深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

Cycle of Seminars by Carlo Pagani

Seminar # 9

High Intensity Proton Linacs
Pulsed and CW

Shenzhen, 28 March 2023 / INFN LASA, 20 May 2025

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INFN LASA

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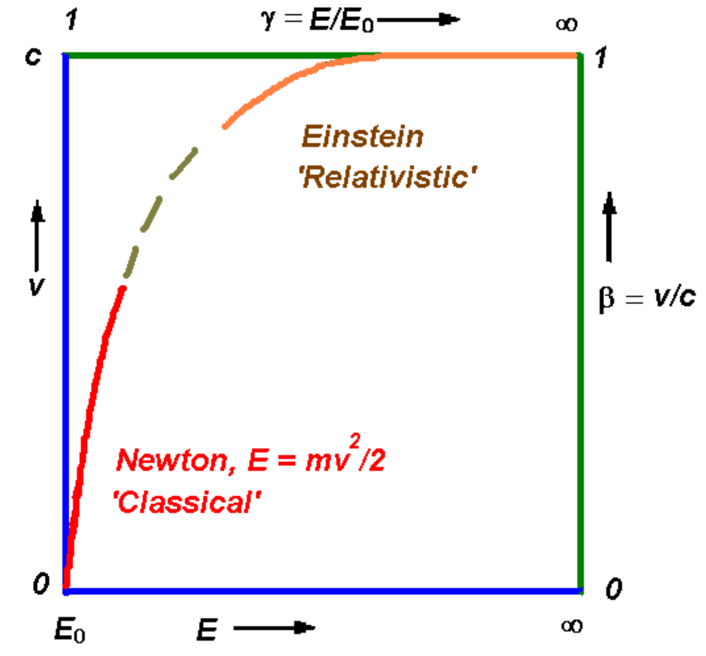
Particle Acceleration

- Particle accelerators accelerate particles to speeds very close to that of light.
- At low energies, the velocity of the particle increases with the square root of the kinetic energy (Newton).
- At relativistic energies, the velocity increases very slowly asymptotically approaching that of light (Einstein).
- It is as if the velocity of the particle 'saturates'.
- One can pour more and more energy into the particle, giving it a shorter De Broglie wavelength ($\lambda = h/p$) so that it probes deeper into the sub-atomic world.

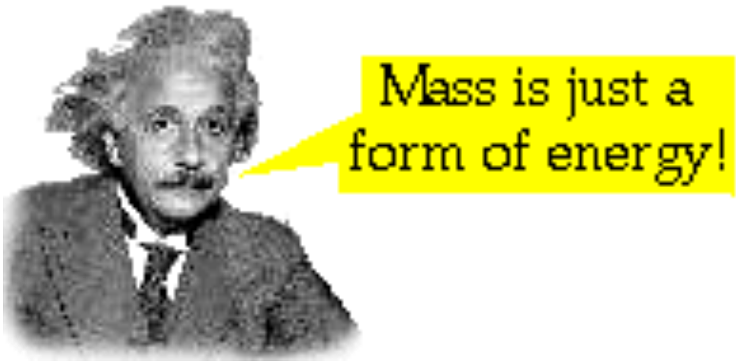


What does special relativity tell us, e.g. for an electron?

The speed increases, but not as spectacularly as the mass. In fact, it would be more correct to speak of the **momentum** ($p = mv$) **increase** .

Energy	1 MeV	→		1 GeV
$\beta = v/c$	0.95	0.99	0.999	0.999 999 9
$\gamma = m/m_0$	3	7	22	2000

Energy and Mass



$$E = mc^2$$

$$m = \gamma m_0$$
$$E_0 = m_0 c^2$$
$$\gamma = 1/\sqrt{1-\beta^2}$$
$$\beta = {}^{v}/_{c}$$

Momentum $p = mv = \gamma m_0 v \approx \gamma m_0 c$ When $v \approx c$

Kinetic energy $W_k = E - E_0 = (\gamma - 1) m_0 c^2$

Speed of light: $c \equiv 2.99792458 \cdot 10^8\ \mathrm{ms^{-1}}$

Energy unit: 1 eV = $1.6021 \cdot 10^{-19}$ J

Electron rest energy: E_0 = 0.511 MeV

Proton rest energy: E_0 = 938 MeV

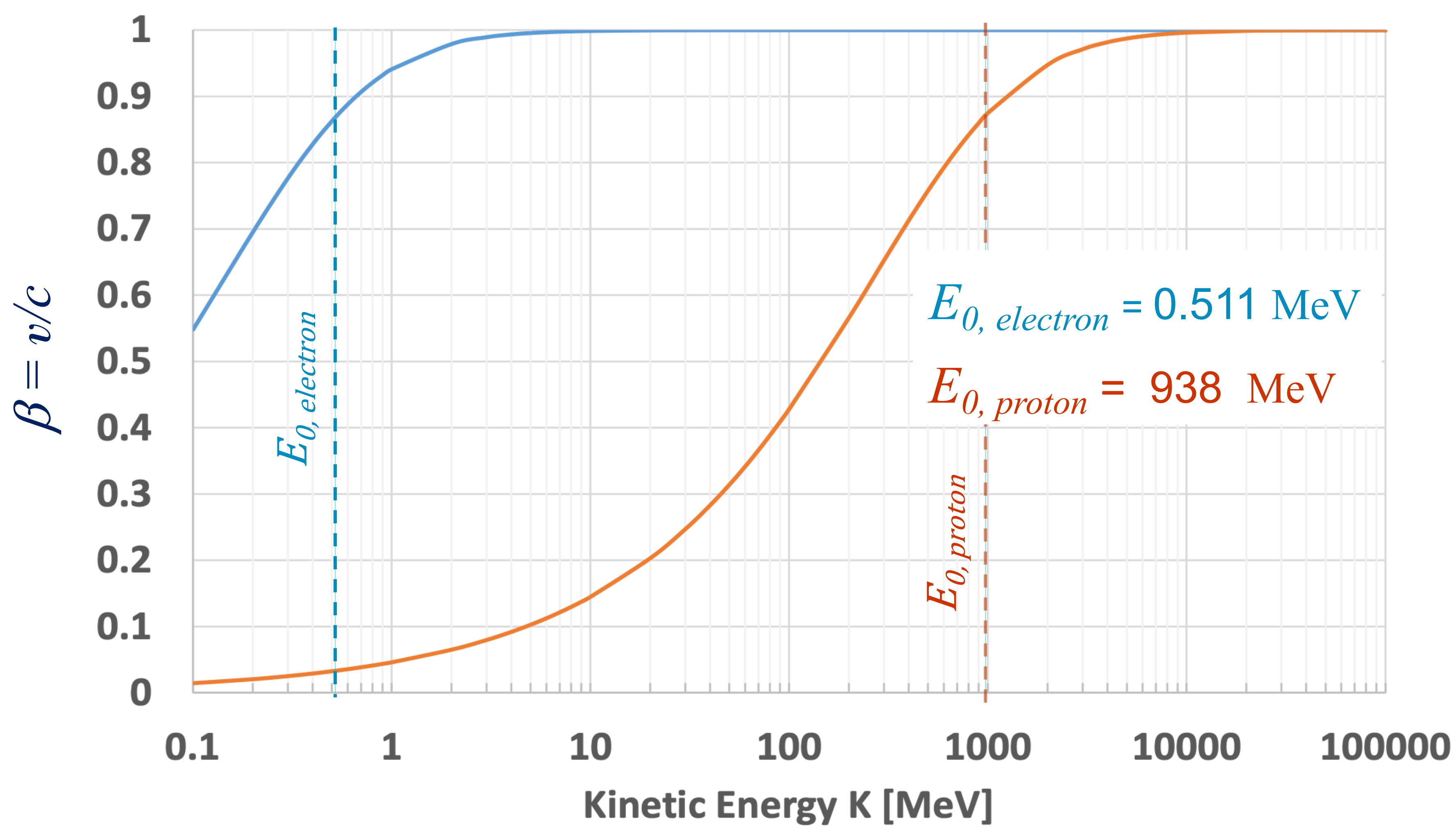
Properties of some charged particles

Particle	Charge (coulomb)	Mass (kg)	Rest Energy (MeV)	A	Z	Z^*
Electron (β particle)	-1.60×10^{-19}	9.11×10^{-31}	0.511	—	—	—
Proton	$+1.60 \times 10^{-19}$	1.67×10^{-27}	938	1	1	1
Deuteron	$+1.60 \times 10^{-19}$	3.34×10^{-27}	1875	2	1	1
Triton	$+1.60 \times 10^{-19}$	5.00×10^{-27}	2809	3	1	1
He^{+}	$+1.60 \times 10^{-19}$	6.64×10^{-27}	3728	4	2	1
He^{++} (α particle)	$+3.20 \times 10^{-19}$	6.64×10^{-27}	3728	4	2	2
C^{+}	$+1.6 \times 10^{-19}$	1.99×10^{-26}	1.12×10^{4}	12	6	1
U^{+}	$+1.6 \times 10^{-19}$	3.95×10^{-25}	2.22×10^{5}	238	92	1

The **electronvolt,** eV, is the amount of (kinetic) energy gained by one elementary charge e moving across an electric potential difference of one $volt$.

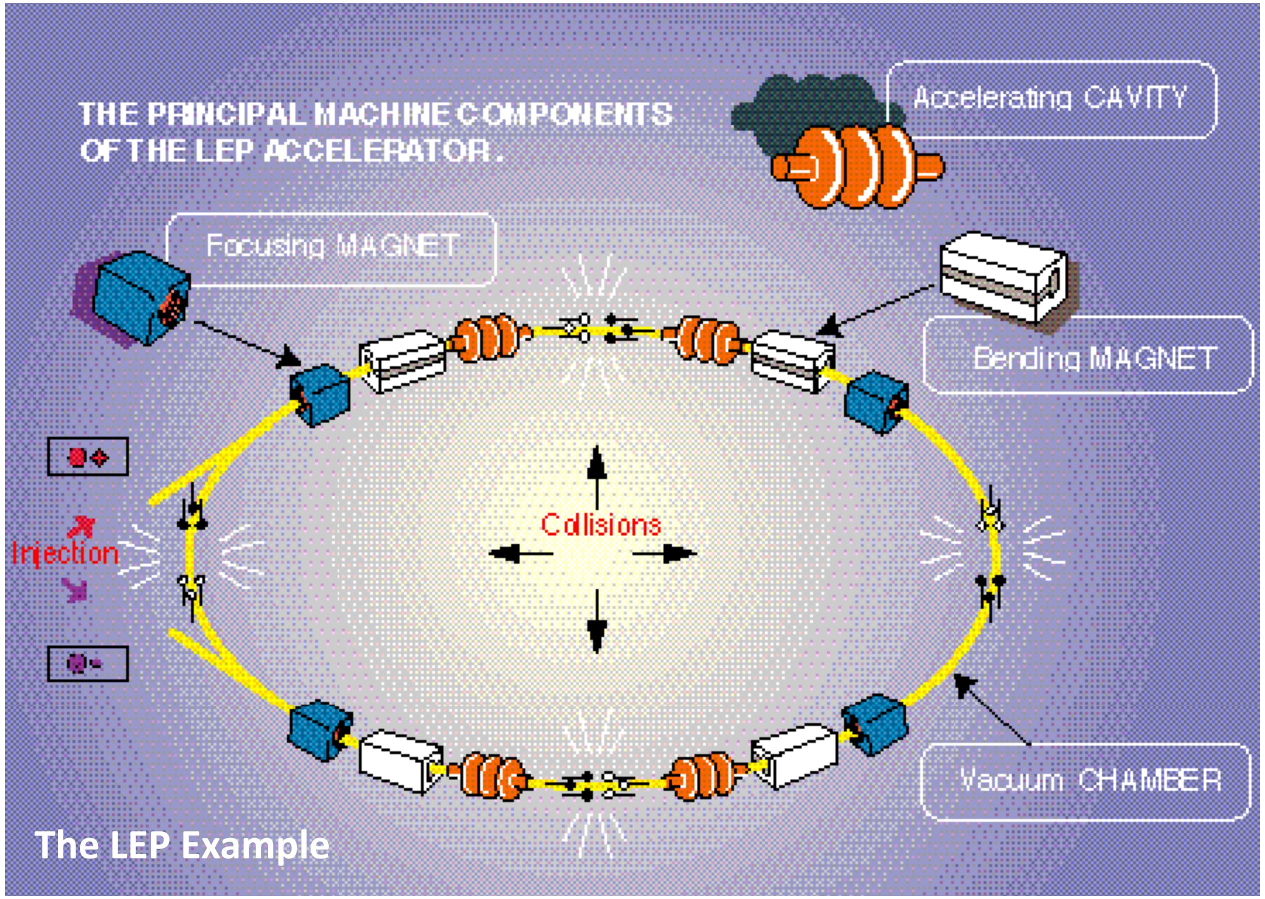
$1\, e * 1\, V = 1\, eV$ $\quad$ $1\, C * 1\, V = 1$ J $\quad$ $1\, e = 1.6021 * 10^{-19}$ C $\quad$ $1\, eV = 1.6021 * 10^{-19}$ J

Speed Increase and its Saturation



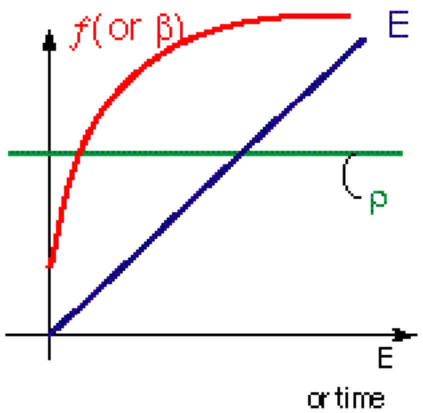
RF acceleration: Synchrotron at $\beta \approx 1$

Cyclotron: constant B **Synchrotron:** constant ρ

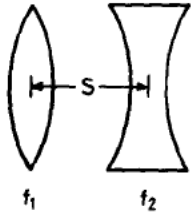


$$B\rho = \frac{mv}{q} = \frac{p}{q}$$

Accelerating cycle



Strong focusing concept



$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{S}{f_1 \cdot f_2}$

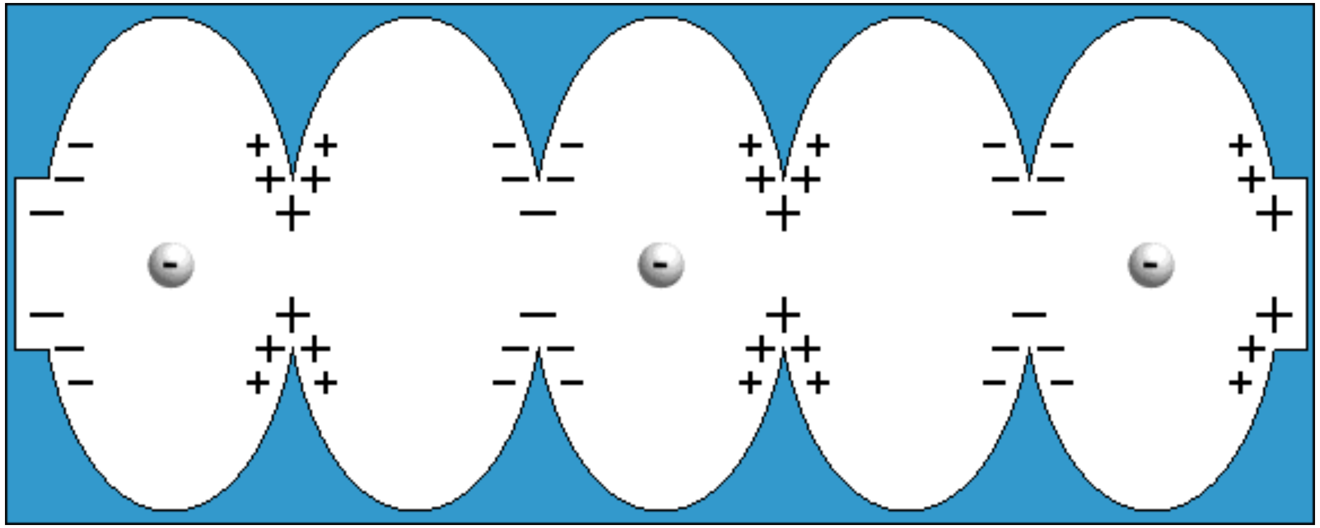
For $v \approx c$ ⟶ $E\,[GeV] \approx 0.3\, B\,[T] \cdot \rho\,[m]$

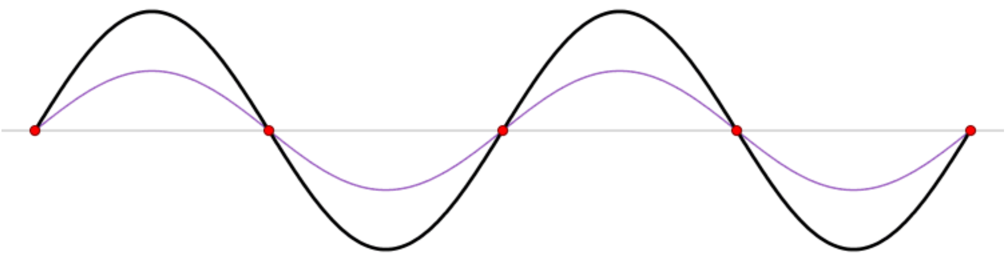
RF Acceleration - Electrons

For electrons the life is easier. A few MV are sufficient to stabilize their speed, close to the speed of light.

The particles of the beam need to be localized in **bunches** and properly phased with respect to the field so that the beam is gaining energy

$$\frac{d(\gamma m_0 c^2)}{ds} = qE_z(s,t) \qquad \beta = \frac{v}{c} = \sqrt{1 - \frac{1}{\gamma^2}} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} = 1 + \frac{W_k}{m_0 c^2} = 1 + \frac{W_k}{E_0}$$





RF Acceleration – Protons (and ions)

With protons, and even worst with ions, a lot of voltage, some GV, must be integrated by the particles before their speed is becoming stable, i.e. close to the speed of light.

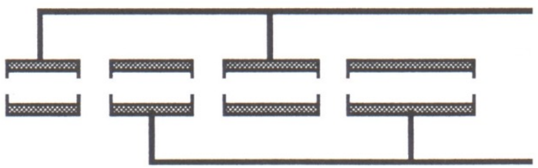
The RF accelerating structures must be designed for different particle speed, from the speed at the source exit ($\mathrm{W_k}$ of the order of one hundred keV, i.e. $\beta = 1.4\ 10^{-2}$) to the speed of light ($\beta = 1$).

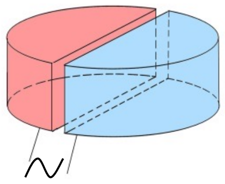
For ions the situation is the same but worst. For the same energy/nucleon the number of cavities must be multiplied by the factor Z/A.

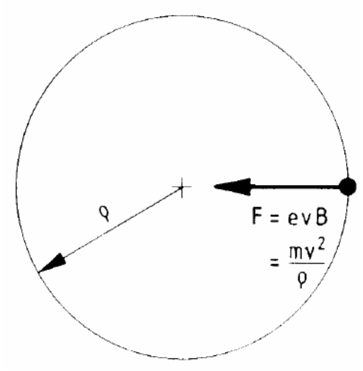
For a CW beam of protons at moderate energy and power the cyclotron is still a valid solution. Several tenth of cyclotrons are used and still built every year for isotope production, and a few for hadron therapy.

Cyclotron for moderate Energy

Folded Wideroe Linac in a constant magnetic field

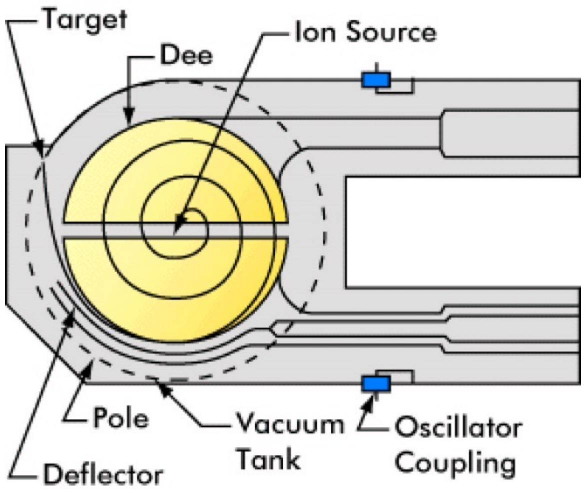




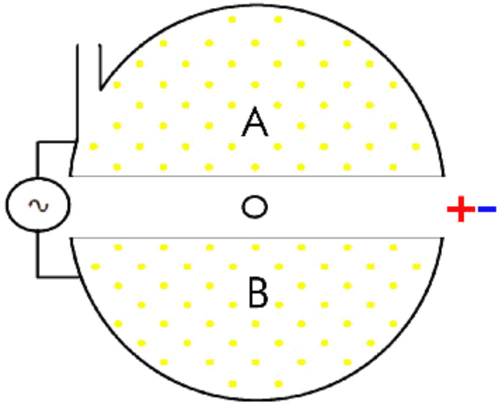


$$\frac{m\,v^2}{\rho} = q\,v\,B$$

$$B\rho = \frac{mv}{q} = \frac{p}{q}$$



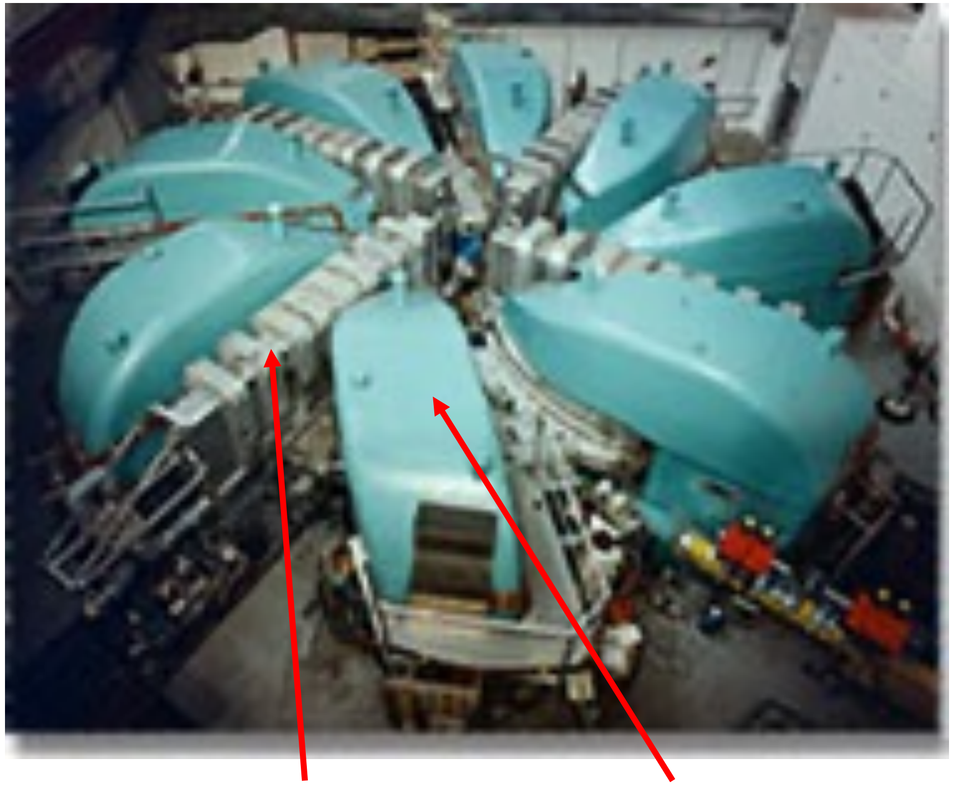
$$f_{rev} = \frac{\omega_{rev}}{2\pi} = \frac{1}{2\pi}\frac{v}{\rho} = \frac{1}{2\pi}\frac{qB}{m}$$



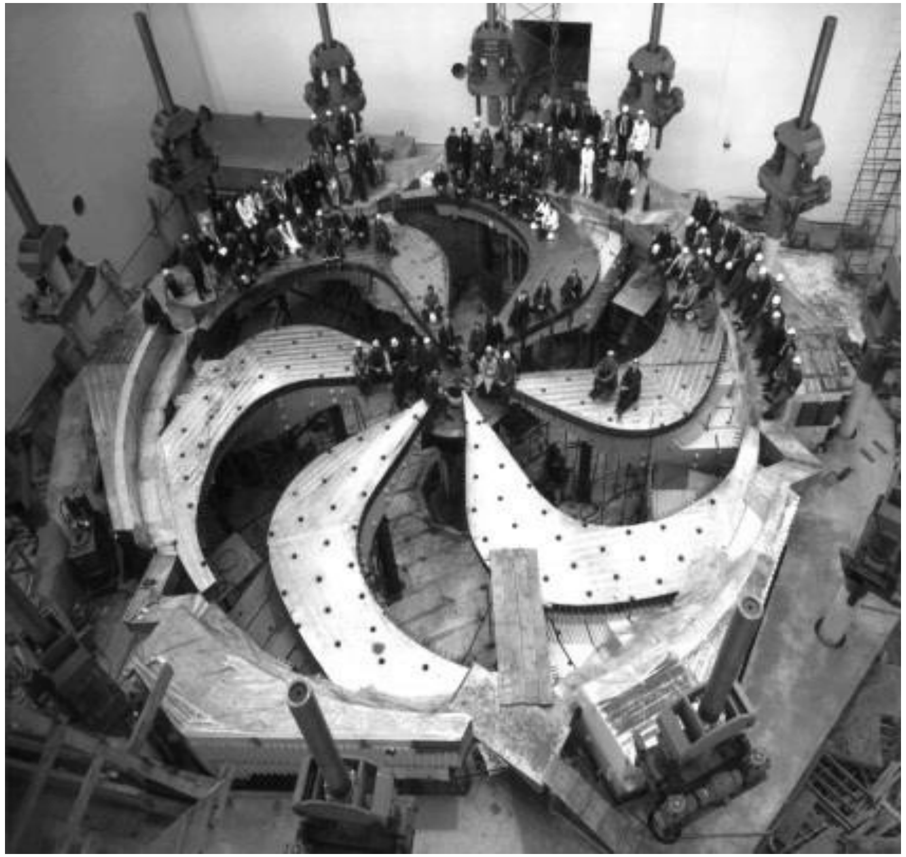
For m and B = constant
also f_{rev} = constant

$$E_c/A\ [\text{MeV}] = K_{cycl.}\ (Z/A)^2$$

The Big Ones: PSI & TRIUNF



accelerating cavity　　sector magnet



PSI: K=590 Cyclotron,
2.5 mA, 590 MeV, P_{beam} > 1MW

TRIUNF: K=500 Cyclotron,
0.2 mA, 500 MeV, P_{beam} > 100 kW

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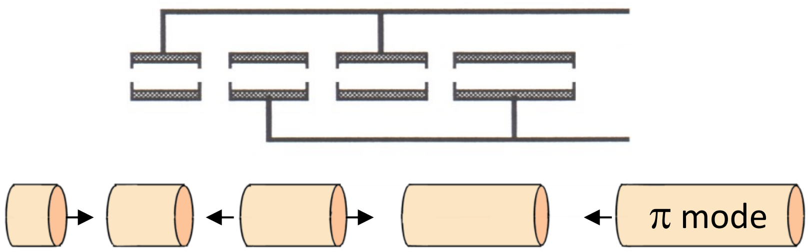
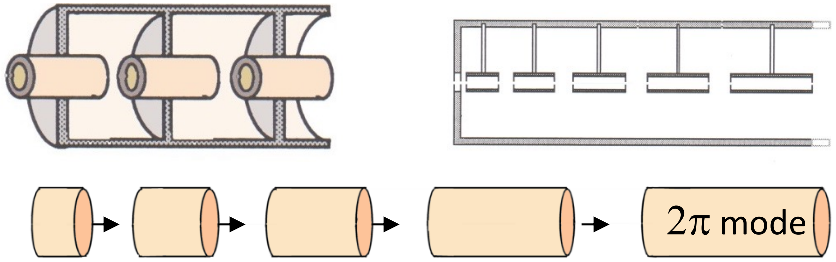
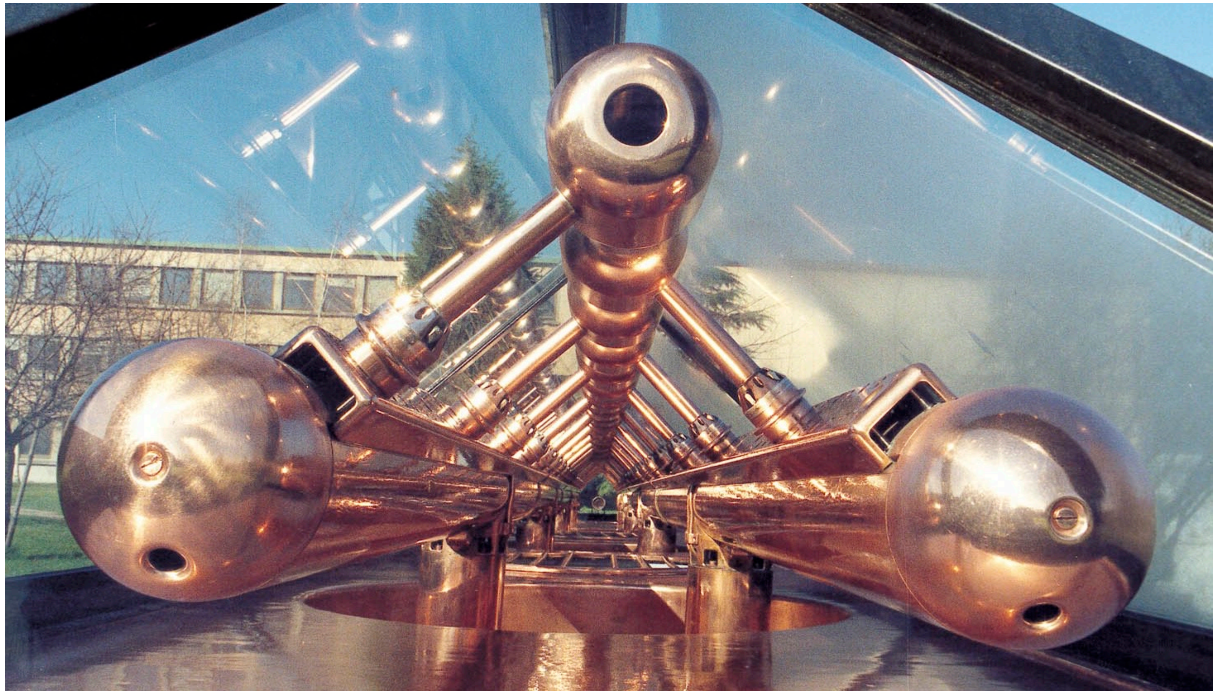
French Linear Accelerators in 1946







Historical examples: a **Wideroe type** structure
(ALICE heavy ion injector, IPN Orsay)

A drift tube linac (**DTL – Alvarez type**)
(Saturne, CEA Saclay)

Since seventies RFQ is a main actor

From the exit of the source and **up to a few hundreds of MeV**, the proton (ion) beam is slightly relativistic, **its speed practically follows the classical mechanics** lows **and it's proportional to the square root of the energy**.

In a DTL (Drift Tube Linac) to maintain the synchronism with a certain frequency, the length of the drift tubes should doubles each time the beam energy change by a factor of four.

It turns out that **a DTL is not performing efficiently when the injection energy is too low (50-100 keV).** The non-trivial effort of developing sources at higher voltage (200 kV and above) was partially overcoming this problem.

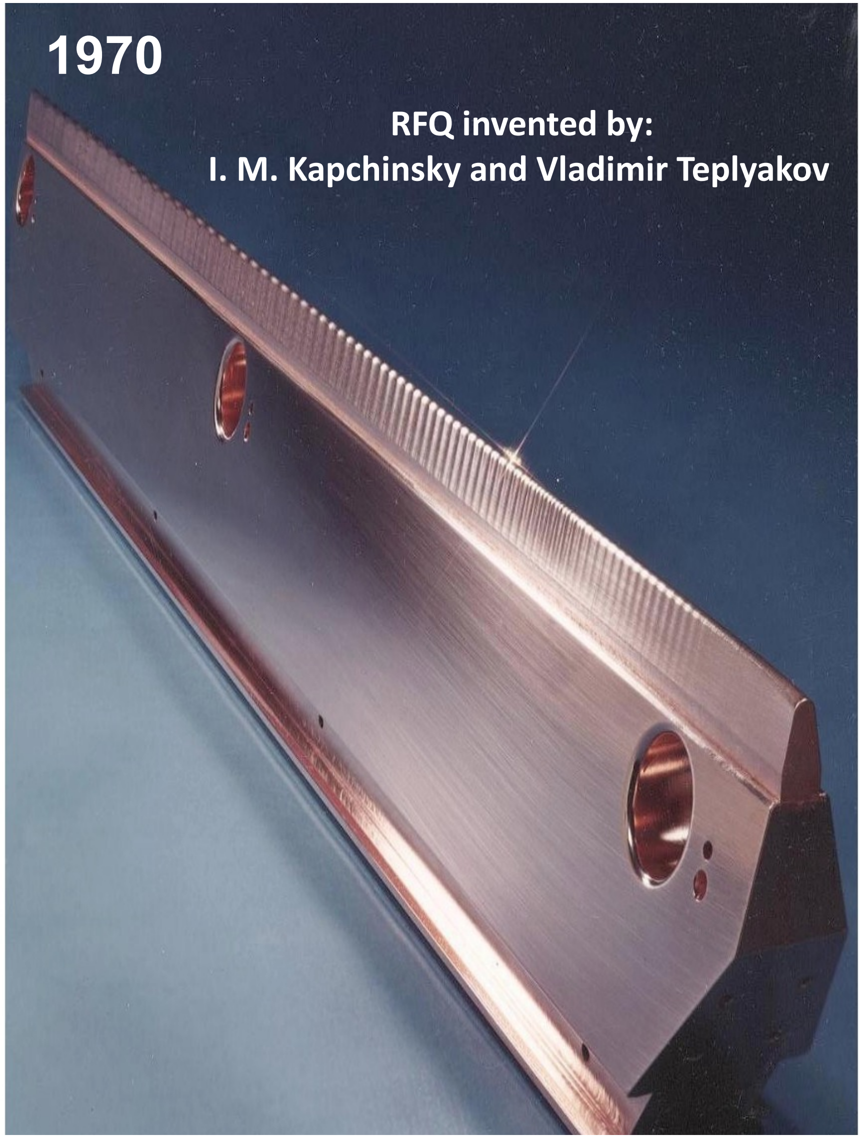
The **invention of the Radio Frequency Quadrupole, RFQ**, gave a bright solution to this problem, smoothly transforming the CW, low energy, beam from the source to **a few MeV bunched beam, ready for the injection into the DTL**.

About the RFQ - 1

The RFQ is a unique kind of accelerator. It is fundamentally an alternating-gradient focusing channel, with acceleration added as a perturbation. In all other accelerator types, the focusing is added as a perturbation to the structure.

The accelerating field profile of an RFQ can be tailored to produce any functional form along the axis. This permits optimizing the accelerating field profile for high acceptance of the beam from the ion source, or optimizing other parameters such as the exit beam emittance.

The longitudinal field profile is almost independent of the transverse quadupole focusing field and is established by the **modulations** along the vane tip.



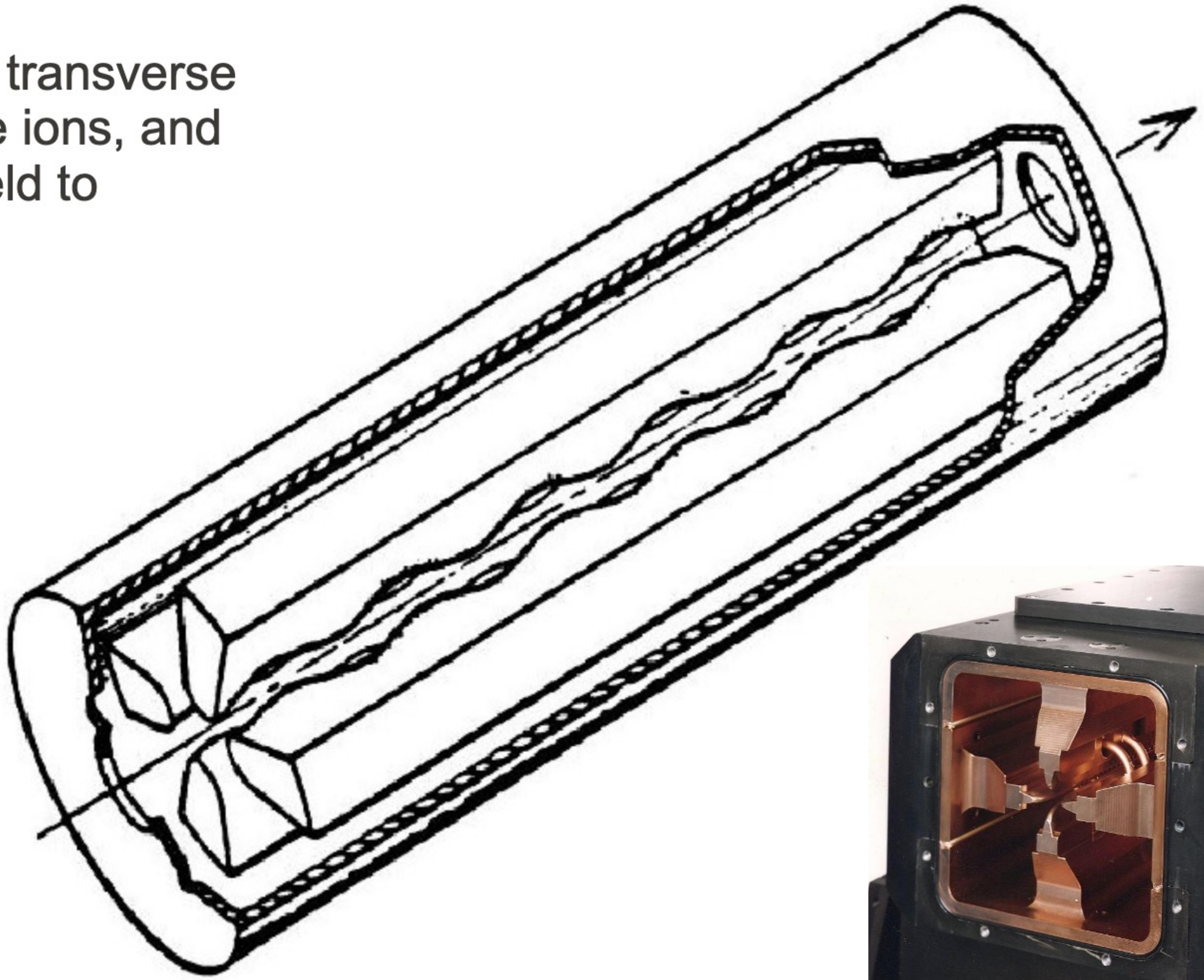
From SNS CDR

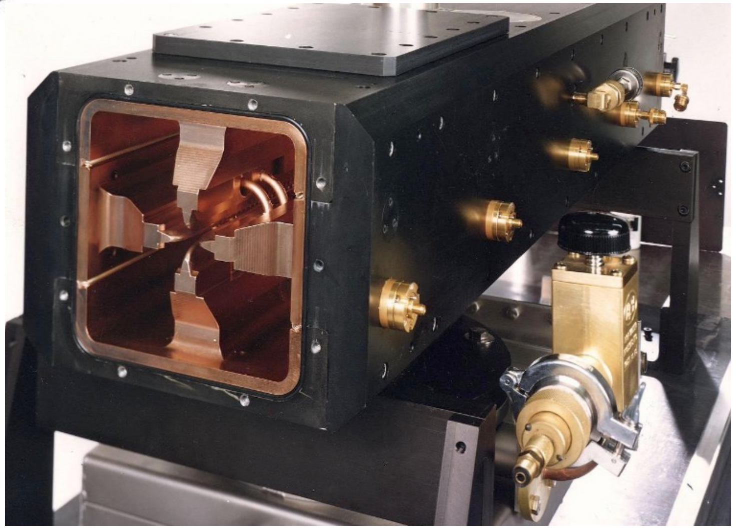
About the RFQ - 2

The RFQ accelerator uses a transverse electrostatic field to focus the ions, and a longitudinal electrostatic field to accelerate the ions.

The transverse alternating-gradient focusing results from the changing polarity of the RF field as the ion travels down the axis.

The ripples on the vane tip generate a longitudinal accelerating field and have only a small effect on the transverse focusing field.



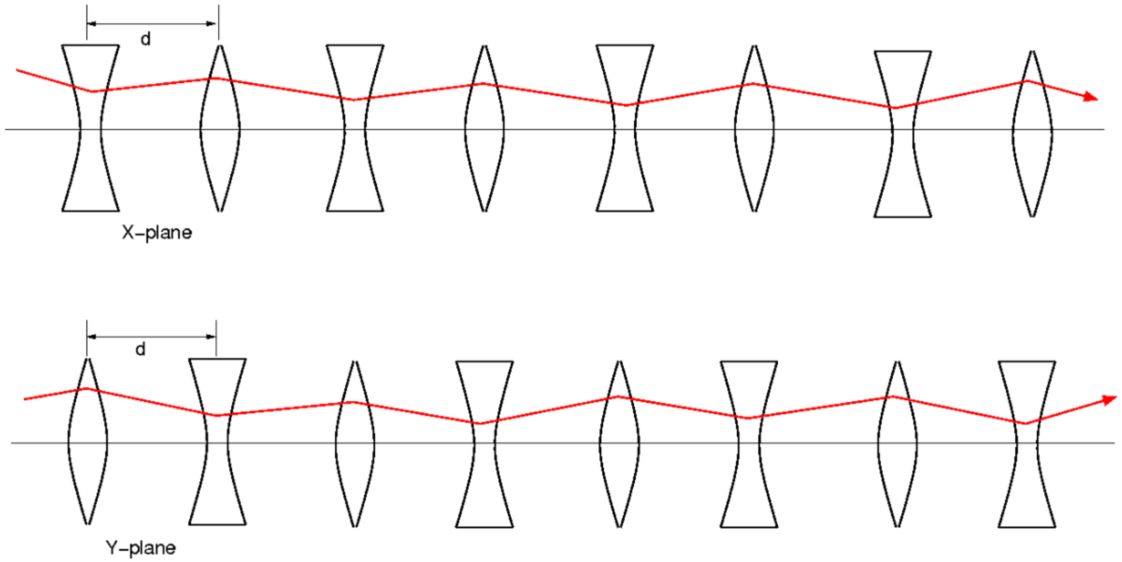


From SNS CDR

About the RFQ - 3

The RFQ is a unique type of accelerator that starts with a focusing lattice and adds acceleration as a perturbation.

Recall that a sequence of focusing and defocusing lenses forms a strong-focusing lattice.



From SNS CDR

For certain valules of the focusing/defocusing strengths and the distance between elements, a stable transport solution exists.

In addition, a matched solution exists that repeats the envelope for each period.

RFQ Technological Problems for CW

RFQ is great but **to be efficient needs very high electric field** to have adequate focussing forces and to reduce the length

For several years RFQ have been designed and built just for **pulsed operation** with a modesf **duty factor < 1%.**

As a consequence RFQs were mainly develotted for low energy proton and ions accelerators for nuclear physics, Good alternative to Tandem and Van der Graaf DC accelerators

First CW RFQ, called LEDA, developped at Los Alamos for the APT/ATW projects at the end of past century. Nominal parameters:

- H^- Injection energy: 75 keV
- Output Energy 6.7 MeV
- CW current >100 mA
- Beam Power >670 kW
- Total RF power > 2 MW
- Cooling power 1.5 MW

LEDA was switched off after ca. 100 hours of succesfull operation !!!

Since then a few CW RFQs have been designed and operated with currents of tenths of mA. The best examples are the two RFQ developped by **IHEP and IMP for the CADS project**

The LEDA RFQ at Los Alamos

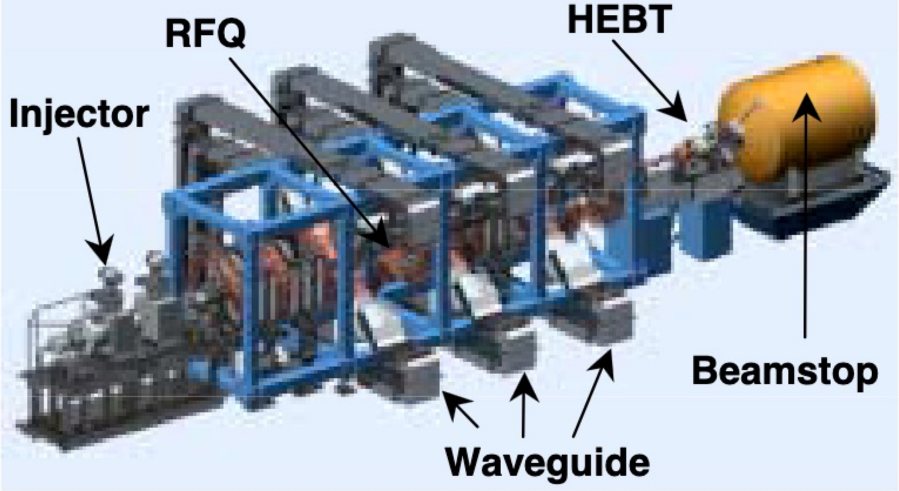


Figure 1. LEDA configuration for RFQ commissioning.

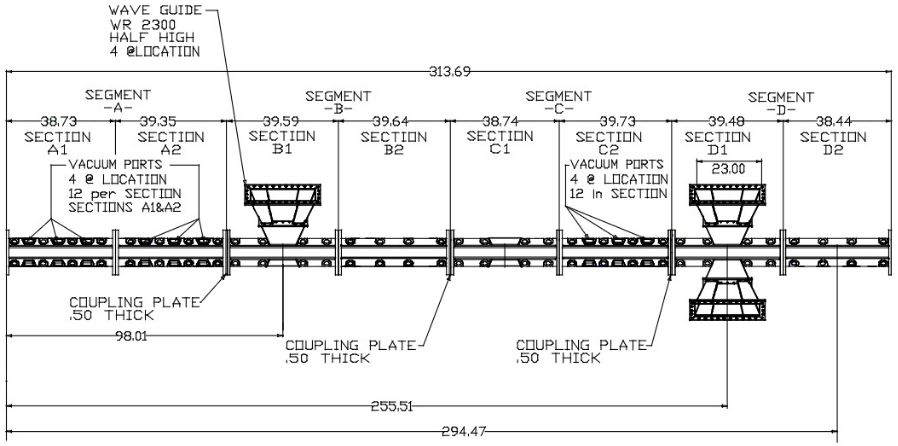
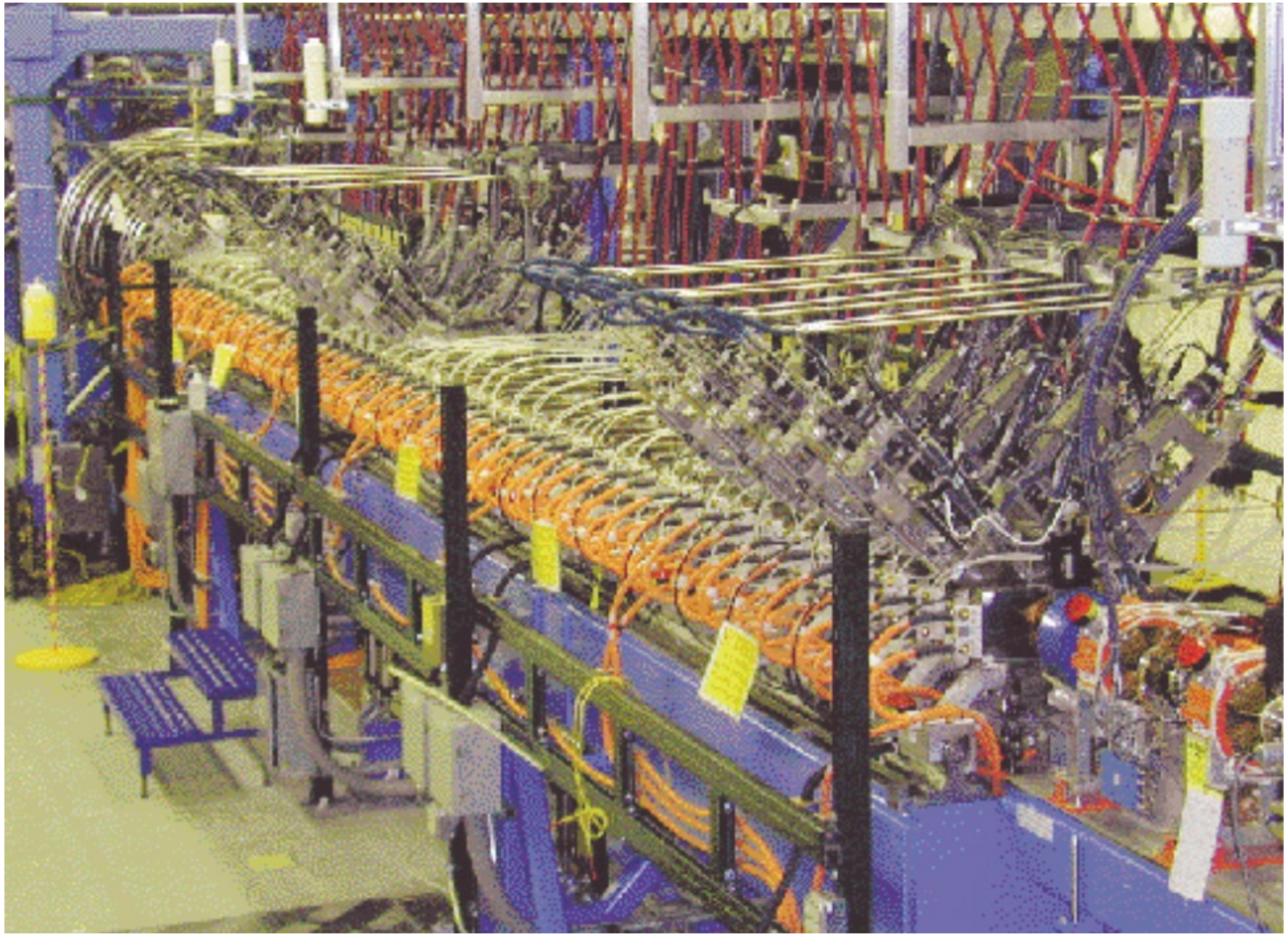


Figure 3. LEDA RFQ configuration.



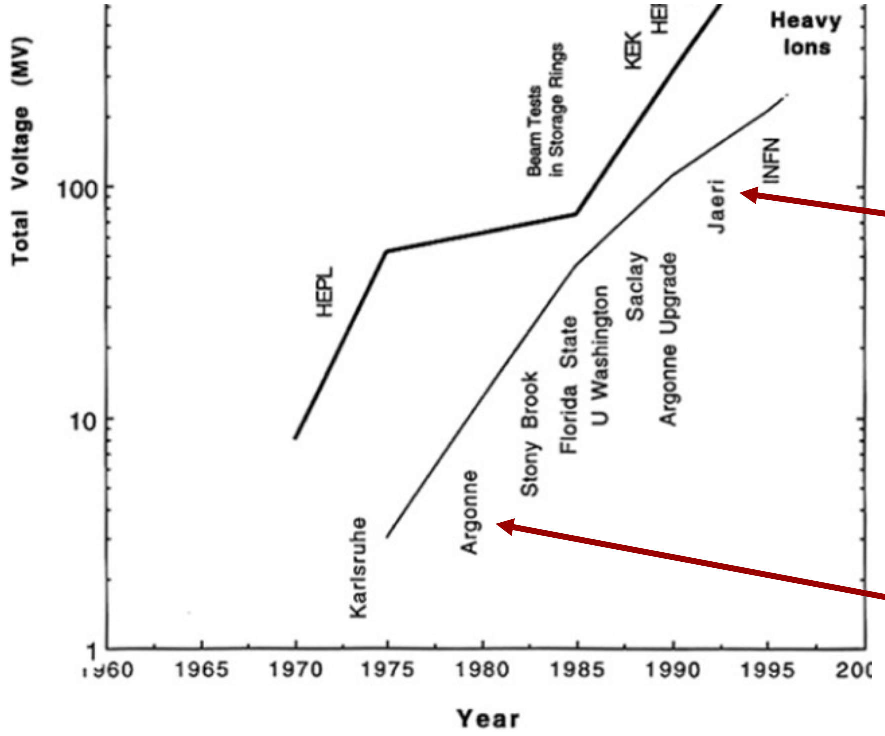
Normal Conducing Linac until mid-nineties

A part of a few CW, low current, ion accelerators, SRF was not considered until mid nineties for high power, non-fully relativistic, proton beams.

Up to mid-nineties all the high intensity proton linacs that have been built were pulsed and normal conducting.

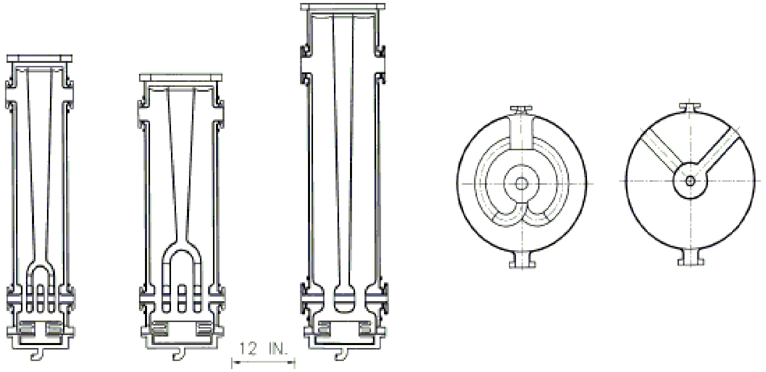
Their scope was substantially that of injecting moderate energy beams (few hundreds of MeV) into large synchrotons (as PS, SPS, TEVATRON, etc.) for high energy collisions.

SRF ion accelerators

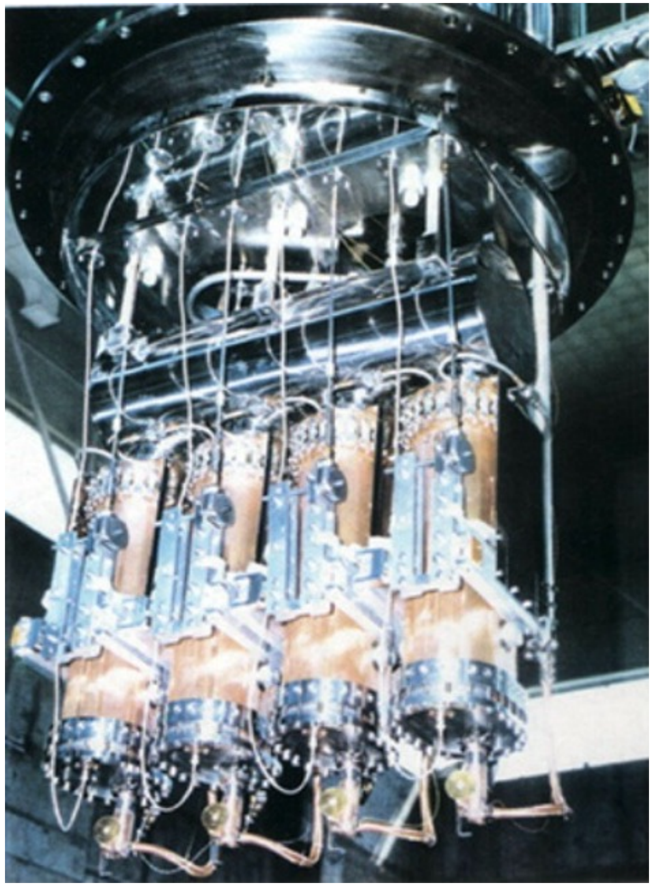


In parallel a few SRF CW Linacs for Ions

- New Projects in the nineties
  - Stony Brook
  - JAERI,
  - Washington University
  - Argonne upgrade,
  - Legnaro
- Improved cavity designs



- Higher accelerating fields, limited by:
  - Microphonics
  - No beam vacuum separation



Group of four Quarter-wave cavities for the JAERI Heavy-ion Linac

Contents

Pioneering Proposal for SRF above 100 MV

LINAC 96

A High Current Proton Linac with 352 MHz SC Cavities

C. Pagani, G. Bellomo, P. Pierini
INFN - Sezione di Milano - LASA, Via Fratelli Cervi 201, 20090 Segrate (MI) Italy

Energy (MeV)	$\bar{\beta}$	L_{active} (m)	L_{FIDO} (m)
100–185	0.47	0.800	7.5
185–360	0.60	1.022	8.4
360–1000	0.76	1.294	9.5

Table 1: Energy range, design $\bar{\beta}$, active length and length of the focussing period, for the three families of 4 cell cavities.

	S. 1	S. 2	S. 3
N. of structures	24	36	96
$\bar{\beta}$	0.47	0.60	0.76
E_{acc} (MV/m)	5.2	5.8	6.0
Section length (m)	45	76	226
10 mA beam current			
RF Power/section (MW)	0.85	1.81	6.35
RF Power/cavity (kW)	35.4	50.3	66.1
couplers/cavity	1	1	1
Klystron/section	1	2	6
120 mA beam current			
RF Power/section (MW)	10.2	21.72	76.2
RF Power/coupler (kW)	212	201	198
couplers/cavity	2	3	4
Klystron/section	≈10	≈20	≈80

$$\Delta T_{\mathrm{cav}}(MeV) = L_{\mathrm{active}}(m) E_{\mathrm{acc}}(MV/m) g\left(\frac{\bar{\beta}}{\beta}\right)\cos(\phi_{\mathrm{RF}})$$

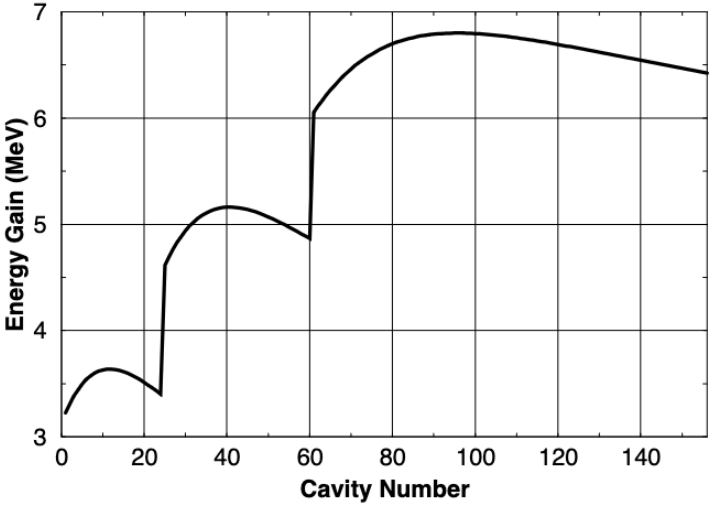
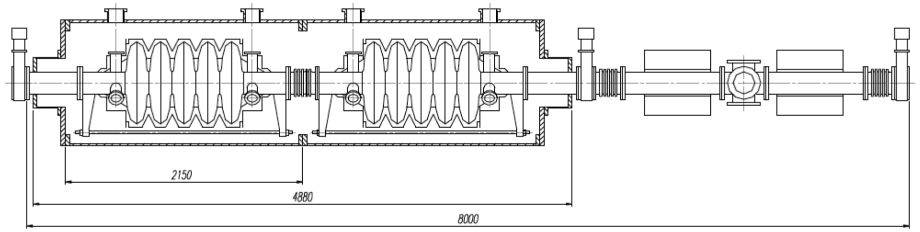


Figure 1: Energy gain along the three linac sections, as a function of the cavity number, keeping the nominal accelerating gradient fixed in each section (see text for details).

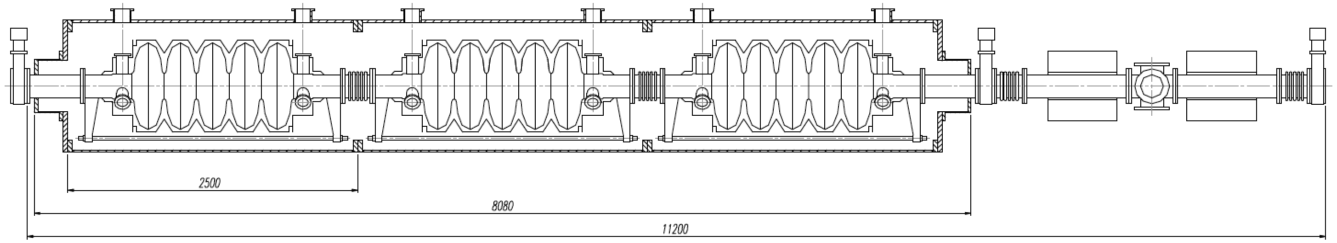
β = 0.85 done with CERN

The TRASCO Project as in 1998

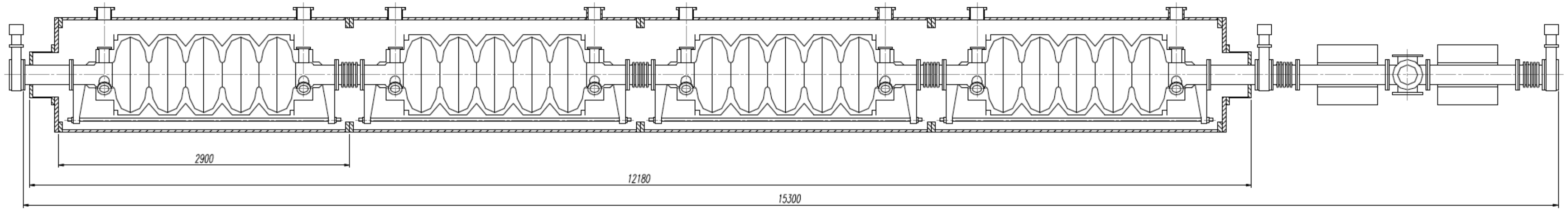
The basic lattice of the SC linac is that of a periodic doublet array with cavity cryomodules in the long drifts between the warm magnets. The linac is divided in three sections.



Section I (β=0.5)
2 cavities/cryomodule, L_{cell}=8. m



Section II (β=0.65)
3 cavities/cryomodule, L_{cell}=11.2 m

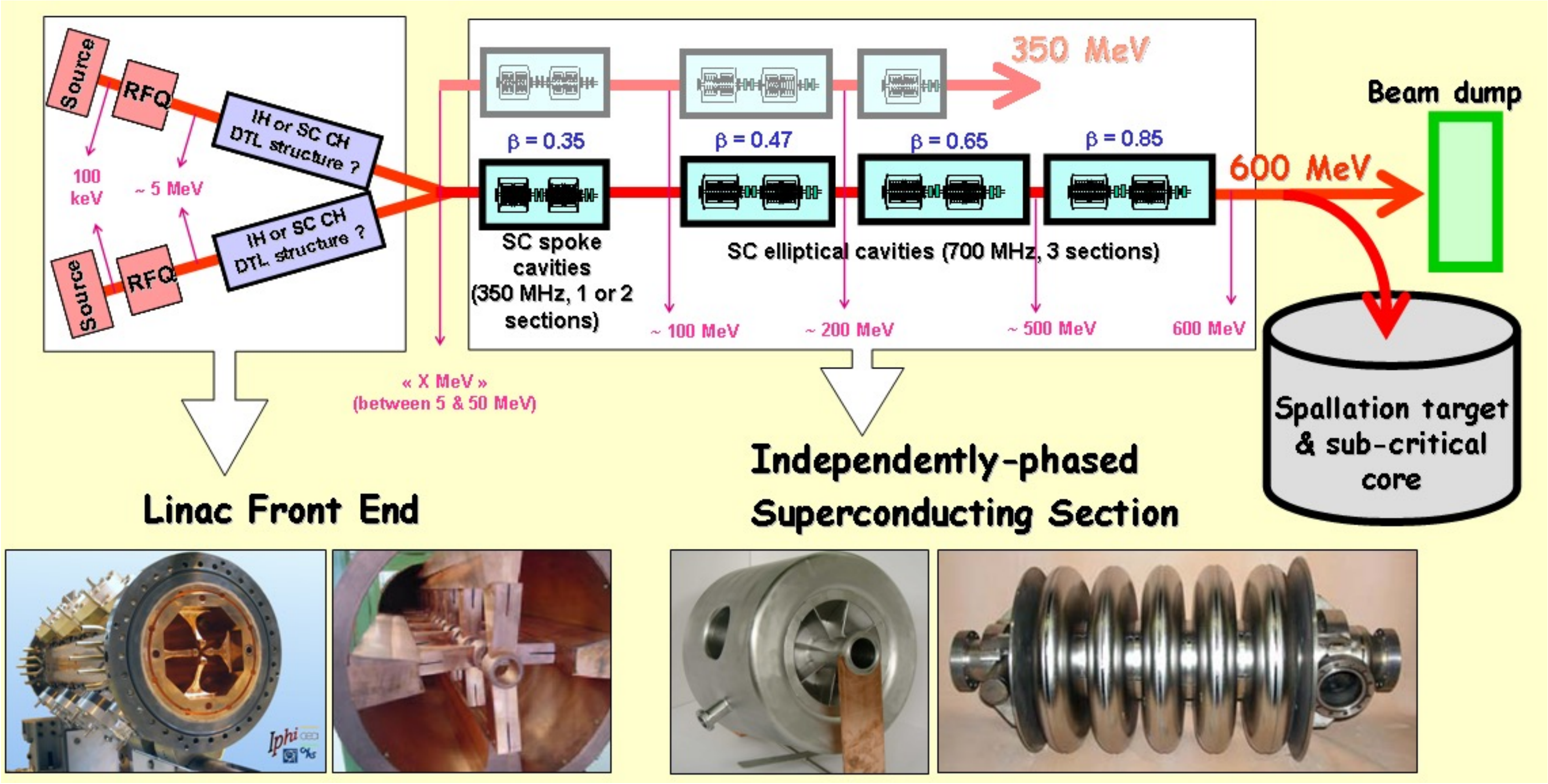


Section III
(β=0.85)
4 cavities/cryom.
L_{cell}=15.4 m

European ADS: EUROTRANS conclusion

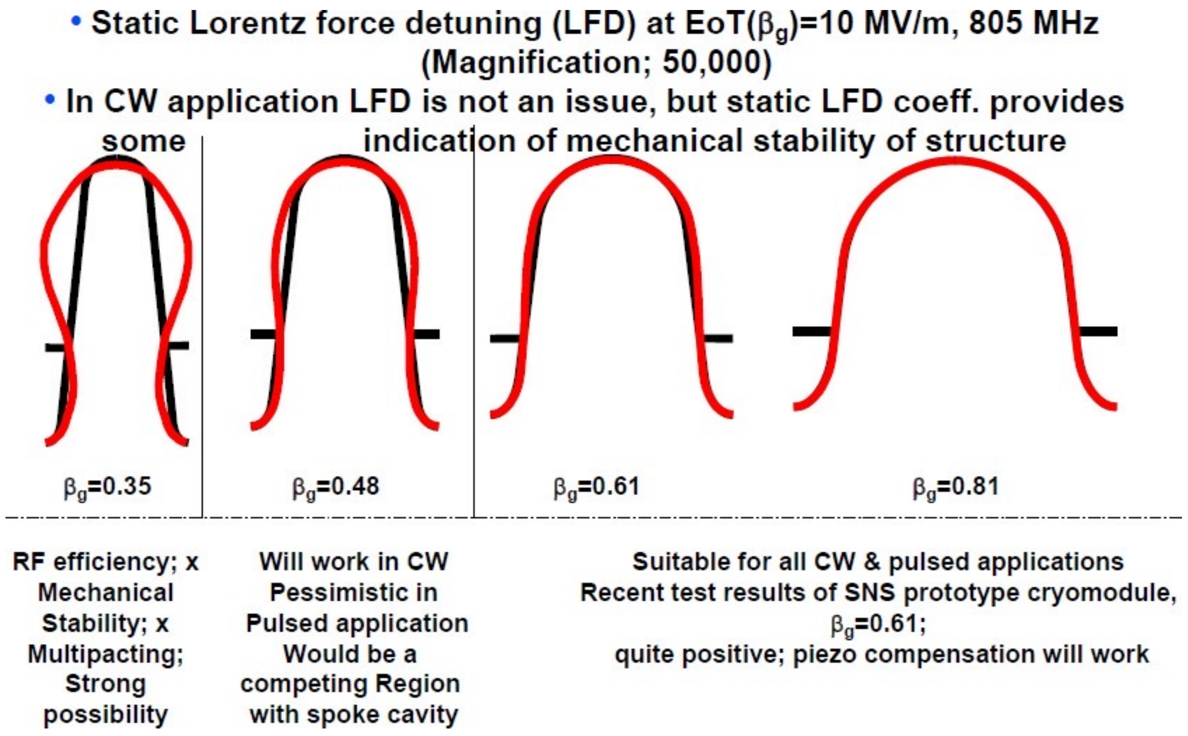
The conceptual design of ADS accelerator once frozen: a highly-modular SC linac

Several R&D activities have been successfully performed, leading to design choices & recommendations



Elliptical Cavity Issues for $\beta < 1$

- elliptical cavities have seen designs starting at $\beta \geq 0.5$ for cw application ($\beta \geq 0.6$ for pulsed for high energy acceleration (SNS, ESS)
- Elliptical cavities have intrinsic problems for lower velocity acceleration – in π mode the cell to cell distance is $\beta\lambda/2$ but the diameter is ~0.9 λ so cell length/diameter~ $\beta/2$ and the cavity starts to look like a bellows – mechanical stability, multipacting and low RF efficiency are all issues



Bob Laxdal - Non Elliptical Cavities SRF 2017

SNS – ASAC Meeting

Brookhaven National Lab
December 6-8, 1999

Proton SRF Activities in Europe

Carlo Pagani

INFN Milano-LASA & University of Milano

ISTITUTO NAZIONALE DI FISICA NUCLEARE
SEZIONE DI MILANO

SNS and RIA acknowledged our contribution

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PAC 2001 - Abstract Information for Author

PAC2001
2001 PARTICLE ACCELERATOR CONFERENCE
CHICAGO, ILLINOIS
JUNE 18-22, 2001

Abstract Title Superconducting Prototype Cavities for the Spallation Neutron Source (SNS) Project*
Submitted 01/16/2001 14:13:27
Modified 01/16/2001
Classification Superconducting RF
Keywords accelerator
superconducting-rf
Presentation Poster (Prefers not to make an oral presentation)
Speaker Peter Kneisel
Funding Agency *This work was supported by the U.S. DOE Contract No DE-AC05-00-OR22725

Abstract ID 2546
Home Page
Session ID
Paper URL
TOC Page #
Primary Author Peter Kneisel *Thomas Jefferson National Accelerator Facility*
Co-author(s) John Brawley, Richard Bundy, Gianluigi Ciovati, Kurt Macha, Danny Machie, John Mammosser, Ron Sundelin, Larry Turlington, Katherine Wilson *Thomas Jefferson National Accelerator Facility* , J. Sekutowicz *Deutsches Elektron Synchrotron* , D. Barni, C. Pagani, R. Parodi, P. Pierini *Istituto Nazionale di Fisica Nucleare* , D. Schrage *Los Alamos National Laboratory* , M. Doleans, S.H. Kim, D. Mangra *Oak Ridge National Laboratory* , P. Ylae-Oijala *Univ. Helsinki*

Abstract

The Spallation Neutron Source project includes a superconducting linac section in the energy range from 192 MeV to 1000 MeV. For this energy range two types of cavities are needed with geometrical β - values of β= 0.61 and β= 0.81. An aggressive cavity prototyping program is being pursued at Jlab, which calls for fabricating and testing of four β= 0.61 cavities and two β= 0.81 cavities. Both types consist of six cells made from high purity niobium and feature one HOM coupler of the TESLA type on each beam pipe and a port for a high power coaxial input coupler. Three of the four β= 0.61 cavities will be used for a cryomodule test at the end of the year 2001. At this time two cavities of each type have been fabricated and the first tests on the β= 0.61 cavity exceeded the design values for gradient and Q - value: E_{acc} = 10.3 MV/m and Q = 6.5 x 10^9 at 2.1K. This paper will describe the cavity design with respect to electrical and mechanical features, the fabrication efforts and the results obtained with the different cavities existing at the time of the conference.

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PAC2001
2001 PARTICLE ACCELERATOR CONFERENCE
CHICAGO, ILLINOIS
JUNE 18-22, 2001

Abstract Title Niobium Cavity Development for the High-Energy Linac of the Rare Isotope Accelerator
Submitted 01/12/2001 16:59:47
Modified 01/12/2001
Classification Superconducting RF
Keywords heavy-ion
linac
rf-structure
superconducting-rf
Presentation Poster (Prefers not to make an oral presentation)
Speaker W. Hartung
Funding Agency

Abstract ID 1491
Home Page
Session ID
Paper URL
TOC Page #
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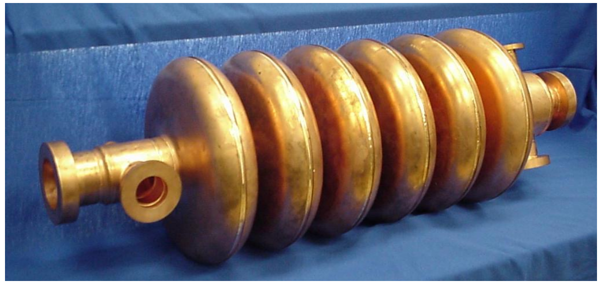
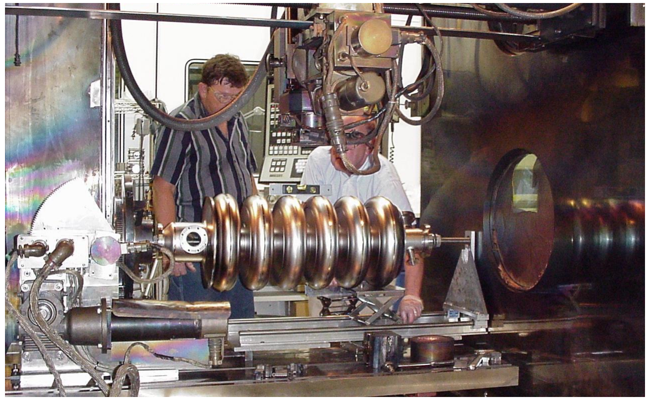
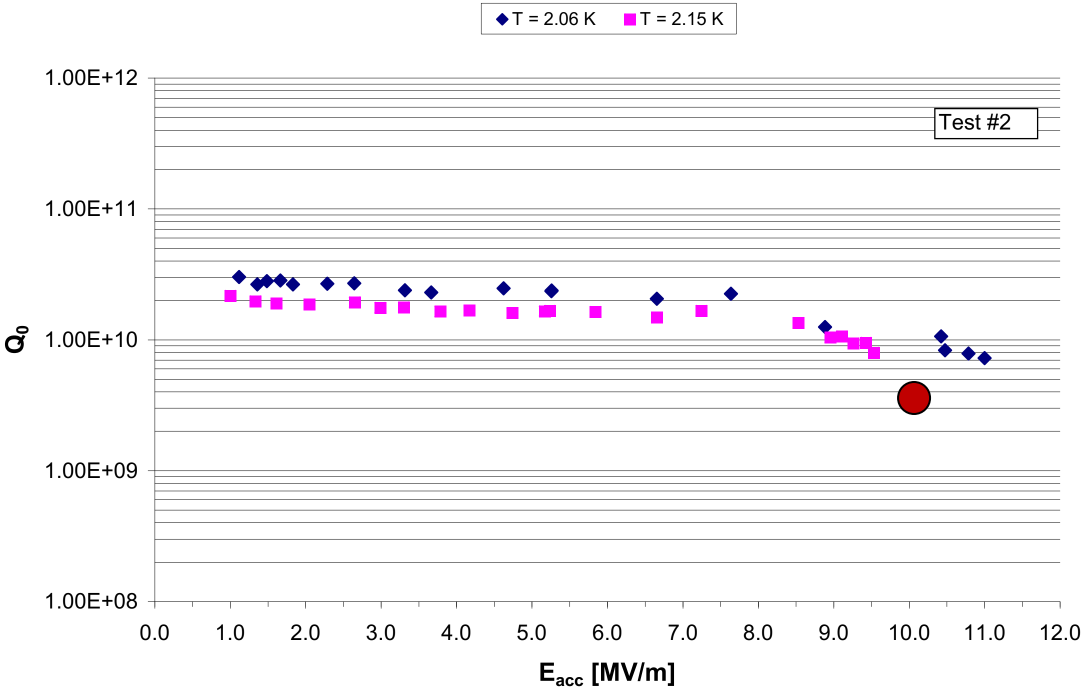
Abstract

The Rare Isotope Accelerator (RIA) is being designed to supply an intense source of exotic isotopes for nuclear physics research. Superconducting cavities are to be used to accelerate RIA's CW beam of heavy ions to 400 MeV per nucleon. Because of the varying velocity of the heavy ion beam along the linac, a number of different types of superconducting structures are needed. For the high-energy end of the linac, 3 different types of axisymmetric multi-cell Nb cavities of elliptical cross-section are planned. For two of these cavities (geometric β = 0.61 and 0.82), the existing designs for the Spallation Neutron Source (SNS) will be adopted. For the third structure (geometric β = 0.47), a new cavity shape has been designed. Design and prototyping of the latter cavity has been undertaken as a collaboration between the National Superconducting Cyclotron Laboratory (NSCL), Thomas Jefferson National Accelerator Facility (JLAB), and the Laboratorio Acceleratori e Superconduttività Applicata (LASA) of INFN Milano. Microphonic excitation of the cavity is of especial concern due to the inherent lack of mechanical rigidity of β < 1 structures and the comparatively light beam loading for RIA relative to SNS. Multipacting is another source of concern. This paper will give an overview of the first results of the design and prototyping efforts resulting from the NSCL/JLAB/LASA collaboration.

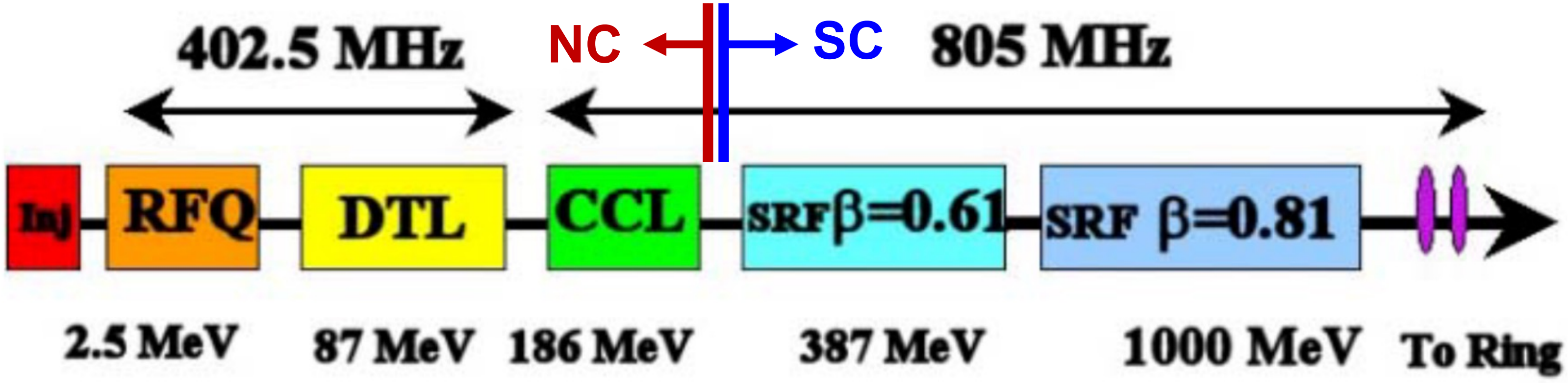
SNS $\beta = 0.61$ 6-cell, 805 MHz



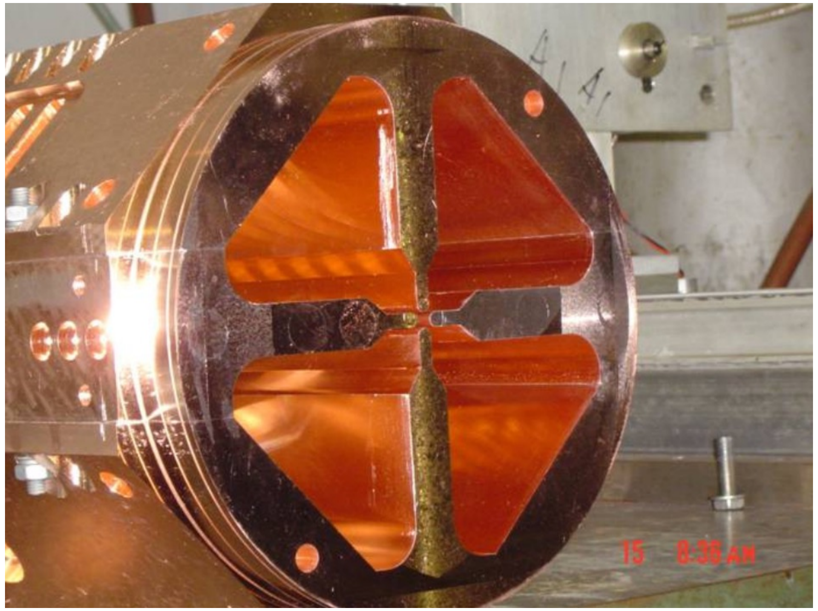




SNS RFQ & Drift Tube Linac (DTL)



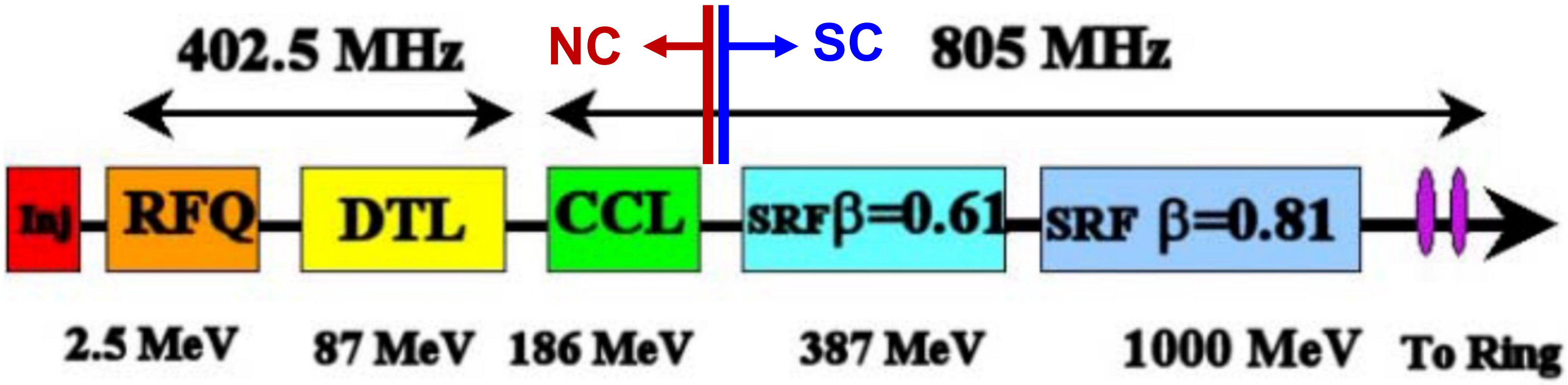
RFQ



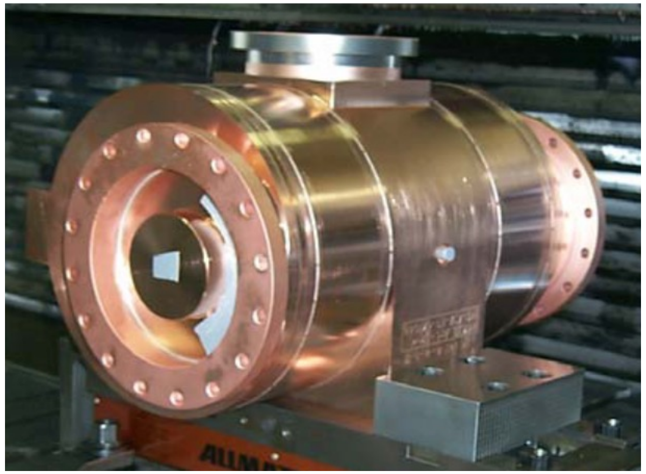
DTL

- *System includes 210 drift tubes, transverse focusing via PM quads, 24 dipole correctors, and associated beam diagnostics*

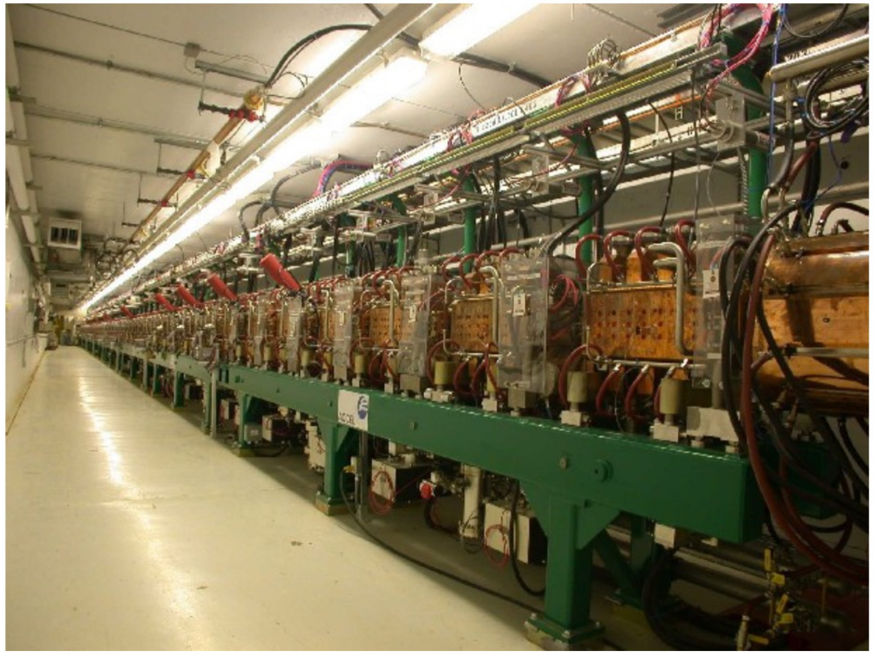
SNS CCL: Coupled Cavity Linac



CCL



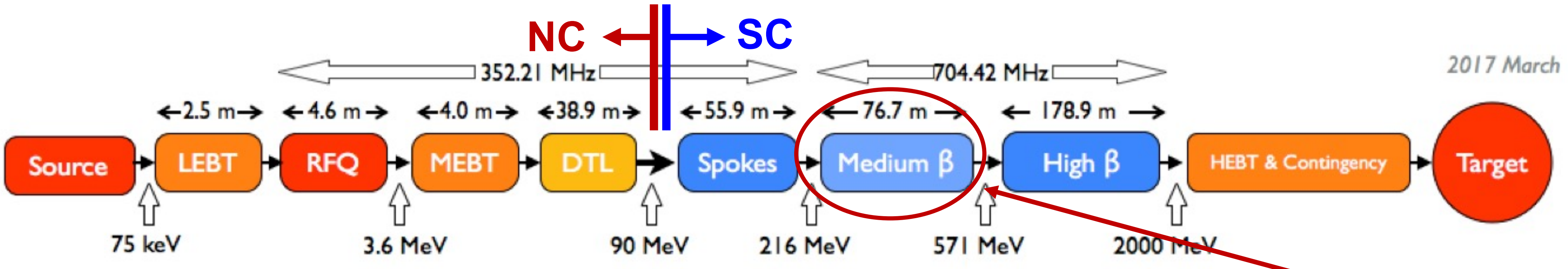
- *System consists of 48 accelerating segments, 48 quadrupoles, 32 steering magnets and diagnostics*



EU Spallation Neutron Source, ESS

ESS Parameters	
Max Energy	2 GeV
Average beam power	5 MW
Peak beam power	125 MW
Peak beam current	62.5 mA
Pulse length	2.86 ms
Repetition rate	14 Hz
Energy from SC sections	96 %

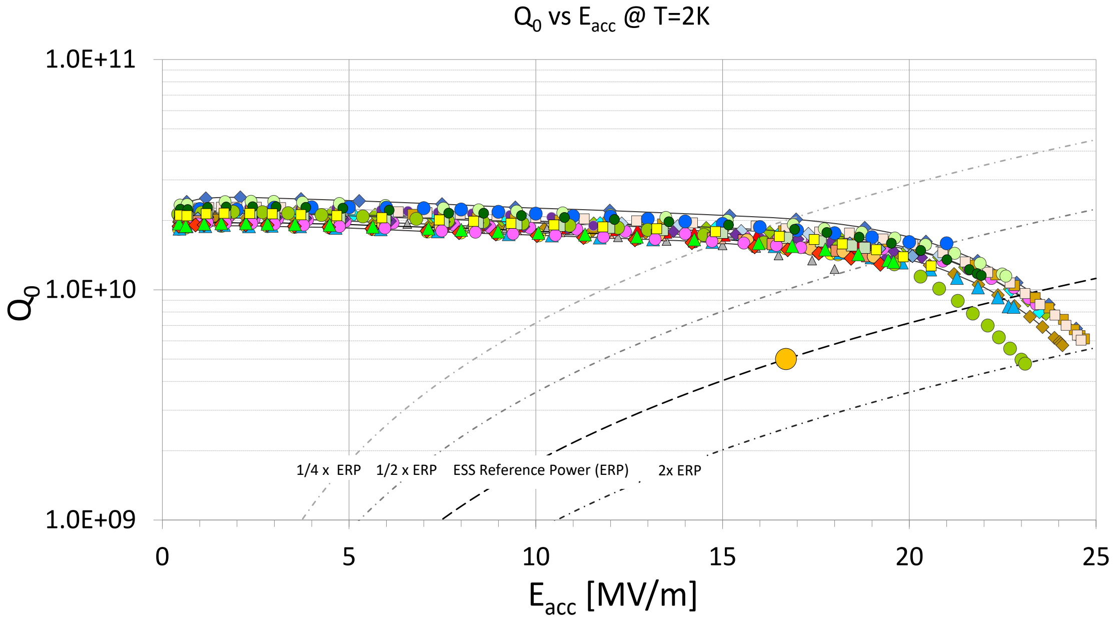
INFN LASA Contribution to ESS



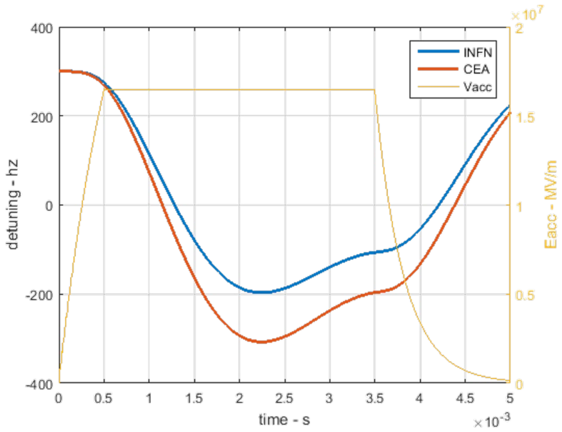
INFN-LASA contribution

•INFN LASA In-Kind contribution

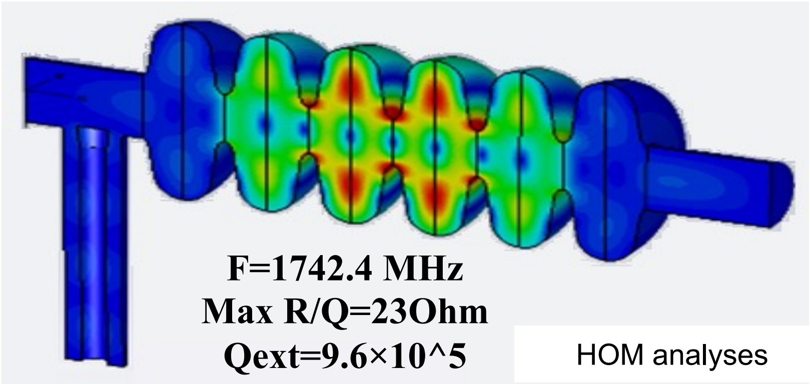
- Design and qualification of the 6-cell cavities for the Medium β Section
- Fabrication of 36 complete cavities in the industry, following a build-to-print strategy
- Cavities delivered ready for the cold test.
  - Analogous strategy as for the XFEL
- Cold test in a qualified infrastructure (DESY).
- Delivery at CEA ready for the cryomodule assembly.
- First cavity, ready for the cold test by November 2018
- Delivery rate: 2 cav/3 weeks

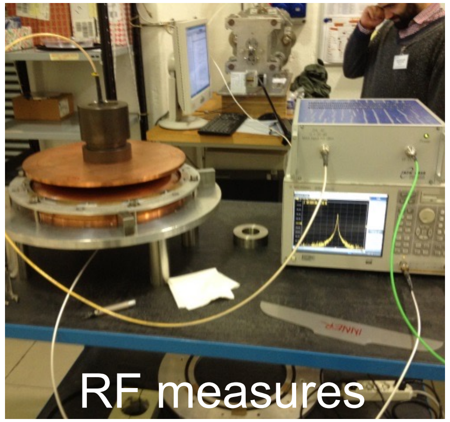


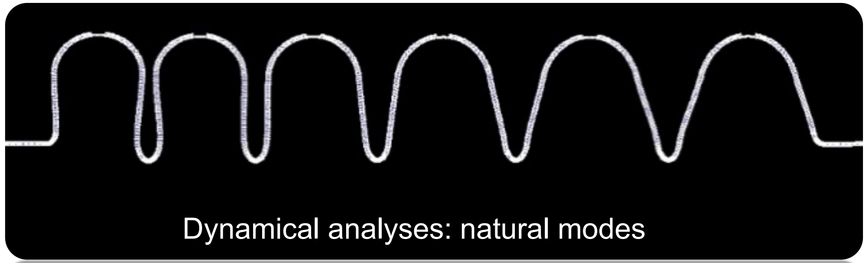
From Design to Prototypes and Production

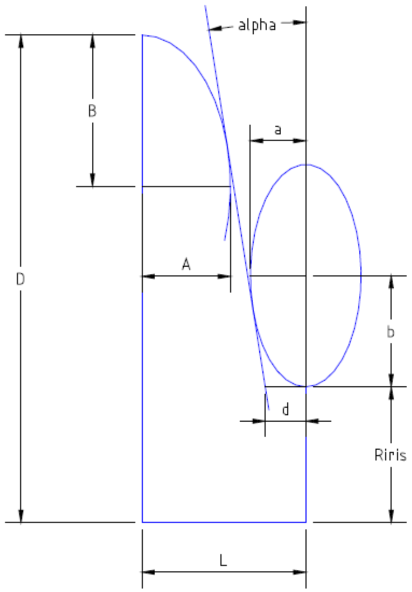


LFD from cavity simulator

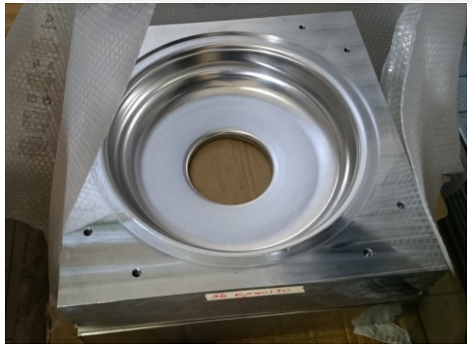


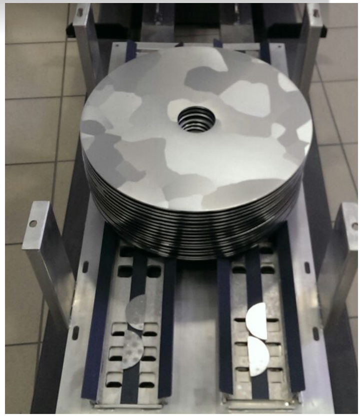


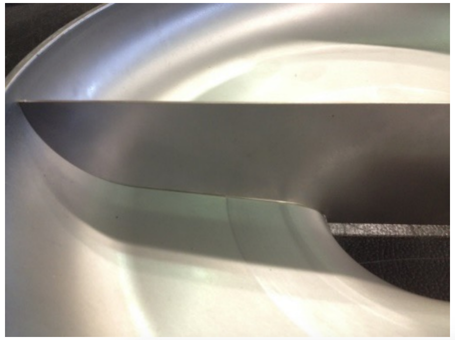




Cell shape design







About the Transit Time Factor

$$\Delta W_{kin} = qE_{acc} L_{cav} T_N(\beta_c, \beta_p) \cos\Phi_s$$

$$T_N(\beta_c, \beta_p) = \frac{4}{\pi N} \frac{\sin\left(N\frac{\pi}{2}\left(1-\frac{\beta_c}{\beta_p}\right)\right)}{1-\left(\frac{\beta_c}{\beta_p}\right)^2}$$

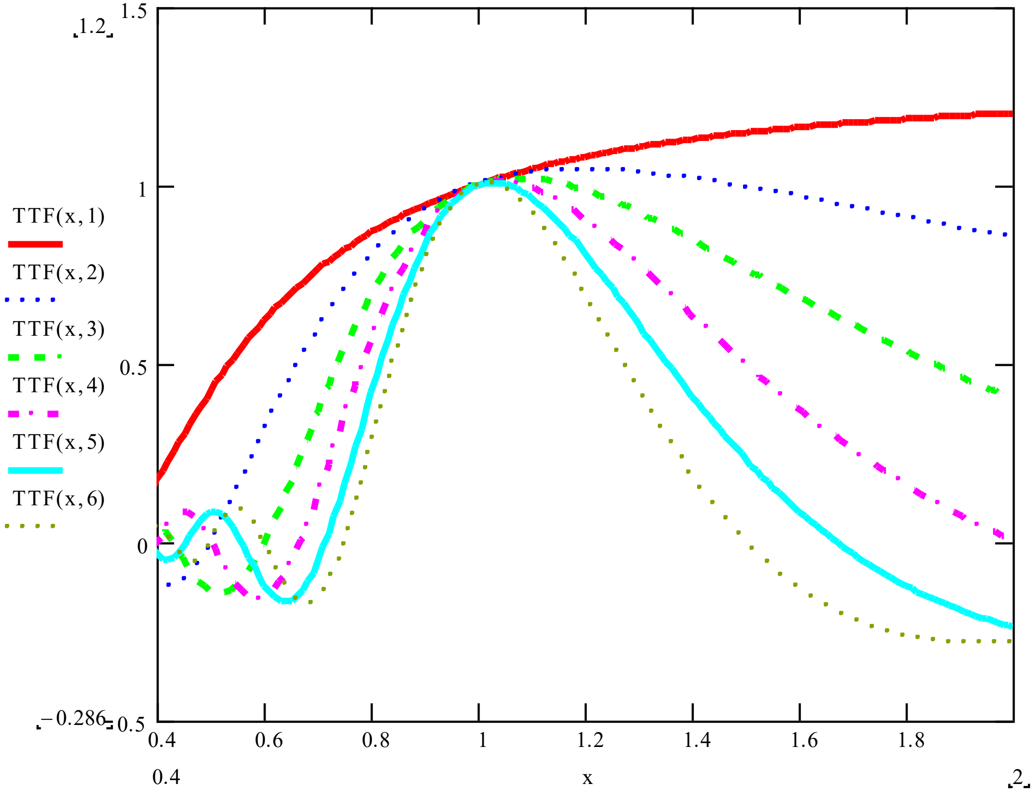
The energy gain of the particle depends on:

- The accelerating field
- The operating synchronous phase
- The velocity mismatch between the particle velocity and the synchronous velocity in the cavity

For high N values the Transit Time Factor is too narrow, i.e. The cavity works efficiently in a small velocity range

Compromise between space efficiency and velocity acceptance

E_{acc} is limited by peak fields!



Low beta designs start to be considered

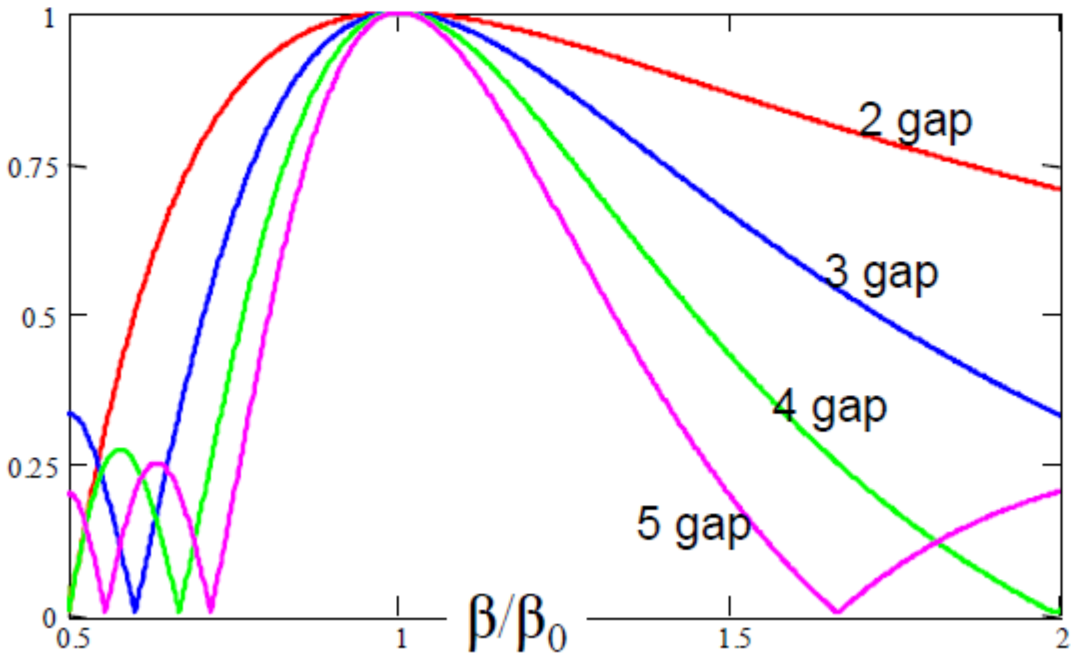
At the RFQ exit $\beta = 0.07 \div 0.12$ and its variation with energy is less dramatic

2 gaps SRF cavities can be a good choice

RF frequency can be higher and cavities with efficient and stable geometries can be developped

Cavities either for **pulsed and CW** operation are then designed and fabricated in different labs

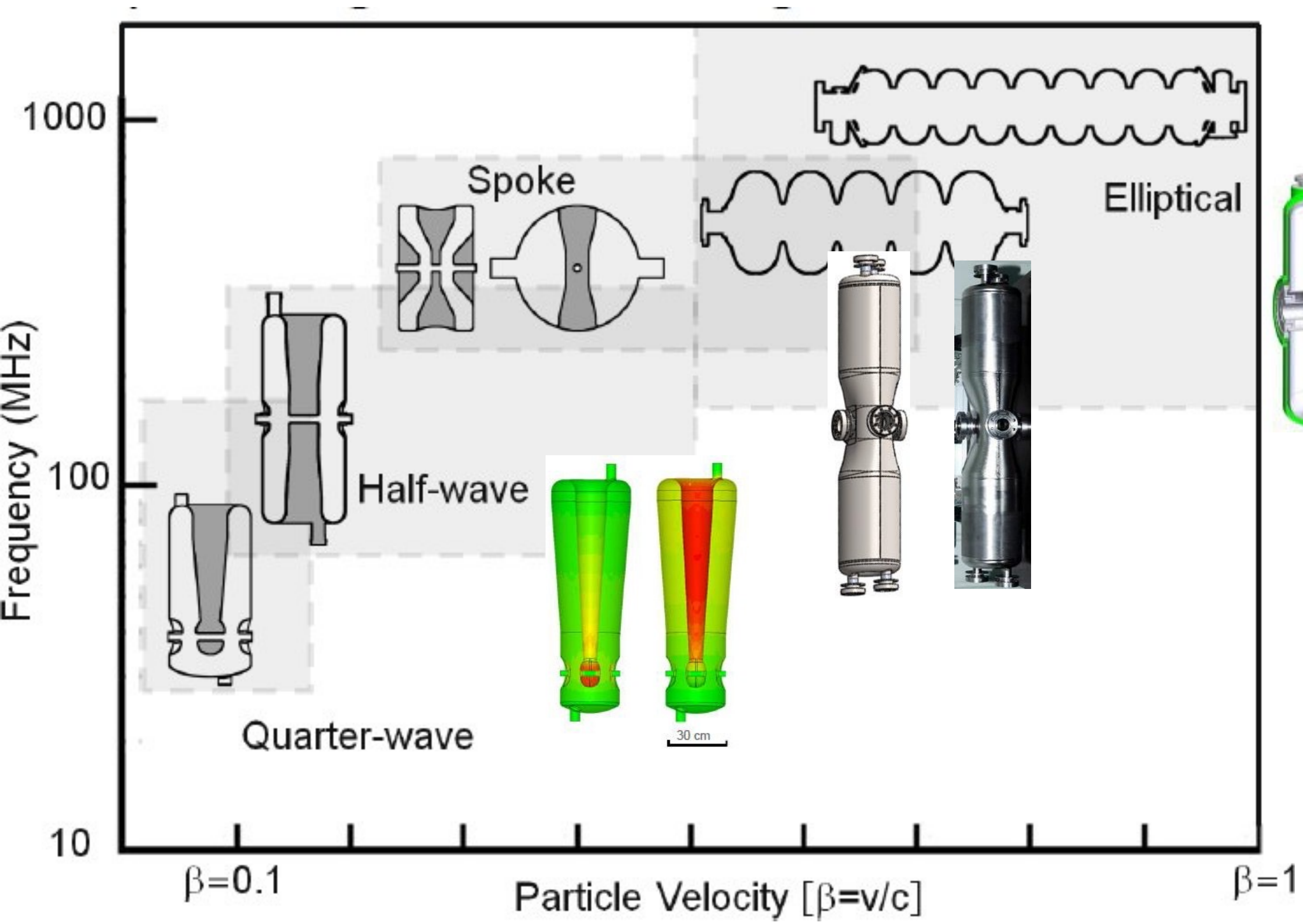
Transit Time Factor

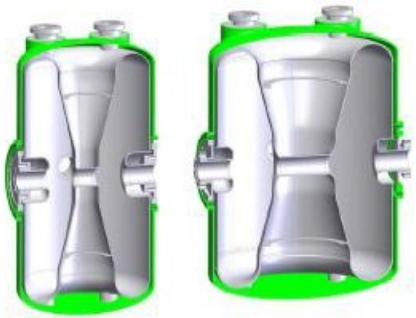


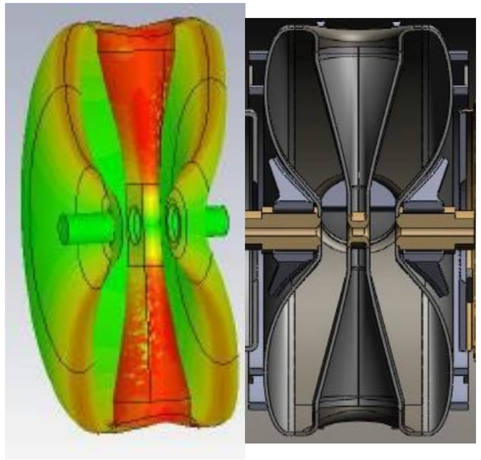
Normalized transit time factor curves vs. normalized velocity, for cavities with different number of gap

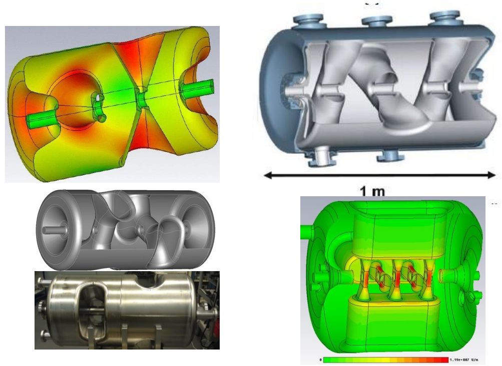
- Multiple gaps (n) will increase the total voltage gain since $V_{eff} = E_{acc} * L_{act}$ and $L_{act} =. n * \beta \lambda/2$
- But the velocity acceptance of the transit time factor is reduced as n increases

A few of the many cavities for low beta









Others designs that I don’t like because of fabrication problems

Contents

CADS asks for CW: ADS project in China

IMP is the leading institute to carry out the research in cooperation with a number of participants.

IMP

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

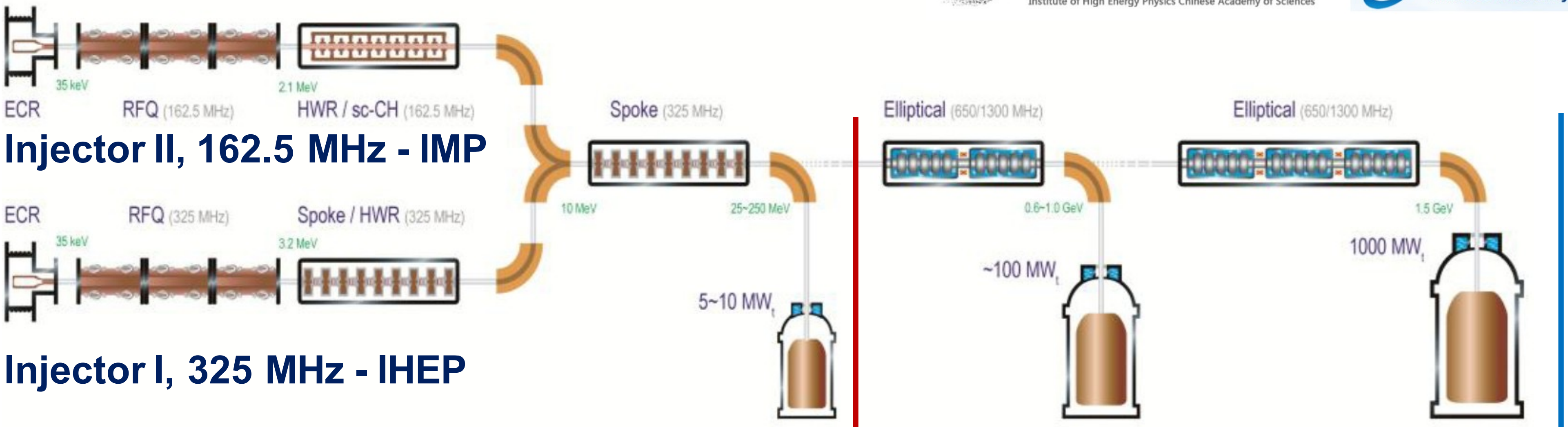
The CAS ADS Program

IHEP

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

CASHIPS

Hefei Institutes of Physical Science
Chinese Academy of Sciences



Injector II, 162.5 MHz - IMP

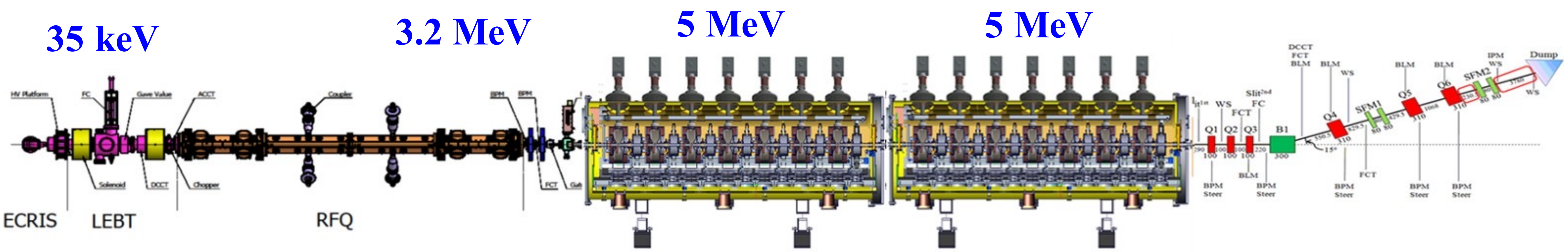
Injector I, 325 MHz - IHEP

Y2011-2016, 1.78 B CNY
"Strategic Technology Pilot Project" of CAS
Key technology R&D

Stage 1 - 10 MW$_t$

Stage 2 - 500 MW$_t$

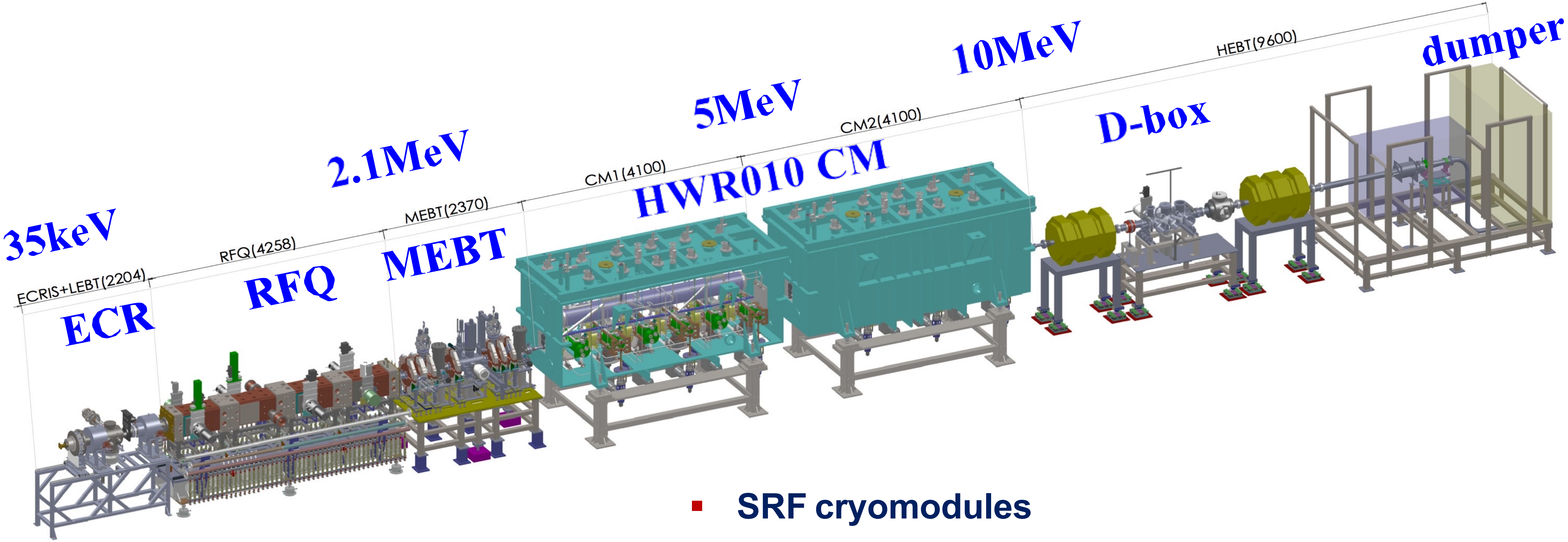
Injector I at IHEP



- **Ion soure**, 35 keV
- **RFQ**
  - frequency **325 MHz**, **3.2 MeV**,
  - RF power 280 kW, four couplers

- **SRF cryomodules**
  - Frequency **325 MHz**, **2 K** operation
  - Spoke beta = 0.12, E_{peak} = 32 MV/m, V_{acc} = 0.78 MV
  - 7 Spokes and 7 solenoids per modulez

CADS Injector II at IMP

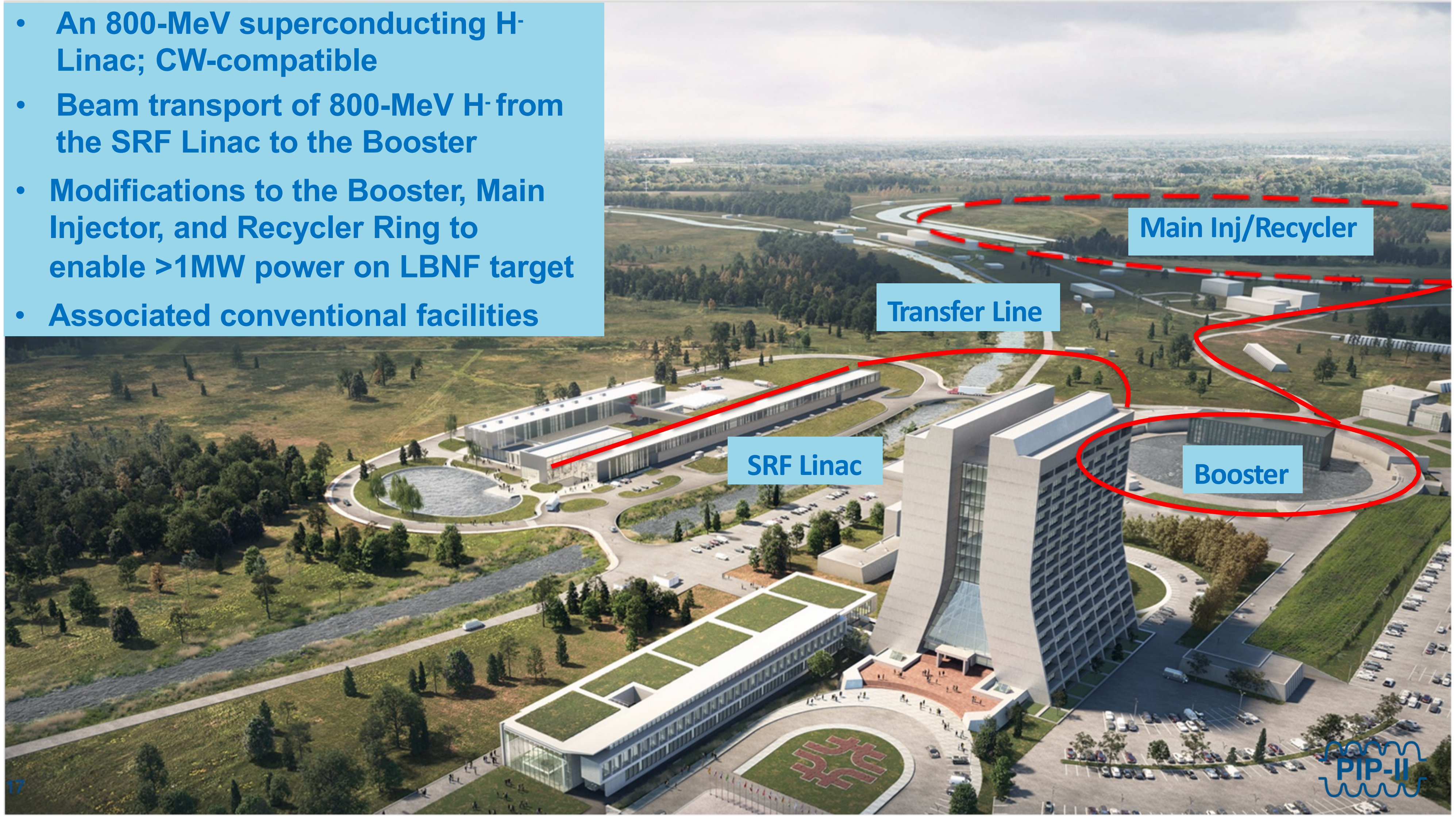


- **SRF cryomodules**
  - Frequency **162.5 MHz**, **4.5 K**
  - HWR beta = 0.1, E_{peak} = 25 MV/m, V_{acc} = 0.78 MV
  - 6 HWRs and 6 solenoids per module

- **RFQ**
  - frequency **162.5 MHz**, **2.1 MeV**,
  - RF power 100 kW, 2 couplers

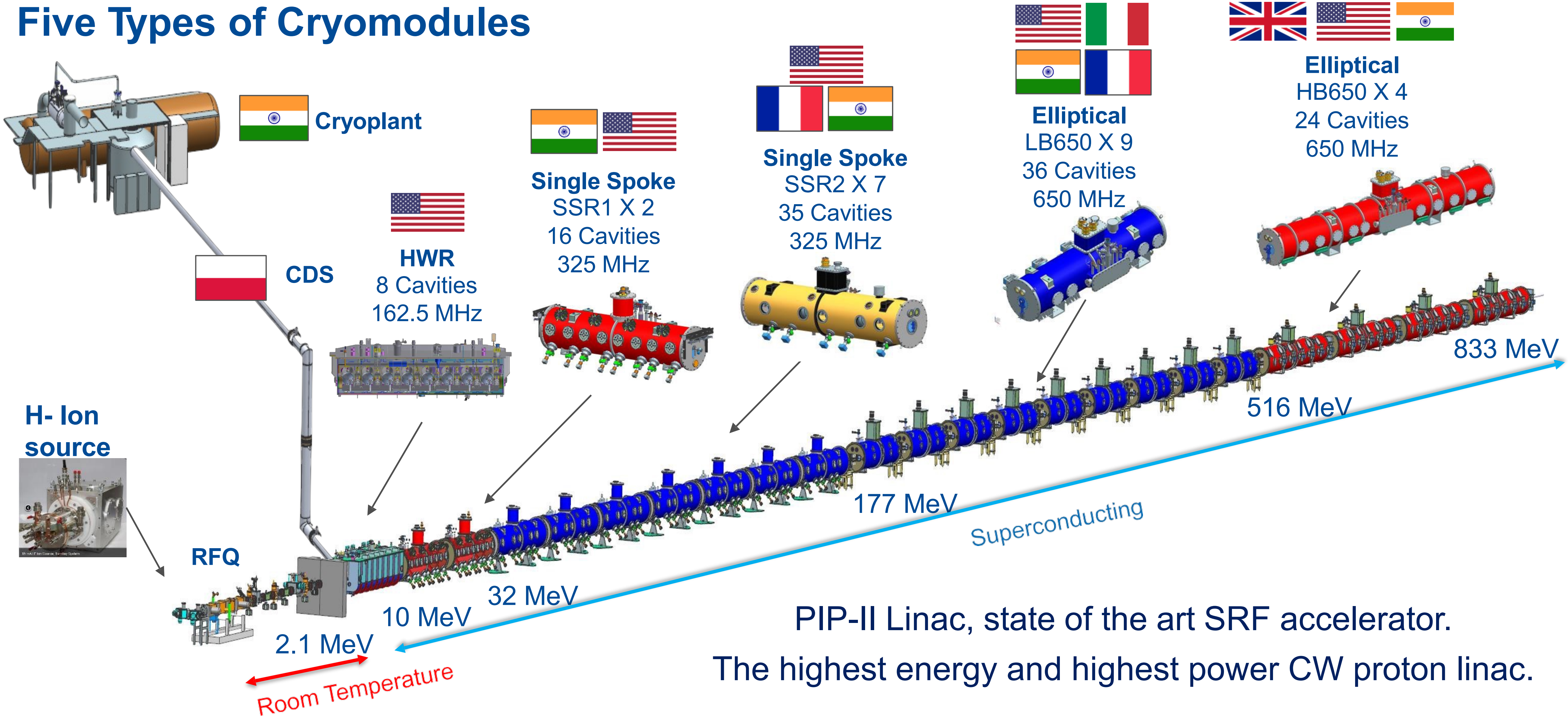
PIP-II at Fermilab

- An 800-MeV superconducting H^- Linac; CW-compatible
- Beam transport of 800-MeV H^- from the SRF Linac to the Booster
- Modifications to the Booster, Main Injector, and Recycler Ring to enable >1MW power on LBNF target
- Associated conventional facilities



PIP-II SRF CW Linac, 2mA, 800 MeV

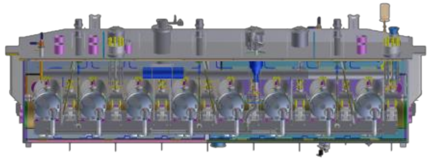
Five Types of Cryomodules



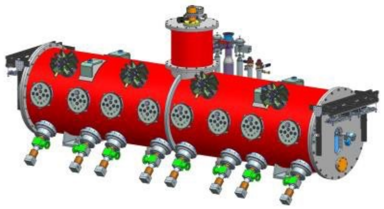
PIP-II Linac, state of the art SRF accelerator.

The highest energy and highest power CW proton linac.

The PIP-II Superconducting RF Systems



5.9 m

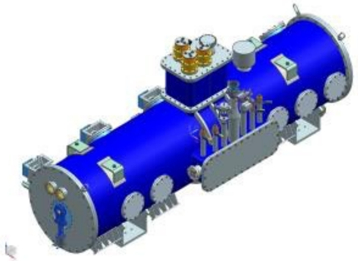


5.3 m

2023

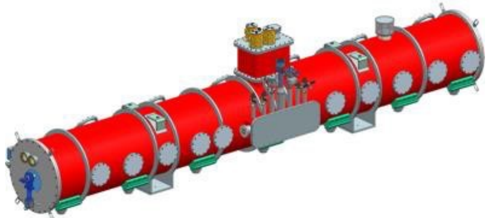
6.5 m

2023

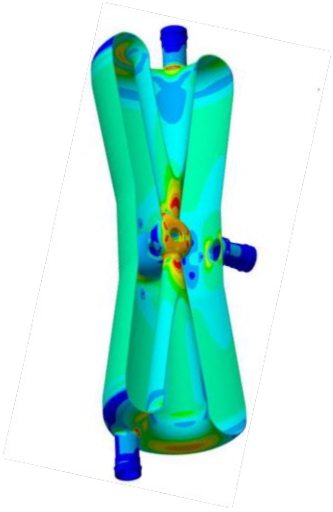


5.5 m

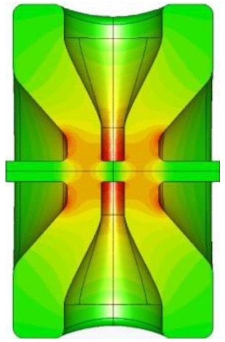
2021-22



9.9 m

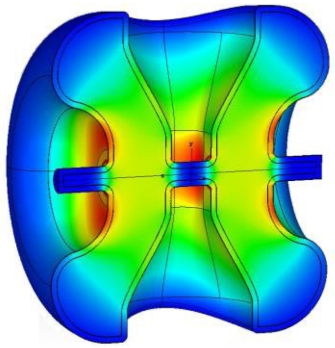


Half Wave Resonator
β=0.11 Q_0 =0.85x10^{10}

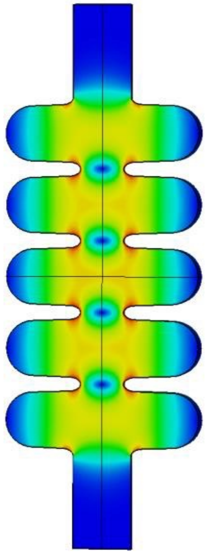


Single Spoke
SSR1
β=0.22 Q_0 =0.82x10^{10}

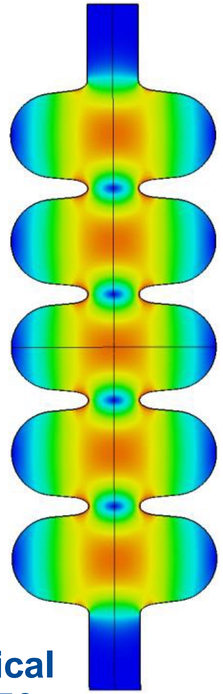
2022



Single Spoke
SSR2
β=0.47 *Q_0 =0.82x10^{10}



Elliptical
LB650
β=0.61 *Q_0 =2.4x10^{10}



Elliptical
HB650
β=0.92 *Q_0 =3.3x10^{10}

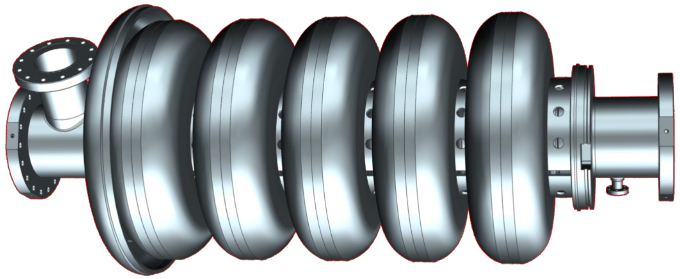
INFN contribution to PIP-II

INFN firstly provided a **novel RF design for the LB650 cavities**, fully plug compatible with the Fermilab technical interfaces and performances specifications.

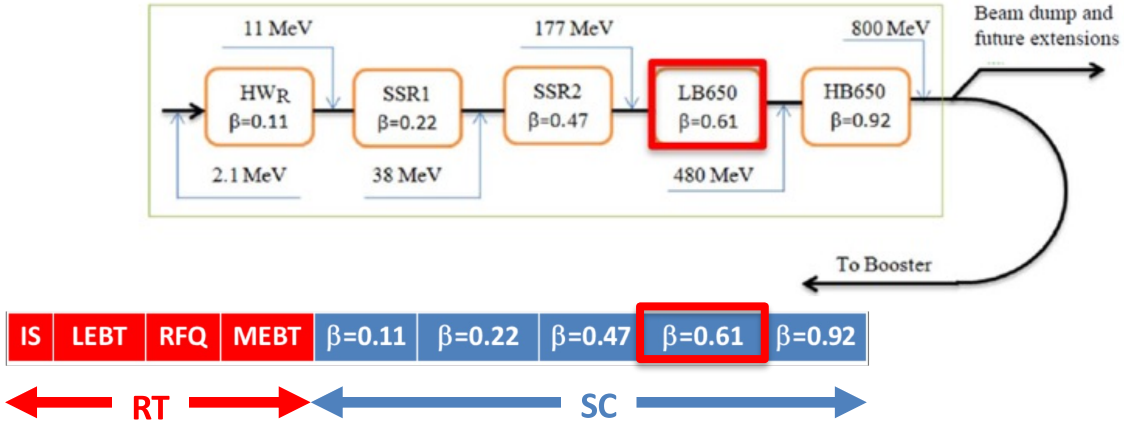
- **Cavity design meets the CW RF performance requirements**

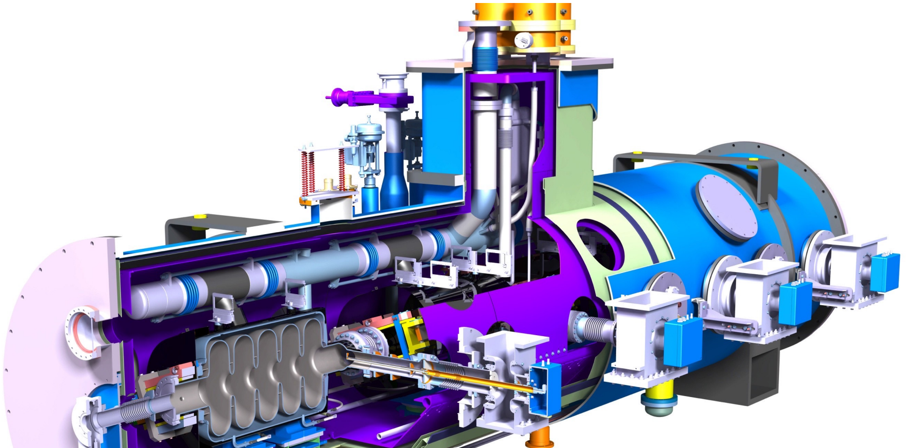
INFN contribution aims to cover the needs of **LB650 section**, and this includes:

- **38 SC cavities** required to equip **9 cryomodules** with 2 spares, delivered **as ready for string assembly**.
- **Qualification** via vertical cold-test provided by INFN through a **qualified cold-testing infrastructure** acting as a subcontractor
- **Compliance** to the **PIP-II technical management plans and interfaces: System Engineering, Project Review, Quality Assurance** and **Risk Management**.



PIP-II LB650 Project Specifications	
Acc. Gradient	16.9 MV/m
Q_0	2.4 10^{10}
RF rep rate	20 Hz to CW
Beta	0.61





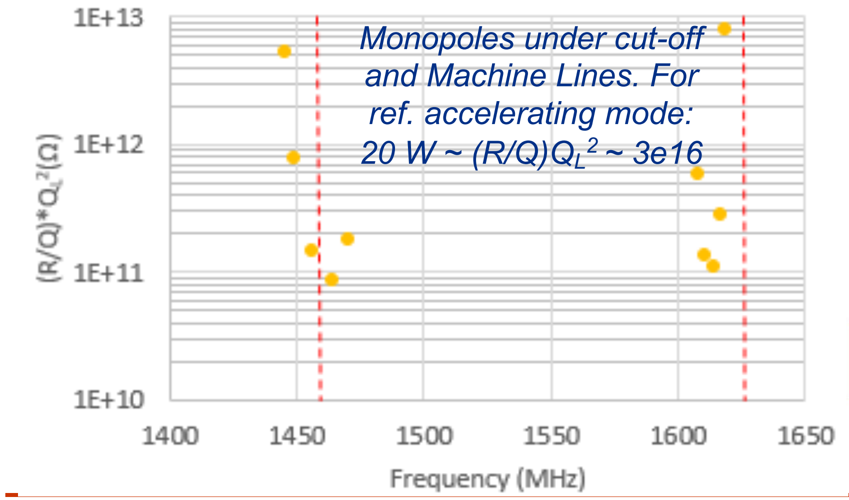
Low-Beta (LB650, b=0.61) cryomodule

Cryomodule picture is a courtesy of Nicolas Bazin, CEA, France

INFN LB650 cavity challenges

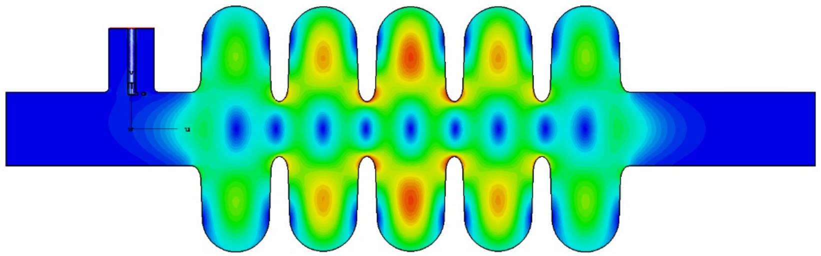
The successful cavity design from INFN-LASA is the result of an interplay of multiple, state-of-the-art competences in **electromagnetic**, **mechanical** and **technical** domains. PIP-II **LB650 cavities** are among the key scientifical **challenges** of the project:

- an **unprecedented quality factor** is required for these resonators.
- Accelerating and **High-Order Modes** must be assessed so that neither instabilities nor additional cryogenic losses are posing critical issues.
- PIP-II operational scenario is **an uncharted territory in terms of detuning control,** and this requires deep understanding of Lorentz Force detuning, pressure sensitivity and mechanical leading parameters as rigidities, yield limits, stresses.
- Detailed finite element analysis to evaluate **compliancy to ASME codes**.



Monopoles under cut-off and Machine Lines. For ref. accelerating mode: 20 W ~ $(R/Q)Q_L^2$ ~ 3e16

High Order Modes analyses. Last mode in 3rd monopole passband, -6.5 MHz away from 10th ML



INFN LB650 for PIP-II, cold cavity	
$\beta_{geometric}$	0.61
Frequency	650 MHz
Number of cells	5
Iris diameter	88 mm
Cell-to-cell coupling, k_{cc}	0.95 %
Frequency separation π-4π/5	0.57 MHz
Eq. diameter - IC	389.8 mm
Eq. diameter - EC	392.1 mm
Wall angle – Inner-End cells	2 °
Effective length (10*L_{hc})	704 mm
Optimum beta β_{opt}	0.65
E_{peak}/E_{acc} @ β_{opt}	2.40
B_{peak}/E_{acc} @ β_{opt}	4.48 mT/(MV/m)
R/Q @ β_{opt}	340 Ω
G @ β_{opt}	193 Ω
Inner cells stiffening radius	90 mm
External cells stiffening radius	90 mm
Wall thickness	4.2 mm
Longitudinal stiffness	1.8 kN/mm
Longitudinal frequency sensitivity	250 kHz/mm
LFD coefficient *k_{ext} at 40 kN/mm*	-1.4 Hz/(MV/m)^2
Pressure sensitivity *k_{ext} at 40 kN/mm*	-11 Hz/mbar
Maximum Pressure *VM stress at 50 MPa*	2.9 bar
Maximum Displacement *VM stress at 50 MPa*	1.5 mm

Thank you for your attention

Carlo Pagani