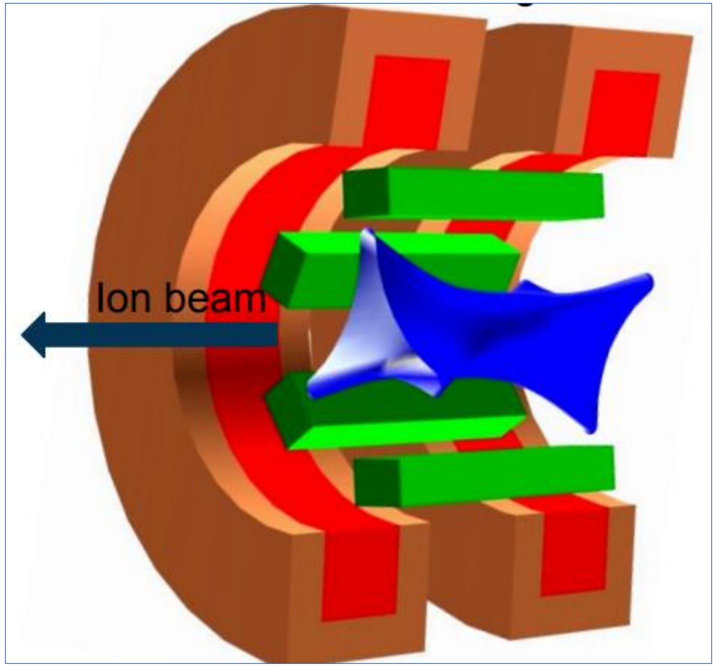
- 88-inch Cyclotron, NS Division, LBNL
  - Brian Bell, Janilee Benitez, Patrick Coleman, Jaime Cruz Duran, Larry Phair, Roman Nieto, Nathan Seidman, Damon Todd, Daniel Xie, Lianrong Xu, Sean Zhong
- Superconducting Magnet Program, ATAP Division, LBNL
  - Jose Ferradas Troitino, Mariusz Juchno, Soren Prestemon, Matt Reynolds, Jose Luis Rudeiros Fernandez, James Swanson, Chet Spencer, Ye Yang

Outline

- Introduction: description and goals of the project
- MARS cold mass design
- Project status
- Annual budget
- Project deliverables and schedule

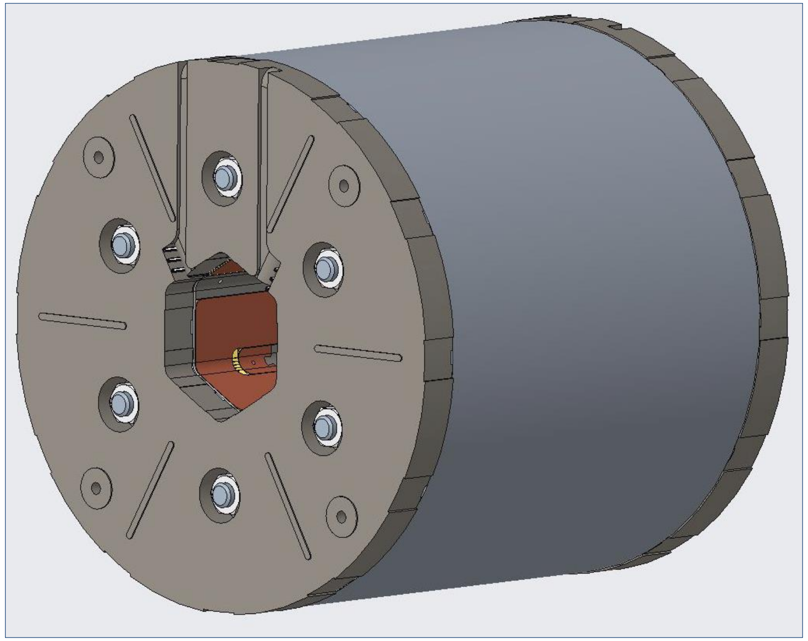
Introduction
ECR Ion Sources

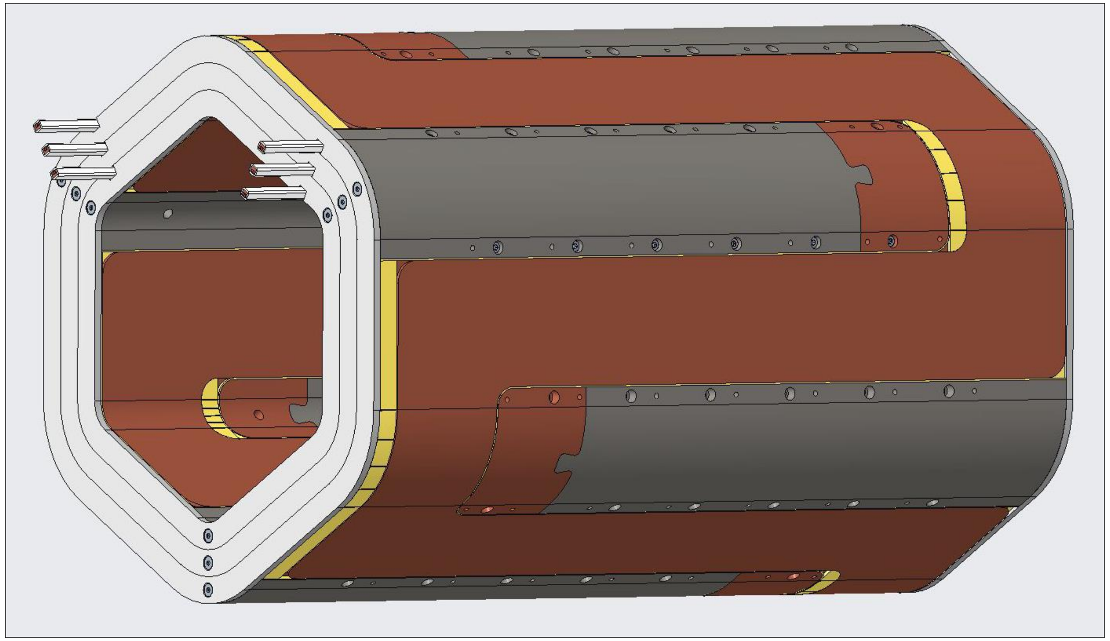
- Produce a plasma from which we extract an ion beam
- Plasma is confined using sextupole and solenoid magnets
- Currently, 3rd generation sources, like VENUS and FRIB, use superconducting magnets
  - Frequency of 28 GHz
  - Solenoid field up to 4T
  - Sextupole field up to 2 T



Introduction
Goal of the project

- Design, fabricate, and test the cold mass of the 4th generation ECR Ion Source MARS capable of reaching a magnetic field that satisfies 45 GHz operation



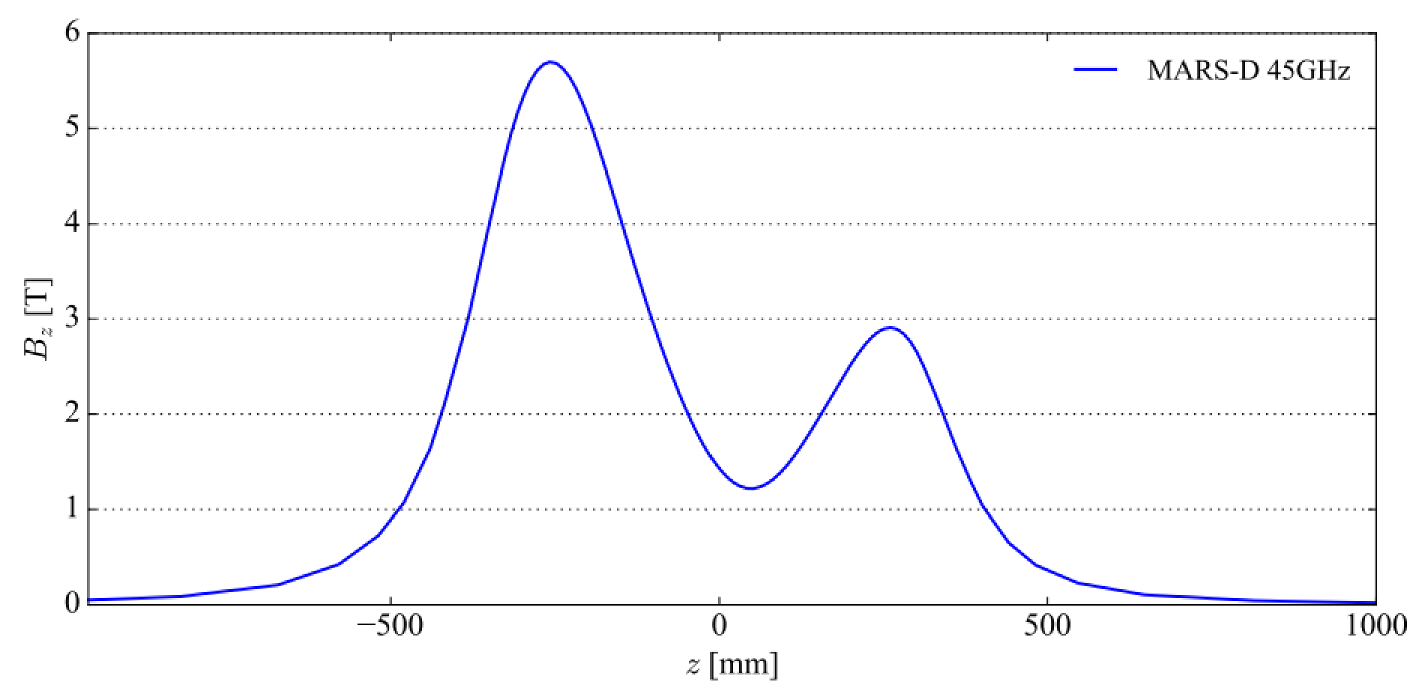


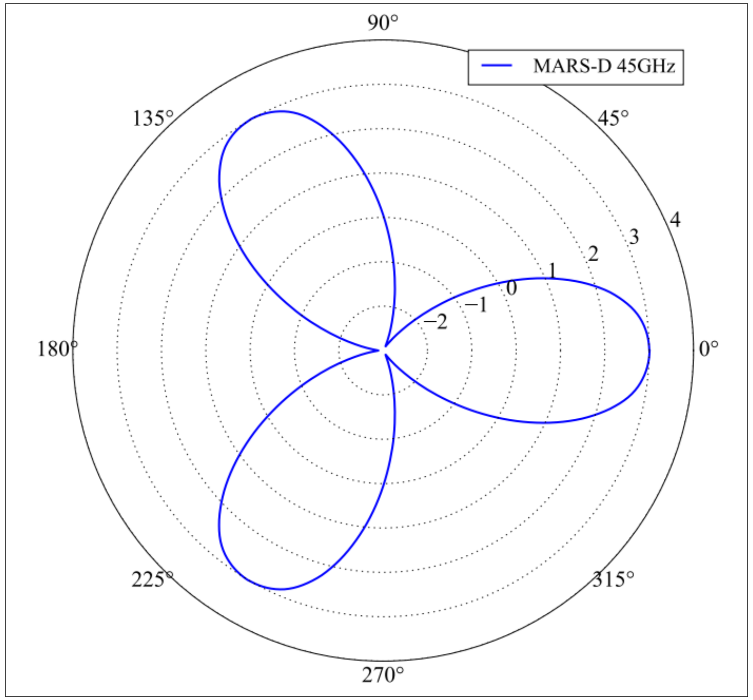
Outline

- Introduction: description and goals of the project
- MARS cold mass design
- Project status
- Annual budget
- Project deliverables and schedule

MARS cold mass design
Magnetic design

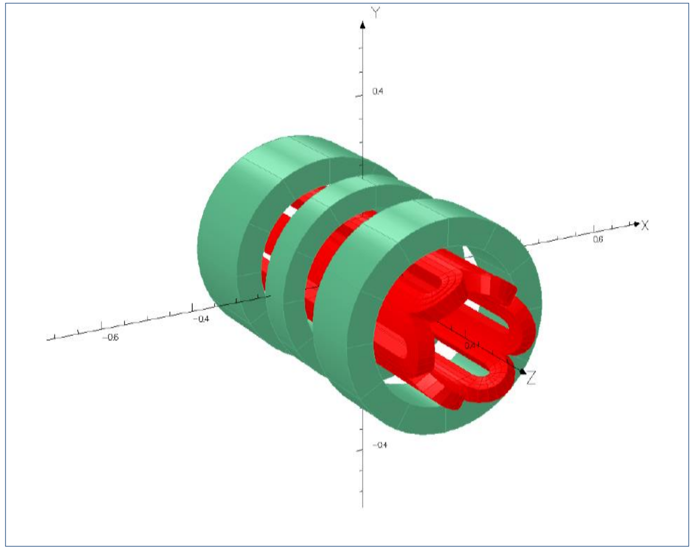
- Requirements for a 45 GHz operation
  - Solenoidal field: 5.7 T – 1.2 T – 2.9 T
  - Sextupole field: 3 T at 94 mm



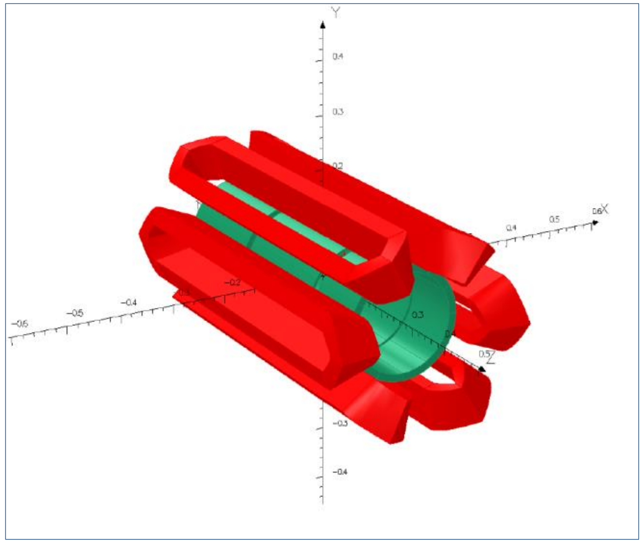


MARS cold mass design
Magnetic design: different options

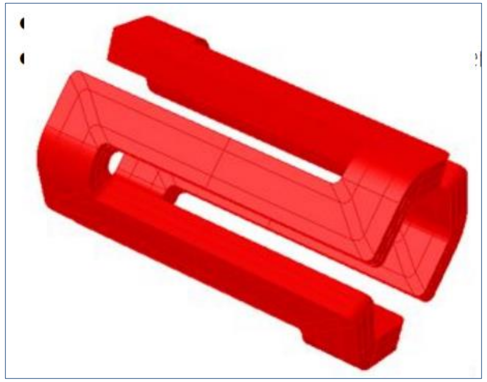
Sextupole in solenoid
VENUS
FRIB

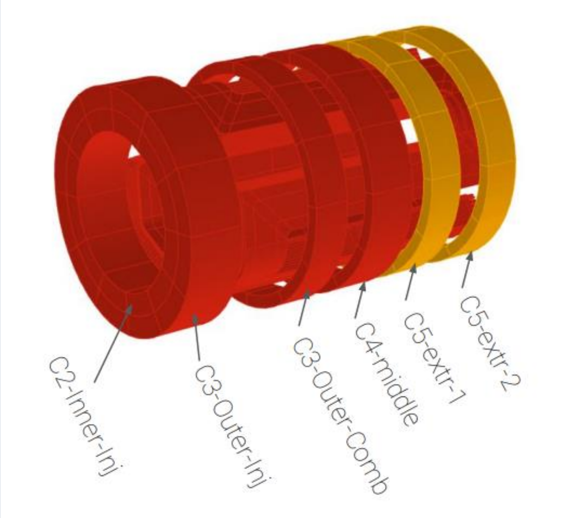


Solenoid in sextupole
SECRAL



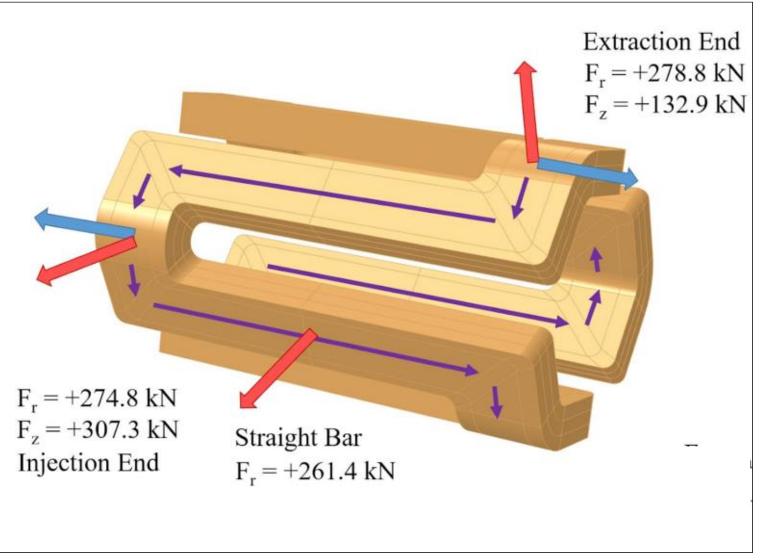
MARS

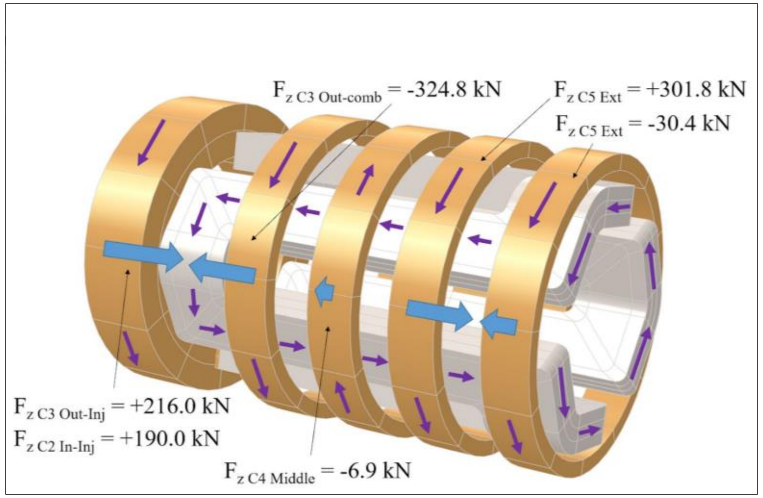




MARS cold mass design
Magnetic design

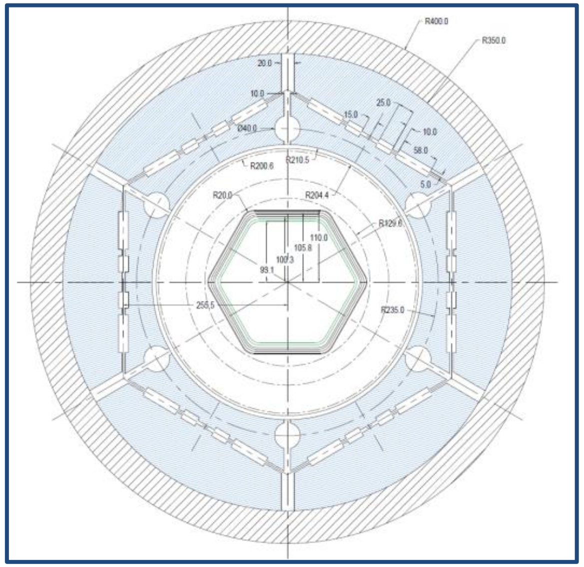
- MARS advantages
  - Efficient magnetic design (sextupole ends contribute to the axial field) →
    - Possibility of reaching 45 GHz with Nb-Ti conductor
      - Similar load-line margin (10-15%) at 45 GHz as FRIB/VENUS configuration at 28 GHz
      - MARS would meet VENUS/FRIB performance with a very safe 40% margin
  - Electro-magnetic forces on the sextupole coil ends face outwards, both axially and radially
    - In VENUS/FRIB alternating end forces between coils
- MARS challenges
  - "Single" sextupole coil
    - Long fabrication process, "one-shot" type of condition



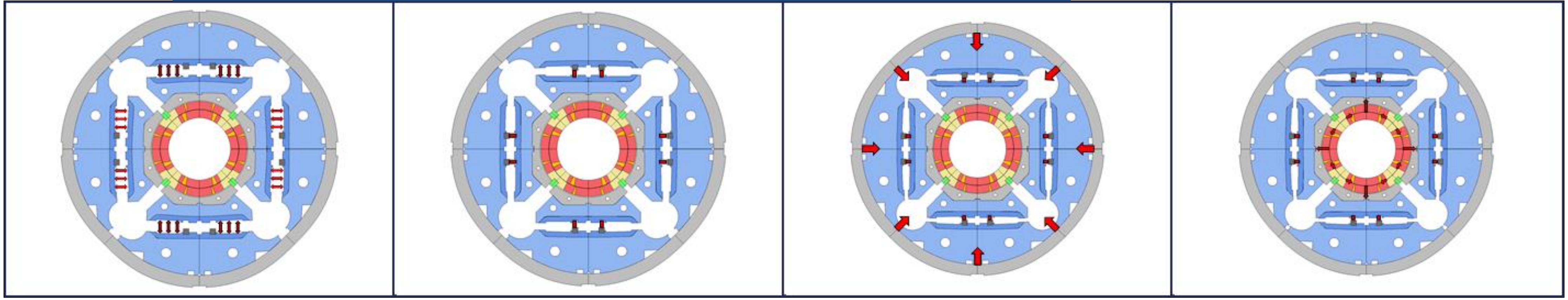


MARS cold mass design
Mechanical design

- Bladder and key support structure
  - Three main component surrounding the coils
    - Iron pad – iron yoke – aluminum shell
  - Room temperature pre-load provided with water-pressurized bladders
  - Additional pre-load provided during cool-down



Synergy with HEP - LHC luminosity upgrade MQXF quadrupole example

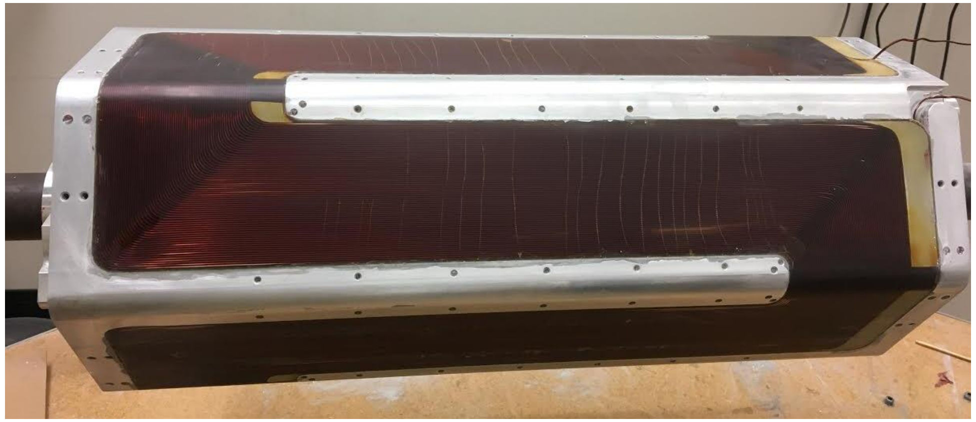


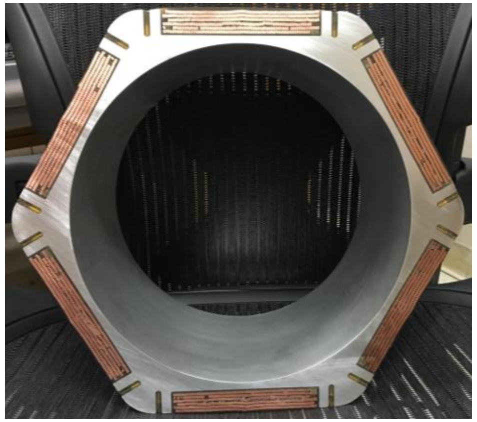
Outline

- Introduction: description and goals of the project
- MARS cold mass design
- Project status
- Annual budget
- Project deliverables and schedule

Project status updates FY23 first quarter

- Review of previous work
  - 2016 copper coil winding and impregnation





- Review of magnetic requirements for 45 GHz operation
- Conceptual design of the cold mass and tooling
  - Coil and structure design, magnetics, mechanics

Project status updates FY23 second quarter

- Internal review of the cold mass design
  - Committee
    - Gianluca Sabbi, Chair
    - Diego Arbelaez, Adrian Hodgkinson, Claude Lyneis, Tengming Shen, Jim Swanson
  - Recommendations
    - Define magnetic parameters
    - Perform quench protection analysis
    - Check conductor with bending radius
    - *“Consideration should be given to performing additional test windings before launching the labor-intensive fabrication of the production coil.”*
- Decision to fabricate practice coil as risk mitigation strategy

MARS

Internal Review of the MARS-D Coldmass Design and Fabrication Plan

February 3, 2023 9:30 am- 12:30 pm

location: hybrid* via zoom and room 06, bldg 47

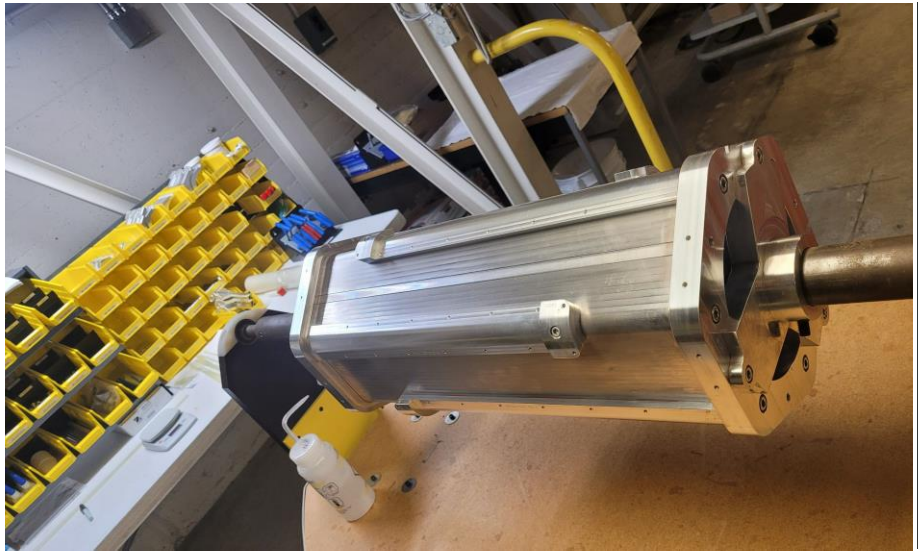
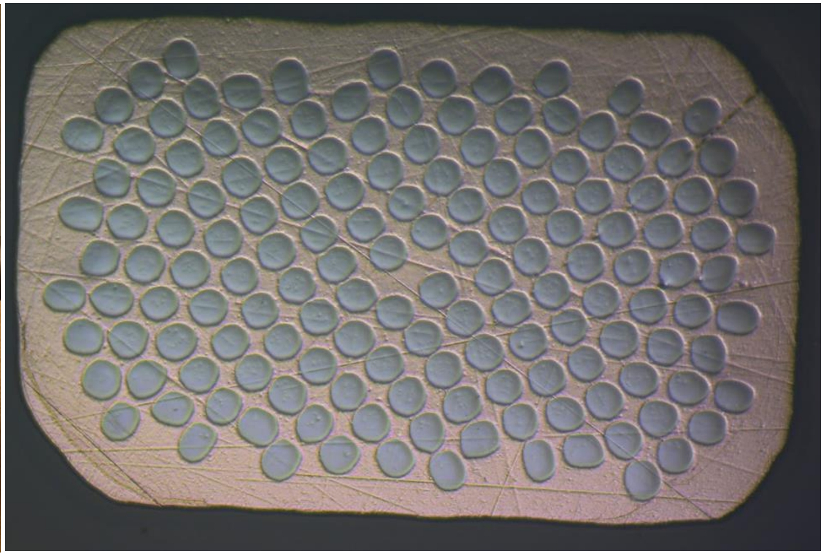
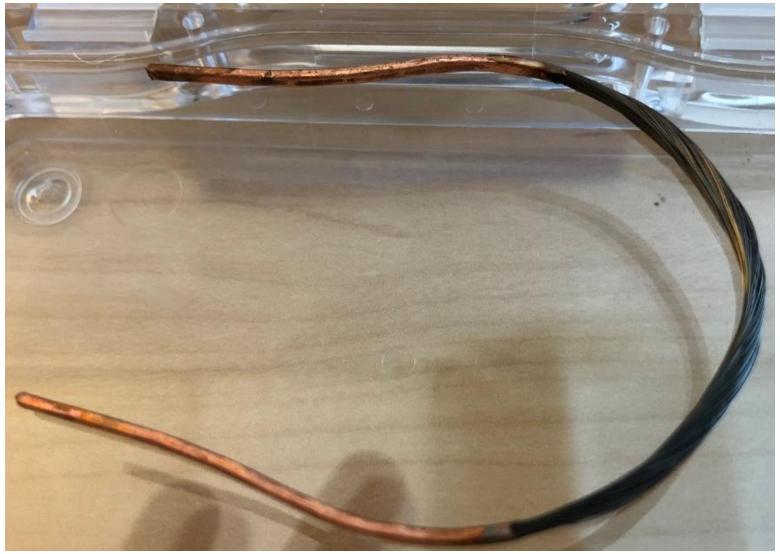
*zoom link can be found in calendar invite

Agenda

Time Start	Duration			Speaker
9:30 AM	0:15		Opening Remarks & Review Goals	Paolo Ferracin
9:45 AM	0:15		Project Overview	Janilee Benitez
10:00 AM	0:15		The MARS Concept	Dan Xie
10:15 AM	0:30		Magnetic Design and Analysis	Damon Todd
10:45 AM	0:30		Mechanical Design and Analysis	Mariusz Juchno
11:15 AM	1:00		Mechanical Design and Fabrication	Dan Xie and Lianrong Xu
12:15 PM	0:15		Q&A and Wrap-up	Paolo Ferracin

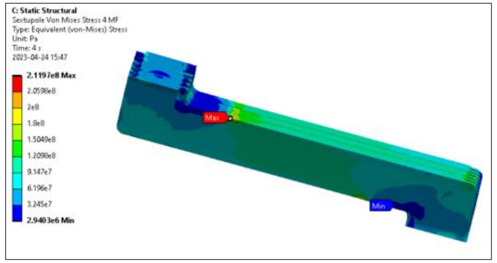
Project status updates
FY23 second quarter

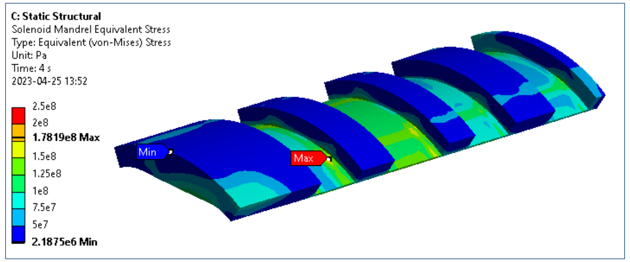
- Tooling preparation for practice winding
  - Final mandrel, but small pole for 4-layer practice coil
- Conductor bending test
  - No broken filaments observed

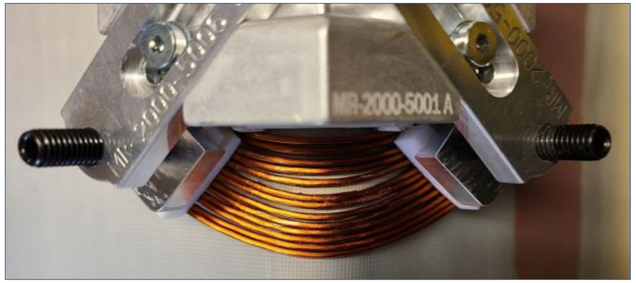




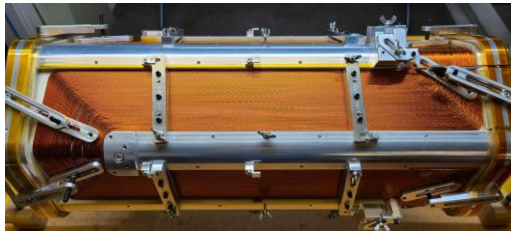
Project status updates
FY23 third quarter

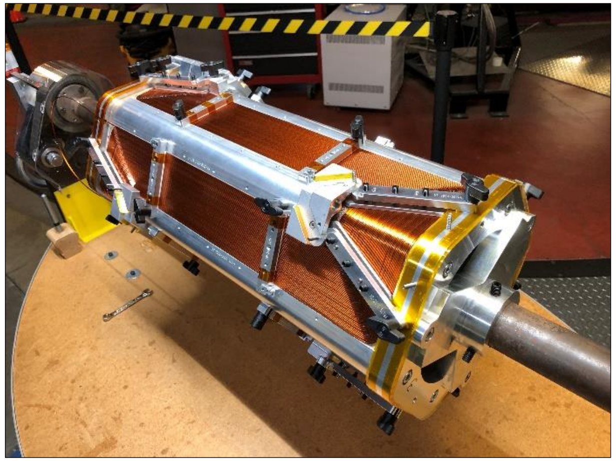
- Mechanical analysis
  - Investigation of stress in coils and mandrels
- Tooling development
  - To guarantee correct positioning of sextupole turns
- Winding practice coil





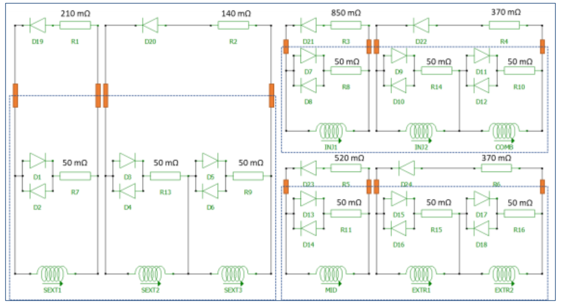


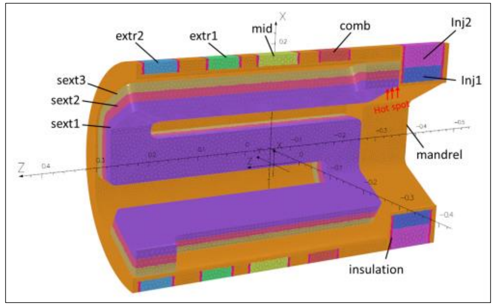




Project status updates
FY23 fourth quarter

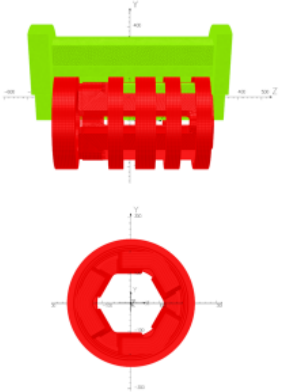
- Quench protection and test analysis
- Definition of requirements
  - Maximum temperature < 200K
  - Maximum external voltage < 80 V @ external resistor for lead protection
  - Maximum to-ground voltage < 500 V
  - Maximum coil internal voltage < 1.5kV
  - No damage on the diode
    - Peak power < 130 kW
  - No damage on the mechanical structure by eddy current effect
- Definition of protection scheme to meet requirements





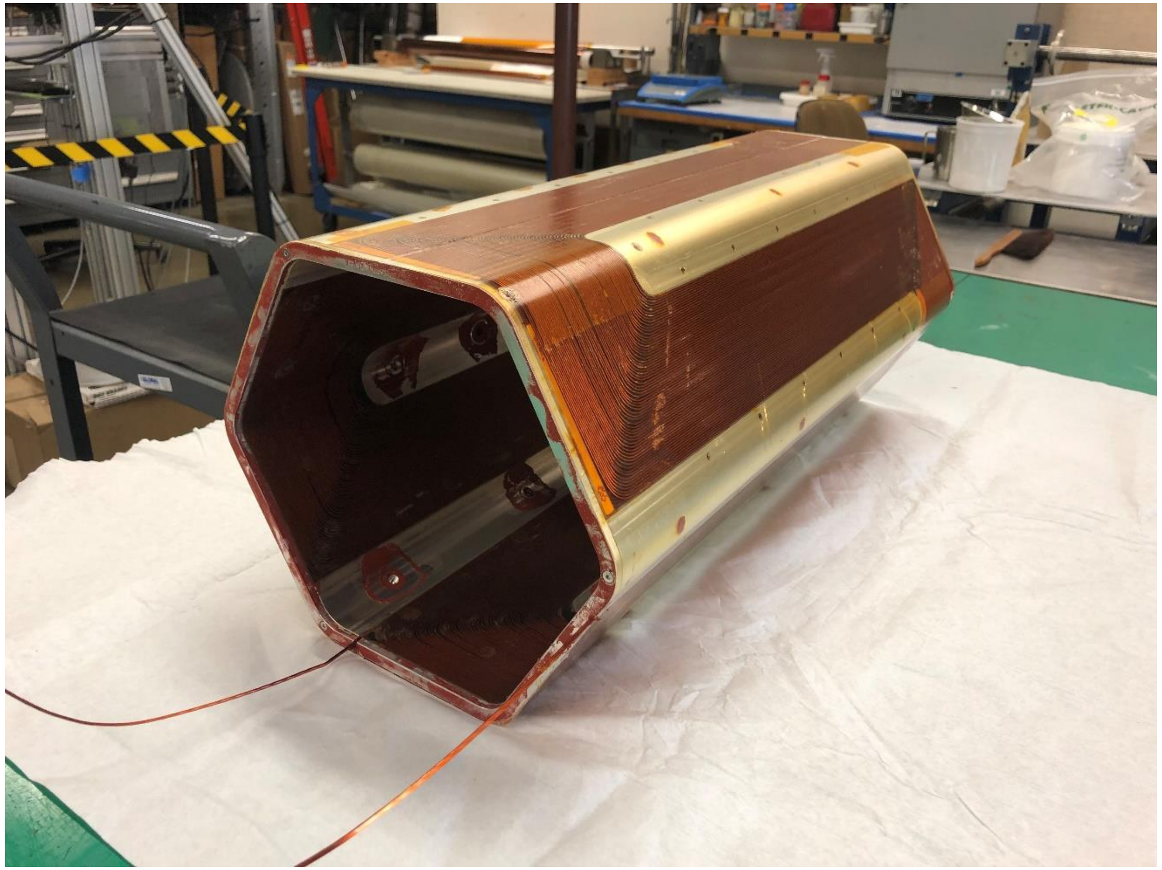
MARS-D (45GHz) Design Parameters

Item	Unit	Value									
Wire	-	NbTi monolithic wire			NbTi monolithic wire						
Bare width	mm	1.84			1.36						
Bare thickness	mm	1.16			0.65						
Insulated width	mm	1.91			1.45						
Insulated thickness	mm	1.23			0.71						
Cu ratio	-	1.3			1.4						
Filament diameter	μm	80			30						
RRR	-	99			70						
Coil name	-	sext1	sext2	sext3	inj_in	inj_out	comb	middle	extr1	extr2	
R0	mm	110	127.5	145	130.1	159.5	181.2	181.2	181.2	181.2	
R1	mm	127.5	145	159.5	159.5	200.5	200.5	200.5	200.5	200.5	
Z0	mm				-370	-370	-150	-40	80	200	
Z1	mm				-280	-280	-90	40	140	260	
height, dR	mm	17.5	17.5	14.5	29.4	41	19.3	19.3	19.3	19.3	
width, dZ	mm	79.1	79.1	79.1	90	90	60	80	60	60	
Coil cross section	mm²	1384.25	1384.25	1146.95	2646	3690	1158	1544	1158	1158	
Layer	-	8	8	7	38	53	25	25	25	25	
Turns per layer	-	63	63	63	61	61	40	54	40	40	
Total turns	-	504	504	441	2318	3233	1000	1350	1000	1000	
Conductor filling factor	-	85.5%	85.5%	90.3%	90.2%	90.2%	88.9%	90.0%	88.9%	88.9%	
Packing factor	-	77.7%	77.7%	82.1%	77.4%	77.5%	76.3%	77.3%	76.3%	76.3%	
Gap per layer	mm	0.278	0.278	0.161	0.064	0.064	0.062	0.062	0.062	0.062	
Gap per turn	mm	0.026	0.026	0.026	0.025	0.025	0.050	0.031	0.050	0.050	
Operating current	A	353.7	530.6	530.6	93.2	257.6	257.6	-153.2	214.7	214.7	
Circuit	-	A	B		C	D		E	F		
Current density	A/mm²	128.78078	193.18938	204.01465	81.64686	225.73174	222.48705	-133.95078	185.40587	185.40587	
Superconducting J	A/mm²	381.1	571.8	571.8	253.0	699.5	699.5	-415.9	582.9	582.9	
Max. field	T	8.36	7.75	7.01	7.96	6.82	6.01	5.01	5.57	4.22	
Load ratio (4.2K)	-	90.5%	87.9%	80.6%	84.1%	81.2%	73.2%	57.8%	66.5%	46.4%	
Tcs	K	4.68	4.80	5.15	5.00	5.12	5.50	6.21	5.81	6.71	
Tc	K	5.04	5.35	5.70	5.24	5.79	6.15	6.58	6.34	6.91	
Jc	A/mm²	880.379	1192.9	1566.09	1086.09	1664.61	2087.6	2645.65	2329.73	3132.59	
Iop/Ic	-	0.433	0.479	0.365	0.233	0.420	0.335	0.157	0.250	0.186	
Coil volume	m³	4.53E-03	4.66E-03	4.79E-03	4.53E-03	4.13E-03	1.37E-03	1.83E-03	1.37E-03	1.37E-03	
Wire length	km	1.65	1.70	1.84	3.97	3.61	1.19	1.60	1.19	1.19	17.04
strand volume	m³	3.88E-03	3.99E-03	4.33E-03	4.09E-03	3.72E-03	1.22E-03	1.65E-03	1.22E-03	1.22E-03	2.53E-02
superconductor volume	m³	1.53E-03	1.58E-03	1.71E-03	1.46E-03	1.33E-03	4.37E-04	5.89E-04	4.37E-04	4.37E-04	9.51E-03
MQE	μJ	7.47	7.87	13.09	5.60	4.08	5.95	12.42	8.21	11.90	
Integral axial force	kN	-120.52	-237.08	-258.88	133.02	440.78	-389.11	18.25	279.44	-8.99	-143.09
Stored energy	kJ	711.17									
Binj	T	5.74									
Bmid	T	1.26									
Bext	T	2.94									
Br at 94mm	T	3.04									



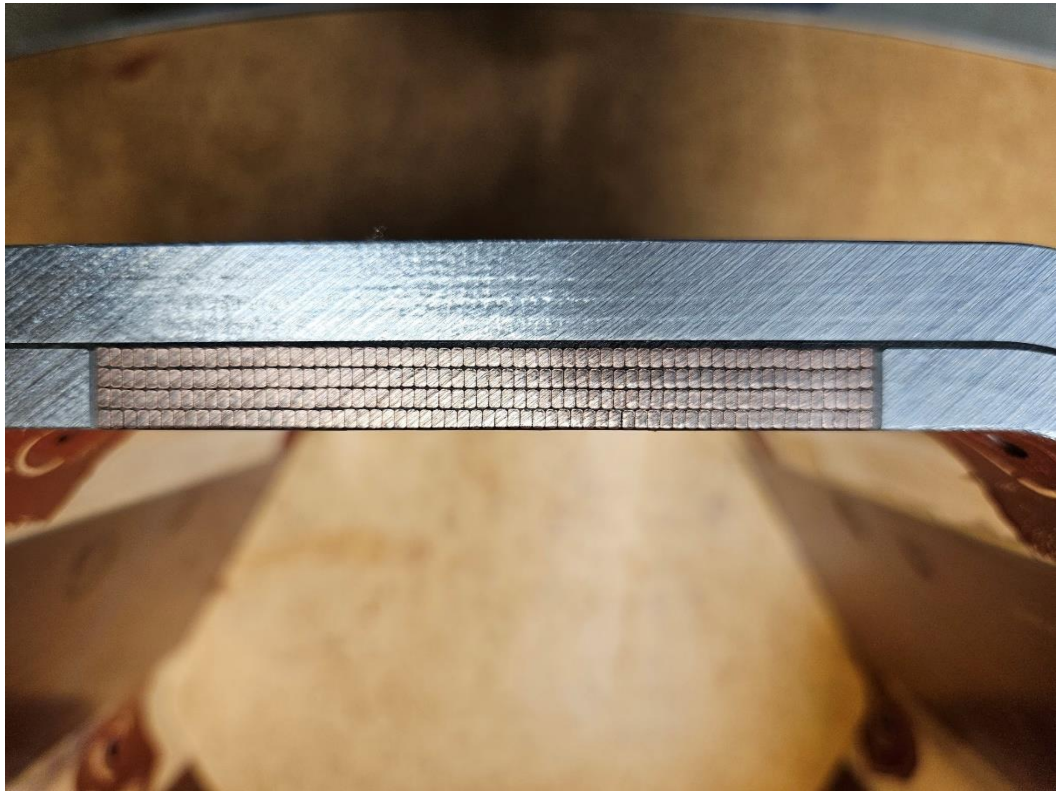
Project status updates
FY23 fourth quarter

- Completion of practice coil and cut to check impregnation



Project status updates
FY23 fourth quarter

- Completion of practice coil and cut to check impregnation



Project status
Additional outcomes/comments

- As additional risk mitigation strategy
  - Fabrication of the solenoids in house and after the sextupole coil fabrication
    - Machining of the solenoid mandrel finalized once sextupole coil completed

- More in general, excellent collaboration between NSD and ATAP team, at all levels
  - Conceptual design, analysis, fabrication….

Outline

- Introduction
  - ECR Ion sources
  - Description and goal of the projects
- MARS Cold mass design
- Project status
- Annual budget
- Project deliverables and schedule

Annual budget

	FY23	FY24	Total
Funds allocated	999	999	1998
Actual cost to date	668	101*	769*

*As of November 1st

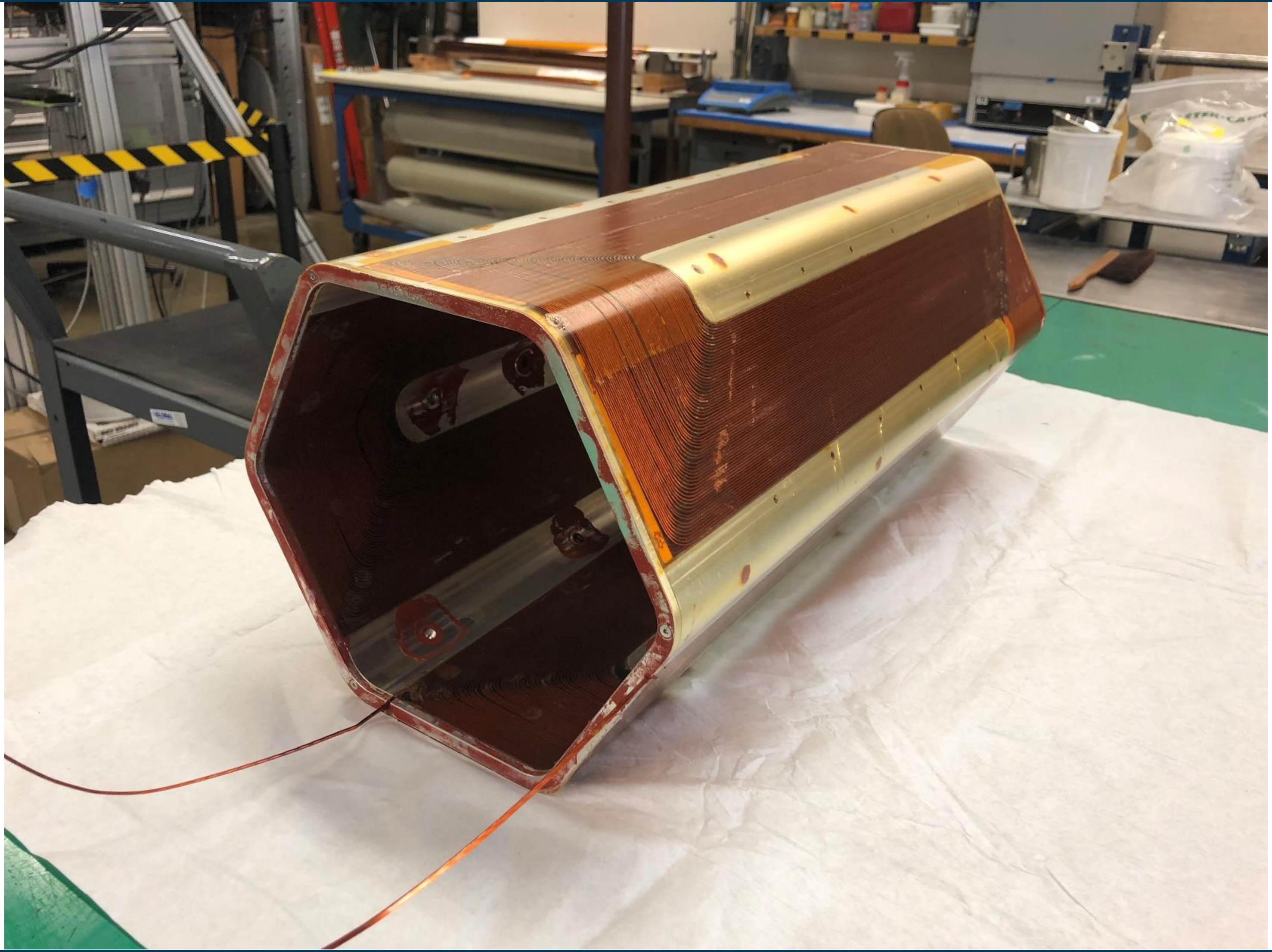
Outline

- Introduction: description and goals of the project
- MARS cold mass design
- Project status
- Annual budget
- Project deliverables and schedule

Project deliverables and schedule (within the allocated funds)

Date	Deliverable
October 2024	Completion of the winding of the sextupole coil
	Engineering design of solenoid and support structure
	Fabrication of solenoid mandrel and support structure
November 2024	Completion (impregnation) of sextupole coil
March 2025	Completion fabrication of solenoid coil

Thank you



Appendix

NSD	FY23	FY24	Total
Funds allocated	526	549	1075
Actual cost to date	508	58*	566

ATAP	FY23	FY24	Total
Funds allocated	473	450	923
Actual cost to date	160	43*	203

*As of November 1st