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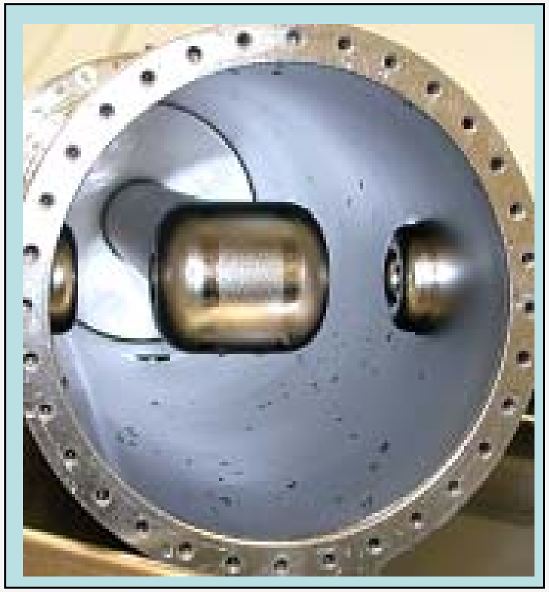

Superconducting Heavy Ion Linacs: New Machines and New Upgrades

Bob Laxdal, June 11, 2009, HIAT09

LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

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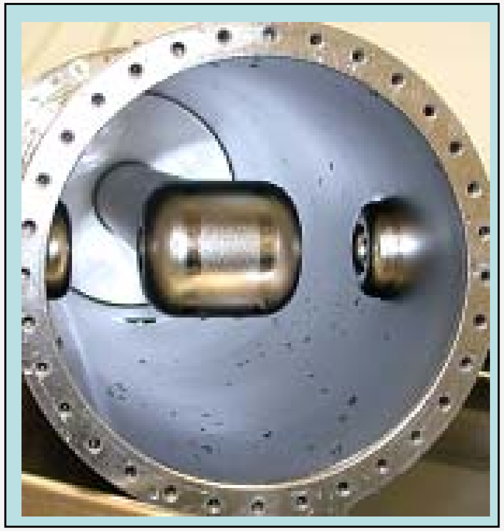
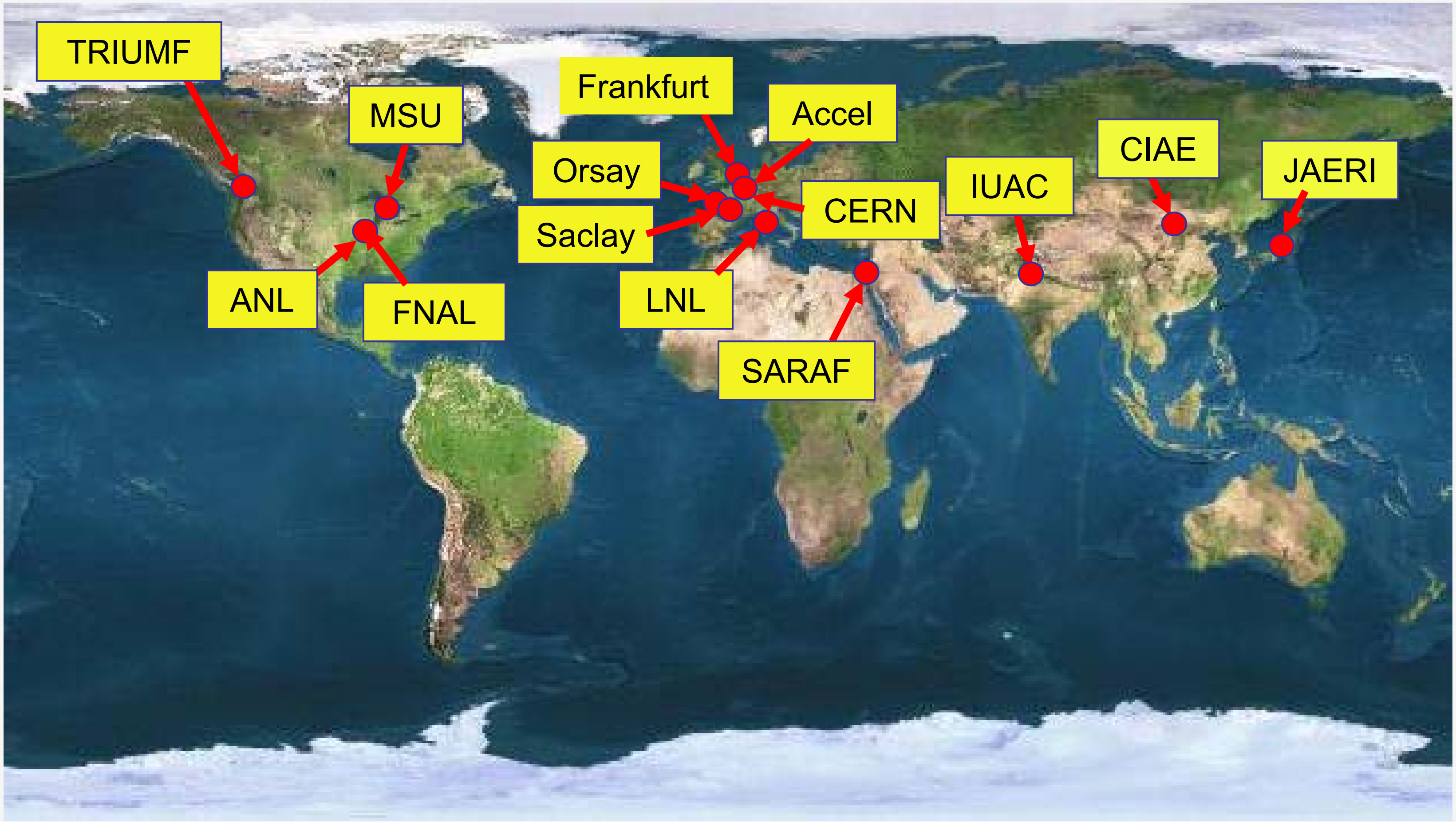
Outline

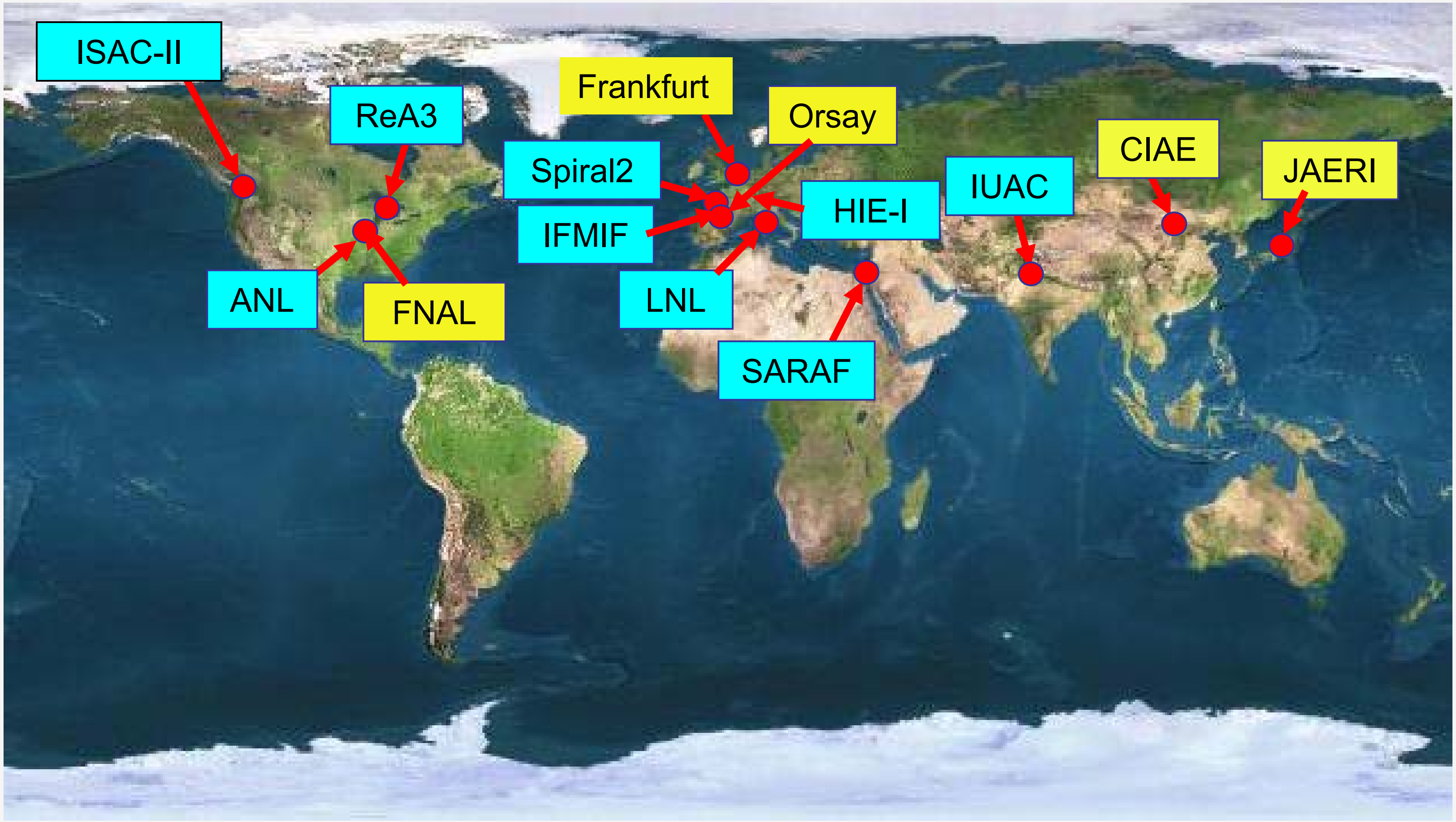
- Introduction
  - Existing facilities, conventions and technical challenges
- Upgrades
  - Argonne, Legnaro, ISAC-II
- New Projects
  - ReA3 and FRIB, SPIRAL-II, SARAF, HIE-ISOLDE, IUAC, IFMIF



Hadron SC-Linac R+D



Hadron Linac Projects



Where are we?

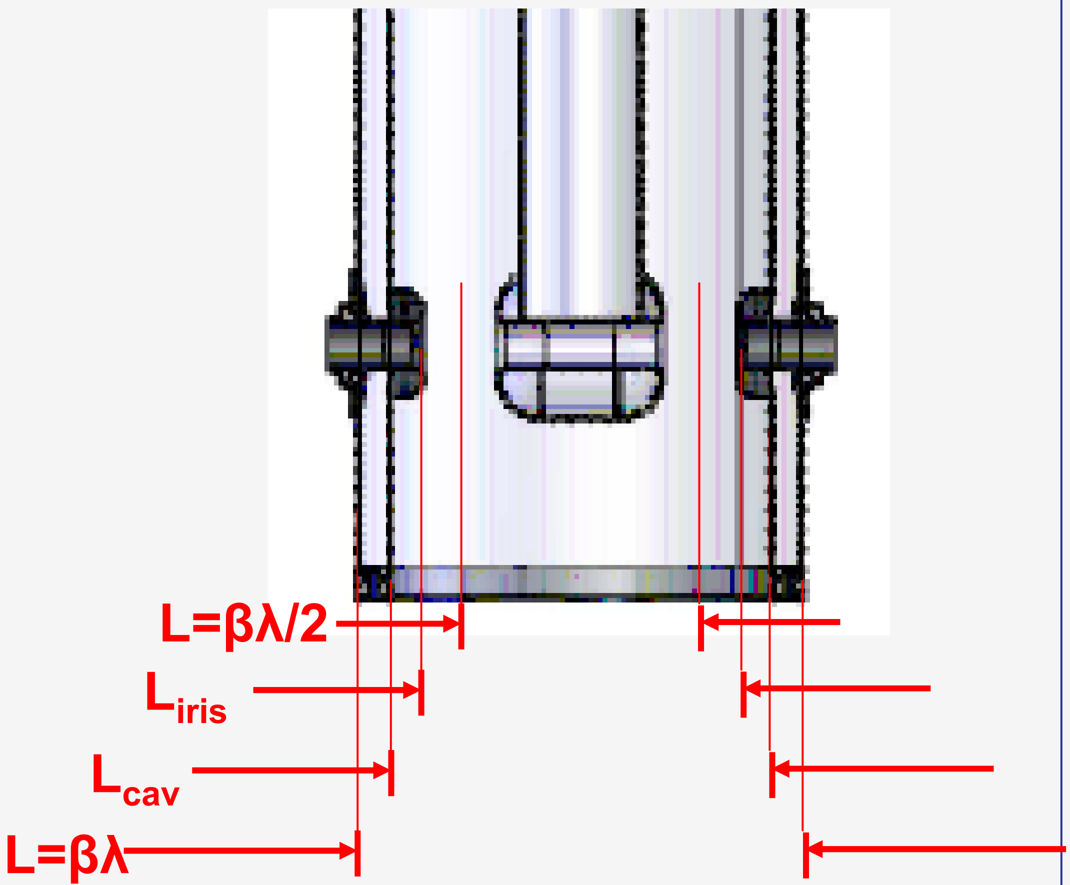
- Traditionally low beta SC resonators were quarter waves (or split rings) used as post-accelerators for heavy ion tandems serving the nuclear physics community (Atlas, INFN-LNL, JAERI)
- Increased interest in Radioactive Ion Beams (RIBs) has created a renaissance in low and medium beta SC cavity development in the last seven years for both post-accelerators and drivers (ISAC-II, SPIRAL2, FRIB)
- High duty cycle driver linacs of protons and light ions are now proposed with SC sections beginning at lower beta values (SARAF, IFMIF)
  - Rise in performance (and relevance) of multi-gap spoke cavities and half-wave resonators (HWR) in the mid-beta regime

General Comments

- Why superconducting?
  - Superconducting allows
    - cw and high duty cycle operation
    - Larger apertures, lower frequencies for increased acceptance
- Applications
  - Drivers – conservative gradient required
    - longer machines typically – large velocity swing – several cavity regimes
      - Treat as almost fixed gradient machine
    - Beam loss (halo) an issue; careful beam dynamics required
    - Beam loading dominates rf power
  - Post-accelerators
    - Shorter machines typically – broad velocity acceptance
    - Utilize maximum gradient to improve performance and/or reduce cost – operate each cavity at fixed power
    - short independently phased cavities give flexibility to beam delivery
    - Beam loading not an issue typically

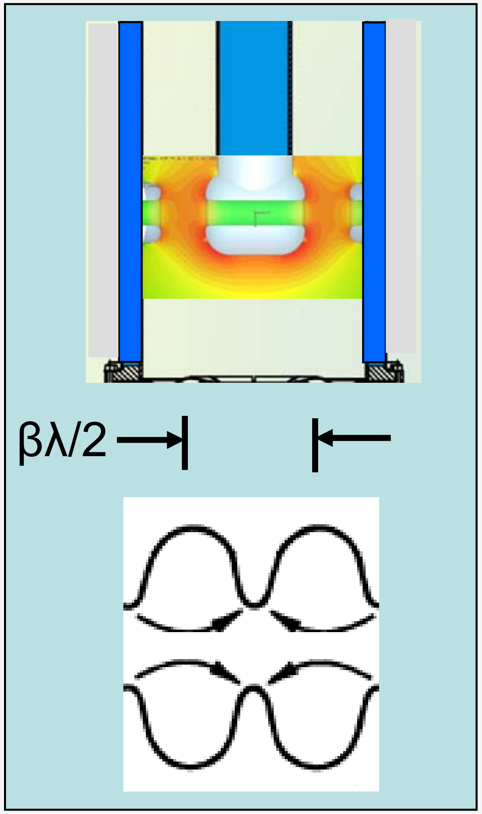
Cavity Gradient - Definition

- Beware: No well accepted definition of cavity length
  - E_a's dependent on definition of cavity length
    - $E_a = V_{eff}/L$
  - ISAC-II beta=0.07 cavity
    - E_a=13, 9, 7 or 6.4MV/m depending on $L=\beta\lambda/2$, L_{iris}, L_{cav} or $L=\beta\lambda$ definition but V_{eff}=1.3MV for all
- E_p and H_p give a meaningful physical measure of cavity performance
  - ISAC-II operation; E_p=35MV/m and H_p=70mT



Low beta (0.1) vs High beta (1) performance: How are we doing?

- E_{peak} at design P_{cav} gives a physical parameter that can be useful in comparing cavity performance
  - Typically E_{peak}/E_a=4-5 for low beta QWR's while E_{peak}/E_a~2 for elliptical cavities.)
- For CW machines performance limited by LHe consumption - P_{cav} (Q at operating point) and not maximum achievable gradient (Cornell ERL Ea~15-20MV/m for elliptical cavities or Ep~30-40MV/m)
- TRIUMF's ISAC-II linac QWR's now operate cw with Ep~35MV/m (Ea~7MV/m)



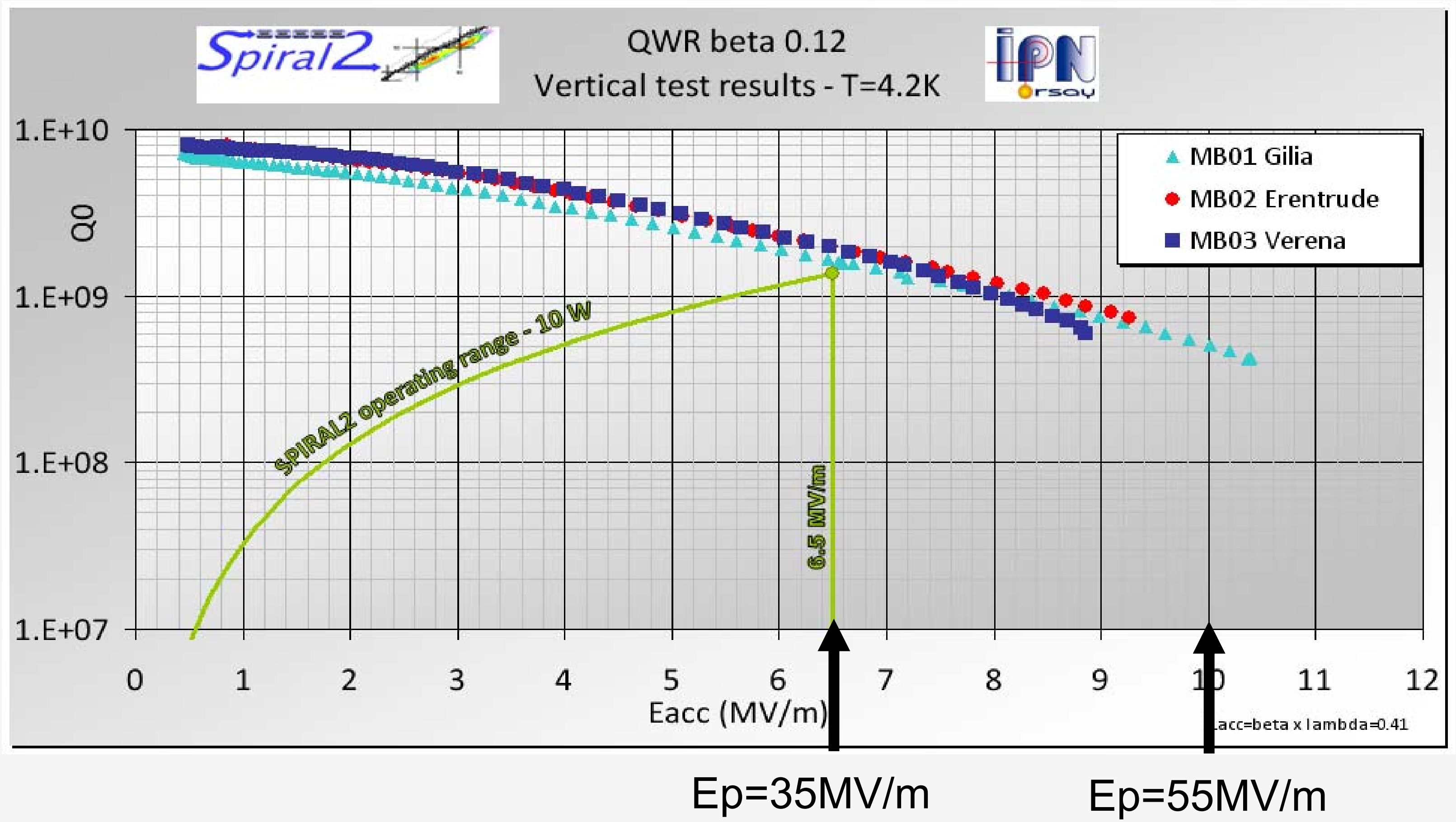
Upgrades, Projects and Proposals for Ions

Project	Lab	Driver	Post-accelerator	Particle	Structure
ISAC-II	TRIUMF		√	HI	QWR
Upgrade	ANL		√	HI	QWR
Upgrade, SPES	LNL		√	HI	QWR
SPIRAL-II	GANIL	√		P, d, HI	QWR
SARAF	SOREQ	√		P, d	HWR
IUAC			√	HI	QWR
ReA3	MSU		√	HI	QWR
FRIB	MSU	√	√	HI/HI	QWR, HWR
HIE-REX	CERN		√	HI	QWR (sputter)
IFMIF		√		d	HWR
EURISOL		√	√	P, d / HI	QWR, HWR, Spoke

Challenges

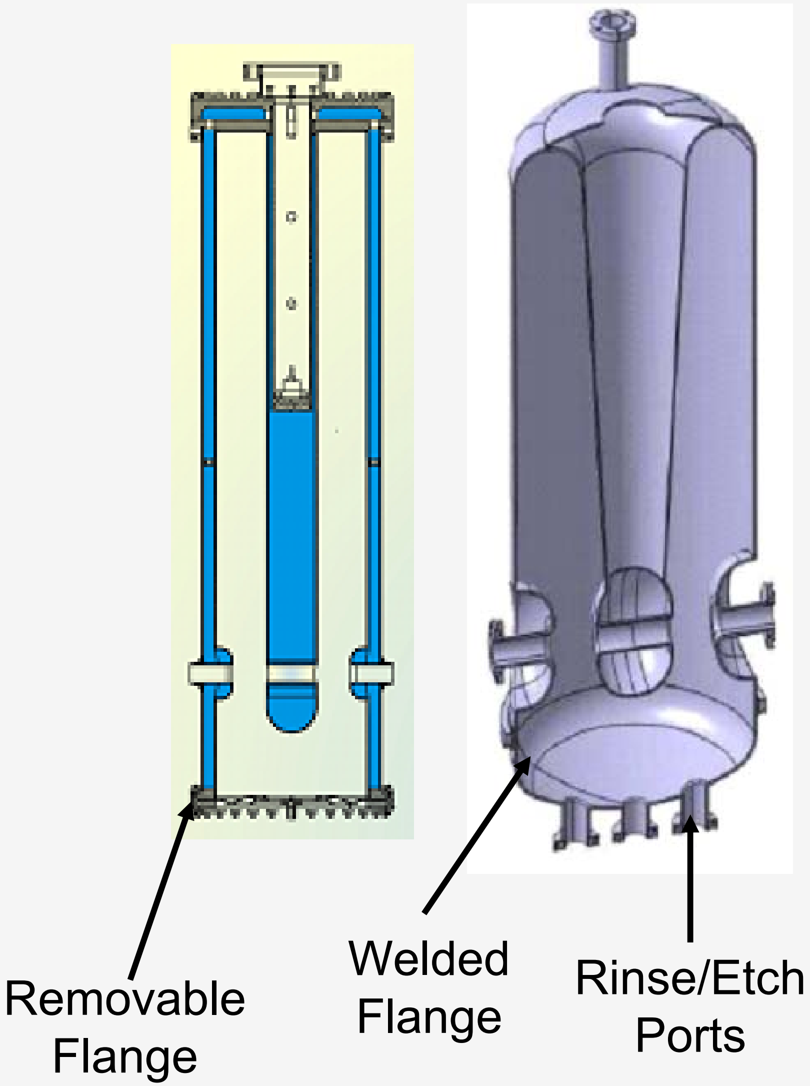
Challenges1 – High Qo

- High duty cycle application is typical
  - High Q_o rather than high E_{peak} is important



Challenges 2 – Cavity Shape

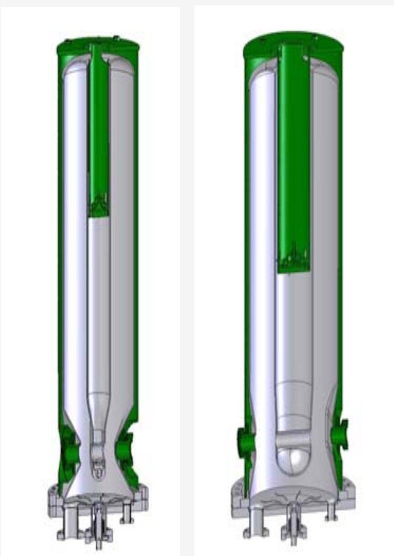
- Optimizing cavity shape – a trade-off
  - Minimize Ep and Hp
    - Leads to formed shapes
  - Allow for rinsing and post-weld etching
    - removable end plates vs welding shut geometry with access ports
  - Allow for cavity tuning
  - Maintain good mechanical stability
    - Minimize sensitivity to helium pressure fluctuations and Lorentz force detuning
      - Reinforcing struts
    - Passively or actively damp microphonics
      - Mechanical dampers
      - Piezo tuners



Example - Quarter waves

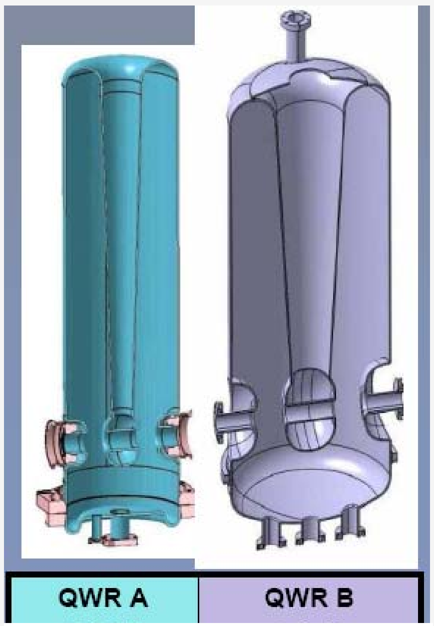
- Many quarter wave prototypes have been built and tested world-wide over the last 15 years

MSU

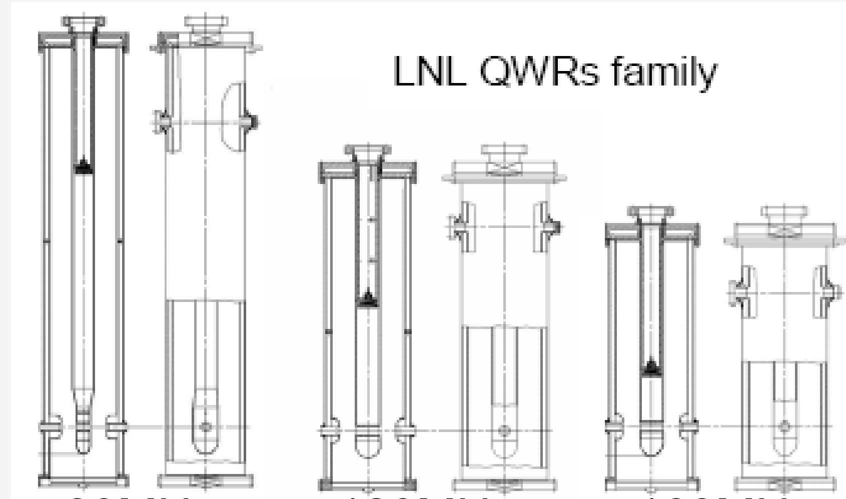


80.5MHz
4.1%, 8.5%

SPIRAL-2



88MHz
7%, 12%

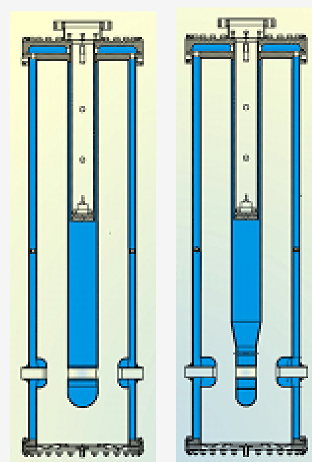


80MHz
4.7%

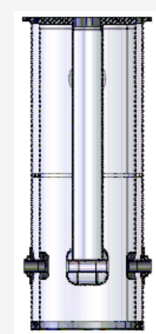
120MHz
8%

160MHz
11%

ISAC-II



106MHz
7%, 5.7%



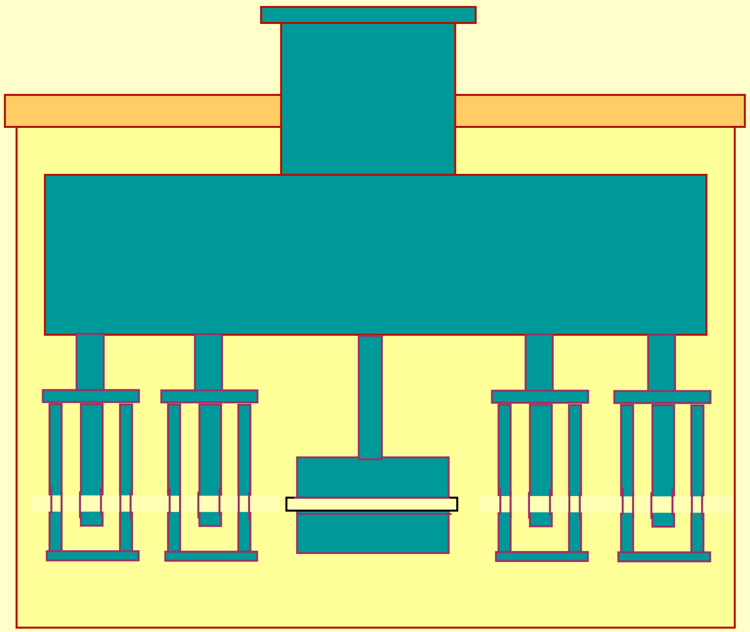
141MHz
12%

ANL

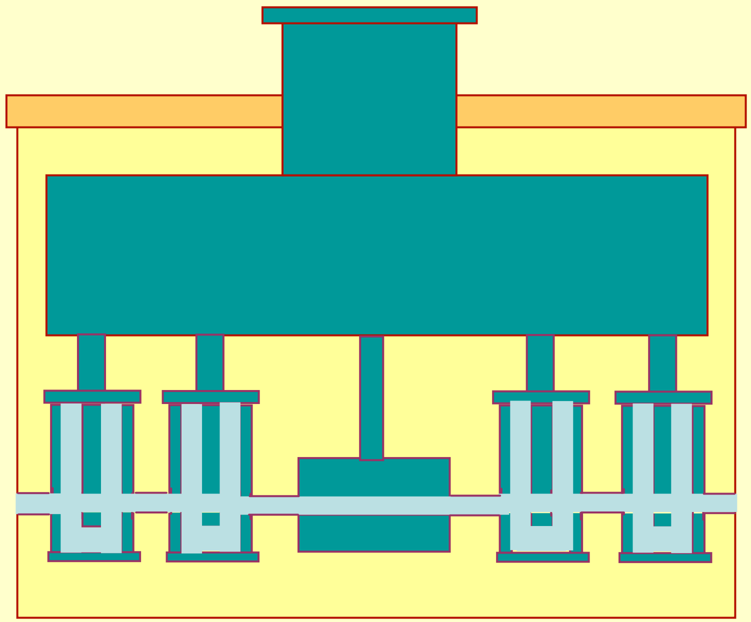
109MHz
14.4%

Challenge 3: Single Vacuum vs Double Vacuum

- Cavity vacuum and thermal isolation vacuum share the same space
- Engineering easier but thermal vacuum must be done carefully (particulate control)
- ISAC-II, ATLAS, Legnaro, JAERI

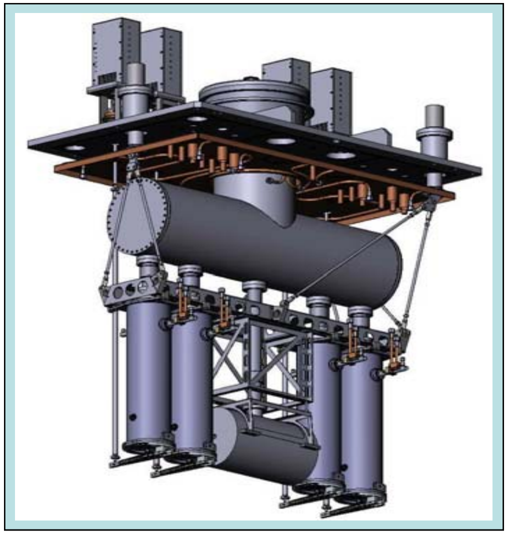


- Cavity vacuum connected through beam pipe and isolated from thermal vacuum
- Engineering more complex but eases cleanliness requirements in thermal vacuum space
- ANL upgrade, SPIRAL-II, SARAF, ReA3



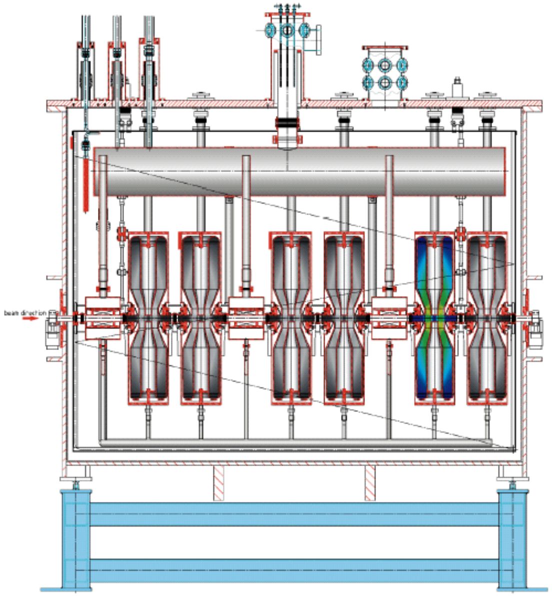
ISAC-II tests – common vacuum- TRIUMF

- Average peak surface field in vertical tests was 38MV/m at 7W
- Average peak surface field in on-line tests (with beam) was 35MV/m at 7W
- Little reduction in performance over the first three years of operation



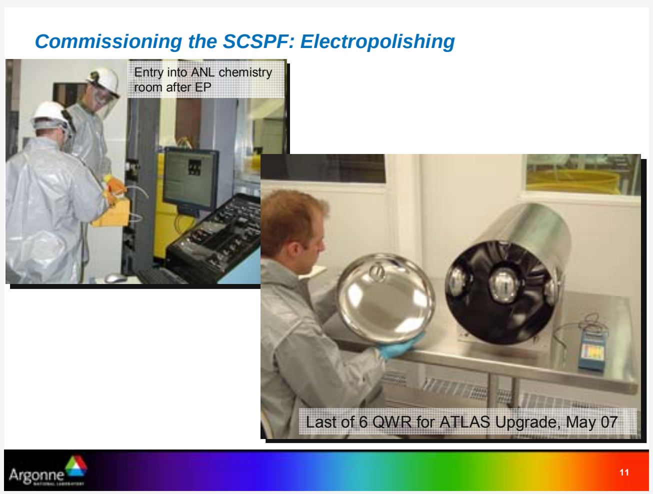
PS1 tests separate vacuum - SARAF

	Vertical Test		Horizontal test	
Cavity	Pcav@25MV/m	Q	Pcav@25MV/m	Q
HWR1	7.3	6e8	5.7	7e8
HWR2	7.3	6e8	9.3	5e8
HWR3	6.3	7e8	16	3e8
HWR4	6.3	7e8	11.2	4e8
HWR5	5.5	8e8	8.7	5e8
HWR6	7.3	6e8	10.9	4e8



Challenges 4 – Surface finish

- Typical etching treatment is Buffered Chemical Polish
  - High duty cycle operation precludes operating at surface fields where EP has an advantage
  - Geometries are not conducive to EP
- Argonne and IUAC Electropolish parts before final weld with a light 5-10mic BCP to treat the weld



Challenge 5 - Technology

- Most projects choose bulk niobium as the technology for cavity fabrication
    - Fabrication of complicated shapes relatively straightforward
    - Technical performance superior – better Q
- Some projects have opted for sputtered niobium on copper
    - INFN-LNL replated ALPI cavities originally lead plated and achieved significant performance gains
    - CERN – REX ISOLDE is choosing to resurrect LEP sputtering expertise to sputter quarter waves for ion acceleration
        - copper substrate less sensitive to helium pressure fluctuations makes tuning less demanding
    - CIAE Beijing – booster linac with QWR

Sputtering chamber

Challenge 6: RF Ancillaries

- Want to supply sufficient rf bandwidth to maintain lock; over coupling, VCX tuner
  - Reduce required bandwidth and required power by
    - controlling microphonics passively
    - Specifying a tuner sufficient to compensate for environmental de-tuning effects like helium pressure and vibrations
- Power coupler must be sized to accommodate expected rf beam loading and forward power with acceptable heat load to helium
- Tuners
  - many designs, very little commonality, from actuating a tuning plate, to squeezing at the beam ports to introducing a plunger into the high magnetic field
- Power couplers
  - Variable vs fixed, capacitive vs inductive, LN2 cooled or helium, many designs

Operating CW heavy ion SC-linacs with Nb technology

- ATLAS at Argonne
  - Bulk niobium – Ep~15-20MV/m
- INFN-Legnaro
  - Sputtered Nb on Cu (former Pb) - Ep~22MV/m
  - Bulk niobium cavities
- JAERI
  - Explosively bonded Nb on Cu – Ep~25MV/m
- ISAC-II
  - Bulk niobium cavities – Ep=~35MV/m

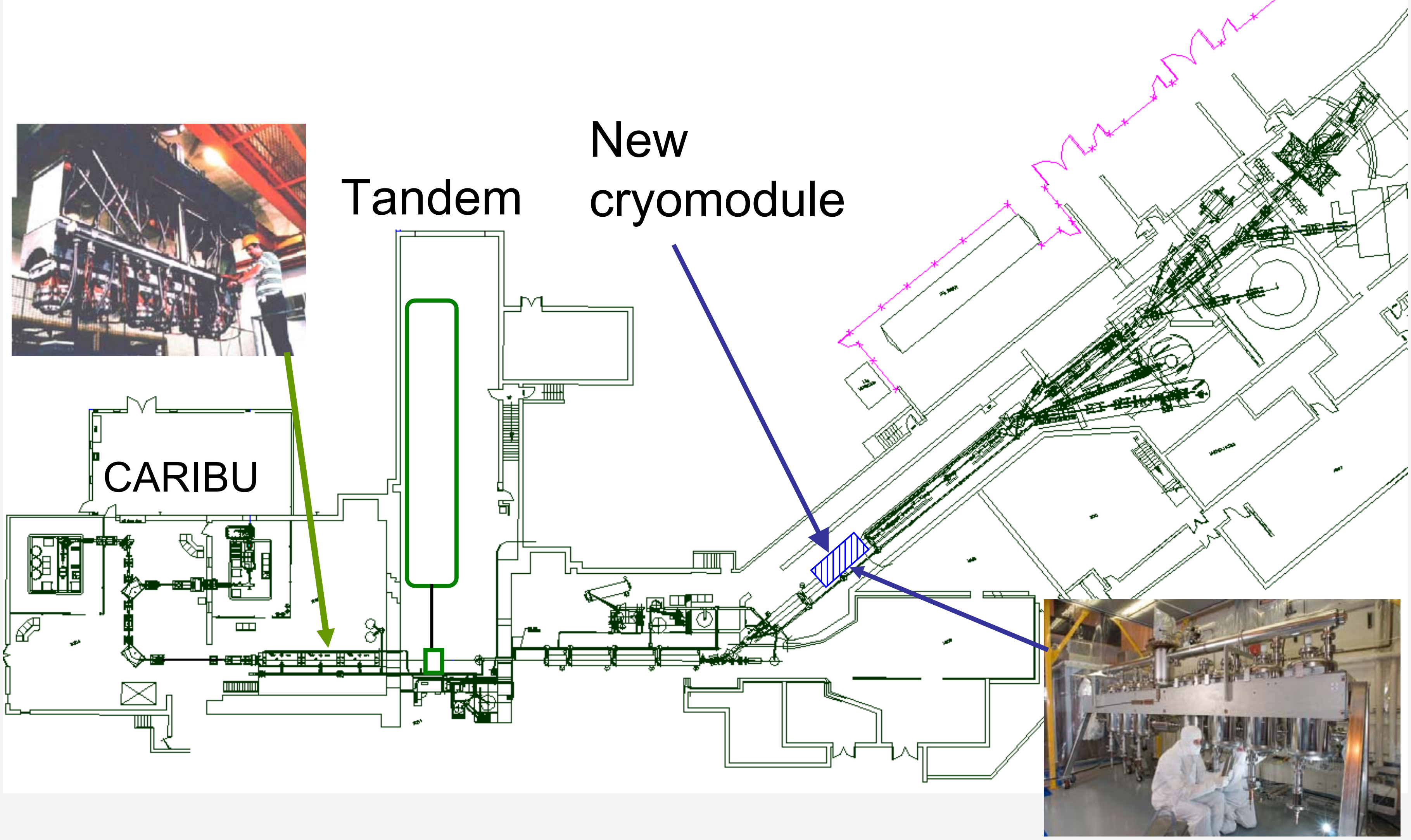
Upgrades

- ATLAS-ANL
- INFN-LNL
- ISAC-II-TRIUMF

ATLAS

- Energy and intensity upgrades forseen in a staged way
  – Install energy upgrade cryomodule – imminent
  – Replace PII (Positive Ion Injector) with RFQ, MEBT and New cryomodule – three years
  – Strategic additions to ATLAS as funding allows
- Proposal for ISOL/applied driver linac

ATLAS Layout, June 2009

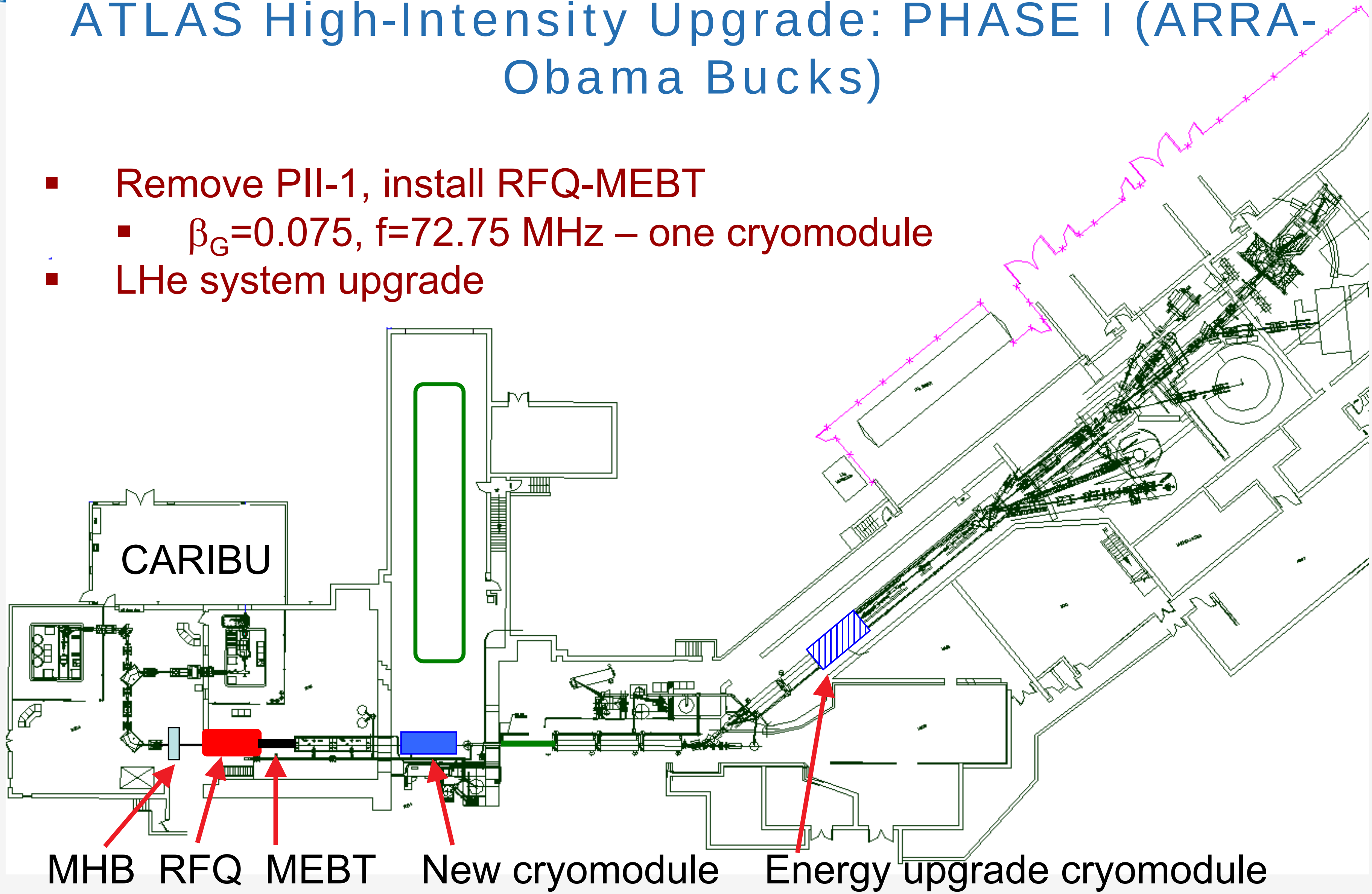


ATLAS Energy Upgrade Cryomodule

- **separate vacuum system – first on-line module**
    - cavity string and couplers assembled and sealed in the clean room
- **seven β=0.15 109 MHz quarter-wave cavities**
- **installation expected in June ’09**
- **Goal is >2 MV/cavity (15 MV total with the seven installed cavities in a 4.65 meter module)**

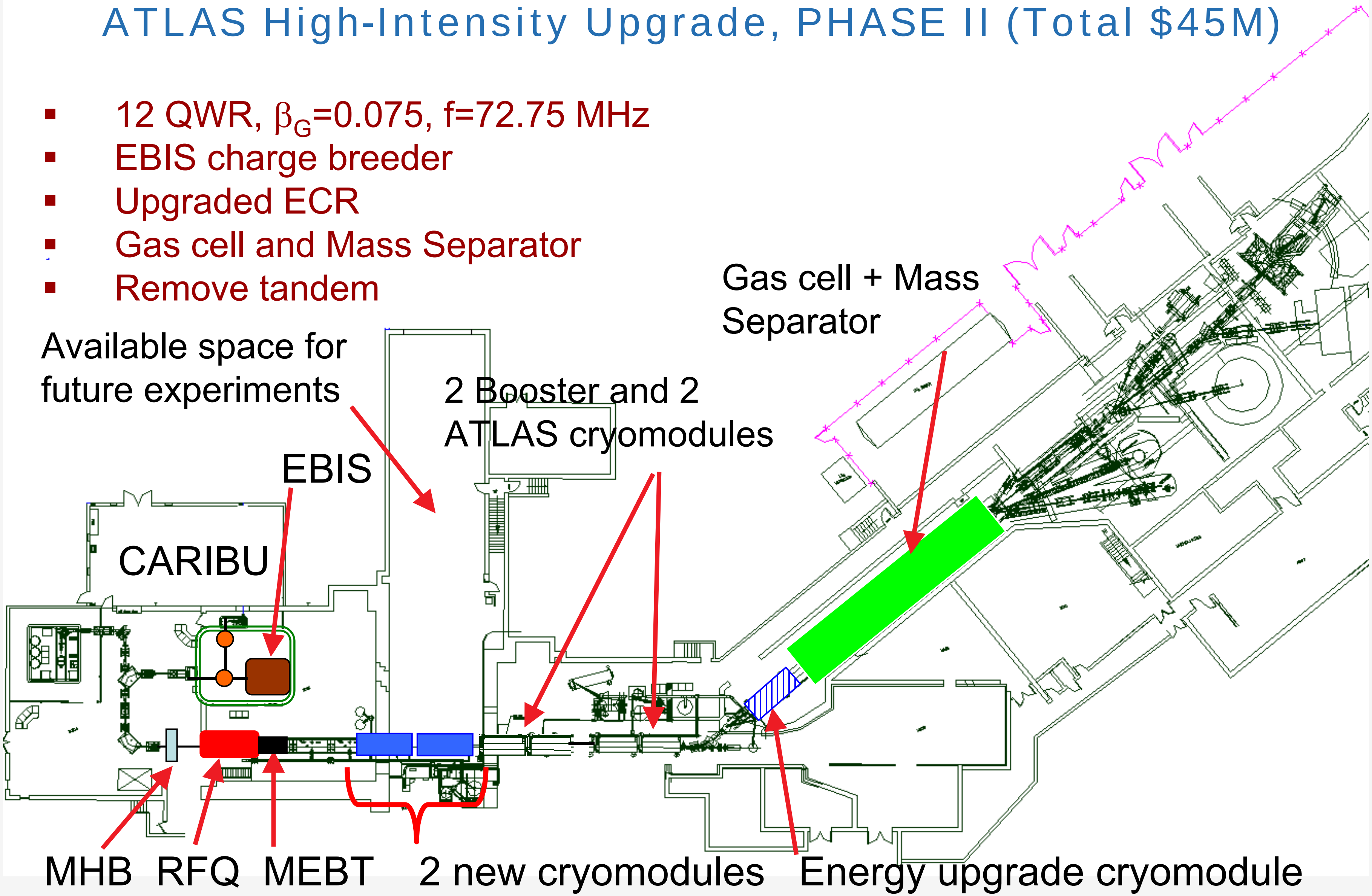
ATLAS High-Intensity Upgrade: PHASE I (ARRA-Obama Bucks)

- Remove PII-1, install RFQ-MEBT
  - β_G=0.075, f=72.75 MHz – one cryomodule
- LHe system upgrade



ATLAS High-Intensity Upgrade, PHASE II (Total $45M)

- 12 QWR, β_G=0.075, f=72.75 MHz
- EBIS charge breeder
- Upgraded ECR
- Gas cell and Mass Separator
- Remove tandem

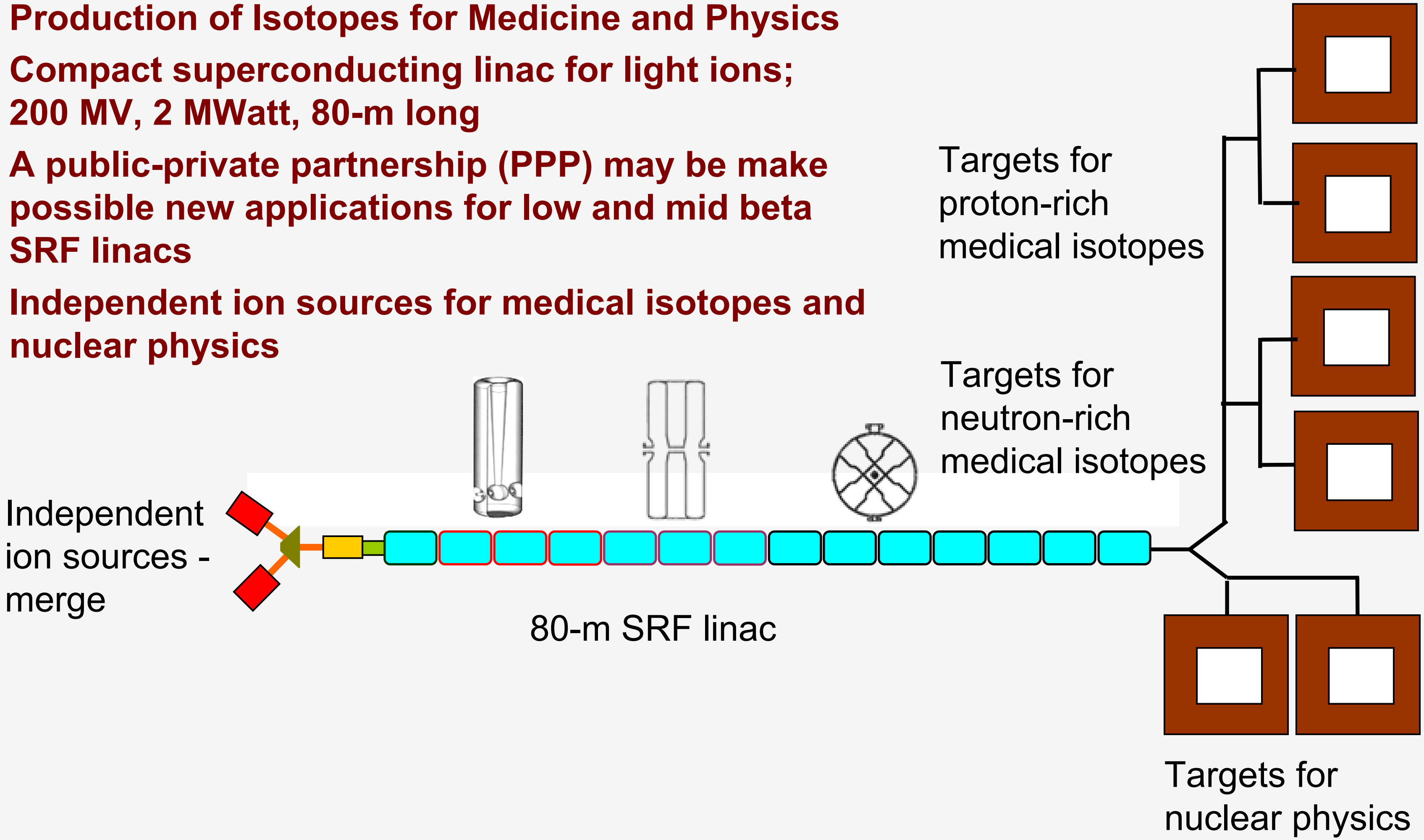


Summary of upgraded ATLAS ion beams and future activities (beam energies are given for 1/7≤Q/A≤1/3)

	PHASE I	PHASE II
Energies of high intensity beams (~10 pμA)	3-5 MeV/u	4-8 MeV/u
Energies of low intensity beams (~1 pμA)	9-23 MeV/u	10-25 MeV/u
Transmission efficiency of CARIBU beams	80%	80%
Major upgrades	1) Replace PII-1 with CW RFQ 2) Build one new cryomodule of beta=0.075 QWR 3) Improve LHe distribution system	1) Upgraded ECR for stable beams, higher intensities 2) EBIS charge breeder 3) One more cryomodule of beta=0.075 QWR 4) Relocated SRF, upgrade of ATLAS sub-systems 5) New experimental equipment

Applications: ANL Proposal for Medical Application and ISOL Production

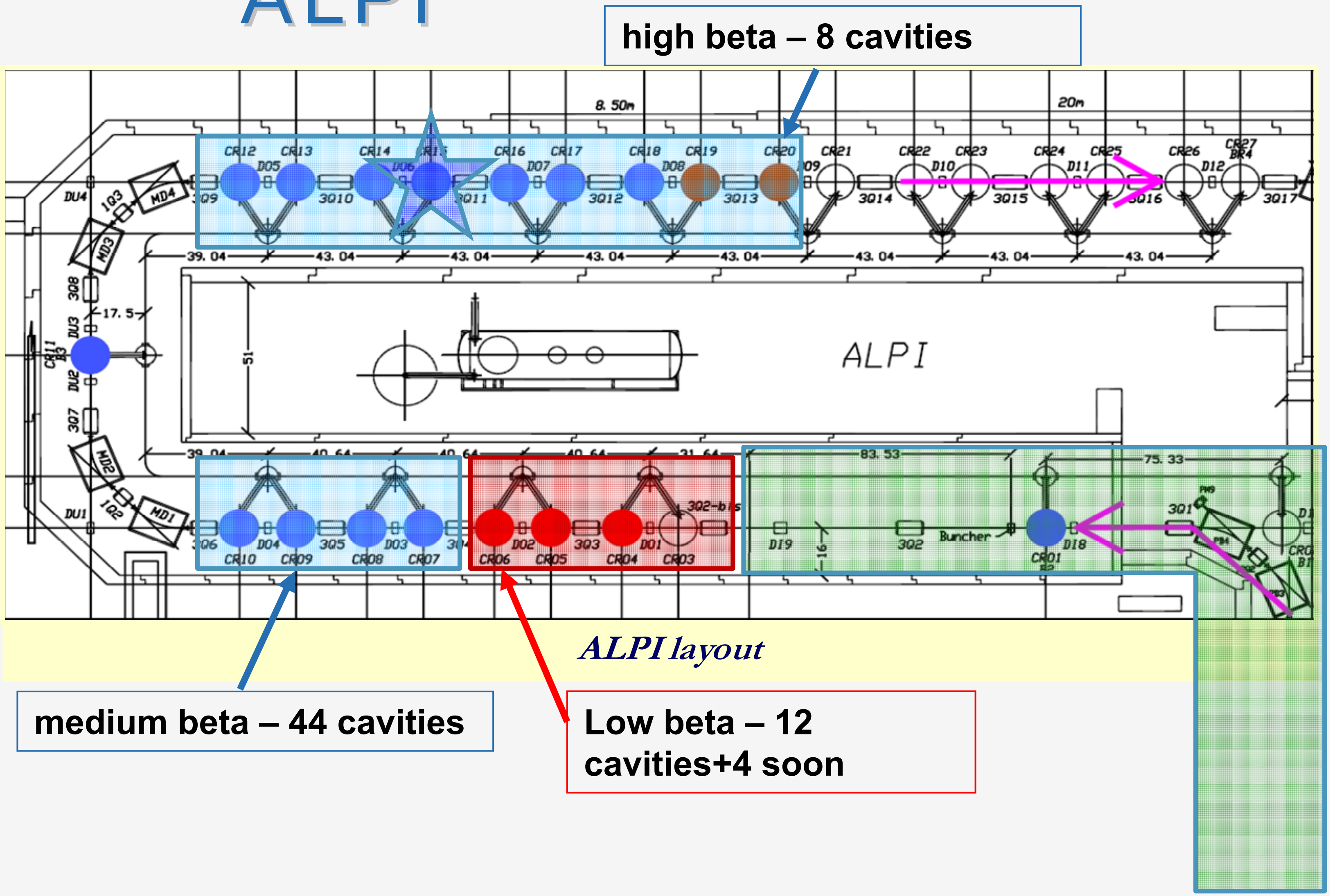
- **Production of Isotopes for Medicine and Physics**
- **Compact superconducting linac for light ions; 200 MV, 2 MWatt, 80-m long**
- **A public-private partnership (PPP) may be make possible new applications for low and mid beta SRF linacs**
- **Independent ion sources for medical isotopes and nuclear physics**



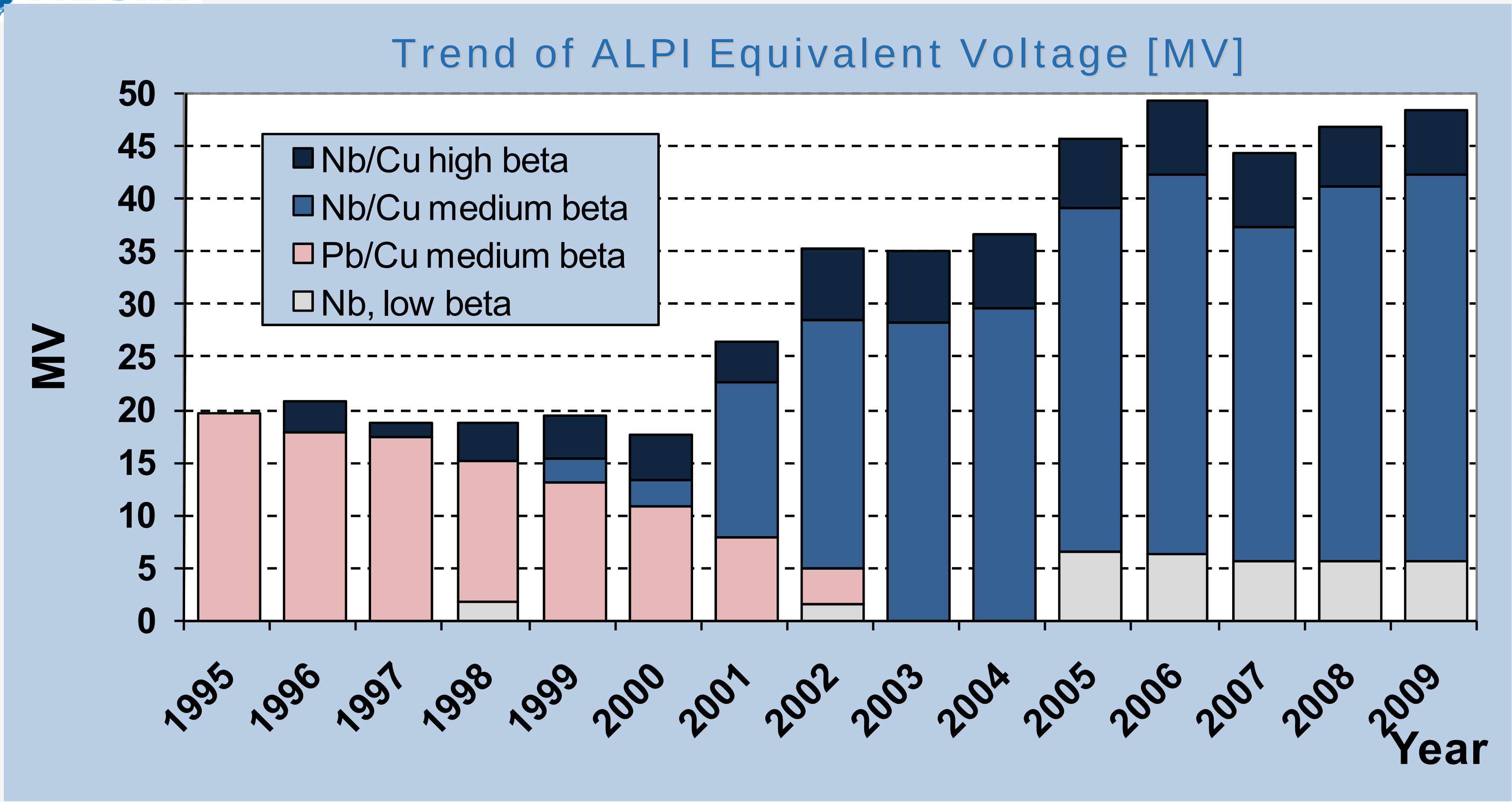
INFN - Legnaro

- Intensity and Energy upgrade plans completed or in progress
  - Replacement of Pb/Cu with Nb/Cu technology - complete
    - new Cu substrate developed for higher gradients – in progress
  - Adding new higher charge state ECR on PIAVE – LEGIS - commissioning
  - Upgrade low beta section for high gradient operation –in progress
  - Refurbish cavities and sub-systems that are not operational – ongoing
  - SPES – future motivation for higher transmission, energy and reliability

ALPI



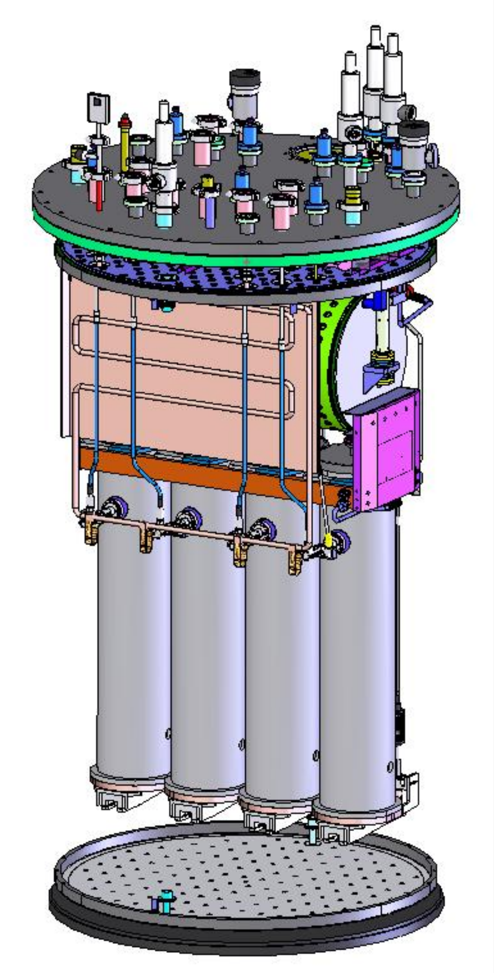
high beta – 8 cavities
medium beta – 44 cavities
Low beta – 12 cavities+4 soon
ALPI
ALPI layout
Buncher



- Medium beta cryostats recovered
- Lower beta cryostats: operational field raised from Ep=15 to 17.5MV/m
- CR03 being completed, CR04-CR05-CR06 to be maintained and upgraded

Low beta - upgrade for Ep=27.5 MV/m operation

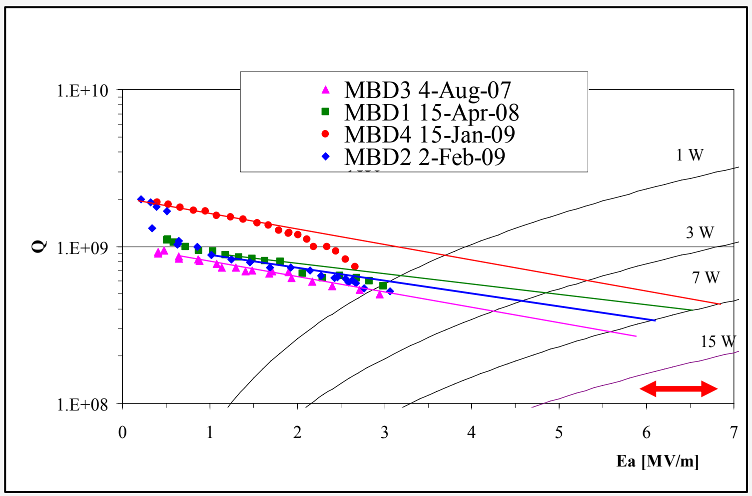
- CR03 will be tested within mid-2009, with routine operation to follow
- If CR03 is successful, all components for upgrade of CR04, CR05 and CR06 will follow
  - Cryostats can be replaced, one by one, starting in 2010, in parallel with regular operation



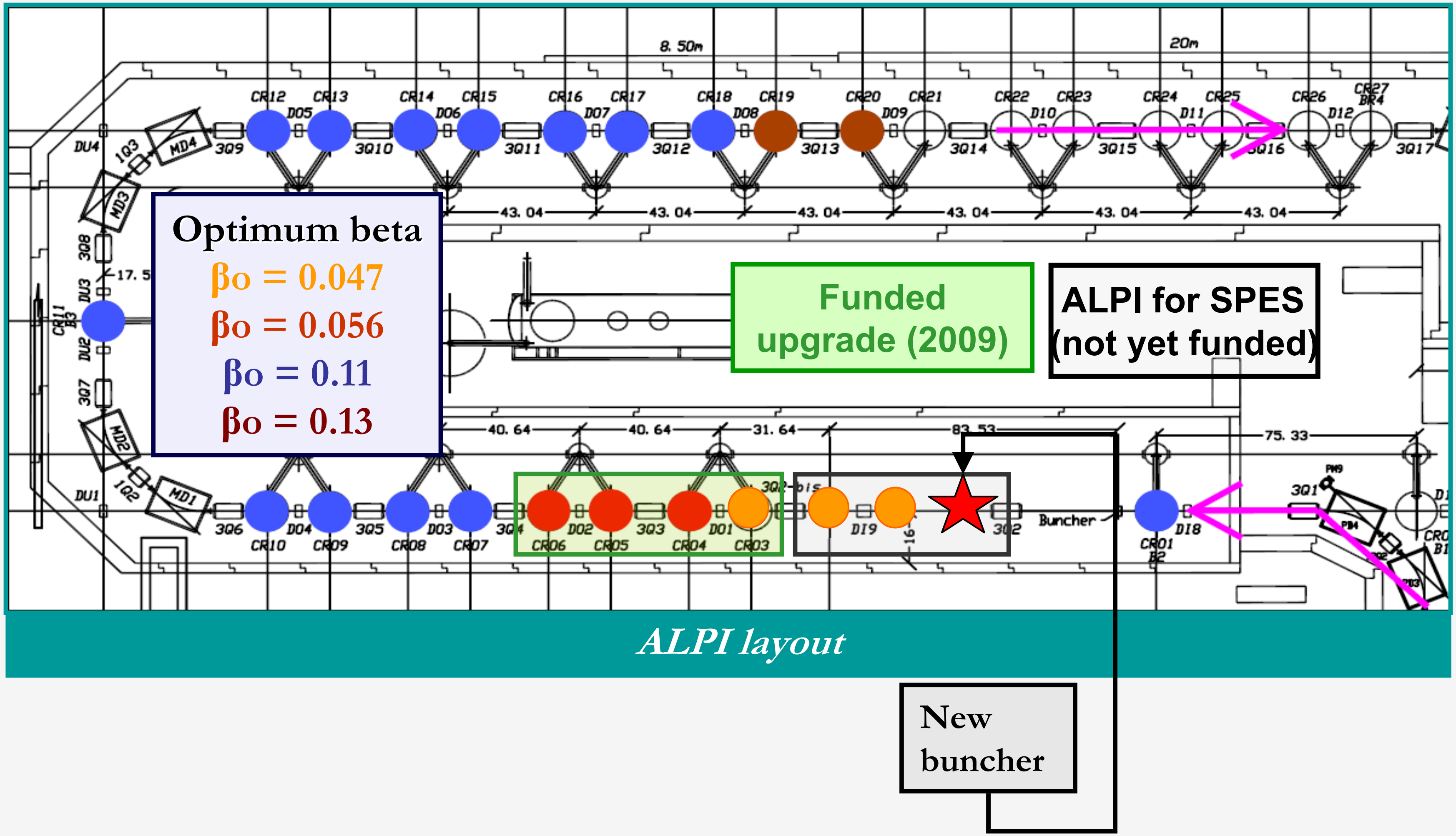
A. Facco

Medium beta - Further Upgrade

- New fabrication procedure of copper substrate for enhanced sputtering performance
- Four cavities were produced
  - Vertical tests shown below – tests limited to Ep=15MV/m by radiation safety – expect Ep=30MV/m @7W performance
  - Cavities are ready for installation in CR15

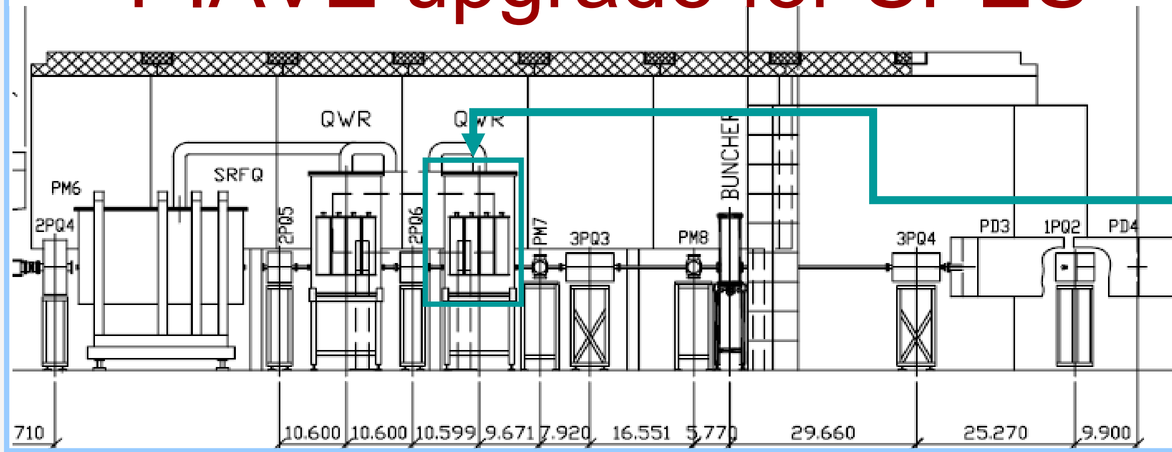


ALPI upgrade for SPES

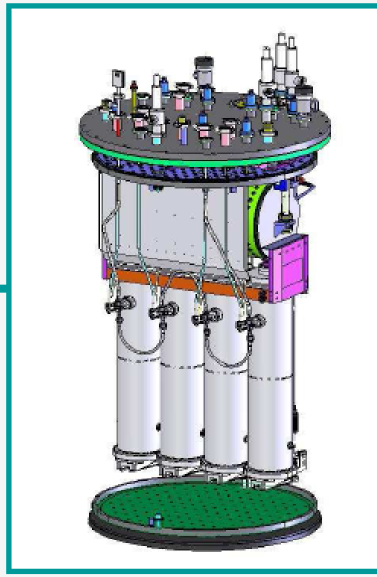


ALPI layout

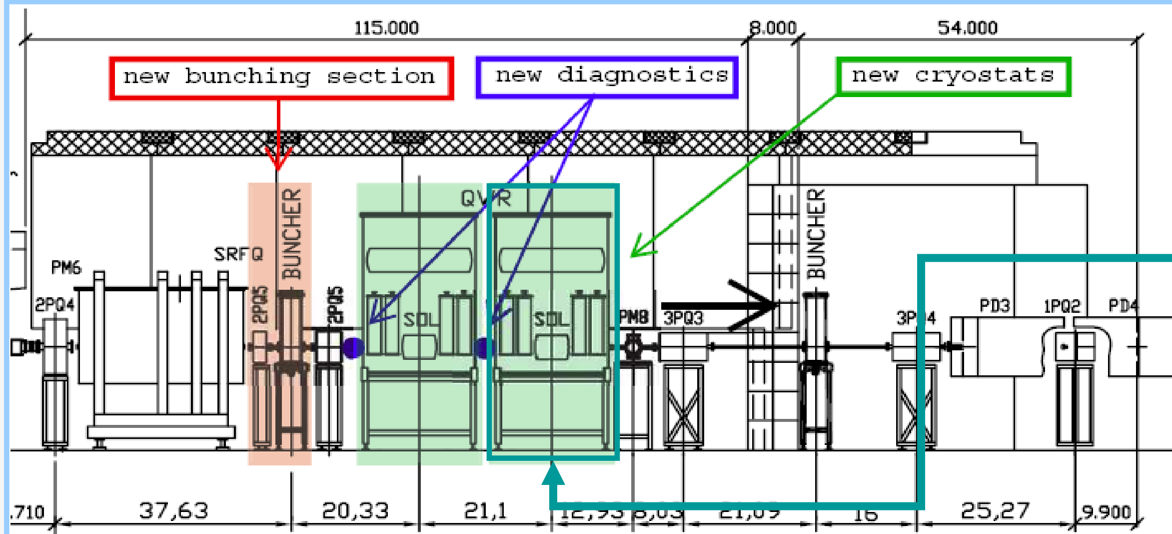
PIAVE upgrade for SPES



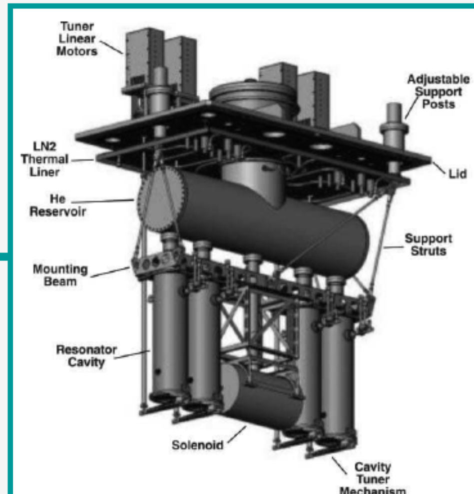
Present layout



PIAVE cryostat

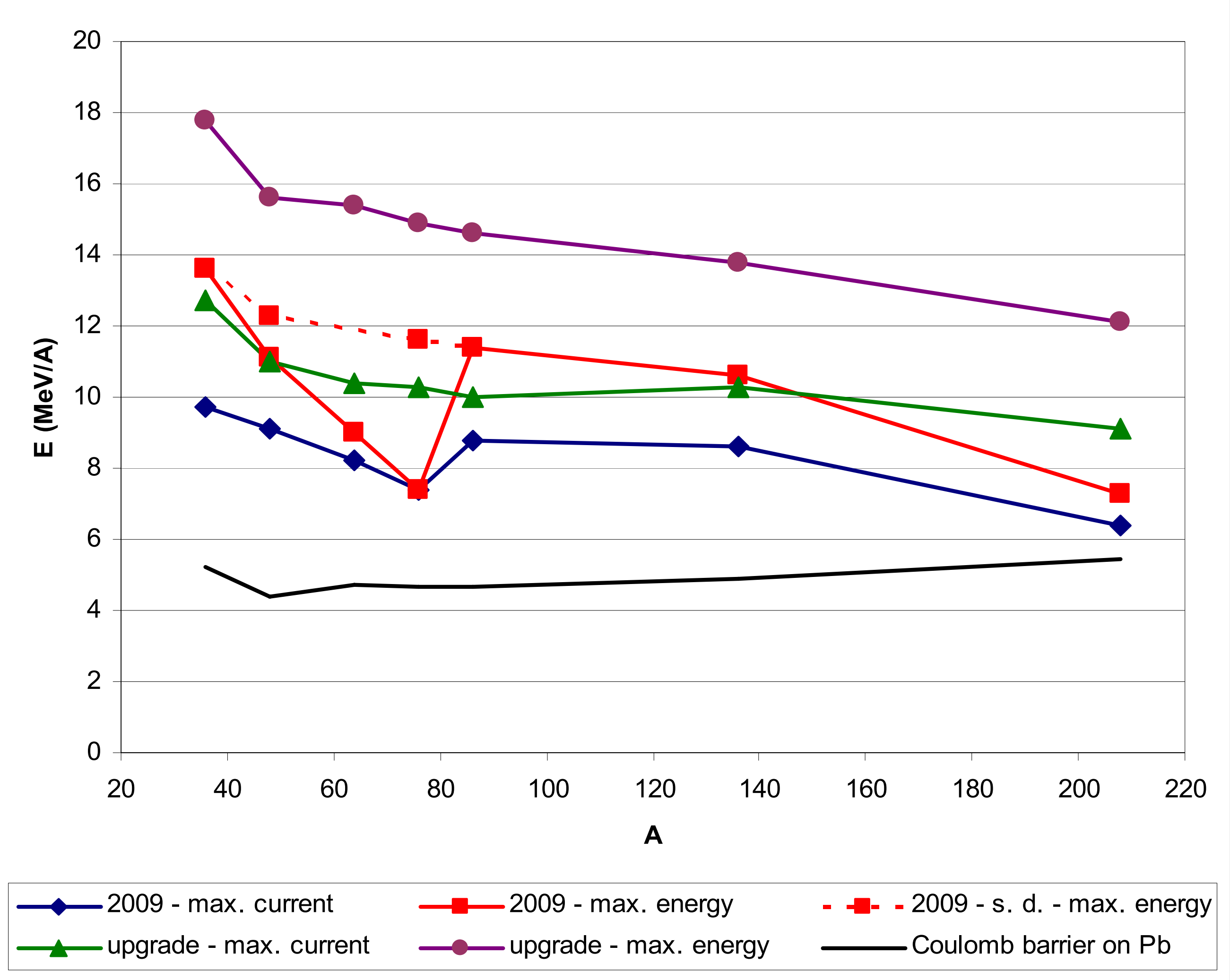


SPES layout



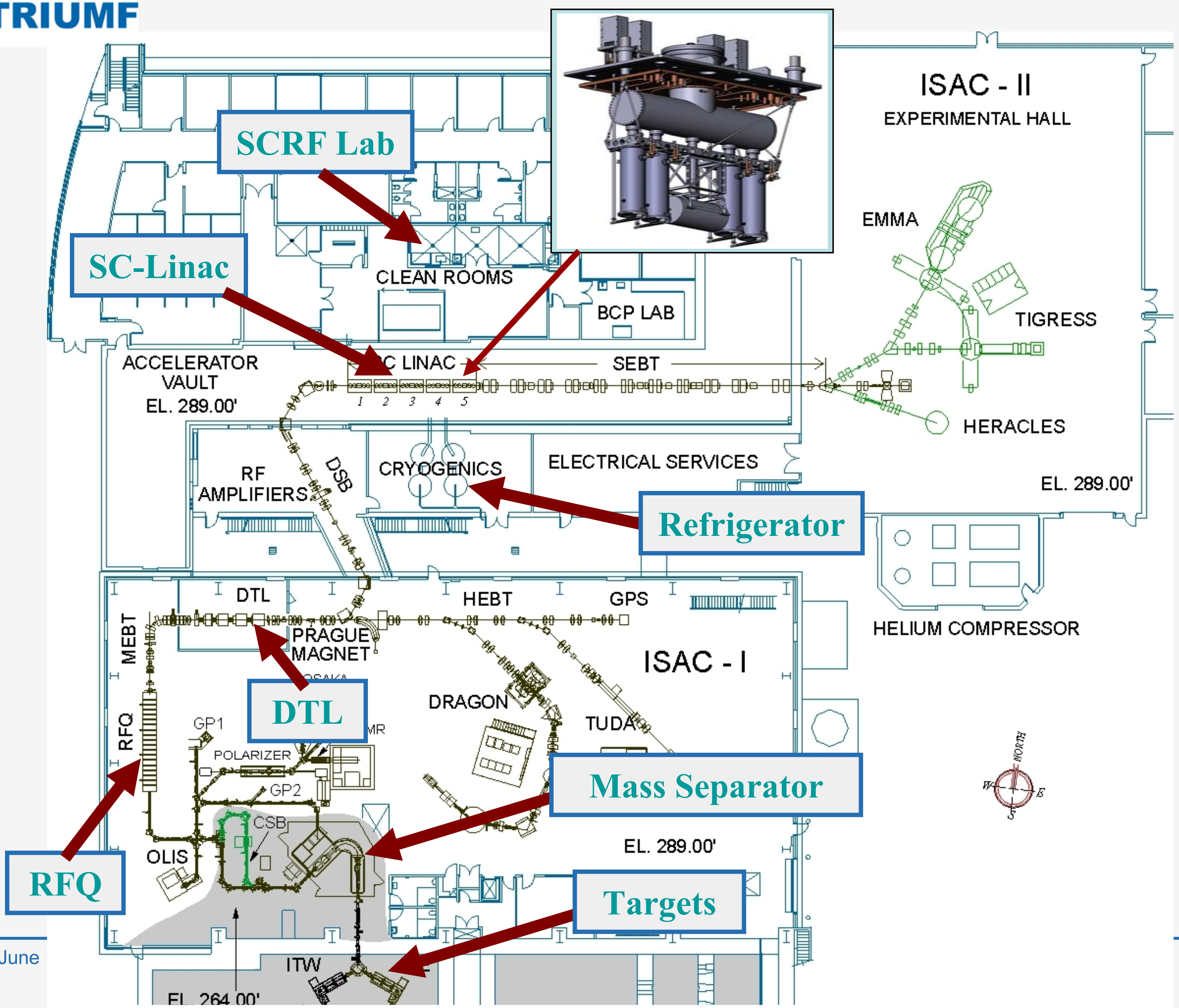
ISACII-like cryostats

Final performance for stable beams: 2010 and SPES scenarios



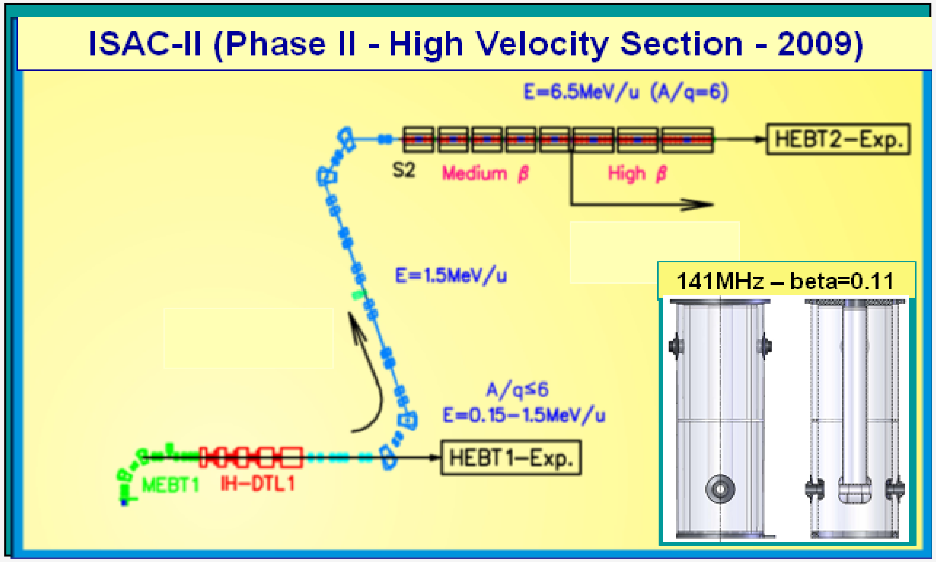
TRIUMF - ISAC-II - ARIEL

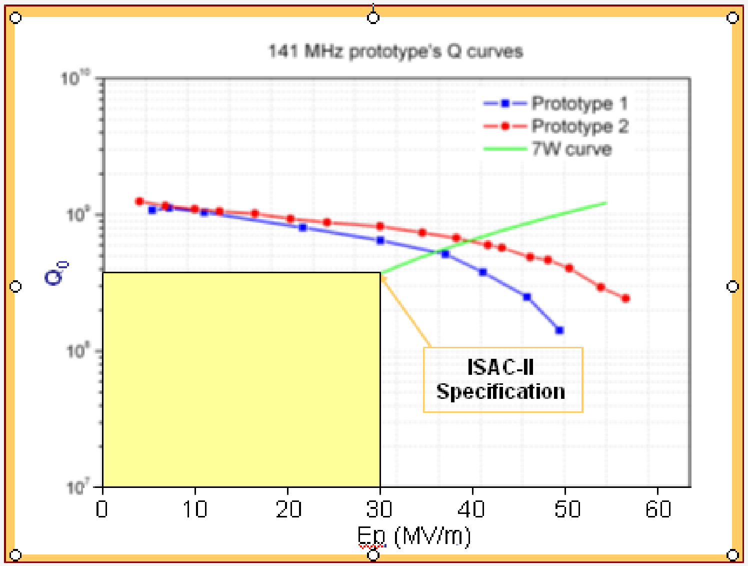
- ISAC-II Phase II
  - consists of the addition of a further 20MV by the end of 2009
  - Add 20 QWR's at beta=0.11
- ARIEL
  - Add a second RIB driver (50MeV e-Linac), new target station and low energy front end by 2013
  - Add EBIT charge breeder 2014


SCRF Lab
SC-Linac
Refrigerator
DTL
RFQ
Mass Separator
Targets
ISAC - II
EXPERIMENTAL HALL
EMMA
TIGRESS
HERACLES
CLEAN ROOMS
BCP LAB
ACCELERATOR
VAULT
EL. 289.00'
SEBT
1 2 3 4 5
RF
AMPLIFIERS
DSB
CRYOGENICS
ELECTRICAL SERVICES
EL. 289.00'
HELIUM COMPRESSOR
DTL
HEBT
GPS
MEBT
PRAGUE
MAGNET
ISAC - I
DRAGON
TUDA
GP1
POLARIZER
GP2
CSB
OLIS
EL. 289.00'
ITW
EL. 264.00'
NORTH

ISAC-II Phase II Linac

- ISAC-II Phase II consists of the addition 20 cavities in three cryomodules to be installed in 2009
- Status
  - **Two prototype cavities tested**
  - **Ten production cavities delivered from local vendor**
  - **First cryomodule cold test June 2009**
  - **Linac installation begins Sept. 2009**

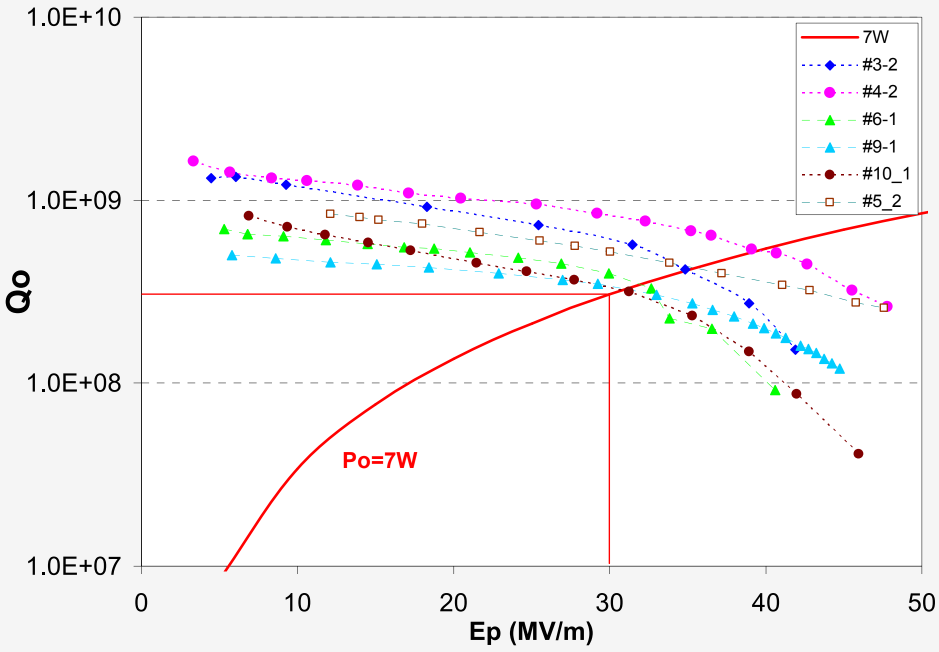


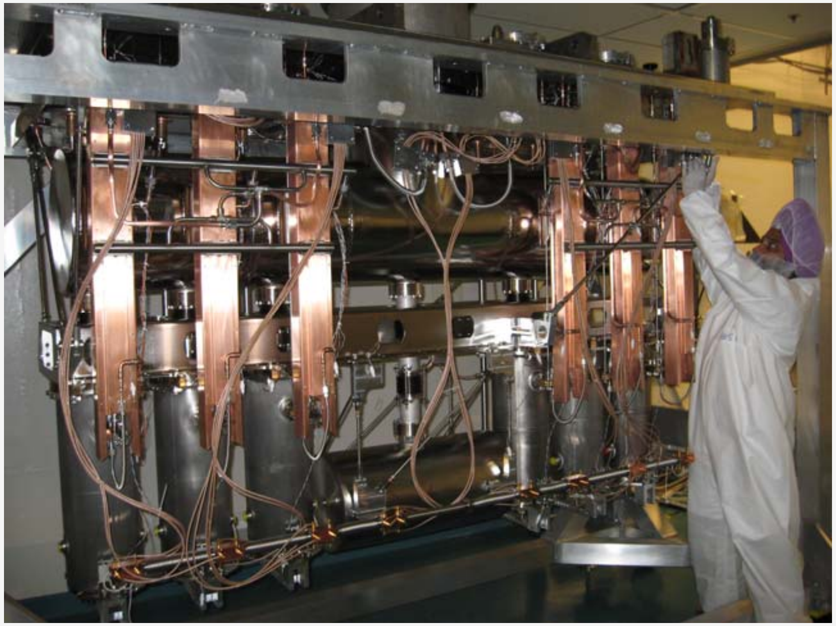


ISAC-II Phase-II Cryomodules

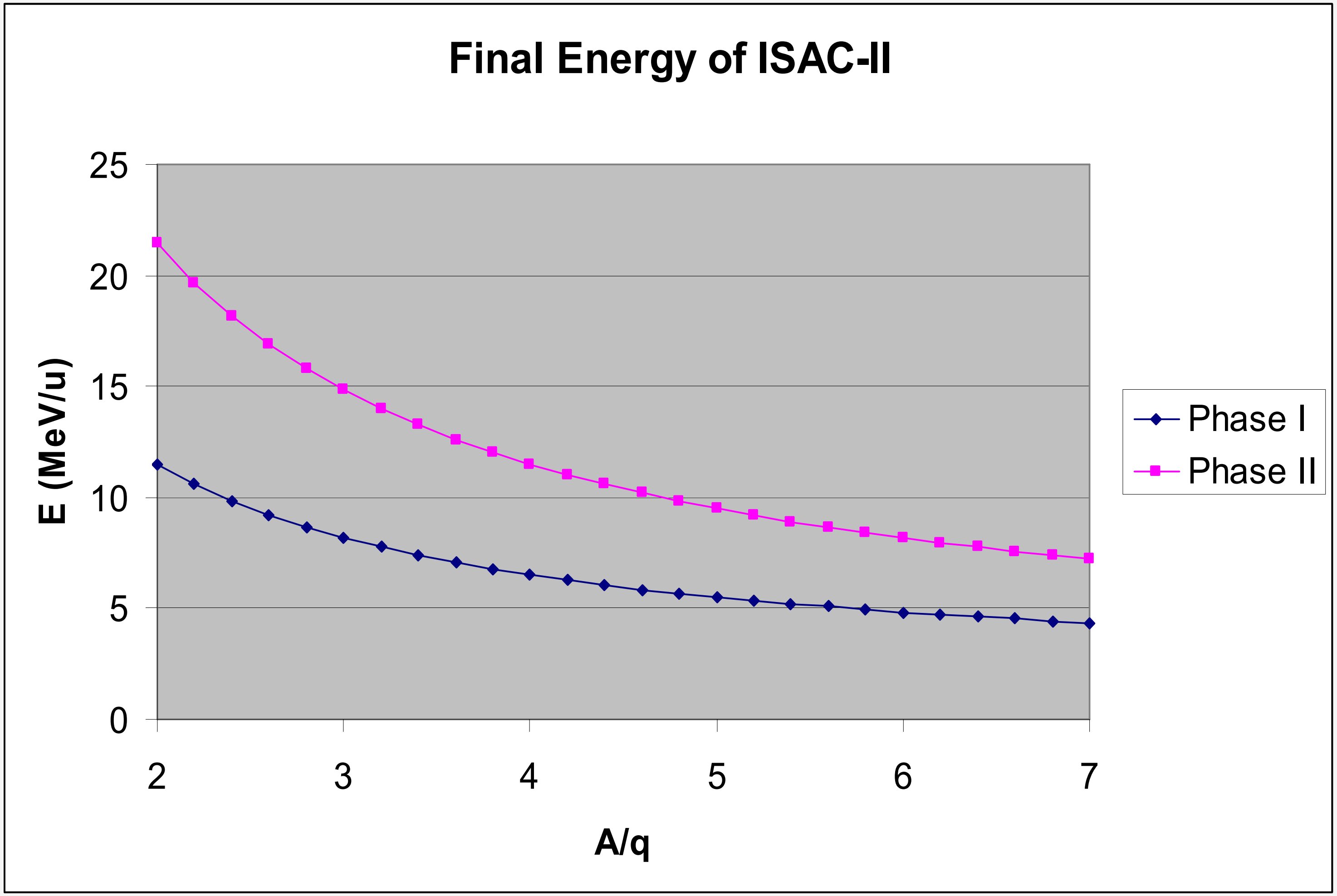
- SCC1 is now being installed in vacuum vessel for cold test next week

- SCC2 – cavities received – to begin assembly in 4 weeks





Expected final energy

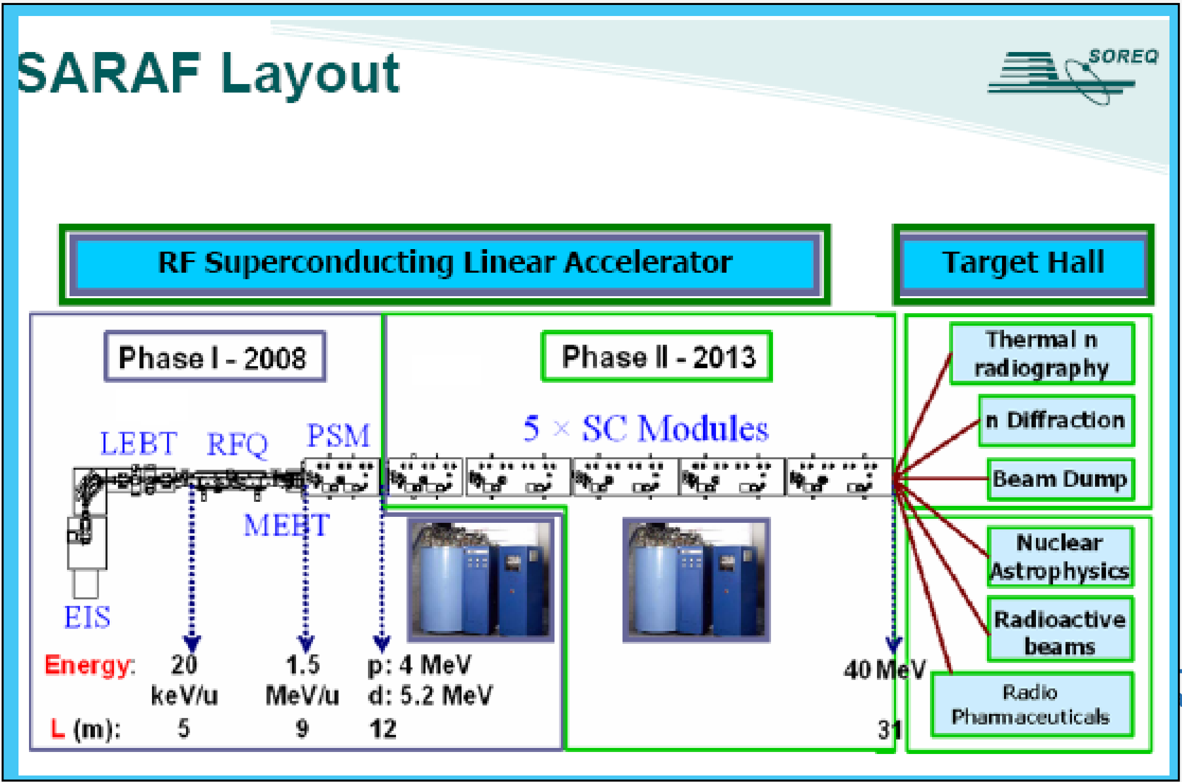


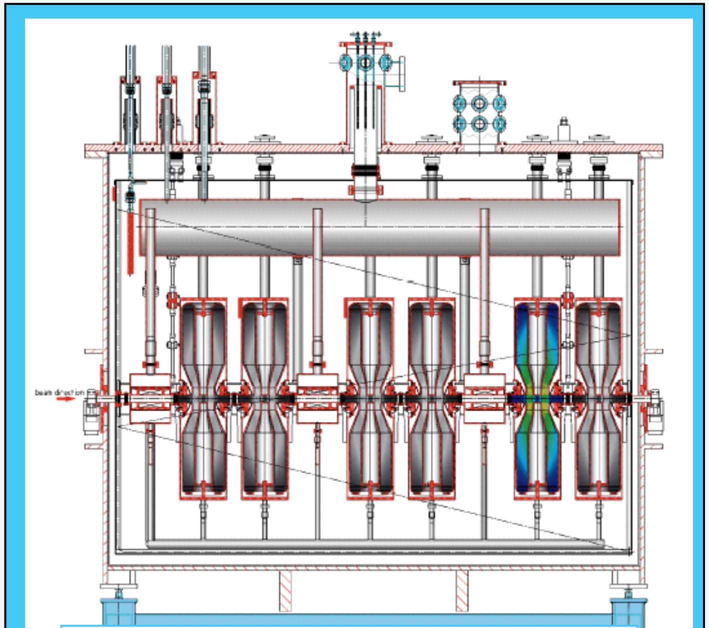
Projects

- SARAF – SOREQ
- SPIRAL-II
- ReA-3, FRIB – MSU
- IUAC – SC Booster
- HIE-ISOLDE
- IFMIF

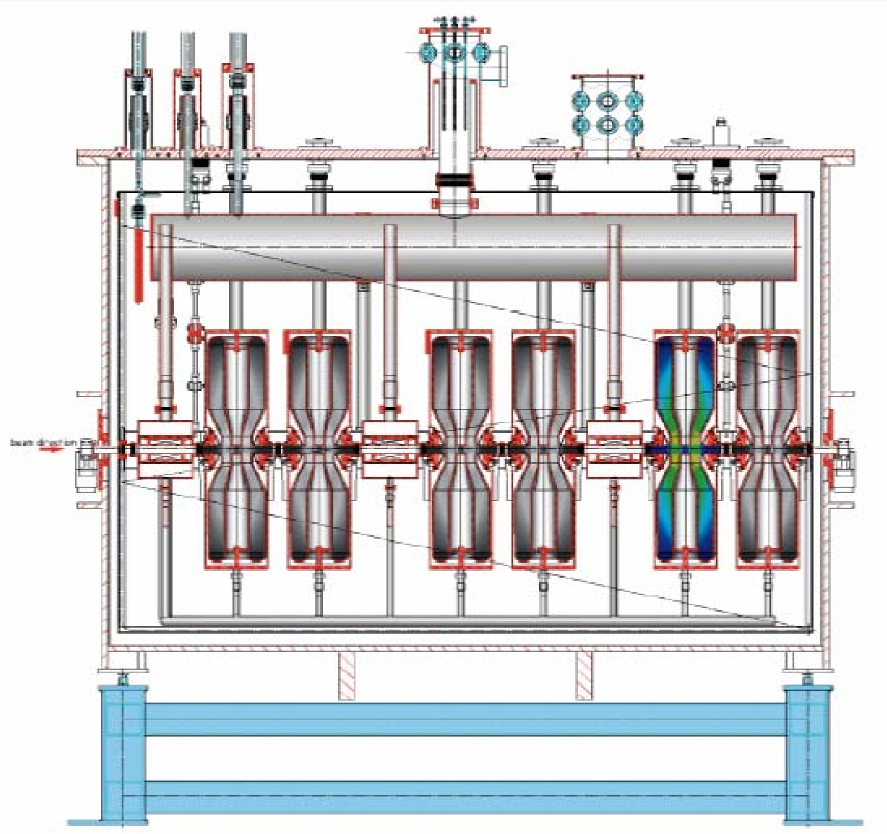
SARAF – High Intensity p-d Driver (20MeV/u - 2mA d+)

- First high intensity proton/deuteron machine using low beta superconducting structures
- Phase I commissioning test in progress
  - 250kW cw RFQ and 6 HWR cavity cryomodule




SARAF Cryomodule

Prototype Superconducting Module



Prototype superconducting module with separate cavity and cryogenic vacuum. Fabrication by ACCEL

- Prototype superconducting module containing 6 HWR β=0.09 in commissioning
- World's 1st halfwave SC cavity linac
  - Cavity choice driven at the time by good beam dynamics properties (small beam steering)
- Goal 0.86 MV/cavity (Epeak=25 MV/m) for10 W @ 4 K
- Additional 5 cryostats with 40 resonators planned for Phase II

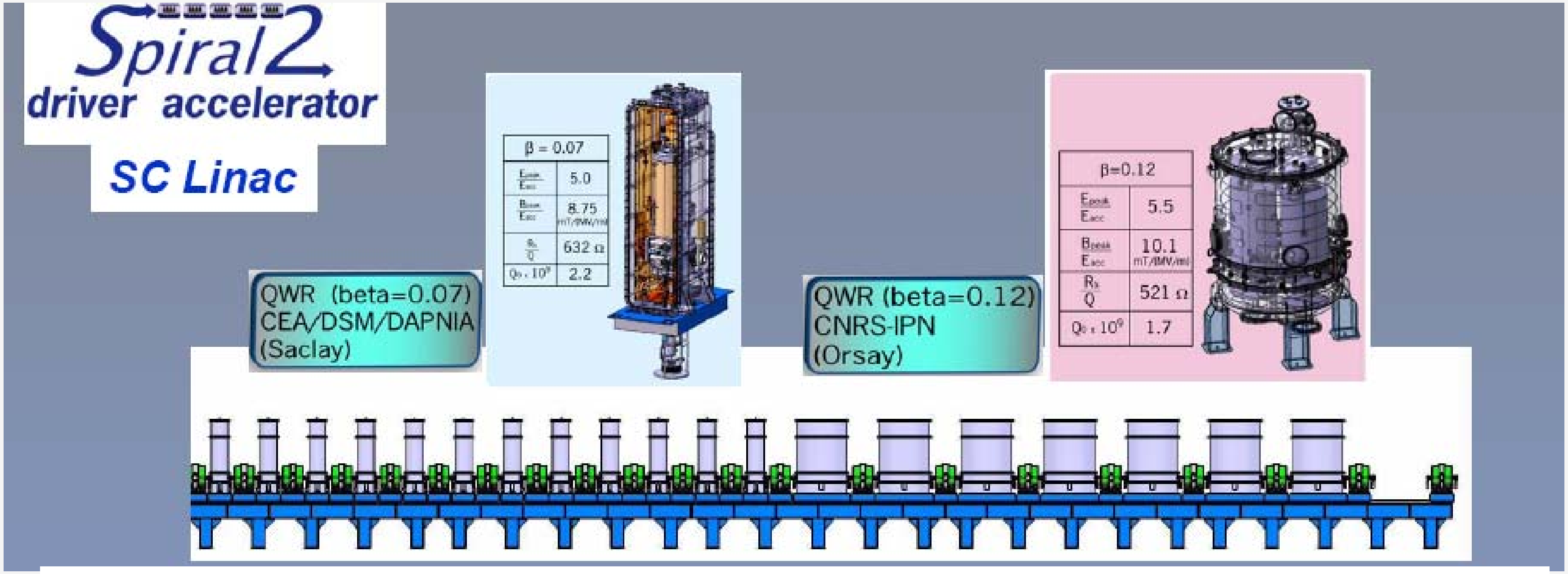
Table 4: PSM RF Status

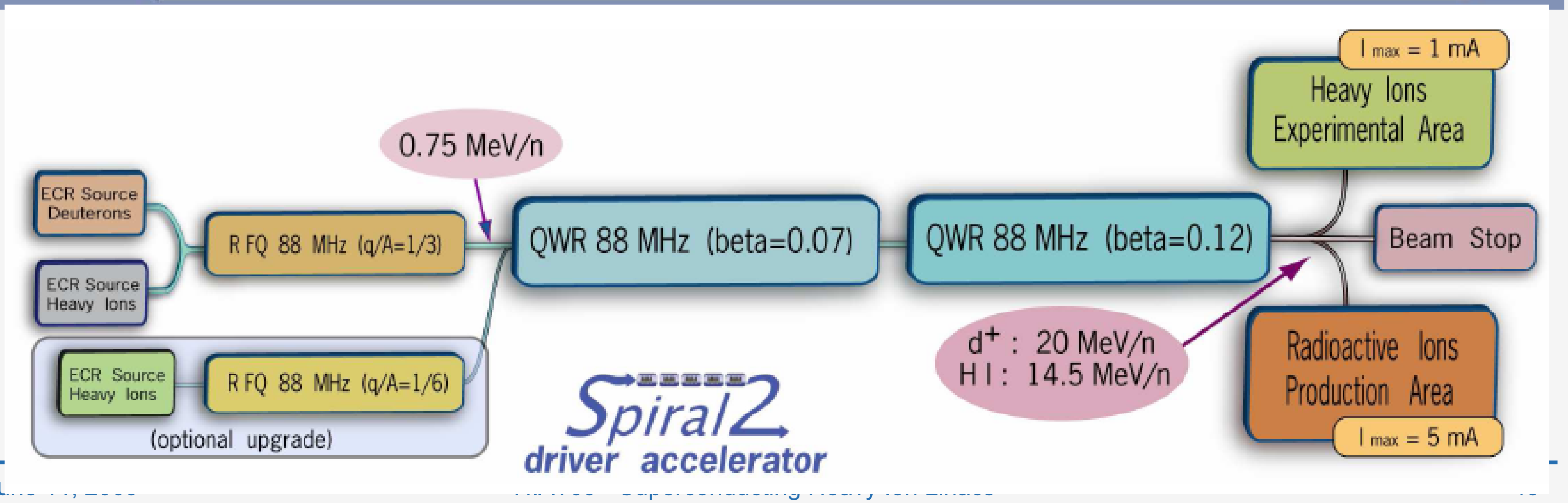
Cavity	$E_{peak}^{FE\_onset}$ [MV/m]	P [W]	$E_{peak}^{Operationt}$ [MV/m]	P [W]
1	20.7	2.4	25.4	5.7
2	21.0	5.3	25.9	9.3
3	20.6	7.4	26.0	16.0
4	20.2	4.0	25.7	11.2
5	21.2	3.7	24.9	8.7
6	20.0	5.4	25.2	10.9
Total		**28.2**		**61.8**

SPIRAL-II

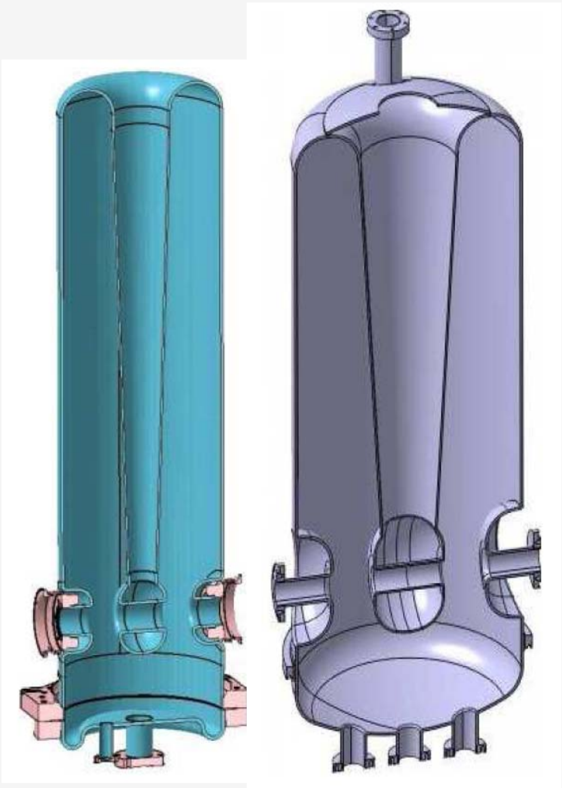
- High intensity p,d and ion linac for RIB production
  - Short cryostats with one or two cavities per module
  - Total of 26 cavities to provide 40 MV accelerating potential
  - Separate cavity and cryogenic vacuum systems
- Schedule
  - Linac tunnel available in February 2011
  - First beam in 2012

SPIRAL-II GANIL (20MeV/u d+, 5mA)





SPIRAL-II Cavities



QWR A β 0.07	QWR B β 0.12
Proto : 1	Proto : 1
Pre series: 1	Pre-series: 2
New pre-series: 2	Series: 6

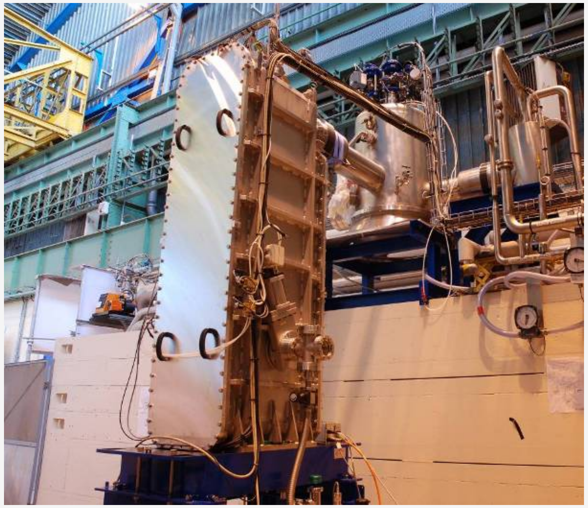
Main parameters

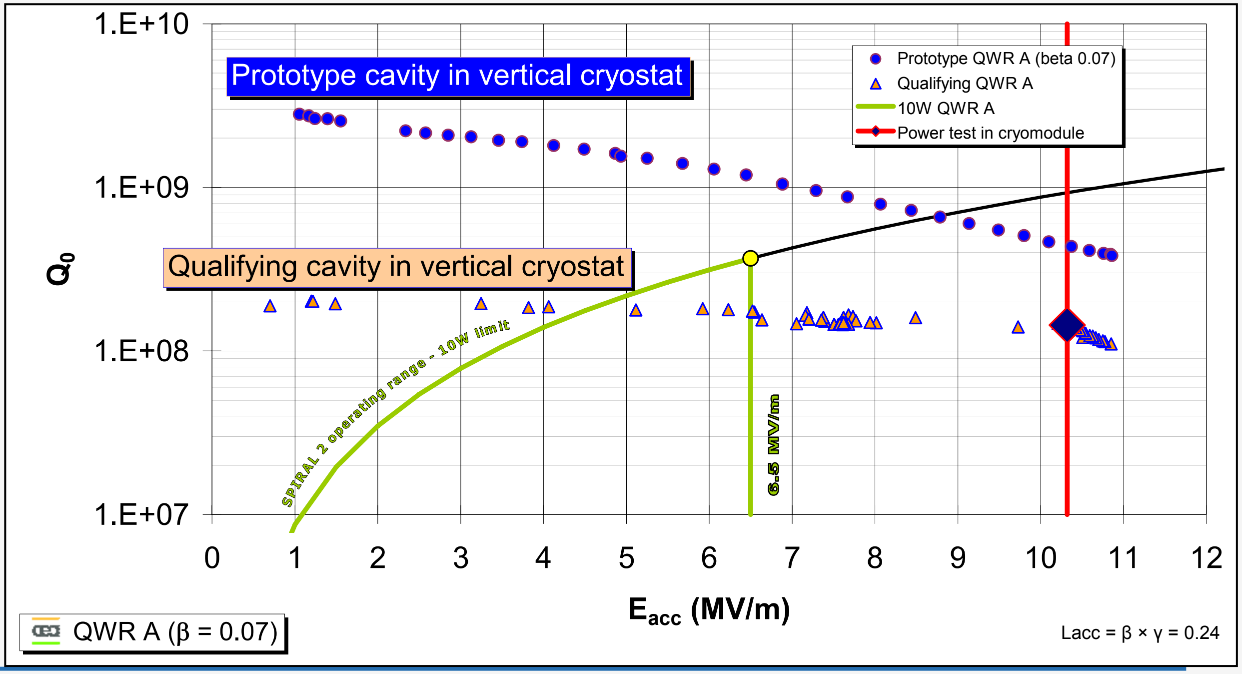
Frequency [MHZ]	88.05	88.05
β_{opt}	0.07	0.12
E_{pk}/E_{acc}	5.0	5.73
B_{pk}/E_{acc} [mT/(MV/m)]	8.7	10.2
r_s/Q [Ω]	632	521
V_{acc} @ 6.5MV/m, β_{opt} [MV]	1.54	2.65
Beam tube ϕ [mm]	38	44
Cavity ext. ϕ [mm]	230	380
Q_{ext}	$6.6\ 10^5$	$1.1\ 10^6$
$L_{acc} = \beta\times\lambda$ [mm]	0.24	0.41

Characteristic of SPIRAL2 $\lambda/4$ cavities

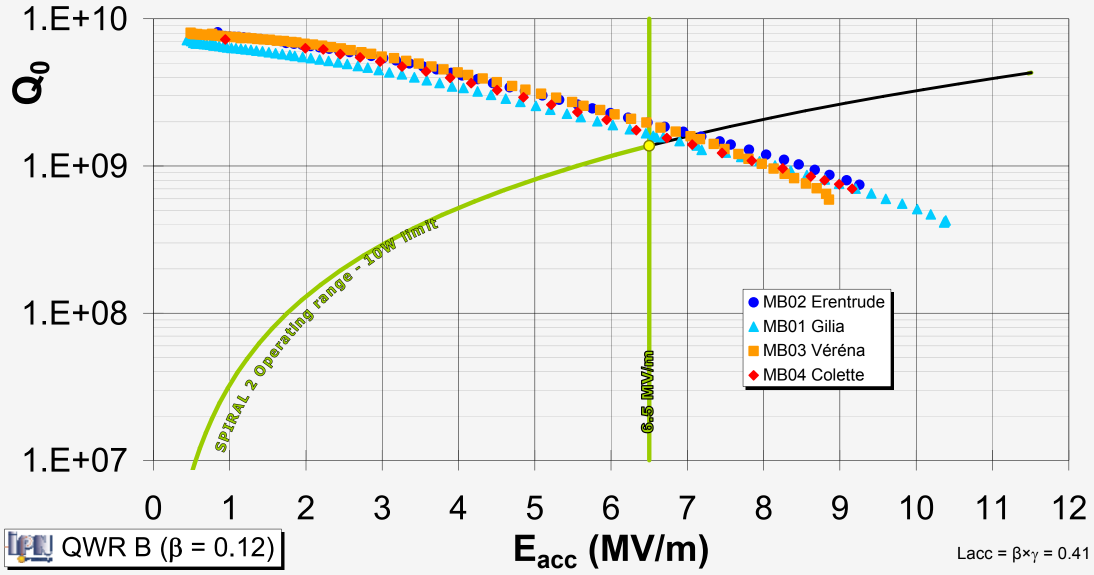
Low beta cavity performances (β = 0.07)

- Maximum gradient reached during the first RF power tests: 10.3MV/m Ep>50MV/m) - Saclay
- 2 cavities tested in May and June 2009 (Zanon and SDMS)
- First series cryostat in January 2010





“High” beta cavity performances (β = 0.12)



- Company RI GmbH (ACCEL) selected for the 16 series cavities
- First 6 cavities delivered
    - 4 already tested
- Last one in January 2010
- Orsay

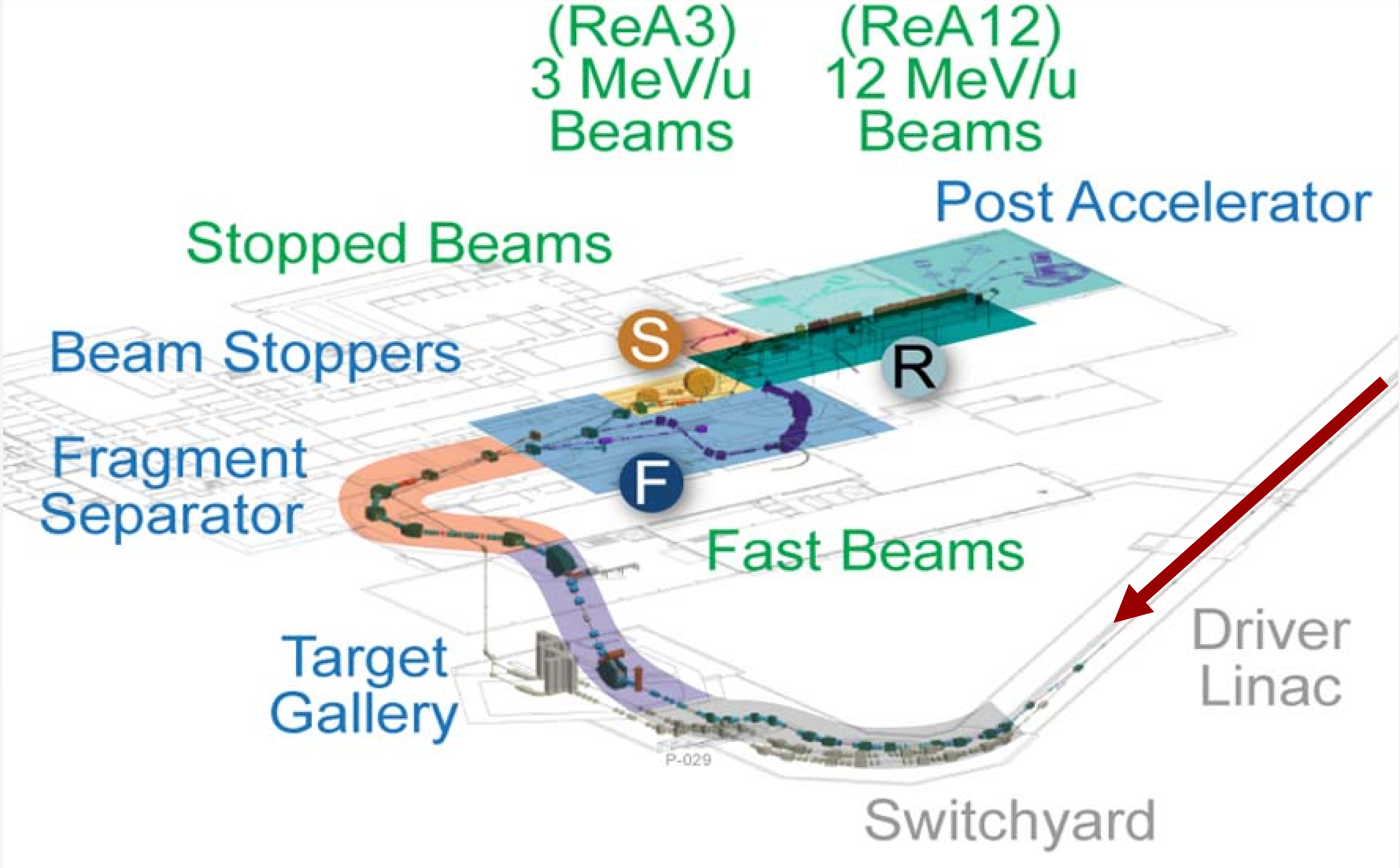
ReA3-FRIB

- ReA3 project
  - Add EBIT, RFQ, and three cryomodules to reaccelerate fragments from gas catcher to 3MeV/u
  - Complete in 2010
- FRIB
  - R+D money in the mail
  - DOE project - 2012? – turn on 2017?

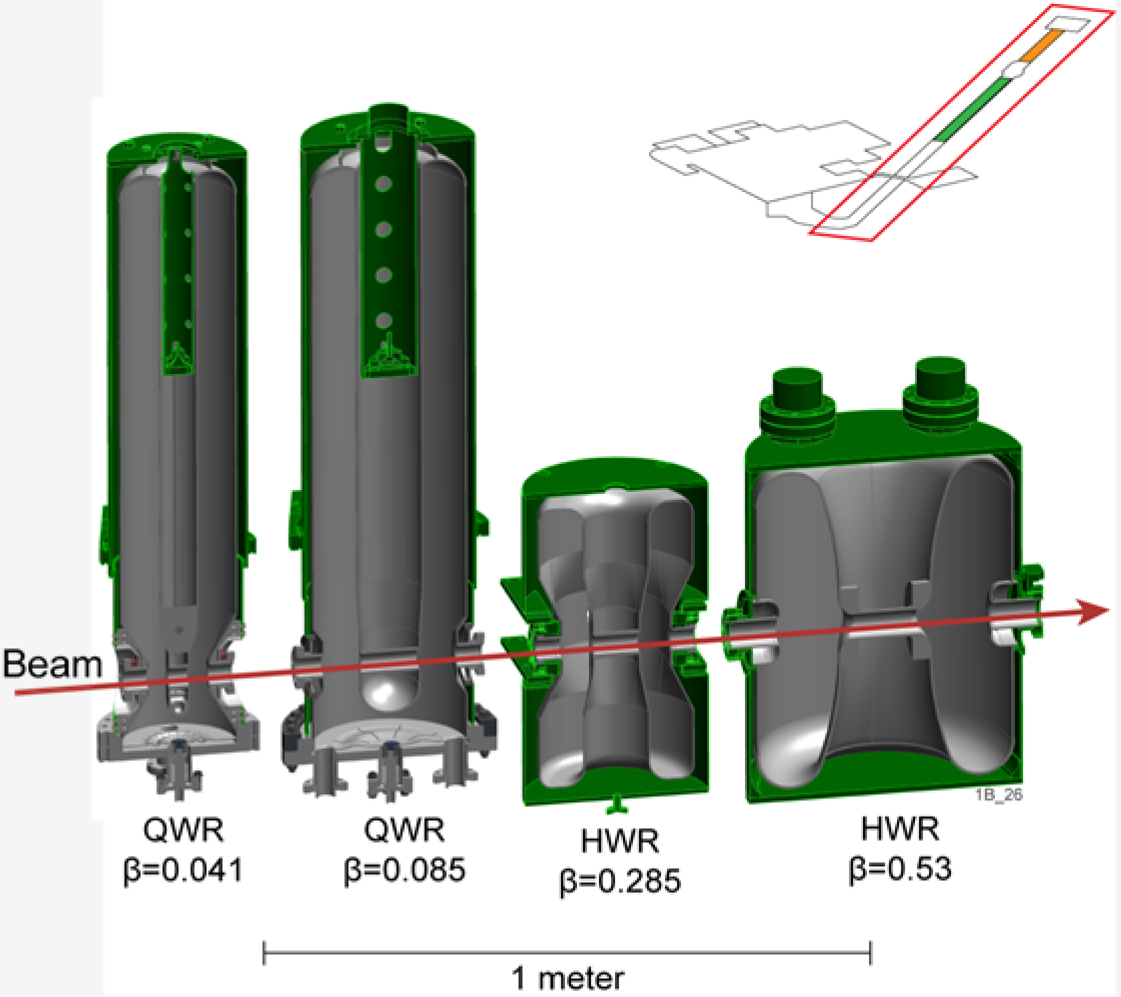
FRIB - Proposed layout

- Dec. 2008 – FRIB Facility Site chosen as MSU
- Proposed Facility for Rare Isotope Beams (FRIB)
  - CW superconducting heavy-ion linac with a minimum energy of 200 MeV/u for all ions at a beam power of 400 kW
  - Facility will have a production area, three-stage fragment separator, ion-stopping stations and post accelerator (reaccelerator) to reach at least 12 MeV/u for all ions
  - Possibility to upgrade to higher beam energy up to 400 MeV/u for uranium and higher for lighter ions

FRIB – Proposed layout



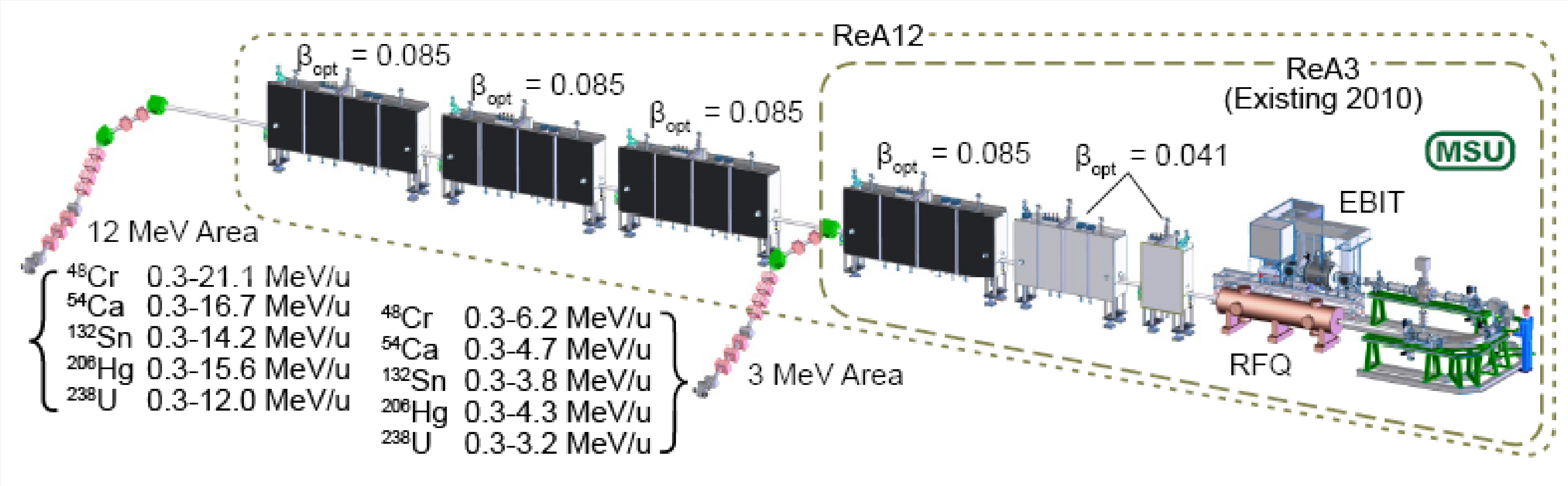
FRIB– Proposed cavity types



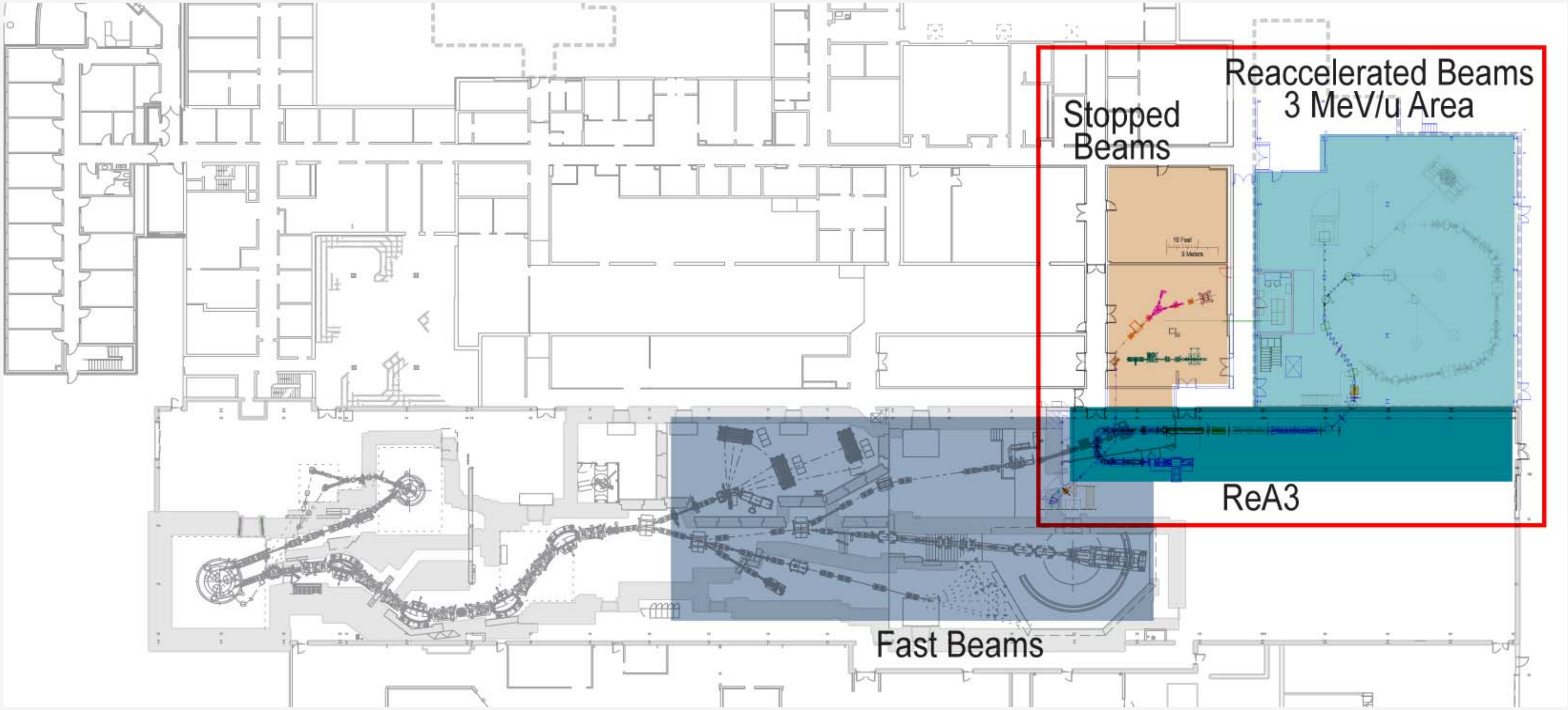
- Four cavity types proposed for whole project
    - 2 QWR's and 2 HWR's for the driver
- 2 QWR's for post accelerator

FRIB – Post-accelerator

- Scope
  - Reacceleration of rare isotopes from gas stopper or from ISOL after upgrade
  - Two types of QWRs needed; used in driver
- Technical specifications
  - High-intensity EBIT as 1+ to n+ charge breeder
  - Modern linear accelerator
  - RT RFQ and QWR SC-Linac
  - Energy range 0.3-3 MeV/u and 0.3-12 MeV/u to 2 experimental areas



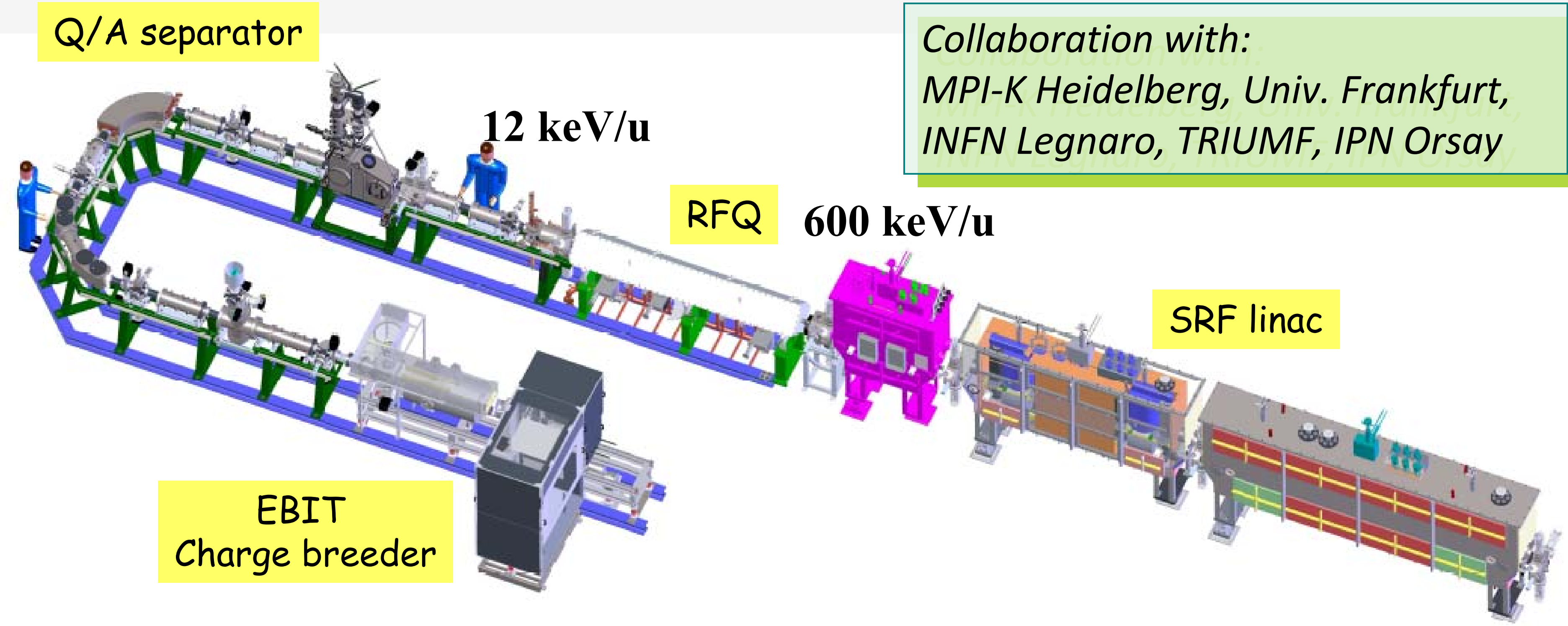
ReA3 at MSU/NSCL



TRIUMF

ReA3 – reacceleration

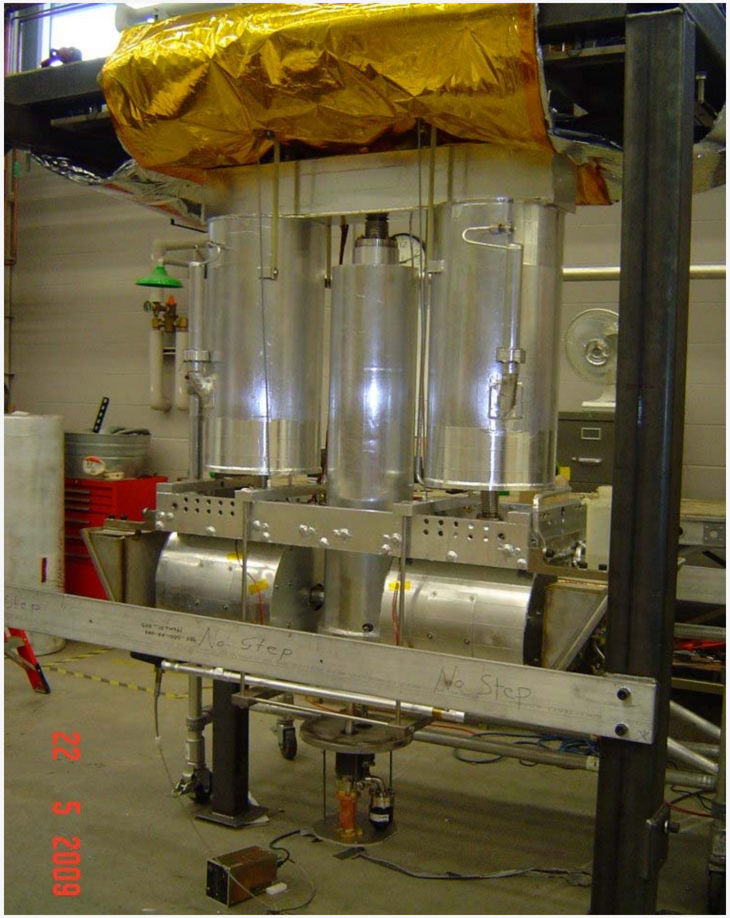
Collaboration with:
MPI-K Heidelberg, Univ. Frankfurt,
INFN Legnaro, TRIUMF, IPN Orsay



- Compact and efficient re-acceleration
  - EBIT charge breeder & Q/A separator
  - Radio-frequency quadrupole (RFQ)
  - Superconducting linac

Beam examples:
- ^{238}U 0.3 – 3 MeV/u
- ^{48}Ca 0.3 – 6 MeV/u

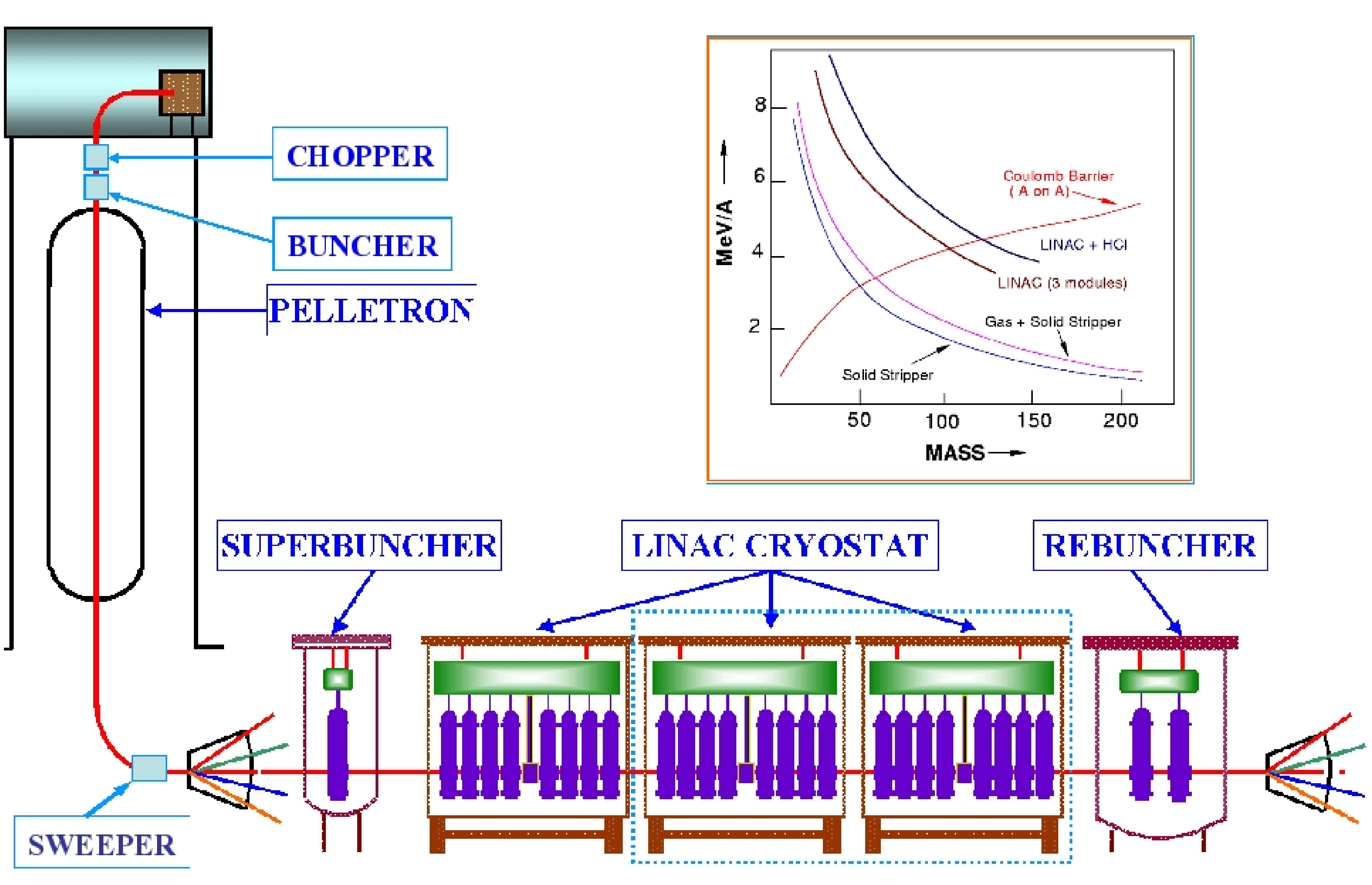
ReA3 – cryomodule



Cold mass 77 K shield Vacuum vessel

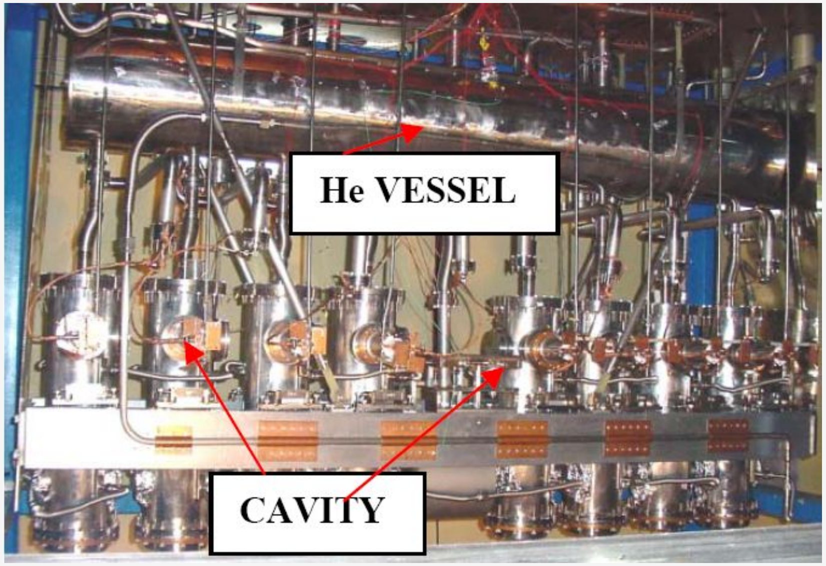
Rebuncher cryomodule for ReA3: assembly in progress

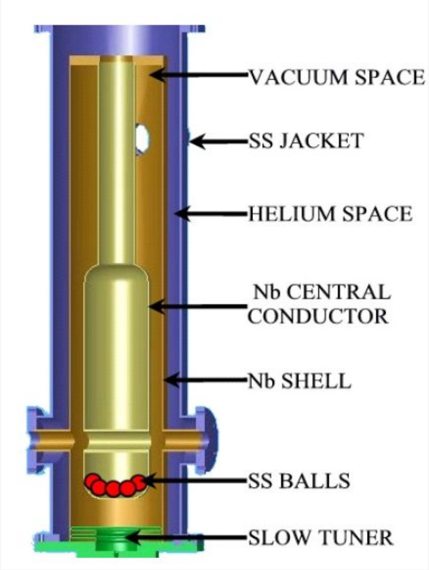
IUAC SC-Linac Booster

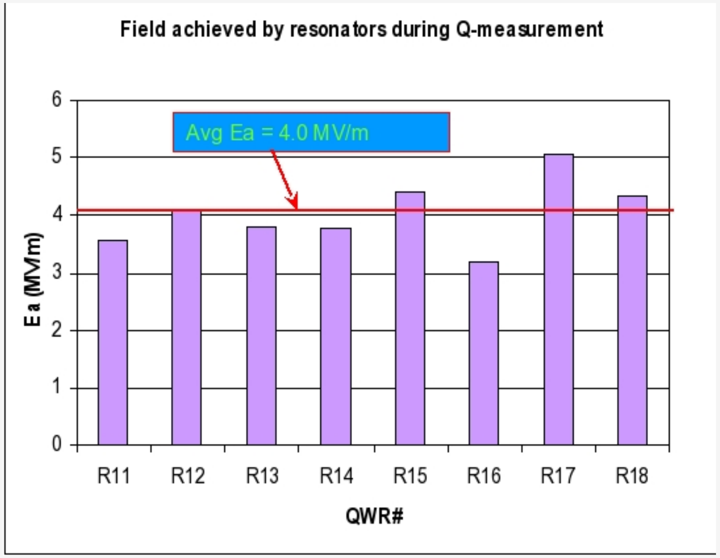


IUAC New Delhi

- In operations one cryostat with eight 97 MHz cavities for β=0.08
- In fabrication an additional 2 cryostats with 16 new cavities
- IUAC has full local cavity fabrication capability (niobium forming, welding, chemistry)
- Performing SRF work for others (FNAL single spoke)



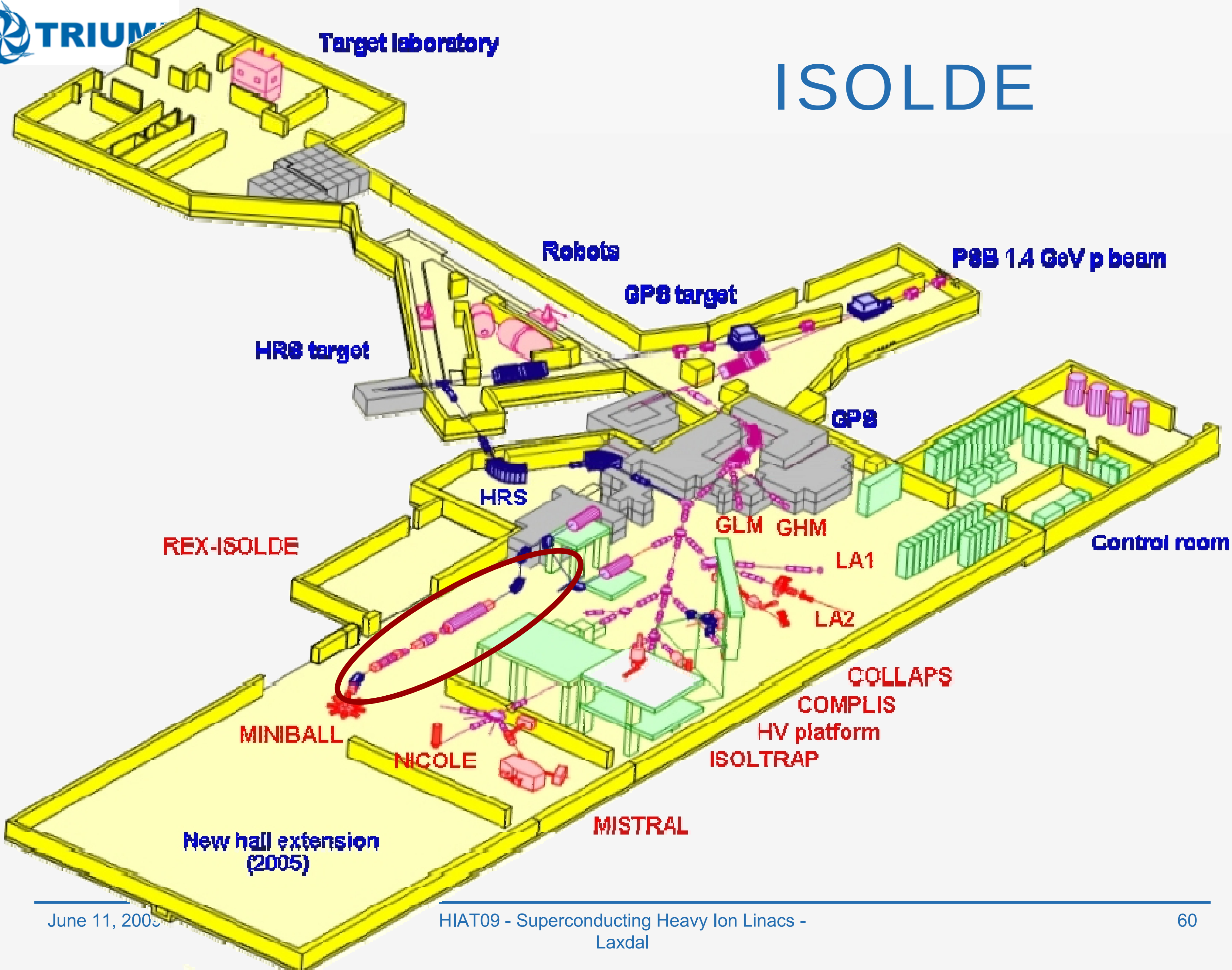




HIE-ISOLDE

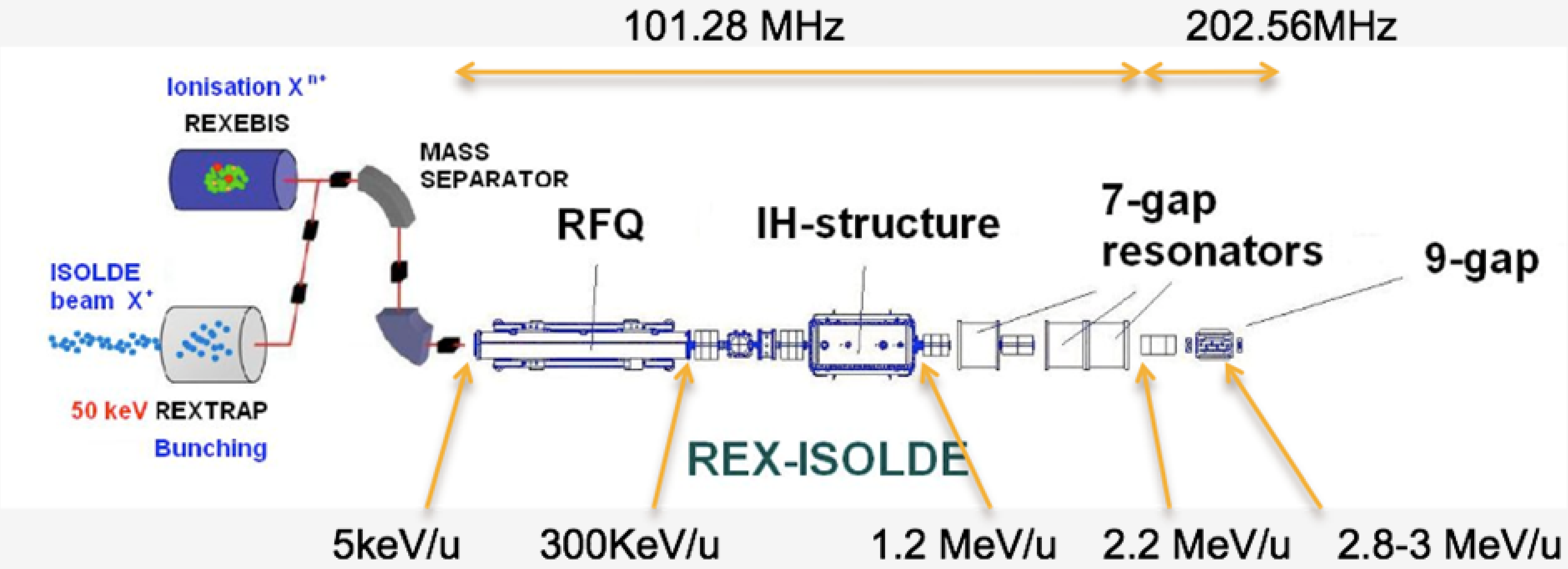
- Energy boost for REX-ISOLDE
  - Accelerate RIBS beyond the Coulomb Barrier
- Staged installations of Nb/Cu sputtered cavities
  - Utilize and enhance CERN technology developed for LEP

ISOLDE



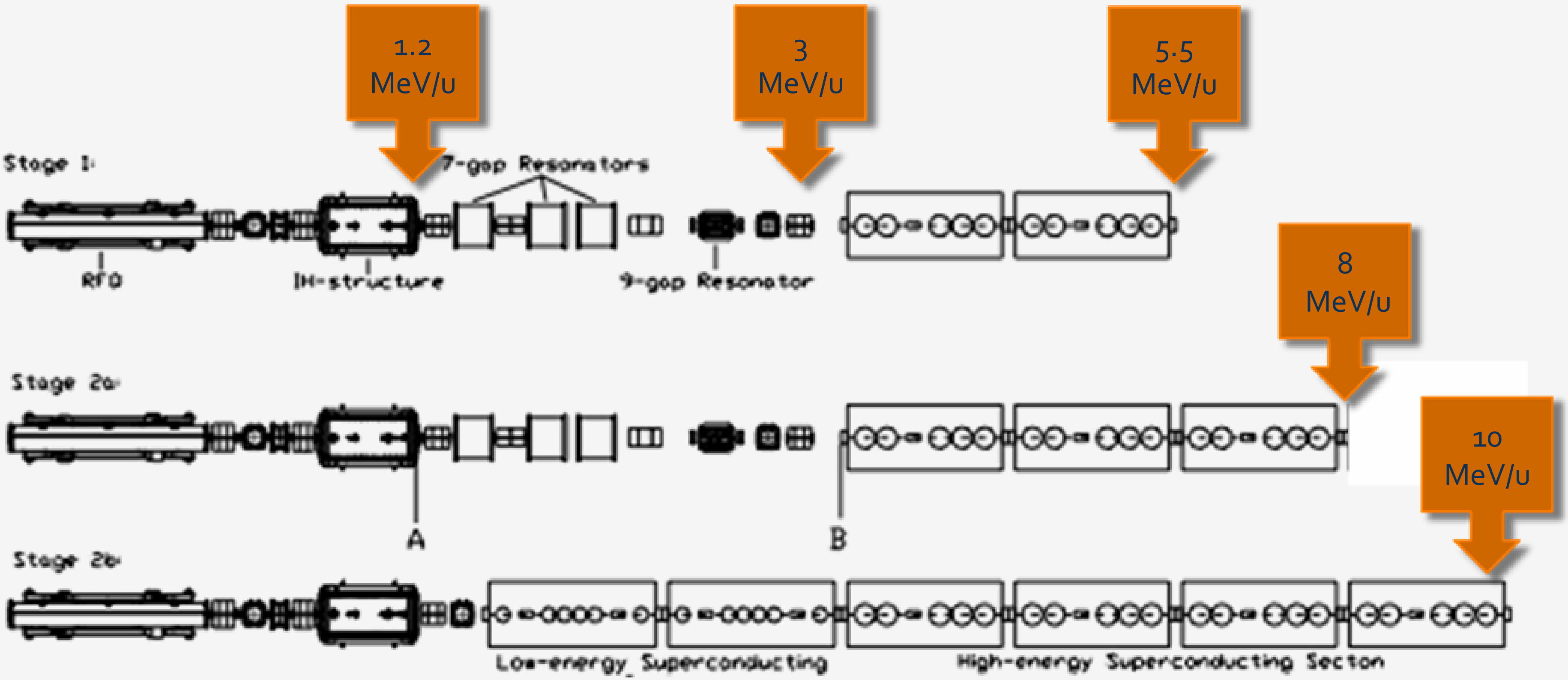
Target laboratory
Robots
PSB 1.4 GeV p beam
GPS target
HRS target
GPS
HRS
GLM
GHM
REX-ISOLDE
LA1
LA2
Control room
COLLAPS
COMPLIS
HV platform
ISOLTRAP
MINIBALL
NICOLE
MISTRAL
New hall extension
(2005)

REX-ISOLDE Post accelerator

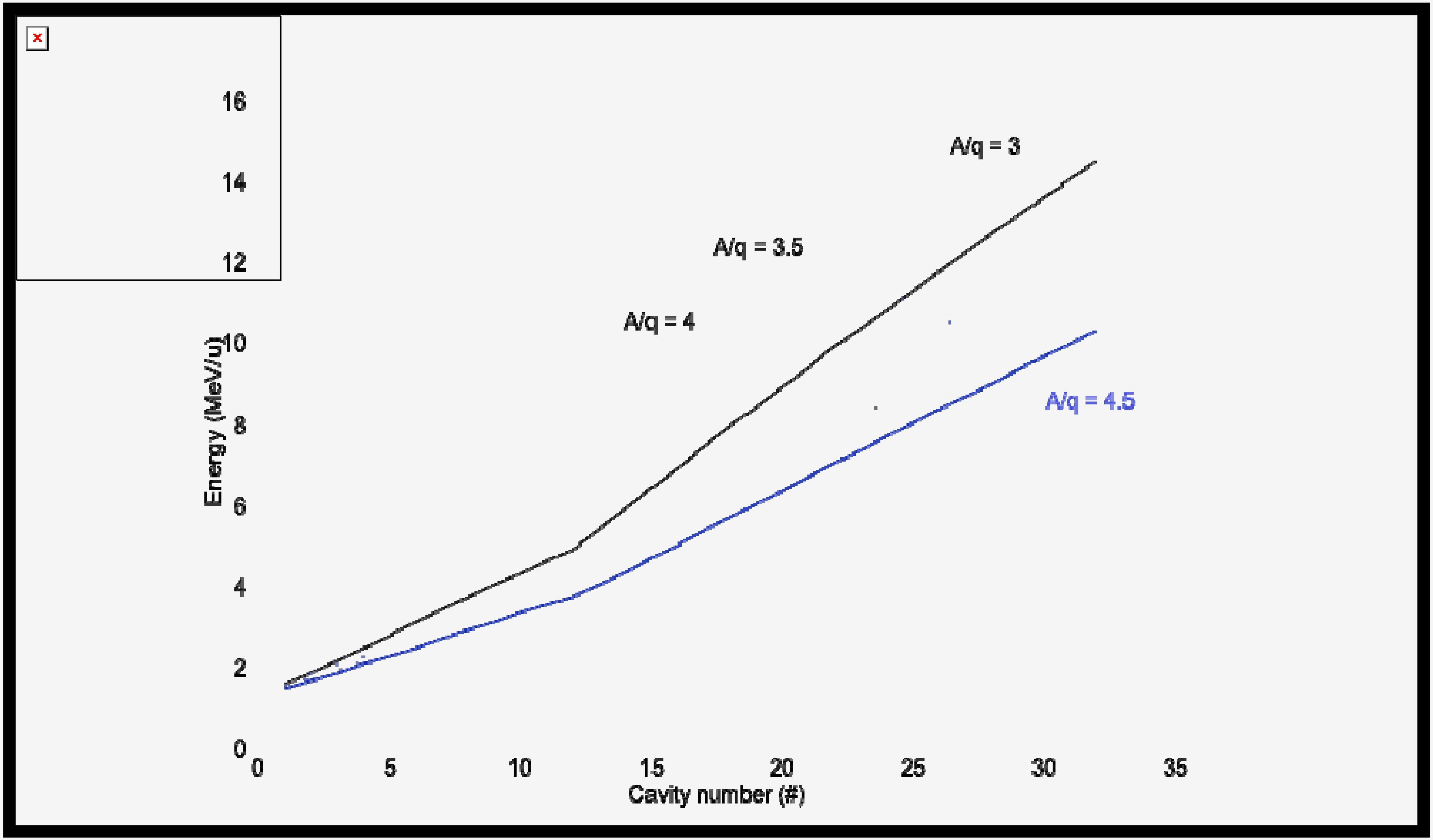


HIE-ISOLDE Upgrade Proposal

- Three stage installation sequence



Final Beam Energies



QWR cavities (Nb sputtered)

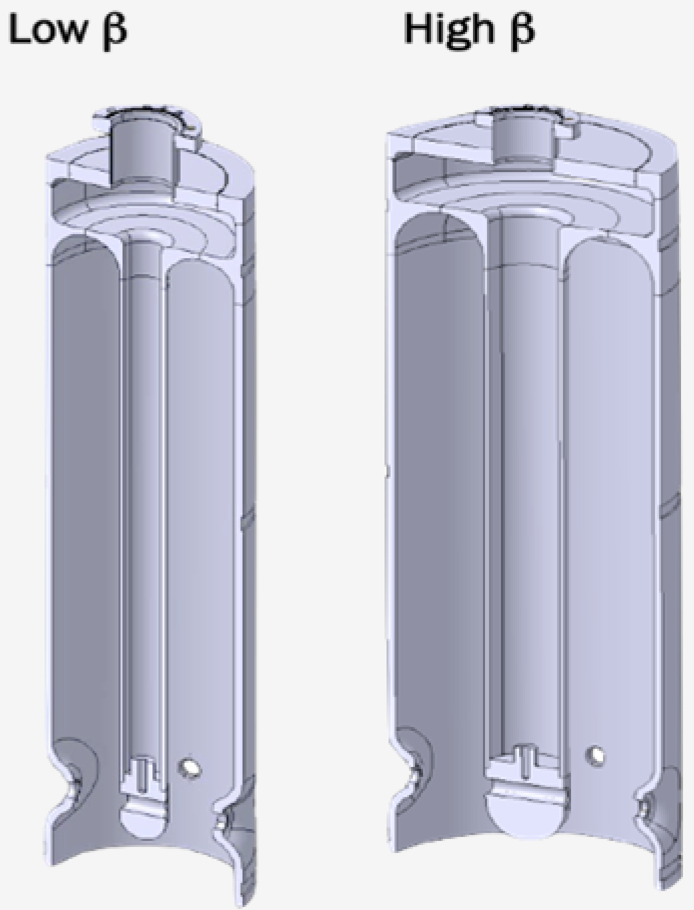


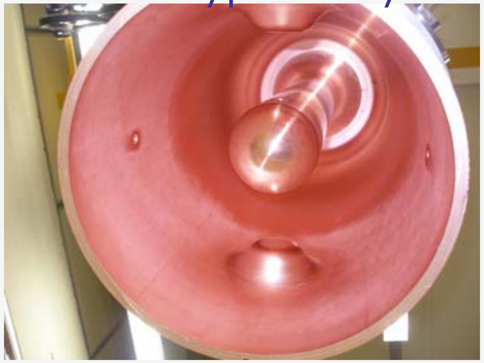
Table 1: Cavity design parameters

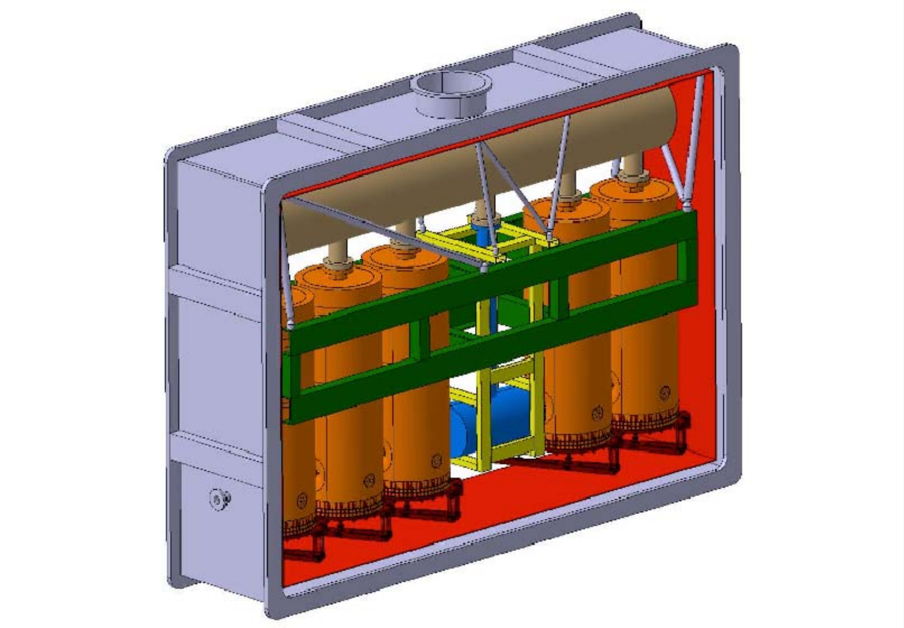
Cavity	Low β	highβ
No. of Cells	2	2
f (MHz)	101.28	101.28
β_0 (%)	6.3	10.3
Design gradient E_{acc}(MV/m)	6	6
Active length (mm)	195	300
Inner conductor diameter (mm)	50	90
Mechanical length (mm)	215	320
Gap length (mm)	50	85
Beam aperture diameter (mm)	20	20
$U/{E_{acc}}^2$ (mJ/(MV/m)^2	73	207
E_{pk}/E_{acc}	5.4	5.6
H_{pk}/E_{acc} (Oe/MV/m)	80	100.7
R_{sh}/Q (Ω)	564	548
$\Gamma = R_S \cdot Q_0$ (Ω)	23	30.6
Q_0 for 6MV/m at 7W	$3.2 \cdot 10^8$	$5 \cdot 10^8$
TTF max	0.85	0.9
No. of cavities	12	20

HIE-ISOLDE Technology

- Critical pieces being prototyped
- Sputtered cavity in production
- Cryomodule design well advanced

Prototype cavity



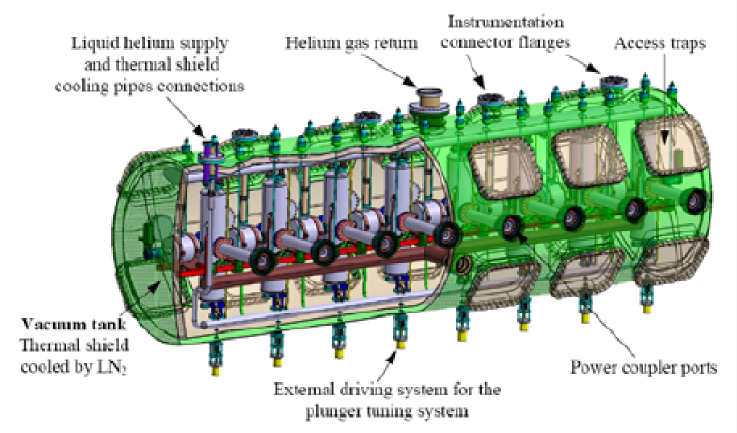


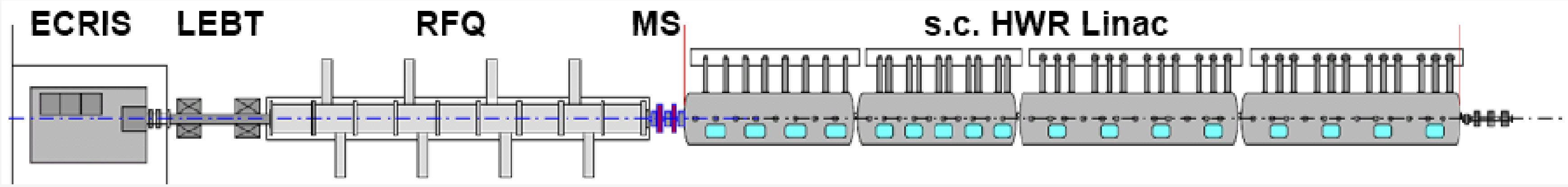
IFMIF

- High current deuteron project
    - Two linacs each125mA at 40MeV
    - ECRIS, RFQ and HWR SC-Linac
- Test linac to 9 MeV (1.2MW) to be installed in Rokasho Mura Japan

Table 1: Main Parameters of the HWR Linac

Cryomodule	1	2	3 & 4
Cavity β	0.094	0.094	0.166
Cavity length (mm)	180	180	280
Beam aperture (mm)	40	40	48
Nb cavities / period	1	2	3
Nb cavities / cryostat	1 x 8	2 x 5	3 x 4
Nb solenoids	8	5	4
Cryostat length (mm)	4.64	4.30	6.03
Output energy (MeV)	9	14.5	26 – 40





Conclusion

- Low to medium beta SC-Linac field is very active with several new projects in building stage
- A renaissance in R+D over the last several years, prompted by work at high beta, has seen performance improve
  - new cavity types now regarded as `standard' building blocks for the projects of the future
- Community must work together to achieve controlled progress where improved performance is understood and repeatable

Thanks for attention!

- Special thanks to the following contributors
  - –Matteo Pasini
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