IFMIF a challenging high-intensity accelerator

20th ICFA Advanced Beam Dynamics Workshop

High Intensity High Brightness Hadron Beams

Fermilab

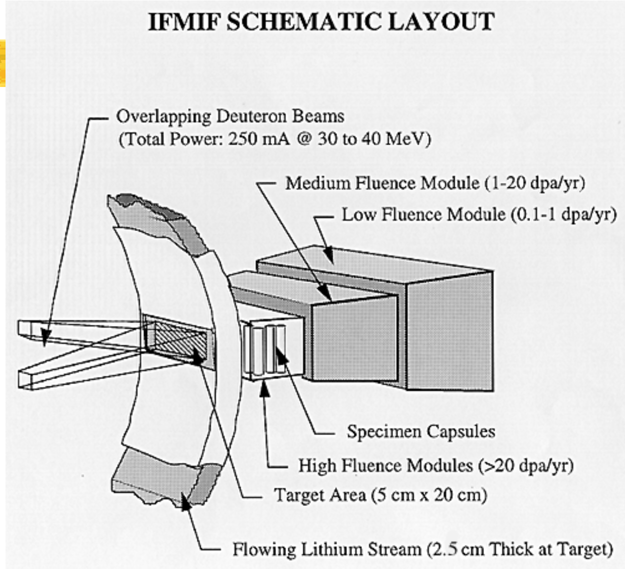
April 8 - 12, 2002

a joint project of EU, Japan,the Russian Federation and the United States of America under the auspices of the International Energy Agency (IEA)

In Europe, under the auspices of EFDA,
contract EFDA 2000/10

Description

- IFMIF : accelerator-based D-Li neutron source
  - production of an intense flux of high energy neutrons
  - sufficient irradiation volume for realistic testing of materials and components up to about a full lifetime of their anticipated use in DEMO and beyond.
  - Must survive exposure to damage from neutrons with energy spectrum peaked near 14 MeV with annual doses of ~20 dpa (displacement per atoms), and total fluences of ~200 dpa.



Neutron Flux	$\geq$ 2 MW/m^2 (@ 500 cm^3)
Operation Availability	70 %
D^+ Beam Current	250 mA (CW, 2 x 125 mA)
D^+ Energy	40 MeV
D^+ Beam Size	200 mm (width) x 50 mm (height)
Li Jet Thickness	19, 25 mm (resp. for 32, 40 MeV D^+)
Li Jet Width	260 mm
Li Jet Velocity	10-20 m/s

Test facility	97.5%
Target facility	95.0%
Accelerator	88.0%
Conventional	99.5%
Central CS	99.5
Total (product)	**80.7%**
online/year	**70%**

Accelerator Team

- Thanks to many participant in many countries:
  - Bob Jameson from USA
  - Horst Klein and his IAP-Frankfurt team
  - Masayoshi Sugimoto and his JAERI Japan team
  - AES people and specially Tim Myers, John Rathke and Chris Piaszczyk *(do not try to pronounce his name !)*
  - CEA-Saclay team

Top level specifications

Requirement	Specification	Details	Comments
Particle Type	D+	H2+ for testing to avoid activation	
Accelerator Type	RF Linac		
RF Frequency	175 MHz		
Output Energy	40 MeV	5 MeV RFQ, 5-40 MeV DTL	32 & 36 MeV Reqm't deleted
Output Current	250 mA	2 accelerators	3 Stages: Phase 1 = 50 mA (1 Accelerator), Phase 2 = 125 mA (1 Accelerator), Phase 3 = 250 mA (2 Accelerators)
Beam Distribution	rectangular flat top	20 cm horizontal x 5 cm vertical on the target	
Output Energy Dispersion	Natural ΔE of beam		Was +/- 0.5 FWHM at CDA
Duty Factor	100%	CW	Pulsed tune-up and start-up
Availability	>0.88 %	during scheduled operation fo 7600 h per annum	>80.7% for overall facility
Maintainability	Hands-on	up to the final bend in HEBT with local shielding as required	design not to preclude capability for remote maintenance
Design Lifetime	40 years		

Cost saving done in 1999

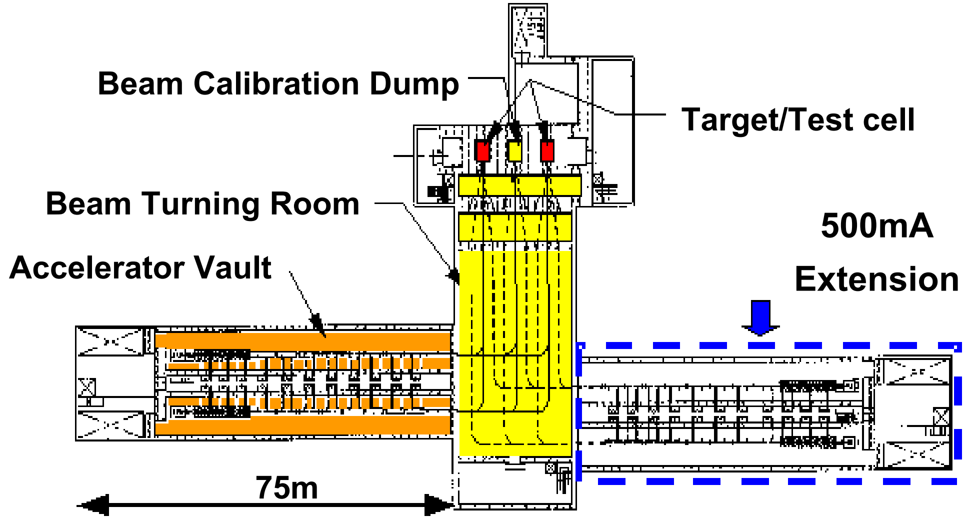
Baseline Design
1996 ($800M)

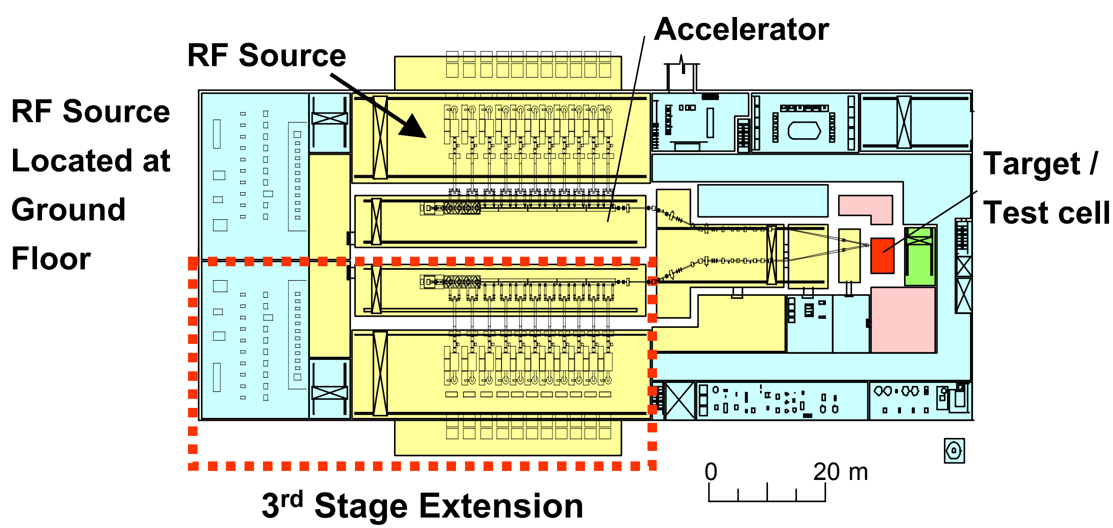
Underground
Floor

Staged Approach
1999 ($490M)

- 1st : 50mA
- 2nd :125mA(RF upgrade)
- 3rd :250mA(2nd Accelerator)

Ground Floor





Accelerator facility

- D^+ beam current generated by two accelerator modules operating in parallel. **RAM is a major concern**
- The two D^+ beams converge on the Lithium target
- 2 modules composed of
  - D^+ source, 150 mA CW @ 95keV
  - RFQ up to 5MeV, CW, 125 mA
  - DTL up to 32 or 40 MeV
  - High Energy Beam Transport
- IFMIF needs 12×2 1MW rf station @ 175MW
- Development and testing of a RF system was identified as the highest impact development item
  - The diacrode will deliver 1 MW CW @ 175 MHz
  - Monitoring of long diacrode test tube (1000h) is under going with success (90hours up to now, CW @ 200MHz, 1MW)

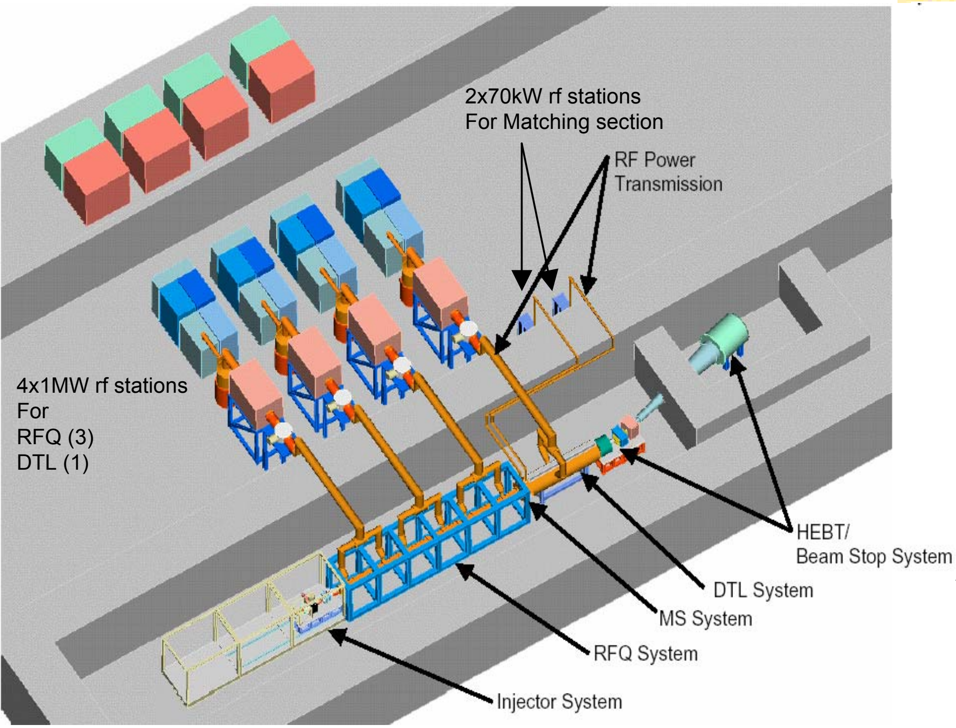
High beam power diagnostics

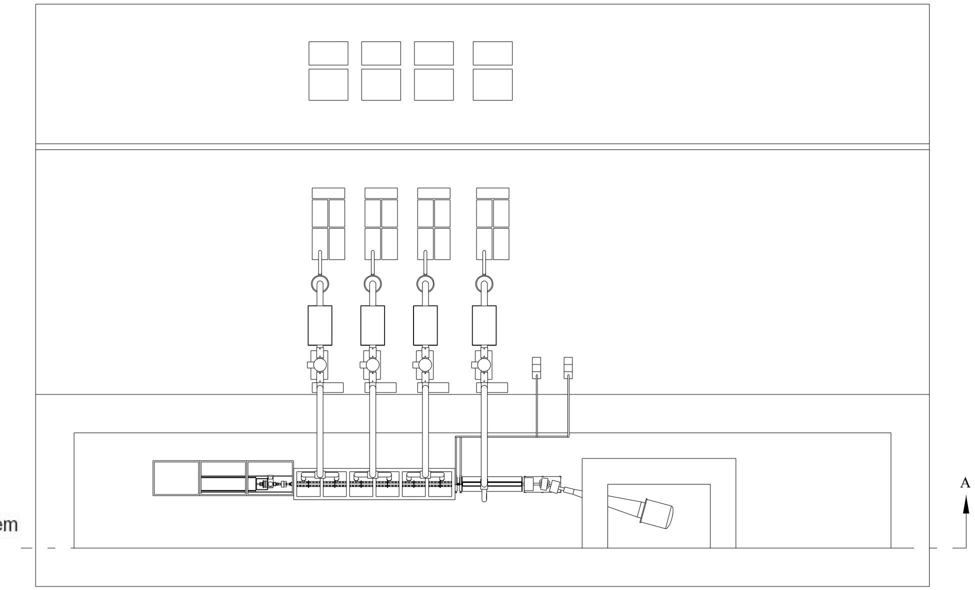
- IFMIF :
  - about 15 kW after the source
  - 625 kW after the RFQ
  - 5 MW in the HEBT after DTL
  - low energy (40 MeV) → deposited in any interceptive diagnostics
- New diagnostics (light analyses, SC, emittance EMU…)

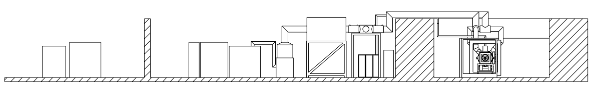
Phasing - Schedule

- KEP (Key Element technology Phase)
- EVEDA (Engineering Validation, Engineering Design Activities) 5 years, could start in 2004 (FPF6 start in 2003)
  - Need a central design team and a site
  - Prototype?
    - Full Performance Accelerator through the first DTL Tank
    - IFMIF Designs have been pursued at Frankfurt and Saclay
    - Best effort to integrate the “most favorable” design into the IFMIF prototype
- Highly depend on ITER decision
- More or less ready to build with a phase I completion in 2010 (50mA)

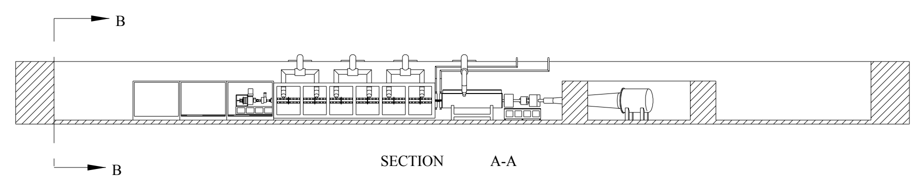
IFMIF Prototype concept







SECTION B-B

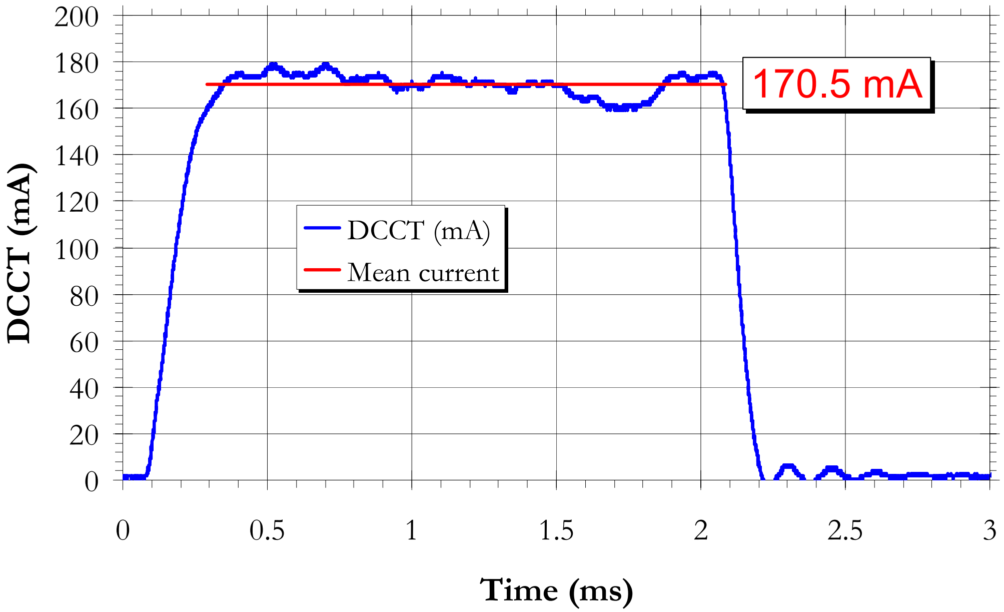


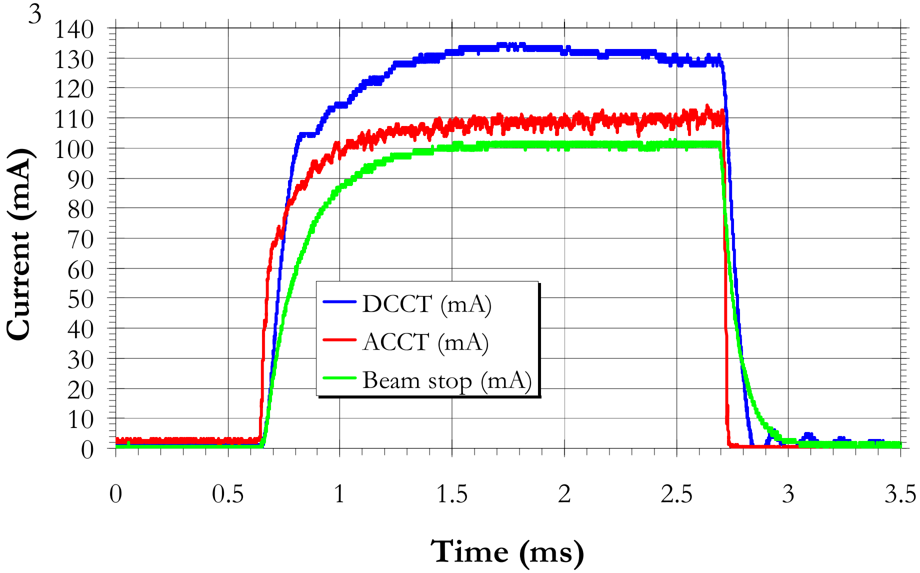
SECTION A-A

Significant Ion Source Progress

- CEA Saclay Source
  - This ECR source produced 95 kV, 70 mA protons with 99.95% availability over 100 hours and 114mA with 99.8% availability over 160 hours (1 spark per day, MTBF=23.1h)
  - Since the design has the RF window behind the bend, there is no electron erosion - no need to change it at all.
  - The source produced deuteron beam
    - To minimize neutron production → pulsed running mode : **2ms/s** (d,D reaction)
    - Experiment done using the 120 mA proton extraction system
    - ***Coherent measurement gives us:***
      - *I > 130 mA (100 kV)*
      - *D^+ > 96 % and D_2^+ < 4 %*
      - *LEBT transparency = 75 %*
      - *rms beam noise = 1.2 % (19 kHz)*
    - Up to 170 mA (267 mA/cm²) !

SILHI performance in D+





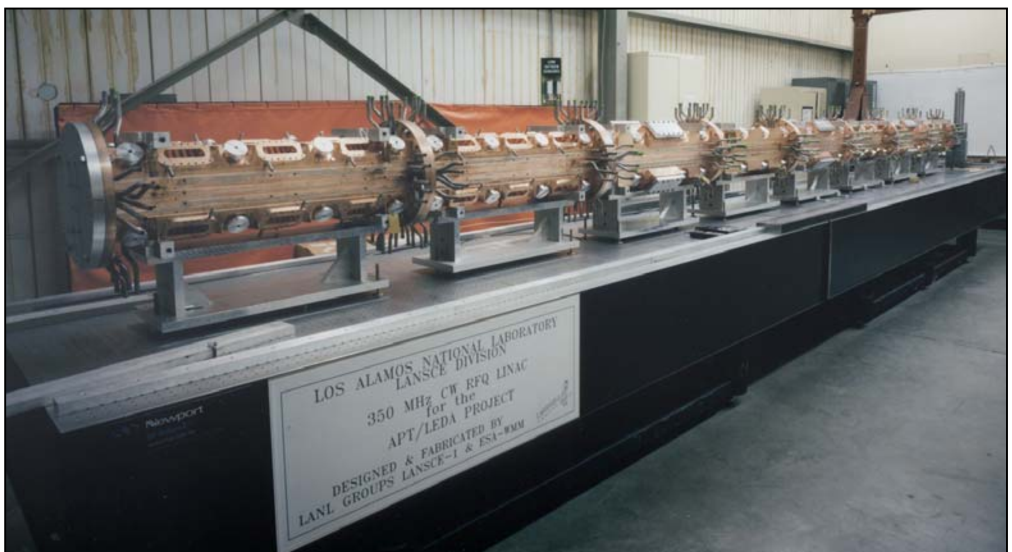
Significant Ion Source Progress

- IAP Frankfurt Source reached also IFMIF design current
  - The volume source produced 200 mA protons (corresponding to 140 mA D^+) in CW mode as well as in pulsed mode (1 msec pulse length, 50 Hz repetition rate) with excellent beam quality and low noise

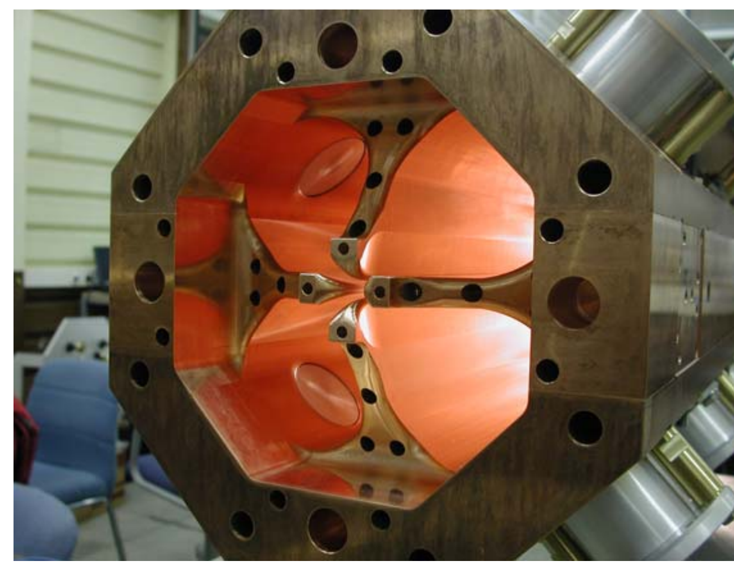
- Parallel testing of 3 ion source candidates on same test stand (same beam extraction system and instrumentation) - at JAERI

RFQ

- 4-vanes RFQ is the reference design (based on LEDA already achieved performances and IPHI developments)
- IAP evaluates the 4-rod type RFQ



LEDA RFQ (LANL)



IPHI RFQ (CEA-Saclay)

RFQ Beam dynamics

Parameters	Values
length	12,498 m
Voltage	106 kV
Peak field	1,82 kp
Minimum aperture	4,41 . . . 5,83 mm
Mean aperture	5,56 . . . 5,83 mm
Modulation	1 . . . 1,52
Frequency	175 MHz
Synchronous phase	-90 . . . -35,25 ř
Input current	130 mA
Input norm. rms ε	0,25 π.mm.mrad
α	2,4
β	14,069 cm/rad
Injection energy	0,095 MeV
Output energy	5 MeV

Table 1: Main parameters

Parameters	Values
Total output current	124,7 mA
Useful output current	124,2 mA
Output norm. rms εx	0,27 π.mm.mrad
αx	-2,56
βx	46,83 cm/rad
Output norm. rms εy	0,27 π.mm.mrad
αy	1,55
βy	24,61 cm/rad
Output rms εz	0,18 deg.MeV
αz	0,01
βz	1225 deg/MeV

Table 2: Main results.

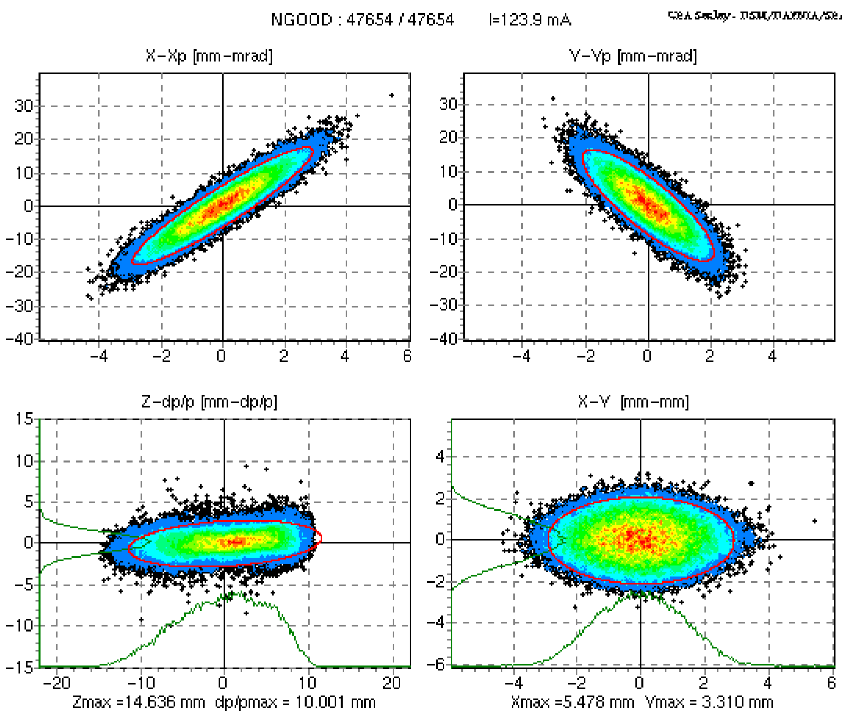
<== Saclay RFQ Design Parameters

Frankfurt EP RFQ Design Parameters ==>

Structure parameter	175 MHz RFQ
Ion	D^+
Design	EP (Jameson)
Number of macroparticles *n*	100,000
Input distribution	4d Waterbag
Frequency *f [MHz]*	175
W_{in} / W_{out} *[MeV]*	0.1 / 5.0
Voltage *V [MV]*	0.111 - 0.151
Kilpatrick factor *b*	1.7
RMS_{in} cells	4
RMS_{out} cells	Crandall cell
Cells / Lenght *[m]*	652 / 12.33
Phase ϕ *[°]*	-90 - -35.27
Input current *[mA]*	140
Output current *[mA]*	130.62
Transmission	93,3%
Modulation *m*	1.00 – 1.73
Input- / Output $\varepsilon^{N,RMS}_{trans}$ *[cm×mrad]*	0.020 / 0.022
Input- / Output $\varepsilon^{N,RMS}_{long}$ *[cm×mrad]*	0 / 0.044

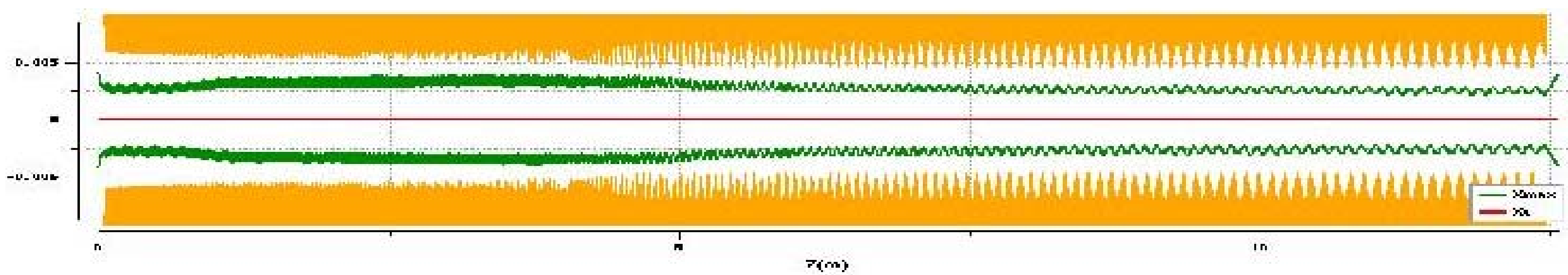
Table of the 1.7 KP IFMIF RFQ from Jameson

SACLAY design using TOUTATIS codes

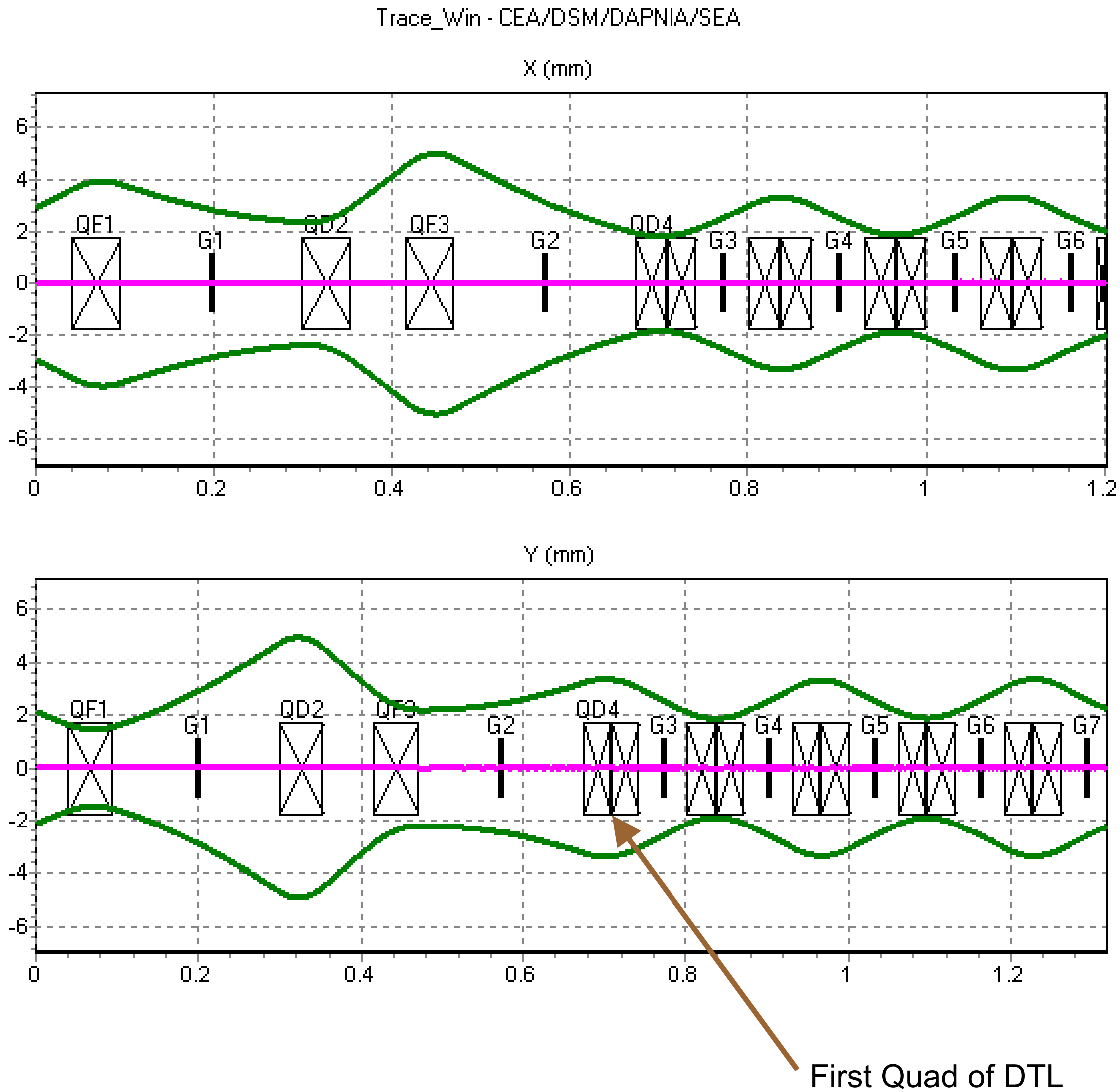


Main parameters

E max	1.82 kp
Voltage	106 kV
Length	12.5 m
Frequency	175 Mhz
Input rms ε (π .mm.mrad)	0.25
Input current (mA)	130
Output Tr. ε (π .mm.mrad)	0.27
Output Lg. ε (π .mm.mrad)	0.45
Output current (mA)	124
Transmission	95.9%



Saclay Matching Section Design



4 quadrupoles and 2 buncher cavities are used, the last quad being the first of the DTL

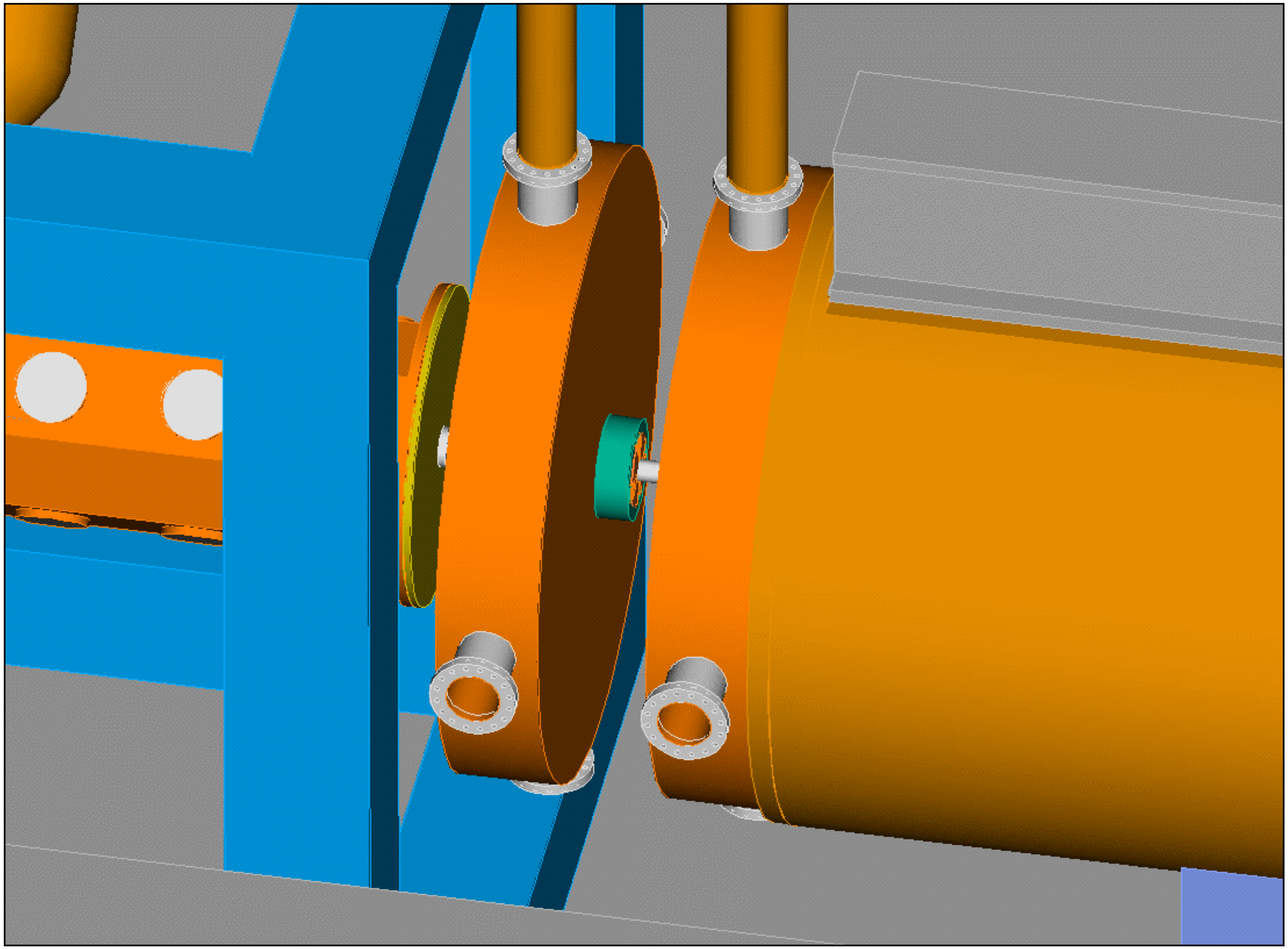
QF1 : 66 T/m, Magnetic length=5.6 cm
QD2 : 82 T/m, Magnetic length=5.6 cm
QF3 : 77 T/m, Magnetic length=5.6 cm
QD4 : 59 T/m, Magnetic length=5.6 cm

Buncher 1->0.178 MV/m Phase –40° Length :12.9 cm
Buncher 2->0.217 MV/m Phase –40° Length :12.9 cm
Buncher working at 175MHz.

Line Length except last quad : 67.33 cm:

RFQ-QF1 =	4 cm
QF1-QD2 =	20.315 cm
QD2-QF3 =	6 cm
QF3-QD4 =	20.215 cm

Matching Section System Layout - Saclay Design



Saclay DTL - 2 Tubes / Tank Design

In order to optimize the global efficiency, we support the idea of using 2 diacrodes per tank. It gives the following design:

Nbr tank	5
Nbr cell	117
Length (m)	26.89
Total length (m)	28.9
Power (kW)	6053
Nbr rf tubes	9

It can be noticed that:

1. There is a gain of one tube, leading to a cost saving.
2. There are also only 4 matching between tanks, instead of 9…
3. There are less cells, since there are less matching sections and therefore less phase losses (Matching is done with the synchronous phase, and lead to losses in term of acceleration)
4. A small gain on the total length is observed

Tank	Nbr cell	Length (m)	Power (kW)	Efficiency (%)	Energy (MeV)
1	32	4.64	678	0.74	9.31
2	28	5.61	1367	0.71	17.08
3	22	5.59	1358	0.72	24.86
4	19	5.66	1367	0.72	32.64
5	16	5.39	1283	0.72	40.07

The first tank uses only one tube (it is already a long tank), while the others use two. Again one cell is removed to stay around the 40 MeV goal.
It can be notice that either the first or the last tank will use only on tube, depending on the energy demand at the end of the linacs (if 32.64 MeV is too low…).

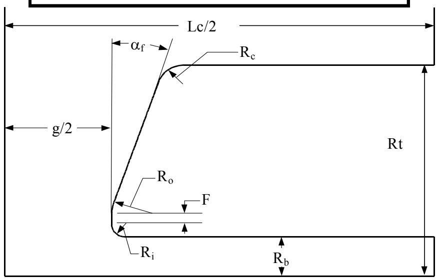
First cell

Including Left Wall
Including 25% marging on Power
Including Stem freq. Shift and Power

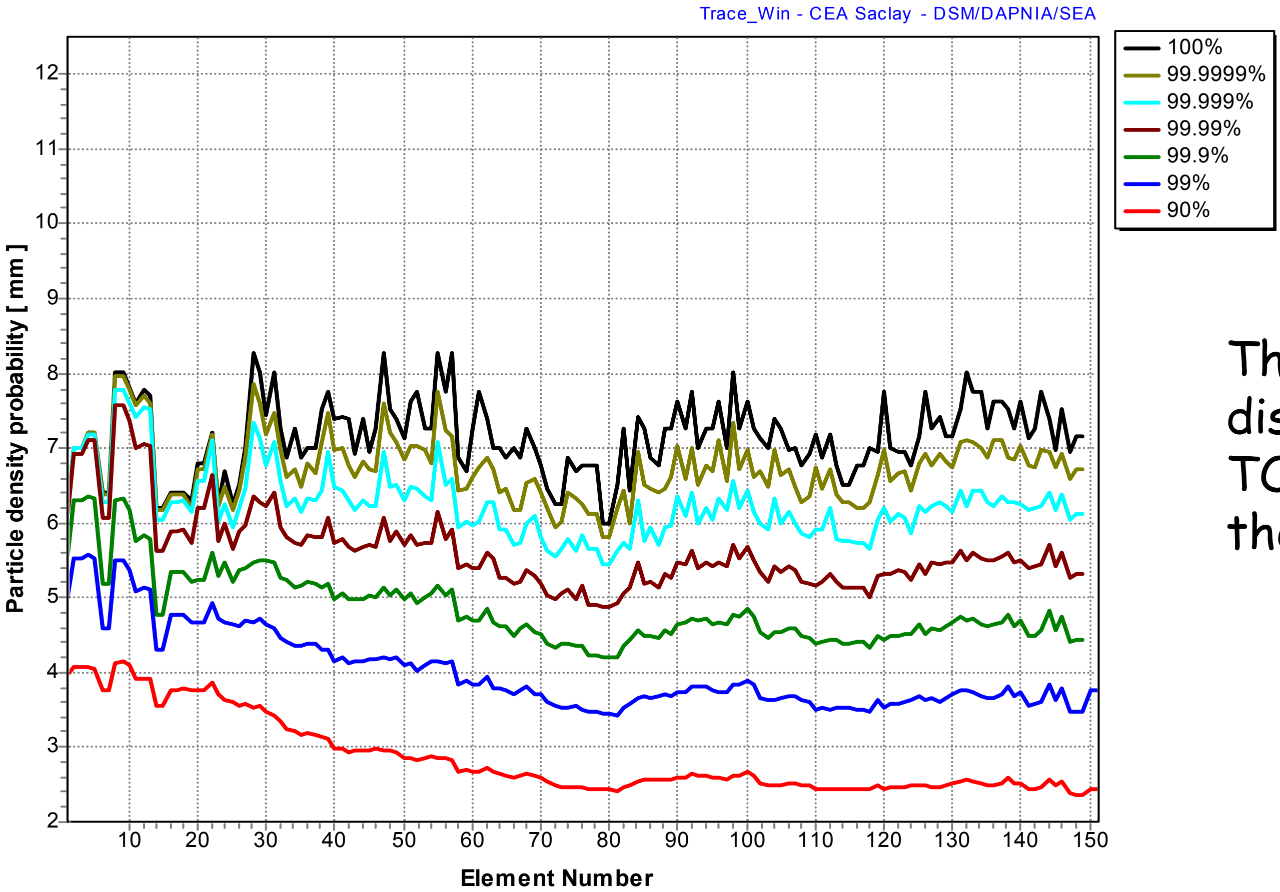
L_c = 12.9046 cm
D = 53.712 cm (inner tank diameter)
Rt = 9.6 cm
R_b = 1.25 cm
R_i = 0.4 cm
R_c = 0.7 cm
Ro = 0.4 cm
F = 0.4 cm
α_f =18.1 degres
gsl = 0.07568

Freq(With stem) : 175 MHz
Eo : 0.5130 MV/m
Emax : 8.036311 MV/m
Kilp : 0.57509
GainE : 0.041911 MeV
T : 0.89531
Zs : 18.184 MOhme/m
ZsT2 : 14.576
Phase Synch : -45 deg
Copper power : 1.8676 kW

Quadrupole Gradient: 75.6 T/m
Quadrupole Length: 7.8 cm
Quadrupole Radius: 6.7 cm



Saclay DTL - beam dynamics



Particle density probability along the DTL
+ matching line

The input beam particle distribution is given by TOUTATIS simulations in the IFMIF RFQ

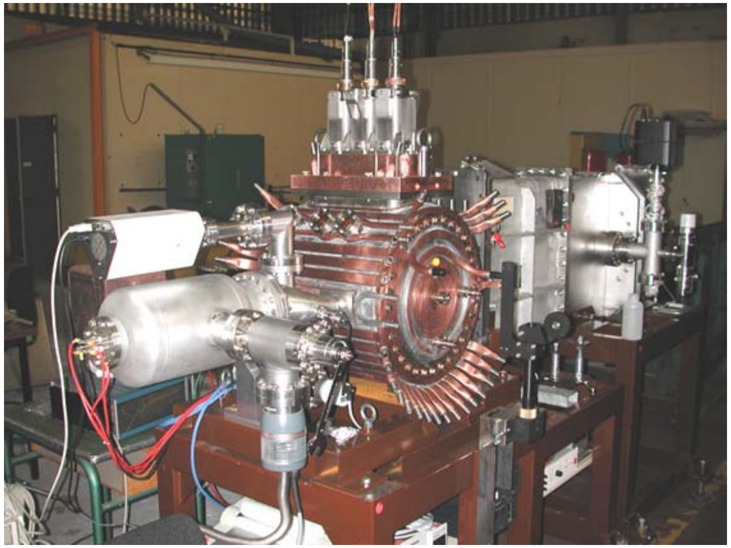
Saclay DTL prototype design

- IPHI 4-cell hot model prototype is being built
- Test the CW, high current DTLs technological feasibility of quadrupole magnet design and fabrication, vacuum problems, cooling, mechanical aspects, etc
- Two drift tubes incorporating two conventional quadrupole magnets have been designed and built. They are of two different types.
- Being even more demanding than the one used in the present IFMIF design

	IPHI		IFMIF	
	1st quad	**37th quad**	**1st quad**	**60th quad**
Gradient (T/m)	64.36	82.39	44	59
Gradient × Magnetic length (T)	3.67	4.70	3.3	4.4
Maximum length (mm)	48.0		70.0	
Maximum outer diameter (mm)	140.0		152	
Minimum aperture (mm)	16.0		25	

	IPHI	IFMIF
Length (mm)	61.76	97.32
External diameter (mm)	170.00	180
Bore diameter (mm)	13.00	25
End cap face angle (°)	4.21	11

DTL prototype



- Quadrupole and drift tube designed by AES and Saclay
- Test to be done soon in CERN
- Methods for Quadrupoles, Drift tube and tanks working in CW mode

	IPHI	IFMIF
Misalignment	± 51 µm	± 100 µm
Transverse rotation	± 0.5 deg	± 0.25 deg
Longitudinal rotation	± 0.3 deg	± 0.25 deg
Gradient	± 0.5 %	± 1%

Quadrupole tolerances

IAP Frankfurt - DTL

- Classical DTL and IH DTL studies

Structure Parameter	Alvarez	
Mass number A	2 (D^+)	
Charge number q	1	
Current I	125.0	mA
Frequency f_{rf}	175.0	MHz
Focusing structure	FODO	
Number of tanks	8	
Average tank length L_T	3.66	m
Drift between tanks $1\beta\lambda$	17.16 – 33.87	cm
Average total power loss per tank $P_{Cu+Beam/T}$	0.726	MW
Average Cu power loss per meter $P_{Cu/L}$	0.0474	MW/m
Injection energy W_{in}	5.0	MeV
Extraction energy W_{out}	40.0	MeV
Total energy gain per meter $W_{tot/L}$	1.12	MeV/m
Number of cells N_c	124	
Cell lenght $\beta\lambda$	12.2 - 34.7	cm
Quadrupole lenght L_q	7.00	cm
Total linac lenght L_{tot}	31.19	m
Electric field amplitude E_o	1.7	MV/m
Effective electric field amplitude E_oT	1.34 - 1.43	MV/m
Synchronous phase ϕ_s	-30.0	deg
Phase before and after drift ϕ_d	-35.0 - -45.0	deg
Rebunching cells per tank n_{rb}	4	
Aperture radius r_o	1.5 - 2.0	cm
Magnetic gradient G	7.00 - 2.40	kG/cm
Magnetic surface field strength B	1.00 - 0.48	T
Gap lenght gl	1.77 - 8.84	cm
Effective shunt impedanz ZT^2	33.90 - 45.18	MΩ/m
Max Kilpatrick factor b	0.90	
Input distribution	6d Wb	
Input- / Output RMS ε^n_{trans}	0.040 / 0.041	cm×mrad
Input- / Output RMS ε^n_{long}	0.080 / 0.082	cm×mrad
Number of lattice periods n_{lat}	62	
Number of macroparticles n	50,000	
Transmission	100	%

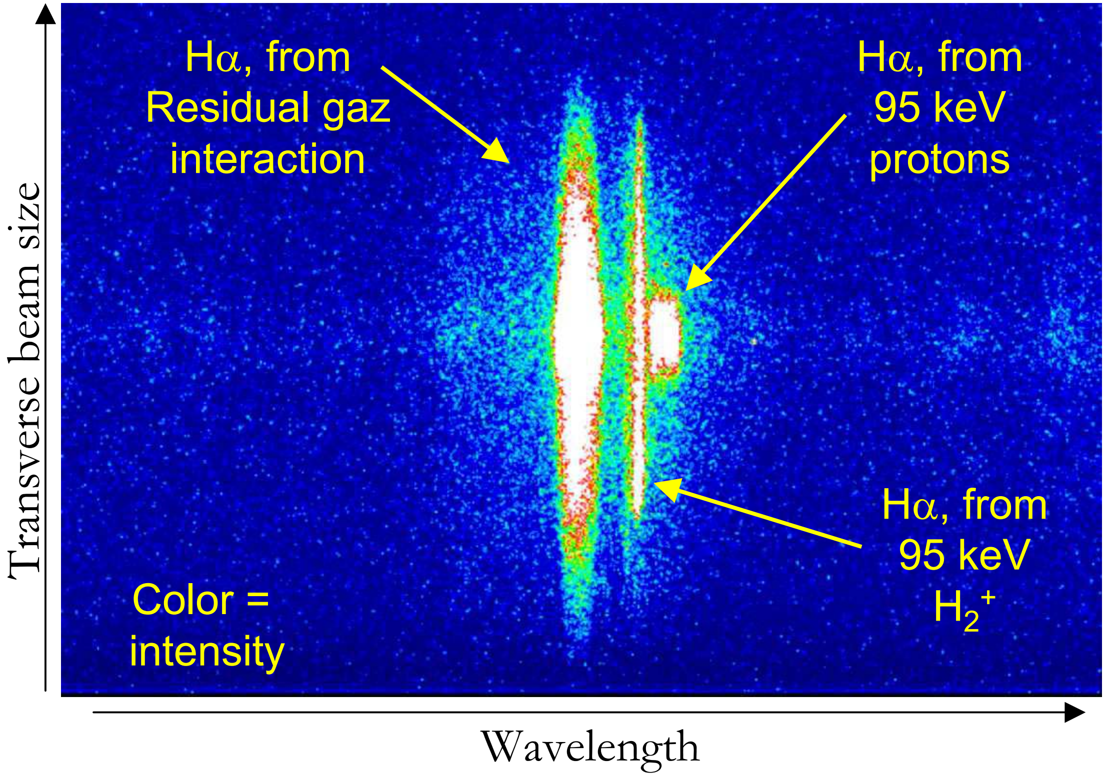
DTL

Structure parameter	IH	
Mass number A	2 (D^+)	
Charge number q	1	
Current I	125.0	mA
Frequency f_{rf}	175.0	MHz
Focusing structure	FDF-DFD	
Number of tanks	10	
Average tank length L_T	1.97	m
Drift between tanks	45.00	cm
Average total power loss per tank $P_{Cu+Beam/T}$	0.536	MW
Average Cu power loss per tank $P_{Cu/T}$	0.095	MW
Average Cu power loss per meter $P_{Cu/L}$	0.0487	MW/m
Injection energy W_{in}	5.0	MeV
Extraction energy W_{out}	40.0	MeV
Total energy gain per meter $W_{tot/L}$	1.51	MeV/m
Number of cells N_c	157	
Cell lenght $\beta\lambda/2$	6.26 - 17.55	cm
Triplet length L_{tr}	19.4 - 35.0	cm
Total linac lenght L_{tot}	23.29	m
Effective electric field amplitude E_oT	1.82 - 0.78	MV/m
Synchronous phase in buncher ϕ_s	-35.0	deg
Number of rebuncher per tank n_{rb}	2 - 6	
Aperture radius r_o	1.5/2.0	cm
Magnetic gradient G	6.55 - 4.76	kG/cm
Magnetic surface field strength B	1.2 - 0.94	T
Gap lenght gl	3.10 - 7.01	cm
Effective shunt impedanz ZT^2	150.00 - 58.27	MΩ/m
Max Kilpatrick factor b	0.43	
Input distribution	4d+2d Hom	
Input- / Output RMS ε^n_{trans}	0.035 / 0.065	cm×mrad
Input- / Output RMS ε^n_{long}	0.070 / 0.098	cm×mrad
Number of lattice periods n_{lat}	11	
Number of macroparticles n	10,000	
Transmission	100	%

IH-DTL

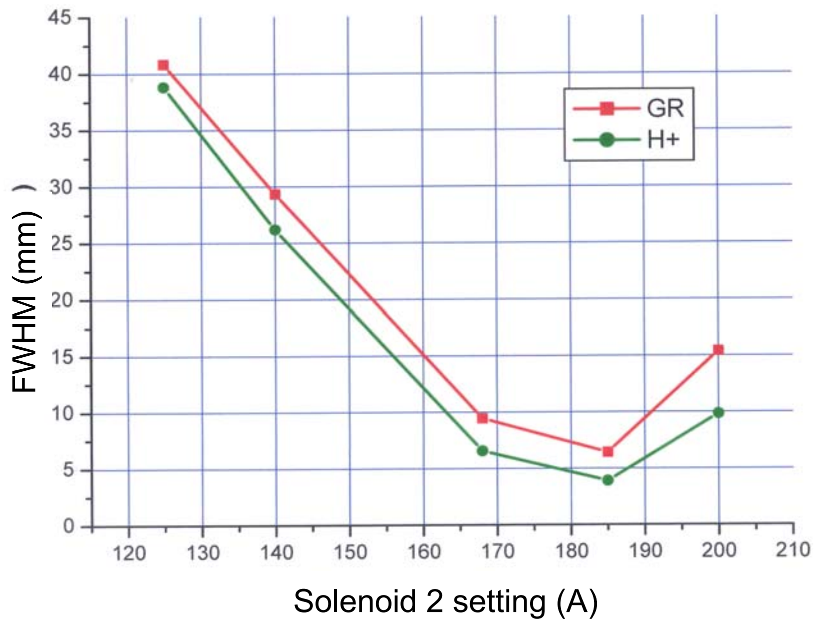
Doppler effect based measurement

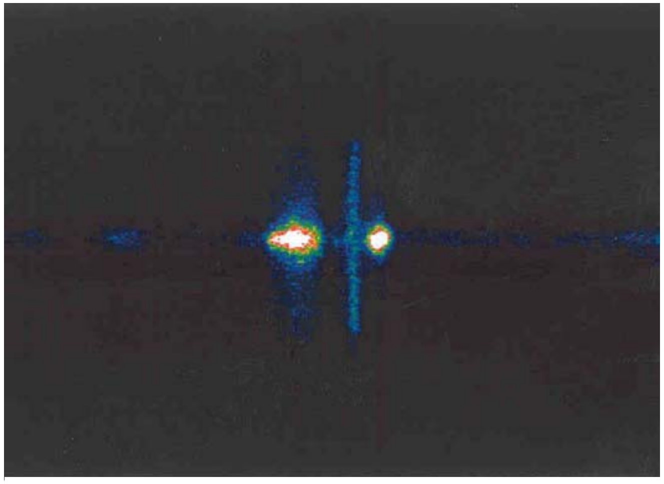
- Emitted light focused on a slit, analyzed through a monochromator set @ 60° of the beam axis.
- Recombination or dissociative recombination of H^+, H_2^+ and H_3^+ particles at 95keV produce Balmer lines
- H_α, H_β or H_γ line analyzed
- Allow uncorrelation of H_2^+ and H_3^+ effects
- Test under different gas injection, beam energy
- Comparison with electrical measurement to be made (difficult)
- Most promising non interceptive measurement



Doppler effect based measurement

- Systematic error as a function of the beam size
- Easy measurement of both H^+ and H_2^+ species





H_β lines for 2 different focalisations